

Gravitational-Wave Astronomy - a Long Time Coming

Livia Conti, for the Virgo Collaboration
Fred Raab, for the LIGO Scientific Collaboration



LIGO Hanford, WA

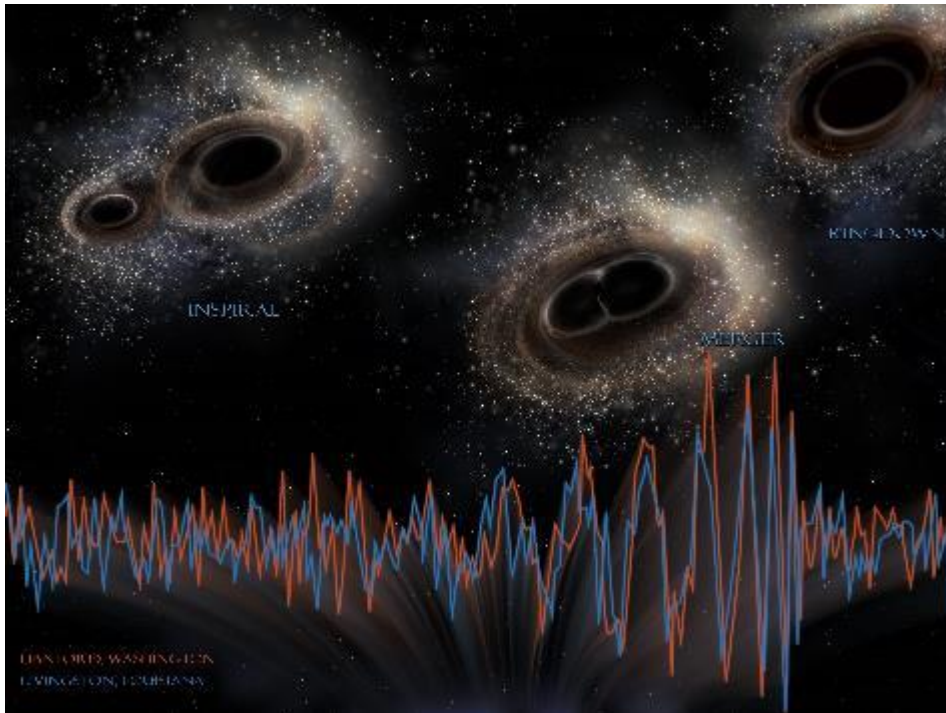


LIGO Livingston, LA

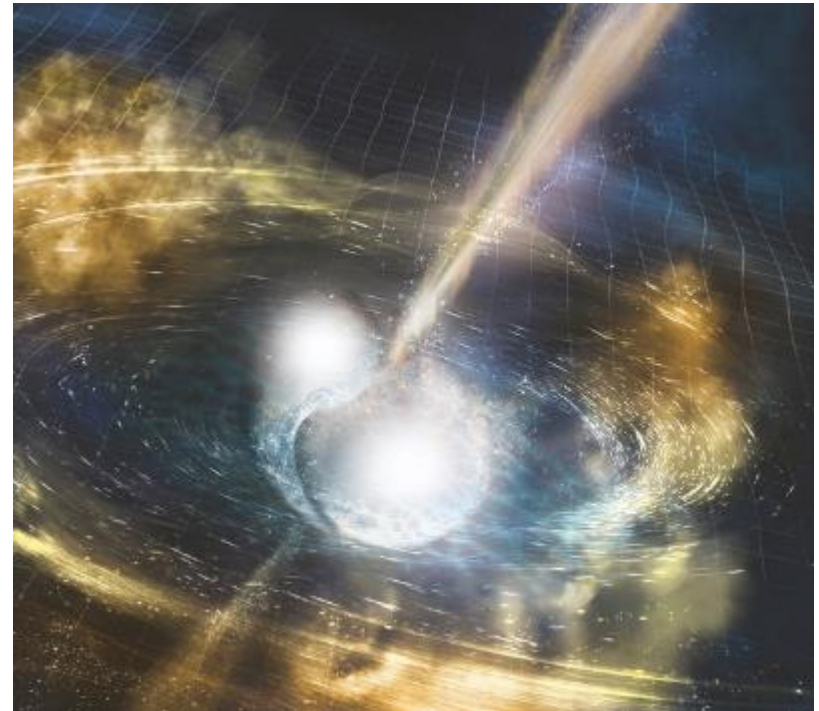


Virgo (Cascina, Italy)

What are we talking about?



Gravitational waves from merging black holes



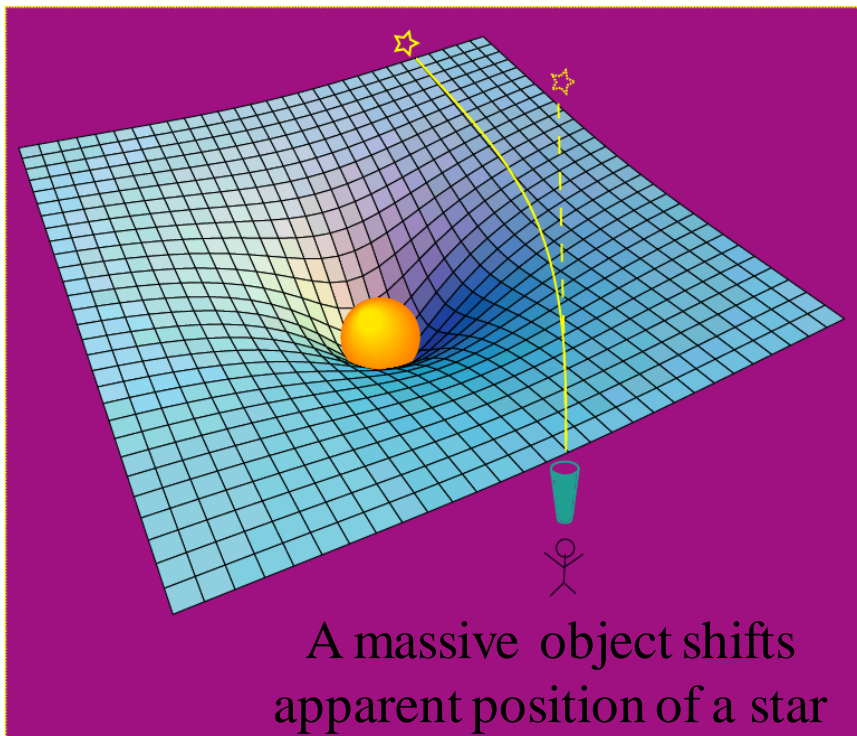
Gravitational waves and electromagnetic waves from merging neutron stars

