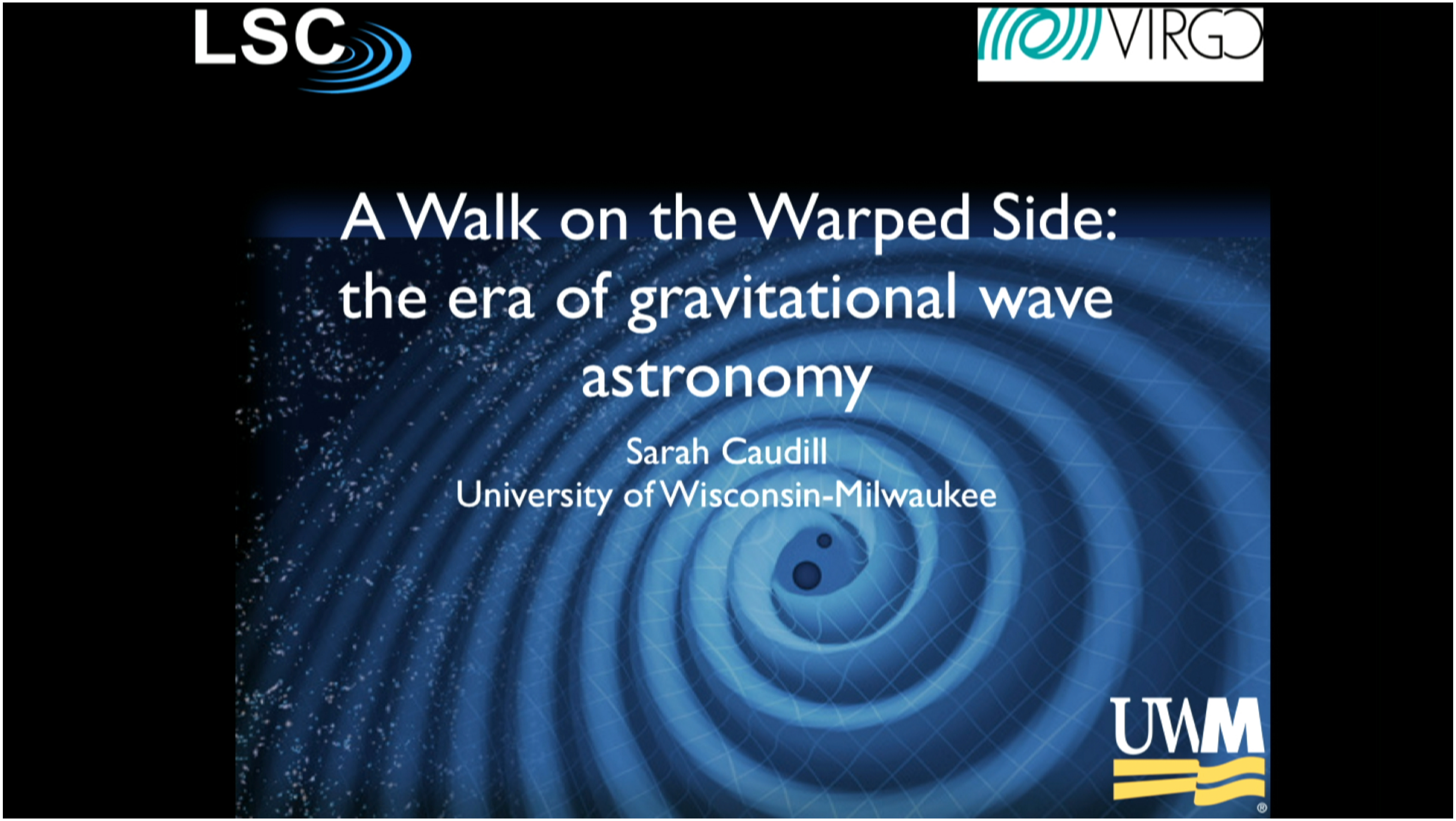
Title: A Walk on the Warped Side: the era of gravitational-wave astronomy

Date: Sep 15, 2016 01:00 PM

URL: http://pirsa.org/16090031

Abstract: <p>LIGO's first observing run which ended in January 2016 yielded two unambiguous gravitational wave signals (GW150914 and GW151226) from the merger of binary black holes as well as a possible third signal (LVT151012). I will review our current estimates of the parameters of the source systems as well as possible formation scenarios. I will discuss how joint analyses of GW150914 and GW151226 allow us to place bounds on departures from general relativity, infer astrophysical binary black hole formation rates, and constrain the mass distribution of coalescing black hole systems. Additionally, I will review the status of searches for other types of gravitational wave signals in data from LIGO's first observing run as well as the implications of the nondetection of gravitational waves from the merger of binary neutron star and neutron-star-black-hole systems. Finally, with the start of LIGO's second observing run within the next few weeks, I will outline our expectations for new detections and scientific prospects.</p>



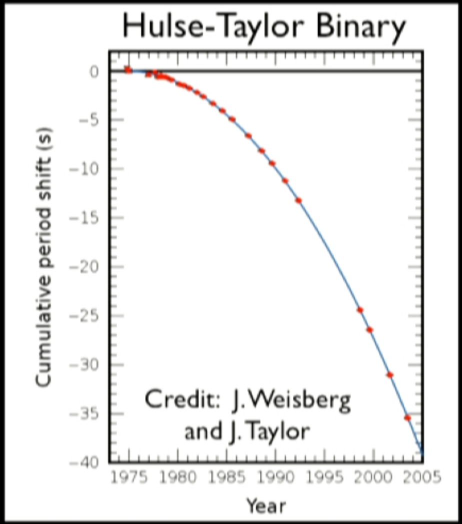
A Walk on the Warped Side: the era of gravitational wave astronomy

Sarah Caudill
University of Wisconsin-Milwaukee

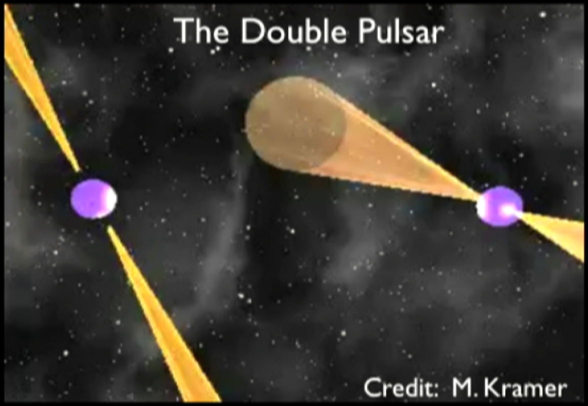
Where we placed our bets...

Advanced LIGO	**Low Detection Rates** (yr^{-1})	**Realistic Detection Rates** (yr^{-1})
Neutron Star Binaries	0.4	40
Neutron Star-Black Hole Binaries	0.2	10
Black Hole Binaries	0.4	20

LVC, Class. Quant. Grav. 27. 173001 (2010)

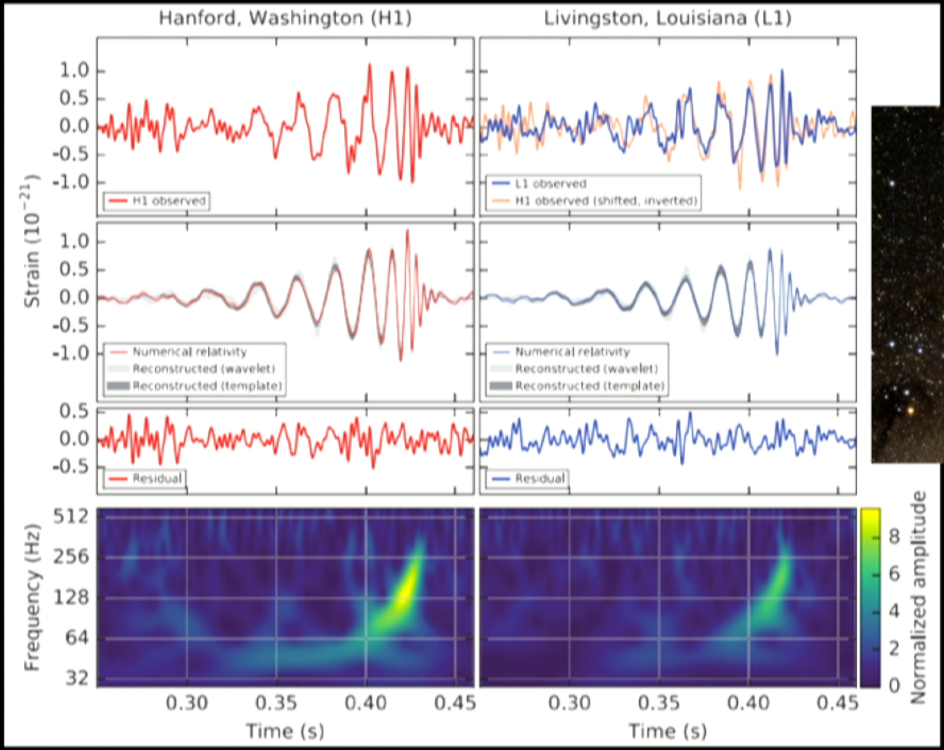


Credit: J. Weisberg and J. Taylor



Credit: M. Kramer

September 14, 2015 at 09:50:45 GMT



LVC, PRL 116, 061102 (2016)

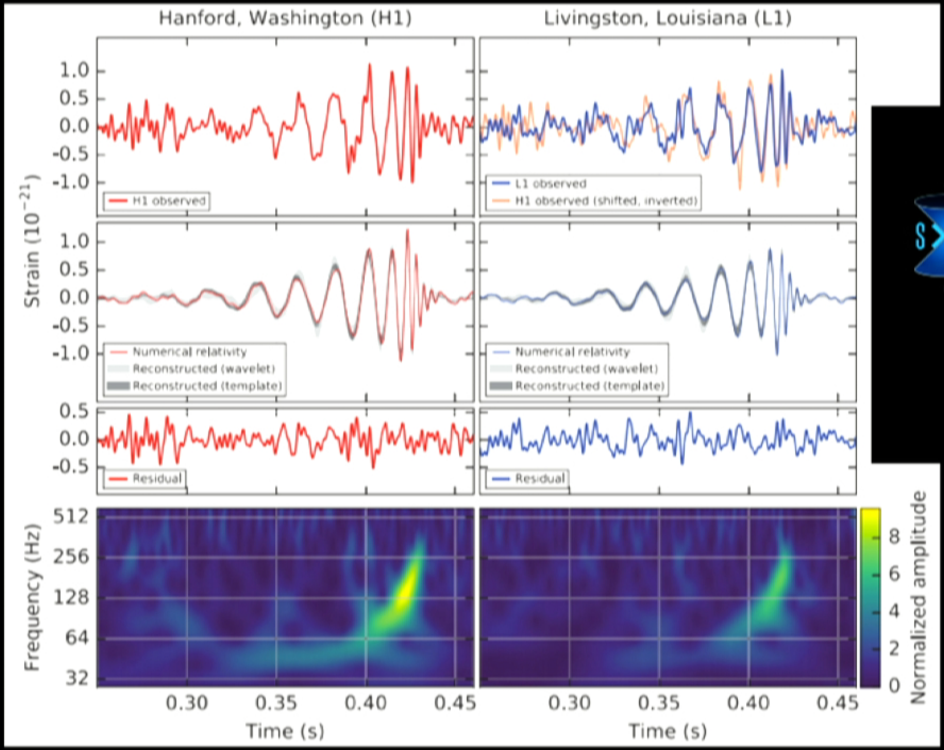
Binary Black Hole Merger!

Courtesy: SXS Collaboration

- Over 1 billion light years away.
- 3 $M_\odot$ radiated as GW energy in fraction of second.

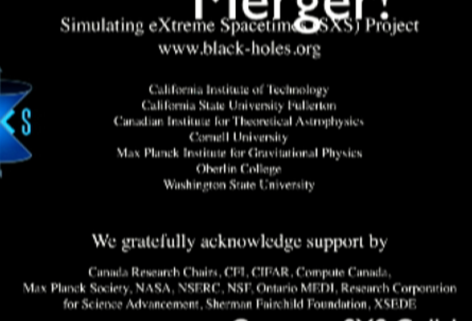
GW150914 found within 3 minutes of arriving.

September 14, 2015 at 09:50:45 GMT



LVC, PRL 116, 061102 (2016)

Binary Black Hole Merger!



Simulating eXtreme Spacetimes (SXS) Project
www.black-holes.org

California Institute of Technology
California State University Fullerton
Canadian Institute for Theoretical Astrophysics
Cornell University
Max Planck Institute for Gravitational Physics
Oberlin College
Washington State University

We gratefully acknowledge support by

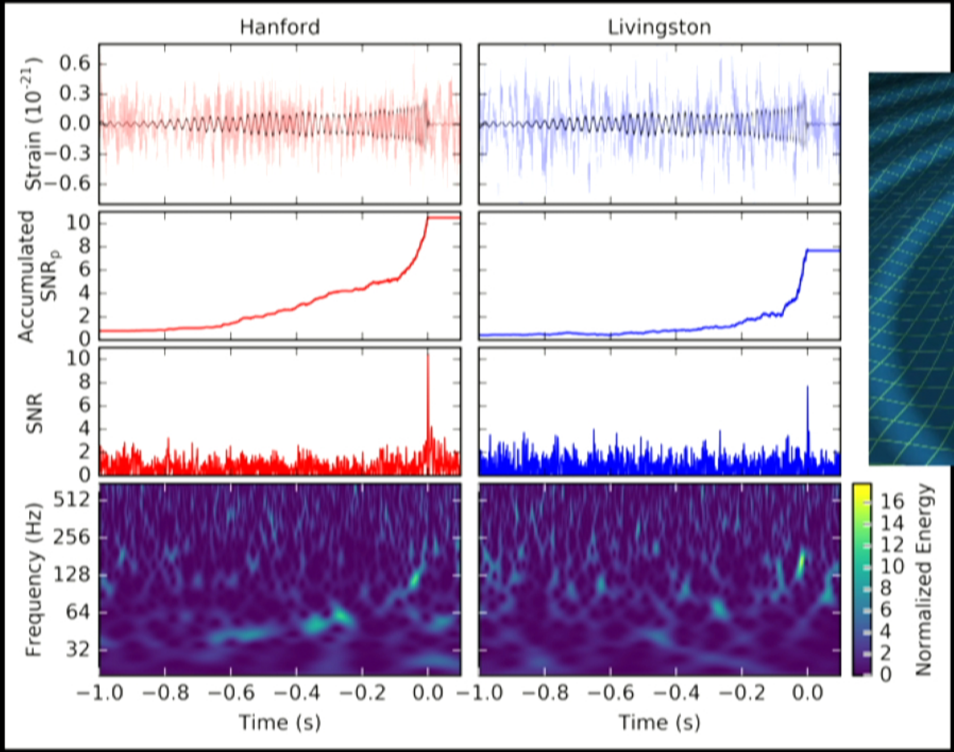
Canada Research Chairs, CFI, CIFAR, Compute Canada,
Max Planck Society, NASA, NSERC, NSF, Ontario MEDI, Research Corporation
for Science Advancement, Sherman Fairchild Foundation, XSEDE

Courtesy: SXS Collaboration

- Over 1 billion light years away.
- 3 M$_\odot$ radiated as GW energy in fraction of second.

