Why the Northern Hemisphere Needs a 30-40 m Telescope and the Science at Stake: Time-domain astronomy

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We outline the science case for a 30–40 m optical/IR telescope in the Northern Hemisphere, optimised for transformative time-domain astronomy in the 2040s. Upcoming multi-wavelength and multi-messenger facilities will reveal fast, faint, rapidly evolving Northern transients whose earliest phases carry decisive diagnostics. A Northern ELT with rapid response, broad wavelength coverage, high time resolution, polarimetry, and diffraction-limited imaging is essential to capture these phases and secure deep spectroscopy and photometry as transients fade. These capabilities will enable recovery of key physical information and detailed characterisation of transient environments, while also enabling unprecedented studies of accretion phenomena at all scales. La Palma uniquely combines atmospheric stability, complementary longitude to ESO's ELT, protected dark skies, and robust infrastructure to host this facility.

1 Introduction and Motivation

Time-domain astronomy in the 2040s will be driven by continuous alert streams from wide-field, multiwavelength surveys and next-generation gravitational-wave (GW; e.g., Einstein Telescope, Cosmic Explorer, LISA) and neutrino detectors. For many faint explosive transients, key signatures are confined to the earliest phases and are rapidly lost as the ejecta expand and cool, making later observations far less constraining. Extracting physical insight from events will thus increasingly rely on optical/IR follow-up within hours of the trigger, when key diagnostic information remains accessible. At the same time, extreme sensitivity will be crucial to probe fainter late-time components and to characterise host environments. Yet, both ELT-class observatories under construction (ESO's 39 m ELT and the Giant Magellan Telescope) are in the Southern Hemisphere (and at nearly the same longitude), from which a substantial fraction of the extragalactic transient sky is obscured by the Galactic Bulge and Centre. Moreover, without a Northern ELT, transients for example in key nearby galaxies (e.g. M31, M33, M81, M82, M101, Arp 299) will be inaccessible or will lack ELT-class sensitivity during their most diagnostic phases. This hemispheric imbalance is further amplified by the fact that many upcoming facilities (e.g. CHORD, ngVLA, LOFAR2.0, CTAO-North) will operate in the North, and IceCube-Gen2 will be most sensitive to up-going neutrinos from the Northern sky.

A Northern Hemisphere ELT with rapid-response capability, broad wavelength coverage, high-time-resolution instrumentation, polarimetric functionality, and advanced adaptive optics (AO) would be transformative for transient studies, while providing capabilities complementary to ESO's ELT. Located on La Palma, such a facility would also offer critical longitudinal complementarity to Chile: it would enable earlier follow-up of fast transients that first reach optimal visibility from La Palma, and extended temporal coverage of rapidly evolving events visible from both hemispheres through coordinated observations as targets transition between the two sites' night-time windows.

The transient classes outlined below are compelling in their own right, but also shape their environments and provide insight into black-hole (BH) formation and growth. Time-domain astronomy thus informs galaxy evolution, chemical enrichment, and even our understanding of the Epoch of Reionisation, making it broadly relevant to the astronomical community.

2 The Science Challenge

Extragalactic transients [*What governs early optical/IR emission in fast transients? Which progenitors and channels produce each class, and how do environment and geometry shape observables? Do fast radio bursts have prompt optical/IR counterparts, and what powers them?*]

Gamma-ray bursts (GRBs) provide direct insight into relativistic jets, compact-object physics, the most powerful cosmic explosions, and their environments (e.g., [1]). Their earliest optical/IR emission encodes diagnostics of jet breakout, photospheric components, energy dissipation, and magnetic-field geometry. These phases remain sparsely sampled, yet they are key for understanding the central engine. Duration alone cannot distinguish collapsars from compact-object mergers: some long GRBs show kilonova signatures, while some short GRBs are from massive-star explosions. Discriminating these pathways requires rapid, deep spectroscopy and photometry within the first hours–days, when kilonova components peak and shift into the IR. A northern 30–40 m telescope would detect these faint, fast-evolving signals out to hundreds Mpc, enabling secure classification and r-process diagnostics via high-resolution IR spectroscopy. GRBs will also be central to multi-messenger astronomy in the era of future GW detectors, which will discover neutron-star (NS) mergers at $z \gtrsim 2$–3, where kilonova emission will be too faint to detect even with an ELT-class facility. For most events, afterglows will thus be the primary means to determine redshift, environment, jet structure, and magnetic-field geometry. A northern ELT with rapid response, NUV–IR coverage, and high-throughput spectroscopy would enable routine early follow-up, delivering early-phase spectra probing dissipation mechanisms and spectropolarimetry constraining jet magnetisation. This capability would make possible systematic GRB/kilonova studies and provide the Northern complement needed to map jet physics, progenitors, and heavy-element production across cosmic time.

Supernovae (SNe). For core-collapse SNe (CCSNe), shock breakout (SBO) is the first electromagnetic signal, encoding information on the progenitor radius, envelope structure, and circumstellar material (CSM)[2]. The SBO emission signatures evolve within hours and peak in the UV/blue (only rarely extending to X-rays), making them largely inaccessible to current facilities. Early-time (<1 d) high-resolution spectroscopy is uniquely diagnostic: transient flash-ionisation lines trace recent mass loss and reveal the kinematics and geometry of the CSM, including binary interaction signatures, but fade rapidly. For thermonuclear SNe (SNe Ia), early spectroscopy can distinguish between single- and double-degenerate progenitor channels and reveal the origin of early flux excesses[3]. For both CCSNe and SNe Ia, early-time polarimetry can constrain ejecta geometry and asymmetries, testing for CSM-induced departures from spherical symmetry. Observations at >300 d, when SNe have faded >3 mag, are currently limited to nearby objects. A 30–40 m-class telescope would enable NUV/optical–IR spectroscopy at these epochs, allowing measurements of progenitor composition, explosion asymmetries, ejecta–CSM interaction, and dust formation. At high redshift, ELT-class IR sensitivity is crucial to use CCSNe to trace the cosmic star-formation history, use SNe Ia to test redshift-dependent evolution and associated cosmological systematics, and identify rare pair-instability SNe from extremely metal-poor (Pop III) stars. In synergy with Northern surveys and next-generation high-energy monitors, a Northern ELT would transform SN studies by linking progenitor evolution, explosion physics, and CSM interaction to finally understand stellar evolution.

Fast X-ray transients (FXTs) encompass a wide range of phenomena and formation channels (e.g., SN SBOs, binary NS mergers, softer analogues of long GRBs, white-dwarf (WD) tidal disruption events, jet-driven explosions from massive stars [4, 5, 6]). Over the past ≈ 1.5 yrs, Einstein Probe has transformed the field by dramatically increasing the discovery rate ($\gtrsim 100$ FXTs reported). This surge in detections and the still small number of securely classified events underscores the need for rapid optical/IR follow-up to access key diagnostics and distinguish among progenitor scenarios: spectroscopy pinpoints redshift and probes the circum-burst environment; multi-band photometry constrains emission mechanisms and colour evolution; and integral-field spectroscopy characterises host galaxies and local environments. In the 2040s, X-ray facilities such as NewAthena and transient-oriented missions like THESEUS and AXIS will provide FXT discoveries for ELT characterisation.

Luminous fast blue optical transients (LFBOTs) are rare, luminous, rapidly evolving events with hot, blue, nearly featureless early spectra [7]. Their bright X-ray and radio emission as well as late-time rapid variability require powerful central engines and dense circumstellar environments, yet their nature remains debated. Proposed channels range from massive-star core collapse with fallback accretion to magnetar-powered explosions, tidal disruptions by intermediate-mass BHs, and exotic compact-object mergers. Discriminating among these scenarios requires rapid, high-S/N spectroscopy to track continuum cooling, emerging features, and ejecta kinematics, together with fast photometry and sensitive polarimetry during the engine-powered phase. A Northern 30-40-m facility can provide hour-cadence spectroscopy for faint events and deep late-time spectra to probe environments and hosts – crucial capabilities as many LFBOTs will be found by Northern surveys.

Tidal Disruption Events (TDEs). The earliest phases of TDEs are key to understand stellar-debris circularisation, accretion-disc formation, and the launch of winds or relativistic jets [8], yet remain largely unobserved. High–S/N spectroscopy during the rise and early peak is required to track photospheric evolution, characterise the ionising continuum, and diagnose fast-evolving line and absorption features signalling outflows. A Northern 30–40-m facility would deliver early, high-throughput spectroscopy of faint, rapidly evolving TDEs at declinations unreachable from southern ELTs, providing the first direct view of disc formation and outflow launching around quiescent massive BHs. Moreover, time-domain surveys will uncover TDEs at higher redshifts, where sources are fainter, offering a unique probe of early supermassive and intermediate-mass BH growth. Spectroscopy will be essential to classify sources and train machine-learning photometric classifiers.

Fast Radio Bursts (FRBs). Despite mounting evidence linking some FRBs to magnetars, no prompt optical/NIR counterpart has yet been detected, likely due to limited sensitivity: current limits reach only ~ 17 mag on ms timescales for extragalactic repeaters and are thus consistent with most emission models. Facilities such as CHORD, DSA-2000, and BURSTT will vastly expand FRB discovery rates in the Northern sky. A northern 30–40 m telescope equipped with ultra-fast photometers would enable ms optical monitoring of repeating FRBs, directly testing whether coherent radio bursts are accompanied by faint optical flashes and placing stringent constraints on emission efficiencies and radiative mechanisms [9, 10]. Diffraction-limited imaging and integral field units (IFU) spectroscopy of host galaxies would link burst properties to their local environments.

Accretion at all scales [*How is angular momentum transported through accretion flows, and how do inflows couple to winds, jets, and magnetic fields across the mass scale? What drives the variability linking accretion and outflows?*] Accretion discs power compact objects from accreting WDs in cataclysmic variables to NSs and BHs in X-ray binaries, and up to supermassive BHs in active galactic nuclei (AGN)[11]. Despite decades of progress, the mechanisms transporting angular momentum and energy in discs (magnetised turbulence, instabilities, winds, and magnetosphere–disc coupling) remain poorly constrained. The key physics is encoded in rapid variability and correlated continuum and line responses, yet many decisive observables (e.g. sub-second variability, evolving line profiles, rapid polarisation changes) remain beyond current sensitivity and cadence, especially for faint systems. A Northern 30–40 m telescope would enable high-throughput, high-cadence optical/IR spectroscopy, photometry, and polarimetry of high-declination targets across accretion state, magnetic field, and mass-transfer rate. In accreting WDs, time-resolved spectroscopy can localise where variability is generated and how it propagates through discs. In NS and BH binaries, the same capabilities would track state transitions, probe disc truncation and wind launching, and isolate synchrotron jet components to map disc–jet coupling. Extending these studies to AGN tests whether characteristic variability timescales scale predictably with mass. Synergy with future Northern radio arrays and high-energy missions would enable coordinated campaigns on high-declination targets, delivering a unified, multi-wavelength view of accretion and outflows from WDs to supermassive BHs, including access to particle acceleration mechanisms in quickly spinning accreting NSs.

3 Capability Requirements for Solving the Challenge

- **Deep sensitivity and rapid response:** A ∼30-40-m aperture enables minute-scale spectroscopy and photometry of transients at $m \approx 23$–25. Achieving this in the earliest and most diagnostic phases requires low overheads, rapid target acquisition, and fast intra-night instrument switching.
- **Broad wavelength coverage:** 0.3–14 μm coverage is required to track SBO continua, high-ionisation emission features, dust-obscured transients, and dust (pre-existing or newly-formed) re-radiation, as well as to probe rest-frame optical/UV emission from high-redshift sources.
- **High-throughput spectroscopy:** Multiple spectral-resolution modes (low/medium for classification; high resolution for CSM and narrow-line diagnostics) are necessary for rapid, information-rich characterisation of transients.
- **High-time resolution capability:** Ultra-fast photometers with kHz–100 kHz sampling rates, sub-ms to μs time stamping, simultaneous multi-band capability, and low-dead-time spectroscopic modes are essential to capture rapid variability, search for FRB optical counterparts, and enable the detection and timing of optical millisecond pulsars.
- **Precision polarimetry and spectropolarimetry:** High-throughput, low-systematics polarimetric and spectropolarimetric modes with rapid modulation are needed to measure evolving magnetic-field geometry, shock asymmetries, and jet/wind contributions in fast-evolving sources.
- **Advanced AO:** Next-generation AO delivering diffraction-limited imaging and AO-fed IFUs are essential to resolve transient environments (particularly those embedded within the nuclear regions of their host galaxies). AO performance at or beyond the ESO ELT level is needed to enable precise host subtraction, localisation, and studies of intrinsically faint or high-redshift transients.
- **Multi-messenger integration & flexible operations:** Seamless integration with alert networks, programmatic ToO triggering compatible with community brokers, and automated priority-based scheduling are critical for time-sensitive events. Quicklook pipelines must deliver rapid classification, redshifts, and data-quality metrics to optimise coordinated follow-up.

4 Summary

In the 2040s, progress on fast, faint, and quickly evolving transients will require ELT-class, minute-to-hour optical/IR follow-up in the Northern Hemisphere. A 30-40 m facility with the capabilities outlined above is essential to access the earliest, most diagnostic phases of explosive, multi-messenger, and accreting events. In combination with ESO's southern ELT, such a facility would deliver near-continuous global access to the transient sky. La Palma uniquely offers the latitude, atmospheric stability, longitudinal complementarity, and protected dark skies required to realise this vision.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake: Shaping Galaxies and Their Stars with Stellar Population Gradients, IMF Variations and Environmental Drivers in Cluster Early-Type Galaxies

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This white paper highlights how stellar population gradients, chemical abundance patterns, stellar initial mass function (IMF) variations, and structural signatures in early-type galaxies (ETGs), measured at faint and large galactocentric radii, out to $\sim 4R_e$*, provide powerful diagnostics of their formation and evolutionary histories. These observables encode the combined effects of early dissipative star formation, subsequent accretion and mergers, and internal feedback processes. Achieving such measurements requires high-signal-to-noise, spatially resolved U-band–optical–near-IR spectroscopy at large radii, with enough spatial resolution to study the variation of these properties on ∼kpc scales. These capabilities can only be delivered by a 30 m-class telescope. Disentangling these internal processes from environmental influences further demands observations of galaxies across clusters spanning a wide range of evolutionary stages and local environments. The nearby Virgo, Perseus, and Coma clusters, without any comparable nearby counterparts in the Southern Hemisphere, offer ideal laboratories for this work. Such observations will place stringent constraints on the formation mechanism of ETGs, connecting local cluster ETGs to their high-redshift progenitors. This white paper outlines several key science cases enabled by such a facility: (1) mapping stellar population gradients across environments; (2) tracing IMF variations as a function of evolutionary stage and environment; (3) reconstructing the three-dimensional structure of galaxies through deep integral-field spectroscopy and imaging; and (4) identifying and studying compact and relic systems as progenitors of present-day ETGs.*

1 Context and motivation

Spatially resolved stellar population gradients in early-type galaxies (ETGs) provide powerful constraints on their formation and structural evolution, especially when studied across diverse environments. In nearby ellipticals, age, metallicity, and abundance-ratio gradients correlate with central velocity dispersion [e.g., 1, 2], reflecting the balance between early dissipative star formation and later internal growth. Although ETGs are dominated by old (> 10 Gyr) stellar populations, with ages corresponding to those of massive ($\log_{10}(M_\star/M_\odot) > 10$) galaxies at $z > 3$ [e.g., 3, 4], their radial variations trace the imprint of feedback, gas accretion, and merger-driven assembly. Radial IMF variations, with M-dwarf–enhanced centers in the most massive systems [e.g., 5, 6], further influence their inferred mass and enrichment histories. Crucially, these processes depend sensitively on the surrounding environment: dense clusters such as Virgo, Perseus, and Coma accelerate quenching, enhance stripping, and modulate accretion and merger rates [e.g., 7]. Small contributions from younger stars [e.g., 8, 9] complicate gradient interpretation, underscoring the need for high-precision measurements in well-characterized cluster settings.

The observed age gradients are mildly positive in the most massive ETGs, consistent with relatively more extended star formation in their centres, but become slightly negative at lower masses ($\log_{10}(M_\star/M_\odot) \sim 10$) [e.g., 10, 11]. Metallicity gradients become steeper with increasing galaxy mass, as traced by central velocity dispersion [e.g., 12, 13], suggesting that remnants of early in-situ formation survive in galaxy cores. The galaxy outskirts (including regions where shells, tidal tails, and other low-surface-brightness features reside) preserve the clearest signatures of environmental processing. Comparisons with compact massive relic galaxies, systems that represent the first phase of two-phase formation and have experienced little to no subsequent accretion [e.g., 14, 2], show significantly flatter metallicity and [Mg/Fe] profiles in typical ETGs. This is consistent with environmentally driven minor mergers depositing chemically evolved, low-[Mg/Fe] material at large radii [15], reinforcing a two-phase formation scenario shaped by internal processes and environment.

However, key questions remain. The partial decoupling of age and [Mg/Fe] gradients, the velocity-dispersion–dependent scatter in [Mg/Fe], all point to additional mechanisms, including IMF variations, affecting ETG chemical evolution [e.g., 16, 17]. While [Mg/Fe] robustly traces enrichment timescales [e.g., 18, 19, 20], much less is known about other diagnostic element ratios, including CO-strong features in the NIR [e.g., 21, 22]. Importantly, [Mg/Fe] has now been measured at high redshift [e.g., 23, 24], providing the opportunity to test whether observed gradients arise primarily from late-time accretion or are established mostly in-situ. Even small fractions of young stars leave strong UV signatures [e.g., 25, 26], making combined multi-wavelength spectroscopy essential for reconstructing both chemical enrichment and star-formation histories.

Recent results from MaNGA [27] indicate that stellar mass surface density, or even local stellar velocity dispersion [28], rather than radial position, predominantly drives the star formation histories within galaxies, with wide-reaching implications for accretion and galactic wind scenarios. Hydrodynamical simulations, however, do not reproduce this pattern [29], highlighting the need to explore these trends across a broad range of environments. Because environmental effects regulate gas supply, merger activity, and stripping efficiency, disentangling in-situ and ex-situ growth requires spatially resolved measurements across diverse cluster conditions [e.g., 30, 31]. To date, existing measurements of stellar population gradients do not reach these low-binding-energy outer regions, typically probing only the inner effective radius with few exceptions [e.g., 32]. As a result, current observational constraints are insufficient to discriminate between competing formation pathways, such as the two-phase scenario, which predicts pronounced changes at large radii, and cannot robustly assess the impact of the environment, imprinted most strongly in the extreme outskirts. Reaching such faint surface brightnesses requires a 30 m class telescope.

2 Mapping Stellar Population Gradients and Galaxy Build-Up Across Cluster Environments and Evolutionary Stages

Studying these processes demands observations extending beyond the effective radius in large galaxy samples, spanning rich clusters such as Virgo (dynamically young and nearby), Perseus (massive and star-forming rich), and Coma (compact, evolved, and dense). Critically, all three benchmark clusters lie in the Northern Hemisphere, with no equivalent ensemble of such nearby, massive, and morphologically diverse systems available in the South, having been extensively studied using 2–10 m class telescopes. These clusters probe a wide spectrum of evolutionary stages and internal environments, from dense cores to infall regions and diffuse outskirts, allowing the response of stellar population gradients in ETGs to both global cluster properties and local environmental mechanisms to be quantified. In this context, simulations predict that local clusters should host the progenitors of ETGs that have largely avoided subsequent accretion, so-called relic galaxies [e.g., 33, 34], although only a few have been identified, primarily in the Perseus Cluster [14]. The absence of spatially resolved stellar population and kinematic studies for these rare systems highlights the need for systematic cluster surveys.

Tracing the high-z build-up epoch of present day ETGs further requires sensitivity to faint spectral features across the U-band–NIR, which encode enrichment timescales and may vary systematically with environment. Discriminating between different models of galaxy formation requires reaching galactocentric distances out to $\sim 4\,R_{\rm e}$ [15], which is the regime where accreted stellar envelopes dominate and the predictions of galaxy formation models diverge [e.g., 35, 36]. Recovering the radial variation of metallicity, [Mg/Fe], and other key species, such as [Na/Fe] and [C/Fe] (see [37]), which together trace the radial chemical enrichment history, along with IMF-sensitive features, is key to disentangling accretion from in-situ enrichment. At $\sim 4\,R_{\rm e}$, surface brightnesses in massive cluster ETGs fall above $\mu_r \sim 25$ mag arcsec^{-2} (even fainter in the NIR), beyond the reach of current 8–10 m facilities.

Northern access to Virgo, Perseus, and Coma ensures coverage of the most diverse and well-studied nearby cluster environments, crucial for isolating environmental effects on stellar population gradients. Combined with advanced integral-field spectroscopy, a 30 m facility will provide the depth, wavelength coverage, and S/N to map gradients continuously from galaxy cores to $\sim 4\,R_{\rm e}$. Synergies with NIR instruments (e.g., EMIR, MOSFIRE) and space facilities (e.g., JWST) will extend the connection to high-redshift progenitors. By linking local cluster ETGs to their compact early-universe ancestors and mapping gradients with unprecedented fidelity, a next-generation 30 m telescope will deliver decisive tests of galaxy formation models and an unparalleled view of how massive galaxies built their stars and metals over cosmic time.

2.1 Galaxy Stellar Population and kinematic Gradients

A multi-wavelength spectroscopic census of galaxy gradients across clusters at different evolutionary stages is essential for distinguishing competing growth scenarios. Gradients in age, metallicity, and elemental abundances encode the interplay between early dissipative processes, internal evolution, and environmental effects. High-S/N (S/N $\gtrsim 40$) spectroscopy at large radii ($R \sim 2$–$4\,R_{\rm e}$) across the U-band–optical–NIR will enable measurements of age- and metallicity-sensitive features, as well as key elemental abundance ratios. NIR stellar population diagnostics such as CO-bands or Na absorption in the K-band are highly sensitive to environment and intermediate-age populations [e.g., 38, 22], while U-band data tightly constrain hot old or young components [e.g., 39]. This combined coverage will refine stellar population models and reveal distinct evolutionary pathways.

