# Gravitational-Wave Astronomy - a Long Time Coming

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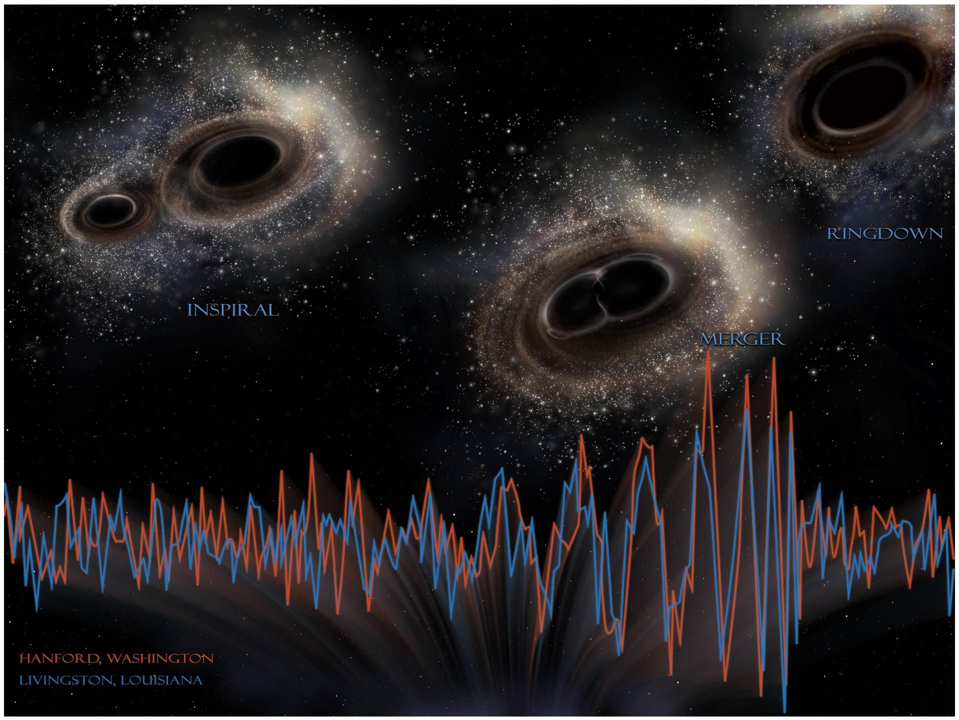
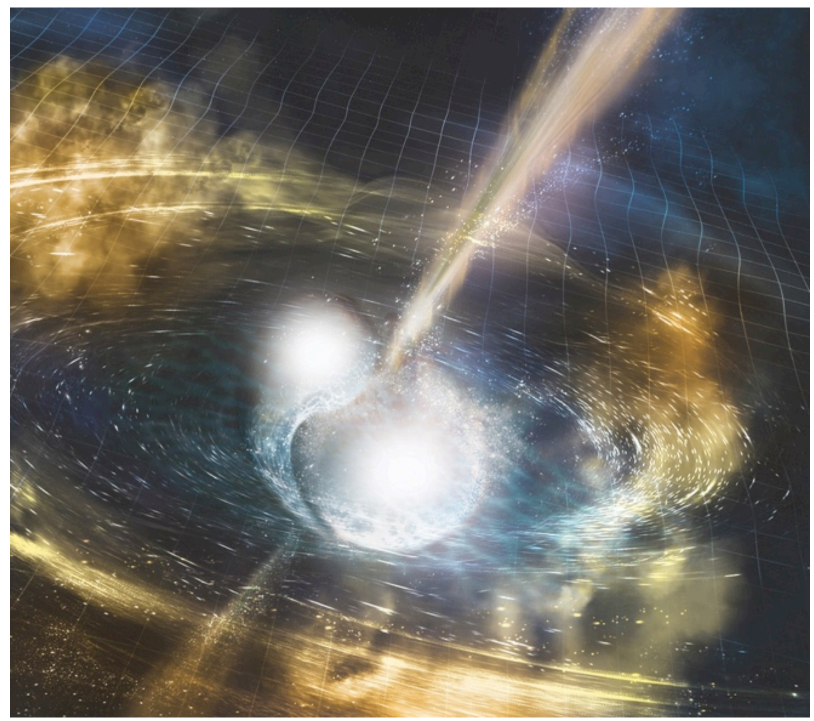
# What are we talking about?




Gravitational waves from merging black holes



Gravitational waves and electromagnetic waves from merging neutron stars

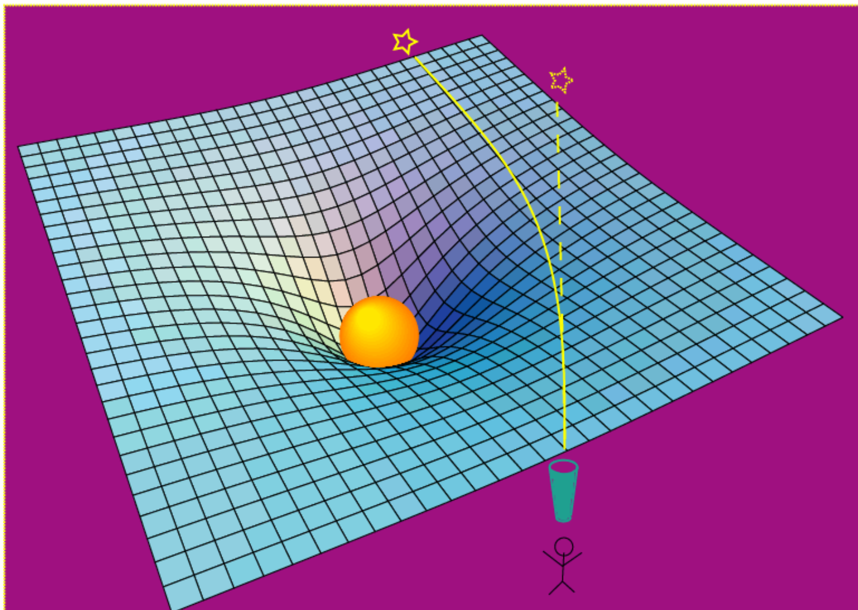
Credits: NSF/LIGO/Sonoma State University/A. Simonnet

