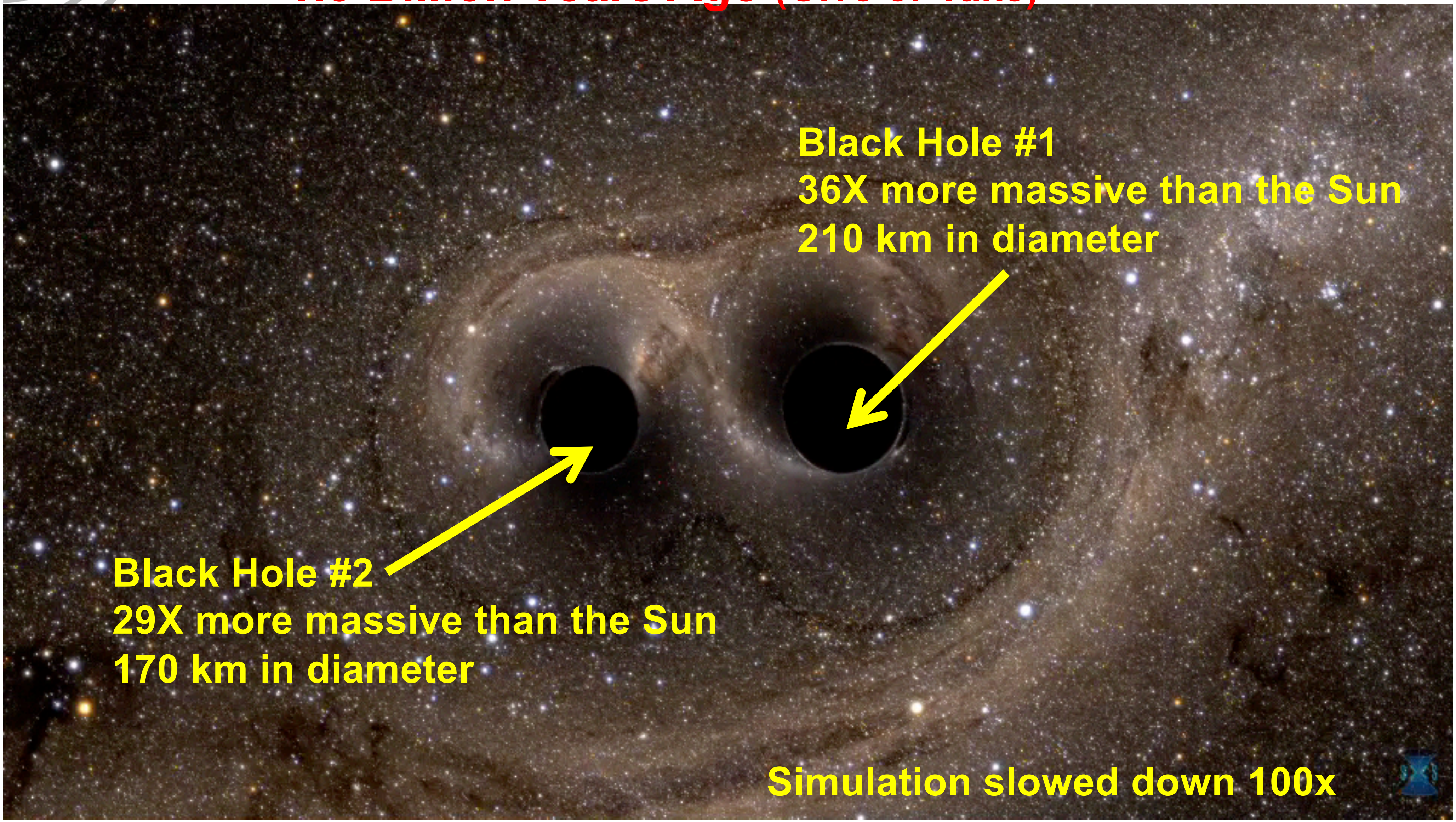
The Ballet of Binary Black Holes 1.3 Billion Years Ago (Give or Take)



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

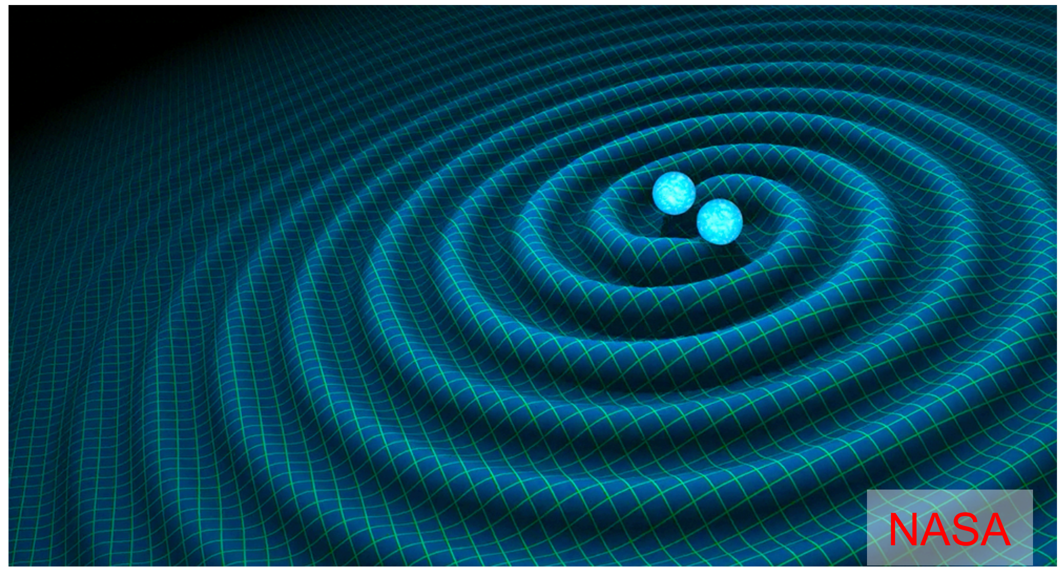
Columbia Physics Colloquium,
Apr 29, 2019

Outline

- Very brief overview of gravitational waves
- Very brief overview of LIGO & Virgo GW detectors
- Where we've been: The O1 / O2 Gravitational-Wave Transient Catalog GWTC-1
- Where we're at: The third LIGO-Virgo observing run
- Where we're heading: The future of GW detection, physics and astrophysics

Gravitational waves

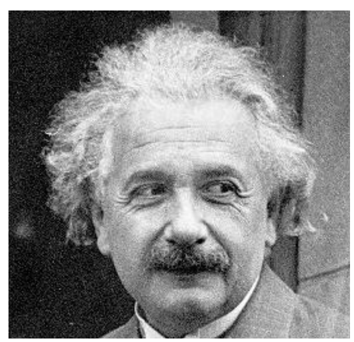
Masses that accelerate
(eg, a binary orbit)
create ripples of changing
gravity (curvature)
in space and time.



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

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

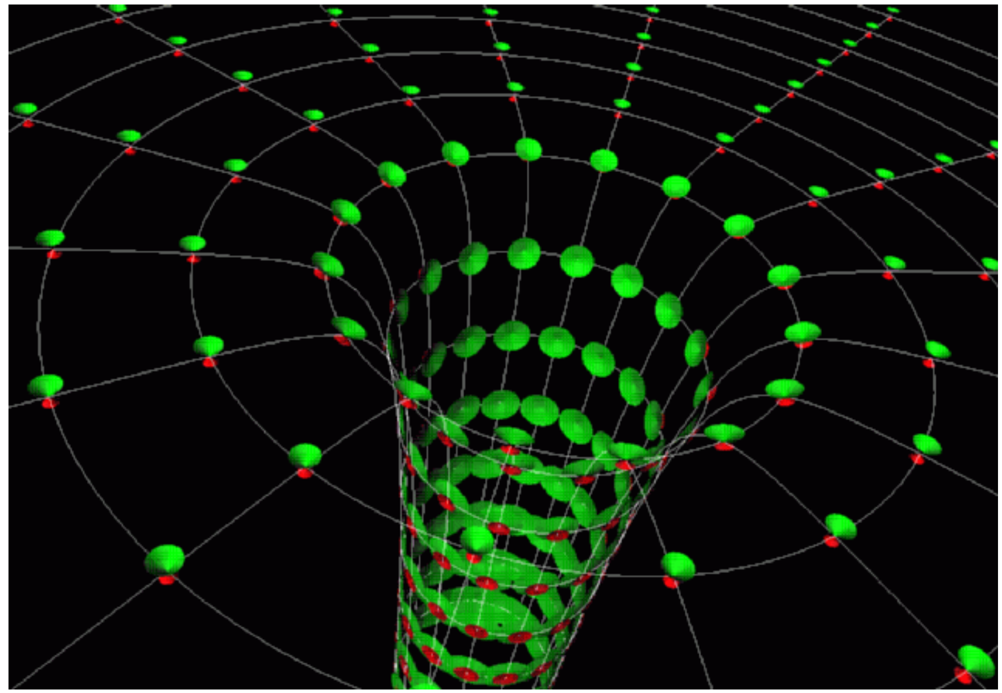
Gravitational waveform can be computed using numerical solutions to ***Einstein's field equations***



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

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

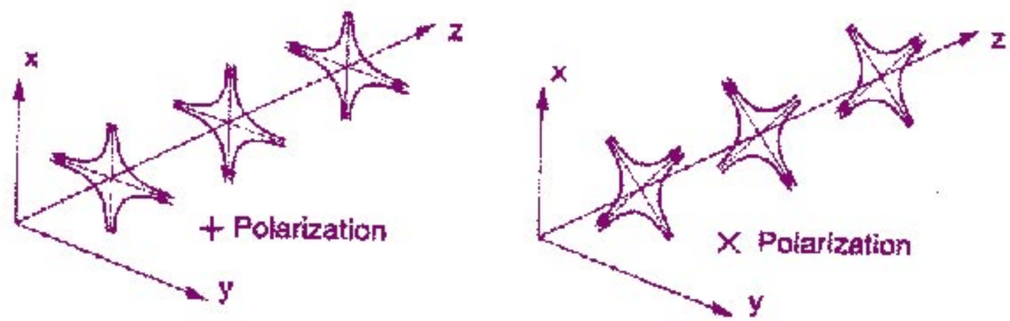
Nature of Gravitational Radiation

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

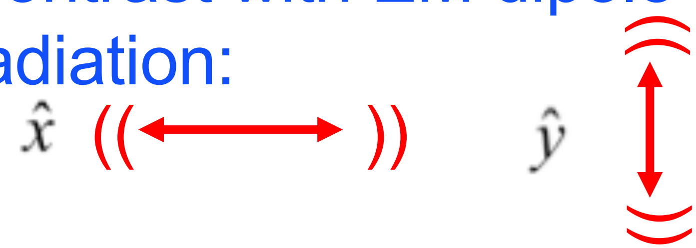
- **Stretches and squeezes space between "test masses" – strain *h = ΔL / L***
- **propagating at speed of light**
  - ***mass of graviton = 0***
- **space-time distortions are transverse to direction of propagation**
- **GW are tensor fields (EM: vector fields) two polarizations: plus (⊕) and cross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

h = ΔL / L

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



Contrast with EM dipole radiation:



Gravitational Waves

$G_{\mu\nu} = 0 \rightarrow$ **Solution for an outward propagating wave in z-direction:**

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

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

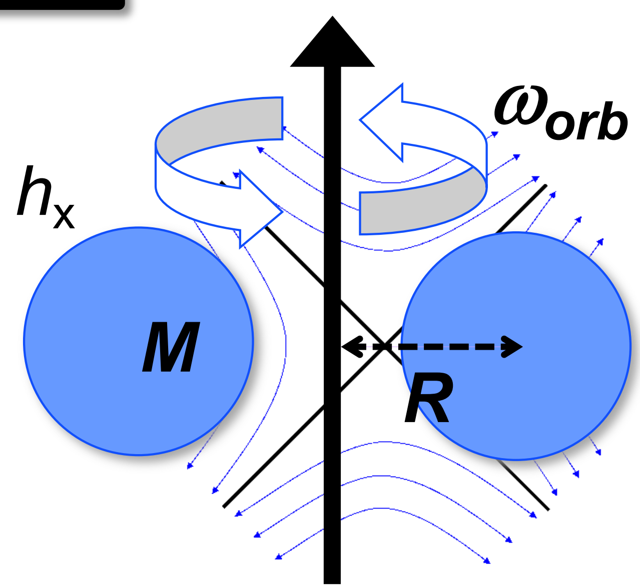
$$h_{\mu\nu} \approx \frac{1}{r}\frac{G}{c^4}\ddot{I}_{\mu\nu}$$

Physically, *h* is a *strain*: ΔL/L

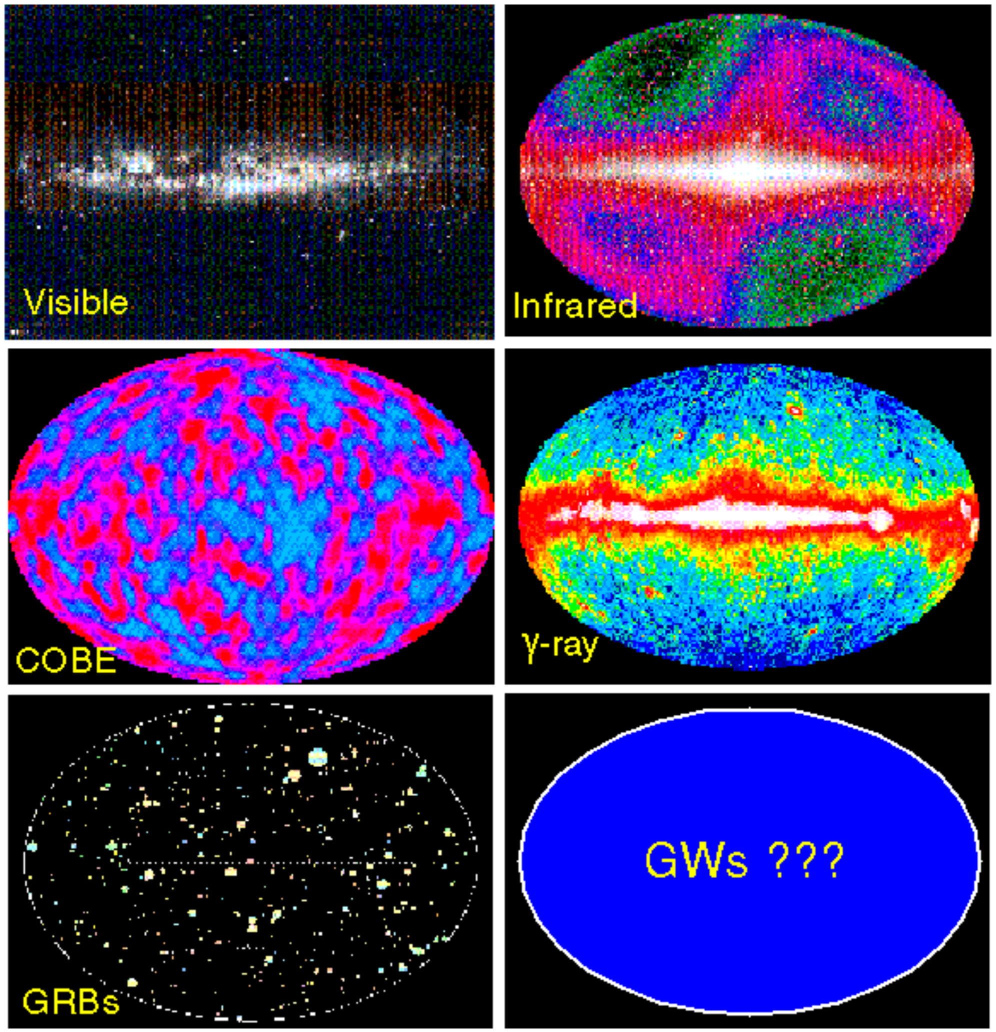
Kepler 3rd: $R^3\ \omega_{orb}^2 = G\ M_{tot}$

h_+

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



A NEW WINDOW ON THE UNIVERSE



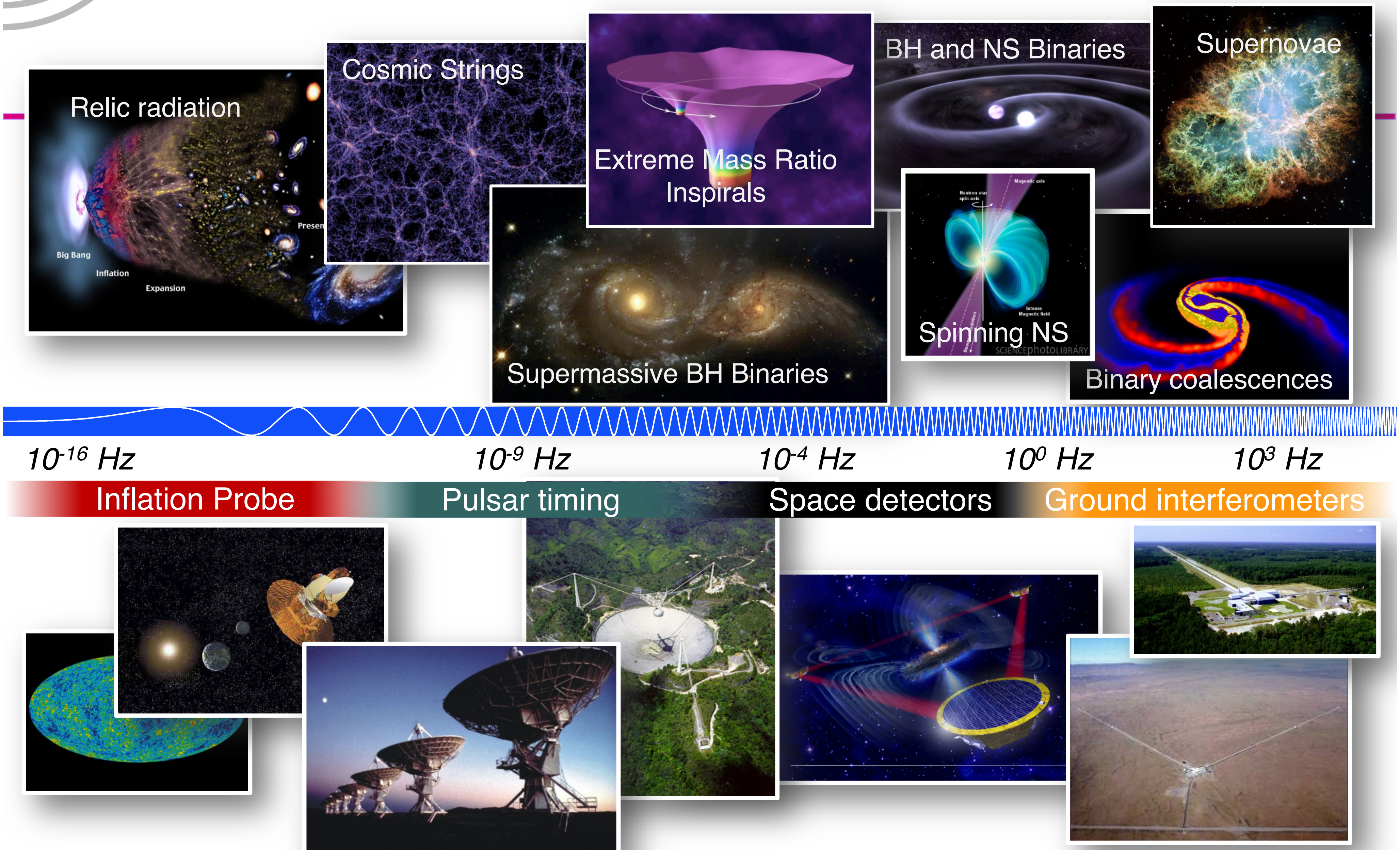
The history of Astronomy: new bands of the EM spectrum opened → major discoveries!

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



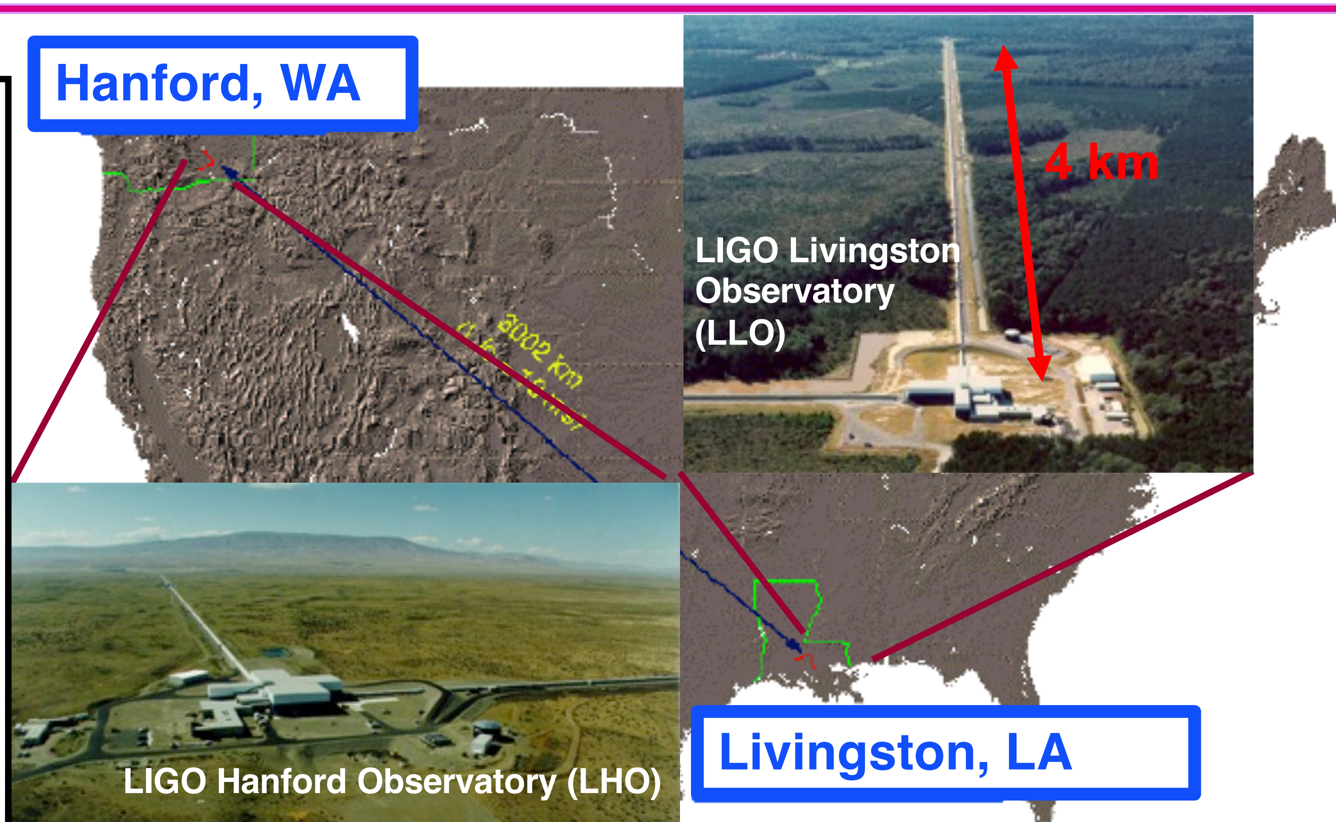
The Laser Interferometer Gravitational Wave Observatory

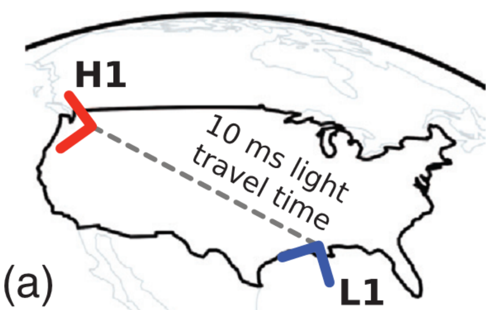
LIGO Laboratory is operated by Caltech and MIT, for the NSF.

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

LIGO Scientific Collaboration:
~ 1200 scientists,
~85 institutions,
15 countries

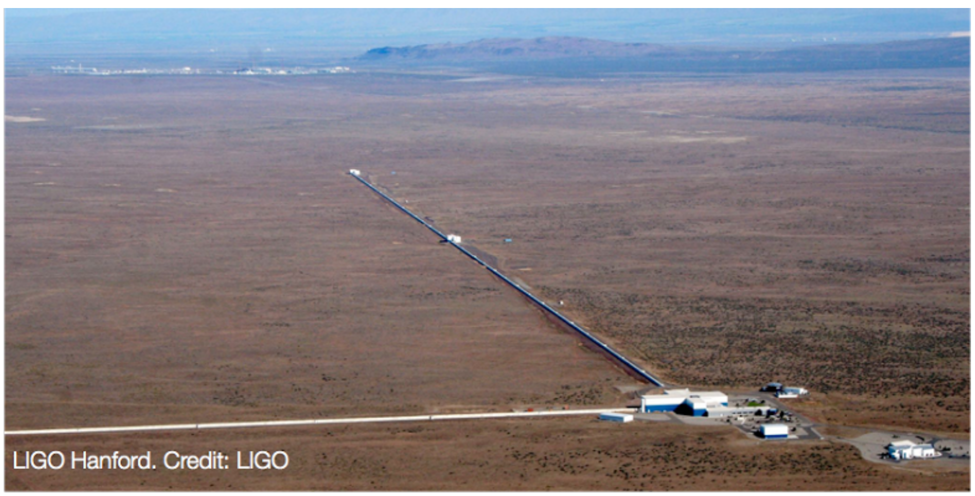
Vigo Collaboration:
~ 250 scientists, Europe





(a)

LIGO-Virgo-GEO Detector network

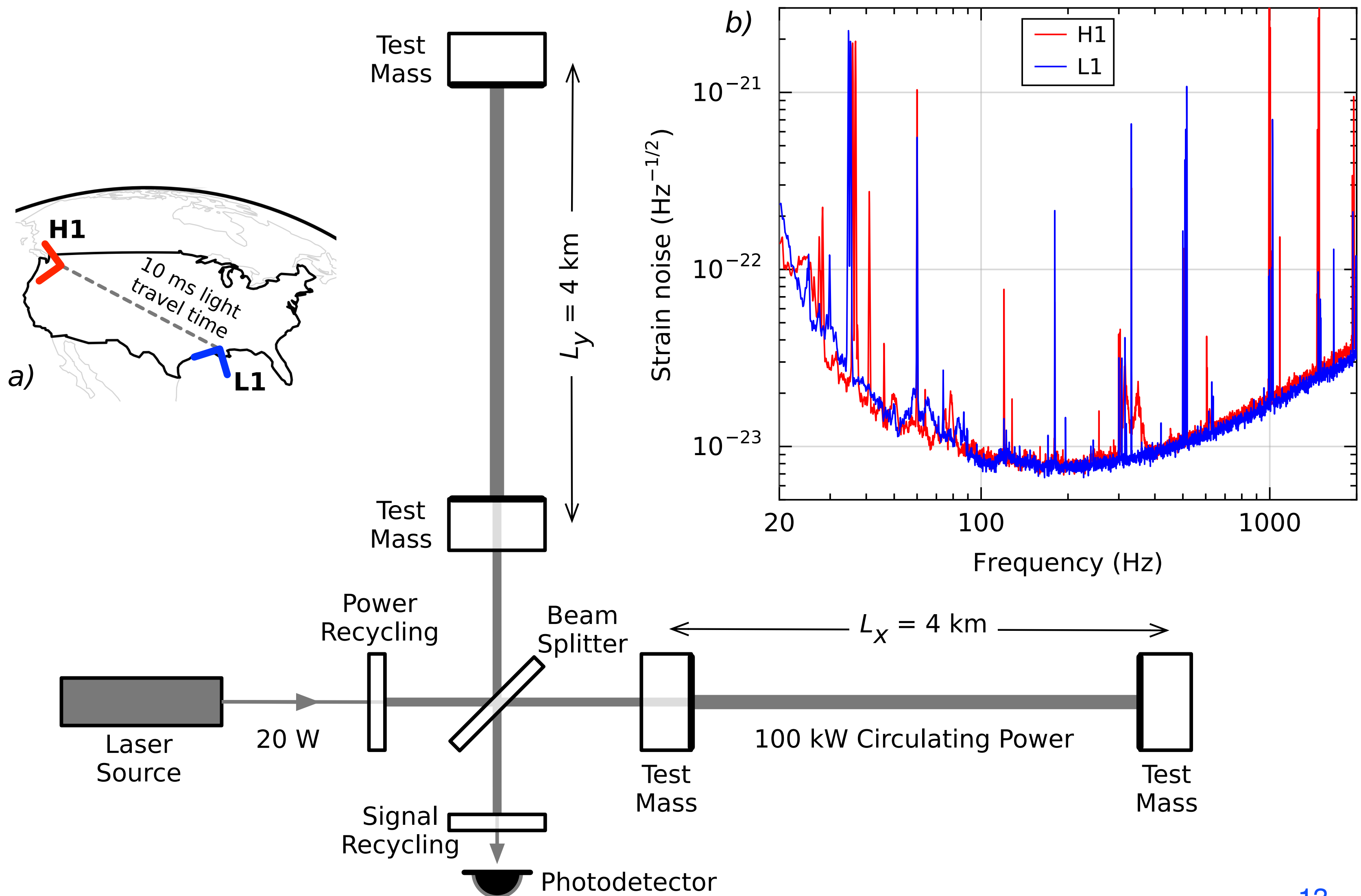


LIGO Scientific Collaboration

LIGO
LSC

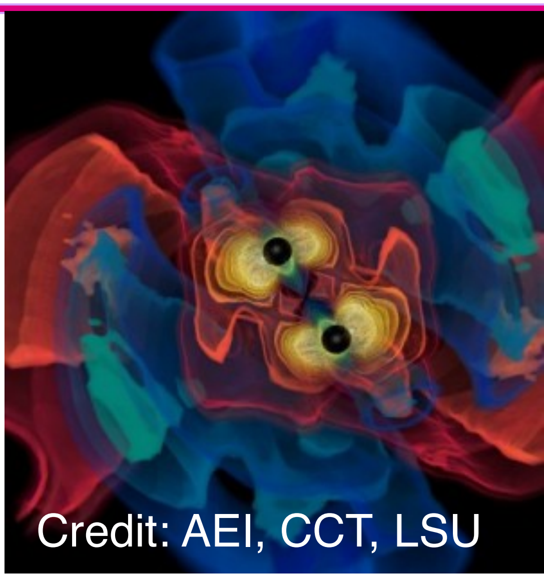
Caltech
American University
Andrews University
Washington State University
California State University Fullerton
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology
Leland Stanford Junior University
The University Of Sheffield.
University of Maryland
indigo
Texas Tech University
PennState
Tsinghua University
Montclair State University
Université de Montréal
Monash University
Max Planck Institute for Gravitational Physics Albert Einstein Institute
International Institute of Physics
Cal State LA
Bellevue College
UIB Universitat de les Illes Balears
University of Cambridge
University of Southampton
Polytechnique Montréal
The University of Adelaide Australia
NCSA
W Bothell
Michigan
Université Libre de Bruxelles
ACU
University of Wisconsin Milwaukee
Trinity University
Australian National University
University of the West of Scotland UWS
University of Oregon
University of Glasgow
Cornell University
Columbia University in the City of New York
Lomonosov Moscow State University
Syracuse University
OzGrav
The University of Western Australia
R·I·T
Eötvös Loránd University Budapest
Sonoma State University
Tsinghua University
Cardiff University Prifysgol Caerdydd
NASA
The University of Chicago
Whitman College
Montana State University
University of Washington
Università degli Studi del Sannio
University of Minnesota
Carleton College
Charles Sturt University
Marshall Space Flight Center
University of Birmingham
King's College London
LSU Louisiana State University
INPE
University of Zurich
UTRGV
University of Strathclyde
The University of Tokyo
Georgia Institute of Technology
Korean Gravitational-Wave Group
ACIGA
Universität Hamburg
Der Forschung | Der Lehre | Der Bildung
University of Szeged
The University of Melbourne
Colorado State University
Hillsdale College
Northwestern
University of Florida
GEO 600
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
Swinburne University of Technology
CITA ICAT
The University of Mississippi
NASA Goddard Space Flight Center

