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# Advanced LIGO and GW Astronomy

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Second SVOM scientific workshop  
Qiannan, Guizhou province, China

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# DISCOVERIES

## Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of  $1.0 \times 10^{-21}$ . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than  $5.1\sigma$ . The source lies at a luminosity distance of  $410^{+160}_{-180}$  Mpc corresponding to a redshift  $z = 0.09^{+0.03}_{-0.04}$ . In the source frame, the initial black hole masses are  $36^{+5}_{-4} M_\odot$  and  $29^{+4}_{-4} M_\odot$ , and the final black hole mass is  $62^{+4}_{-4} M_\odot$ , with  $3.0^{+0.5}_{-0.5} M_\odot c^2$  radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

# DISCOVERIES

## GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.*<sup>\*</sup>

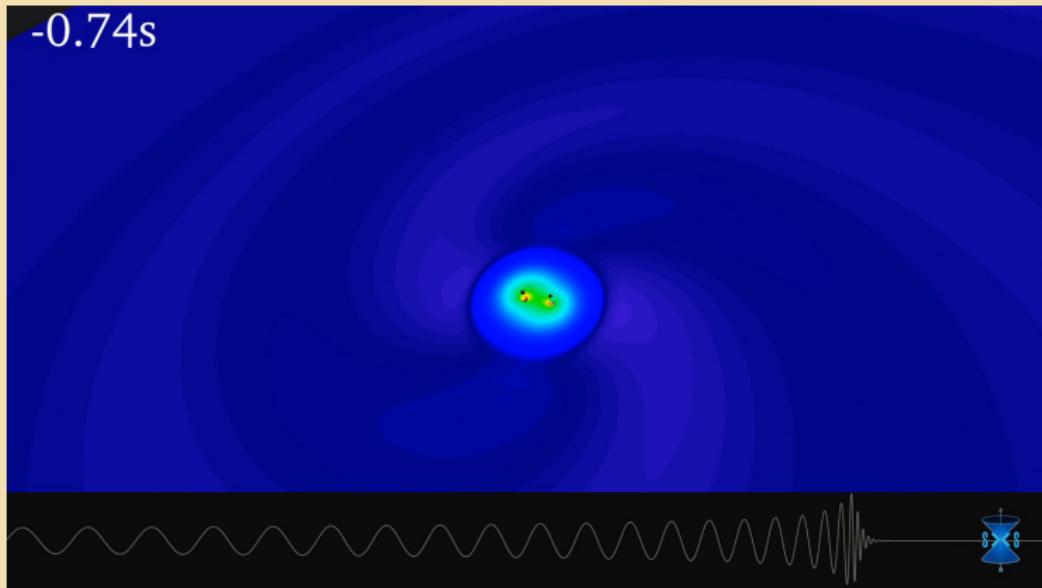
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 31 May 2016; published 15 June 2016)

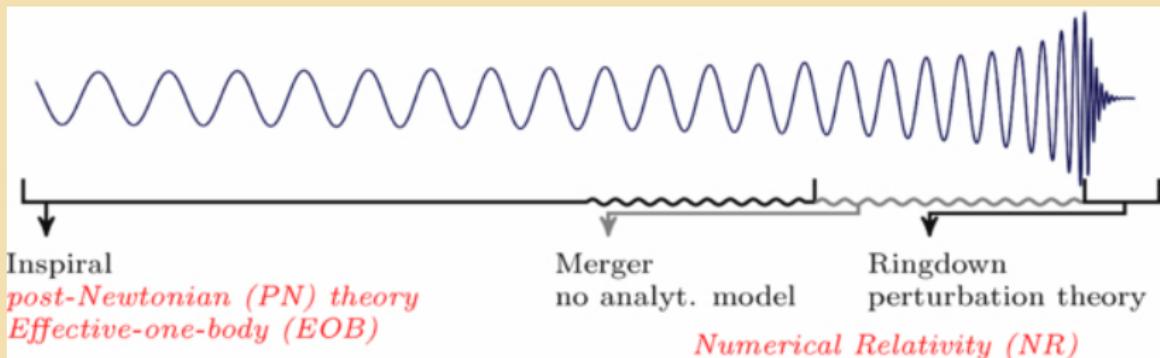
We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than  $5\sigma$ . The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of  $3.4_{-0.9}^{+0.7} \times 10^{-22}$ . The inferred source-frame initial black hole masses are  $14.2_{-3.7}^{+8.3} M_\odot$  and  $7.5_{-2.3}^{+2.3} M_\odot$ , and the final black hole mass is  $20.8_{-1.7}^{+6.1} M_\odot$ . We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of  $440_{-190}^{+180}$  Mpc corresponding to a redshift of  $0.09_{-0.04}^{+0.03}$ . All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

B. P. Abbott *et al.* *Physical Review Letters* 116.24, 241103 (June 2016)

BINARY MERGERS

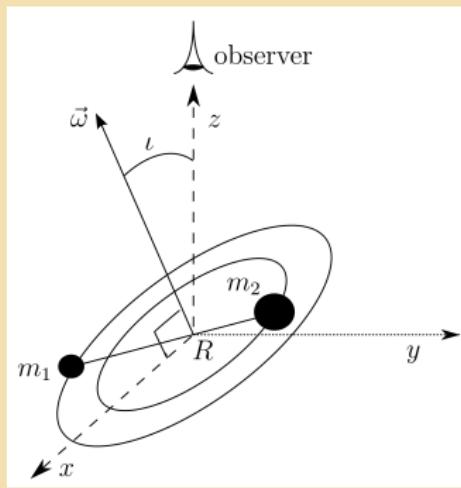


## ANATOMY OF BINARIES



- ▶ Inspiral: Emission of GWs removes energy / angular momentum
  - ▶ Merger: Two objects will merge into single object
  - ▶ Ringdown: Single object reaches quiescent state

## PARAMETERS OF A BINARY



Parameter	Description
$m_1, m_2$	Component Masses
$\vec{S}_1, \vec{S}_2$	Component Spins
$\theta, \phi$	Sky Position
$\iota, \psi$	Orientation
$d_L$	Distance
$\varphi_c, t_c$	Reference phase/time

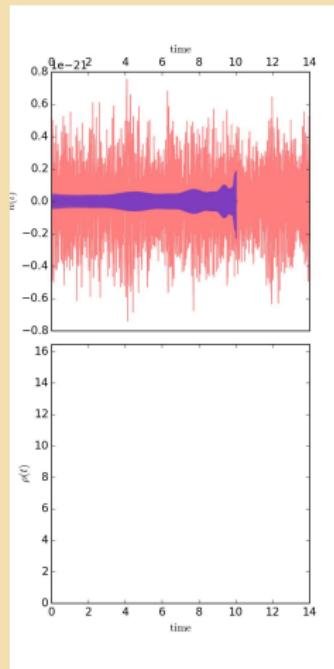
$$h_+ = \frac{4\mathcal{M}_c^{5/3}\omega^{2/3}}{r} \frac{1 + \cos^2\iota}{2} \cos(2\omega t),$$

