Max Planck Institute
for Gravitational Physics
Albert Einstein Institute

Listening for compact binary collisions: On the first observations of the gravitational-wave sky

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Overview

- Why we're excited by compact binary mergers
- Short introduction to gravitational waves and gravitational-wave observatories
- Observing compact binary mergers with gravitational-wave facilities
- What can we learn from gravitational-wave observations of compact binary mergers?

Why we're excited by compact binary mergers

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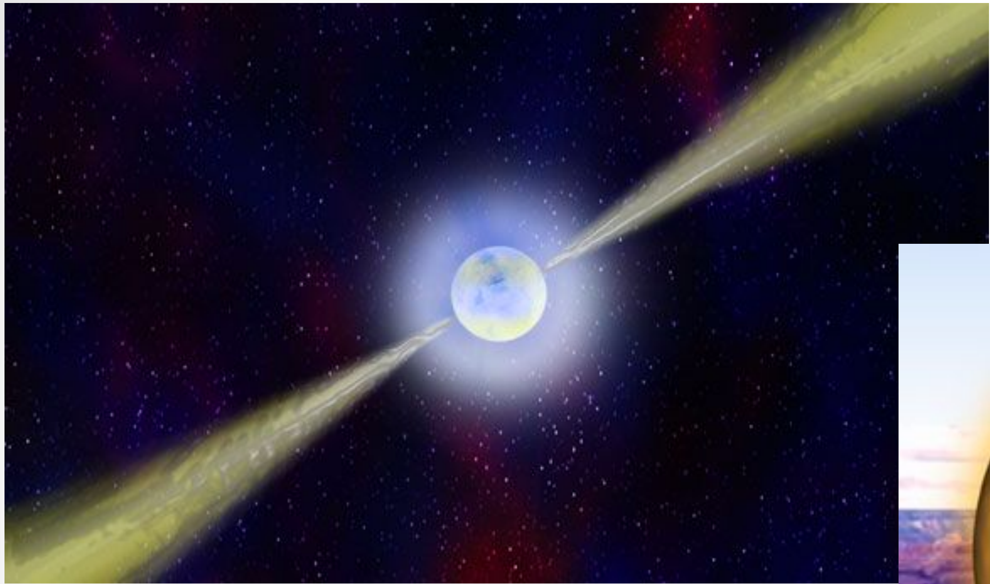
Neutron star



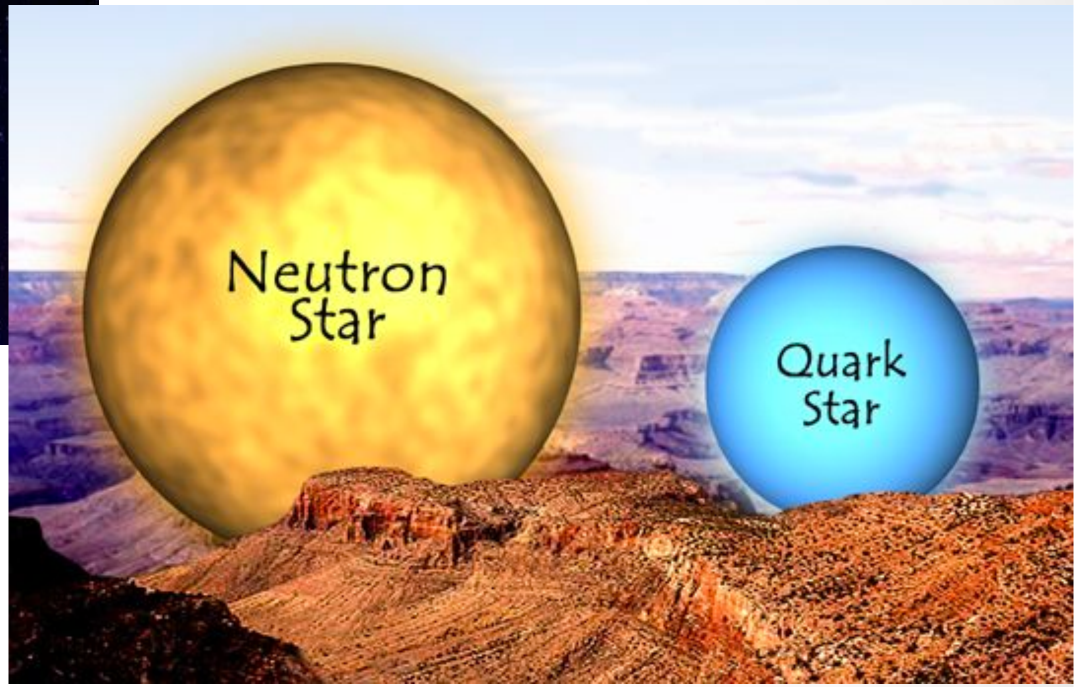
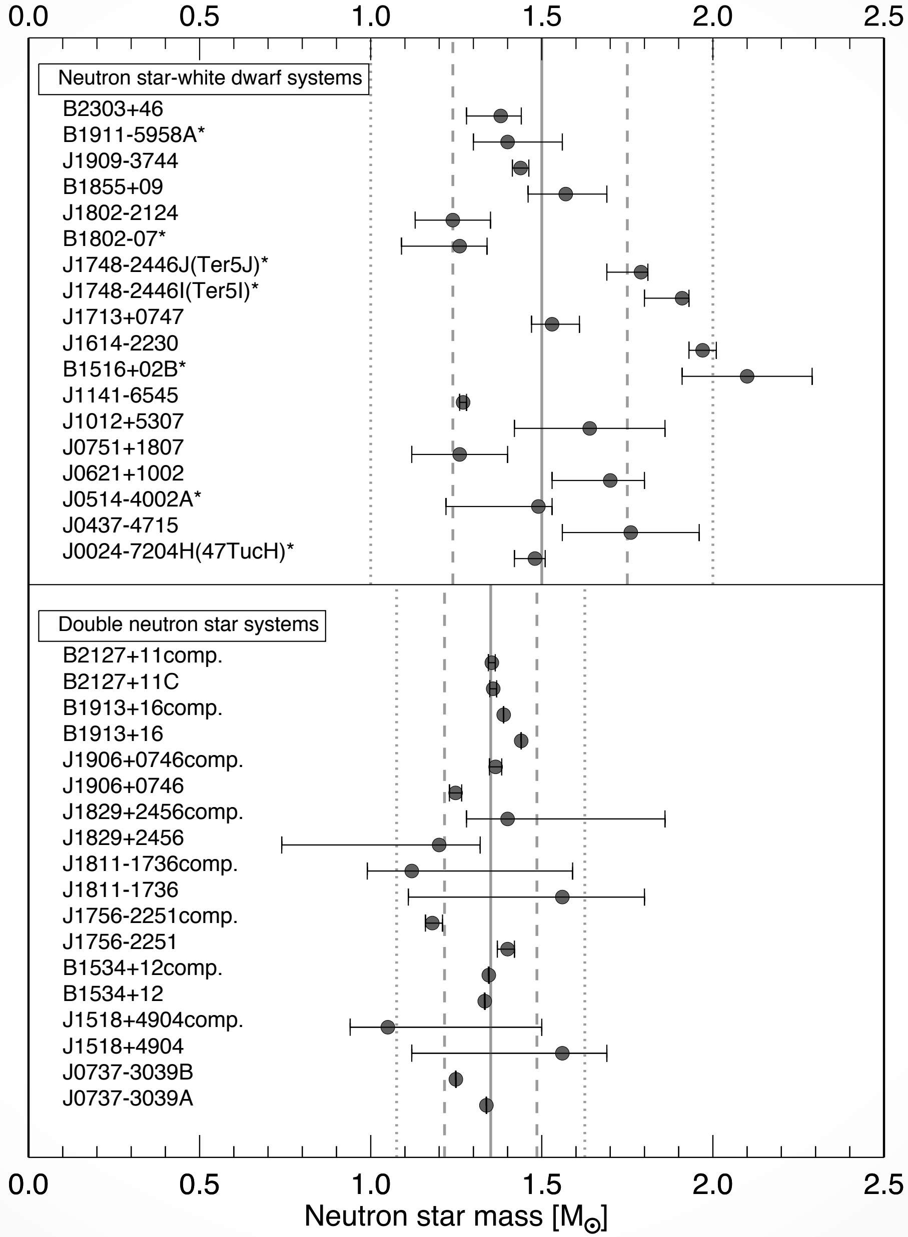


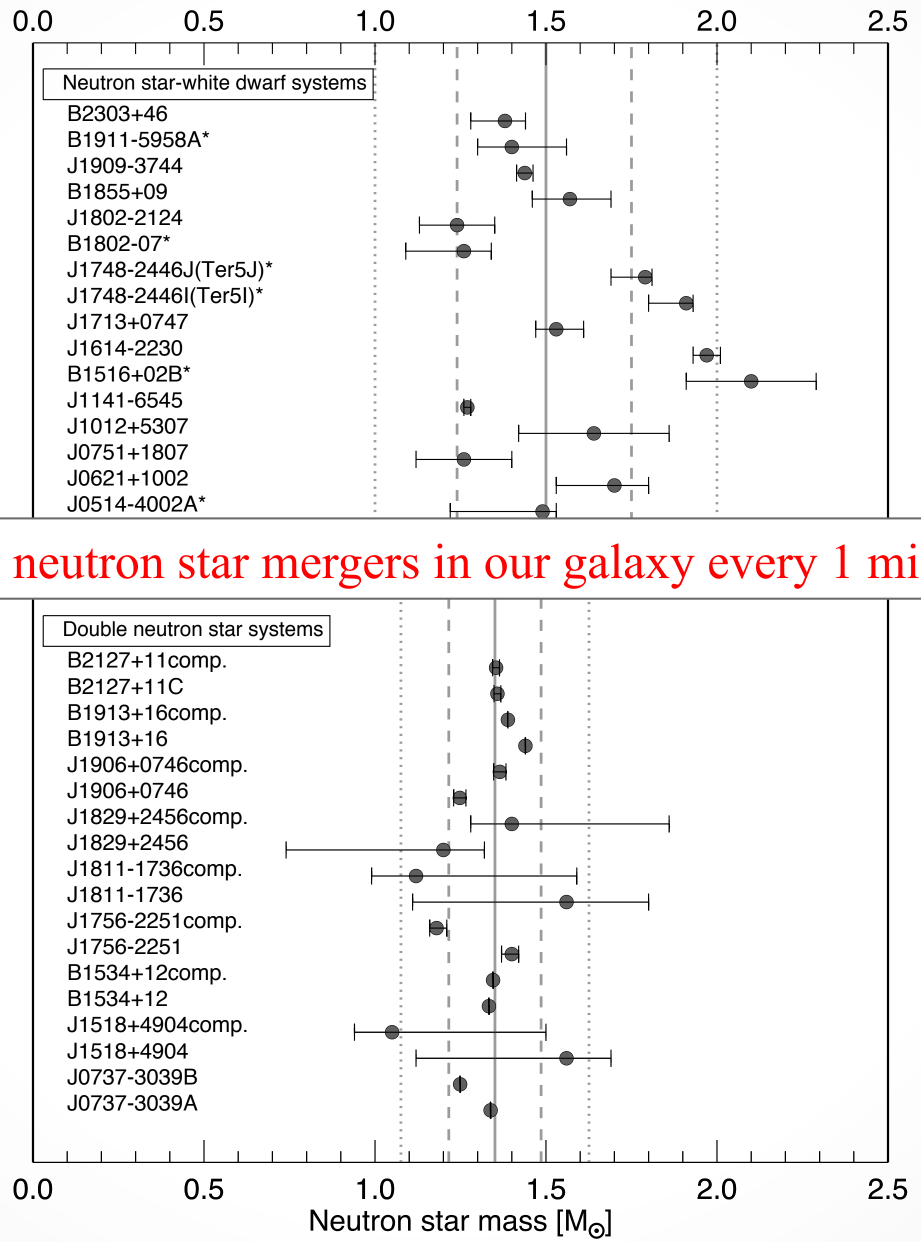
Image credit: NRAO and Chandra.harvard.edu

Existence of neutron-star binaries



Kiziltan et al. arXiv:1011.4291

Existence of neutron-star binaries



83 binary neutron star mergers in our galaxy every 1 million years

Kalogera et al. ApJ. 601, L179 (2004)

Gravitational waves from compact binaries

- Binary pulsar PSR1913+16
  - Pulsar provides a very accurate clock
  - Ideal "laboratory" for testing general relativity
  - Binary is losing energy as gravitational waves at precisely the rate predicted by general relativity

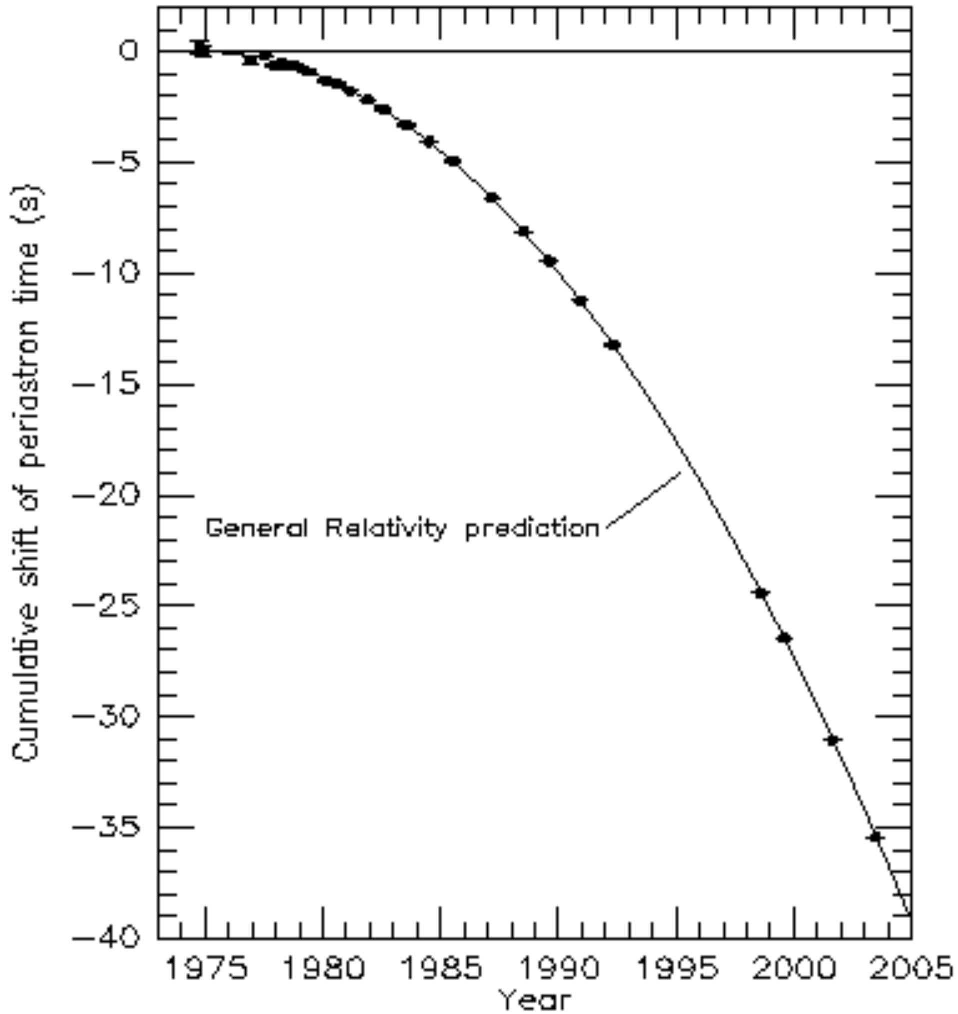
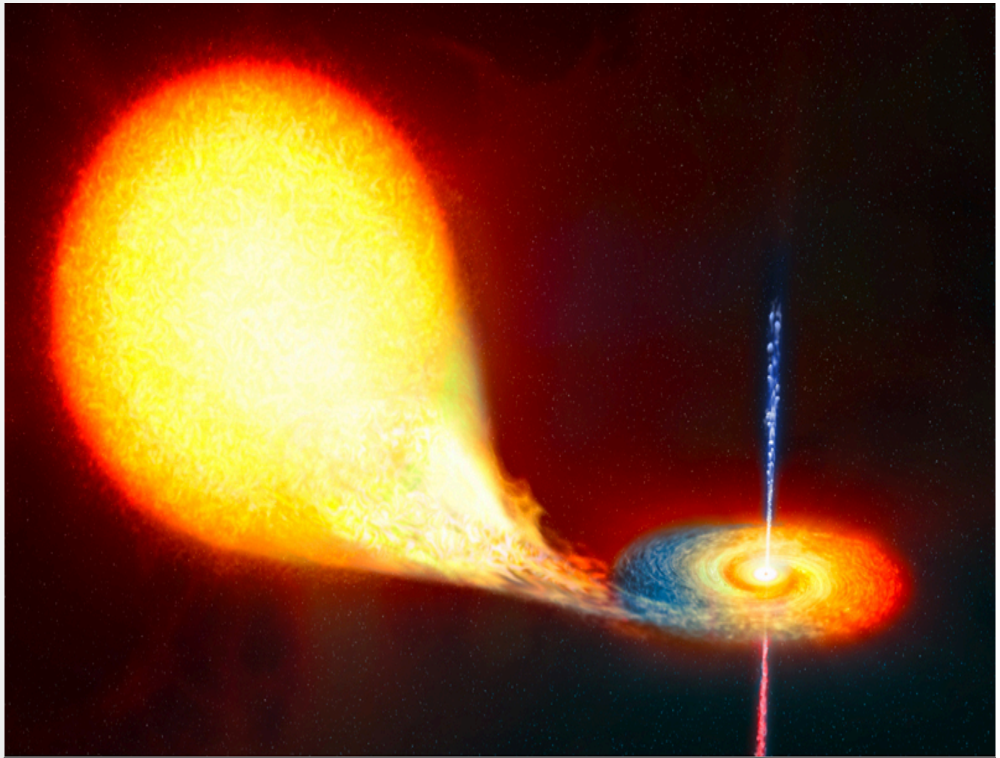
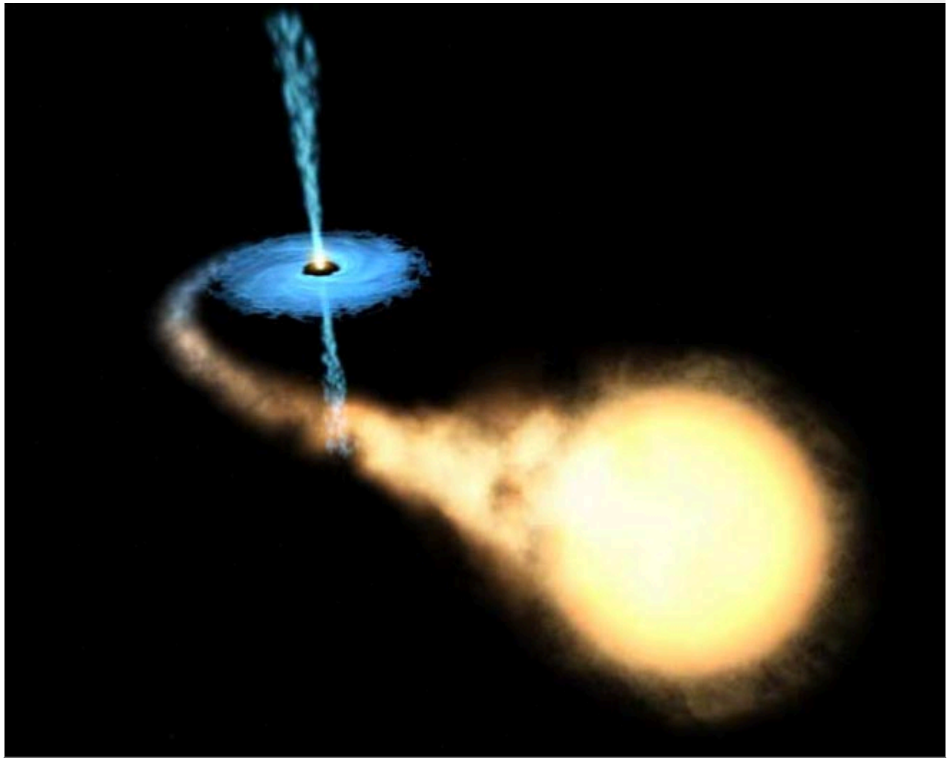


Figure from Weisberg+Taylor (2004).

