LIGO Status

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LIGO Hanford Observatory/Caltech
For the LIGO Scientific and Virgo Collaborations

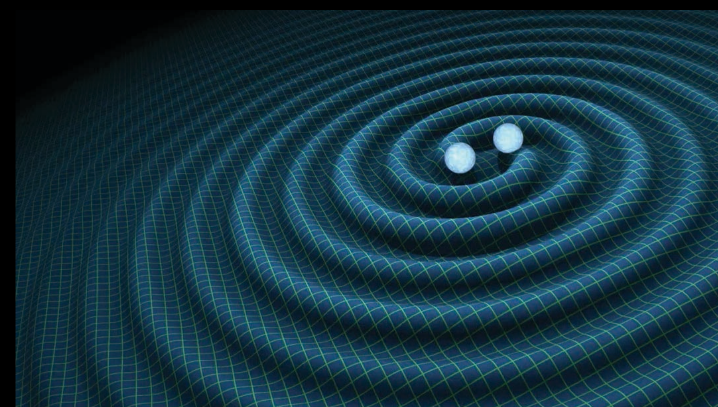
TMT Pasadena, 26 Apr 2018

“Colliding Neutron Stars”
NSF/LIGO/Sonoma State University/A. Simonnet

Gravitational Waves

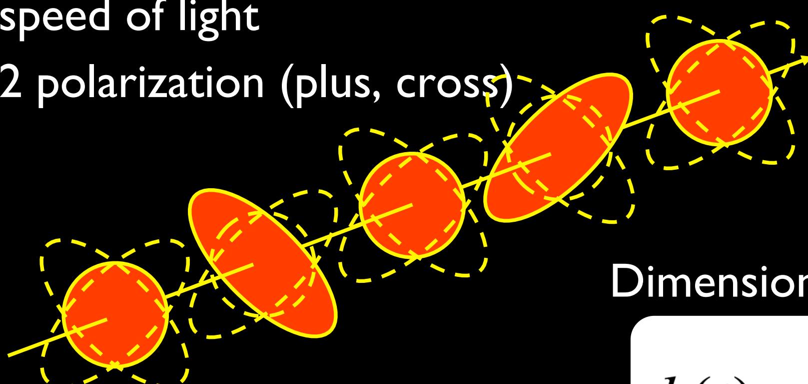
- Perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$



Credits: R. Hurt - Caltech / JPL

- speed of light
- 2 polarization (plus, cross)



Dimensionless strain:

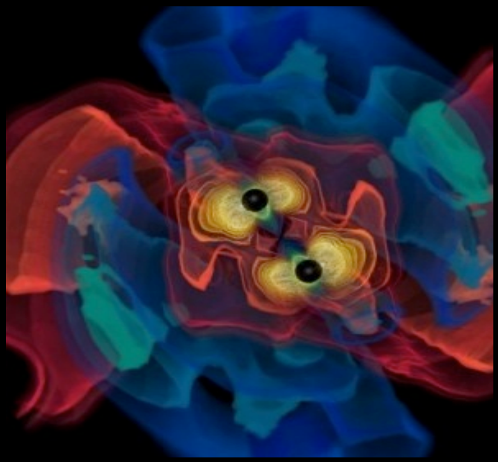
$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$$

I = source mass quadrupole moment

R = source distance

Gravitational waves carry information from the coherent, relativistic motion of large masses

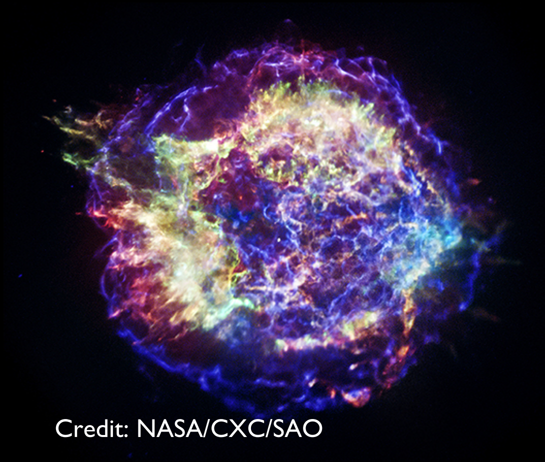
Gravitational Wave Astrophysics



Credit: AEI, CCT, LSU

Coalescing Binary Systems

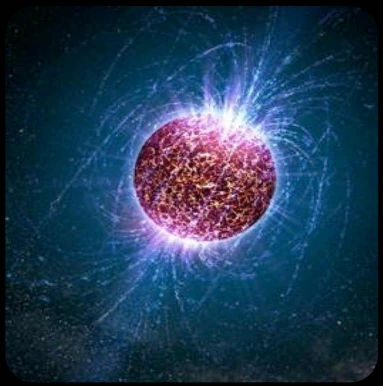
Neutron Stars, Black Holes



Credit: NASA/CXC/SAO

'Bursts'

asymmetric core collapse supernovae
cosmic strings
???

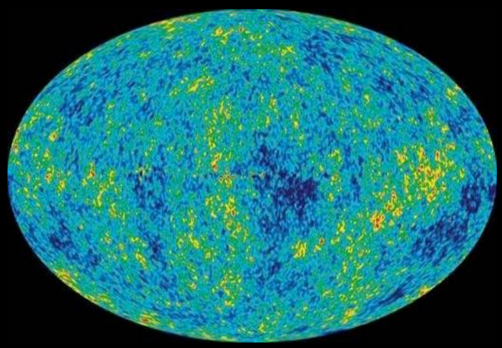


Casey Reed, Penn State

Continuous Sources

Spinning neutron stars

crustal deformations, accretion



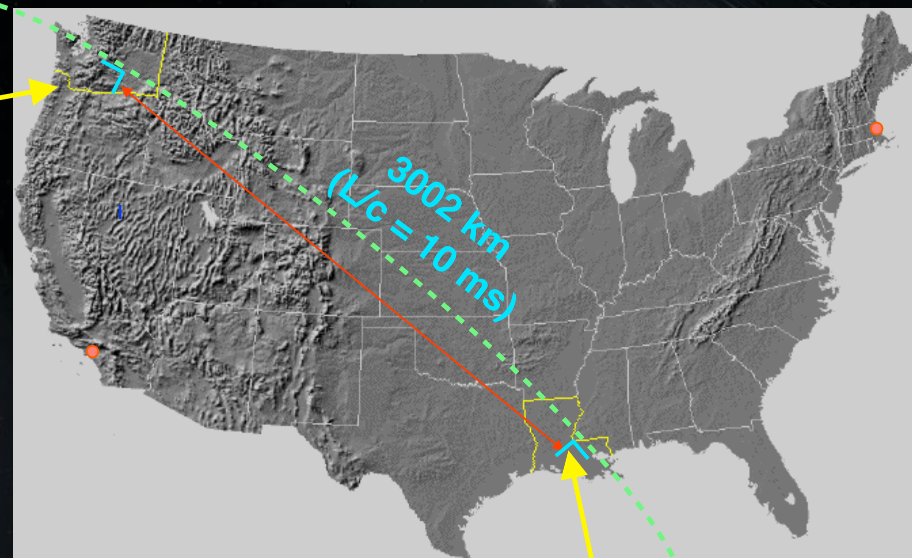
NASA/WMAP Science Team

Cosmic GW background

stochastic, incoherent background

NSF's LIGO: Laser Interferometer Gravitational-wave Observatory

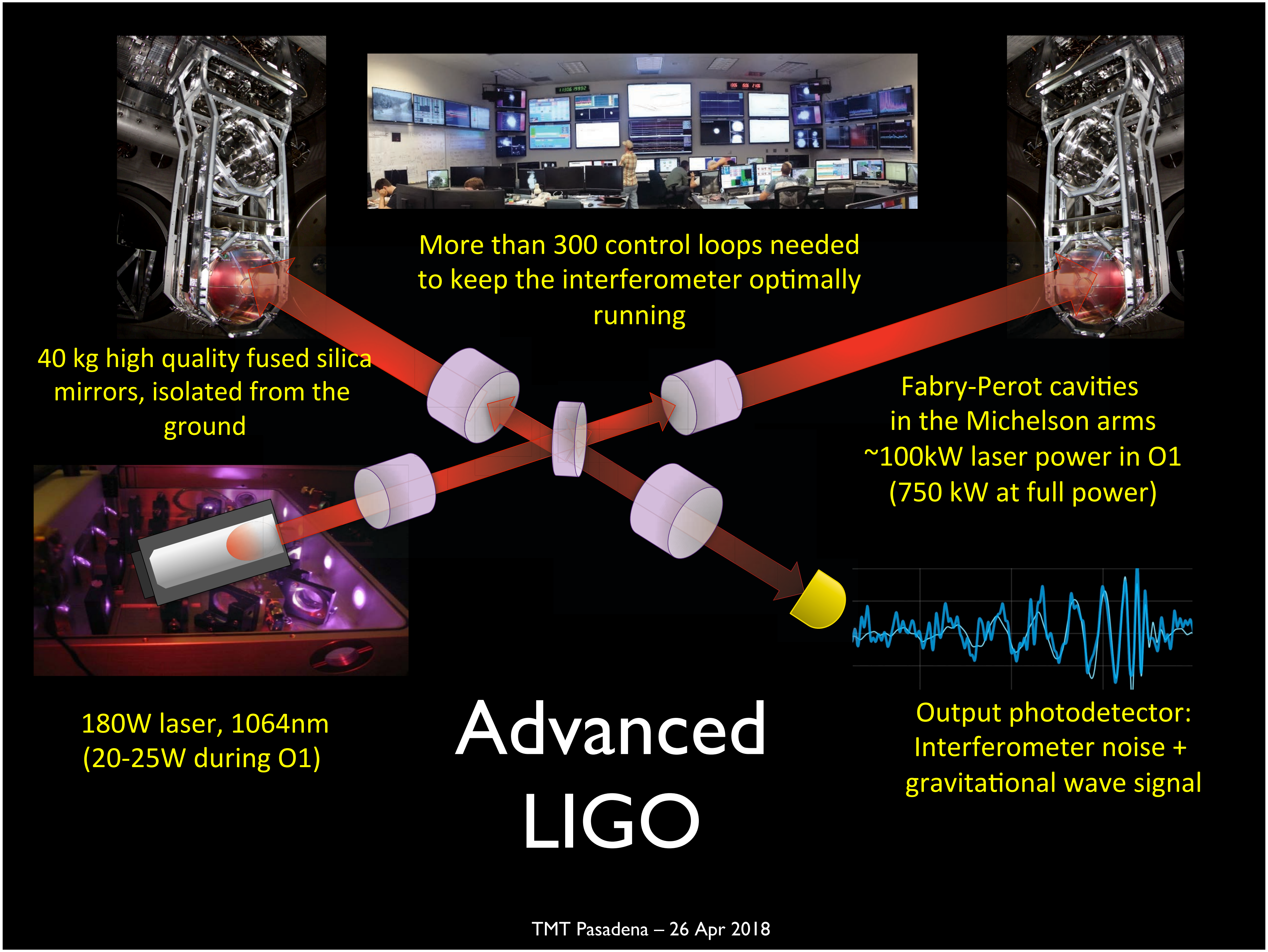
Hanford, WA



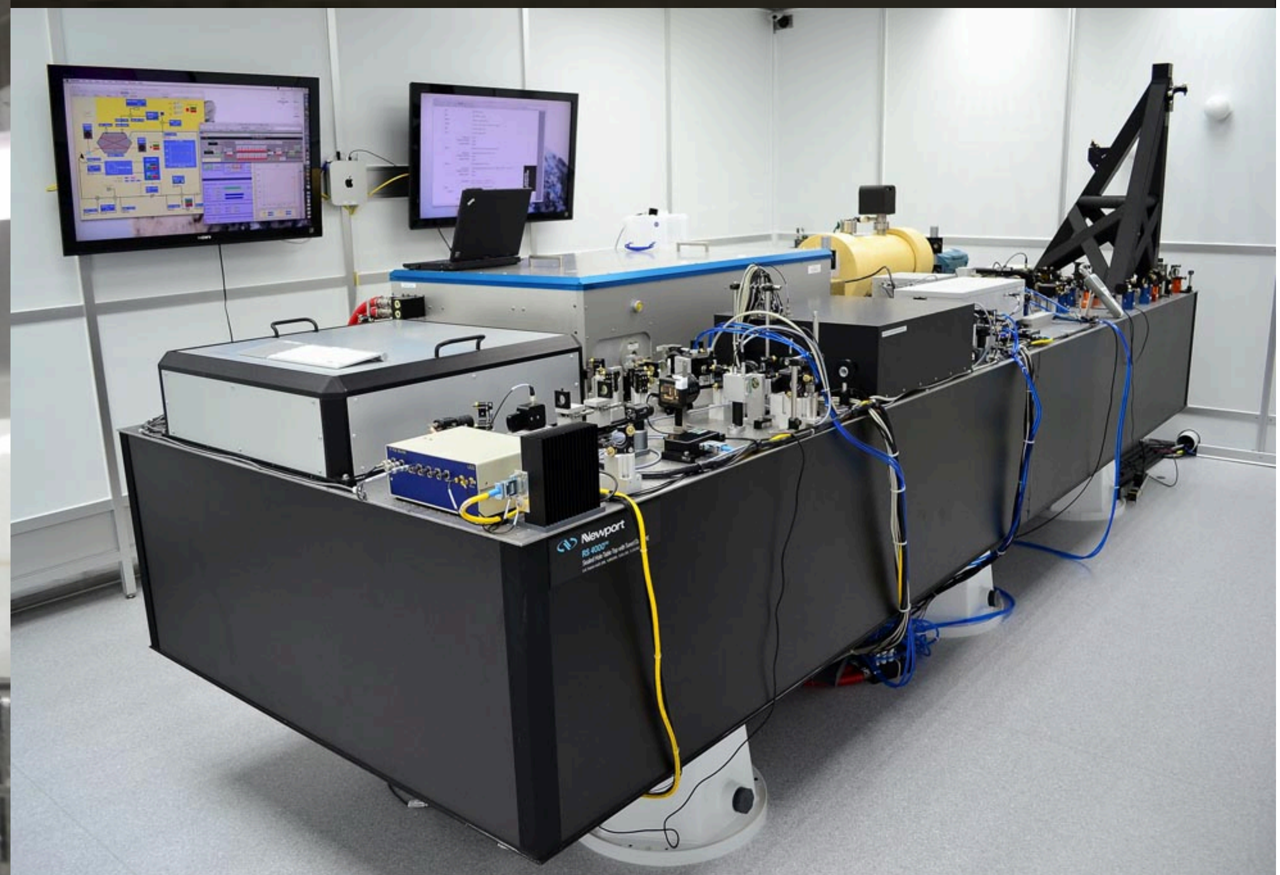
Livingston, LA

The LIGO Laboratory is jointly operated by Caltech and MIT through a Cooperative Agreement between Caltech and NSF

