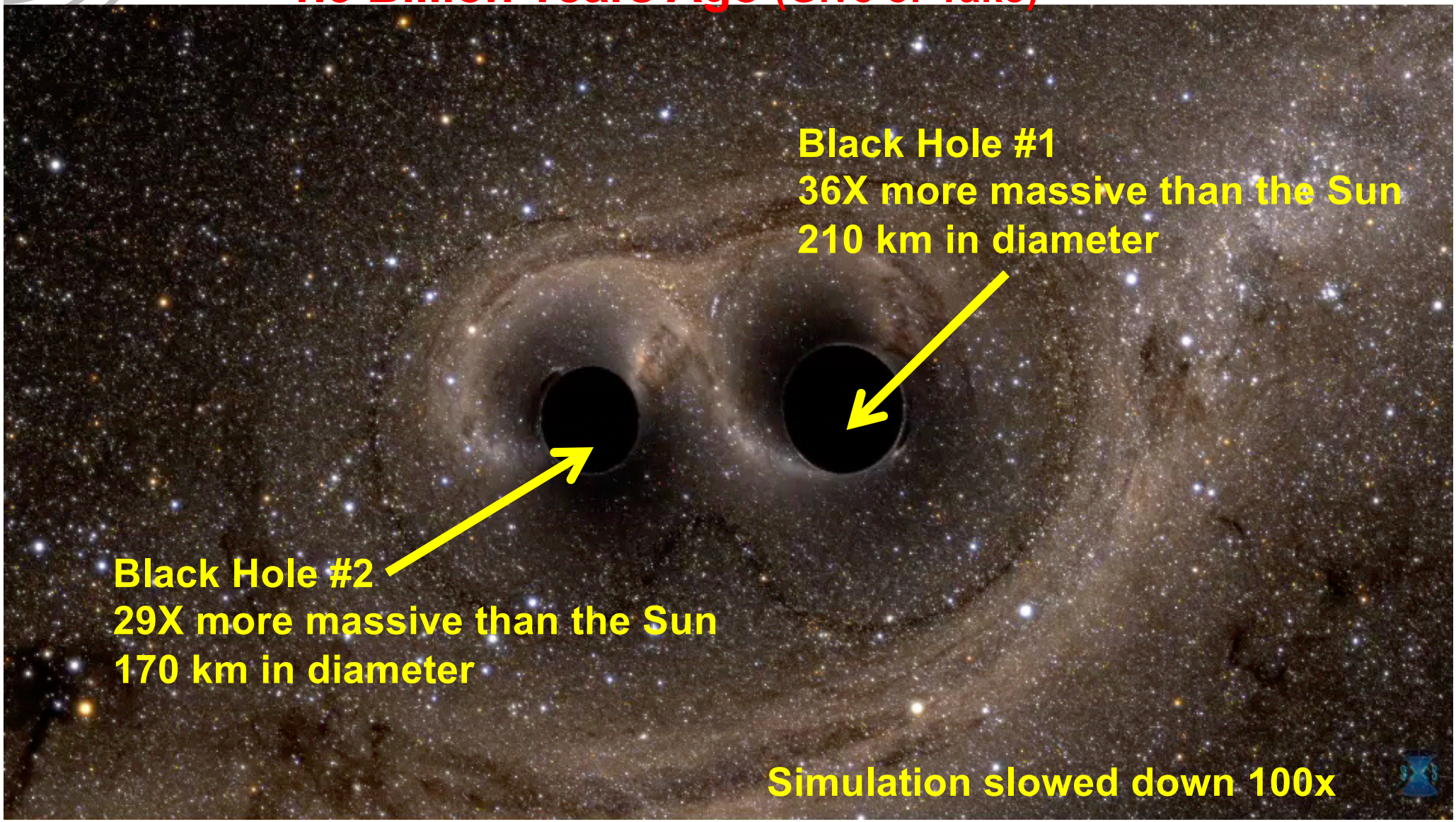
The Ballet of Binary Black Holes
1.3 Billion Years Ago (Give or Take)



Numerical relativity (solution to $G_{\mu\nu} = 0$) simulation

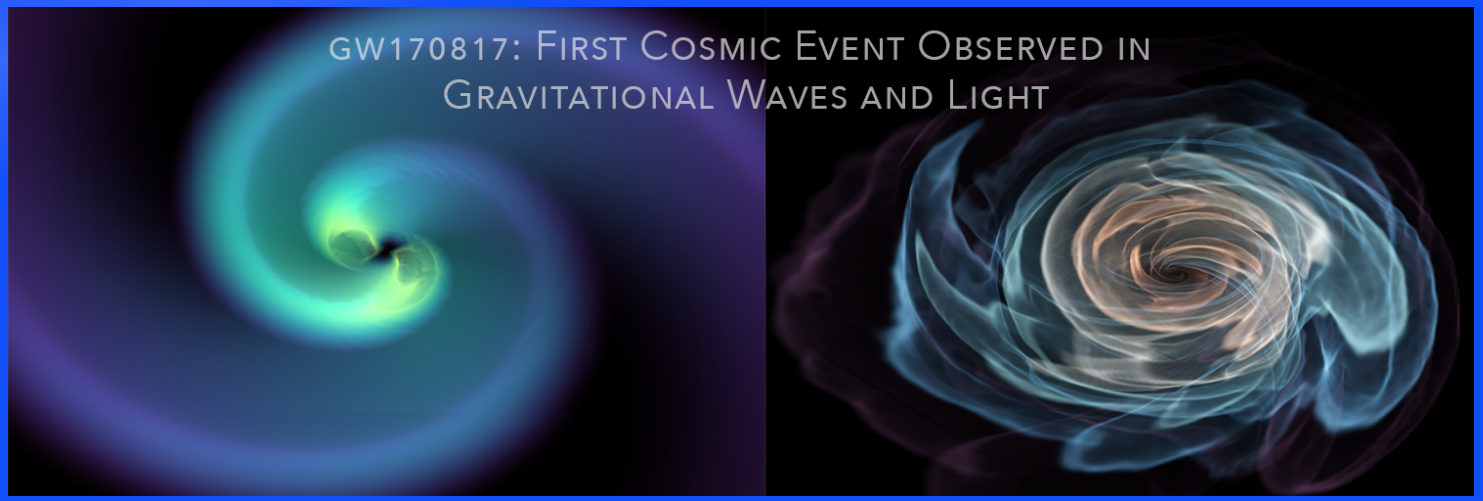
(SXS Collaboration, http://www.black-holes.org/)

Andy Bohn, François Hébert, and William Throwe, SXS

The Detection of Gravitational Waves by LIGO and Virgo

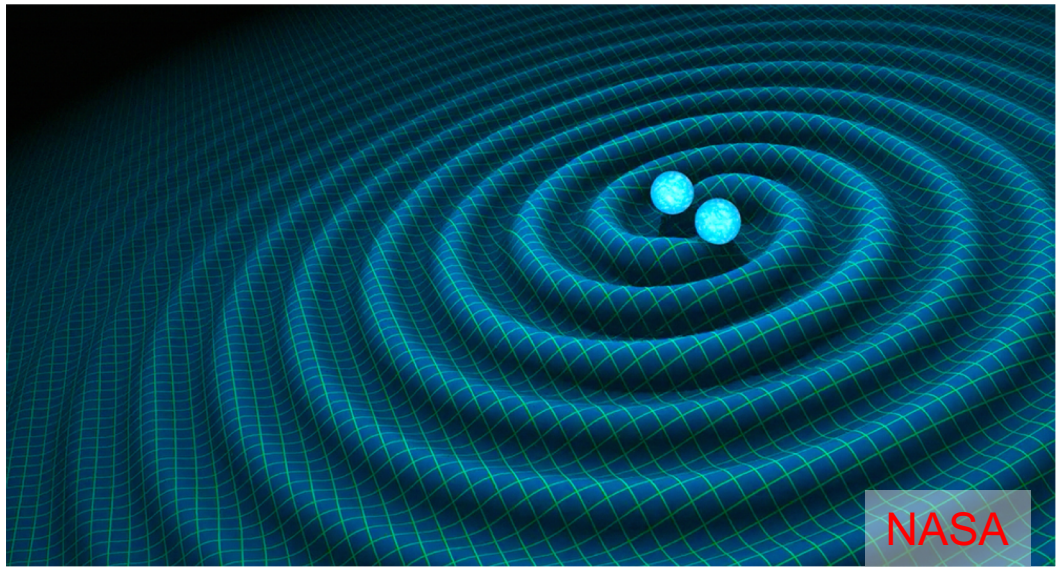
Alan J Weinstein
LIGO Laboratory, Caltech
for the LIGO and Virgo Collaborations

Physics 10, Caltech
October 10, 2018



Gravitational waves

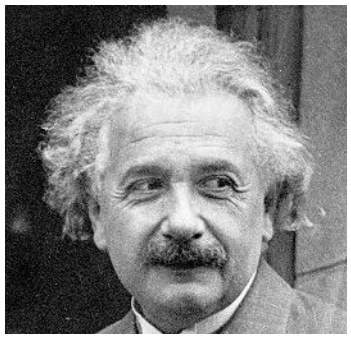
Masses that accelerate
(eg, a binary orbit)
create ripples of changing
gravity (curvature)
in space and time.



The "news" of this changing
gravity is carried by
gravitational waves

Predicted by Einstein in 1916
(and discovered 100 years later)

Gravitational waveform
can be computed using
numerical solutions to
Einstein's field equations

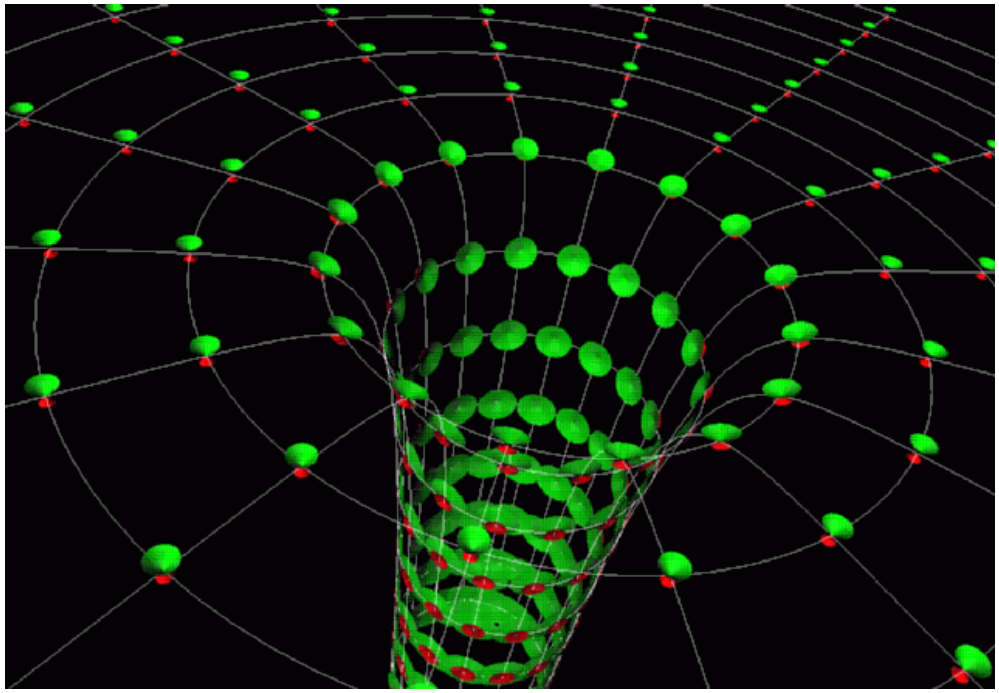


$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Strong-field



- Most tests of GR focus on small deviations from Newtonian dynamics (post-Newtonian weak-field approximation)
- Space-time curvature is a *tiny* effect everywhere except:
  - The universe in the early moments of the big bang
  - Near/in the horizon of black holes
- This is where GR gets *non-linear* and interesting!
- We aren't very close to any black holes (fortunately!), and can't see them with light or other EM radiation…



But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics

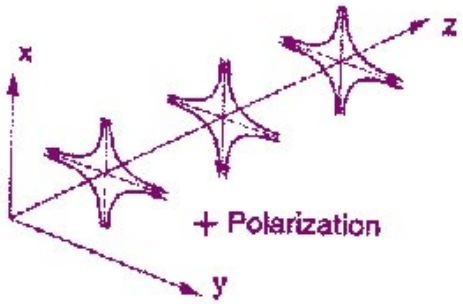
Nature of Gravitational Radiation

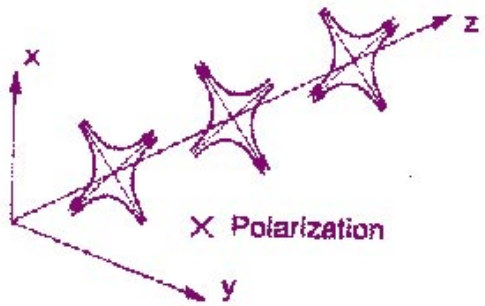
General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in fabric of spacetime

- **Stretches and squeezes space between "test masses" – strain $h = \Delta L / L$**
- **propagating at speed of light**
  - ***mass of graviton = 0***
- **space-time distortions are transverse to direction of propagation**
- **GW are tensor fields (EM: vector fields)**
  two polarizations: plus (⊕) and cross (⊗)
  (EM: two polarizations, *x* and *y*)
  Spin of graviton = 2



$$h(t,z) = h_{\mu\nu} e^{i(\omega t - kz)} = h_{+}(t - z/c) + h_{\times}(t - z/c)$$

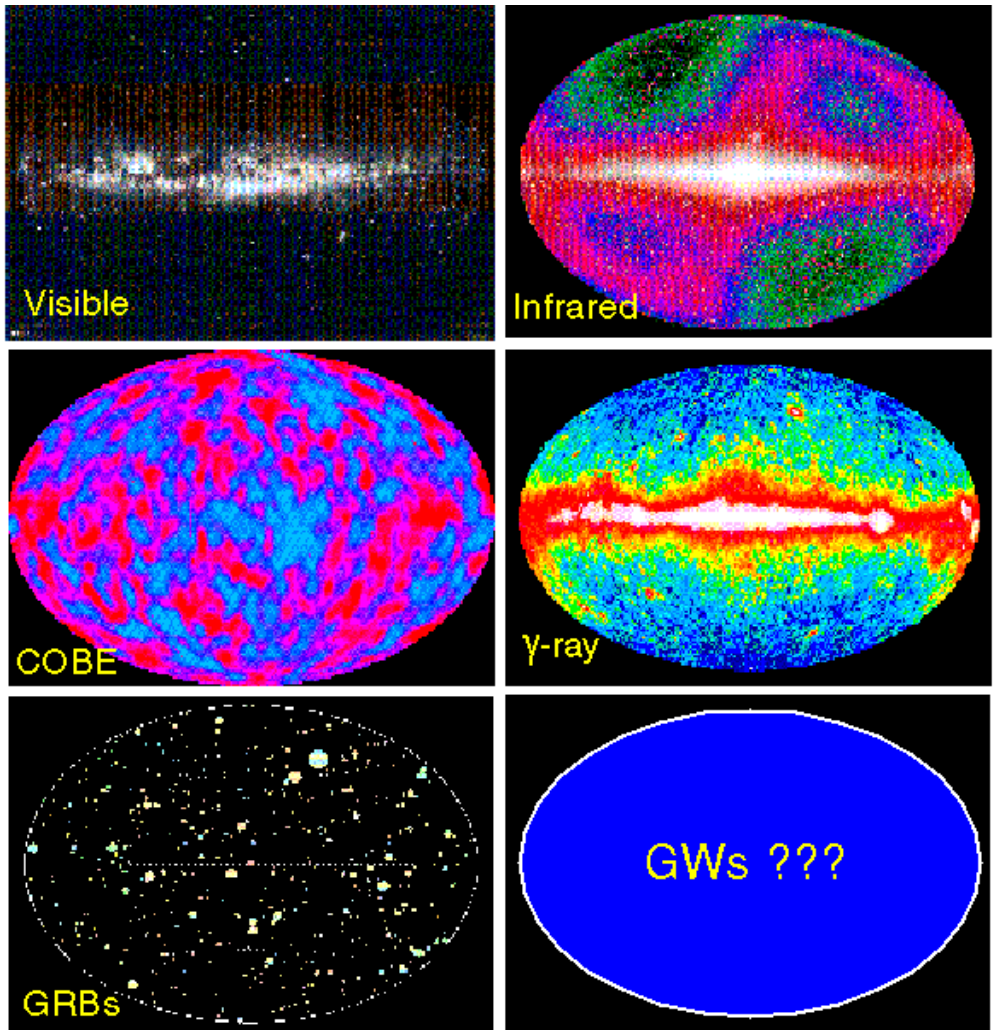




Contrast with EM dipole radiation:

$\hat{x}$ ((⟷)) $\hat{y}$ 

A NEW WINDOW ON THE UNIVERSE



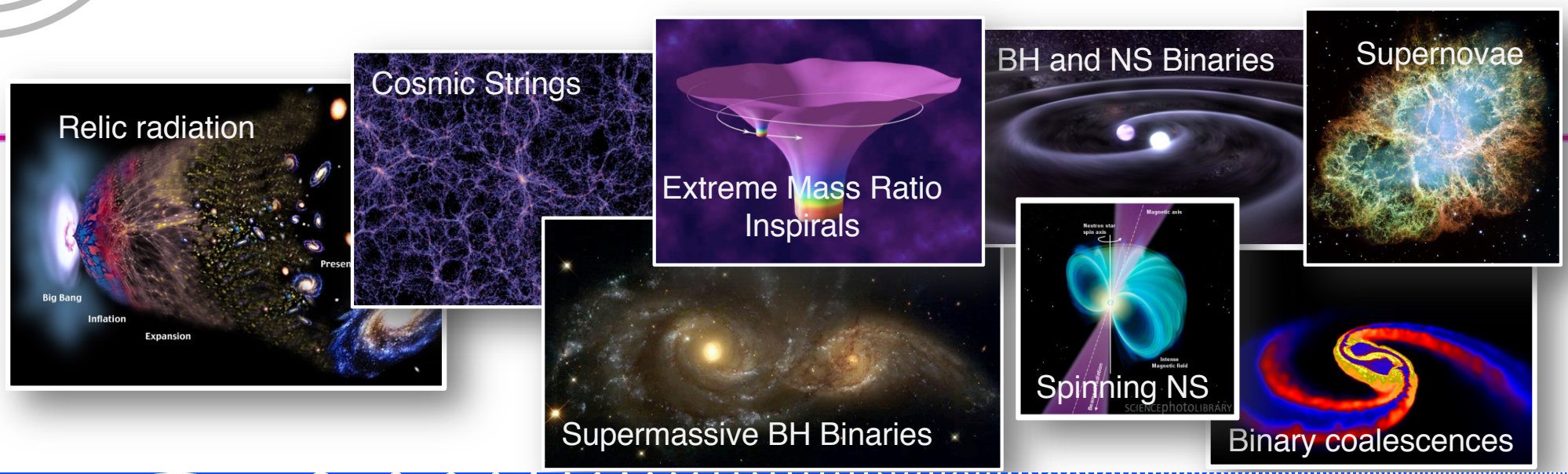
The history of Astronomy:
new bands of the EM spectrum opened → major discoveries!

GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

The GW Spectrum





10^{-16} Hz | 10^{-9} Hz | 10^{-4} Hz | 10^{0} Hz | 10^{3} Hz

Inflation Probe | Pulsar timing | Space detectors | Ground interferometers



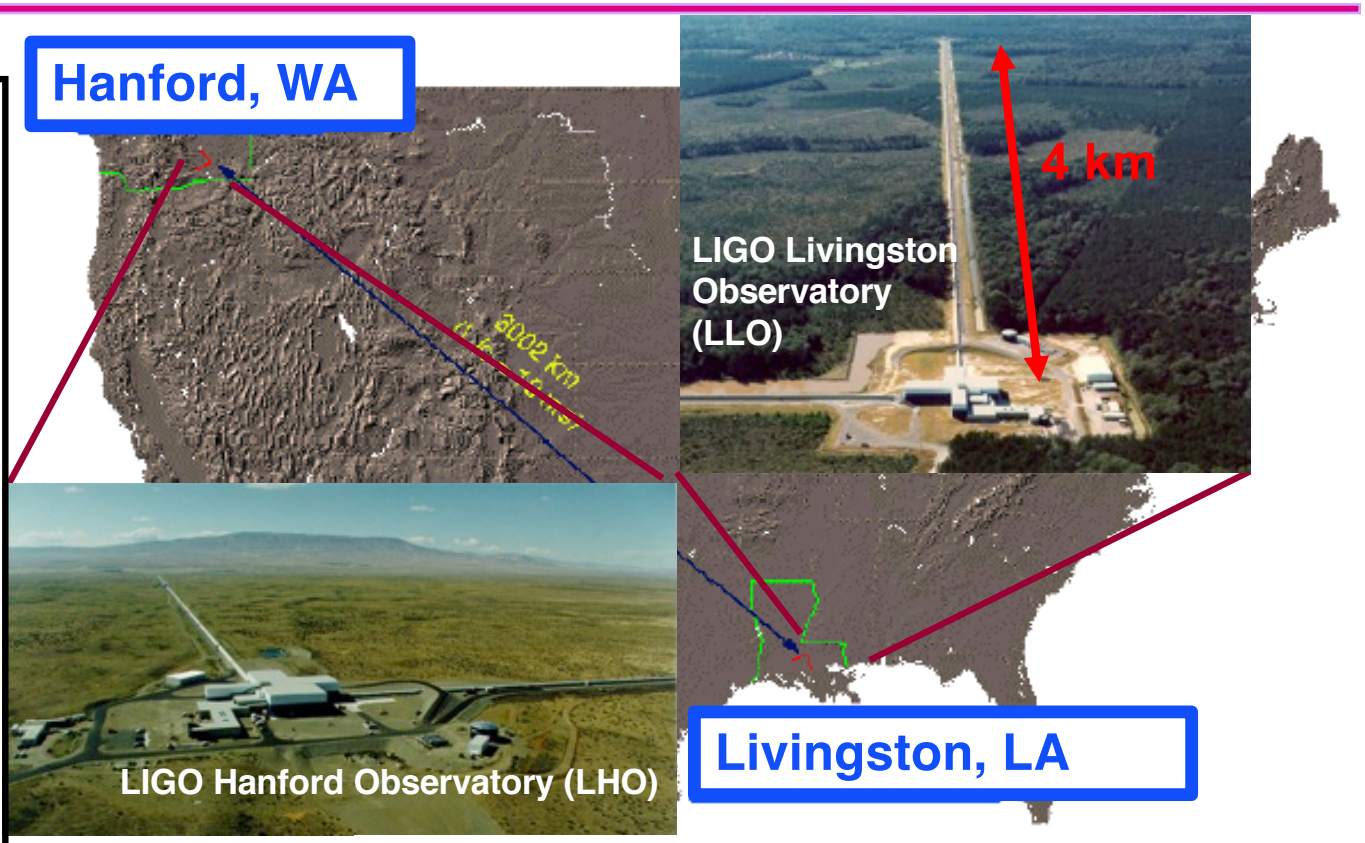
The Laser Interferometer Gravitational Wave Observatory

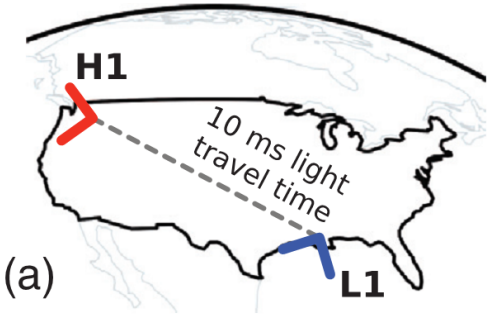
LIGO Laboratory is operated by Caltech and MIT, for the NSF.

