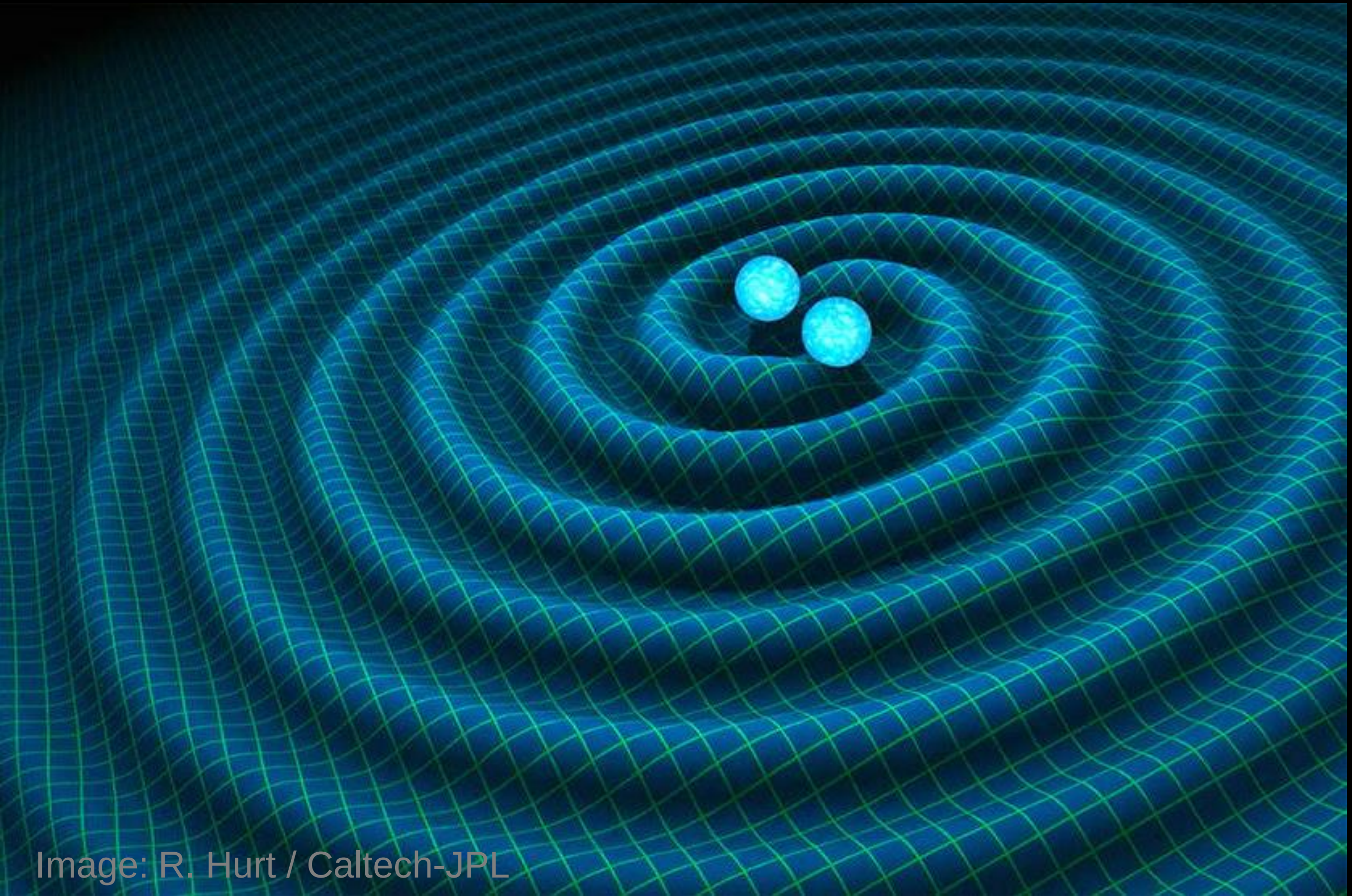
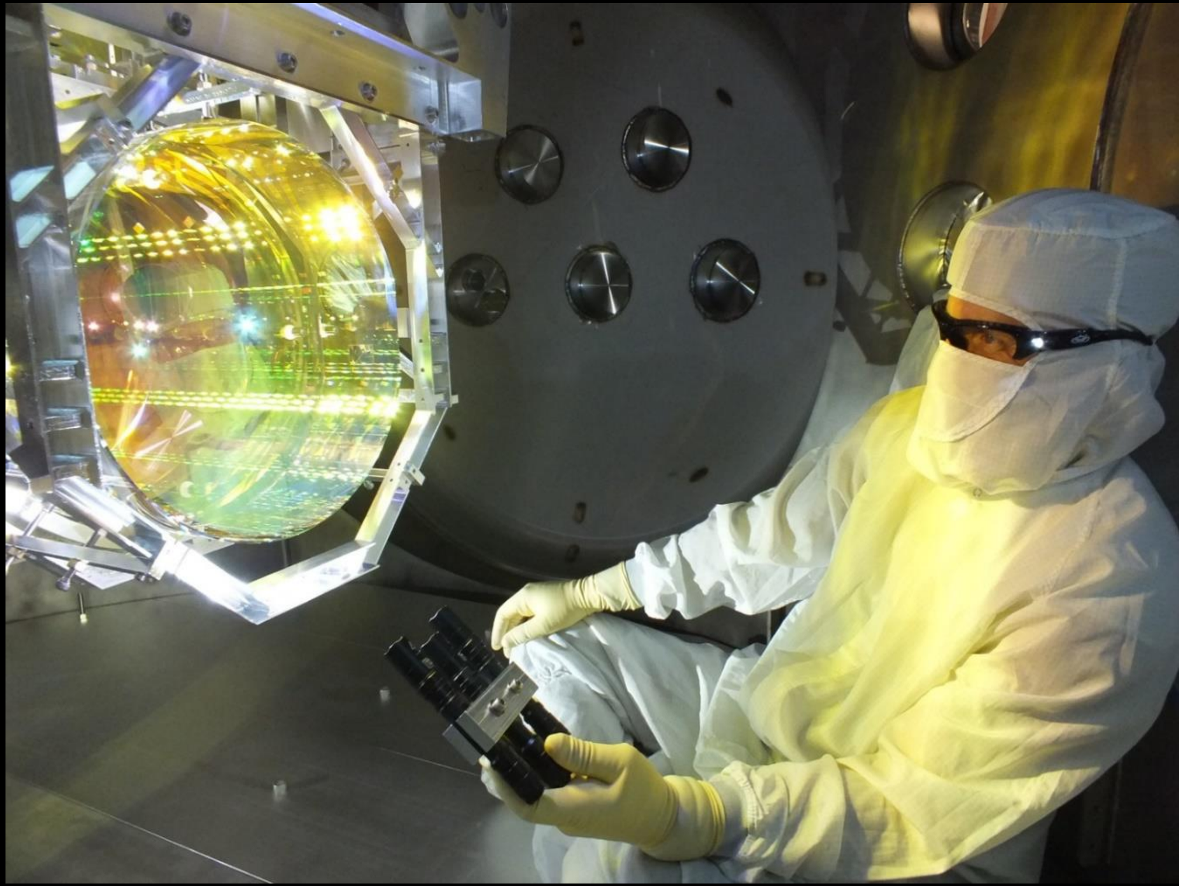
Detection of Gravitational Waves, and What They Are Telling Us

Peter Shawhan
The University of Maryland





UMD QuarkNet
August 12, 2025

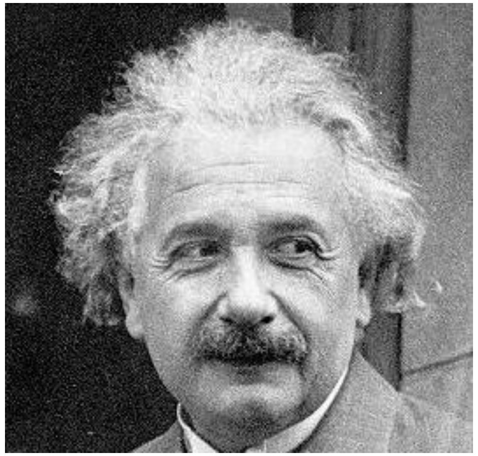
What is gravity, really?

Isaac Newton described the properties of gravity:

- ▶ It acts between all objects that have mass
- ▶ Its strength depends on the amount of mass and the distance between the objects
- ▶ Gravity causes things to accelerate, so it must be a force

… but did not try to explain what causes it:

"Hitherto I have not been able to discover the cause of those properties of gravity from the phenomena, and I frame no hypothesis…"



Albert Einstein realized that space and time must be fundamentally connected for the laws of physics to be self-consistent ⇒ ***spacetime***

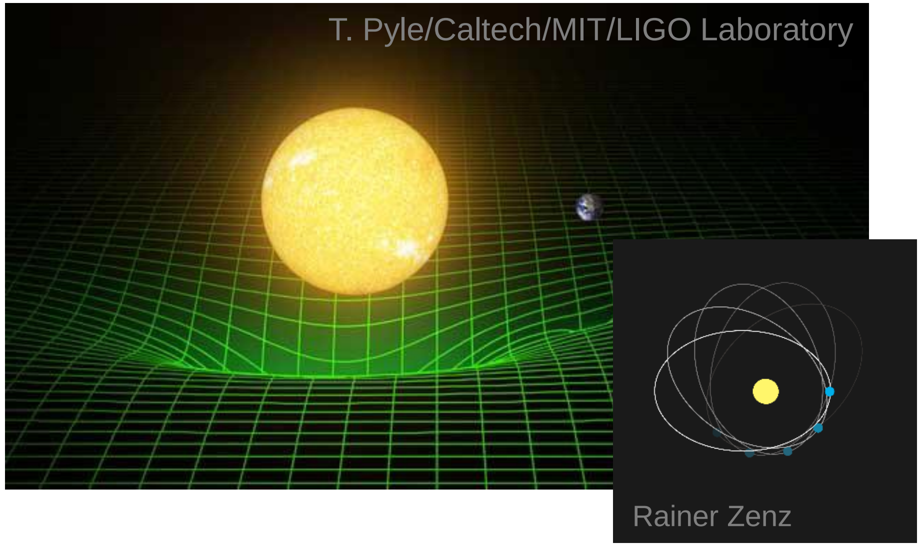
His 1915 **general theory of relativity (GR)** says that gravity is really due to ***curvature*** *in the geometry of spacetime*, caused by the presence of mass

- ▶ It is not a force!
- ▶ Things move along "straight" paths (geodesics) *in curved spacetime*

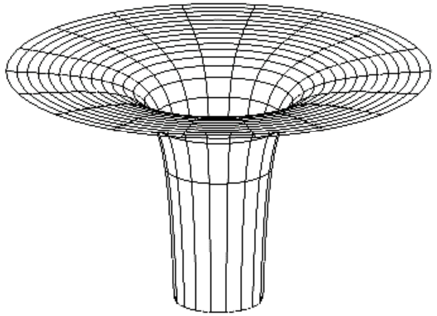
How can we know if GR is a correct theory?

By looking at what predictions it makes that are different from Newton's theory, and making careful observations or doing experiments to test those predictions

The elliptical orbit of Mercury precesses faster than Newtonian gravity predicts
➔ This was a puzzle that GR solved!

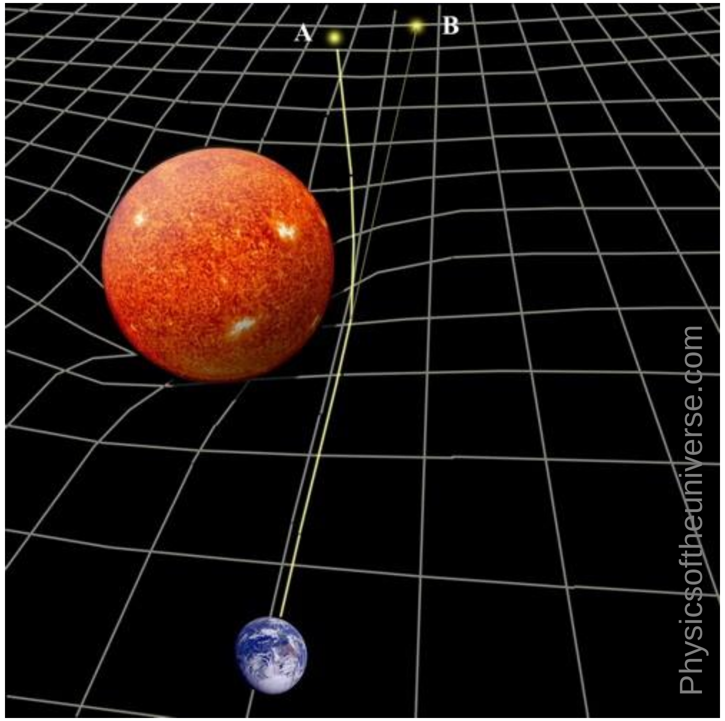


Black holes can exist!

