Status and Prospects of Gravitational-Wave Astrophysics

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Discoveries So Far

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)

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

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 31 May 2016; published 15 June 2016)

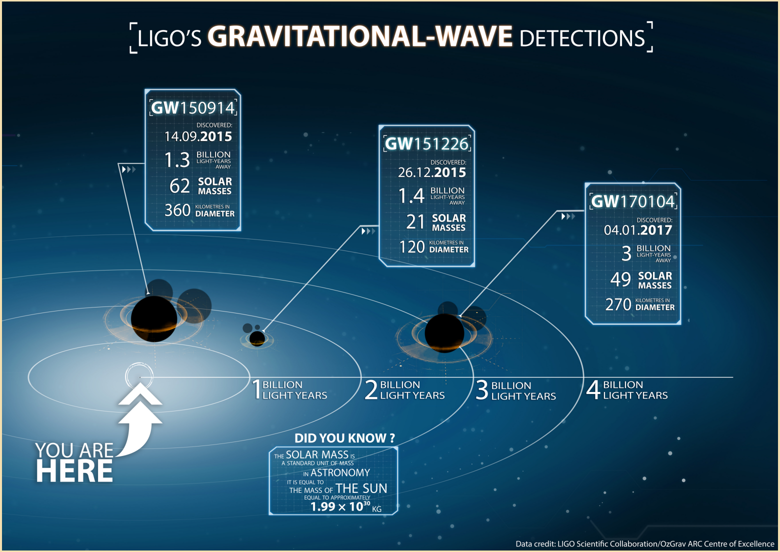
GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott *et al.*[*]

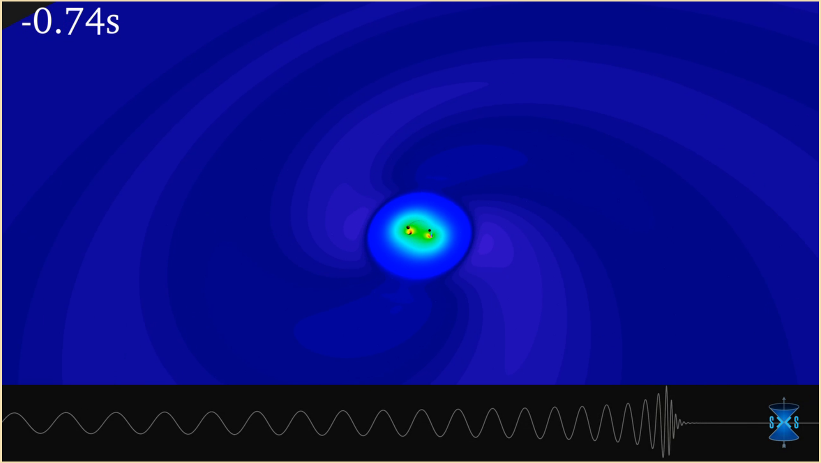
(LIGO Scientific and Virgo Collaboration)

(Received 9 May 2017; published 1 June 2017)

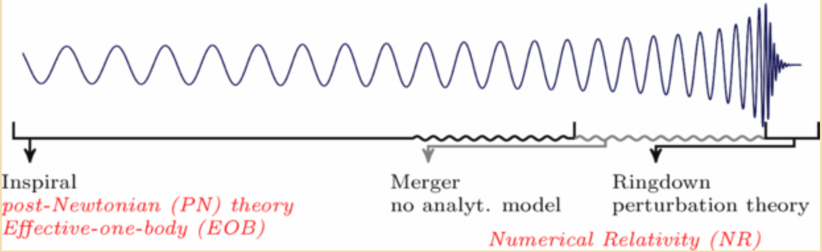
Discoveries So Far



Binary mergers

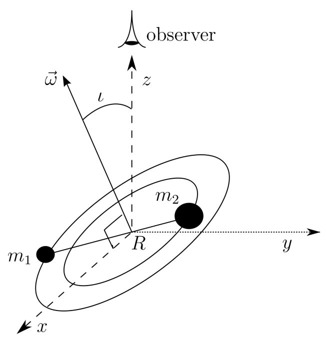


Anatomy of binaries



- 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



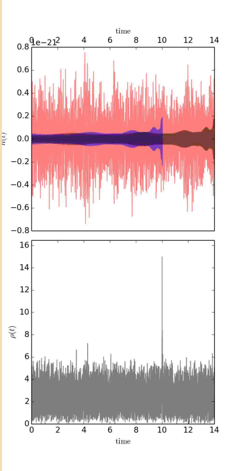
Parameter	Description
$m_1,\ m_2$	Component Masses
$\vec{S}_1,\ \vec{S}_2$	Component Spins
$\theta,\ \phi$	Sky Position
$\iota,\ \psi$	Orientation
d_L	Distance
$\varphi_c,\ t_c$	Reference phase/time
e	Eccentricity
$\lambda_1,\ \lambda_2$	Tidal deformability