~180 staff located at Caltech, MIT, LHO, LLO

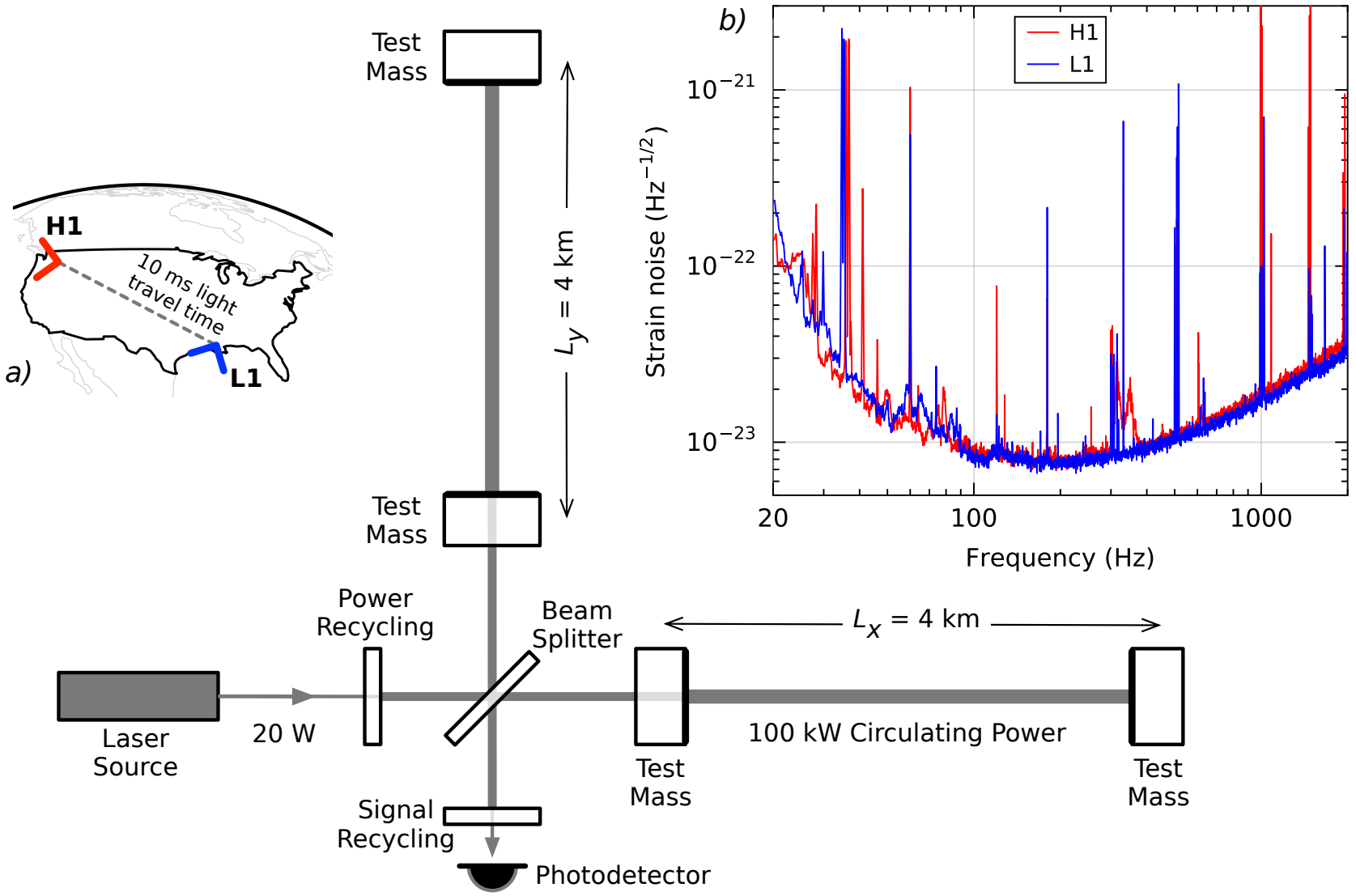
LIGO Scientific Collaboration:
~ 1000 scientists,
~80 institutions,
15 countries

Vigo Collaboration:
~ 250 scientists, Europe



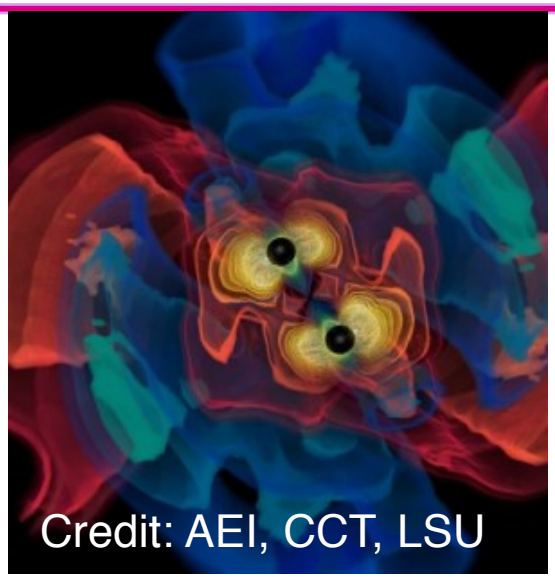


The Advanced LIGO detectors



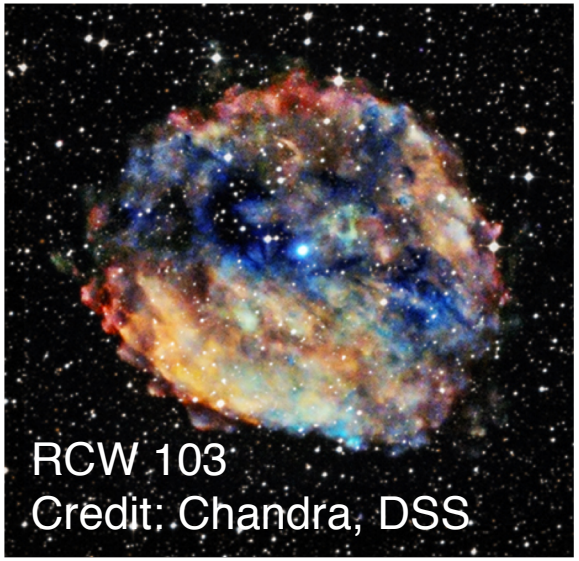
https://dcc.ligo.org/LIGO-P1500237/public/main

GW sources for ground-based detectors: The most energetic processes in the universe



Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,
- (effectively) transient



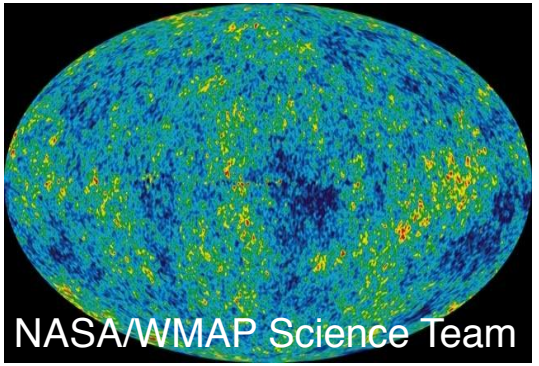
Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class



Spinning neutron stars

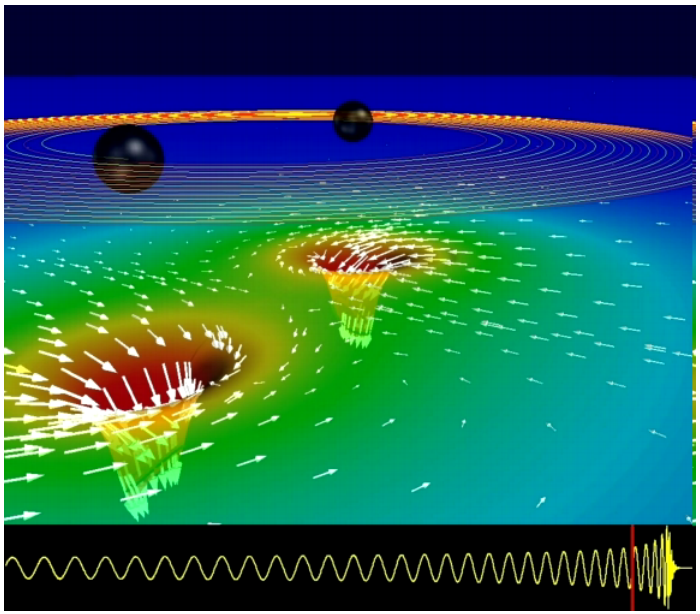
- (effectively) monotonic waveform
- Long duration



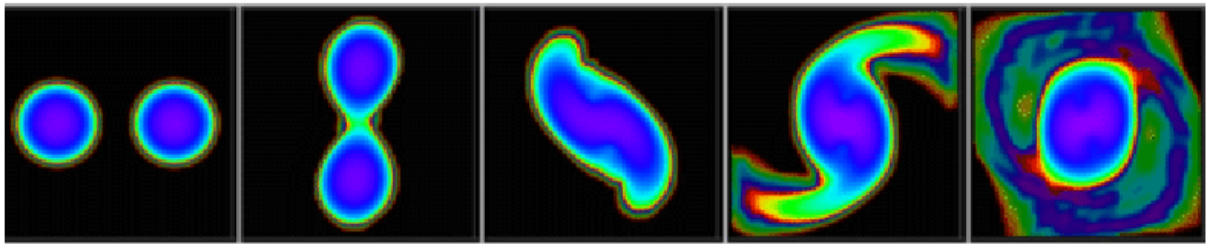
Cosmic Gravitational-wave Background

- Residue of the Big Bang, long duration
- Long duration, stochastic background

GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)



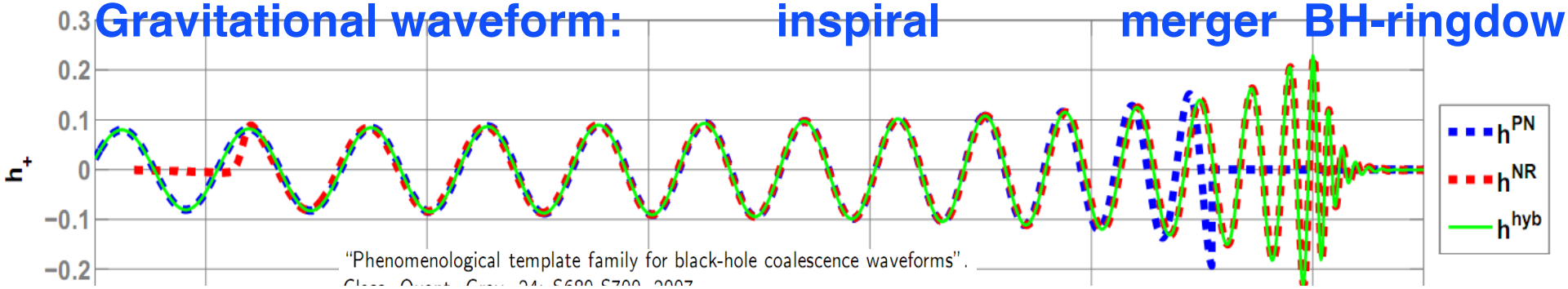
- Neutron star – neutron star (Centrella et al.)



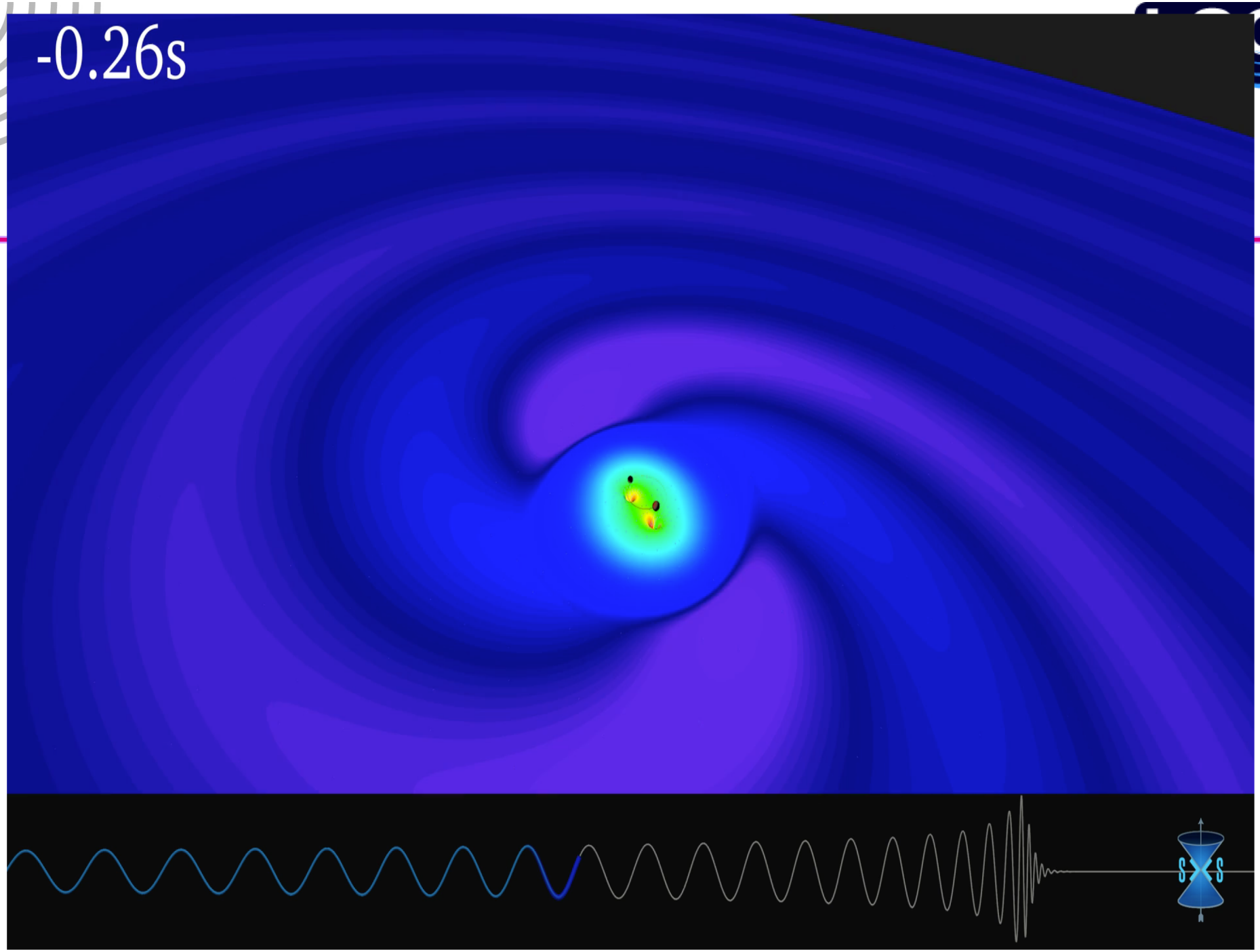
Tidal disruption of neutron star

A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

Gravitational waveform: inspiral merger BH-ringdown



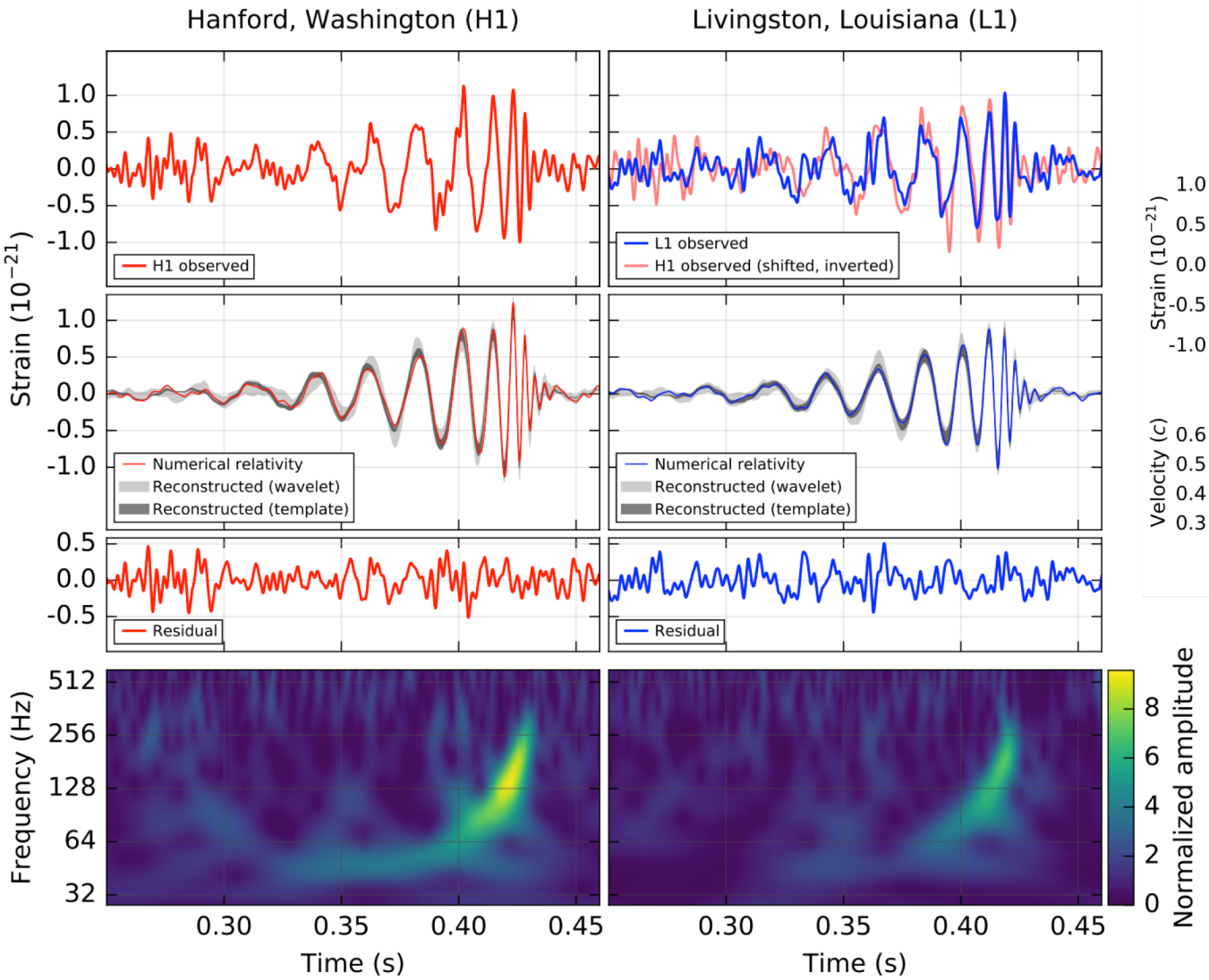
Waveform carries lots of information about binary masses, orbit, merger



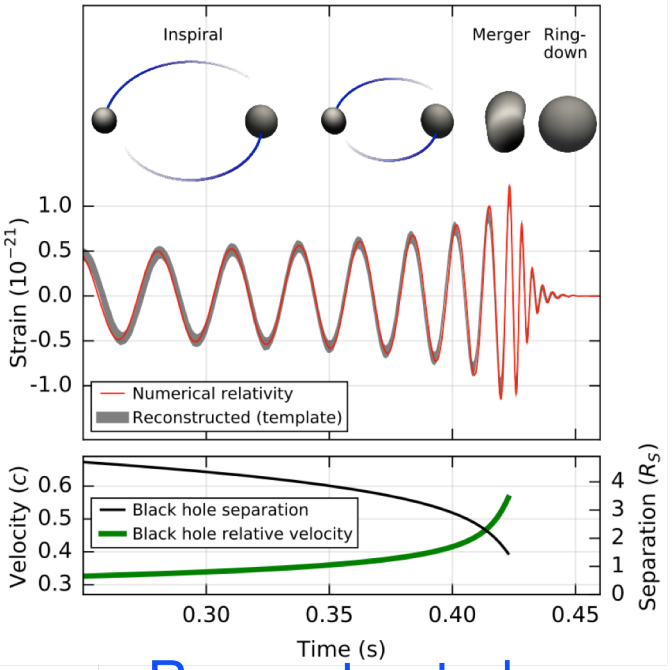
https://www.black-holes.org/explore/movies

GW150914

Phys. Rev. Lett. 116, 061102 – Published 11 February 2016
https://dcc.ligo.org/LIGO-P150914/public/main



Whitened and band-passed [40-300] Hz



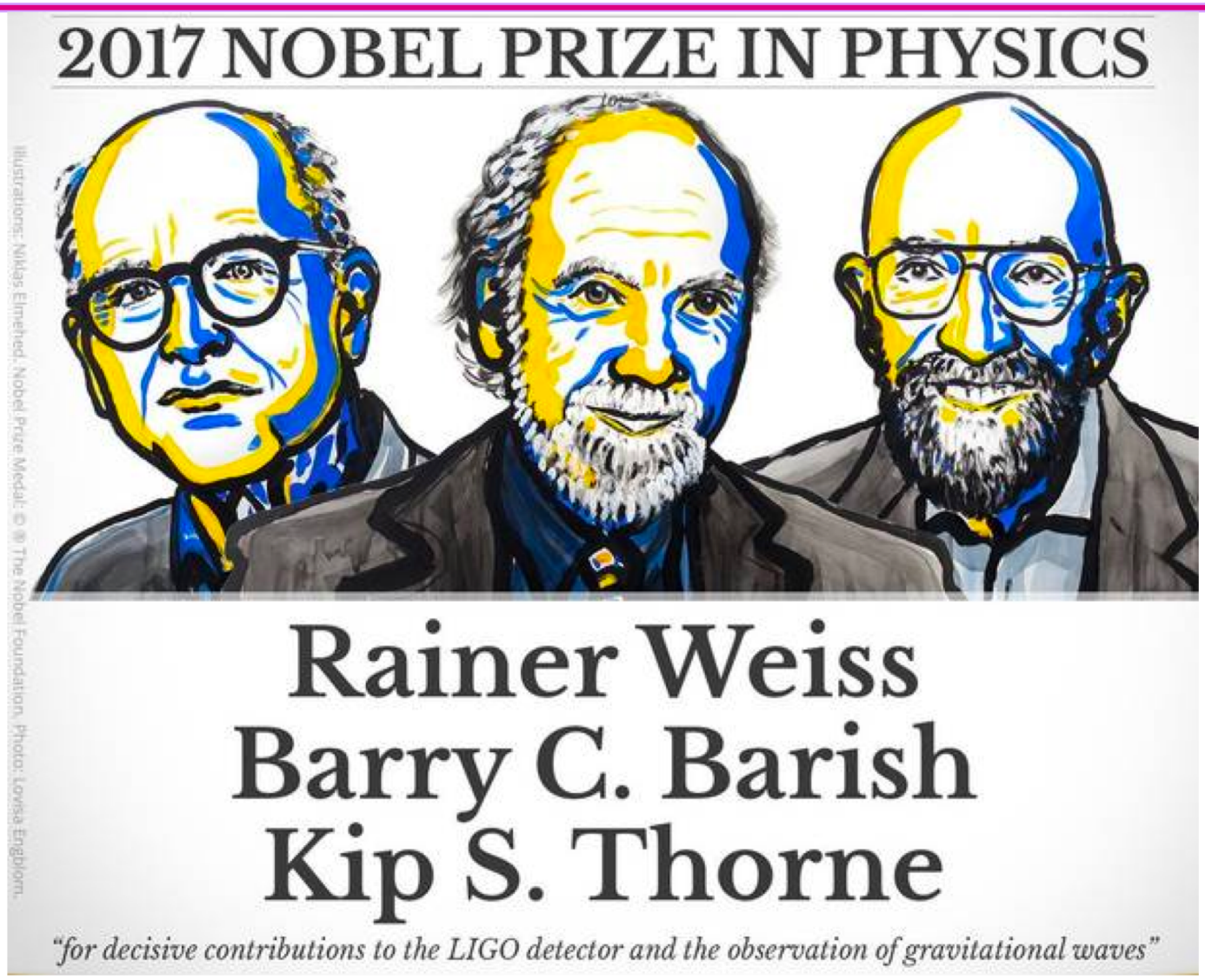
Reconstructed (no whitening)

Audio:

- filtered data
- freq-shifted data
- reconstructed & shifted

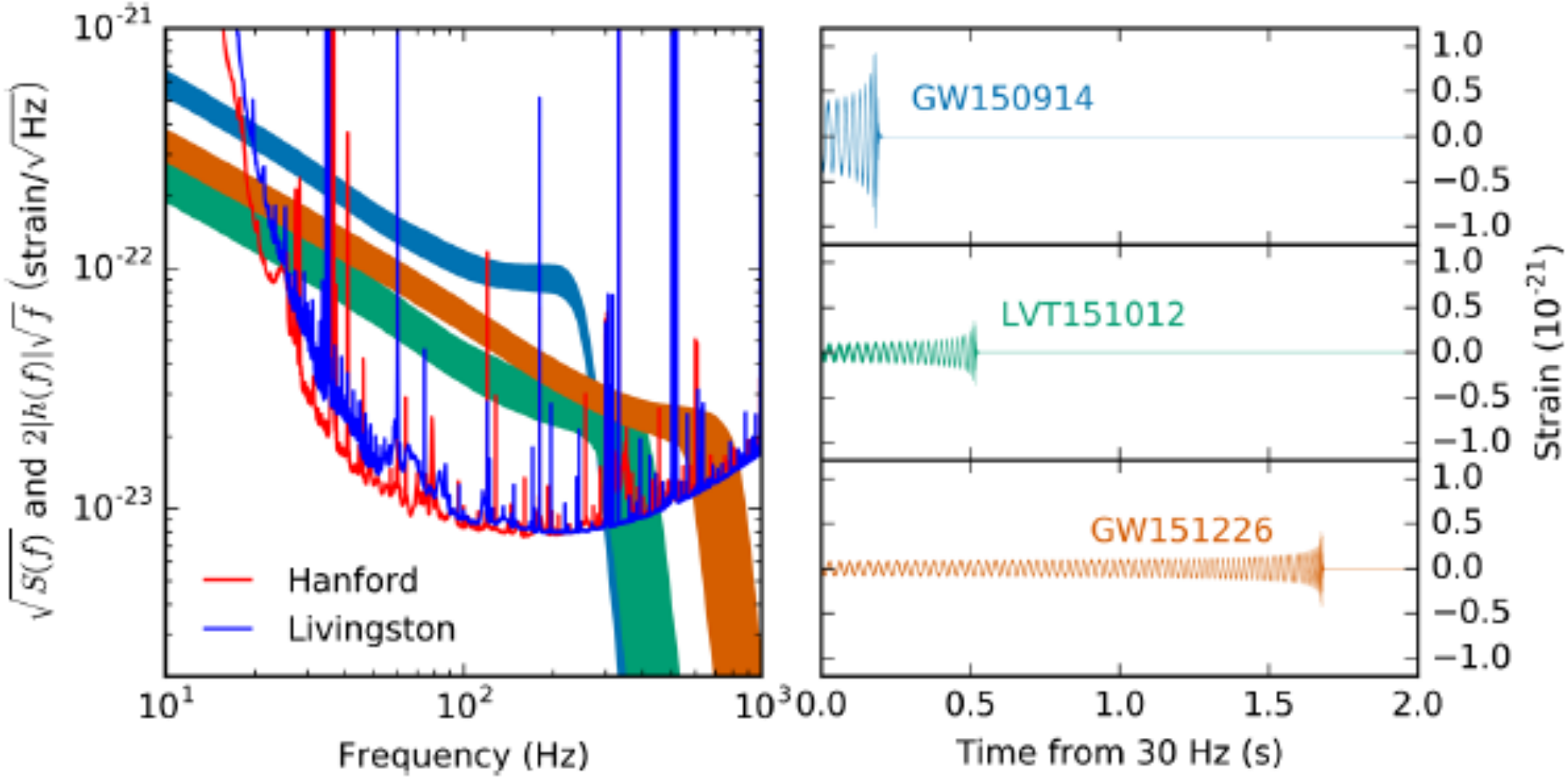


Founders of the LIGO project at Caltech and MIT





Three BBH events, compared



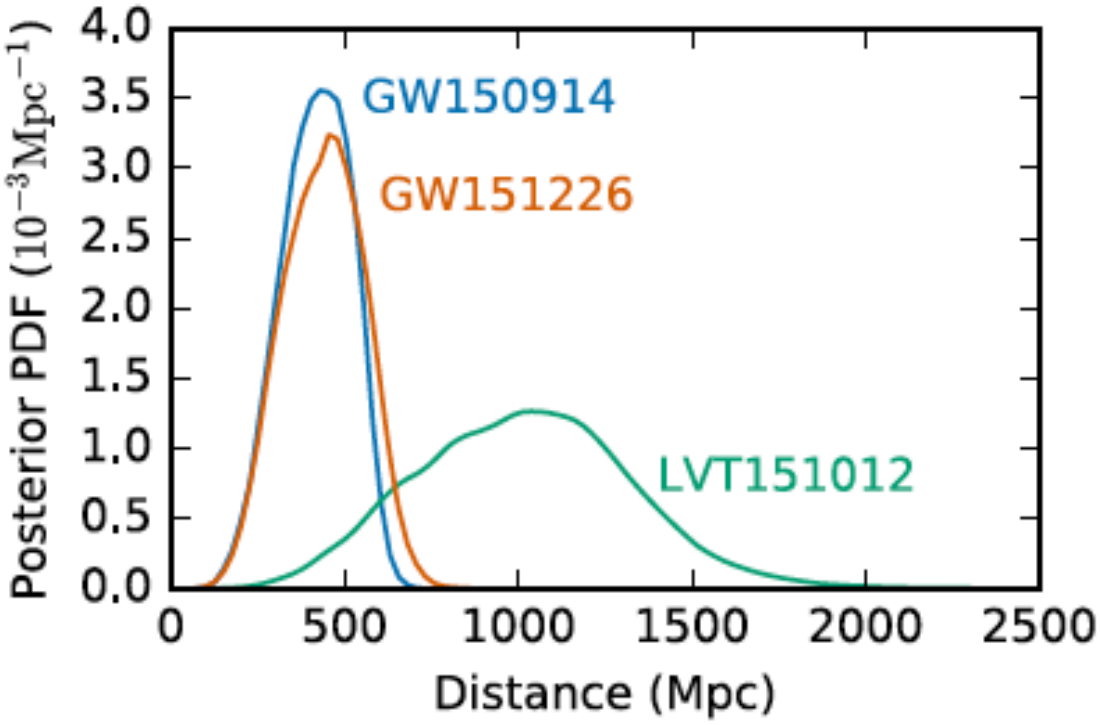
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, https://arxiv.org/abs/1606.04856, Phys. Rev. X 6, 041015 (2016)

Three BBH events, distances

It's hard to measure distances in astronomy!
(few "standard candles")

BBH events are "standardizable sirens"
(need to know their masses, orbital orientation, etc).

Distances measured poorly with only two detectors.



Our two loud events are far away!
(400 Mpc ~ 1.3 Gly) – merged 1.3 By ago!

Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", https://arxiv.org/abs/1606.04856, Phys. Rev. X 6, 041015 (2016)

Radiated energy & luminosity

- GW150914:

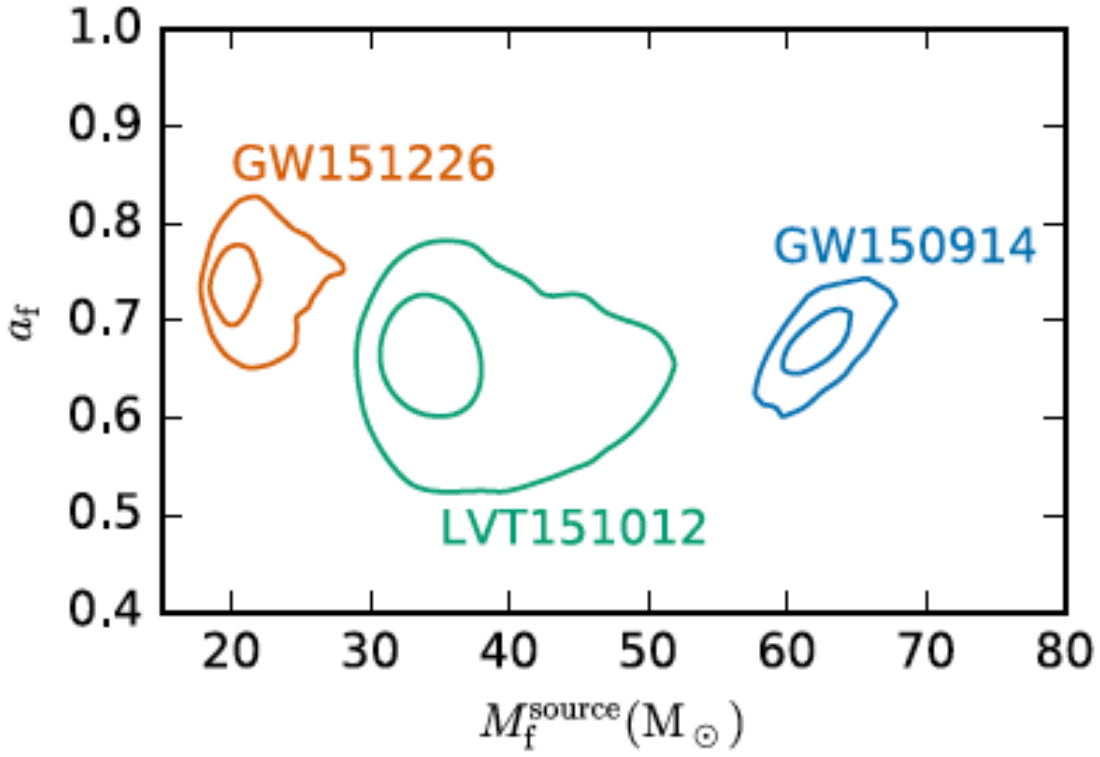
$$E_{\rm rad} = 3.0^{+0.5}_{-0.4}\,{\rm M}_\odot c^2$$
$$\ell_{\rm peak} = 3.6^{+0.5}_{-0.4} \times 10^{56}{\rm erg/s}$$

- GW151226:

$$E_{\rm rad} = 1.0^{+0.1}_{-0.2}\,{\rm M}_\odot c^2$$
$$\ell_{\rm peak} = 3.3^{+0.8}_{-1.6} \times 10^{56}{\rm erg/s}$$

- LVT151012:

$$E_{\rm rad} = 1.5^{+0.3}_{-0.4}\,{\rm M}_\odot c^2$$
$$\ell_{\rm peak} = 3.1^{+0.8}_{-1.8} \times 10^{56}{\rm erg/s}$$



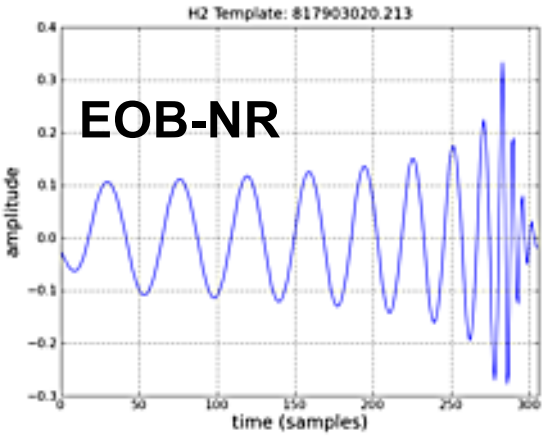
- GW150914: $E_{GW} \approx 3\,M_\odot c^2$, or ~4.5% of the total mass-energy of the system.
- Roughly 10^{80} gravitons.
- Peak luminosity $L_{GW} \sim 3.6 \times 10^{54}$ erg/s, briefly outshining the EM energy output of all the stars in the observable universe (by a factor ~ 50).

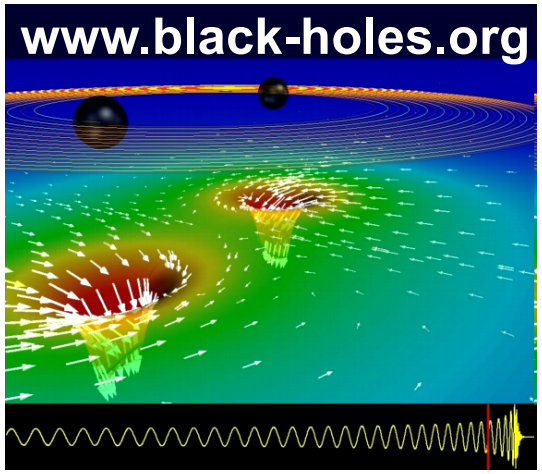
Testing General Relativity in the strong-field, dynamical regime

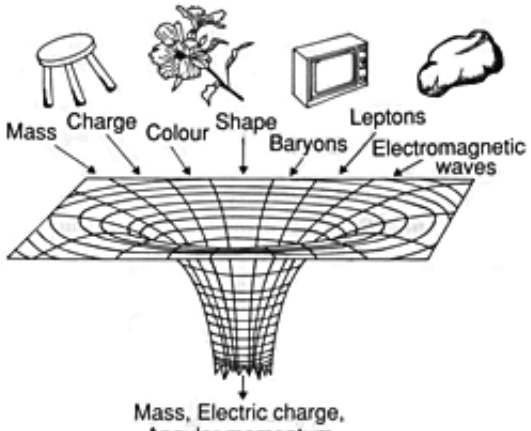
- **Test post-Newtonian expansion of inspiral phase.**

$$\Psi(f) \equiv 2\pi f t_0 + \varphi_0 + \frac{3}{128\eta v^5}\left(1 + \sum_{k=2}^{7} v^k \psi_k\right).$$

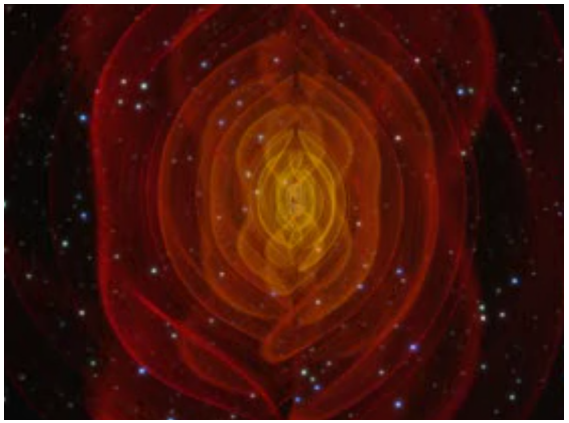
- **Test Numerical Relativity waveform prediction for merger phase.**
- **Test association of inspiral and ringdown phases: BH perturbation theory, no-hair theorem.**



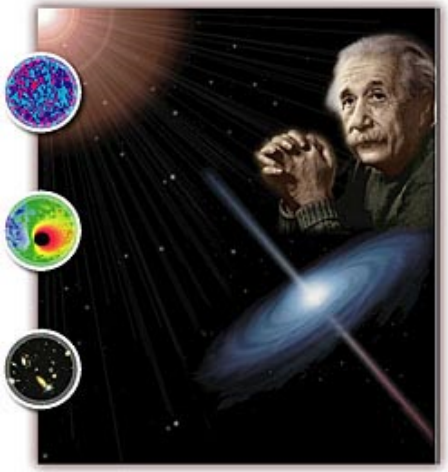




nonlocal.com/hbar/blackholes.html



Testing beyond-GR



- Constrain beyond-GR parameters (Will, 2006)
- Directly measure speed of gravitational waves constrain (or measure) the mass of the graviton.
- Constrain (or measure) longitudinal or other polarizations.
- Constrain (or measure) parity-violating effects in wave generation/propagation (Yunes et al, 2010).
- Constrain "parameterized post-Einsteinian framework" (Yunes & Pretorius, 2009)
- Test specifically for scalar-tensor and other alternative-gravity theories

Mass of the graviton

A propagating graviton with mass m_g

$$E^2 = p^2c^2 + m_g^2c^4$$

and associated Compton wavelength

$$\lambda_g = h/(m_g c)$$

results in frequency-dependent velocity

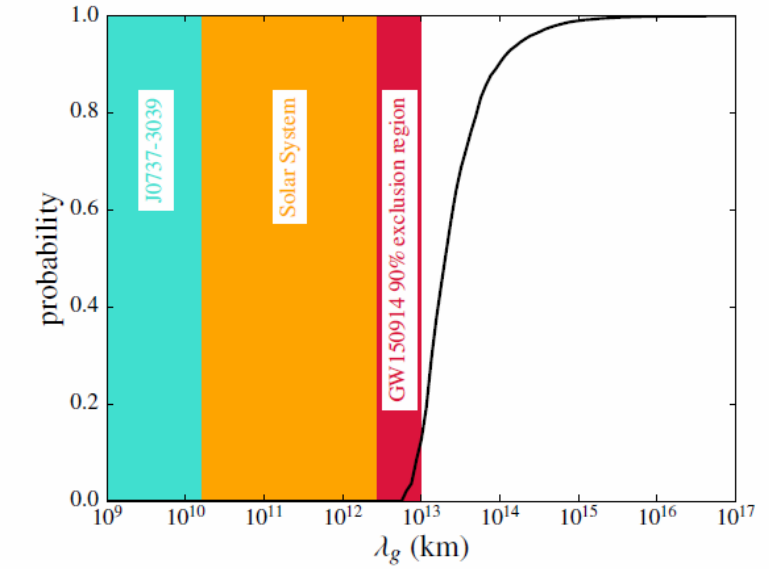
$$v_g^2/c^2 \equiv c^2p^2/E^2 = 1 - h^2c^2/(\lambda_g^2 E^2)$$

and dispersion causes distortion of the phase evolution of the waveform (wrt massless theory)

$$\Phi_{\rm MG}(f) = -(\pi D c)/[\lambda_g^2(1+z)f]$$

Agreement of observed waveform with theory allows us to set the bound:

$$m_g \leq 1.2 \times 10^{-22}\ \mathrm{eV/c^2}\ \text{at 90\% confidence}$$



$$\lambda_g \geq 10^{13}\mathrm{km}\ (90\%)$$

$$m_g \leq 1.2 \times 10^{-22}\mathrm{eV/c^2}\ (90\%)$$

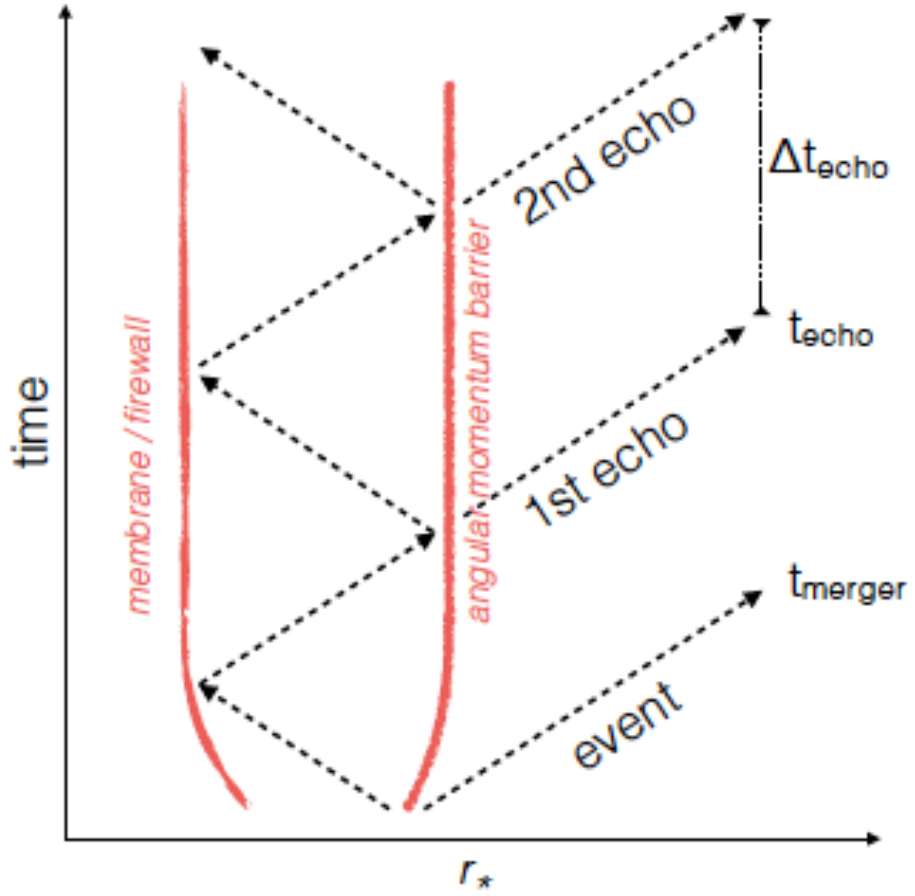
Tests of General Relativity with GW150914
Phys. Rev. Lett. 116, 221101 (2016)

Speed of gravitational waves

- GR predicts that GWs propagate at the maximum speed supportable by space-time (massless graviton)
- Same as the speed of light (massless photon)
- Detecting a signal (eg, from a BNS merger) at nearly the same time as a flash of light from the merger (assuming one can unambiguously associate the two, and estimate the distance to the source) will constrain the GW speed relative to light speed.
- Or, it can be constrained using only the GWs from a continuous source.

What if GR black holes … aren't?

- Exotic forms of highly-compressible matter (gravastars), or
- Planck-scale departures from GR (firewalls, fuzzballs) near their horizons
- can lead to post-merger "echoes" of GW ringdowns.
- repeating damped echoes with time-delays of *8M logM*



Echoes from the Abyss:

arXiv:1612.00266v1, Abedi, Dykaar, and Afshordi

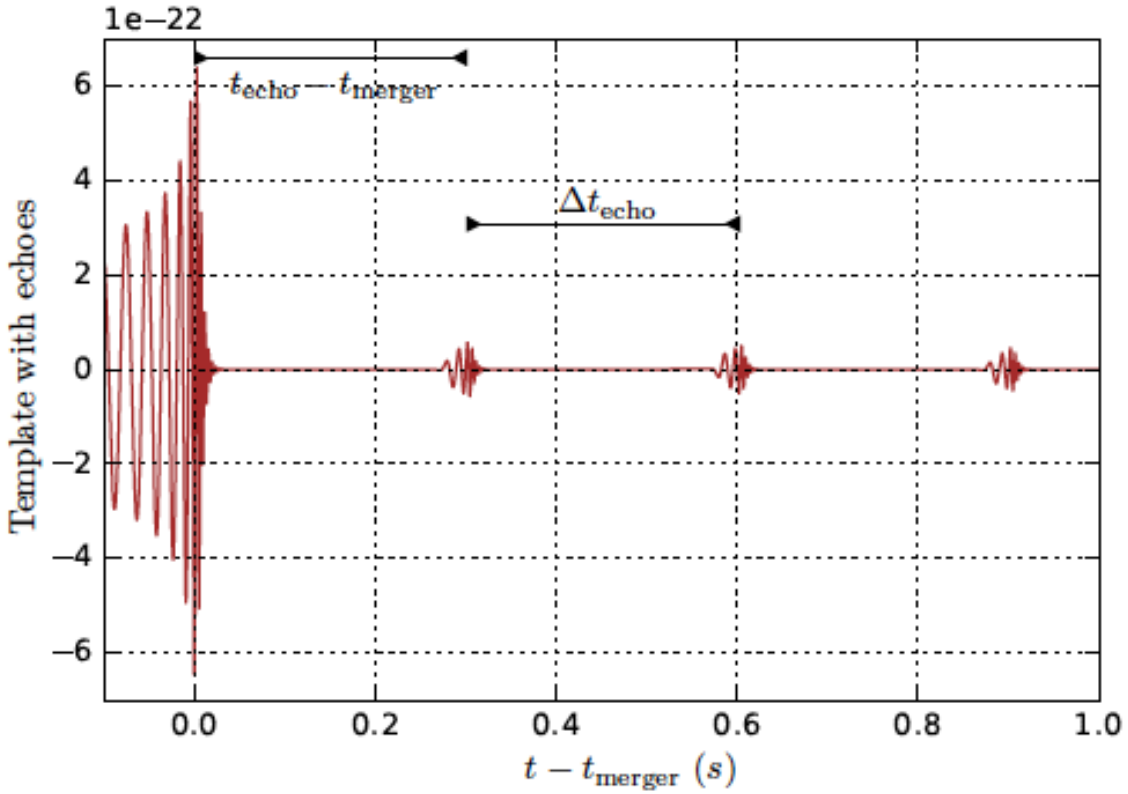
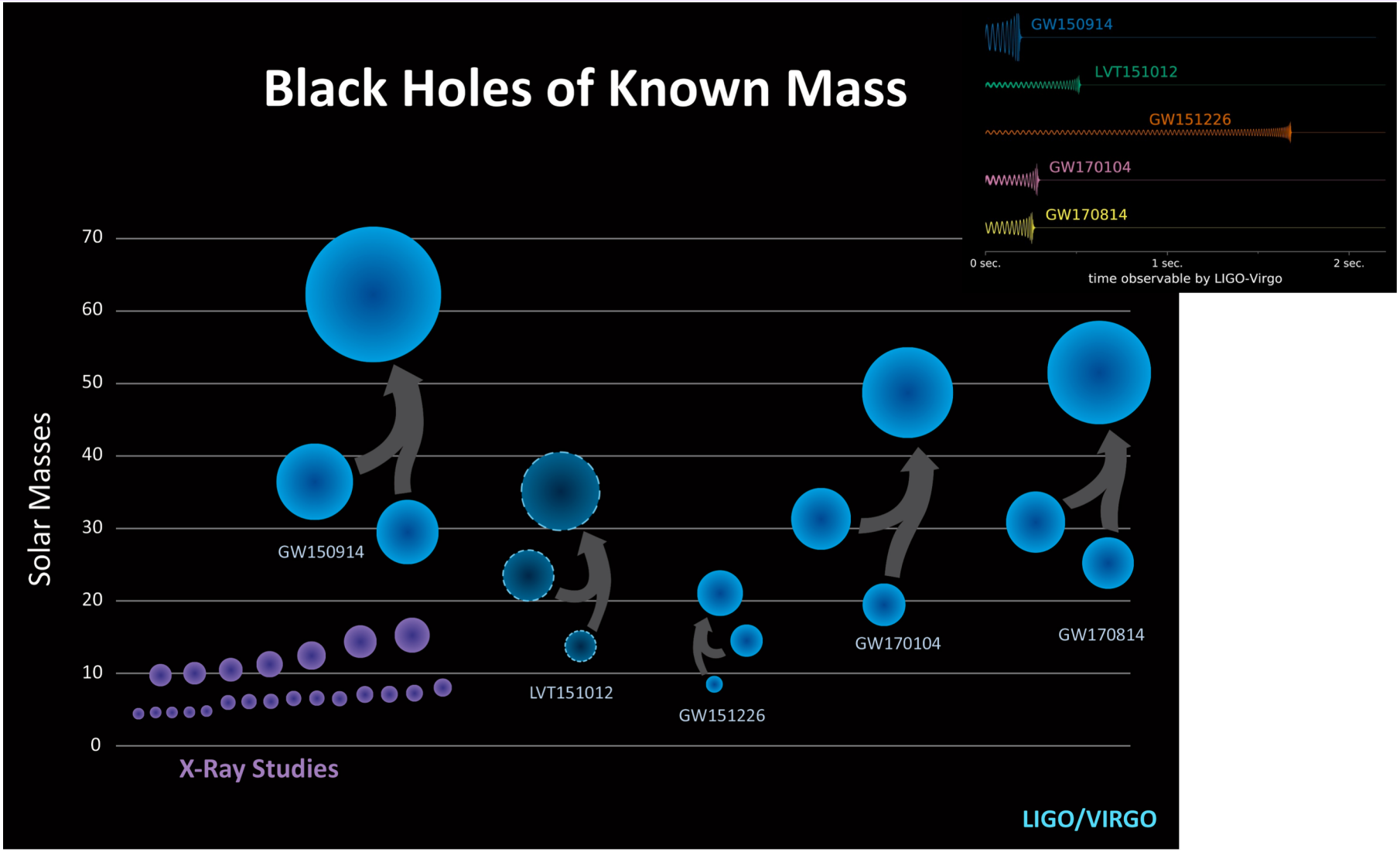


FIG. 2: LIGO original template for GW150914, along with our best fit template for the echoes.