2.2 Initial Mass Function Within Galaxies

The stellar IMF governs mass budgets and the chemical evolution of the Universe, gas thermodynamics, star and dust formation, and the build-up of stellar populations over cosmic time. Observations suggest increasingly bottom-heavy IMFs with increasing galaxy mass, and spatially resolved data reveal strong central IMF variations within ETGs [e.g., 5]. Testing whether the IMF correlates with environment requires deep spectroscopy ($\mathrm{S/N} \sim 50-100$) near $\sim 1\,\mu$m, where IMF-sensitive indices reside, and must reach the low-surface-brightness outskirts at $\sim 4\,R_{\mathrm{e}}$; such observations are only feasible with 30 m class telescopes. The Virgo, Perseus, and Coma clusters provide ideal laboratories to probe IMF variations across diverse environments, both within and among clusters, and to link IMF gradients with local star-formation conditions.

2.3 Extreme Laboratories of Cluster-Driven Evolution

Rare massive compact relic galaxies, local analogues of high-redshift red nuggets [e.g., 40], preserve ancient stellar populations, making them key probes of early formation. Their survival and evolution depend strongly on environment: dense cores may shield or erode them through tidal interactions. Conversely, lower-mass compact systems trace dynamical stripping and cluster tides. Deep spatially resolved spectroscopy across the full mass range, combined with gradient and IMF measurements, will elucidate the interplay between in-situ and environmental processes, revealing the diversity of evolutionary pathways in clusters and the role of environment in shaping galaxy structures.

2.4 3D Views of Cluster Galaxies: Towards High-Precision Cosmology

Integral-field spectroscopy and deep imaging enable reconstruction of the 3D structure of cluster galaxies by linking stellar populations, kinematics and morphology. Access to faint outskirts (including shells, tails and streams) provides evidence of past interactions, mergers and stripping. Combining structural diagnostics with stellar population and IMF gradients, reaching the semi-resolved regime, will provide a holistic view of galaxy build-up across environments, while mapping mass profiles and orbital anisotropies will inform dark matter models and allow high-precision cosmology.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake: Cosmology and High-z Universe

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Full sky coverage with 30-40 meter-class telescopes is essential to answer fundamental questions in Astrophysics, Cosmology, and Physics, such as the composition of the Universe and the formation of the first stars and supermassive black holes. An ELT/TMT-like telescope in the Northern Hemisphere is a fundamental and necessary facility to provide multiplexing of observing power, diversity of instrumentation, rapid response, and statistical power required to address the questions and the problems, current and future, unveiled by full sky observatories such as JWST, Euclid, or Roman space telescopes. The Northern ELT/TMT will expedite the study of unique, extreme, rare, transient, and/or high-energy events which will give the most information about fundamental Physics problems in the era of multi-messenger and time-domain Astronomy.

1 Introduction: Cosmology challenges

The composition of the Universe and the origin of the first stars, supermassive black holes (SMBHs) and galaxies after the Big Bang, are two of the most fundamental questions of science. This paper argues that the deployment of an extremely large optical/infrared telescope (30-40 meters diameter) in the Northern Hemisphere would transform our ability to answer these questions.

The composition of the Universe. In order to explain astronomical observations, our cosmological model posits that 95% of the mass-energy budget of the Universe is composed of so-called Dark Matter and Dark Energy. Dark matter is hypothesized to be made of particle(s) beyond the standard model of Particle Physics that do not interact with light, and are likely massive and non- or weakly interactive ("cold" dark matter; CDM). So far, CDM has eluded direct or indirect detection in ground based detectors and accelerators, while astronomical observations have set limits on its properties such as abundance, self-interaction and baryonic cross section, and free streaming length [3, 5]. Dark energy is responsible for the accelerated expansion of the Universe during the past few billion years. Recent observations by the DESI experiment suggest that Dark Energy may not be as simple as the cosmological constant (Λ), but it may be a dynamical quantity. The discrepancy between the current expansion rate of the Universe and that predicted in standard cosmology from early Universe probes, known as the "Hubble Tension" [21], could require further additions to the cosmological model, such as, for example, an early dark energy phase or new particles. As we will discuss in the next section, a 30-40 m telescope in the Northern Hemisphere would enable breakthroughs in the identification of the dark matter particle(s), the clarification of the nature of dark energy, and the resolution of the Hubble Tension.

The dawn of galaxies and SMBHs. In the dark matter - dark energy (ΛCDM) cosmological model, galaxies arise hierarchically from primordial fluctuations enhanced by gravity over cosmic time. However, we still do not know how and when the first stars and galaxies formed. Furthermore, although SMBHs are found ubiquitously at the centers of nearby galaxies, it is not known whether they form from stellar remnants or from direct collapse, and whether they predate or co-evolve with galaxies. A parallel and profound question is whether primordial black holes (PBHs) also exist, what is their mass spectrum and what are their connections with the dark sector and Cosmology.

The existence of very massive galaxies at early cosmic epochs, assembled in an anti-hierarchical way rather than following the bottom-up evolution of dark matter halos, has been known for more than two decades now [7]. Although early results from JWST reporting over-massive galaxies at $z = 7-9$, which would have formed more stars than possible based on the current cosmological paradigm [4], have been discarded, other results still challenge our view of the early Universe. These might have implications on the ΛCDM paradigm, even requiring new Physics such as non-standard dark matter, new particles, modified gravity, varying fundamental constants, and/or dynamical dark energy. Among those challenging results, we highlight the abundance of galaxies with strong emission in the rest-frame ultraviolet (typically a strong continuum and some relatively faint lines) discovered by JWST in the first 500 Myr of cosmic history, which exceeds expectations of galaxy formation simulations by at least an order of magnitude. The results have been achieved with different datasets, by different teams around the world, and have been corroborated after confirming the high redshift nature of many galaxies with spectroscopy (see references in [1]). The current redshift frontier is $z \sim 14.5$, i.e., galaxies that existed just 280 Myr after the Big Bang [16]. Photometric candidates now exist up to $z \sim 25$ [17] and even $z \sim 30$ [9], which would place the end of the Dark Ages just 100 Myr after the Big

Bang. Possible explanations for this higher than expected abundance of $z \gtrsim 10$ galaxies rely on baryon physics, e.g., invoking feedback-free starbursts in primeval galaxies, resulting on higher star formation efficiencies and possible quick metal enrichment and dust production and/or a distinct Initial Mass Function in the early Universe (e.g., [6]). Other alternatives could have more fundamental implications about the distribution and nature of dark matter [2, 23, 24, 18, 19, 13].

The question about the nature of dark matter links to a second problem with strong cosmological implications and of fundamental origin in Astrophysics. A physical explanation is needed not only for the high abundance of high redshift galaxies, but also for the ubiquity of active galactic nuclei in the early Universe found by JWST [11], with a special attention to a newly discovered type of objects called Little Red Dots (LRDs; [15]). The origin of SMBHs, their seeding in the early Universe [10], their influence and, maybe, prominence over star formation at early epochs, and the possible link to PBHs [14], most probably have strong implications on the foundations of Physics in the Universe.

2 The need for a 30-40-meter class telescope in the North

The fundamental problems outlined in the previous Section can be addressed through the observations of the distant Universe, but they require higher sensitivity and finer angular resolution than what is enabled by the most powerful telescopes currently operating, including all the top-of-their-class facilities, namely, VLT, Keck, GTC, JWST, and ALMA (see Section 3).

Answering these questions was one of the key scientific drivers of the ESO European Large Telescope (ELT), currently under construction in Chile. We argue that building a comparable (30-40 m diameter) Extremely Large Telescope in the Northern Hemisphere will transform the landscape by enabling access to the entire sky, improving time domain coverage, allowing for independent verification of fundamental results, and providing complementary scientific capabilities, enabling transformative science to solve the open cosmological questions.

In the nearby Universe (from the Solar System to the Local Group and vicinity), the benefits of full sky coverage are obvious, enabling observations of unique targets. In the distant universe, the Cosmological Principle ensures that there is no preferred direction and therefore no strictly unique targets. However, in addition to intrinsically rare targets, there are multiple scientific reasons that make full-sky coverage much more valuable than a single hemisphere. Those include:

- First of all, discovery of new physics requires extraordinary proof. Having two telescopes to carry out independent experiments with different instruments, approaches and techniques will be key to convince the community that indeed new physics might be required.
- Unique, extreme, rare, transient, and/or high-energy events are the most promising to provide answers to the fundamental questions presented in the Introduction. Among these special events, we can mention high redshift pair instability supernovae from Population III stars, electromagnetic counterparts or hosts of Gravitational Waves (GWs) sources, implications of high-energy neutrinos, gamma ray bursts at $z > 10$ from early stars, and lensed type Ia supernovae. These events probe the seeding and early evolution of stars and SMBHs. In addition, rare and extreme events include powerful cosmological probes such as standard clocks (gravitational lensing time delays), standard candles (high-z supernovae), and standard sirens (counterparts to GWs).

  The list of source types presented above point to the fact that the key in the next decades to probe the composition of the Universe will be multi-messenger time-domain astronomy. Identifying and following-up observations of GWs with observatories such as LIGO, GEO600, VIRGO, KAGRA, the Einstein Telescope, LISA and/or neutrino sources (e.g., those detected by ICECUBE - which are mostly in the North) will require full sky coverage to avoid missing (some of) the most interesting sources among the few events expected every few years. The combination of ELTs in Chile and a 30-40 m class telescope in the North (e.g., in La Palma) will provide a long longitudinal baseline for intra-day time domain astronomy of sources visible from both telescopes. Even though one telescope such as ELT can observe around two thirds of the sky at high enough elevation, at least one observatory in each hemisphere is needed to follow-up intrinsically (rapidly) variable sources for long enough times. We remark that studying the (strong and/or quick) variability of this kind of sources is essential to understand their nature.
- Ongoing and future missions such as JWST, Euclid and Roman, are not restricted to a single hemisphere. Full sky, fast-response follow-up spectroscopic capability for long-enough periods with a 30-40 m telescope is crucial for fully exploiting these datasets. In

particular, nearly continuous observations of the equatorial belt could be possible with a 30-40 m class telescope in each hemisphere.

The uniqueness of some astronomical objects only accessible through an observatory covering the Northern sky is currently demonstrated with sources such as the highest redshift active galactic nuclei, GNz11 [12], the earliest example of a galaxy where a highly embedded SMBH is clearing its host galaxy's ISM and quenching star formation, GNz7q [8], and the prototype of dusty starburst galaxies HDF850.1 [22], which is supposed to be the main phase in the formation of the largest galaxies known in the local Universe (i.e, ellipticals). This is in part related to the unique fields accessible only from the North, such as the original Hubble Deep Field (extended to the GOODS-N field) or the North Ecliptic Pole field (very important for time-domain observations).

There are other important reasons, at the instrumental and operations level, that also justify an investment in a 30-40 m class telescope in the North:

- Having a second 30-40 m class telescope would also help with diversifying the array of instrumentation, opening different discovery spaces, and doubling, at the very least, the discovery power. This strategy has been shown to be very effective in the four VLTs. In this sense, we remark that ELT is designed to use fully adaptive optics (AO) in a relatively large FoV and optimized for near-infrared observations. Other optic configurations could favor higher Strehl ratios over smaller field of views in the near-IR AO, and be optimized for UV/blue wavelengths in seeing-limited mode.
- A pair of telescopes with full sky coverage would enable coordinated Key Programs, with large amounts of time devoted to answering some of the most fundamental and pressing questions, optimizing targets and instrumentation.

3 Capability Requirements for Solving the Challenge

Pushing the frontiers of high redshift science requires breaking barriers in sensitivity and angular resolution, especially for spectroscopic observations. As demonstrated once and again, and most recently by JWST, dramatic improvements in sensitivity lead infallibly to new discoveries. A few examples of the discoveries that require a 30-40 m class telescope are given below:

- To resolve the sphere of influence of the largest SMBHs at virtually any distance/redshift, thus enabling the most direct and reliable measurements. Current telescopes (JWST, VLT, GTC, Keck) do not have sufficient angular resolution.
- To measure narrow line flux ratios and stellar kinematics of distant gravitational lenses to constrain the nature of dark matter and dark energy [e.g. 20, 25]. It would also allow detailed studies of the extreme physical conditions of the early star-forming galaxies with high SNR, e.g., nebular vs. stellar continuum, intervening HI Damped Lyman-α absorption, ionization condition from UV spectral features. Current telescopes do not have sufficient angular resolution and sensitivity.
- To resolve the internal structure of galaxies at Cosmic Dawn and Noon to study their internal structure and (dark, baryonic) mass content, which are currently barely resolved with JWST and require a 30-40 m class telescope.
- To observe the electromagnetic counterparts to GWs and high-energy neutrinos will require 30+-m telescopes for spectroscopy, being too faint and ephemeral for the $<$ 10-m class.

More details on the science case and requirements for the study of the composition of the Universe and the dawn of galaxies and SMBHs can be found in the science case documents for ELT and for TMT.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake.
How do Planetary Systems Form?

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Current facilities have revealed the diversity of exoplanets around mature stars and the complex structures of protoplanetary disks around young stars, yet we lack the crucial observational link between them: a statistically meaningful census of protoplanets caught in the act of formation. Such a breakthrough requires a 30-40 m telescope that complements the ELT by covering the Northern hemisphere. That is key to obtaining diffraction-limited imaging of protoplanets and disks across the entire sky, enabling robust demographics, leveraging synergies with other observatories covering the North, and ensuring that Europe remains at the forefront of the planet-formation revolution in the coming decades.

1 Scientific context

Thousands of exoplanets have been discovered since a planet around a star other than the Sun was first detected 30 years ago by the Nobel laureates [1]. Instrumental developments and telescopes covering both hemispheres (Fig. 1, left) have revealed the extraordinary abundance and diversity of the exoplanet zoo, which has changed our vision of Earth's place in the Universe. Nevertheless, almost all known exoplanets orbit around mature stars mostly in the main sequence (MS) phase. Consequently, our understanding of planet formation is incomplete as it is empirically based on already formed planets on the one hand, and the gas and dust properties of protoplanetary disks - the sites of planet formation - on the other. In particular, how and when dust grains and pebbles grow into planetesimals and planets, or the exact mechanisms driving early orbital migration, remain poorly understood [2]. The heterogeneous characteristics in terms of, e.g., initial structure, composition, and lifetime of protoplanetary disks with rings, gaps, spirals, and arcs/crescents, also present significant unknowns whose specific influence on planetary system outcomes is not yet clear [3, 4]. In short, we are still far from establishing a clear connection between the widely diverse protoplanetary disk's properties and the observed exoplanet populations.

The key missing piece to bridge the previous gap is establishing a solid observational census of protoplanets forming in disks around young stars. Only recently we have started to detect this type of forming planets (Table 1). Thus, the detection and characterization of protoplanets in disks is an emerging field that is taking off now and will represent a major revolution during the coming decades. The Extremely Large Telescope (ELT) will undoubtedly revolutionize protoplanet studies even with its first-light instruments [e.g. 5, 6], owing to its exquisite sensitivity and angular resolution reaching the mid-IR regime and capable of resolving the finest structures in protoplanetary disks. However, the low latitude of the Cerro Armazones observatory will inevitably leave half of the most relevant targets poorly covered or inaccessible. This white paper argues that this is not a trivial geographical issue, and that a 30-40 m telescope is also necessary in the Northern hemisphere for Europe to stay at the forefront of the planet formation revolution.

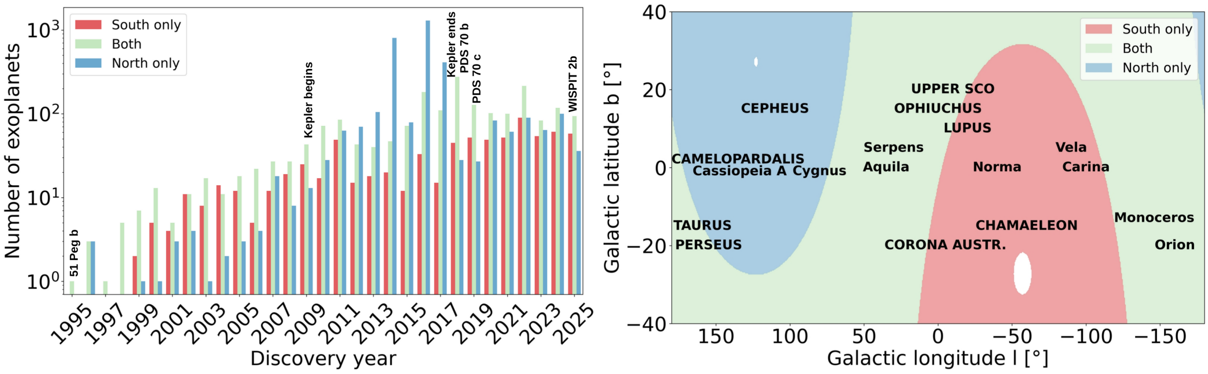

Figure 1: **(Left)** Exoplanet discoveries through the years (from the Encyclopaedia of exoplanetary systems; https://exoplanet.eu/). **(Right)** Galactic coordinates of the main star forming regions. The closest ones partially or totally located at distances $\leq$ 300 pc are indicated with capital letters. **(Both)** The colour code indicates whether the sources can be observed only from the South (declination $\delta \lesssim$ -31°), only from the North ($\delta \gtrsim 35°$), or from both hemispheres. The Cerro Armazones and La Palma observatories are taken as reference, assuming that a source cannot be observed for elevations $< 30°$. Roughly half of the exoplanets and protoplanetary disks can be better or only covered from the North.

Table 1: Representative subsample of confirmed and main candidate protoplanets

Name	Observability	Host	Discovery Technique	Status	References
PDS 70 b, c	S	T Tauri	AO spectro-imaging	Confirmed	[7, 8]
WISPIT 2b	S & N	T Tauri	AO Imaging	Confirmed	[9]
IRAS 04125+2902 b	N	T Tauri	Transit	Candidate	[10]
AB Aur b	N	Herbig	AO Imaging	Candidate	[11]
MWC 758 c	N	Herbig	AO Imaging	Candidate	[12]
HD169142 b	S	Herbig	AO Imaging	Candidate	[13]
HD163296 b, c, d	S	Herbig	Velocity Kinks	Candidates	[14, 15, 16]

Notes: The "Observability" column refers to the hemisphere from which adaptive optics performance is best suited, meaning that the source has an elevation $\gtrsim 40°$ from Cerro Armazones (S) or La Palma (N). The last column indicates the discovery paper.

2 The Northern Opportunity: unique sky coverage

Table 1 serves as a guide for future searches for protoplanets. First, most discoveries have required the use of high-angular resolution techniques. This implies that adaptive optics (AO) systems are essential to reach diffraction-limited imaging at optical/IR wavelengths, and long baseline interferometry (e.g. ALMA for HD 163296) is required at (sub-)mm wavelengths. This observational approach is not expected to change significantly, at least in the short term. Indeed, the classical radial velocity and transit methods valid for MS stars are not generally applicable to pre-MS stars because of the presence of variable accretion disks (IRAS 04125+2902 is an exception due to its particular star-disk-planet configuration). Second, although the most common young stellar objects are the low-mass "T Tauri" stars, many protoplanet candidates have more massive hosts. This is related to current limitations of high-angular resolution techniques and the fact that disks are generally larger and better resolved for less numerous, intermediate-mass "Herbig" stars. Similarly, future surveys should also consider relatively uncommon hosts, for which observing from both hemispheres is necessary for the best possible statistical coverage. Last but not least, although the number of known protoplanets is expected to significantly increase in the coming decades, each target will have the maximum scientific priority, and roughly half will require a Northern observatory to carry out high-quality AO-assisted observations.

The angular resolution achievable by an AO-assisted, 35 m telescope is $\sim$ 4 - 9 mas in Hα -a main tracer of ongoing planet formation- and the near-IR, which translates into a spatial resolution $\lesssim$ 1 - 3 au for distances closer than $\sim$ 300 pc. This high angular resolution is thus fundamental for detecting protoplanets in disks around young stars, which are mostly located in star-forming regions (SFRs). Future surveys will prioritise the nearest SFRs (indicated with capital letters in Fig. 1, right), given that protoplanetary and circumplanetary disks, protoplanets, and their interactions can be observed in these regions at unprecedented levels of detail.

Taurus stands out as one of the most iconic SFRs. Not only does Taurus contain one of the richest collections of young sources with protoplanetary disks (including the prototypical "T-Tauri" star), but it is among the closest regions ($\sim$ 140 pc). However, because of its latitude, the ELT will observe Taurus only at low elevation. This will have a direct impact on the AO performance, which is severely degraded for elevations $\lesssim 40°$, causing protoplanets to become undetectable in the unmitigated glow of their host star. In addition, the thermal background will also be very high, affecting the sensitivity at mid-IR wavelengths, a key observing range to detect protoplanets and their circumplanetary disks [5].

The large population of young stars in Taurus, along with those in the northern SFRs Cepheus and Perseus, represents roughly half of the most informative planet-forming laboratories in the solar neighbourhood. Observing them with a 30-40 m telescope in the North is essential to probe a wide range of physical conditions and build solid observational demographics of protoplanets in disks. By observing the most relevant SFRs in both hemispheres we will probe different evolutionary stages and environments that have an effect on planet formation, e.g. in terms of stellar and gas densities, external UV radiation or chemical composition [e.g. 17, 18]. Moreover, a 30-40 m telescope in the North will give us access to other sources for which the samples are too scarce to be covered from a single hemisphere, probing not only Herbig stars, but also faint brown dwarfs and free-floating planets, or bright enough Massive Young Stellar Objects.

Finally, it is a major advantage that many young stars, either in SFRs or isolated [19], are accessible from both hemispheres. Variability is not only a defining characteristic of young stars with circumstellar disks, but also of protoplanets [e.g. 20]. Monitoring them over different timescales is essential to constrain protoplanet orbits and to access the temporal behaviour that encodes the physics of protoplanet assembly and the properties of their forming atmospheres.

