The Bright Future of Gravitational-Wave Astronomy

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the LIGO Scientific Collaboration (LSC)
& the Virgo Collaboration

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Main messages

- A new era of astrophysics has dawned with great fanfare, but more importantly, it is poised to rapidly accelerate.
- The rate of discovery over the next decades – your professional lifetimes – and the science that can be extracted from discoveries will be driven by an international community of experimental physicists and engineers developing better understanding of detector physics and new detector technologies.
- India will be an important stage for these developments.

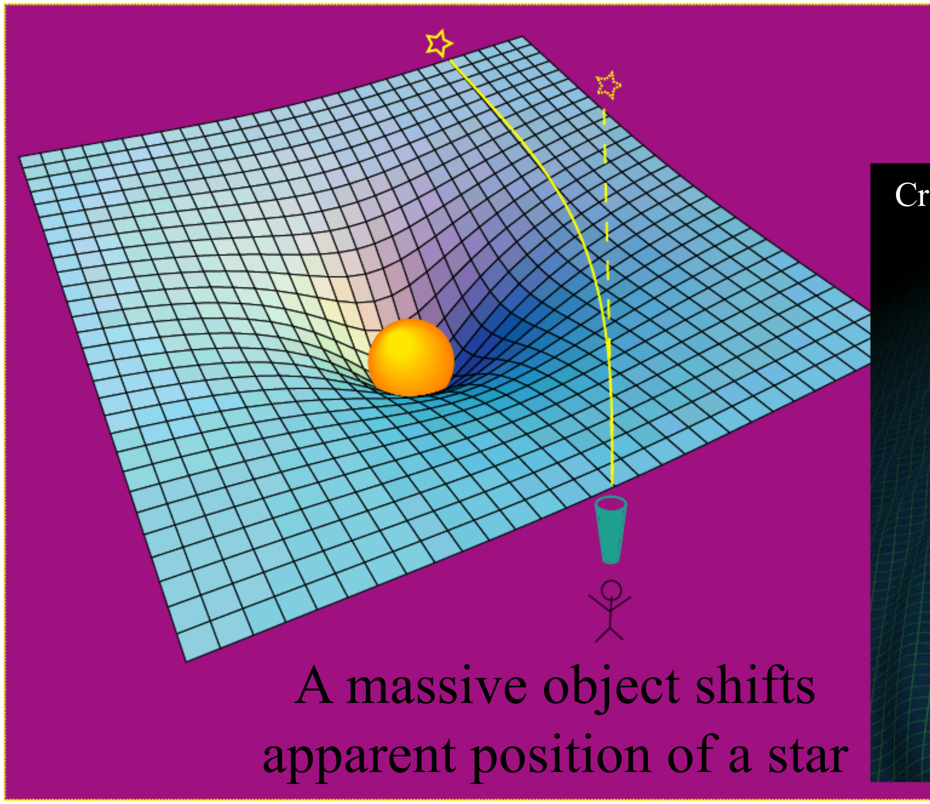
Astronomy 3.0

- Astronomy 1.0 – millennia of naked-eye astronomy
- Astronomy 2.0 – four centuries developing new telescopes to view “light” across the electromagnetic spectrum
- Astronomy 3.0 – multi-messenger astronomy, viewing the universe across the electromagnetic spectrum, hearing the universe across the spectrum of gravity, and using astro-particle detectors to study the universe

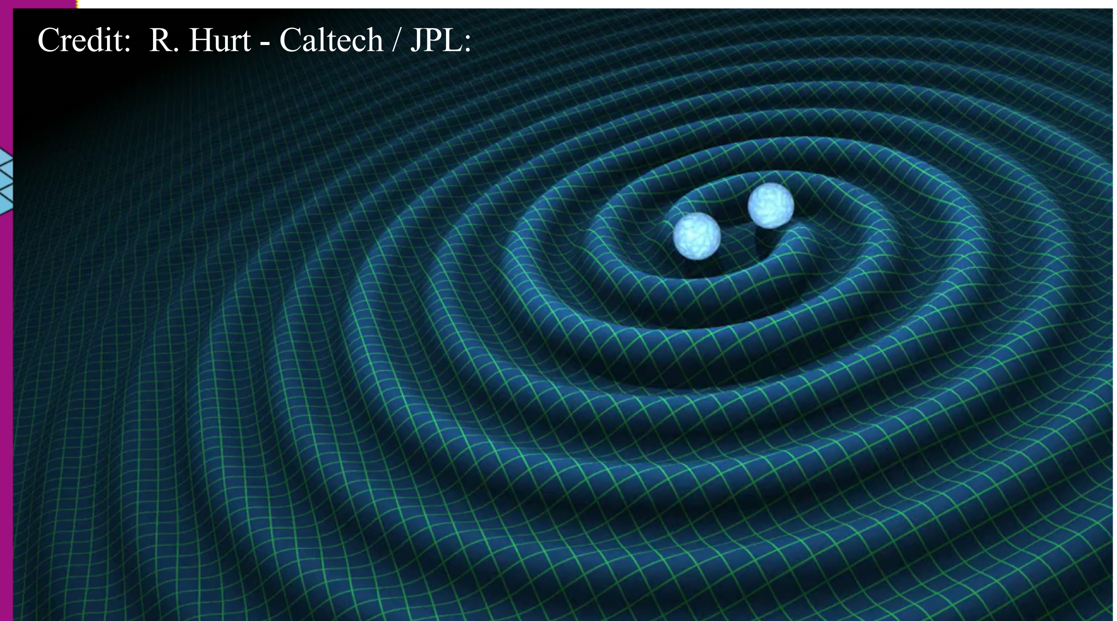
Basics of General Relativity and Gravitational Waves

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



dynamic deformation of spacetime



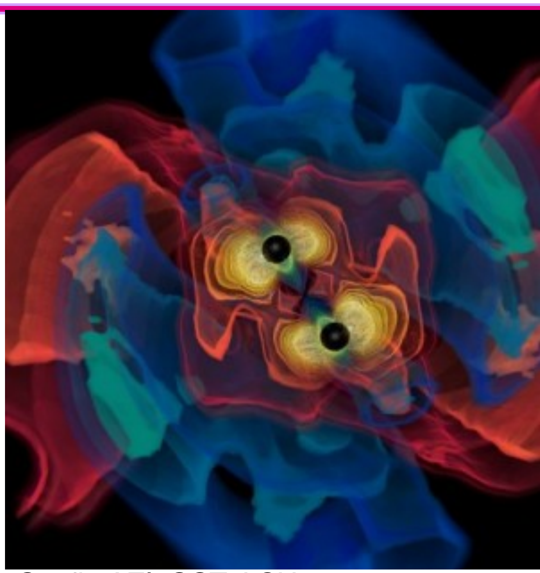
Empty space and time are things, with real physical properties. Space has a shape, a stiffness and a maximum speed for information transfer.

Sources of Gravitational Waves

Accelerating Quadrupole Mass Moments

LIGO-G1900266

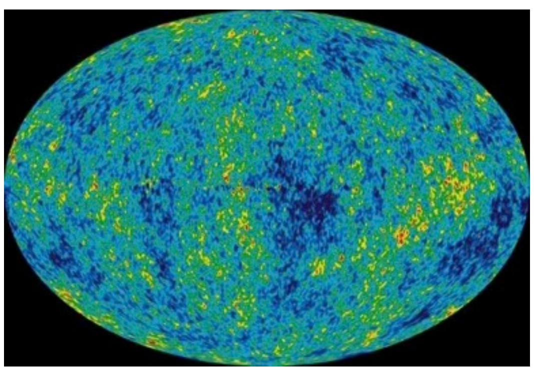
Astrophysical Sources of Gravitational Waves



Credit: AEI, CCT, LSU

Coalescing Compact Binary Systems:
Neutron Star-NS, Black Hole-NS, BH-BH

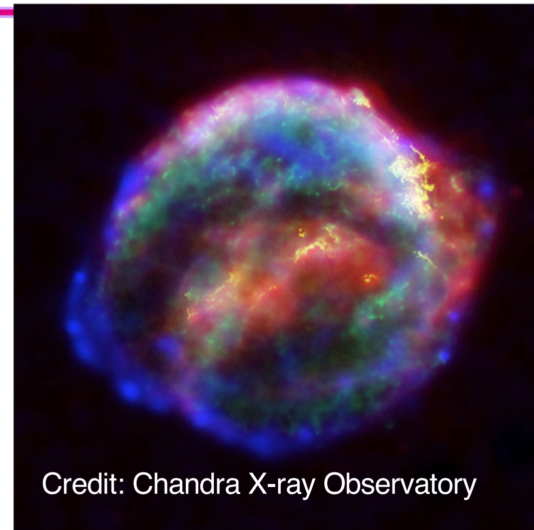
- Strong emitters, well-modeled,
- (effectively) transient



NASA/WMAP Science Team

Cosmic Gravitational-wave Background

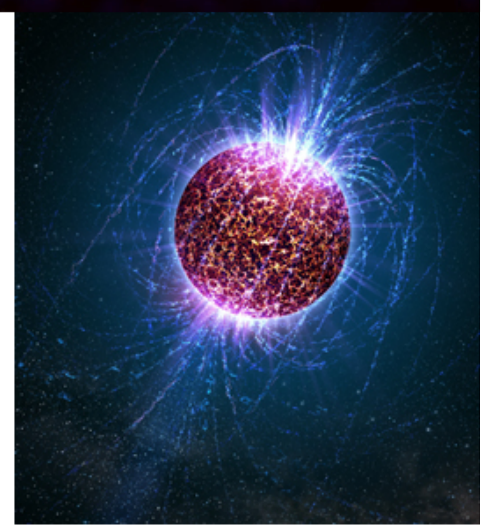
- Residue of the Big Bang
- Long duration, stochastic background



Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

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

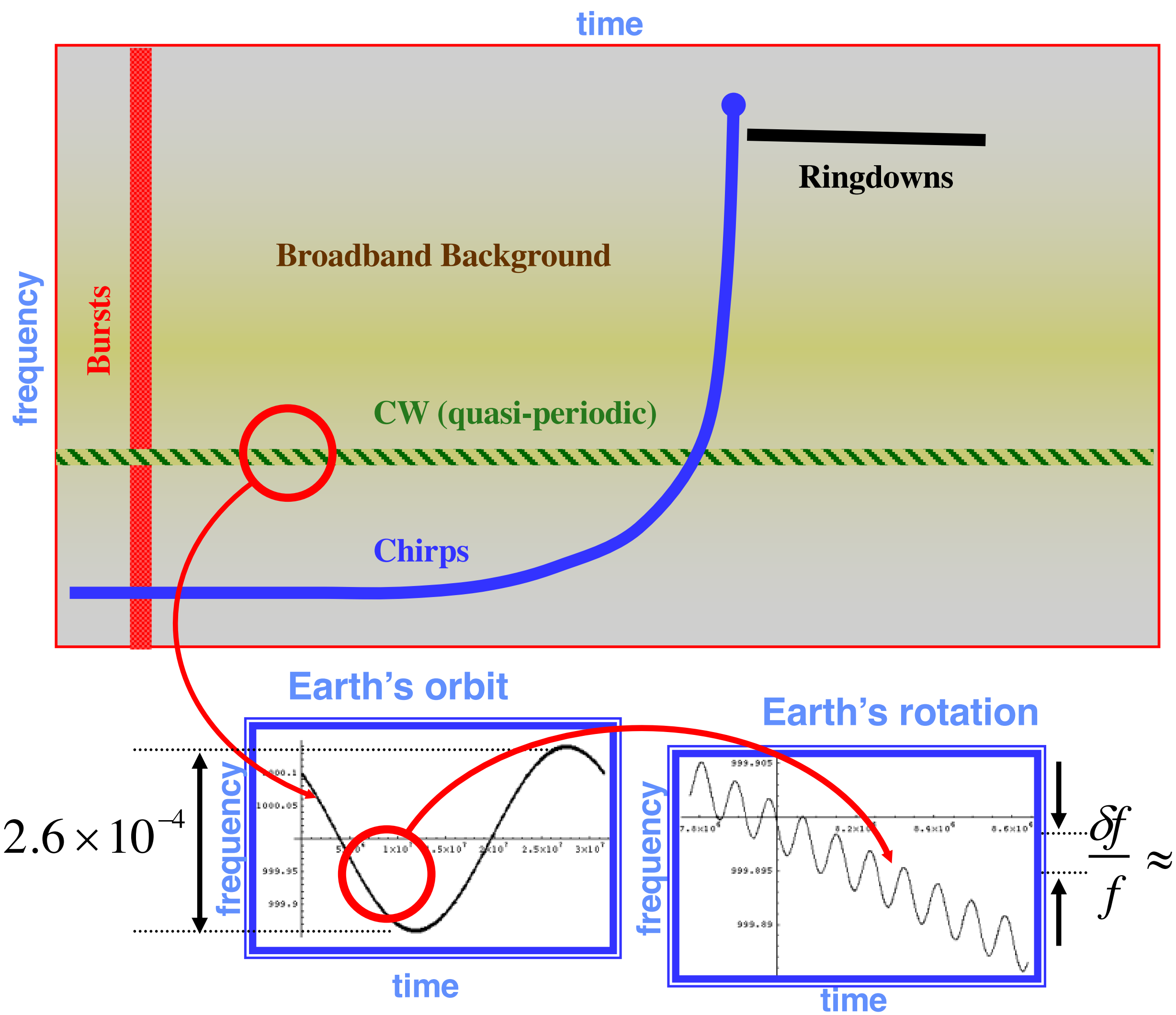


Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform
- Long duration

Distinct Frequency-Time Characteristics of GW Sources



$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$

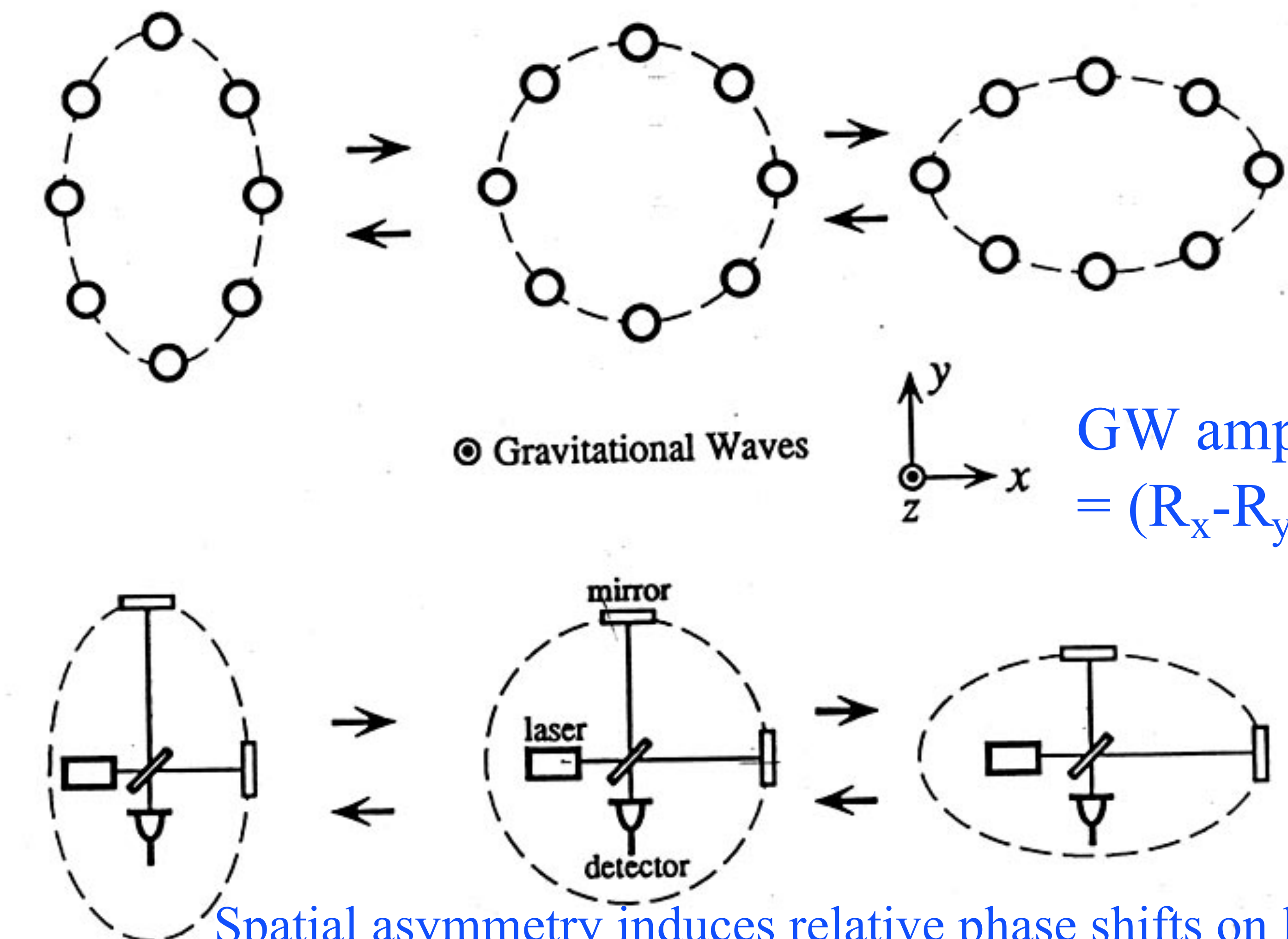
$$\frac{\delta f}{f} \approx 4 \times 10^{-6}$$

Detectors of Gravitational Waves

No Law of Physics Forbids Them

LIGO-G1900266

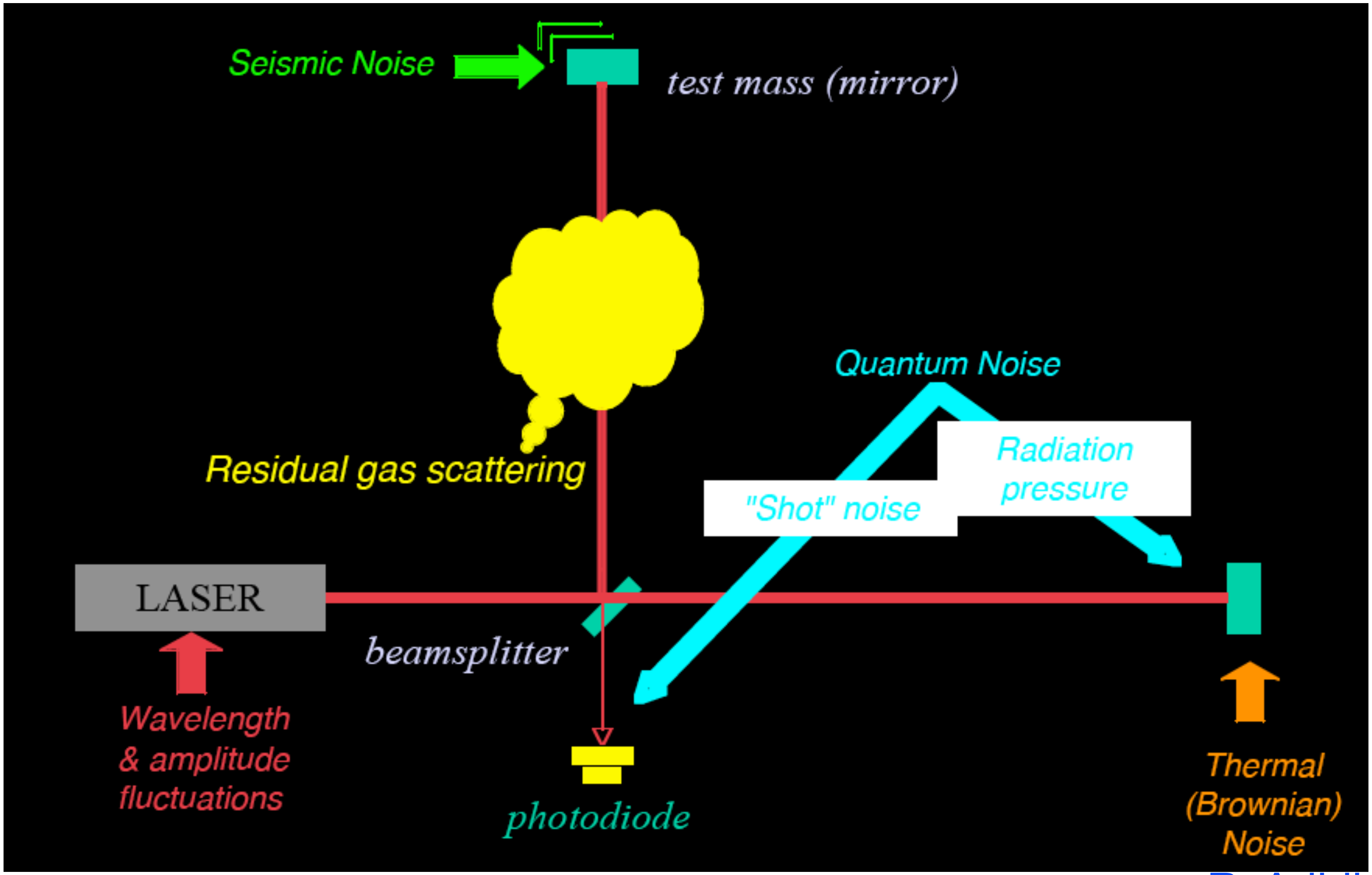
Basic idea is simple



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

Spatial asymmetry induces relative phase shifts on light in arms

Noise cartoon



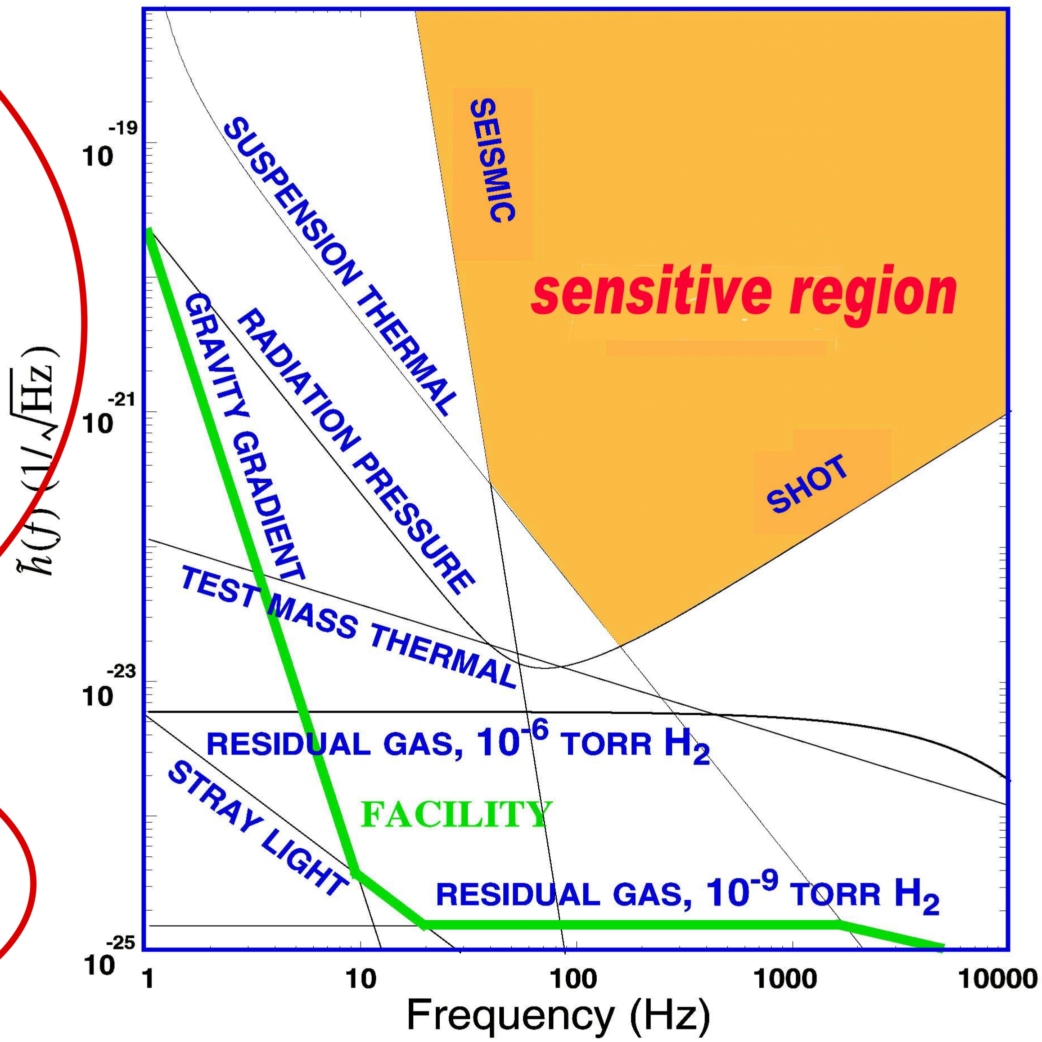
R. Adhikari

What Limits Sensitivity of Interferometers?