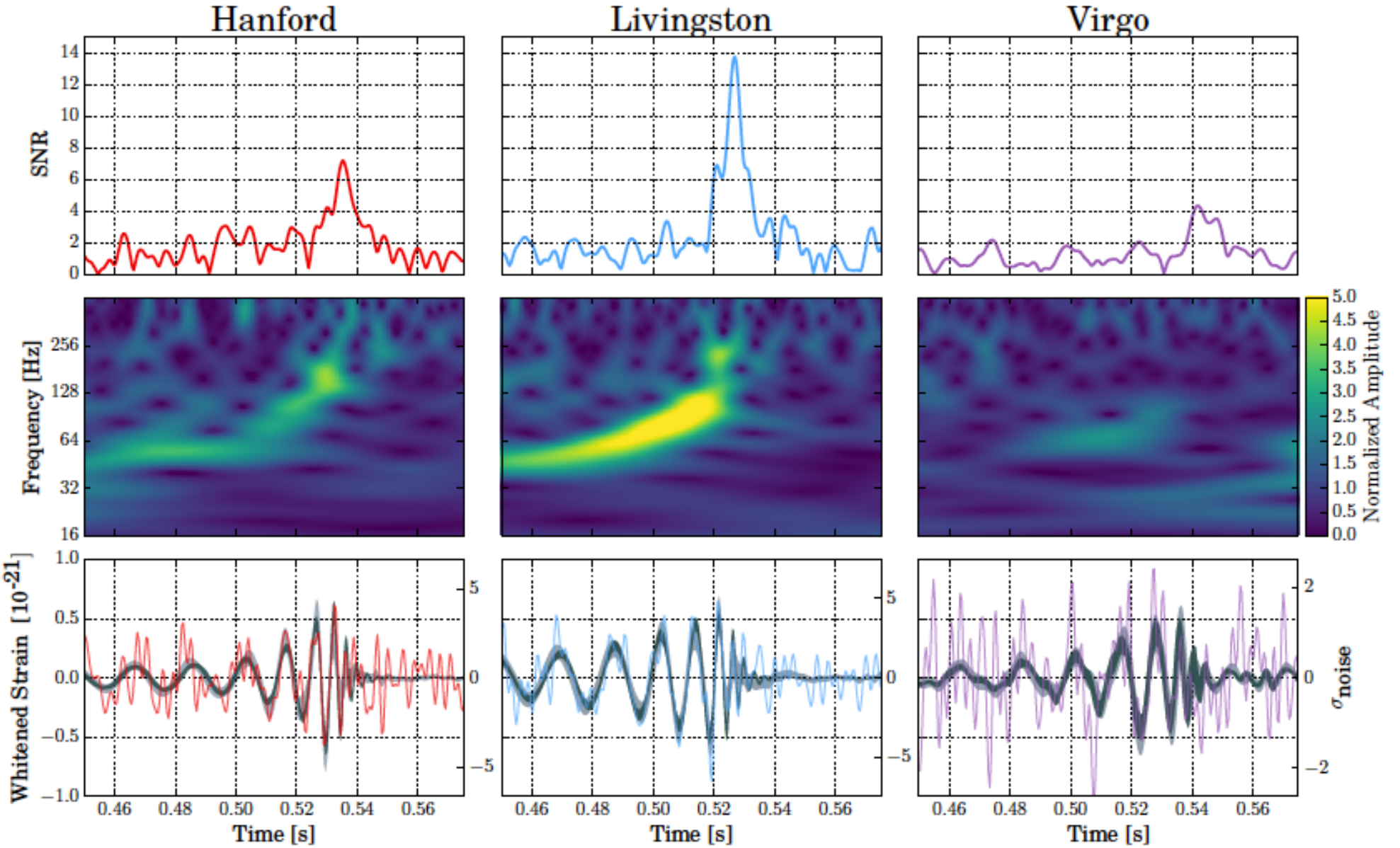
"… we find tentative evidence for Planck-scale structure near black hole horizons at 2.9σ significance level"

MORE BBHs, in O2.
Starting to build up a mass distribution



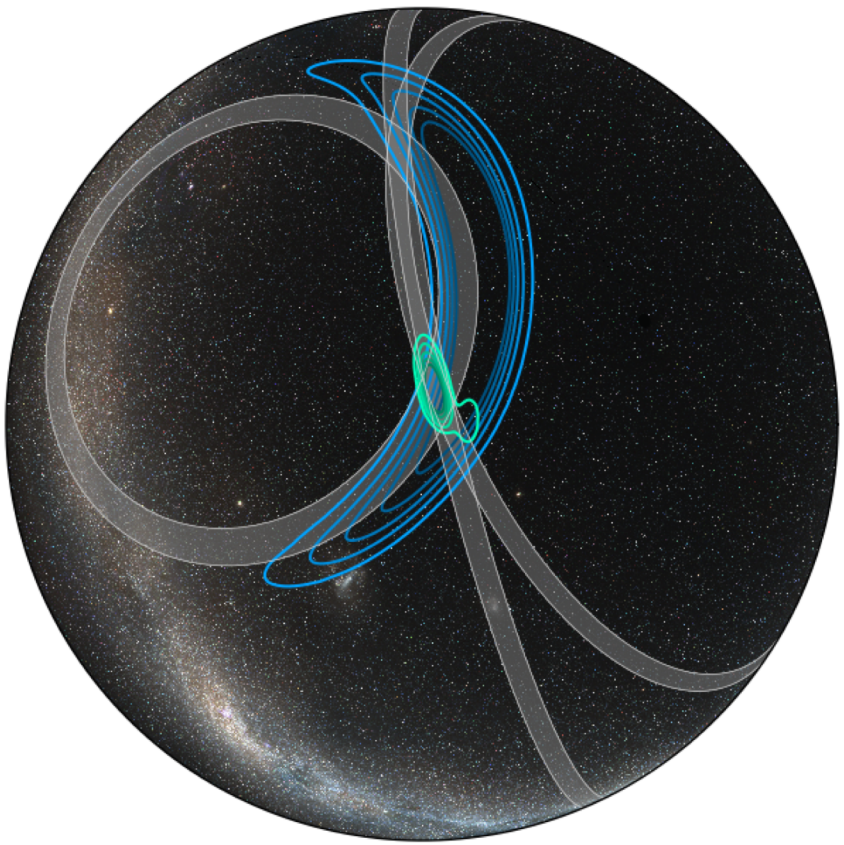
http://ligo.org/detections/GW170814.php

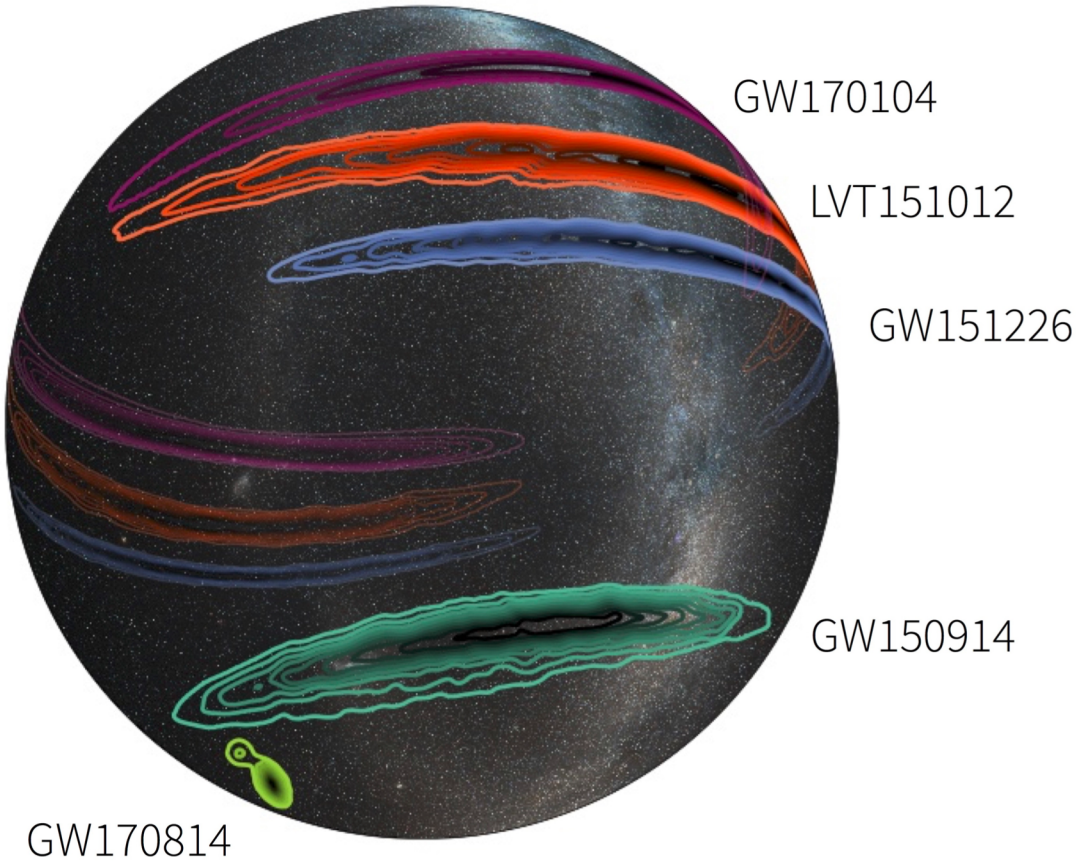
GW170814



http://ligo.org/science/Publication-GW170814/index.php

Greatly improved sky localization (but, these are black holes…)





Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

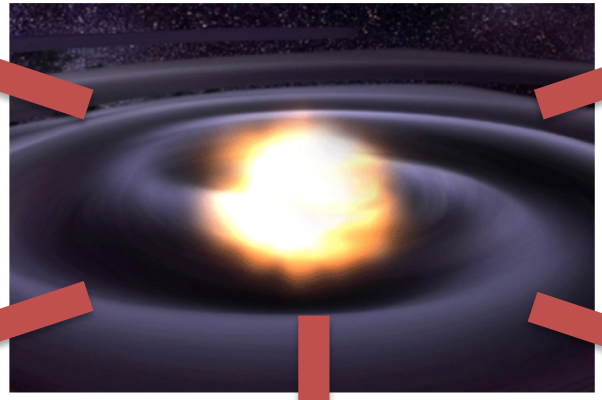
http://ligo.org/detections/GW170814.php

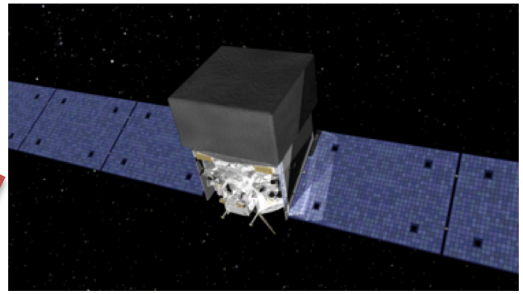
Multi-messenger Astronomy with Gravitational Waves



GWs

astrophysical fireball

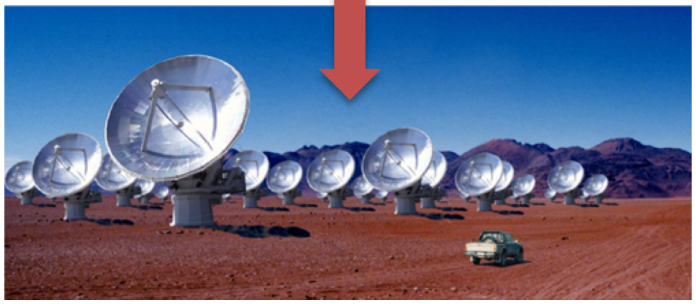




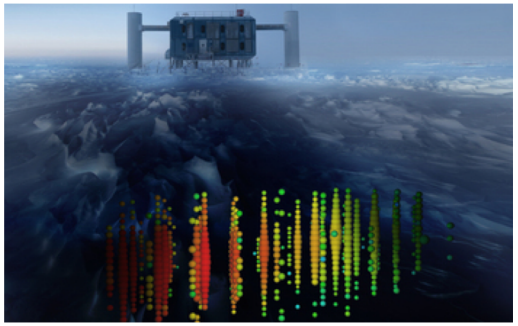
X-rays, γ rays



UV,optical,IR



radio



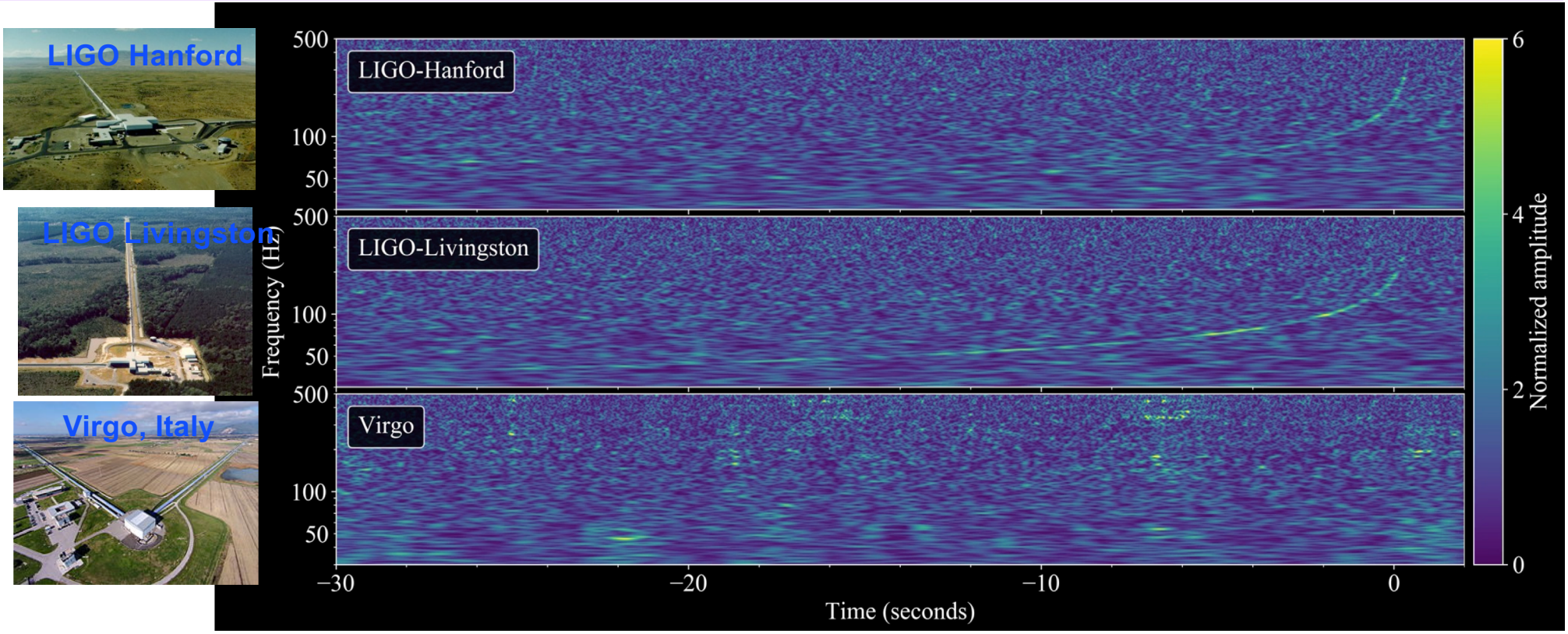
neutrinos

Then came something completely different…
130 million years ago, in a galaxy far, far away …



https://www.youtube.com/watch?v=e7LcmWiclOs

This is what I woke up to on August 17, 2017, just before 6am PT…

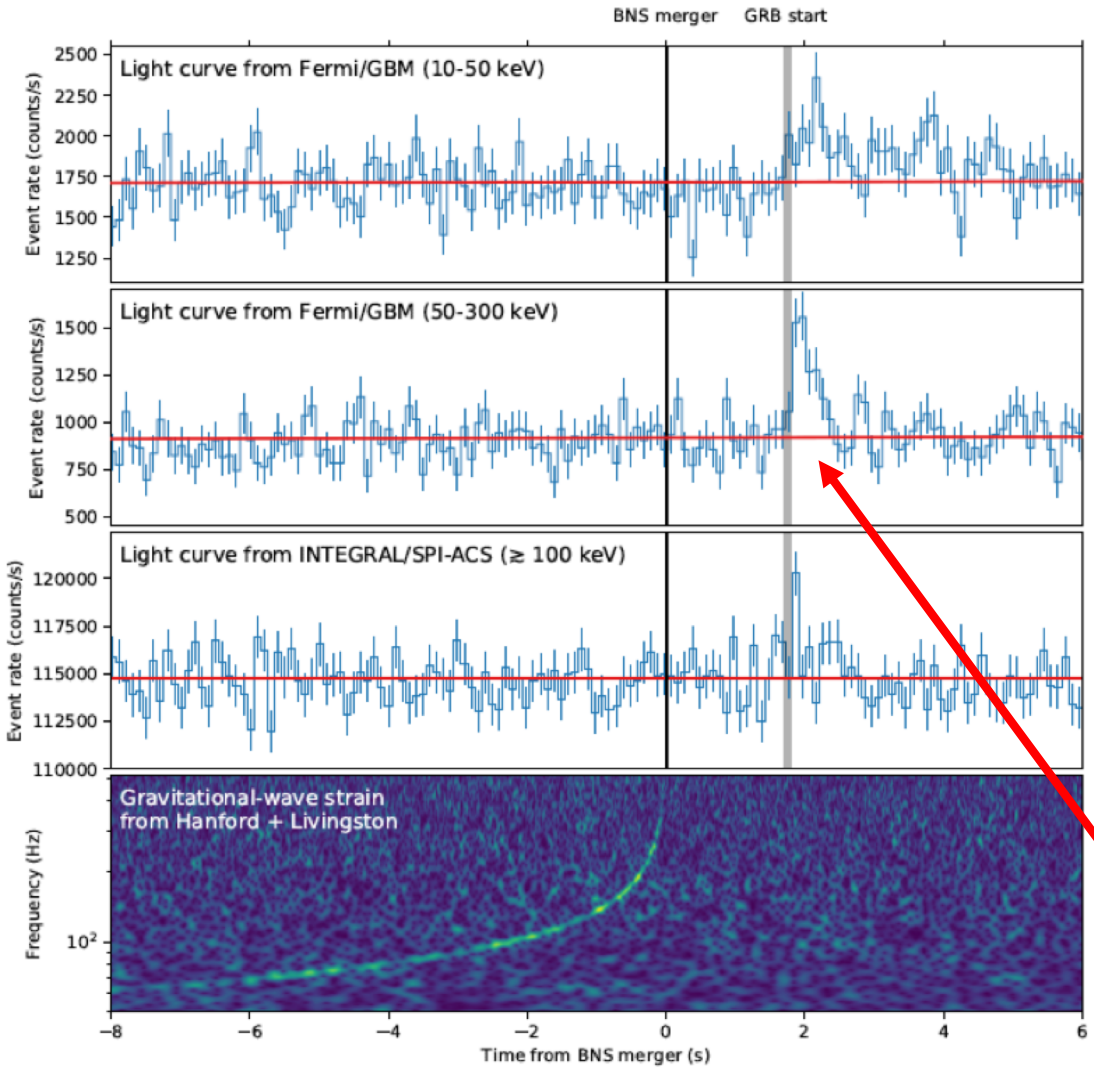


GW170817

A Binary Neutron Star Merger! (!!!!!!)

http://ligo.org/detections/GW170817.php

LIGO To add to the excitement: a gamma-ray burst (GRB)!



