UNIVERSITY OF BIRMINGHAM | GRAVITATIONAL WAVE ASTRONOMY

NWO | Netherlands Organisation for Scientific Research

LIGO VIRGO

INTRODUCTION TO GW OBSERVATIONS OF COMPACT BINARY MERGERS (SO FAR)

LIGO DCC-G2100976

PATRICIA SCHMIDT

LVC GW OPEN DATA WORKSHOP #4

MAY 11, 2021 (ONLINE)

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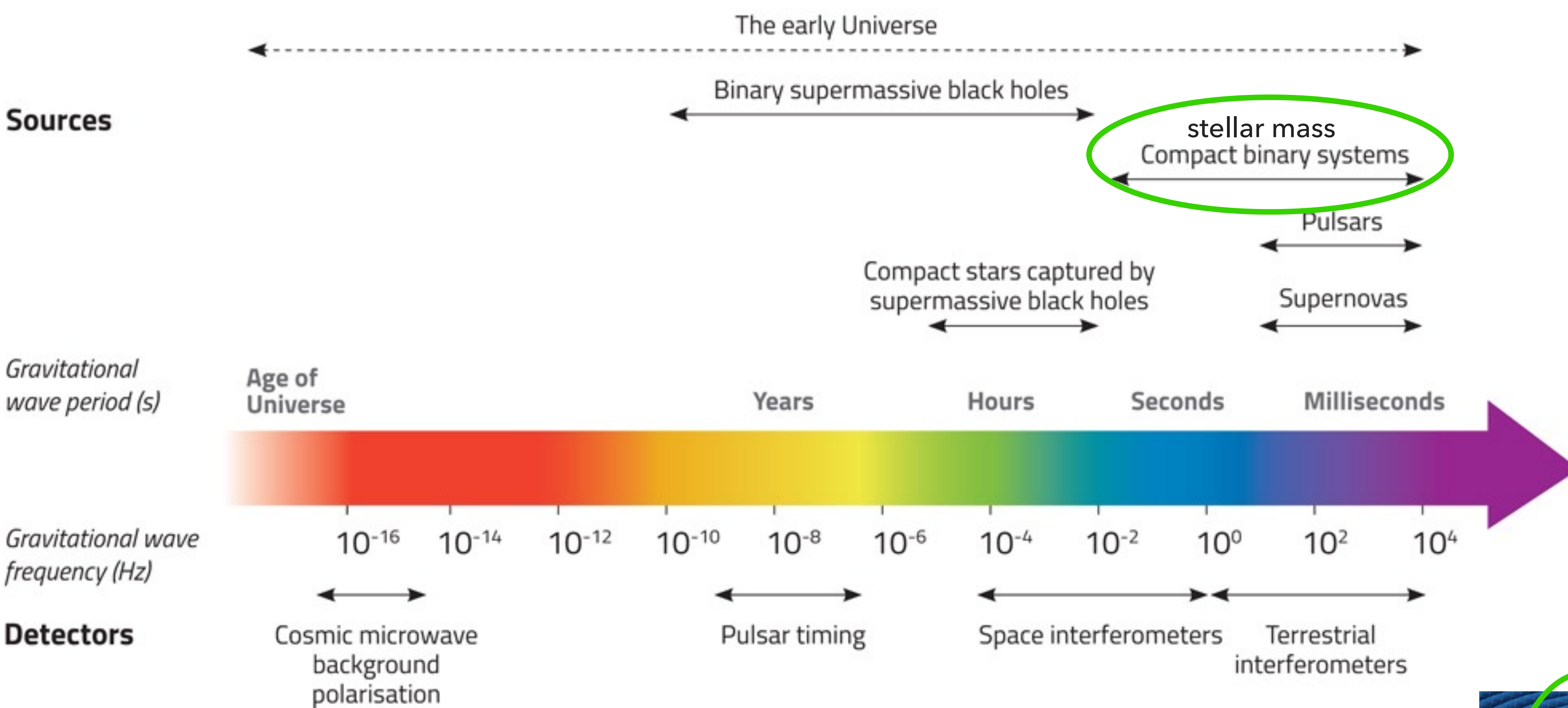
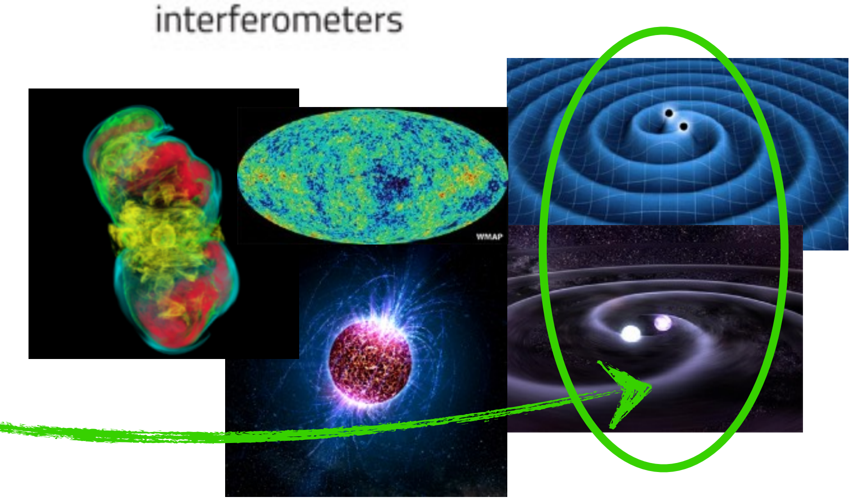
Birmingham Institute for Gravitational Wave Astronomy

THE GRAVITATIONAL WAVE SPECTRUM

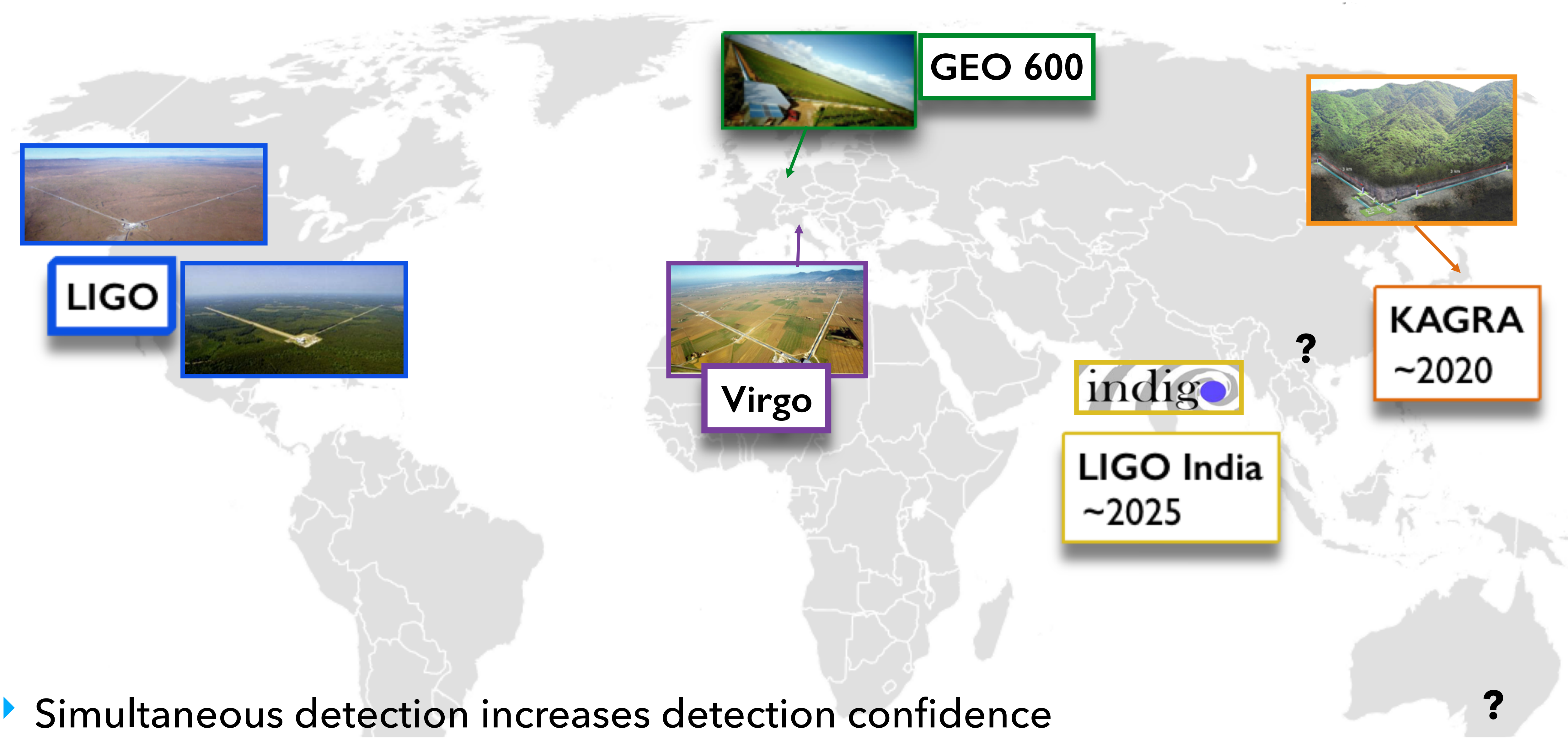
Image credits: WMAP, NASA, P. Mösta



stellar-mass compact binary mergers



A GLOBAL GW DETECTOR NETWORK



- Simultaneous detection increases detection confidence
- Improved sky localisation & polarisation
- Increased duty cycle

ADVANCED DETECTOR ERA

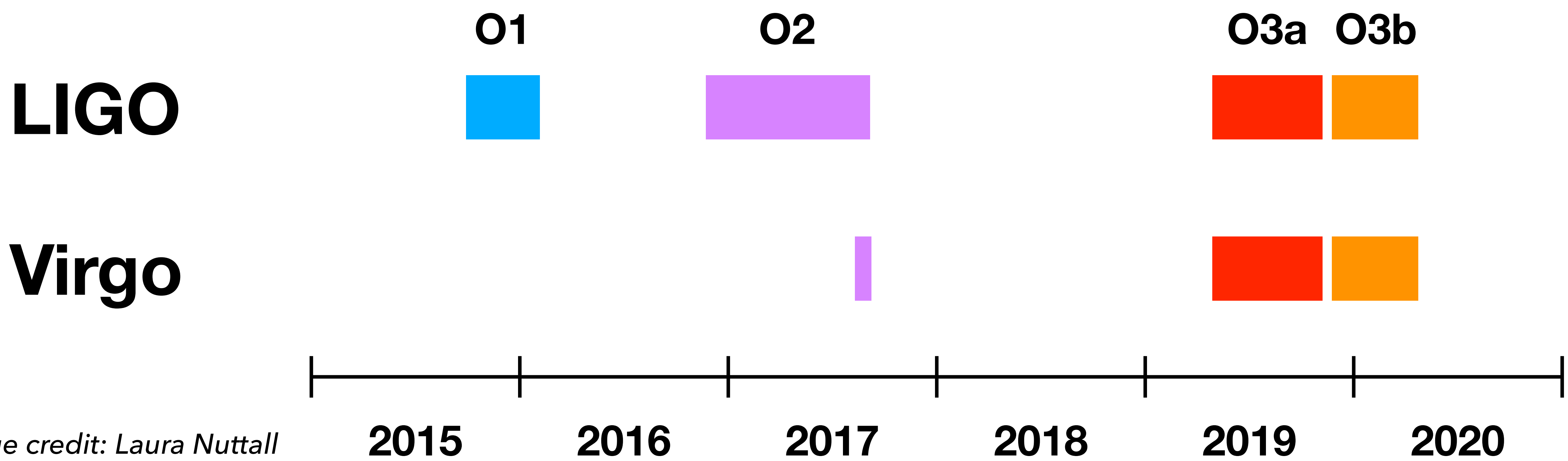
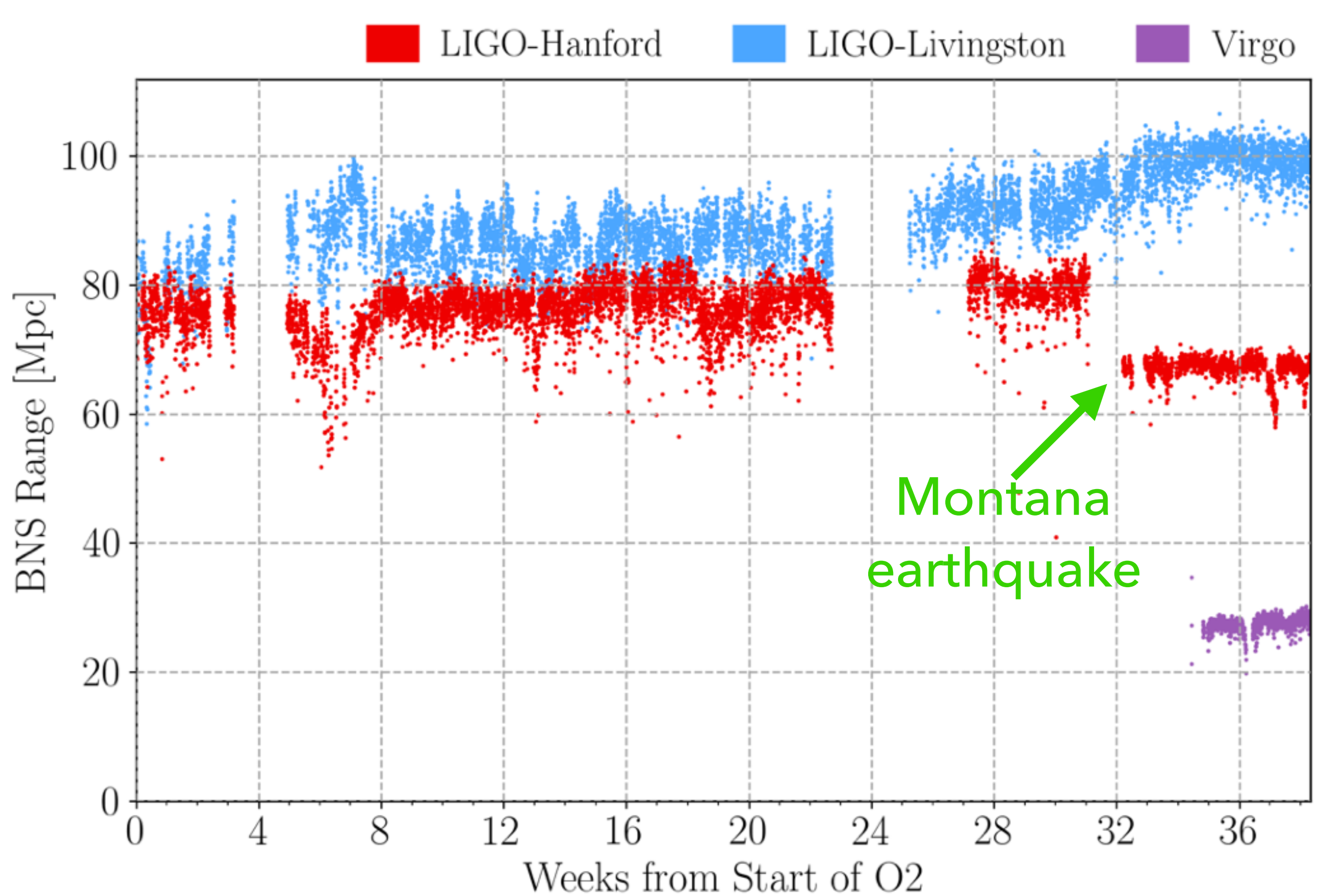


Image credit: Laura Nuttall

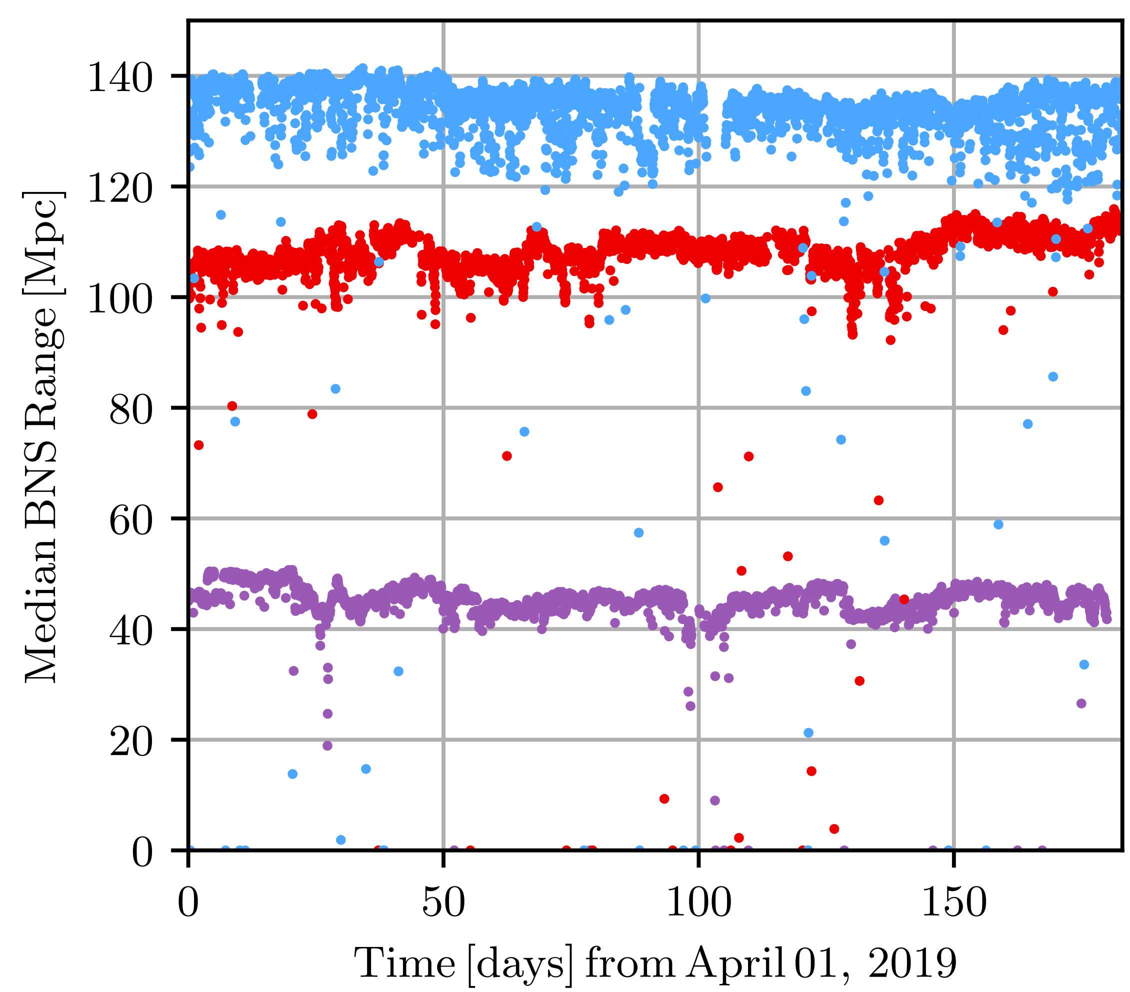
- O1: Sept 12,2015 - Jan 30, 2016
  - HL coincident time: 48.6 days
- O2: Nov 30, 2016 - Aug 25, 2017
  - HL-coincident time: 118 days
  - HLV-coincident time: 15 days
- O3a: April 1, 2019 - Oct 1, 2019
  - HLV coincident time: 81.4 days
- O3b: Oct 1, 2019 - March 27, 2020