# 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".

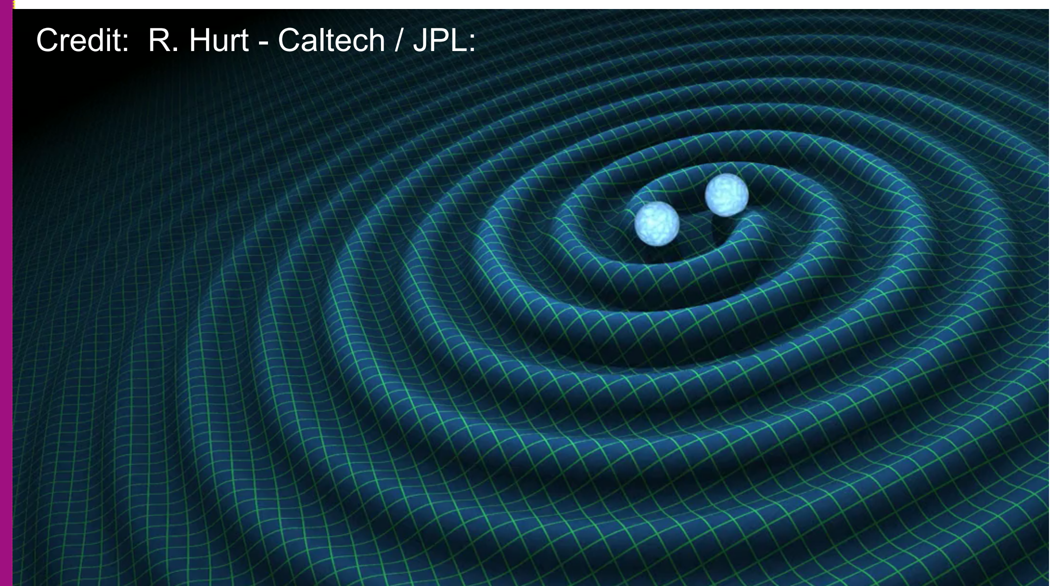
# Einstein's General Relativity: gravity is a manifestation of space-time curvature

curved spacetime can bend light, too!



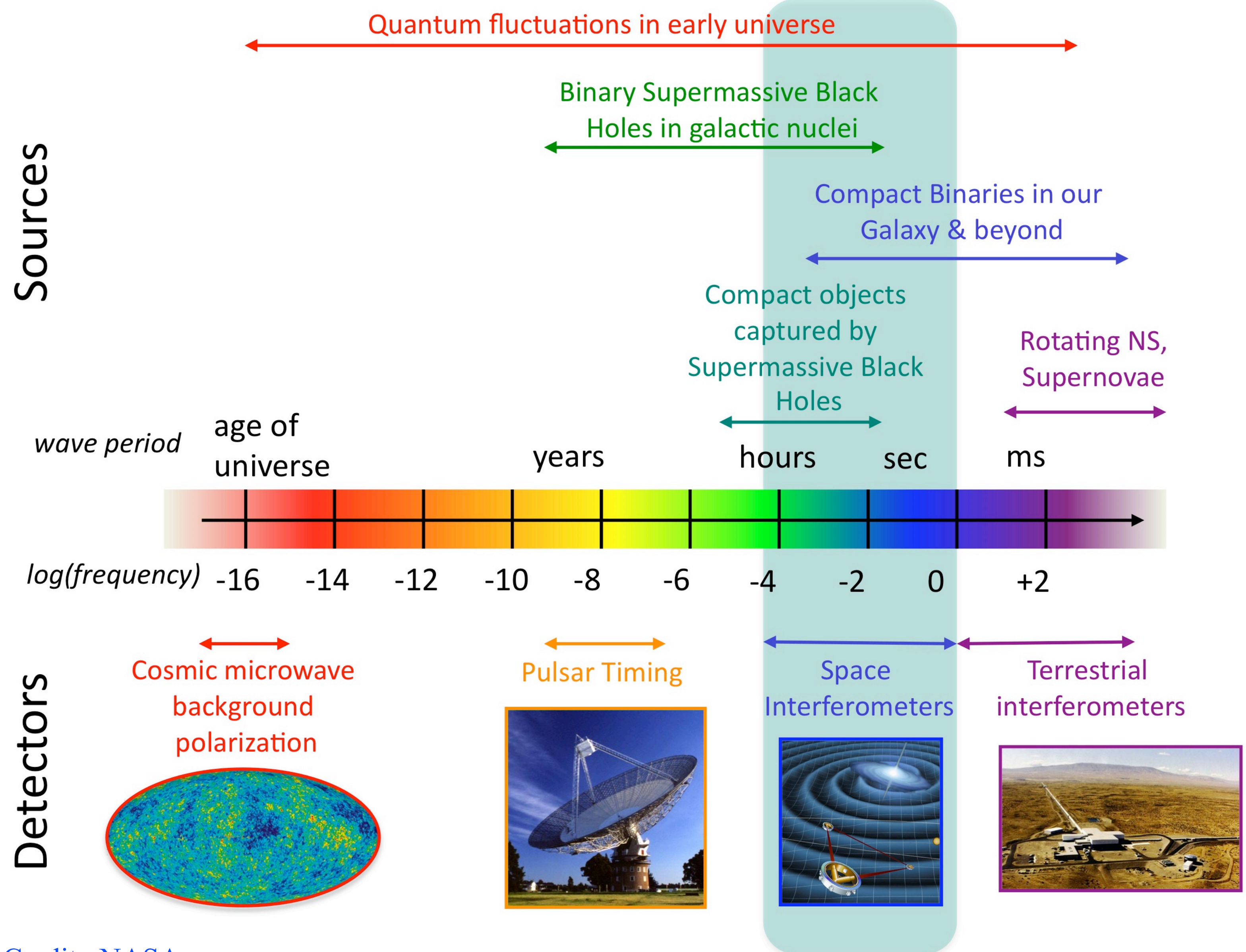
A massive object shifts apparent position of a star