- LIGO Observatories construction: 1994-2000
- Initial LIGO operation: 2002-2010
- Advanced LIGO: 2015-now

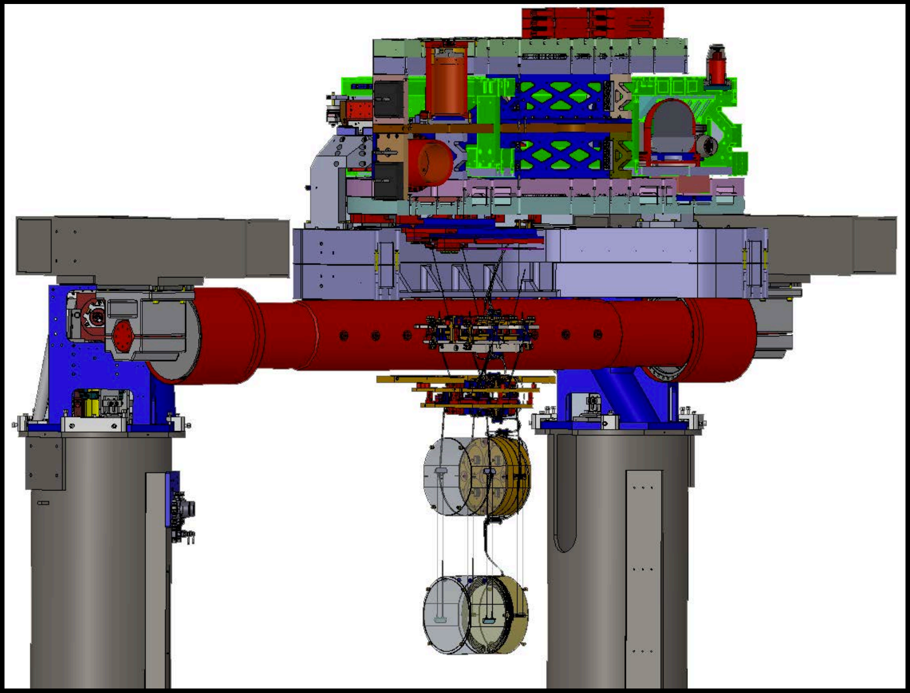

More than 300 control loops needed to keep the interferometer optimally running
40 kg high quality fused silica mirrors, isolated from the ground
Fabry-Perot cavities in the Michelson arms
~100kW laser power in O1
(750 kW at full power)
180W laser, 1064nm
(20-25W during O1)
Advanced LIGO
Output photodetector: Interferometer noise + gravitational wave signal
TMT Pasadena – 26 Apr 2018

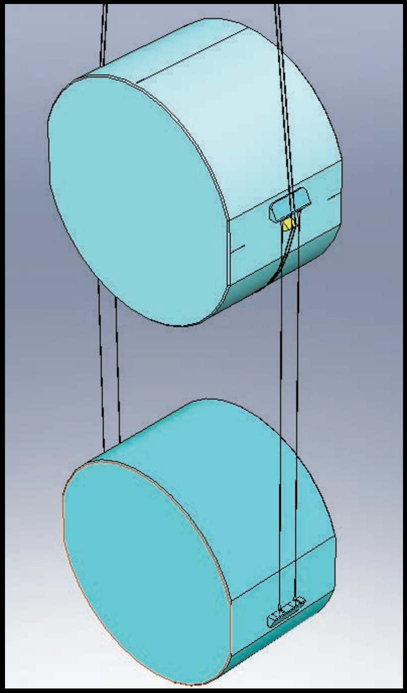
Two fundamental things

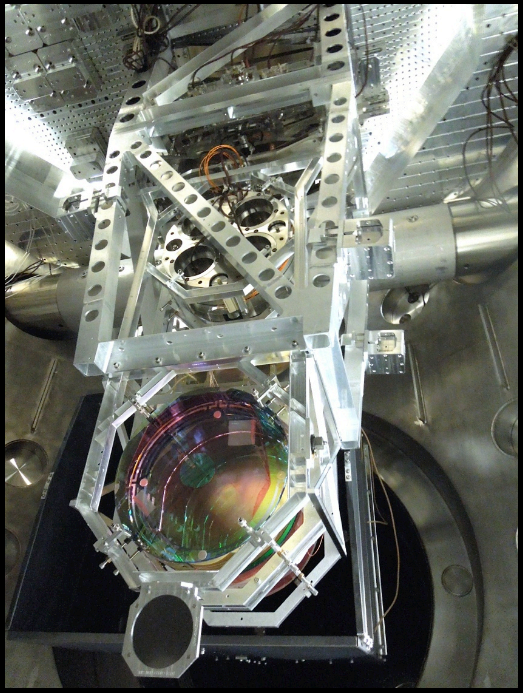


Isolating Mirrors

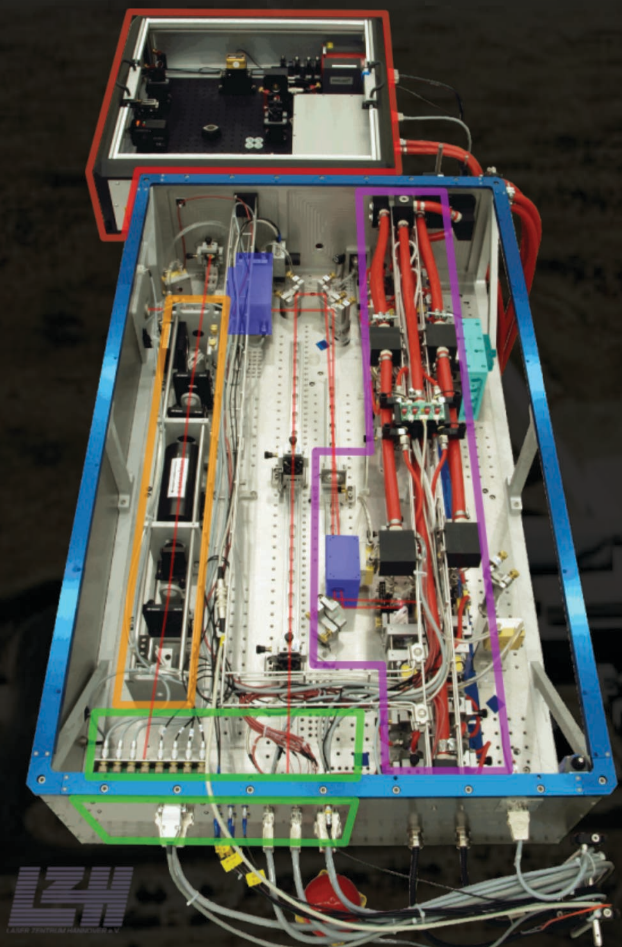
- Ground Motion at 10 [Hz] ~ 10^{-9} [m/rtHz]
- Need 10 orders of magnitude, to make mirrors still enough
- Test masses are suspended from 7 stages of active and passive vibration isolation