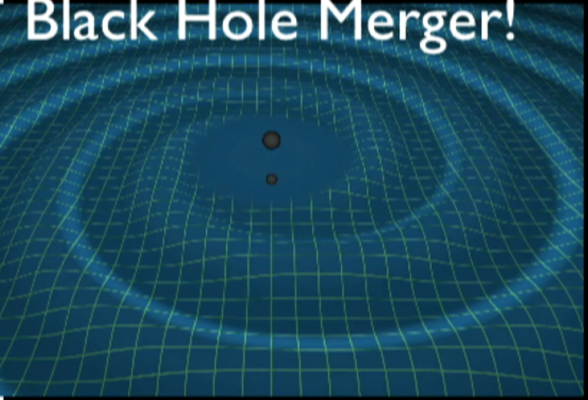
GW150914 found within 3 minutes of arriving.

December 26, 2015 at 03:38:53 GMT



LVC, PRL 116, 241103 (2016)

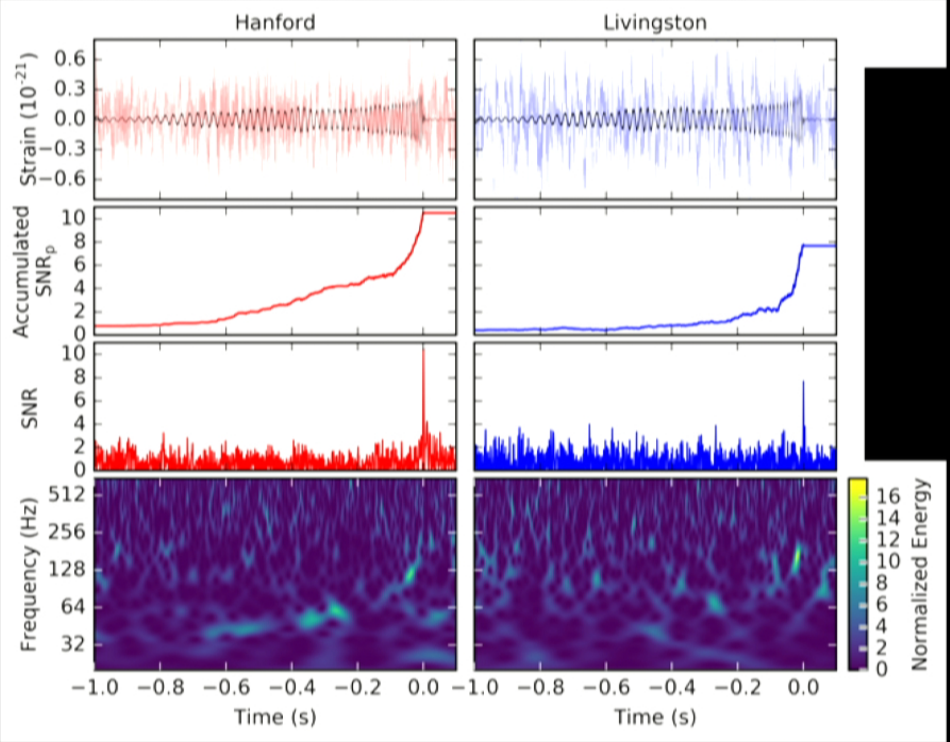
Another Binary Black Hole Merger!



- Over 1 billion light years away.
- 1 M$_\odot$ radiated as GW energy in ~1 second.

GW151226 found within 70 seconds of arriving.

December 26, 2015 at 03:38:53 GMT



LVC, PRL 116, 241103 (2016)

Another Binary Black Hole Merger!

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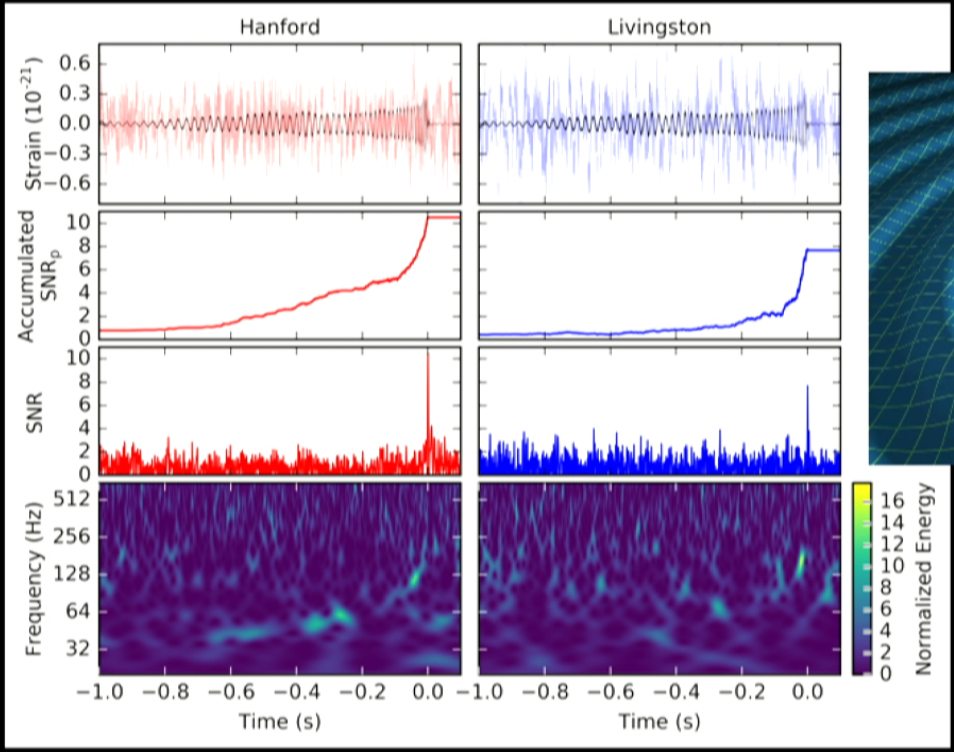
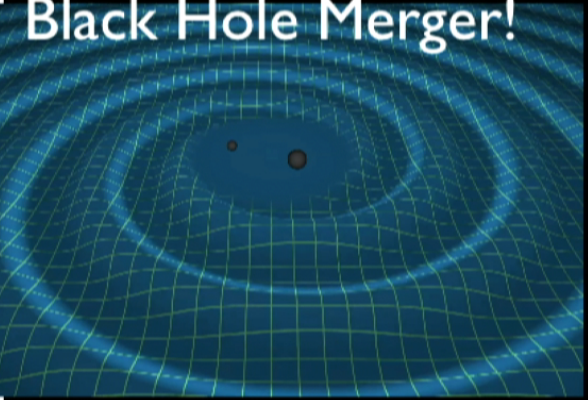


LVC, PRL 116, 241103 (2016)

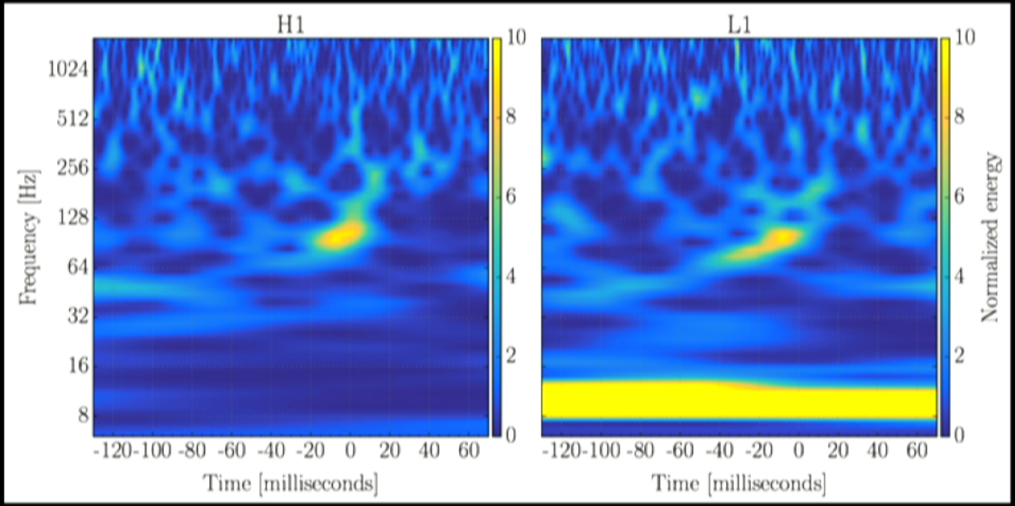
Another Binary Black Hole Merger!



- Over 1 billion light years away.
- 1 $M_{\odot}$ radiated as GW energy in ~1 second.

GW151226 found within 70 seconds of arriving.

October 12, 2015 at 09:54:43 GMT
A third detection?

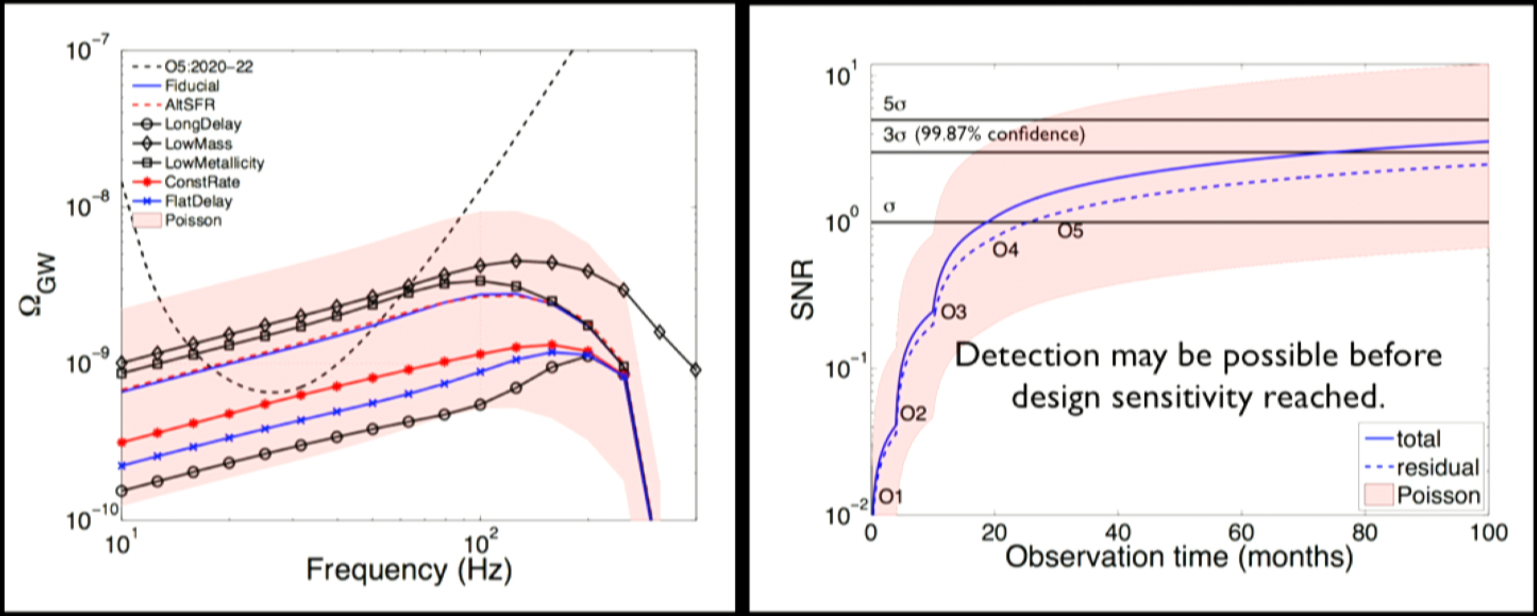


LVC, CQG 33, 134001 (2016)

- 2% chance LVT151012 could be due to noise.
- It would also be a binary black hole.

A stochastic background of gravitational waves from binary black holes?

$$\Omega_{\rm GW}(f < 100{\rm Hz}) \propto M_c^{5/3} f^{2/3}$$



LVC, Phys. Rev. Lett. 116, 131102 (2016)

How significant were these signals?

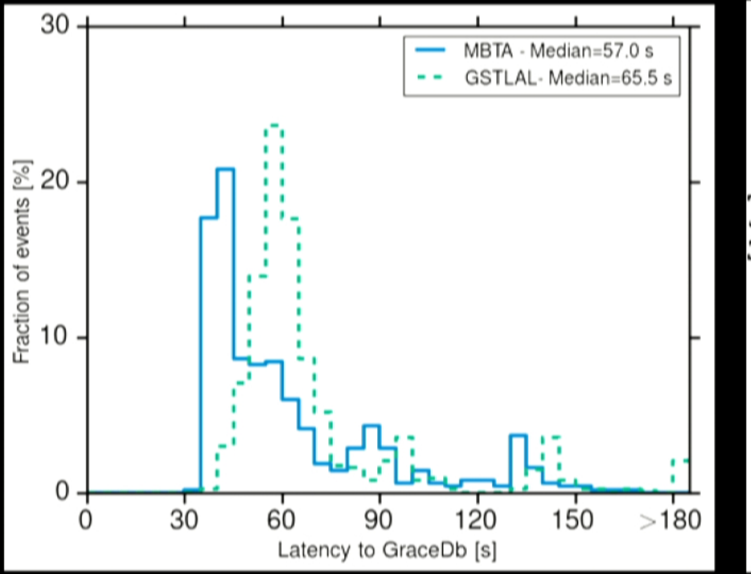
gstLAL - low-latency and archival matched-filter searches

gstreamer

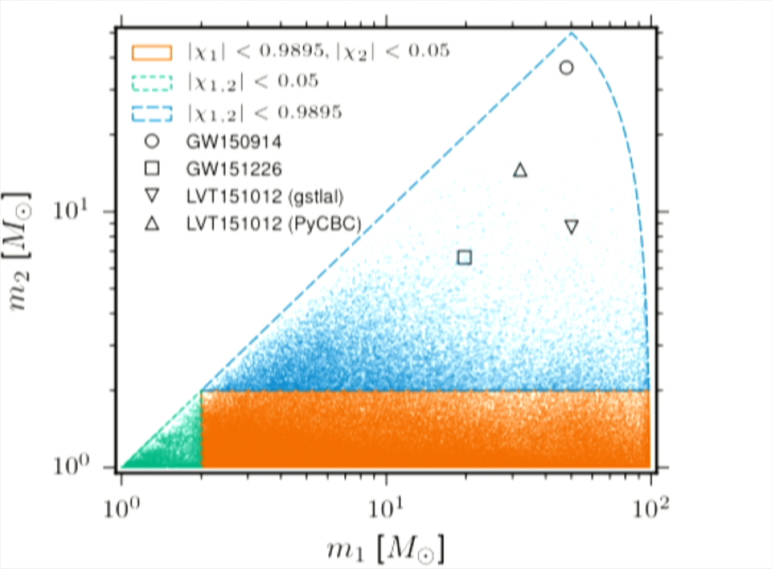
- an open source media library
- used for low-latency processing of LIGO data

