Gravitational wave astronomy

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Science & Environment

Einstein's waves detected in star smash

Scientists detect the warping of space generated by the collision of two neutron stars.

16 October 2017

Science & Environment | 420

Penguins die in 'catastrophic' season

13 October 2017

Science & Environment

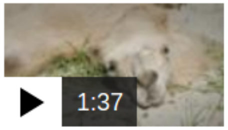
525

Watch/Listen

The sound of two colliding neutron stars

16 October 2017

Science & Environment



How this camel ended up in Norway

16 October 2017 | Europe

Floating bin sucking up sea's rubbish

13 October 2017

Science & Environment

Inside a flying volcano lab

10 October 2017

Science & Environment

How do you clear out a

Gravitational waves

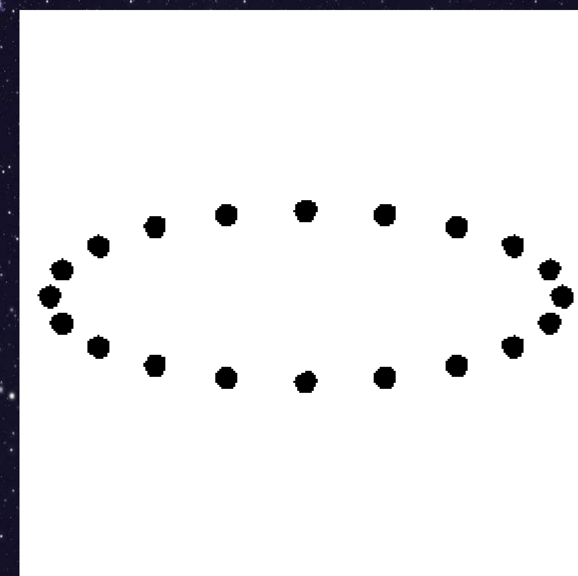
- What are gravitational waves?
- Why suddenly detectable now?
- What are we learning?
- Where are we going in the future?

What are gravitational waves?

$$G_{ab} = 8\pi G T_{ab}$$ Einstein equation

Small linear perturbation $$g_{ab} = \eta_{ab} + h_{ab}$$

$$\nabla^2 \bar{h}_{ab} = 0$$ Wave equation



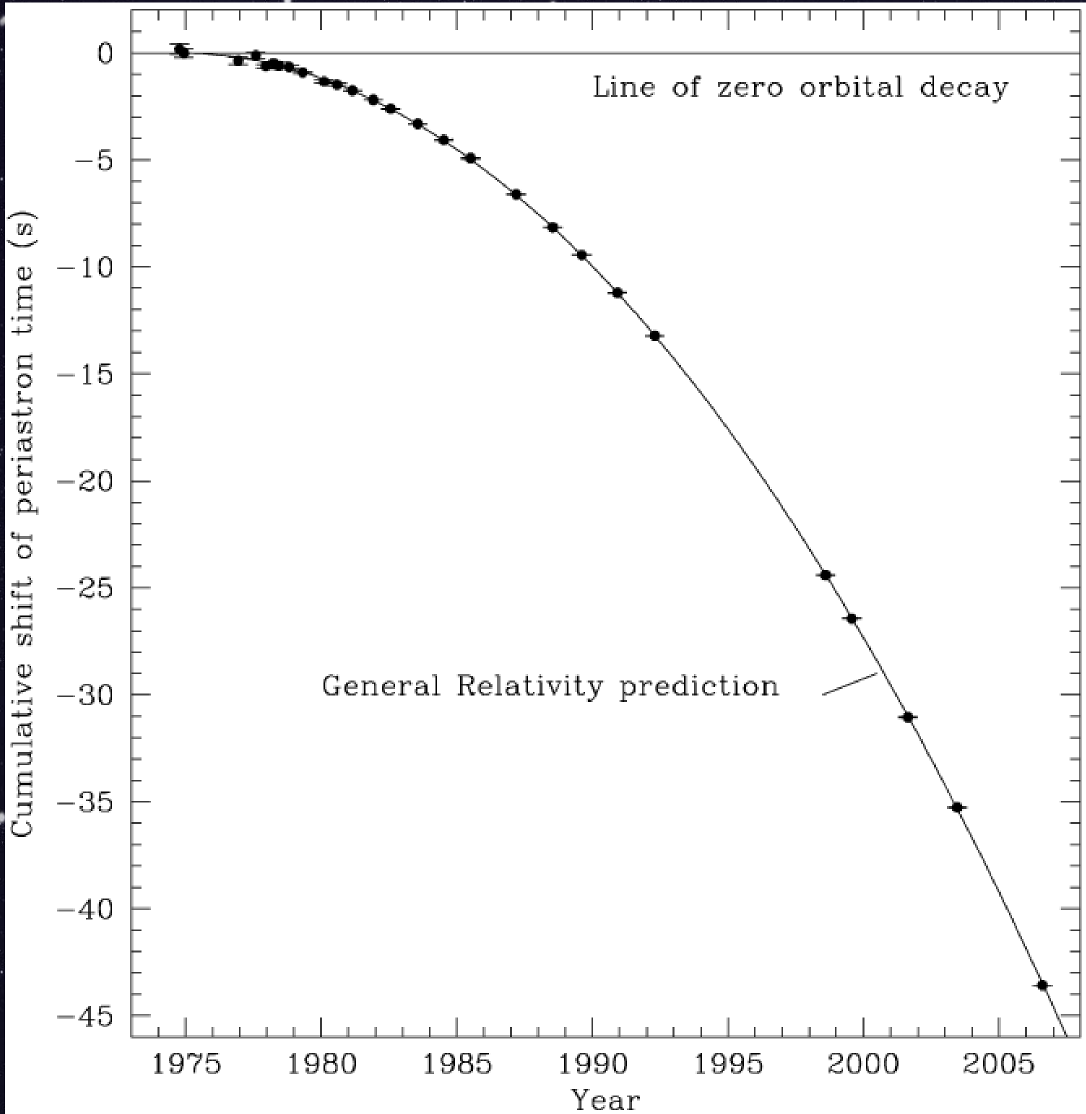
$$Q_{ij} \equiv \int d^3x \rho \left(x_i x_j - \frac{1}{3} r^2 \delta_{ij} \right)$$

Einstein quadrupole formula $$h_{ij} = \frac{2G}{d_L} \frac{d^2 Q_{ij}}{dt^2}$$

Einstein's changing attitude to gravitational waves

- **19 Feb 1916, letter to Schwarzshild:** *"Es gibt also keine Gravitationswellen, welche Lichtwellen analog wären".*
- **22 Jun 1916, article:** *"...so sieht man, daß A (die Ausstrahlung des Systems durch Gravitationswellen pro Zeiteneinheit) in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß."* *Nährungsweise Integration der Feldgleichungen, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 1916 688*
- **31 Jan 1918, article:** *"Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen."Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 1916 154*
- **1936 undated letter to Max Born:** *"Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they have been assumed a certainty to the first approximation."*
- **1936 Princeton lecture:** *"If you ask me whether there are gravitational waves or not, I must answer that I do not know. But it is a highly interesting problem."*

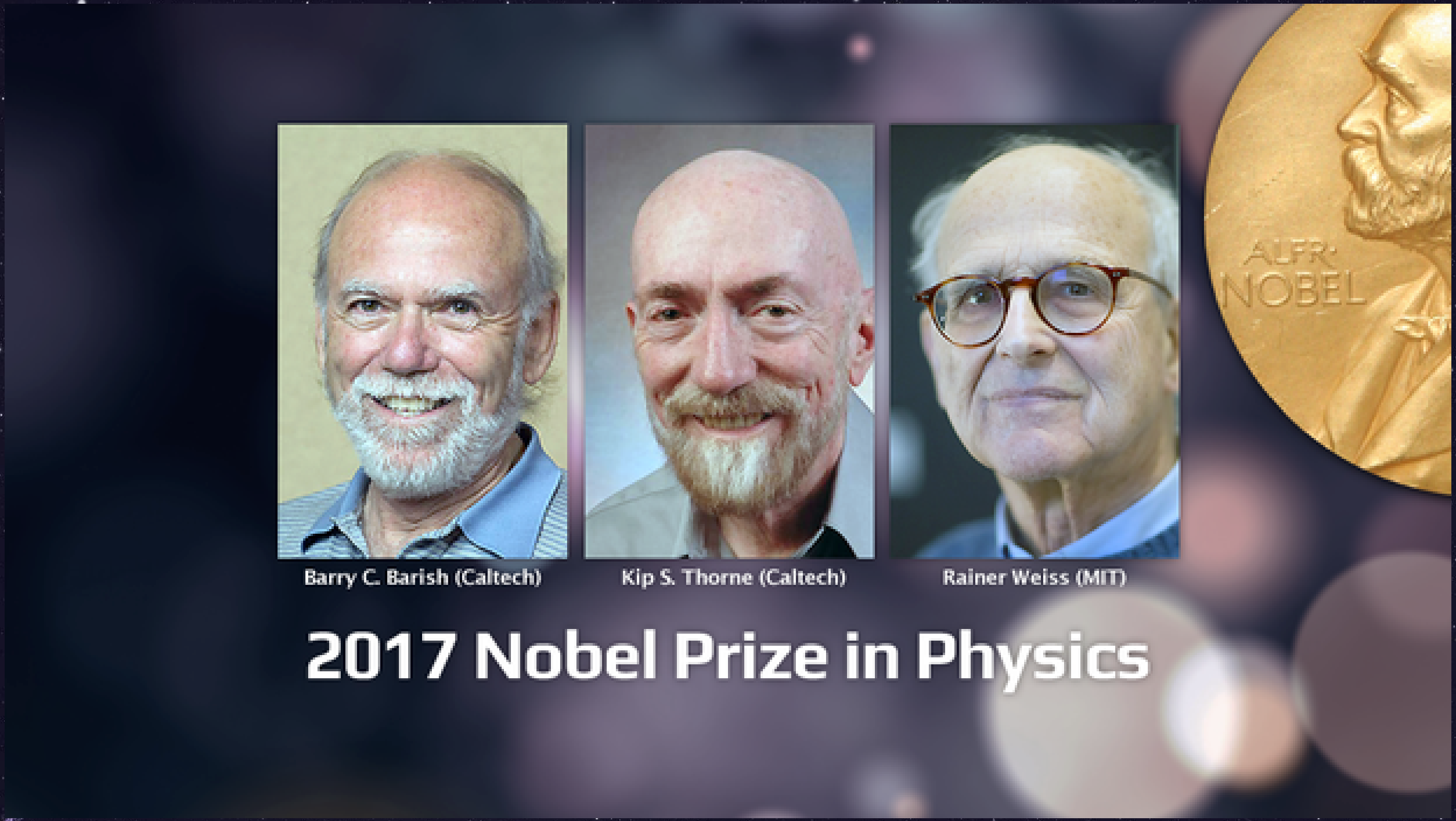
Hulse-Taylor binary PSR B1913+16



1993 Nobel Prize for Physics

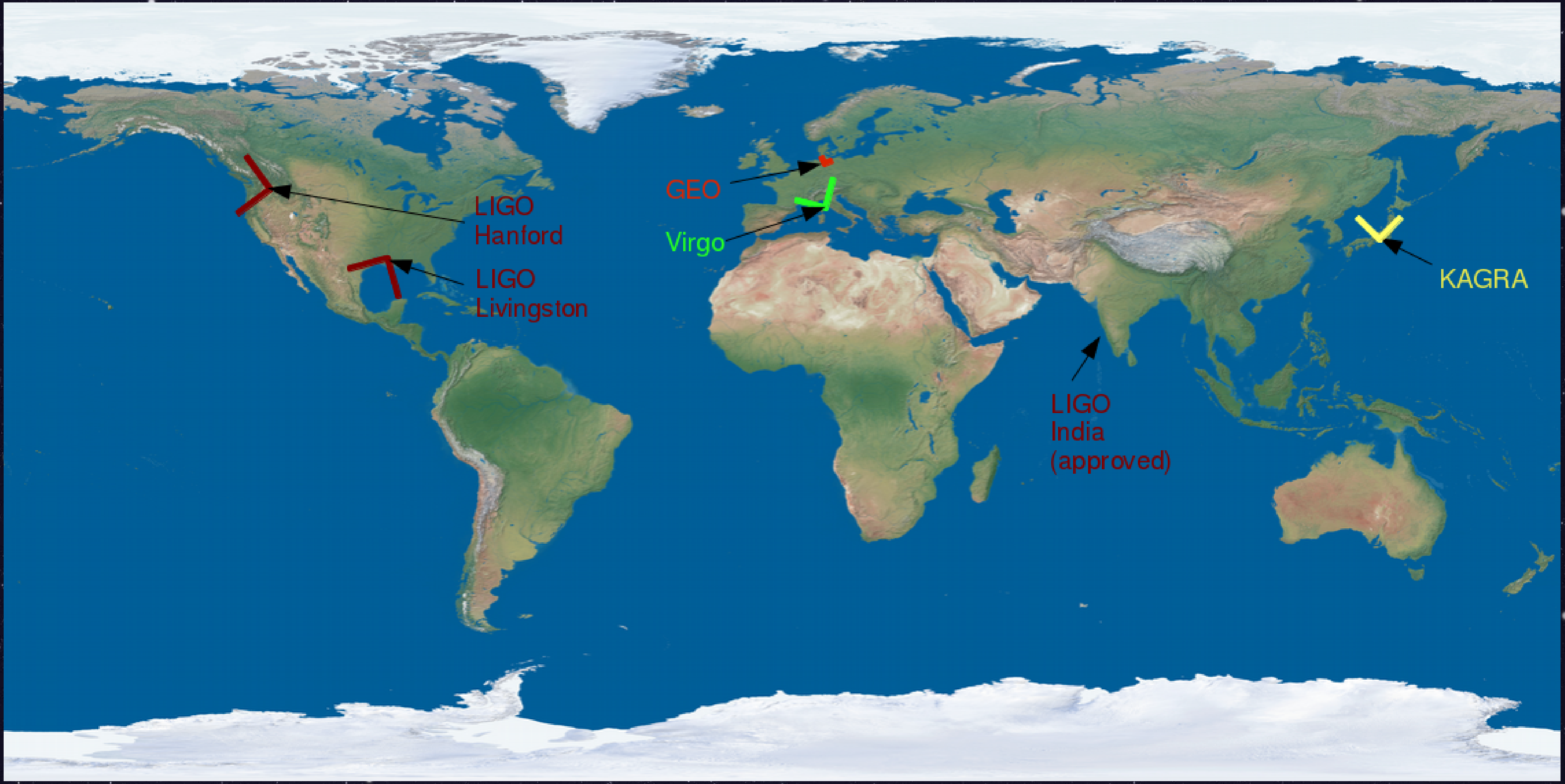
"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