3 The Northern Opportunity: synergy with other facilities

A 30-40 m telescope in the North would complement the capabilities of current and future space (e.g. JWST, Gaia, HWO, PLATO, Ariel and LIFE) and ground-based (e.g. NOEMA and next-generation VLA) facilities covering that hemisphere. Concerning the detection and characterization of protoplanets, here we emphasize the synergies with two major observatories.

First, ngVLA [21] will have superb sensitivity and resolution, and a larger coverage of the Northern sky compared to ALMA or SKA. The ngVLA will cover the frequency range between 1.2 to 116 GHz, probing the critical grain-growth barrier between millimetre to centimetre dust sizes, essential to understand pebble and planet formation. The maximum angular resolution achieved by the ngVLA will be of 0.2 mas at 30 GHz (1 cm), which will enable the imaging of the innermost regions in protoplanetary disks down to angular resolutions of 0.03 au at 140 pc, probing well into the rocky planet formation region in disks around Solar and M-type stars. The superb sensitivity of the ngVLA will measure the planetary initial mass function down to 5-10 Earth masses. Therefore, the synergy between a 30-40 m telescope and ngVLA will probe in a continuous manner the whole population of protoplanets from 5-10 Earth masses to gas giants.

Particularly relevant is also the synergy with Gaia, which will provide between 7500 and 120,000 new planet candidates during DR4 (expected for December 2026) and DR5 ($\sim$ 2030) [22]. This is a factor 10-100 larger than the currently known exoplanet population. Among the previous exoplanet candidates, a non-negligible fraction will be located in protoplanetary disks around young stars, given that Gaia astrometry serves to identify (sub-)stellar companion candidates also in such type of systems [23, 24]. The potential launch of GaiaNIR in 2040 (https://www.gaianir.org/) could significantly expand the number of protoplanet candidates by providing 10-20 times better proper motions, including young embedded sources not covered by Gaia. Roughly half of all Gaia(NIR) candidates will be preferentially accessible from the North, and a 30-40 m telescope will be the best facility capable of confirming and characterizing them.

4 Concluding remarks

This white paper is one of a coordinated series demonstrating the scientific need for establishing a 30-40 m telescope in the Northern hemisphere. Here we have focused on protoplanets —objects that, like mature exoplanets, are exquisitely valuable. Each one offers a unique and irreplaceable view of planet formation in action. Missing those located in the North would mean losing the opportunity to fully understand how the variety of planetary systems is built.

Crucially, the core capabilities required for this science are already being developed through the ELT, which is a benchmark for future technological developments. What is required is committing those capabilities to a site that provides access to all the main planet-forming laboratories and to the synergies offered by major facilities covering the North. A Northern 30-40 m telescope would therefore not duplicate the ELT but complement it, filling the observational gap that currently limits our ability to trace the origins of planetary systems.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake: Ultra–Low-Mass Dwarf Galaxies Across the Boreal Cosmic Web

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1 Scientific context

Dense clusters serve as powerful laboratories for studying environmental processing. The Coma Cluster – one of the densest nearby systems with no counterpart in the Southern Hemisphere – is exceptionally rich in dwarf galaxies and exhibits an extreme environment in which tidal interactions, galaxy harassment, and ram-pressure stripping operate with high efficiency [9, 16, 2]. With its high velocity dispersion, deep gravitational potential, and dense intracluster medium, Coma represents a regime where multiple environmental mechanisms act simultaneously, often on short timescales. Integral-field spectroscopic studies of Coma dwarfs have revealed detailed internal kinematics, spatially resolved stellar-population gradients, and clear signatures of transformation-driven substructures, including embedded discs, bars, spiral features, and kinematically decoupled components [7, 8, 4, 19]. These signatures indicate that many dwarfs retain memory of their progenitor morphologies or accretion histories, even after significant environmental processing. Such morphological and dynamical features provide direct clues to their origins—whether they are long-lived cluster members that formed early, recently accreted late-type galaxies currently undergoing transformation, or products of tidal interactions such as harassment or tidal stirring [5, 6]. Understanding which pathways dominate requires large, homogeneous spectroscopic samples with sufficient spatial resolution to map internal structure and detect low-surface-brightness components.

While Coma exemplifies the most extreme end of environmental influence, dwarf ellipticals and other low-luminosity systems dominate the number counts in rich clusters [18, 1], and their structural and kinematic properties show a strong dependence on local environment [10, 17]. The prevalence of quenched, pressure-stripped, and dynamically heated dwarfs toward cluster centers highlights the cumulative impact of dense environments on low-mass galaxy evolution. However, developing a complete picture of dwarf-galaxy evolution requires sampling across the full hierarchy of environments. Filaments, galaxy groups, and the outskirts of massive structures—including those in the Northern Hemisphere such as Virgo, Coma, and Pisces–Perseus—provide intermediate-density regimes where preprocessing, backsplash orbits, and gentle stripping can be disentangled from the more violent mechanisms acting in cluster cores [23, 14]. These regions host galaxies at different evolutionary stages, from infalling systems just beginning to experience environmental influence, to backsplash dwarfs that have already passed through cluster environments and now reside at large radii. Mapping how internal kinematics, gas content, and stellar populations vary across these environments is essential for reconstructing the relative importance and timescales of environmental processes.

By observing matched stellar-mass dwarf galaxies in Coma, Virgo, infalling groups, filaments, and low-density regions, a northern 30–40 m telescope would enable a systematic, controlled comparison of how star formation, chemical enrichment, and mass assembly depend on both local density and position within the cosmic web [11, 13]. Such a facility would, for the first time, allow spatially resolved spectroscopy of ultra–low-surface-brightness dwarfs over a representative range of environments, providing dynamical mass estimates, orbital histories, and chemo-dynamical diagnostics for thousands of systems. Isolated dwarfs in underdense regions serve as essential baselines—representing minimally perturbed evolutionary pathways against which environmentally processed systems can be directly evaluated [22]. Combining these baselines with observations of environmentally transformed dwarfs will yield stringent constraints on environmental quenching efficiency, the role of dark-matter halo structure in shaping dwarf evolution, and the balance between internal and external drivers of galaxy transformation.

2 Science Challenge

Ultra-low-mass galaxies with stellar masses between 10^5 and $10^7\,\mathrm{M}_\odot$ dominate galaxy number counts and are central to understanding galaxy formation and evolution. Their shallow potentials amplify the effects of stellar feedback, reionization, and stochastic chemical enrichment [22], while their internal dynamics directly probe the nature of dark matter [3]. The lowest-mass dwarfs retain signatures of early star formation and reionization [12], and are sensitive to alternatives to cold dark matter such as warm or self-interacting dark matter [15, 21]. They therefore connect astrophysics to fundamental cosmology.

Yet despite their importance, the faintest dwarfs remain largely unexplored spectroscopically. Even in the Local Volume, only a subset of systems have velocity dispersions, metallicity distributions, or spatially resolved stellar-population gradients measured with sufficient precision to confront theoretical models. At distances beyond $\sim$5–10 Mpc, current 8–10 m facilities reach only the brightest dwarfs in Virgo and Fornax, and cannot resolve internal kinematics or stellar-population gradients in Coma-like environments [20]. This gap severely limits our ability to assess the relative roles of internal versus external processes, and to quantify the diversity of dark-matter halos at the lowest masses. However, nowadays intruments and facilitie shave transformed the field: they have revealed the diversity of dwarf-galaxy populations in clusters and groups, uncovered the role of environmental quenching, and provided the first detailed measurements of internal kinematics and chemical enrichment in systems down to $M_\star \sim 10^{7-8}\,M_\odot$. These advances have clarified key questions—such as the efficiency of ram-pressure stripping, the timescales of preprocessing, and the connection between dark-matter halos and star-formation histories—yet they also highlight a fundamental limitation: the faintest and most weakly bound dwarfs, those with $M_\star < 10^{5-7}\,M_\odot$, remain essentially inaccessible beyond the Local Group. Ultra–low–mass dwarf galaxies will be prime targets in the Local Group for deep resolved stellar–population studies with the ELT. *Crucially, these same low–mass systems can also be studied in integrated light out to Virgo and Coma, allowing 30–40 m telescopes to link resolved and unresolved views of dwarf–galaxy evolution within a unified framework.*

Achieving robust measurements of dark-matter-dominated systems across different environments requires the leap in sensitivity, spatial resolution, and multiplexing provided by a 30–40 m aperture. Such a facility offers transformative capabilities: it allows spatially resolved spectroscopy of dwarfs an order of magnitude fainter than currently possible; it enables chemodynamical mapping of systems with surface brightnesses $\mu_r > 25$–$27\,\mathrm{mag\,arcsec^{-2}}$; and it provides the depth needed to probe dwarfs embedded in the dense intracluster medium of Coma or in the filamentary structures feeding the Pisces–Perseus supercluster. This ultra–low–mass regime is crucial because it is where feedback becomes extreme, where reionization is expected to leave the strongest signatures, and where environmental effects operate with maximum efficiency. Understanding how these galaxies form, survive, or are disrupted is essential for testing galaxy-formation models, constraining dark-matter physics, and completing the empirical picture of quenching across the cosmic web.

The northern hemisphere contains unique structures spanning the full environmental spectrum: Virgo, Coma, and the Pisces–Perseus supercluster [11]. Together they provide an unparalleled laboratory in which to trace dwarf-galaxy evolution from dense cluster cores to infalling groups, filaments, and isolated void-like regions. The ability to construct matched stellar-mass samples across these environments allows a direct, controlled measurement of environmental effects, overcoming current limitations imposed by sample inhomogeneity and observational bias. This science case also benefits from strong synergies with ongoing and future northern surveys (DESI, SDSS, WEAVE, CAVITY, Euclid, HST, JWST). These facilities will deliver exquisitely deep imaging, high-precision distances, statistical redshift samples, and resolved stellar populations. A 30–40 m telescope provides the crucial spectroscopic follow-up required to transform these photometric detections into physically interpretable constraints on dark matter, star formation, and chemical enrichment.

Combining a wide environmental view of ultra-low-mass dwarfs across the northern sky yields a coherent set of ambitious science goals that extend beyond traditional galaxy-evolution studies:

- **Map the environmental dependence of dwarf-galaxy properties.** Measure ages, metallicities, abundance patterns, and star-formation histories for dwarfs across cluster cores, infalling groups, filaments, and low-density regions, and quantify how these properties vary with environment at fixed stellar mass. A 30-meter–class telescope is required because only its resolving power can access few-parsec physical scales that current facilities cannot reach, even in much closer systems such as Virgo or Fornax. Such resolution also enables detection of the rare, extremely luminous tracers of underlying stellar populations (globular and super star clusters, planetary nebulae, and the brightest supergiants), which remain inaccessible for dwarf galaxies beyond the Local Group and especially for the ultra–low-mass regime.

- **Identify and characterise internal substructures.** Use spatially resolved kinematics and line-strength maps to detect embedded discs, bars, spiral features, and kinematically decoupled components in dwarfs, and to relate them to formation and transformation channels.

- **Constrain mass distributions and dark-matter content.** Derive dynamical mass profiles for dwarfs, including dark-matter fractions within effective radii, and test whether cluster dwarfs occupy the same scaling relations (e.g. Fundamental Plane analogues) as their more massive counterparts.

- **Disentangle formation pathways in dense regions.** In Coma, determine whether dwarfs are primordial cluster members, transformed late-type galaxies that have been quenched and heated, or products of tidal interactions and mergers. Compare their properties to dwarfs in less extreme environments.

- **Connect local dwarfs to cosmological models.** Use the observed distribution of structural, kinematic, and stellar-population properties to test predictions of hierarchical galaxy-formation models and to constrain the role of feedback, reionization, and environmental quenching at the lowest masses.

3 Capability Requirements for Solving the Challenge

This program aims to constrain the mass distributions and dark-matter content of dwarf galaxies by deriving dynamical mass profiles, measuring dark-matter fractions within effective radii, and testing whether cluster dwarfs follow scaling relations analogous to the Fundamental Plane; to disentangle dwarf-galaxy formation pathways in dense environments by distinguishing primordial cluster members from transformed late-type systems or products of tidal interactions and mergers and comparing them with dwarfs in lower-density environments; and to connect local dwarf populations to cosmological models by using their structural, kinematic, and stellar-population properties to test hierarchical galaxy-formation predictions and constrain the roles of feedback, reionization, and environmental quenching at the lowest masses. Ultra–low–mass dwarfs ($10^5 - 10^7\,M_\odot$) are extremely compact and faint, with effective radii of $R_\mathrm{e} \sim 50$–$300\,\mathrm{pc}$ ($0.2''$–$0.8''$ at Virgo and Coma), mean surface brightnesses $\mu_r \sim 24$–27 mag arcsec^{-2}, colors $(g-r) \sim 0.3$–0.8, and stellar velocity dispersions of only 5–20 km s^{-1}, placing them beyond the practical limits of current 8–10 m telescopes for resolved or high-S/N spectroscopy beyond the Local Group. Meeting these goals requires a deployable, multi-object integral-field spectrograph covering roughly 3500–9000 Å at $R \sim 5000$, with IFUs of 1×1 arcsec and sub-arcsecond spatial sampling to encompass dwarf effective radii at Coma distances, combined with high multiplexing over a wide field matched to dwarf surface densities from one to several per arcmin^2 to enable efficient surveys of tens to hundreds of galaxies across diverse environments. All this should be assisted with AO capabilities.

The resulting dataset will provide an essential bridge between near-field cosmology and galaxy-formation theory, establishing dwarf galaxies over the entire range of masses as precision laboratories for both astrophysics and fundamental physics.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake: A Low Surface Brightness Science Case

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The Extragalactic Low Surface Brightness (LSB, $\mu_V \gtrsim 27$ mag/arcsec^2) Universe represents a crucial, yet largely unseen, frontier in modern astrophysics. This faint realm holds the keys to completing our understanding of galaxy evolution, hierarchical assembly, and even the fundamental nature of dark matter. Our current theoretical models are inherently incomplete, largely mirroring the properties of the brightest, most easily observed objects. To overcome this critical bias and unlock the secrets of this realm, a transformative leap in observational capability is required. A 30 to 40m class telescope, leveraging unprecedented sensitivity and spatial resolution, especially with adaptive optics, is the essential tool to fundamentally probe these faint, low-density stellar regimes. This white paper details the transformative LSB science that such a facility, strategically positioned in the Northern Hemisphere (NH) to access crucial nearby structures and rich environments, can achieve.

1 General Cases

A 30m class telescope will revolutionize our understanding of the LSB Universe in two main ways. First, its high-resolution imaging, aided by adaptive optics (AO), will enable us to resolve individual stars in nearby LSB systems (out to $\sim$ 15 Mpc) [1]. This capability is essential for dissecting stellar populations, allowing us to obtain detailed chemical compositions and accurate stellar ages. Second, the telescope's immense sensitivity will be crucial for analysing the integrated light of more distant systems ($>$ 15 Mpc), providing key constraints on their overall stellar populations and formation histories.

The building blocks of the Universe

LSB galaxies and dwarf systems constitute the bulk of the galaxy population by number [2] and are fundamental to understanding cosmic structure. They are crucial for two primary reasons: first, they are the key to understanding star formation efficiency in low-mass dark matter halos [3]; and second, they are the recognized building blocks through which larger galaxies, including the Milky Way, are assembled [4, 5]. Despite their cosmological significance, these galaxies, which represent the faintest and most dark-matter-dominated systems in the Universe, remain poorly characterized. Yet, analyzing their star formation histories provides one of the most stringent tests of contemporary galaxy formation models, holding the key to unraveling the complex interplay of physics driving galaxy evolution.

A 30m class telescope will finally provide statistically significant samples and probe significantly lower-luminosity galaxies than currently possible. This leap in capability will clarify the formation mechanisms of these galaxies, test the influence of feedback processes (such as supernovae) in low-mass dark matter halos, determine the mechanism for their quenching, and constrain how cosmic reionization shaped their early evolution [6,7].

The history of assembly of structure

The most revealing signature of the hierarchical assembly in galaxies, groups and clusters of galaxies is the intricate web of faint stellar features that surrounds them. These outer regions constitute a major component of the host's halo, preserving a detailed record of galaxies destroyed during the hierarchical assembly of the host. They, thus, provide direct evidence of the accretion history of the host [8, 9]. These regions are composed of a globally smooth component such as the stellar halo and the intragroup/intracluster light (intrahalo light or IHL for short) [10, 11], but also contain substructures formed by the disruption of satellite galaxies, including stellar streams, shells, and other tidal signatures. A 30m class telescope will be instrumental for characterizing the stellar populations of these outer regions.

For individual galaxies, this capability will allow us to reconstruct their entire formation history across a statistically large and diverse sample [12]. This crucial step extends our view beyond the Milky Way and M31, providing the necessary dataset to robustly compare against cosmological simulations, which is an essential exercise given the inherent stochastic nature of galaxy assembly. Furthermore, a 30m telescope will also enable “chemical tagging” to trace and discover faint streams, analogous to the techniques employed in the Milky Way halo [13]. It will also reveal the location of galaxy edges or truncations—both in nearby systems via resolved star counts and in more distant and fainter systems via integrated light—providing key boundary conditions for models of galaxy assembly and stellar migration [14]. For galaxy groups and clusters, it will allow us to unveil their recent dynamical history via the study of tidal features and substructure within the IHL [15, 16]. Furthermore, for the closest clusters, the telescope's deep sensitivity will enable spatially resolved mapping of the stellar populations across the cluster (see Section 2 for more details).

The nature of dark matter

The stars of the LSB Universe exist in regimes where dark matter dominates the gravitational potential. This makes these stars a unique, collisionless tracer of the dark matter halos they inhabit. Without the precise kinematic information (velocities and velocity dispersions) made accessible only by a 30m class telescope, stellar orbits cannot be accurately measured. Consequently, the gravitational potential cannot be constrained with the precision needed to differentiate between competing models of dark matter. Accessing this kinematic data is therefore essential for testing the fundamental nature of dark matter itself.

LSB Galaxies: The capabilities of a 30m telescope will allow measuring the stellar velocity dispersions and rotation curves to probe the dark matter density profiles of LSB galaxies. Particularly interesting are LSB systems with low stellar masses, specifically those below 10^5–10^6 $M_\odot$. In these low-mass halos, stellar feedback is expected to have a negligible effect on the central dark matter distribution [17, 18]. This makes the internal stellar kinematics of these systems critical tracers of the central gravitational potential, allowing for the direct discrimination between "core" and "cusp" halo profiles. Probing these dark matter density profiles is critical for testing the fundamental nature of dark matter itself [19, 20, 21]. Furthermore, the 30m telescope will enable an independent determination of the LSB galaxies' dark matter content through analysis of the dynamics of their associated globular cluster systems [22].

Extragalactic Stellar Streams: Obtaining kinematic measurements of stellar streams, either through individual stars [23] or via spectroscopy of tracers like Planetary Nebulae (PNe) or globular clusters (GCs) [24], is critical for breaking the well-known degeneracies found in N-body simulations [25], thereby enabling definitive constraints on the total mass, shape, and gravitational potential of the dark matter halo of their host galaxies.

Intrahalo light: Similarly as in stellar streams, the stars in the smooth IHL are an effective, large-scale tracer of the global gravitational potential of its host halo [26]. Crucially, the total stellar mass and spatial distribution of these halos are a direct consequence of the nature of dark matter itself [27]. Therefore, acquiring kinematic measurements of IHL tracers, individual stars, GCs [28] and PNe [29] or integrated light spectroscopy when there are few tracers, is essential. These measurements are vital to map the host halo's global potential, probe its properties, identify substructure, and ultimately place rigorous constraints on the nature of dark matter.

Detecting Dark Subhalos: These are predicted cold dark matter halos with masses smaller than 10^9 $M_\odot$ that have never formed stars. The passage of these dark matter sub-haloes across other visible structures (tidal streams, gravitational lenses) will leave imprints that will be observable and quantifiable [30] beyond the Local Group with a 30m telescope. However, they may also be detected through a characteristic ring-like emission pattern to be expected in Hα, caused by the recombination of the outer shell of the gas in the halos, ionized by the cosmic UV background [31]. These very faint signals need a 30m telescope to be detected.

• In addition, a 30m telescope will allow for follow-up of peculiar objects discovered in ultra-deep imaging surveys like LIGHTS, Euclid, ARRAKIHS and part of the LSST footprint.

2 Objects in the Northern Hemisphere

M31 and its Satellites: A 30m class telescope will provide unprecedented insight into the evolutionary history of M31. Using AO, it will measure the proper motions, radial velocities and chemistry of individual solar-type stars in the outer halo, which together with deep color-magnitude diagrams, will enable the reconstruction of M31's star formation and chemical enrichment histories. Furthermore, the telescope's sensitivity is essential for studying M31's large satellite population [33, 34]. Specifically, the faintest satellites (below $M_* \sim 10^5$–10^6 $M_\odot$) [35, 36] which are critical for constraining competing dark matter models. It will also confirm candidate ultra-faint dwarfs, completing the galaxy's luminosity function. The study of the low surface brightness components of the M31 systems is highly complementary to the science proposed in the white paper by Gallart et al.

The Richest Galaxy Clusters: The NH hosts the richest and most relaxed galaxy clusters in the nearby universe: Coma (z=0.023, 100 Mpc) and Perseus (z=0.018, 75 Mpc). These massive

overdensities are fertile grounds for discovering and studying the most extreme systems. Their dense environments are ideal for the formation —or survival— of galaxies exhibiting either very little or an unusually large amount of dark matter. Recent discoveries of ultradiffuse galaxies exemplify this diversity [37], as these very faint systems occur in large numbers within rich clusters, with increasingly extreme examples continuing to be found. Due to their extreme faintness, these systems are accessible only through the deep spectroscopy afforded by instruments on 30m class telescopes.
These massive clusters also serve as perfect laboratories for the in-depth study of their IHL. A 30m telescope will extend spectroscopy into the ICL's faintest limits [38], providing the necessary signal-to-noise to characterize the stellar populations of the diffuse light, which is essential for studying assembly processes throughout the cluster. Furthermore, kinematic tracers like GCs and PNe will allow us to obtain detailed kinematics and map the gravitational potential of these massive clusters.

