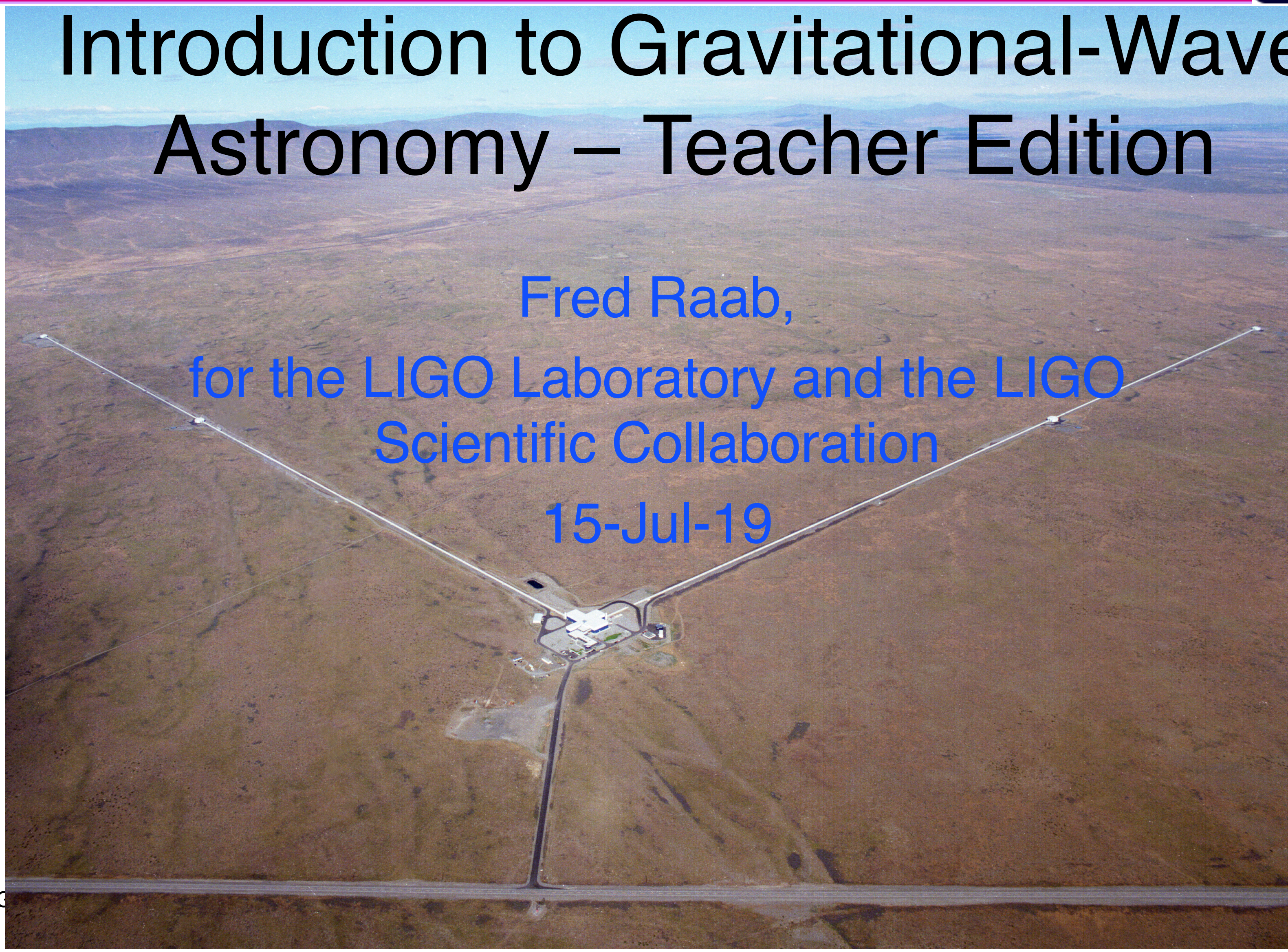
Introduction to Gravitational-Wave Astronomy – Teacher Edition

Fred Raab,

for the LIGO Laboratory and the LIGO Scientific Collaboration

15-Jul-19



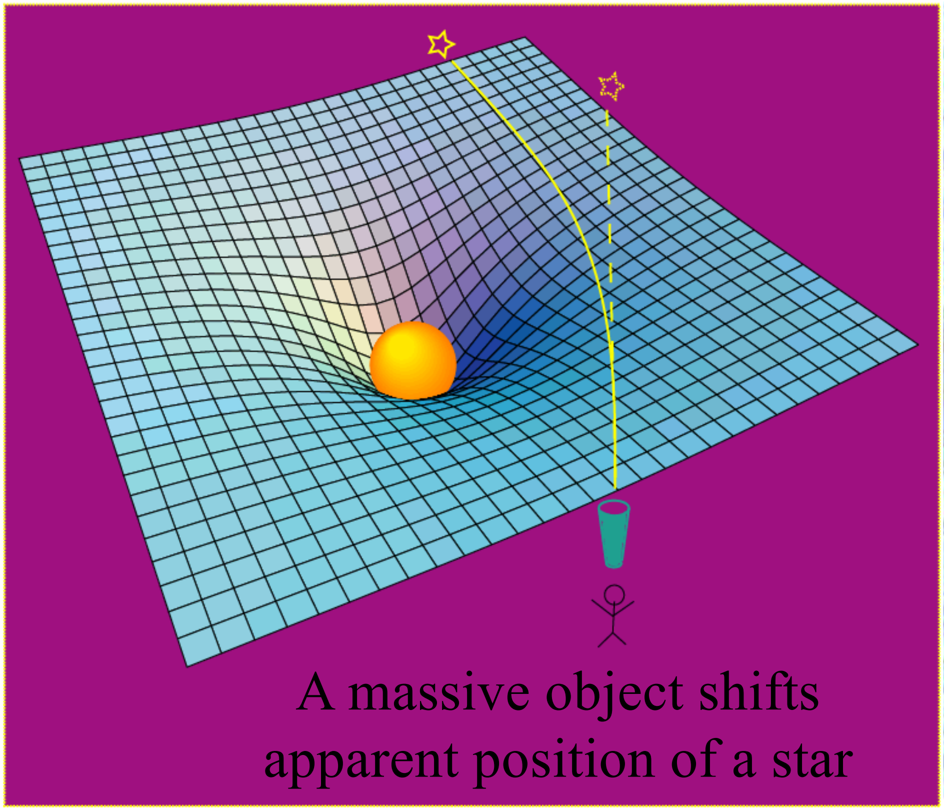
Outline

- My talk today
  - » Basics of General Relativity and Gravitational Waves
  - » Sources of Gravitational Waves
  - » Detectors of Gravitational Waves
  - » Some history
  - » International Network of Terrestrial GW Detectors
  - » The future

Basics of General Relativity and Gravitational Waves

Wherein it is realized that space and time are things whose properties are manifested by phenomena that we collectively refer to as "gravity".

Einstein's General Relativity re-wrote the rules of space and time

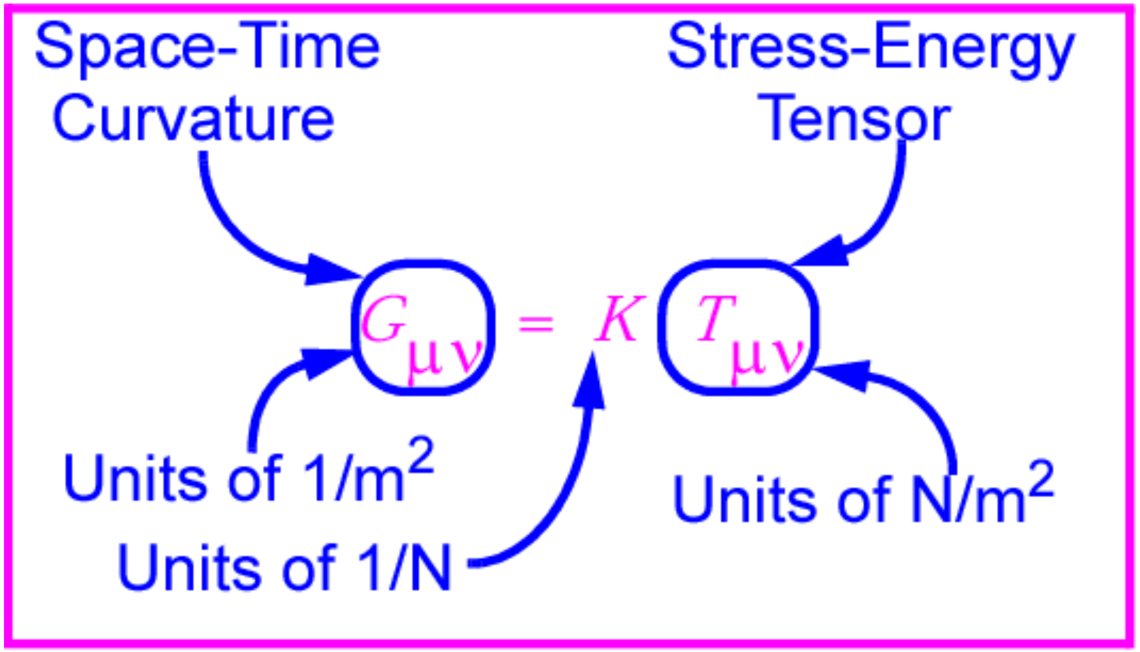


Empty space and time are things, with real physical properties. Space has a shape, a stiffness and a maximum speed for information transfer.

The problem with checking relativity in Einstein's time

- A figure of merit for manifesting relativistic effects is *v/c.*
- In Einstein's time, there was not a lot of *v/c* available to observe and rulers and clocks were not so good.
  - » *v/c for a locomotive is approximately* 10^{-7}
  - » Ruling engines could get down to micron resolution (10^{-6} m)
  - » Clocks could keep time to a second per day
- Today
  - » *v/c reached 0.5 for GW150914*
  - » LIGO resolution is approximately 10^{-20} m
  - » Clocks keep time to a second per 300 million years
  - » Al+ clock accurate to a second in 32 Gyr announced today!

Gravitational waves: hard to find because space-time is stiff!



- $K \sim [G/c^4]$ is lowest order combination of G, c with units of 1/N

$$K \sim 10^{-44}\ N^{-1}$$

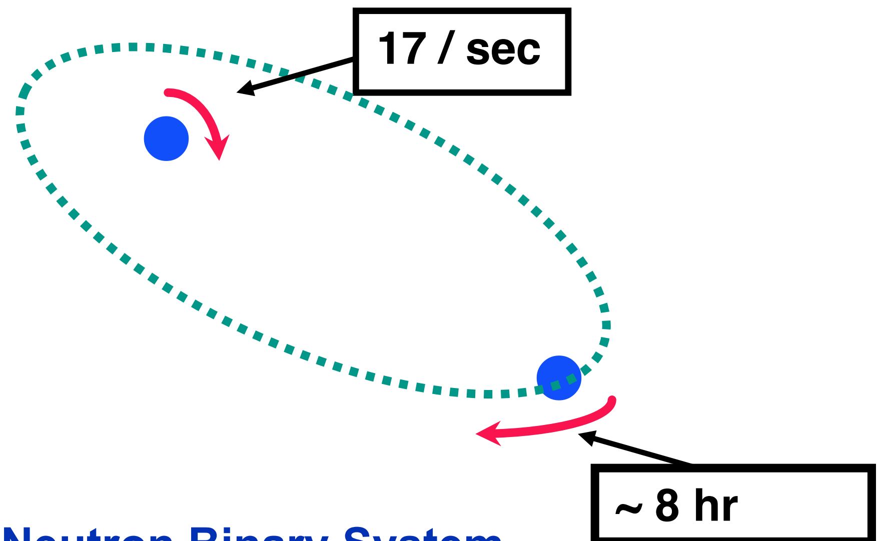
$\Rightarrow$ **Wave can carry huge energy with miniscule amplitude!**

Gravitational Waves

hard to find, but known to exist

Neutron Binary System – Hulse & Taylor

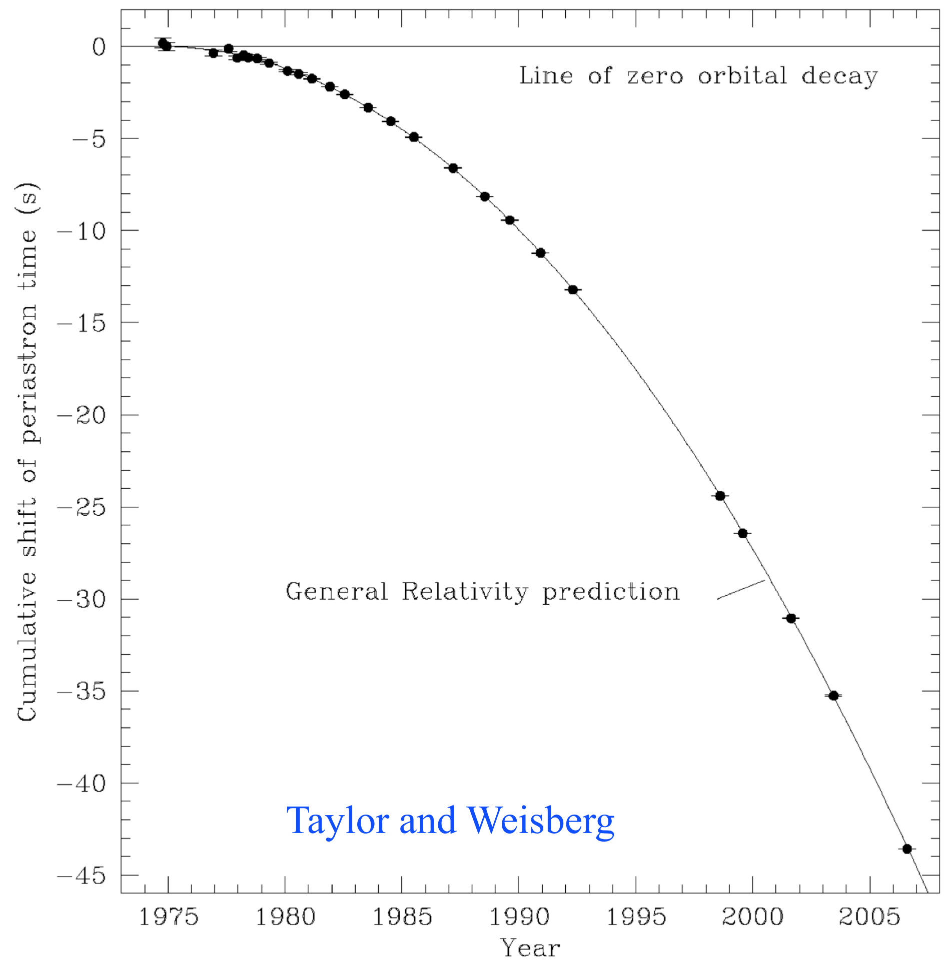
PSR 1913 + 16 -- Timing of pulsars



Neutron Binary System
- **separated by 10^6 miles**
- **$m_1 = 1.4m_{\odot}$; $m_2 = 1.36m_{\odot}$; $\varepsilon = 0.617$**