Highlights from O1

- Implemented überbank for low-latency searches
- Identified GW151226 within 70s
- Demonstrated use of timeslide-less background estimation
- Development of IMBH matched-filter search



LVC, arXiv:1607.07456



LVC, PRD. 93, 122003 (2016)

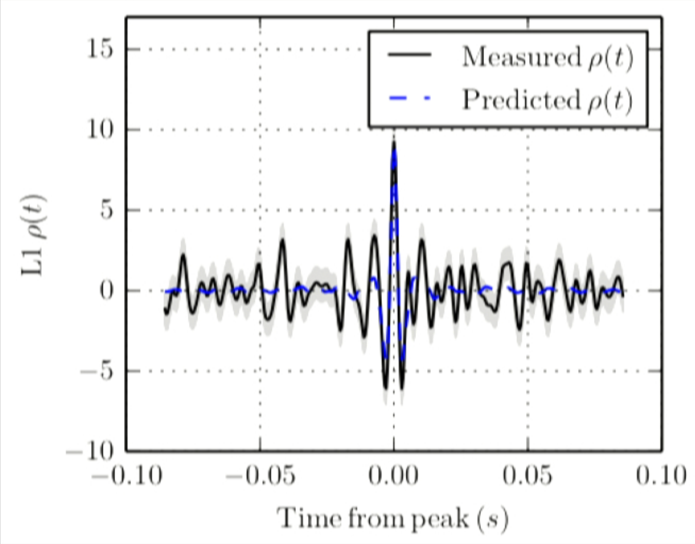
Some features of the GstLAL pipeline

- Time-domain matched-filtering
  - Template bank compression by SVD/multibanding

$$\mathrm{SNR}(t) = \rho(t) = 2\int_{-\infty}^{\infty} \mathrm{d}\tau\, \hat{h}_i(\tau)\hat{d}(t+\tau)$$

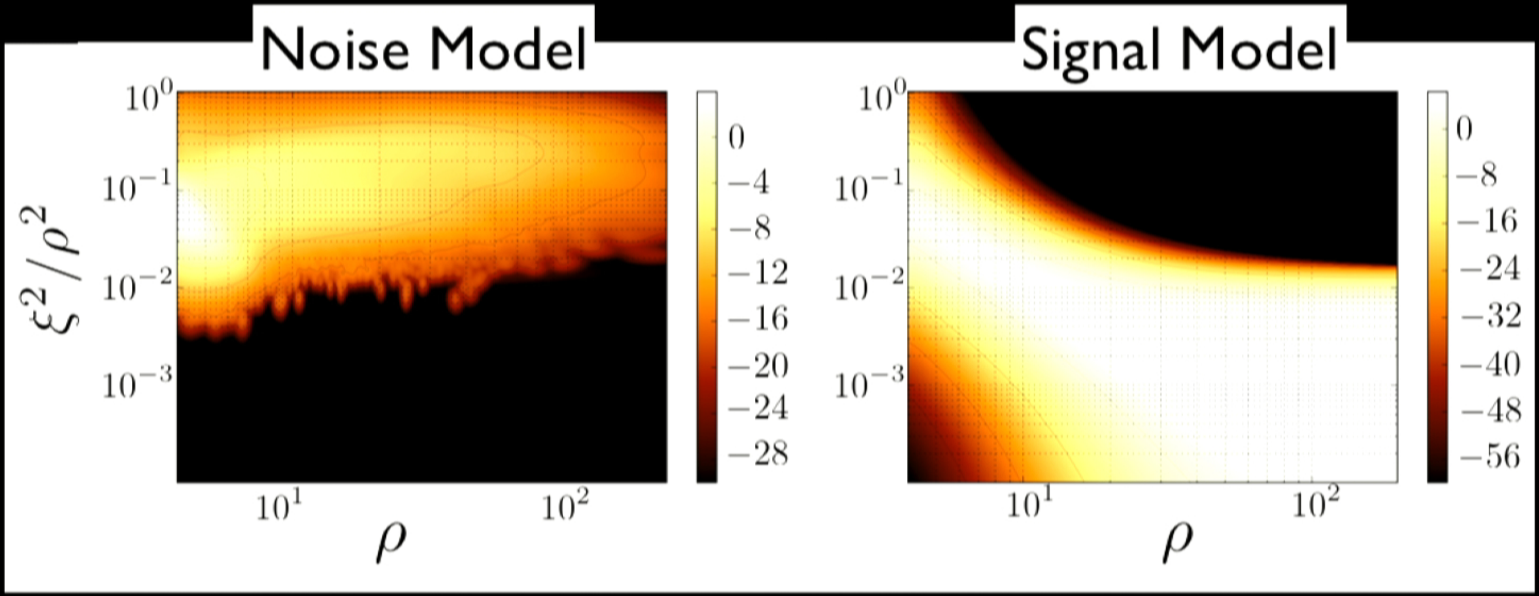
- Autocorrelation-based least squares test ξ^2
- Likelihood ratio ranking statistic
  - Noise model built from non-coincident triggers. No timeshifts!
  - Signal model assumes uniform-in-volume sources and 10% waveform mismatch.

Ingredients for computing ξ^2



Messick, et al, arXiv:1604.04324

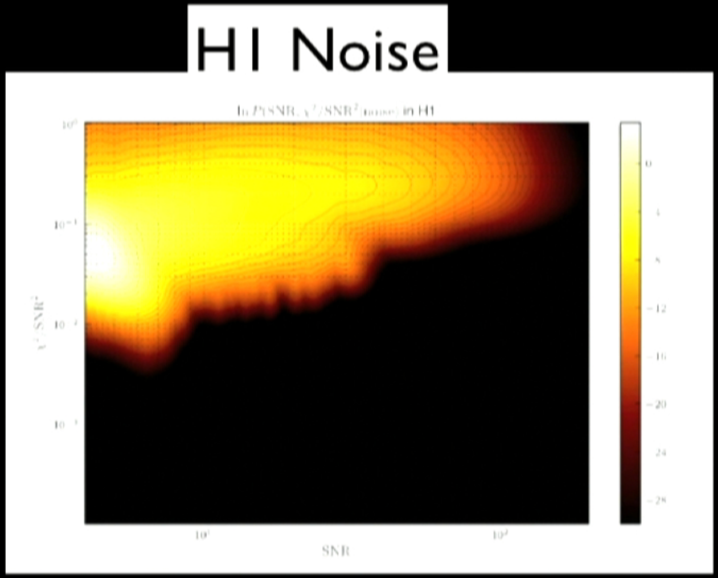
The likelihood ratio

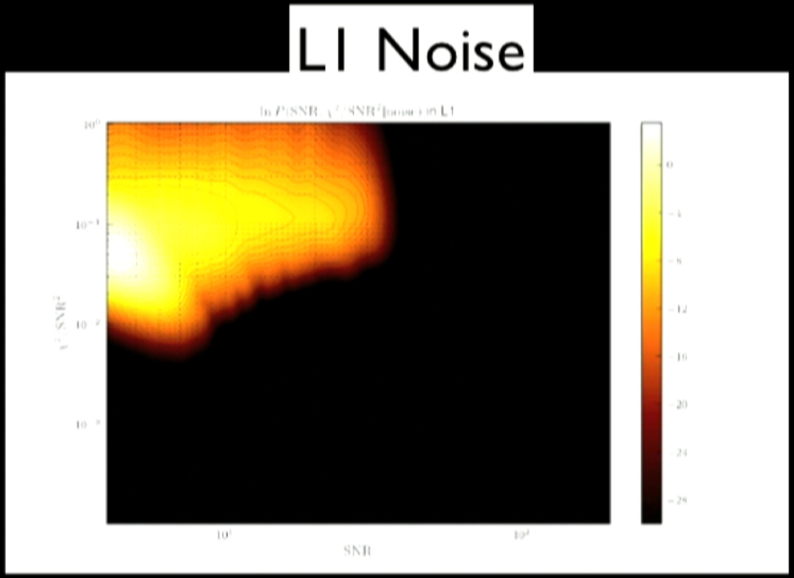


$$\mathcal{L} = \frac{P\left(\mathbf{x}_{\mathrm{H}}, \mathbf{x}_{\mathrm{L}}, D_{\mathrm{H}}, D_{\mathrm{L}} | \bar{\theta}, \mathrm{signal}\right)}{P\left(\mathbf{x}_{\mathrm{H}} | \bar{\theta}, \mathrm{noise}\right) P\left(\mathbf{x}_{\mathrm{L}} | \bar{\theta}, \mathrm{noise}\right)}$$

$$\mathbf{x}_{\mathrm{H,L}} = \left\{\rho, \xi^2, \ldots\right\}$$

Modeling the noise for different template regions

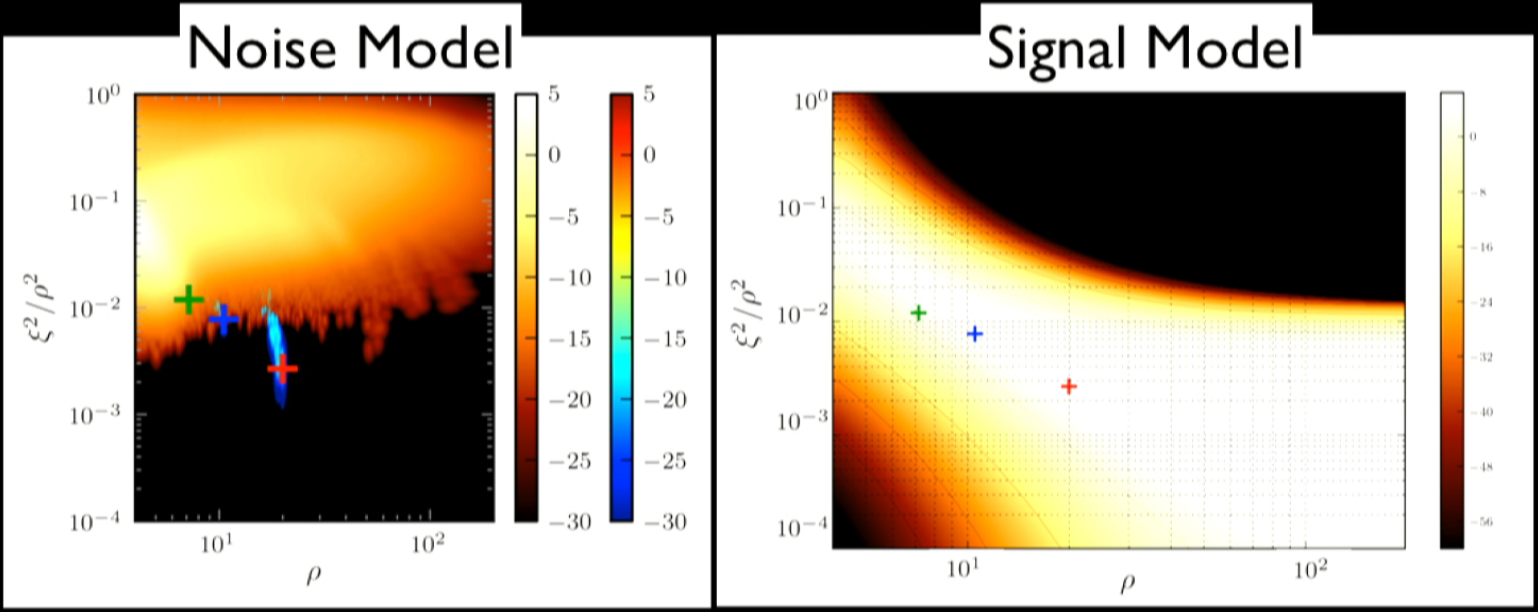

H1 Noise


L1 Noise

Movie shows evolution of $\{\rho, \xi^2\}$ from low mass to high mass.

Linearly dependent templates are grouped together for noise modeling.

Where do the events fall?



Noise Model

Signal Model

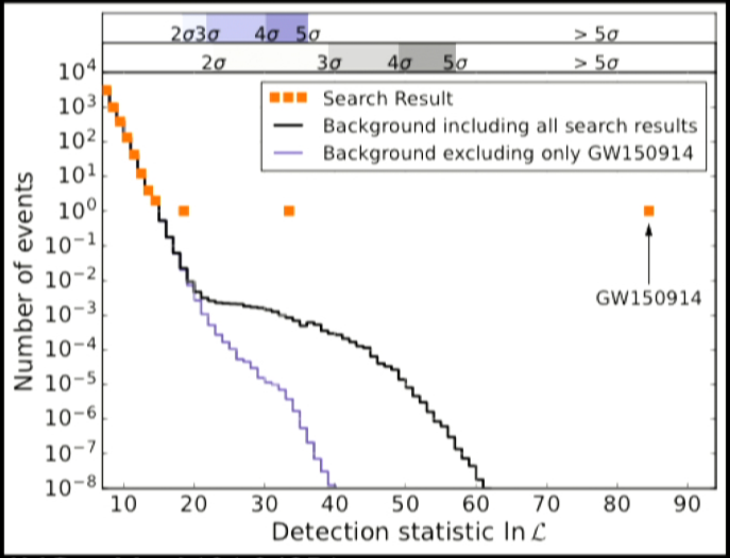
Credit: S. Sachdev (CIT), C. Messick (PSU)