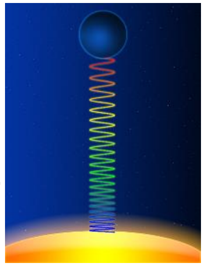


➔ Indirect (but good) evidence from astronomy observations since 1972

The path of light is bent as it passes through a gravitational field
➔ First measured for starlight during the 1919 total solar eclipse



Wikipedia



The wavelength of light changes as it goes up or down in a gravitational field ("gravitational redshift")
➔ Measured in an experiment at Harvard in 1959

Gravitational waves

... are oscillating variations of the *spacetime metric* –
the definition of *distance* between points in space and time –
in accordance with the *Einstein field equations*

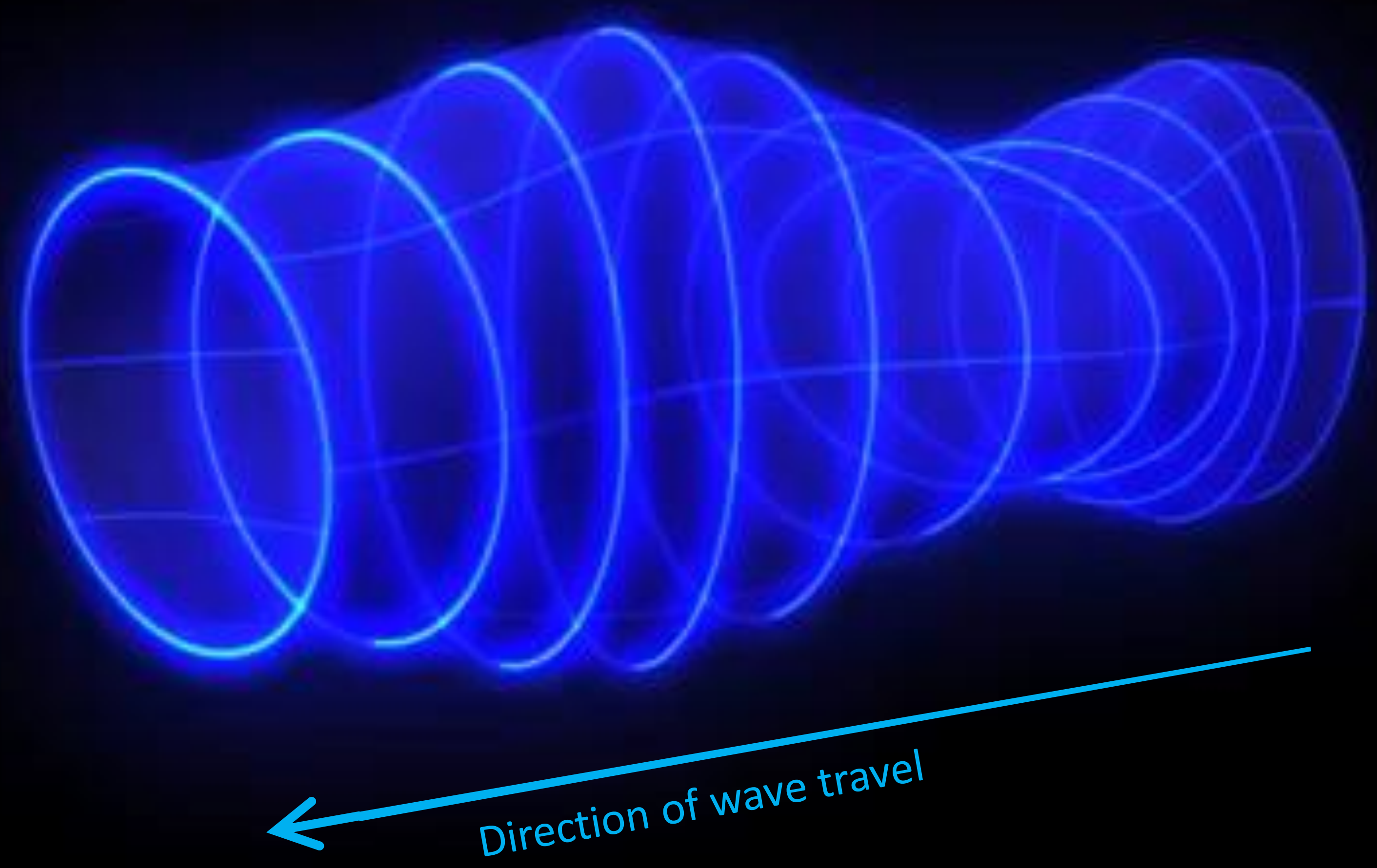
$$R_{\mu\nu} - \frac{1}{2} R \boldsymbol{g}_{\boldsymbol{\mu\nu}} + \Lambda \boldsymbol{g}_{\boldsymbol{\mu\nu}} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Perturbations of the spacetime metric take the form of waves
which travel at the speed of light

➔ The geometry of spacetime is dynamic, not fixed!

Looking at a fixed place in space while a gravitational wave travels past,
the waves alternately *s t r e t c h* and *shrink* space
(and anything in the space)

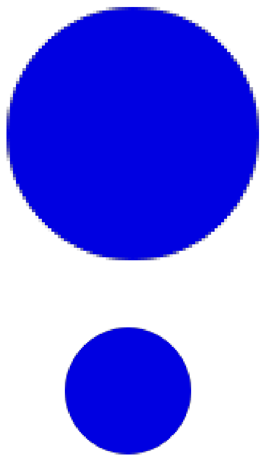
3D View of a Gravitational Wave
(distortion of the geometry of spacetime)

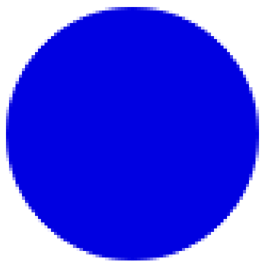


Generating a gravitational wave

A gravitational wave can be launched when a lot of mass changes its shape or orientation rapidly

For example, two massive, compact objects (neutron stars or black holes) in a tight orbit launch a wave which deforms space with a frequency which is twice the orbital frequency





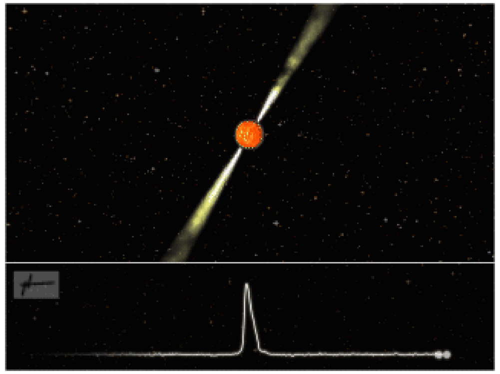
It's a fractional stretching/shrinking, described by a dimensionless *strain*: $h = \frac{\Delta L}{L}$

h is inversely proportional to the distance from the source.

Rare events in the universe occur mostly very far away, so at Earth, $h \sim 10^{-21}$ or even smaller !

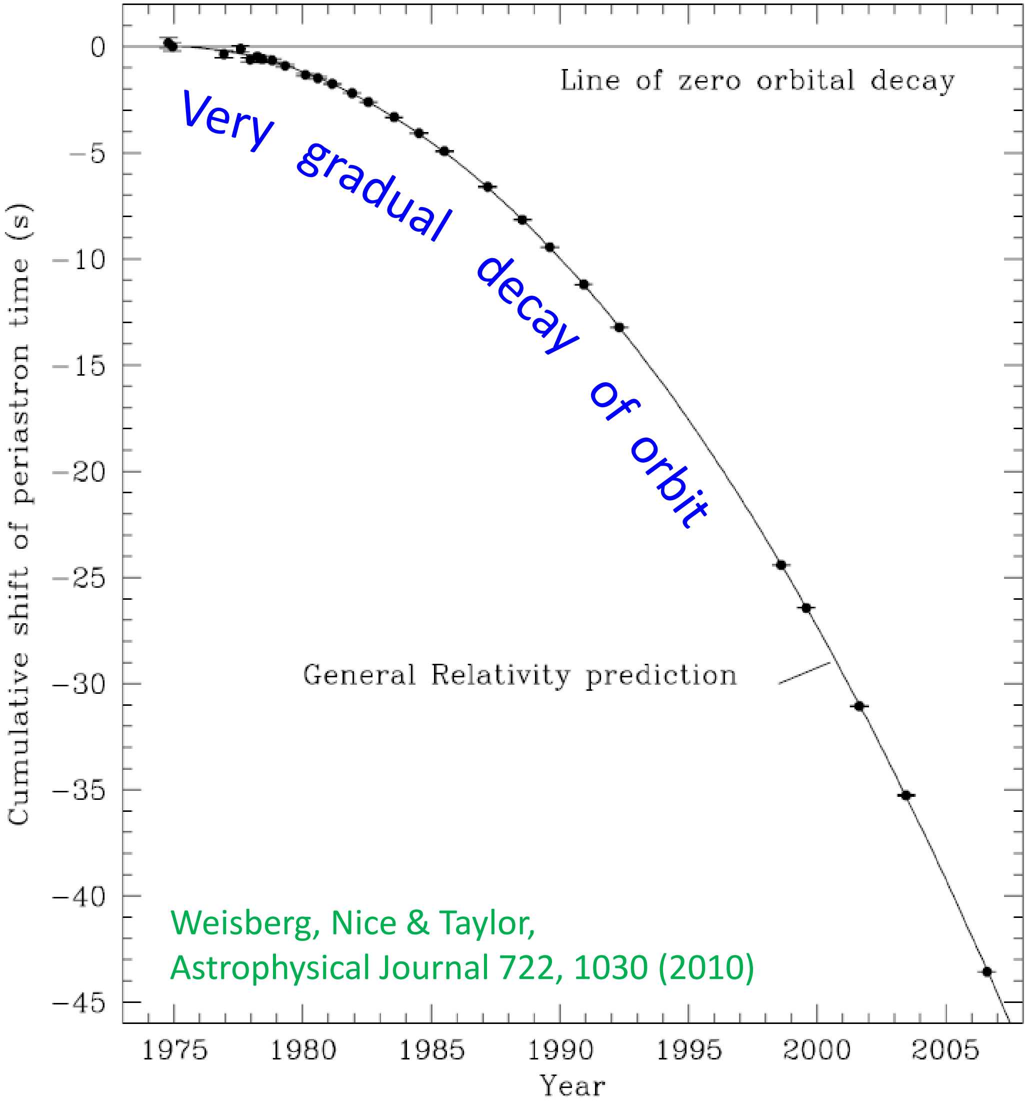
Gravitational waves carry energy

Joeri van Leeuwen



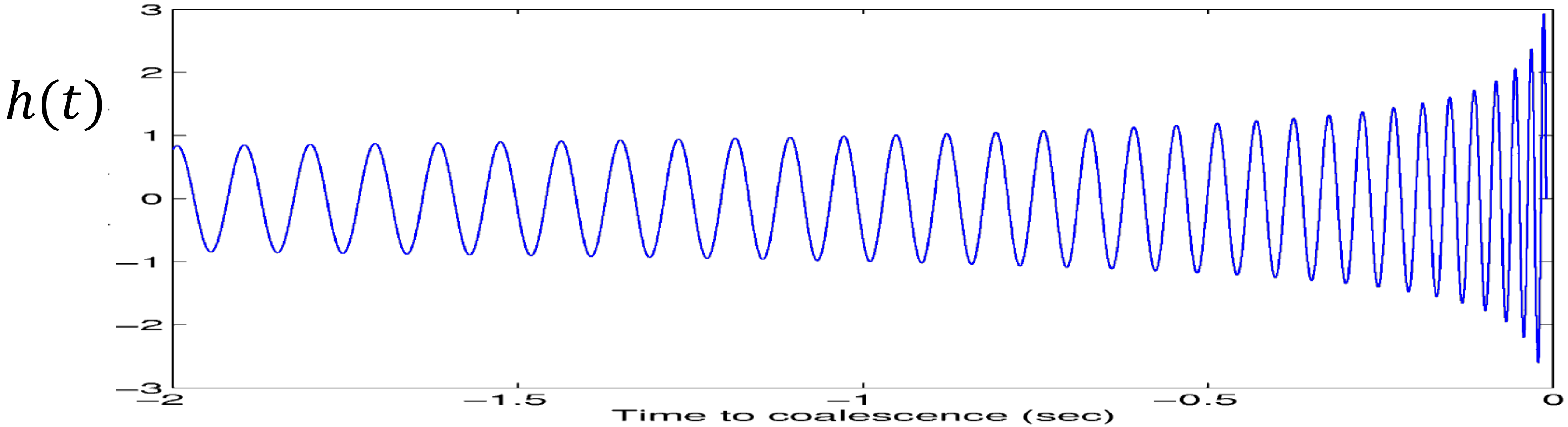
- For instance, Arecibo radio telescope observations of the binary pulsar B1913+16 told us the masses (1.44 and 1.39 $M_{\odot}$) and orbit parameters

- ... and showed that this binary neutron star system's orbit is changing as energy is carried away, just as general relativity predicts!



The fate of B1913+16

The binary orbit will continue to decay—“inspiral”—over the next ~300 million years, until…



The neutron stars will merge !

And probably collapse to form a black hole!

Gravitational waves are not sound waves, but we can convert them to sound

The final minute or so will be in audio frequency range *(theoretical GW signal)*

We describe this distinctive sound as a ***chirp***

What do you need to do to detect gravitational waves?

Make a nonlocal connection

A gravitational wave does not move an object, nor apply any force to the object, in the object’s locally inertial reference frame.

➔ So a single small object or sensor cannot detect a gravitational wave.

It only changes the effective distance between different points in spacetime.

➔ To measure that distance change, you need something to connect and compare things at different places

A rigid or semi-rigid mechanical link

Ranging with light

Joe Weber's resonant GW detectors

Special Collections and University Archives, University of Maryland Libraries

Weber constructed resonant "bar" detectors on the University of Maryland campus in the 1960s and collected data to search for GW signals

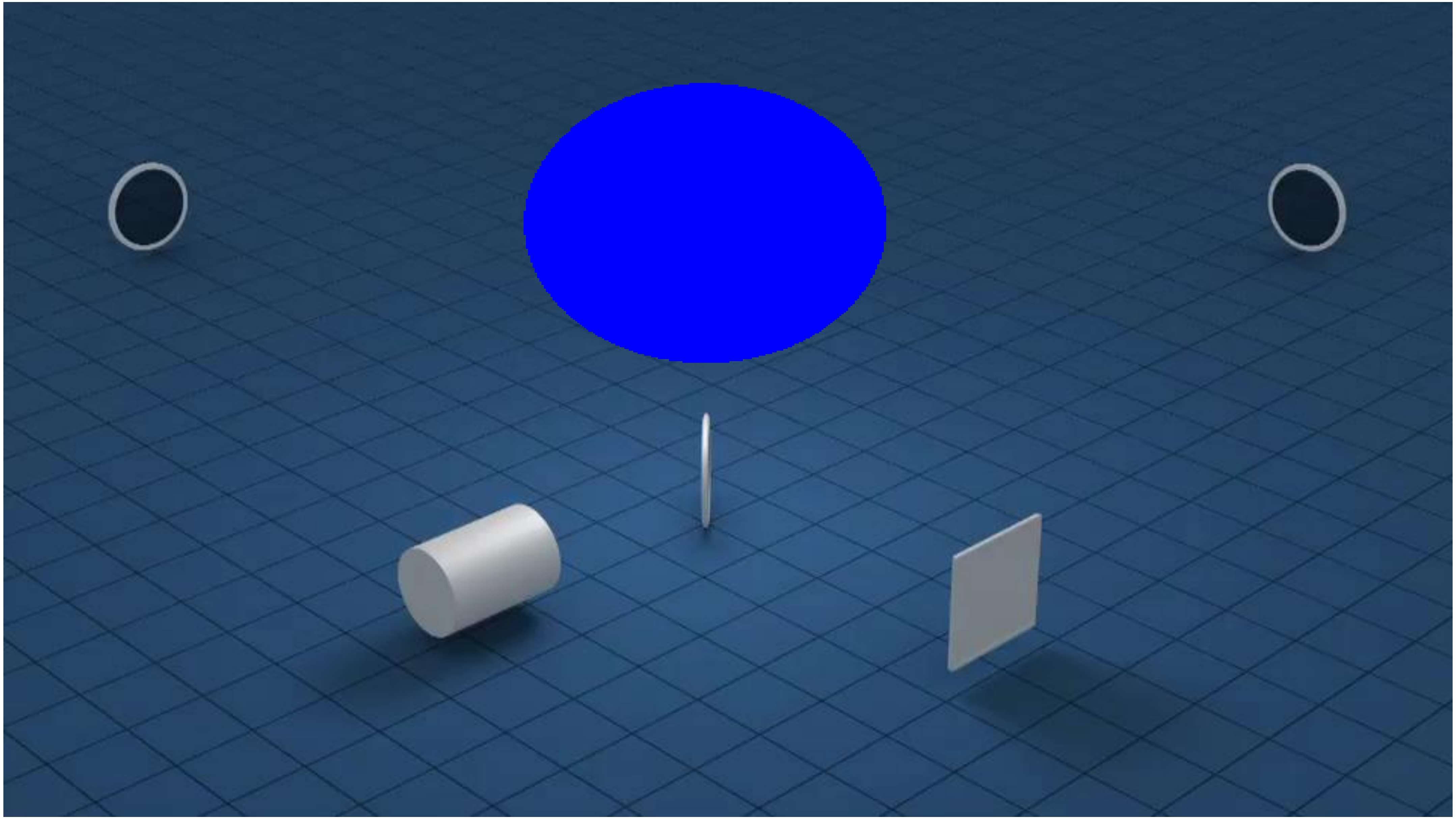
"Detection and generation of gravitational waves", Phys. Rev. **117**, 306 (1960)

He even claimed, in 1969, to have detected coincident signals in widely separated bars!

