



Fundamental physics with Gravitational Waves



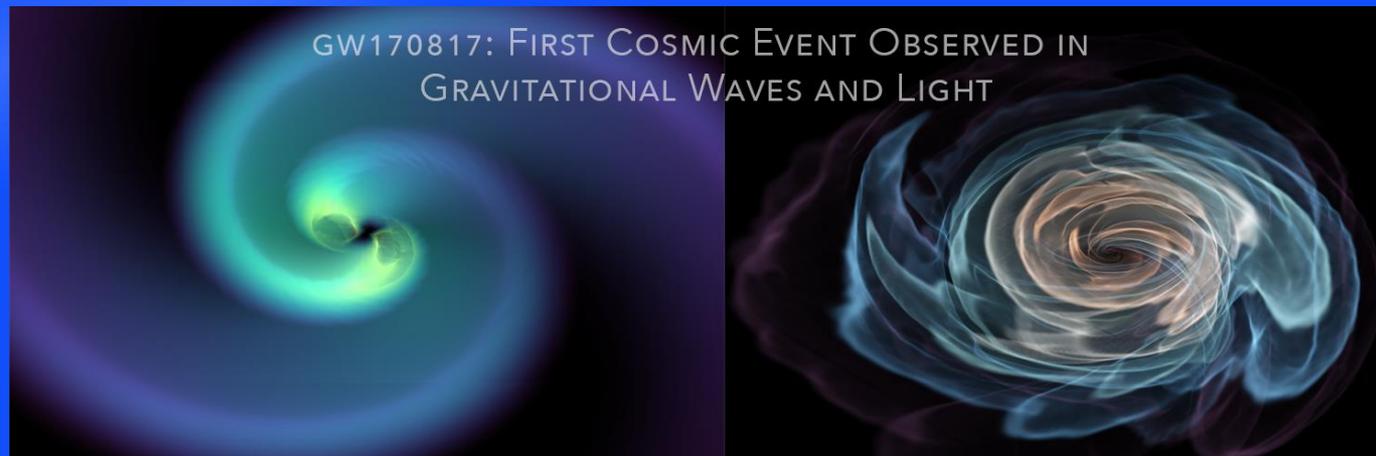
Caltech

Alan J Weinstein

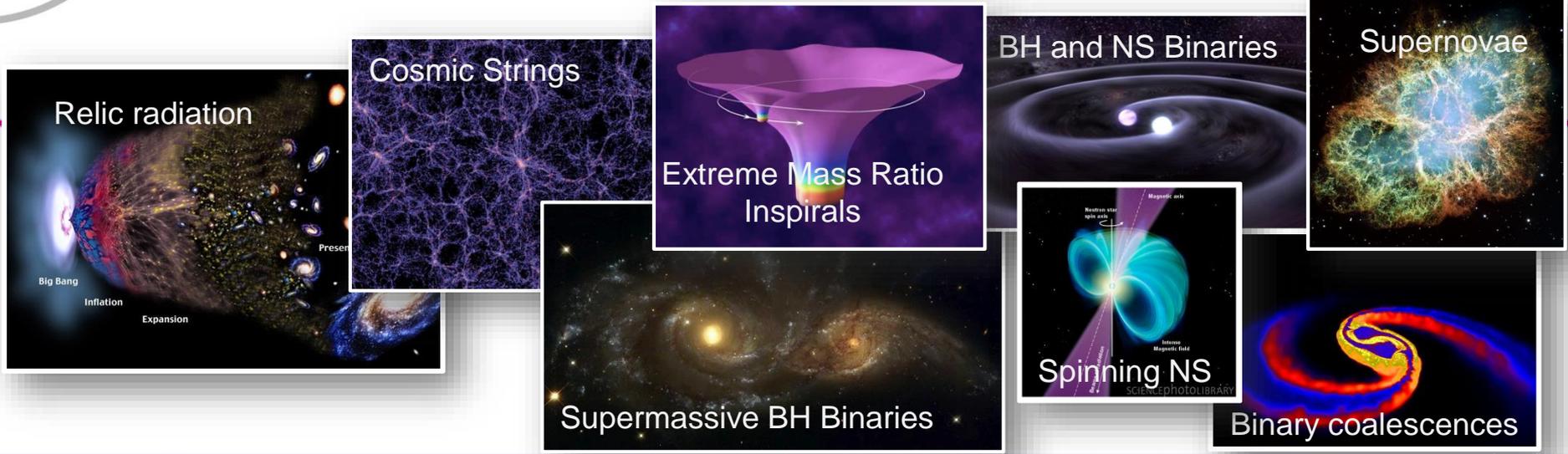
LIGO Laboratory, Caltech / NSF
for the LIGO and Virgo Collaborations



Fermilab LPC Seminar, May 29, 2018

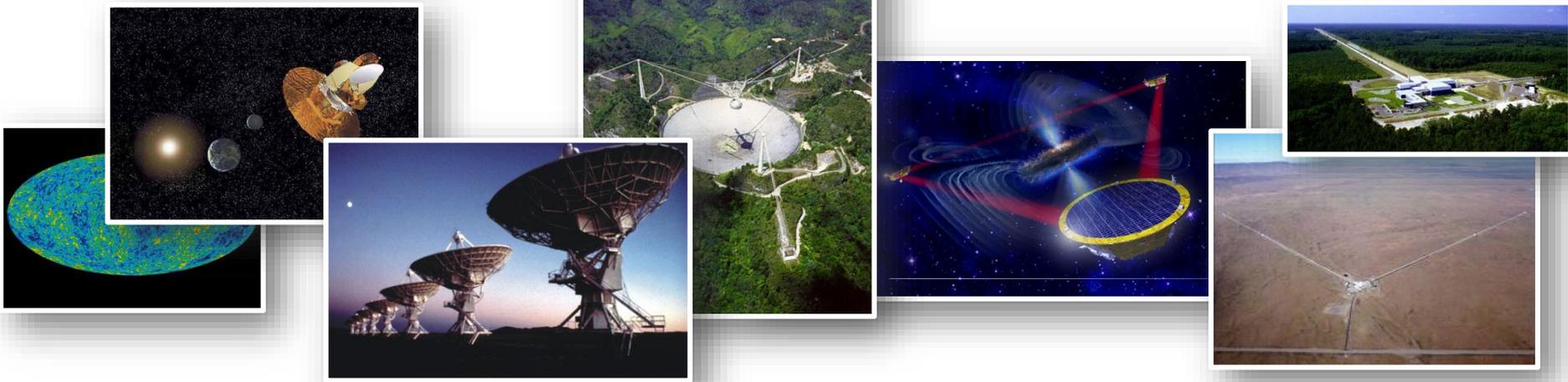


- What I won't be talking about (or will only just mention):
 - » What are Gravitational Waves (you know!)
 - » The LIGO detectors (another talk!)
 - » GW source searches: CBC, Burst, CGWs, cosmological GWs
 - » BBHs and BNS discovered by LIGO & Virgo
 - » Multi-messenger astronomy with GWs (another talk!)
 - » Astrophysics with GWs – BH populations, binary formation mechanisms, etc. (another talk!)
- **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**



10⁻¹⁶ Hz **10⁻⁹ Hz** **10⁻⁴ Hz** **10⁰ Hz** **10³ Hz**

Inflation Probe **Pulsar timing** **Space detectors** **Ground interferometers**



The Laser Interferometer Gravitational Wave Observatory

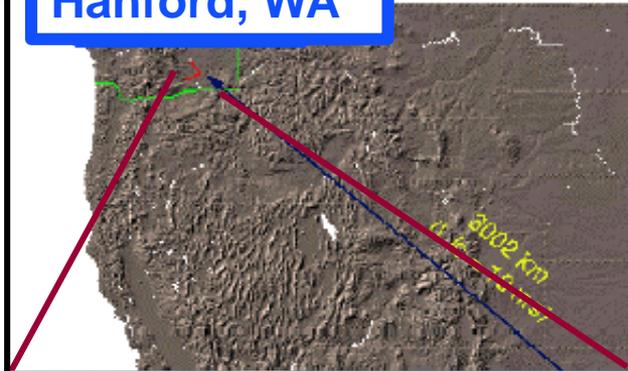
**LIGO Laboratory
is operated by
Caltech and MIT,
for the NSF.**

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

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

**Vigo Collaboration:
~ 250 scientists, Europe**

Hanford, WA

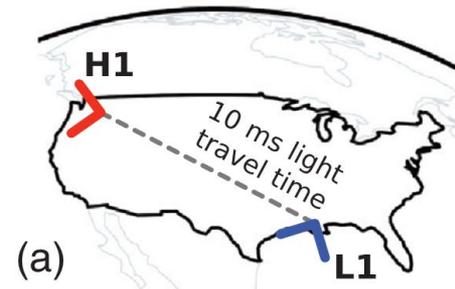


**LIGO Livingston
Observatory
(LLO)**



LIGO Hanford Observatory (LHO)

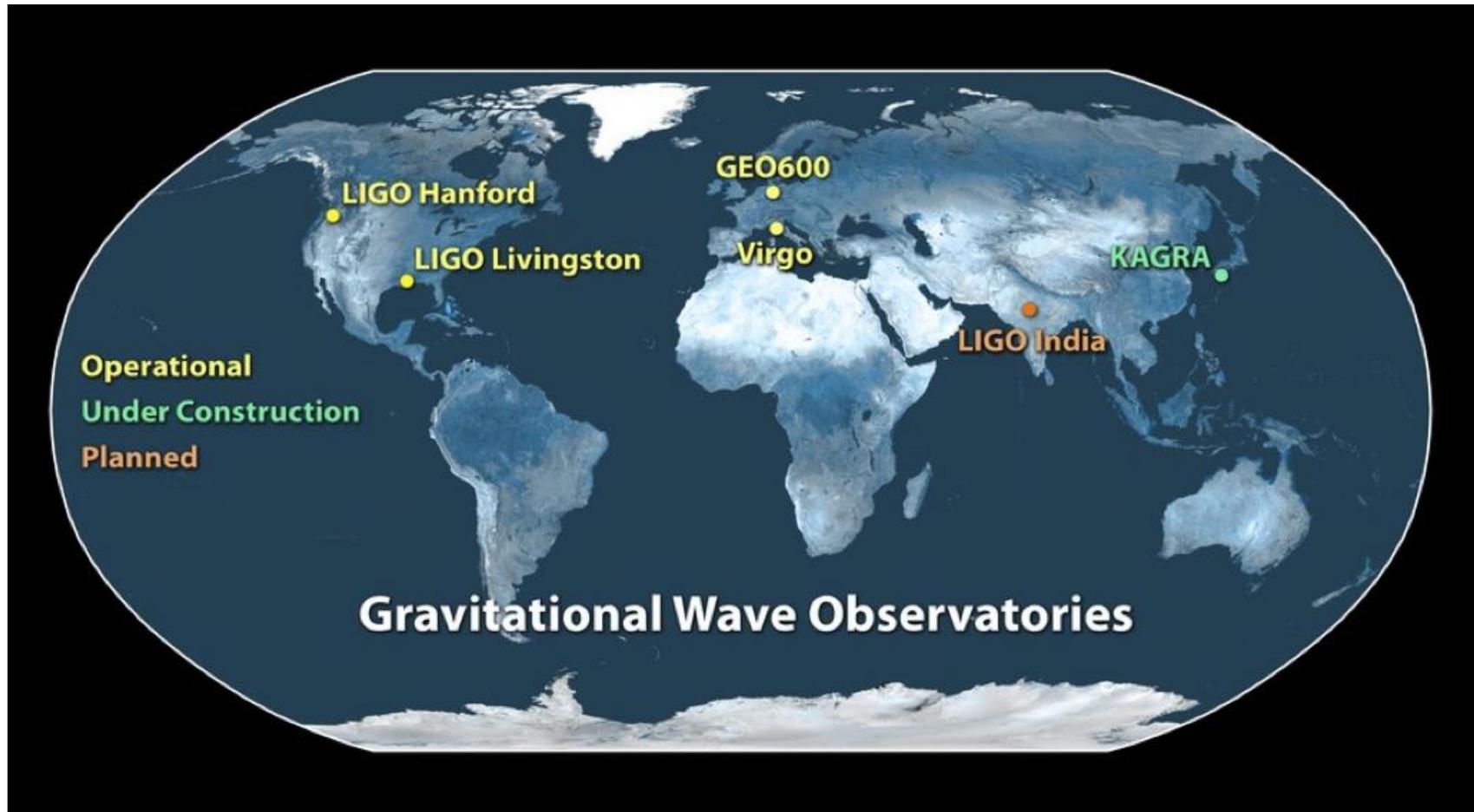
Livingston, LA



(a)



Coming years: more, and more sensitive detectors



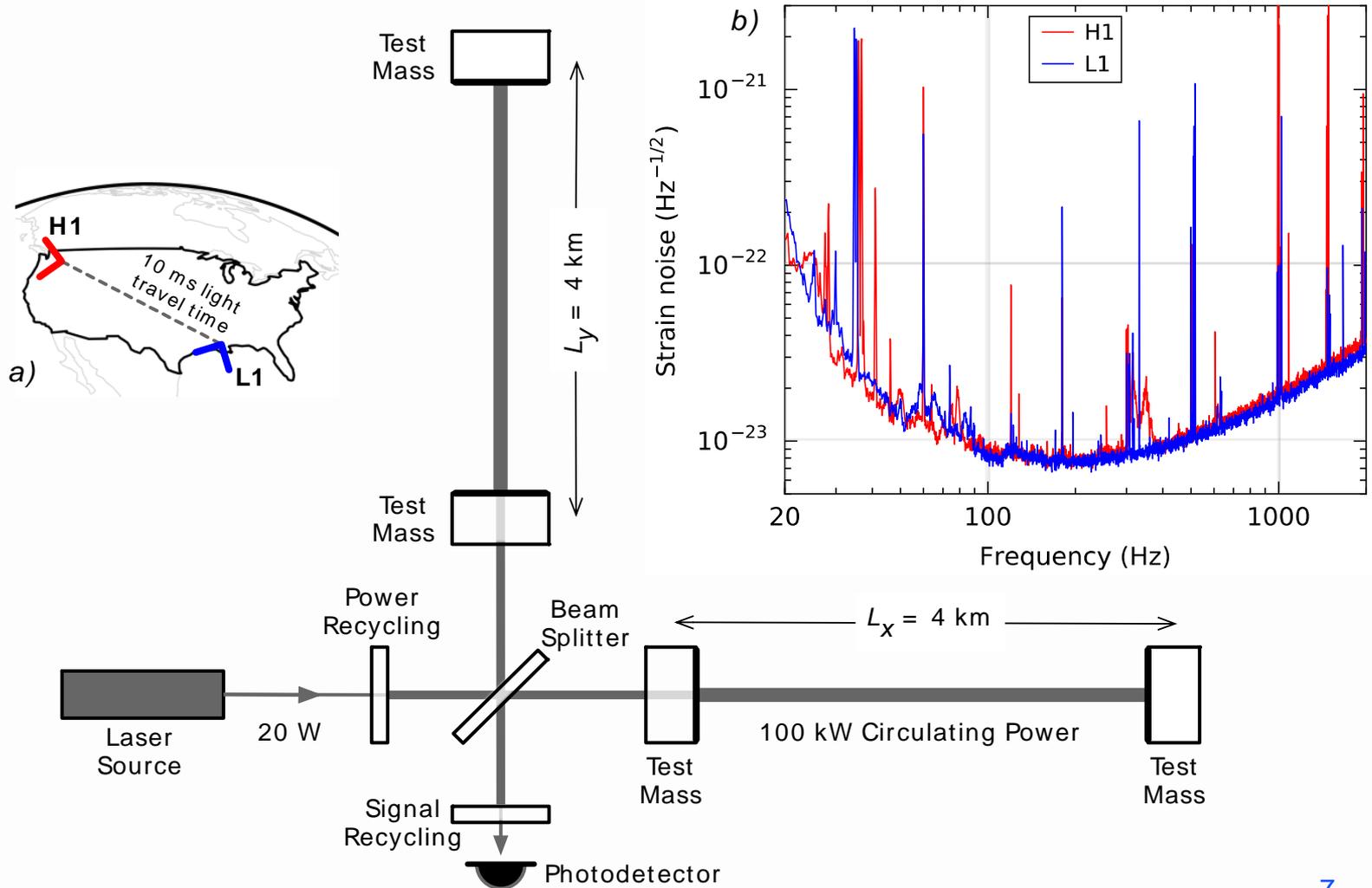
<http://ligo.org/detections/GW170817.php>

LIGO

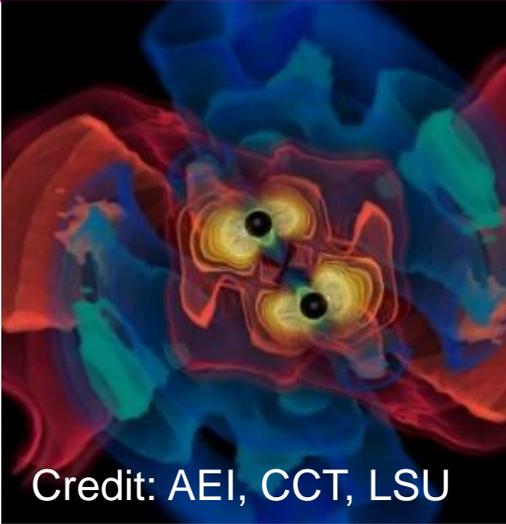
LIGO Scientific Collaboration



The Advanced LIGO detectors



The most energetic processes in the universe

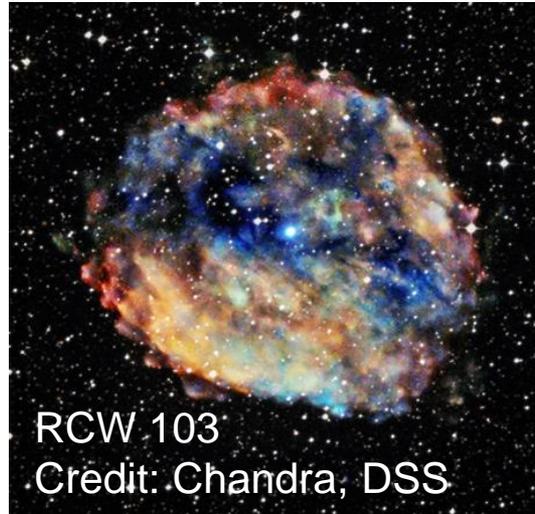


Credit: AEI, CCT, LSU

Coalescing Compact Binary Systems:

Neutron Star-NS, Black Hole-NS, BH-BH

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

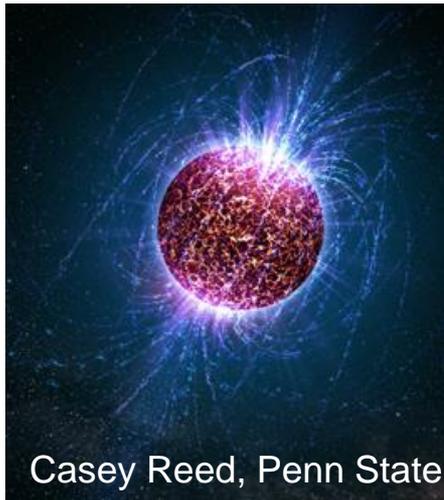


RCW 103

Credit: Chandra, DSS

Asymmetric Core Collapse Supernovae

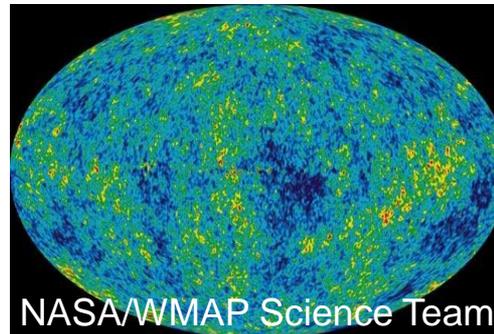
- Weak emitters, not well-modeled ('bursts'), transient
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class



