Physics and astronomy from gravitational-wave observations

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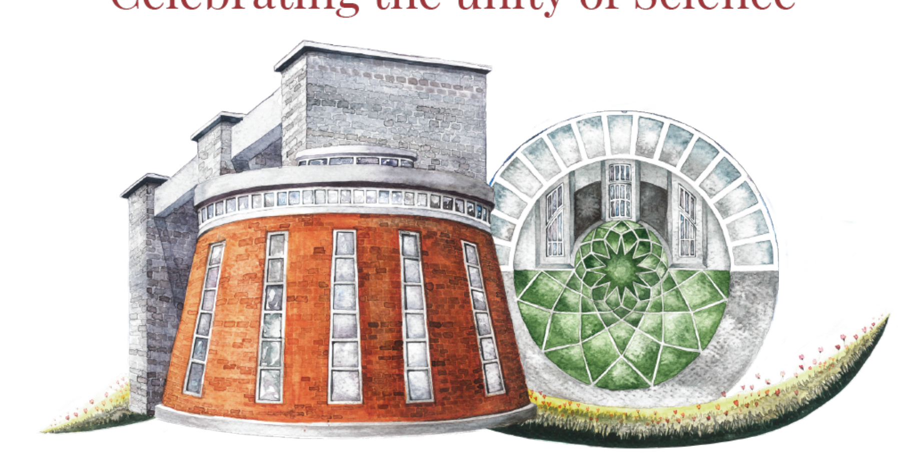
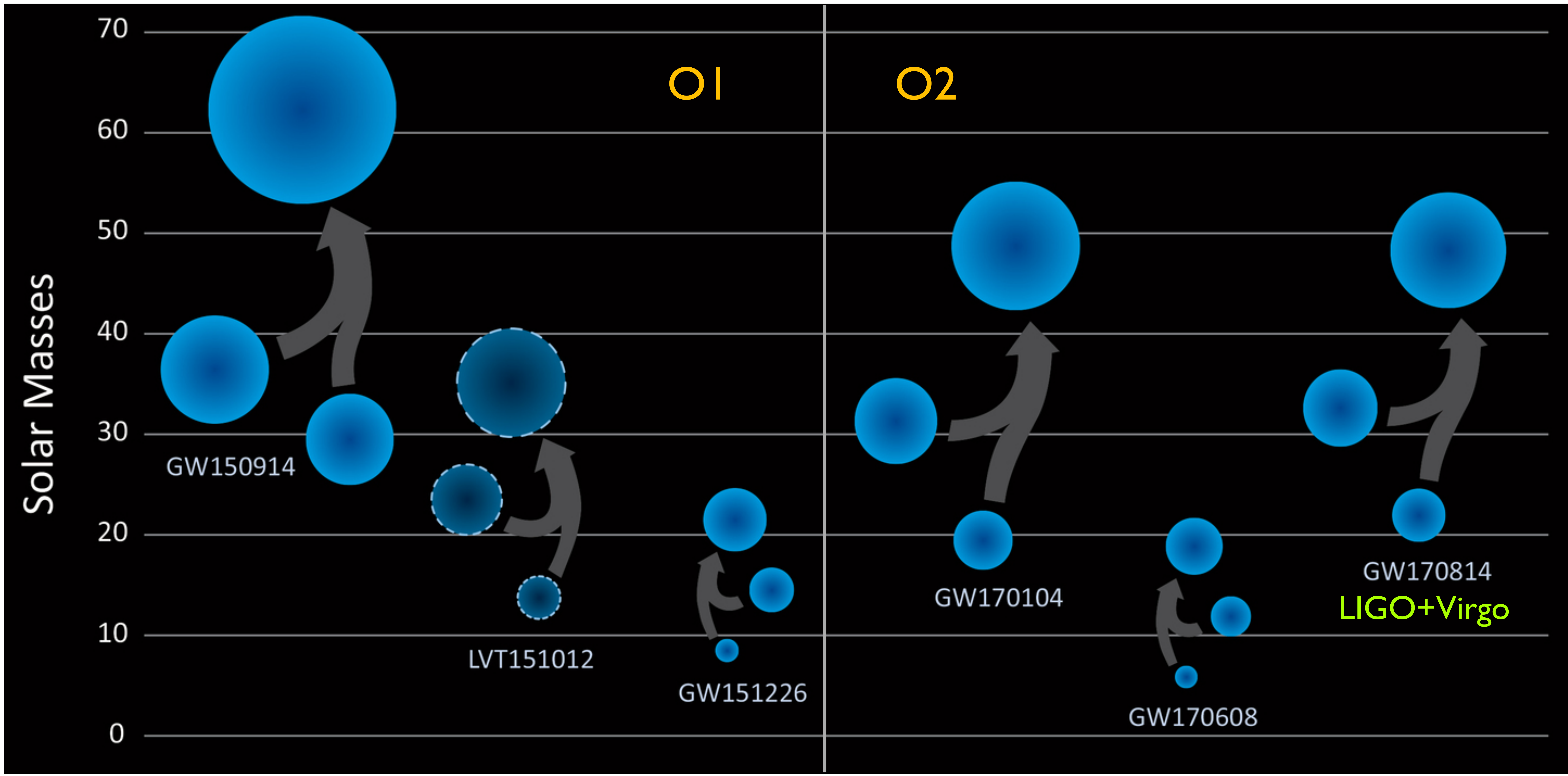
ICTS at Ten
Celebrating the unity of Science



LIGO-G1800009-v2

Several binary black hole detections by LIGO/Virgo



[LIGO-Virgo/Frank Elavsky/Northwestern]

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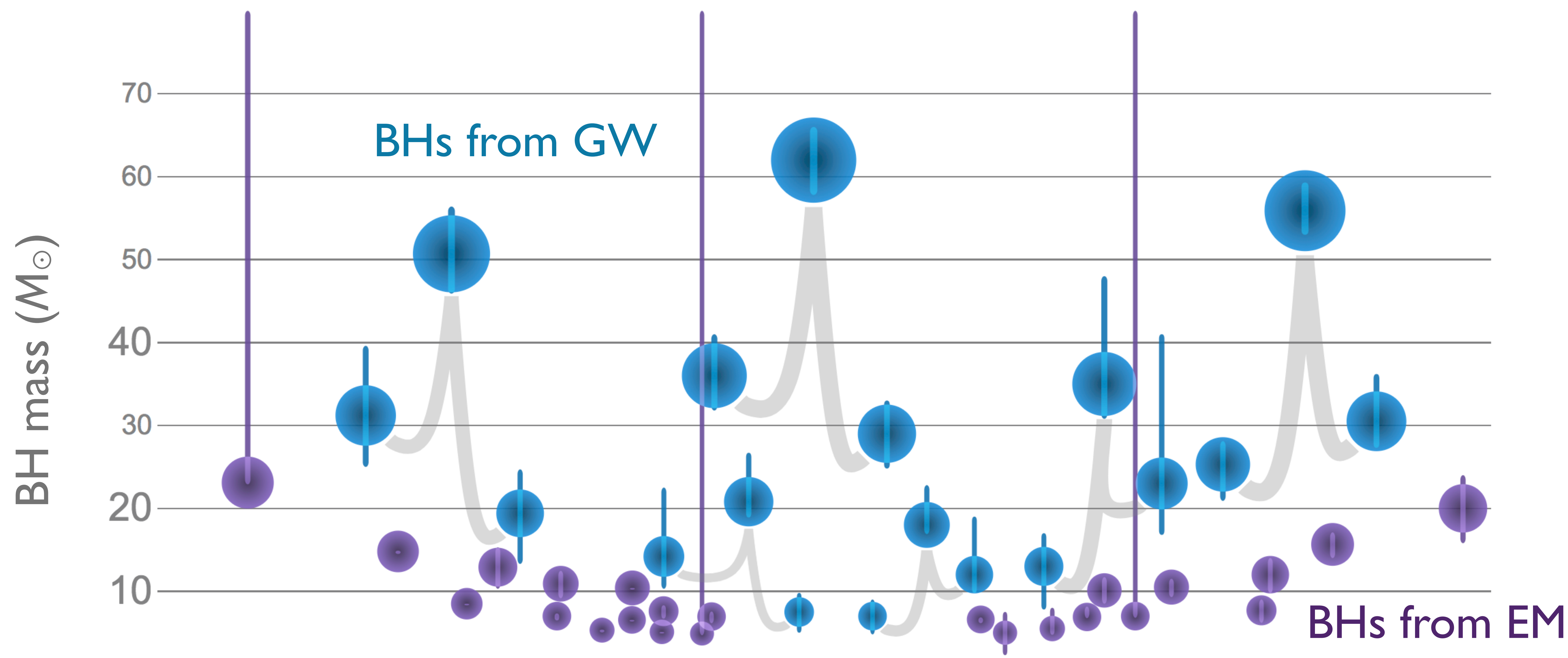
[LIGO-Virgo/Frank Elavsky/Northwestern]



- First detections of merging binary black holes.
- First observations of stellar-mass black holes with mass ≳ 30 $M_\odot$
- First tests of General Relativity in the highly relativistic regime.

GW170817: Multimessenger observation of a neutron star merger

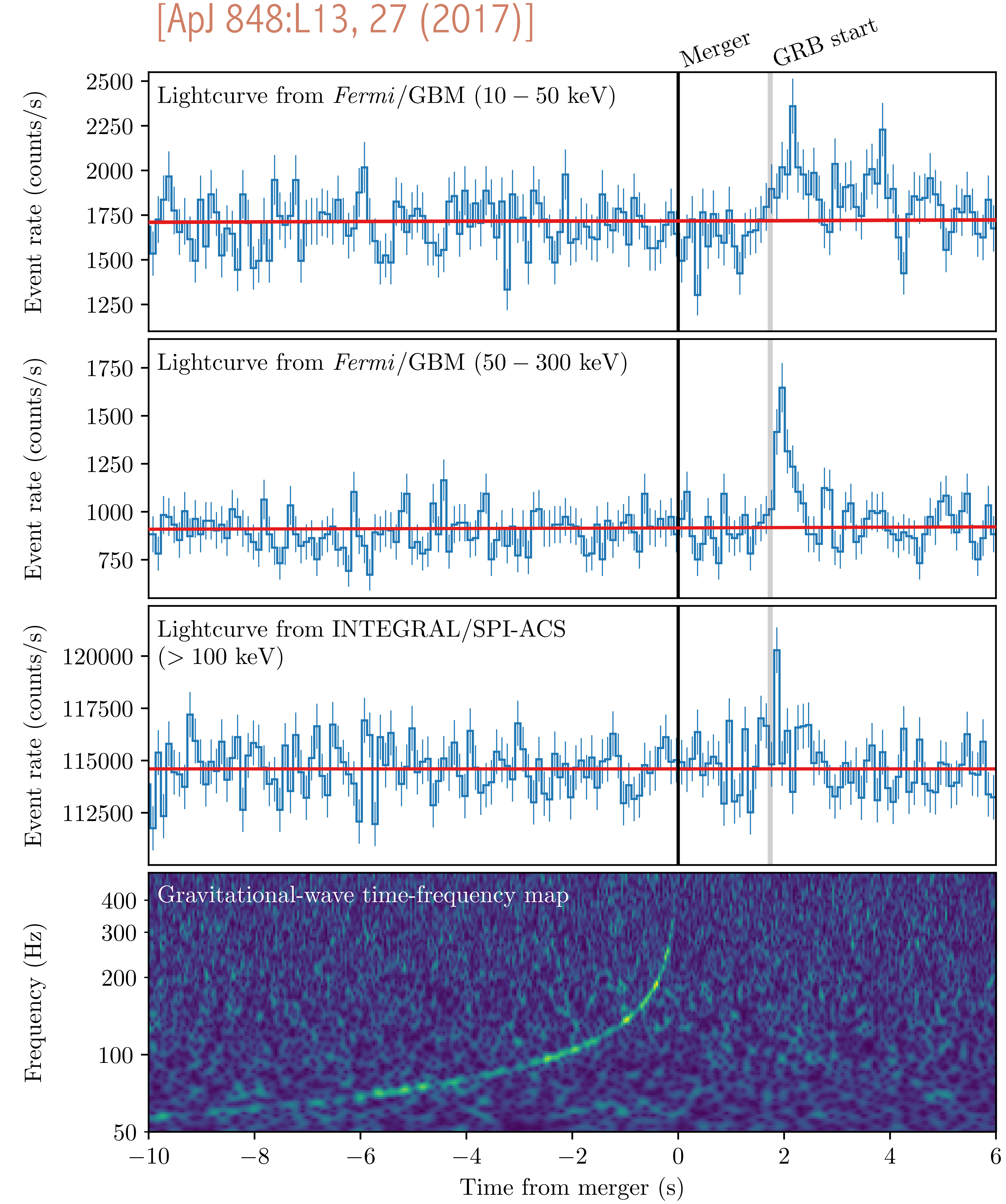
$m_1 = 1.36 - 1.60 M_\odot$
$m_2 = 1.17 - 1.36 M_\odot$

Assuming
Low spin priors

$m_1 = 1.36 - 2.26 M_\odot$
$m_2 = 0.86 - 1.36 M_\odot$

Assuming
High spin priors

[ApJ 848:L13, 27 (2017)]