dynamic deformation of spacetime




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

# The Gravitational Wave Spectrum

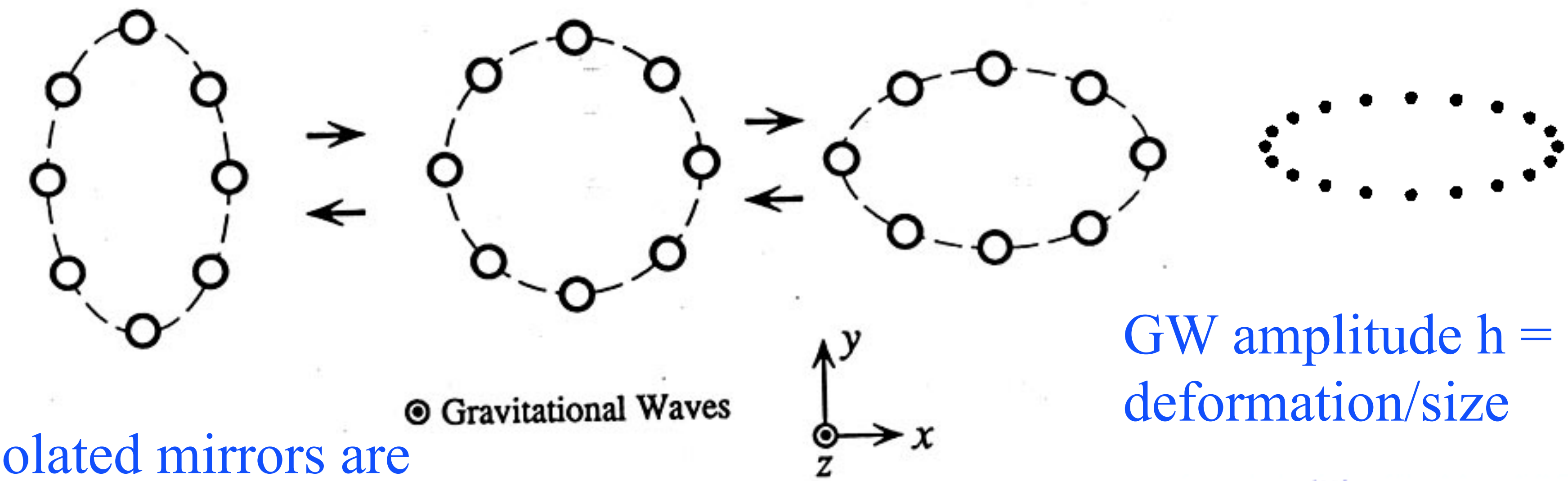



Credit: NASA

# Detectors of Gravitational Waves

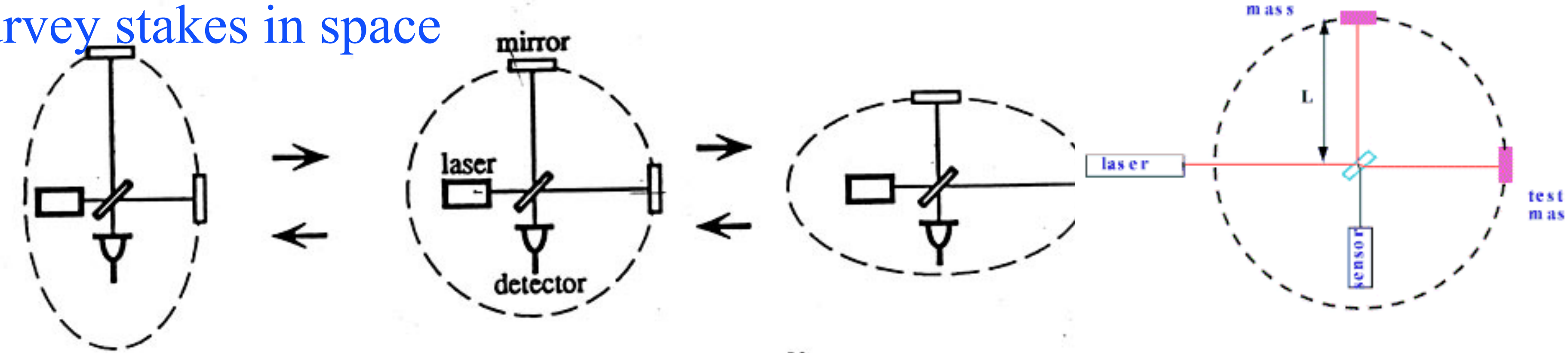
No Law of Physics Forbids Them

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