Evidence for existence of black hole binaries



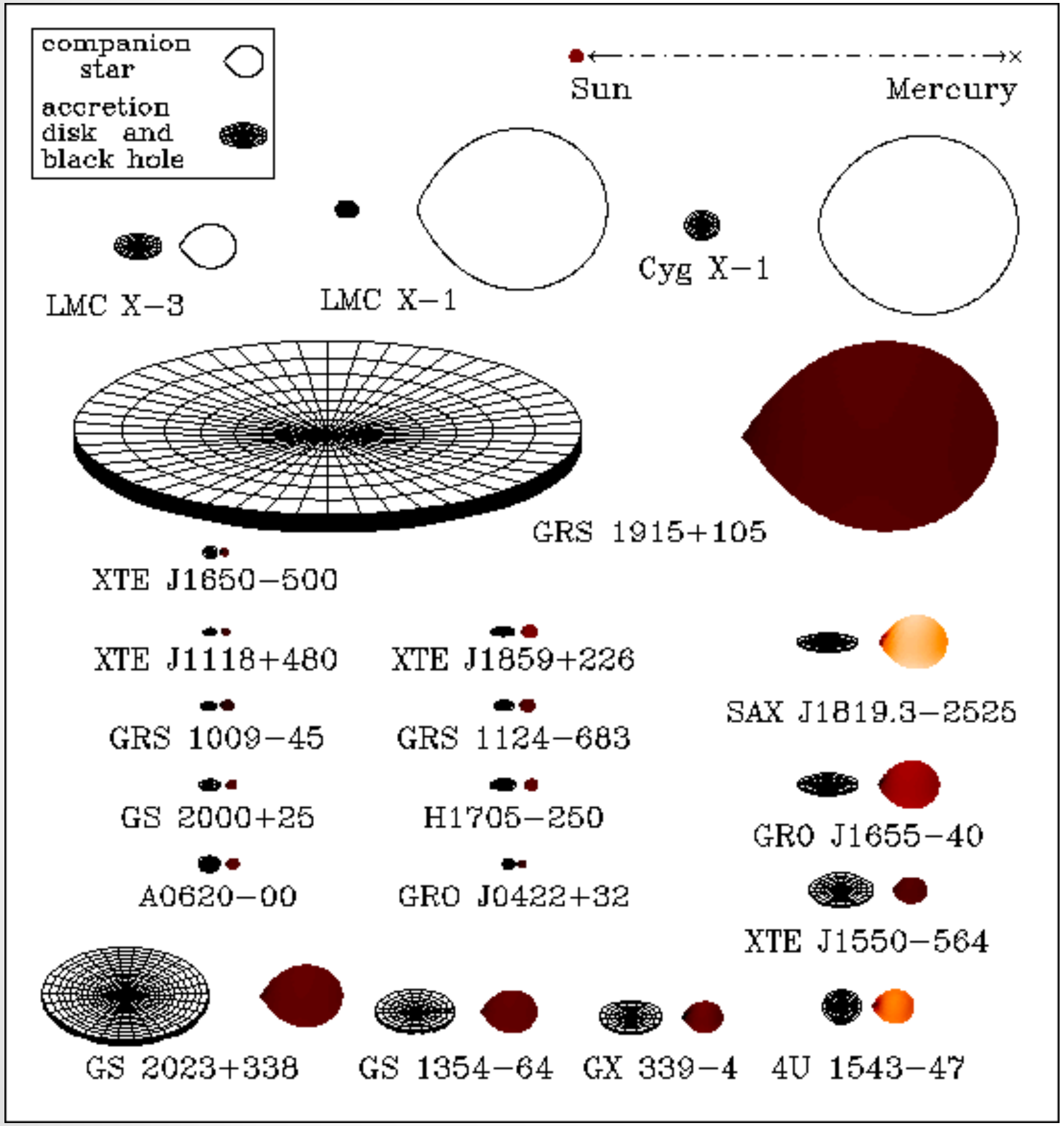
Low mass X-ray binary (LMXRB)



High mass X-ray binary (HMXRB)

Image credit: ESA (left) NASA/ESA/Felix Mirabel (right)

Evidence existence of stellar mass black hole binaries



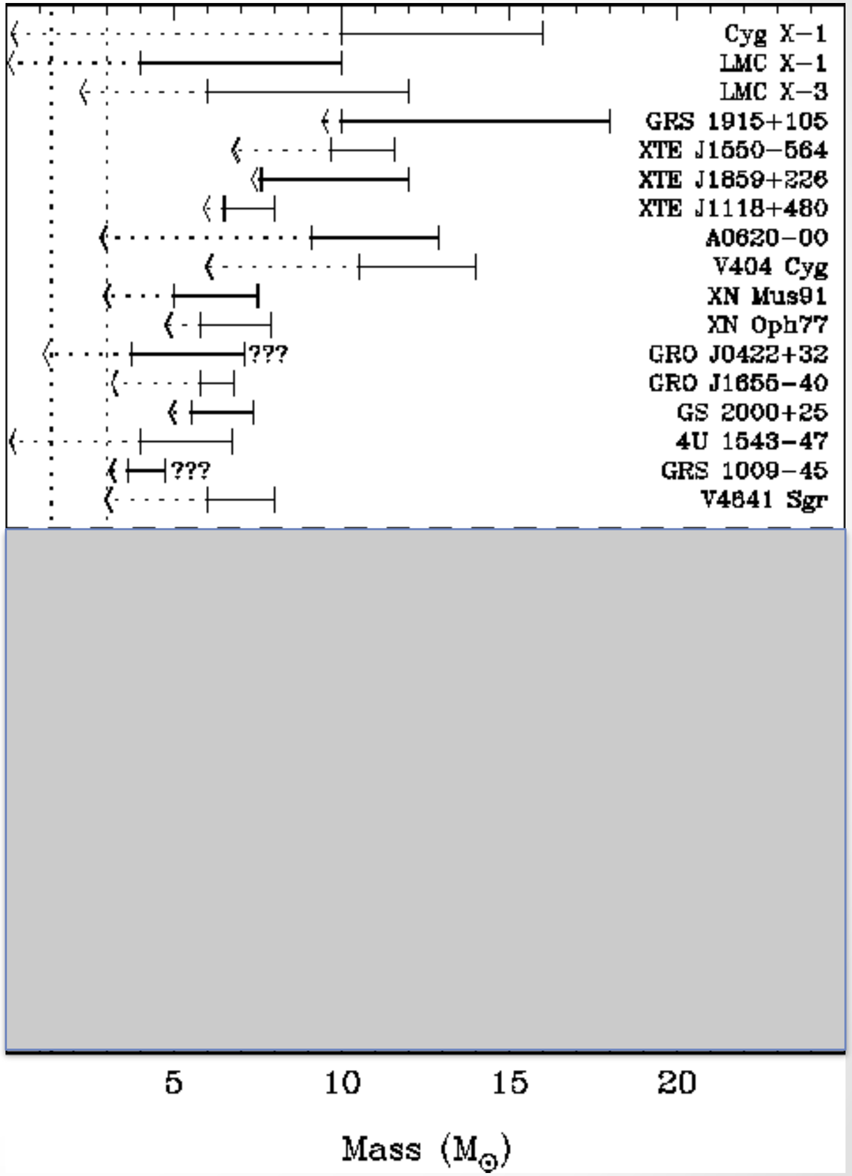
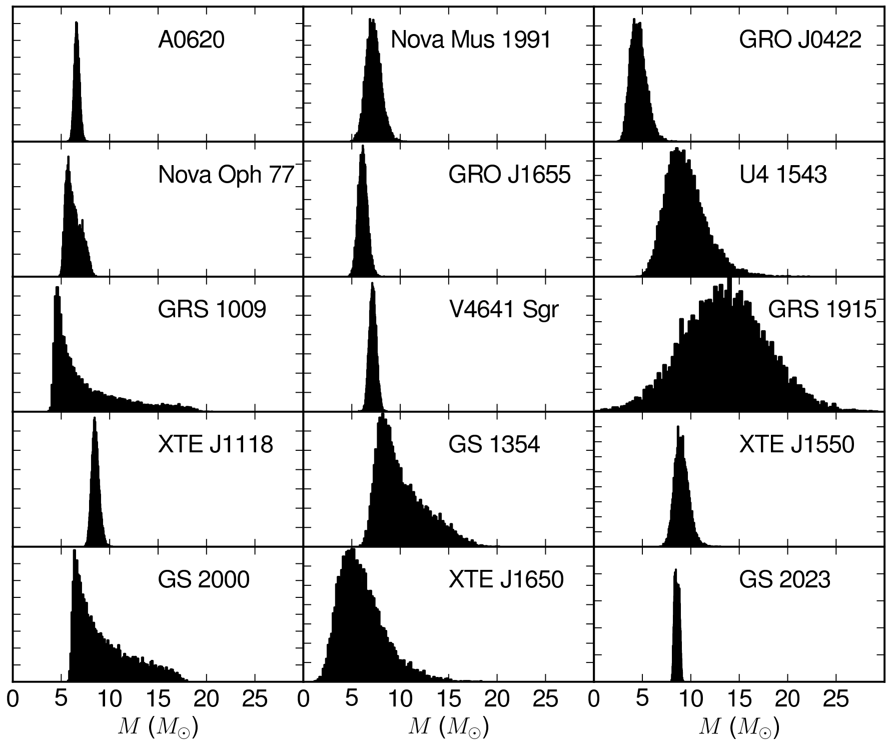
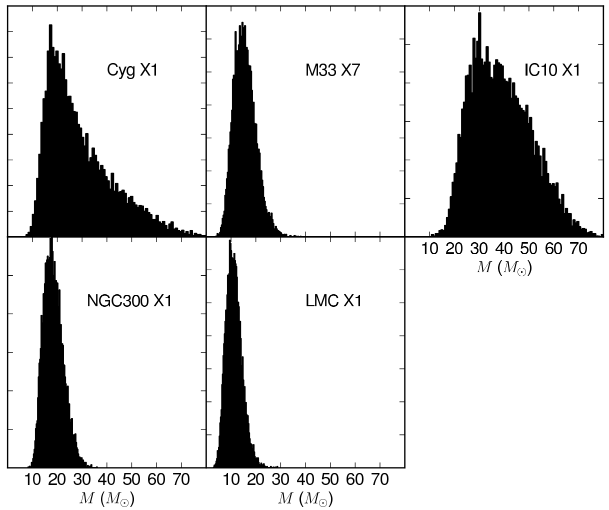


Image credit: J. Orosz

Evidence existence of stellar mass black hole binaries





Farr et al. ApJ 741, 103

Merger rates per Milky Way-like Galaxy

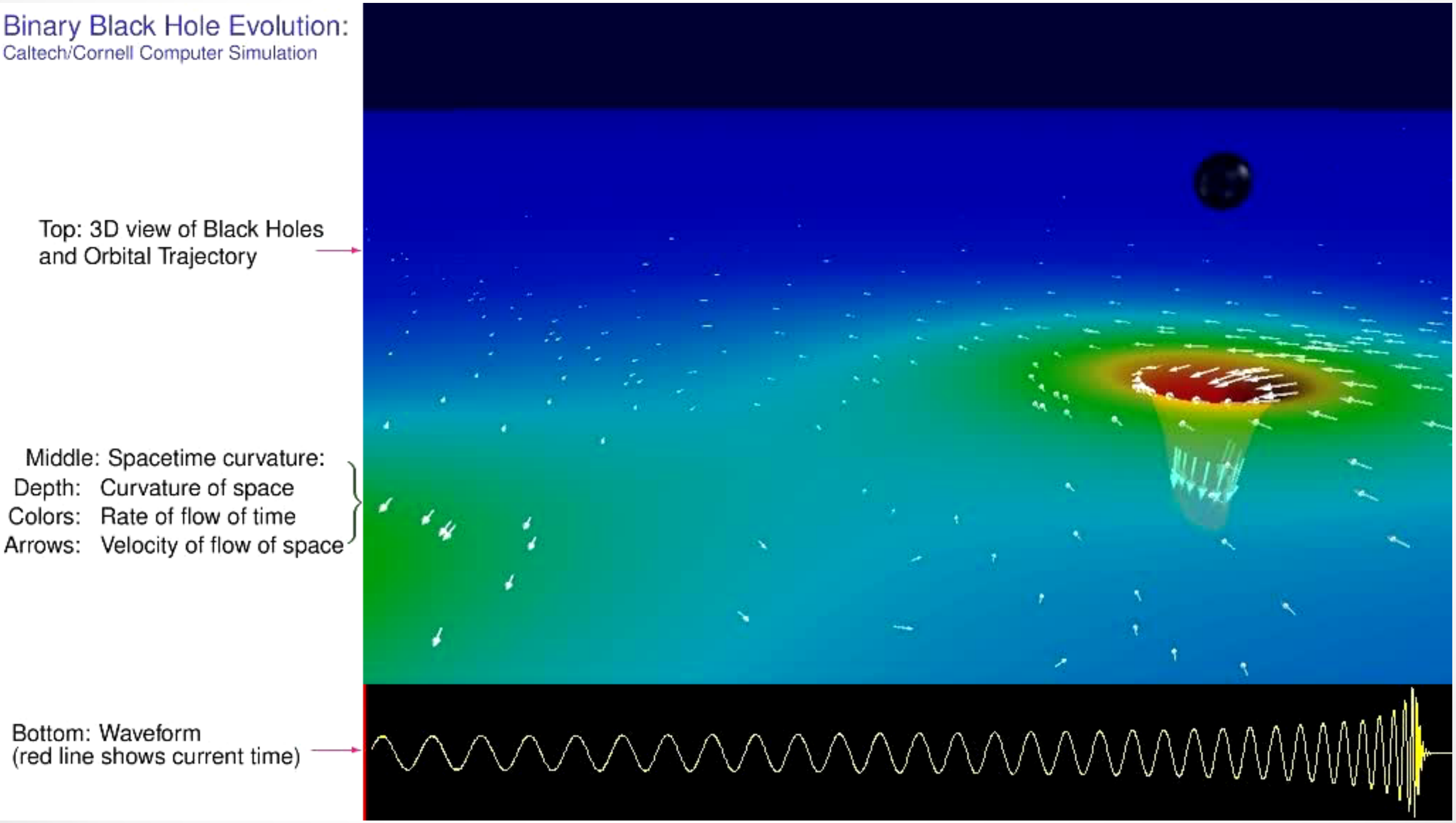
TABLE II: Compact binary coalescence rates per Milky Way Equivalent Galaxy per Myr.