Nearby Milky-Way Analogs: ∼2/3 excess of the largest galaxies in the sky (diameter > 10') are observable from the NH. That allows the characterization in detail of their satellite population and their outer regions. In particular, the three nearest edge-on Milky Way analogs are in the NH (NGC 891, NGC 4565 and NGC 5907 at ∼10 Mpc) which are exceptional laboratories for studying vertical disk structure, disk stability in the outskirts and faint stellar halos. Their edge-on orientation allows exploration of vertical disk profiles and of stellar migration and heating due to bombardment by dark-matter substructures [39, 40]. Questions such as whether the Milky Way's inner halo is typical and how disk thickness evolves with height above the plane can be addressed in these galaxies with the power of a 30m-class facility.

The Virgo Cluster: This nearby cluster is composed of the main galaxy groups (Virgo A and B) and numerous smaller substructures currently accreting along cosmic filaments [41, 42]. Its proximity and varied environments —dense cores to low-density infall regions— make it a critical laboratory for understanding LSB galaxies and their stellar properties [43, 44]. A 30m class telescope is also uniquely positioned to conduct detailed, resolved studies of diffuse light across this full range of environments.

3 Other considerations

The level of detail provided by a 30m class telescope is necessary to understand the full history and composition of our cosmic landscape. The light collecting power and spacial resolution of such a facility are required to advance this field, which is currently limited to studying only a handful of objects or relying primarily on shallow broadband imaging. For the LSB science described throughout this paper, a field of view larger than what is typical in the currently planned 30-m telescopes would substantially enhance the efficiency and statistical power.

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Why the Northern Hemisphere Needs a 30-40m Telescope and the Science at Stake: from Interstellar Visitors to Planetary Defence

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Small Solar system Objects (SSOs) preserve the physical, chemical, and dynamical signatures of the Sun's protoplanetary disk. Upcoming surveys will discover vast numbers of new objects, yet their scientific value will depend on follow-up observations requiring far greater sensitivity and resolution than those currently available. A 30-m class telescope like the Extremely Large Telescope (ELT) will be transformative, but its Southern location leaves significant regions of the sky poorly covered or even non accessible.**A Northern 30-40m telescope is therefore essential to achieve full-sky coverage and fully exploit the small body discoveries of the 2030–2050 era**, in particular for targets of opportunity or unexpected discoveries, like those of interstellar objects and potentially hazardous asteroids, as well as for distant trans-Neptunian objects and space mission targets.

1 Introduction and Motivation

Forthcoming advancements in survey facilities, most notably the Vera C. Rubin Observatory but also the NEO Surveyor mission [1], will vastly expand the known inventory of small bodies. However, without a 30-m class facility like the ELT, the scientific return from these discoveries will be limited, and key science questions, including the origin of water in the inner Solar System and the search for the origin of life, the planetary differentiation processes and the collisional history of SSOs, or the physical drivers of cometary activity, will remain only partially explored. Looking toward the 2040s, while the ELT will transform many areas of planetary science, its Southern location will leave substantial portions of the ecliptic and northern sky inaccessible or only marginally observable, potentially leading to missed chances for discovering target-of-opportunity objects, such as interstellar objects and Earth's virtual impactors. A northern 30-m telescope is therefore not redundant but rather highly complementary and necessary, and together, the northern and southern facilities would enable full-sky access to the most interesting small bodies, ensuring that the global astronomical community fully exploits the scientific potential of the upcoming era, as evidenced by the achievements of recent years.

2 The Science Challenge

A 30-40m telescope facility in the Northern hemisphere presents unique opportunities for SSOs studies over long time scales: 1) Northern hemisphere surveys are less affected by the crowdedness of the densest galactic areas (including the bulge), that are present in the Southern counterpart. Deep searches for faint objects are thus less biased and can provide more uniform coverage. This will improve the search for faint trans-Neptunian objects (TNOs) requiring uniform coverage to dynamically constrain the existence and position of potential distant massive perturbers (e.g. Planet X); 2) For the next decades, giant planets will have positive declinations, thus favoring observations from the North. That's the case for Saturn (until 2040) and Uranus (until 2050). Neptune will be favored for the next ∼80 years, and so will its Trojan clouds, in particular the L4 [2]). Proper characterization of primordial Trojans is essential to constrain the evolution of the Solar System, and for understanding the formation and evolution of planetary systems.

We identify several scientific questions that will be adversely impacted due to a combination of a loss of sky coverage and opportunities, if a northern 30-40m class telescope in the 2040s is not available.

2.1 Interstellar Objects (ISOs)

The importance of having the above described capabilities has grown even more critical with the recent discovery of interstellar objects (ISOs) entering the Solar System. The first detections, 1I/'Oumuamua in 2017 [3, 4], 2I/Borisov in 2019 [5], and 3I/ATLAS in 2025 [6, 7, 8], revealed that material from other planetary systems regularly traverses interplanetary space, offering unprecedented opportunities to directly investigate the building blocks of planetary systems beyond the Sun. Discovered ISOs had **short observability windows** and rapid sky motions (see Fig.1). Characterizing their physical and chemical properties requires sensitive, high-resolution spectroscopy and imaging on timescales of hours to days, before they get too faint. Consequently, a 30-40m class facility will allow for a complete characterization at inbound (and outbound) trajectories at distances before the onset of cometary activity or significant modification of its surface by solar heating, resulting in **unique, transformative science**. The spatial distribution of incoming ISOs is expected to be essentially isotropic, reflecting the random velocities of planetesimals ejected from other stellar systems throughout the Galaxy. Interestingly, recent

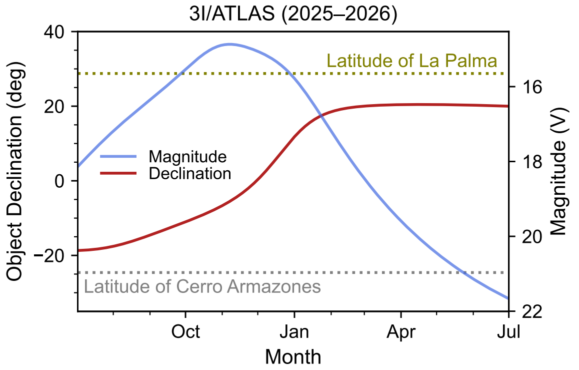

Figure 1: Declination and apparent visual magnitude of interstellar object 3I/ATLAS between July 1, 2025 and July 1, 2026. The dotted horizontal lines indicate the latitude of Cerro Armazones (location of ELT) and La Palma (as reference for a Northern location).

models place the most likely radiants towards the Northern hemisphere [9], in the direction of the Solar Apex (∼18h30, +30deg N). In the absence of a Northern 30-40m class telescope we will be disadvantaged in the characterization of high inclination objects: those entering from the South would be discovered and tracked initially, but then potentially lost (likely after perihelion passage), while those approaching from the North would not be detected from the South until late (or too late), and possibly in unfavorable observing conditions. Both situations must be avoided to fully characterize these objects during their inbound and outbound paths and to compare extrasolar planetesimals with native SSOs.

2.2 Distant trans-Neptunian objects

Distant or extreme trans-Neptunian objects (ETNOs) are defined as bodies with perihelia beyond ∼50 au and semi-major axes exceeding ∼150 au. A 30-40m telescope is indispensable for detailed physical and compositional studies of ETNOs: these objects are very faint ($V > 25$), often at magnitudes beyond the reach of current 8–10m class facilities, and mid-resolution spectroscopy and imaging are required to determine their surface composition, detect binary companions, and measure rotation periods. In the last years, JWST spectroscopy from 2 to 5 μm has proven successful to study compositional diversity, from Neptune Trojans to ETNOs [e.g 10, 11]. However, at the time of this writing, less than 6 out of the more than 40 currently known ETNOS with reliable orbital determinations have any physical or compositional information. Such observations will provide much needed insight on the formation conditions in the outermost regions of the Solar System, the collisional history of the trans-Neptunian belt, and the migration history of the giant planets.

Detailed orbital characterization, requiring precise astrometry over multiple oppositions, is essential to constrain the orbits of these objects, detect subtle clustering in their orbital elements, and distinguish between random distributions and gravitational sculpting. Gaps in the orbital coverage, that affect more strongly southern declinations due to locally extreme stellar density, would prevent high-precision modeling of their dynamical evolution. Failure to build a northern 30-m class facility would mean that a substantial fraction of distant TNOs discovered by upcoming surveys, including those most dynamically sensitive to the hypothesized Planet X [12], would remain poorly studied or non characterized, leaving a significant portion of the outer Solar System effectively inaccessible, and therefore, limiting our knowledge of the collisional history of the trans-Neptunian population, and the migration history of the giant planets.

2.3 Space mission support and coordination

A 30-40m telescope in the Northern hemisphere may be a critical asset for supporting future spacecraft missions to small bodies, particularly for targets which are primarily or exclusively observable from Northern latitudes in the years preceding encounter. Ground-based observations are a key element of successful mission planning, both for maximizing scientific return (early characterization of physical properties) and for spacecraft control and engineering purposes (i.e., reduction of ephemeris uncertainties). Also important are the rapid-response observations associated with active mission events, impacts, flybys, or other transient phenomena, which often occur at specific geometries relative to Earth. Two past examples are 1) the NASA Deep Impact mission, which struck 9P/Tempel 1 in July 2005, excavating subsurface material and producing a rapidly evolving ejecta plume. Although an extensive worldwide campaign was organized [13], only a small number of ground-based observatories were able to observe the moment of impact, in particular those stationed in Hawaii [14, 15]; 2) the DART impact to Dimorphos in September 22, also excavating a rapid evolving plume. In contrast to Deep Impact, no major ground-based facility captured the moment of impact; instead, the first VLT-class observations began hours after [16, 17]. Earth-based accessibility, especially in the first minutes post-event, is strongly latitude and longitude dependent. Although we cannot predict which objects or mission events will be most crucial in the coming decades, experience shows that rapid follow-up ground-based observations maximize scientific output of space missions. A Northern 30-40m facility would provide flexibility and capability needed to respond to these developments.

2.4 Earth virtual impactors: Planetary Defence

Beyond advancing fundamental science, a Northern 30-40m class telescope would play a critical role in planetary defence. At the time of this writing, the total number of near-Earth asteroids (NEAs) is slightly over 40,000. Of those, asteroids having a diameter $D > 140$ m and orbits that bring them at distances to Earth < 0.05 au, are classified as potentially hazardous (PHAs). While we have identified all NEAs with $D > 1$ km, our current estimates indicate that we have only identified $\sim$50% of NEAs in the size range between 140 m and 1 km (small asteroids). Therefore, a substantial fraction of PHAs and virtual impactors (VIs), objects whose orbits carry a non-zero probability of Earth collision, **remain small, faint, or located at high northern declinations**. Rapid, high-sensitivity follow-up observations are essential to refine orbital parameters, assess impact probabilities, and model physical properties such as rotation, shape, composition, and interior structure [18]. The combination of high angular resolution (to reduce ephemeris uncertainties) and spectral sensitivity provided by a 30-40m telescope would allow detailed compositional and surface characterization of PHAs and VIs, enabling better predictions of their mechanical behavior and potential response to mitigation efforts. Determining whether a small body is a rubble pile, a monolithic rock, or volatile-rich can inform the design of mitigation strategies, including deflection missions or kinetic impactor strategies. This was the case of the NASA DART mission and its target, asteroid (65803) Didymos [19, 20]. In this sense, Northern facilities do not merely complement Southern surveys; they are an **indispensable component of a global planetary defence infrastructure** capable of providing full-sky coverage and rapid response in the event of a near-Earth threat. A good example was the case of asteroid 2024 YR4, that activated for the first time in human history the UN Planetary Defence Protocol, and needed for large telescopes at all latitudes. In addition, both the NEO Surveyor and, in a more distant future, the ESA NEOMIR telescope [21], will also require the support of large, ground-based facilities in the North. Without access to a 30-40m Northern-aperture facility, critical warnings could be delayed, leaving limited time for mitigation strategies or deflection campaigns in the event of a threatening object. This is currently of major concern for space agencies such as NASA and ESA, and for the European Commission.

3 Capability Requirements

We include here some technical requirements needed for the scientific cases described above: 1) Wide field visible imaging for NEAs/PHAs/VIs and ISOs characterization and astrometry/recovery, as well as for comet characterization; 2) Small field fast imaging with absolute sub-ms time tagging capabilities for local high-precision astrometry of TNOs and for occultations; 3) High-contrast and high-resolution imaging (AO) for large TNOs; 4) Low-mid resolution from near-UV (0.3 μm) up to mid-infrared (2-5 μm and 10 μm) spectroscopy for compositional characterization of NEAs/PHAs/VIs, TNOs, gas emission in comets and ISOs; 5) Spectro-polarimetric capabilities, in particular for ISOs, as their phase angle varies quickly; 6) Timing accuracy and tracking modes; 7) IFU + AO (spaxel of few mas) + mid-resolution, to characterize extended objects (disk-resolved large objects) + coma in active objects + resolving close multiple systems.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake:
Mapping formation pathways of nuclear star clusters across galaxies

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Nuclear star clusters (NSCs) are dense, compact stellar systems only a few parsecs across, located at galaxy centers. Their small sizes make them difficult to resolve spatially. NSCs often coexist with massive black holes, and both trace the dynamical state and evolution of their host galaxies. Dense stellar environments such as NSCs are also ideal sites for forming intermediate-mass black holes (IMBHs). To date, spatially resolved NSC properties, crucial for reconstructing dynamical and star-formation histories, have only been obtained for galaxies within 5 Mpc, using the highest-resolution instruments on the current class of very large telescopes. This severely limits spectroscopic studies, and a systematic, unbiased survey has never been accomplished. *Because the vast majority of known NSCs are located in the Northern Hemisphere, only a 30-m–class telescope in the North can provide the statistical power needed to study their physical properties and measure the mass of coexisting central black holes.* ***We propose leveraging the capabilities of a 30-m-class Northern telescope to obtain the first comprehensive, spatially resolved survey of NSCs, finally allowing us to unveil their formation pathways and their yet unknown connection with central massive black holes.***

1 Introduction and Motivation

NSCs are among the densest stellar systems, only few parsecs across and with stellar masses from 10^4 to several $10^8\,\mathrm{M}_\odot$ [e.g., 1]. Located at galaxy centers, they often coexist with massive black holes (MBHs, $\geq 10^3\,\mathrm{M}_\odot$), and their stellar content traces the mechanisms that drive stars and gas into galactic nuclei [2]. Two non-mutually exclusive formation channels are commonly invoked: star-cluster inspiral through dynamical friction [3] and in situ star formation after gas inflow [e.g., 4]. Observations point to a combination of both [e.g., 5].

NSCs occur in more than 60% of galaxies with stellar masses between 10^8 and $10^{10}\,\mathrm{M}_\odot$, peaking at 90% near $10^9\,\mathrm{M}_\odot$ [6]. Their frequency drops in low-mass systems and in high-mass early-type galaxies (ETGs), while remaining high in massive late types (LTGs) [2]. These mass-dependent trends, together with chemical and age distributions [e.g., 7], suggest a transition from cluster-dominated at low masses to in situ formation at higher mass, closely tied to the presence and growth of their MBHs. Yet the coexistence (or absence) of MBHs in NSC-hosting galaxies remains unsolved, as well as the possibility that intermediate-mass black holes (IMBHs) in low-mass galaxies are not absent but undetectable with current observatories. Kinematic and stellar population studies show younger, rotation-dominated NSCs in LTGs, mostly assembled via in situ star formation, while those in ETGs exhibit slower rotation and more complexity, resulting from past mergers [e.g., 8, 9]. NSC incidence also increases in dense environments [10], linking NSC formation to broader galaxy evolution. Another open question is whether NSCs, located at the galactic center, contain the first stars that formed in a galaxy, making them key to understanding the first stages of galaxy formation.

Theoretical studies reproduce aspects of both NSC formation pathways, but systematic simulations across galaxy mass, morphology, and environment remain scarce. High-resolution N-body models support the efficiency of cluster inspiral, while hydrodynamical simulations show that in situ star formation is required to reproduce observations [e.g., 11, 12]. Although larger samples and a cosmological framework are needed to evaluate the balance of internal and external drivers of NSC and MBH growth, current cosmological simulations are still limited in resolution and in their ability to recover realistic galaxies. Thus, observations remain essential for constraining NSC formation pathways, yet detailed spectroscopic mapping is currently only feasible for very nearby systems (within ∼5 Mpc) using the most sensitive, large-aperture facilities [e.g., 9].

2 The Science Challenge

With current facilities, parsec-scale stellar mapping in NSCs is feasible only within ∼5 Mpc, which limits the number of currently classified NSCs to fewer than 25, and to 11 if we only consider the ones with parsec-scale integral-field spectroscopy (IFS) to date. Likewise, mass measurements of black holes (BHs), especially low-to-intermediate mass ones, require resolving their small spheres of influence, demanding angular resolutions of $\lesssim$0.02", thus limiting observations to galaxies closer than 10 Mpc. A statistically robust picture of NSC formation and its link to galaxy evolution requires data for a larger, more diverse and unbiased galaxy sample, allowing for the investigation of trends with host-galaxy properties. Extending detailed NSC studies to a distance of 20 Mpc will increase the number of reachable NSCs by a factor of more than 20 (visible either from the North or the South).

About 70% of the total sample of detected NSCs in these catalogs, hosted by galaxies of different masses, morphological types and environments (in the field, in galaxy groups, and in the Virgo Cluster), will not be visible from the Extremely Large Telescope (ELT) since they are located in the Northern Hemisphere. Therefore, a 30-m-class telescope in the North is essential for building this unbiased dataset. Of the very large sample visible from the North (from the latitude of the Roque de los Muchachos Observatory, in La Palma, but now including the ones with declinations above -20°, visible also from the South), ∼60% of NSCs are located within 20 Mpc. Such a facility will enable the first systematic and statistically significant survey of an unprecedentedly large and unbiased sample of 334 NSCs, with high-quality spatially resolved kinematics and stellar populations. The galaxy sample spans the full stellar-mass range of nucleated galaxies, between $\sim 10^6$ and $\sim 4 \times 10^{11}$ $M_\odot$ (with most galaxies around 10^9 $M_\odot$, where the nucleated fraction is maximum), allowing to explore with IFS the lowest and highest mass ranges, which is mostly uncharted territory. Within our sample, approximately half are members of the Virgo cluster, and the rest are field or group galaxies. It will finally be possible to quantify the relative contributions of in situ star formation and cluster inspiral to NSC assembly [7] and to assess how these channels vary with galaxy mass, morphology, and environment. Determination of central BH masses across a wide galaxy parameter space will complement crucial insight into NSC–BH coevolution.

2.1 Detailed zoom-in analysis of NSC

With such a facility, we will be able to spatially resolve NSC kinematics and stellar populations in a large sample of galaxies (Fig. 1, left panel), allowing us to measure gradients within the NSC-dominated region and identify complex NSC structures with different components in the same NSC. Kinematically decoupled components in an NSC will trace the role of star or star cluster accretion, and thus galaxy mergers, in the formation of the first NSC seed and in its growth (see more examples for very nearby galaxies in [9]). Different stellar population components dominating age and metallicity maps at different radii will thus uncover substructures of various sizes within the same NSC, formed in different epochs of galaxy evolution. This has been done with current facilities for larger structures such as nuclear disks, unveiling the signatures of specific scenarios such as inside-out formation [13]. The comparison with the surrounding galaxy will be key to linking with the host-galaxy evolution [14].

2.2 Revealing hidden IMBHs and expanding direct BH measurements

NSCs are the most promising environments to search for IMBHs and to constrain the low-mass end of the BH occupation fraction. Parsec-scale kinematic mapping within BH spheres of influence will enable robust dynamical mass measurements [16, 17, 18] across a broad range of galaxy masses and morphologies, finally revealing BHs in the elusive IMBH regime. This capability, recently investigated for ELT/HARMONI [19], is essential because the low-mass end of MBH–galaxy scaling relations remains sparsely populated (see Fig. 1, right panel). The diversity of low-mass galaxy types produces significant scatter and/or apparent flattening below $\sim 10^9$ $M_\odot$ (e.g., [15]), with NSCs and other compact galaxies such as ultracompact dwarfs, playing a key role in driving such complexity. However, the gap seen at the lowest stellar masses might be mostly driven by the current telescope limitations for resolving and measuring the smallest MBHs. Accurate kinematics represent the most efficient method for finding IMBHs, as IMBHs appear to have exceptionally low accretion efficiencies compared to other classes of BHs, making them challenging to detect through multiwavelength observations [20].