Prediction from general relativity
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

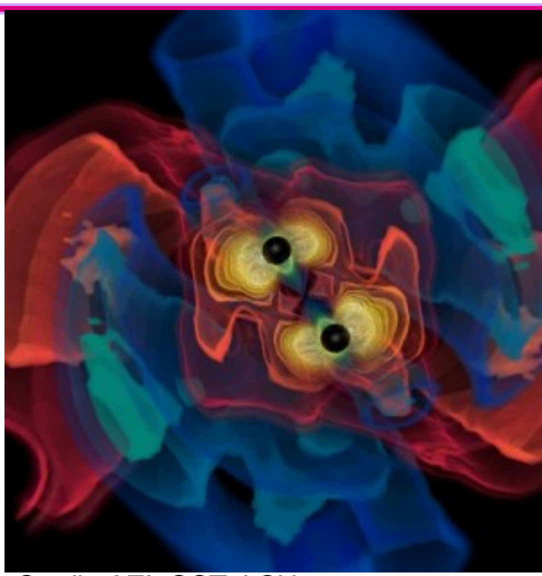
Emission of gravitational waves



Sources of Gravitational Waves

Accelerating Quadrupole Mass Moments

Astrophysical Sources of Gravitational Waves

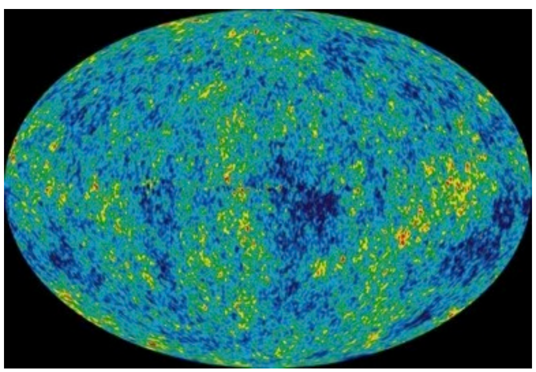


Credit: AEI, CCT, LSU

__Coalescing Compact Binary Systems__:
Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,

- (effectively) transient

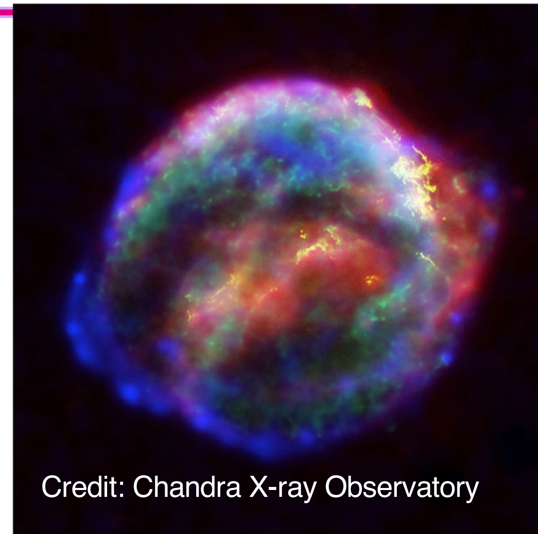


NASA/WMAP Science Team

__Cosmic Gravitational-wave Background__

- Residue of the Big Bang

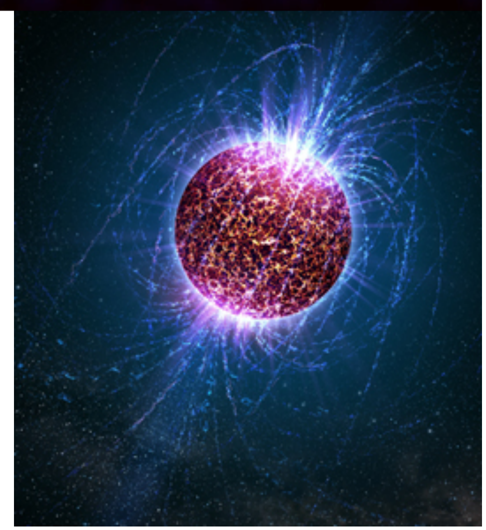
- Long duration, stochastic background



Credit: Chandra X-ray Observatory

__Asymmetric Core Collapse Supernovae__

- Weak emitters, not well-modeled ('bursts'), transient



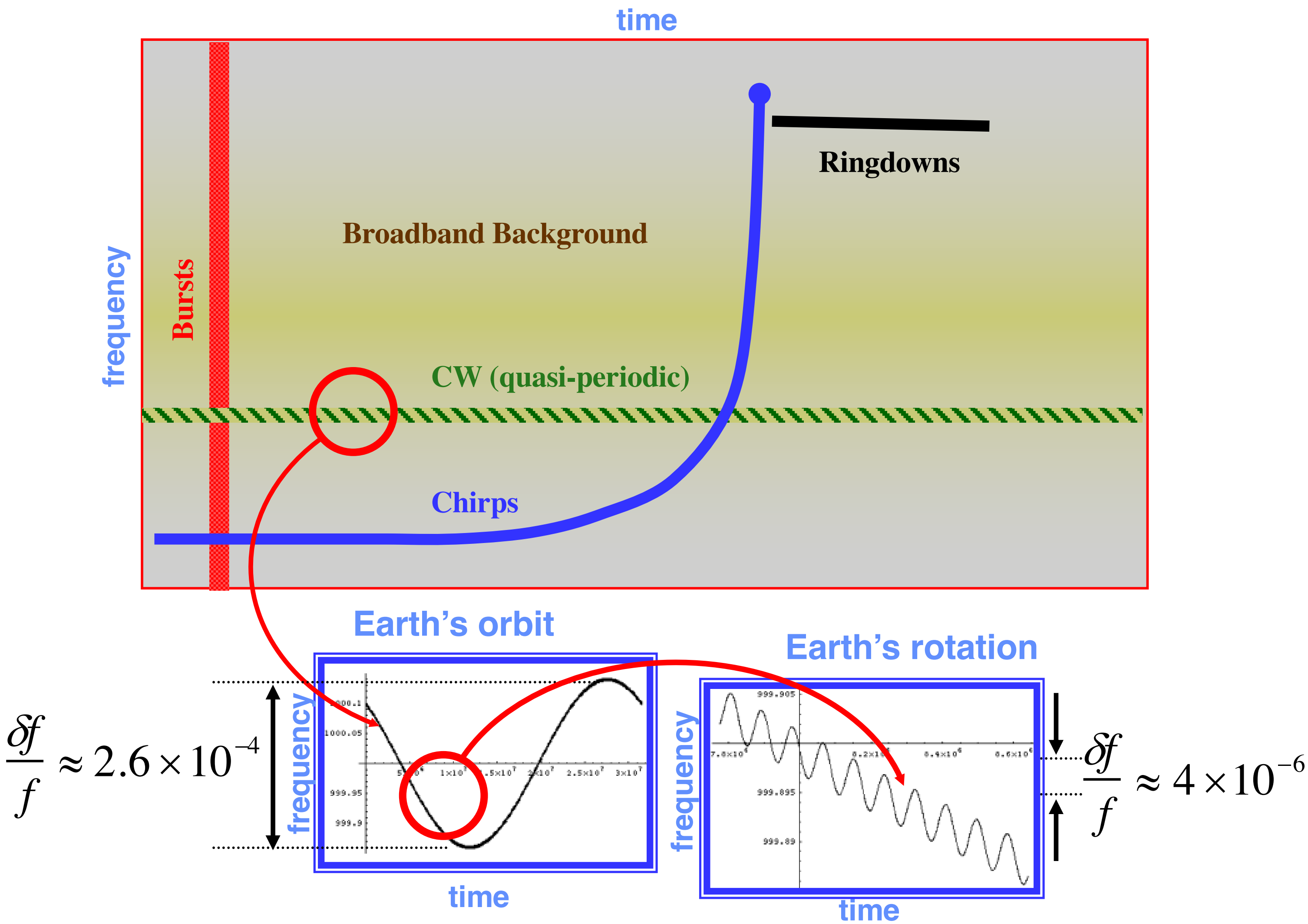
Casey Reed, Penn State

__Spinning neutron stars__

- (nearly) monotonic waveform

- Long duration

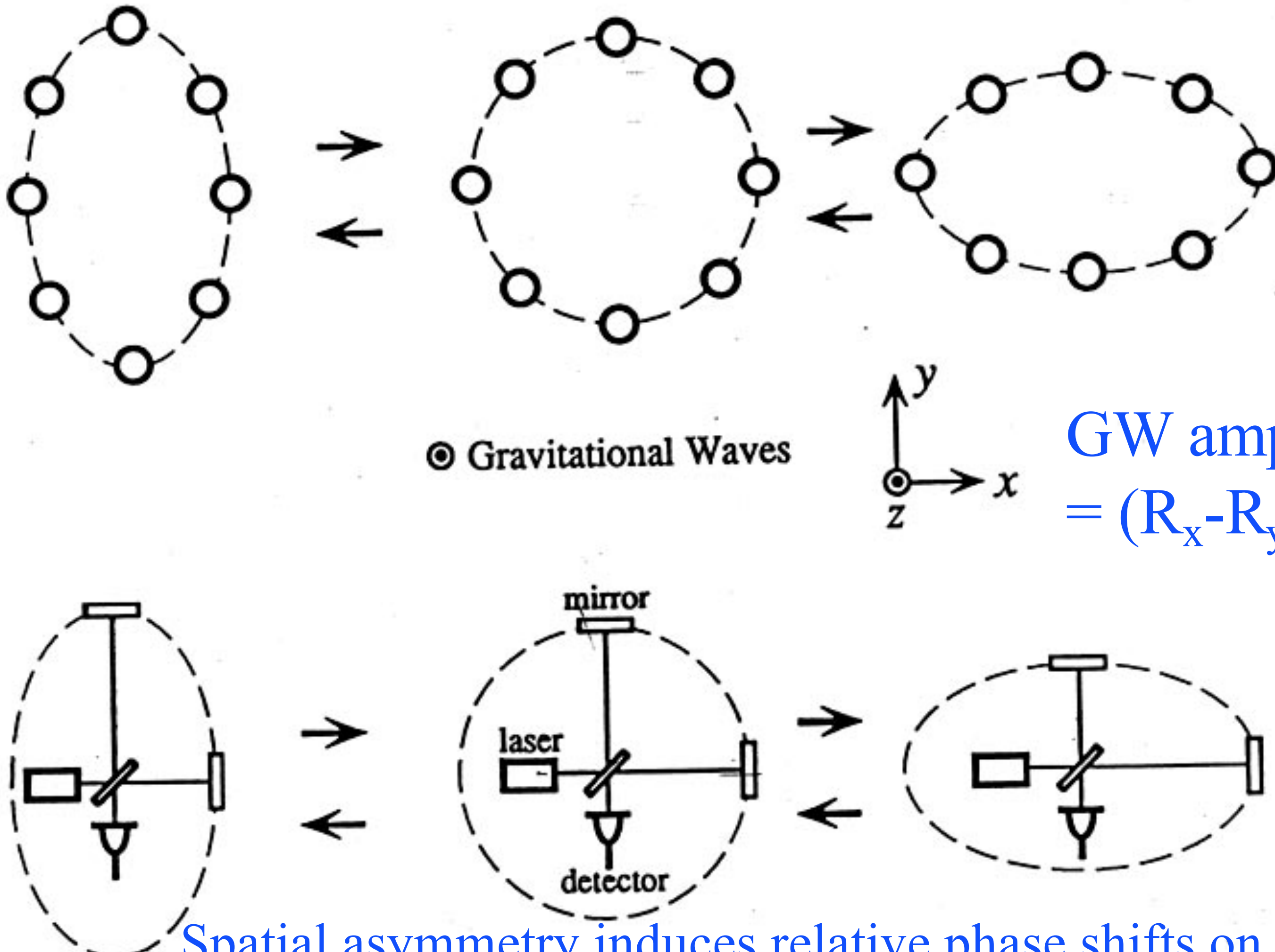
Frequency-Time Characteristics of GW Sources