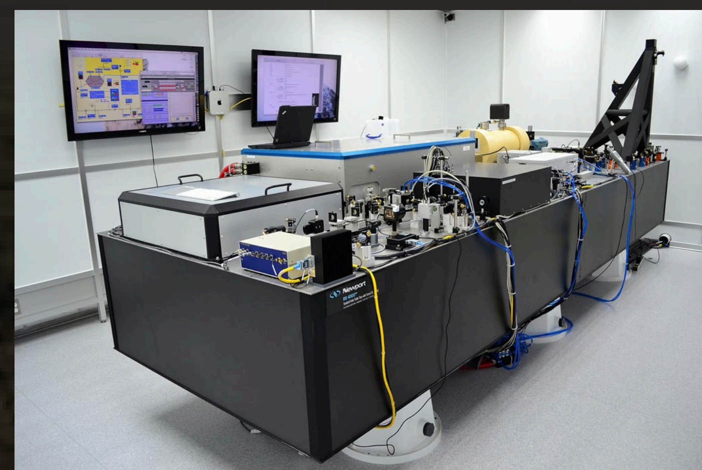






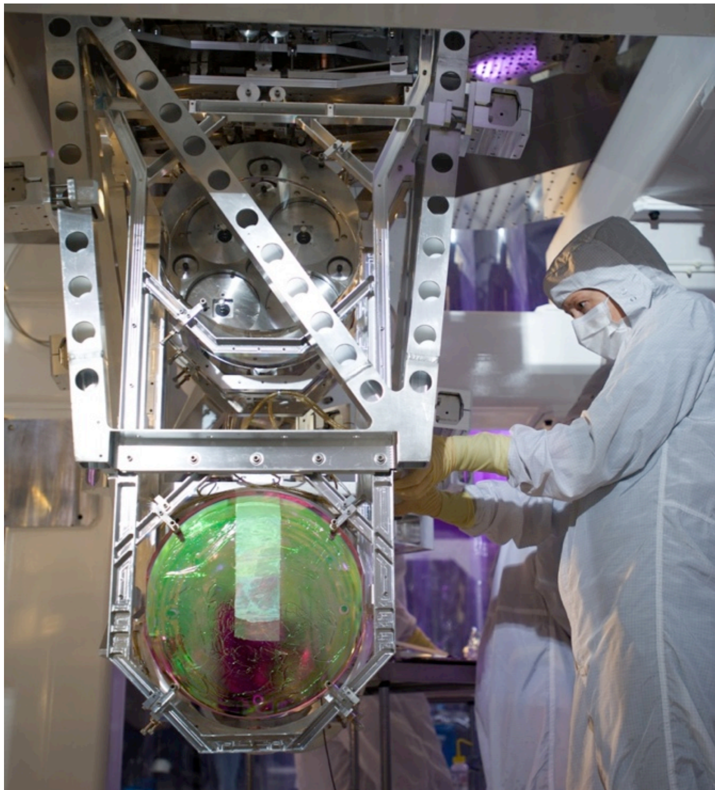
200W Nd:YAG laser

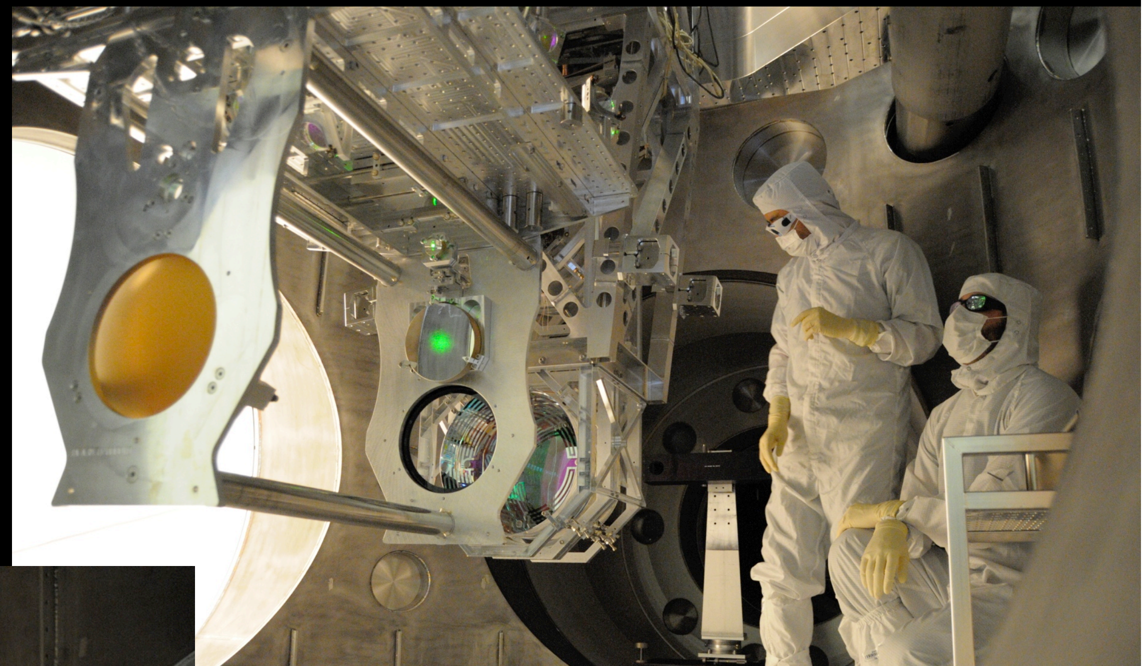


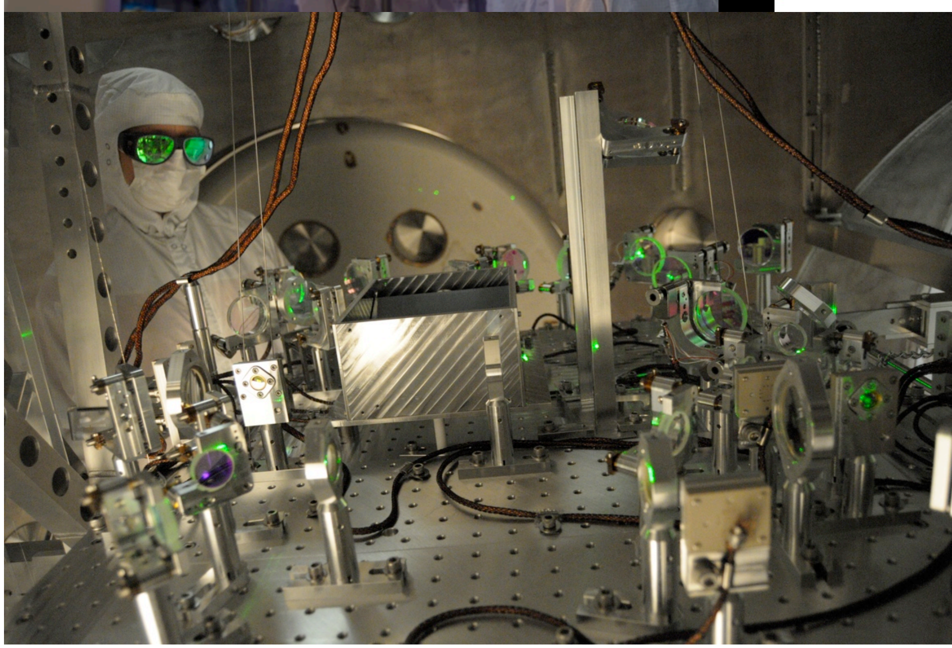


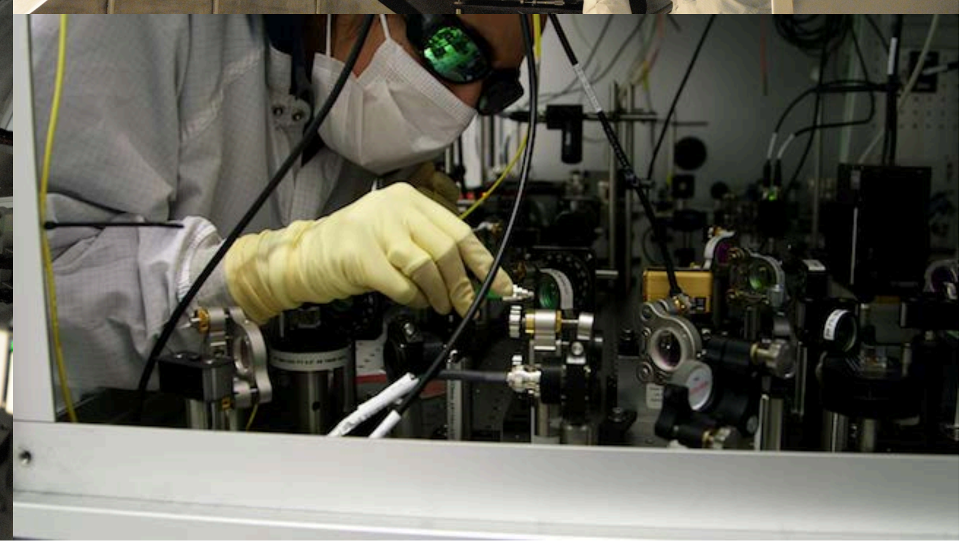
- Stabilized in power and frequency – using techniques developed for time references
- Uses a monolithic master oscillator followed by injection-locked rod amplifier
- Delivers the required shot-noise limited fringe resolution

Complexity

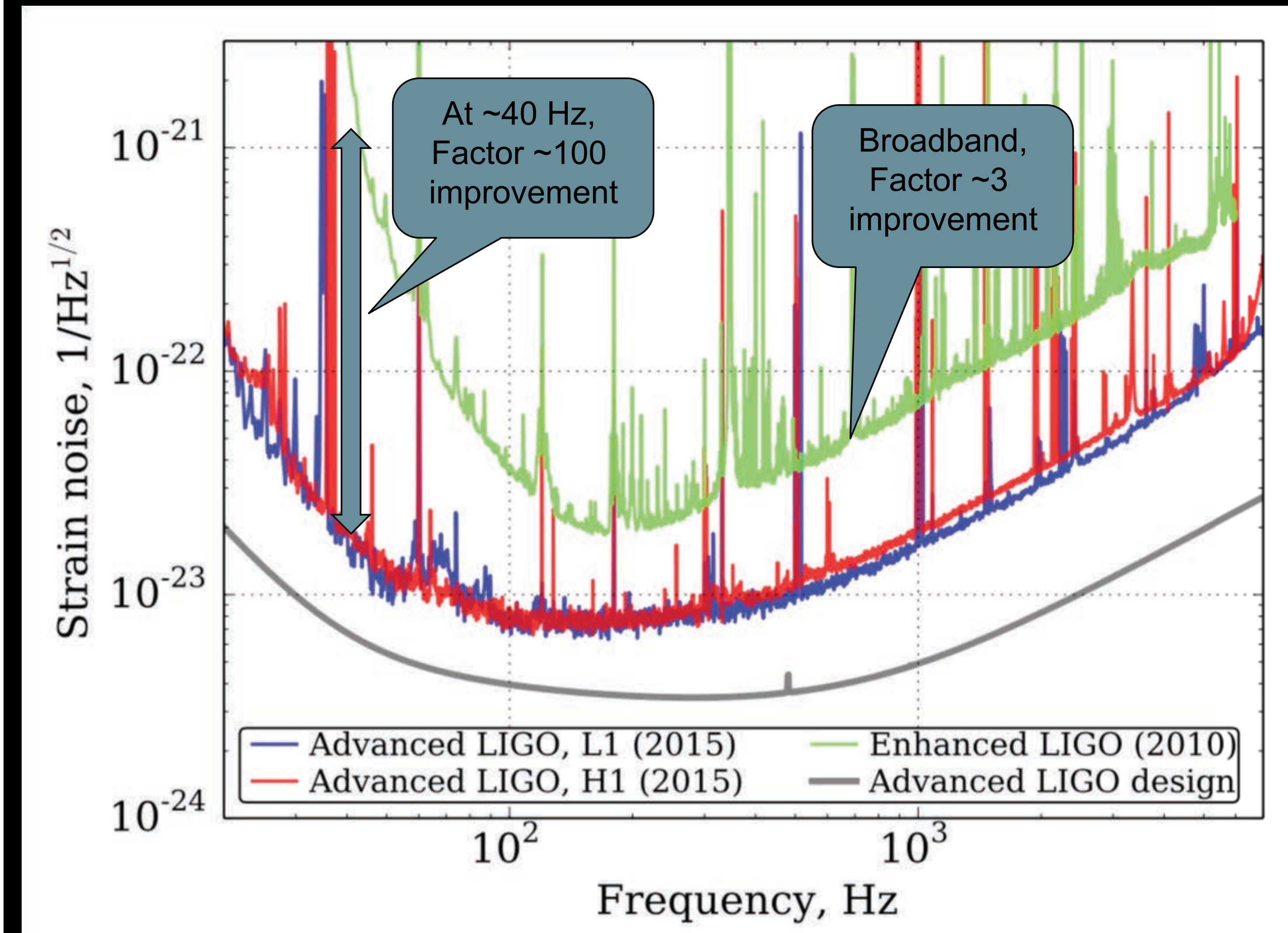








Noise curves



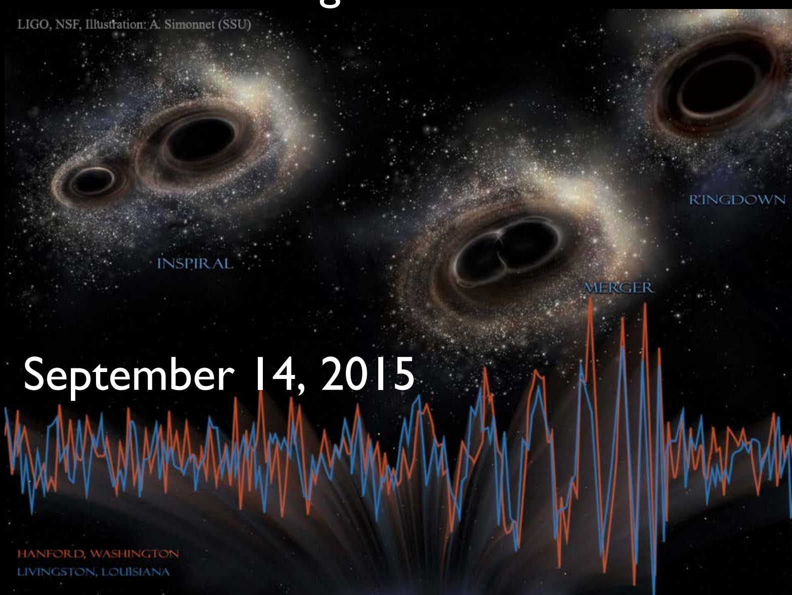
Initial LIGO

O1 aLIGO

Design aLIGO

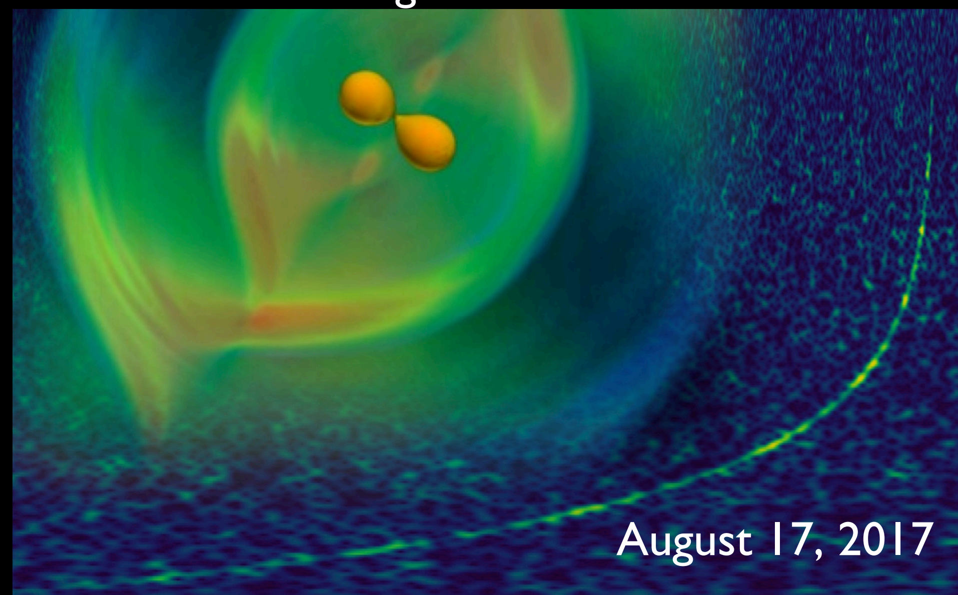
GW150914 and GW170817
Two discoveries that launched gravitational wave astrophysics

