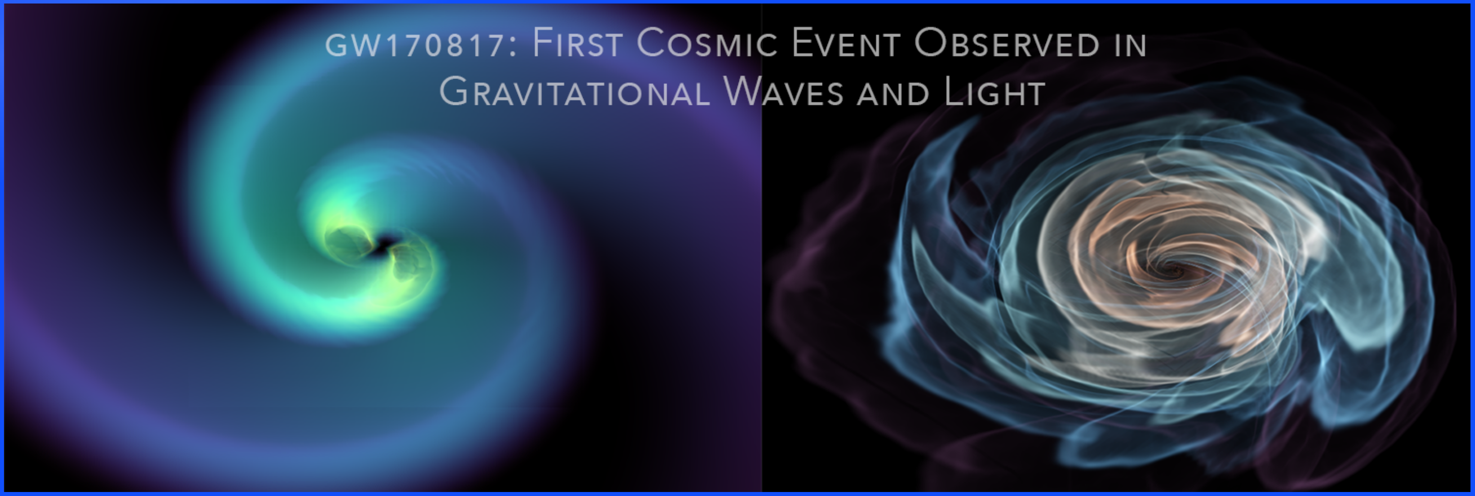
Fundamental physics with Gravitational Waves

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

2018 NASA Fundamental Physics Workshop

La Jolla, CA - April 9-11, 2018

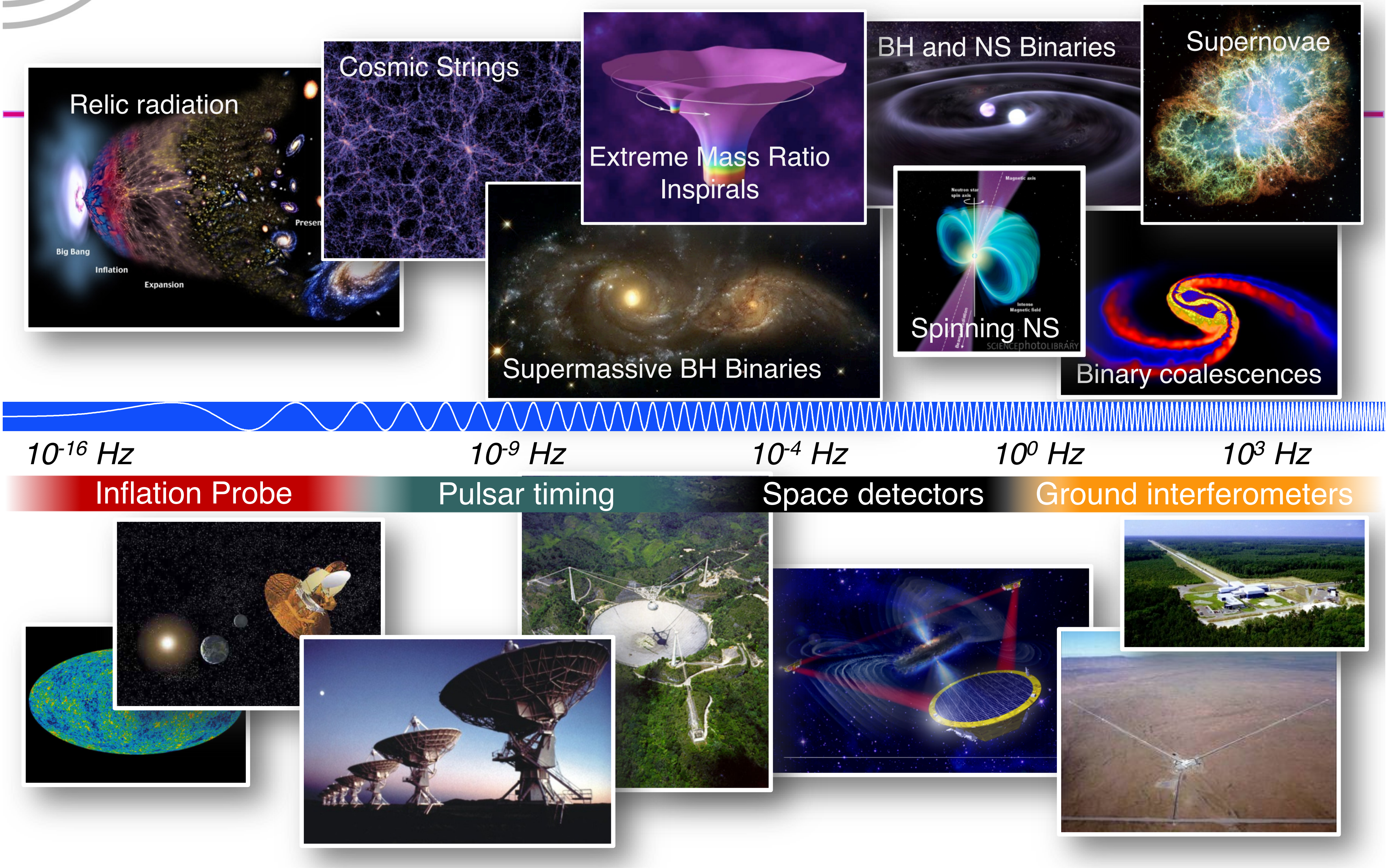


GW170817: First Cosmic Event Observed in Gravitational Waves and Light

Today’s talk – Fundamental Physics with Gravitational Waves

- What I won’t be talking about (or will only just mention):
  - What are Gravitational Waves (you know!)
  - The LIGO detectors (another talk!)
  - GW source searches: CBC, Burst, CGWs, cosmological GWs
  - BBHs and BNS discovered by LIGO & Virgo
  - Multi-messenger astronomy with GWs
  - Astrophysics with GWs – BH populations, binary formation mechanisms, etc.
- **What I will focus on: Fundamental physics with GWs**
  - **Fundamental properties of GWs:**
speed, polarization, dispersion, m_g
  - **Local Hubble parameter**
  - **Tests of GR in the strong-field, highly-dynamical regime**

The GW Spectrum



Relic radiation

Cosmic Strings

Extreme Mass Ratio Inspirals

BH and NS Binaries

Supernovae

Supermassive BH Binaries

Spinning NS

Binary coalescences

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

Inflation Probe

Pulsar timing

Space detectors

Ground interferometers

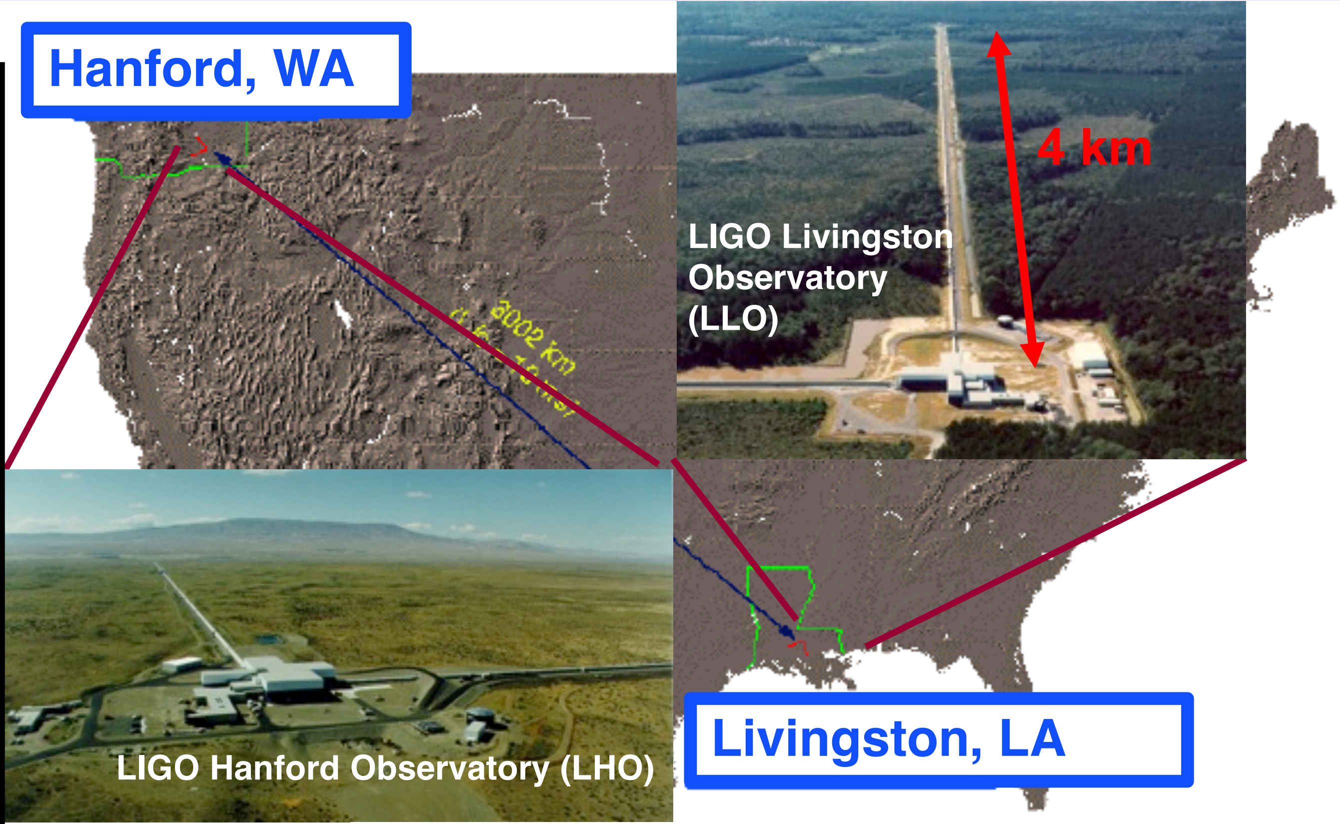
The Laser Interferometer Gravitational Wave Observatory

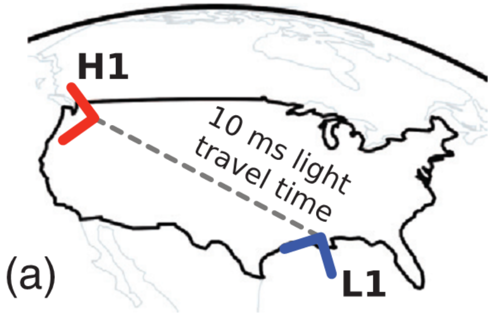
LIGO Laboratory is operated by Caltech and MIT, for the NSF.

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

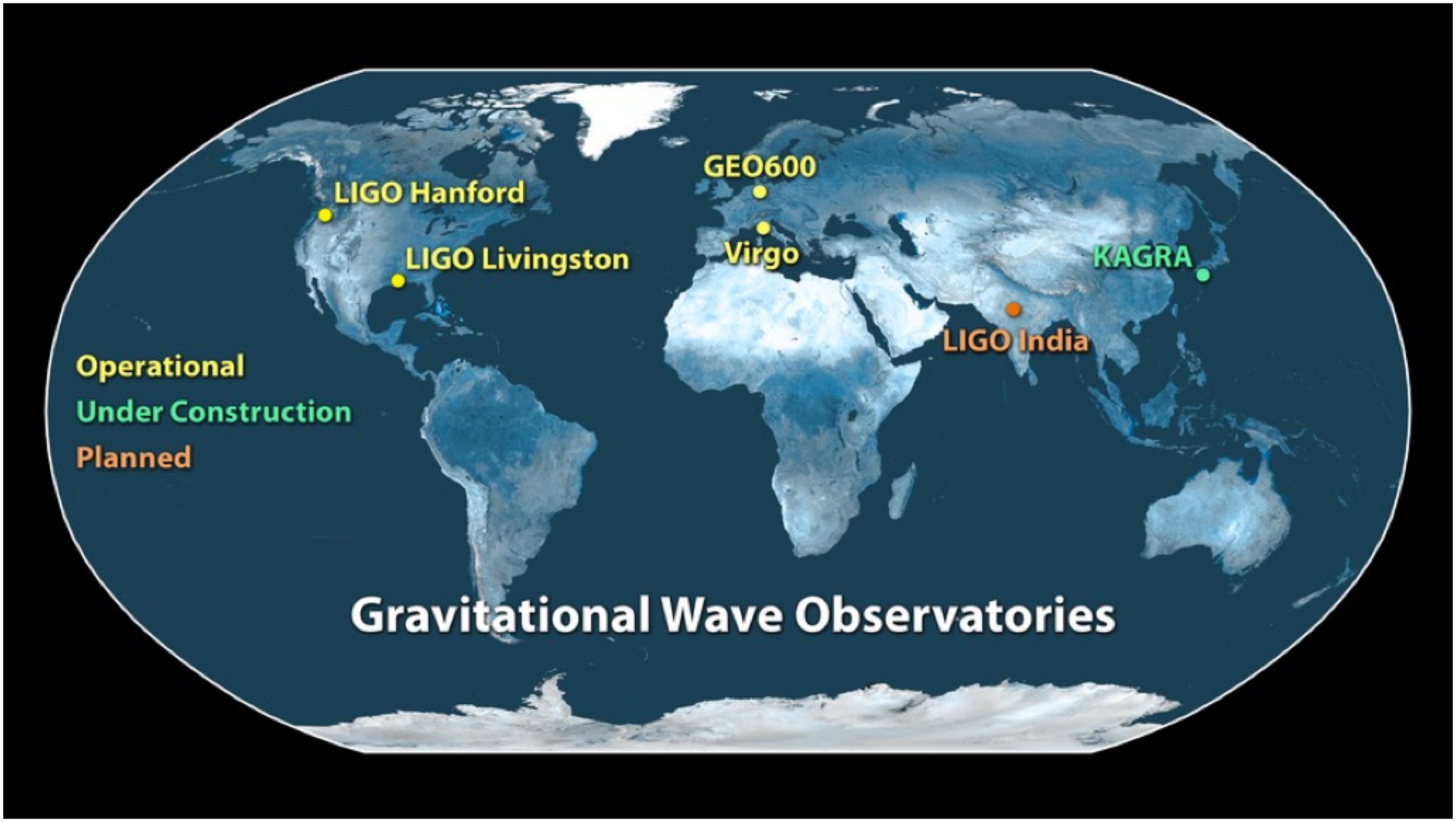
LIGO Scientific Collaboration:
~ 1000 scientists,
~80 institutions,
15 countries

Vigo Collaboration:
~ 250 scientists, Europe





Coming years: more, and more sensitive detectors



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

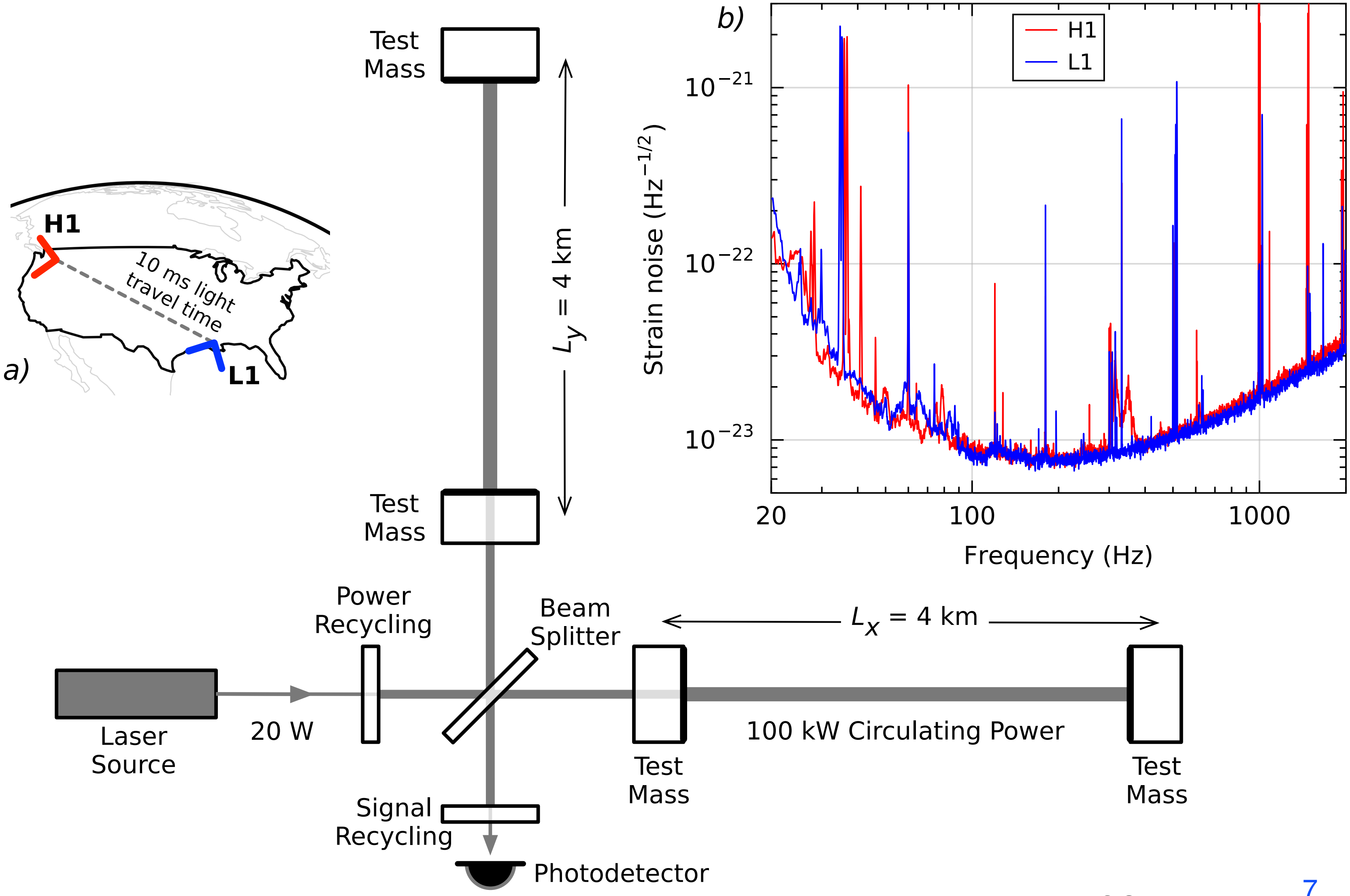
LIGO

LIGO Scientific Collaboration

LSC

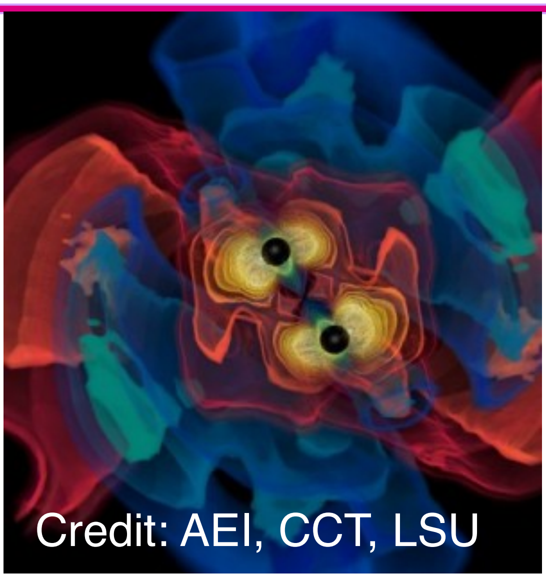
Caltech
American University Washington, DC
Andrews University
Washington State University
California State University Fullerton
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology
Leland Stanford Junior University 1891
The University Of Sheffield.
University of Maryland 1856
indigo
Texas Tech University.
PennState
清華大学 Tsinghua University
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
University of Southampton
Université de Montréal
Monash University
Polytechnique Montréal Le génie en première classe
The University of Adelaide Australia
NCSA
W Bothell
Michigan
Universitas Bruxellensis
ACU
University of Wisconsin UW Milwaukee
Trinity University
Australian National University
University of the West of Scotland UWS
University of Glasgow
Cornell University Founded A.D. 1865
Columbia University in the City of New York
Lomonosov Moscow State University
Syracuse University Founded AD 1870
OzGrav
The University of Western Australia
R·I·T
Universitas Budapestinensis de Rolando Eötvös nominata
Sonoma State University
Tsinghua University
University of Minnesota
Carleton College Northfield, Minn. 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
UH Universität Hamburg Der Forschung | Der Lehre | Der Bildung
ACIGA
Universitas Scientiarum Szegediensis
The University of Melbourne
Colorado State University
Hillsdale College
Northwestern
UF University of Florida
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

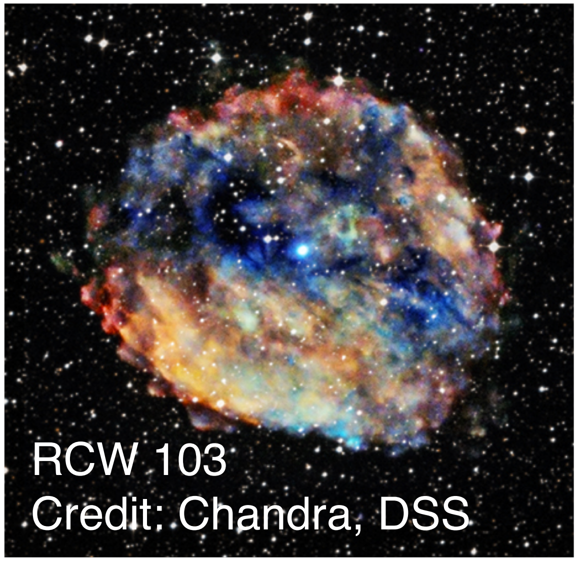
GW sources for ground-based detectors: The most energetic processes in the universe



