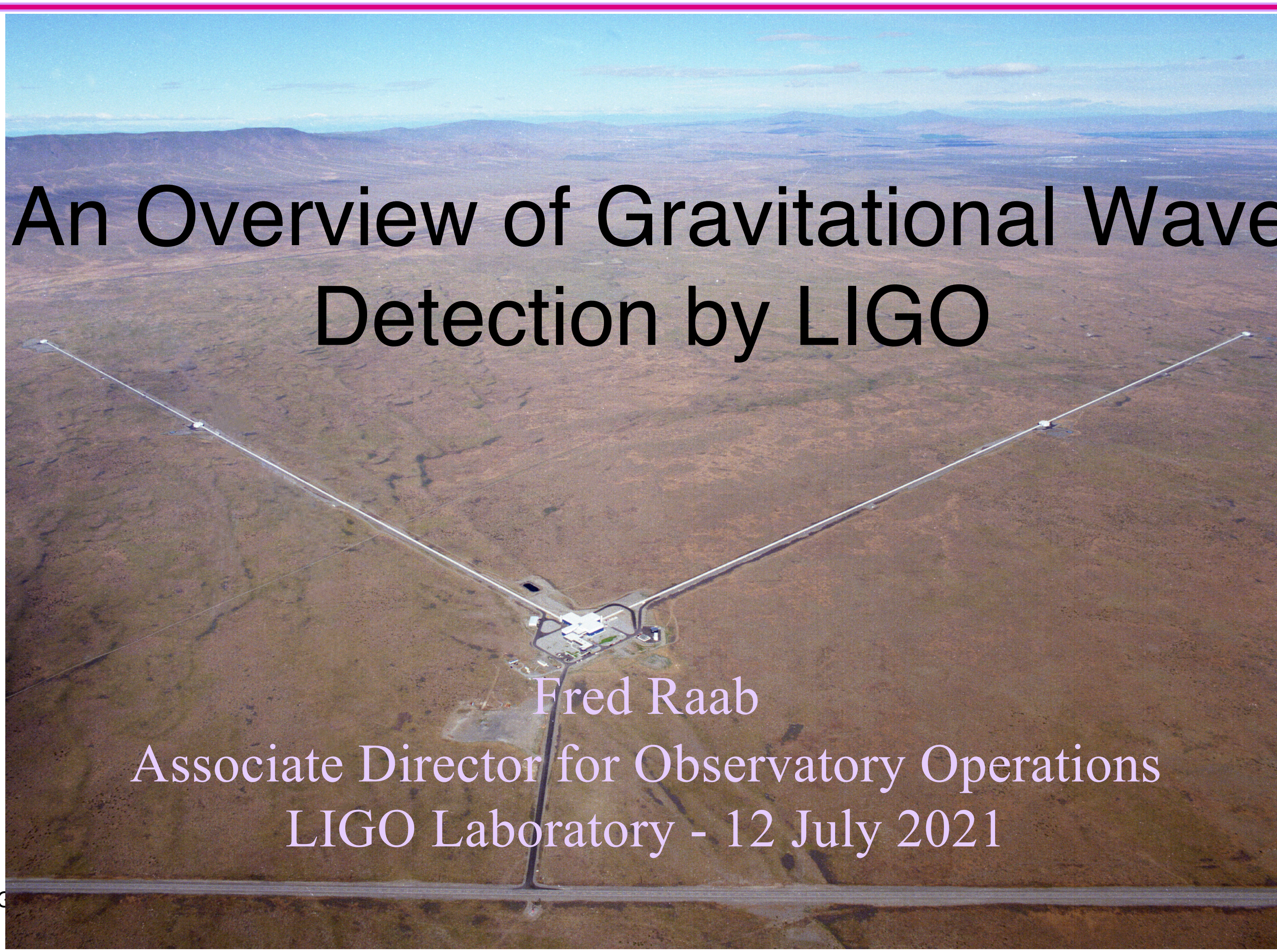
An Overview of Gravitational Wave Detection by LIGO



Fred Raab
Associate Director for Observatory Operations
LIGO Laboratory - 12 July 2021

Outline

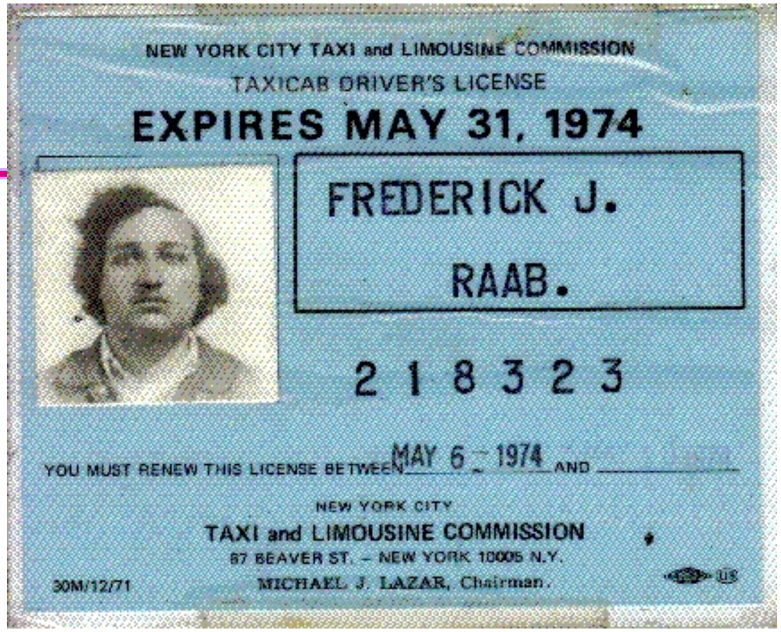
- What do we do? Who are we?
- Basics of Gravitational Waves (GWs)
- What do real GW detectors look like?
- Breakthroughs!
- The future.

What do we do at LIGO and how do we do it? (elevator version)

The LIGO team works to explore the most extreme regions of space and time and the most extreme forms of matter in the universe.

We do this by detecting the ripples in space-time, called gravitational waves, that are produced by black holes and neutron stars in some of the most violent events in our universe.

Who Am I?


NEW YORK CITY TAXI and LIMOUSINE COMMISSION
TAXICAB DRIVER'S LICENSE
EXPIRES MAY 31, 1974
FREDERICK J.
RAAB.
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YOU MUST RENEW THIS LICENSE BETWEEN MAY 6 - 1974 AND
NEW YORK CITY
TAXI and LIMOUSINE COMMISSION
87 BEAVER ST. – NEW YORK 10005 N.Y.
MICHAEL J. LAZAR, Chairman.
30M/12/71

- Born to US immigrants in NYC in 1951.
- Had an "OK" but not "strong" high school science background.
- Fan of space; fell in love with Physics.
- Struggled in my first college physics course, but persevered.
- BS-Manhattan College, PhD-SUNY Stony Brook (1980).
- U. Washington research scientist.
- Kip Thorne recruited me to Caltech in 1988.