The Advanced LIGO detectors



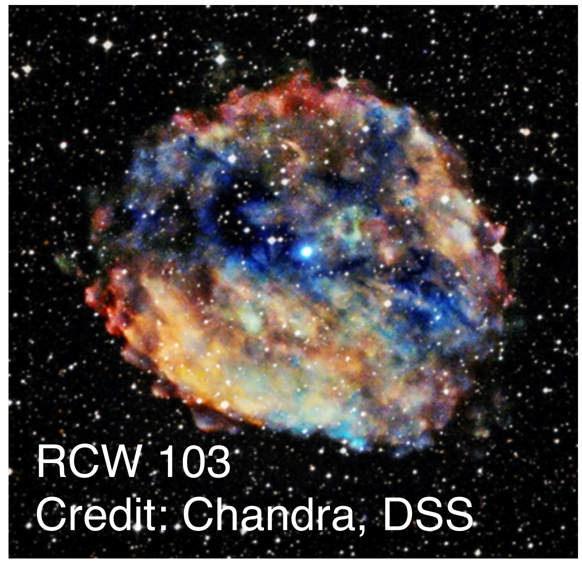
https://dcc.ligo.org/LIGO-P1500237/public/main

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

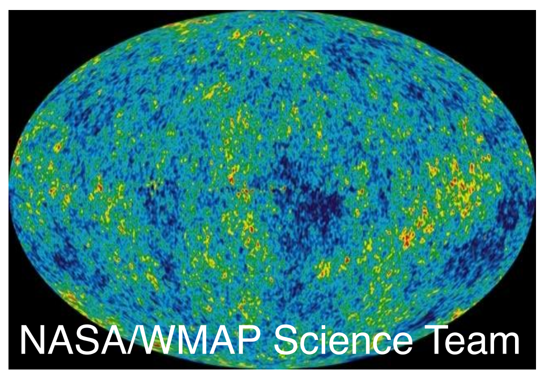


Asymmetric Core Collapse Supernovae

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

Spinning neutron stars

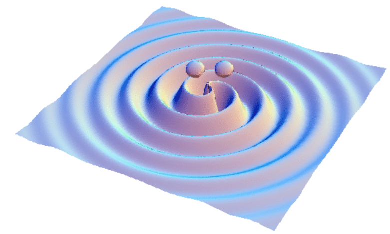
- (effectively) monotonic waveform
- Long duration

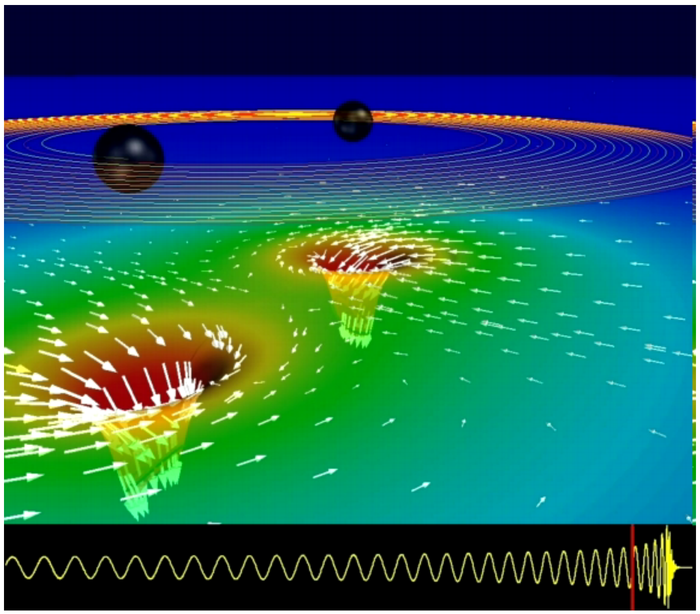


Cosmic Gravitational-wave Background

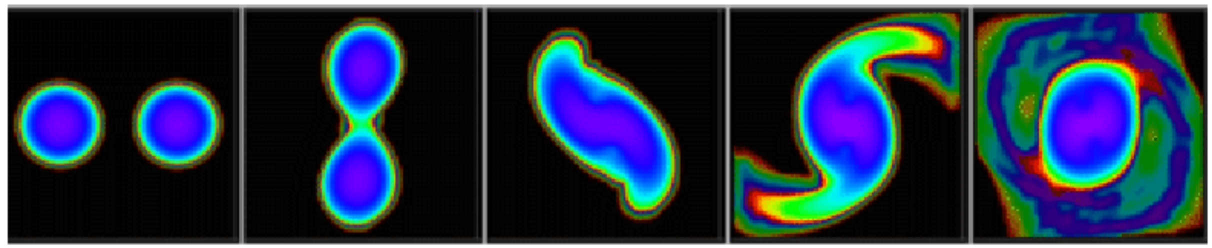
- Residue of the Big Bang, long duration
- Long duration, stochastic background

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





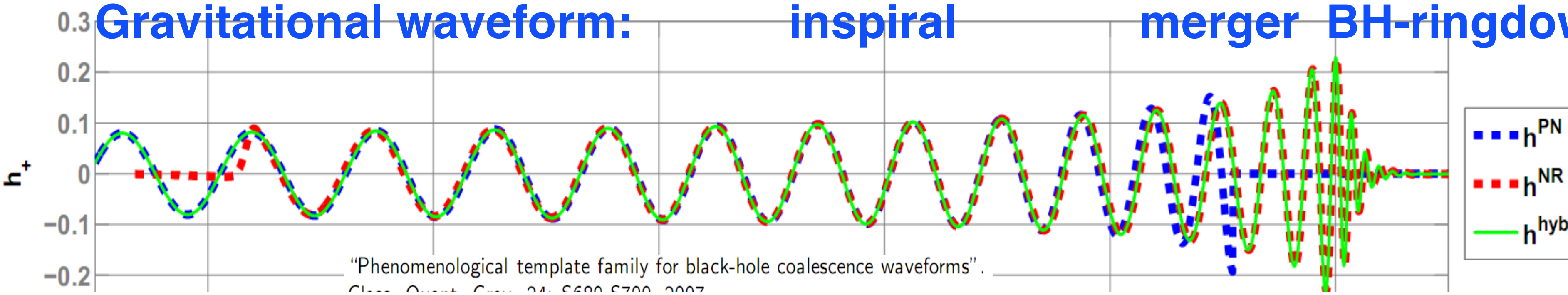
- Neutron star – neutron star (Centrella et al.)



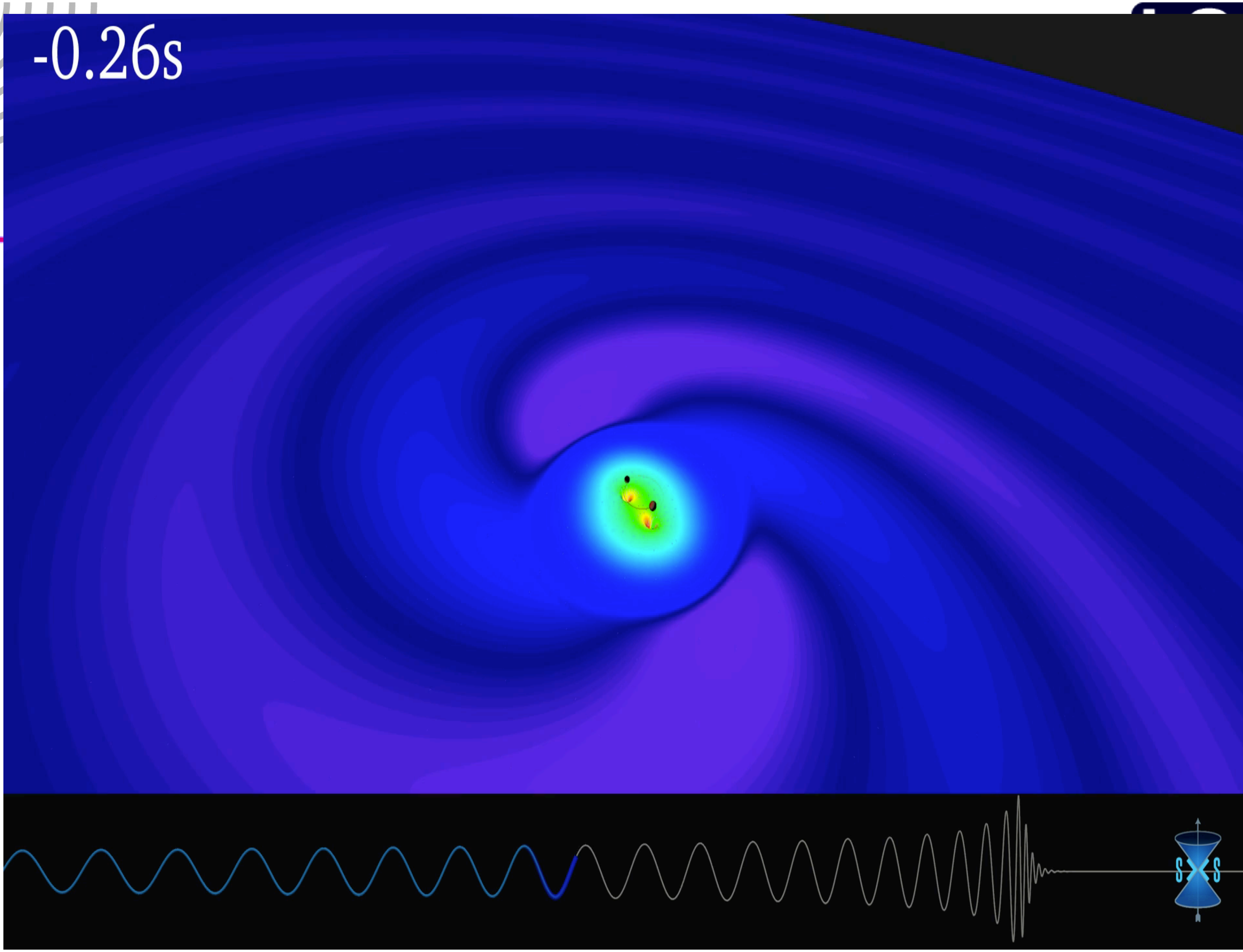
Tidal disruption of neutron star

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



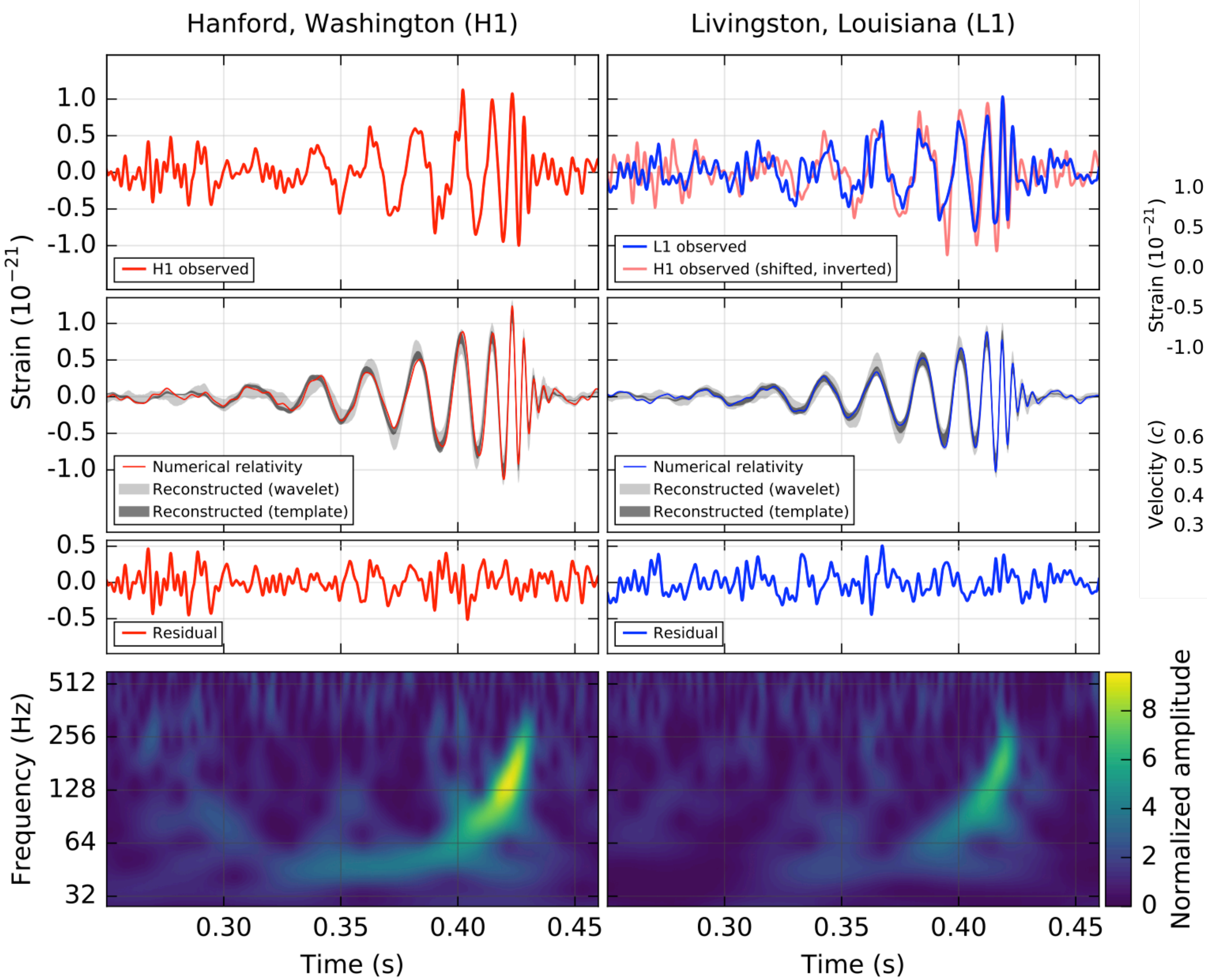
Waveform carries lots of information about binary masses, orbit, merger



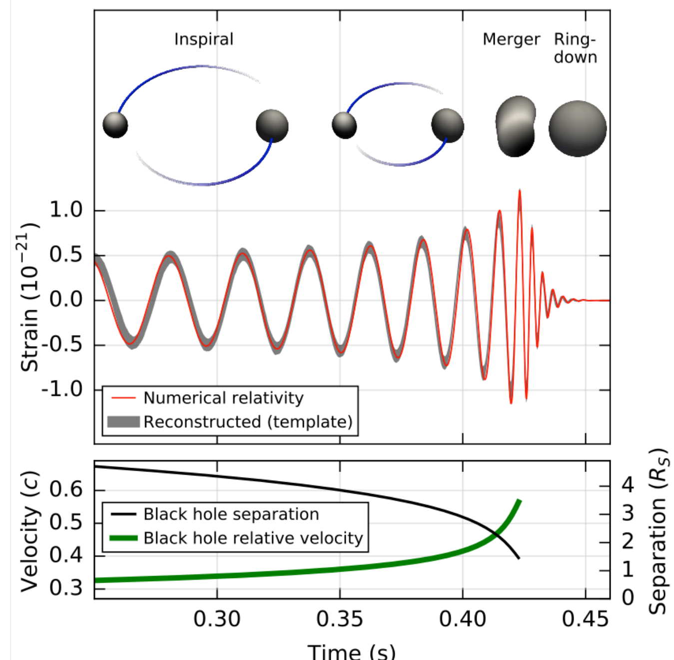
https://www.black-holes.org/explore/movies

GW150914

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



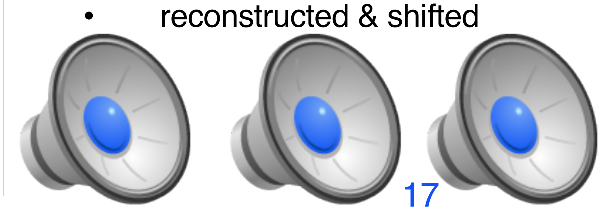
Whitened and band-passed [40-300] Hz



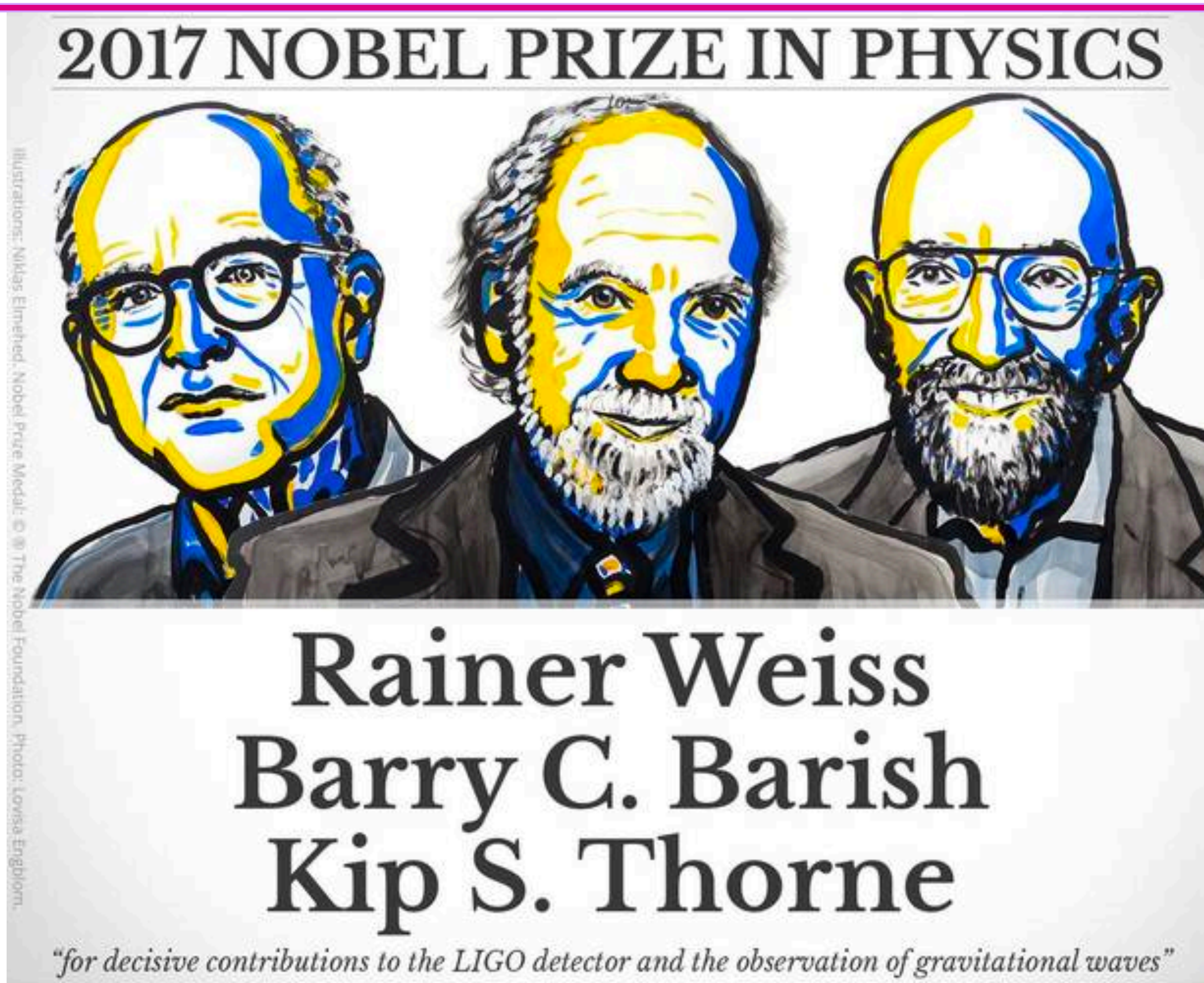
Reconstructed (no whitening)

Audio:

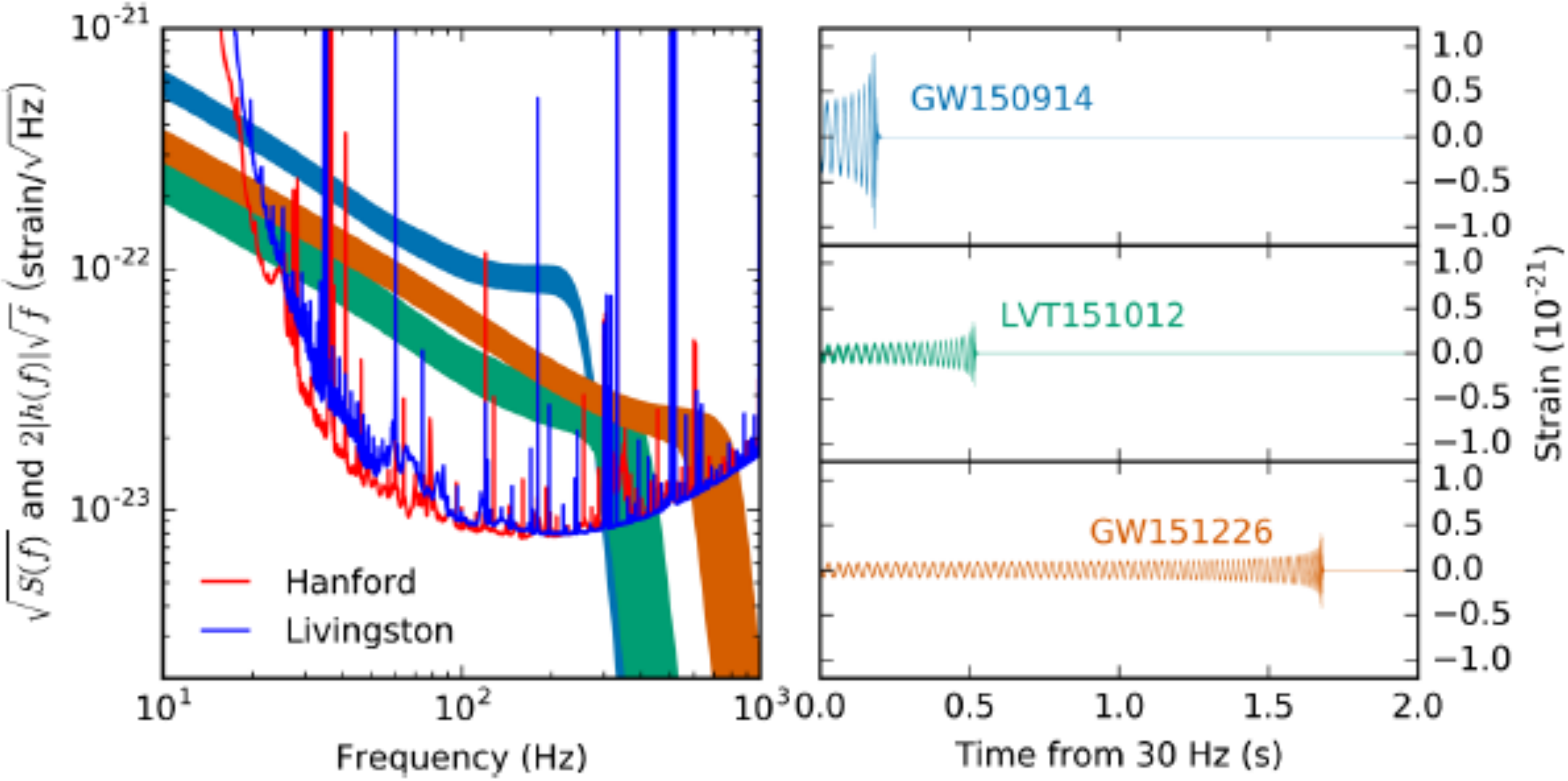
- filtered data
- freq-shifted data
- reconstructed & shifted