Spin measurements from binary black holes

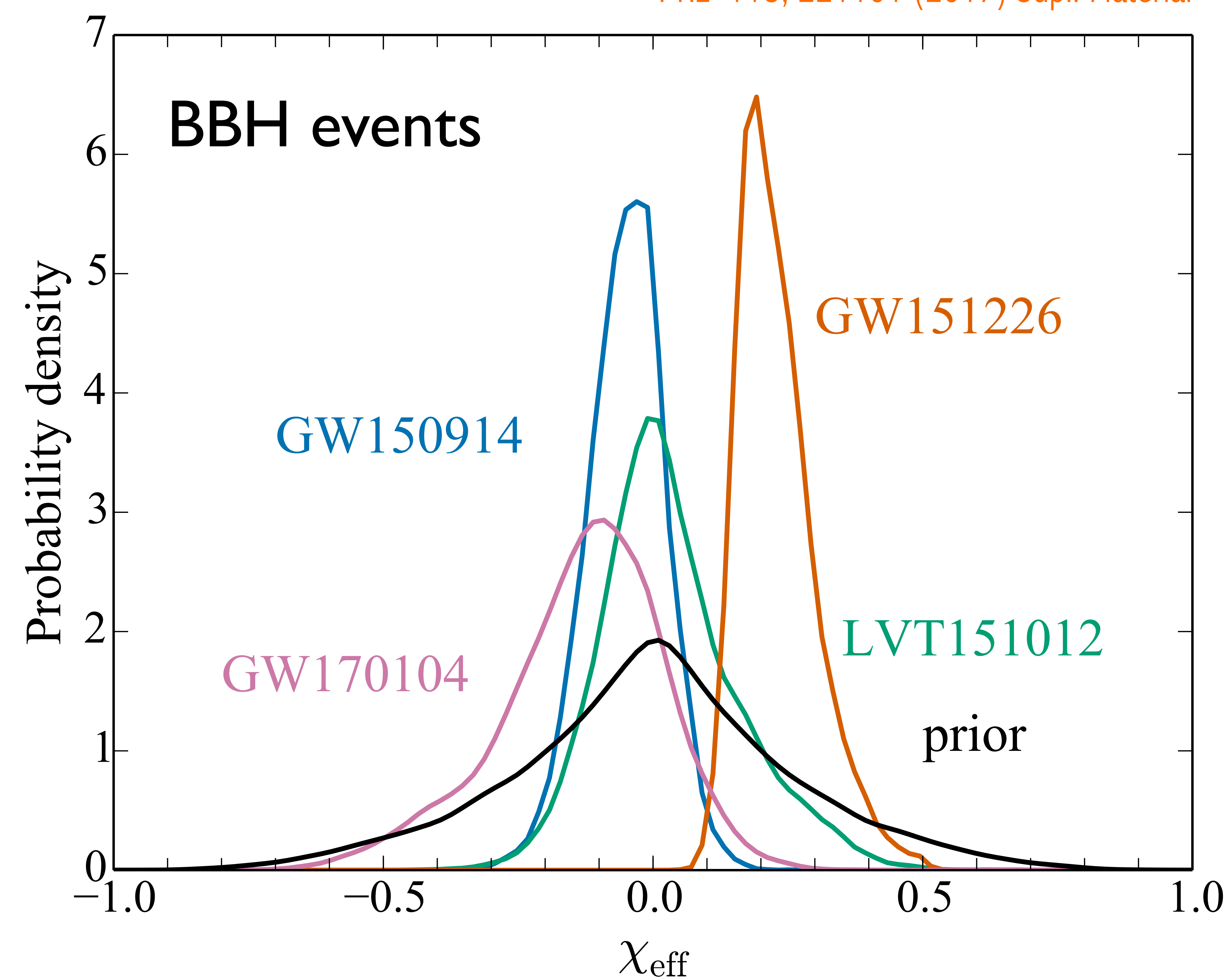
- Individual spins are not well measured. Constraints can be placed on the 'effective spin'.

$$\chi_{\text{eff}} = (m_1\boldsymbol{\chi}_1 + m_2\boldsymbol{\chi}_2)\cdot\mathbf{L}/M$$

  - So far, observations are consistent with weak/modest spins.

Implications on astrophysical formation models.

PRL 118, 221101 (2017) Supl. Material

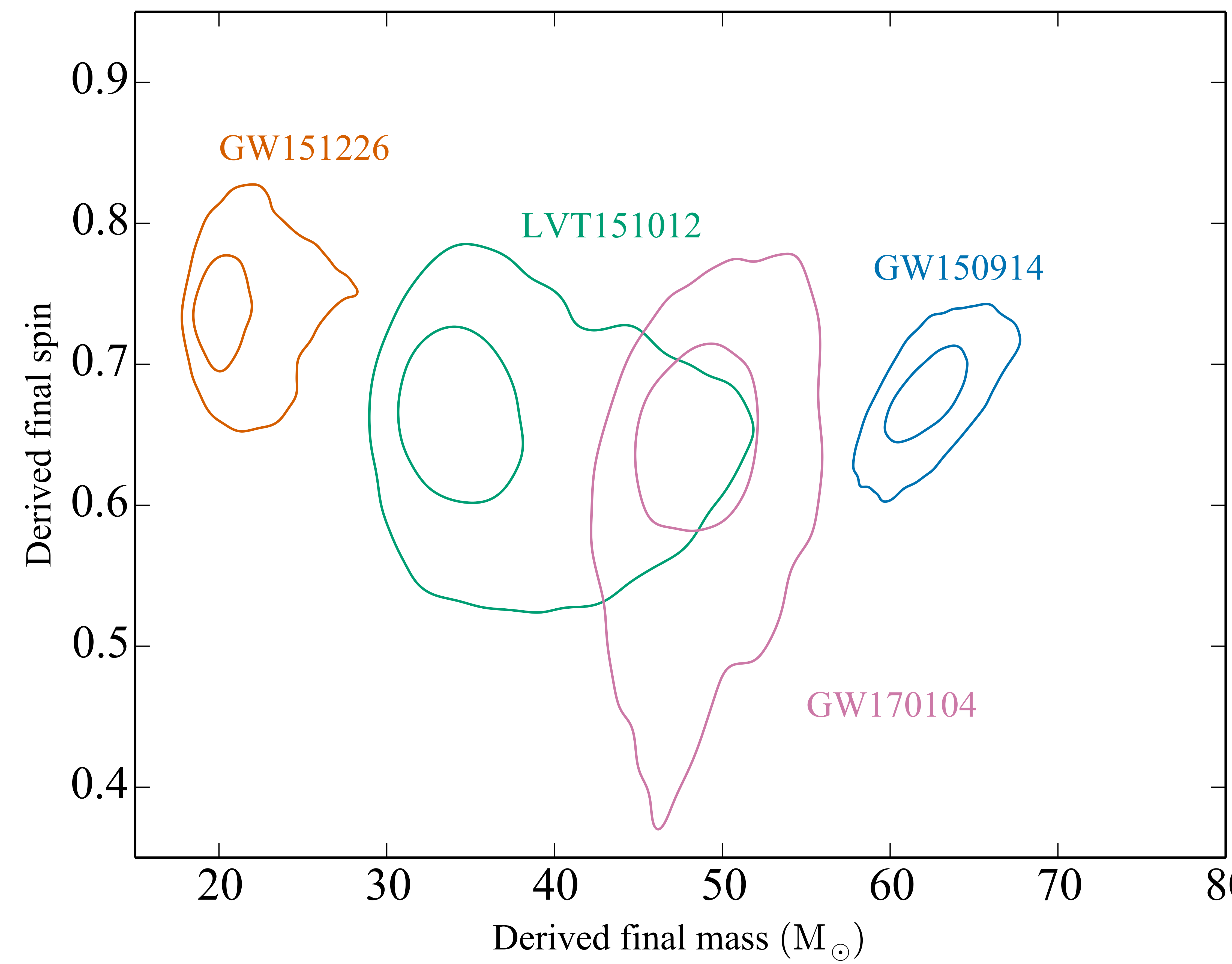


Mass and spin of remnant black holes

- Mass & spin of the remnant BH accurately inferred making use of numerical relativity simulations.

Some of the best BH spin estimates in astronomy.

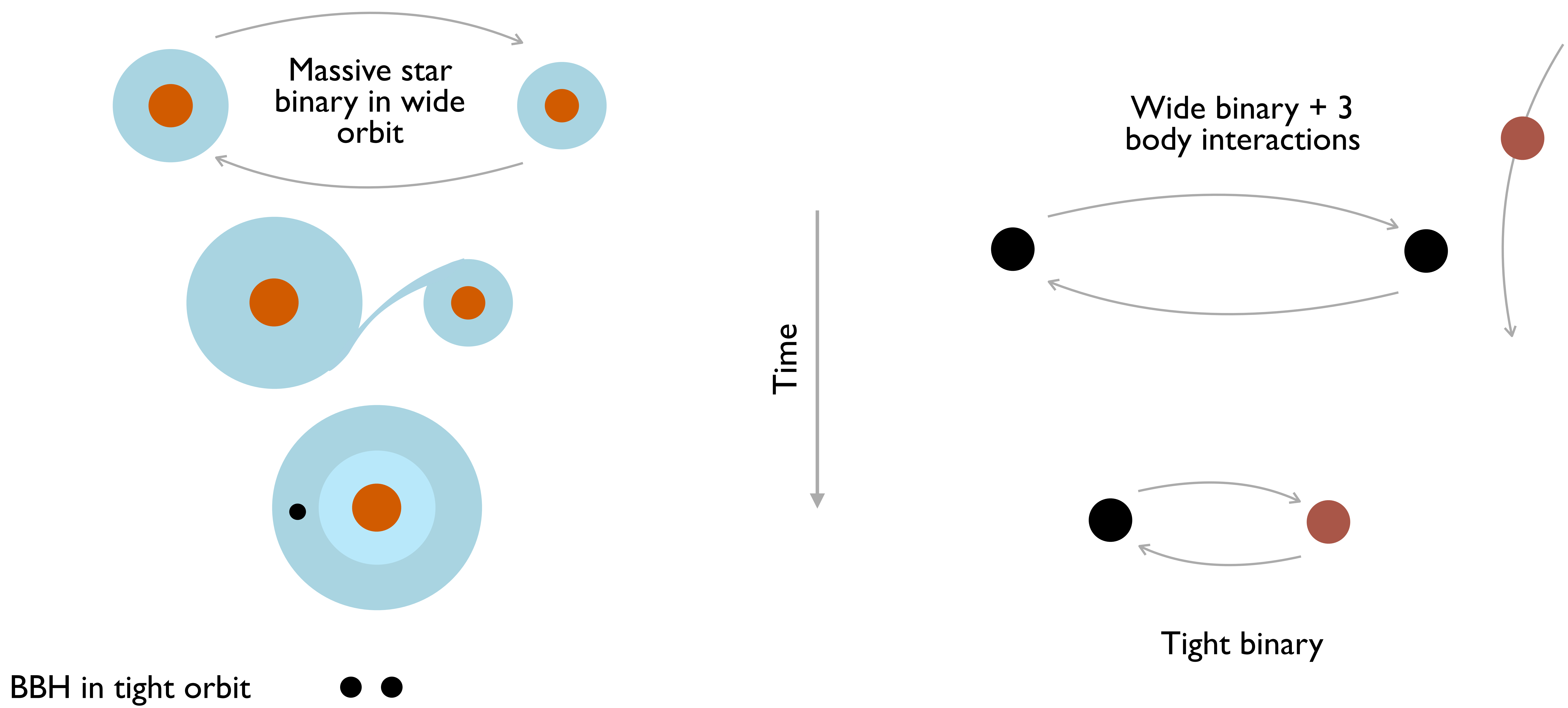
[LVC+, PRL 118, 221101 (2017) Supl. Material]



Astrophysical formation channels of BBHs: Not well understood

Isolated binary evolution

Dynamical formation



Astrophysical formation channels of BBHs: Not well understood

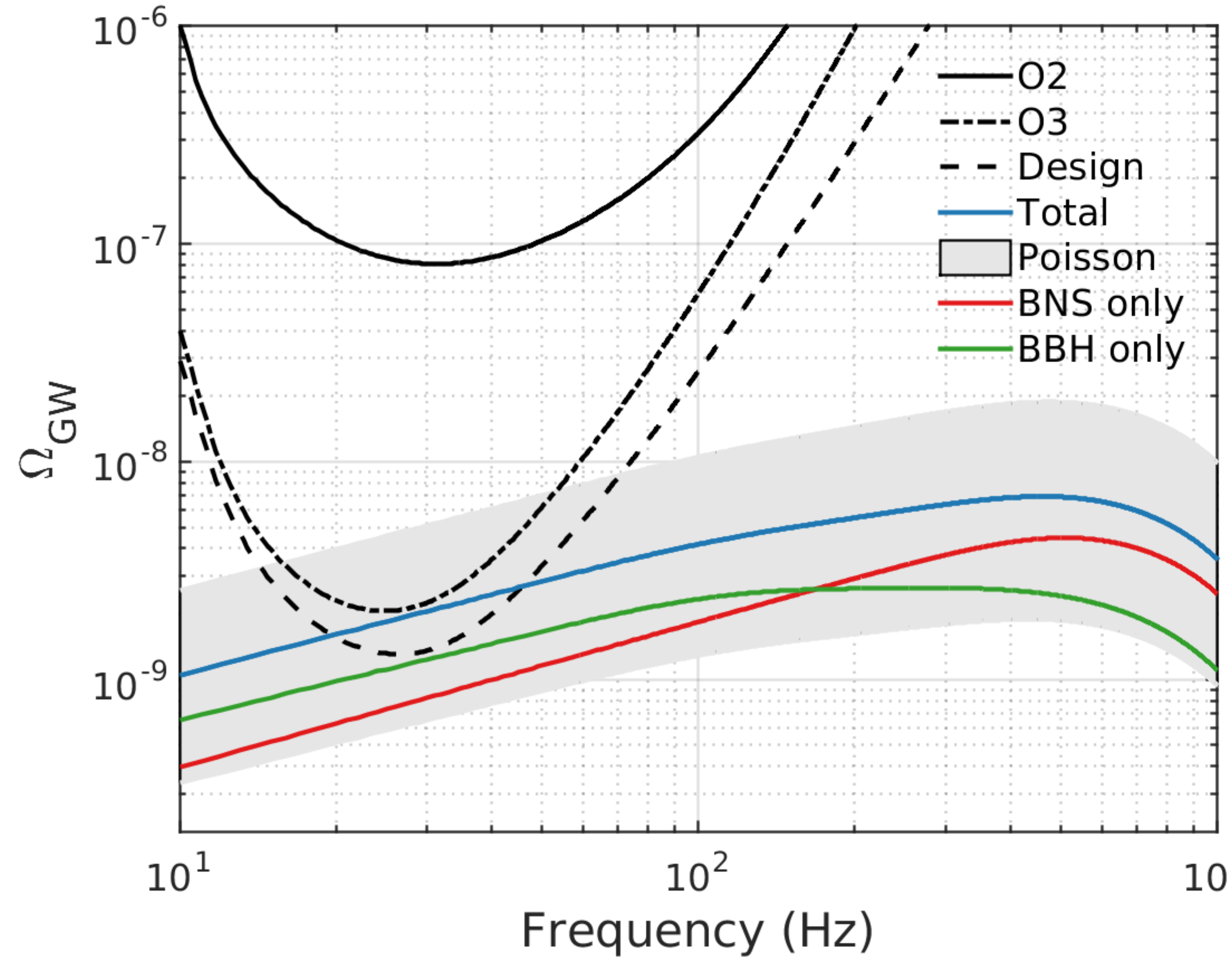
- Possible more exotic scenarios:
    - Primordial black holes.
    - Remnants of Population-III stars.

