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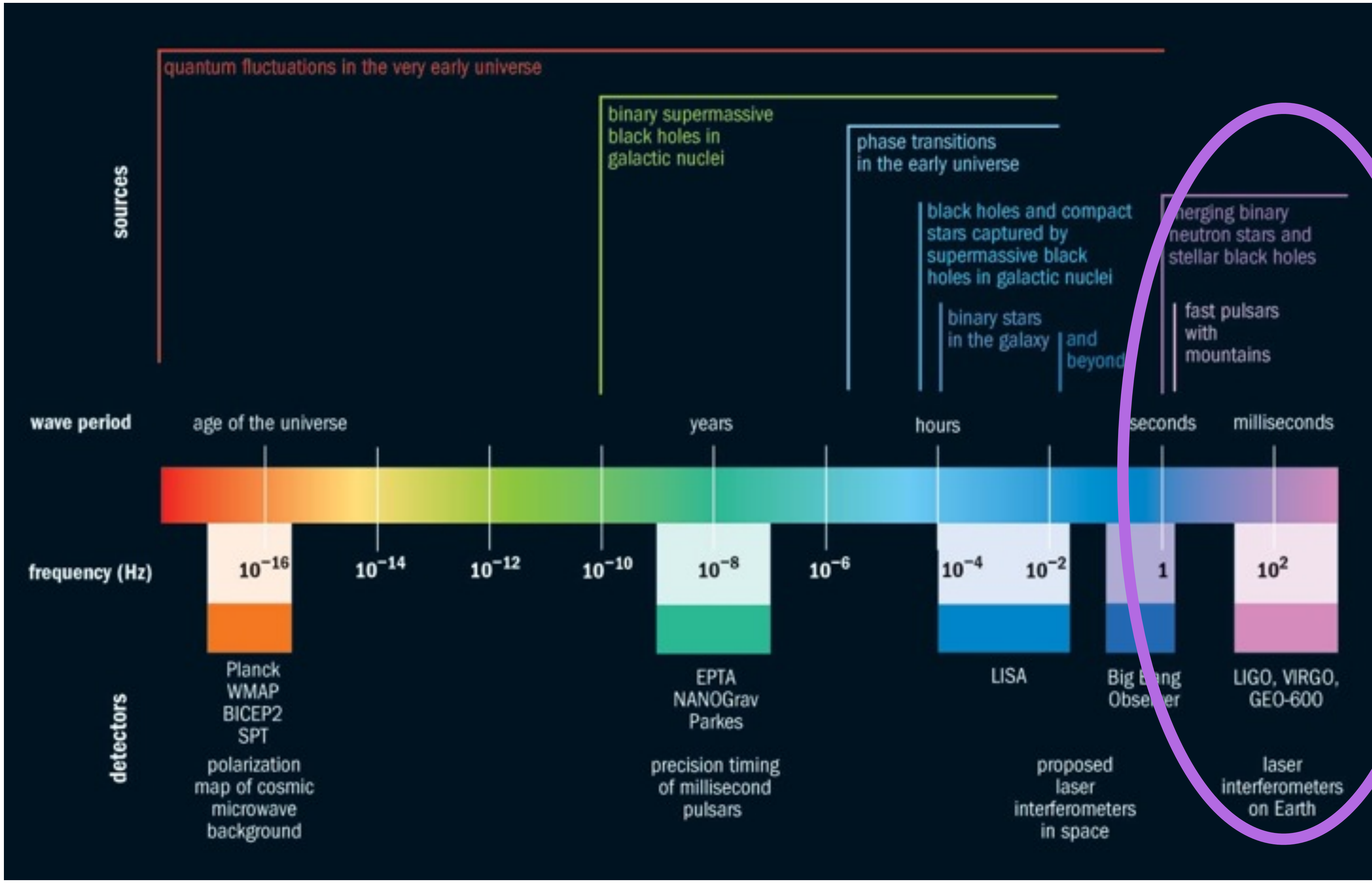
on behalf of the LIGO Scientific and Virgo Collaborations

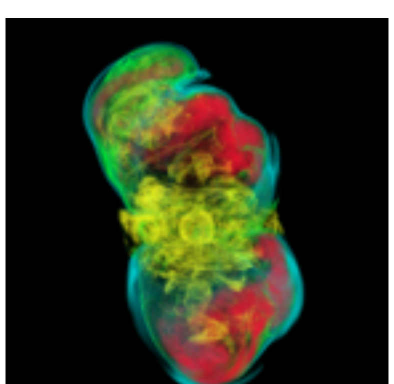
The symphony of the universe: Highlights from the first and second observing runs of Advanced LIGO & Advanced Virgo

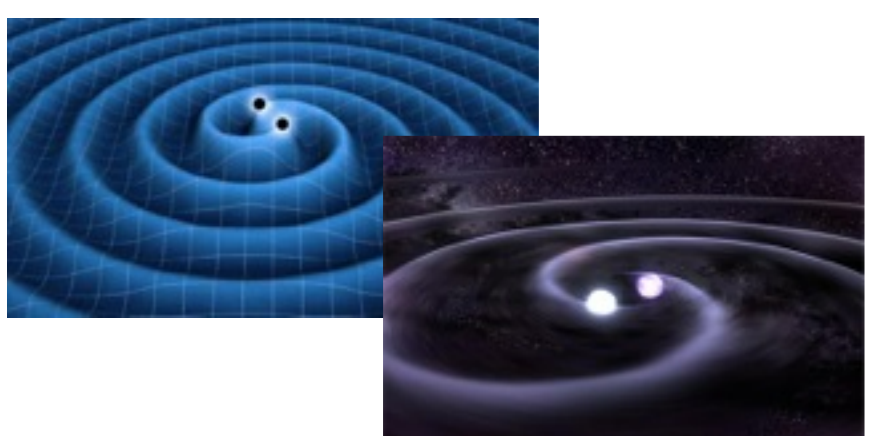
Solvay Workshop: SuGAR 2018, January 23-26 2018

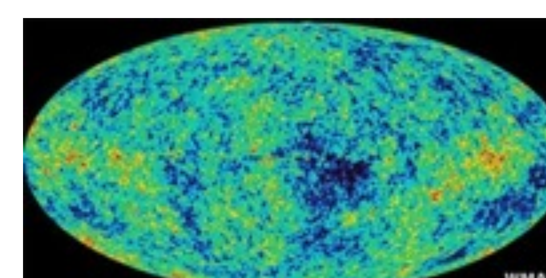
Netherlands Organisation for Scientific Research

The GW Spectrum









Ground-based GW observatories

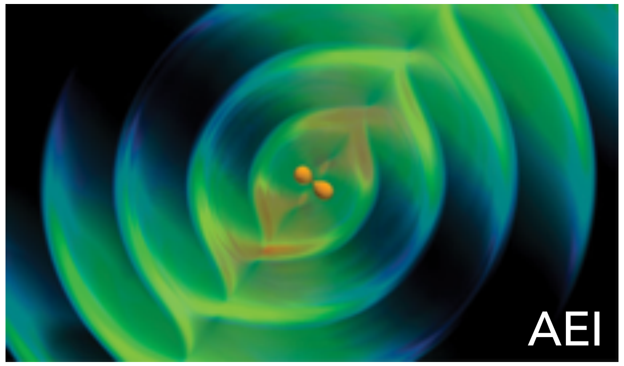
- Interferometric GW observatories
- Operating: LIGO Livingston, LIGO Hanford, Virgo, GEO600
- Under construction: KAGRA (~ 2020)
- Planned: LIGO India

First Observing run (O1):

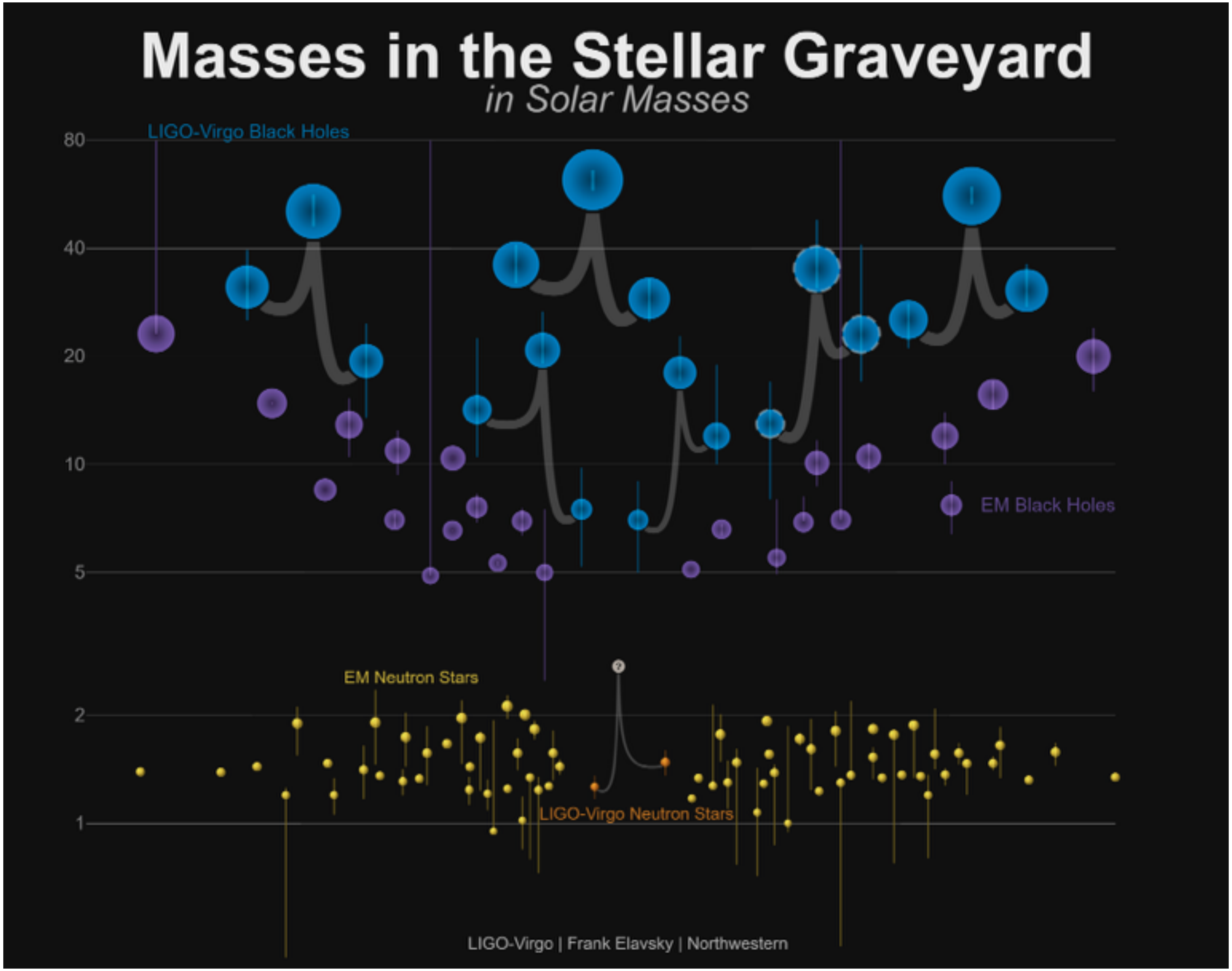
- 12/09/2015 - 19/01/2016
- ~ 49 days of coincident LIGO data
- 2 BBH detections: GW150914, GW151226
- 1 BBH candidate: LVT151012

Second Observing run (O2):

- 30/11/2016 - 25/08/2017
- Virgo joined on August 1st 2017 with a BNS horizon range of ~ 27 Mpc
- ~ 117 days of coincident LIGO data
- ~ 15 days of coincident LIGO-Virgo data
- 3 BBH detections: GW170104, GW170608, GW170814
- 1 BNS detection: GW170817

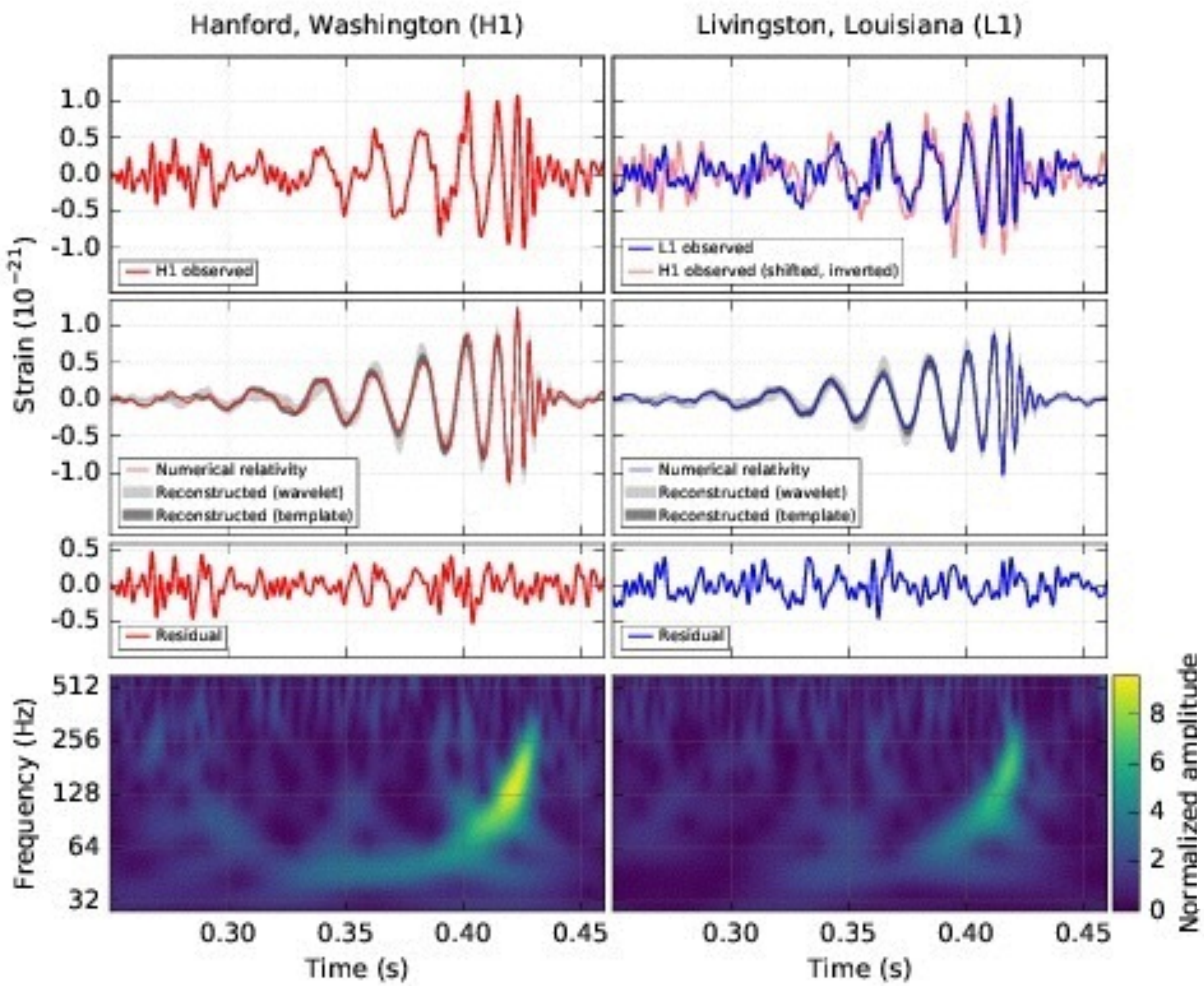


The GW binary zoo

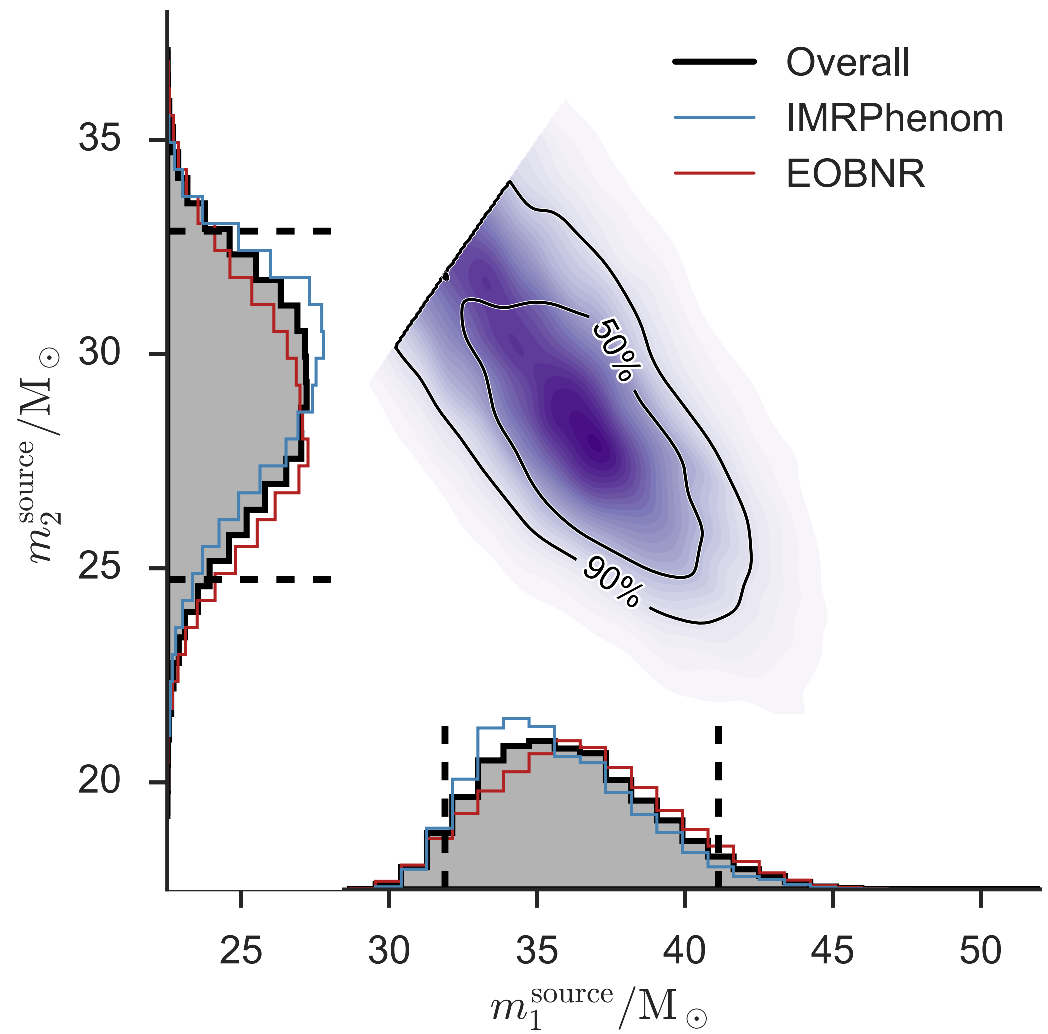


GW150914: The first ever observation of GWs

- On September 14 2015 Advanced LIGO detected the first binary black hole coalescence with a signal-to-noise ratio (SNR) of ~25



