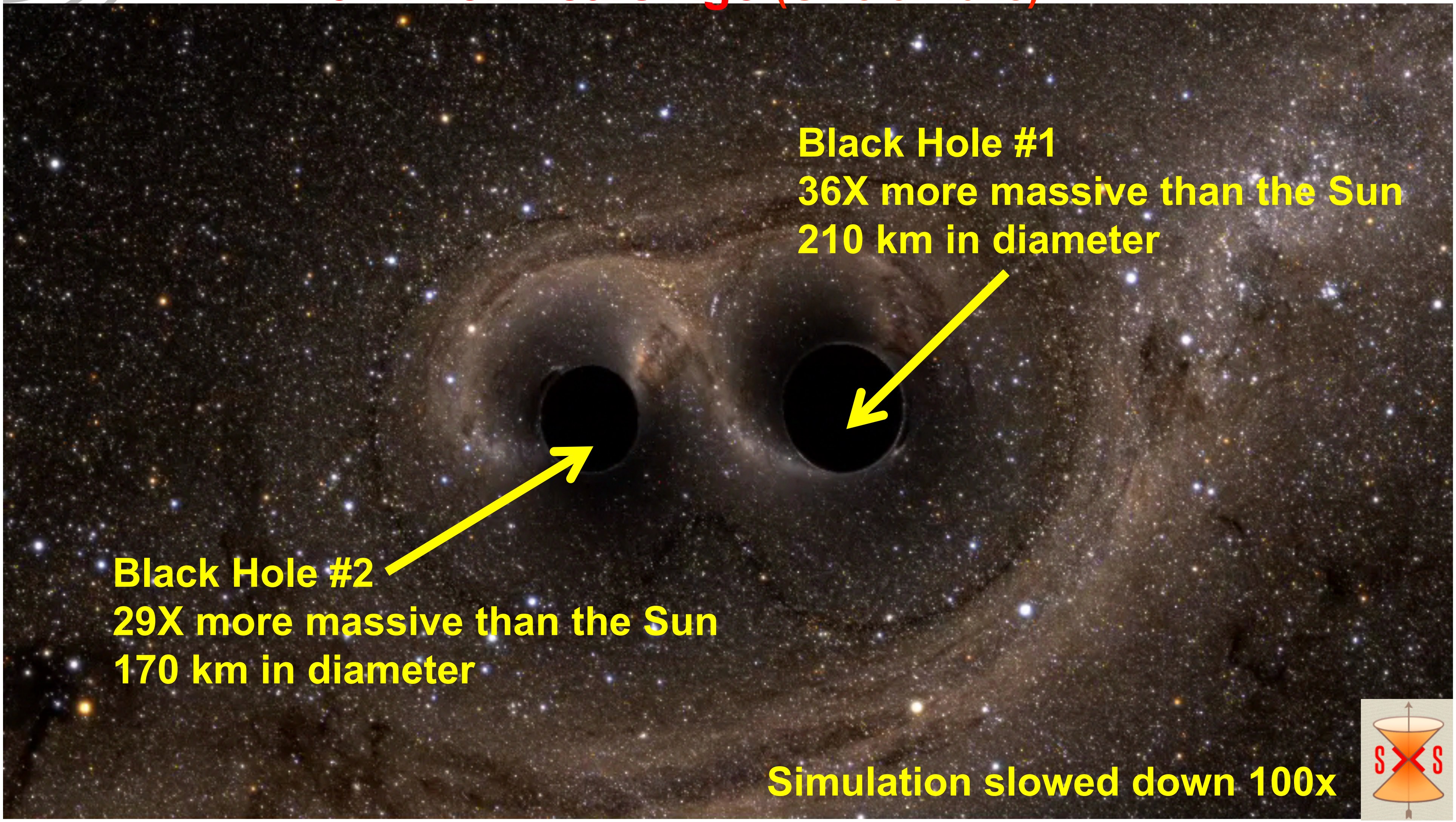
The Ballet of Binary Black Holes 1.3 Billion Years Ago (Give or Take)



Numerical relativity (solution to $G_{\mu\nu} = 0$) simulation

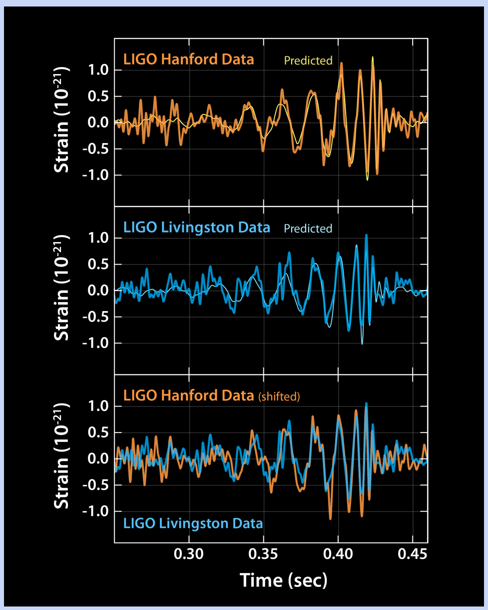
(SXS Collaboration, http://www.black-holes.org/)

Andy Bohn, François Hébert, and William Throwe, SXS

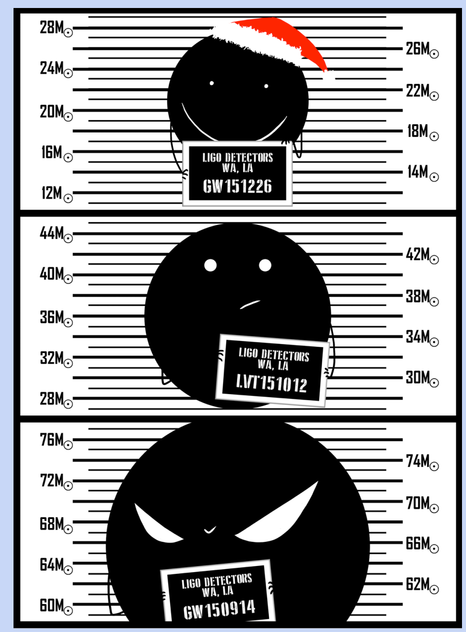
Gravitational Waves Observed by LIGO: Astrophysical implications

Alan J Weinstein
LIGO Laboratory, Caltech
LIGO Scientific Collaboration

Caltech Astronomy Colloquium
Feb 8, 2017

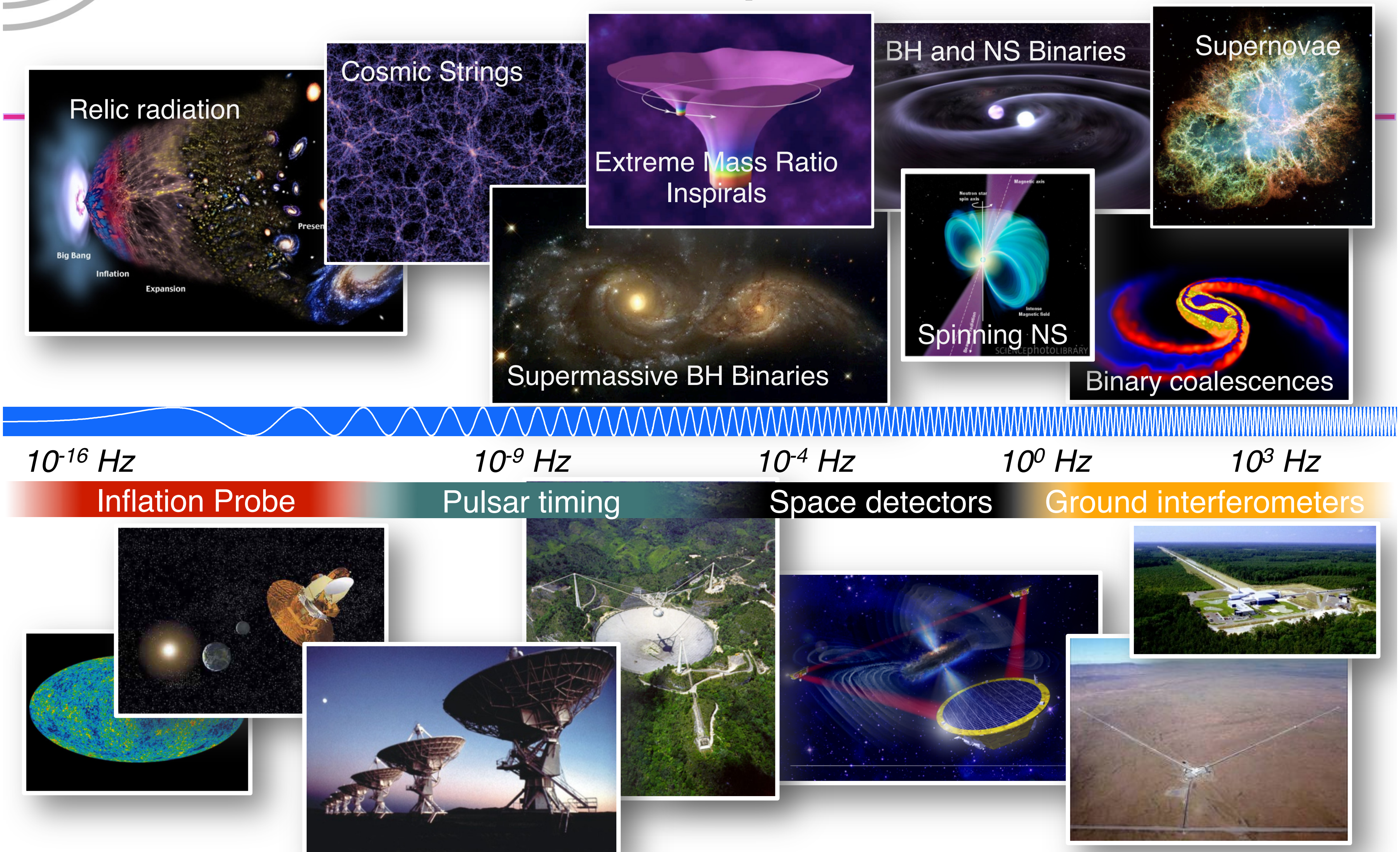


LIGO Laboratory, Caltech



N. Kijbunchoo, LIGO

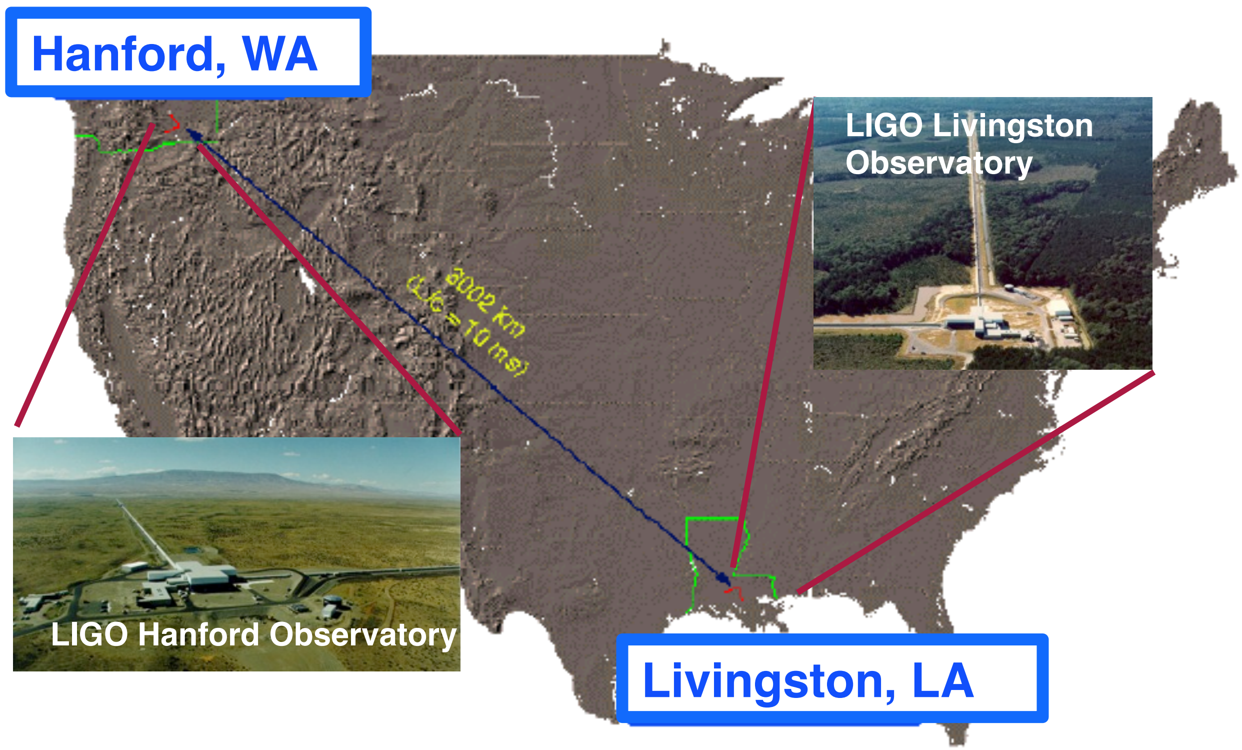
The GW Spectrum



The Laser Interferometer Gravitational Wave Observatory

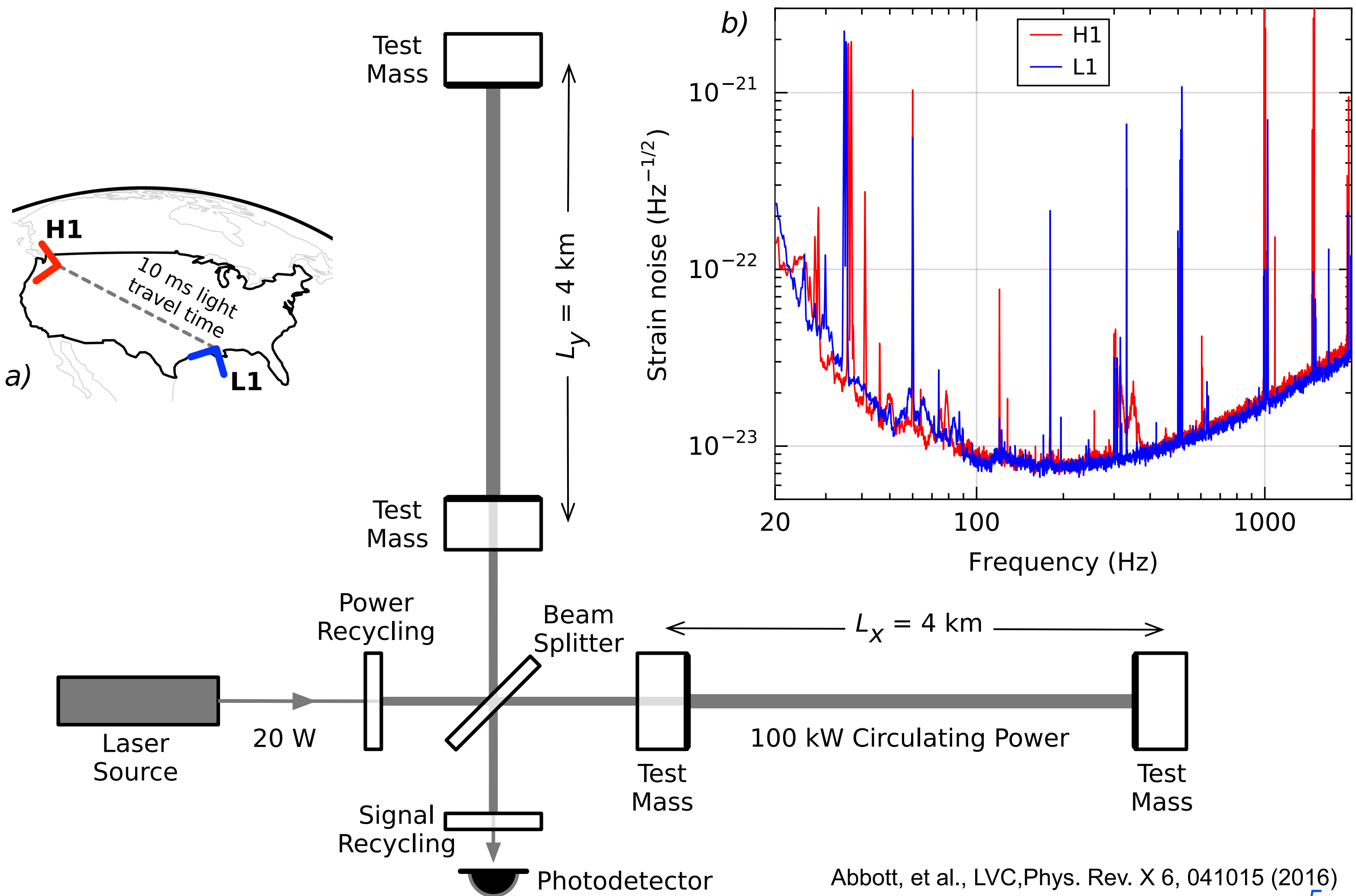
LIGO Laboratory:
180 staff located at Caltech, MIT, Hanford, Livingston

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



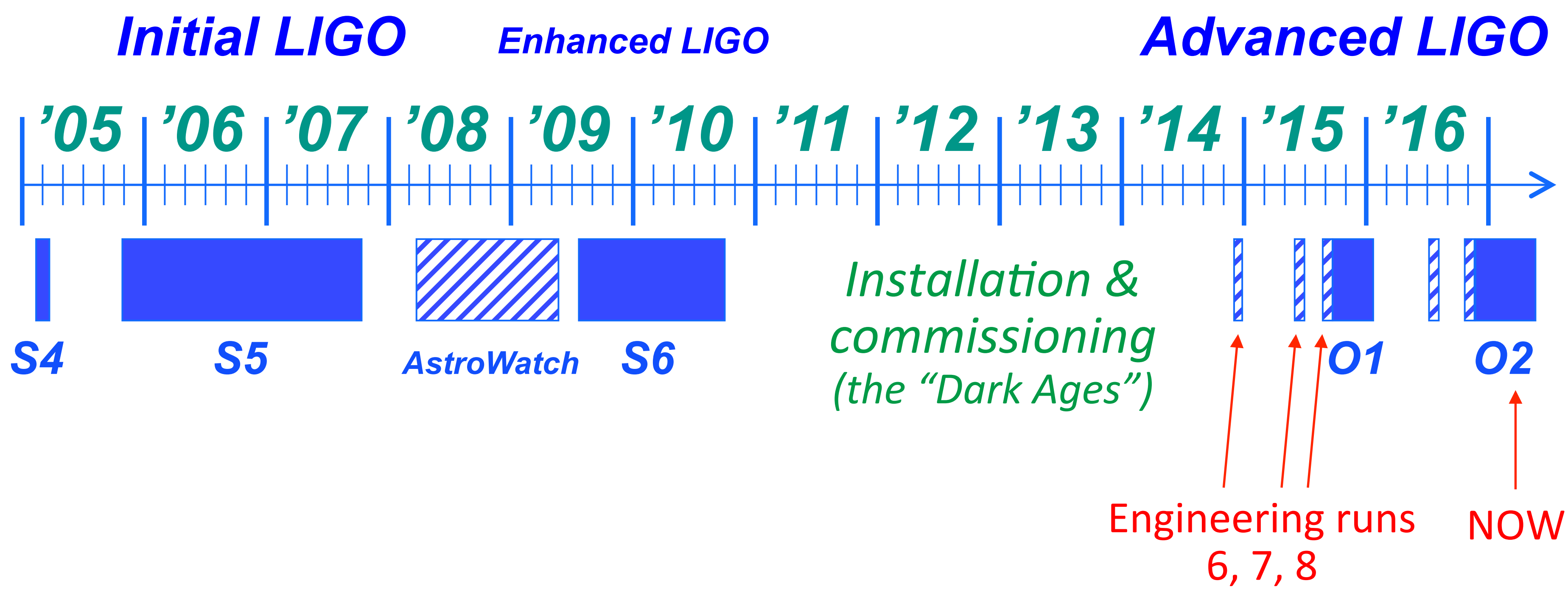
LIGO Laboratory is operated by Caltech and MIT, for the NSF

The Advanced LIGO detectors

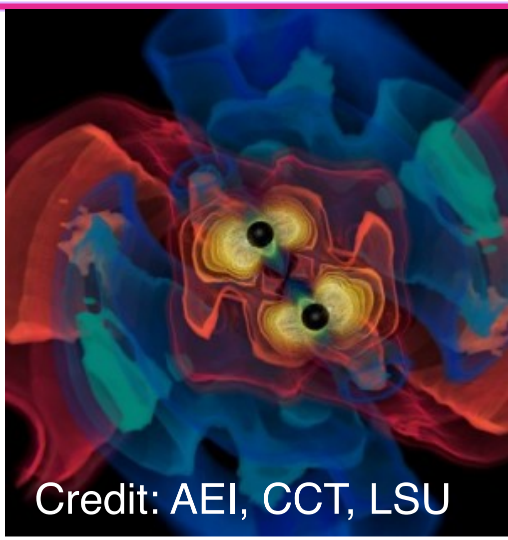


Abbott, et al., LVC,Phys. Rev. X 6, 041015 (2016)

Initial LIGO → Enhanced LIGO → Advanced LIGO



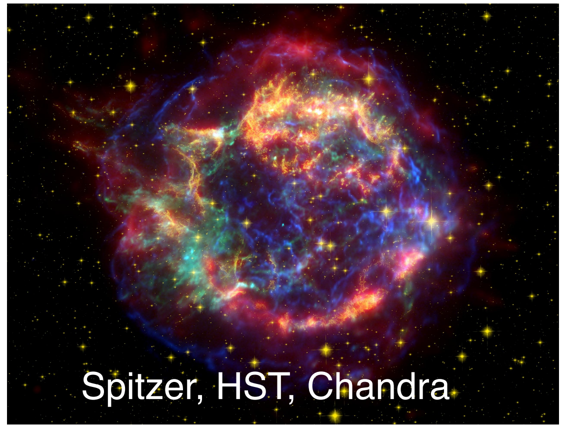
GW sources for ground-based detectors: The most energetic processes in the universe



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

- Strong emitters, well-modeled,

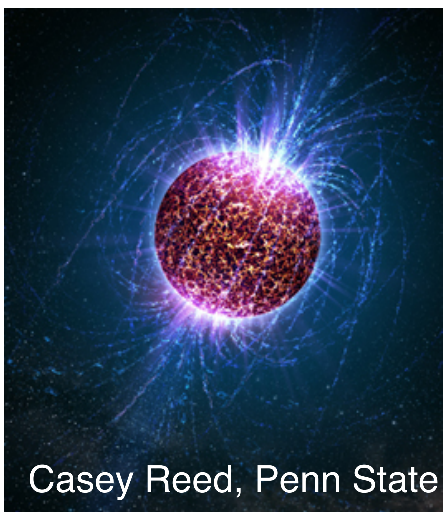
- (effectively) transient



Asymmetric Core Collapse Supernovae

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

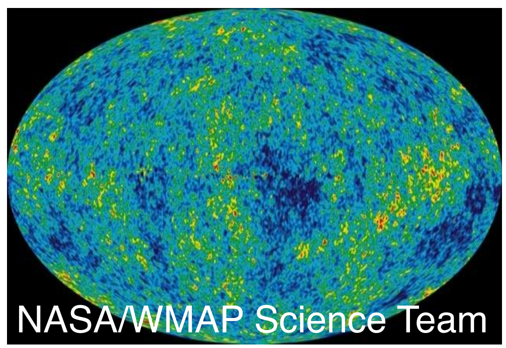
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class



Spinning neutron stars

- (effectively) monotonic waveform

- Long duration

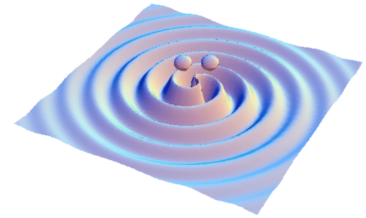


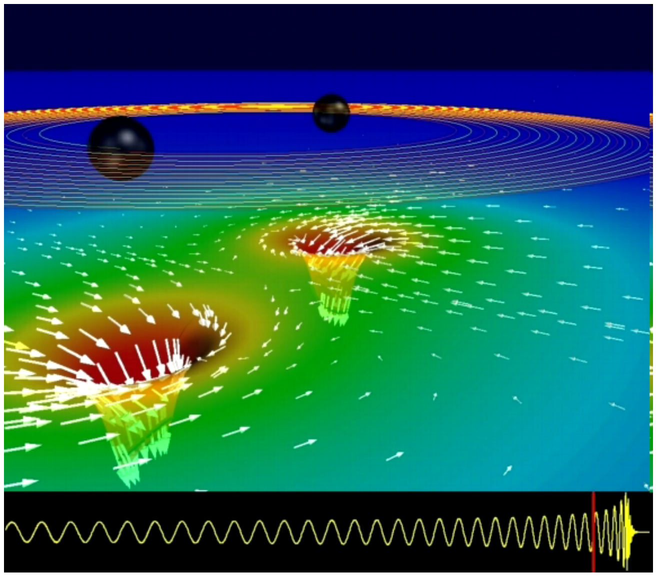
Cosmic Gravitational-wave Background

- Residue of the Big Bang, long duration

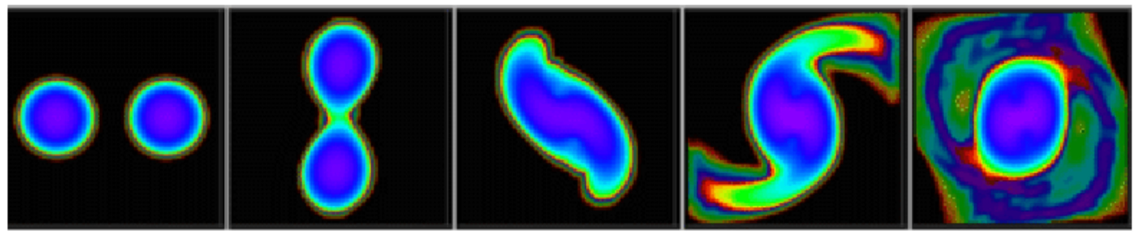
- Long duration, stochastic background

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





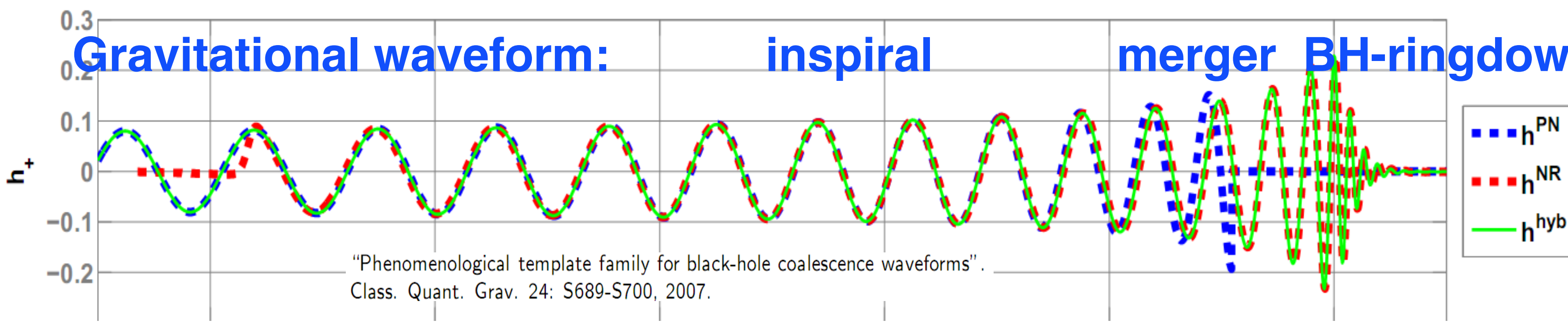
- Neutron star – neutron star (Centrella et al.)