Distributions of source parameters (masses, spins, eccentricity, distance) should enable us to uncover the leading formation channels.

Merger rates and stochastic GW background

- Merger rates
  - **BNS** 320 — 3200 / Gpc³ / yr
  - **BBH** 12 — 213 / Gpc³ / yr
  - Consistent with the inferred rate from galactic BNS systems & from pop synthesis models. **Expect hundreds of detections with Adv detectors.**
- Stochastic GW background from BNS & BBH mergers potentially detectable by Adv detectors.

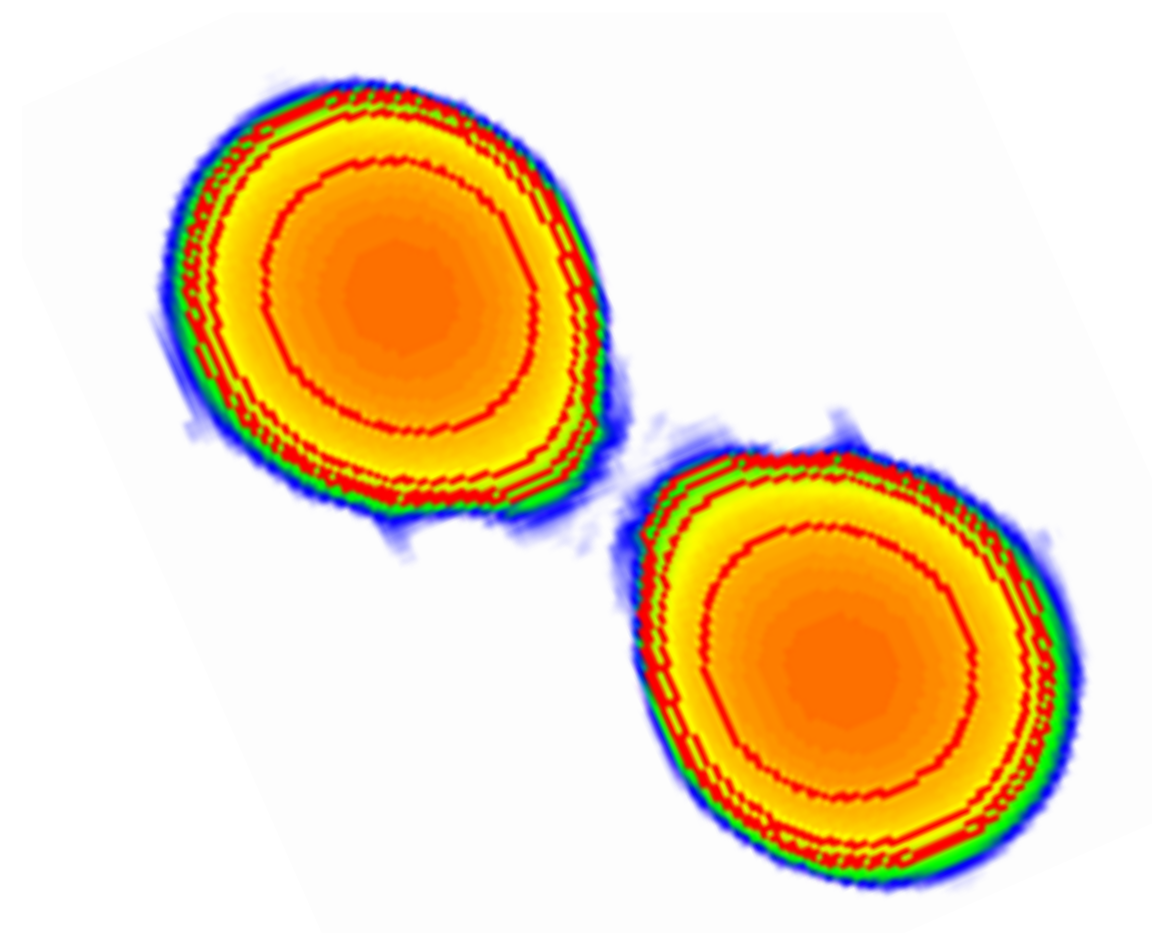
[LVC+, arXiv:1710.05837 [gr-qc]]



Equation of state of neutron stars

- Details of the internal structure of the objects becomes important at close separations.
  - Tidal deformability Λ: Ratio of the induced quadruple moment to the external tidal field.

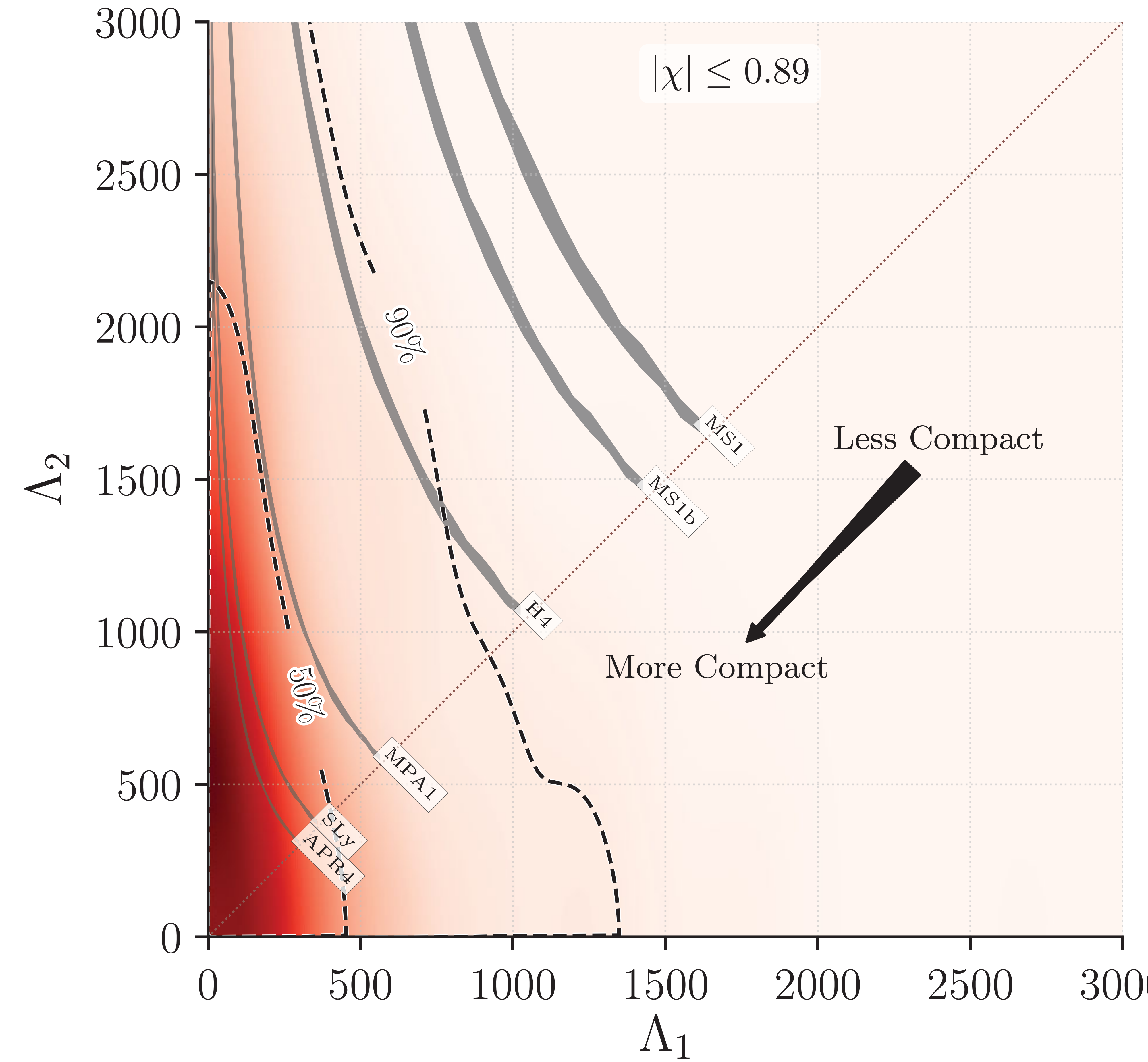
$$Q_{ij} = -\Lambda\,\mathcal{E}_{ij}$$



Equation of state of neutron stars

- Details of the internal structure of the objects becomes important at close separations.
  - Tidal deformability Λ: Ratio of the induced quadruple moment to the external tidal field.
- Constraints on Λ disfavor EoSs that predict less compact stars.

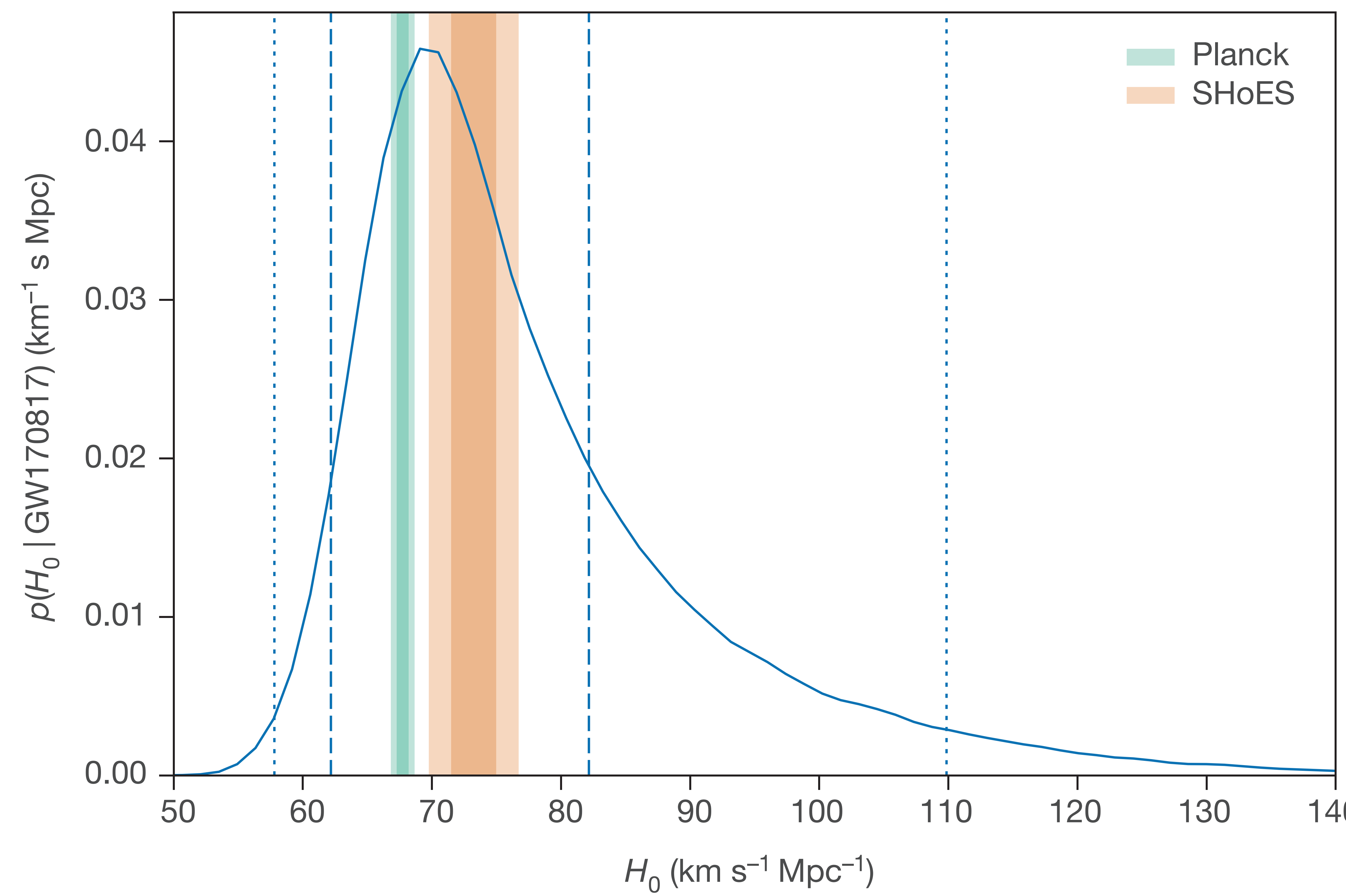
[LVC+, PRL 119, 161101 (2017)]



