Gravitational waves

Sylvia J. Zhu

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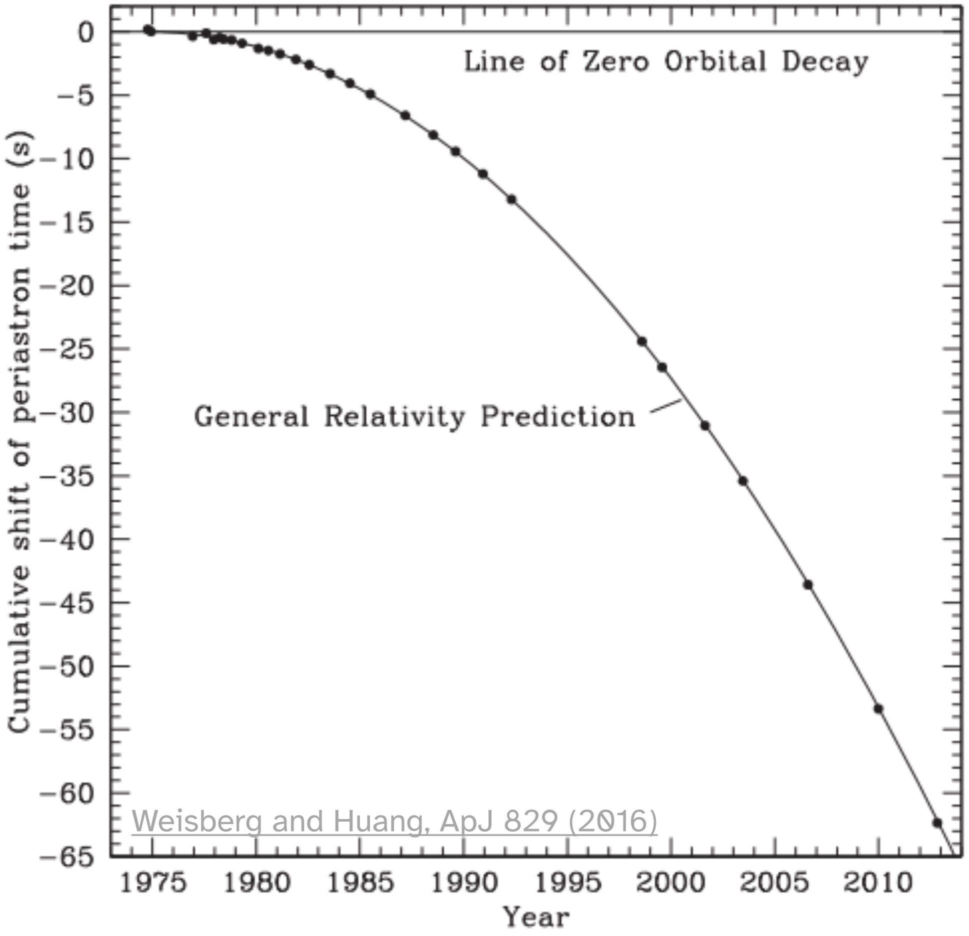
astroparticle division (H.E.S.S.)

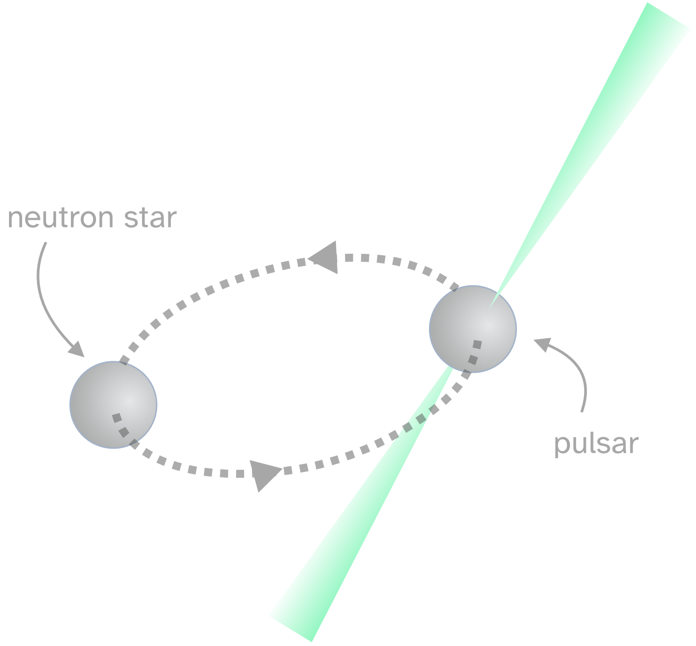
Friction is a result of electromagnetism

Something similar happens with gravity

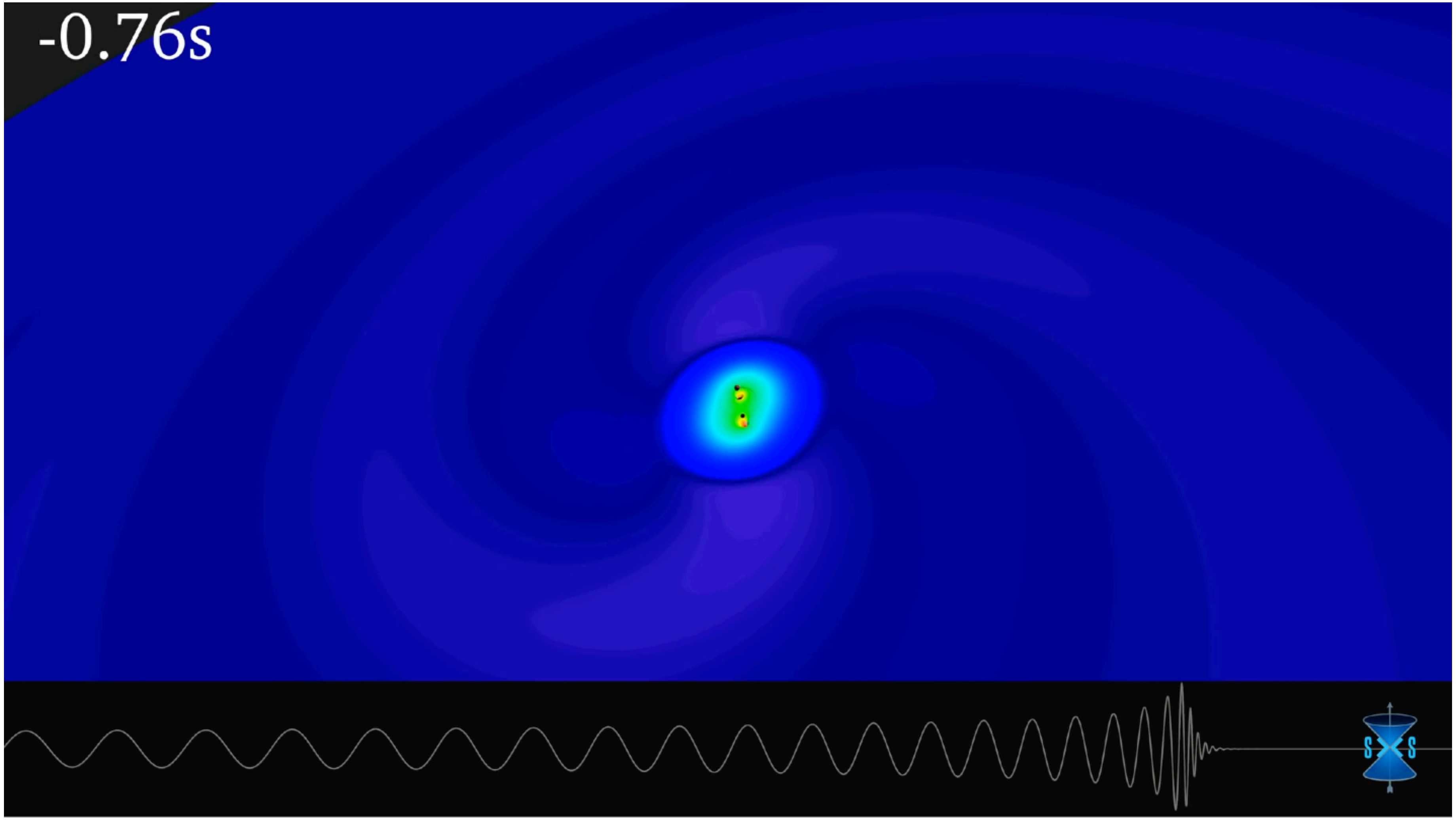


Weisberg and Huang, ApJ 829 (2016)

Hulse-Taylor binary

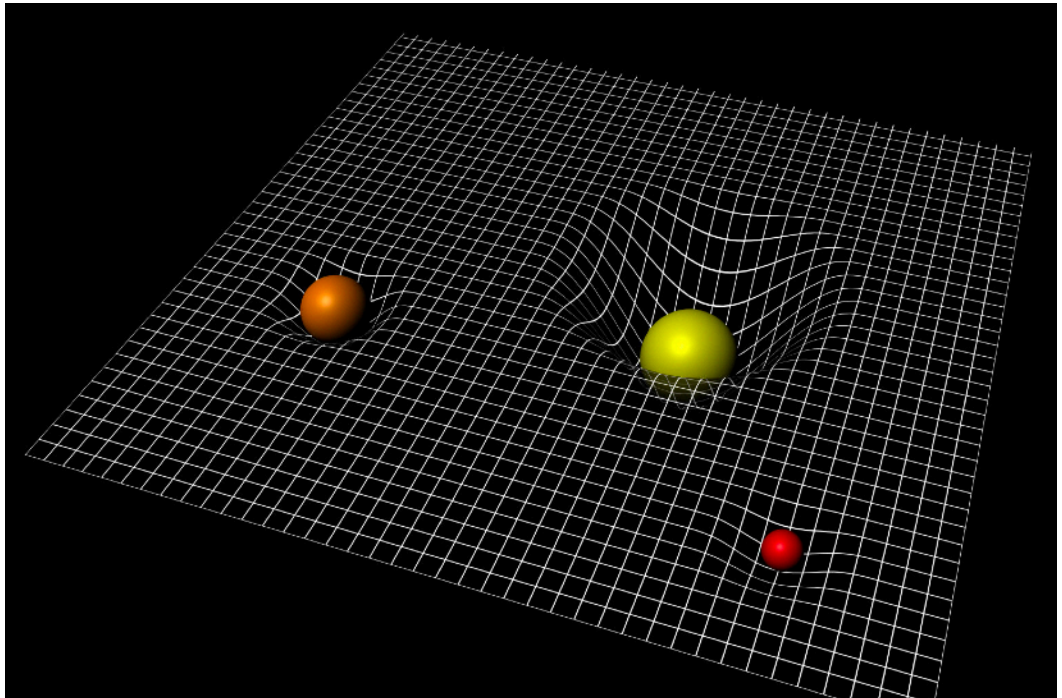


Gravitational waves from binary mergers



Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)
Video and explanation: https://www.ligo.caltech.edu/video/ligo20160211v10

VERY short general relativity overview


ESA - C. Carreau

Einstein's field equations:

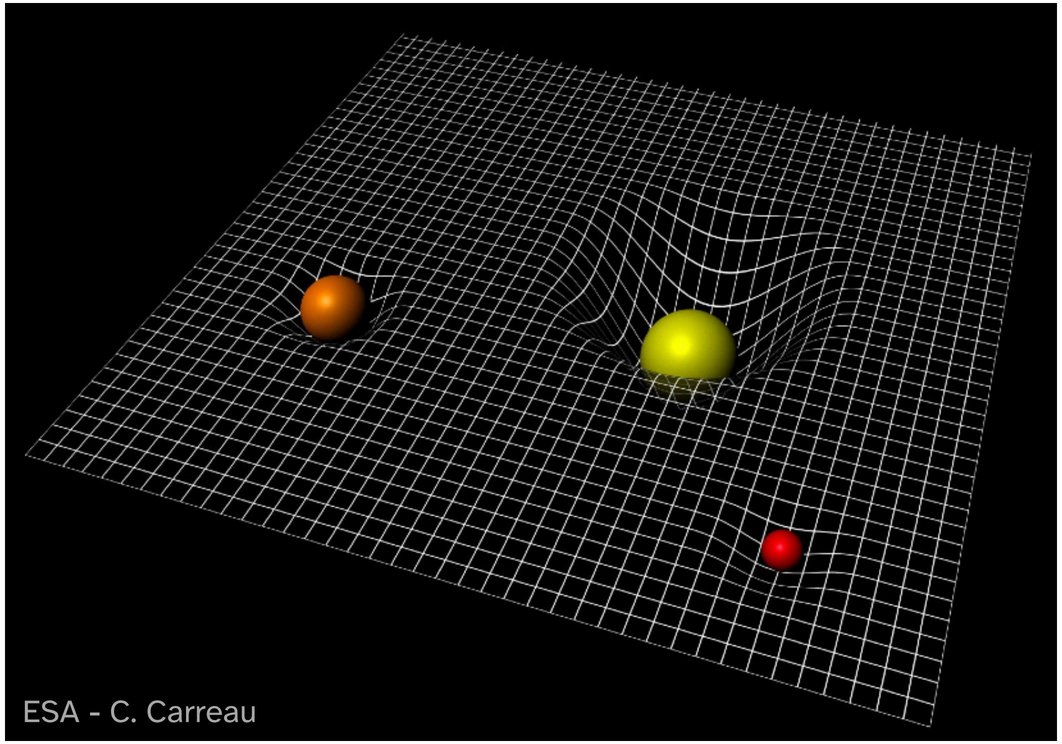
stress-energy tensor
(what energy/momentum is doing)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein tensor
(how spacetime is curved)

"Spacetime tells matter how to move;
matter tells spacetime how to curve."
- J. A. Wheeler