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

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

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

Matched Filtering



- Data $d(t)$, template $h(t)$, noise spectral density $S_n(f)$
- Calculate signal-to-noise

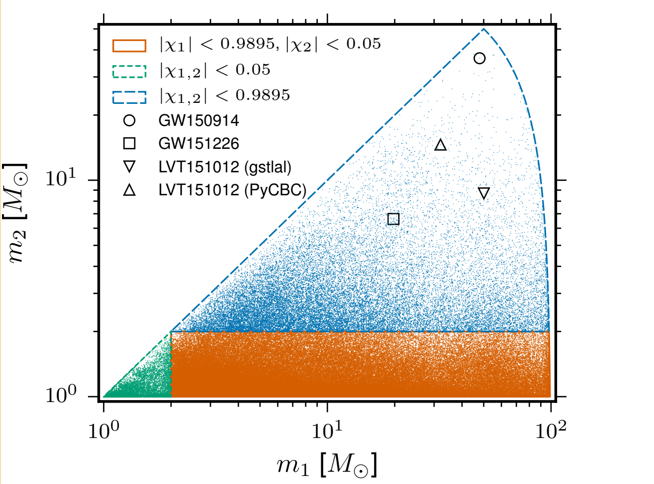
$$\rho(\tau) = 4\Re\left\{\int_0^\infty \frac{\tilde{d}^*(f)\tilde{h}(f)}{S_n(f)} e^{2\pi\imath f\tau}\, df\right\}$$

- Calculate a signal-based veto χ^2

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

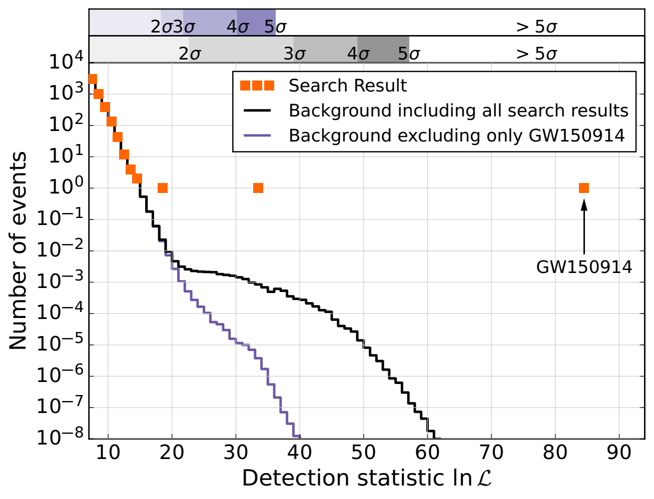
$$\chi^2 = \frac{1}{p}\sum_{j=1}^{p}\left(\sum_{k=1}^{p} z_k - p z_j\right)^2$$