Tidal disruption of neutron star

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

Gravitational waveform: inspiral merger BH-ringdown



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

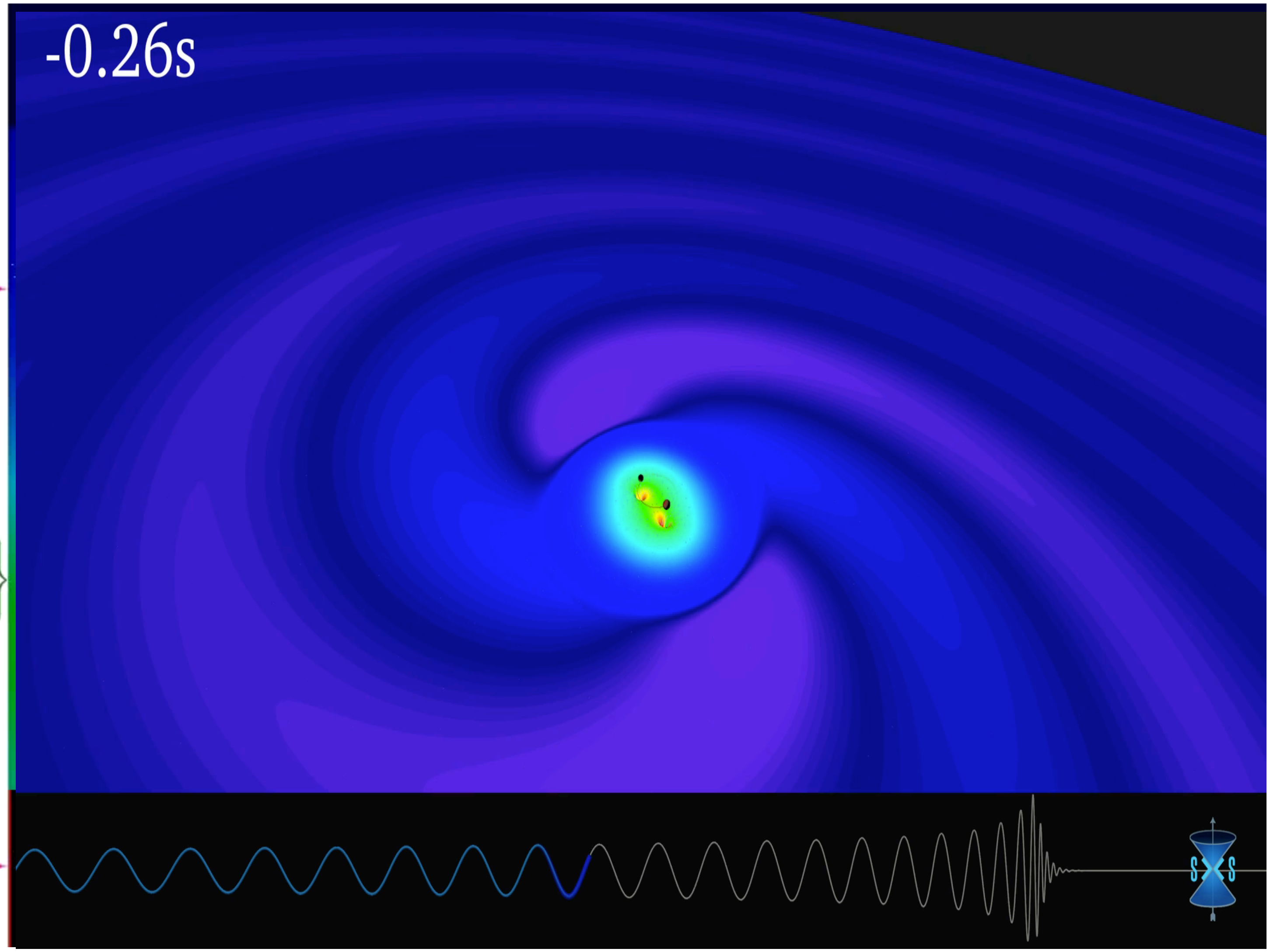
Binary black hole inspiral, merger, ringdown

Binary Black Hole Evolution:
Caltech/Cornell Computer Simulation

Top: 3D view of Black Holes and Orbital Trajectory

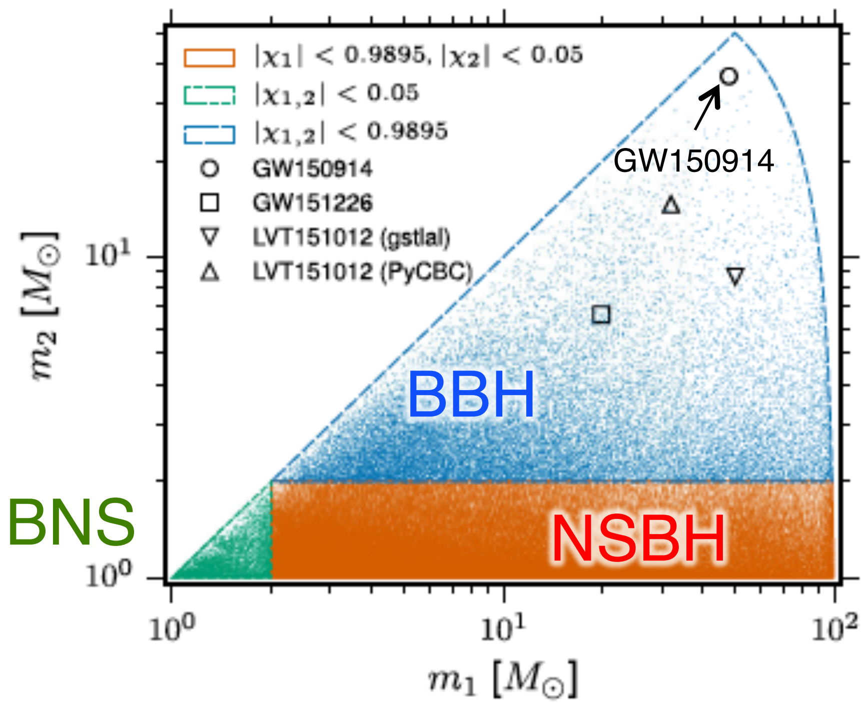
Middle: Spacetime curvature:
Depth: Curvature of space
Colors: Rate of flow of time
Arrows: Velocity of flow of space

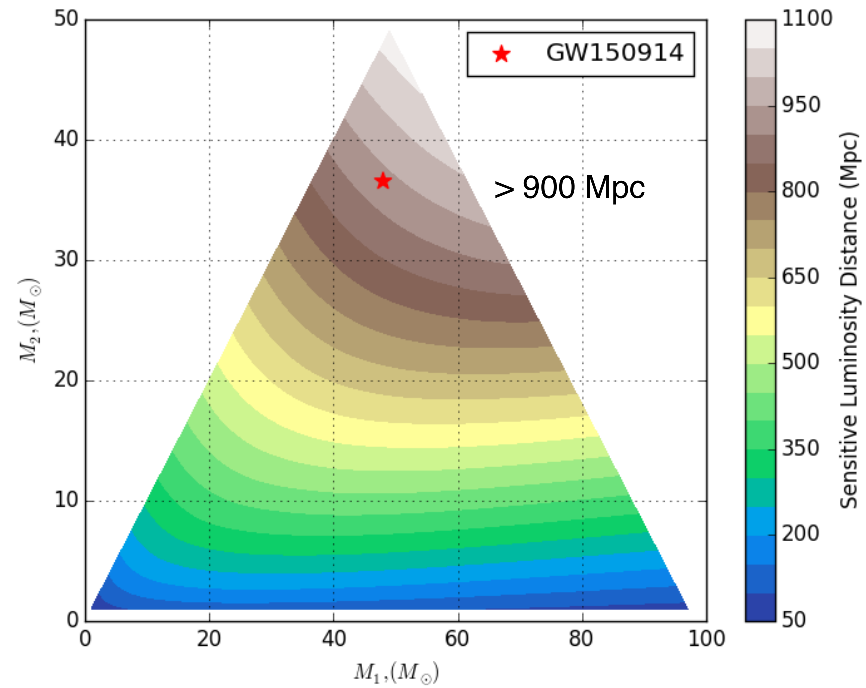
Bottom: Waveform
(red line shows current time)



http://www.black-holes.org

Template-based searches



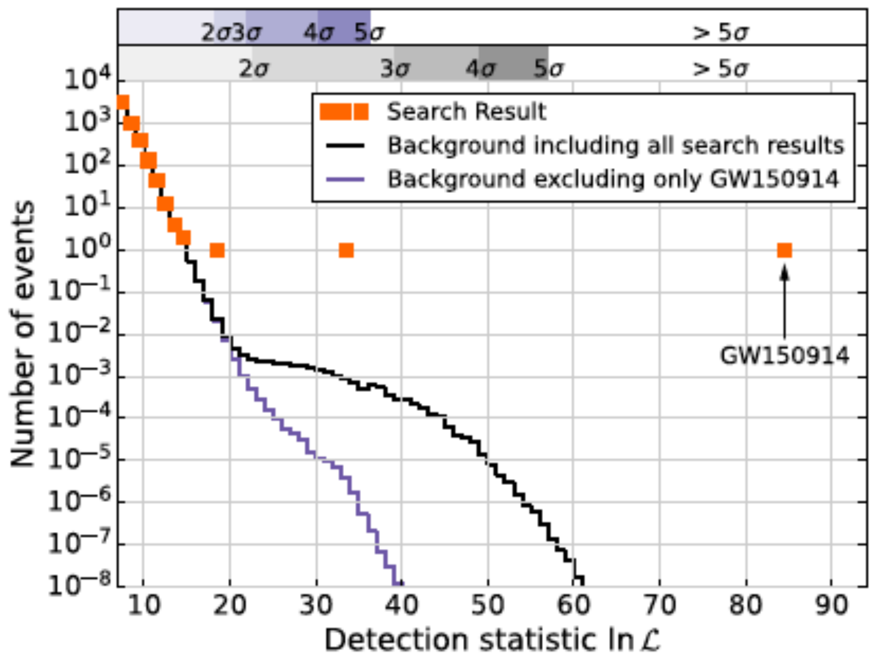


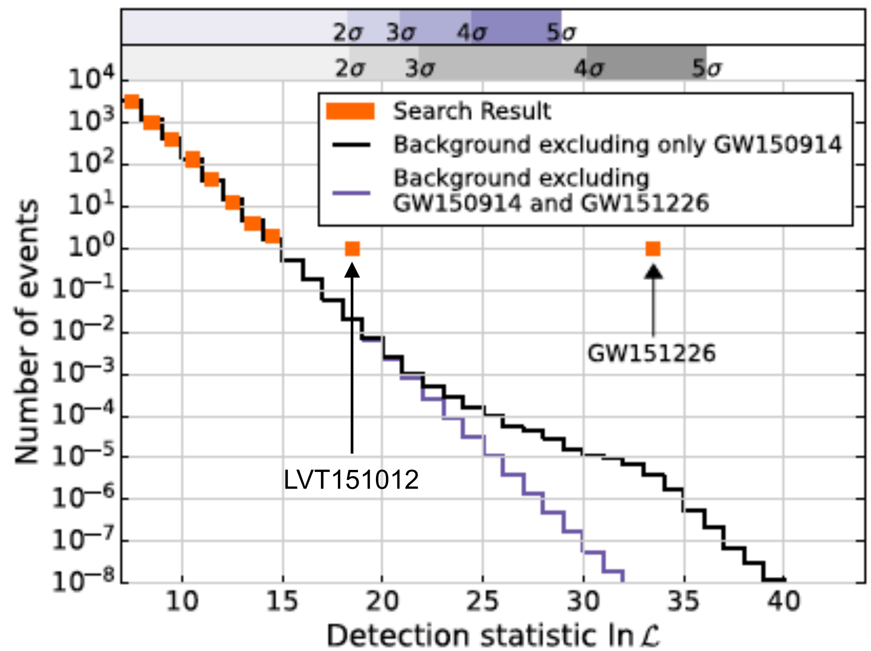
Masses and (aligned) spins
Templates spaced for < 3% loss of SNR: 250K templates.

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

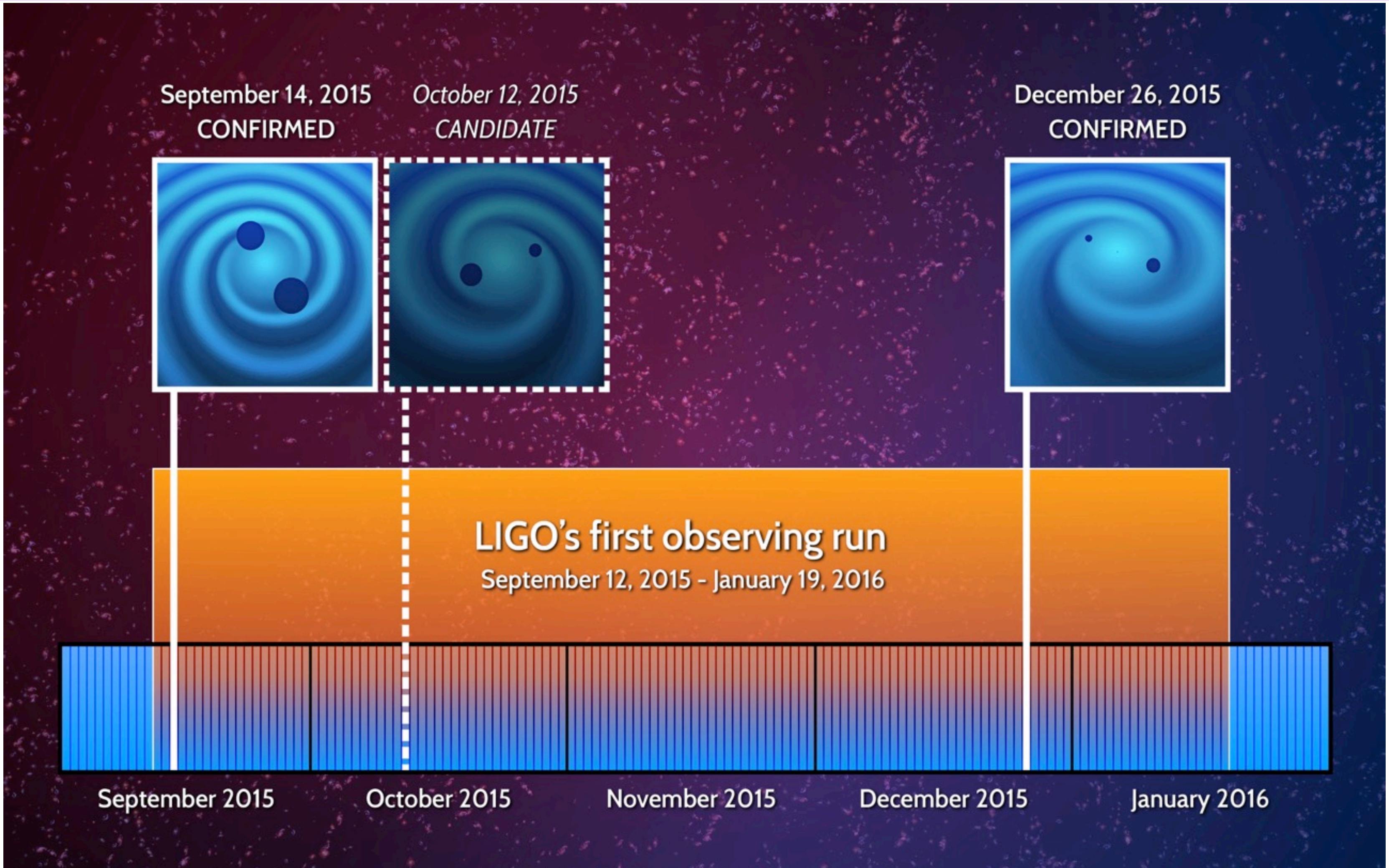




Three events above the estimated "background" from accidental coincidence of noise fluctuation triggers. Two have high significance (> 5σ).

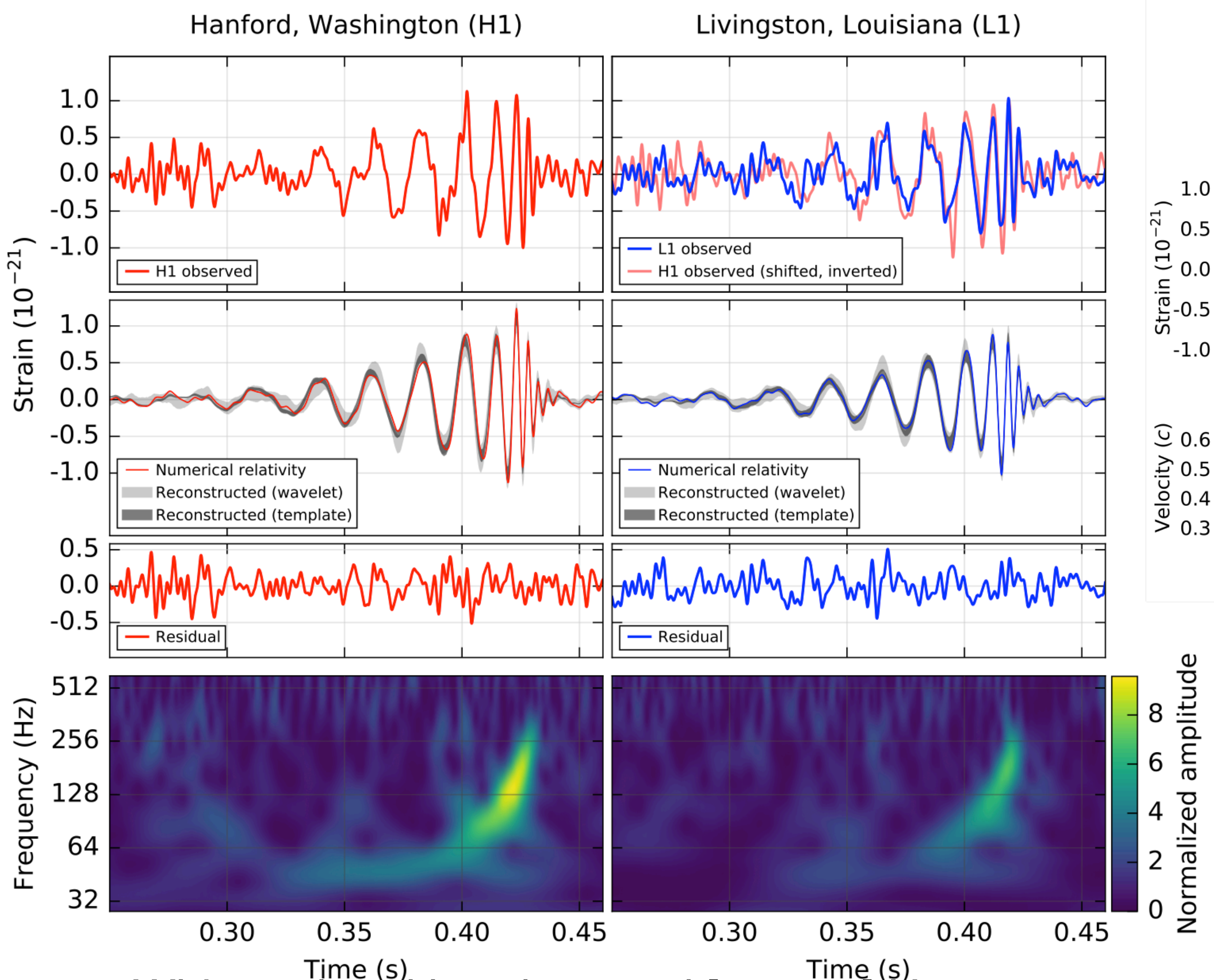
Abbott, et al., LVC, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", Phys. Rev. X 6, 041015 (2016)

Search results
Advanced LIGO Observing Run O1

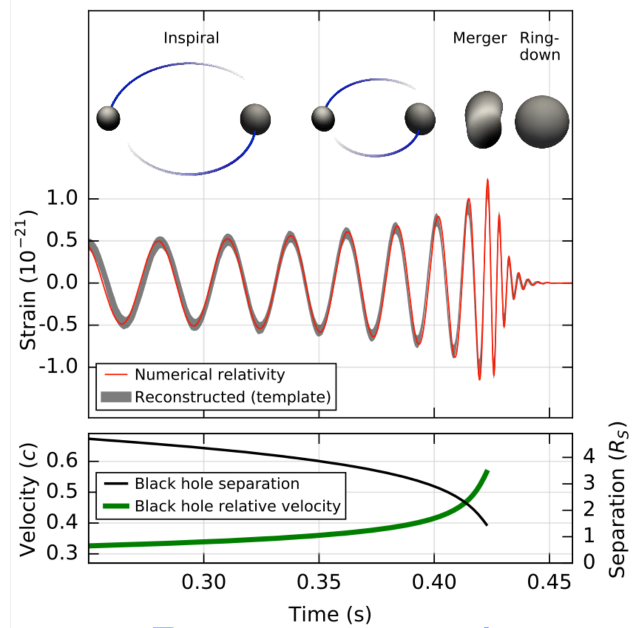


GW150914

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



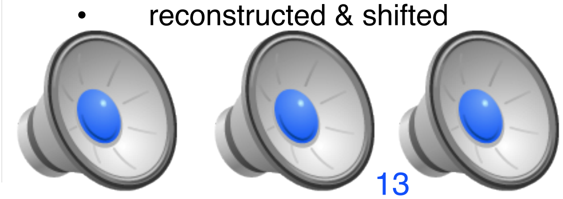
Whitened and band-passed [40-300] Hz



Reconstructed (no whitening)

Audio:

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



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 simultaneousl … al sweeps upwards in
frequency from 35 to 250 … natches 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 … rger.