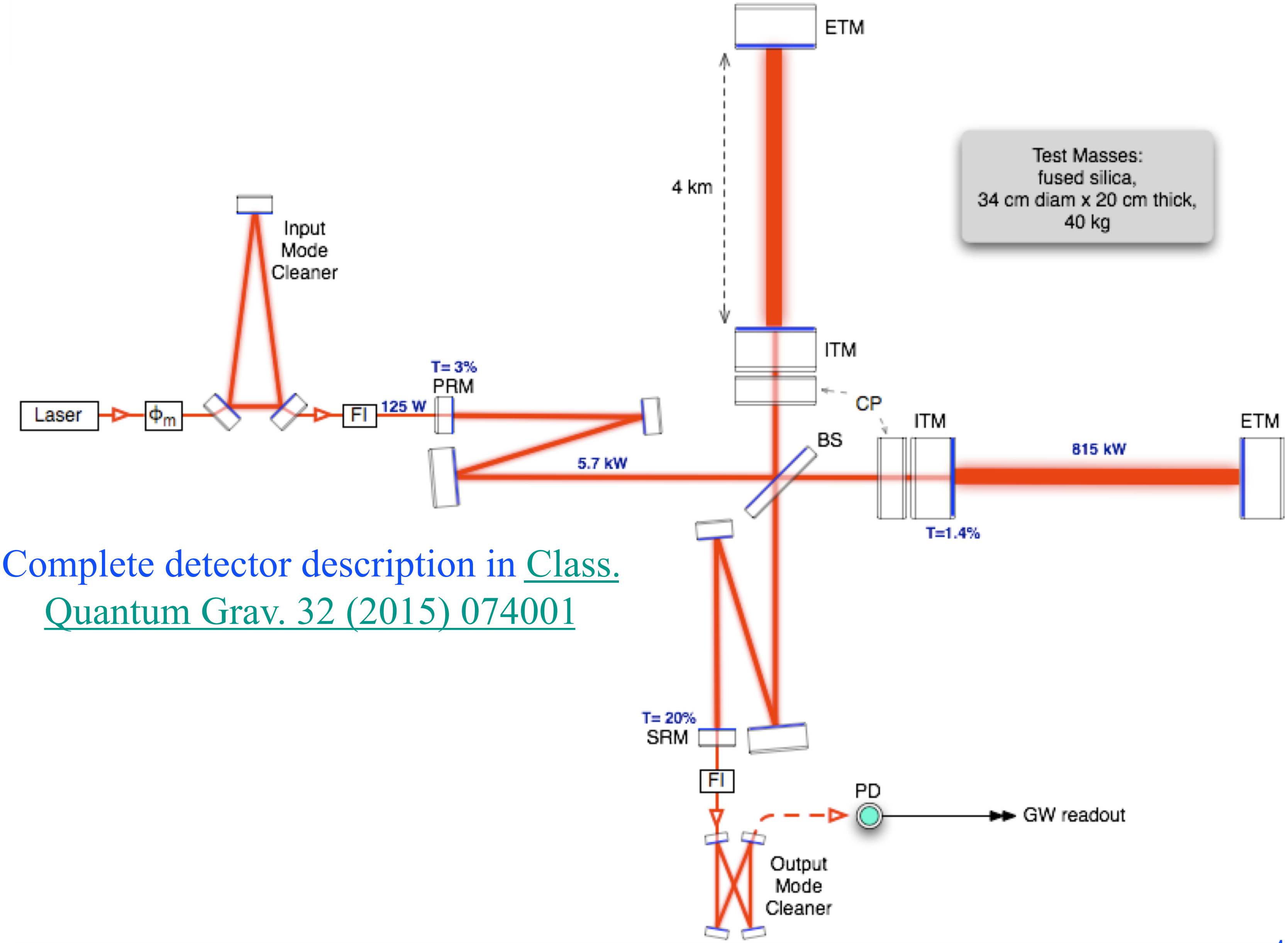
DESIGN

- Seismic noise & vibration limit at low frequencies
- Brownian (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



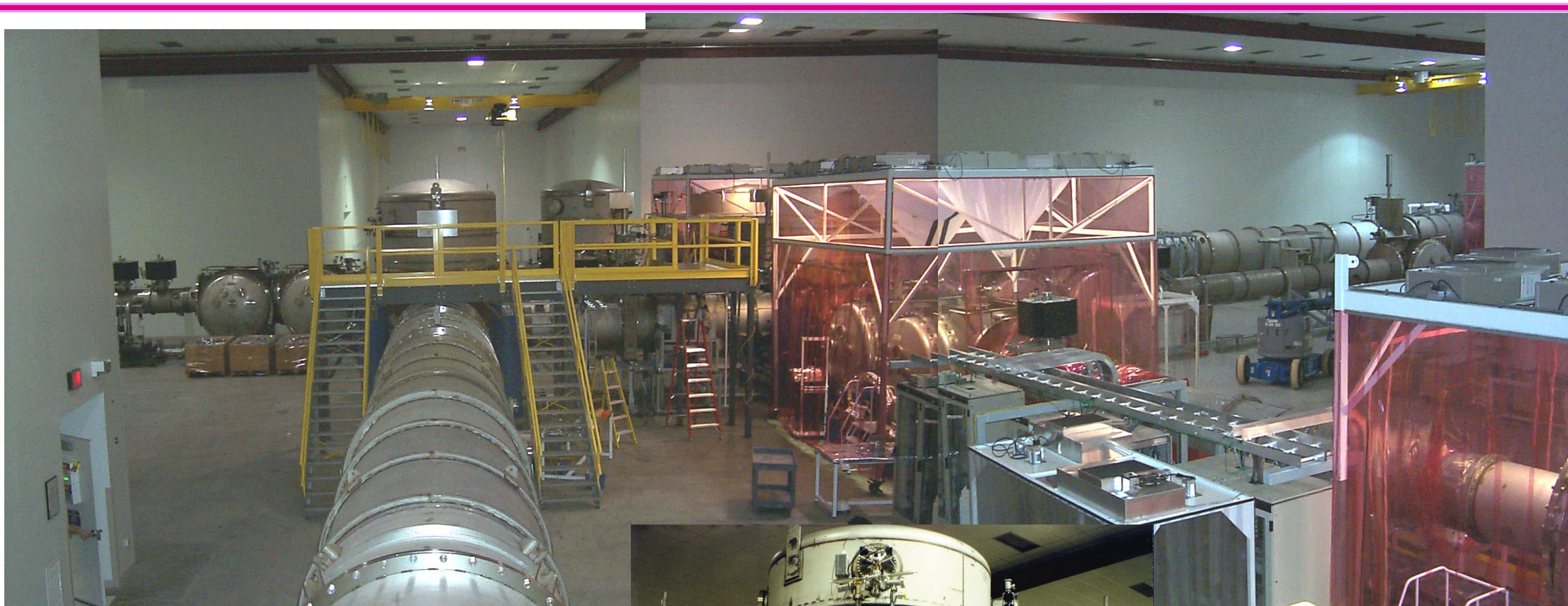
Complete detector description in Class. Quantum Grav. 32 (2015) 074001