Basics of General Relativity and Gravitational Waves

Big idea: space and time are things, whose properties are manifested by the phenomena that we collectively refer to as “gravity”.

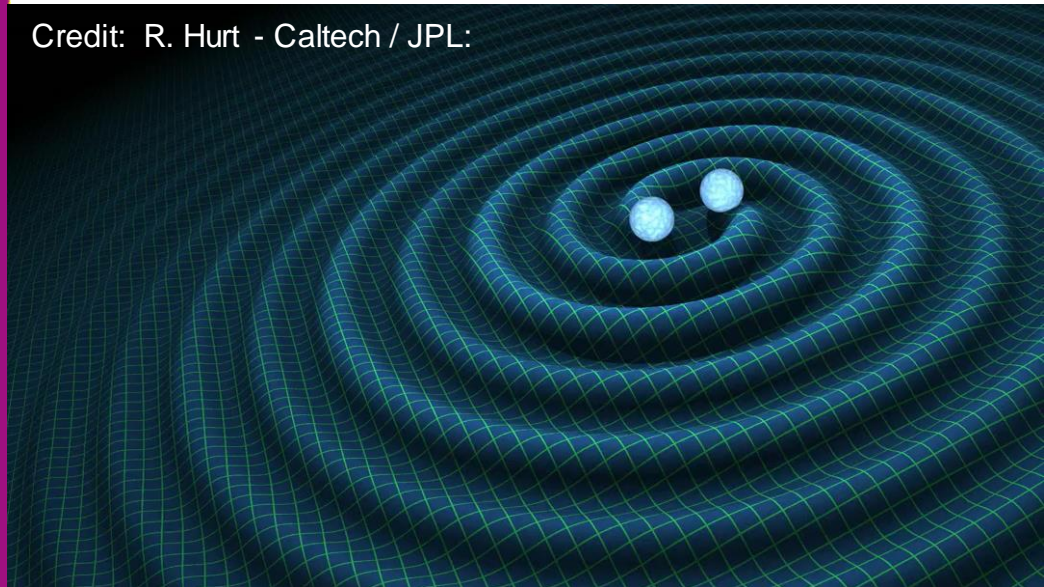
Einstein's General Relativity: gravity is a manifestation of space-time curvature

curved spacetime can bend light, too!