2.3 Capability Requirements

NSCs have small sizes (between 1 and ∼20 pc, [1]) and low stellar velocity dispersion (down to $\lesssim 10$ km s^{-1}, [9]). Their surface brightness can drop to $\gtrsim 22$ mag arcsec^{-1} [21] at the edges

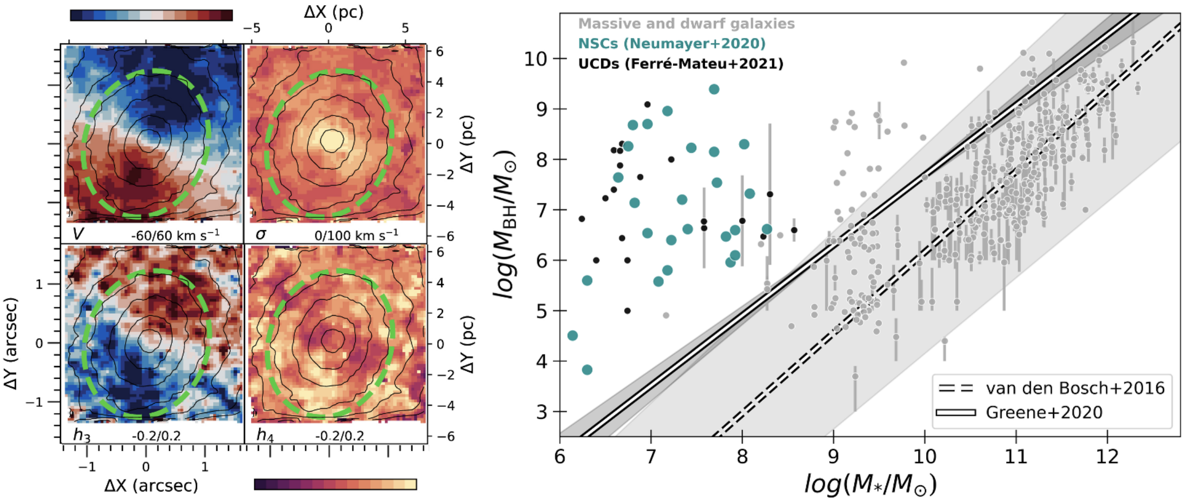

Figure 1: *Left panel:* Stellar kinematic maps of the NSC in M 32 adapted from [9]. From left to right, from top to bottom, mean velocity V, velocity dispersion σ, skewness h_3 and kurtosis h_4. Isophotes are shown in black and the NSC effective-radius ellipse in dashed green. *Right panel:* BH mass versus stellar masses of NSCs and a variety of galaxy types, from the low mass ultracompact dwarfs, to the most massive systems, adapted from [15].

of the very central region where they dominate, and this makes it challenging to obtain the required signal-to-noise ratio for stellar-population mapping using high-resolution instruments (with small spaxels due to the high spatial sampling). Thus, spatially resolving NSC properties requires a specific set of instrumental capabilities beyond what 8–10 m telescopes can provide:

- Milliarcsec angular resolution, at the diffraction limit of a >30-m telescope using adaptive optics (AO), to resolve sub-parsec spatial scales at distances of up to 20 Mpc.
- Advanced AO performance (with high Strehl ratios) and point-spread-function (PSF) stability, to preserve spatial resolution across the field of view. This is critical to fully exploit the very high spatial resolution and to avoid systematic errors in the derived properties.
- Relatively high spectral resolution (R>8000) to measure NSC velocity dispersions of 10–30 km s^{-1}, h_3 and h_4, with the required accuracy for BH-mass measurements. This cannot be achieved from space, making a 30-40 m ground-based telescope the only way forward.

A 30-m-class telescope represents the minimal infrastructure capable of meeting these requirements. It is therefore **the essential enabling technology for transforming NSC studies into a precision field and resolving the long-standing question of IMBH occupation in low-mass galaxies. This will significantly advance our understanding of black-hole demographics and formation, NSC assembly, and their co-evolution with host galaxies, thereby filling a critical gap in our understanding of galaxy evolution.**

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Science Enabled by a 30-Meter-Class Telescope in the Northern Hemisphere: Massive Stars at Low Metallicity

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Massive stars are at the core of our observations of the Universe up to the reionization epoch, both through their intense ionizing fluxes and through the energetic end products that release fresh elements into the interstellar medium. Our interpretation of very high redshift galaxies and transient phenomena depends on knowledge derived from massive star populations in the Milky Way and nearby galaxies, with characteristics that only remotely resemble the conditions in the early Universe. However, the models supporting these interpretations have been tested in a narrow range of environments and carry significant uncertainties when extrapolated. Advancing in our understanding of the Universe beyond the Local Volume therefore requires extending massive star studies to conditions representative of the early Universe. The next generation of telescopes has the potential to accomplish this goal.

1 Massive stars at low metallicity

Understanding the Cosmic Dawn Epoch is among the most exciting challenges of modern Astrophyiscs. How the first stars and galaxies formed, how the reionization of the Universe proceeded, how its chemical composition and Star Formation Rates (SFR) evolved with time, are very compelling open questions. Massive stars, with their very energetic ionizing fluxes processed through the interstellar and intergalactic media are key tools to explore the Universe and interpret the information in the light coming from very early ages, like in the cases of Earendel [at z =6.2 35] and JADES-GS-z14-0 [at z =14.32 5]. Moreover, their final products like Supernovae, neutron stars, Gamma-Ray Bursts, black holes and gravitational wave events (GWE) trace the high energy Universe.

Using massive stars as cosmic tools requires an understanding of the physics governing their properties and evolution. Yet, physical conditions vary greatly across space and time. On the one hand, SFR increases, peaks at redshift z ∼2 and then decreases with time. On the other, the abundances of chemical elements heavier than helium increased by orders of magnitude since the Big Bang until the present day [24].

Metallicity (Z) is a fundamental parameter for the stellar structure, but in the case of massive stars it also determines the strength of their stellar winds, affecting not only the mass lost by the star during its evolution, but also the opacity of their external layers and the spectral distribution of its ionizing flux. Their mechanical and ionizing feedback in turn strongly alters the properties of the surrounding medium [19, 28, 15].

Other physical processes also play an important role in modifying the structure and evolution of massive stars. A large fraction of them are born in binary or multiple systems, opening new evolutionary channels through binary interaction and mergers [30, 8, 25]. Rotation drives mixing processes bringing nuclear burning products and angular momentum to the surface, whilst magnetic fields, pulsations and turbulence alter the structure of the stars and their final fate [20]. These effects are not independent of each other, and for instance binary interaction modifies the rotational properties of the stars through tides and mass and angular momentum transfer. Underlying all these processes, the stellar chemical composition shapes them to a significant extent, affecting star formation and evolution across the Universe.

There have been important advances in our understanding of massive stars. The Milky Way (MW) and the Magellanic Clouds (MCs) have enabled the exploration of the 2 to 1/5 $Z_\odot$ range. We have characterized stellar winds present in massive stars down to $Z_{\rm SMC}$ [e.g., 26, 28], developing a theory that can potentially be extended towards lower metallicities. However, uncertainties persist or have newly emerged, when approaching the average chemical composition of early epochs. It is unclear whether the currently accepted Radiatively Driven Wind (RDW) theory breaks for (relatively) low luminosities as well as for low metallicities [e.g., 4, 14]. This may have a significant impact on our estimated budget of ionizing photons by reducing the opacity in the wind and photosphere.

Fundamental predictions concerning the behaviour of massive stars at low Z are presently being challenged. Contrary to expectations, there is no evidence that stars at low metallicities undergo chemically homogeneous evolution, a hypothetical channel that may result in very different evolutionary paths, power HeII nebular emission and lead to the formation of massive double black holes in close orbits and gravitational waves [34, 9]. It remains also unclear whether the upper mass limit increases with decreasing Z, a key property for the expectation of extreme masses for the first stars (∼ 1 000 $M_\odot$, [18]), and a consequence of inhibited gas fragmentation in the absence of enough metals to cool down molecular gas. There is intriguing evidence that a substantial fraction of the black hole masses inferred from GWE are significantly higher than those of the most massive black holes measured in the Local Universe [1]. Since the winds of massive stars are known to weaken markedly with decreasing Z [e.g., 14], current observations strongly suggest that stellar physics changes once a critical Z threshold is reached. Finally, the evolution of low-metallicity stars with masses above $\approx 70\ M_\odot$ may lead to a pair-instability supernova [29] that entirely disrupts the star, leaving no remnant. But at even higher masses or lower metallicities, more massive CO cores may instead undergo photodestintegration instability and directly collapse into high-mass black holes. These events are believed to manifest as superluminous supernovae [e.g., 27] or other exotic transients whose extreme luminosities may render them powerful tracers of the early universe.

These uncertainties amplify when we try to extend our knowledge below Z_{SMC}. The Initial Mass Function (IMF), chemical yields, binary fractions, mechanical feedback, fluxes ionizing the surrounding medium and stellar end products are strongly affected, while critical for synthetic stellar populations and the interpretation of observations when no spatial resolution is possible [21, 11].

2 Our laboratory: the nearby low metallicity star-forming galaxies

The lucky circumstance of having the MCs close to our Galaxy has allowed dedicated surveys to explore the Z-effects in the range covered by all three galaxies [12, 13, 32]. However, to extend our knowledge beyond this range we need to expand our observations to farther galaxies.

Fig. 1 represents the way in which this objective could be reached. It shows different galaxies labeled by their distance, representative Z and redshift, and coloured according to their declination. The MW and the MCs constitute the first steps in this ladder. But with a characteristic Z between 0.1 and 0.01 $Z_\odot$ at the peak of SFR in the Universe, their metallicity is way too high.

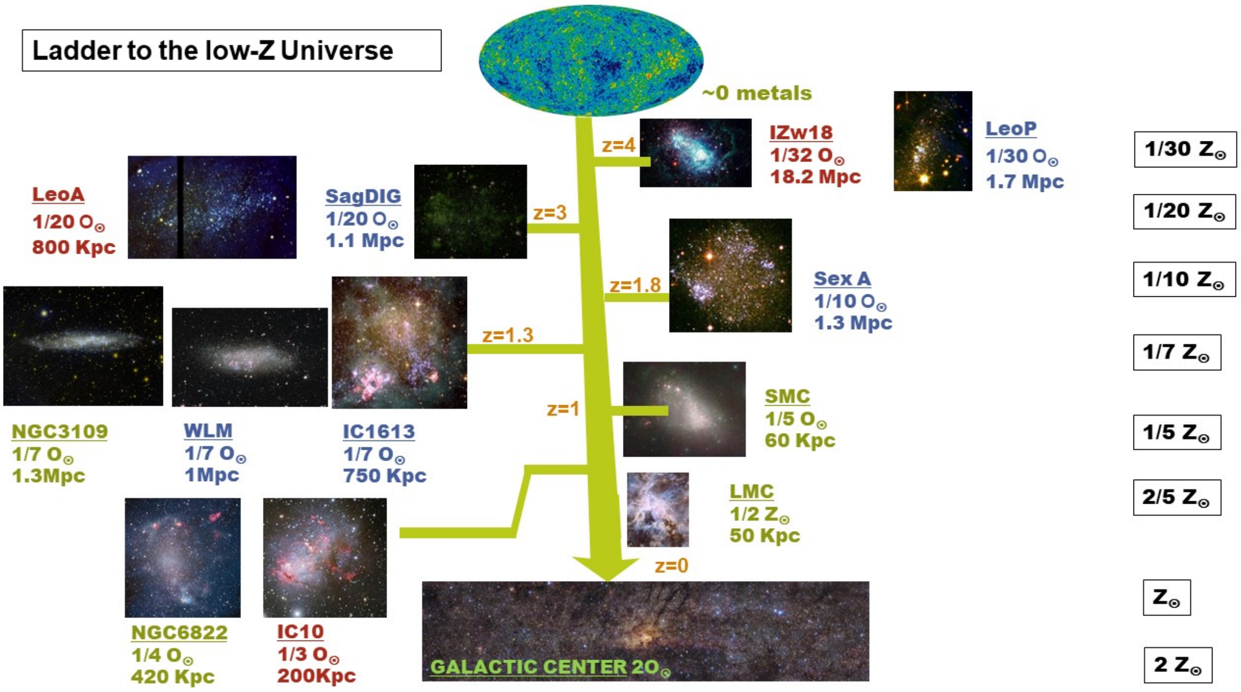

Figure 1: Metallicity ladder to Cosmic Dawn. Colours represent the sky hemisphere where galaxies can be observed: North (red), South (green) or both (blue). Present-day facilities allow us to reach 1/10 $Z_\odot$ metallicities. Beyond, larger telescopes of the 30-m class are required. I Zw18, with very low-Z and strong SFR, is the ideal environment to confront massive star evolution and RDW theories.

Sex A breaks the 0.1 $Z_\odot$ frontier required to enter the deep Universe, and simultaneously represents the distance limit for extensive spectroscopic surveys of individual massive stars with present-day instrumentation. The recent catalog of massive stars in Sex A by [22] provides a solid ground for extending our Z baseline down to values representative of the young Universe. However, it also constitutes a clear example of the challenge we face in this endevour.

Beyond $Z_{\rm SexA}$ (and at larger distances) we find some galaxies with a strong potential for studies at low metallicity. The challenge to enter into the typical Z range of the early epochs means reaching galaxies like Leo A, Leo P, SagDig and specially I Zw18 (that combines very low Z with high SFR).

Exploiting the potential offered by the low-Z nearby galaxies implies to carry out large spectroscopic surveys. At the distances involved, the requirement of high signal-to-noise ratio and spectral and spatial resolution is highly demanding. At the same time, those surveys have to be very extensive, to allow a statistically significant exploration of all possible massive stars evolutionary channels.

3 The crucial role of the Northern Hemisphere: IC 10 and I Zw18

The debate whether the upper-end of the IMF depends on Z cannot be resolved within the Local Group. The most massive resolved stars known to date have $\gtrsim$200M$_\odot$ and are located in the Large Magellanic Cloud (LMC, 1/2 Z$_\odot$) at the core of the 30 Doradus star forming region [7, 16]. Worldwide efforts to scrutinize metal-poorer environments have failed to detect more massive stars than 60-80 M$_\odot$ [23, 2]. Deep infrared photometric studies pending, evidence suggests that most nearby metal-poor galaxies have too low present-day SFR and gas reservoir to form stars over 100 M$_\odot$. The two most promising candidates for further progress are located in the northern hemisphere.

With lower metallicity than the LMC and sufficiently high SFR, IC 10 is the only other metal-poor galaxy of the Local Group that could host very massive stars (VMSs) and enable studies of the metallicity dependence of the IMF. However, this galaxy has been scarcely studied because it experiences high internal extinction, has a low galactic latitude (-3°) and blue massive stars are faint in the IR. [6] identified 26 WR stars, but observations squeezed the Gemini-N telescope to their limits and deeper surveys will require a 30m-class telescope.

Nonetheless, the most important landmark is I Zw18, that exhibits a present-day SFR= 0.6 M$_\odot$ yr^{-1} [3]. With a rich gas reservoir, I Zw18 foreseeably hosts a wealthy population of massive stars that makes it the ideal place to figure out low-Z specific evolutionary pathways and look for VMSs. It is also key to understand the origin of HeII and other high ionization nebular emission lines, whose origin remains a mistery and keeps challenging current stellar models in the low Z regime [10, 17, 33]. The relevance of this galaxy is such that it is one of the highlighted scientific cases of the Habitable Worlds Observatory (HWO), and resolving massive stars in this galaxy is a chief driver for one of the proposed instruments: an integral field unit operating in the UV [31]. However, analog observations attempting to resolve its population in the NIR and optical ranges, critical to determine stellar properties, will never be carried out with the current plans for instrumentation. The task is unfeasible with 10m-class telescopes, the JWST is not sensitivity enough, and the galaxy is out of reach to the ELT.

So far, our observations in Sex A have only begun to probe early-Universe conditions. The next step in the Z ladder (Fig. 1) will become accessible with 30 m-class telescopes equipped with high-multiplex spectrographs and adaptive optics. Combined with space-based facilities such as HST, JWST, and HWO, these capabilities will enable us to study the massive-star populations of galaxies beyond Sex A. Ultimately, our goal is to characterize massive stars and their interaction with the interstellar medium in a galaxy like I Zw18, either through observations of individual stars or population synthesis analyses of small clusters, but grounded in robust knowledge of low-Z stars.

This major effort will provide a solid basis for interpreting observations across many areas of astrophysics, from extremely metal-poor stars and high-redshift galaxies to gamma-ray and gravitational wave progenitors, from the peak of cosmic star formation to the epoch of reionization.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake: Resolved Stellar Populations studies in M31 and its Satellites

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A 30m class optical/near-IR telescope in the Northern Hemisphere, equipped for diffraction-limited imaging and high-resolution, multi-object spectroscopy of faint stars, would enable a transformational investigation of the formation and evolution of M31 and its satellite system—on par with what Gaia, the HST, and other major photometric and spectroscopic facilities have achieved for the Milky Way (MW) and its satellites. The unprecedented detail obtained for our home system has reshaped our understanding of the assembly of the MW disk, halo, and bulge, and that of its satellites, which now serve as a benchmark for galaxy formation and evolution models. Extending this level of insight to the M31 system —that of the nearest massive spiral and the only one for which such a comprehensive, resolved stellar population study is feasible, will allow us to address a fundamental question: how representative is the MW and its satellite system within the broader context of galaxy evolution?

1 Introduction and Motivation

Disk and dwarf galaxies contain a substantial fraction of the stellar mass in the present-day Universe, yet the physical processes that drive their formation and evolution remain only partially understood. Current hydrodynamic cosmological simulations have made remarkable progress in producing realistic disks and reconciling predictions of ΛCDM paradigm with small scale structure but fundamental questions at the heart of galaxy formation and evolution theory persist. Central challenges involve the diverse physical mechanisms that regulate star formation and feedback, the efficiency and radial dependence of stellar migration, the formation of stable disks, the origin and longevity of spiral structure, the origin of thick and thin disks, bulges and bars, as well as the role of mergers, satellite and gas accretion in shaping present day galactic components. These processes are tightly interwoven with the hierarchical growth of structure, and the details remain highly debated.

Two complementary strategies dominate the study of galaxy formation and evolution, each facing distinct limitations when applied independently. The study of distant galaxies through integrated light reveals broad evolutionary trends across cosmic time but cannot disentangle the complex, multi-generational processes that build individual systems. In contrast, "galactic archaeology" reconstructs the full evolutionary history of individual systems with unparalelled accuracy by analysing their resolved stellar populations. Deep color–magnitude diagrams (CMDs) reaching the oldest main sequence turnoffs (oMSTOs) yield precise ages and time-resolved star-formation histories (SFH); high-resolution spectroscopy provides chemical abundance patterns that trace enrichment processes; finally, chemo-dynamics reveals the imprints of accretion, mergers, and internal evolution.

However, at present, this level of detail is achievable only for the MW and its nearest neighbours within the Local Group. The transformative impact of Gaia and large spectroscopic surveys has revolutionized our understanding of the formation of the Galaxy's disk, halo, and bulge, which are becoming a critical benchmark for galaxy models. Yet it is key to understand whether the evolution of the MW and its system of satellites is typical. The nearest large spiral galaxy, M31 (Andromeda), and its satellites, is the only external system for which a similarly comprehensive and detailed approach will ever be feasible, and it is only accessible from the ground in the Northern Hemisphere. M31 and the MW are comparable in mass, luminosity, and Hubble type, but they also exhibit striking differences—ranging from disk structure and bulge prominence to the properties of their satellites and halo populations [1]. These contrasts strongly suggest different assembly histories, making M31 an essential laboratory for testing the generality of the evolutionary patterns inferred for the MW. Moreover, Andromeda's companions, including the smaller disk galaxy M33 and dwarf ellipticals such as M32, NGC 205, and NGC 147, offer uniquely diverse objects in which to examine the interplay between environment, star formation, and chemical evolution.

2 The needed multi-faceted approach

2.1 Detailed star formation histories

The SFH of a galaxy is central to understanding its formation and evolution. It can be defined as the amount of mass transformed into stars, as a function of time and metallicity, necessary to account for its current baryonic content and chemical enrichment. It is the result of, and thus, it allows to identify, major evolutionary events such as mass accretion, interactions, or bar and spiral arm formation. It therefore provides key information to constrain theoretical models of the physical processes that govern the Universe. The most direct way to derive a precise and quantitative SFH is through the analysis of the resolved stars CMD. [2] have shown that the comparison of CMDs reaching the oMSTO with model CMDs are able to yield extremely precise age-metallicity distributions that are directly linked to spatially resolved SFHs. A large amount of HST and JWST observing time has been used to obtain such CMDs for a few fields in the external parts of M31 [3,4], M33 [5], and in low surface brightness dwarf galaxies at similar distances [6,7]. However, central areas of spirals and denser dwarfs need an order of magnitude higher spatial resolution as well as sensitivity, to obtain the required deep CMDs (down to K_{AB}=27.5) at the distance of $\simeq$ 1 Mpc. This is achievable with a diffraction limited (ideally down to $\simeq 1\mu m$) 30m class telescope [8].

2.2 Detailed chemodynamics

The morphological differentiation of galaxies, including the origin of the dwarf galaxy types, results from the combination of hierarchical and secular processes that shape their structure and kinematics. In parallel, star formation transforms the baryonic content and leads to chemical enrichment. The analysis of MW stellar populations has revealed that combining information on their kinematics and chemistry is essential to identify groups of stars formed in different environments [9].

A 30m class telescope providing precise positions, stellar and cluster proper motions, accurate radial velocities and detailed chemical abundances across the M31 system would allow us to replicate many of the studies currently only feasible for the MW, such as identifying chemodynamic substructures in the halo and bulge and characterizing the globular cluster (GC) population. This information would also be essential to characterize the origin and evolution of the disk components that are the defining features of a whole class of galaxies in the Universe.

For this purpose, the discriminating abundance ratio [α/Fe] could be easily measured with a precision of $\sim$0.15 dex in spectra of R$\sim$5000 and S/N$\sim$30 for large samples of RGB stars (K_{AB} $\sim$19.5-21.5), allowing to gather sufficient stellar samples to explore distinct chemical trends. Larger spectral resolution would allow to measure more precise abundances, and is usually required for individual key elements like Na, O and Al, needed to explore the chemical anti-correlations observed in GCs, or n-capture elements like Ba. Access to a wide range of chemical species allows tighter constraints on disk formation models, with a level of detail currently achievable only in the MW.

3 Is the MW typical? A comparable study of the M31 system

A 30m class telescope would allow a study of the M31 system of similar scope as the one afforded by Gaia and major ground-based spectroscopic and photometric surveys for the MW and its satellite system. This study has revolutionised the understanding of our immediate neighbourhood and the physical models of galaxy formation and evolution. However, a single template may lead to biased conclusions, and thus, a comparable study of the M31 system, only visible from the North, is essential. Thanks to the spatial resolution and huge light collecting power, the impact of a 30m class telescope would be critical to study the highest surface brightness regions, which would provide a high target density, and thus, the required statistically large samples. In the following, we highlight the scientific questions in which the contribution of such a facility is essential.