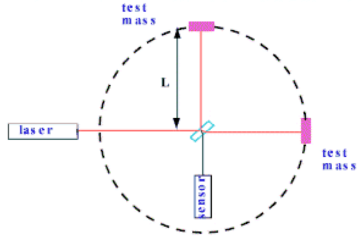

GW amplitude h = deformation/size

Isolated mirrors are survey stakes in space

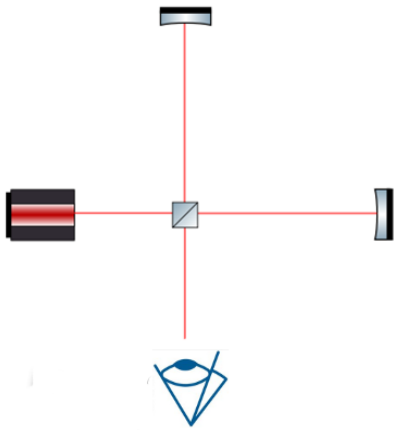


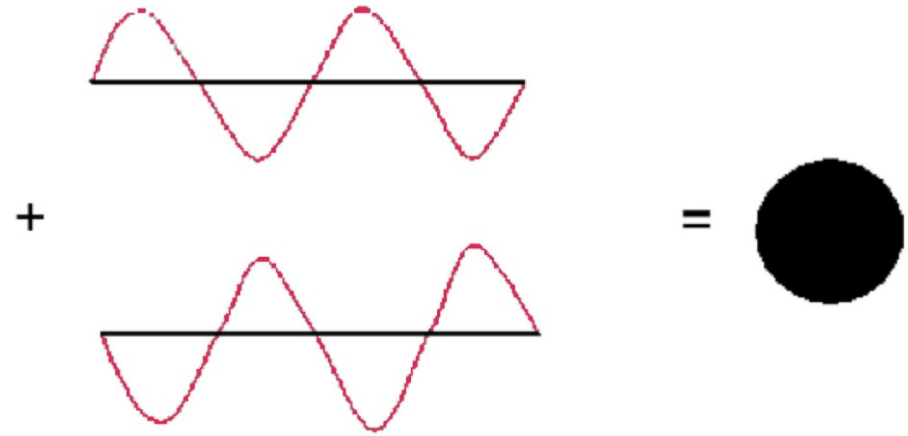

Light takes more (less) time to travel the longer (shorter) path

# Interferometer as GW detector

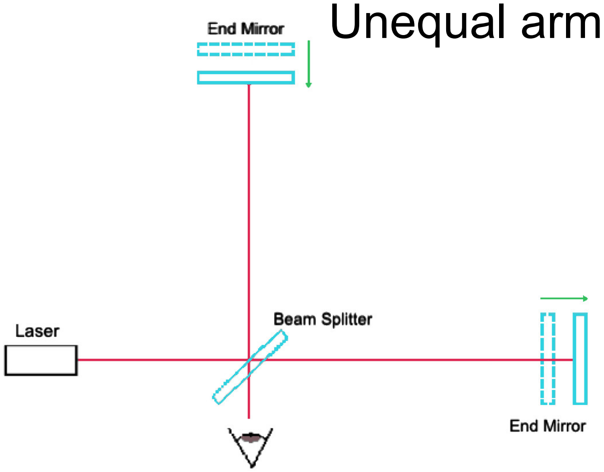


