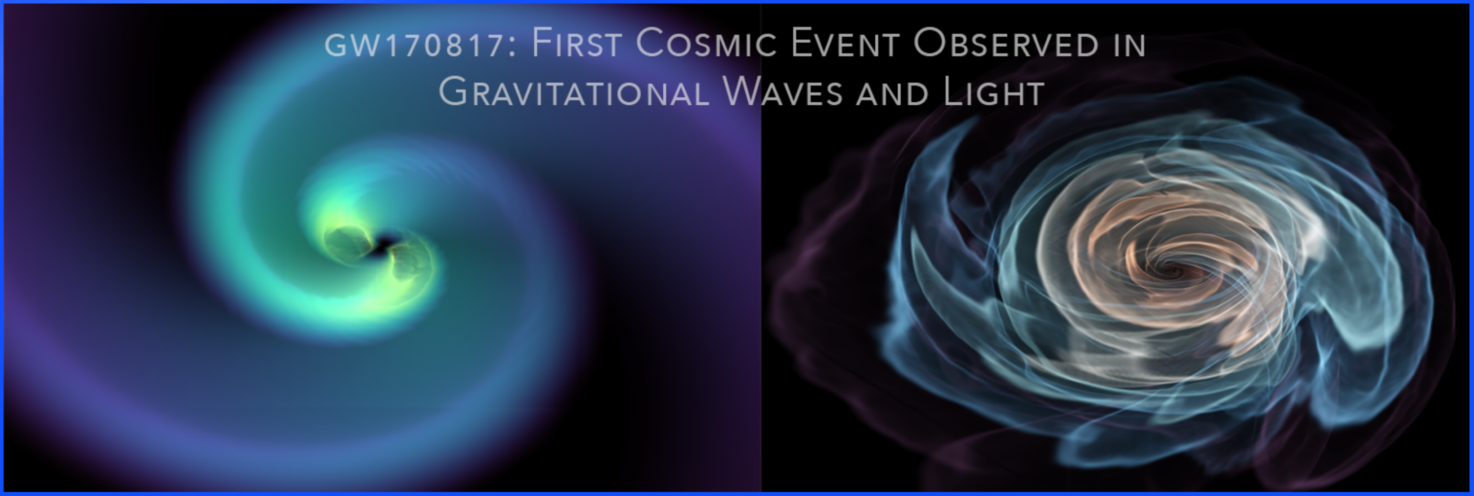
The Detection of Gravitational Waves by LIGO and Virgo: astrophysical implications

Alan J Weinstein, LIGO Laboratory, Caltech

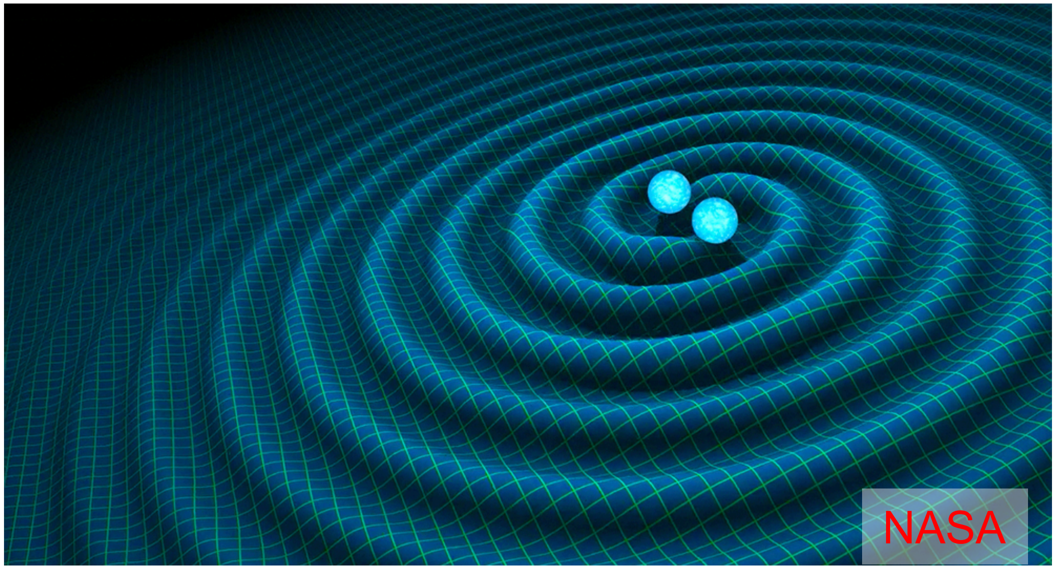
Caltech Faculty Meeting
November 15, 2017



GW170817: First Cosmic Event Observed in Gravitational Waves and Light

Gravitational waves

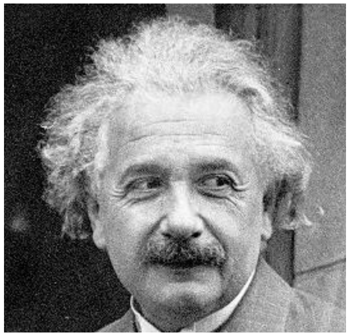
Masses that accelerate
(eg, a binary orbit)
create ripples of changing gravity (curvature)
in space and time.


NASA

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

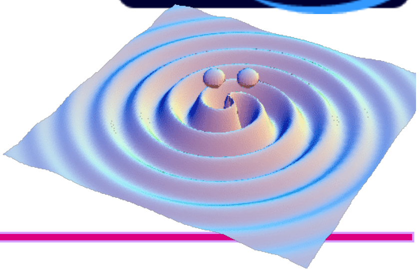
Predicted by Einstein in 1916
(and discovered 100 years later)

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



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

Nature of Gravitational Radiation



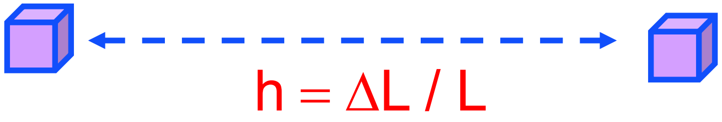
General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in fabric of spacetime

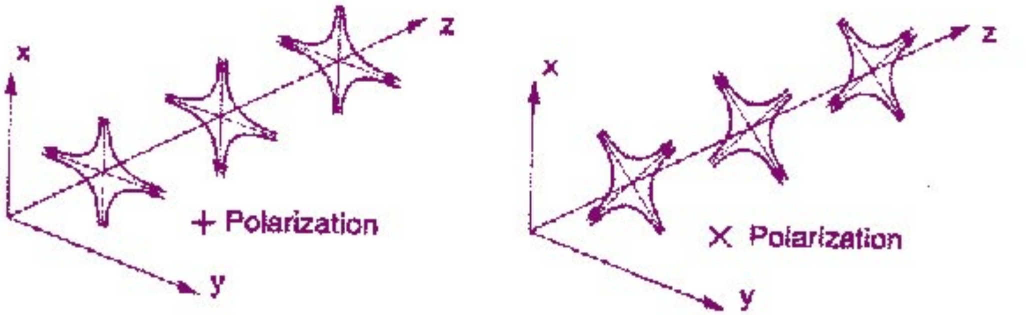
- **Stretches and squeezes space between "test masses" – strain *h* = *ΔL / L***
- **propagating at speed of light**
  - ***mass of graviton = 0***
- **space-time distortions are transverse to direction of propagation**
- **GW are tensor fields (EM: vector fields)**

  two polarizations: plus (⊕) and cross (⊗)

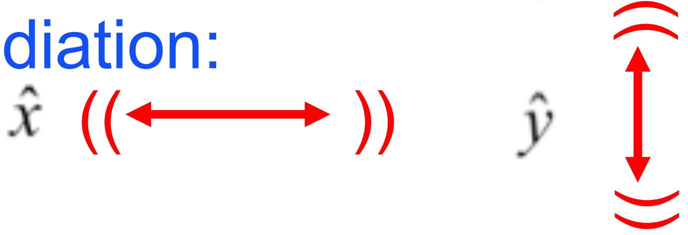
  (EM: two polarizations, *x* and *y*)

  Spin of graviton = 2





Contrast with EM dipole radiation:



Gravitational Waves

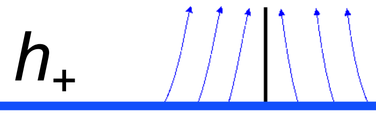
Solution for an outward propagating wave in z-direction:

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

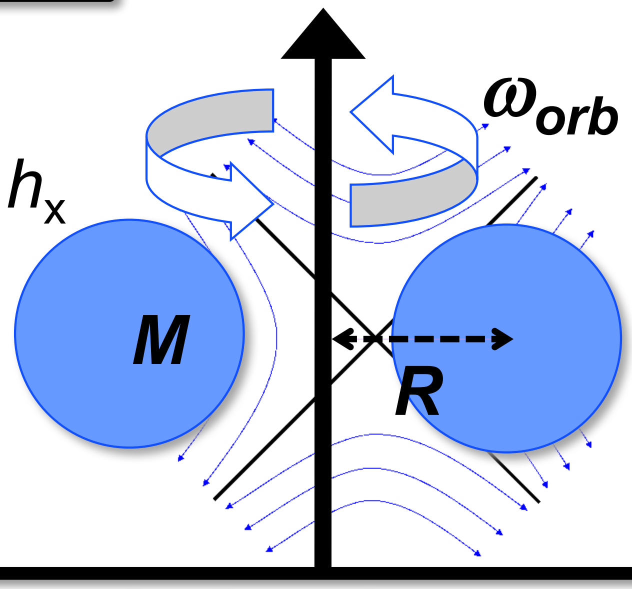
$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$h_{\mu\nu} \approx \frac{1}{r}\frac{G}{c^4}\ddot{I}_{\mu\nu}$$

Physically, *h* is a *strain*: ΔL/L



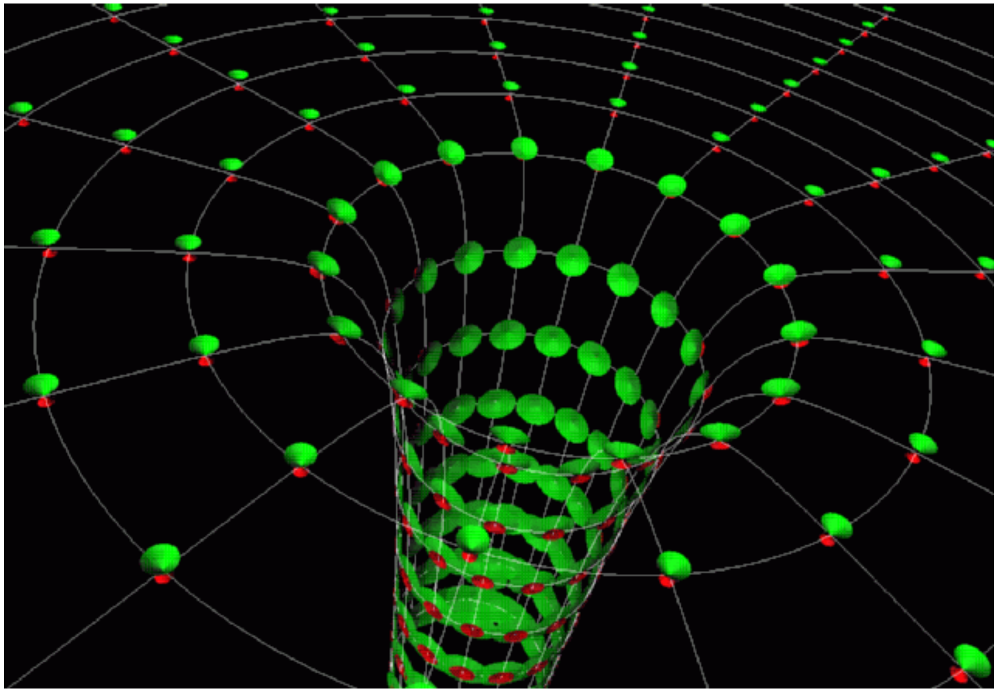
$$h \approx \frac{8GMR^2\omega_{orb}^2}{rc^4} \sim 10^{-21}$$



Kepler 3rd: $R^3\ \omega_{orb}^2 = G\ M_{tot}$

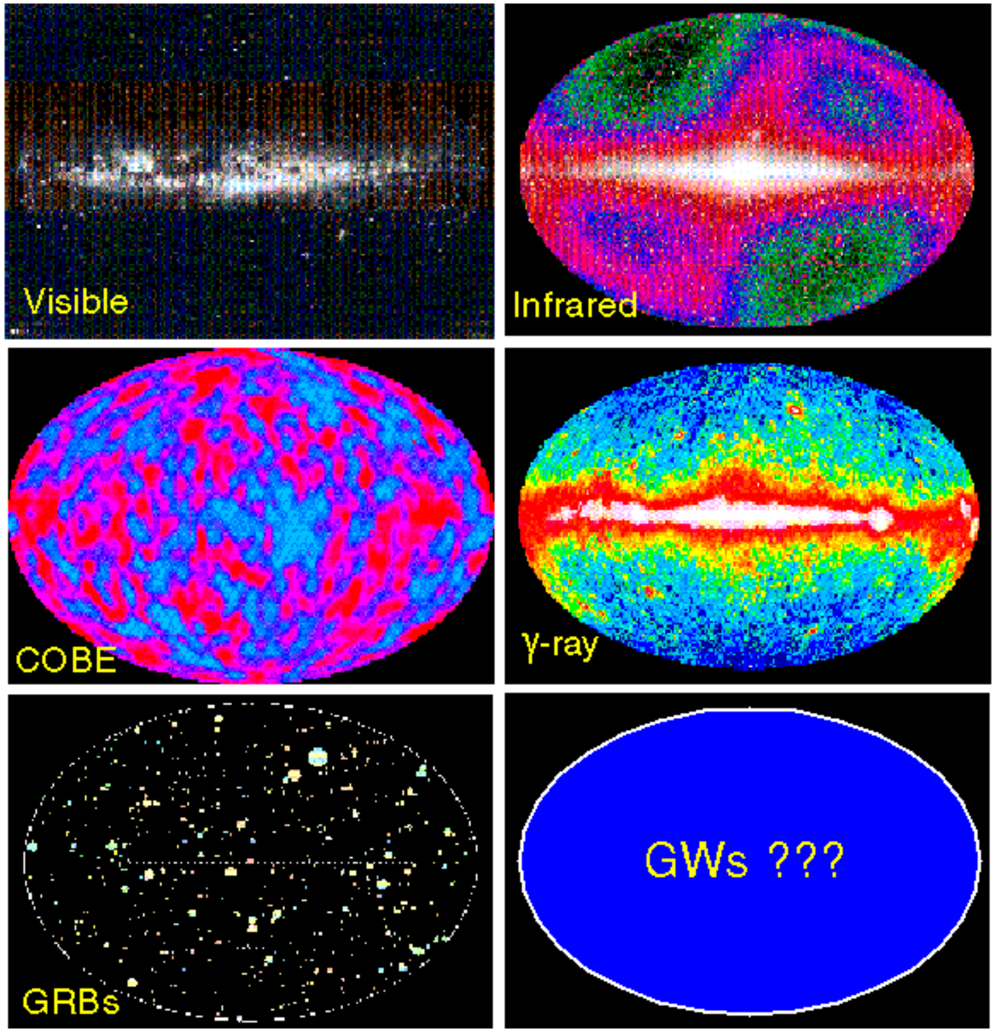
Strong-field

- 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

A NEW WINDOW ON THE UNIVERSE



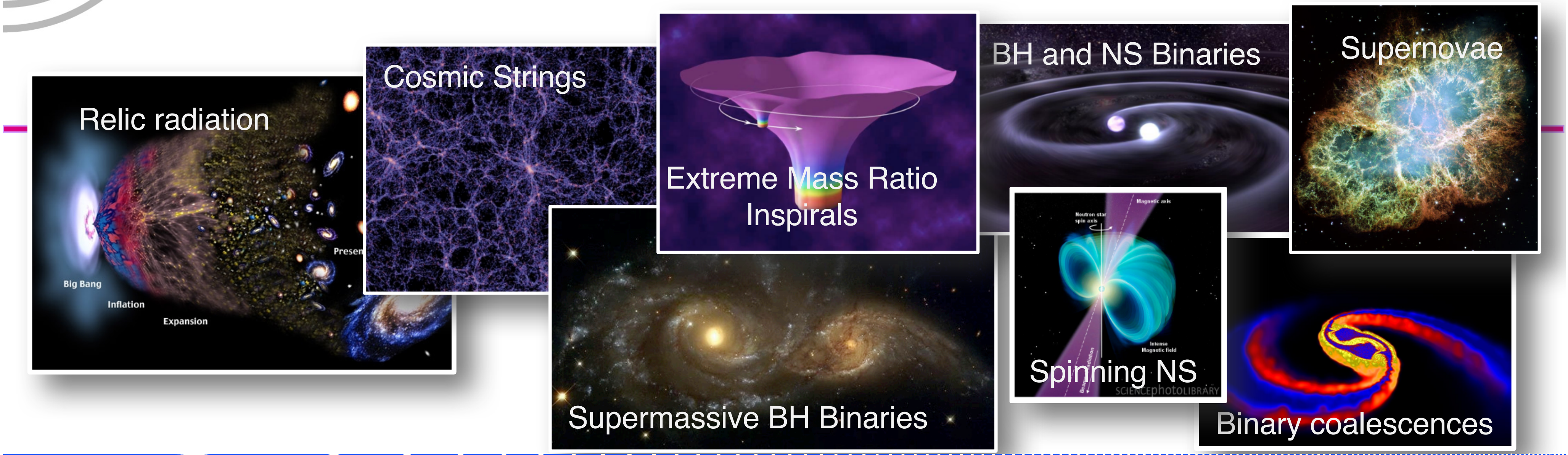
The history of Astronomy: new bands of the EM spectrum opened → major discoveries!

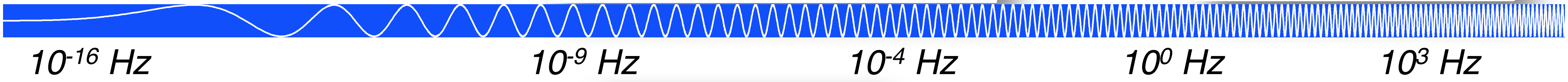
GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

- 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





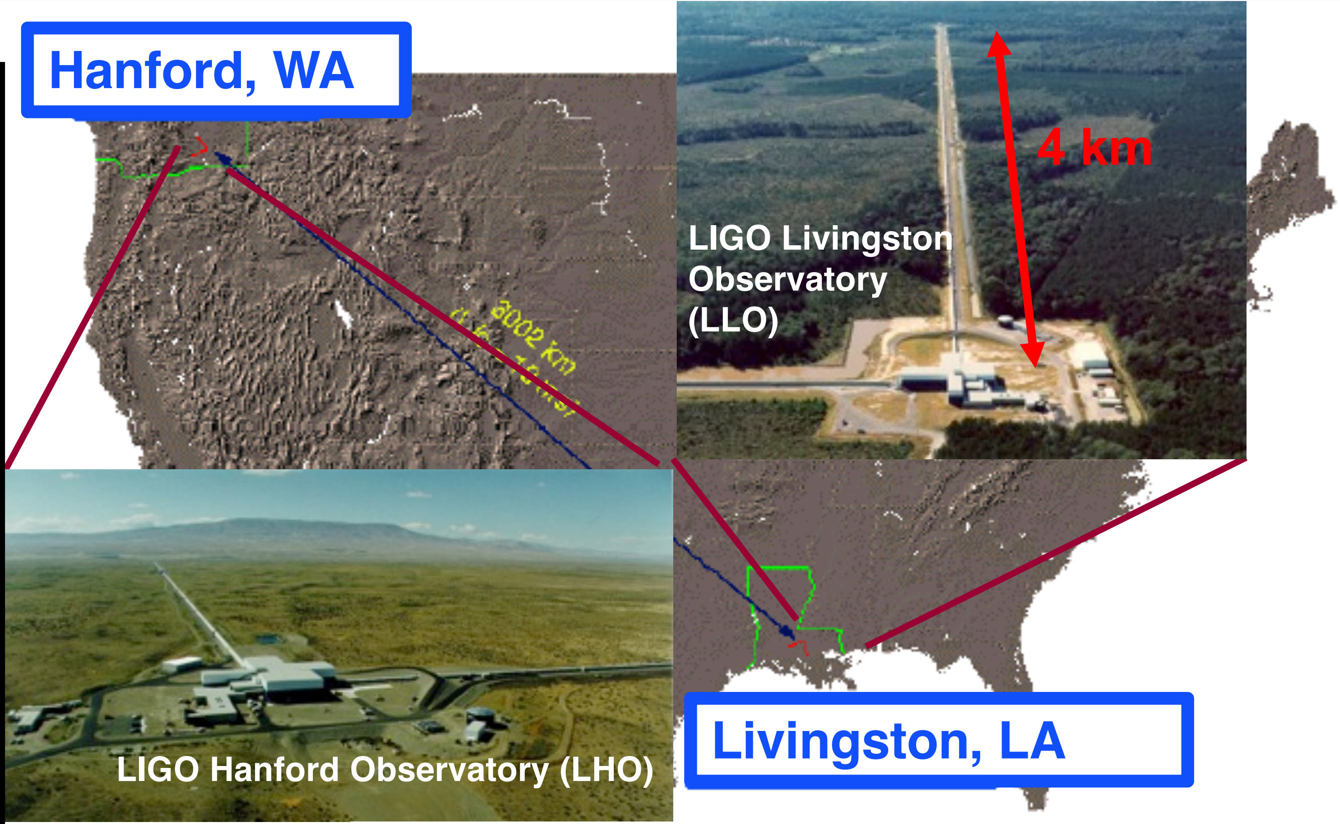
Inflation Probe | Pulsar timing | Space detectors | Ground interferometers

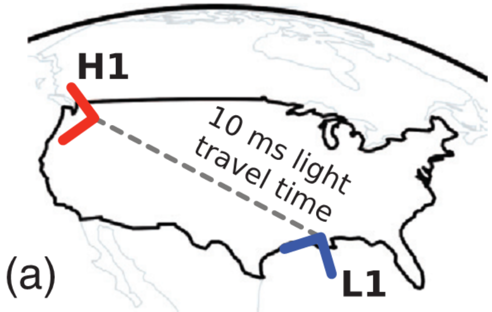
The Laser Interferometer Gravitational Wave Observatory

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





LIGO

LSC

LIGO Scientific Collaboration

Caltech

American University
Washington, DC

Andrews University

Washington State University

California State University Fullerton

Southern University and Agricultural & Mechanical College

Massachusetts Institute of Technology

Leland Stanford Junior University 1891

The University Of Sheffield.