1.3 Billion Years Ago….



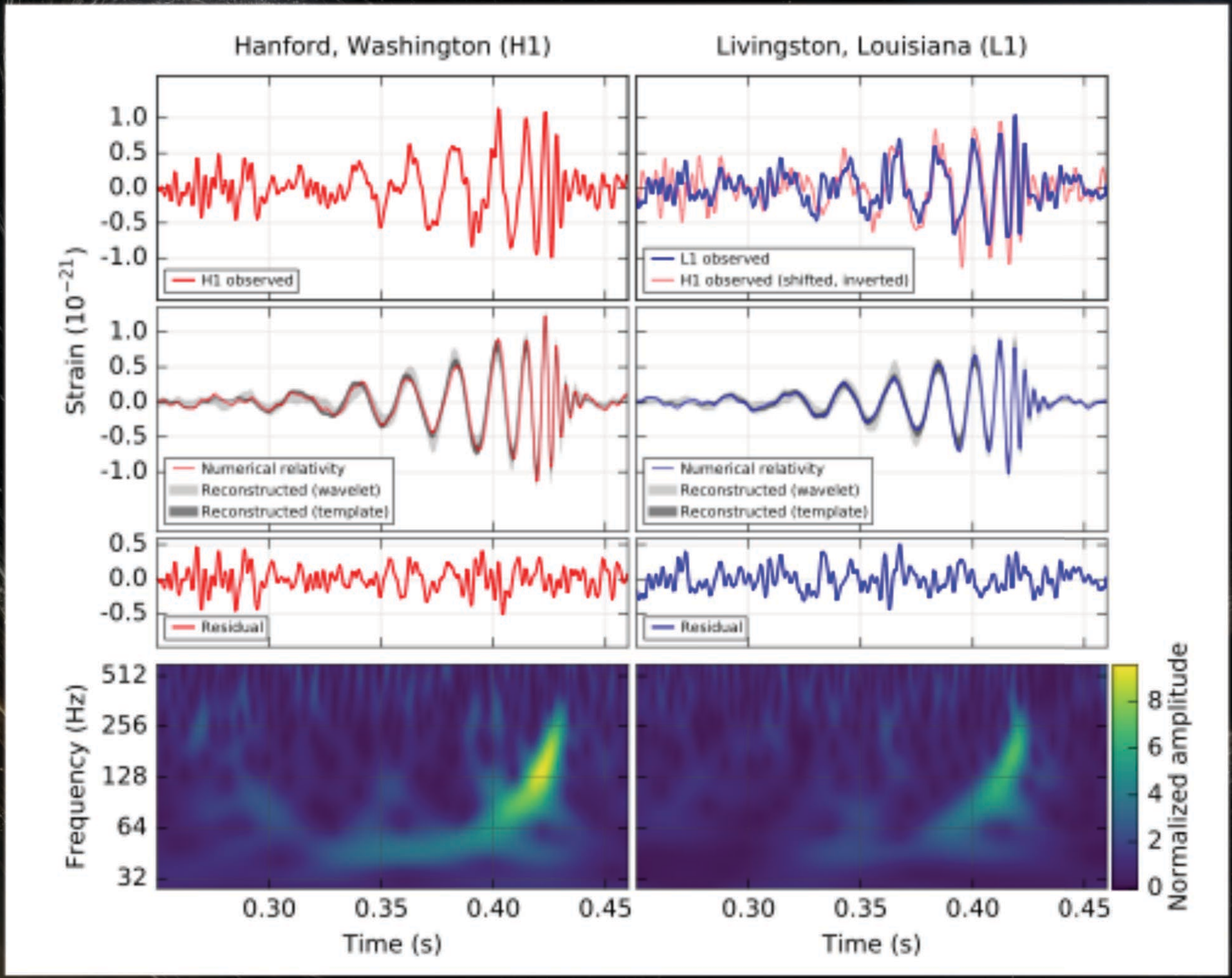
Binary Black Hole Coalescence

135 Million Years Ago….

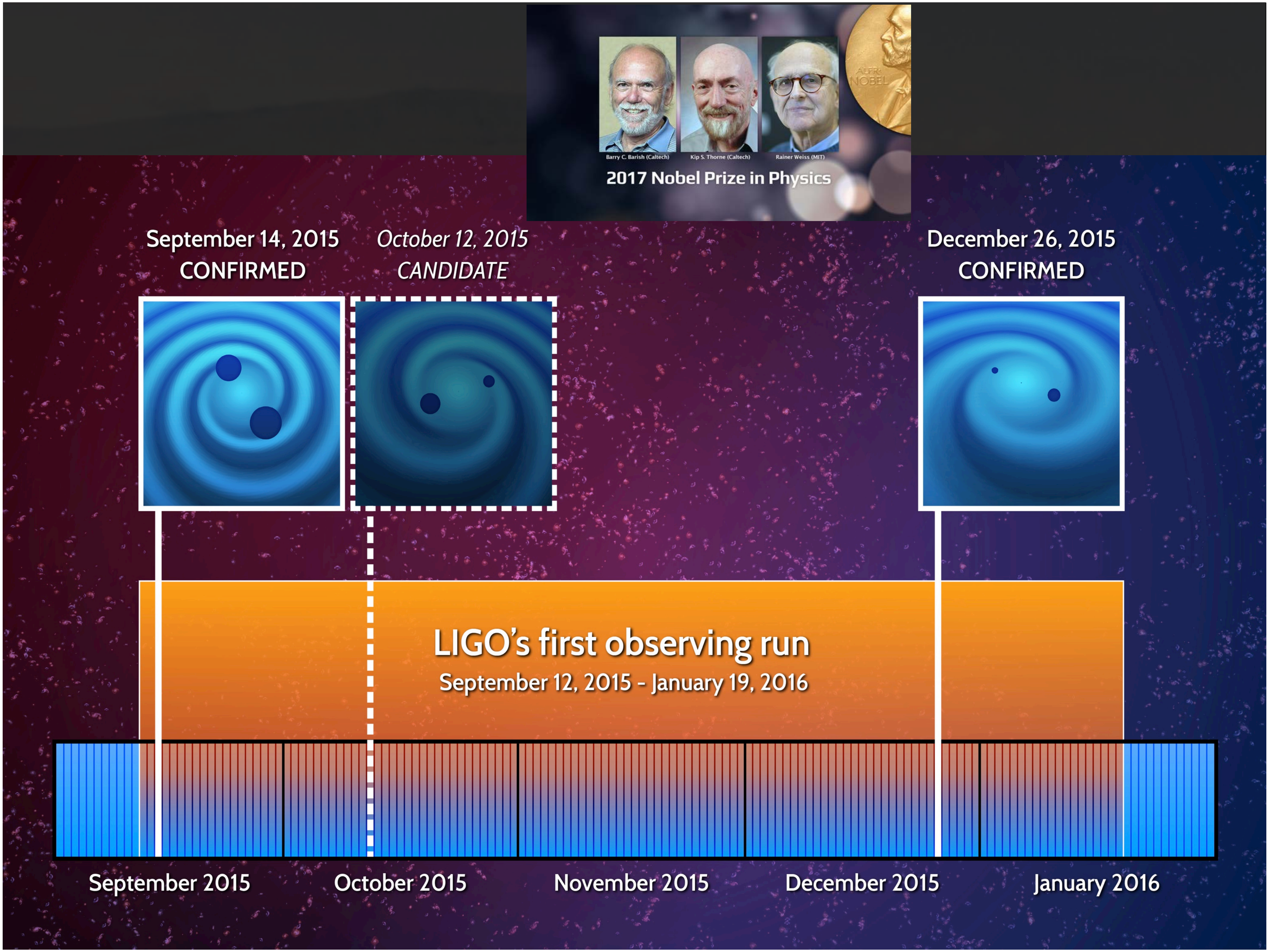


Binary Neutron Star Coalescence

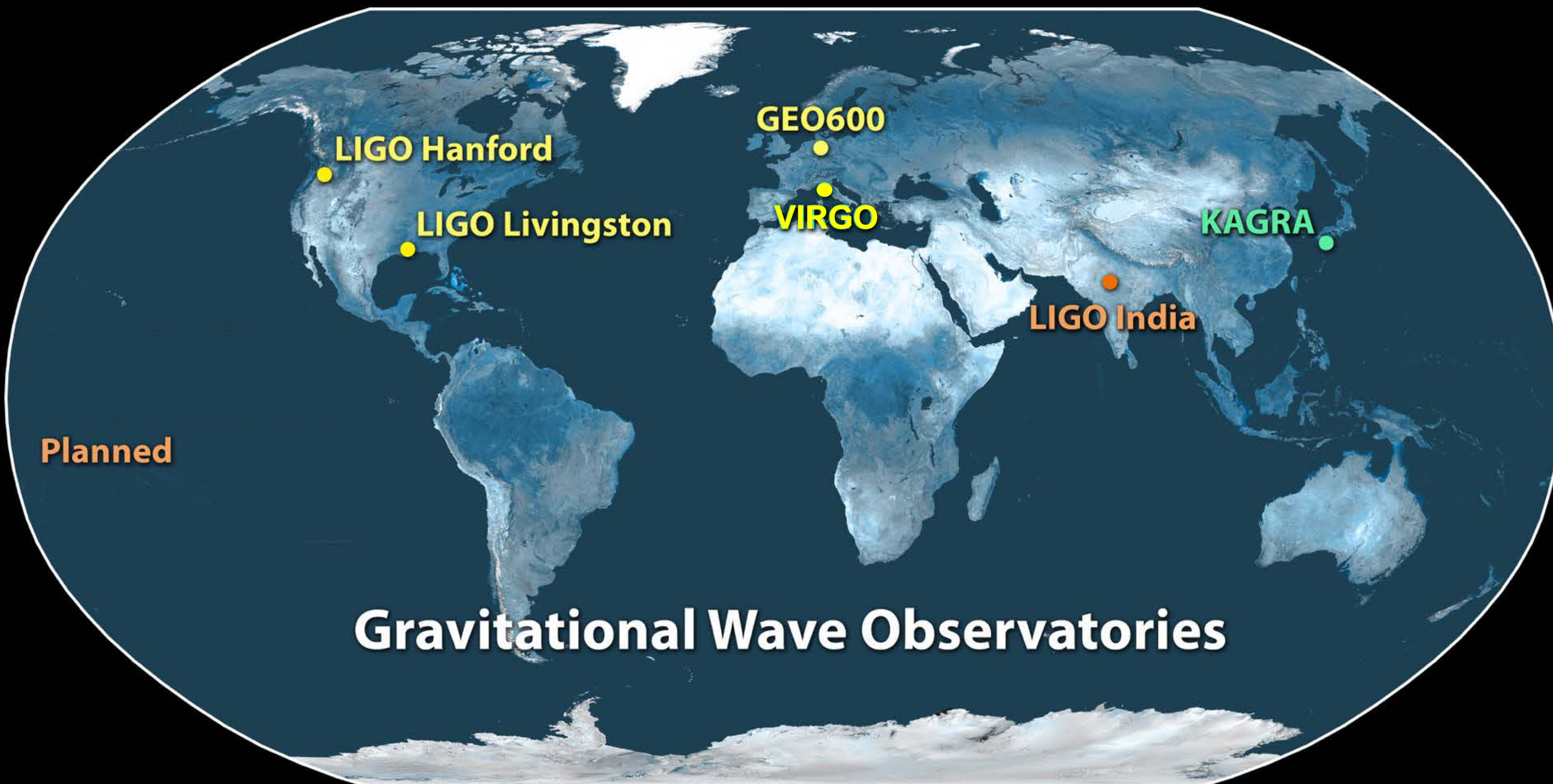
First Discovery: GW150914



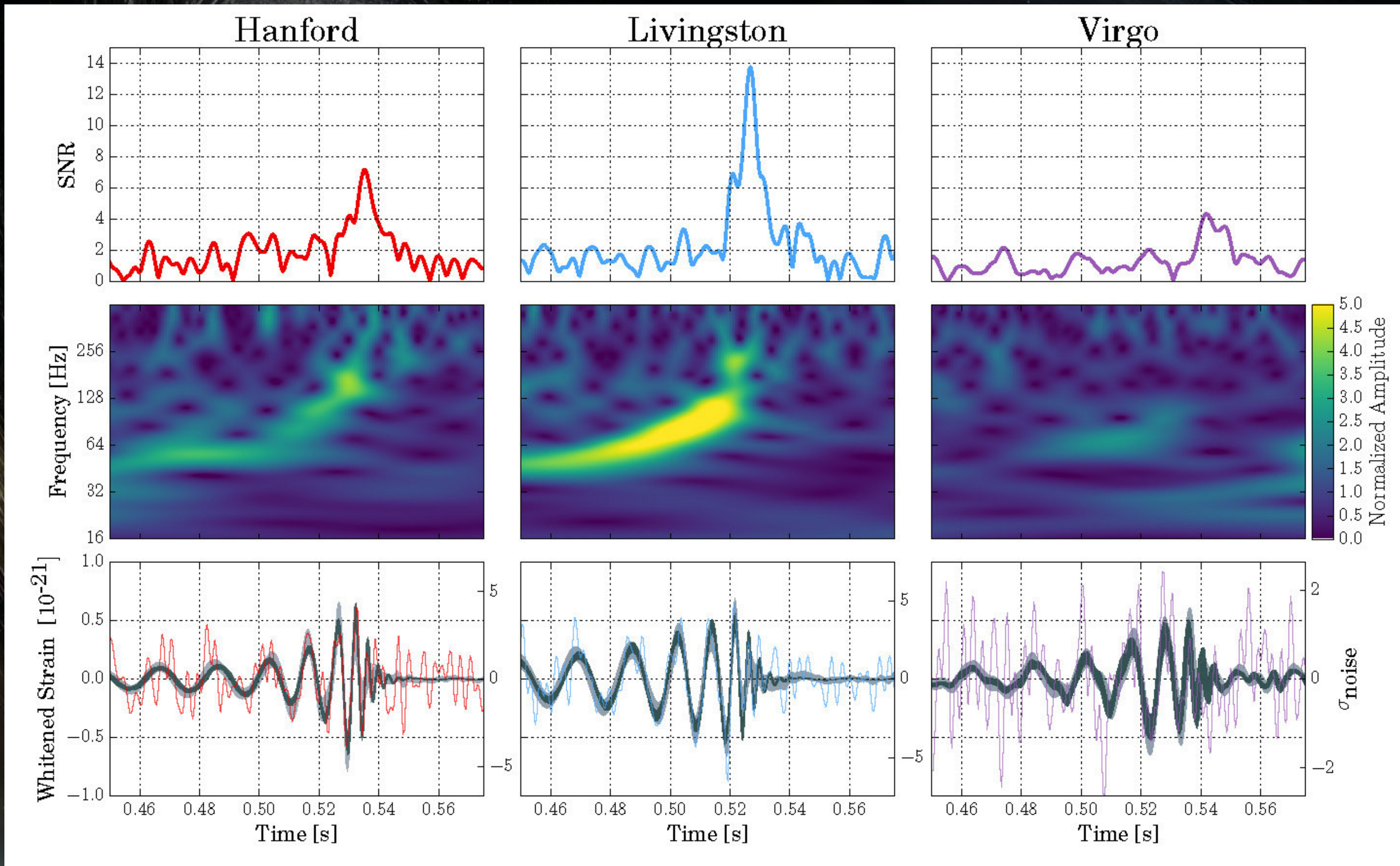
Observation of Gravitational Waves from a Binary Black Hole Merger
Phys. Rev. Lett., 116:061102, 2016


Barry C. Barish (Caltech)
Kip S. Thorne (Caltech)
Rainer Weiss (MIT)
2017 Nobel Prize in Physics
September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

The Global Network

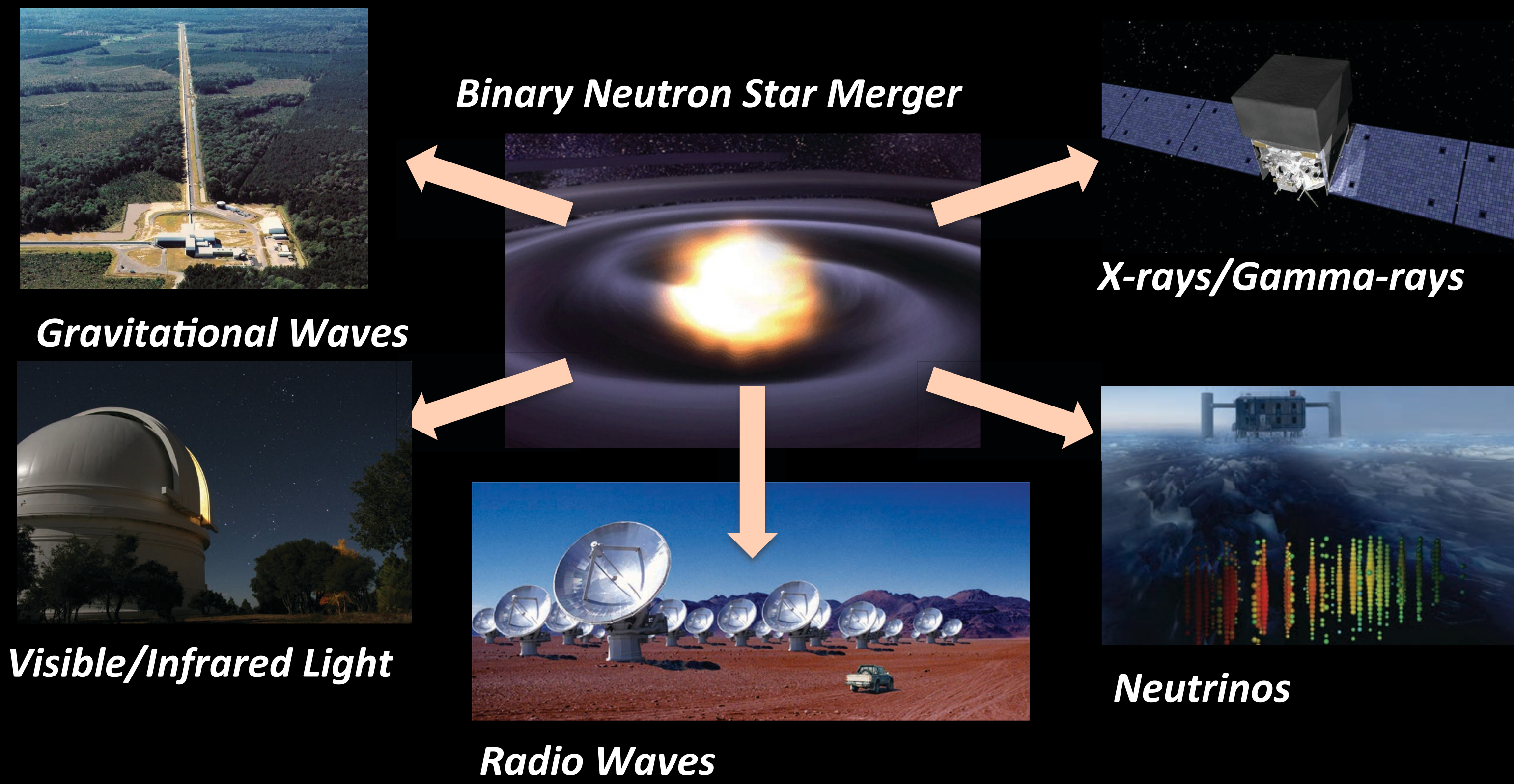


Three detectors: GW170814



A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence
Phys. Rev. Lett., 119:141101, 2017