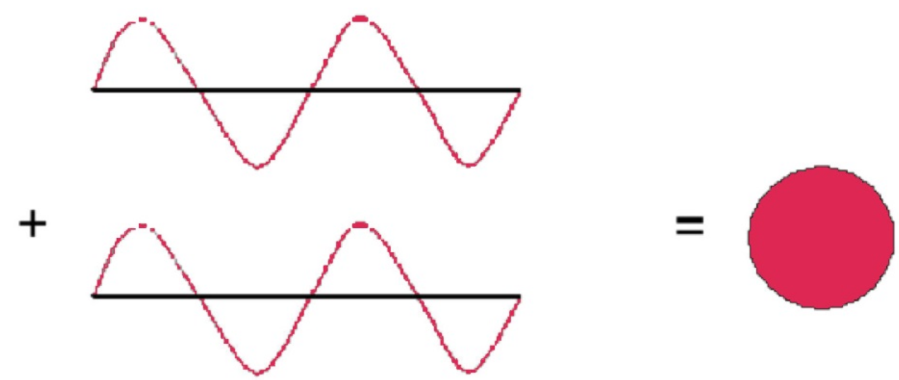

## Equal arm length → destructive interference



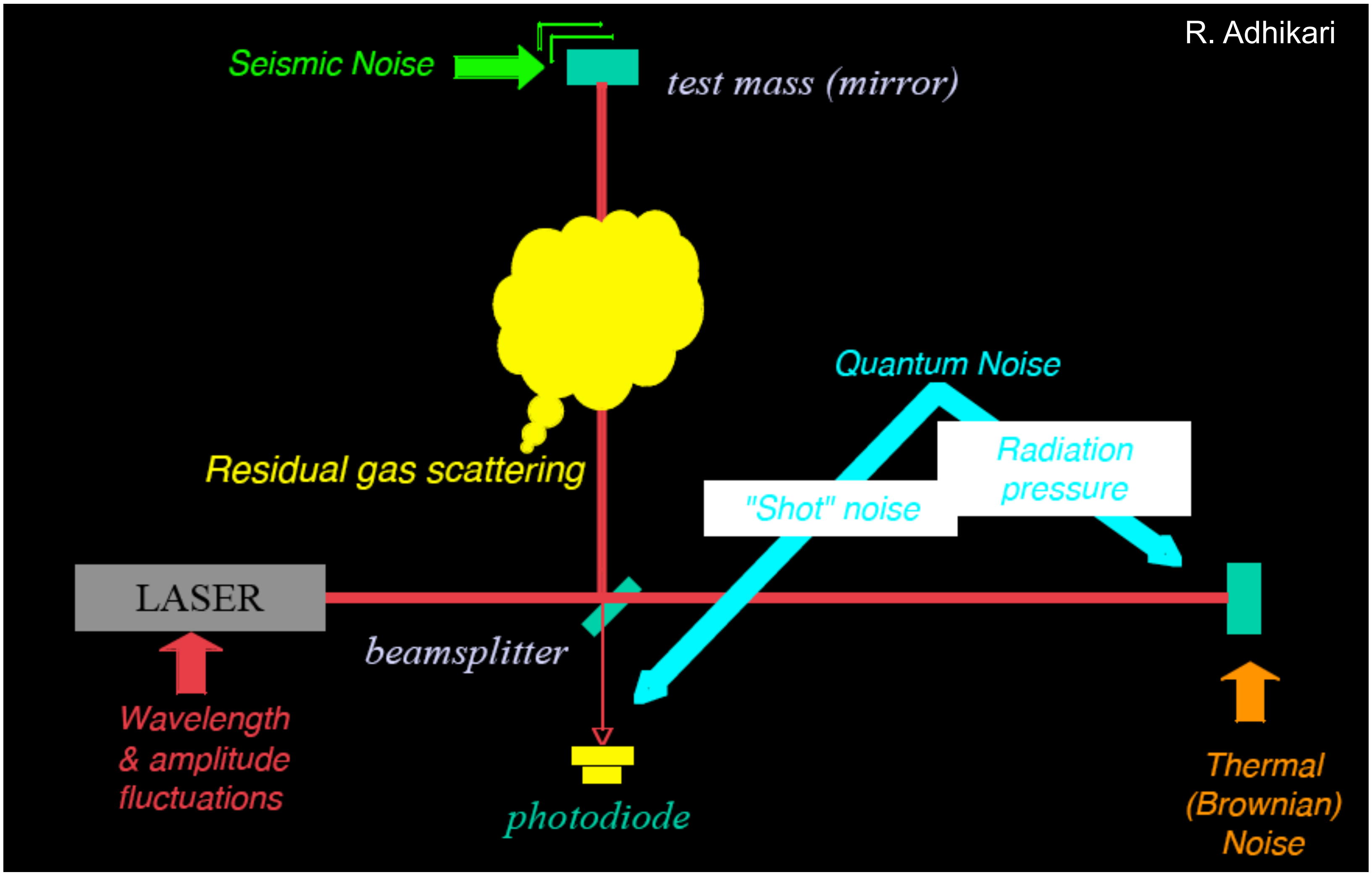



## Unequal arm length → constructive interference



# 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.

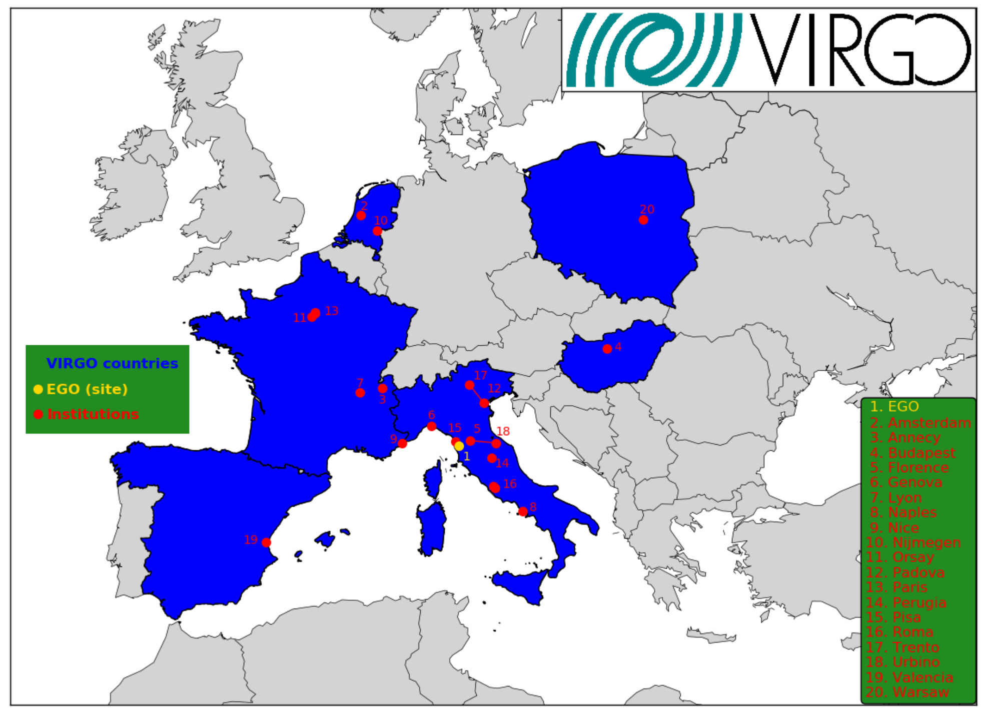
LSC and Virgo Collaboration established an MOU for joint operations in 2007.