University of Maryland 1856

indigo

Texas Tech University

PennState

Tsinghua University

清华大学

Montclair State University

Max Planck Institute for Gravitational Physics
Albert Einstein Institute

International Institute of Physics
Federal University of Rio Grande do Norte

Cal State LA

Bellevue College

UIB Universitat de les Illes Balears

University of Cambridge

Université de Montréal

Monash University

Southampton University of

Polytechnique Montréal
Le génie en première classe

The University of Adelaide Australia

NCSA

Université Libre de Bruxelles

ACU

University of Wisconsin UW Milwaukee

Trinity University

Australian National University

University of the West of Scotland UWS

University of Glasgow

W Bothell

Michigan

Columbia University in the City of New York

Lomonosov Moscow State University

Syracuse University Founded AD 1870

OzGrav

Cornell University Founded A.D. 1865

The University of Western Australia

R·I·T

Eötvös Loránd Tudományegyetem Budapestinensis

Sonoma State University

Tsing Hua University

МПД РАН

University of Minnesota

Carleton College Northfield, Minn. A.D. 1866

Cardiff University
Prifysgol Caerdydd

NASA

Marshall Space Flight Center

The University of Chicago

Whitman College

Montana State University

University of Washington

Università degli Studi del Sannio

LSU Louisiana State University

INPE

Charles Sturt University

University of Zurich

UTRGV

University of Strathclyde

University of Birmingham

King's College London

東京大学 The University of Tokyo

Georgia Institute of Technology

Korean Gravitational-Wave Group

ACIGA

Universitas Scientiarum Szegediensis Szegedi Tudományegyetem

The University of Melbourne

Colorado State University

Hillsdale College

Northwestern

UF University of Florida

UHH Universität Hamburg
Der Forschung | Der Lehre | Der Bildung

GEO 600

Embry-Riddle Aeronautical University

Leibniz Universität Hannover

Swinburne University of Technology

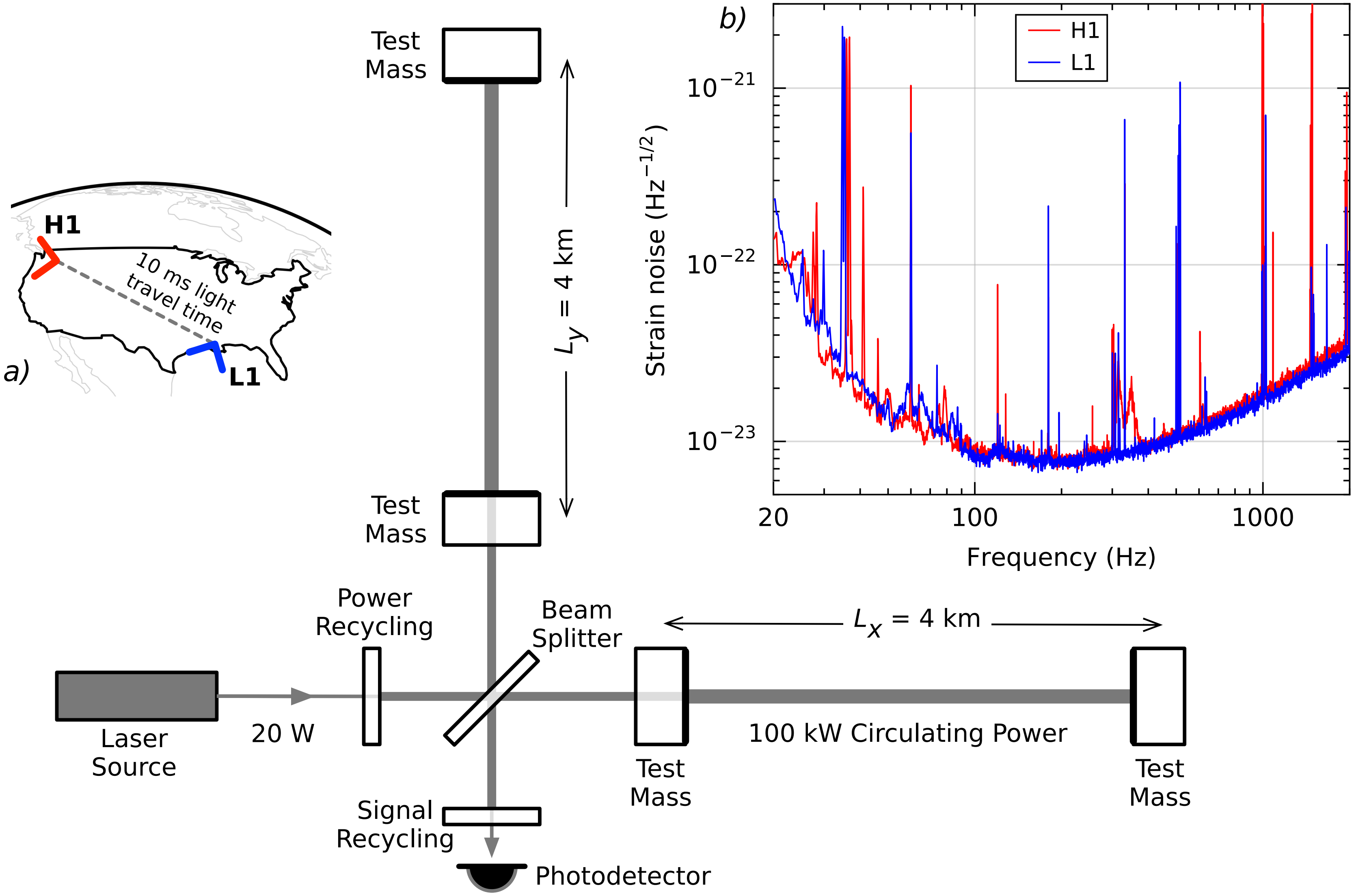
CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

DISCE

The University of Mississippi 1848

NASA Goddard Space Flight Center

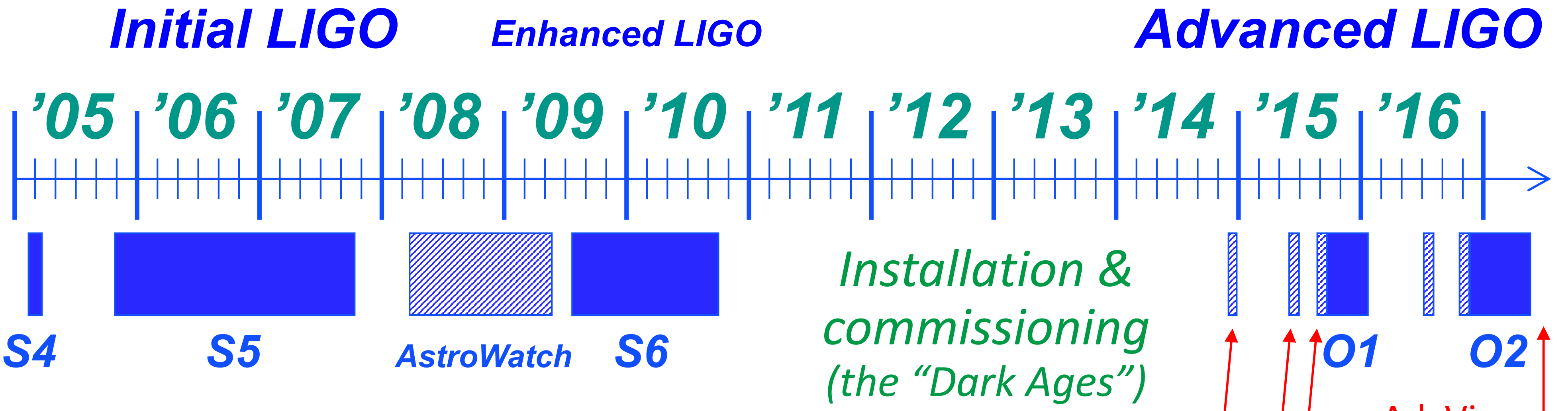
The Advanced LIGO detectors



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

Initial LIGO → Advanced LIGO emerging from “the dark ages”

- Transition the LIGO gravitational wave detectors back to observing operations after a 5-year shutdown to carry out the Advanced LIGO upgrade project

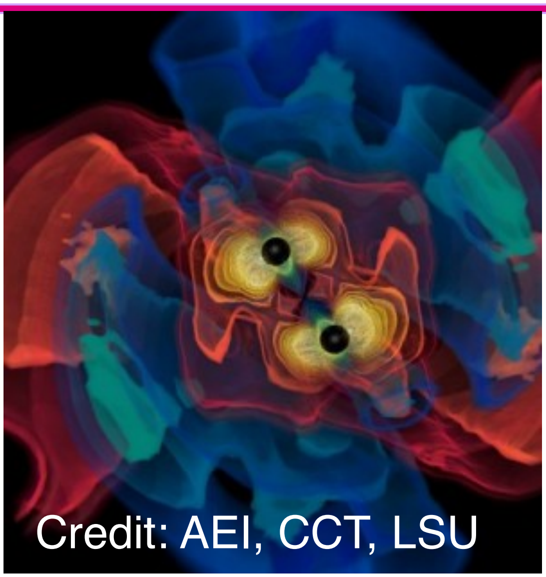


AdvVirgo joins, Aug 2017

Engineering runs 6, 7, 8

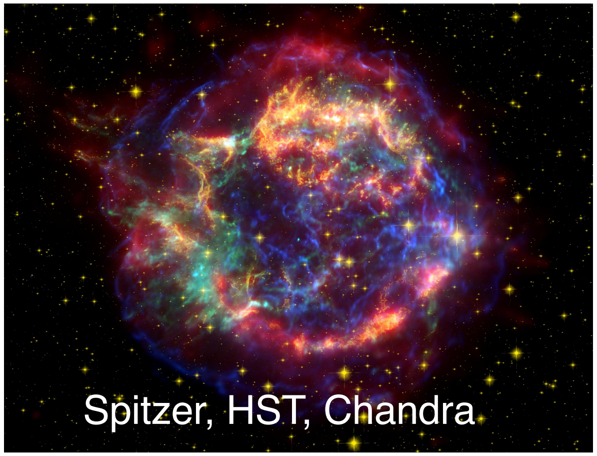
Observing run 2 (O2) ended Aug 25, 2017.
Both LIGO and Virgo are offline for upgrades;
plan to start O3 in fall 2018.

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


Credit: AEI, CCT, LSU

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

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


Spitzer, HST, Chandra

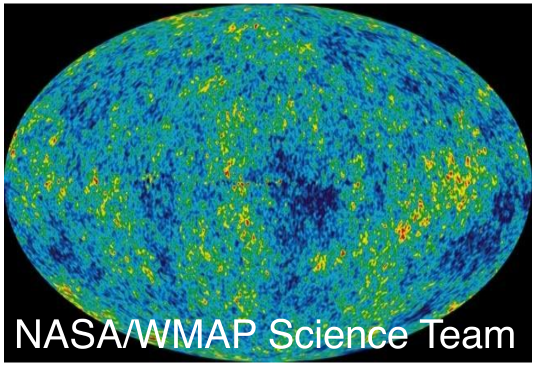
Asymmetric Core Collapse Supernovae

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


Casey Reed, Penn State

Spinning neutron stars

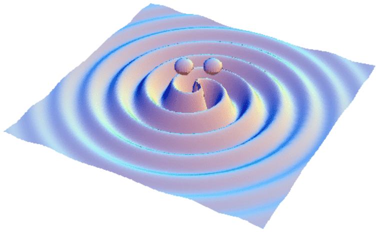
- (effectively) monotonic waveform
- Long duration

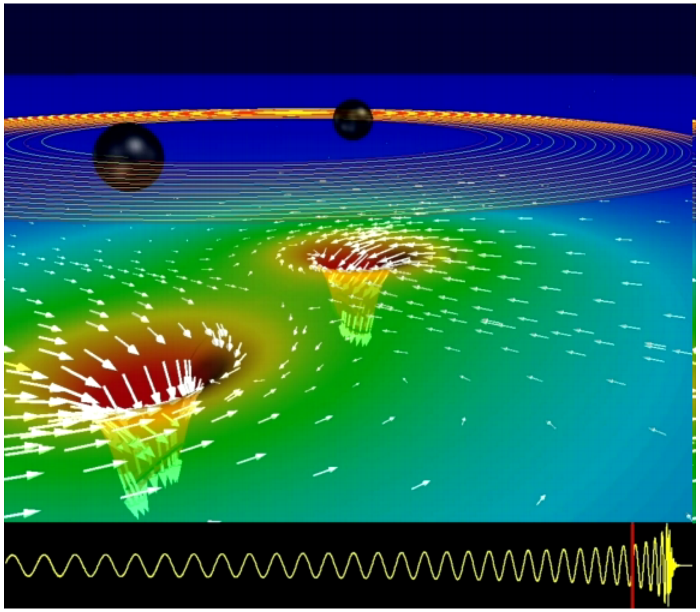

NASA/WMAP Science Team

Cosmic Gravitational-wave Background

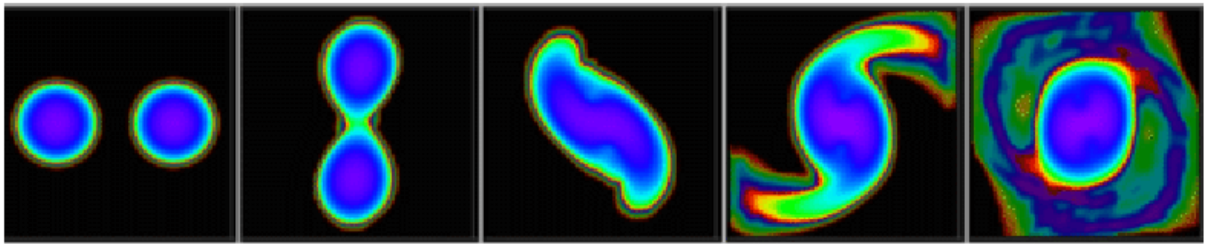
- Residue of the Big Bang, long duration
- Long duration, stochastic background

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





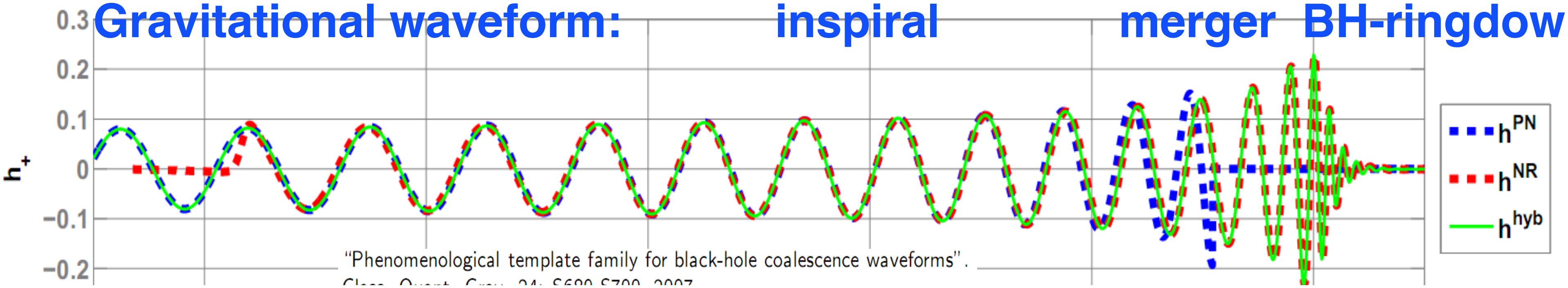
- Neutron star – neutron star (Centrella et al.)



Tidal disruption of neutron star

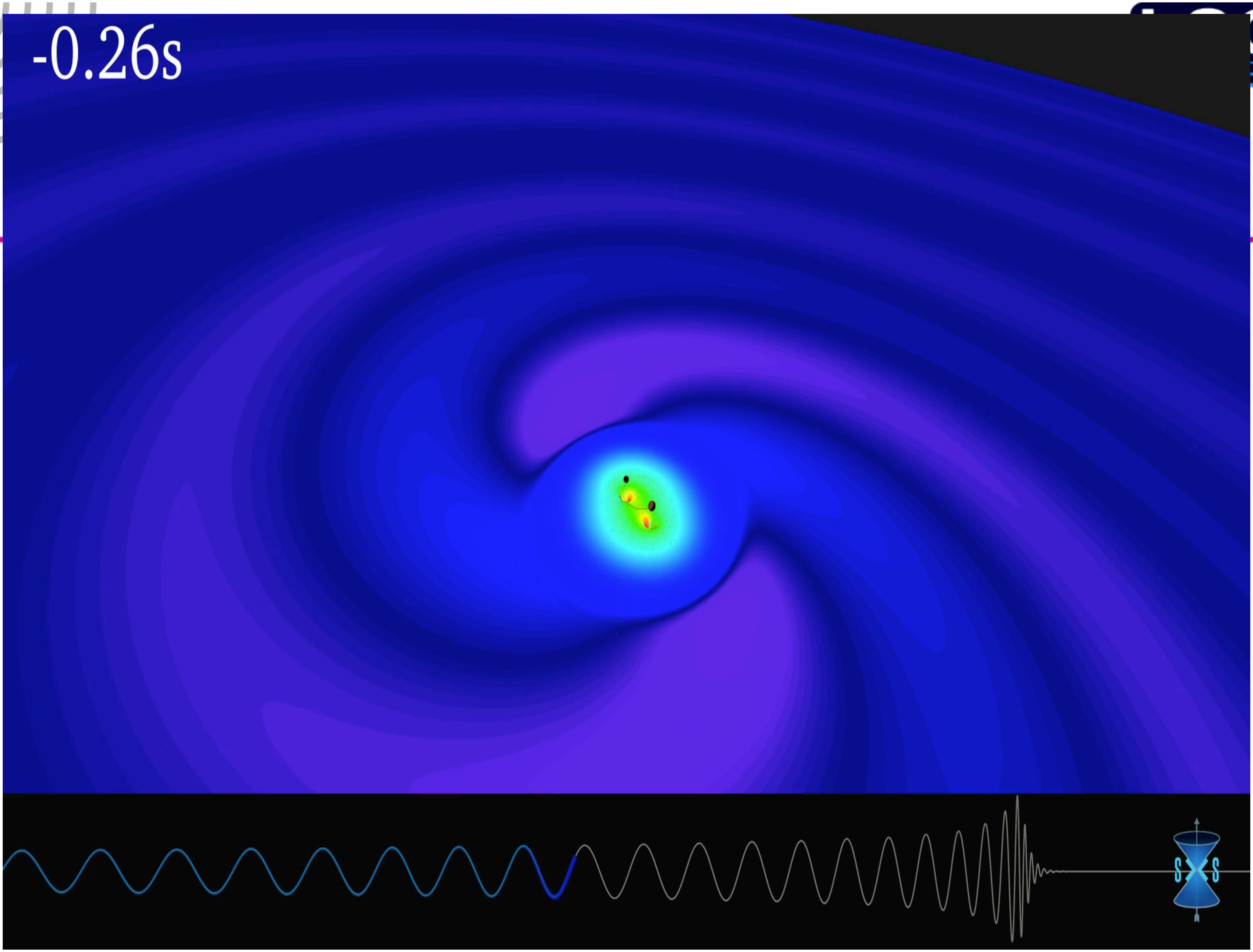
A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

Gravitational waveform: inspiral merger BH-ringdown



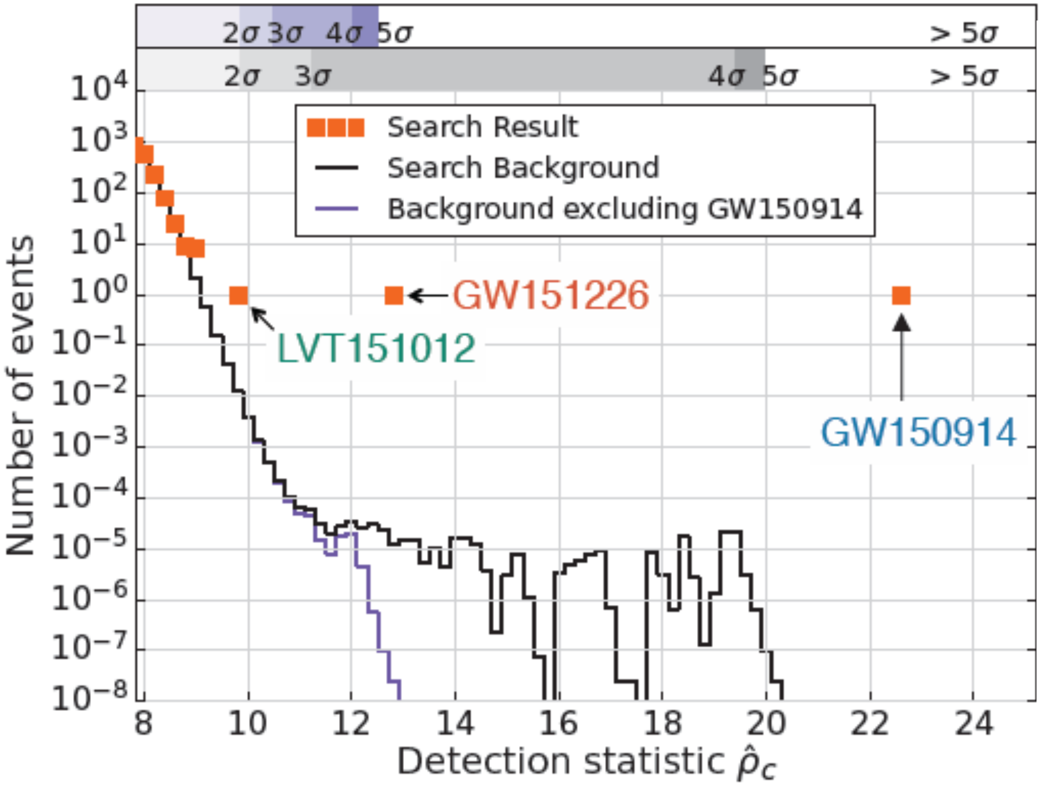
"Phenomenological template family for black-hole coalescence waveforms".

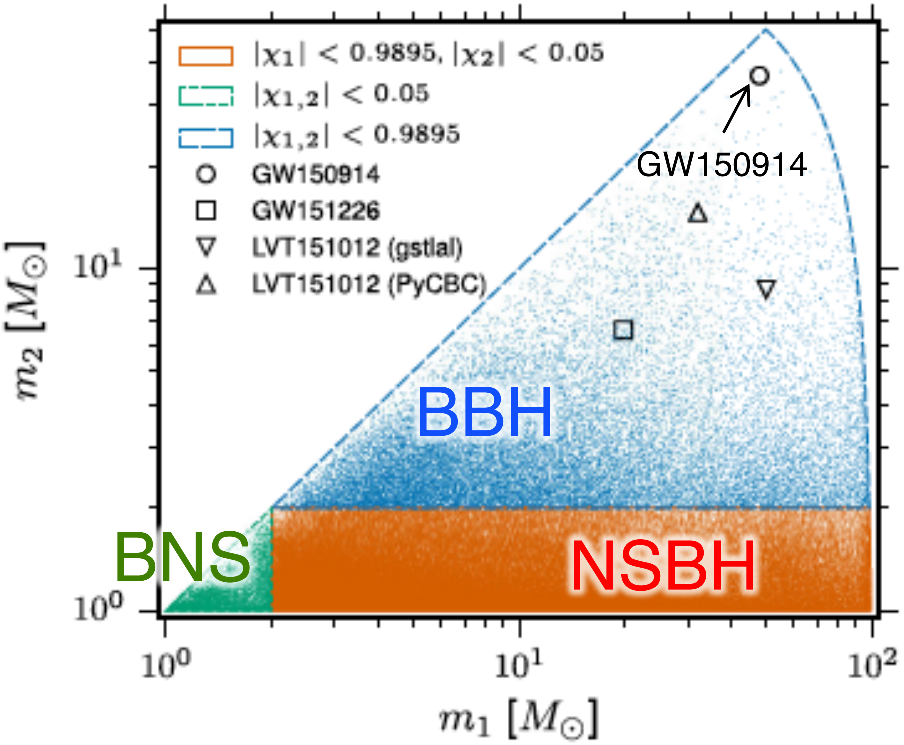
Waveform carries lots of information about binary masses, orbit, merger



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

Search results
Advanced LIGO Observing Run O1



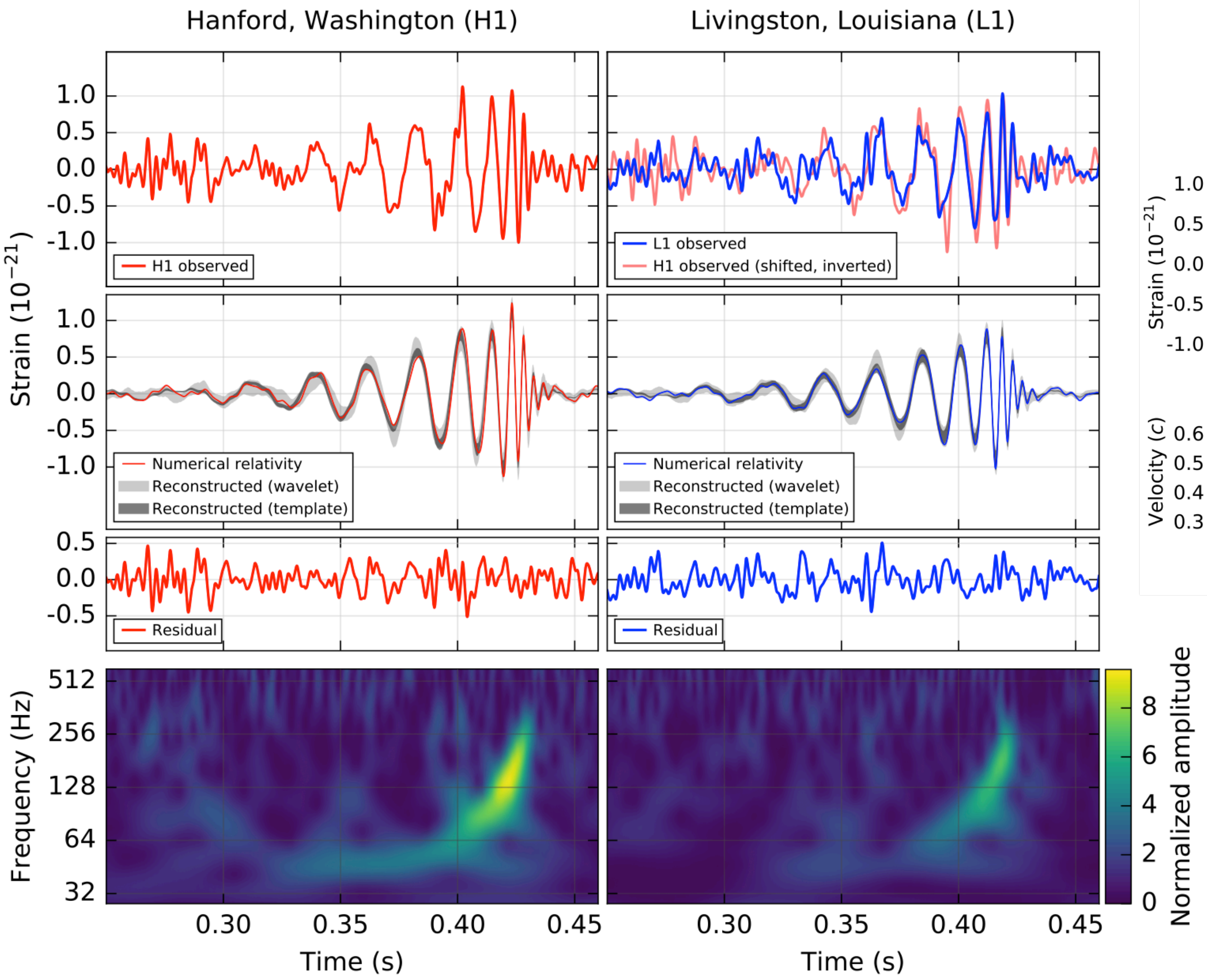


Three events above the estimated “background” from accidental coincidence of noise fluctuation triggers. Two have high significance (> 5σ).