Founders of the LIGO project at Caltech and MIT

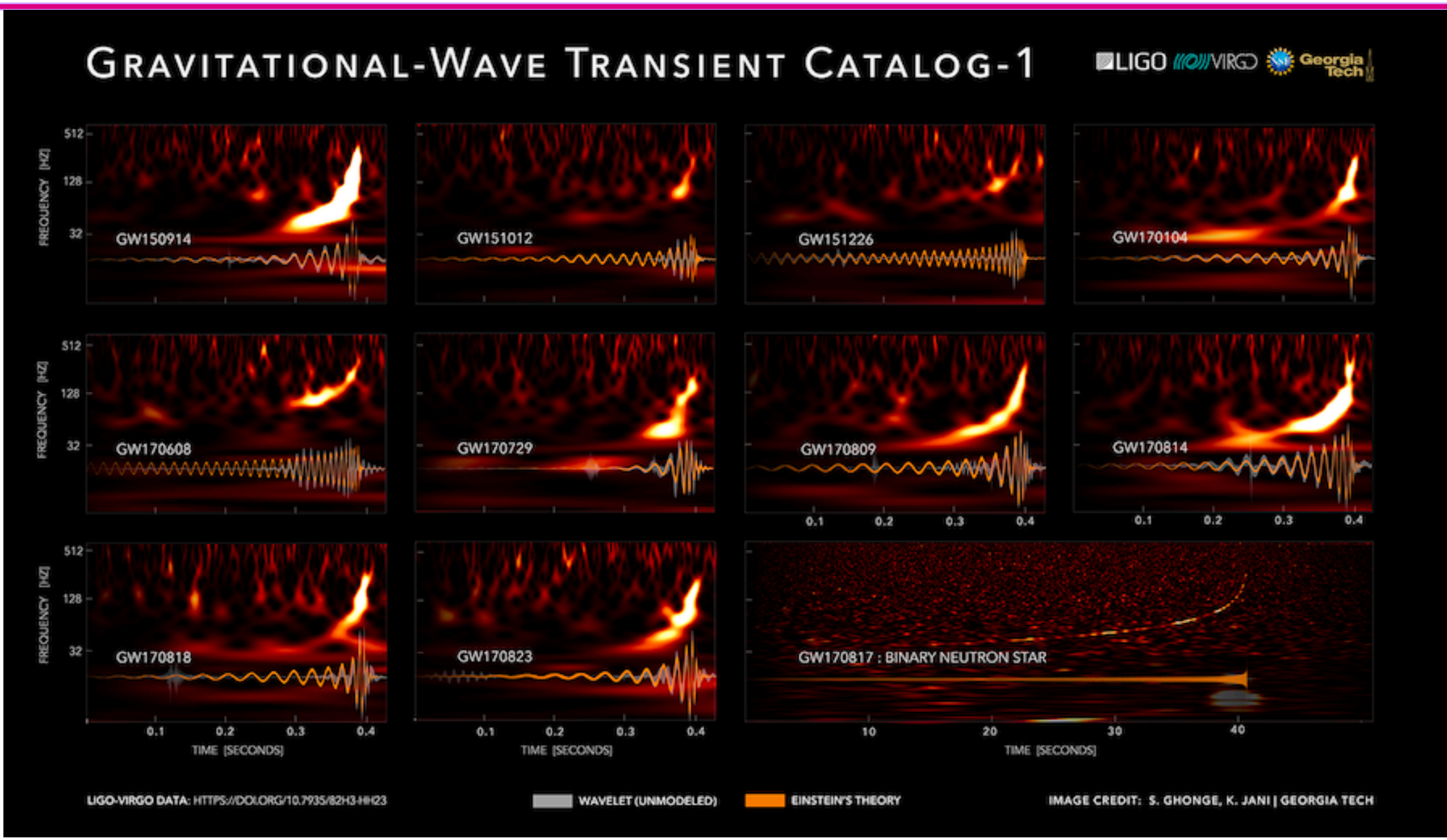


Three BBH events, compared

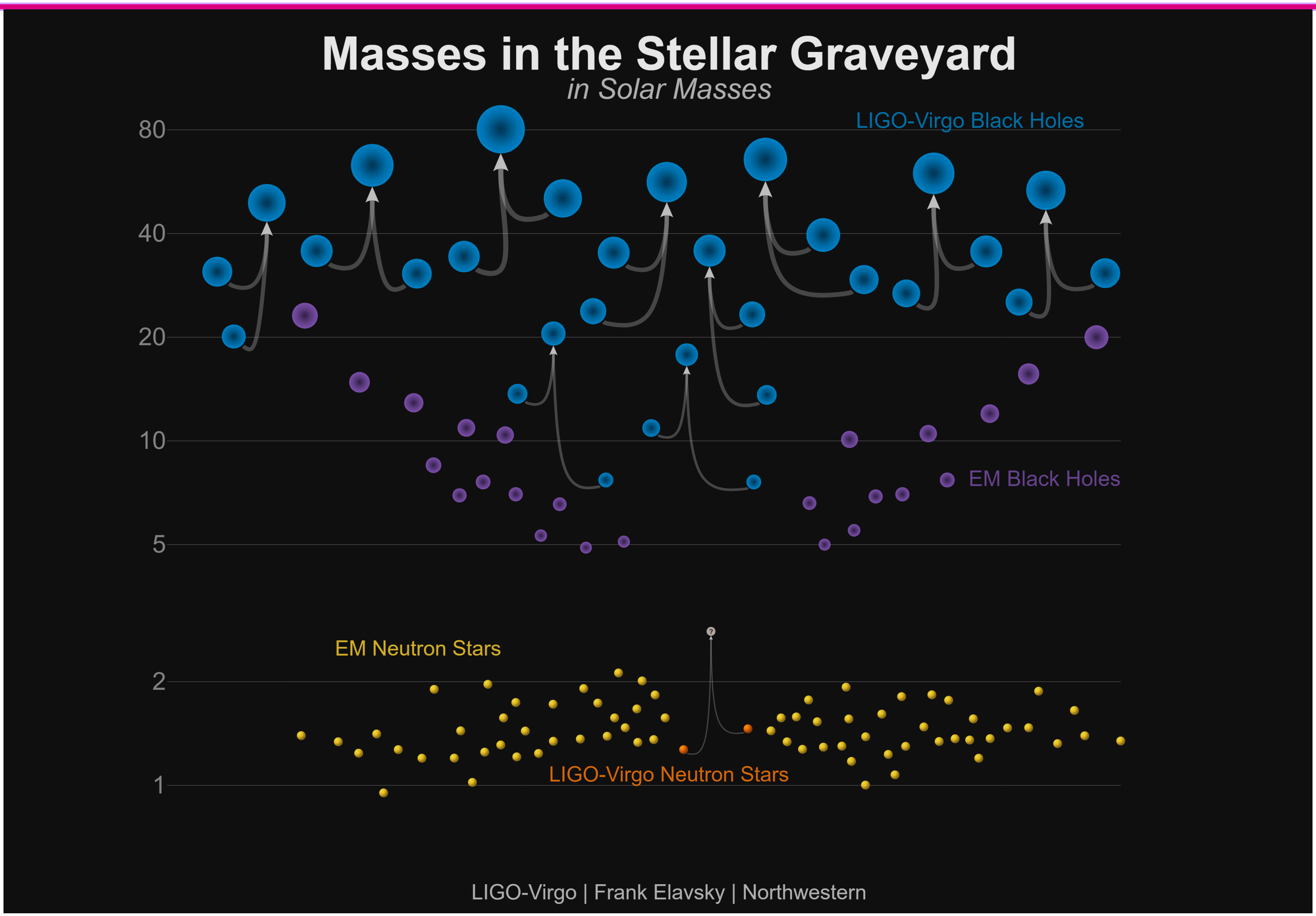


Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", https://arxiv.org/abs/1606.04856, Phys. Rev. X 6, 041015 (2016)

GWTC-1 - #UpToEleven



Starting to build up a mass distribution



Data release - https://www.gw-openscience.org/catalog/

- GWTC-1 strain data, parameter estimation samples, skymaps, …

- Full O1 & O2 strain data

- Tutorial, software
- Detector status
- Event alerts
- Lots more!

Gravitational Wave Open Science Center

Data ▾ Software ▾ Online Status ▾ About GWOSC ▾

Catalog GWTC-1-confident

Confident detections from GWTC-1, the Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs.

Catalog Description

For strain data:
- Click an event name
- Or see the JSON file list.

JSON Parameter Table

Show/hide columns

SORT: EVENT (A-Z)

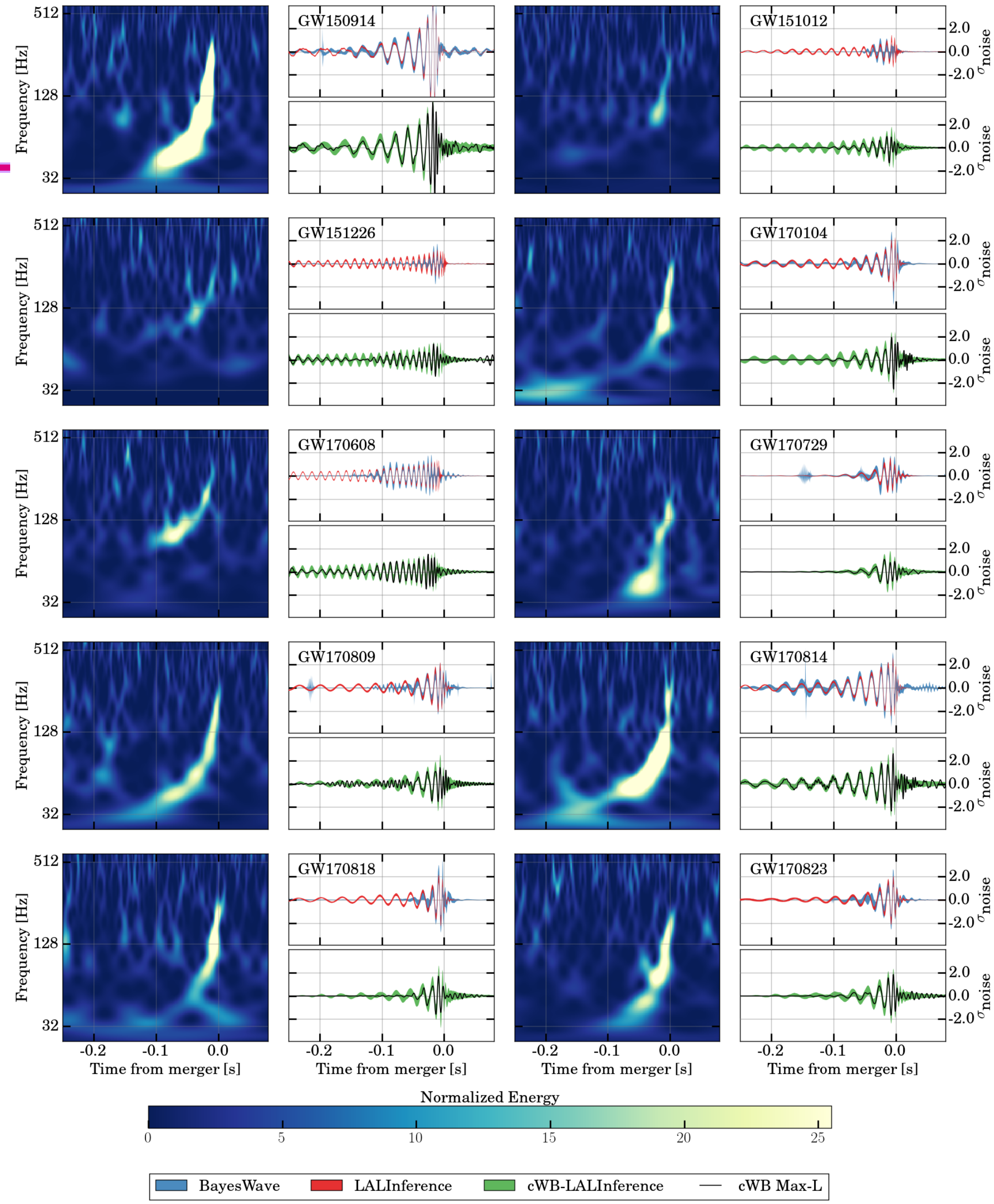
Event	Primary mass (M_sun)	Secondary mass (M_sun)	Effective inspiral spin	chirp mass (M_sun)	Final spin	Final mass (M_sun)	Luminosity distance (Mpc)	GPS time (s)
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$-0.01^{+0.12}_{-0.13}$	$28.6^{+1.6}_{-1.5}$	$0.69^{+0.05}_{-0.04}$	$63.1^{+3.3}_{-3.0}$	430^{+150}_{-170}	1126259462.4
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$0.04^{+0.28}_{-0.19}$	$15.2^{+2.0}_{-1.1}$	$0.67^{+0.13}_{-0.11}$	$35.7^{+9.9}_{-3.8}$	1060^{+540}_{-480}	1128678900.4
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$0.18^{+0.20}_{-0.12}$	$8.9^{+0.3}_{-0.3}$	$0.74^{+0.07}_{-0.05}$	$20.5^{+6.4}_{-1.5}$	440^{+180}_{-190}	1135136350.6
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$-0.04^{+0.17}_{-0.20}$	$21.5^{+2.1}_{-1.7}$	$0.66^{+0.08}_{-0.10}$	$49.1^{+5.2}_{-3.9}$	960^{+430}_{-410}	1167559936.6
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$0.03^{+0.19}_{-0.07}$	$7.9^{+0.2}_{-0.2}$	$0.69^{+0.04}_{-0.04}$	$17.8^{+3.2}_{-0.7}$	320^{+120}_{-110}	1180922494.5
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$0.36^{+0.21}_{-0.25}$	$35.7^{+6.5}_{-4.7}$	$0.81^{+0.07}_{-0.13}$	$80.3^{+14.6}_{-10.2}$	2750^{+1350}_{-1320}	1185389807.3
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$0.07^{+0.16}_{-0.16}$	$25.0^{+2.1}_{-1.6}$	$0.70^{+0.08}_{-0.09}$	$56.4^{+5.2}_{-3.7}$	990^{+320}_{-380}	1186302519.8
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$0.07^{+0.12}_{-0.11}$	$24.2^{+1.4}_{-1.1}$	$0.72^{+0.07}_{-0.05}$	$53.4^{+3.2}_{-2.4}$	580^{+160}_{-210}	1186741861.5
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$0.00^{+0.02}_{-0.01}$	$1.186^{+0.001}_{-0.001}$	≤ 0.89	≤ 2.8	40^{+10}_{-10}	1187008882.4
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$-0.09^{+0.18}_{-0.21}$	$26.7^{+2.1}_{-1.7}$	$0.67^{+0.07}_{-0.08}$	$59.8^{+4.8}_{-3.8}$	1020^{+430}_{-360}	1187058327.1
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$0.08^{+0.20}_{-0.22}$	$29.3^{+4.2}_{-3.2}$	$0.71^{+0.08}_{-0.10}$	$65.6^{+9.4}_{-6.6}$	1850^{+840}_{-840}	1187529256.5

Waveform reconstructions

- Model-independent (burst) waveform reconstructions.
- Capable of capturing unmodeled features (HOMs, eccentricity, tidal distortion, beyond-GR effects).
- BayesWave:

  sum of sine-Gaussian wavelets $h(\vec{\lambda};t) = \sum_{j=1}^{N} \Psi(\vec{\lambda}_j;t)$

  with parameters $\vec{\lambda}$ determined from MCMC.
- Coherent WaveBurst (cWB): extract coherent (signal) part of h(t) from H, L.
- Only capable of picking out portions of waveform with significant SNR.
- By contrast, model-dependent (template-based) extraction integrates full SNR, even when buried in noise (as in GW170817).
- Broad, semi-quantitative agreement with GR model from LALinference



The LIGO / Virgo Observing Run 3 (O3) began on April 1, 2019

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | LATEST | DOCUMENTATION | LOGIN

Latest — as of 27 April 2019 20:53:46 UTC

Public!

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

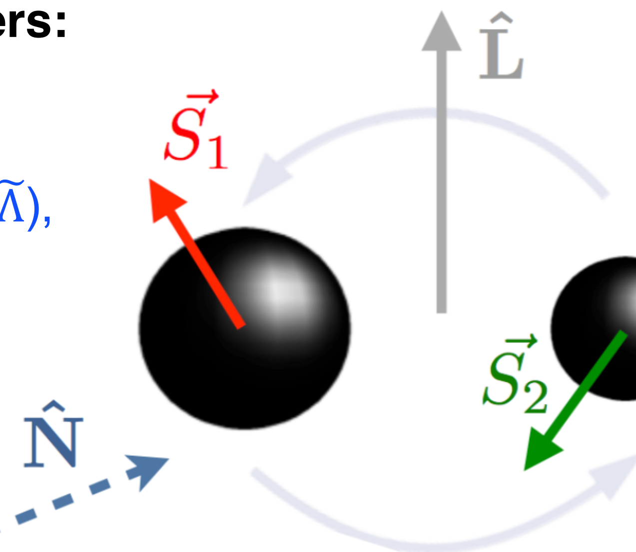
Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190426c	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT ADVOK	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	DQOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY ADVOK GCN_PRELIM_SENT PE_READY	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVNO	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

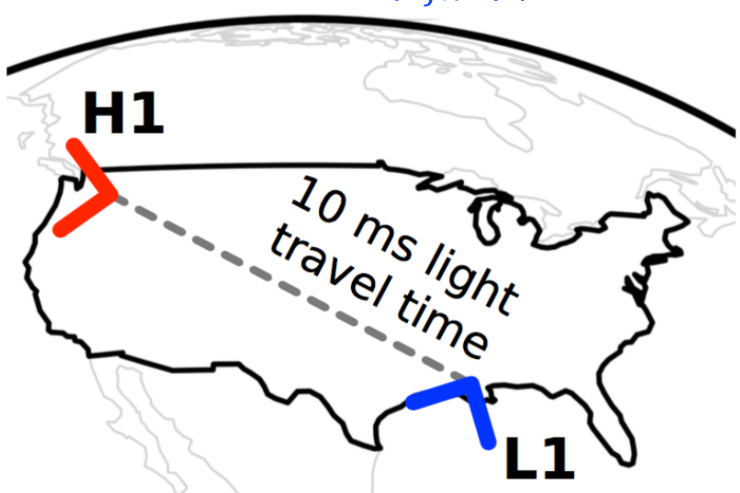
- Possible BH-NS event (😂)
- Possible BNS event (😁)
- Three BBH events (😑)
- Mistake (😖)

Binary merger Model parameters

Intrinsic parameters:
masses (m_1, m_2) ,
spins $(\vec{S}_1, \vec{S}_2)$,
tidal deformability $(\tilde{\Lambda})$,
eccentricity



Extrinsic parameters:
time (t_c), reference phase (φ_c),
sky position (α, δ), distance (d_L),
orbital orientation (θ_{Jn}, ψ),



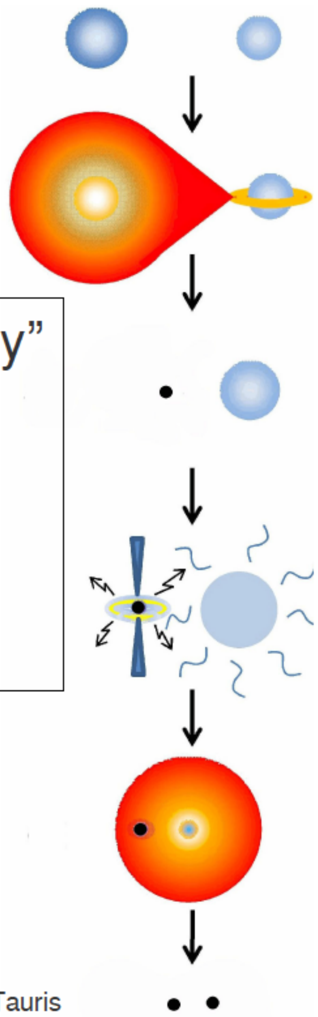
Spin magnitudes and orientations, eccentricity, … tell us something about how these binaries formed

Credit: LIGO/Virgo

Formation channels

https://dcc.ligo.org/LIGO-P1500262/public/main

Isolated binary



“ordinary”
or
rapid
rotation
or
PopIII

5 Fig. after Tauris

Dynamical formation

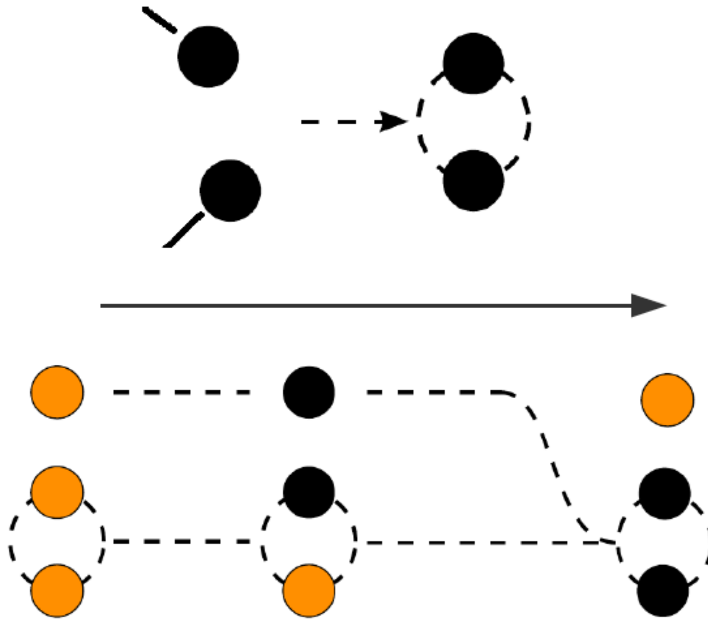
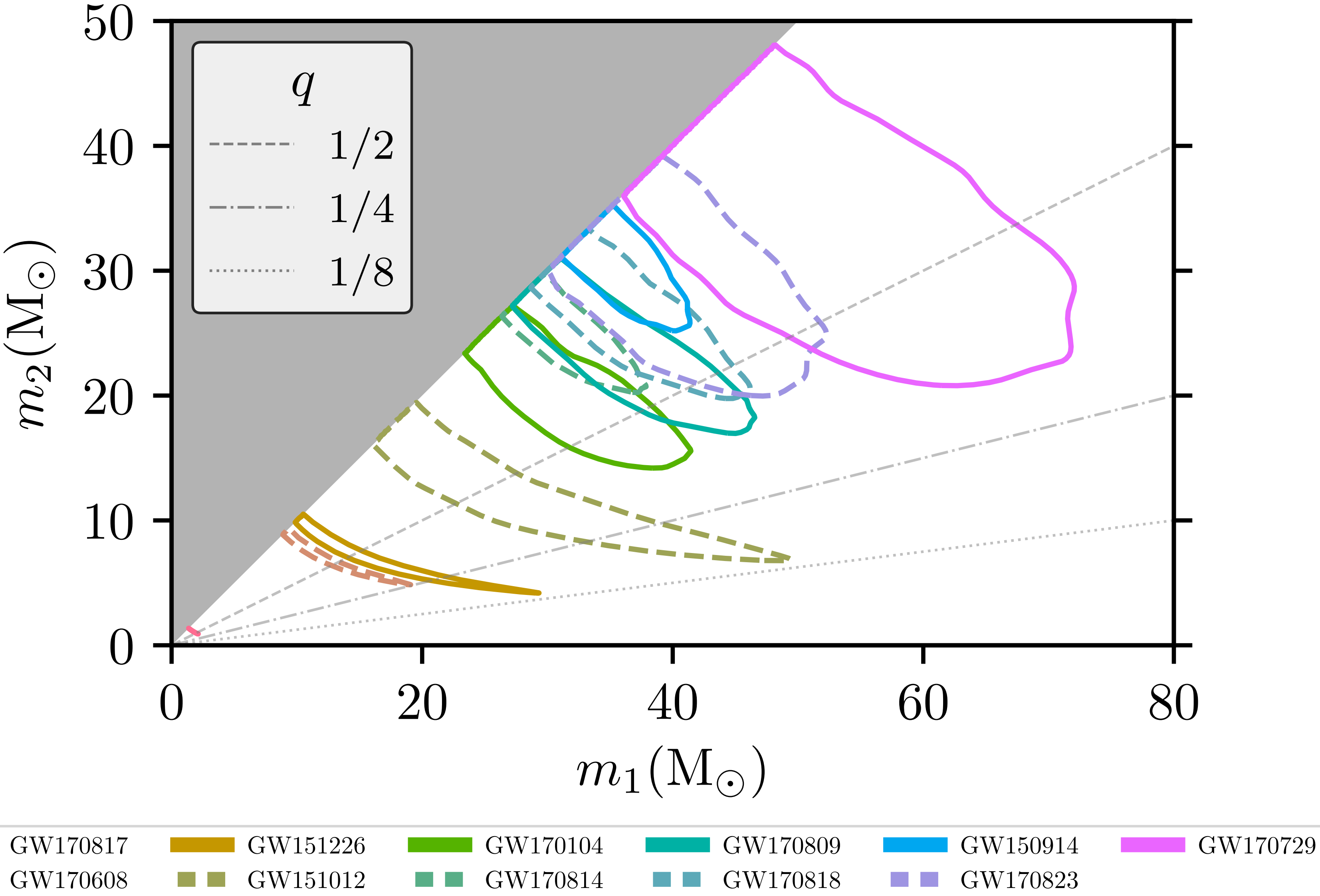