DOI: 10.1103/PhysRevLett.1

Detection Papers

papers.ligo.org

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

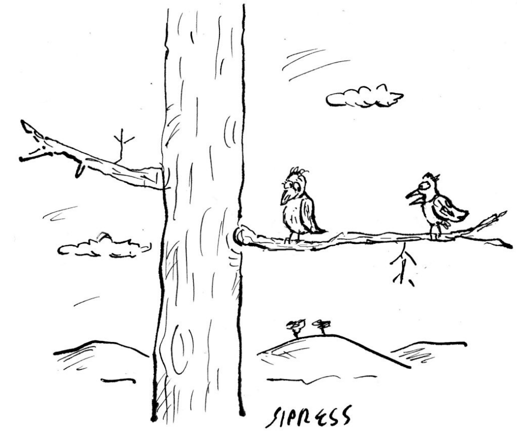
Related papers

- "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

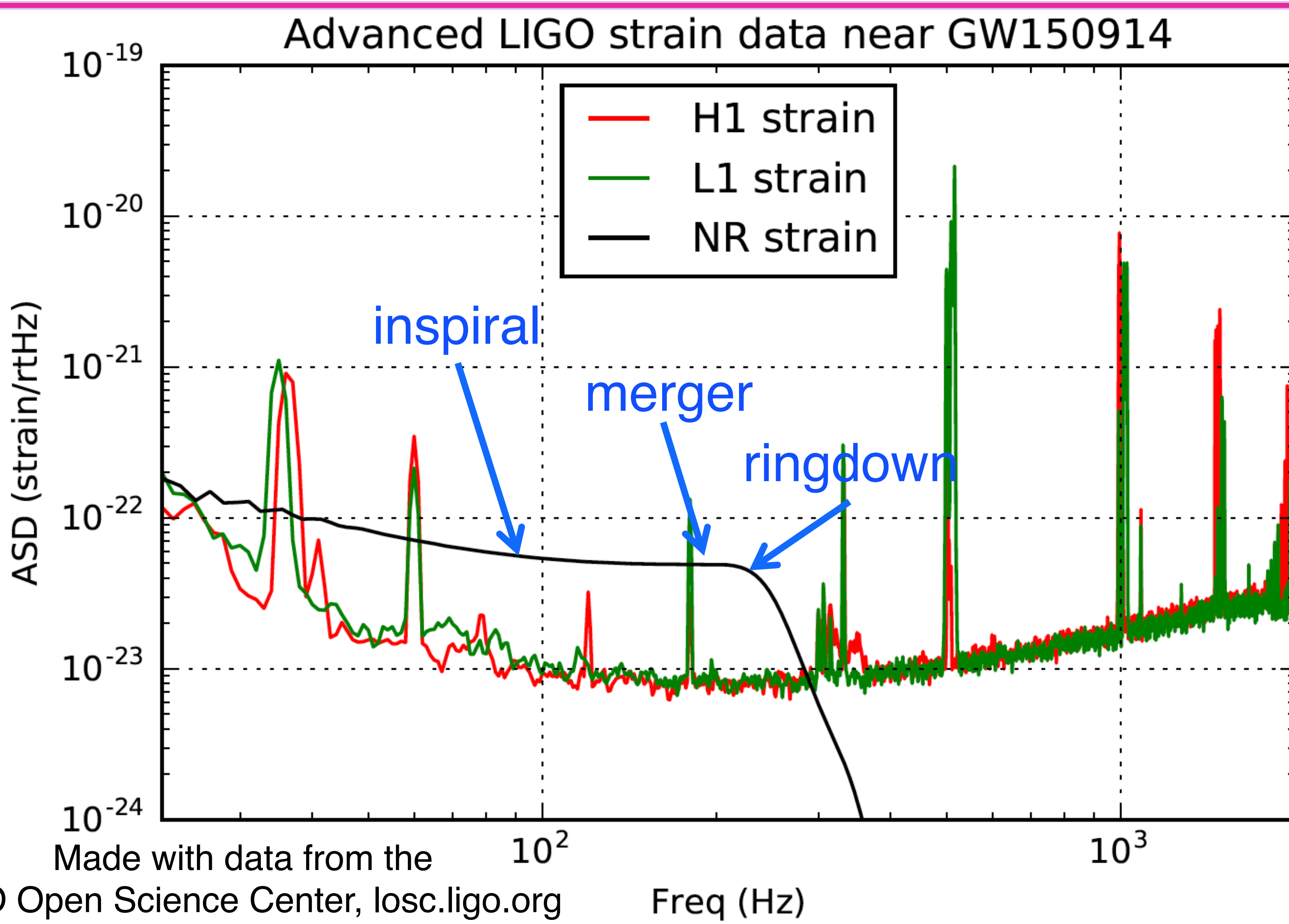
GW150914 Data Release

After it hit our detectors … it hit the media



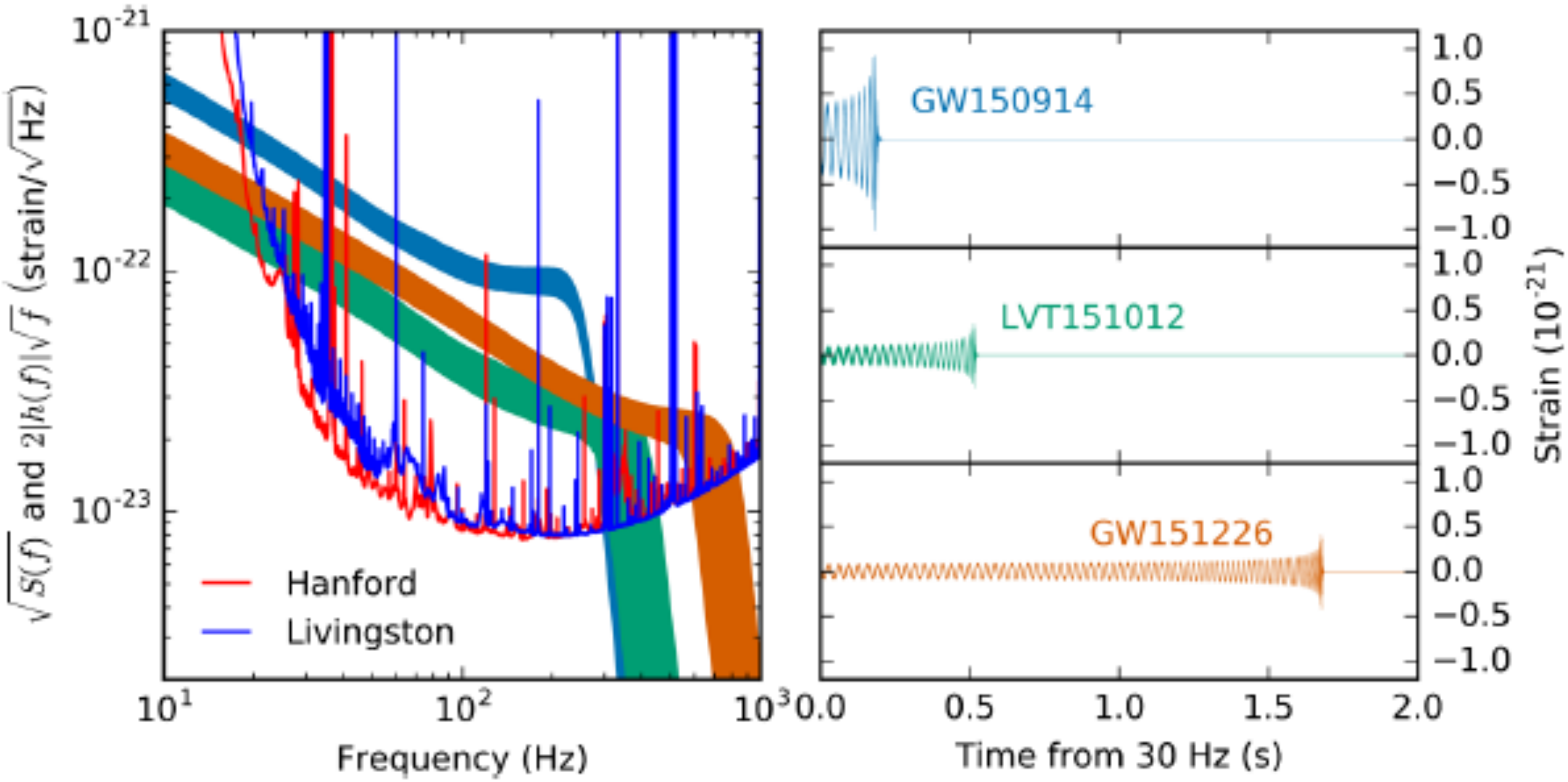
"Was that you I heard just now, or was it two black holes colliding?"
The New Yorker

GW150914 in the frequency domain



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

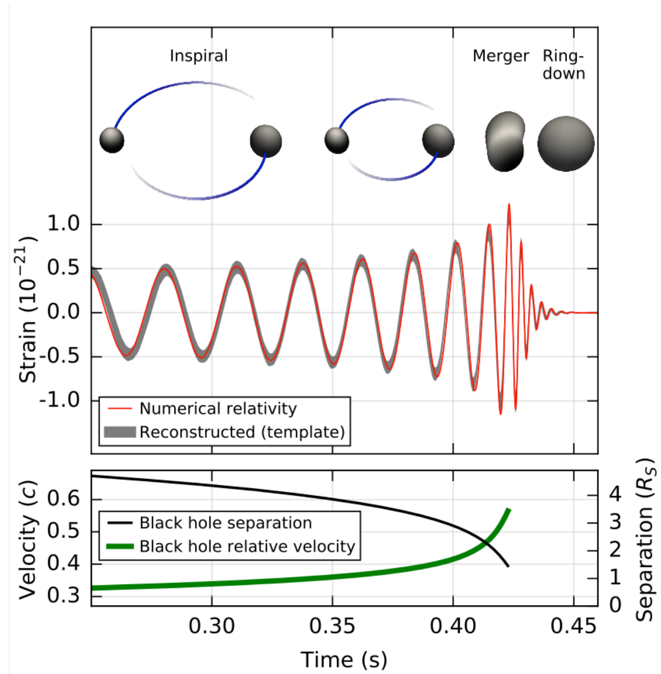
Three BBH events, compared



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

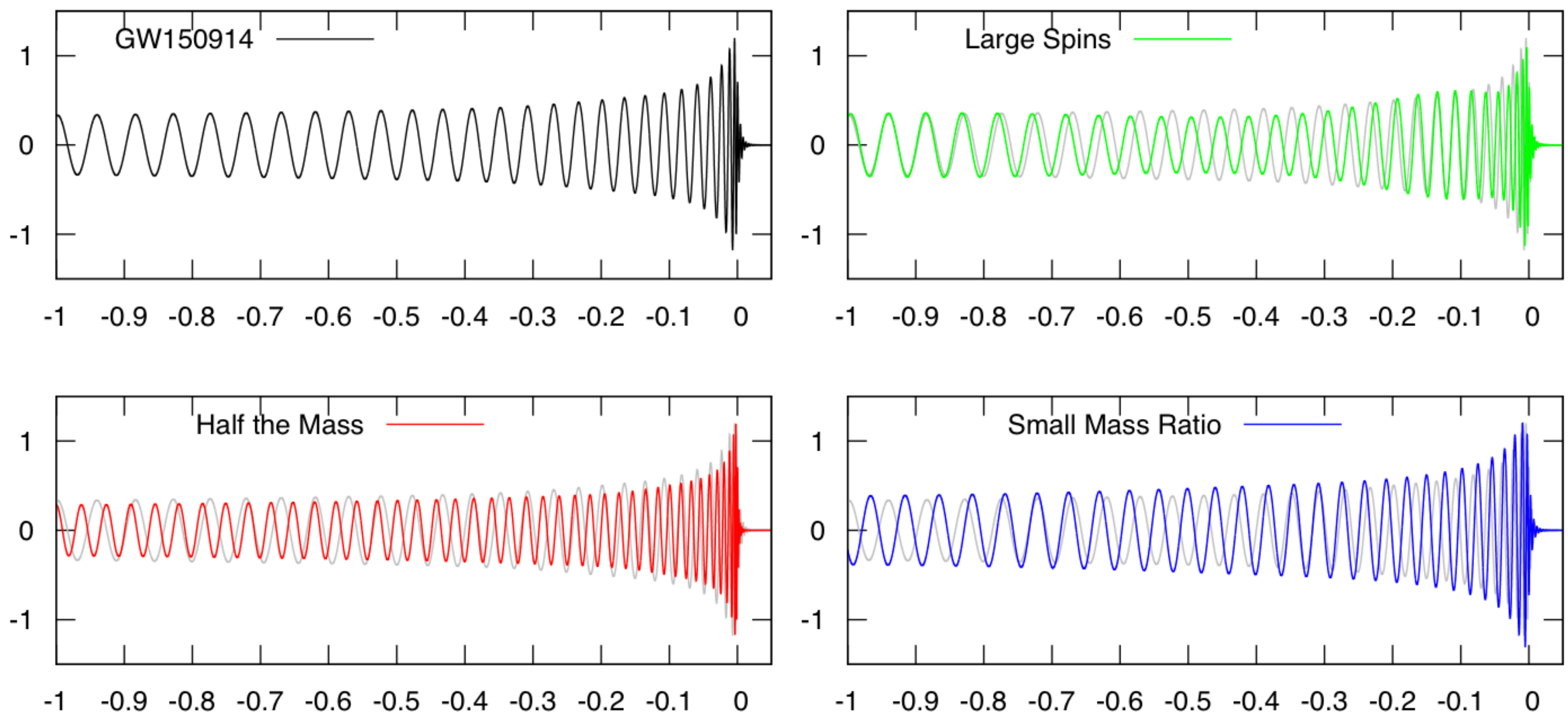


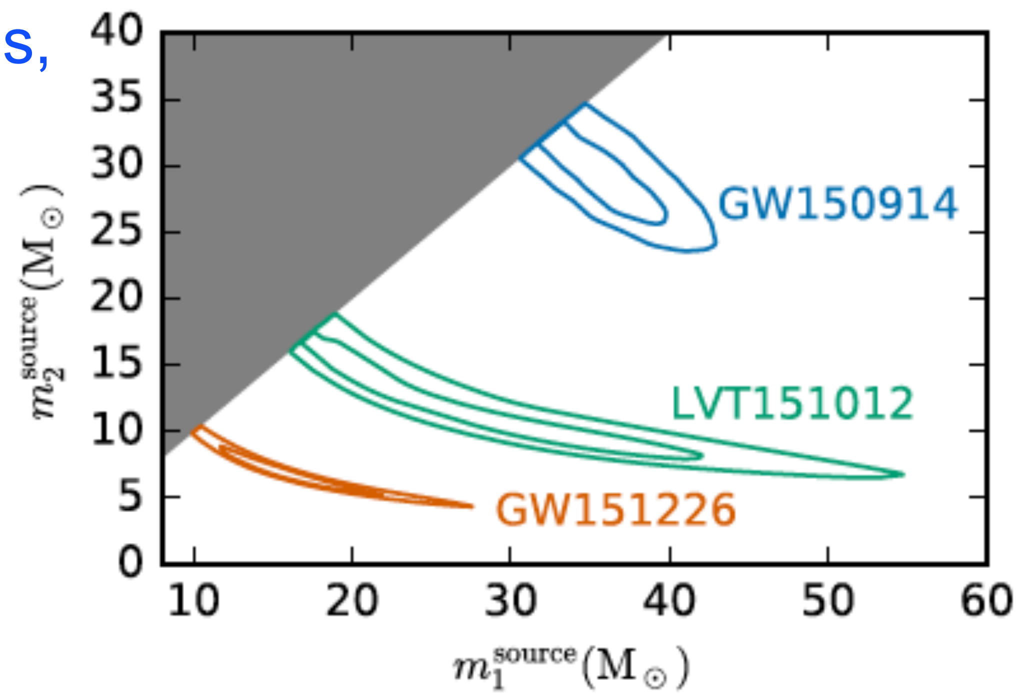
Illustration by N. Cornish and T. Littenberg

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”

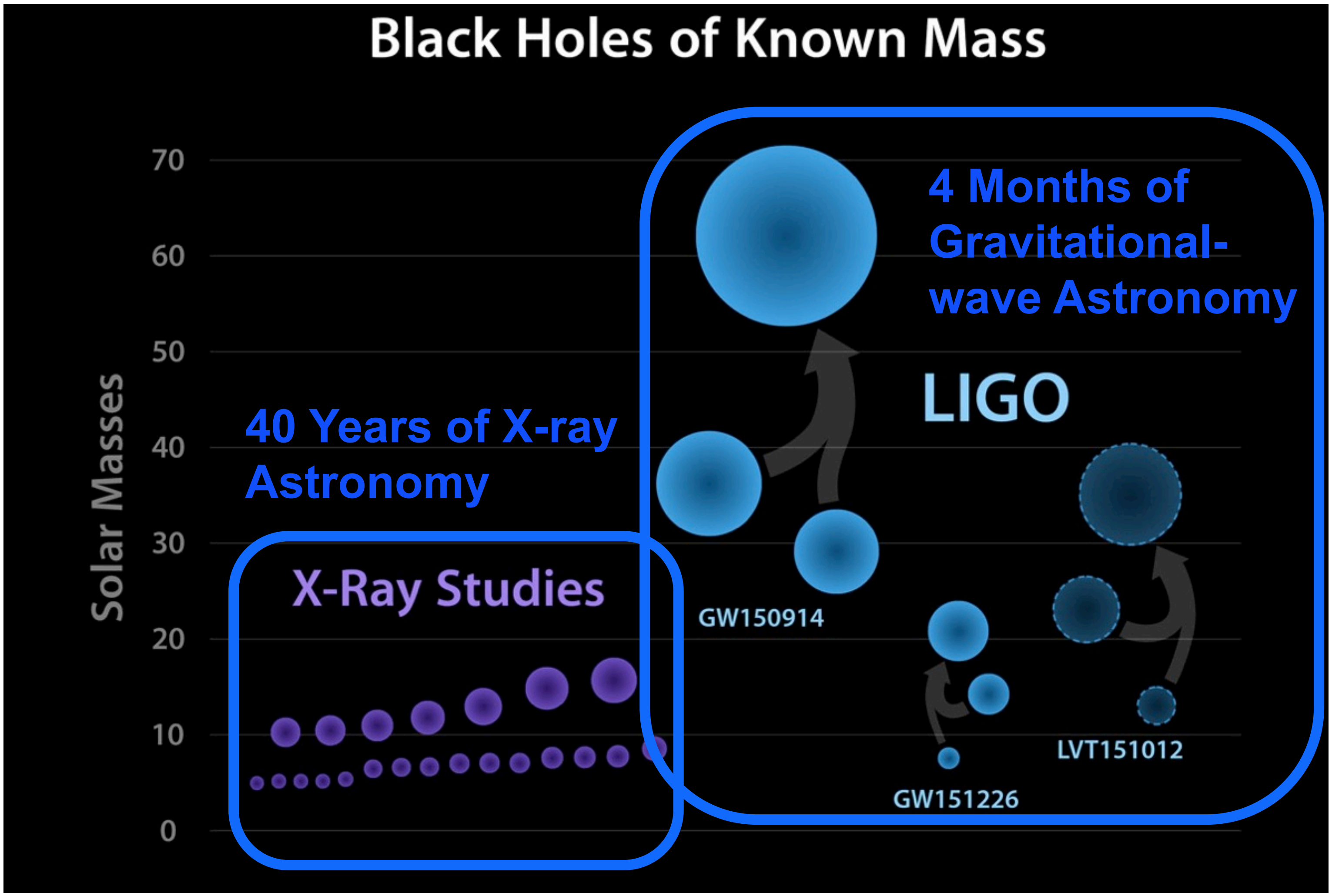
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$



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

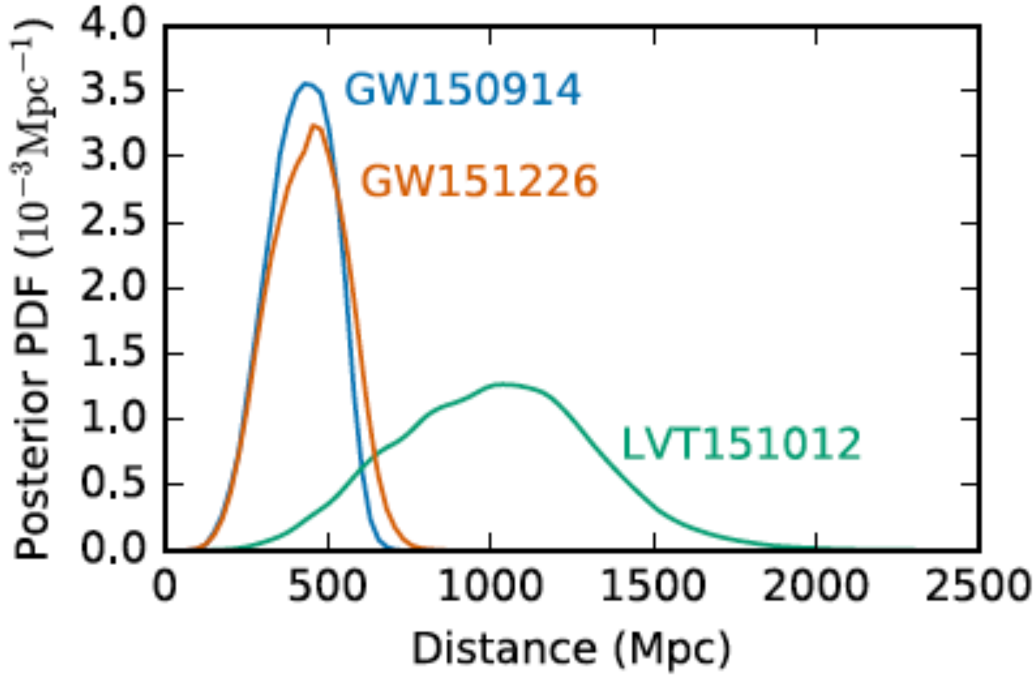


Three BBH events, distances

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.

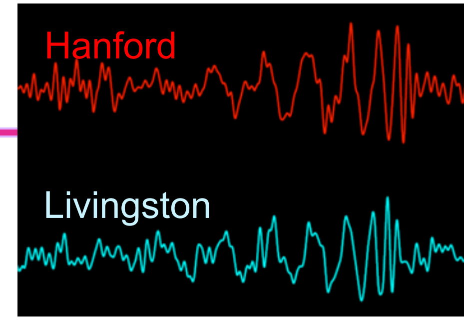


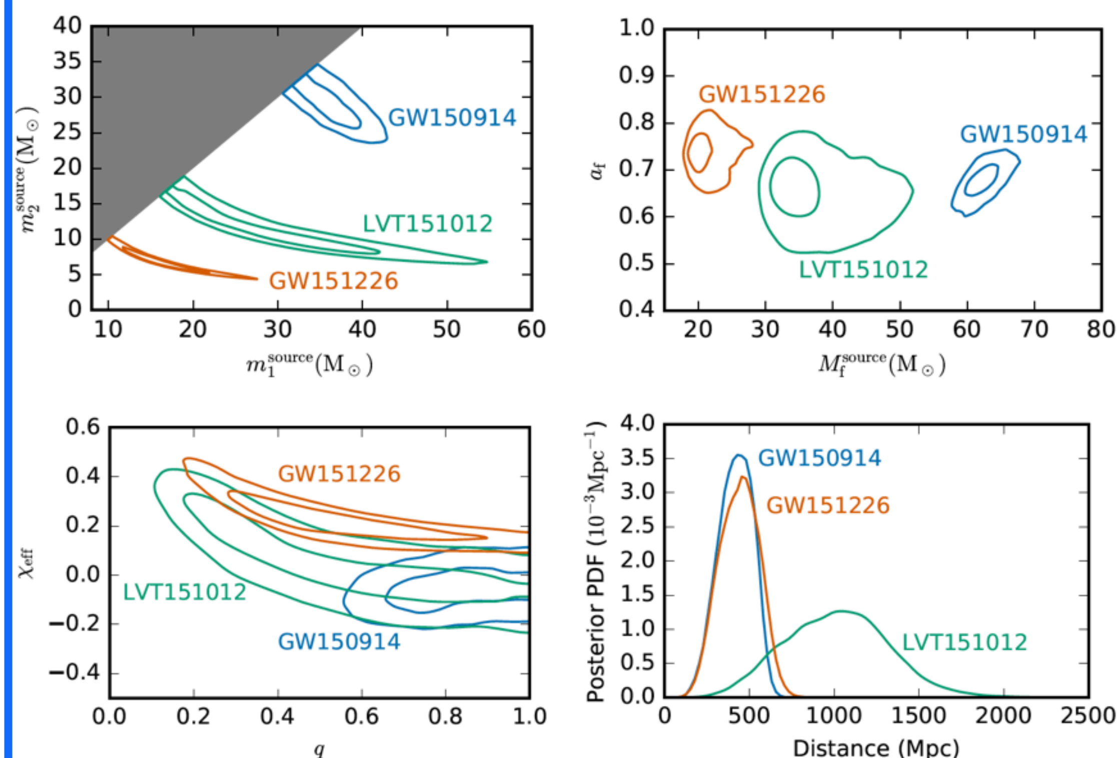
Our two loud events are far away!
(400 Mpc ~ 1.3 Gly) – merged 1.3 By ago!