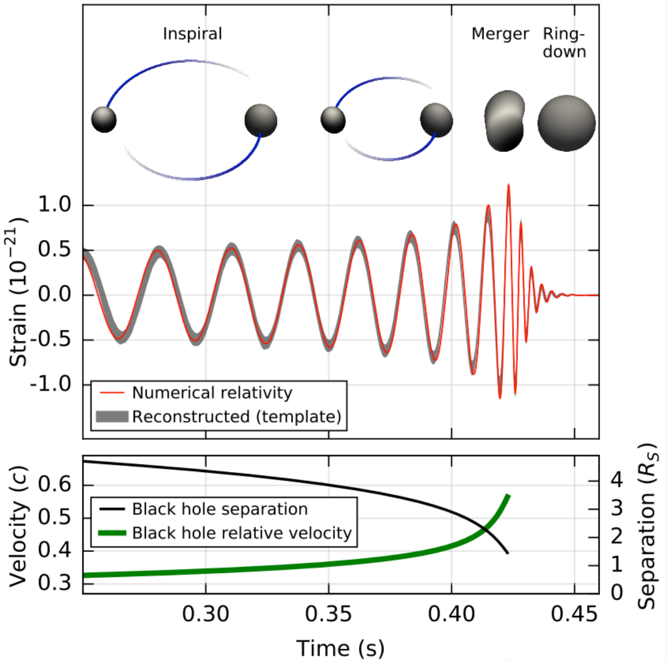
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, https://arxiv.org/abs/1606.04856, Phys. Rev. X 6, 041015 (2016)

GW150914

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



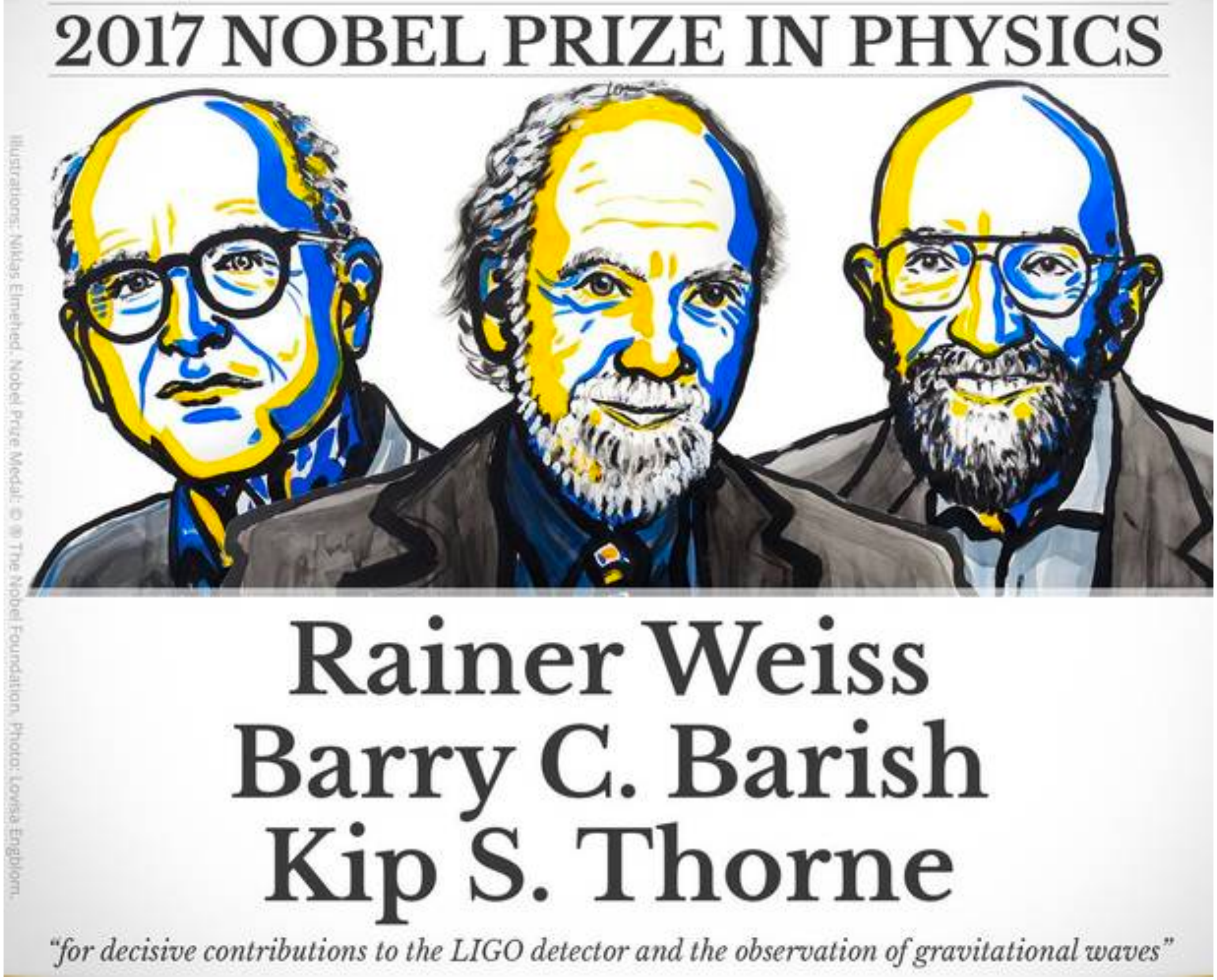
Whitened and band-passed [40-300] Hz



Reconstructed (no whitening)

Audio:
- filtered data
- freq-shifted data
- reconstructed & shifted

Founders of the LIGO project at Caltech and MIT

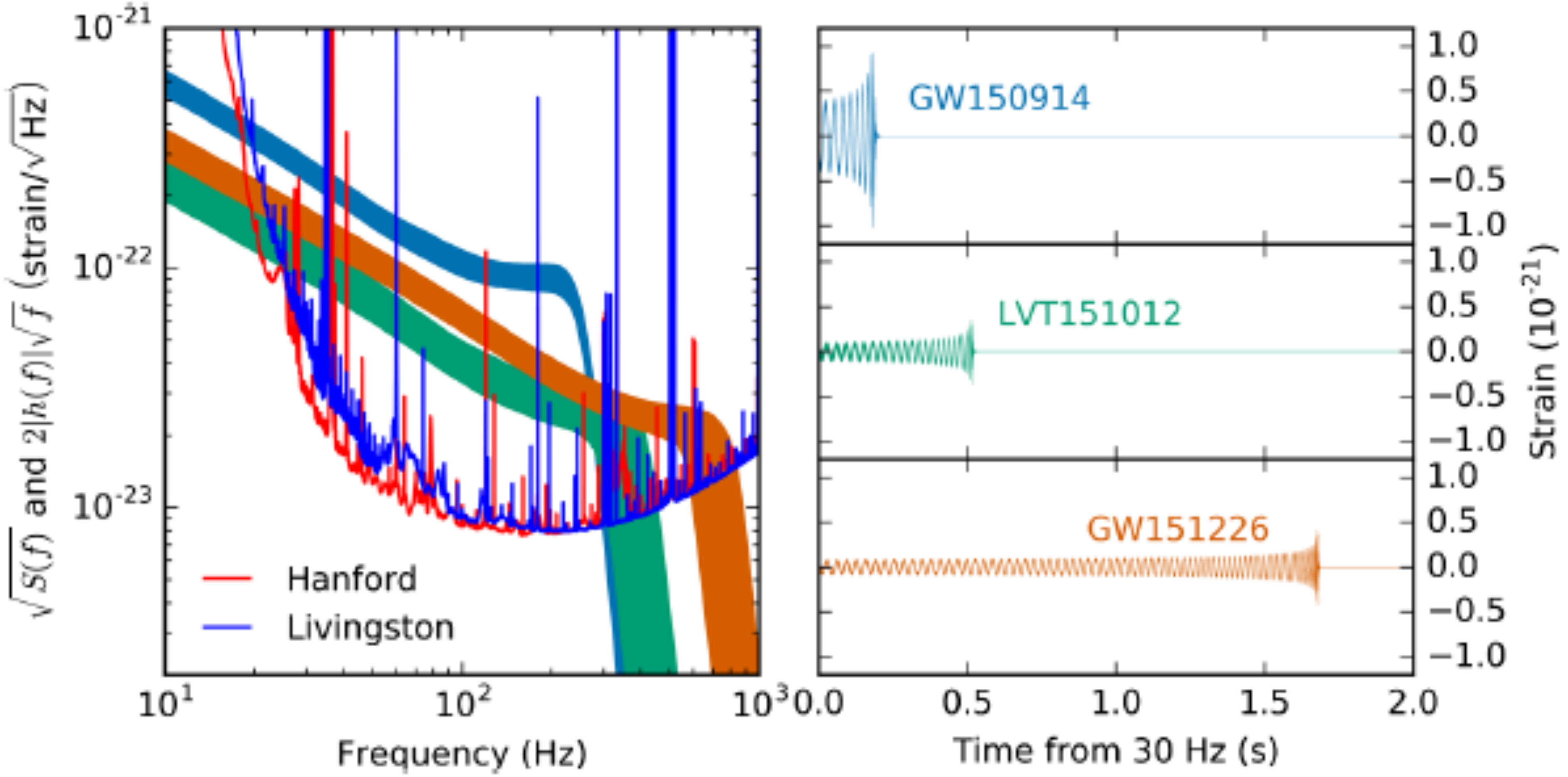


2017 NOBEL PRIZE IN PHYSICS

Rainer Weiss
Barry C. Barish
Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Three BBH events, compared



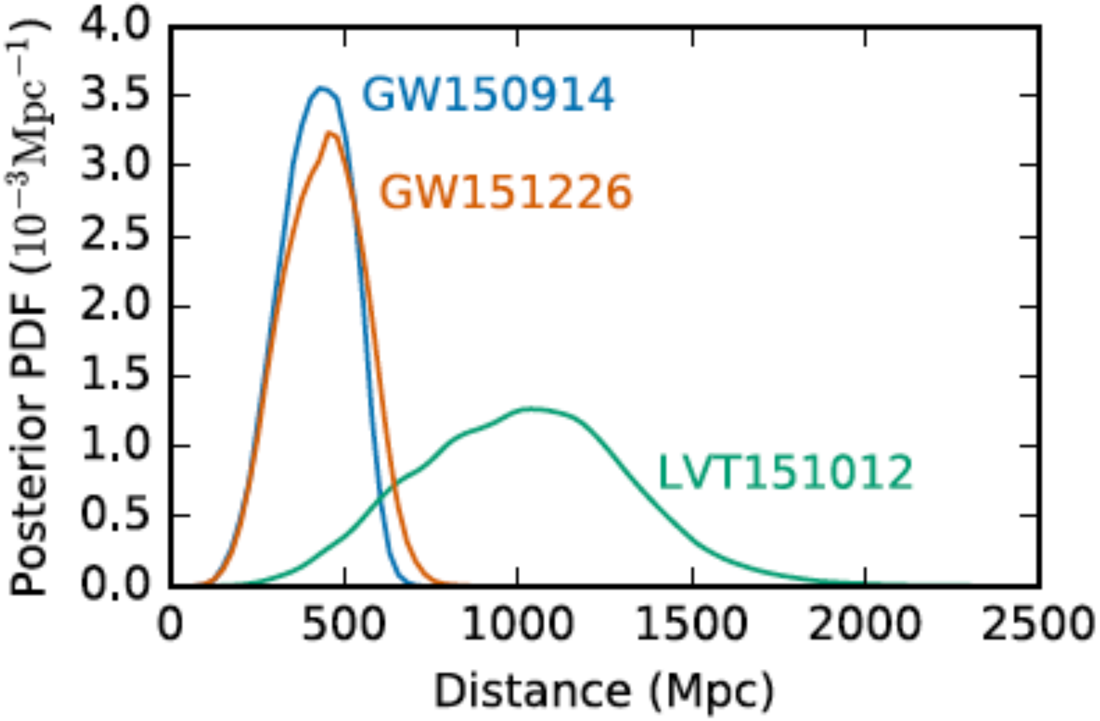
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, https://arxiv.org/abs/1606.04856, Phys. Rev. X 6, 041015 (2016)

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).

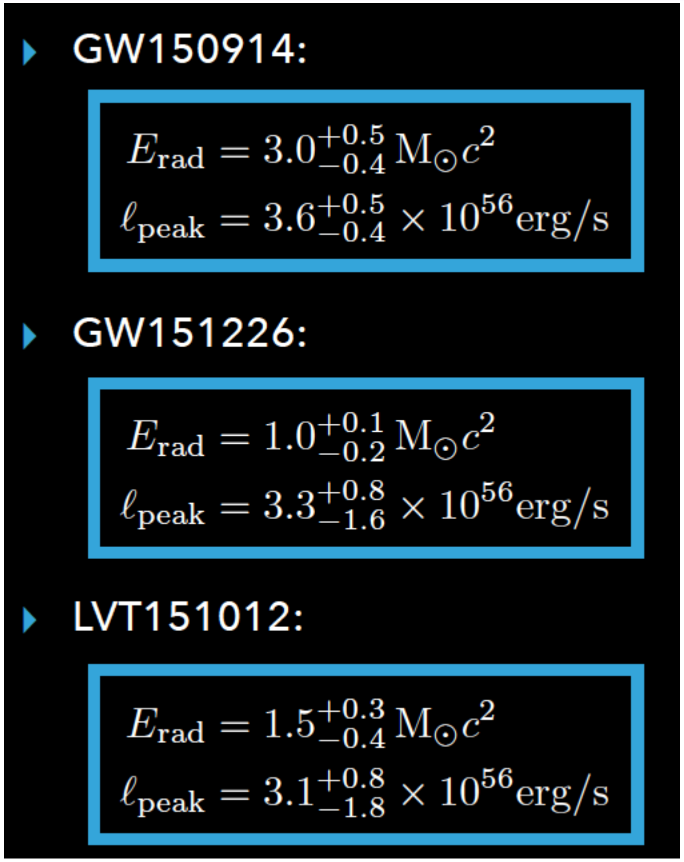
Distances measured poorly with only two detectors.



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:**

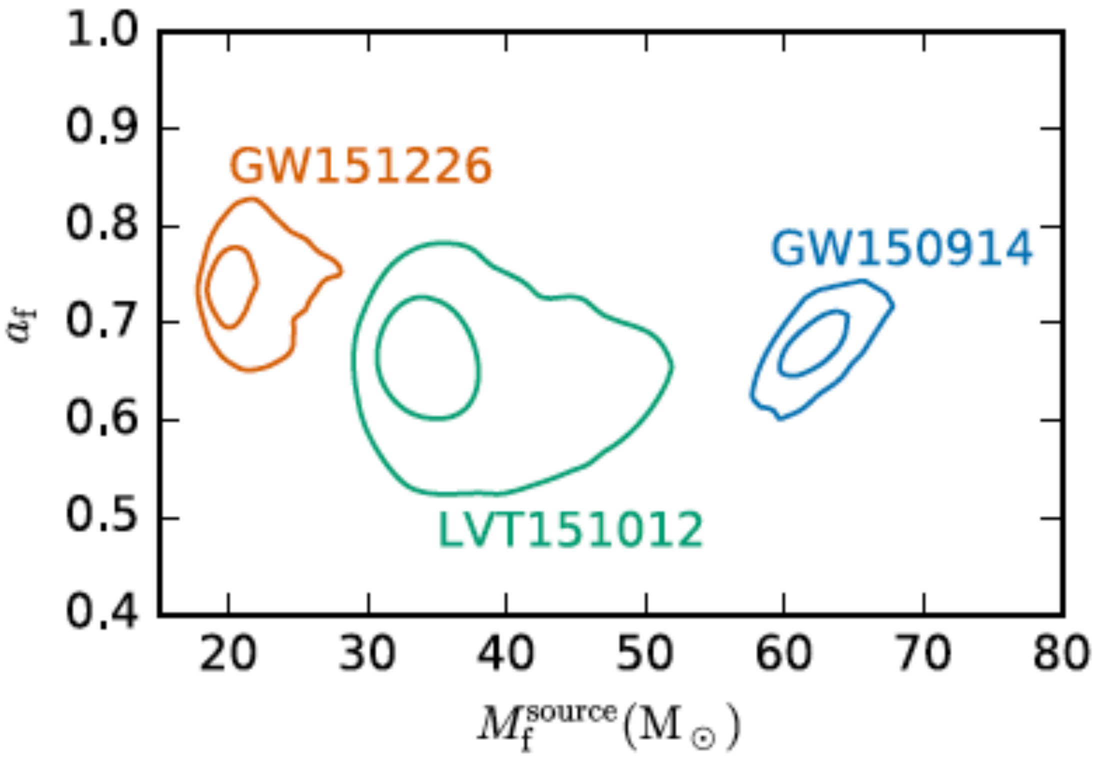
$$E_{\rm rad} = 3.0^{+0.5}_{-0.4}\,{\rm M}_\odot c^2$$
$$\ell_{\rm peak} = 3.6^{+0.5}_{-0.4} \times 10^{56} {\rm erg/s}$$

- **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:**

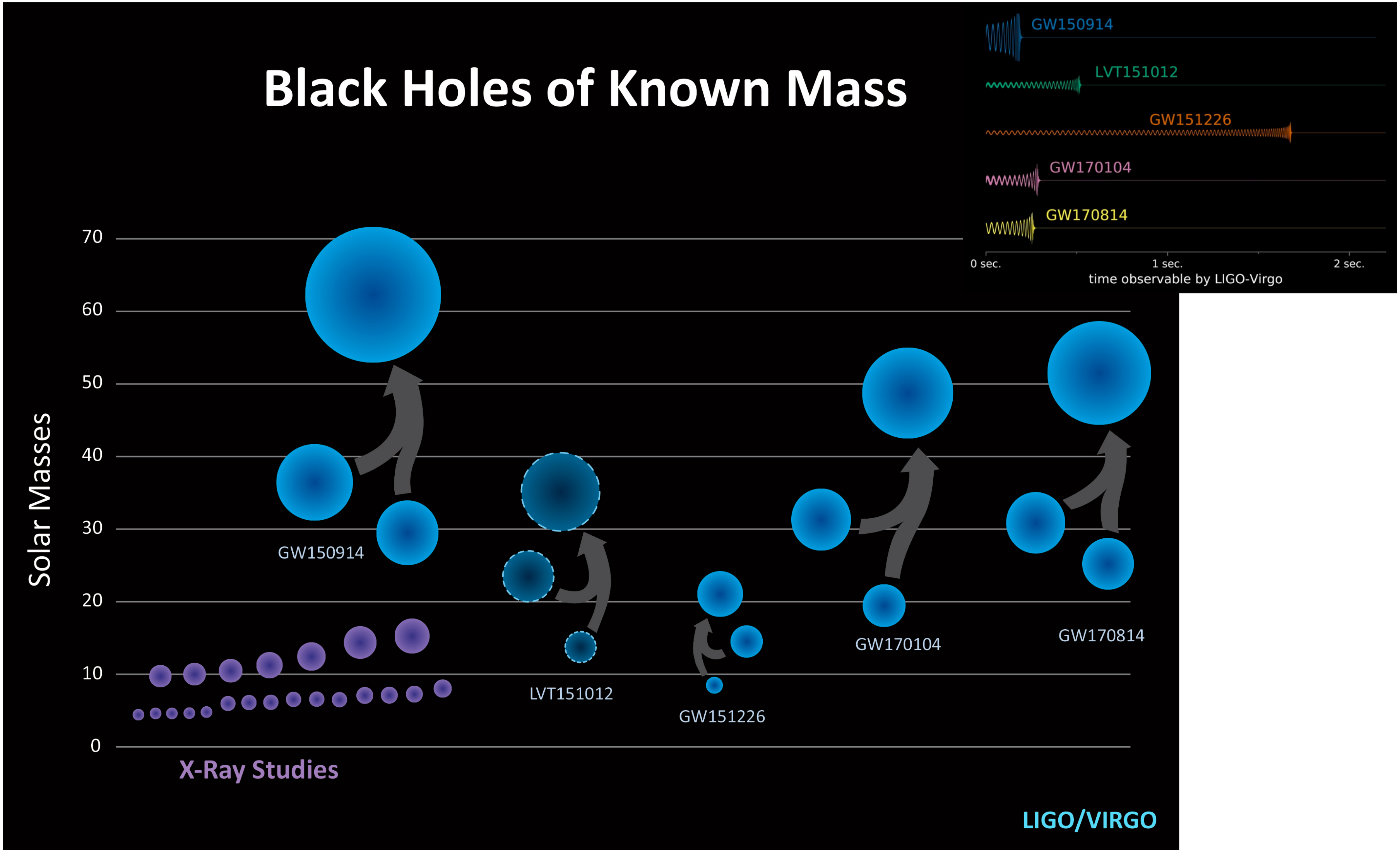
$$E_{\rm rad} = 1.5^{+0.3}_{-0.4}\,{\rm M}_\odot c^2$$
$$\ell_{\rm peak} = 3.1^{+0.8}_{-1.8} \times 10^{56} {\rm erg/s}$$



- 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).

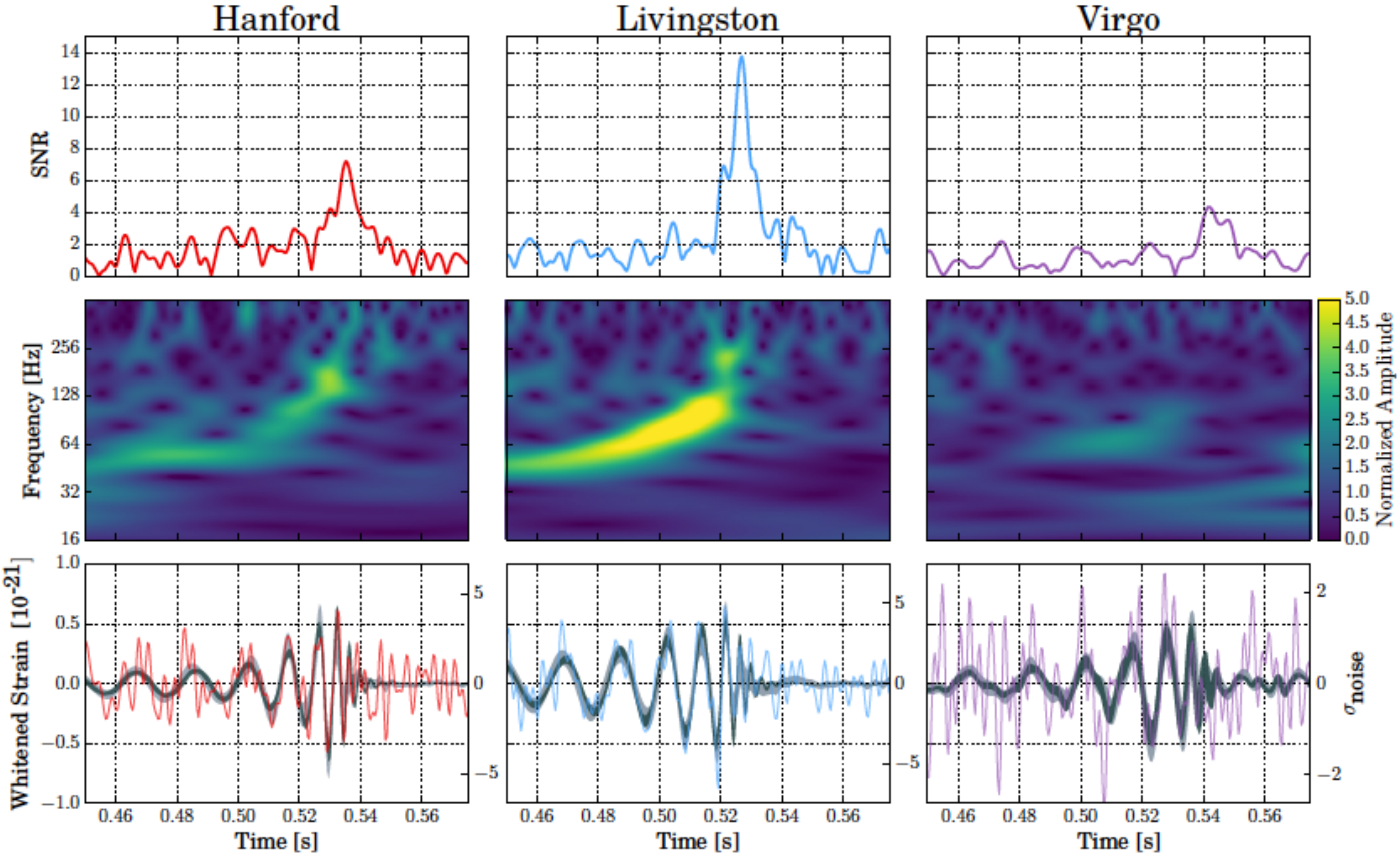
MORE BBHs, in O2.

Starting to build up a mass distribution



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

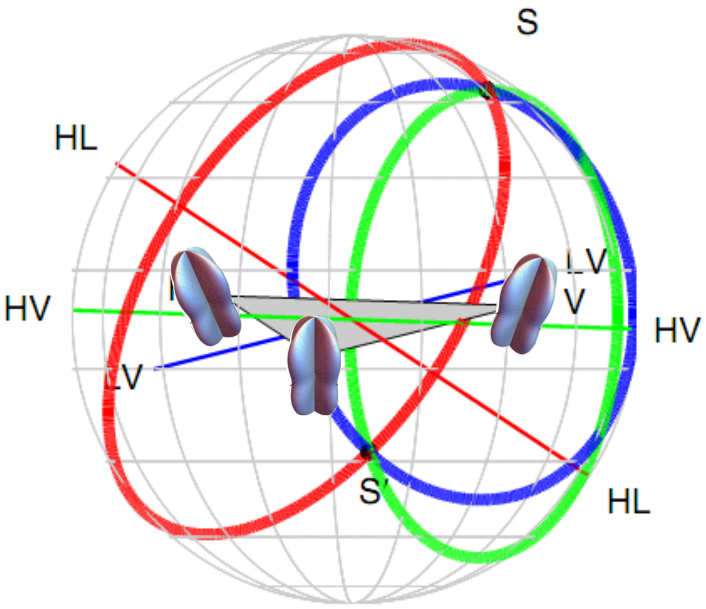
GW170814



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

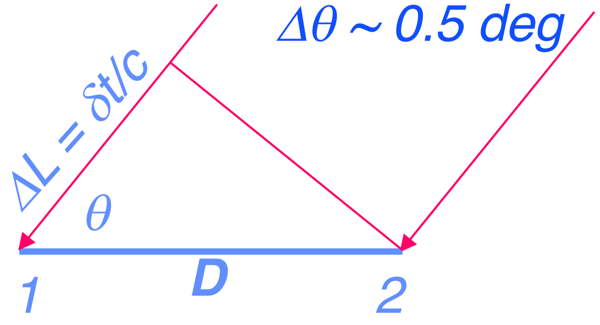
Event Localization With An Array of GW Interferometers

- Gravitational-wave astronomy is *greatly* enhanced by having a multiplicity of interferometers distributed over the globe.
  - GW interferometry, ‘Aperture synthesis’
- Advantages include:
  - Source localization *in near real time*
  - Enhanced network sky coverage
  - Maximum time coverage – a fraction of the detectors are‘always listening’
  - Detection confidence - coincidence
  - Source parameter estimation
  - Polarization resolution