Detectors of Gravitational Waves

No Law of Physics Forbids Them

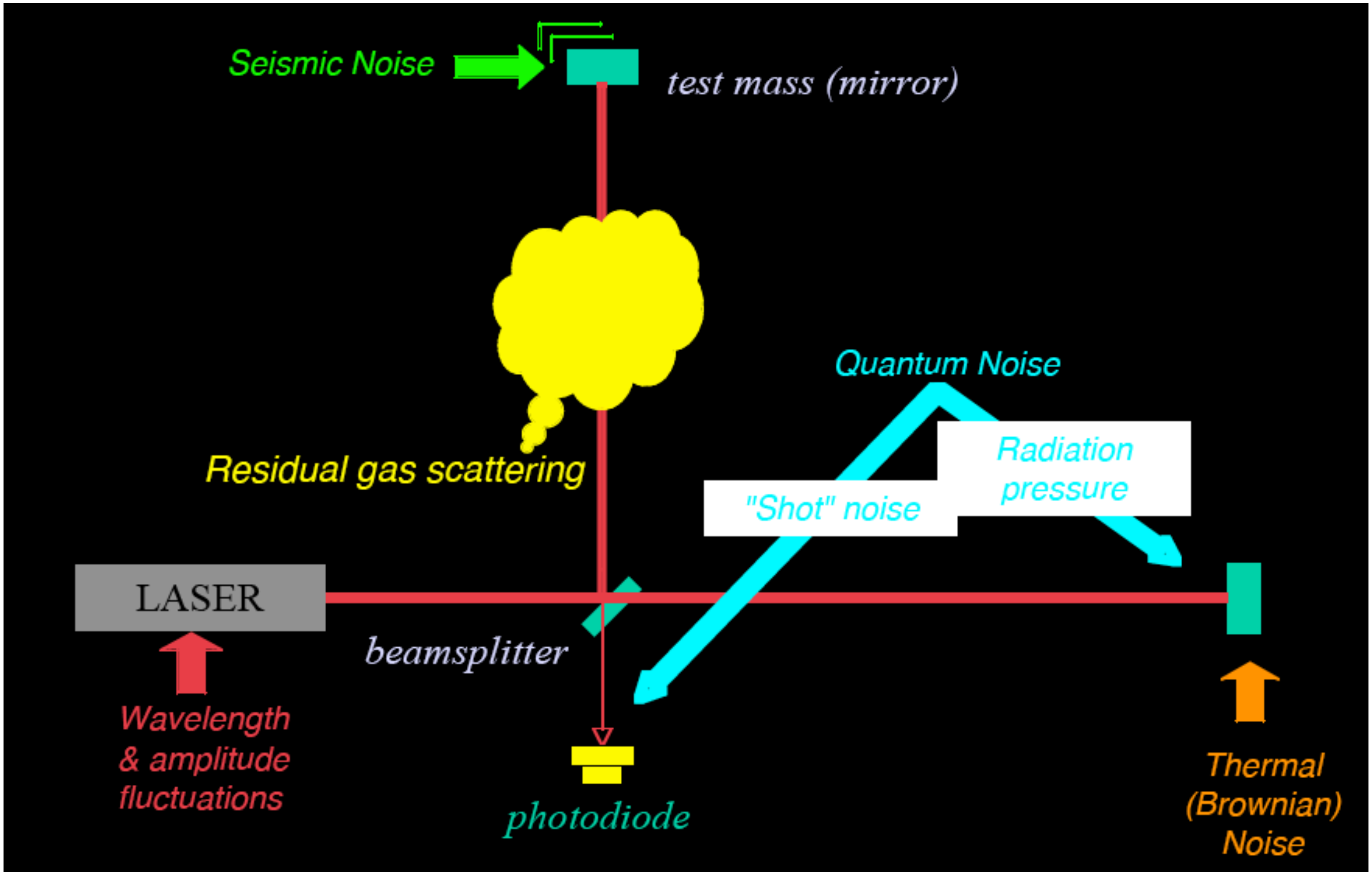
Basic idea is simple



GW amplitude h
$= (R_x - R_y)/R$

Spatial asymmetry induces relative phase shifts on light in arms

Noise cartoon



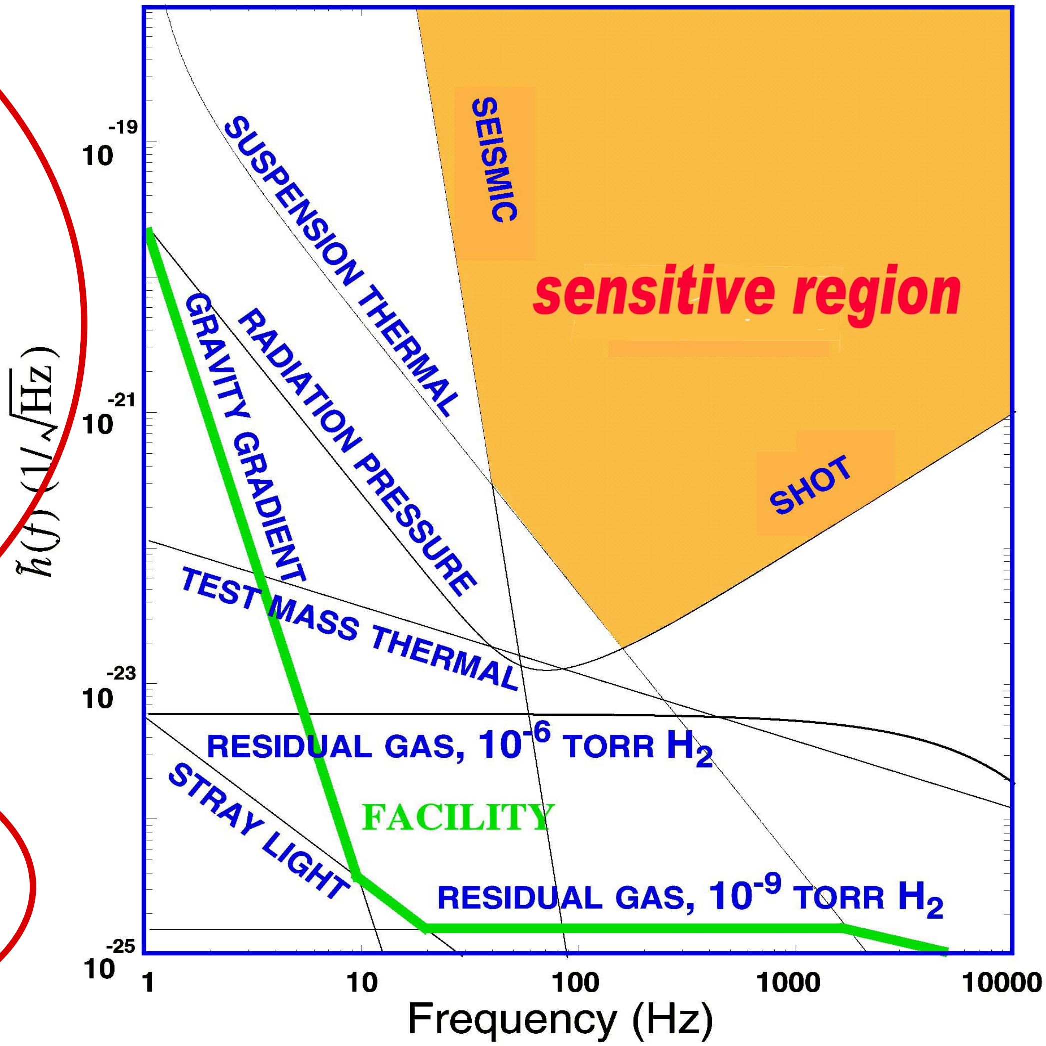
R. Adhikari

What Limits Sensitivity of Interferometers?

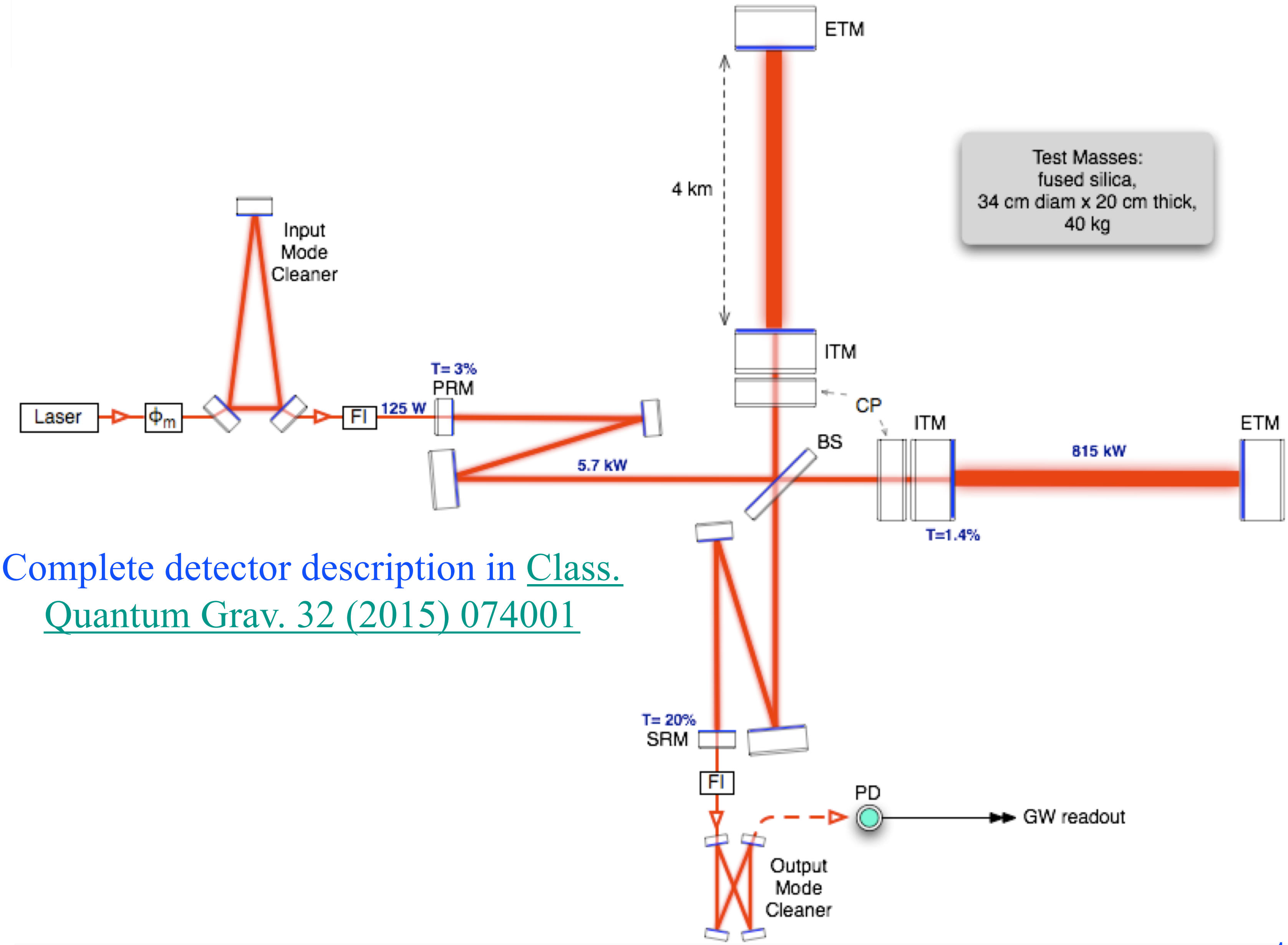
DESIGN

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

COMMISSIONING



Optical configuration



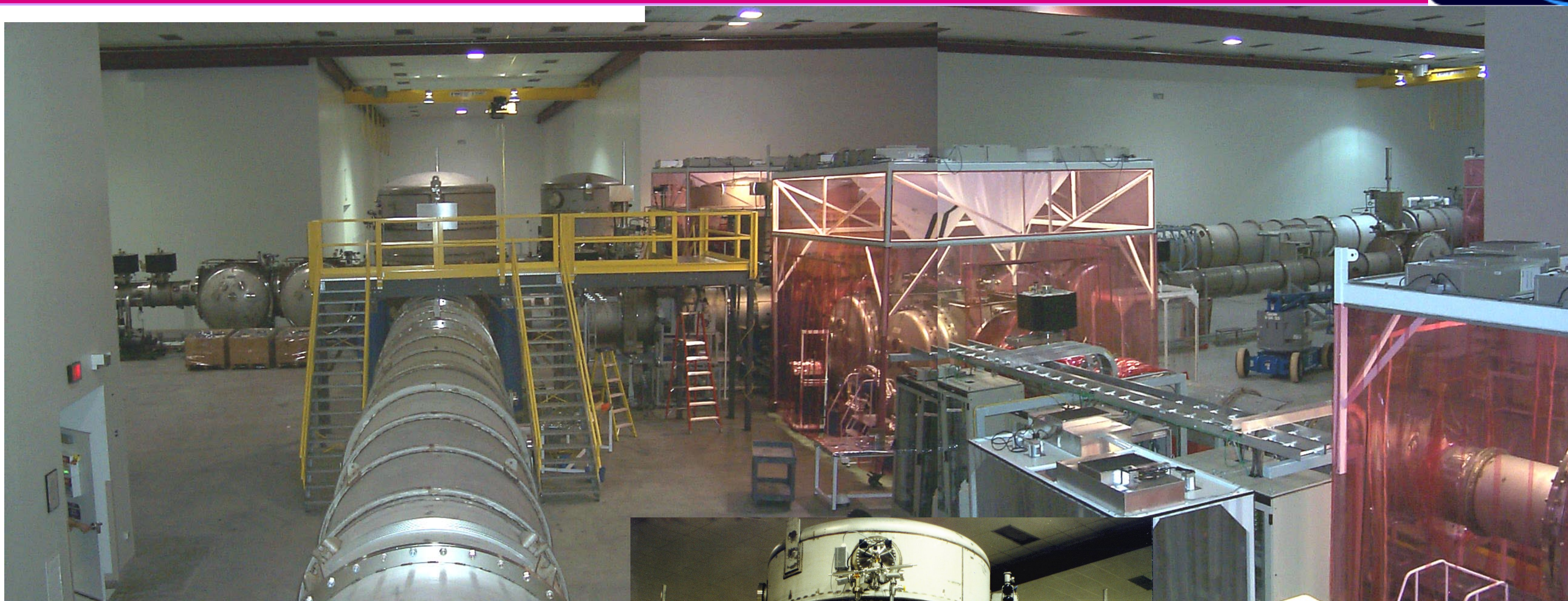
Complete detector description in [Class. Quantum Grav. 32 (2015) 074001]

