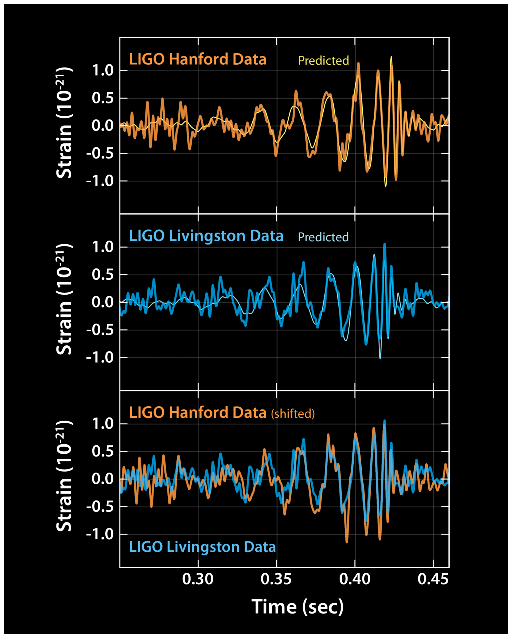
Gravitational Waves Observed by LIGO

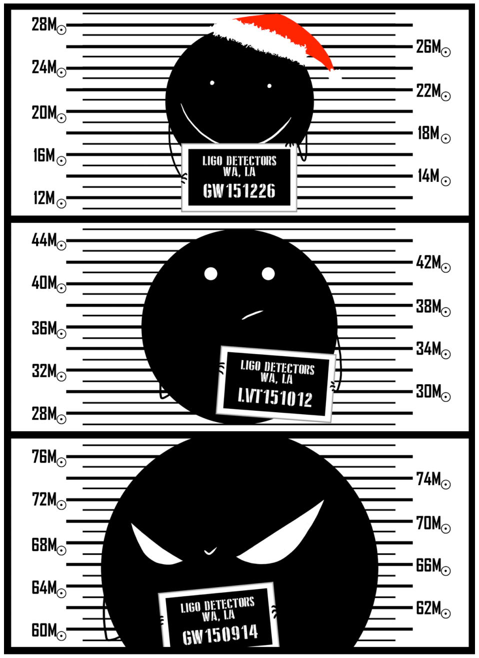
Alan J Weinstein
LIGO Laboratory, Caltech
LIGO Scientific Collaboration

Aspen 2017 Winter Conference
"From the LHC to Dark Matter and Beyond"
March 22, 2017

ASPEN
CENTER
FOR
PHYSICS



LIGO Laboratory, Caltech



N. Kijbunchoo, LIGO

LIGO-G1700584

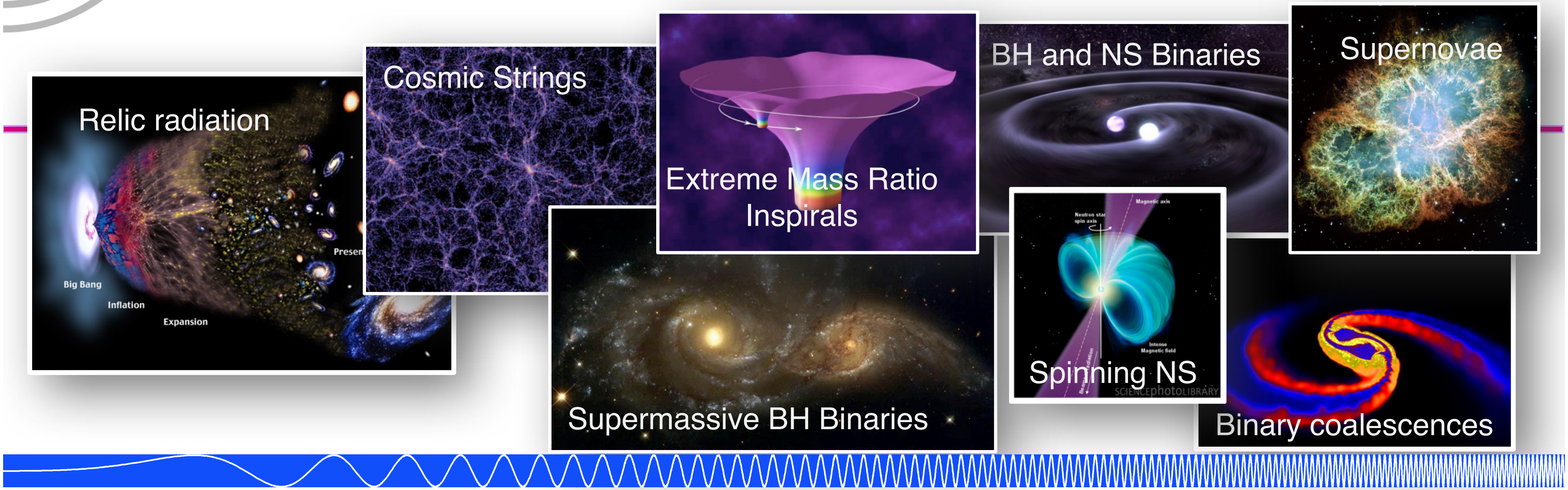
Outline

- Gravitational waves
- LIGO detectors and the global network
- Astrophysical sources
- Compact Binary Coalescence
- CBC searches
- Results from O1: BBH events observed
- Event properties
- Tests of General Relativity
- Astrophysical population properties
- Astrophysical formation scenarios
- Binary neutron stars
- Nuclear equation of state
- Summary and Future

Outline

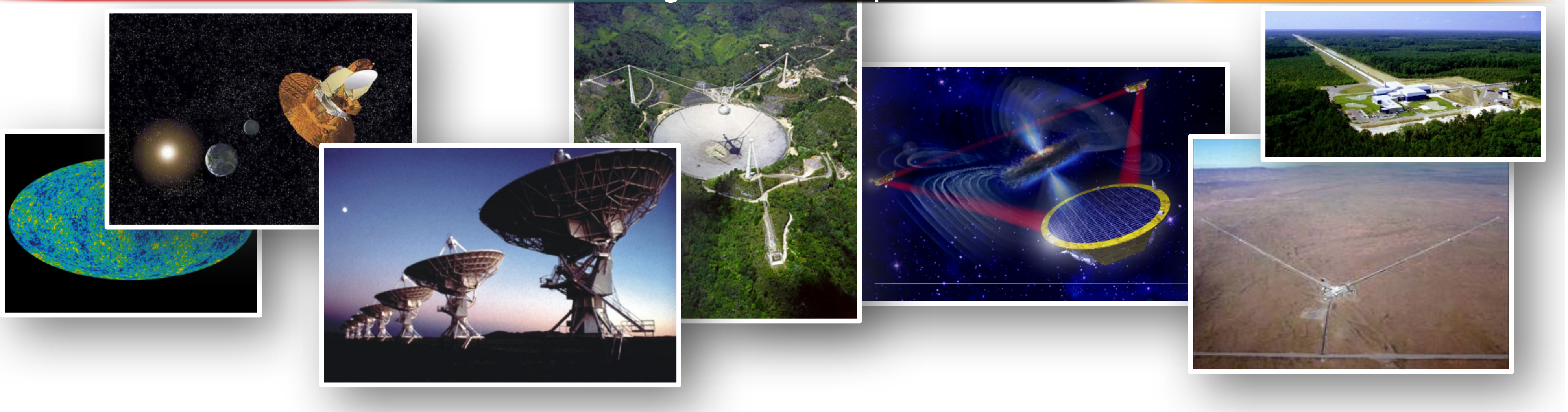
- Gravitational waves
- LIGO detectors and the global network
- Astrophysical sources
- Compact Binary Coalescence
- CBC searches
- Results from O1: BBH events observed
- Event properties
- Tests of General Relativity
- Astrophysical population properties
- Astrophysical formation scenarios
- Binary neutron stars
- Nuclear equation of state
- Summary and Future

The GW Spectrum



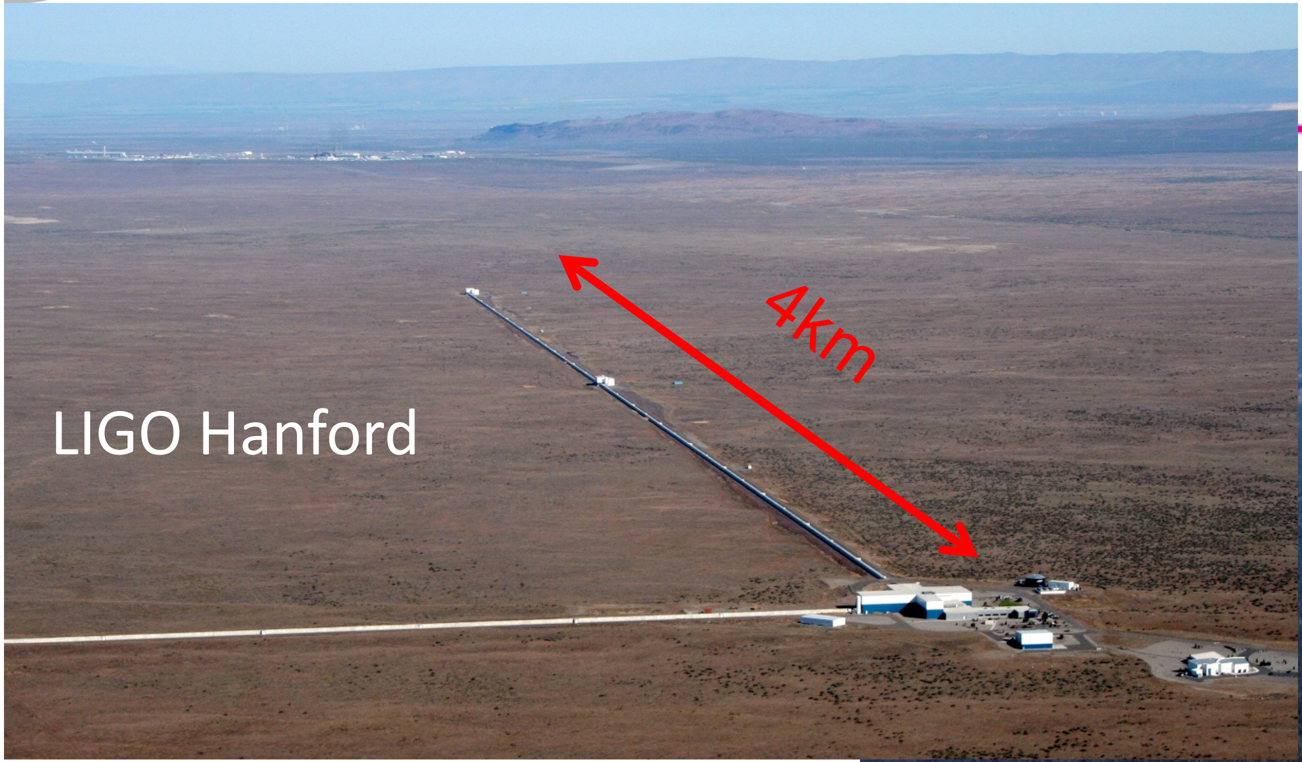
10^{-16} Hz 10^{-9} Hz 10^{-4} Hz 10^{0} Hz 10^{3} Hz

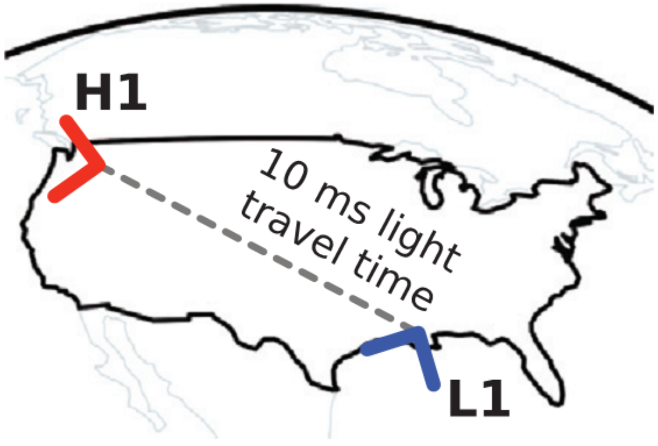
Inflation Probe Pulsar timing Space detectors Ground interferometers



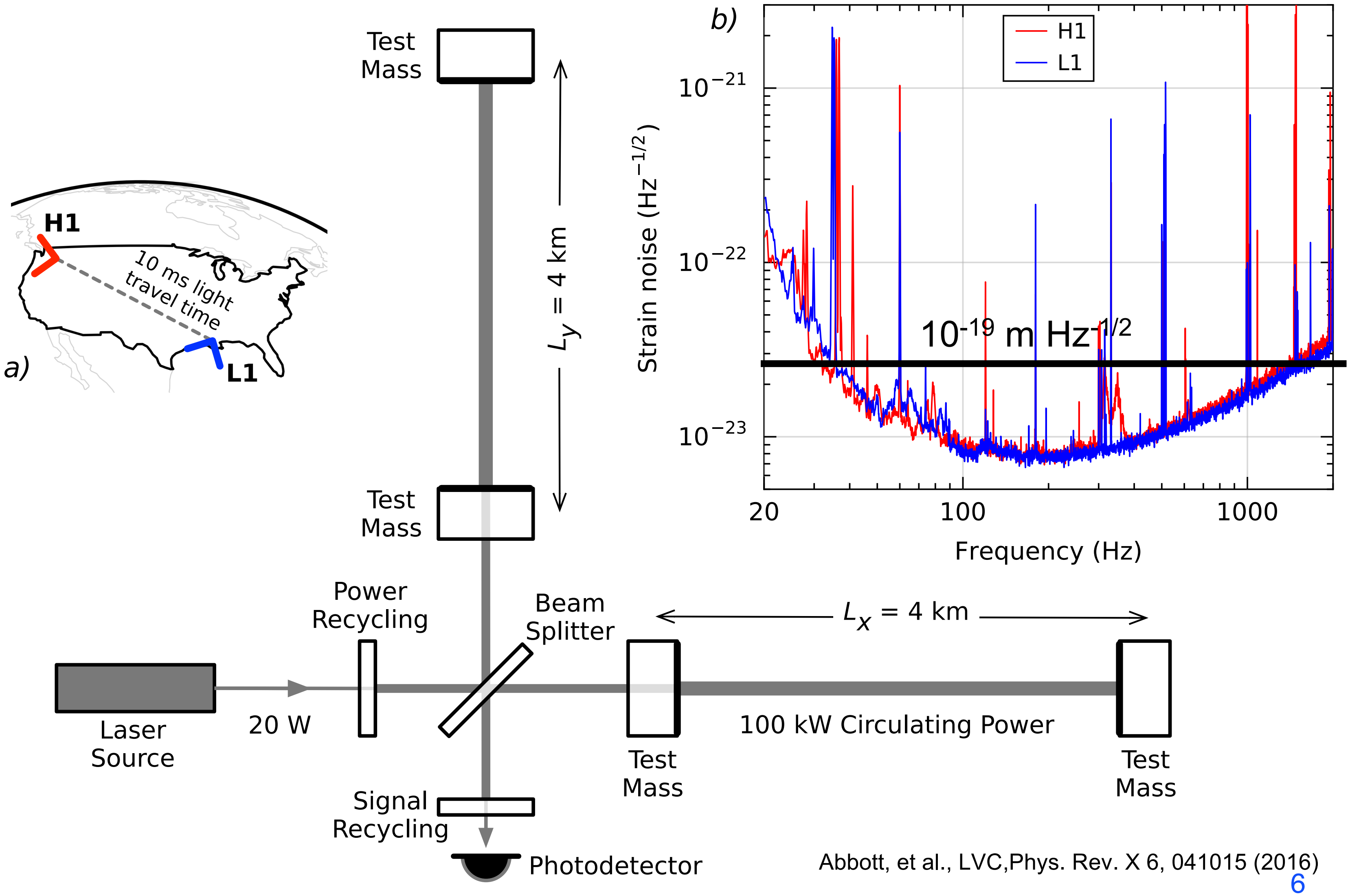
The LIGO* Observatories

* LIGO = Laser Interferometer Gravitational-wave Observatory



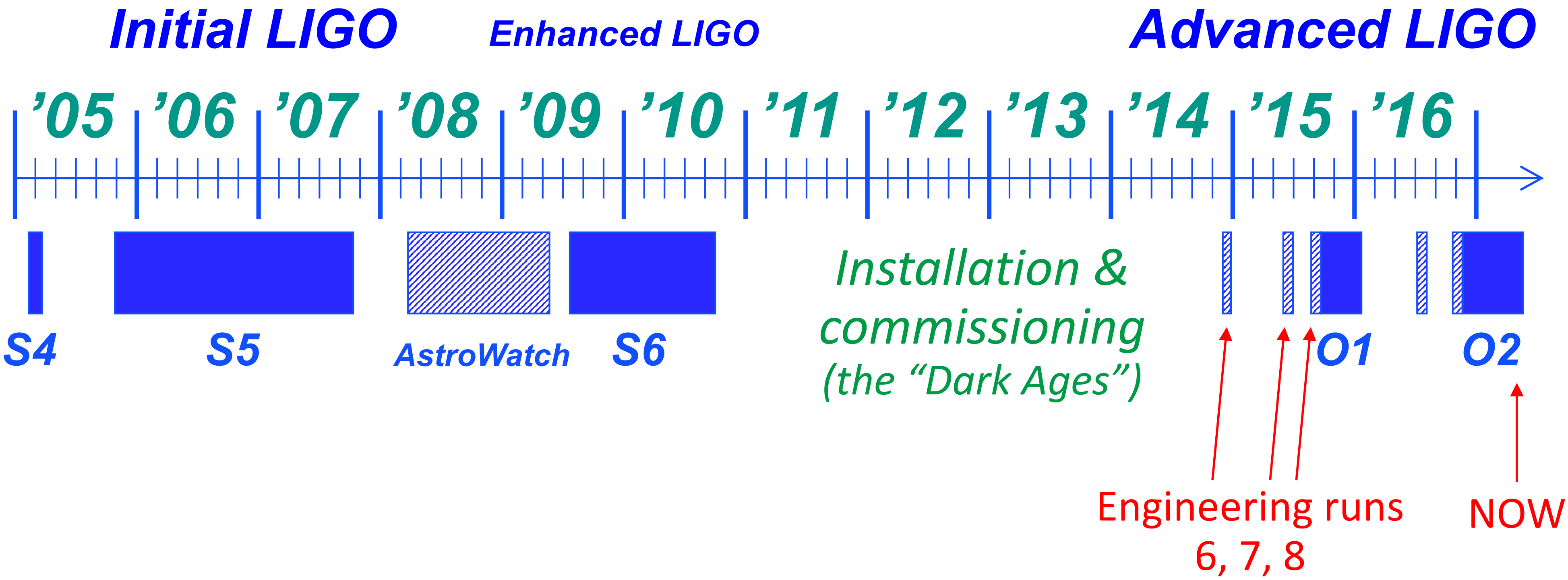


The Advanced LIGO detectors

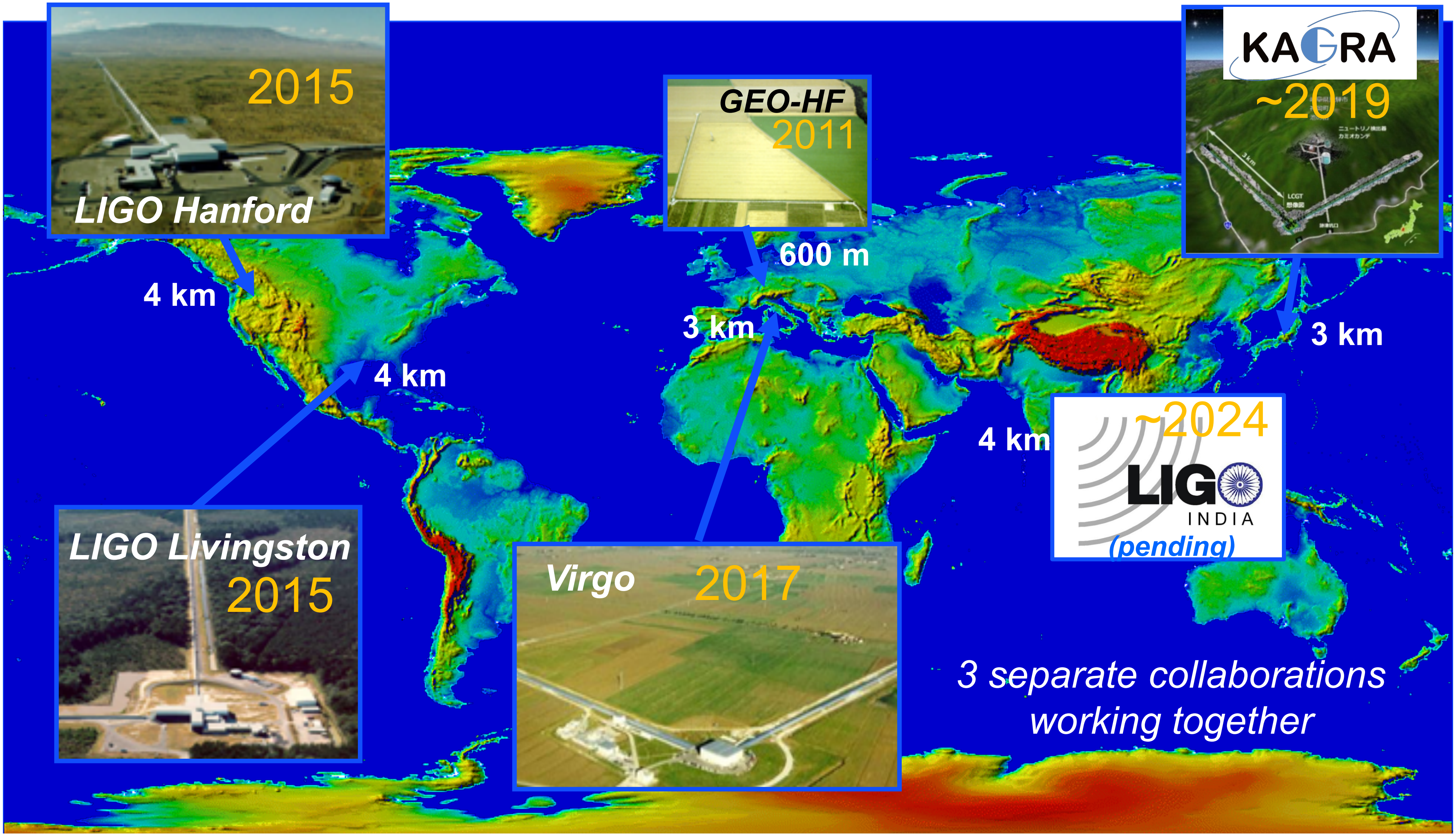


Abbott, et al., LVC,Phys. Rev. X 6, 041015 (2016)