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
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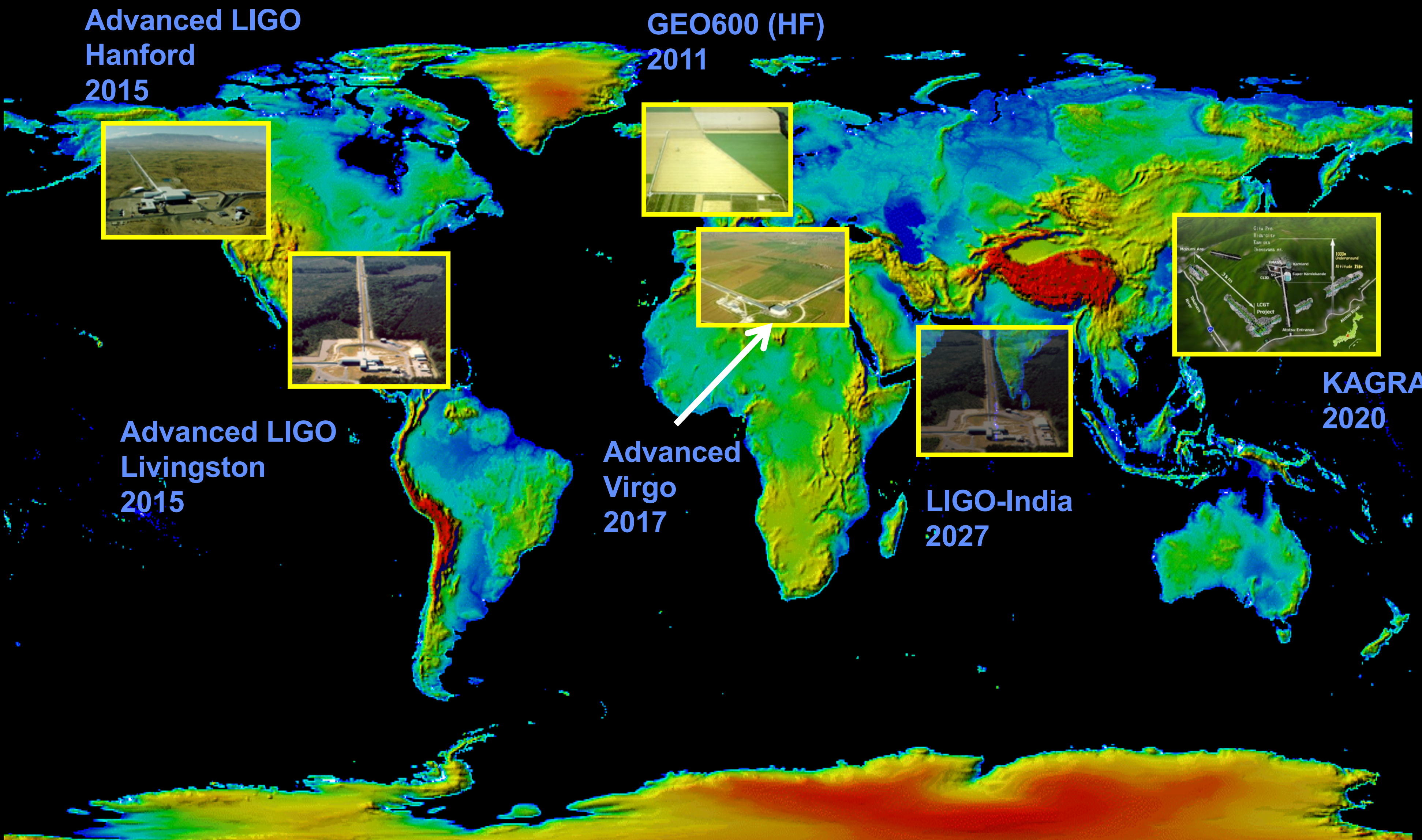
Who else is working on terrestrial GW detectors

- LIGO Laboratory: 180 members.
- LIGO Scientific Collaboration: 1100+ members in 108 institutions across 18 countries on 5 continents.
- Virgo Collaboration: 650+ members in 14 countries in Europe.
- KAGRA Collaboration: 200+ members from 90 institutions in 15 countries.

- Science is a team sport!

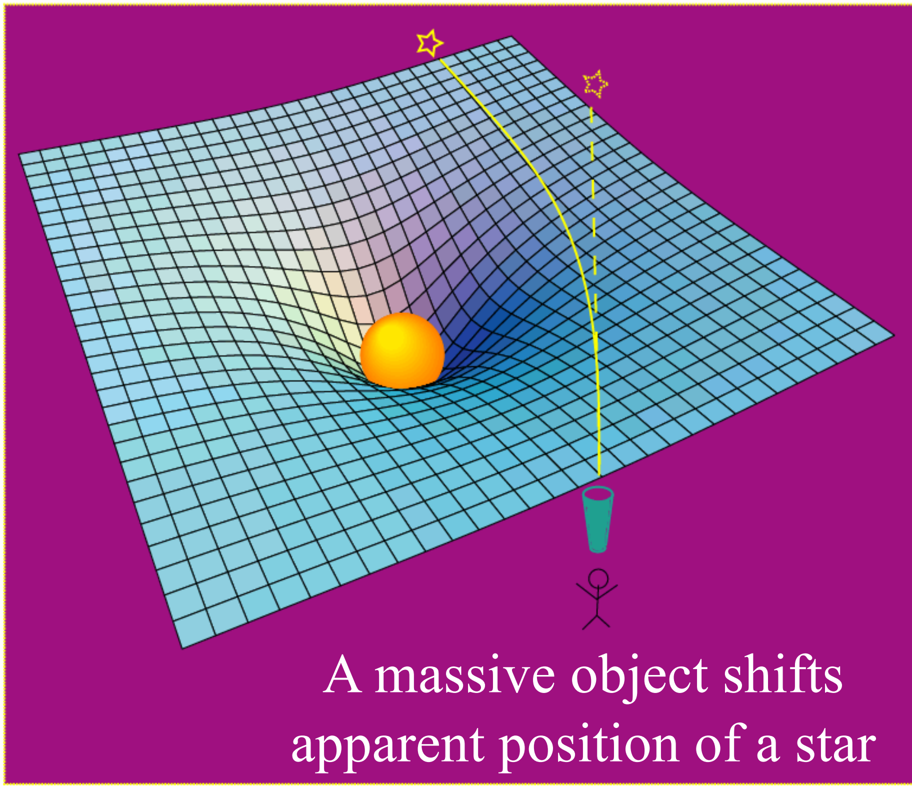
The advanced GW detector network: 2015-2030



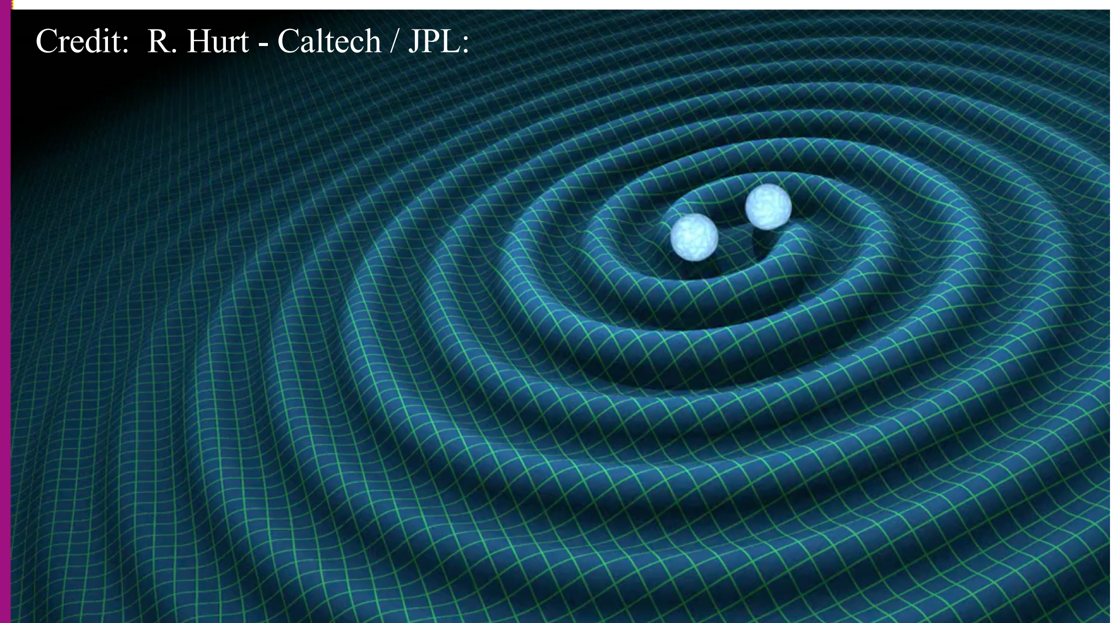
Basics of Gravitational-Waves

Einstein's General Relativity: gravity is a manifestation of space-time curvature

curved spacetime can bend light, too!



dynamic deformation of spacetime



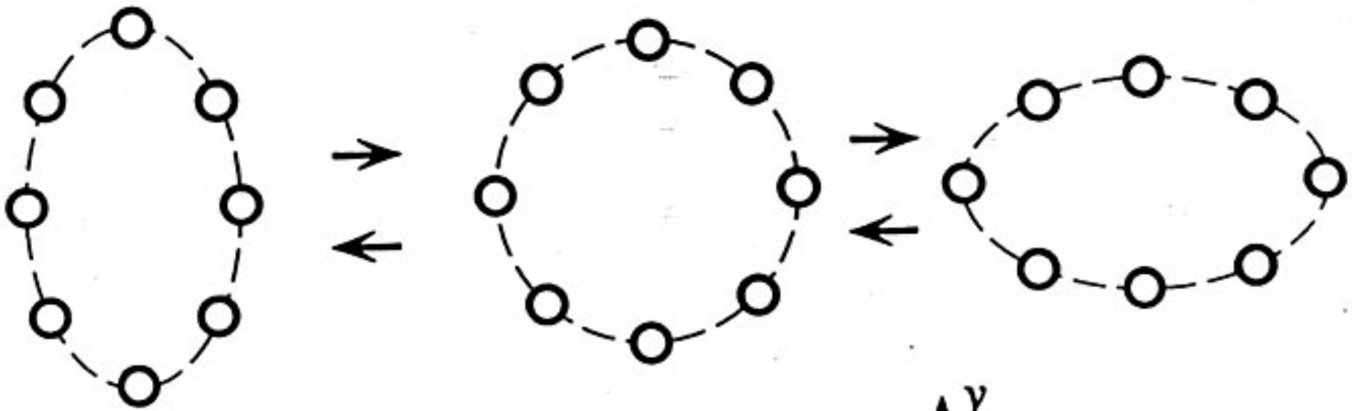
Space has a shape, a stiffness and a maximum speed for information transfer.