# The Laser Interferometer Gravitational-wave Observatory


# The Laser Interferometer Gravitational-wave Observatory

# VIRGO

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

LIGO

# VIRGO

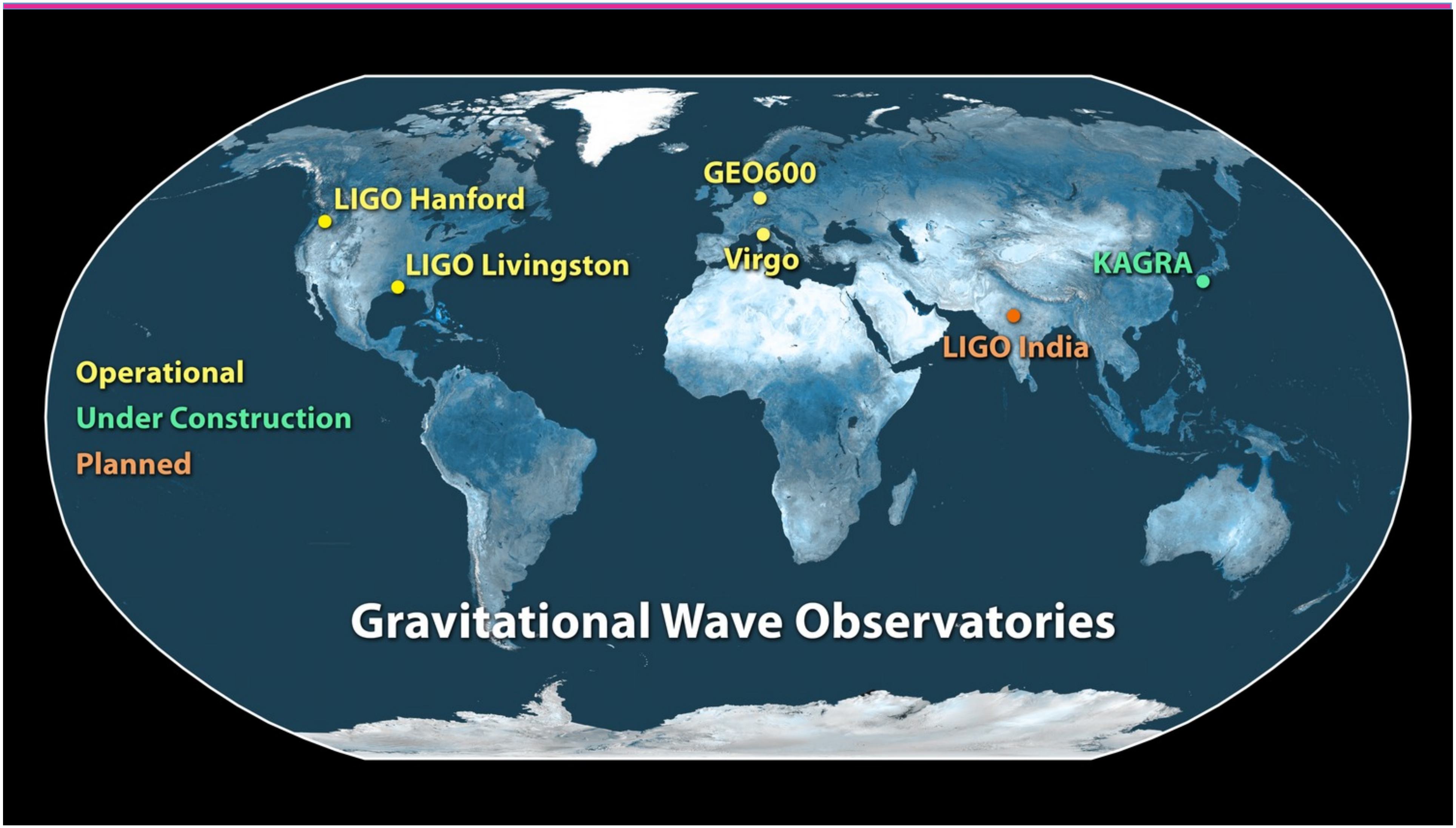
Advanced Virgo

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

cnrs INFN Nikhef EGO EUROPEAN GRAVITATIONAL OBSERVATORY wigner INSTITUTE OF MATHEMATICS VNIVERSITAT D VALÈNCIA


Cascina (Pisa), Italy

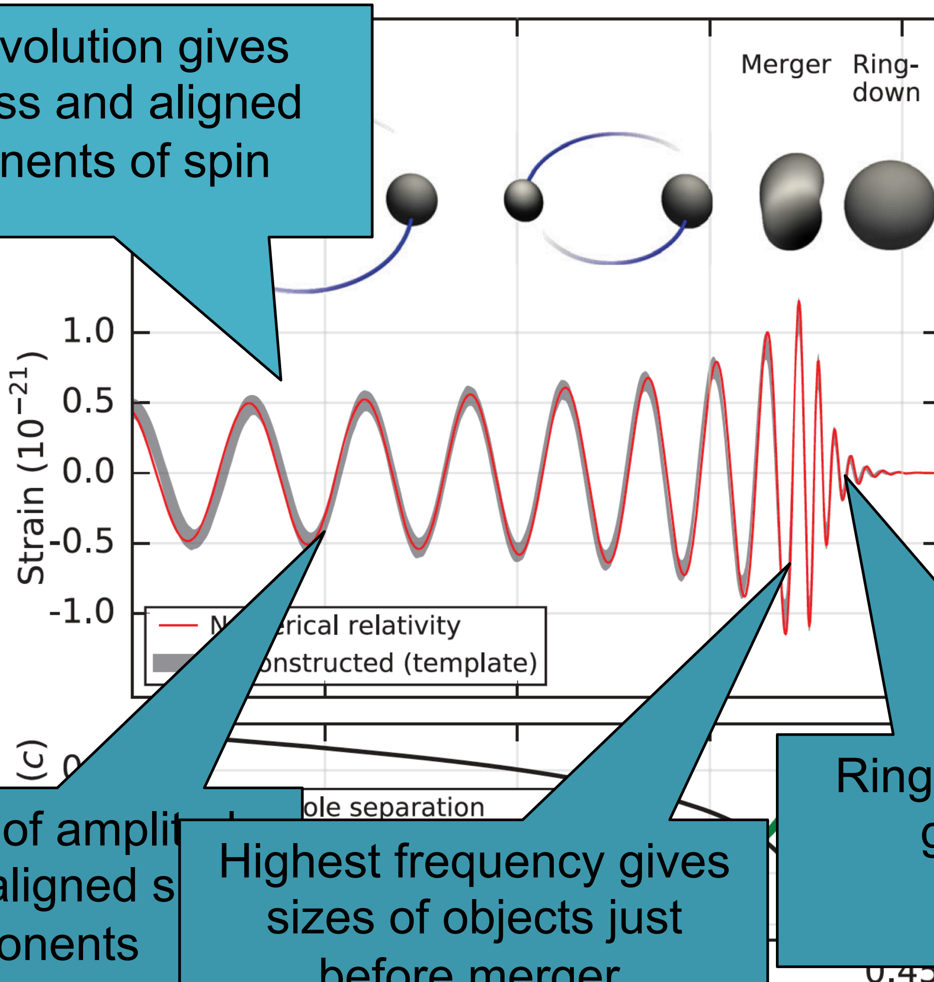
# *The advanced GW detector network: 2015-2025*



# 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

Modulation of amplit… gives nonaligned s… components

Highest frequency gives sizes of objects just before merger.