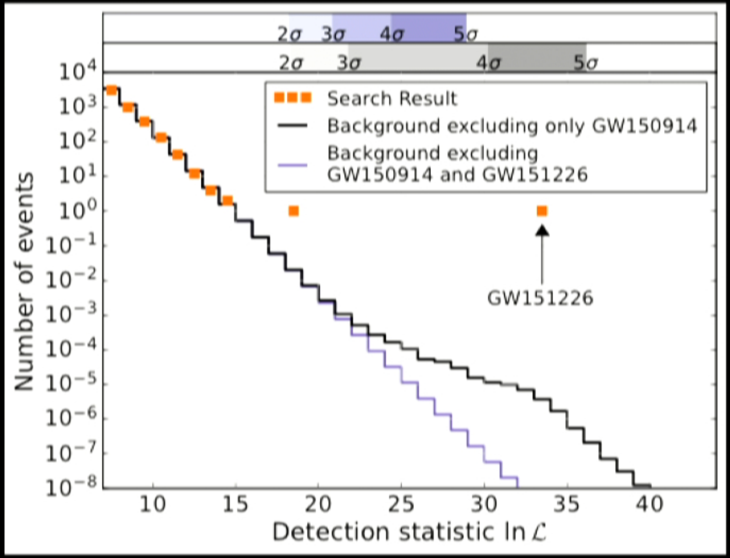
+ GW150914

+ GW151226

+ LVT151012

Search results from the GstLAL pipeline

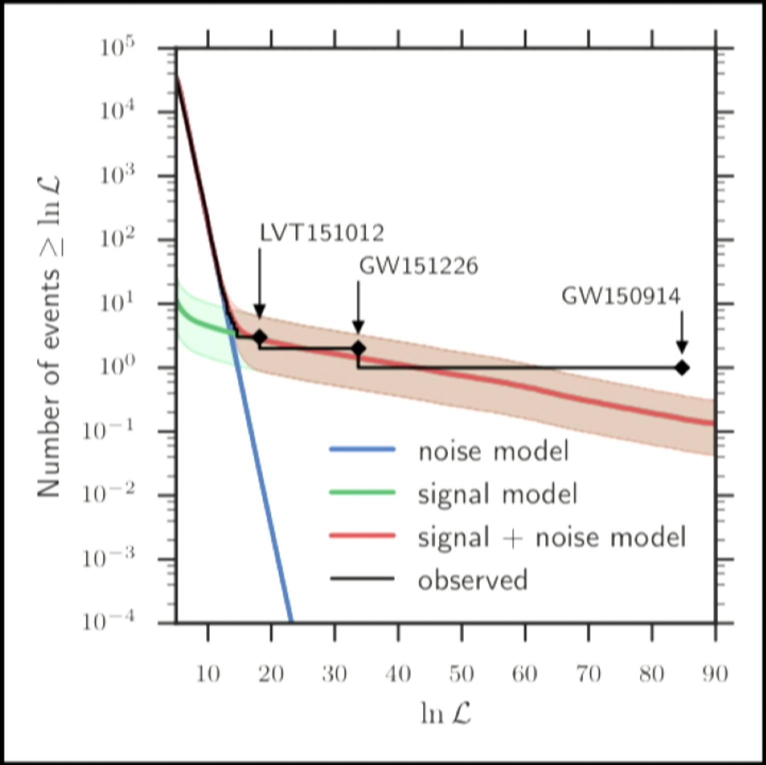




LVC, arXiv:1606.04856

	$\ln \mathcal{L}$	Significance
GW150914	84.7	$> 5\sigma$
GW151226	22.6	4.5σ
LVT151012	18.1	2.0σ

Cumulative distribution of observed triggers

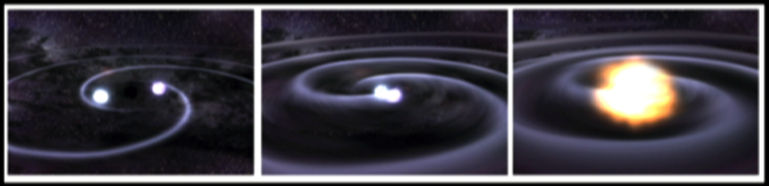


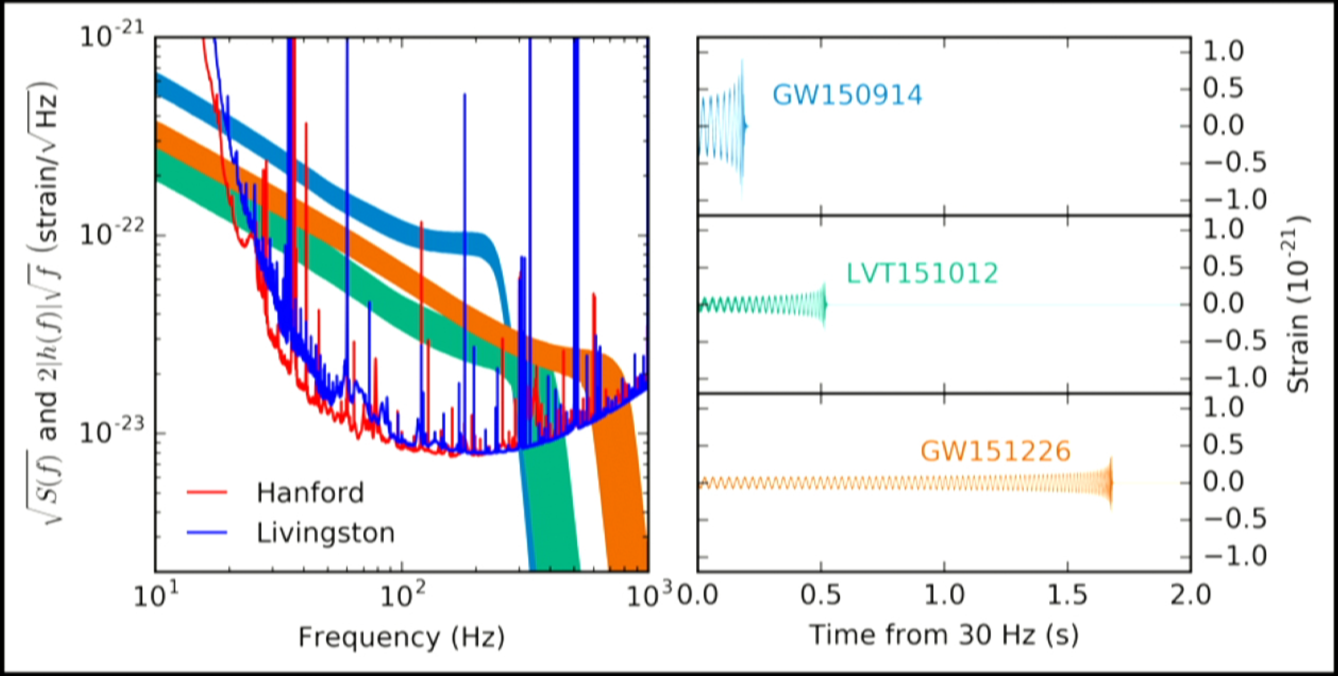
LVC, arXiv:1606.04856

	Probability of astrophysical origin
GW150914	1.0
GW151226	1.0
LVT151012	0.86

Probability of astrophysical origin for all remaining events < 15%.

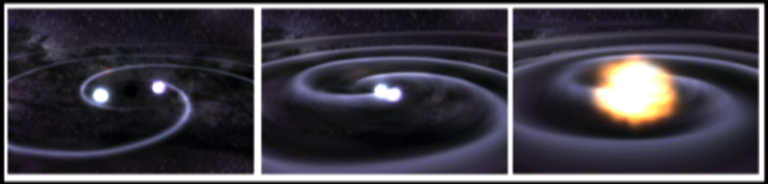
Detector noise and signal waveforms

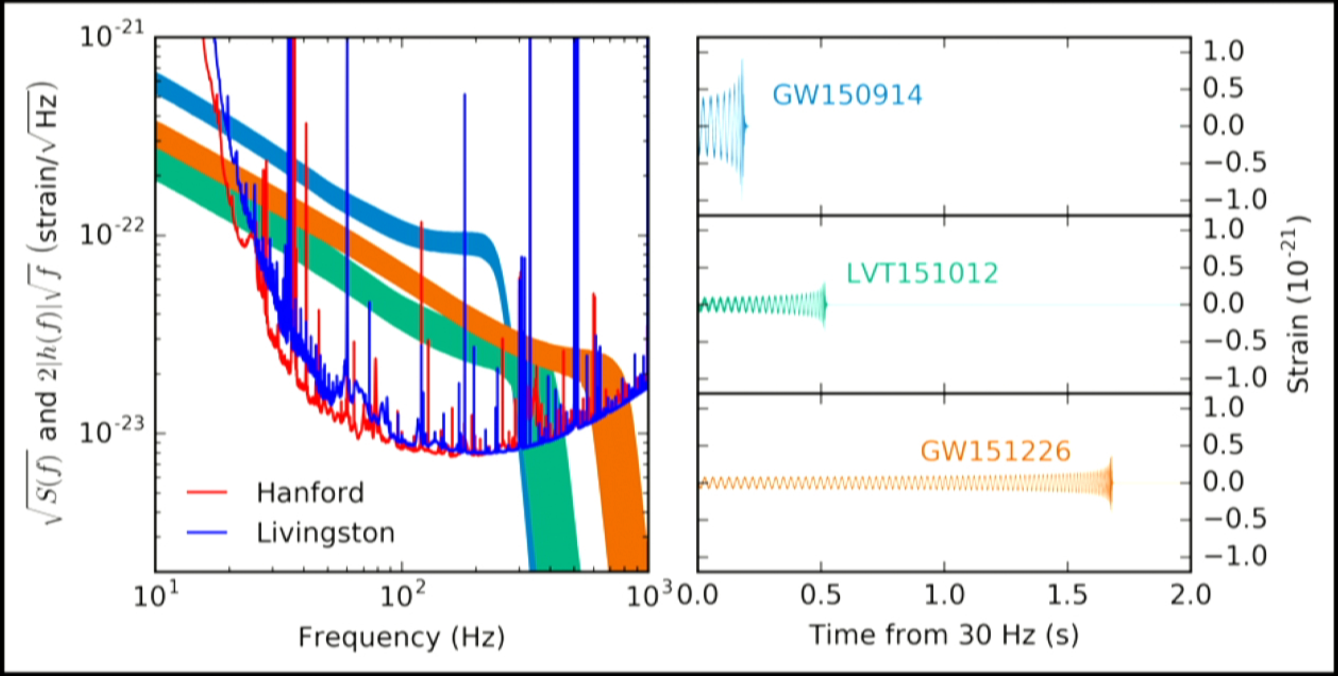




LVC, arXiv:1606.04856

Detector noise and signal waveforms





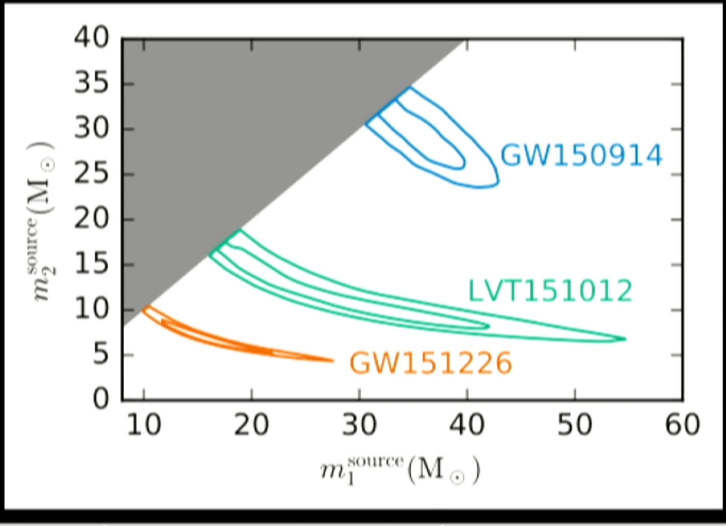
LVC, arXiv:1606.04856

Component masses from Bayesian stochastic sampling

From early inspiral:

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$
$$\simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

$$q = m_2/m_1$$



From late inspiral:

$$M_{\rm total} = m_1 + m_2$$

	$m_1\ (\mathrm{M}_\odot)$	$m_2\ (\mathrm{M}_\odot)$
GW150914	$36.2^{+5.2}_{-3.8}$	$29.1^{+3.7}_{-4.4}$
LVT151012	23^{+18}_{-6}	13^{+4}_{-5}
GW151226	$14.2^{+8.3}_{-3.7}$	$7.5^{+2.3}_{-2.3}$

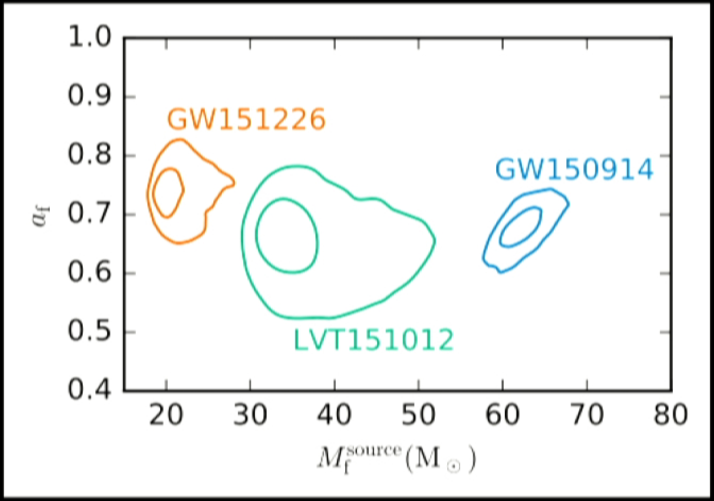
LVC, arXiv:1606.04856

Final BH parameters from Bayesian stochastic sampling

From late inspiral and merger:

$$M_{\mathrm{final}},\ a_{\mathrm{final}} = \frac{c}{GM_{\mathrm{final}}^2}\left|\vec{S}_{\mathrm{final}}\right|$$

$$E_{\mathrm{rad}} = M_{\mathrm{total}} - M_{\mathrm{final}}$$



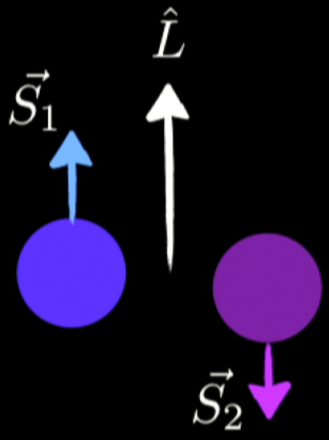
	$M_{\mathrm{final}}\ (M_\odot)$	$E_{\mathrm{rad}}\ (M_\odot c^2)$	a_{final}
GW150914	$62.3^{+3.7}_{-3.1}$	$3.00^{+0.47}_{-0.39}$	$0.68^{+0.05}_{-0.06}$
LVT151012	35^{+14}_{-4}	$1.50^{+0.33}_{-0.43}$	$0.66^{+0.09}_{-0.10}$
GW151226	$20.8^{+6.1}_{-1.7}$	$1.00^{+0.10}_{-0.20}$	$0.74^{+0.06}_{-0.06}$