Source	R_{low}	R_{re}	R_{high}	R_{max}
NS-NS (MWEG^{-1} Myr^{-1})	1 [1][a]	100 [1][b]	1000 [1][c]	4000 [16][d]
NS-BH (MWEG^{-1} Myr^{-1})	0.05 [18][e]	3 [18][f]	100 [18][g]	
BH-BH (MWEG^{-1} Myr^{-1})	0.01 [14][h]	0.4 [14][i]	30 [14][j]	
IMRI into IMBH (GC^{-1} Gyr^{-1})			3 [19][k]	20 [19][l]
IMBH-IMBH (GC^{-1} Gyr^{-1})			0.007 [20][m]	0.07 [20][n]

Abbott et al. CQG 27, 173001 (2010)

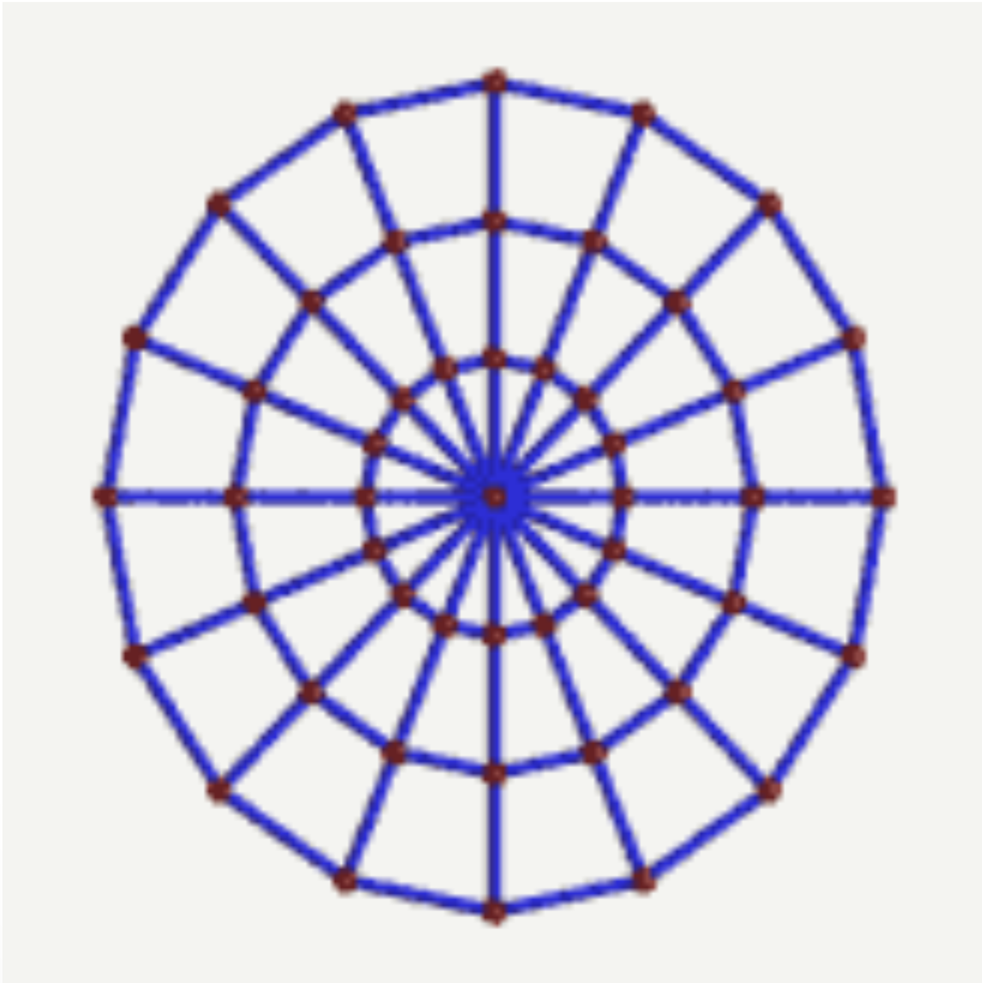
A Short introduction to gravitational waves and gravitational-wave observatories

Gravitational waves from merging black holes

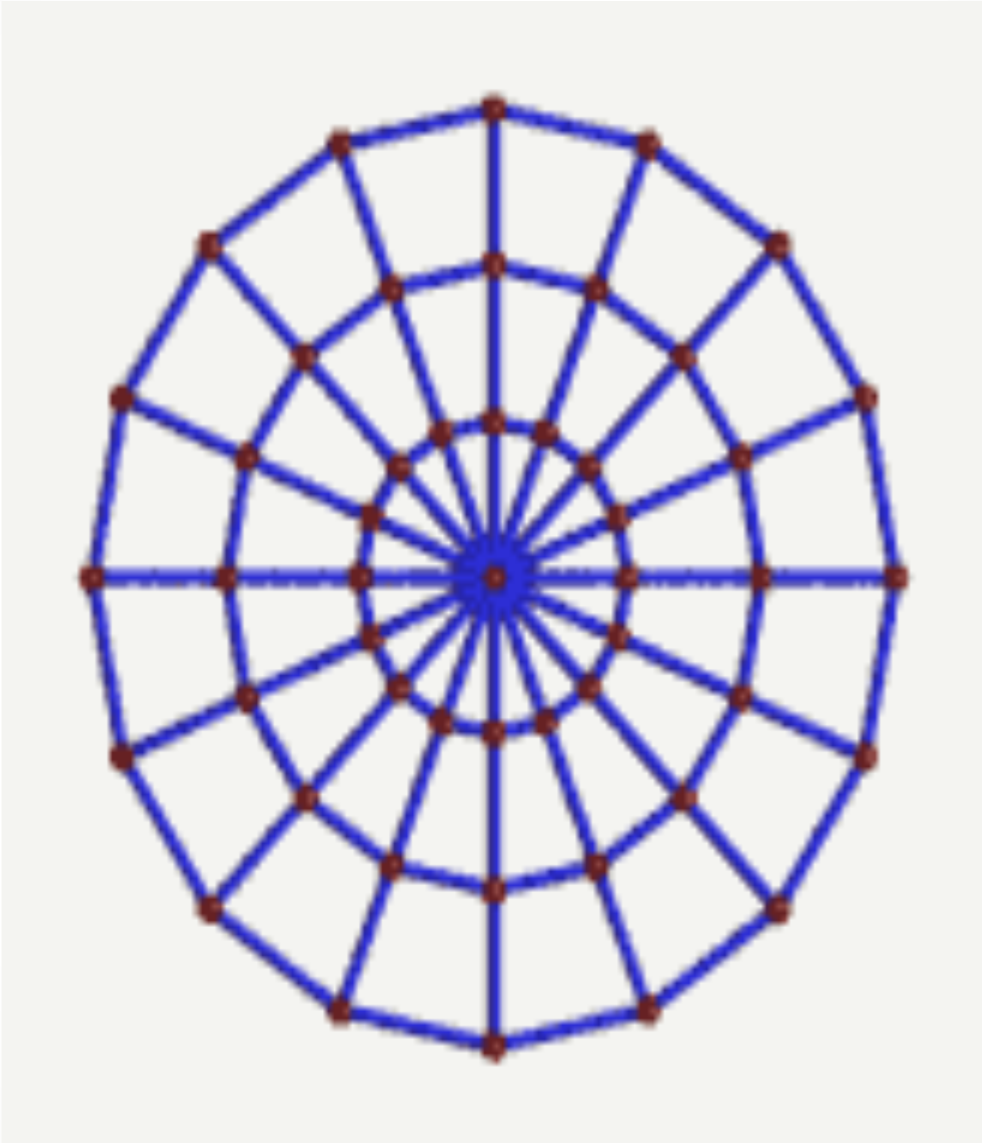


Simulation courtesy of the Simulating eXtreme Spacetimes (SXS) collaboration

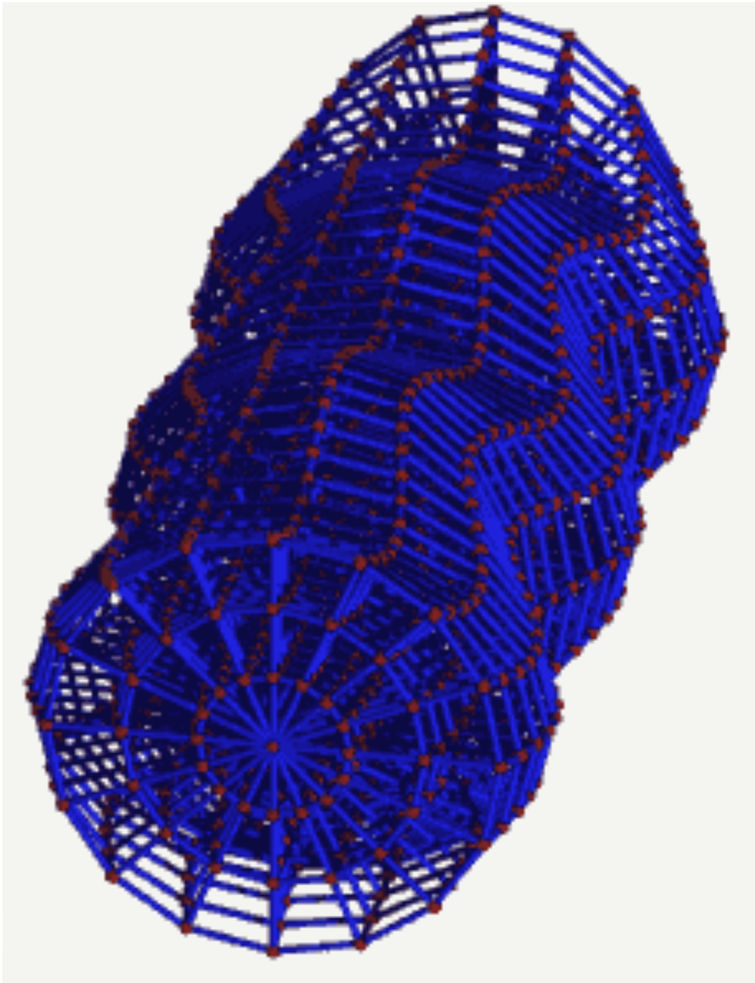
Effect of a gravitational wave



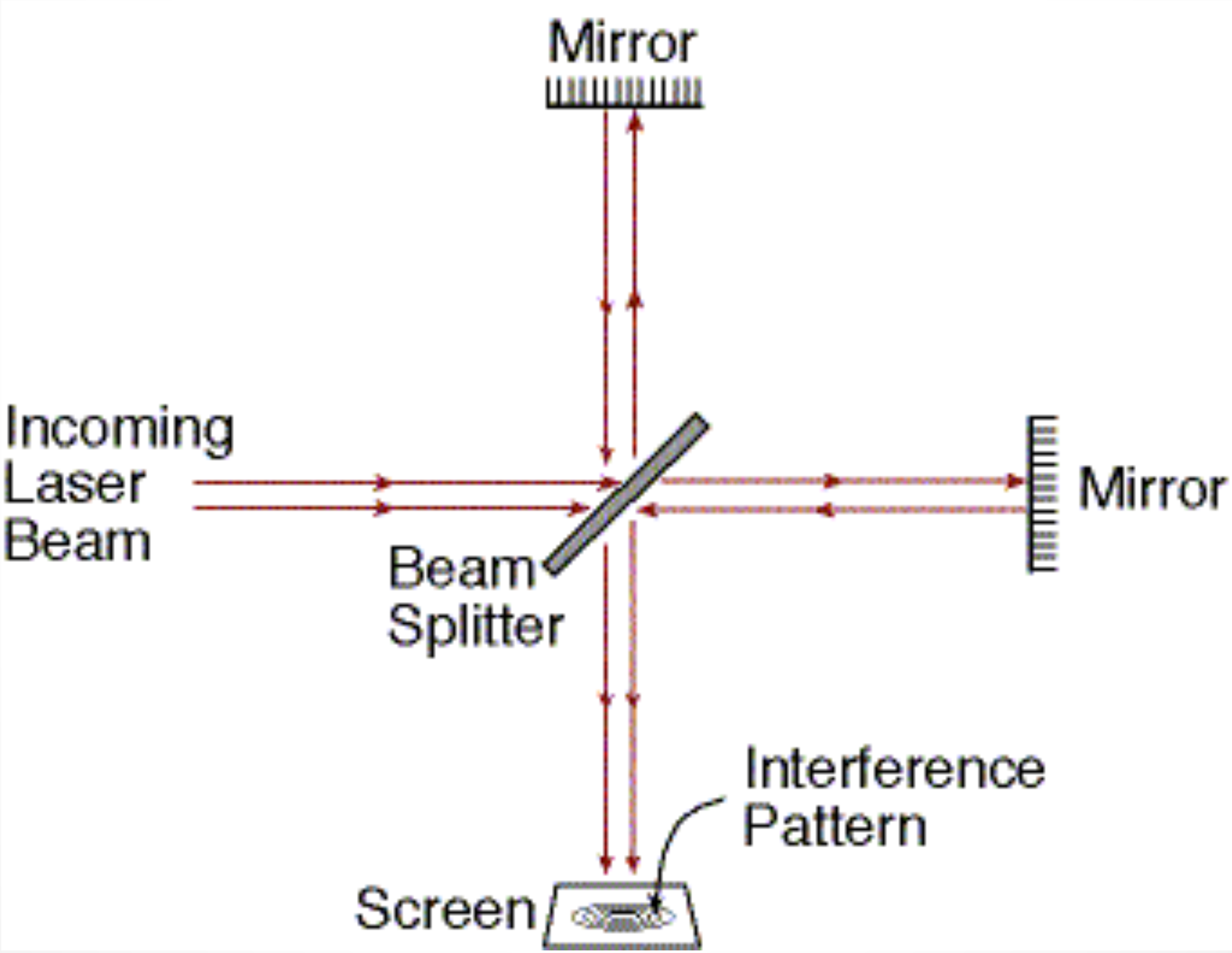
Effect of a gravitational wave



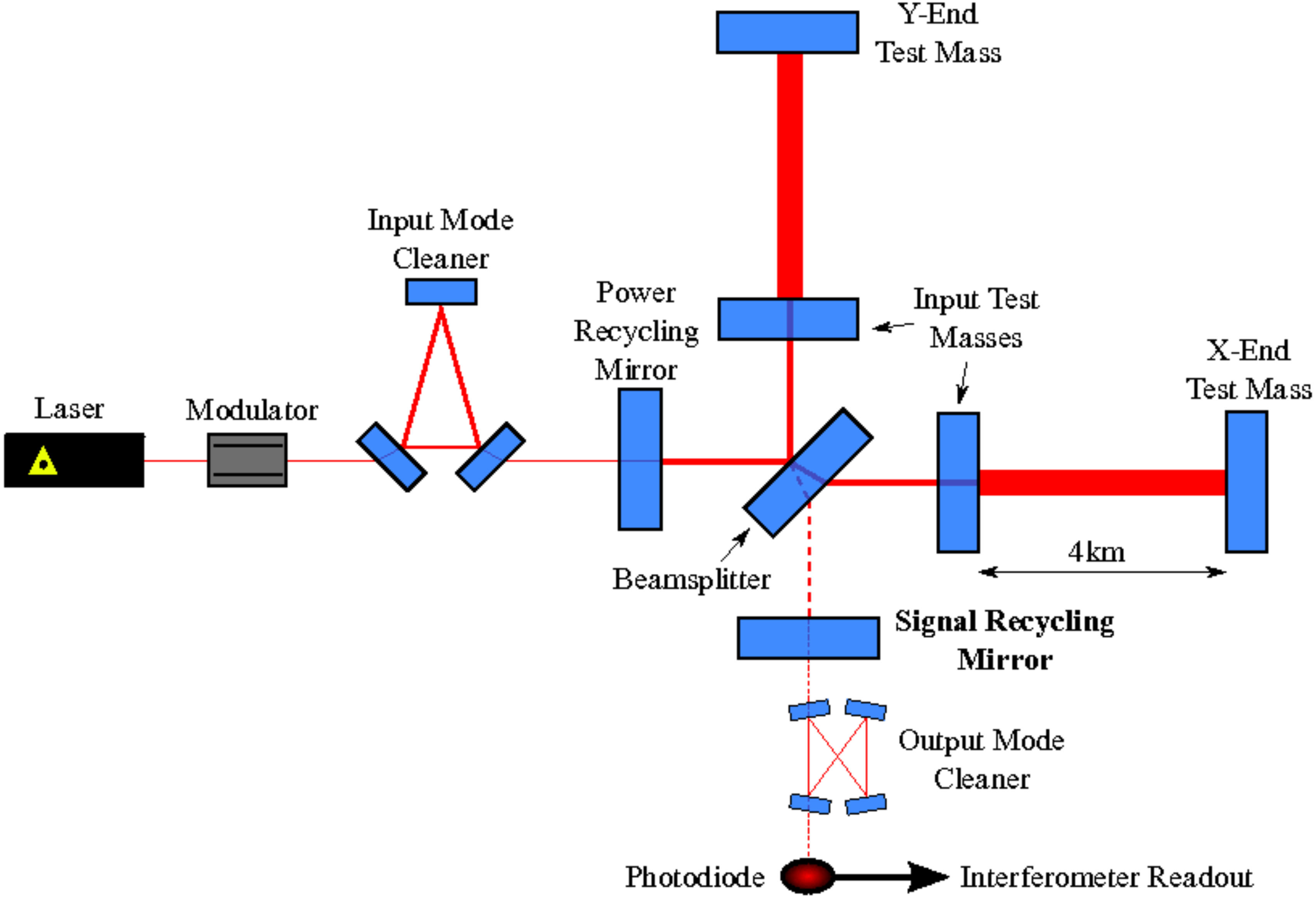
Effect of a gravitational wave



Basic Michelson Interferometer



A LIGO Interferometer



Ground-based interferometers

LIGO Hanford, WA

LIGO Livingston, LA

Virgo
Cascina
Italy

Advanced and Initial LIGO and Virgo

- Initial LIGO operated between 2002-2010
- Initial Virgo between 2007-2011
- No observations were made
- Advanced LIGO ~~will become~~ is operational this year
- Advanced Virgo will follow next year
- At design sensitivity will be 10x more sensitive
  - 10x distance = 1000x more volume
- Observatories in Japan and India hope to join in the 2020+ timescale.
- The first direct observations of gravitational wave sources from colliding black holes and/or neutron stars are expected soon!

What can we learn from gravitational-wave observations of compact binary mergers?

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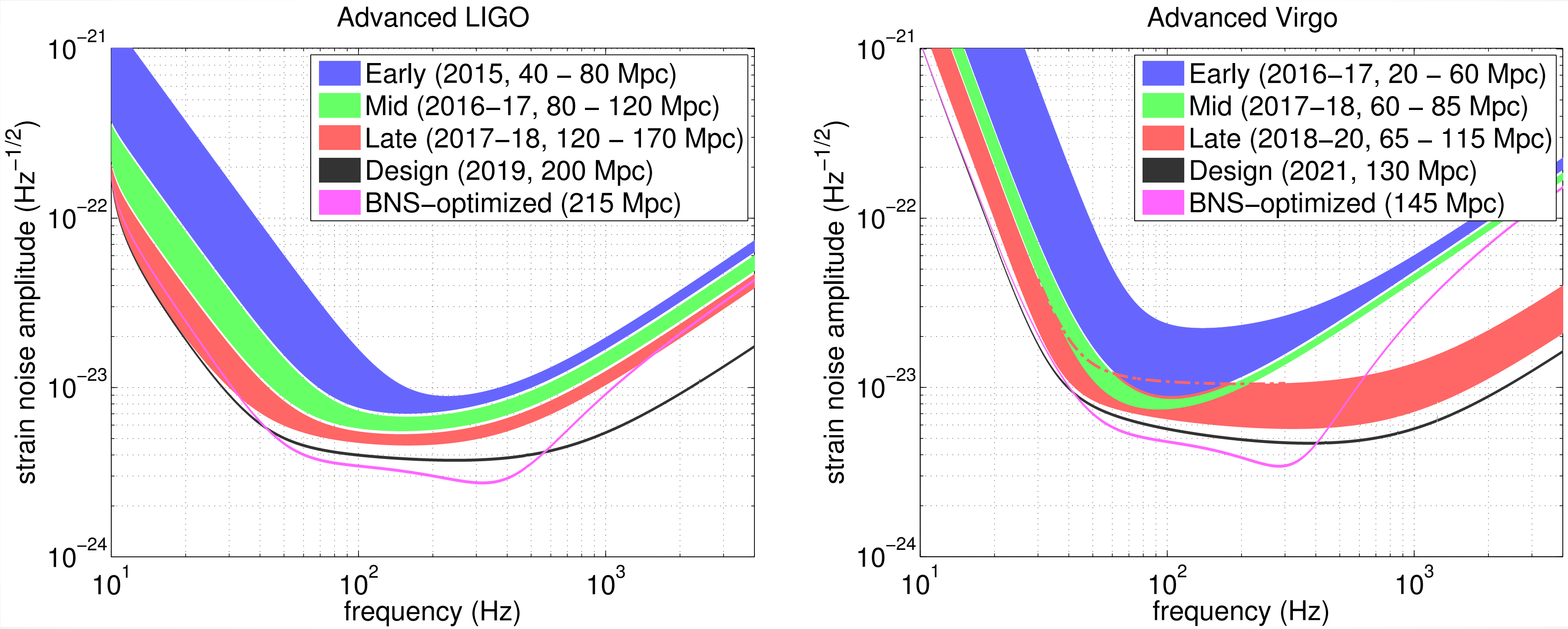
Distance reach