Initial LIGO → Enhanced LIGO → Advanced LIGO

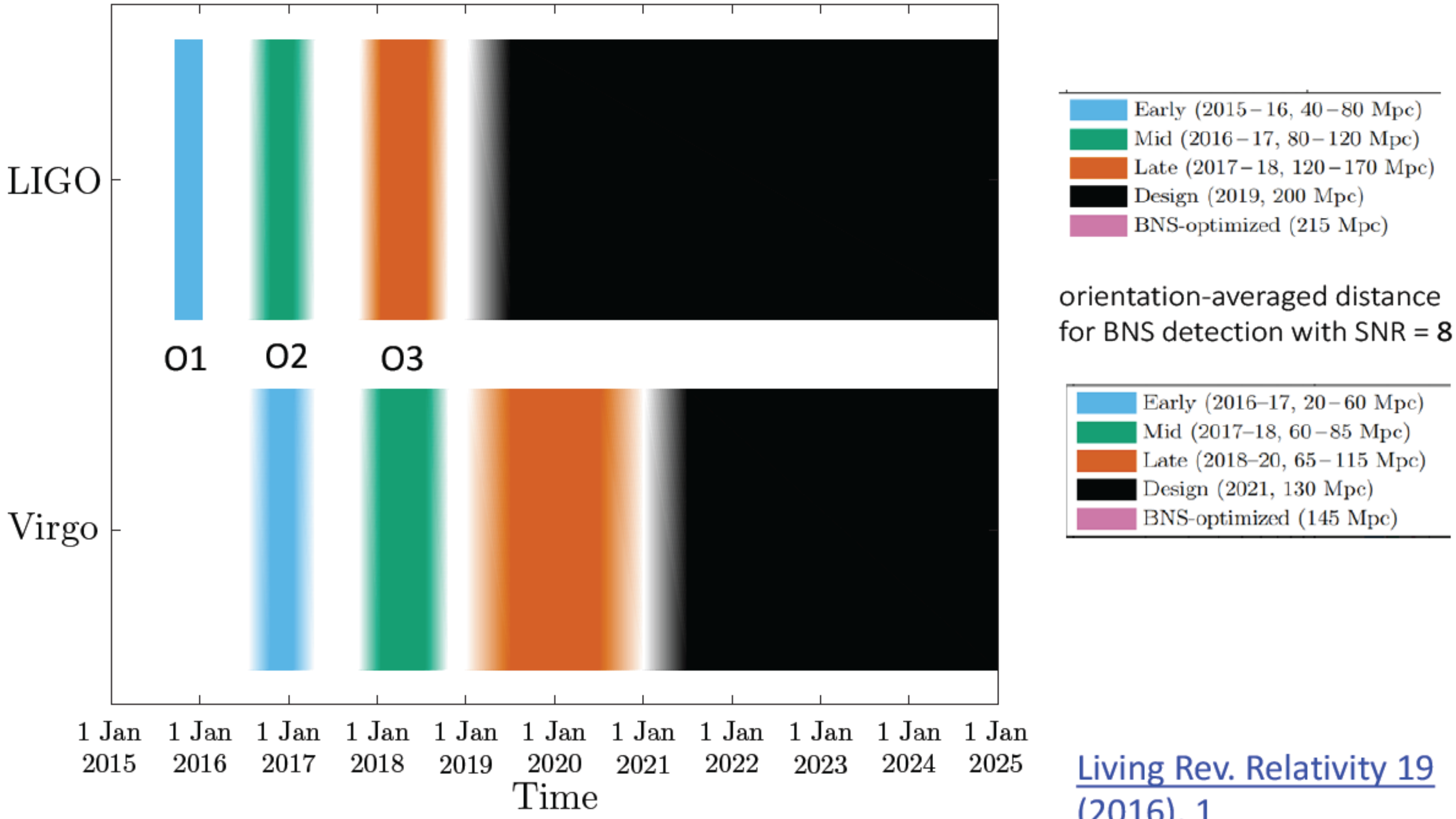


The emerging Advanced GW Detector Network



3 separate collaborations working together

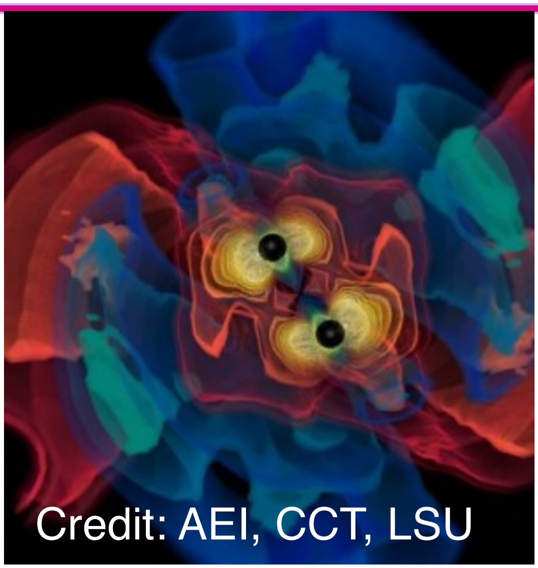
Near-term observing plan, LIGO and Virgo



orientation-averaged distance for BNS detection with SNR = 8

Living Rev. Relativity 19 (2016), 1

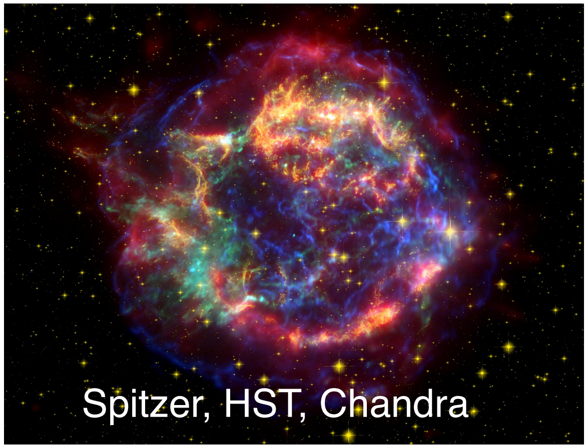
GW sources for ground-based detectors: The most energetic processes in the universe


Credit: AEI, CCT, LSU

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

- Strong emitters, well-modeled,

- (effectively) transient


Spitzer, HST, Chandra

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient

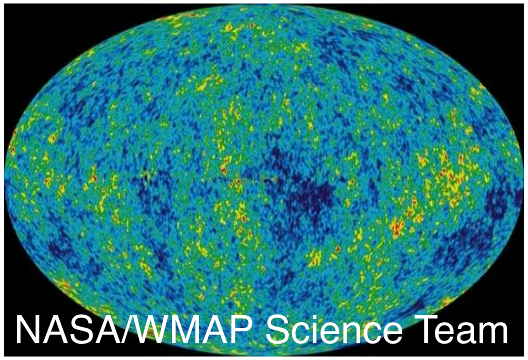
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class


Casey Reed, Penn State

Spinning neutron stars

- (effectively) monotonic waveform

- Long duration

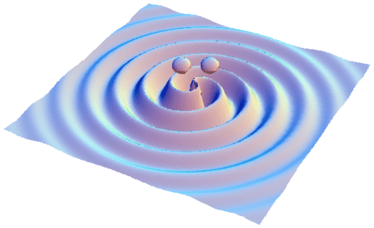

NASA/WMAP Science Team

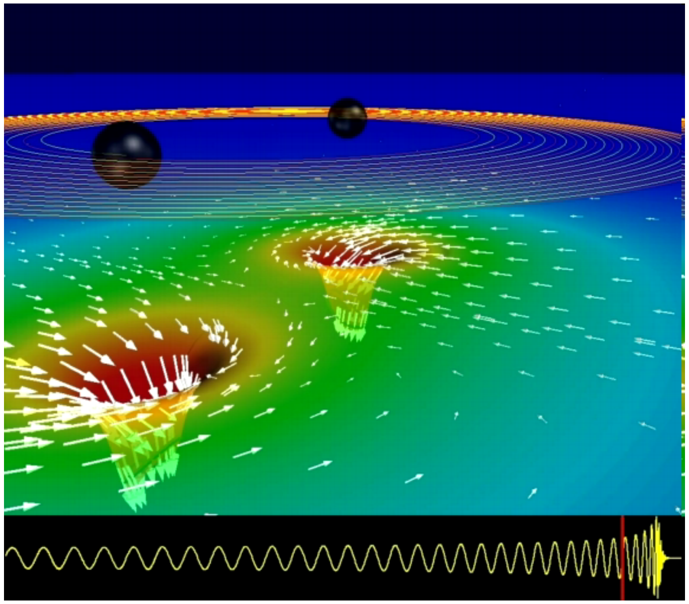
Cosmic Gravitational-wave Background

- Residue of the Big Bang, long duration

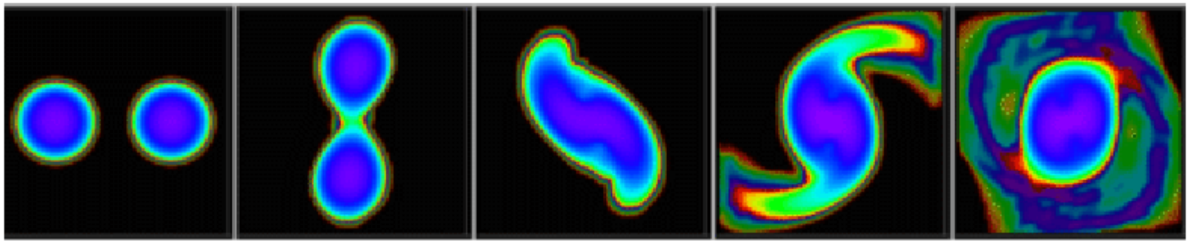
- Long duration, stochastic background

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





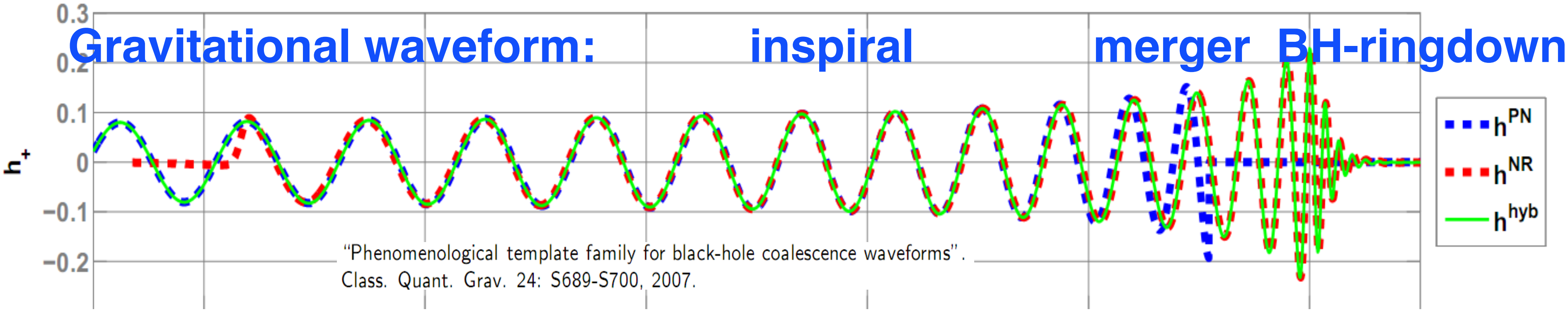
- Neutron star – neutron star (Centrella et al.)



Tidal disruption of neutron star

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

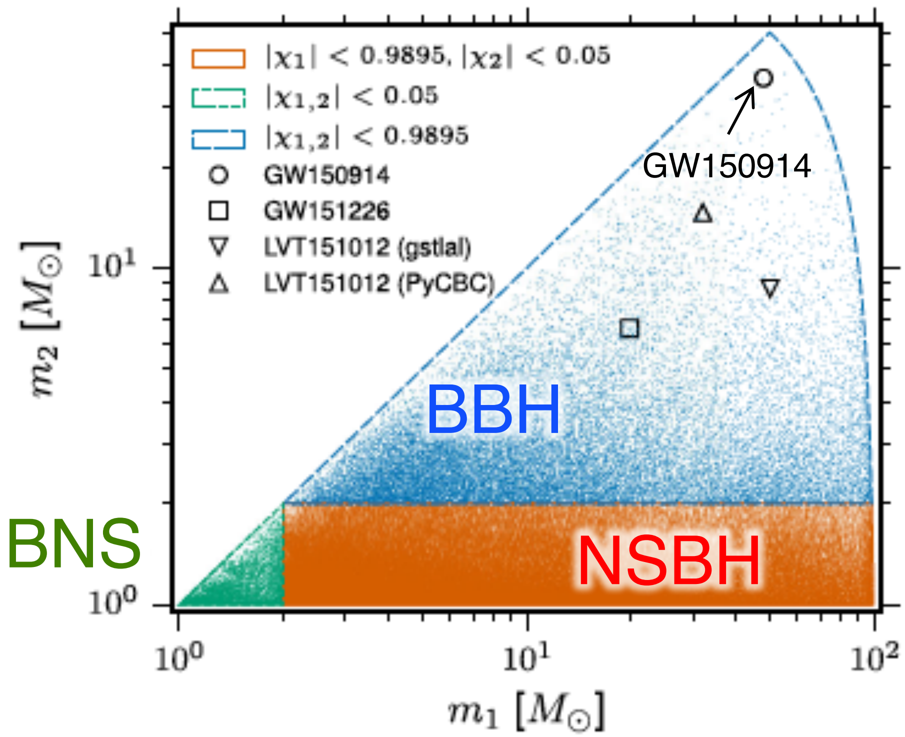
Gravitational waveform: inspiral merger BH-ringdown

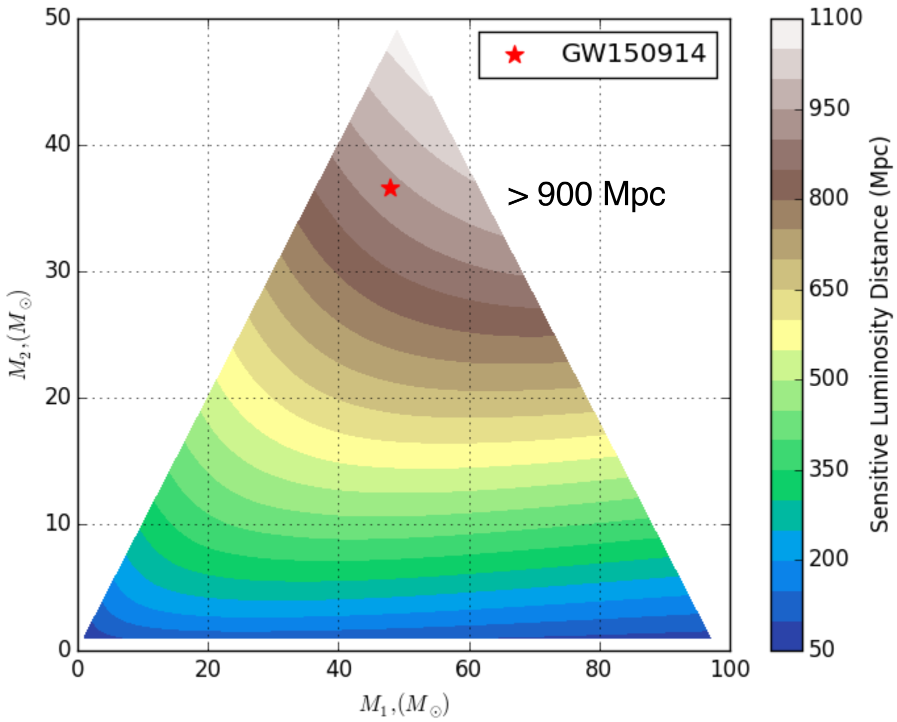


"Phenomenological template family for black-hole coalescence waveforms". Class. Quant. Grav. 24: S689-S700, 2007.

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

Template-based searches



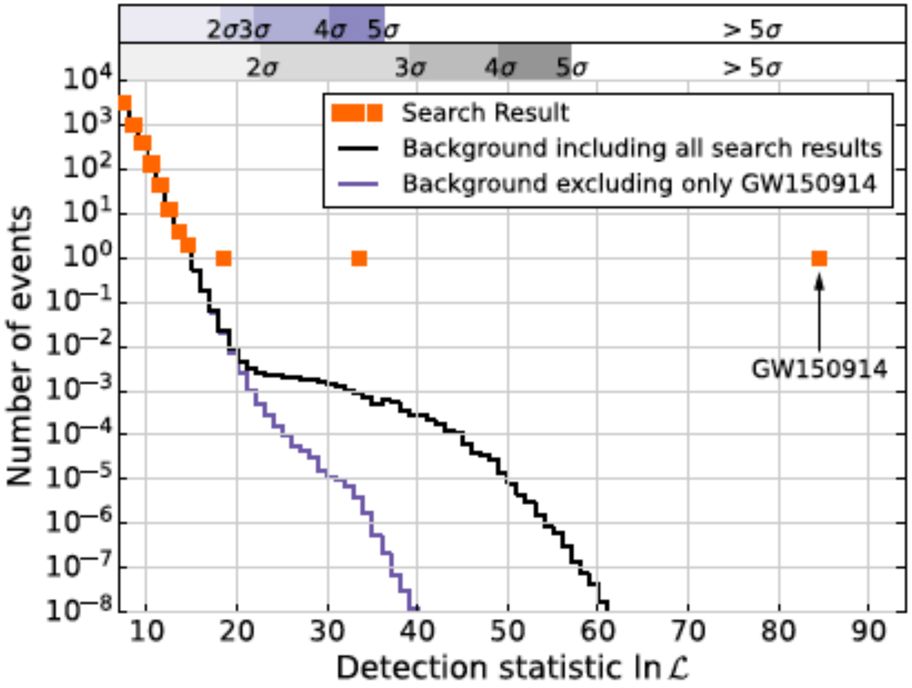


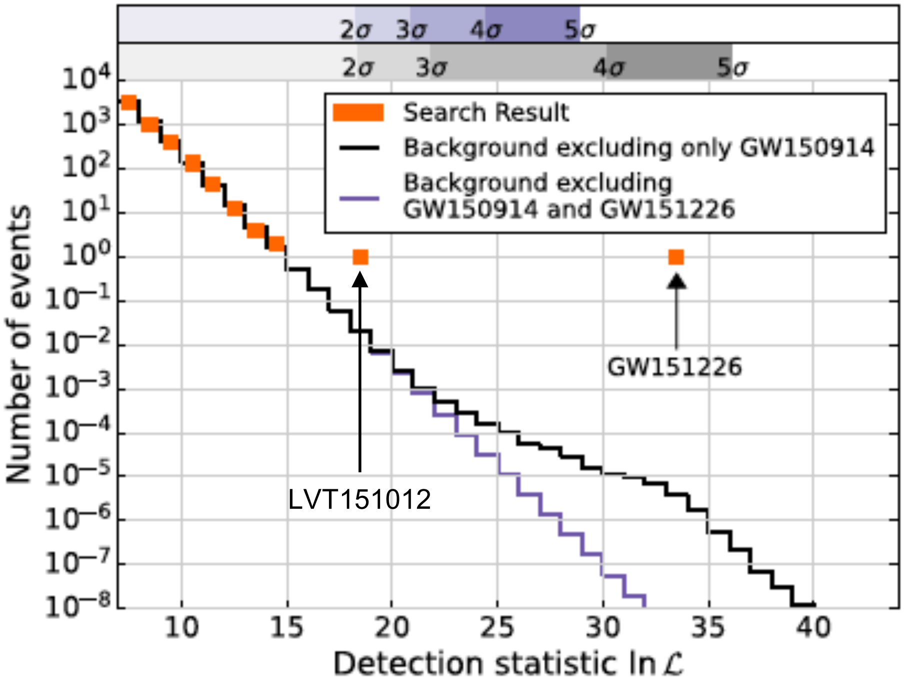
Masses and (aligned) spins
Templates spaced for < 3% loss of SNR: 250K templates.