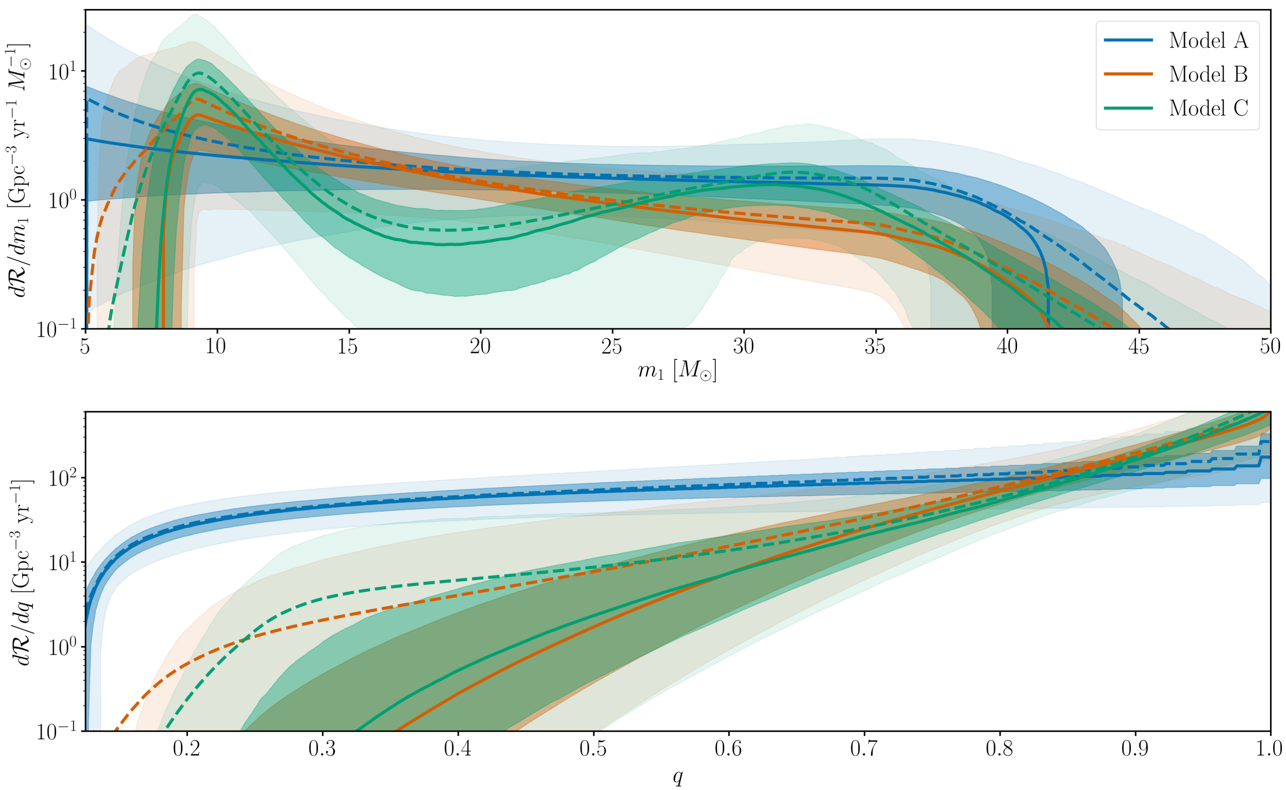
Fig. after Ziosi

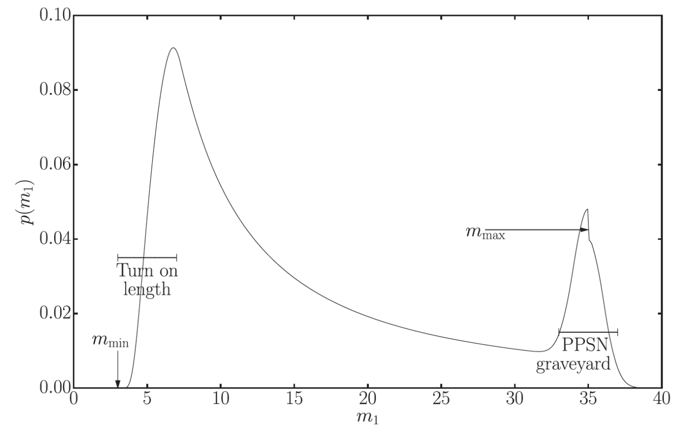
Globular/young clusters/gal. nuclei

Component masses



Mass distributions, 10 BBH events



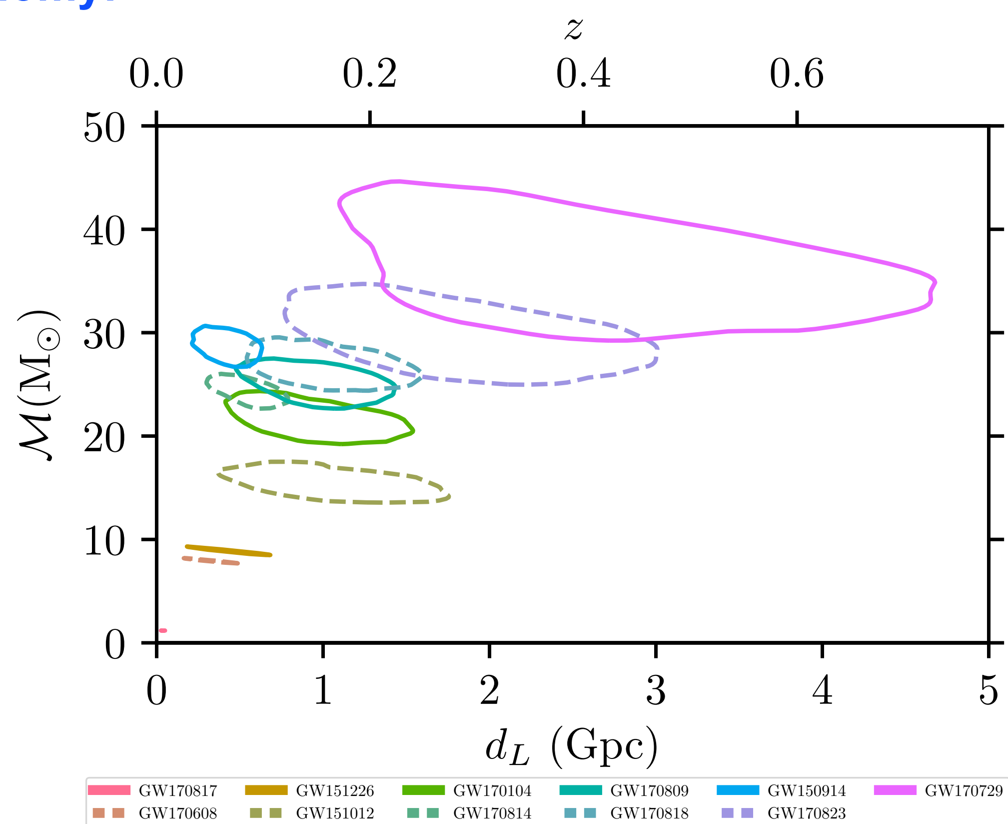


Projection by
Talbot & Thrane (2018)
arXiv:1801.02699

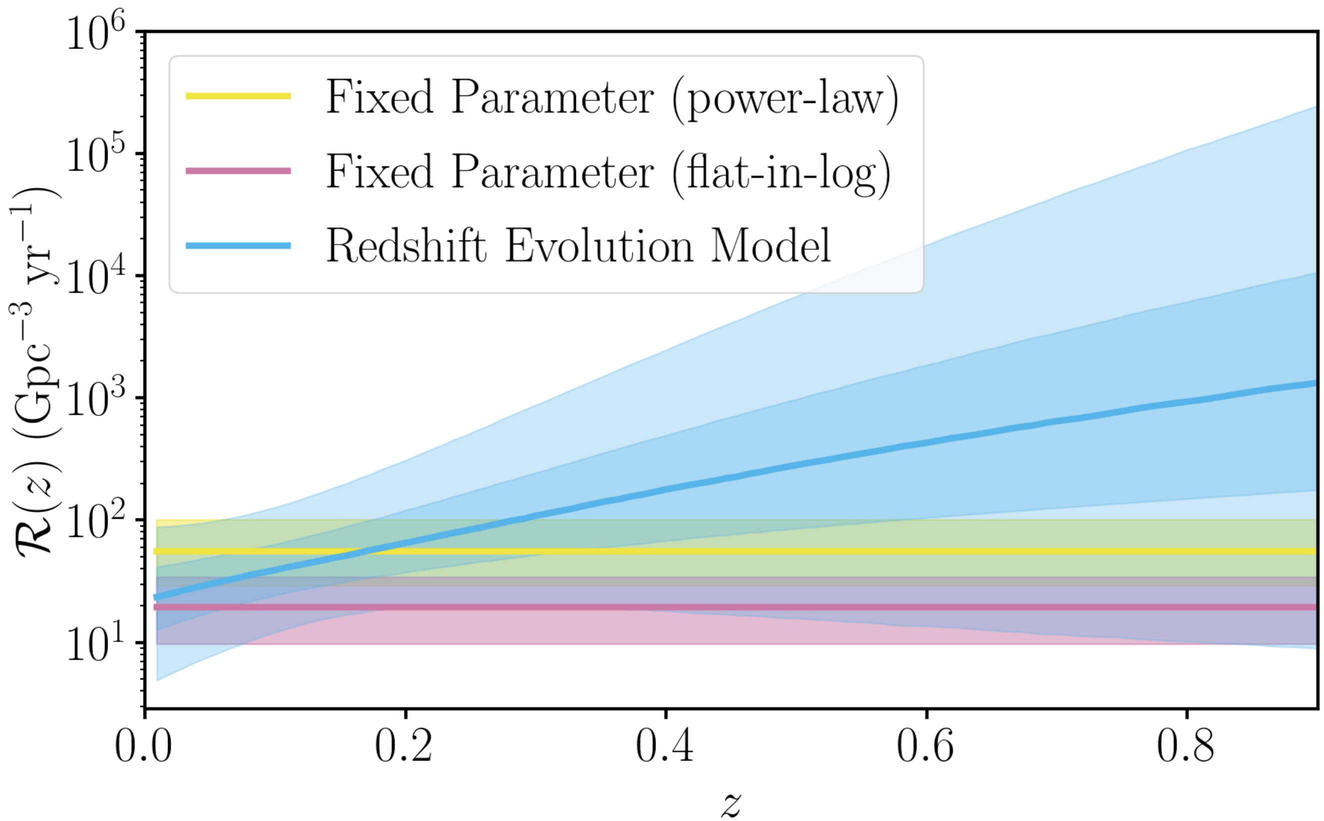
LVC: https://arxiv.org/abs/1811.12940 (2018)

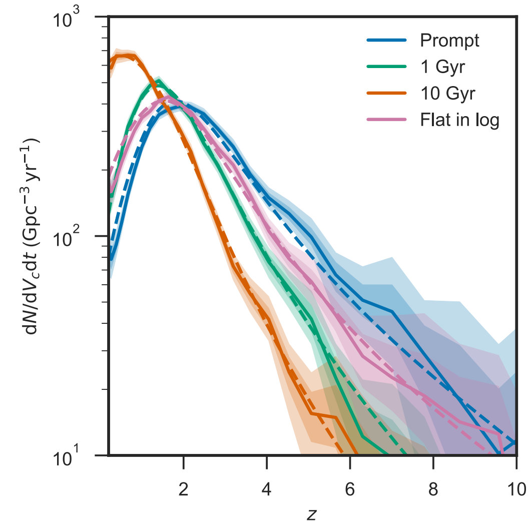
Distances, redshift, lensing

- **It's hard to measure distances in astronomy! (few "standard candles")**
- **BBH events are "standardizable sirens" (need to know their sky location, masses, orbital orientation, etc).**
  - **The more distance sources have red-shifted waveforms ⇒ redshifted masses!**
- **Distances measured poorly with only two detectors.**
- **Our most massive and distant events are at cosmological distances**
  - **GW170729 merged more than 6 By ago!**
- **These signals *may* have been (de-)magnified by gravitational lensing … we may not be measuring their distances (or masses) at all!**



Evolution of merger rate with redshift z





Projection by
Vitale S and Farr W
arxiv:1808.00901

$$\frac{dR}{dm_1 dm_2}(z) = R_0 p(m_1, m_2 \mid \alpha, m_{\max})(1+z)^{\lambda}$$

- No evidence (yet) of evolution with redshift

LVC: https://arxiv.org/abs/1811.12940 (2018)

Radiated energy & luminosity

- GW150914:

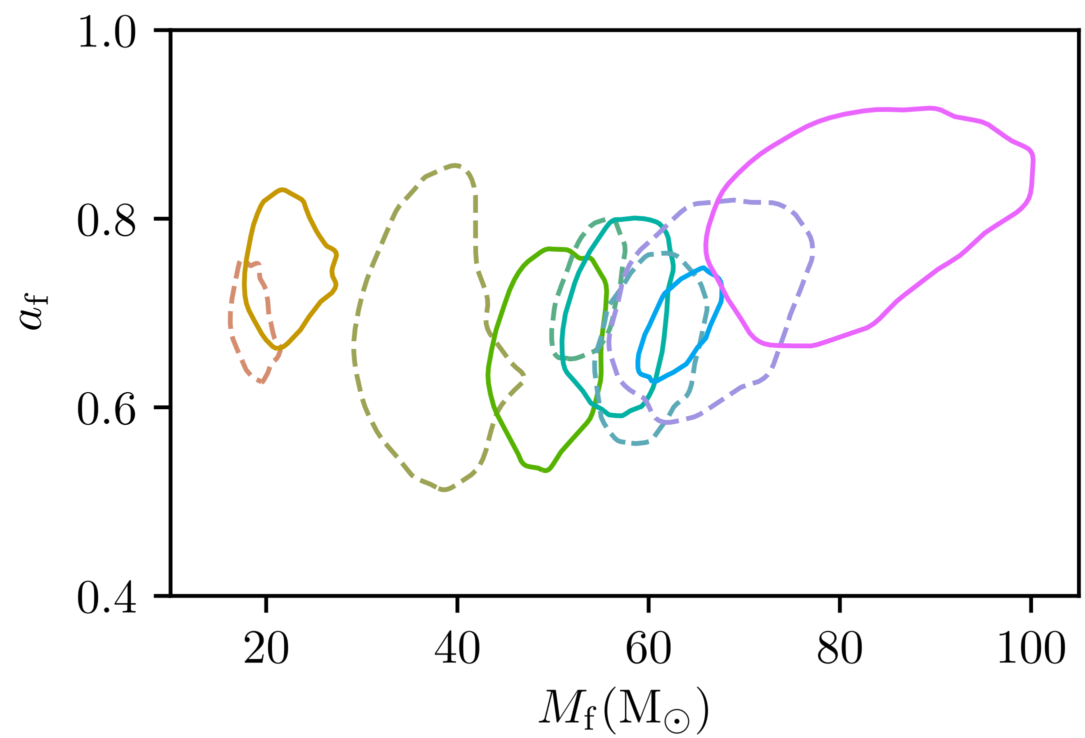
$$E_{\rm rad} = 3.0^{+0.5}_{-0.4}\,{\rm M}_\odot c^2$$
$$\ell_{\rm peak} = 3.6^{+0.5}_{-0.4} \times 10^{56} {\rm erg/s}$$

- GW151226:

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

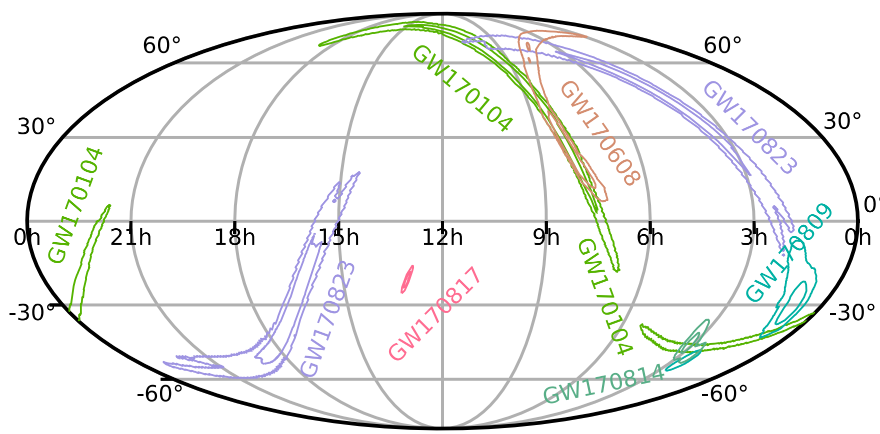
- LVT151012:

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

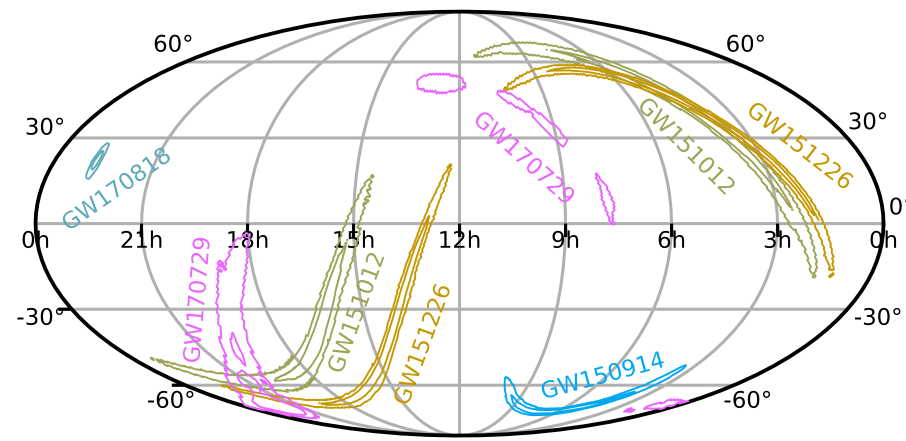


- GW150914: $E_{GW} \approx 3\ M_\odot c^2$, or ~4.5% of the total mass-energy of the system.
- Roughly 10^{80} gravitons.
- Peak luminosity $L_{GW} \sim 3.6 \times 10^{54}$ *erg/s*, briefly outshining the EM energy output of all the stars in the observable universe (by a factor ~ 50).

Sky localization



O2 GW events for which alerts were sent to EM observers.

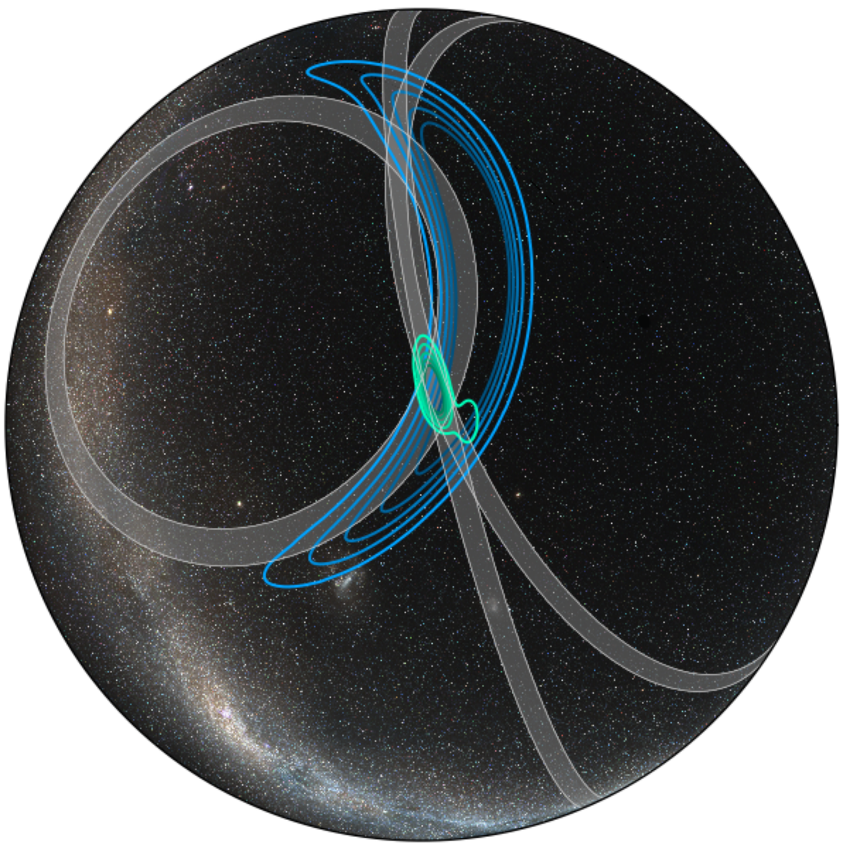


O1 events along with O2 events (GW170729, GW170818) not previously released to EM observers.

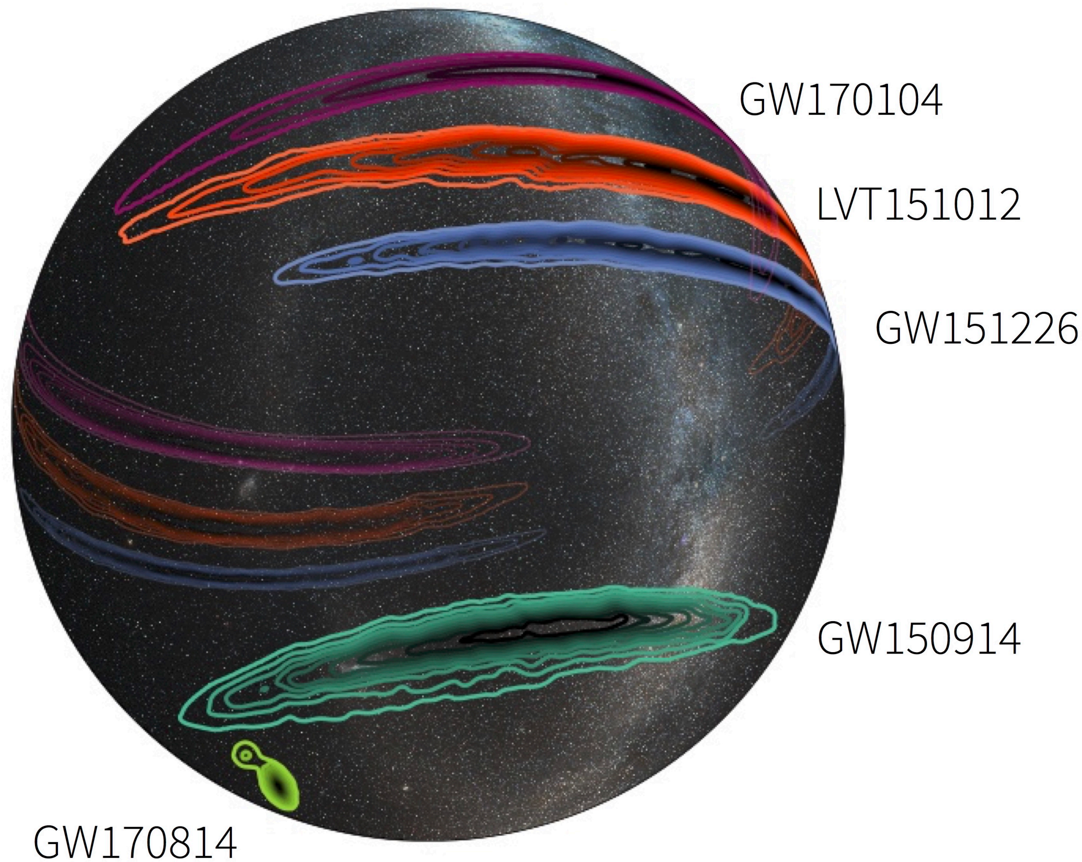
- Inclusion of Virgo greatly improves sky localization: importance of a *global GW detector network* for accurate localization of GW sources (GW170814, GW170817, GW170818)

- GW170818 (LV) is best localized BBH to date: with a 90% area of 39 deg^2

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

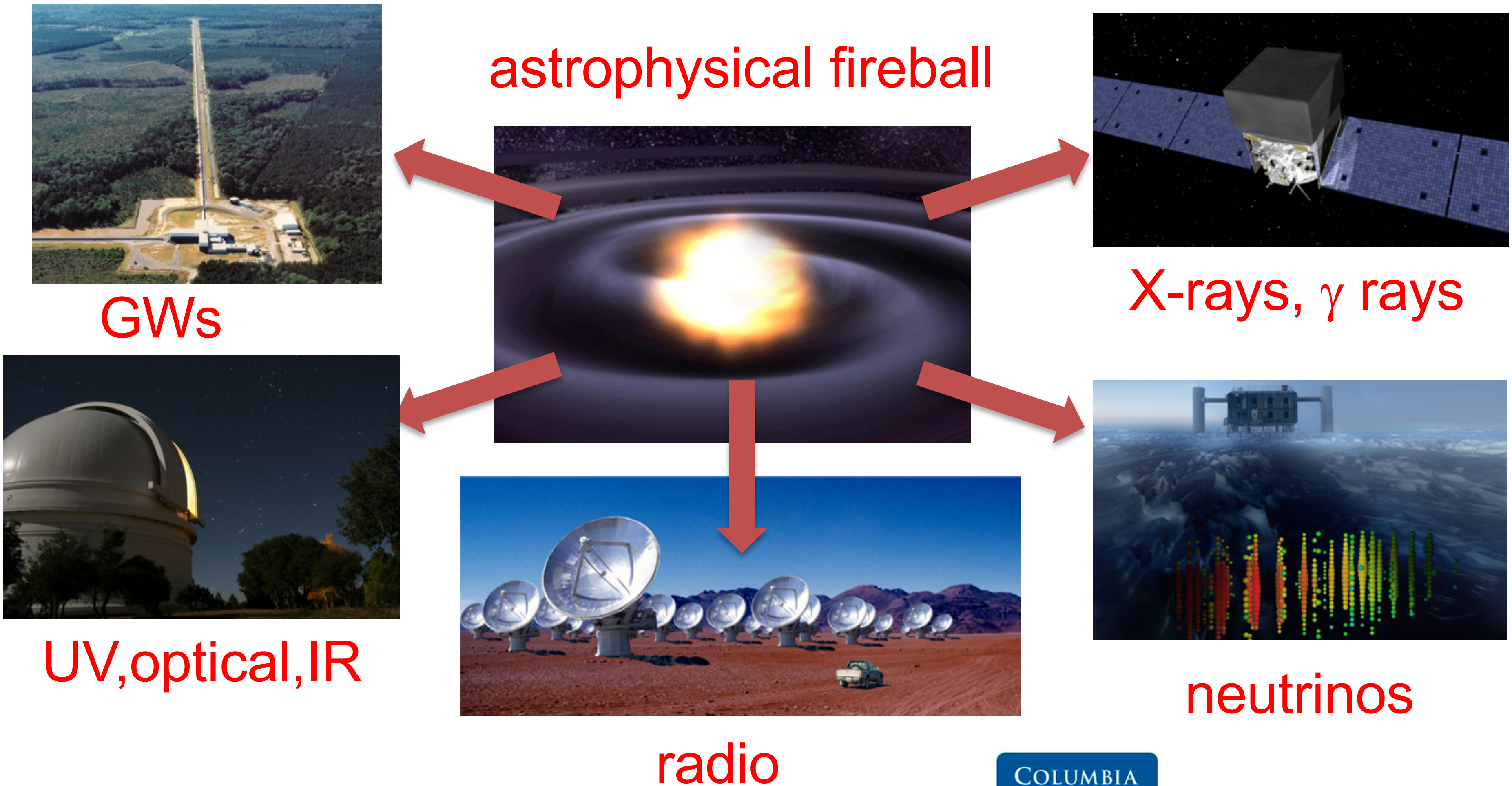


Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)



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

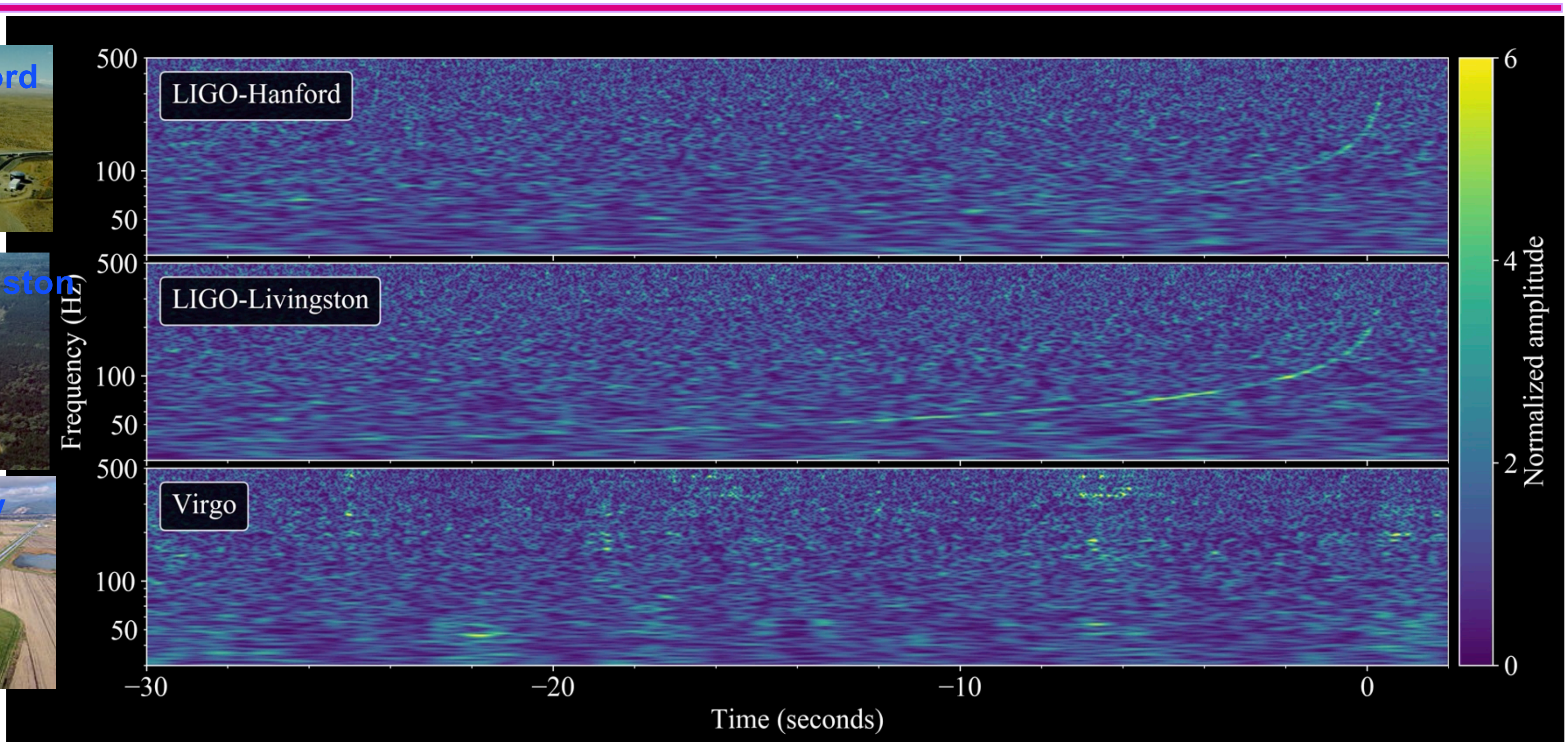
Multi-messenger Astronomy with Gravitational Waves



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

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

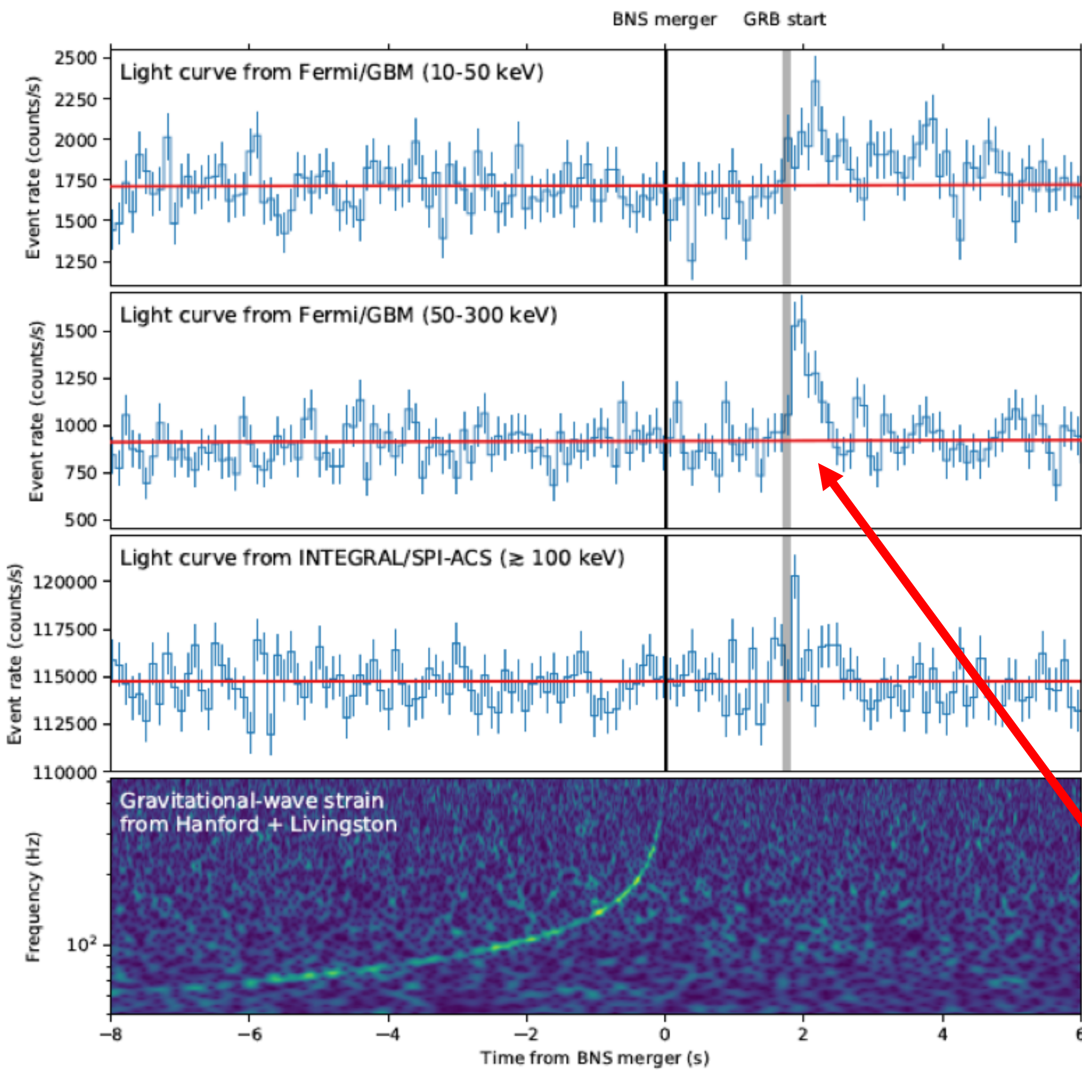
This is what I woke up to on August 17, 2017, just before 6am PT…



GW170817
A Binary Neutron Star Merger! (!!!!!!)