Template Bank



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

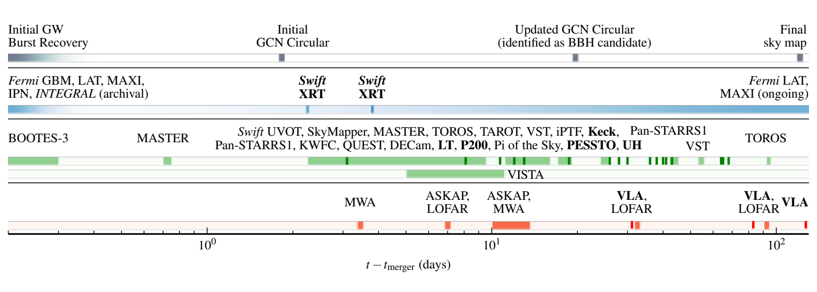
Detection Statistics



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

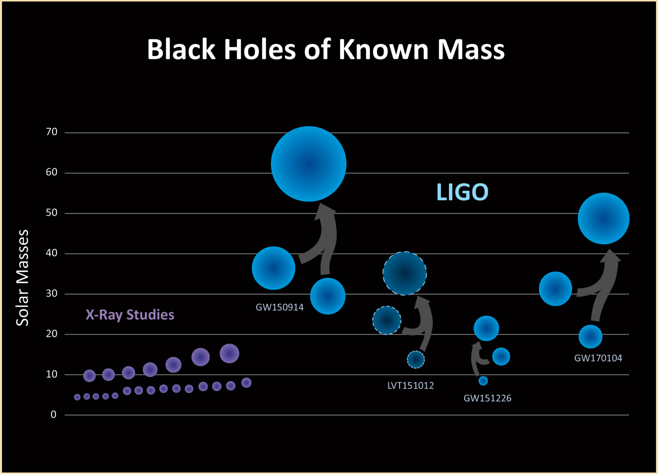
EM Follow-up

- Many facilities and telescopes have signed MoUs
- Provide GW event candidate alerts within tens of minutes
- 3D sky maps are released for binaries
- Provide ”EM-bright” flag if event possibly includes NS



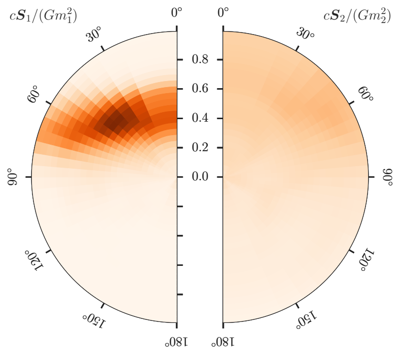
B. P. Abbott et al. *ApJ* 826, L13 (July 2016)

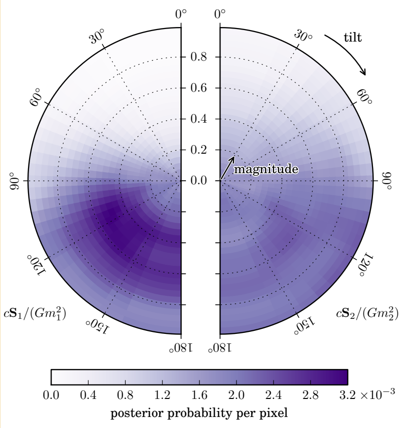
Black Hole Mass Census



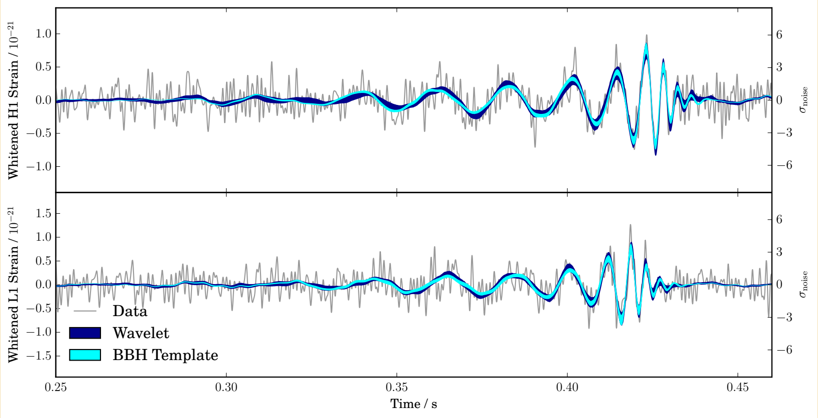
credit: LIGO

Spin


$cS_1/(Gm_1^2)$
$cS_2/(Gm_2^2)$
0°
30°
60°
90°
120°
150°
180°
0.8
0.6
0.4
0.2
0.0