Evacuated Beam Tubes Provide Clear Path for Light

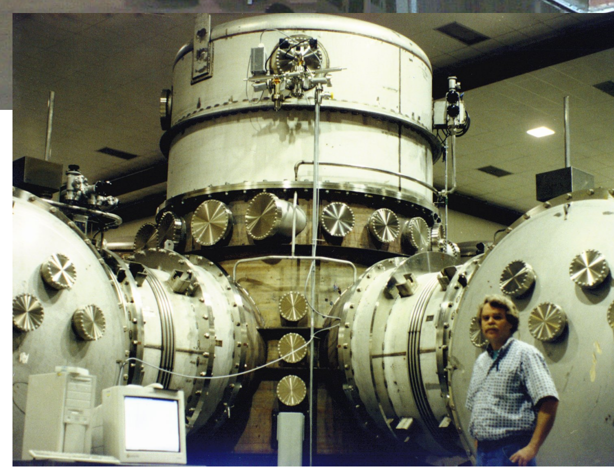
$P < 10^{-9}$ Torr

Portable power supply for bakeout

Vacuum Chambers Provide Quiet Homes for Mirrors



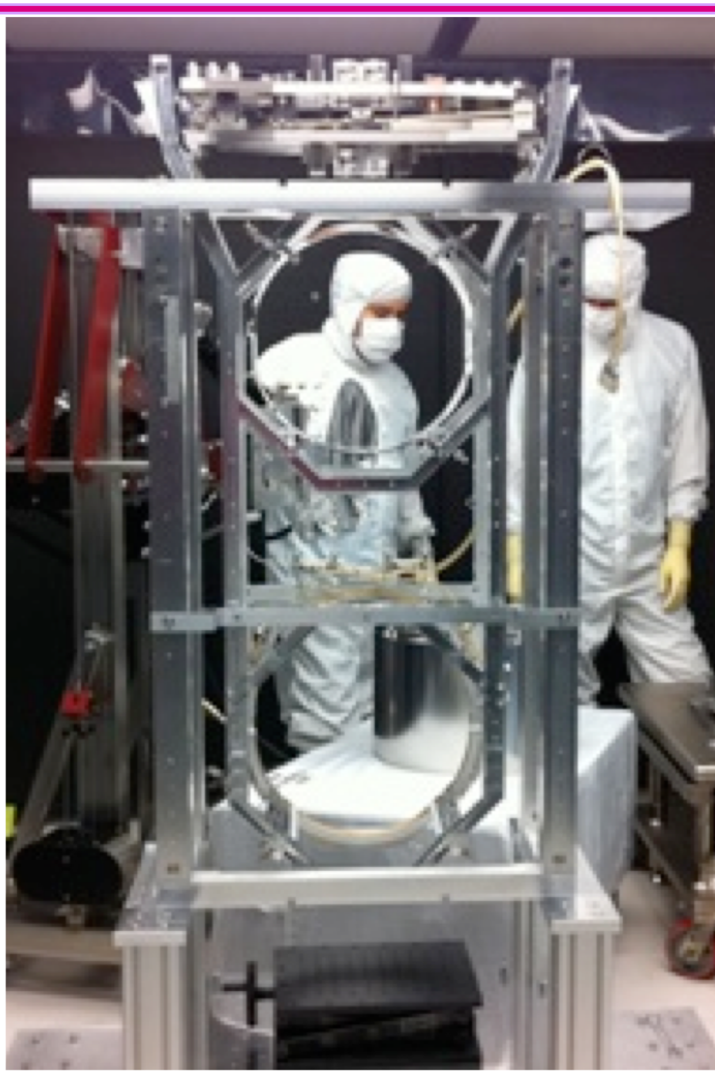
View inside Corner Station

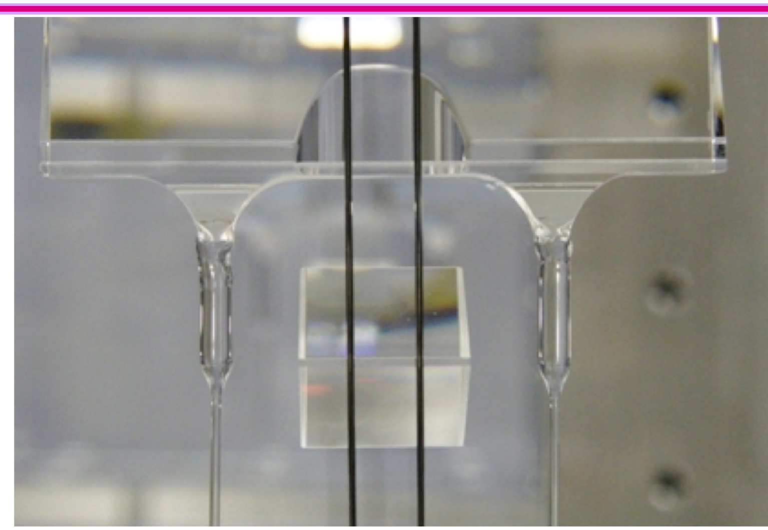


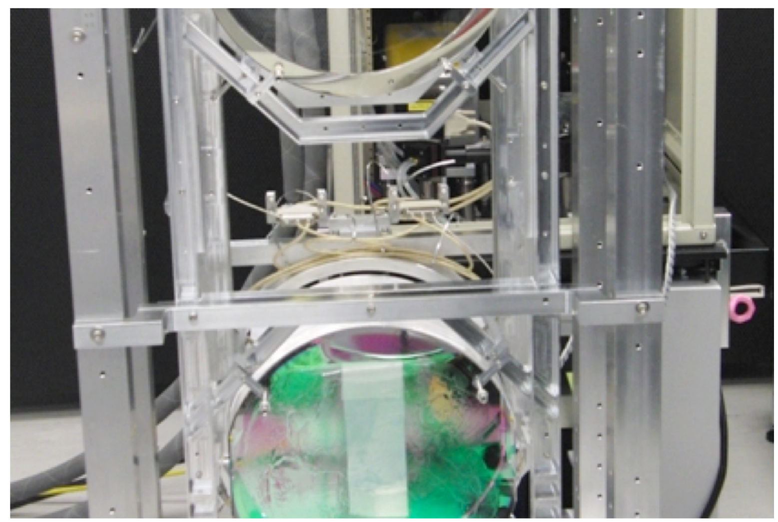
Standing at vertex beam splitter

BSC Internal Seismic Isolator

Advanced LIGO Monolithic Suspension







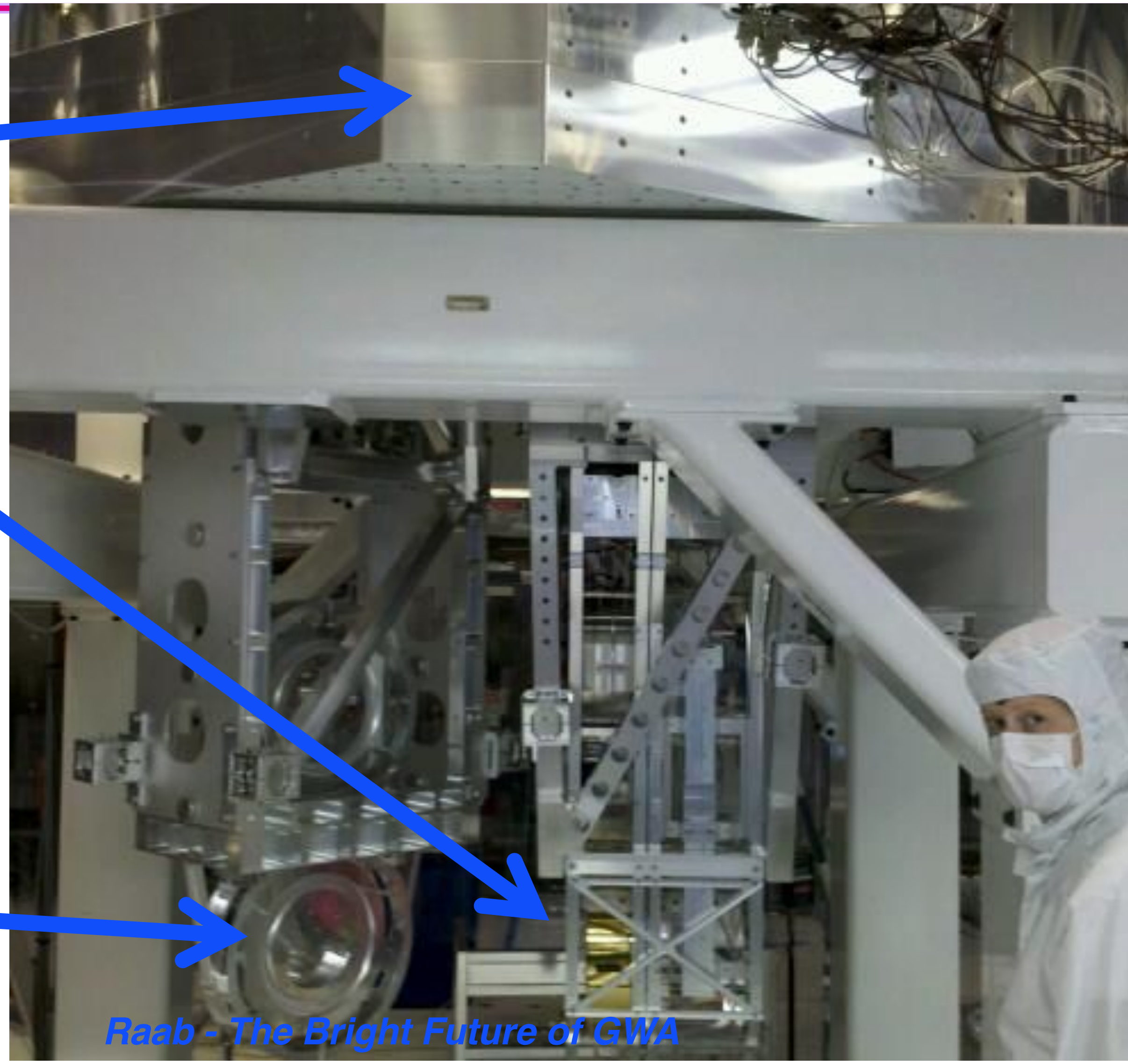
Advanced LIGO installation in progress

Putting it together: Seismic & Suspension & Optics

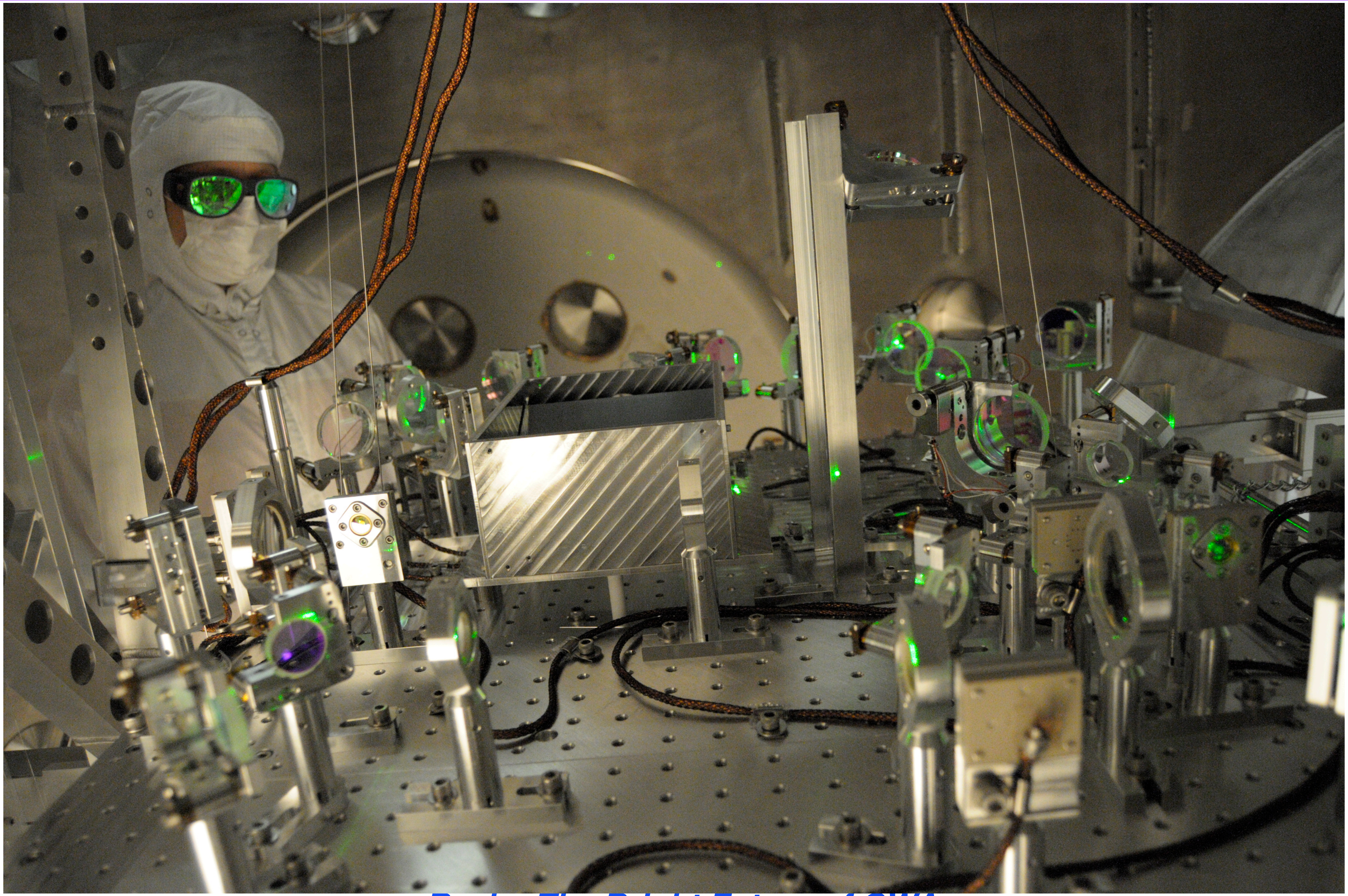
Seismic isolation

Test mass suspension

Folding mirror suspension

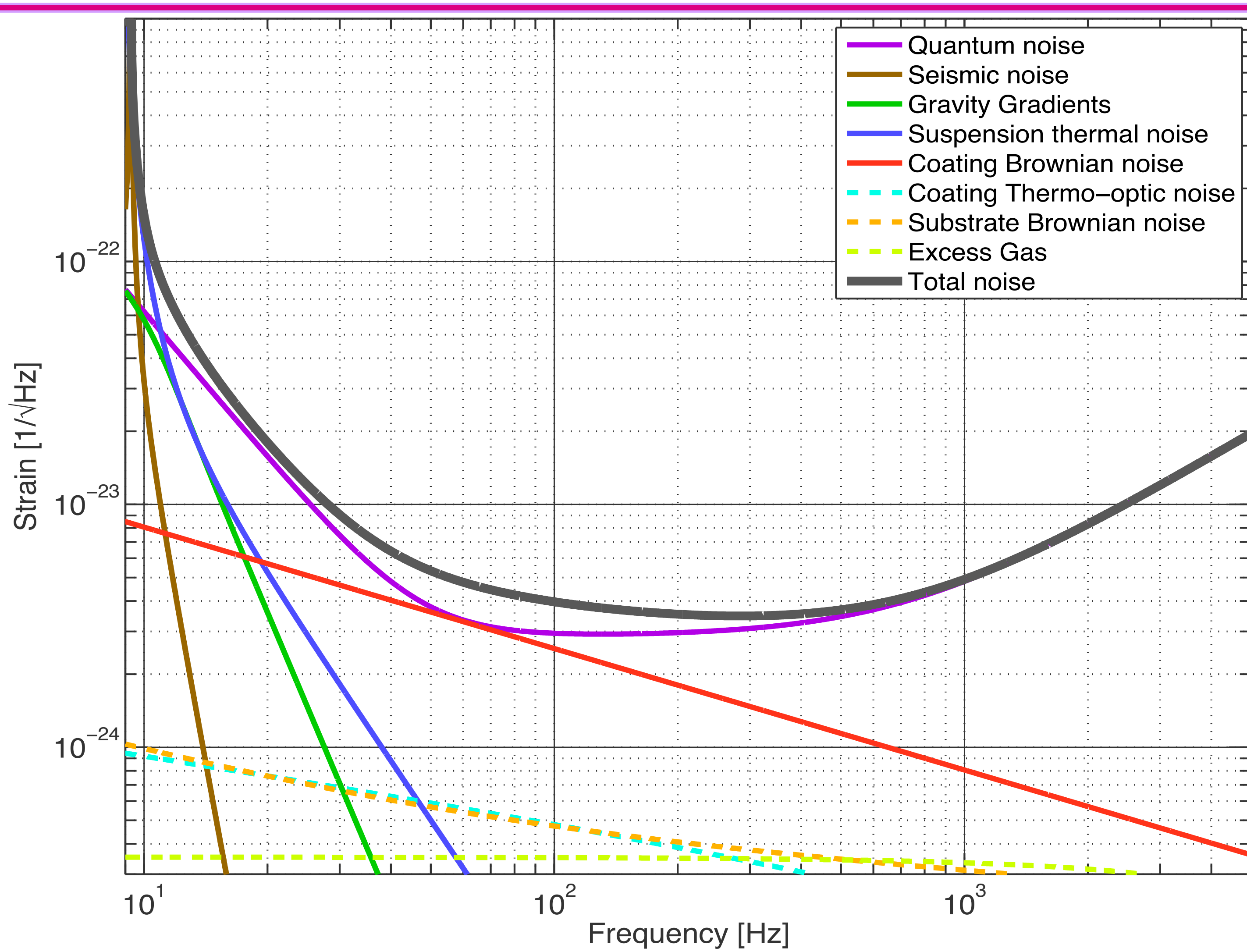


Lock Acquisition: Arm Locking Subsystem



aLIGO Pre-stabilized laser

Principal noise terms



Some History

Strategy: Build Facilities That Could House Evolving Generations of More Powerful Detectors as Part of an International Network