2017 Nobel Prize in Physics



“"for decisive contributions to the LIGO detector and the observation of gravitational waves"”

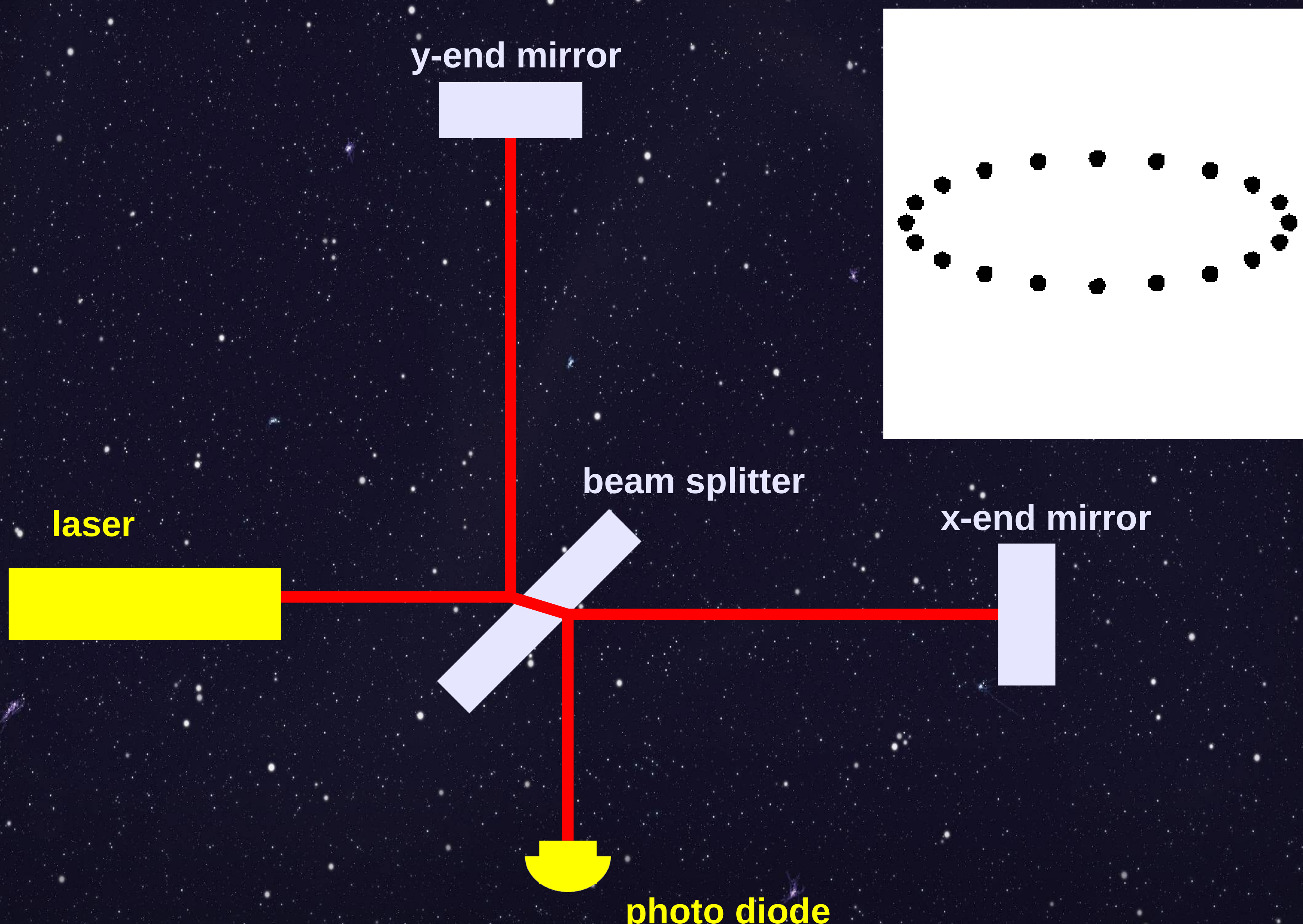
Worldwide network



Source: Virgo/LAPP, T. Patterson

Source: LIGO Lab

Interferometers

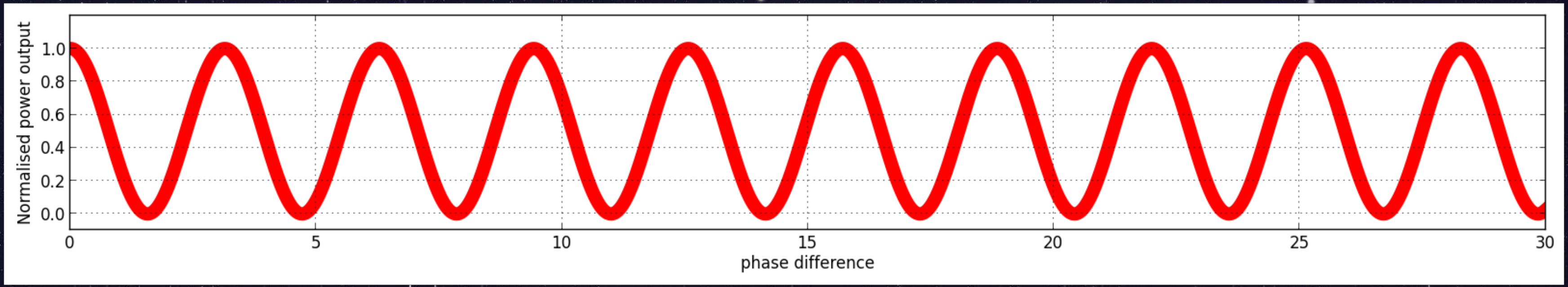


How LIGO really works

- **Long arms**: Earth's curvature over 4km is ~1m
- **High power laser**: 20W 1064 nm Nd:YAG (neodymium-doped yttrium aluminium garnet) (will be up to 200W)
- **Higher power beams**: Fabry-Perot cavities, 100kW, power and signal recycling
- **Near-dark photo diodes**: 50 mW
- **High vacuum**: One trillionth atm, 10^{-9} torr in $10{,}000 m^3$
- **Active seismic isolation**: at $\sim 10^{-13}$ m
- **Passive suspension**: at $\sim 10^{-19}$ m
- **Heavy test-mass mirrors**: 40kg suspended by fused-silica wires 0.4mm thick

Reading between the lines

Interference pattern: $P_{out} = P_{max} \cos^2 \Delta \phi$



$\Delta \phi = \frac{\pi}{2} + B \frac{c \Delta T}{\lambda}$:Accumulated phase difference

Displacement sensitivity: $\Delta L = \frac{\lambda}{B} \sqrt{\frac{P_{out}}{P_{max}}}$

Spectral lines

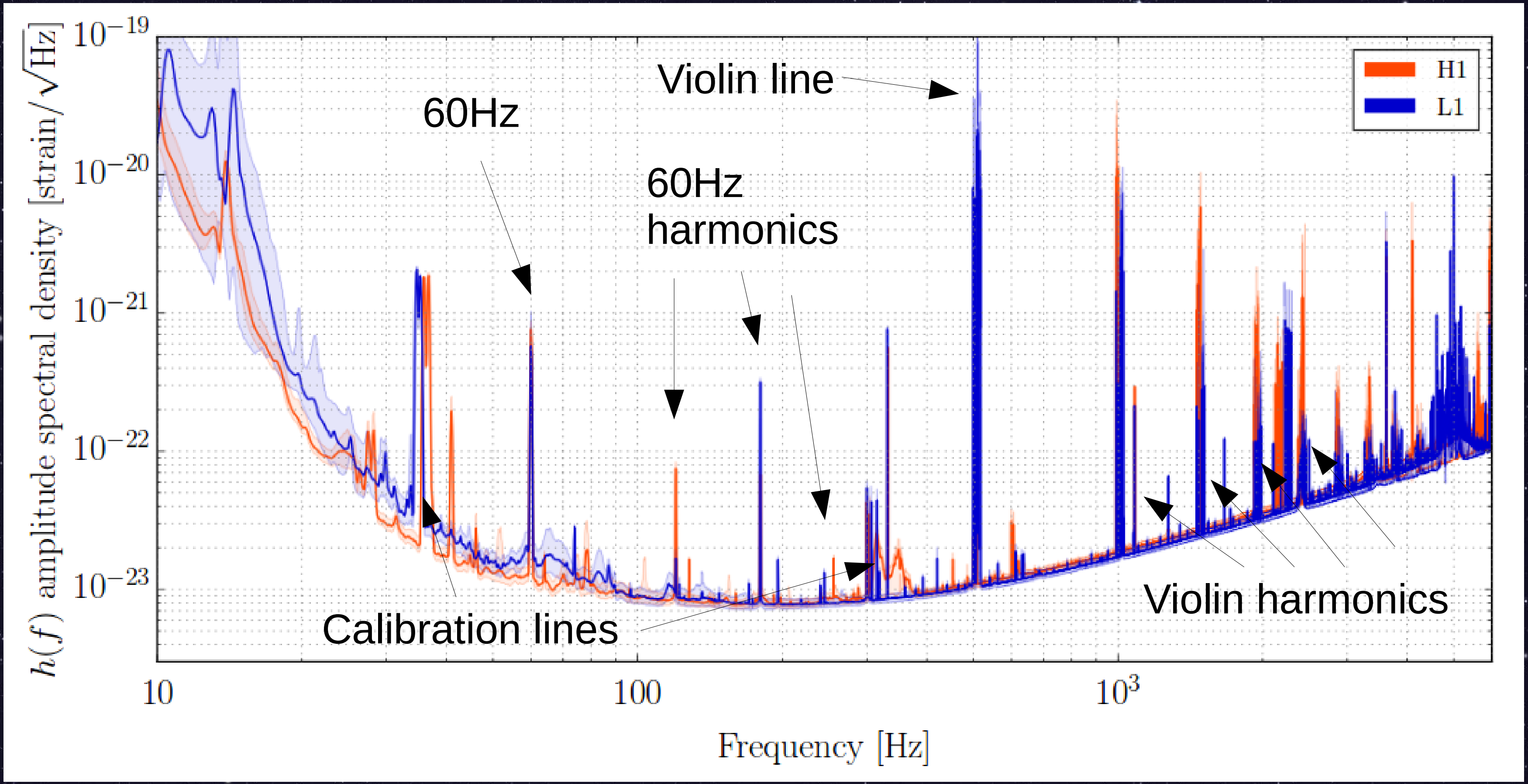
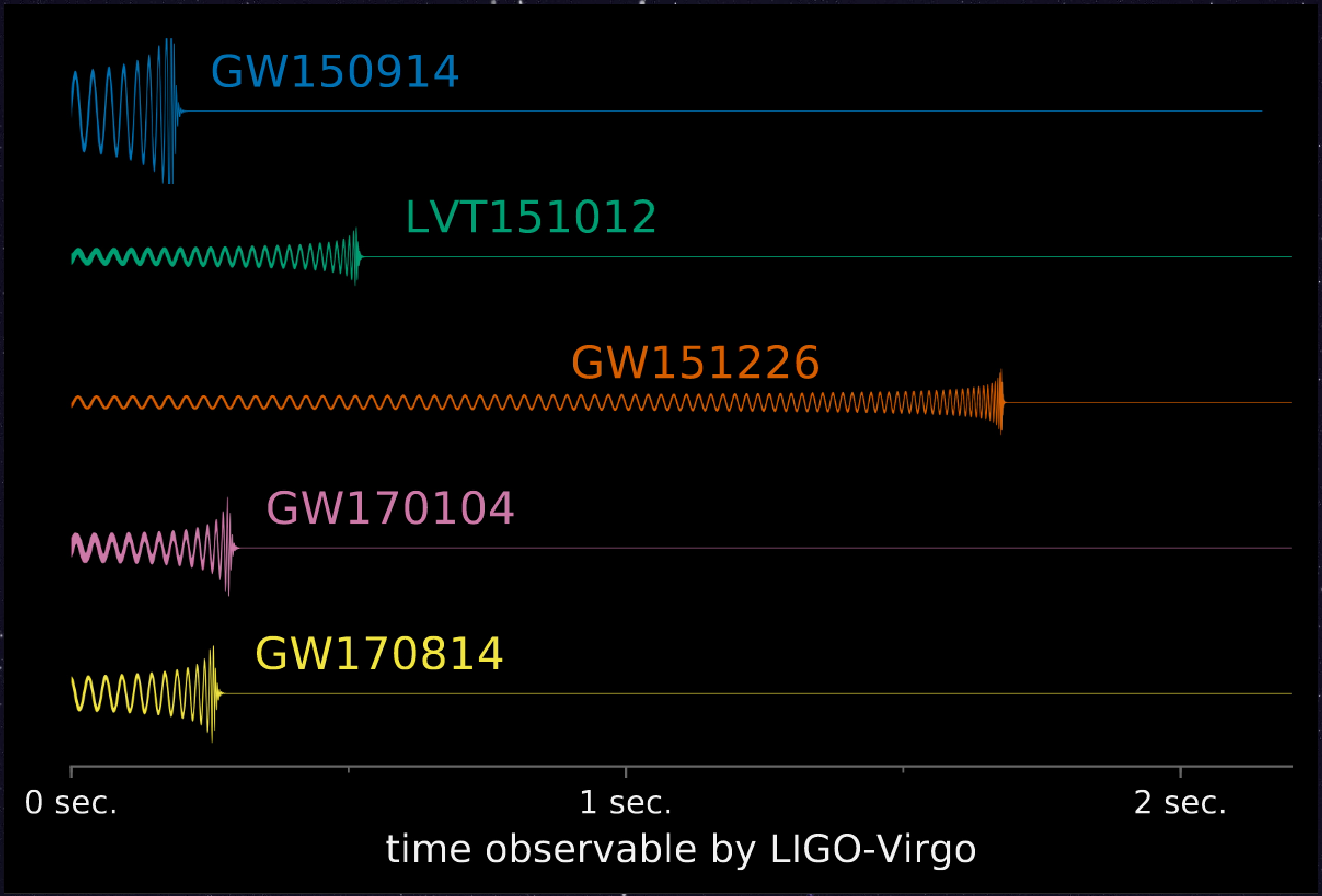
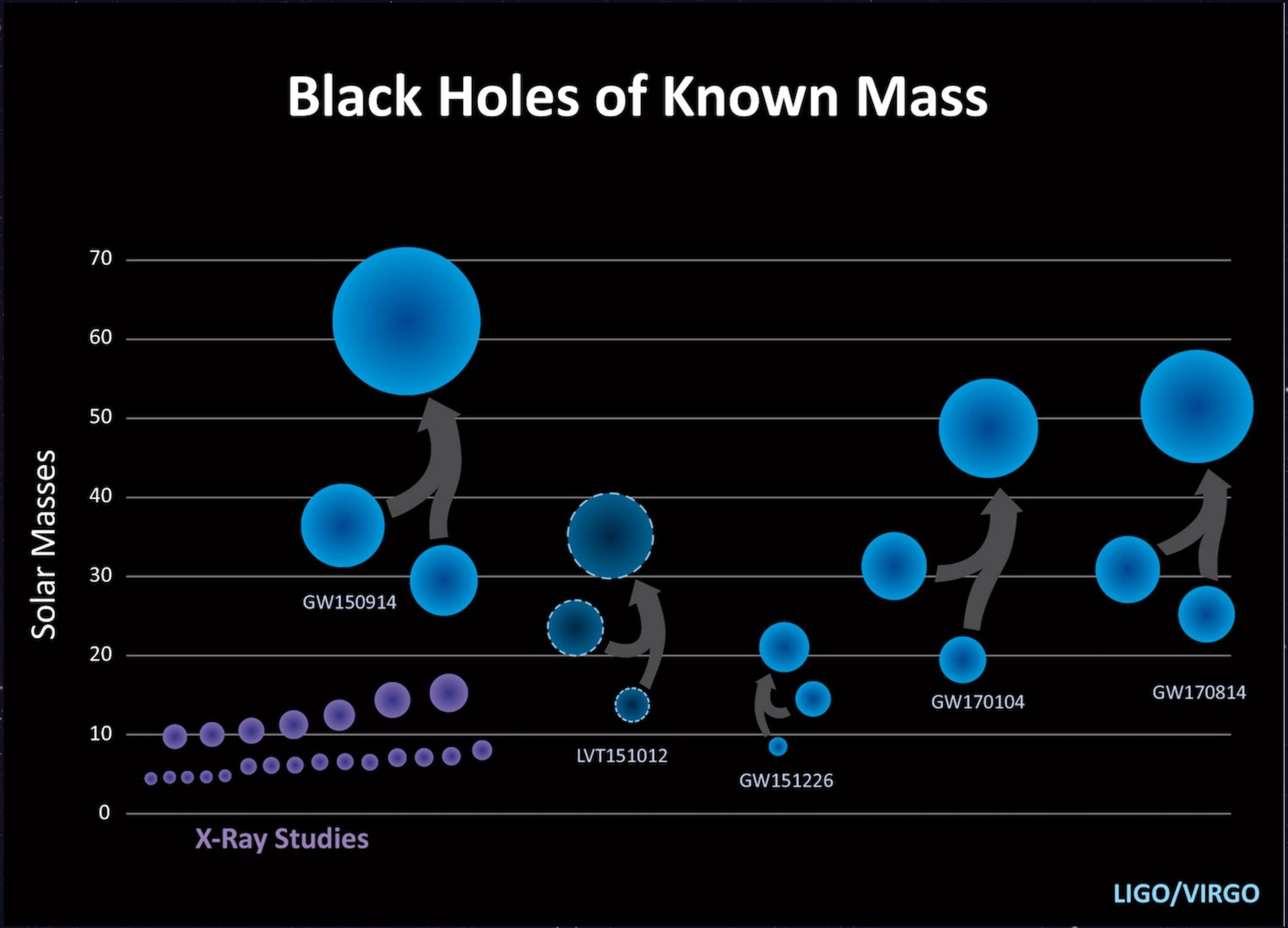