VERY short general relativity overview



Assuming perturbations to spacetime are small
(and then doing a bunch of math …)
we get **gravitational waves**
when we have a **changing mass quadrupole**

$$h \propto \frac{\mathcal{M}^{5/3}}{d} f_{\mathrm{rot}}^{2/3}$$

~ mass

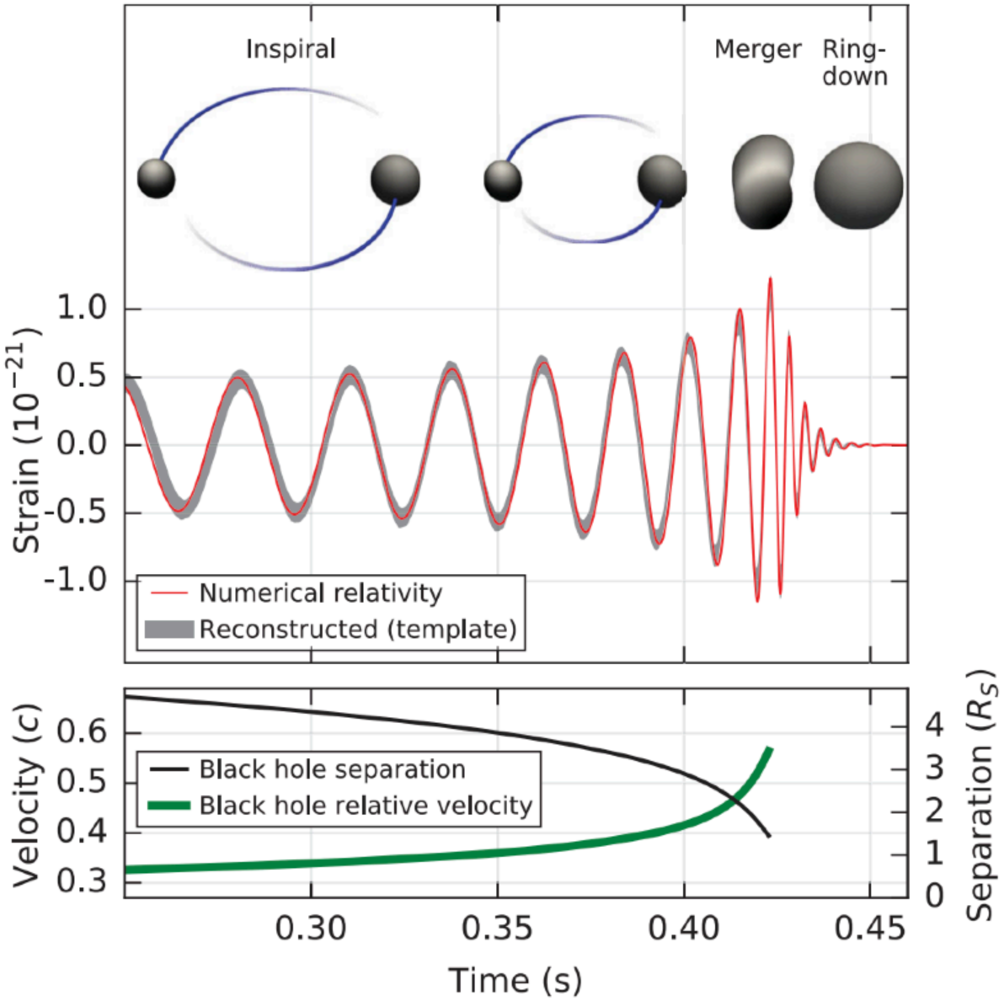
gravitational-wave strain (fractional change in length of spacetime)

distance

rotational requency

VERY short general relativity overview

B. P. Abbott et al., PRL 116, 061102 (2016)



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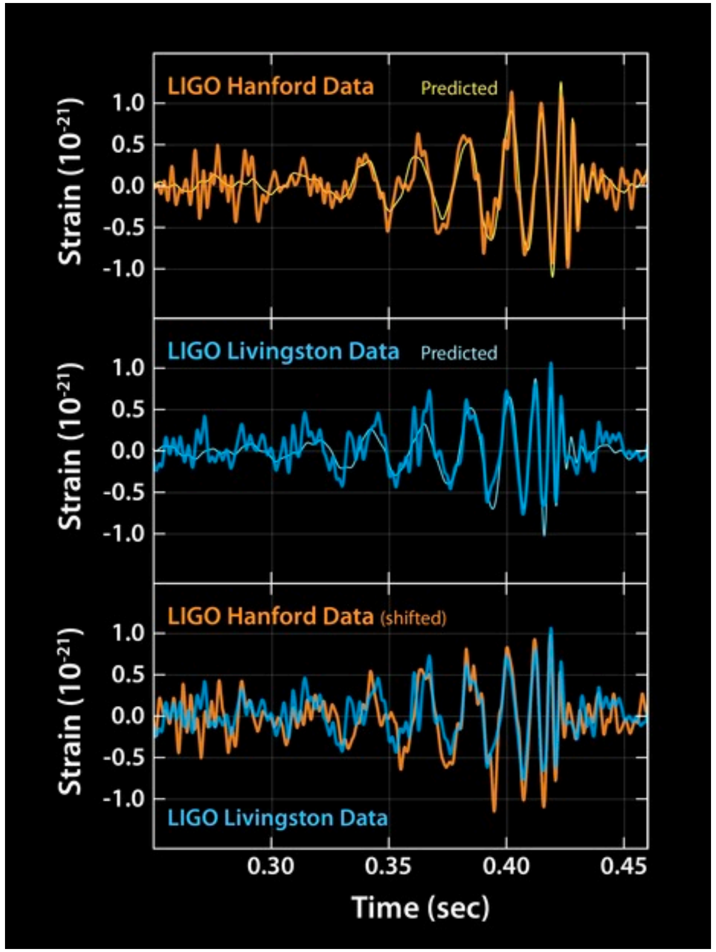
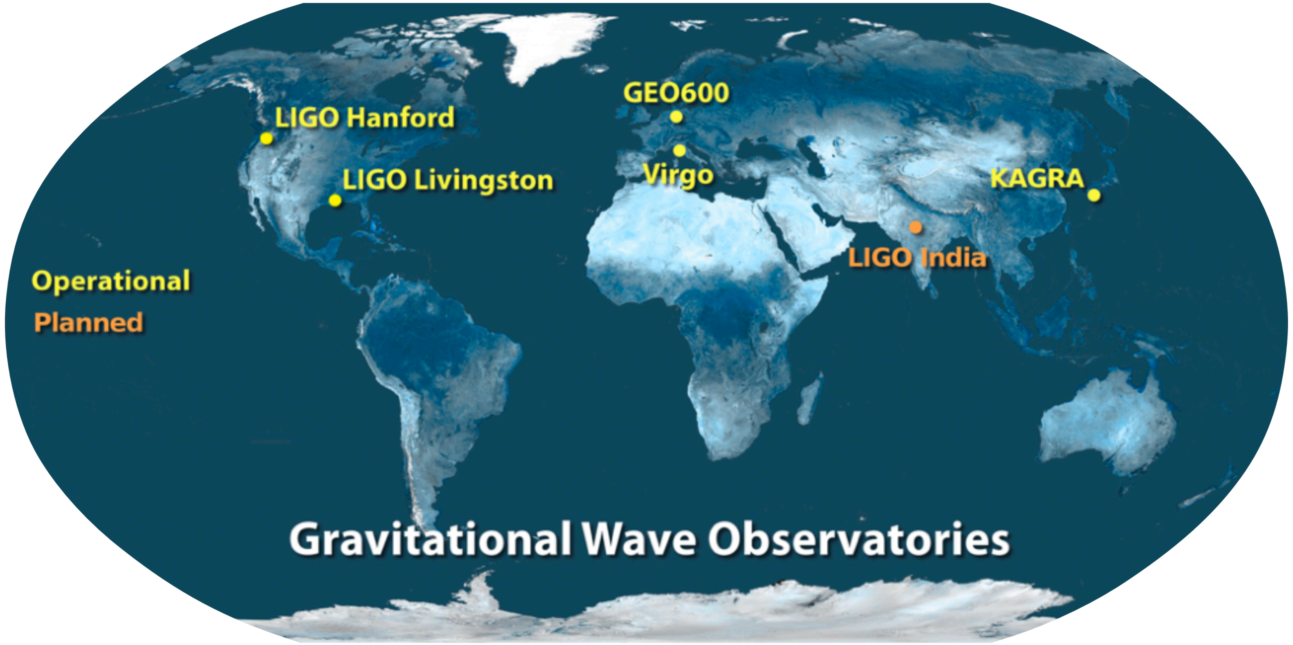
The first detection of gravitational waves in 2015

Caltech/MIT/LIGO Lab



signal plus detector noise

Caltech/MIT/LIGO Lab

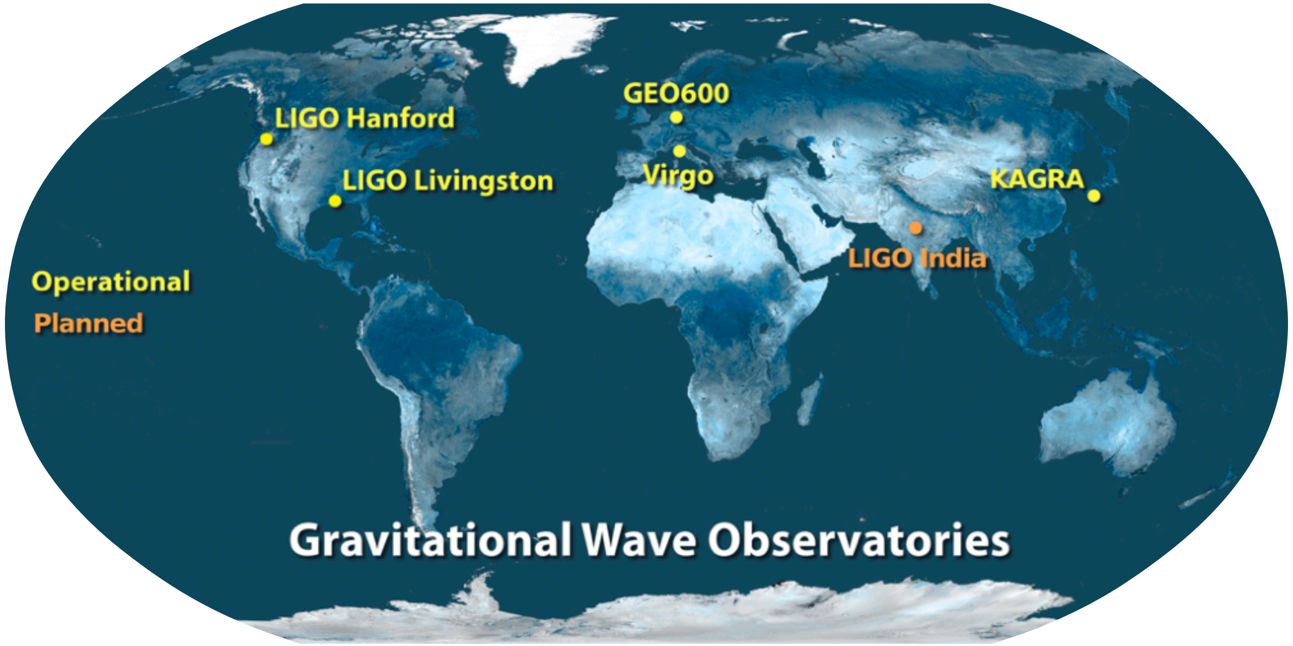


GW observatories, current and planned

The first detection of gravitational waves in 2015

GEO600 is in Germany and anyone can visit!
See https://www.geo600.org/23408/visiting-geo600 for more info

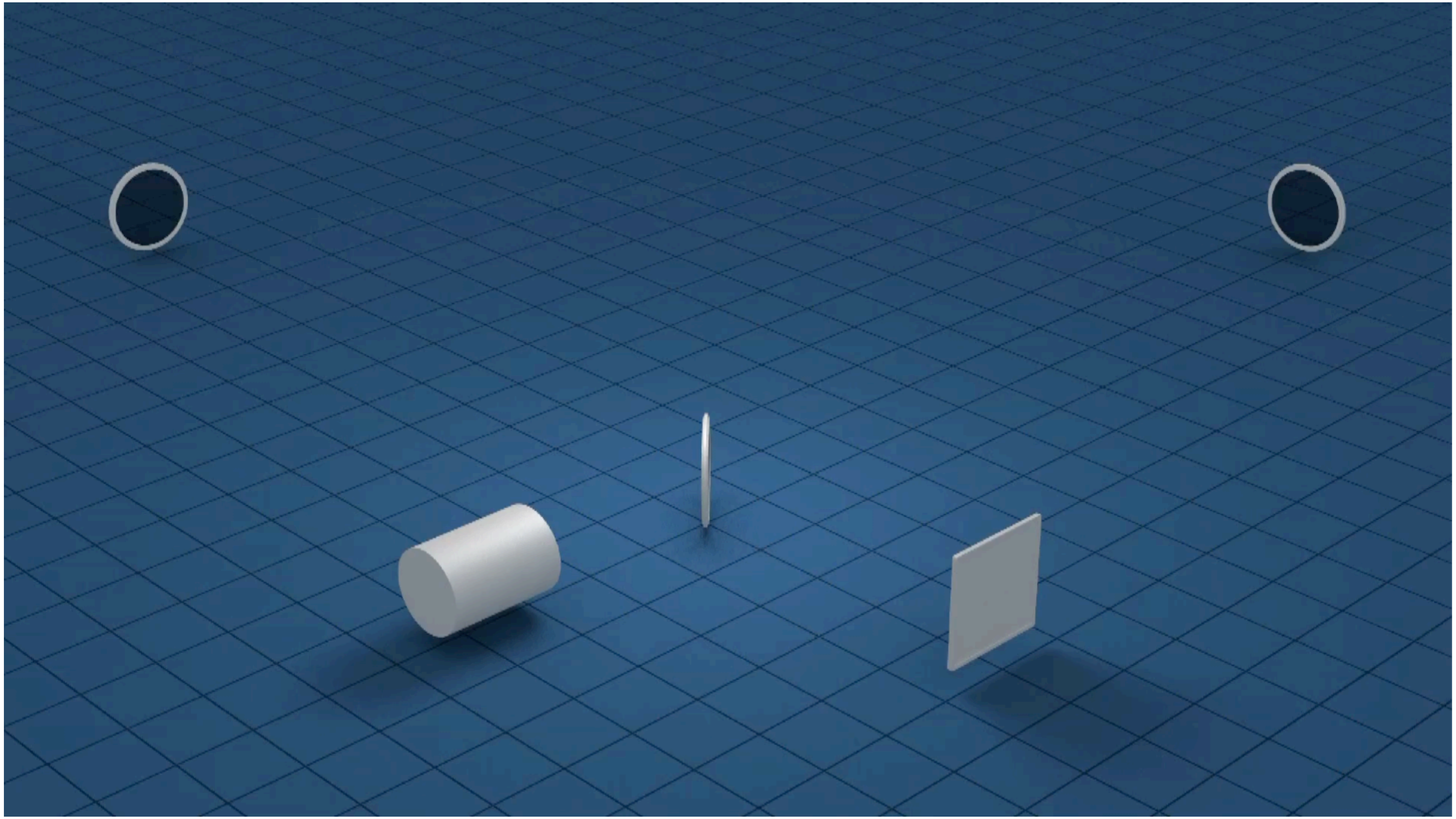
Caltech/MIT/LIGO Lab



GW observatories, current and planned

How do GW interferometers work?