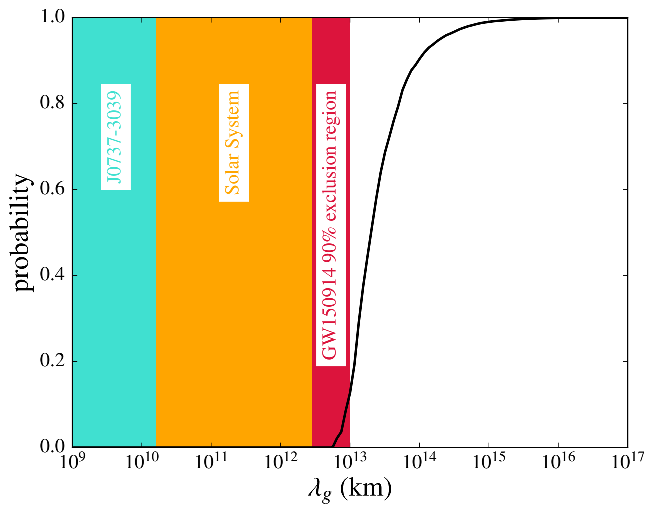

0°
30°
60°
90°
120°
150°
180°
tilt
magnitude
0.8
0.6
0.4
0.2
0.0
$c\mathbf{S}_1/(Gm_1^2)$
$c\mathbf{S}_2/(Gm_2^2)$
0.0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2 $\times10^{-3}$
posterior probability per pixel

Consistent with GR?



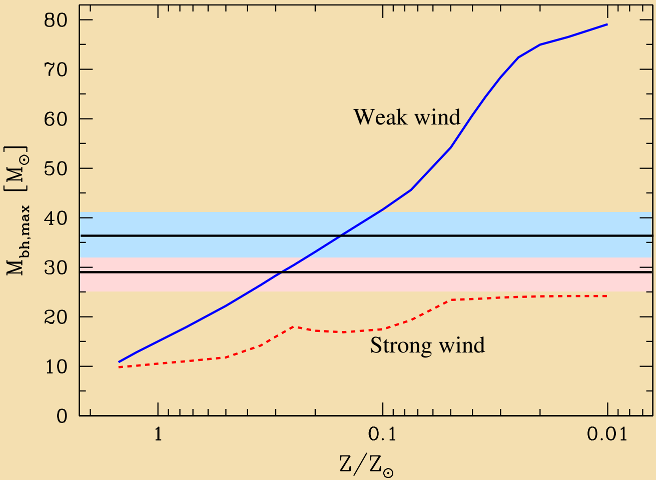
B. P. Abbott et al. *Physical Review Letters* 116.6, 061102 (Feb. 2016)

Test of General Relativity



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

Astrophysical Implications

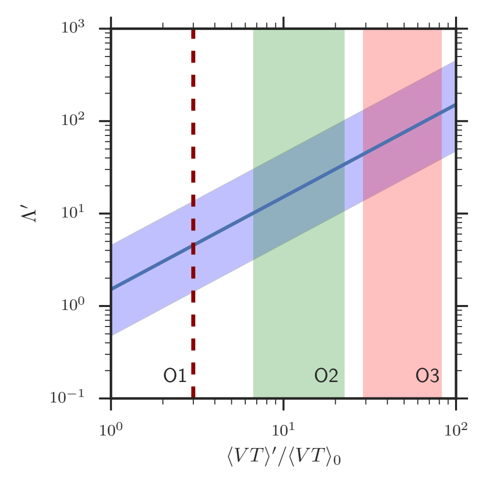


B. P. Abbott et al. *ApJ* 818, L22 (Feb. 2016)

2nd Generation GW Network

- Advanced LIGO
  - Estimate it could take at least 12–15 months after ending O2 to complete this work before beginning O3.
- Advanced Virgo (2017)
  - Joined Advanced LIGO since 1 August 2017
- 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

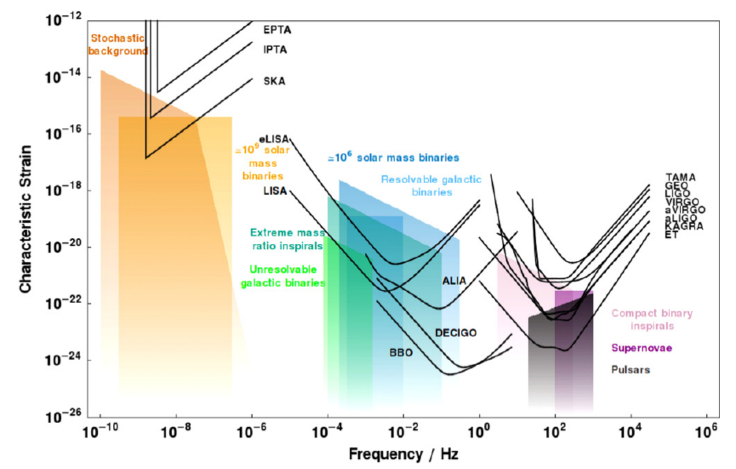
Expected Detection Rate



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.