Fig. 1 Abbott et al. CQG33 (2016) 134001

Now five BBH events...



Credit: LSC



[Image credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)]

X-ray binaries masses and spin

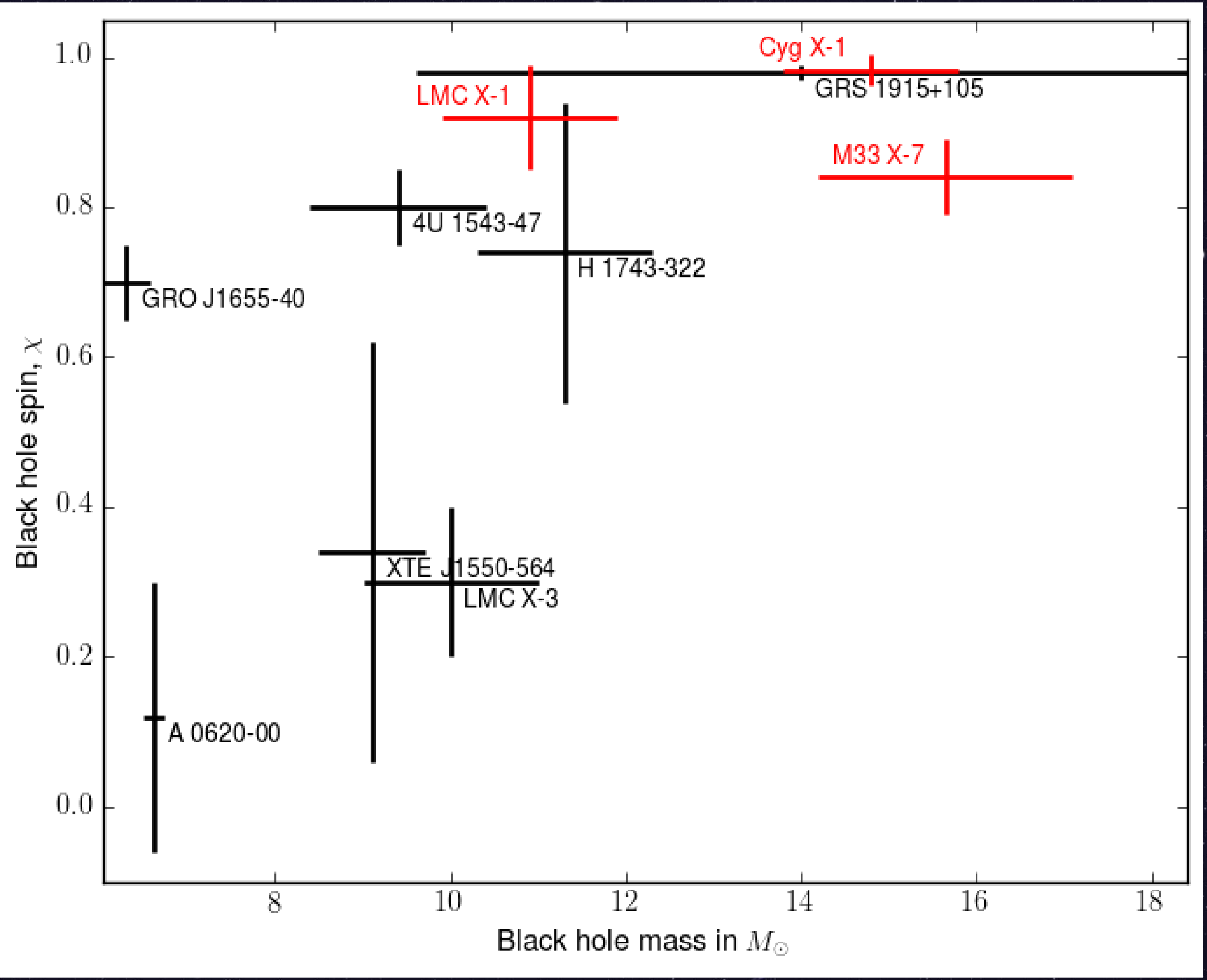
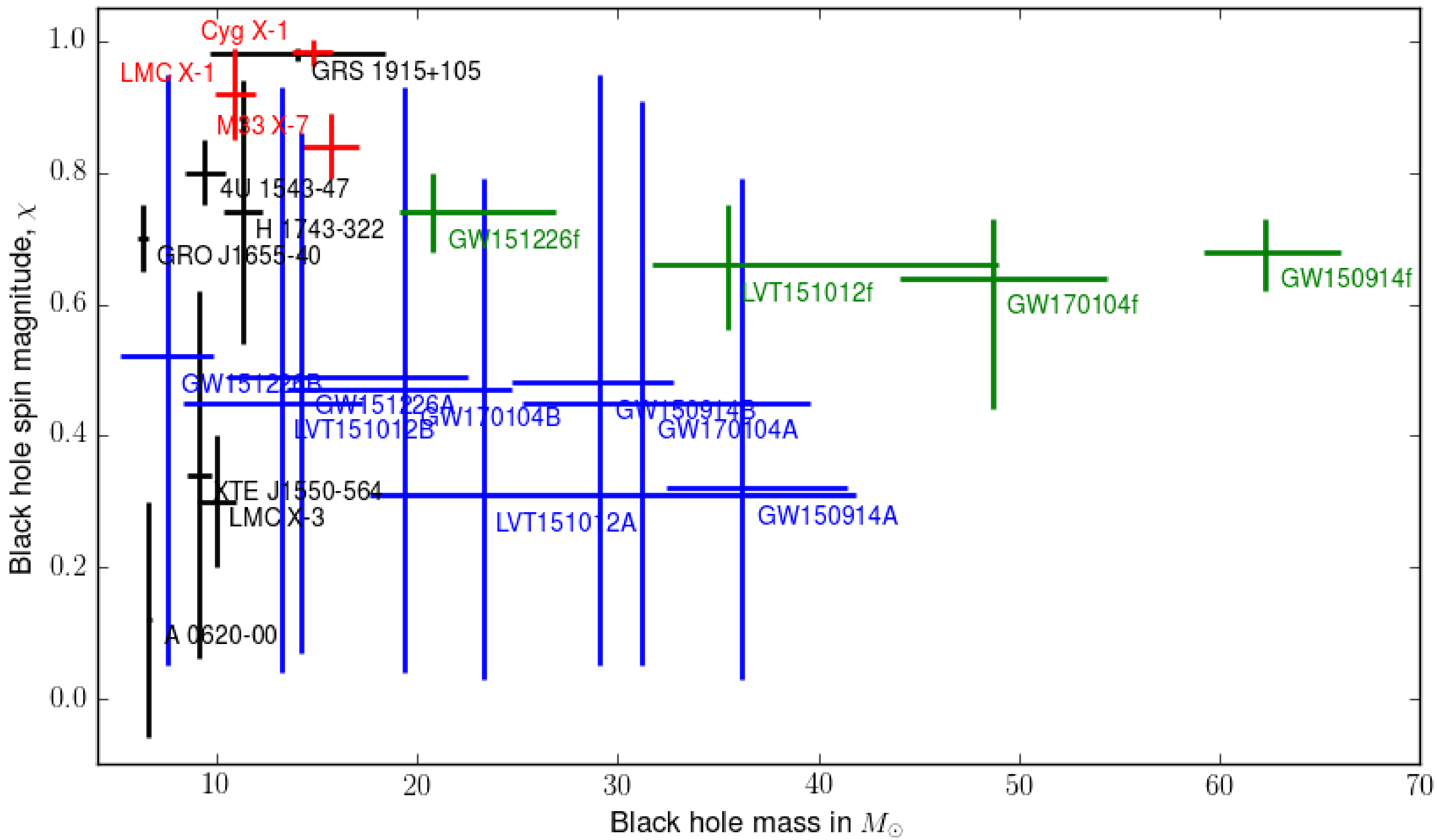


Fig. 1 of Nielsen J.Phys.Conf.Ser. 716 (2016) no.1, 012002

X-ray + GW masses and spins



Astrophysics

- Formation of heavy black holes – direct collapse?
- Time to merge from 1AU by GW alone,
  ~ 100x age of universe - common envelope?
- Formation of binary still open – cluster or field?