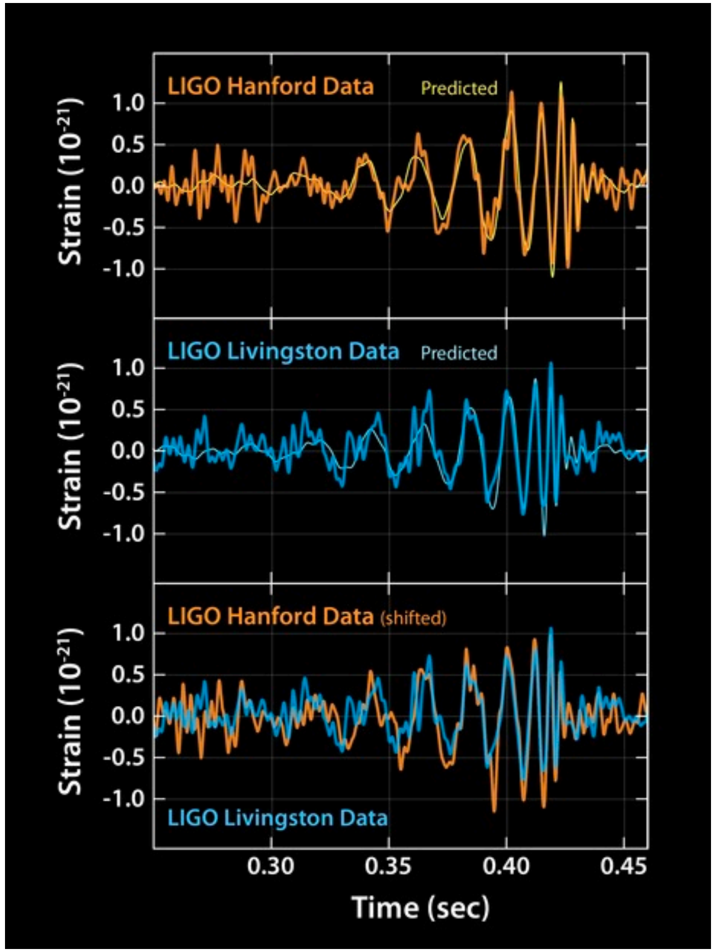
LIGO/T. Pyle



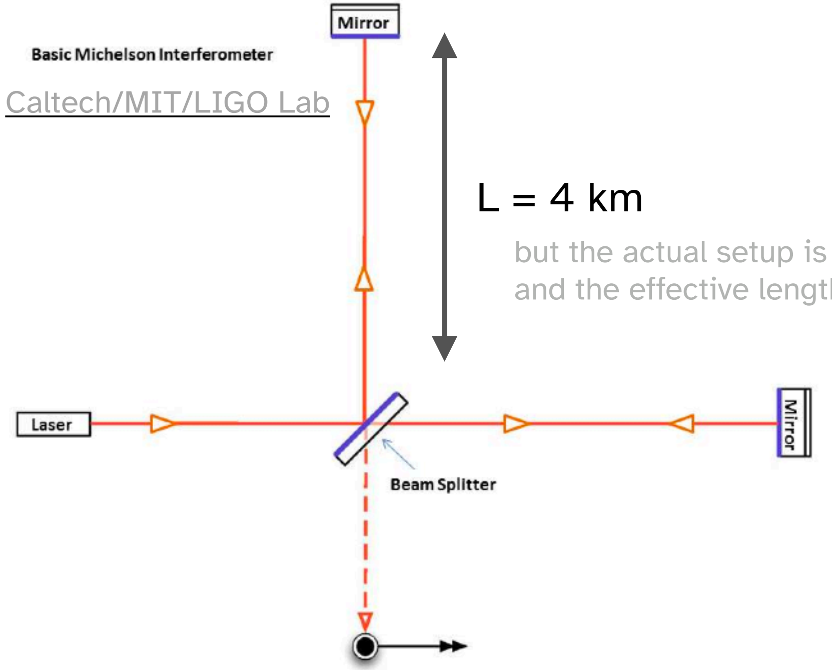
This is a simplification; for more details, see https://www.ligo.caltech.edu/page/ligos-ifo

How do GW interferometers work?

Caltech/MIT/LIGO Lab



Caltech/MIT/LIGO Lab



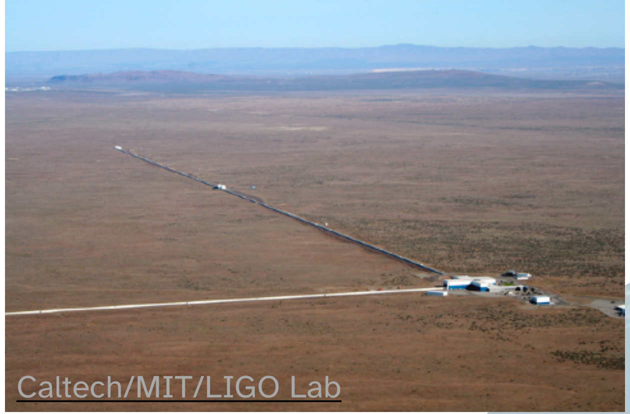
L = 4 km

but the actual setup is more complicated than this, and the effective length is more like 1000 km

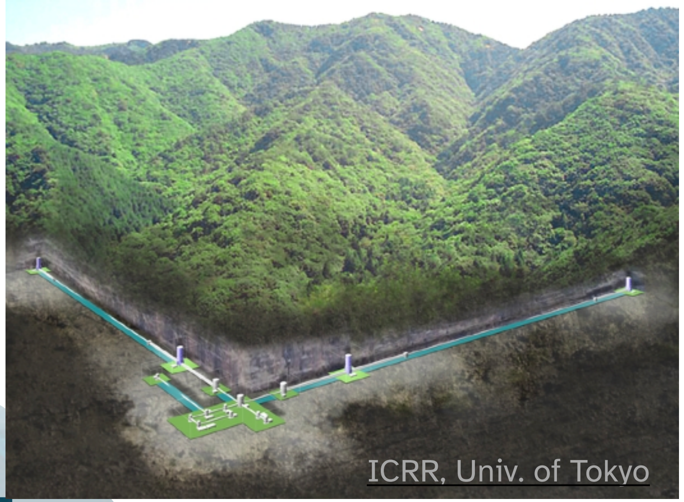
$$h = \frac{\Delta L}{L} = 10^{-21} \quad \text{so} \quad \Delta L \sim 10^{-18}\ \text{m}$$

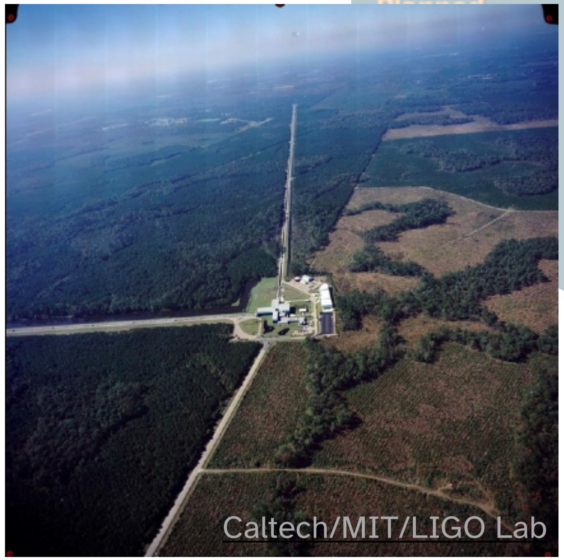
(in comparison, a proton radius is 10^{-15} m)

GW detectors


Caltech/MIT/LIGO Lab

Caltech/MIT/LIGO Lab

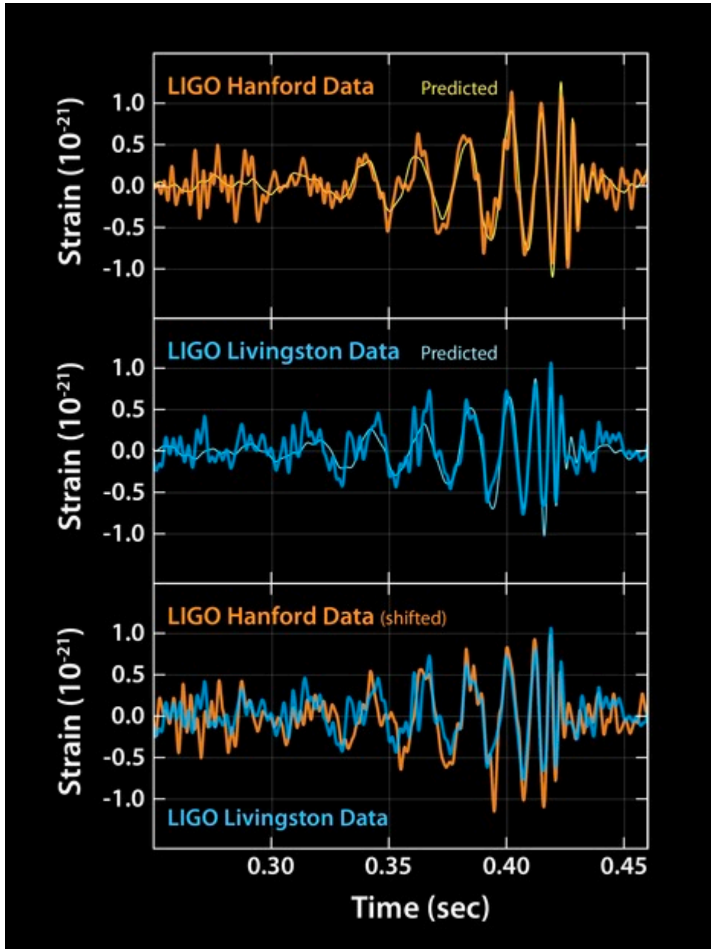

ICRR, Univ. of Tokyo


Caltech/MIT/LIGO Lab

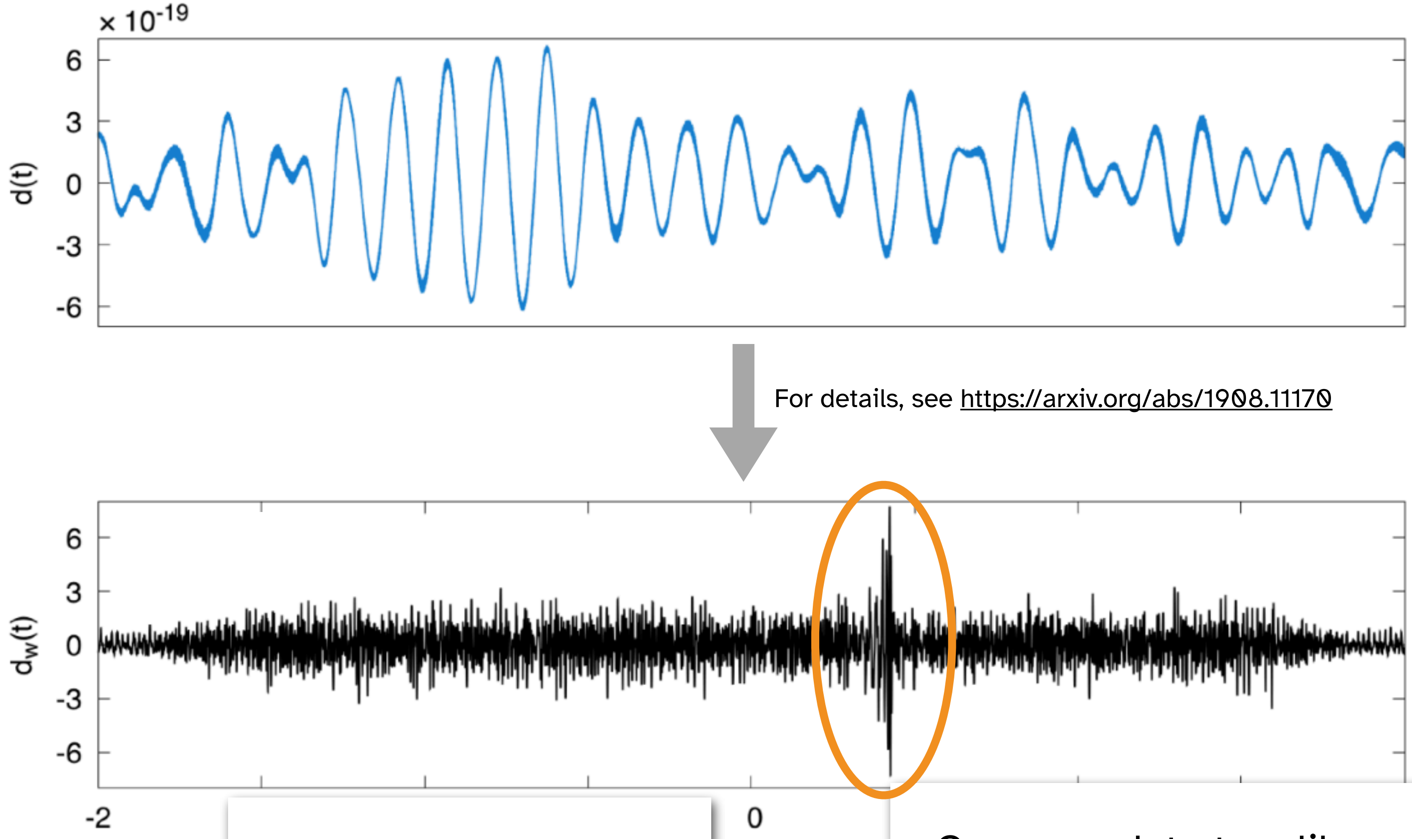

The Virgo collaboration

How are GW signals found?