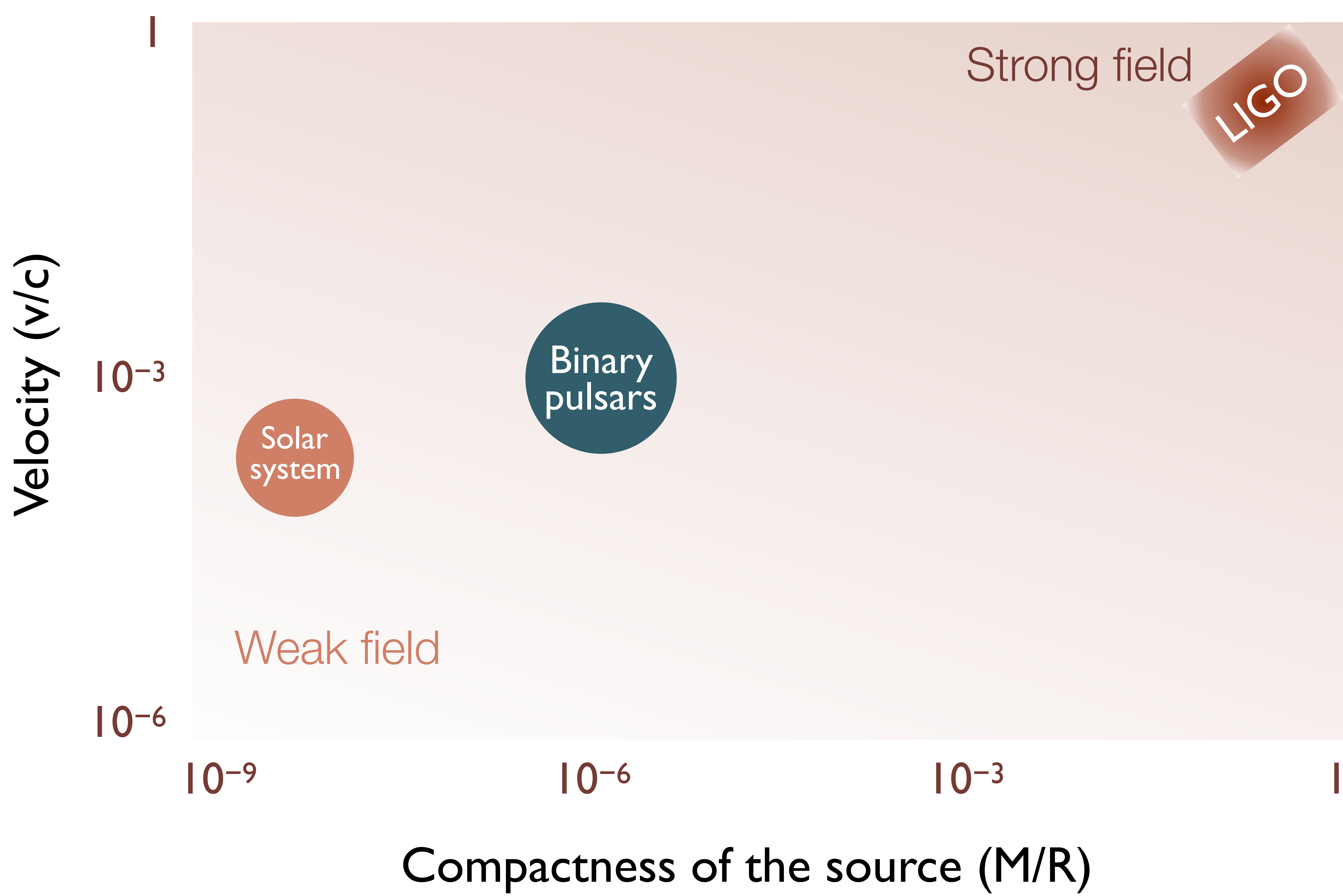
Independent measurement of the Hubble constant

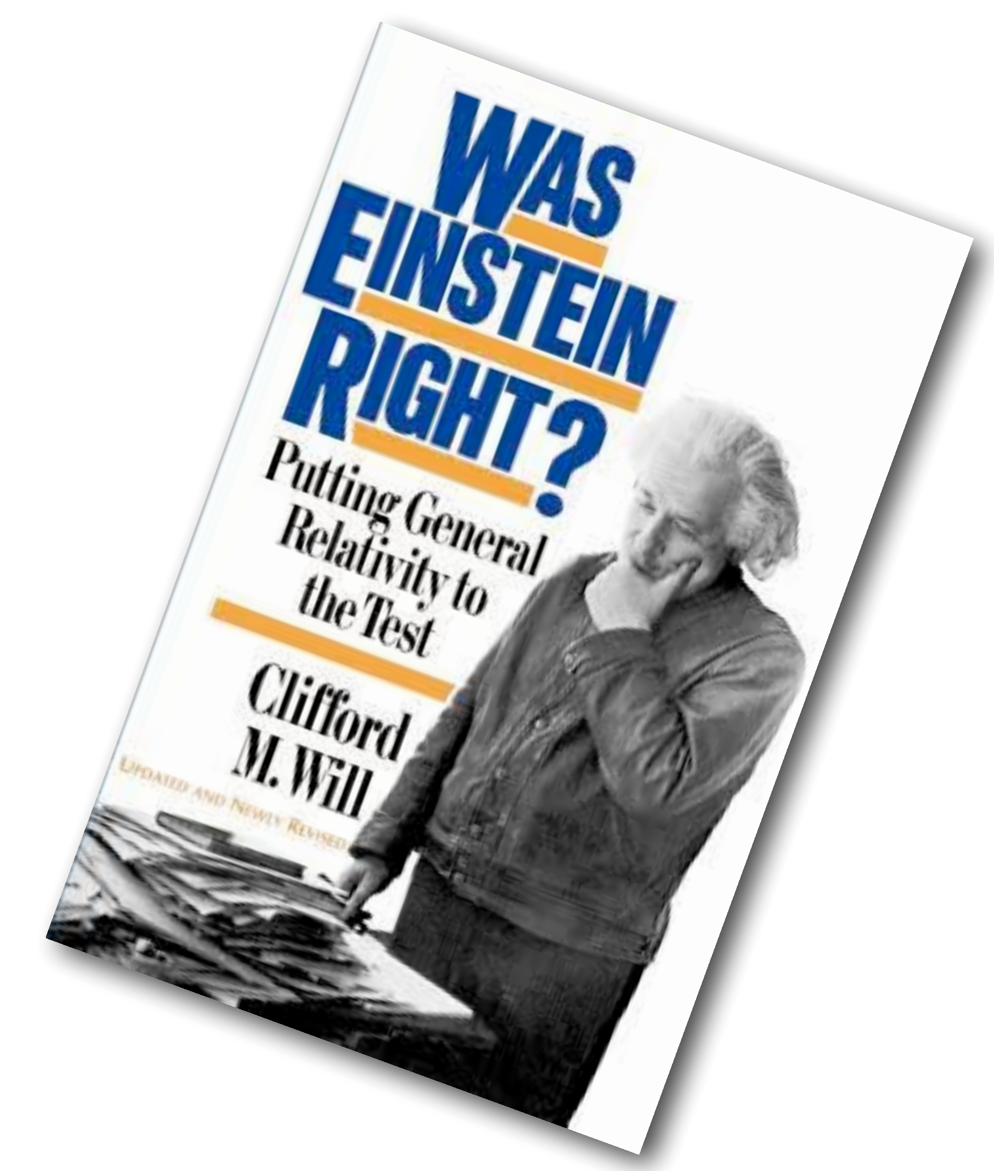
- Compact binaries are self calibrated ‘standard candles’.
  - GW observations provide an absolute measurement of the luminosity distance (without relying on the distance ladder).
  - EM observations provide the cosmological redshift.

[Nature 551, 81 (2017)]



Astrophysical tests of GR: The landscape

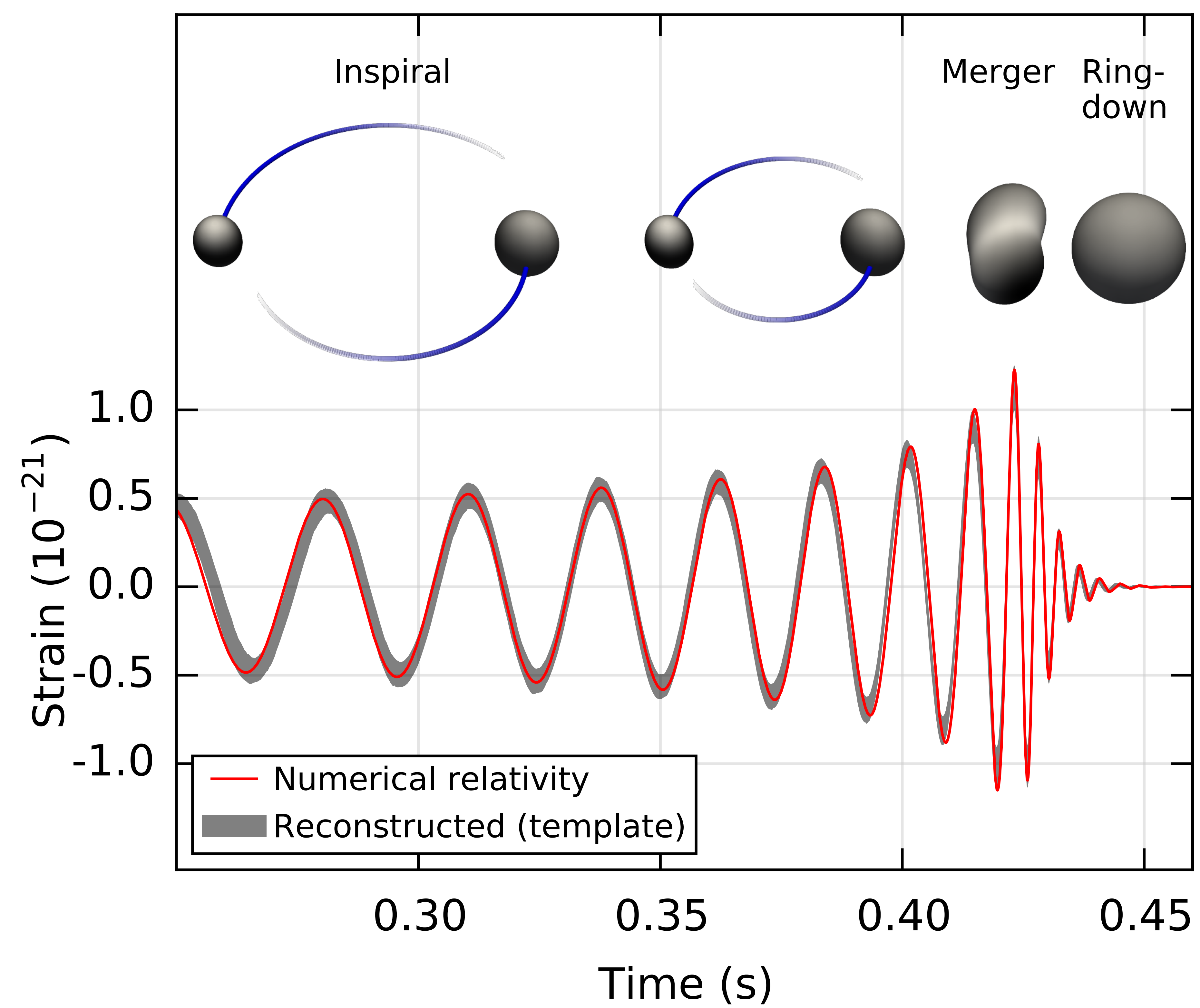




Testing post-Newtonian gravity from the inspiral signal

- Measure the deviations from the known PN coefficients of the GW phase by treating each coefficient as a free parameter.
  - Analogous to the tests of GR using binary pulsars

[LVC+ PRL 116, 061102 (2016)]



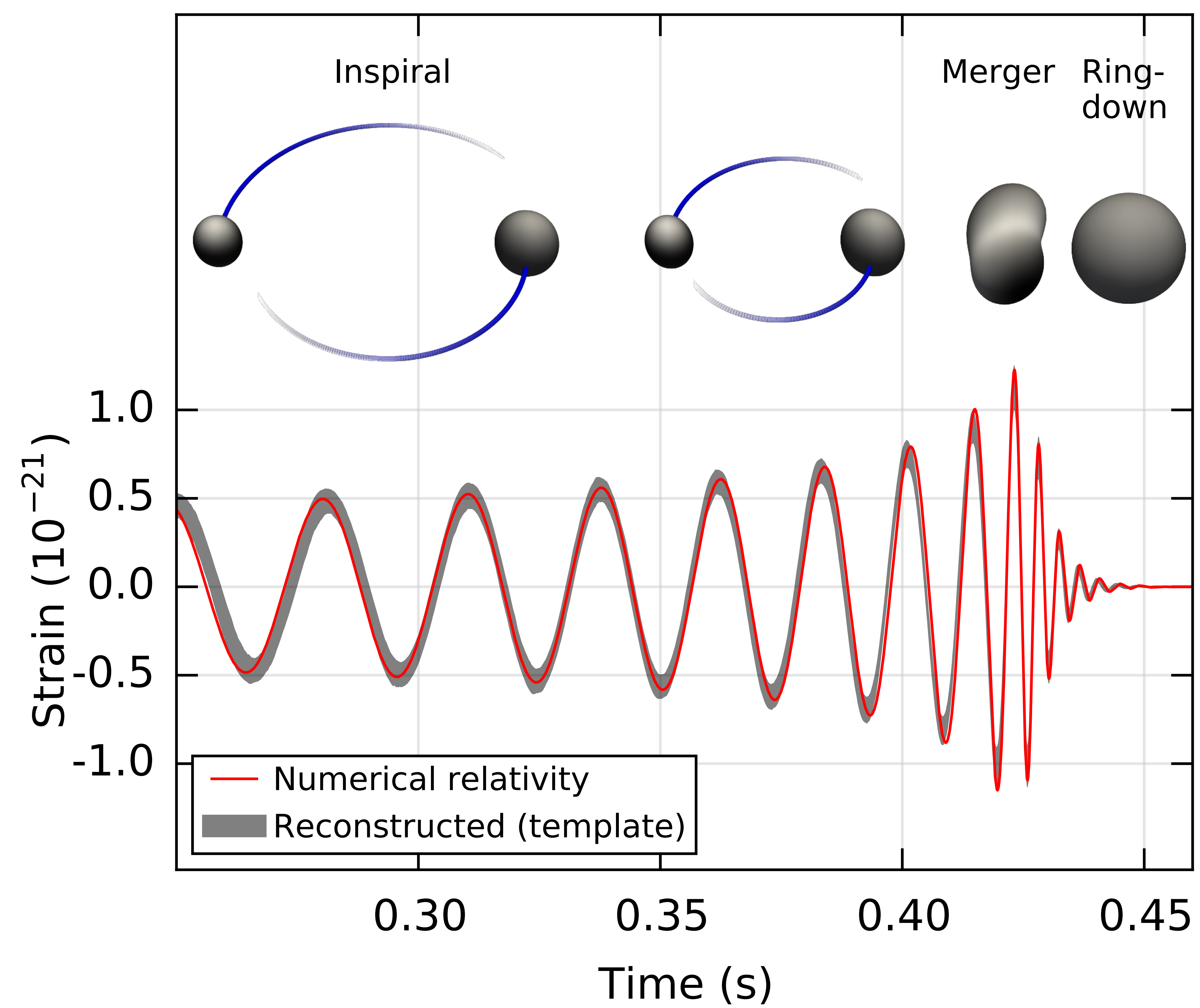
Testing post-Newtonian gravity from the inspiral signal