"Evidence for discovery of gravitational radiation", Phys. Rev. Lett. **22**, 1320 (1969)

... But other researchers did not confirm those claims with their own detectors

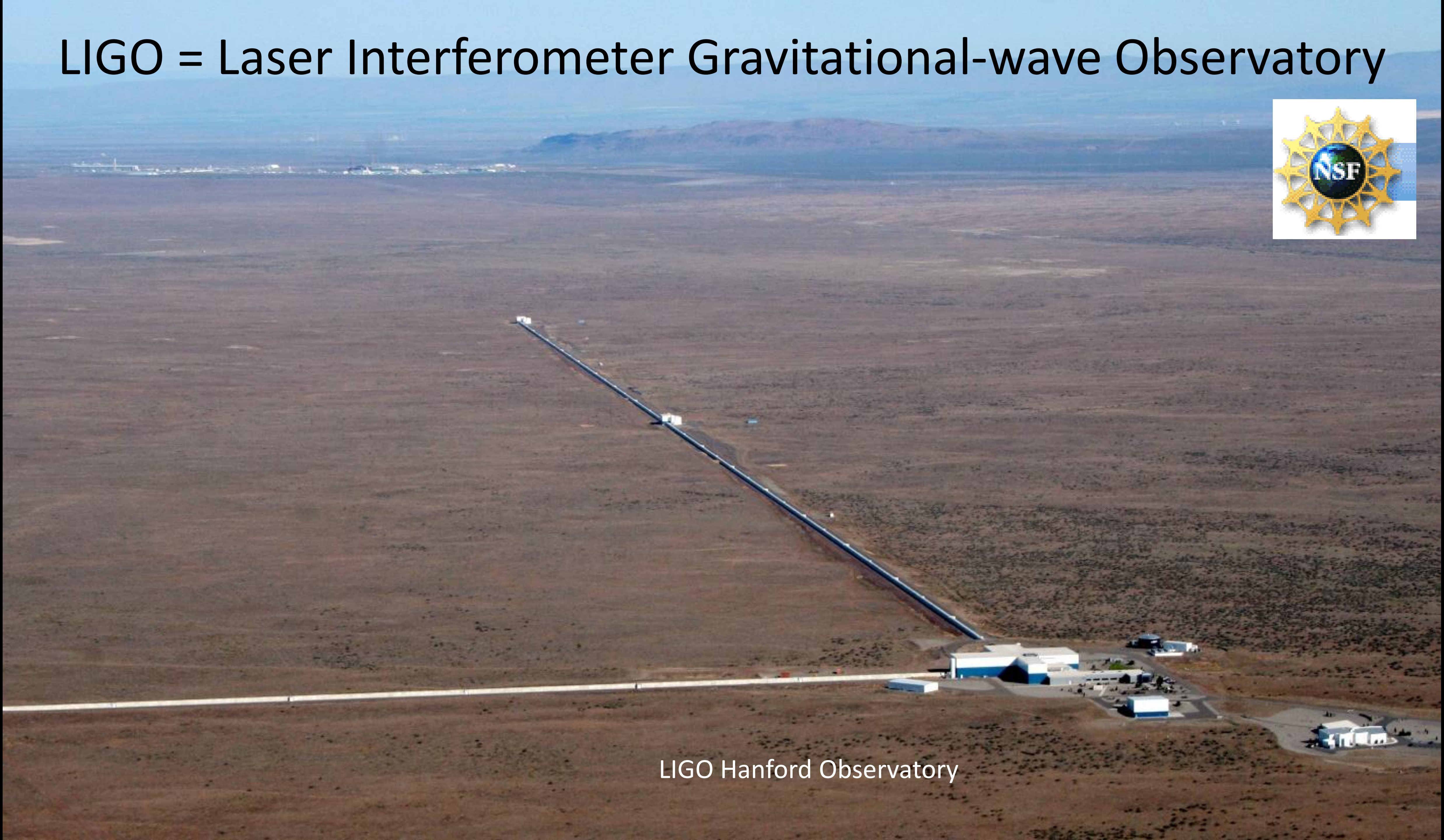
Laser interferometers can detect such signals!



LIGO / T. Pyle

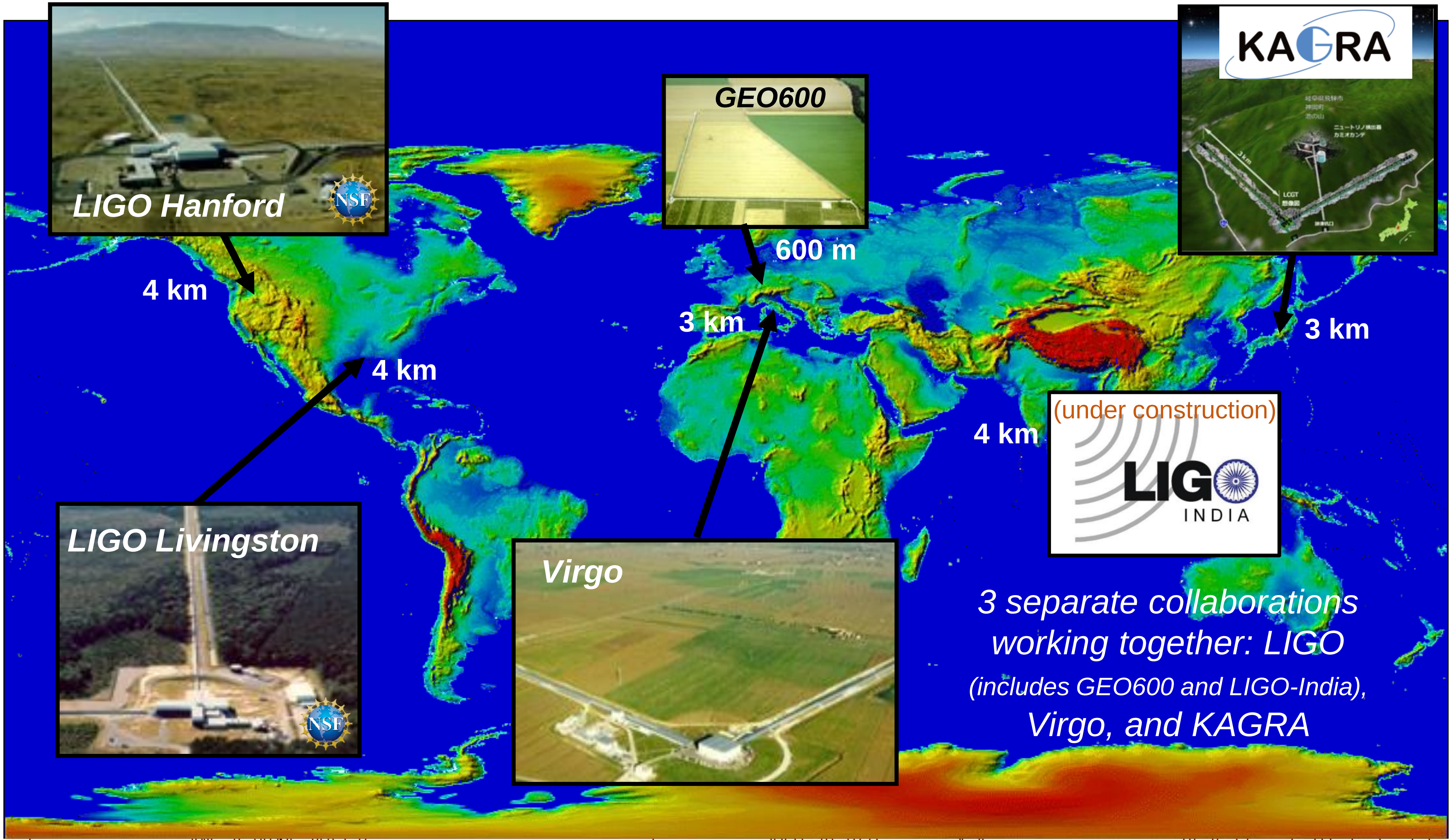
Four decades of developing and improving highly sensitivity detectors...

LIGO = Laser Interferometer Gravitational-wave Observatory



LIGO Hanford Observatory

The International Gravitational-Wave Detector Network

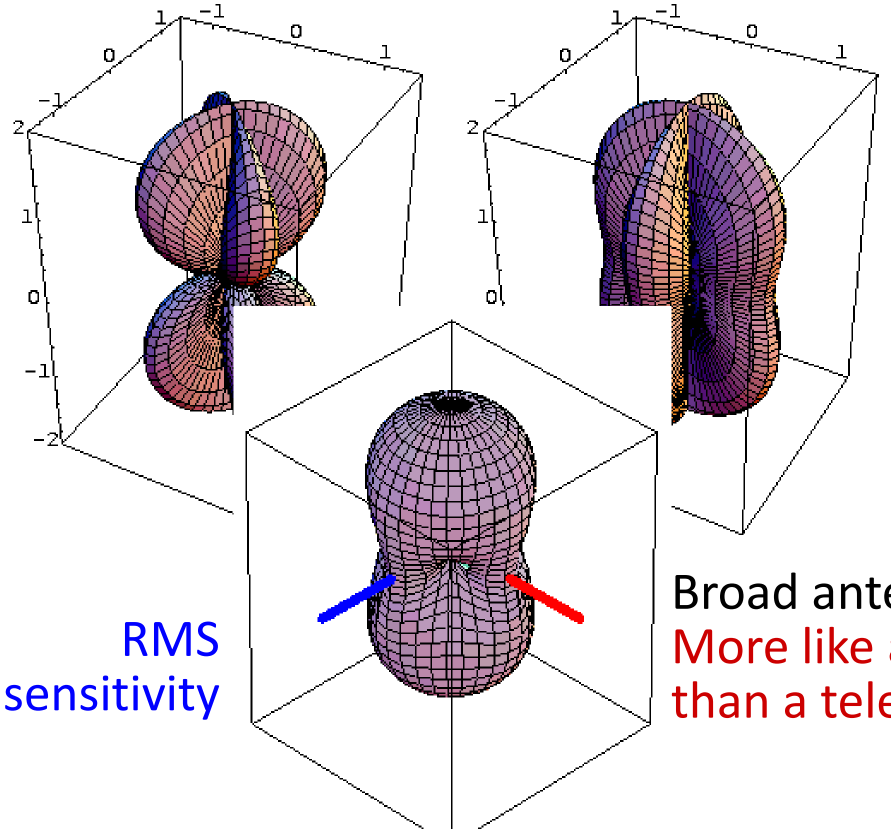


Antenna response of an interferometric detector

LIGO, Virgo and KAGRA use interferometry to measure *differential* changes in the lengths of their two orthogonal arms

➔ Their response to a GW depends on the arrival direction and polarization of the incoming wave

× polarization* + polarization*



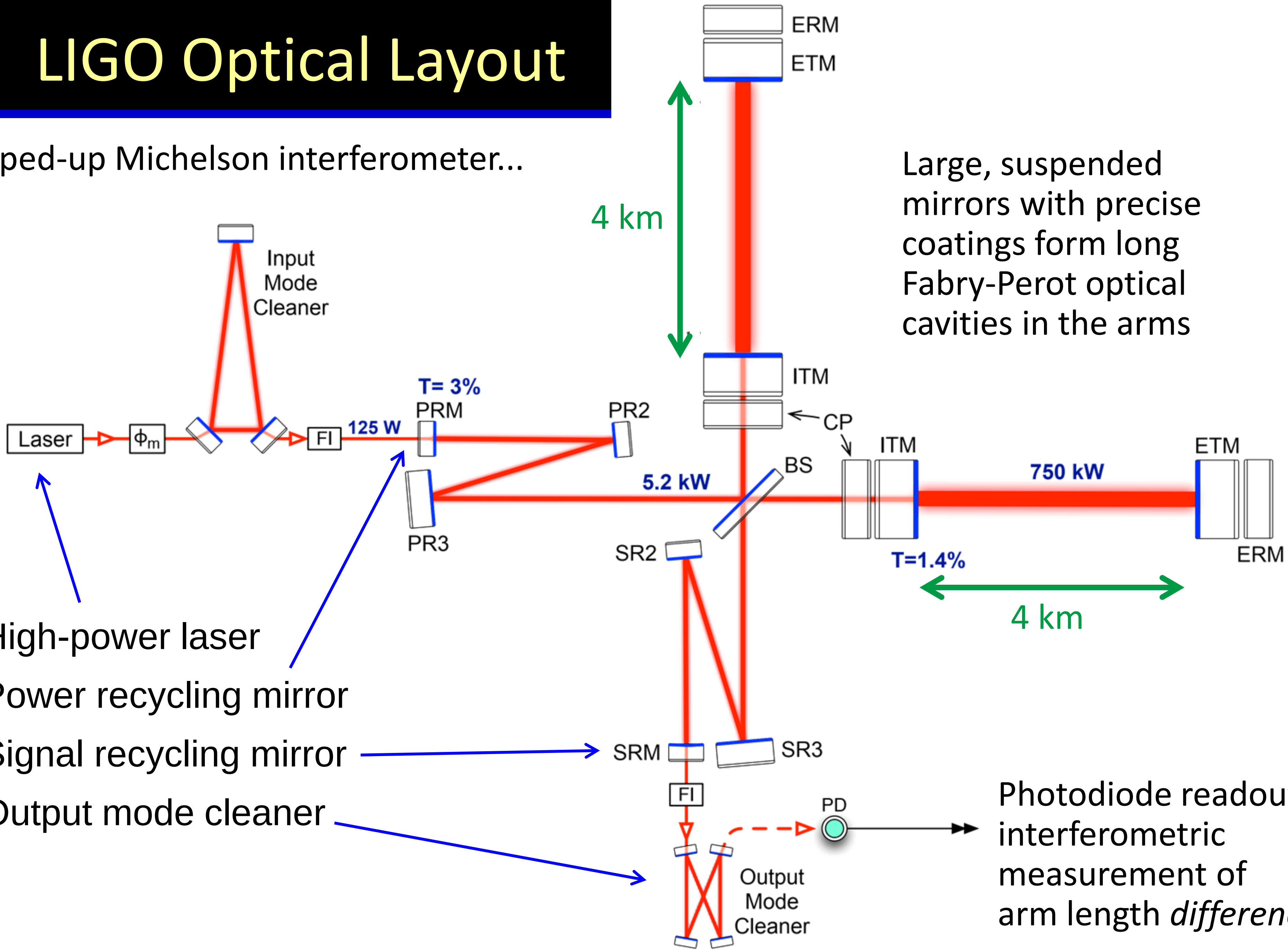
* (in some wave frame basis)