FROM O2 TO O3

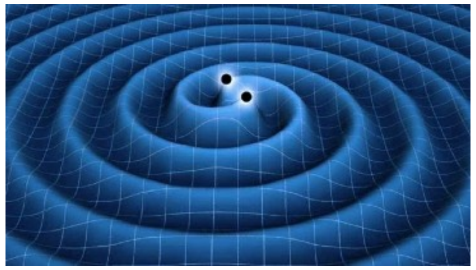
- Significant improvement in sensitivity *[see Eleonora's talk]*



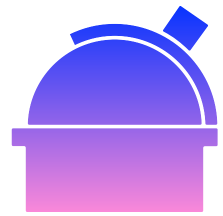
[LVC, PRX 9, 031040 (2019)]



[LVC, arXiv:2010.14527]



Low-latency (online) analyses



See Eleonora Capocasa's talk

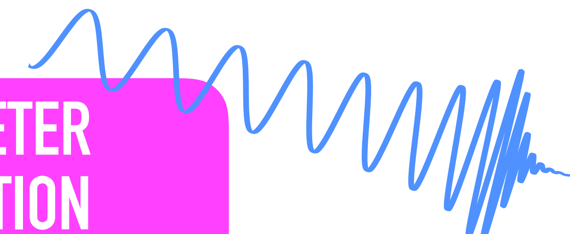
DATA QUALITY

See Laura Nuttall's talk

(OFFLINE) GW SEARCHES

See Gareth Davies' talk

PARAMETER ESTIMATION



See Shanika Galaudage's talk

ASTROPHYSICS

TESTS OF GENERAL RELATIVITY

COSMOLOGY

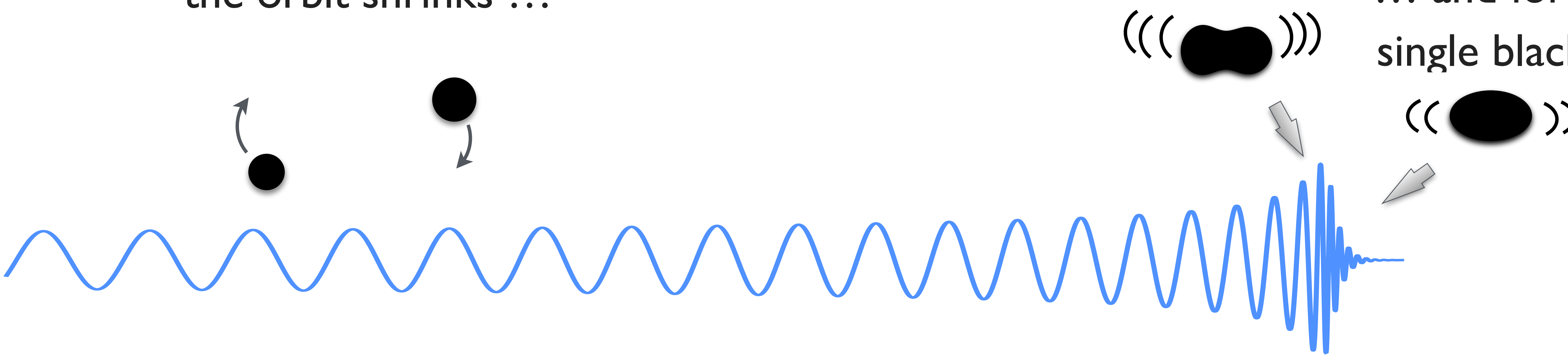
FUNDAMENTAL PHYSICS

MORPHOLOGY OF COMPACT BINARIES

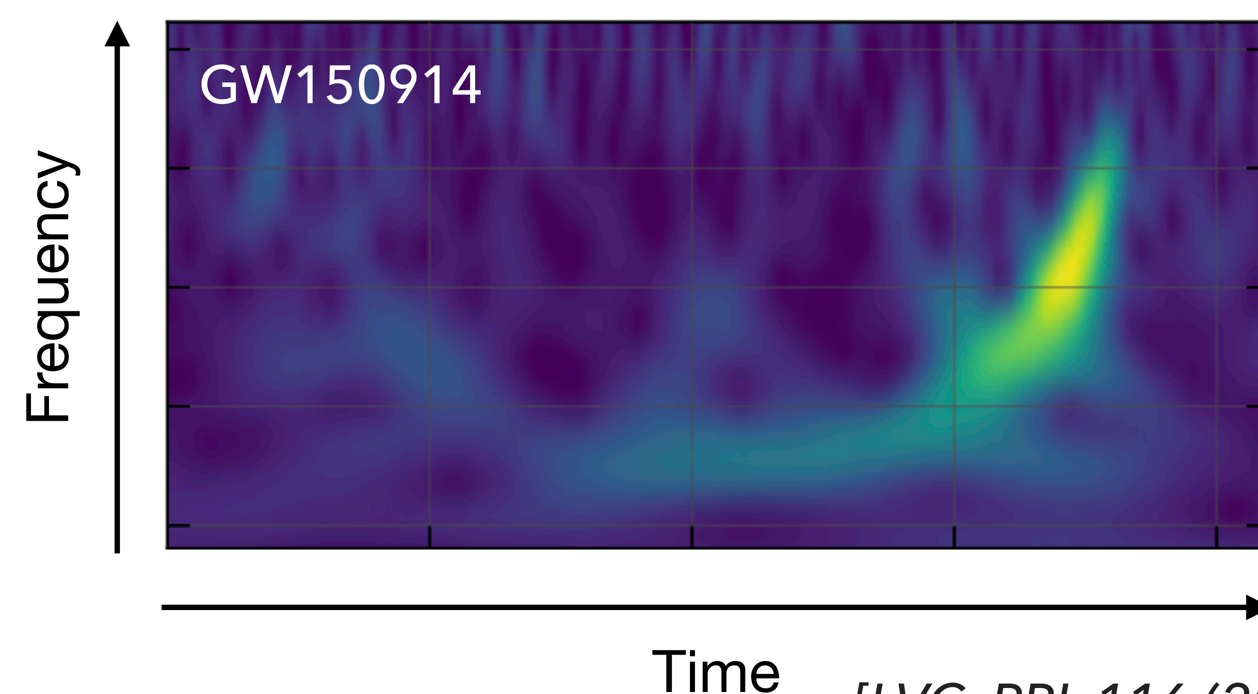
Inspiral
the orbit shrinks …

Merger
… until they collide

Ringdown
… and form a single black hole



- Signal „sweeps“ through the detector’s sensitivity band: “chirp signal”
- GWs carry **characteristic information** about the binary such as **masses & spins**



[LVC, PRL 116 (2016)]

BINARY PARAMETERS

- GW signal encodes fundamental properties:

$$\vec{\theta}_{\rm BBH} = \{\underbrace{m_1, m_2, \vec{\chi}_1, \vec{\chi}_2}_{\rm intrinsic}, \underbrace{D_L, \psi, \iota, \alpha, \delta, \phi_c, t_c}_{\rm extrinsic}\}$$

$$\vec{\theta}_{\rm BNS} = \vec{\theta}_{\rm BBH} + \vec{\theta}_{\rm tidal} \qquad \vec{\theta}_{\rm tidal} = (\Lambda_1, \Lambda_2, \ldots)$$

"tidal deformabilities"

- Extraction via Bayesian inference: *[see Shanika's talk]*

$$p\left(\vec{\theta}|d,\mathcal{H}\right) \propto \mathcal{L}\left(d|\vec{\theta},\mathcal{H}\right)\pi\left(\vec{\theta}|\mathcal{H}\right)$$

posterior probability

signal hypothesis

(uninformative) prior

WAVEFORM – A KEY INGREDIENT

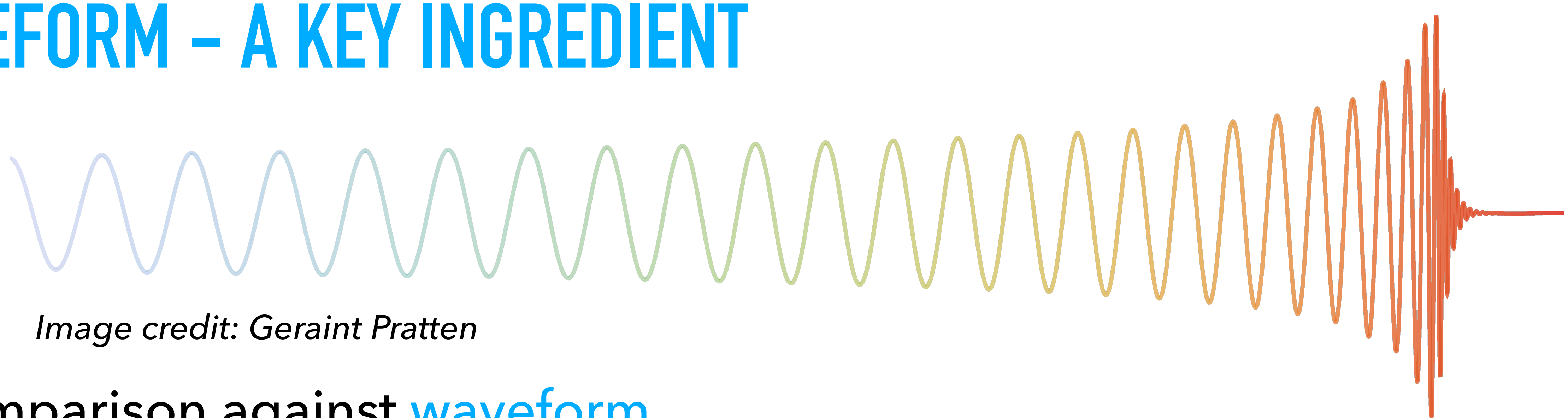
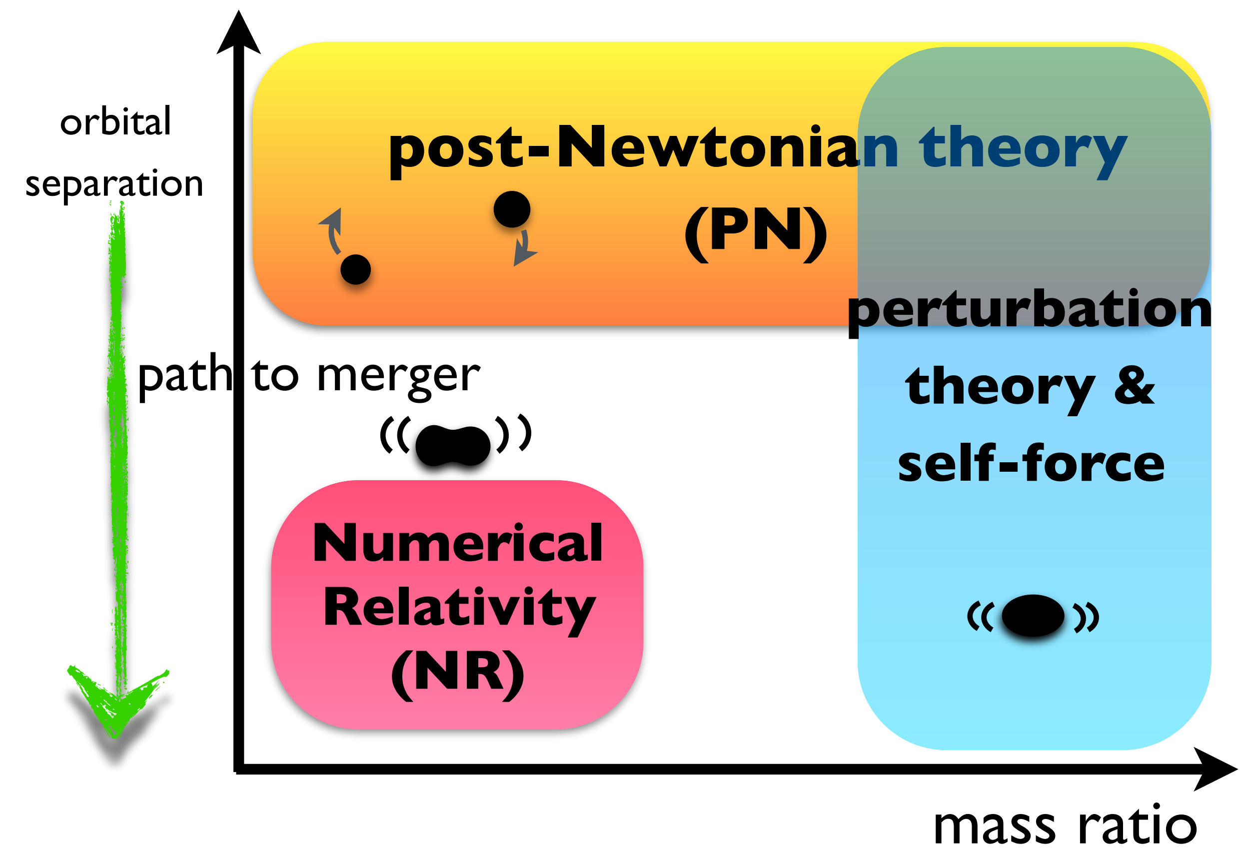
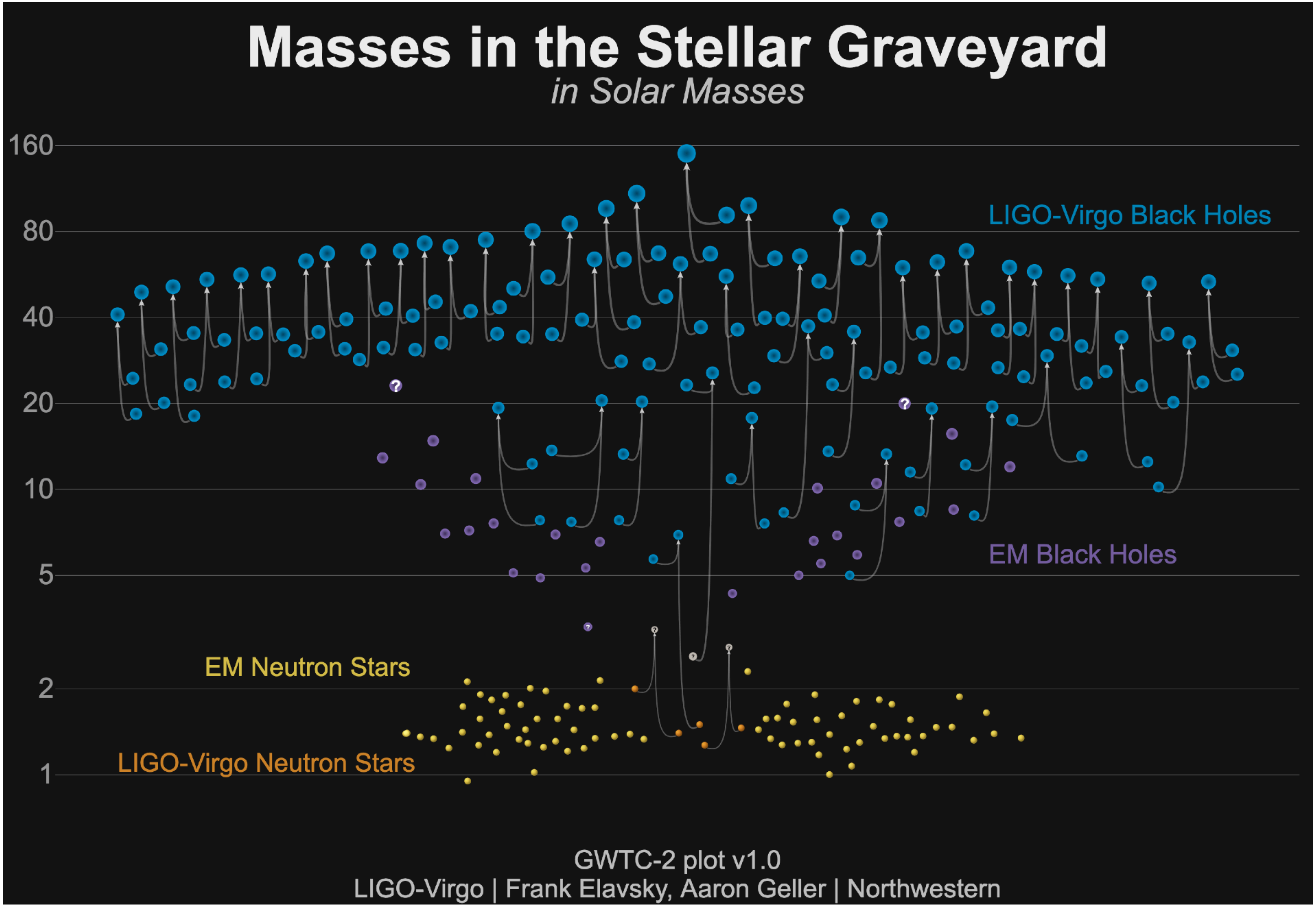