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 FAR/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 $m_1^{\rm source}/{\rm M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\rm source}/{\rm M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\rm source}/{\rm M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin $\chi_{\rm eff}$	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin $a_{\rm f}$	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	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 $\Delta\Omega/{\rm deg}^2$	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:

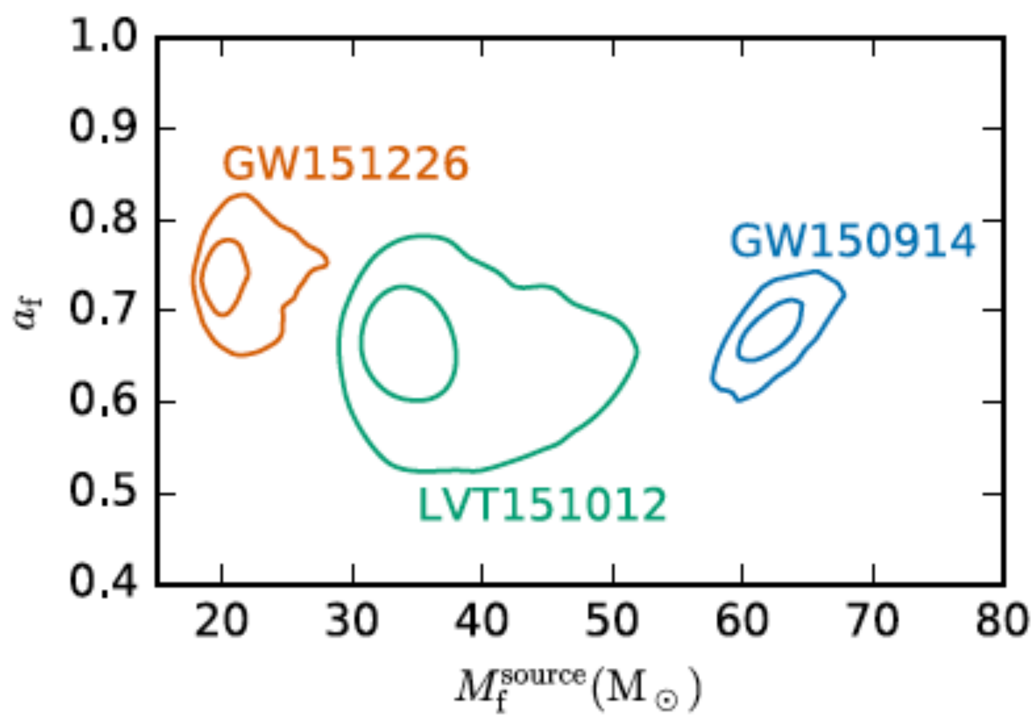
$$E_{\rm rad} = 3.0^{+0.5}_{-0.4}\,{\rm M}_{\odot}c^2$$
$$\ell_{\rm peak} = 3.6^{+0.5}_{-0.4} \times 10^{56}{\rm erg/s}$$

- 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:

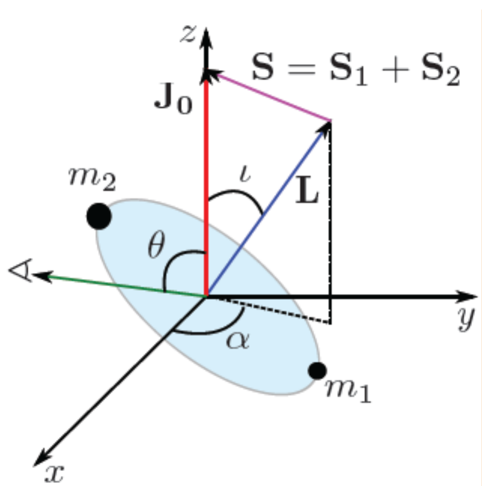
$$E_{\rm rad} = 1.5^{+0.3}_{-0.4}\,{\rm M}_{\odot}c^2$$
$$\ell_{\rm peak} = 3.1^{+0.8}_{-1.8} \times 10^{56}{\rm erg/s}$$



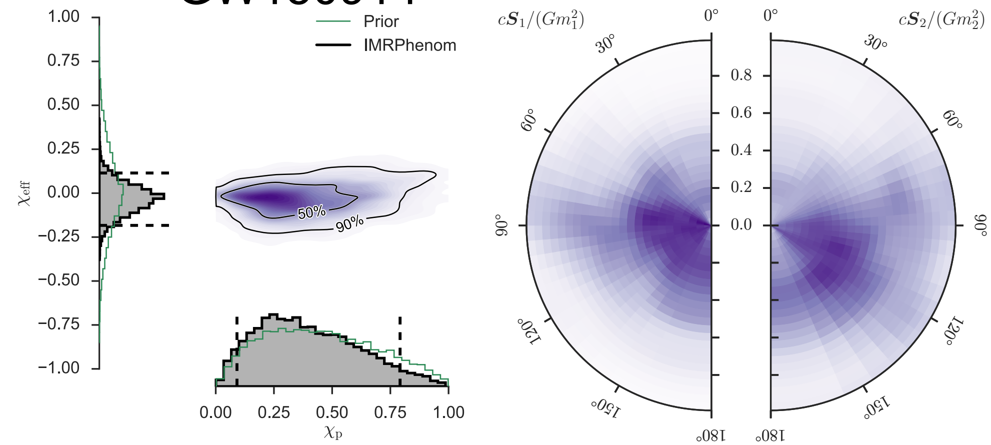
- GW150914: $E_{GW} \approx 3\,M_{\odot}c^2$, or ~4.5% of the total mass-energy of the system.
- Roughly 10^{80} gravitons.
- Peak luminosity $L_{GW} \sim 3.6\times10^{54}$ *erg/s*, briefly outshining the EM energy output of all the stars in the observable universe (by a factor > 20).

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

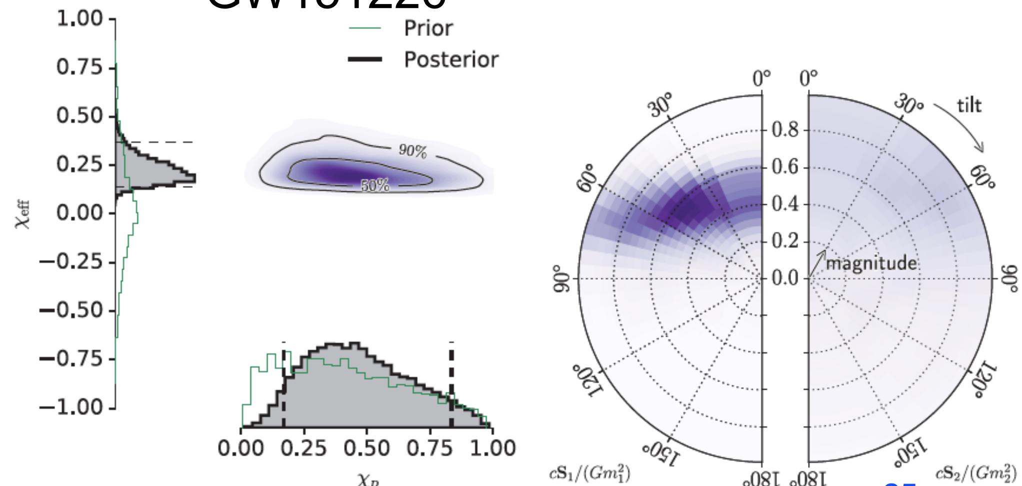
- The component BH spins measurably modulate the inspiral frequency evolution.
- Spin-orbit couplings cause the orbital plane to precess, producing amplitude modulation at the detectors.
- Parameterize with aligned spin χ_{eff} and "precessing" spin χ_P



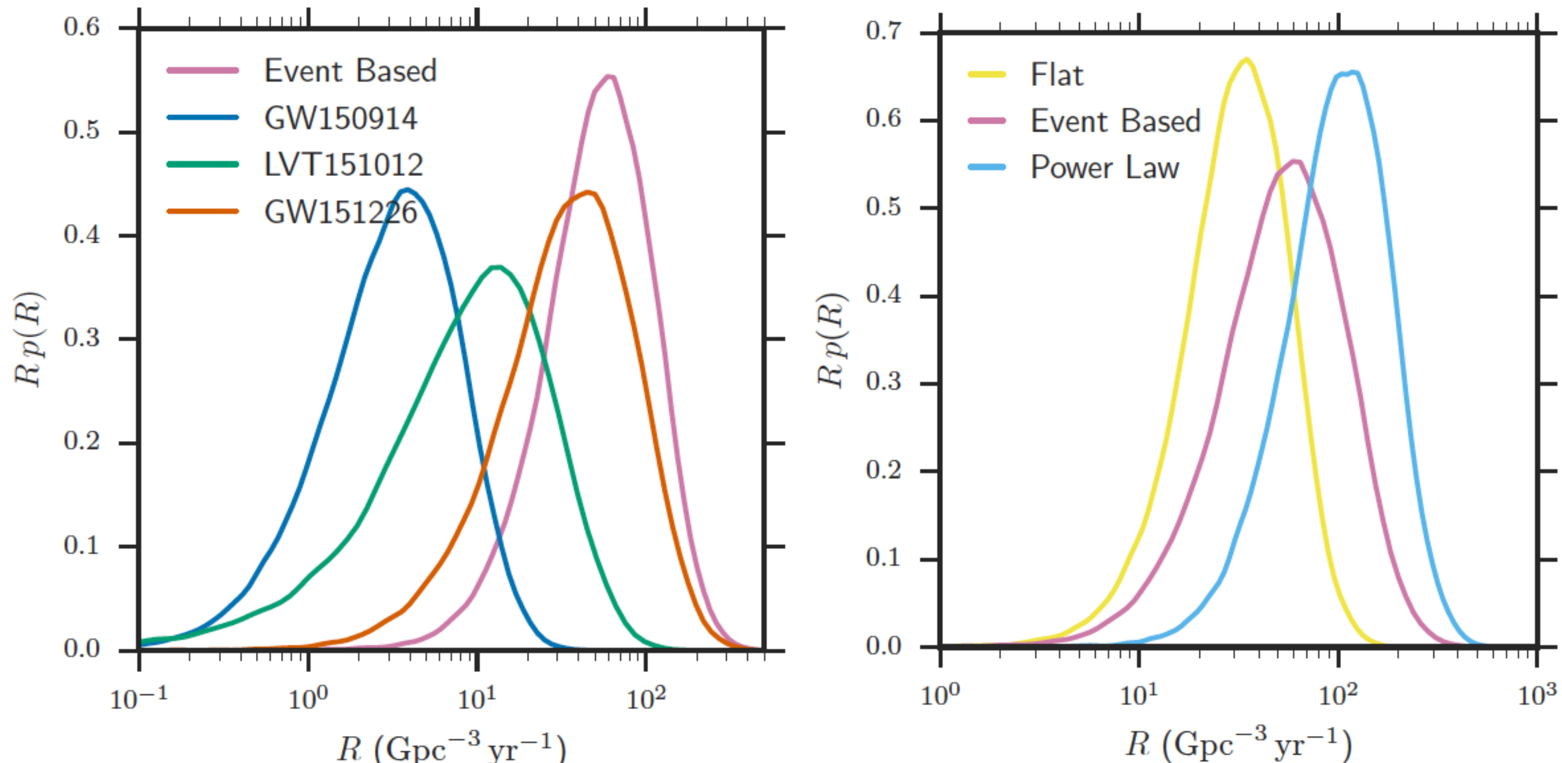
GW150914



GW151226



Astrophysical rate density

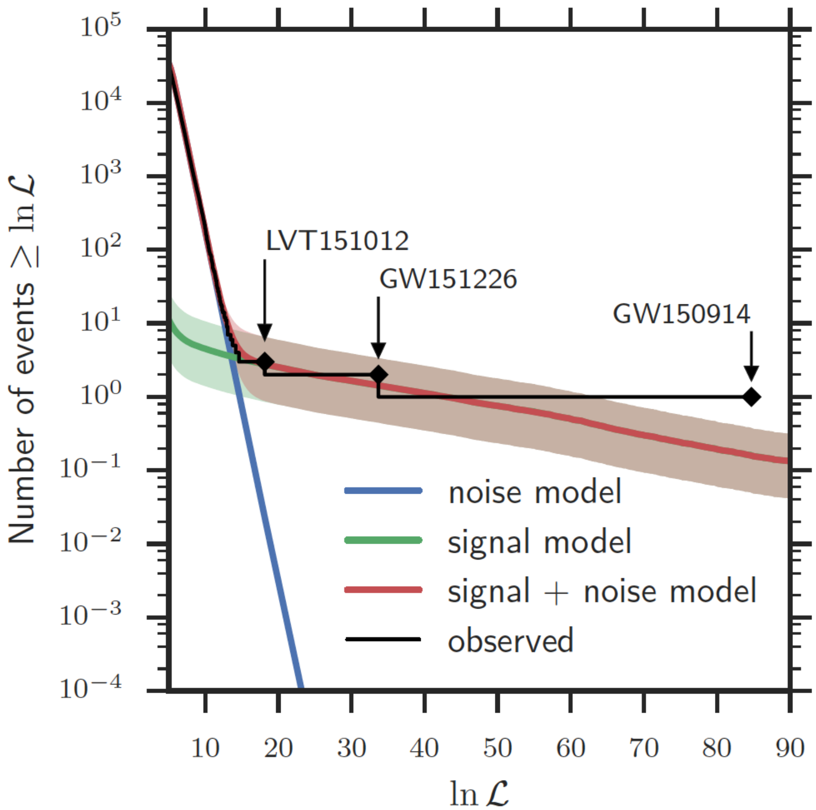


Roughly consistent with astrophysical expectations from:

- 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}

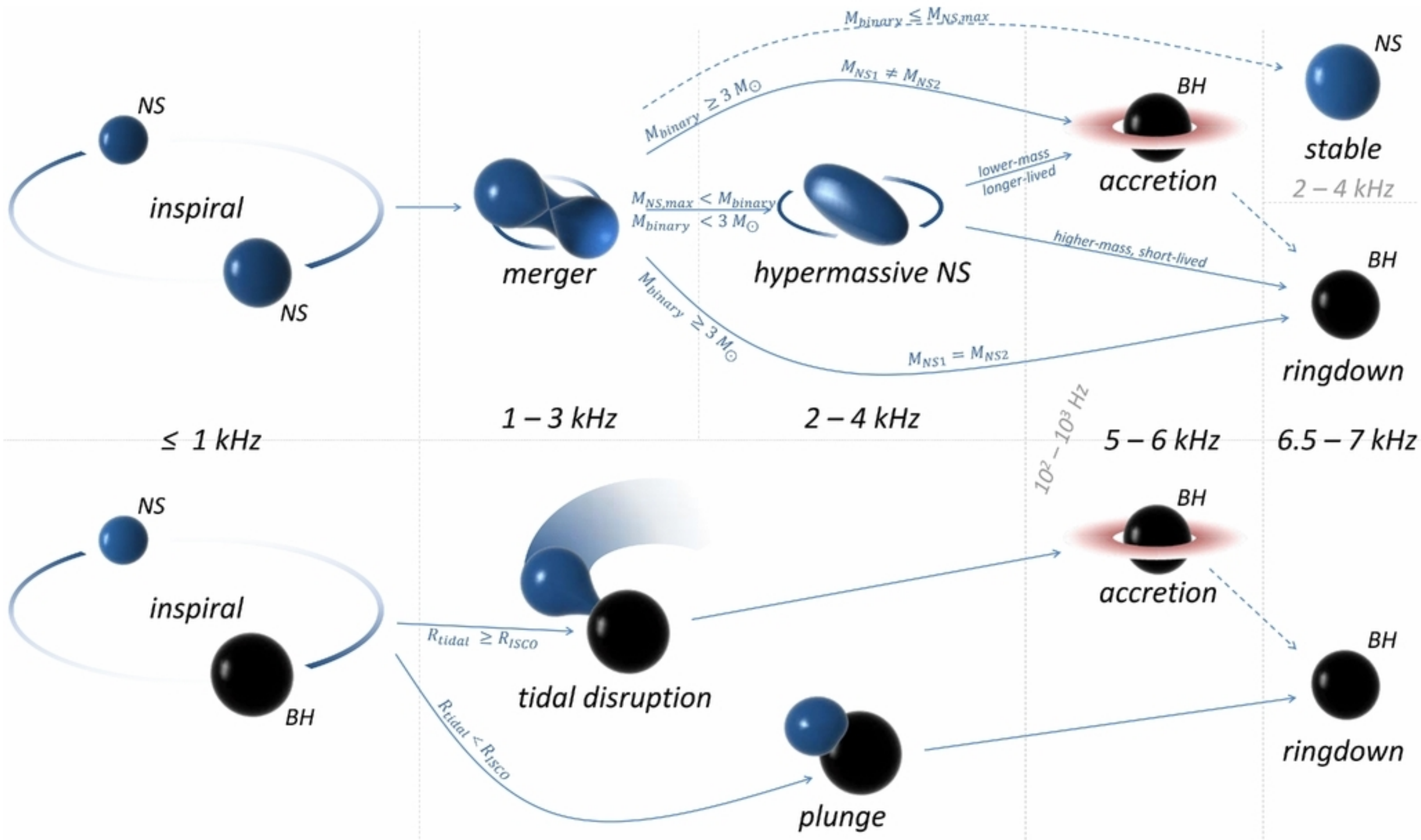
Same ballpark as population synthesis models, CCSN rate, etc

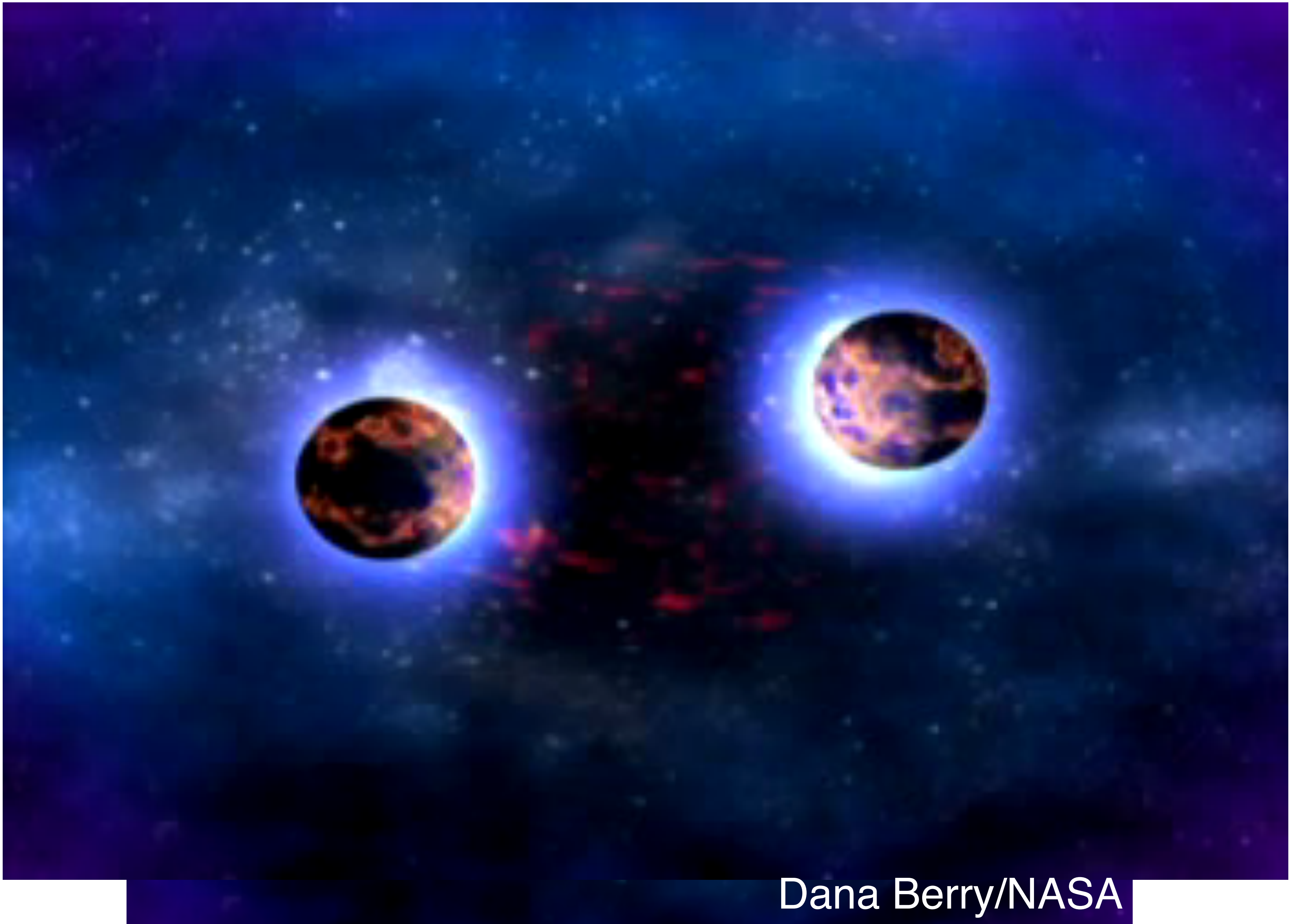
iLIGO+eLIGO BBH rate upper limit: ~< 420 Gpc^{-3} yr^{-1}

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

BNS and NSBH mergers

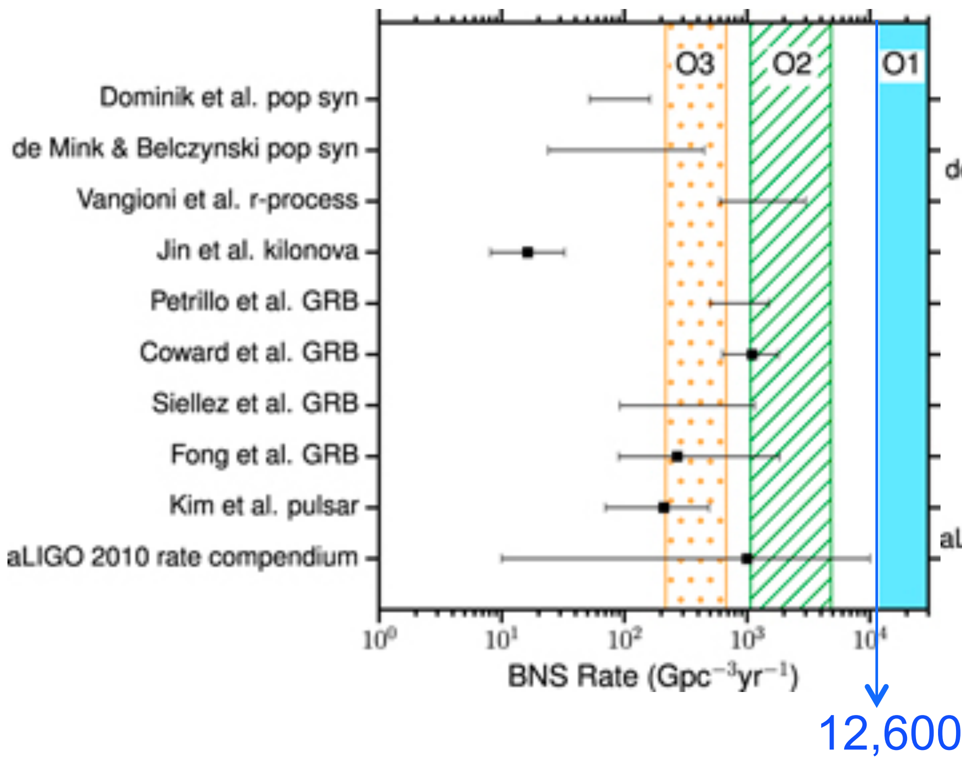
Figure 1 from I Bartos et al 2013 Class. Quantum Grav. 30 123001