Caltech/MIT/LIGO Lab



Raw data must be treated to remove noise and extract signal



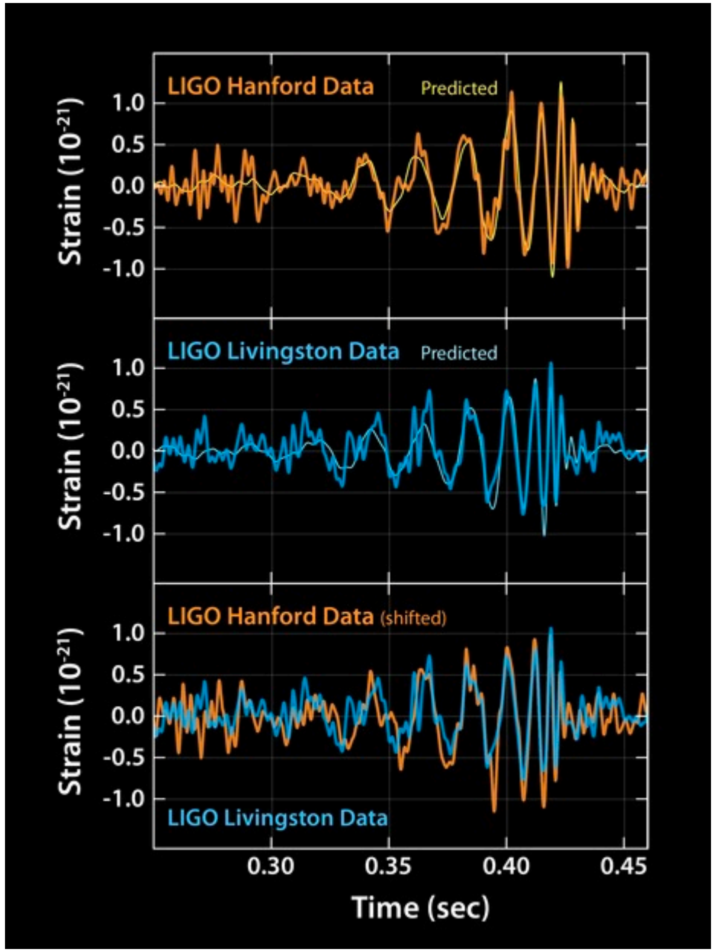
Look for excess power

or

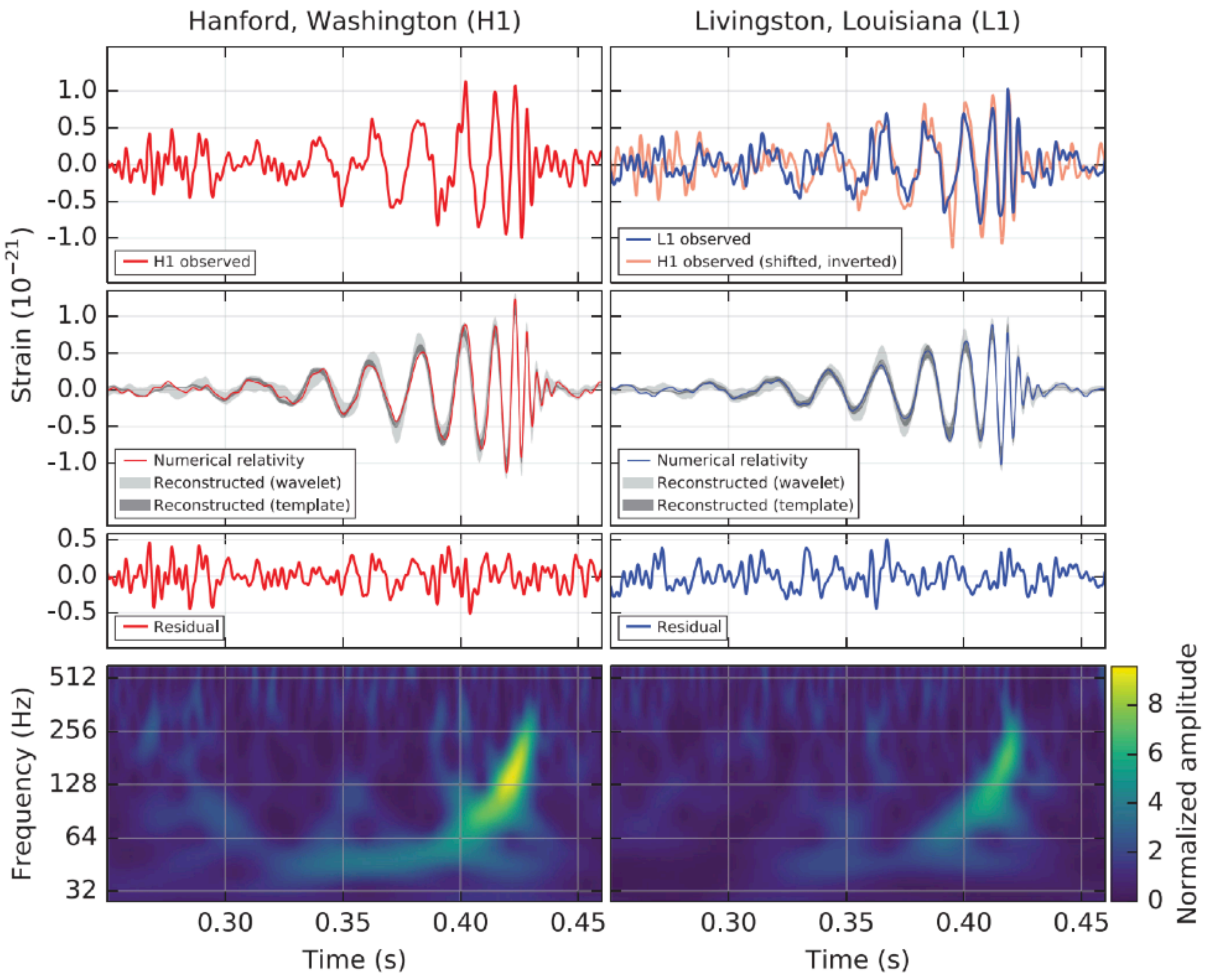
Compare data to a library of signal models (“match-filter”)

How are GW signals found?