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

- Strong emitters, well-modeled,

- (effectively) transient



Asymmetric Core Collapse Supernovae

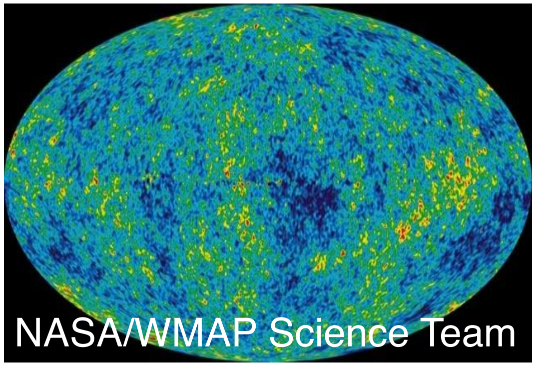
- Weak emitters, not well-modeled (‘bursts’), transient

- Cosmic strings, soft gamma repeaters, pulsar glitches also in ‘burst’ class

Spinning neutron stars

- (effectively) monotonic waveform

- Long duration

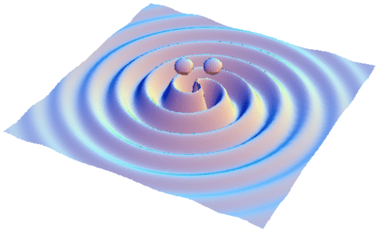


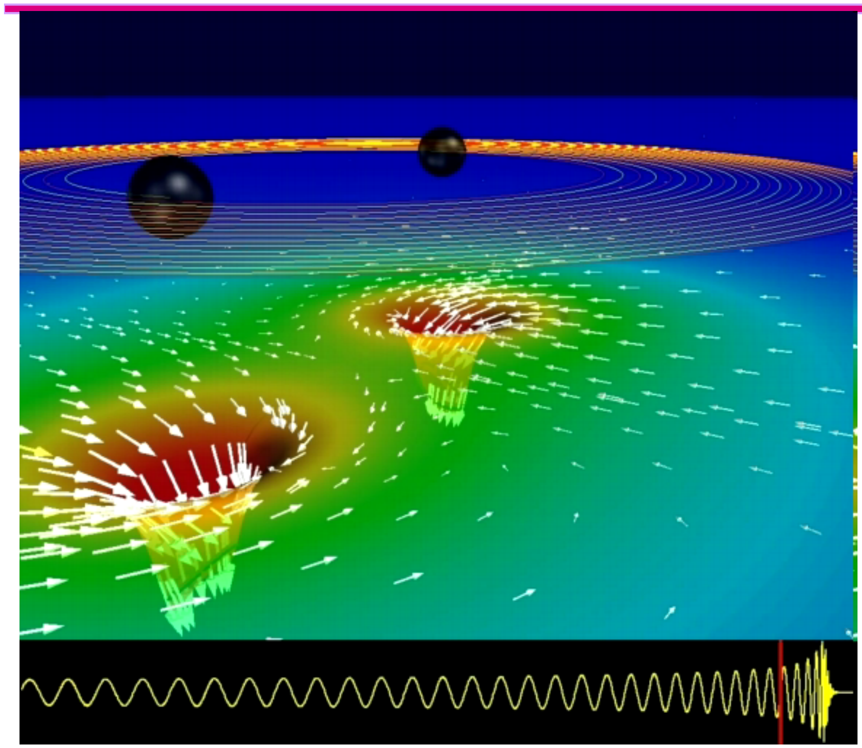
Cosmic Gravitational-wave Background

- Residue of the Big Bang, long duration

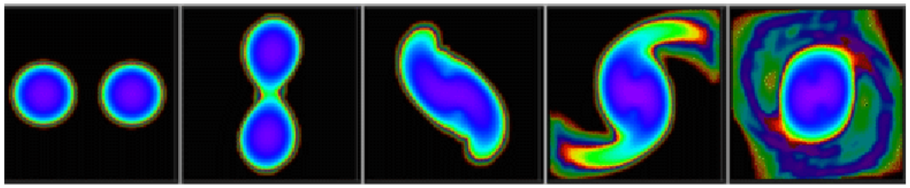
- Long duration, stochastic background

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

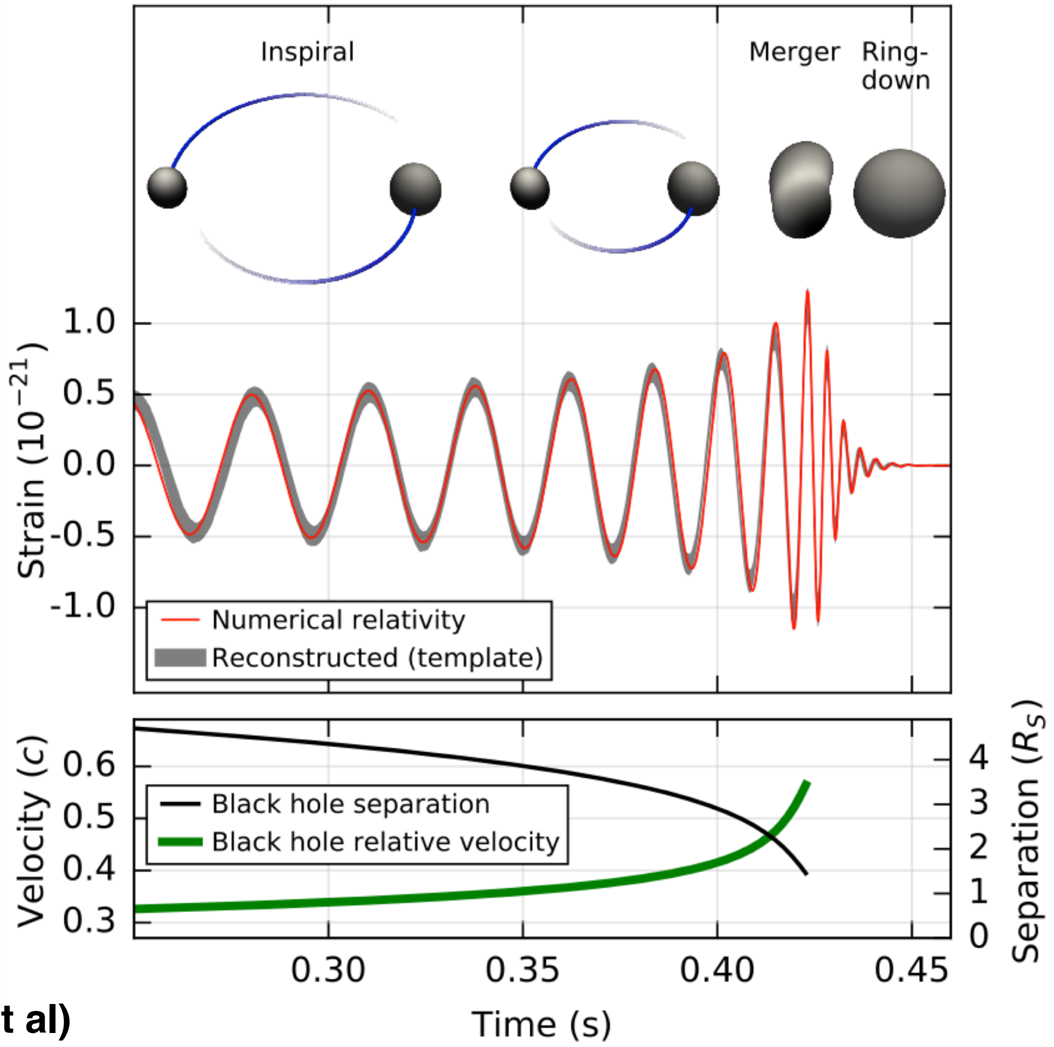




Numerical relativity computation of BBH merger (SXS Collaboration)

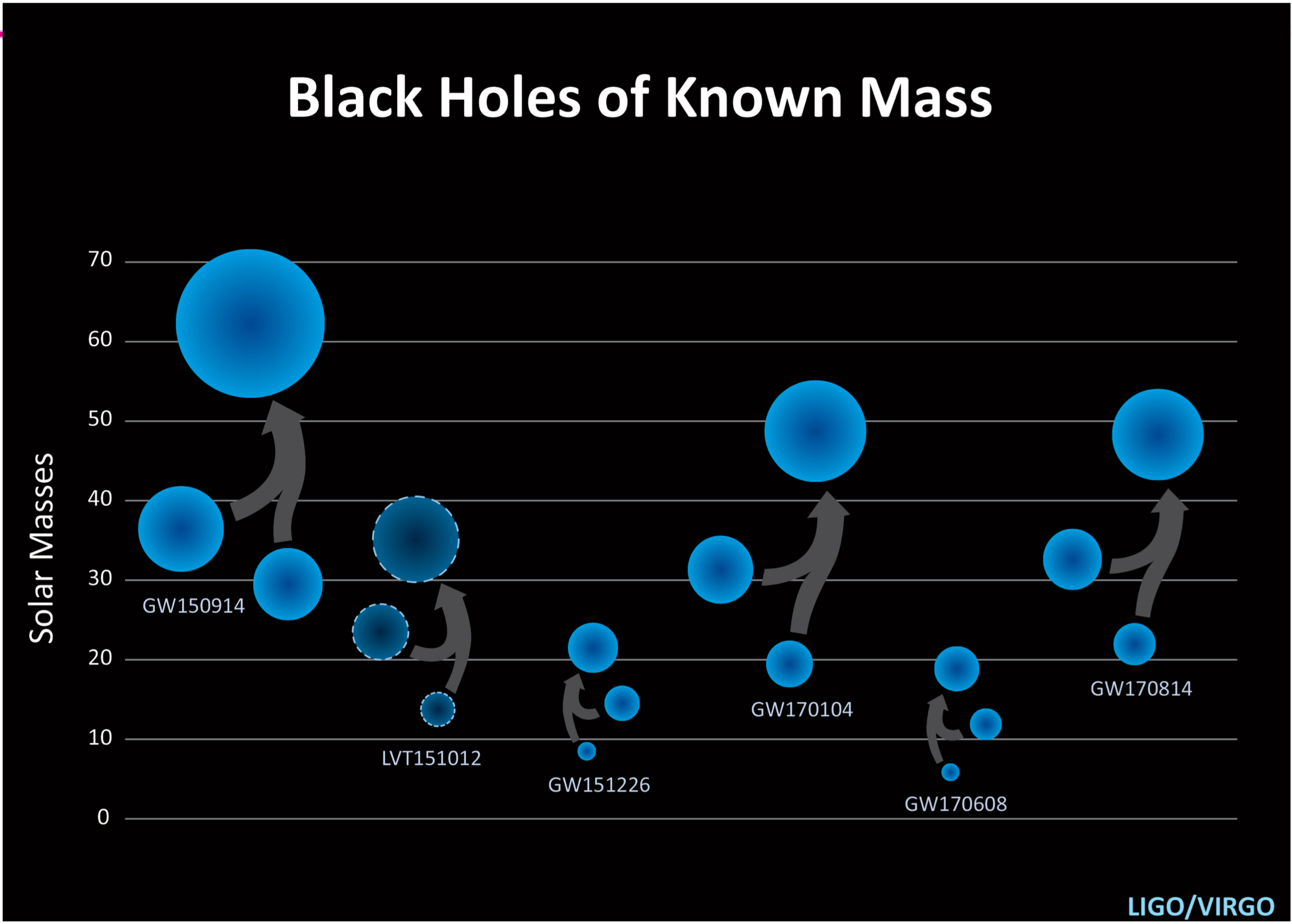


Tidal disruption of binary neutron stars (Centrella et al)

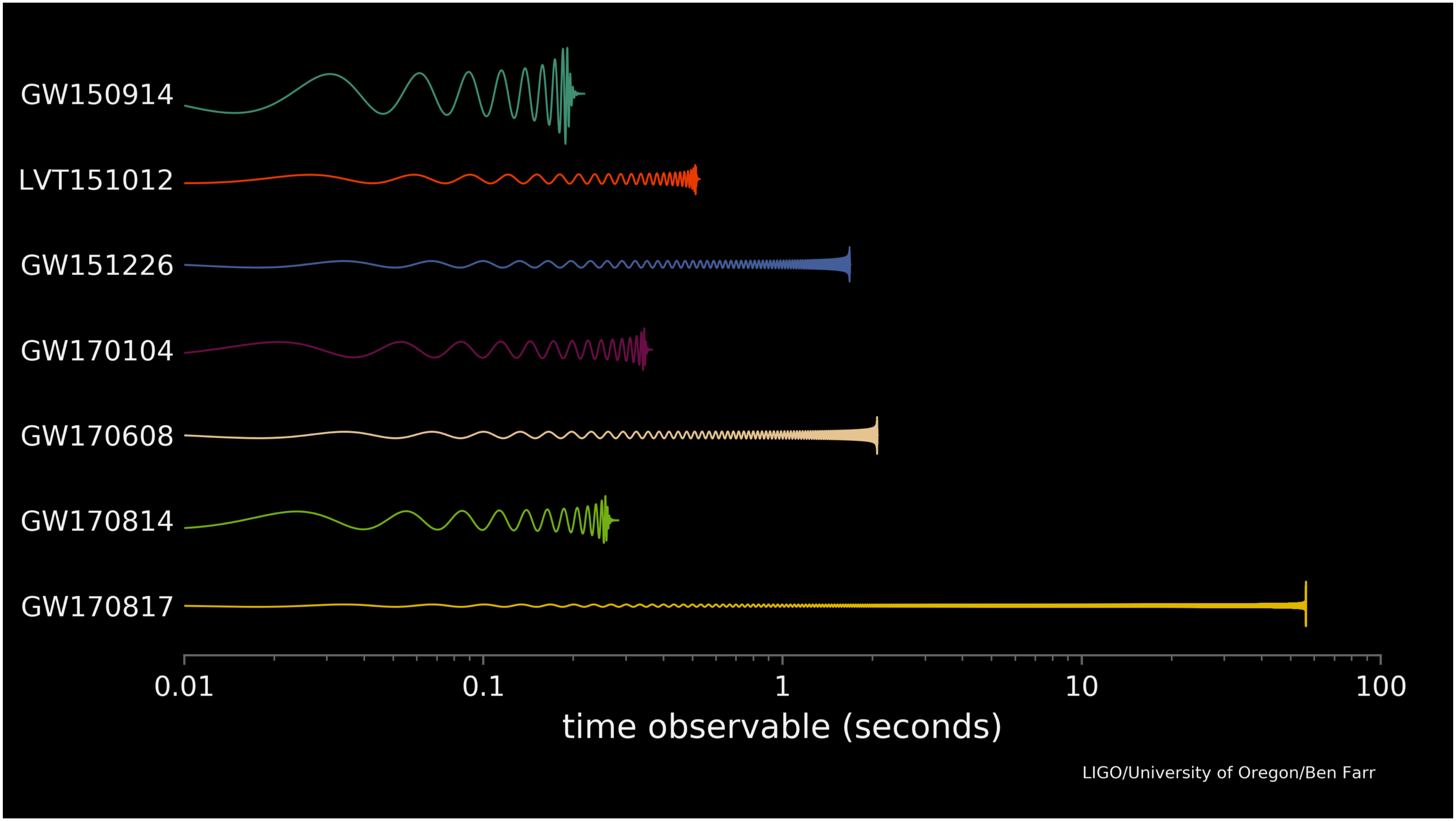


Waveform carries wealth of information about binary masses, orbit, merger

BBHs observed with LIGO.
Starting to build up a mass distribution

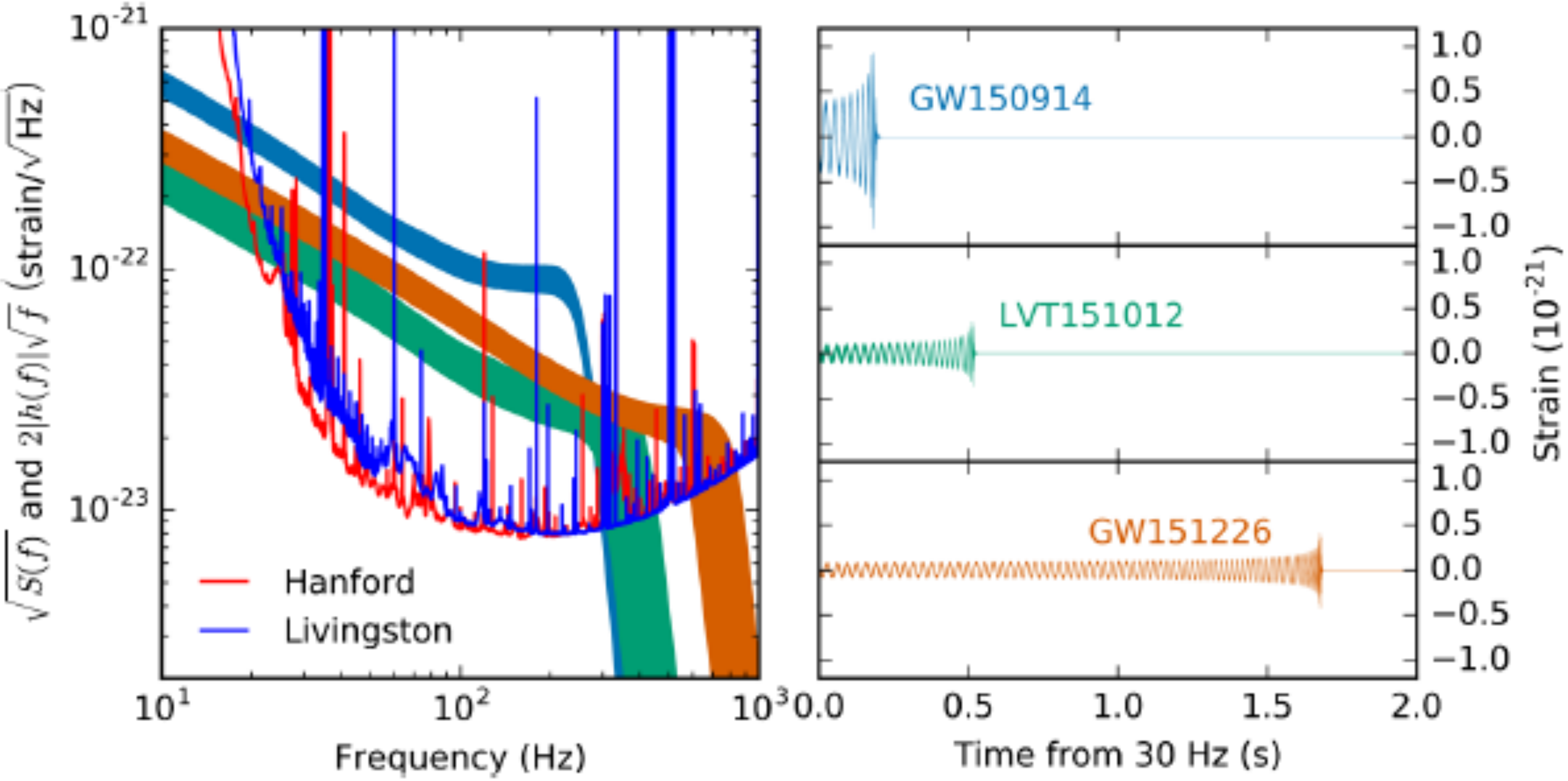


Observed signal durations (above ~30 Hz)



LIGO/University of Oregon/Ben Farr

Three BBH events, compared



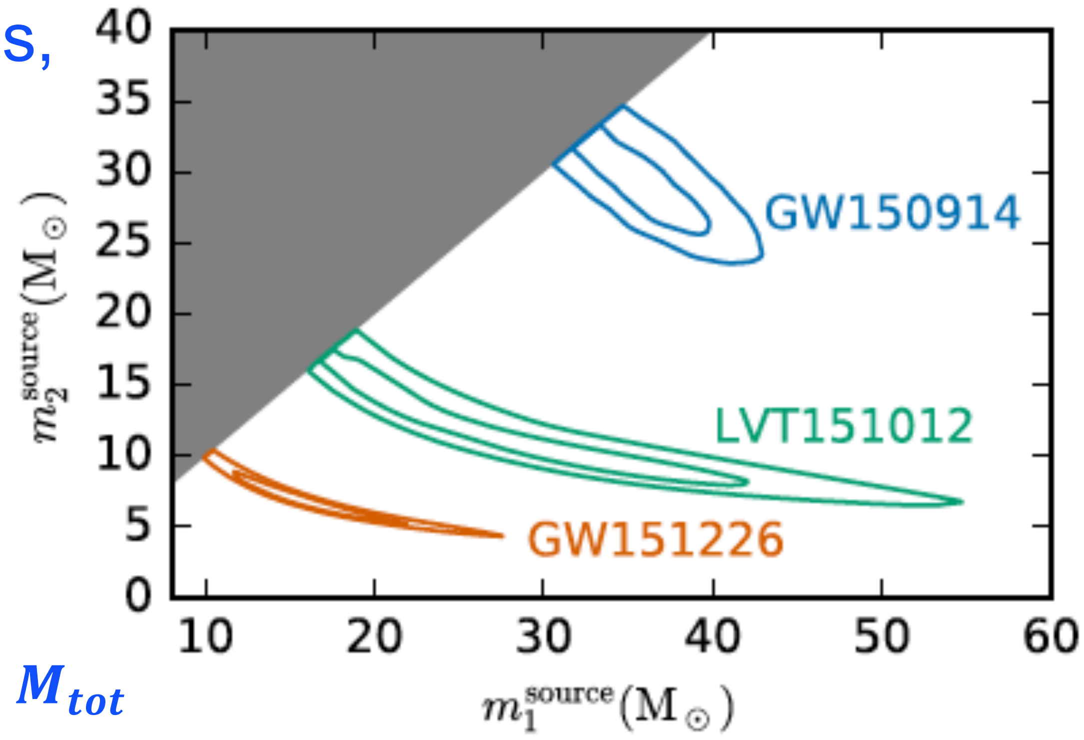
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, https://arxiv.org/abs/1606.04856, Phys. Rev. X 6, 041015 (2016)

Three BBH events, black hole masses

For the higher mass systems, we see the merger, measure $M_{tot} = m_1 + m_2$

For lower mass systems, we see the inspiral, measure the “chirp mass”

$$M_{ch} = \frac{(m_1 m_2)^{3/5}}{M_{tot}^{1/5}} = \left(\frac{m_1 m_2}{M_{tot}^2}\right)^{3/5} M_{tot}$$

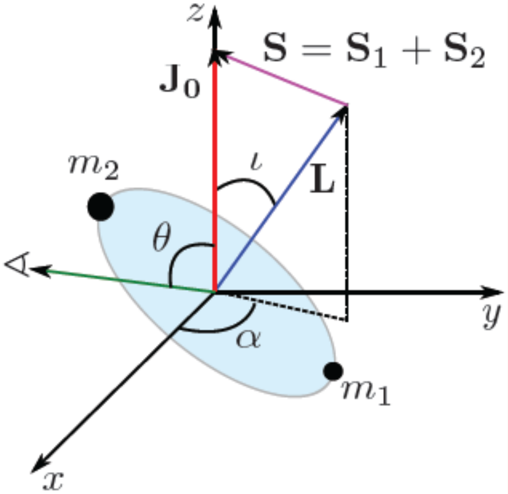


These masses are surprisingly large!