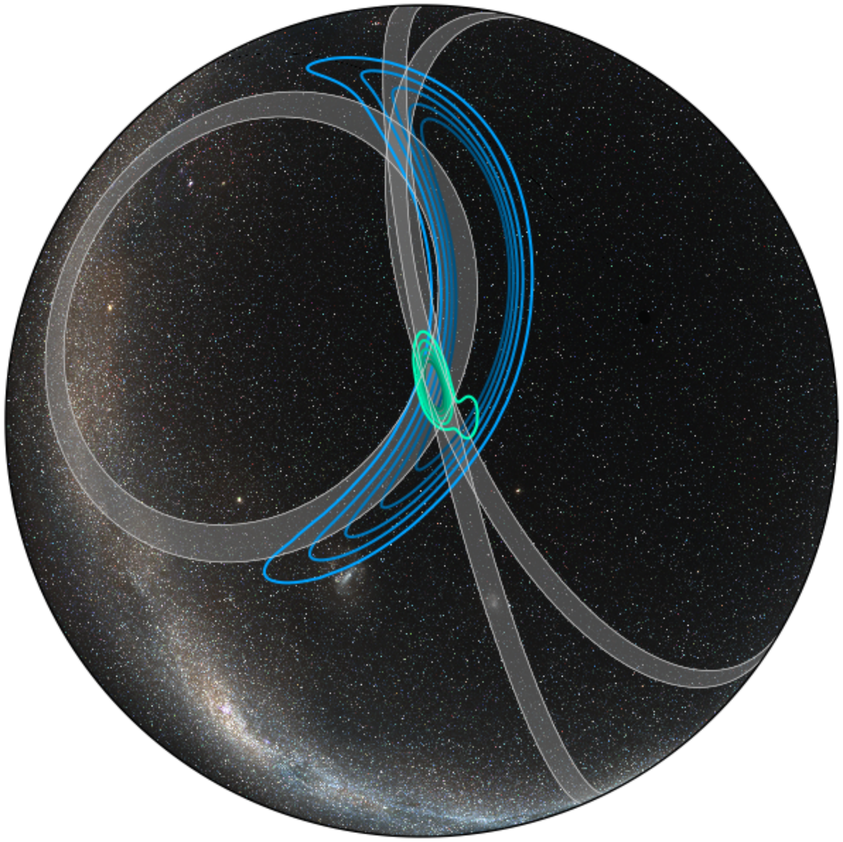


$\cos\theta = \delta t \,/\, (c\, D_{12})$

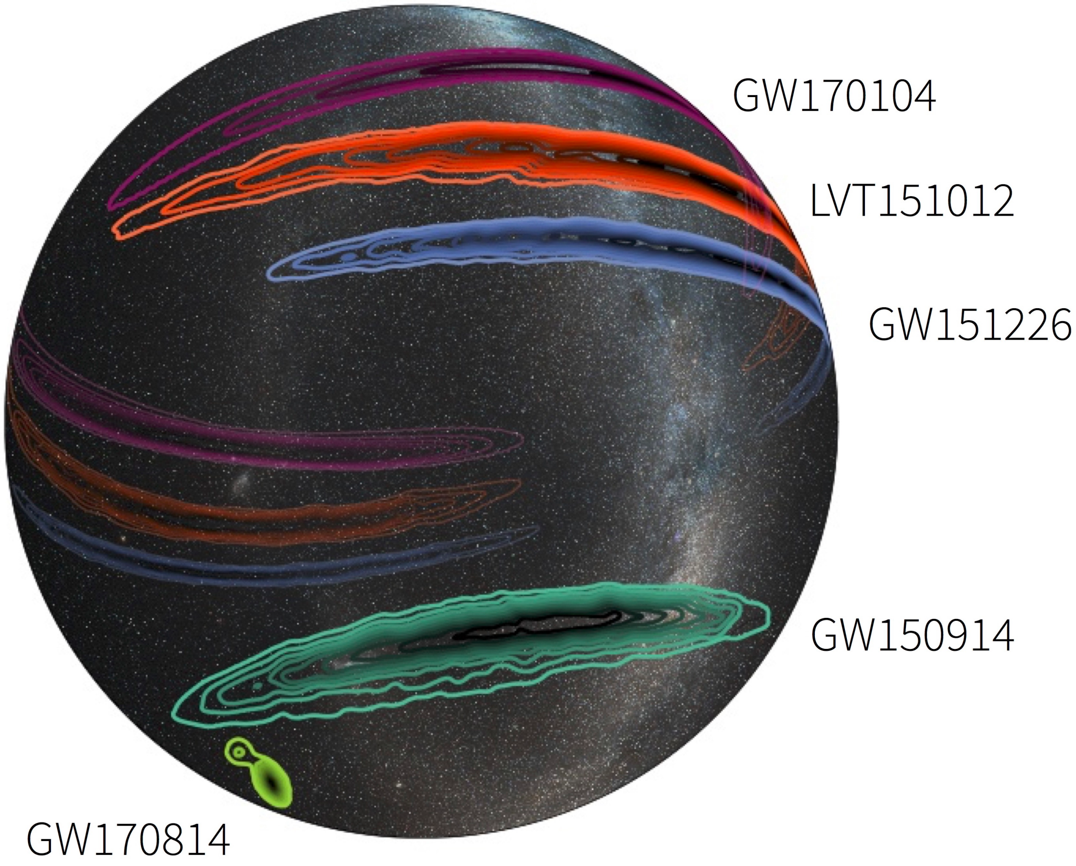
$\Delta\theta \sim 0.5$ deg



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



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

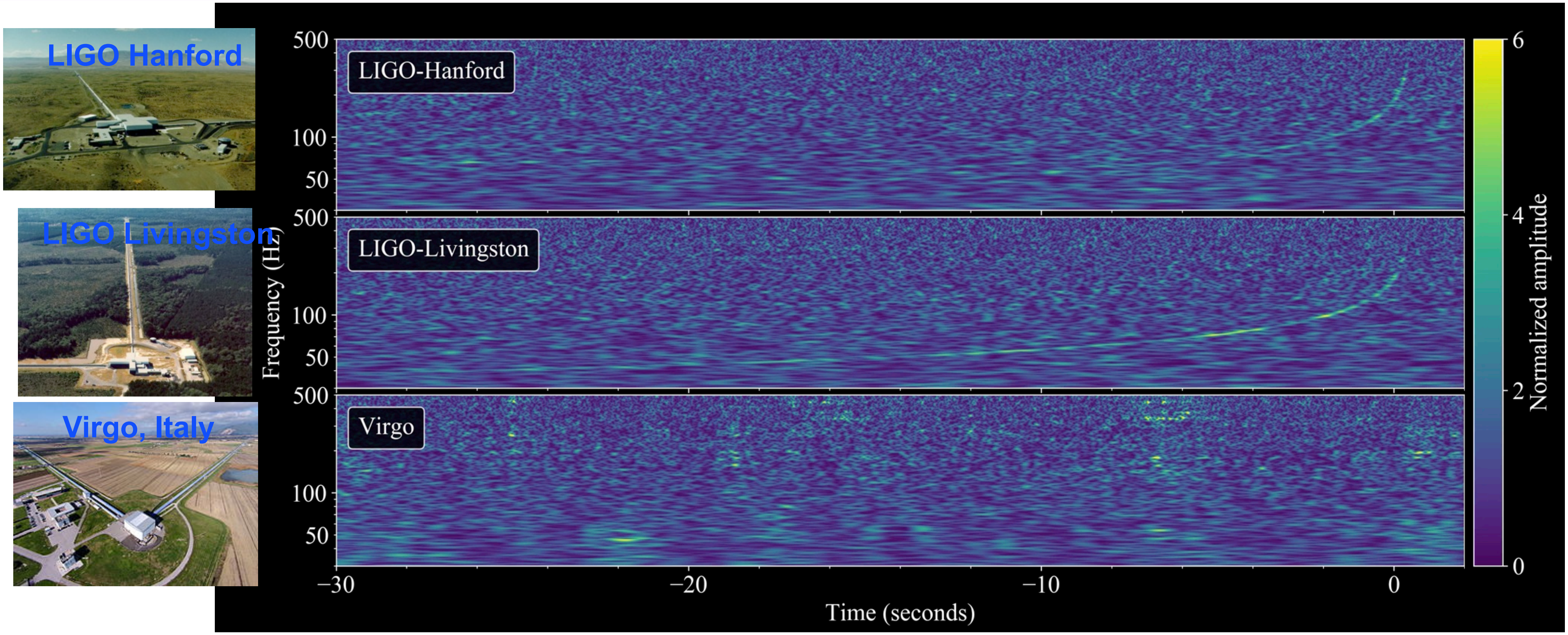


http://ligo.org/detections/GW170814.php

Then came something completely different…
130 million years ago, two neutron stars merged

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

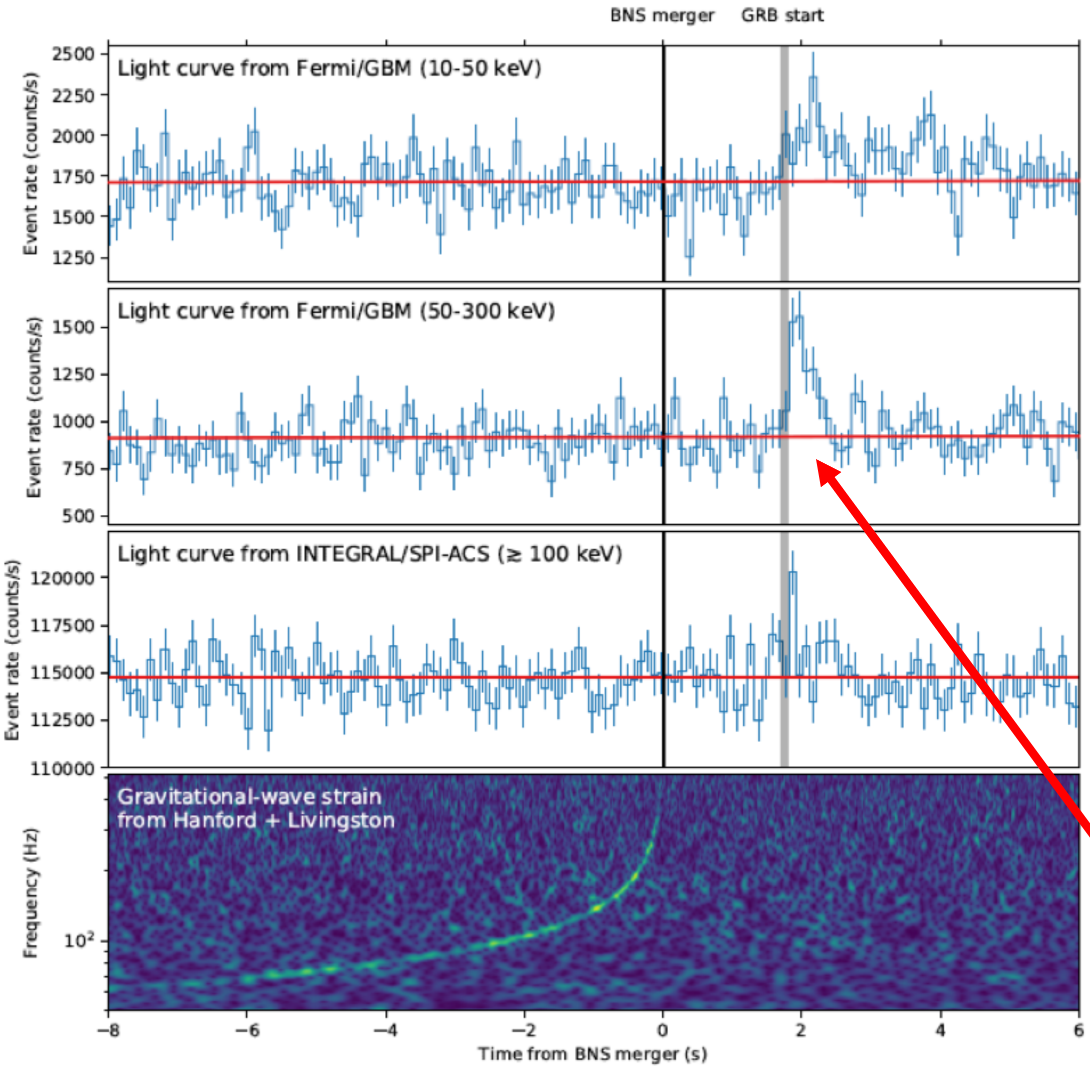
This is what I woke up to on August 17, 2017, just before 6am PT…



GW170817

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

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



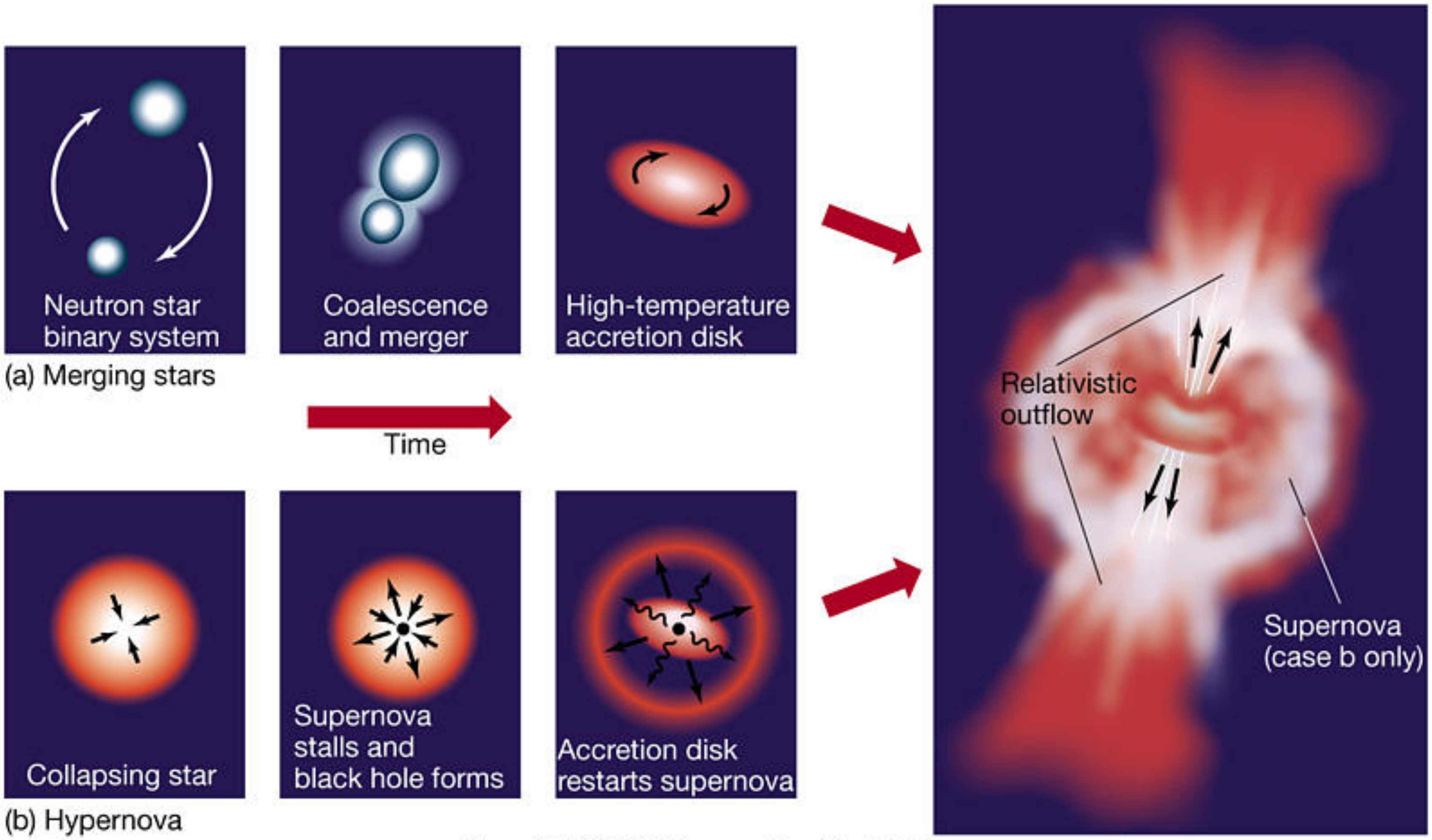
1.7 seconds later, duration < 2s

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

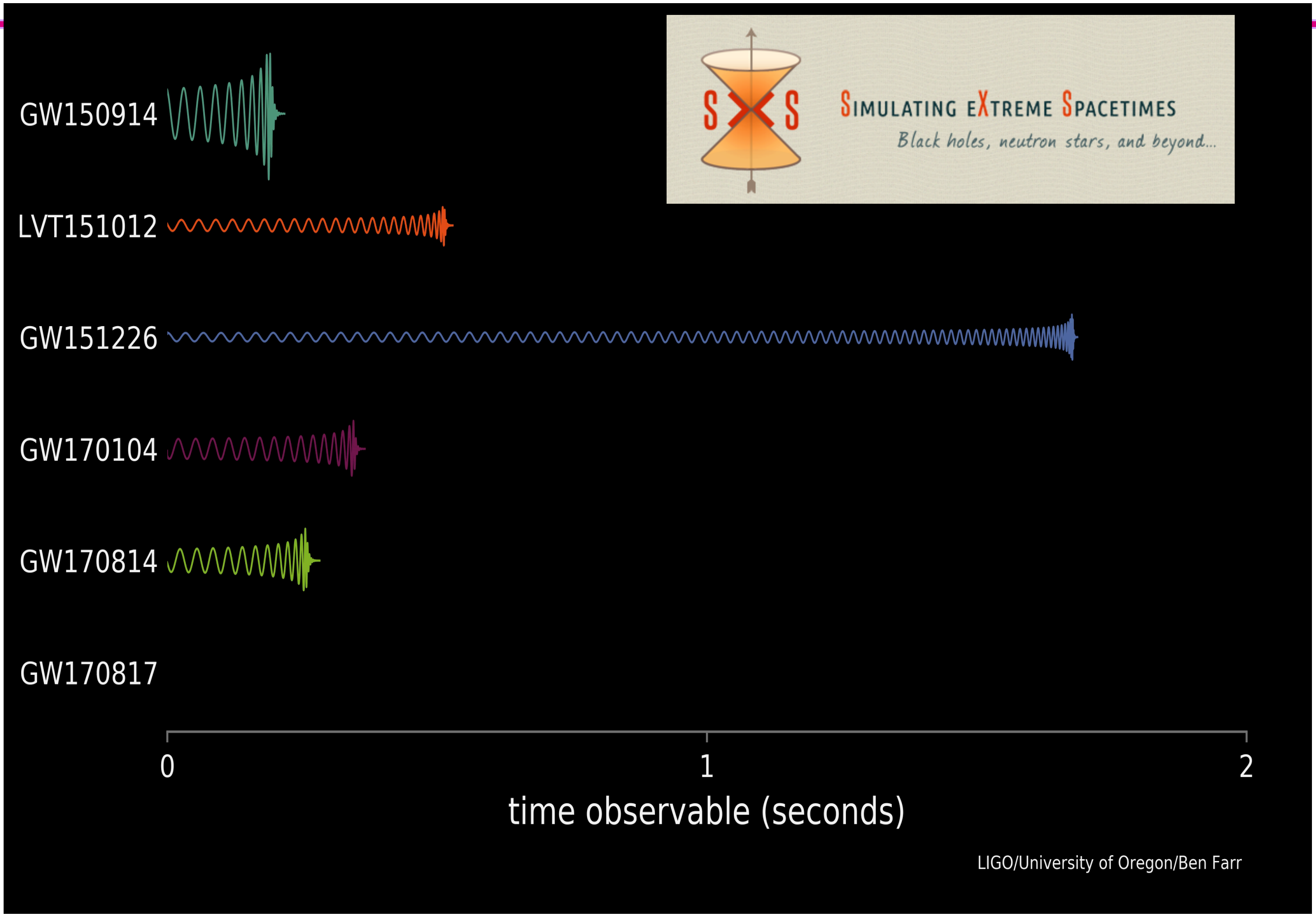
kinda wimpy, though…

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

Short-hard and Long-soft GRBs



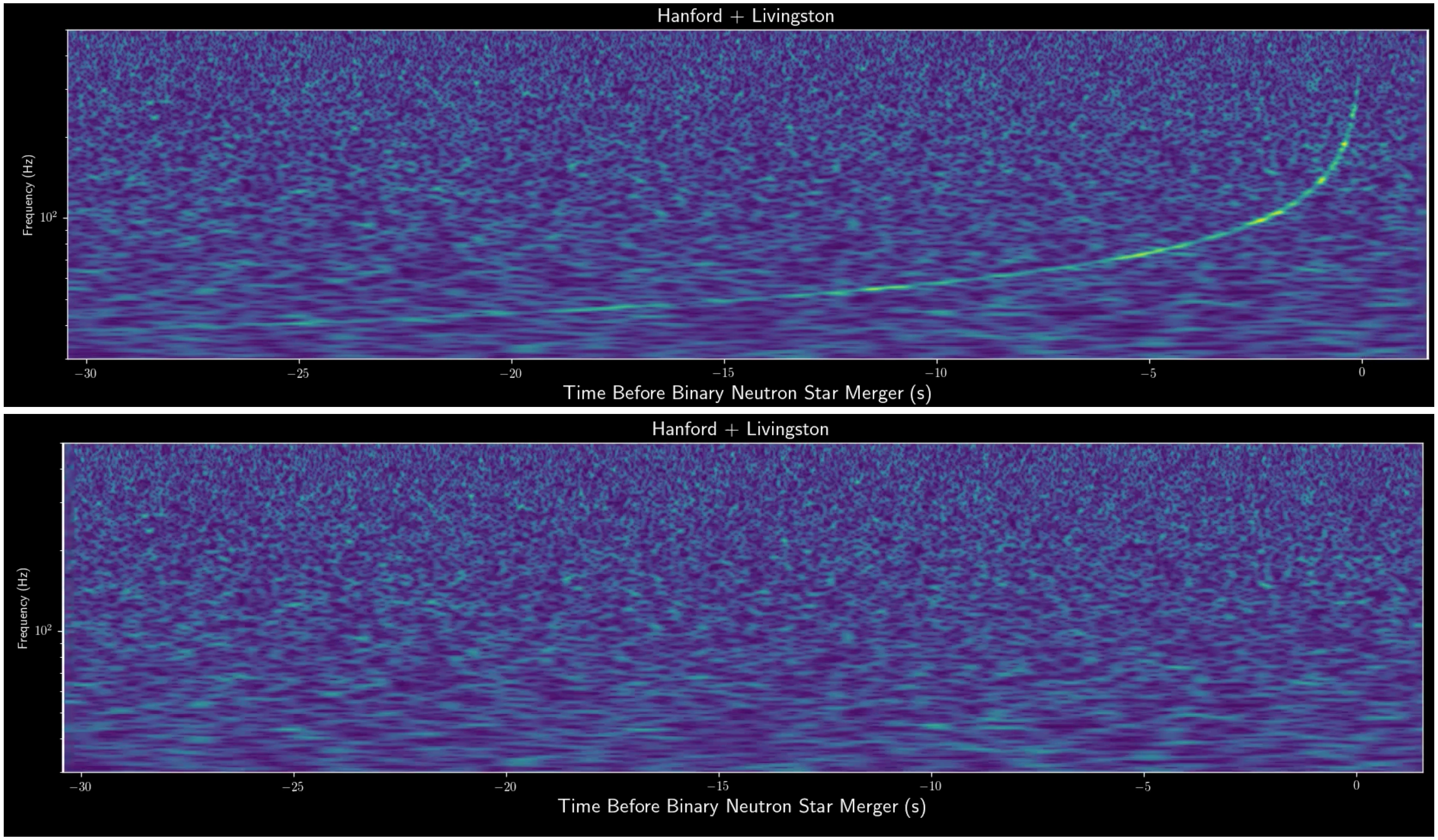
Our automated software ("pipeline") matched the GW signal to a predicted waveform for a binary neutron star merger



The longest (~ 100 s), loudest (SNR ~ 32), closest (40 Mpc) signal we've ever observed!

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

Subtract the predicted waveform from the data ….

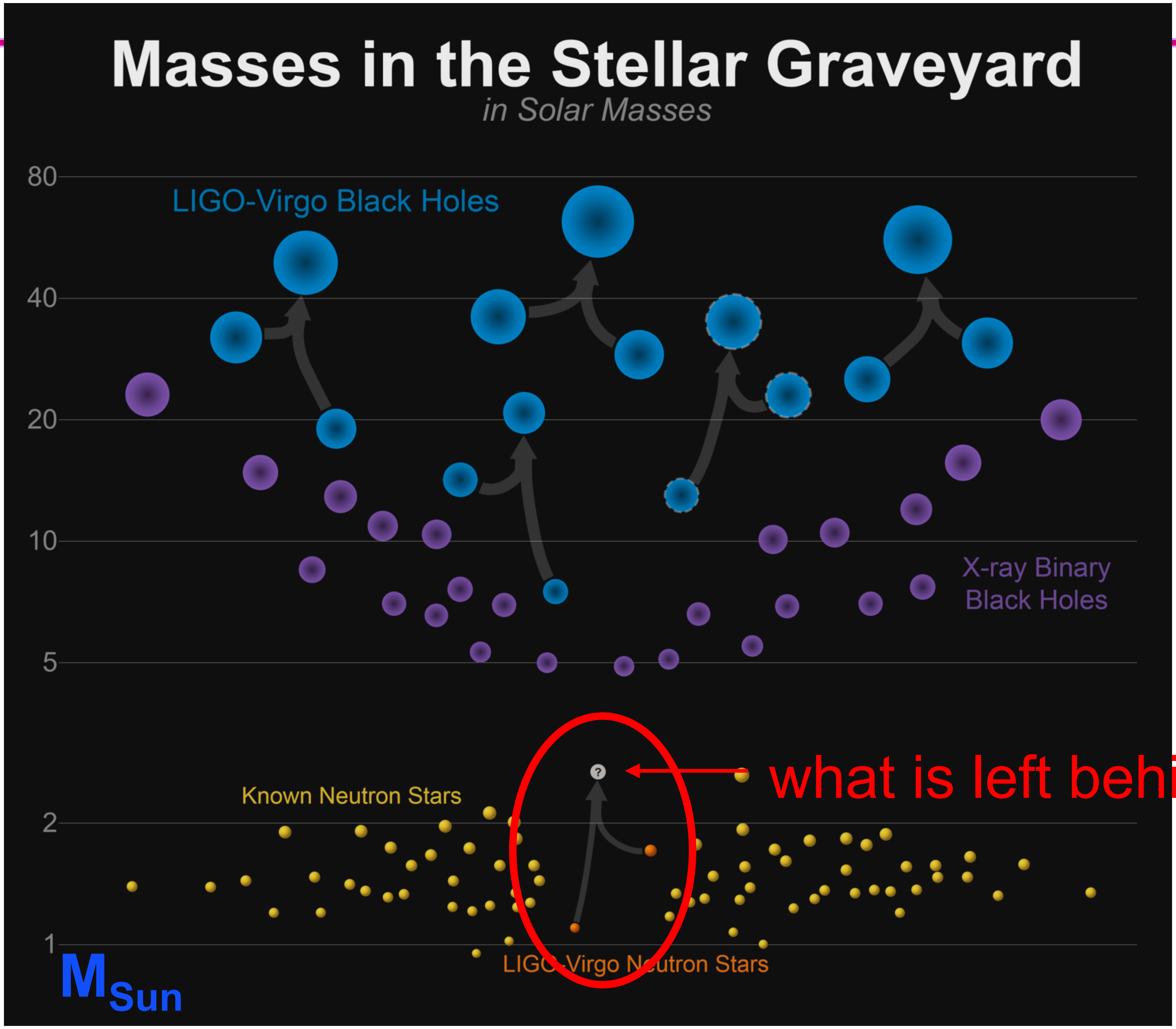


All that's left is random detector noise…

Our waveform template, all ~3000 in-band cycles, matches well!

https://www.youtube.com/watch?time_continue=1&v=_SQbalLipjY

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



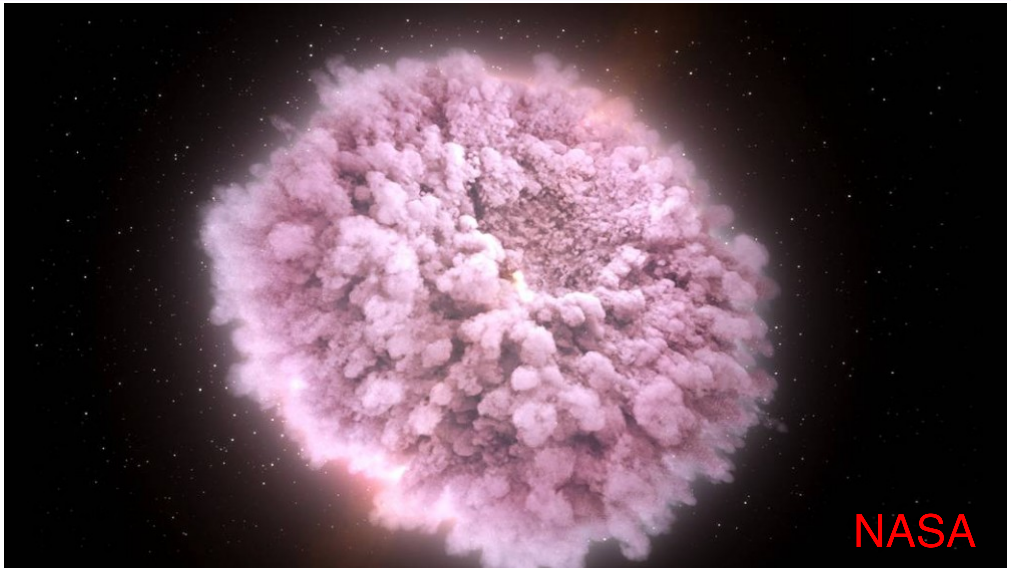
“stellar mass” black holes

“mass gap”?