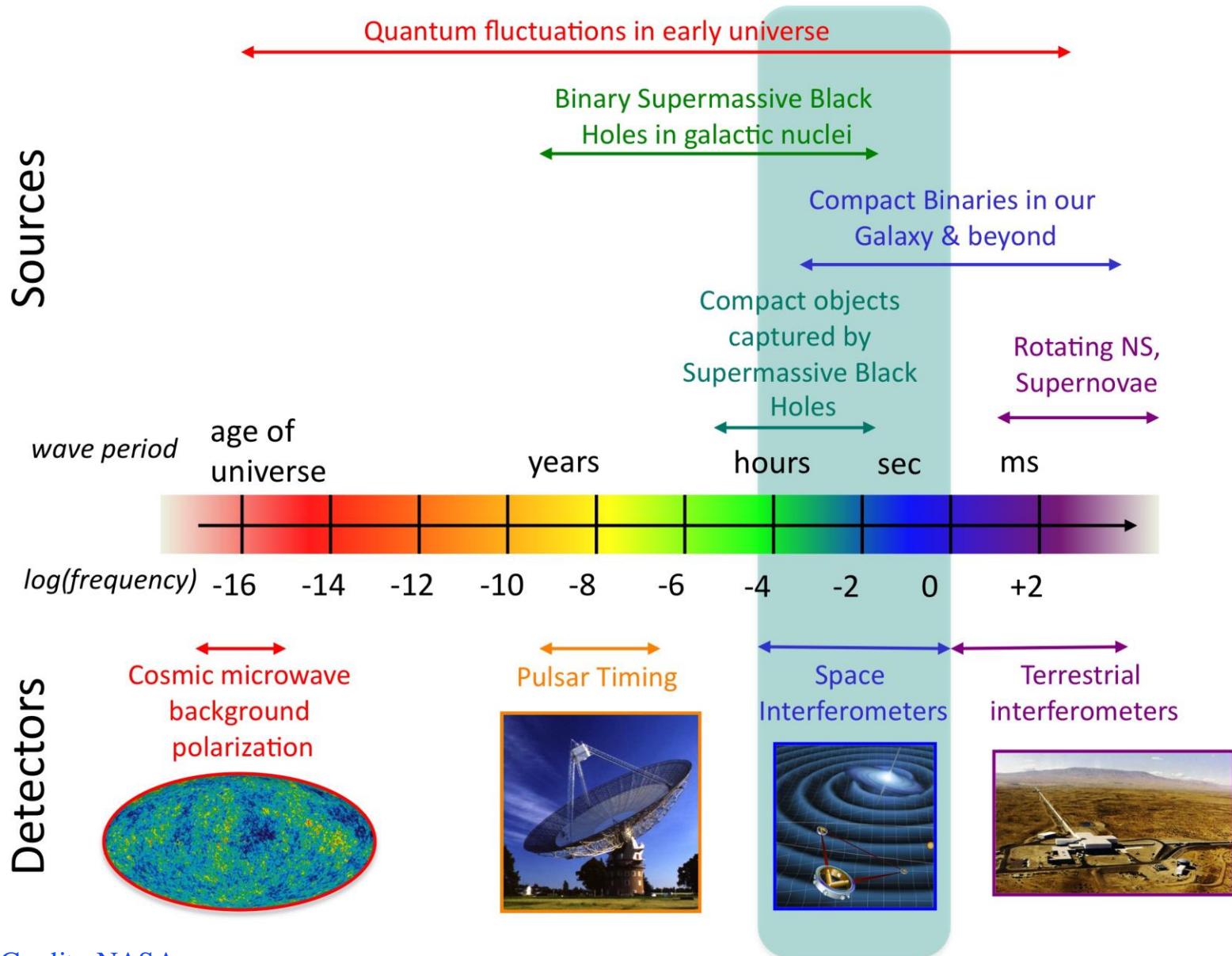
dynamic deformation of
spacetime

Credit: R. Hurt - Caltech / JPL:



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

The Gravitational Wave Spectrum

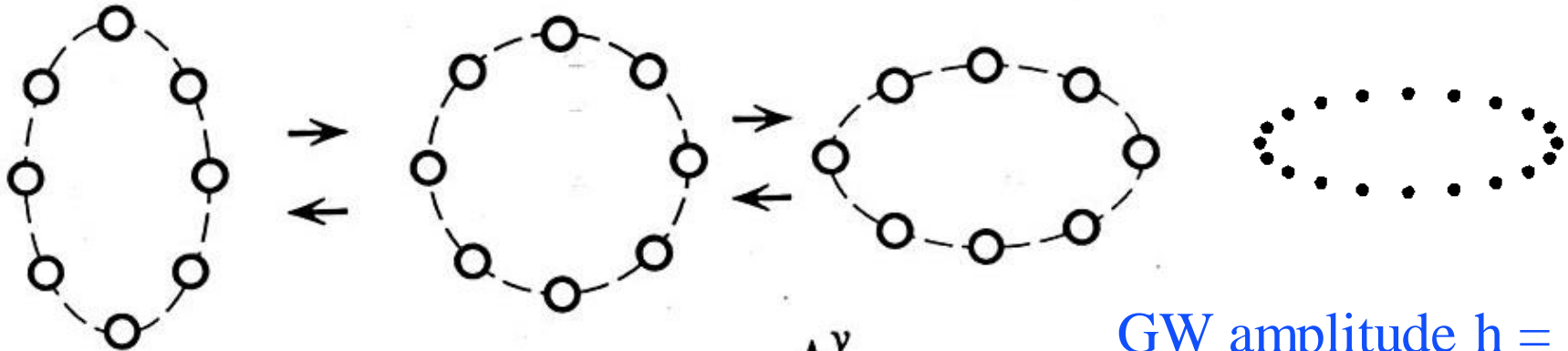


Credit: NASA

Detectors of Gravitational Waves

No Law of Physics Forbids Them

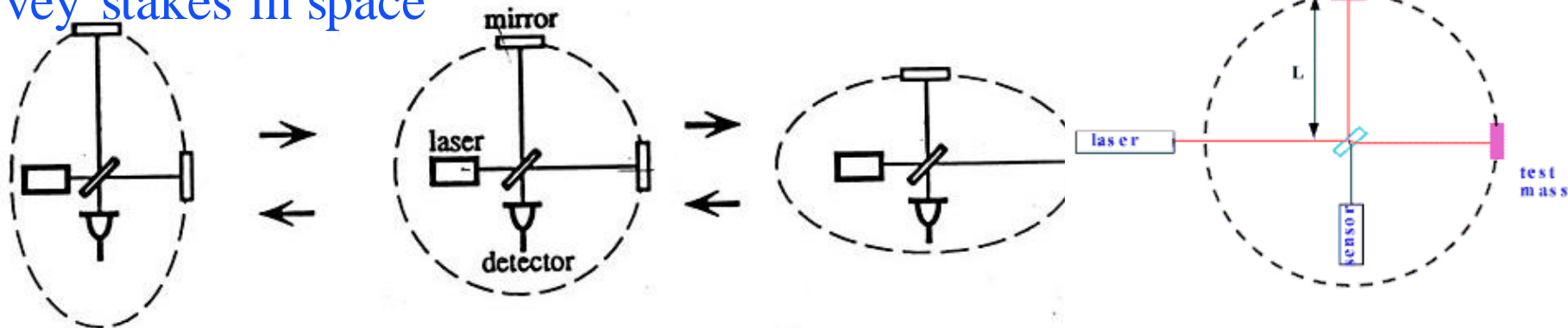
Basic idea is simple:
a GW causes a circle of space to go out of round