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

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



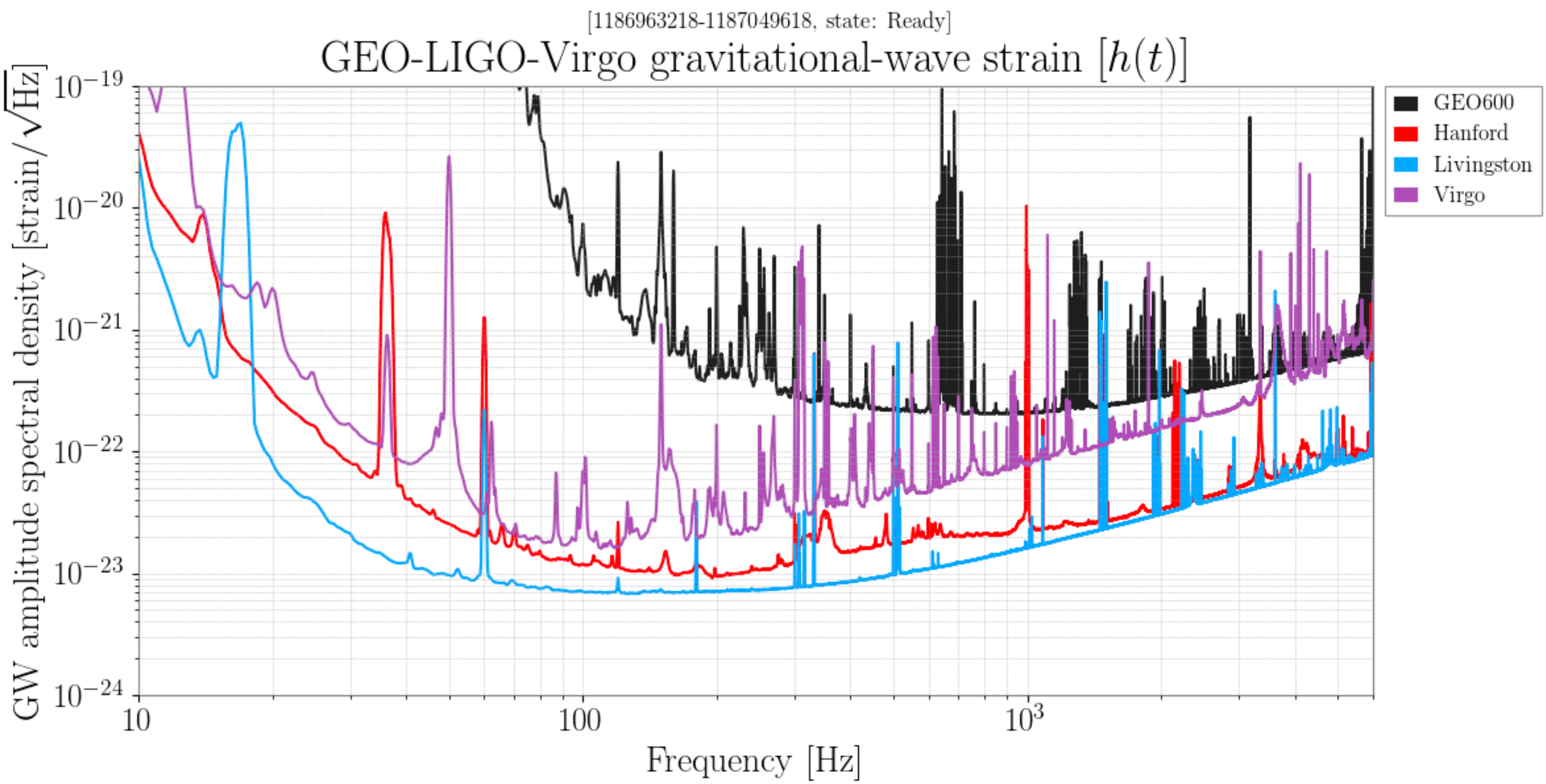
1.7 seconds later, duration < 2 seconds

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

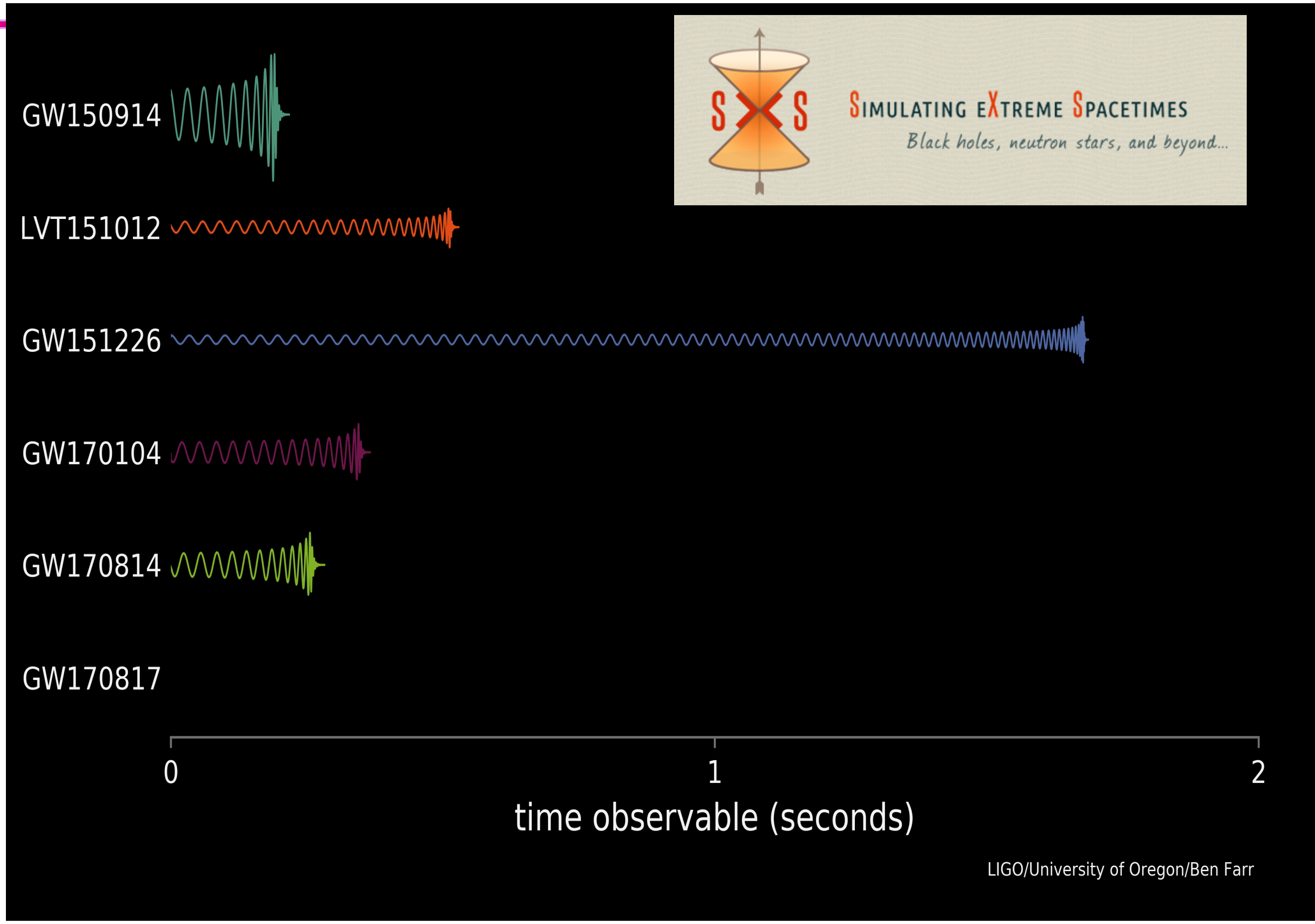
kinda wimpy, though…

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

HLVG – four-detector network for GW170817!



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

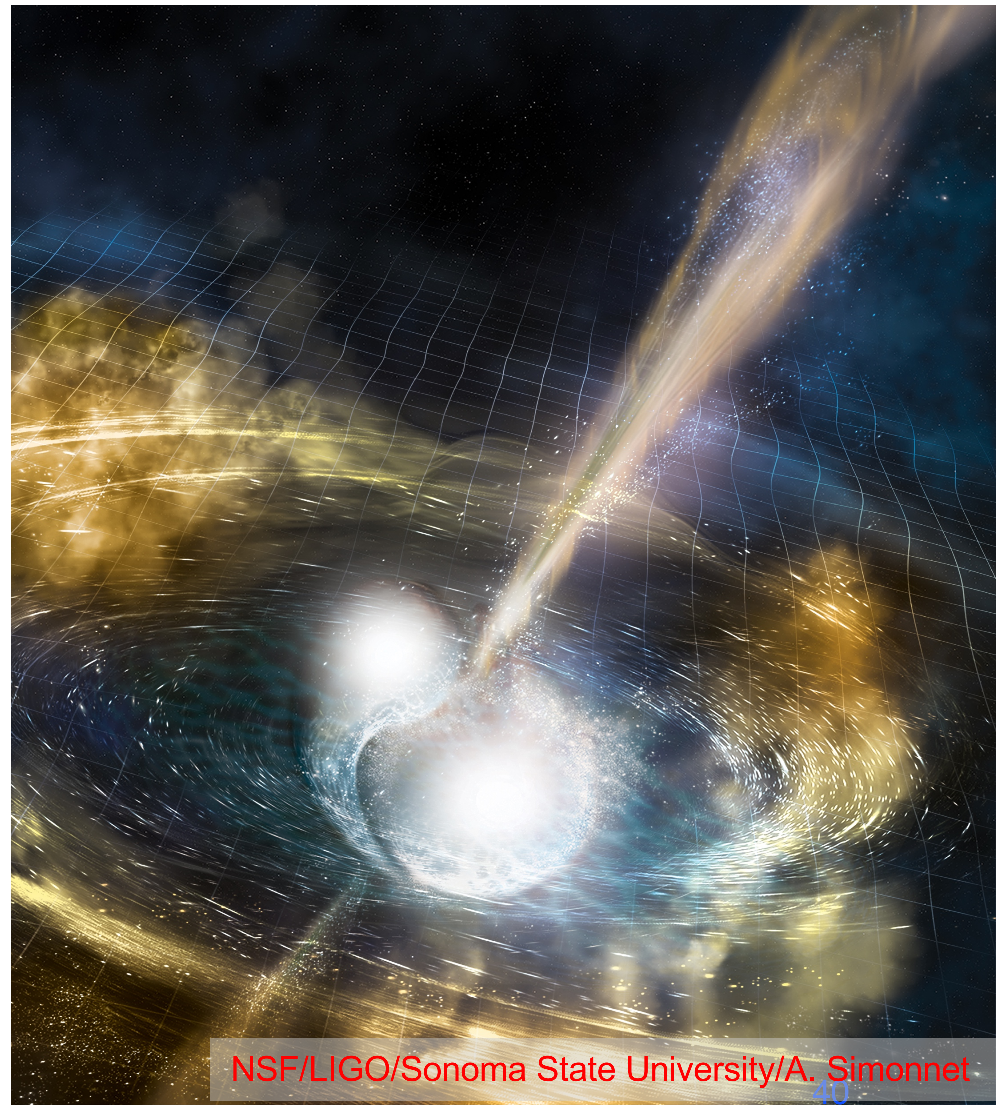


The longest (~ 60 s), loudest (SNR ~ 32), closest (40 Mpc) signal LIGO has ever observed!

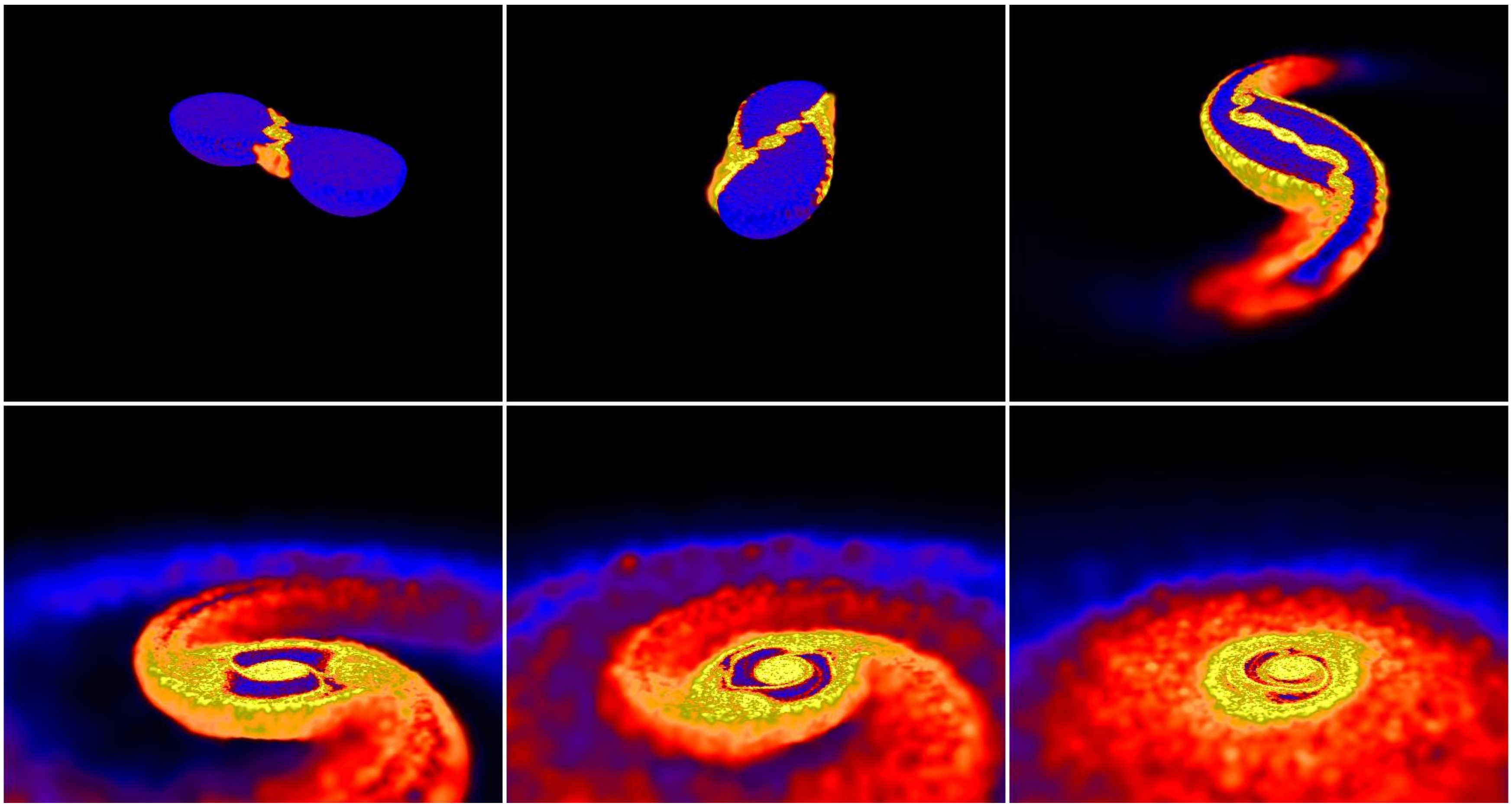
https://www.youtube.com/watch?v=WoDCPTLgxh4

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

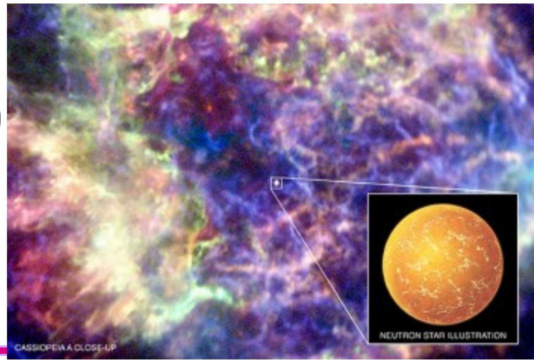
The disruption of the stars results in a huge outflow of neutron-rich "dynamical ejecta" that powers a GRB and broad-band afterglow



BNS mergers, tidal distortion and disruption

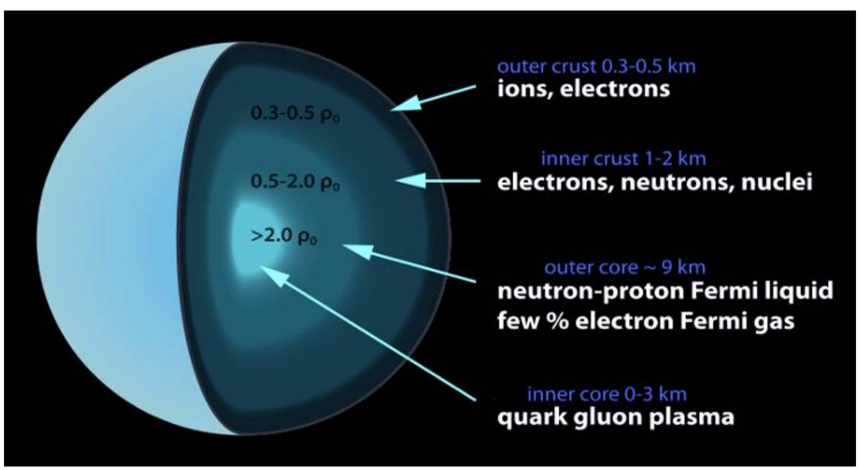


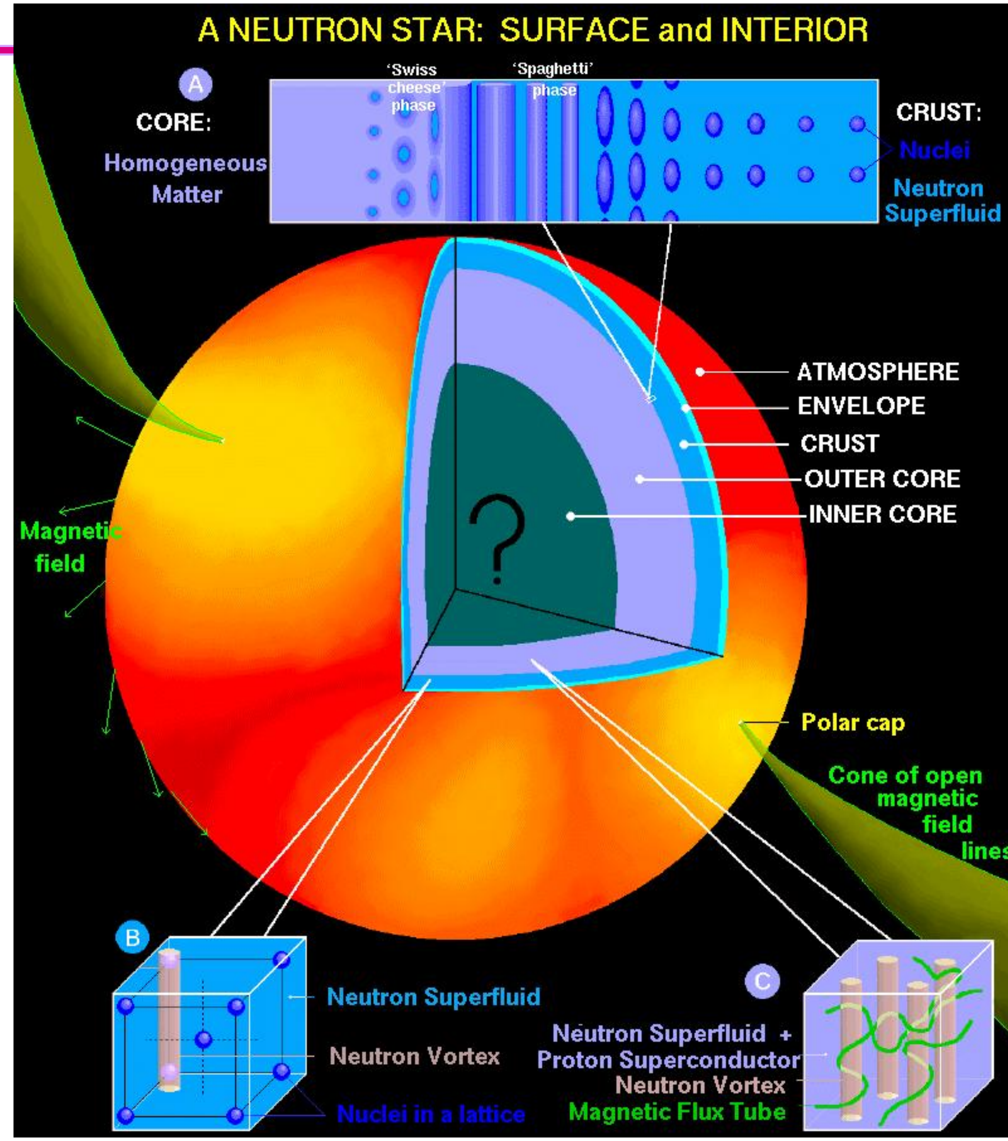
Credit: Daniel Price and Stephan Rosswog



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**



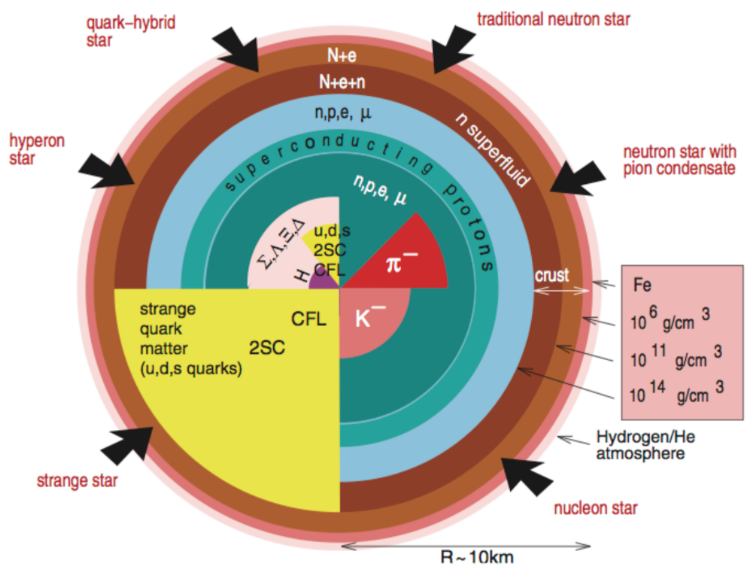


http://www.astro.umd.edu/~miller/nstar.html

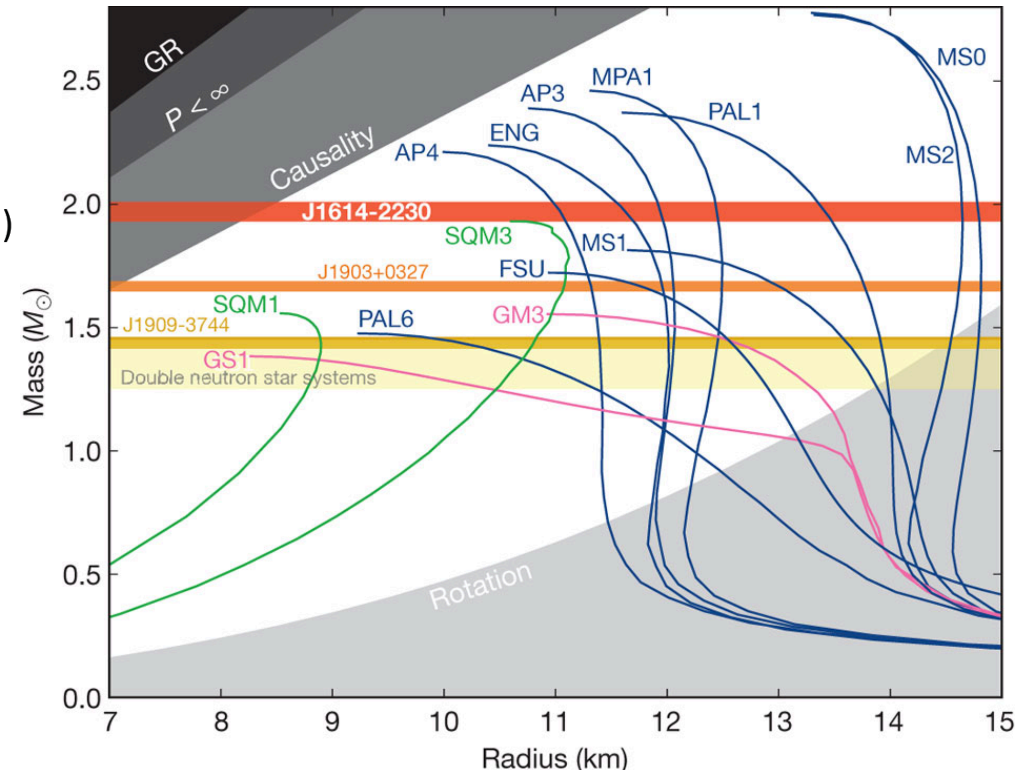
NEOS, NS structure, and NS mass-radius relation

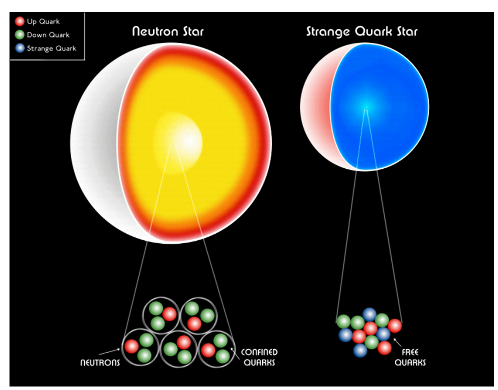
Neutron Star Equation of State

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



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

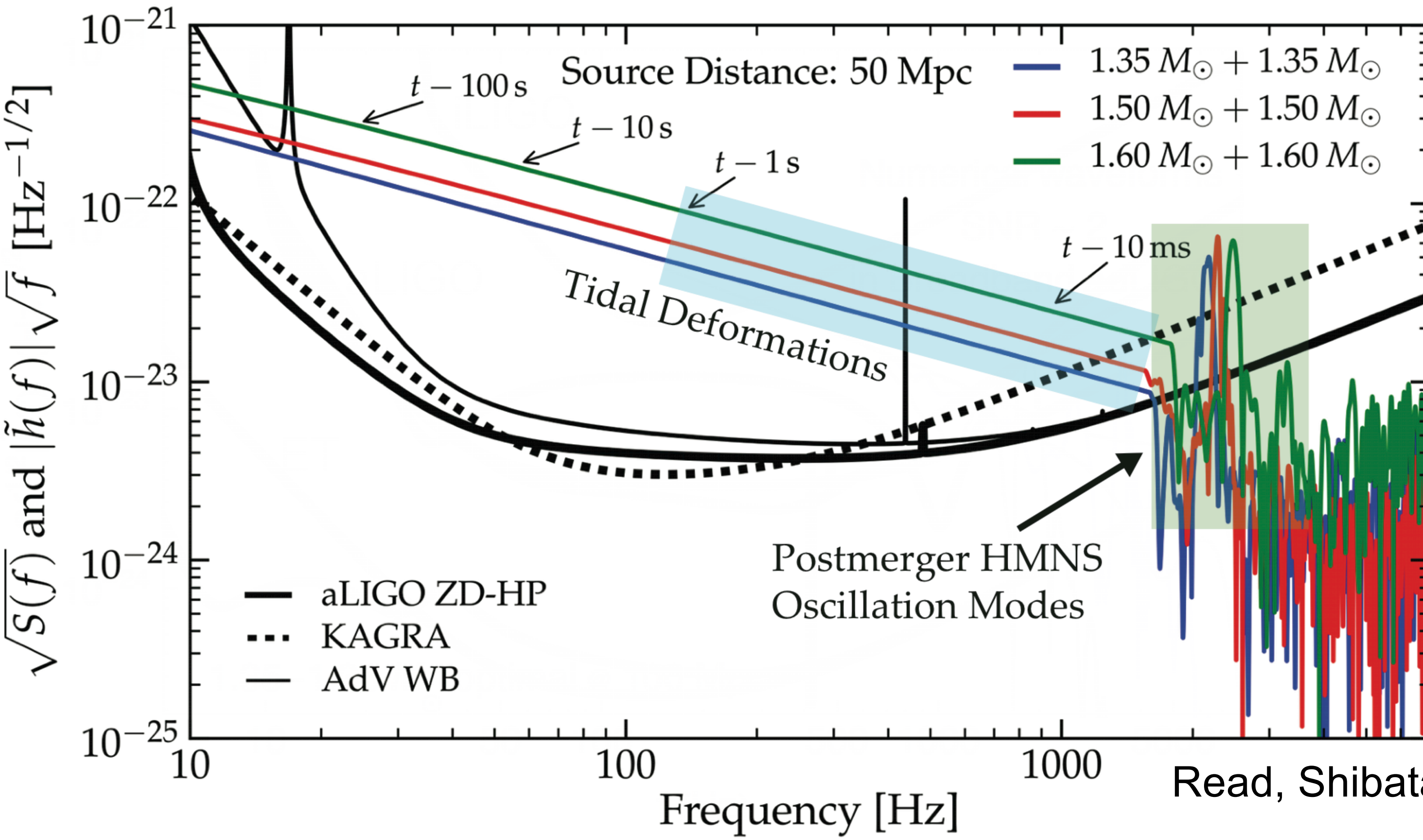




LIGO

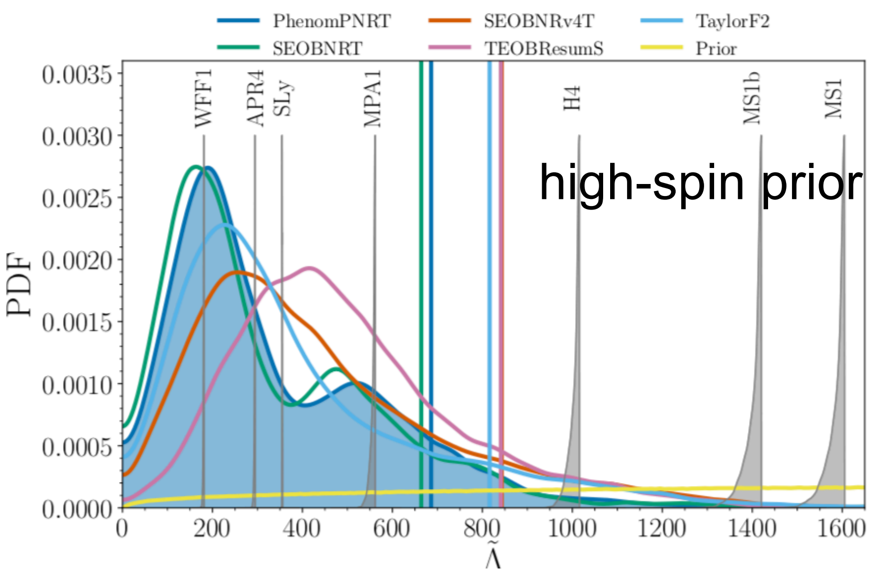
Tidal disruption of neutron stars near merger