RMS sensitivity

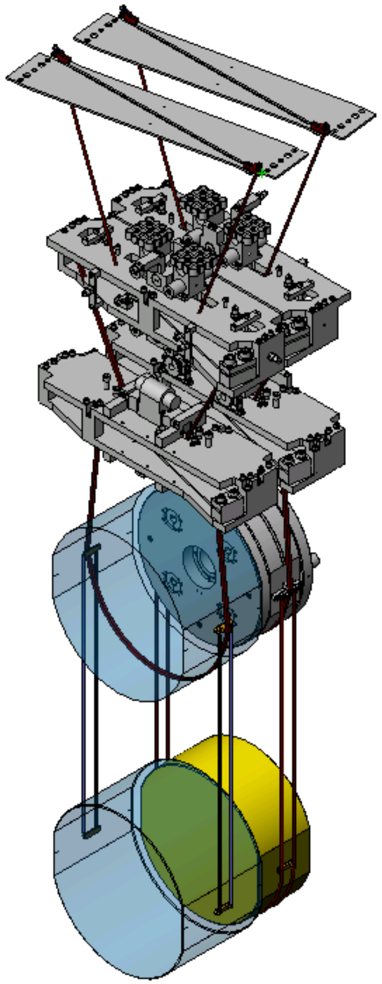
Broad antenna pattern ⇒ More like a radio receiver than a telescope

LIGO Optical Layout

A souped-up Michelson interferometer...



Large, suspended mirrors with precise coatings form long Fabry-Perot optical cavities in the arms



High-power laser

Power recycling mirror

Signal recycling mirror

Output mode cleaner

Photodiode readout for interferometric measurement of arm length *difference*

Laser beams travel inside evacuated tubes

Vacuum System in Corner Station

Approximating "freely falling" test masses

We cannot literally drop our mirrors.
We need to suspend them in the lab frame.

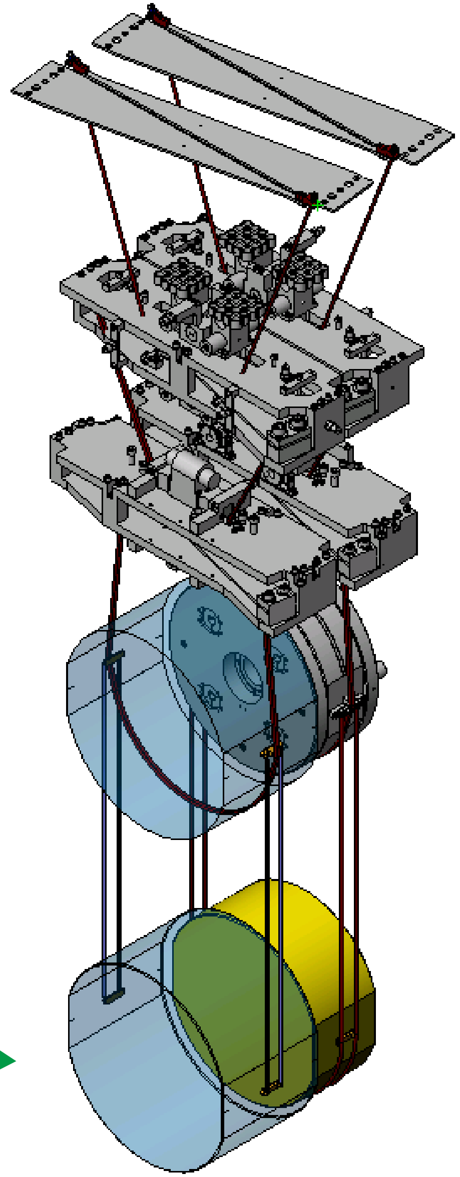
A "pendulum" suspension isolates the mirror from vibrations of the ground & lab, transmitted through the support structure

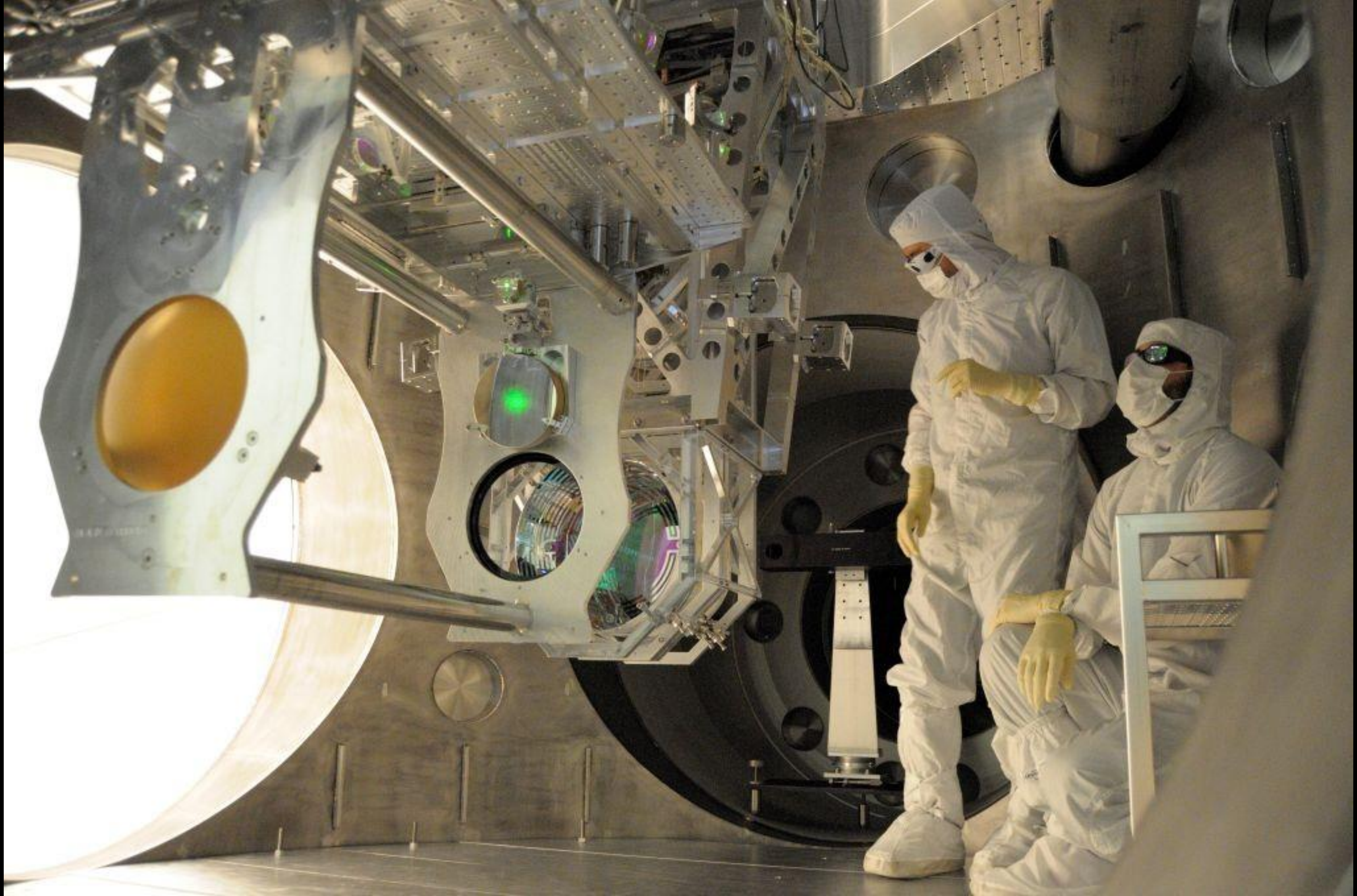
We call that *seismic noise* regardless of its source

We use multiple pendulum suspensions in layers,
and also active feedback systems, to achieve a very steeply falling transfer function for vibrations as a function of frequency

Also carefully manage noise introduced by feedback systems used to gently control the positions and angles of the mirrors