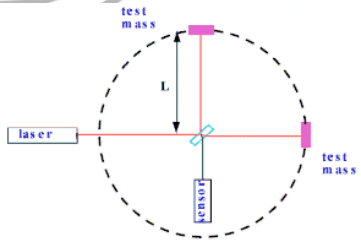
⊙ Gravitational Waves

GW amplitude h =
deformation/size

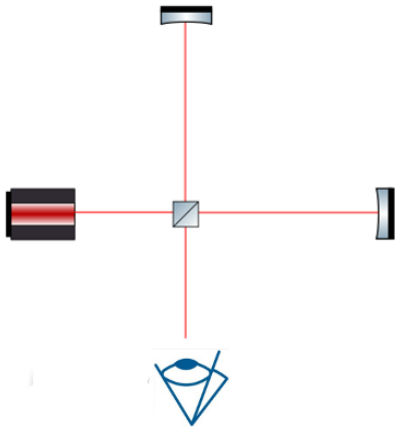
Isolated mirrors are
survey stakes in space



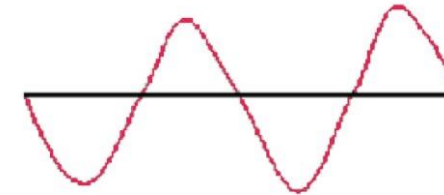
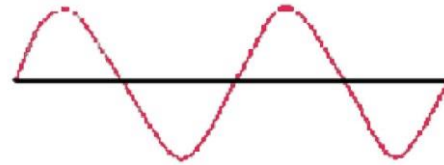
Light takes more (less) time to travel the longer (shorter) path



Equal arm length \rightarrow destructive interference



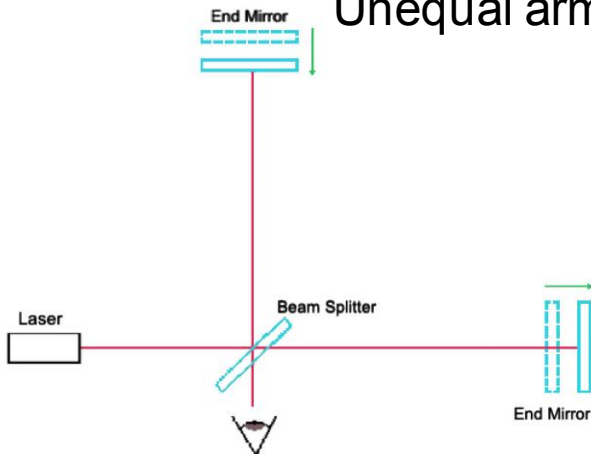
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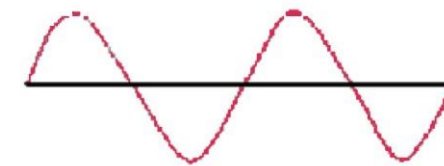
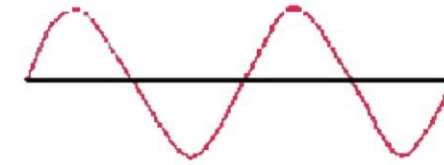
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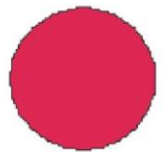
Unequal arm length \rightarrow constructive interference



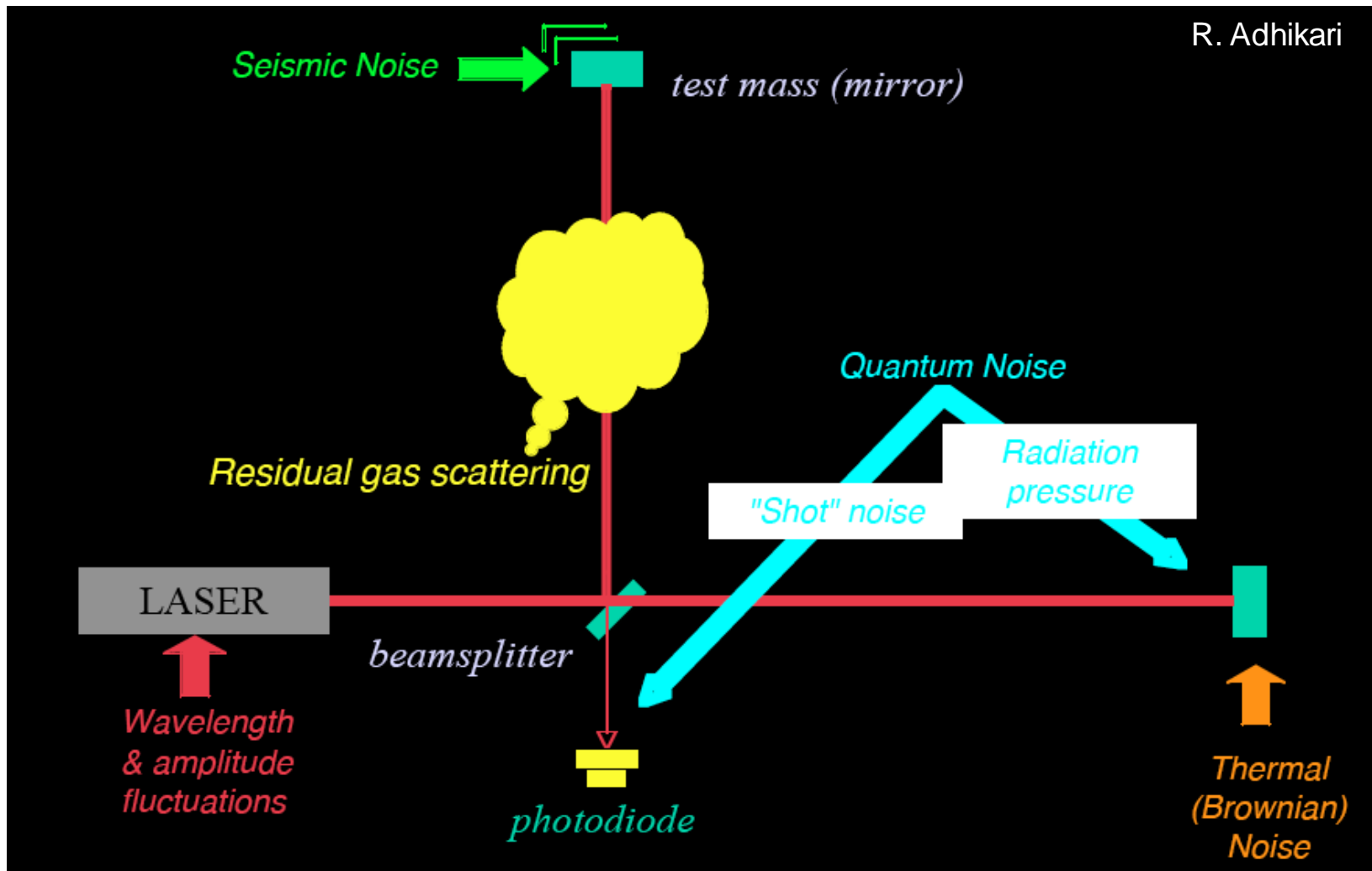
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Noise cartoon