- Measure the deviations from the known PN coefficients of the GW phase by treating each coefficient as a free parameter.
  - Analogous to the tests of GR using binary pulsars

binary Pulsars (radio) → binary black holes (LIGO/Virgo)

$$\frac{v}{c} \sim 10^{-3} \quad \rightarrow \quad 0.1 - 0.5$$

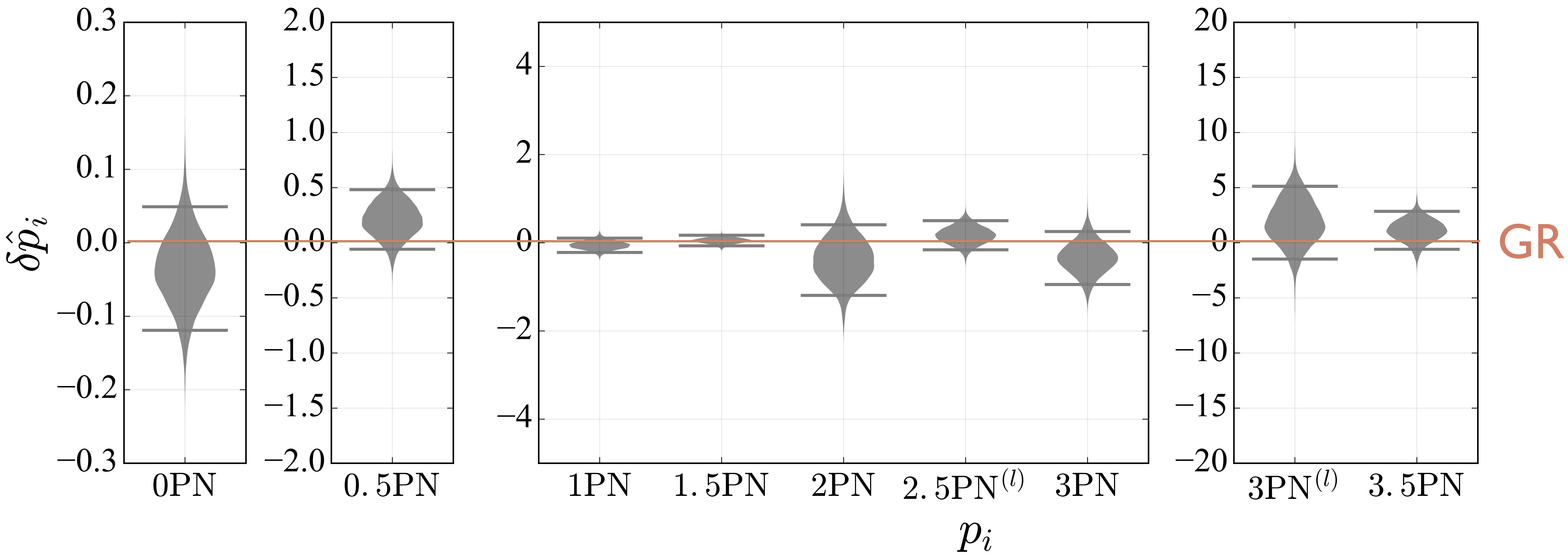
[LVC+ PRL 116, 061102 (2016)]



Testing post-Newtonian gravity from the inspiral signal

- Post-Newtonian coefficients estimated from the data consistent with the theory prediction.

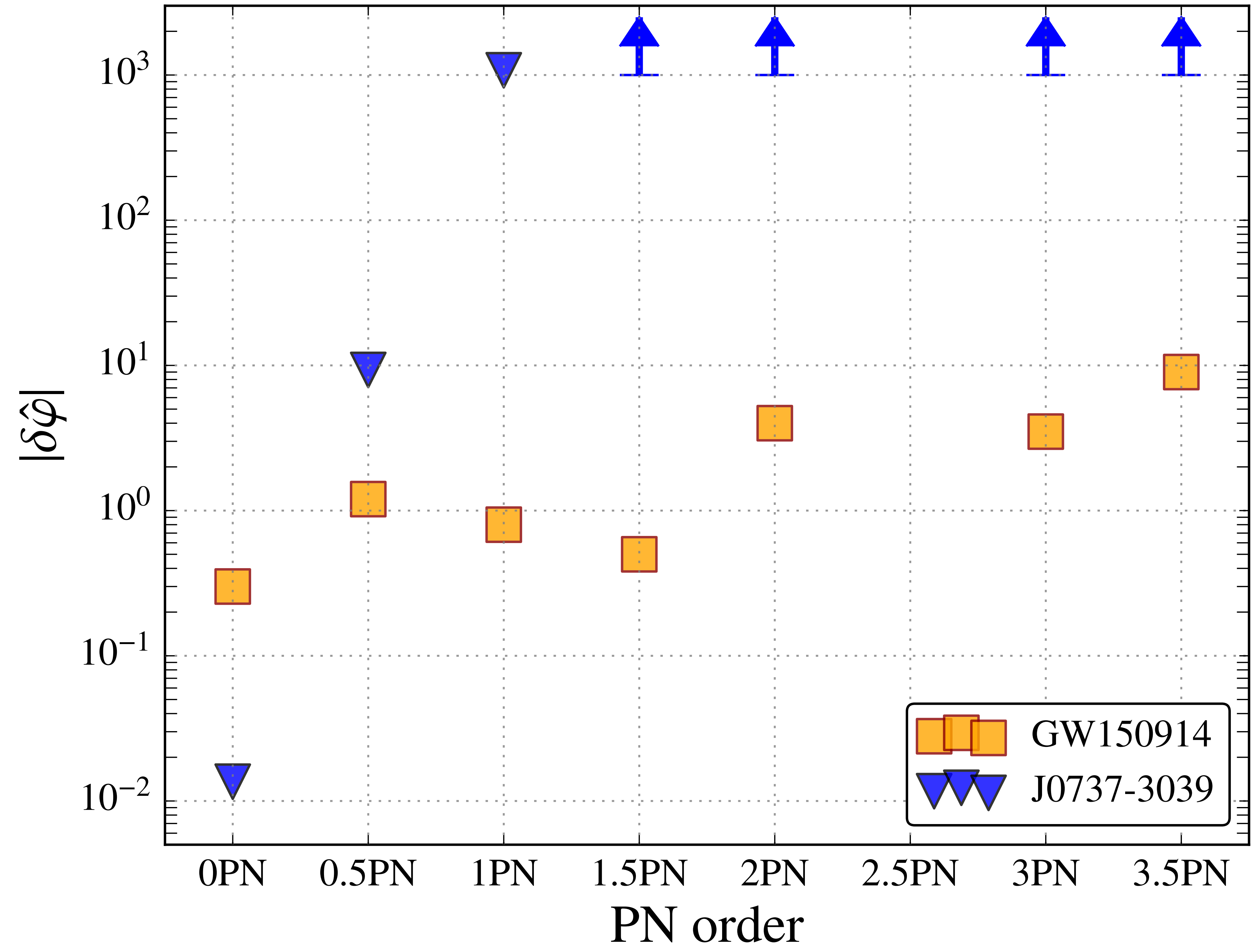
[LVC+, PRL 118, 221101 (2017) Supl. Material]



Testing post-Newtonian gravity from the inspiral signal

- Post-Newtonian coefficients estimated from the data consistent with the theory prediction.
  - First constraints on higher order PN coefficients.

[LVC+ PRL 116, 221101 (2016)]



Evidence of quasi-normal modes

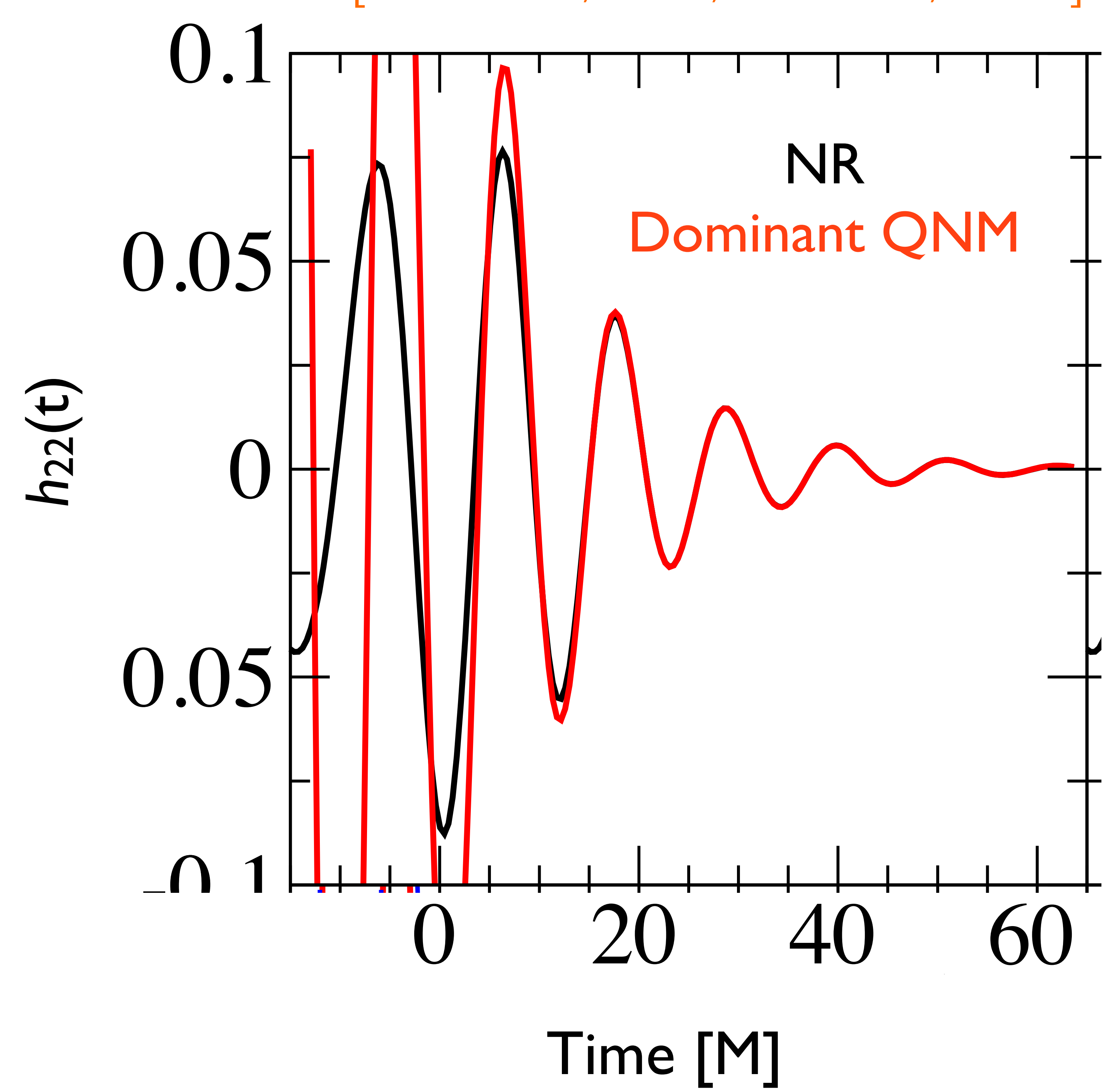
- During the late stages of the ringdown of the final black hole, waveform is described by a spectrum of quasi-normal modes.

$$h(t) = \frac{M}{r} \sum_{\ell m} Y_{\ell m} \, A_{\ell m} \, e^{-i\Omega_{\ell m} t}$$

$h_+ - ih_\times$

$\omega_{\ell m} - i/\tau_{\ell m}$

[Buonanno, Cook, Pretorius, 2006]

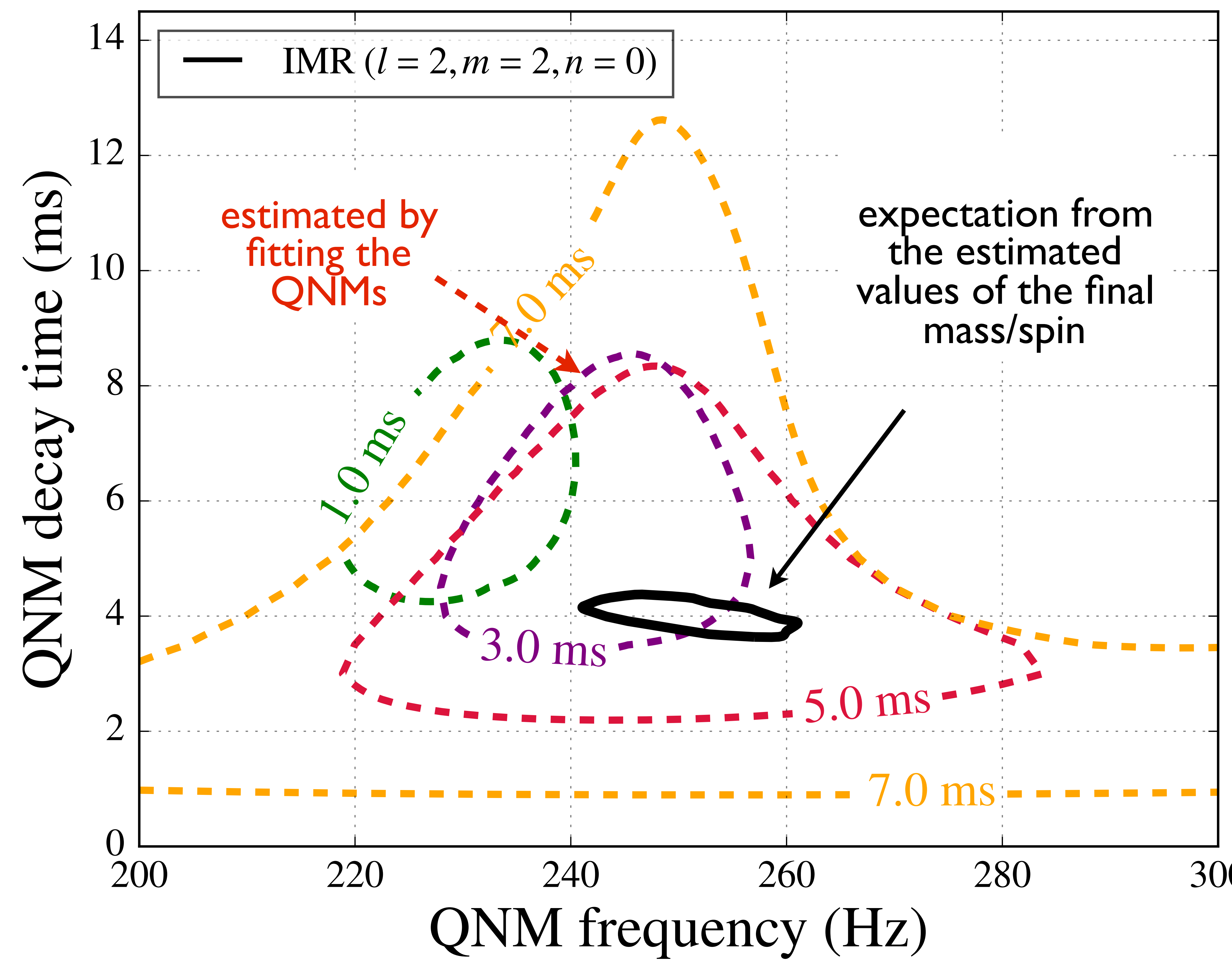


Perturbed black holes settle to their stationary states through emission of characteristic radiation modes — QNMs.