Testing gravity

- Compact and dynamic

$$\left(\frac{\pi G M f}{c^3}\right)^{1/3} \sim \sqrt{\frac{GM}{c^2 r}} \sim \frac{v}{c} \sim 0.5$$

- Curvature scale corrections to gravity?

$$K l_p^4 \sim \frac{3}{4} \frac{\hbar^2 c^2}{G^2 M^4} \ll 1$$

- Horizon scale corrections to gravity?

$$\langle B | \hat{T}_{ab} | B \rangle \Rightarrow \infty$$

- Peak energy flux 200^{+30}_{-20} solar masses per second

Inspiral-merger-ringdown consistency

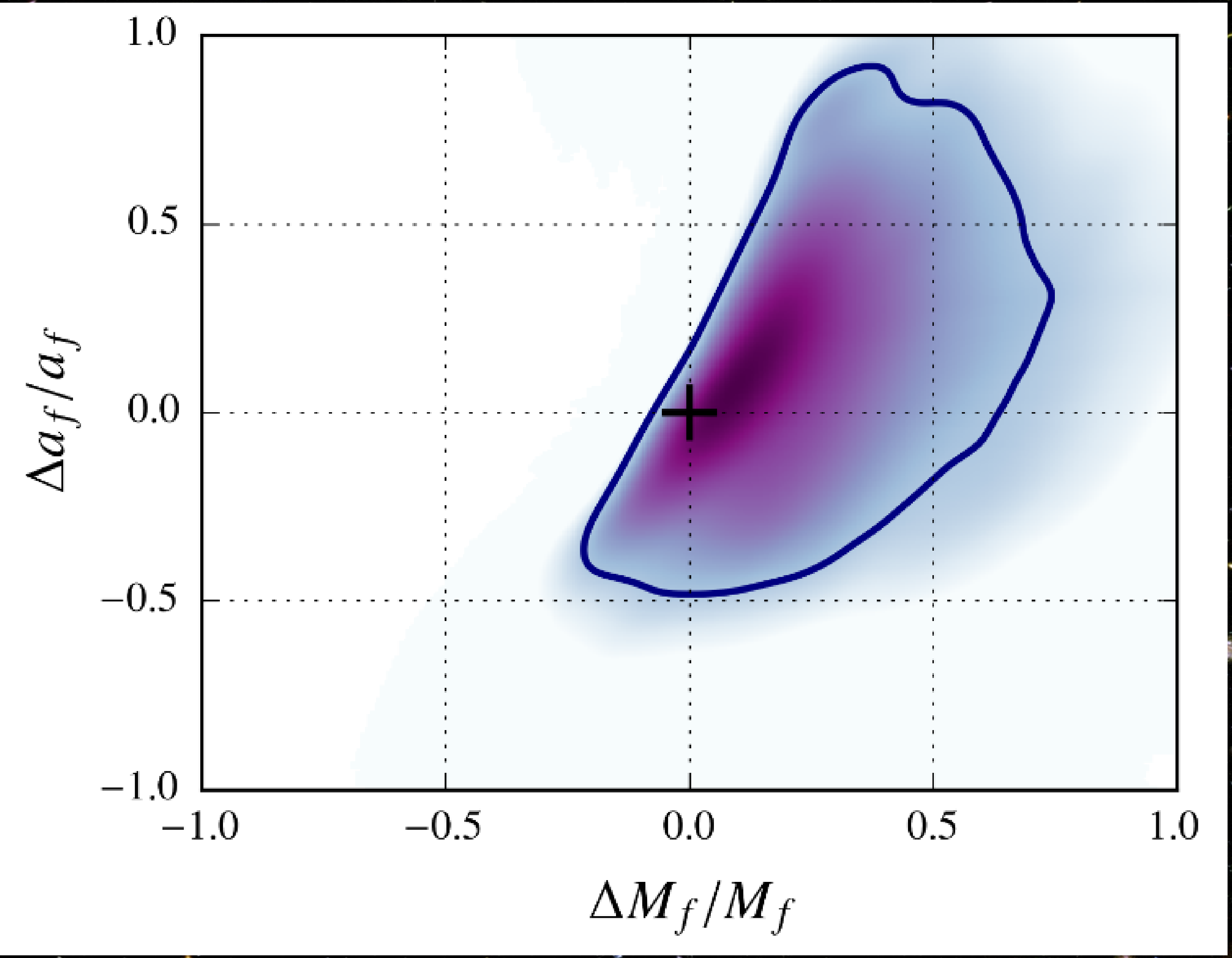
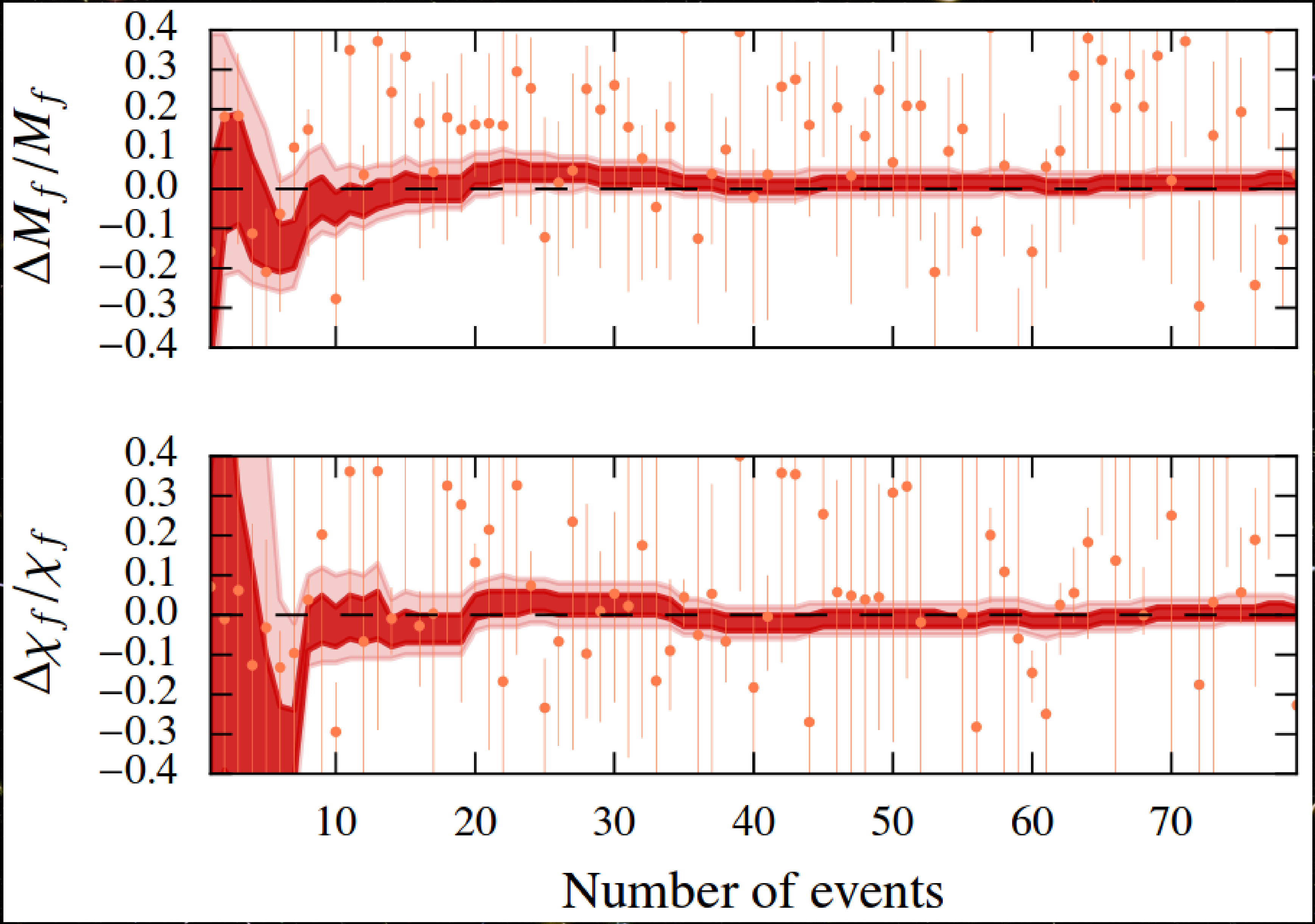


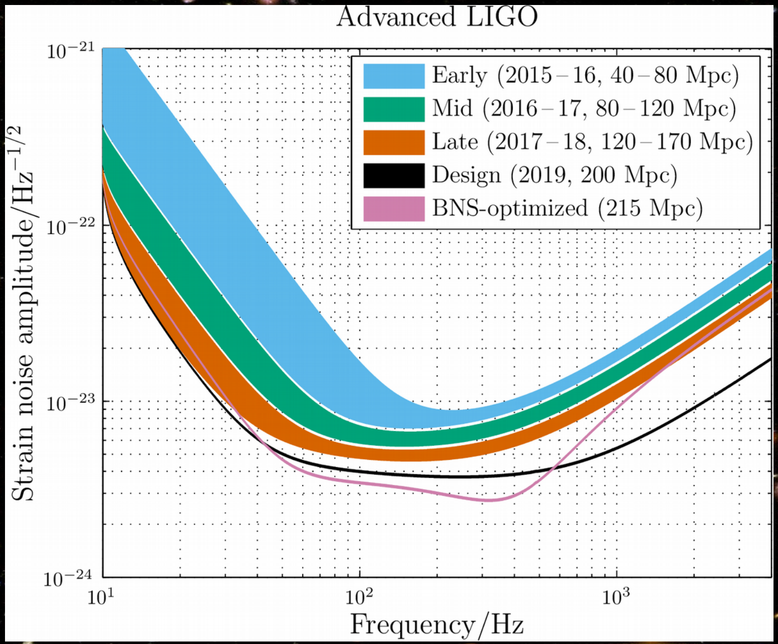
Fig. 3 (bot) of LVC PRL 16 (2016) 221101