History: the story of how problems
became opportunities

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.

LIGO The Laser Interferometer Gravitational-wave Observatory





LIGO The Laser Interferometer Gravitational-wave Observatory

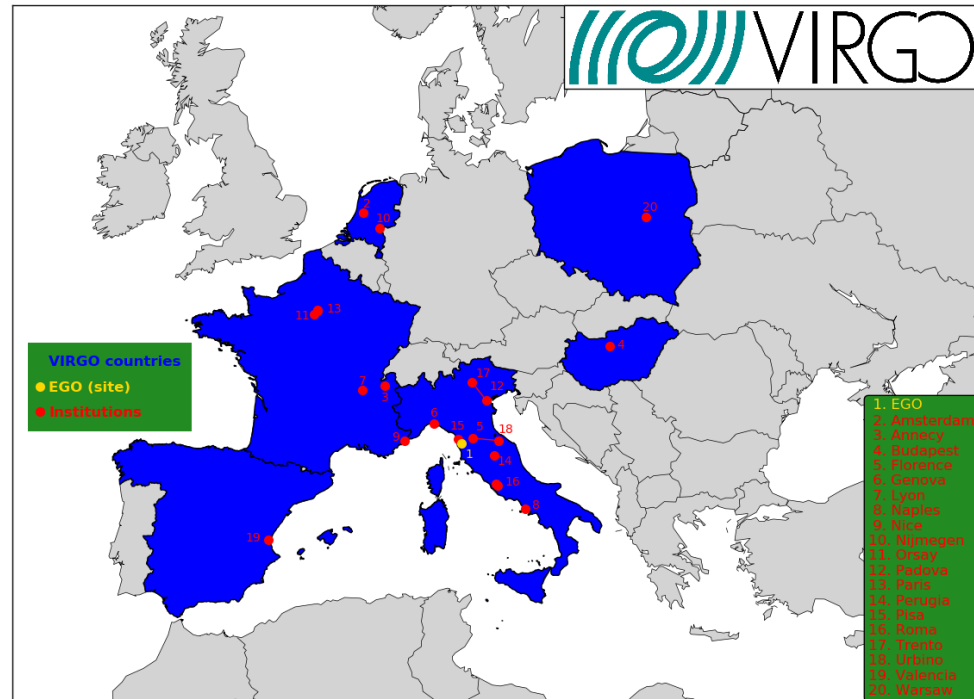
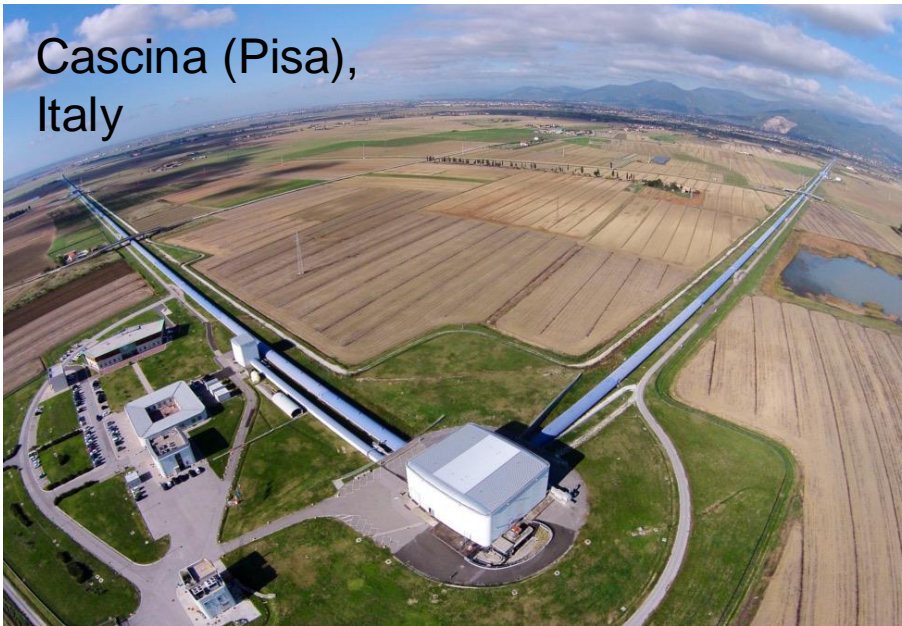


LSC Institutions



A collaboration made up of 20 laboratories in 6 european countries, involving more than 280 physicists and engineers