Casey Reed, Penn State

Spinning neutron stars

- (effectively) monotonic waveform
- Long duration

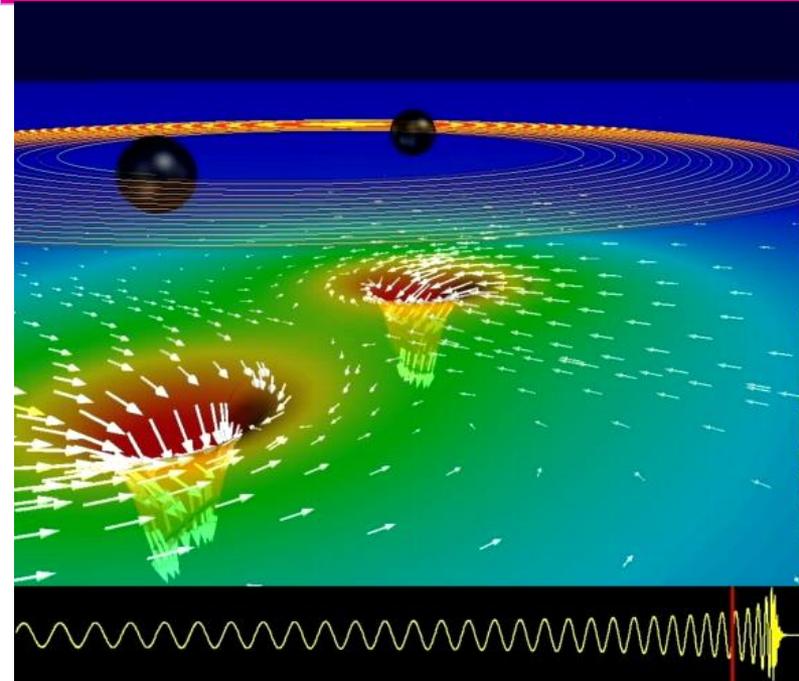
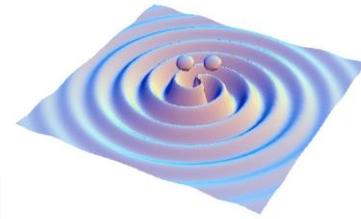


NASA/WMAP Science Team

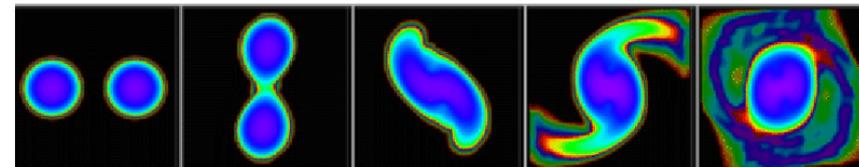
Cosmic Gravitational-wave Background

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

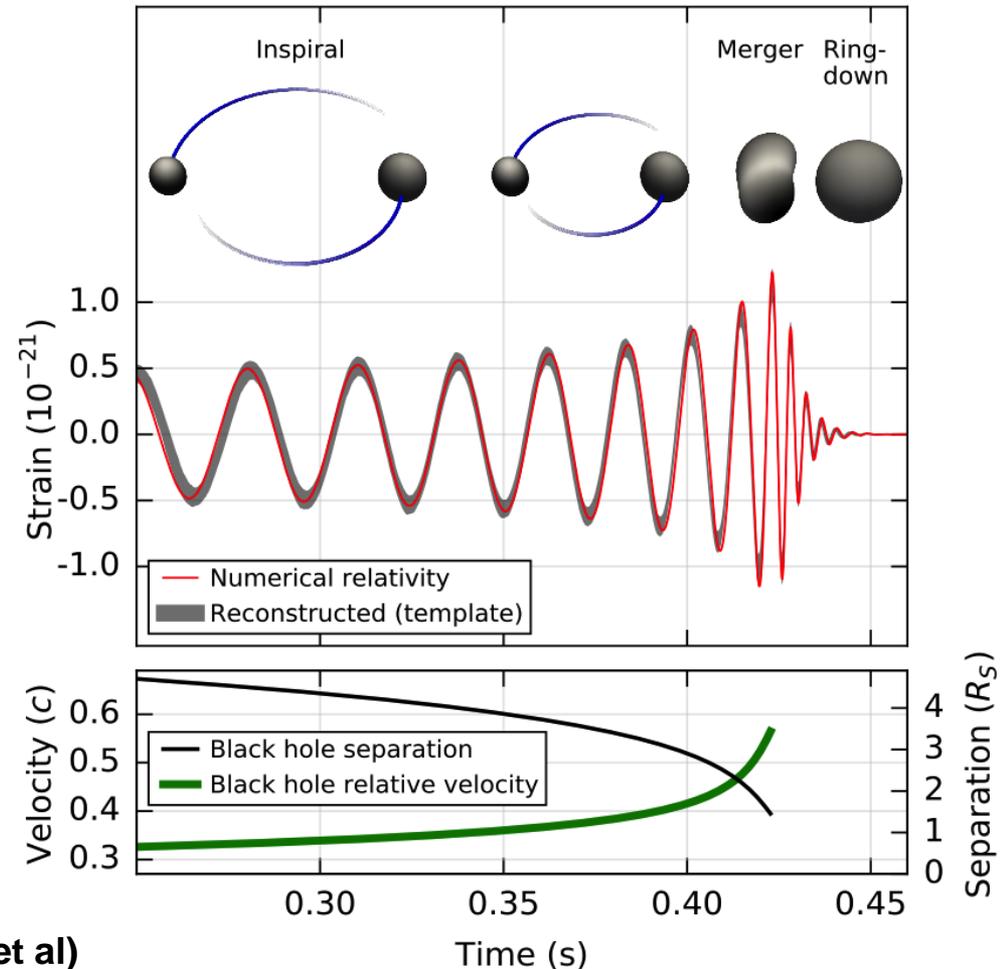
LIGO GWs from coalescing compact binaries (NS/NS, NS/BH, BH/BH)



Numerical relativity computation of BBH merger (SXS Collaboration)



Tidal disruption of binary neutron stars (Centrella et al)

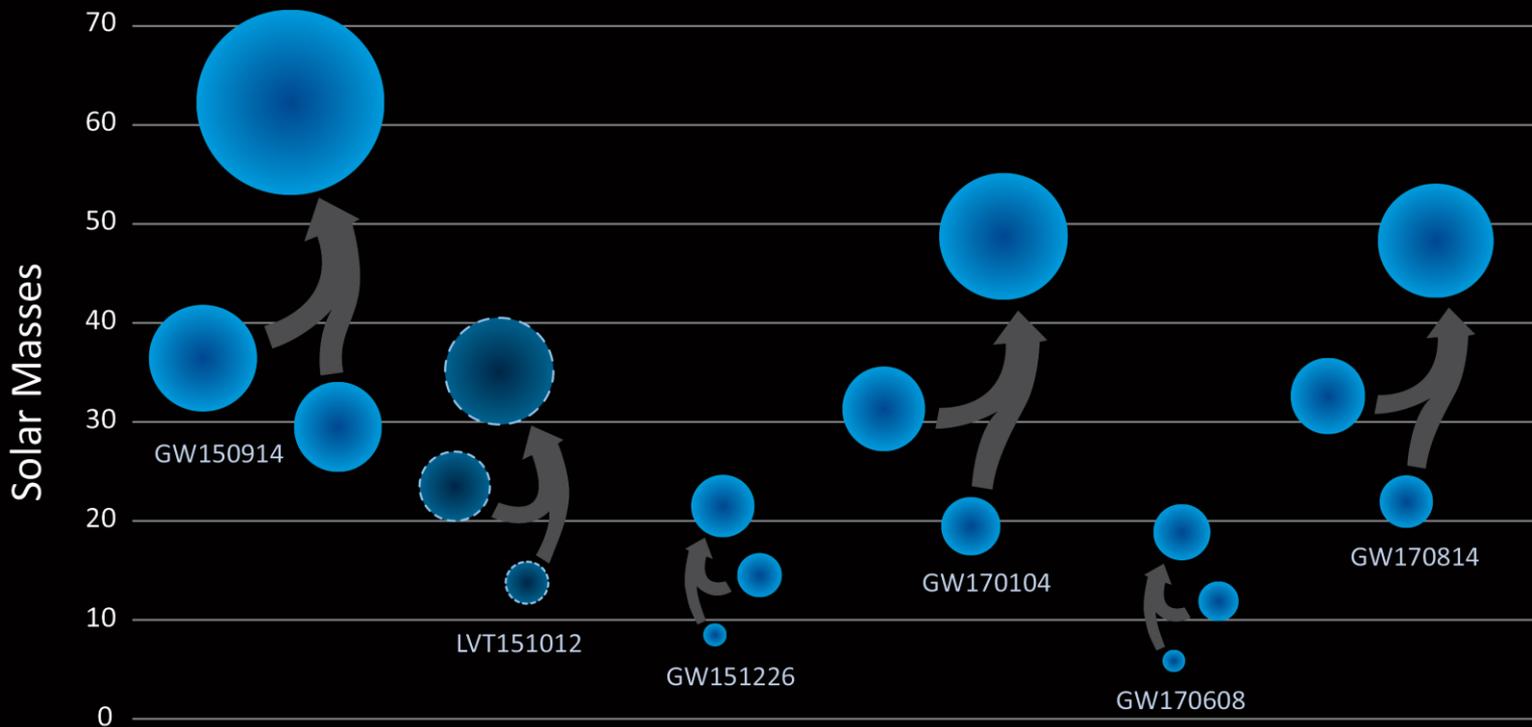


Waveform carries wealth of information about binary masses, orbit, merger

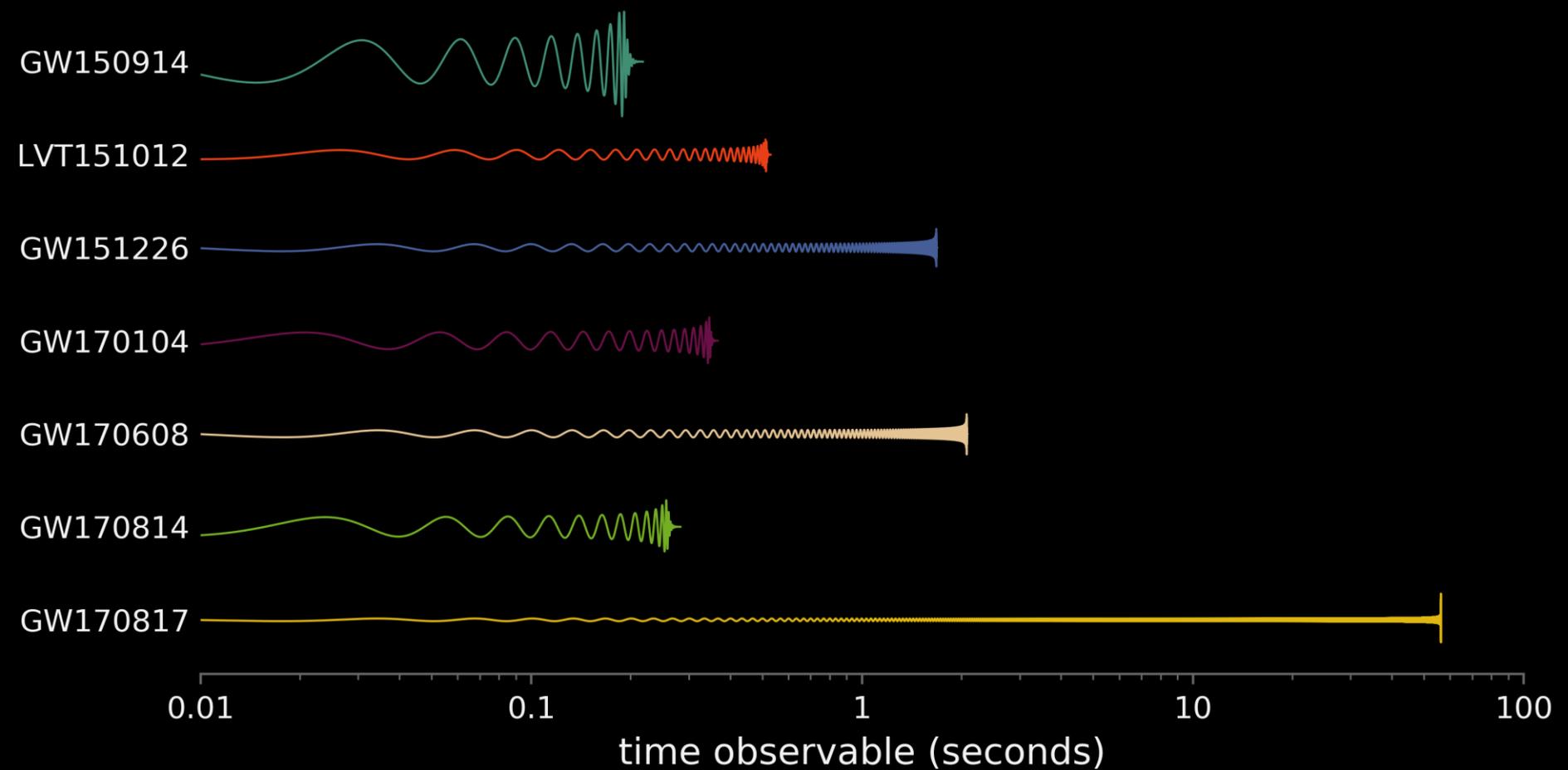
BBHs observed with LIGO.

Starting to build up a mass distribution

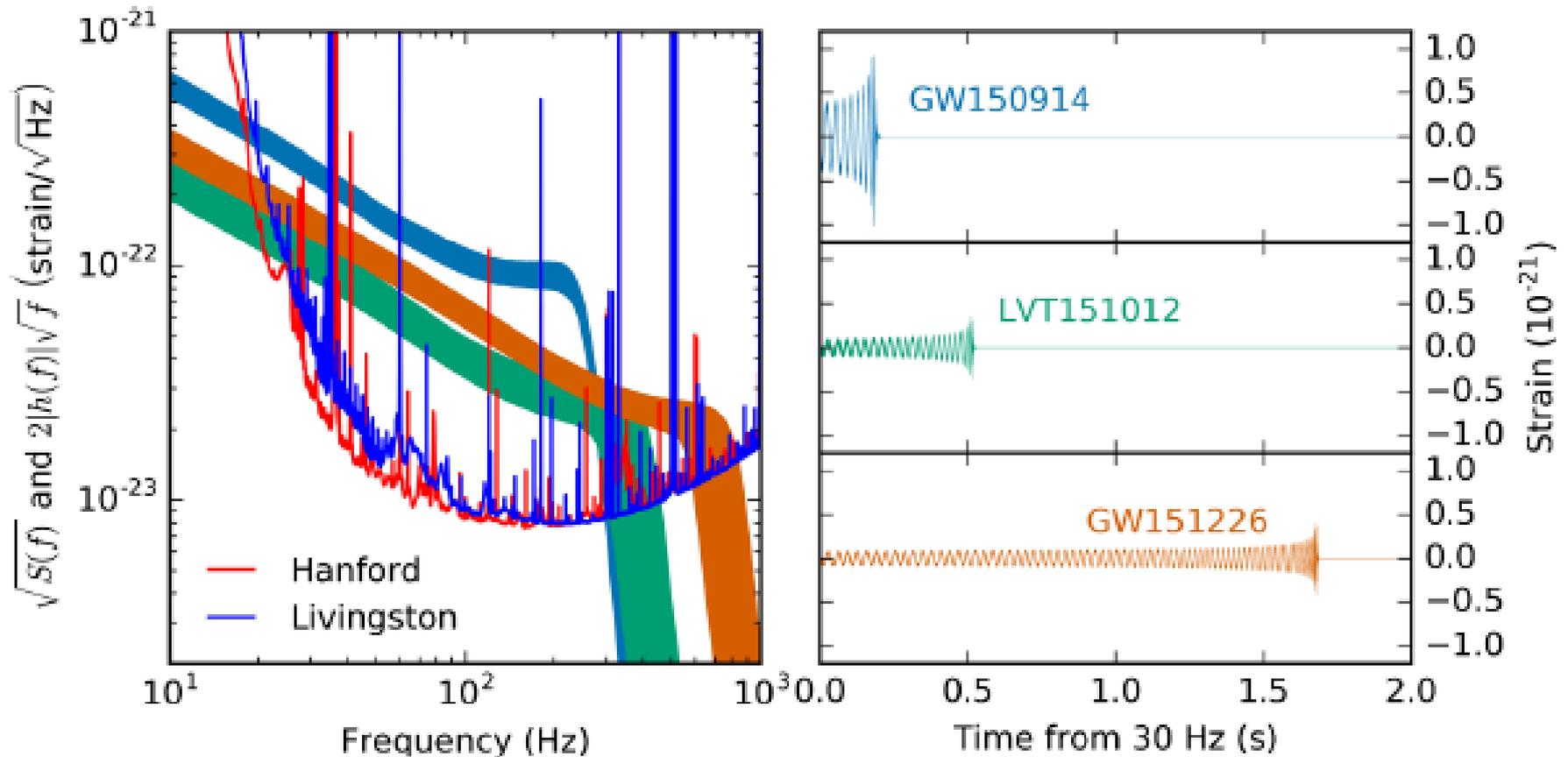
Black Holes of Known Mass



Observed signal durations (above ~30 Hz)



Three BBH events, compared



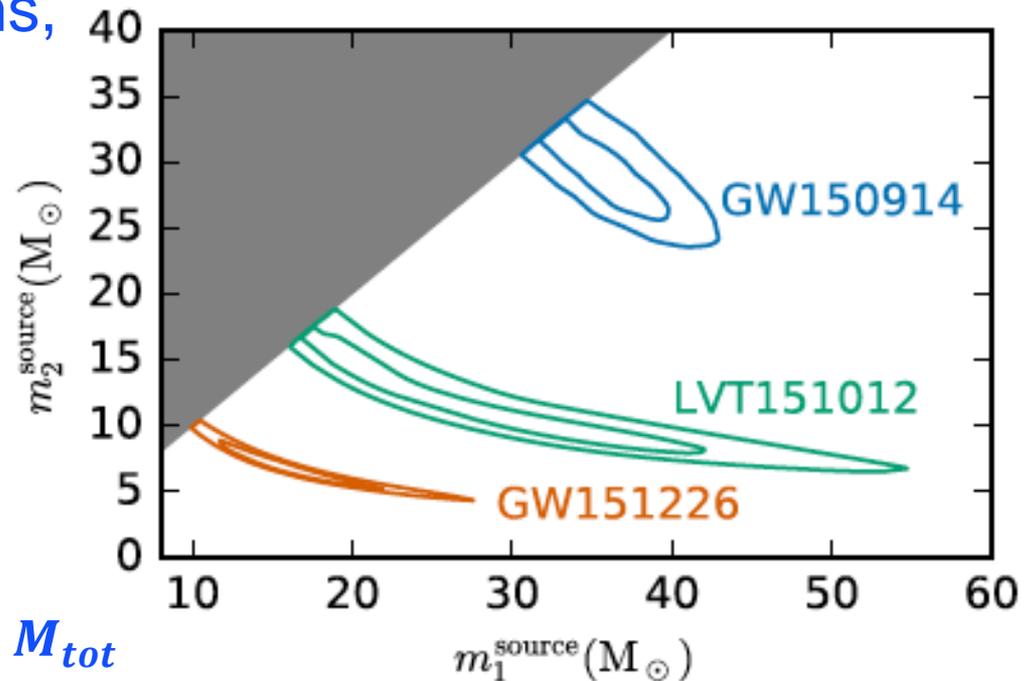
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", <https://arxiv.org/abs/1606.04856>, Phys. Rev. X 6, 041015 (2016)