$$h_x = \frac{4\mathcal{M}_c^{5/3}\omega^{2/3}}{r} \cos \iota \sin(2\omega t).$$

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

# MATCHED FILTERING

- ▶ Data  $d(t)$ , template  $h(t)$
- ▶ Calculate signal-to-noise



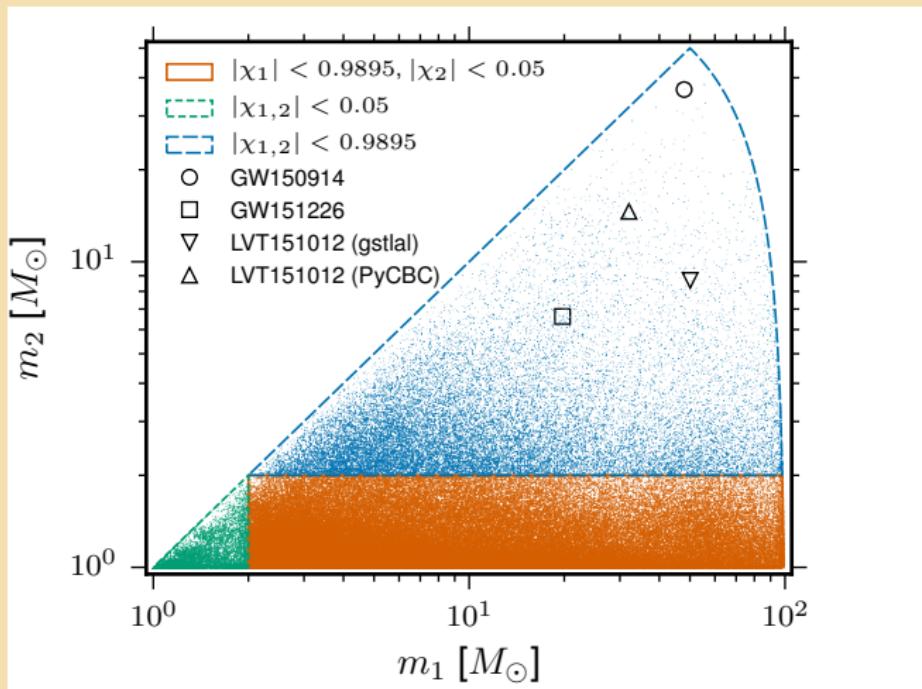
$$\rho(\tau) = 4\Re \left\{ \int_0^\infty \frac{\tilde{d}^*(f)\tilde{h}(f)}{S_n(f)} e^{2\pi\imath f\tau} df \right\}$$

- ▶ Calculate a signal-based veto  $\chi^2$

$$z_j = 4\Re \left\{ \int_{f_{j-1}}^{f_j} \frac{\tilde{d}^*(f)\tilde{h}(f)}{S_n(f)} df \right\}$$

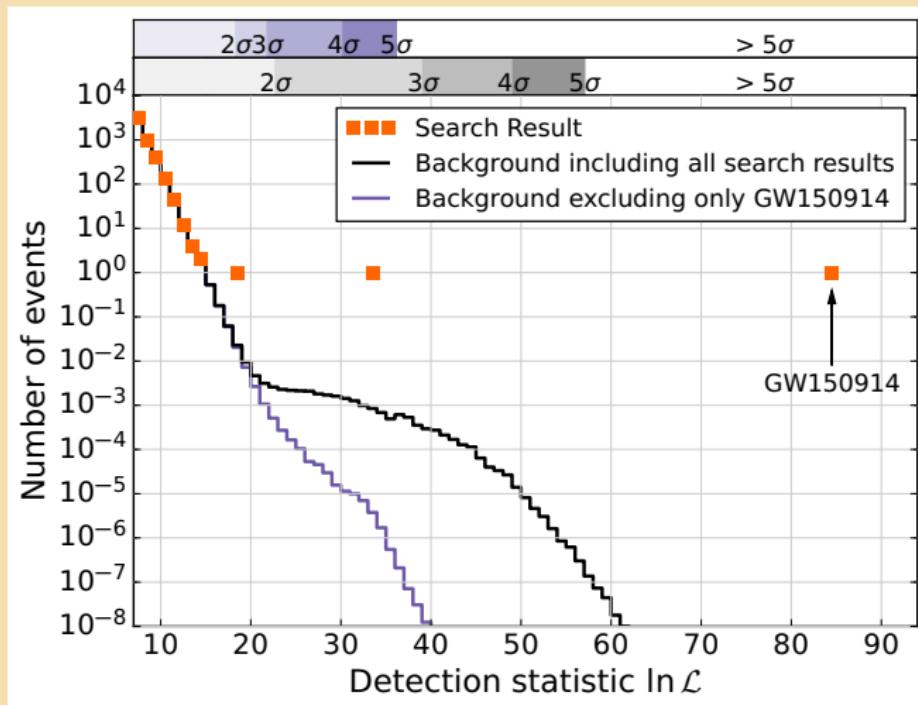
$$\chi^2 = \frac{1}{p} \sum_{j=1}^p \left( \sum_{k=1}^p z_k - p z_j \right)^2$$

## TEMPLATE BANK



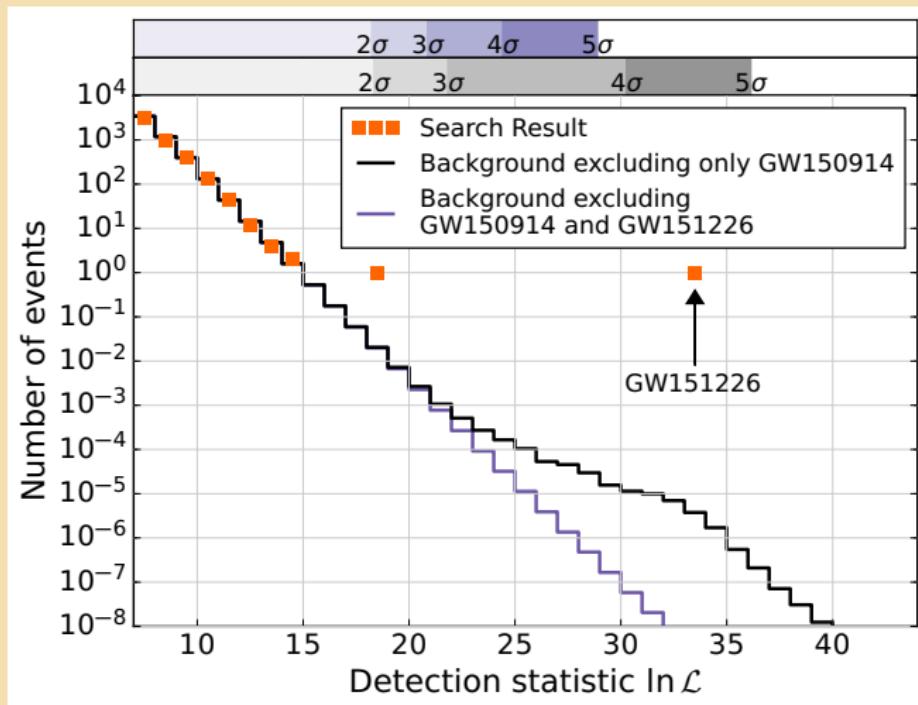
B. P. Abbott et al. *Physical Review X* 6.4, 041015 (Oct. 2016)

# DETECTION STATISTICS



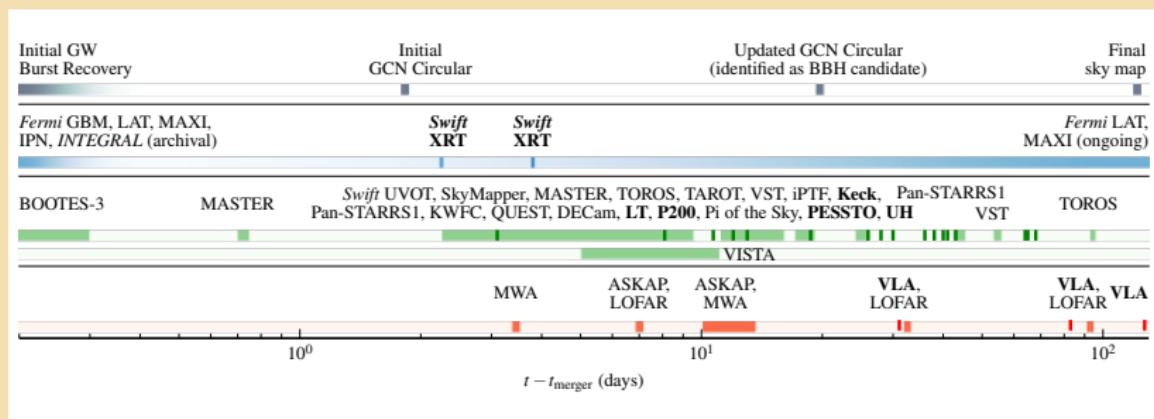
B. P. Abbott et al. *Physical Review X* 6.4, 041015 (Oct. 2016)