B. P. Abbott et al. *ApJ* 833, L1 (Dec. 2016)

Full GW Spectrum



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

BBH – Quasi-Normal Modes

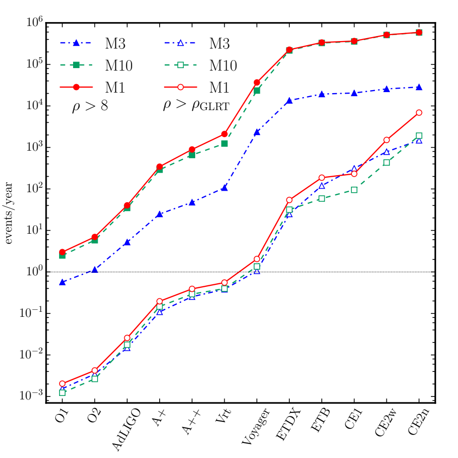
- Deformed black holes emit quasi-normal modes (ringdown)

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

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

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

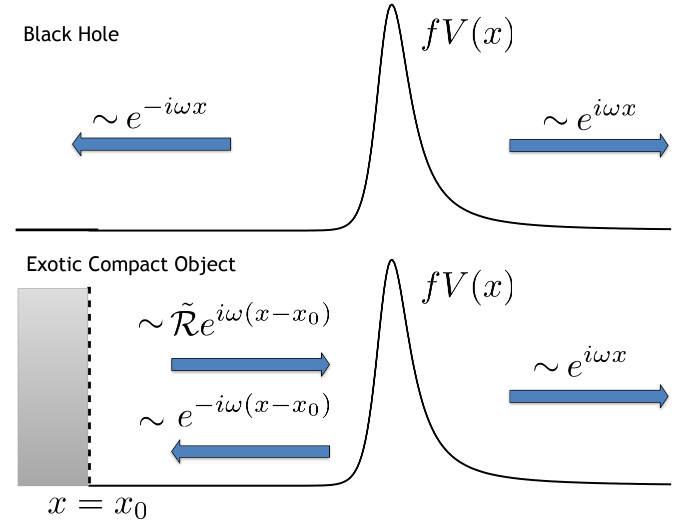
Quasi-Normal Modes Prospects



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

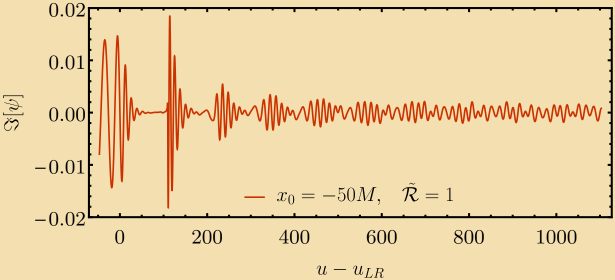
E. Berti et al. *Physical Review Letters* 117.10, 101102 (Sept. 2016)