Three BBH events, black hole masses

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

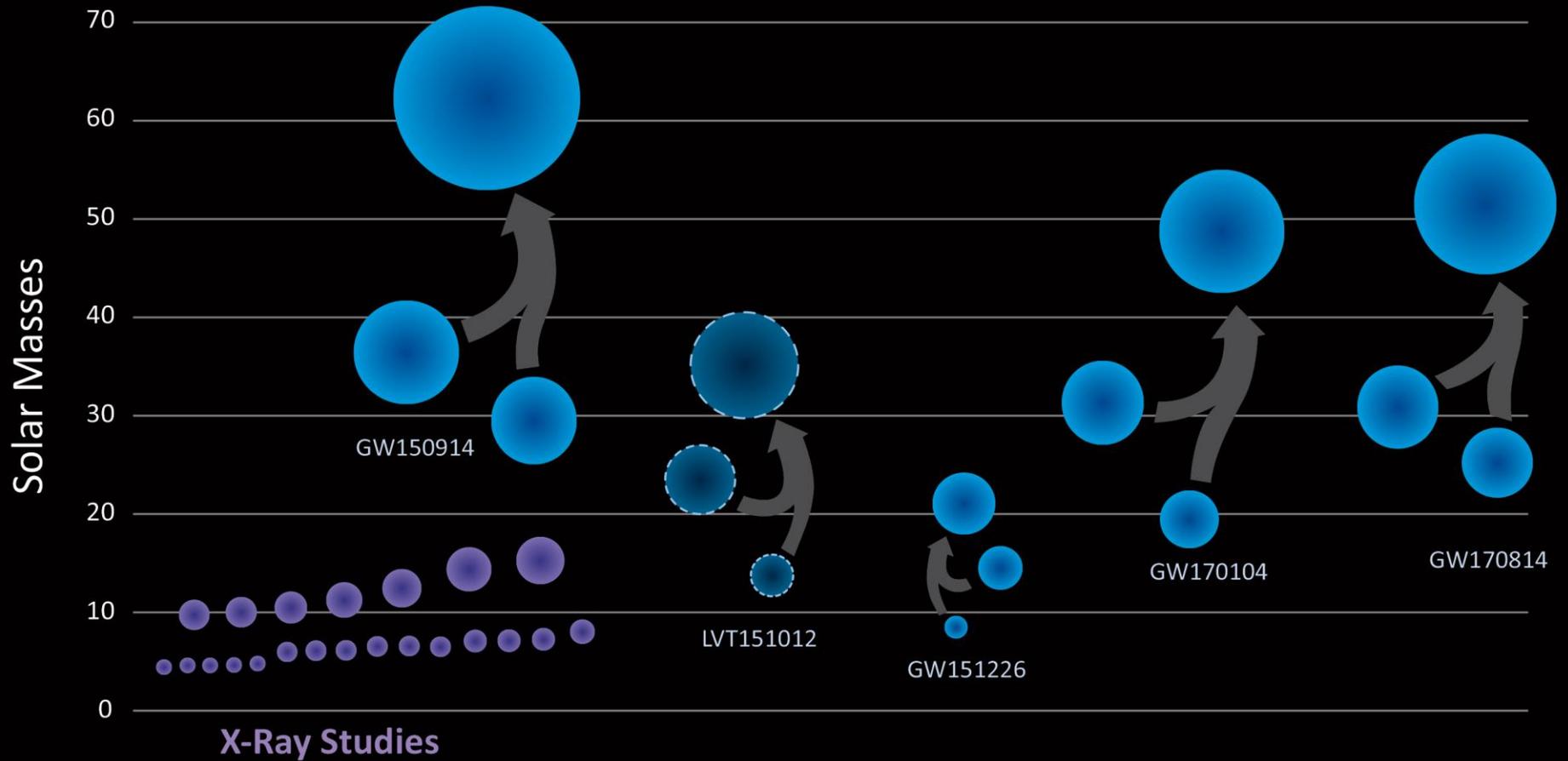
For lower mass systems,
we see the inspiral,
measure the “chirp mass”

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



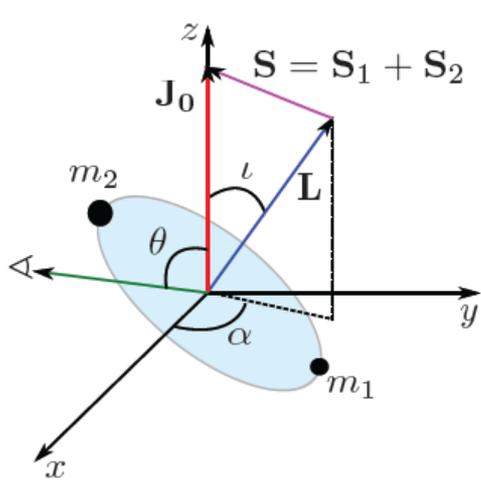
Waveform, and thus masses, are cosmologically red-shifted.
These masses are surprisingly large!

Black Holes of Known Mass

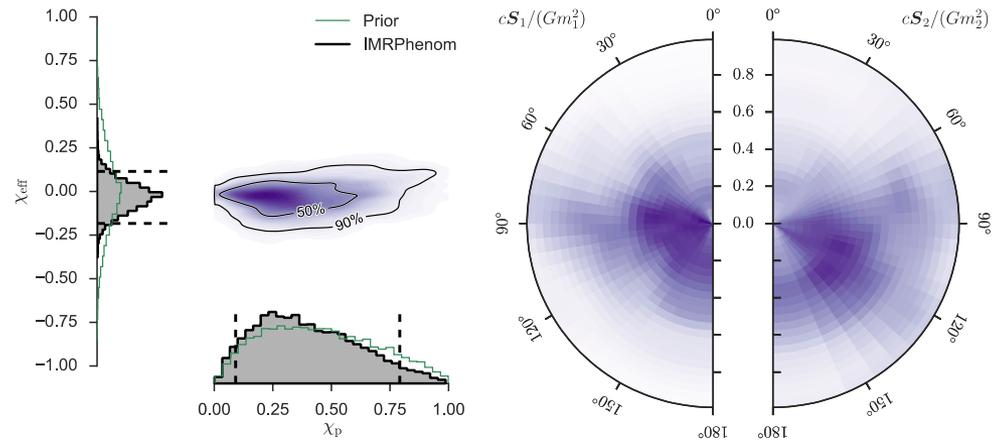


BH spins – aligned with orbital angular momentum, and precessing spin

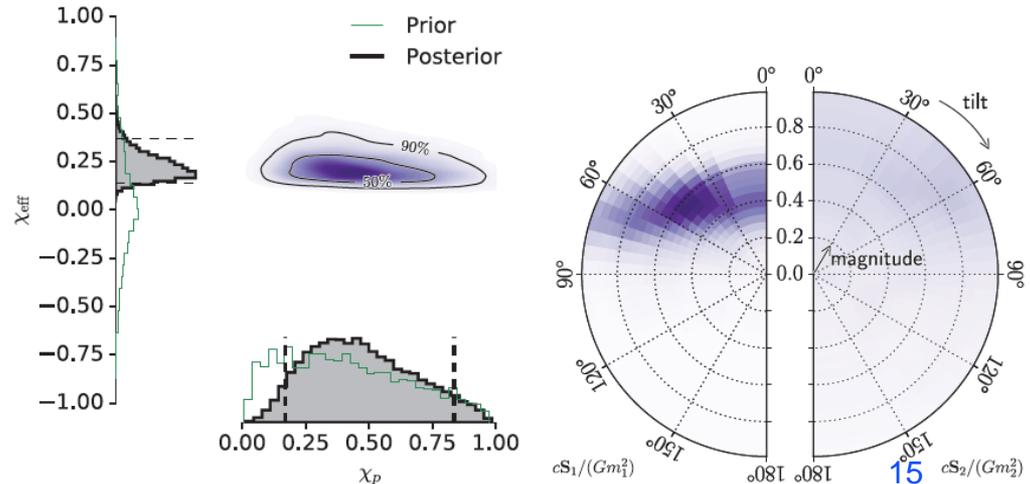
- The component BH spins measurably modulate the inspiral frequency evolution.
- Spin-orbit couplings cause the orbital plane to precess, producing amplitude modulation at the detectors.
- Parameterize with aligned spin χ_{eff} and “precessing” spin χ_P



GW150914

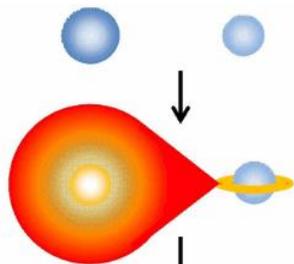


GW151226



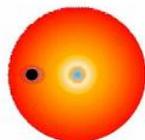
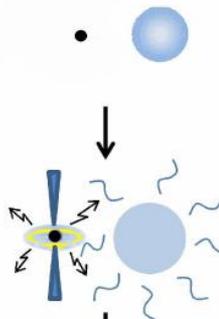
<https://dcc.ligo.org/LIGO-P1500262/public/main>

Isolated binary

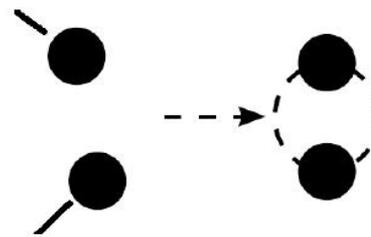


Mostly aligned spins

“ordinary”
or
rapid rotation
or
PopIII



Dynamical formation



uncorrelated spin alignment

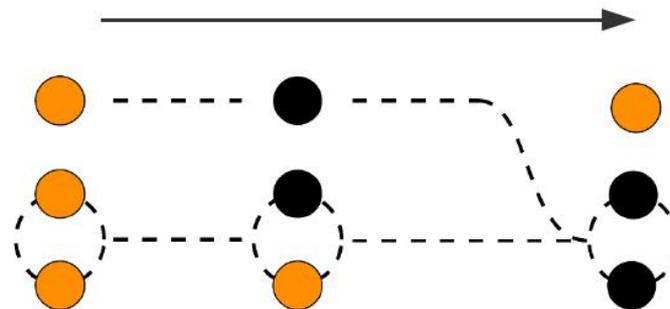


Fig. after Ziosi

Globular/young clusters/gal. nuclei

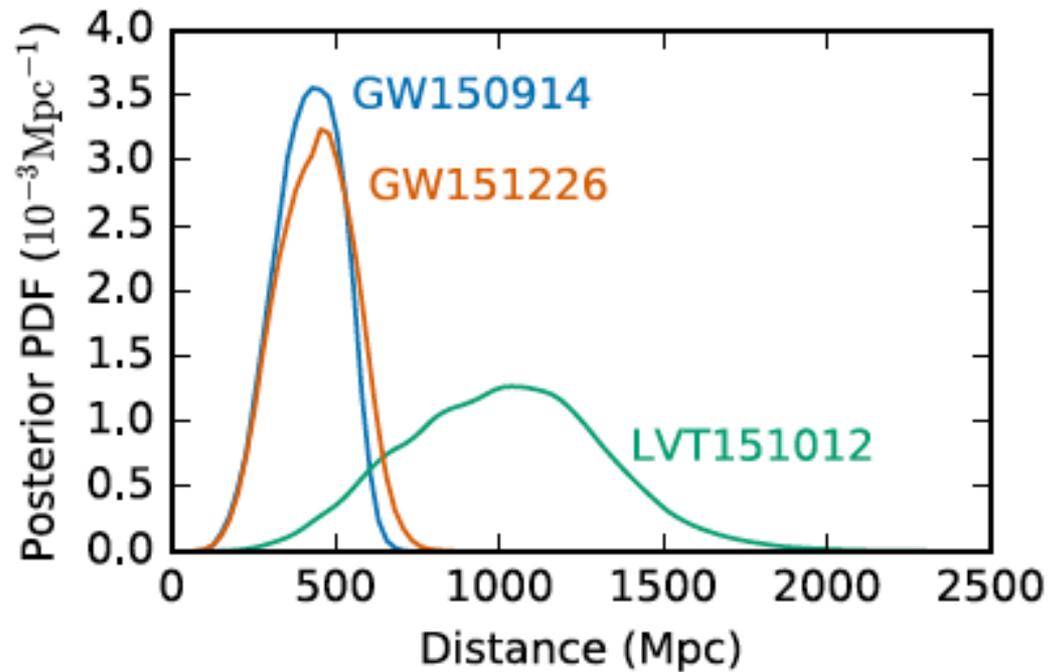
Three BBH events, distances

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!



Radiated energy & luminosity

▶ GW150914:

$$E_{\text{rad}} = 3.0^{+0.5}_{-0.4} M_{\odot} c^2$$

$$\ell_{\text{peak}} = 3.6^{+0.5}_{-0.4} \times 10^{56} \text{ erg/s}$$

▶ GW151226:

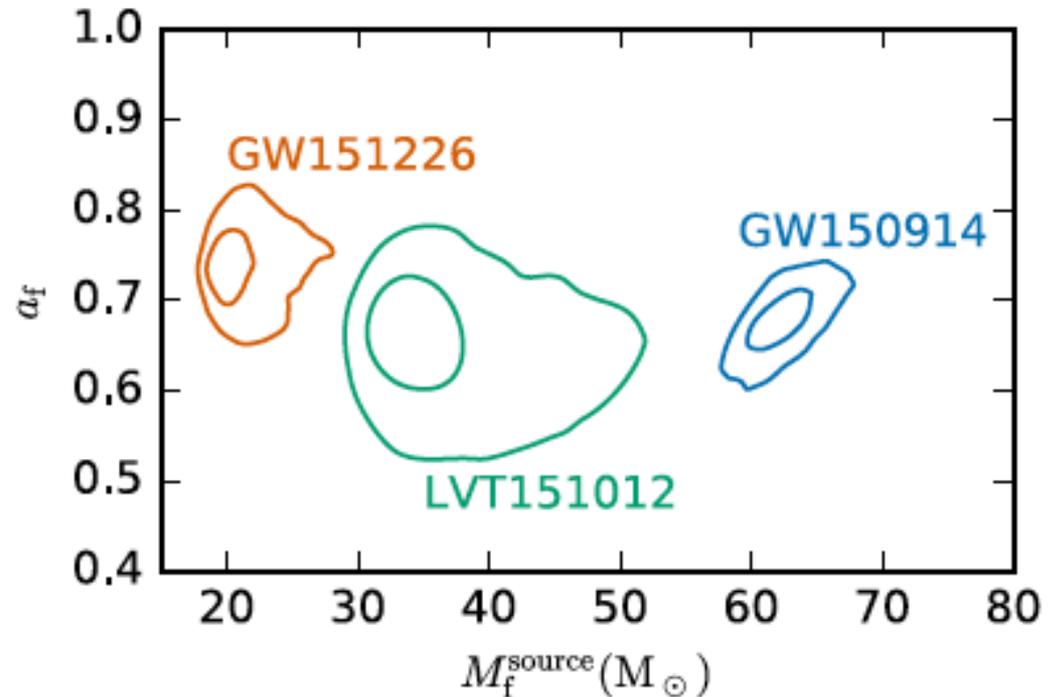
$$E_{\text{rad}} = 1.0^{+0.1}_{-0.2} M_{\odot} c^2$$

$$\ell_{\text{peak}} = 3.3^{+0.8}_{-1.6} \times 10^{56} \text{ erg/s}$$

▶ LVT151012:

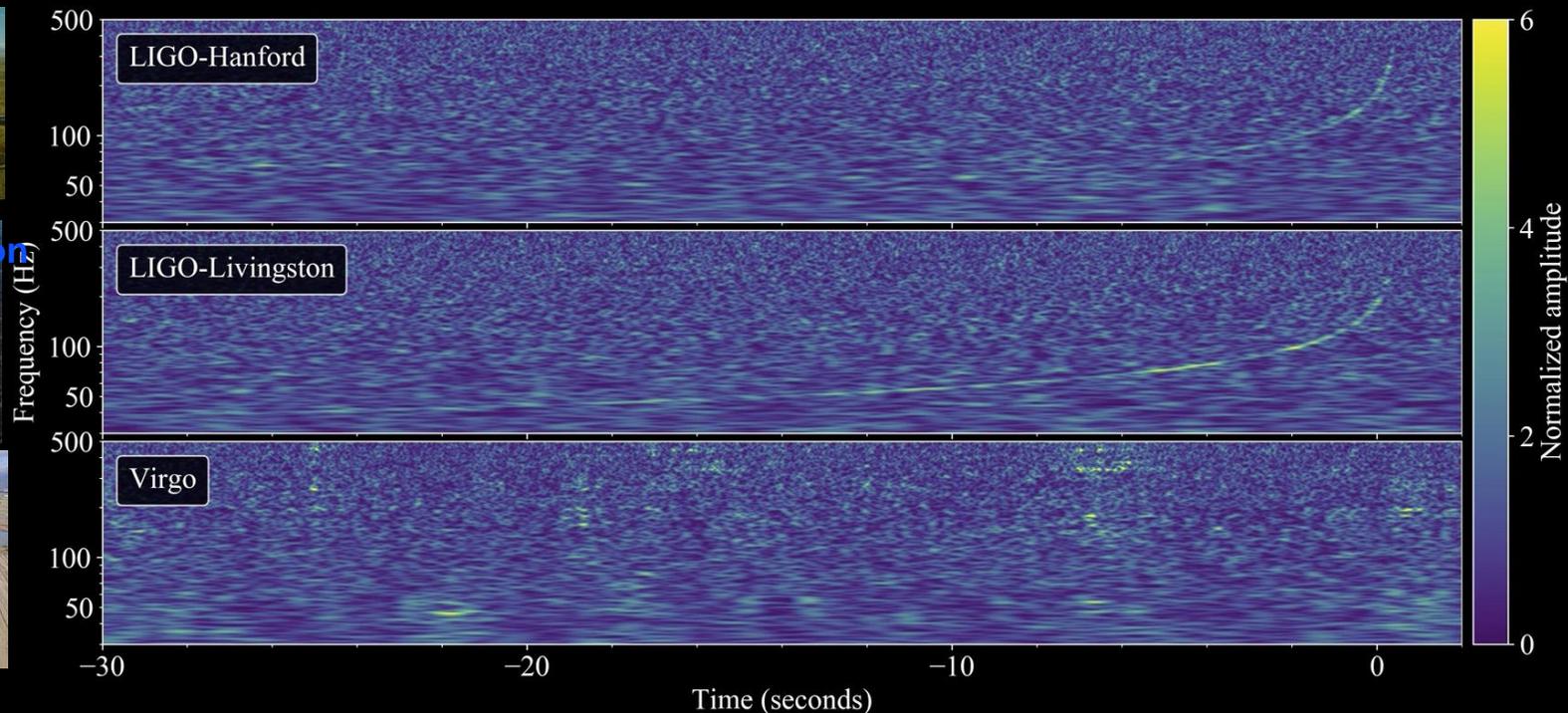
$$E_{\text{rad}} = 1.5^{+0.3}_{-0.4} M_{\odot} c^2$$