Multi-messenger Astronomy with Gravitational Waves

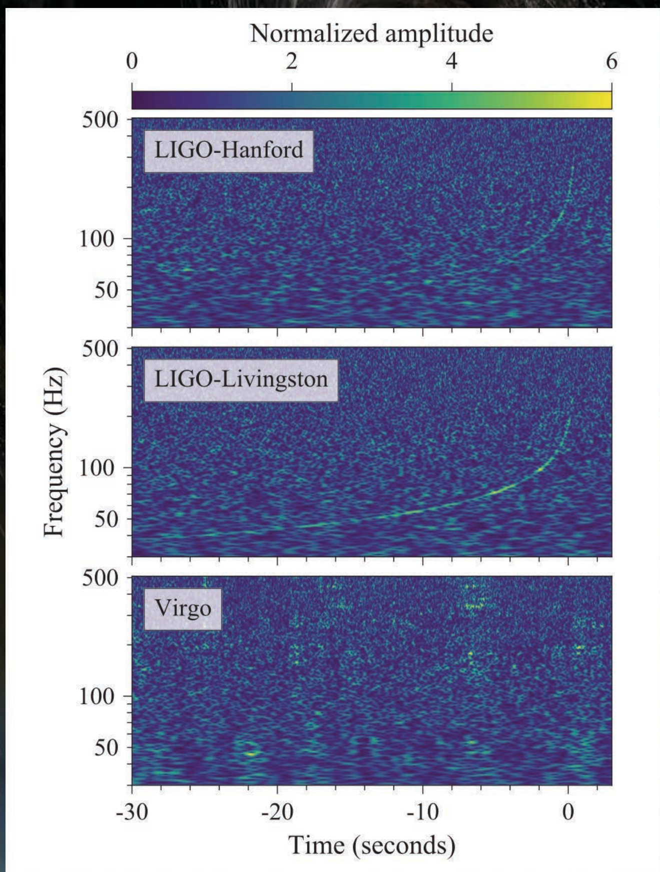


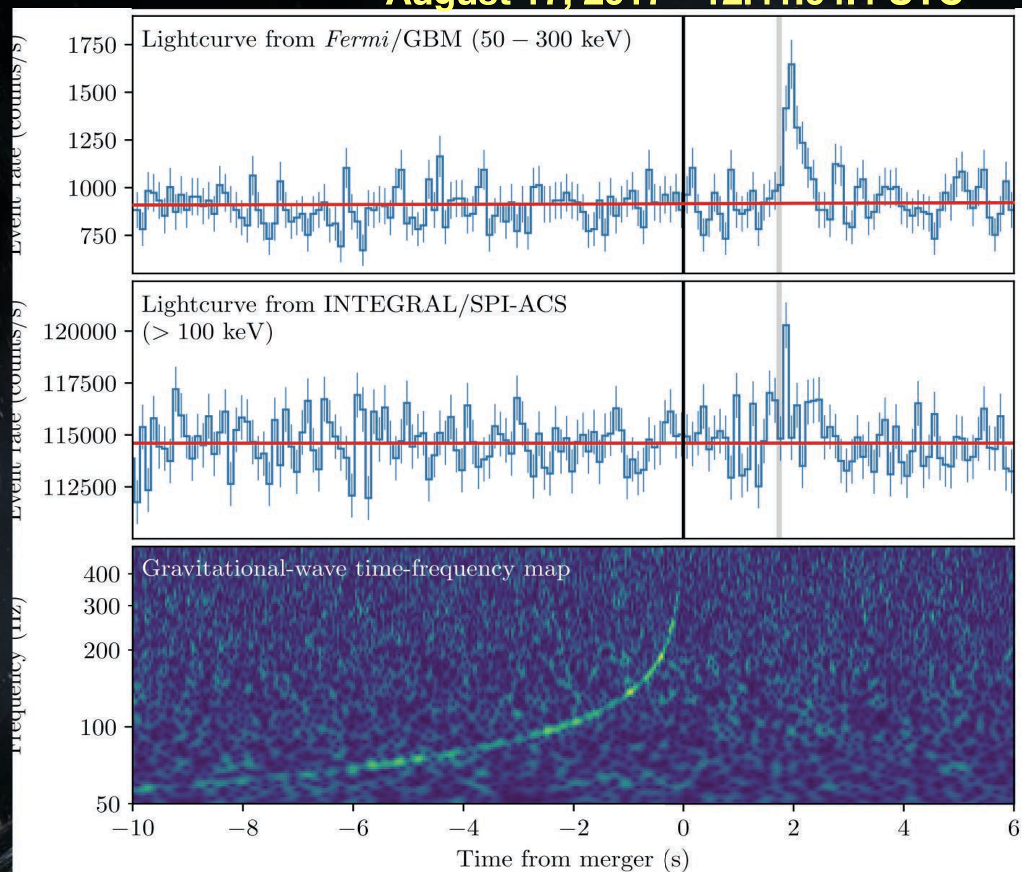
LIGO and Virgo signed agreements with 95 groups for EM/neutrino followup of GW events

- ~200 EM instruments - satellites and ground based telescopes covering the full spectrum from radio to very high-energy gamma-rays
- Worldwide astronomical institutions, agencies and large/small teams of astronomers

Discovery of a Binary Neutron Star

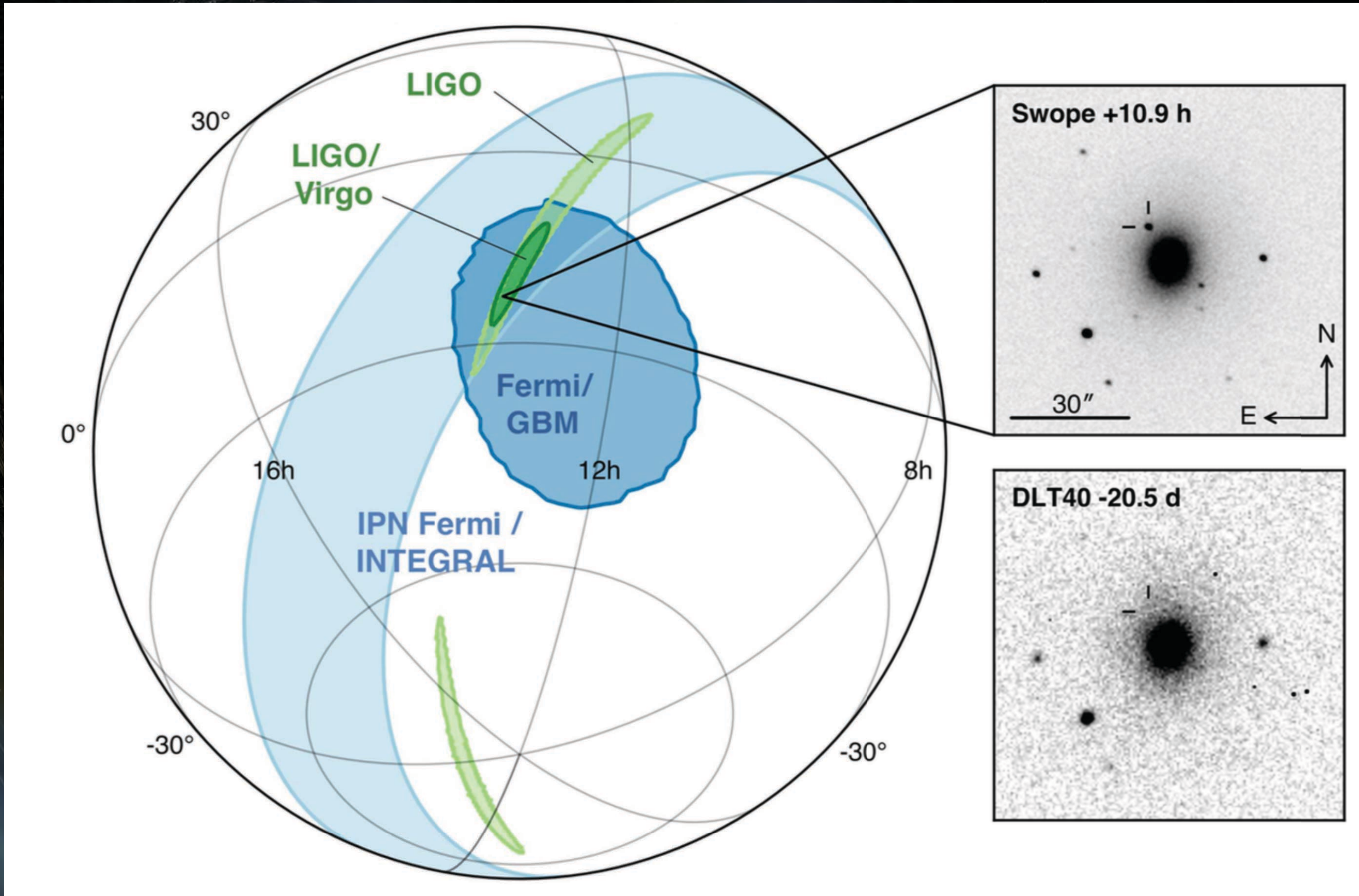
August 17, 2017 - 12:41:04.4 UTC





GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
Phys. Rev. Lett., 119:161101, 2017

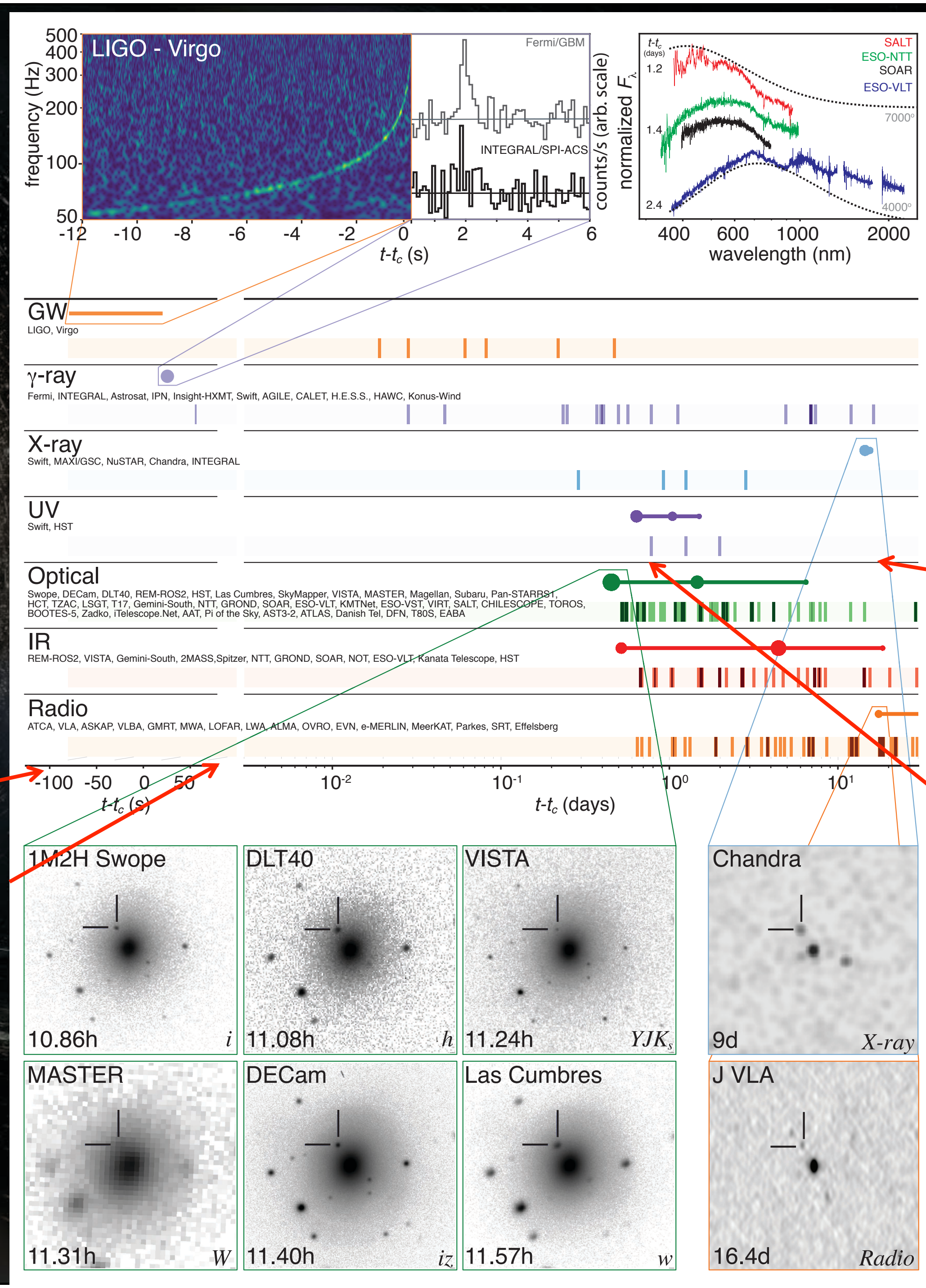
Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A
The Astrophysical Journal Letters, 848:L13, 2017