Caltech/MIT/LIGO Lab

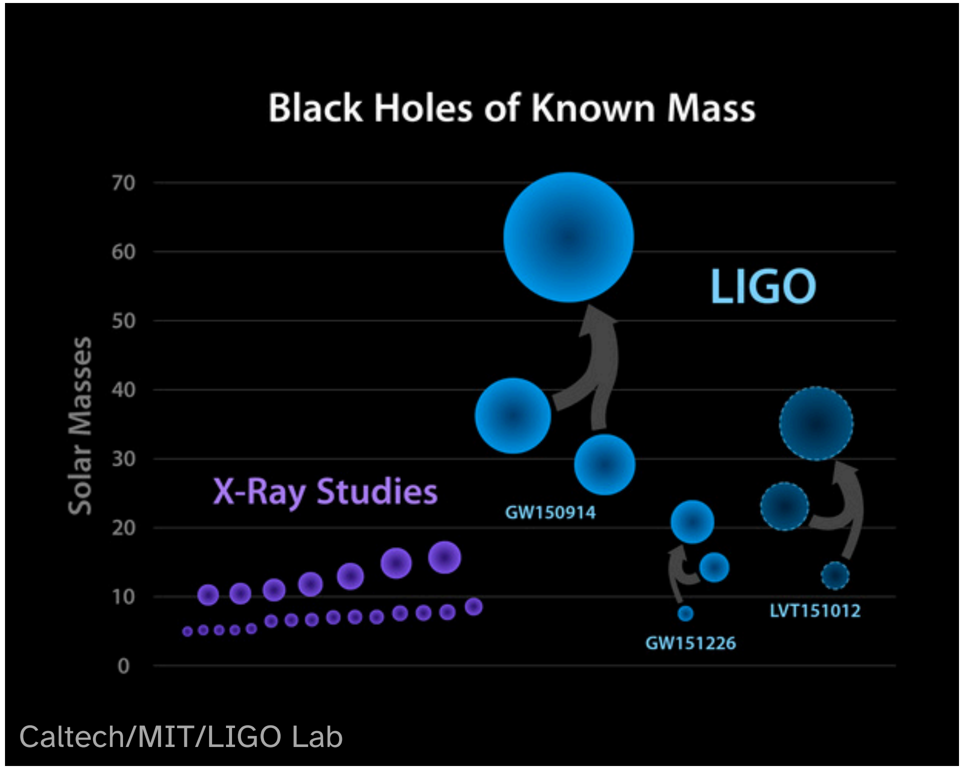


B. P. Abbott et al., PRL 116, 061102 (2016)



GW detections, and what we’ve learned from them

This is what the GW landscape looked like in 2016 …



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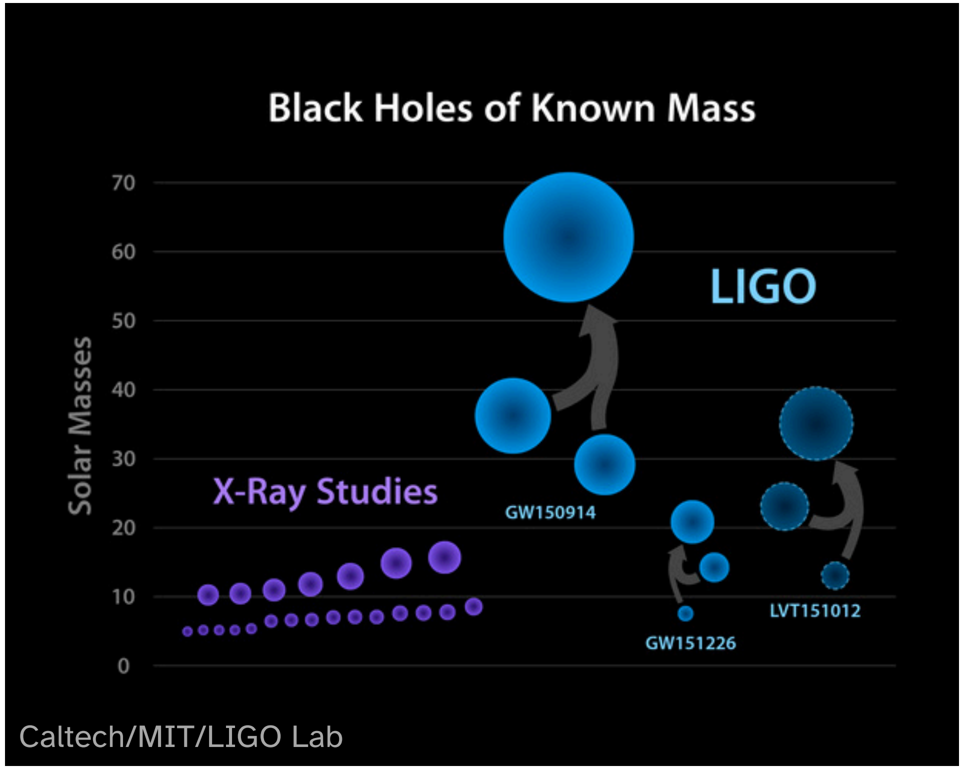
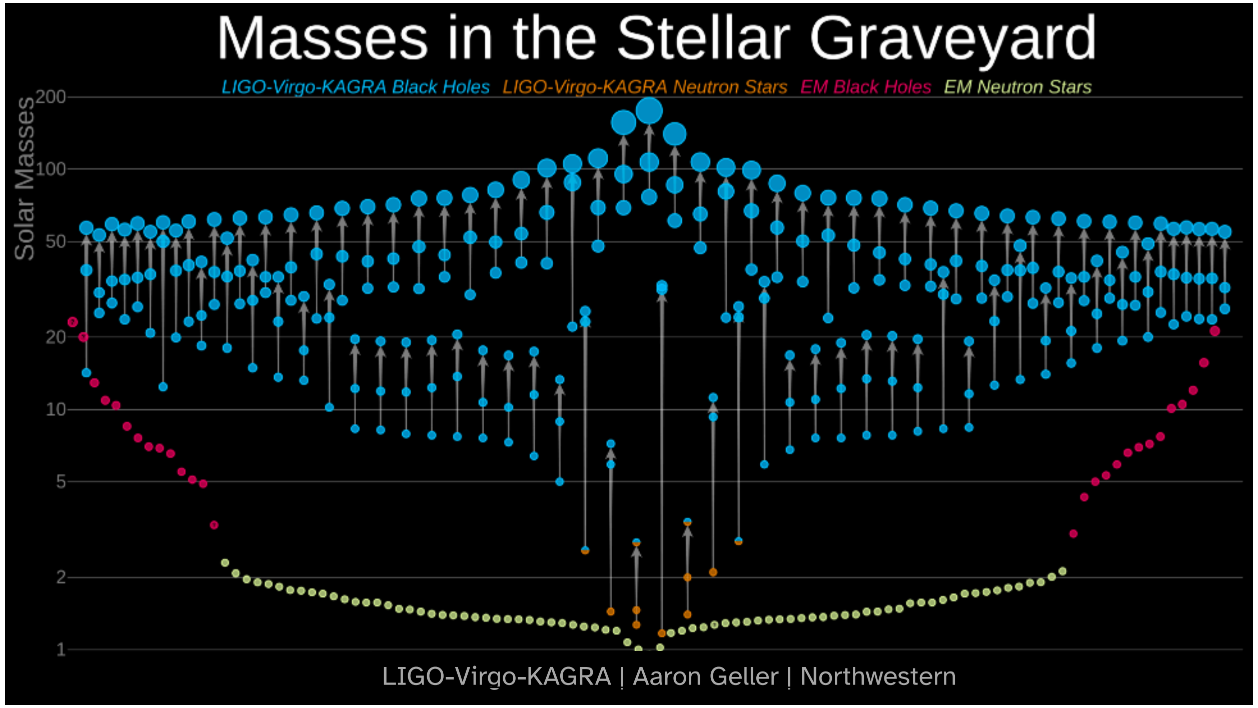
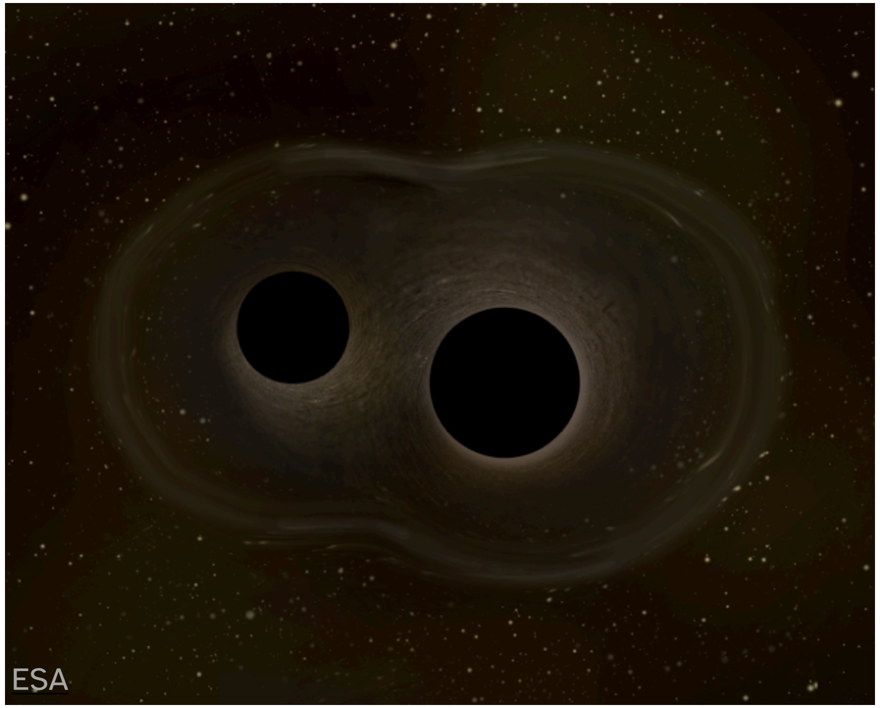


… and this is what it looks like now

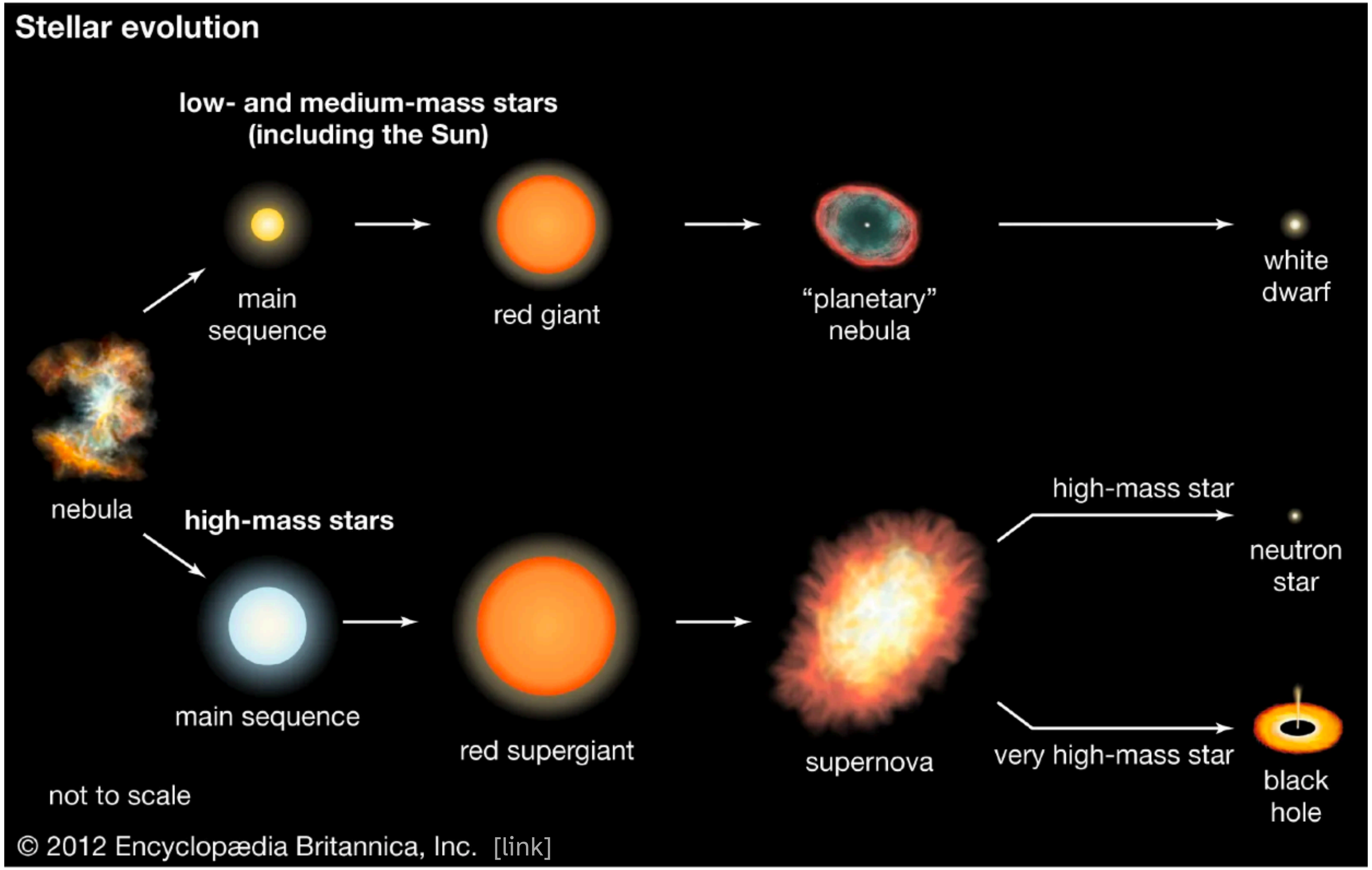


What we can learn from binary black hole mergers

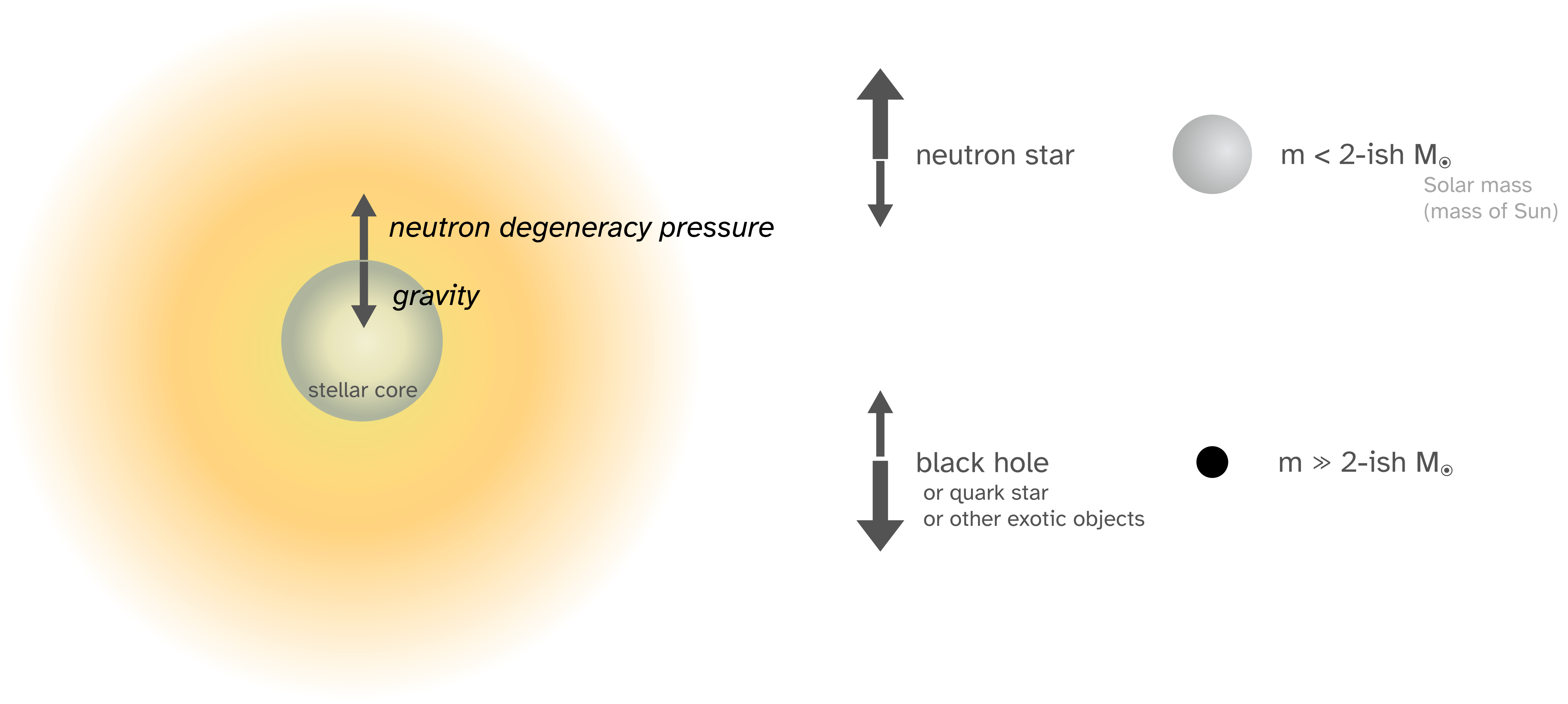


How do two black holes form a binary and eventually merge?
How heavy can black holes be? How light can they be?
How quickly do they spin?
Do they have any charge? Magnetic field?
Is general relativity correct?
How do we know they're black holes and not something else?

Black hole or neutron star (or something else?)

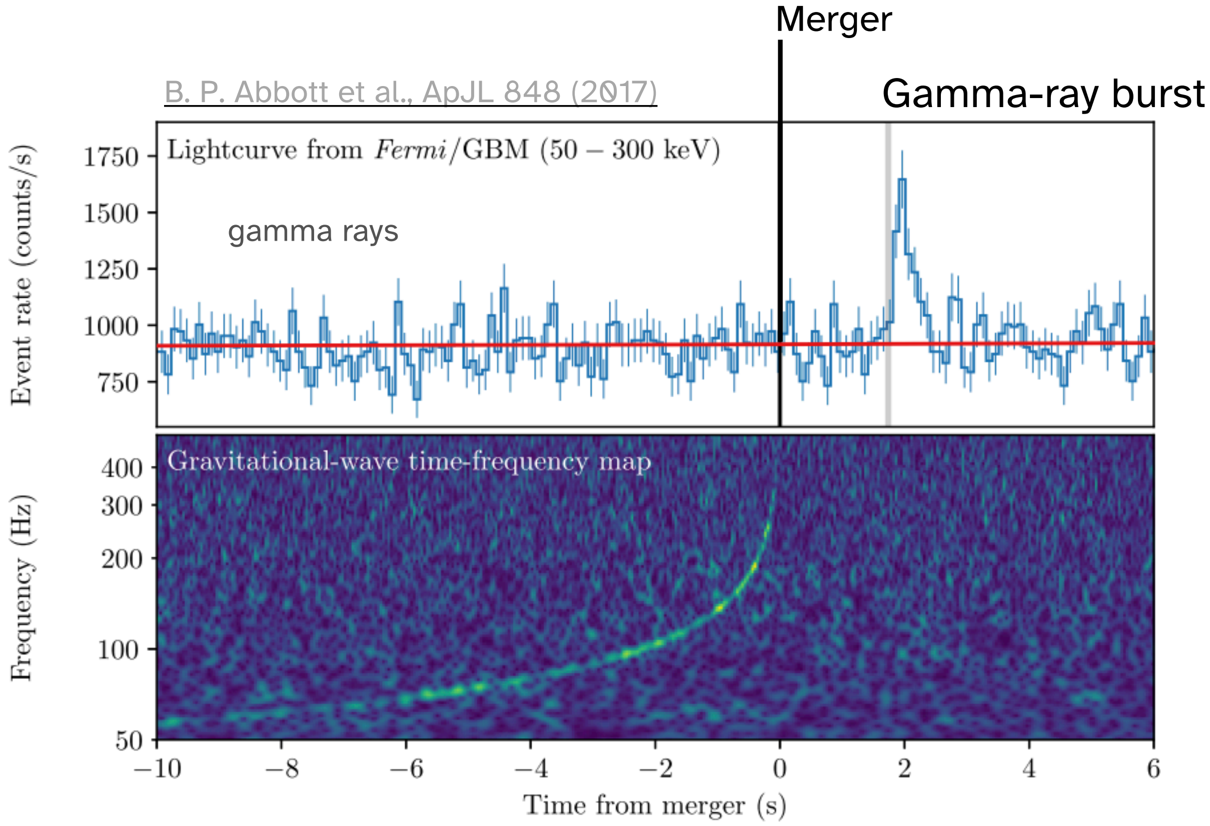


Black hole or neutron star (or something else?)