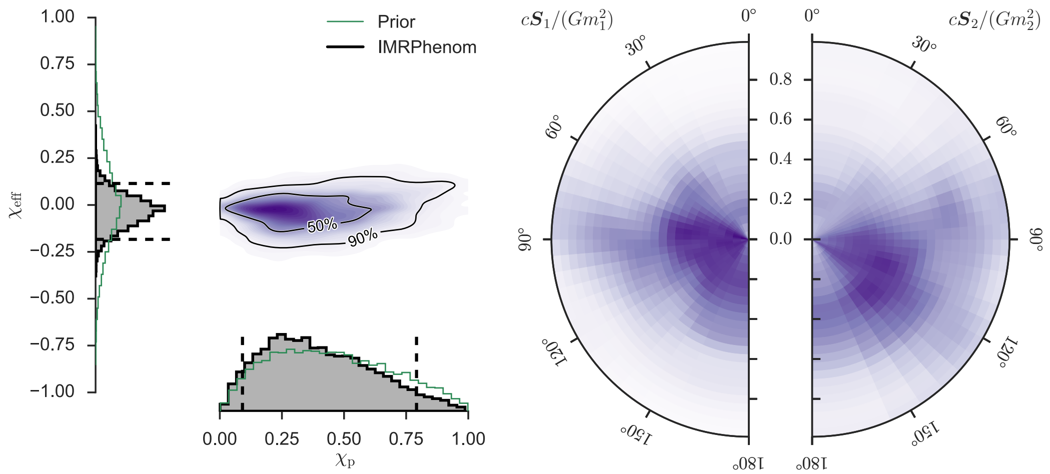
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, https://arxiv.org/abs/1606.04856, Phys. Rev. X

BH spins – aligned with orbital angular momentum, and precessing spin

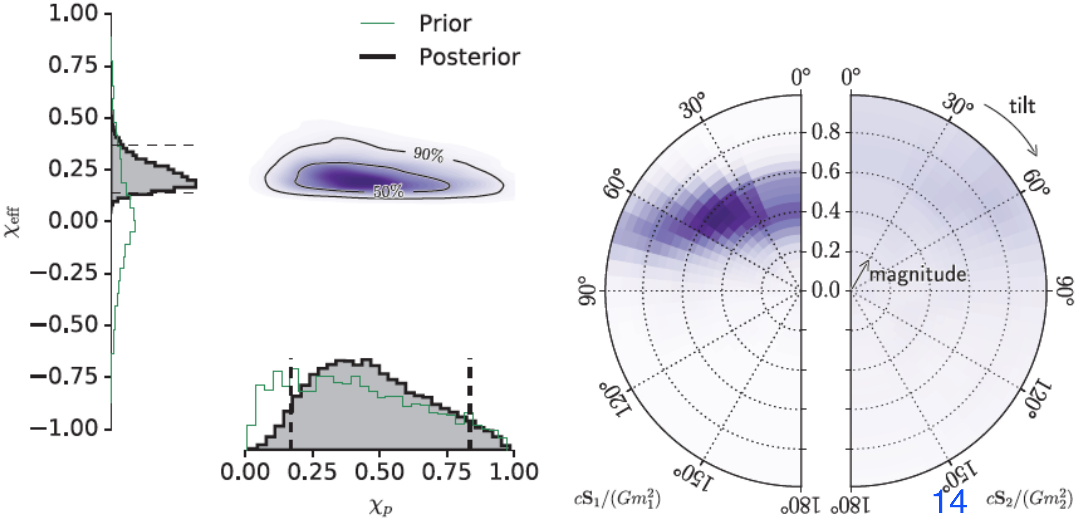
- The component BH spins measurably modulate the inspiral frequency evolution.
- Spin-orbit couplings cause the orbital plane to precess, producing amplitude modulation at the detectors.
- Parameterize with aligned spin χ_{eff} and “precessing” spin χ_P



GW150914



GW151226

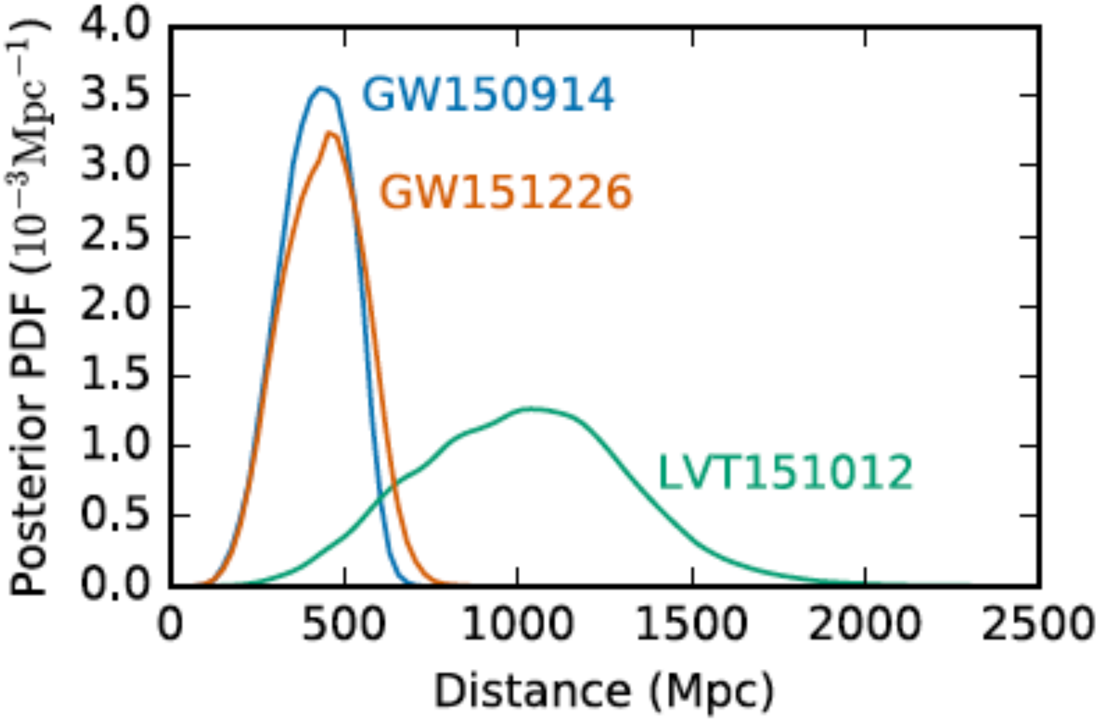


Three BBH events, distances

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

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

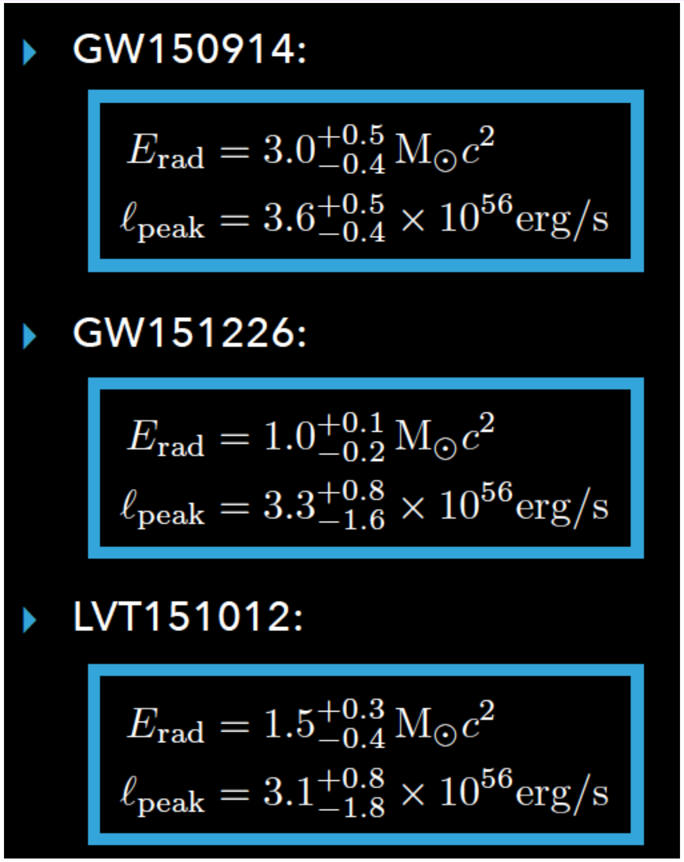
Distances measured poorly with only two detectors.



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:

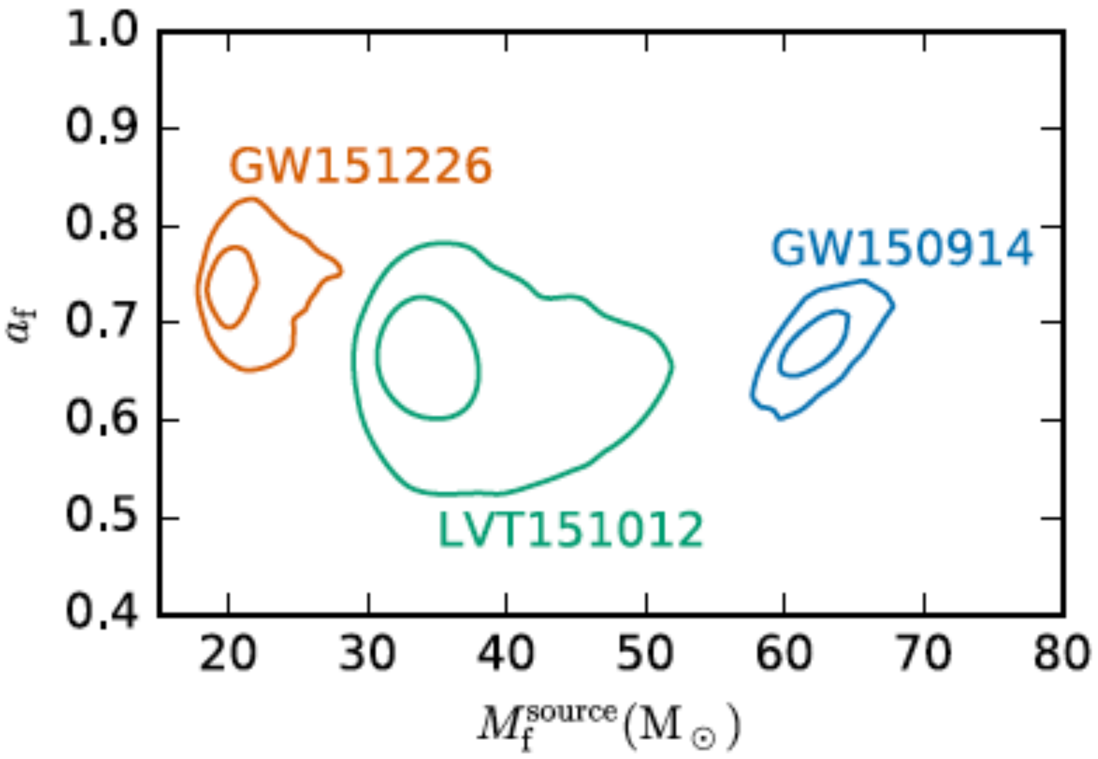
$$E_{\rm rad} = 3.0^{+0.5}_{-0.4}\,\mathrm{M}_\odot c^2$$
$$\ell_{\rm peak} = 3.6^{+0.5}_{-0.4} \times 10^{56}\,\mathrm{erg/s}$$

- GW151226:

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

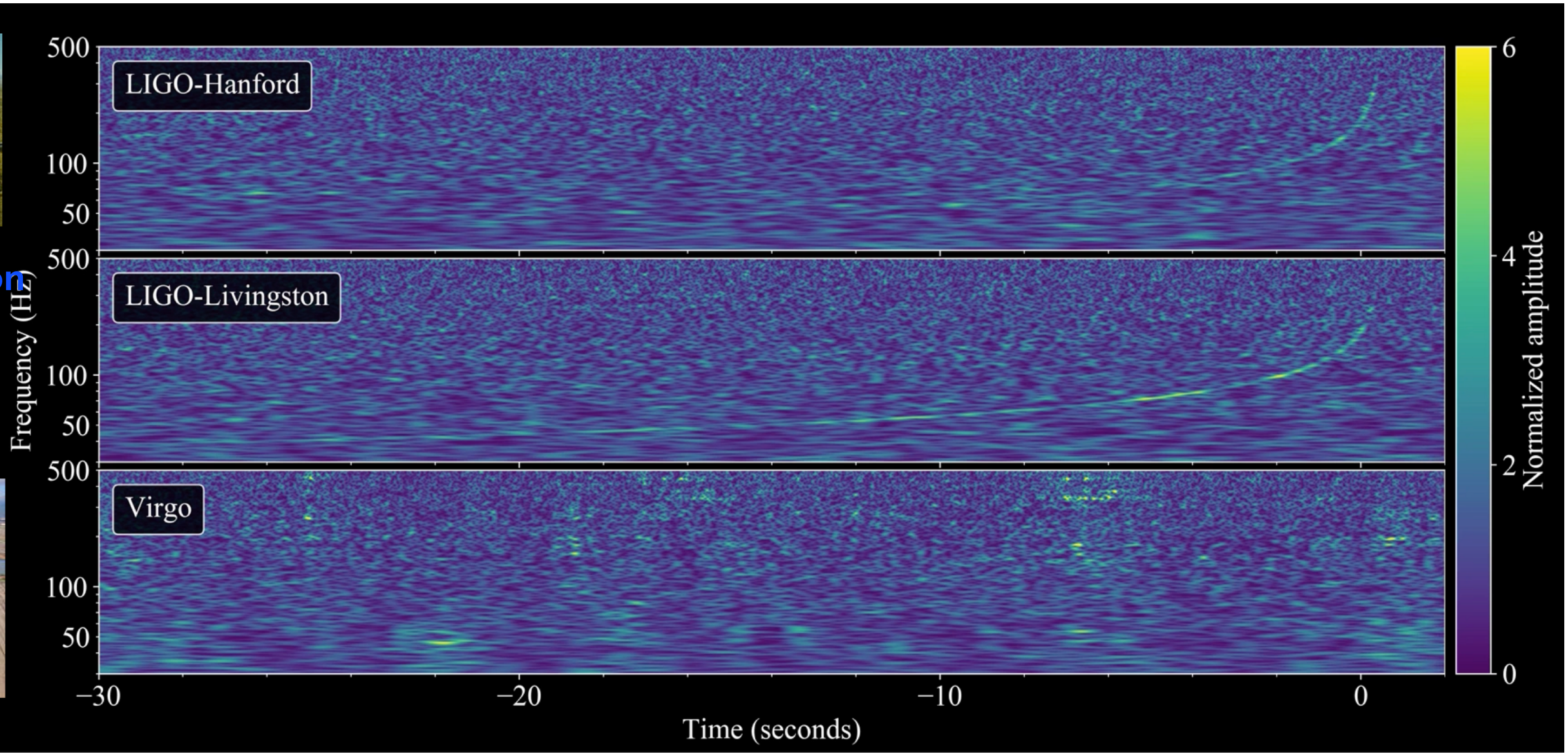
- LVT151012:

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



- 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).

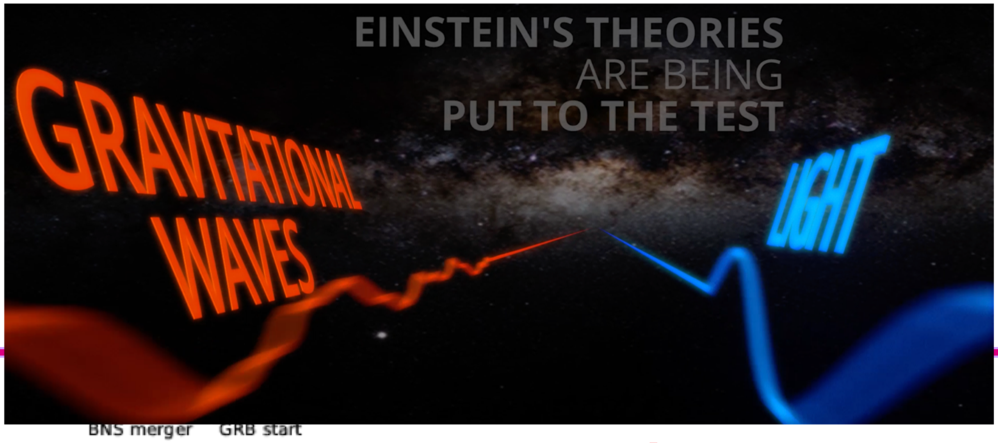
GW170817: the loudest, closest, longest duration GW signal observed so far…

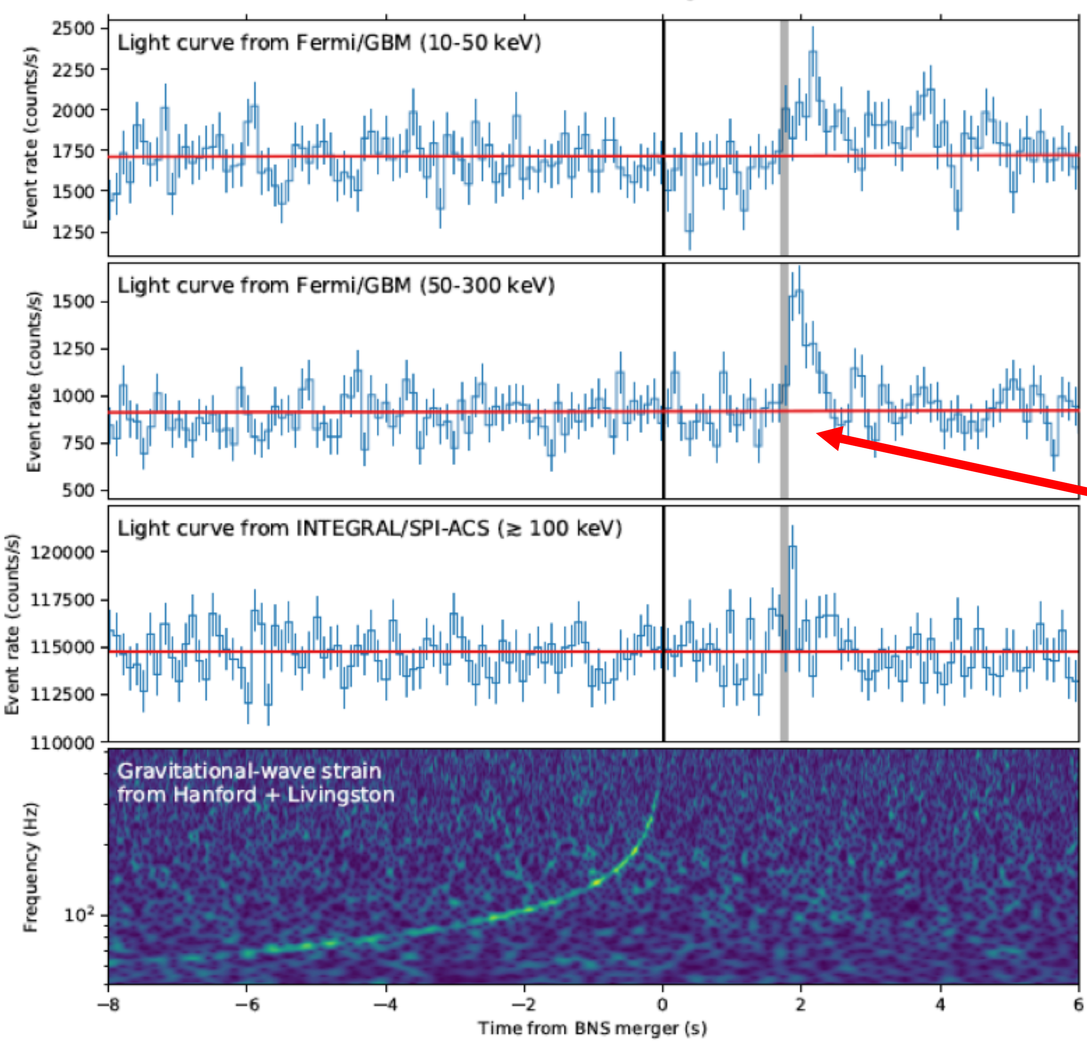


GW170817

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

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





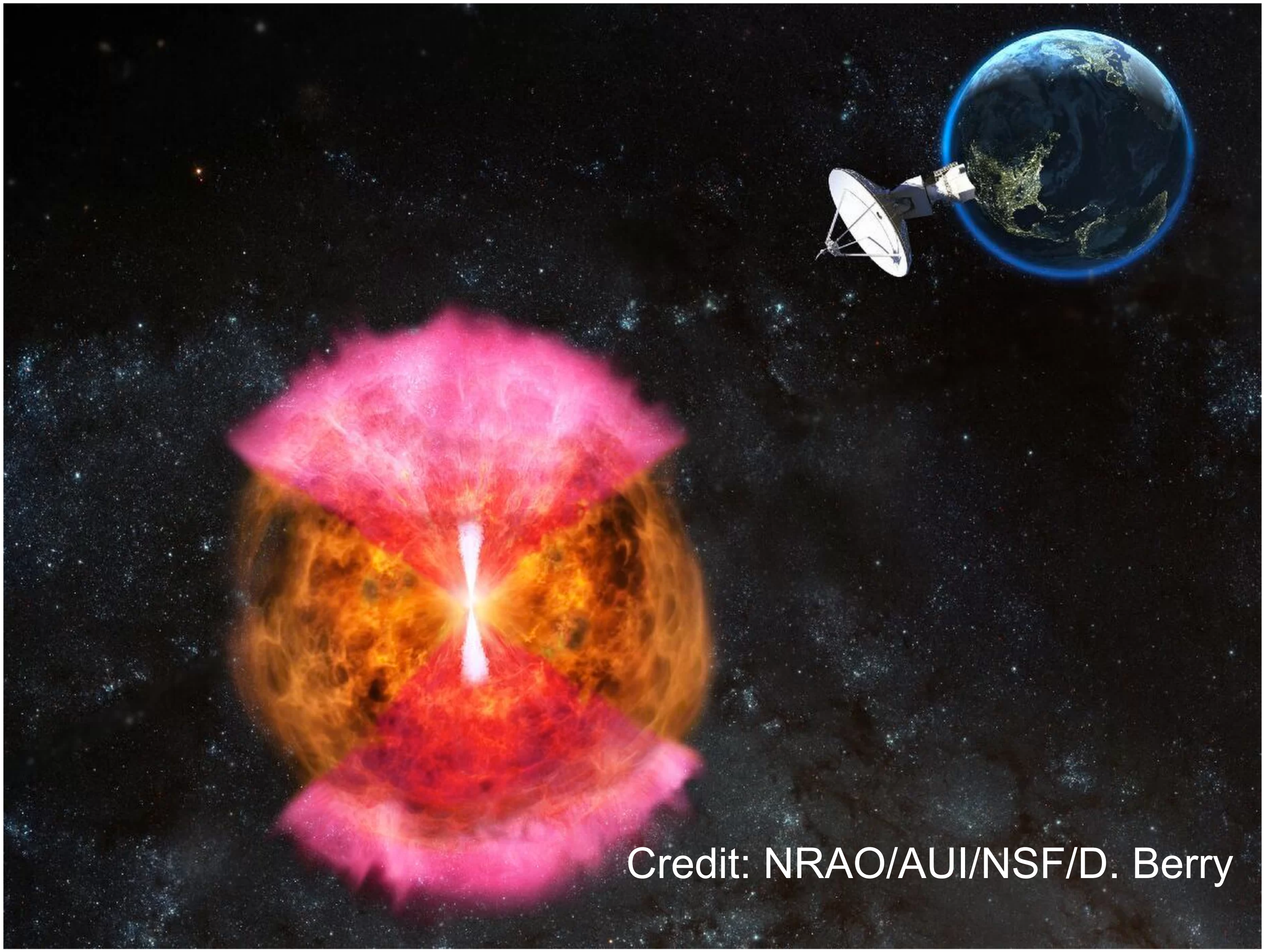
1.7 seconds later,
A short GRB!