3.1 The inner region

The MW is currently the only galaxy in which quantitative resolved stellar population studies of the bulge can be performed. They revealed a superposition of populations and the secular evolution of a bar component and pseudo-bulge, with evidence for merger debris and a spheroidal component [10]. Extending such detailed fossil-record analysis to external bulges is essential for placing the MW bulge in context and for understanding how common such composite structures are. A 30m class telescope in the North would allow us to resolve the bulge of M31, which offers the best opportunity for this comparison, with the added advantage of a lower reddening and contamination by the disk population. M31's bulge shows strong evidence of a composite nature with both a spheroidal component and a bar-related boxy/peanut structure [11], hosting stars with ages ranging from intermediate to old [12]. However, current observing facilities do not offer the necessary depth and resolution. Resolved spectroscopy of individual stars and deep photometry across M31's bulge and inner disc would reveal the ages, metallicities, and kinematics of its subcomponents, clarifying the origin and evolution of M31's inner regions.

3.2 The globular cluster systems

GCs are fossil records of the earliest epochs of galaxy assembly. Properly characterizing their ages, chemistry and dynamics is crucial to reconstruct the early events that shaped a galaxy's evolution. The exquisite chrono/chemo/dynamical characterization of MW GCs has enabled the accurate distinction between accreted and in-situ objects. Moreover, the link with the accreted field populations led to the identification of each GC former galaxy progenitor [13] and to a reconstruction of the MW merger tree. Once again, using a single system as template can lead to biased conclusions, and thus a detailed characterization of the M31's cluster population is essential.

In fact, the MW and M31 cluster systems show notable differences. While displaying a relatively wide range of ages, metallicities, and masses, the MW GCs are relatively homogeneous from a structural point of view, while M31 possesses a significant population of luminous and compact GCs and a number of extended GCs with no counterparts in the MW [1]. There are also some indications suggesting that GCs in M31 span a wider age range. The determination of ages, abundances, proper motions and radial velocities of M31's GCs would allow us to understand the origin of these differences and to securely assign clusters to distinct accretion events.

Additionally, the existence of multi-populations in GCs, whose origin is still not understood, has been a spectacular finding that challenged our view of GCs as prototypes of simple stellar populations. This phenomenon was first identified through light element anti-correlations in RGB stars and then traced to splits in different CMD sequences. Determining the ubiquity of multi-populations by analysing the GC systems of external galaxies is an important step to identify their origin. High resolution spectroscopy of RGB stars in GCs of the M31 system would allow to analyse light element anti-correlations, and provide an important benchmark in the quest for the origin of multi-populations in GCs, specially considering the wider age and mass range of M31's GCs.

3.3 Disk formation

The disk is the defining structural component of MW-like galaxies, and revealing its formation and evolution is a key goal of galaxy evolution theory. The MW disk appears to consist of a thick and a thin disk components, broadly characterized by different kinematics and abundance patterns showing intricate relationships between them [14]. Thanks to Gaia and ground based spectroscopy, there has been important progress in the determination of the formation epoch of the MW disk and the characteristics of the chemodynamical duality [14,15,16], which however are difficult to reproduce from a theoretical point of view. The detailed observations required to date the emergence of the disk, and to analyse the (possible) chemical dichotomy with resolved stars are now only possible in the MW, with state-of-the art observations for M31 leading to conflicting conclusions [17,18]. A detailed chemical analysis of M31 would help to understand the ubiquity of this dichotomy and its link with the SFH, the accretion history and the environment of a galaxy. As Gaia, WEAVE, 4MOST and future surveys transform our view of the MW, parallel efforts to obtain detailed spectroscopic coverage of M31 will be crucial for placing both galaxies in a cosmological context.

3.4 The dE companions and M33

The M31 satellite system includes galaxy types not present in the MW system. Most notably, it contains dSph galaxies significantly more luminous and higher surface brightness than the most luminous MW dSph satellites and a true dE galaxy, M32, which is possibly the closer counterpart (albeit with drastic differences) of larger elliptical galaxies. These are galaxy types that abound in galaxy clusters, and we have the rare opportunity of study them in detail locally. Finally, M33 offers the opportunity to study a dwarf spiral galaxy and understand how the formation of spiral structure and stellar disks depend on different galactic sizes.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake:

Galactic Archaeology from the Northern Sky

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Abstract

By the 2040s–50s, facilities such as *Gaia*, WEAVE, 4MOST, Rubin, *Euclid*, *Roman*, and the ESO ELT will have transformed our global view of the Milky Way. Yet key questions will remain incompletely resolved: a detailed reconstruction of the Galaxy's assembly from its earliest building blocks, and robust tests of dark matter granularity using the fine structure of the stellar halo and outer disk—particularly in the Galactic anticenter. Addressing these questions requires high-resolution spectroscopy of faint main-sequence stars (typically 1–2 mag below the turnoff) and turnoff stars ($r \sim 21$–23) in low-surface-brightness structures: halo streams and shells, ultra-faint dwarf galaxies, the warped and flared outer disk, and anticenter substructures. We argue that addressing this science case requires a 30 m-class telescope in the northern hemisphere, equipped with wide-field, highly multiplexed, high-resolution spectroscopic capabilities. Such a facility would enable (i) a Northern Halo Deep Survey of $\sim 10^5$–10^6 faint main-sequence and turnoff stars out to $\sim$ 150–200 kpc, (ii) chemodynamical mapping of dozens of streams to measure perturbations from dark matter subhalos, and (iii) tomographic studies of the anticenter and outer disk to disentangle perturbed disk material from accreted debris. A northern 30 m telescope would provide the essential complement to ESO's southern ELT, enabling genuinely all-sky Milky Way archaeology and delivering stringent constraints on the small-scale structure of dark matter.

1 Introduction and Motivation

By the 2040s the Milky Way will be mapped in unprecedented depth and dimensionality. Astrometric and photometric surveys such as *Gaia* [1], (potentially *GaiaNIR* [2]), Rubin [3], *Euclid* [4], and *Roman* [5] will have mapped billions of stars and low-surface-brightness structures across the sky, while large spectroscopic efforts (e.g., LAMOST, WEAVE, 4MOST, SDSS-V) will have provided radial velocities and medium-resolution abundances for tens of millions of relatively bright targets. The ESO Extremely Large Telescope (ELT) [6] will deliver exquisite, but largely targeted, high-resolution spectroscopy and resolved imaging of selected regions of the Galaxy, particularly in the southern hemisphere. Together, these facilities will establish an impressive global picture of the Milky Way's structure and kinematics. However, some of the most fundamental questions about the Galaxy's *detailed* assembly history and the *granularity* of its dark matter halo will remain only partially addressed. In particular, current and planned facilities are not optimized to obtain high-resolution, high signal-to-noise spectra for faint main-sequence stars (typically 1–2 mag below the turnoff) and turnoff stars that dominate the outer halo, stellar streams, ultra-faint dwarf galaxies (UFDs), and outer disk —best targetted from the northern sky in the direction of the Galactic anticenter.

Central question: *How did the Milky Way assemble, in detail, from its earliest building blocks, and what does the fine structure of its stellar halo, including the surviving UFDs, and outer disk—particularly in the Galactic anticenter—reveal about the nature and granularity of dark matter?*

The key fossil record of the Milky Way's formation is encoded in the chemodynamical properties of these stars. Their multi-element abundance patterns trace the conditions in their birth environments and allow us to chemically tag distinct accretion events [7]. The larger building blocks, such as Gaia–Enceladus [8], contain a large number of bright targets that are allowing a fair study with current or upcoming facilities. Their full phase-space distribution, including precise radial velocities, constrains the Galaxy's gravitational potential and its small-scale structure, including perturbations from substructure as inferred from stream dynamics [9,10]. In addition to the accreted and UFD systems themselves, many of the most informative outer-disk and anticenter substructures can be connected to disk perturbations and warp/flare phenomena [11,12]. However, for smaller or low surface brightness systems (which census is expected to grow substantially in the coming years [13]), observing faint stars is crucial. A substantial step forward in these issues requires deep, highly multiplexed ground-based spectroscopy over degree-scale fields. We therefore argue that addressing this central question requires a 30 m-class telescope equipped with wide-field, highly multiplexed, high-resolution spectroscopic capabilities. In the same way as the observation of the Galactic Center has favoured the construction of the ELT and other observing facilities in the South, placing such new facility in the Northern Hemisphere is warranted by the need to study in detail the Galactic anticenter, in addition to the streams and UFD equally observable from both Hemispheres. With MSE no longer moving forward, there is a timely opportunity to pursue a northern facility that can deliver wide-field, highly multiplexed, high-resolution spectroscopy for Milky Way archaeology at the required scale [14]. In practical terms, it would enable survey-scale acquisition of $R \sim 30{,}000$ spectra for faint main-sequence and turnoff stars over wide northern fields (halo, streams, and the anticenter). Without such a capability, progress would rely mainly on small, targeted samples that cannot reach the required statistics. At the same time, such a facility would be much better suited for targeted follow-up of particularly valuable tracers identified by these surveys, including extremely metal-poor stars and the most distant blue horizontal-branch stars. It would also ensure that the northern sky contributes on equal footing to the ELT era, enabling genuinely all-sky chemodynamical mapping and maximizing the scientific return of *Gaia*, Rubin, *Euclid*, and *Roman*.

2 Why a Northern 30 m-class Telescope is Essential

The science case in Section 1 requires a combination of depth, spectral resolution, multiplexing, and sky coverage, best delivered by a Northern Hemisphere 30 m–class telescope with optimal access to the Galactic anticenter.

Faint main-sequence stars as a primary fossil record. The brightest giants have been and will remain indispensable tracers of the distant halo and stellar streams. However, a complete reconstruction of the Galaxy's assembly history requires large samples of faint main-sequence stars (typically 1–2 mag below the turnoff) and turnoff stars, particularly in the outer halo and anticenter. These stars are far more numerous, preserve relatively unprocessed chemical abundance patterns, are less affected by internal mixing, and provide significantly tighter age constraints. At Galactocentric distances of tens to hundreds of kiloparsecs, and in low-latitude anticenter structures, they typically have apparent magnitudes $r \sim 21$–23. Current 8–10 m facilities, and even targeted observations with ELT class telescopes, cannot obtain *high-resolution, high signal-to-noise spectra for large samples* of such stars over wide areas of the sky. Without high-quality chemodynamical data for these faint tracers, any reconstruction of the Milky Way's assembly history and halo potential will remain incomplete.

The role of a 30 m-class telescope. A 30 m aperture, combined with high-resolution, highly multiplexed spectroscopy, provides the photon-collecting power and survey efficiency needed to reach these stellar populations. It would enable the acquisition of $\sim 10^5$–10^6 high-quality spectra of faint main-sequence (1–2 mag below the turnoff) and turnoff stars at $r \sim 21$–23 in (i) the northern halo, (ii) numerous stellar streams and shells, and (iii) the outer disk and Galactic anticenter region. Reaching these limits (typically $r \sim 21$ for key tracers) enables precise $v_{\rm rad}$ and MDFs that, together with proper motions, can constrain spatial variations in the Galactic potential and help reconstruct its time-dependent evolution.

The necessity of the northern hemisphere. Many of the most informative structures for Galactic archaeology and dark matter studies are located in the *northern* sky: extensive networks of halo streams and shells, a substantial population of ultra-faint dwarf galaxies and low-mass clusters, and the Galactic outer disk and anticenter region, including its warp, flare, and low-latitude overdensities. Robust inference on substructure requires accounting for baryonic perturbers (e.g., giant molecular clouds) and leveraging full chemo-kinematic information.

Representative survey programs enabled by a northern 30 m. The capabilities of a northern 30 m-class facility would allow a set of survey programs that are not feasible with existing or planned instruments:

- **Anticenter and Outer Disk Tomography:** deep spectroscopy of outer disk and disk–halo transition stars to characterize the warp and flare, Monoceros/TriAnd-like structures, and the global halo geometry.
- **Northern Halo Deep Survey:** high-resolution abundances and velocities for $\sim 10^5$ faint main-sequence and turnoff halo stars out to ~ 150–200 kpc, decomposing the halo into its constituent accretion events and constraining the total mass and shape of the halo.
- **Northern Streams and Substructure Programme:** chemodynamical mapping of dozens of northern streams to constrain the granularity of the Galactic potential by combining precise $v_{\rm rad}$, MDFs, and proper motions, while accounting for baryonic perturbers.

- **Northern Cluster and Satellite Chronology:** precise ages and detailed abundances for clusters and dwarf galaxies in the outer disk and halo, establishing a time-resolved sequence of the Milky Way's assembly.

Synergy with the ELT. A northern 30 m-class facility would provide the essential complement to ESO's southern ELT, enabling truly all-sky Milky Way archaeology and maximizing synergies with current and future space missions.

3 Science Goals

The science case developed in this White Paper can be framed in terms of the following science goals:

- **Milky Way assembly history:** How can we reconstruct, in a quantitatively robust way, the detailed assembly history of the Milky Way by using the chemo-dynamical properties of faint main-sequence (1–2 mag below the turnoff) and turnoff stars in the outer halo and outer disk? Giants are powerful long range tracers, but they are comparatively rare and can yield sparse, selection-biased samples in low surface brightness structures, limiting a fully quantitative reconstruction [7]. Faint main-sequence and turnoff stars provide much higher tracer densities and cleaner chemical tagging, enabling detailed chemodynamical decomposition of the outer halo and disk [9,10].
- **Small-scale structure of dark matter:** What does the fine structure of stellar streams, shells, ultra-faint dwarf galaxies, and outer-disk perturbations—particularly in the halo and Galactic anticenter region—reveal about the granularity of the Galactic potential and the role of substructure when combined with full chemo-kinematic information?
- **A time-resolved, all-sky picture of the Galaxy:** How can we combine measurements for field stars in the MW disk, clusters, and satellites to establish a time resolved, all-sky view of the Milky Way's formation that is fully complementary to, and synergistic with, studies based on southern facilities such as the ELT and space-based surveys?

4 Summary

By the 2040s–2050s, ongoing and forthcoming astrometric, photometric, and spectroscopic surveys will have revolutionized Milky Way mapping and sharpened the inventory of halo substructure, streams, and satellites. Yet robust constraints on the Galaxy's detailed assembly and dark matter granularity will remain limited by the lack of high-resolution, highly multiplexed spectroscopy for large samples of faint main-sequence (1–2 mag below the turnoff) and turnoff stars in the anticenter and halo. A northern 30 m-class telescope equipped with a wide-field, high-resolution, high-multiplex spectroscopic facility would fill this gap and provide the essential complement to southern ELT-class capabilities. It would deliver the radial velocities and multi-element abundances needed to chemodynamically tag early building blocks and to separate accreted debris from perturbed outer disk material in the anticenter. Combined with proper motions, it would map spatial variations in the Galactic potential and enable time-dependent constraints on halo growth through the chemo-kinematic evolution of streams and outer-disk substructure. Beyond survey mapping, the same capability would provide efficient high-resolution follow-up of rare, high-value targets identified by these surveys (e.g., extremely metal-poor stars and the most distant halo tracers), maximizing the scientific return of the 2040s Milky Way data ecosystem.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake:

Northern Local Star-forming Dwarf Galaxies. Analogues of the First Galaxies and Probes of the Cosmic Metallicity Scale

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Abstract

Star-forming dwarf galaxies in the local Universe, especially extremely metal-poor ones, can be considered analogous to early galaxies of the Epoch of Reionization ($z \geq 6$). Currently available telescopes cannot adequately detect and measure heavy element recombination lines and certain faint collisionally excited lines, which are essential for exploring the effects and biases that potential inhomogeneities in electron temperature and density of the ionized gas may have on determining the chemical composition of these galaxies. On the other hand, the origin of very high-ionization lines (e.g. He ii*, [Ne* v*], C* iv*]) measured in the spectra of an important fraction of these objects remains unknown and a challenge to current stellar models, suggesting the presence of Population III-like stars and/or the existence of non-conventional ionizing sources. Obtaining very deep spectra for a selected sample of local star-forming dwarf galaxies would provide unprecedented constraints on their nature, ionization and true chemical abundances, and could change the metallicity scale we assume to understand the chemical evolution of galaxies over cosmic time.*

1 Introduction and Motivations

Understanding the star-formation history of galaxies requires a detailed analysis of how stellar mass assembly occurs across cosmic time. A key tool for studying galaxy evolution is the chemical enrichment of the interstellar medium (ISM) produced by successive generations of stars, whose nucleosynthetic products offer insight into the processes driving the baryon cycle. Local star-forming dwarf galaxies (SFDGs) contain a large mass of ionized gas characterized by an emission-line spectrum. The most extreme SFDGs in the Local Universe include the best local analogues to reionization galaxies, such as HII galaxies, blue compact dwarfs (BCDs) or green pea (GP) galaxies [1, 2, 3]. They are exceedingly rare compact starbursts, including the most extremely metal-poor galaxies (EMPGs, <10% solar) known [4]. With remarkably similar properties to primeval galaxies (e.g. lowest metallicities, highest star formation per unit mass, and highly ionized and turbulent ISM), they provide excellent local analogues and ideal laboratories for studying massive star formation, chemical enrichment, feedback processes, and the baryon cycle in environments that resemble those frequently observed at higher redshifts [5, 6]. Precise measurements of the chemical abundances and physical conditions in such local analogues open a pathway to understanding the evolution of galaxies over cosmic time.

The chemical composition of SFDGs is usually derived from the intensity of collisionally excited lines (CELs). The abundance of oxygen (O) –the most abundant heavy element in the Universe and proxy for metallicity in the extragalactic domain– can be determined using optical CELs. To obtain precise values of the O abundance, we need to apply the so-called direct method [7], which requires a determination of the electron temperature, T_e, through the measurement of faint auroral CELs of certain ions, on which the intensity depends exponentially on T_e. When the direct method cannot be applied, metallicity is then estimated through the so-called strong line methods based on the intensity of bright nebular CELs, which are calibrated using empirical abundances [8, 9, 10] or photoionization models [11, 12]. These are routinely used in surveys dedicated to studying large samples of faint SFDGs [13, 14, 15] or faint/high-metallicity H ii regions within spiral galaxies [16, 17, 18]. It is important to note that, similar to local analogues, the abundances of primeval galaxies observed with JWST can now be determined using the direct method [19, 6, 20, 21, 22].

In addition to CELs, nebular spectra also feature recombination lines (RLs), whose intensity depends very weakly on T_e. The brightest RLs are those of H i or He i but the O ii, O i, or C ii RLs are also present although very faint, at most 10^{-3} to 10^{-4} times the intensity of Hβ. Since 1942 [23], we know that optical RLs provide systematically higher abundances than the CELs of the same ion. This is the so-called abundance discrepancy (AD), quantified by the AD factor (ADF, difference between the abundances derived from RLs and CELs). In H ii regions, the ADF of O^{2+}, ADF(O^{2+}), is a factor between 2 and 5 [24, 25]. Such a dramatic difference calls into question whether the routine methods based on CELs are providing the true metallicities of star-forming regions. The origin of the AD has been largely unknown, but [26], found a correlation between the ADF and temperature fluctuations (variations in the spatial distribution of T_e, parameterized by t^2[27]). [26] also demonstrated that the presence of t^2 only affects in a significant way to the high ionization zone of nebulae (where O^{2+} ion is located) and therefore only the value of T_e([O iii]) should be affected by t^2, not T_e([N ii]) or T_e([O ii]). In conclusion, the effect of t^2 onto T_e

determinations implies that abundances determined using T_e([O III]) –the only T_e determinations available for SFDGs in the vast majority of cases– could be severely underestimated, especially in low-metallicity H II regions and SFDGs. The AD/t^2 problem also affects the application of strong-line methods such as R23, N2 and O3N2, which are calibrated either on CEL-based T_e measurements or on photoionization models. They yield mutually inconsistent abundance scales and can differ by $\gtrsim 0.5$ dex at fixed line ratios, propagating large systematics into the mass-metallicity and other fundamental metallicity relations [28, 29]. For all the aforementioned reasons, it is essential to obtain more RL-based abundance determinations in SFDGs and EMPGs where available data are extremely limited [26].

In addition to a dependence on T_e, abundance calculations also rely on precise determination of the electron density, n_e. In the last years, the use of 10m-class telescopes, has permitted the community to derive n_e from different CEL ratios ([S II], [O II], [Cl III], [Ar IV], [Fe III]) in the spectra of extragalactic H II regions and SFDGs, moving beyond the typical determination solely based on [S II] $\lambda6717/\lambda6731$. [30] found that n_e tends to be underestimated when only [S II] diagnostic is used; this is caused by the non-linear n_e dependence of the different line ratios, suggesting the ubiquity of density inhomogeneities in H II regions. The average underestimate in the available local sample is ∼300 cm^{-3}, which introduces systematic overestimates in the T_e calculations. In general, the n_e underestimate has a small impact on abundances derived from optical CELs, being less than ∼0.1 dex. However, the n_e effects are critical when using infrared fine structure CELs. Although those puzzling results are currently restricted to local, low-n_e (10^1-10^3 cm^{-3}), and relatively bright objects, they could have a more significant effect when using the rest-frame UV-optical spectra of high-z galaxies. Recent work suggests a cosmic evolution of n_e, reaching values on the order of 10^4-10^5 cm^{-3} in high-z galaxies [31, 32]. In that case, the adopted value of the standard [S II] diagnostic is largely inadequate and can result in incorrect abundance determinations biased toward lower values, thereby altering our understanding of the chemical evolution of primeval galaxies. A further need to study the n_e and T_e structure of local SFDGs in much greater detail arises from unexpected measurements of extremely high N/O ratios in high-z galaxies [33, 34, 35]. While the origin of N overabundance challenges our understanding of its nucleosynthesis in metal-poor systems, the impact of n_e on metallicity has important consequences for key scaling relations, such as the mass-metallicity relation that is closely linked to galaxy formation and evolution.

Another frontier goal of observational astrophysics is to understand the epoch of reionization (EoR) and its connection to the young stellar populations of the first galaxies. In the EoR, galaxies consistently exhibit stronger nebular emission lines due to their bursty star formation and possible black hole (BH) activity, and their ionized ISM show more extreme properties than found locally [36]. They have larger EWs, n_e and T_e, reflecting hard radiation fields and more extreme ISM conditions, as evidenced by strong high ionization lines, e.g. He II, [Ne V] or C IV. The combination of these properties with a highly turbulent ISM due to bursty star formation and strong feedback, mostly from massive stars and SNe, facilitate the escape of ionizing photons to the intergalactic medium, thus contributing to reionization.