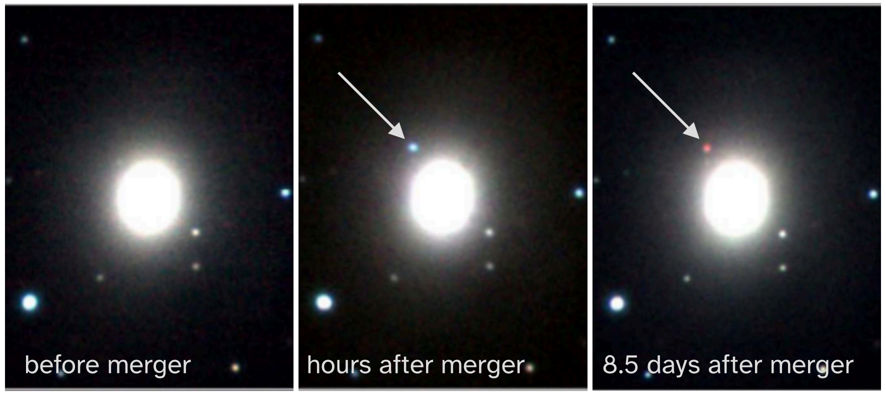


GW170817: binary neutron star merger

Everything becomes more complicated when you add matter

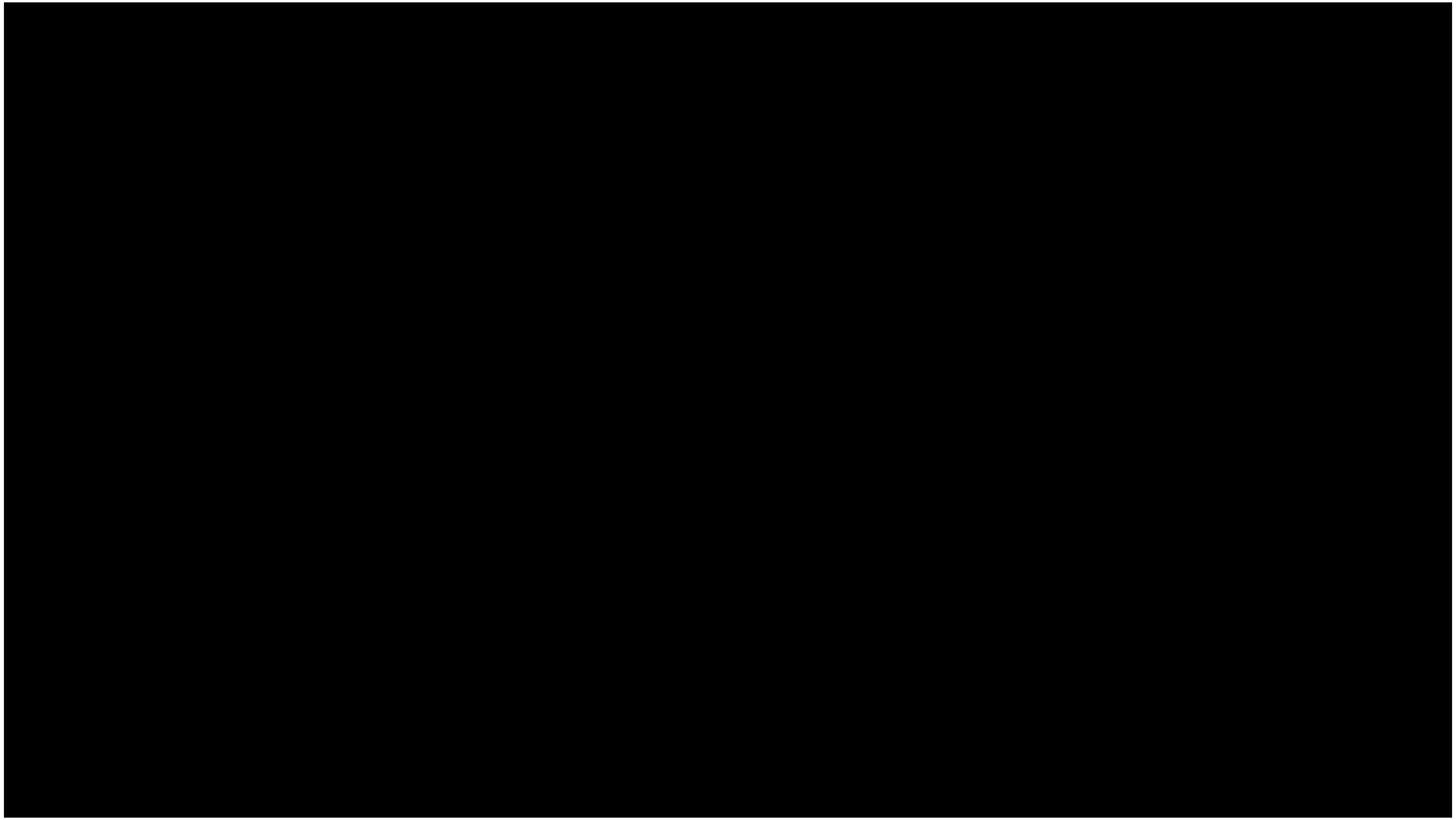


N. R. Tanvir et al., ApJL 848 (2017)



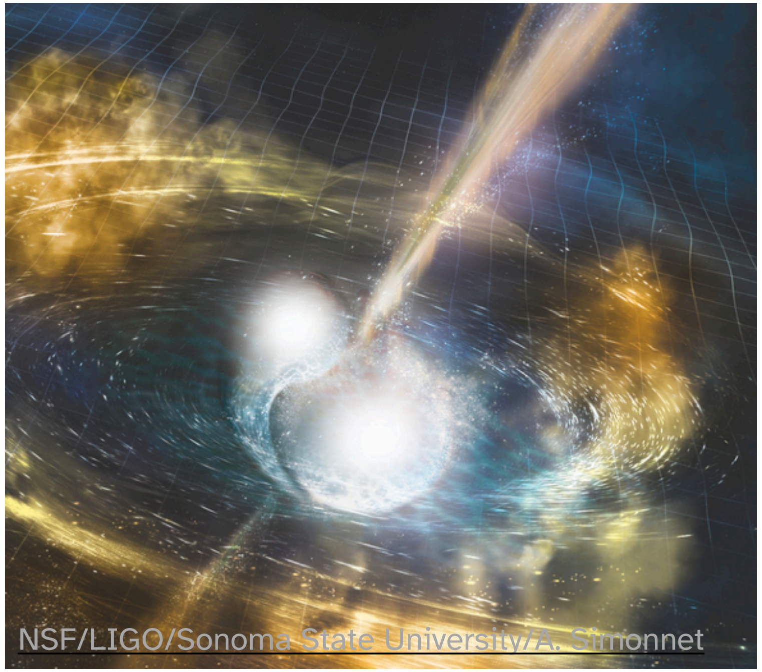
kilonova (mostly optical light)

GW170817: binary neutron star merger



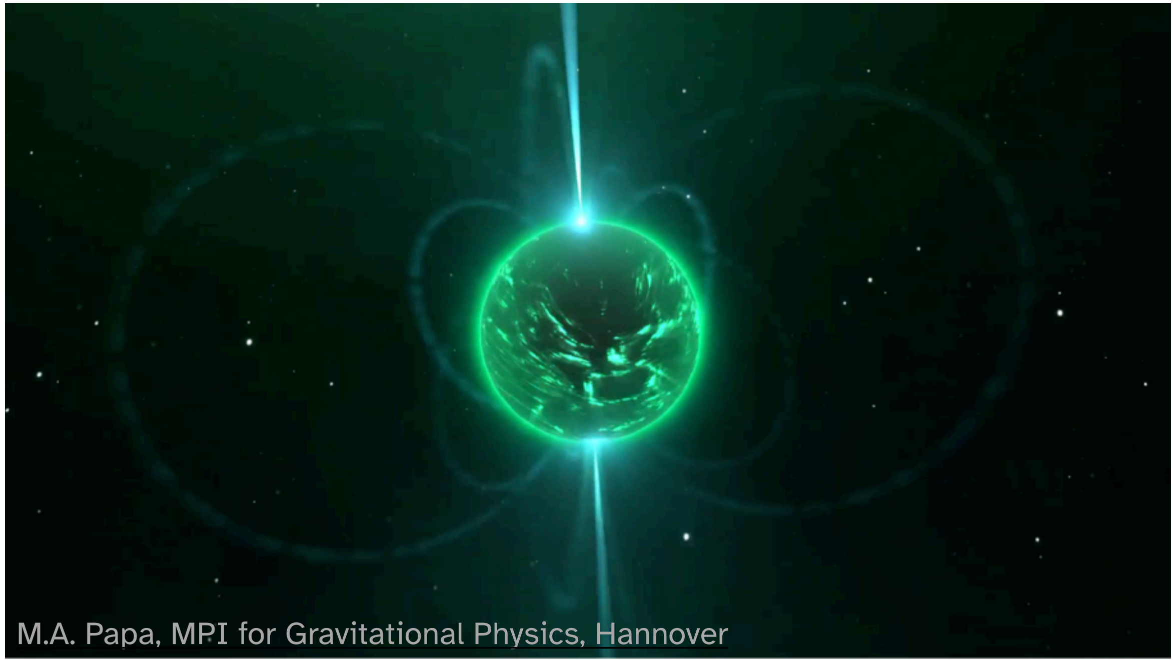
NASA's Goddard Space Flight Center / CI Lab

What we can learn from binary neutron star mergers

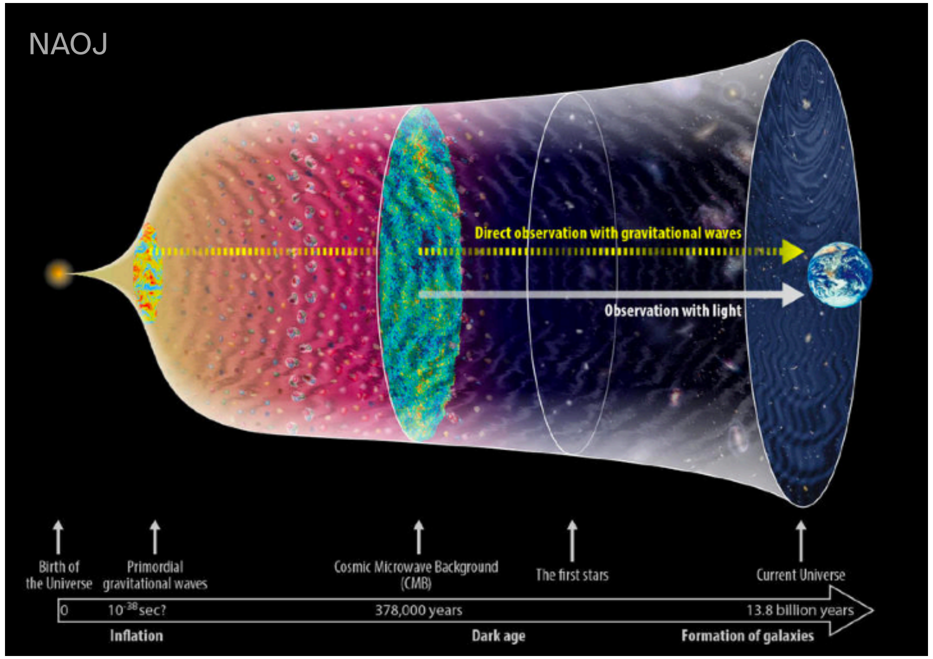


How heavy can neutron stars get?
What does the interior of a neutron star look like?
How do two neutron stars form a binary and then merge?
What is left when two neutron stars merge?
Where are the heavy elements in the Universe produced and how?
Do light and gravity travel at the same speed?
How do neutron star mergers produce neutrinos?