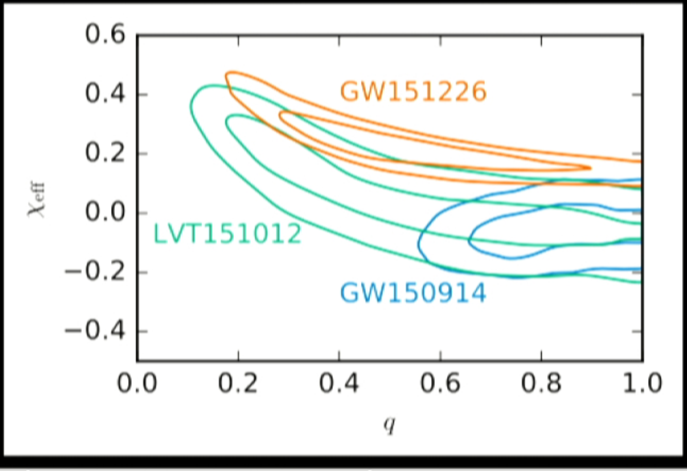
LVC, arXiv:1606.04856

More binary parameters from Bayesian stochastic sampling

LVC, arXiv:1606.04856

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\vec{S}_1}{m_1}+\frac{\vec{S}_2}{m_2}\right)\cdot\frac{\vec{L}}{\left|\vec{L}\right|}$$

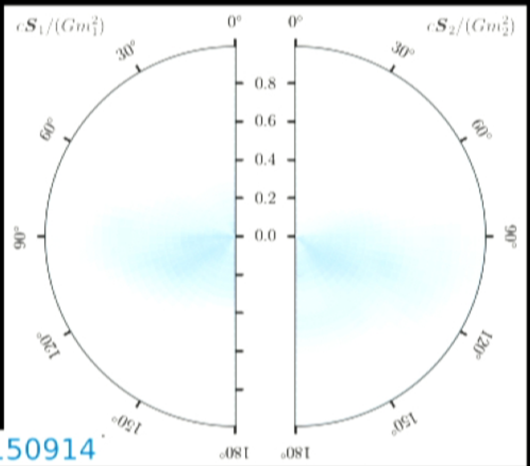




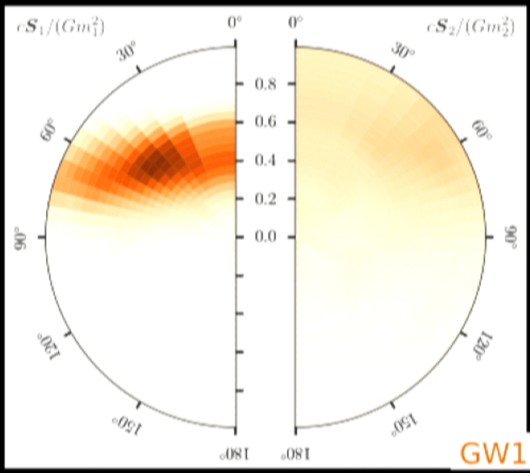
	$\chi_{\rm eff}$	Mass ratio q
GW150914	$-0.06^{+0.14}_{-0.14}$	$0.81^{+0.17}_{-0.20}$
LVT151012	$0.0^{+0.3}_{-0.2}$	$0.57^{+0.38}_{-0.37}$
GW151226	$0.21^{+0.20}_{-0.10}$	$0.52^{+0.40}_{-0.29}$

At least one component has spin ≥ 0.2 at 99% credible level.

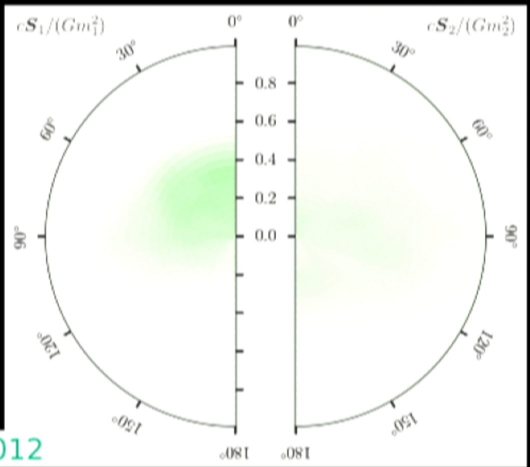
Component spin parameters from Bayesian stochastic sampling



GW150914



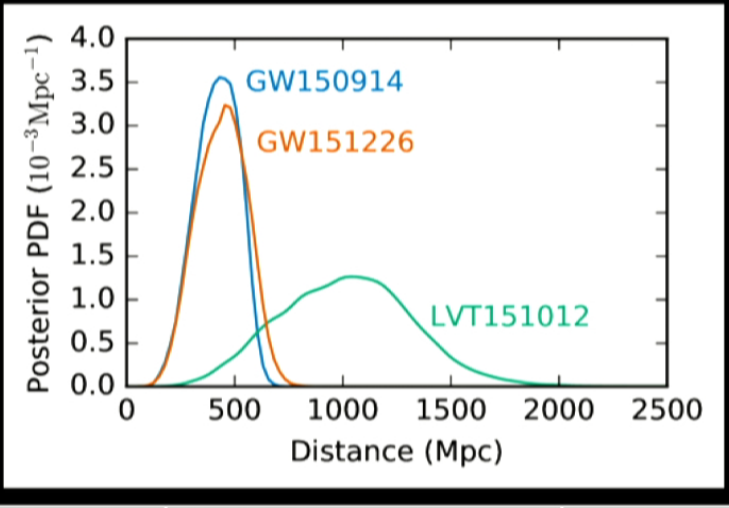
GW151226



LVT151012

LVC, arXiv:1606.04856

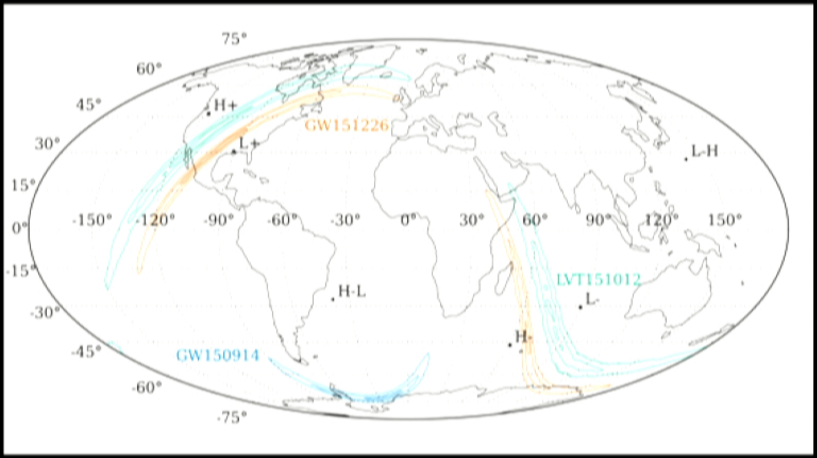
Distance parameters from Bayesian stochastic sampling



	D_L (Mpc)	Redshift z
GW150914	420^{-180}_{+150}	$0.09^{-0.04}_{+0.03}$
LVT151012	1000^{-500}_{+500}	$0.20^{-0.09}_{+0.09}$
GW151226	440^{-190}_{+180}	$0.09^{-0.04}_{+0.03}$

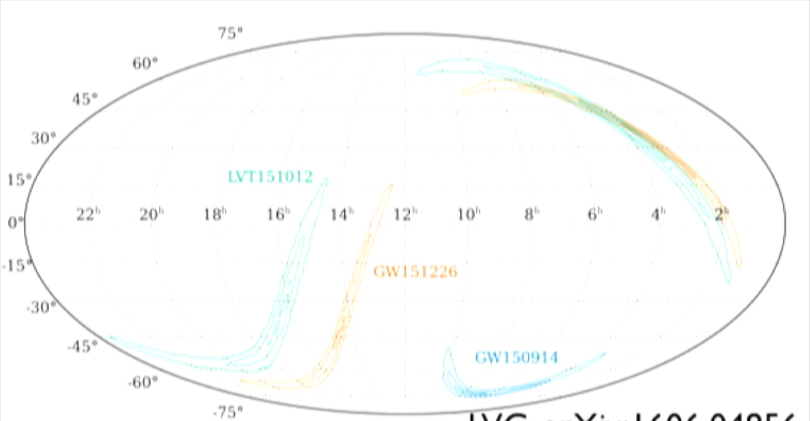
LVC, arXiv:1606.04856

Sky location parameters from Bayesian stochastic sampling



	$\Delta t_{\mathrm{HL}}(\mathrm{ms})$
GW150914	$7.0^{-0.2}_{+0.2}$
LVT151012	$-0.6^{+0.6}_{-0.6}$
GW151226	$1.1^{+0.3}_{-0.3}$

	sky area
GW150914	230 deg^2
LVT151012	1600 deg^2
GW151226	850 deg^2

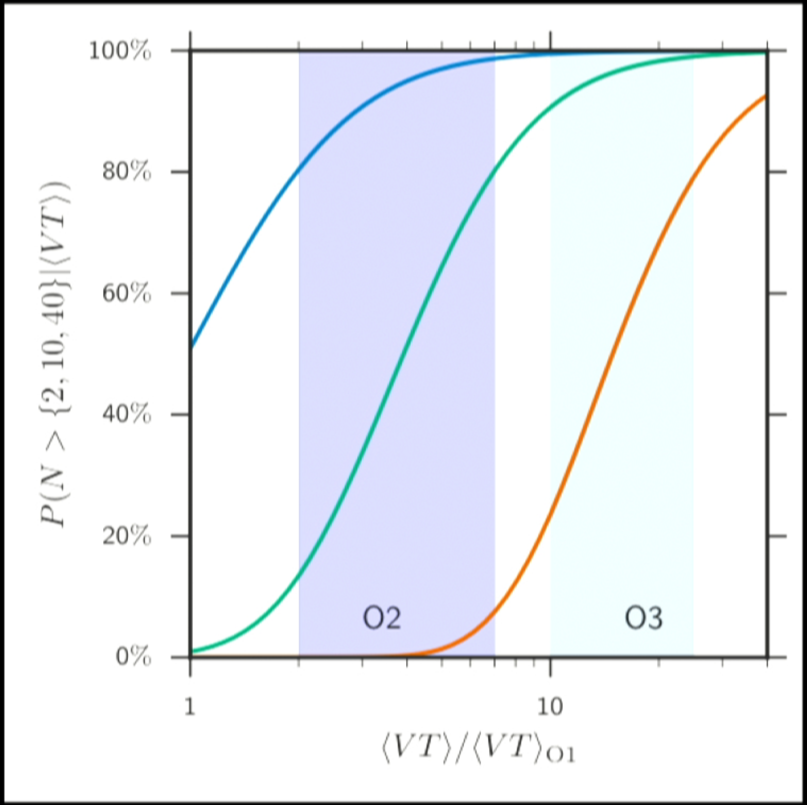


LVC, arXiv:1606.04856

What are the implications of these signals?

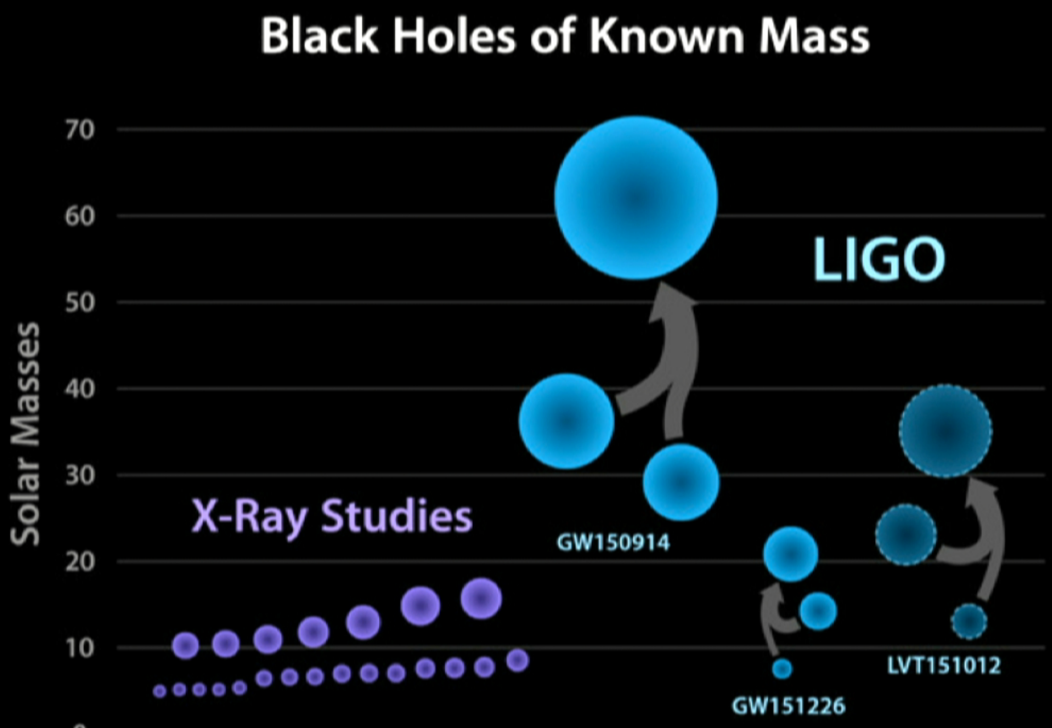
Revised binary black hole merger rates

Advanced LIGO	**Rates** (Gpc^{-3} yr^{-1})
Previous estimates	0.1 - 300
Only GW150914, LVT151012, GW151226	14 - 154
Overall rates	9 - 240