However, the origin of such properties and the unambiguous characterization of the ionizing sources leading to such strong ionization lines, remains unknown. In particular, the high-energy ionizing continuum (>54 eV) is completely unconstrained, especially in the most metal-deficient SFDGs, where the high-ionization phenomenon is expected to be common. This translates to an alarming issue when interpreting the spectra of high-z galaxies (e.g. [37]). Moreover, understanding the physics behind the nebular He II $\lambda4686$ line is notably relevant as this line is considered a potential diagnostic of the elusive Pop III stars and their primeval hosts, which are in turn believed to have strongly contributed to the cosmic reionization [38, 39].

2 The Science Challenge

The accumulated knowledge of local SFDGs has been largely built from samples accessible from the Northern Hemisphere, which allows observations of ∼70% of the known Local Volume SFDGs (e.g. from [40]). Many classical SFDGs, including well-studied nearby analogs to high-z galaxies, such as I Zw 18, II Zw 40, NGC 2366/Mrk71, NGC 1569, Leo P, CGCG 007-025, and SBS0335−052E, have been the subject of deep observational campaigns from northern telescopes, consolidating their role as reference objects. Furthermore, the main surveys that identified and classified most known SFDGs primarily covered the Northern Hemisphere, including the historical Palomar Observatory Sky Survey (POSS) [1], the Sloan Digital Sky Survey (SDSS)

[14], or the most recent DESI and J-PAS spectrophotometric surveys [41, 42], which can provide the most complete local samples. Therefore, the density of high-quality targets, systematic catalogs, and historical continuity of observations has favored a better understanding of northern SFDGs, including the best analogues to high-z galaxies. However, nearby iconic prototypes of extreme SFDGs, such as I Zw 18, Leo P or SBS0335-052E, widely studied with exquisite datasets from the ground and from space, and well visible from the North, still lack optical spectroscopic observations with sufficient depth to measure RLs of heavy elements (multiplet 1 of O II at about λ4650 and C II λ4267) or the faintest CELs (such as [N II] λ5755, [Cl III] $\lambda\lambda$5518,5538, [Fe III] λ4702), all of which are needed to perform an adequate exploration of the presence and effects of T_e and n_e inhomogeneities and their impact on chemical abundances.

Similarly, the two nearby starbursting dwarfs I Zw 18 and SBS 0335−052E are the most metal-poor (few % solar) He II and [Ne V] emitters at $z = 0$ [43]. However, unveiling the origin of such intrinsically faint high-ionization lines remains a strong challenge and, despite many observational and theoretical attempts, the source of the high-ionizing SED (E $>$ 54 eV) keeps challenging current stellar models in these galaxies (e.g., [44]). The possibility remains that nebular high-ionizing lines (e.g. He II, [Ne V]) are powered by predicted peculiar hot massive stars (e.g. Pop III-like, chemically homogeneous evolving stars, see e.g. [45, 46, 47, 48, 49]). In I Zw 18, direct measurements of T_e[O III] values of $\sim$22000 K are spatially coincident with the He II ionizing gas [50], and discrepancies between observed and theoretical O^{3+}/H^{+} values [51] indicate the existence of additional ionizing sources other than the conventional ones (e.g., WRs, X-ray sources).

A tenfold increase in the photon-collecting capacity of a 30m-class telescope –coupled with a high-throughput optical spectrographs and AO-fed IFUs– in La Palma could undoubtedly provide detections and reliable measurements of the aforementioned relevant but faint RLs and CELs in sizeable samples of local SFDGs, EMPGs, and H II regions, overcoming the present limitation to a handful of bright objects. This will allow us to quantify n_e and T_e inhomogeneities and the ADF, shown to be crucial for avoiding severe underestimates of the O abundance especially at low metallicity, and to derive an empirical RL-based calibration of classical strong-line indicators (e.g. O23, O3N2, N2) and photoionization models across a wide range of ionization parameter and excitation. These deeper observations would yield unprecedented constraints on the nature, ionization and true chemical abundances of SFDGs, and are necessary to recalibrate strong line methods. Recalibration of the rest-frame optical/UV diagnostics used for galaxies at $z \gtrsim 2-10$ is essential to provide a robust metallicity baseline and interpret JWST and ELT surveys, and to reassess the cosmic evolution of the mass–metallicity relation and the baryon cycle.

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Why the Northern Hemisphere Needs a 30–40 m Telescope and the Science at Stake: Key Targets of Opportunity on Gas and Ice Giants and their satellites

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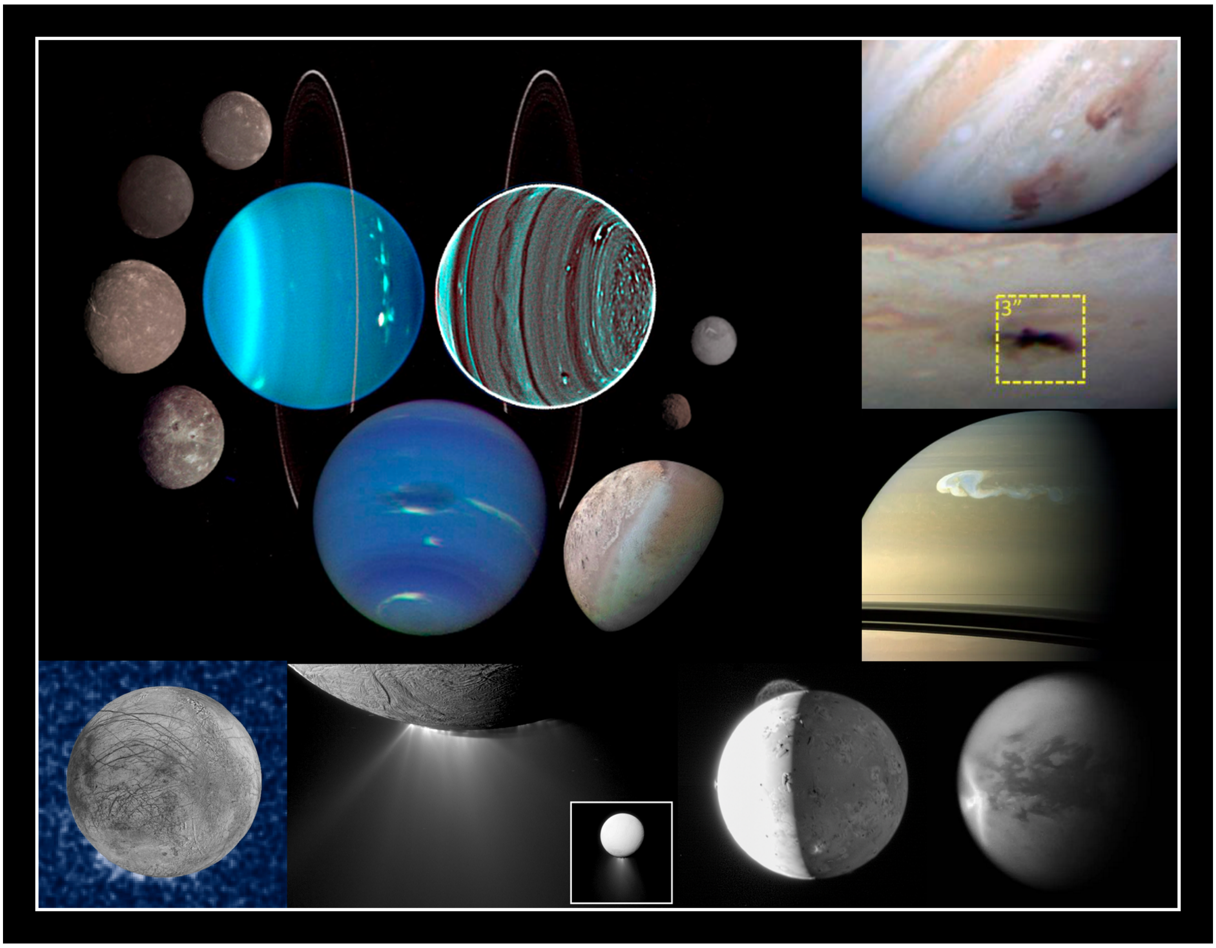

The Extremely Large Telescope (ELT) will transform our knowledge of the outer planets and their satellite systems; however the visibility of unique targets of opportunity with high scientific value will be reduced for northern objects. Uranus' declination favors observations from the Northern Hemisphere until 2055, and Neptune will be favored from the Northern Hemisphere from 2027 for the next 90 years. Jupiter and Saturn experience cycles of better observability from either hemisphere on cycles of 10 and 30 years. These planets and their satellite systems often offer unique opportunities for discovery through time-critical observations. **We argue that a 30-m class size telescope in the Northern Hemisphere with complementary scientific instrumentation to that on the ELT will secure the possibility of observing high-impact unpredictable phenomena in these systems.**

Solar System Science in the 2040s

Breakthrough science in the Solar System in the 2040s will be accomplished with a combination of space missions, space telescopes, and extremely large ground-based telescopes using Adaptive Optics (AO) [1, 2]. Two key science themes in Solar System science in that decade will be: **(1)** The exploration of the moons of the giant planets and their potential for habitability and biosignatures [3], and **(2)** The in-depth characterization of Uranus and Neptune, which remain largely unexplored and hold fundamental information about the formation of the Solar System, being our closest and best examples of a class of planetary objects that dominates the census of exoplanets [4].

While there are no space missions selected to Uranus and Neptune, missions to these targets are some of the highest priorities for space agencies [4, 5]. Key areas of study for ice giants are their planetary origins [6], atmospheric dynamics [7], and unique magnetospheres that interact in complex ways with the solar wind and upper atmosphere [8]. Exploring Uranus' moons and Neptune's captured dwarf planet Triton will provide crucial insights into the formation and activity of ocean worlds in our solar system. While Jupiter's moons will be explored by the JUpiter ICy moons Explorer (JUICE) and Europa Clipper missions in the 2030s [9, 10], and ESA is developing a mission to Enceladus in the 2050s [3], their geological activity is time-dependent and is unconstrained by existing observations.

Observability of Outer Planets and their moon systems

Figure 1a shows the declination of the Outer planets. Saturn, and thus Enceladus and Titan, are favored from the south hemisphere in the 2040s, but the situation inverts in 2055. Uranus and Neptune are largely favored in the Northern Hemisphere over multiple decades, and Jupiter experiences periods of 5 yr of better observability from either hemisphere. AO systems are more efficient for high elevation targets (> 30°) [11]. This has a strong impact on the number of nights and number of hours per night each target is accessible for astronomical observations with AO (see 1b).

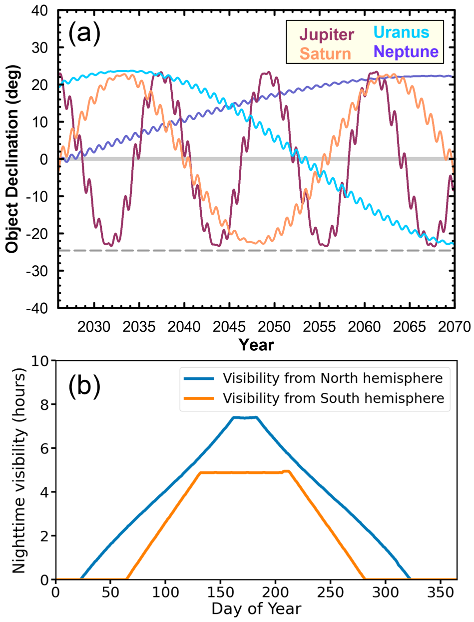

Figure 1: (a) Declination of the outer planets and their satellite systems. The dashed gray line shows the latitude of Cerro Armarzones. (b) Number of nighttime hours for a target with declination 23.7° at elevations above 30° from equivalent latitudes at ±24.6°. Stronger differences can be found for targets with oppositions near the Northern Winter.

Critical Targets of Opportunity

Unexpected solar system phenomena observed in the past have triggered target of opportunity observations (ToOs) that have led to important discoveries. Solar system ToOs typically require targeting specific locations on a rotating planet surface (e.g., giant impacts [12, 13] and convective storms [14]), or specific moments in time, such as giant eruptions on Io [15], Io in eclipse from Jupiter, or minor satellites of Uranus and Neptune at their largest elongation from the planet. The following is a set of examples of rare phenomena that cannot be anticipated, require time-critical observations, and can provide high-impact advances to our understanding of planetary processes.

Impacts on Giant Planets: Impacts on giant planets are rare phenomena able to provide unique insights into impactor populations, the physics of high-velocity atmospheric impacts, and giant planet stratospheric chemistry and circulation. Two large impacts have been witnessed on Jupiter from comet SL9 [12] and an asteroid object in 2010 [13, 16]. Statistics of these and smaller impacts [13, 17] imply that Jupiter may receive impacts from objects that can leave a visible trace in Jupiter's atmosphere once per decade. The observation of these events could significantly advance our knowledge of cosmic impacts. However, depending on the size of the impactor, its atmospheric trace could disappear in days to weeks or months, and the most interesting science is linked to observations acquired as quickly as possible. A high-resolution imaging and spectroscopic investigation of the contamination in the atmosphere can reveal the impactor direction, the energy released, the dynamics of the upper atmosphere from the evolution of aerosols, and the atmospheric penetration and density of the object. Spectroscopy can reveal the presence of hydrocarbons, nitriles, and CO, and the water and oxygen content of the impactor and the dark debris in the atmosphere can reveal its origins and chemical make-up. Given their effective area, impacts on Saturn, Uranus, and Neptune could occur from less than once per decade for Saturn to once per century for Uranus and Neptune.

Outer planet storms: Superstorm eruptions on Jupiter and Saturn, and the sudden formation of meteorological systems on the calmer Uranus and Neptune are key to understanding heat transport within hydrogen-dominated atmospheres. Outstanding questions include the development of moist convection under inhibition from molecular weight stratification [18], and the basic nature and depth of vortices in Uranus and Neptune [19]. A 30-m size class telescope can resolve the detailed vertical and horizontal structure of these features, reveal the desiccation of the atmosphere produced by convective storms [20, 21] and determine the energetics of these phenomena from their effect on winds and cloud top altitudes [14]. For Uranus and Neptune, 30-m class size telescopes will achieve spatial resolutions approaching the best observations achieved by the unique *Voyager-2* flyby.

Extreme eruptions on Io: Io's intense volcanism is driven by tidal heating from its orbit in Laplace resonance with Europa and Ganymede. The details of how tidal heating produces eruptions remain unclear. Spacecraft data and monitoring with 6-8-m size telescopes show persistent but highly variable activity, including rare outbursts that can briefly double Io's thermal emission. Early detection of these events can yield clues about Io's interior and magma generation. Telescopes in the 30-m size class will provide much sharper spatial and spectral data, will be able to resolve multiple hot spots within single lava lakes, and track rapid changes occurring over minutes to days [22]. Time-critical observations following the discovery of a major eruption on Io will deepen our understanding of Io's volcanism and support studies of cryovolcanism on ocean worlds such as Europa.

Cryovolcanism: Europa, Enceladus, Triton and small ocean worlds: Geyser-like plumes on Jupiter's moon Europa are a debated topic. Their presence will be investigated by the Europa Clipper and JUICE missions in the early 2030s [23, 9]. If Europa is an active cryovolcanic world, the activity will be tenuous, variable, and only accessible for observations with extremely large apertures. Infrared/NIR spectroscopy can characterize water emissions and organics emitted from Europa's interior. Among the Icy moons with active cryovolcanism, Triton remains the most difficult target for investigation. *Voyager-2* discovered active geysers [24], but with a size of 0.12 arcsec when observed from Earth, no current facility (not even JWST) can investigate geysers on Triton, and only stellar occultations can unveil part of the atmospheric evolution over a Triton year. Neptune and Triton will remain difficult to observe from the ELT due to Neptune's declination, but a 30-m class size telescope in the Northern hemisphere will allow to map compositional contrasts on the Uranian and Neptunian satellites with a spatial resolution comparable to what JWST can do for the Galilean satellites today.

Rings and small moons: Planetary rings provide natural laboratories for disk processes and clues to the origin and evolution of planetary systems. Rings are active systems that produce short-lived ring arcs, spokes and orbital variations in some of the minor moons [25]. Advances in the understanding of the rings of Neptune and the interactions between the unstable complex systems of Uranus moons require time-domain observations that would be complex to obtain from the southern hemisphere for decades.

Finally, northern and southern large telescopes will enable complementary spectral and imaging capabilities, contributing to deeper insights into long-term processes than a single instrumental setup in a single large telescope.

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Why the northern hemisphere needs a 30–40 m telescope and the science at stake: Massive stars in spiral galaxies

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Abstract

This document discusses the three main lines expected to dominate massive-star research in the 2040s, namely:

- **(1)** The role of metallicity in stellar evolution, especially in determining the end products such as gravitational-wave progenitors.
- **(2)** The initial mass function from the most massive stars to substellar objects.
- **(3)** The role of the environment in the different modes of star formation from compact star clusters to born-this-way associations and from massive clusters to small stellar groups.

More specifically, we present the contributions to such science that would be enabled by a 30 m type telescope in the northern hemisphere studying spiral galaxies. Those can be grouped in three: our own Galaxy, the Milky Way; the other two spiral galaxies in the Local Group, M31 and M33; and other galaxies within 25 Mpc, such as M101, M51, and NGC 6946. This work is based on the fact that, as of today, no construction of a 30 m telescope has yet started in the northern hemisphere, so even in the best case scenario of such a hypothetical telescope, its full operation would not start until the late 2030s or early 2040s. It makes no assumptions about its location but supposes an instrumentation development similar to that of ELT.

1 Introduction

Massive stars are the great galactic influencers as, solar mass for solar mass, no other astronomical objects exert as many effects in galactic evolution in the form of ionising radiation, chemical enrichment, and injection of kinetic energy into the surrounding stars and ISM. Yet, they are scarce and often located in dust-enshrouded environments, which often makes massive-star astronomy a game of picking the right location to study its targets. Under those circumstances, in this white paper we first present the main lines of research expected to be significant for massive stars in the 2040s and then we point the locations in spiral galaxies that are unique to the northern hemisphere and not accessible from the southern hemisphere. Those are divided in three blocks: the Milky Way (with the Cygnus sightline as the most inetresting location); M31 and M33 in the Local Group; and other northern spiral galaxies such as M51, M101, and NGC 6946.

2 Main research lines for massive stars in the 2040s

The main lines of research that we expect to be significant for massive stars in the 2040s are:

(1) The role of metallicity Z – ranging from near-primordial to supersolar – in stellar evolution. Metallicity impacts the evolution of massive stars primarily through mass loss, which is higher at large values of Z. This, in turn determines the nature of the final end products, which we are observing as gravitational-wave (GW) progenitors. Nearby spiral galaxies are an excellent laboratory to explore this issue, as a 30 m telescope offers the possibility of spatially resolved analyses of individual stars across their metallicity gradients.

(2) The initial mass function (IMF) from the most massive stars to substellar objects. At near-primordial metallicities the IMF is expected to be top heavy, with a significant number of very massive stars (VMSs, with masses above 120 $M_\odot$), but such stars are also observed in galaxies such as the Large Magellanic Cloud (LMC).

(3) The role of the environment in the different modes of star formation (SF), from compact star clusters to born-this-way associations and from massive clusters to small stellar groups. Is the IMF constant in different environments? How soon is the present-day mass function (PDMF) observed in clusters altered by dynamical events such as stellar ejections? How does massive-star feedback into the ISM alter galactic structure and future star formation?

3 The Cygnus sightline in the Milky Way

The sightline in the direction of Cygnus is not accessible from most of the southern hemisphere and is unique in the sky because it is a MW spiral-arm tangent that contains: (a) the site of most intense recent SF within 2 kpc (Cyg OB2); (b) the most-massive O-type binary within 1 kpc (Bajamar star); (c) other massive-star forming regions in the MW Local Arm; and (d) more distant objects located in other MW spiral arms such as Cyg X-3. Despite the proximity, the location at a tangent makes extinction exceptionally large and requires large telescopes (even 30 m-class ones) to acquire high-quality data in the blue-violet region of the spectrum, where the information content for OB stars is by far the highest. As examples, three stars in Fig. 1, Bajamar star, Cyg OB2-12, and 2MASS J20395358+4222505, would be among the brightest in the northern hemisphere if it were not for extinction. Instead they are hard to locate in that image because they have $A_{5495} > 10$ mag [19, 11].

Optical multi-object spectroscopy with a 30 m telescope would allow to fully characterize the massive- and intermediate-mass stellar population in the North America nebula, Cyg OB2 and elsewhere along the sightline within 2 kpc, even for the targets with the highest extinctions. Equivalent NIR multi-object spectroscopy would allow to do the same with the low-mass and substellar pre-main sequence (PMS) populations. This comprehensive characterization would lead to the derivation of a robust IMF across the full mass spectrum and to explore the role of environmental conditions and stellar feedback in shaping the IMF and the dynamical evolution of young massive clusters at near-solar metallicities. The proximity of the analysed regions would allow for the inclusion of the full effects of binarity [18] and ejected stars [21] and from there determine the possible existence of variations from the canonical Kroupa IMF [14].

Other Galactic sightlines should provide complementary information on the IMF. A 30 m northern telescope should also be able to peer into the very young W3 region (the Fish Head Nebula) and to analyze the IMF for the full mass spectrum (including brown dwarfs) in the outer regions of the MW, with metallicities expected to approach those of the SMC but at an order of magnitude in distance closer.

4 M31 and M33: the Rosetta stones for spiral galaxies

M31 and M33 are the two other spiral galaxies in the Local Group besides the MW, which makes them the Rosetta stones for the study of spiral galaxies. They are only accessible from the northern hemisphere and, at the distance of M31 and M33, a 30-meter telescope should be able to resolve compact massive clusters for massive and intermediate-mass stars (Table 5 in [24] and Fig. 2).