100 Mpc = 326Mly = redshift (z) of 0.024

Aasi et al. 1304.0670

Distance reach

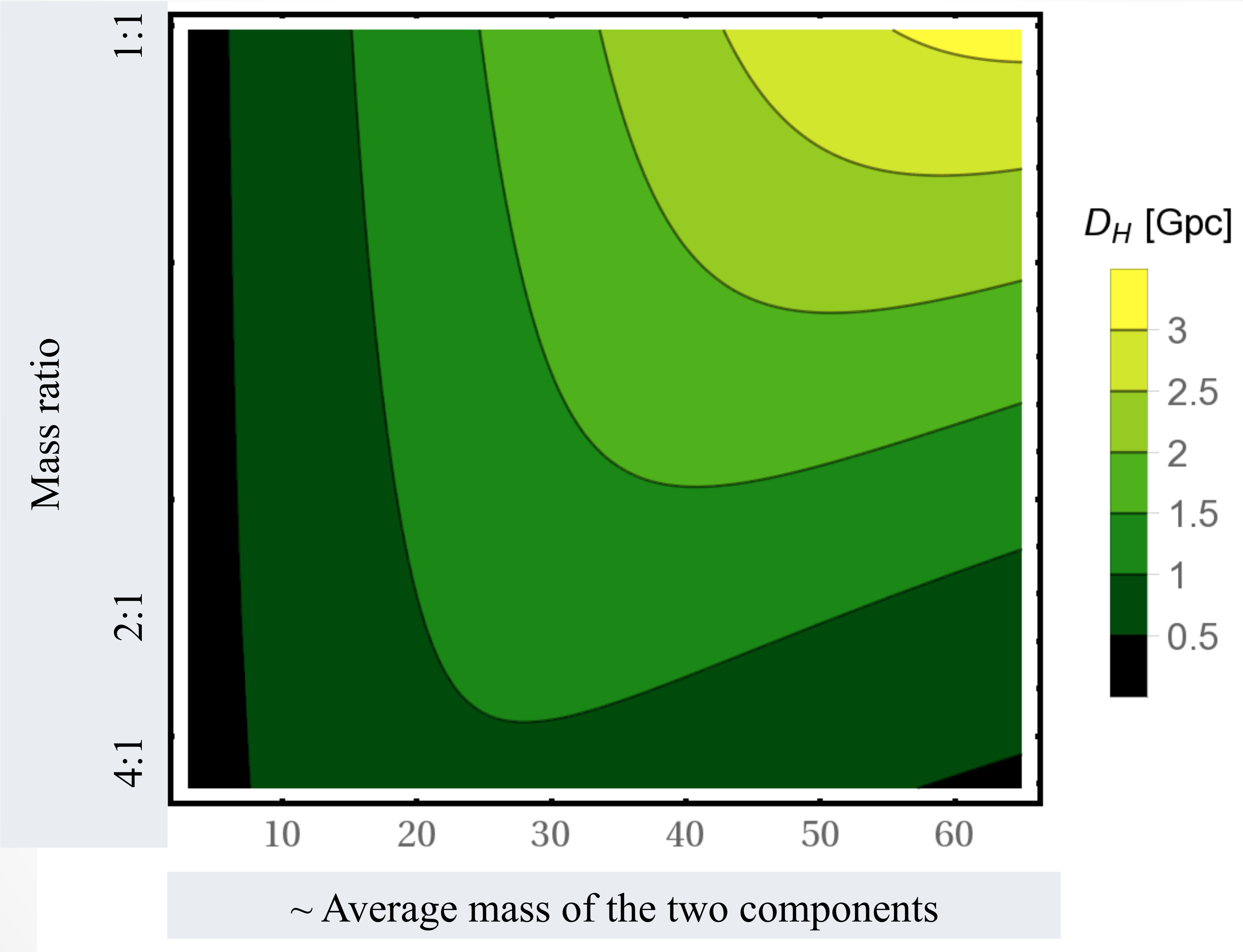
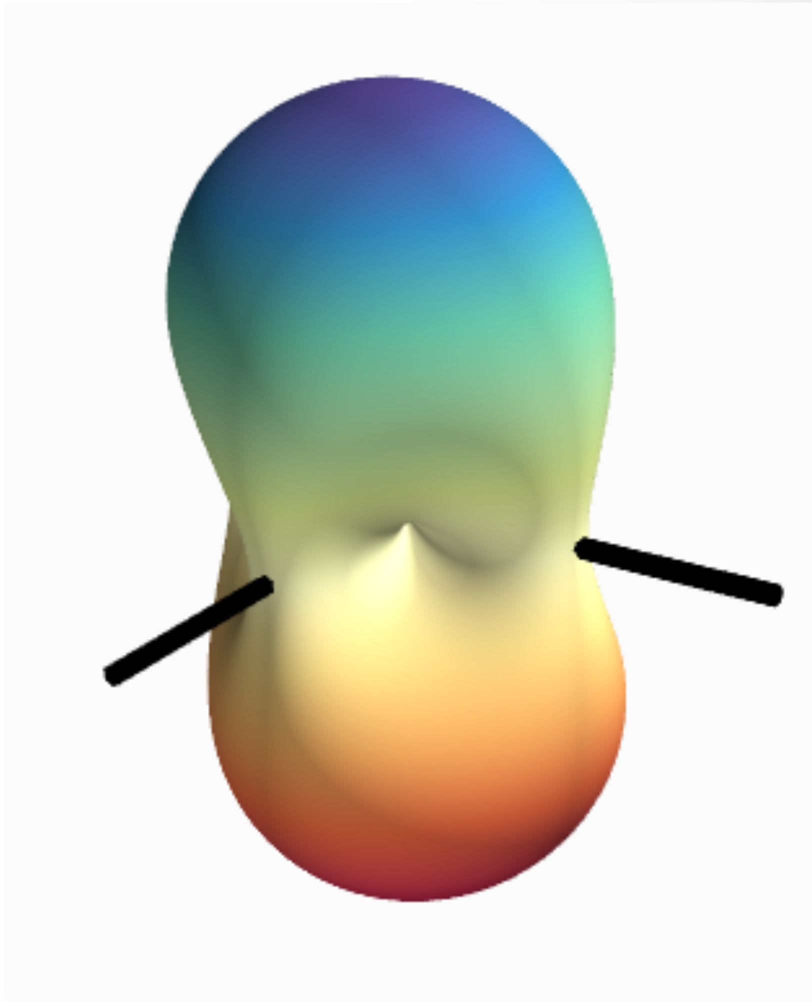


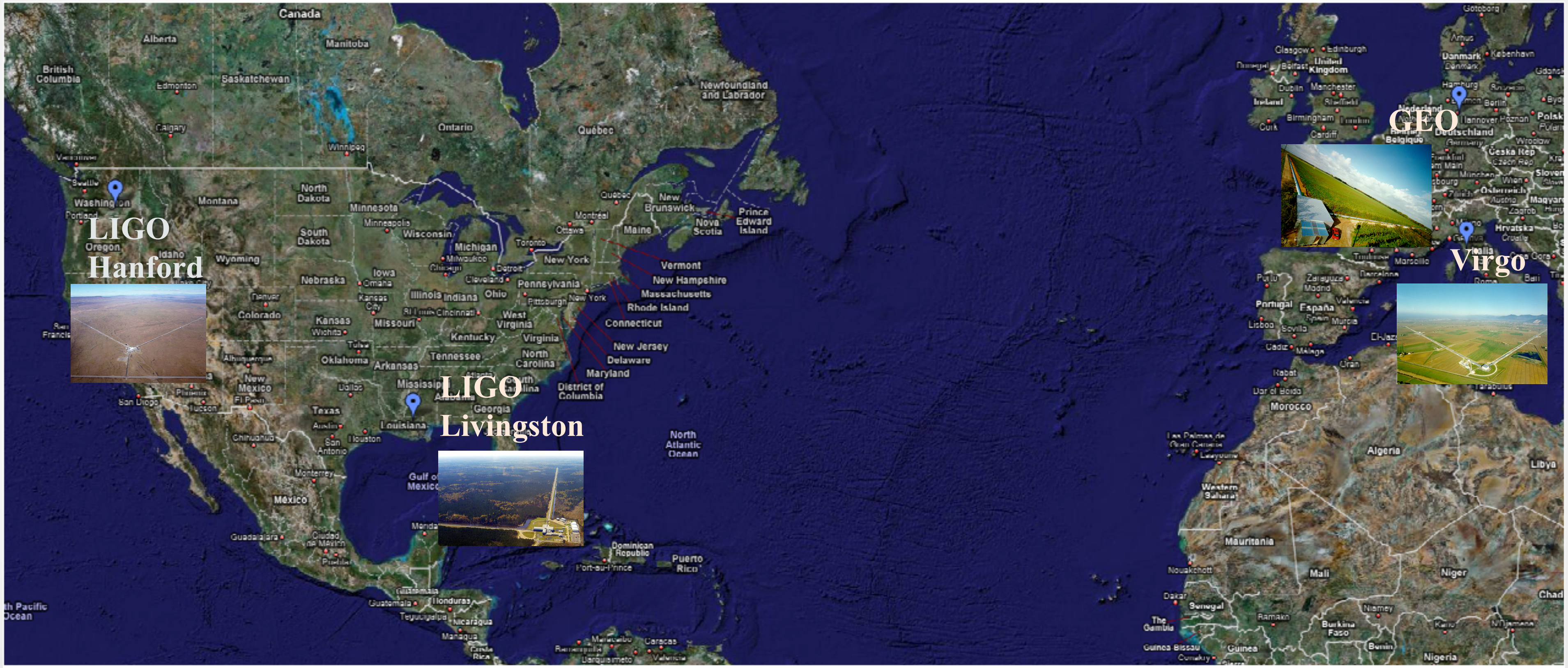
Image credit: Stevenson et al. 1504.07802

Directional Sensitivity

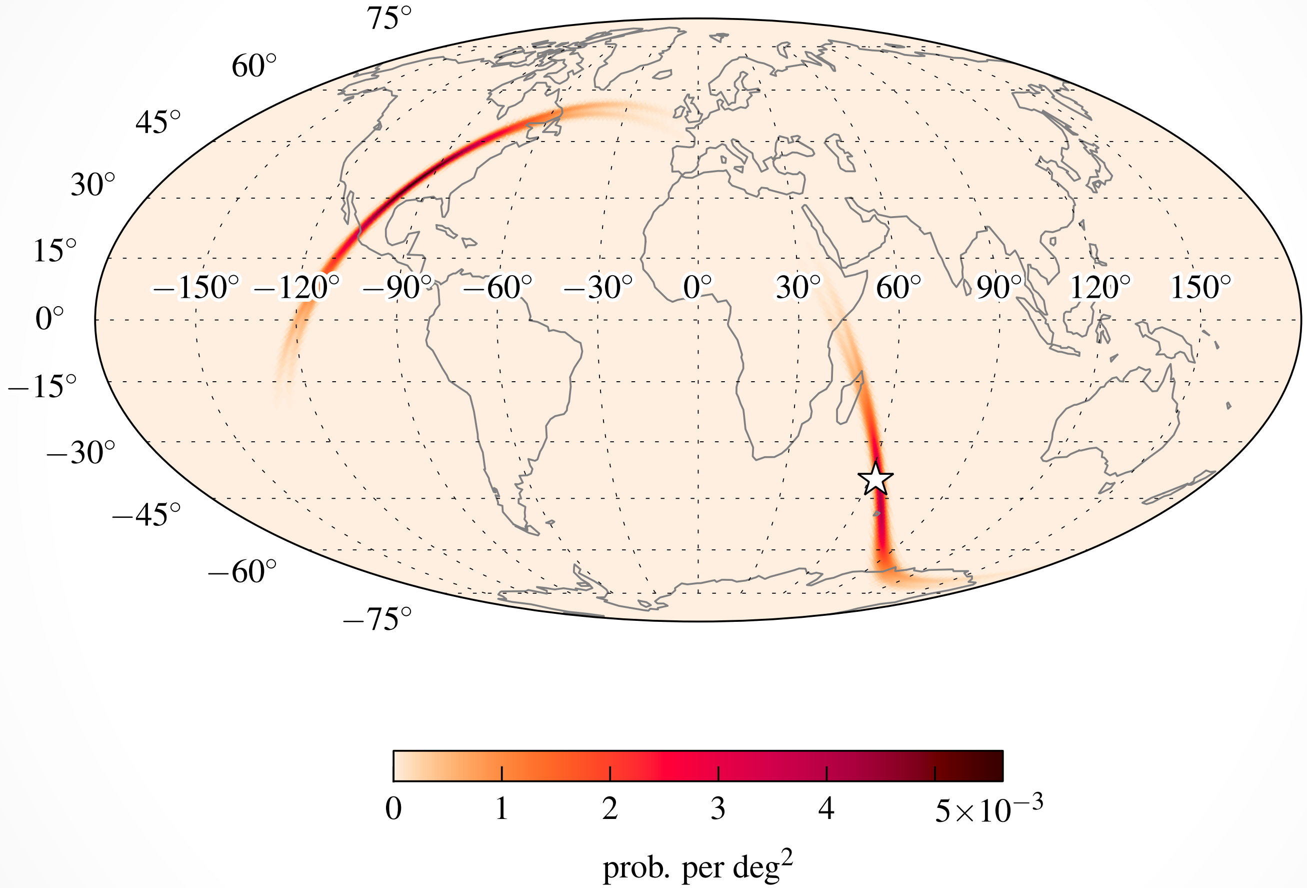
- Gravitational wave detectors are sensitive to sources from many directions
  - Do not require “pointing”
  - Makes source localization difficult