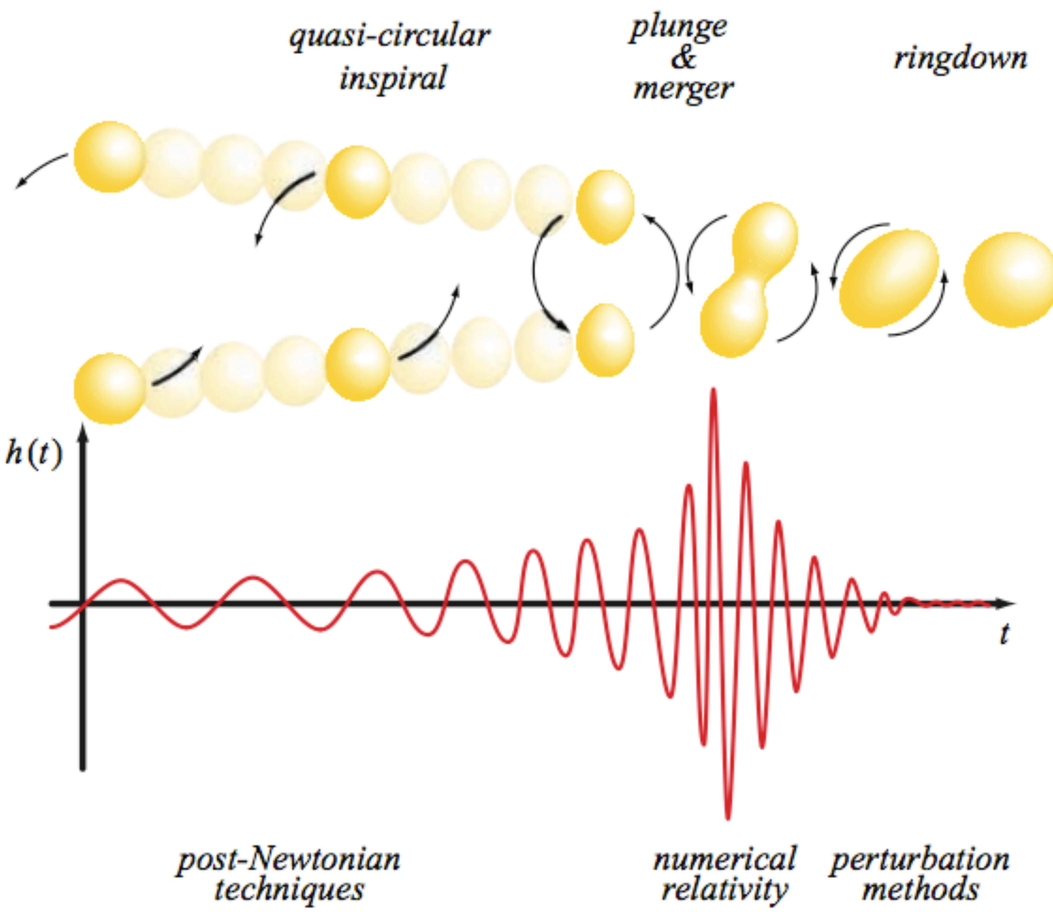
LVC, PRL 116, 061102 (2016)

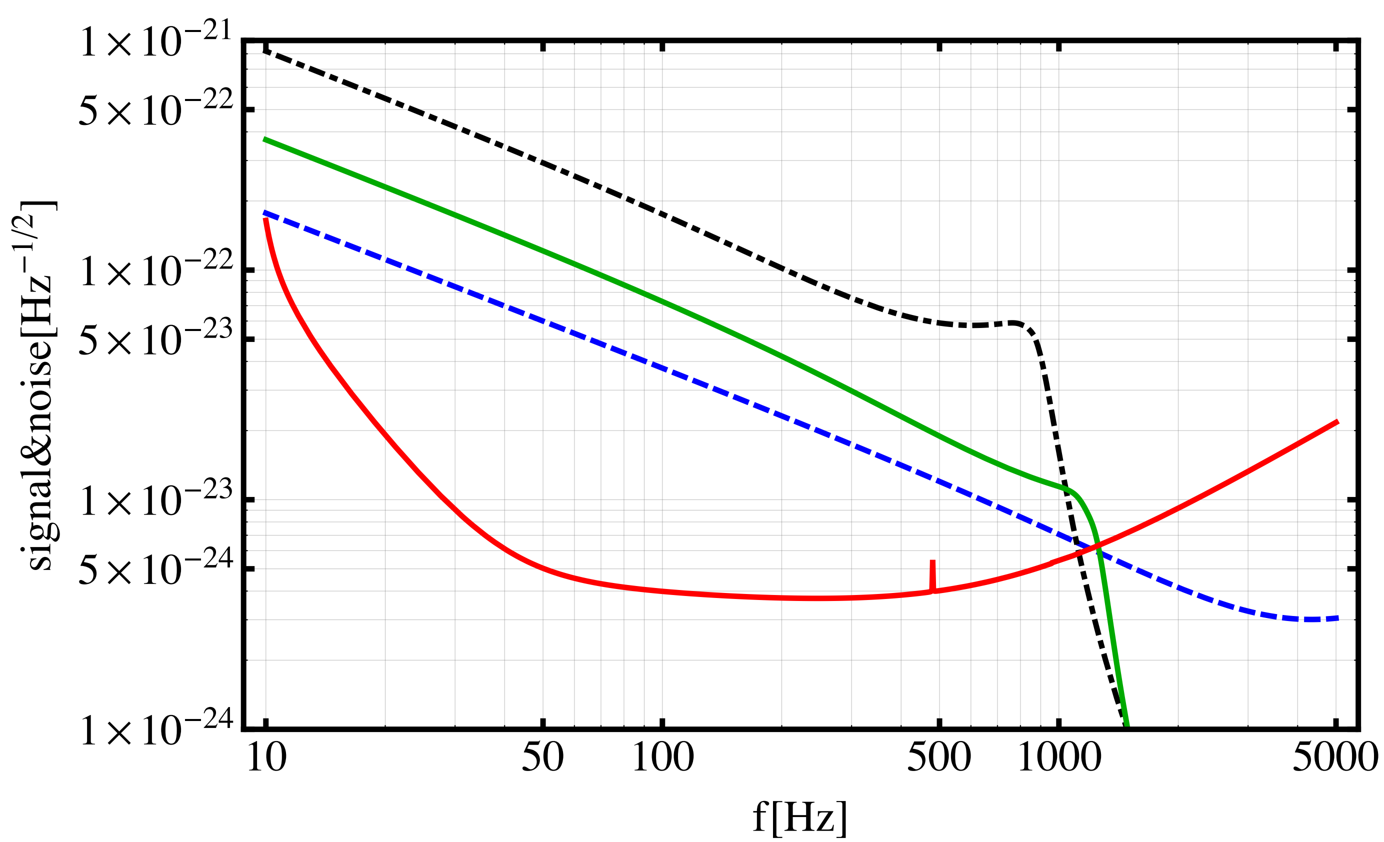


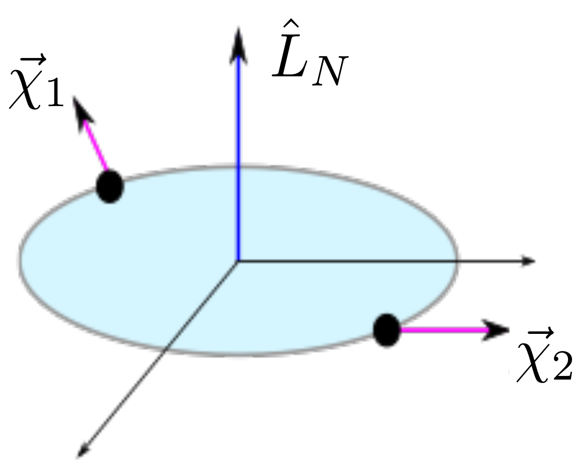
LVC, PRL, 116, 241102 (2016)

Decoding the chirp signal from coalescing binaries

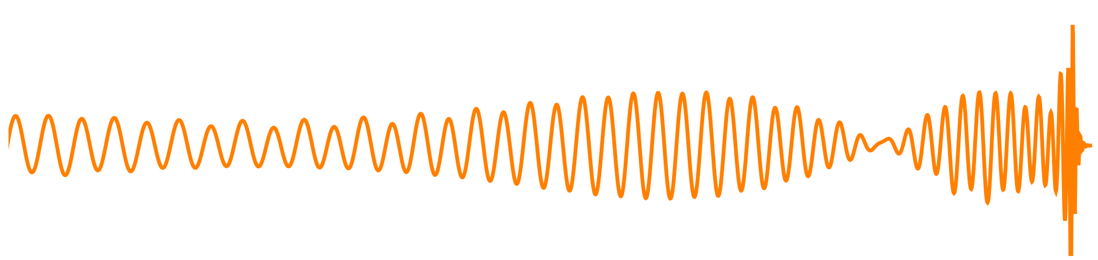
- GWs encode the characteristic properties of the source, e.g. masses and spins







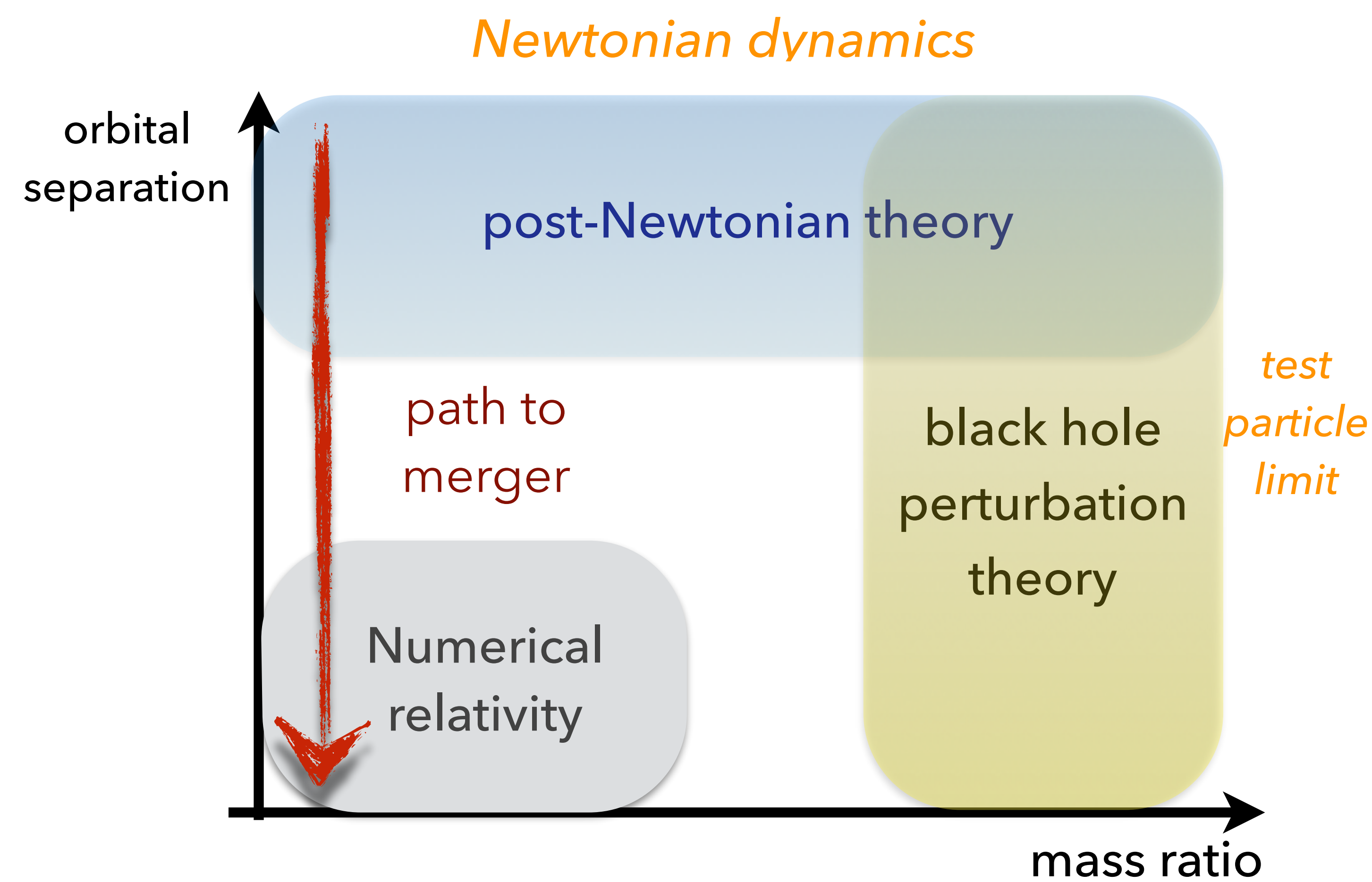
$$\lambda = \{\underbrace{m_1, m_2, \vec{\chi}_1, \vec{\chi}_2}_{intrinsic}, \underbrace{D_L, \theta_{\rm JN}, \iota, \alpha, \delta, \phi_C, t_C, \psi}_{extrinsic}\}$$



precessing spins

Decoding the chirp signal from coalescing binaries

- Decoding requires prior knowledge of the waveform predicted in General Relativity
  - Waveform models of coalescing compact binaries combine analytic approximations with numerical relativity (see e.g. Hannam+, Ajith+, Buonanno+, Pan +, Taracchini+, Khan+)



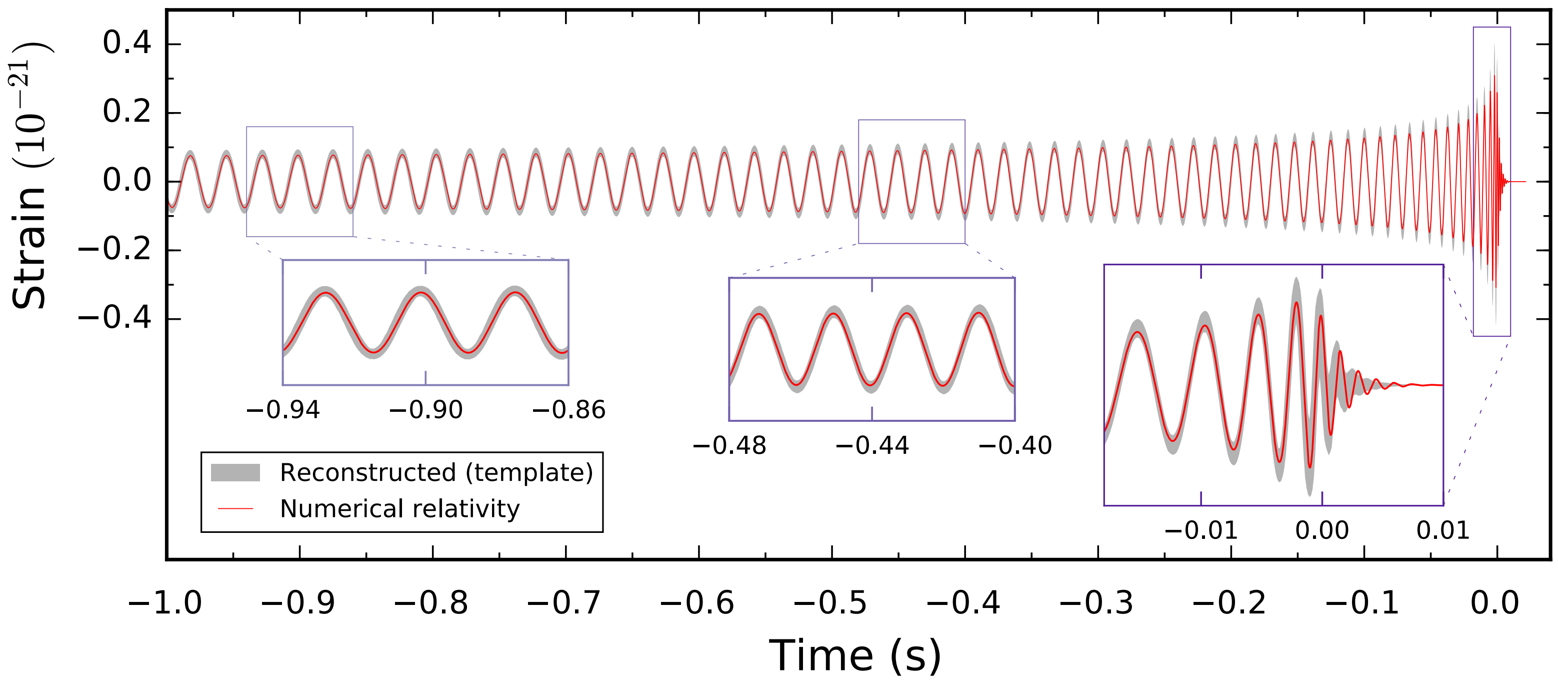
- Low-mass signals (≤ 12 M_{sun}): dominated by the inspiral
  - The best measured parameter is the chirp mass