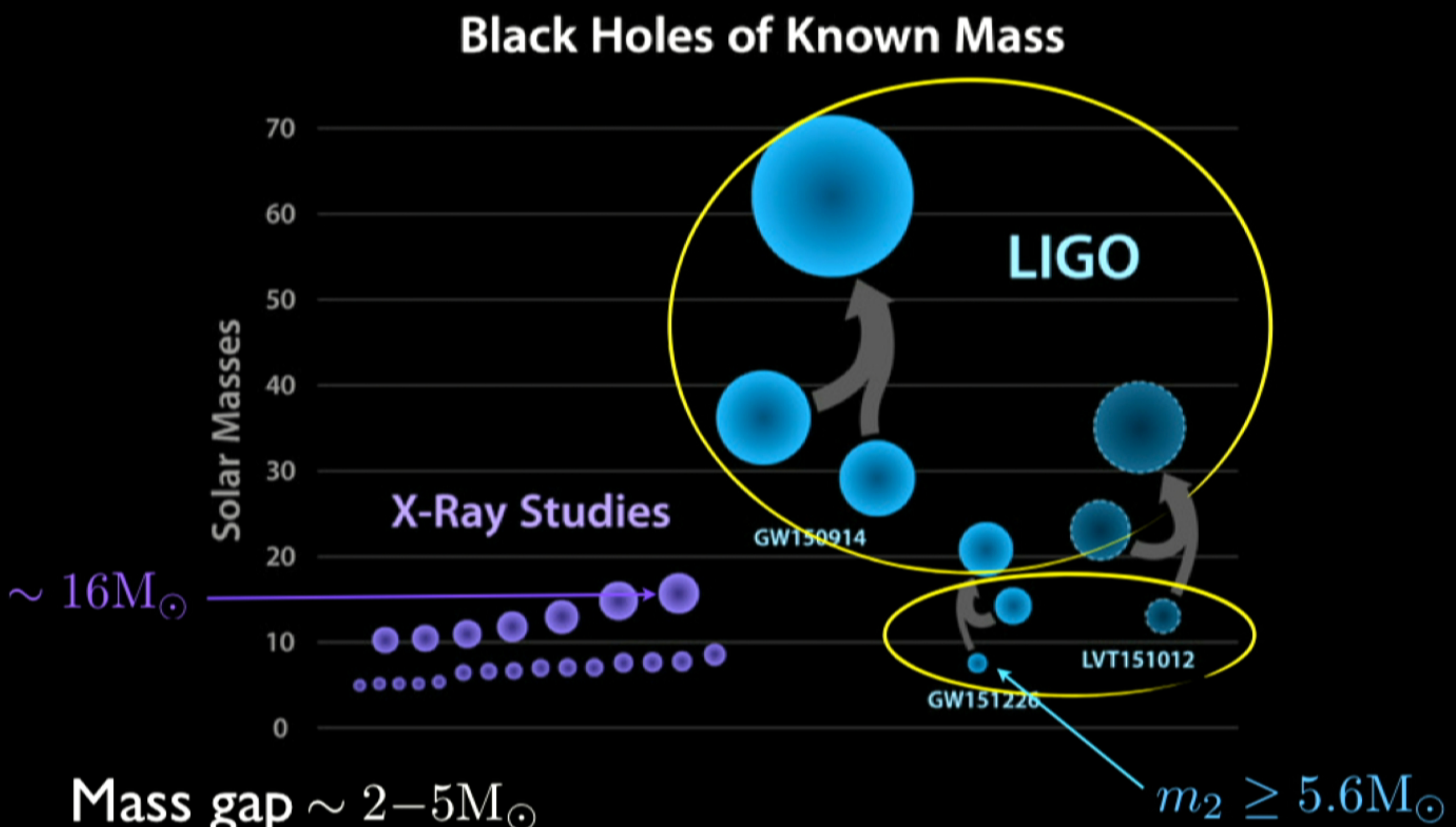
LVC, arXiv:1606.04856

Summary of stellar black hole masses



Credit: LIGO

Summary of stellar black hole masses


Black Holes of Known Mass

$\sim 16\mathrm{M}_\odot$

$m_2 \geq 5.6\mathrm{M}_\odot$

Mass gap $\sim 2\text{--}5\mathrm{M}_\odot$

Maximum neutron star mass $\sim 3\mathrm{M}_\odot$

Credit: LIGO

First attempt at constraining BBH merger mass distribution

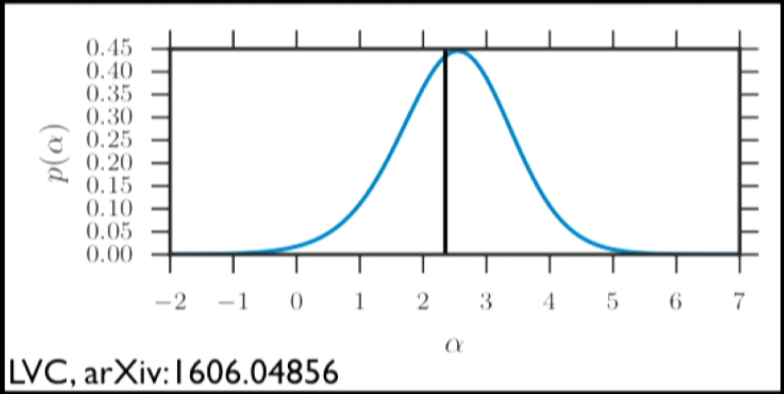
Model as general power law:

$$p\left(m1, m2, |\alpha\right) \propto \frac{m_1^{-\alpha}}{m_1 - M_{\min}}$$

Some assumptions:

$$M_{\min} = 5$$
$$m_1 + m_2 \leq 100\mathrm{M}_{\odot}$$

- Flat distribution in mass ratio.
- Redshift-independent merger rate.



LVC, arXiv:1606.04856

Weak constraint of:

$$\alpha = 2.5^{+1.5}_{-1.6}$$

Consistent with Salpeter IMF-like power law used for our rates calculation:

$$\alpha = 2.35$$

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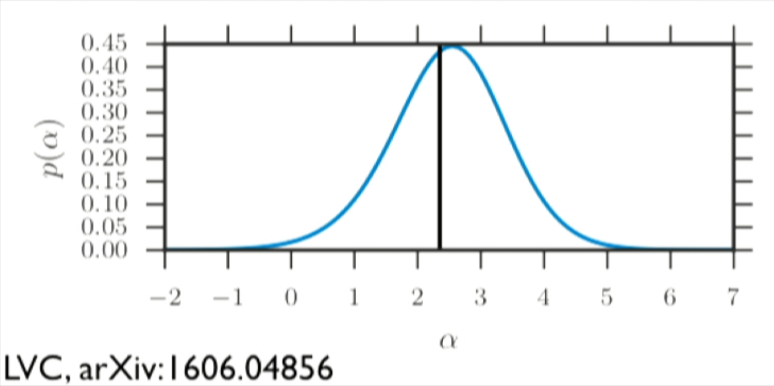

LVC, arXiv:1606.04856

Weak constraint of:

$$\alpha = 2.5^{+1.5}_{-1.6}$$

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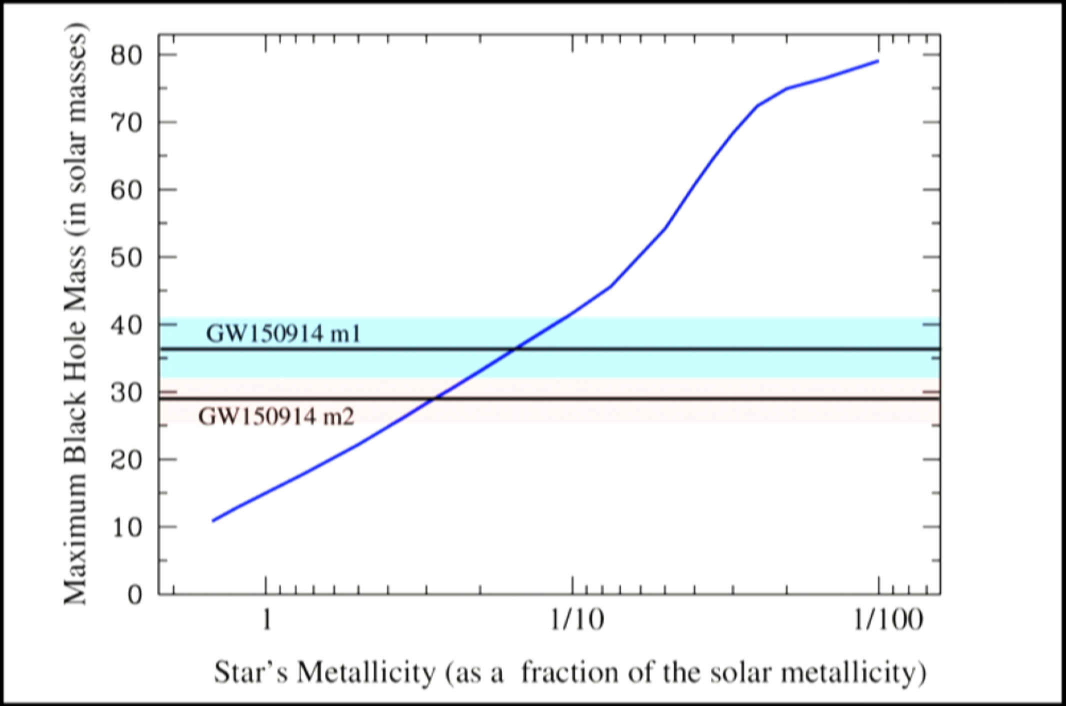
How do high stellar-mass black holes form?

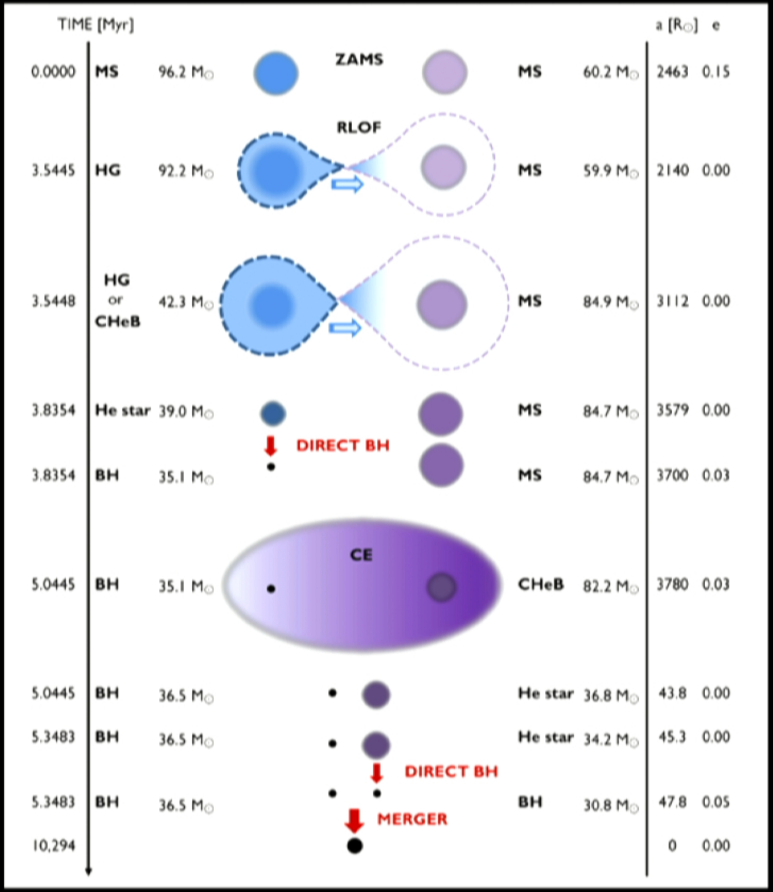


LVC, ApJL 818, 2 (2016).

Stars at lower metallicities exhibit weaker winds and reduced mass loss.