A global network

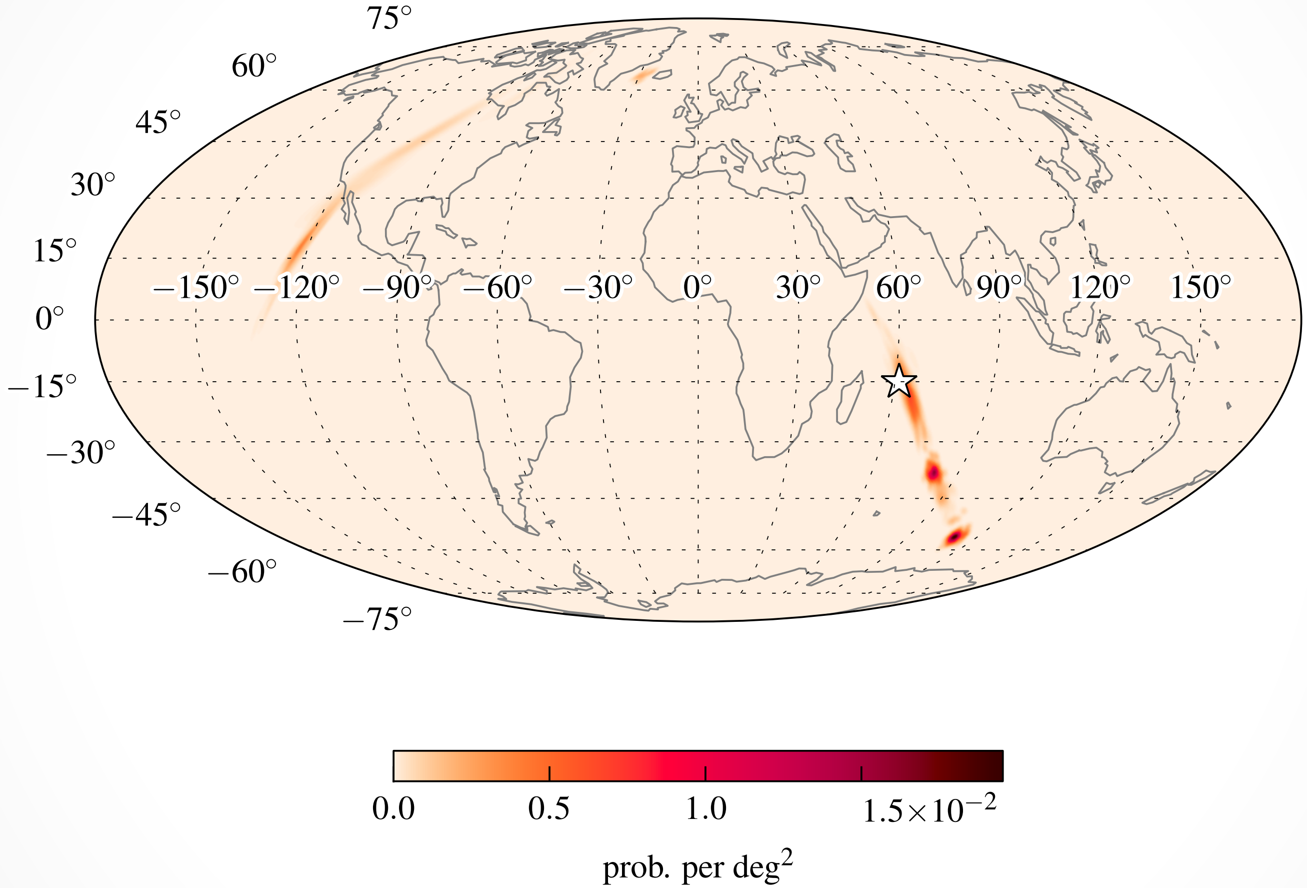


Sky localization



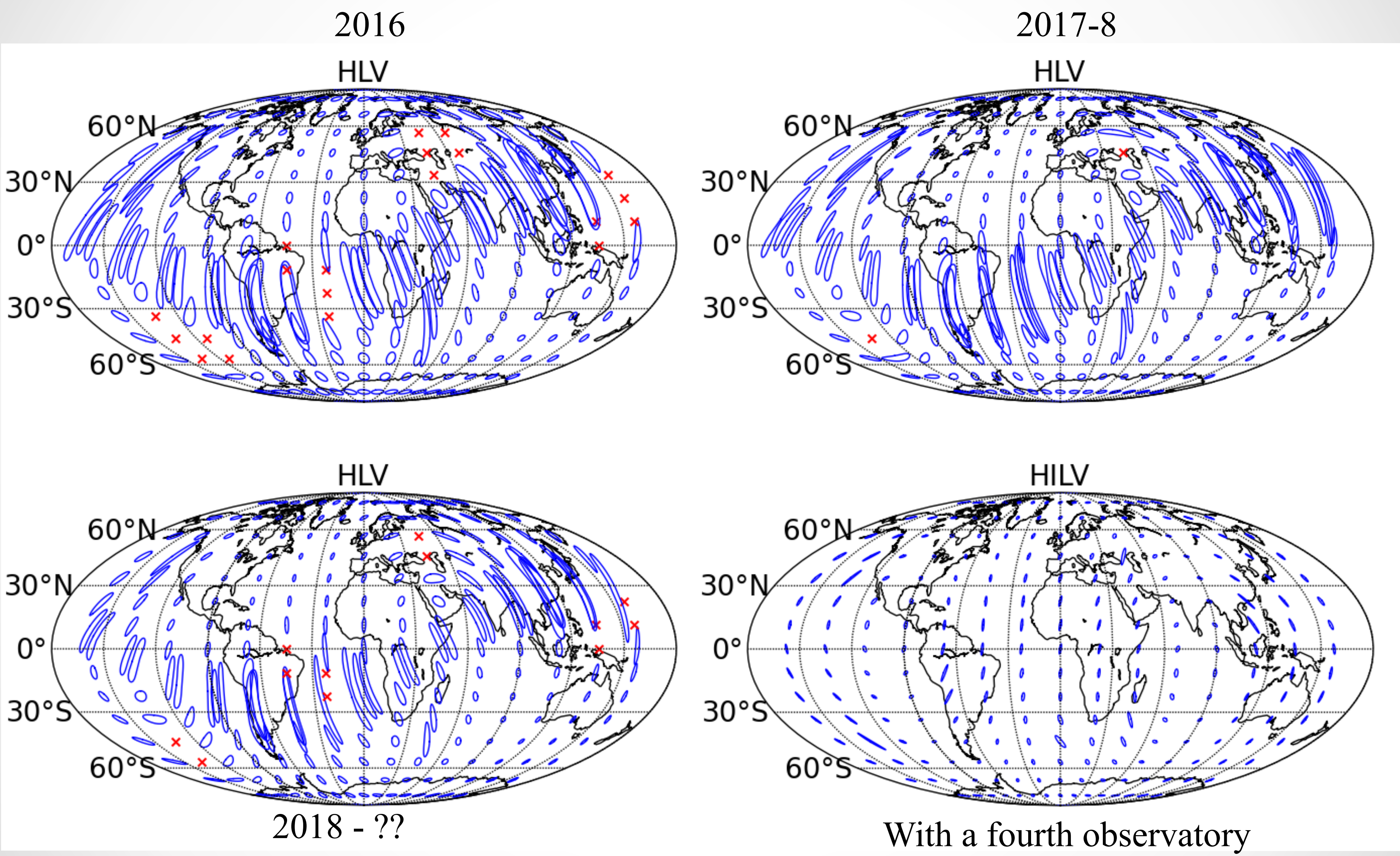
Singer et al. ApJ 795 (2014), 2, 105

Sky localization



Singer et al. ApJ 795 (2014), 2, 105

Sky localization



Aasi et al. 1304.0670

Distance reach

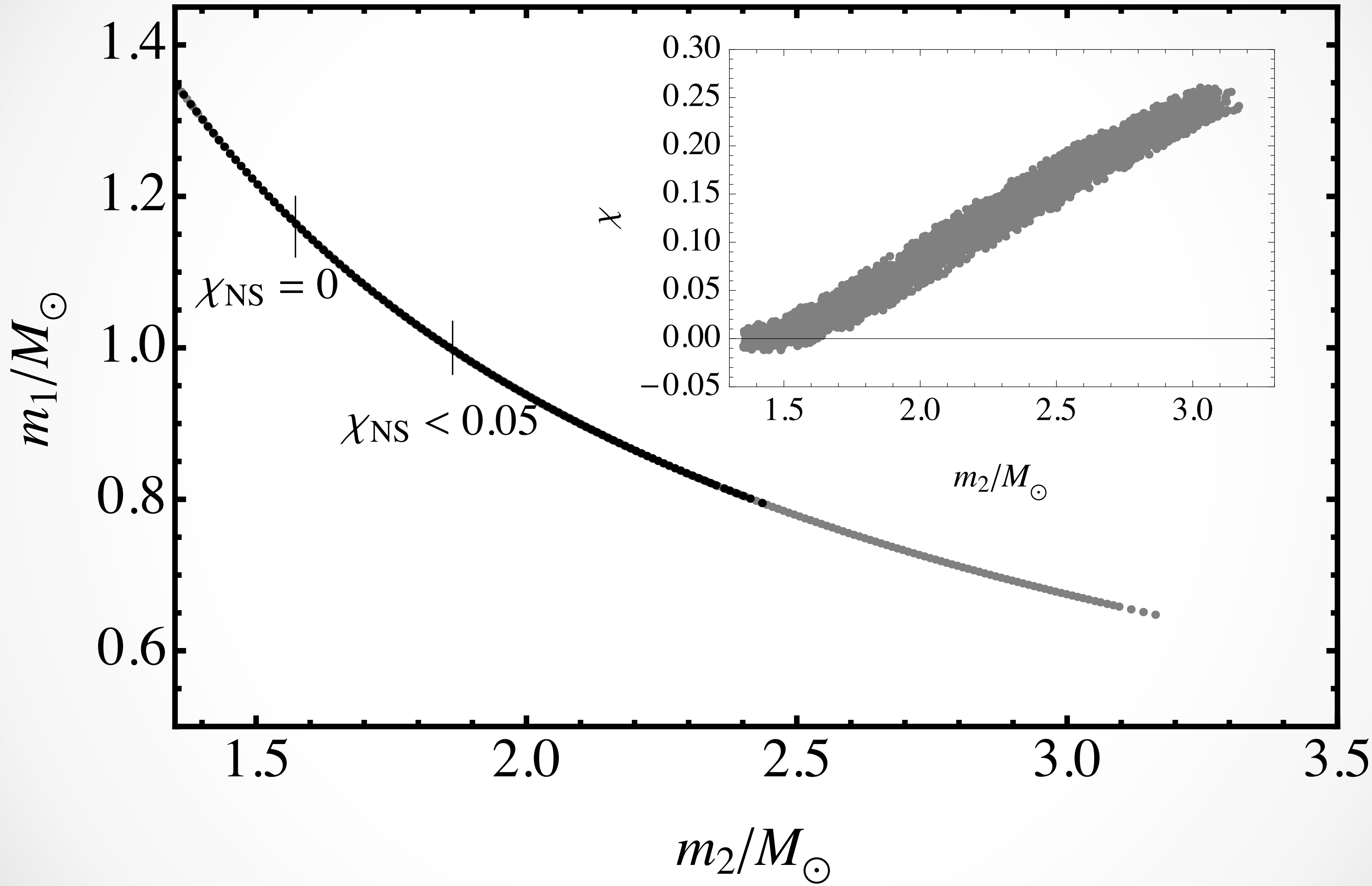
Epoch	Estimated Run Duration		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
			LIGO	Virgo		$5\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
2015	3 months		40 – 80	–	0.0004 – 3	–	–
2016–17	6 months		80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months		120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)		200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)		200	130	0.4 – 400	17	48

Table 1: Summary of a plausible observing schedule, expected sensitivities, and source localization with the advanced LIGO and Virgo detectors, which will be strongly dependent on the detectors' commissioning progress. The burst ranges assume standard-candle emission of $10^{-2} M_{\odot} c^2$ in GWs at 150 Hz and scale as $E_{\mathrm{GW}}^{1/2}$. The burst and binary neutron star (BNS) ranges and the BNS localizations reflect the uncertainty in the detector noise spectra shown in Fig. 1. The BNS detection numbers also account for the uncertainty in the BNS source rate density [28], and are computed assuming a false alarm rate of $10^{-2}\,\mathrm{yr}^{-1}$. Burst localizations are expected to be broadly similar to those for BNS systems, but will vary depending on the signal bandwidth. Localization and detection numbers assume an 80% duty cycle for each instrument.

Aasi et al. 1304.0670

Abbott et al. CQG 27, 173001 (2010)

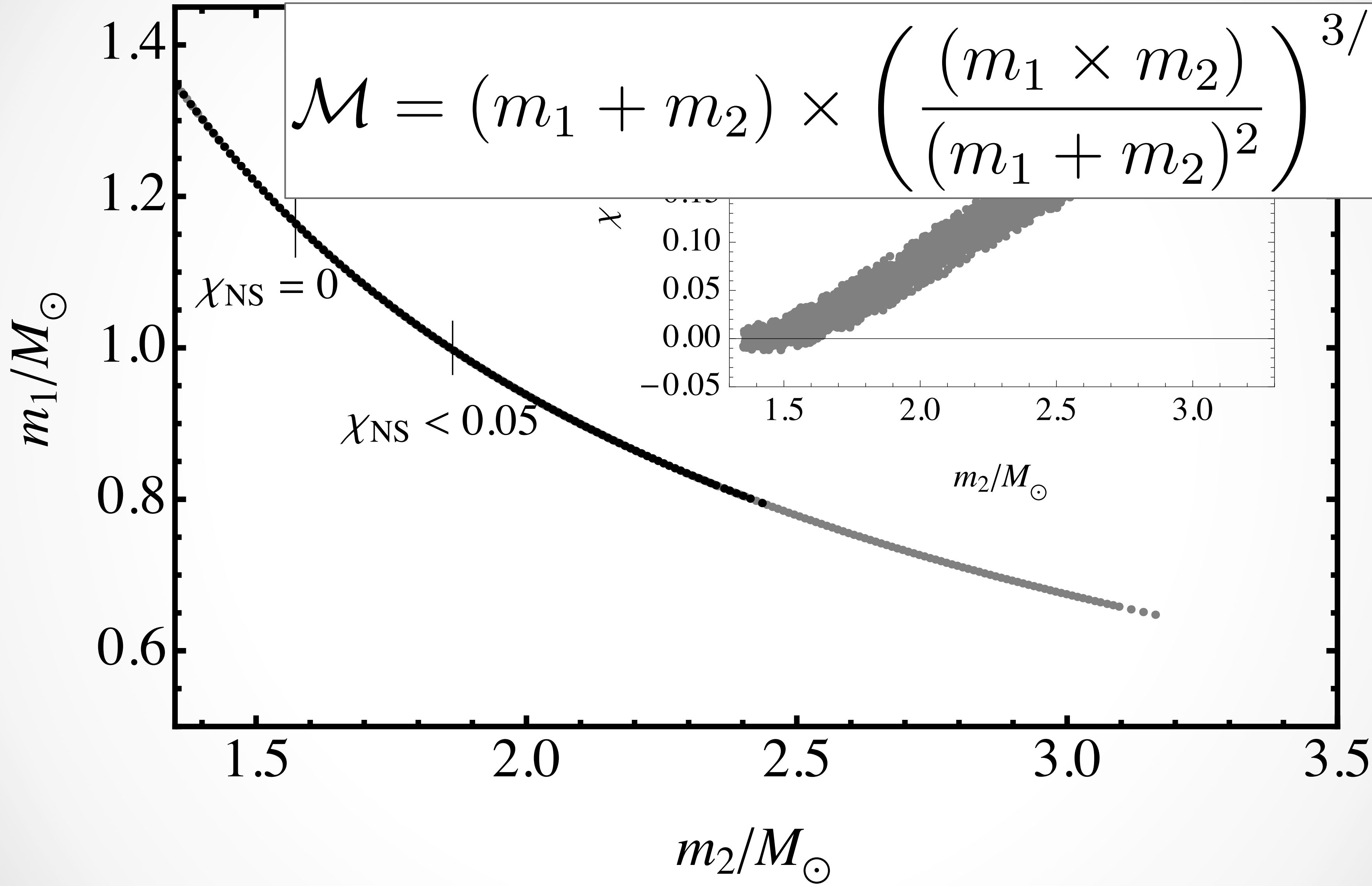
Mass and spin measurements



Hannam, IH, et al. Astrophys.J. 766 (2013) L14

Mass and spin measurements

$$\mathcal{M} = (m_1 + m_2) \times \left(\frac{(m_1 \times m_2)}{(m_1 + m_2)^2} \right)^{3/5}$$



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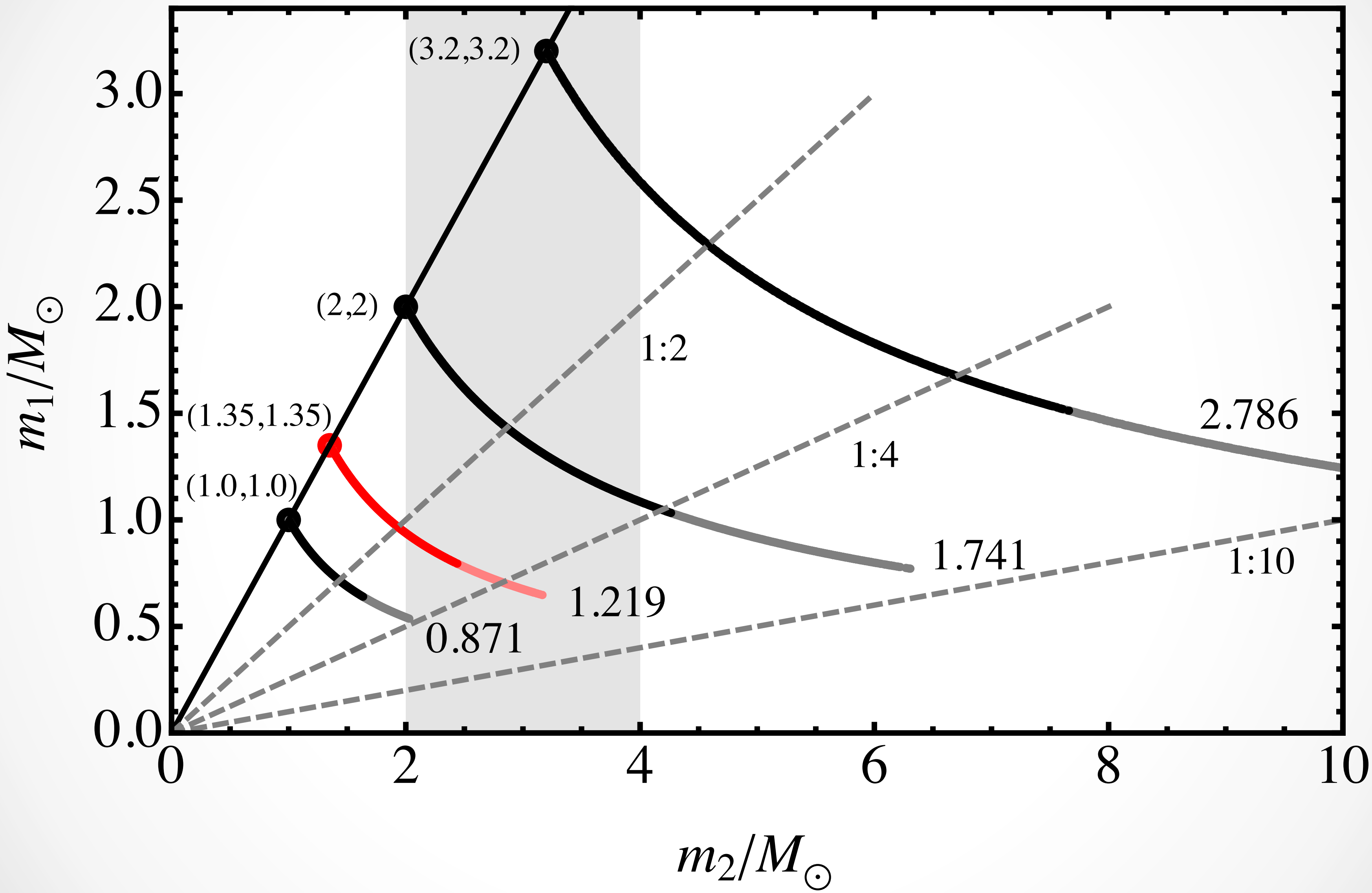

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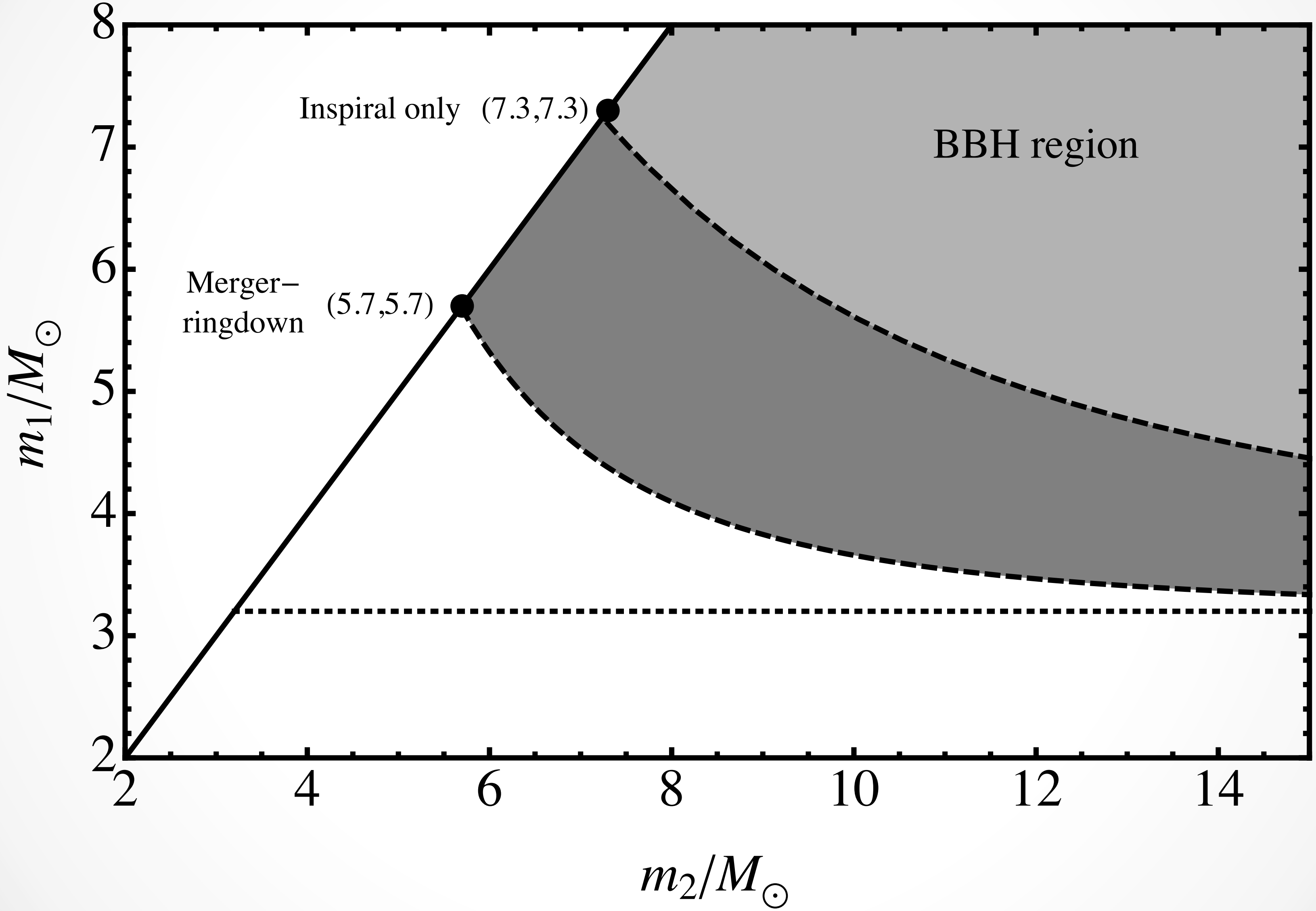