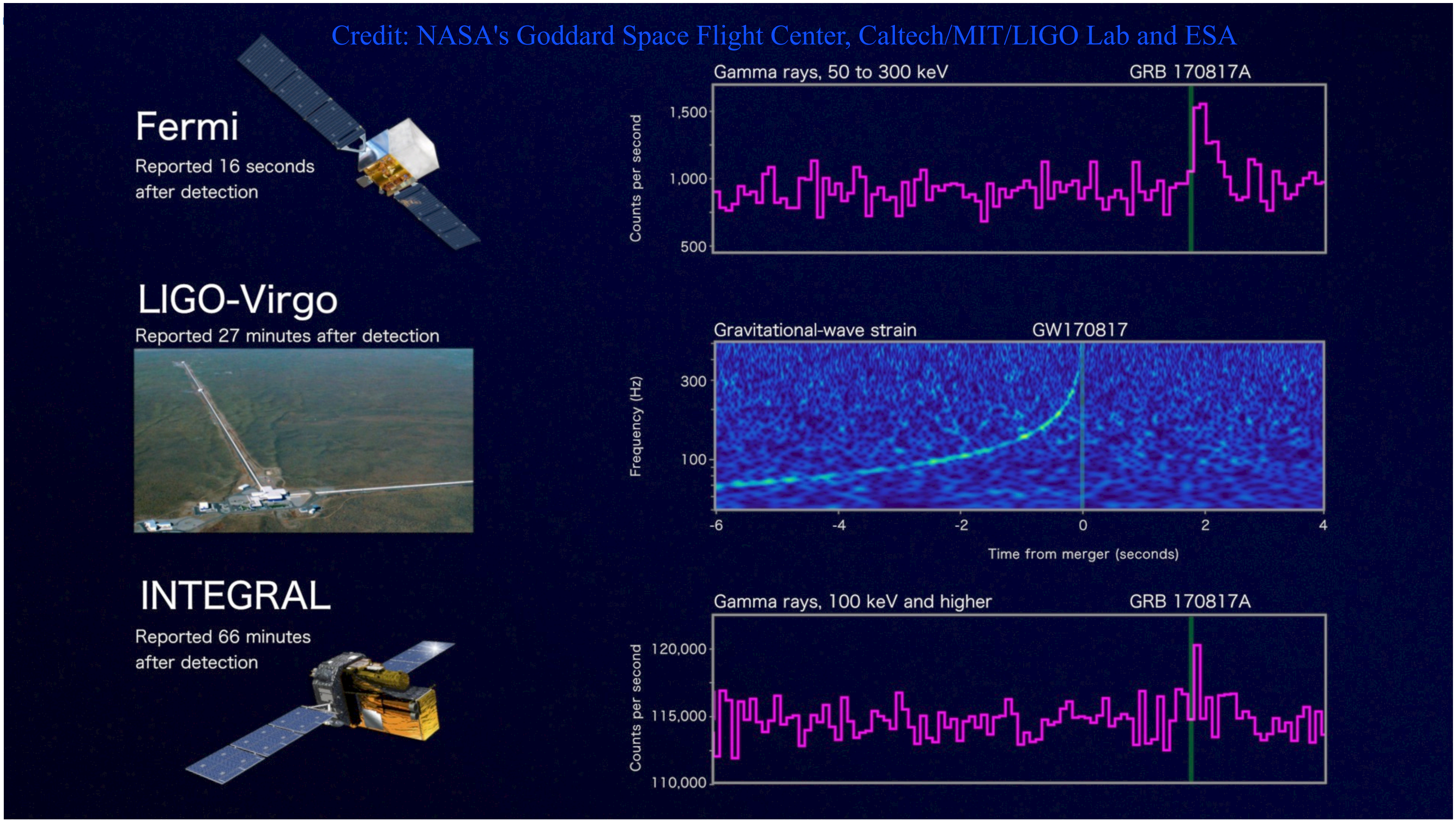
Ringdown frequency and *Q* give mass and spin of final black hole