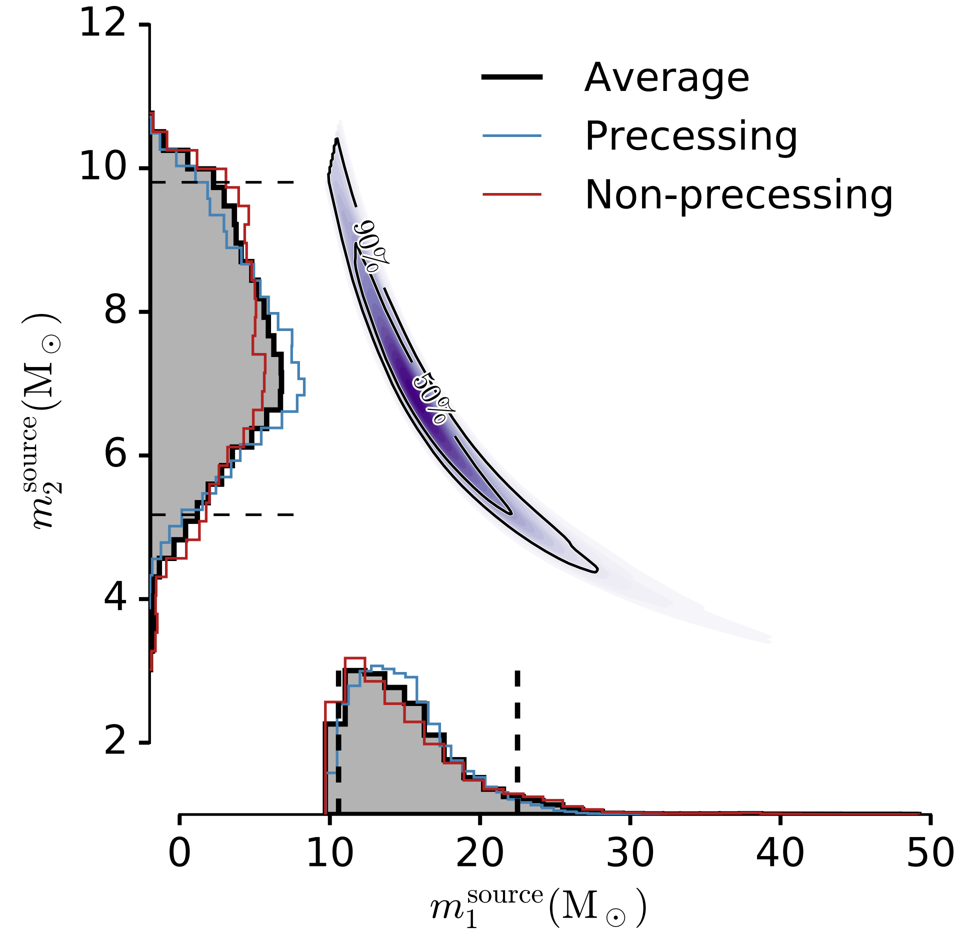
$$\mathcal{M} := \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

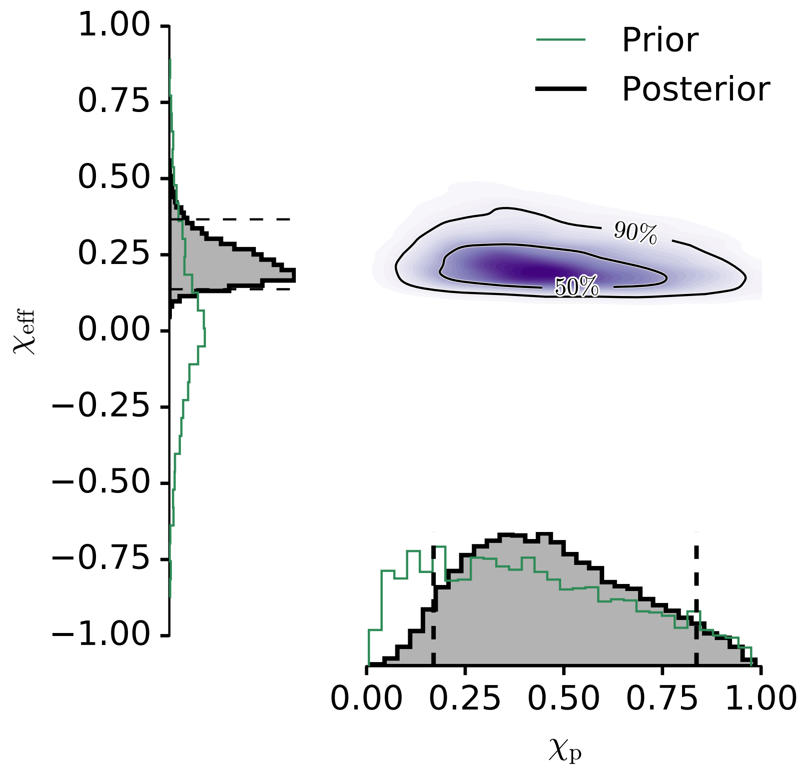
- High-mass signals: inspiral, merger & ringdown are visible
  - Requires numerical solutions of the general relativistic two-body problem
  - Total mass becomes the defining parameter
  - Ringdown: frequency & decay time of quasi-normal modes

GW151226: The first low-mass BBH

- Recorded on December 26th, 2015 at 03:38:53 UTC with an SNR of ~13







$$\chi_{\mathrm{eff}} = \frac{m_1 a_{1,\parallel} + m_2 a_{2,\parallel}}{m_1 + m_2}$$

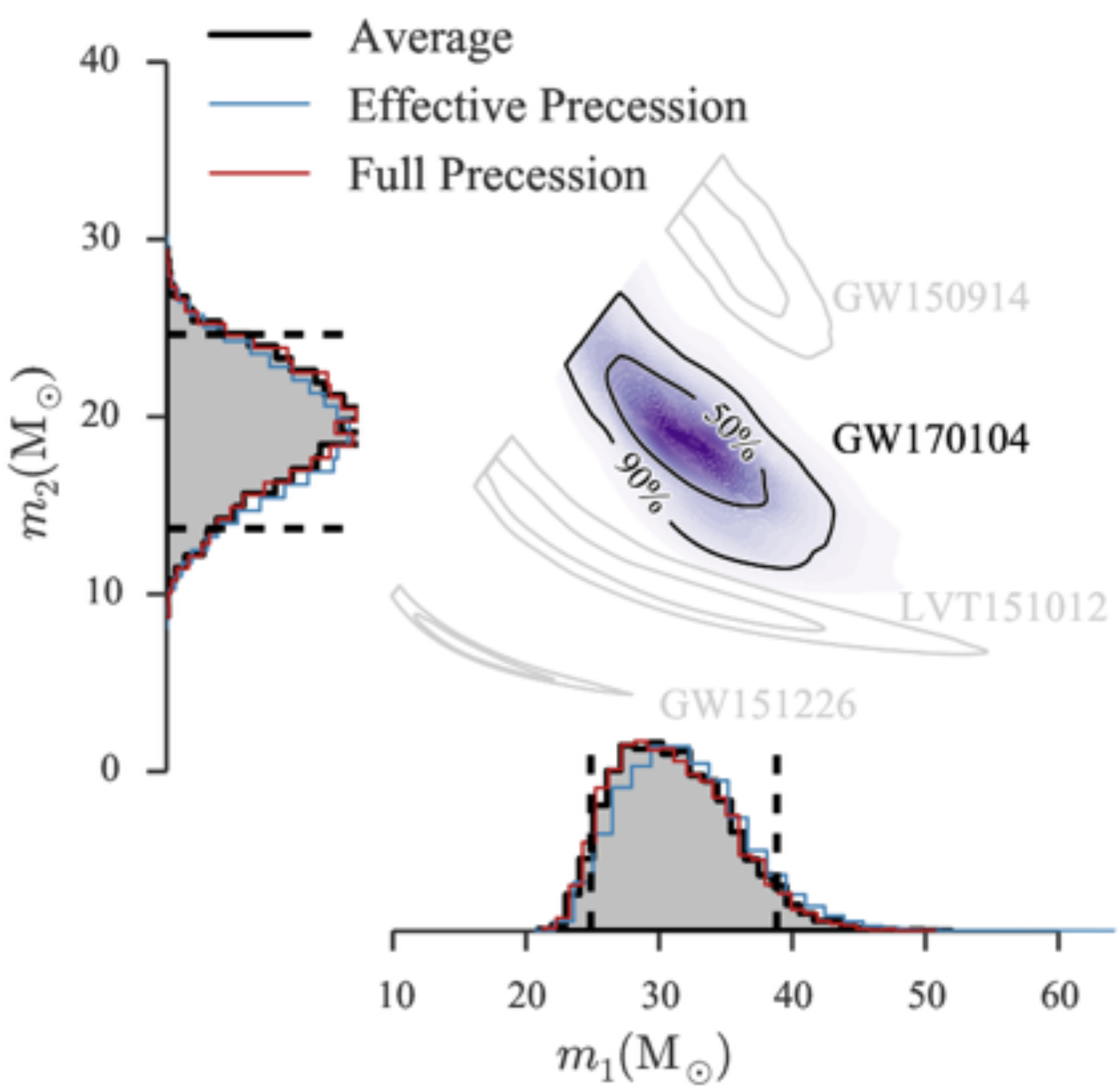
~ spins parallel to L set inspiral rate [Racine08]

$$\chi_{\mathrm{p}} \sim (a_{1,\perp}, a_{2,\perp})$$

~ spins orthogonal to L drive the precession [Schmidt+14]

Phys. Rev. Lett. 116, 241103 (2016)

- On **January 4th 2017** at 10:11:58 UTC Advanced LIGO recorded the GW of another high mass BBH with an SNR of ~13



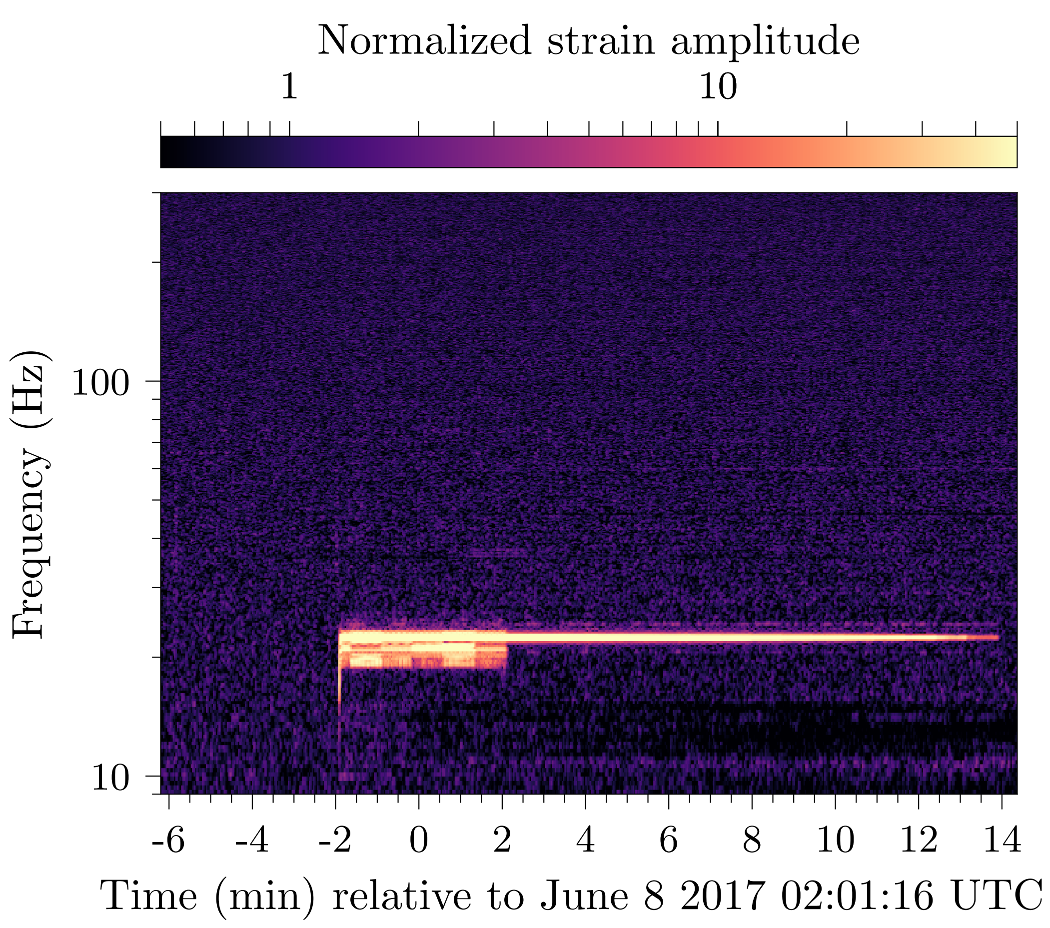
Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy $E_{\rm rad}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.1^{+0.7}_{-1.3} \times 10^{56} {\rm erg\ s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

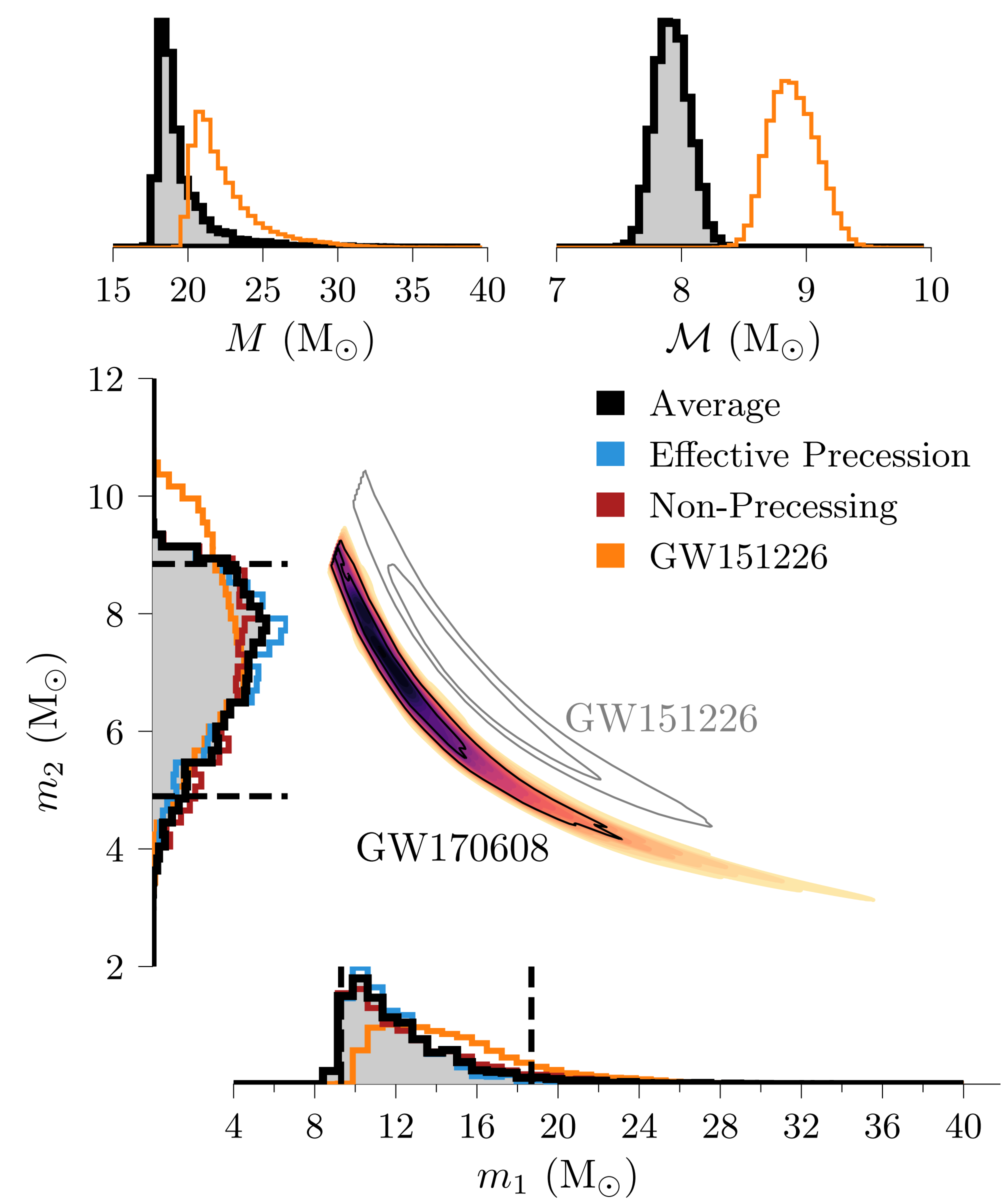
disfavours large positive spins

Phys. Rev. Lett. 118, 221101, (2017)

GW170608: The (almost) elusive low mass BBH

- On June 8 2017 Advanced LIGO detected its lightest black hole binary yet (SNR~)
- Single detector trigger in L1
- H1 was not in observing mode due to beam re-centering procedure