Image credit: Geraint Pratten

- Comparison against waveform models:
  - Inspiral-only: PN (low mass)
  - Inspiral-merger-ringdown: Phenom, Effective-One-Body (all masses/mass ratios)
  - Late inspiral-merger-ringdown: NRSurrogates (high masses, restricted mass ratios)

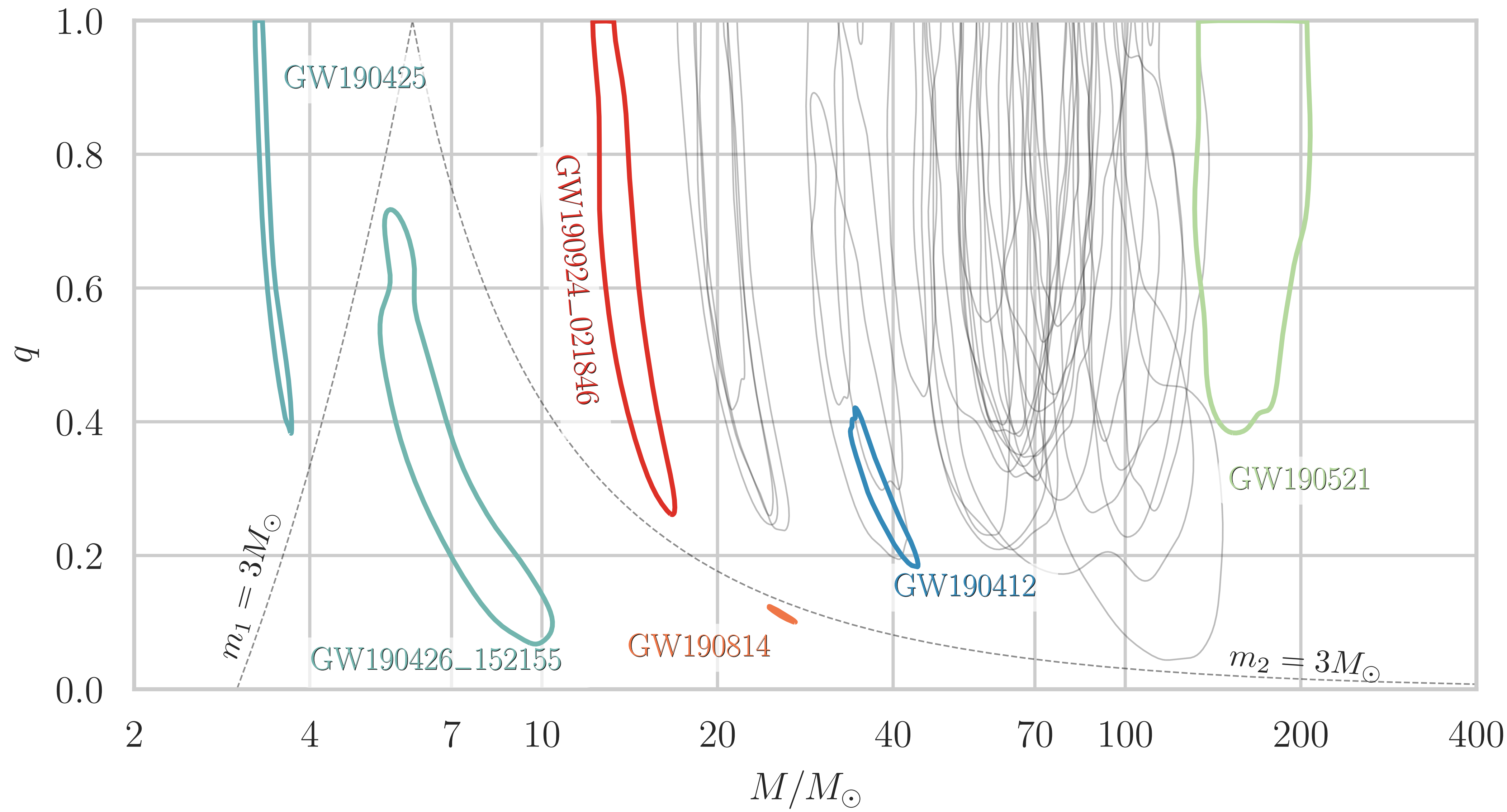



Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GWTC-2

[LVC, arXiv:2010.14527]

- 39 new GW candidate events (FAR < 2/yr)
- Includes the least (GW190924_021846) and the most massive (GW190521) BBH observed
- Includes the NSBH candidate GW1909426_152155



HIGHLIGHTS FROM O3A

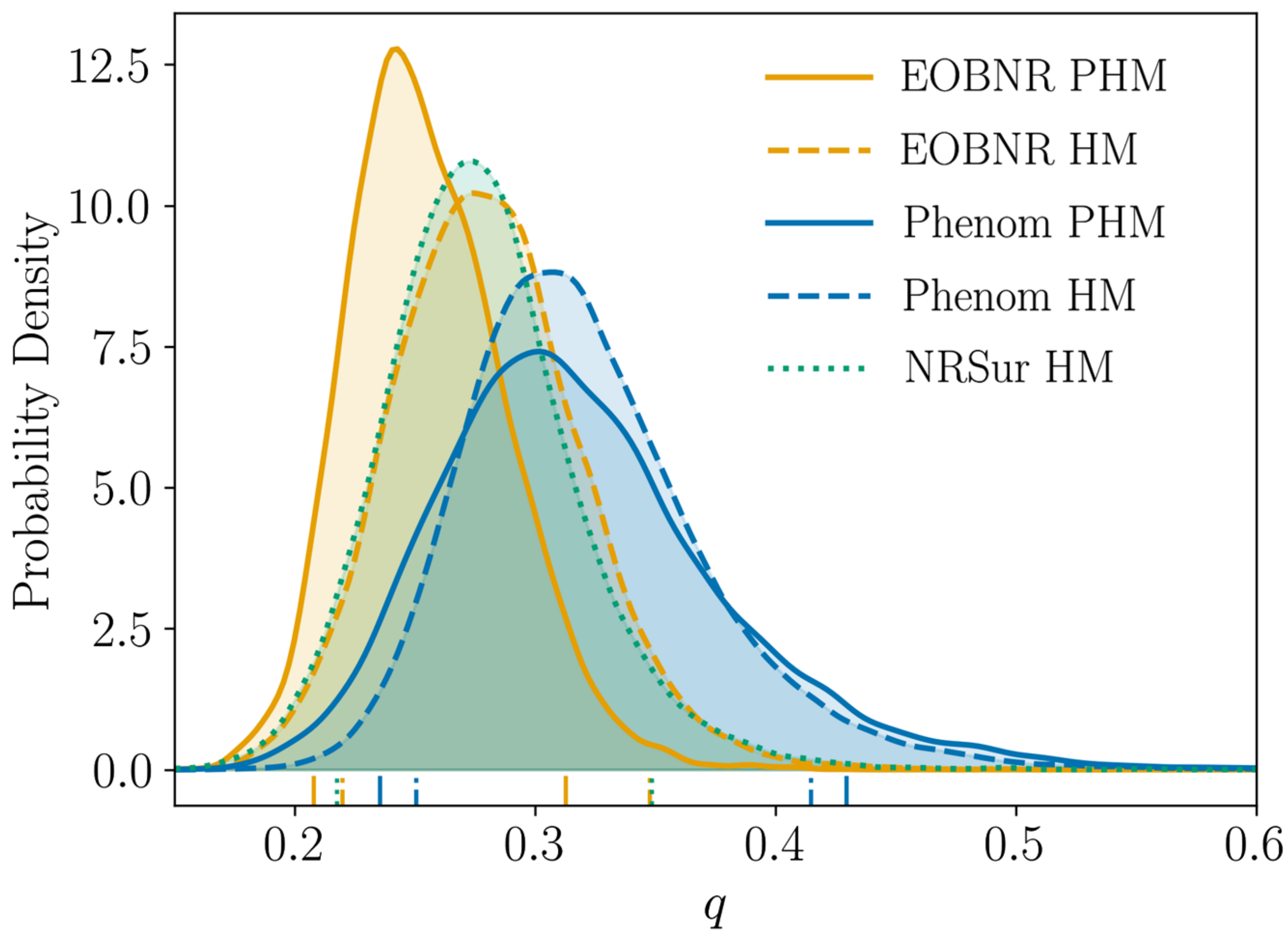
GW190412

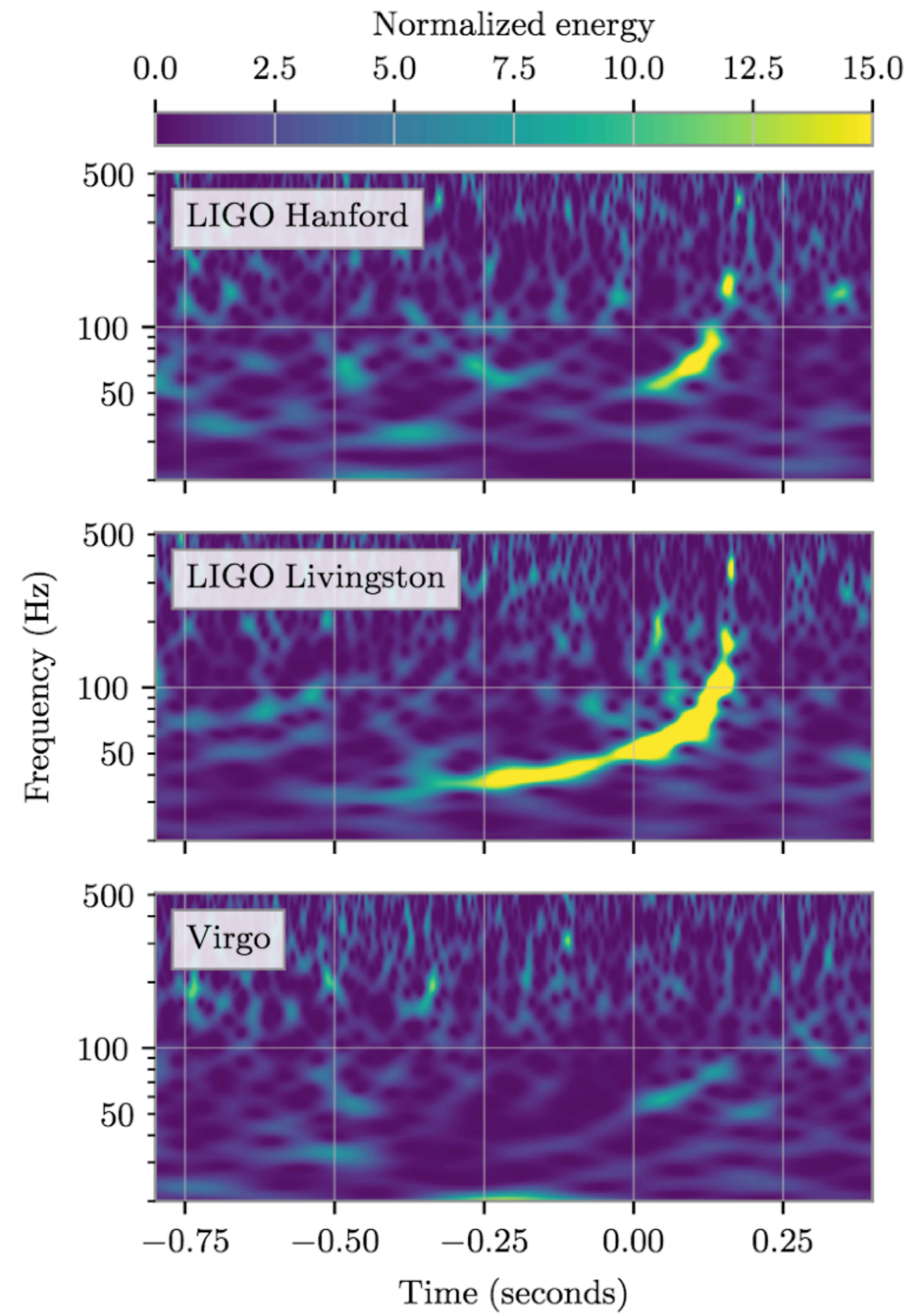
[LVC, PRD 102, 043015 (2020)]

- The first clear asymmetric (=unequal mass) BBH detection

$$m_1 \sim 30 M_\odot,\ m_2 \sim 8 M_\odot$$

$$q = 0.28^{+0.12}_{-0.07}$$





GW190521

- Most massive BBH observed to date:

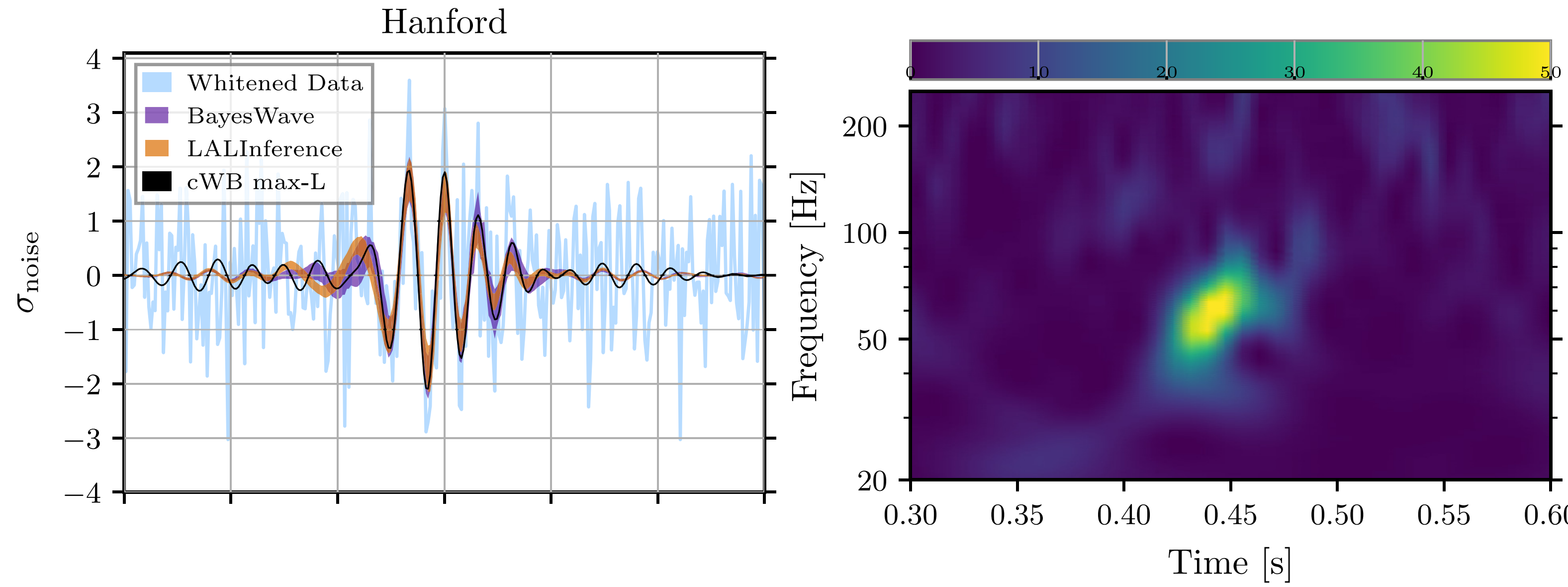
$$m_1 = 85^{+21}_{-14} M_\odot$$

$$m_2 = 66^{+17}_{-18} M_\odot$$

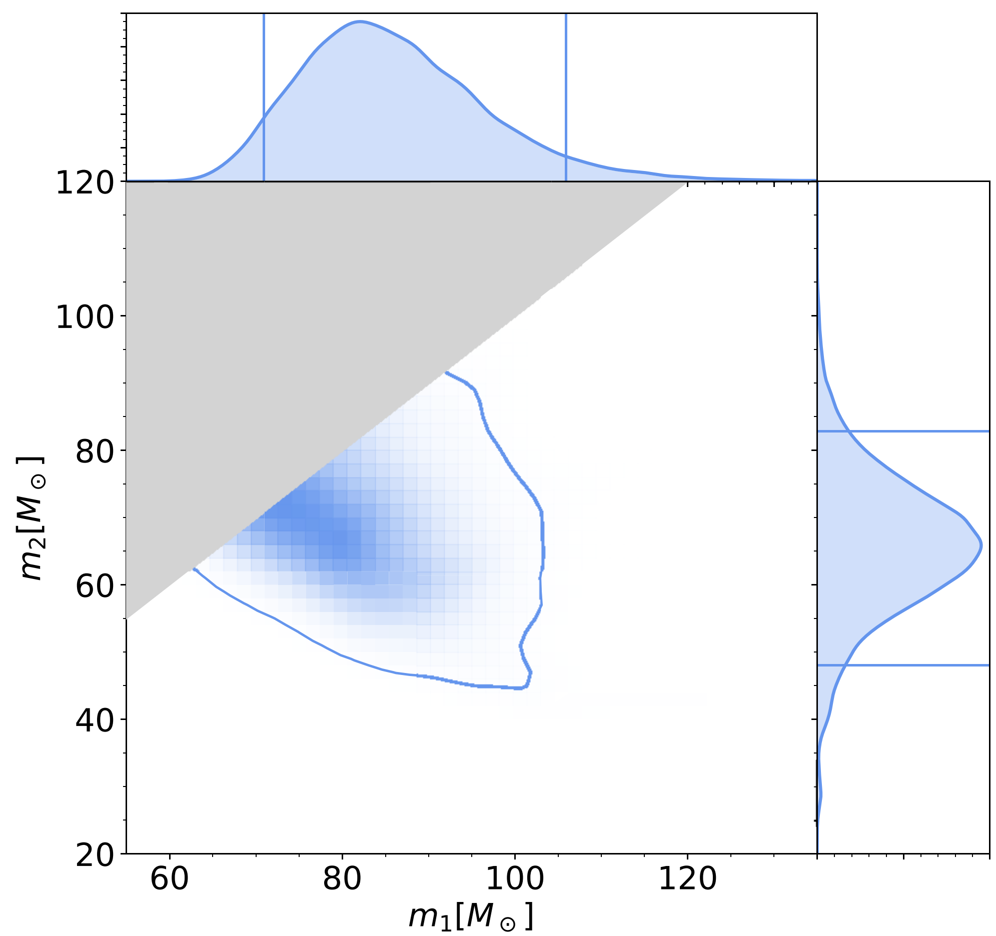
- Remnant mass:

$$142^{+28}_{-16} M_\odot$$

Intermediate mass black hole!