Cascina (Pisa), Italy





LIGO

VIRGO



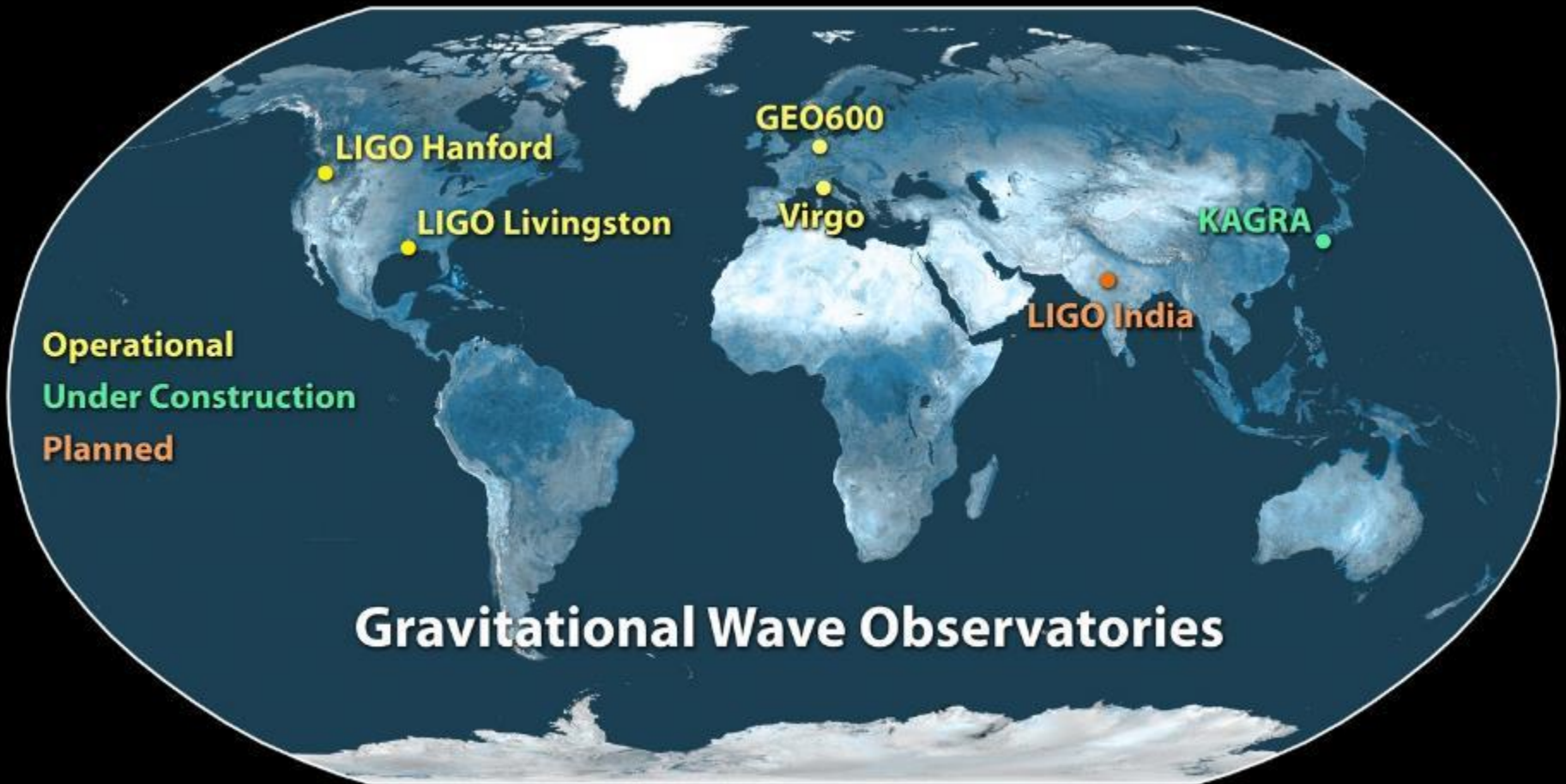
A collaboration made up of 20 laboratories in 6 countries involving the following institutions:



Cascina (Pisa), Italy



The advanced GW detector network: 2015-2025

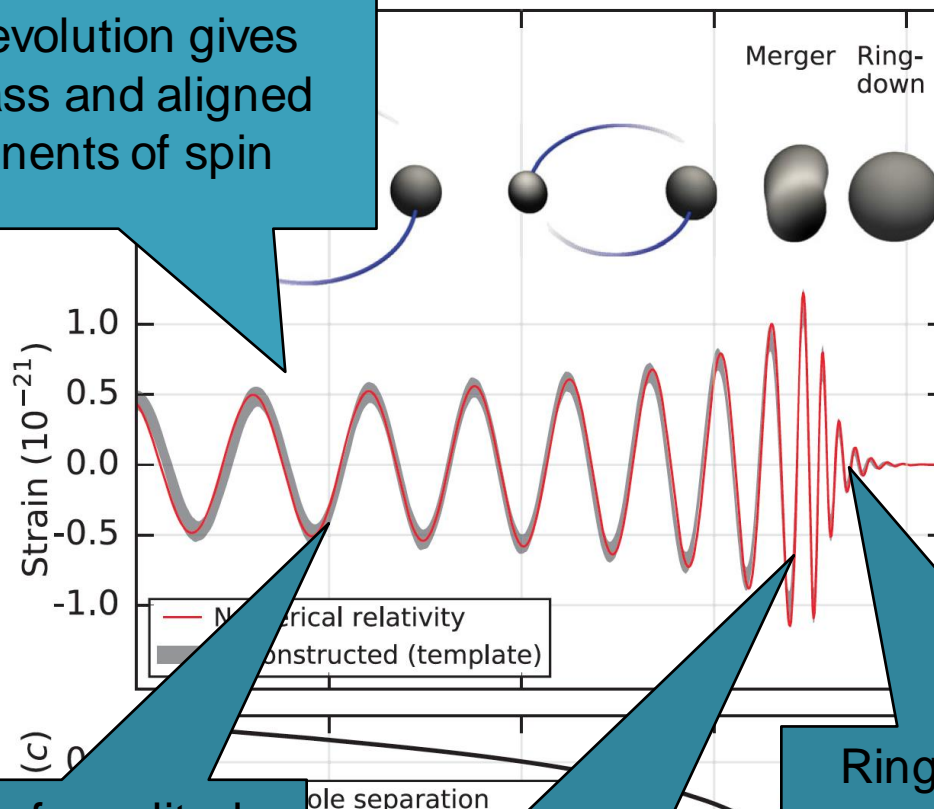


First Direct Detection of Gravitational Waves

Opening a New Window on the Universe

What can we learn from $h(t)$?