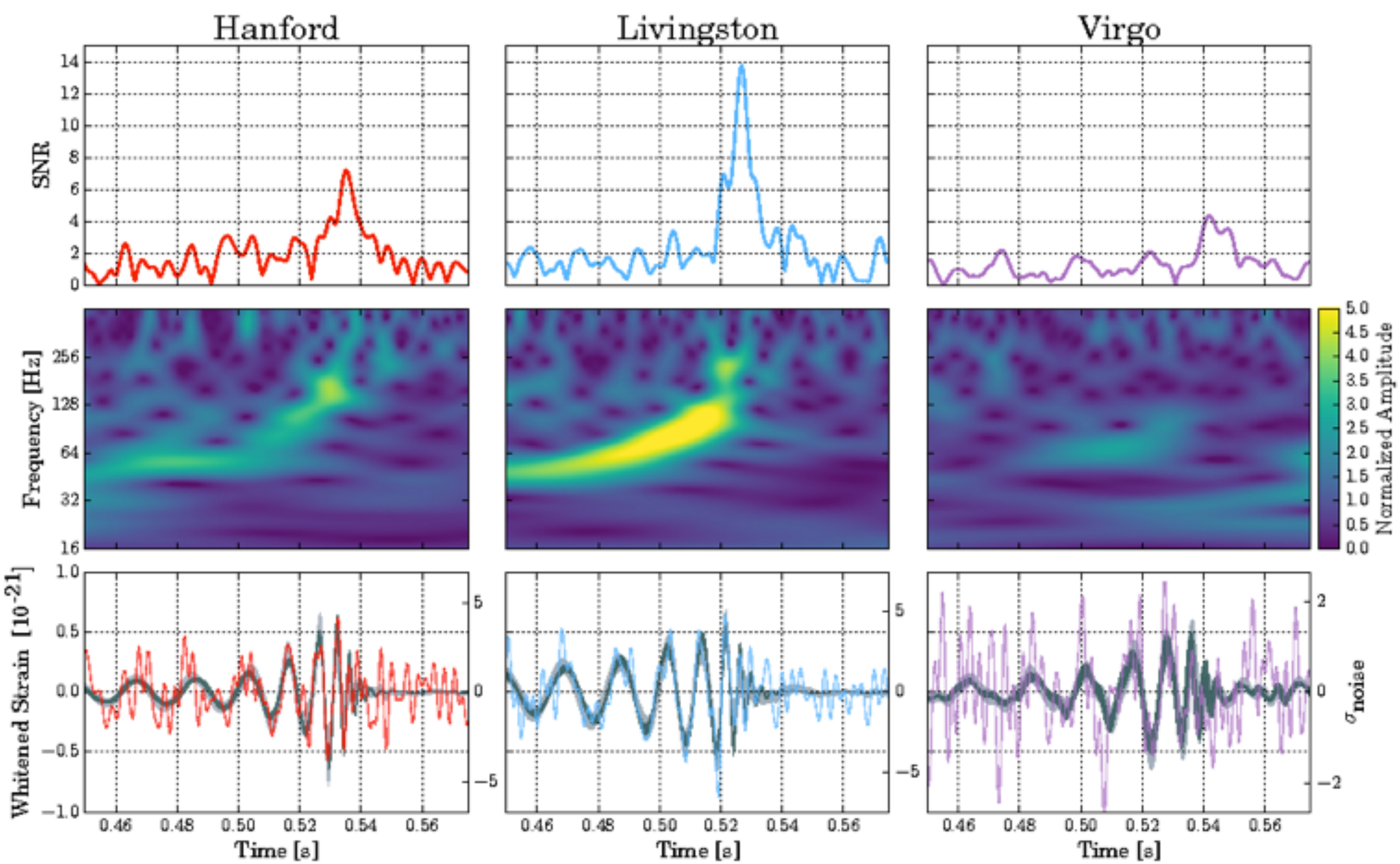




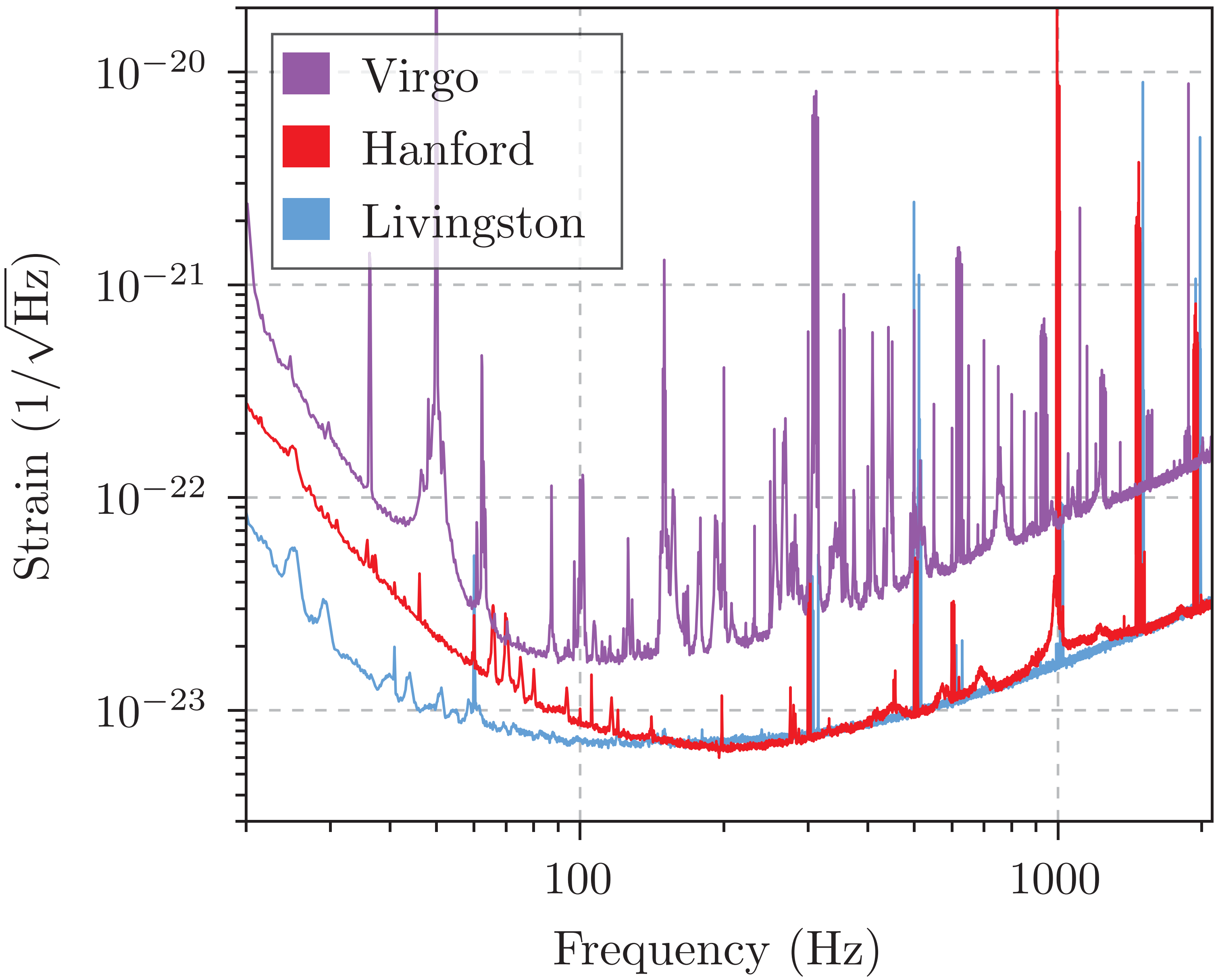
Astrophys. J. Lett. 851, L35

GW170814: The first HLV binary aka „the triple“

- On **August 14th 2017** at 10:30:43 UTC Advanced LIGO and Advanced Virgo coincidentally detected the signal of a high mass binary black hole coalescence



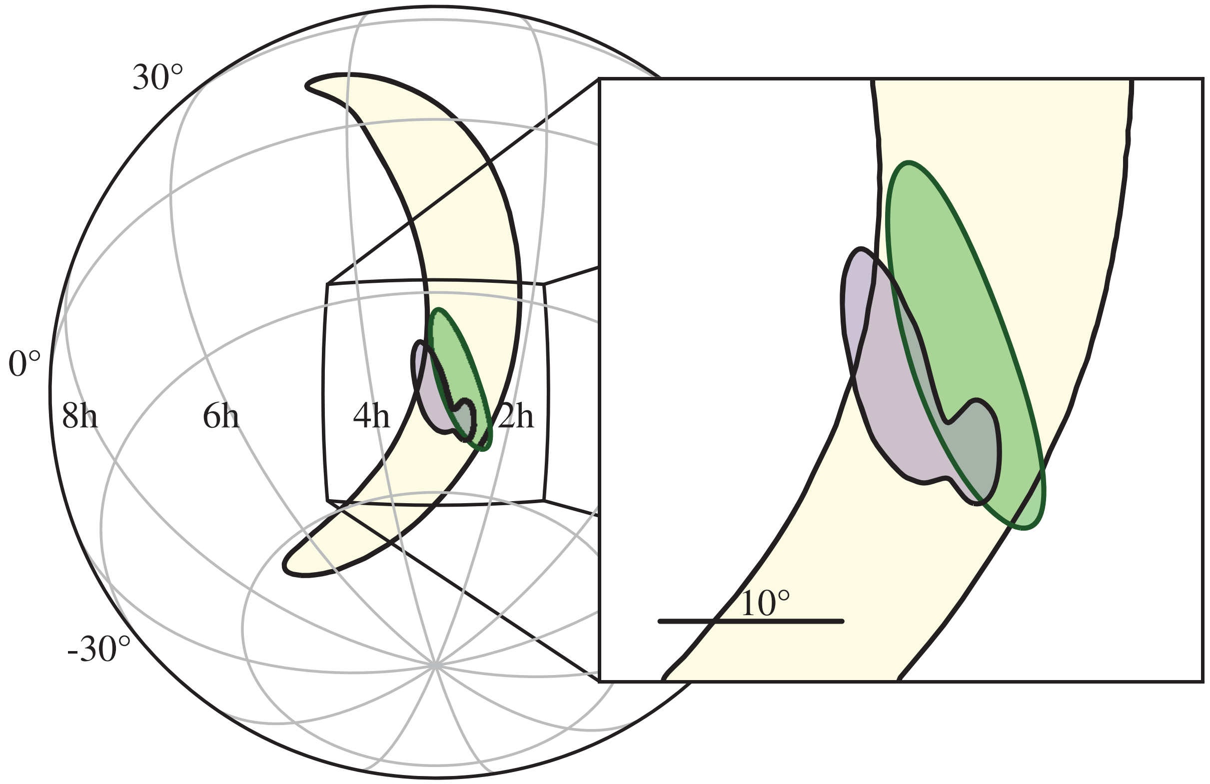
PRL, 119, 141101 (2017)



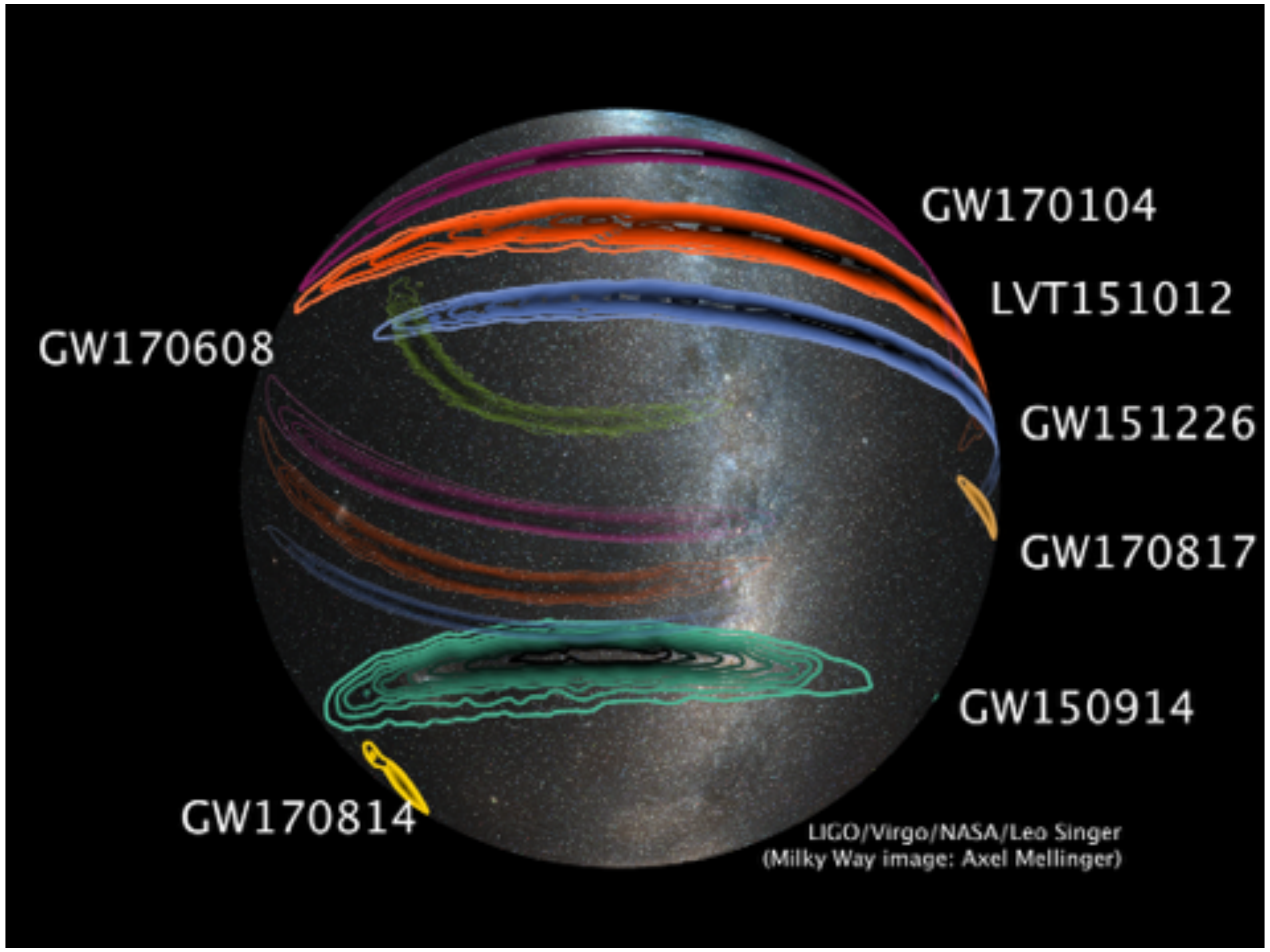
PRL, 119, 141101 (2017)

GW170814: The Triple

- 3-detector network SNR ~18
- The addition of Advanced Virgo allows for much tighter sky localisation
    - 1160 deg^2 to ~60 deg^2

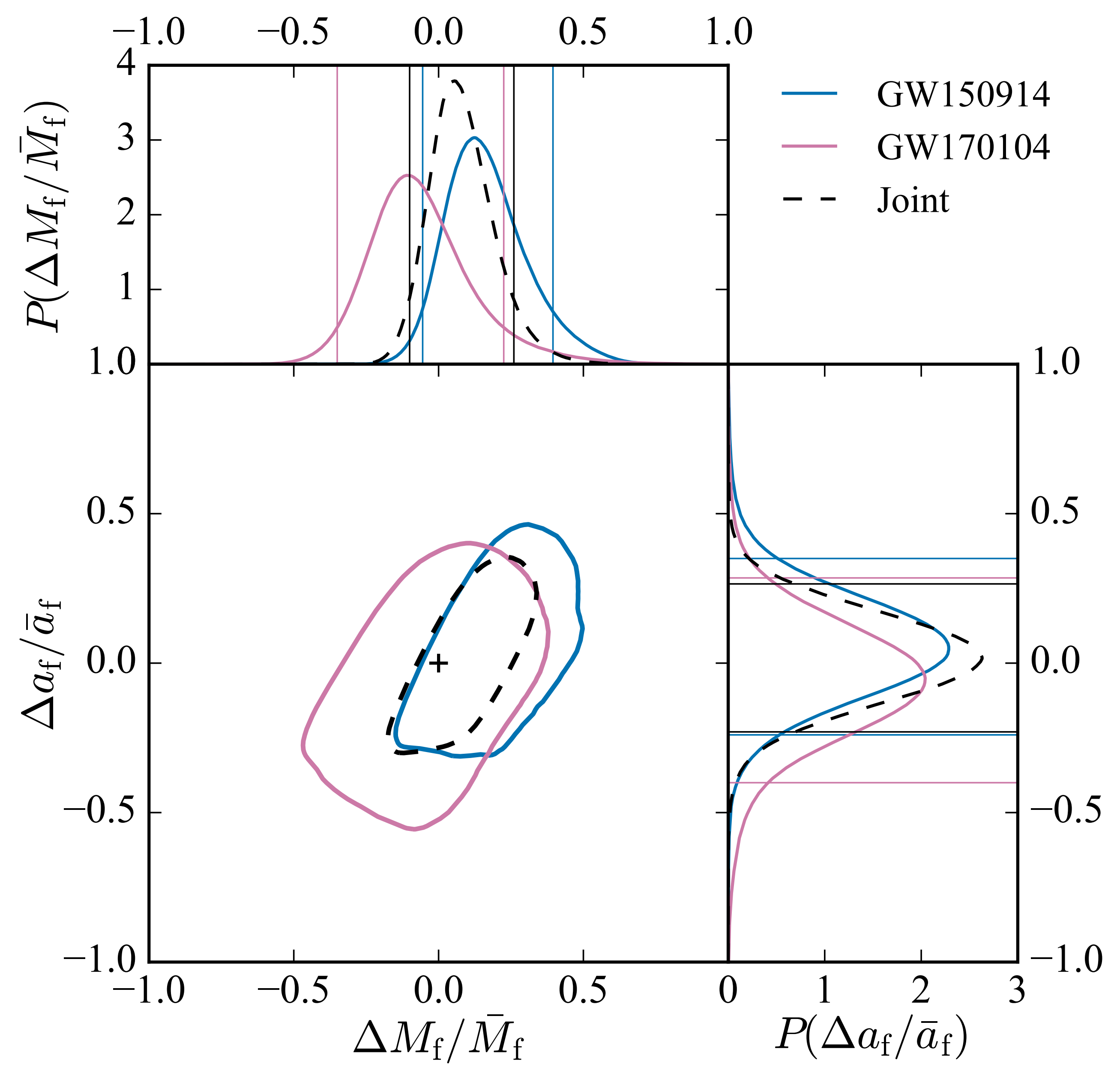


PRL, 119, 141101 (2017)



Tests of General Relativity with BBH

- Inspiral-merger-ringdown (IMR) consistency test
- Is the final state as predicted from GR?
- Infer final mass and spin from inspiral and merger-ringdown separately
- Null test of GR
- So far everything is highly consistent with estimates from binary black holes as predicted in GR



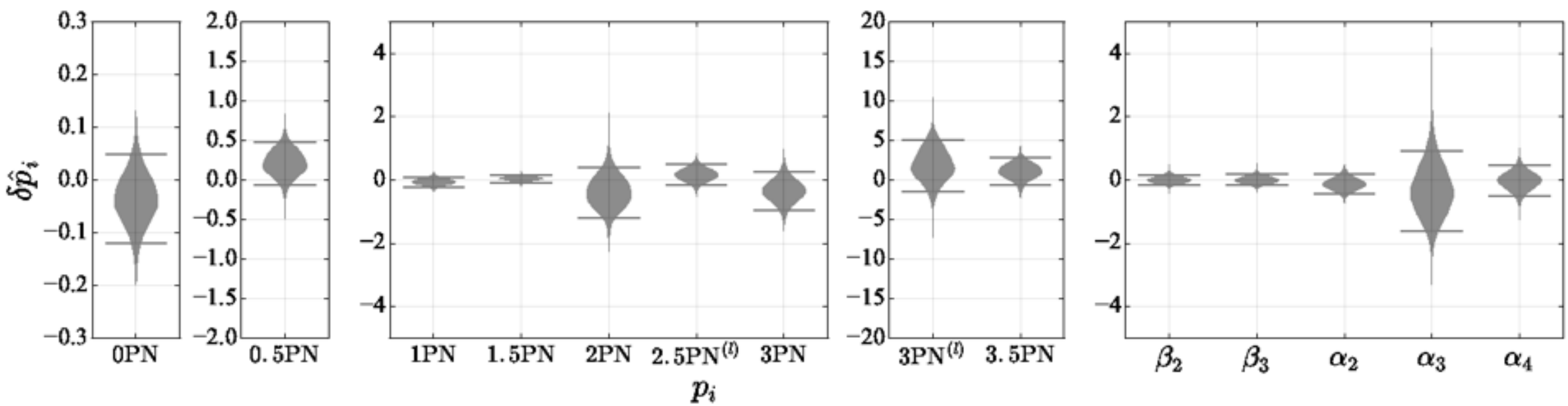
Phys. Rev. Lett. 118, 221101, (2017): Supplementary Material