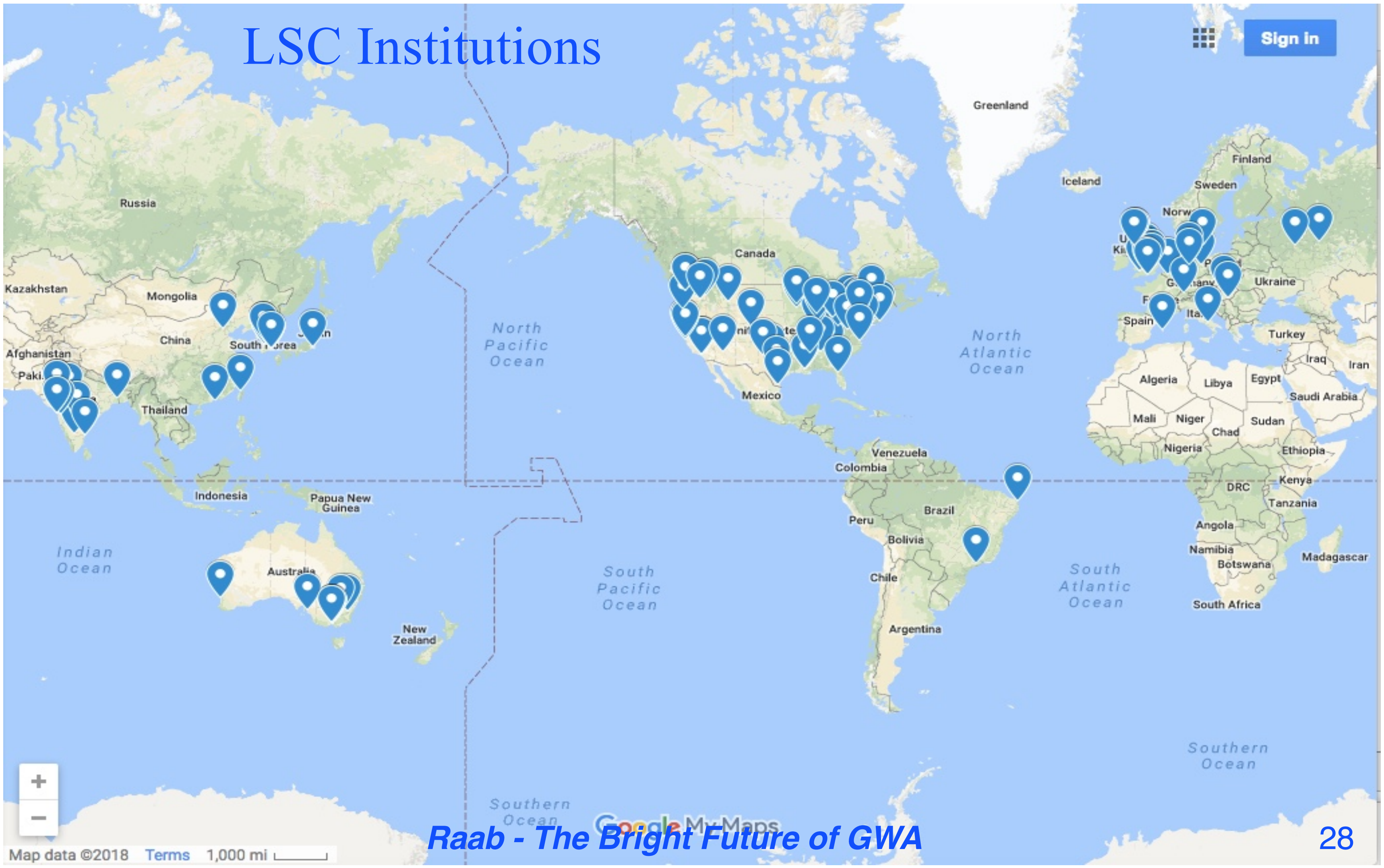
- LIGO proposed in 1989.
- LIGO Observatories constructed from 1994-2000.
- LIGO establishes international LIGO Scientific Collaboration (LSC) in 1997.
- Initial LIGO operated from 2002-2010.
- Advanced LIGO construction 2008-2015.

- Virgo proposed in 1989.
- Virgo construction from 1996 to 2003.
- Virgo and LIGO establish a common data format for GW observatories.
- Initial Virgo operated from 2007 to 2011.
- Advanced Virgo construction from 2011 to 2016.

LSC and Virgo Collaboration established an MOU for joint operations in 2007.

The Laser Interferometer Gravitational-wave Observatory

The LIGO Scientific Collaboration



VIRGO

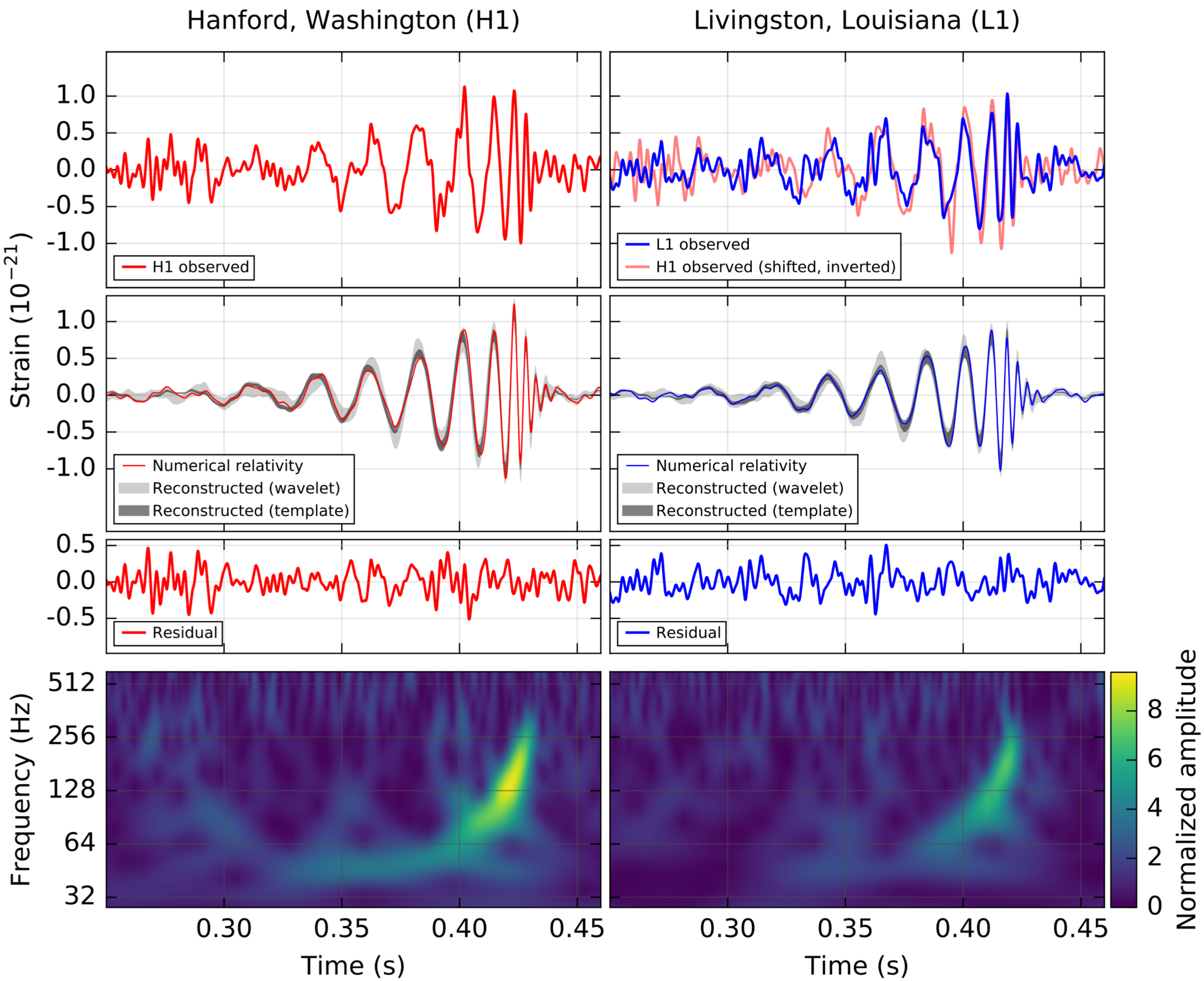
The Virgo Collaboration is currently composed of approximately 350 scientists, engineers and technicians from about 70 institutes from Belgium, France, Germany, Hungary, Italy, the Netherlands, Poland and Spain