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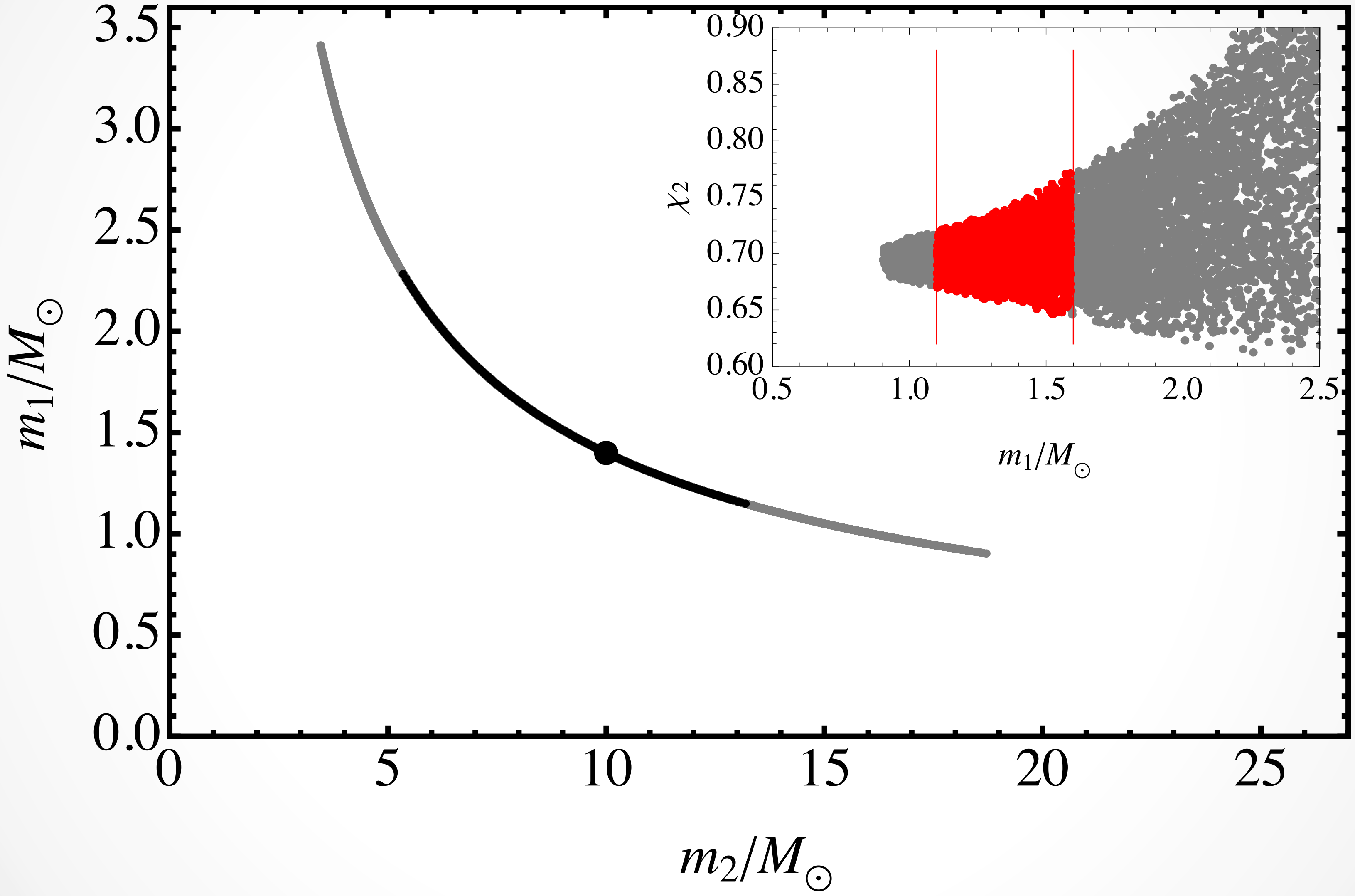

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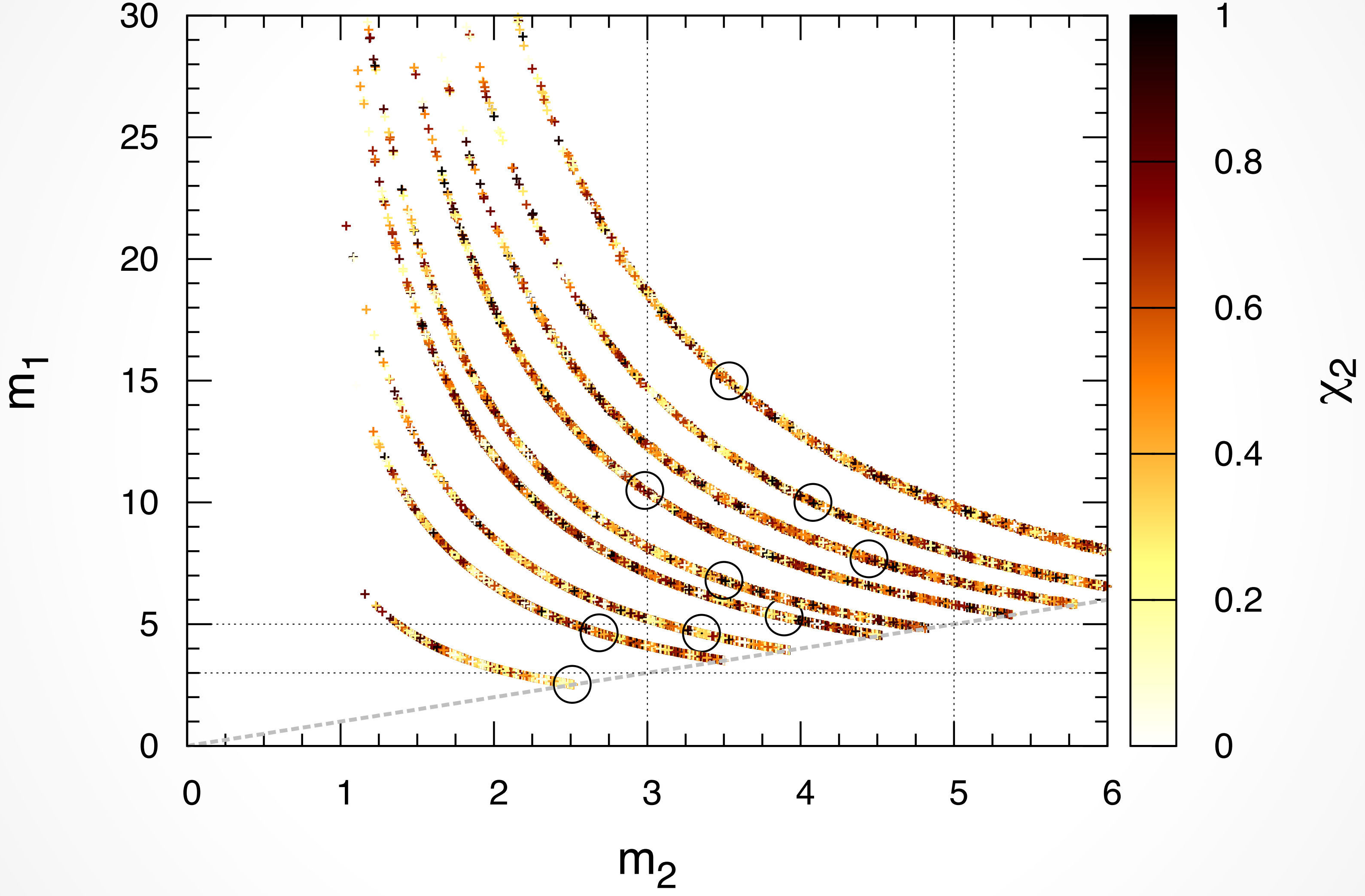
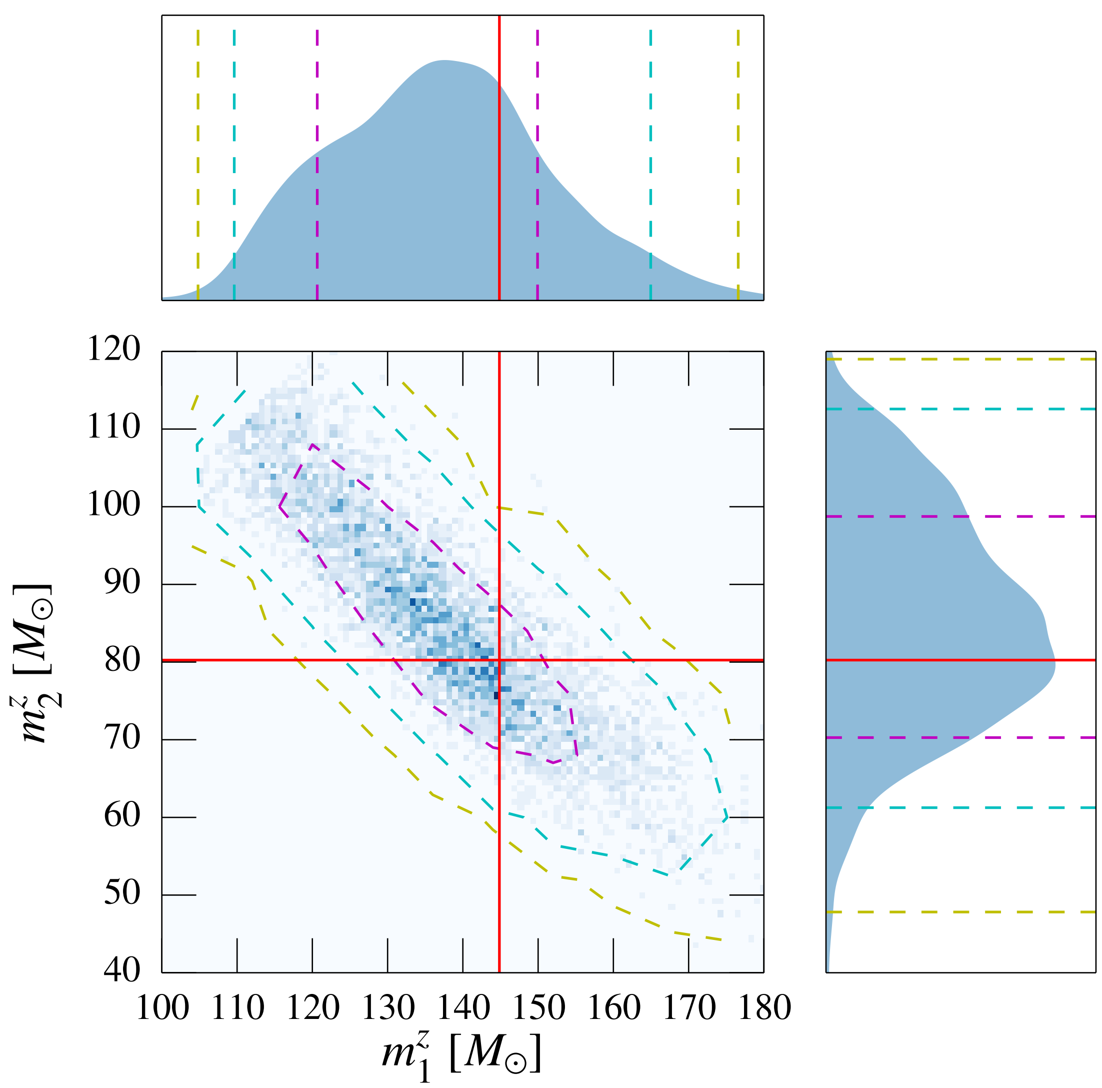


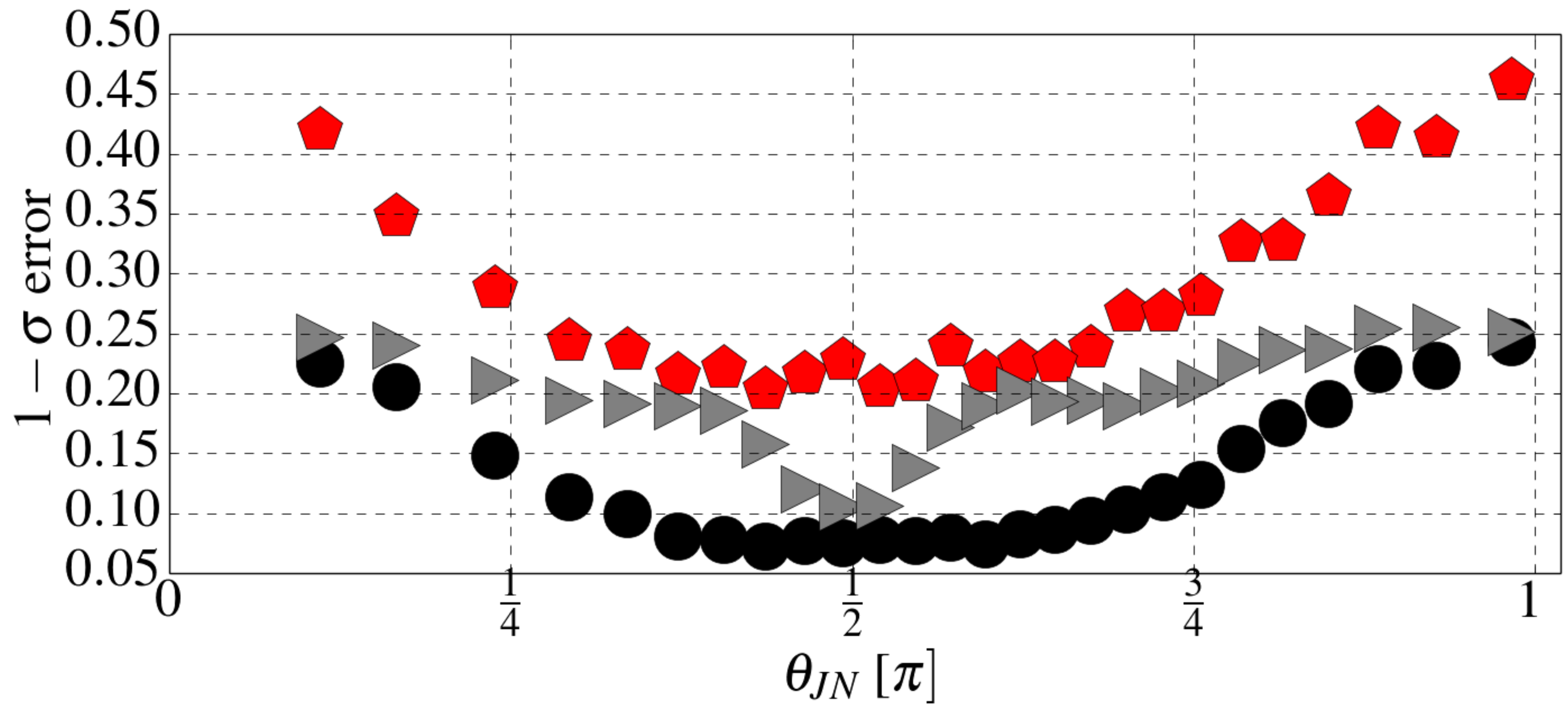
Littenberg, et al. 1503.03179

Mass measurements



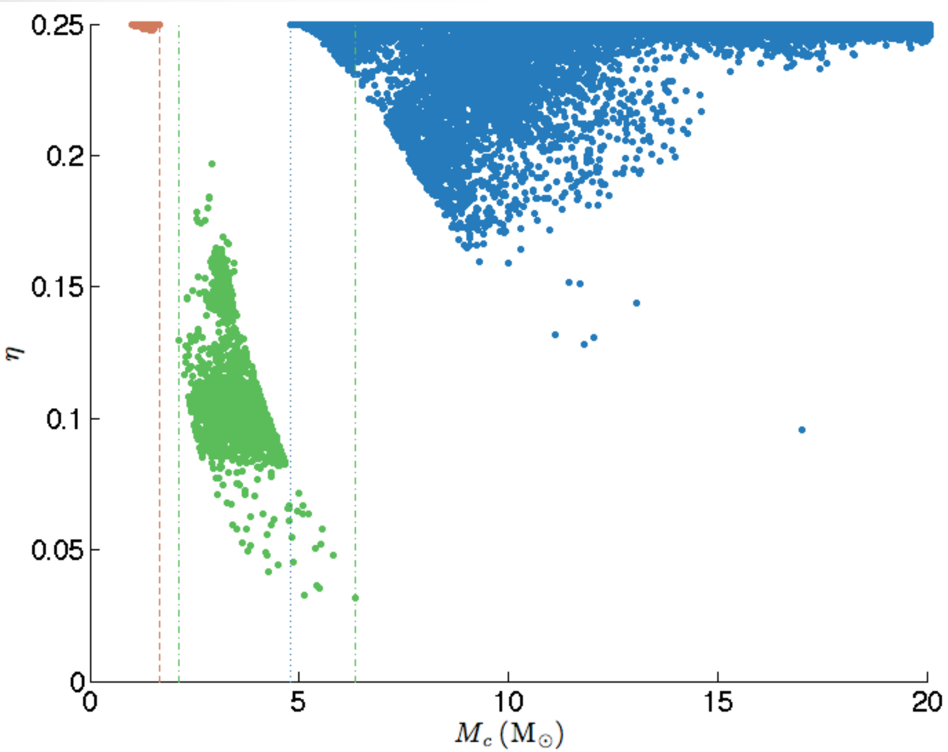
Ghosh et al. arXiv: 1505.0560

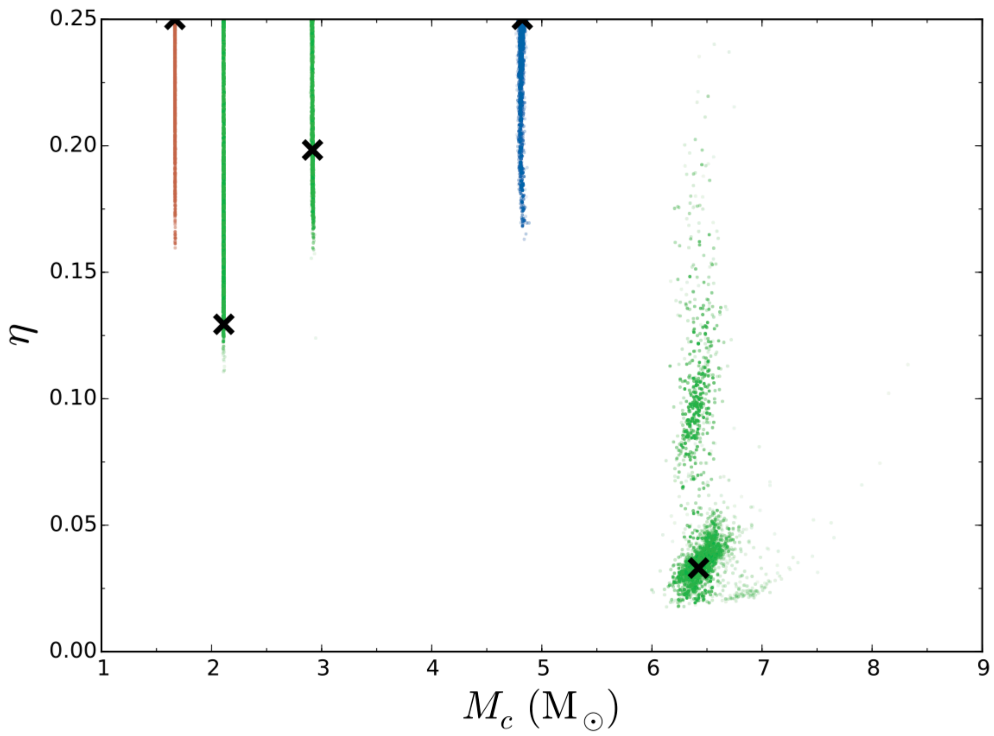
Spin measurements



Vitale et al. PRL 112, 251101 (2014)