Multi-messenger Observations of a Binary Neutron Star Merger

The Astrophysical Journal Letters, 848:L12, 2017

EM Followup Campaign



10 days

1 day

-100s

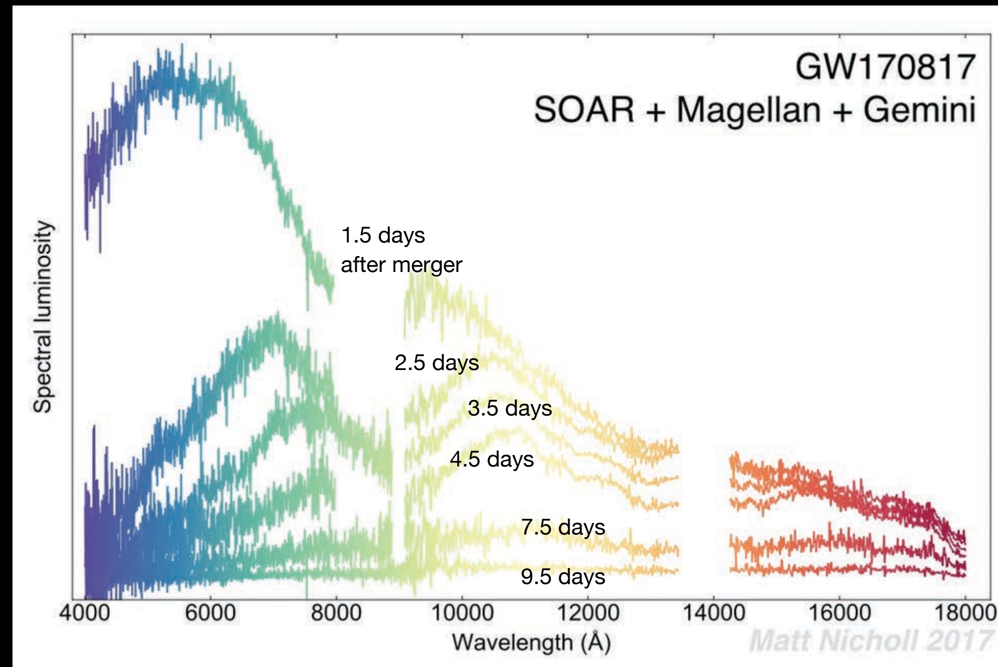
Merger

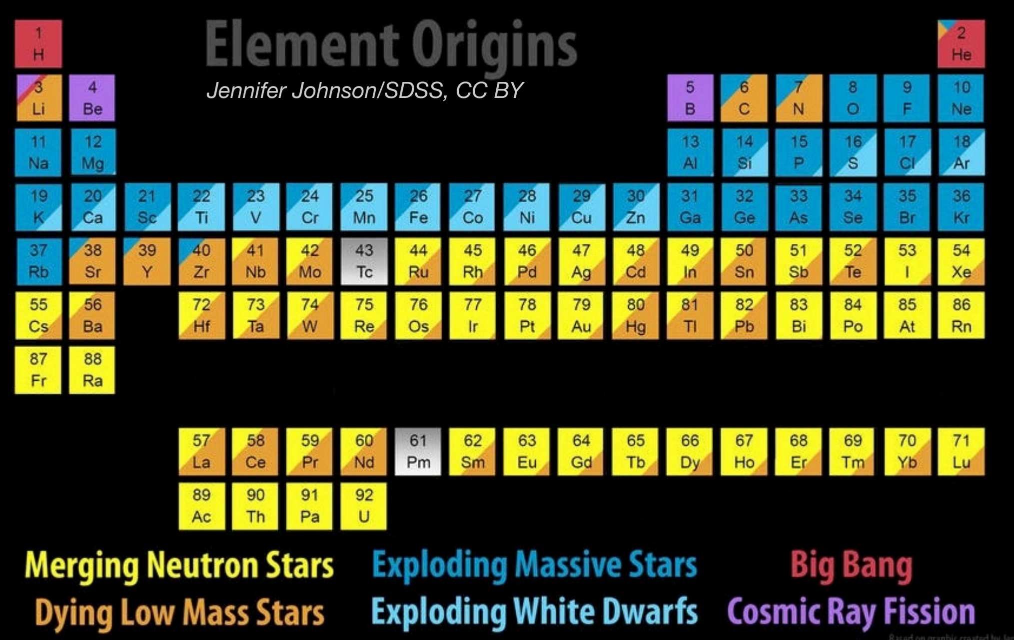
Multi-messenger Observations of a Binary Neutron Star Merger

The Astrophysical Journal Letters, 848:L12, 2017

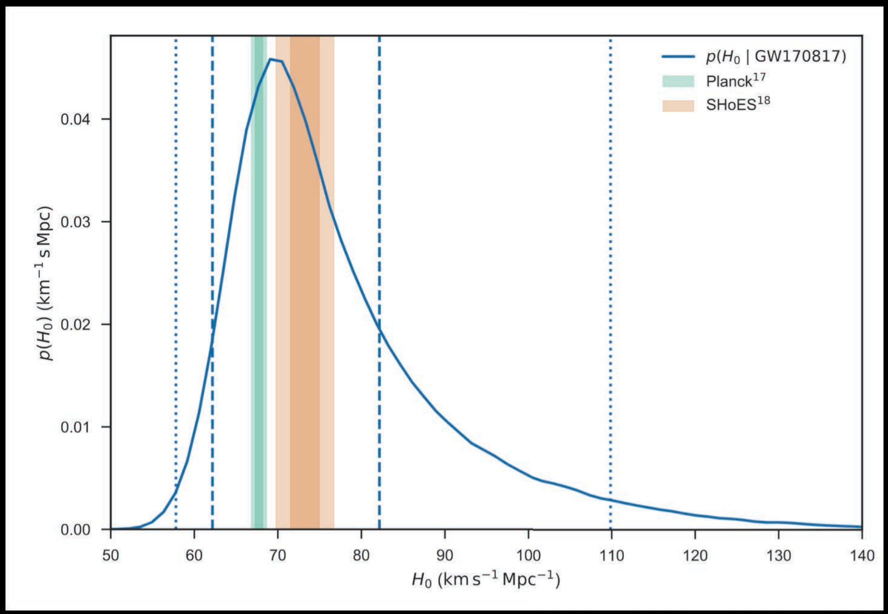
Kilonova

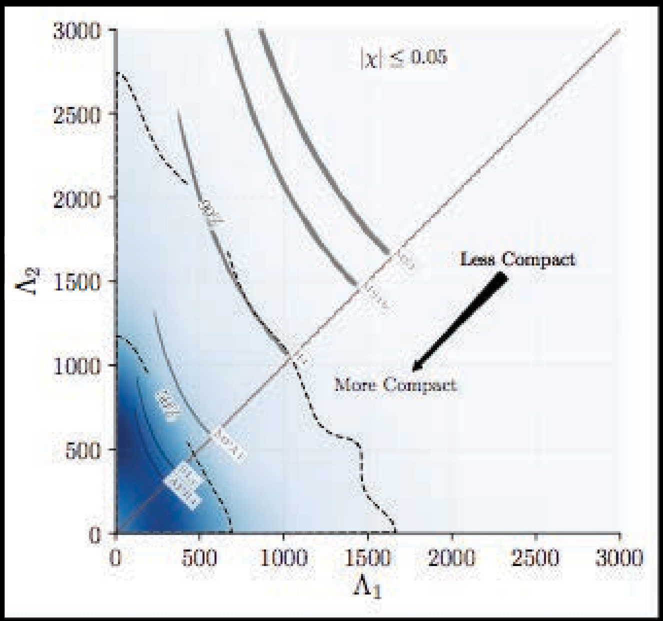

SSS17a
August 17, 2017
August 21, 2017
Swope & Magellan Telescopes


GW170817
SOAR + Magellan + Gemini
Spectral luminosity
1.5 days
after merger
2.5 days
3.5 days
4.5 days
7.5 days
9.5 days
4000
6000
8000
10000
12000
14000
16000
18000
Wavelength (Å)
Matt Nicholl 2017


Element Origins
Jennifer Johnson/SDSS, CC BY
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission

New Science Enabled





Gravitational wave cosmology:
BNS as standard sirens to measure the rate of expansion of the Universe

A gravitational-wave standard siren measurement of the Hubble constant
Nature, 551:85, 2017

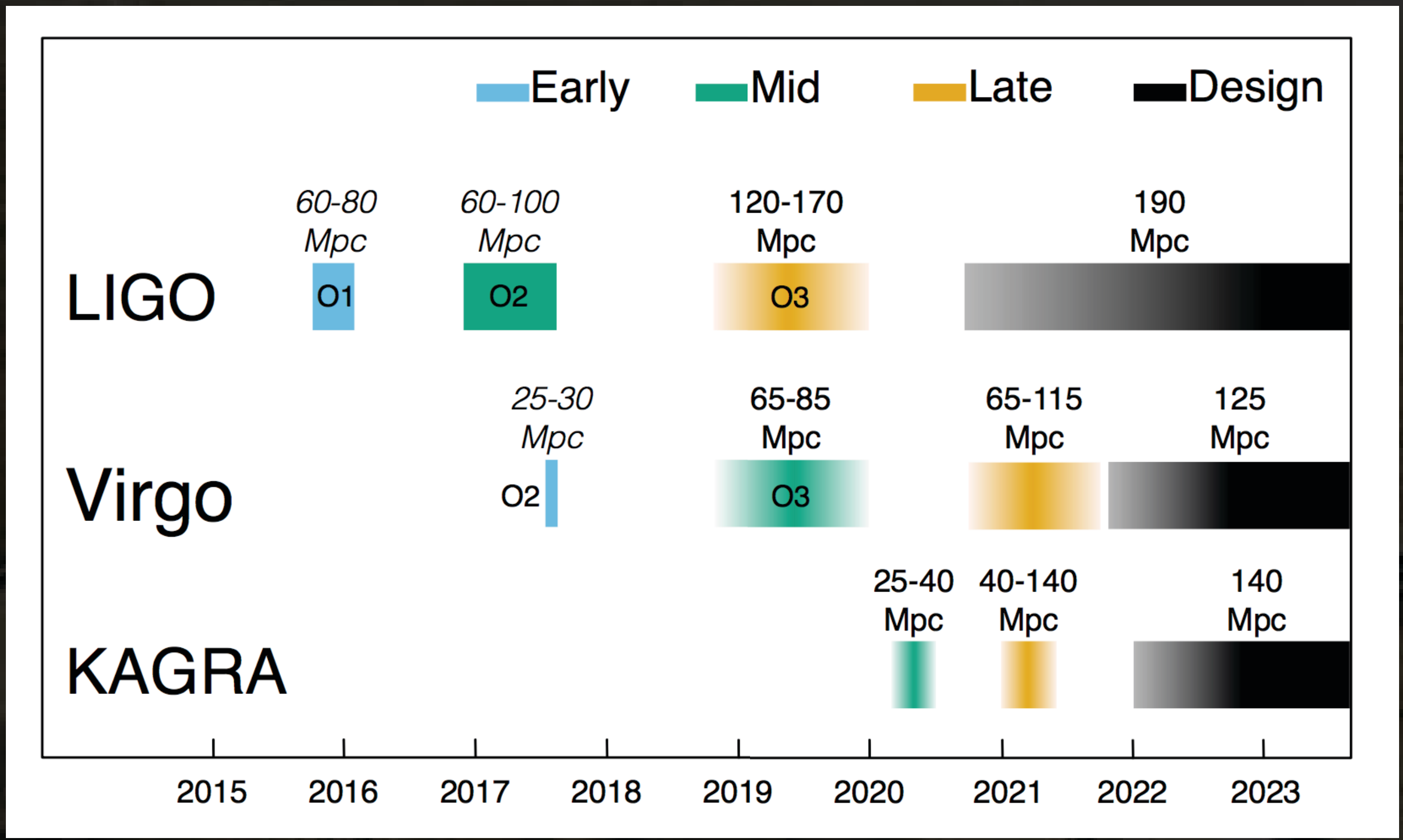
Gravitational waves and nuclear physics:
Constraining properties of nuclear matter via neutron star equation of state and tidal disruption, encoded in the BNS GW waveform.