$$\ell_{\text{peak}} = 3.1^{+0.8}_{-1.8} \times 10^{56} \text{ erg/s}$$

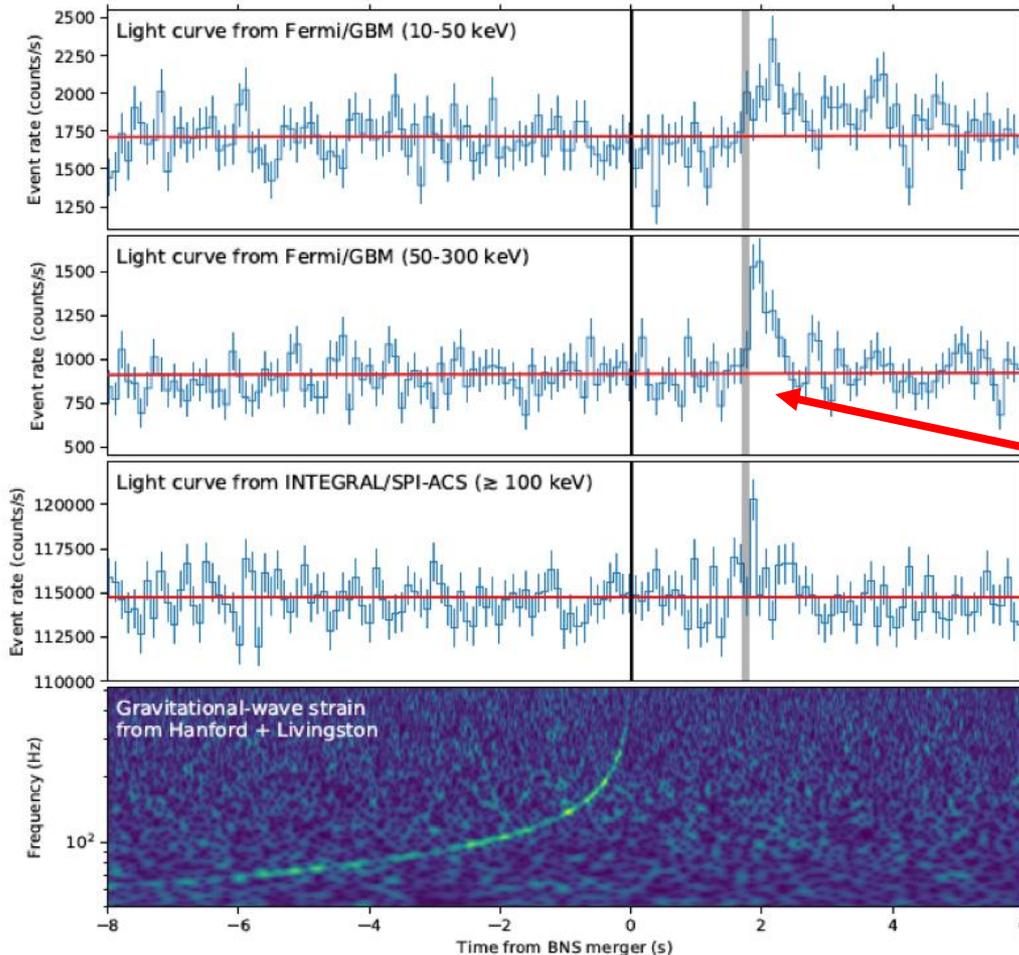
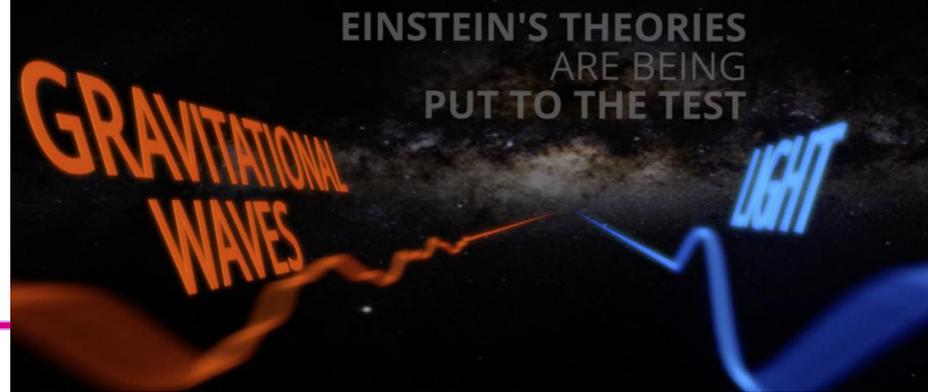


- GW150914: $E_{\text{GW}} \approx 3 M_{\odot} c^2$, or $\sim 4.5\%$ of the total mass-energy of the system.
- Roughly 10^{80} gravitons.
- Peak luminosity $L_{\text{GW}} \sim 3.6 \times 10^{54} \text{ erg/s}$, briefly outshining the EM energy output of all the stars in the observable universe (by a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

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



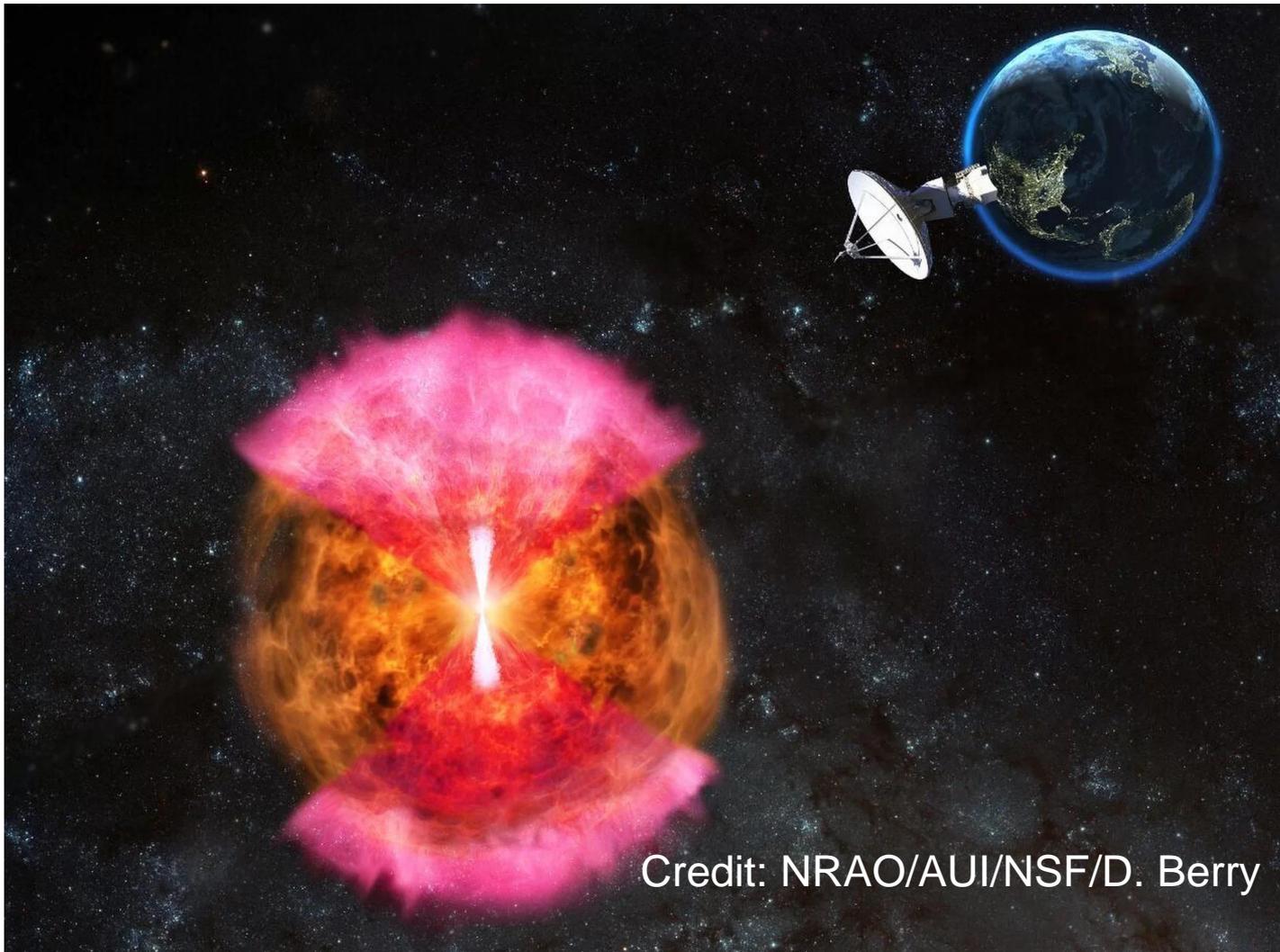
GW170817 A Binary Neutron Star Merger! (!!!!!!!)



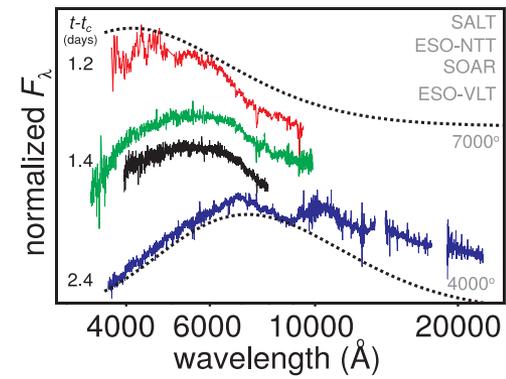
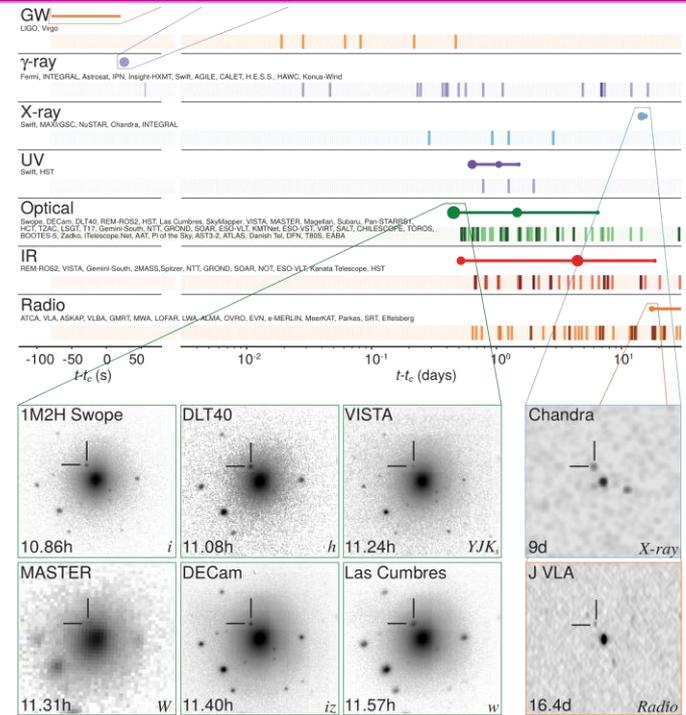
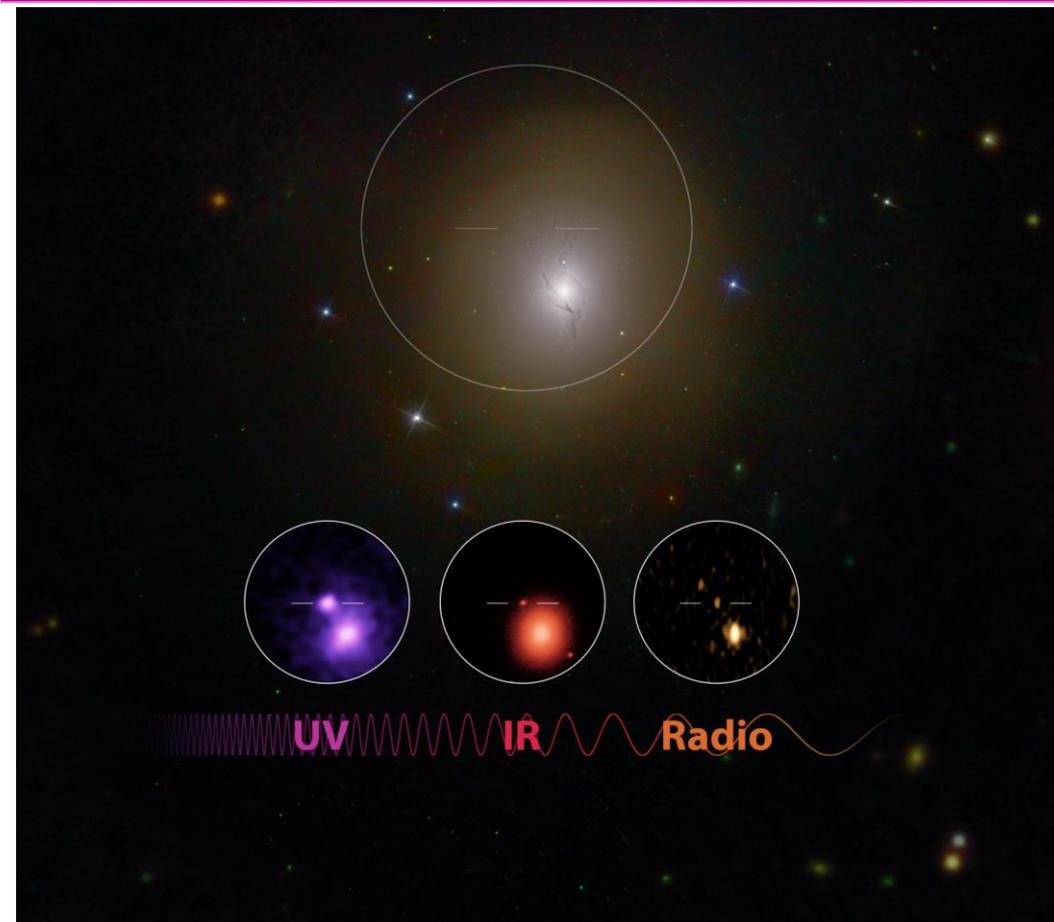
1.7 seconds later, A short GRB!

- 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!

GW170817 burst of gamma rays: choked jet “cocoon” model



Light at Every Wavelength

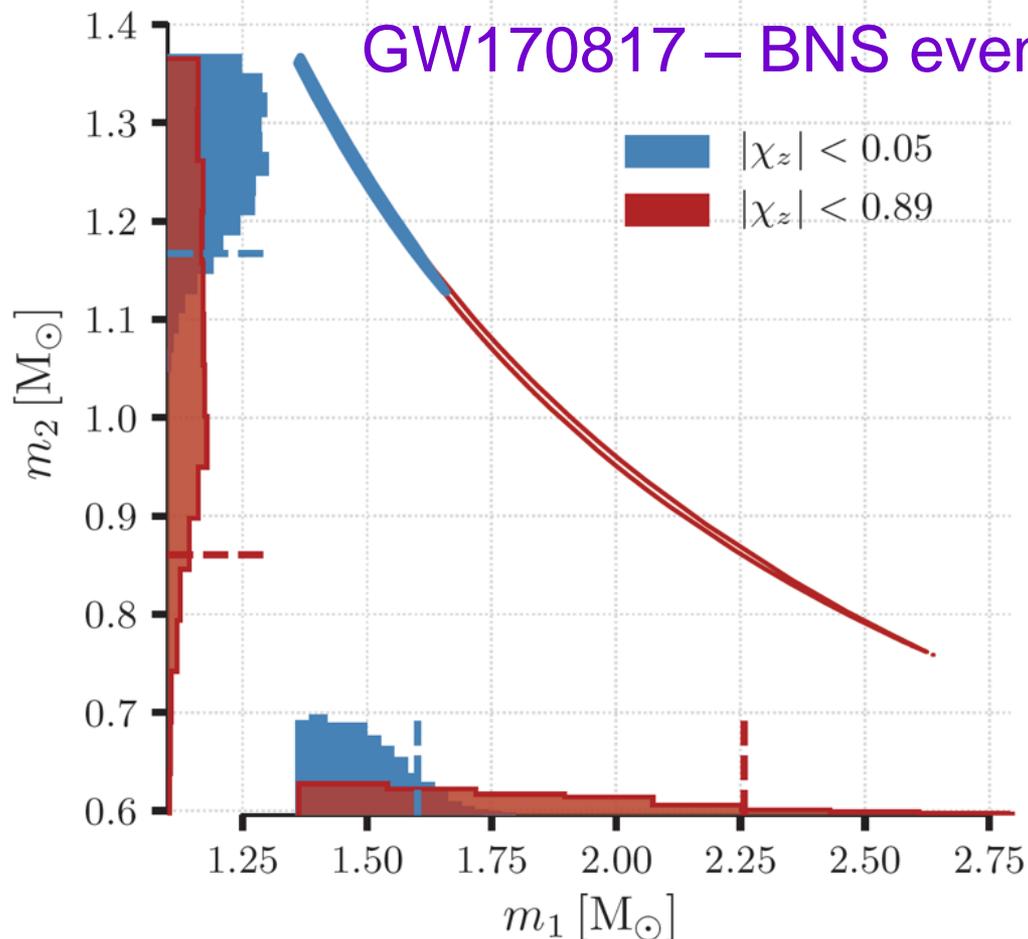


Host galaxy: NGC 4993; redshift: ~ 0.01

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

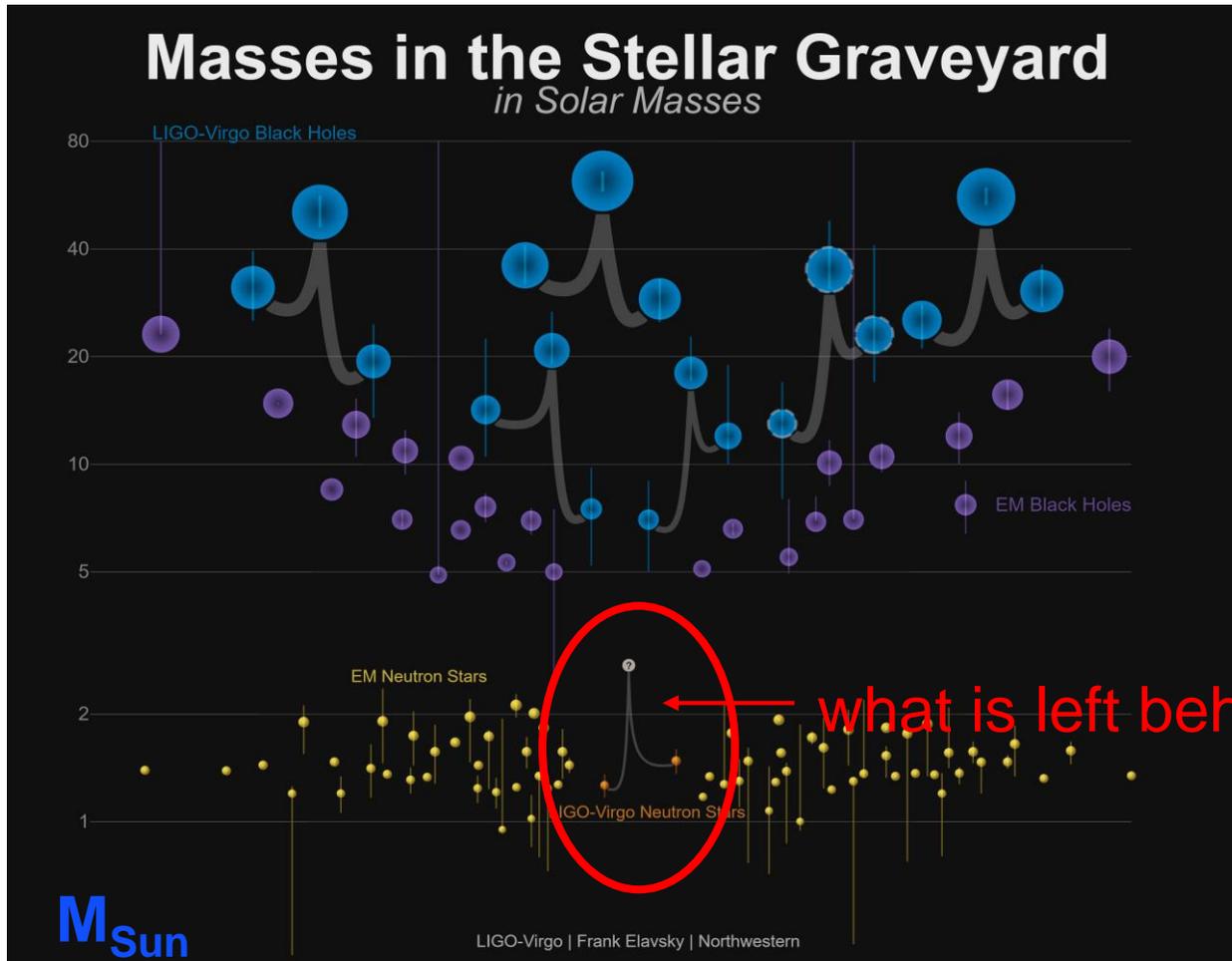


And it depends on whether we think neutron stars spin a lot or only a little.