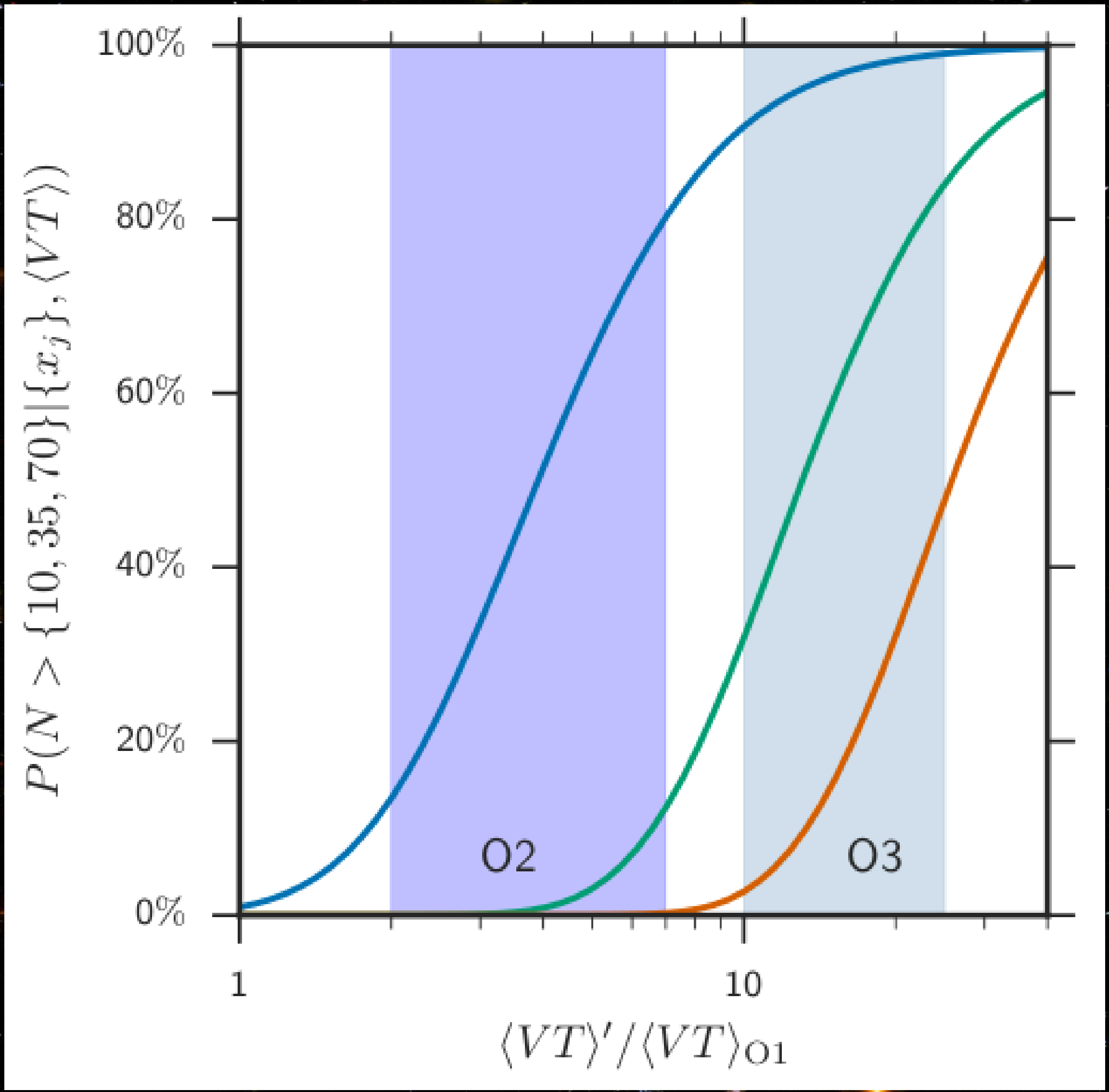
IMR consistency going forward



Source: Ghosh et al PRD94 (2016) 021101

Event rate estimates





Multiple detections by the end of observing run O3 is quite likely

Fig 12 of LVC 1606.04856 PRX6 041015

Binary Neutron Star GW170817

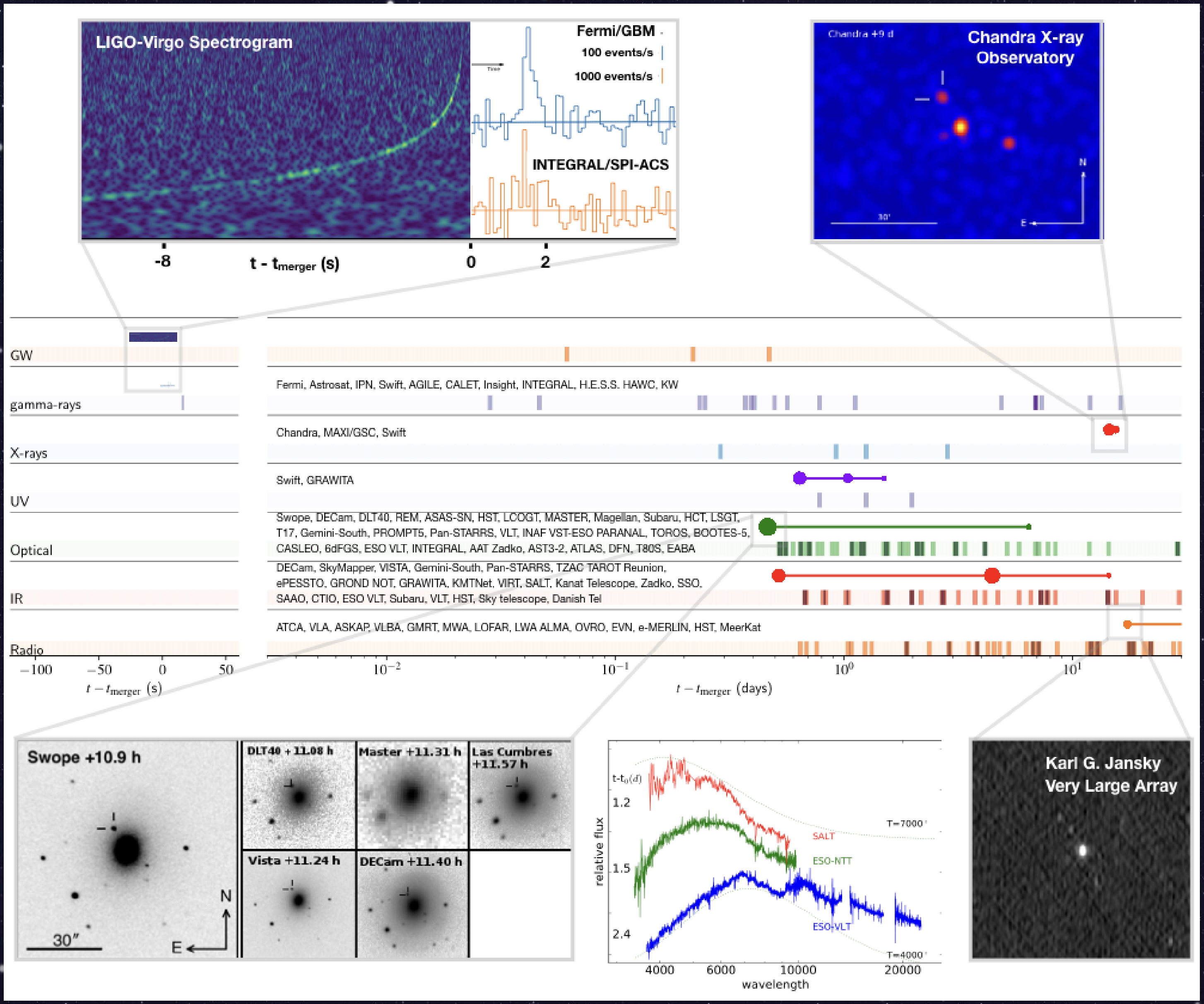
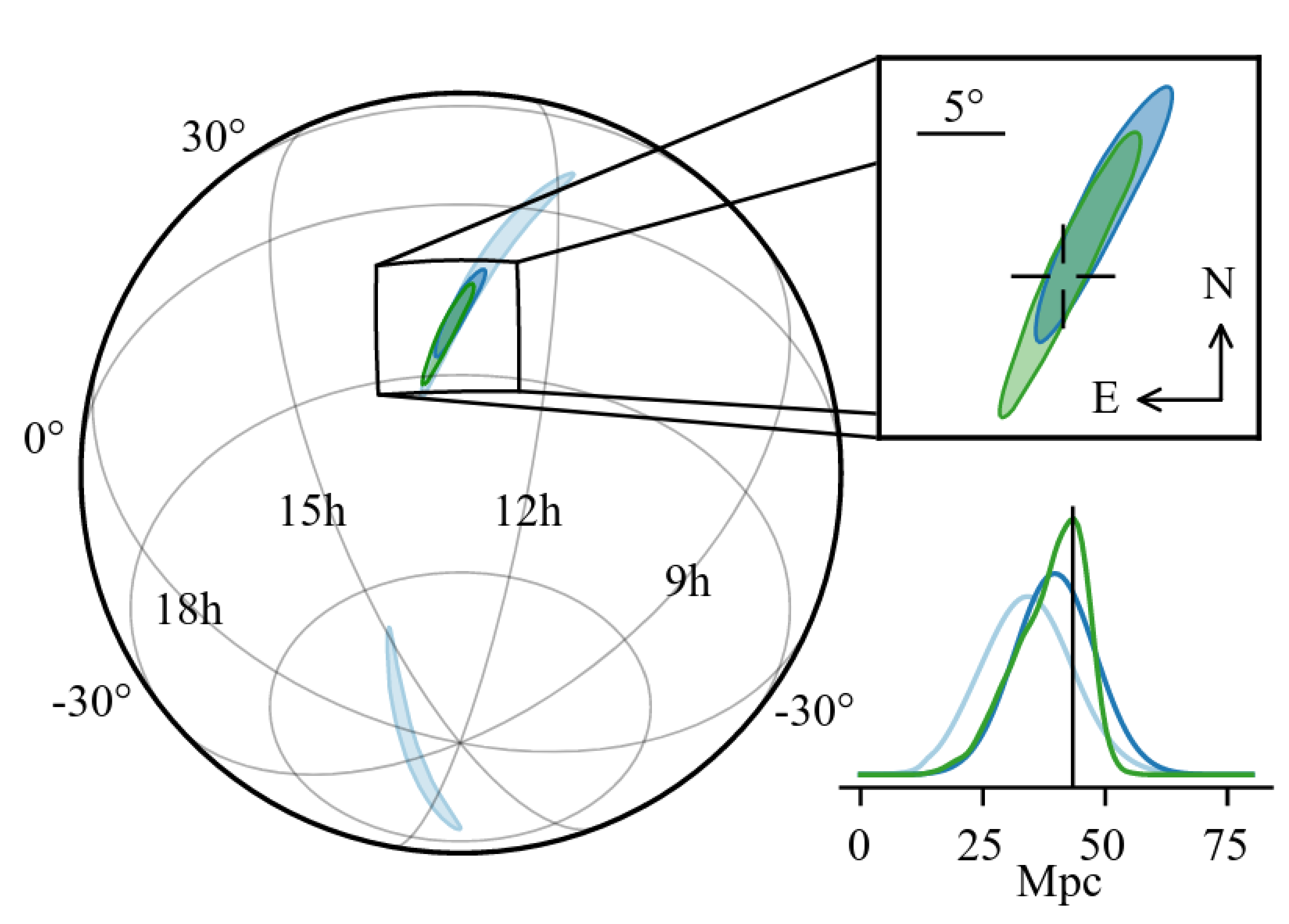


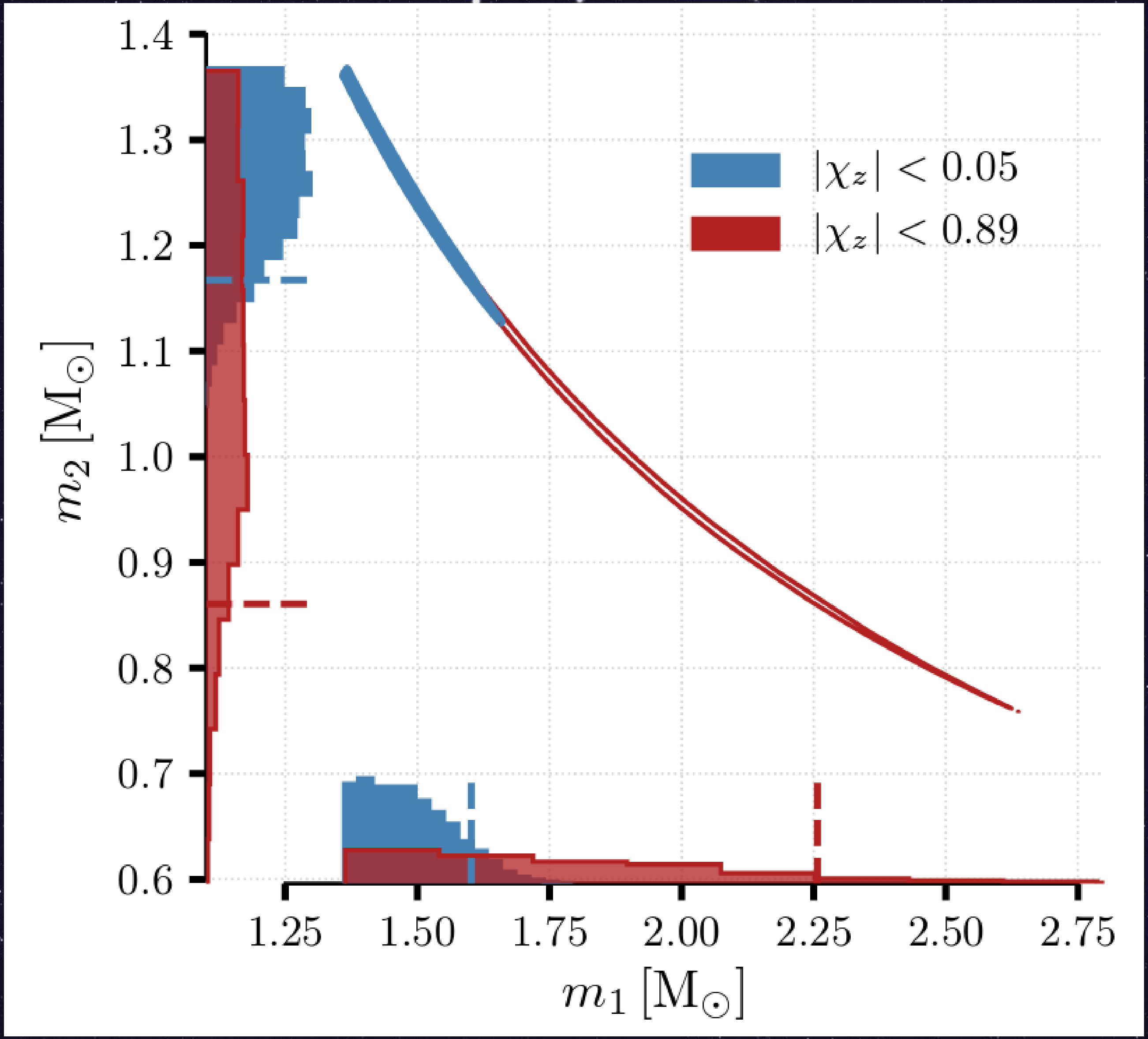
Fig 2, ApJL848, (2017) L12

Sky location



LVC detection, Fig 3, PRL119 (2017) 161101

Component Masses

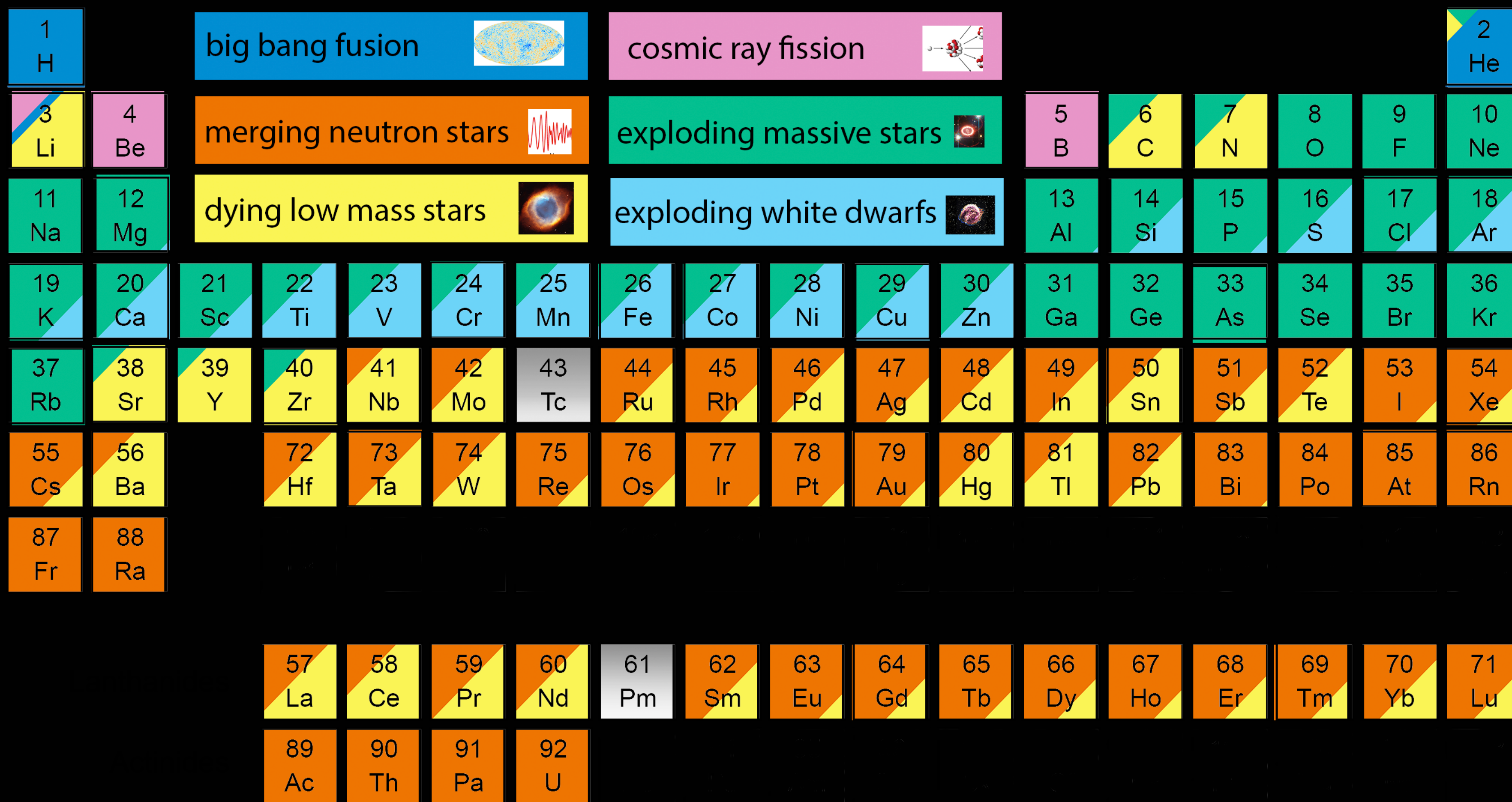


LVC, Fig 4, PRL119 (2017) 161101

BNS, short GRB

- Luminosity distance 40^{+8}_{-14} Mpc, Fermi GRB 1.7 sec later
- Hubble constant 70^{+12}_{-8} km per second per Mpc
- 2010 "realistic" rates projection 1000 per Gpc^3 per year, range 10 to 10,000
- Measured now to be 1540^{+3200}_{-1220} per Gpc^3 per year
- Speed of gravity $-3\times 10^{-15} \leq \frac{\delta v}{v_{EM}} \leq 7\times 10^{-16}$