- It has long been theorized that sGRBs come from binary neutron star mergers.
- A ~2 s delay is long for most models, but not implausible…
- But, far too wimpy for a GRB at 40 Mpc!
- “Cocoon” models could explain it.

- Fundamental properties of GWs, unique new tests of GR!

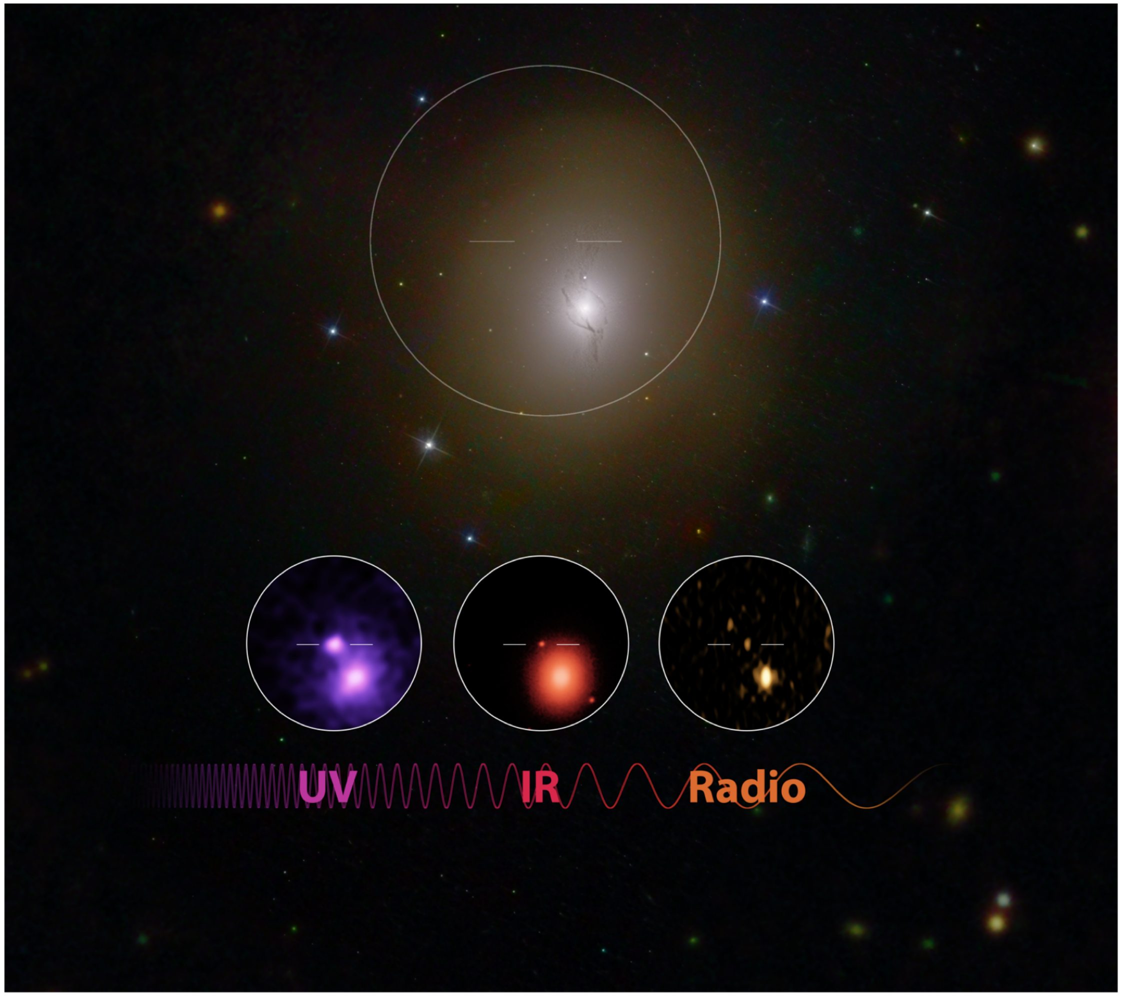
B. Abbott et al, LIGO-Virgo,
Astroph.J.Lett. 848, 2, L13 (2017)

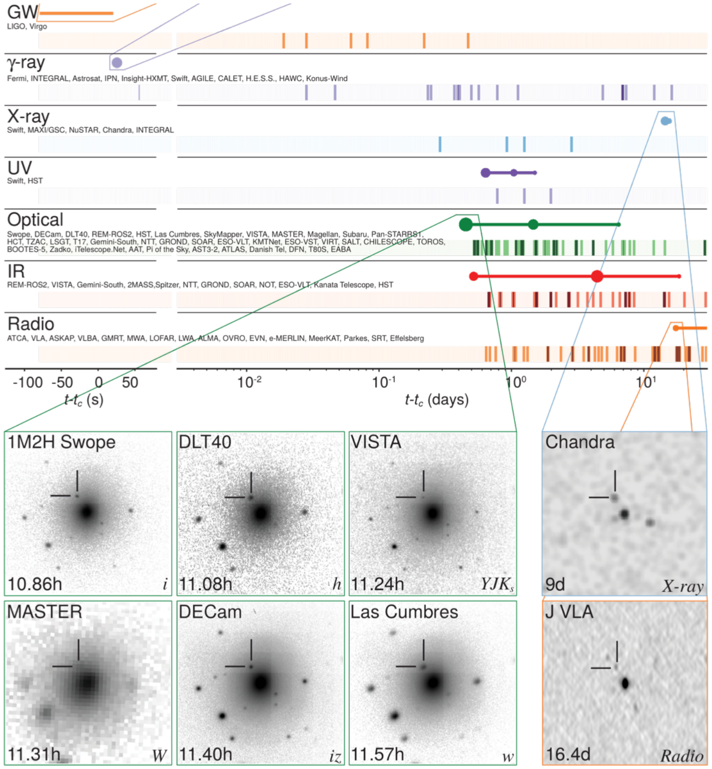
GW170817 burst of gamma rays: choked jet "cocoon" model

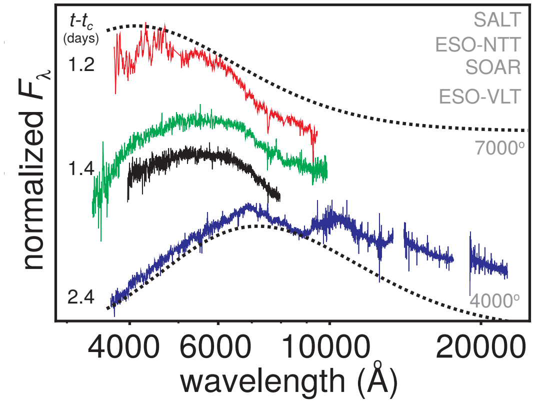


Credit: NRAO/AUI/NSF/D. Berry

Light at Every Wavelength





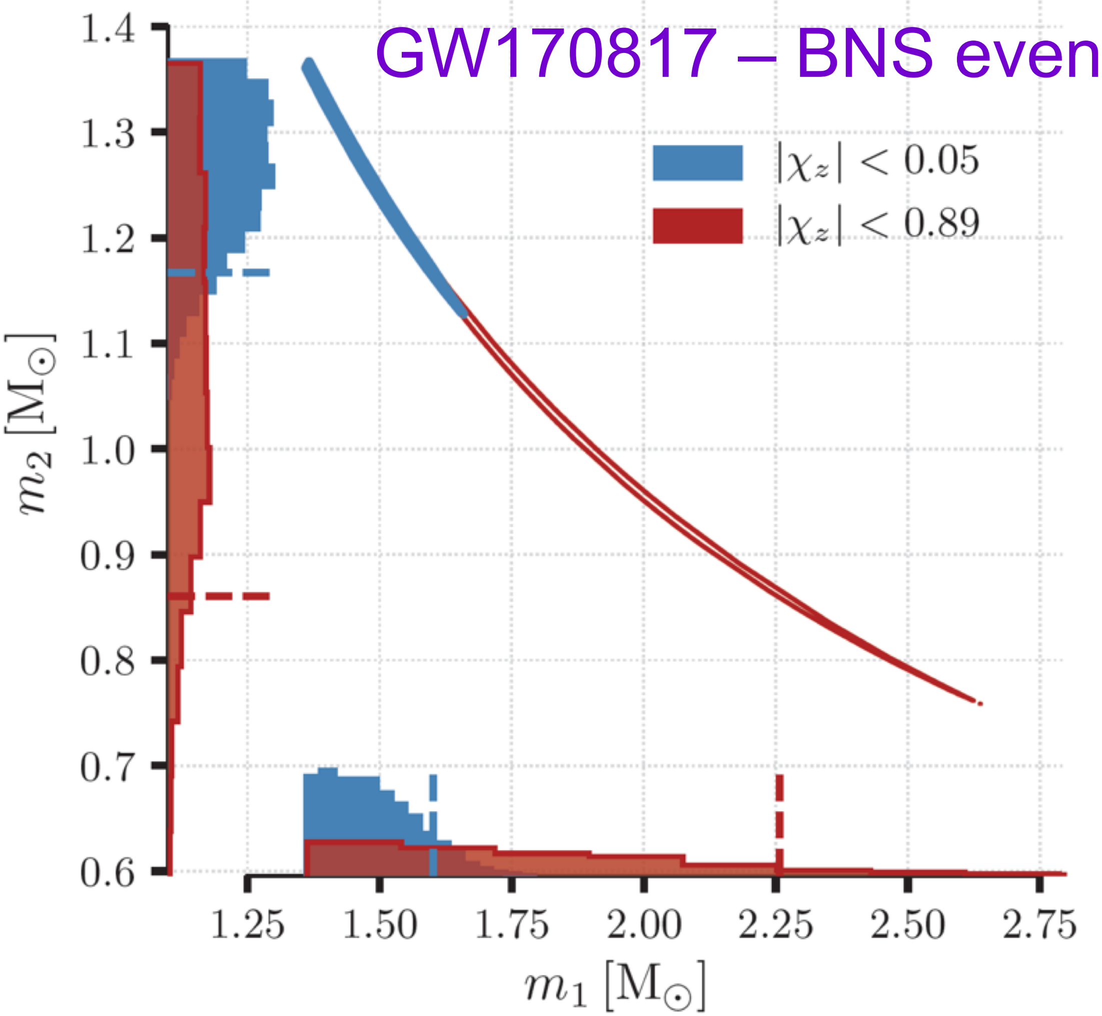


Host galaxy: NGC 4993; redshift: ~ 0.01

B. Abbott et al, LIGO, Virgo, many others, Astrophys. J. Lett. 848, L12 (2017)
Multi-messenger Observations of a Binary Neutron Star Merger

GWs measure the chirp mass best, the mass ratio less well.

GW170817 – BNS event



And it depends on whether we think neutron stars spin a lot or only a little.

Total mass: $M_{tot} = M_1 + M_2$

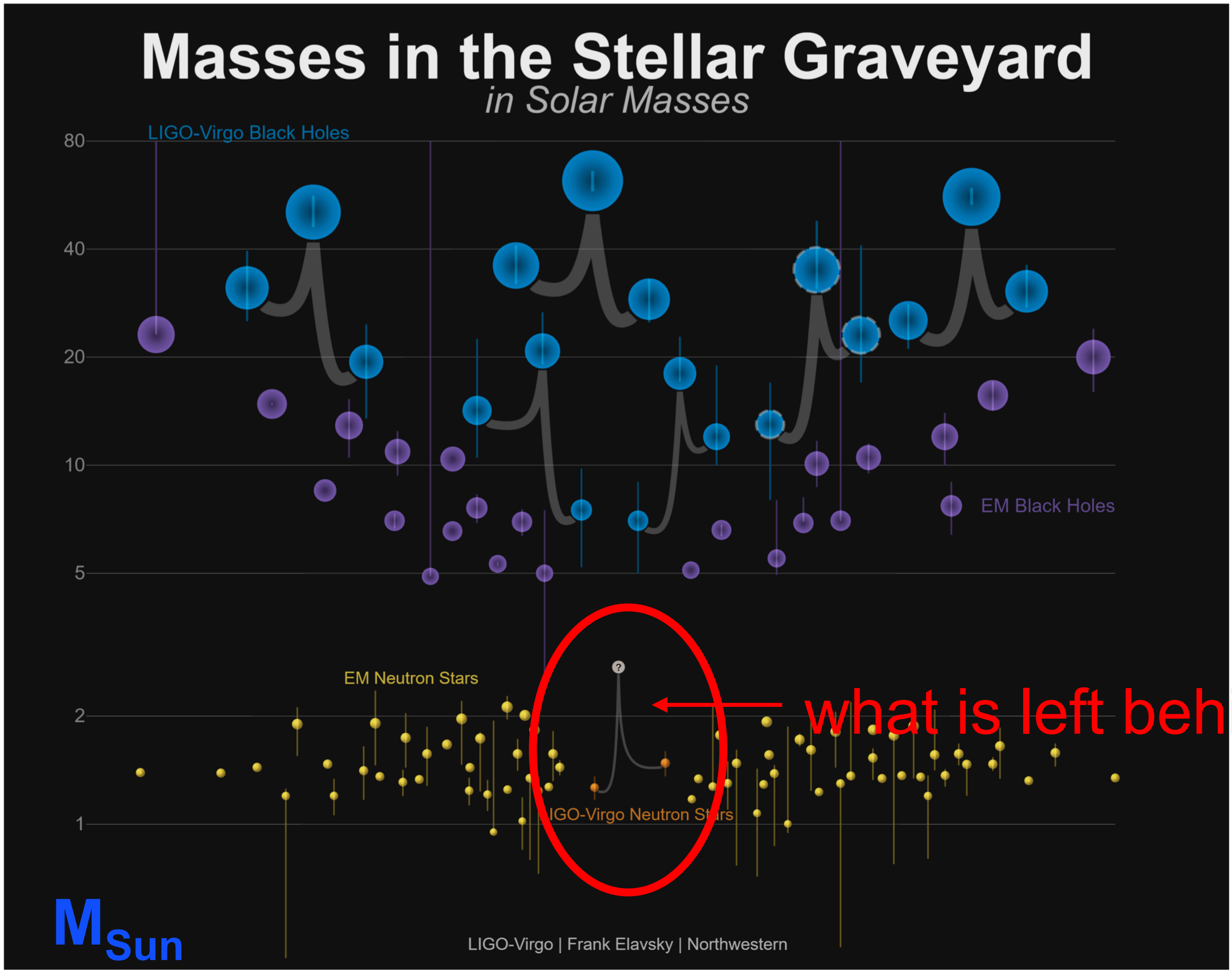
Symm. mass ratio: $\eta = M_1 M_2 / M_{tot}^2$

Chirp mass: $M_{ch} = M_{tot}\, \eta^{3/5}$

Assuming low spin, component masses are in the range 1.17 to 1.60 M$_\odot$, typical of pulsars (NSs) in binaries

B. Abbott et al, LIGO-Virgo, Phys. Rev. Lett. 119, 161101 (2017)
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

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



M_{Sun}

what is left behind?

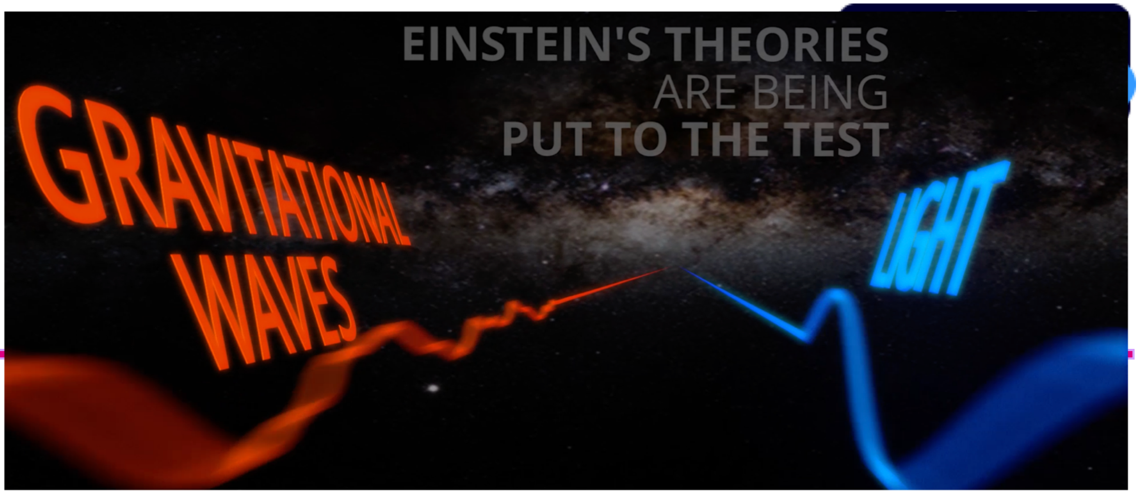
“stellar mass” black holes

“mass gap”?

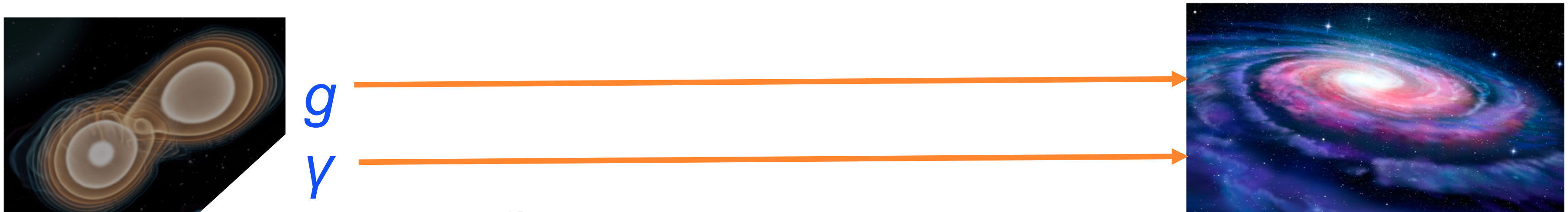
Neutron stars (pulsars)

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

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 < 13 km
- GWs, and γ-rays travelled for 130 million years (4×10^{15} s), arrived within 2 seconds of each other. The γ-rays travelled at the speed of light…
- The *"speed of gravity"* : $V_{GW} = V_{light}$ to one part in 10^{15} !
- *No dispersion: mass of the graviton* $m_g < (\text{few}) \times 10^{-23}$ 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 .



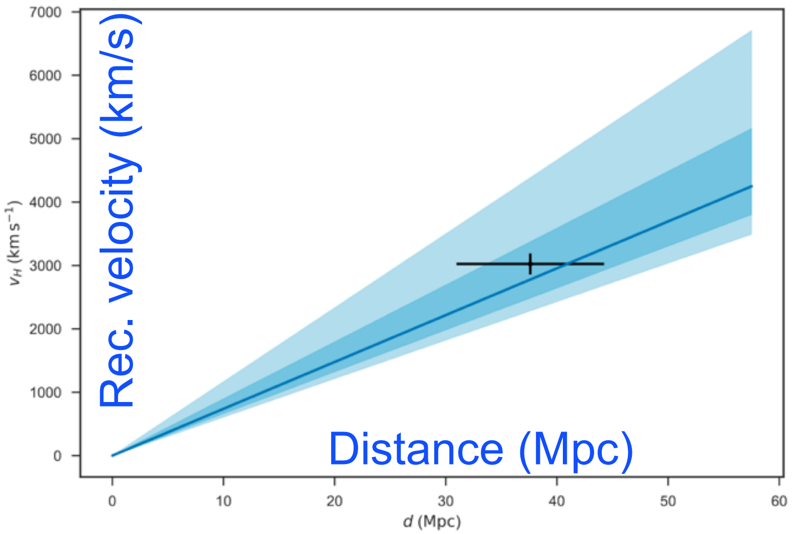
PRL 119, 161101 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

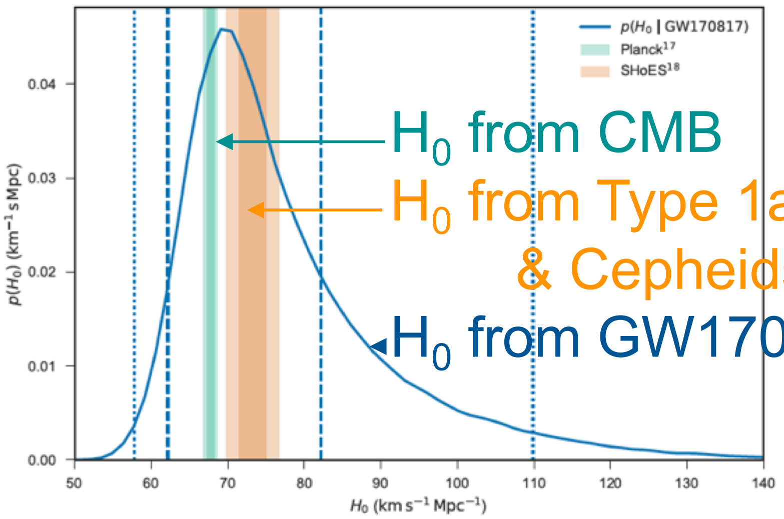
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

Tests of GR with GW170817: in prep

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!)