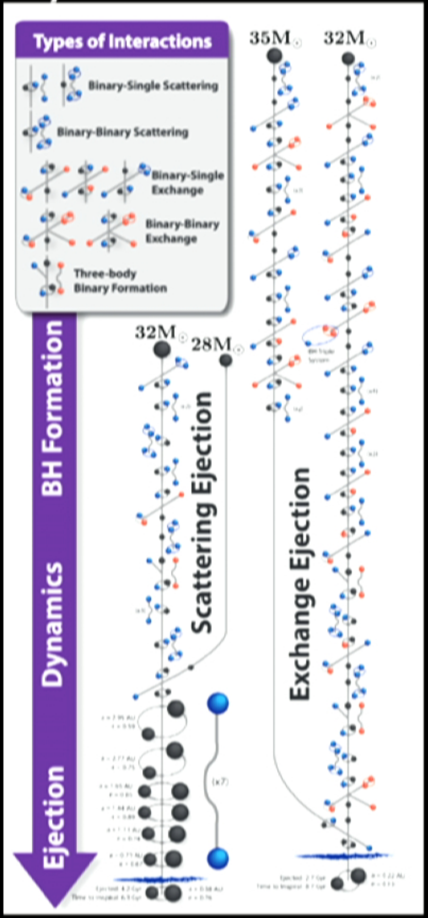
Possible formation pathways

I. Isolated stellar environment

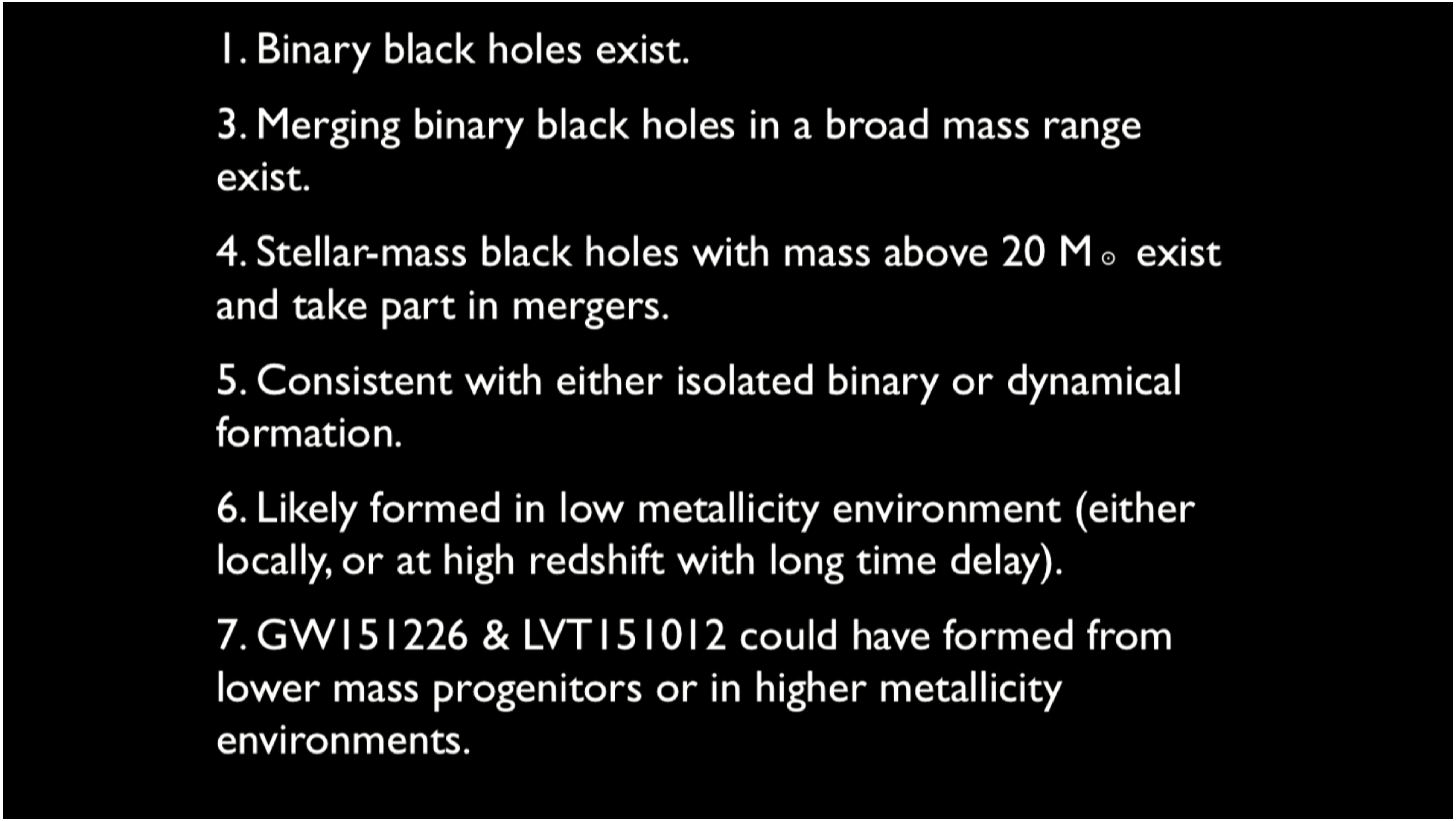


K. Belczynski, *et al.* arXiv: 1602.04531

II. Dynamical formation



C. Rodriguez, *et al.* arXiv:1604.04254



1. Binary black holes exist.

3. Merging binary black holes in a broad mass range exist.

4. Stellar-mass black holes with mass above $20\ M_\odot$ exist and take part in mergers.

5. Consistent with either isolated binary or dynamical formation.

6. Likely formed in low metallicity environment (either locally, or at high redshift with long time delay).

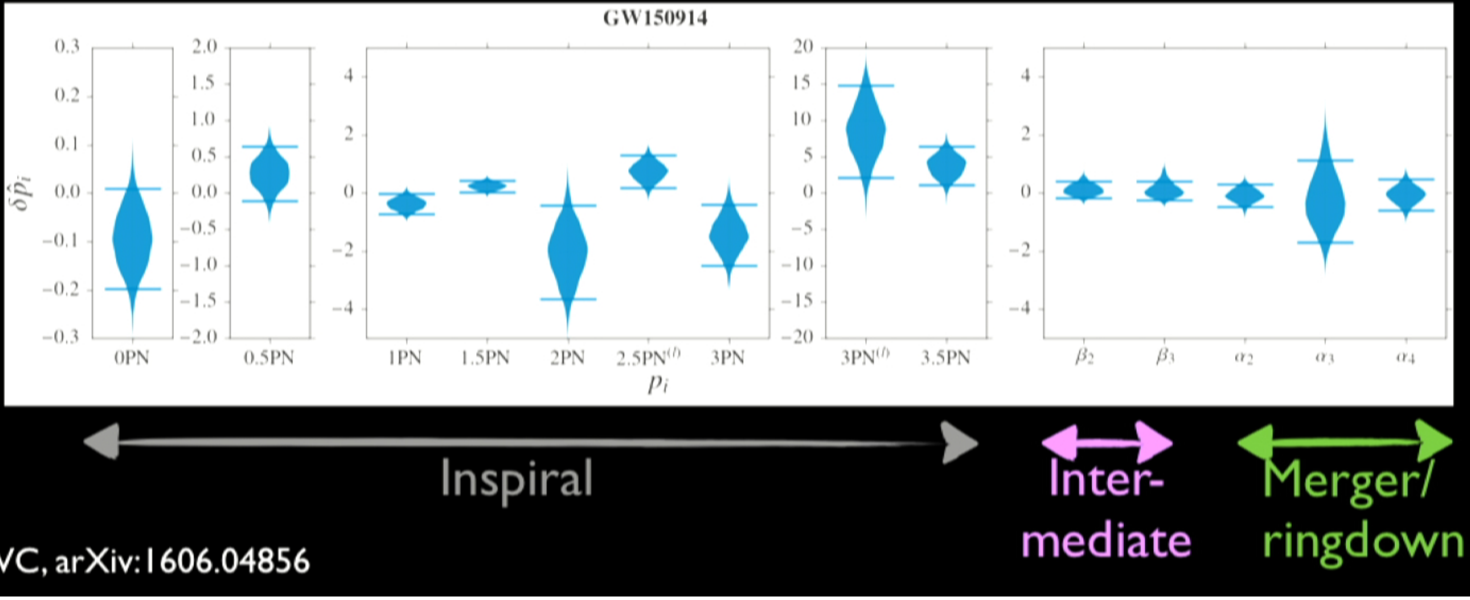
7. GW151226 & LVT151012 could have formed from lower mass progenitors or in higher metallicity environments.

Tests of General Relativity

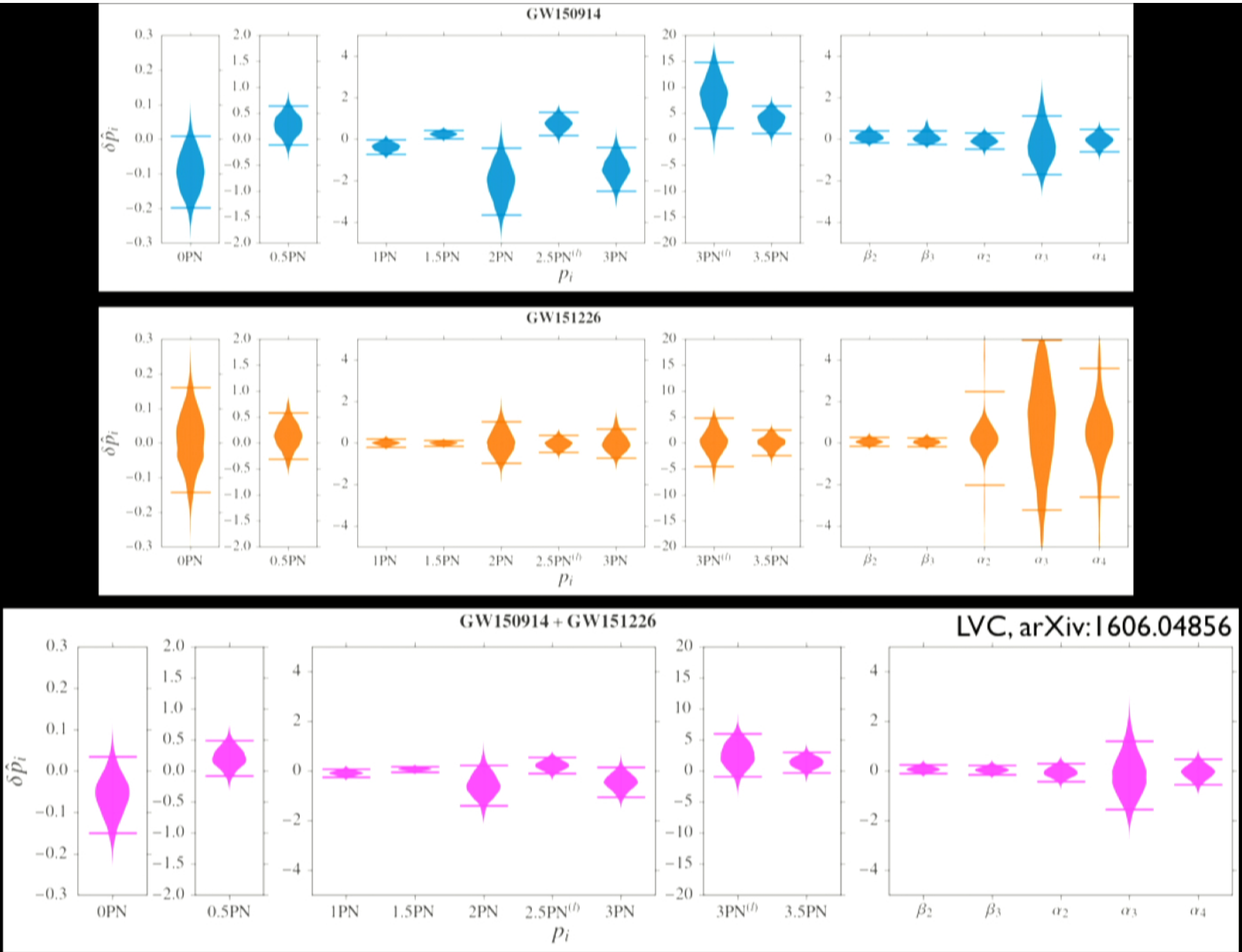
Phase of waveform characterized by coefficients: $\{p_i\}$

Allow for departures from GR: $\{p_i\} \rightarrow (1 + \delta\hat{p}_i)\, p_i$

Inspiral: $\left\{\delta\hat{\phi}_i\right\}$ Intermediate: $\left\{\delta\hat{\beta}_i\right\}$ Merger/ ringdown: $\{\delta\hat{\alpha}_i\}$

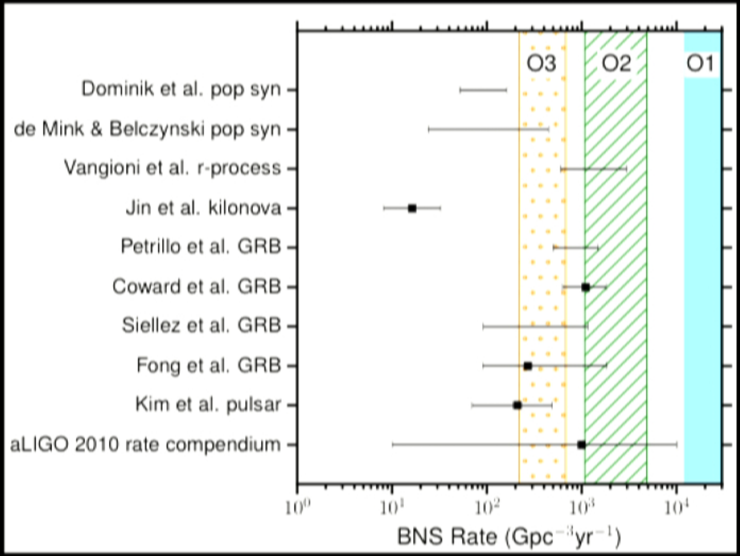


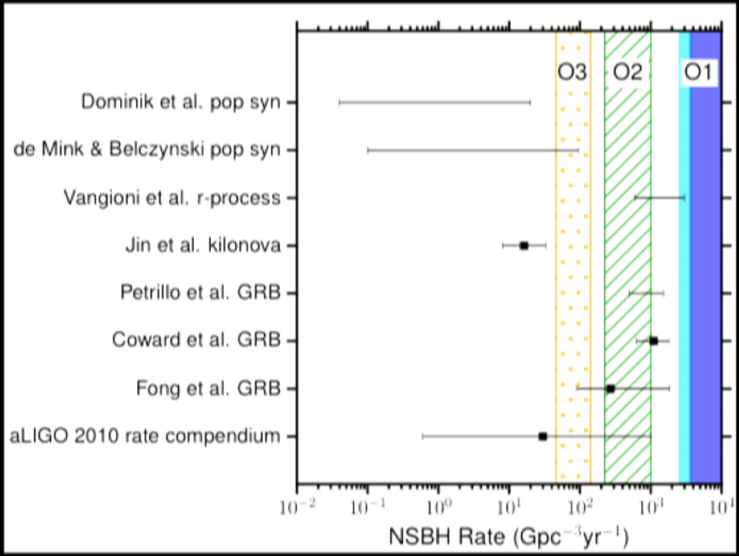
LVC, arXiv:1606.04856



LVC, arXiv:1606.04856

Binary neutron star and neutron-star-black-hole merger rates





Masses $(\mathrm{M}_{\odot})$	Component spins	$R_{90\%}\ (\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$
$[1.0, 3.0]$	$[0, 0.05]$	$< 12,600$
$1.4,\ 5.0$	$[0, 0.04]\ ,\ [0, 1.0]$	$< 3,600$

LVC, arXiv:1607.07456

Intermediate-mass Black Hole Binaries

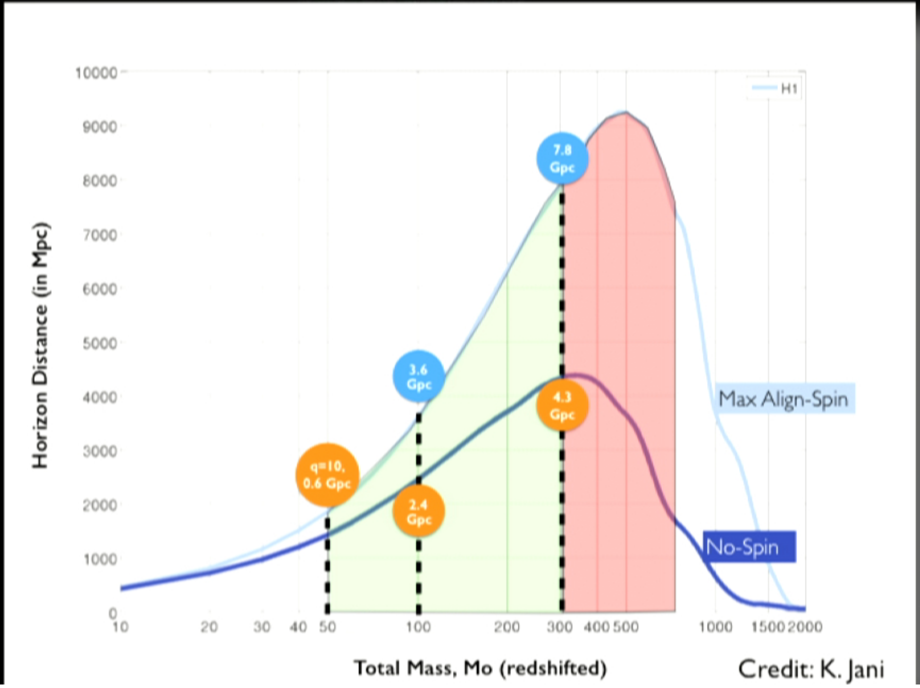
NGC 4485 and NGC 4490: two potential ULXs