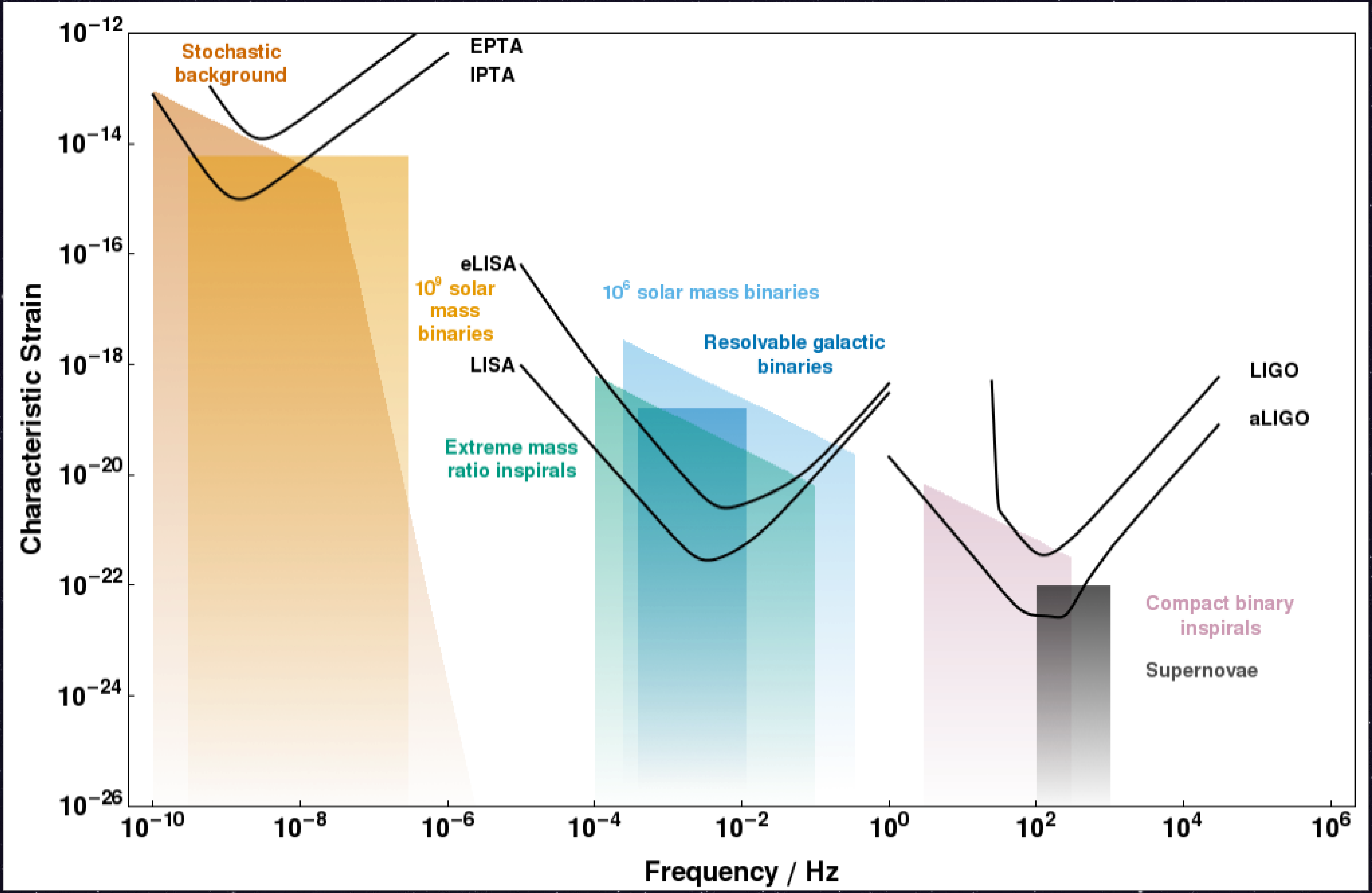
The Origin of the Solar System Elements



Astronomical Image Credits:
ESA/NASA/AASNova

Graphic created by Jennifer Johnson

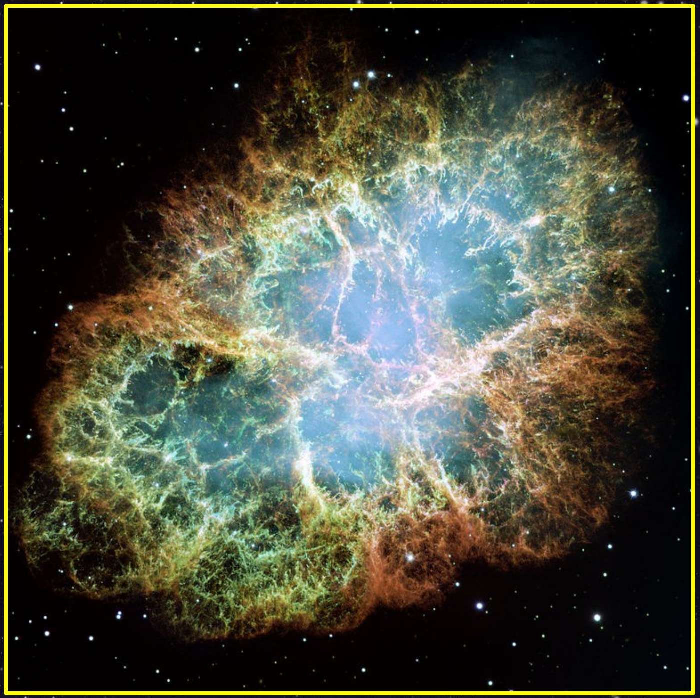
Full GW spectra



Source: Wikimedia; C. Moore, R. Cole and C. Berry

Other potential GW sources

- Neutron star-black hole binaries
- Deformed rotating neutron stars
- Supermassive black holes
- White dwarf “verification binaries”
- Tensor-mode CMB polarisations
- Galactic supernovae
- Astrophysical background
- Cosmic strings
- First-order phase transitions
- Inflationary particle production
- Non-perturbative preheating
- Inflationary vacuum fluctuations



Source: NASA/HST

O1 upper limits

- Neutron star binaries
  $<12{,}600\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ *ApJ 832 (2016) L21*

- Intermediate black holes
  $<0.93\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ *arXiv 1704.04628*

- Deformed rotating neutrons
  8 below spin-down limit *ApJ 839 (2017) 12*

- Stochastic background
  $\Omega_0 < 1.7*10^{-7}$ PRL 118 (2017) 121101

Summary

- LIGO has detected gravitational waves
- Binary black hole systems exist
- Binary neutron stars cause short GRBs
- The future is likely to bring more

Thank you

References and links

- Abbott et al. *“The basic physics of the binary black hole merger GW150914”* arXiv:1608.01940, Annalen Phys. (2016) 041015
- Abbott et al. *“Binary Black Hole Mergers in the first Advanced LIGO Observing Run”* arXiv: 1606.04856, PRX6 (2016)
- Abbott et al. *“Properties of the Binary Black Hole Merger GW150914”* arXiv: 1602.03840, PRL 116 (2016) 241102
- LIGO Open Science Center: https://losc.ligo.org

- (BBH was 0.1-300, realistic 5 and is measured to be 55+103-41)

Squeezed light

- Heisenberg uncertainty in amplitude, phase
- Inject phase-locked squeezed vacuum state into output port
- Periodically poled potassium titanyl phosphate
- Hoped for ~30% gain in sensitivity

PRL **117,** 110801 (2016) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2016

Detection of 15 dB Squeezed States of Light and their Application for the Absolute Calibration of Photoelectric Quantum Efficiency

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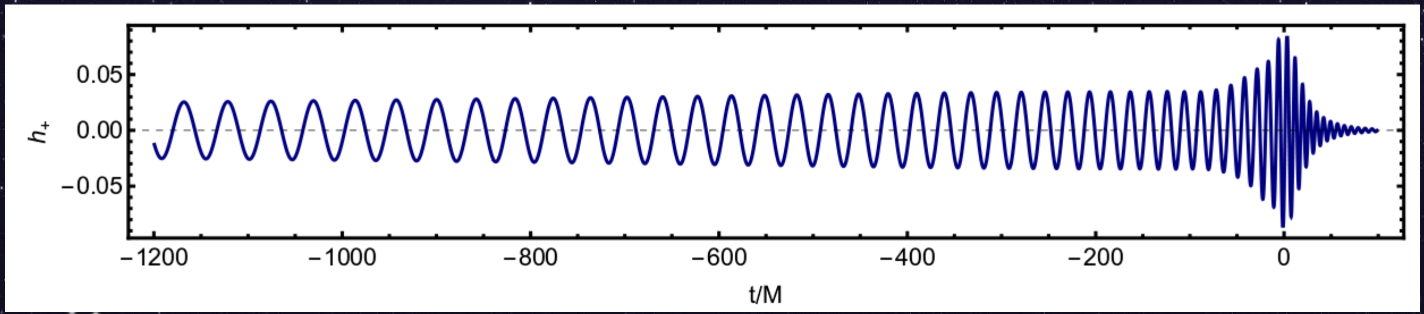
(Received 15 June 2016; published 6 September 2016)

Gravitational Waveforms

- **Numerical relativity**
  either finite differencing or spectral methods

- **Effective One Body (EOBNR)**
  maps two body problem to one body problem via effective Hamiltonian and calibrated to numerical simulations

- **IMRPhenom**
  combines post-Newtonian inspiral with phenomenological fit model of numerical simulations of late inspiral and merger, and quasi-analytical ringdown phase



Source: Khan et al. PRD 93 (2016) 044007

What was seen II

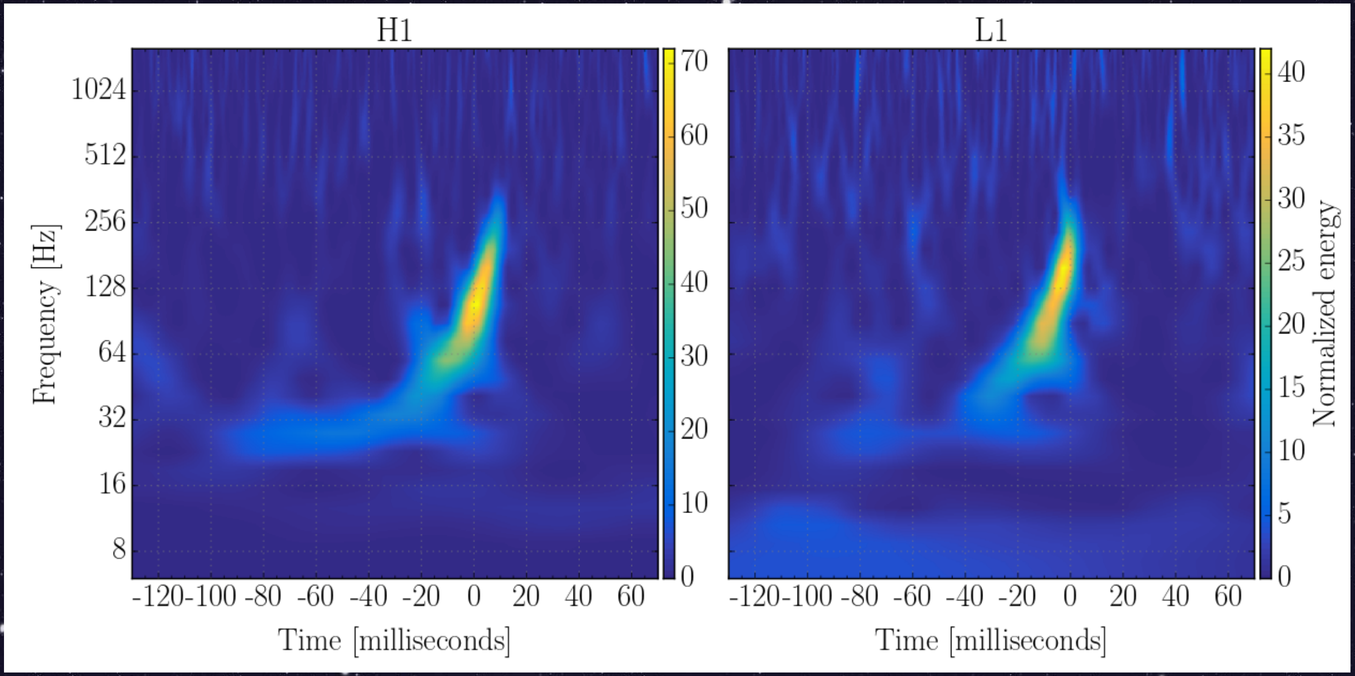


Fig. 10 of LVC CQG33 (2016) 134001

Frequency ~30 Hz to ~250 Hz
Wavelength ~10,000 km to ~1,000 km
Visible duration ~ 0.1 secs
Increasing amplitude, increasing frequency = chirp
0.007 secs earlier in Livingston
The same signal in both detectors!

