Probes of strong gravity using gravitational waves

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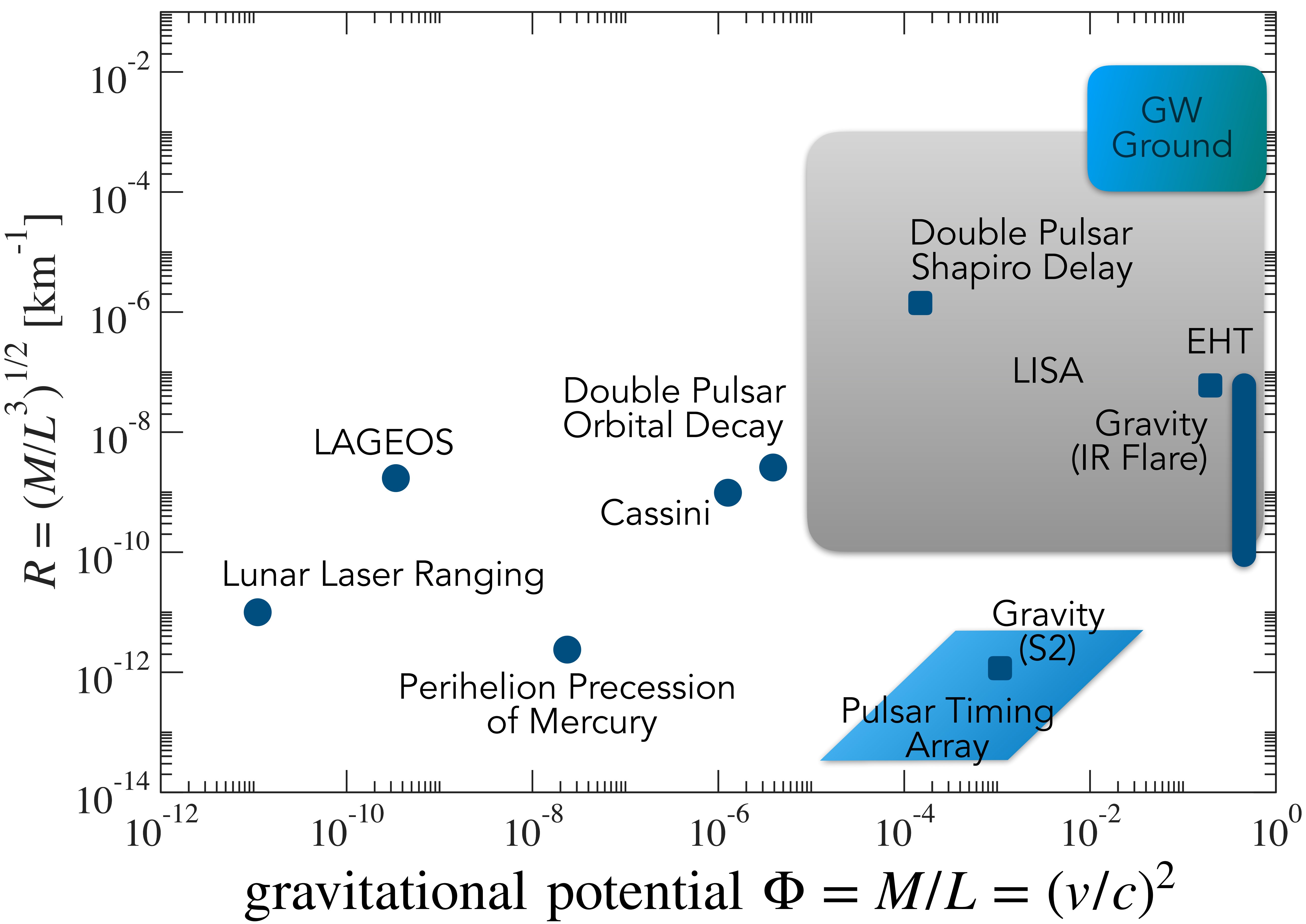
Probes of strong gravity using Advanced LIGO and Virgo

[arXiv:1903.09221]



Probes of strong gravity using Advanced LIGO and Virgo

- Detection of GW signals that are broadly consistent with GR predictions!