Sensitive distance in Mpc

Abbott, et al., LVC, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, Phys. Rev. X 6, 041015 (2016)

Search results
Advanced LIGO Observing Run O1

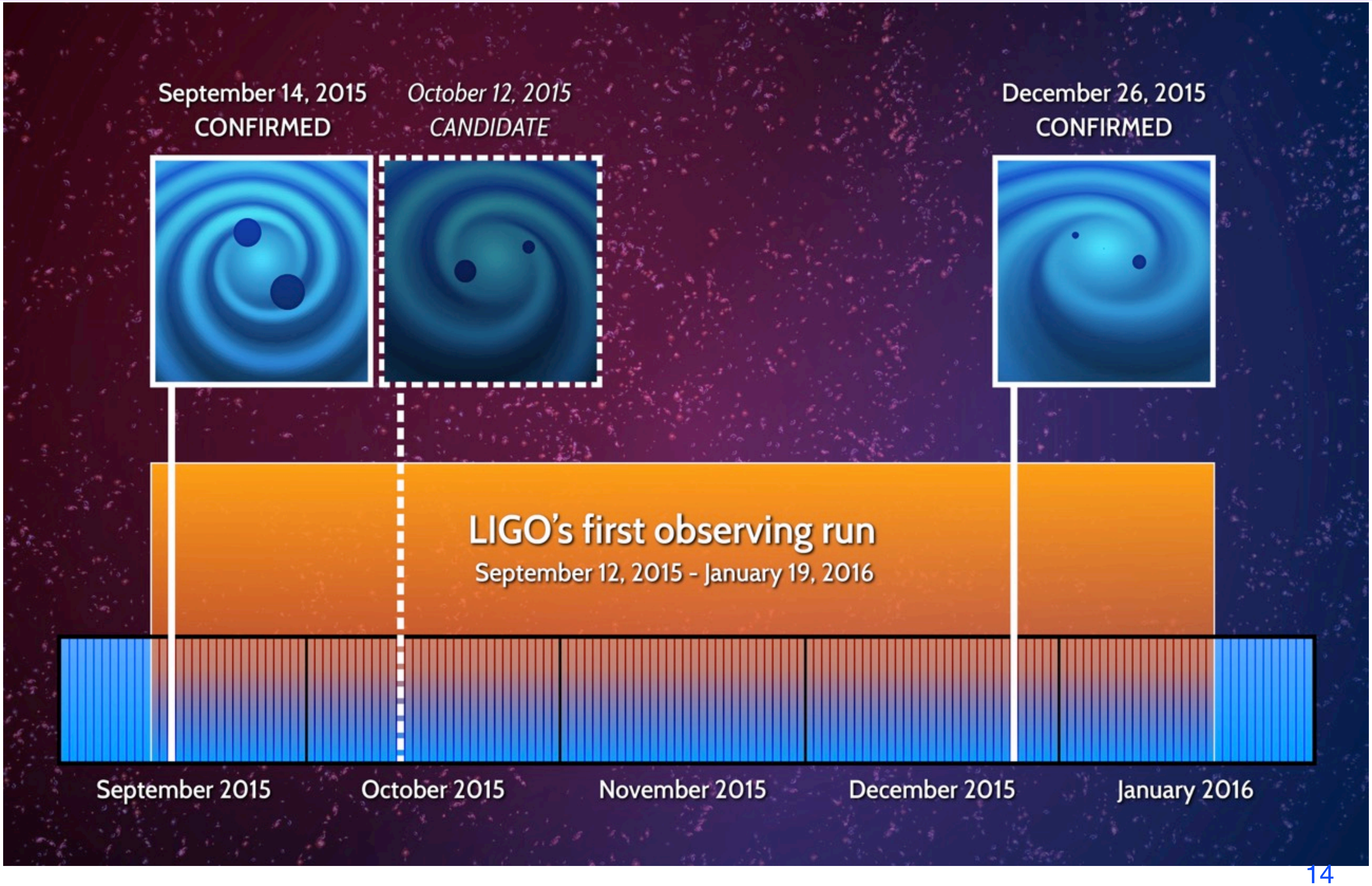




Three events above the estimated “background”
from accidental coincidence of noise fluctuation triggers.
Two have high significance (> 5σ).

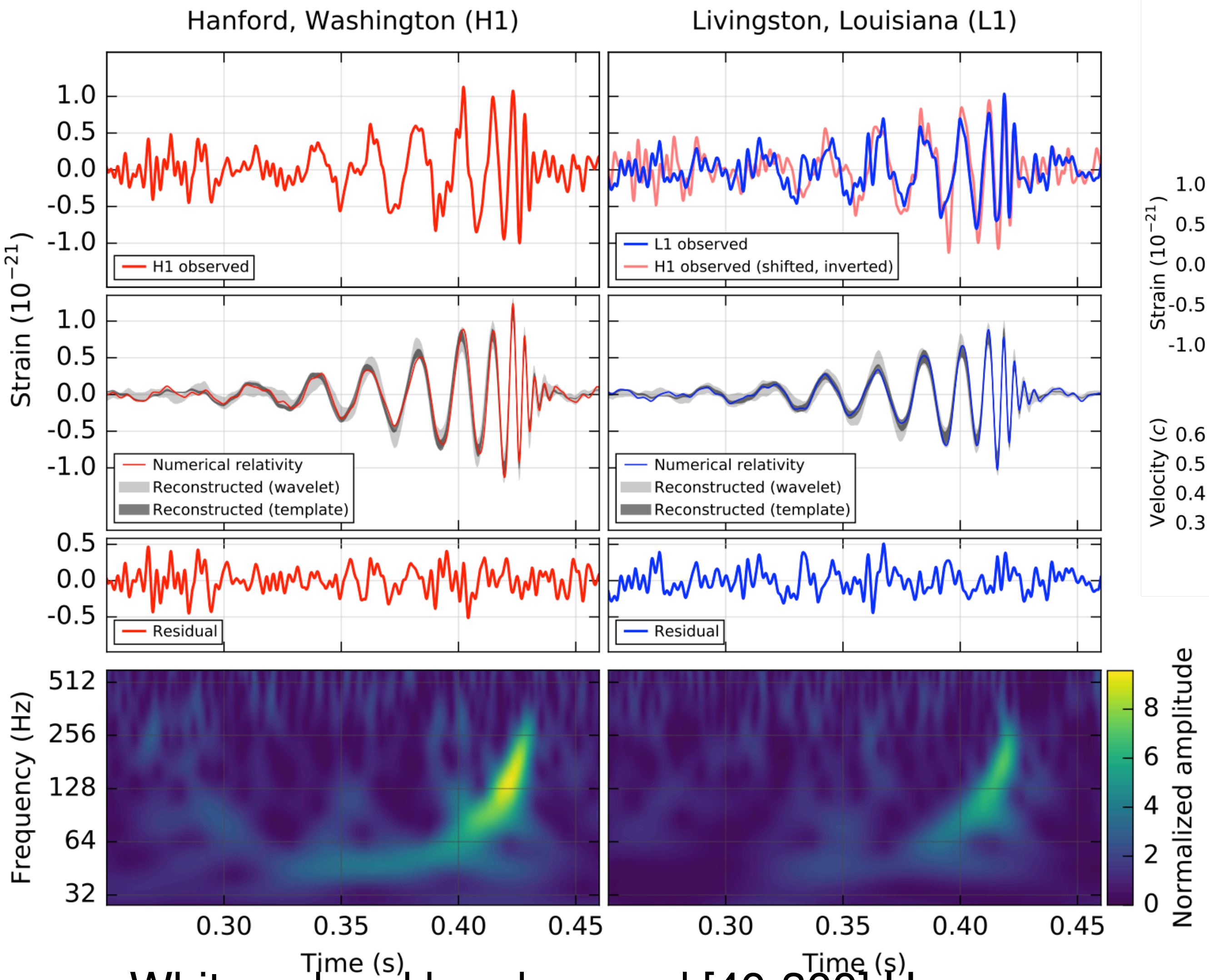
Abbott, et al., LVC, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, Phys. Rev. X 6, 041015 (2016)

Search results
Advanced LIGO Observing Run O1

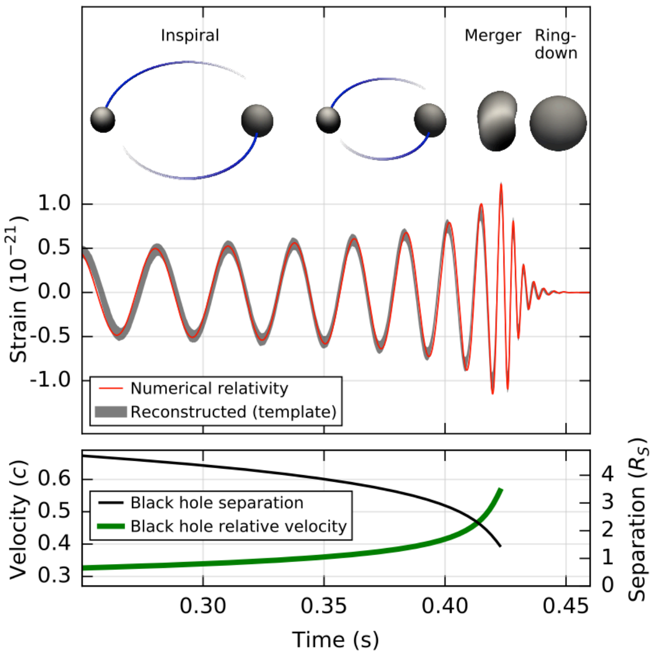


GW150914

Phys. Rev. Lett. 116, 061102 – Published 11 February 2016



Whitened and band-passed [40-300] Hz

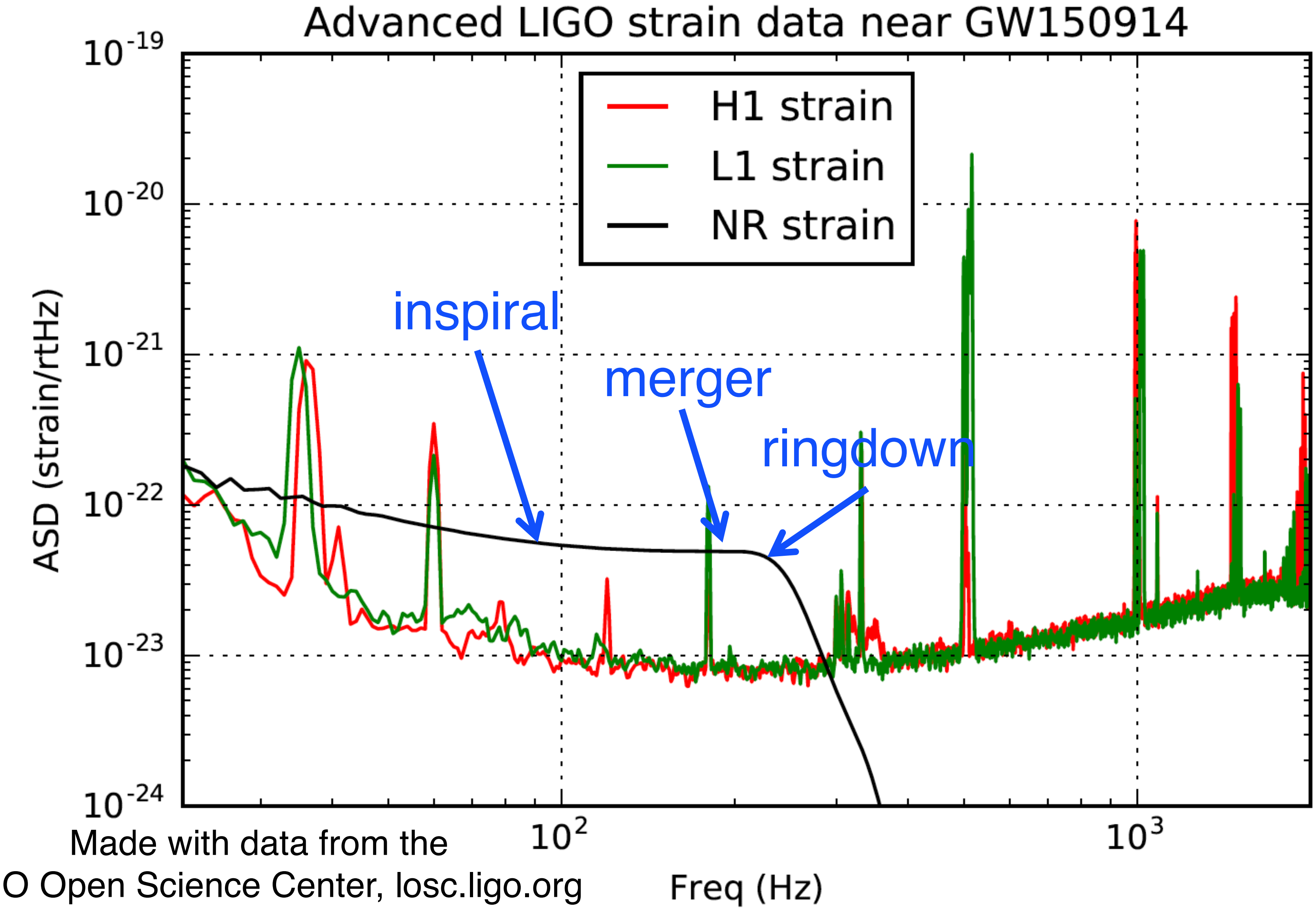


Reconstructed (no whitening)

Audio:

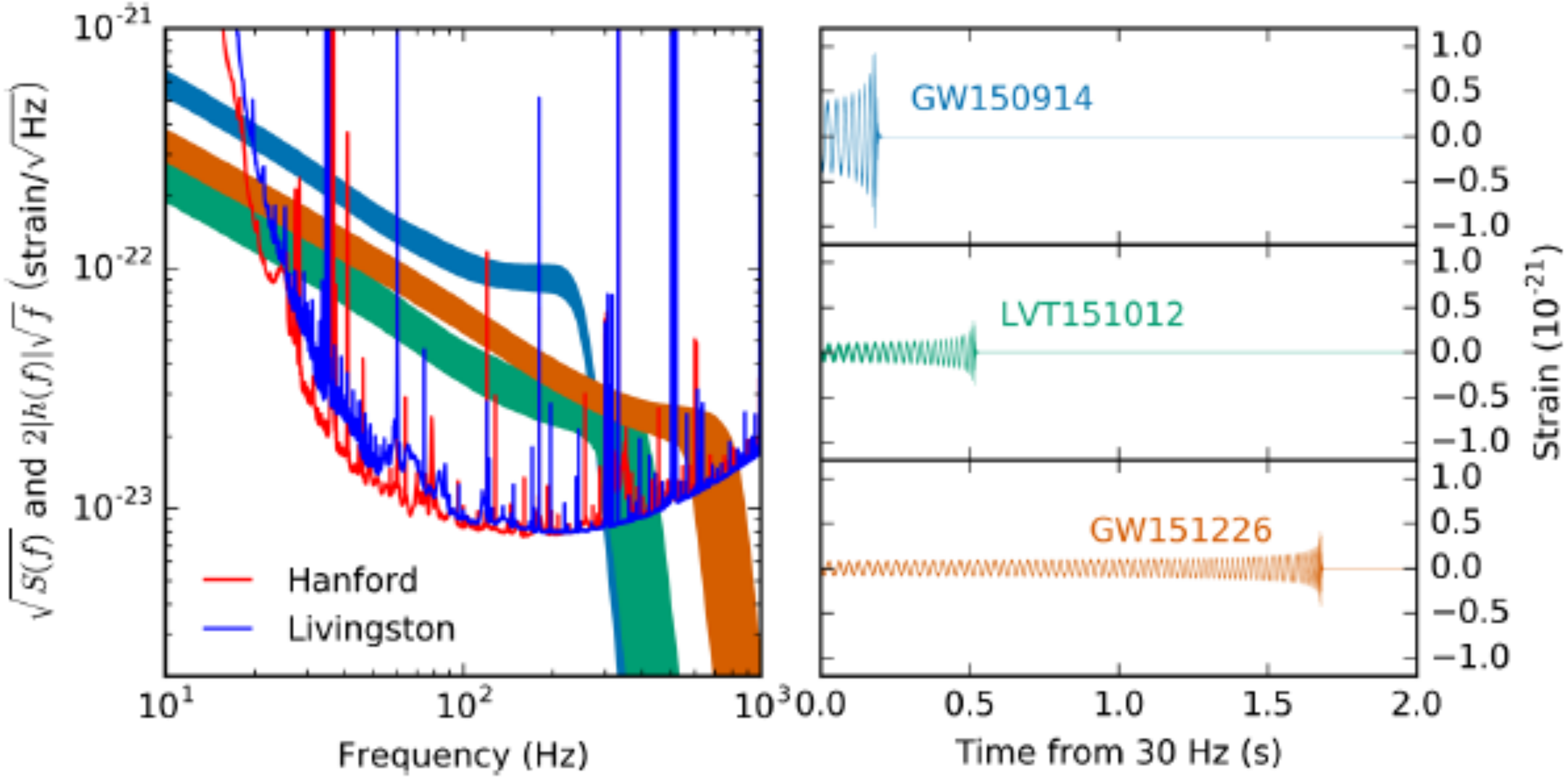
- filtered data
- freq-shifted data
- reconstructed & shifted

GW150914 in the frequency domain



Made with data from the
LIGO Open Science Center, losc.ligo.org

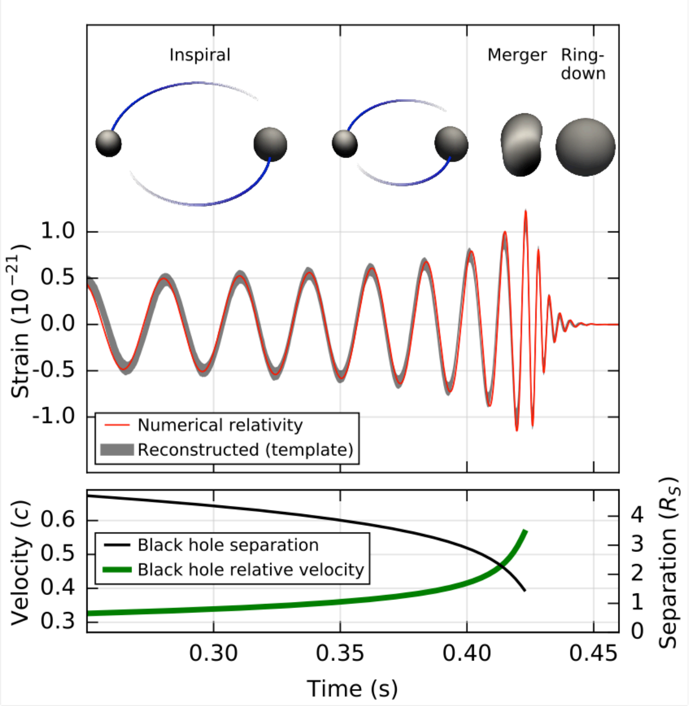
Three BBH events, compared



Abbott, et al., LVC, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, Phys. Rev. X 6, 041015 (2016)

What can we learn from a few events?

- Such high frequency chirps require extremely **compact orbiting objects of ~ stellar mass**.
- **Black holes (strongly-curved spacetime with event horizons) EXIST**, and emit waves of curved spacetime when perturbed.
  - » Previously, observations of high energy radiation from in-falling matter only told us that compact objects with strong gravity (and perhaps, with event horizons) were present.
- **Binary black holes exist**! Formation scenarios involving common evolution require the binary to survive two core-collapse supernovas.
  Other formation scenarios may be important!
- Two black holes merge into one, which rings down, consistent with **black hole perturbation theory**.
- Excellent **consistency between the observed waveform and the prediction from GR (numerical relativity)** tell us that we are seeing the inspiral of two black holes moving at 0.5c, merging into one BH, which subsequently rings down.
- **GR is tested, for the first time, in the strong (non-linear) and highly dynamical regime**.
- **Masses, spins, sky location, rates, formation mechanisms…**



Exploring the Properties of GW150914

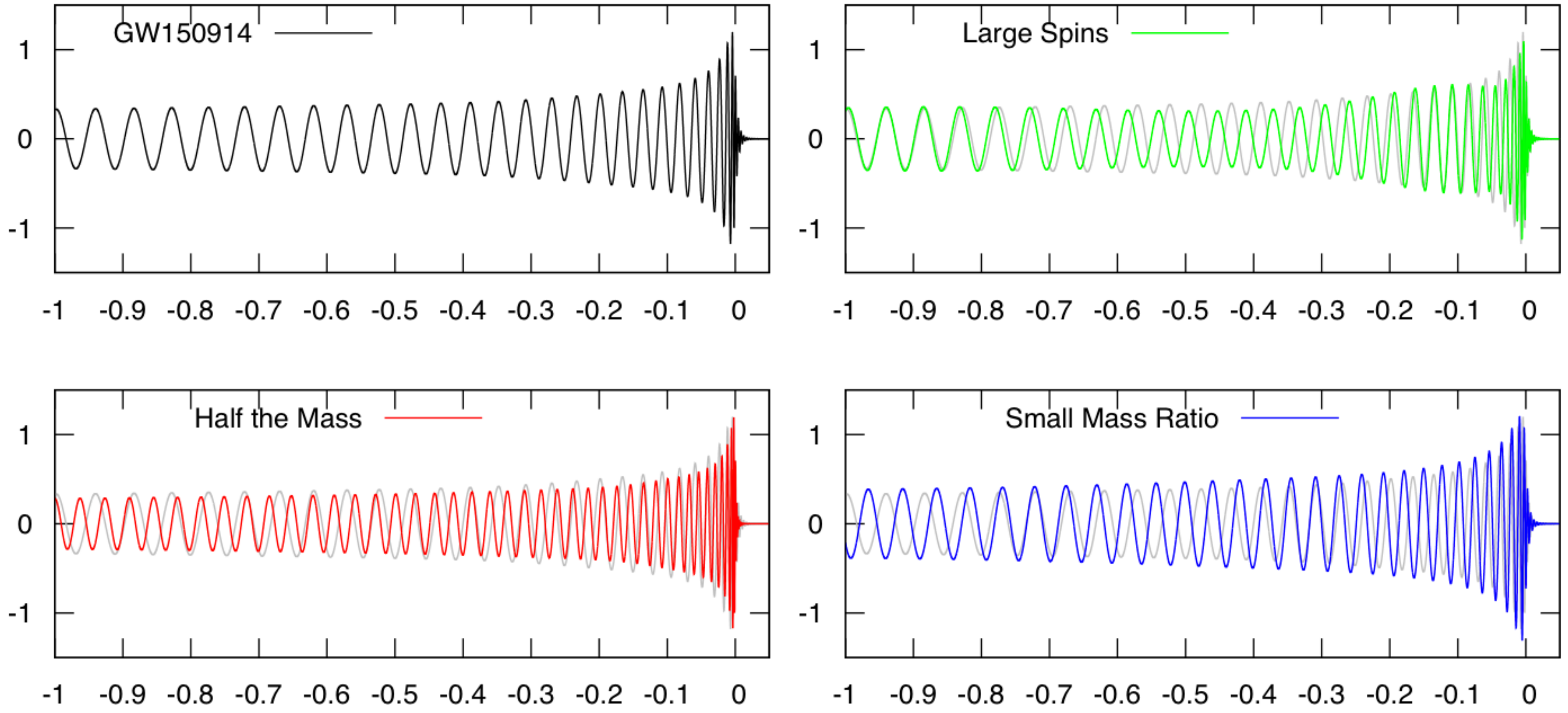


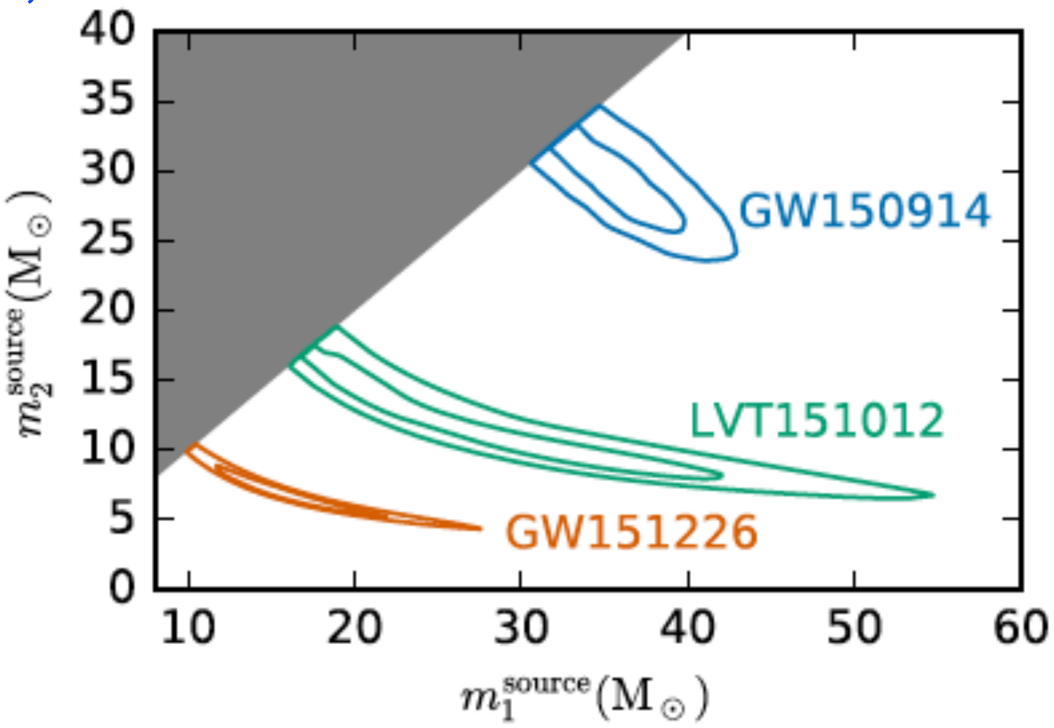
Illustration by N. Cornish and T. Littenberg