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

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



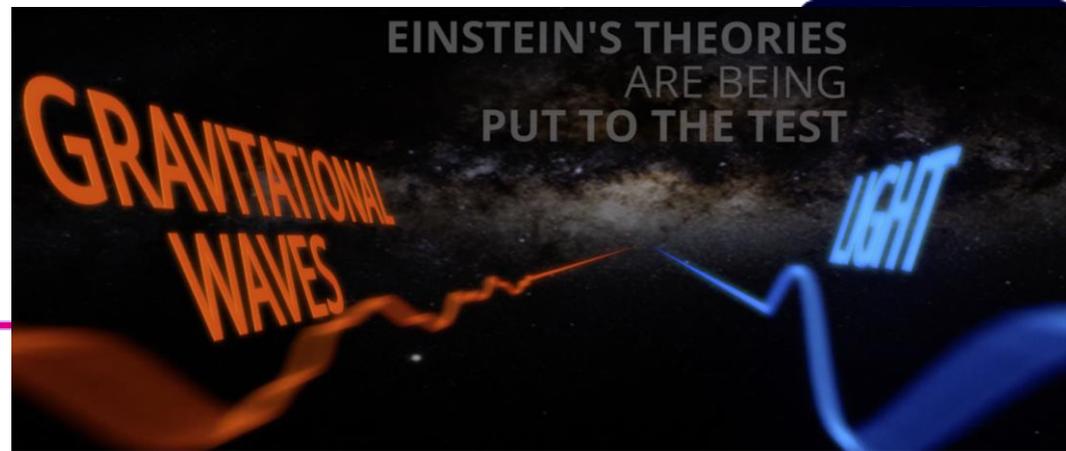
“stellar mass”
black holes

“mass gap”?

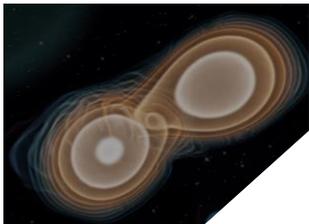
Neutron stars
(pulsars)

what is left behind?

LIGO 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 \times), 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* $m_g < (\text{few}) \times 10^{-23} \text{ eV}/c^2$, *consistent with 0*.
- Improved Lorentz invariance violation limits; constrained to one part in 10^{13} .
- Both the gravitons and the photons "fell" into the Milky Way Galaxy over the same time: *the Equivalence Principle holds between gravitons and photons* .

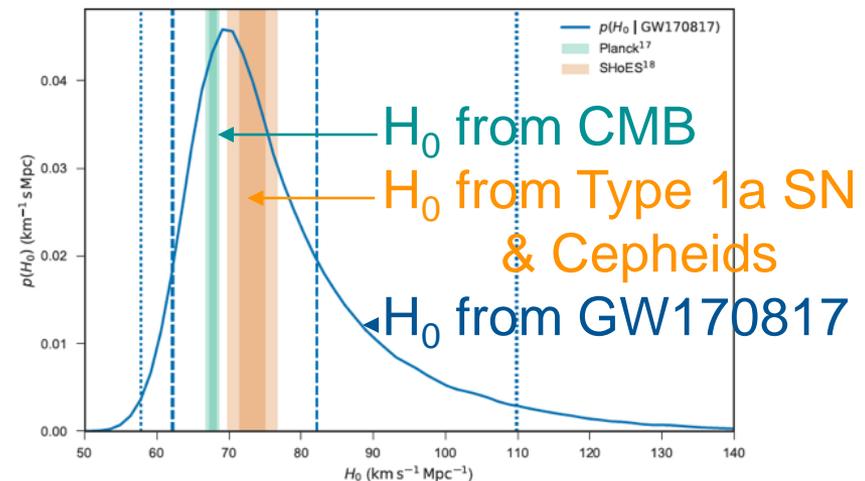
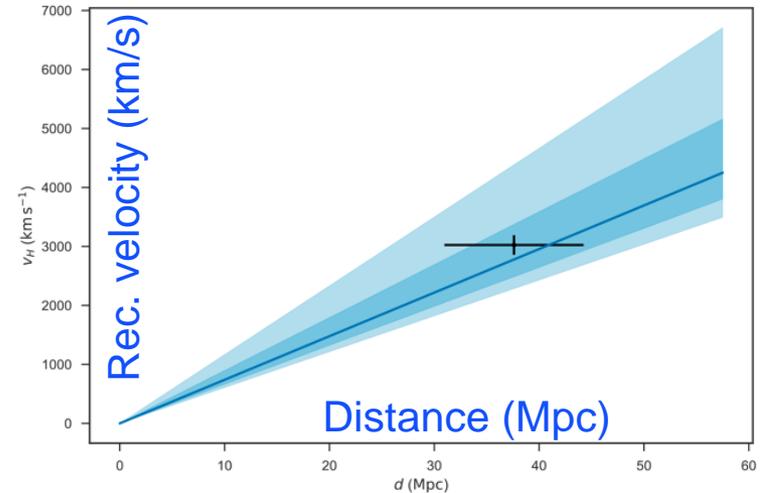


g
 γ



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

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



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

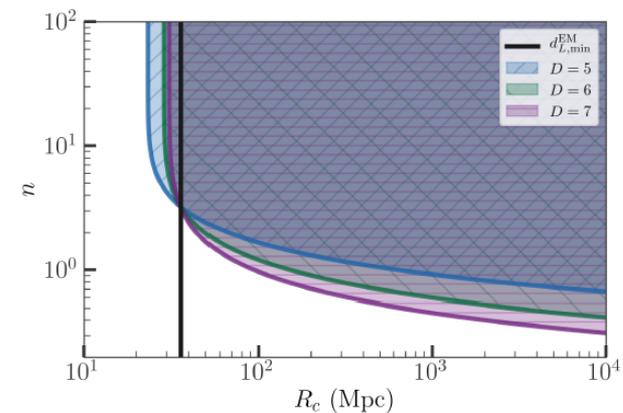
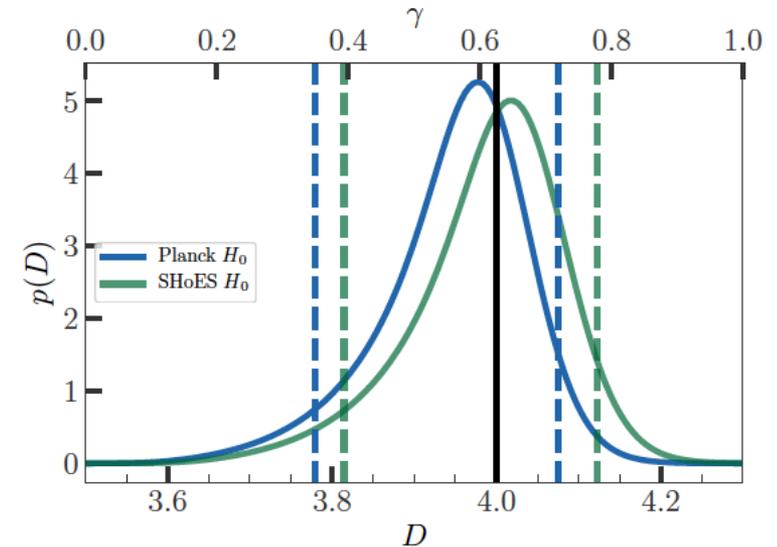
A gravitational-wave standard siren measurement of the Hubble constant

- Define “EM luminosity distance” via Hubble relation: $v_H = H_0 d_L^{\text{EM}}$
- HW luminosity distance, measured from the strain amplitude: $h_{\text{GR}} \propto \frac{1}{d_L}$
- Allow GW amplitude to leak into extra ($D > 4$) dimensions: $h \propto \frac{1}{d_L^\gamma}$, $\gamma = \frac{D-2}{2}$.

- Consider a screening scale:

$$h \propto \frac{1}{d_L \left[1 + \left(\frac{d_L}{R_c} \right)^{n(D-4)/2} \right]^{1/n}}$$

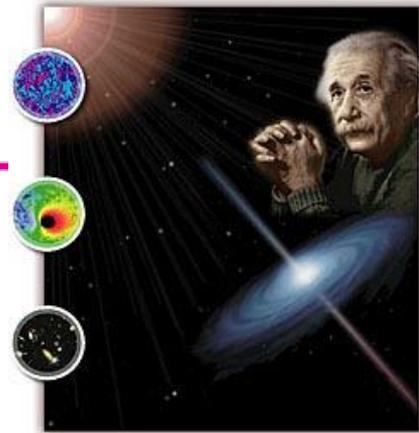
H_0 prior km s ⁻¹ Mpc ⁻¹	γ	D
$H_0 = 73.24 \pm 1.74$ [22]	$1.01^{+0.04}_{-0.05}$	$4.02^{+0.07}_{-0.10}$
$H_0 = 67.74 \pm 0.46$ [21]	$0.99^{+0.03}_{-0.05}$	$3.98^{+0.07}_{-0.09}$



Limits on the number of spacetime dimensions from GW170817

Kris Pardo,^{1,*} Maya Fishbach,² Daniel E. Holz,^{2,3,4} and David N. Spergel^{1,5}

<https://arxiv.org/abs/1801.08160>



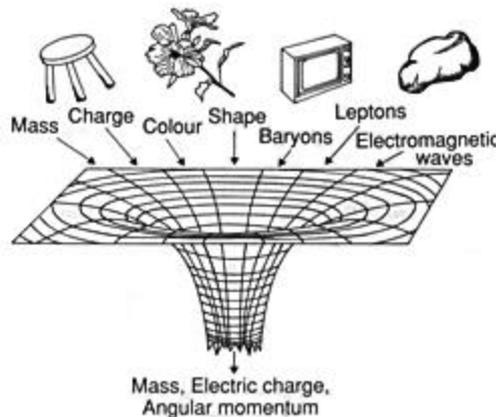
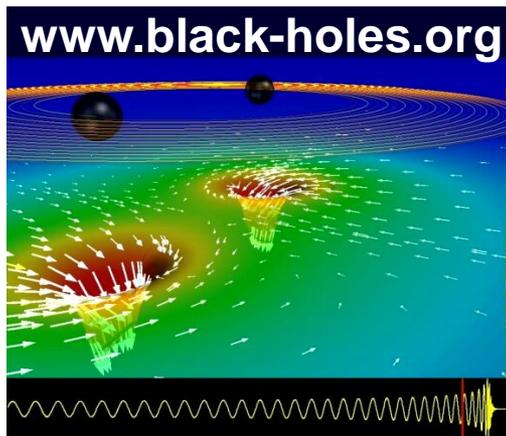
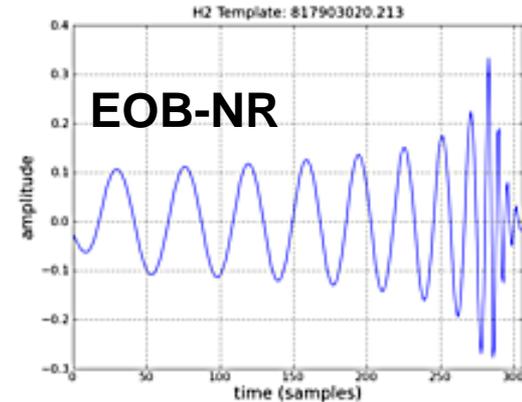
- **We can test GR in the new regime of strong-field, highly dynamical gravity!**
- **Gravitational lensing & multiple “images” (not beyond GR!)**
- **Constrain “parameterized post-Einsteinian framework” (Yunes & Pretorius, 2009)**
- **Directly measure speed of gravitational waves ($c_{\text{GW}} \neq c_{\text{light}}$), 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.

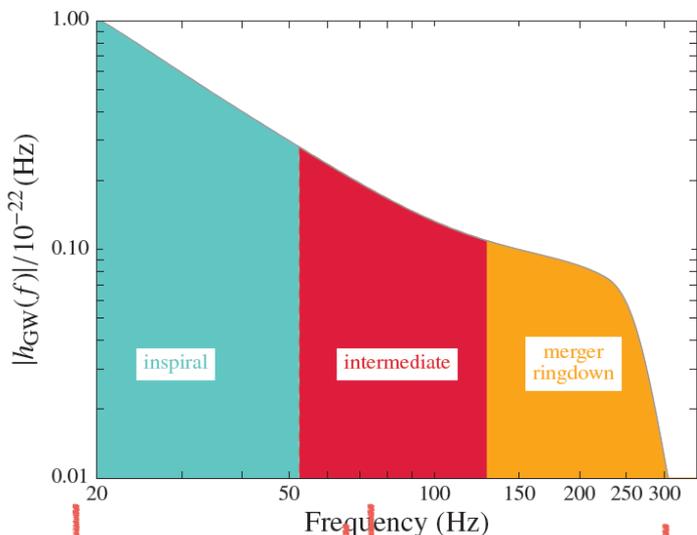
$$\Psi(f) \equiv 2\pi f t_0 + \varphi_0 + \frac{3}{128\eta v^5} \left(1 + \sum_{k=2}^7 v^k \psi_k \right).$$

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



nonlocal.com/hbar/blackholes.html





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

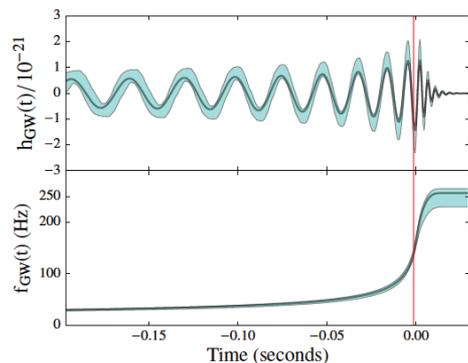
$$h(f) = A(f)e^{i\Phi(f)} \quad v_{orb}^3 = \pi G M_{tot} f_{GW}$$

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

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

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

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



Tests of consistency with predictions from General Relativity

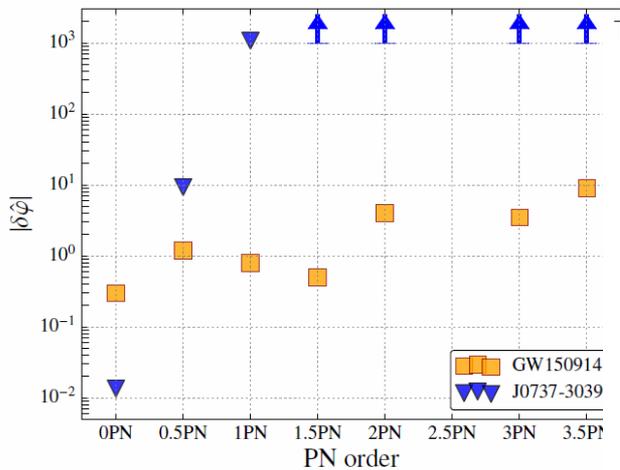
- Waveform models are described by post-Newtonian and phenomenological coefficients calibrated against numerical relativity (NR) solutions
- We allow for fractional changes with respect to the GR value

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

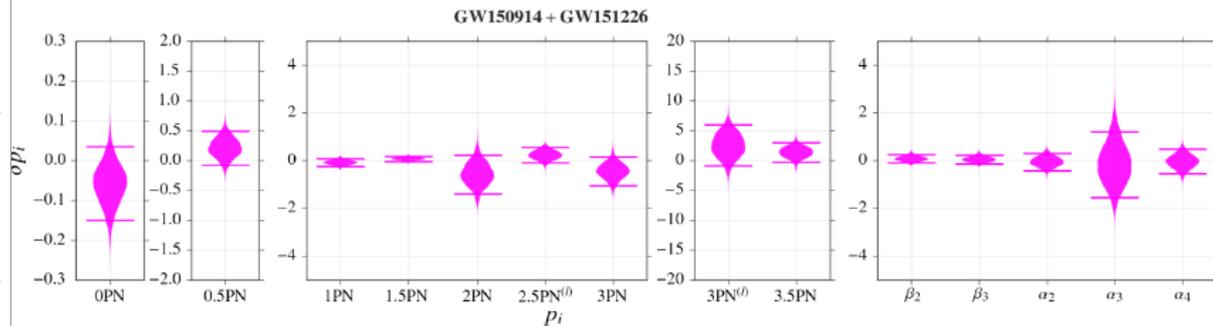
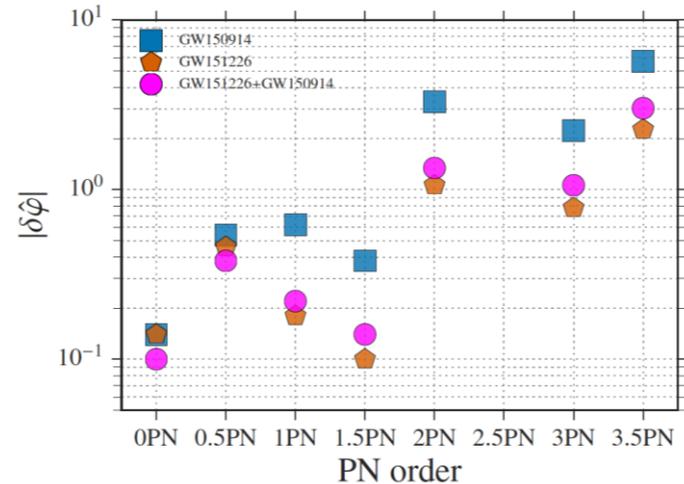
- Obtain constraints on “generic” deviations from GR

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

Consistency with predictions from GR – results from GW150914

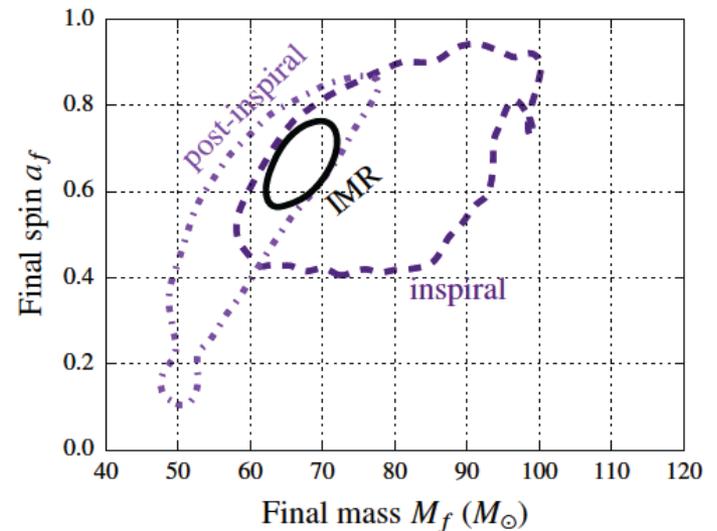
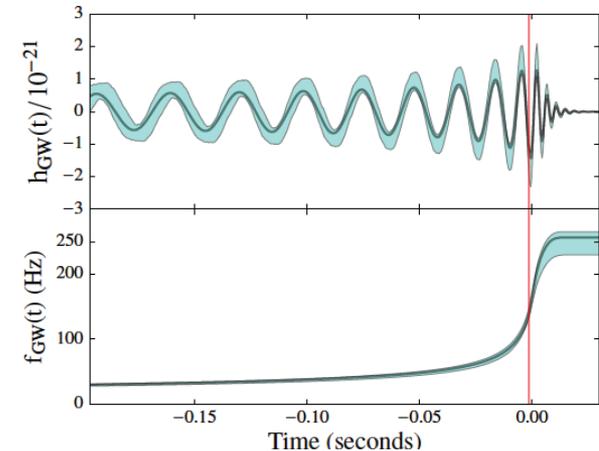


waveform regime	parameter	f -dependence	median		GR quantile		$\log_{10} B_{\text{model}}^{\text{GR}}$	
			single	multiple	single	multiple	single	multiple
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$	$-0.1^{+0.1}_{-0.1}$	$1.3^{+3.0}_{-3.2}$	0.94	0.30	1.9 ± 0.2	
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	$0.3^{+0.4}_{-0.4}$	$-0.5^{+0.6}_{-0.6}$	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	3.7 ± 0.6
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	$0.8^{+0.5}_{-0.6}$	$-1.4^{+18.6}_{-16.9}$	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	
merger-ringdown regime	$\delta\hat{\varphi}_{6l}$	$f^{1/3} \log(f)$	$8.9^{+6.8}_{-6.8}$	$-1.9^{+19.1}_{-16.1}$	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	
	$\delta\hat{\alpha}_3$	$f^{3/4}$	$-0.3^{+1.9}_{-1.5}$	$0.0^{+4.4}_{-4.4}$	0.60	0.51	0.7 ± 0.2	2.1 ± 0.4
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af + b)$	$-0.1^{+0.5}_{-0.5}$	$-0.1^{+1.1}_{-1.0}$	0.68	0.62	1.1 ± 0.2	