- Challenges astrophysical formation scenarios due to PISN
- Multiple mergers?



[LVC, Phys. Rev. Lett. 125, 101102 (2020)]

RELATIVISTIC SPIN PRECESSION

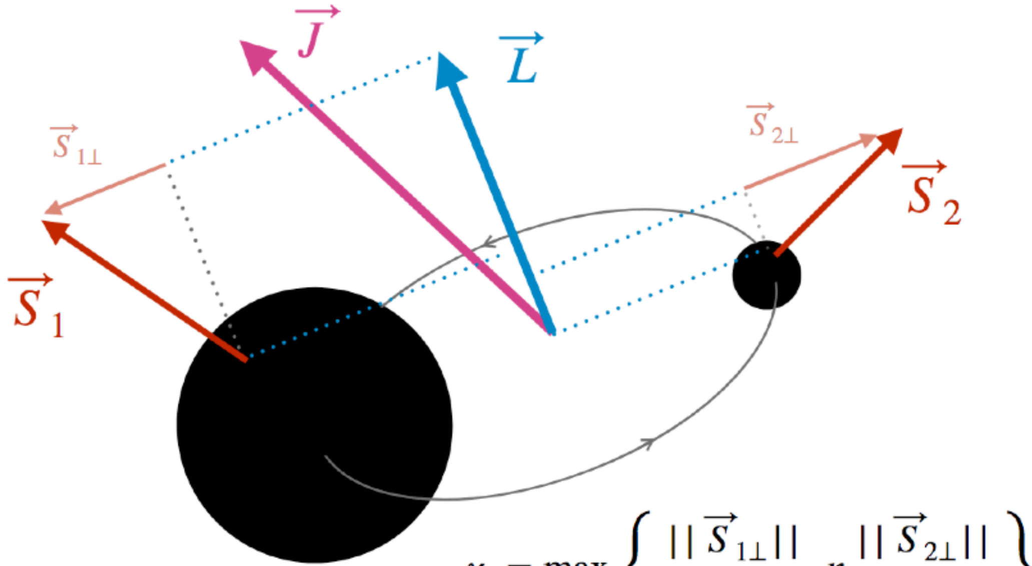
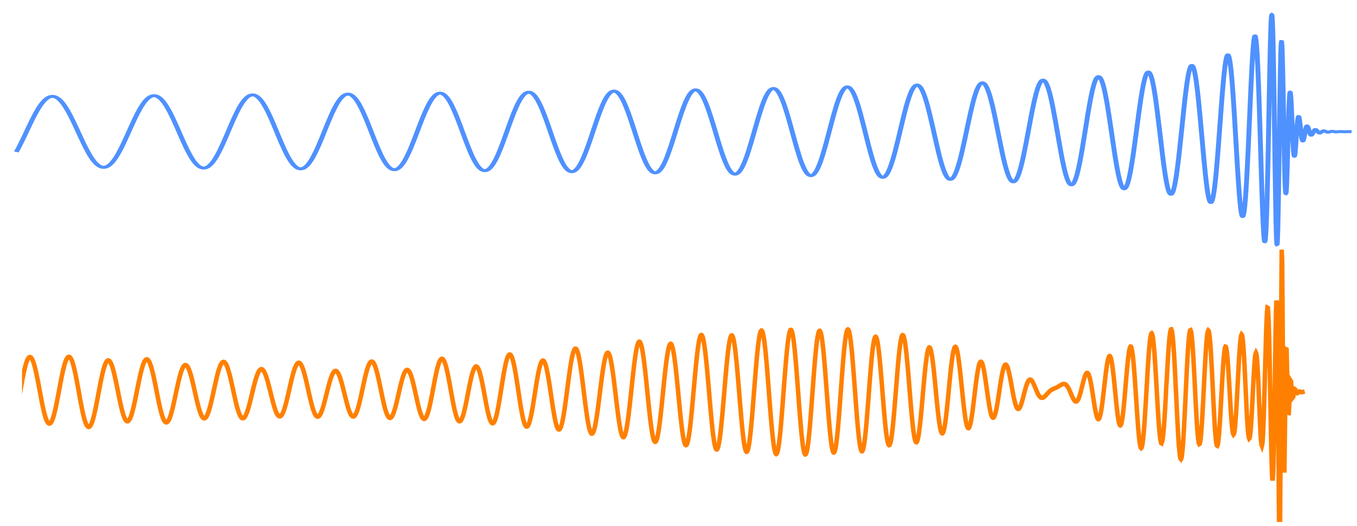
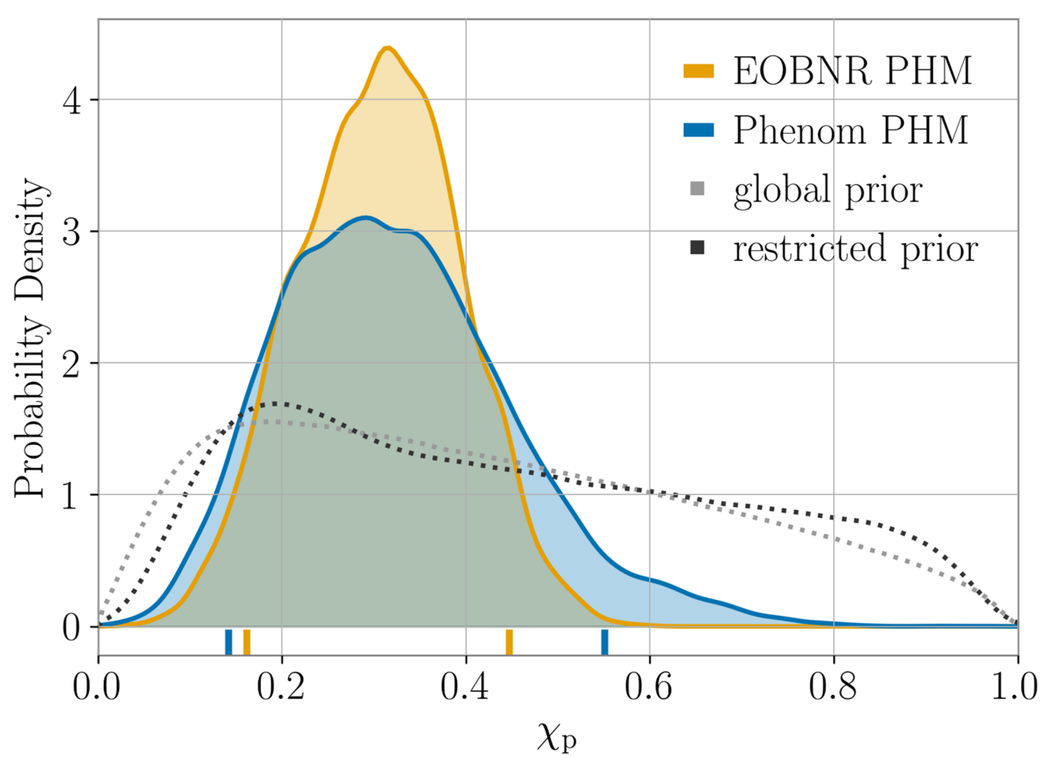


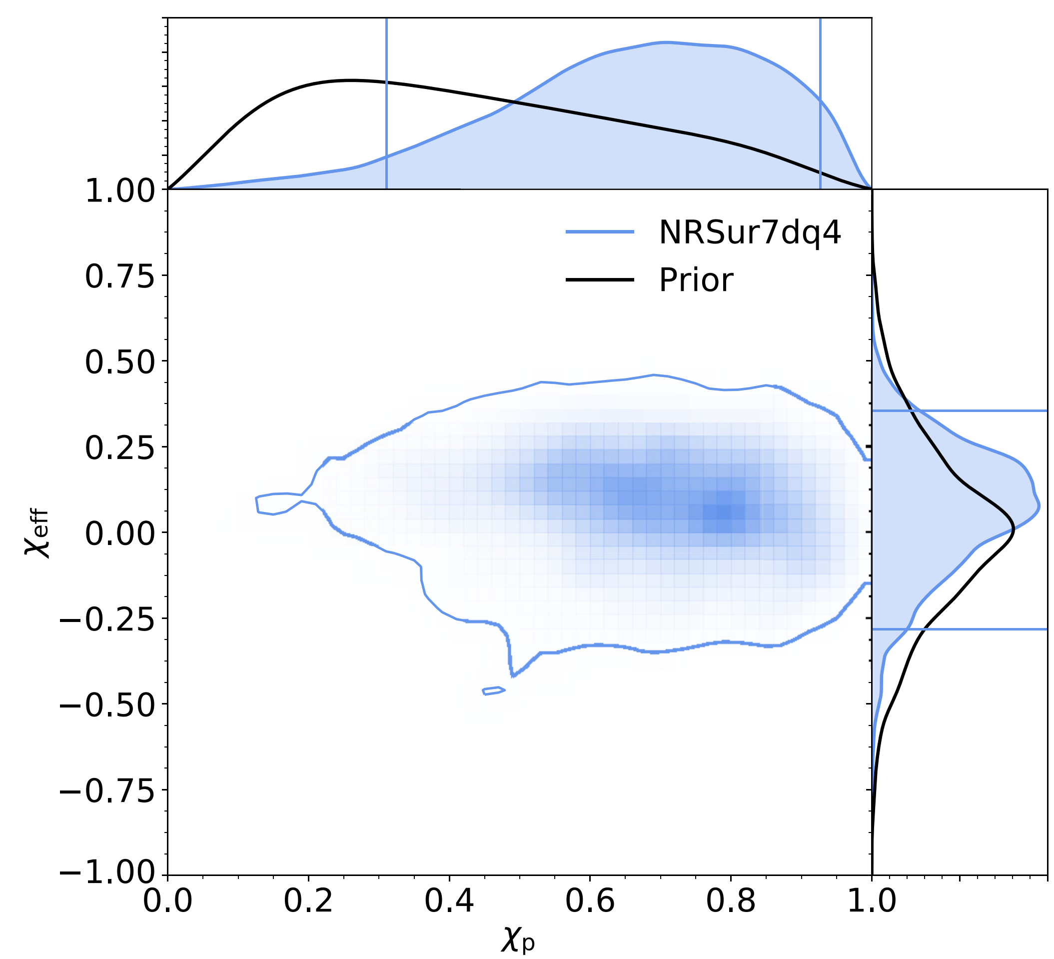
Image credit: Max Isi

$$\chi_p = \max\left\{\frac{||\vec{S}_{1\perp}||}{m_1^2}, \kappa\frac{||\vec{S}_{2\perp}||}{m_2^2}\right\}$$

$$\kappa = q(4q+3)/(4+3q)$$





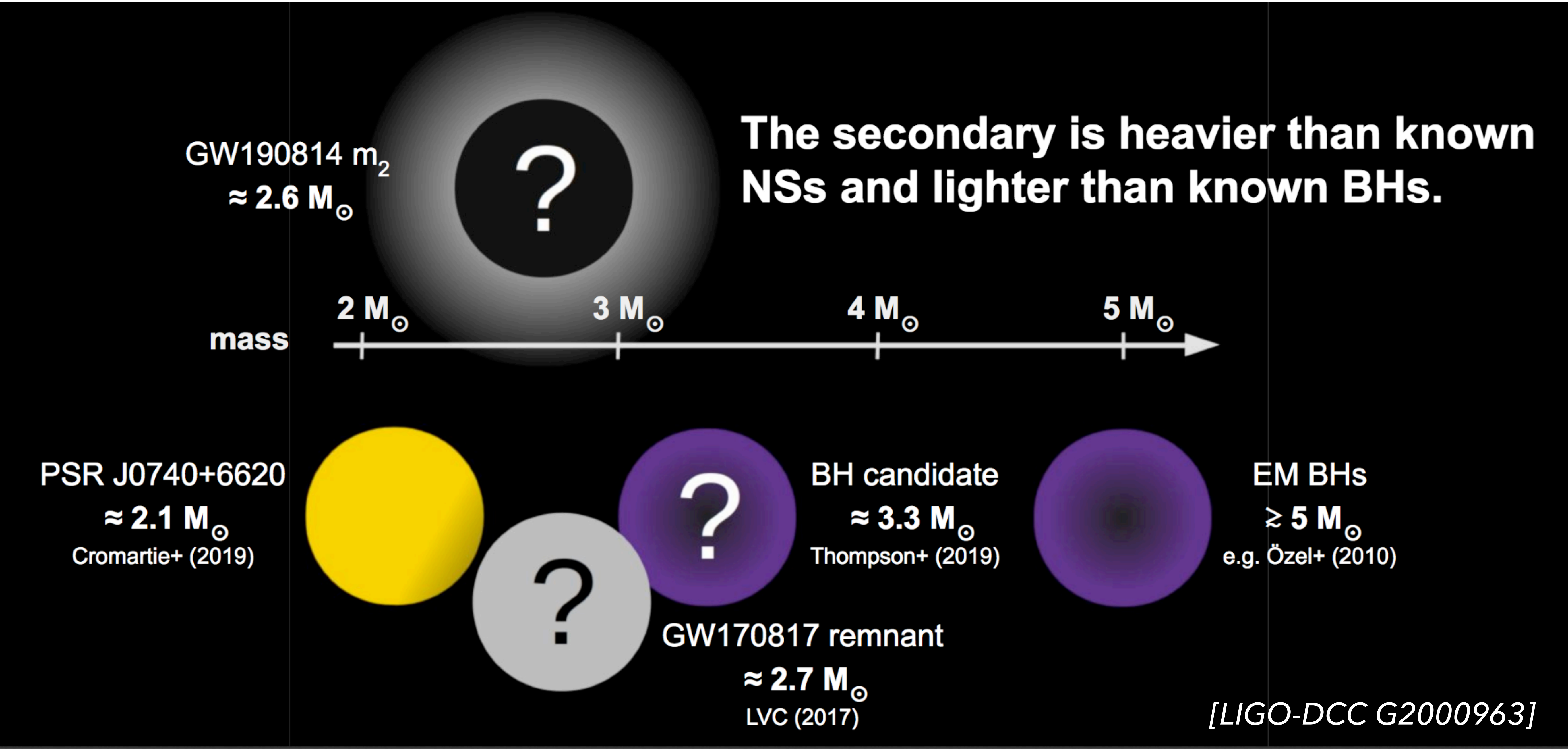


GW190814

[LVC, ApJL 896:L44 (2020)]

- A neutron star – black hole binary?

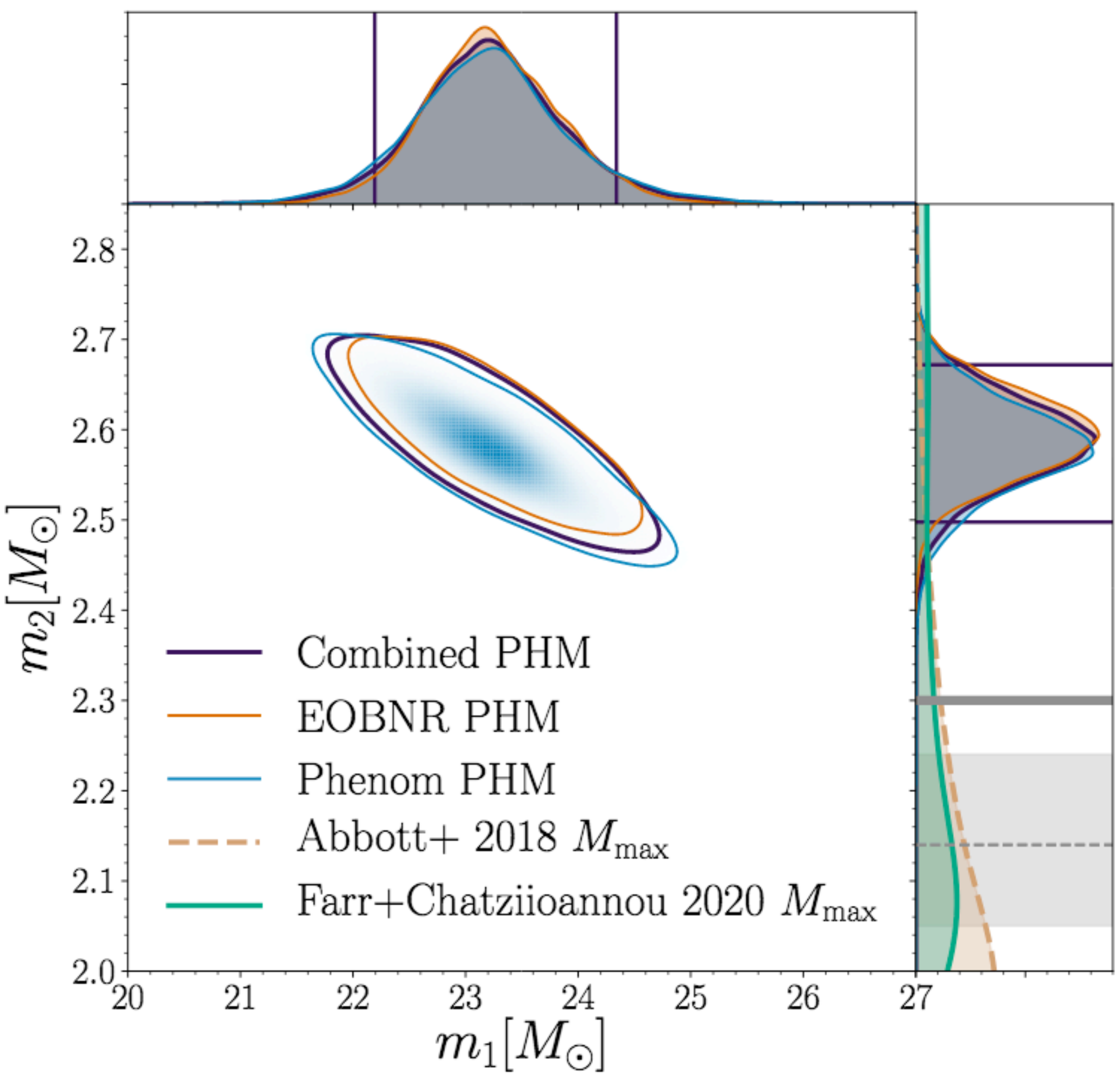
$$m_1 = 22.2 - 24.3 M_\odot \quad m_2 = 2.50 - 2.67 M_\odot$$