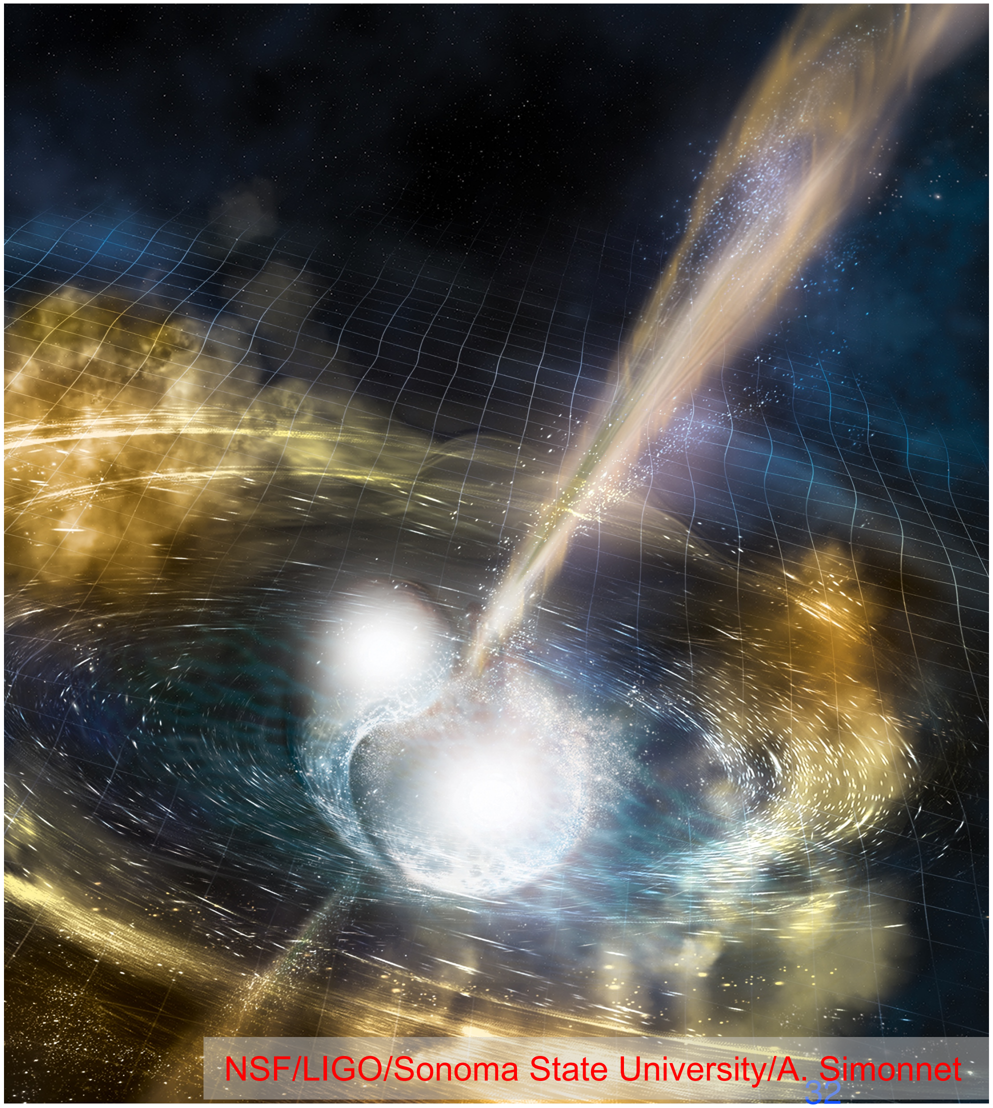
Neutron stars (pulsars)

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

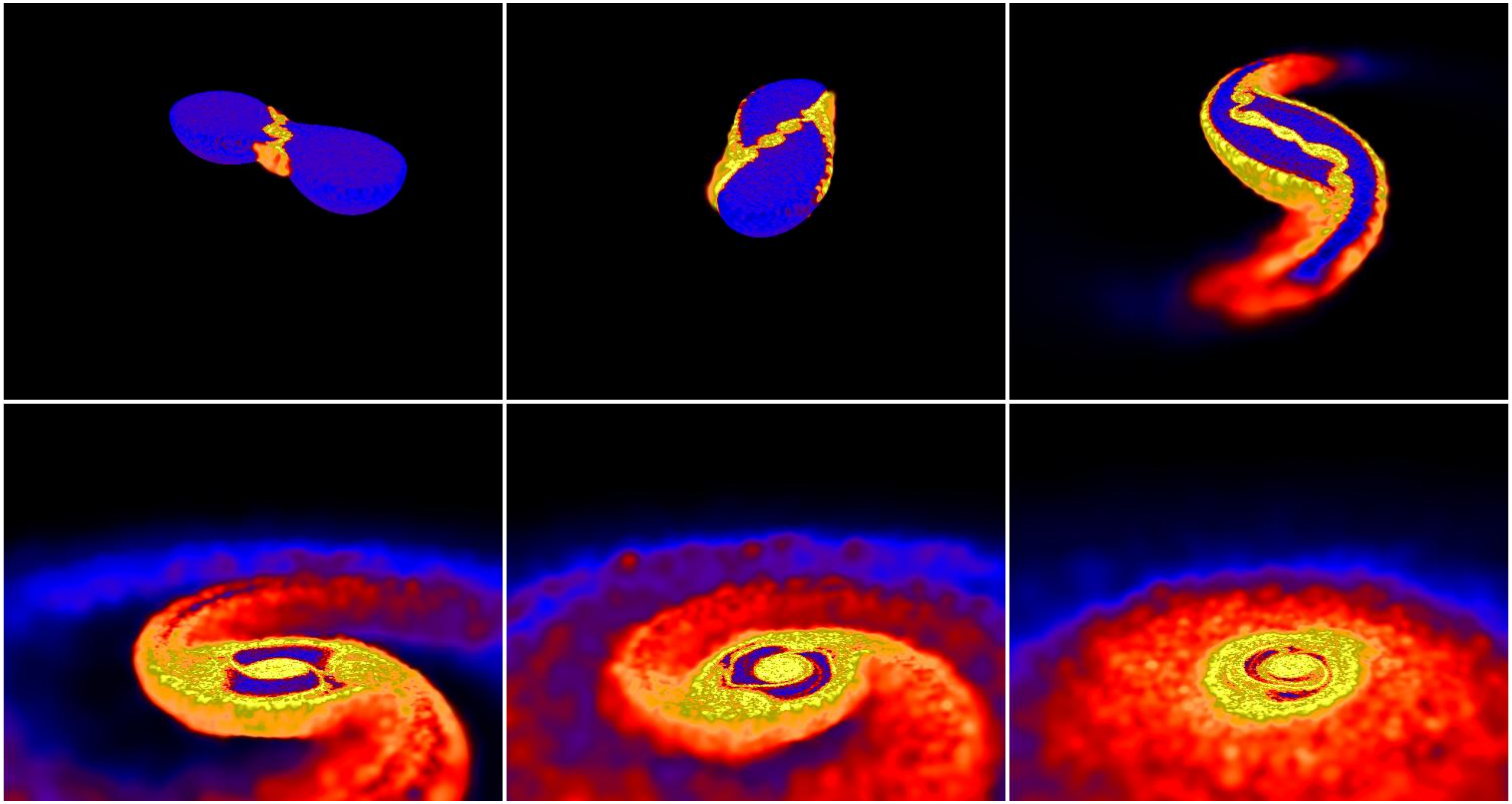
As the stars spiral together, they get torn apart by each other's gravity: Tidal distortion → Disruption!


NASA

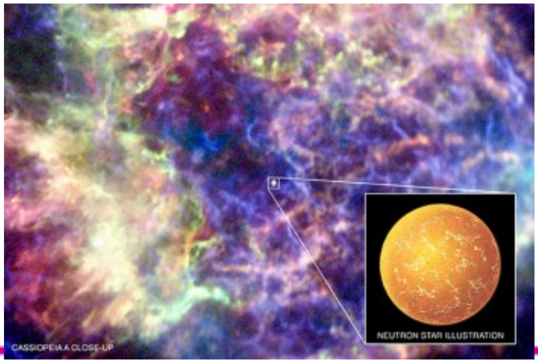
The disruption of the stars results in a huge outflow of neutron-rich "dynamical ejecta" that powers a GRB
and broad-band afterglow


NSF/LIGO/Sonoma State University/A. Simonnet

BNS mergers, tidal distortion and disruption

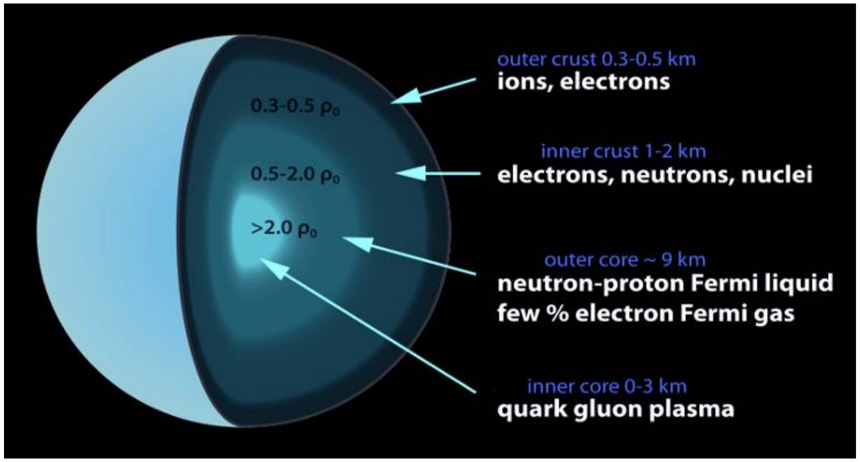


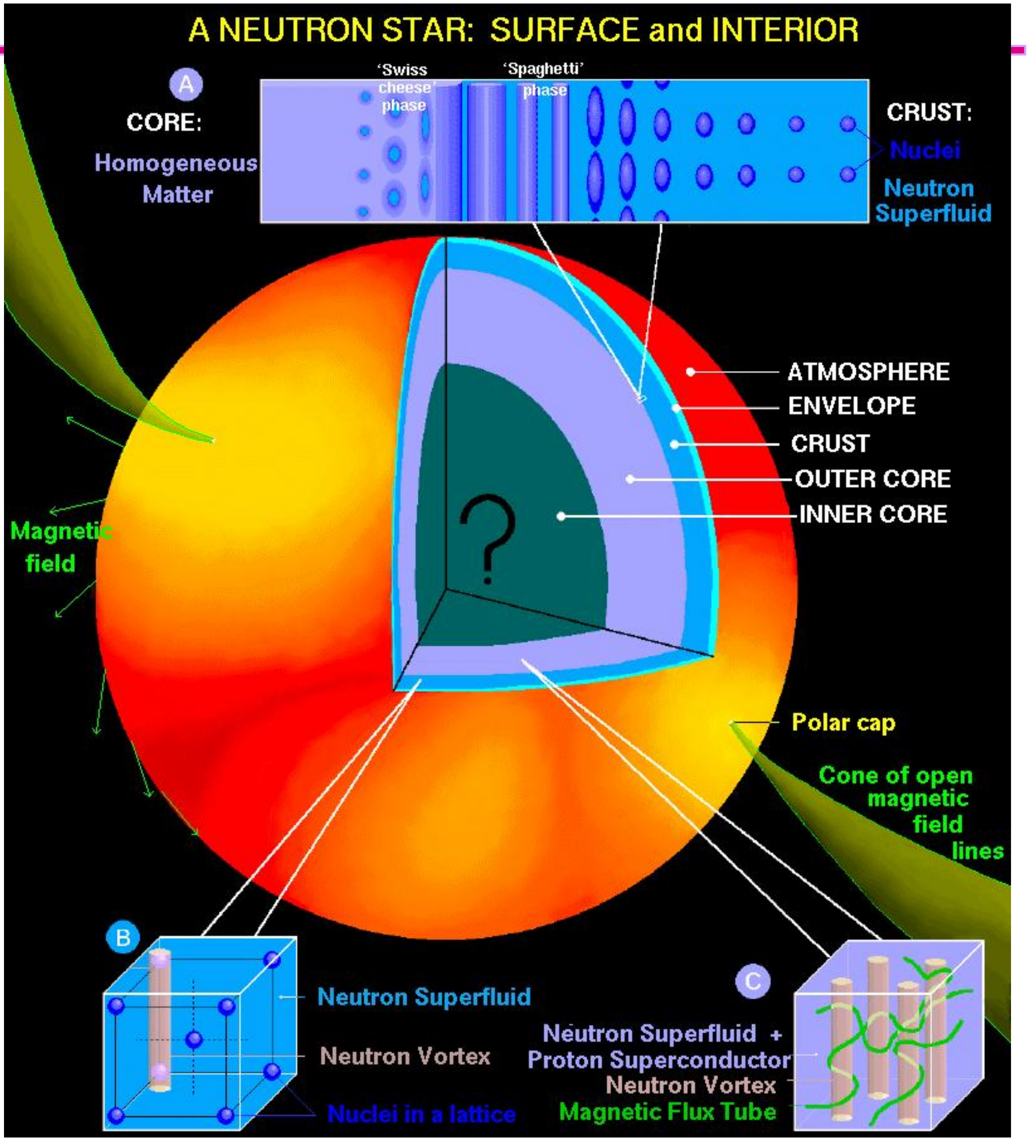
Credit: Daniel Price and Stephan Rosswog



Neutron stars

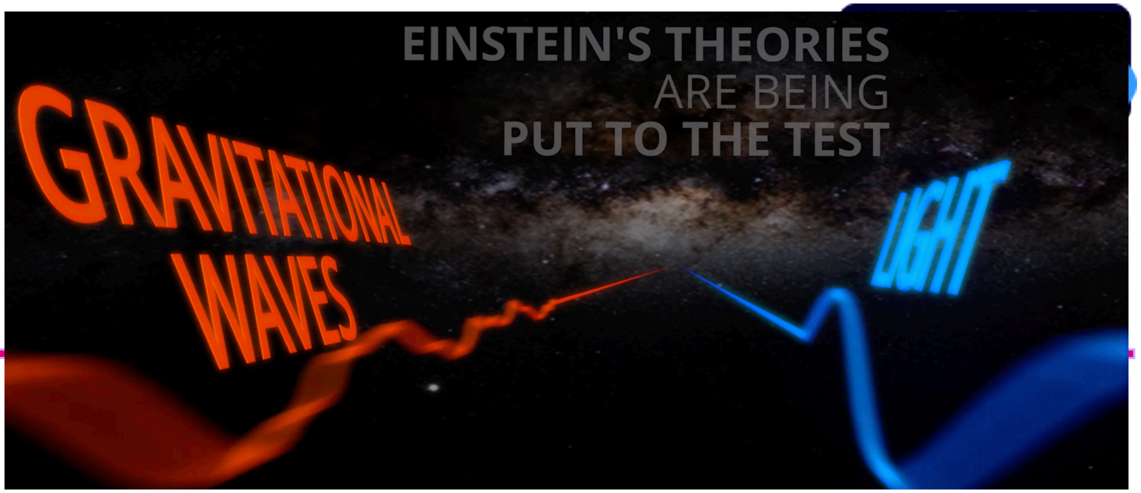
- **Dead remnants of massive star core collapse supernovae**
- **A unique laboratory for fundamental physics**
- **All four forces of nature, Strong, Weak, EM, gravity – all under *the most extreme beyond-laboratory conditions***
- **Structure can be revealed through binary mergers**



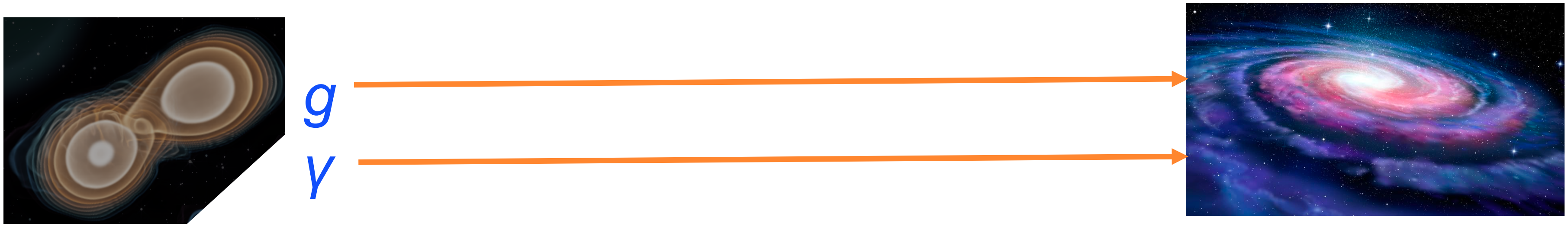


http://www.astro.umd.edu/~miller/nstar.html

For the physicists: Fundamental properties of GWs and NSs



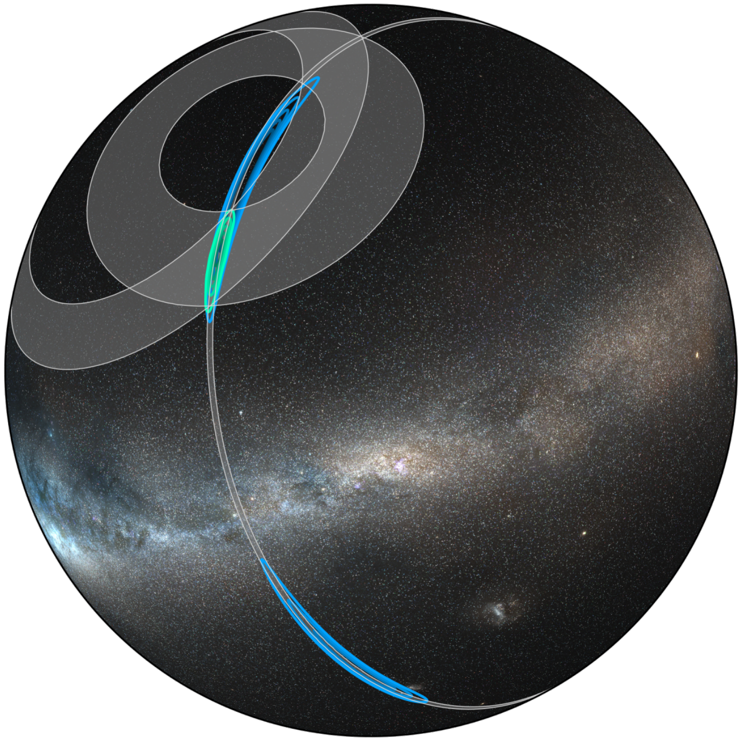
- The GW signal is *fully consistent with General Relativity, over thousands of cycles*.
- *GW polarization is consistent with"tensorial"* – (+ and ×), not (pure) vector or scalar.
- Tidal disruption is weak: NEOS is not stiff, NS radius < 14 km
- GWs, and γ-rays travelled for 130 million years (4×10^{15} 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) $\times 10^{-23}$ 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 *.*



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

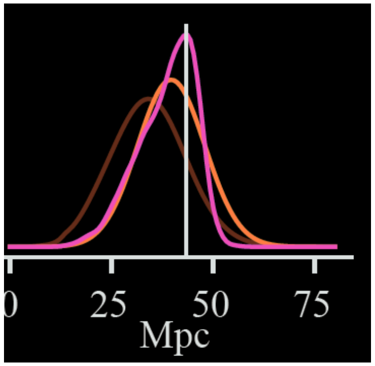
Time is of the essence!

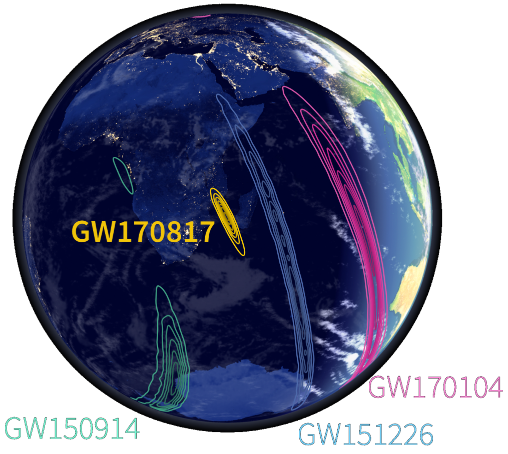
(Initial alert sent out *27 minutes* after the GWs passed through LIGO)



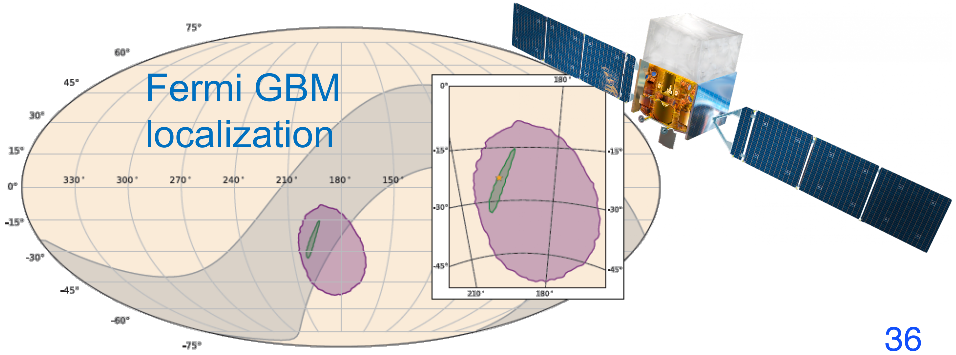
Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