Tests of General Relativity with BBH

- Parameterised tests of General Relativity
    - Employs modifications to the GR phase: $p_i \rightarrow p_i(1 + \delta\hat{p}_i)$

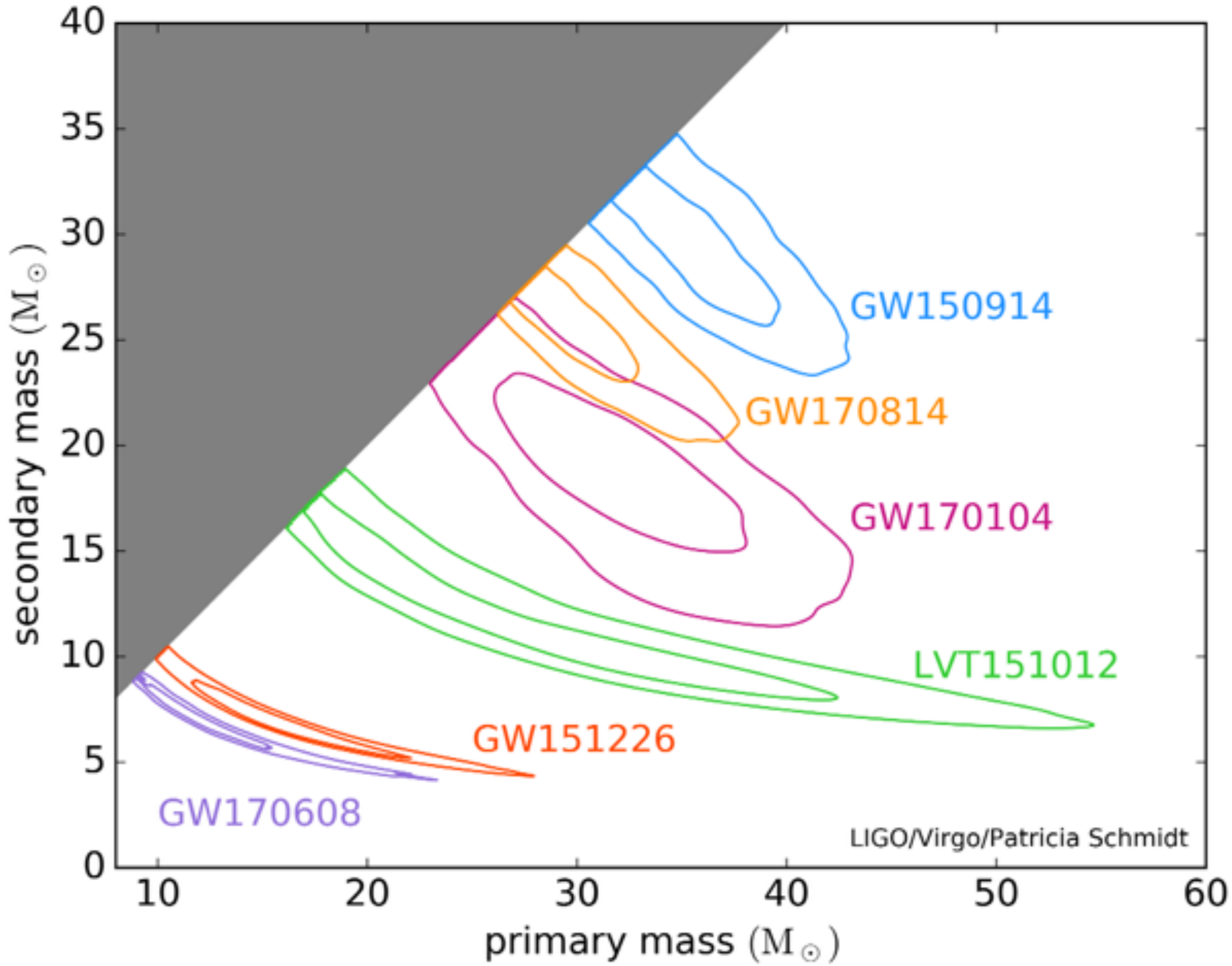
$$\psi_{\rm insp}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4}\sum_{i=0}^{7}[p_i + p_i^{(l)} \ln f] f^{(j-5)/3}$$

- Combined results (GW150914 , GW151226, GW170104) show consistency with General Relativity



Phys. Rev. Lett. 118, 221101, (2017): Supplementary Material

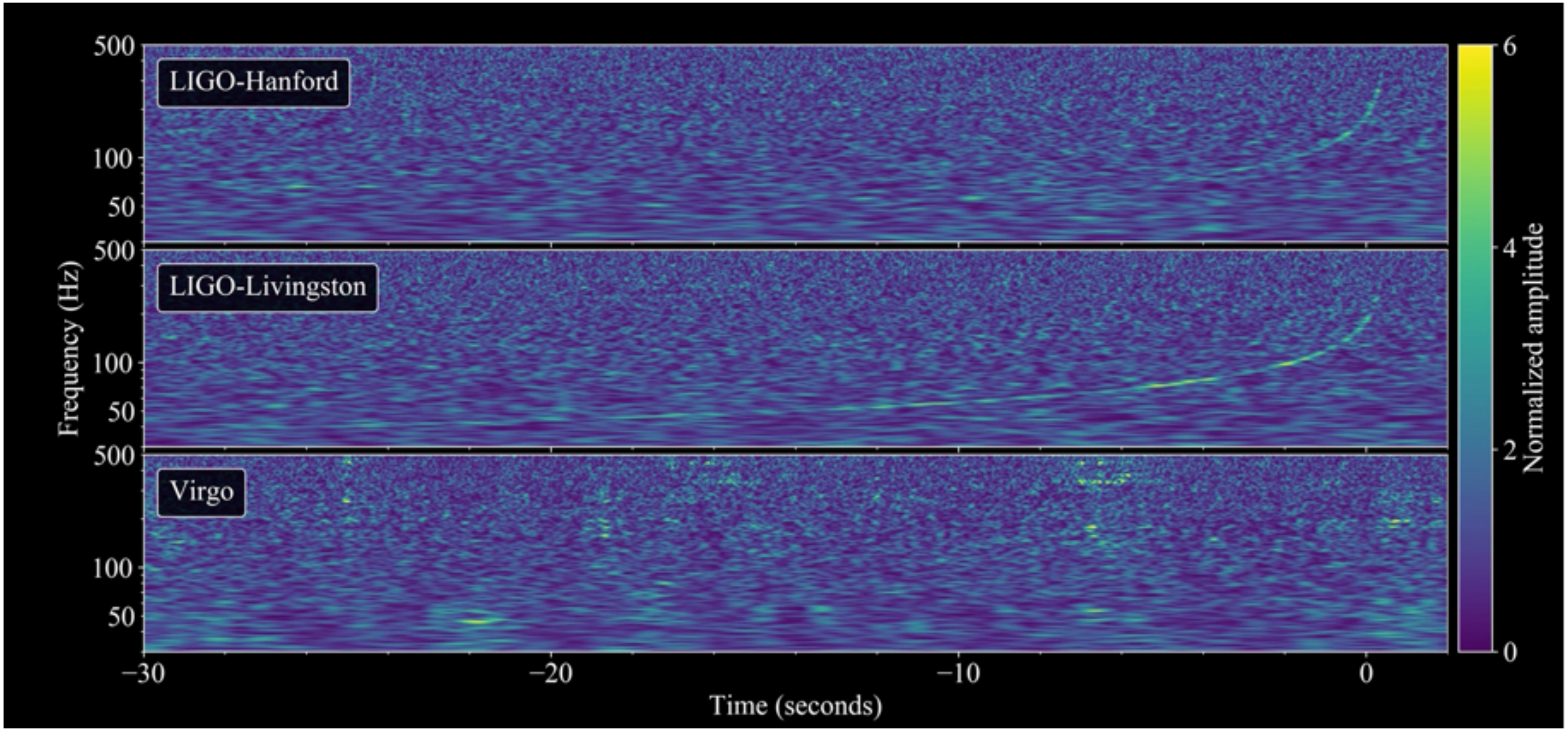
LIGO's & Virgo's BBH



- Two distinct populations?
  - Different environments
- Spin constraints are very wide
  - Could help distinguish formation channels
  - Individual spins are difficult to measure
- More statistics needed!

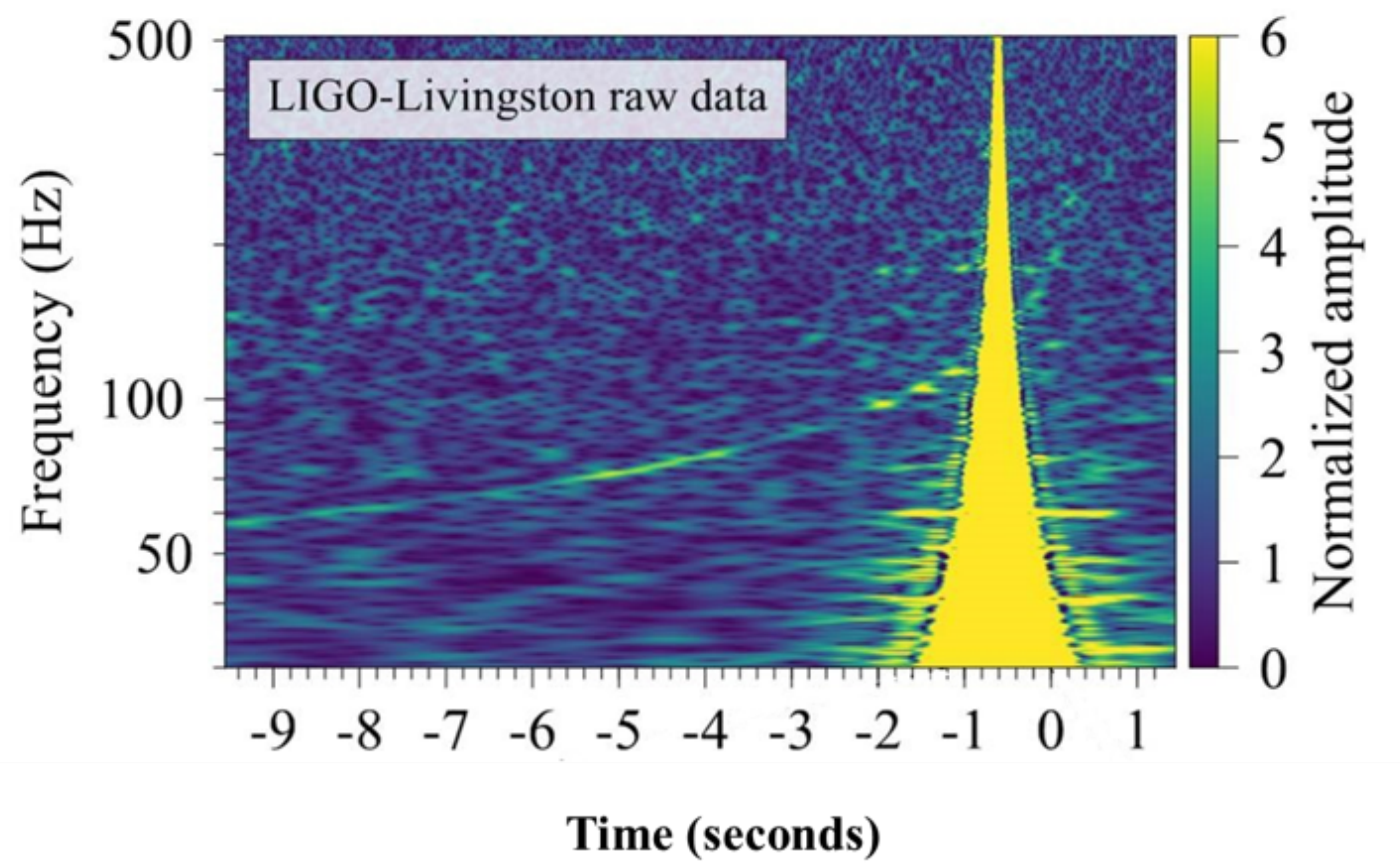
GW170817: A binary neutron star inspiral

- On August 17 2017 at 12:41:04 UTC the signal from a binary neutron star was detected by LIGO & Virgo



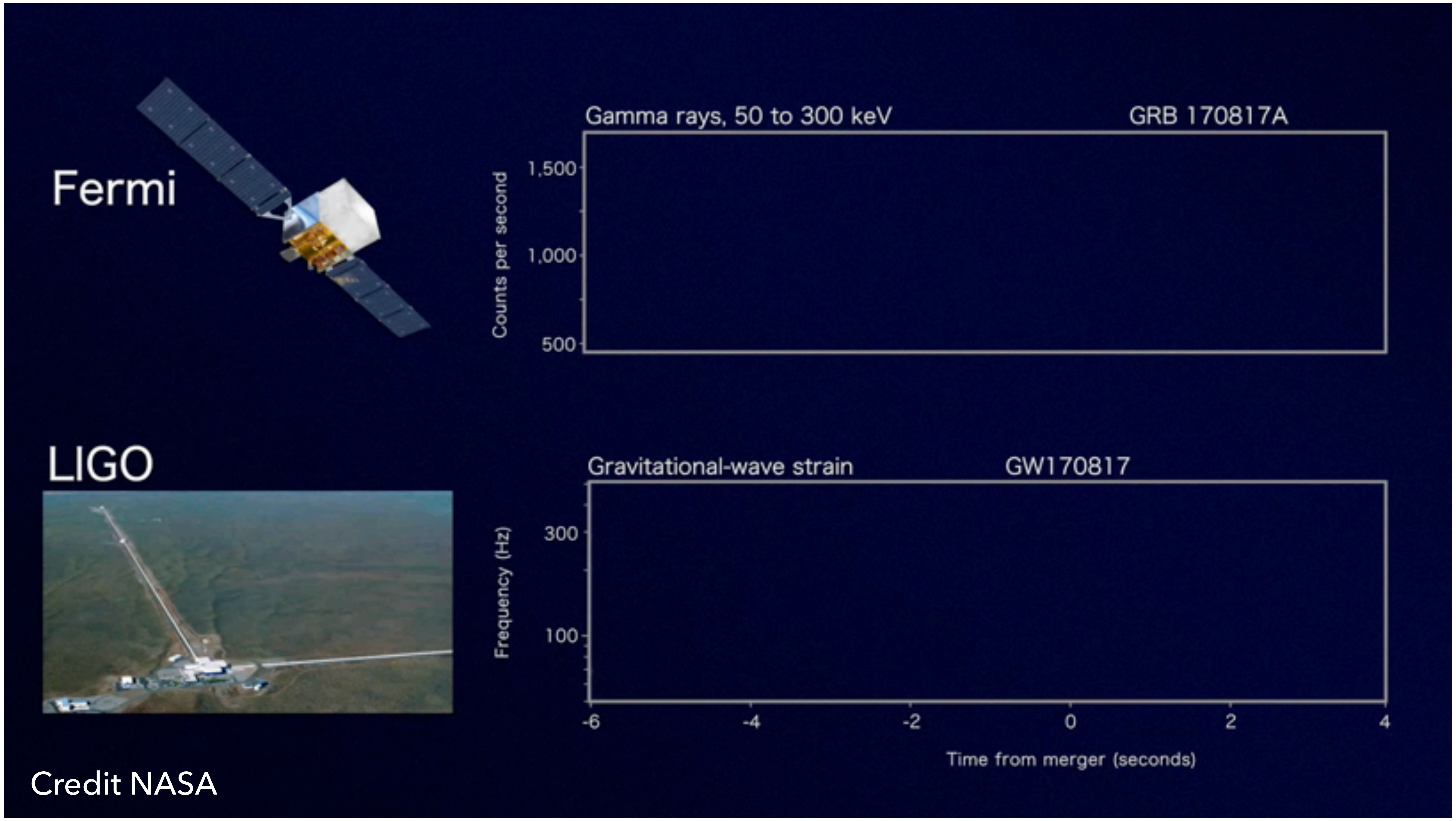
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
PRL., 119, 161101 (2017)

- Glitch in LIGO Livingston
  - Prevents automatic triggering
  - Manual removal of glitch necessary



GW170817: A binary neutron star inspiral

- 1.7s after the GW signal a GRB was observed by Fermi
- A dedicated follow-up campaign identified the EM counterpart