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
Phys. Rev. Lett., 119:161101, 2017

More being learned

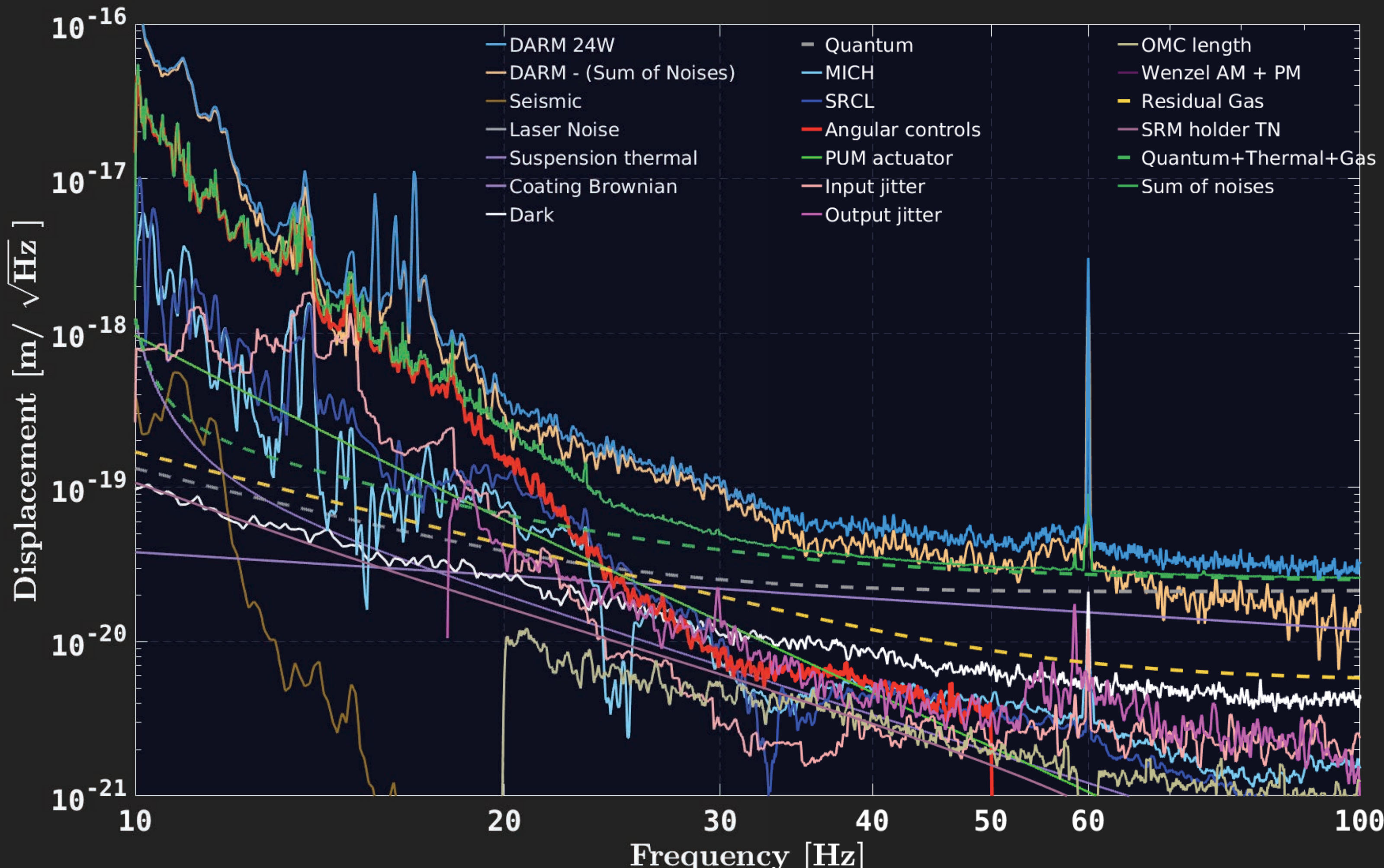
- Gravitational waves travel at the same speed as light, to a precision of about 10^{-15}: *first direct measurement of the speed of gravity*
- We've begun to explore the mechanism of short hard GRBs and kilonovae.
- We can probe the distribution of black hole and neutron star masses.

Observing Scenario

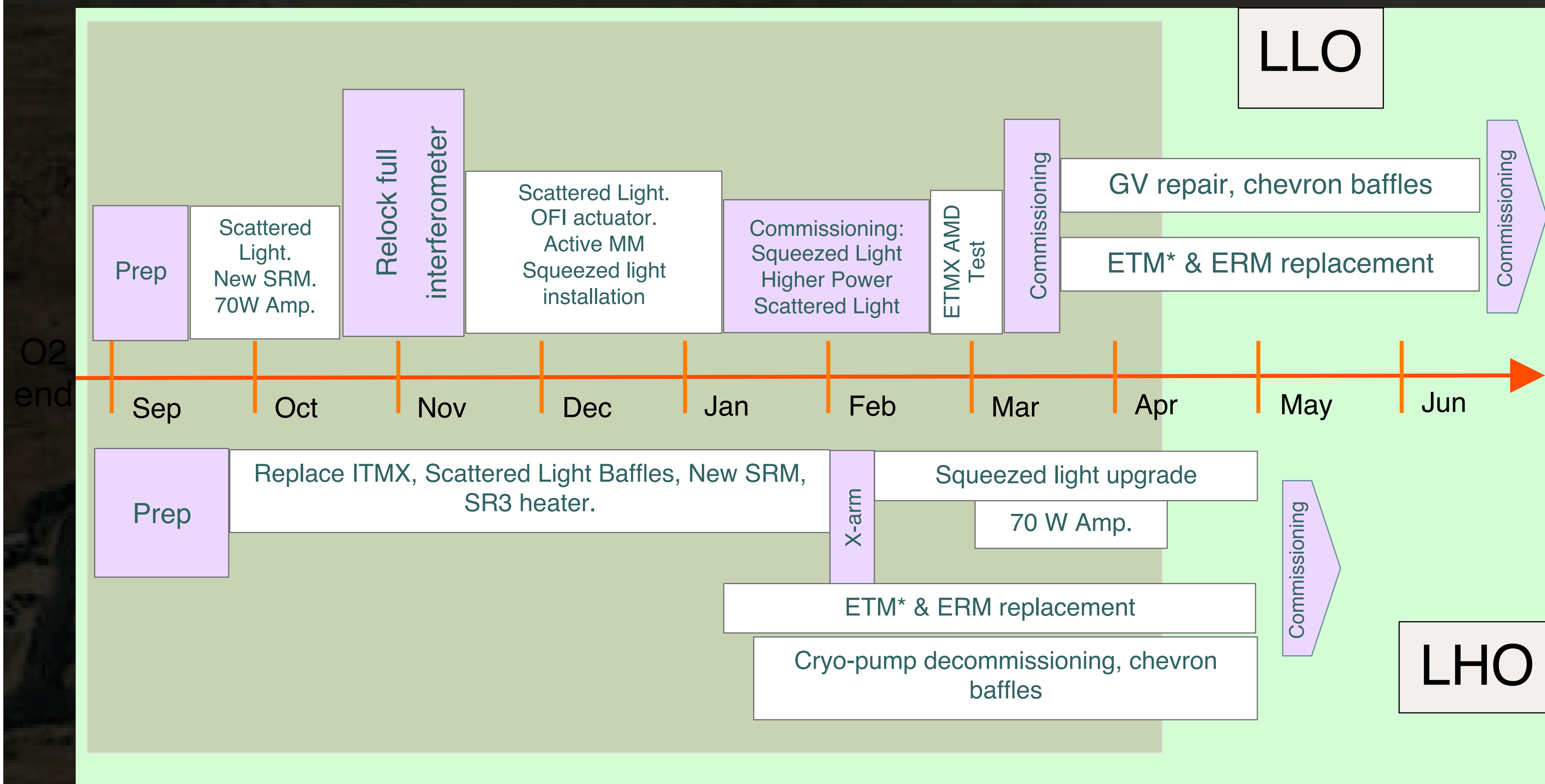


Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo and KAGRA https://dcc.ligo.org/LIGO-P1200087/public

LLO Noise Budget



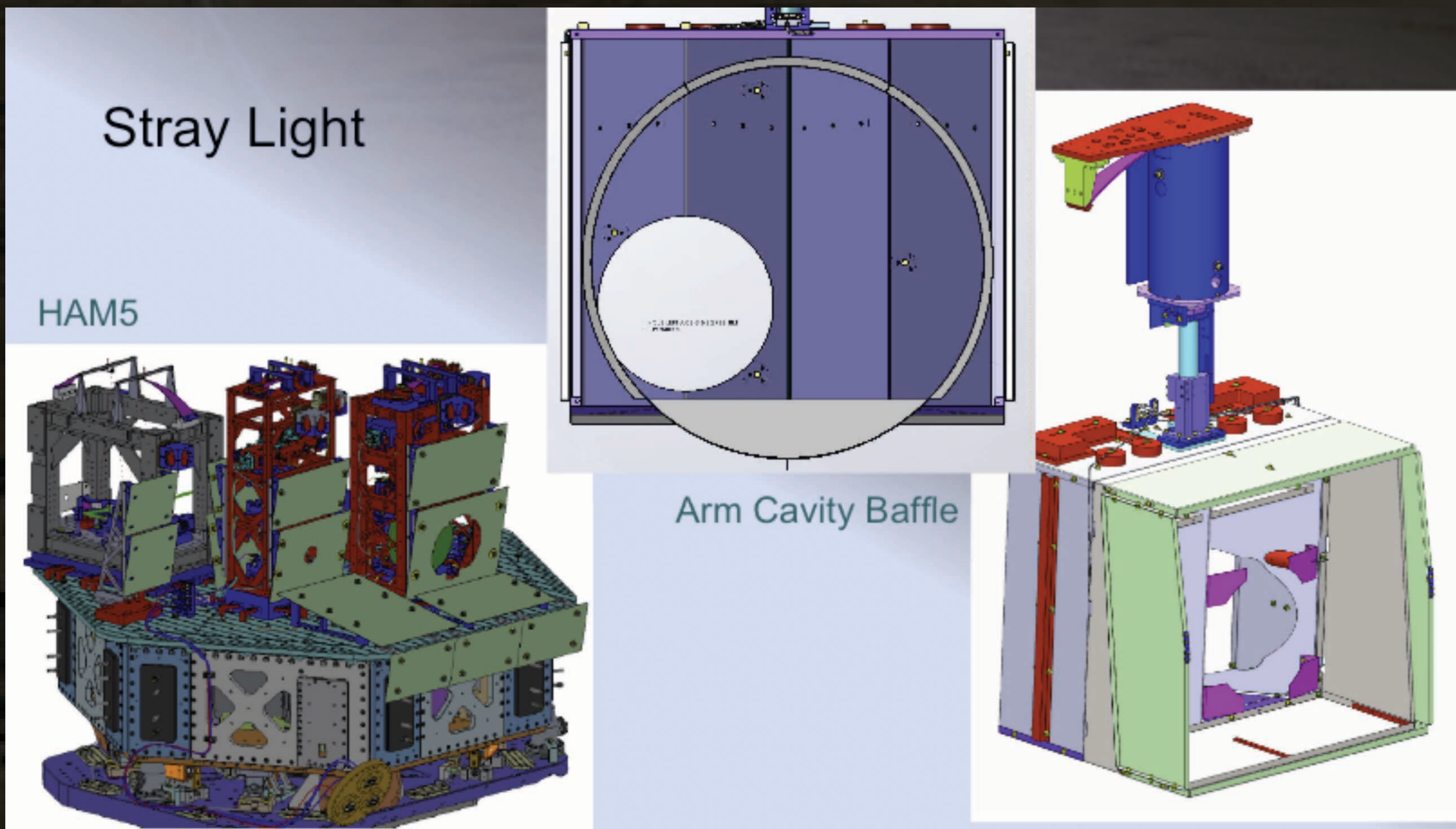
Post O2 Installation



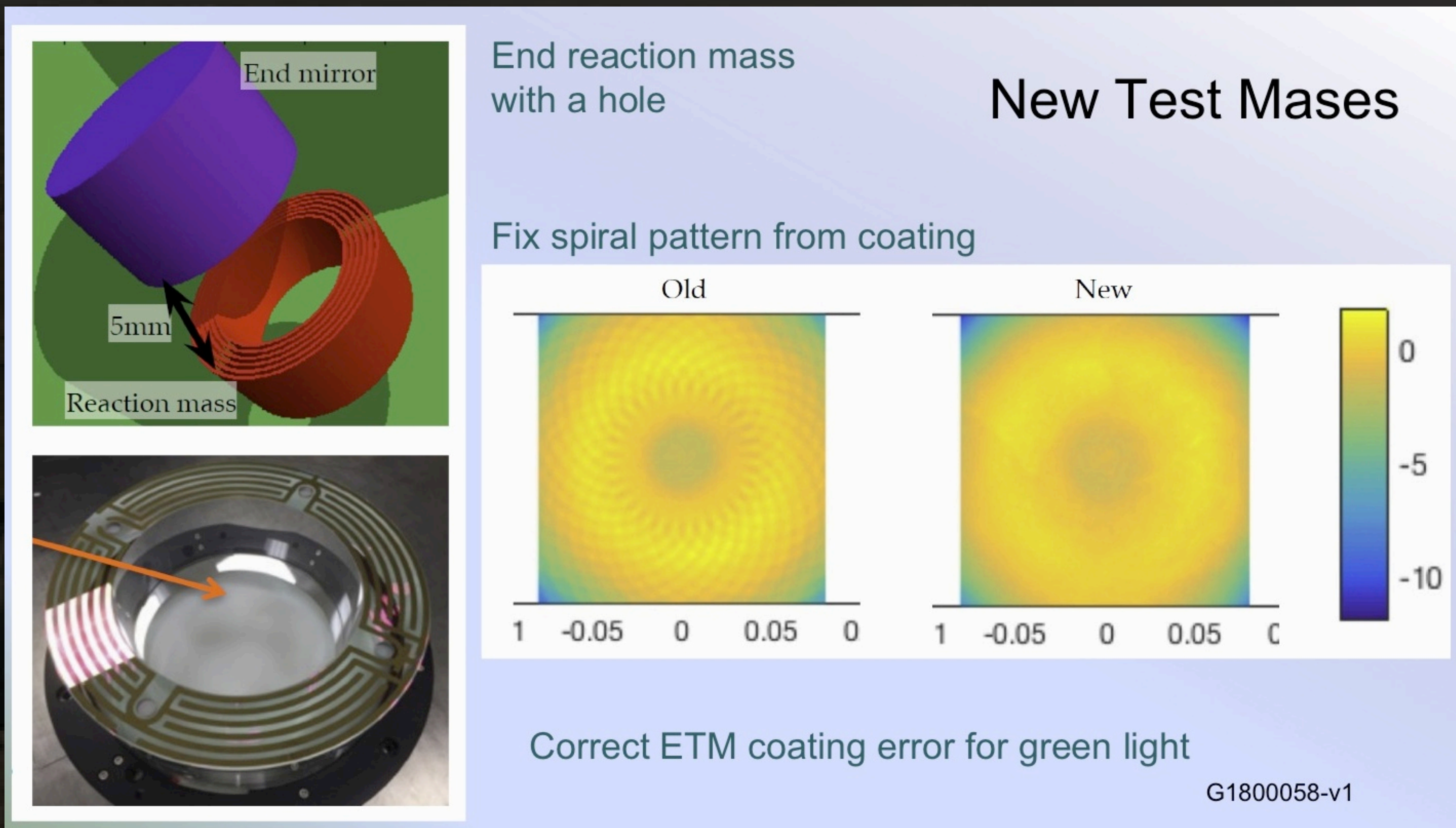
Commissioning Activities

- Optics, Cavities and Wavefronts
- High Power Operations
- Alignment
- Environmental Disturbances
- Back Scattered Light
- Squeezed Light Injection
- Sensitivity Improvements: Goal 120Mpc