Credit: NASA

Globular cluster Mayall II

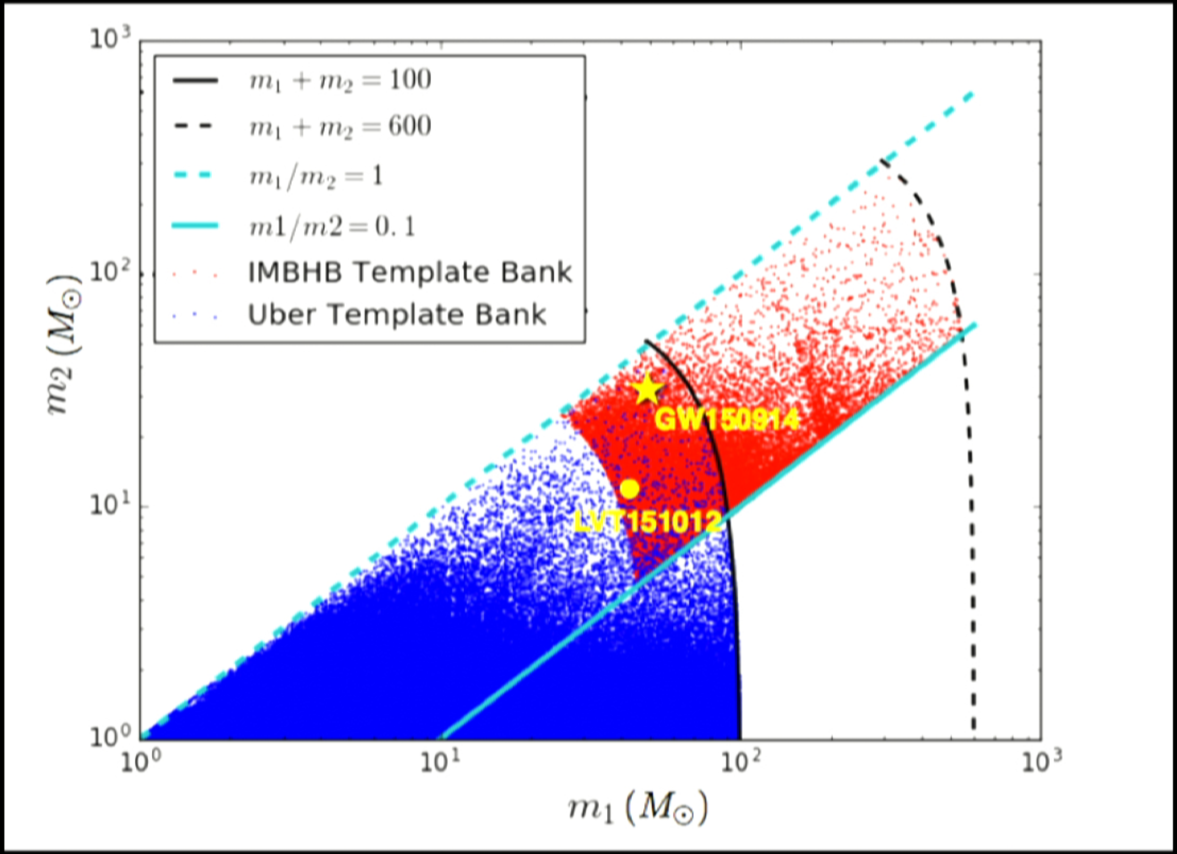
Credit: M. Rich, K. Mighell, J. Neill (Columbia), W. Freedman (Carnegie), NASA

Do intermediate-mass black holes exist in binaries?



Credit: K. Jani

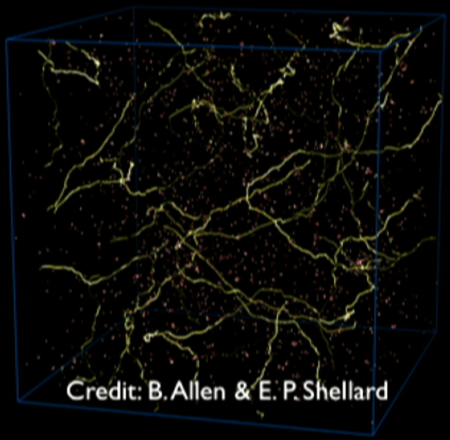
Searching for Intermediate Mass Black Holes

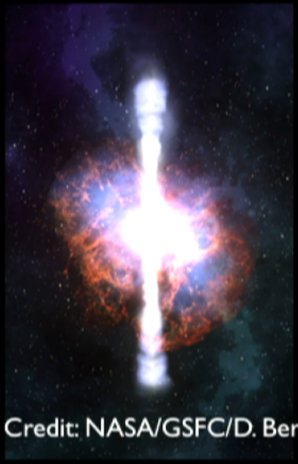


Credit: L. Sadeghian (UWM)

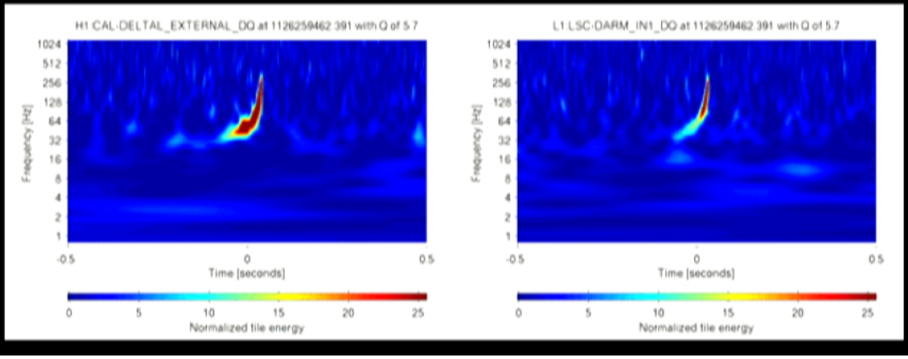
Generic GW Transient Searches

- GW Burst Signal:
  - Binary black holes
  - Supernovae
  - Cosmic strings
  - Pulsar glitches
  - Something unexpected


Credit: B. Allen & E. P. Shellard


Credit: NASA/GSFC/D. Berry

GW150914 was identified by an online burst search within 3 minutes.

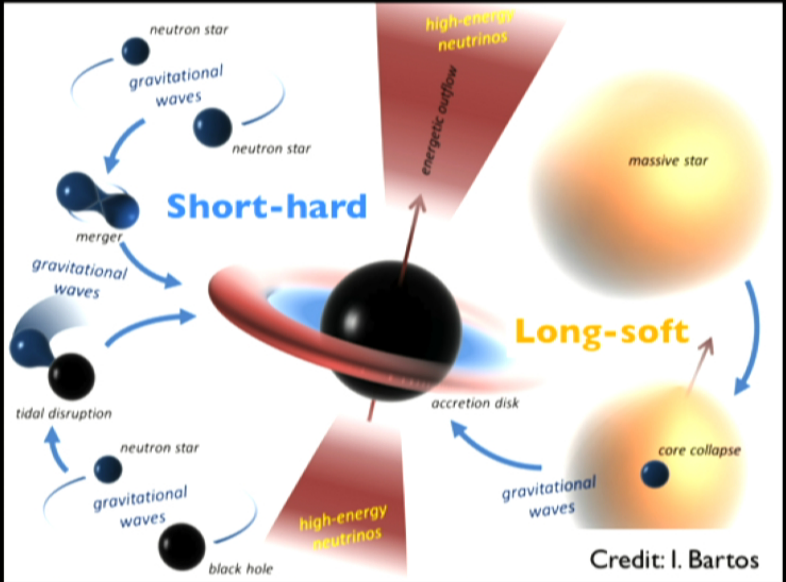


cWB
Coherent WaveBurst
a joint LSC-Virgo project

LVC, arXiv: 1602.03843
S. Klimenko, et al, Class. Quant. Grav. 25, 114029 (2008)

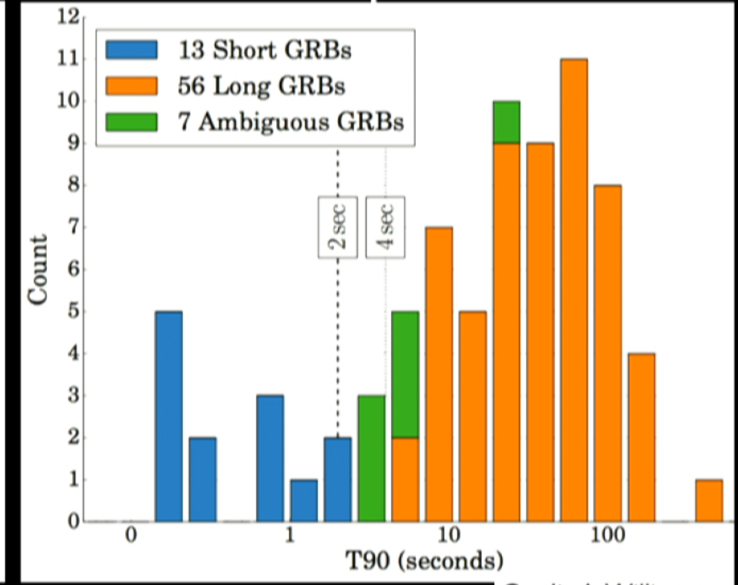
Other Burst Searches:
R. Lynch, et al, arXiv: 1511.05955
N. Cornish, Class. Quant. Grav. 32, 135012 (2015)

Gravitational Waves associated with Gamma-ray Bursts during O1



Credit: I. Bartos

76 GRBs reported in GCN



Credit: A. Williamson

Two dedicated searches:

CBC - matched filtering for short GRBs

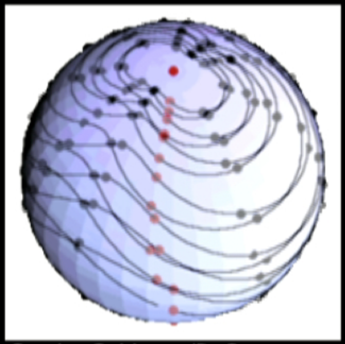
Burst - excess power search for all GRBs

Partners:

Fermi, Swift

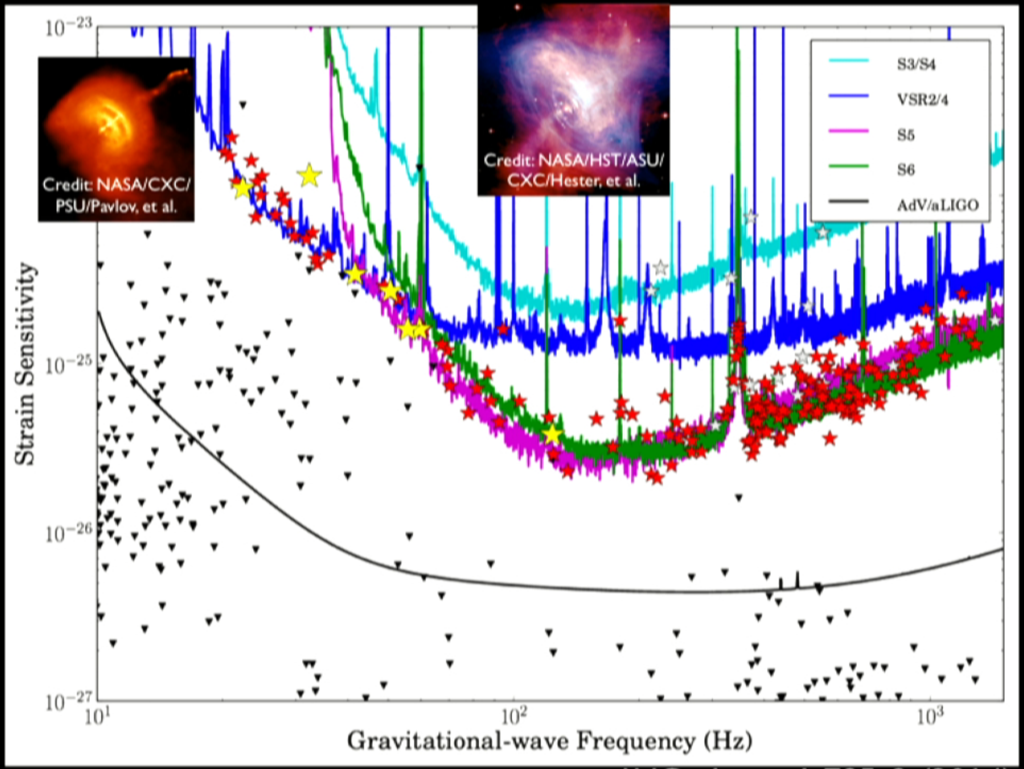
Also, ~20 IPN GRBs

Spinning Neutron Stars



Credit: C. Hanna/B. Owen

- Continuous wave searches:
  - Targeted
  - Directed
  - All-sky
- Are computationally limited. No results yet but stay tuned....



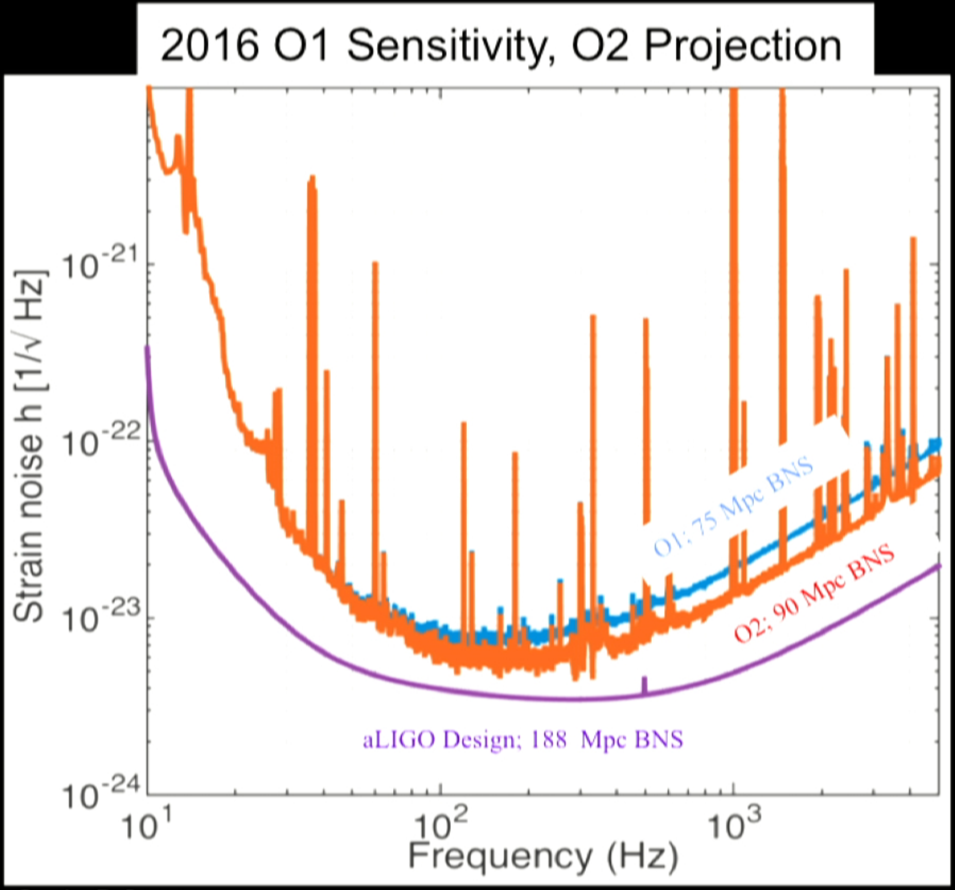
Credit: NASA/CXC/PSU/Pavlov, et al.

Credit: NASA/HST/ASU/CXC/Hester, et al.

LVC, Astro. J. 785, 2 (2014).

Use your computer's idle time to search for weak signals from spinning NS.

Expected O2 Improvement



Credit: D. Reitze

15 - 25% sensitivity improvements:

- Laser power: 20→50W
- Low frequency noise not well understood; no gains for O2
- 75→90 Mpc BNS range