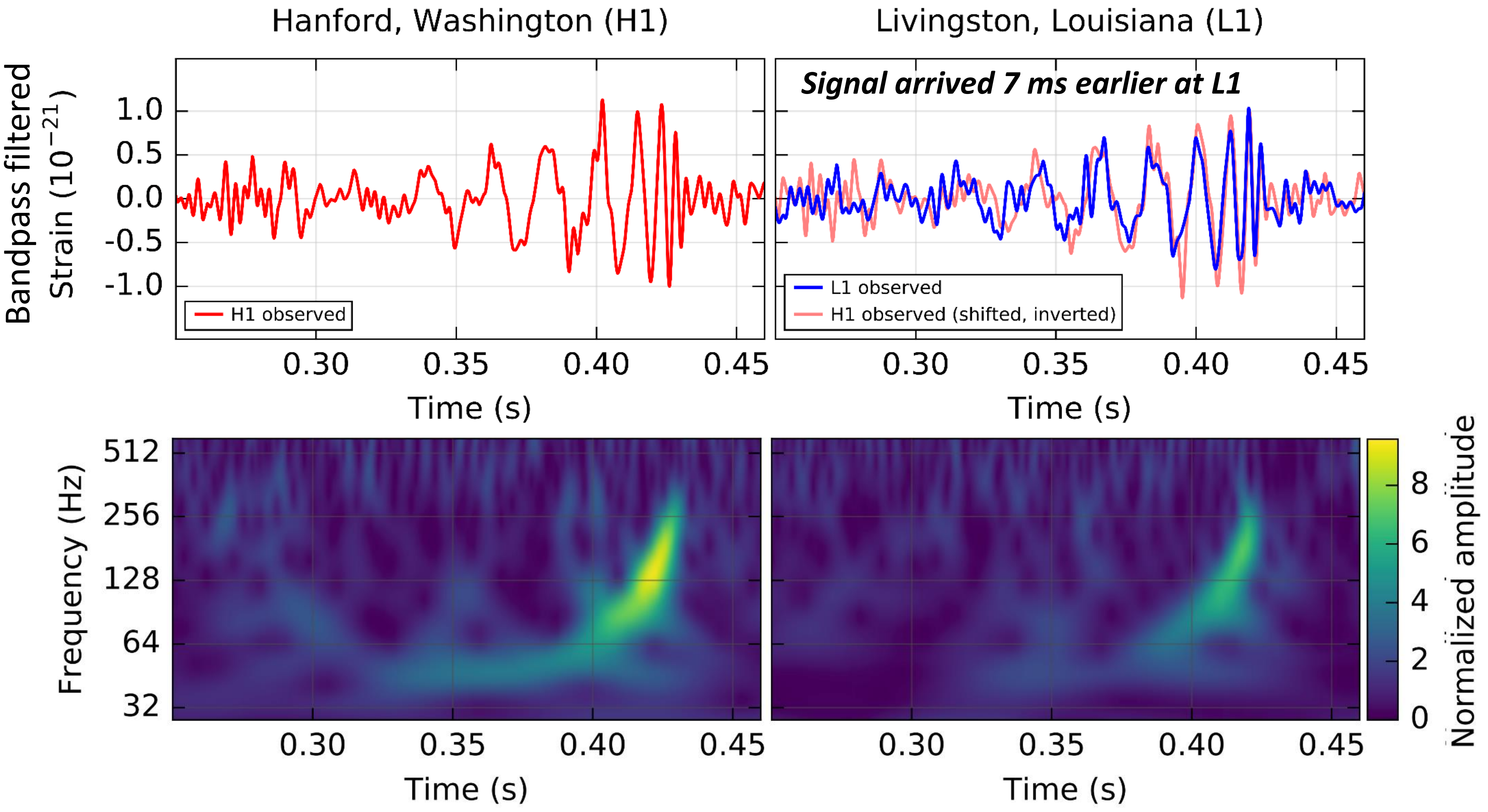
This mirror is the actual test mass

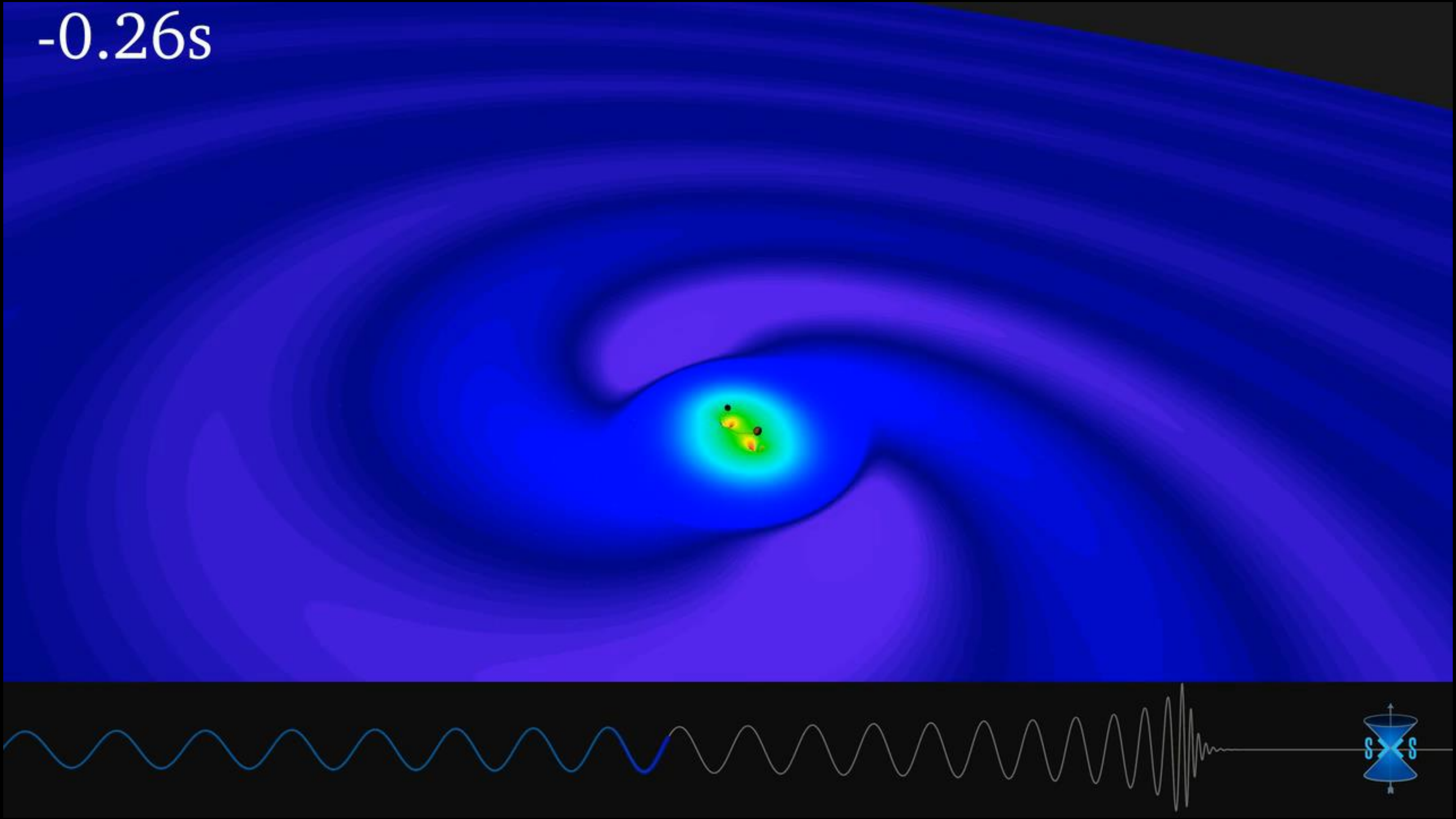




Detection!

First detection! GW150914




-0.26s

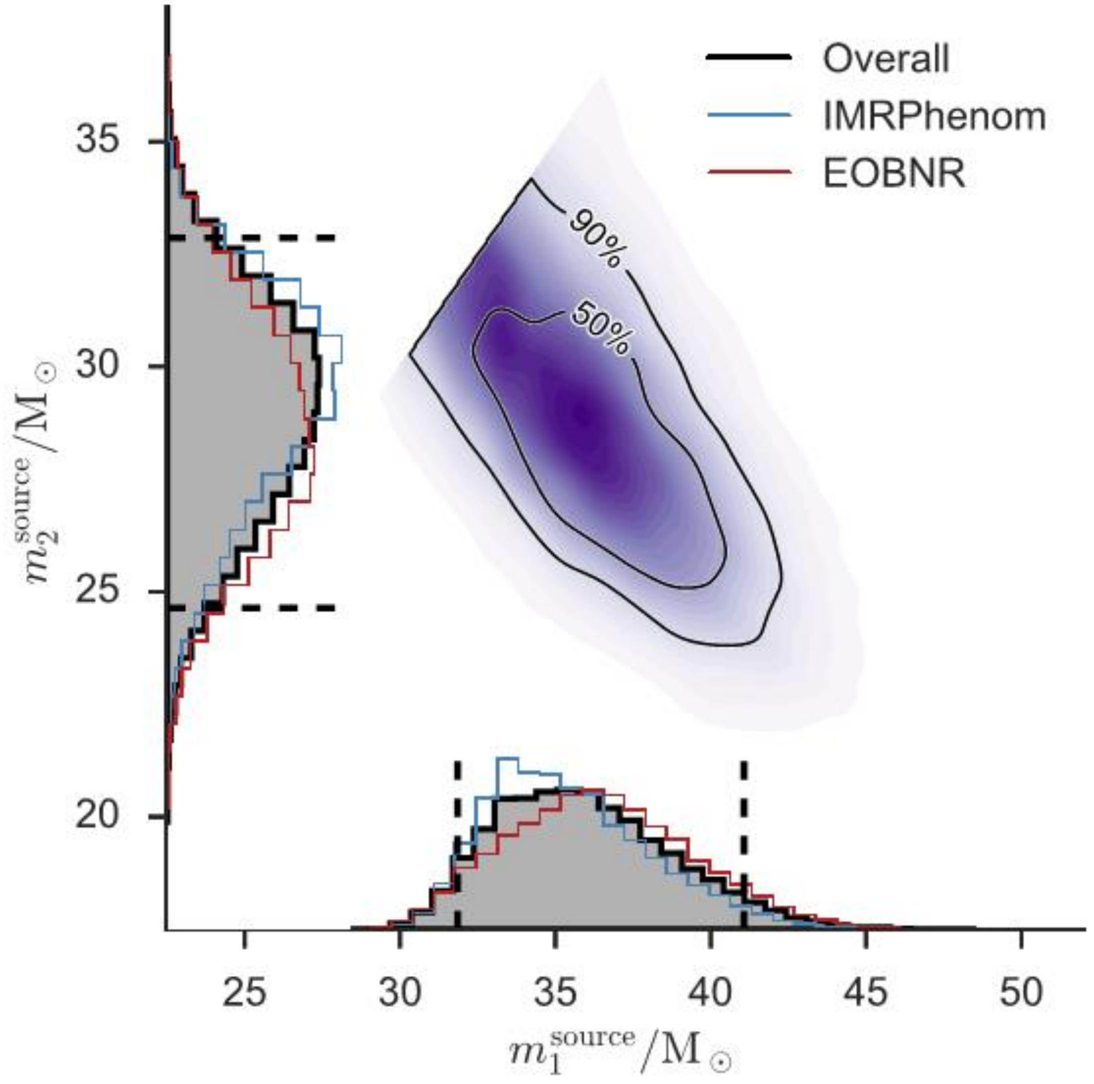
Physical scales

From the details of the signal waveforms, determined that these black holes had masses of about **36** and **29** times the mass of the Sun

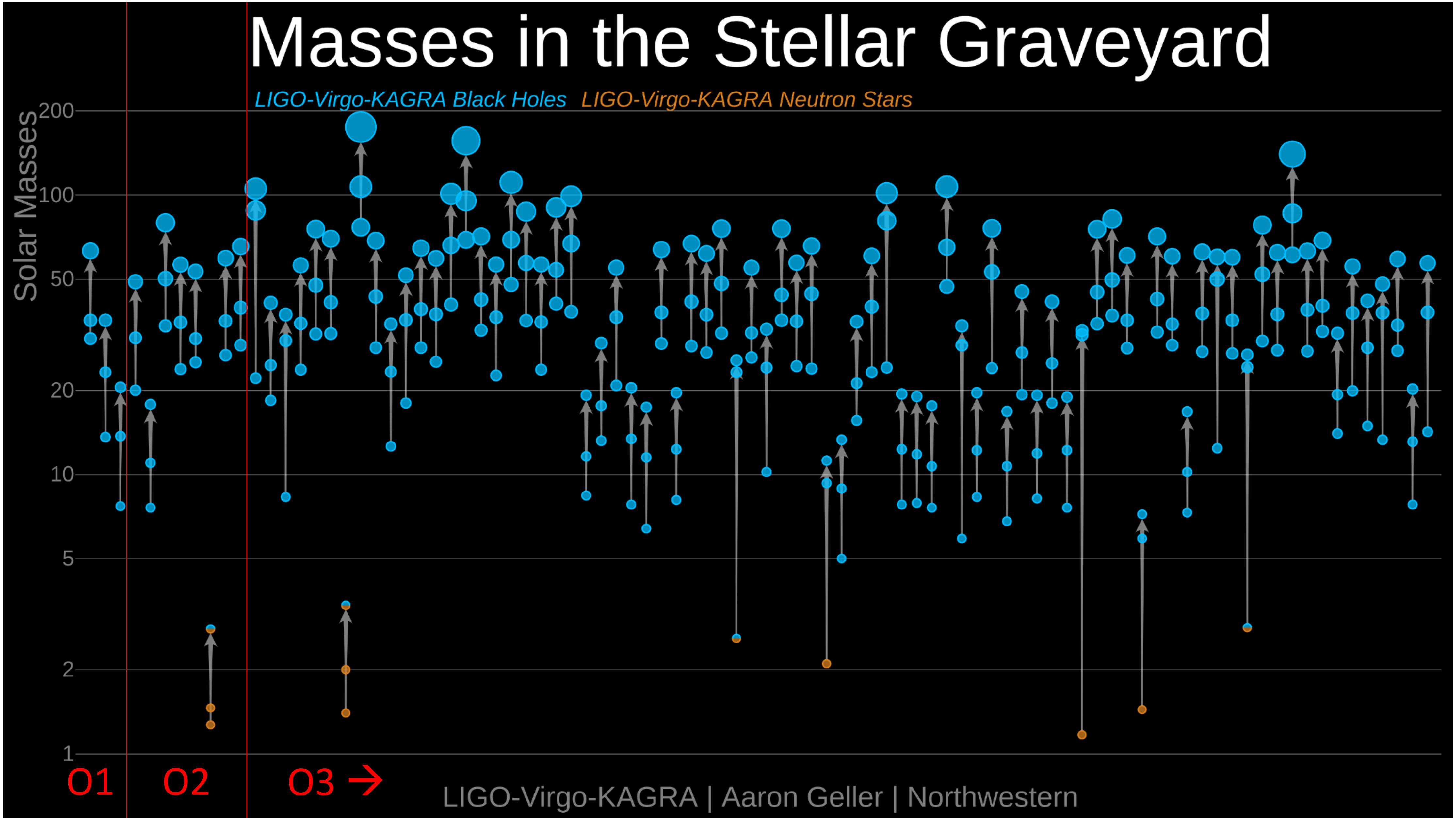
With Schwarzschild radii of about **100 km**

They released about **3** solar masses of energy ($E = mc^2$) in the form of gravitational waves as they spiraled together and merged

They merged about 1.3 billion light years ($\sim 10^{22}$ km) away from Earth

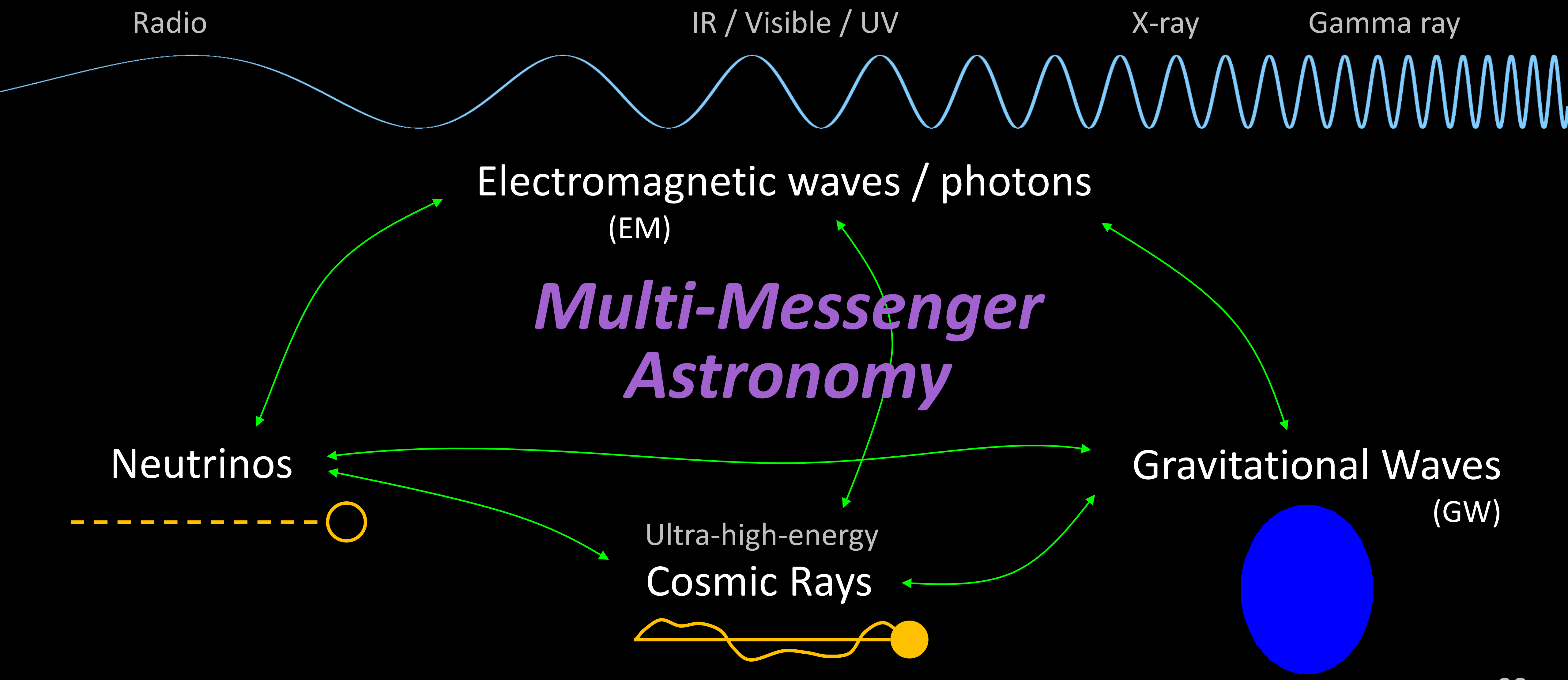


GW signals confidently identified & published by LVK from data collected in 2015–2020



Multi-Messenger Astronomy and Astrophysics

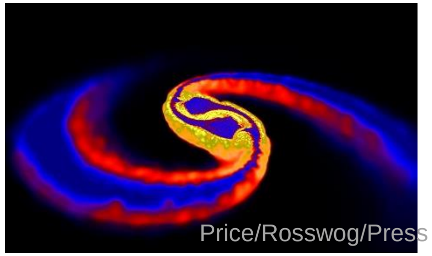
Astrophysical “Messengers”



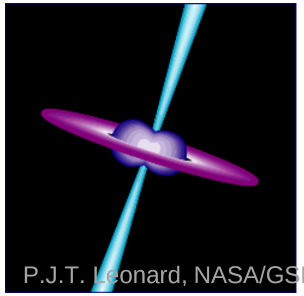
Expectations for Multi-Messenger Sources!