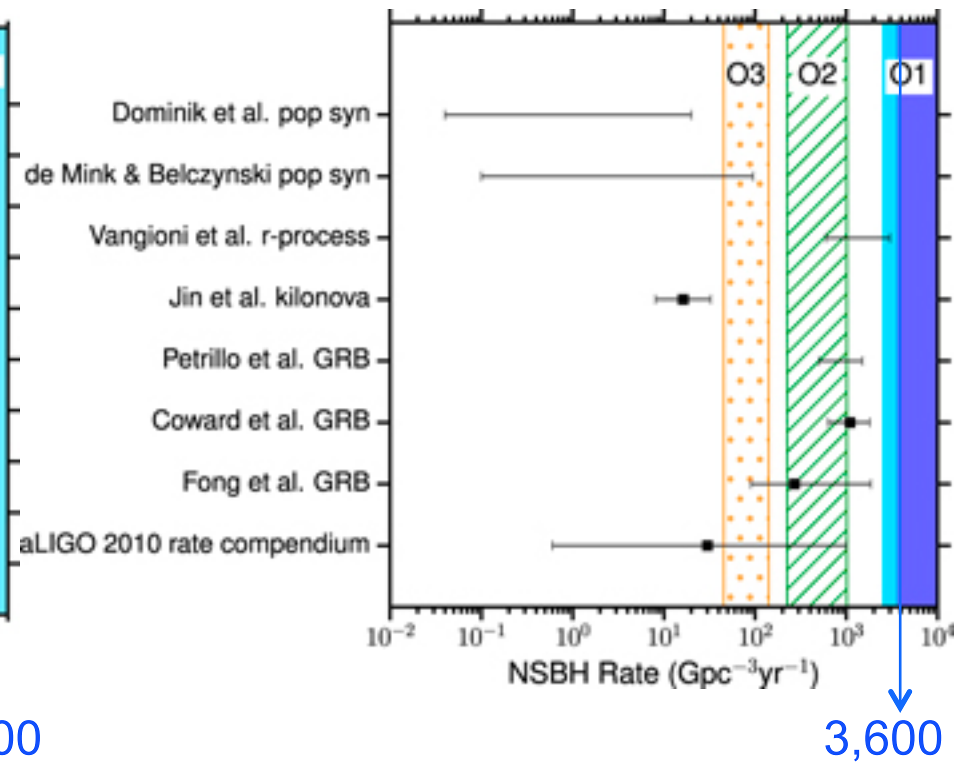




http://www.nasa.gov/mission_pages/swift/bursts/short_burst_nsu_multimedia.html

BNS and NSBH merger rate limits from O1, and predictions



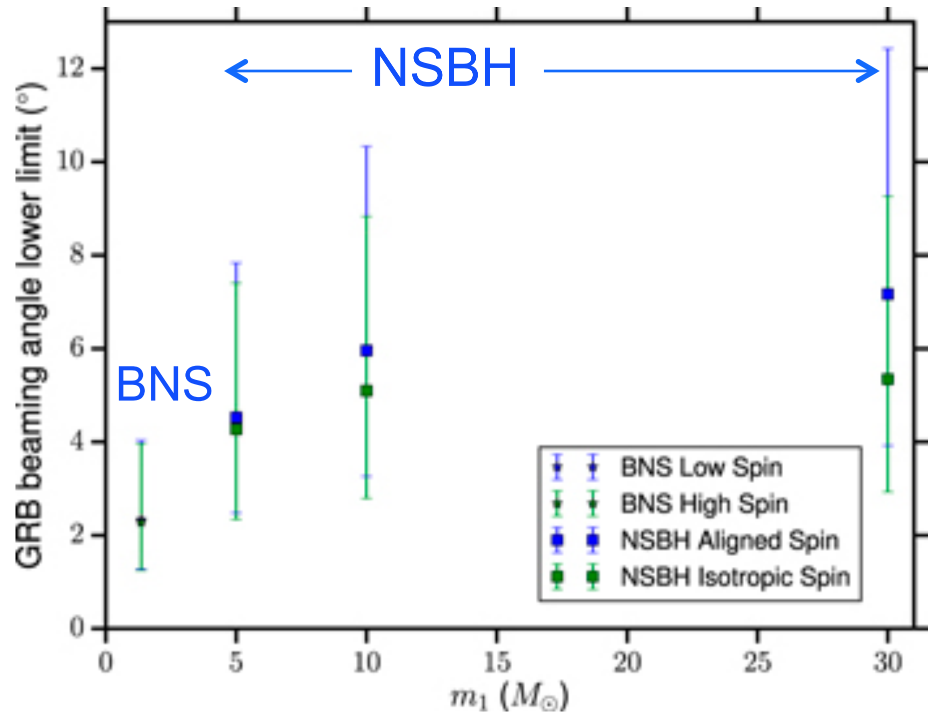


O1 <BNS range> ~ 70 Mpc

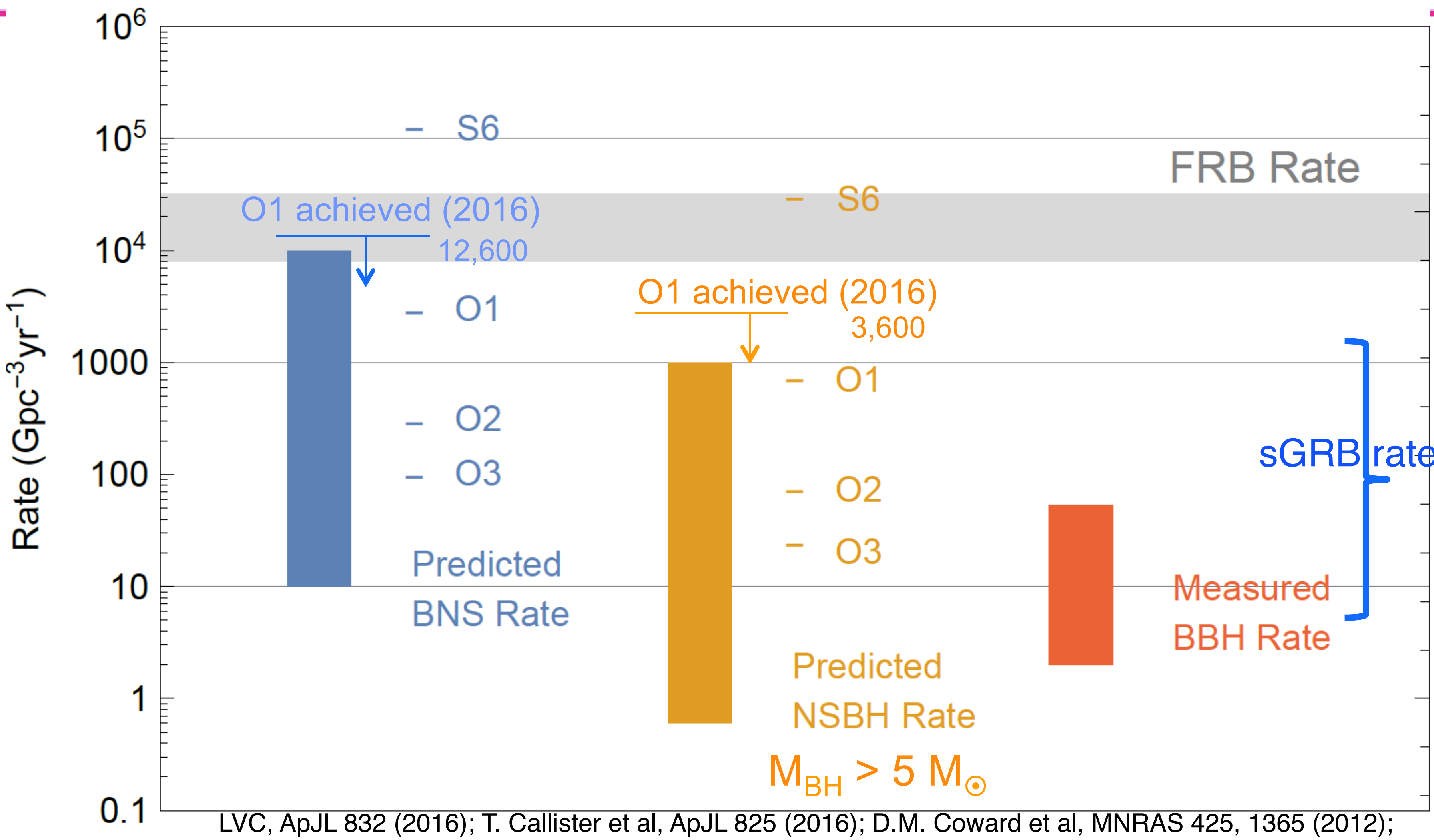
O1 <NSBH range> ~ 110 Mpc

Lower limit on the beaming angle of short GRBs from non-observation in O1

- Use observed short GRB rate of 10^{+20}_{-7} Gpc^{-3} yr^{-1}
- Use 90% rate upper limit on BNS and NSBH from LIGO O1.
- assume all short GRBs are produced by each case in turn.
- assume all have the same beaming angle θ_j.
- Error bars from uncertainty in sGRB rate.



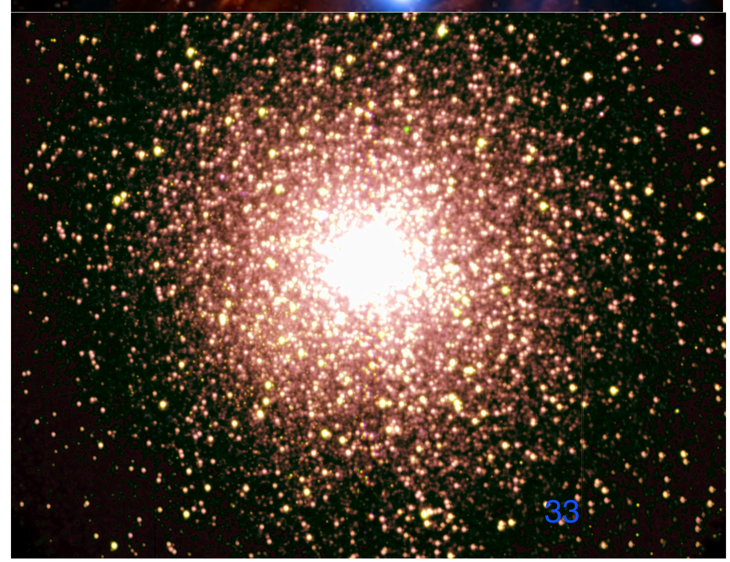
Predicted and measured compact binary merger rates



LVC, ApJL 832 (2016); T. Callister et al, ApJL 825 (2016); D.M. Coward et al, MNRAS 425, 1365 (2012); B. Abbott et al, Living Rev. Relativity, 19, 1 (2016) arXiv:1304.0670.

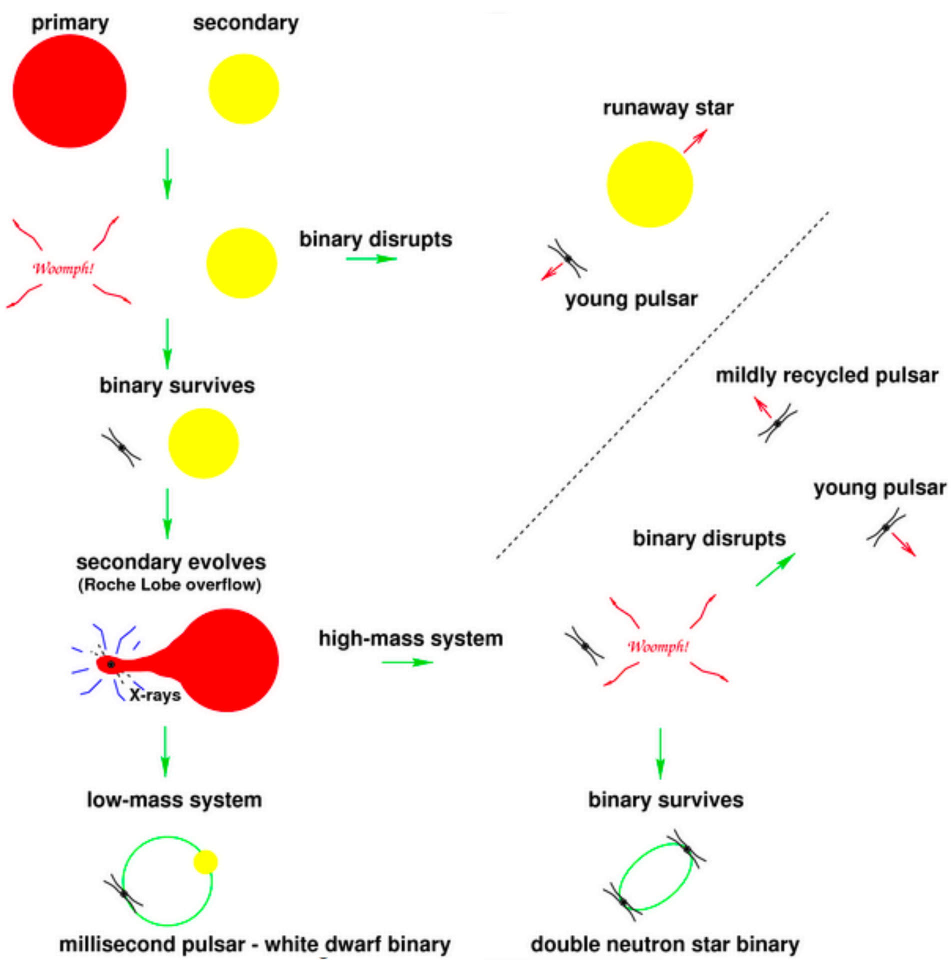
Formation mechanisms

- 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 (~ 0.1 $Z_{\odot}$).
- https://dcc.ligo.org/LIGO-P1500262/public/main



Formation channels

Isolated binary



Dynamical formation

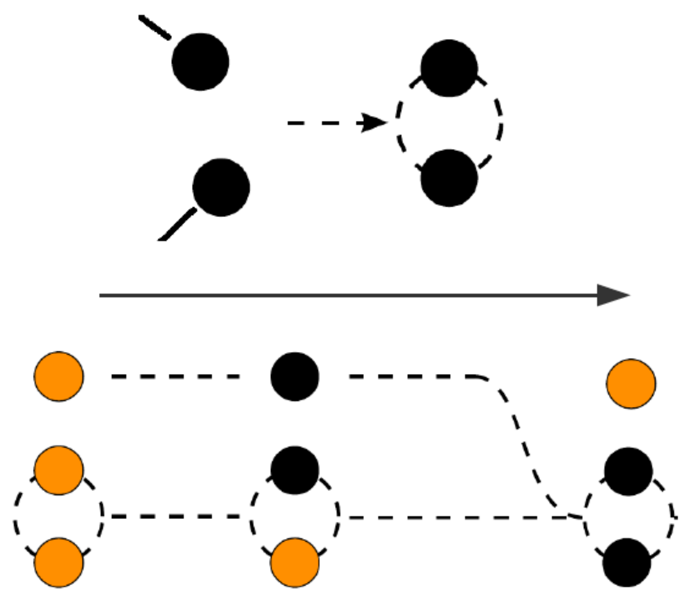


Fig. after Ziosi

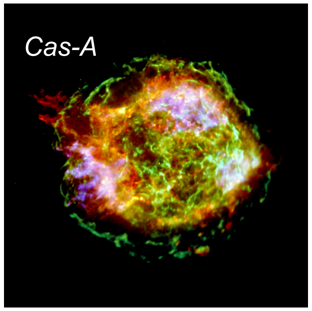
Globular/young clusters/gal. nuclei

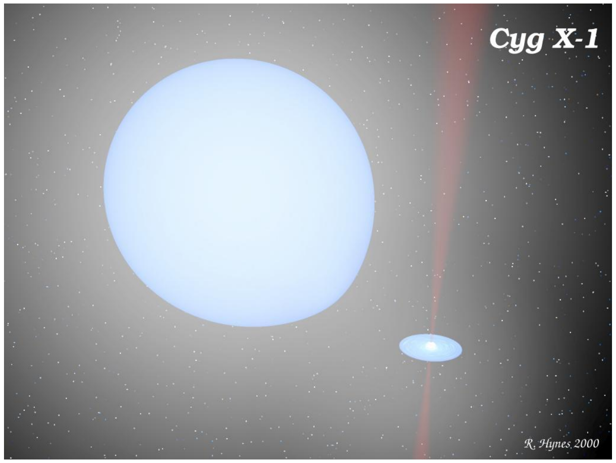
Radboud Universiteit Nijmegen

Compact Binary Merger Population Synthesis Models

These are necessarily complex models involving many poorly-constrained parameters:

- Formation and evolution pathways (common-envelope evolution, dynamical interactions, triples and Kozai cycles, …)
- Star Formation Rate vs redshift
- Stellar Initial Mass Function (at the high mass end)
- Stable/unstable Roche lobe overflow, common-envelope evolution
- Stellar-wind mass loss, metallicity (Pop-III, W-R, LBVs) <- dominant for high mass BHs
- Natal CCSN kicks
- remnant compact object mass and spin
- merger delay time, processes that tighten binary orbits
- Role of Pop-III stars





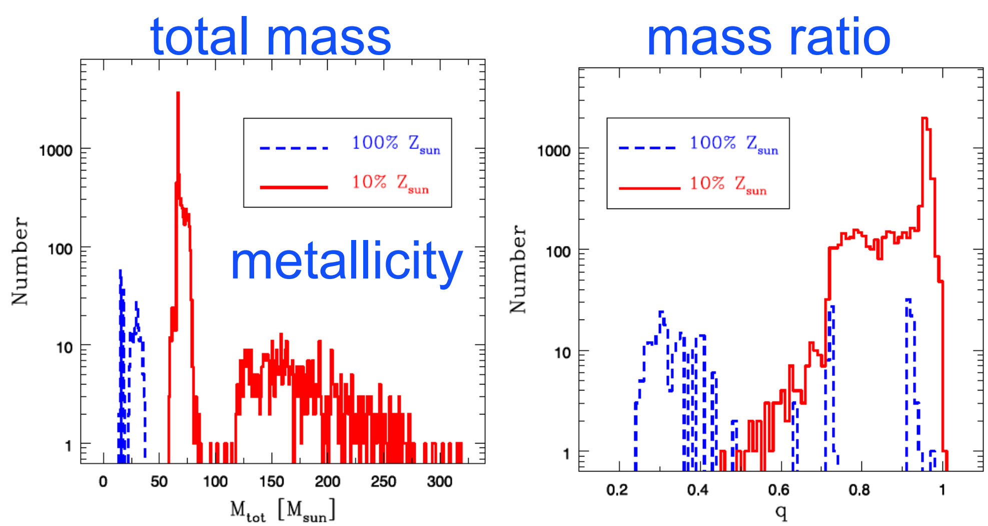
Constrained by:

- CCSN rates vs redshift
- sGRB rates
- cosmic chemical abundances from r-process nucleosynthesis
- Nearby compact binaries (galactic pulsars in binaries, LMXBs)

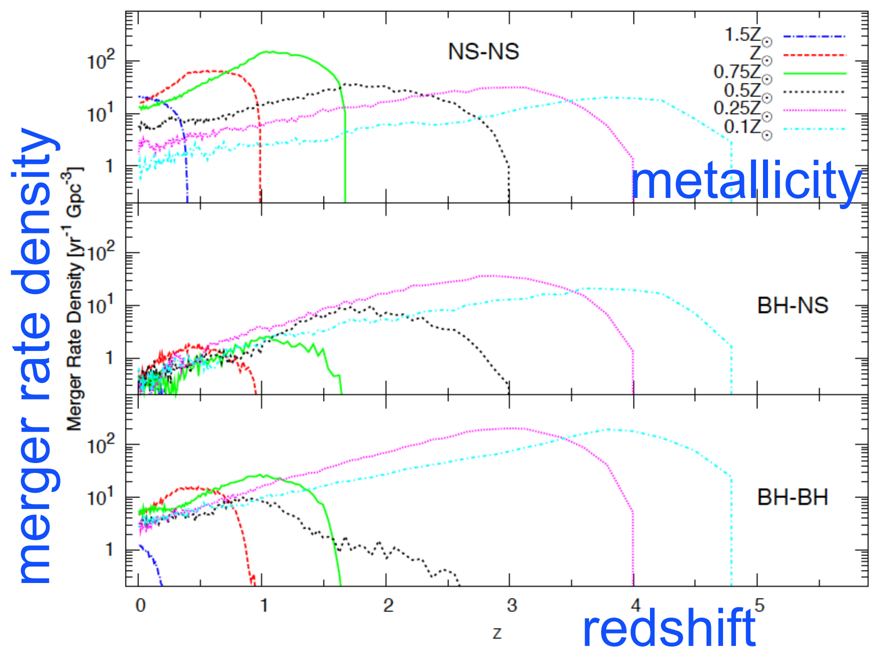
Compact Binary Merger Population Synthesis Models

Can predict:

- Merger rates (and GW detections) vs masses, mass ratios, spins
- redshift distribution
- host galaxy type and metallicity, …



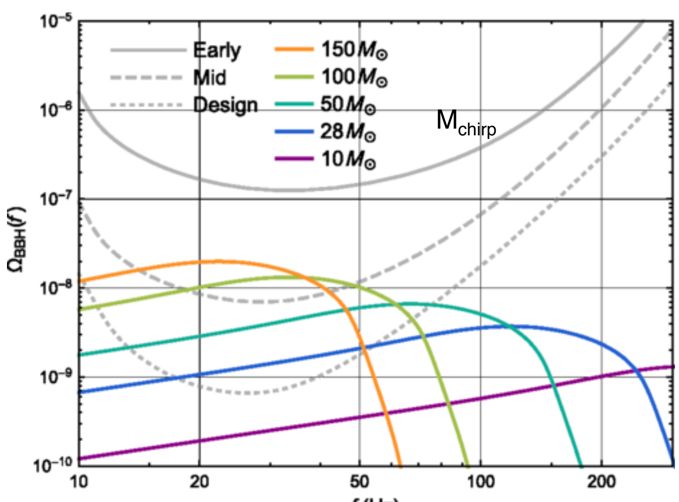
K. Belczynski et al, ApJ 789 (2014)

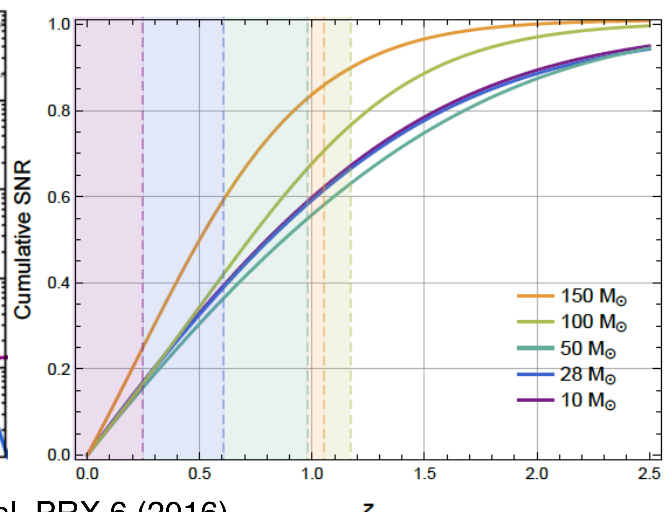


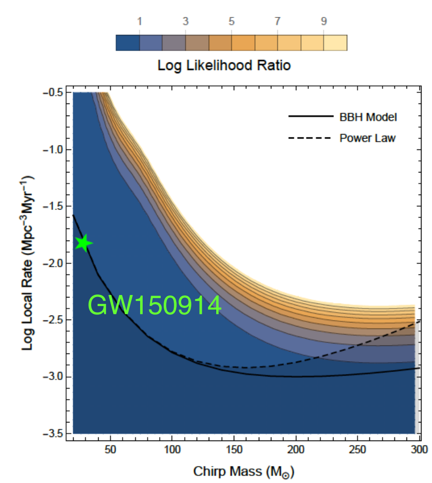
Dominik et al, ApJ 779 (2013)

Contribution to a stochastic astrophysical background

- In addition to individual *foreground* events, we expect a *stochastic background* of many unresolved, distant events from all directions at essentially all times (“popcorn noise”).
- A stochastic signal can constrain metallicity, merger delay time, SFR of underlying population
- There will be a (redshifted) cutoff frequency, depending on the average chirp mass of the systems that dominate this background (depends on <metallicity>(z)).
- Foreground events account for only a fraction of the total SNR in the stochastic signal.
- The background associated with events like GW150914 may be marginally detectable (at SNR ~ 3) with Advanced LIGO after three years of observation.
- However, the cutoff frequency distribution will be indistinguishable from a simple power-law.