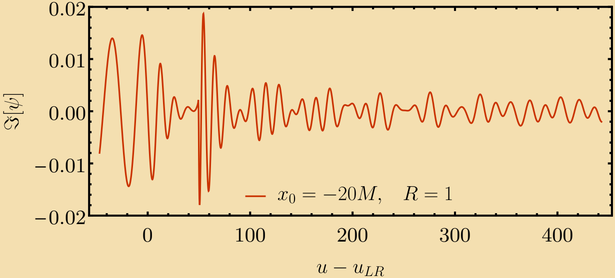
Gravitational-Wave Echos



Z. Mark et al. *ArXiv e-prints* (June 2017)

Gravitational-Wave Echos

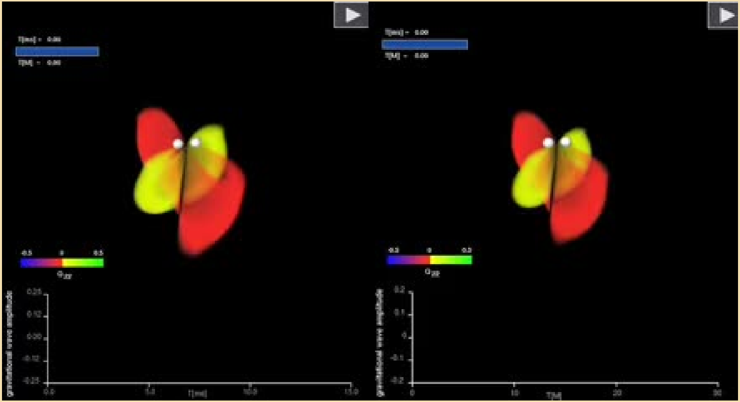




Binary Neutron Stars

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

Nuclear Equation of State



credit: Rezolla *et al.*

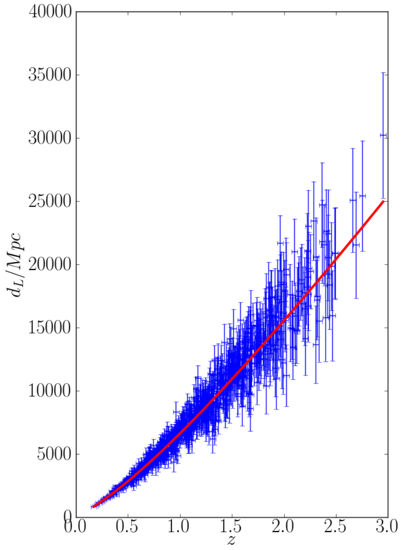
Cosmology

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

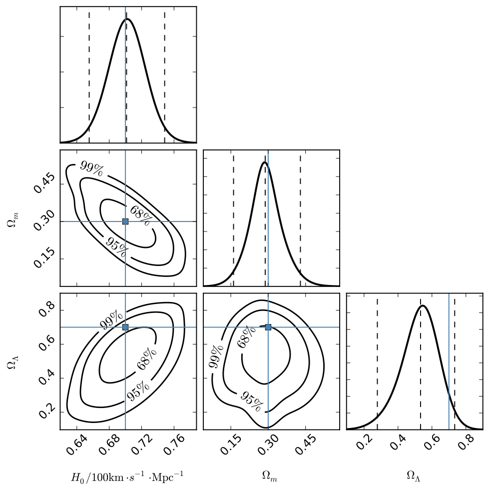
- Measure *distance* and *recession velocity* of celestial objects

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

H_0	Hubble constant
Ω_m	Matter density
Ω_k	Spatial curvature
Ω_Λ, w	Dark energy



Cosmology – 3rd Generation



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

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

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

[1] B. P. Abbott et al. "Binary Black Hole Mergers in the First Advanced LIGO Observing Run". *Physical Review X* 6.4, 041015 (Oct. 2016), p. 041015.

[2] B. P. Abbott et al. "Localization and Broadband Follow-up of the Gravitational-wave Transient GW150914". *ApJ* 826, L13 (July 2016), p. L13. arXiv: `1602.08492 [astro-ph.HE]`.

[3] B. P. Abbott et al. "Observation of Gravitational Waves from a Binary Black Hole Merger". *Physical Review Letters* 116.6, 061102 (Feb. 2016), p. 061102. arXiv: `1602.03837 [gr-qc]`.

[4] B. Abbott et al. "Tests of General Relativity with GW150914". *Phys. Rev. Lett.* 116.22 (2016). URL: `http://dx.doi.org/10.1103/PhysRevLett.116.221101`.

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[5] B. P. Abbott et al. "Astrophysical Implications of the Binary Black Hole Merger GW150914". *ApJ* 818, L22 (Feb. 2016), p. L22. arXiv: 1602.03846 [astro-ph.HE].

[6] B. P. Abbott et al. "The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914". *ApJ* 833, L1 (Dec. 2016), p. L1. arXiv: 1602.03842 [astro-ph.HE].

[7] C. J. Moore et al. "Gravitational-wave sensitivity curves". *Classical and Quantum Gravity* 32.1, 015014 (Jan. 2015), p. 015014. arXiv: 1408.0740 [gr-qc].

[8] E. Berti et al. "Spectroscopy of Kerr Black Holes with Earth- and Space-Based Interferometers". *Physical Review Letters* 117.10, 101102 (Sept. 2016), p. 101102. arXiv: 1605.09286 [gr-qc].

References III

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[10] K. Kiuchi et al. “High resolution magnetohydrodynamic simulation of black hole-neutron star merger: Mass ejection and short gamma ray bursts”. *Phys. Rev. D* 92.6, 064034 (Sept. 2015), p. 064034. arXiv: 1506.06811 [astro-ph.HE].

[11] W. Del Pozzo et al. “Cosmological inference using only gravitational wave observations of binary neutron stars”. *Phys. Rev. D* 95 (2017), p. 043502. URL: http://link.aps.org/doi/10.1103/PhysRevD.95.043502.