Evidence of quasi-normal modes in GW150914

- Post-merger part is consistent with the presence of the least damped QNM as predicted by GR.

[LVC+ PRL 116, 221101 (2016)]

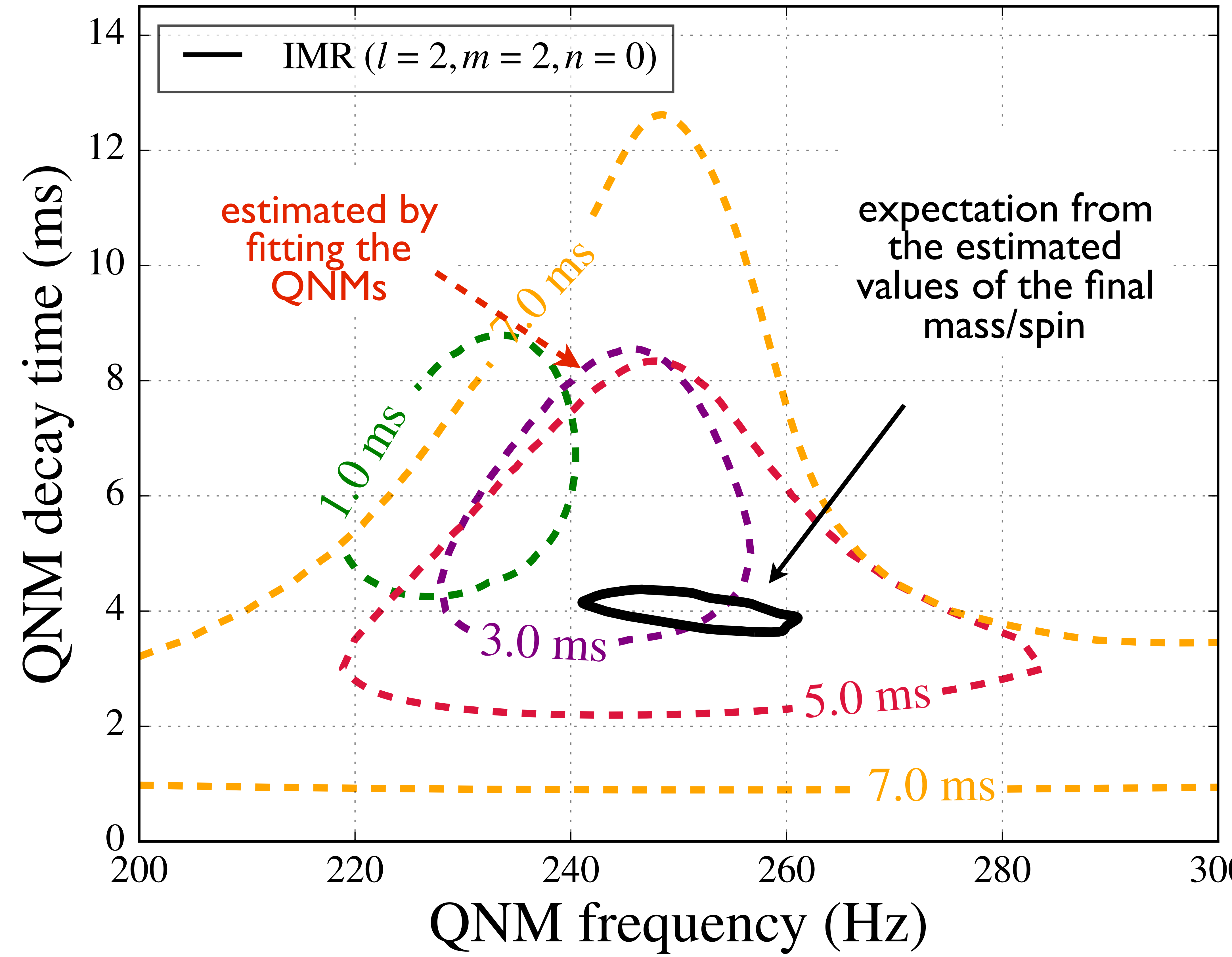


Evidence of quasi-normal modes in GW150914

- Post-merger part is consistent with the presence of the least damped QNM as predicted by GR.

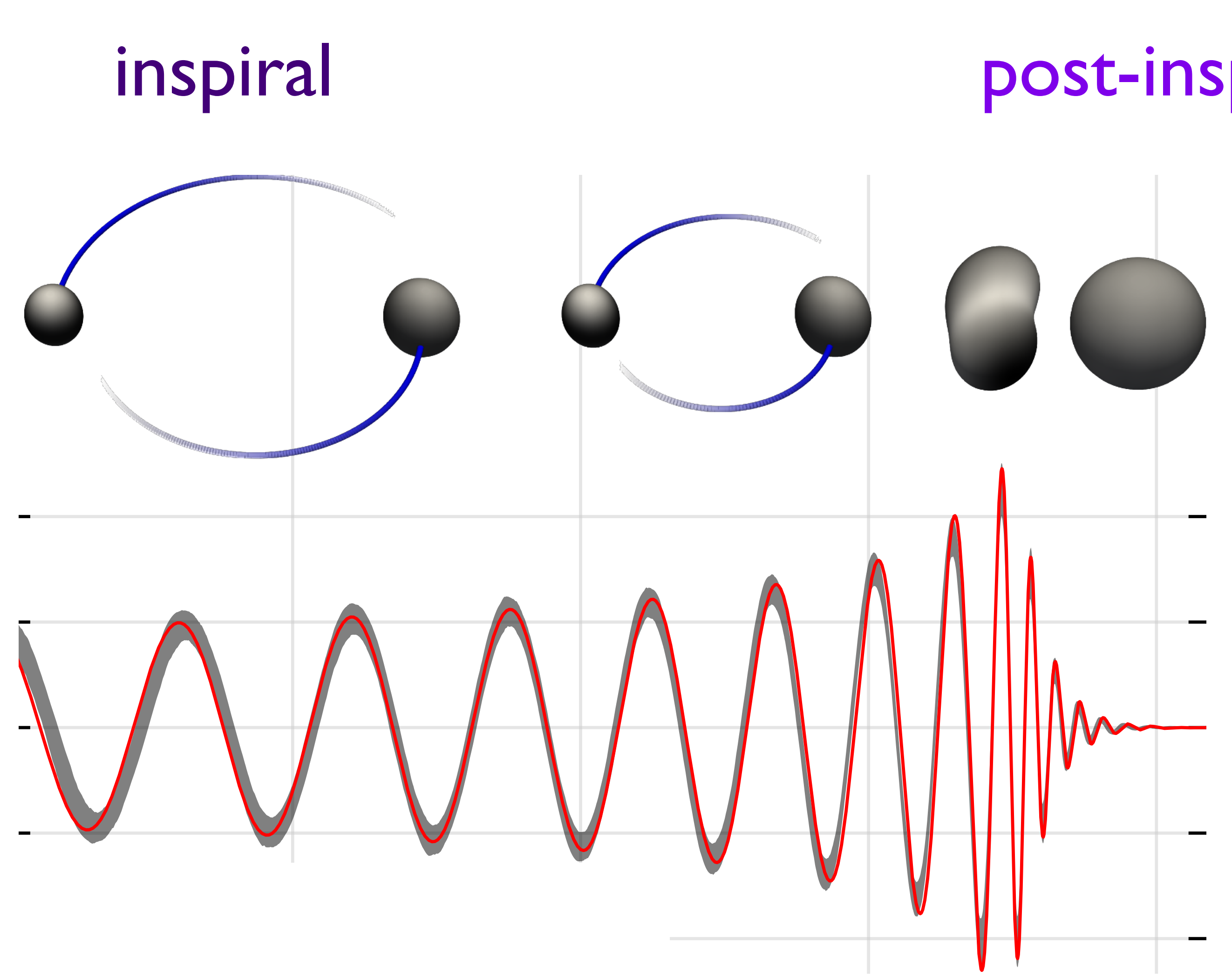
Future observations should allow us to fit multiple QNMs, and hence to test the “no-hair”theorem.

[LVC+ PRL 116, 221101 (2016)]



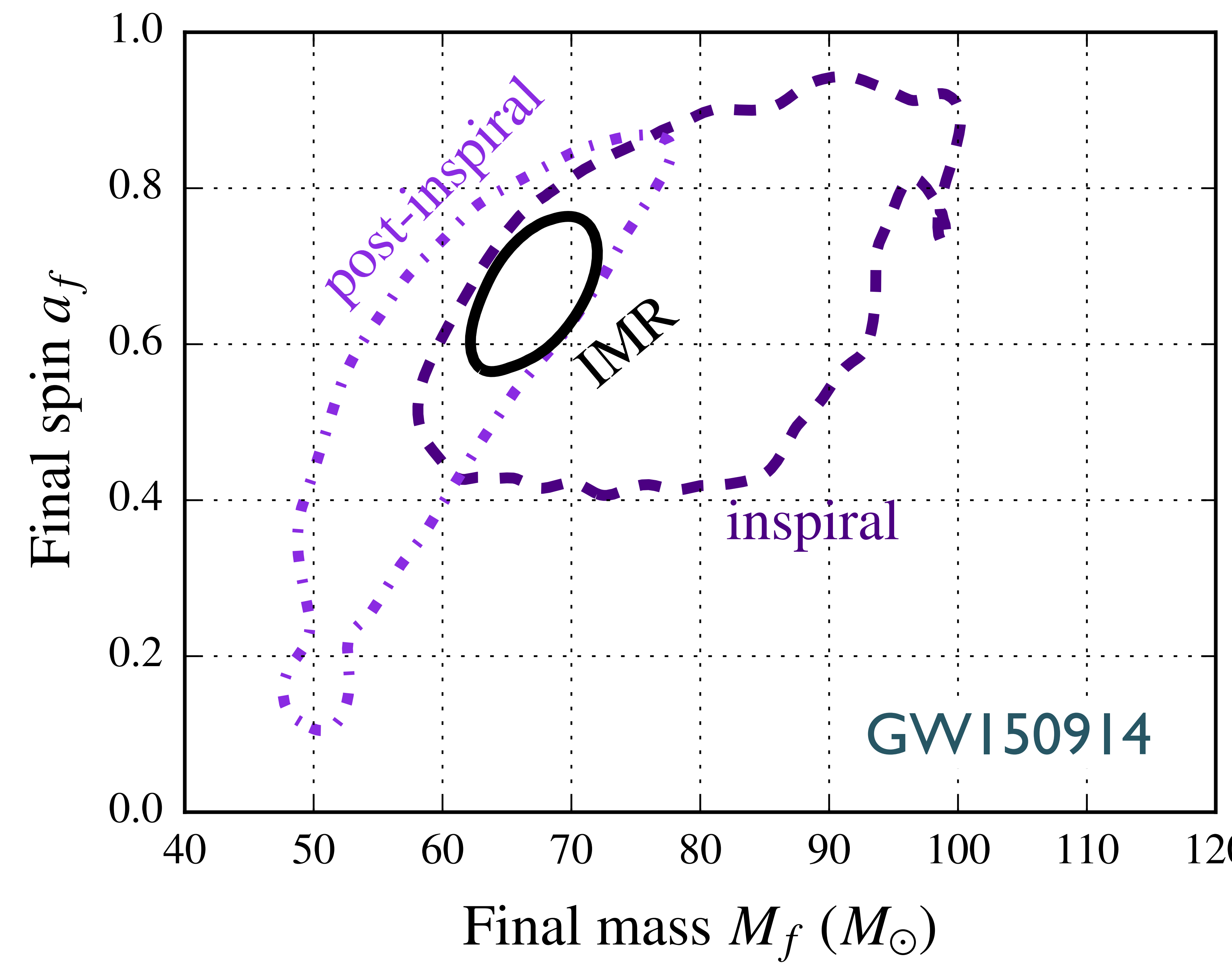
Consistency between the inspiral, merger and ringdown

- Mass and spin of the final BH estimated from the inspiral and post-inspiral parts are consistent with each other.