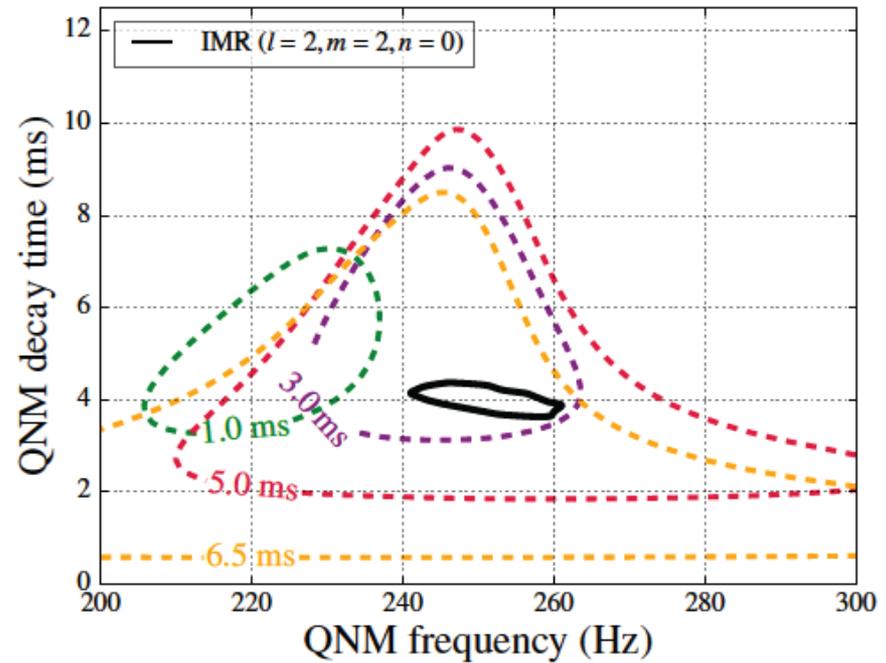
Tests of consistency with predictions from General Relativity

- 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



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)

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: $\lambda_g > 10^{13}$ [km] and $m_g < 1.2 \times 10^{-22}$ [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

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

and associated Compton wavelength

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

results in frequency-dependent velocity

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

and dispersion causes distortion of the

phase evolution of the waveform

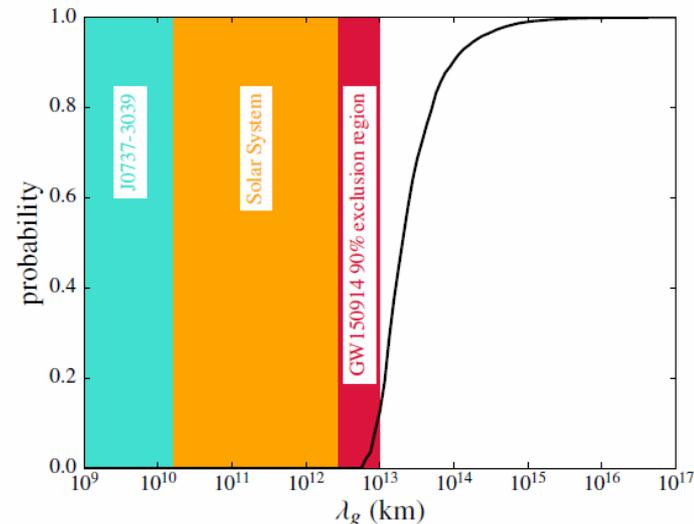
(wrt massless theory)

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

Agreement of observed waveform with

theory allows us to set the bound:

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



$$\lambda_g \geq 10^{13} \text{ km (90\%)} \quad \text{u.u.}$$

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

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:
 - $\lambda_g > 1.6 \times 10^{13}$ km
 - $m_g \leq 7.7 \times 10^{-23}$ eV/ c^2

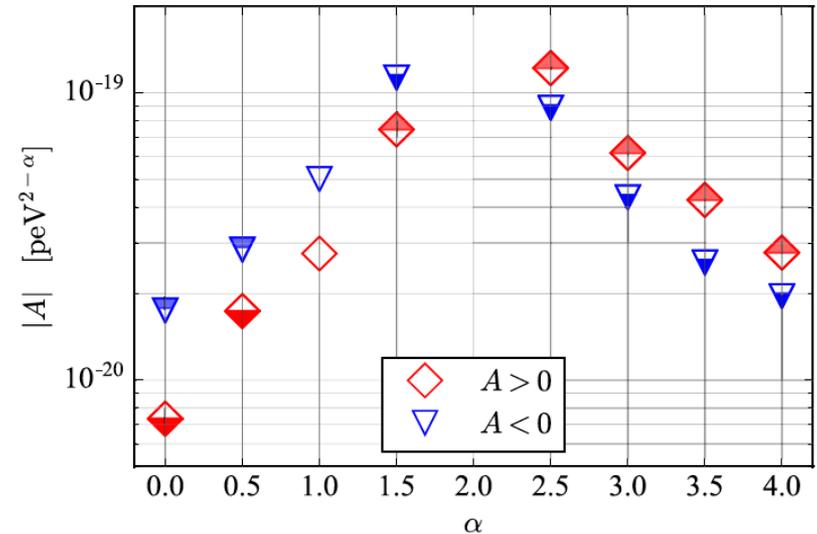


FIG. 5. 90% credible upper bounds on $|A|$, the magnitude of dispersion, obtained combining the posteriors of GW170104 with those of GW150914 and GW151226. We use picelectron-

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

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

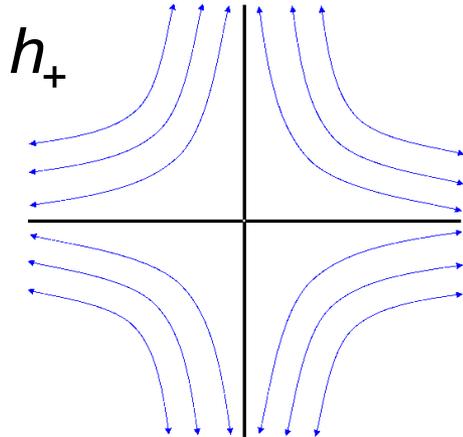
Gravitational Wave Polarization

Solution for an outward propagating wave in z-direction:

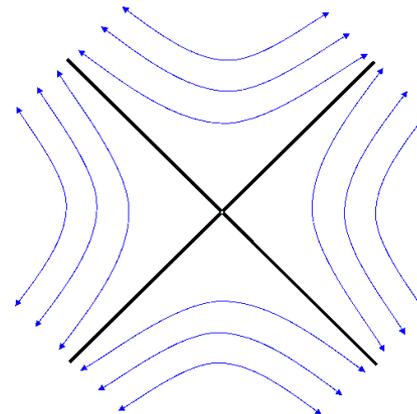
$$h(t, z) = h_{mn} e^{i(\omega t - kz)} = h_+(t - z/c) + h_\times(t - z/c)$$

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

$$h_{mn} \gg \frac{1}{r} \frac{G}{c^4} I_{mn}$$



h_\times

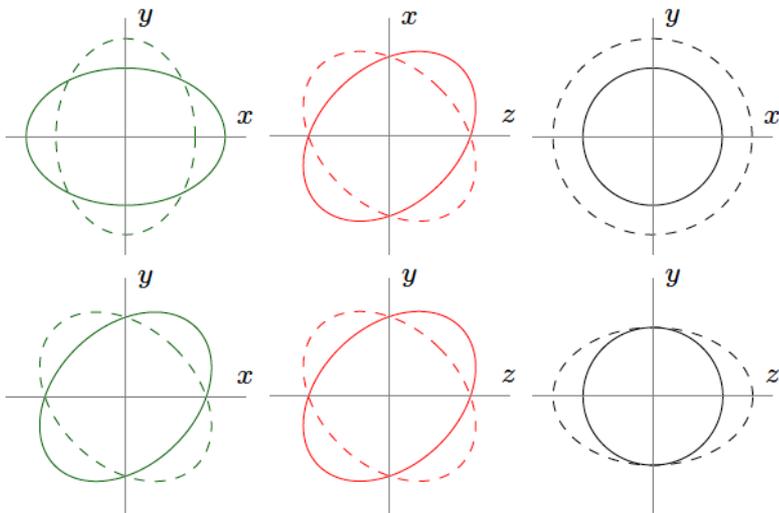


Non-tensor polarization

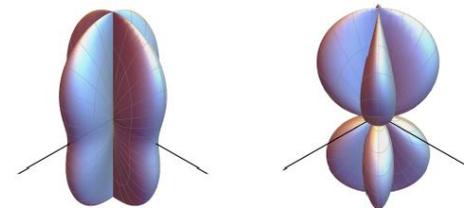
(Spatial part of the)
general metric field
tensor:

$$[h_{ij}] = \begin{pmatrix} h_b + h_+ & h_x & h_x \\ h_x & h_b - h_+ & h_y \\ h_x & h_y & h_l \end{pmatrix}$$

Effect on a ring of test masses:

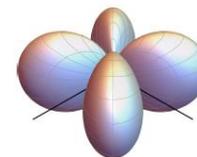


Antenna patterns:

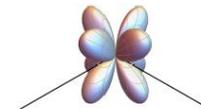


(a) Plus (+)

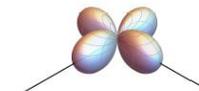
(b) Cross (x)



(c) Vector-x (x)

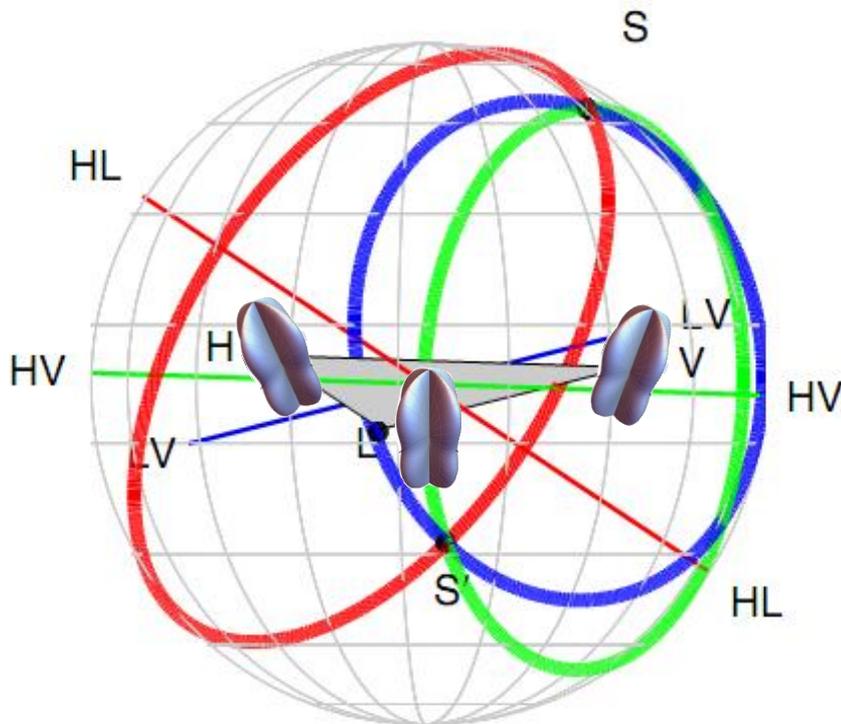


(d) Vector-y (y)



(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

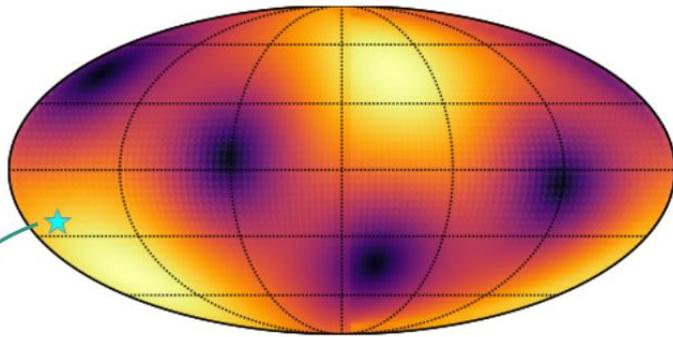
Pure tensor is strongly favored over pure vector or pure scalar. (*EXTREME* models!)

This would not have been possible without Virgo!

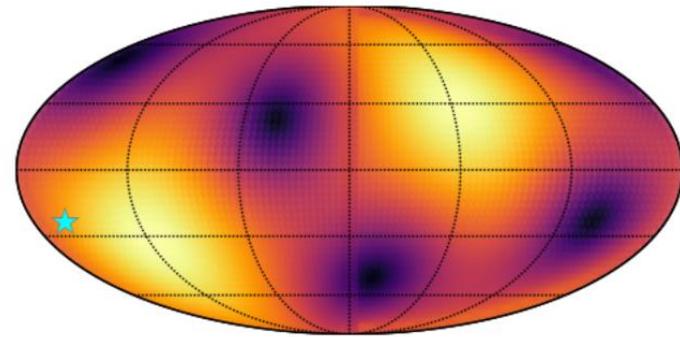
To measure small admixtures of S,V in dominant T requires *five non-co-oriented detectors*

What can we do with GW170817?