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

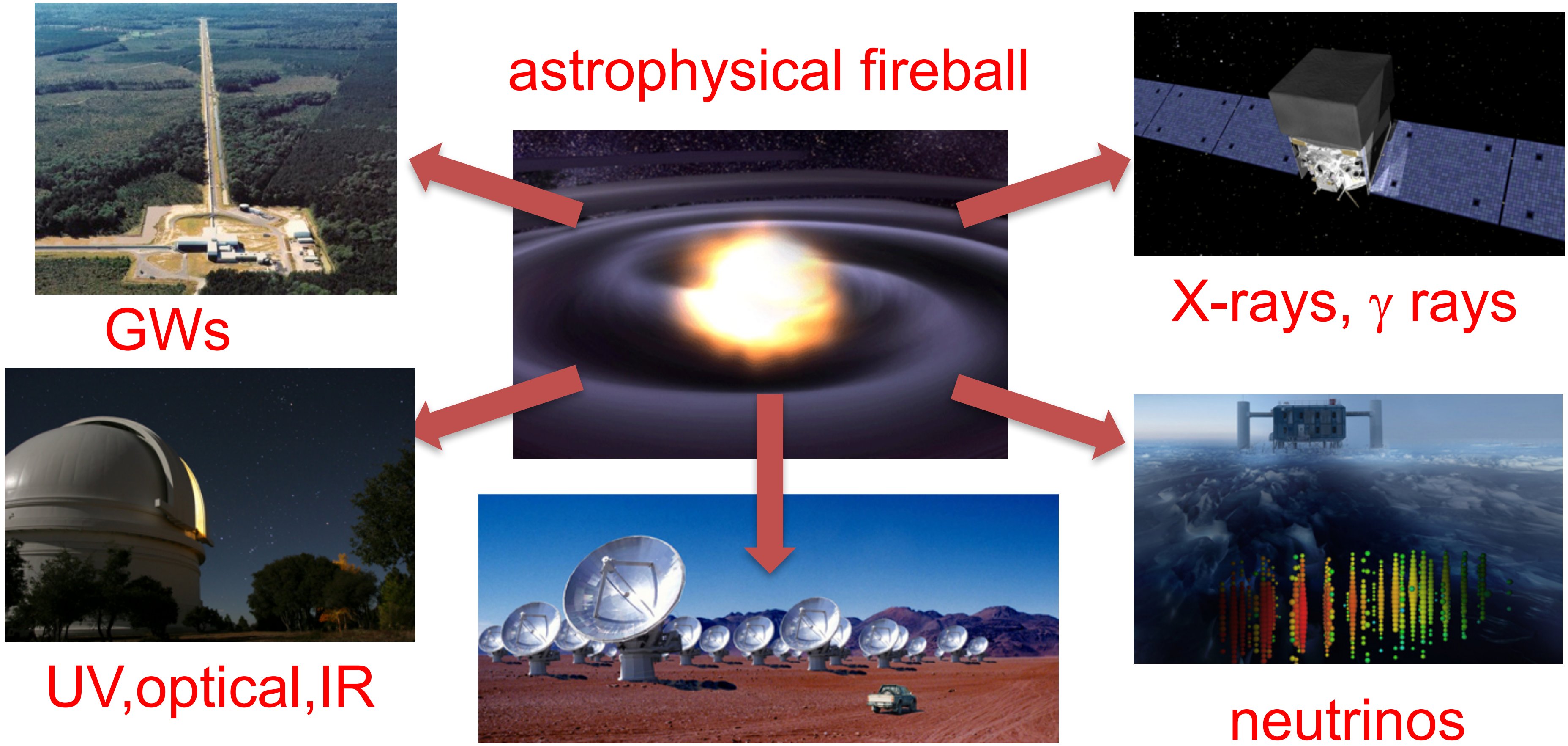




Credit: LIGO/Virgo/NASA/Leo Singer



Multi-messenger Astronomy with Gravitational Waves



astrophysical fireball

GWs

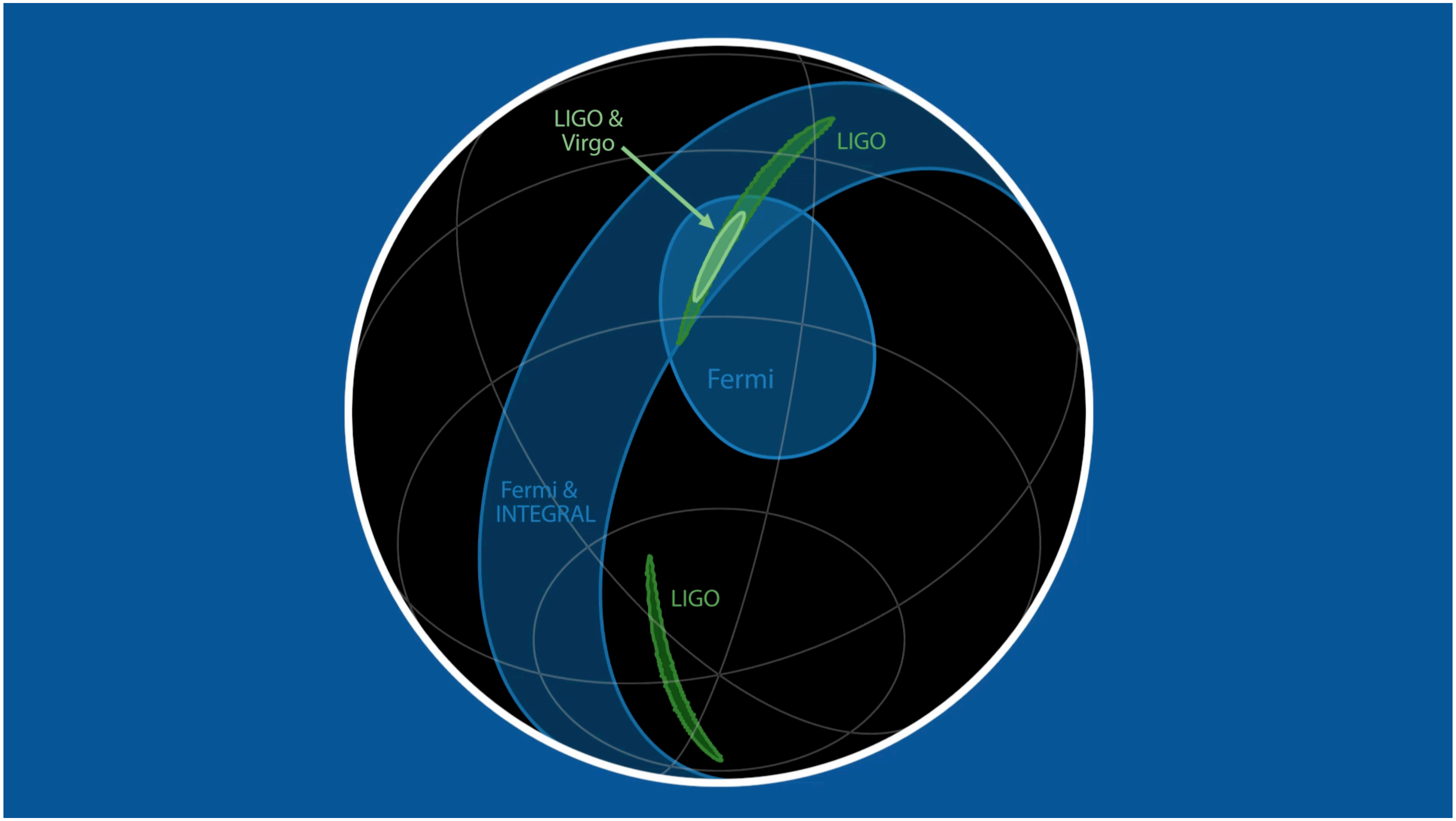
X-rays, γ rays

UV,optical,IR

neutrinos

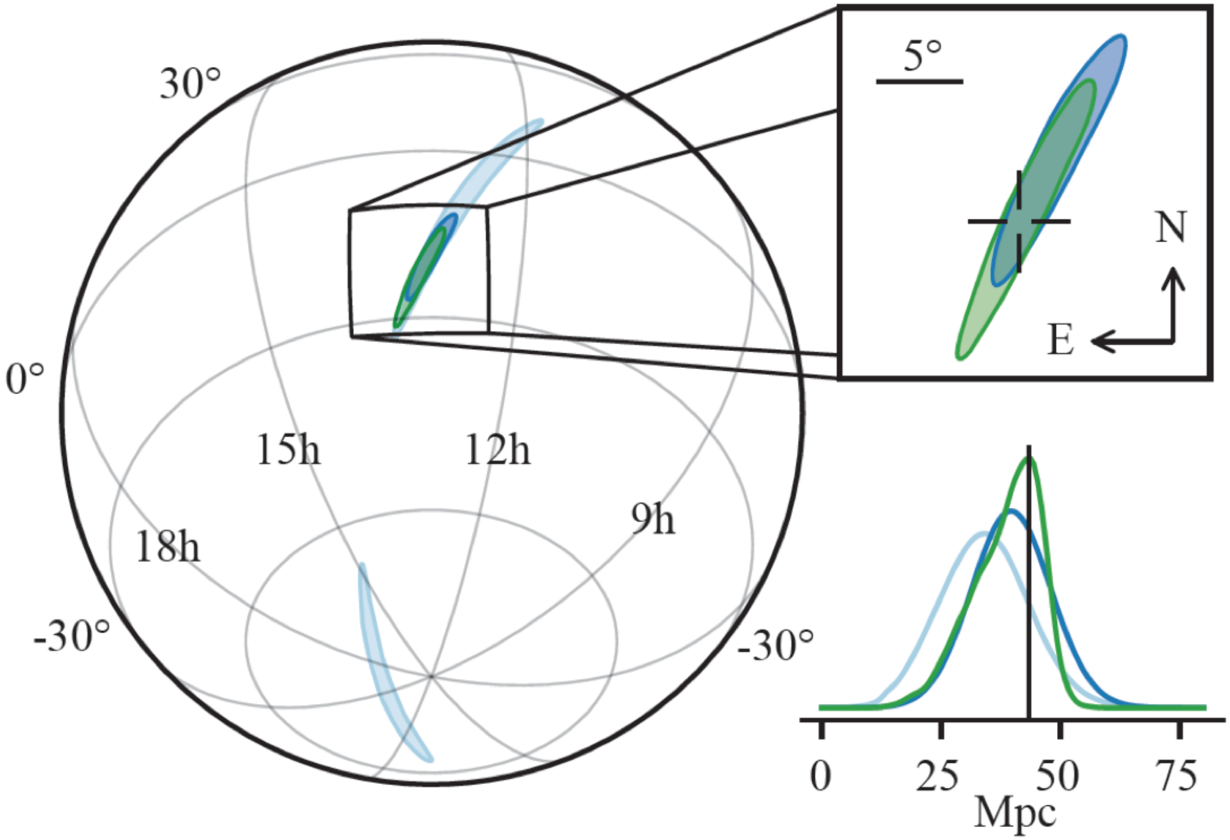
radio

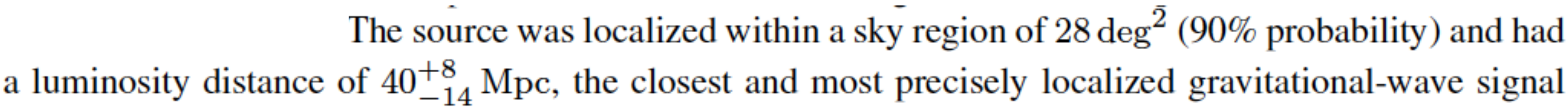
Sky localization with GWs and gamma rays



https://www.youtube.com/watch?time_continue=2&v=4X1j2b2atGM

3-dimensional localization



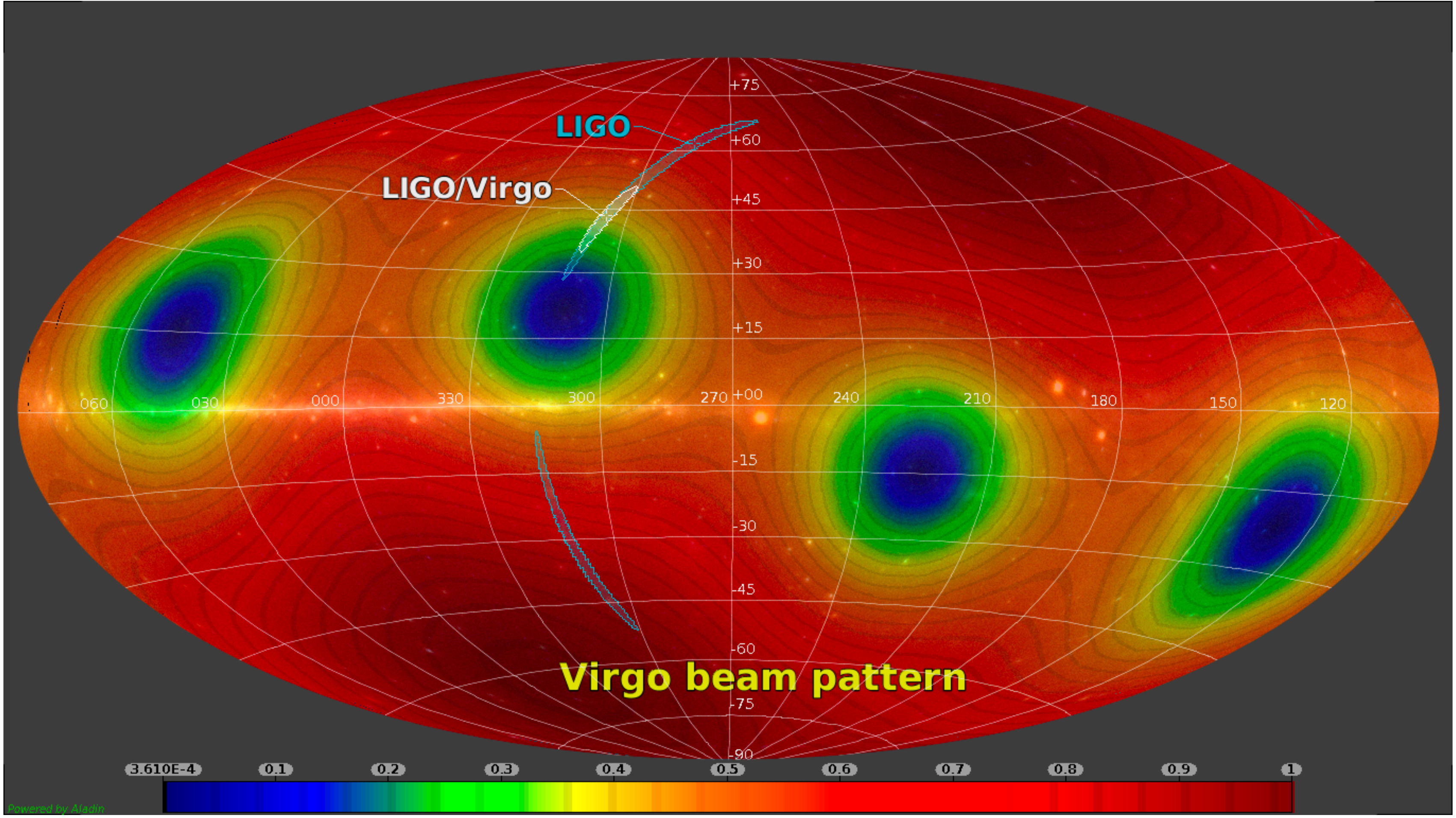


The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal

B. Abbott et al, LIGO-Virgo, Phys. Rev. Lett. **119**, 161101 (2017)

Virgo "non-detection" was very important!

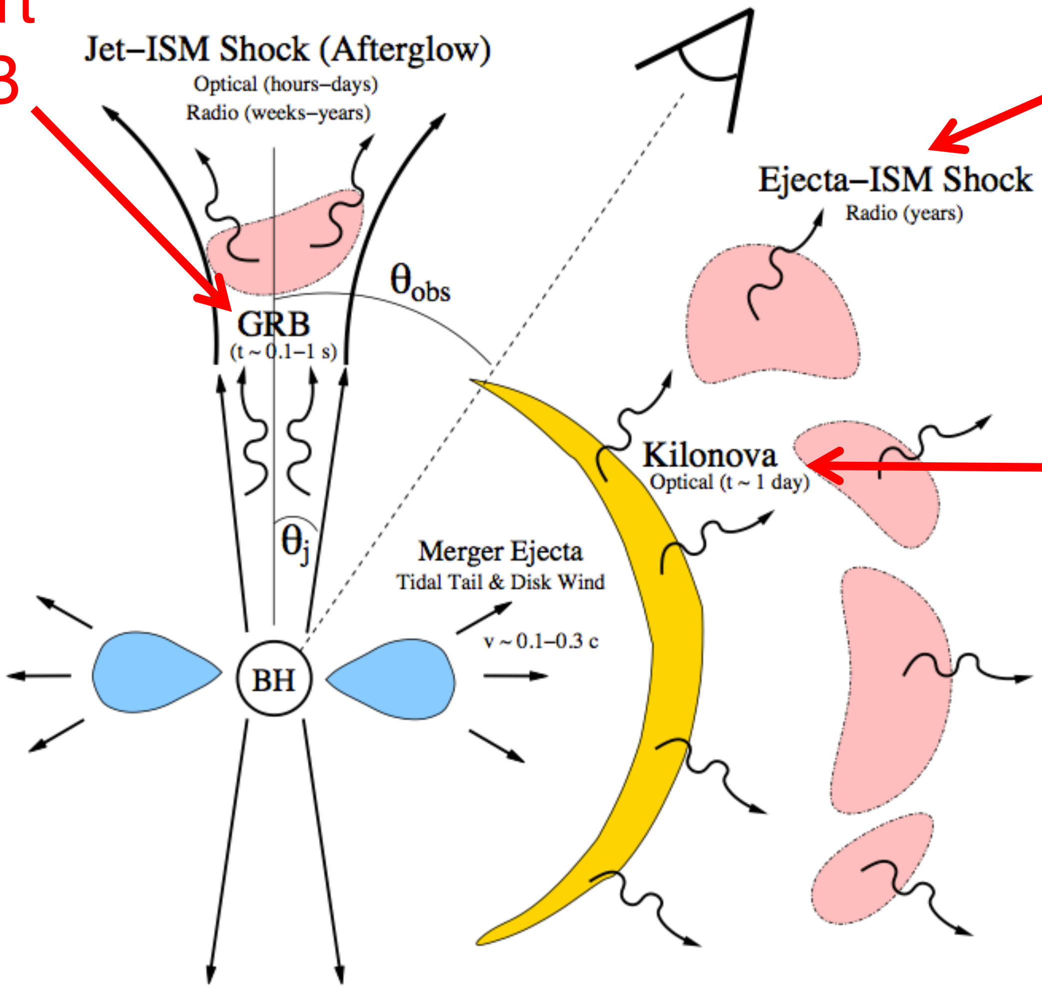
It appears that the signal was in Virgo's "blind spot".



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

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

Electromagnetic radiation from sGRB progenitors



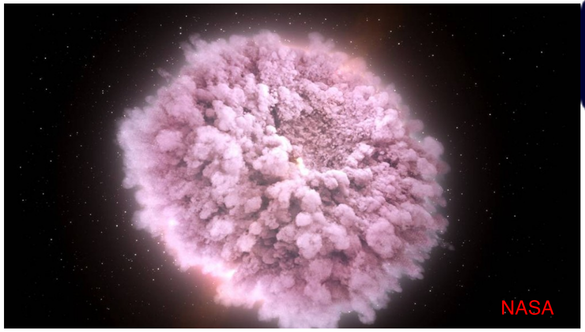
Short GRB

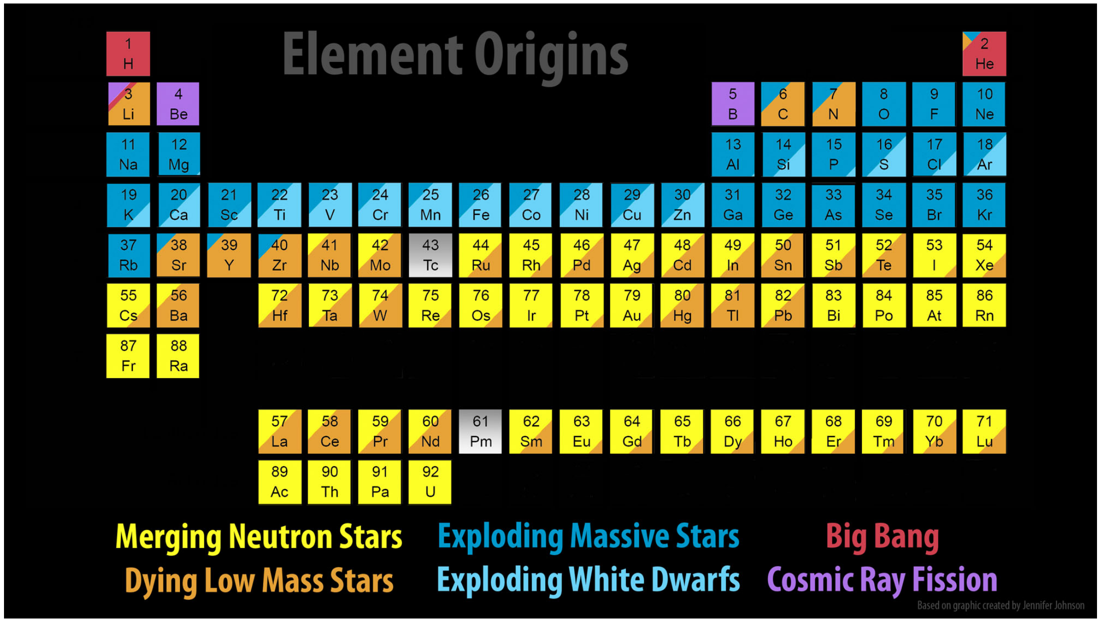
Ejecta-ISM shock radio emission from days to years

“kilonova”
Prompt optical emission from seconds to days

Metzger & Berger 2011

The origin of the (heavy) elements



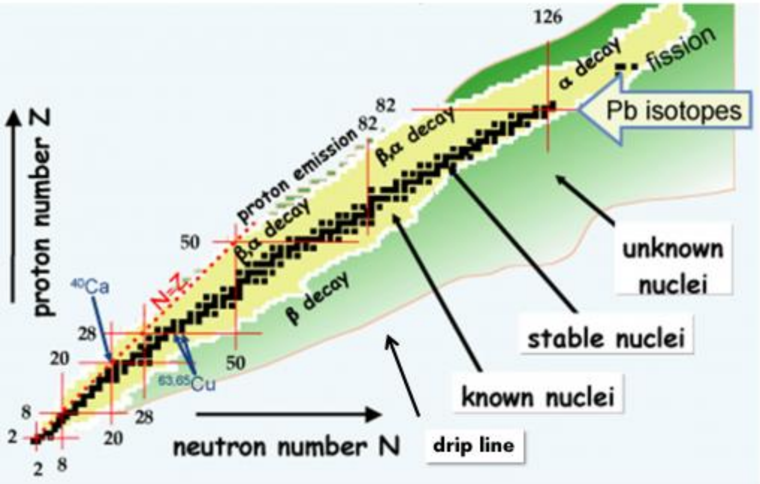


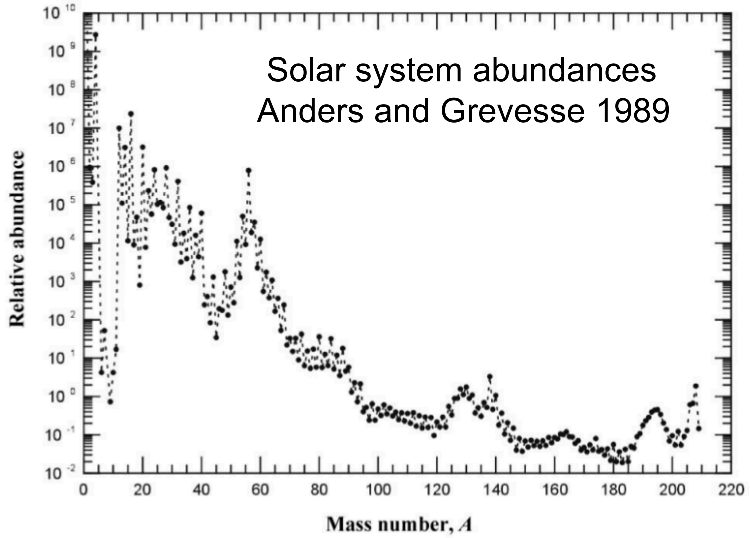
Element Origins

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U												

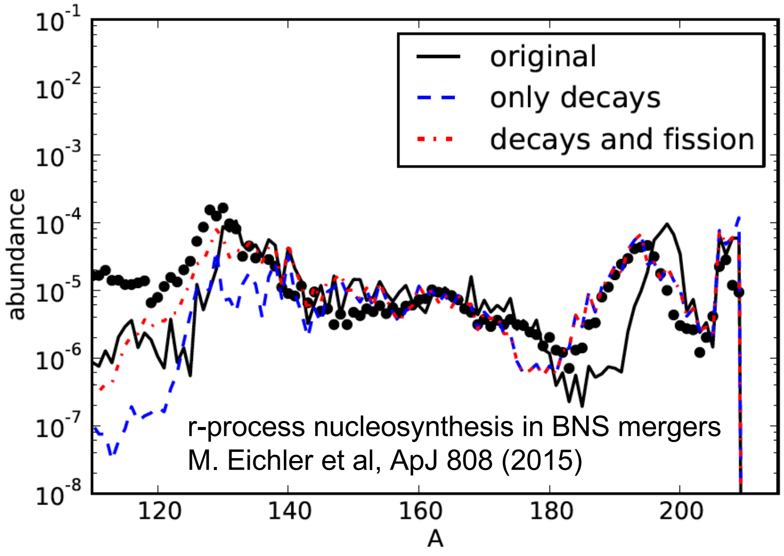
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission

Based on graphic created by Jennifer Johnson



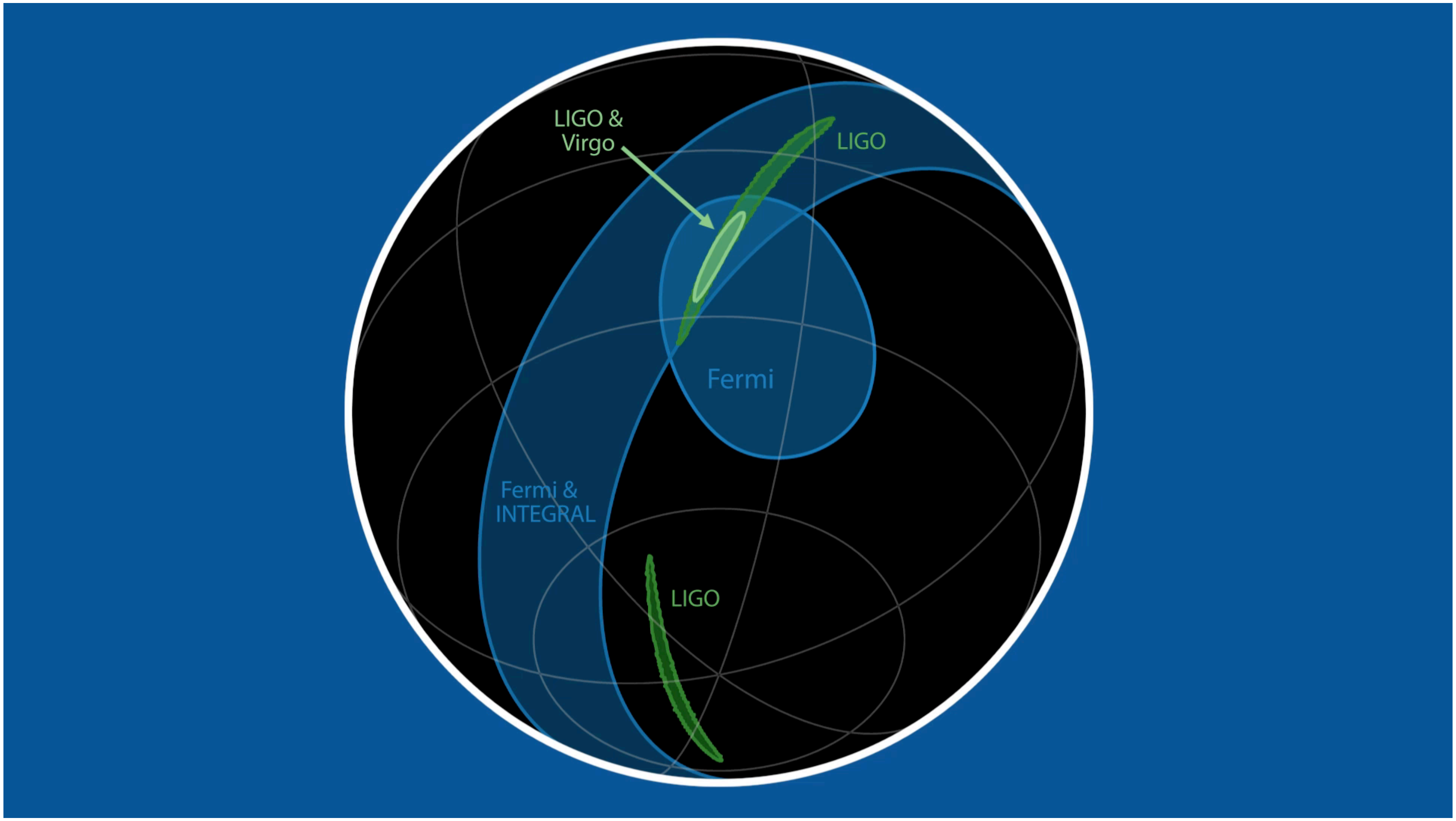


Solar system abundances
Anders and Grevesse 1989



r-process nucleosynthesis in BNS mergers
M. Eichler et al, ApJ 808 (2015)