The problem with checking relativity in Einstein's time

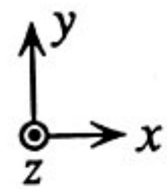
- A figure of merit for manifesting relativistic effects is *v/c.*
- In Einstein's time, there was not a lot of *v/c* available to observe and rulers and clocks were not so good.
  - » *v/c for a locomotive is approximately* 10^{-7}
  - » *v/c for Mercury is approximately* 1.5×10^{-4}
  - » Ruling engines 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
  - » Strontium atomic clocks are accurate to a second in 15 billion years!

LIGO

Basic idea for detection is simple



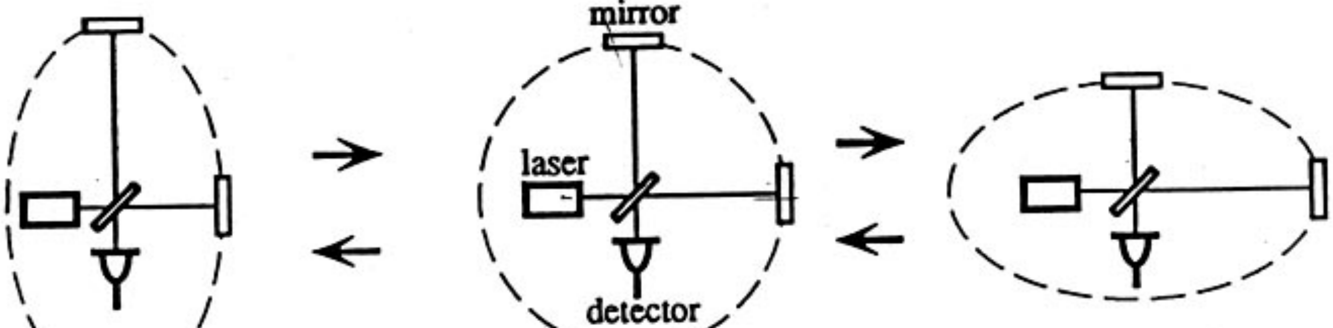
⊙ Gravitational Waves



GW amplitude

$h = (R_x - R_y)/R$

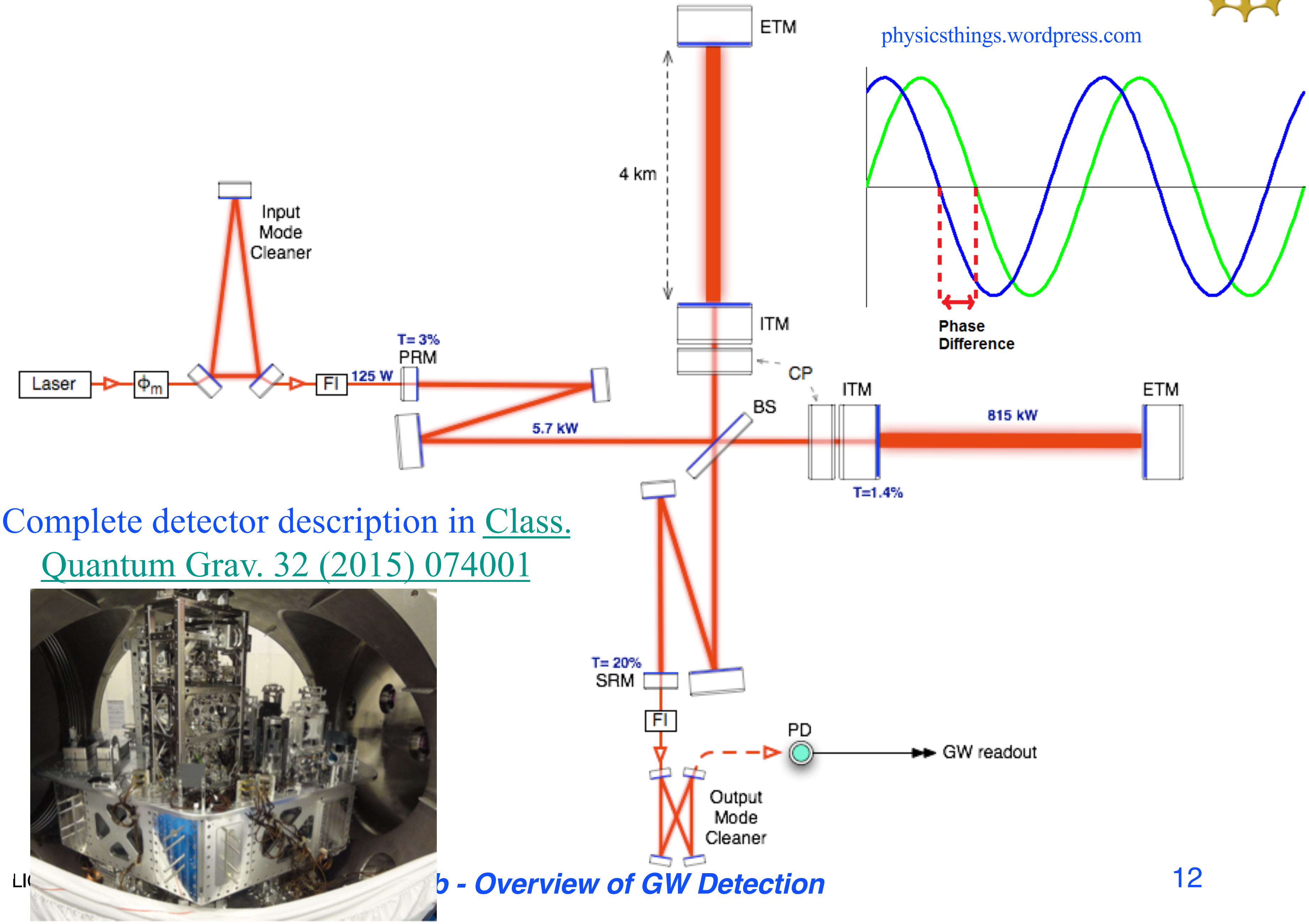
When the arm lengths are equal, no light reaches the detector.



It takes longer for light to travel the longer arm path, which allows light to reach the detector.

What do real GW detectors look like?