Phase evolution gives
chirp mass and aligned
components of spin



B. P. Abbott et al. (LIGO Scientific
Collaboration and Virgo
Collaboration), Phys. Rev. Lett.
116, 061102 (2016)

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

0.45

Multi-Messenger Astronomy

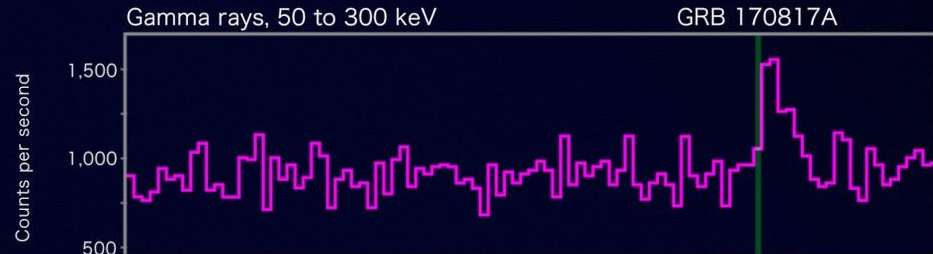
- These first observations of dynamic extreme spacetimes with BBHs show us that GR is reasonably accurate in this regime and can be used as a tool for examining and interpreting extreme states of matter.