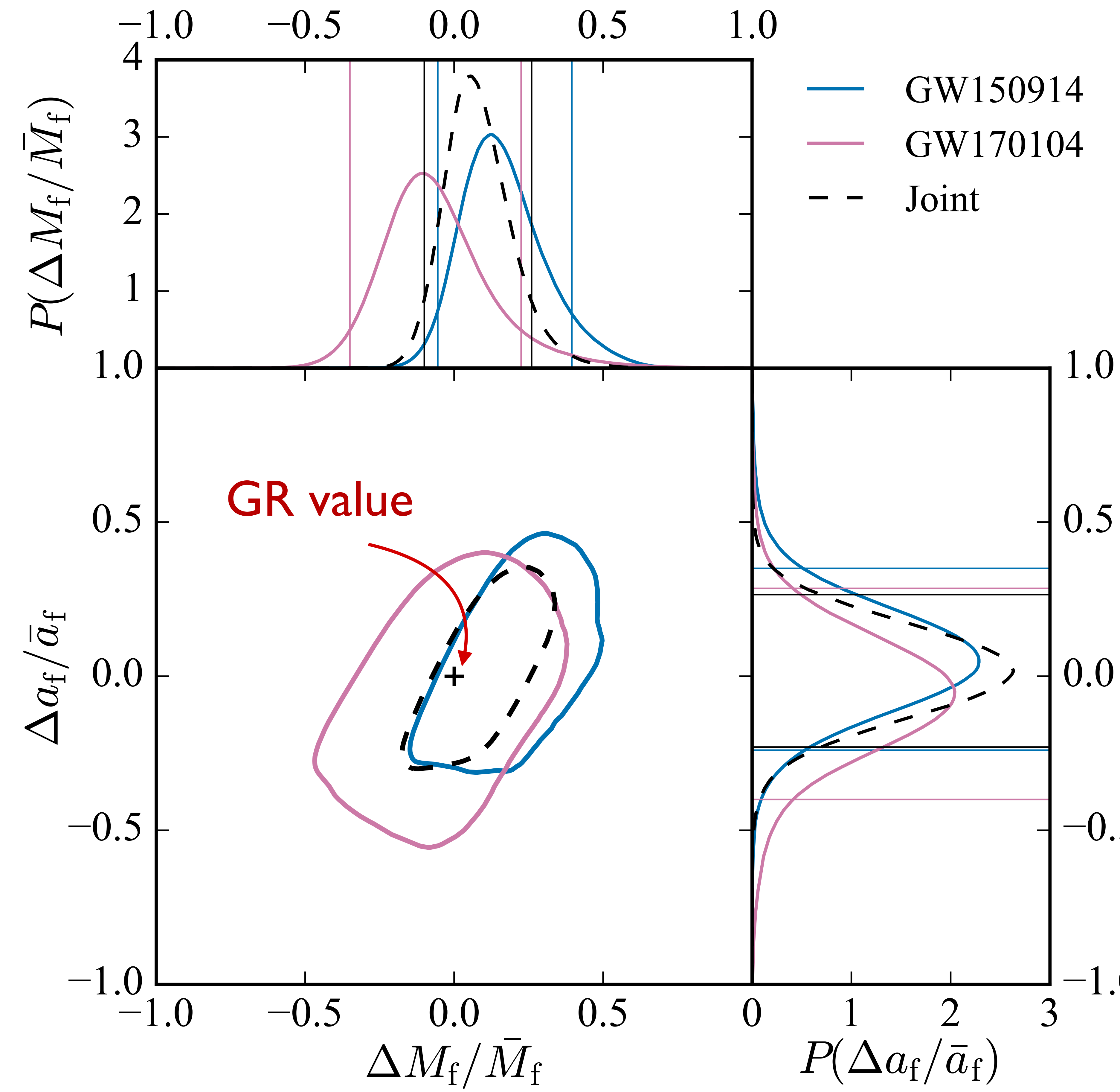
[LVC+ PRL 116, 061102 (2016)]

[LVC+ PRL 116, 221101 (2016)]



Consistency between the inspiral, merger and ringdown

- Posteriors on parameters describing deviations from GR consistent with (0,0).
  - Tighter constraints on deviations from GR predictions by combining multiple events



[LVC+ PRL 118, 221101 (2017) Supl. Material]

Constraining dispersion and the graviton mass

- Constrain a modified dispersion relation

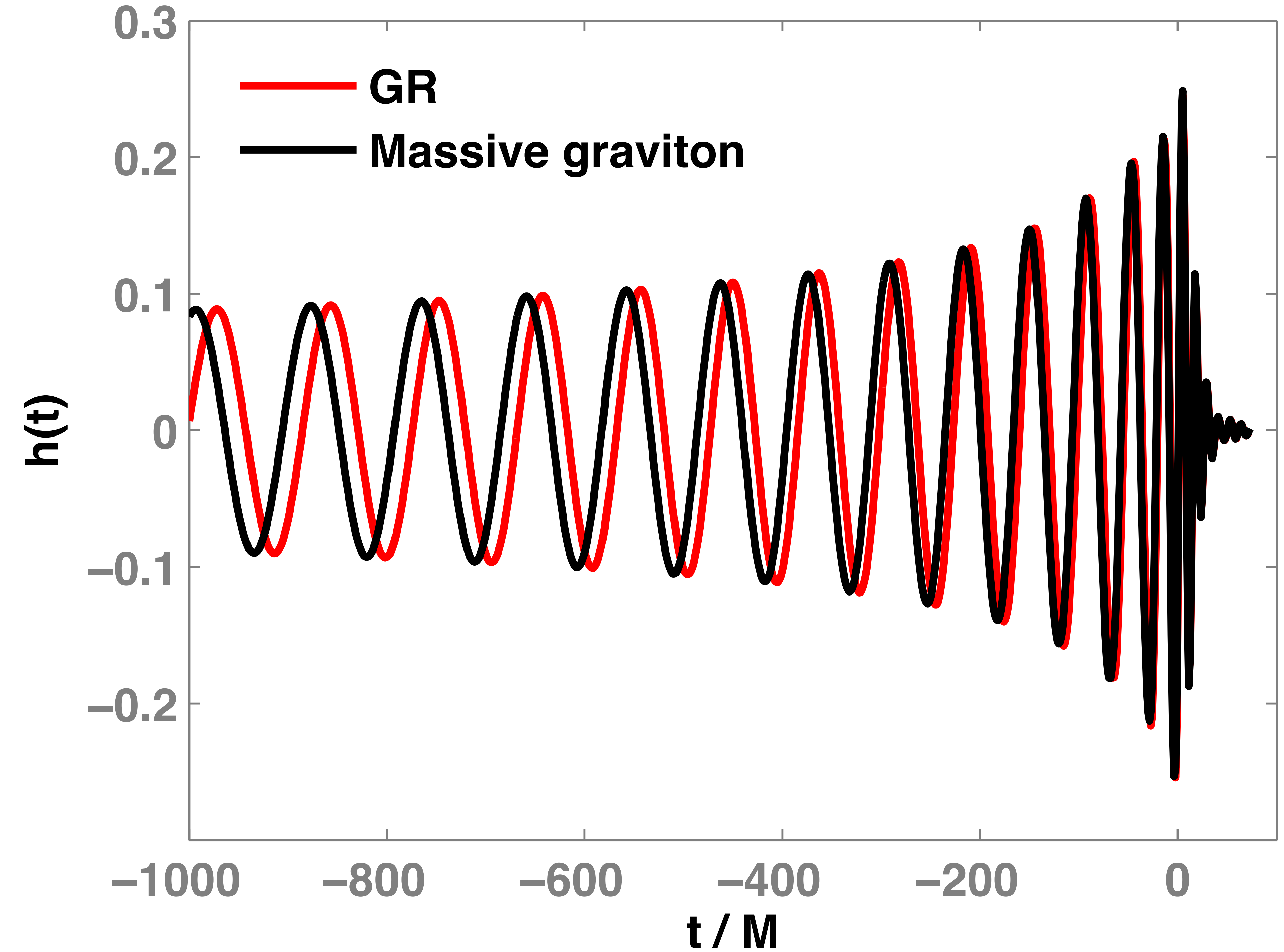
$$E^2 = p^2c^2 + A\, p^\alpha c^\alpha, \ \alpha \geq 0$$

Energy & momentum of GWs

Amplitude of dispersion (A = 0 in GR)

- Different frequency components will travel with different velocities ⇒ characteristic deformation in the observed waveform.

- Special case; massive graviton: $A > 0, \alpha = 0$



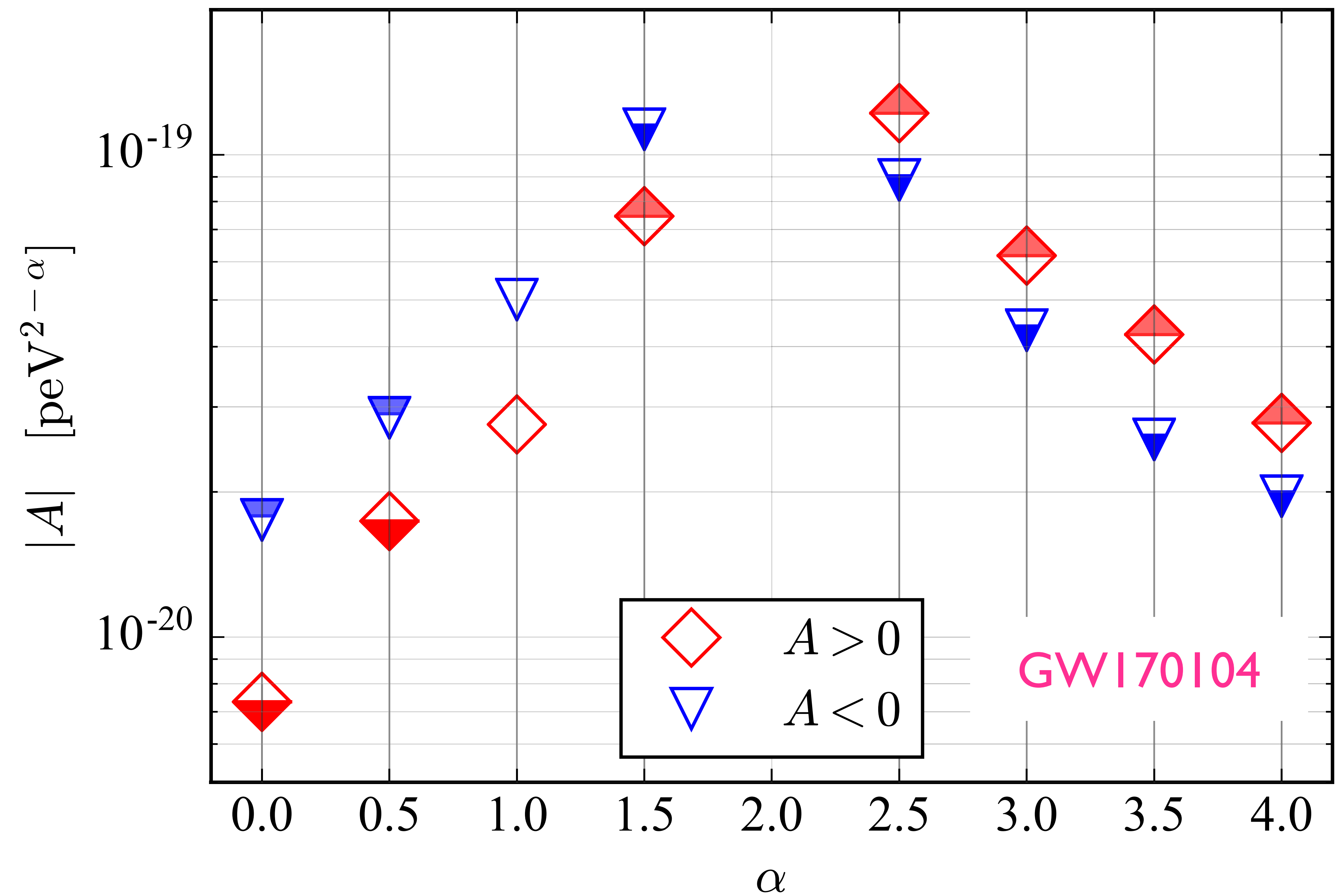
Constraining dispersion and the graviton mass

LIGO bounds on the mass of the graviton

$$\lambda_g > 1.6 \times 10^{13} \text{ km}$$

$$m_g \leq 7.7 \times 10^{-23} \text{ eV}/c^2$$

90% credible upper bounds on parameters describing the modified dispersion relation



[LVC+ PRL 118, 221101 (2017)]

Speed of GWs from multimessenger observations

- Constraints on the speed of GWs from the near simultaneous arrival (delay 1.7 s) of GW and gamma ray signal.
  - Test of the equivalence principle.
  - Tests of Lorentz violation.

Fractional difference between speed of GWs & EMWs

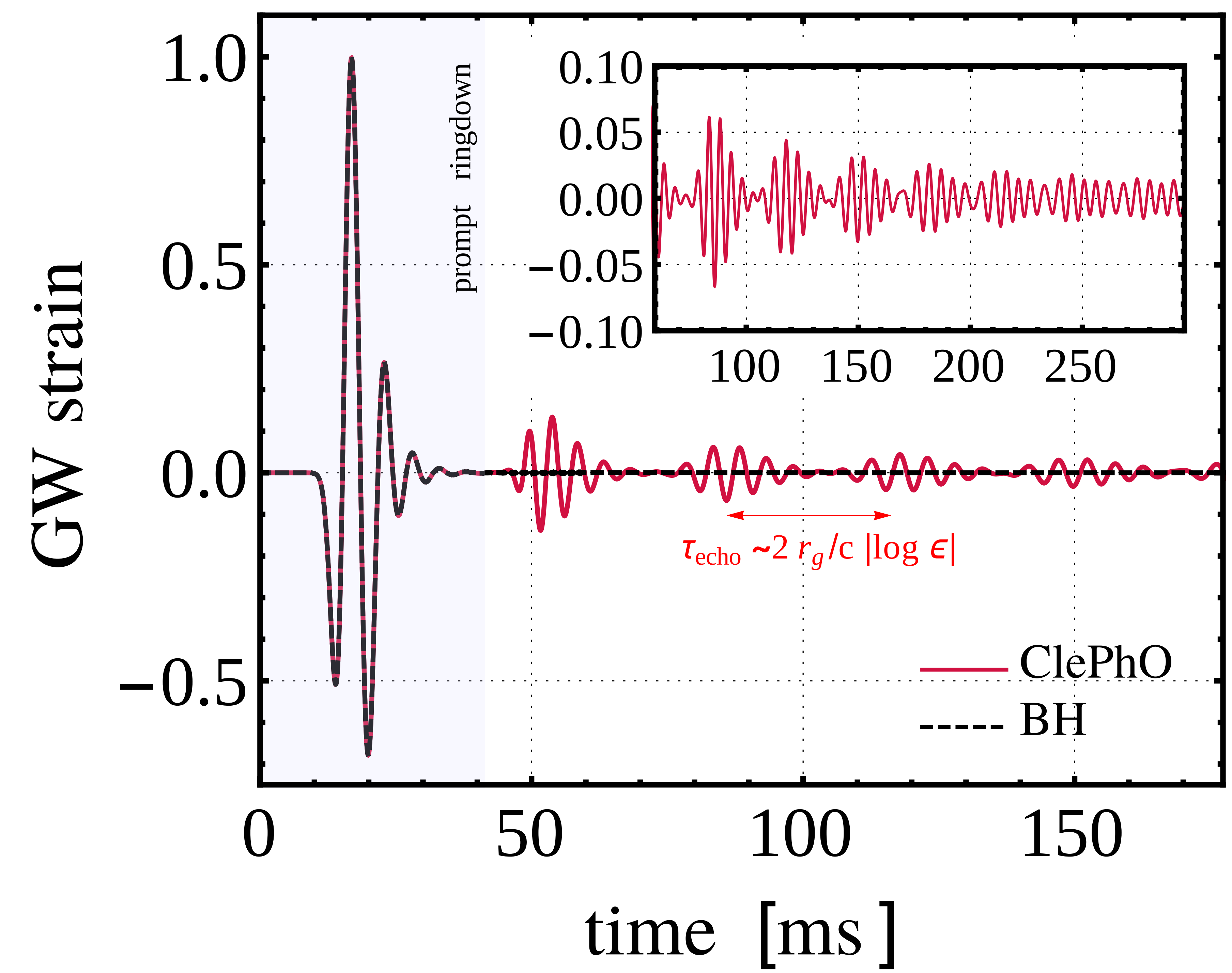
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

[ApJ 848:L13, 27 (2017)]

Constraining "black hole mimickers”

- **Echoes** For a horizon-less ultra compact object, the BH horizon is replaced by a partially outgoing boundary condition.
  - Modes (semi) trapped between the photon ring and the boundary can reach the outside observer, producing a series of late-time echoes.