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

# 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



# LIGO-Virgo network localization enables discovery of optical counterpart

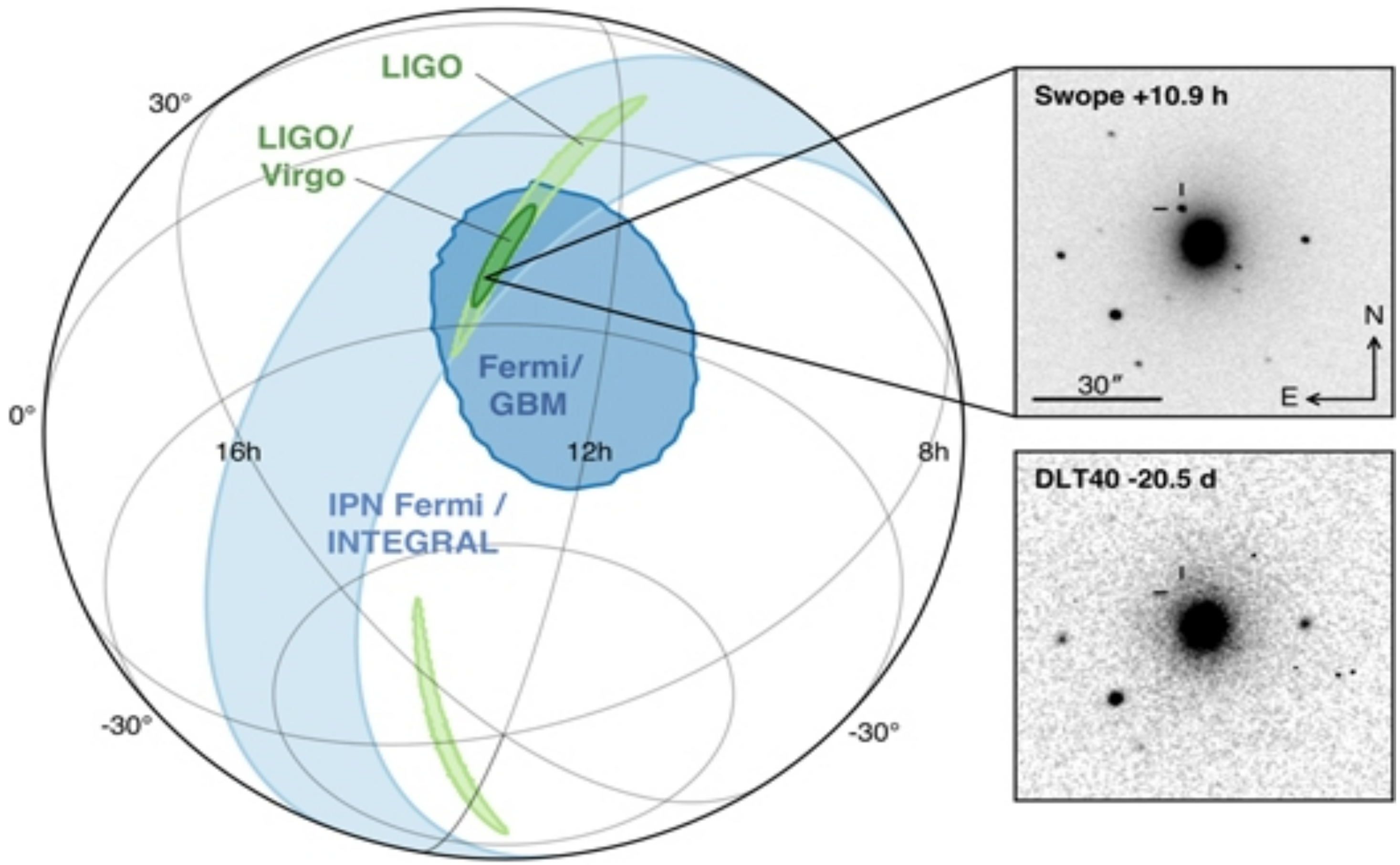
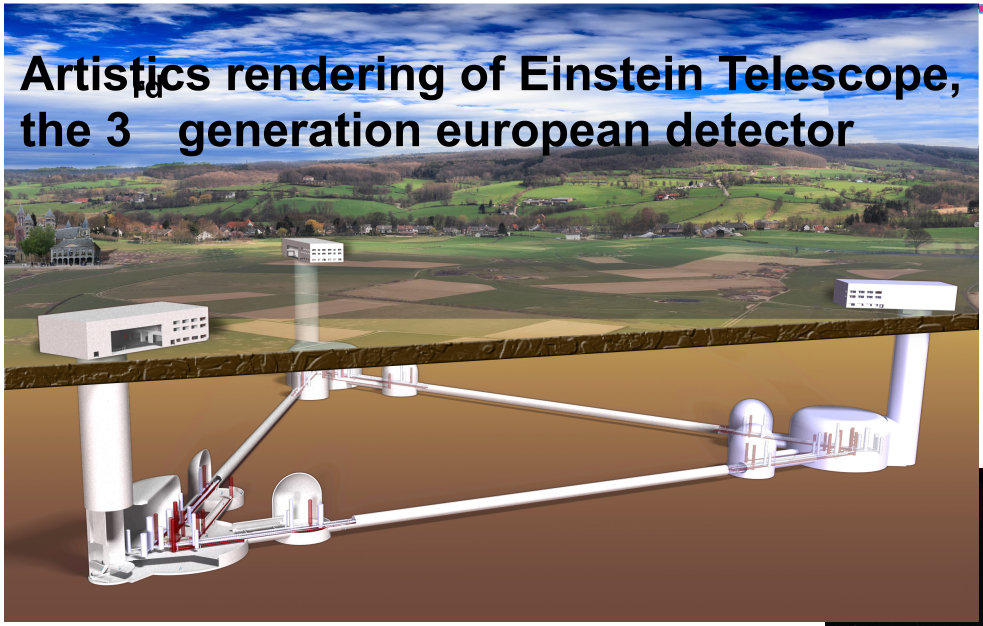


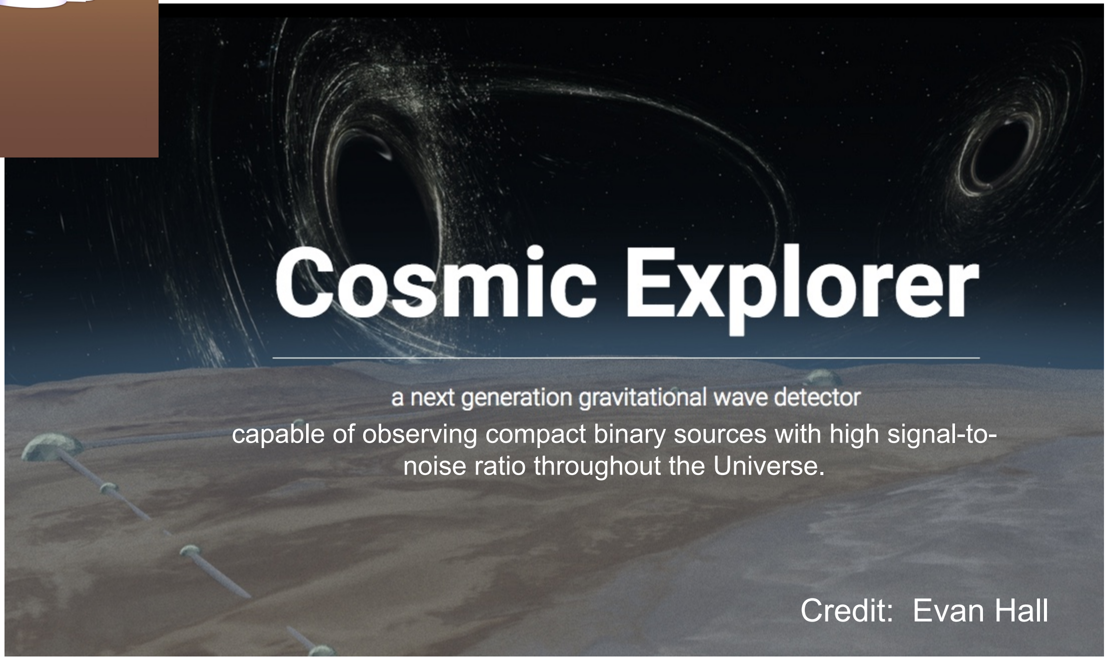

Figure 1 from Multi-messenger Observations of a Binary Neutron Star Merger
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

# 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



# 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.

# Personal reflections, continued

- Before detection
  - one needs to be deeply convinced that the effort is worth and that the final science goal can be reached, even if seems still far
  - impossible to have publication rates comparable to those of collegues in high energy physics who we are often compared to
  - little space for R&D on new ideas
- After detection
  - increased interest in the public: almost anyone now involved in outreach activities
  - increased interest among colleagues: opening of new positions and collaborations
  - more freedom to work on the next step: to ‘listen’ better and farther the Universe we need to overcome the limits of the existing infrastructures