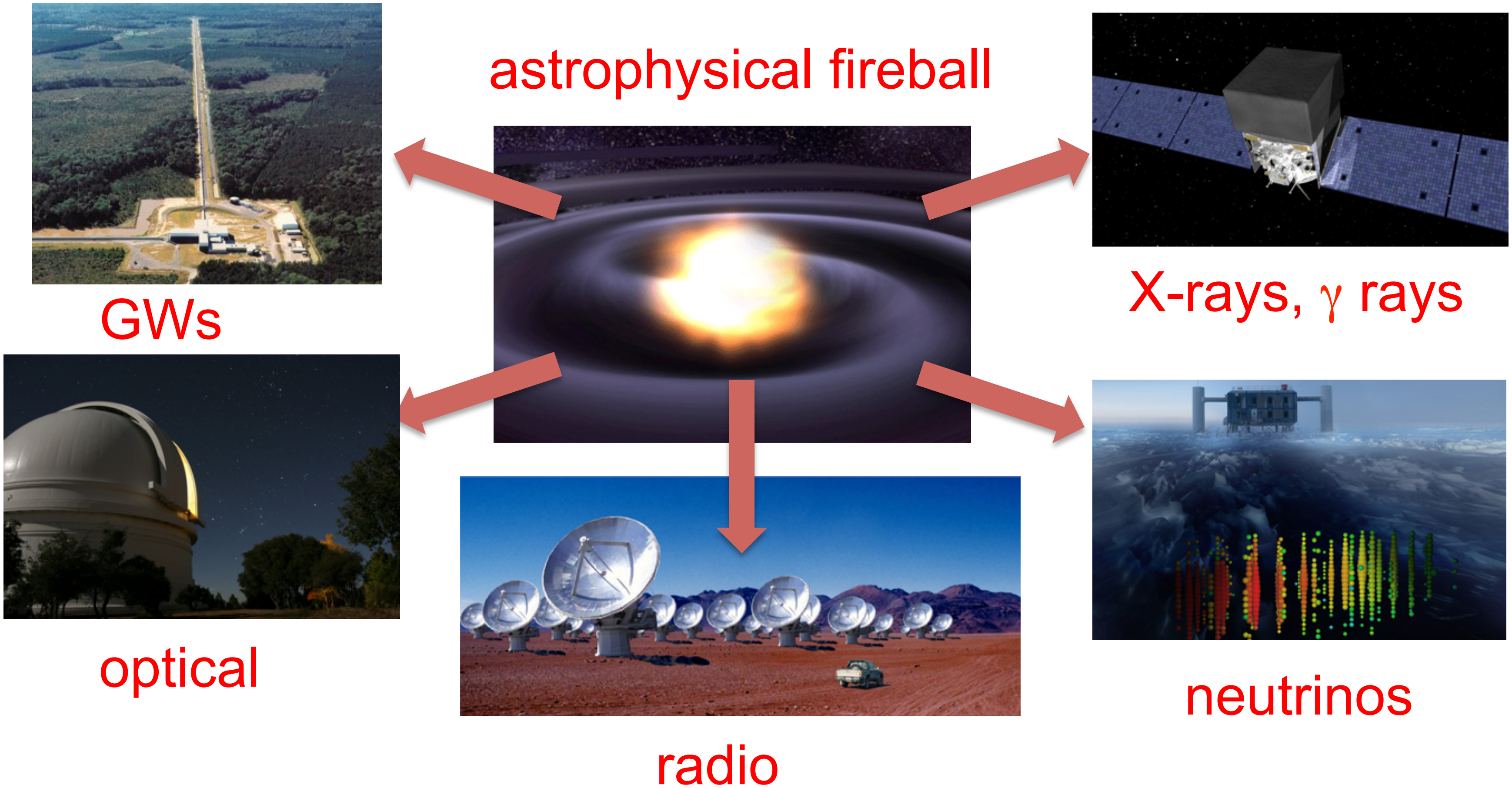




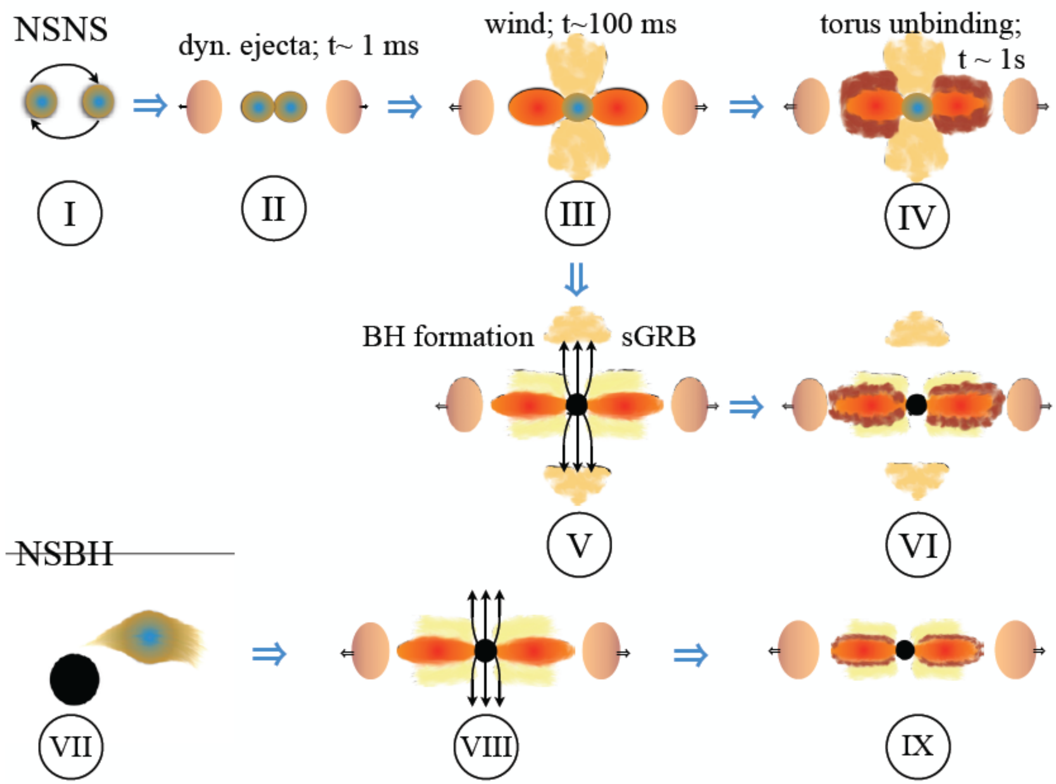


LVC, ApjL 818 (2016); T. Callister et al, PRX 6 (2016)

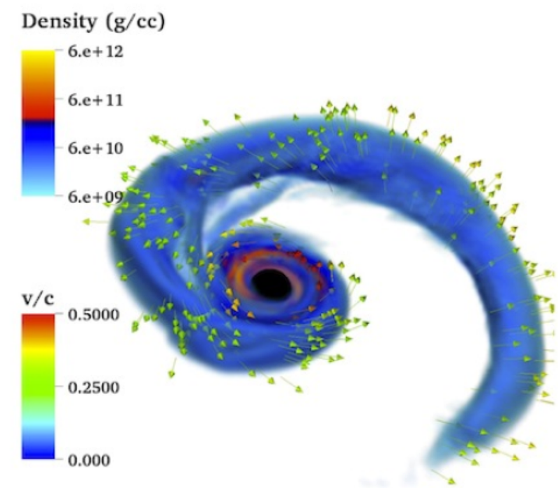
Multi-messenger Astronomy with Gravitational Waves



sGRBs and kilonovas from BNS and NSBH mergers



S. Rosswog et al, arXiv:1611.09822

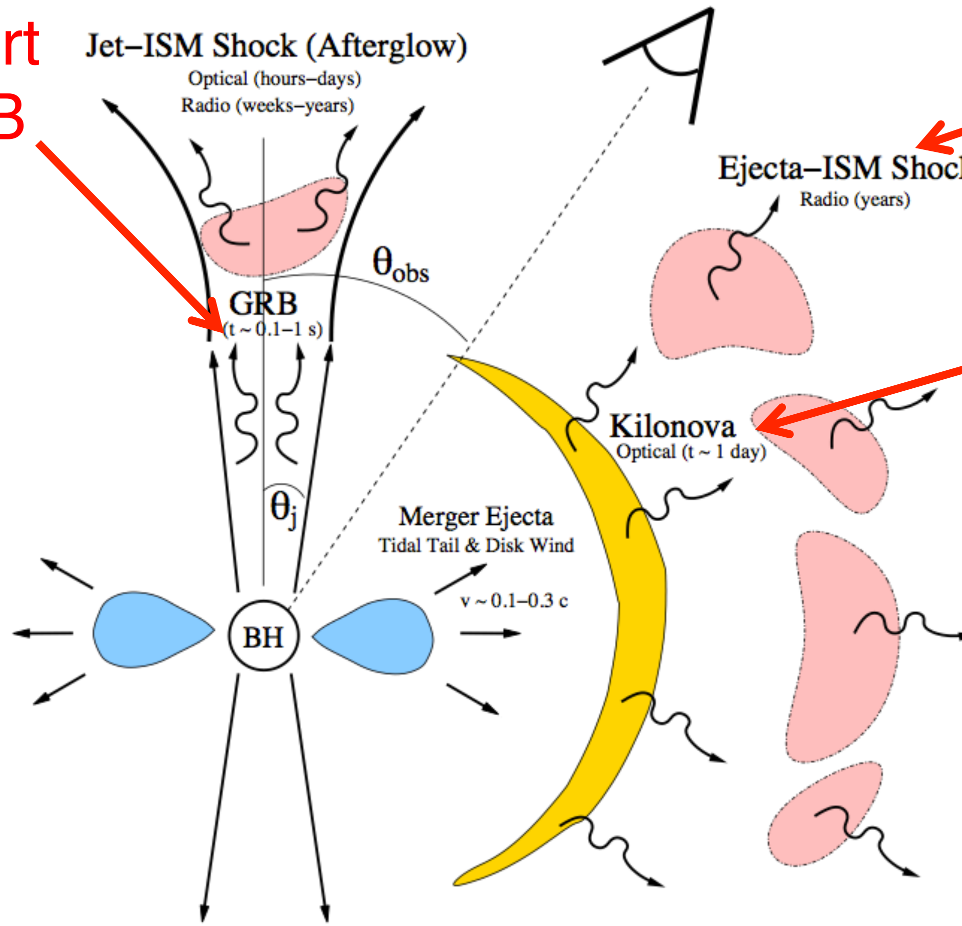


0.14 $M_\odot$ of ejected material
20ms after merger

Foucart et al, PRD, 87, 084006 (2013)
Simulations and models used
to predict "EM Brightness"
as a function of M_{BH}

Electromagnetic radiation from sGRB progenitors

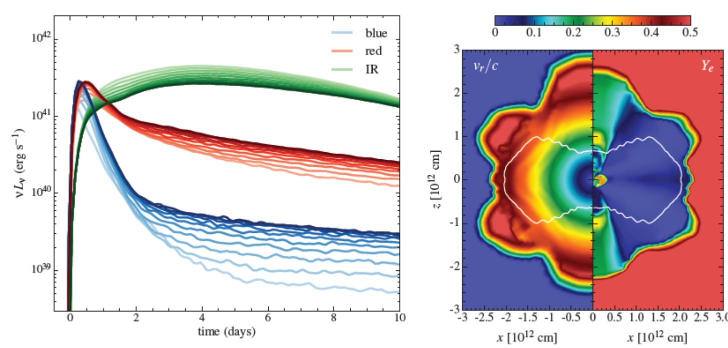
Short GRB



Metzger & Berger 2011

Ejecta-ISM shock radio emission from days to years

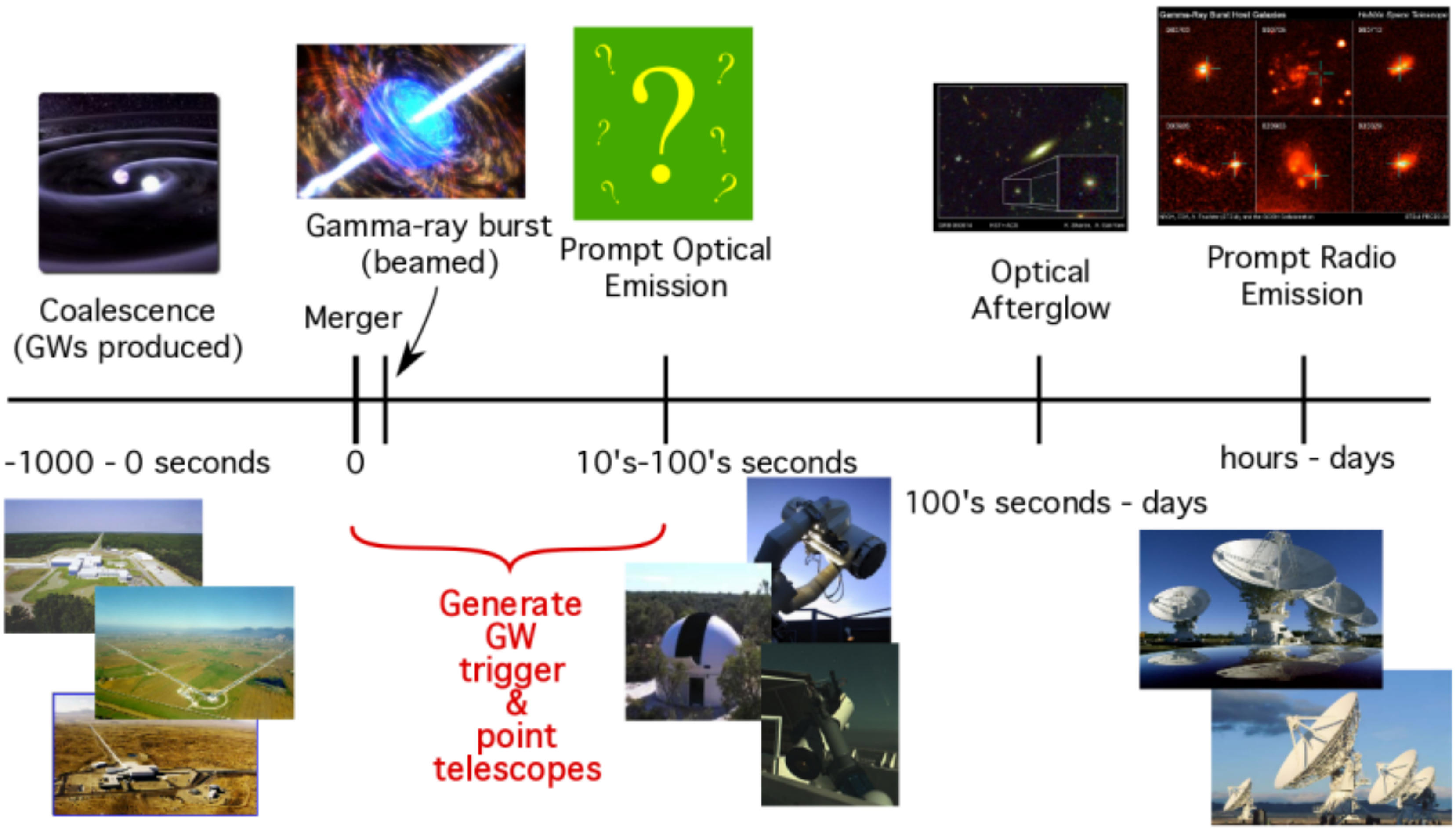
“kilonova”
Prompt optical emission from seconds to days



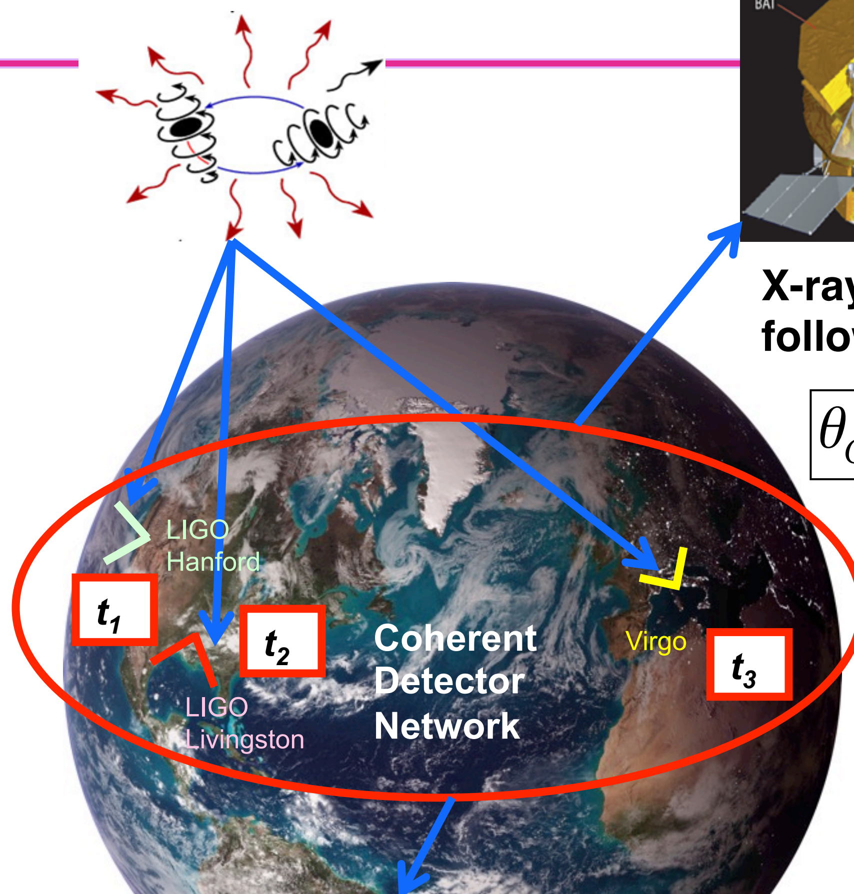
R. Fernandez et al, arXiv:1612.04829

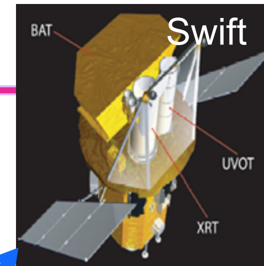
Low-latency identification of transients for rapid (< ~100s) followup

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



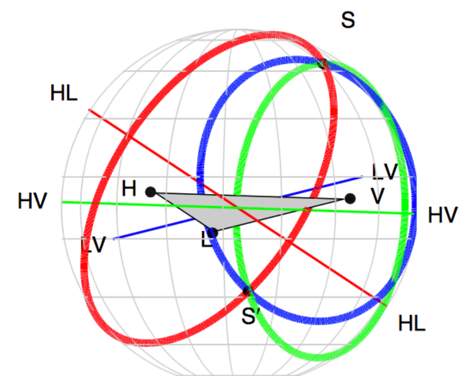
Enabling multi-messenger astronomy with gravitational waves

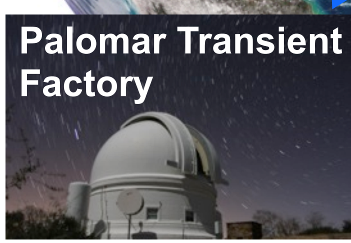




X-ray, γ-ray follow-up

$$\theta_{GW} \sim \lambda_{GW} / d \sim \text{few degrees}$$





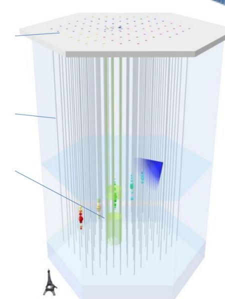
Optical follow-up

Image:
http://earthobservatory.nasa.gov/

Abadie, et al, (LSC & Virgo Collaborations)
Astron. Astrophys. **541** (2012) A155.
Nissanke, Kalsiwal, Georgieva,
Astrophysical J. **767** (2013) 124.
Singer, Price, et al., Astrophysical J., 795 (2014) 105.

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)



Some of our papers have not just a long author list and institution list, but even a long list of collaborations!

THE ASTROPHYSICAL JOURNAL LETTERS, 826:L13, 2016 JULY 20
Preprint typeset using LaTeX style AASTeX6 v. 1.0

LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION,
THE AUSTRALIAN SQUARE KILOMETER ARRAY PATHFINDER (ASKAP) COLLABORATION, THE BOOTES COLLABORATION,
THE DARK ENERGY SURVEY AND THE DARK ENERGY CAMERA GW-EM COLLABORATIONS, THE *Fermi* GBM COLLABORATION,
THE *Fermi* LAT COLLABORATION, THE GRAVITATIONAL WAVE INAF TEAM (GRAWITA), THE *INTEGRAL* COLLABORATION,
THE INTERMEDIATE PALOMAR TRANSIENT FACTORY (IPTF) COLLABORATION, THE INTERPLANETARY NETWORK,
THE J-GEM COLLABORATION, THE LA SILLA–QUEST SURVEY, THE LIVERPOOL TELESCOPE COLLABORATION,
THE LOW FREQUENCY ARRAY (LOFAR) COLLABORATION, THE MASTER COLLABORATION, THE MAXI COLLABORATION,
THE MURCHISON WIDE-FIELD ARRAY (MWA) COLLABORATION, THE PAN-STARRS COLLABORATION,
THE PESSTO COLLABORATION, THE PI OF THE SKY COLLABORATION, THE SKYMAPPER COLLABORATION,
THE *Swift* COLLABORATION, THE TAROT, ZADKO, ALGERIAN NATIONAL OBSERVATORY, AND C2PU COLLABORATION,
THE TOROS COLLABORATION, AND THE VISTA COLLABORATION
See the Supplement, Abbott et al. 2016g, for the full list of authors.