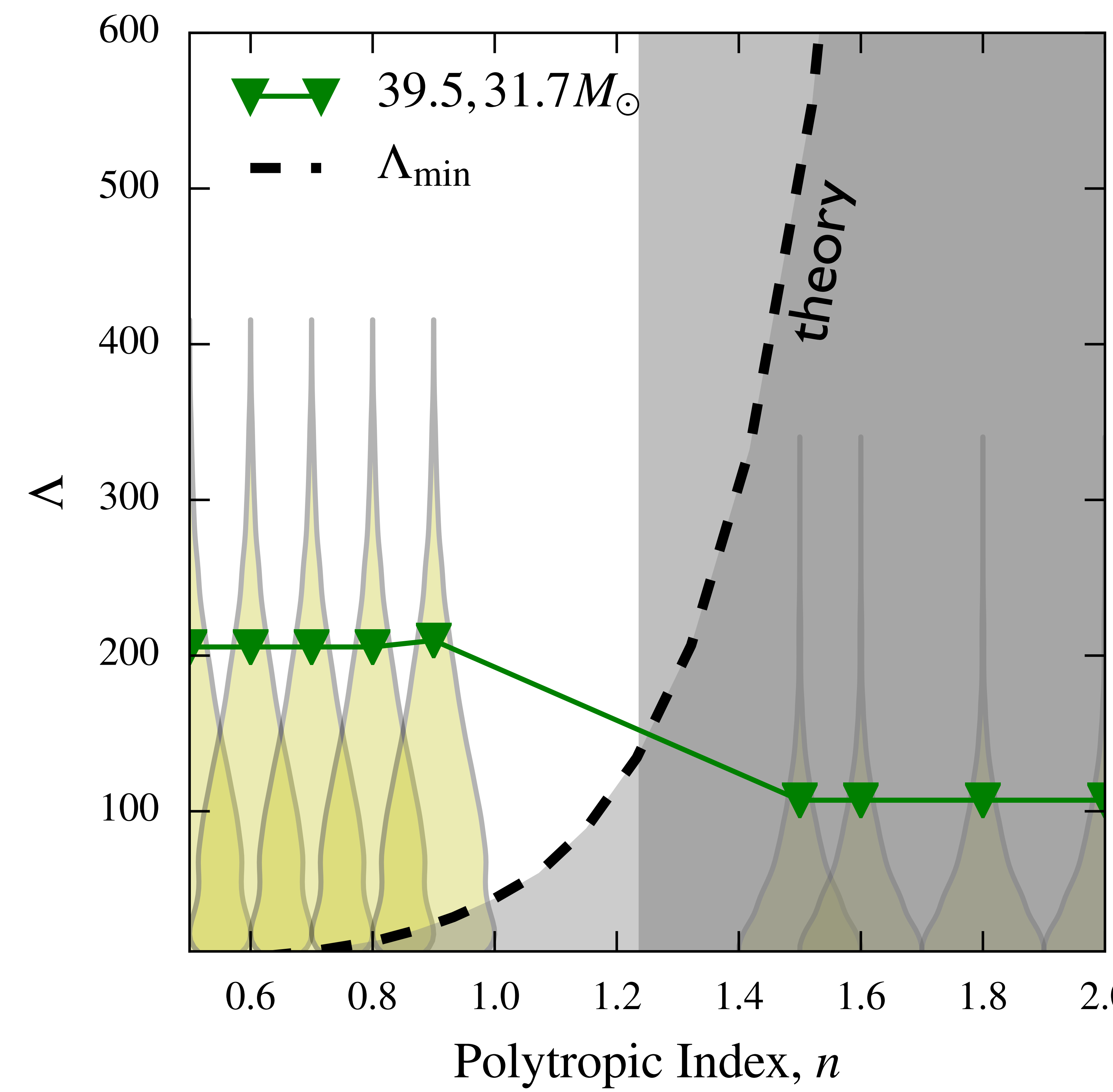
[Cardoso & Pani (2017)]



Constraining "black hole mimickers"

- **Tidal effects** During the late inspiral, the object will get tidally deformed, producing an imprint in the observed signal.
  - Constraints on the tidal deformation constraints the properties of BH mimickers.

$$Q_{ij} = -\Lambda\, \mathcal{E}_{ij}$$



[Johnson-McDaniel et al, In prep]

Expected constraints for compact objects described by polytropic EoS from a GW150914 like observation

Constraining "black hole mimickers"

- **Spin induced effects** Constrain the spin-induced quadruple moment.

$$Q = -\kappa\, m^3\, \chi^2$$

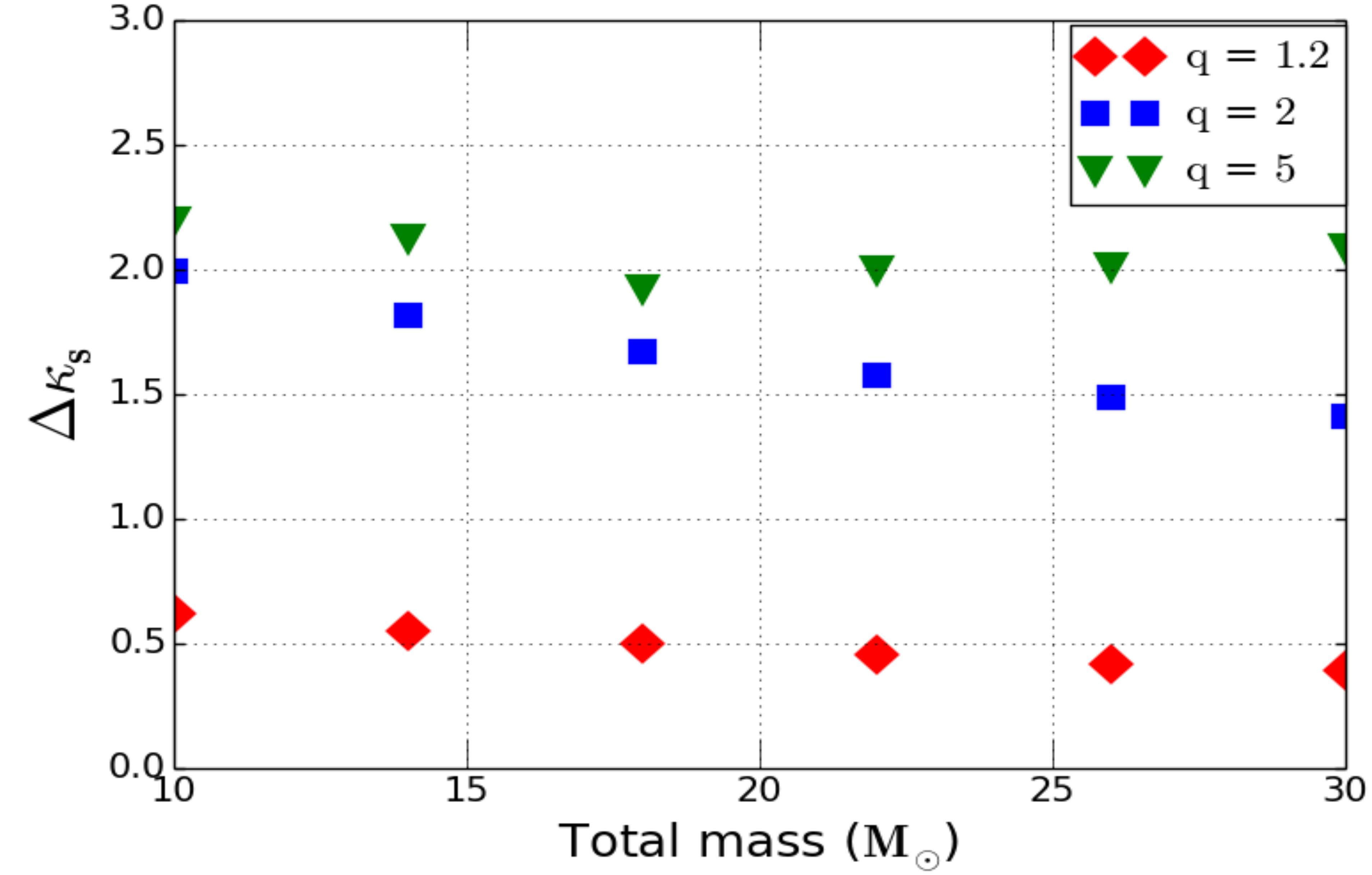
κ = 1 for BHs

Spin induced quadruple moment

Mass

spin

[Krishnendu et al, PRL 119, 091101 (2017)]

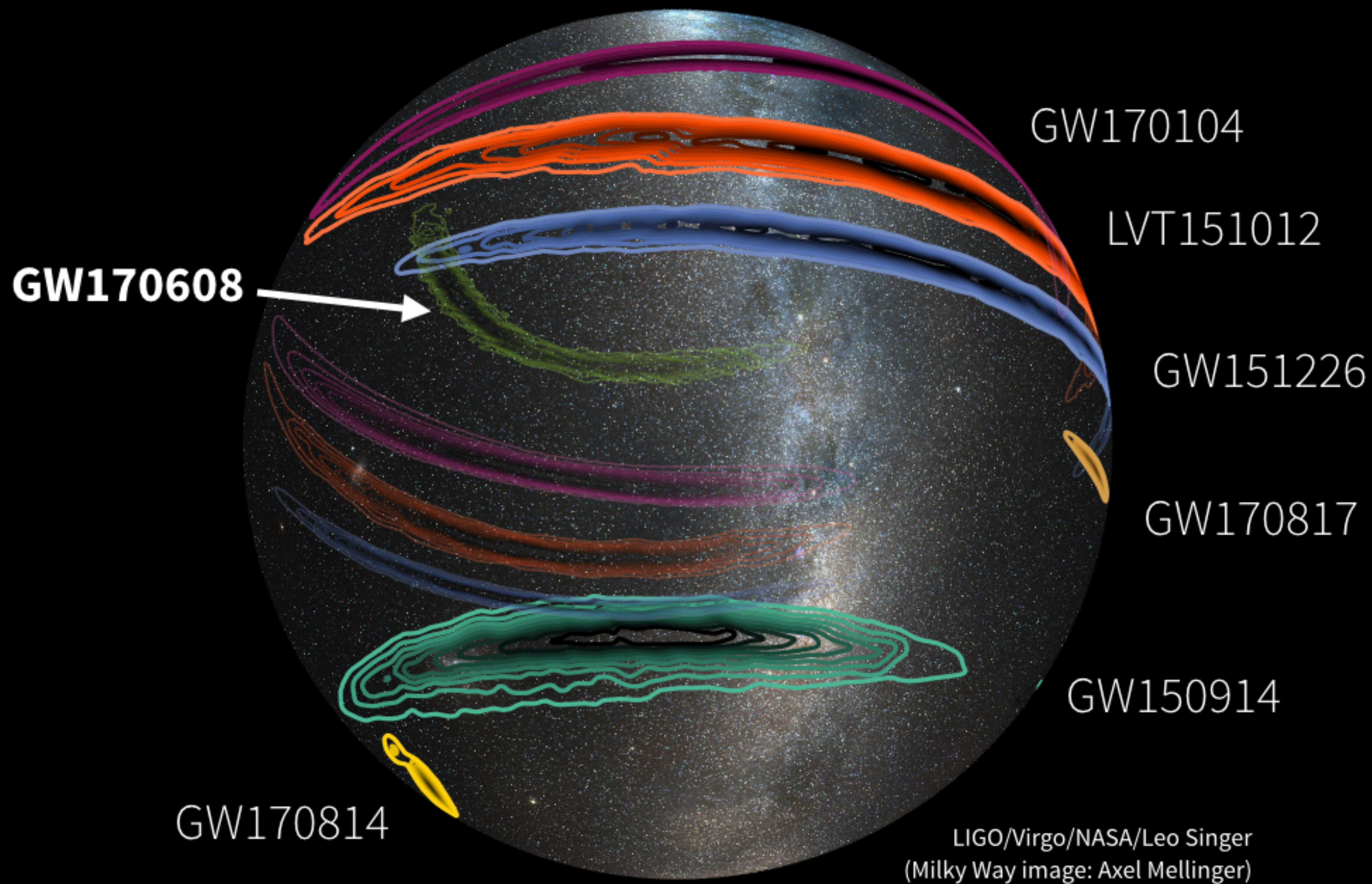


Expected precision in measuring **κ** in Advanced LIGO with SNR ~ 10.

Summary

- Recent GW observations by LIGO & Virgo have opened up a new branch of observational astronomy.
  - First detections of binary BHs, first tests of GR in the highly relativistic regime, possible new BH populations.
  - Multi-messenger detection of a binary neutron star merger, tentative evidence for the BNS engine of short GRBs, constraints on the nuclear EoS, independent measurement of the Hubble constant.
- Hundreds of detections anticipated in the next few years, potential detection of an astrophysical stochastic GW background.

Thank you!


GW170104
LVT151012
GW170608
GW151226
GW170817
GW150914
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LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)