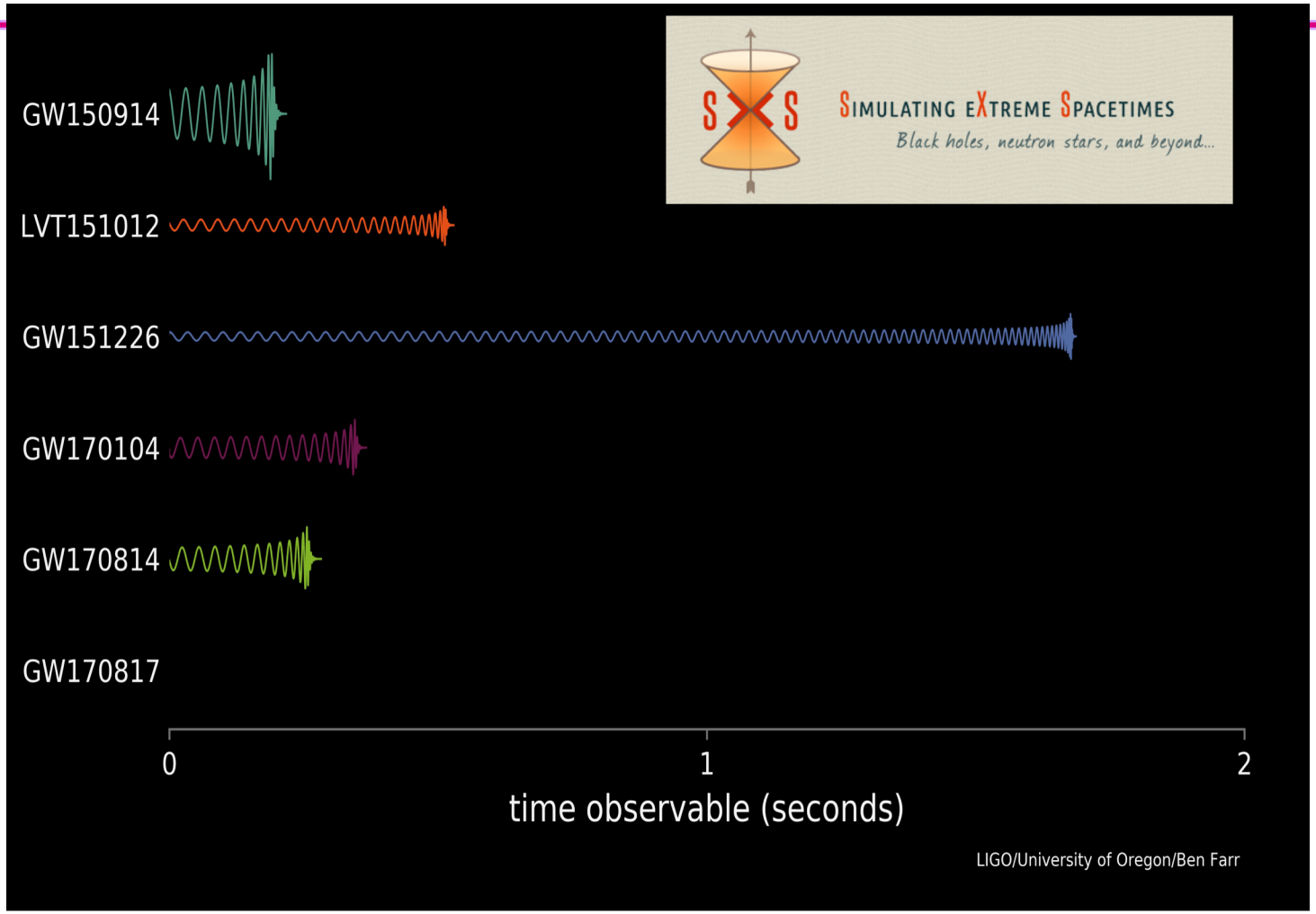
1.7 seconds later, duration < 2 seconds

It has long been theorized that sGRBs come from binary neutron star mergers, and a ~2 s delay fits typical models…

kinda wimpy, though…

B. Abbott et al, LIGO-Virgo, Astroph.J.Lett. 848, 2, L13 (2017)

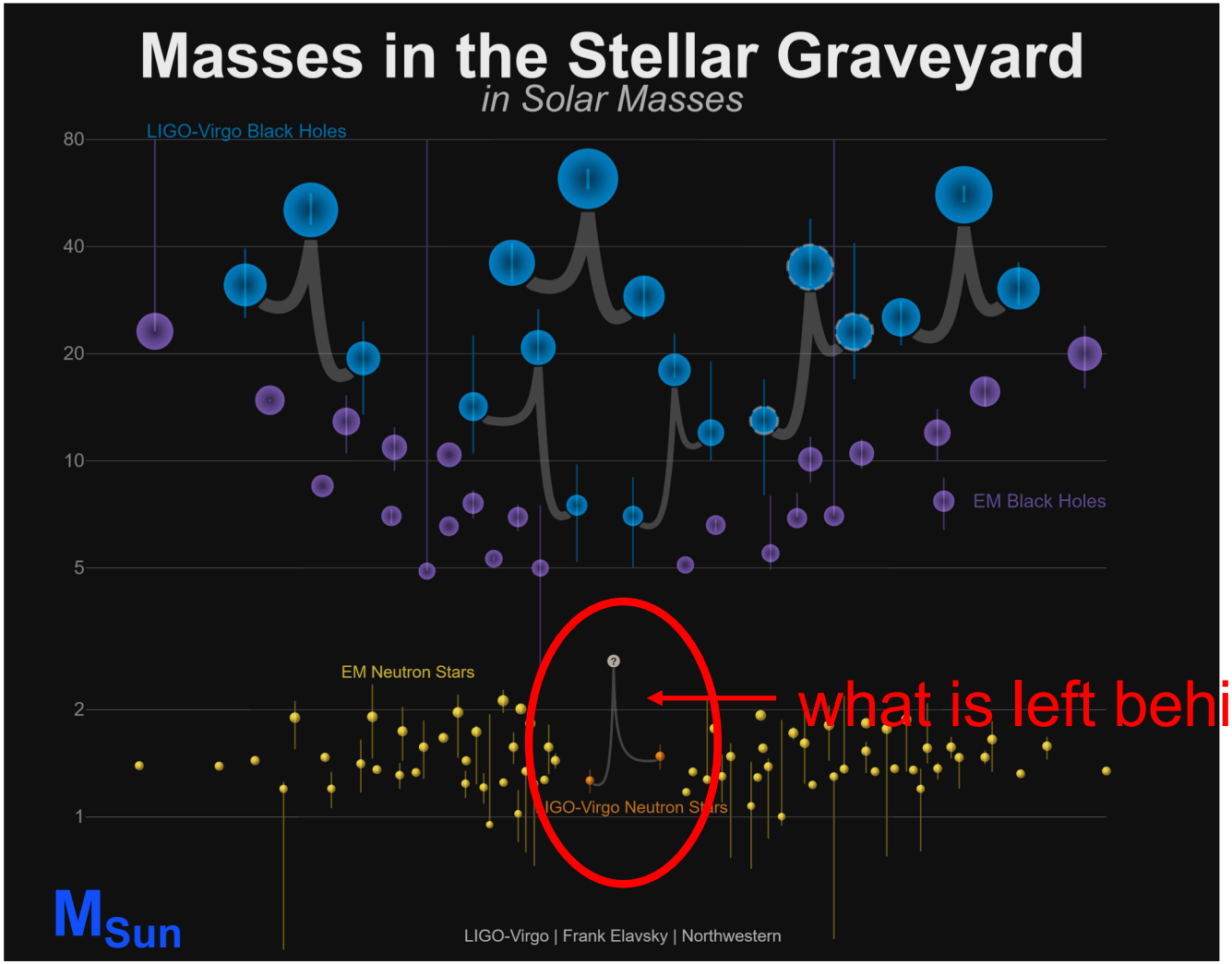
Our automated software ("pipeline") matched the GW signal to a predicted waveform for a binary neutron star merger



The longest (~ 60 s), loudest (SNR ~ 32), closest (40 Mpc) signal LIGOhas ever observed!

https://www.youtube.com/watch?v=WoDCPTLgxh4

We can measure the masses (in the combination “Chirp mass”) very well:



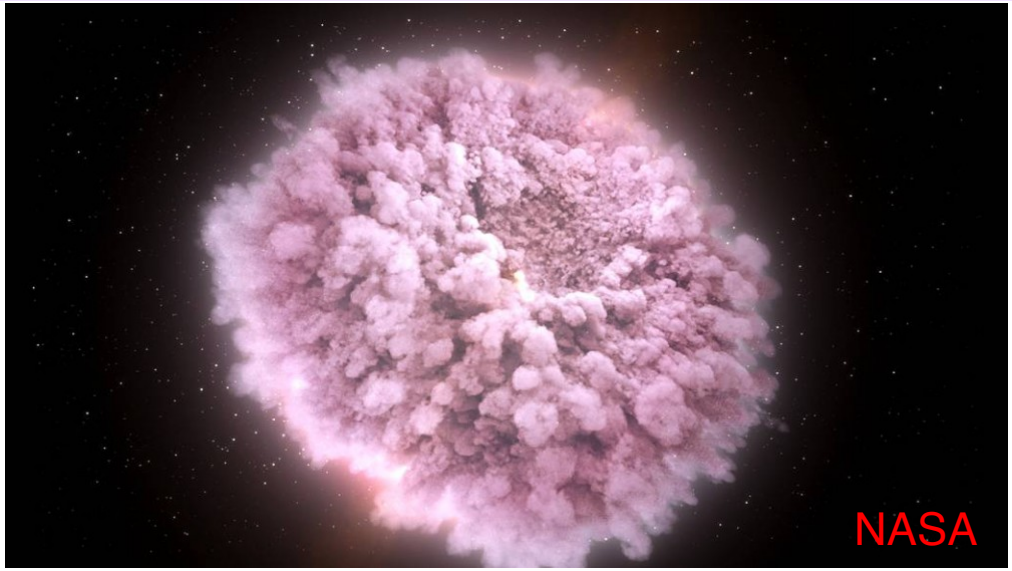
“stellar mass” black holes

“mass gap”?

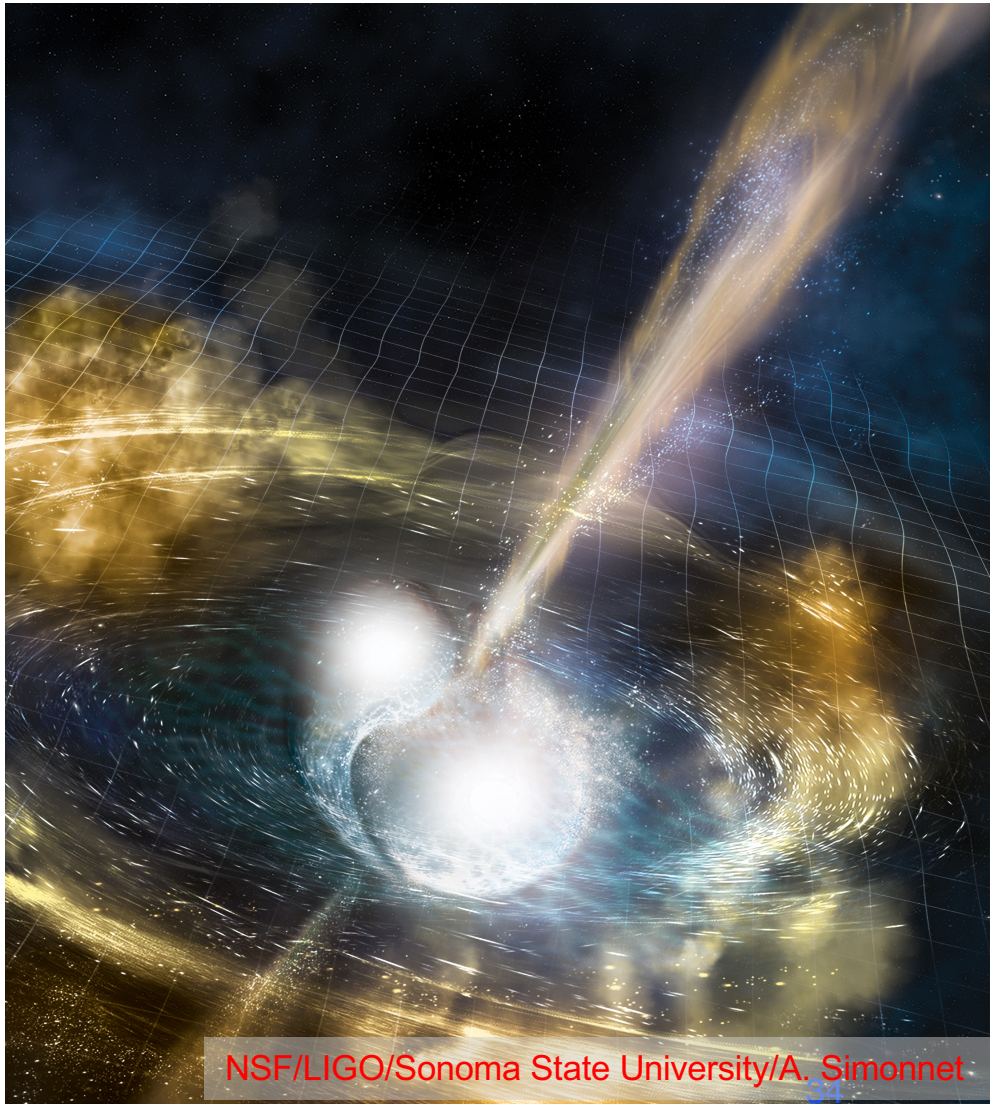
Neutron stars (pulsars)

http://ligo.org/detections/GW170817.php

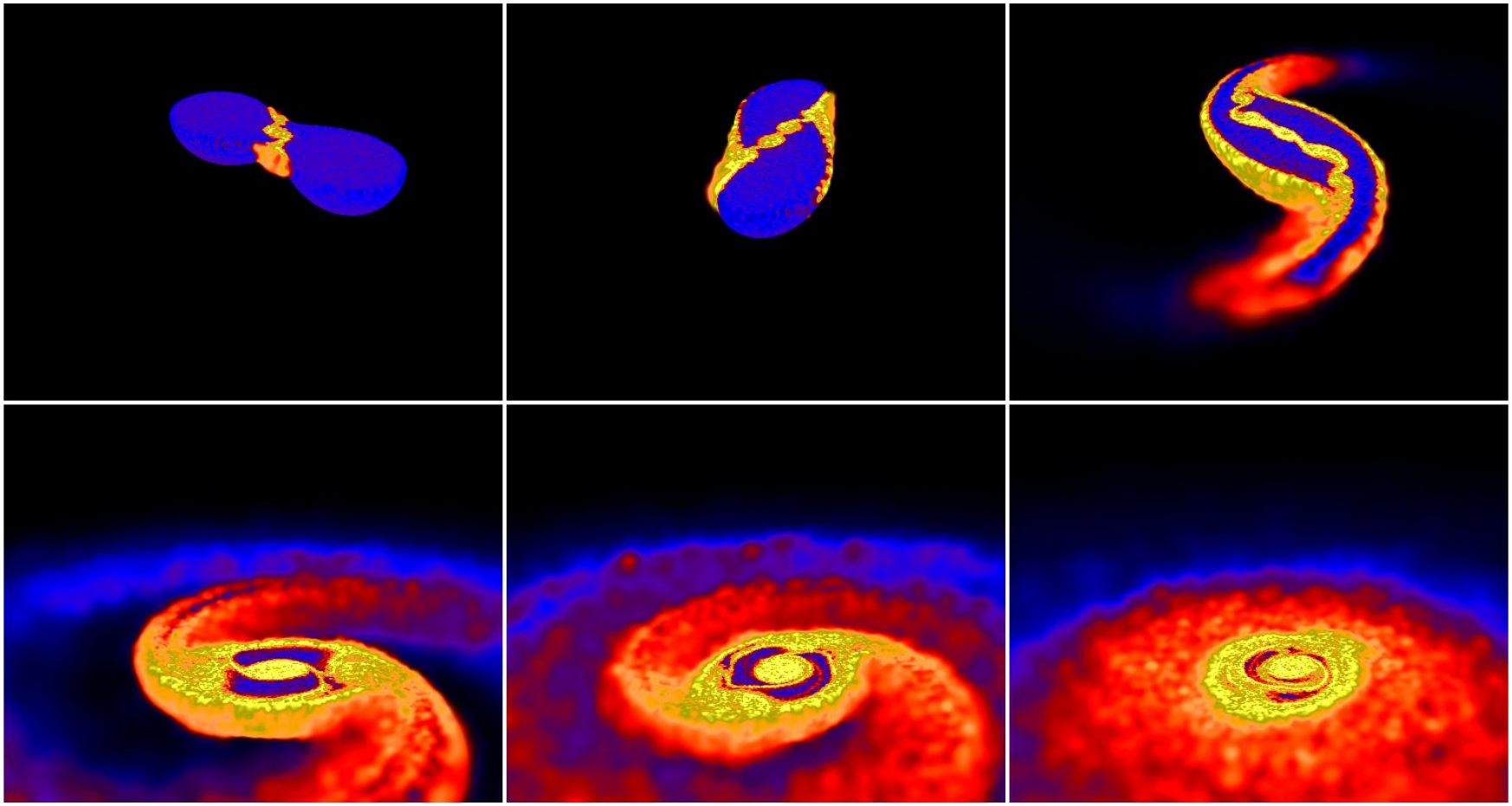
As the stars spiral together, they get torn apart by each other's gravity: Tidal distortion → Disruption!



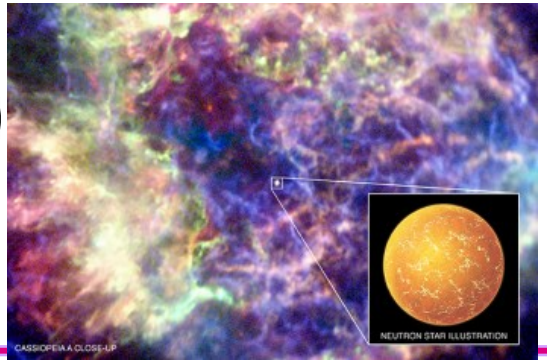
The disruption of the stars results in a huge outflow of neutron-rich "dynamical ejecta" that powers a GRB and broad-band afterglow



BNS mergers, tidal distortion and disruption

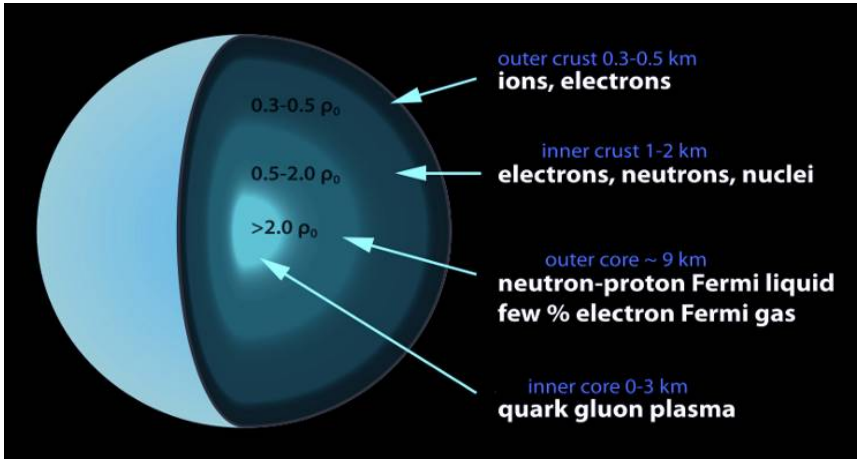


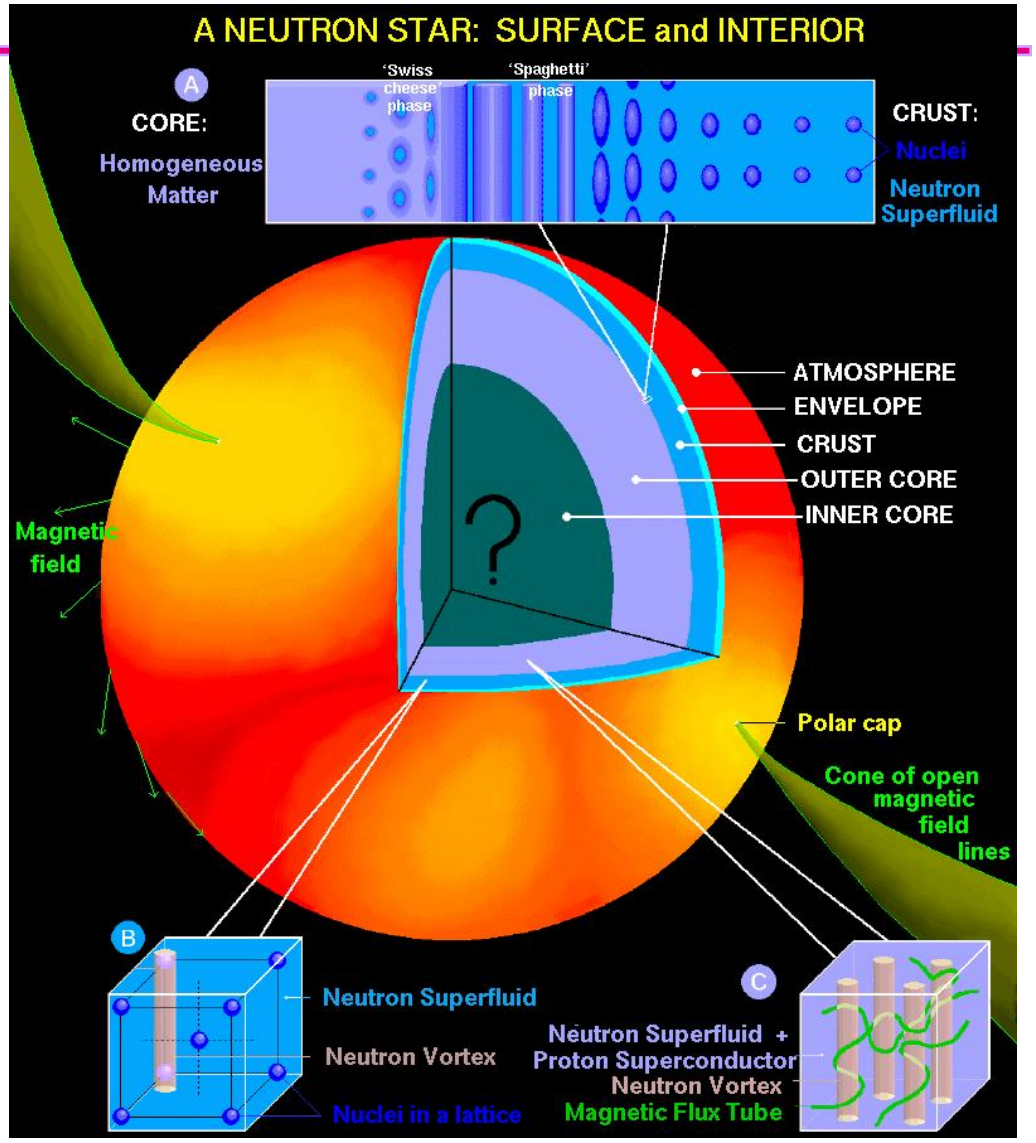
Credit: Daniel Price and Stephan Rosswog



Neutron stars

- Dead remnants of massive star core collapse supernovae
- A unique laboratory for fundamental physics
- All four forces of nature, Strong, Weak, EM, gravity – all under *the most extreme beyond-laboratory conditions*
- Structure can be revealed through binary mergers



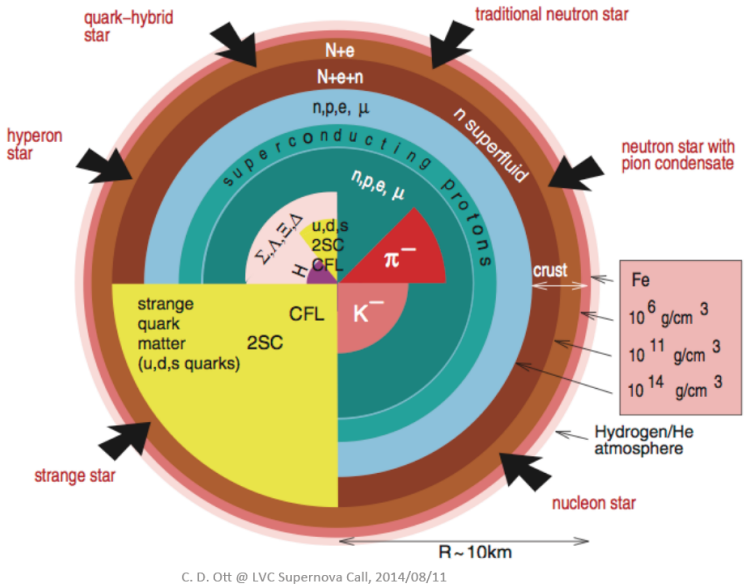


http://www.astro.umd.edu/~miller/nstar.html

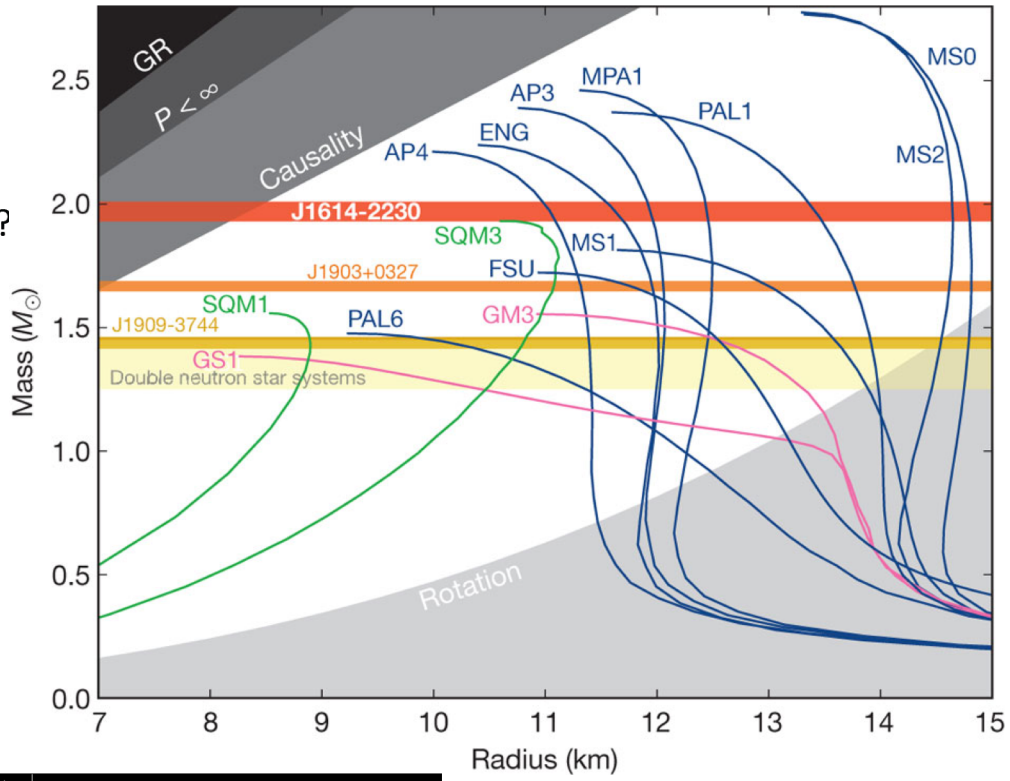
NEOS, NS structure, and NS mass-radius relation

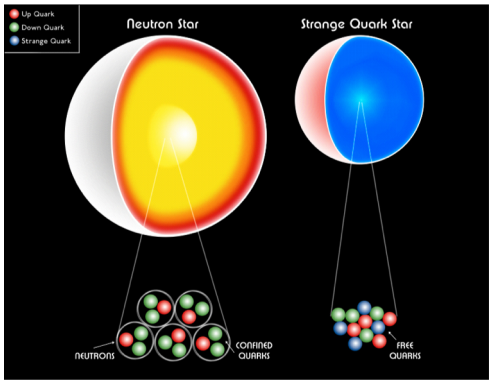
Neutron Star Equation of State

- Simplification: T=0, pure neutron & proton gas. Appropriate (?) for interior of cold neutron stars.