Optical configuration



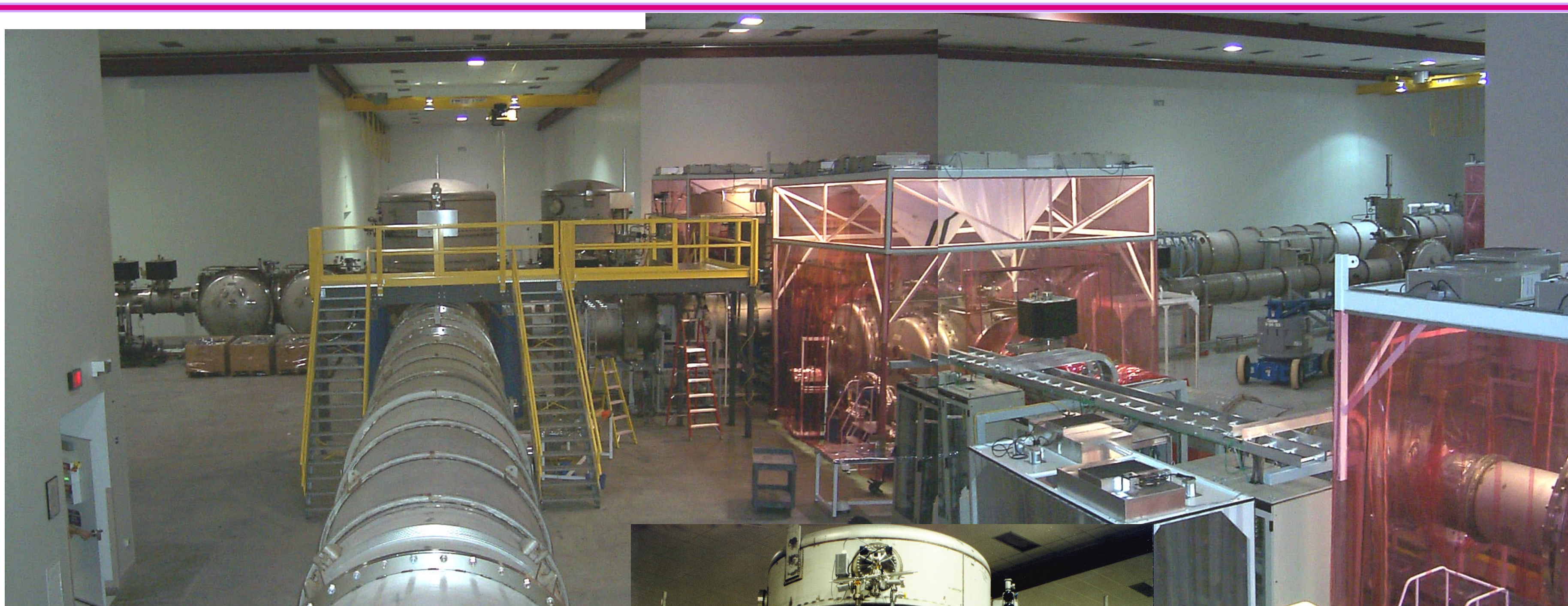
Complete detector description in [Class. Quantum Grav. 32 (2015) 074001]