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”

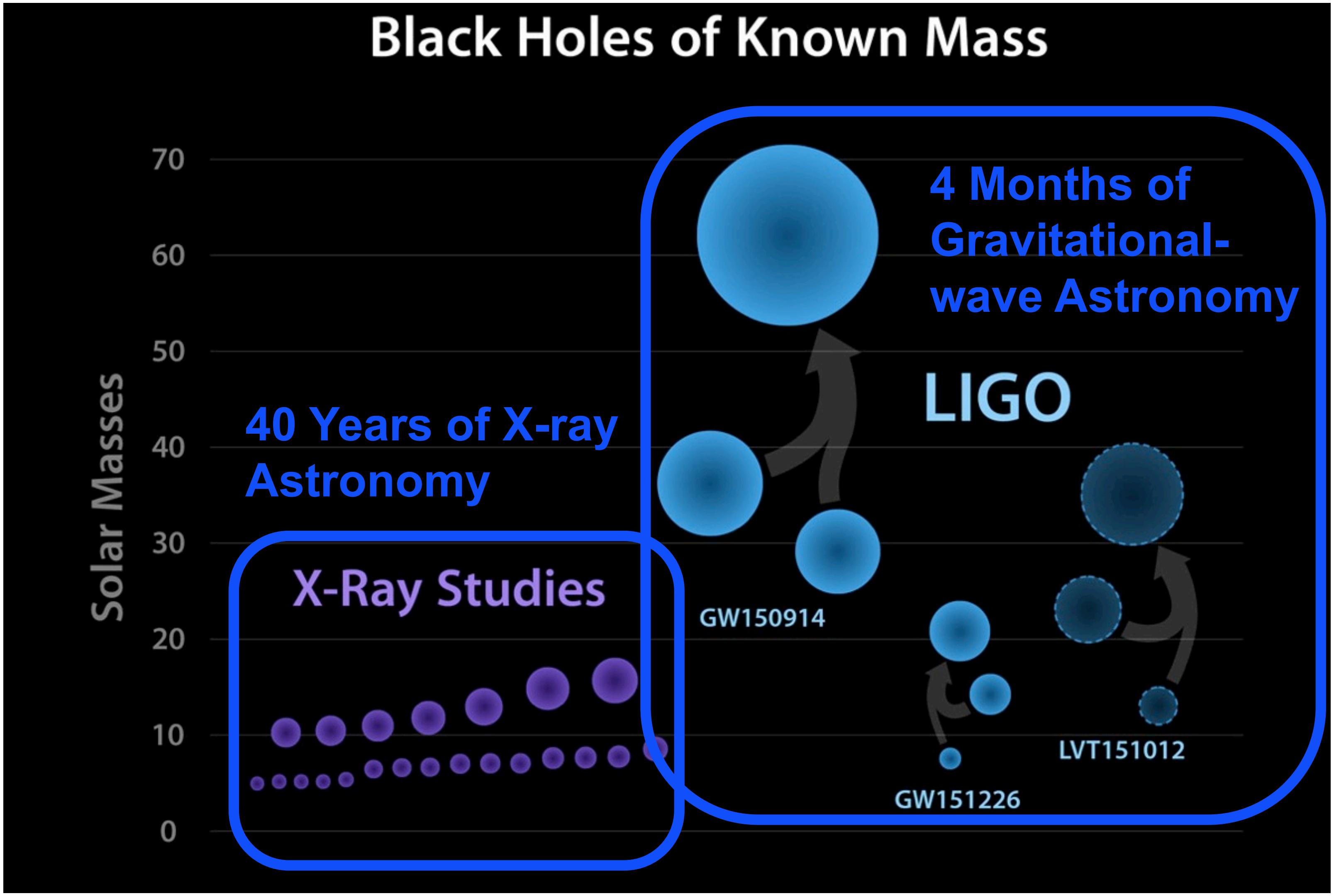
$$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$



Source masses are redshifted!
These masses are surprisingly large!

Abbott, et al., LVC, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, Phys. Rev. X 6, 041015 (2016)

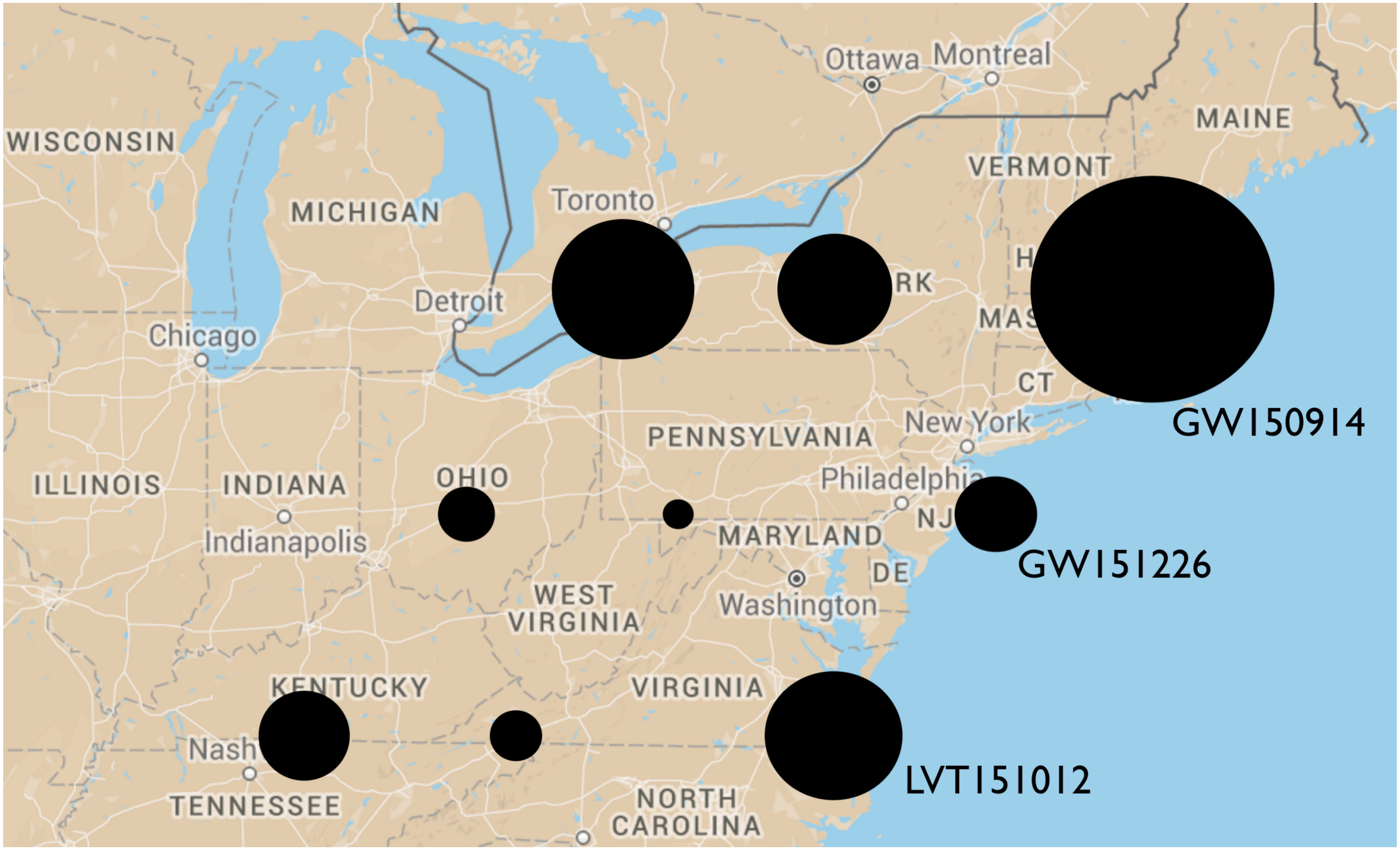
The Black Hole Mass Menagerie



40 Years of X-ray Astronomy

4 Months of Gravitational-wave Astronomy

These are big black holes

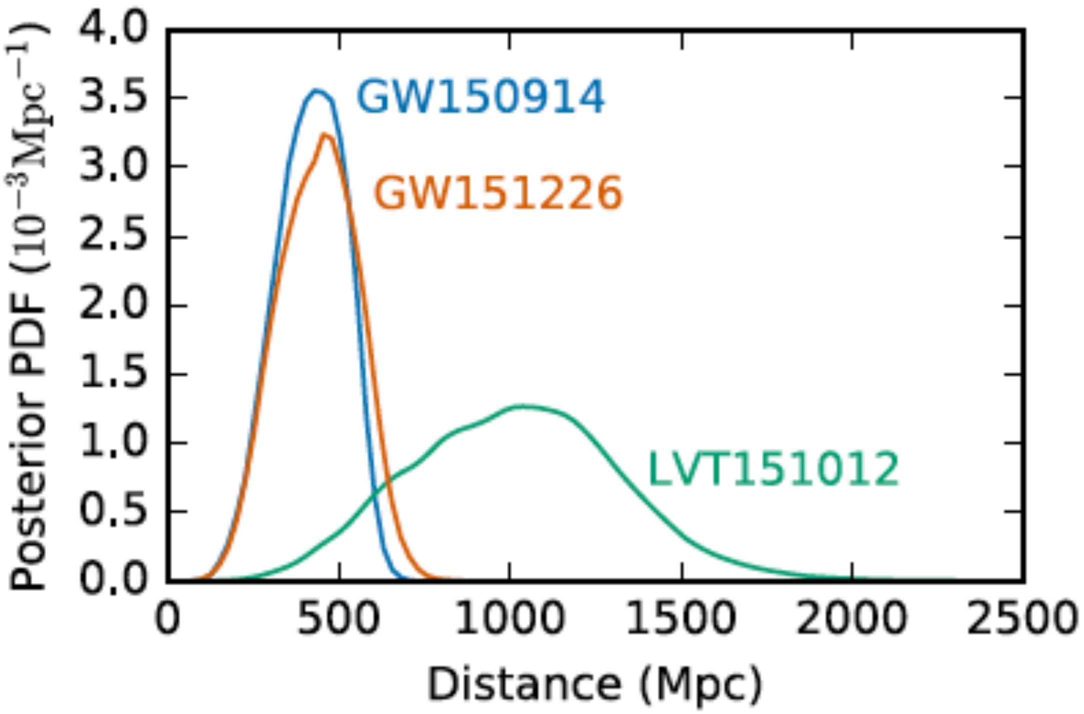


Three BBH events, distances

It’s hard to measure distances in astronomy!
(few “standard candles”)

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

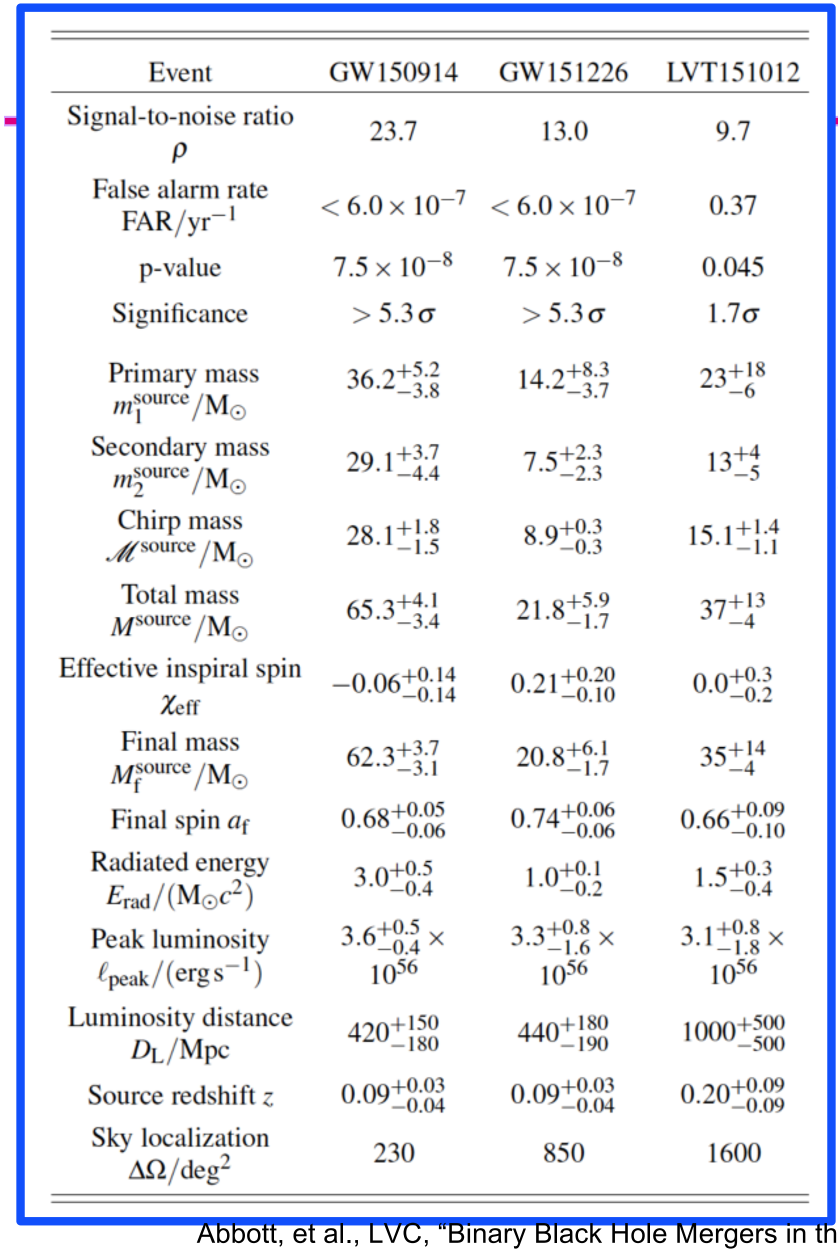
Distances measured poorly with only two detectors.



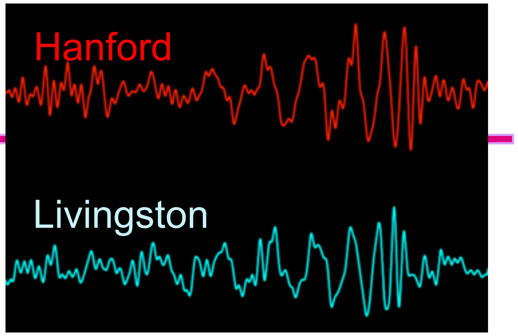
Our two loud events are far away!
(400 Mpc ~ 1.3 Gly) – merged 1.3 By ago!

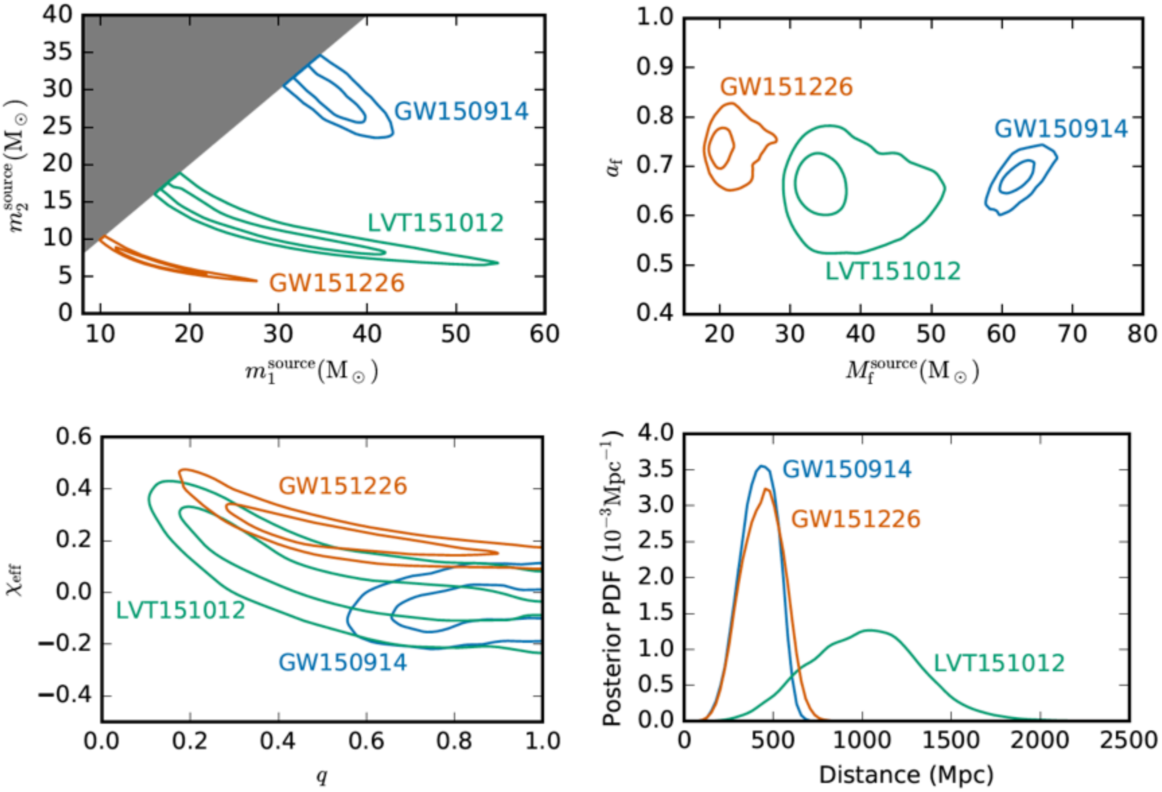
Abbott, et al., LVC, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, Phys. Rev. X 6, 041015 (2016)

Extracting Astrophysical Parameters from Detections



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600





Abbott, et al., LVC, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", Phys. Rev. X 6, 041015 (2016)

Radiated energy & luminosity

- GW150914:

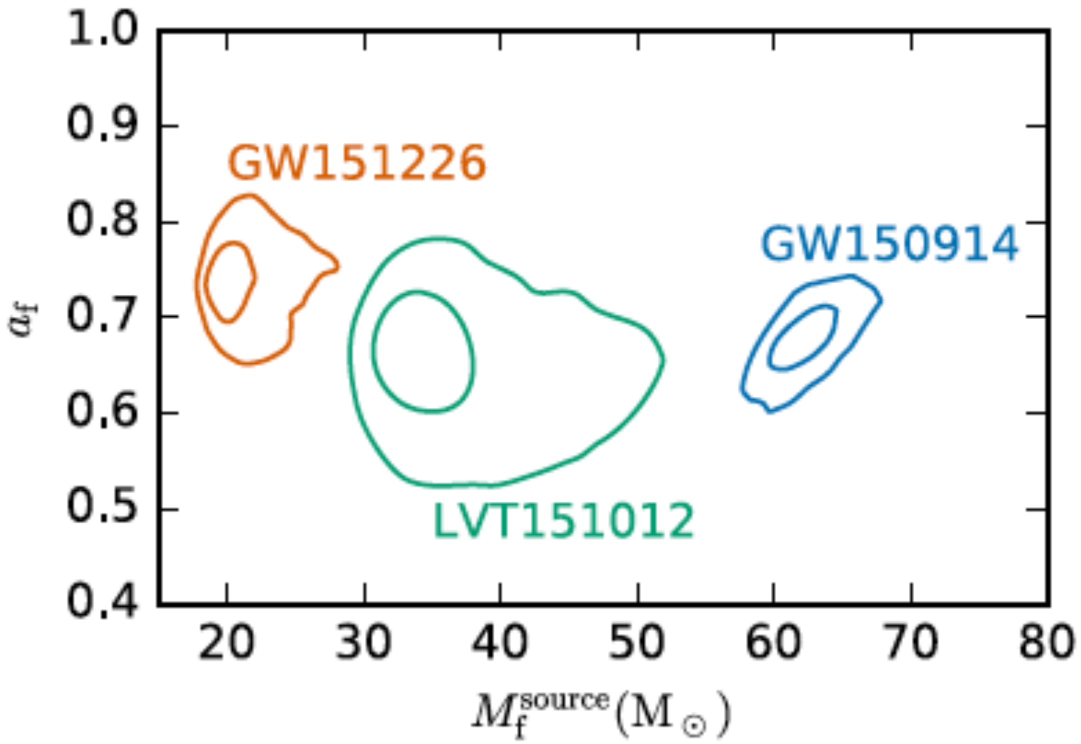
$$E_{\rm rad} = 3.0^{+0.5}_{-0.4}\,{\rm M}_\odot c^2$$
$$\ell_{\rm peak} = 3.6^{+0.5}_{-0.4} \times 10^{56}{\rm erg/s}$$

- GW151226:

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

- LVT151012:

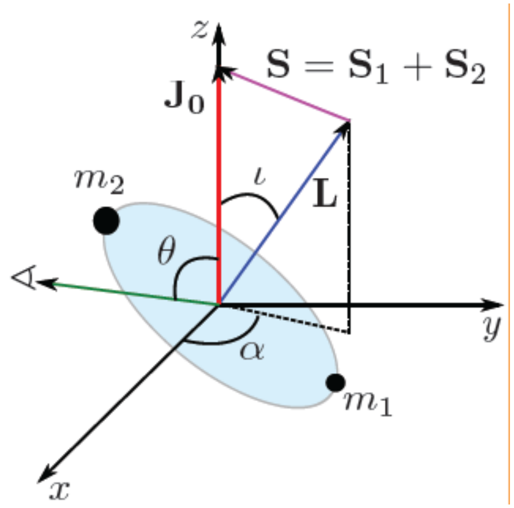
$$E_{\rm rad} = 1.5^{+0.3}_{-0.4}\,{\rm M}_\odot c^2$$
$$\ell_{\rm peak} = 3.1^{+0.8}_{-1.8} \times 10^{56}{\rm erg/s}$$



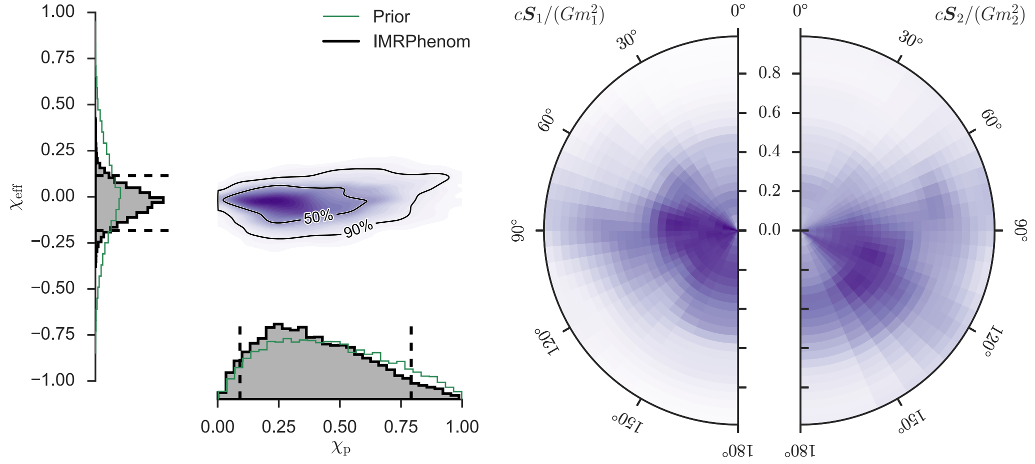
- GW150914: $E_{GW} \approx 3\,M_\odot c^2$, or ~4.5% of the total mass-energy of the system.
- Roughly 10^{80} gravitons.
- Peak luminosity $L_{GW} \sim 3.6 \times 10^{54}$ erg/s, briefly outshining the EM energy output of all the stars in the observable universe (by a factor > 20).

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

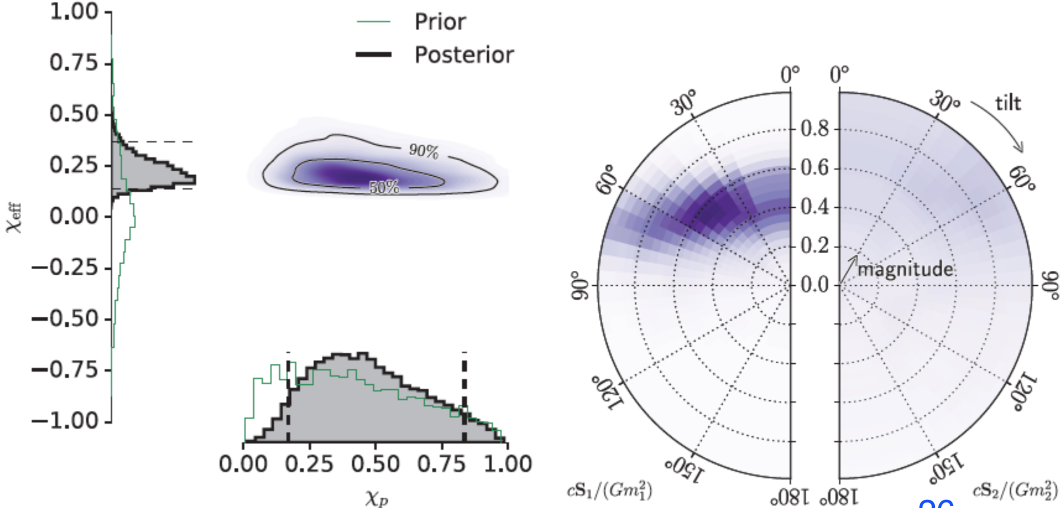
- The component BH spins measurably modulate the inspiral frequency evolution.
- Spin-orbit couplings cause the orbital plane to precess, producing amplitude modulation at the detectors.
- Parameterize with aligned spin χ_{eff} and "precessing" spin χ_P



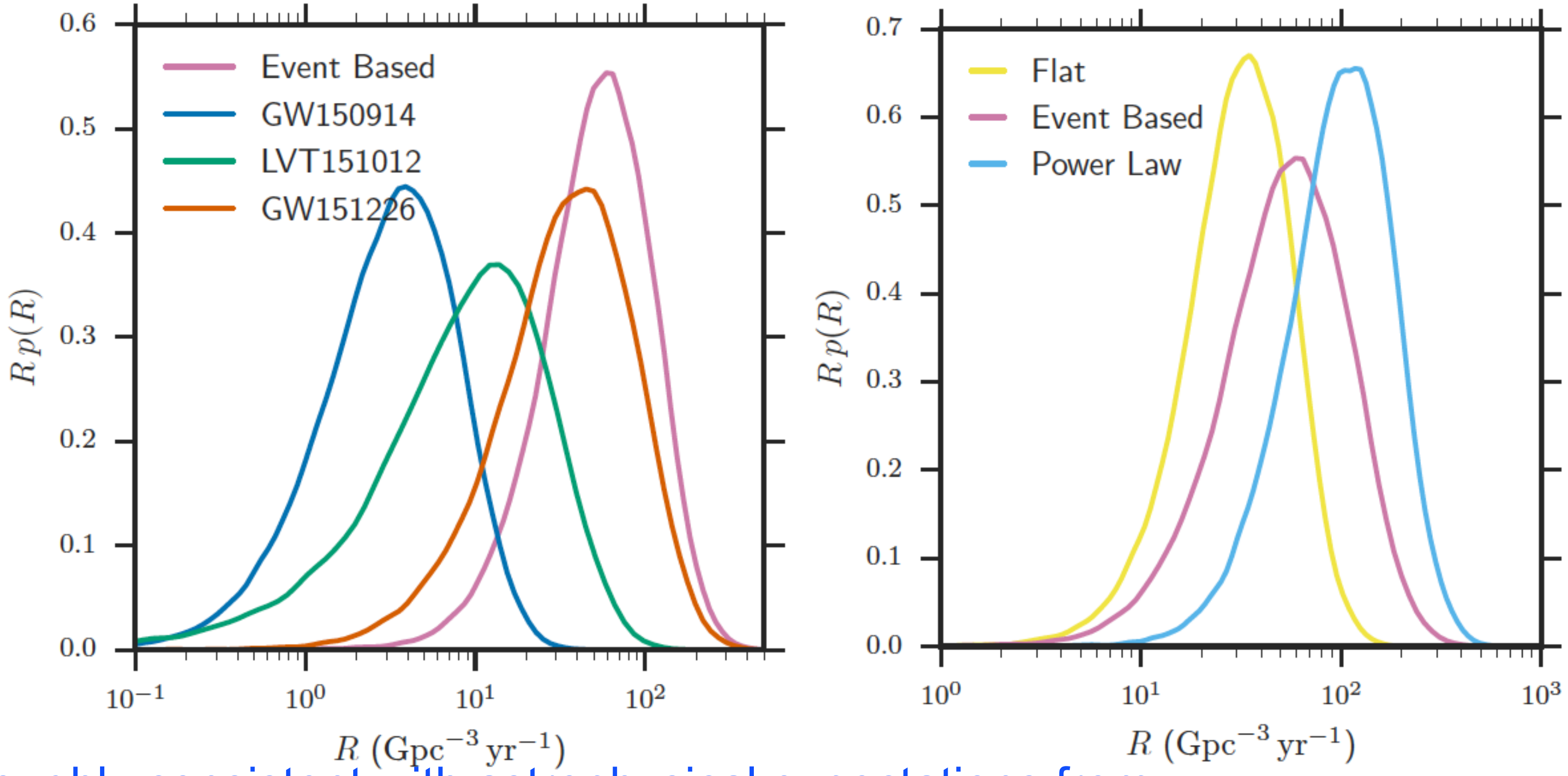
GW150914



GW151226



Astrophysical rate density

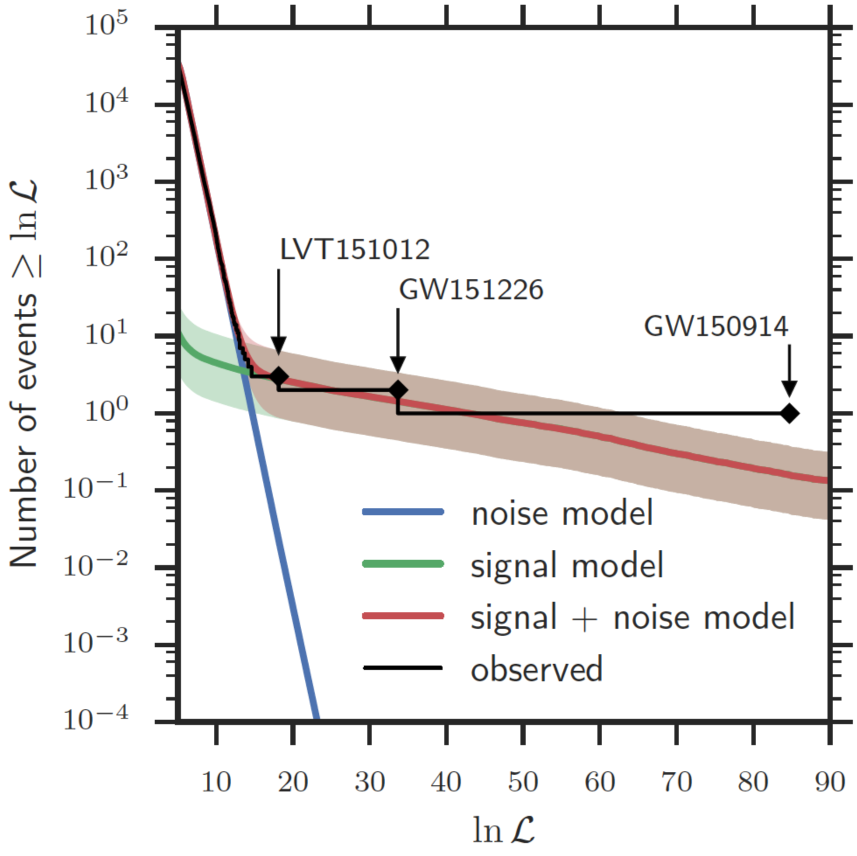


Roughly consistent with astrophysical expectations from:

- Core collapse supernova rate
- Short GRB rate
- Astrophysical modeling of compact binary formation ("population synthesis")
- A half-dozen BNS systems in our galaxy (including Hulse-Taylor)

Observed BBH merger rate

Abbott, et al., LVC, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, Phys. Rev. X 6, 041015 (2016)



The observed BBH merger rate (comoving frame) from these three events, in number / Gpc^3 / yr

Event-based:

GW150914	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.4^{+30.4}_{-8.7}$
GW151226	37^{+92}_{-31}
All	55^{+99}_{-41}

Astrophysically motivated:

Flat in log mass	30^{+43}_{-21}
Power Law (−2.35)	99^{+138}_{-70}

Same ballpark as population synthesis models, CCSN rate, etc

iLIGO+eLIGO BBH rate upper limit: ~< 420 Gpc^{-3} yr^{-1}

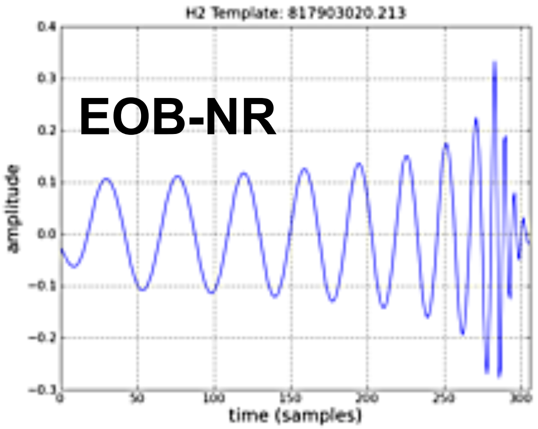
Aasi, J. et al. 2013, Phys. Rev. D, 87, 022002, arXiv:1209.6533

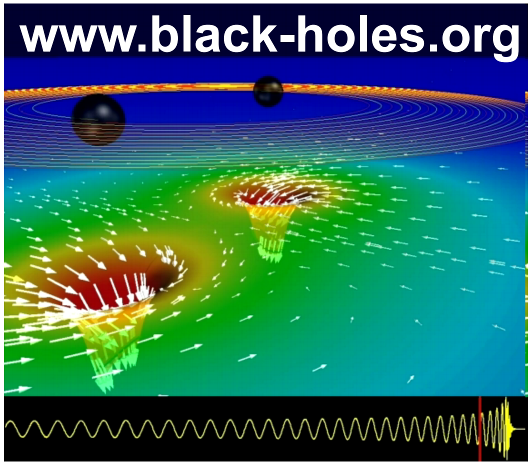
Testing General Relativity in the strong-field, dynamical regime

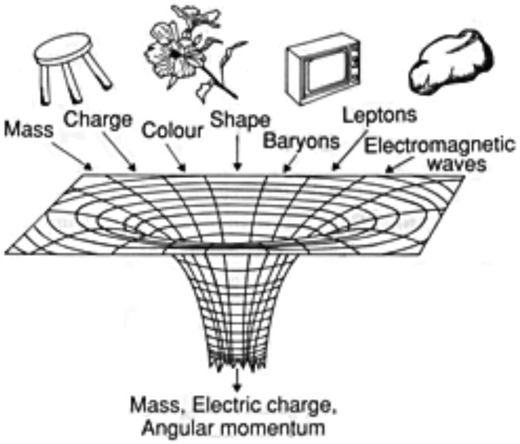
- **Test post-Newtonian expansion of inspiral phase.**

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

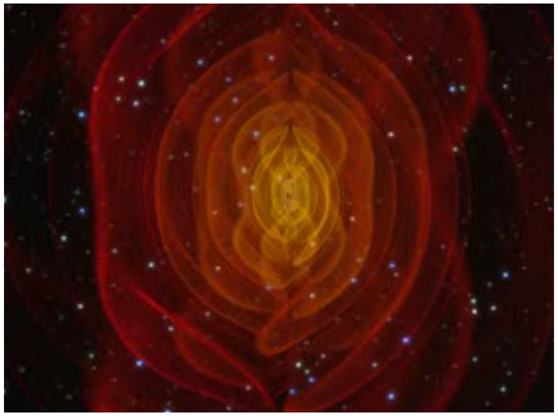
- **Test Numerical Relativity waveform prediction for merger phase.**
- **Test association of inspiral and ringdown phases: BH perturbation theory, no-hair theorem.**



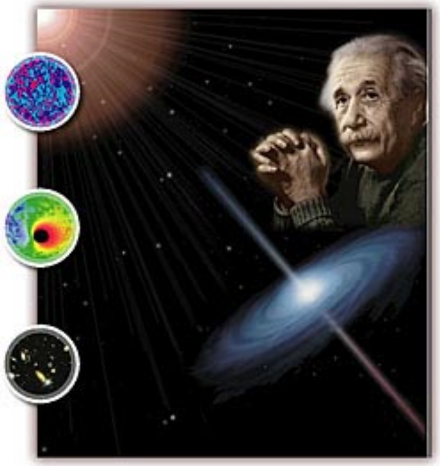




nonlocal.com/hbar/blackholes.html



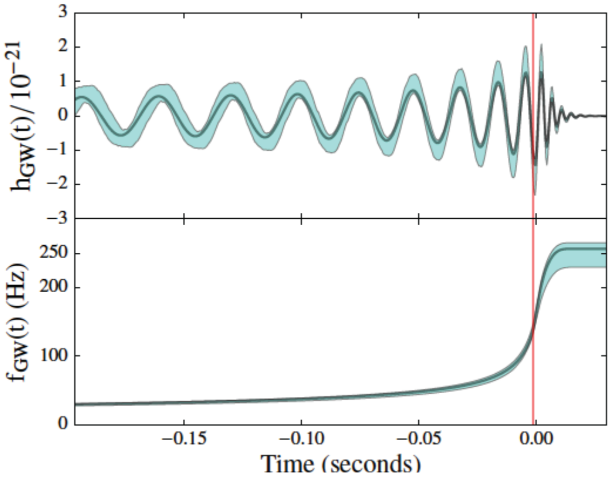
Testing beyond-GR in wave generation and propagation

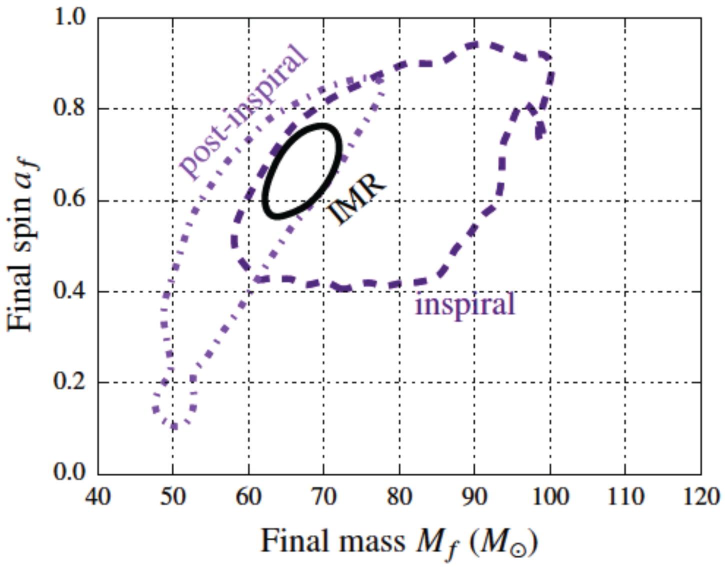


- We can test GR in the new regime of strong-field, highly dynamical gravity!
- Gravitational lensing & multiple "images" (not beyond GR!)
- Constrain "parameterized post-Einsteinian framework" (Yunes & Pretorius, 2009)
- Directly measure speed of gravitational waves ($c_{GW} \neq c_{light}$), constrain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

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

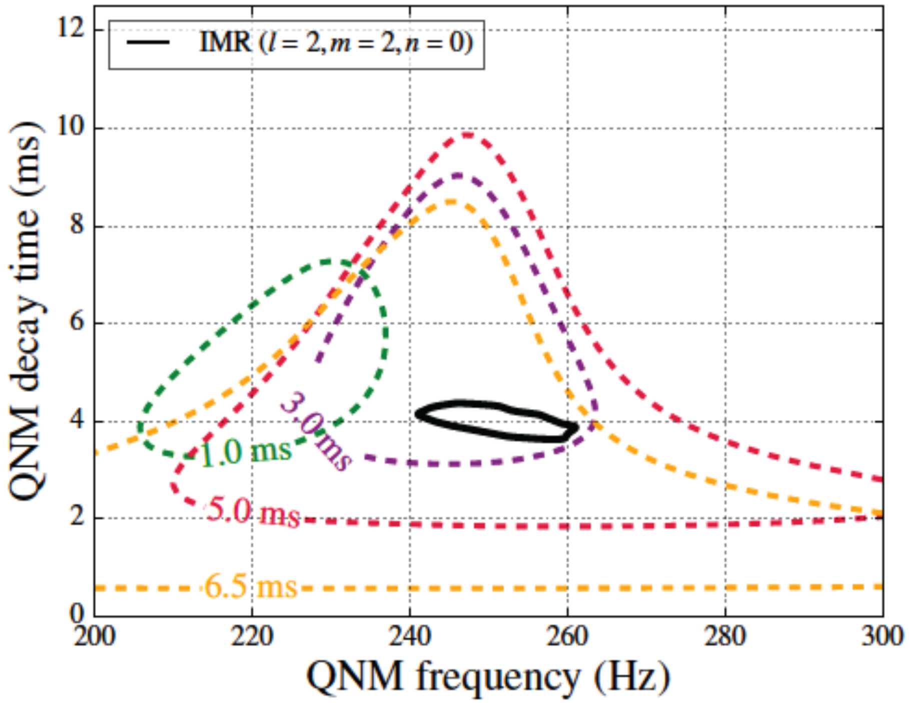




Tests of General Relativity with GW150914
Phys. Rev. Lett. 116, 221101 (2016)