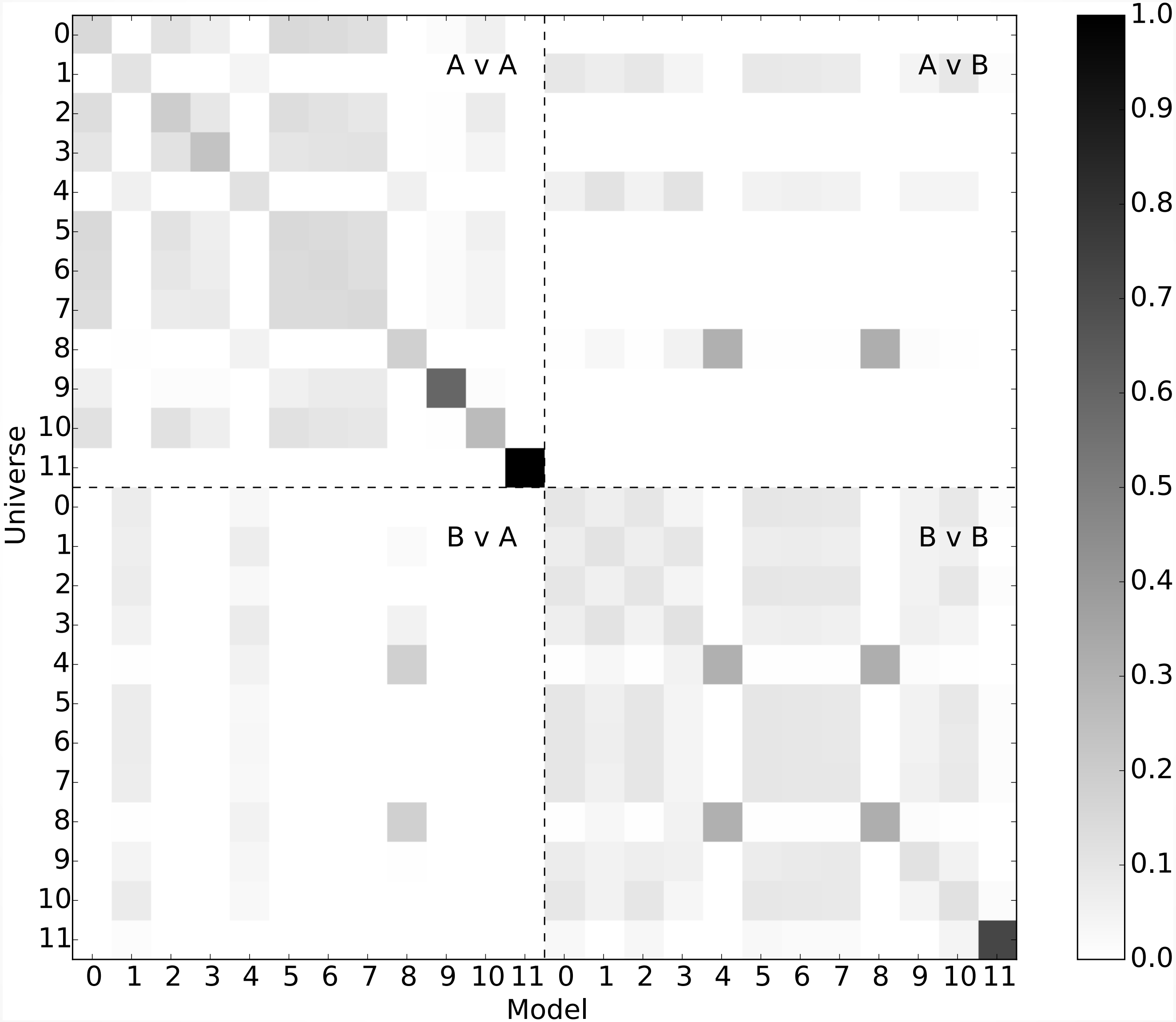
Sub-populations





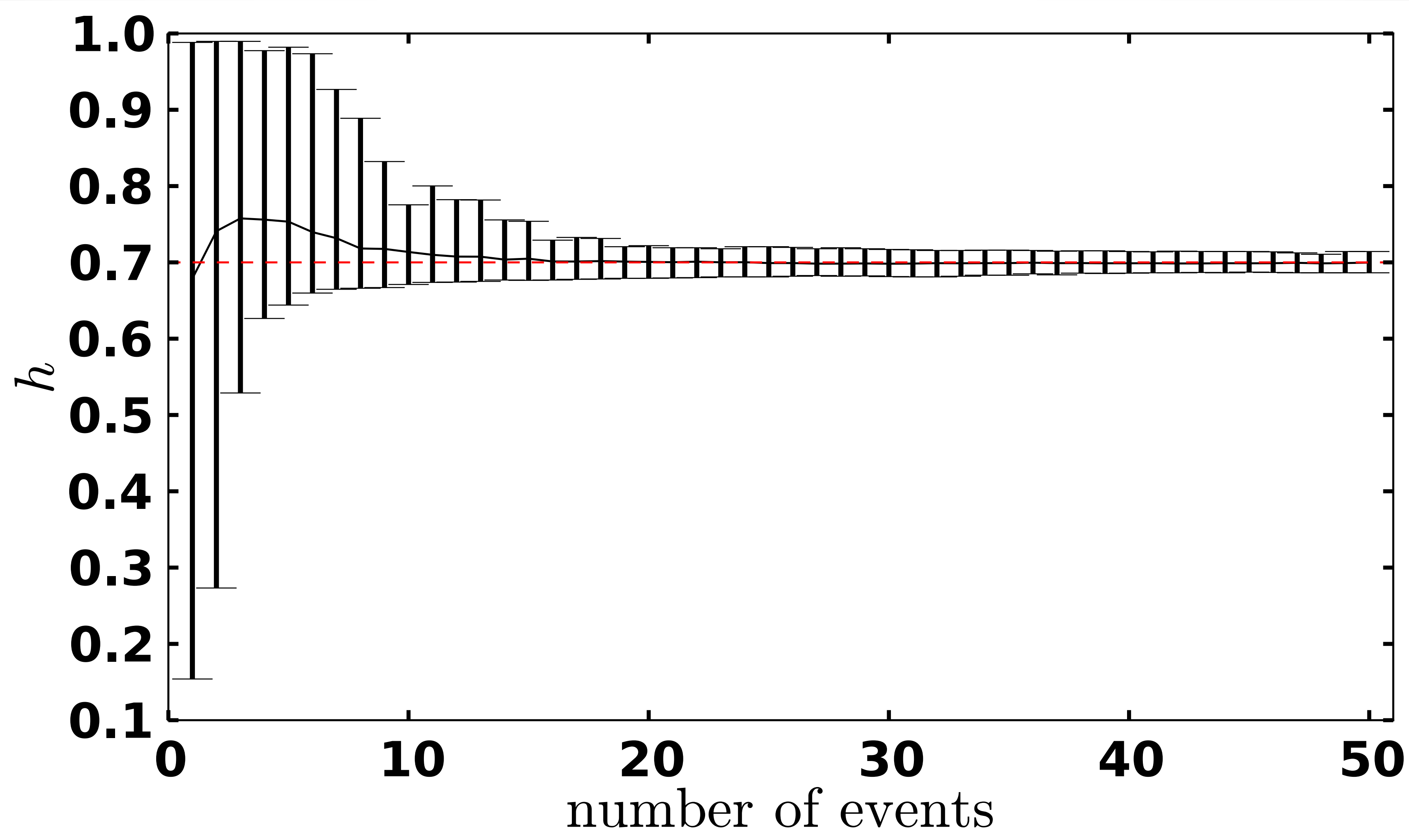
Mandel et al. MNRAS 450, L85

Discriminating population models



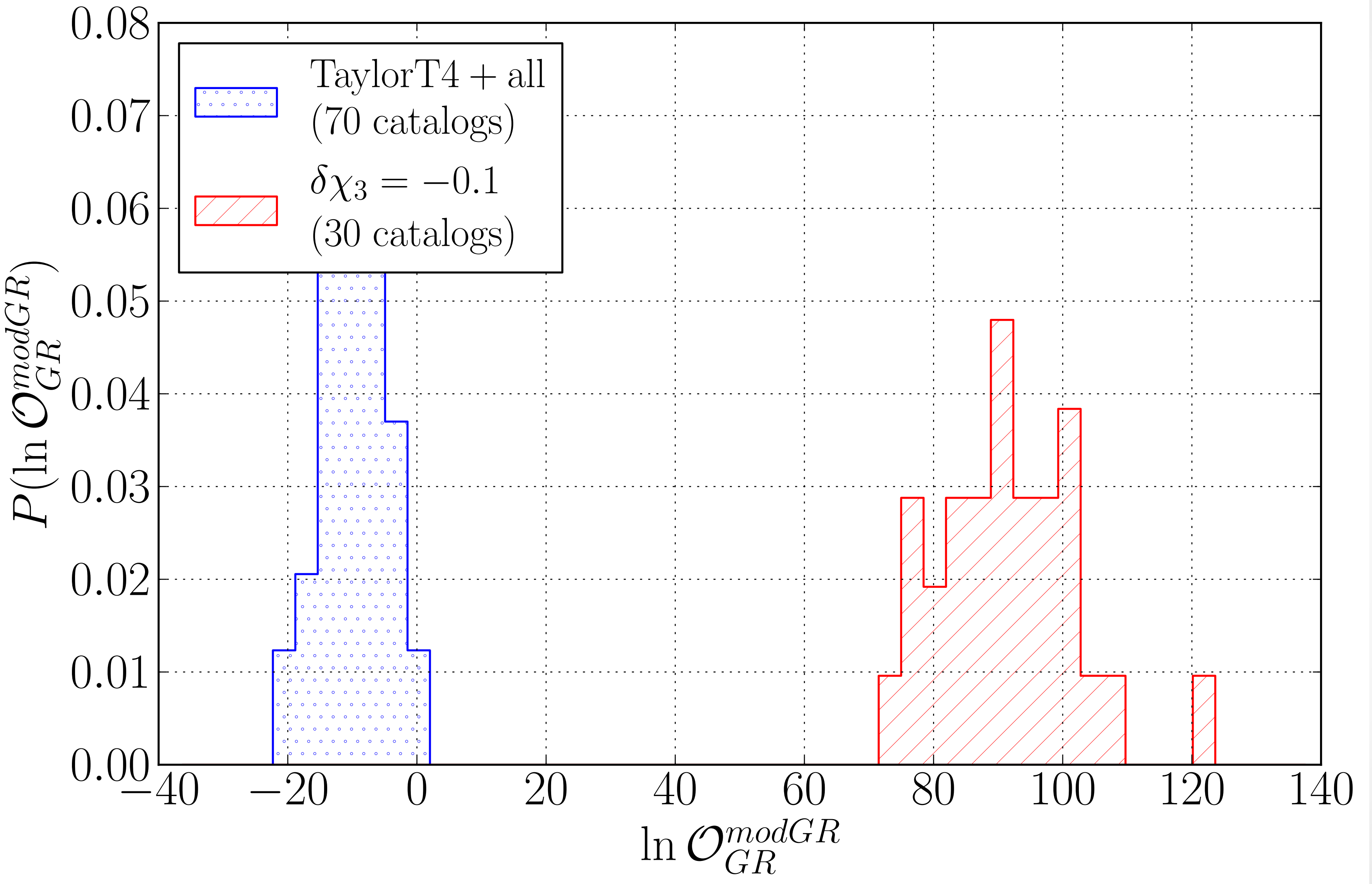
Stevenson et al. 1504.07802

Cosmology



W. Del Pozzo, Phys. Rev. D 86, 043011 (2012)

Testing GR



M. Agathos et al., Phys. Rev. D 89, 082001 (2014)

Conclusions

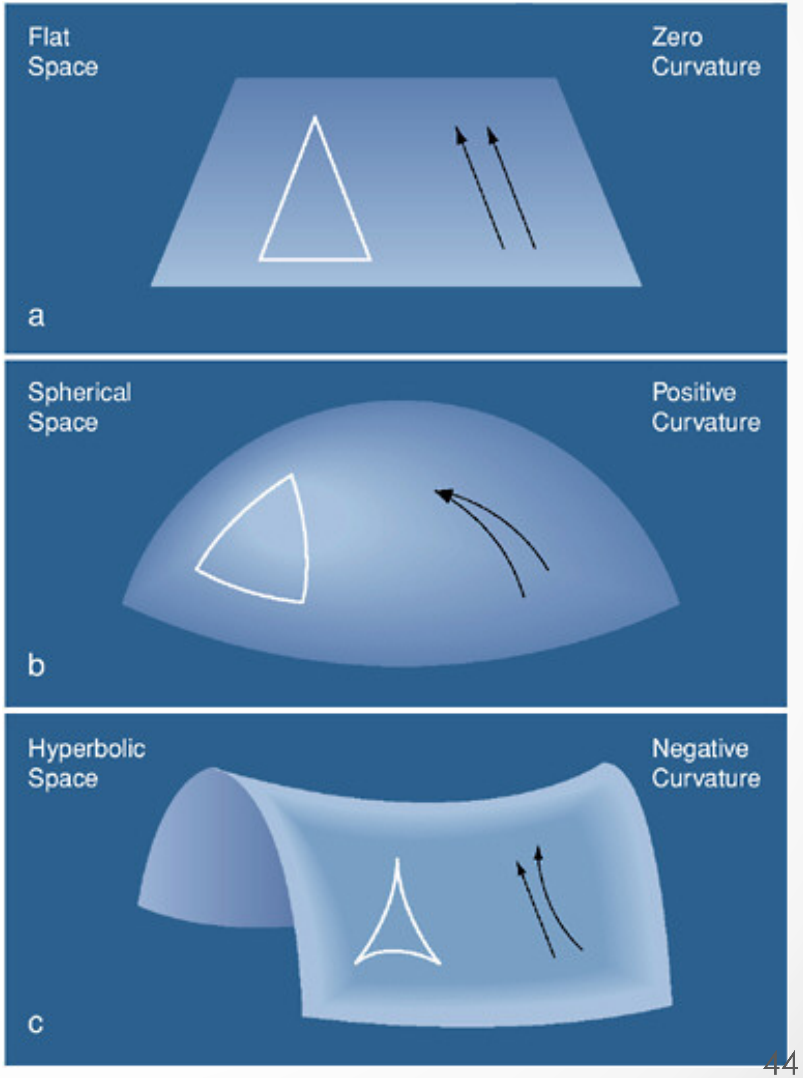
- We expect gravitational-wave astronomy to begin in the next years
- Compact binary mergers are a key target for these systems
- I hope to have given you a flavour of what we can learn from observing such systems

THANK YOU

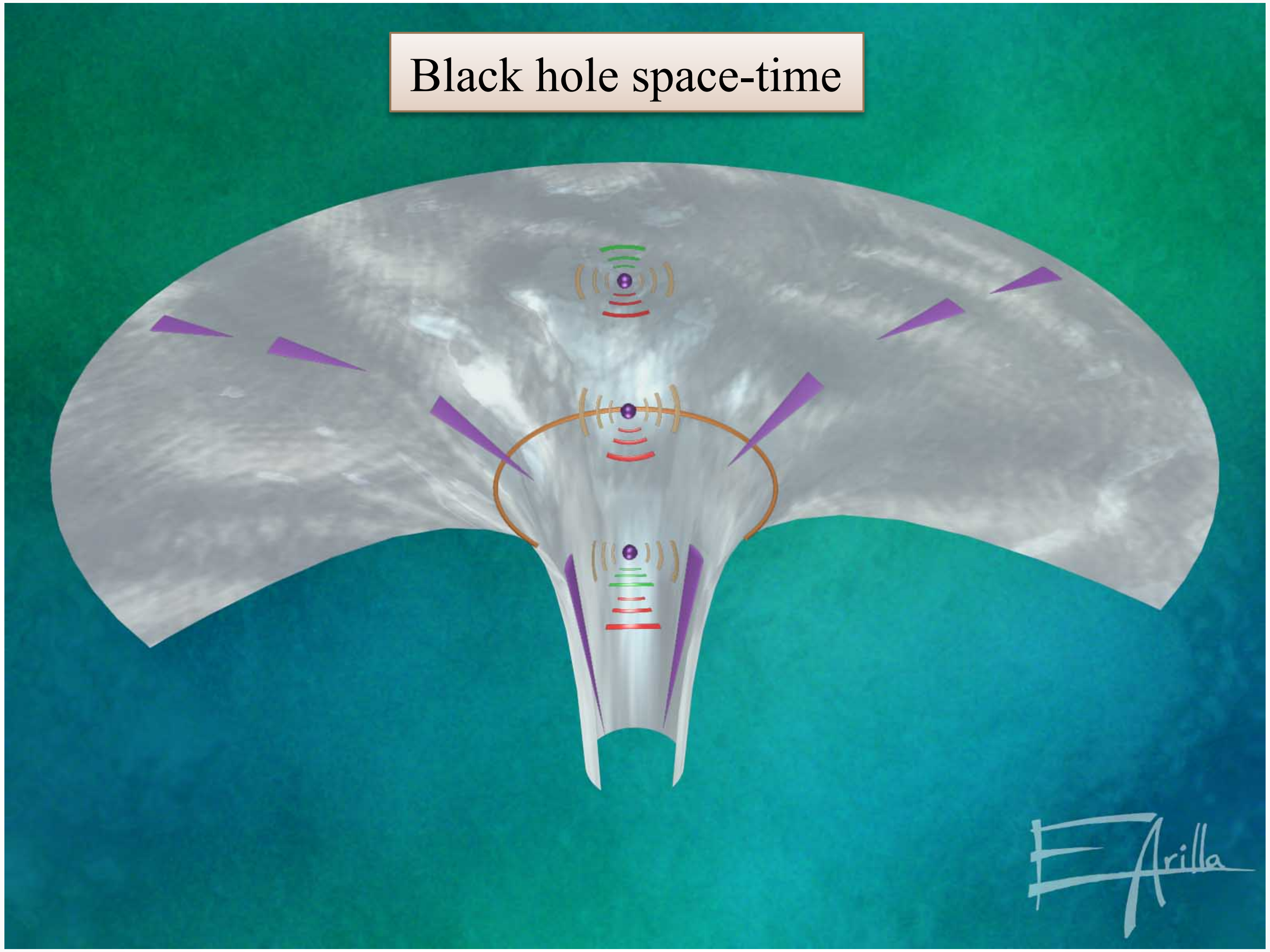
Any questions?