Onto the study of the most extreme states of matter – GW170817

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

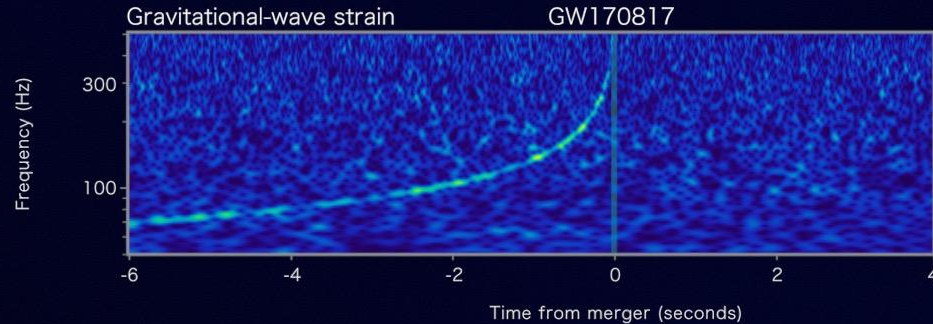
Fermi

Reported 16 seconds after detection



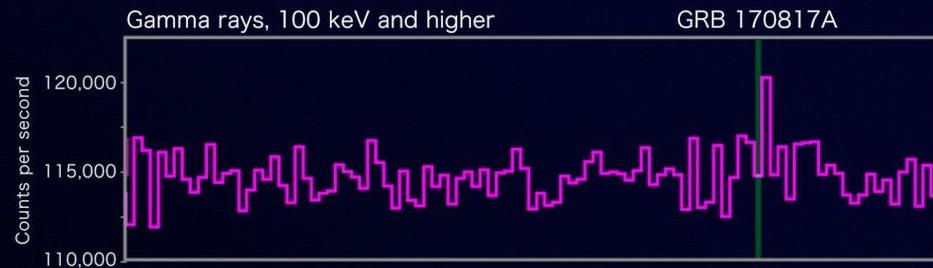
LIGO-Virgo

Reported 27 minutes after detection



INTEGRAL

Reported 66 minutes after detection



LIGO-Virgo network localization enables discovery of optical counterpart

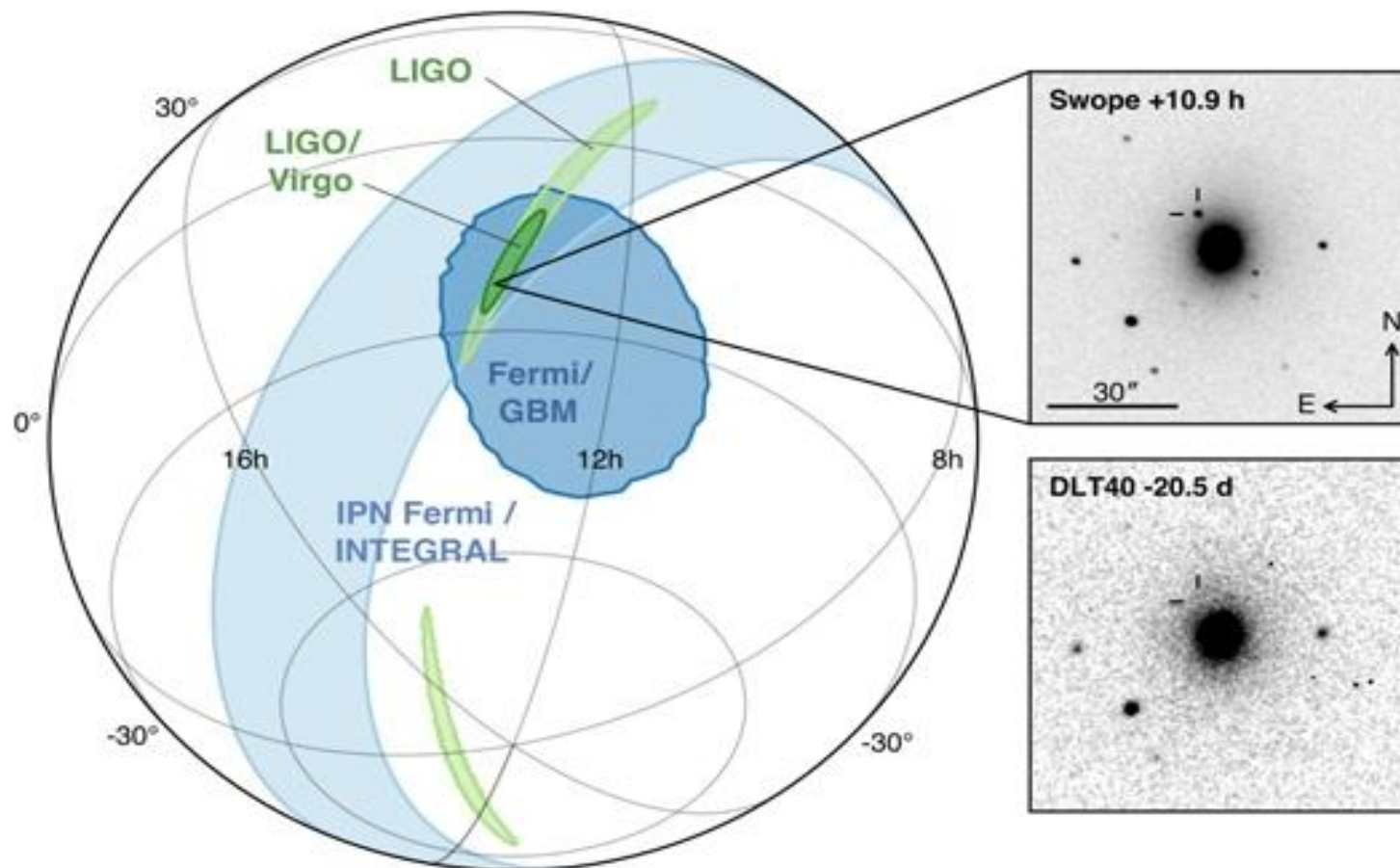


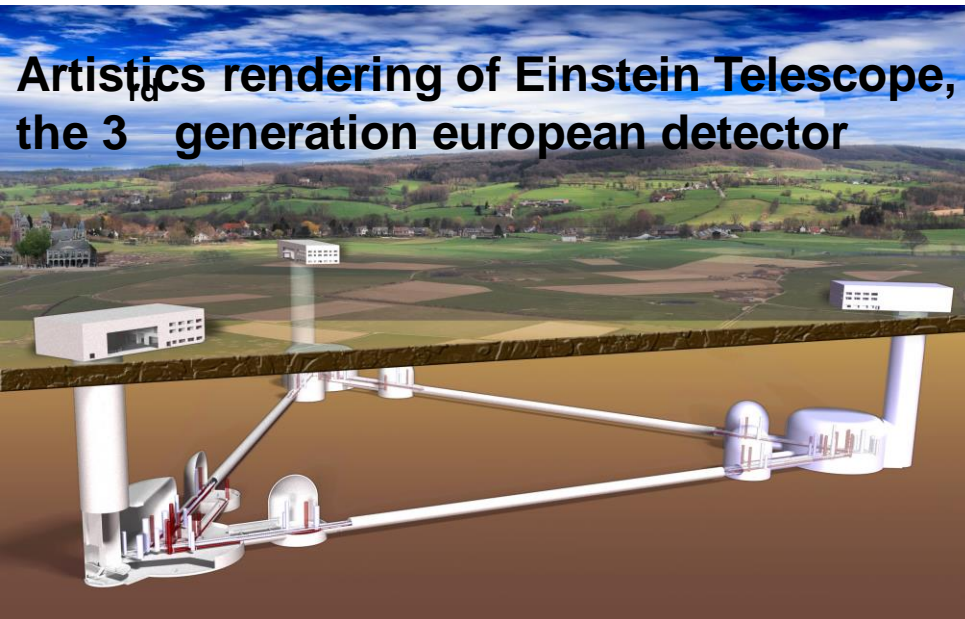
Figure 1 from Multi-messenger Observations of a Binary Neutron Star Merger
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

The Future

We now know that black hole binaries merge several times an hour somewhere in the universe; with new detectors and facilities, we should be able to see them out to the first generations of stars.

Concepts Under Study for Future Gravitational-Wave Observatories

Artistic rendering of Einstein Telescope, the 3rd generation european detector



Cosmic Explorer

a next generation gravitational wave detector
capable of observing compact binary sources with high signal-to-noise ratio throughout the Universe.

Personal reflections in summary

- There were dozens of reasons not to pursue this, but a single compelling reason to do it: it was good for science.
- It was obvious from the start that building the facilities and generations of detectors to make the first detections was a decades-long project.
- It took villages across the world to accomplish this and it will take even more villages, with even more diverse participation to pursue the promise of the future.
- Scientists do not own these facilities; the people taxed to build them and their children own them. We must do our utmost to share our discoveries with them in meaningful ways.
- No good deed goes unpunished! The collaborations, which were optimized for making the first direct detections with high confidence, now must evolve rapidly toward optimizing the throughput of new results to the larger scientific communities in astrophysics, cosmology, nuclear physics, astro-particle physics.