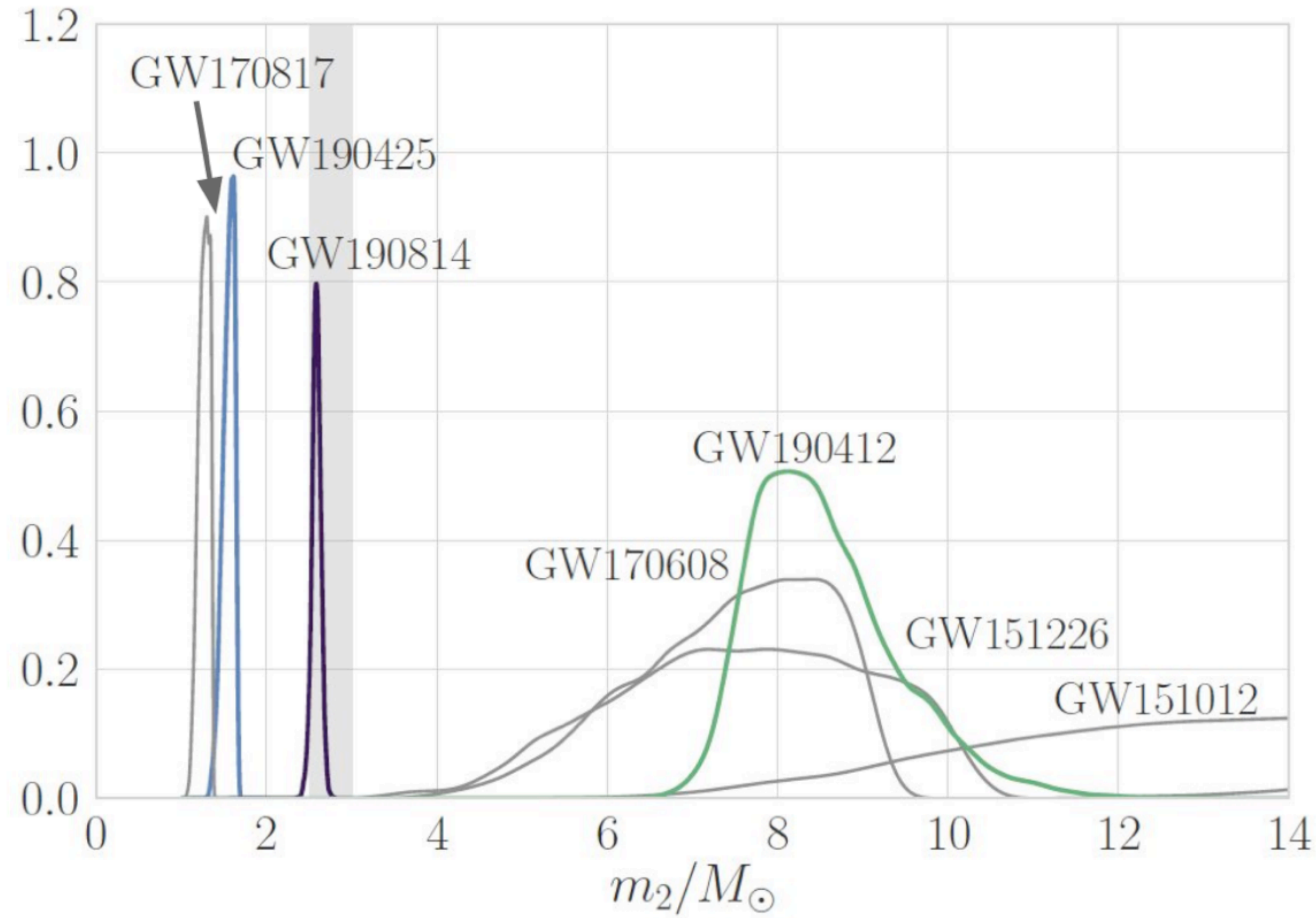


[LIGO-DCC G2000963]

GW190814

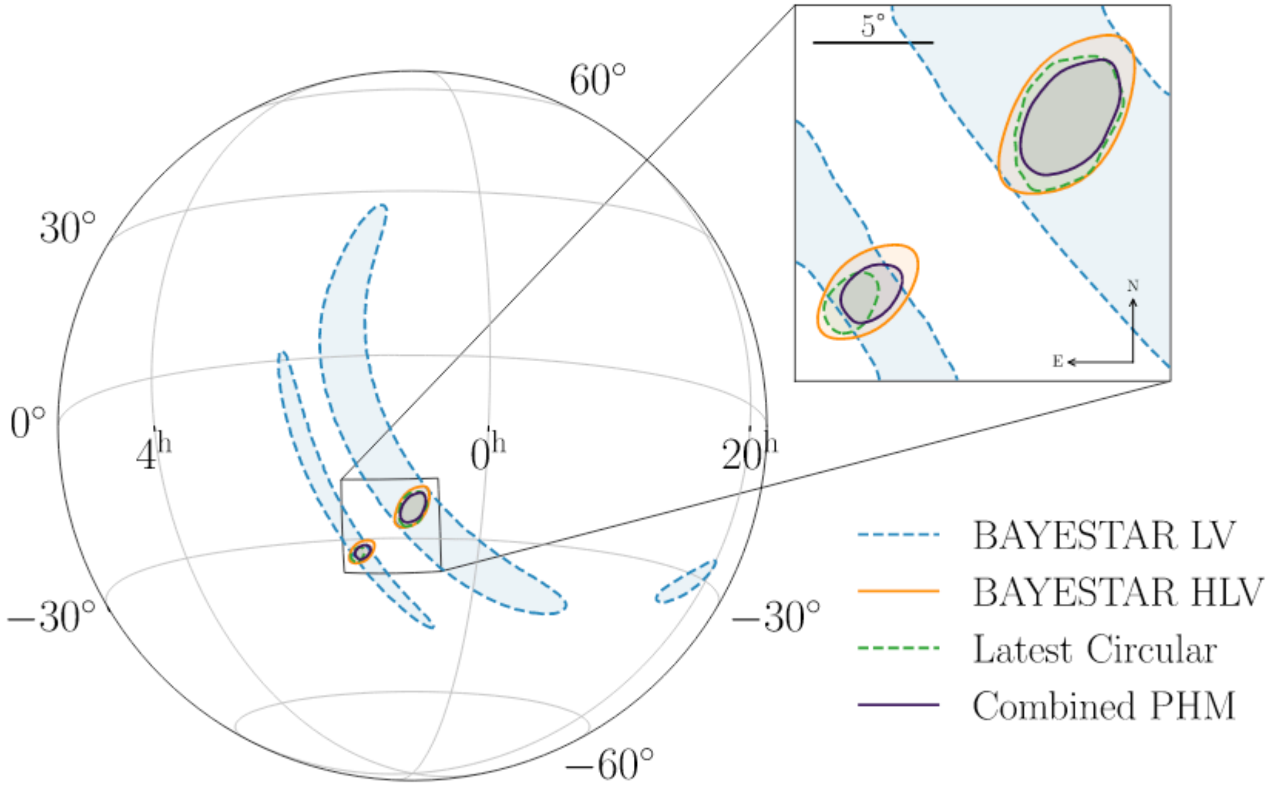
[LVC, ApJL 896:L44 (2020), LIGO-DCC G2000963]





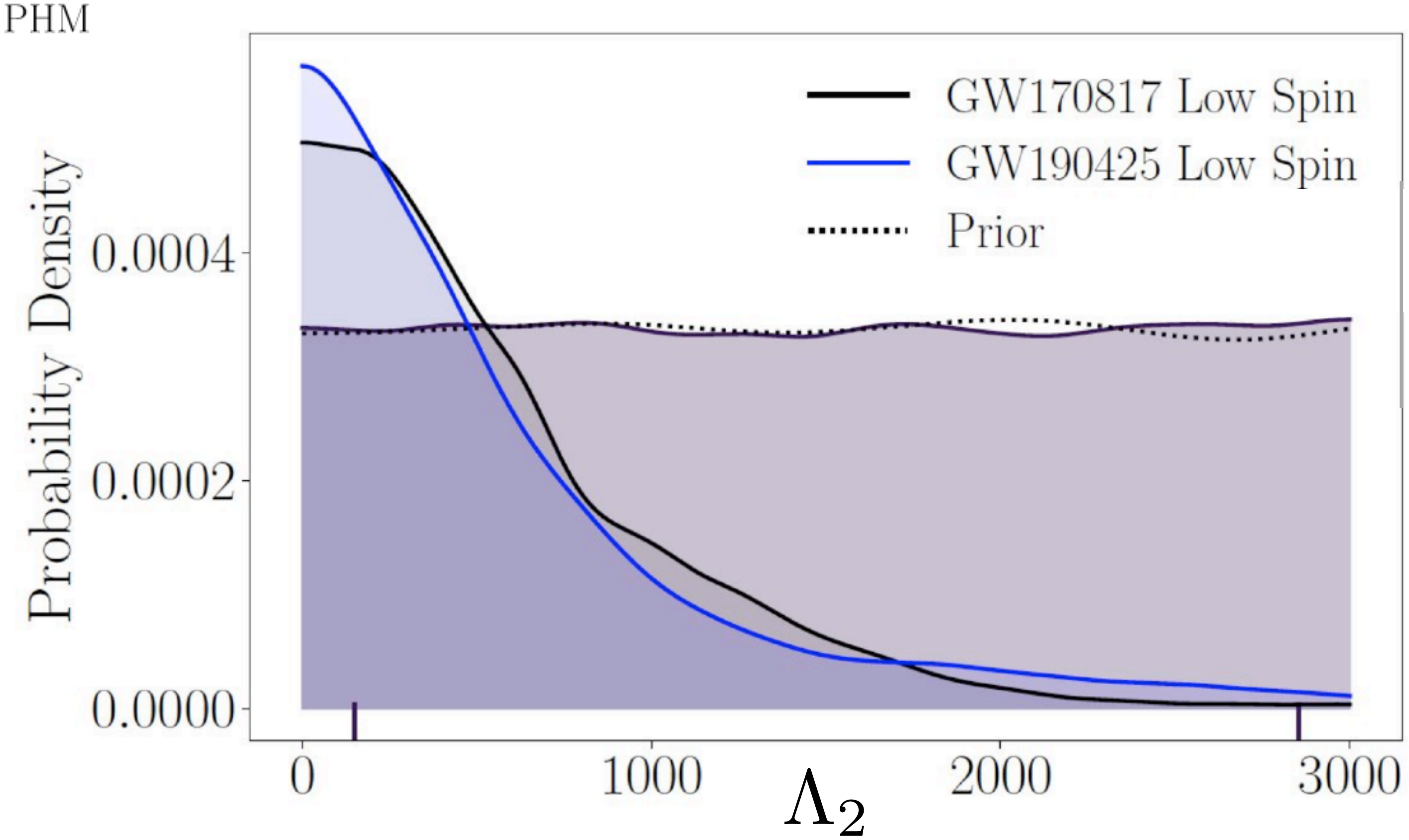
Difficult to reconcile with neutron star maximum mass constraints.

- What about tides or an EM/neutrino counterpart?



- Sky map issued within ~20 minutes
- No EM or neutrino counterpart discovered to date

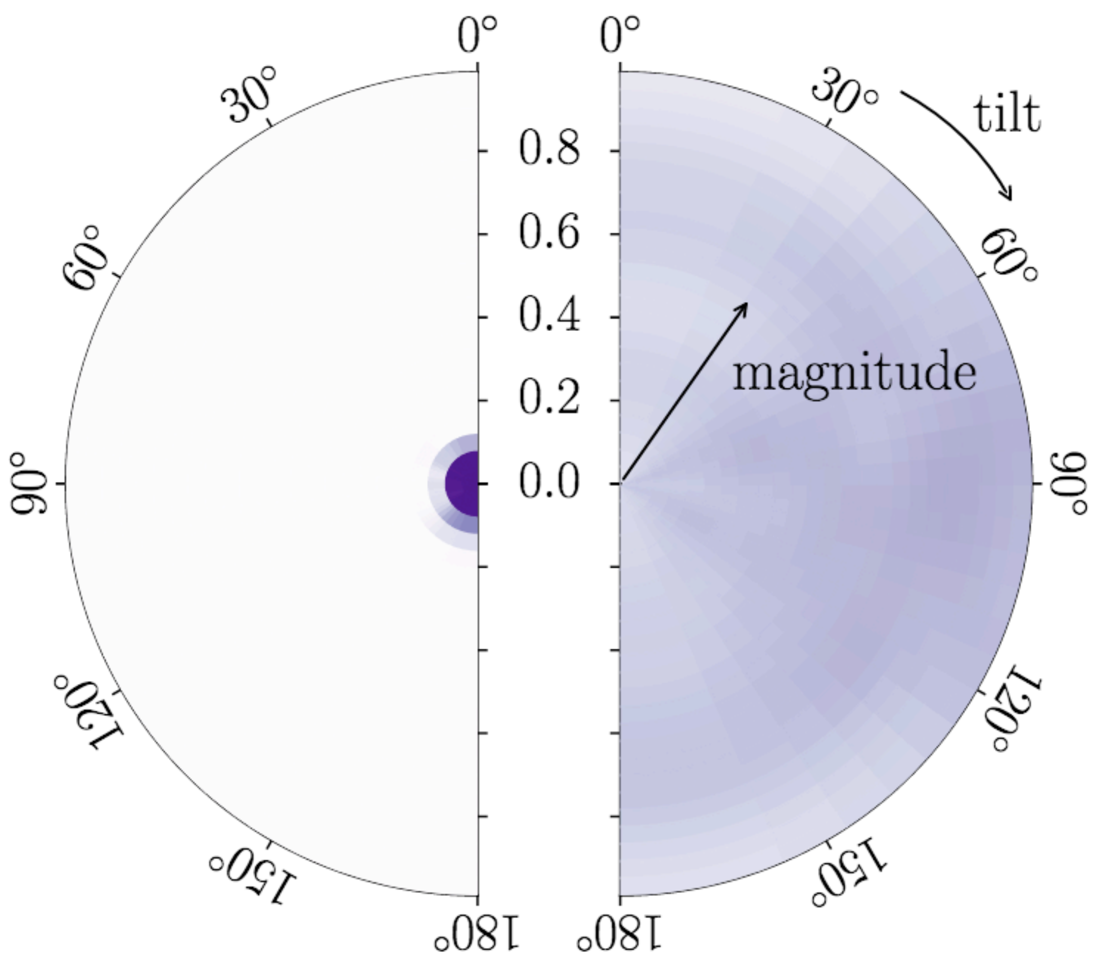
[LVC, ApJL 896:L44 (2020), LIGO-DCC G2000963]

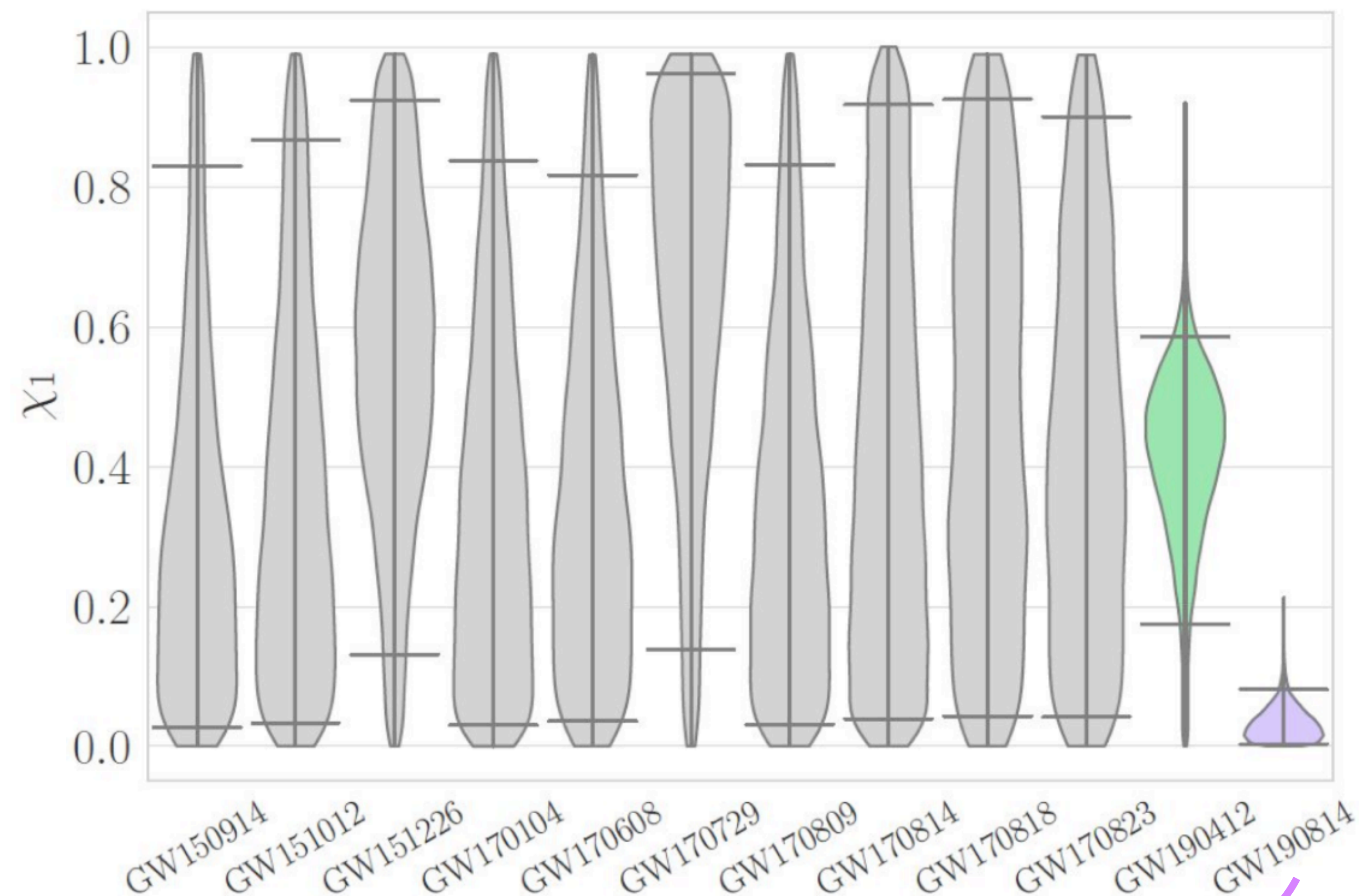


- No information about the tidal deformability of the lighter companion
- Tidal effects suppressed by asymmetric mass ratio