Evacuated Beam Tubes Provide Clear Path for Light

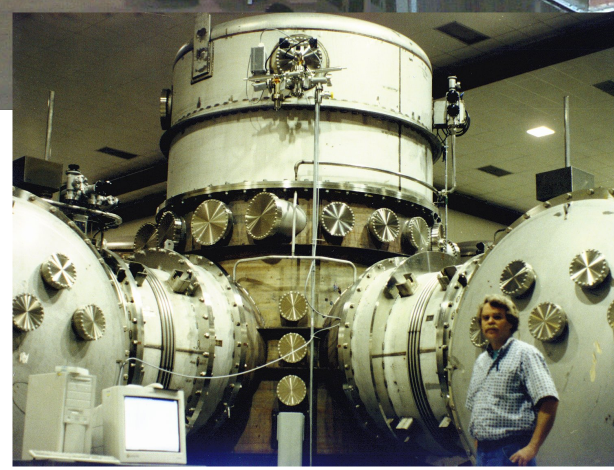
P< 10^{-9} Torr

Portable power supply for bakeout

Vacuum Chambers Provide Quiet Homes for Mirrors



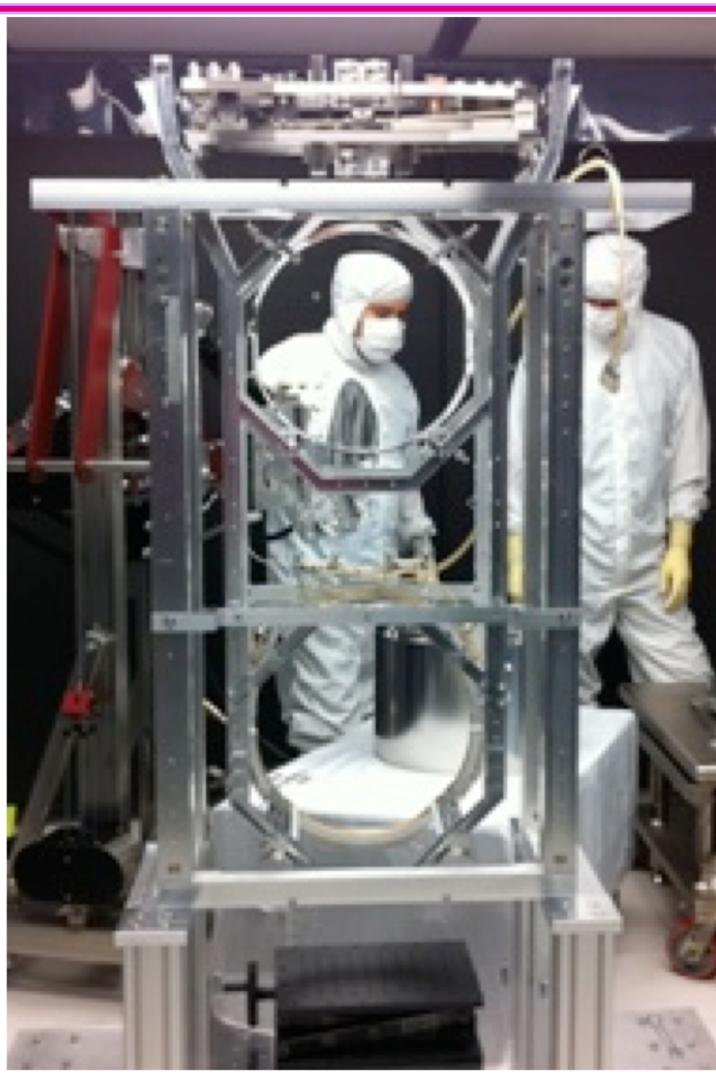
View inside Corner Station

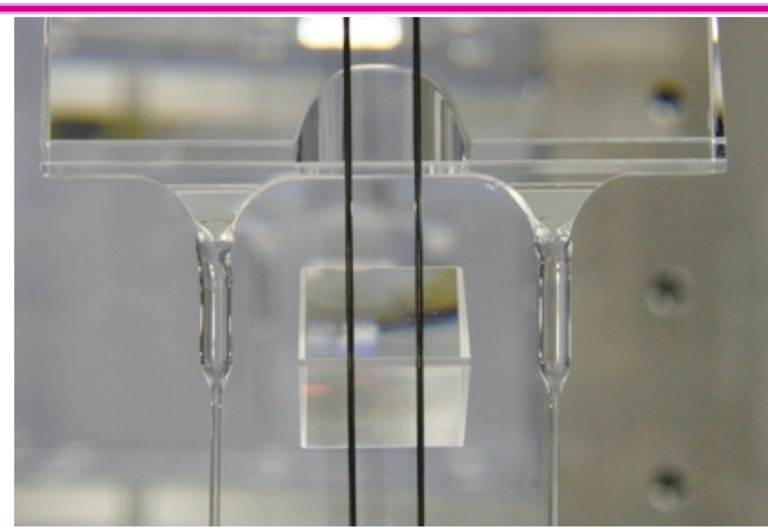


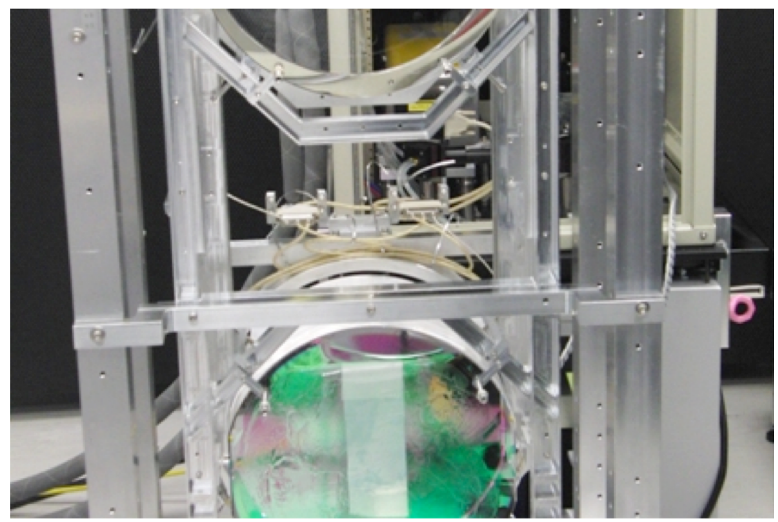
Standing at vertex beam splitter

BSC Internal Seismic Isolator

Advanced LIGO Monolithic Suspension







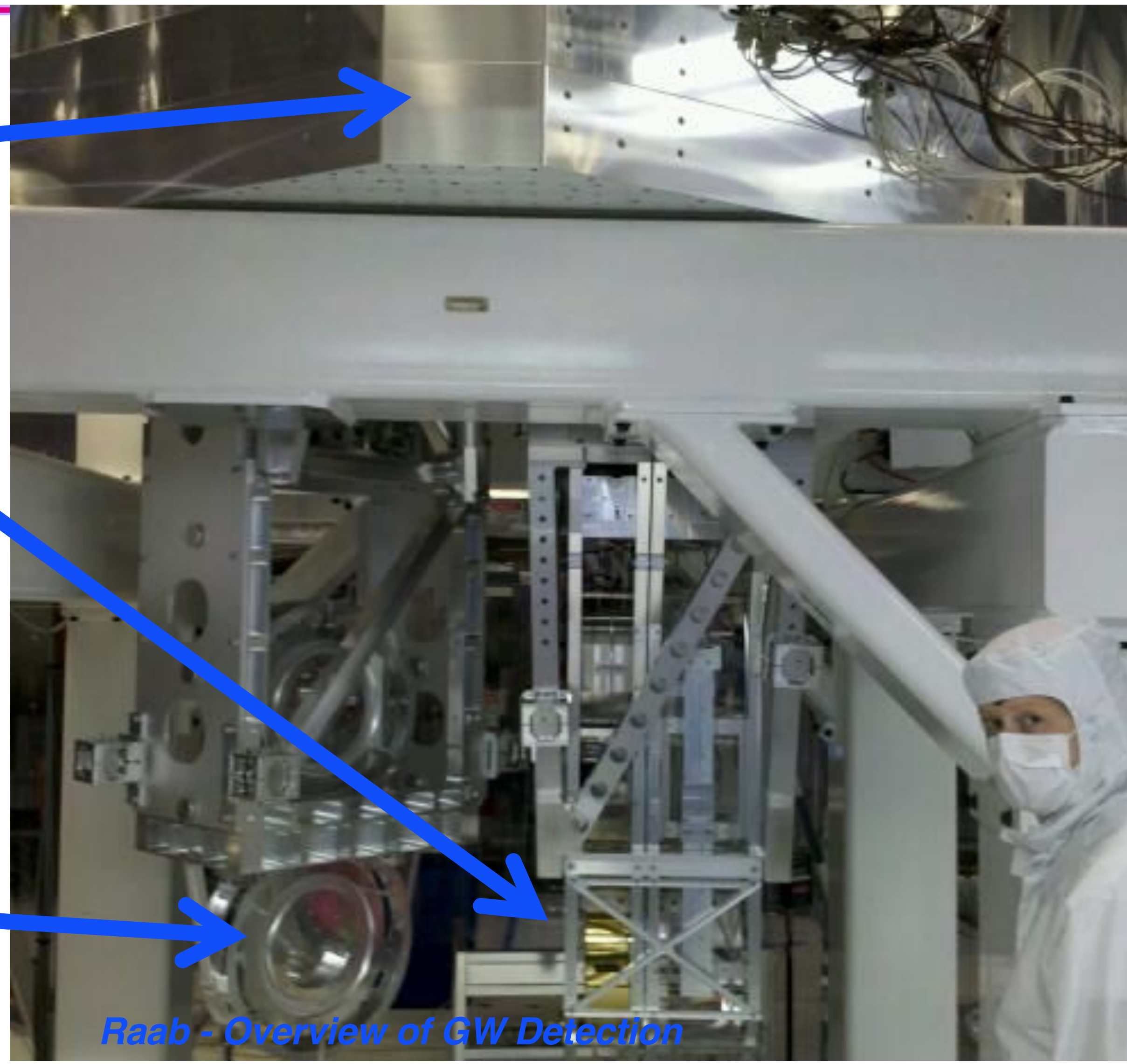
LIGO Advanced LIGO installation in progress