# DETECTION STATISTICS



B. P. Abbott et al. *Physical Review X* 6.4, 041015 (Oct. 2016)

# EM FOLLOW-UP



B. P. Abbott et al. *ApJ* 826, L13 (July 2016)

# COMMUNICATION WITH EM PARTNERS

## Gamma ray Coordinates Network (GCN)

- ▶ Machine-readable notices
- ▶ Short bulletins (Circulars) with human descriptions of the events
- ▶ Releases candidate triggers and their skymaps
- ▶ Restricted to MoU partners until the event has been published

## Gravitational wave Candidate Data Base (GraceDB)

- ▶ Organize candidate events from gravitational-wave searches
- ▶ Provide an environment to record information about follow-ups
- ▶ Bulletin board to coordinate EM follow-up observations

# EXAMPLE FROM O1

## GW150914

- ▶ 14-Sep: GW140915 detected with a FAR below threshold
- ▶ 20-Sep: GCN 18330 sent to MoU partners
- ▶ Skymap area of  $630 \text{ deg}^2$  (90% probability)

Gamma-ray	$\sim 100\%$
X-rays (2-20 keV)	84%
Radio	86%
Optical	50%

# INFERRING SYSTEM PARAMETERS

$$\Pr(\vec{\theta} | d, I) = \frac{\Pr(d | \vec{\theta}, I) \Pr(\vec{\theta} | I)}{\Pr(d | I)}$$

Input

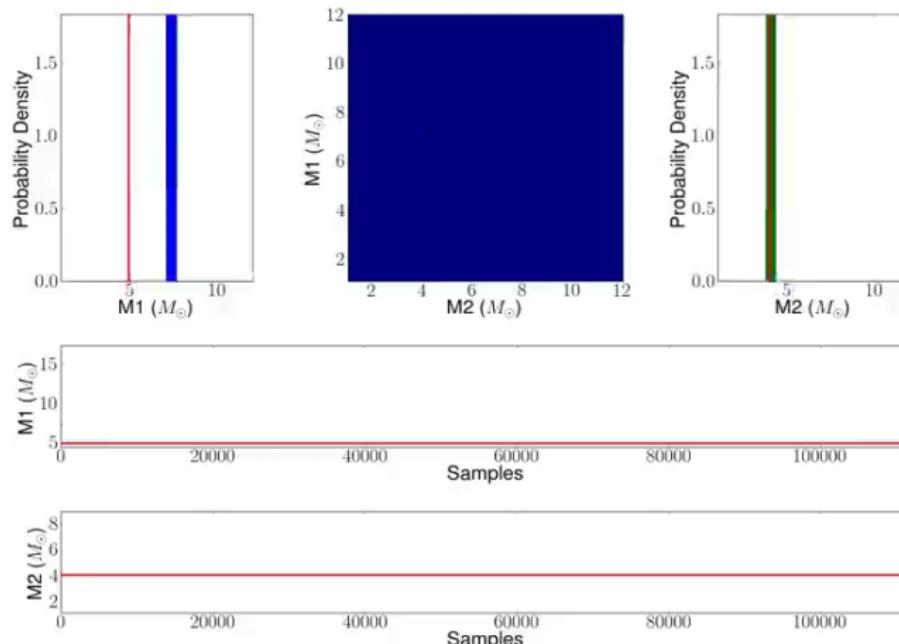
$\Pr(d | \vec{\theta}, I)$ : Likelihood  
 $\Pr(\vec{\theta} | I)$ : Prior

Output

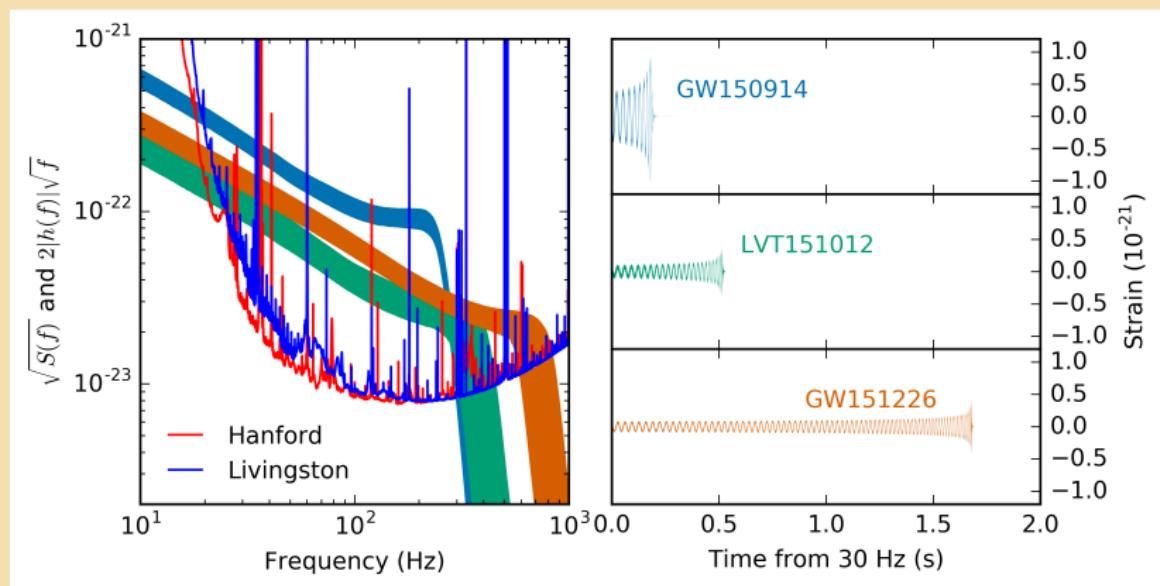
$\Pr(\vec{\theta} | d, I)$ : Posterior  
 $\Pr(d | I)$ : Evidence