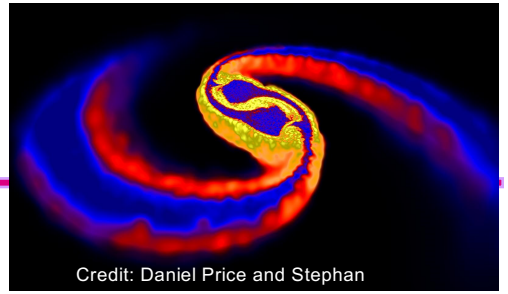


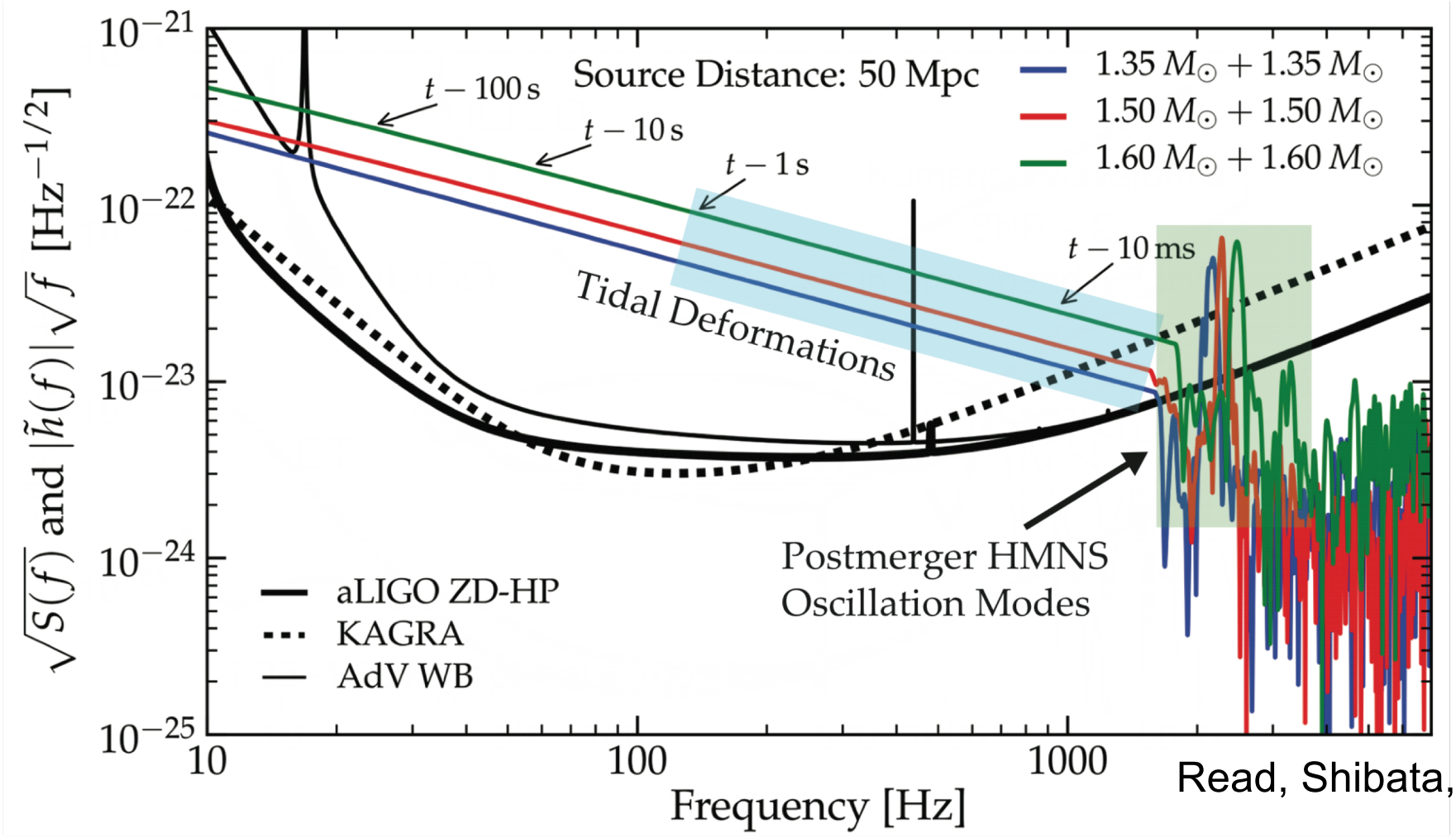
C. D. Ott @ LVC Supernova Call, 2014/08/11





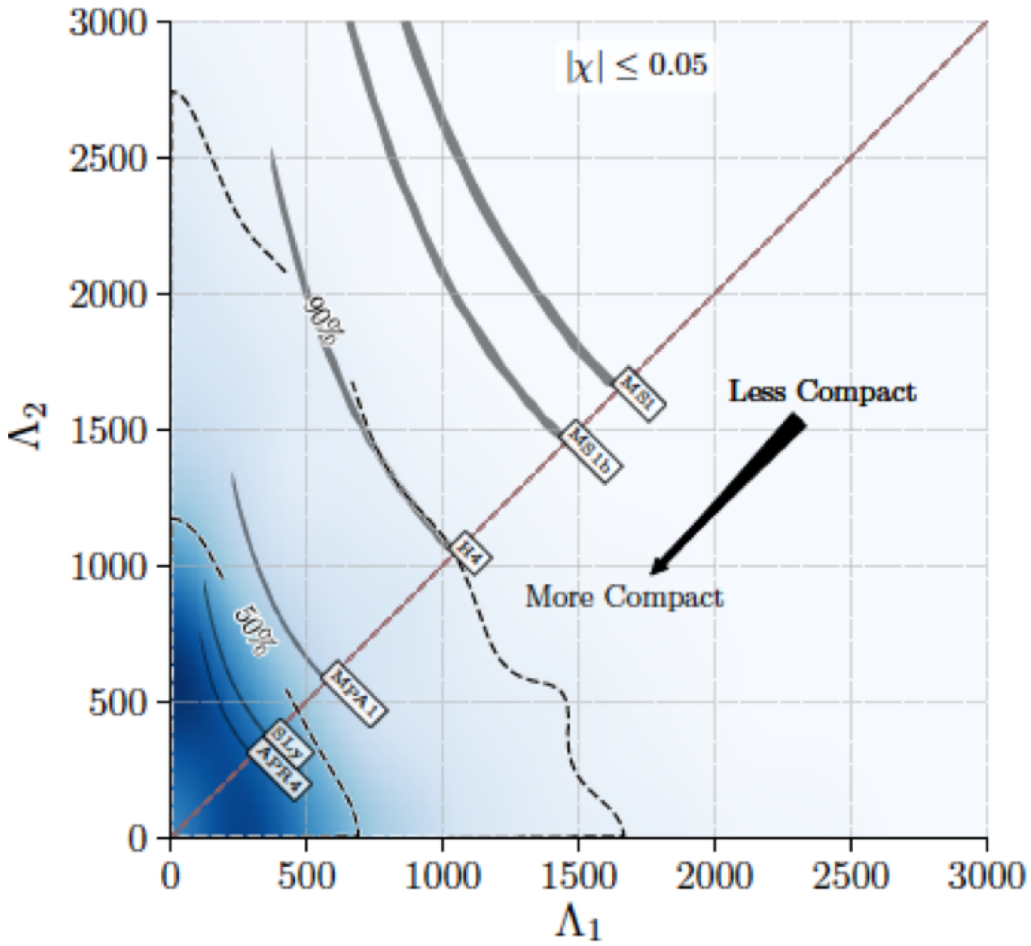
Tidal disruption of neutron stars near merger





Read, Shibata, et al

Constraints on tidal distortion

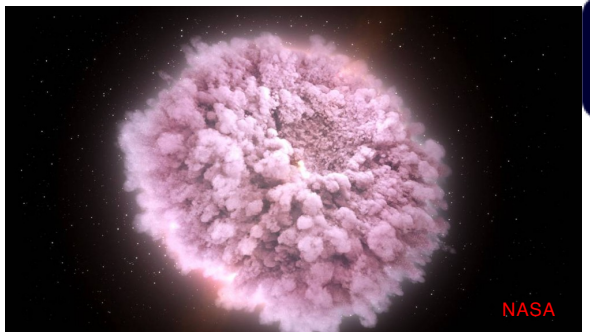


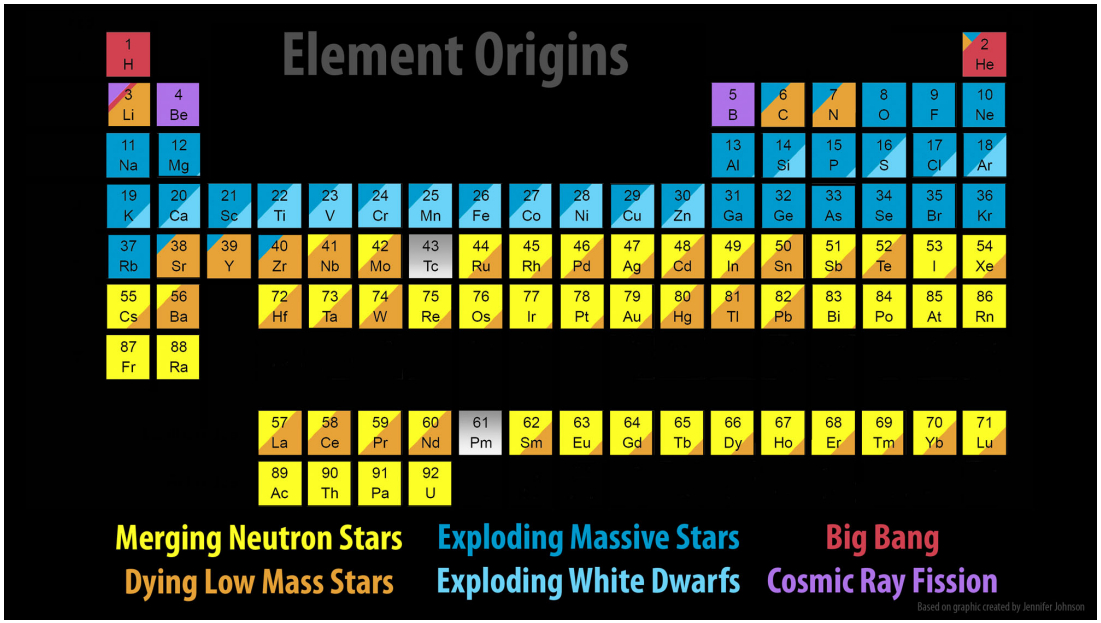
- Tidal deformability:

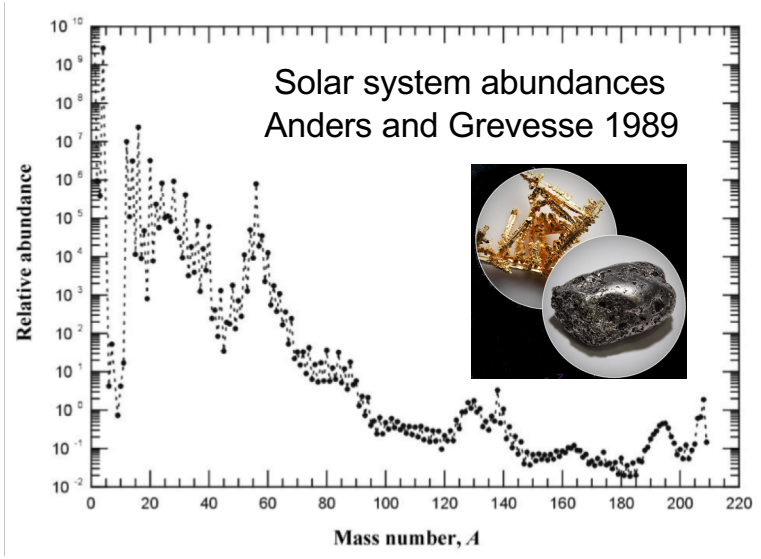
$$\Lambda = \frac{2}{3} k_2 \frac{c^2}{G} \left(\frac{R}{M}\right)^5$$

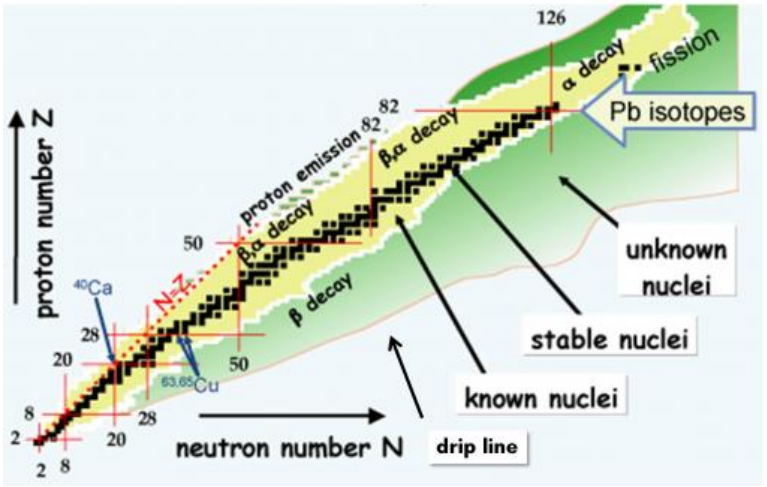
- k_2 is the 2nd Love number
- R and M are the radius and mass of the star
- LIGO results for GW170817 are most consistent with more compact stars, R < 14 km

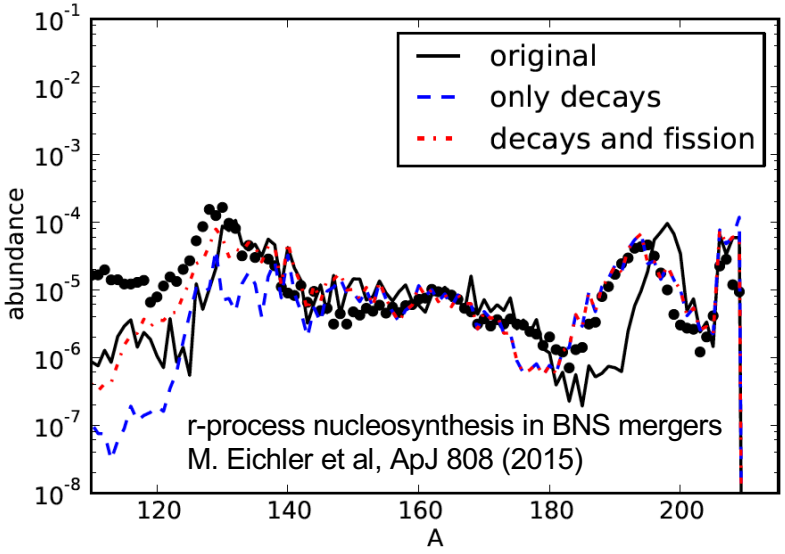
The origin of the (heavy) elements

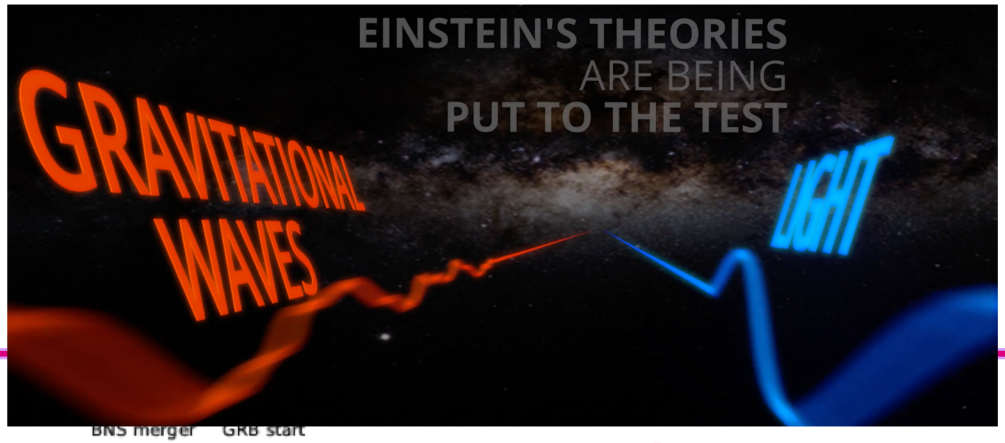


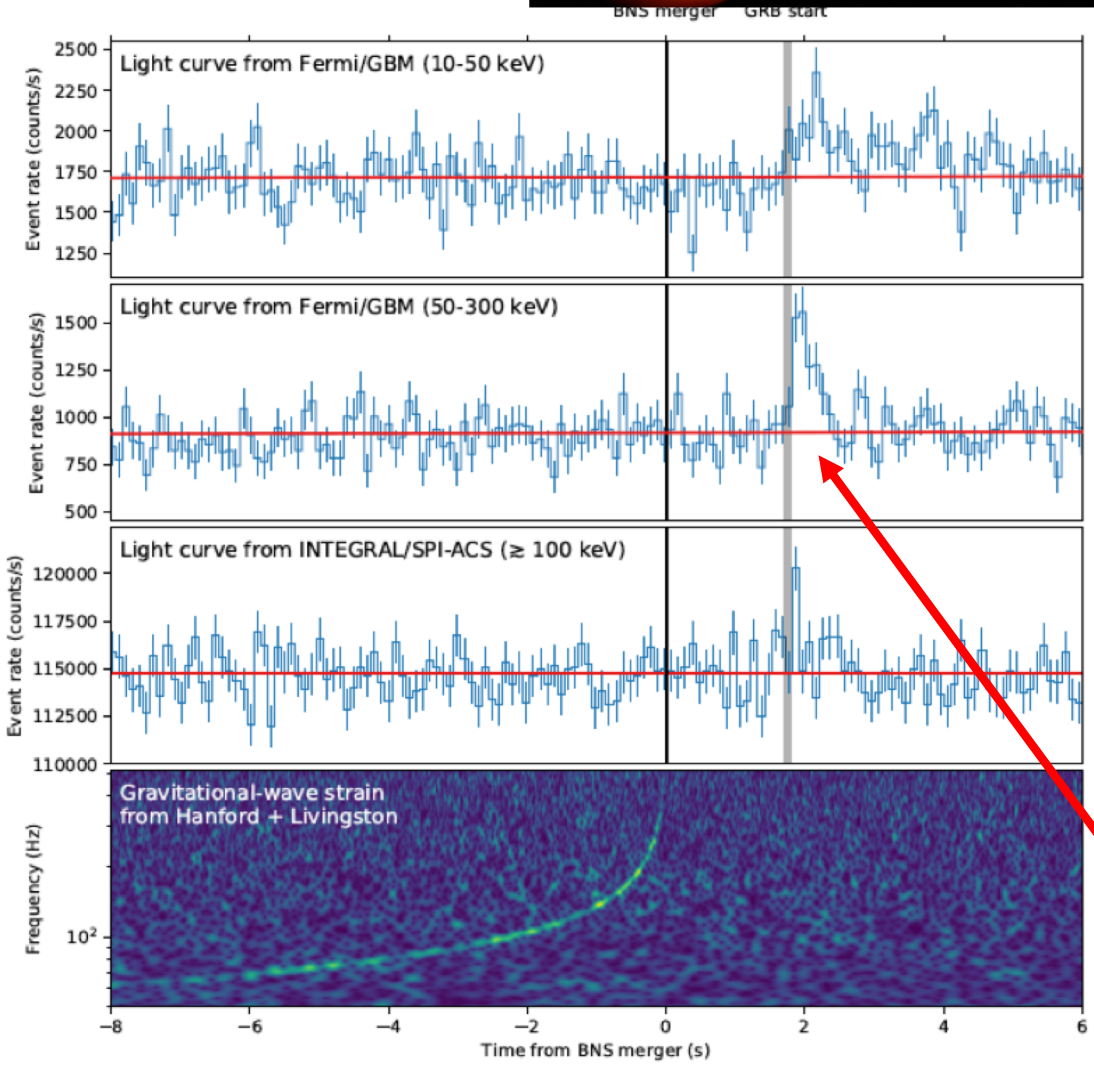












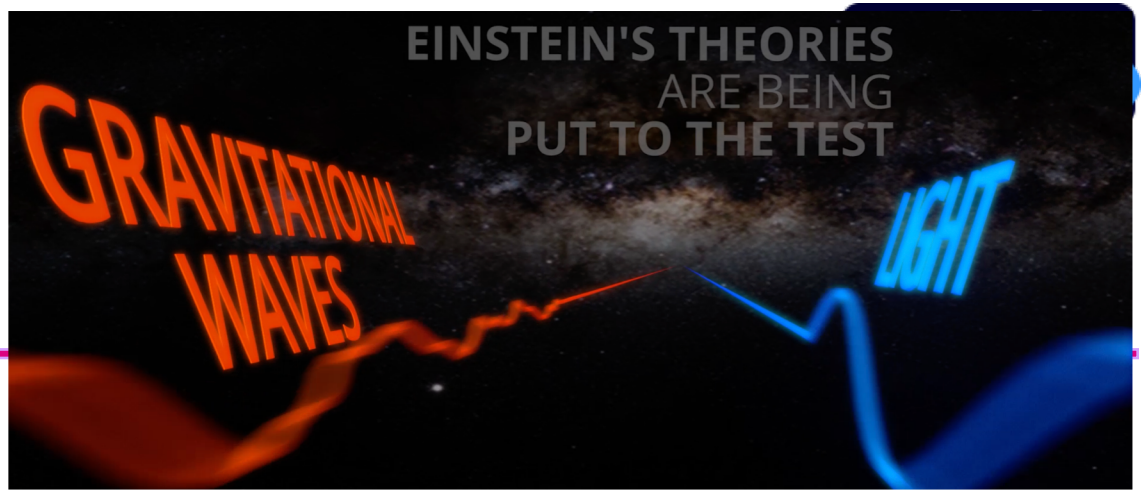
1.7 seconds later, duration < 2 seconds

What can we learn using just the GWs and the γ-rays?

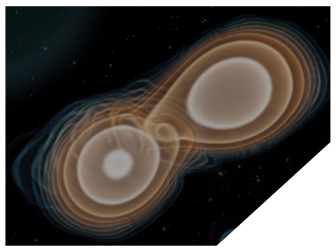
Fundamental properties of GWs, unique new tests of General Relativity!