H_0 from CMB

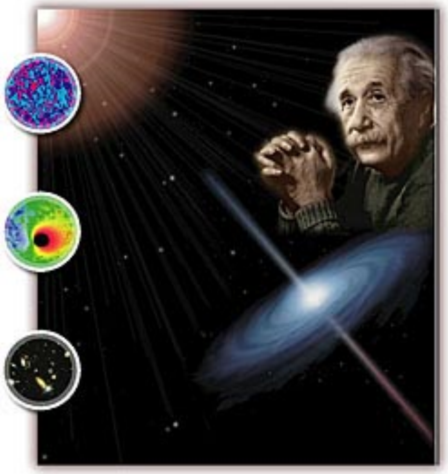
H_0 from Type 1a SN & Cepheids

H_0 from GW170817

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

A gravitational-wave standard siren measurement of the Hubble constant

Testing beyond-GR in wave generation and propagation



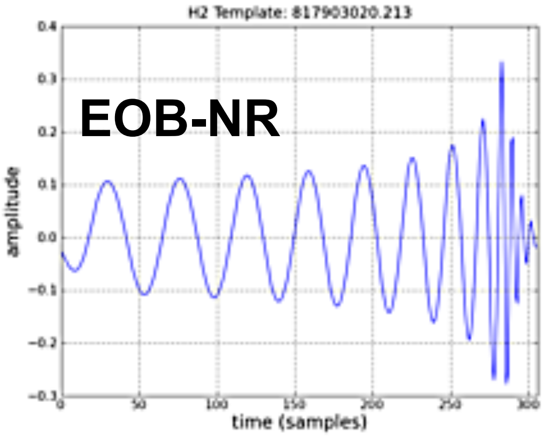
- We can test GR in the new regime of strong-field, highly dynamical gravity!
- Gravitational lensing & multiple "images" (not beyond GR!)
- Constrain "parameterized post-Einsteinian framework" (Yunes & Pretorius, 2009)
- Directly measure speed of gravitational waves ($c_{GW} \neq c_{light}$), constrain (or measure) the mass of the graviton.
- Constrain (or measure) longitudinal (vector, scalar) polarizations.
- Constrain (or measure) Lorentz violating effects.
- Constrain (or measure) cosmic anisotropies.
- Constrain (or measure) parity-violating effects.
- Constrain (or measure) dissipative gravity effects.
- Test specifically for scalar-tensor and other alt-gravity theories
- Quantum Gravity: echoes from "firewalls", …

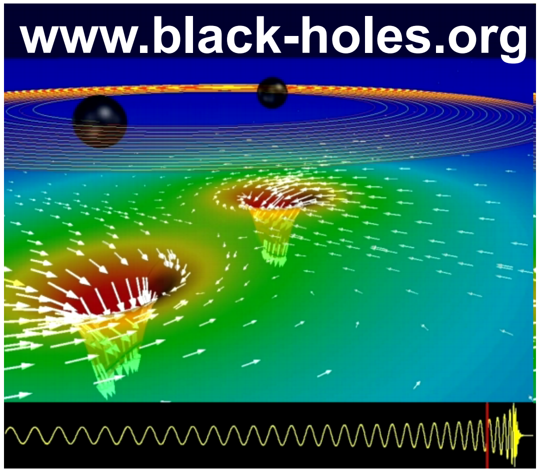
Testing General Relativity in the strong-field, dynamical regime

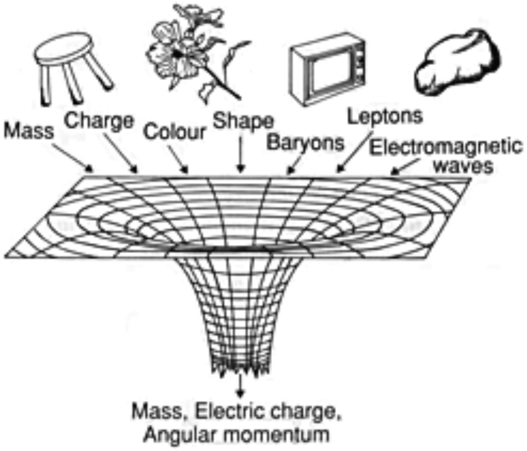
- **Test post-Newtonian expansion of inspiral phase.**

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

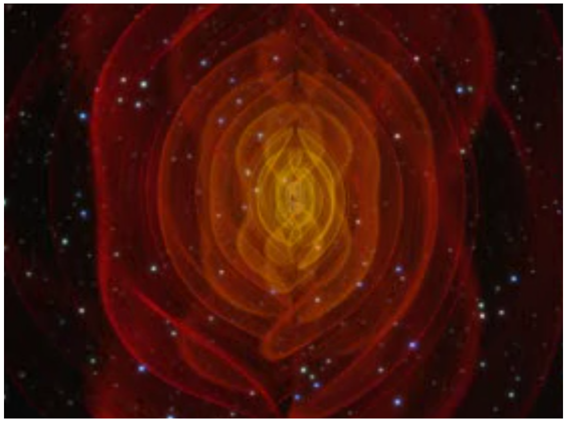
- **Test Numerical Relativity waveform prediction for merger phase.**
- **Test association of inspiral and ringdown phases: BH perturbation theory, no-hair theorem.**



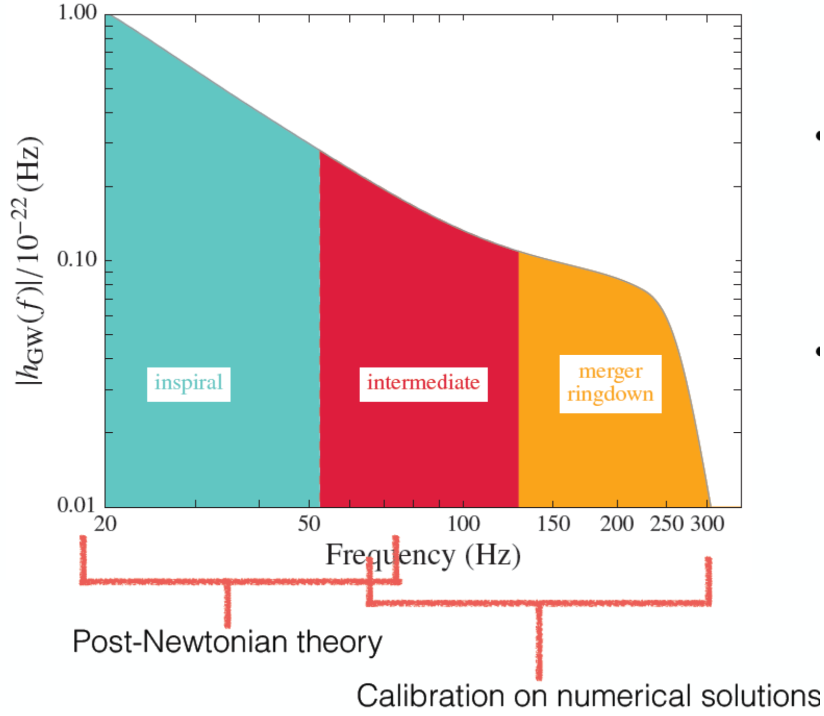

www.black-holes.org

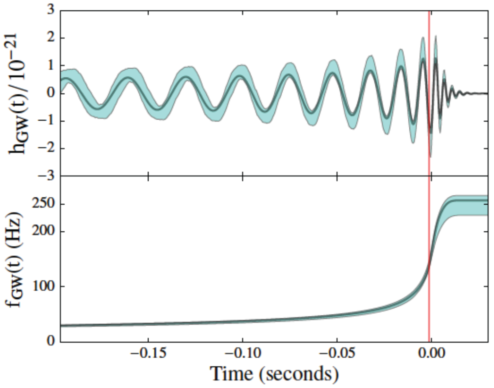


nonlocal.com/hbar/blackholes.html



Parameterized waveforms for tests of General Relativity





- Waveform models are described by post-Newtonian and phenomenological coefficients calibrated against numerical relativity (NR) solutions

$$h(f) = A(f)e^{i\Phi(f)} \qquad v_{orb}^3 = \pi G M_{tot}\, f_{GW}$$

$$\Phi(f) = \sum_{k=1}^{7}(\varphi_k + \varphi_k^l \log(f))f^{(5-k)/3} + \sum_{i\neq k}\varphi_i f^i$$

$$\varphi_j \equiv \varphi_j(m_1, m_2, \vec{s}_1, \vec{s}_2)\ \forall j = k, i$$

$$\phi_{\text{Int}} = \frac{1}{\eta}\left(\beta_0 + \beta_1 f + \beta_2 \operatorname{Log}(f) - \frac{\beta_3}{3}f^{-3}\right).$$

$$\phi_{\text{MR}} = \frac{1}{\eta}\left\{\alpha_0 + \alpha_1 f - \alpha_2 f^{-1} + \frac{4}{3}\alpha_3 f^{3/4} + \alpha_4 \tan^{-1}\left(\frac{f - \alpha_5 f_{\text{RD}}}{f_{\text{damp}}}\right)\right\}.$$

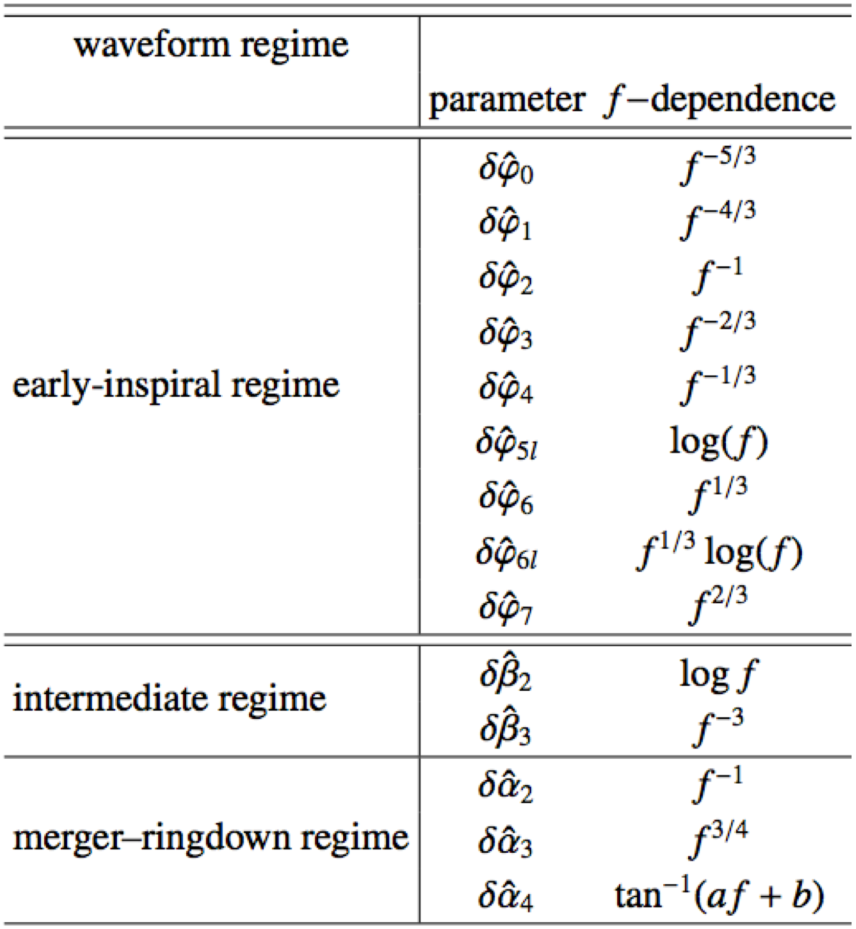
Tests of General Relativity with GW150914
Phys. Rev. Lett. 116, 221101 (2016)

Tests of consistency with predictions from General Relativity

- Waveform models are described by post-Newtonian and phenomenological coefficients calibrated against numerical relativity (NR) solutions
- We allow for fractional changes with respect to the GR value

$$\hat{\varphi}_j \rightarrow \varphi_j^{\mathrm{GR}}(1 + \delta\hat{\varphi}_j)$$

- Obtain constraints on “generic” deviations from GR



waveform regime	parameter	f–dependence
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$
	$\delta\hat{\varphi}_1$	$f^{-4/3}$
	$\delta\hat{\varphi}_2$	f^{-1}
	$\delta\hat{\varphi}_3$	$f^{-2/3}$
	$\delta\hat{\varphi}_4$	$f^{-1/3}$
	$\delta\hat{\varphi}_{5l}$	$\log(f)$
	$\delta\hat{\varphi}_6$	$f^{1/3}$
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$
	$\delta\hat{\varphi}_7$	$f^{2/3}$
intermediate regime	$\delta\hat{\beta}_2$	$\log f$
	$\delta\hat{\beta}_3$	f^{-3}
merger–ringdown regime	$\delta\hat{\alpha}_2$	f^{-1}
	$\delta\hat{\alpha}_3$	$f^{3/4}$
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af + b)$

Tests of General Relativity with GW150914
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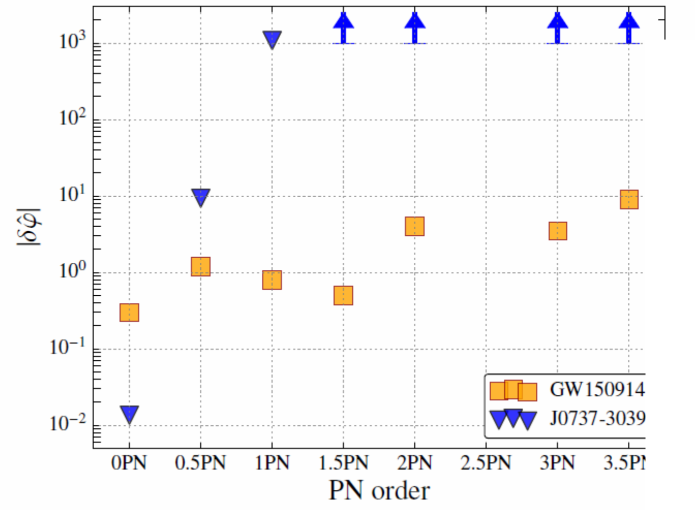
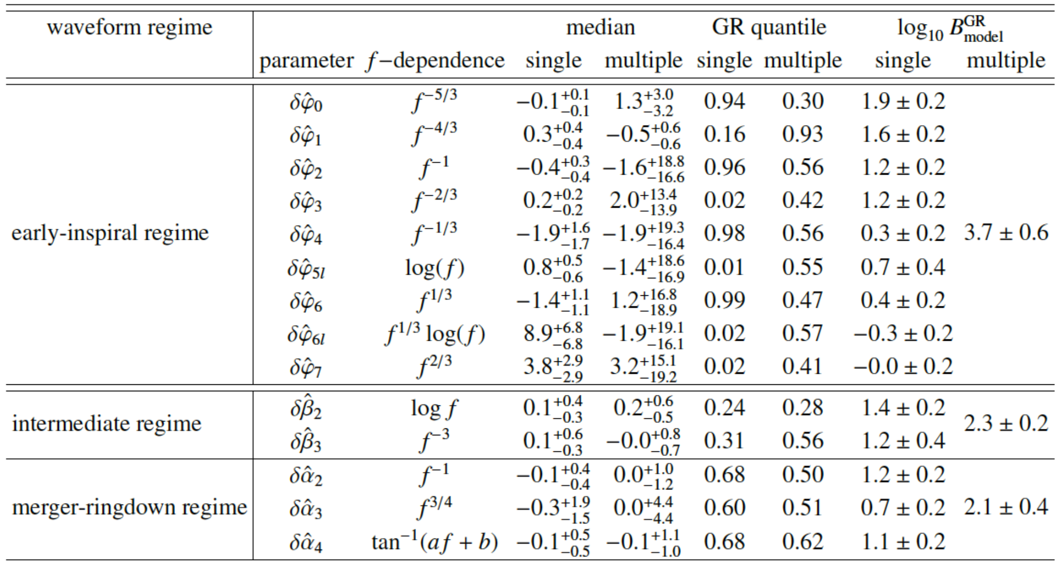
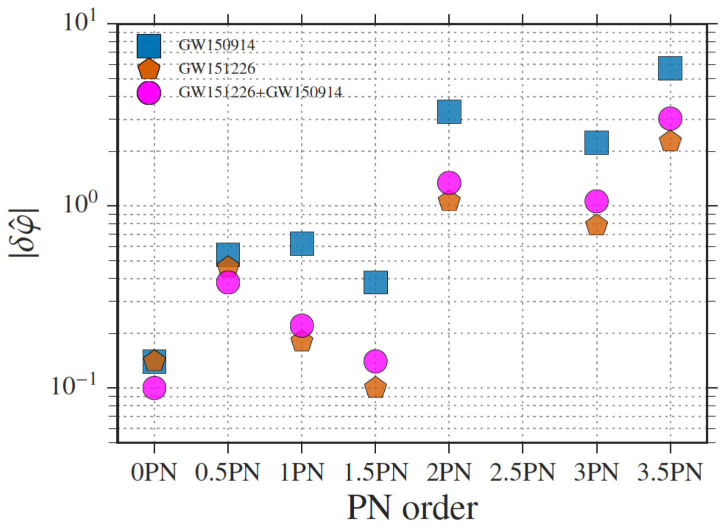
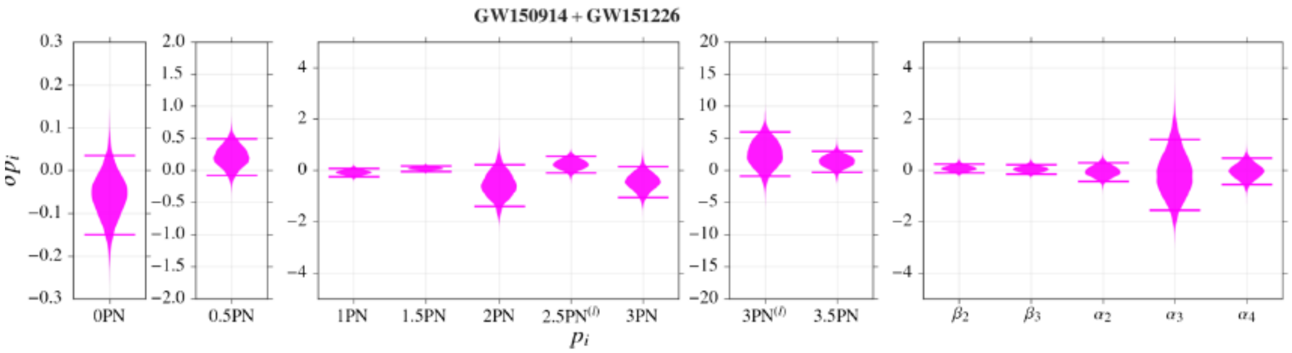
Consistency with predictions from GR – results from GW150914





waveform regime			median		GR quantile		$\log_{10} B^{\mathrm{GR}}_{\mathrm{model}}$	
	parameter	f−dependence	single	multiple	single	multiple	single	multiple
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$	$-0.1^{+0.1}_{-0.1}$	$1.3^{+3.0}_{-3.2}$	0.94	0.30	1.9 ± 0.2	3.7 ± 0.6
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	$0.3^{+0.4}_{-0.4}$	$-0.5^{+0.6}_{-0.6}$	0.16	0.93	1.6 ± 0.2	
	$\delta\hat{\varphi}_2$	f^{-1}	$-0.4^{+0.3}_{-0.4}$	$-1.6^{+18.8}_{-16.6}$	0.96	0.56	1.2 ± 0.2	
	$\delta\hat{\varphi}_3$	$f^{-2/3}$	$0.2^{+0.2}_{-0.2}$	$2.0^{+13.4}_{-13.9}$	0.02	0.42	1.2 ± 0.2	
	$\delta\hat{\varphi}_4$	$f^{-1/3}$	$-1.9^{+1.6}_{-1.7}$	$-1.9^{+19.3}_{-16.4}$	0.98	0.56	0.3 ± 0.2	
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	$0.8^{+0.5}_{-0.6}$	$-1.4^{+18.6}_{-16.9}$	0.01	0.55	0.7 ± 0.4	
	$\delta\hat{\varphi}_6$	$f^{1/3}$	$-1.4^{+1.1}_{-1.1}$	$1.2^{+16.8}_{-18.9}$	0.99	0.47	0.4 ± 0.2	
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$	$8.9^{+6.8}_{-6.8}$	$-1.9^{+19.1}_{-16.1}$	0.02	0.57	-0.3 ± 0.2	
	$\delta\hat{\varphi}_7$	$f^{2/3}$	$3.8^{+2.9}_{-2.9}$	$3.2^{+15.1}_{-19.2}$	0.02	0.41	-0.0 ± 0.2	
intermediate regime	$\delta\hat{\beta}_2$	$\log f$	$0.1^{+0.4}_{-0.3}$	$0.2^{+0.6}_{-0.5}$	0.24	0.28	1.4 ± 0.2	2.3 ± 0.2
	$\delta\hat{\beta}_3$	f^{-3}	$0.1^{+0.6}_{-0.3}$	$-0.0^{+0.8}_{-0.7}$	0.31	0.56	1.2 ± 0.4	
merger-ringdown regime	$\delta\hat{\alpha}_2$	f^{-1}	$-0.1^{+0.4}_{-0.4}$	$0.0^{+1.0}_{-1.2}$	0.68	0.50	1.2 ± 0.2	2.1 ± 0.4
	$\delta\hat{\alpha}_3$	$f^{3/4}$	$-0.3^{+1.9}_{-1.5}$	$0.0^{+4.4}_{-4.4}$	0.60	0.51	0.7 ± 0.2	
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af+b)$	$-0.1^{+0.5}_{-0.5}$	$-0.1^{+1.1}_{-1.0}$	0.68	0.62	1.1 ± 0.2	

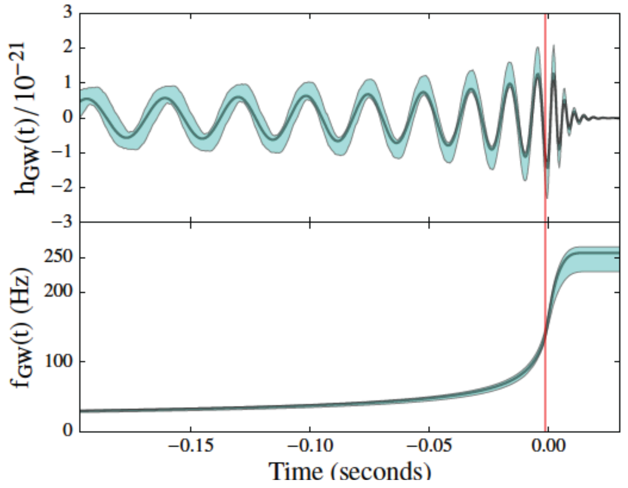


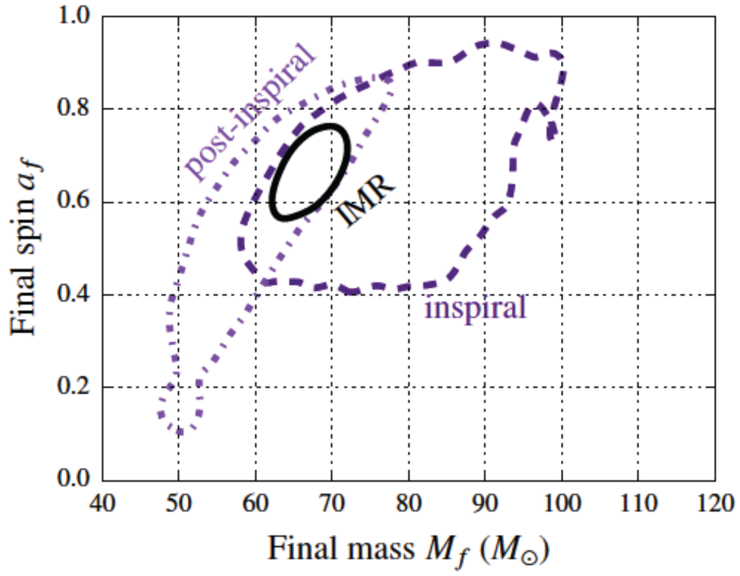


Tests of General Relativity with GW150914
Phys. Rev. Lett. 116, 221101 (2016)