Putting it together: Seismic & Suspension & Optics

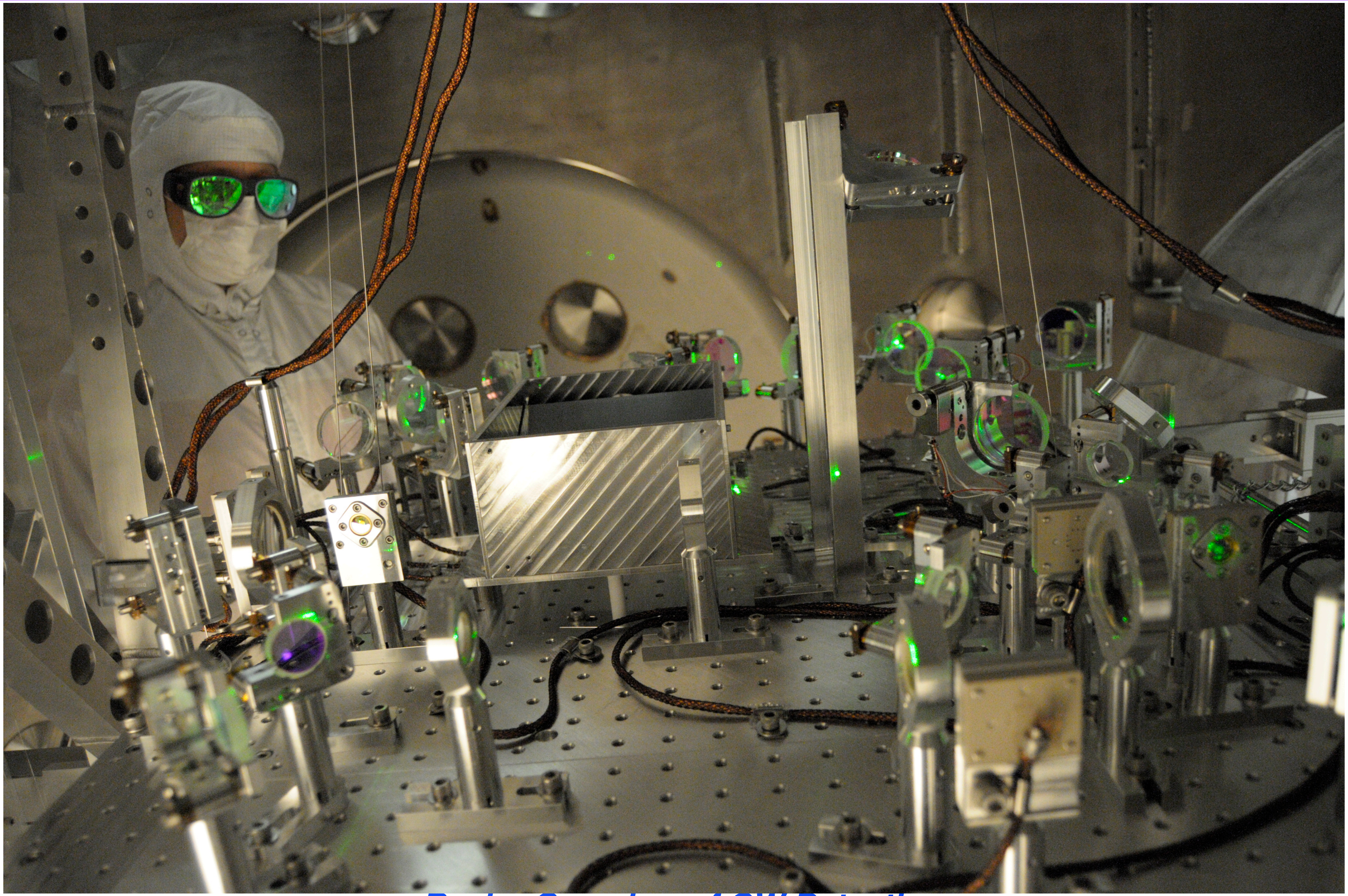
Seismic isolation

Test mass suspension

Folding mirror suspension

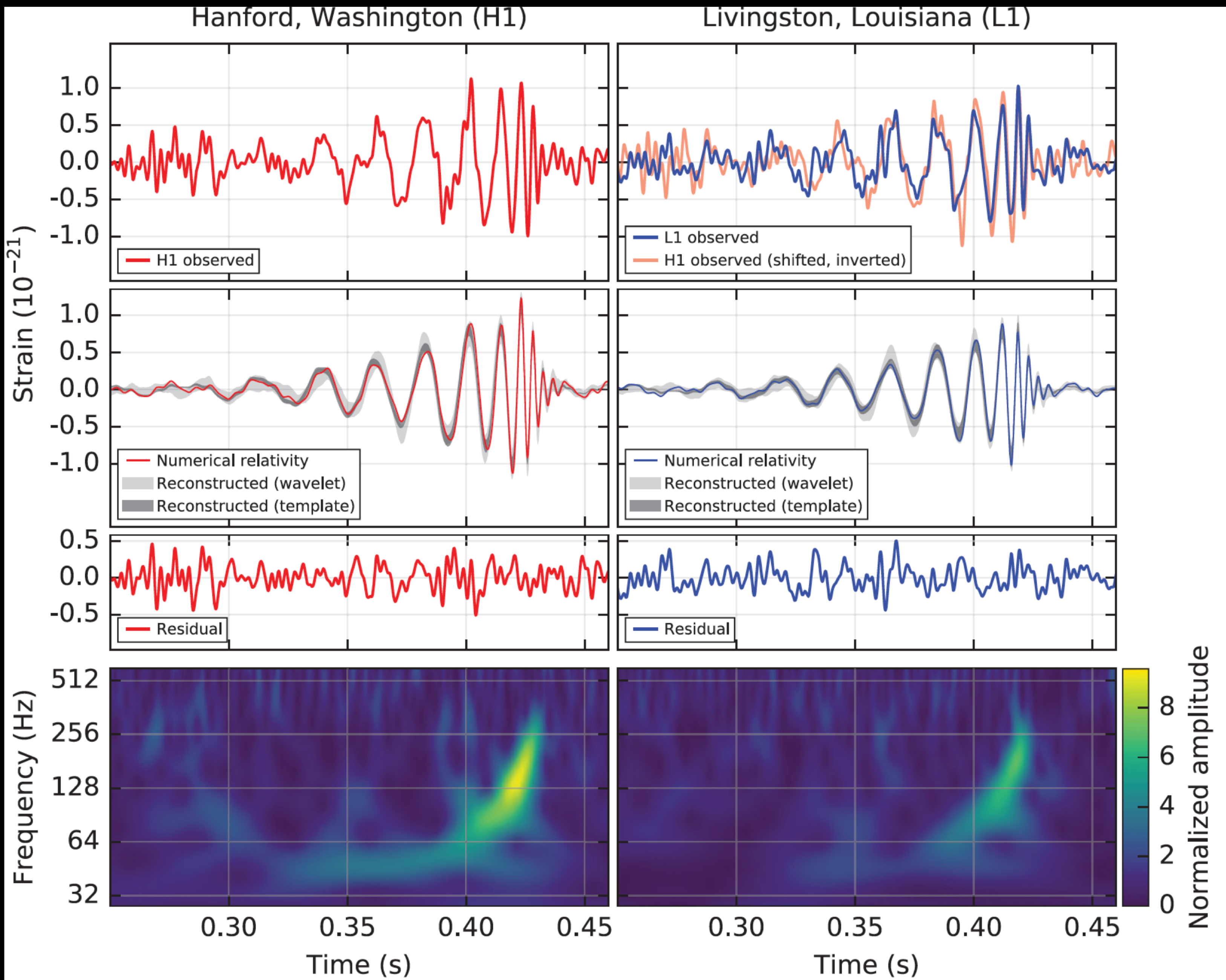


Lock Acquisition: Arm Locking Subsystem



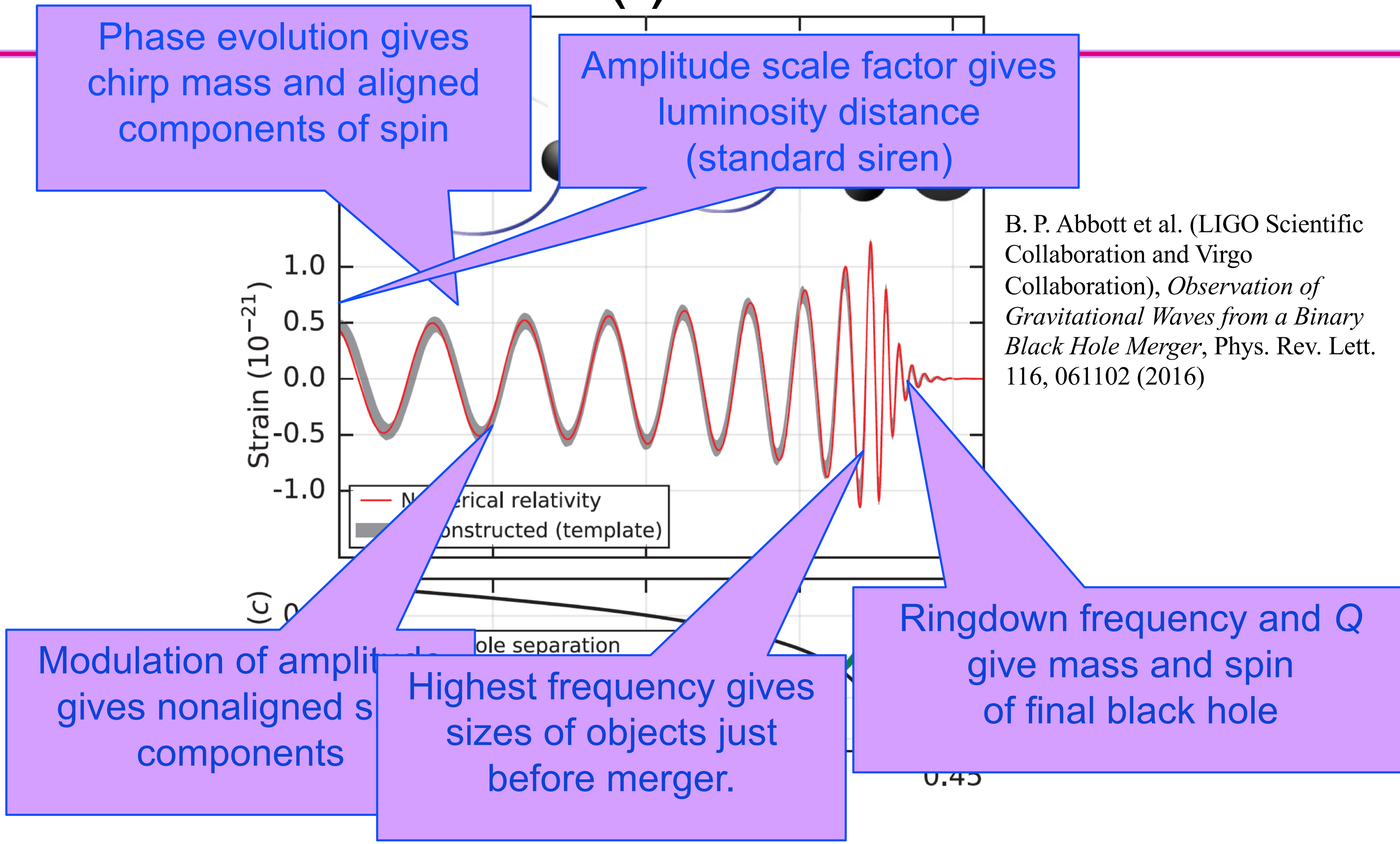
aLIGO Pre-stabilized laser

Breakthroughs



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)