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 (and that, just barely).**
- **The measured frequency and decay time for the least damped QNM are consistent with IMR waveforms from numerical relativity simulations.**
- **We can “stack” multiple events to test for deviations from GR predictions.**



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

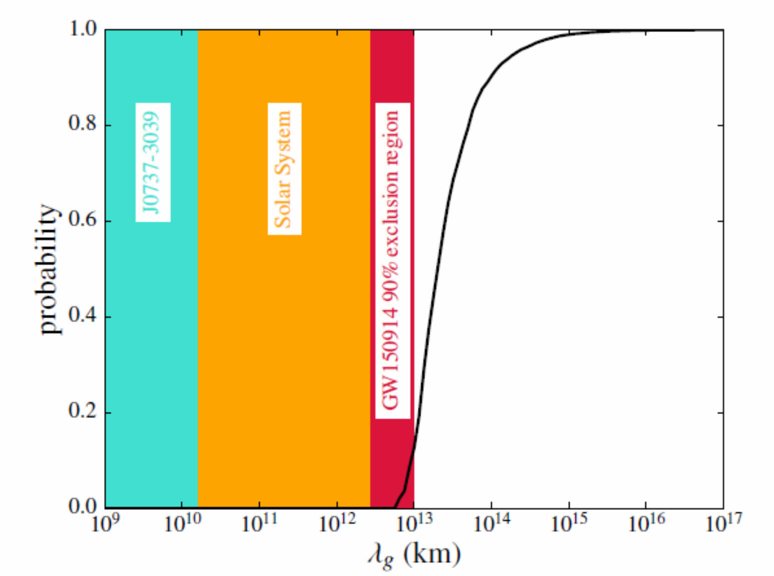
$$v_g^2/c^2 \equiv c^2p^2/E^2 = 1 - h^2c^2/(\lambda_g^2E^2)$$

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

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

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

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



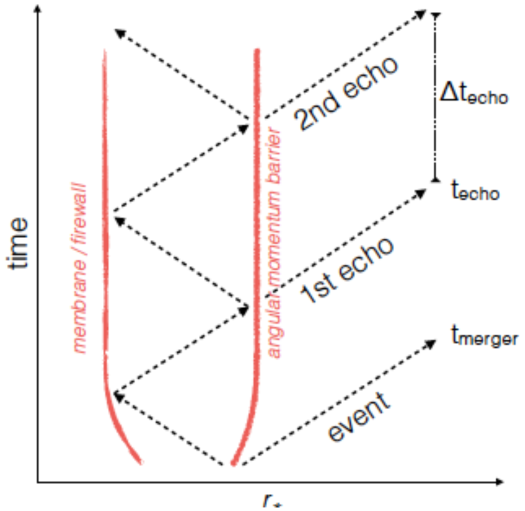
$$\lambda_g \geq 10^{13}\mathrm{km}\ (90\%)$$

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

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

What if GR black holes … aren't? "Echoes from the abyss"

- When is a BH *not* a BH?
- Planck-scale departures from GR (firewalls, fuzzballs, gravastars) near the putative BH horizons can lead to "echoes".
- repeating damped echoes with time-delays of *8M logM*
- Abedi, Dykaar, and Afshordi, arXiv:1612.00266v1
- "… we find tentative evidence for Planck-scale structure near black hole horizons at 2.9σ significance level"
- But… if you look for ringdowns in LIGO strain noise, you will find it *everywhere*
- (They used 32s of data around GW150914 to estimate the background).



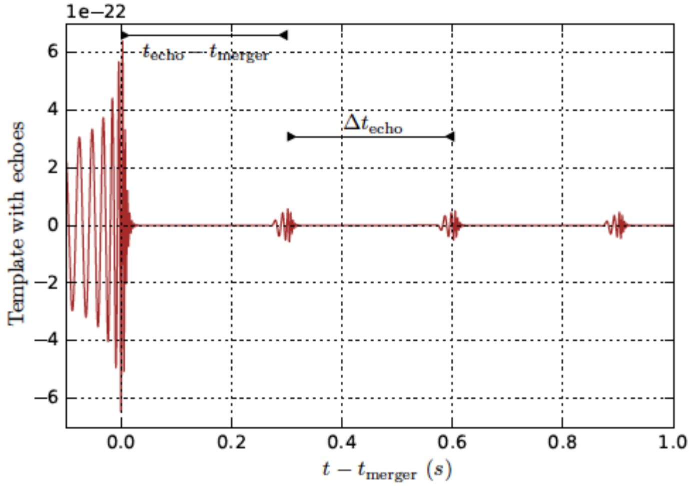


FIG. 2: LIGO original template for GW150914, along with our best fit template for the echoes.

Physics and astrophysics with gravitational waves

The advanced GW detector era has begun!

- **The exploration of the GW sky;**
- **Unique tests of General Relativity in the strong-field, highly non-linear and dynamical regime;**
- **joint observations and discoveries with EM and neutrino telescopes;**
- **nuclear equation of state, r-process nucleosynthesis;**
- **and a rich new branch of astrophysics.**

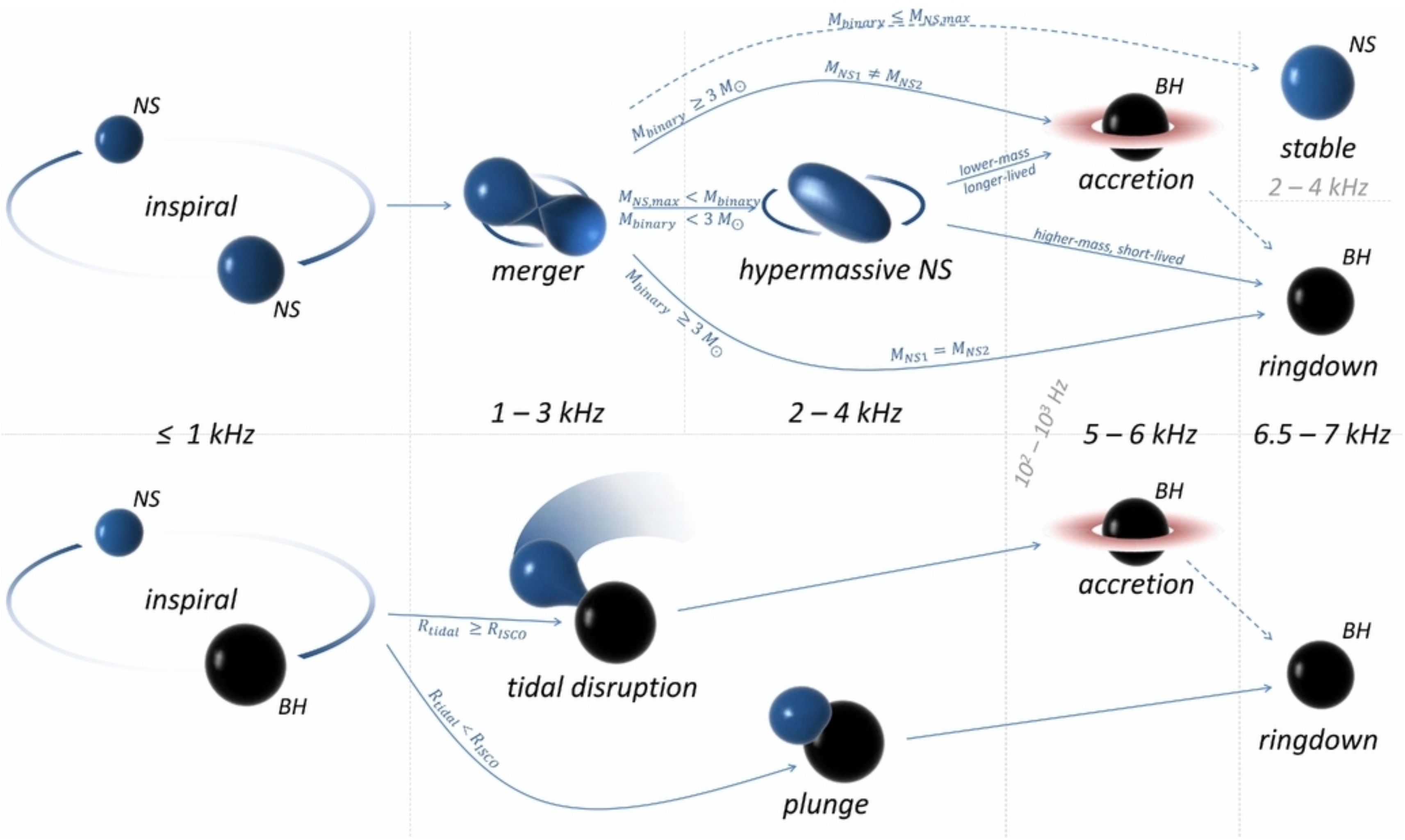
But most of all, we look forward to …

Thank You!

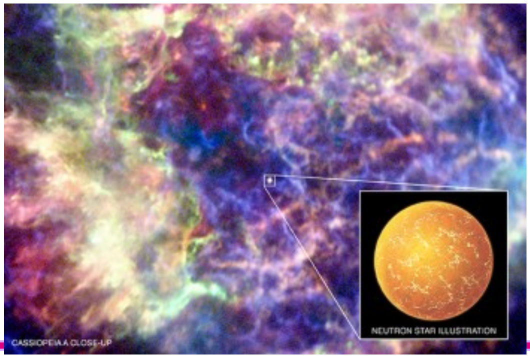
the unexpected!

BNS and NSBH mergers

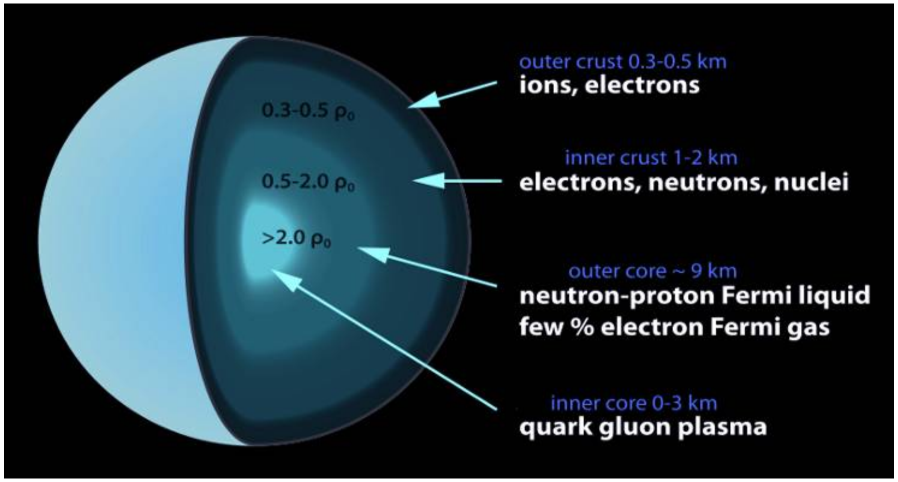
Figure 1 from I Bartos et al 2013 Class. Quantum Grav. 30 123001

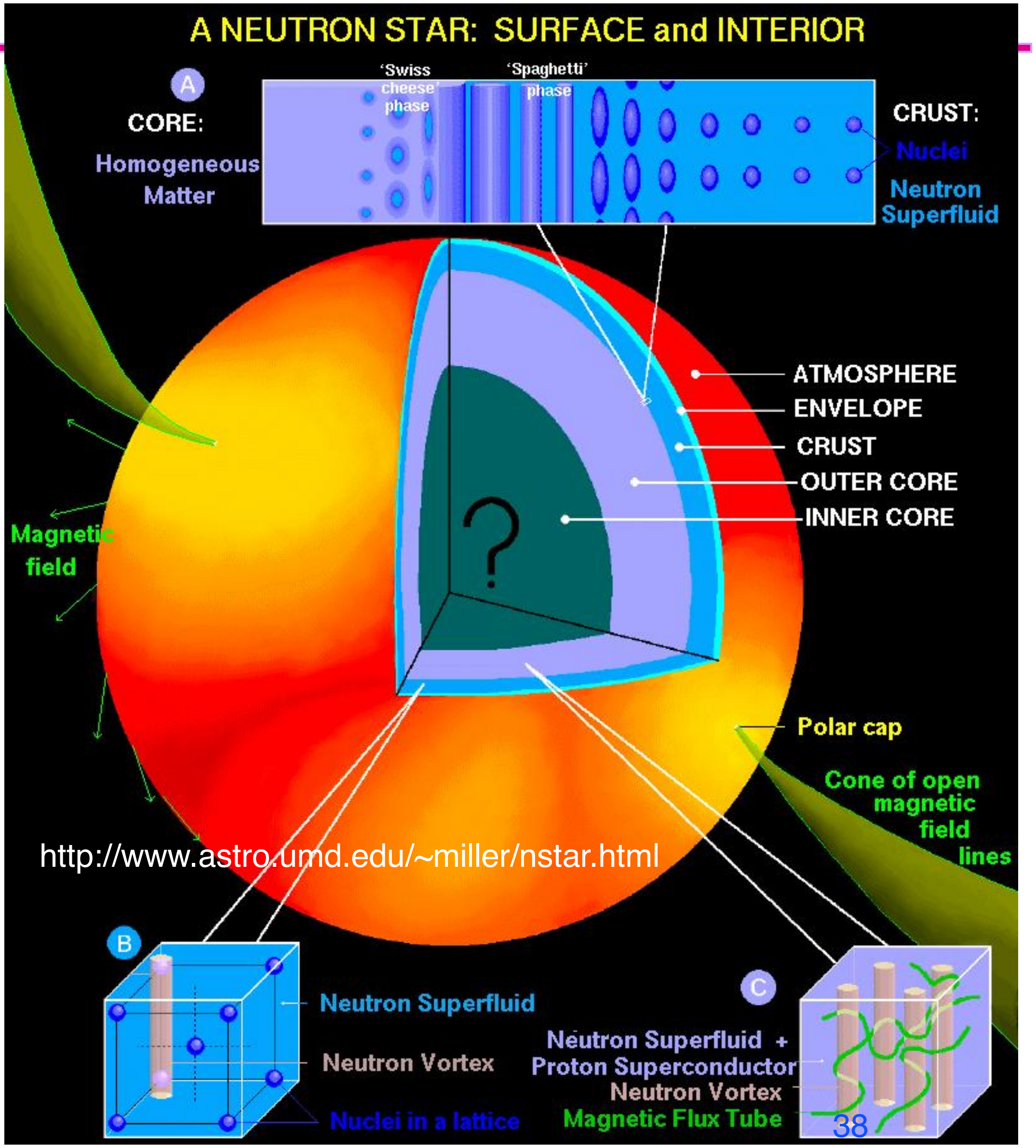


Neutron stars



- Remnants of core collapse supernovae
- A unique laboratory for fundamental physics
- Strong, Weak, EM, gravity – all under the most extreme conditions
- Structure can be revealed through binary mergers

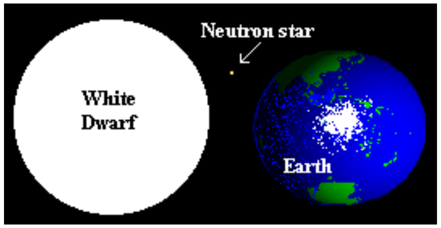


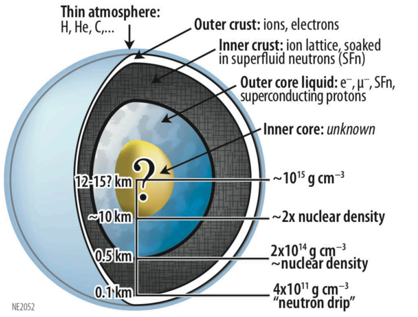


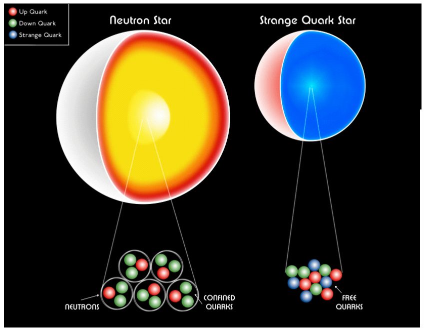
http://www.astro.umd.edu/~miller/nstar.html

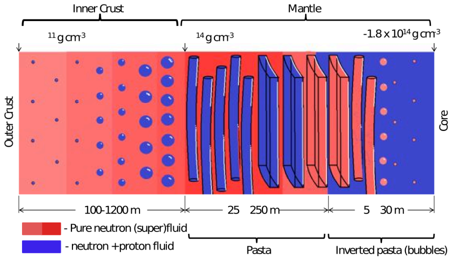
All four fundamental forces under the most extreme conditions

- Gravity: Compact stars have gravitational fields $GM/c^2R \sim O(1)$, strong tidal effects, strong curvature, highly relativistic
- Strong interaction at > 2x nuclear density in core
    - » Hard repulsive core of nucleon-nucleon interaction plays crucial role
    - » Potential transition to hyperonic matter, strange quark matter, QGP
    - » Complex ionic crystal lattice structure in crust: “nuclear pasta”
- Weak interaction under extreme conditions with neutrino trapping -> beta equilibrium
- EM: Superfluid core supporting extreme magnetic fields (perhaps > 10^{15} Gauss at surface), flux tube pinning in core

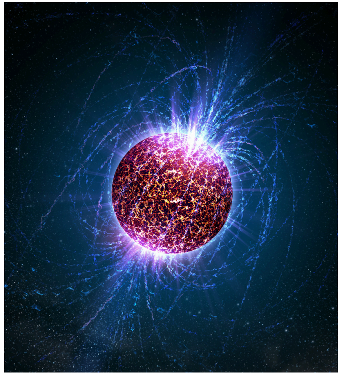


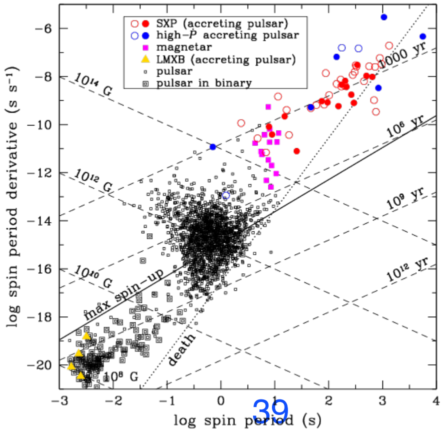




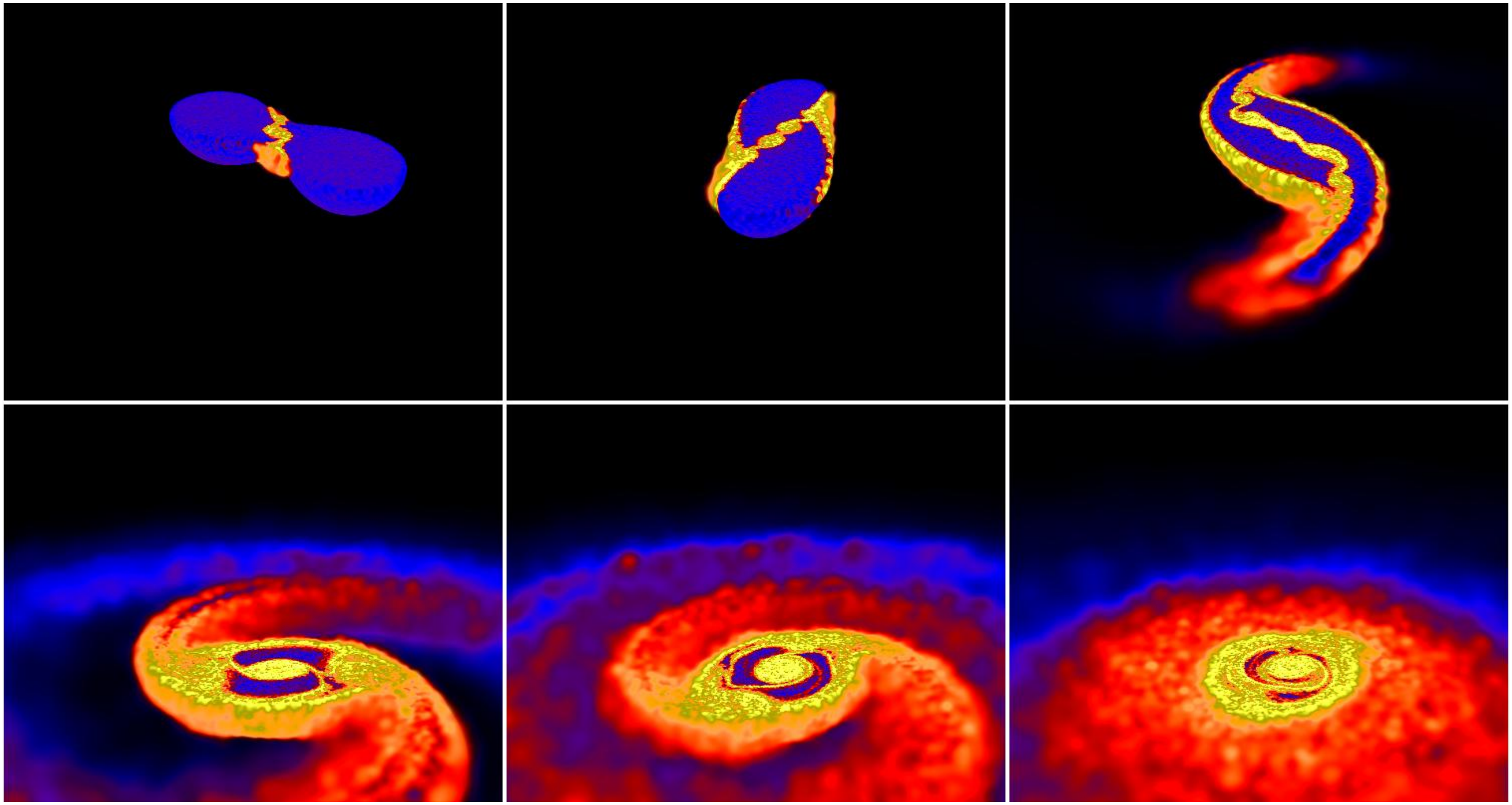


$$
\begin{aligned}
e^- + p &\rightarrow n + \nu_e, \\
e^+ + n &\rightarrow p + \bar{\nu}_e, \\
n &\rightarrow p + e^- + \bar{\nu}_e.
\end{aligned}
$$