Use Markov-Chain Monte-Carlo techniques to sample the probability distributions

# MARKOV-CHAIN MONTE CARLO EXAMPLE

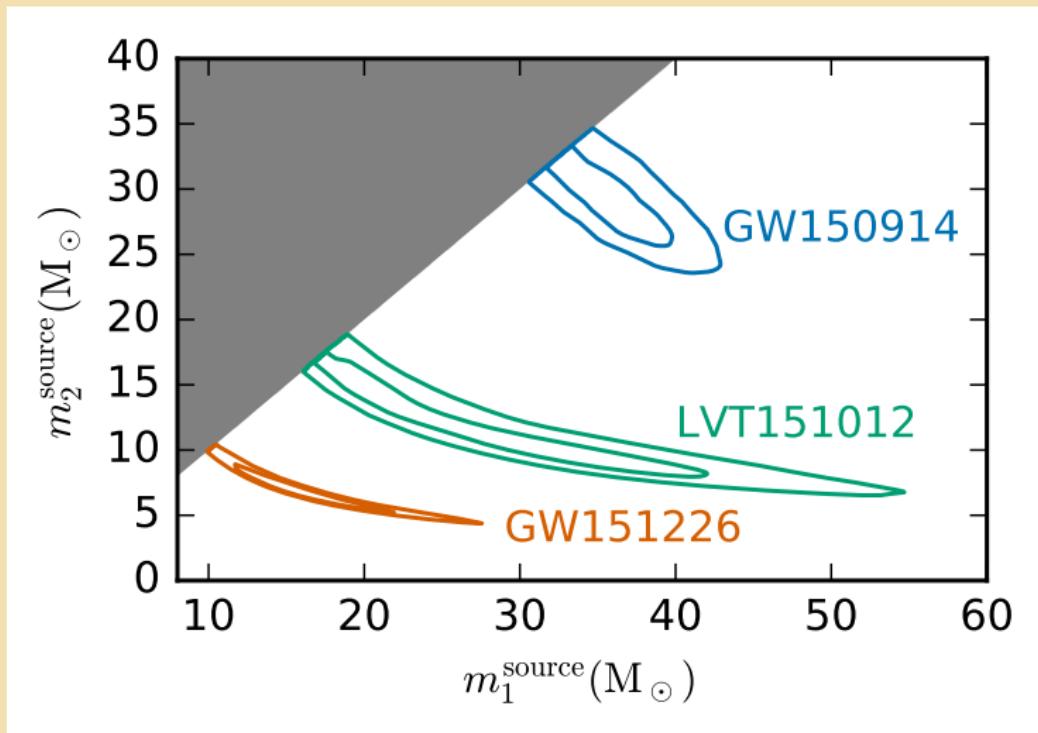


# DETECTED SIGNALS SO FAR



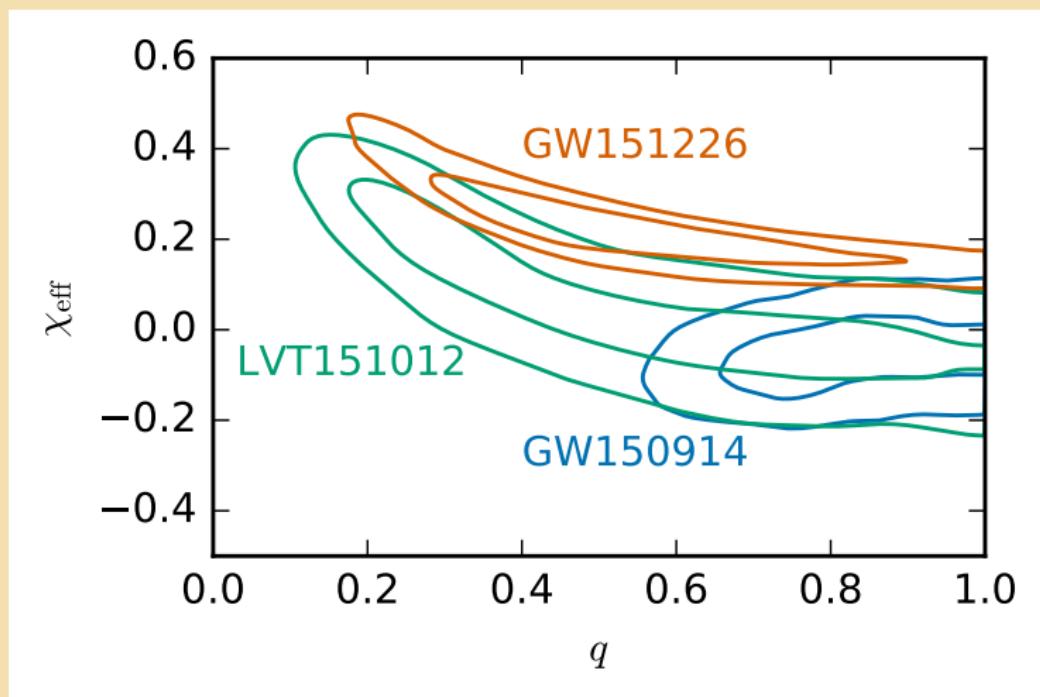
B. P. Abbott et al. *Physical Review X* 6.4, 041015 (Oct. 2016)

MASS



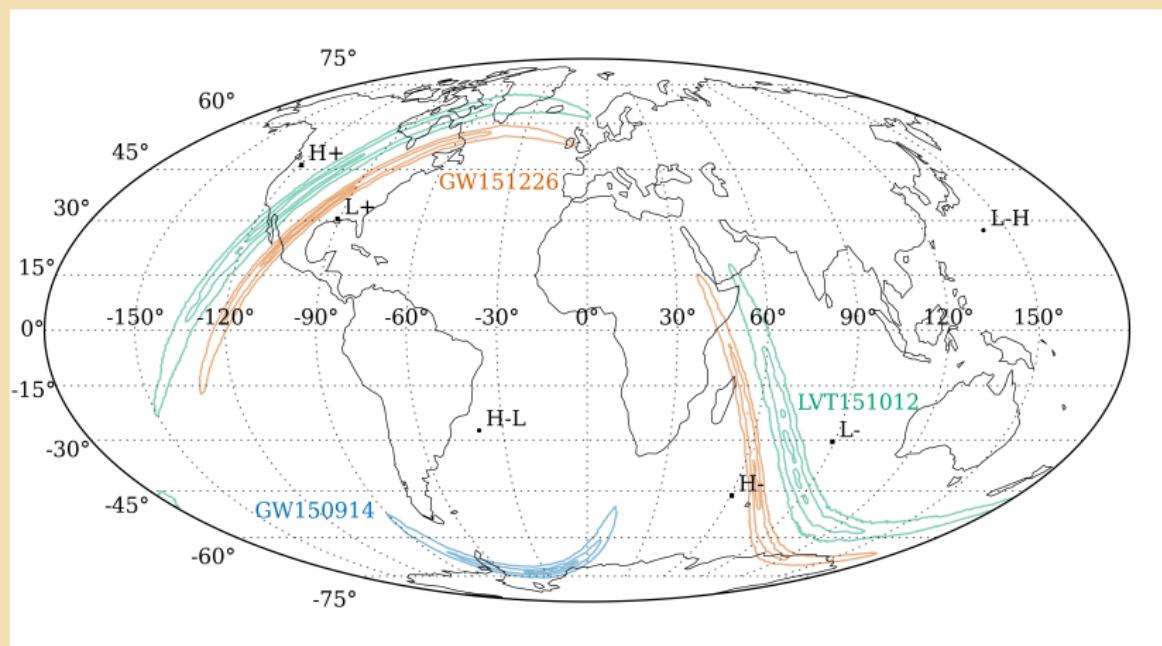
B. P. Abbott et al. *Physical Review X* 6.4, 041015 (Oct. 2016)

## SPIN



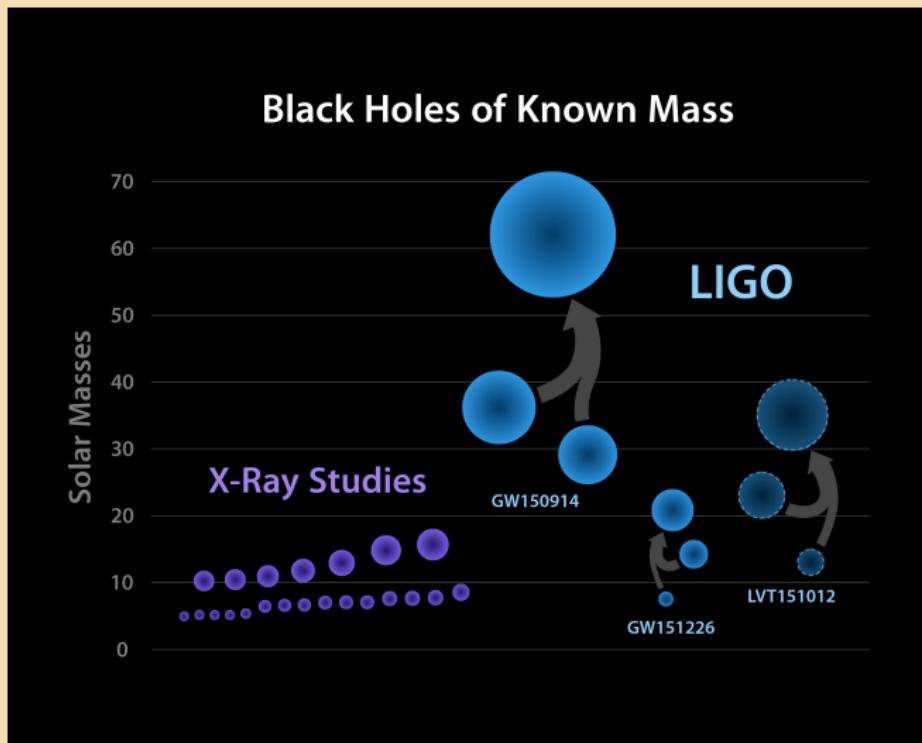
B. P. Abbott et al. *Physical Review X* 6.4, 041015 (Oct. 2016)