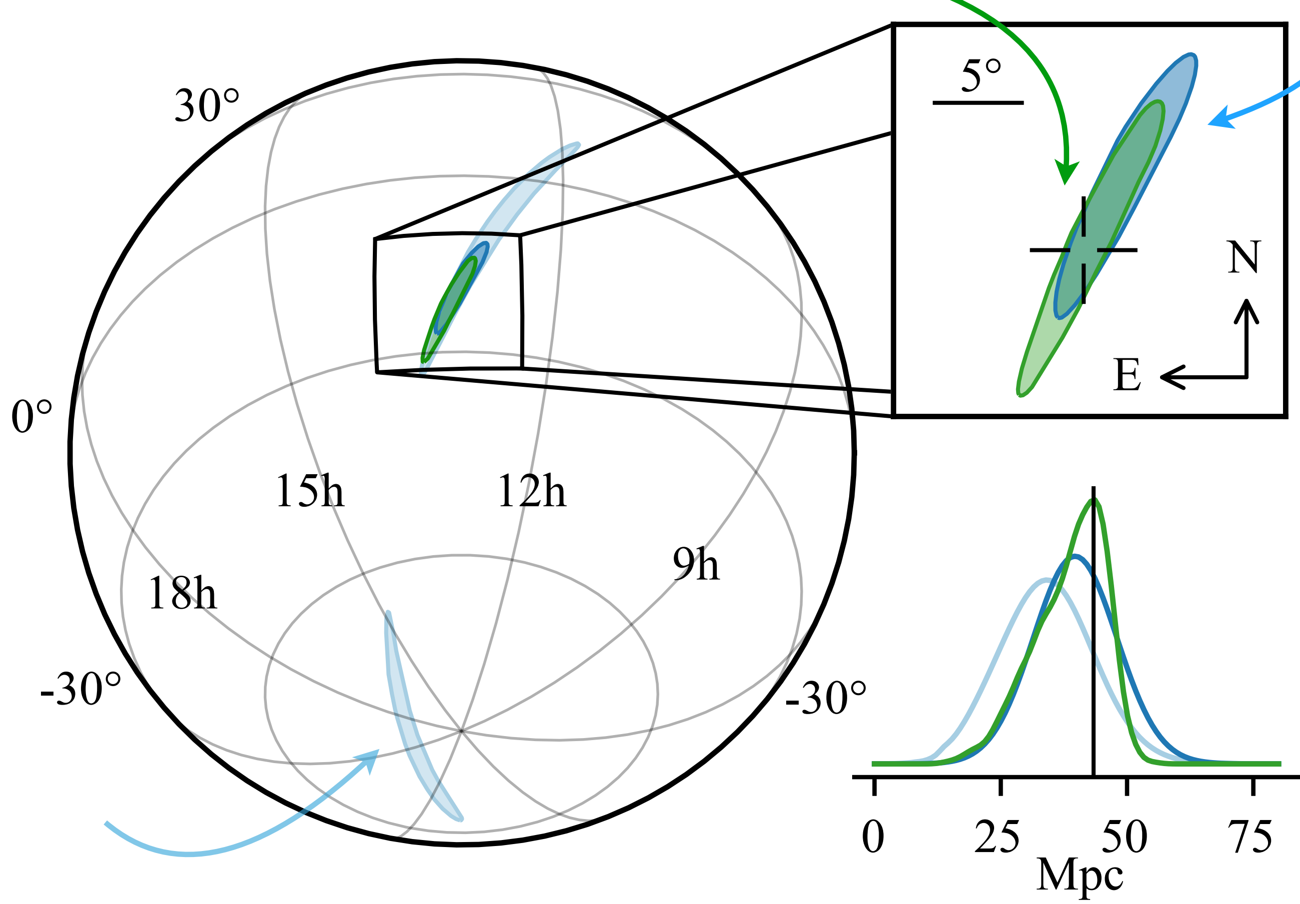
Coincident GW + EM observation

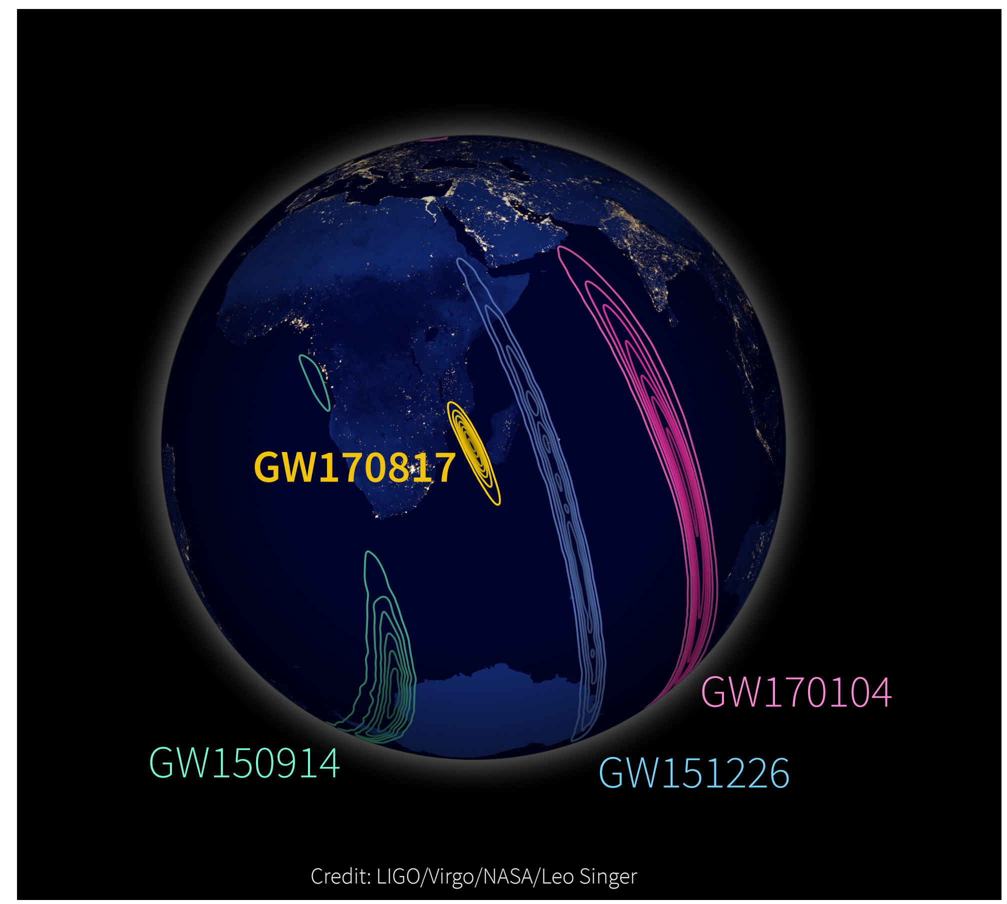
GW170817: A binary neutron star inspiral

- Network SNR: 32.4 - Loudest signal seen by Advanced LIGO & Virgo
- Duration of signal ~ 100s making it the longest signal to date
- False alarm rate in 5.9 days of data is < than 1 per 8 x 10^4 years - highly significant event!

High latency follow up: 28 deg^2 ,380 Mpc^3

Rapid localisation with LIGO + Virgo: 31 deg^2





Rapid localisation with LIGO: 190 deg^2

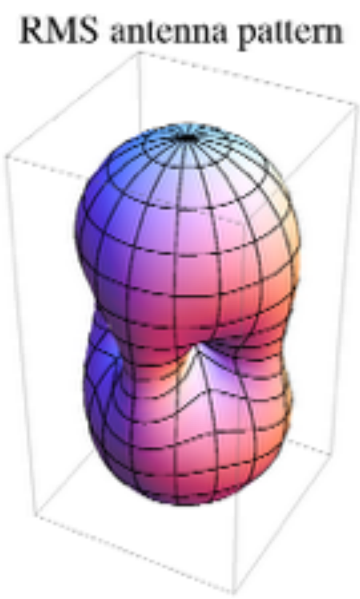
Luminosity distance: ~40Mpc

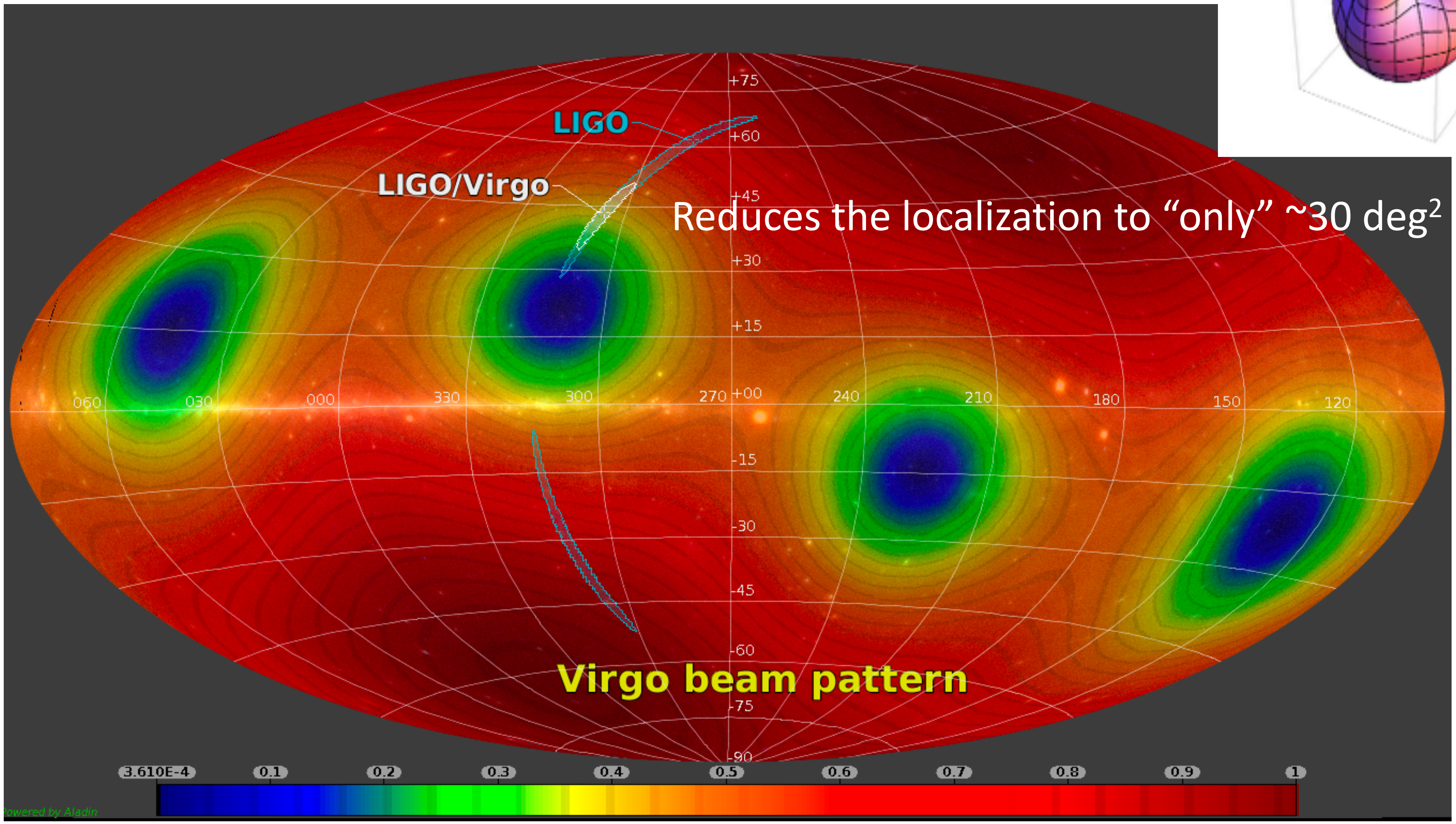
closest GW

best localised GW

GW170817: A binary neutron star inspiral

- GW170817 lies in Virgo's „blind spot" which is crucial for the sky localisation





GW170817: Sky localisation

GW170817: Source properties

- Best measured combination of masses is the chirp mass: $\mathcal{M} := \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

$$\mathcal{M}_c^{\rm det} = 1.1977^{+0.0008}_{-0.0003}\ M_\odot$$

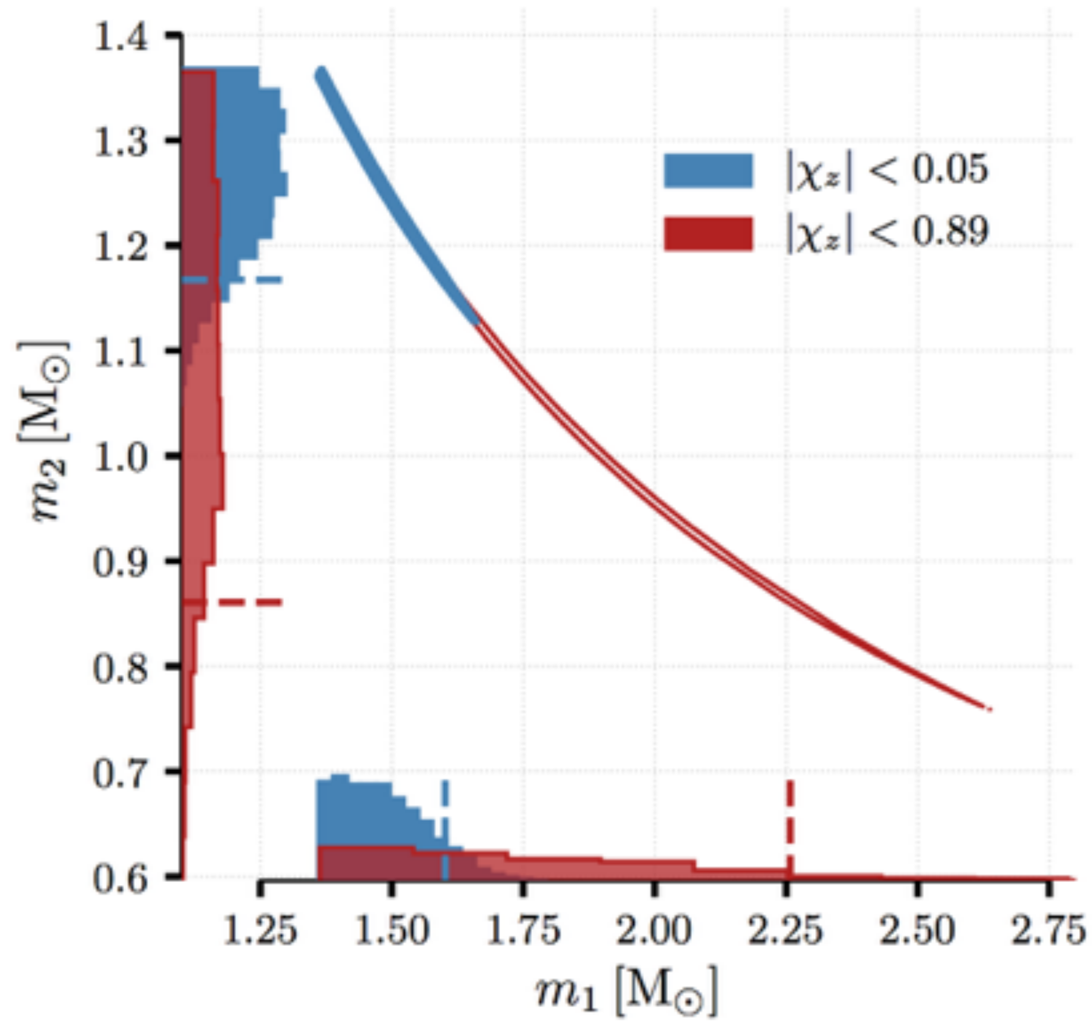
- The total mass:

$$2.73 < M_{\rm Total} < 3.29\ \mathrm{M}_\odot$$

- Constraints on component masses :

$$0.86 < m_i < 2.26\ \mathrm{M}_\odot$$

  - Known NS total masses: $2.57 - 2.88\,\mathrm{M}_\odot$



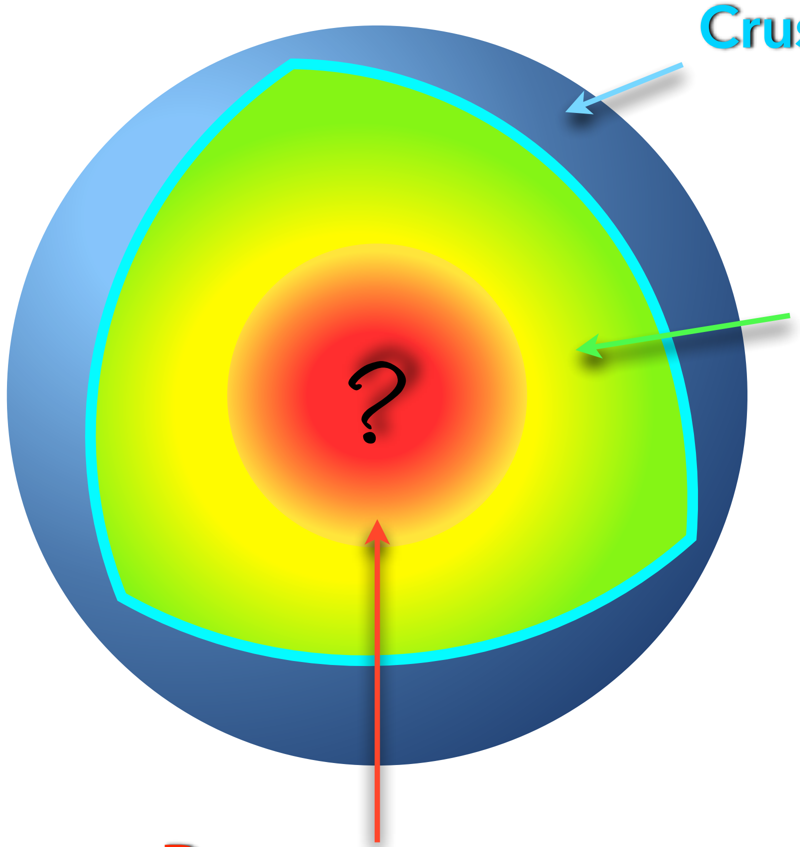
- Luminosity distance:

$$D_L = 40^{+8}_{-14}\ \mathrm{Mpc}$$

- Distance correlated with inclination angle: face-off

$$\cos\theta_{JN} = \hat{\mathbf{J}}\cdot\hat{\mathbf{N}} \leq -0.54$$

GW170817: Probing matter at its extreme



Crust:

neutron rich ions, free neutrons

Outer core:

Uniform liquid (mostly neutrons)

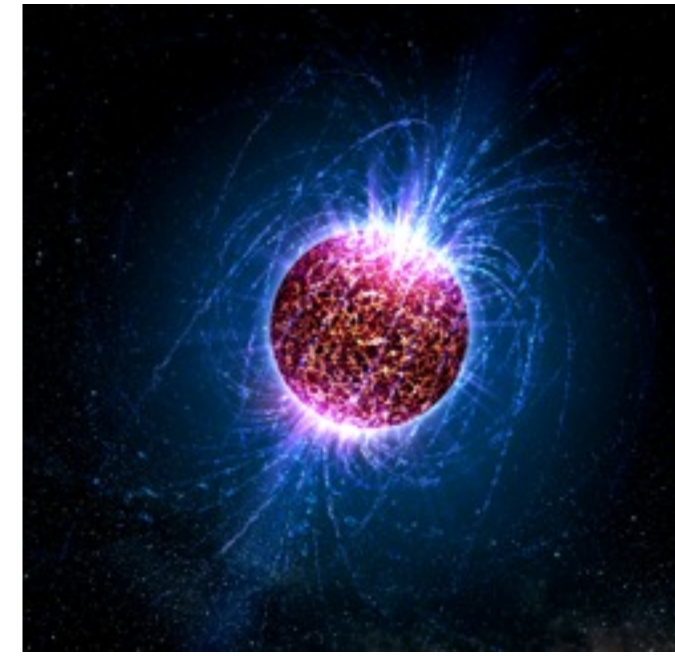
Deep core

density~2-10x nuclear density

Exotic states of matter?

Deconfined quarks?

Condensates?