4.1 M31

M31 is the largest member of the Local Group and the closest spiral, at a distance of 790 kpc. Despite its proximity, our knowledge of its chemical properties is more imprecise in comparison with M33 or even more distant galaxies such as M101 due to its high inclination (77°), making the extinction stronger than in face-on galaxies. Bright, large H II regions are scarce and, additionally, those observed have usually low excitation (hence making more difficult the determination of abundances via direct methods). There are few studies using H II regions since the pioneering works by [9, 1]. More recently, [10] determined a metallicity gradient of -0.06 dex/kpc for 20 H II regions but based on the indirect method. The only analyses using massive stars (blue supergiants, or BSGs) are those by [30, 25, 27] do not show evidence of a significant gradient but they only have a total of seven stars and significant scatter due to low number statistics: a larger sample is clearly needed, and this could be obtained with 10 m class telescopes in the next decade, as the PHAT survey done at HST resolution [8] allows us to pick isolated BSGs with relative ease. However, a 30-m telescope incorporating mid- and high-resolution nIR spectroscopy (including both single object and IFU) will be needed to achieve, for the first time, a full characterization of the massive star population in M31, leveraging the limitations imposed by extinction. Eventually, this will provide unique datasets to perform investigations of the IMF of clusters and associations as a function of metallicity with emphasis on spatial resolution and a larger mass range compared to M51/M101

4.2 M33

M33 is the third largest member of the Local Group of galaxies after M31 and the MW. It was the first of the galaxies in which a radial abundance gradient was recognised [23]. Thanks to its modest distance (810 kpc) and almost face-on orientation (Fig. 2), it is the spiral galaxy with the largest amount of H II data to study the distribution of abundances, using either direct or indirect methods [22]. Surprisingly, that paper found an intrinsic oxygen abundance scatter of 0.11 dex at a given radius, implying the the ISM is not well mixed. As a consequence, the abundance gradient is difficult to determine if the number of analyzed objects is not large enough (e.g. the slope changes from -0.027 to -0.054 dex/kpc following [22] or [16], with 61 and 14 H II regions, respectively). The only comprehensive study of the metallicity gradient using massive stars (BSGs) to date is that of [28], who obtain -0.06 dex/kpc, but only considering 11 stars. M33 was also nearly fully imaged at HST resolution by PHATTER [31], thus allowing us to already have a good selection of young stellar clusters to derive the IMF with a 30 m telescope (e.g. lower right panel of Fig. 2). The galaxy hosts NGC 604, the prototype Scaled OB Association, in its outskirts ([17] and upper right panel of Fig. 2). Together with 30 Dor (which has a higher proportion of younger stars) it is the richest low-extinction site of star-formation in the Local Group and, hence, a prime target for a 30 m telescope. In particular, the relatively strong gradient in M33 brings its metallicity from solar at the center to values intermediate between the LMC and the SMC in the outskirts. This makes M33 a perfect laboratory where to independently test our current massive stars winds and evolution knowledge as well as the impact of metallicity and environmental effects of massive star formation and evolution. In parallel, achieving a 2D map of abundances of the blue massive star population of M33 will allow to perform a comprehensive study of both radial and azimuthal variations of metallicity across the disc of M33, providing useful constraints for studies of the chemical evolution of this large-scale pure-disc spiral galaxy.

5 Beyond the Local Group

Going beyond the Local Group implies losing spatial resolution and being able to analyse a smaller range of stellar masses in the IMF. On the other hand, it provides us with a larger sample of spiral galaxies and, more specifically, of massive face-on grand-design ones. It is there where a larger range of star-formation intensities can be explored and, with that, their effect on the environment. In this respect, the three best galaxies in the local universe are M101, M51, and NGC 6946, only accessible from the northern hemisphere.

M101 is a face-on grand-design spiral galaxy located at a distance of 7.5 Mpc. It was other spiral galaxy used by [23, 26] to establish the presence of an abundance gradient in spirals using H II regions. The most comprehensive determination of the abundance gradient was done by [13], who used 20 H II regions to determine a value of -0.027 dex/kpc. The study was extended to the inner high-Z disk by [2]. A recent study by [5] analysed 13 BSGs in M101, ranging in metallicity from 1.3 $Z_{\odot}$ to 0.3 $Z_{\odot}$. Note, however, than the outskirts of M101 have an even lower metallicity, such as the one for NGC 5471 (Fig. 3).

M51 is another large-design face-on spiral galaxy at a similar distance (7.2 Mpc) that has been interacting with the close-by small galaxy NGC 5195 in the past hundreds of millions of years. This interaction has been certainty affecting its star formation mode, hence making M51 an ideal and unique laboratory for environmental studies (e.g. [12]). Figure 4 shows how the ISM "in negative" in the form of dark dust lanes in the optical becomes an ISM "in positive" in the MIR due to dust emission.

As a third case, NGC 6946 is also grand spiral with a high inclination at a similar distance as than M101 and M51 (7.7 Mpc). It has a high star-formation rate and a large number of H II regions across its face, that allows for the determination of its 2D abundance distribution [7]. In particular, [6] have detected azimuthal metallicity variations across spiral arms.

The massive star population of these galaxies (and some other, such as M81, NGC 2403, IC342 and M94) offers the possibility to extend the studies in M31 and M33. There are only a handful of studies analyzing individual massive stars beyond the Local Group (e.g. [29] for NGC 300, [15] for M81 or [4] for NGC 2403). Thus we could study the upper end of the IMF, the Z-dependence of the massive stellar physics (also taking into account the possibility of finding supersolar metallicities in these galaxies). Although spatial resolution will often be insufficient to resolve the stellar clusters with a 30 m-class telescope, we will be able to conduct spectral synthesis analyses in relatively small regions. These could be later extended to further galaxies. The comparison of results for H II regions with the stellar abundances will provide a solid ground to determine metallicities at large distances.

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Figures

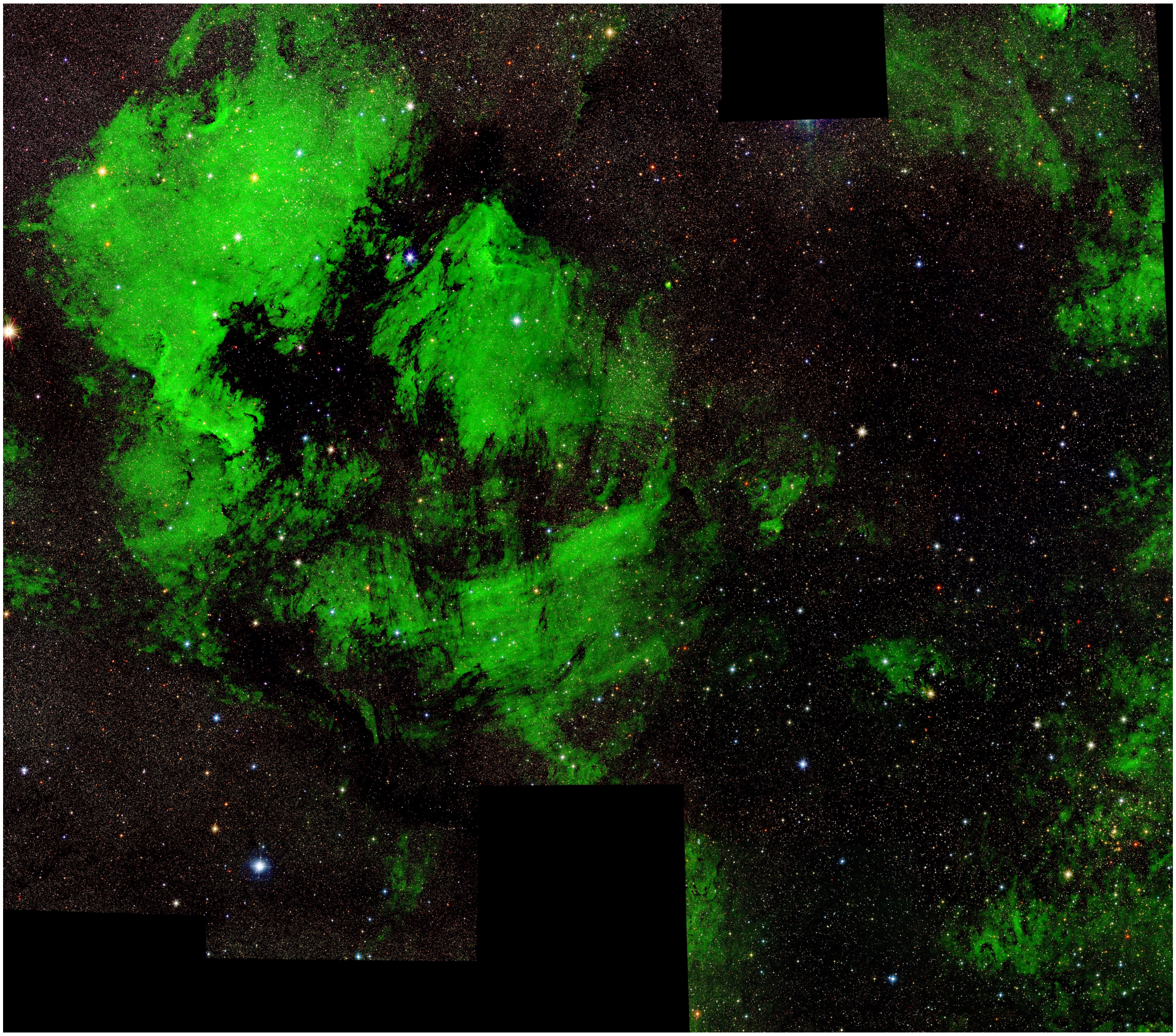

Figure 1: 6.05×5.37 sq.dg. (180 pc × 159 pc at a distance of 1.7 kpc) portion of the Cygnus sightline from the GALANTE survey [20] in F861M (R), F660N (G), and F515N (B). The North America and Pelican nebulae are in the upper left (d ~800 pc) and the massive Cyg OB2 region is in the lower right (d ~1.7 kpc, both in the Local spiral arm), where we also find more distant highly extinguished objects such as Cyg X-3 (d ~7.4 kpc). Extinction is highly variable, with cases of $A_{5495} > 10$ mag even at distances less than 1 kpc. North is up and East is left.

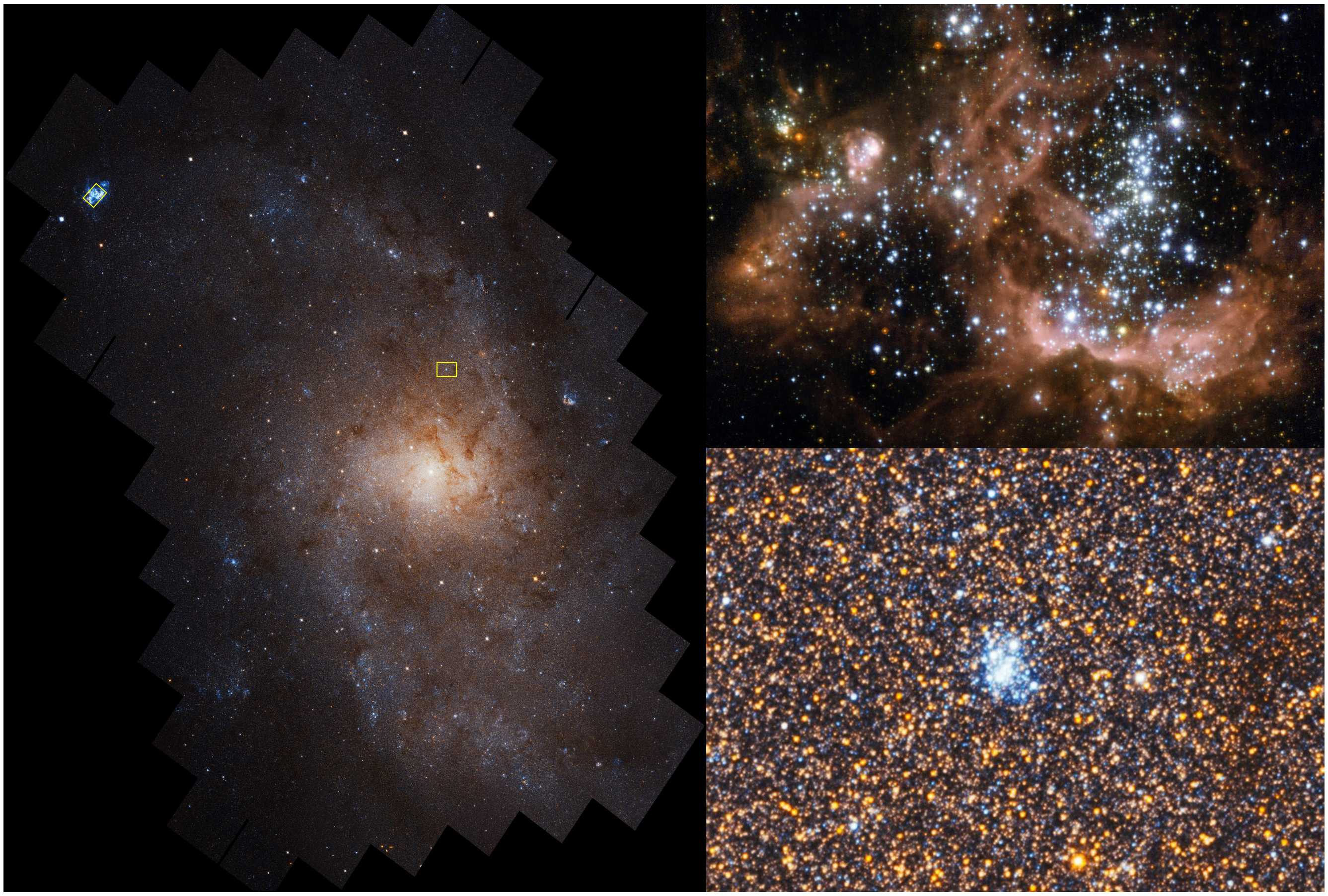

Figure 2: (left) $18.8' \times 23.8'$ (4.60 kpc × 5.82 kpc) HST/ACS-WFC M33 mosaic from the PHATTER project [31] with F435W used for the cyan channel and F814W for the orange channel. North is up and East is left and the yellow rectangles correspond to the two $31.35'' \times 22.50''$ (128 pc × 92 pc) regions on the right panels. (top right) HST/ACS-HRC image of NGC 604, the scaled OB association that is the largest site of recent massive-star formation in M33. The colors are from a combination of UV+optical filters (see `https://esahubble.org/images/potw1019a/`) obtained from HST program GO 9419 (P.I.: Rodolfo Barbá). Given the intensity of SF and the location in the outer region of M33, most stars seen in the image are young and members of NGC 604. (bottom right) Zoom-in of the left panel into a young stellar cluster in the inner region of M33. The population in this case is dominated by the field, with a mixture of masses and ages and most of the light originating in low- and intermediate-mass red giants. Given the compactness of the cluster, it is only partially resolved even with HST but could be easily resolved by a 30 m telescope with adaptive optics.

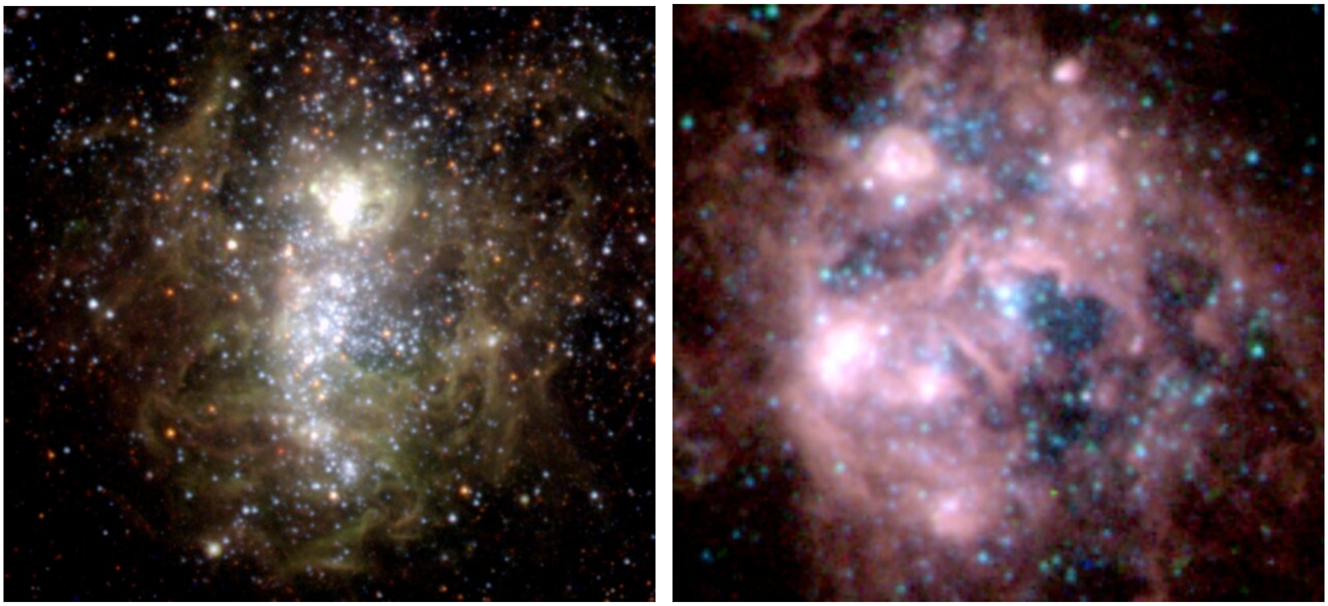

Figure 3: Two giant H II regions in M101 [3]. (left) 20.9″ × 19.1″ (690 pc × 630 pc) HST/WFC3 mosaic of NGC 5455 with F600LP in the red channel, F555W in the green channel, and F438W in the blue channel. (right) 20.9″ × 19.1″ (690 pc × 630 pc) HST/WFPC2 mosaic of NGC 5471 with F656N in the red channel, F675W in the green channel, and F547W in the blue channel.

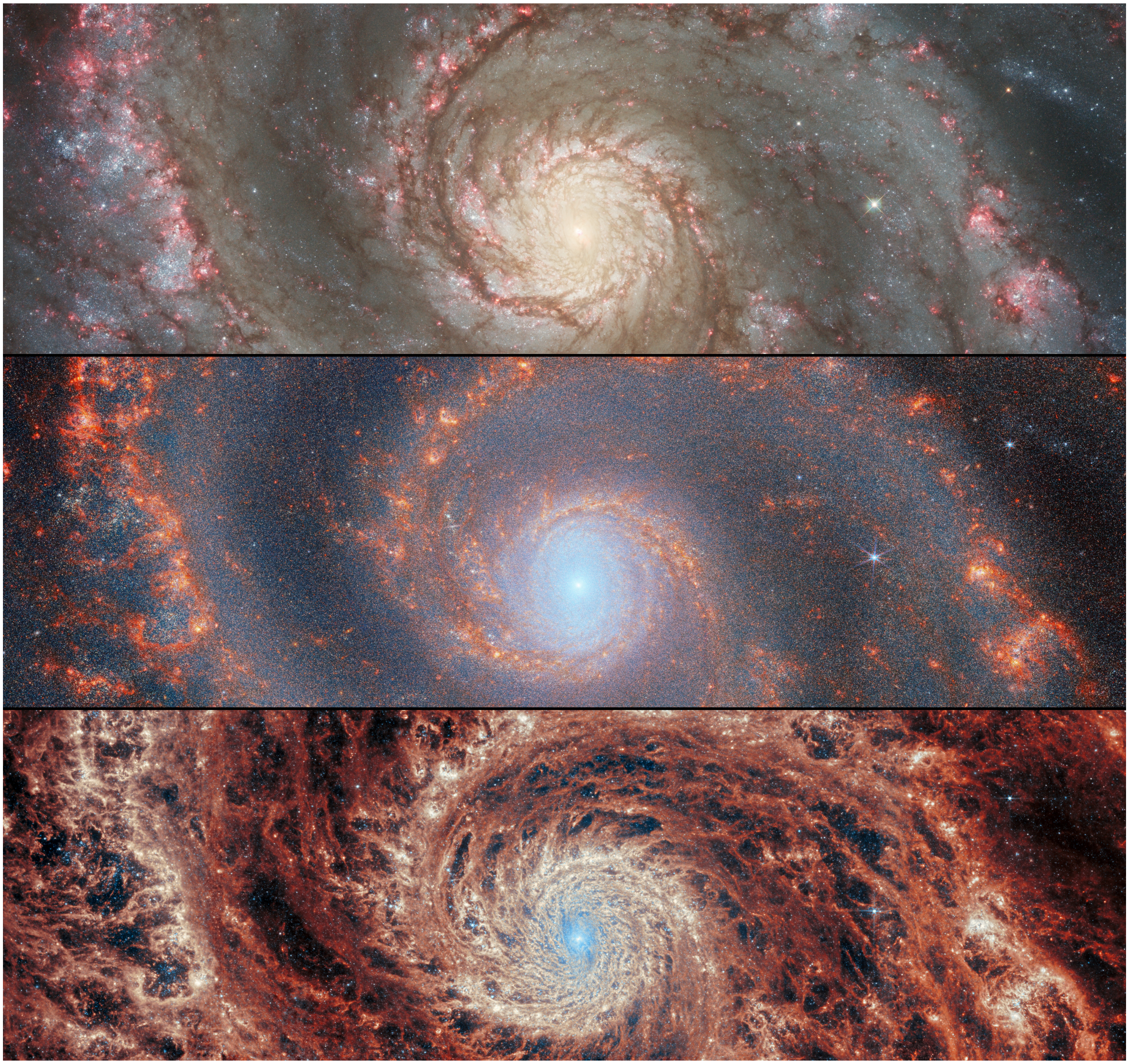

Figure 4: (left) 5.52′ × 1.71′ (12.0 kpc × 3.8 kpc) images of M51 in the [top] visible (HST/ACS-WFC), [center] NIR (JWST/NIRCam), and [bottom] MIR (JWST/MIRI). North is 44° left of the vertical. The top panel can be used to trace low-extinction massive stars and their associated H II regions, as well as the location of high-extinction regions marked by dust lanes. The center panel traces both low- and high-extinction H II regions as well as the red-giant population. The bottom panel traces the warm dust heated by hot massive stars located mostly around dense gas, when looked as a positive image, and the cavities produced by massive-star feedback, when looked as a negative image.