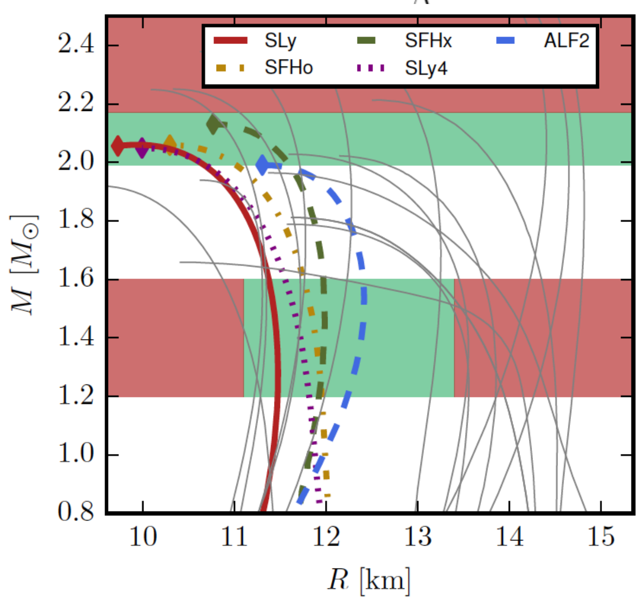
LSC



Read, Shibata, et al

Constraints on tidal distortion from GW170817



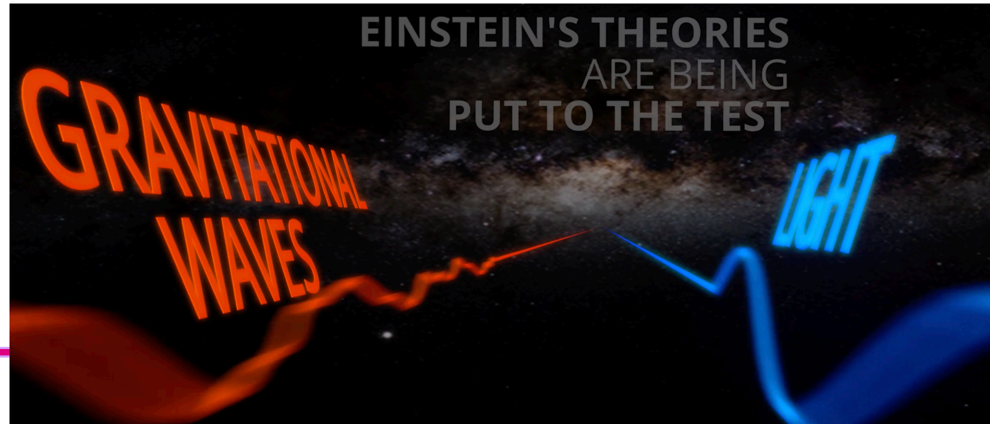


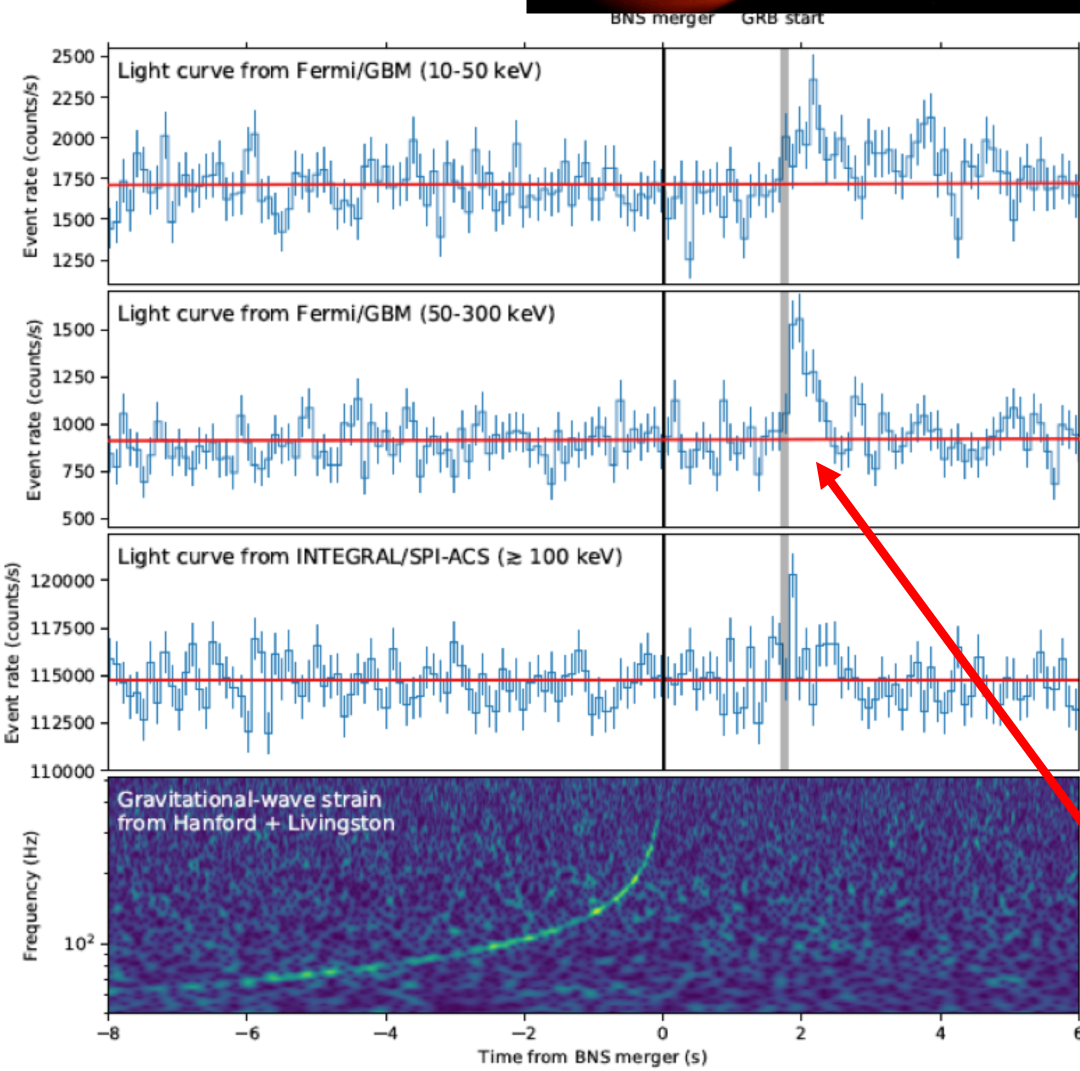
- Tidal deformability:

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

- 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

Coughlin, Dietrich, Margalit, Metzger
arXiv:1812.04803 (2018)





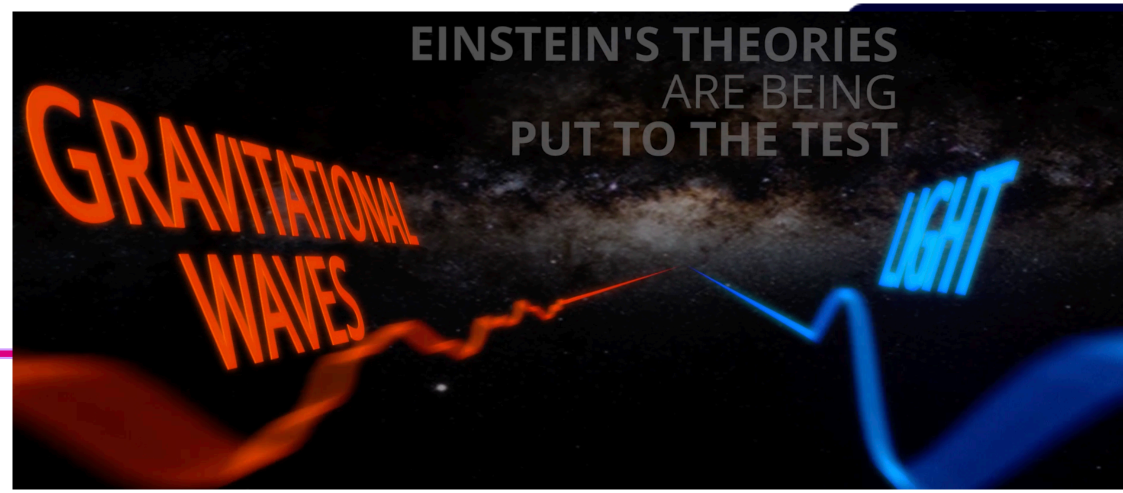
1.7 seconds later, duration < 2 seconds

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

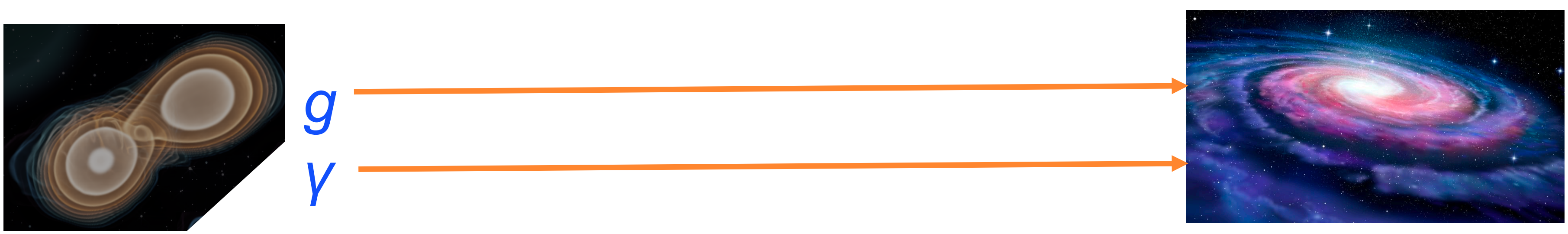
Fundamental properties of GWs, unique new tests of General Relativity!

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) $\times 10^{-23}$ 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 *.*

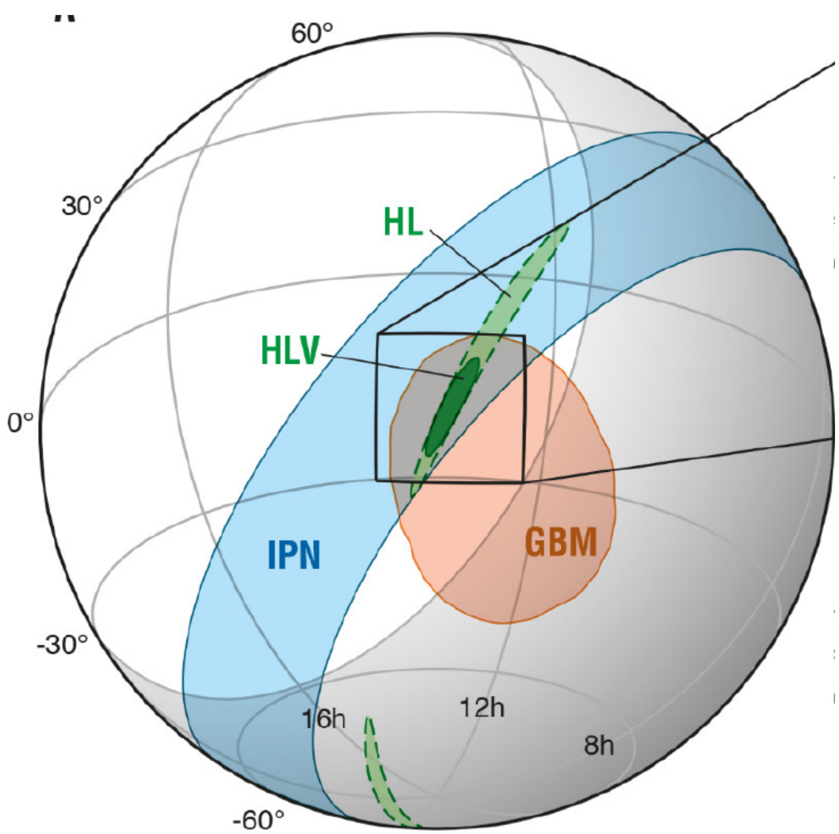


For the astronomers: within minutes, locate the source on the sky, tell telescopes where to point.

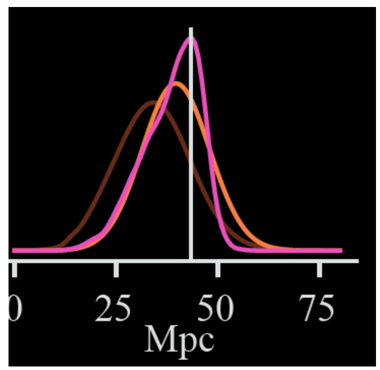
Source located to 28 sq deg, and ~ 40 Mpc.

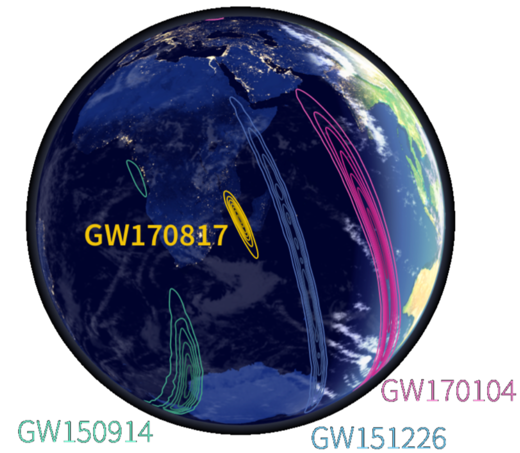
Time is of the essence!

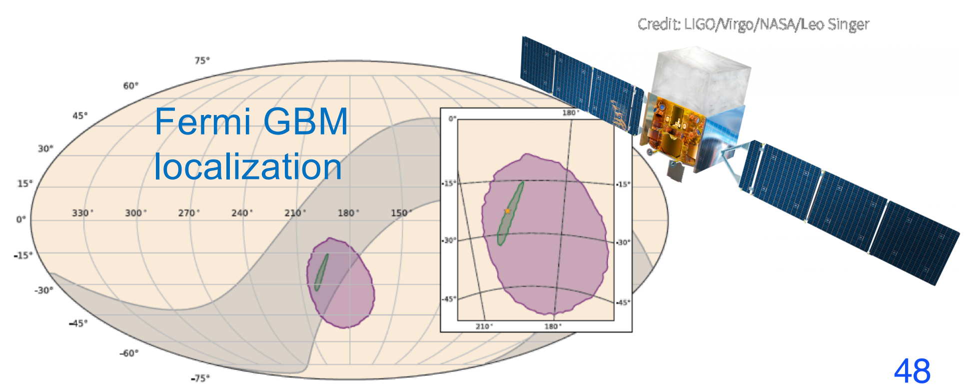
(Initial alert sent out *27 minutes* after the GWs passed through LIGO)



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

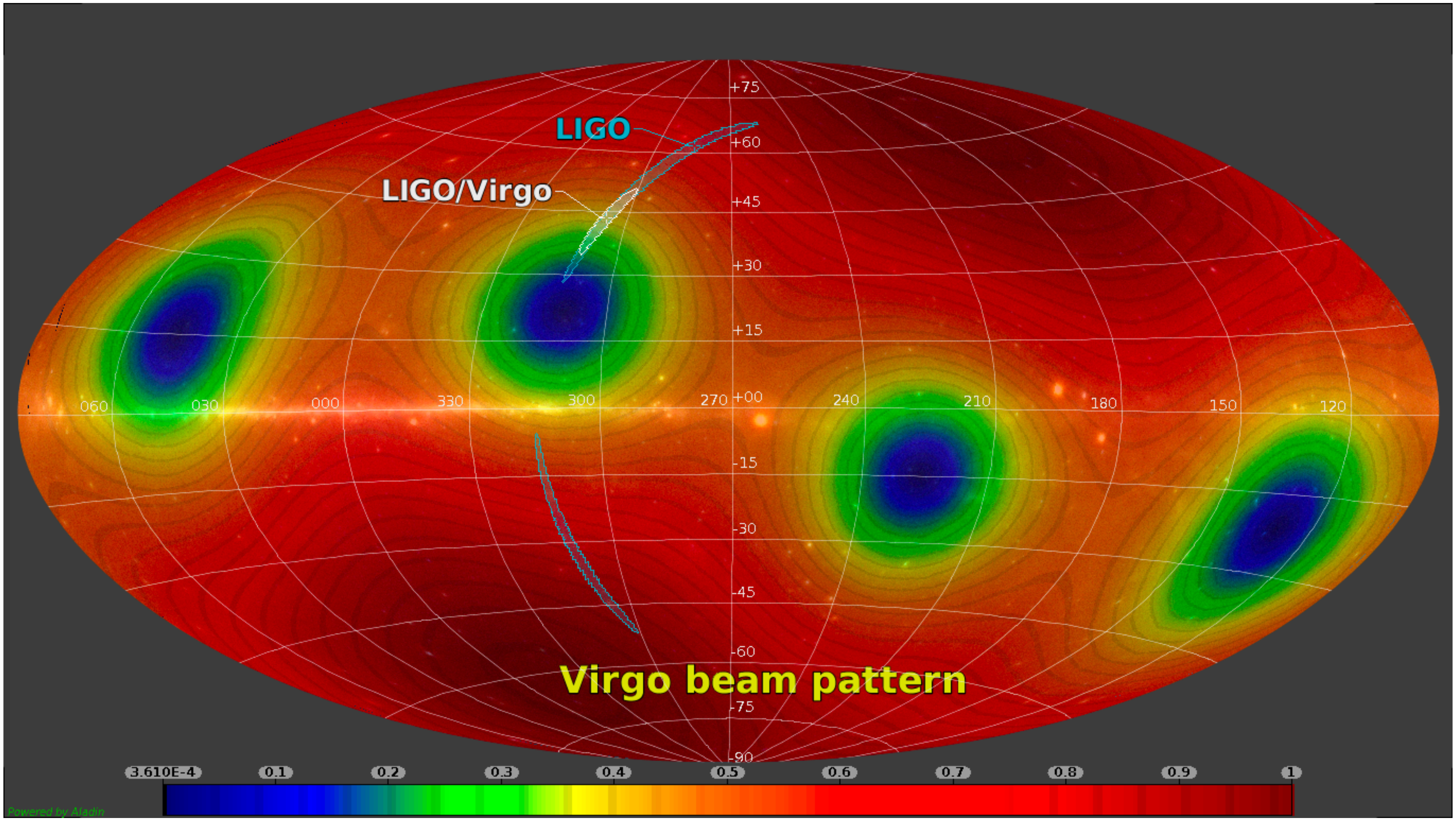






Virgo "non-detection" was very important!

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



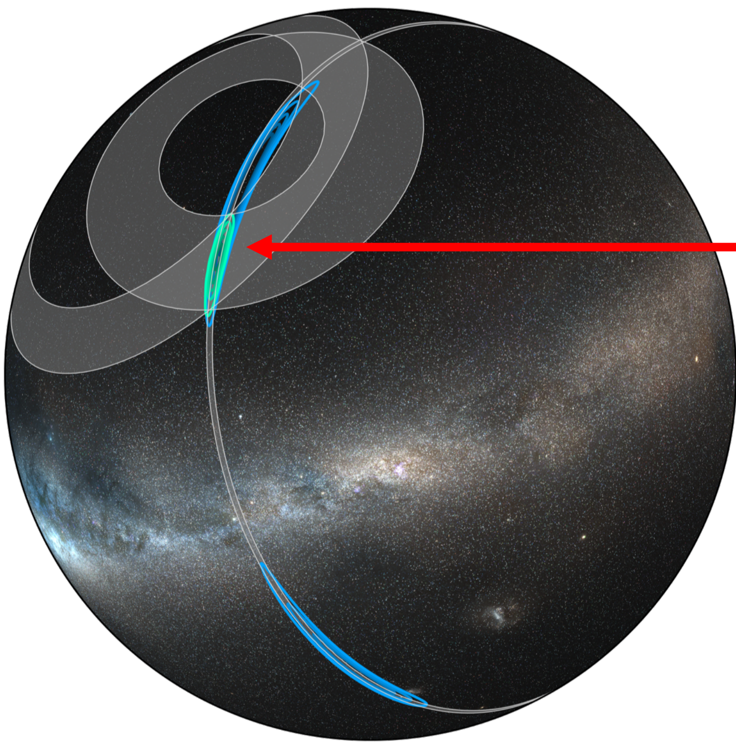
Reduces the localization patch to "only" ~28 deg^2

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

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

POINT YOUR TELESCOPES!

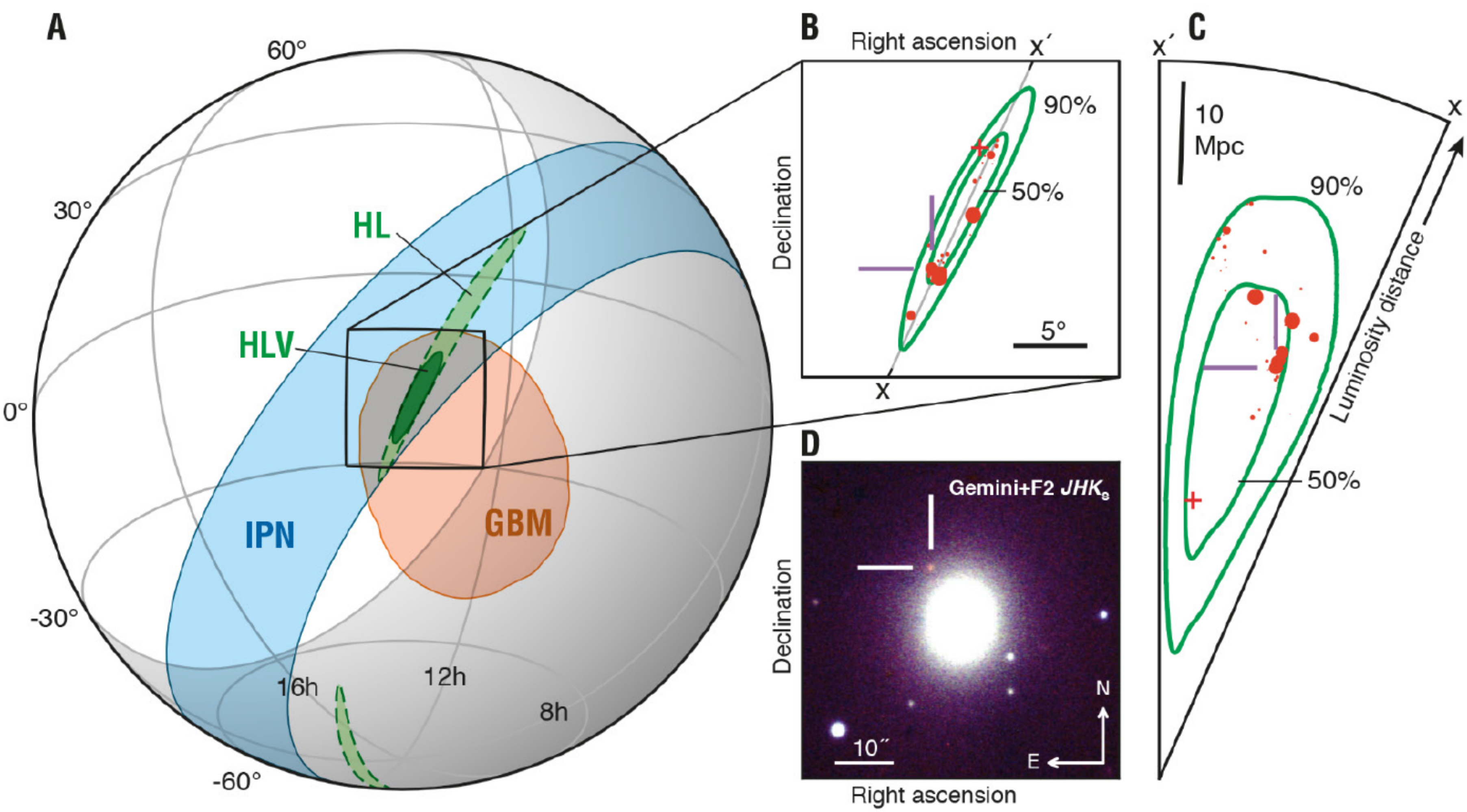
This is the REAL THING!!!



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

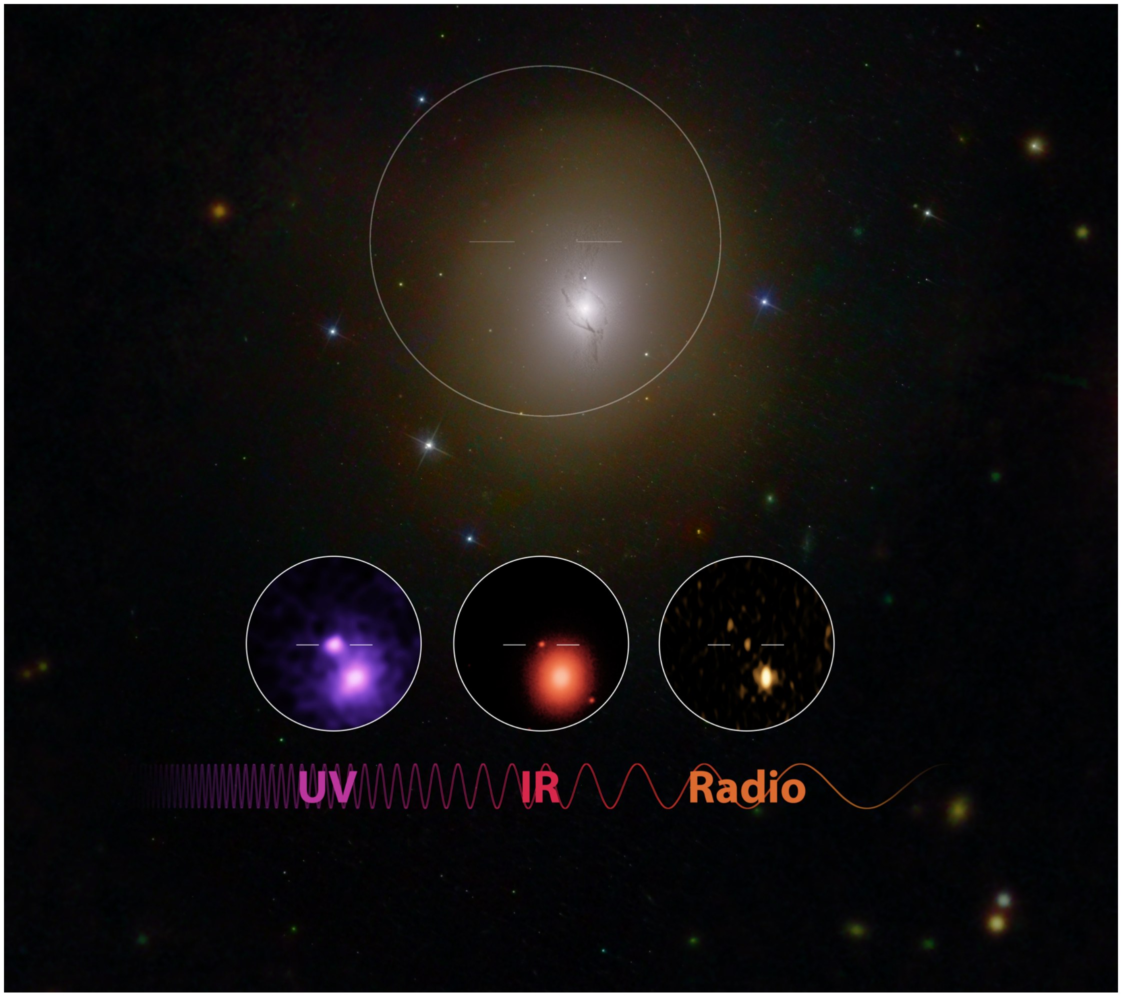
Is the the dawn of GW-multi-messenger astronomy?