Other sources of gravitational waves



Continuous gravitational waves

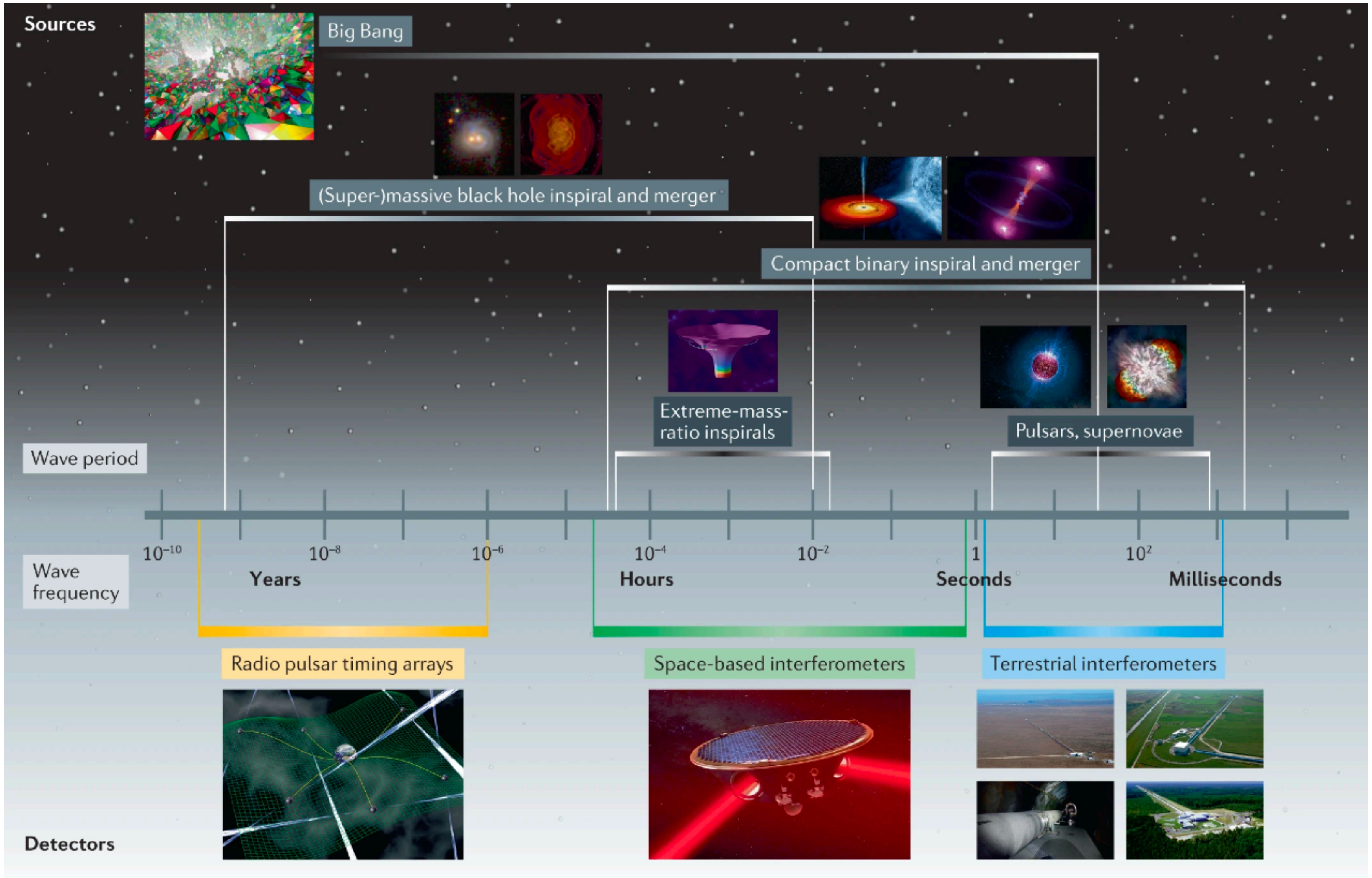


Stochastic gravitational-wave background

+ other, more exotic sources

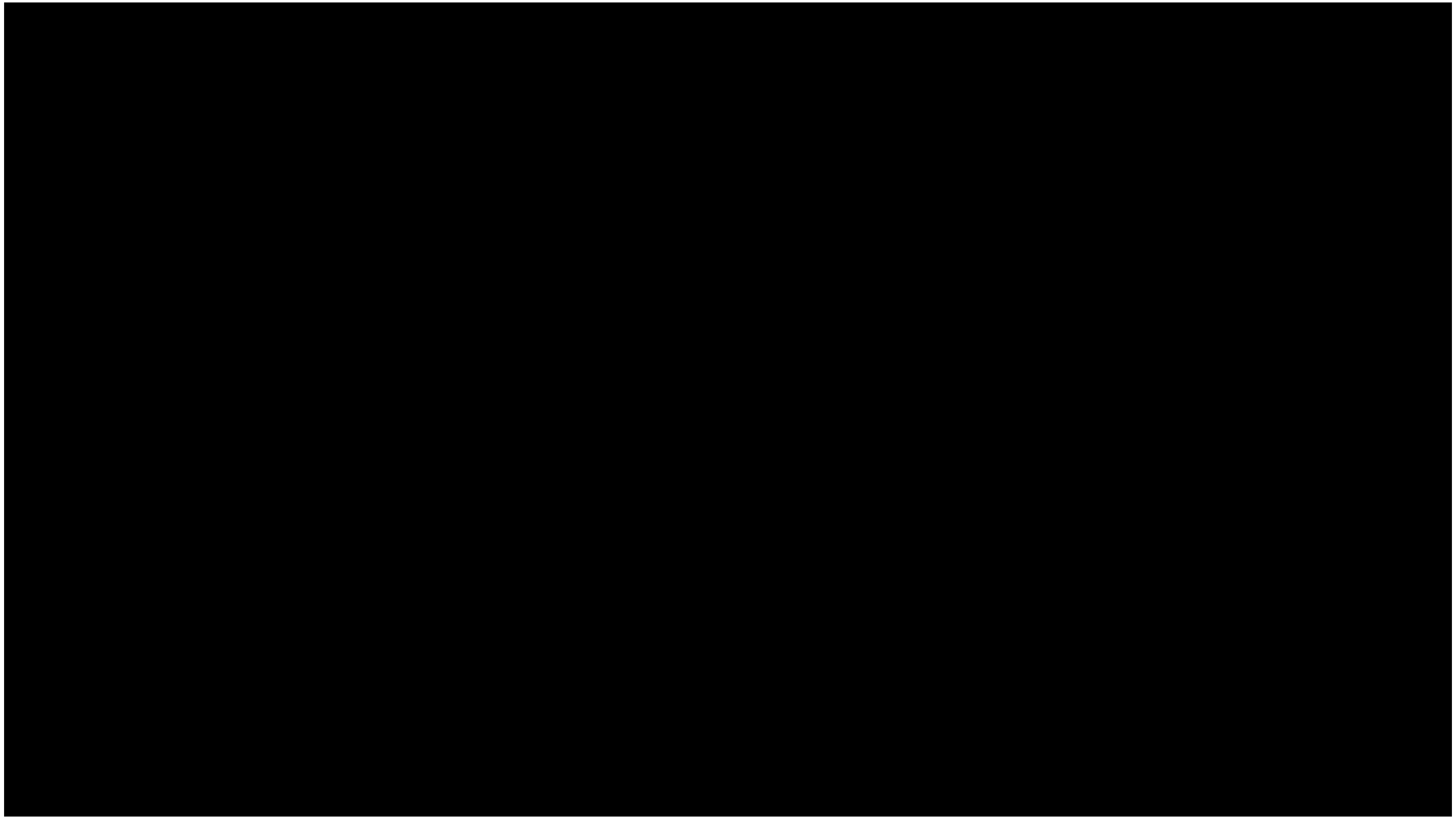
The gravitational-wave spectrum

M. Bailes et al., Nature Reviews Physics 3 (2021)



Binaries of (super)massive black holes

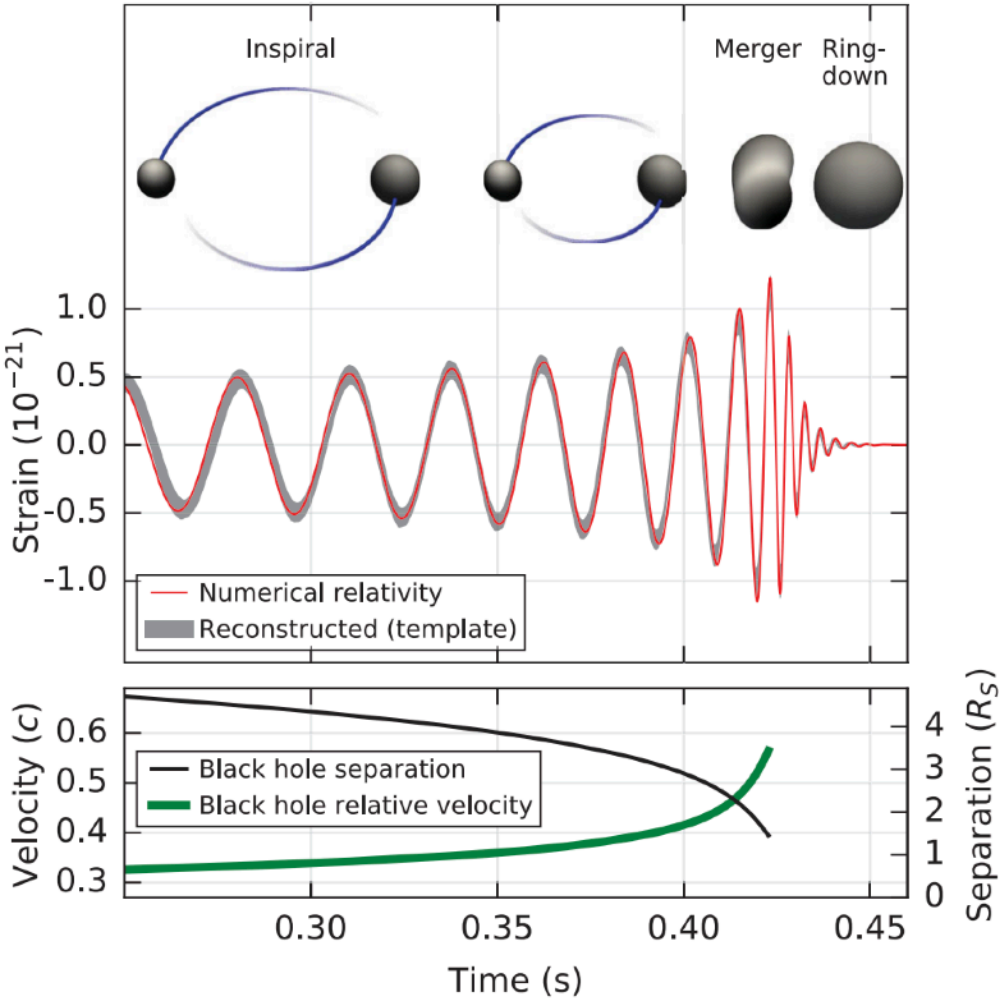
We have snapshots of Galaxies that seem to be in binaries



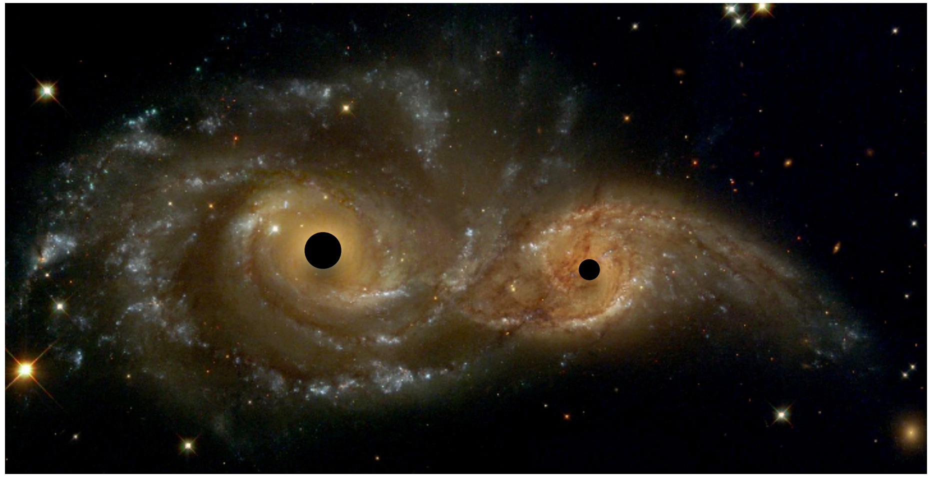
NASA, ESA, and F. Summers (STScI)

Gravitational waves from supermassive black hole binaries

B. P. Abbott et al., PRL 116, 061102 (2016)



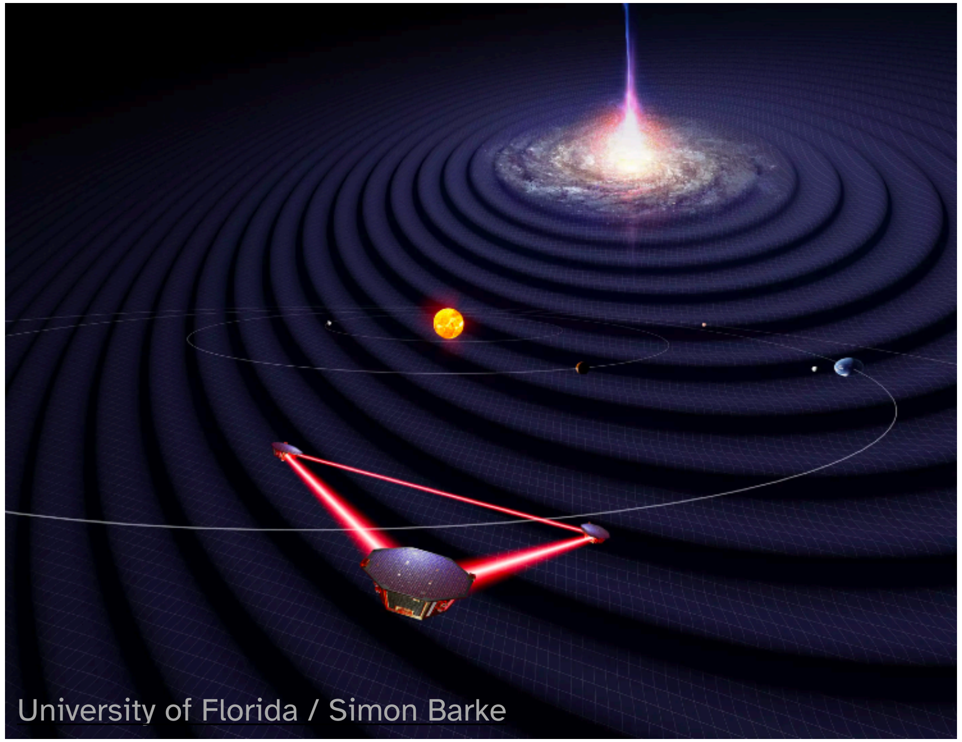
NASA/ESA and The Hubble Heritage Team (STScI)