B. Abbott et al, LIGO-Virgo, Astroph.J.Lett. 848, 2, L13 (2017)

For the physicists: Fundamental properties of GWs and NSs



- The GW signal is *fully consistent with General Relativity, over thousands of cycles*.
- *GW polarization is consistent with"tensorial"* – (+ and ×), not (pure) vector or scalar.
- Tidal disruption is weak: nuclear EOS is not stiff, NS radius < 14 km
- GWs, and γ-rays travelled for 130 million years (4×10^{15} s), arrived within 2 seconds of each other:
- The *"speed of gravity"* : $V_{GW} = V_{light}$ to one part in 10^{15} !
- *No dispersion: mass of the graviton* m_g < (few) × 10^{-23} eV/c^2 , *consistent with 0*.
- Improved Lorentz invariance violation limits; constrained to one part in 10^{13}.
- Both the gravitons and the photons "fell" into the Milky Way Galaxy over the same time: *the Equivalence Principle holds between* gravitons and photons .



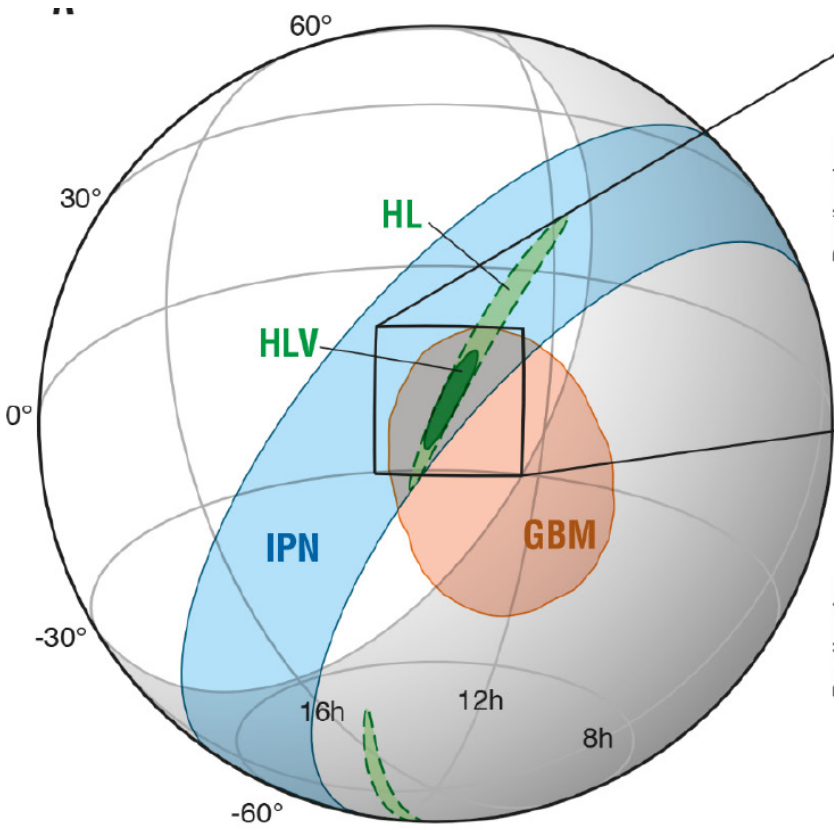
g

γ

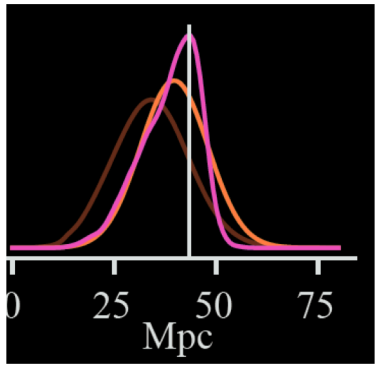


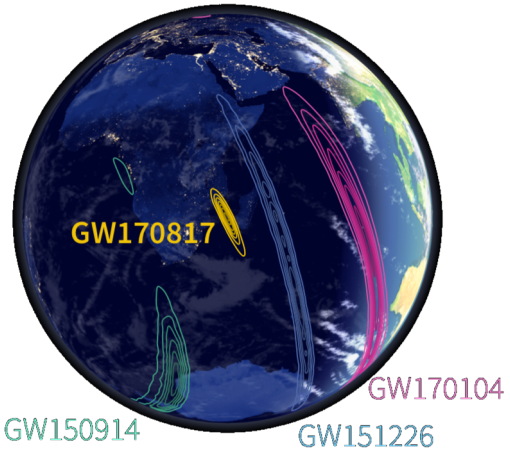
For the astronomers:
within minutes, locate the source on the sky, tell telescopes where to point.

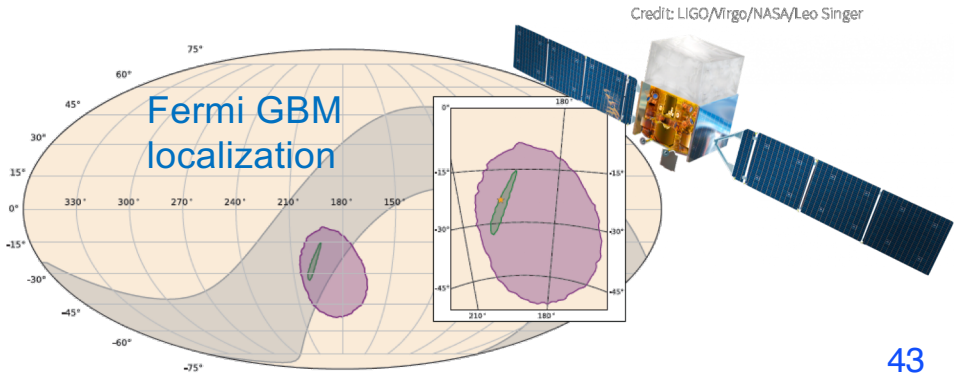
Source located to 28 sq deg, and ~ 40 Mpc.
Time is of the essence!
(Initial alert sent out *27 minutes* after the GWs passed through LIGO)



We can locate the source in 3D
– GWs are "standard sirens"

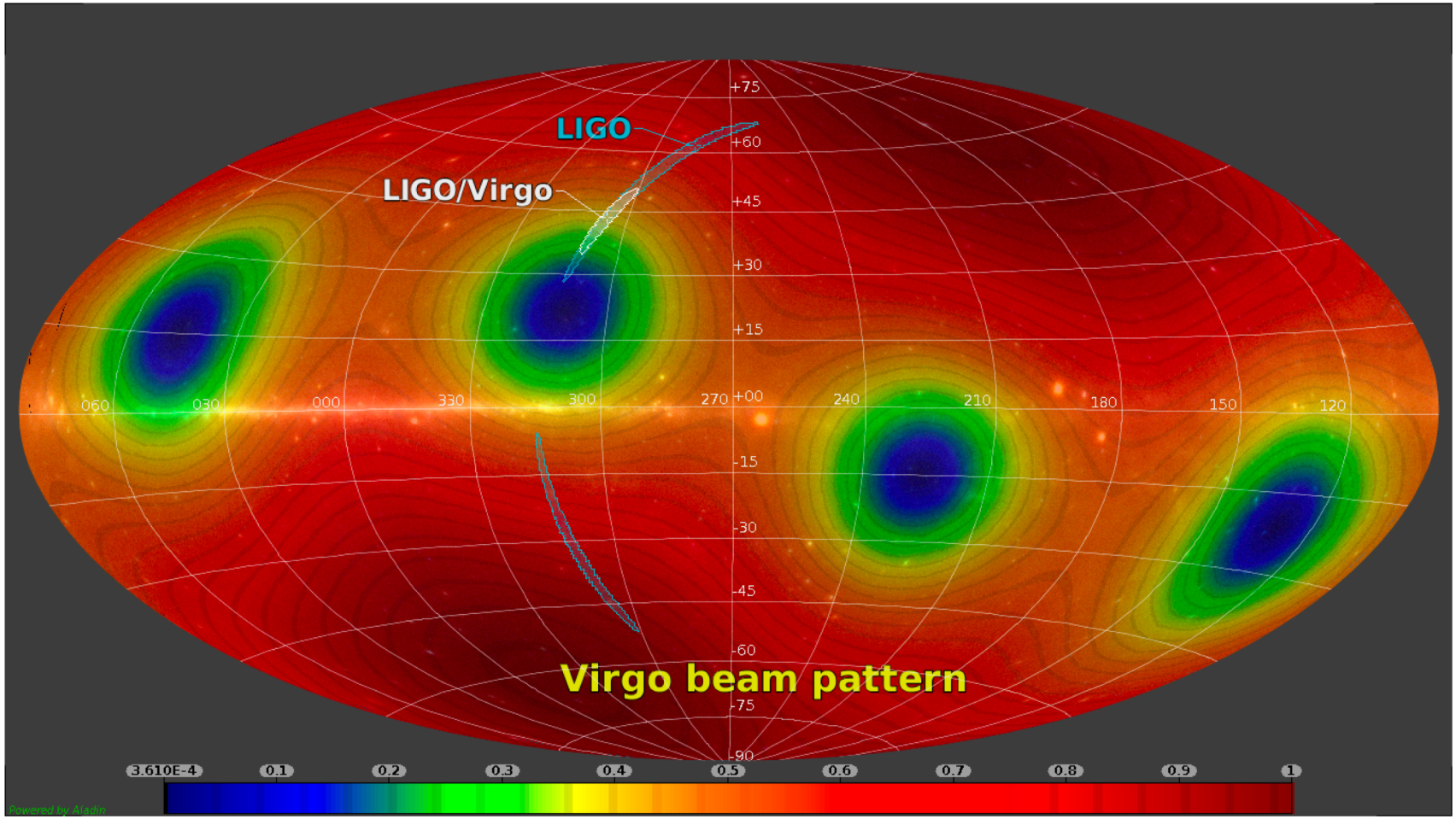






Virgo "non-detection" was very important!

It appears that the signal was in Virgo's "blind spot".



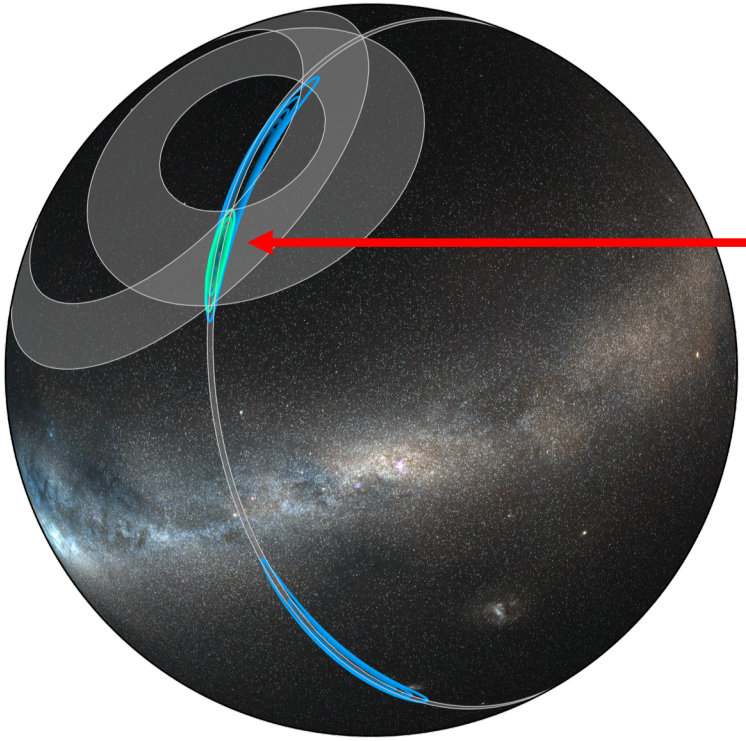
Reduces the localization patch to "only" ~28 deg^2

LIGO-Virgo / Greco, Arnaud, Vicere (2017). Background: Fermi/NASA

Is there anything to be found in that spot on the sky?

POINT YOUR TELESCOPES!

This is the REAL THING!!!





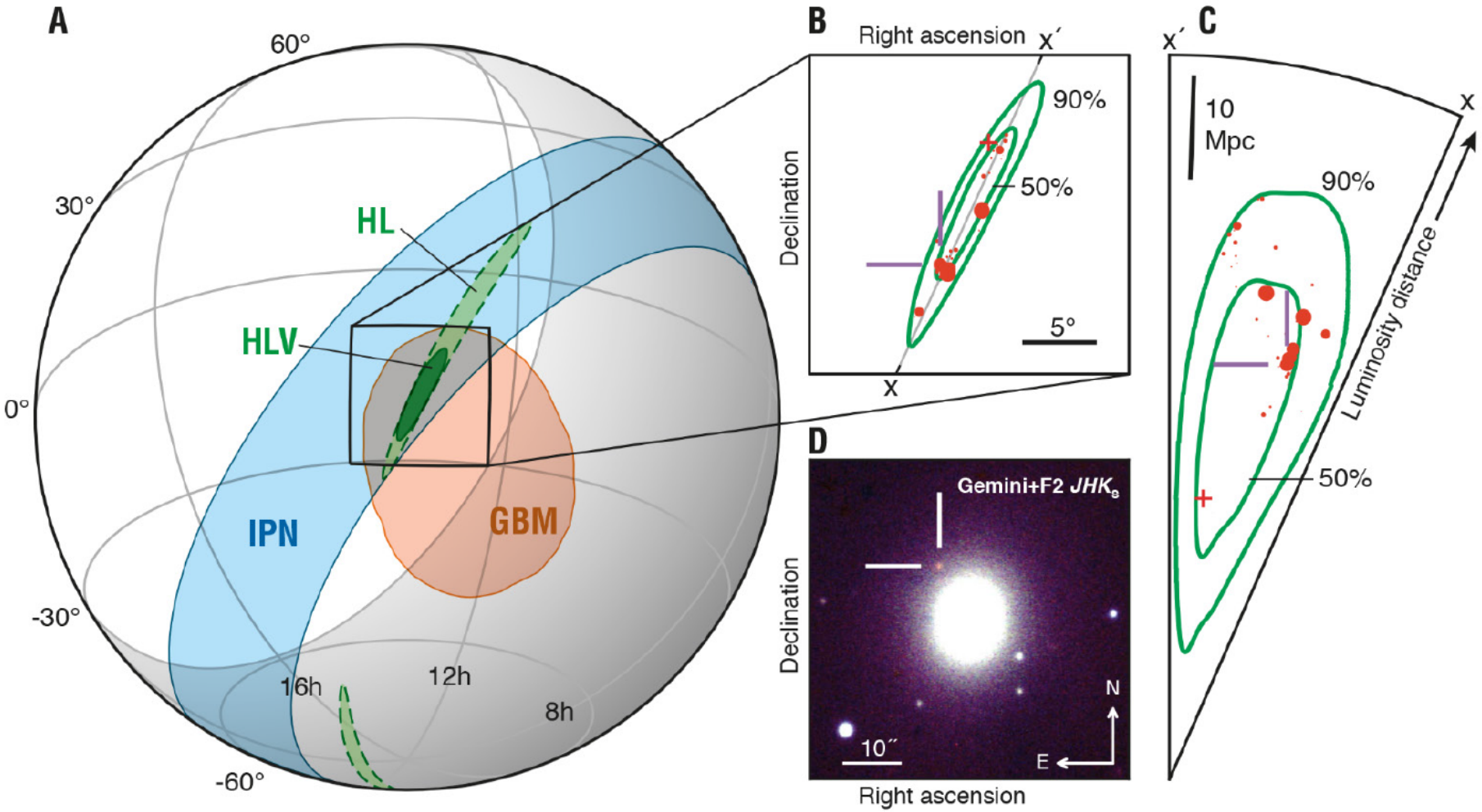




Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

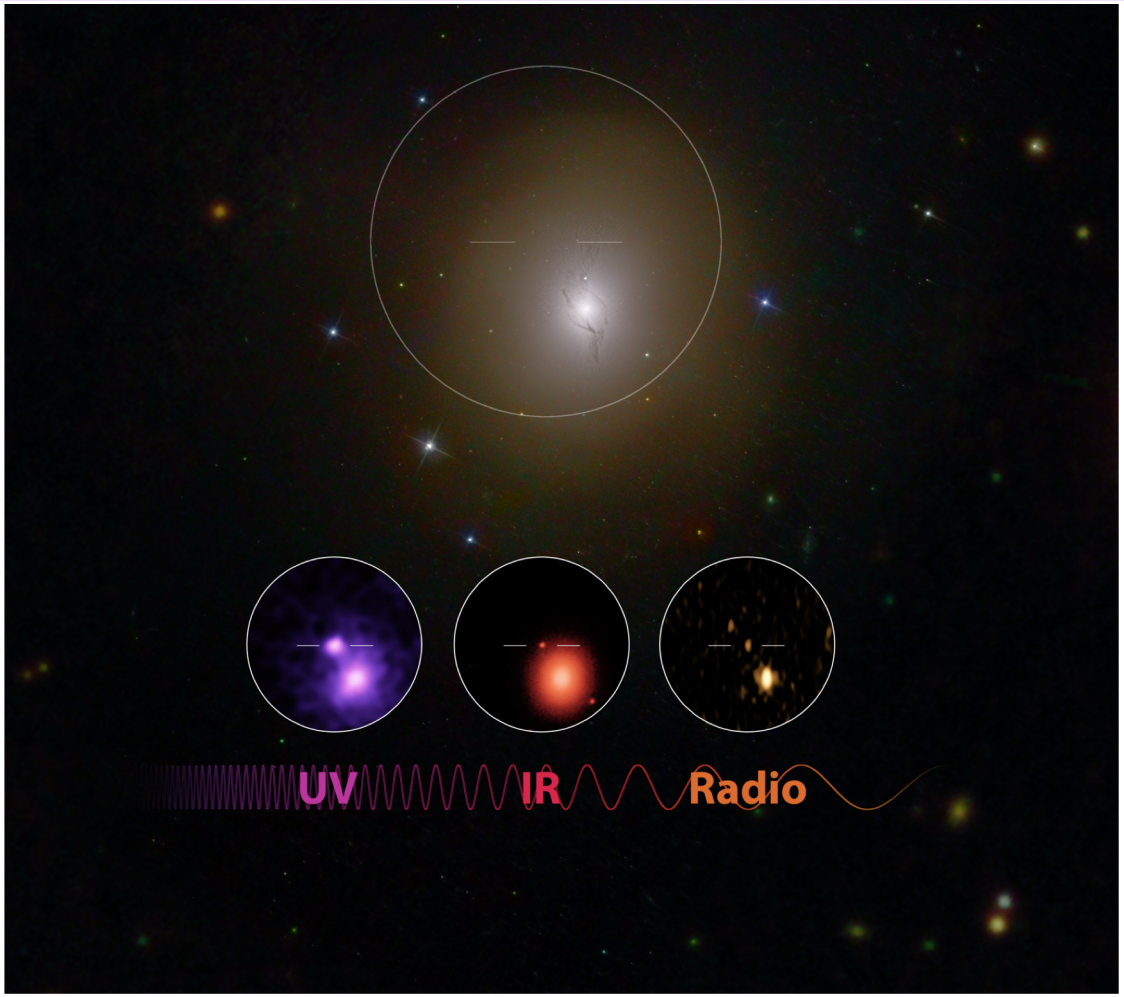
Is the the dawn of GW-multi-messenger astronomy?

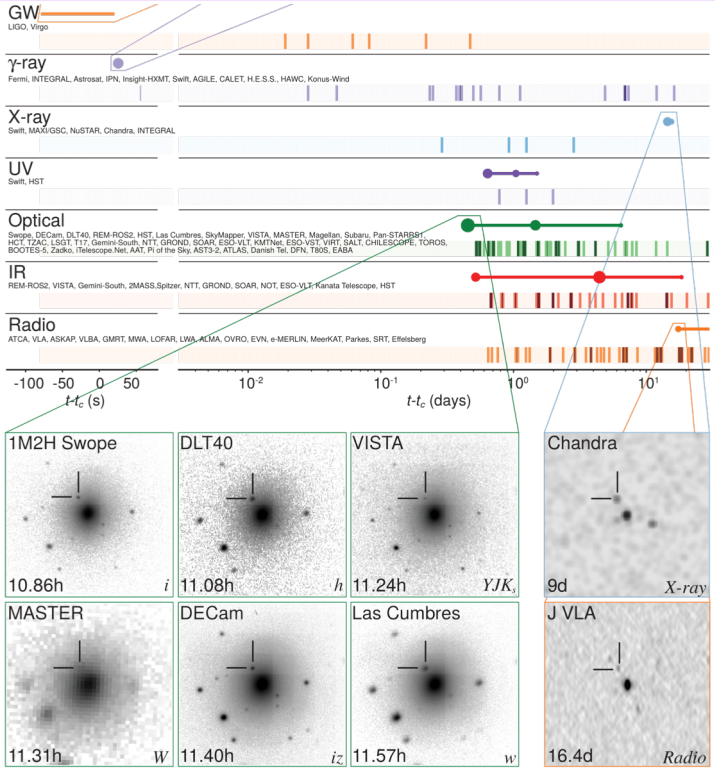
The next evening: they got it!

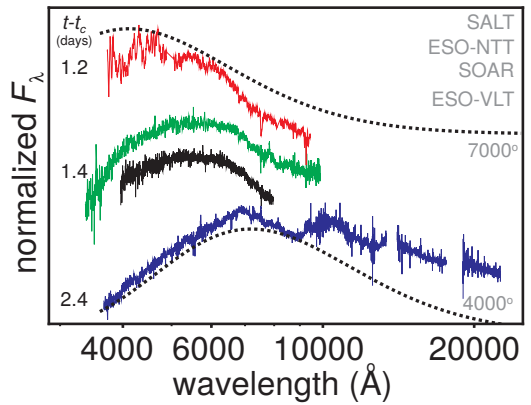


M. M. Kasliwal *et al.*, *Science* 10.1126/science.aap9455 (2017).

Light at Every Wavelength



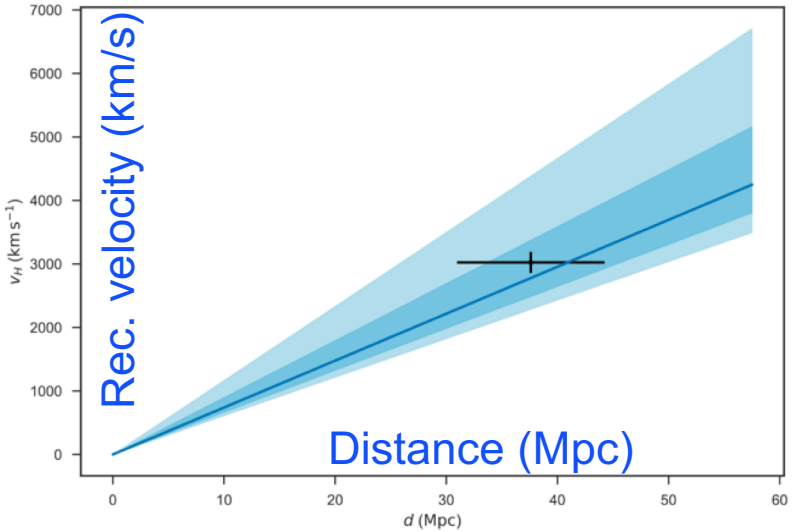


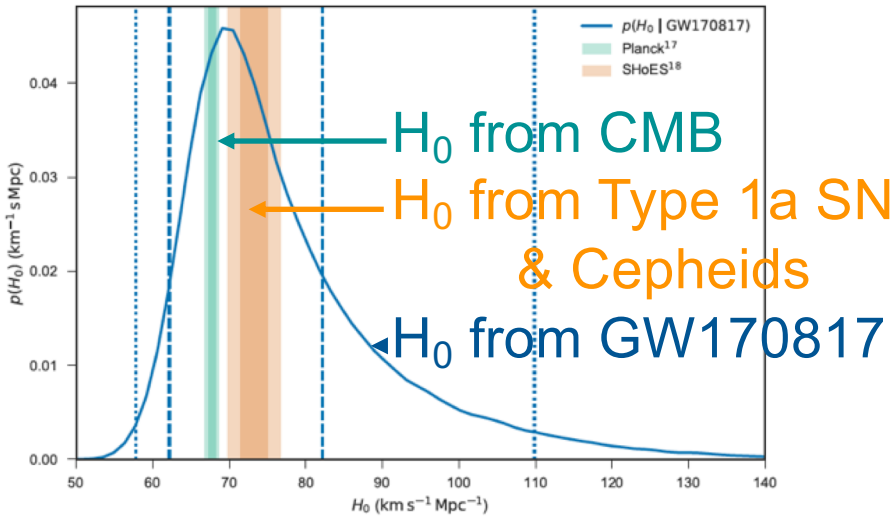


Host galaxy: NGC 4993; redshift: ~ 0.01

Measuring the expansion rate of the universe in an entirely new way!