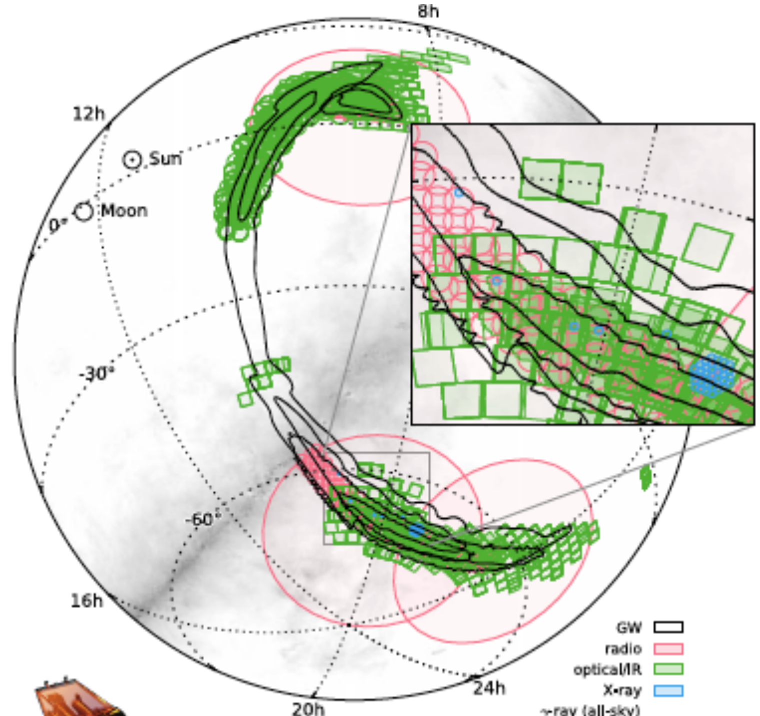
(Received 2016 February 29; Accepted 2016 April 26; Published 2016 July 20)

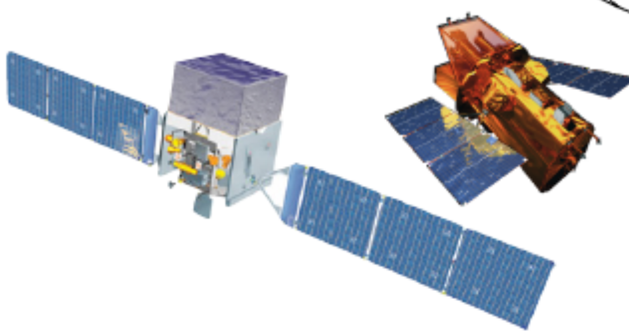
ABSTRACT

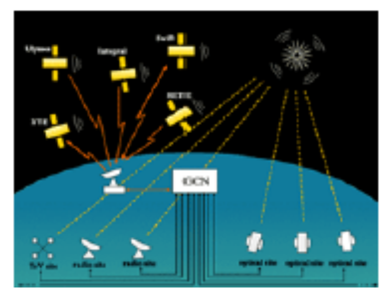
A gravitational-wave (GW) transient was identified in data recorded by the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) detectors on 2015 September 14. The event, initially designated

Localization and broadband follow-up of the first LIGO event

- Consortium between LIGO and 63 teams using ground and space facilities
- Gamma-ray, X-ray, optical, infrared, and radio wavelengths
- Key NASA contributions come from high-energy observational assets: ***Fermi***, ***Swift***, ***GCN network***

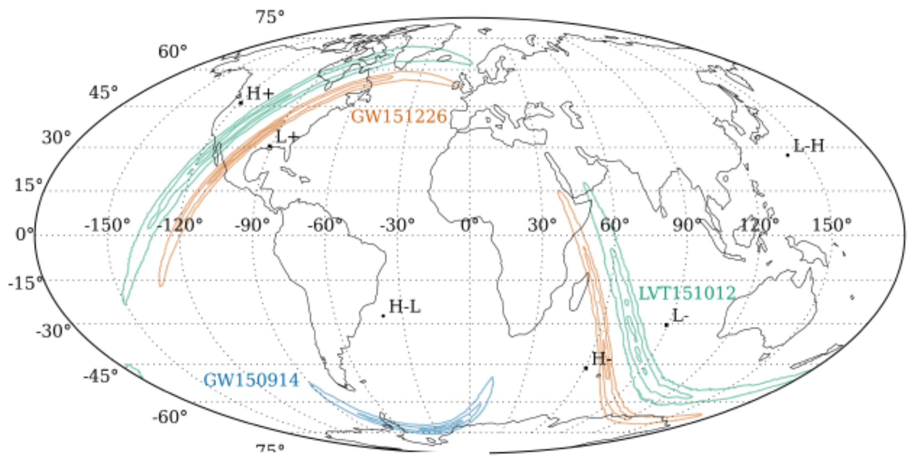


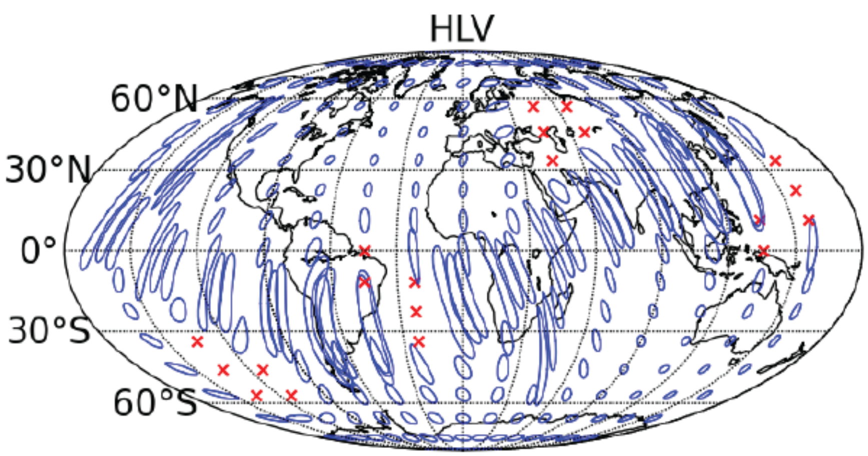


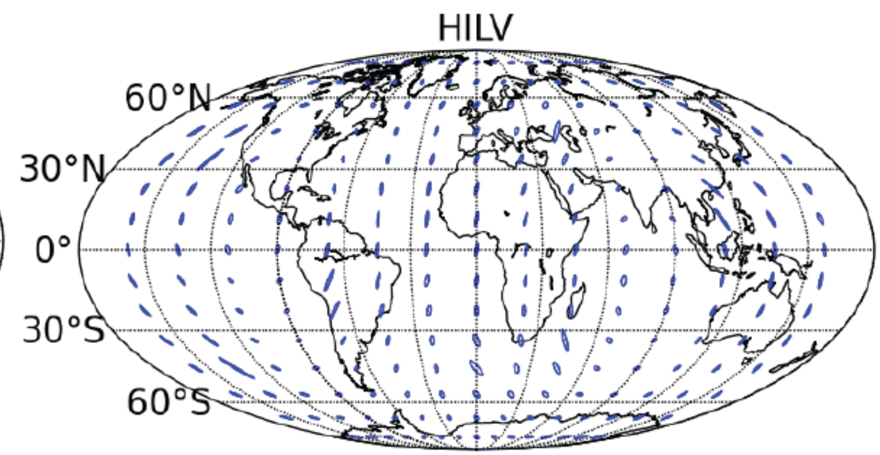


Localization and Broadband Follow-up of the Gravitational-wave Transient GW150914
Astrophys. J. Lett. 826, L13 (2016)

Source localization with the global network of GW detectors



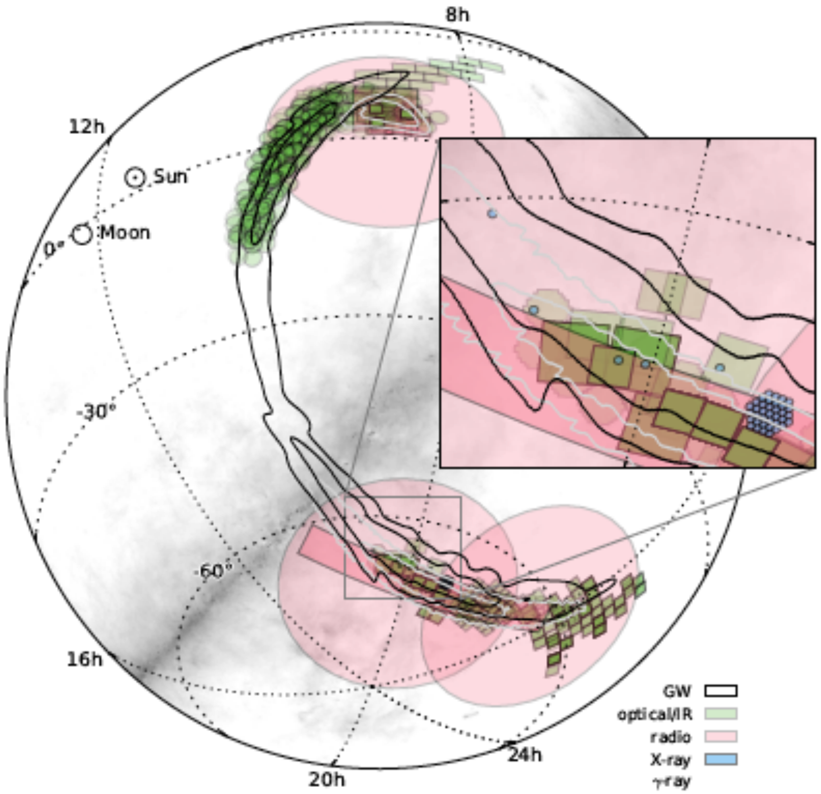




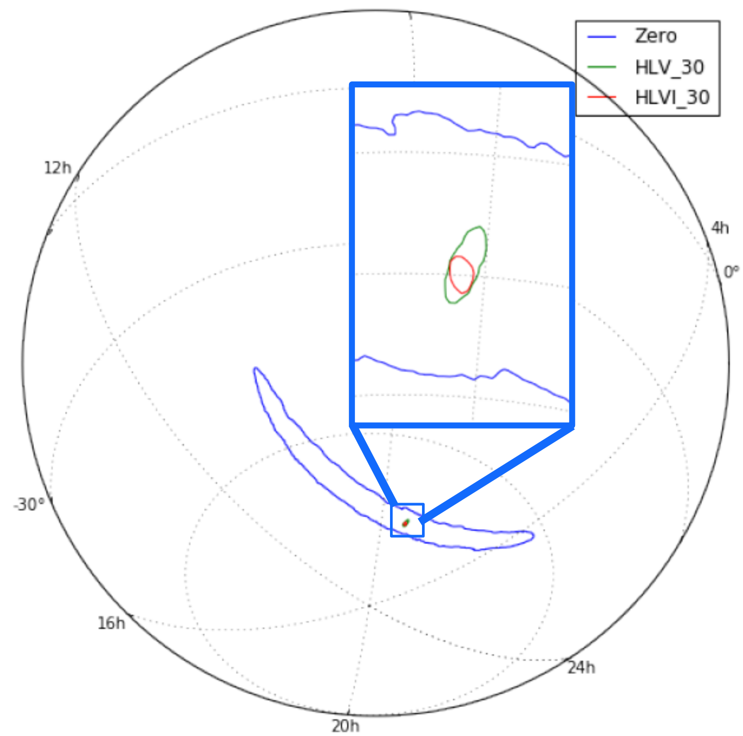
Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo
http://www.livingreviews.org/lrr-2016-1

Improved Localization: LIGO→Virgo→ LIGO-India

GW150914: LIGO only

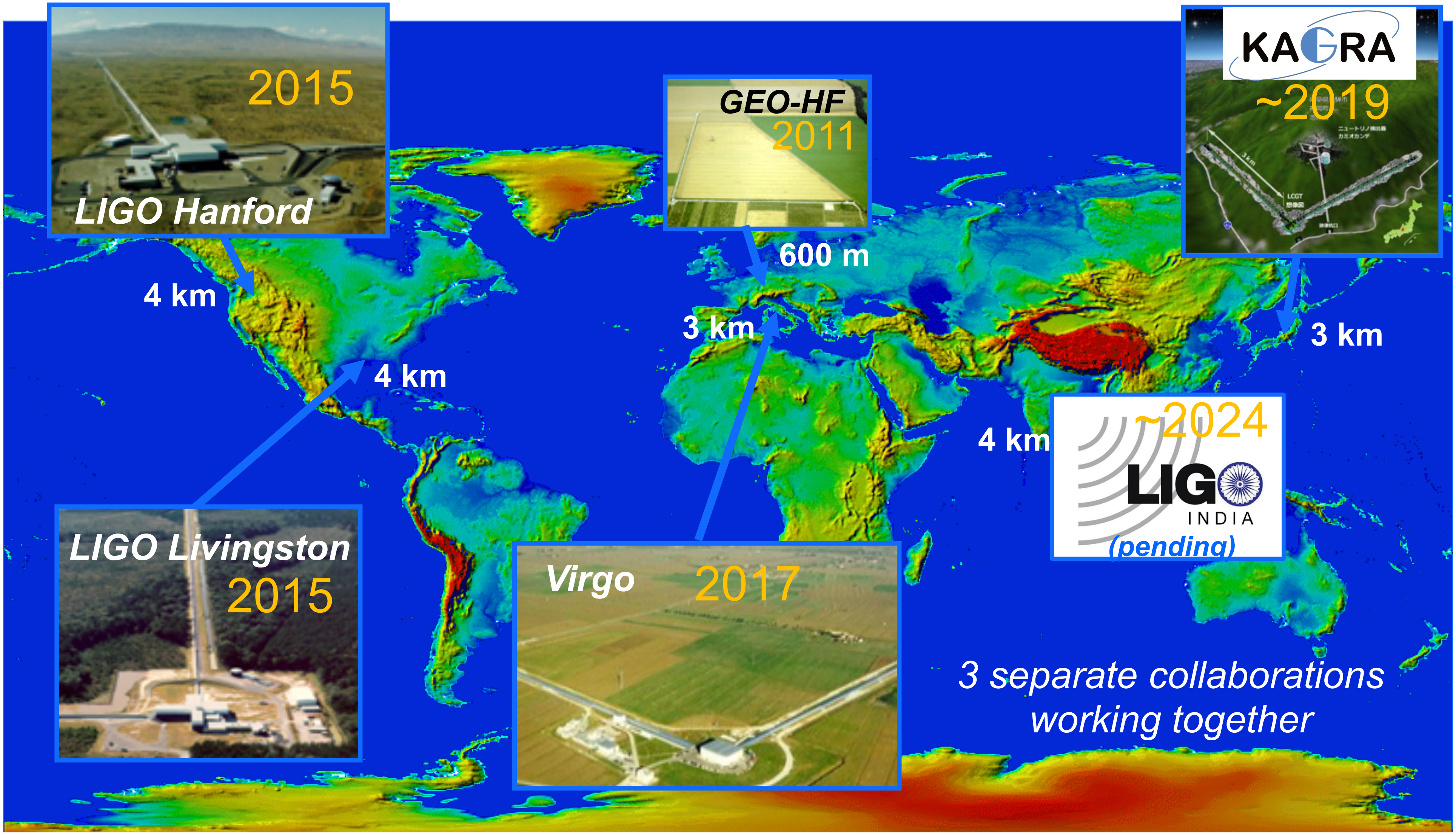


GW150914: LIGO → LV → LVI
(Preliminary)

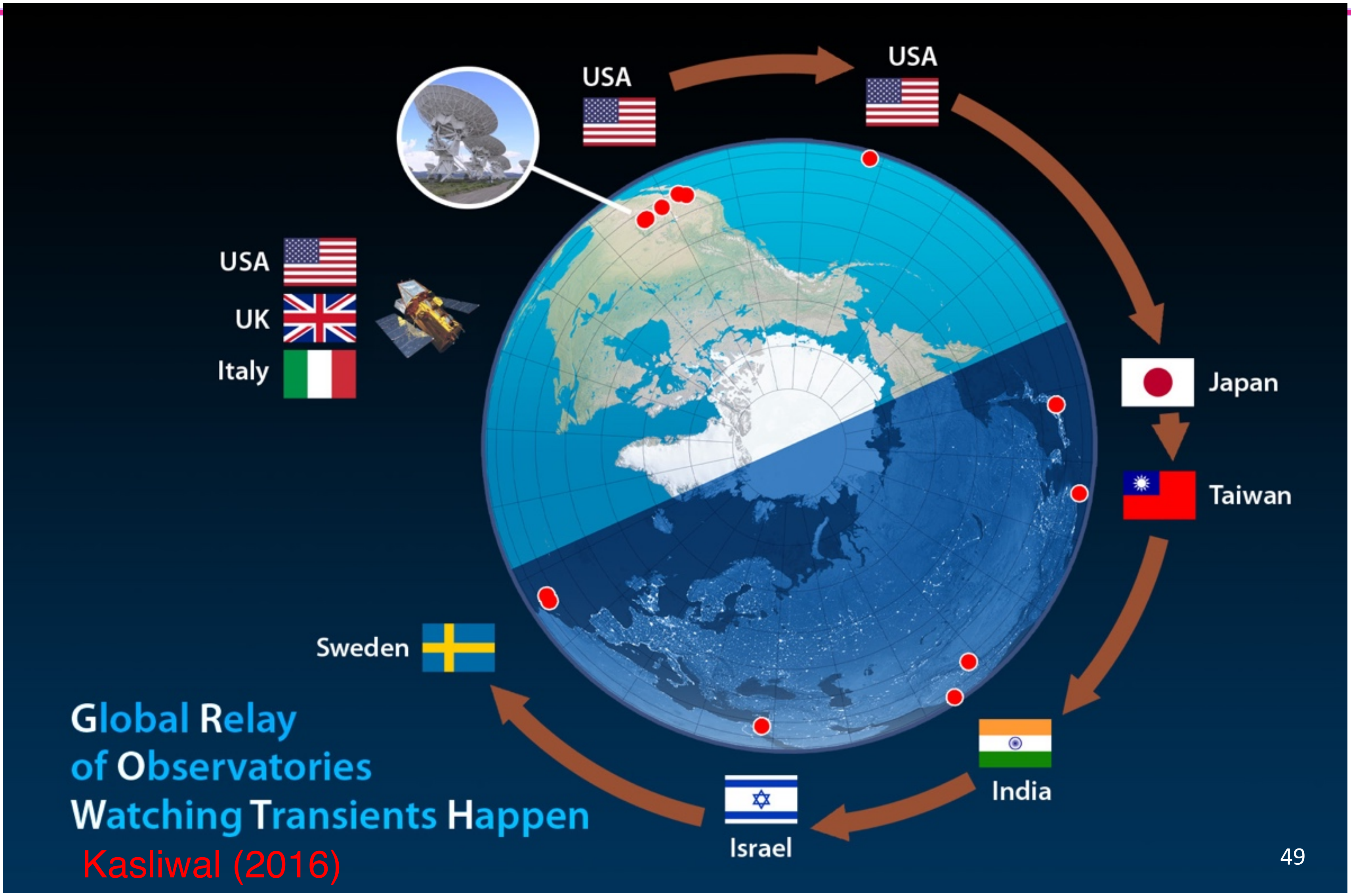


375° → 9.3° → 7.8°
(99% confidence level)

The emerging Advanced GW Detector Network

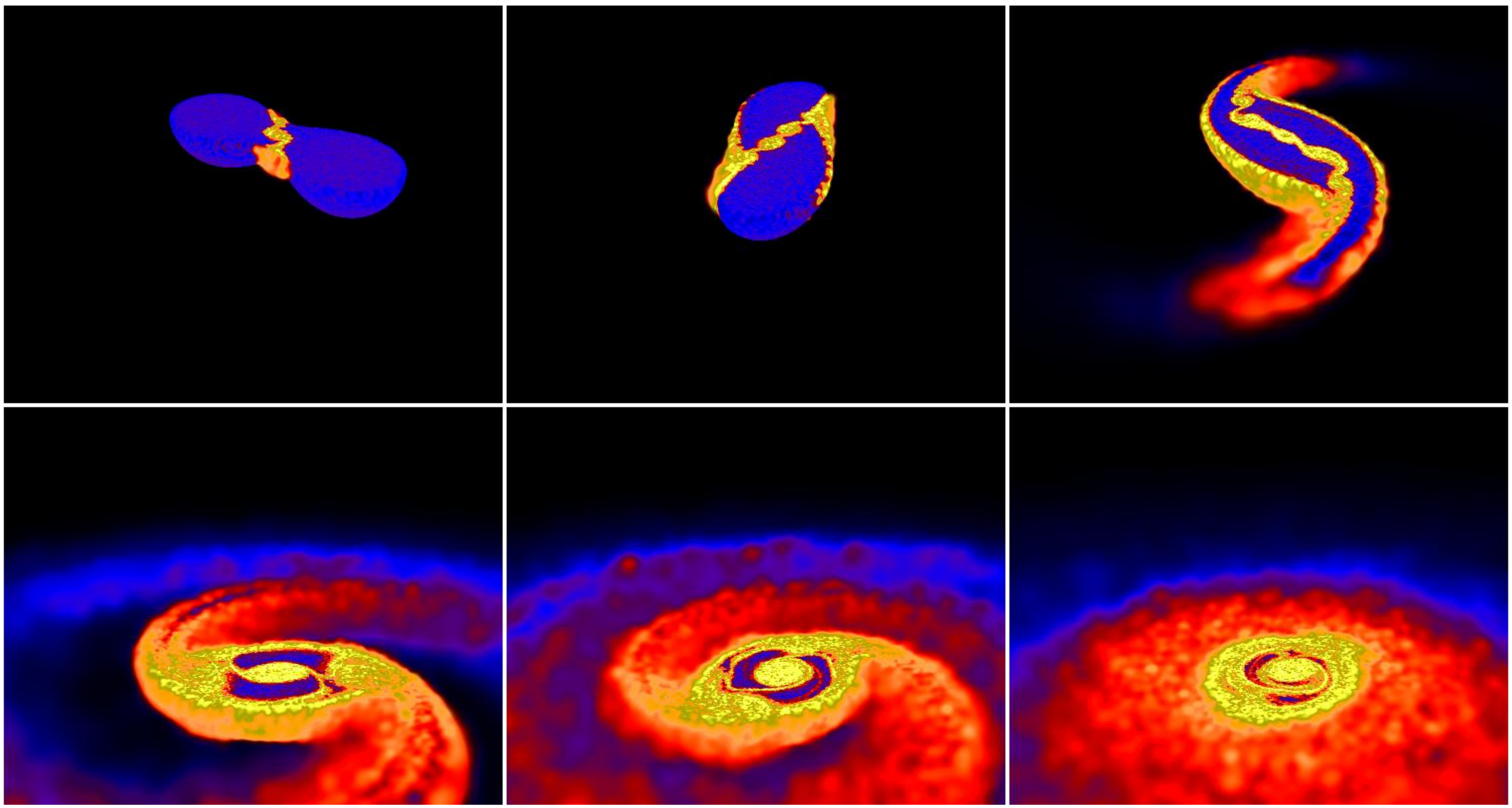


“GROWTH” Network



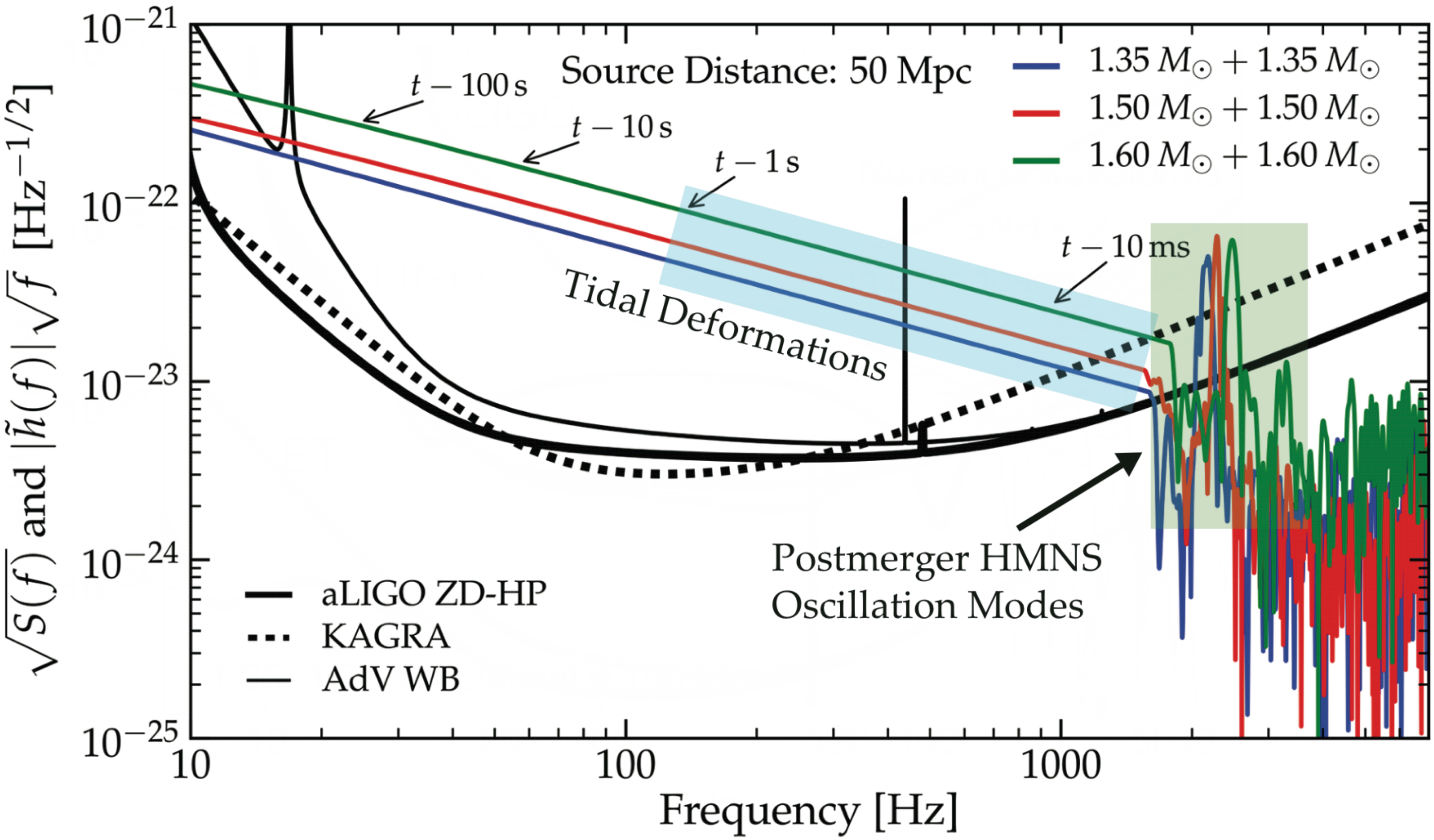
Kasliwal (2016)