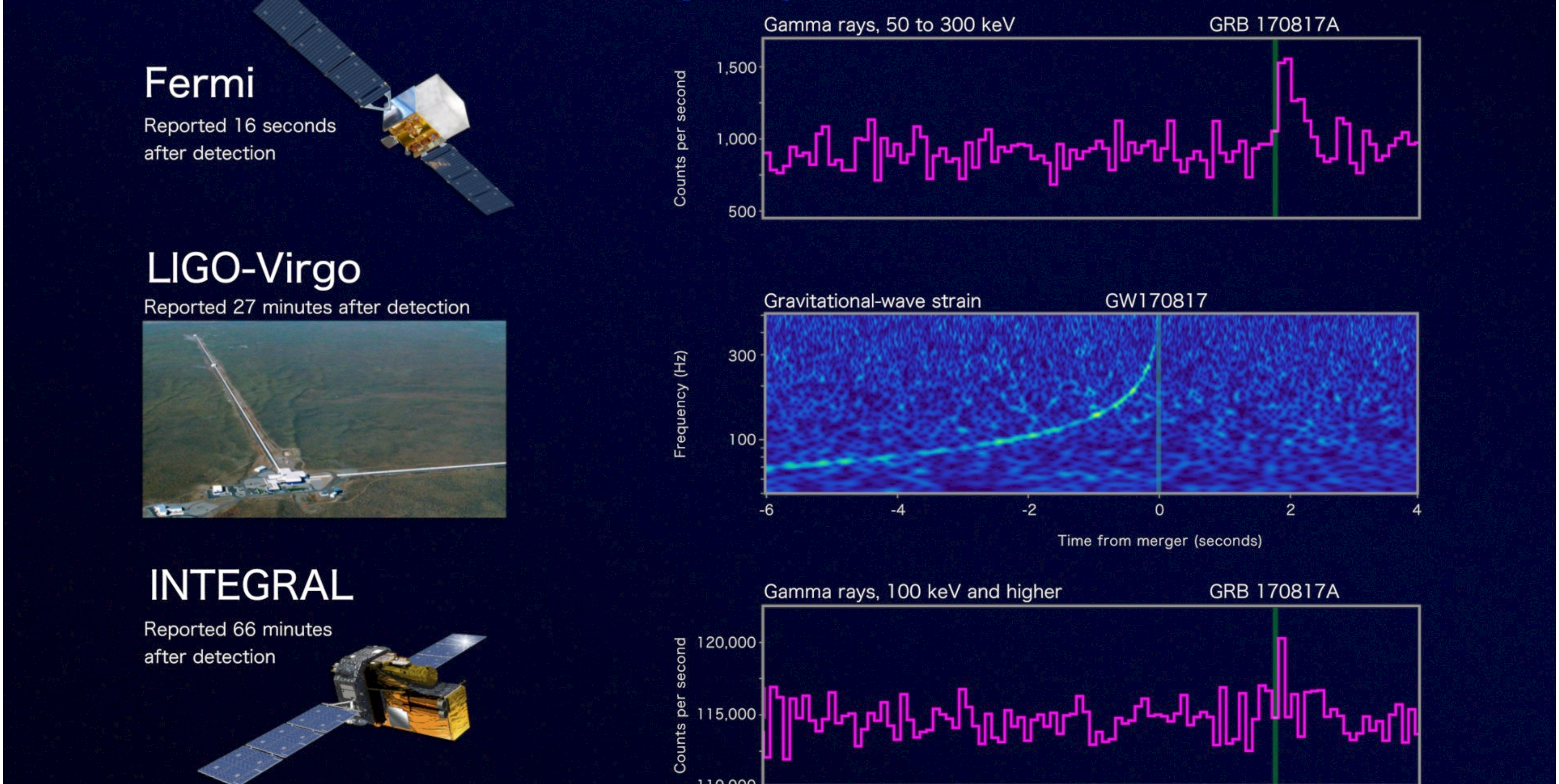
What can we learn from h(t)?



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)

- 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.

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

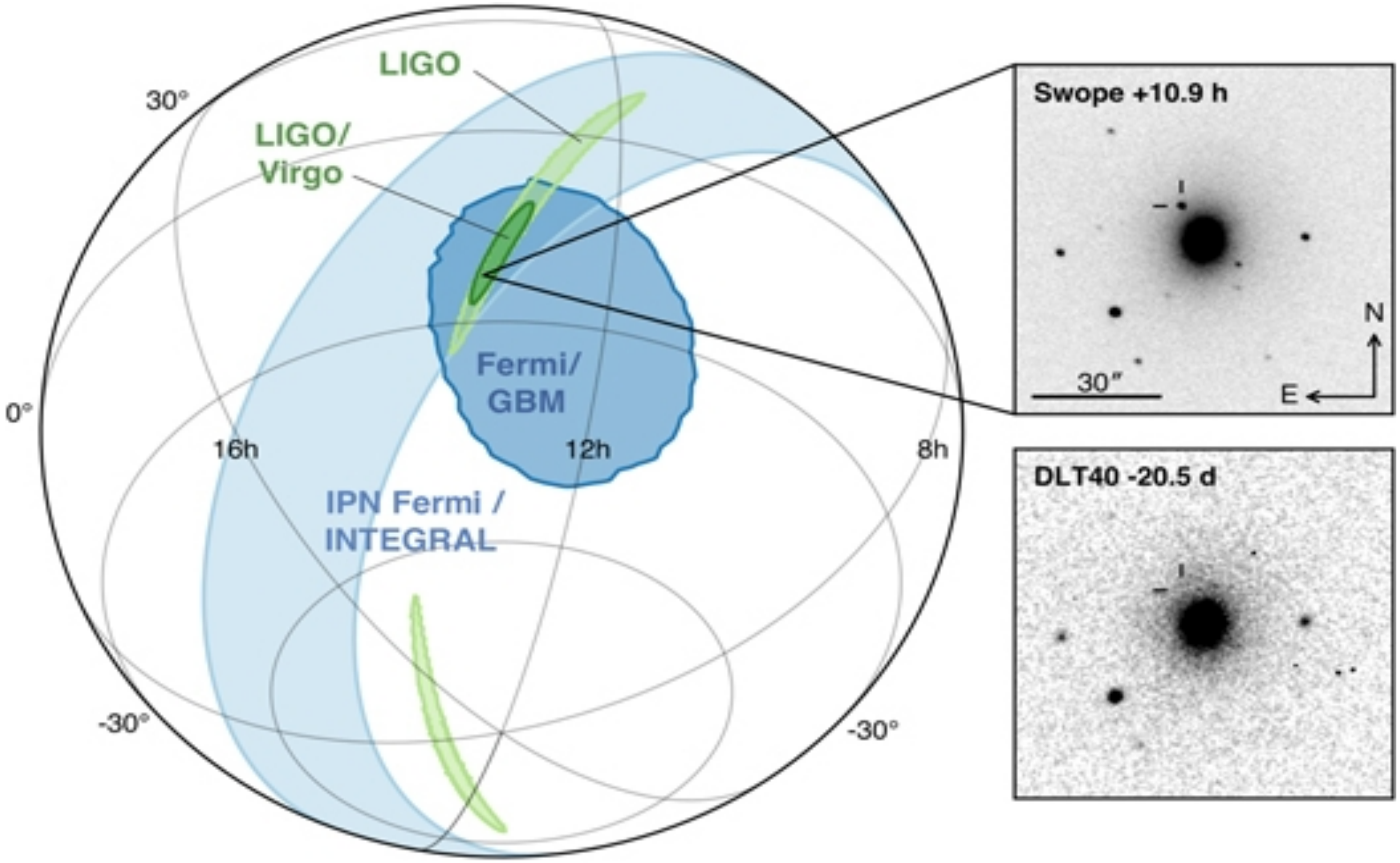


Figure 1 from Multi-messenger Observations of a Binary Neutron Star Merger
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