Evacuated Beam Tubes Provide Clear Path for Light

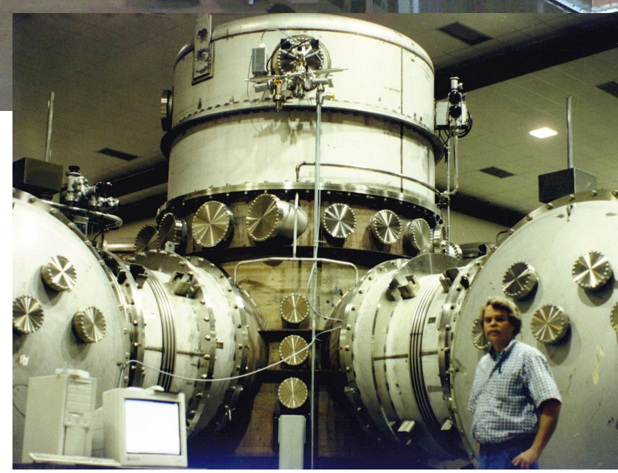
P< 10^{-9} Torr

Portable power supply for bakeout

Vacuum Chambers Provide Quiet Homes for Mirrors

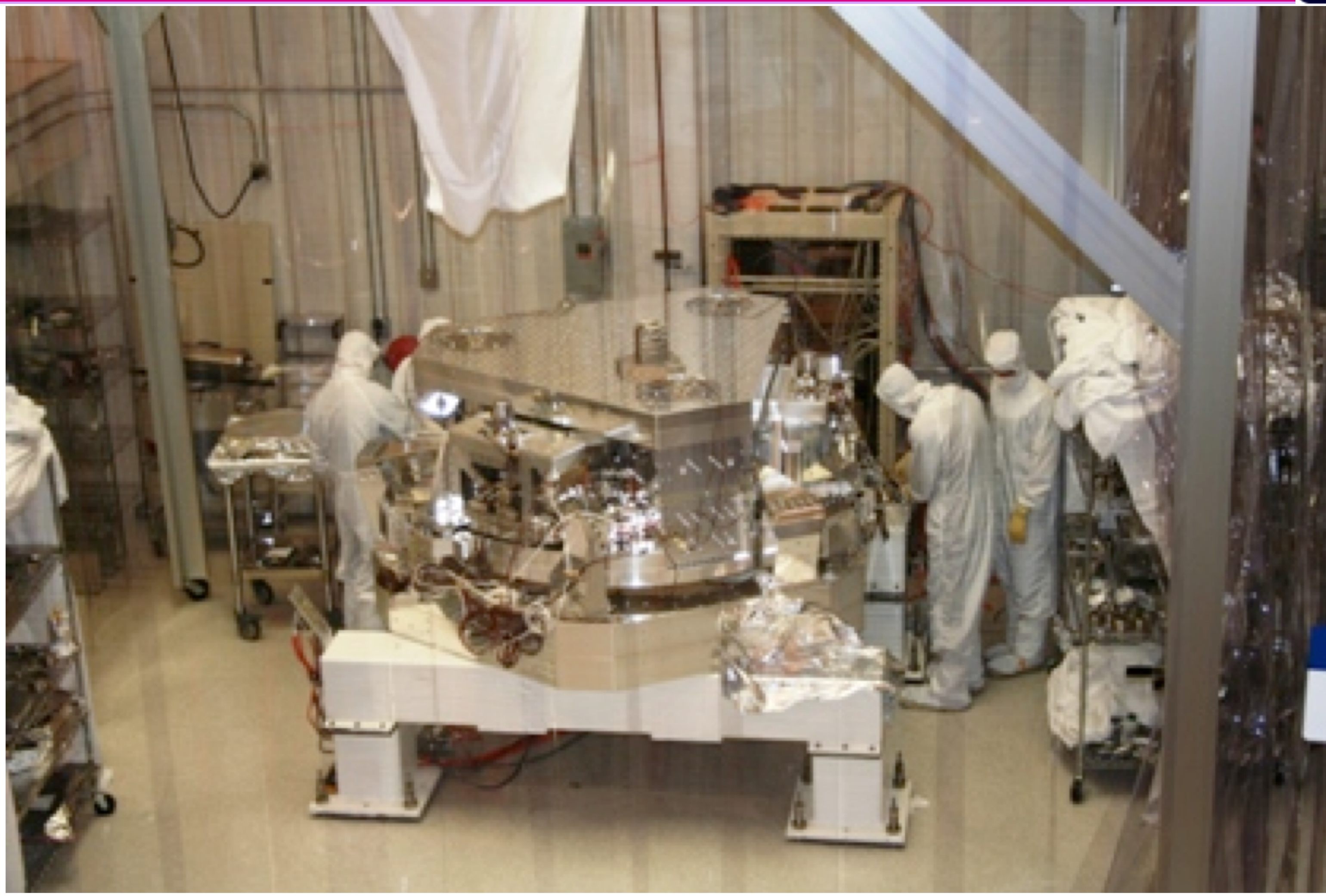


View inside Corner Station

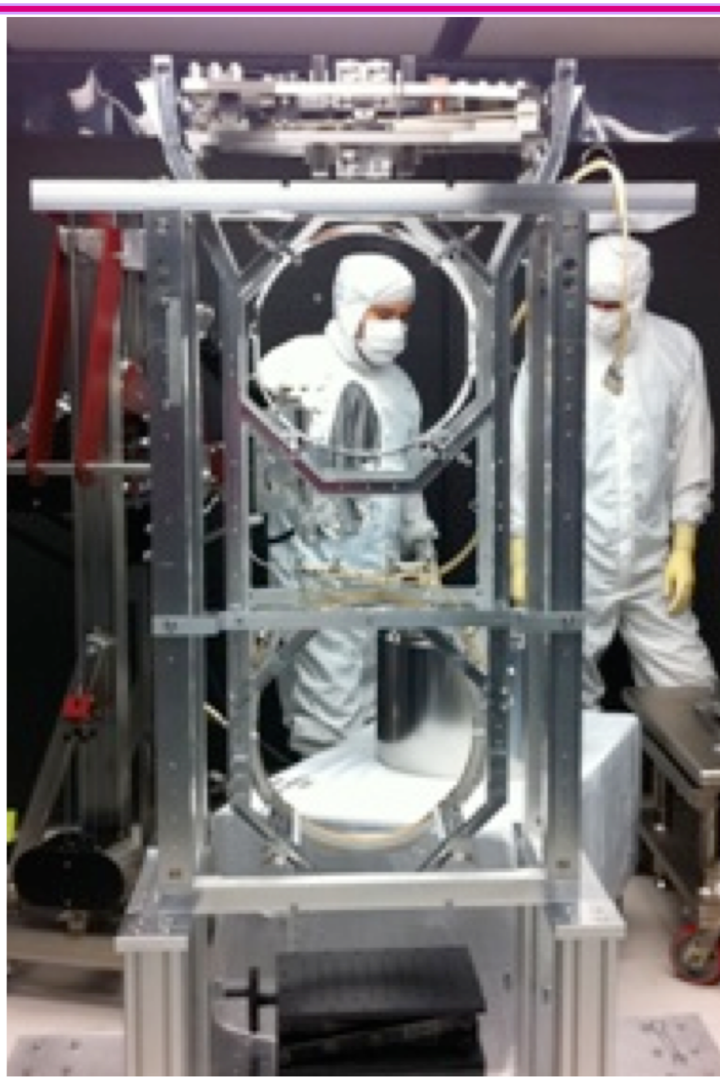


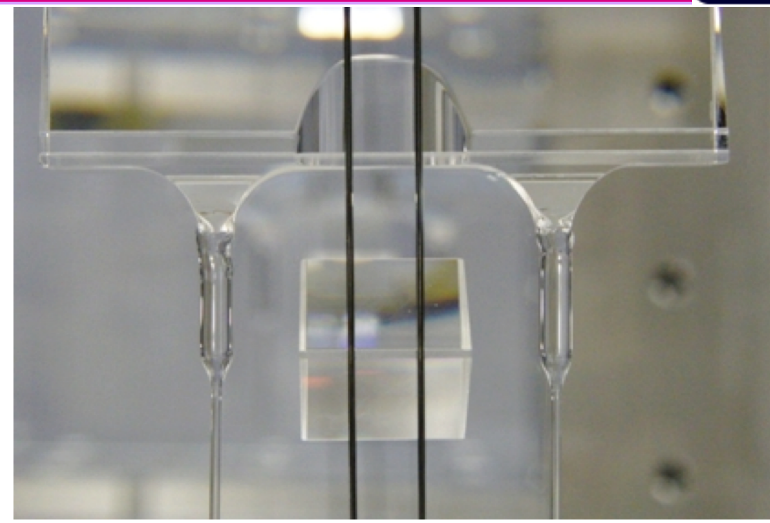
Standing at vertex beam splitter

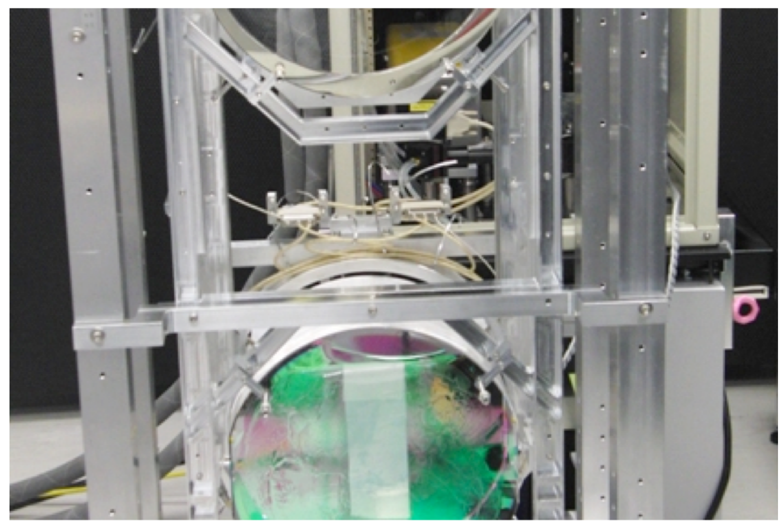
BSC Internal Seismic Isolator



Advanced LIGO Monolithic Suspension

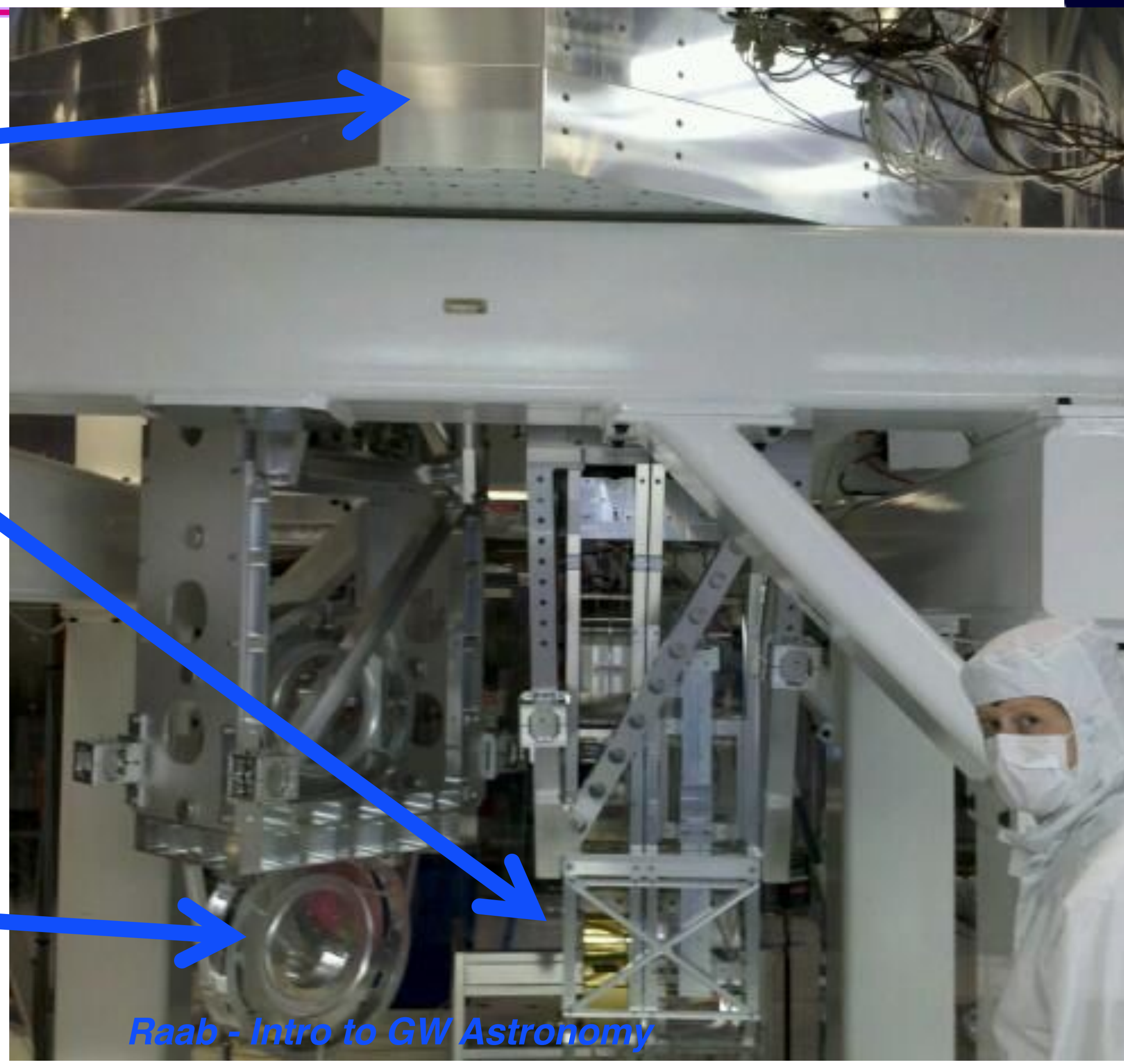






Advanced LIGO installation in progress

Putting it together: Seismic & Suspension & Optics

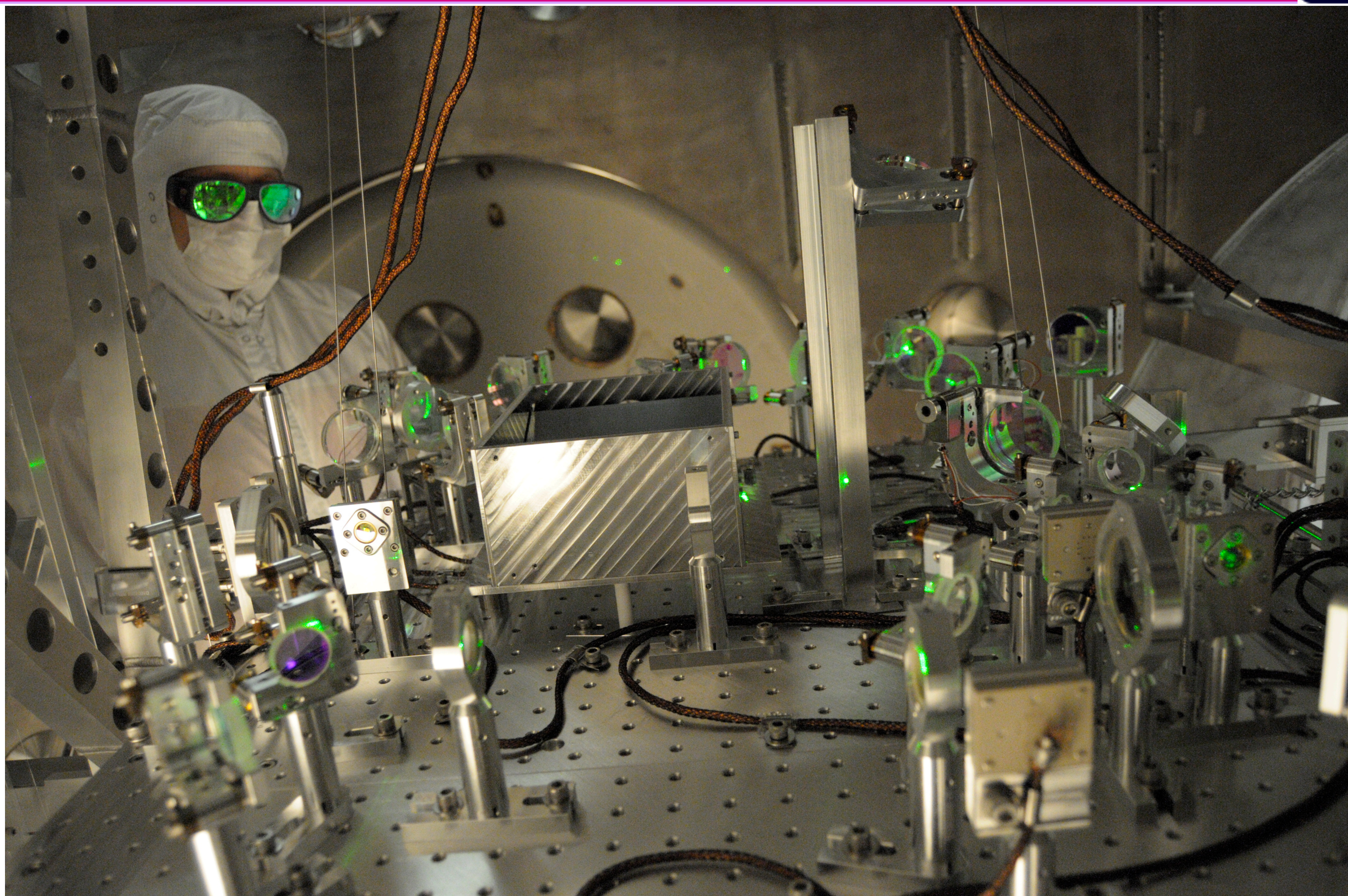


Seismic isolation

Test mass suspension

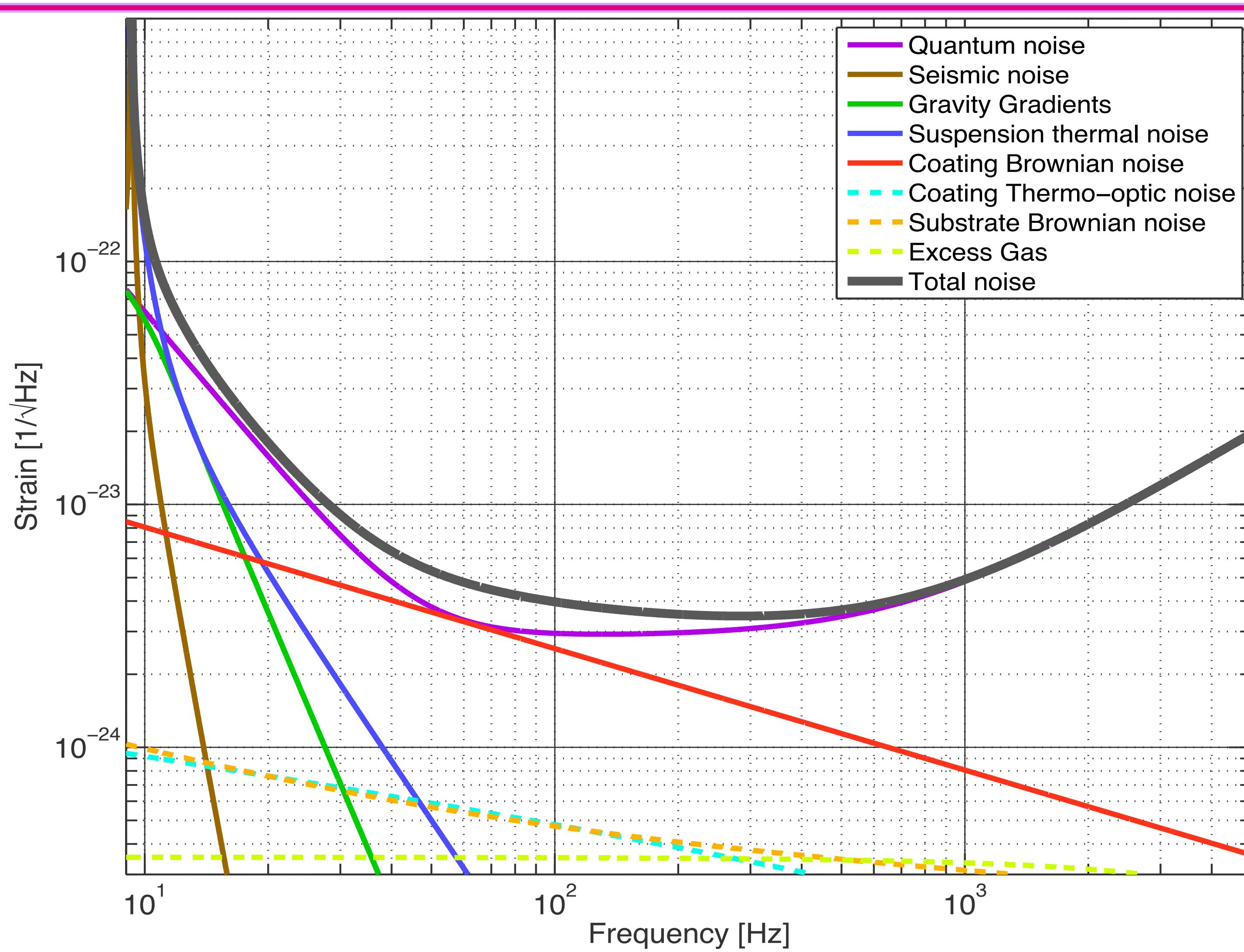
Folding mirror suspension

Lock Acquisition: Arm Locking Subsystem



aLIGO Pre-stabilized laser

Principal noise terms



Some History

Strategy: Build a Facility That Can House Evolving Generations of More Powerful Detectors

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

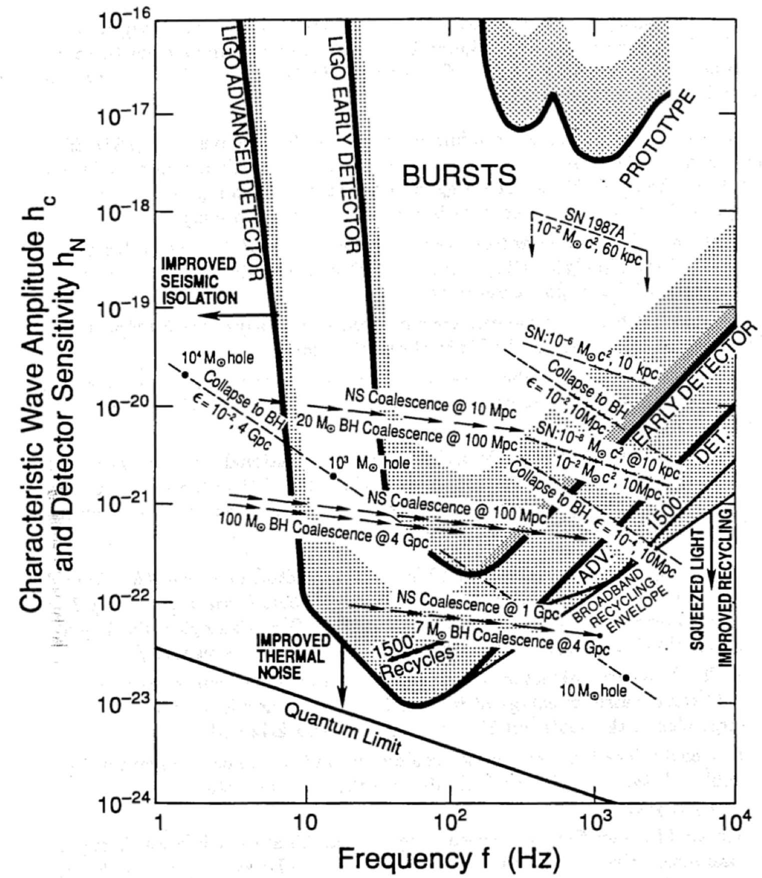