BNS inspiral+merger

Disrupted NS material

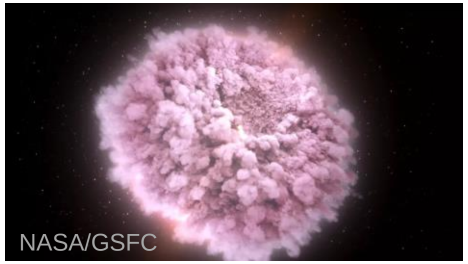

Price/Rosswog/Press

Accretes around remnant, makes **jet**


P.J.T. Leonard, NASA/GSFC

→ Gamma-ray burst (GRB)
→ “Afterglow” at many EM wavelengths
→ High-energy neutrinos?

Forms heavy elements which fly away & **decay**


NASA/GSFC

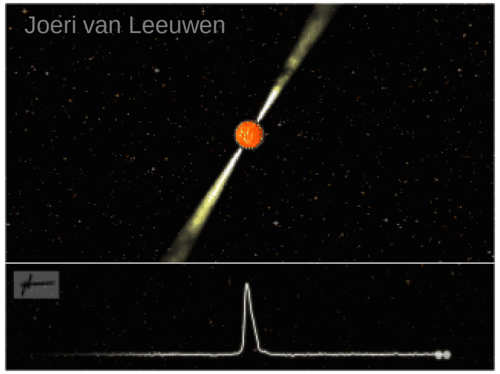
→ “Kilonova” signature of UV / visible / infrared light (thermal emission)

Core collapse of a high-mass star


Bill Saxton, NRAO/AUI/NSF

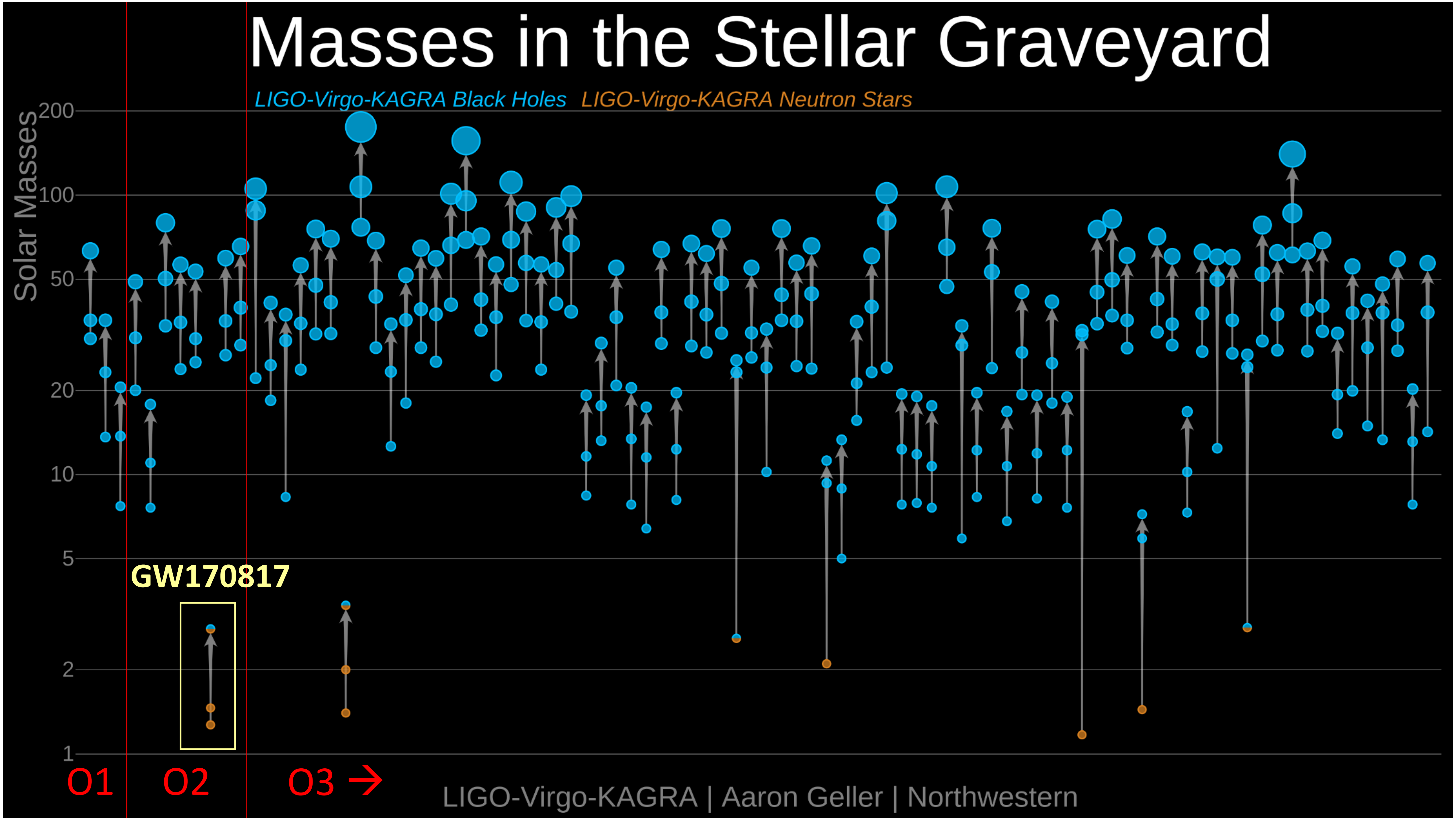
Nuclear reactions → Neutrinos
Expanding envelope → Visible/infrared
Shock acceleration → Cosmic rays

A rapidly rotating neutron star


Joeri van Leeuwen

→ Pulsed radio, X-ray or gamma-ray emission (“pulsar”)

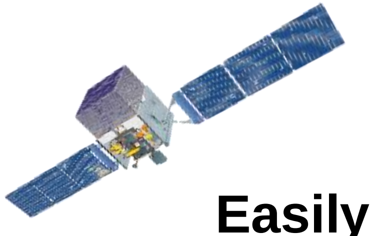
First binary neutron star (BNS) merger!



GW170817 announces itself!

Trigger G298048

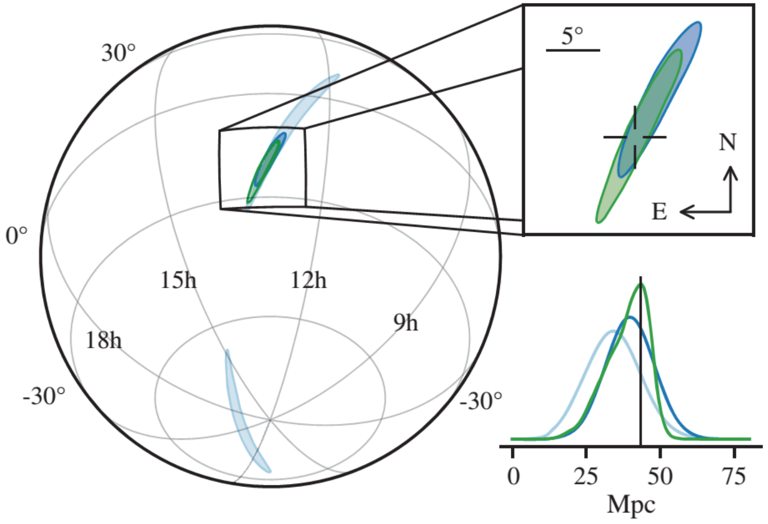
Initially found using a template with typical neutron star masses



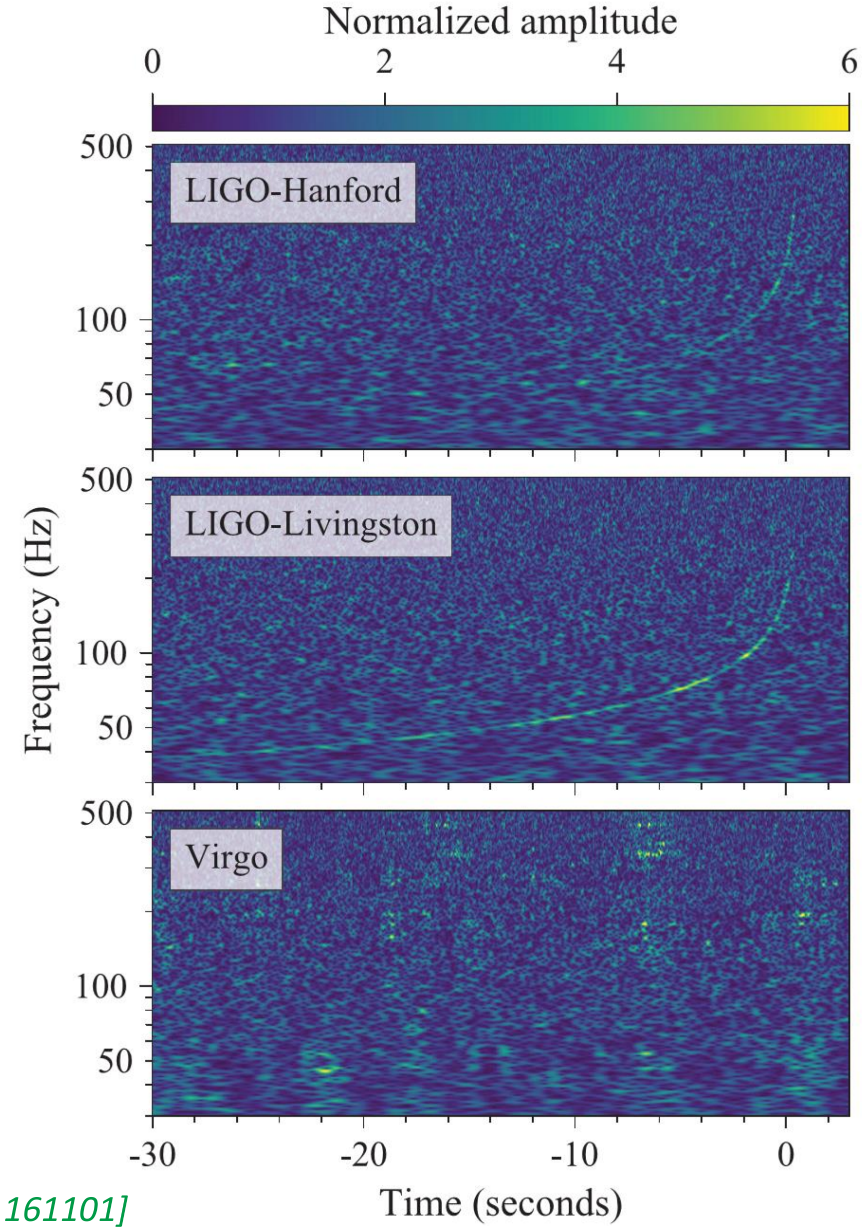
Accompanied (within ~2 sec) by a short gamma-ray burst (GRB) detected by the GBM instrument on NASA's Fermi satellite!

Easily visible in LIGO data spectrograms!

LIGO+Virgo located it in the sky it pretty well



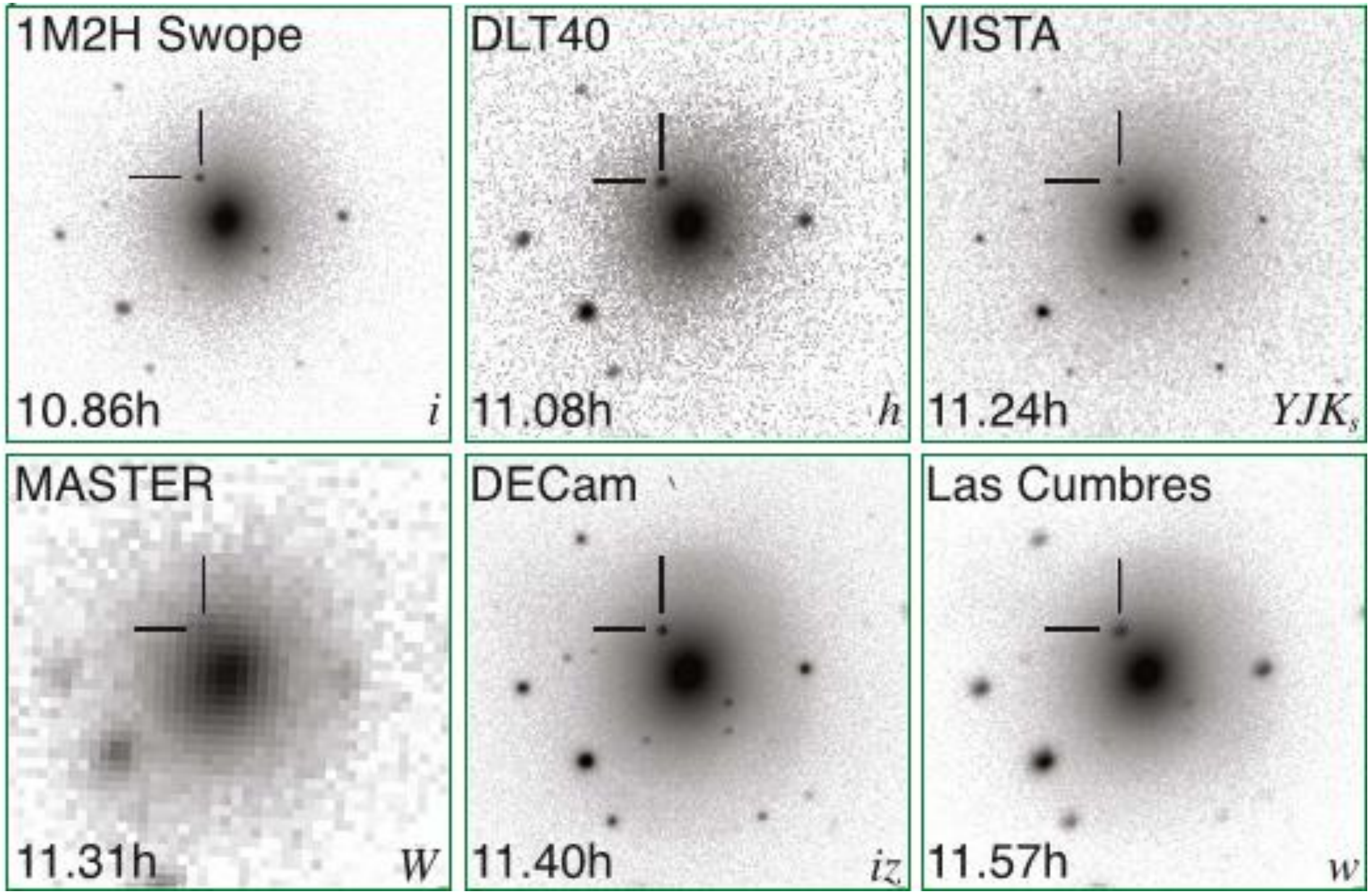
To an area of ~31 deg^2
(after working around a glitch in the LIGO-Livingston data),
ultimately to ~16 deg^2



[Abbott et al. 2017, PRL 119, 161101]

Astronomers found the optical counterpart!