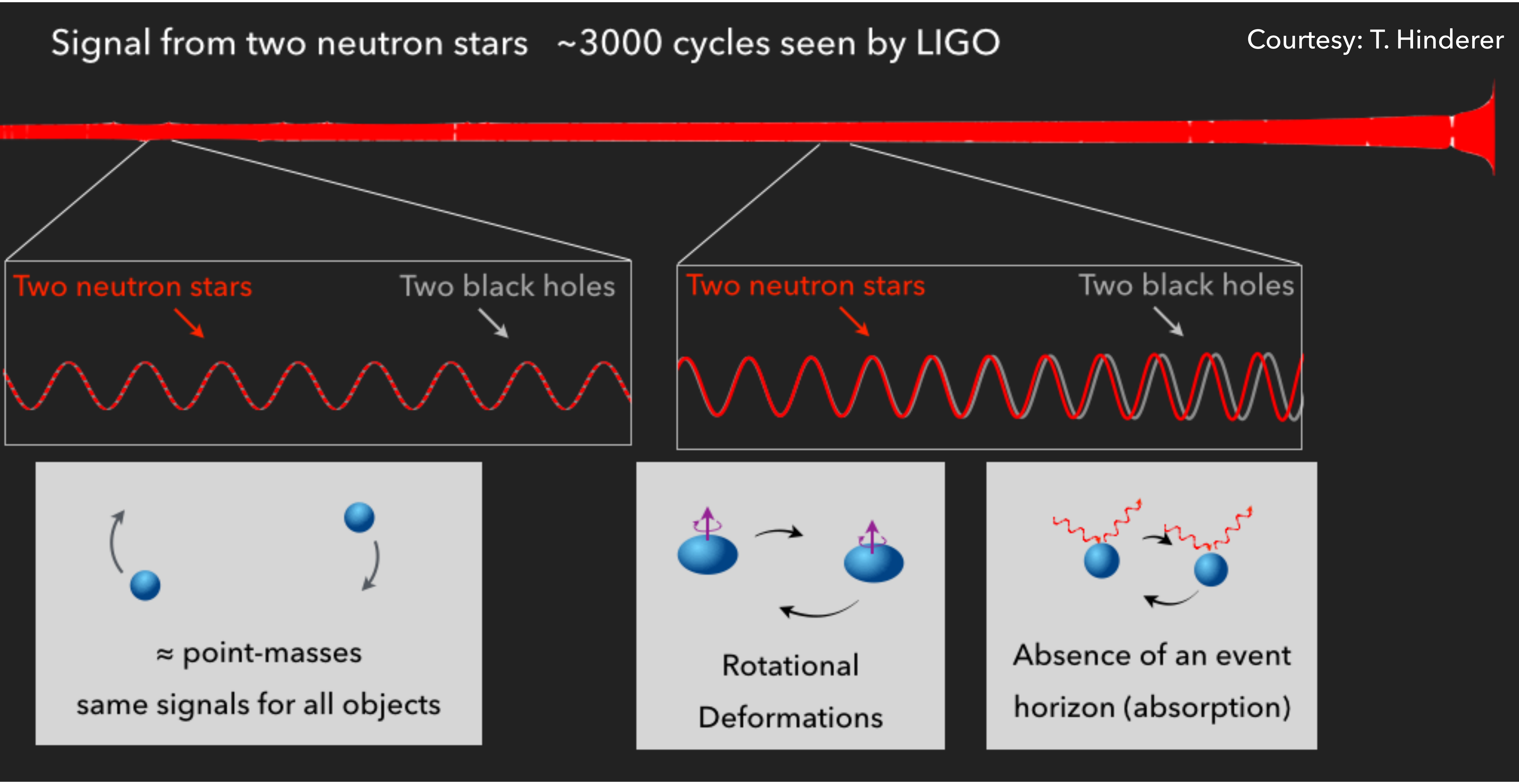


- NS are laboratories of extreme matter
- Properties of dense matter can be mapped to properties of the neutron star

Nuclear equation of state (EOS) ⟷ mass-radius relation, maximal mass, tidal deformability

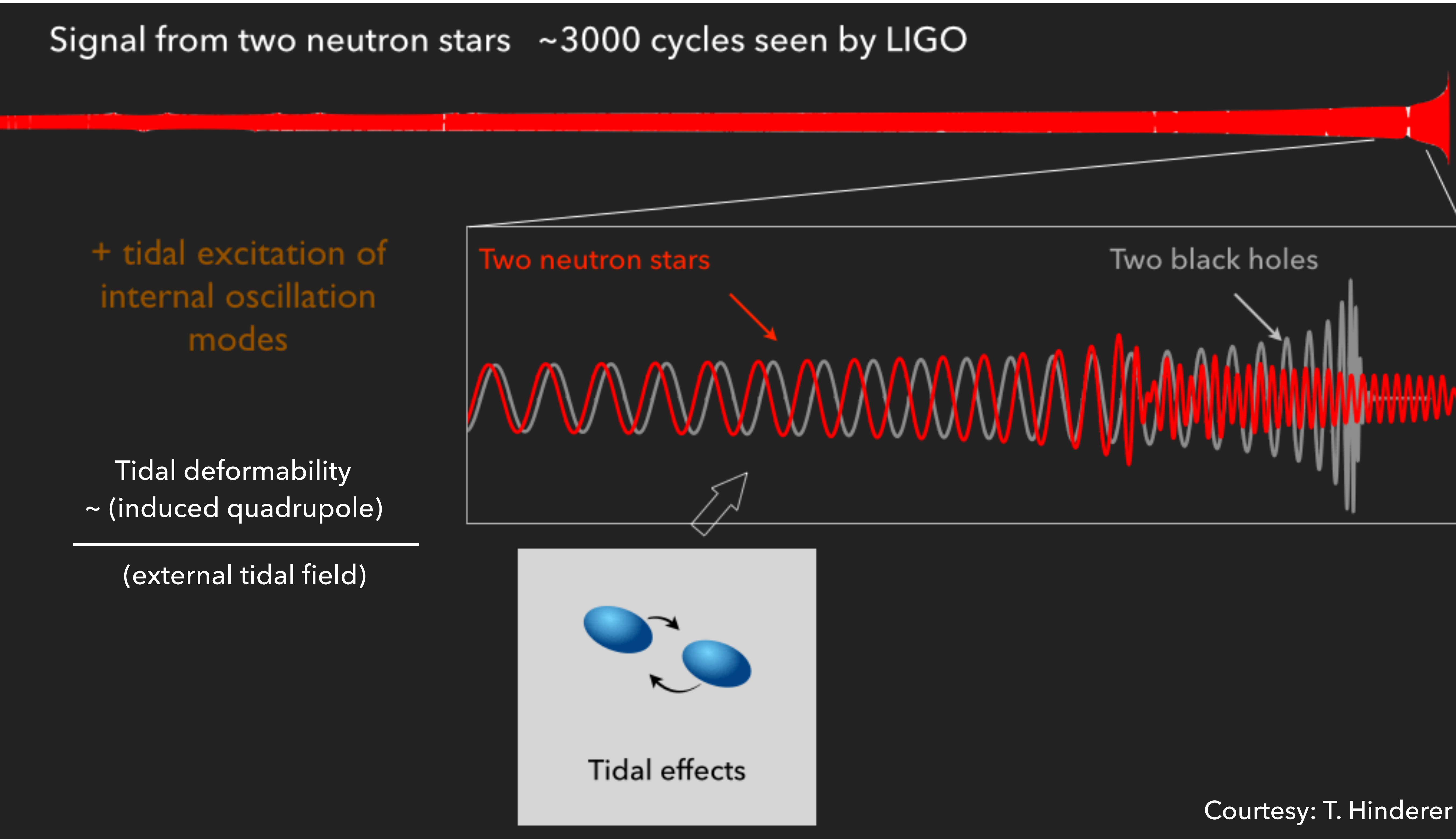
GW170817: Tides

- Internal structure of neutron star becomes important as orbital separation shrinks
- Tidal field of companion induces a mass-quadrupole moment



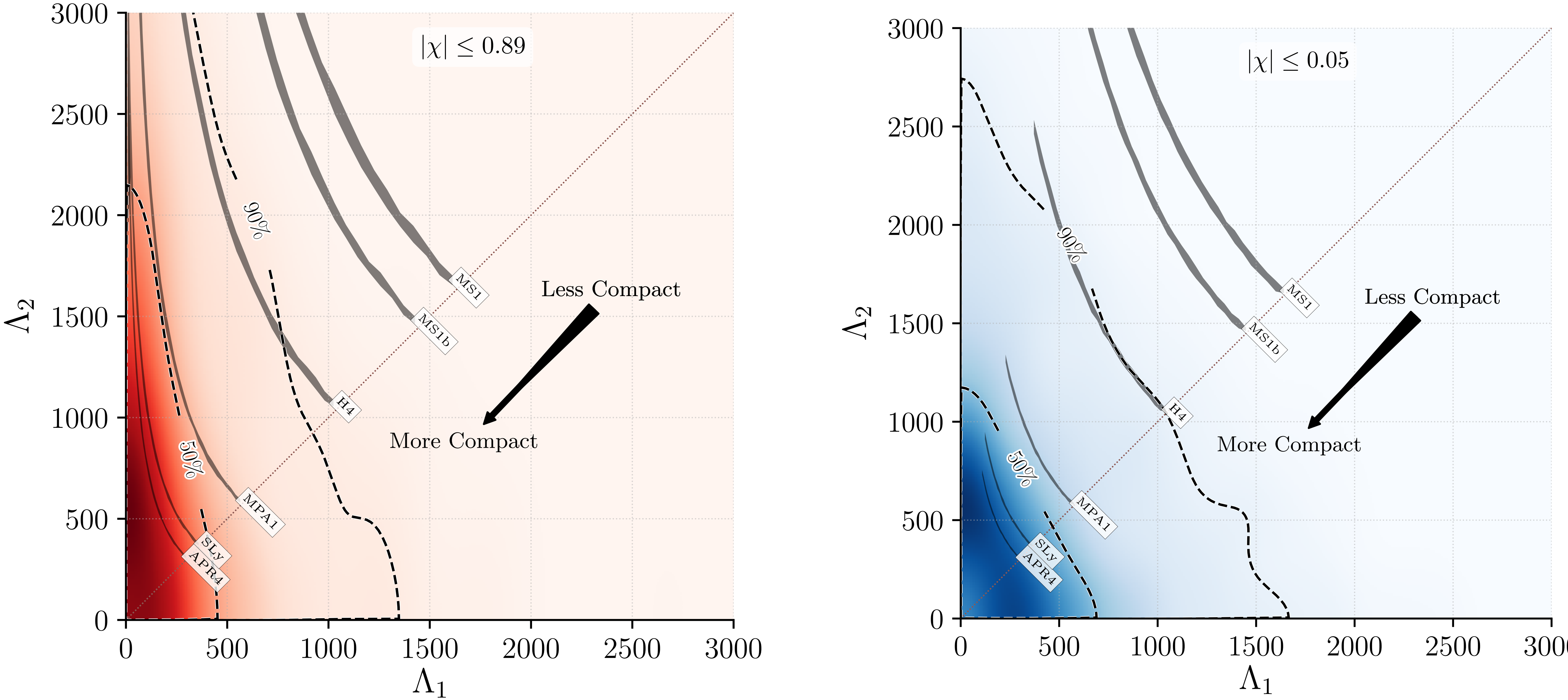
GW170817: Tides

- Expect tidal effects to become significant above ~600Hz



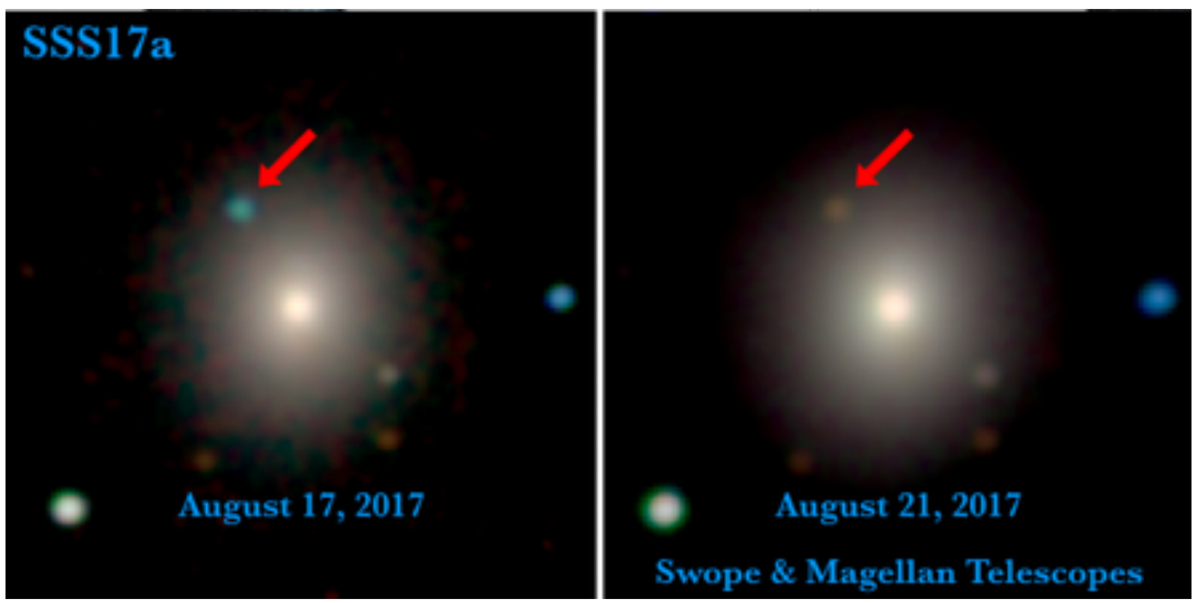
GW170817: Tidal Measurements

- Perform analysis with different spin priors
- Leading GW phase determined by: $$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$
- Most consistent with compact stars: R < 14km

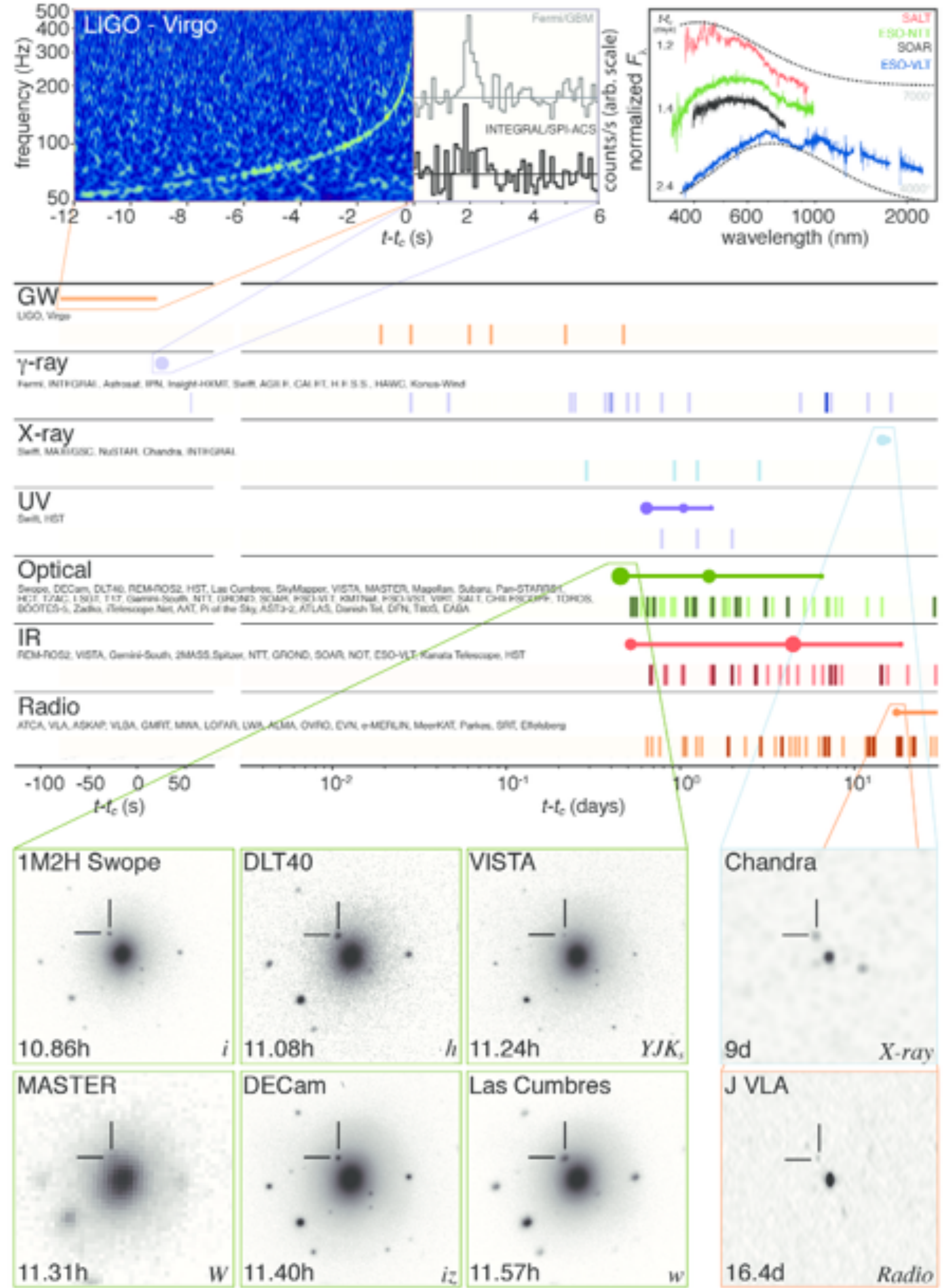


PRL, 119, 161101 (2017)

- GCN alert sent ~27 minutes after GW detection
- First observation of optical counterpart ~11h later by Swope (SSS17a/AT 2017gfo)
- Localisation to NGC 4993



- Rapid fading of blue component
- Redward evolution for ~10 days
- No UHE gamma-rays or neutrinos
- No initial X-ray and radio emission