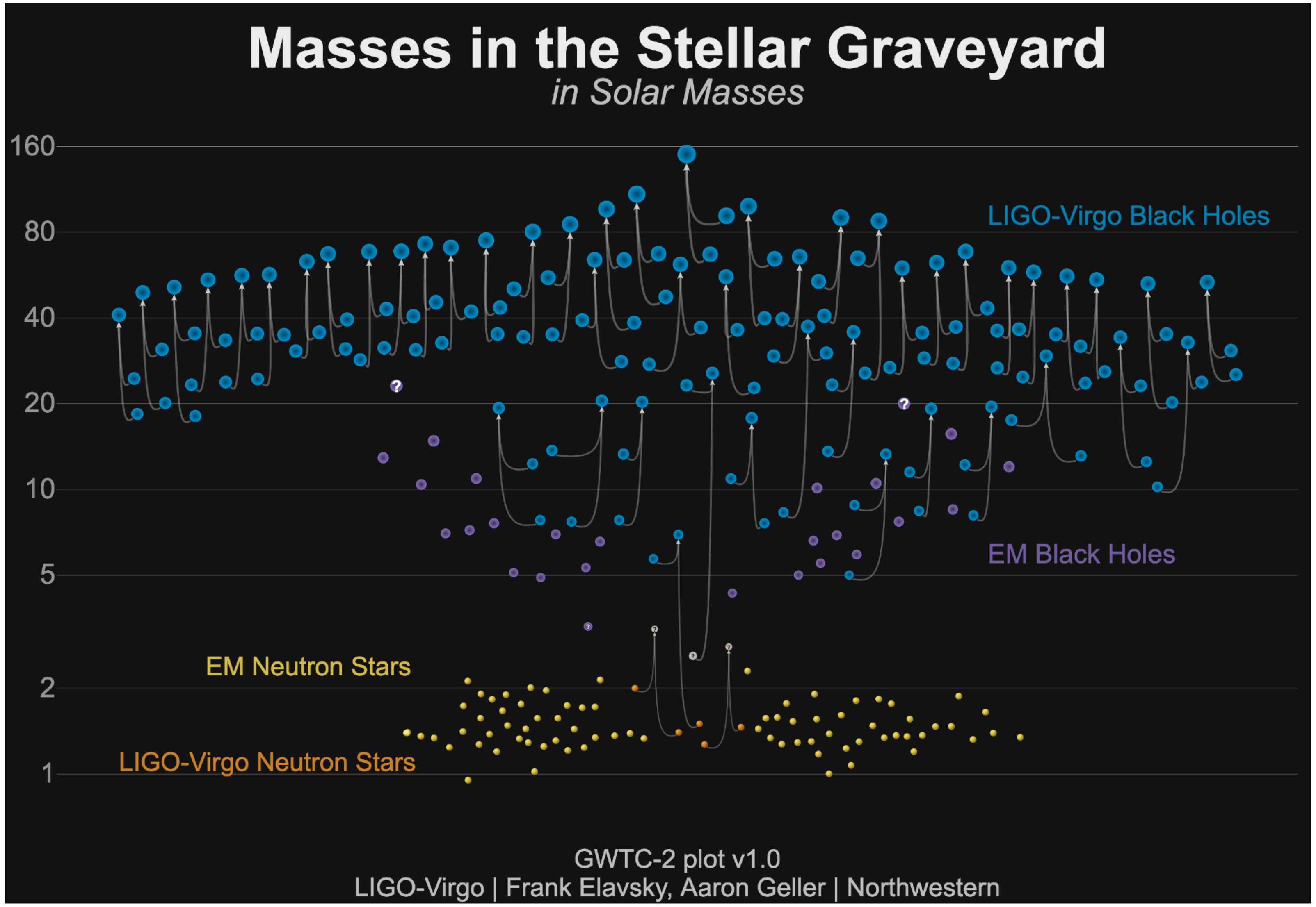
GW190814: SPINS

[LVC, ApJL 896:L44 (2020), LIGO-DCC G2000963]





low BH spin makes tidal disruption even more unlikely

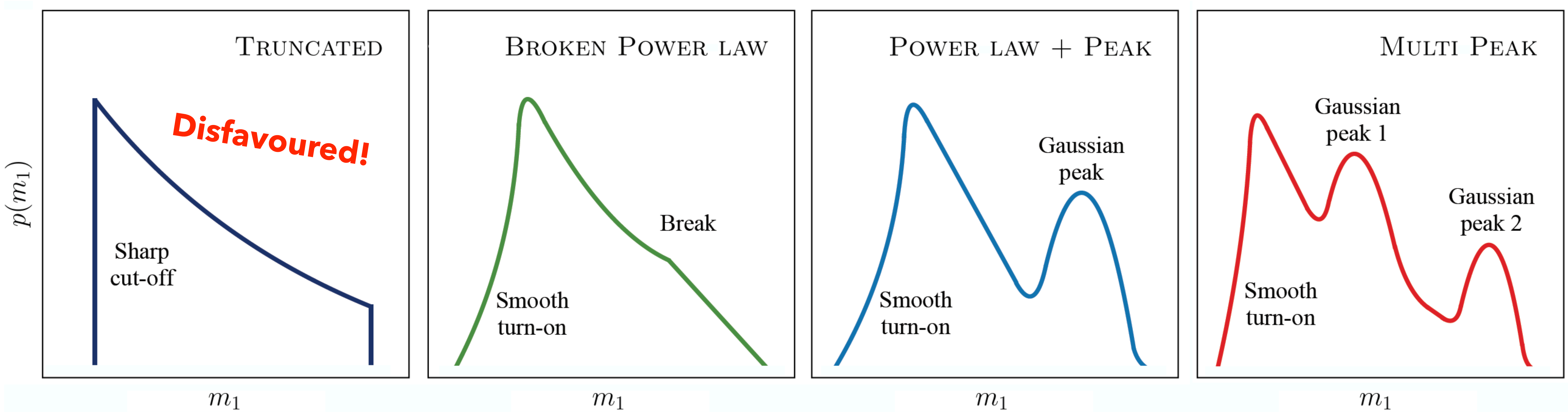


BINARY POPULATIONS

POPULATIONS OF BLACK HOLES

[LVC, arXiv 2010.14533 (2020)]

- Primary mass distribution most consistent with a broken power law or a power law with a Gaussian feature



- Feature appears at $\sim 37 M_\odot$
- BH mass spectrum likely turns over at $\sim 7.8 M_\odot$
- Minimum BH mass in BBH is $\lesssim 5.7 M_\odot$: larger than the mass of BH candidates found in galactic binaries
- Models fail to fit GW190814 - Part of a distinct population?

WHAT ABOUT SPINS?

[LVC, arXiv 2010.14533 (2020)]

- Spin distributions tightly coupled to formation channel

$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot \hat{L}_N}{M}$$

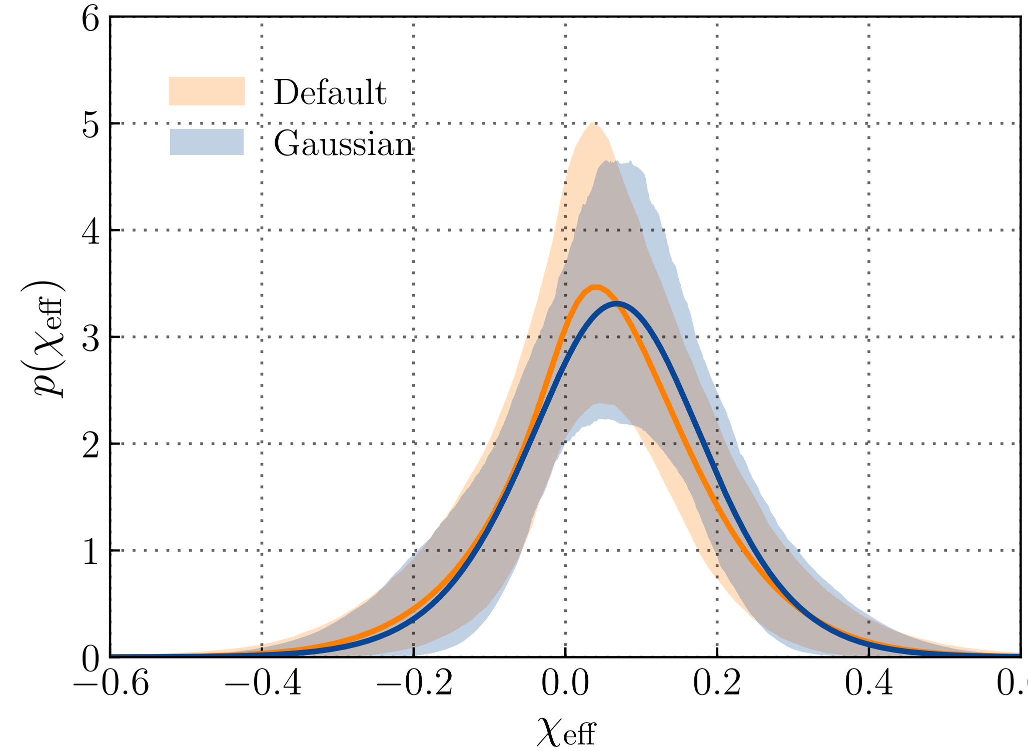
[Damour, PRD (2001);Racine, PRD (2008); Ajith+, PRL (2011)]

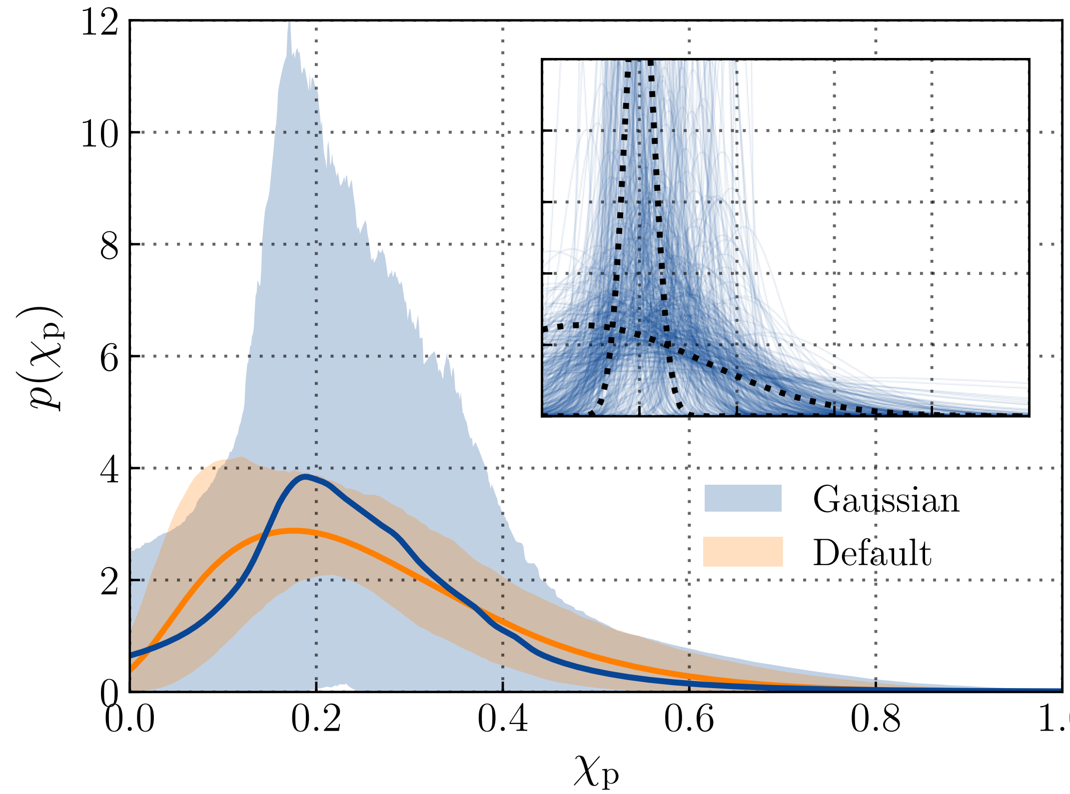
$$\chi_p := \max\left\{\frac{||\vec{S}_{1\perp}||}{m_1^2}, \kappa\frac{\vec{S}_{2\perp}||}{m_2^2}\right\}$$

$$\kappa = q(4q+3)/(4+3q)$$

[Schmidt+, PRD (2015)]

- >7% (at 99% CI) of BBH have $\chi_{\rm eff} < 0$
- Weak evidence of orbital precession among the population of BBHs in GWTC-2

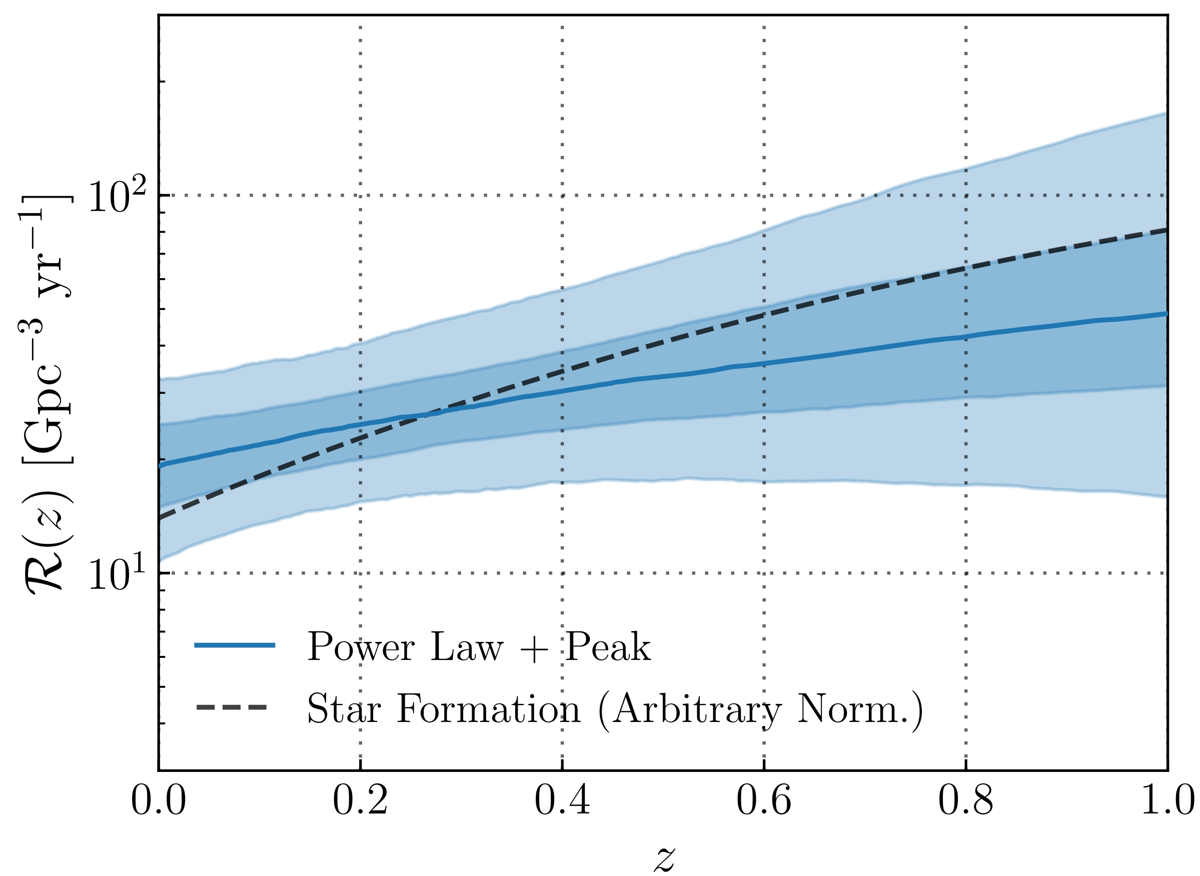




MERGER RATE OF COMPACT BINARIES

[LVC, arXiv 2010.14533 (2020)]

- Data are consistent with
  - a constant merger rate
  - a merger rate that tracks the local star formation rate (SFR)
- Preferred rate somewhere in between the two!



$$\mathcal{R}_{\rm BBH} = 23.9^{+14.3}_{-8.6}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

$$\mathcal{R}_{\rm BNS} = 320^{+490}_{-240}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