Figure II–2 A comparison of the strengths of gravitational waves (characteristic amplitude h_c and frequency f) for burst signals from various sources (dashed lines and arrows), and benchmark sensitivities h_N (solid curves and stippled strips atop them) for interferometric detectors today (*prototype*) and in the proposed LIGO (*early detector*, *advanced detector*). See the caption of Figure A-4a (a duplicate of this figure) and the associated discussion in Appendix A for more details.

The Laser Interferometer Gravitational-wave Observatory

LSC

NSF

- LIGO Observatories constructed from 1994-2000
- LSC created 1997
- Initial LIGO operated from 2002-2010
- Advanced LIGO 2015

Advanced LIGO detectors:

MAX-PLANCK-GESELLSCHAFT

Science & Technology Facilities Council

Australian Government
Australian Research Council

LIGO Scientific Collaboration

~ 1000 members ~ 80 institutions, 16 countries

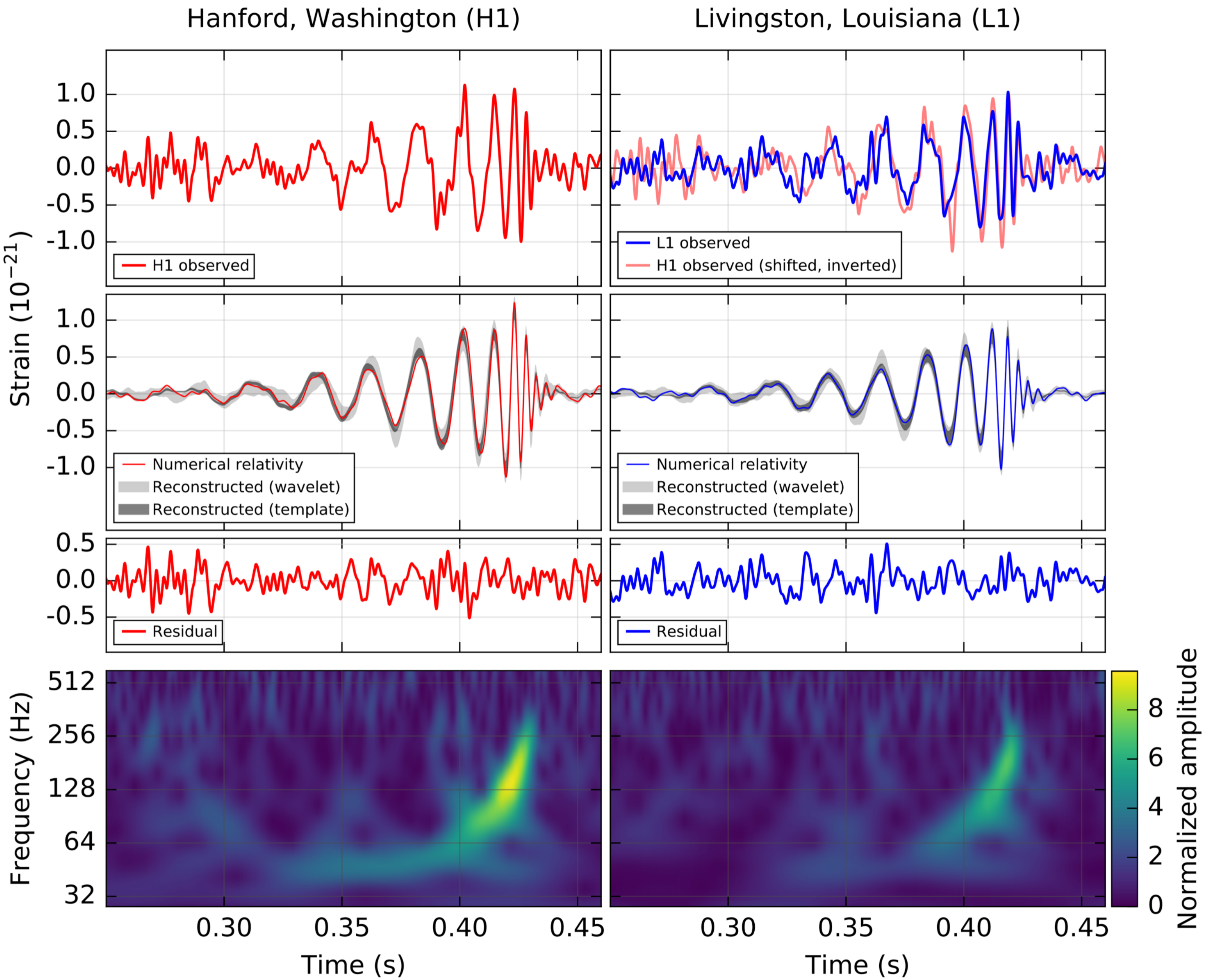
First Direct Detection of Gravitational Waves

Opening a New Window on the Universe

LIGO-G1600932

GW150914: What was observed?