# SKY MAP



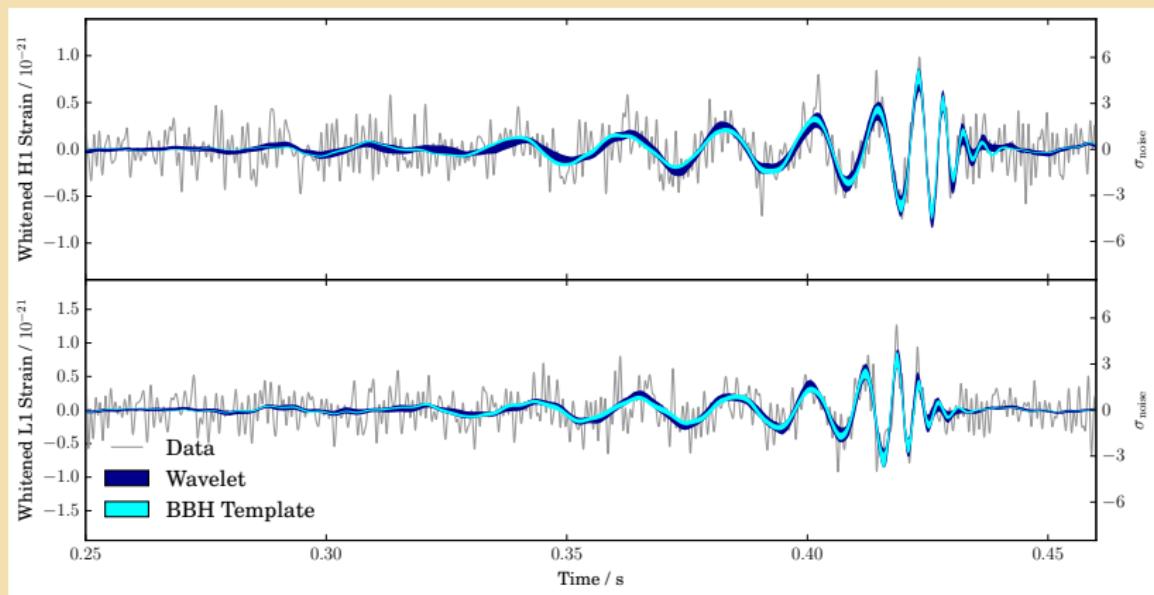
B. P. Abbott et al. *Physical Review X* 6.4, 041015 (Oct. 2016)

# BLACK HOLE MASS CENSUS



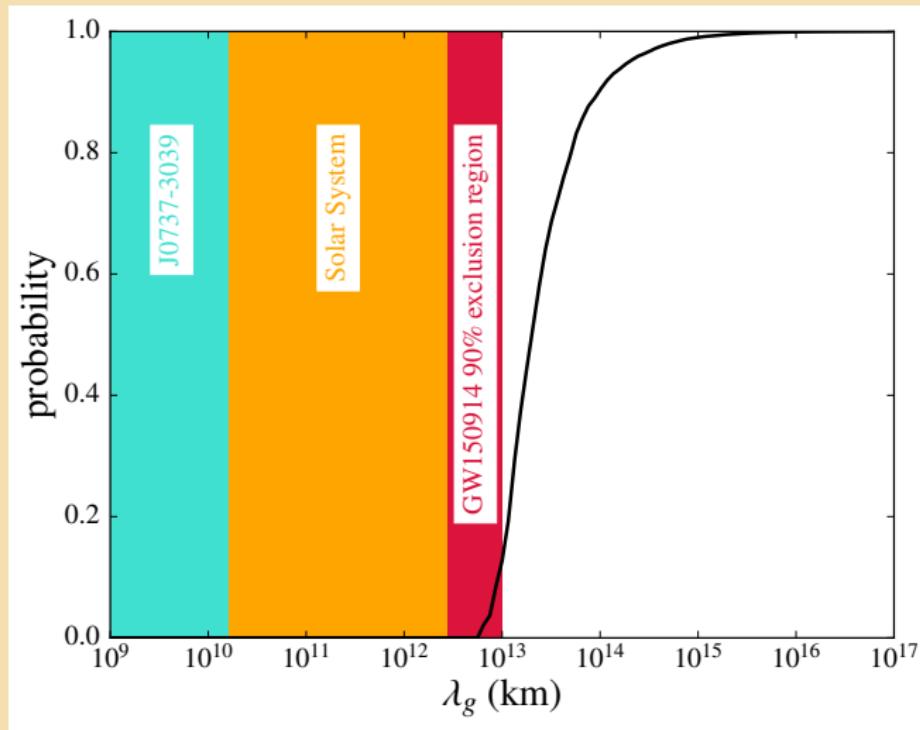
credit: LIGO

# CONSISTENT WITH GR?



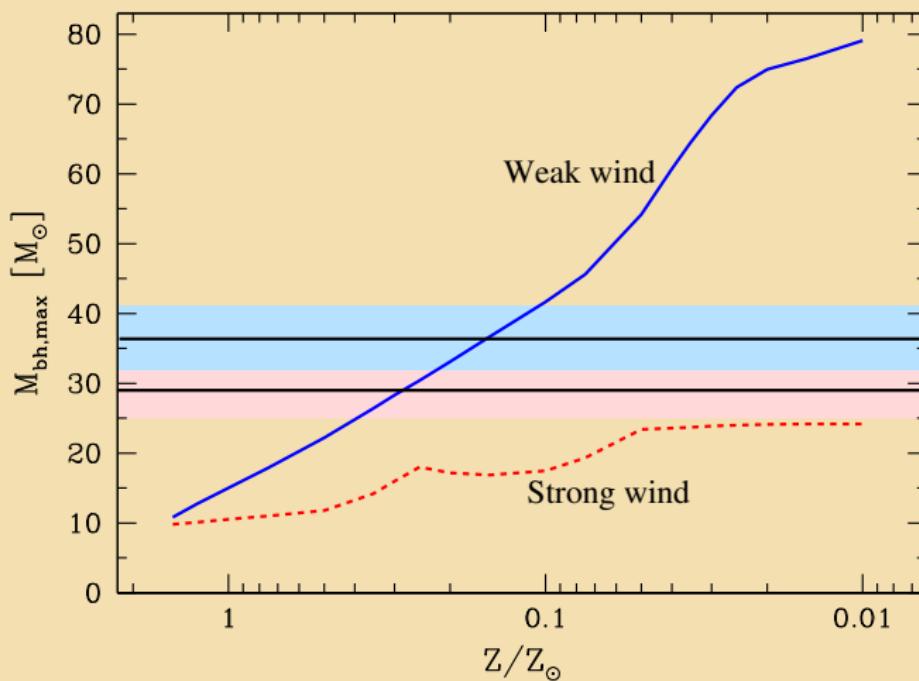
B. P. Abbott et al. *Physical Review Letters* 116.6, 061102 (Feb. 2016)