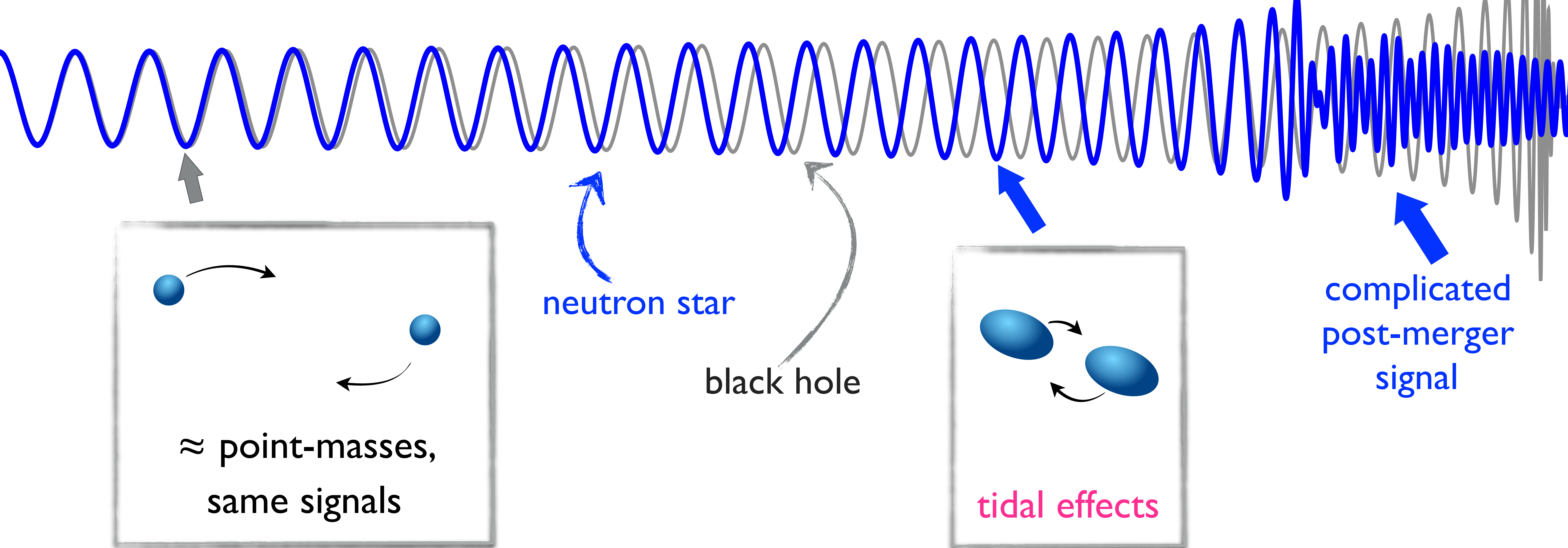
$$\frac{\mathcal{R}_{\rm BBH}(z=1)}{\mathcal{R}_{\rm BBH}(z=0)} = 2.5^{+8.0}_{-1.9}$$

$$\frac{\mathcal{R}_{\rm SFR}(z=1)}{\mathcal{R}_{\rm SFR}(z=0)} \sim 6$$

FUNDAMENTAL PHYSICS WITH GRAVITATIONAL WAVES

IMPRINT OF MATTER ON THE GW SIGNAL

Image: T. Hinderer, T. Dietrich



+ tidal excitation of internal oscillation modes

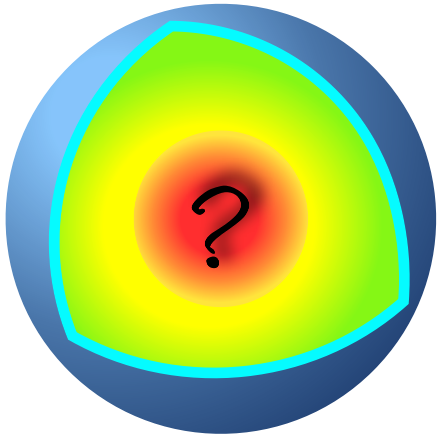
Tidally induced quadrupole moment

Some energy used to deform the NS

Moving tidal bulges produce GWs

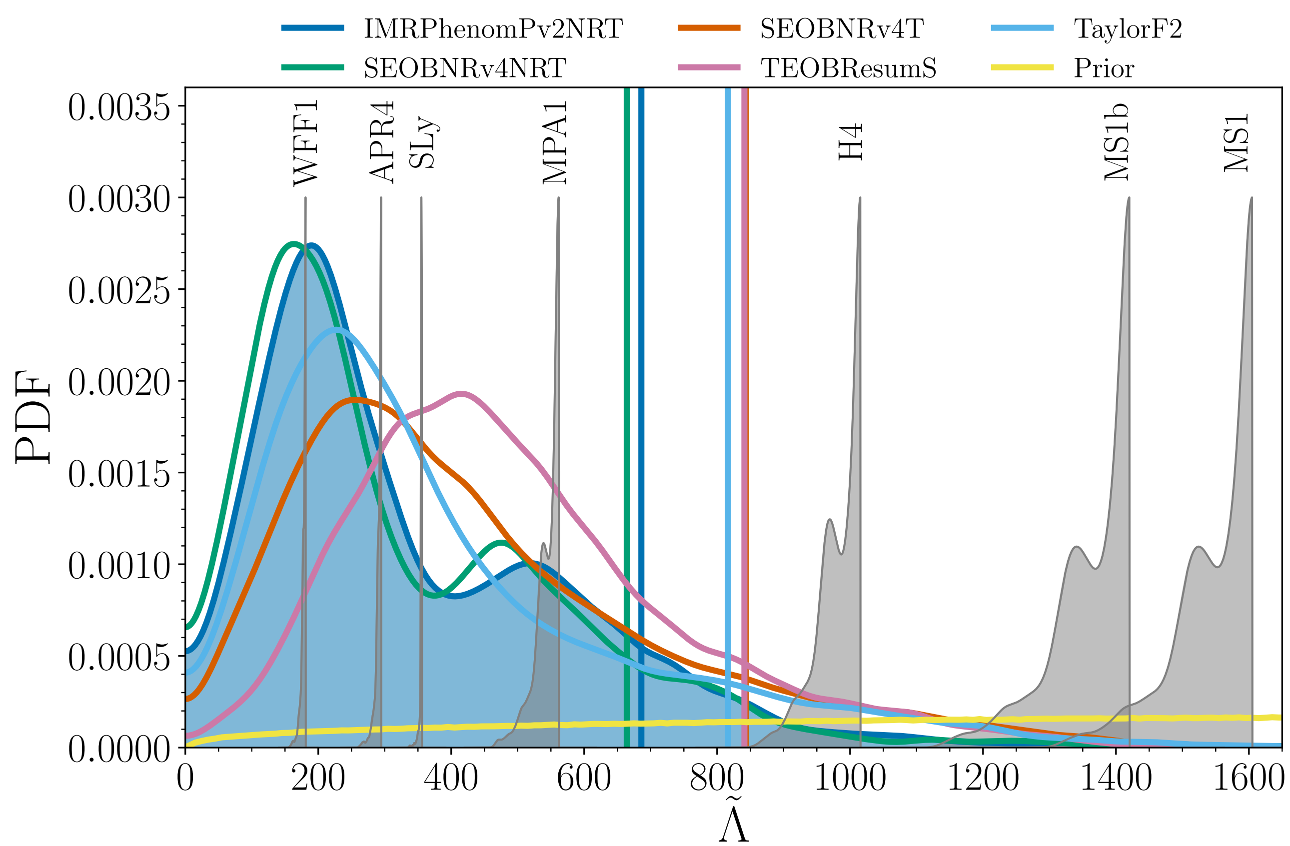
$$\dot{E}_{\rm GW} \sim \left[\frac{d^3}{dt^3}\left(Q_{\rm orbit} + Q_{\rm NS}\right)\right]^2$$

NUCLEAR PHYSICS WITH GW170817

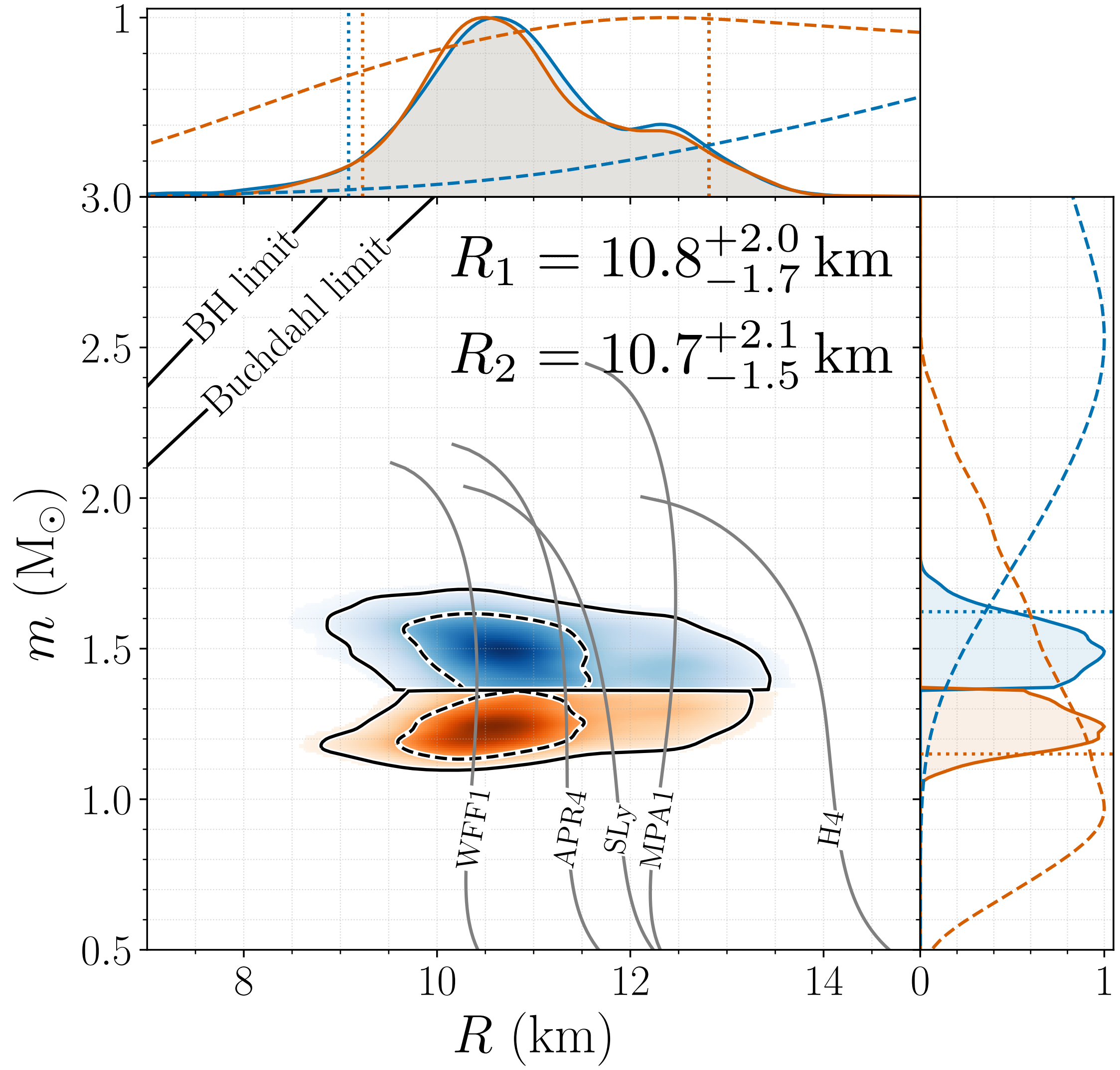


- GWs are unique probes of the neutron star interior

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$$



[LVC, PRX 9 (2019)]



[LVC, PRL 121 (2018)]

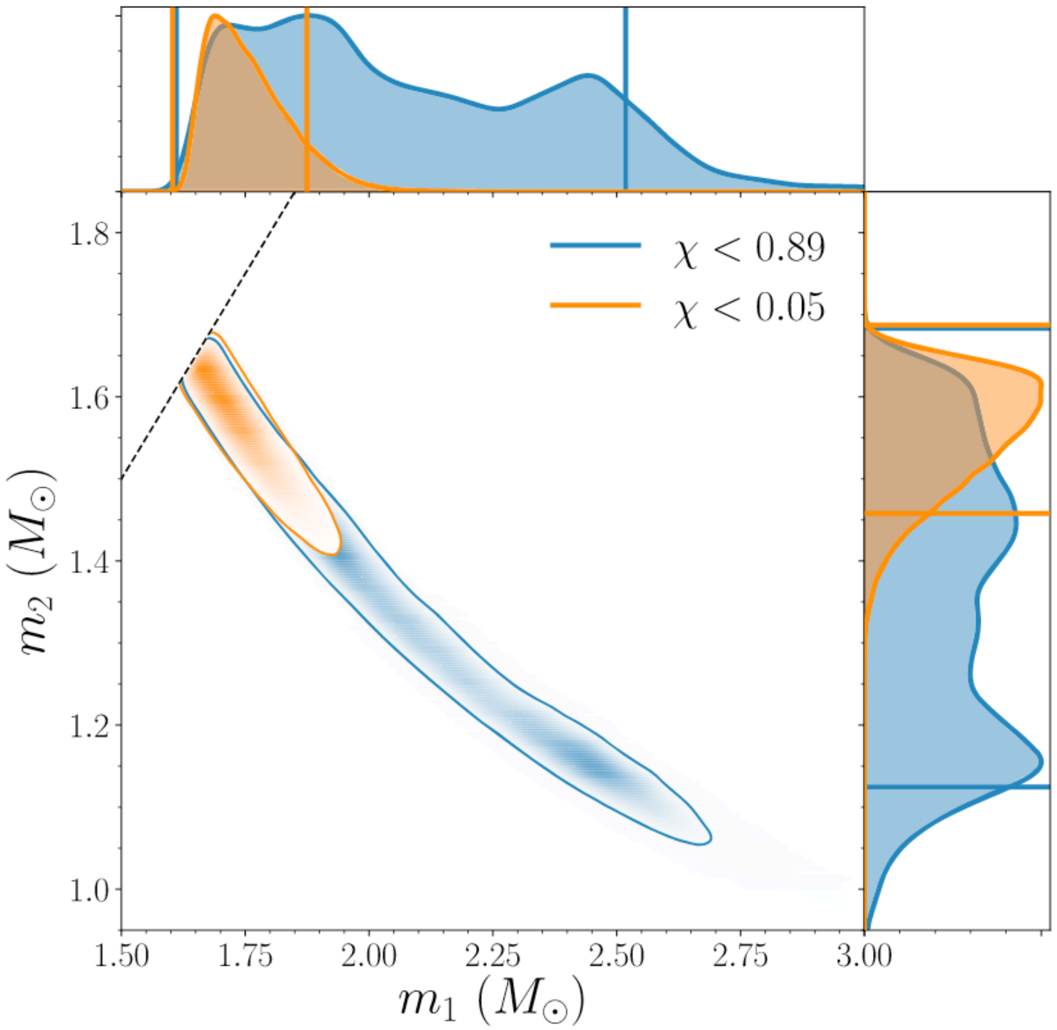
GW190425

[LVC, ApJL 892:L3 (2020)]

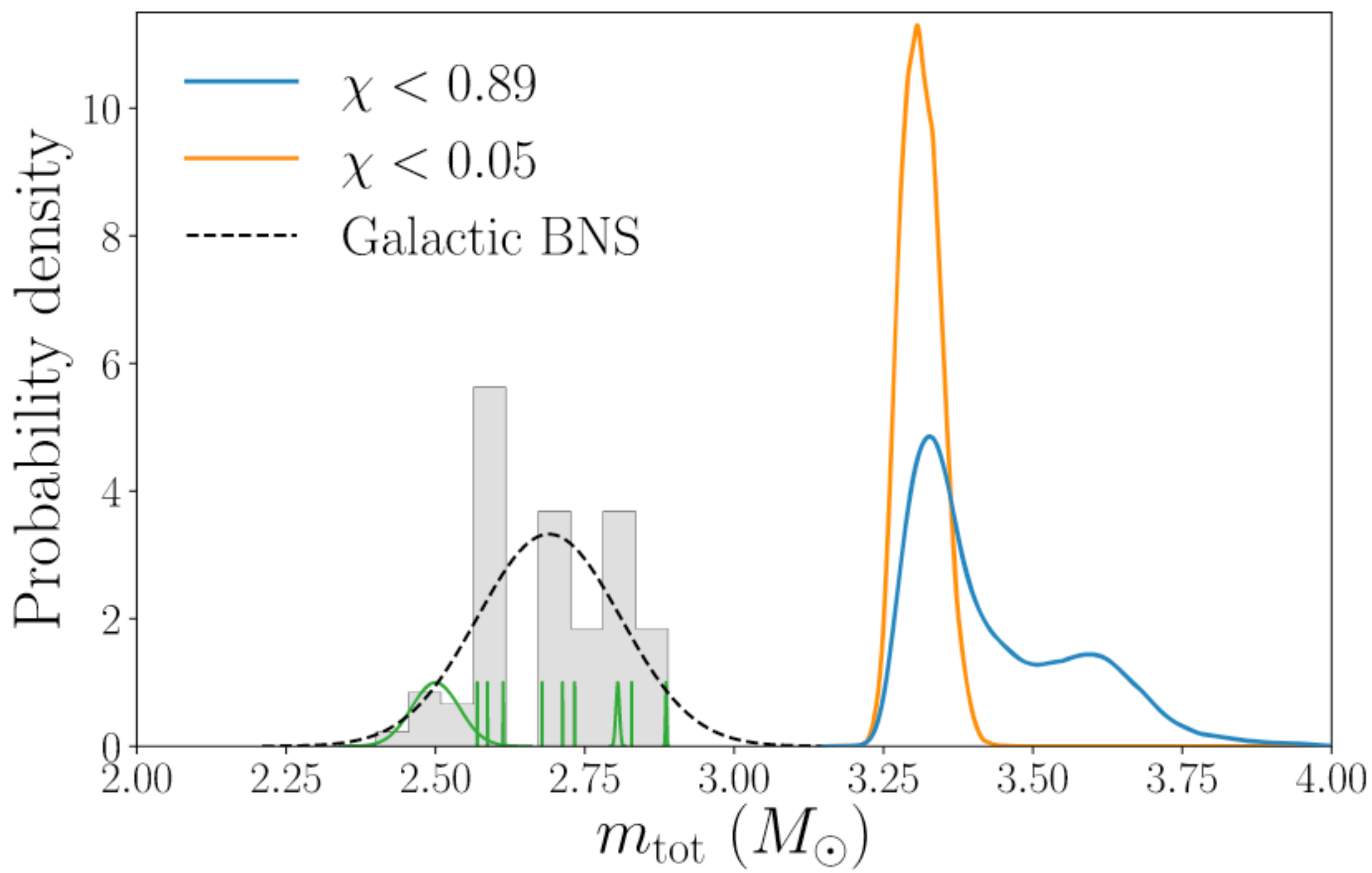
- Consistent with a neutron star binary

$$1.12 - 2.52 M_\odot (1.46 - 1.87 M_\odot)$$

  - Inconsistent with galactic BNS population
  - Tidal parameters consistent with GW170817 but less constraining