LVT151012

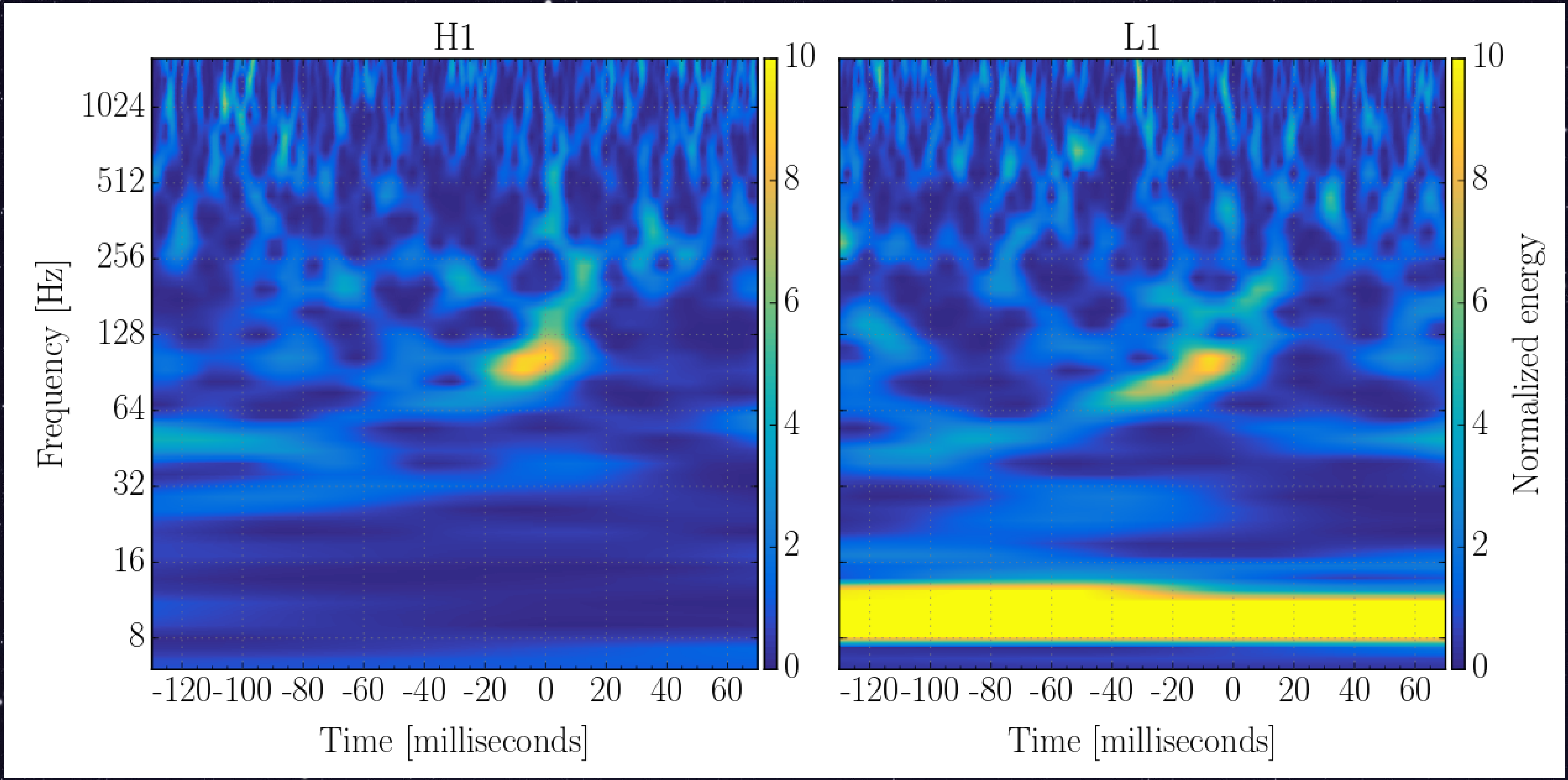
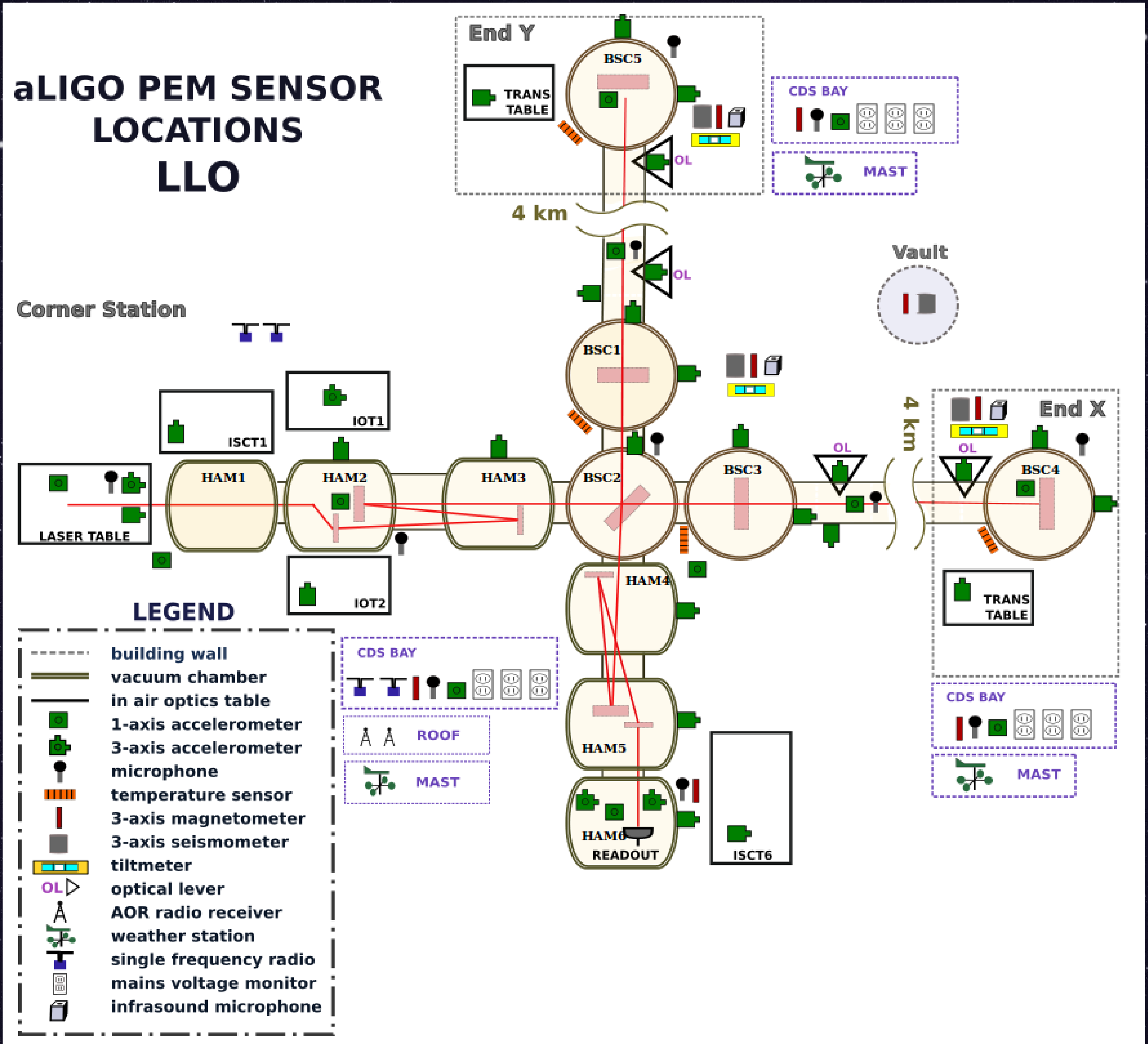