Breakthroughs

Opening a New Window on the Universe

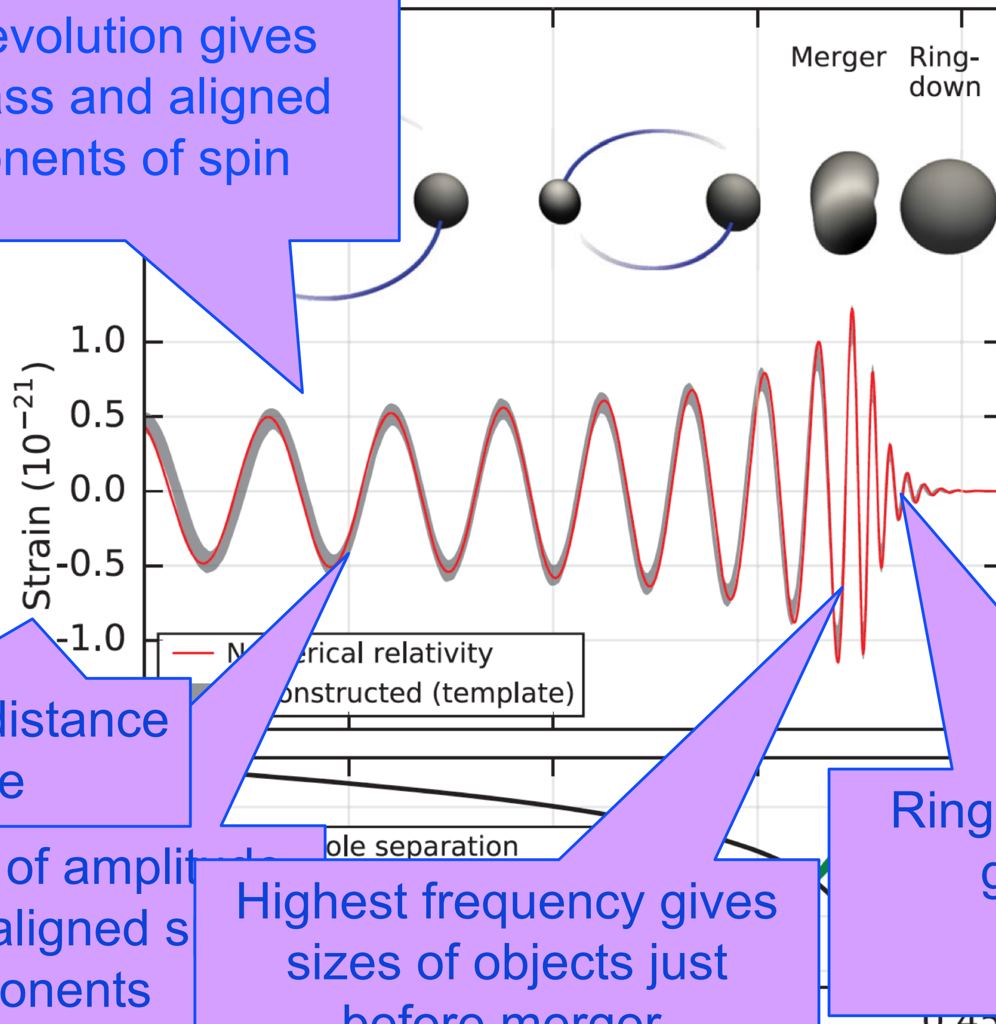
GW150914: What was observed?

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

Signal size gives distance to the source

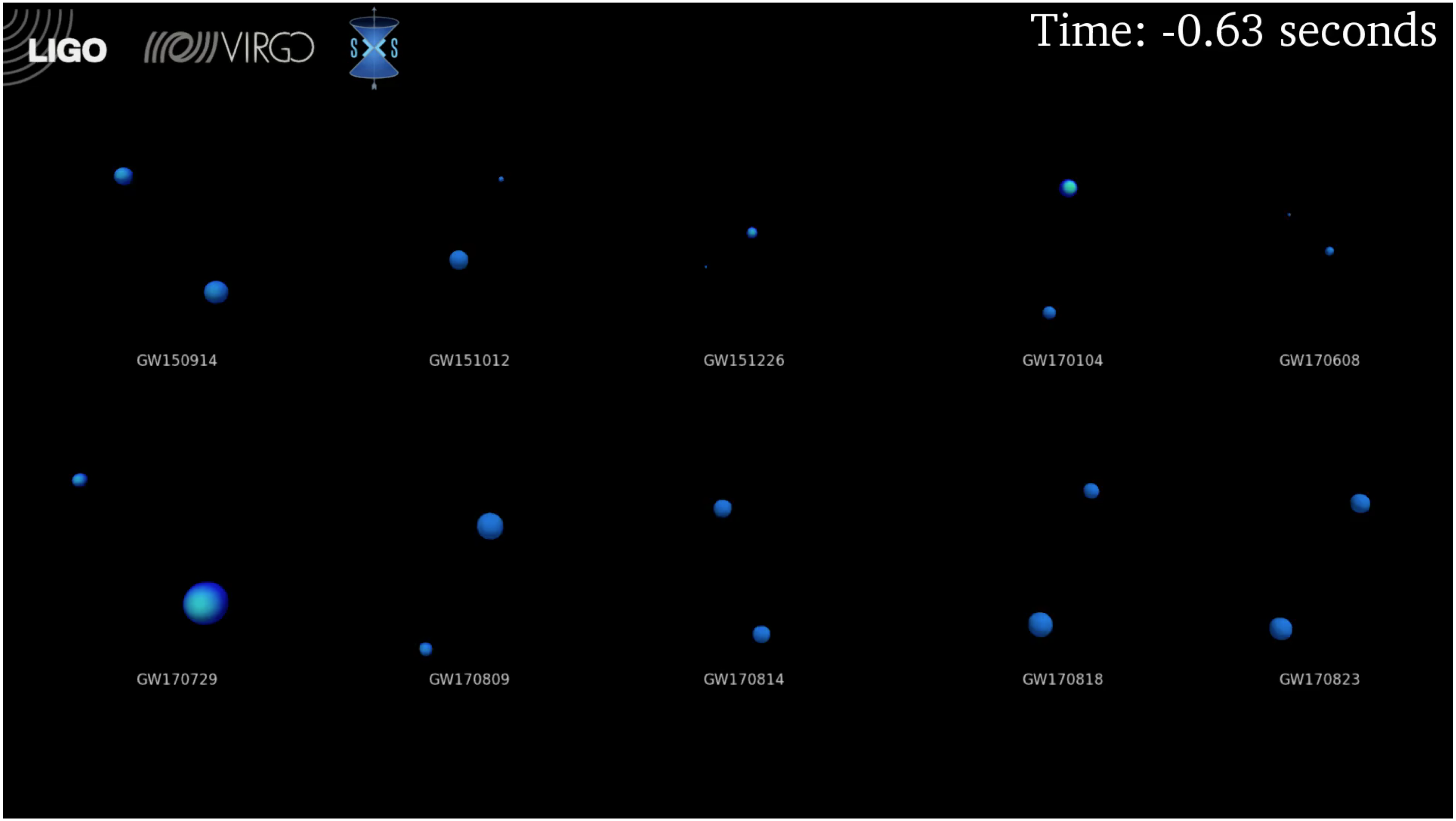
Modulation of amplitude gives nonaligned spin components

Highest frequency gives sizes of objects just before merger.

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

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)

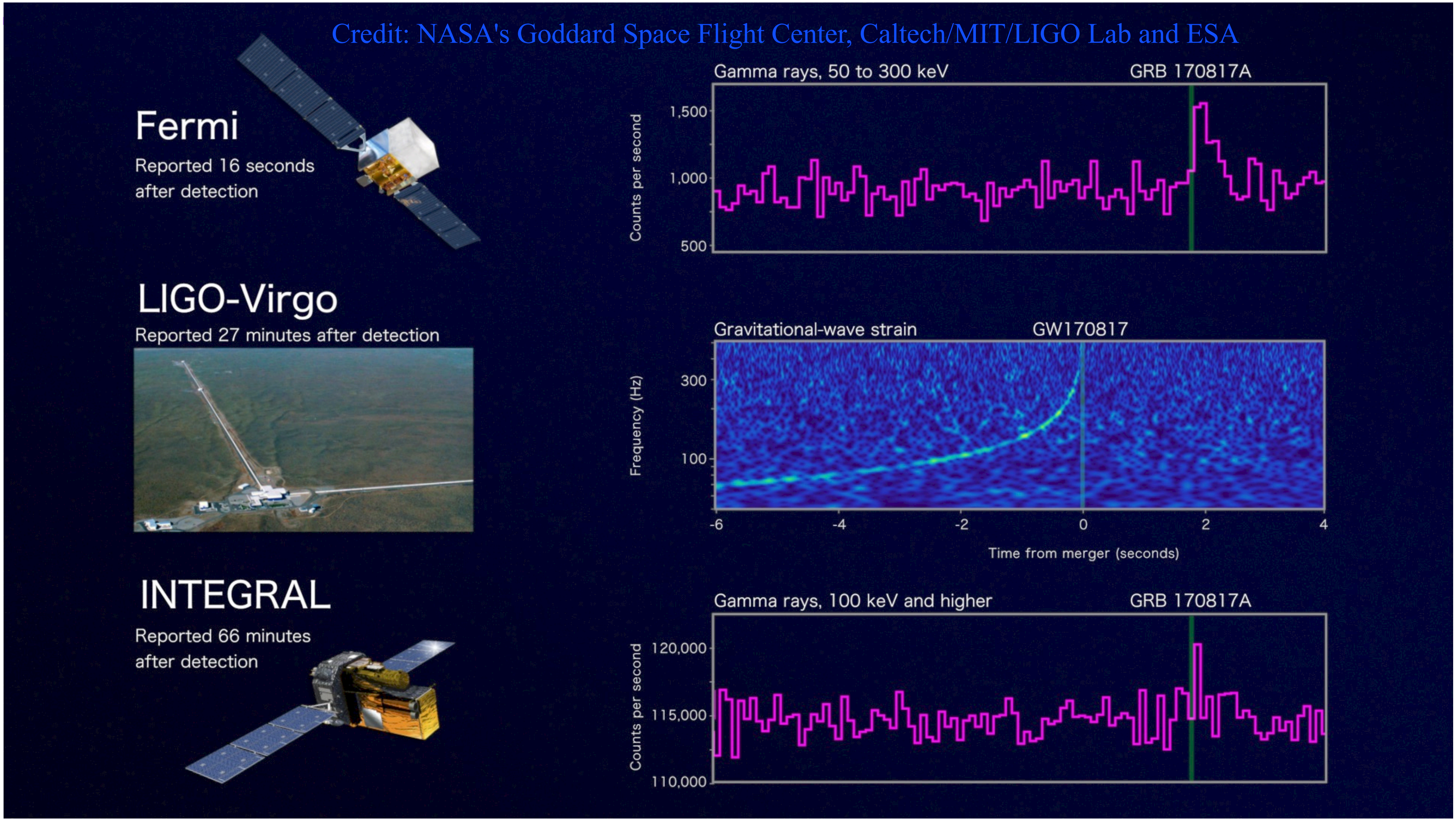
Comparison of BBH GW Waveforms from GWTC-1