Highlights learned from GW170817

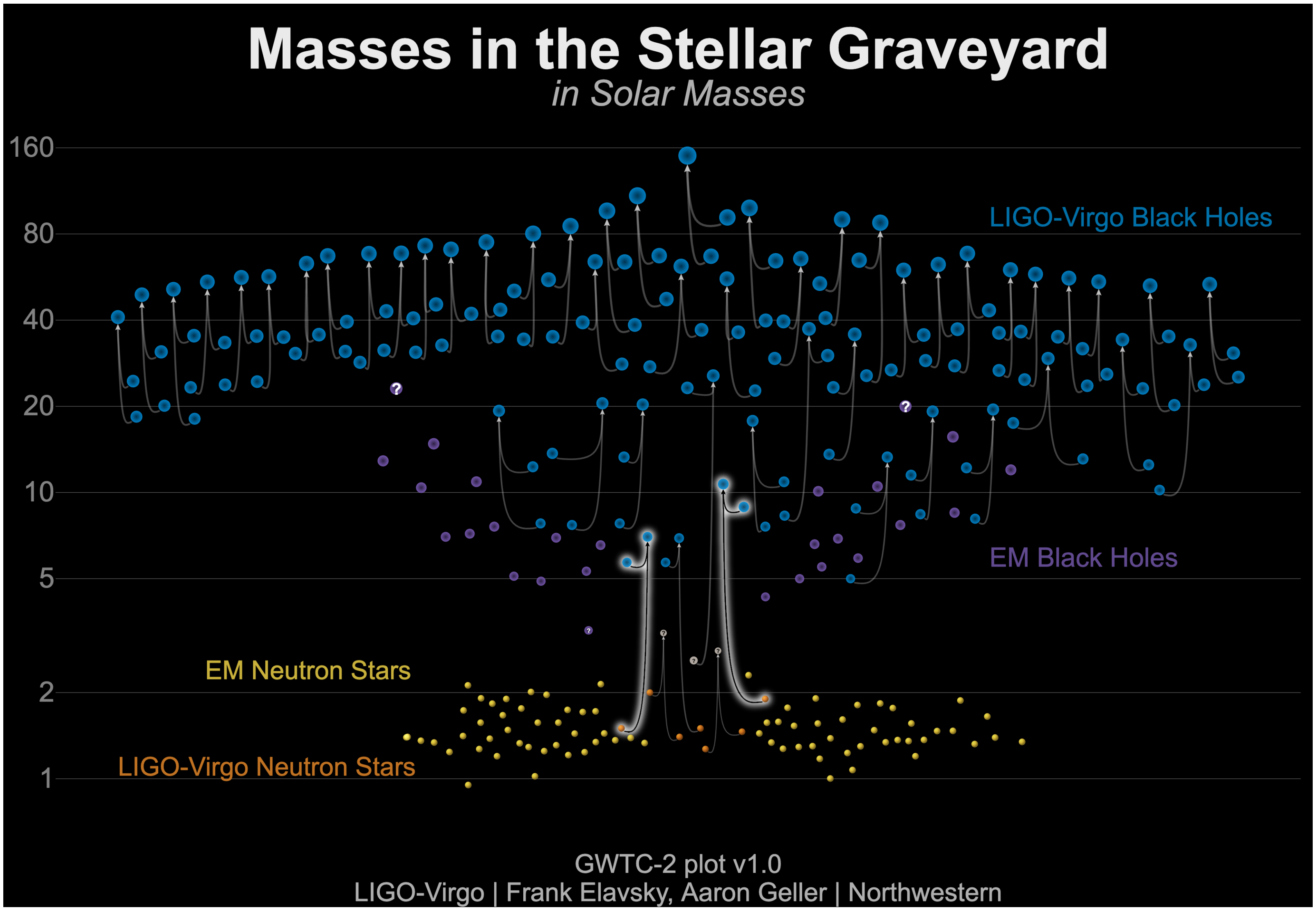
- First GW from binary neutron star inspiral and merger detected.
- GW detection of tidal distortions as neutron stars rip each other apart provide constraints on neutron-star equation of state.
- GW follow-up conducted at 70 observatories on Earth and in space, covering EM spectrum from gamma rays to radio waves.
- Confirmed that speed of gravity is equal to speed of light, at least to 15-digit accuracy.
- Confirmed neutron-star-merger origin of short gamma-ray bursts.
- Confirmed “kilonova” description of matter following merger.
- Confirmed the formation mechanism for most of the abundance of the elements heavier than iron.
- First measurement of Hubble constant using GWs.

The power of a "catalog" of GW detections

- Astronomical catalogs tabulate astronomical objects that share common attributes, but whose representation and differences reveal fundamental information about the nature of the objects and how they form.
- For example, star catalogs that tabulated colors of stars eventually led to understanding the composition of stars and how stars progress from birth to death.
- Similarly, catalogs of GW-detected sources and their properties can reveal the nature of the objects involved, how they formed and the environments that they have encountered.
- Think of black holes and neutron stars as the fossils of the universe.

Known Masses of Stellar Remnants – July 2021

https://arxiv.org/abs/2010.14527



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: gw-openscience.org

Some clues from GW Transient Catalog (GWTC-2)

https://arxiv.org/abs/2010.14533

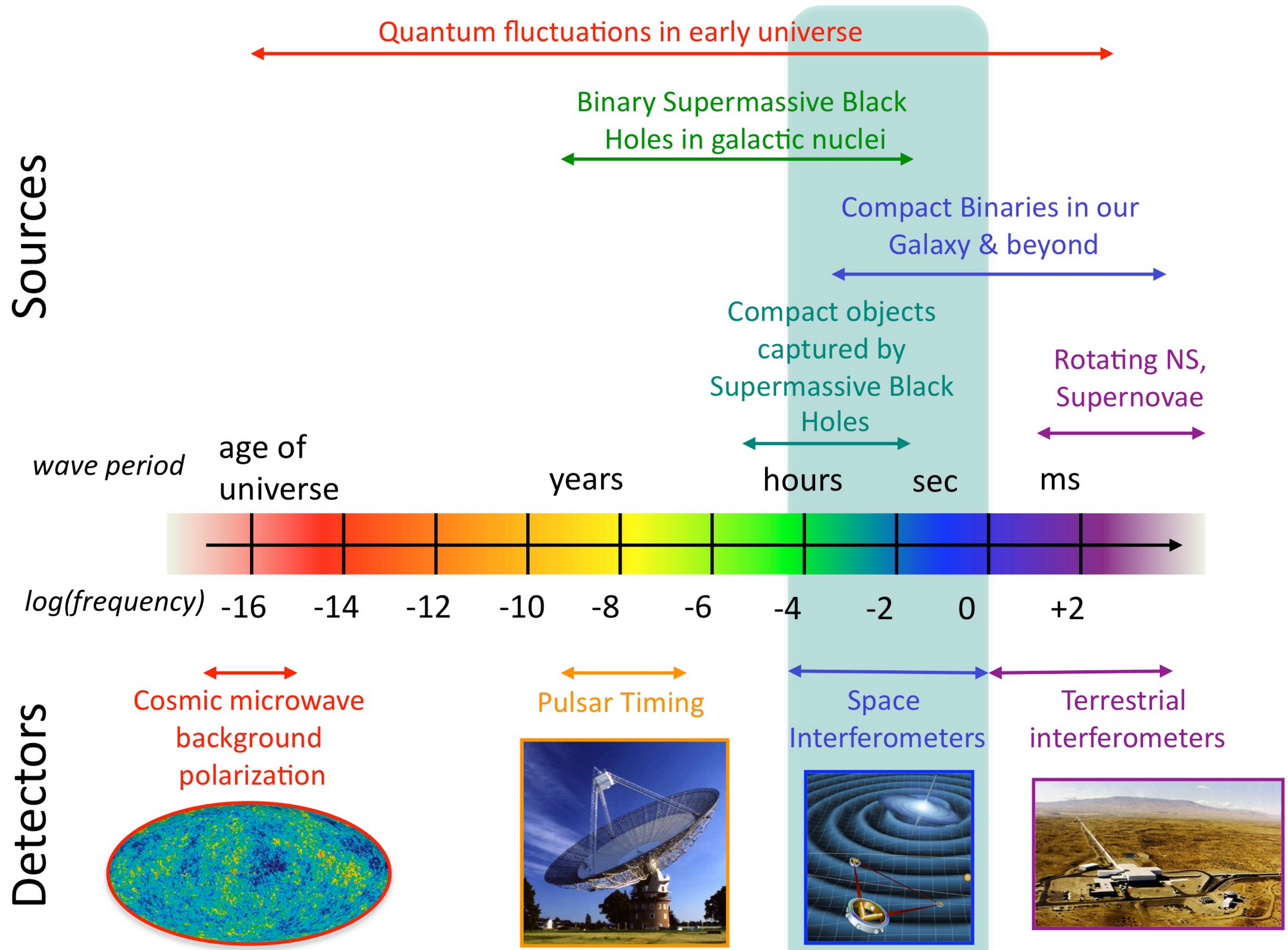
- Black-hole binaries are merging many times per hour somewhere in the observable universe.
- Black hole binaries can have a range of mass ratios.
- Black holes can form from mechanisms other than core-collapse supernovae.
- Some black holes in binaries are spinning.
- Some black holes have spins aligned with their binaries, but some do not, suggesting different mechanisms for how these binaries were formed.
- Intermediate-mass black holes exist in the mass range between stellar-mass BHs and supermassive BHs at the centers of galaxies.
- There appear to be objects in the suspected “mass gap” between neutron stars and black holes.

The future

When you come to a fork in the road, take it. – Yogi Berra

- Extending the reach of GW detectors
  - The path traveled by LIGO's detected waves expanded by a few times 10% as the universe expanded since the waves were launched.
  - We can now imagine how to develop detectors to observe the universe when it was tens of times smaller and the first generations of stars were forming and dying.
  - We now know that somewhere in the universe black holes mergers occur many times each hour and eventually we could observe each one.
- Extending the spectrum of gravitational-wave observations.

The Gravitational Wave Spectrum



Raab - Overview of GW Detection

Credit: NASA