B. P. Abbott *et al.*, Phys. Rev. Lett. 116, 061102

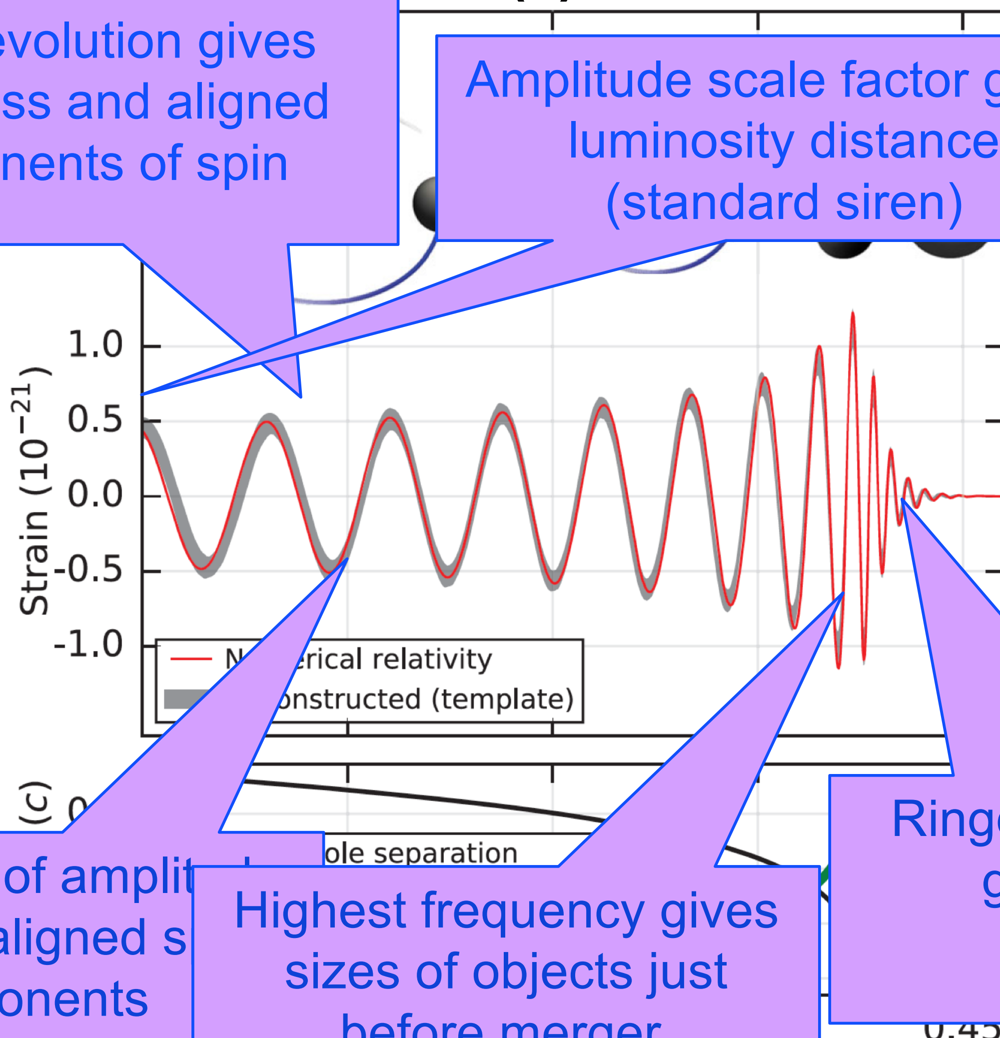


LI

What can we learn from h(t)?

Phase evolution gives chirp mass and aligned components of spin

Amplitude scale factor gives luminosity distance (standard siren)



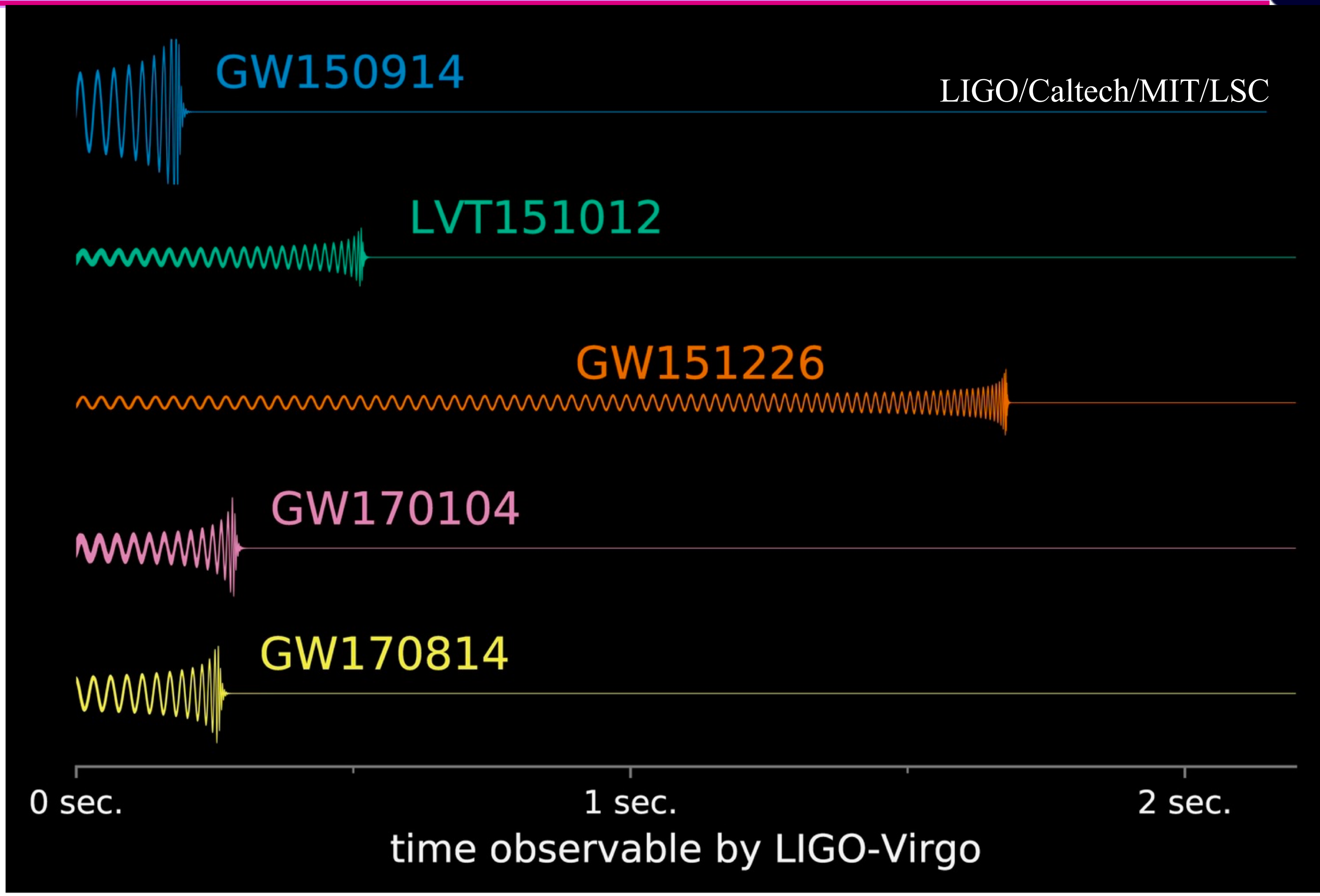
B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

Modulation of amplit… gives nonaligned s… components

Highest frequency gives sizes of objects just before merger.

Ringdown frequency and Q give mass and spin of final black hole

Comparison of GW Waveforms from BBHs (Sep 2017)

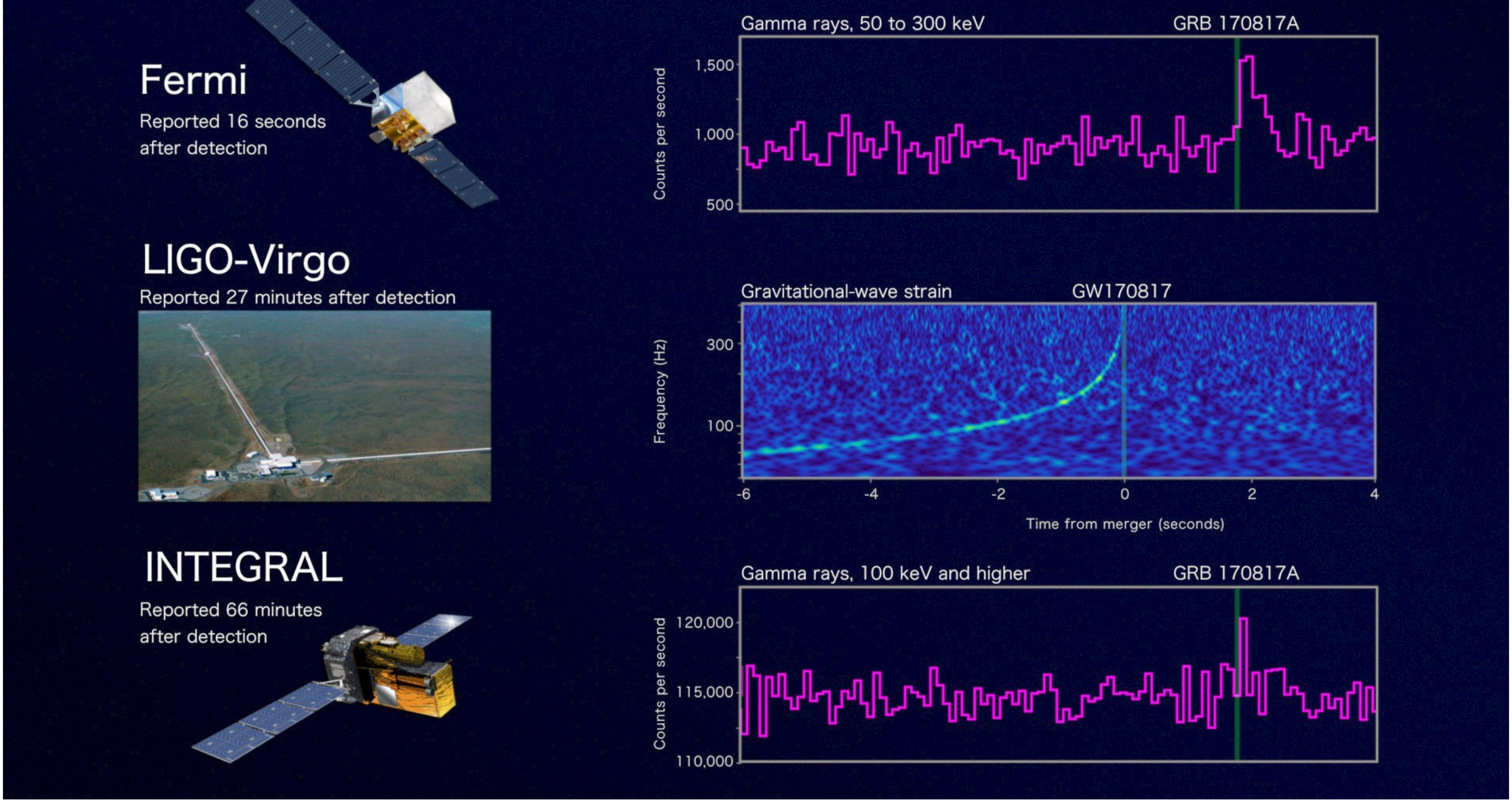


Multi-Messenger Astronomy

- These first observations of dynamic extreme spacetimes with BBHs show us that GR is reasonably accurate in this regime and can be used as a tool for examining and interpreting extreme states of matter.
- There are a rich collection of sources still to be examined!