Fig. 13 of LVC CQG33 (2016) 134001

False Alarm Rate, 1 per 2.3 years



http://pem.ligo.org/

Non-Gaussian transients

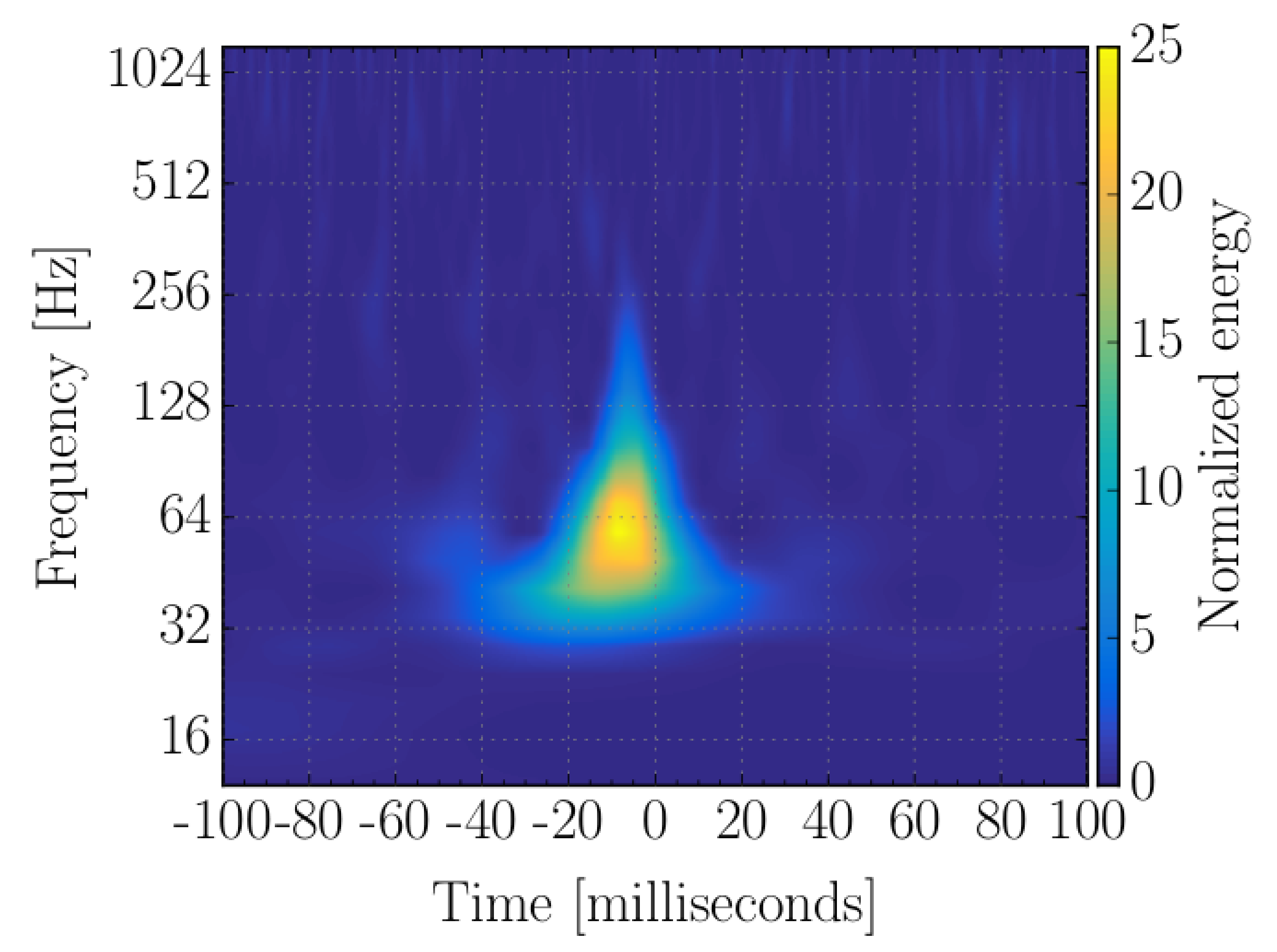


Fig. 3 LVC CQG33 (2016) 134001

Search significance

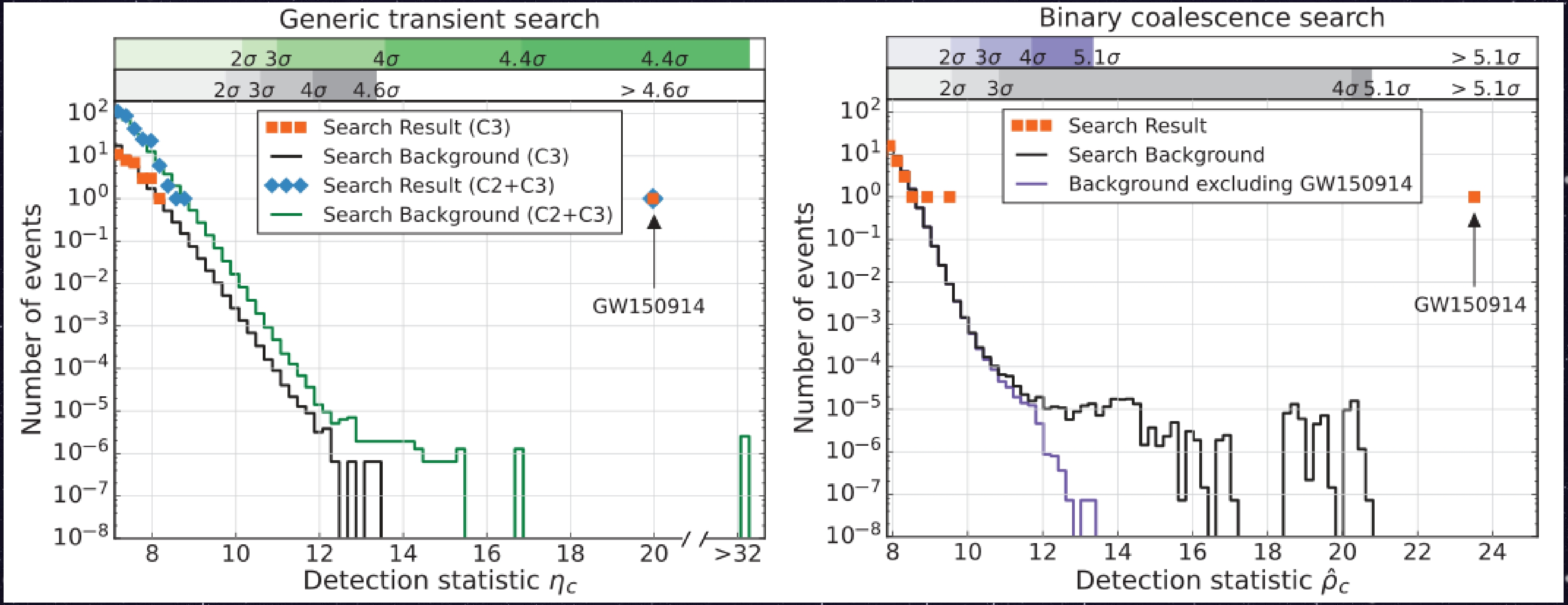


Fig 4 Abbott et al. PRL 116 (2016) 6, 061102

Daytime versus nighttime

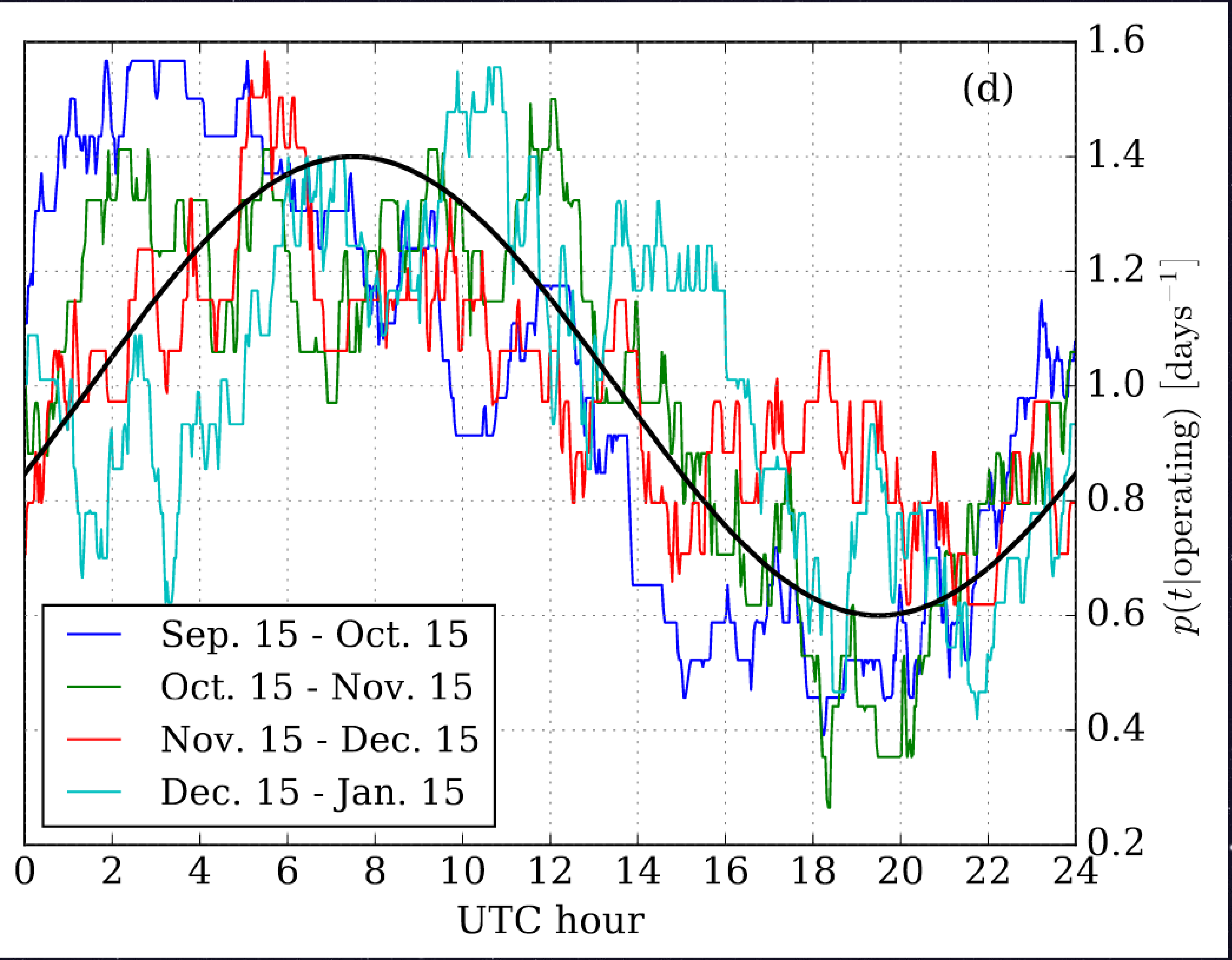


Fig. 1 (right) of Chen et al. ApJ 835 (2017) 31

Post-Newtonian expansion (2-2 phase)

PN order	Includes (amongst other things)
0PN	Kepler Newtonian Gravity
0.5PN	Zero in GR
1PN	Pericenter advance (cf zero) PPN parameters γ, β, ξ
1.5PN	Spin-orbit couplings Gravitational tails (backscatter)
2PN	Spin-spin couplings (Newtonian) quadrupole-monopole (GR BH) (Newtonian) magnetic dipole-dipole (cf zero)
3PN	Tails of tails
5PN	(Newtonian) Adiabatic tidal deformations

Bounds on PN coefficients from GW150914 and GW151226

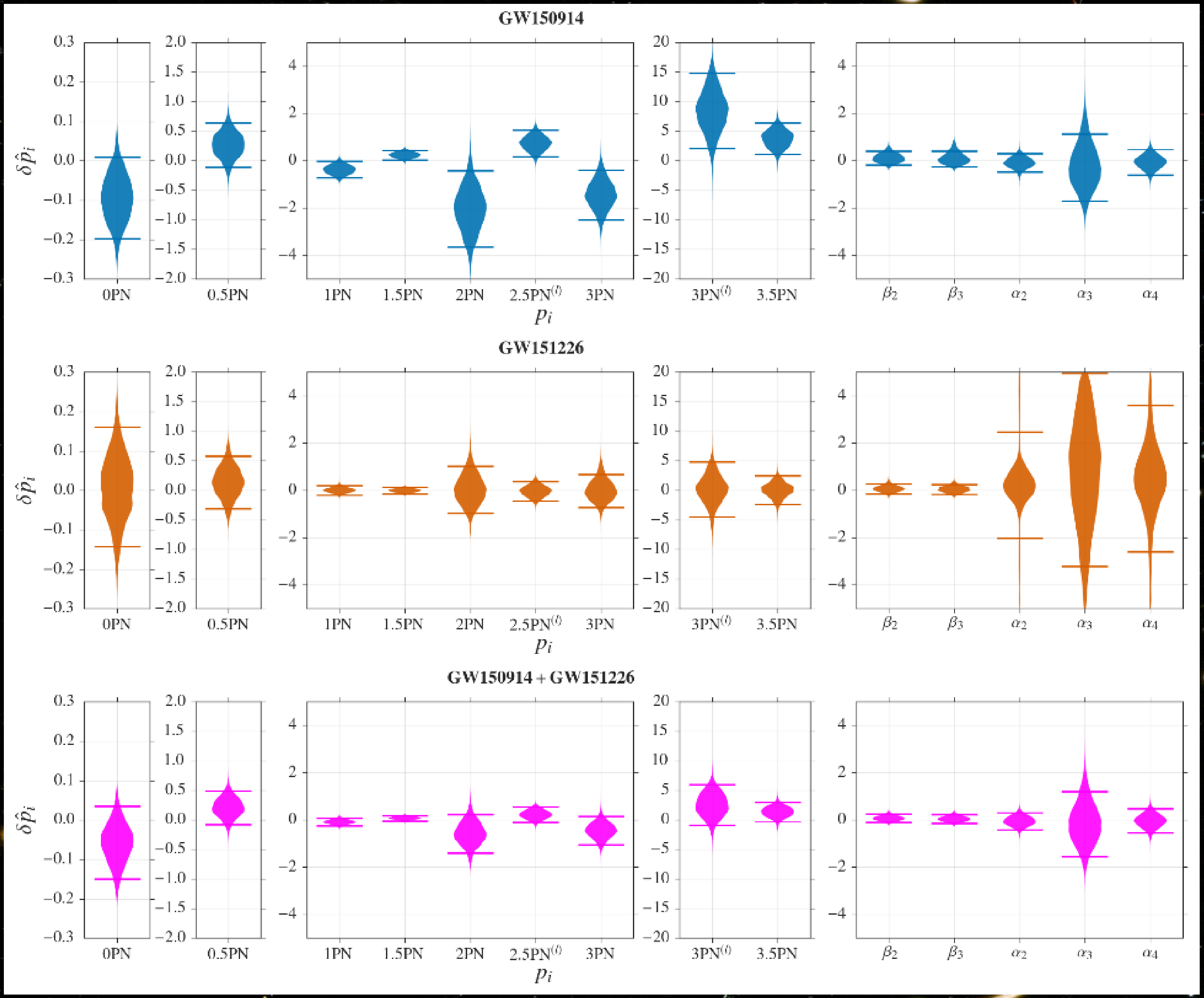


Fig 6 of LVC 1606.04856 PRX6 041015

Masses

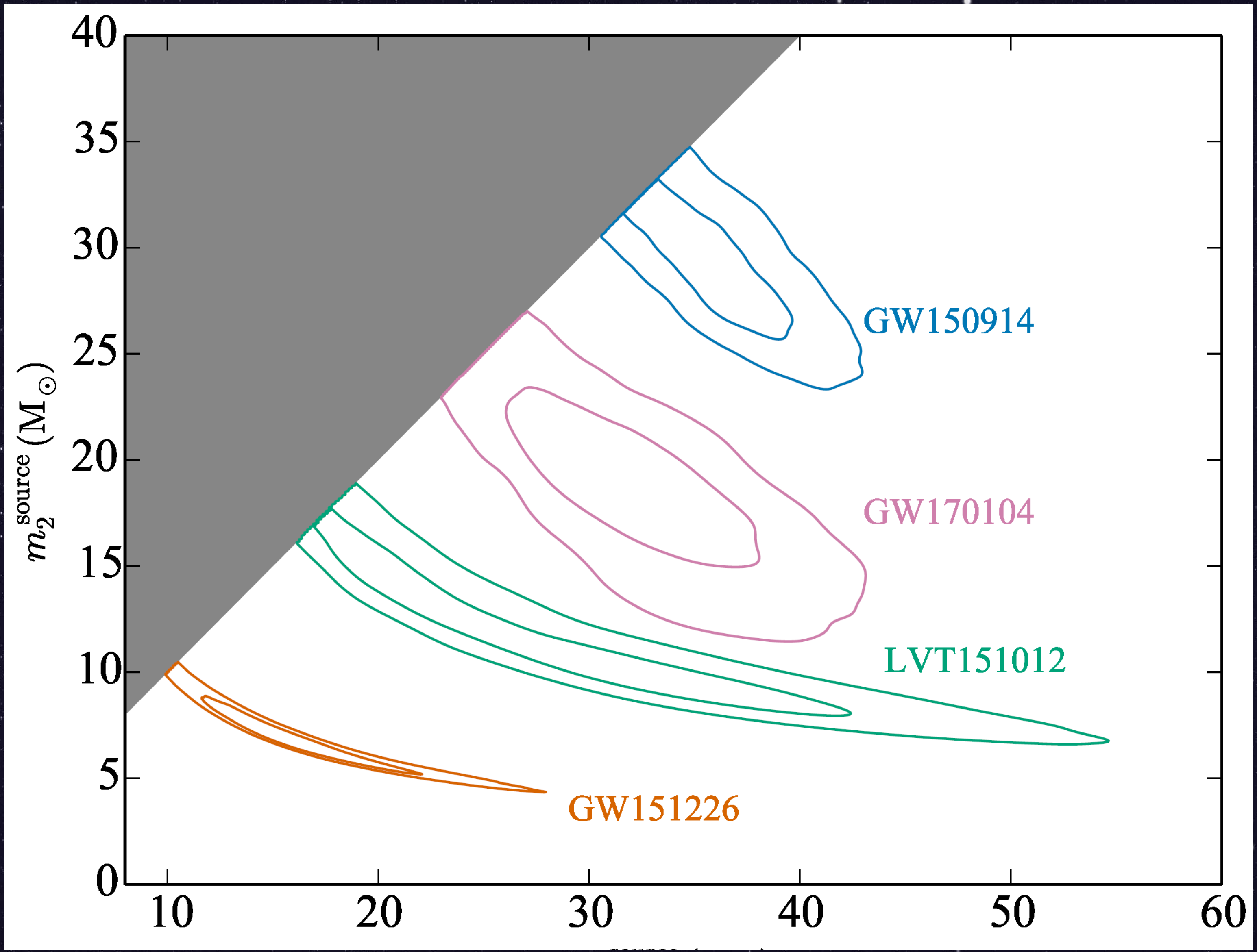


Fig. 2 of LVC 1706.01812, PRL 118 221101

Source parameters

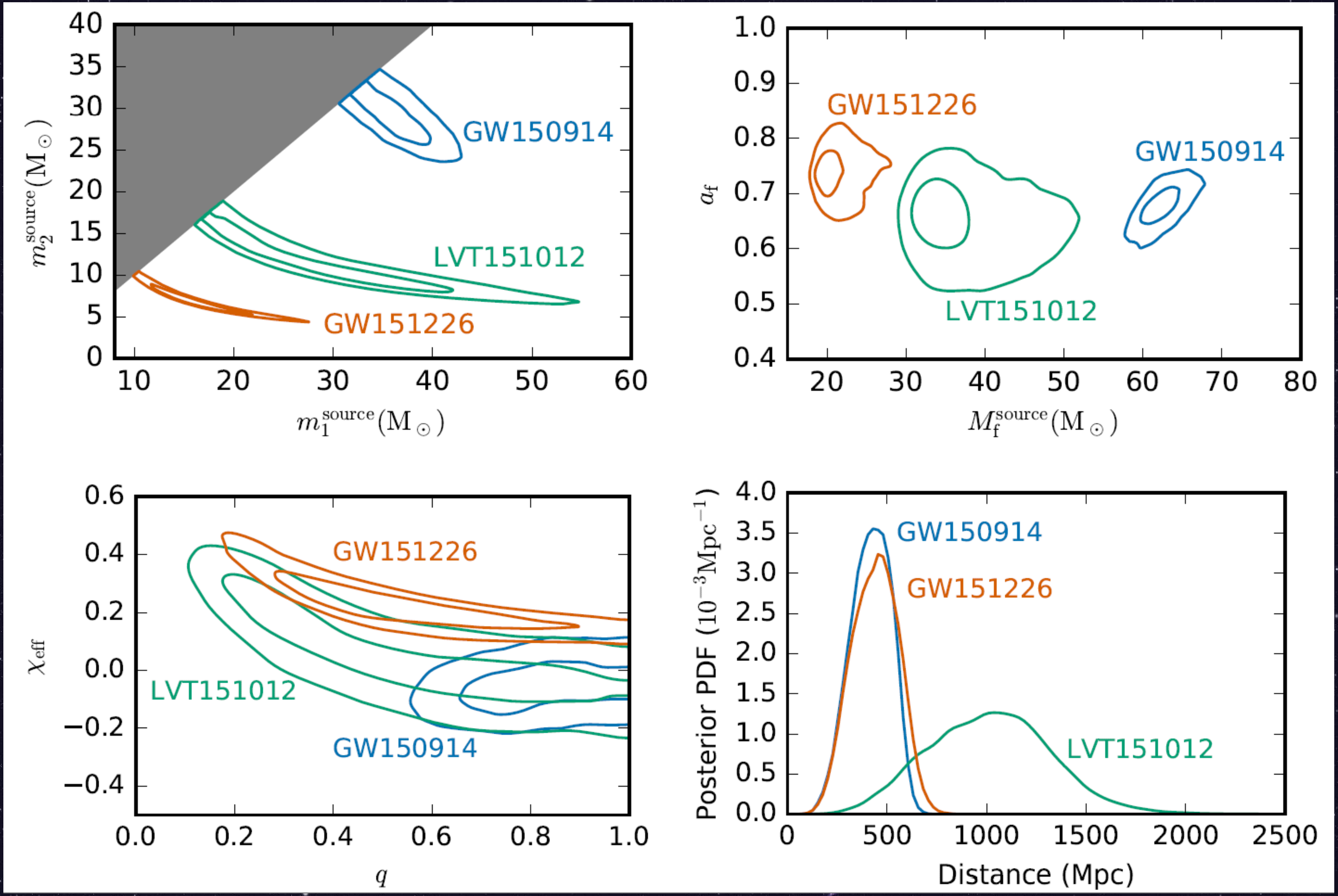


Fig. 4 of LVC 1606.04856, PRX6 041015