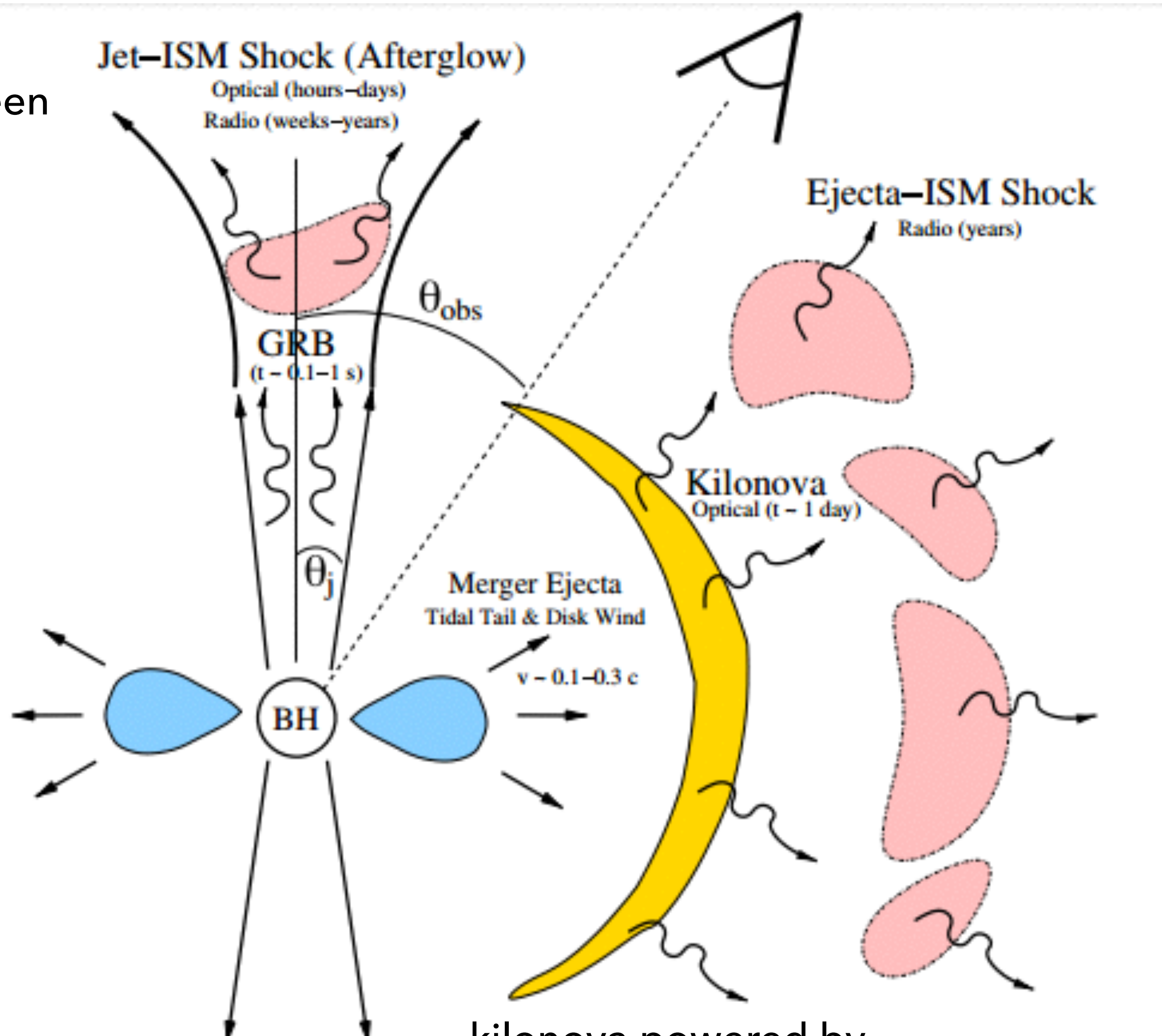
Astrophys. J. 848 (2017) L12

GW170817: The EM counterpart

- Hypothesis: the engines of short GRBs are mergers of compact binaries (BNS, NSBH)

interaction between jet and ISM

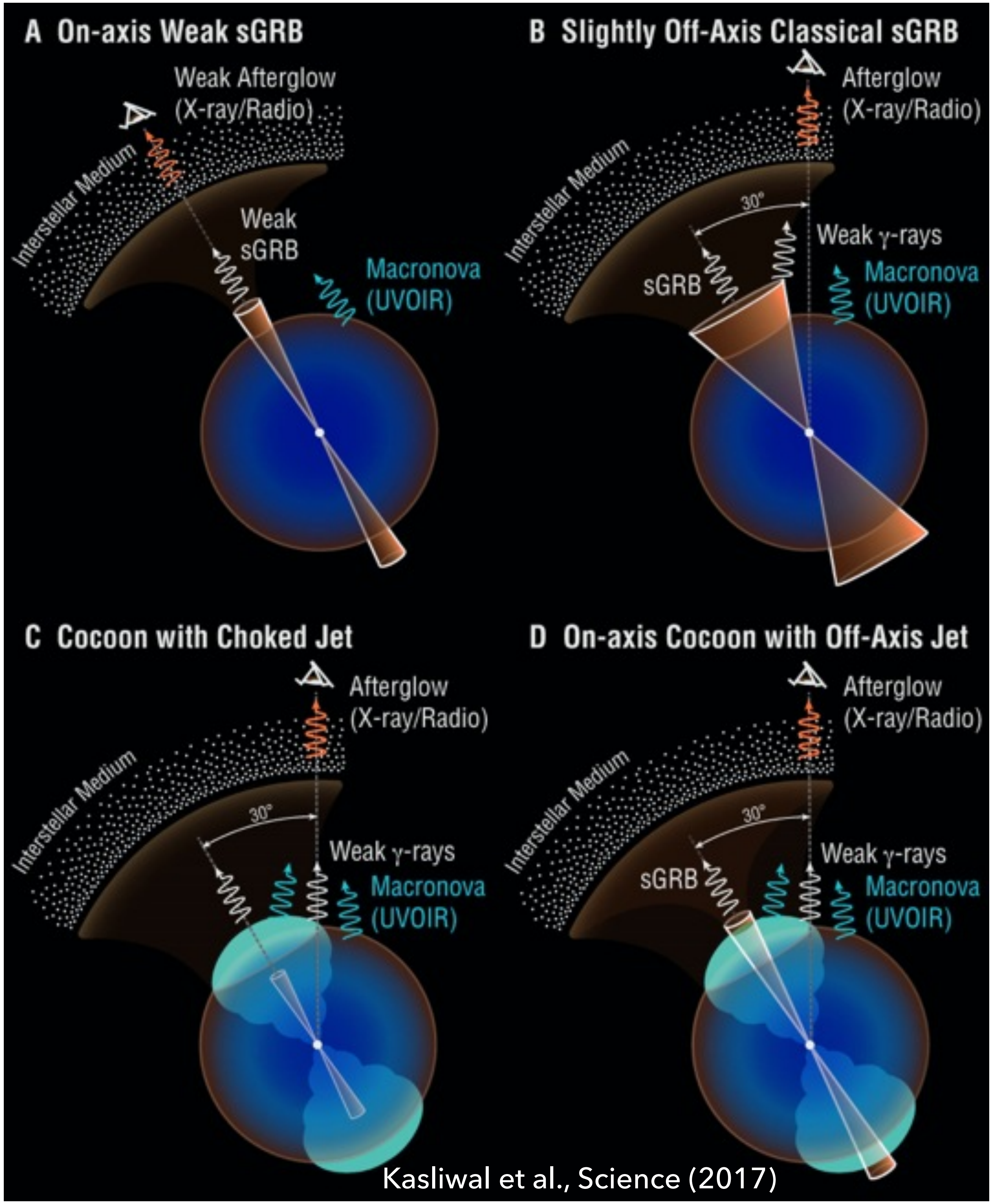
accretion onto central engine powers jet



kilonova powered by dynamical ejecta from tidal tails (decay of r-process elements)

GW170817: The EM counterpart

- Gamma-rays: short, soft and surprisingly weak
- Optical & UV: bright but faded quickly; blue faded first
- First x-rays after ~9 days (Chandra)
- First radio detection after ~16 days (VLA)
- Spectroscopic measures broadly match predictions from kilonova models, i.e. signatures of decay of r-process elements and production of lanthanides



Kasliwal et al., Science (2017)

GW170817: A BNS standard siren

- GWs are standard sirens [Schutz 86]
- From GWs we measure the redshifted chirp mass & luminosity distance

Phase proportional to redshifted chirp mass

$$\propto \mathcal{M}(1+z)$$

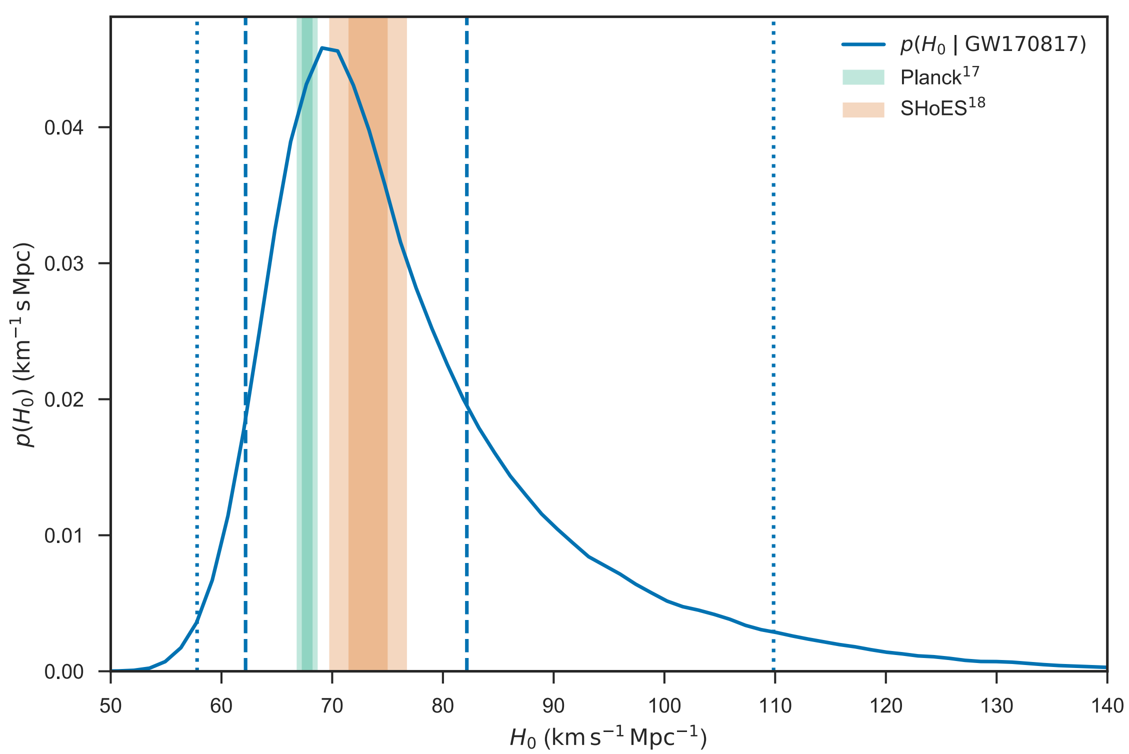
$$\Psi(f) \propto 2\pi f t_c - \Phi_c - \frac{\pi}{4} + \frac{3}{128}\left(\pi \mathcal{M}_z f\right)^{-5/3}\left[1 + \ldots\right]$$

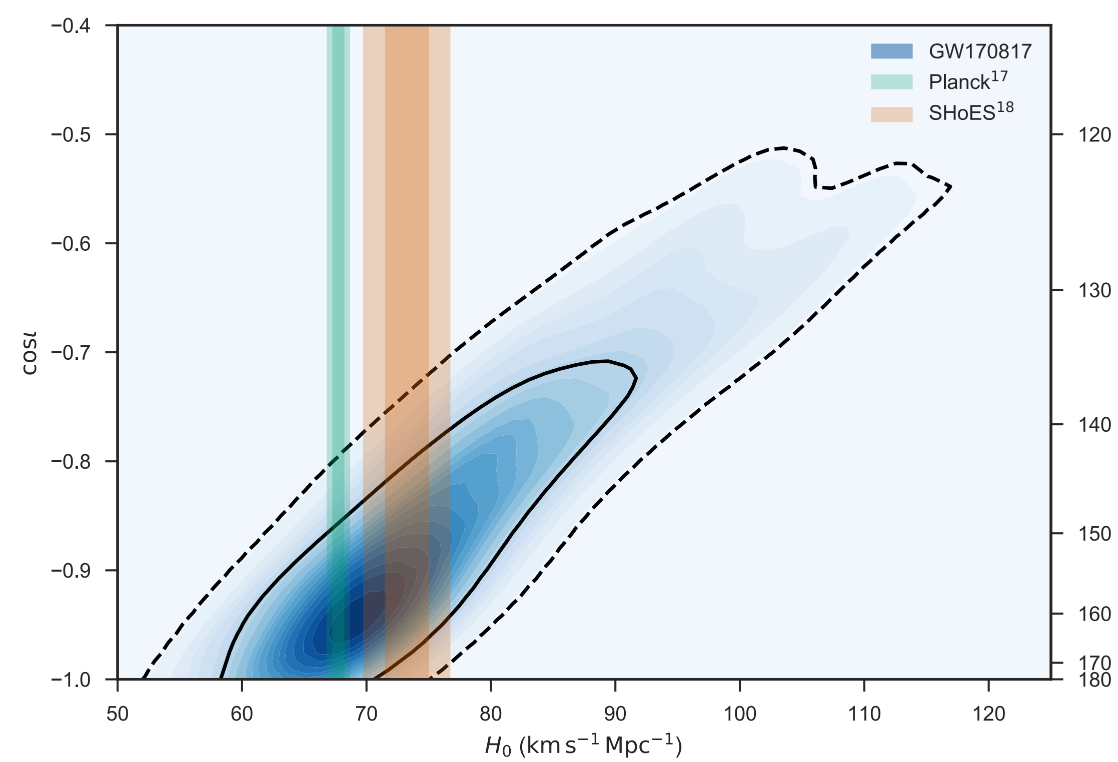
Amplitude proportional to redshifted chirp mass and luminosity distance

$$\tilde{h}_+(f) \propto A_0 \frac{\mathcal{M}_z^{5/6}}{D_L}\left[1+\cos^2 \iota\right] f^{-7/6} e^{i\Psi(f)}$$

Inclination angle introduces an additional degeneracy

- From EM we obtain a redshift measurement and can relate it to the distance thereby measuring the Hubble constant H_0



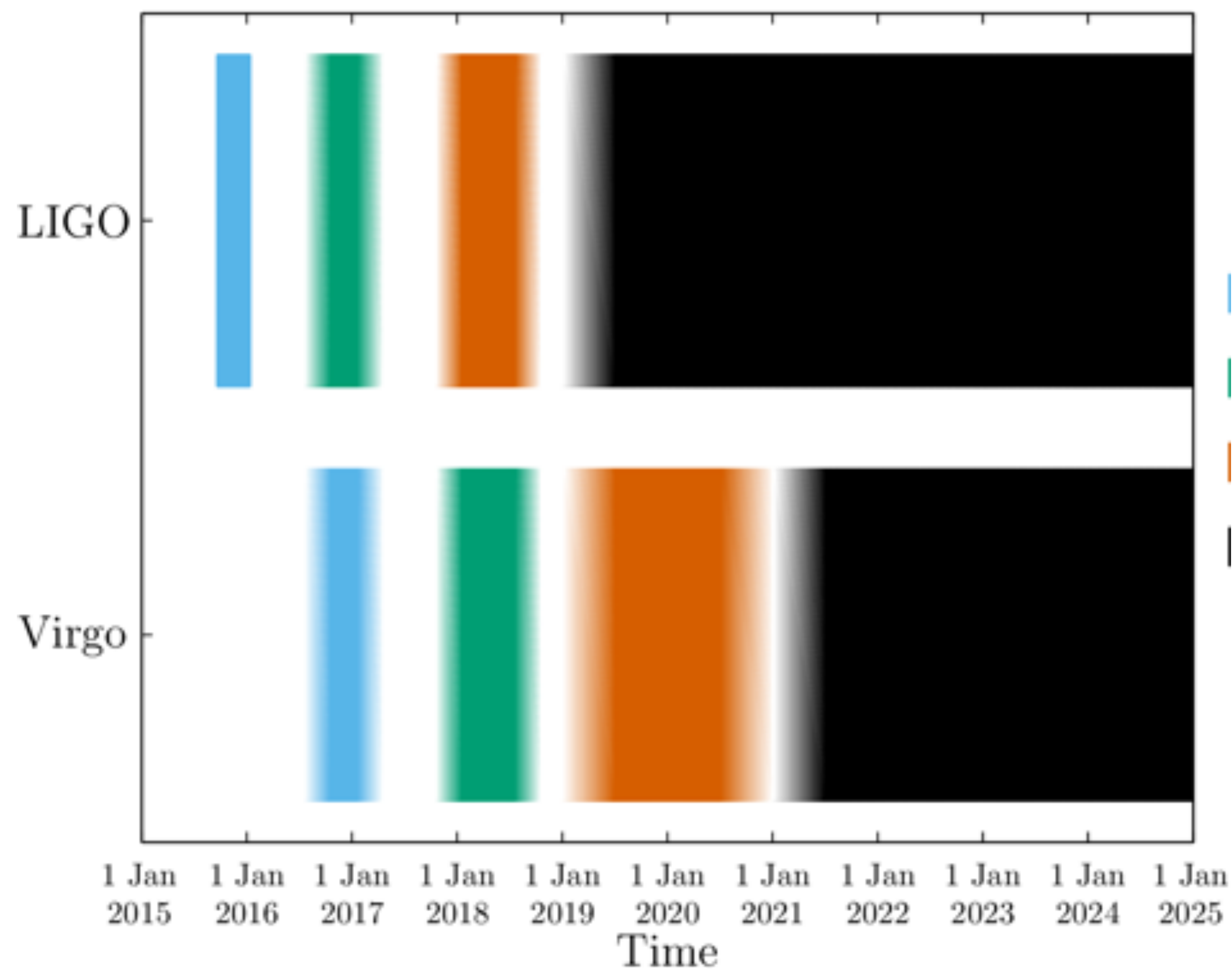


Nature 551,85–88 (02 November 2017)

Outlook

- O2 has finished but we are still analysing data!
- O3 is anticipated to start in late 2018
  - aLIGO BNS Range: 120-170 Mpc
  - aVirgo BNS Range: 65-85 Mpc
- KAGRA is projected to join the ground-based network in ~ 2020
- See public Observing Scenarios document for more details:

https://dcc.ligo.org/LIGO-P1200087/public



The future is loud & bright!