# TEST OF GENERAL RELATIVITY



B. Abbott et al. *Phys. Rev. Lett.* 116.22 (2016)

# ASTROPHYSICAL IMPLICATIONS



B. P. Abbott et al. *ApJ* 818, L22 (Feb. 2016)

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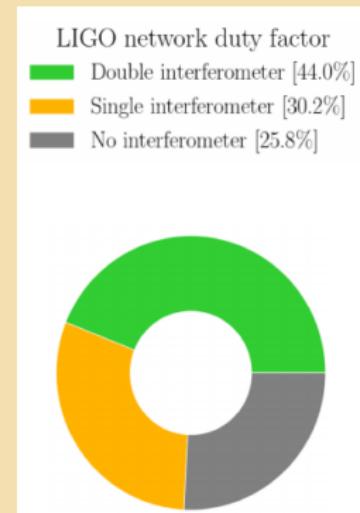
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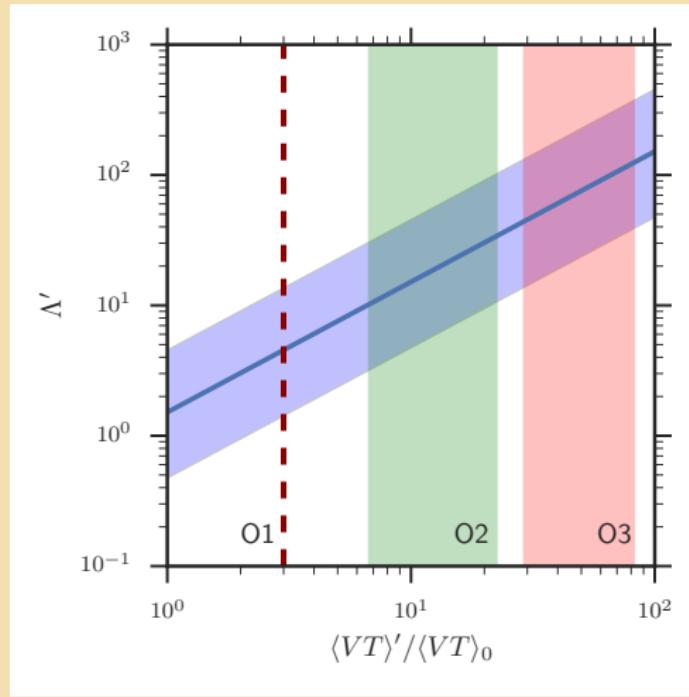
## Future Prospects

# UPCOMING PLANS – ADVANCED LIGO

- ▶ Extending O2 run to August
  - ▶ Timing of Virgo joining O2 could potentially extend the run past August.
  - ▶ Running through the summer will take advantage of the environmentally more quiet summer months
- ▶ Post O2
  - ▶ Estimate it could take at least 12–15 months after ending O2 to complete this work before beginning O3.



# EXPECTED SIGNALS



Highly significant events as a function of surveyed time-volume in an observation. The expected range of values for the observations in O2 and O3 are shown as vertical bands.

# EM FOLLOW-UP IN O2

- ▶ O2 started on November 30, 2016 and is still ongoing.
- ▶ Nearly hundreds of facilities among space- and ground-based telescopes have signed MoUs
- ▶ Provide GW event candidate alerts within tens of minutes
- ▶ 3D skymaps are released for binaries
- ▶ Provide "EM-bright" flag if event possibly includes NS

As of March 23, 6 triggers have been identified by online analysis using a FAR threshold of one per month and shared with partner astronomers. Investigations of the data and offline analysis are so far still in progress

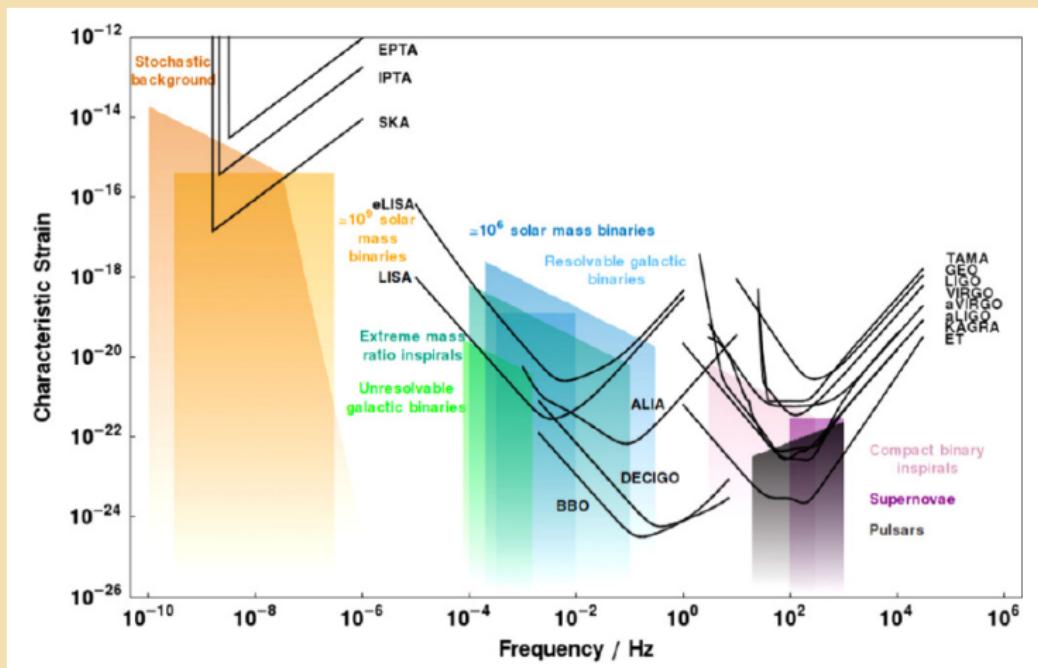
# 2ND GENERATION GW NETWORK

- ▶ Advanced Virgo (2017)
  - ▶ Acquired first lock
  - ▶ May join Advanced LIGO during O2
- ▶ KAGRA (2019-20)
  - ▶ iKAGRA run in 2016
  - ▶ Developing cryogenics, Advanced vibration isolation, optics, ...
- ▶ LIGO-India (2024)
  - ▶ Site acquisition underway
  - ▶ Preparing export licenses for aLIGO detector components

# BEYOND 2ND GENERATION DETECTOR

- ▶ A+: modest update of Advanced LIGO (2022)
- ▶ LIGO Voyager: major update of Advanced LIGO (2027-28)
- ▶ Einstein Telescope: 3x 10km arms (2035+)
- ▶ Cosmic Explorer: new GW facility (2035+)

# FULL GW SPECTRUM



C. J. Moore et al. *Classical and Quantum Gravity* 32.1, 015014 (Jan. 2015)

# BBH – QUASI-NORMAL MODES

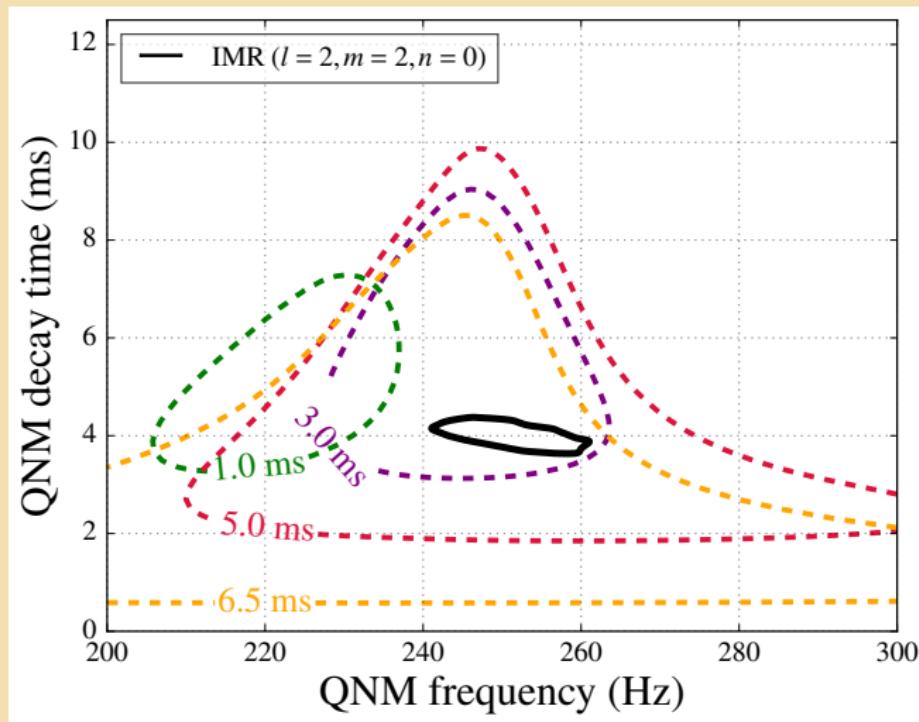
- Deformed black holes emit quasi-normal modes (ringdown)

$$h_+(t) = \frac{M}{r} \sum_{l,m>0} A_{l|m|} e^{-t/\tau_{lm}} Y_+^{lm} \cos(\omega_{lm} t - m\phi)$$

$$h_\times(t) = -\frac{M}{r} \sum_{l,m>0} A_{l|m|} e^{-t/\tau_{lm}} Y_\times^{lm} \sin(\omega_{lm} t - m\phi)$$