Mitigating Scattered Light

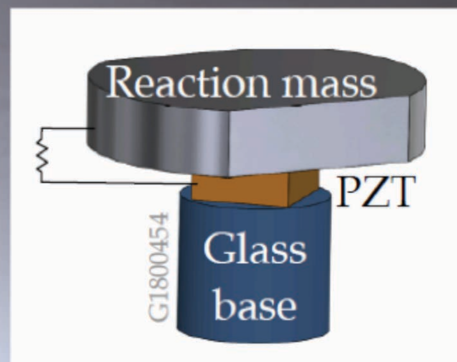


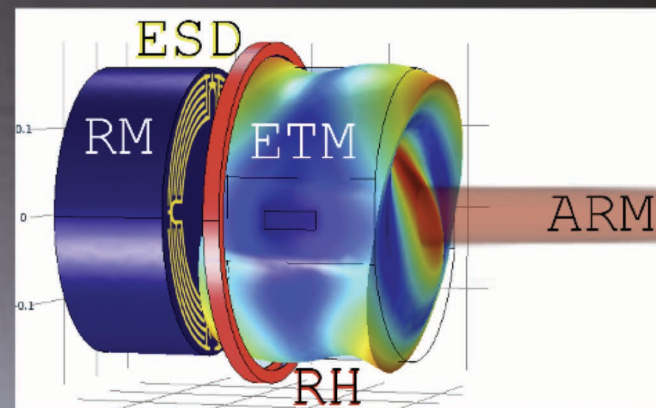
Replacing Mirrors



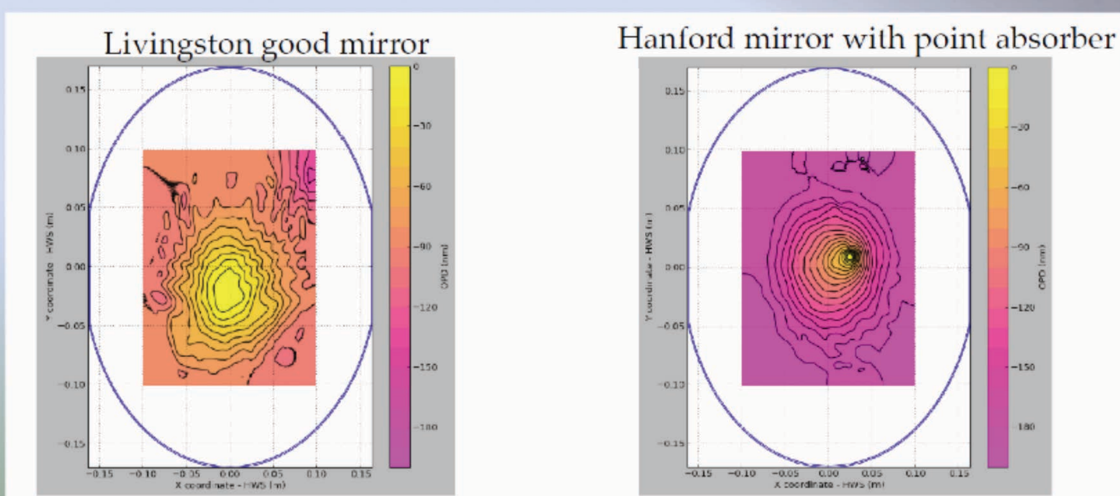
Suppressing Optic Modes

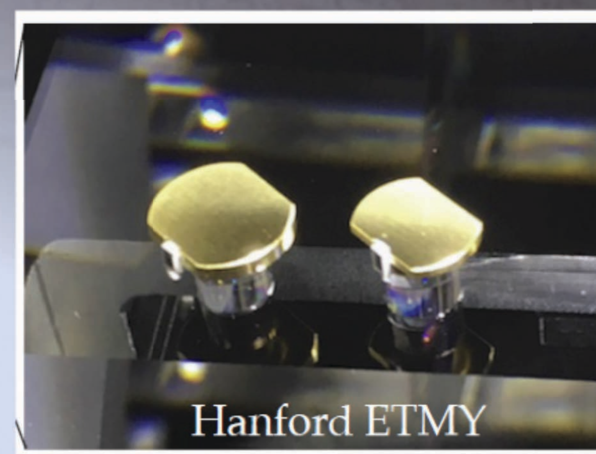
Acoustic
Mode
Dampers





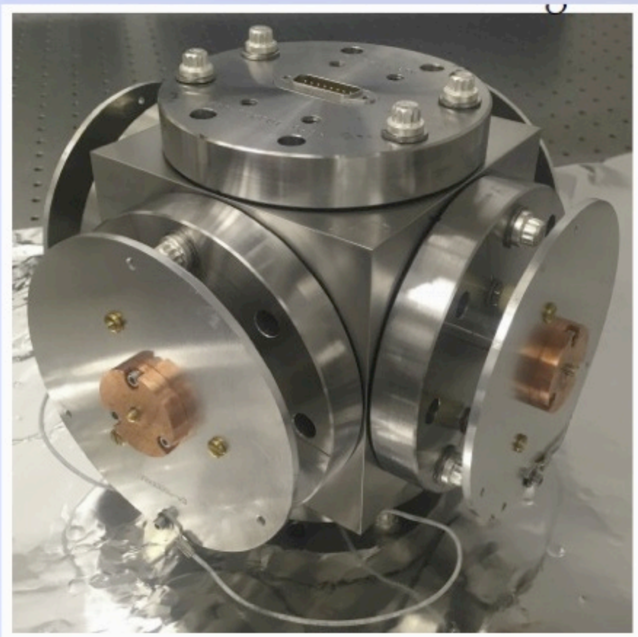
Fix point absorber on ITM





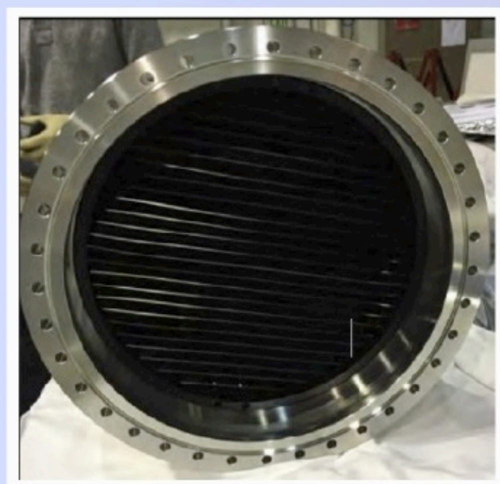
G1800058-v1

Charging and Electro-statics



Electric Field Meter

TMDS



Ion Pump Baffles

Charge

Environmental Couplings

MYSTERY SOLVED PHYSICS

How ravens caused a LIGO data glitch

The birds used ice on a pipe as a thirst quencher

BY EMILY CONOVER 3:00PM, APRIL 18, 2018

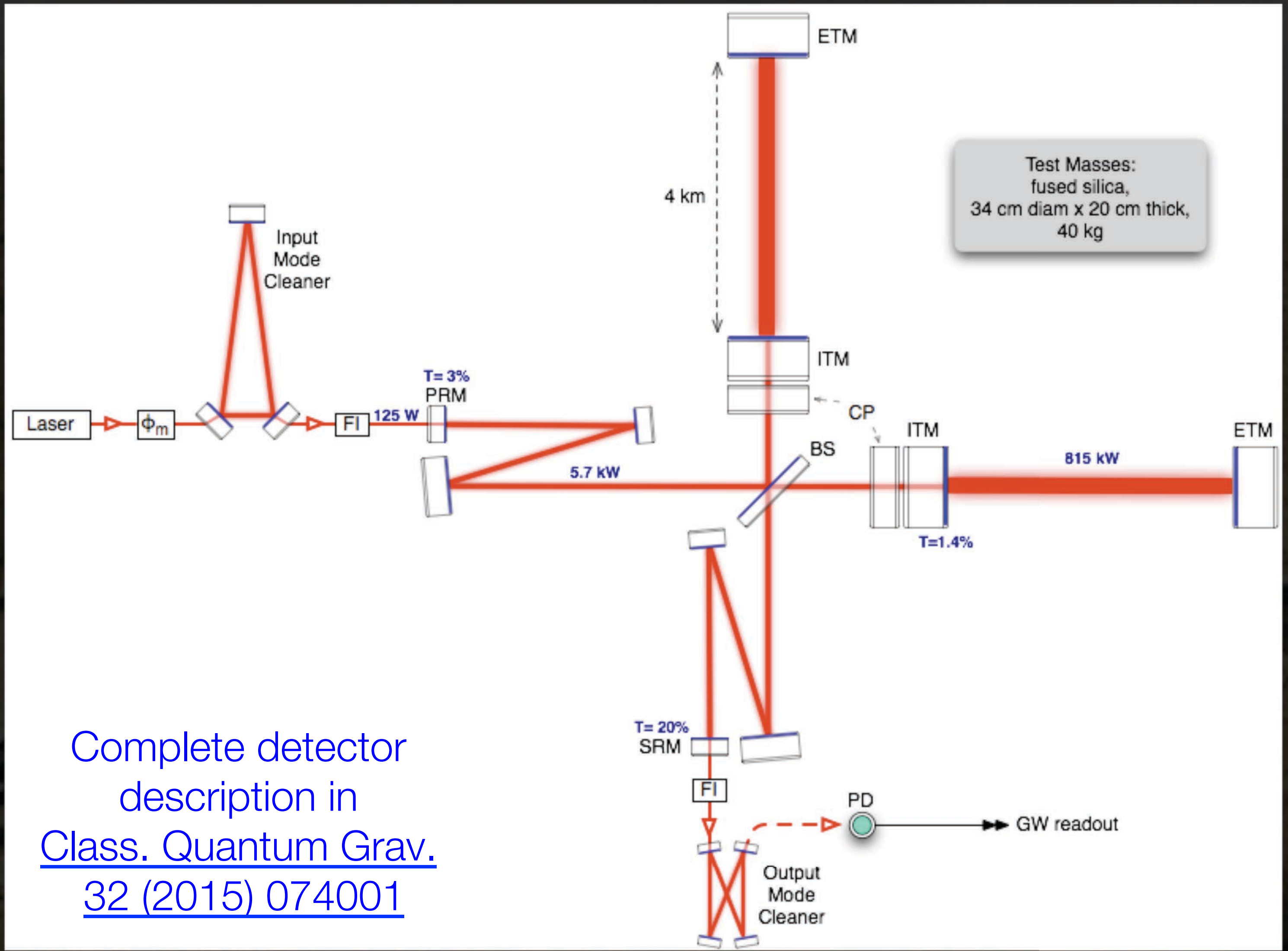
Summary

- The era of gravitational wave astronomy, and multi-messenger astronomy, is upon us
- LIGO, Virgo, and KAGRA are driving towards observing runs at or near design sensitivities in the coming few year
- Expected rates of detection in the 12-month O3 run include a few BBH per month, or more, and 1-10 BNS (total). Could get new sources and/or surprises. Lots of transients to follow up.
- Additionally we have medium and long-term upgrade plans

LIGO Scientific Collaboration

~ 1200 members ~ 100 institutions, 18 countries

Optical configuration



Complete detector description in [Class. Quantum Grav. 32 (2015) 074001]

Near Term Future: The Next Decade

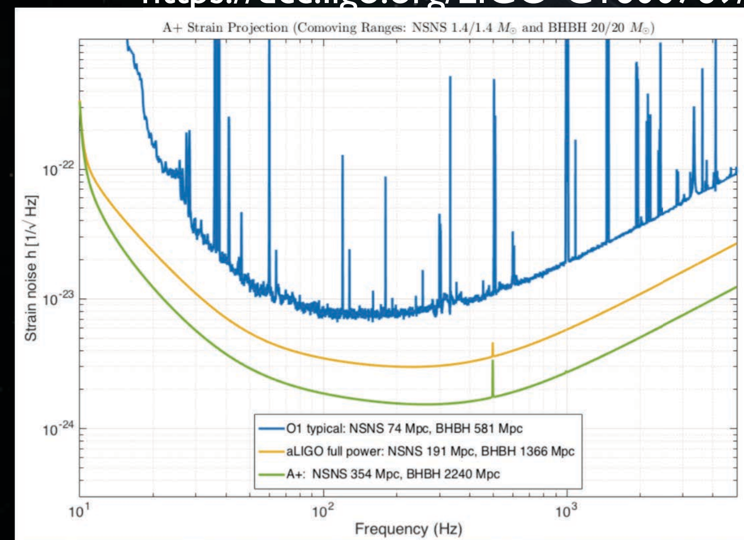
Advanced LIGO Plus (A+)

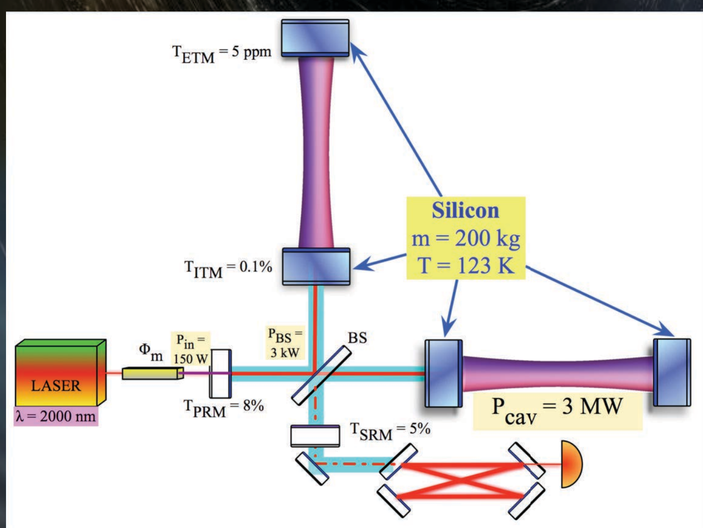
An incremental upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment and moderate risk

Target: x1.7 increase in range over aLIGO
x5 greater event rate

Existing infrastructure, known technology (frequency-dependent squeezed light, improved coatings)

https://dcc.ligo.org/LIGO-G1600769/





LIGO Voyager

additional x2 sensitivity broadband improvement, lower frequency 20Hz -> 10Hz

larger Si masses, cryogenic operation, new laser wavelength

3G detectors

Einstein Telescope

- European conceptual design study
- Multiple interferometers underground, 10 km arm length, in triangle. Assumes 10-15 year technology development.
- ~10^5 binary coalescences per year

Cosmic Explorer

- US-based design just starting
- Based on LIGO Voyager technology, expanded to 40 km arms.