Independently found by 6 teams, within a span of ~45 minutes, in the galaxy NGC 4993



GRB 170817A

GW170817

SSS17a

DLT17ck

MASTER J130948.10-232253.3

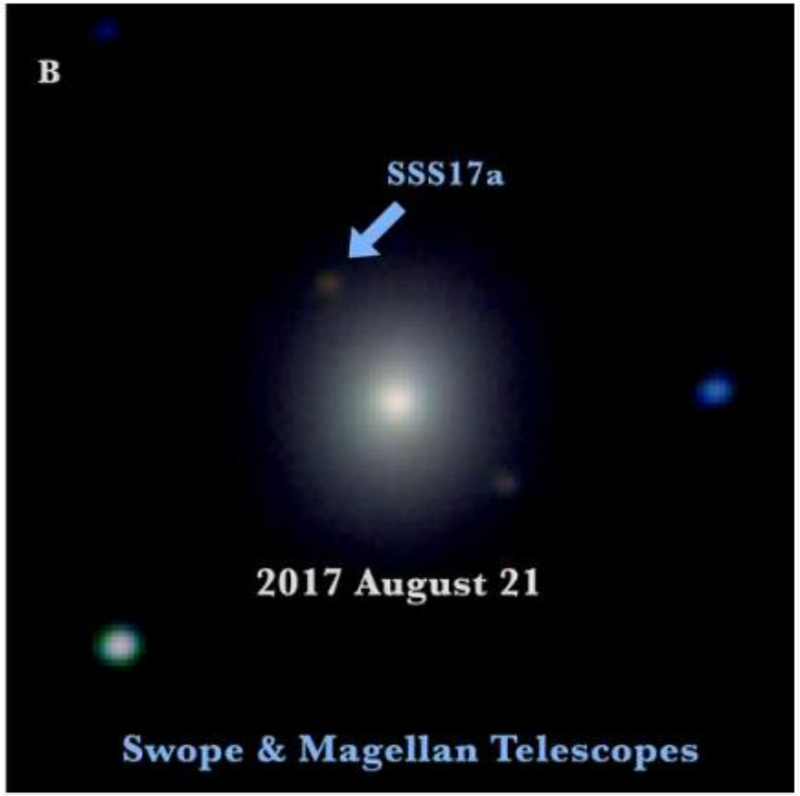
→ AT 2017gfo

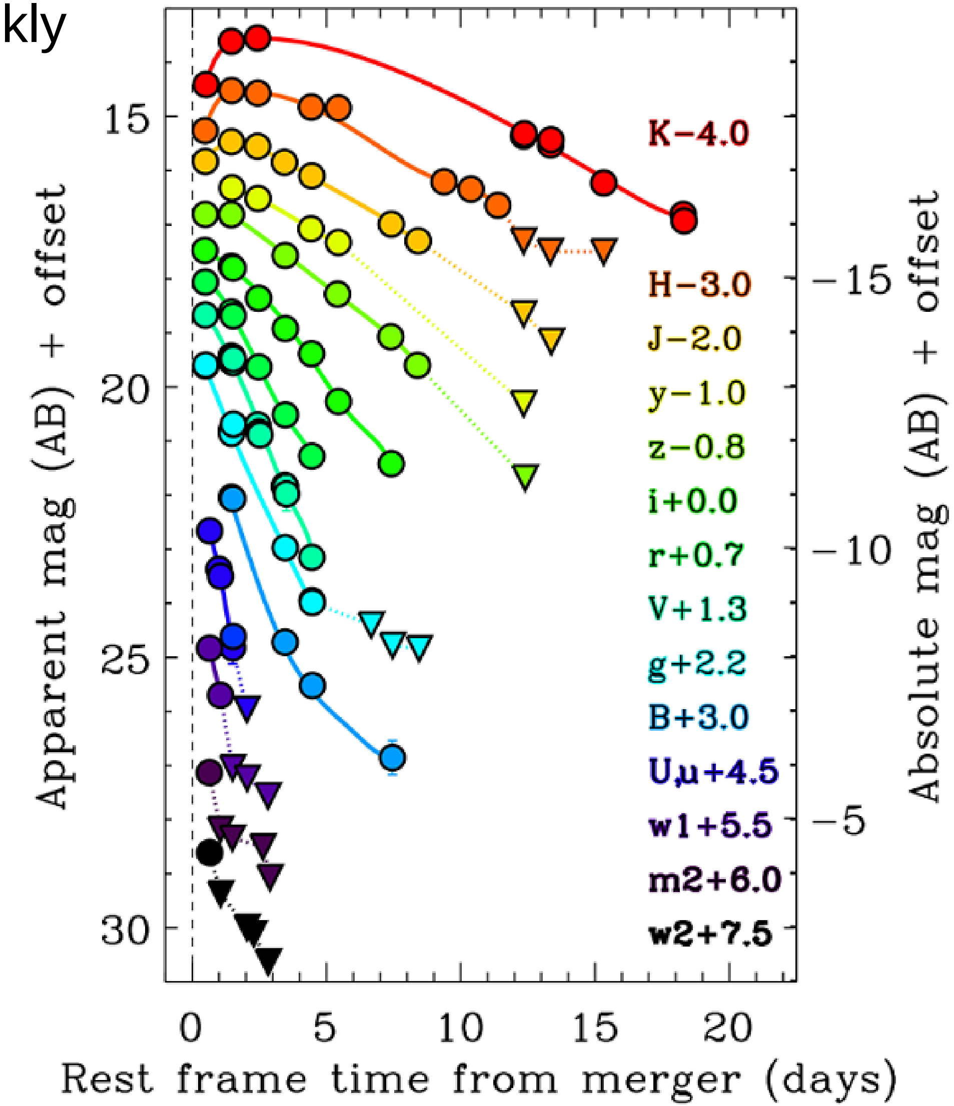
[Abbott and many others 2017, ApJL 848, L12]

Watching it fade – and change color

Initially visible in ultraviolet and blue—but those faded quickly

Infrared peaked after 2-3 days, remained visible for weeks as the remnant cooled…

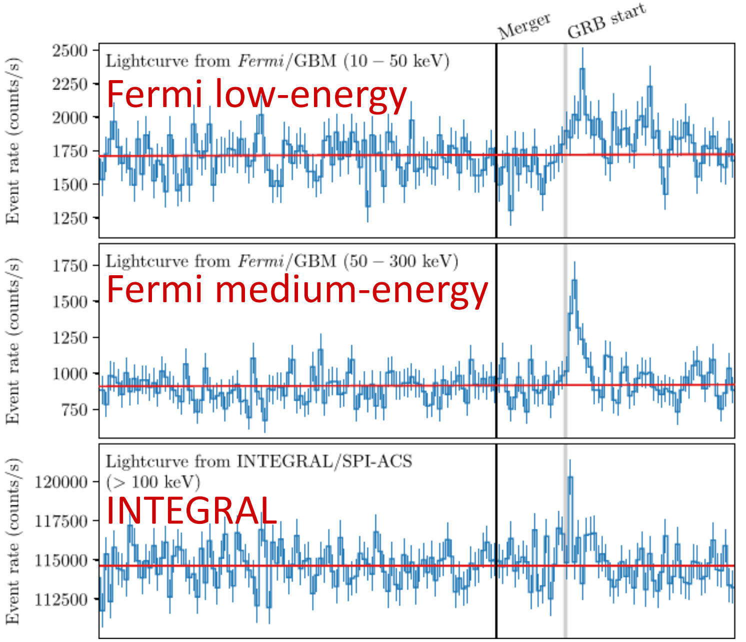




[Drout et al. 2017, Science 10.1126/science.aaq0049]

GRB 170817A / AT2017gfo Electromagnetic Signatures

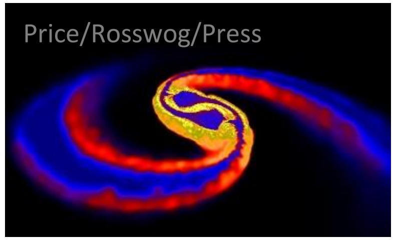
Gamma-Ray Burst



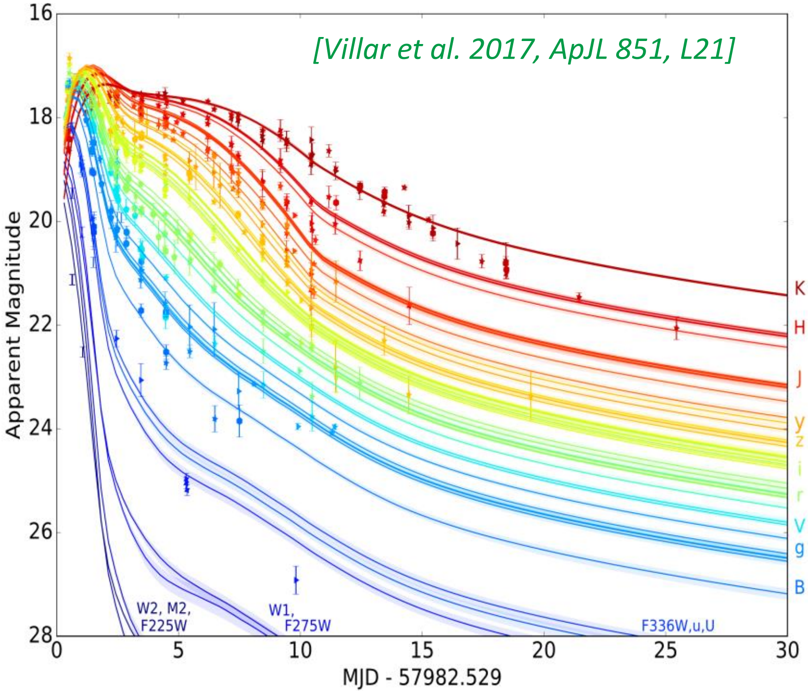
[LSC, Fermi-GBM and INTEGRAL 2017, ApJL 848, L13]

Pretty typical observed properties, but very dim (i.e., low E_{iso}) considering how close it was

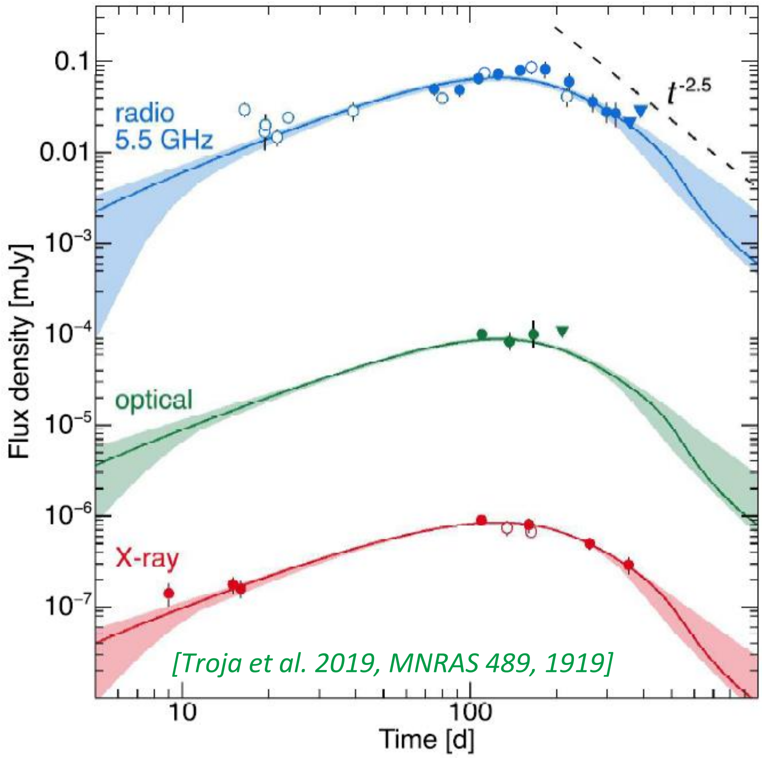
Kilonova



Thermal emission from ejected material, heated by decay of *r*-process elements formed in event