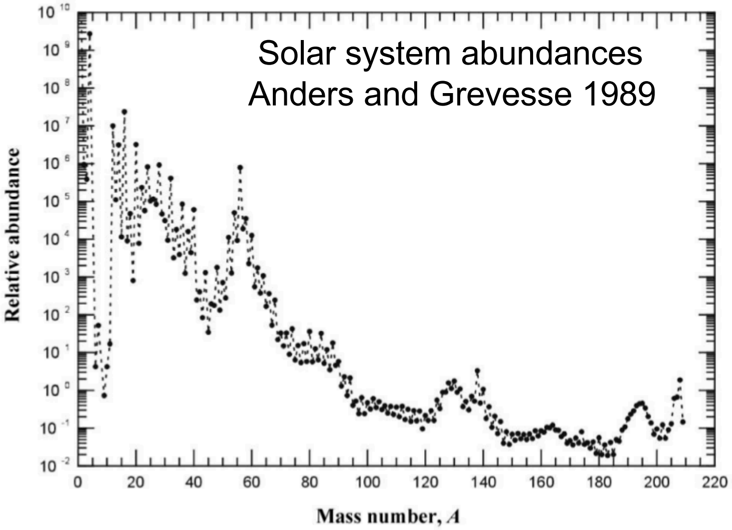
BNS mergers,
tidal distortion and disruption

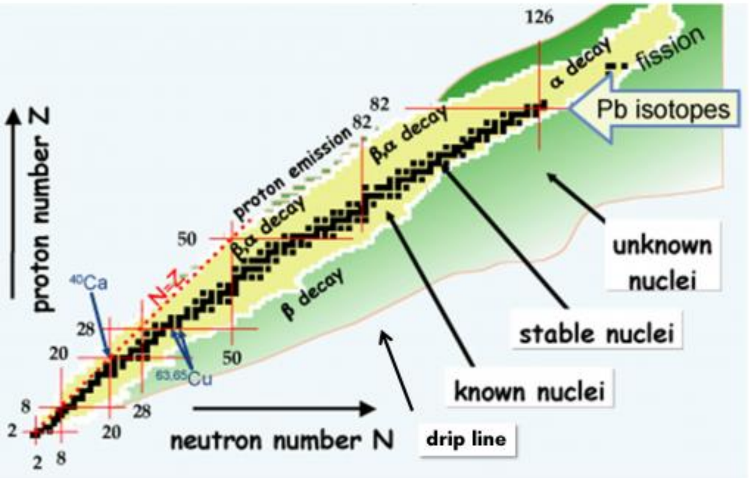


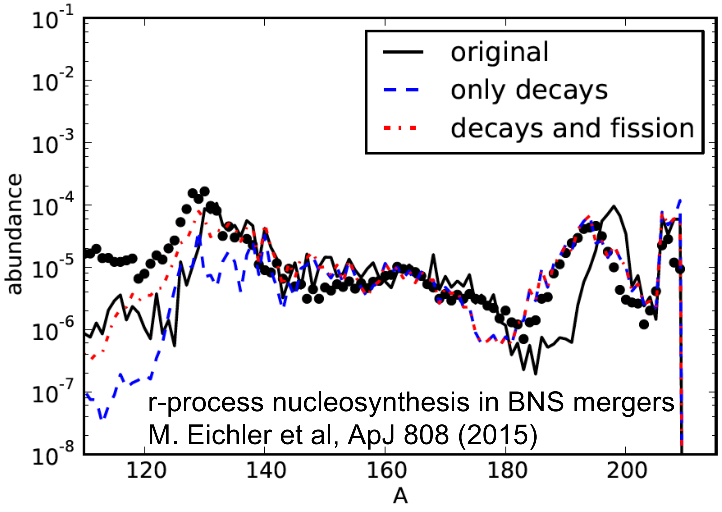
Credit: Daniel Price and Stephan Rosswog

The origin of the (heavy) elements

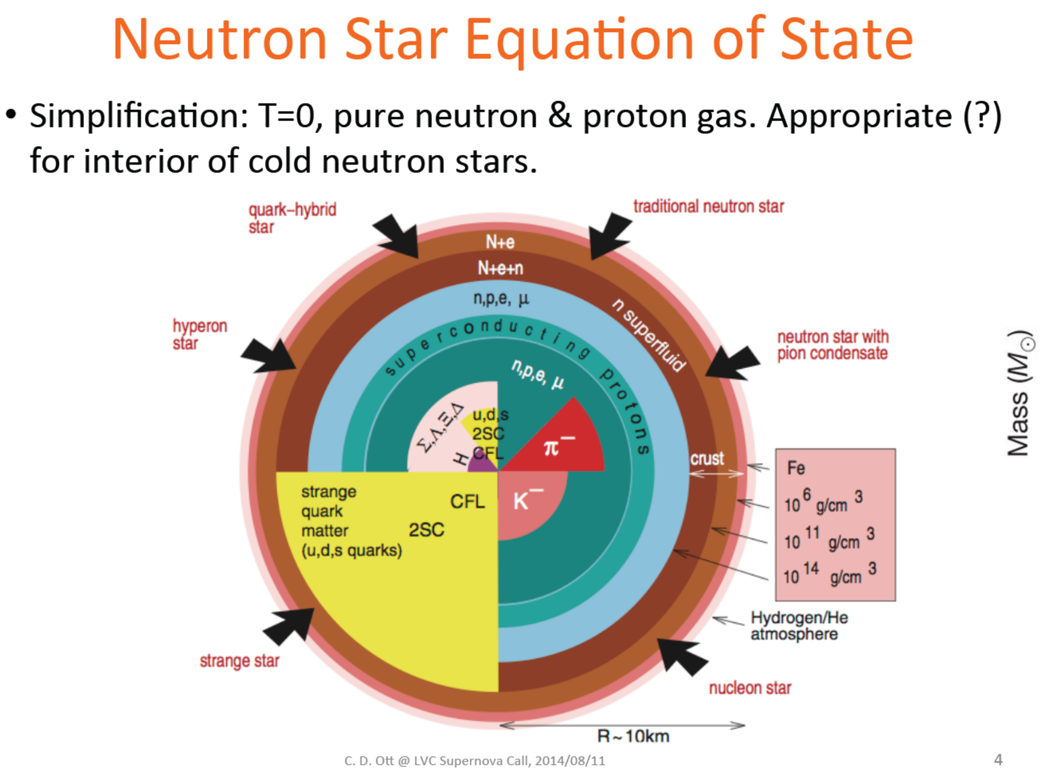
- Lightest elements (H, He, Li) forged in Big Bang
- Heavier elements (C, O, N, … Fe) forged in the core of massive stars, distributed to ISM by core-collapse supernovae (the death of massive stars)
- Elements beyond Fe (like Cu, Au, Pt, U…) are forged during the SN (“r-process”);
- but most of them might come from binary neutron star mergers (second-death)


Solar system abundances
Anders and Grevesse 1989




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

NEOS and NS mass-radius relation

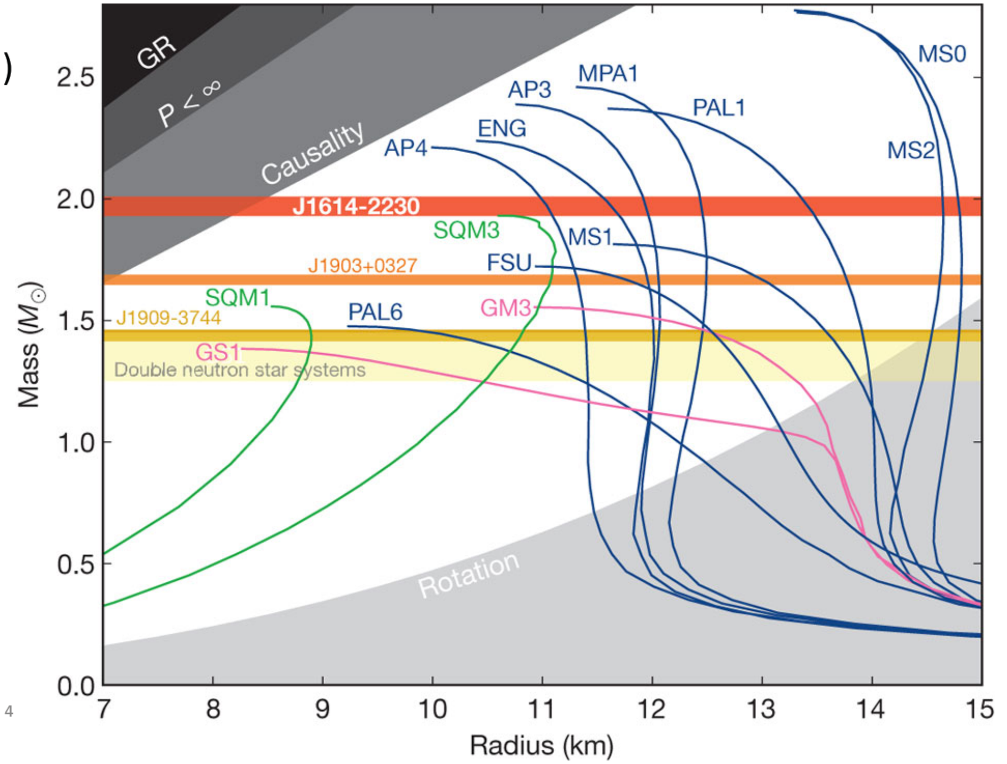


Neutron Star Equation of State

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

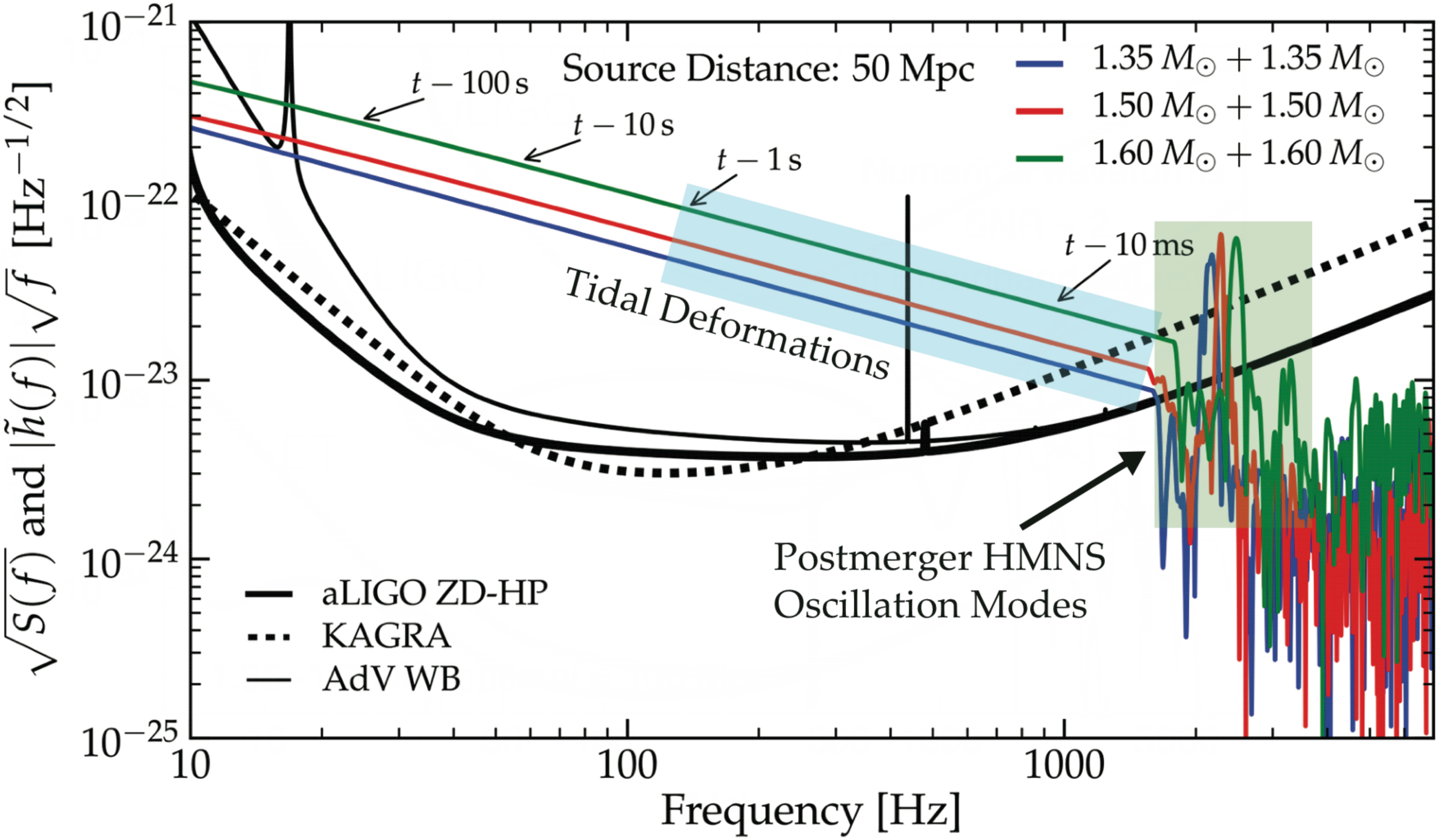
C. D. Ott @ LVC Supernova Call, 2014/08/11

4

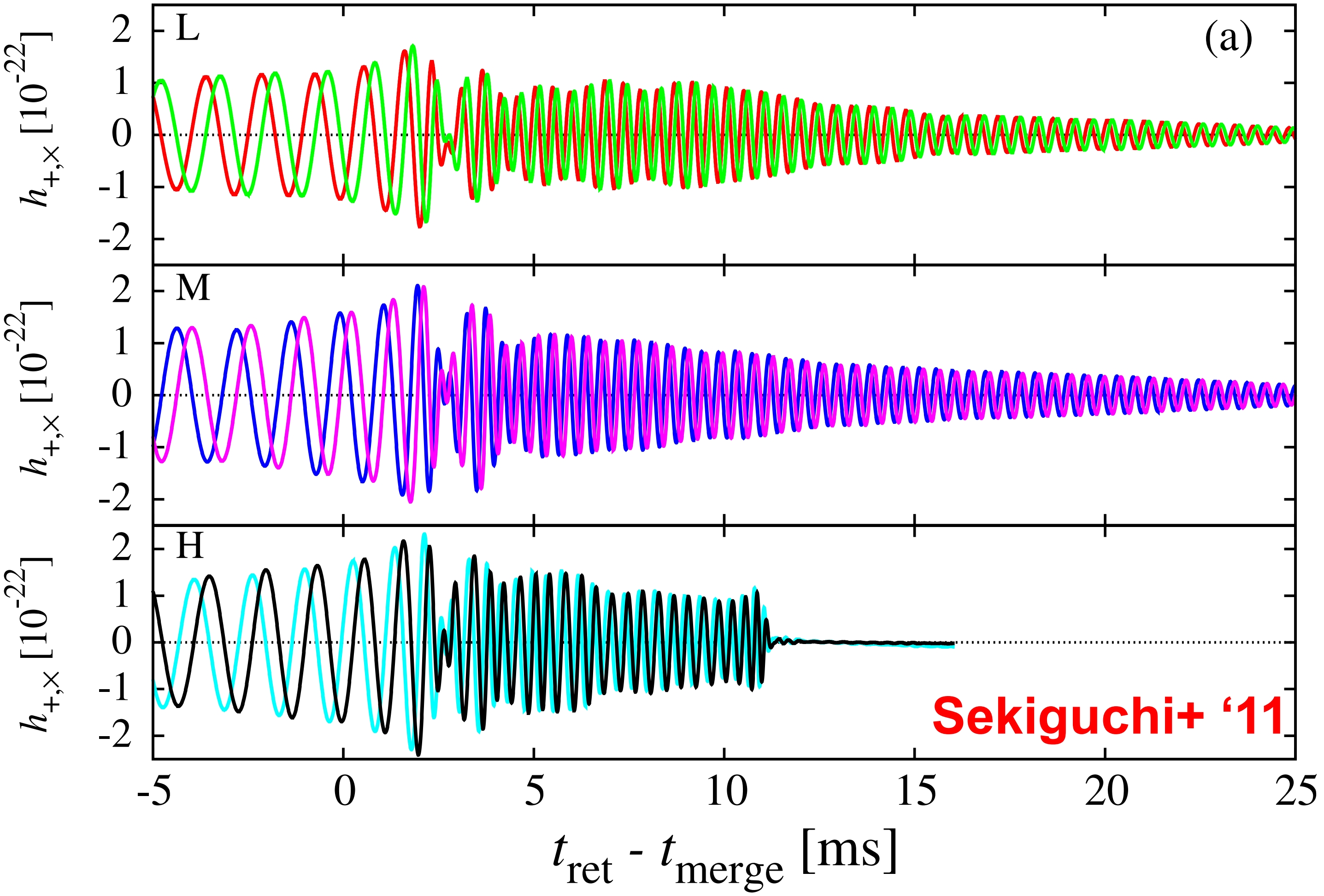


Tidal disruption of neutron stars near merger


Credit: Daniel Price and Stephan



Nuclear Astrophysics: BNS Merger GW waveforms



1.35 + 1.35

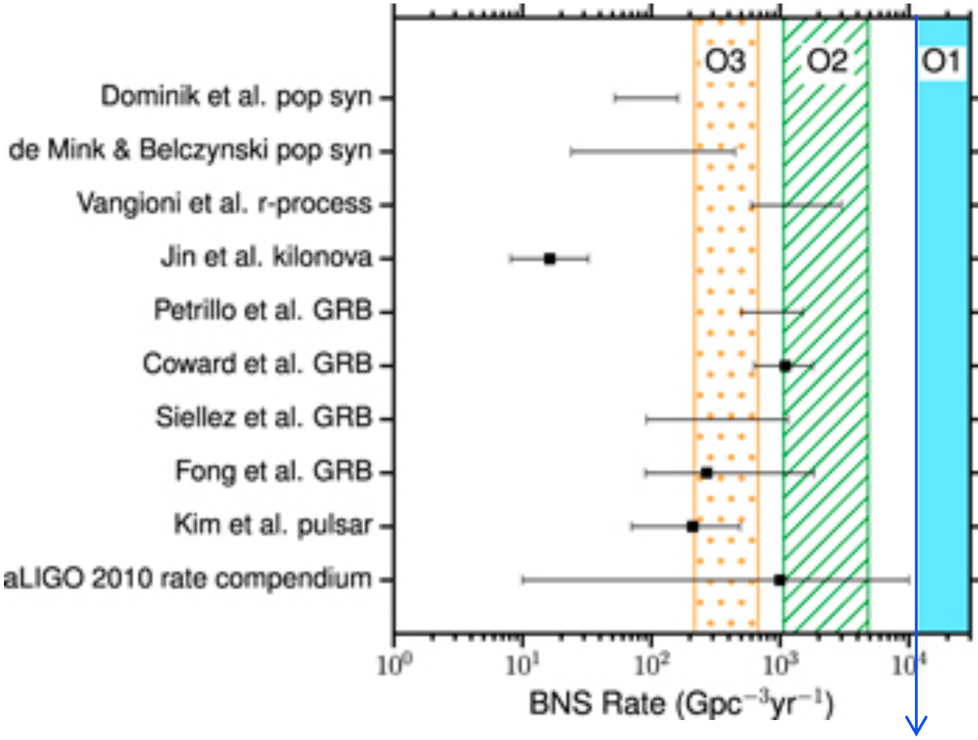
1.50 + 1.50

1.60 + 1.60

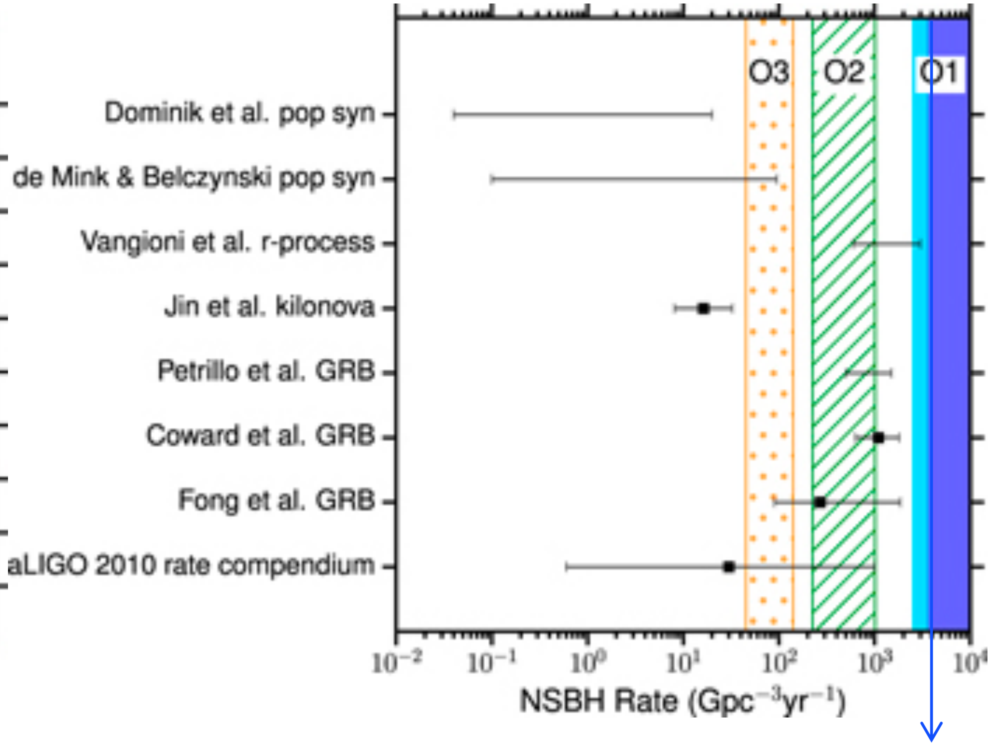
Mass [$M_{\rm Sun}$]

Sekiguchi+ 11: Full GR NS-NS simulation with realistic microphysics, finite-temperature nuclear EOS of H. Shen+ '98,'11 (+MHD, ν-transport since then!)