Tests of consistency with predictions from General Relativity

- From the inspiral phase evolution, determine initial masses and spins
- In GR, the mass and spin of the remnant BH is determined from the initial ones and the orbital dynamics
- Predict final mass and spin from the “inspiral” using NR formulae
- Measure directly from the merger & ringdown (post-inspiral)
- Consistency test on the waveform and thus, on the corresponding GR solution
- No evidence for violations of GR

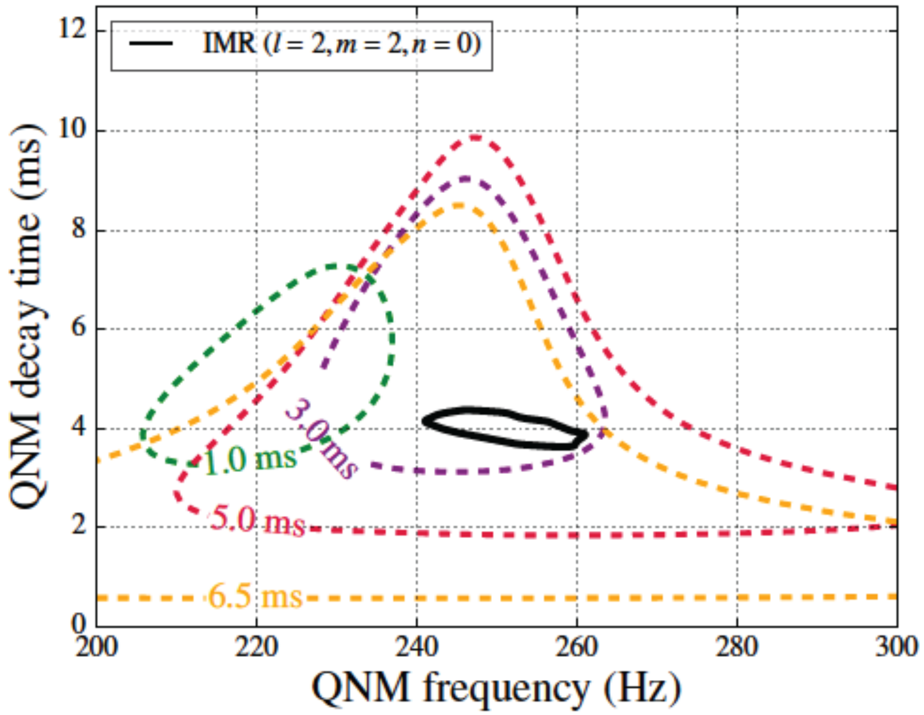




Tests of General Relativity with GW150914
Phys. Rev. Lett. 116, 221101 (2016)

Ringdown in GW150914

- Ringdowns of perturbed (newly formed) BHs are predicted from BH perturbation theory.
- Expect a spectrum of ringdown quasi-normal modes (QNMs) with predictable frequencies and decay times.
- GW150914 was not loud enough to detect more than one ringdown mode
- The measured frequency and decay time for the least damped QNM are consistent with IMR waveforms from numerical relativity simulations.



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

Dispersion and polarization in GR and beyond GR

Previous works have modified *dispersion*,

- Massive graviton, [Will, 1998]
- Massive graviton & Lorentz violating,
  [Mirshekari, Yunes, Will, 2012]
- Lorentz violating,
  [Kostelecký, Tasson, 2015] & [Kostelecký, Mewes, 2016].

GW150914+GW151226: $\lambda_g > 10^{13}\,[\mathrm{km}]$ and $m_g < 1.2 \times 10^{-22}\,[\mathrm{eV}/c^2]$.
[LSC+Virgo, PRL 116, 221101 (2016); LSC+Virgo, arXiv:1606.04856]

Previous works have modified *polarization*,

- Lorentz violating [Kostelecký, Mewes, 2016],
- Parity violating [Yunes, O'Shaughnessy, et al, 2010],
- Bigravity [Narikawa, Ueno, et al, 2015].

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

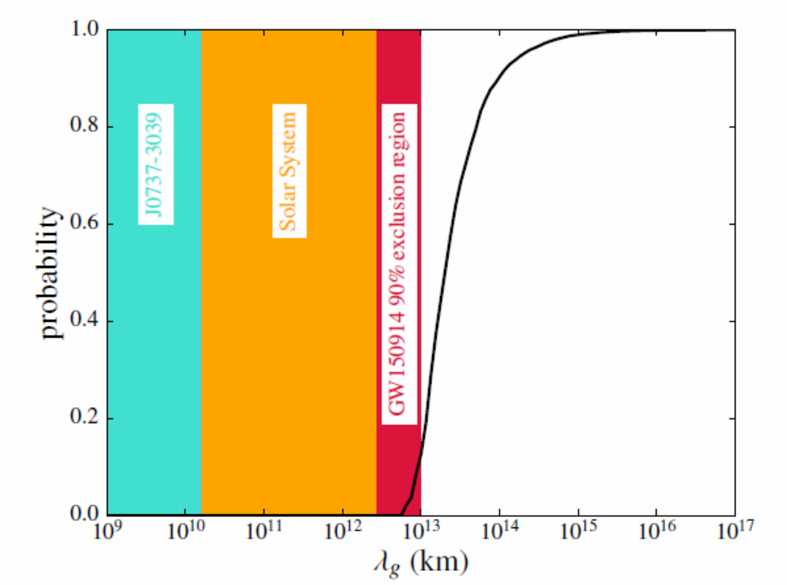
$$v_g^2/c^2 \equiv c^2p^2/E^2 = 1 - h^2c^2/(\lambda_g^2E^2)$$

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

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

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)

Modified dispersion

- Modified dispersion relation leads to dephasing of wave w.r.t. GR.
- Massive graviton: $\alpha = 0, A>0$
- Lorentz violating:
  - multifractal spacetime: $\alpha = 2.5$
  - Horava-Lifshitz and extradimensional theories: $\alpha = 4$
- both superluminal and subluminal propagation velocities are possible, depending on the sign of A and the value of α
- Bounds from 3 GWs:

$$\lambda_g > 1.6 \times 10^{13}\ \mathrm{km}$$

$$m_g \leq 7.7 \times 10^{-23}\ \mathrm{eV}/c^2$$

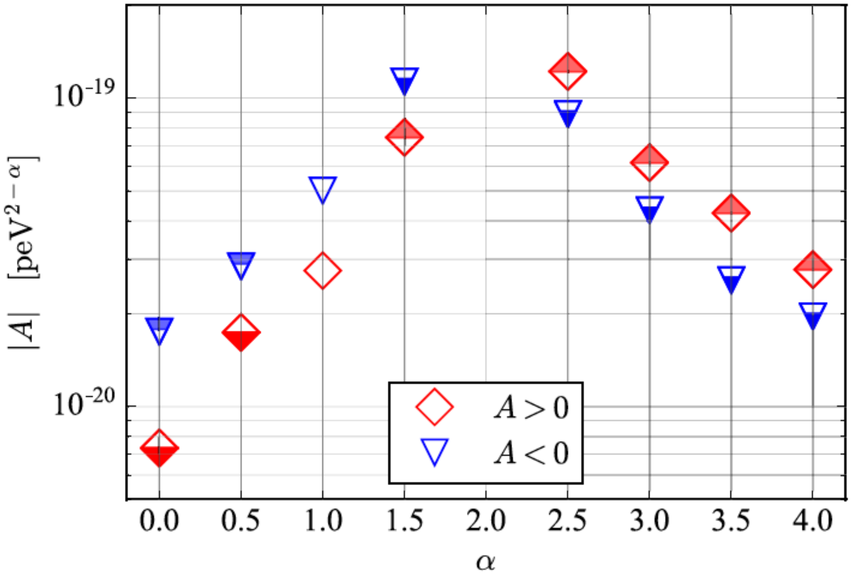


FIG. 5. 90% credible upper bounds on $|A|$, the magnitude of dispersion, obtained combining the posteriors of GW170104 with those of GW150914 and GW151226. We use picoelectron-

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \alpha \geq 0$$

$$v_g/c = 1 + (\alpha - 1)AE^{\alpha-2}/2$$

PRL **118,** 221101 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott *et al.*[*]
(LIGO Scientific and Virgo Collaboration)

Gravitational Wave Polarization

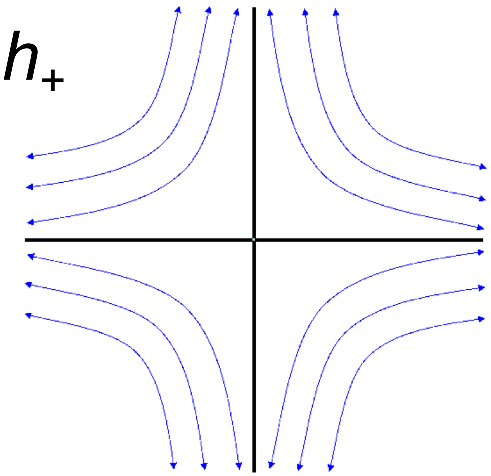
Solution for an outward propagating wave in z-direction:

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

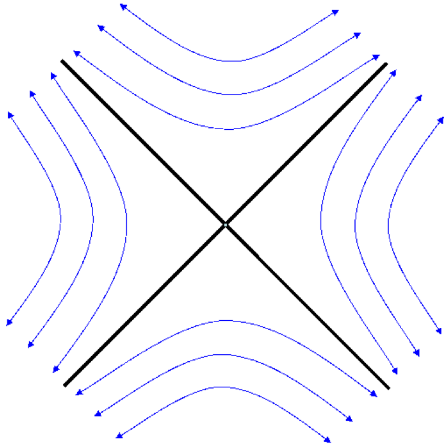
$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

h_+



h_x

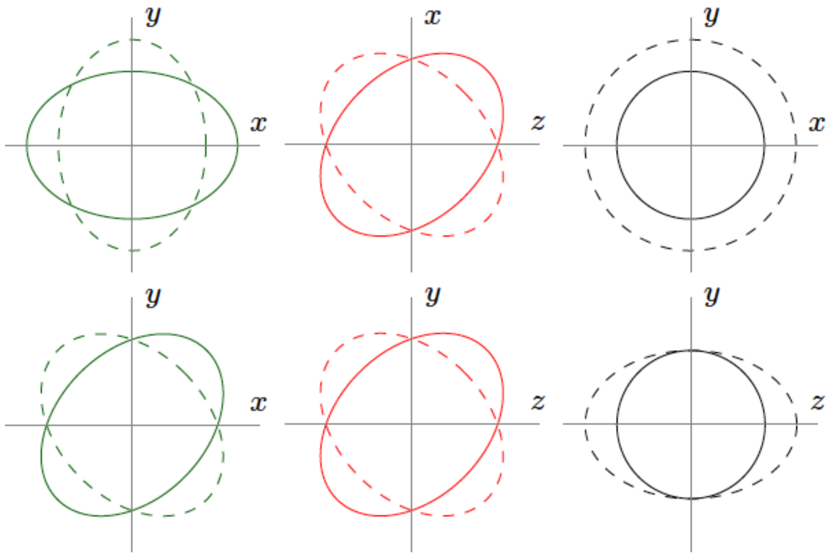


Non-tensor polarization

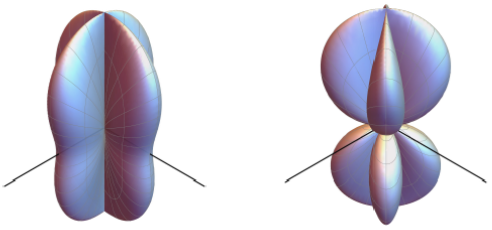
(Spatial part of the) general metric field tensor:

$$[h_{ij}] = \begin{pmatrix} h_\mathrm{b} + h_+ & h_\times & h_\mathrm{x} \\ h_\times & h_\mathrm{b} - h_+ & h_\mathrm{y} \\ h_\mathrm{x} & h_\mathrm{y} & h_\mathrm{l} \end{pmatrix}$$

Effect on a ring of test masses:

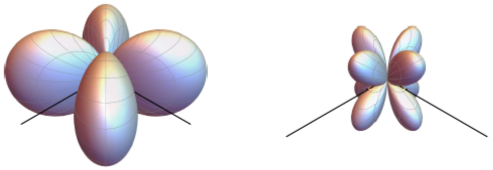


Antenna patterns:



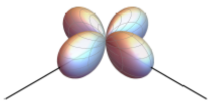
(a) Plus (+)

(b) Cross (×)



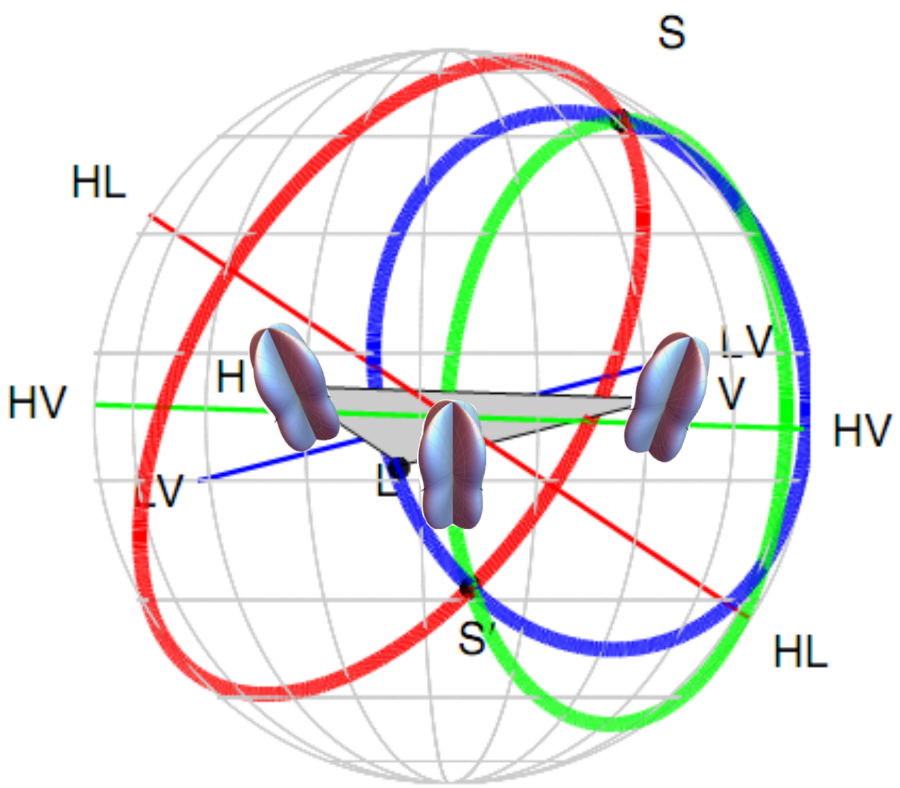
(c) Vector-x (x)

(d) Vector-y (y)



(e) Scalar (s)

Measuring the response in *three non-co-oriented detectors* permits a measurement of GW polarization for the first time!



From the pattern of signal amplitudes in three detectors:

For GW170814, detected by Hanford,Livingston, Virgo (no optical counterpart),

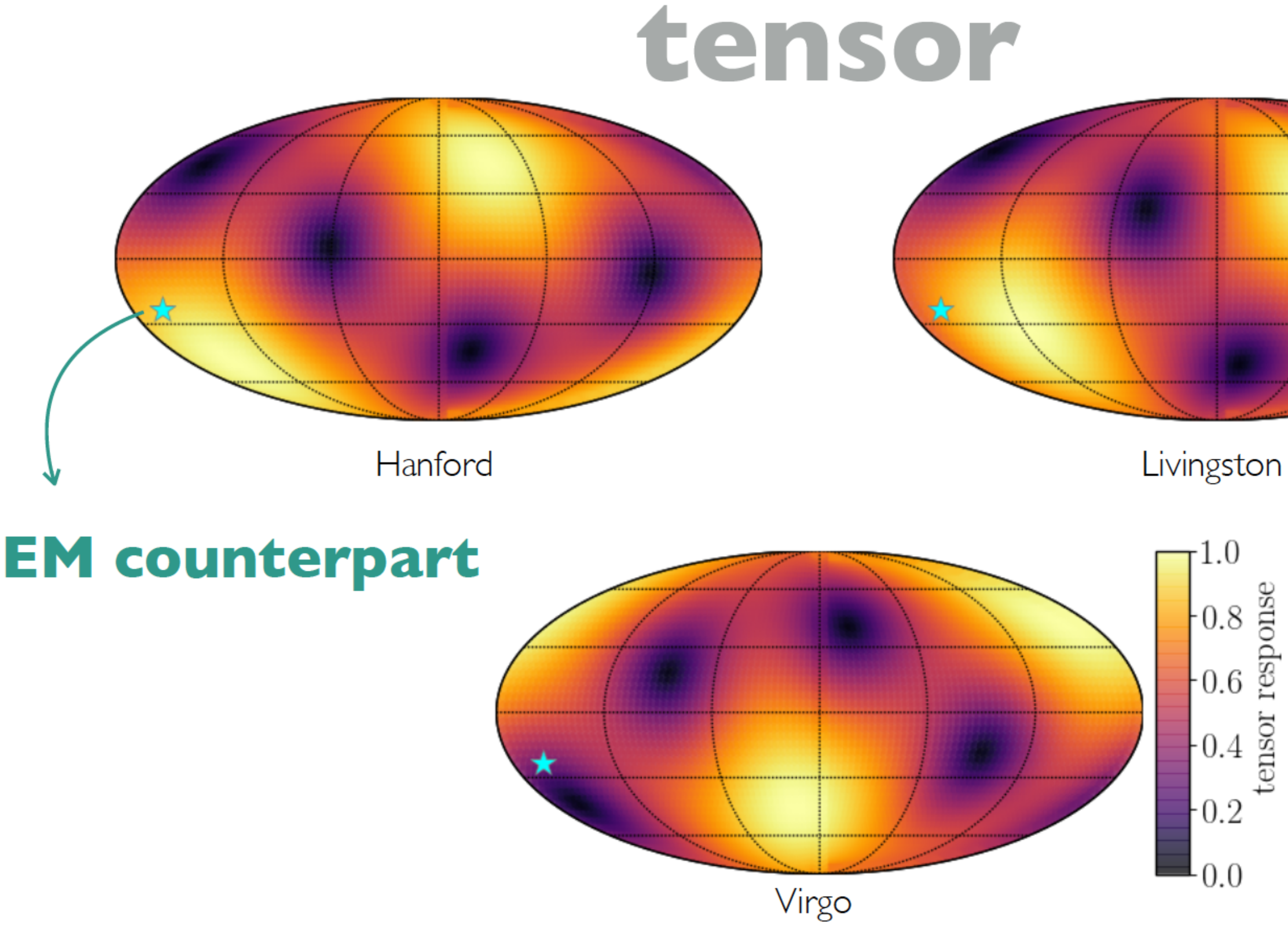
Bayes factor (T/V) = 300 ± 36
Bayes factor (T/S) = 1011 ± 138

Pure tensor is strongly favored over pure vector or pure scalar. (*EXTREME* models!)

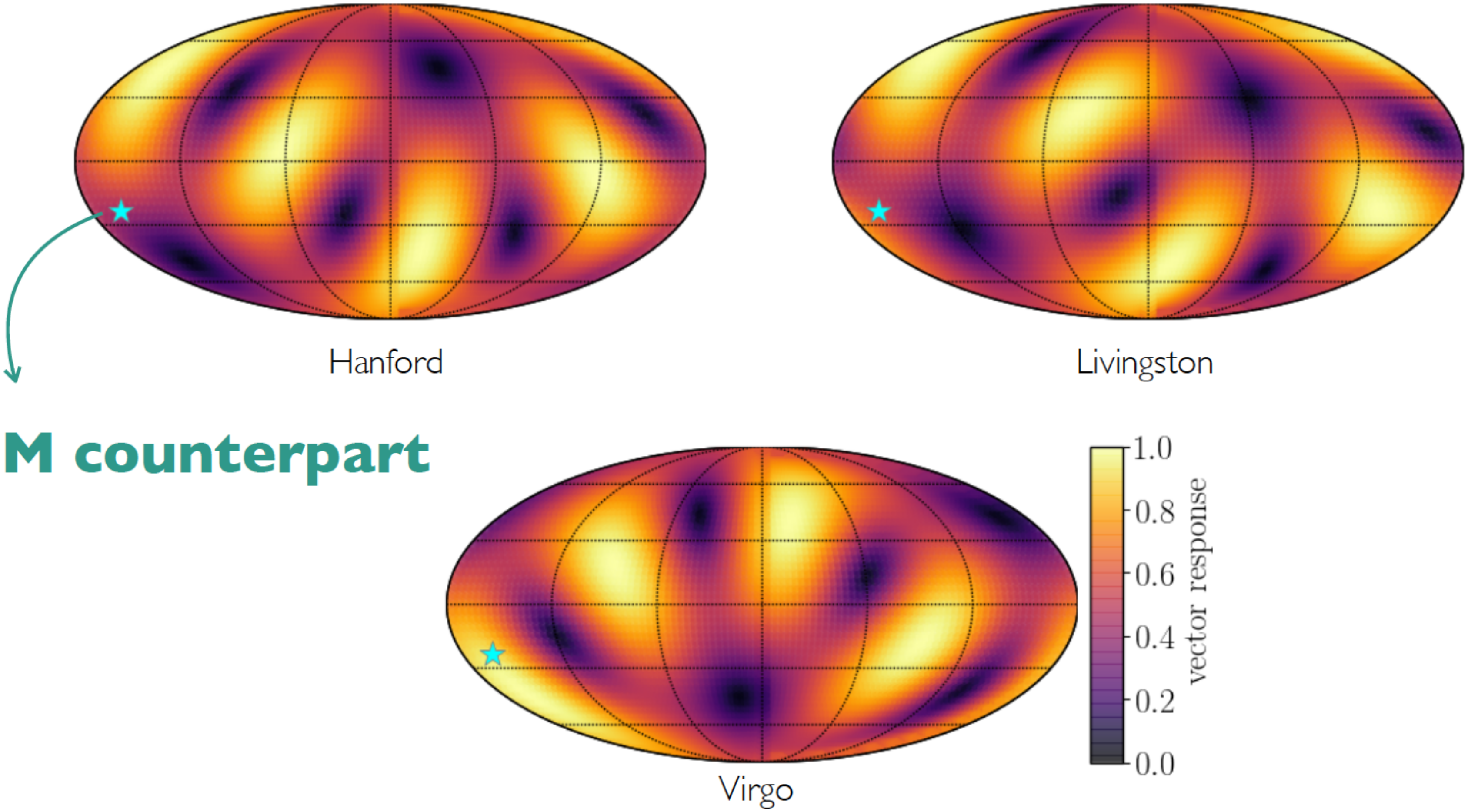
This would not have been possible without Virgo!