(super)massive black hole binaries:
~ same GW signal, much different scales

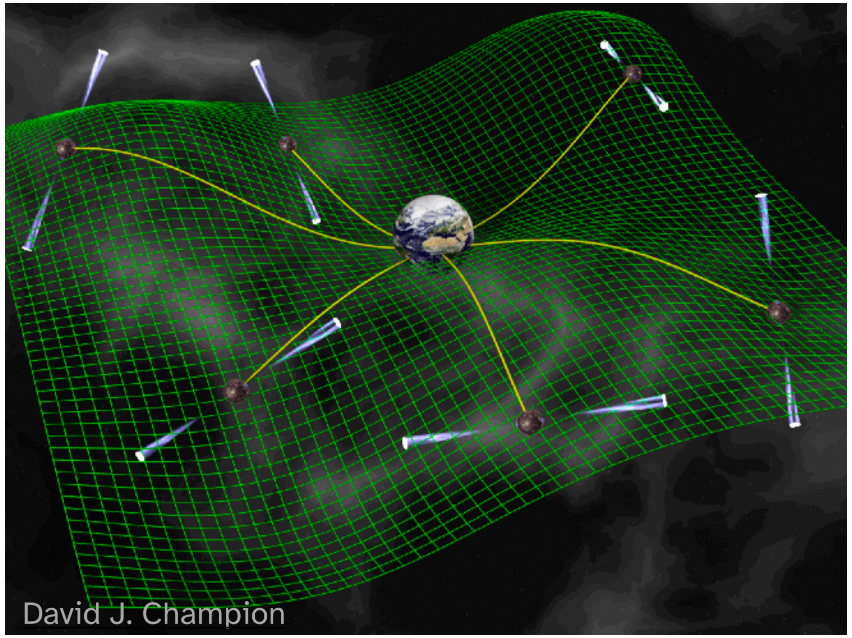
LISA: Laser Interferometer Space Antenna

Launch: late 2030s
Arm length: 2.5 million km

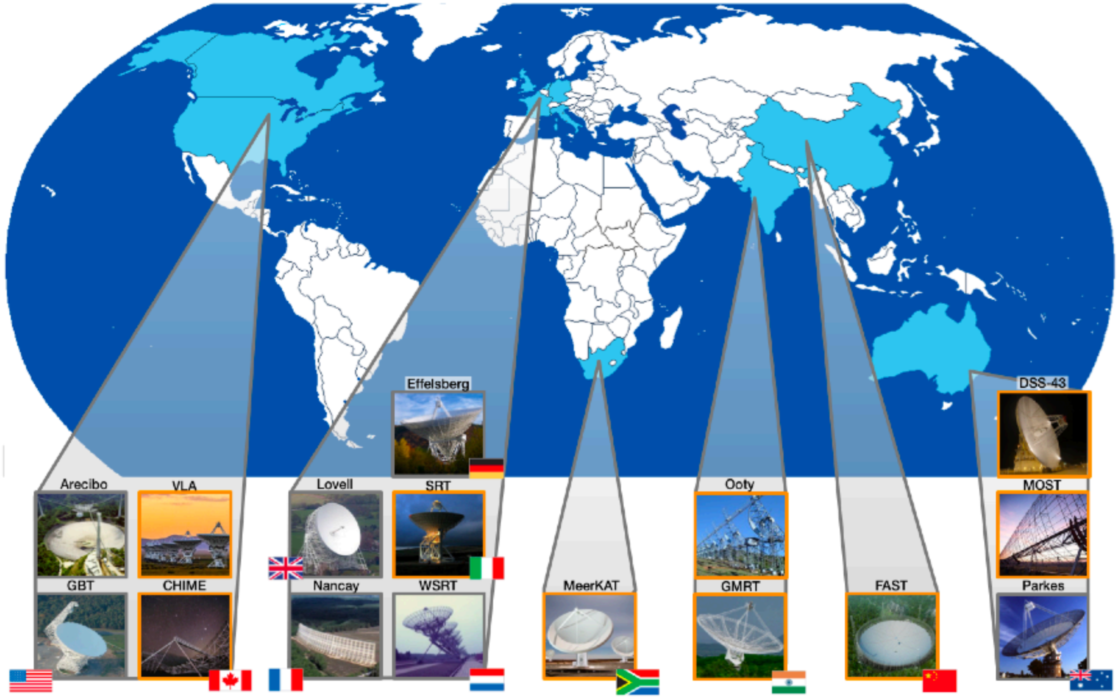

University of Florida / Simon Barke


AEI / Milde Marketing

Pulsar timing arrays

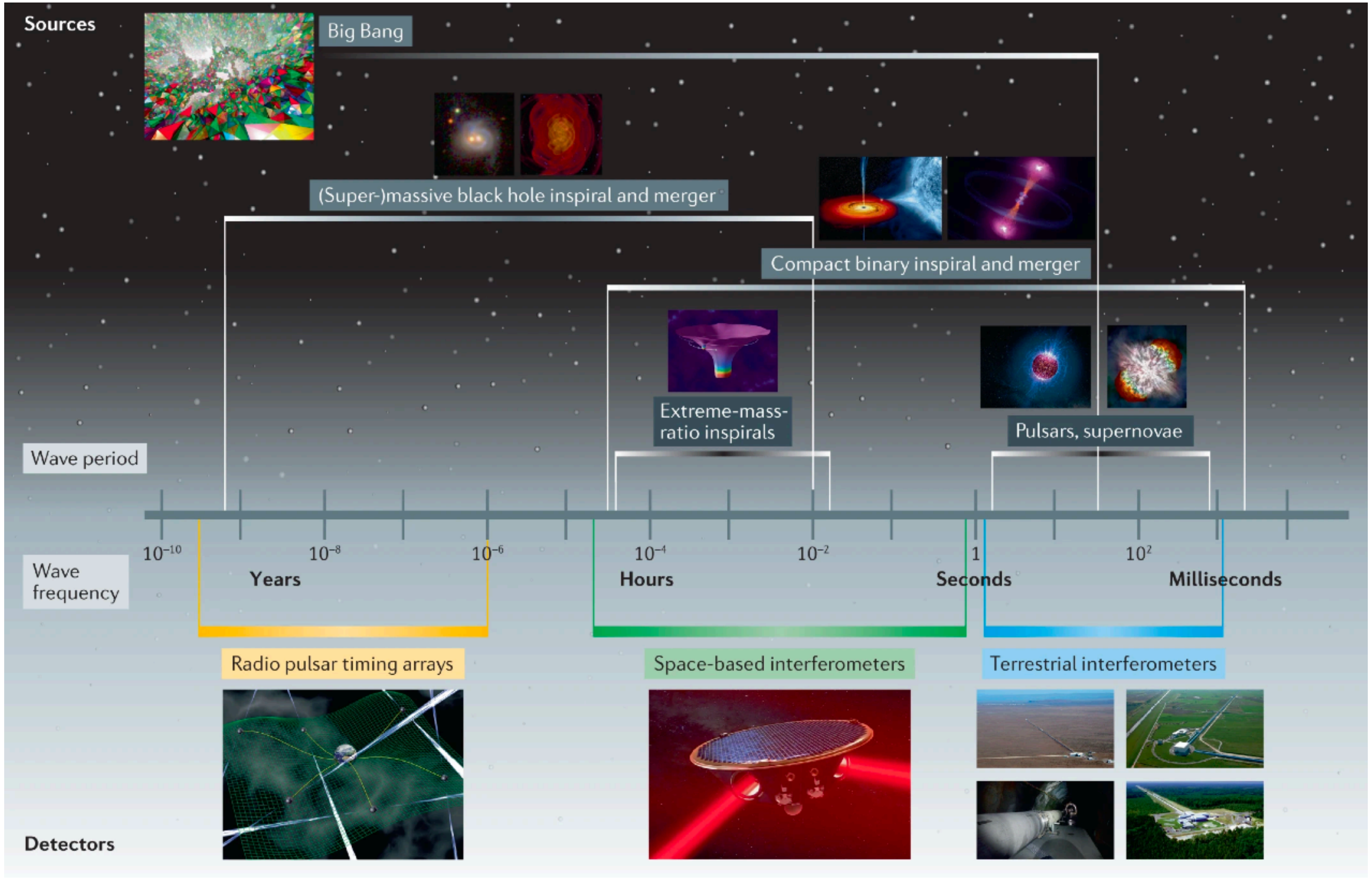


NANOGrav Collaboration



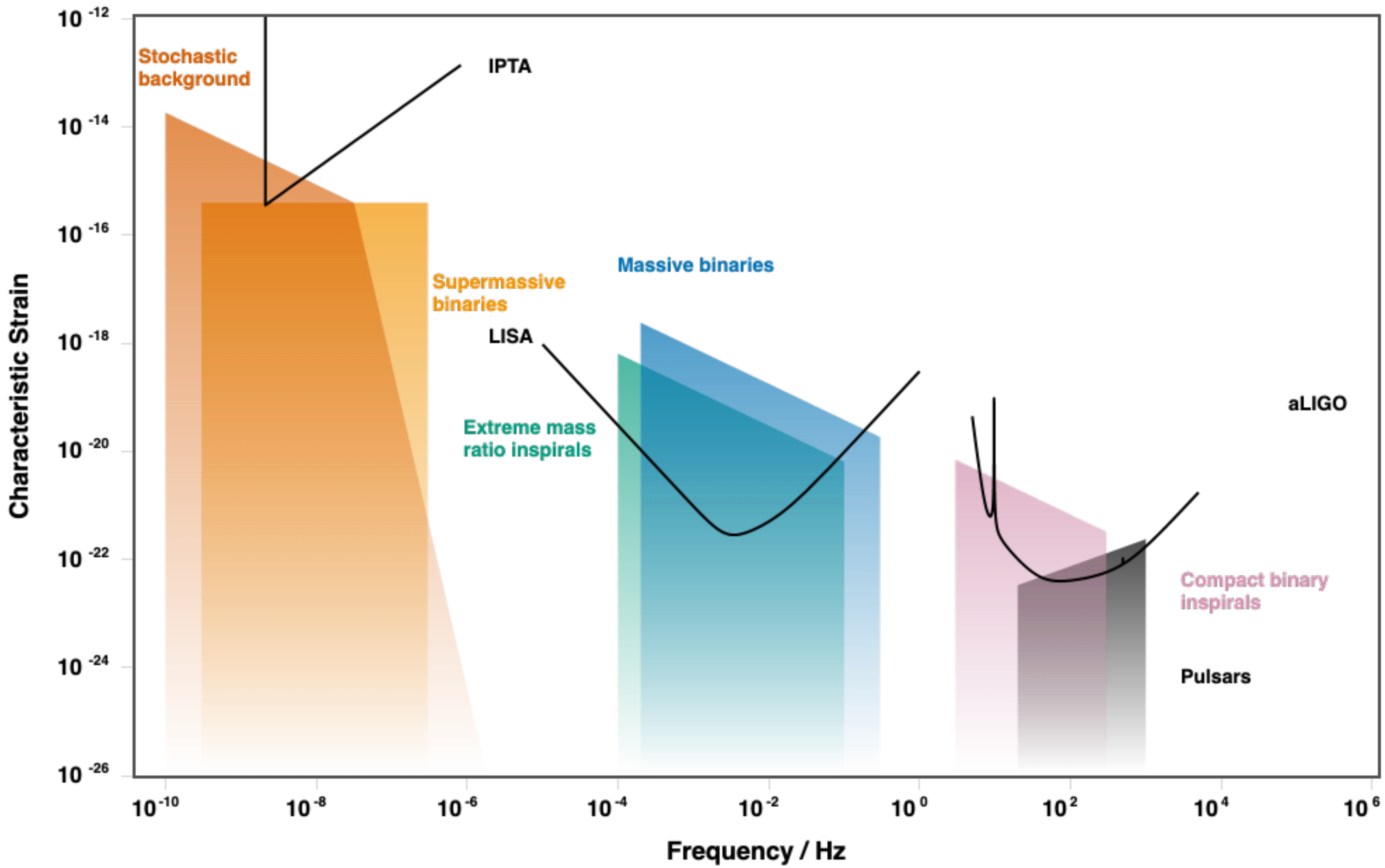
The gravitational-wave spectrum

M. Bailes et al., Nature Reviews Physics 3 (2021)



The gravitational-wave spectrum

gwplotter



A few good resources for further reading or study

General information

- https://www.ligo.caltech.edu/
- https://www.lisamission.org/articles/lisa-mission/lisa-mission-gravitational-universe
- https://www.nature.com/articles/s42254-021-00303-8

Full LIGO-Virgo-KAGRA publication list

- https://pnp.ligo.org/ppcomm/Papers.html

LIGO data analysis and hands-on tutorials

- https://www.gw-openscience.org/tutorials/
- https://cplberry.com/2020/02/09/gw-data-guides/#data-analysis-guide