Onto the study of the most extreme states of matter

Credit: NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA



LIGO-Virgo network localization enables discovery of optical counterpart

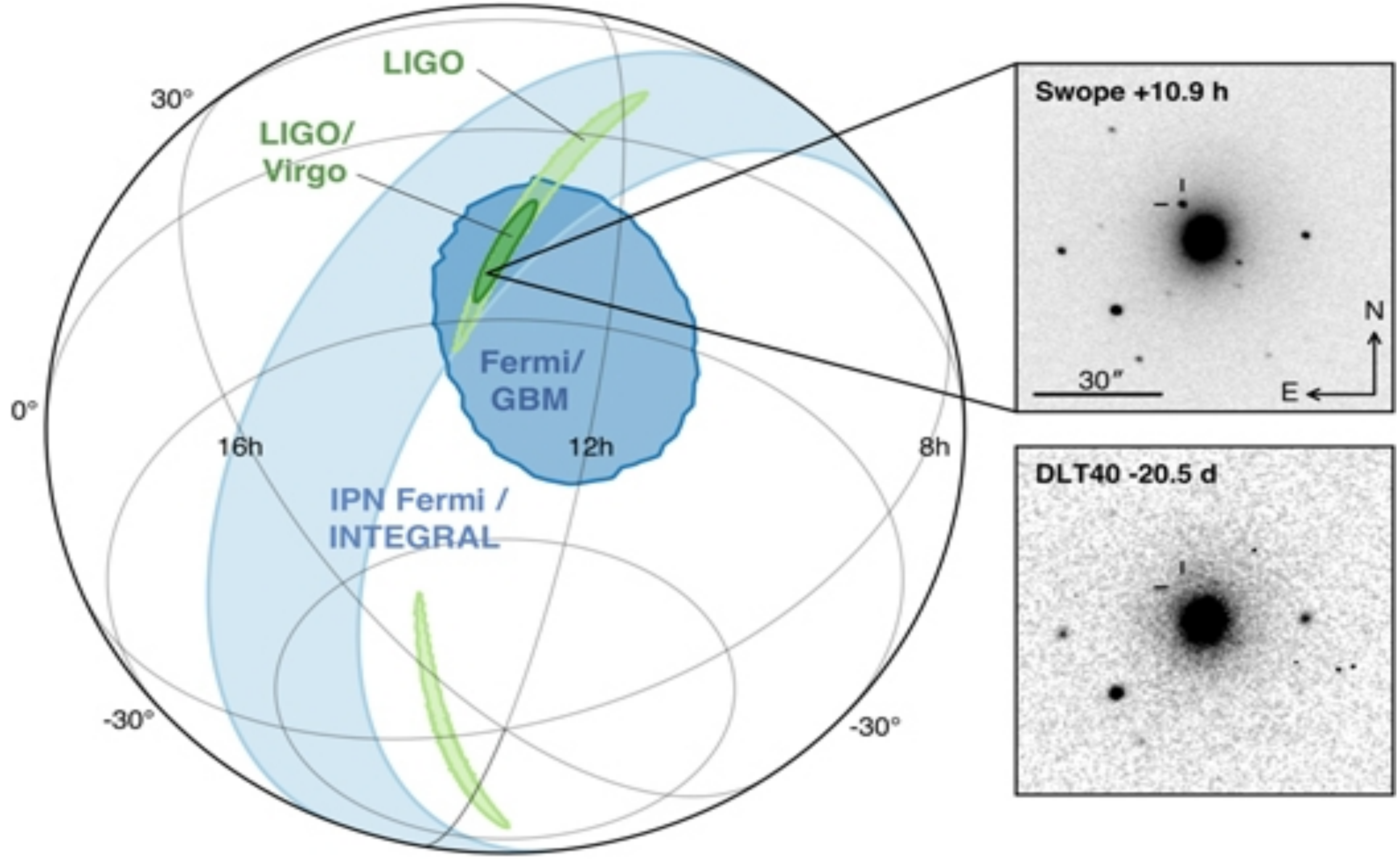
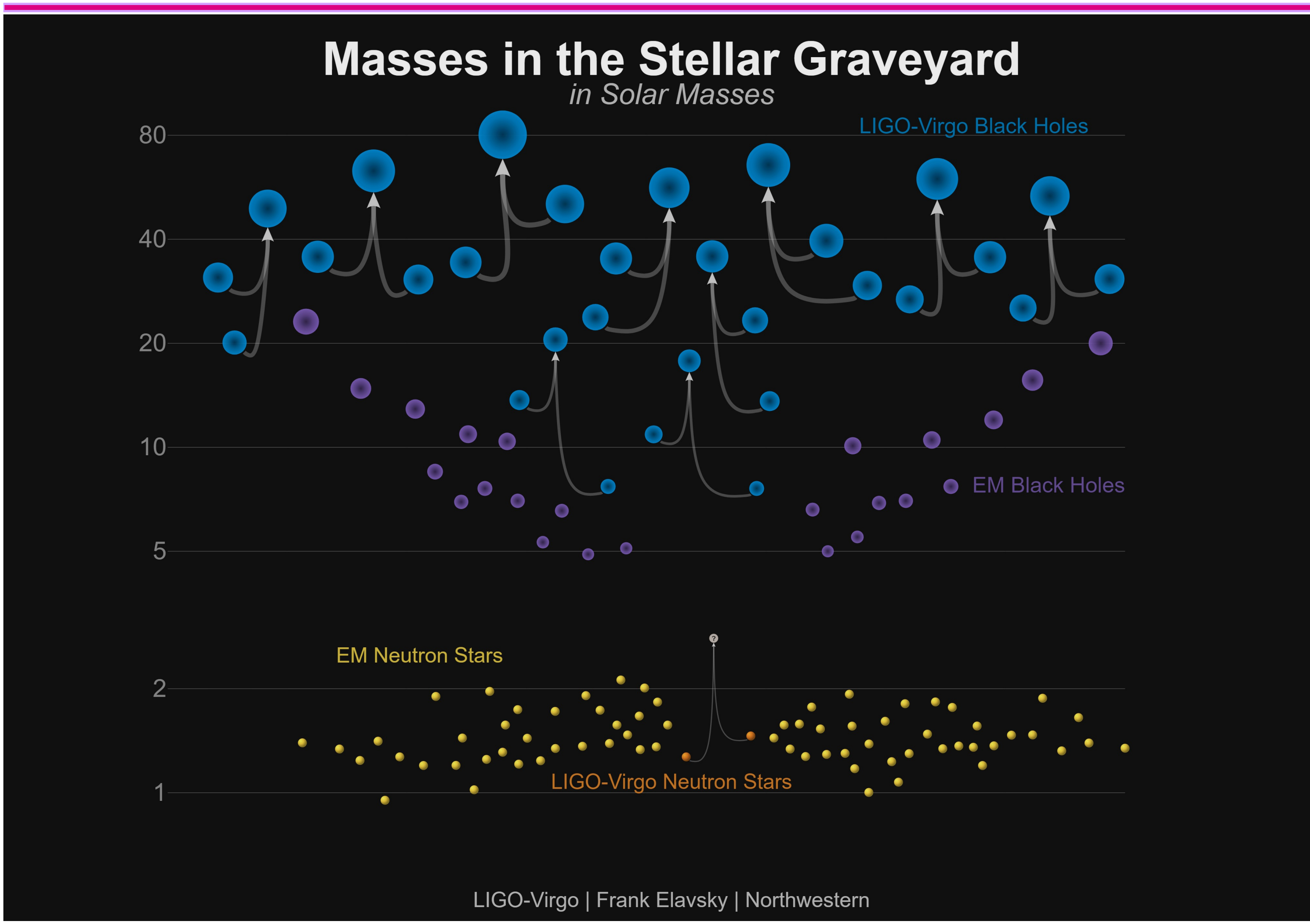


Figure 1 from Multi-messenger Observations of a Binary Neutron Star Merger
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

Known Masses of Stellar Remnants – Dec 2018

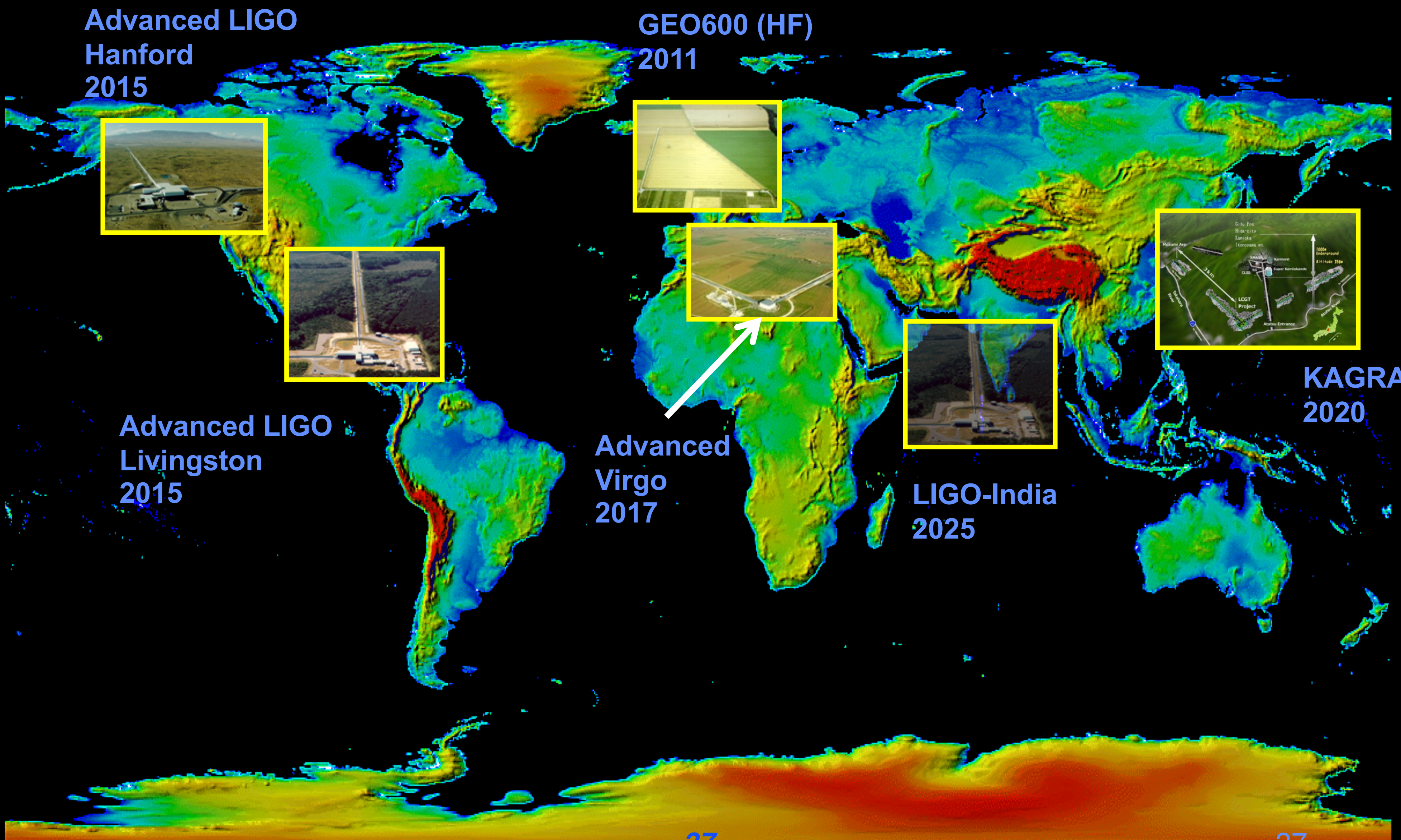


Non-LIGO Data Sources: Neutron Stars: http://xtreme.as.arizona.edu/NeutronStars/data/pulsar_masses.dat

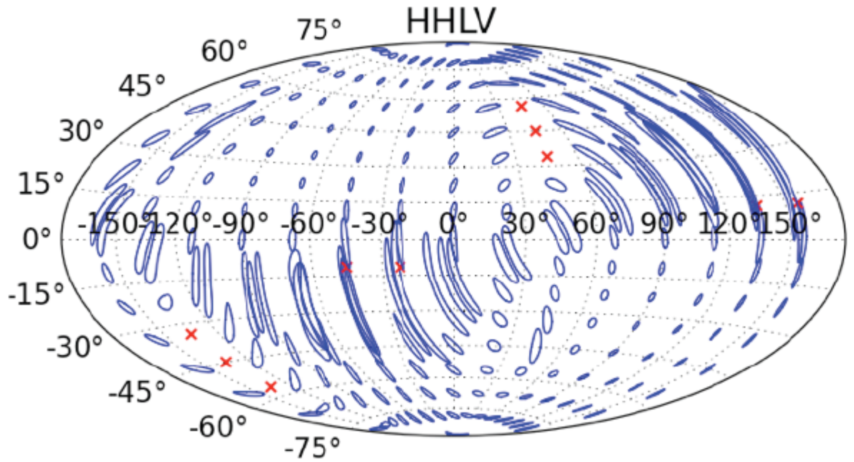
Black Holes: https://stellarcollapse.org/sites/default/files/table.pdf |

LIGO-Virgo Data: https://losc.ligo.org/events/

The advanced GW detector network: 2015-2025

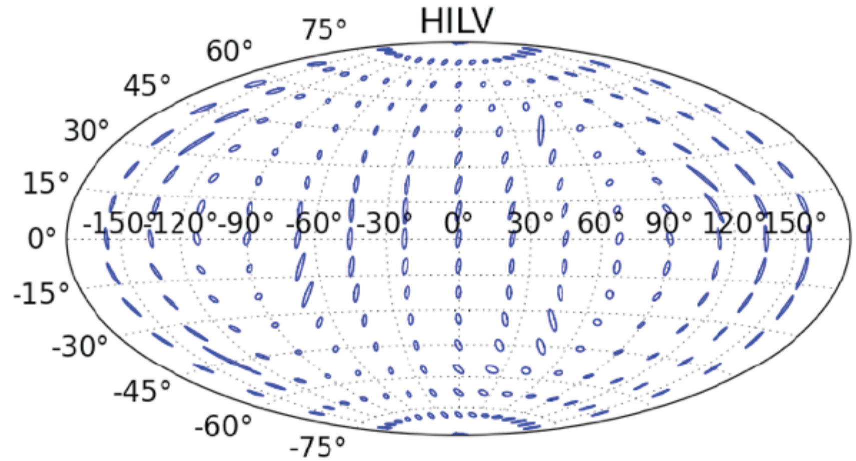


The compelling case for LIGO-India is Multi-Messenger Astronomy



Fairhurst 2011

Red crosses denote regions where the network has blind spots



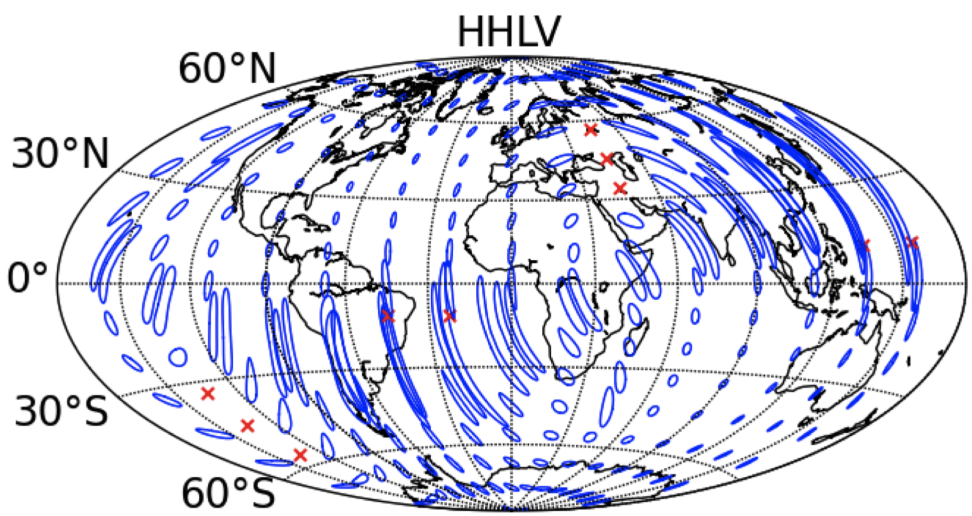
Fairhurst 2011

LIGO+Virgo only

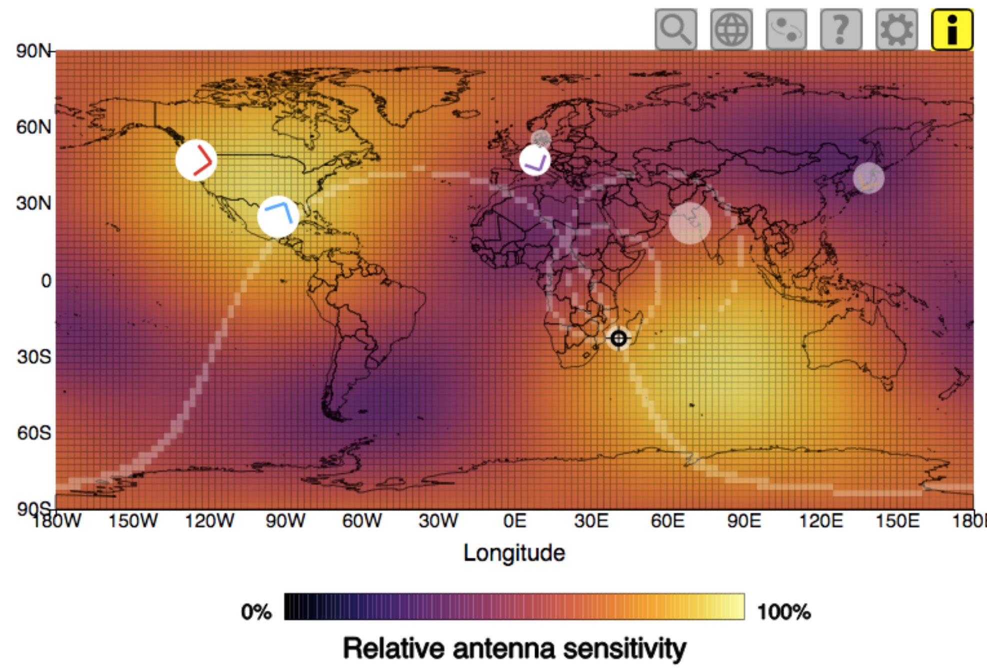
LIGO+Virgo+LIGO-India

It is rare for the birth of a new field of astrophysics to be pinpointed to a singular event. …One thing is certain, however: 2017 August 17 will always be remembered as the singular moment when multi-messenger GW–EM astronomy was born. - Edo Berger, *Focus on the Electromagnetic Counterpart of the Neutron Star Binary Merger GW170817*, ApJL **848**.