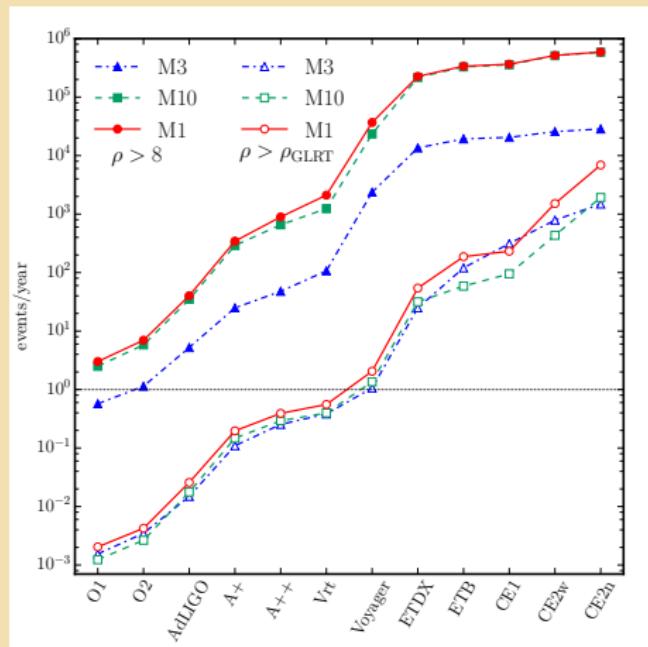
- Frequencies ( $\omega_{lm}$ ), decay times ( $\tau_{lm}$ ) depend on mass and spin
- Measuring two or more modes provides smoking gun evidence of black holes and GR.

# BBH – QUASI-NORMAL MODES



B. Abbott et al. *Phys. Rev. Lett.* 116.22 (2016)

# QUASI-NORMAL MODES PROSPECTS



- ▶ Observable ringdown signal (filled)
- ▶ Significant ringdown signal (hollow)
- ▶ Future detectors can do ringdown only science

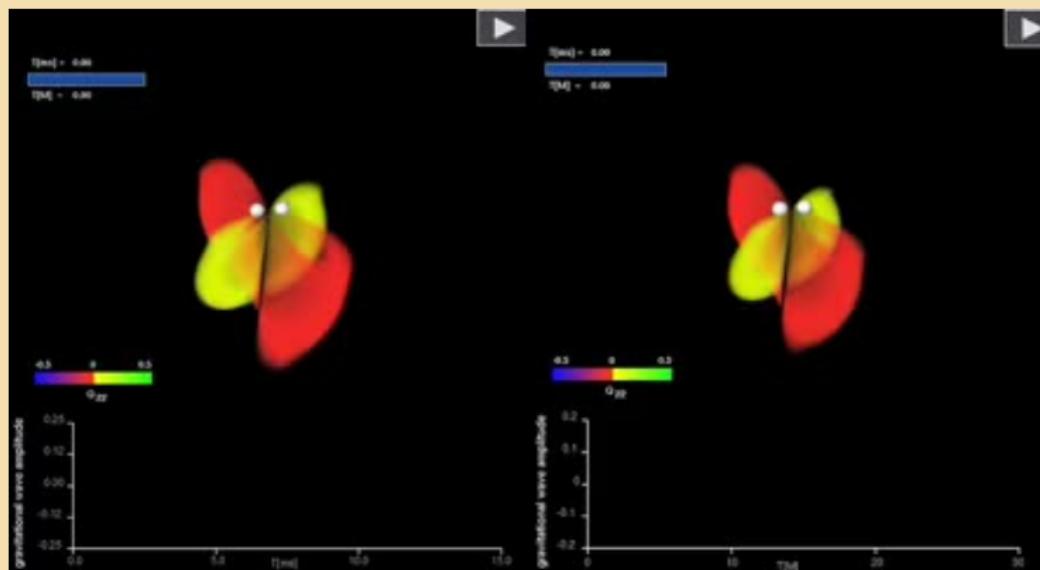
E. Berti et al. *Physical Review Letters* 117.10, 101102  
(Sept. 2016)

# BINARY NEUTRON STARS



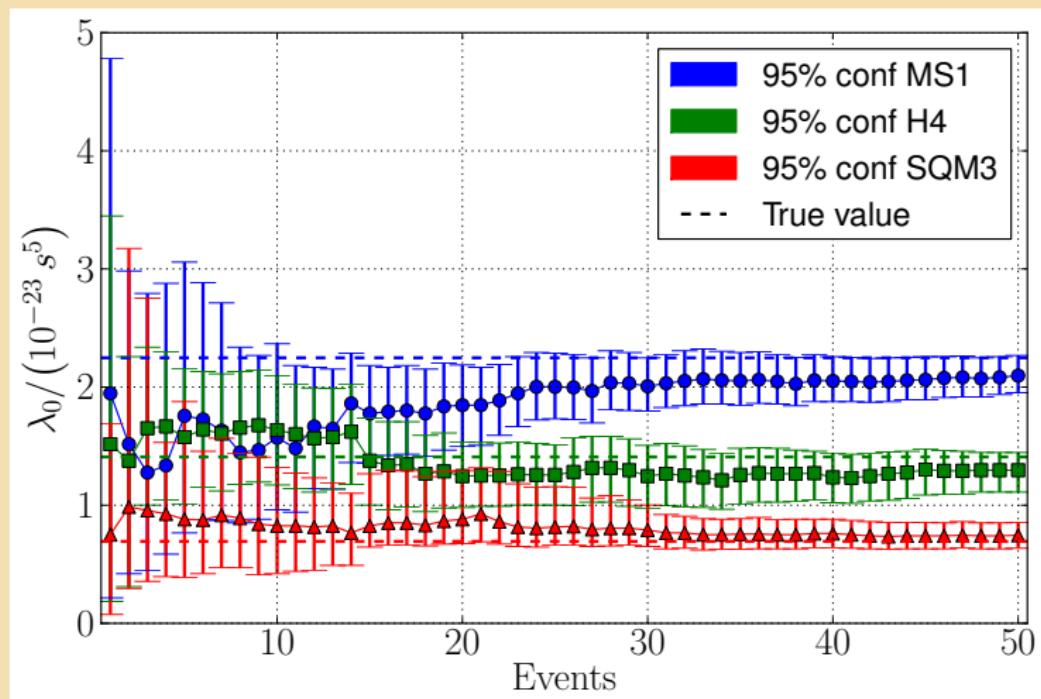
K. Kiuchi et al. *Phys. Rev. D* 92.6, 064034 (Sept. 2015)