- From the GWs, we can measure the distance to the source fairly accurately 40 Mpc or 130 Mly
- From the optical afterglow we can measure the redshift(recessional velocity) of the source galaxy NGC4993.
- Combining them gives the Hubble expansion rate H_0.
- Not terribly accurate yet, but in good agreement with measurements made in entirely different ways (which don't agree with each other!)





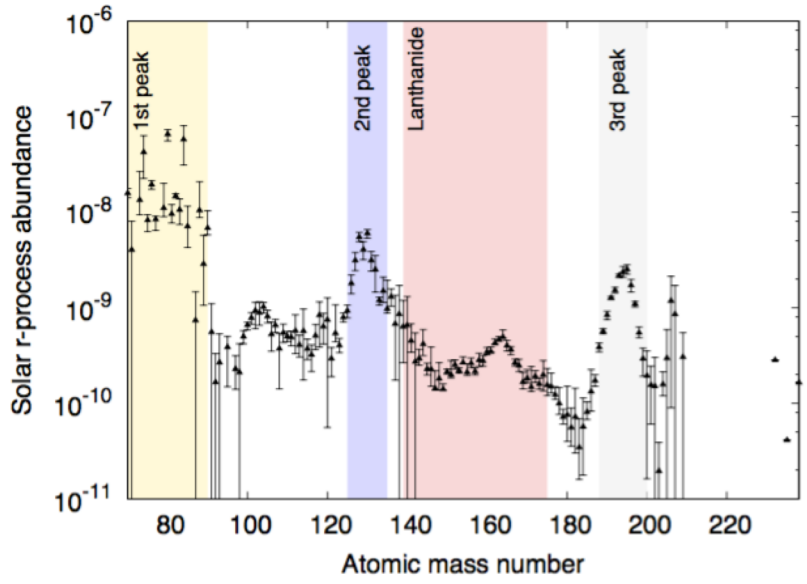
LIGO-Virgo, B.P. Abbott et al. Nature (2017)

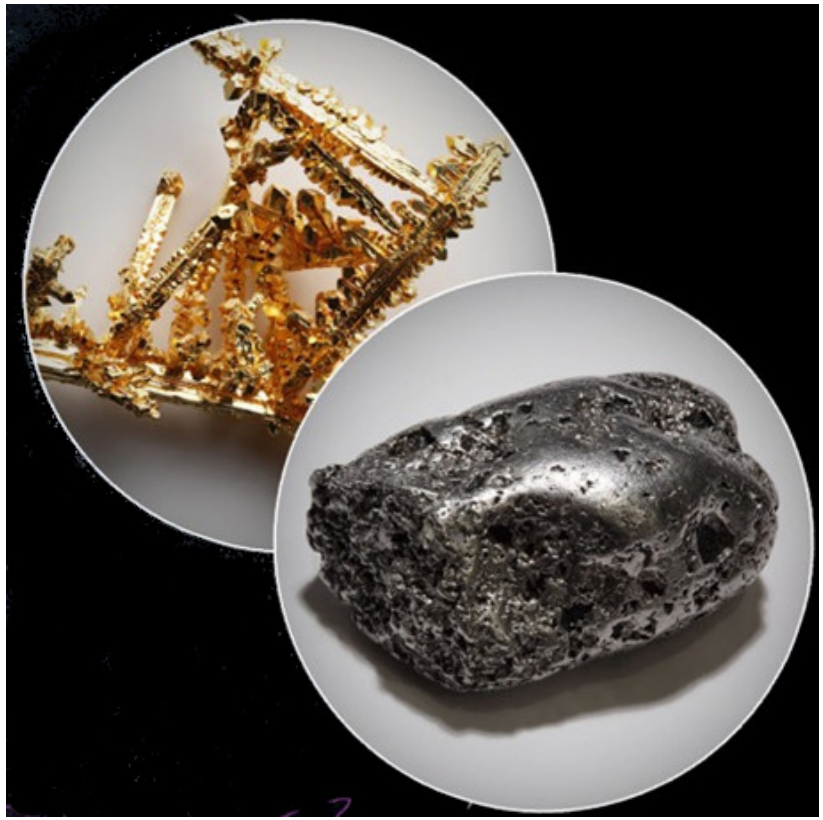
Not just a site, but *the* site of heavy element production?

Observed Solar Abundance

= Quantity per merger x Rate of Mergers

>~0.05 solar-mass x >~300/Gpc^3/yr



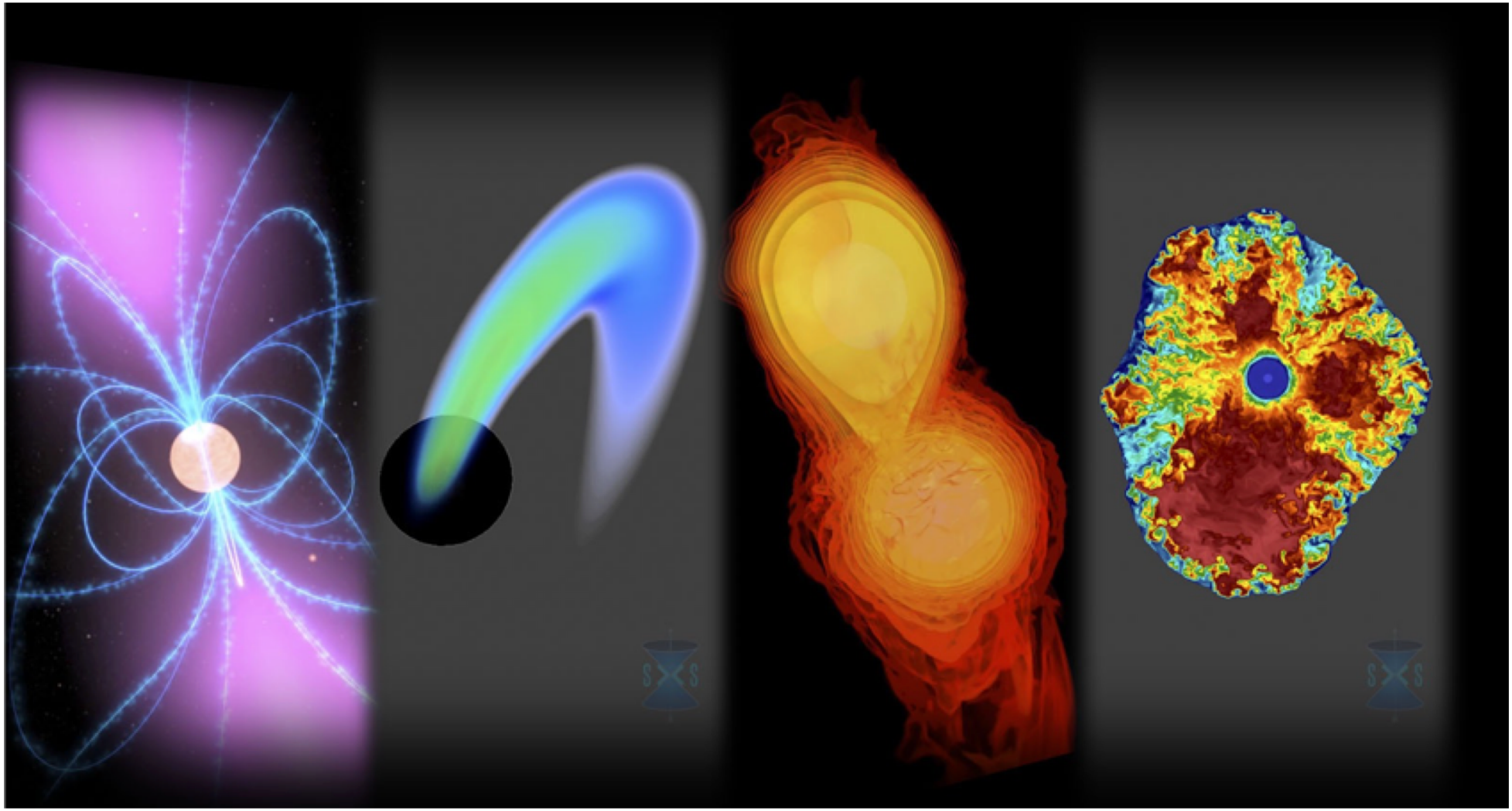


Ejecta mass estimate: ~0.05 solar mass

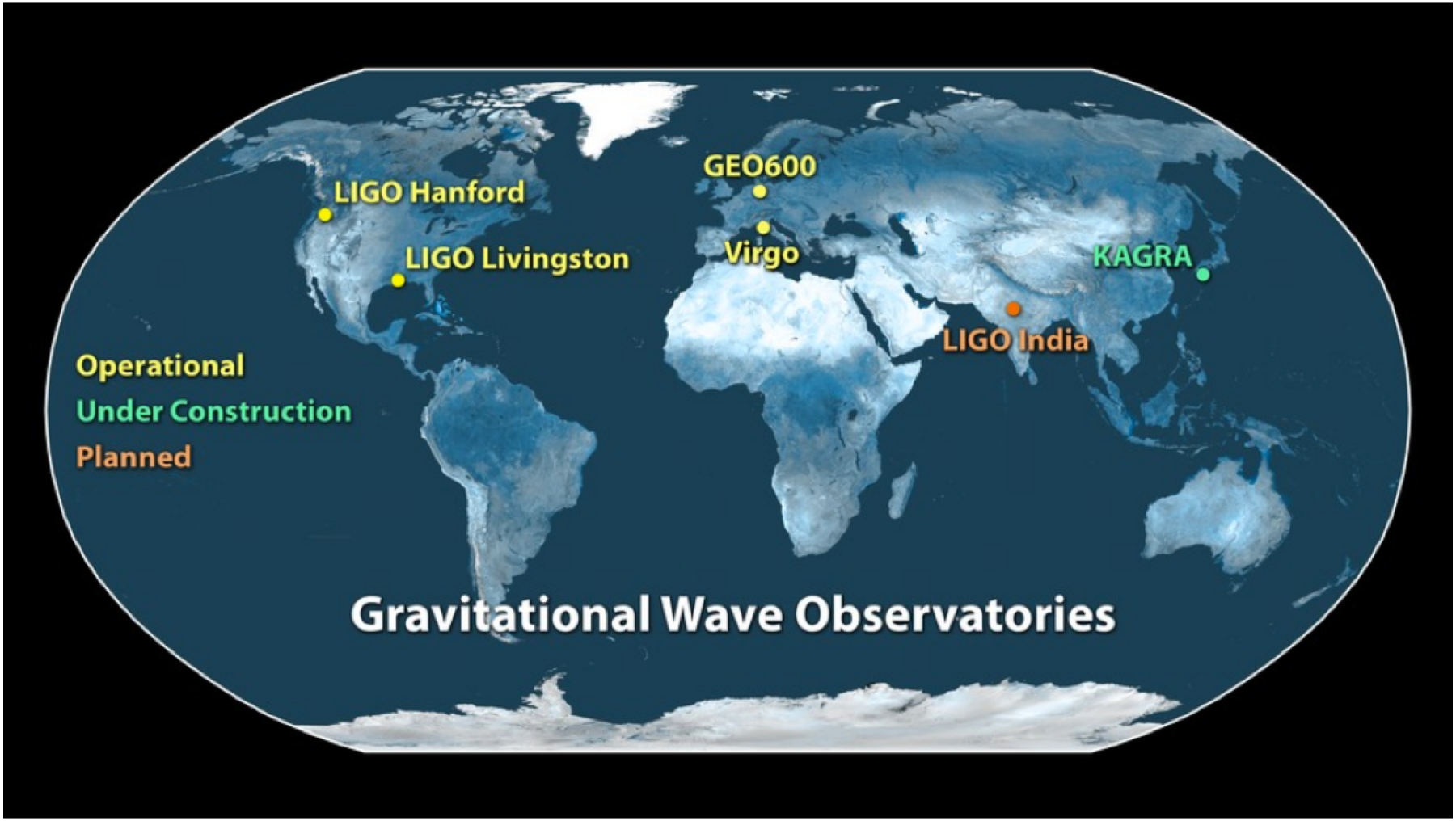
Merger rate estimate: $R = 1540^{+3200}_{-1220}\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Consistent!

The future of Gravitational-wave astronomy

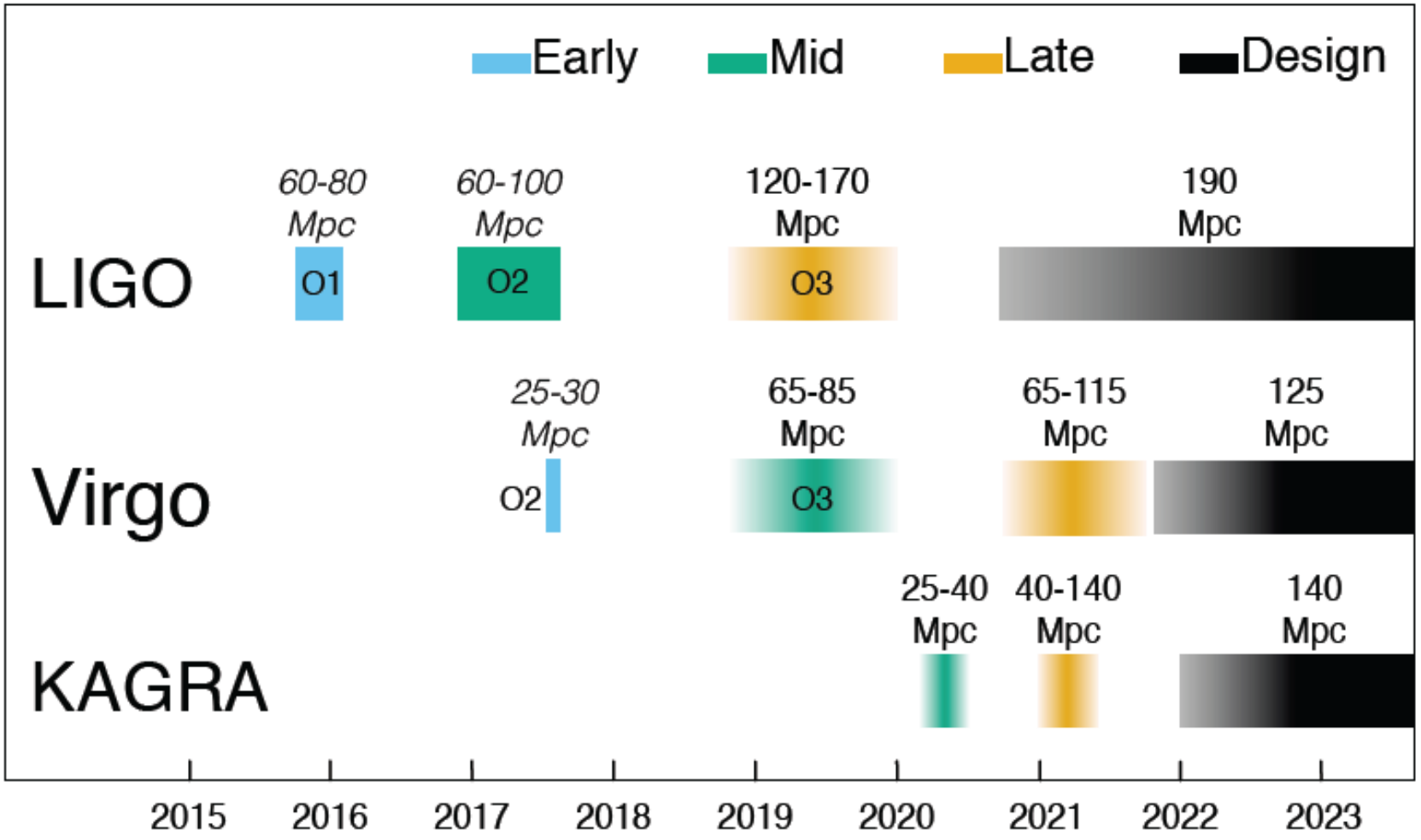


Coming years: more, and more sensitive detectors



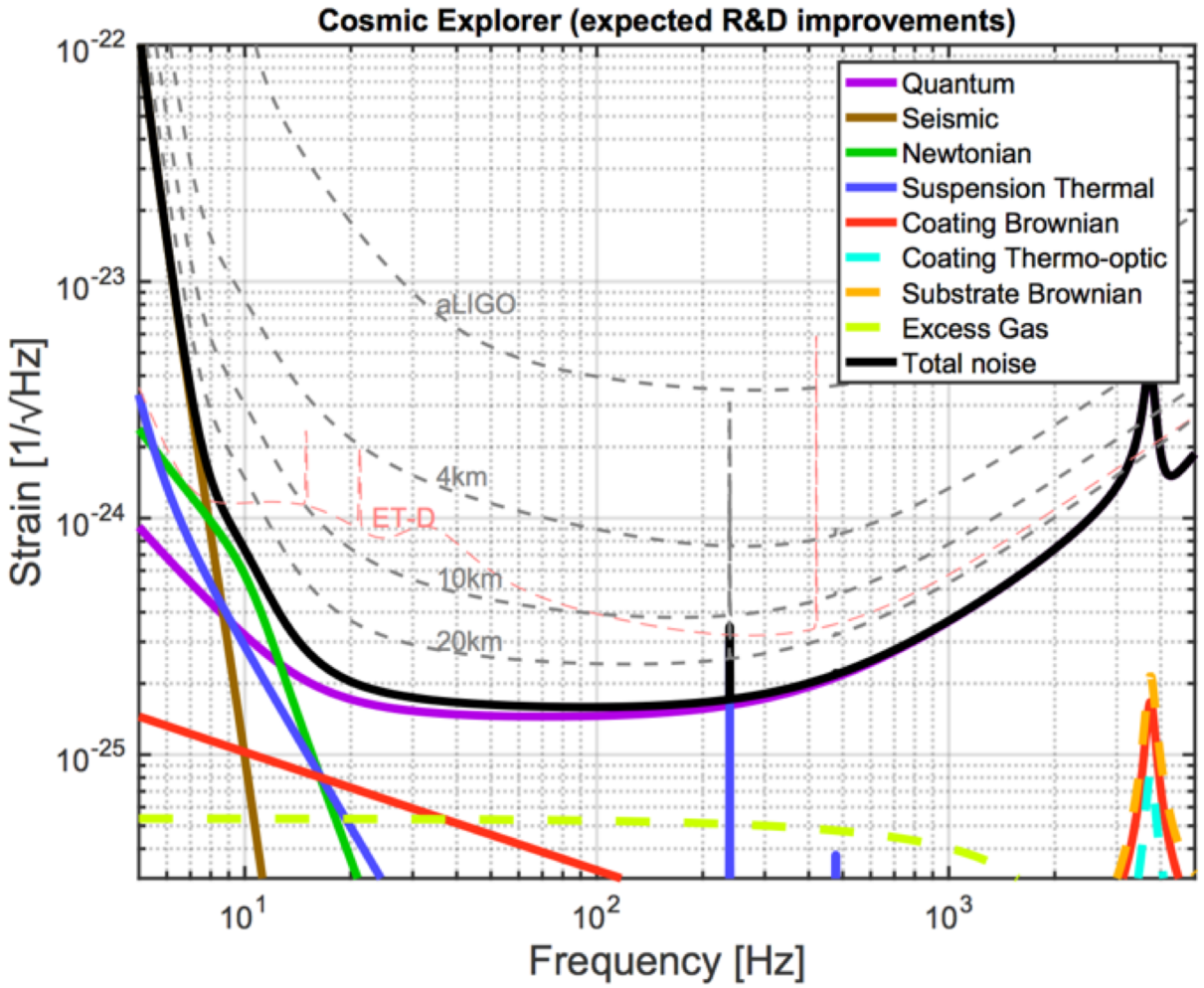
http://ligo.org/detections/GW170817.php

Coming years: more, and more sensitive detectors



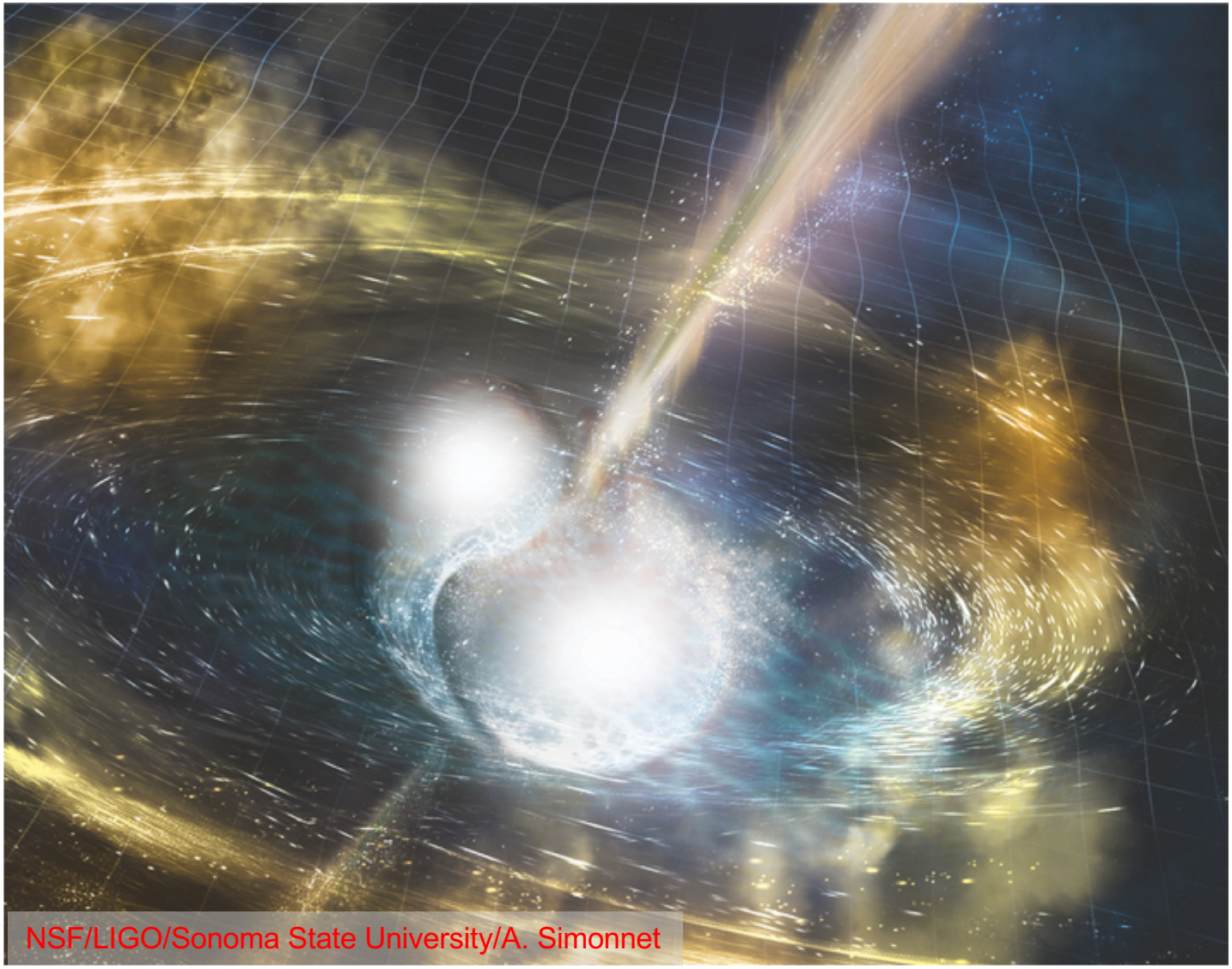
https://arxiv.org/abs/1304.0670

Future prospects for terrestrial gravitational wave astronomy



B. P. Abbott et al. CQG 34 (2017)
http://iopscience.iop.org/article/10.1088/1361-6382/aa51f4

The future of gravitational wave astrophysics is … golden!



THANKS to Caltech, MIT, and the NSF!

THANKS to my LIGO & Virgo collaborators, and to the 100's of EM astronomers who found GRB170817A and EM170817!

And…
thank you for your attention!