tensor

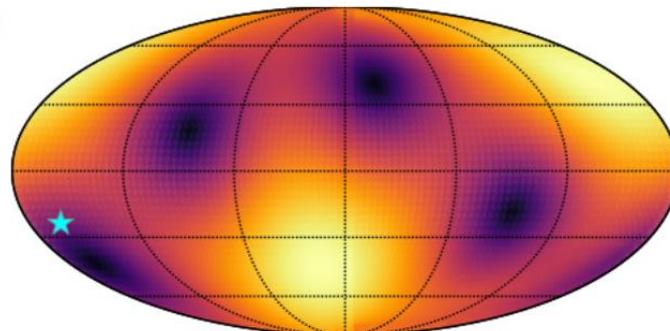


Hanford

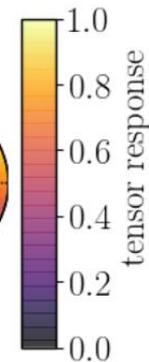


Livingston

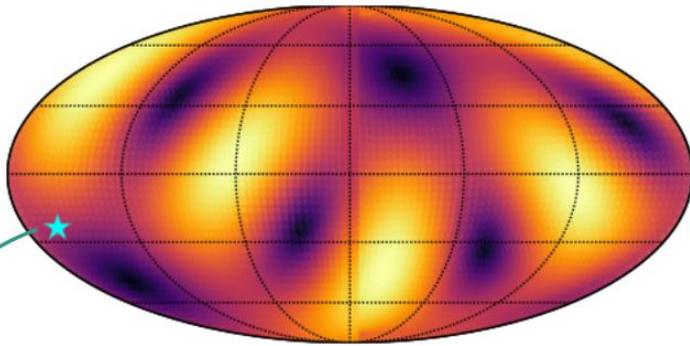
EM counterpart



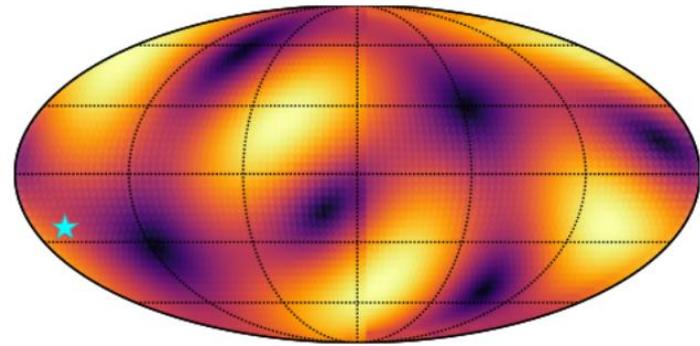
Virgo



vector

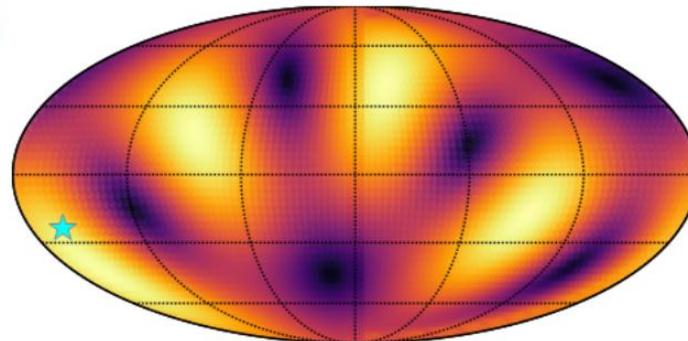


Hanford

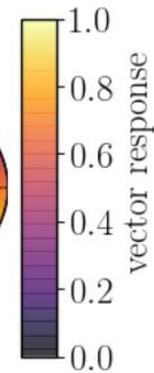


Livingston

EM counterpart

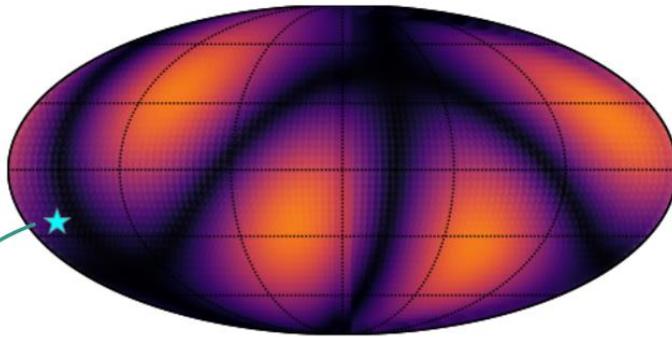


Virgo

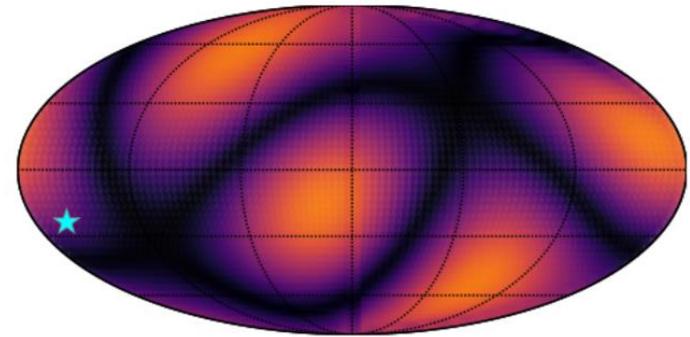


Stay tuned for V/T, S/T polarization constraints from GW170817

scalar

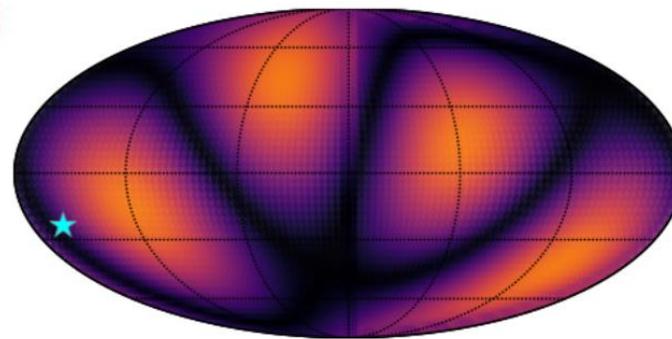


Hanford

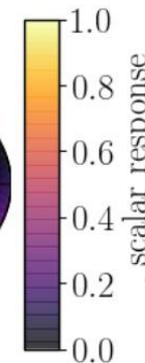


Livingston

EM counterpart

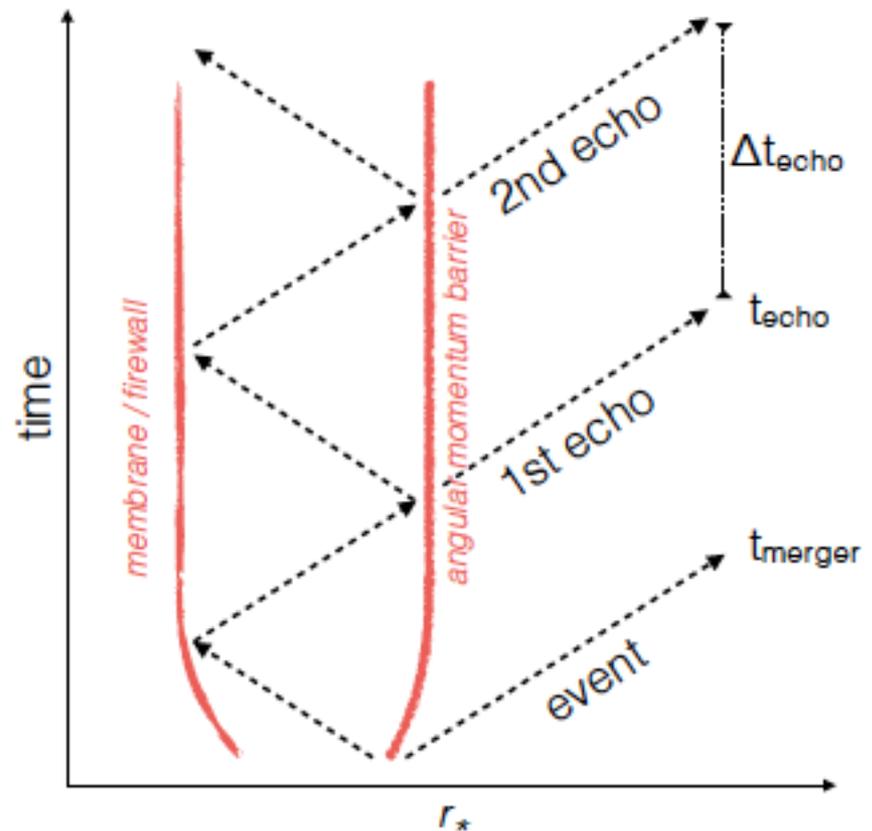


Virgo



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 $8M \log M$



Echoes from the Abyss:

arXiv:1612.00266v1, Abedi, Dykaar, and Afshordi

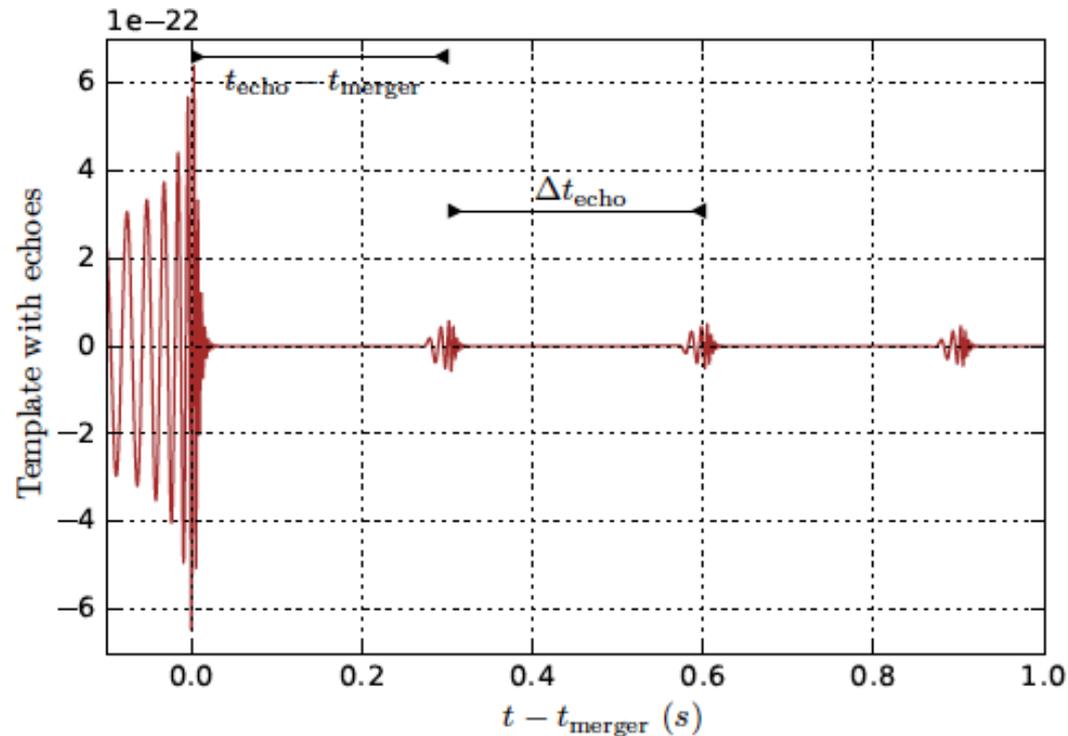
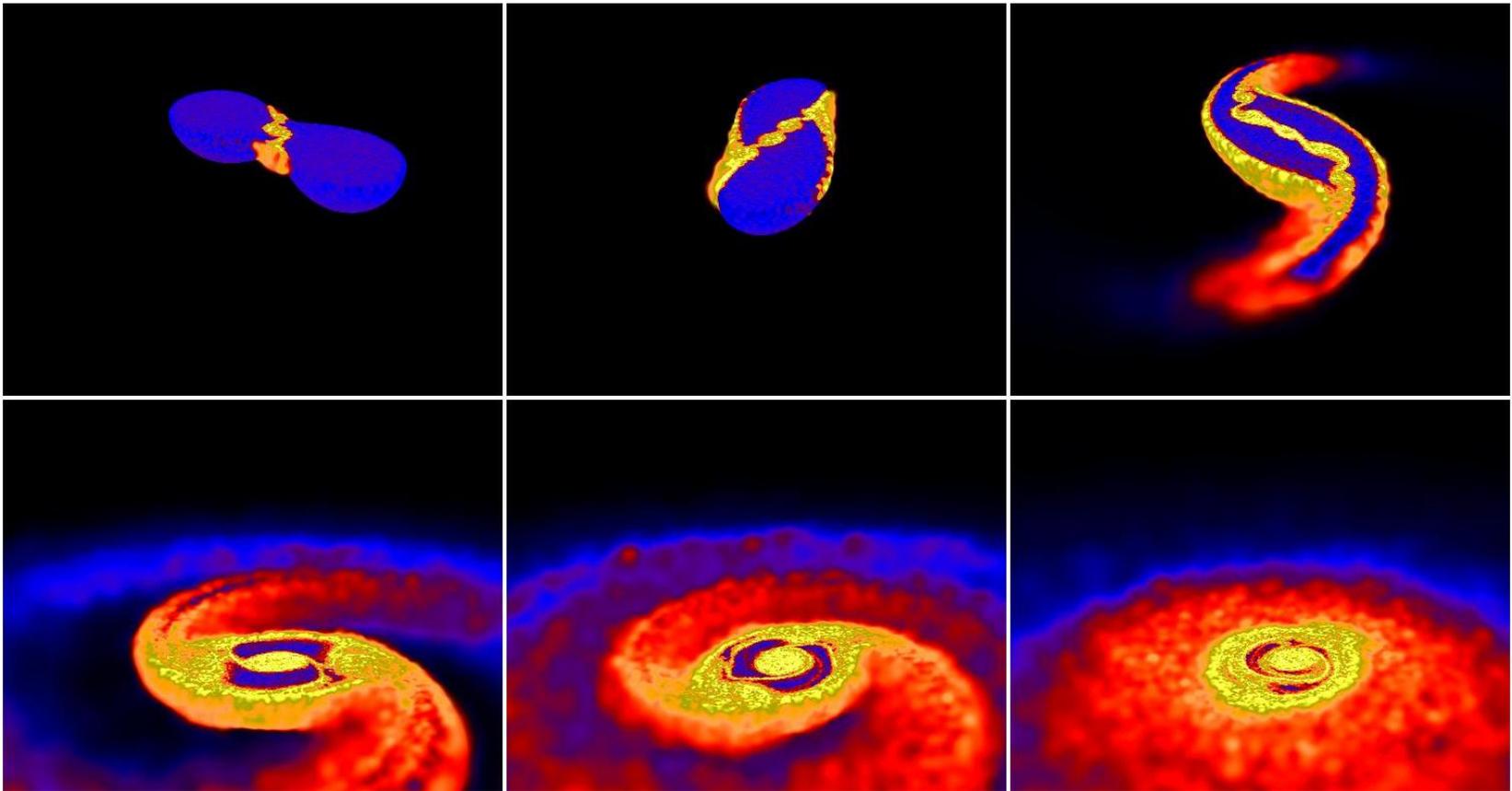


FIG. 2: LIGO original template for GW150914, along with our best fit template for the echoes.

“... we find tentative evidence for Planck-scale structure near black hole horizons at 2.9σ significance level”

BNS mergers, tidal distortion and disruption

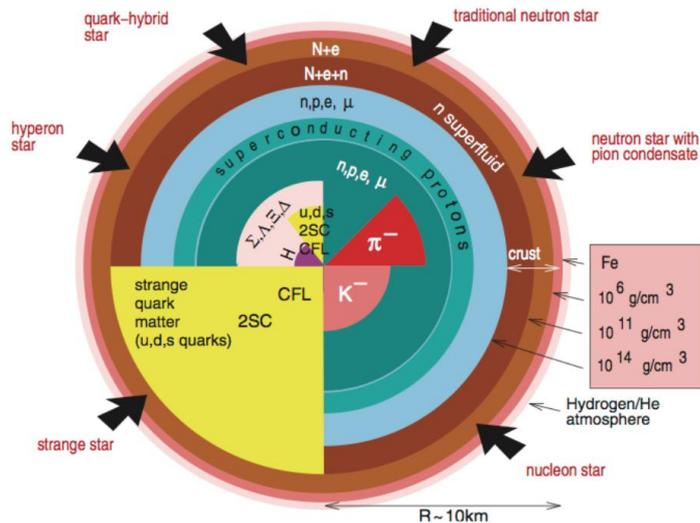


Credit: Daniel Price and Stephan Rosswog

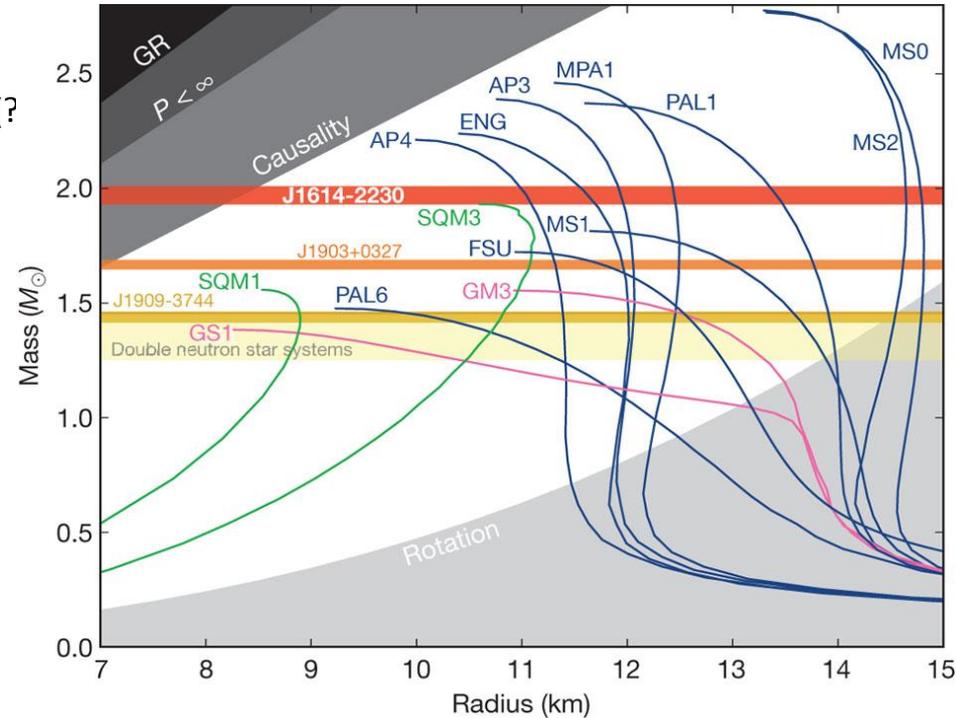
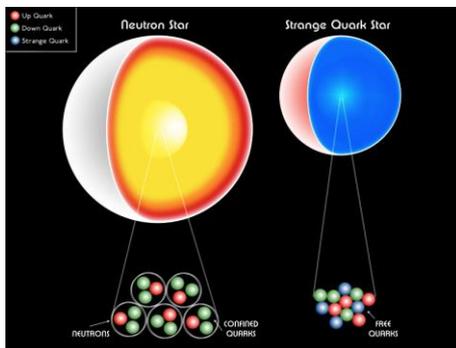
NEOS, NS structure, and NS mass-radius relation

Neutron Star Equation of State

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

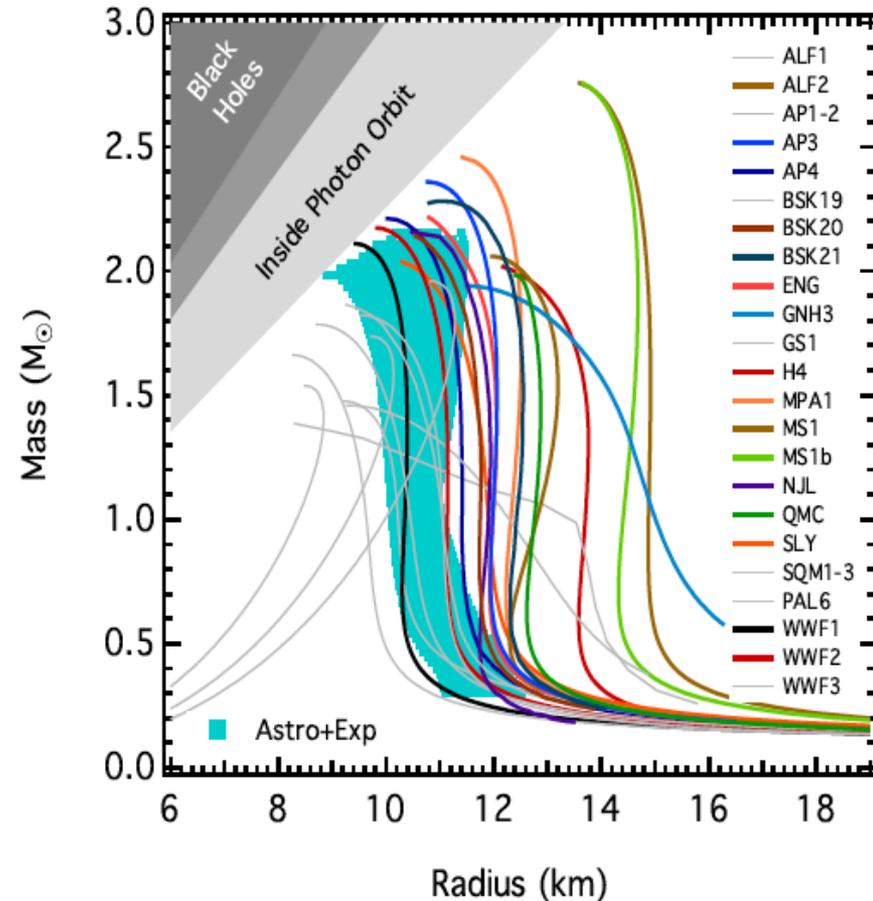
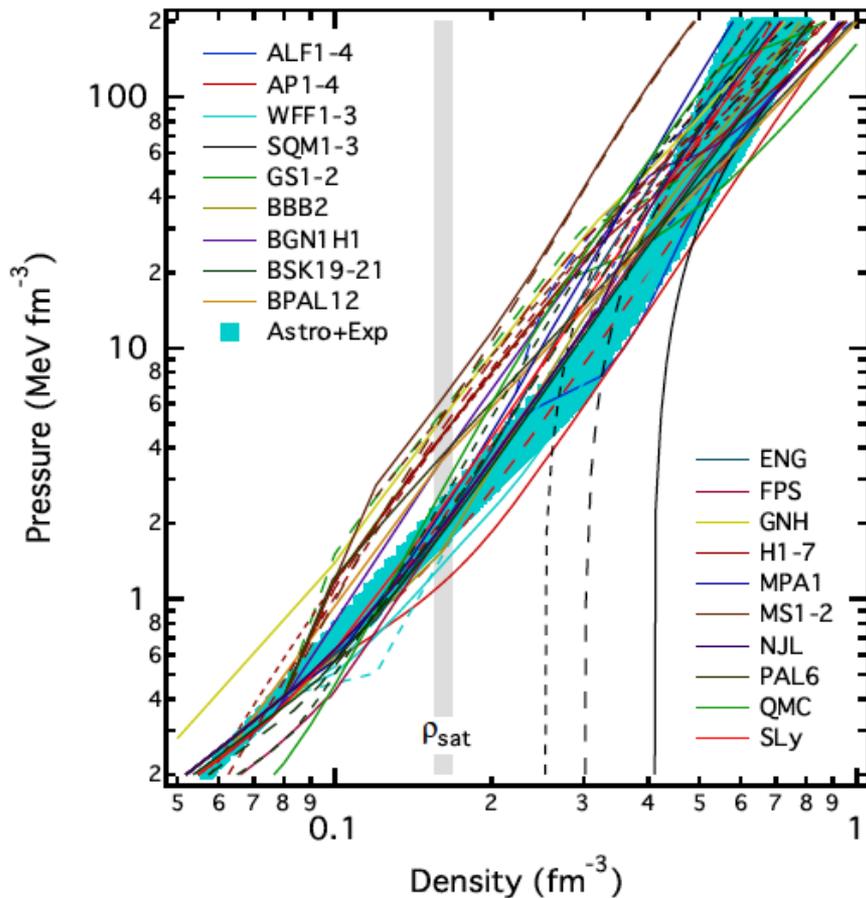