Afterglow

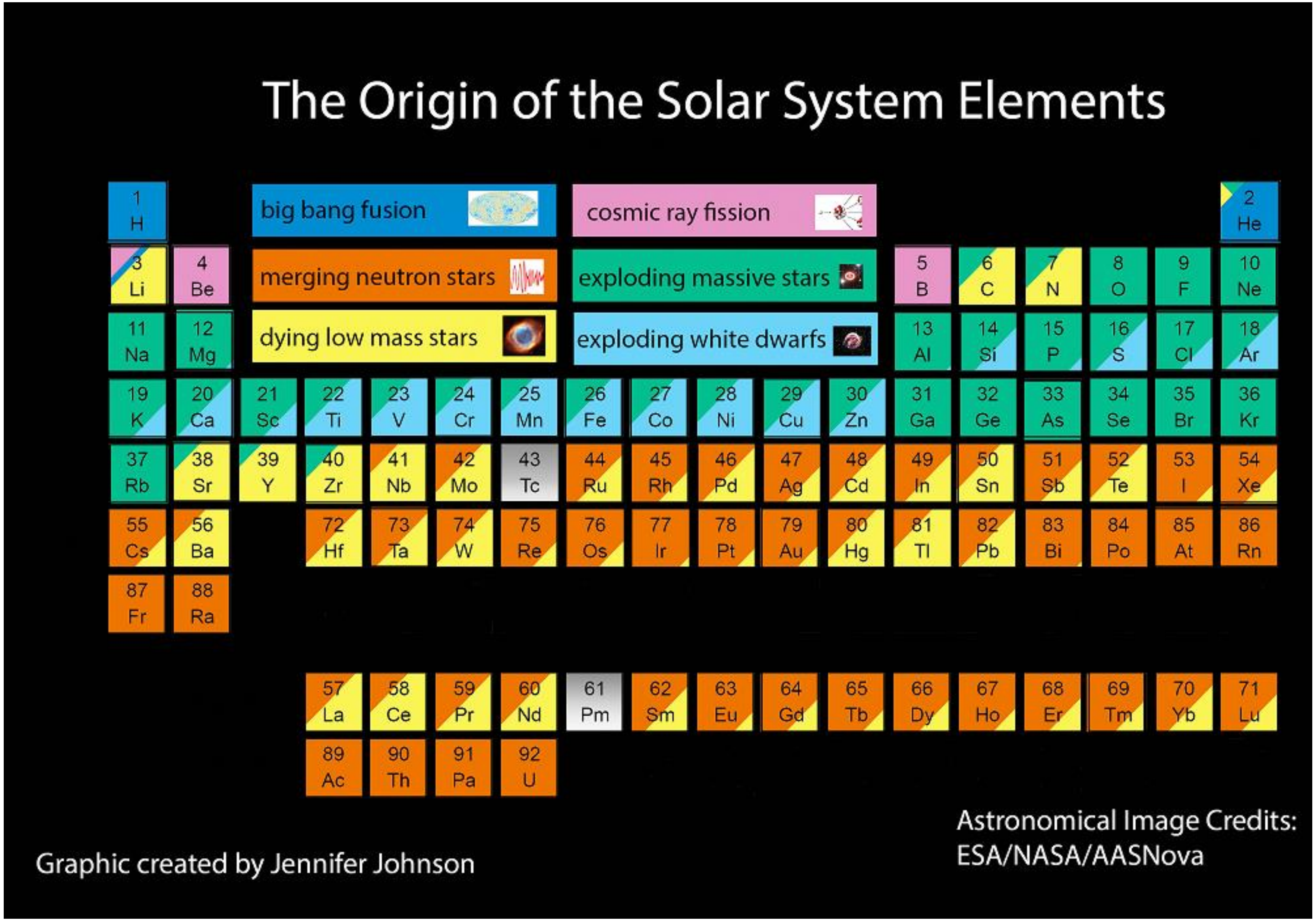


Slow onset and rise, constant spectral index completes picture of a successful jet off-axis by around ~20°

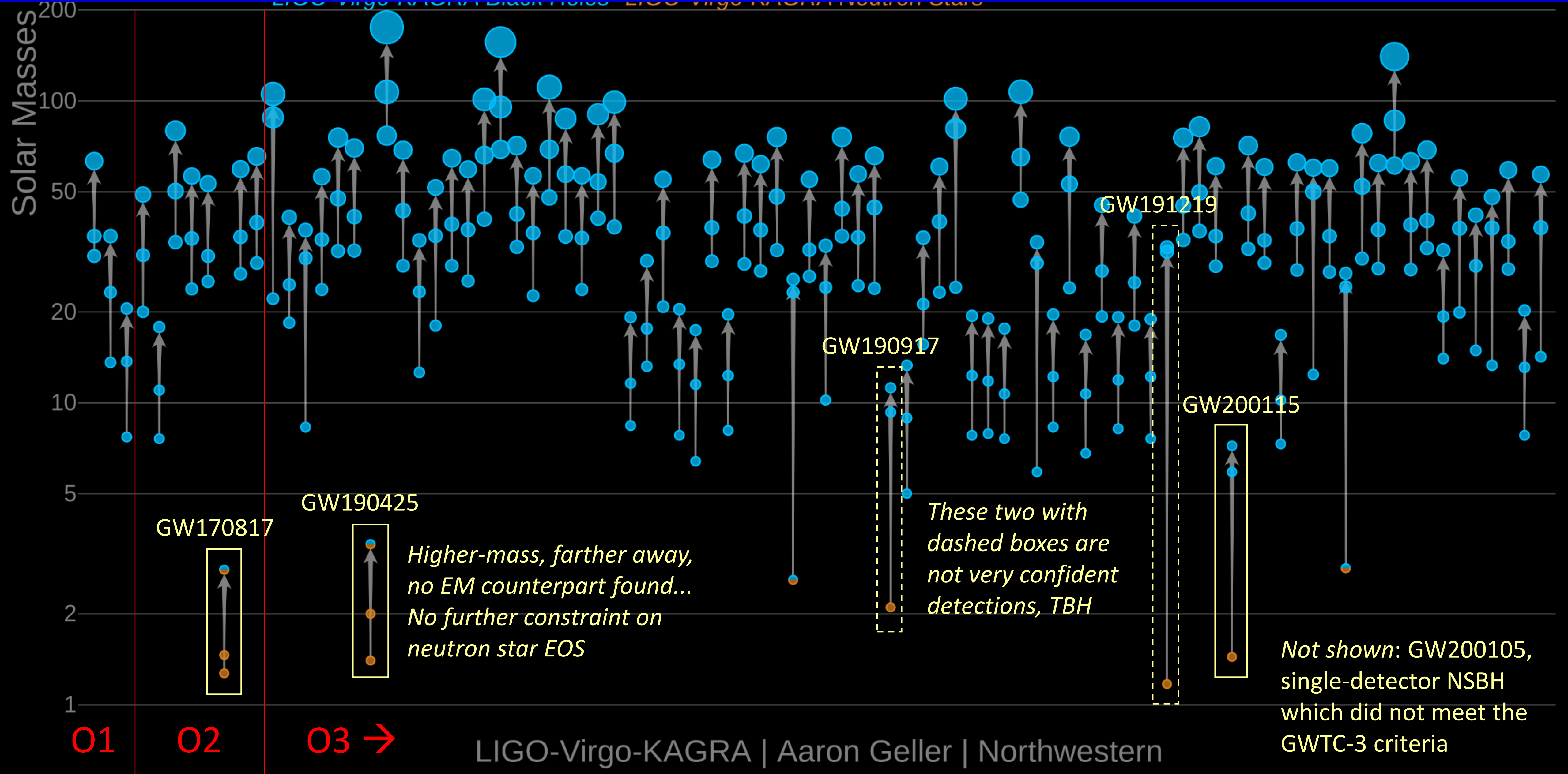
Nuclear Physics Implications

It has become more clear in recent years that neutron star mergers probably produced a majority of the very heavy elements in the periodic table –
"r-process nucleosynthesis" from **r**apid neutron capture

The details are still a matter of debate, though.

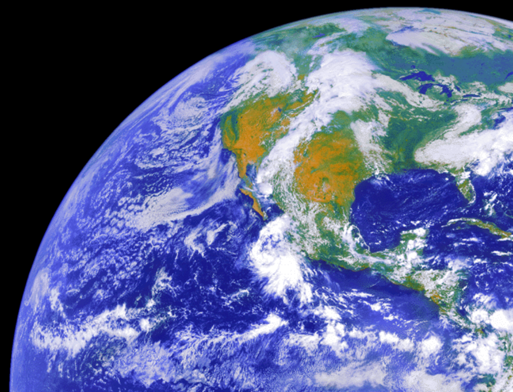


Eagerly awaiting more NS binary detections!



How can gravitational wave detectors tell us about nuclear and particle physics?

- Via the details of the GW signal from a neutron star binary merger
- From electromagnetic emissions associated with a neutron star binary merger
- Through GW signals from ultralight boson clouds which may form around black holes
- By direct interaction of exotic particle states with the mirrors of GW detectors



What do you mean, a *boson cloud*?

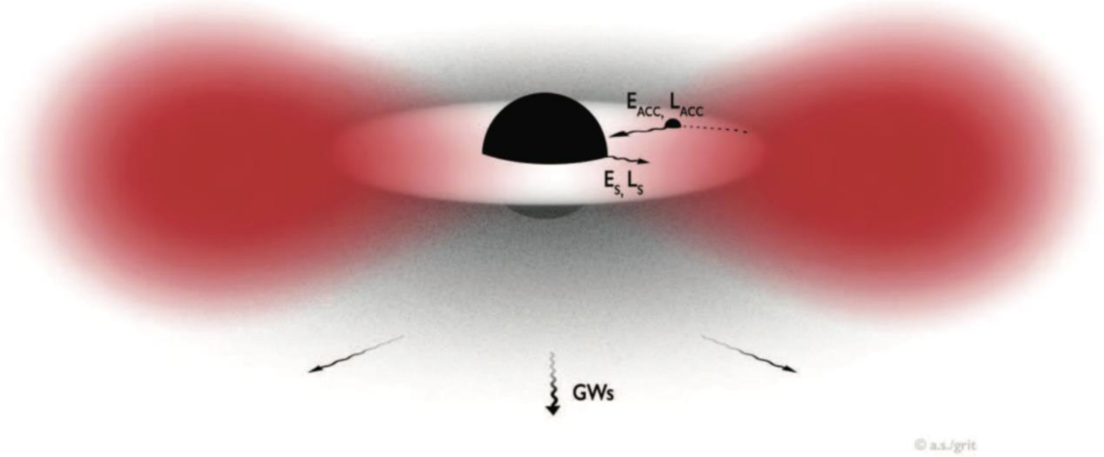
Suppose there is a very light bosonic particle state, with mass $\sim 10^{-12}$ eV

It may interact weakly with standard model particles, or not at all

The Compton wavelength of such a particle would be comparable to the Schwarzschild radius of an astrophysical black hole

So a coherent state could interact and be bound by the black hole's gravitational potential, as a sort of *gravitational atom* but with bosons instead of electrons

If the black hole is spinning rapidly enough, *superradiance* can occur:
an instability causes the particle condensate to grow by extracting energy and angular momentum from the black hole's spin



e.g. see Brito et al. 2017, PRD 96, 064050

Gravitational waves from ultralight boson clouds

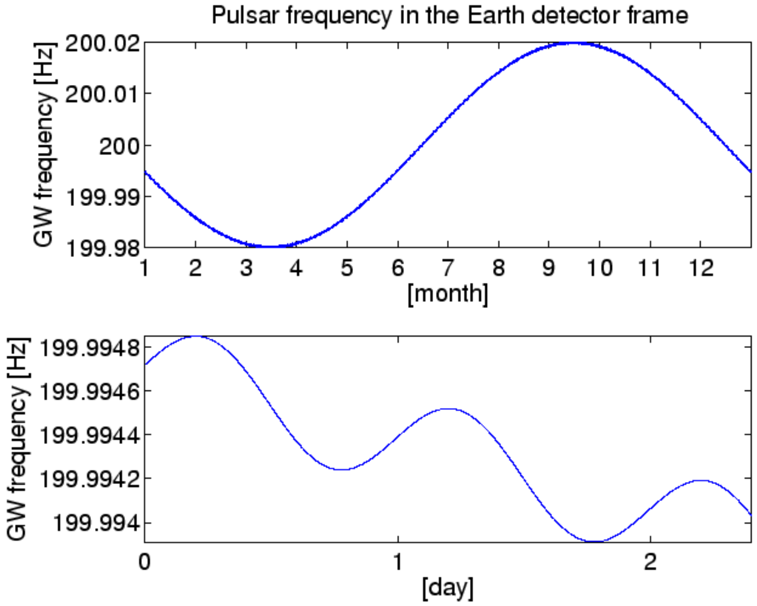
There could be some BHs with clouds in the nearby universe at any given time

After forming quickly (evolving until the superradiant condition is no longer satisfied), the condensate would decay by annihilation of bosons to gravitons, emitting gravitational waves over a timescale of $\sim 10^3$ to 10^6 years

These GWs would be detected as a nearly monochromatic oscillating signal with a frequency of a few hundred Hz — perfect for LIGO/Virgo/KAGRA !

The signal would not be perfectly monochromatic, because:

- The frequency will shift slightly (upward) as the cloud is depleted
- The GW detectors are located on the spinning, orbiting Earth, so the signal received by them has a time-dependent Doppler correction which depends on where in the sky it is coming from



Online Resources

ligo.org website

Resources ⌄ Collaboratio

- Multimedia
- Education
- Science Summaries
- LIGO Magazine
- Request Speaker
- Press Guide
- FAQ

2025

▾ **Looking for short-duration gravitational wave sources in the deep dark sky**
2025-07-22 PDF: [en] [it] [ja] [vi]

▾ **All-sky search for long-duration gravitational-wave transients in the first eight months of the fourth Advanced LIGO-Virgo-KAGRA observing run**
2025-07-22 PDF: [en] [ca] [es] [it] [ja] [pt] [vi]

▾ **GW231123: The most massive black hole binary detected through gravitational waves**
2025-07-14
PDF: [en] [bn] [ca] [de] [el] [es] [fi] [fr] [hi] [it] [ja] [ma] [mr] [pt] [ta] [vi] [zh-Hans]

▾ **No continuous gravitational waves from 45 known pulsars in O4a data**
2025-01-10 PDF: [en] [ca] [de] [es] [gl] [it] [ja] [nl] [ro] [vi] [zh-Hant]

2024

- **[gl]**: Galician (Galego)
- **[he]**: Hebrew (Ivrit / עִבְרִית)
- **[hi]**: Hindi (मानक हिन्दी)
- **[hu]**: Hungarian (Magyar)
- **[it]**: Italian (Italiano)
- **[ja]**: Japanese (Nihongo / 日本語)
- **[ko]**: Korean (Hanguk-eo / 한국어)
- **[ma]**: Malayalam (മലയാളം)
- **[mr]**: Marathi (मराठी)
- **[ne]**: Nepali (नेपाली)
- **[nl]**: Dutch (Nederlands)
- **[pl]**: Polish (Polski)
- **[pt]**: Portuguese (Português)
- **[ro]**: Romanian (Română)
- **[ru]**: Russian (Rússkiy / русский)
- **[ta]**: Tamil (தமிழ்)
- **[vi]**: Vietnamese (Tiếng Việt)
- **[zh]**: Chinese (Hànyǔ); sometimes two versions are available:
  - **[zh-Hans]** (simplified

Gravitational Wave

Open Science Center

Discover Gravitational-Wave Observatory Data, Tutorials, and Software Tools.

Explore Data

Learn

gwosc.org

Event Catalog

The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of events detected by LIGO, Virgo, and KAGRA.

Open Data Workshop

Participants will receive a crash-course in gravitational-wave data analysis that includes lectures, software tutorials, and a data challenge.

Tutorials

Learn with tutorials that will lead you step-by-step through some common data analysis tasks.