The next evening: they got it!

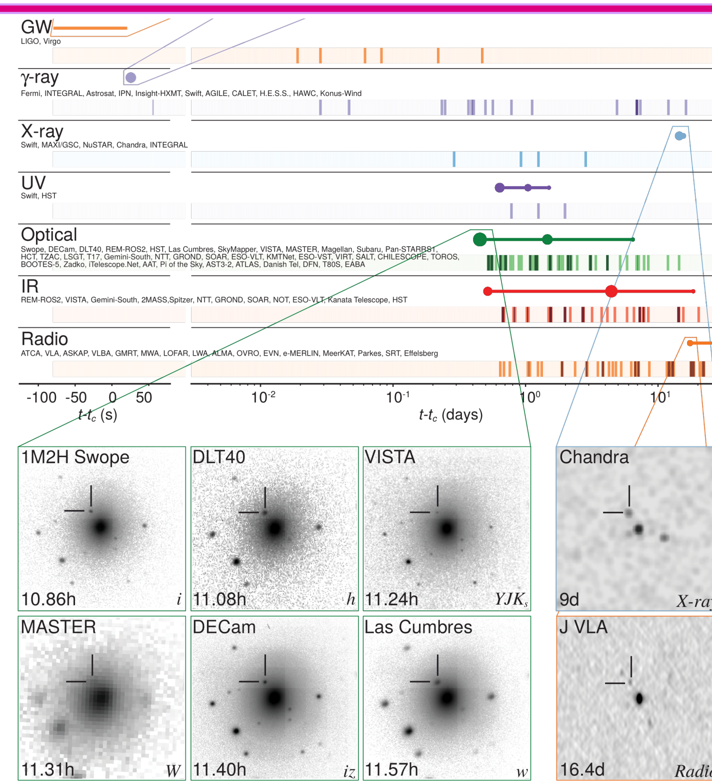


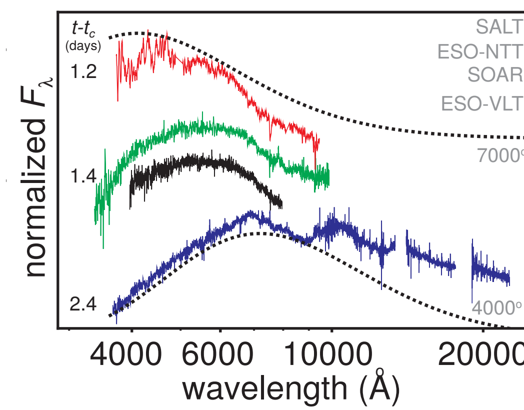
M. M. Kasliwal *et al.*, *Science* 10.1126/science.aap9455 (2017).

Light at Every Wavelength

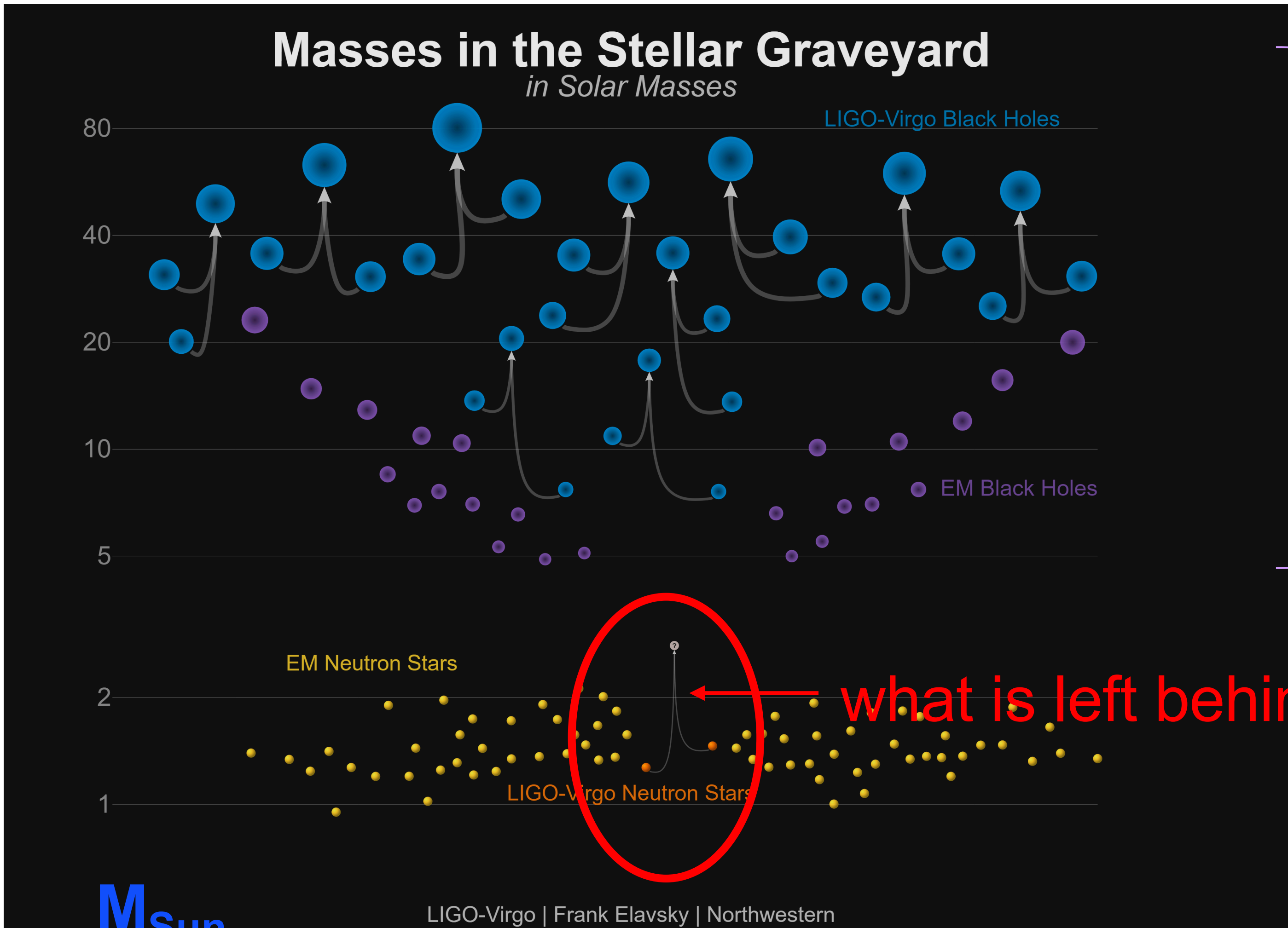


Host galaxy: NGC 4993; redshift: ~ 0.01





What did the binary NS merger leave behind??



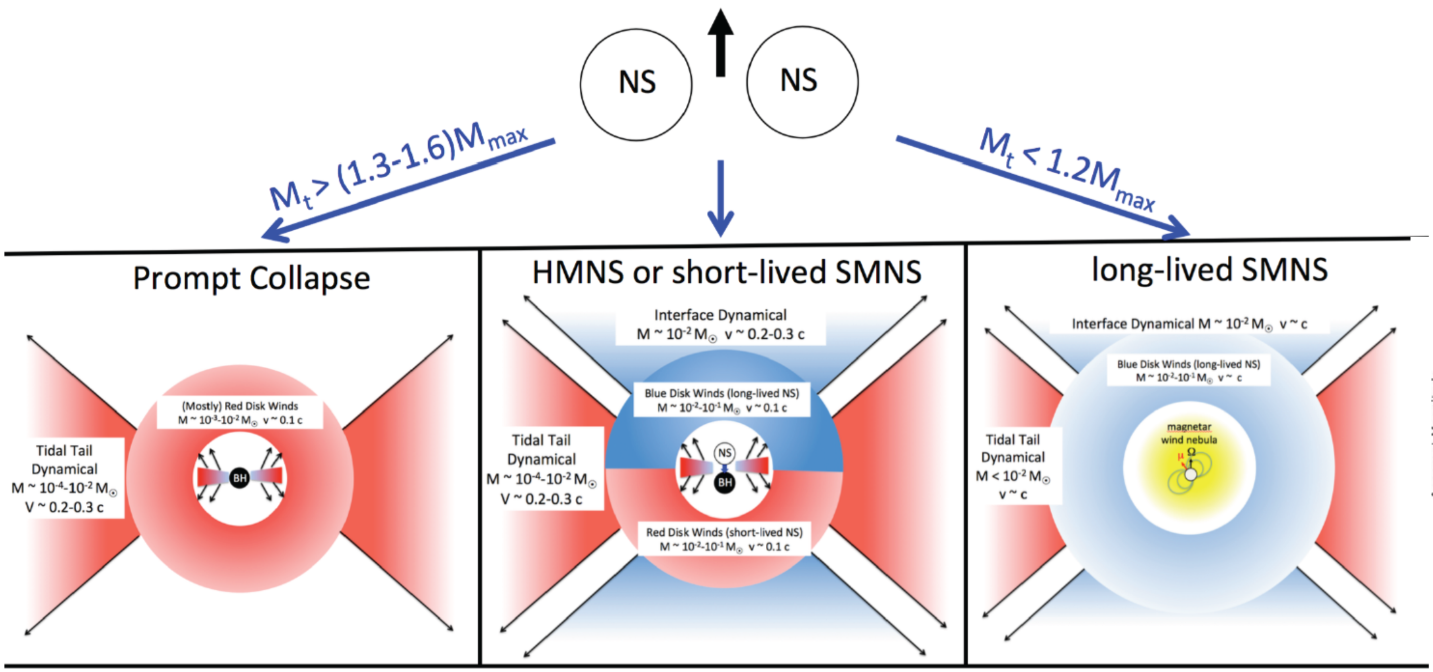
“stellar mass” black holes

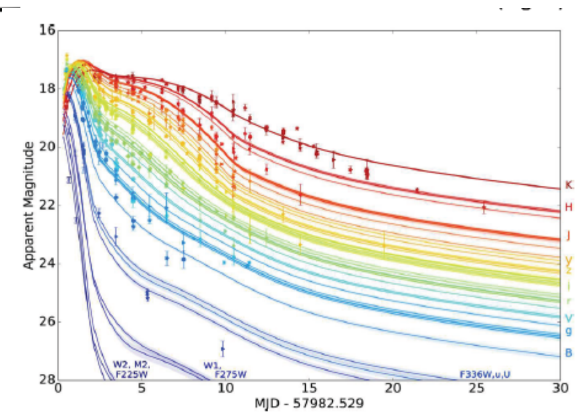
“mass gap”?

Neutron stars (pulsars)

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

The fate of BNS mergers – What is left behind?



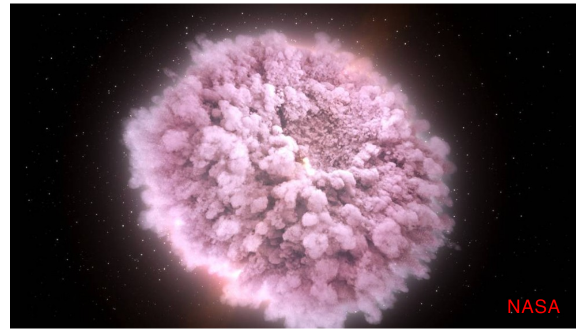


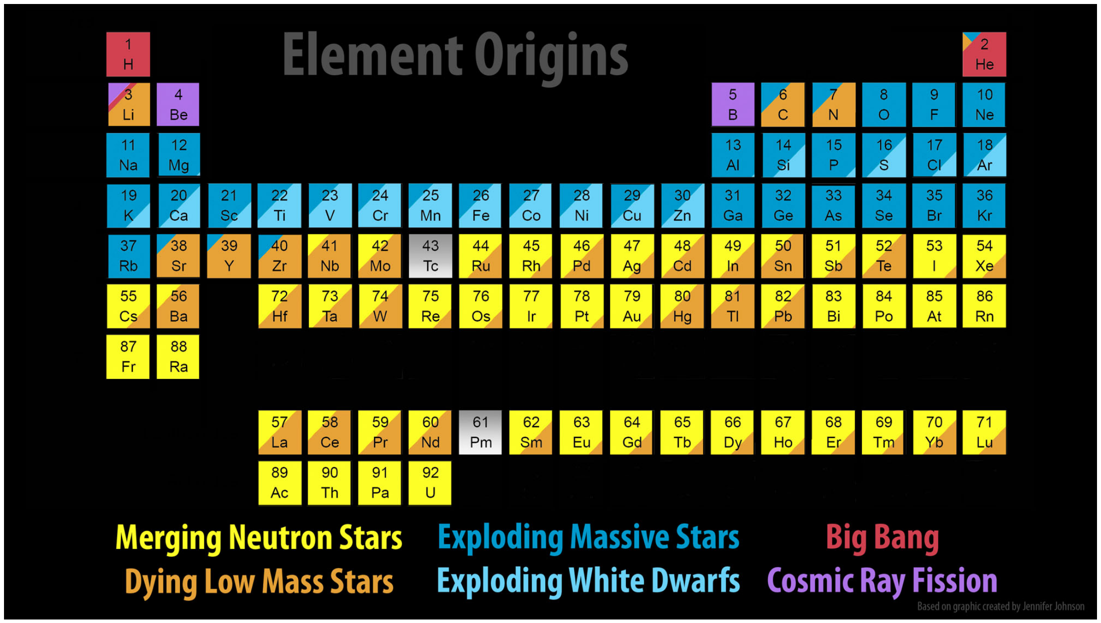
UVOIR light curves of the kilonova associated with GW170817

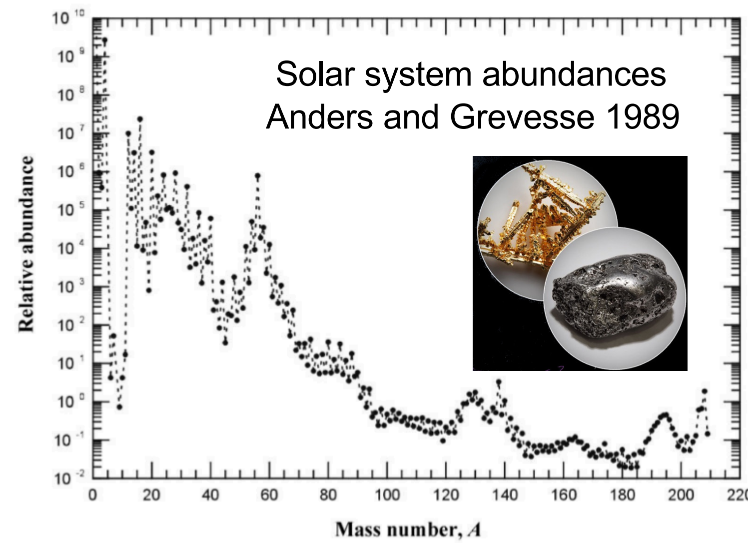
Hyper-massive NS, or supra-massive NS

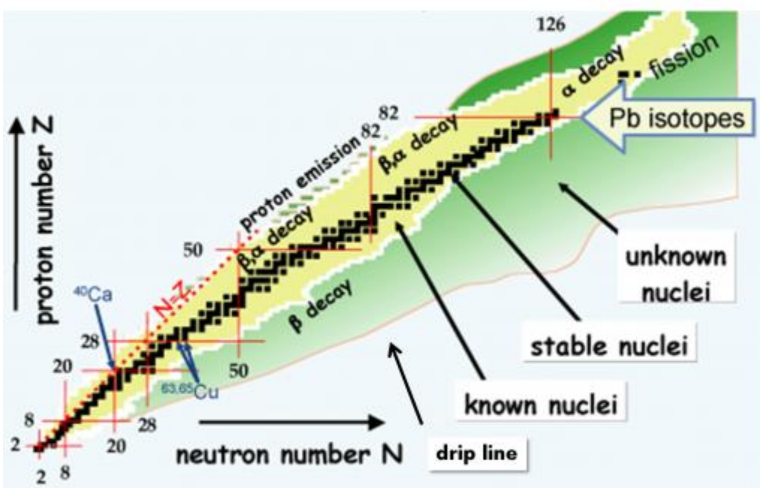
Margalit & Metzger (2017), Ap J L 850:L19

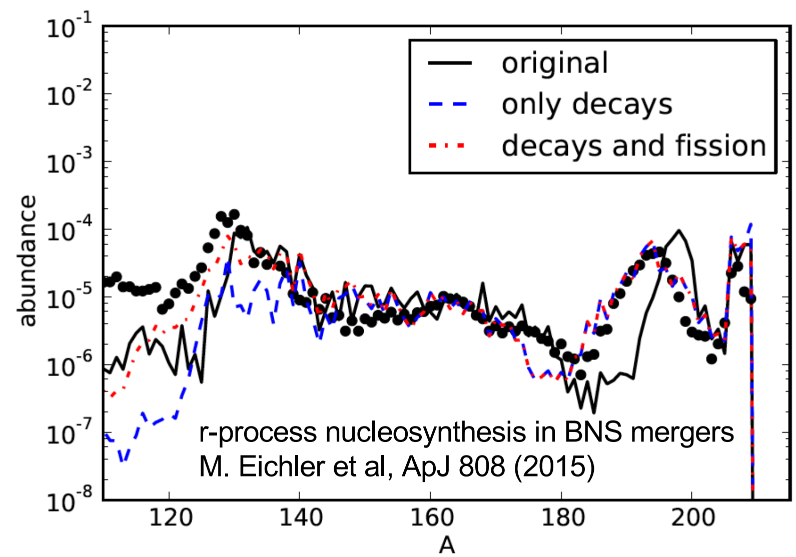
The origin of the (heavy) elements





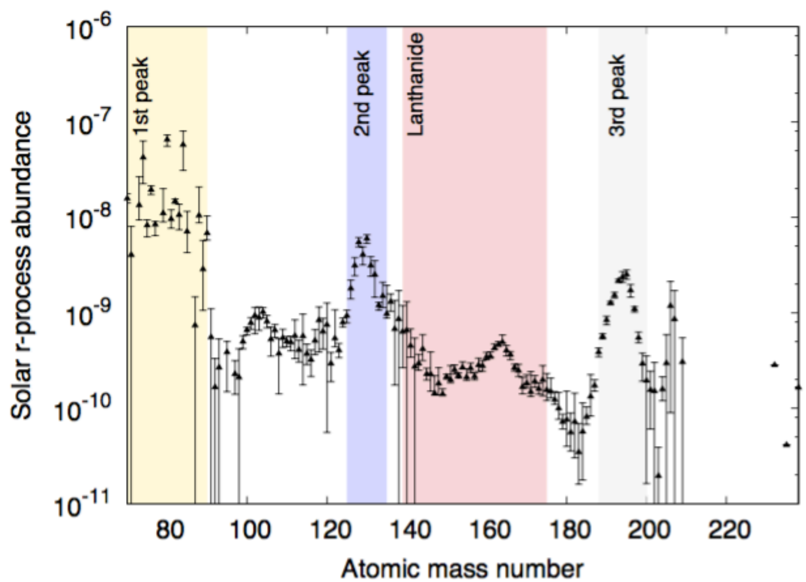


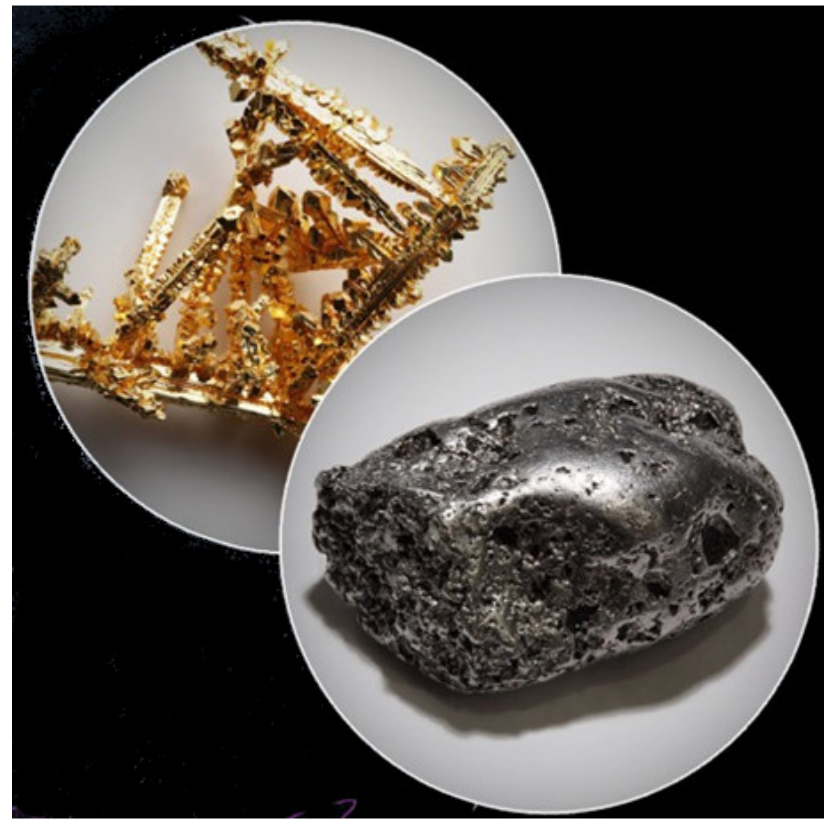




Not just a site, but *the* site of heavy element production?

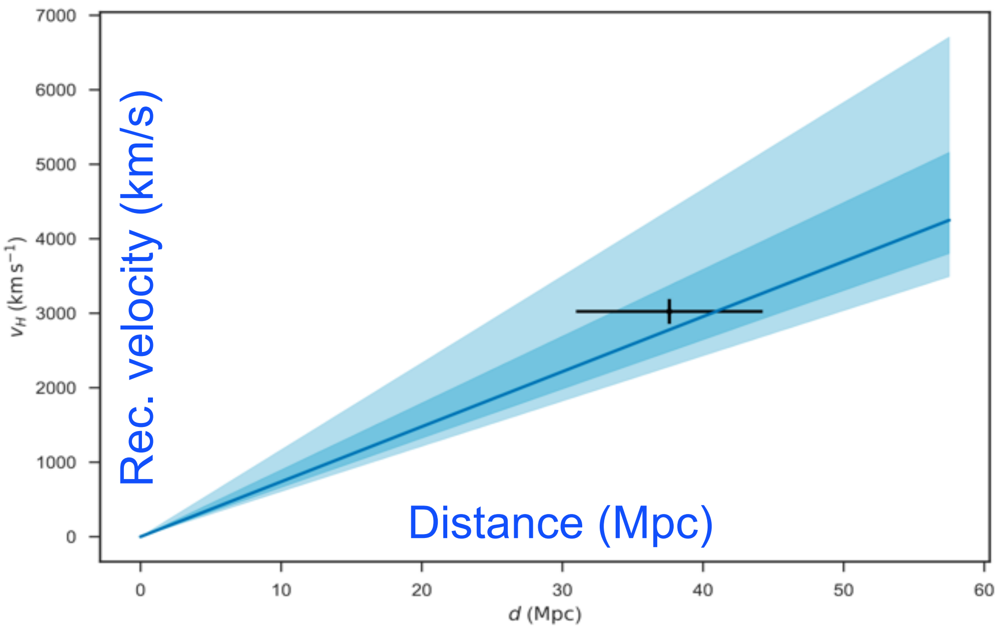
Observed Solar Abundance
= Quantity per merger x Rate of Mergers
>~0.05 solar-mass x >~300/Gpc^3/yr

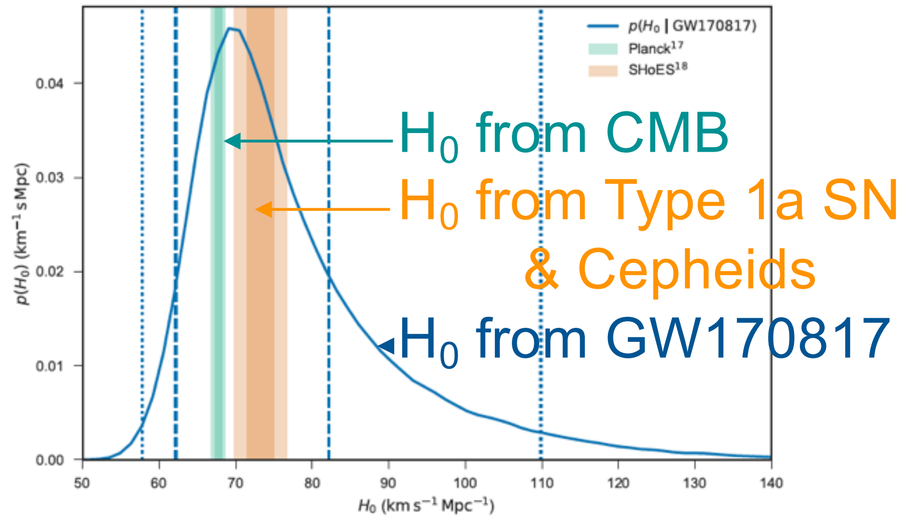




Ejecta mass estimate: ~0.05 solar mass
Merger rate estimate: $R = 1540^{+3200}_{-1220}\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
Consistent!