BNS and NSBH merger rate limits from O1, and predictions



12,600



3,600

O1 <BNS range> ~ 70 Mpc

O1 <NSBH range> ~ 110 Mpc

Initial LIGO limit (2012) on BNS: 130,000 Gpc^{-3} yr^{-1}

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016)

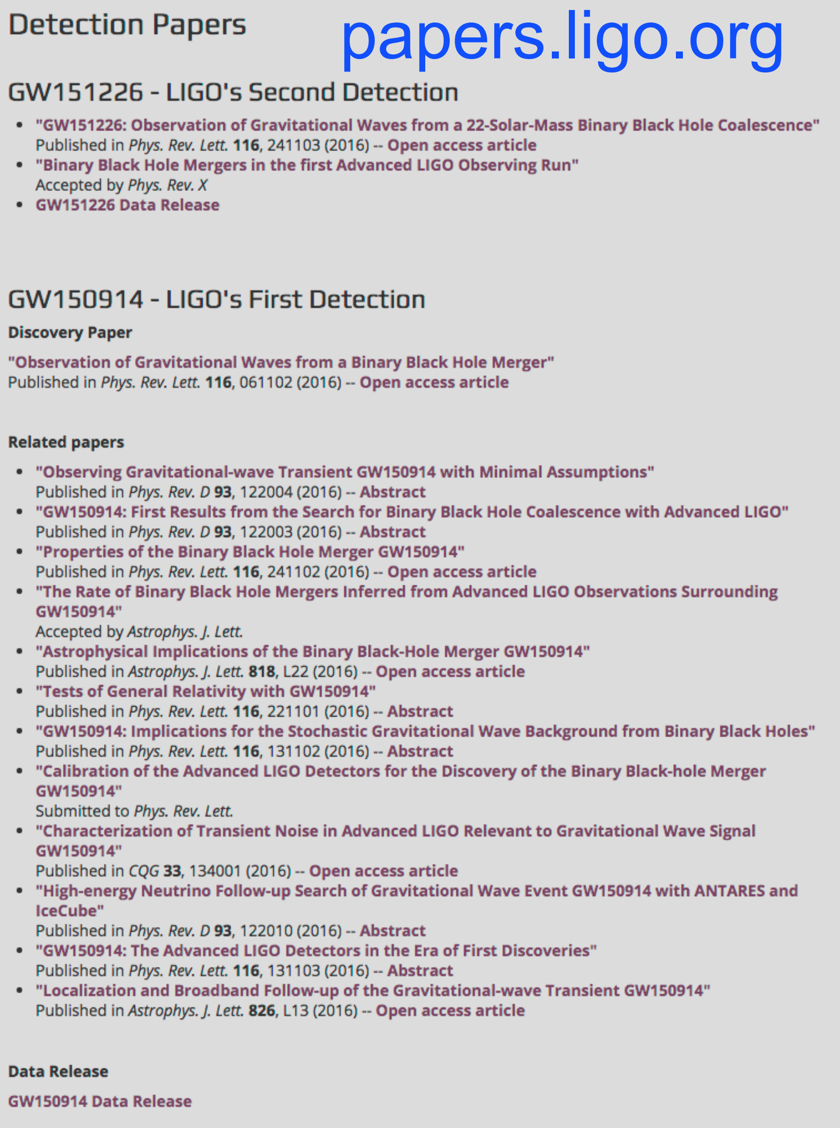
week ending
12 FEBRUARY 2016

Observation of G
Hole Merger

(LIG
)
(R

On September 14, 2015
er Gravitational-Wave
Observatory simultaneous
al sweeps upwards in
frequency from 35 to 250
matches the waveform
predicted by general relati
d the ringdown of the
resulting single black hole
oise ratio of 24 and a
false alarm rate estimated
a significance greater
than 5.1σ. The source lies
edshift $z = 0.09^{+0.03}_{-0.04}$.
In the source frame, the ini
nal black hole mass is
$62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot}$
0% credible intervals.
These observations demon
. This is the first direct
detection of gravitational
ger.

DOI: 10.1103/PhysRevLett.1



papers.ligo.org

Detection Papers

GW151226 - LIGO's Second Detection

- "GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence"
  Published in *Phys. Rev. Lett.* **116**, 241103 (2016) -- Open access article
- "Binary Black Hole Mergers in the first Advanced LIGO Observing Run"
  Accepted by *Phys. Rev. X*
- GW151226 Data Release

GW150914 - LIGO's First Detection

Discovery Paper

"Observation of Gravitational Waves from a Binary Black Hole Merger"
Published in *Phys. Rev. Lett.* **116**, 061102 (2016) -- Open access article

Related papers

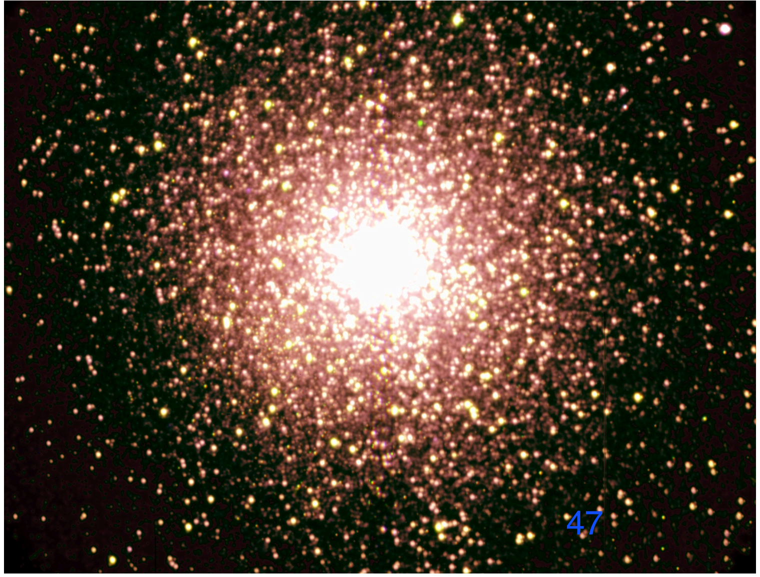
- "Observing Gravitational-wave Transient GW150914 with Minimal Assumptions"
  Published in *Phys. Rev. D* **93**, 122004 (2016) -- Abstract
- "GW150914: First Results from the Search for Binary Black Hole Coalescence with Advanced LIGO"
  Published in *Phys. Rev. D* **93**, 122003 (2016) -- Abstract
- "Properties of the Binary Black Hole Merger GW150914"
  Published in *Phys. Rev. Lett.* **116**, 241102 (2016) -- Open access article
- "The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914"
  Accepted by *Astrophys. J. Lett.*
- "Astrophysical Implications of the Binary Black-Hole Merger GW150914"
  Published in *Astrophys. J. Lett.* **818**, L22 (2016) -- Open access article
- "Tests of General Relativity with GW150914"
  Published in *Phys. Rev. Lett.* **116**, 221101 (2016) -- Abstract
- "GW150914: Implications for the Stochastic Gravitational Wave Background from Binary Black Holes"
  Published in *Phys. Rev. Lett.* **116**, 131102 (2016) -- Abstract
- "Calibration of the Advanced LIGO Detectors for the Discovery of the Binary Black-hole Merger GW150914"
  Submitted to *Phys. Rev. Lett.*
- "Characterization of Transient Noise in Advanced LIGO Relevant to Gravitational Wave Signal GW150914"
  Published in *CQG* **33**, 134001 (2016) -- Open access article
- "High-energy Neutrino Follow-up Search of Gravitational Wave Event GW150914 with ANTARES and IceCube"
  Published in *Phys. Rev. D* **93**, 122010 (2016) -- Abstract
- "GW150914: The Advanced LIGO Detectors in the Era of First Discoveries"
  Published in *Phys. Rev. Lett.* **116**, 131103 (2016) -- Abstract
- "Localization and Broadband Follow-up of the Gravitational-wave Transient GW150914"
  Published in *Astrophys. J. Lett.* **826**, L13 (2016) -- Open access article

Data Release

GW150914 Data Release

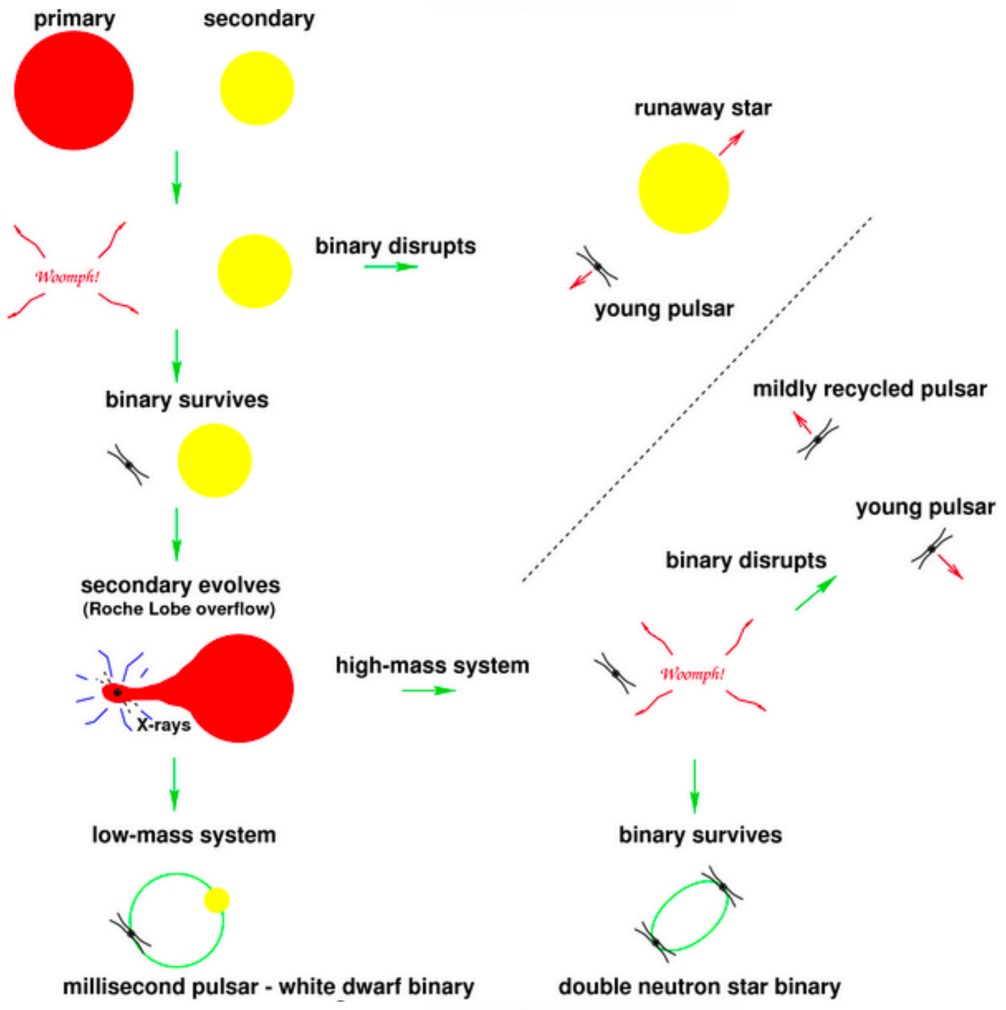
Formation mechanisms

- How do massive binary black hole systems form?
- Common envelope evolution of isolated binaries: two massive stars survive successive CCSNe
- Dynamical capture of isolated black holes in N-body exchange interactions.
- Even the most massive stars (60-100 $M_\odot$) can only produce black holes with mass > 20 $M_\odot$ only in low-metallicity environments ($\sim 0.1\ Z_\odot$).
- https://dcc.ligo.org/LIGO-P1500262/public/main



Formation channels

Isolated binary



Dynamical formation

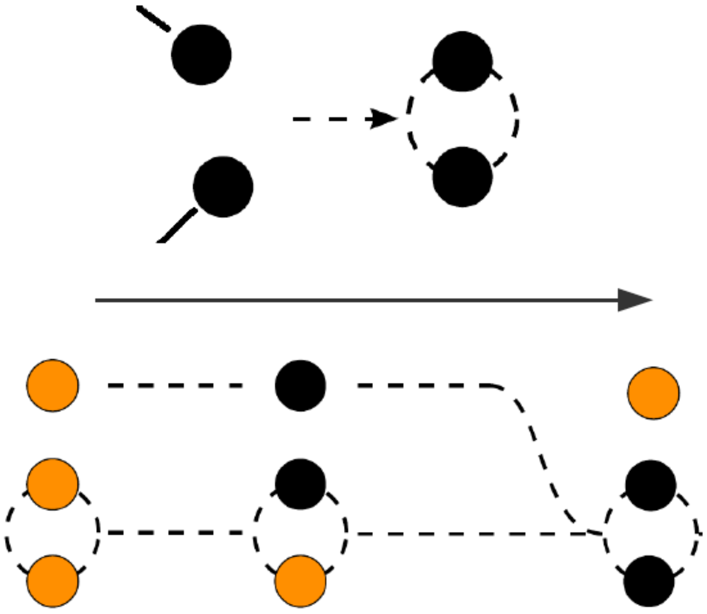
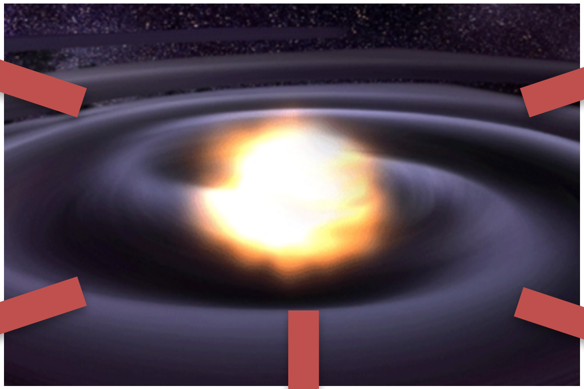


Fig. after Ziosi

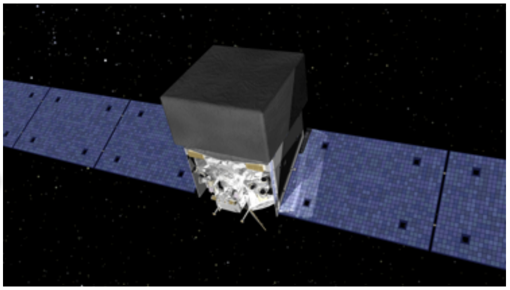
Globular/young clusters/gal. nuclei

Multi-messenger Astronomy with Gravitational Waves

astrophysical fireball

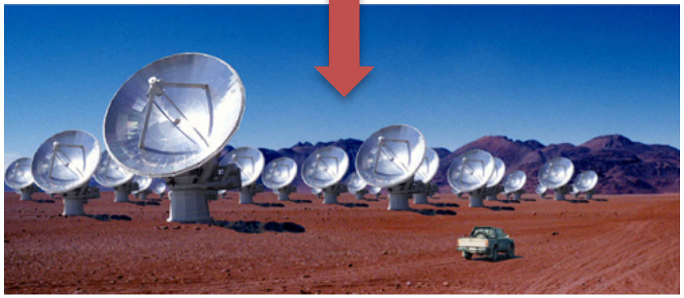


GWs

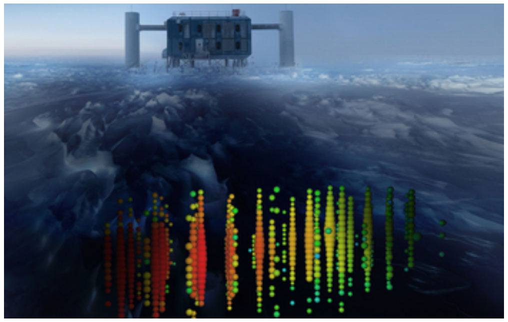


X-rays, γ rays

optical



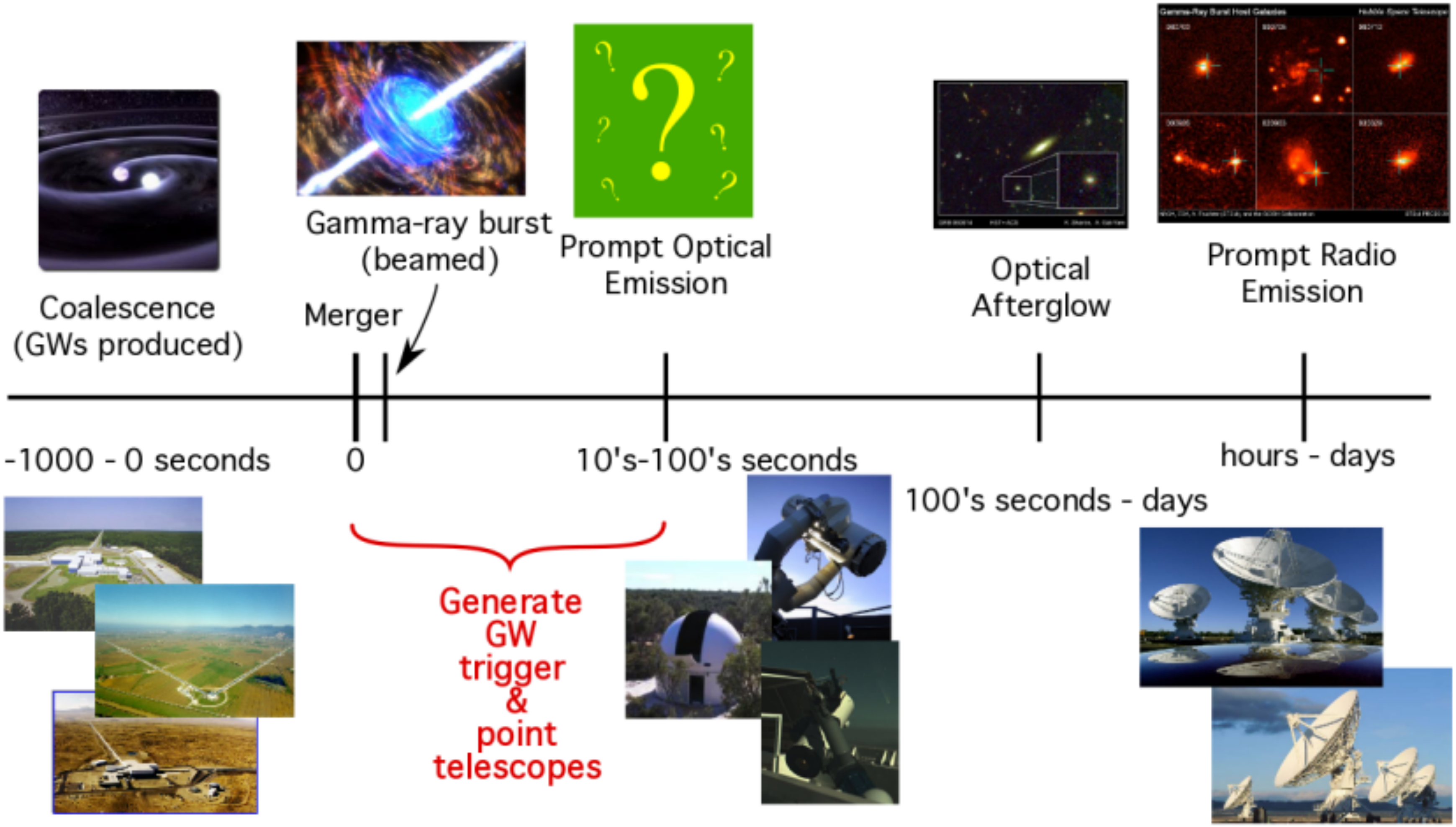
radio



neutrinos

Low-latency identification of transients for rapid (< ~100s) followup

EM counterparts to GW sources (if any) are short-lived and faint



Coalescence (GWs produced)

Gamma-ray burst (beamed)

Merger

Prompt Optical Emission

Optical Afterglow

Prompt Radio Emission

-1000 - 0 seconds

0

10's-100's seconds

100's seconds - days

hours - days

Generate GW trigger & point telescopes

EM- and neutrino follow-up

- Low-latency alerts go out to MOU partners via the GRB Coordinates Network (GCN), notices & circulars (machine-readable).
- These will be public (not just “MOU partners”, sworn to secrecy), hopefully in the near future!
- Fastest we’ve ever accomplished is ~30 min, but could do < 2 minutes if we could only agree…
- Literally dozens of (mostly wide-field, survey) optical and radio telescopes; most notably, Palomar Transient Factory iPTF -> ZTF, Owens Valley Long Wavelength Array (LWA)
- Also notable: PanSTARRS, DES, ASKAP, MWA, ...
- Space-based x-ray and gamma-ray telescopes: Swift, Fermi, INTEGRAL, Interplanetary Network (IPN)
- Neutrino detectors: Ice-Cube, ANTARES, (Super-K)