To measure small admixtures of S,V in dominant T requires *five non-co-oriented detectors*

What can we do with GW170817?

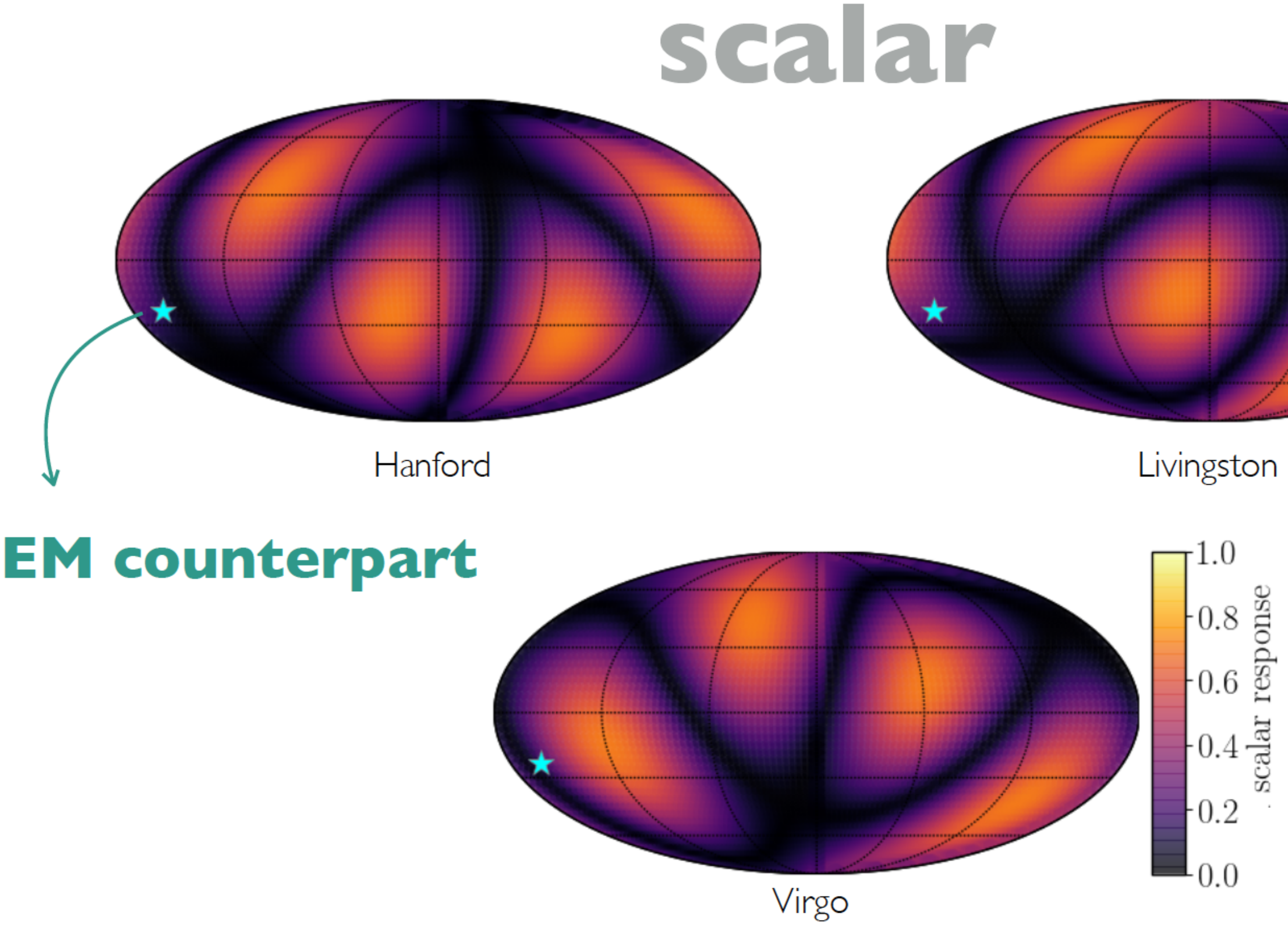


vector



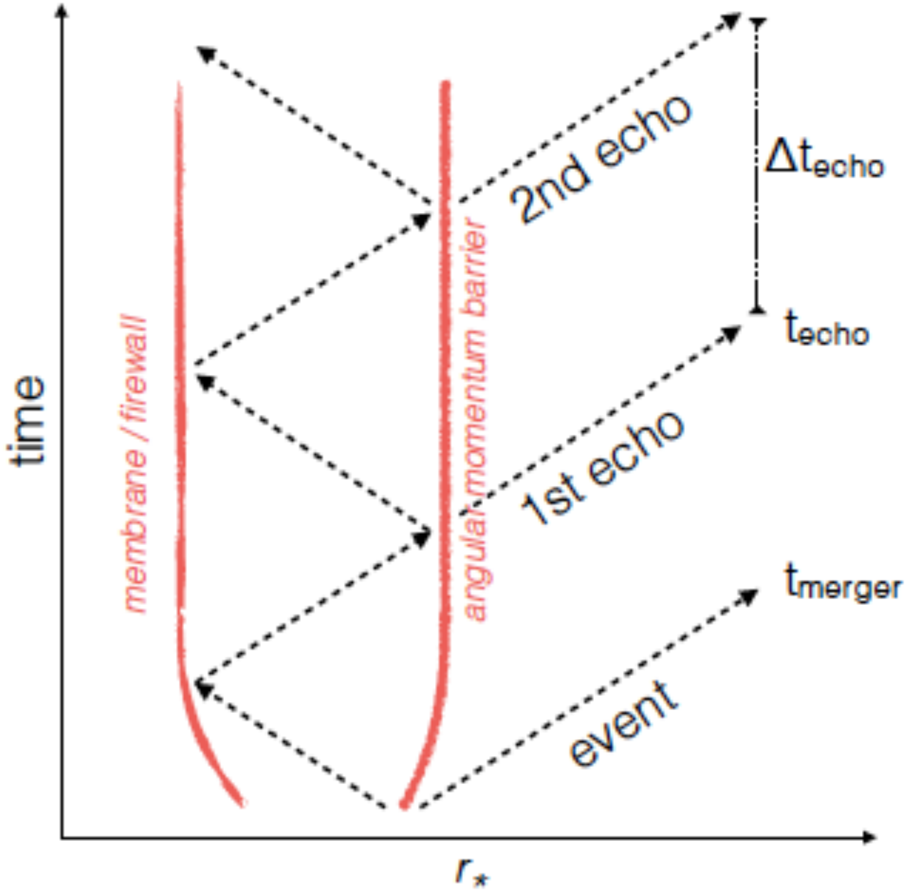
EM counterpart

Stay tuned for V/T, S/T polarization constraints from GW170817



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

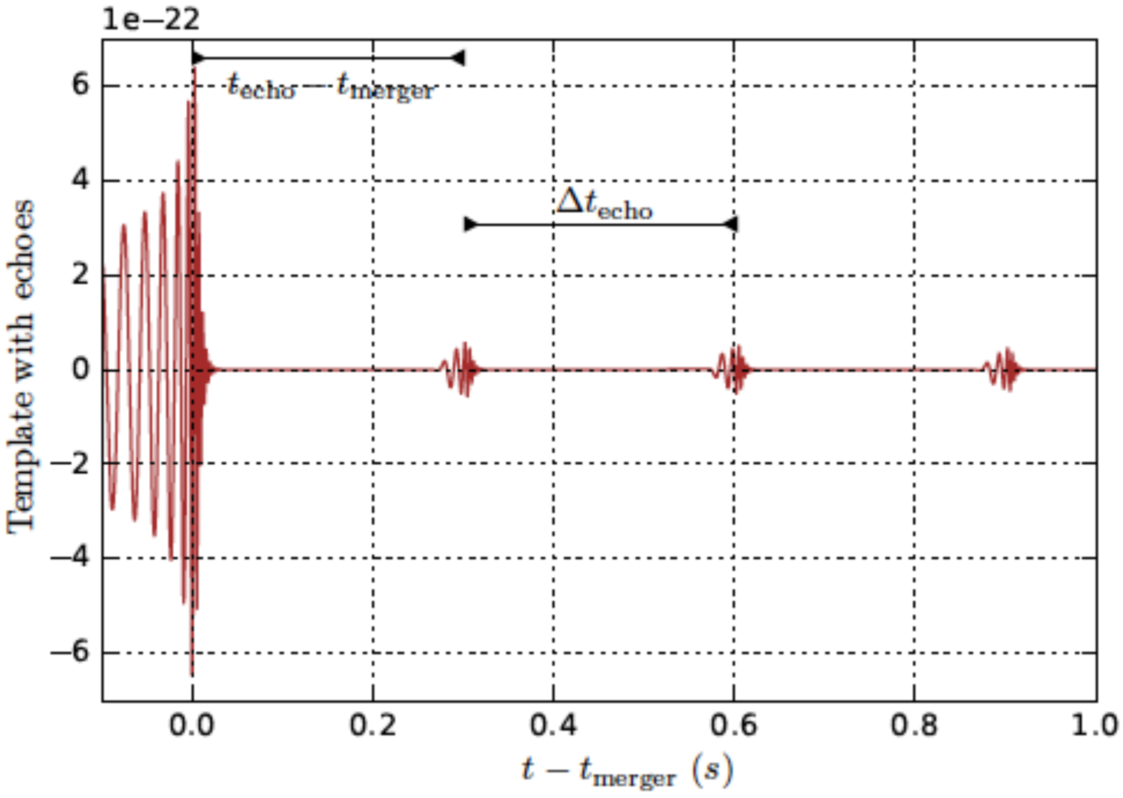
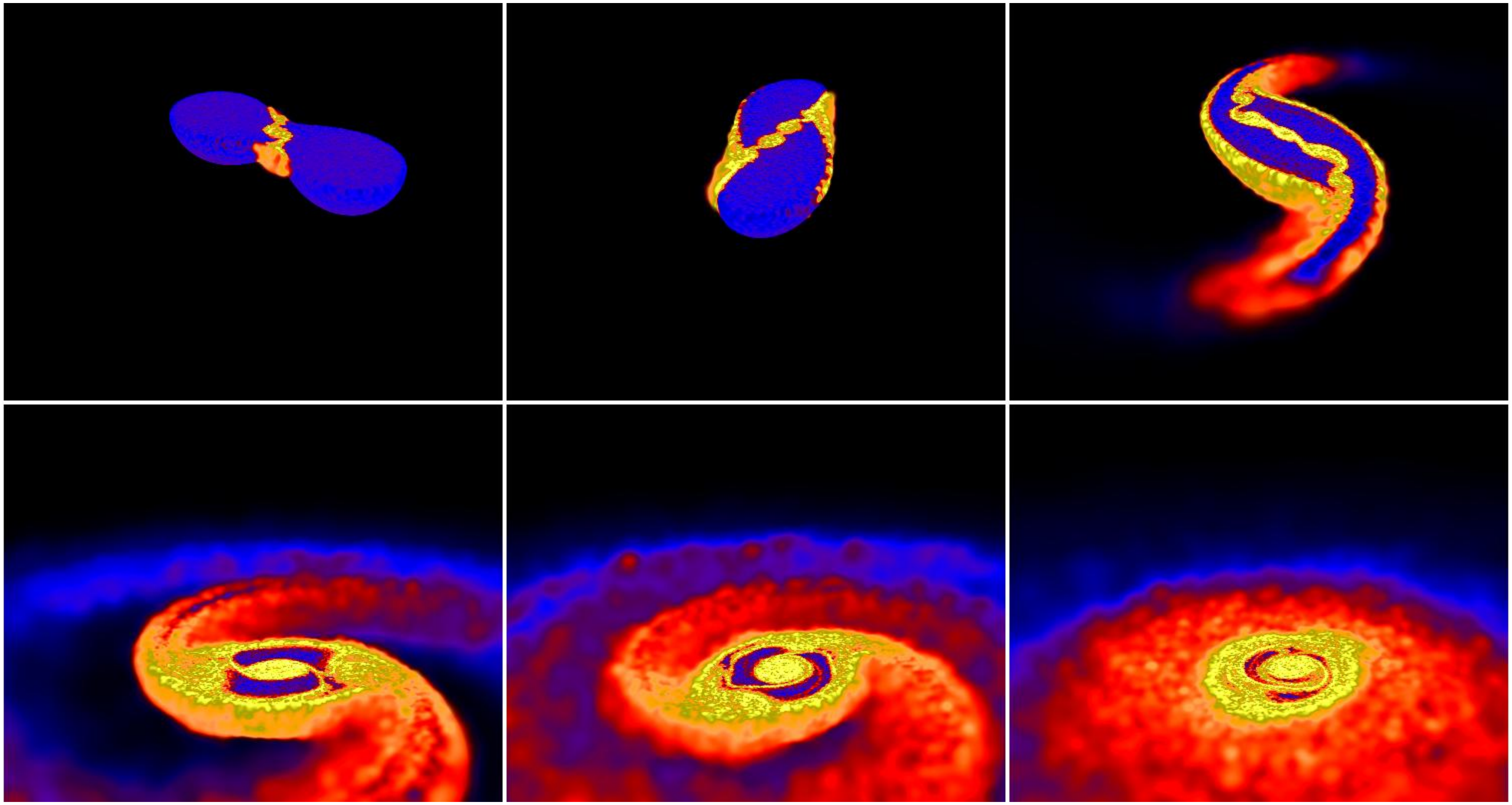


FIG. 2: LIGO original template for GW150914, along with our best fit template for the echoes.

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

BNS mergers,
tidal distortion and disruption

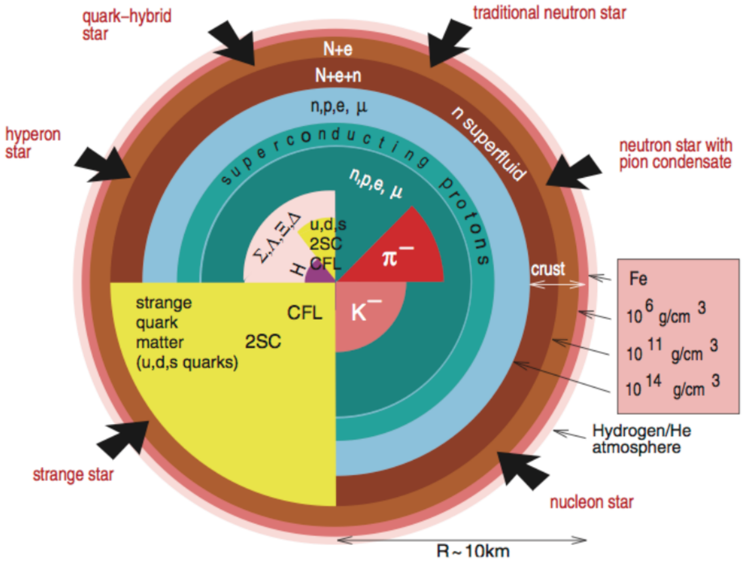


Credit: Daniel Price and Stephan Rosswog

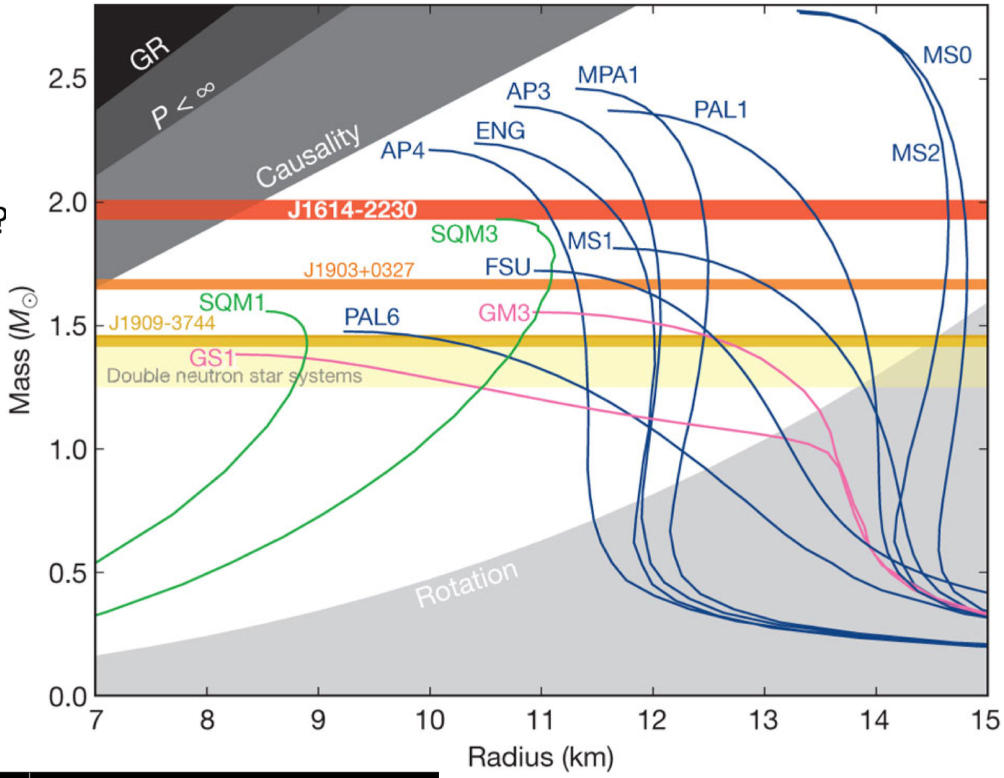
NEOS, NS structure, and NS mass-radius relation