BNS mergers, tidal distortion and disruption

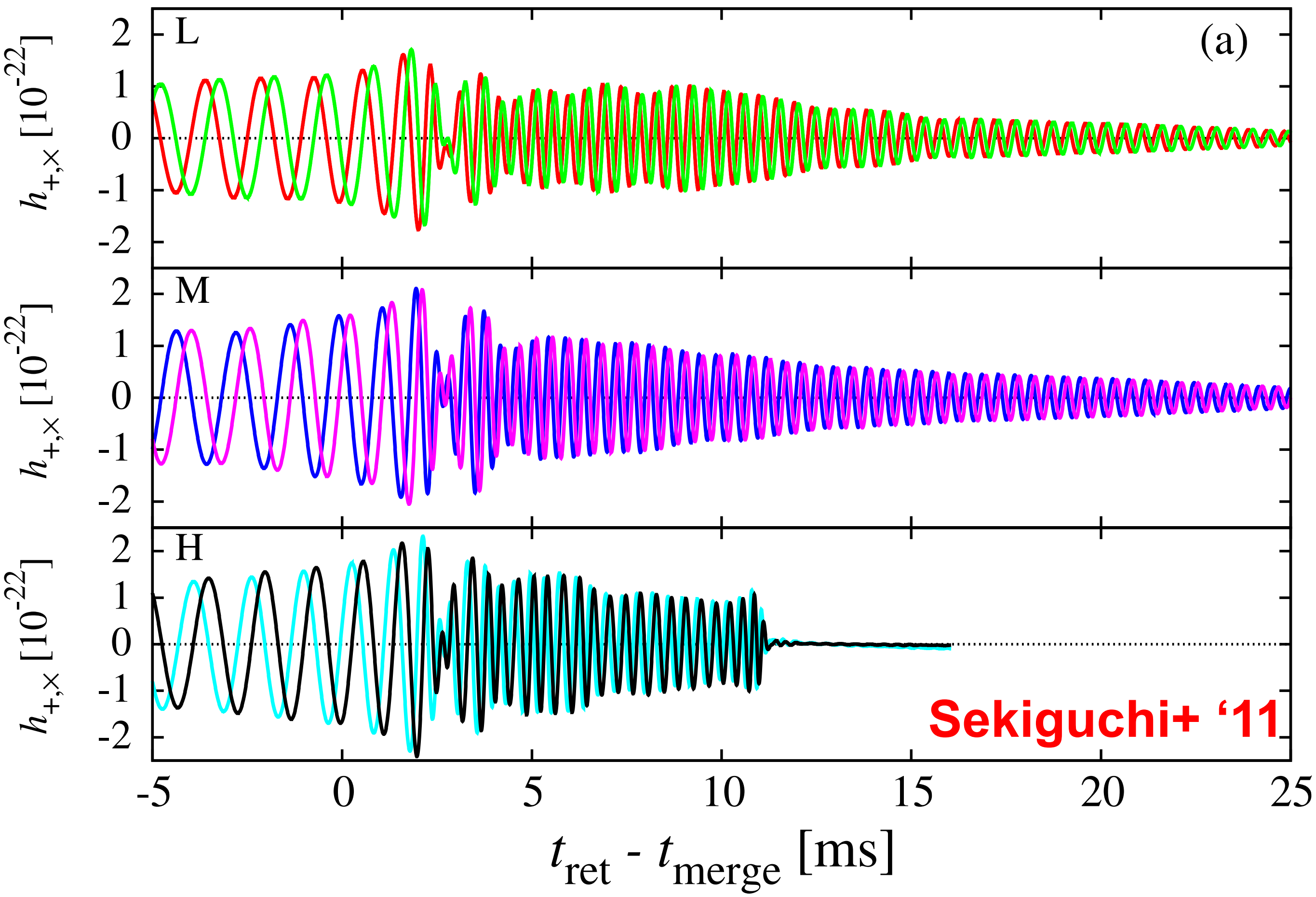


Credit: Daniel Price and Stephan Rosswog

Tidal disruption of neutron stars near merger



Nuclear Astrophysics: BNS Merger GW waveforms



1.35 + 1.35

1.50 + 1.50

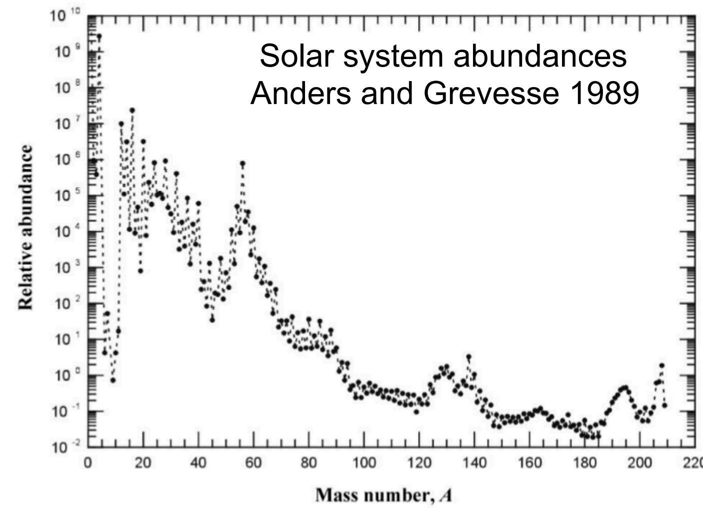
1.60 + 1.60

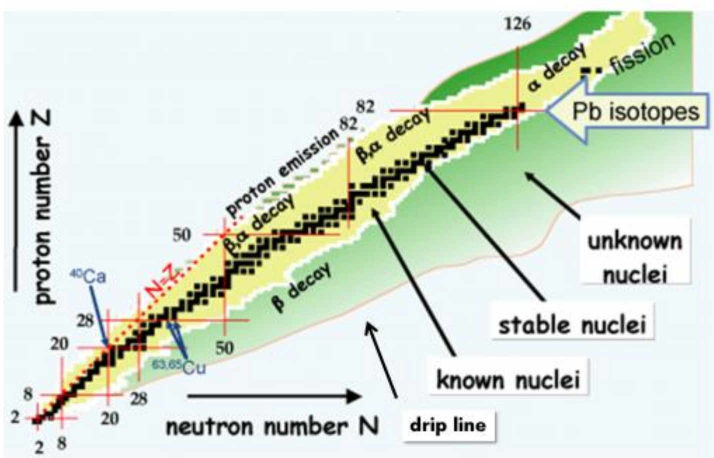
Mass [M_{Sun}]

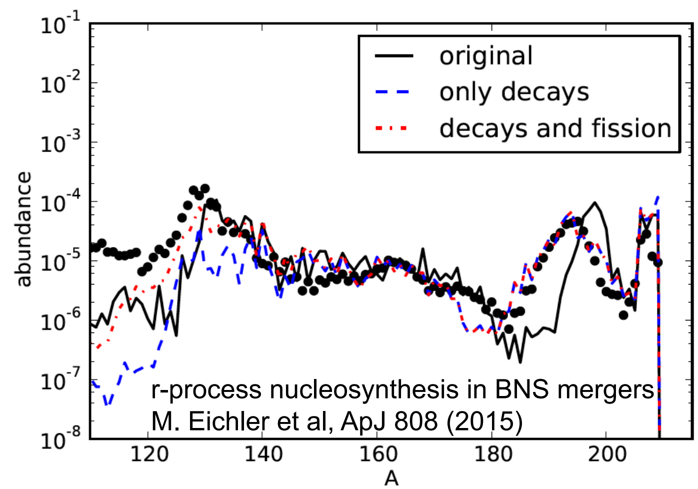
Sekiguchi+ 11: Full GR NS-NS simulation with realistic microphysics, finite-temperature nuclear EOS of H. Shen+ ‘98,’11 (+MHD, ν-transport since then!)

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, Pb, Pt, U…) are forged during the SN ("r-process");
- but most of them might come from binary neutron star mergers (second-death)





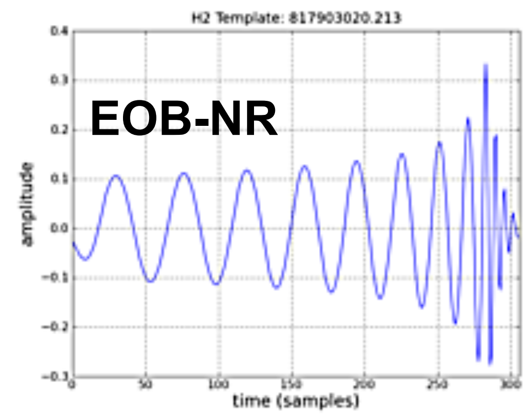


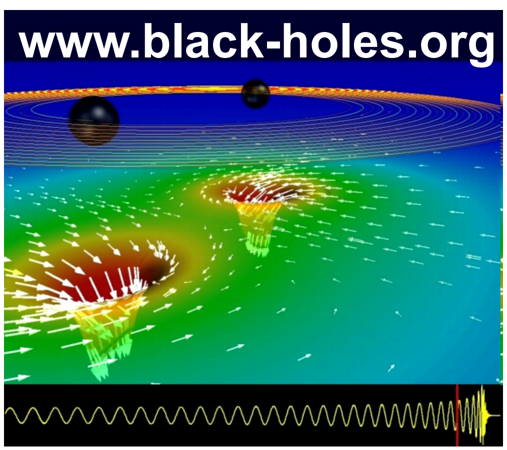
Testing General Relativity in the strong-field, dynamical regime

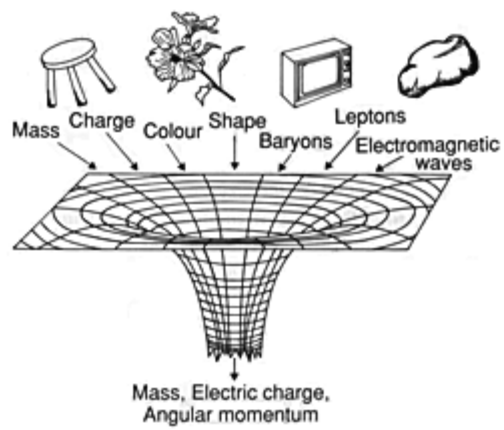
- **Test post-Newtonian expansion of inspiral phase.**

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

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

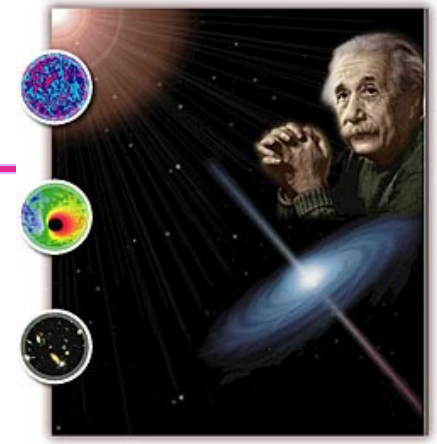






nonlocal.com/hbar/blackholes.html

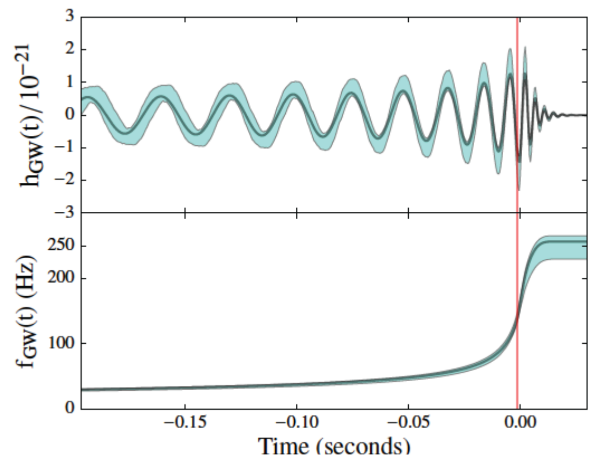
Testing beyond-GR in wave generation and propagation

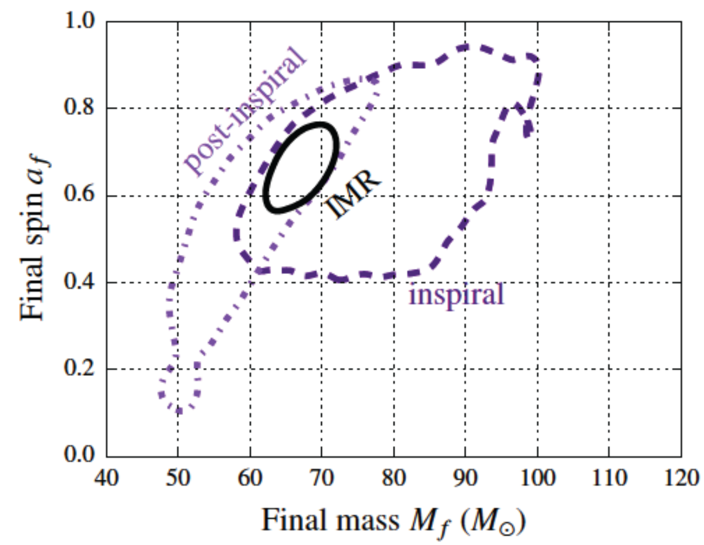


- **We can test GR in the new regime of strong-field, highly dynamical gravity!**
- **Gravitational lensing & multiple "images" (not beyond GR!)**
- **Constrain "parameterized post-Einsteinian framework" (Yunes & Pretorius, 2009)**
- **Directly measure speed of gravitational waves ($c_{GW} \neq c_{light}$),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

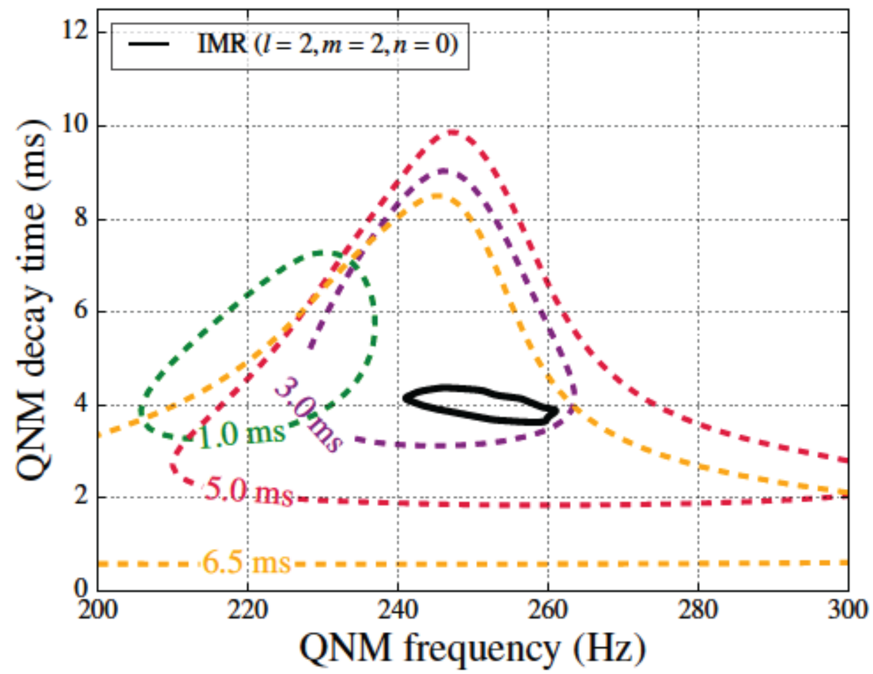




Tests of General Relativity with GW150914
Phys. Rev. Lett. 116, 221101 (2016)

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

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

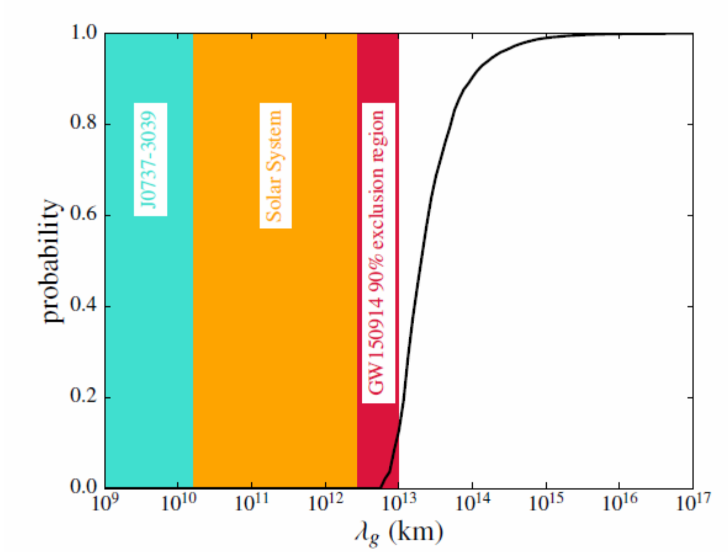
results in frequency-dependent velocity

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

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:



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

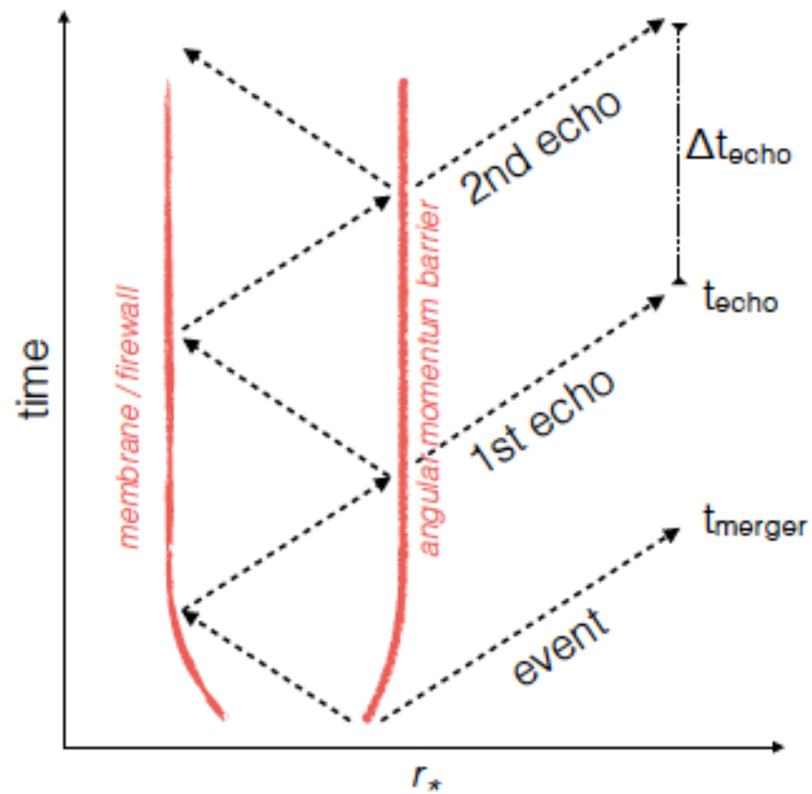
$$m_g \leq 1.2 \times 10^{-22}\,\mathrm{eV/c^2}\ (90\%)$$

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

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

What if GR black holes … aren't?

- **Planck-scale departures from GR (firewalls, fuzzballs, gravastars) near their horizons can lead to "echoes" of the BH ringdown GW.**
- **"Echoes from the Abyss: Evidence for Planck-scale structure at black hole horizons", Abedi, Dykaar, Afshordi arXiv:1612.00266v1**
- **repeating damped echoes with time-delays of *~ 8M logM***



Echoes from the Abyss:

arXiv:1612.00266v1, Abedi, Dykaar, and Afshordi

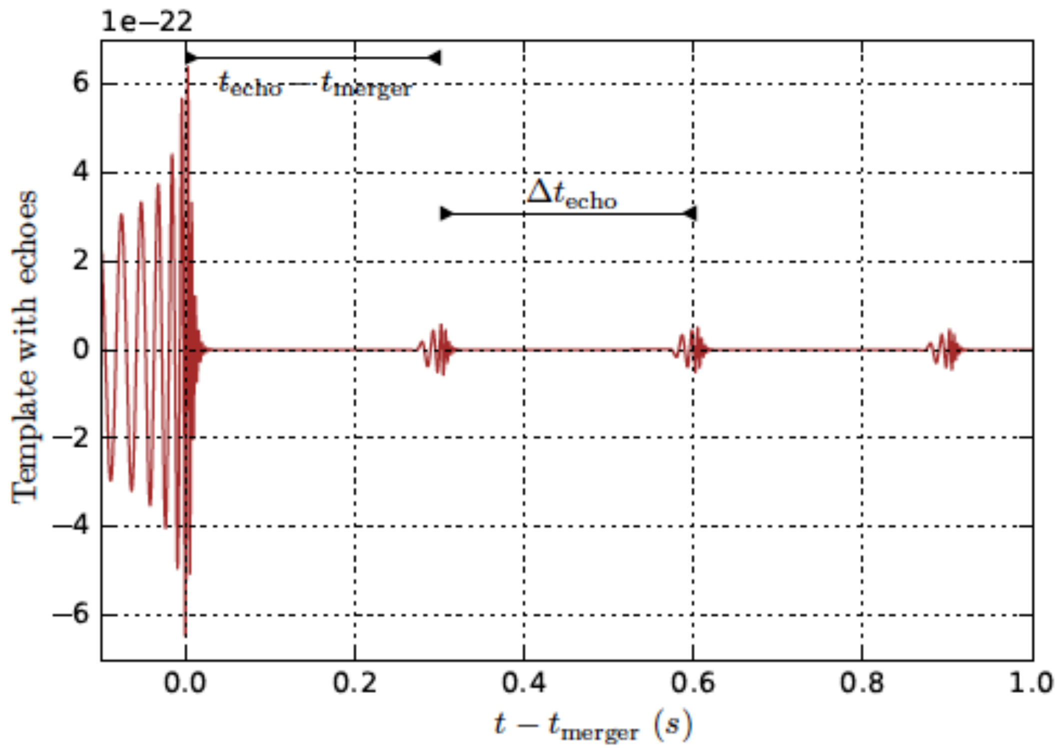
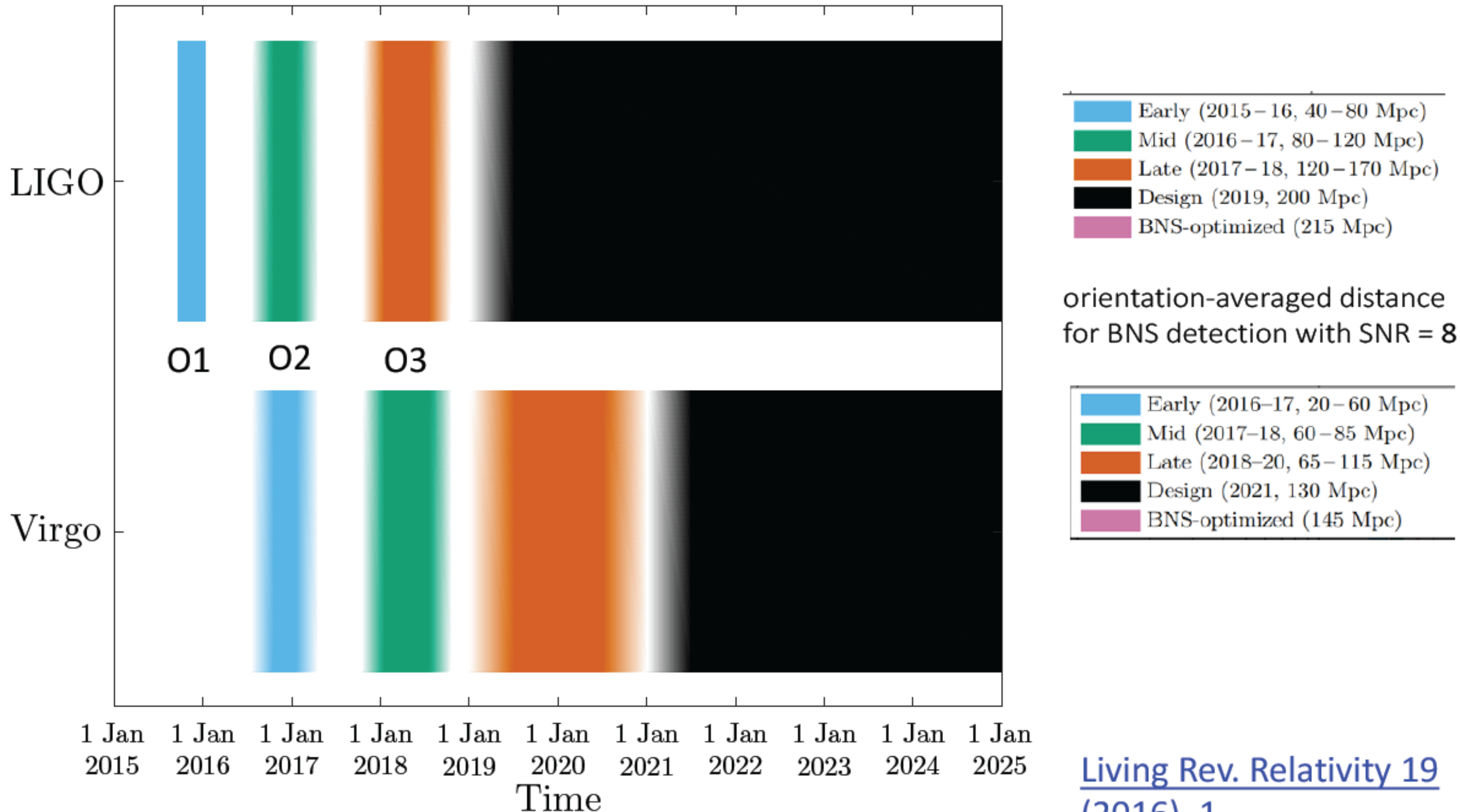


FIG. 2: LIGO original template for GW150914, along with our best fit template for the echoes.

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

Near-term observing plan, LIGO and Virgo



orientation-averaged distance for BNS detection with SNR = **8**

Living Rev. Relativity 19 (2016), 1

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;**
- **and a rich new branch of astrophysics.**

But most of all, we look forward to …

the unexpected!

Thank You!

And Happy Λ Day!