Finding the optical counterpart

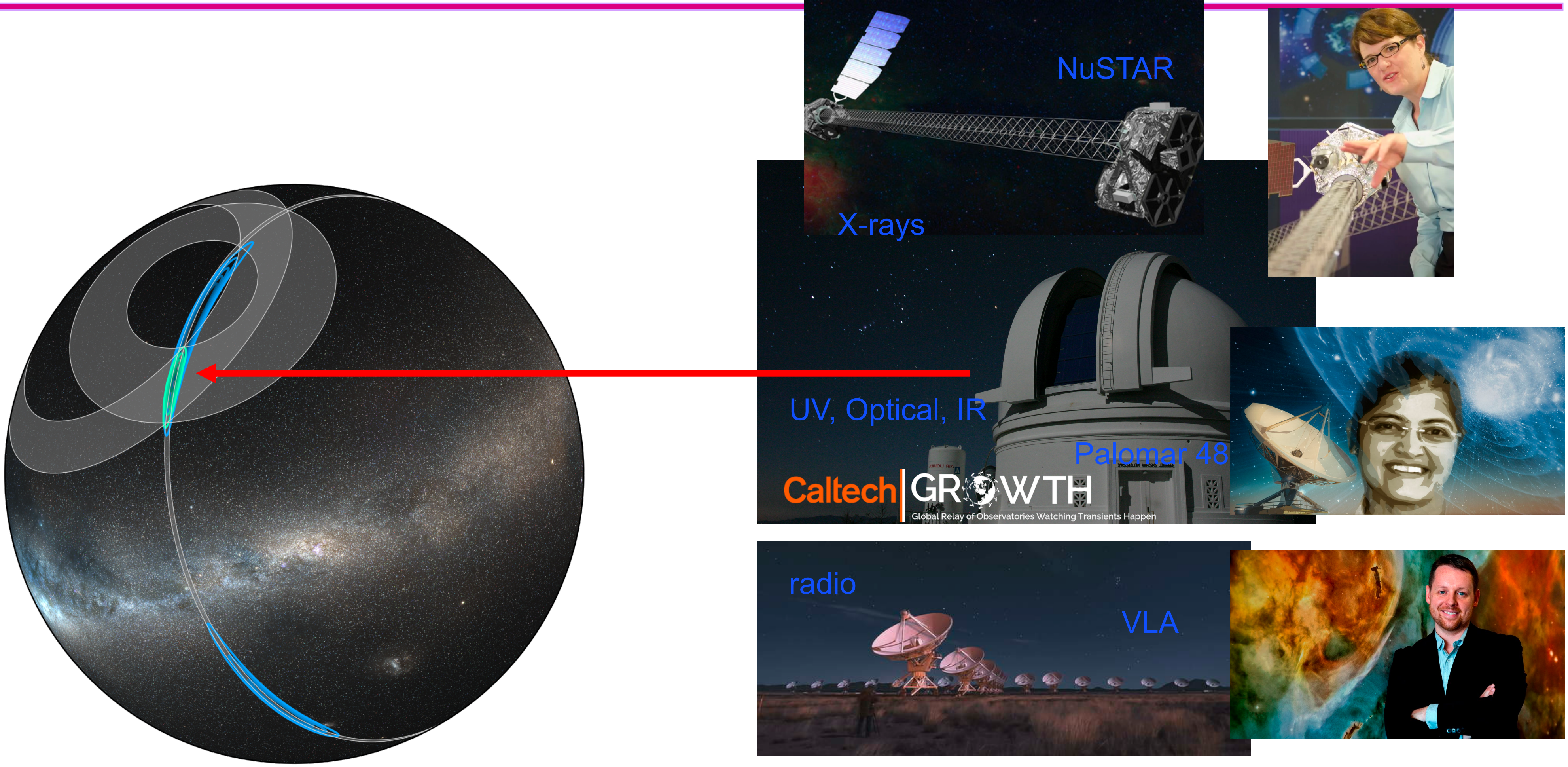


Credit: R. Hurt

https://www.youtube.com/watch?time_continue=2&v=4X1j2b2atGM

Is there anything to be found in that spot on the sky? Mansi? Gregg? Fiona? POINT YOUR TELESCOPES!

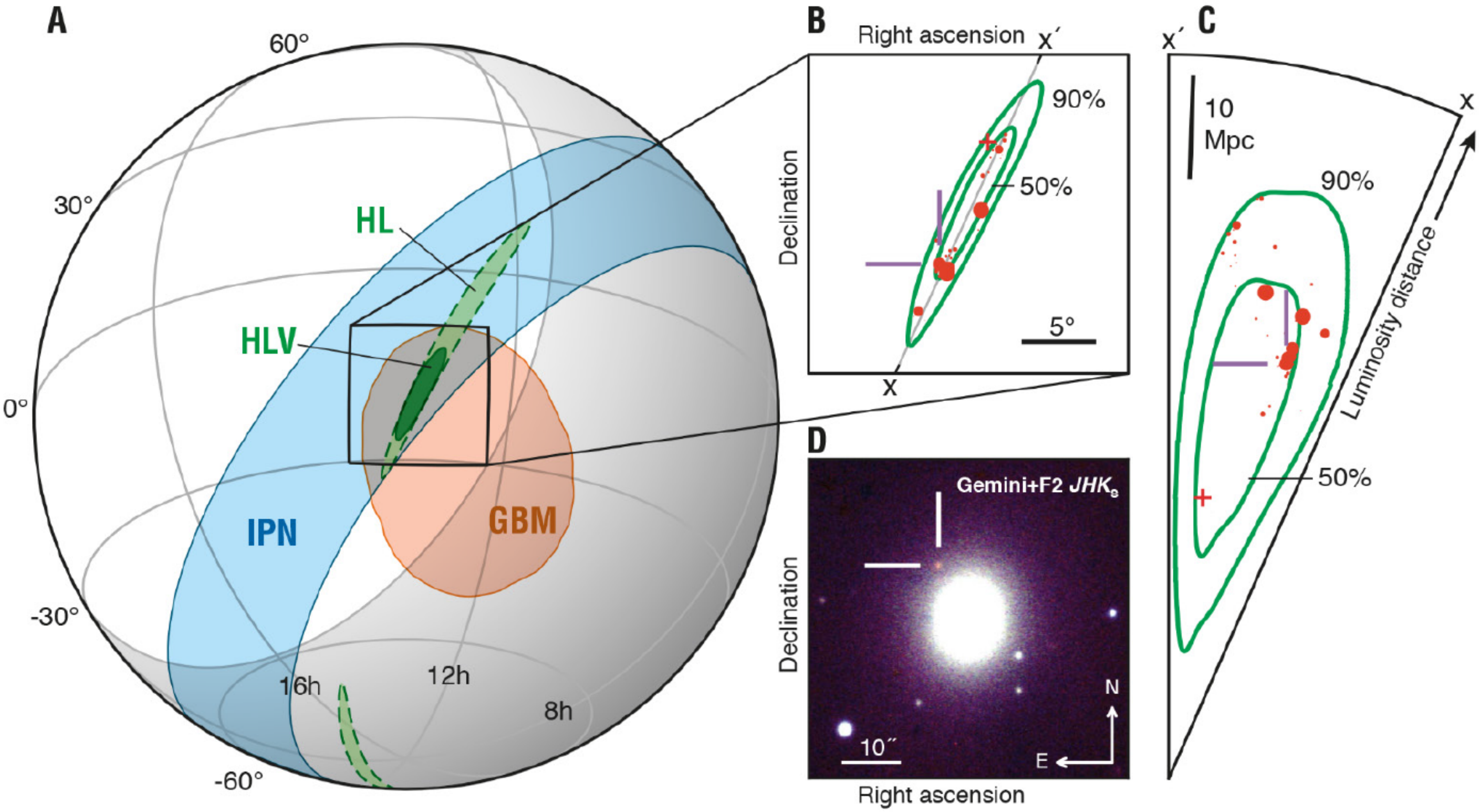
This is the REAL THING!!!



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

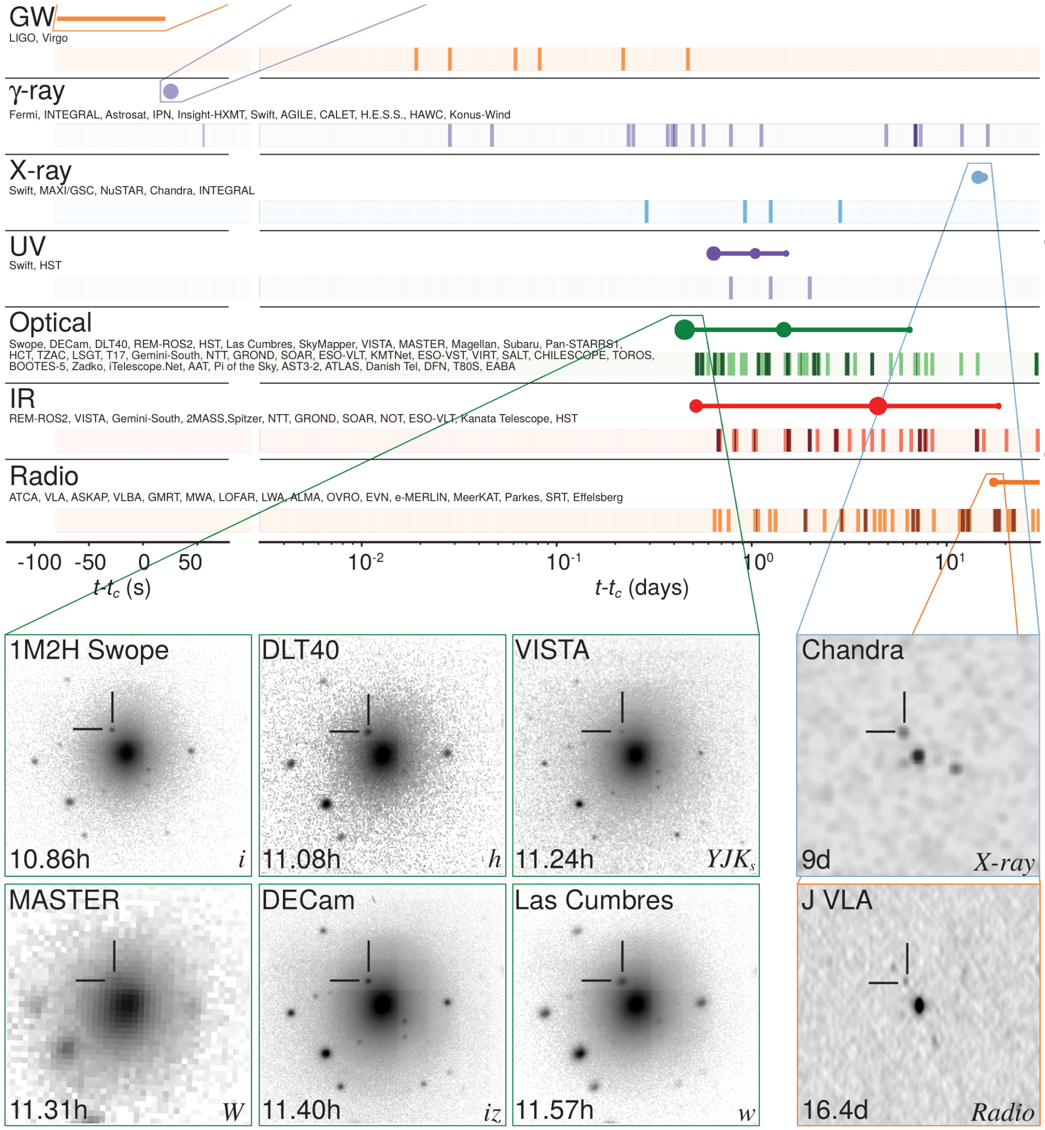
Is the the dawn of GW-multi-messenger astronomy?

The next evening: they got it!

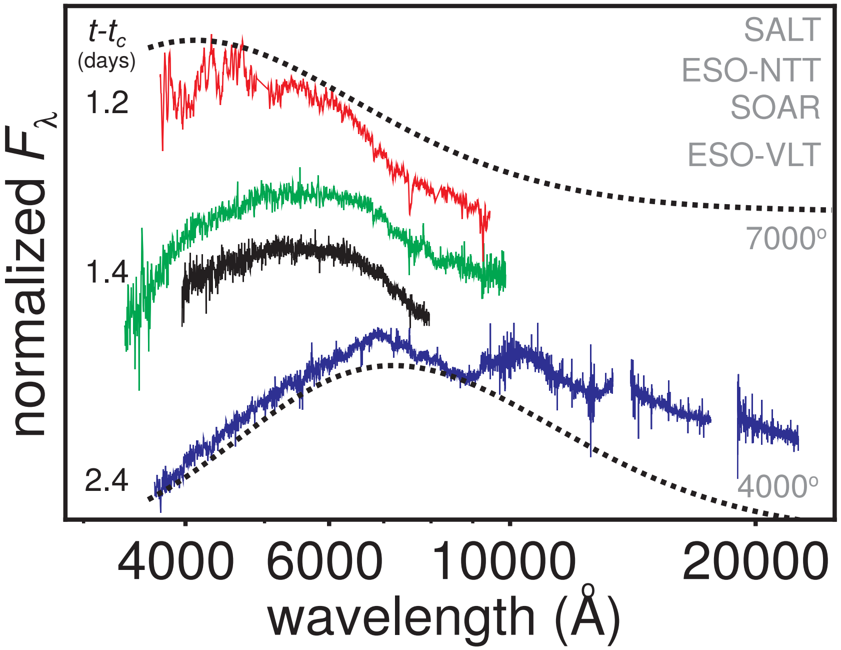


M. M. Kasliwal *et al.*, *Science* 10.1126/science.aap9455 (2017).

EM counterpart, in all bands!

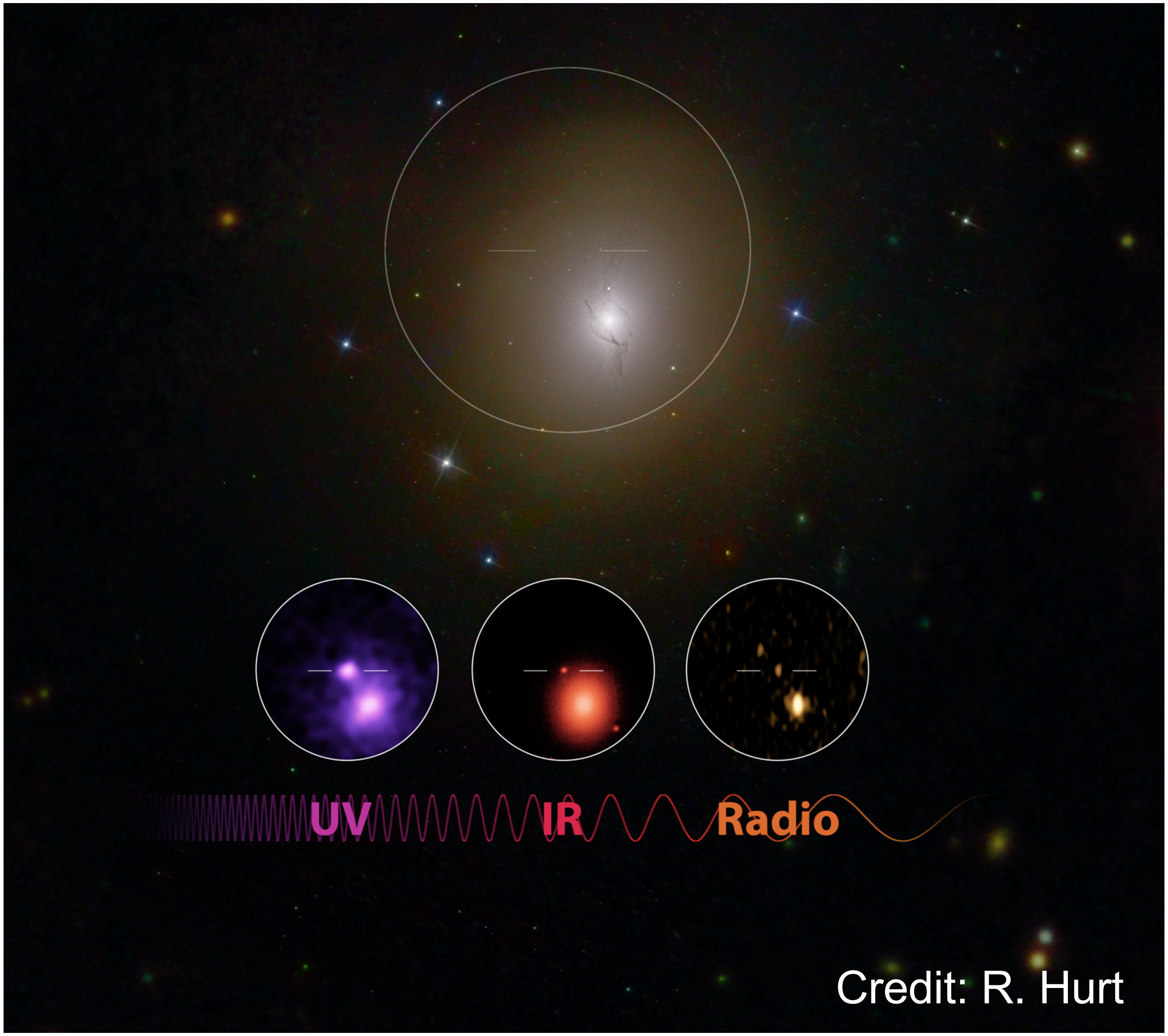


EM170817



LIGO, Virgo, many astronomers:
http://iopscience.iop.org/article/10.3847/2041-8213/aa91c9

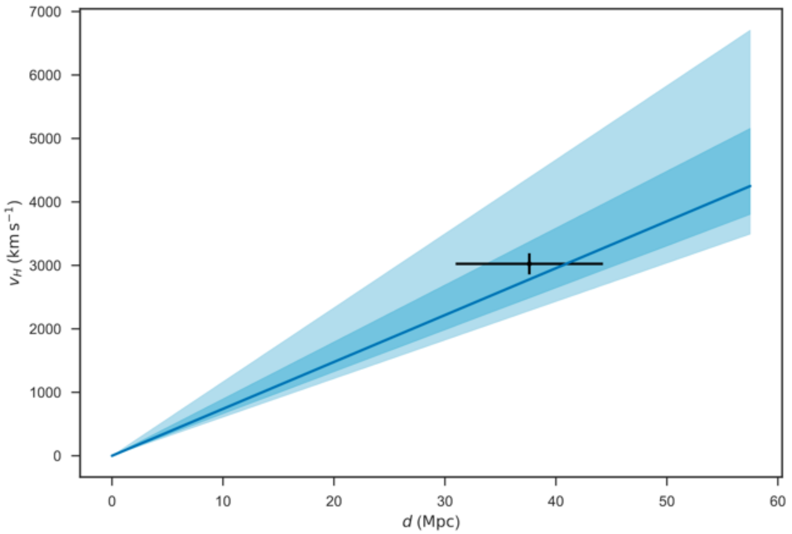
Light at Every Wavelength

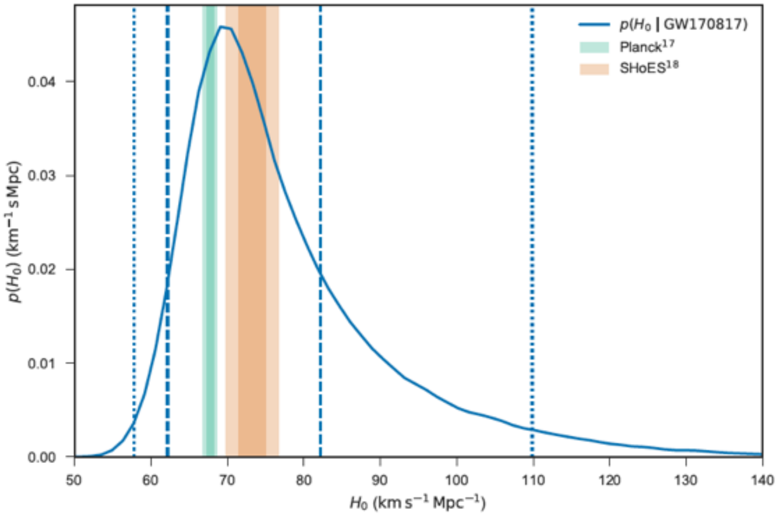


Credit: R. Hurt

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

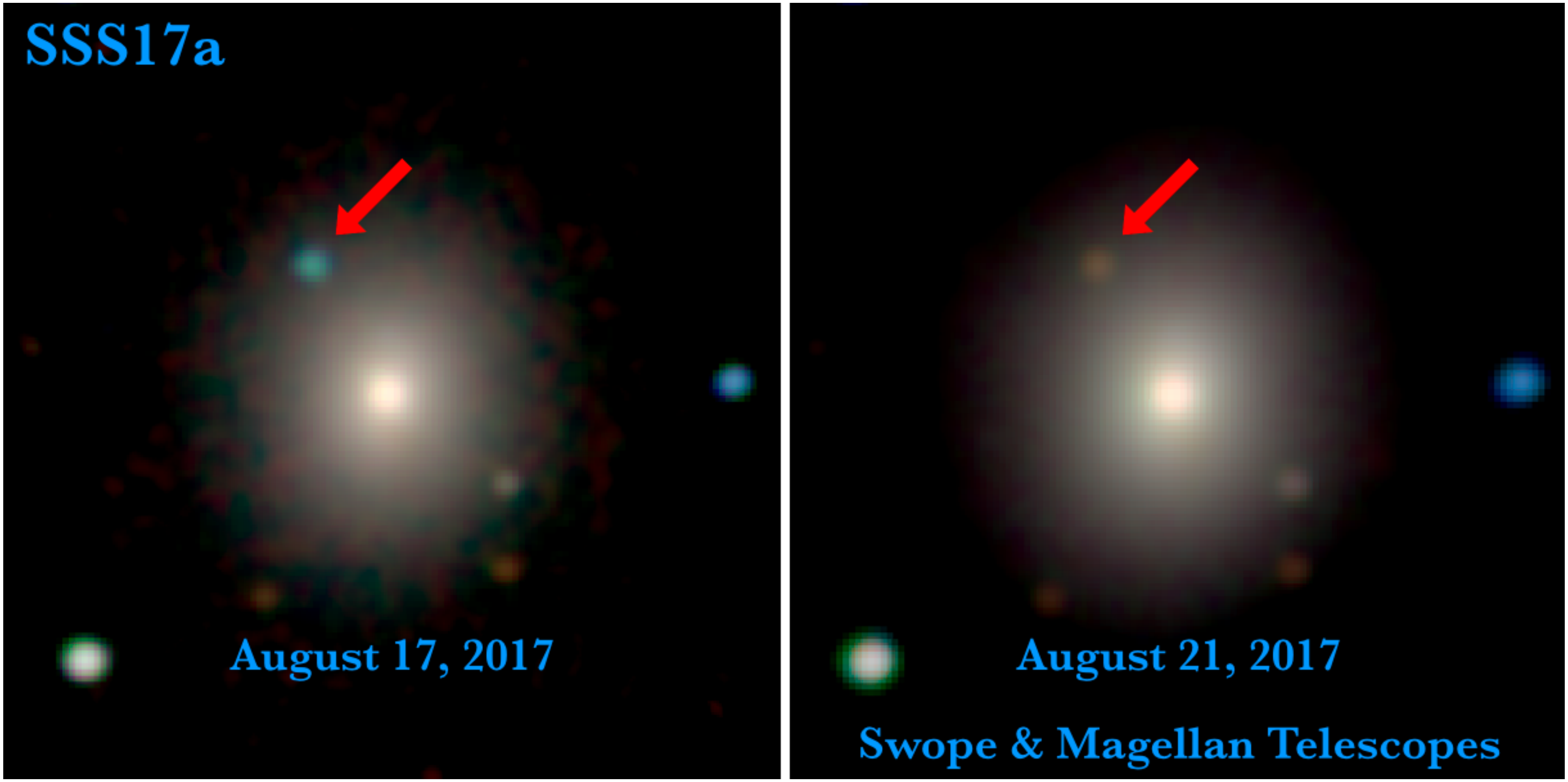
- From the GWs, we can measure the distance to the source fairly accurately: 40 Mpc or 130 Mly
- From the optical afterglow we can measure the redshift of the source (recessional velocity).
- Combining them gives the Hubble expansion rate.
- Not terribly accurate yet, but in good agreement with measurements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





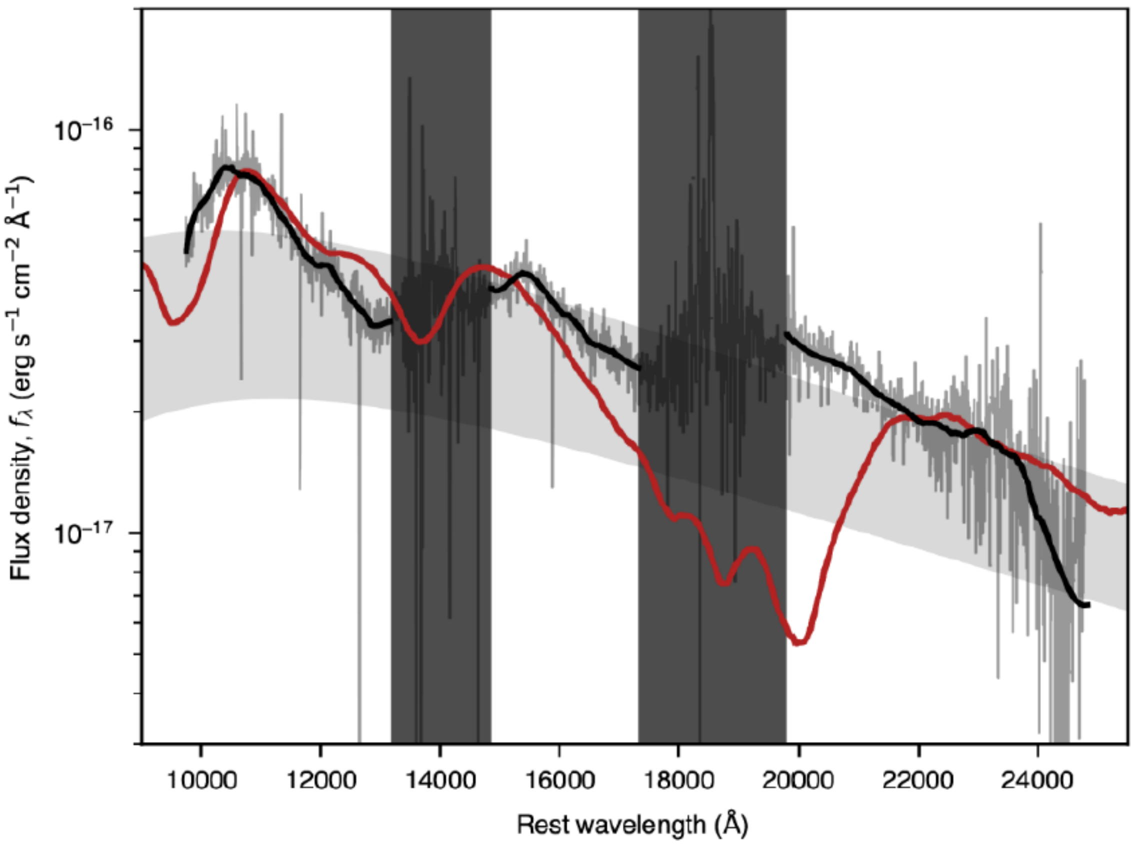
LIGO-Virgo, B.P. Abbott et al. Nature (2017)