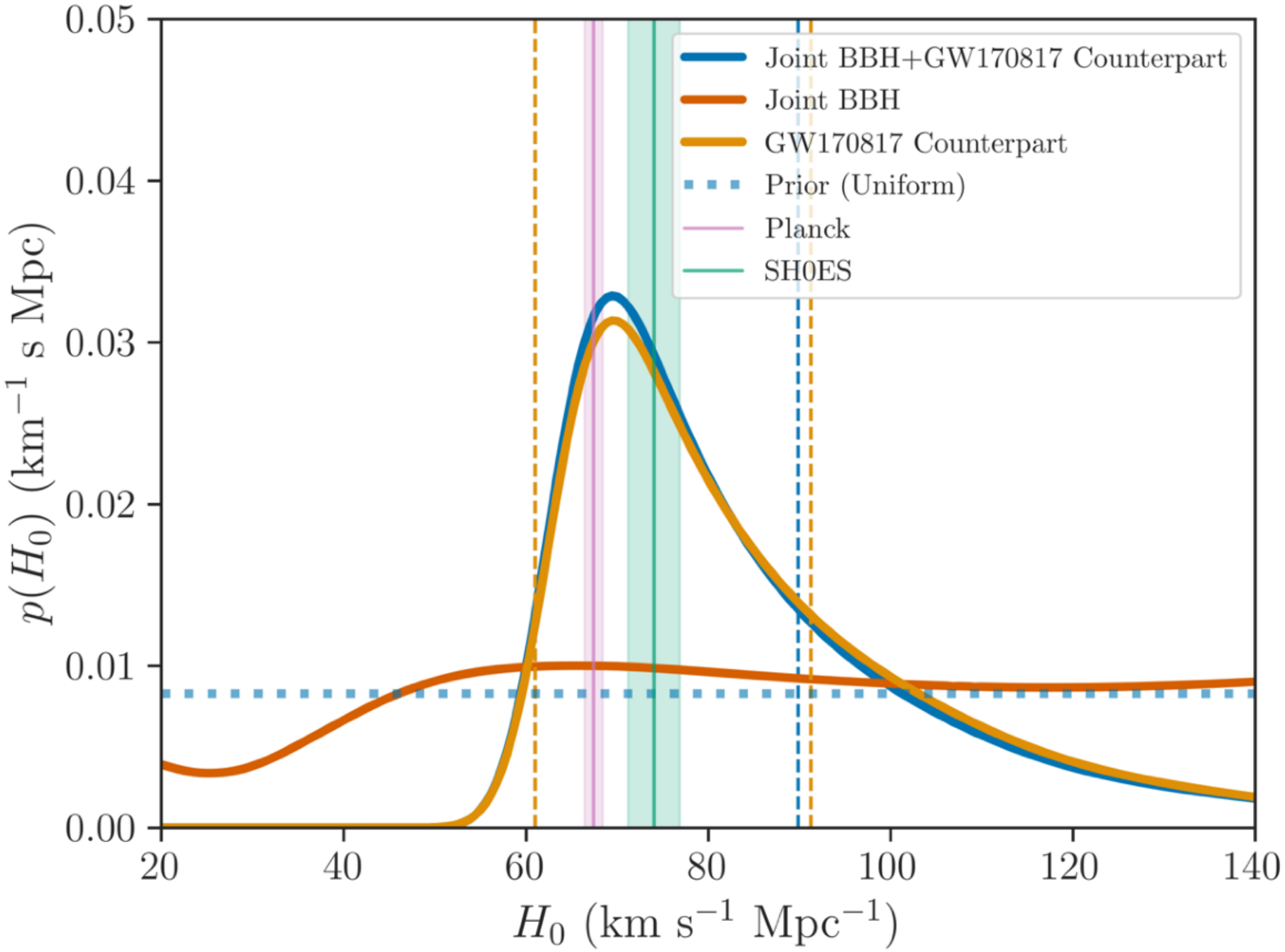


$$m_{\rm tot} \sim 3.4 M_\odot$$



COSMOLOGY WITH GRAVITATIONAL WAVES

01+02 ESTIMATE OF THE HUBBLE PARAMETER



- With EM counterpart: Determine recessional velocity from EM

$$v = H_0 d$$

- Without EM counterpart: Statistical analysis through cross-correlation with galaxy catalogues

$$H_0 = 69^{+16}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

[LVC, Astrophys J. 909, 218 (2021)]

TESTS OF GENERAL RELATIVITY

TESTING GENERAL RELATIVITY

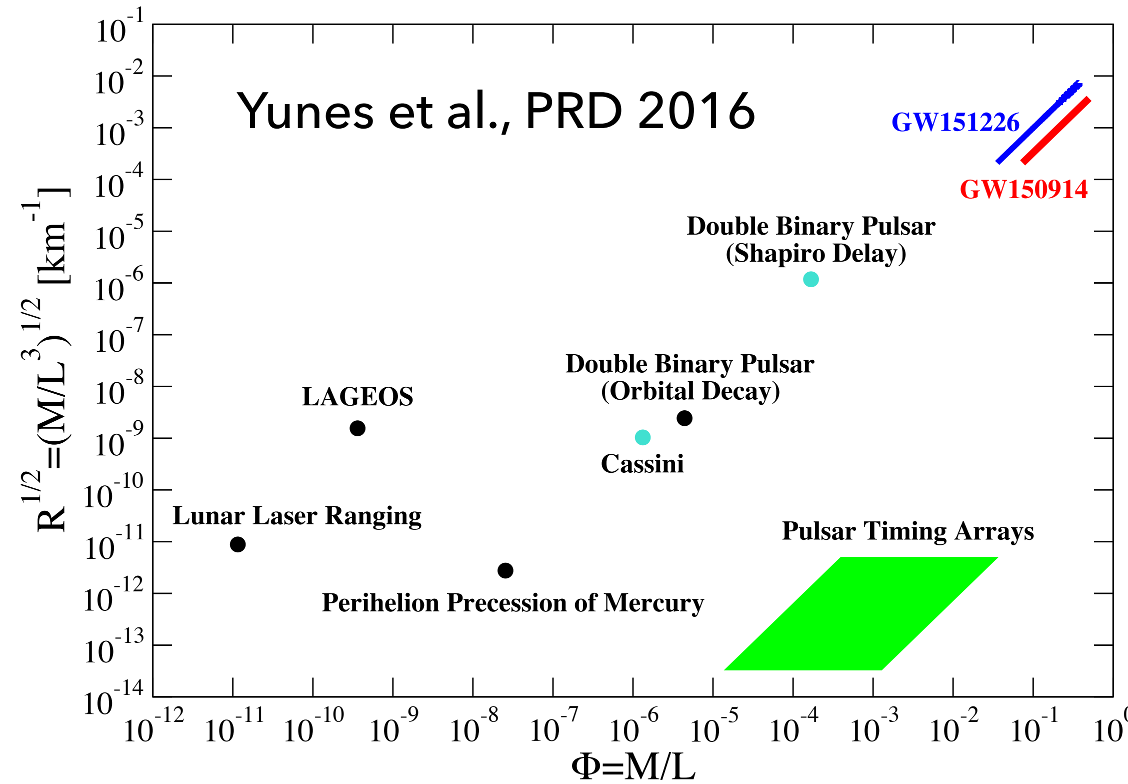
- Residual power
- Propagation of gravitational waves (dispersion)

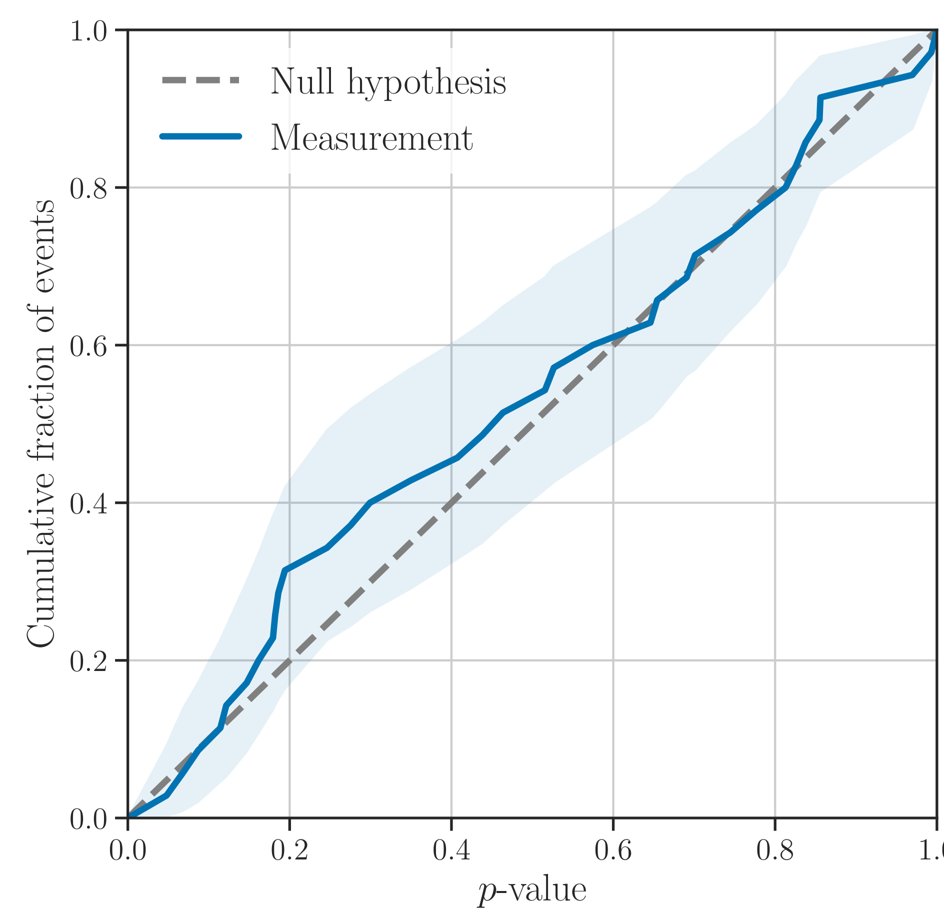
$$m_g \leq 1.76 \times 10^{-23}\,\mathrm{eV/c^2}$$

- Generation of gravitational waves (parameterised tests)
- Polarisation tests
- Tests of the nature of the remnant
- Consistency between progenitor and remnant

We find no evidence for new physics beyond general relativity, for black hole mimickers, or for any unaccounted systematics.

[LVC, arXiv:2010.14529]





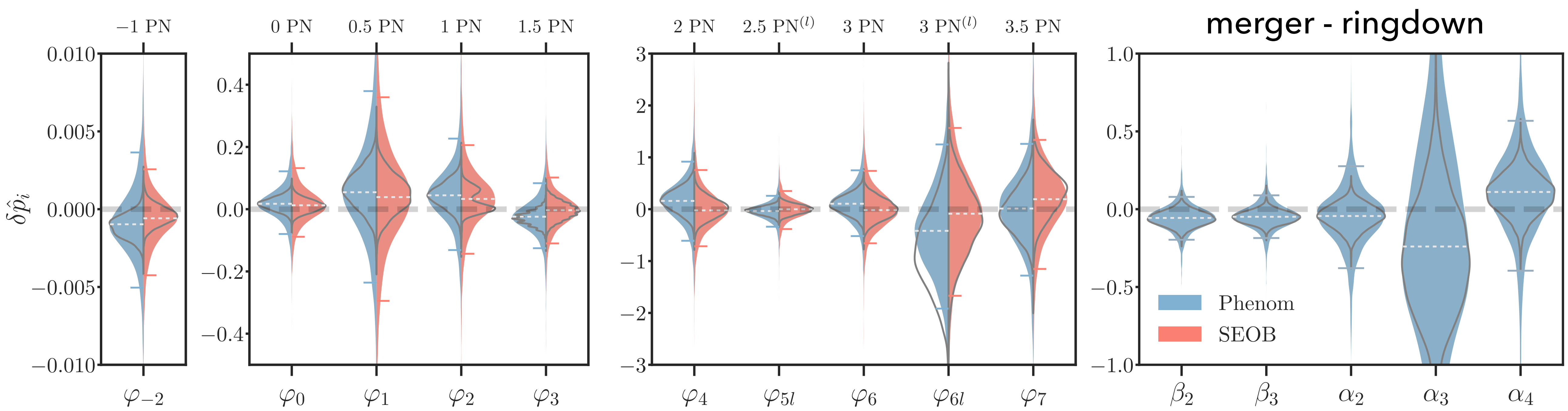
TESTING GENERAL RELATIVITY

[LVC, arXiv:2010.14529]

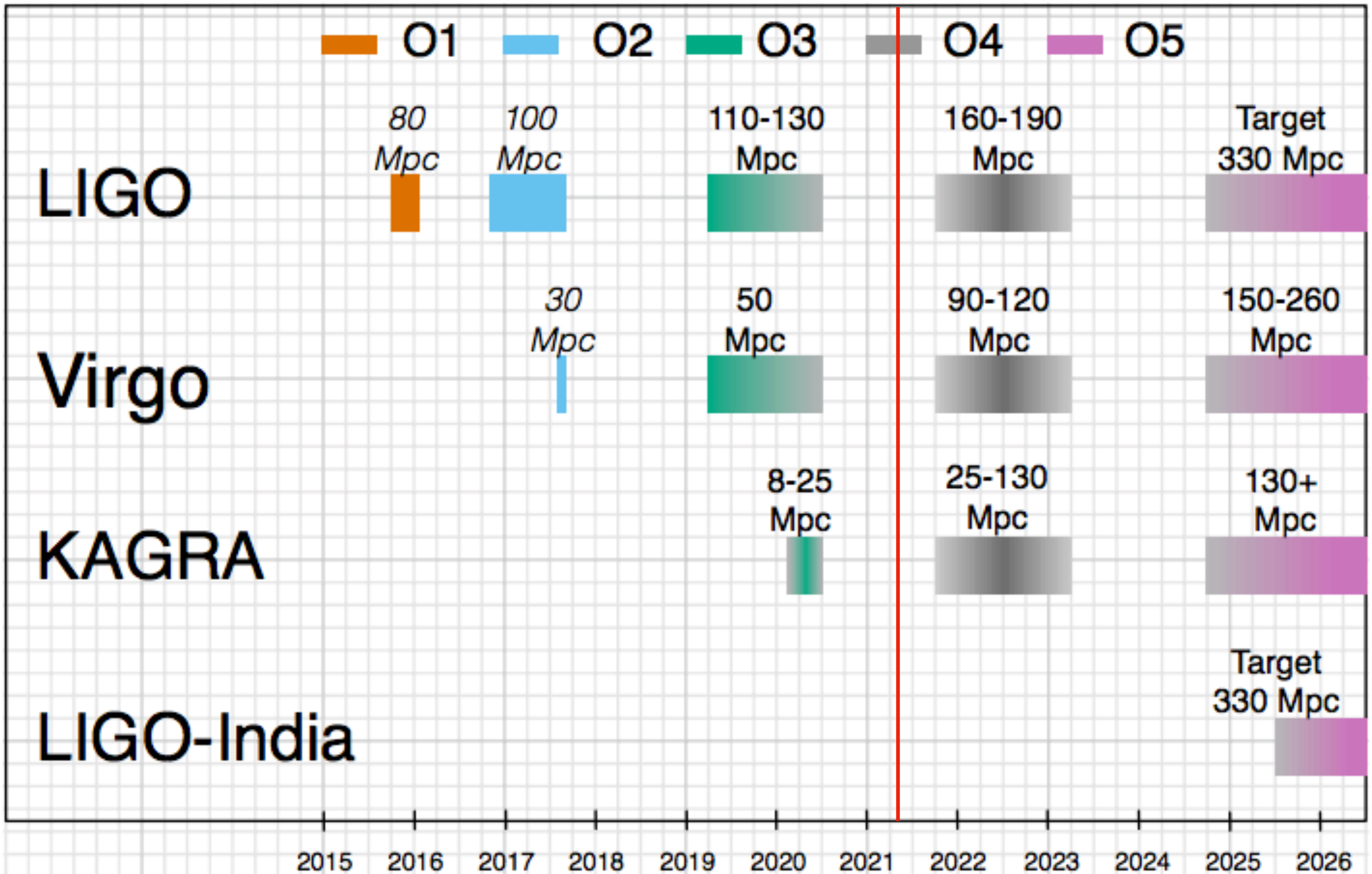
- Example: Parameterised tests
  - Test the generation of GWs as predicted by GR
  - Parameterised modifications to the GW phase

$$\Phi_{\rm ins}(v) = v^{-5}\left[\phi_0 + \phi_1 v + \phi_2 v^2 + \ldots + \phi_{5l}\ln(v)v^5 + \ldots + \phi_7 v^7\right]$$

$$\phi_i \to \left(1 + \delta\hat{\phi}_i\right)\phi_i$$



WHAT'S NEXT FOR 2G?



[B. P. Abbott et al., Living Rev Relativ (2020) 23:3]