# NUCLEAR EQUATION OF STATE



credit: Rezolla *et al.*

# NUCLEAR EQUATION OF STATE



W. Del Pozzo et al. *Physical Review Letters* 111.7, 071101 (Aug. 2013)

# COSMOLOGY

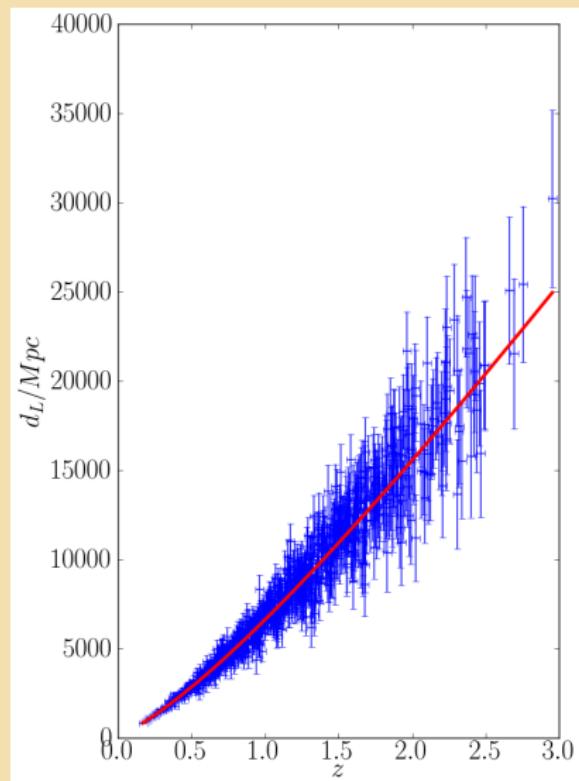
- ▶ Our Universe is expanding
- ▶ Large-scale structure → how it expands
  

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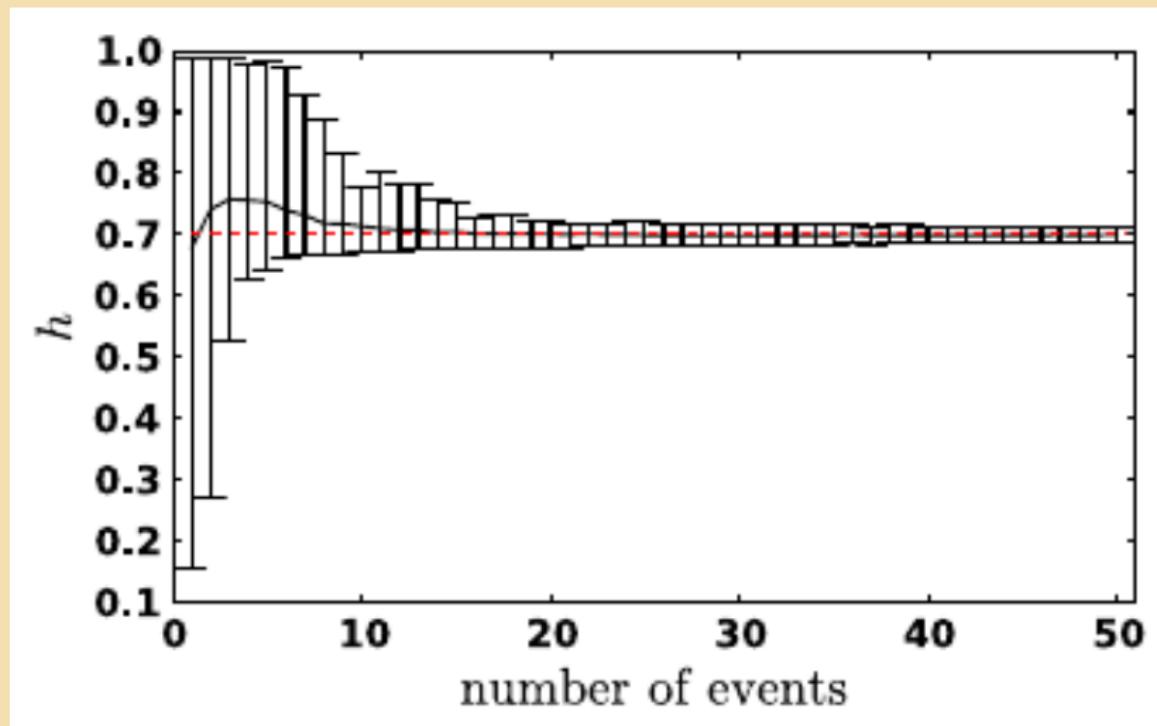
- ▶ Measure *distance* and *recession velocity* of celestial objects

$$d_L(z; \underbrace{H_0, \Omega_m, \Omega_k, \Omega_\Lambda, w}_{\text{Cosmological parameters}})$$

- |                     |                   |
|---------------------|-------------------|
| $H_0$               | Hubble constant   |
| $\Omega_m$          | Matter density    |
| $\Omega_k$          | Spatial curvature |
| $\Omega_\Lambda, w$ | Dark energy       |

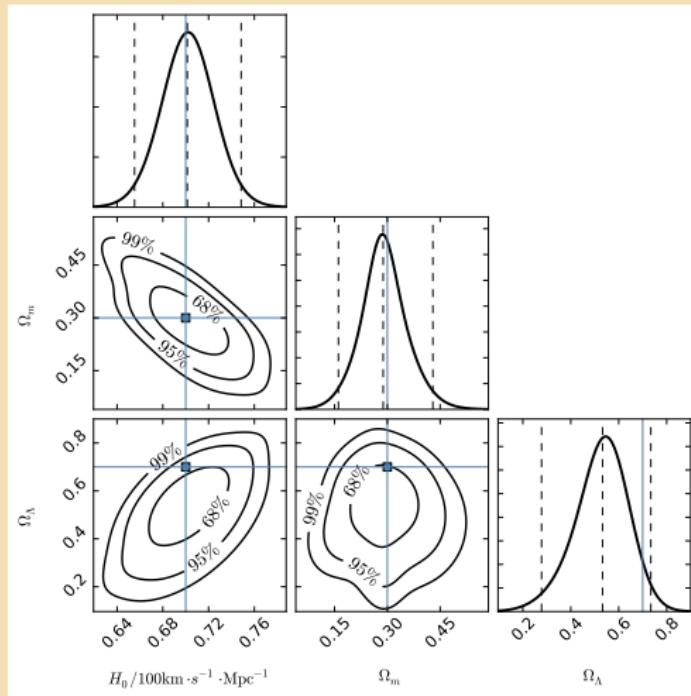


## COSMOLOGY – 2ND GENERATION



W. Del Pozzo. *Phys. Rev. D* 86.4, 043011 (Aug. 2012)

# COSMOLOGY – 3RD GENERATION



- ▶ Probe the Hubble parameter with 2nd generation
- ▶ Dark energy with 3rd generation

W. Del Pozzo et al. *Phys. Rev. D* 95 (4 2017)

# OTHER SOURCES

## Continuous Waves Sources

- ▶ Spinning neutron stars can have ellipticity and emit GWs
- ▶ Spin-down limit already beaten for a few pulsars
- ▶ O1 analysis not yet concluded

## Core Collapse Supernovae

- ▶ Supernova explosion still mystery
- ▶ Interplay amongst all branches of physics
- ▶ GW can probe the explosion mechanism

## Stochastic Background

- ▶ Superposition of unresolvable (binary) sources
- ▶ Useful to study populations

# SUMMARY

- ▶ Census of compact objects in binaries: masses, spins, merger rate over time
- ▶ Precision tests of general relativity
- ▶ Probing the nature of black holes or more exotic objects
- ▶ Internal structure of neutron stars
- ▶ Large-scale structure and evolution of the Universe
- ▶ Supernovae explosion mechanism
- ▶ Multi-Messenger studies

# Appendix

# REFERENCES I

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- [11] W. Del Pozzo et al. “Demonstrating the Feasibility of Probing the Neutron-Star Equation of State with Second-Generation Gravitational-Wave Detectors”. *Physical Review Letters* 111.7, 071101 (Aug. 2013), p. 071101. arXiv: 1307.8338 [gr-qc].
- [12] W. Del Pozzo. “Inference of cosmological parameters from gravitational waves: Applications to second generation interferometers”. *Phys. Rev. D* 86.4, 043011 (Aug. 2012), p. 043011. arXiv: 1108.1317 [astro-ph.CO].
- [13] W. Del Pozzo et al. “Cosmological inference using only gravitational wave observations of binary neutron stars”. *Phys. Rev. D* 95 (4 2017), p. 043502. URL: <http://link.aps.org/doi/10.1103/PhysRevD.95.043502>.