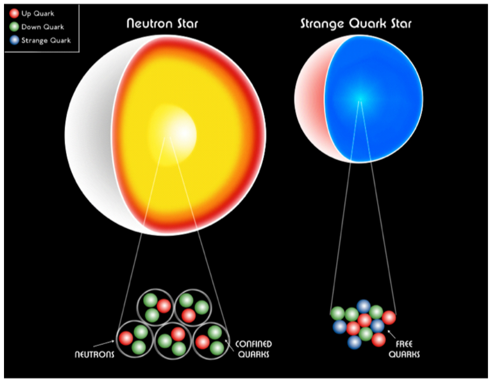
Neutron Star Equation of State

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

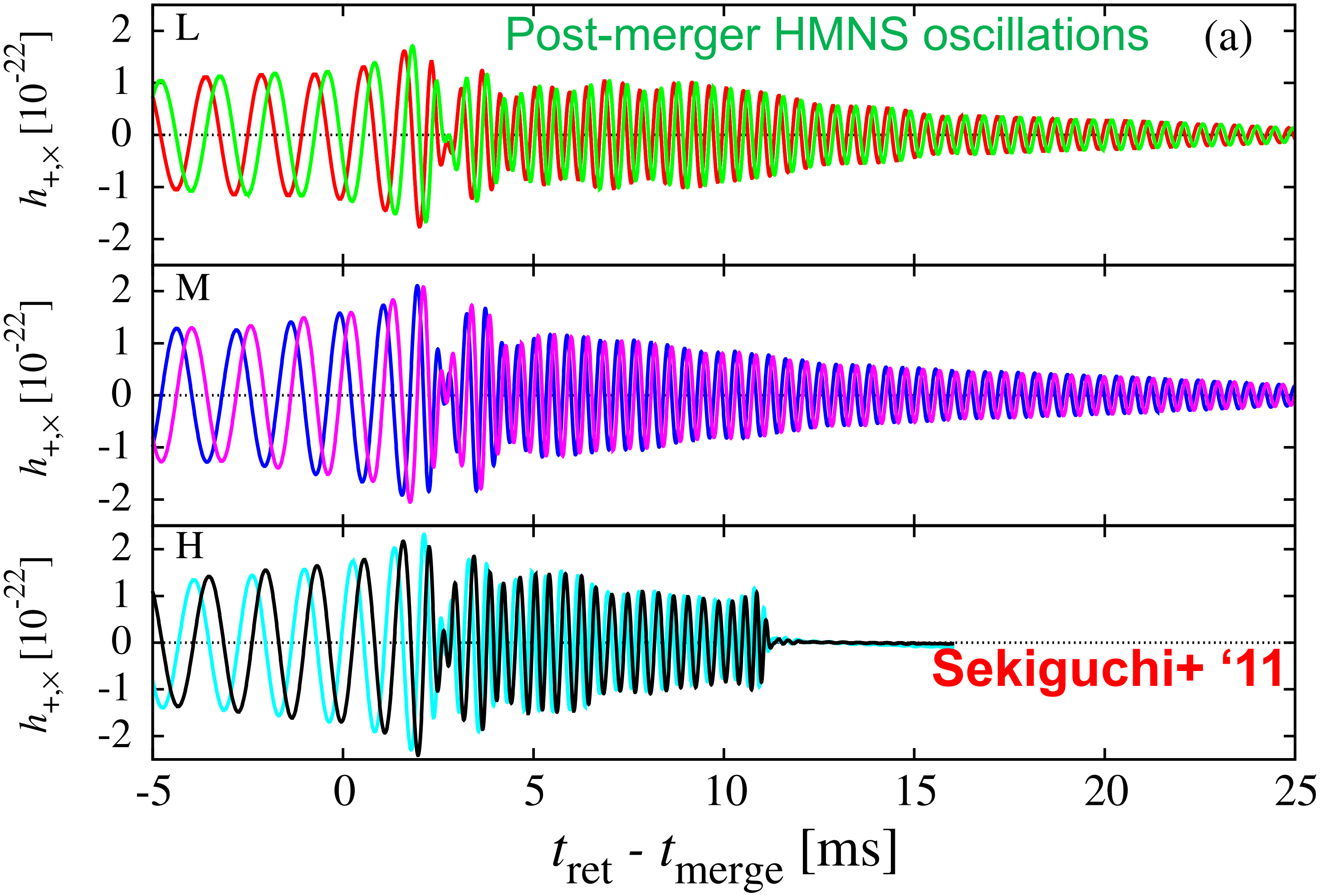


C. D. Ott @ LVC Supernova Call, 2014/08/11





Nuclear Astrophysics: BNS Merger waveforms



1.35 + 1.35

1.50 + 1.50

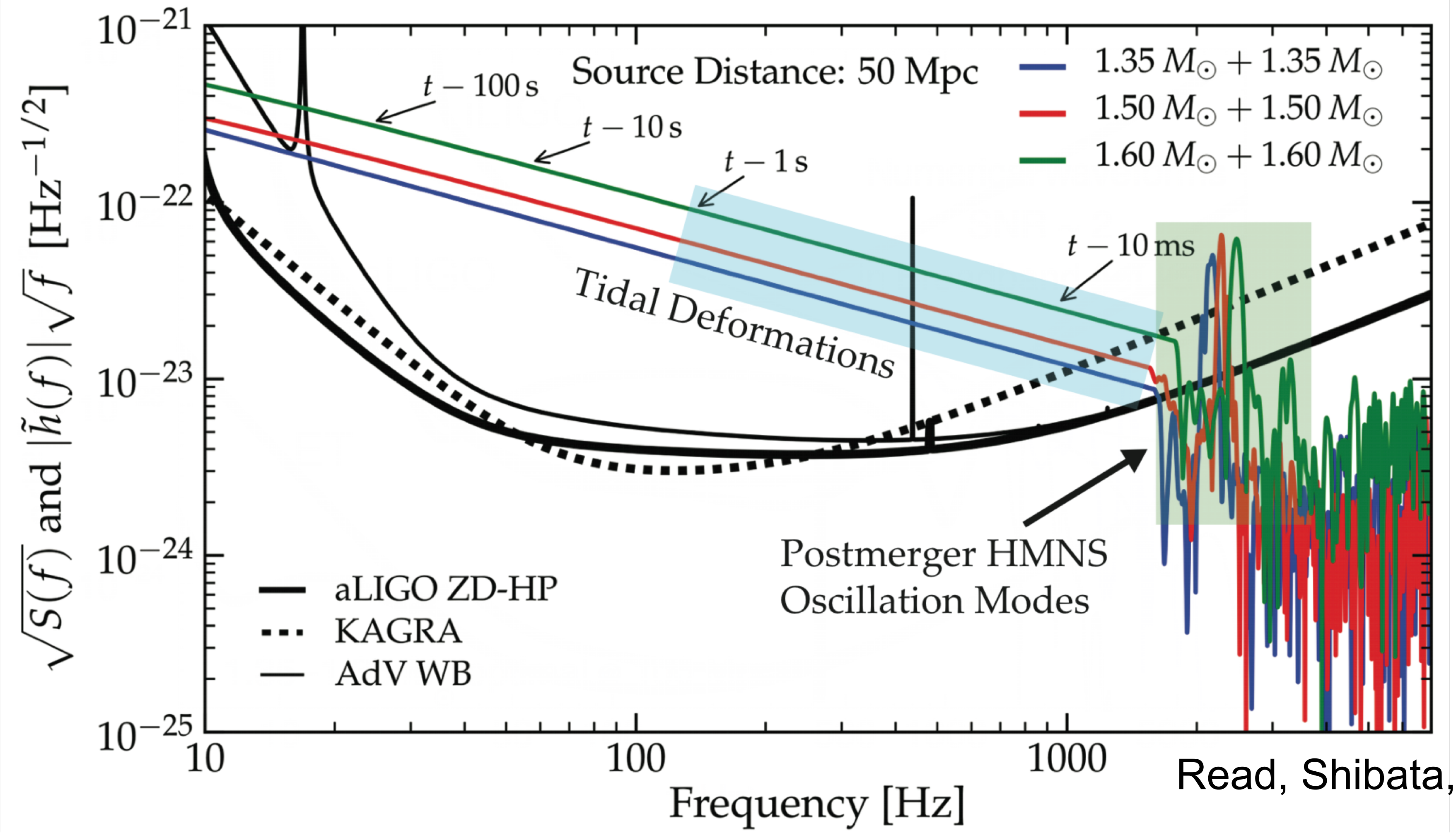
1.60 + 1.60

Mass [M_{Sun}]

Sekiguchi+ 11: First full GR NS-NS simulation with realistic microphysics, finite-temperature nuclear EOS of H. Shen+ '98,'11

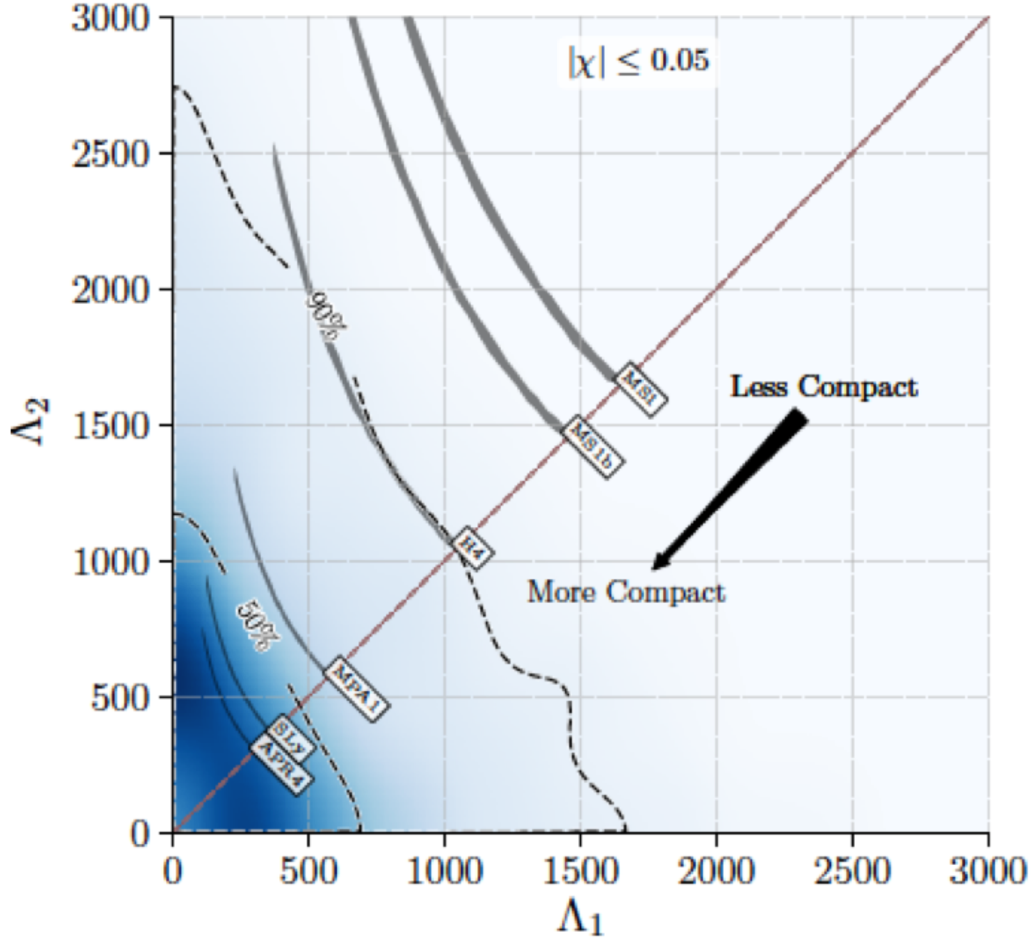
Tidal disruption of neutron stars near merger


Credit: Daniel Price and Stephan



Read, Shibata, et al

Constraints on tidal distortion



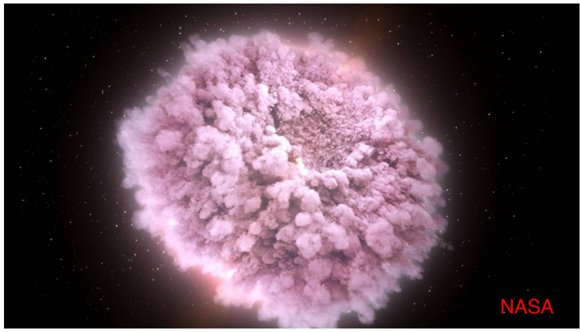
- Tidal deformability:

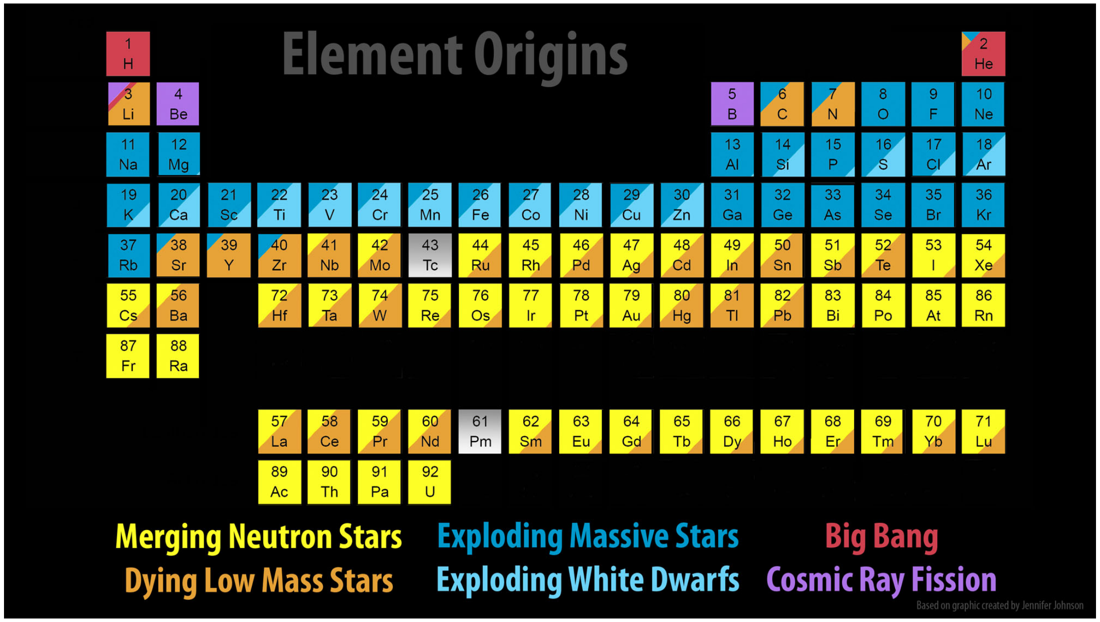
$$\Lambda = \frac{2}{3} k_2 \frac{c^2}{G} \left(\frac{R}{M}\right)^5$$

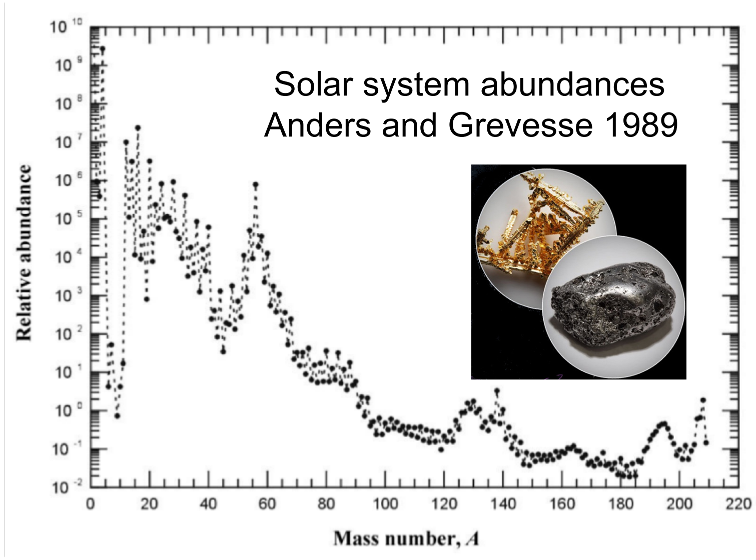
- k_2 is the 2nd Love number
- R and M are the radius and mass of the star
- LIGO results for GW170817 are most consistent with more compact stars, R < 13 km

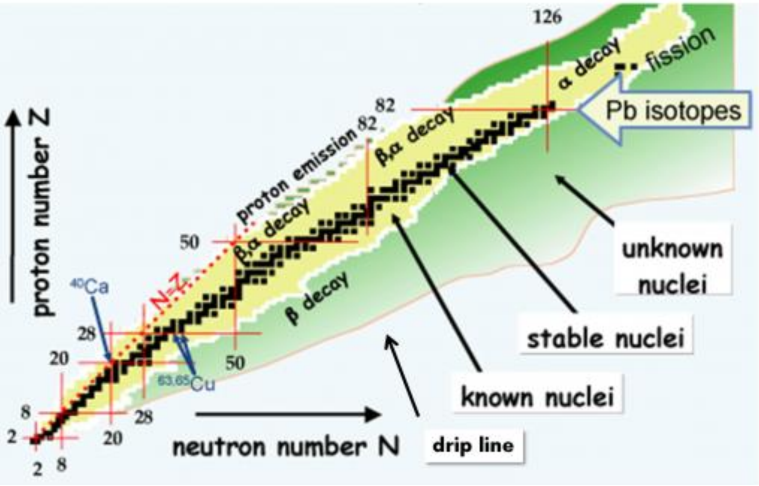
B. Abbott et al, LIGO-Virgo, Phys. Rev. Lett. 119, 161101 (2017)
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

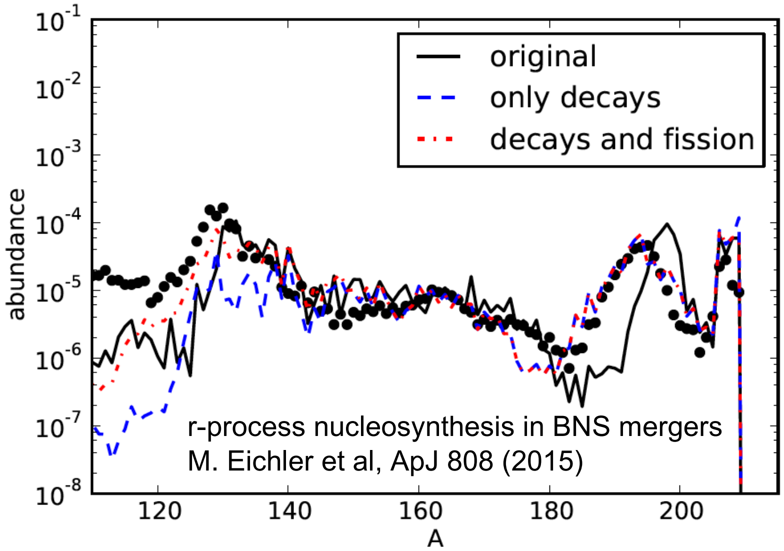
The origin of the (heavy) elements


NASA




Solar system abundances
Anders and Grevesse 1989



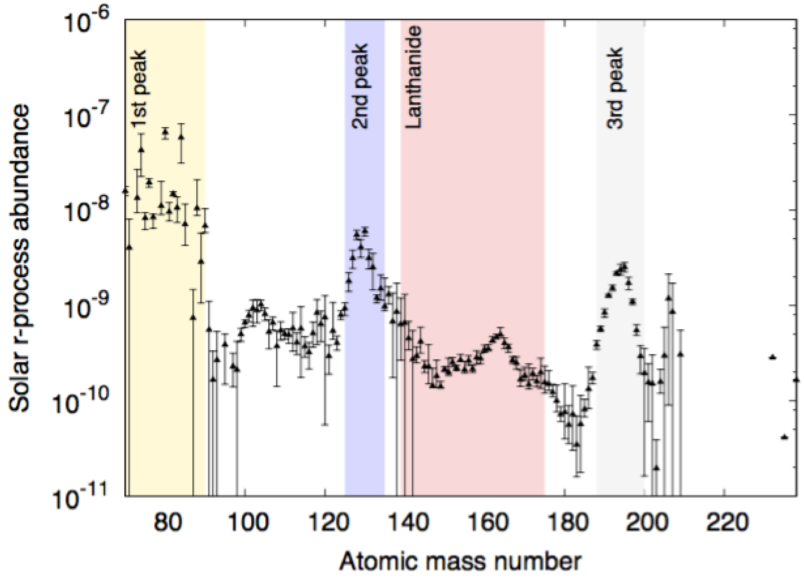

r-process nucleosynthesis in BNS mergers
M. Eichler et al, ApJ 808 (2015)

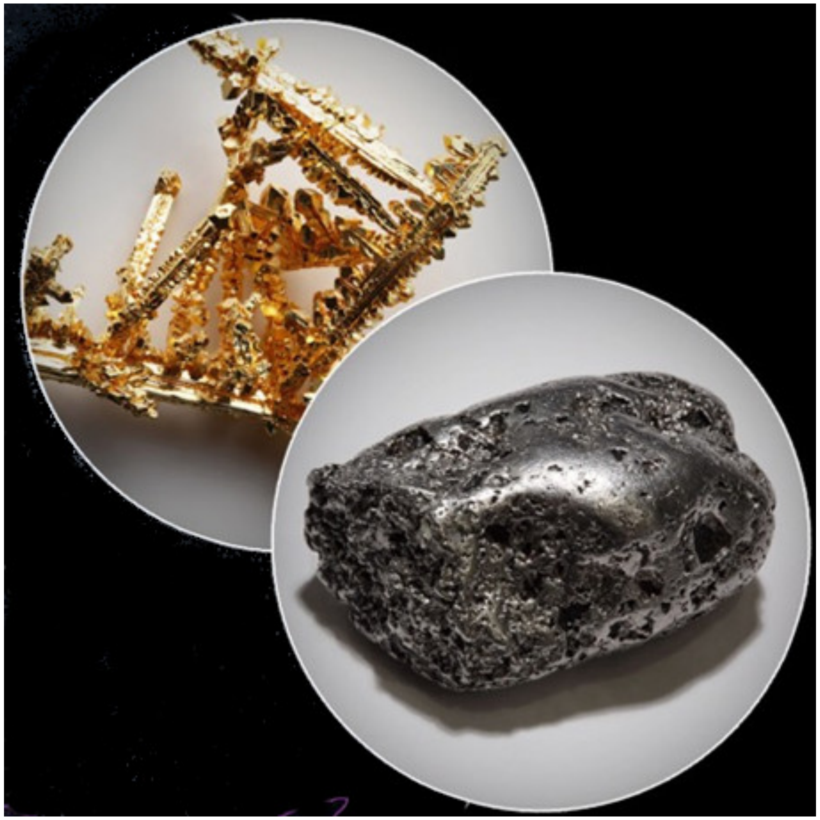
Not just a site, but *the* site of heavy element production?

Observed Solar Abundance

= Quantity per merger x Rate of Mergers

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



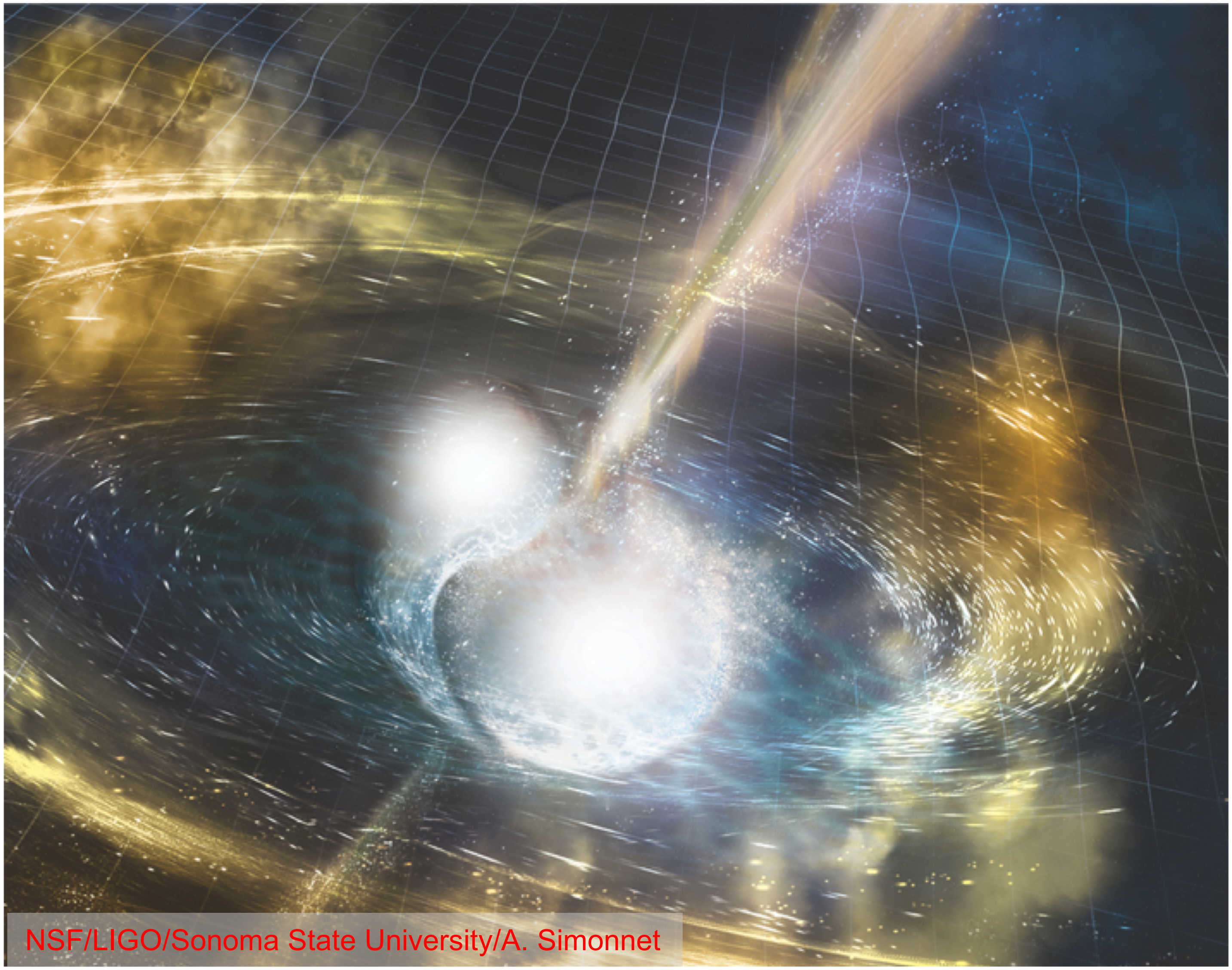


Ejecta mass estimate: ~0.05 solar mass

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

Consistent!

The future of gravitational wave astrophysics is … golden!


NSF/LIGO/Sonoma State University/A. Simonnet

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And…
thank you for your
attention!

THANK YOU!