From nothing, to blue, to red

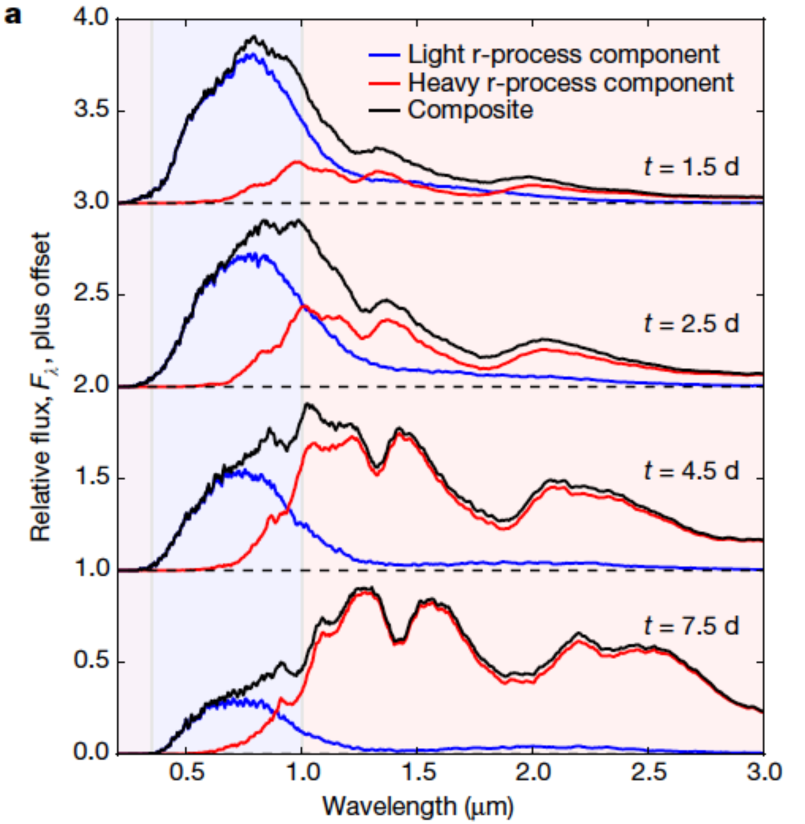


Credit: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley
http://ligo.org/detections/GW170817.php

From the IR spectrum: evidence of Heavy Element production



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



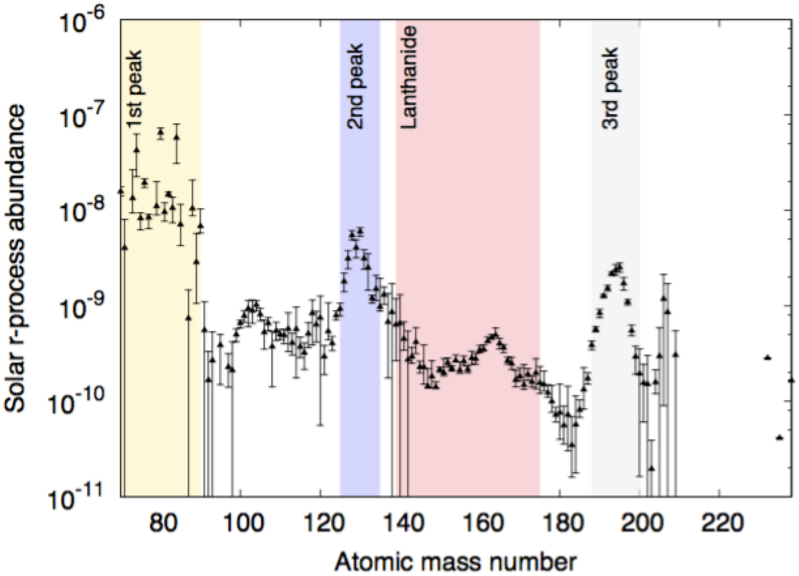
Models by D. Kasen *et al.*, (2017)
doi:10.1038/nature24453

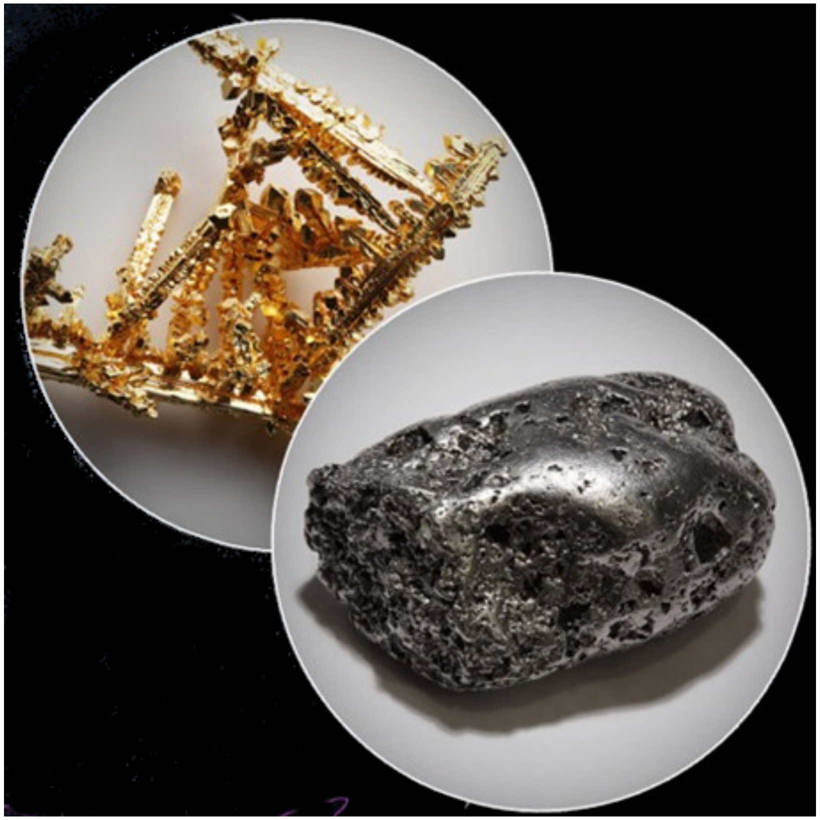
Not just a site, but *the* site of heavy element production?

Observed Solar Abundance

= Quantity per merger x Rate of Mergers

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



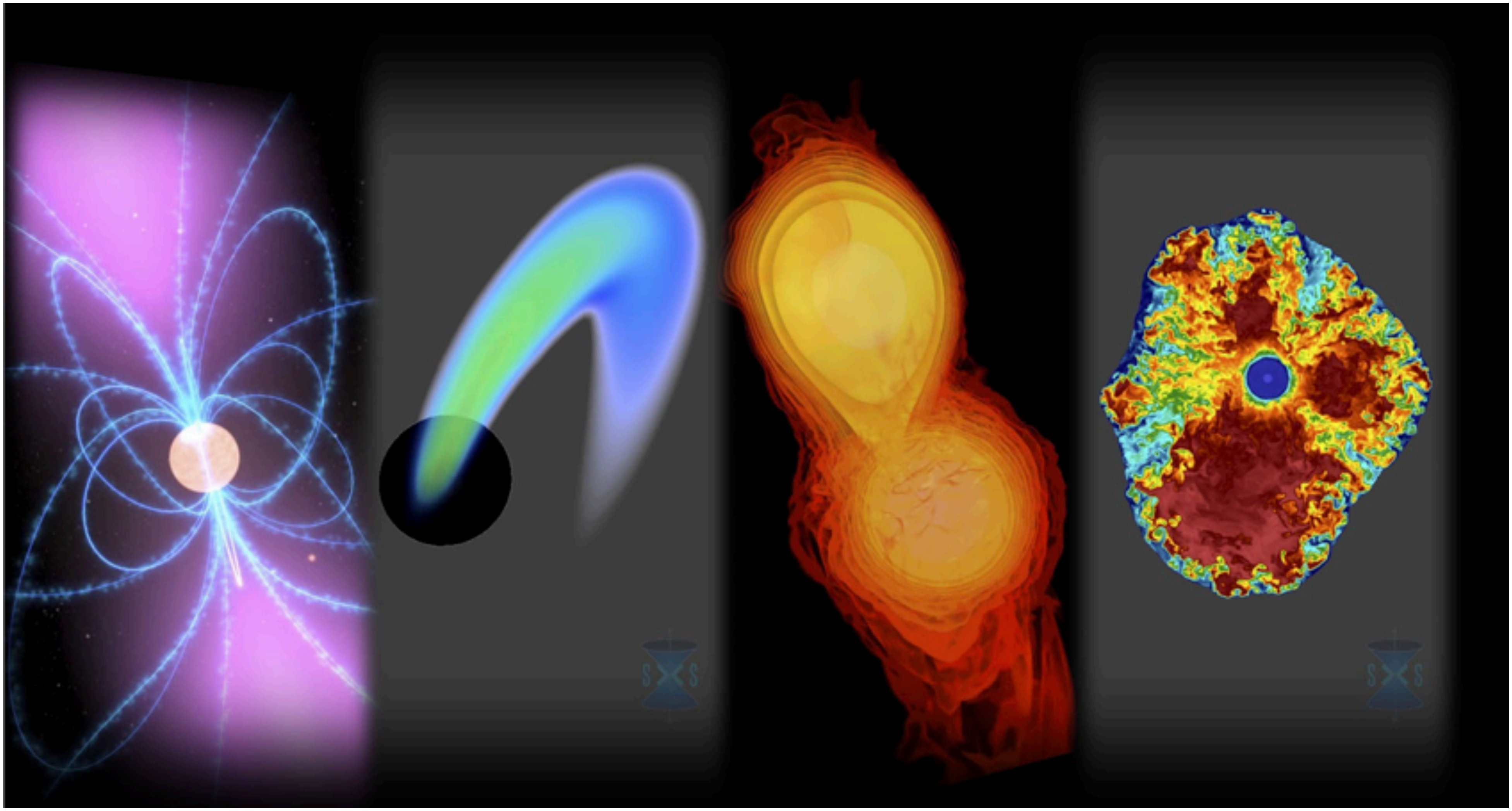


Ejecta mass estimate: ~0.05 solar mass

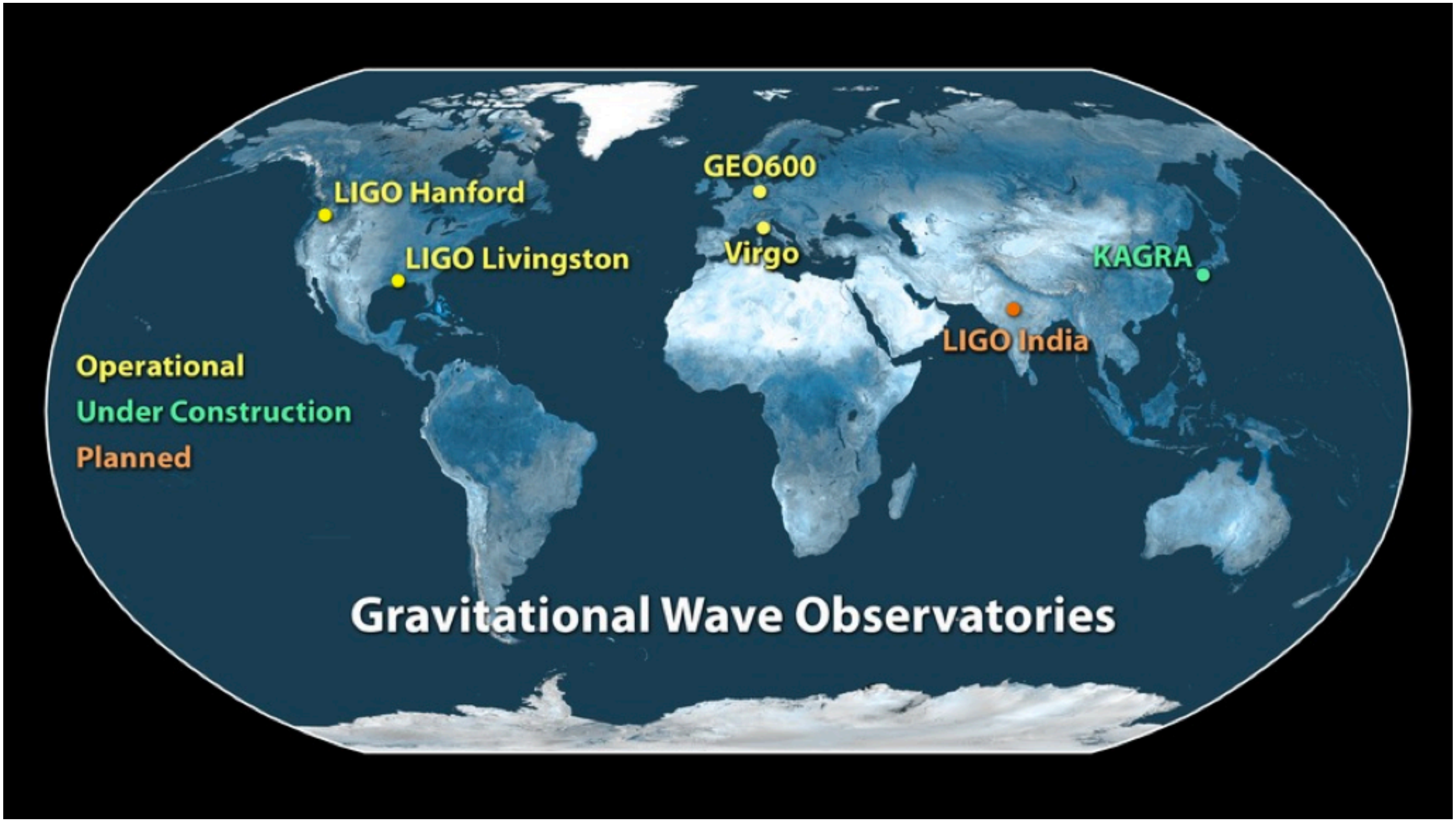
Merger rate estimate: $R = 1540^{+3200}_{-1220}\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Consistent!

The future of Gravitational-wave astronomy

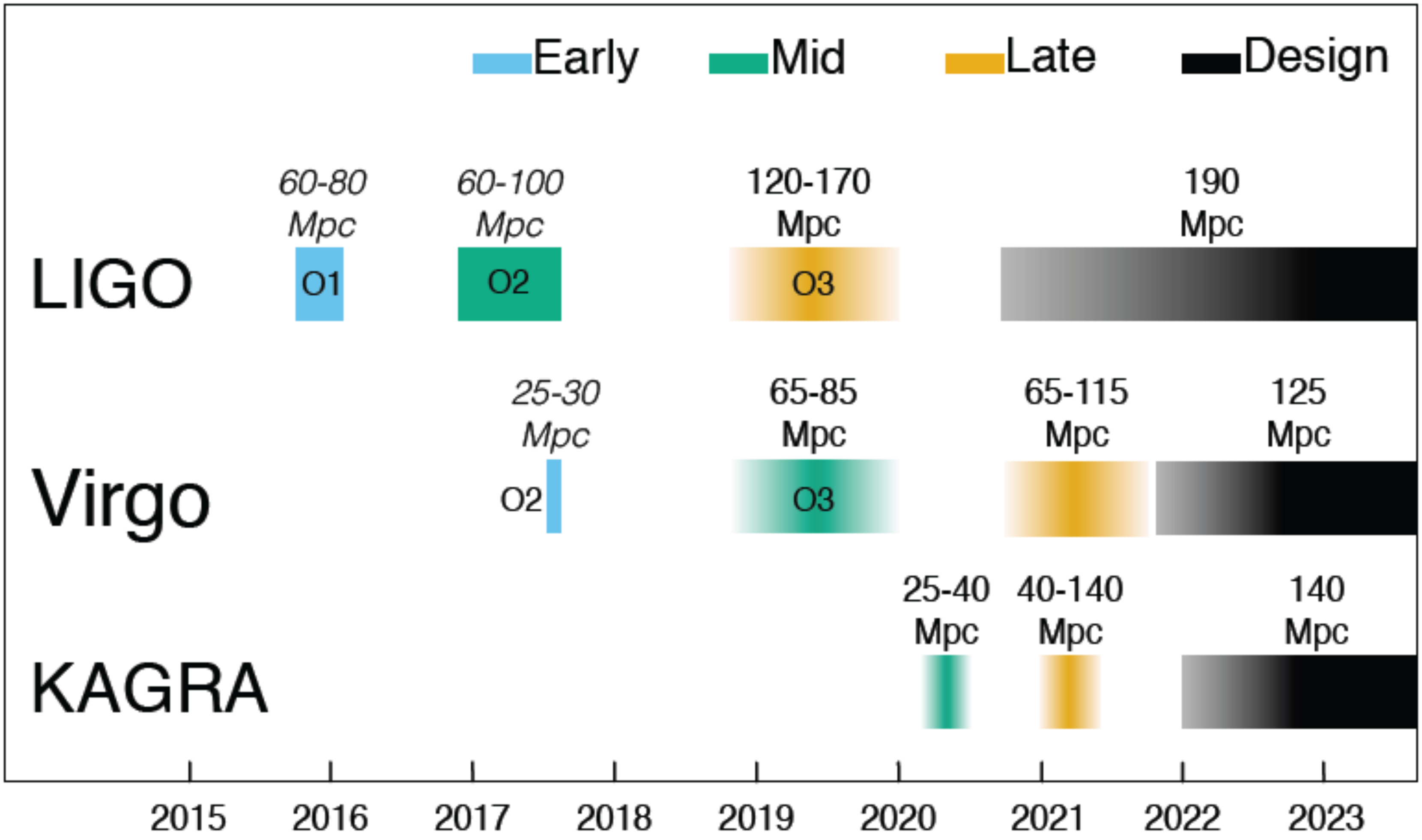


Coming years: more, and more sensitive detectors



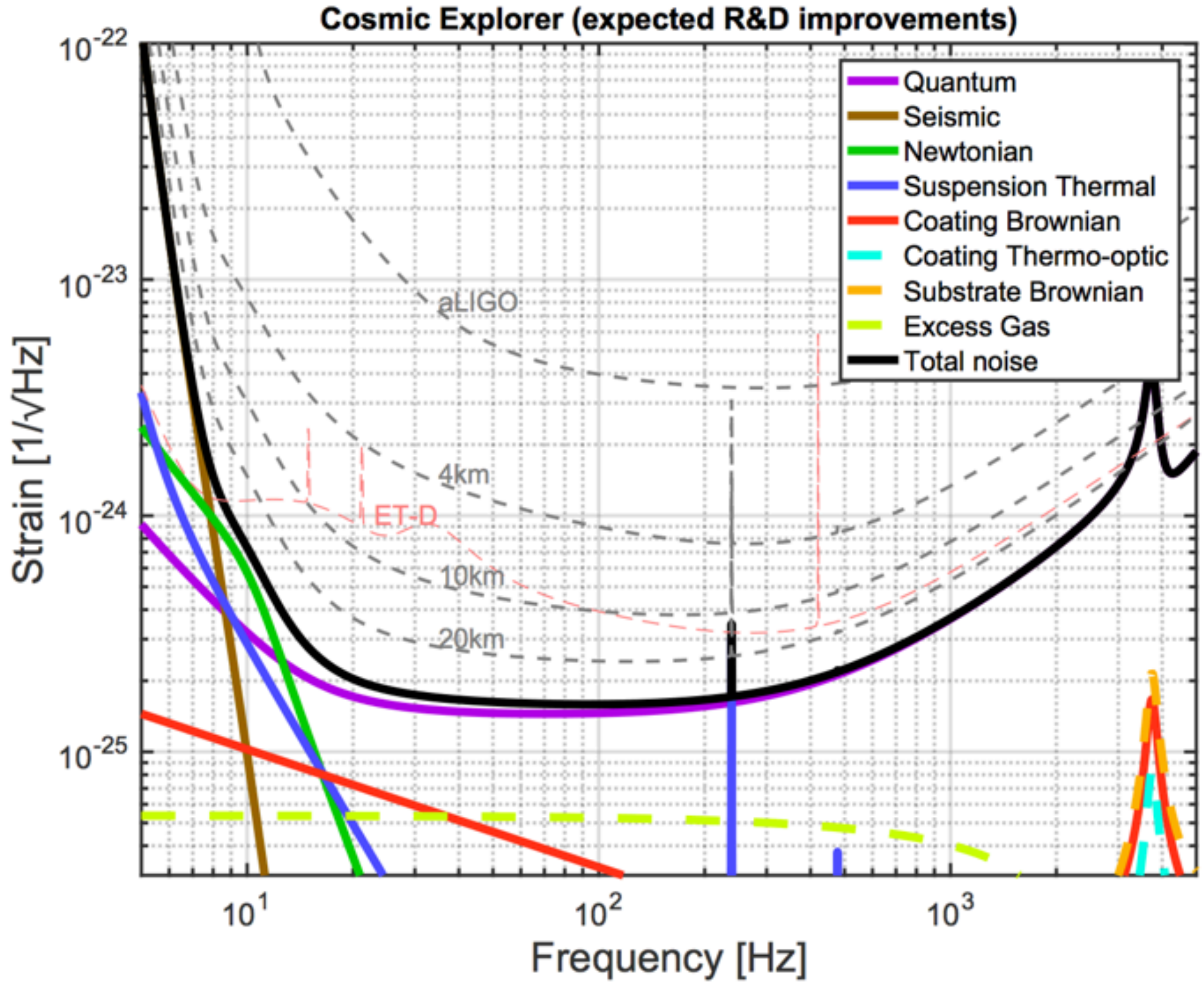
http://ligo.org/detections/GW170817.php

Coming years: more, and more sensitive detectors



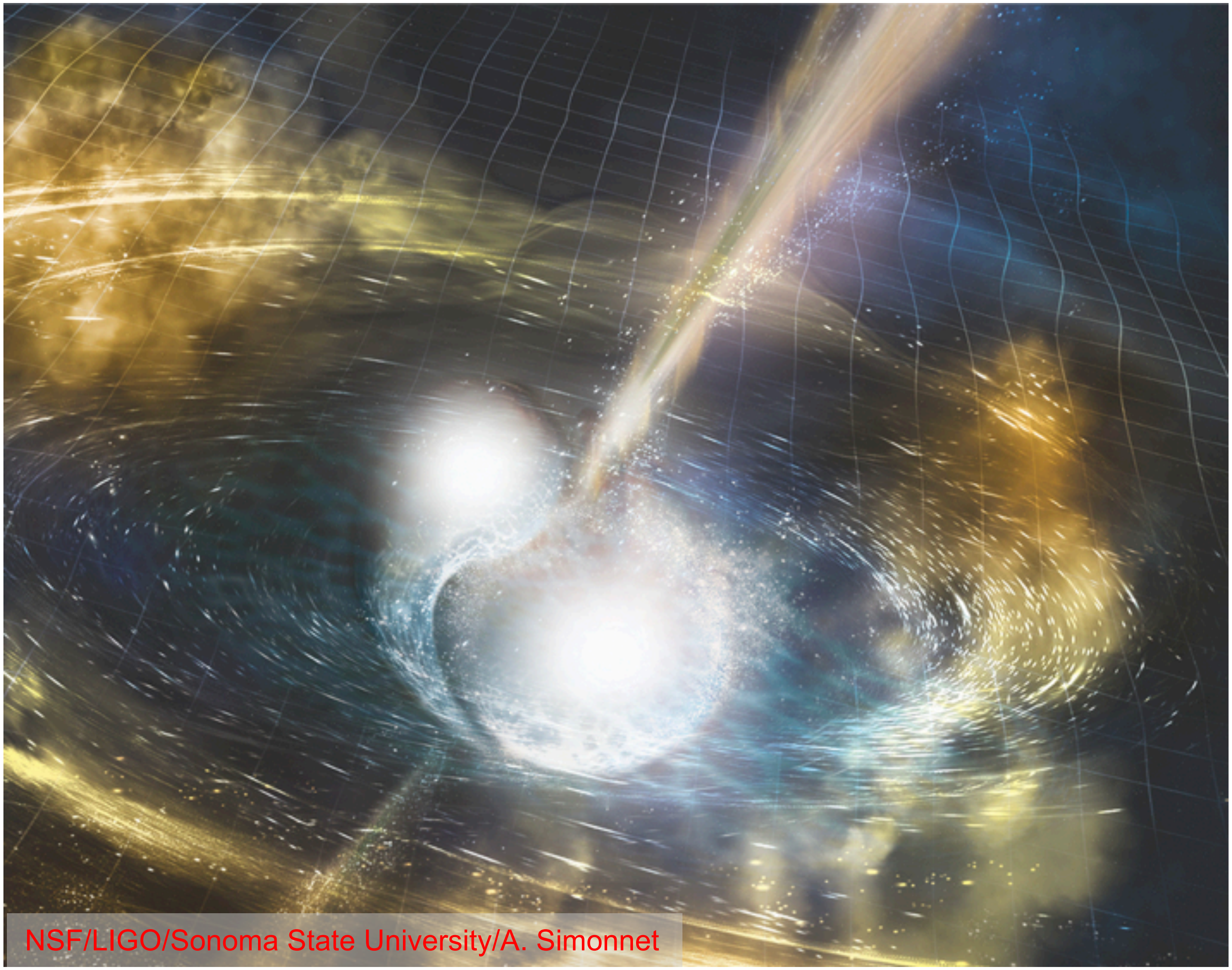
https://arxiv.org/abs/1304.0670

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 bright!



NSF/LIGO/Sonoma State University/A. Simonnet

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!