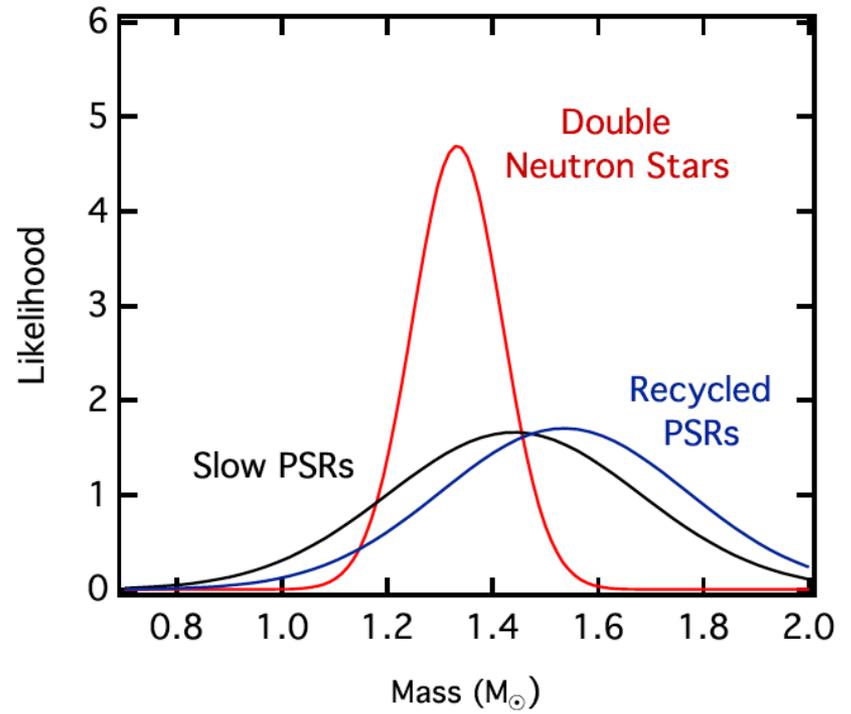
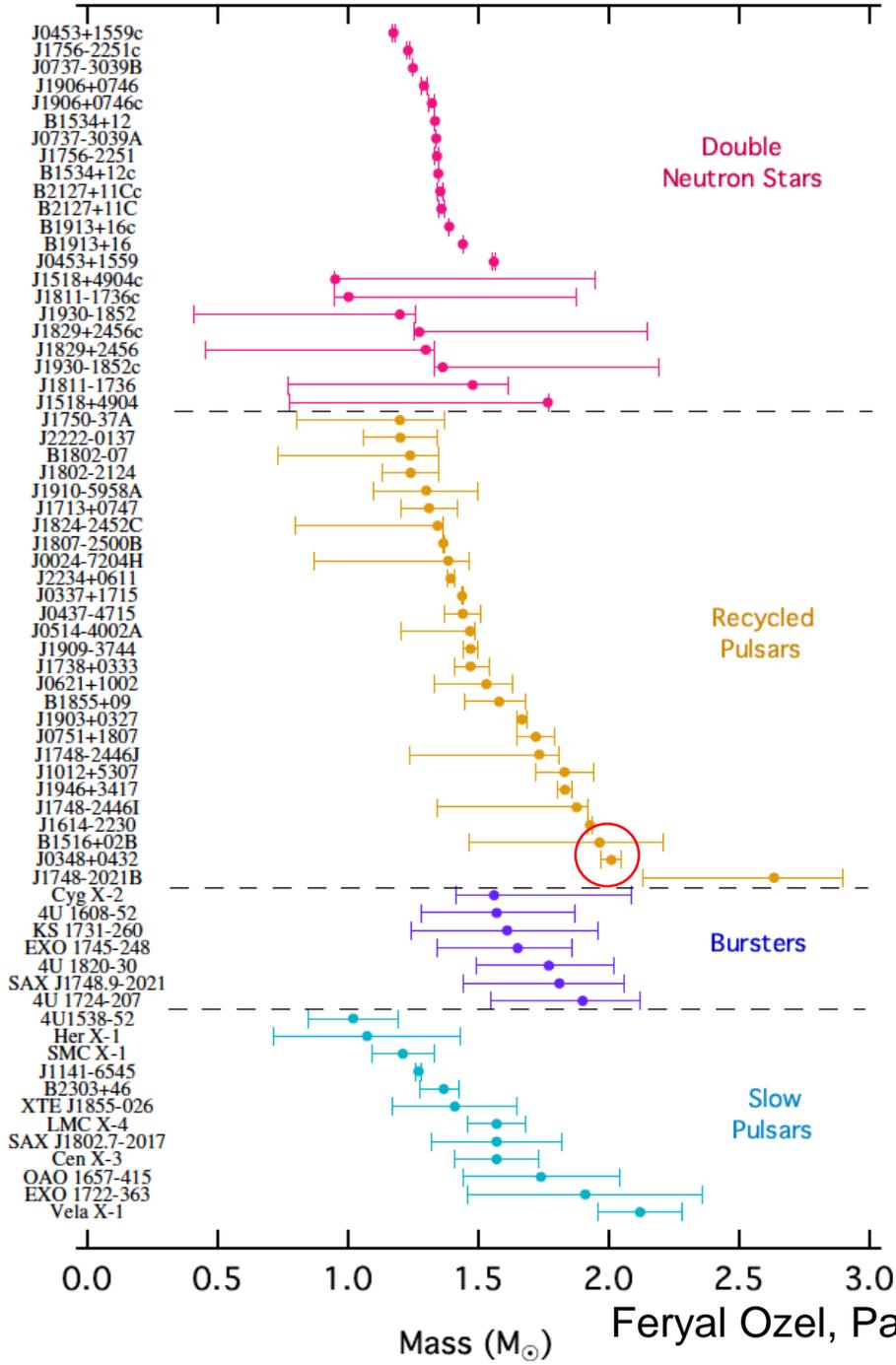
C. D. Ott @ LVC Supernova Call, 2014/08/11

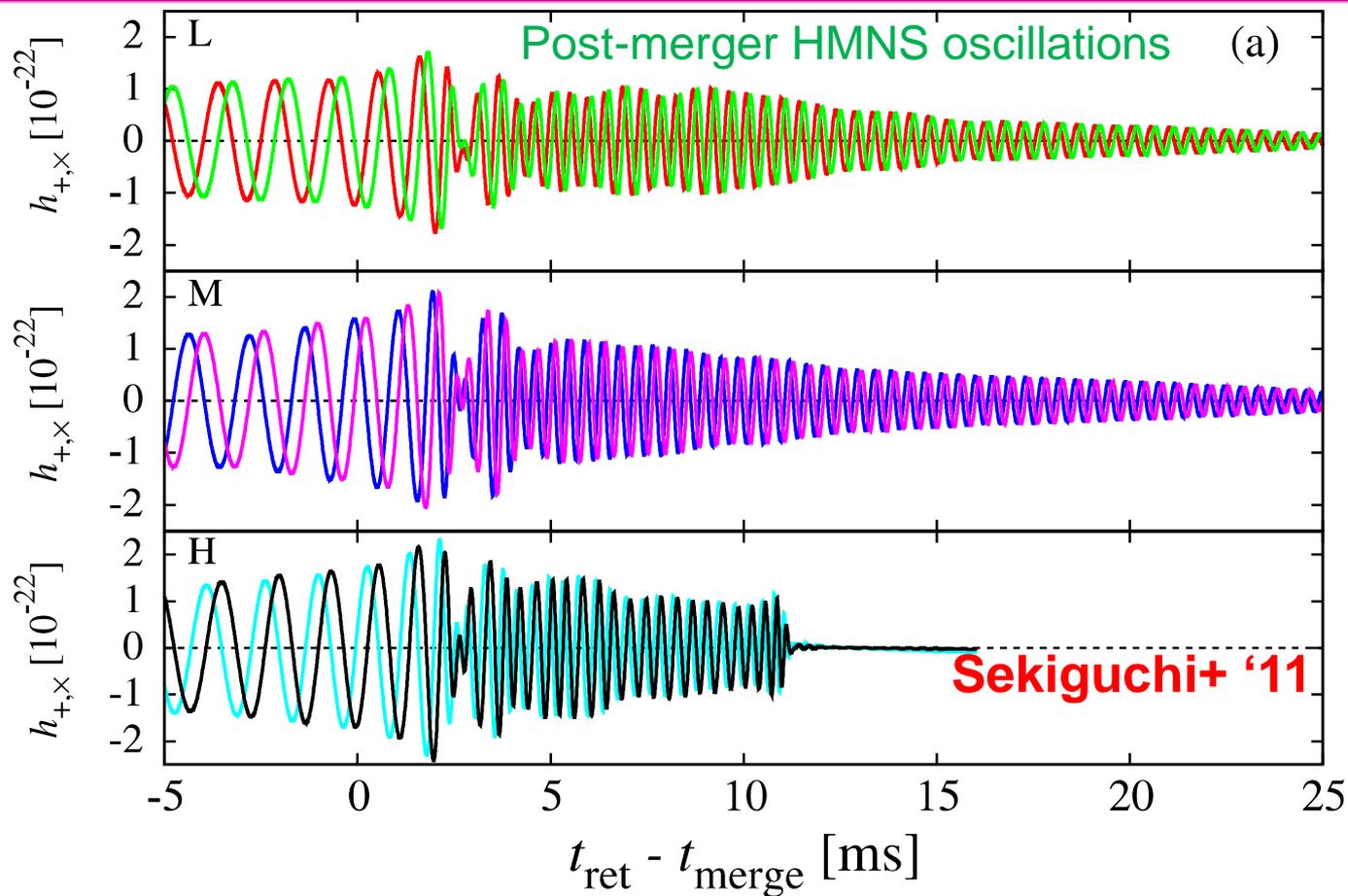


Astrophysical NS cores can exceed ~ 6 times nuclear densities ($2 \times 10^{15}\text{ g/cm}^3$)

NEOS -> M-R relation







$1.35 + 1.35$

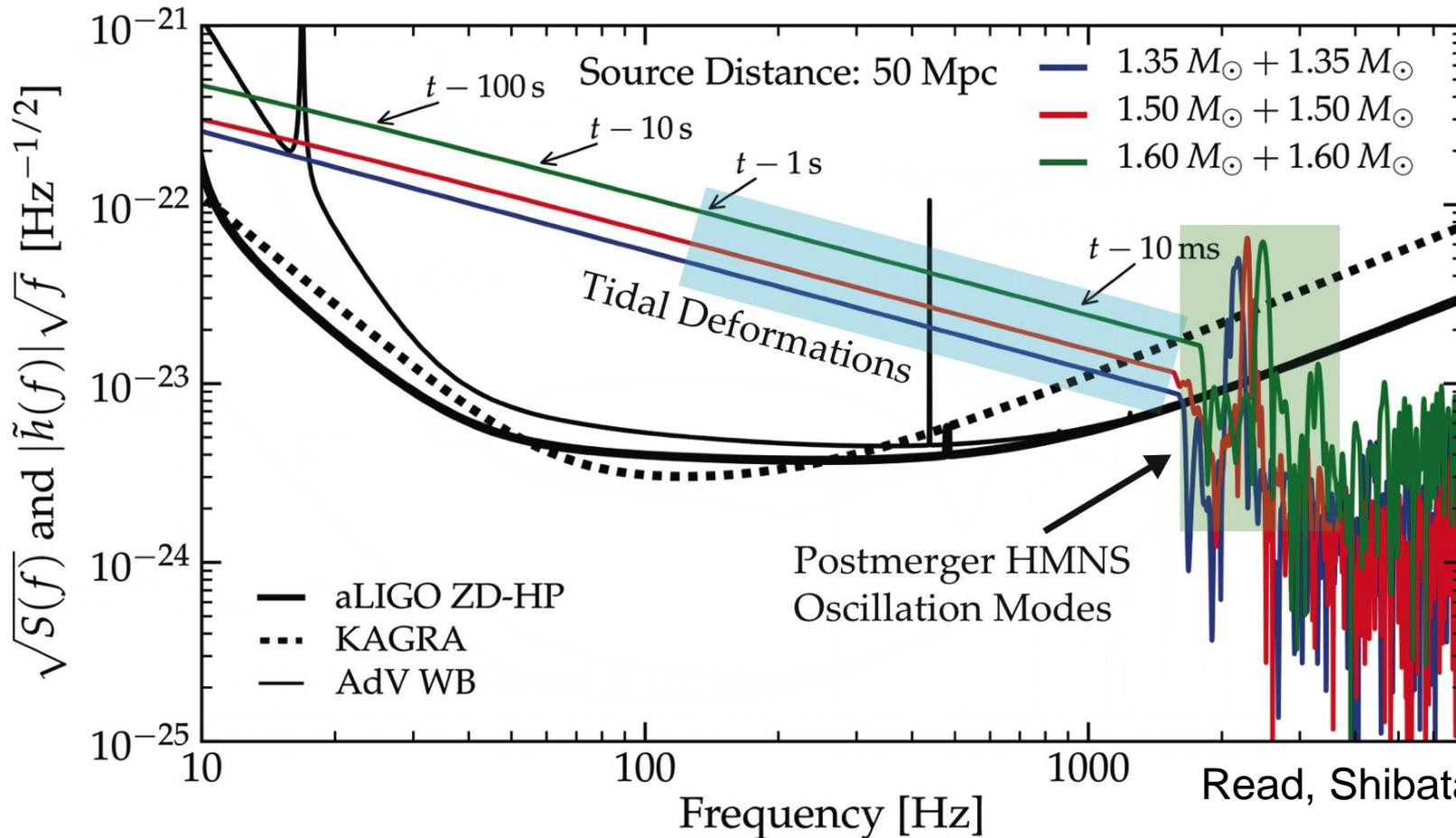
$1.50 + 1.50$

$1.60 + 1.60$

Mass [M_{Sun}]

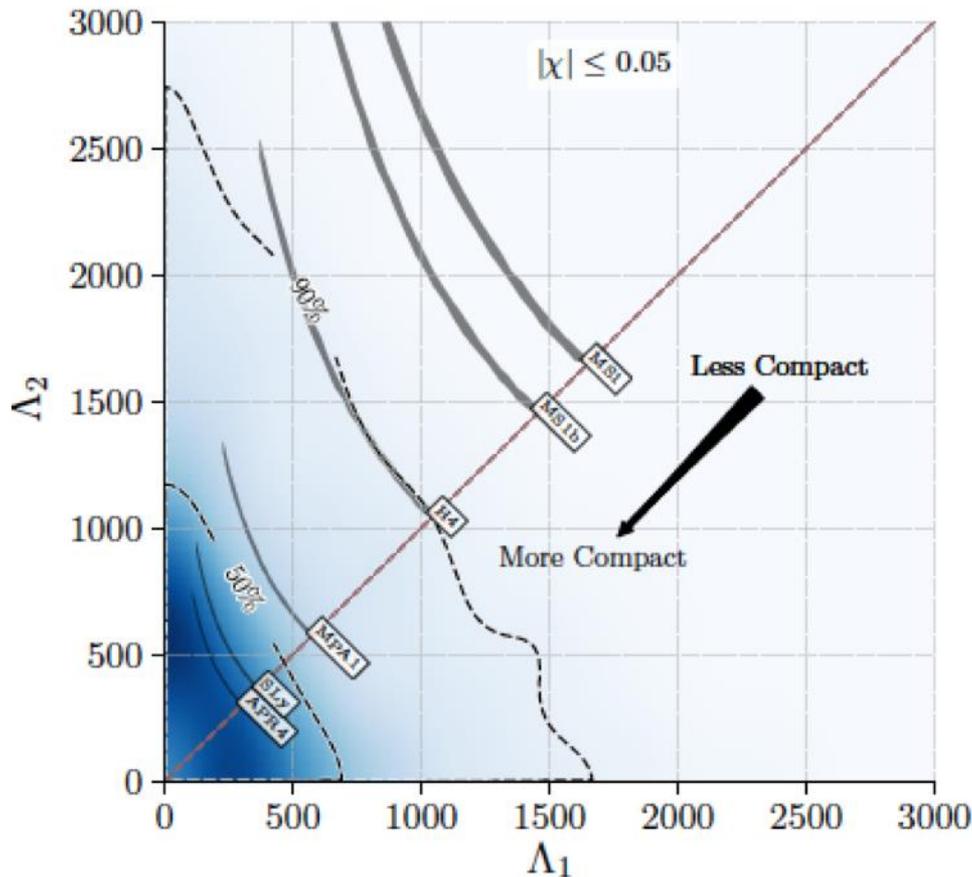
Sekiguchi+ 11: First full GR NS-NS simulation with realistic microphysics,
finite-temperature nuclear EOS of H. Shen+ '98, '11

Tidal disruption of neutron stars near merger



Read, Shibata, et al

Constraints on tidal distortion



- Tidal deformability:

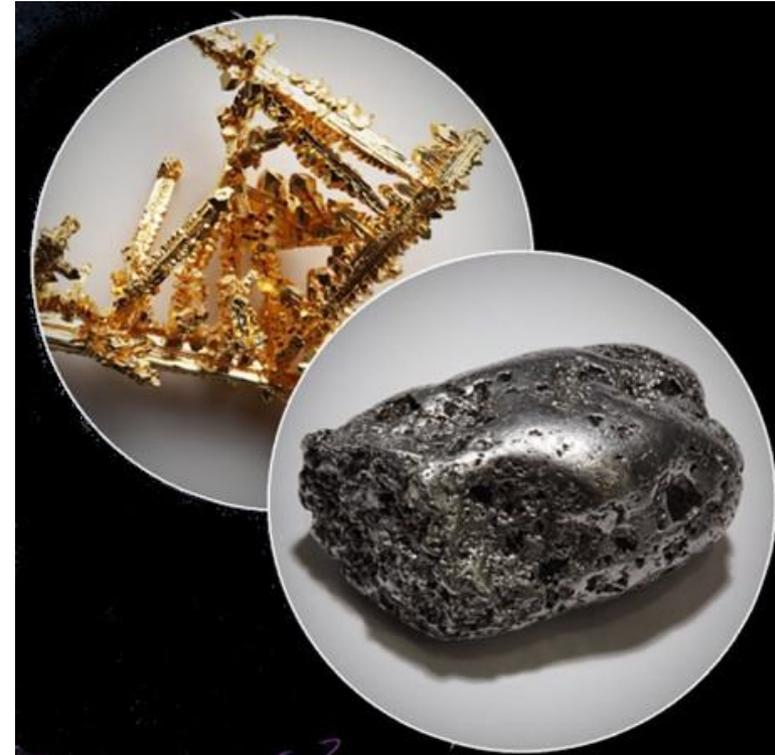
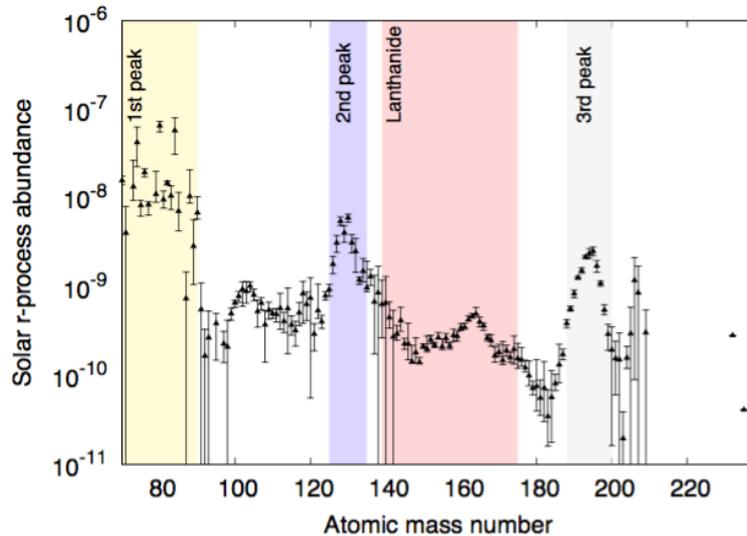
$$\Lambda = \frac{2}{3} k_2 \frac{c^2}{G} \left(\frac{R}{M} \right)^5$$
- k_2 is the 2nd Love number
- R and M are the radius and mass of the star
- LIGO results for GW170817 are most consistent with more compact stars, $R < 13$ km
- Improved results on the way!

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/Gpc³/yr



Ejecta mass estimate: ~0.05 solar mass

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

Consistent!

The future of gravitational wave astrophysics is ... golden!

**THANKS to
Caltech, MIT,
and the NSF!**

**THANKS to my
LIGO & Virgo
collaborators,**

**and to the 100's of
EM astronomers
who found
GRB170817A and
EM170817!**

**And...
thank you for your
attention!**



THANK YOU!