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



LIGO-Virgo network localization enables discovery of optical counterpart

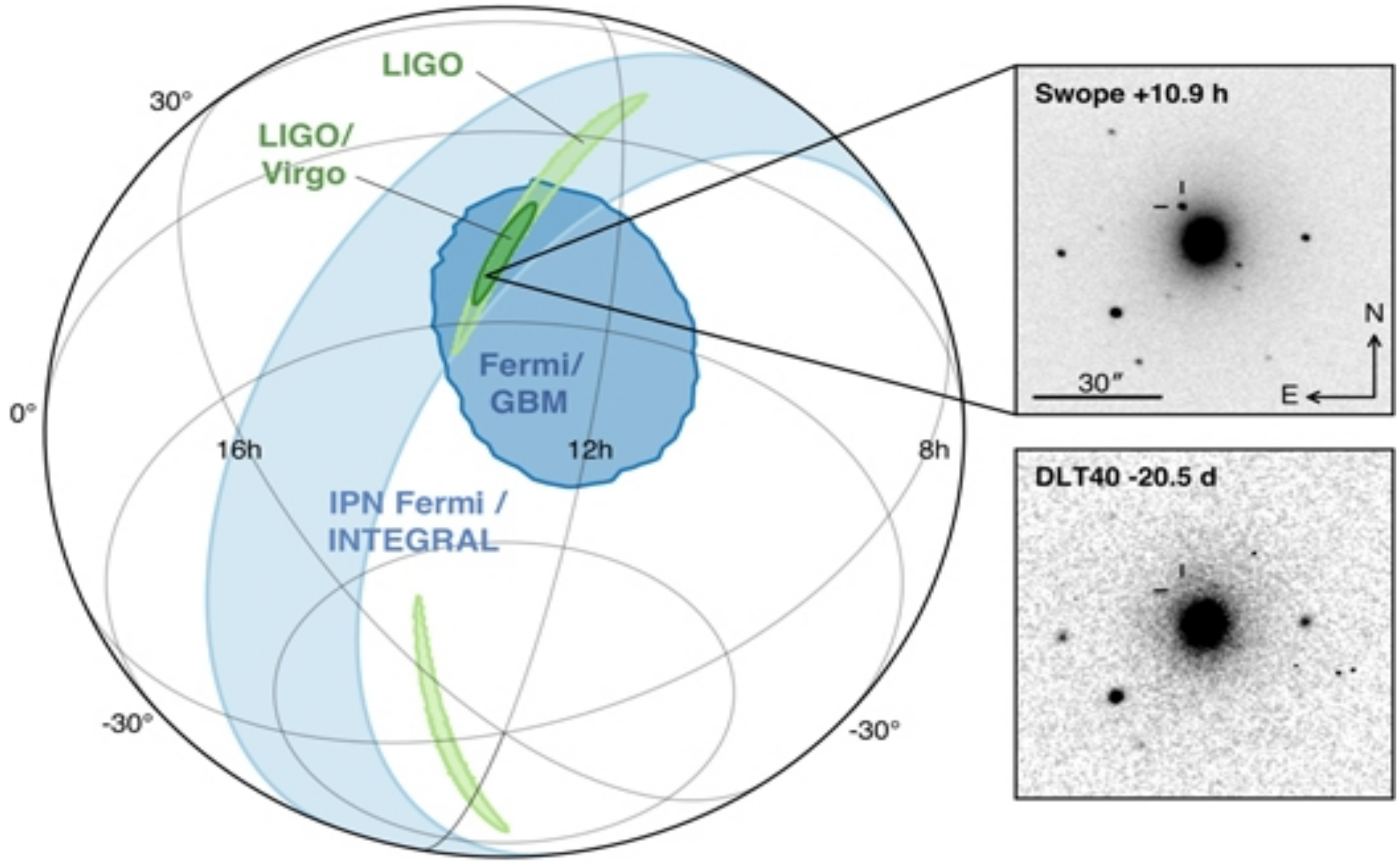
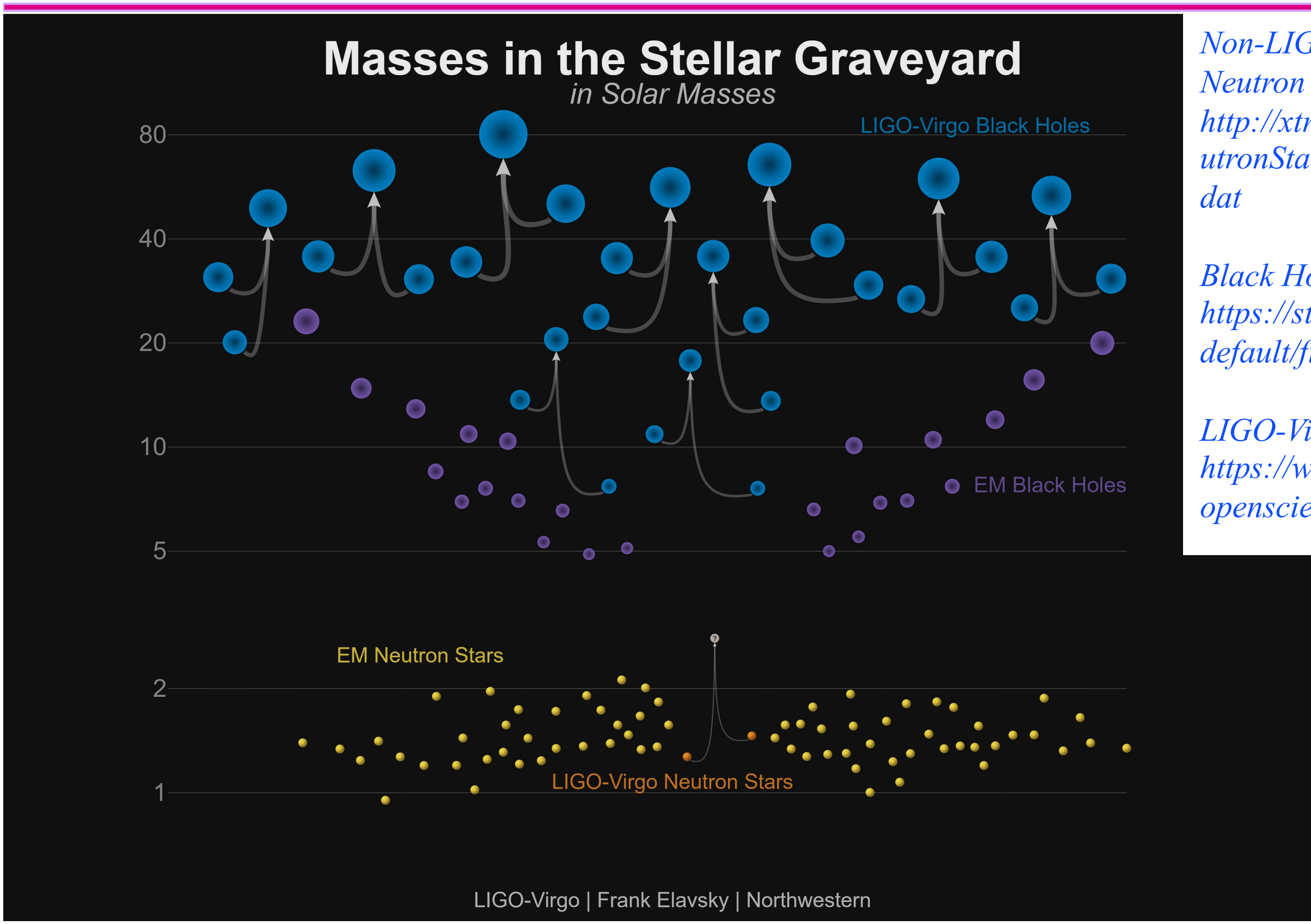


Figure 1 from Multi-messenger Observations of a Binary Neutron Star Merger
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

Known Masses of Stellar Remnants – GWTC-1



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://www.gw-openscience.org/catalog/

The Future

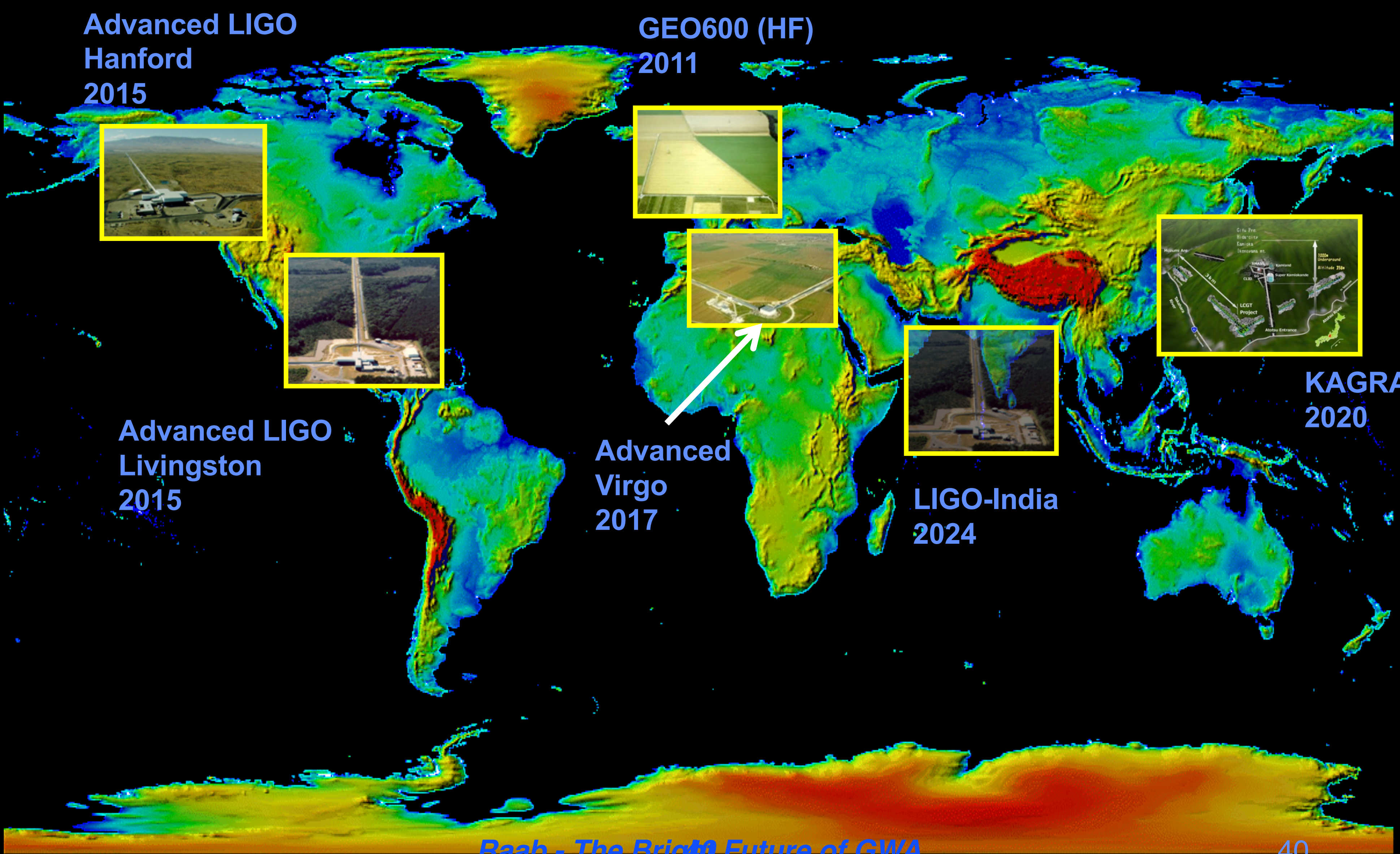
Headline: "*Get Ready For Gravitational Waves All Day, Every Day*" – *Sophia Chen, Wired 2/20/19*

https://www.wired.com/story/get-ready-for-gravitational-waves-all-day-every-day/

Future directions

- Build out the terrestrial network of kilometer-scale GW observatories
- Extend the reach of GW observatories
  - Upgrade detector technologies to fully exploit the facilities limits of the kilometer-scale facilities
  - Build a new generation of tens-of-kilometer-scale facilities
- Extend the spectrum of GW observatories