GW170817 Landed in a Good Region of Sky When 3 Detectors Were Up

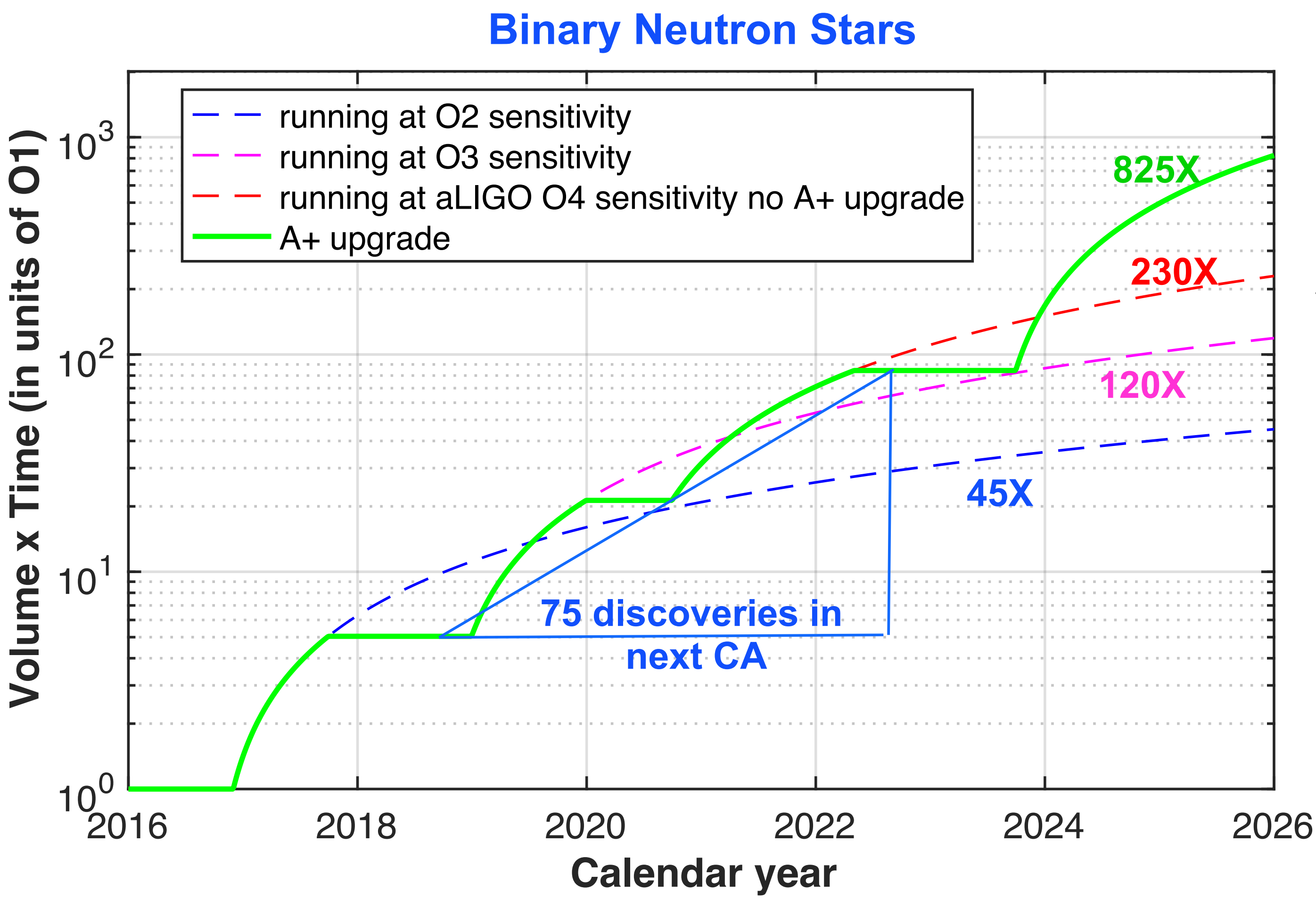


S. Fairhurst - P1200054



Visualization courtesy of Chris North

LIGO Science is Sensitivity Driven



1) Rates

$N_{events} = \langle R \rangle VT$

<R>: average astrophysical rate

V: volume of the universe probed → $(Range)^3$

T: coincident observing time

2) *Many sources require higher SNR to uncover new astrophysics*

- tidal disruption in BNS mergers
- tests of alternative theories of gravity
- Black hole ringdowns
- Stochastic background
- Isolated neutron stars
- Galactic supernova
- ....

Science drives Requirements

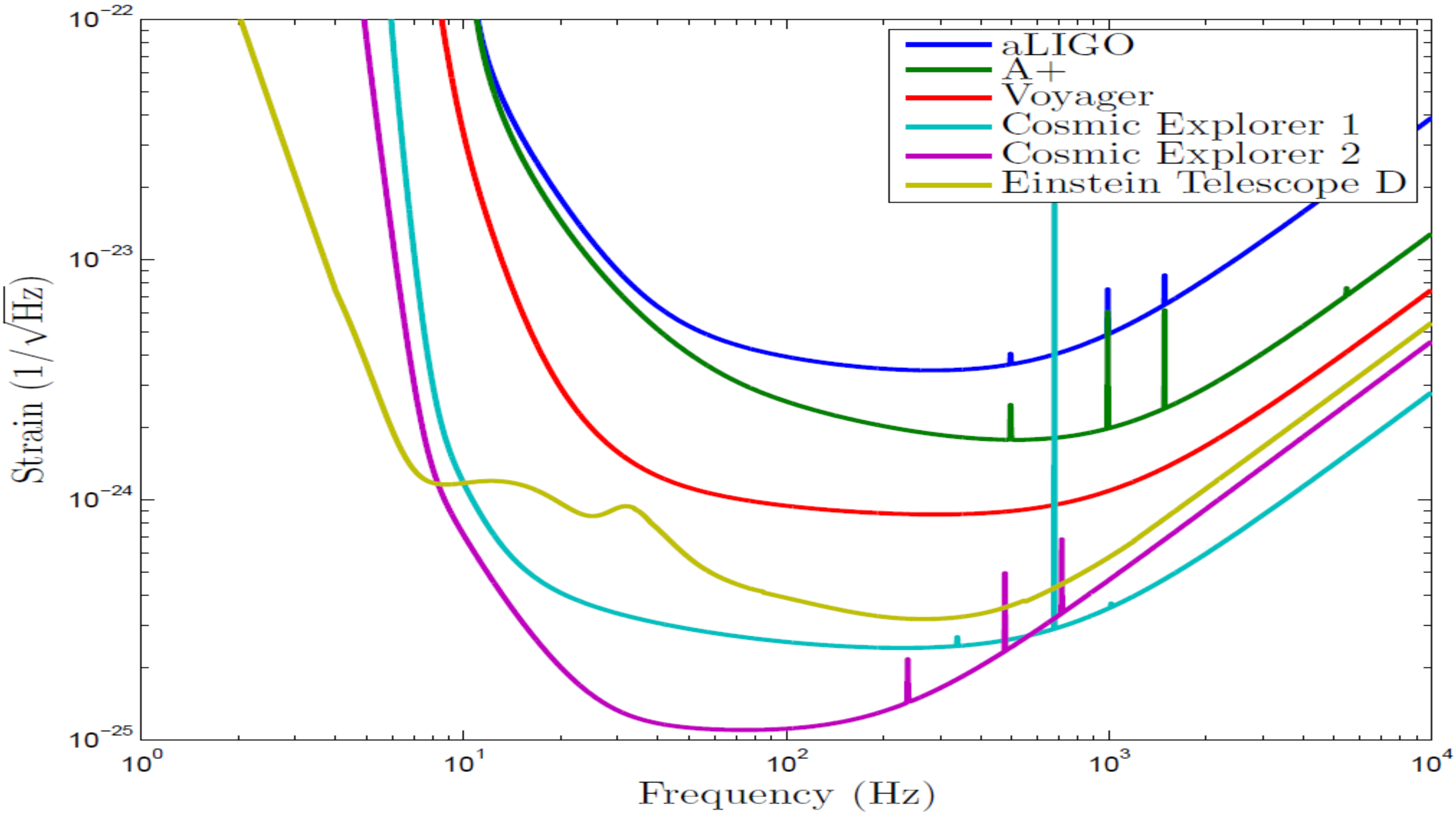
- **Stellar Evolution at High Red-Shift: Black Holes from the first stars (Population III)**
  - » Reach z>~10
  - » At least moderate GW luminosity distance precision
- **Independent Cosmology and the Dark Energy Equation of State**
  - » Needs precision GW luminosity distance and localization for EM follow-ups (for redshift)
- **Checking GR in extreme regime**
  - » High SNR needed
  - » GW luminosity distance and localization not essential

Advanced LIGO upgrade path

- Advanced LIGO is limited by quantum noise & coating thermal noise

- Squeezed vacuum to reduce quantum noise
- Options for thermal noise:
  - » Better coatings
  - » Cryogenic operation
  - » Longer arms (new facility)

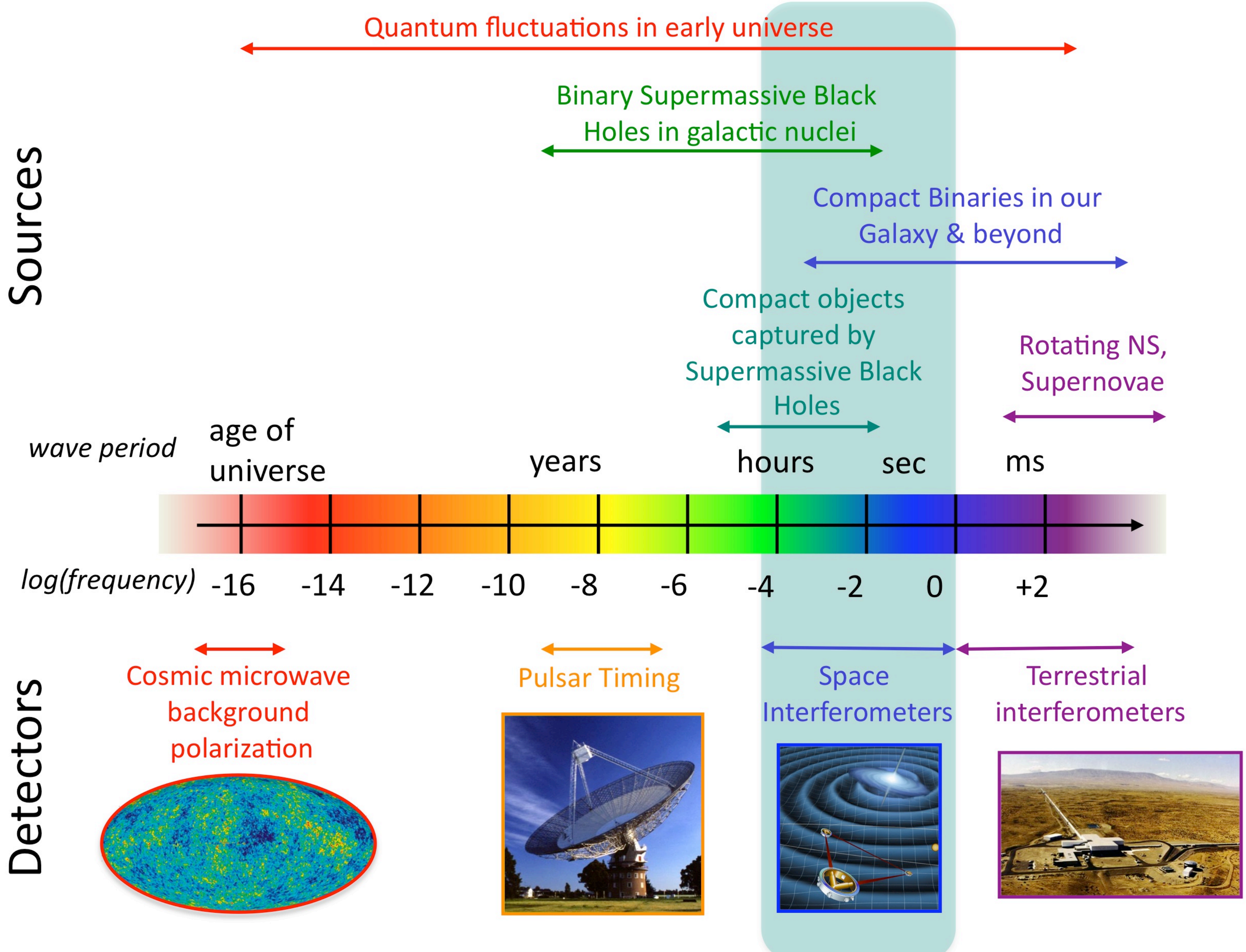
Upgrade possibilities



Summary of Terrestrial Gravitational-wave Astronomy

- GW150914 initiates Gravitational-Wave Astronomy.
- General Relativity provides a powerful framework from Earth-bound physics to mergers of stellar mass black holes at velocities near the speed of light.
- An emerging international network of detectors will provide more accurate positions of sources to enable EM follow-ups of GW events and improved polarization information.
- There is still room within the laws of physics to develop more powerful generations of detectors.

The Gravitational Wave Spectrum



Credit: NASA