General Relativity

- Gravity is described as a warping of space and time
  - Caused by the mass and energy in the universe



A black hole



How might we directly see black holes?

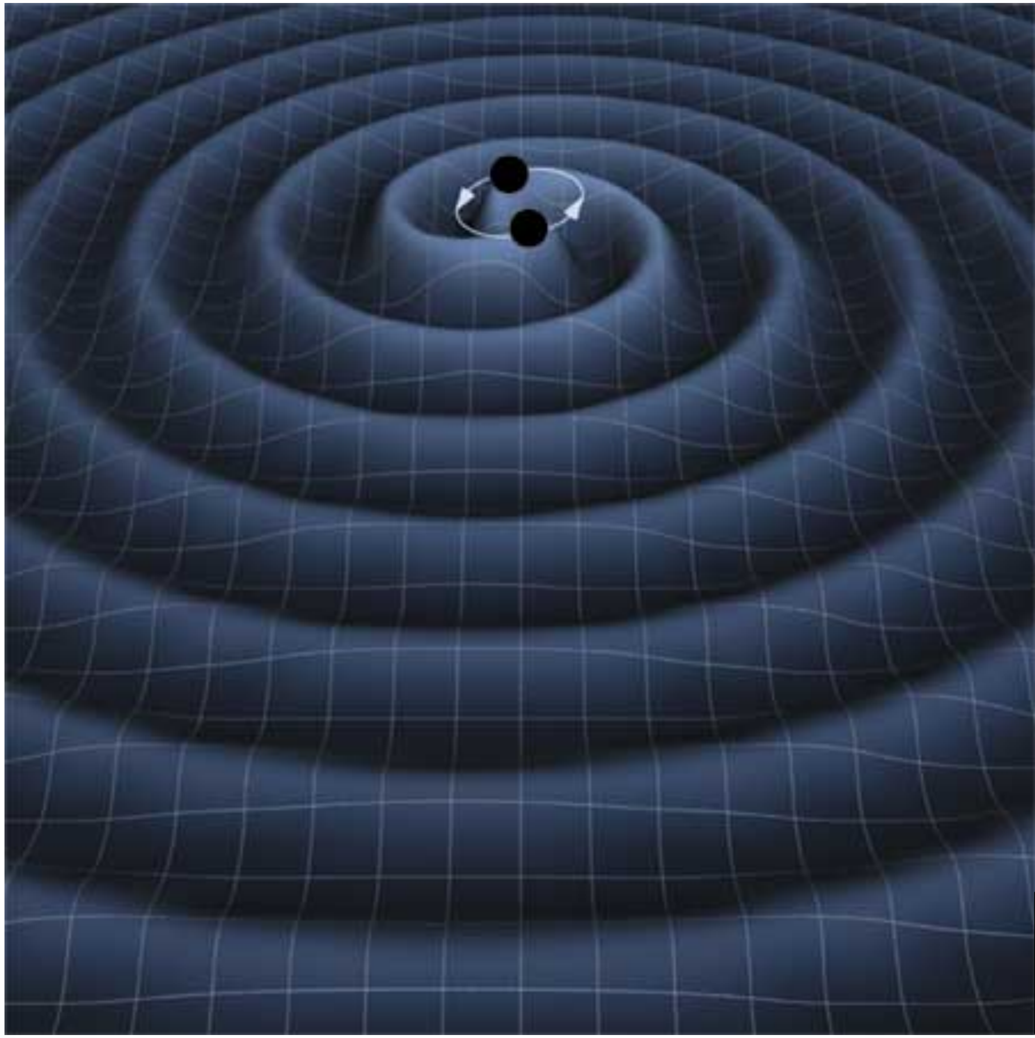
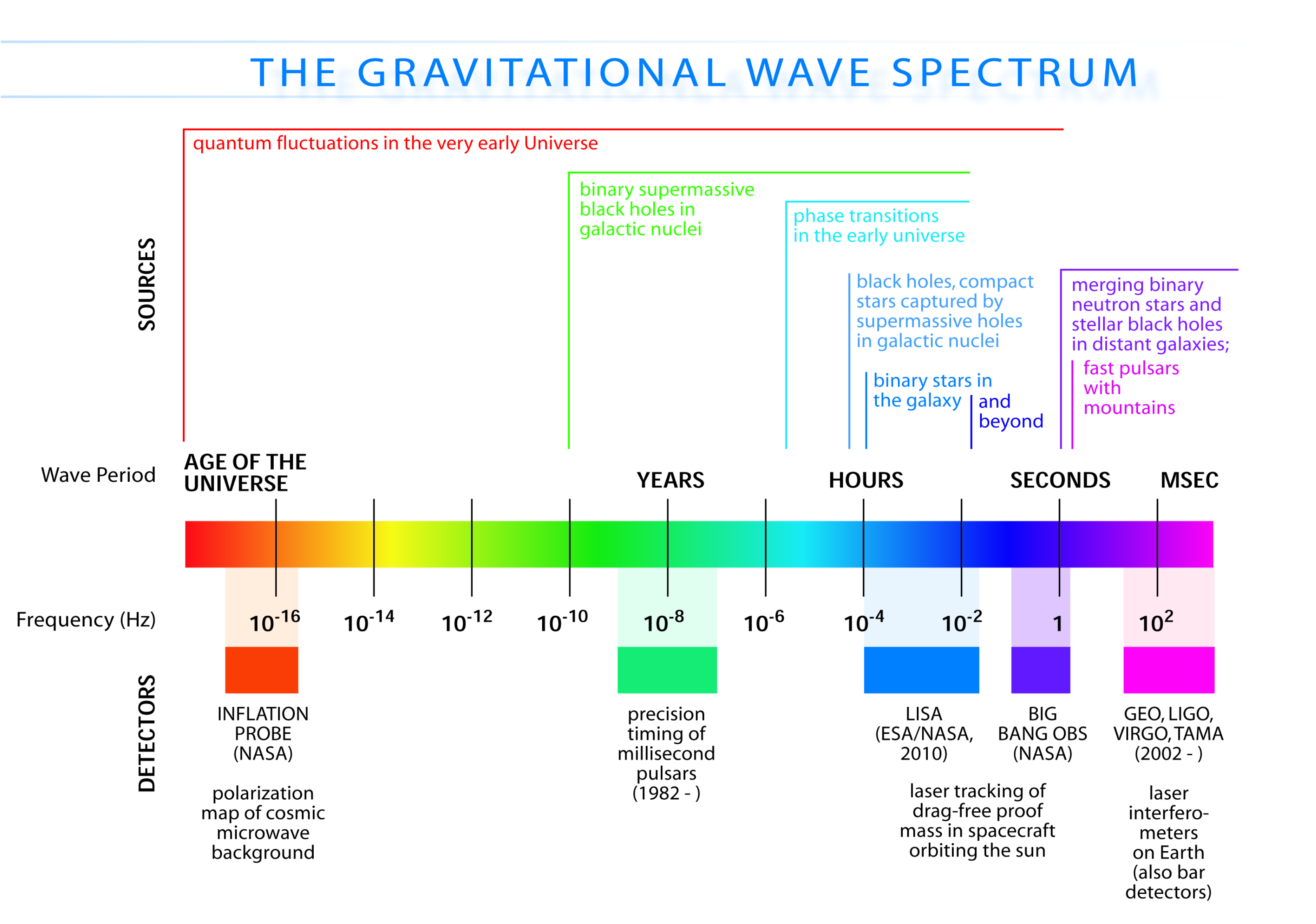


Image: T. Carnahan (NASA GSFC)

The gravitational-wave spectrum



Observing compact binary mergers with gravitational-wave facilities

Searching for and observing black hole collisions

- How would we know when there is a black hole signal in data from LIGO and Virgo?
- PROBLEM: The data is contaminated by other noise sources: seismic, thermal, human ….
- PROBLEM: Unless the black holes are really close, data with a signal in it will look indistinguishable from data with no signal in it.
- SOLUTION: Matched-filtering

Matched filtering

- Optimal if looking for a known signal buried in noise.

$$(s|h) = 4\,\mathrm{Re}\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^\star(f))}{S_h(f)}$$

Wainstein and Zubakov "Extraction of signals from noise", 1962
Allen et al. Phys.Rev. D85 (2012) 122006
Babak, … ,IH, et al. Phys.Rev. D87 (2013) 024033

Matched filtering

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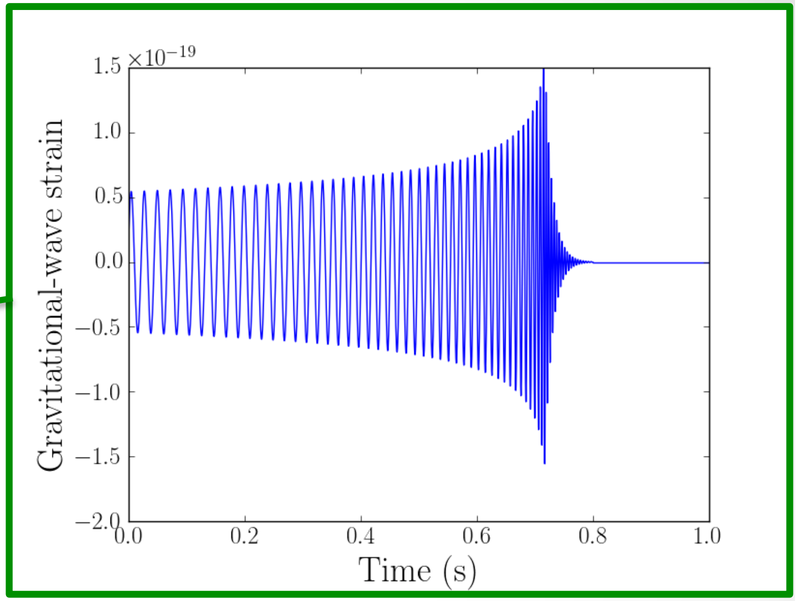
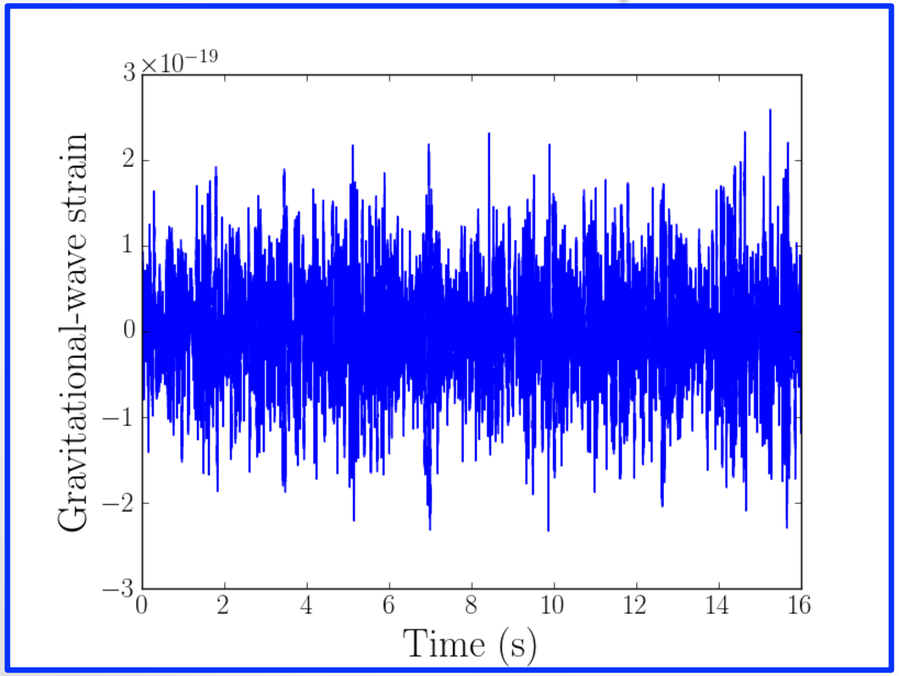
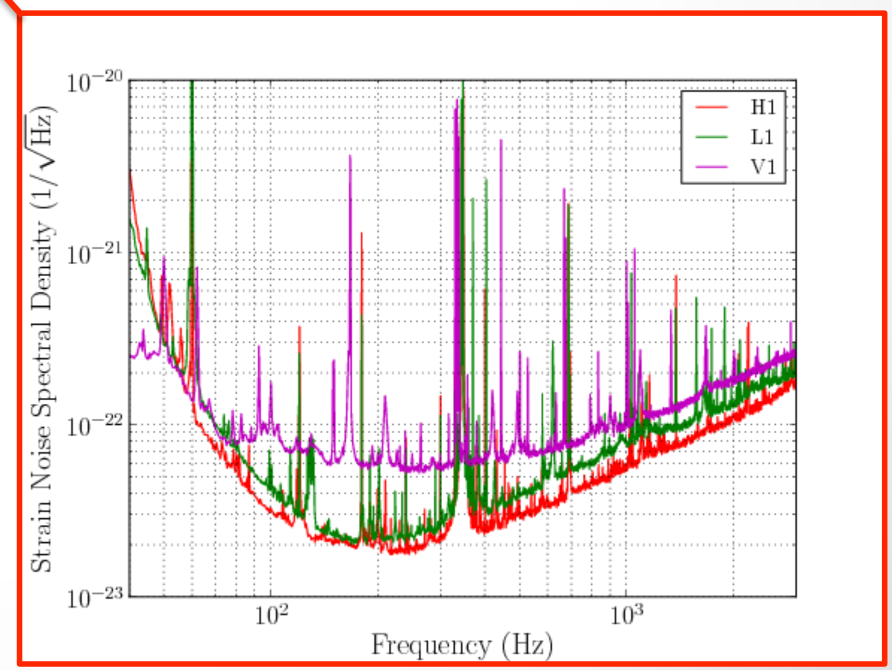


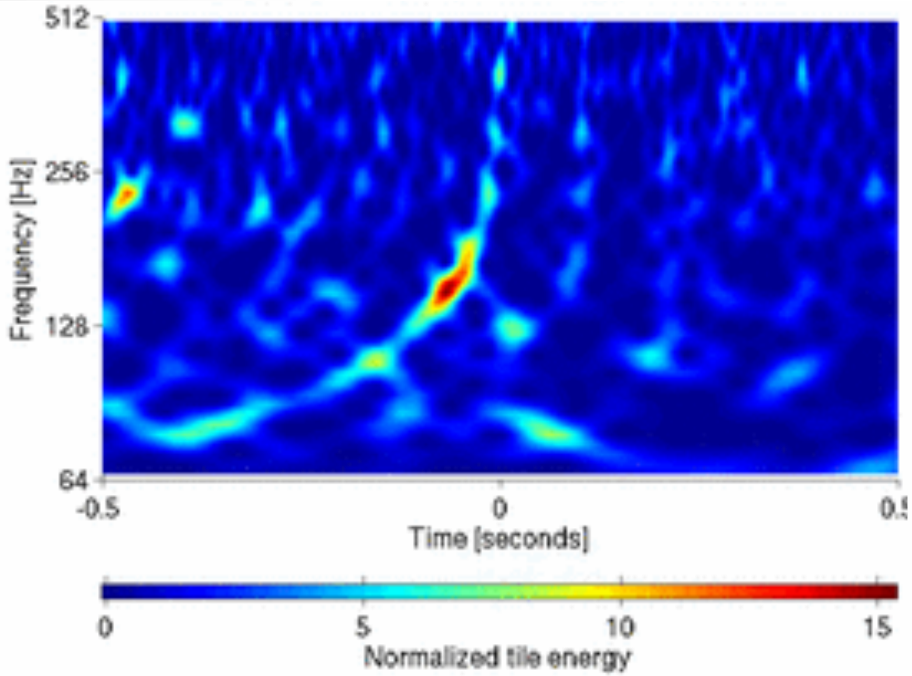




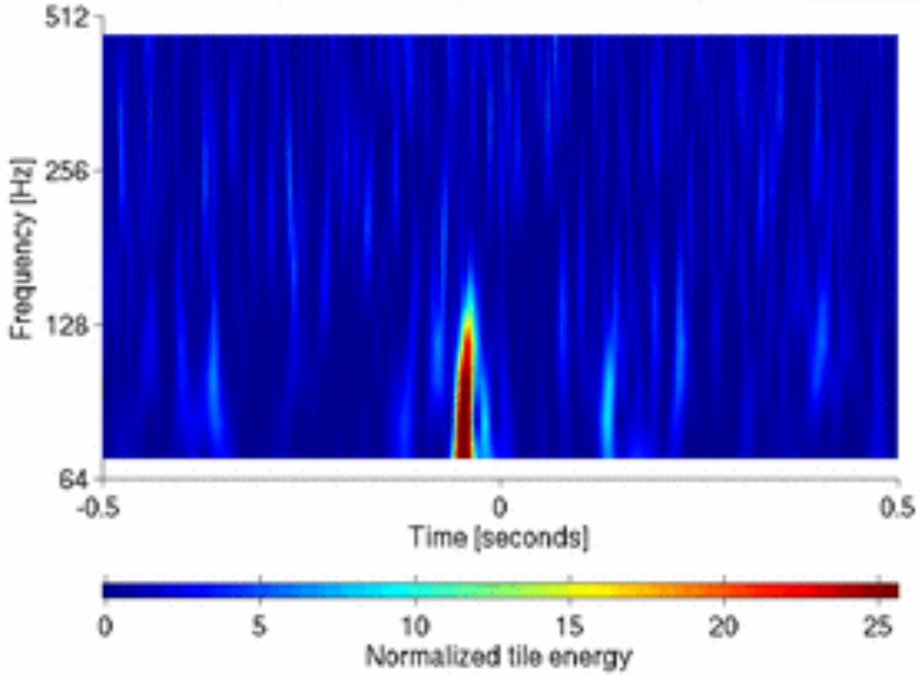
Life isn't Gaussian

Time-frequency spectrograms showing power

Loud simulated black hole merger



A noise artifact



Life isn't Gaussian

- Flag times of poor data quality
- Use a variety of monitors to identify instrumental misbehaviour
- Require "coincident" signal in several detectors
- Make use of signal consistency tests