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

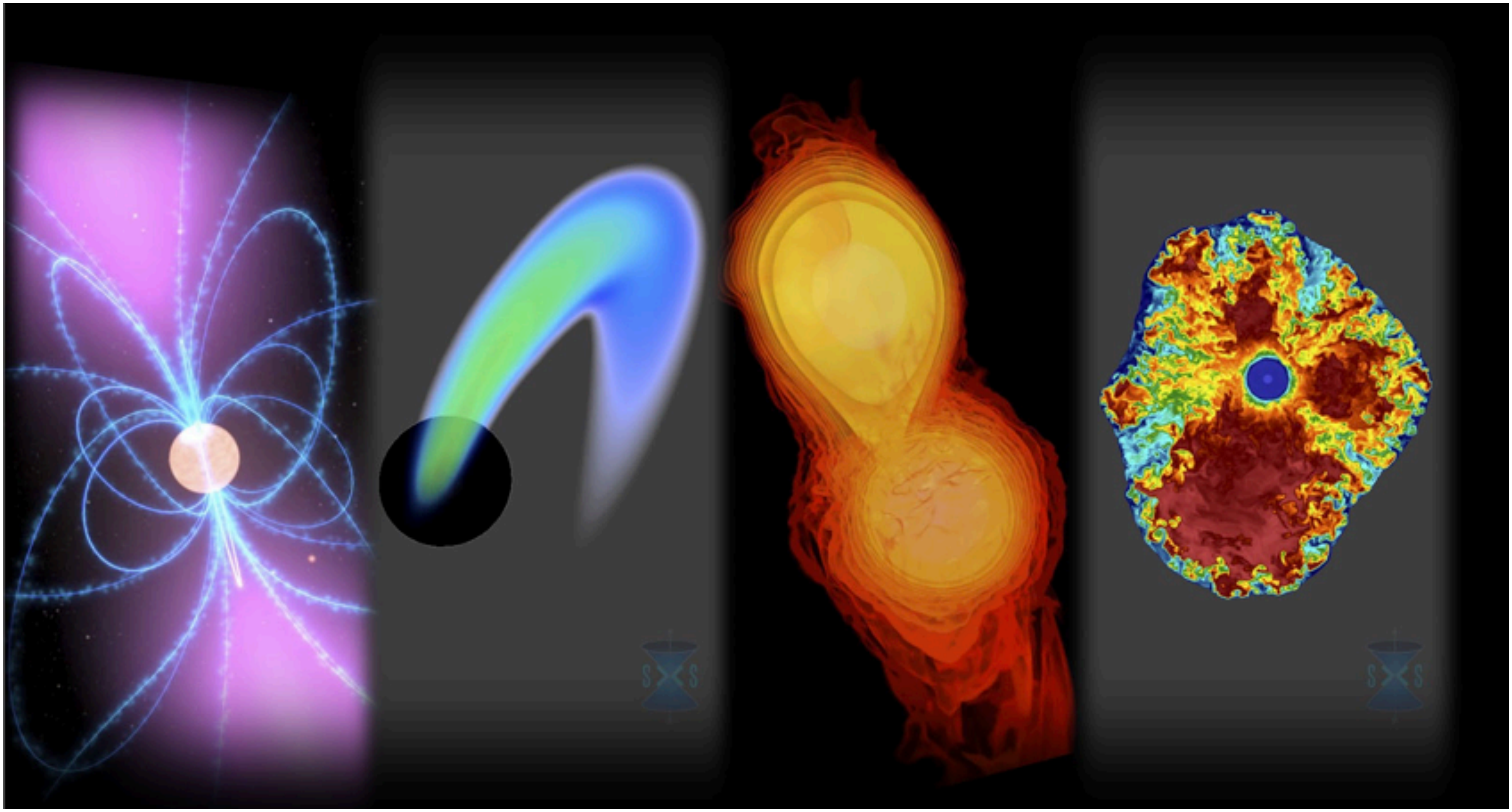




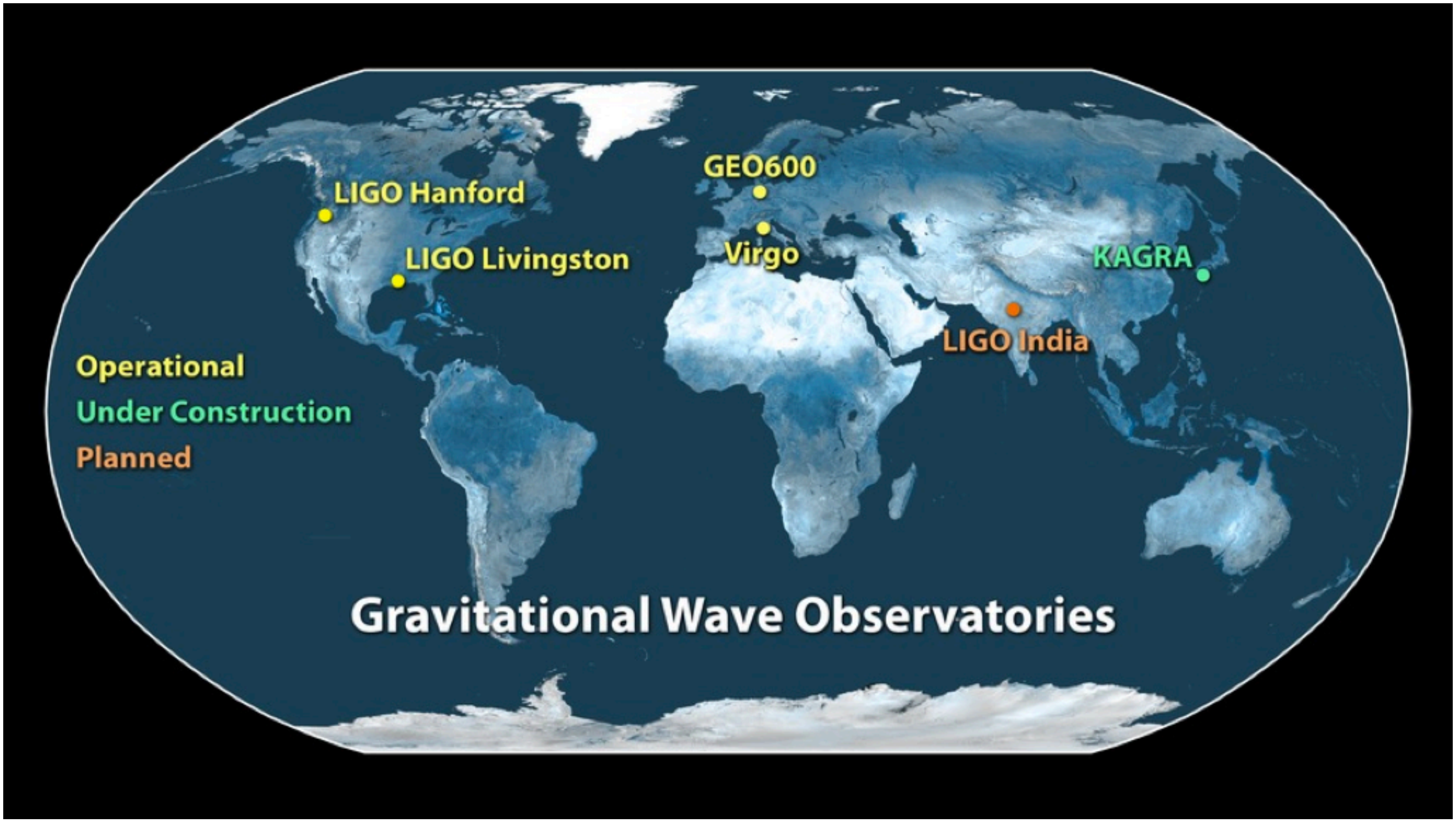
LIGO-Virgo, B.P. Abbott et al. Nature (2017)

- **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!)**

The future of Gravitational-wave astronomy

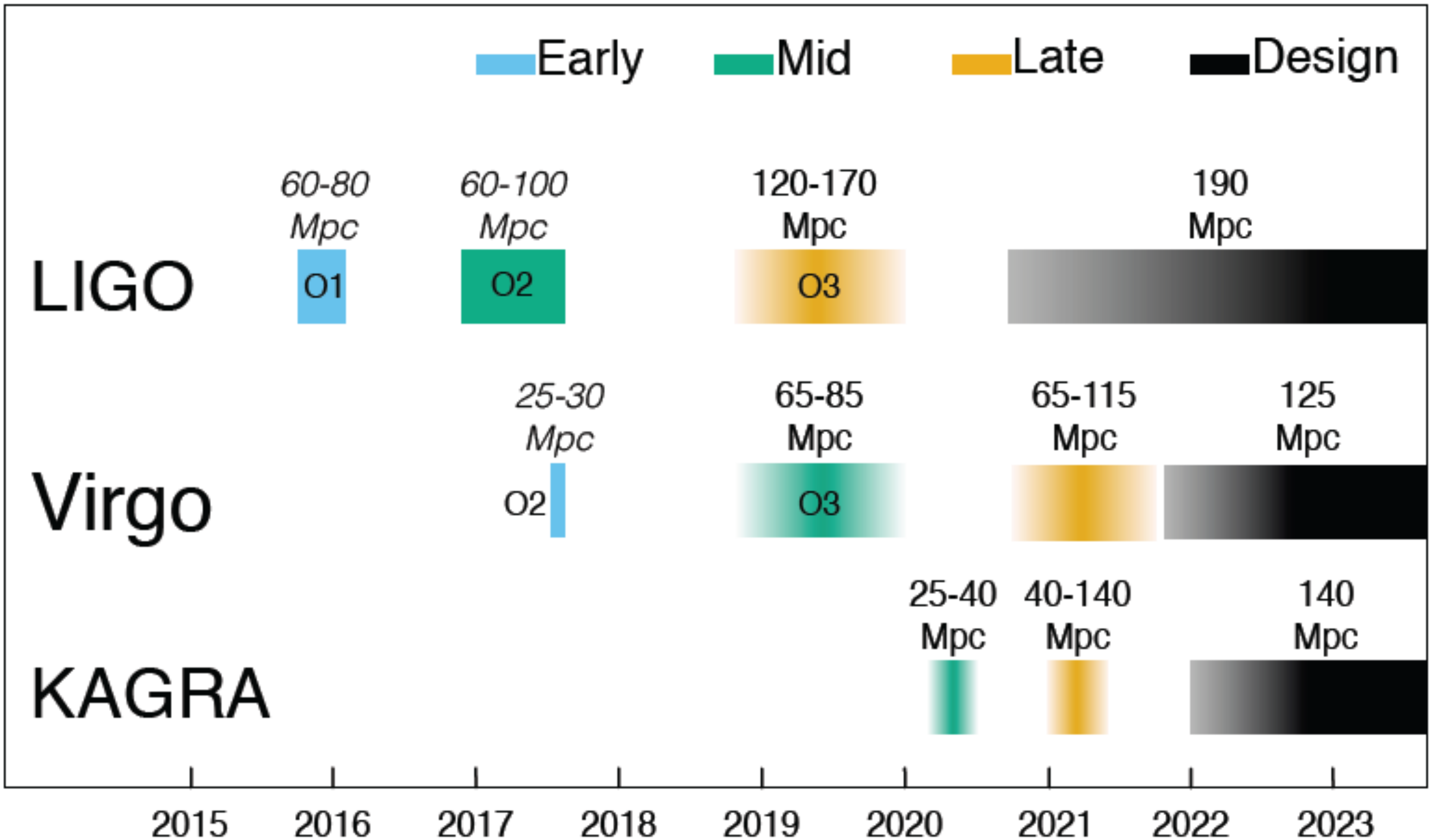


Coming years: more, and more sensitive detectors



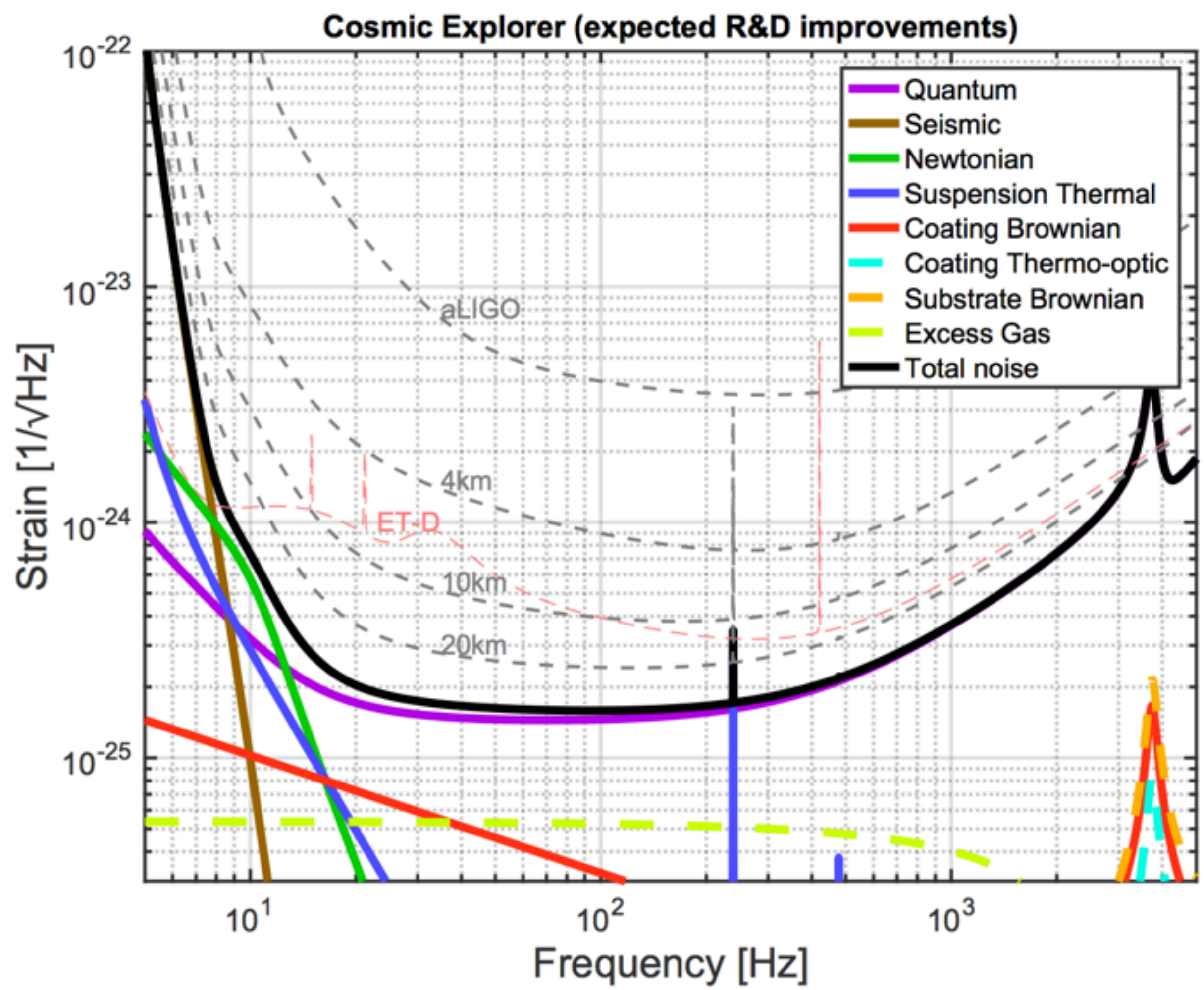
http://ligo.org/detections/GW170817.php

Coming years: more, and more sensitive detectors



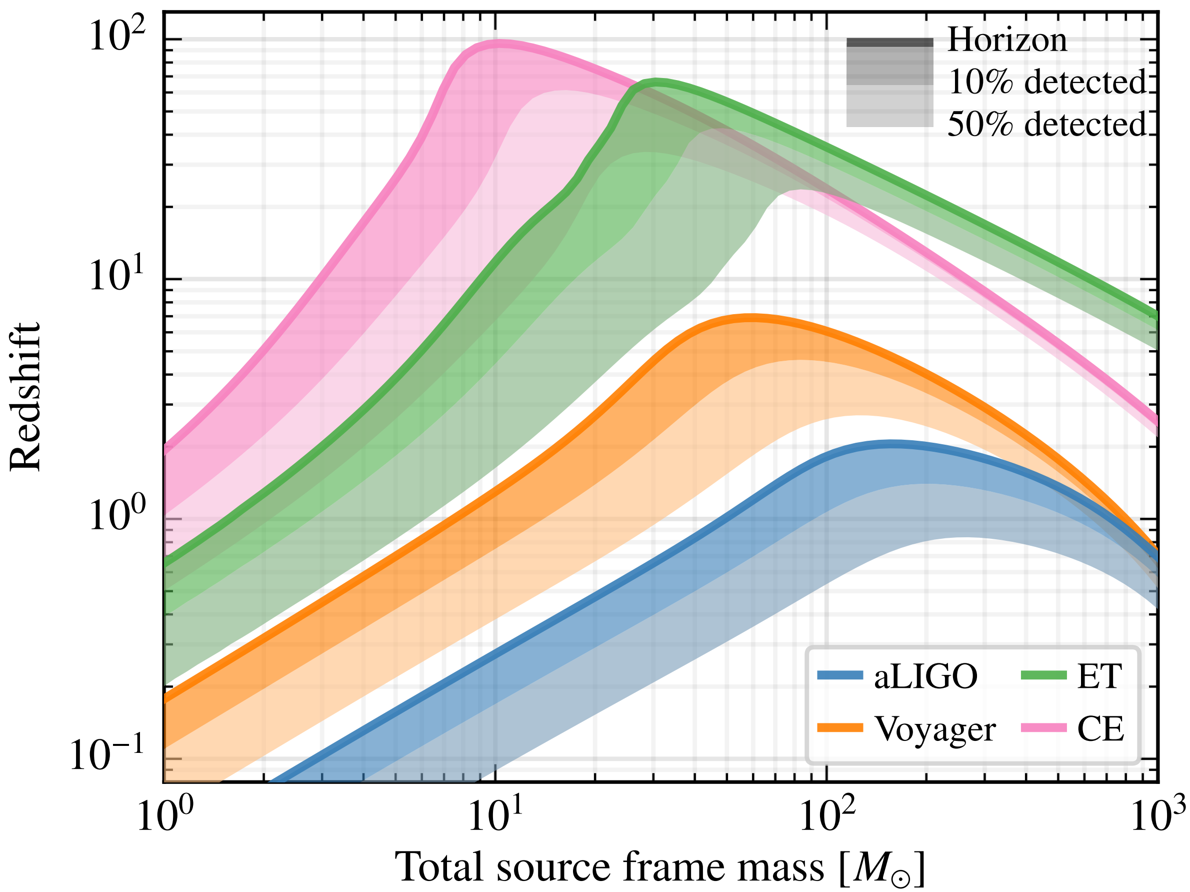
https://arxiv.org/abs/1304.0670

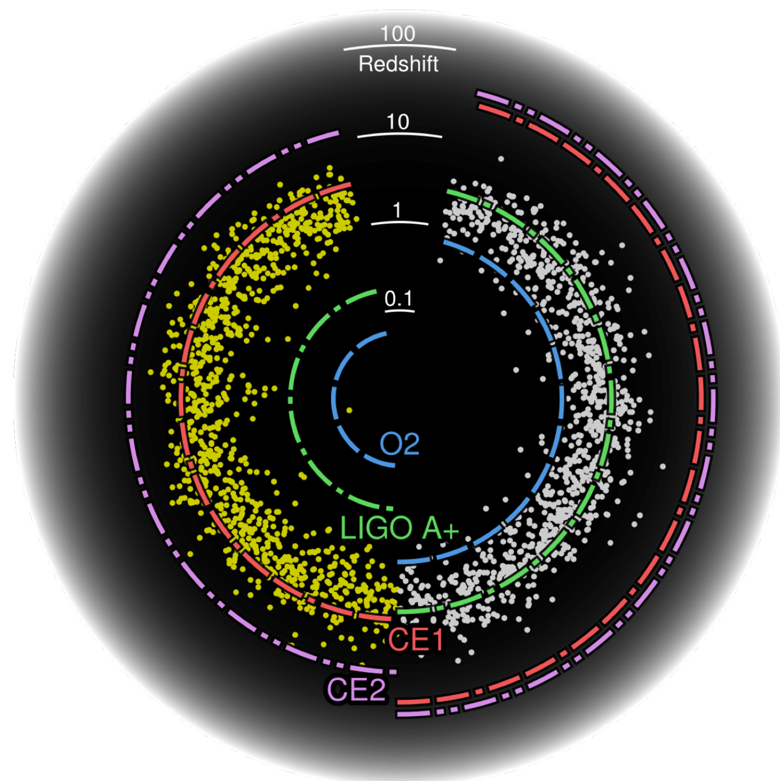
Future prospects for terrestrial gravitational wave astronomy



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

Seeing to the edge of the (astrophysical) universe

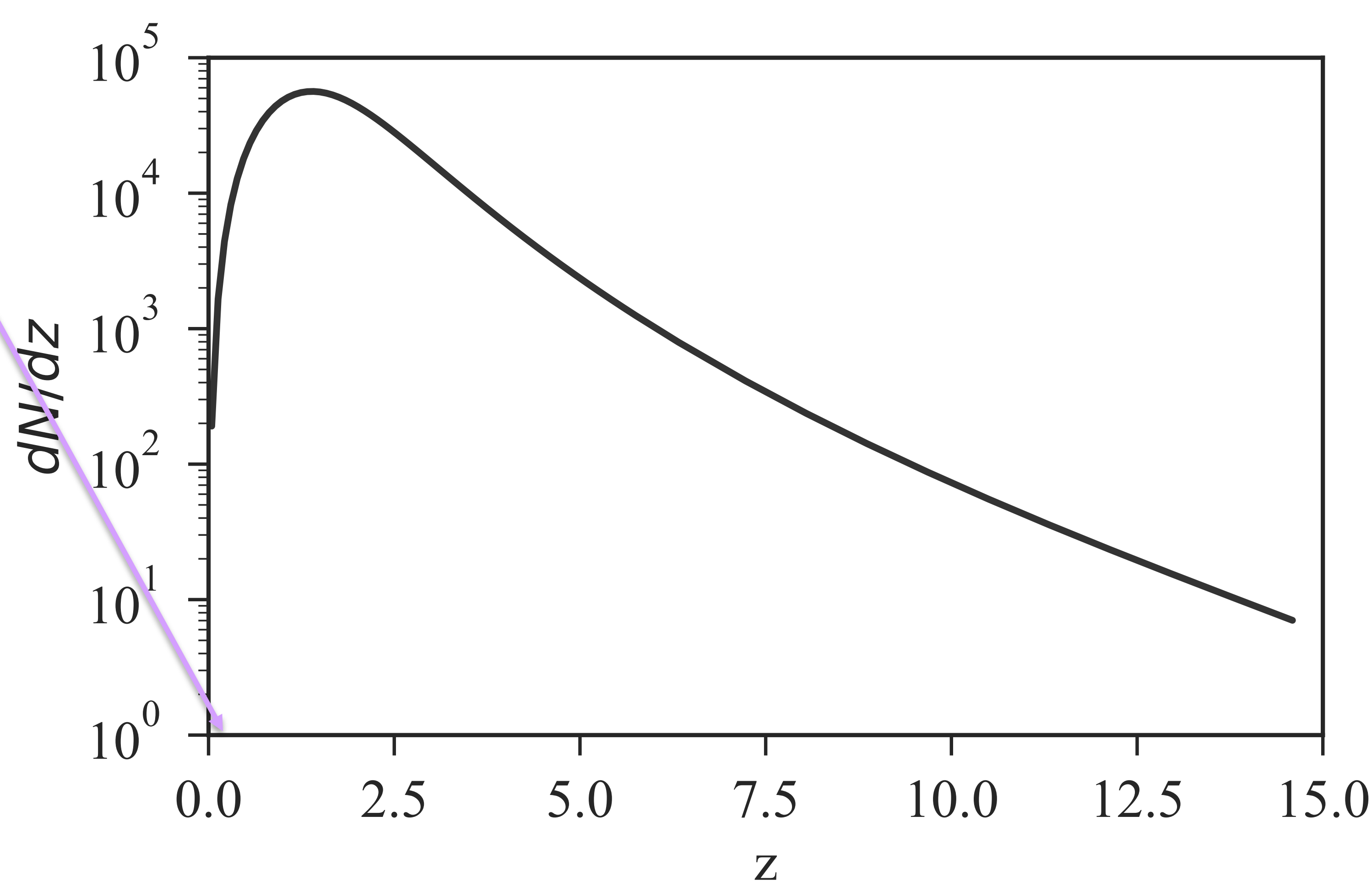




Evan Hall / Salvo Vitale

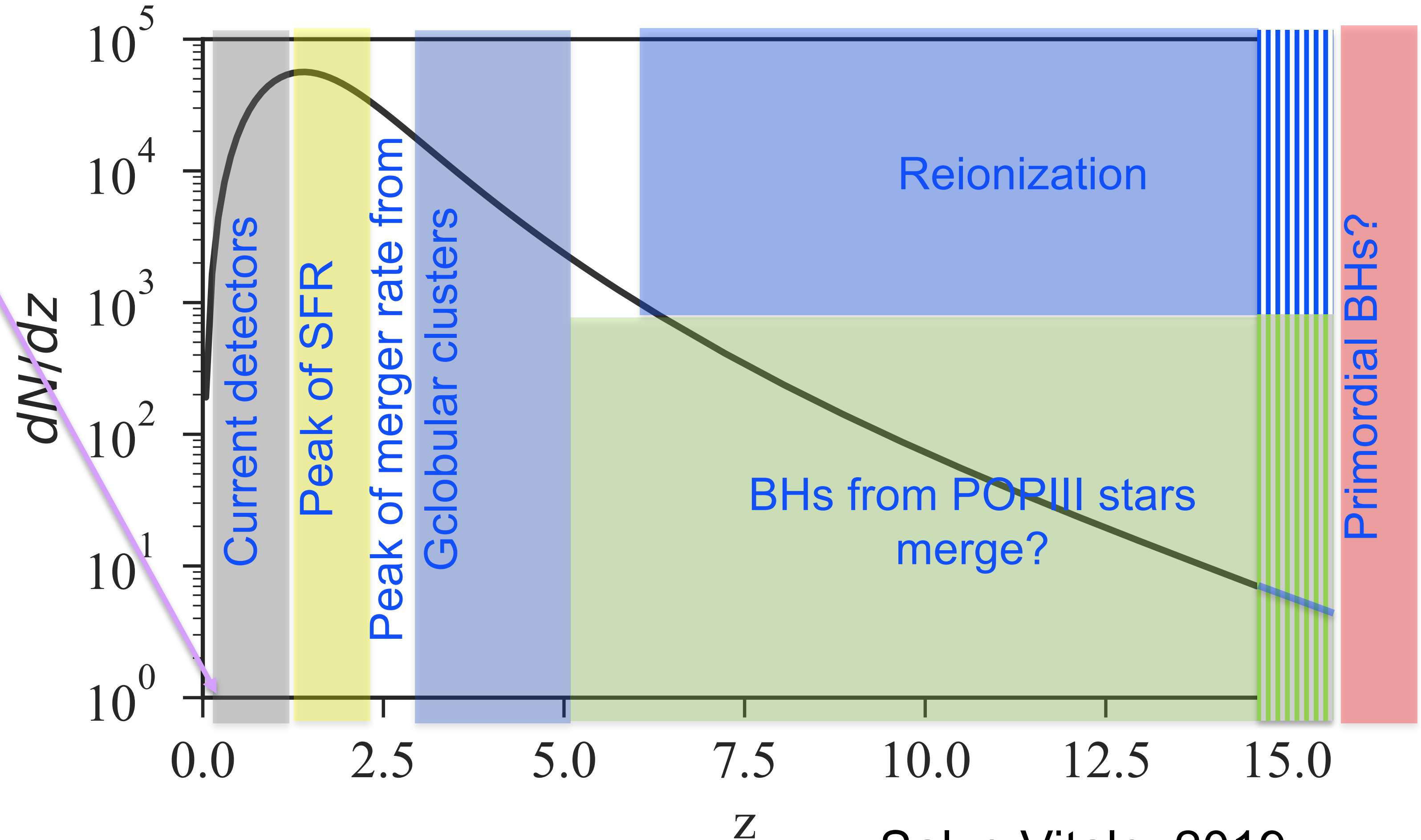
Where are we?

You are here!



Where do we go from here?

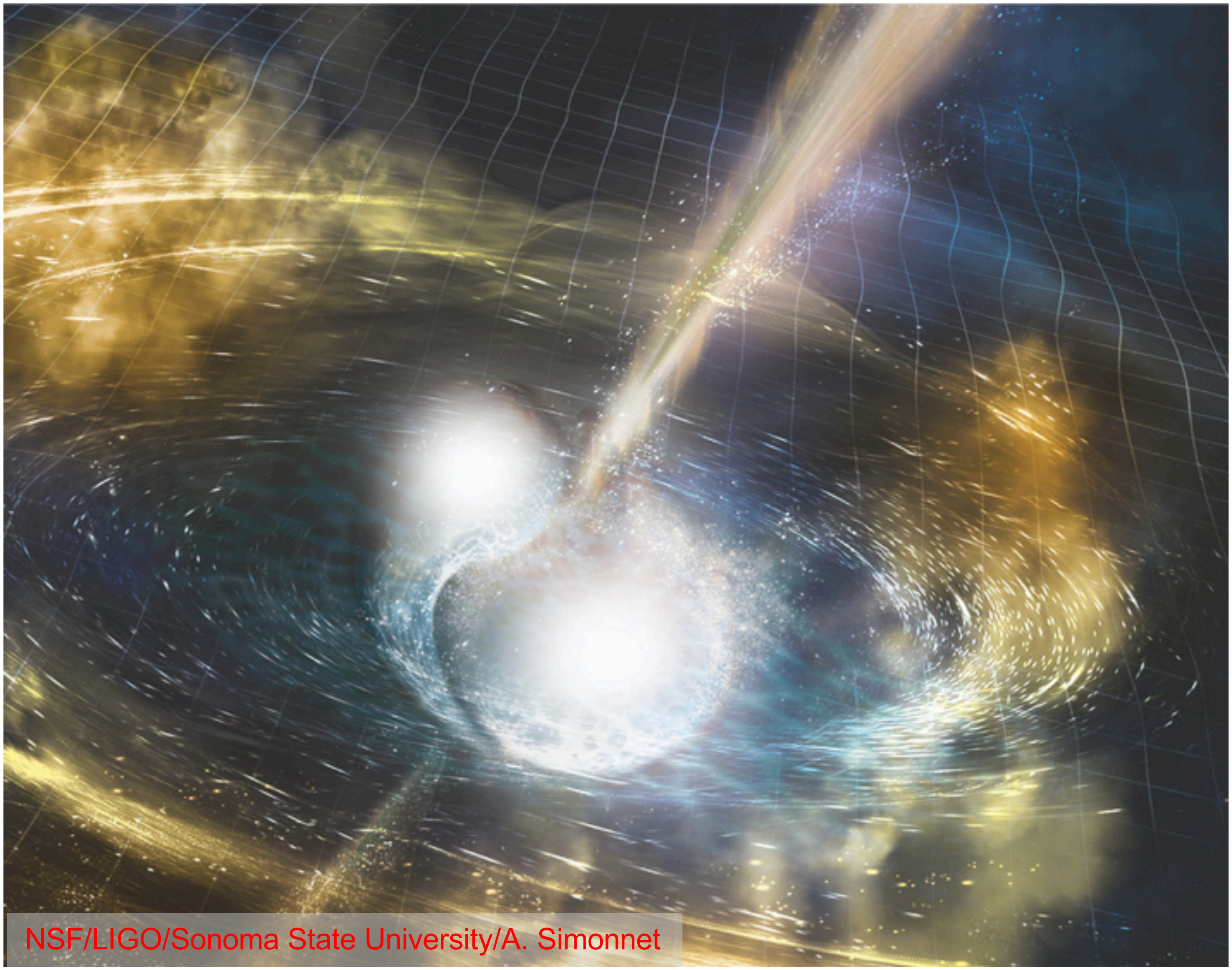
You are here!



Salvo Vitale, 2019

Obligatory ending cliché:

The future of gravitational wave astrophysics is … golden!



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

Thanks to the NSF!

And… thank you for your attention!