The advanced GW detector network: 2015-2025

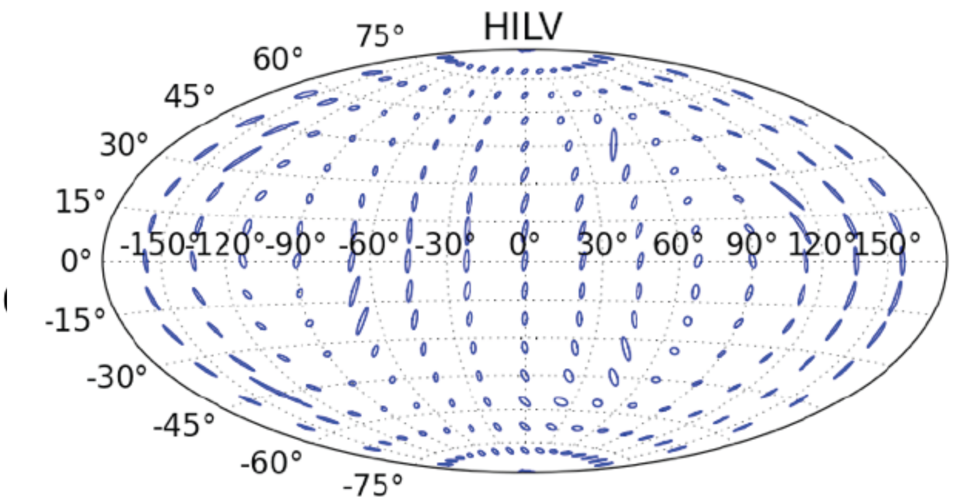


LIGO-India

http://www.ligo-india.in
http://www.gw-indigo.org/

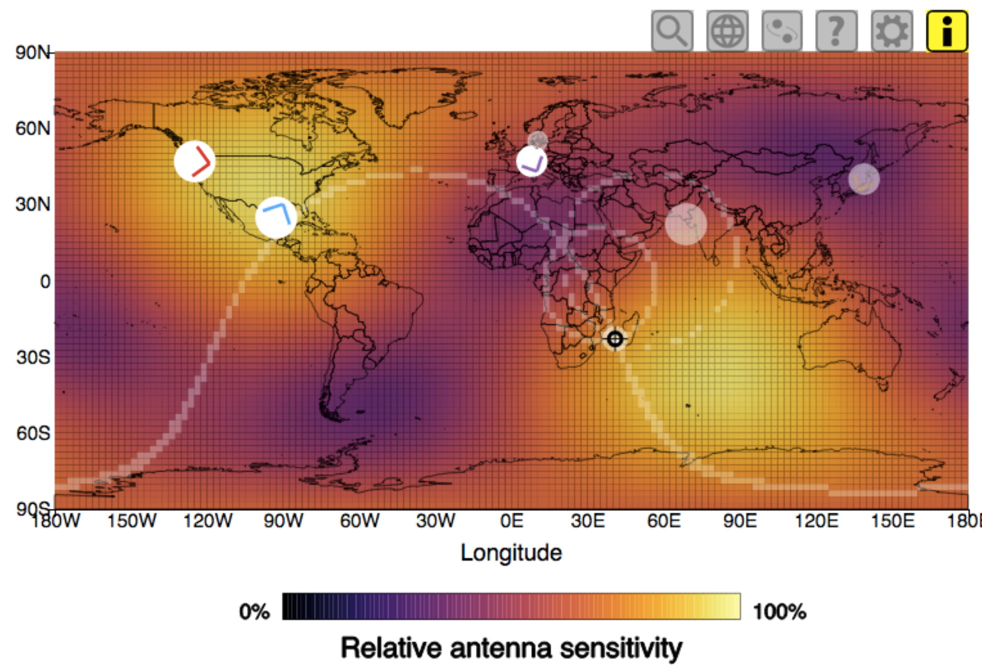
- Partner Agencies
  - Department of Atomic Energy
  - Department of Science & Technology
  - US National Science Foundation
- LIGO-India Institutes:
  - Institute for Plasma Research(IPR), Gandhinagar
  - Inter-University Centre for A&A (IUCAA), Pune
  - Raja Ramanna Centre for Advanced Technology (RRCAT), Indore
  - Directorate of Construction, Services and Estate Management (DCSEM), Mumbai
  - LIGO Laboratory, Caltech & MIT
- R&D at institutes across India

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



Fairhurst 2011

Effect of adding LIGO-India to LIGO + Virgo



Visualization courtesy of Chris North

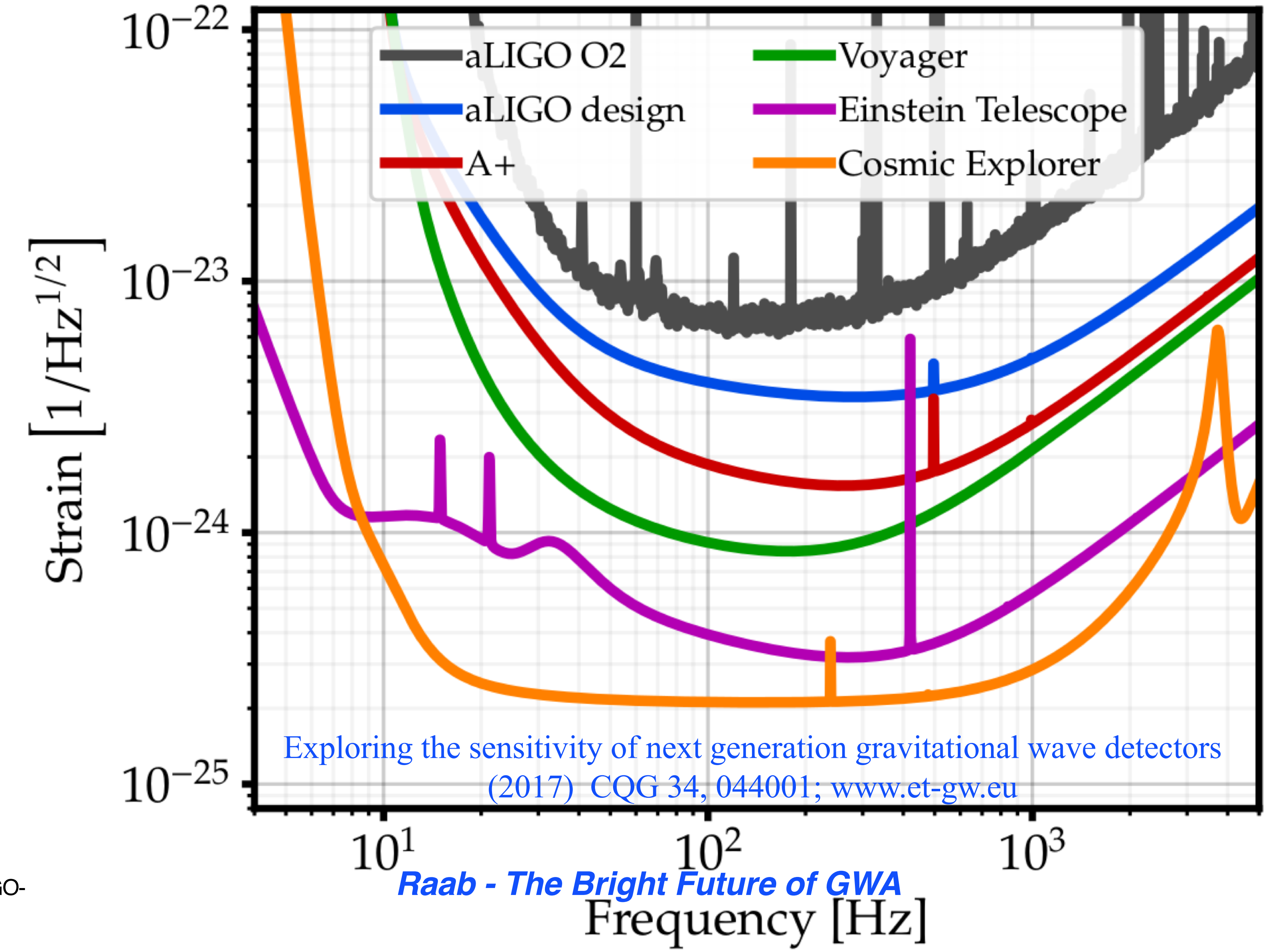
Extending the Reach: Science goals drive Requirements

- **Stellar Evolution at High Red-Shift: Black Holes from the first stars (Population III)**
  - » Reach $z > \sim 10$
  - » 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

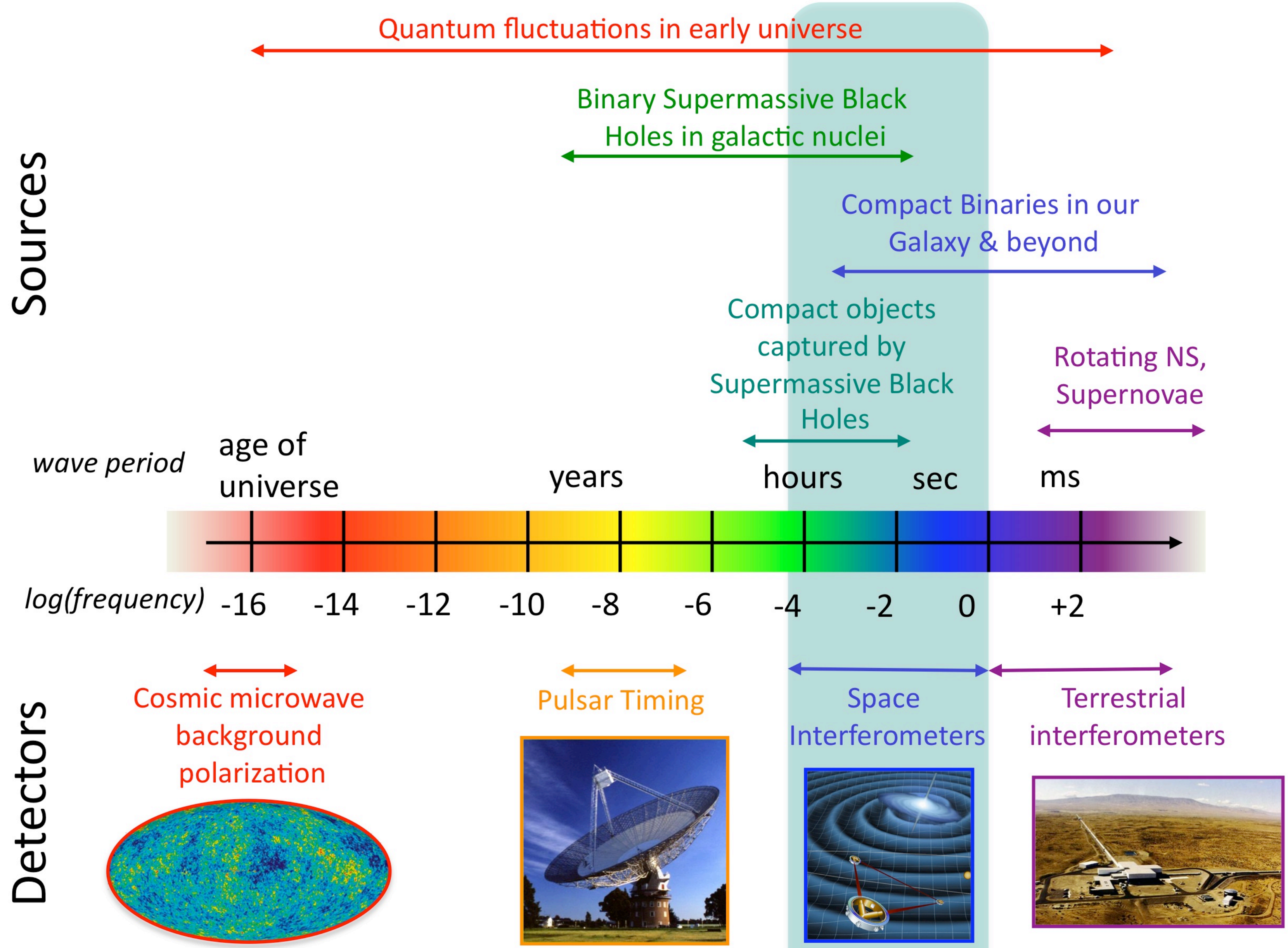
Technological path to the future

- Advanced LIGO is limited by quantum noise & mirror coating Brownian noise
- Squeezed vacuum can reduce quantum noise
- Options for Brownian noise:
  - » Better mirror coatings (high optical quality; low mechanical losses)
  - » Cryogenic operation (new mirror materials & coatings, new lasers, photo-detectors, vacuum-squeezers, etc.)
  - » Longer arms (new longer-arm observatory facilities)

Upgrade possibilities



The Gravitational Wave Spectrum



Credit: NASA

Raab - The Bright Future of GWA

Summary

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- India will be an important stage for these developments.

Will you ride the new wave in astronomy?