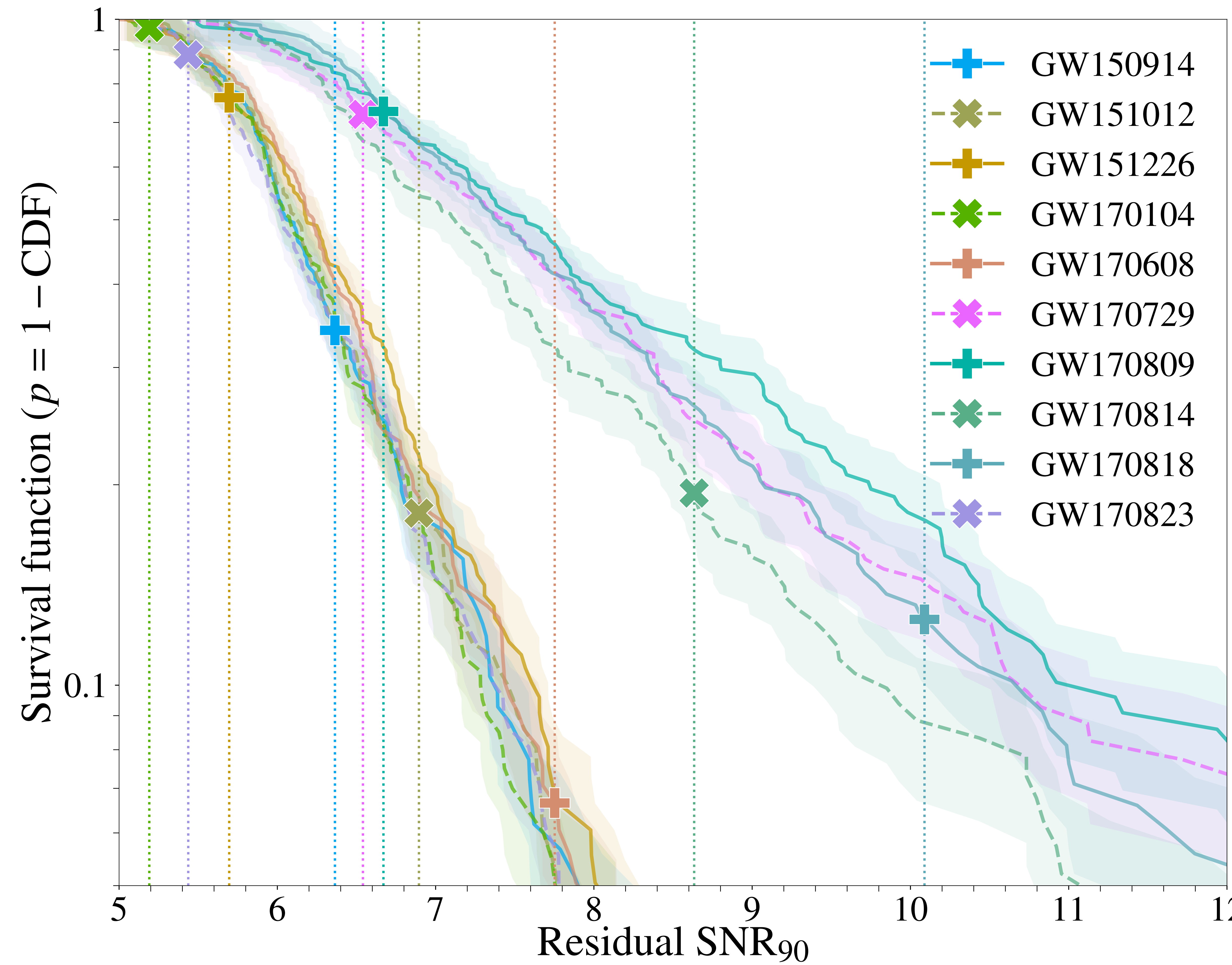
Probes of strong gravity using Advanced LIGO and Virgo

- Detection of GW signals that are broadly consistent with GR predictions!
- In the absence of reliable predictions from alternative theories, the current philosophy is to test the degree of consistency of the data with GR (and black holes in GR).
  - Signal consistency tests, GW generation & propagation, nature of GW polarizations, probes of horizons, etc.

Signal consistency tests: Testing residuals

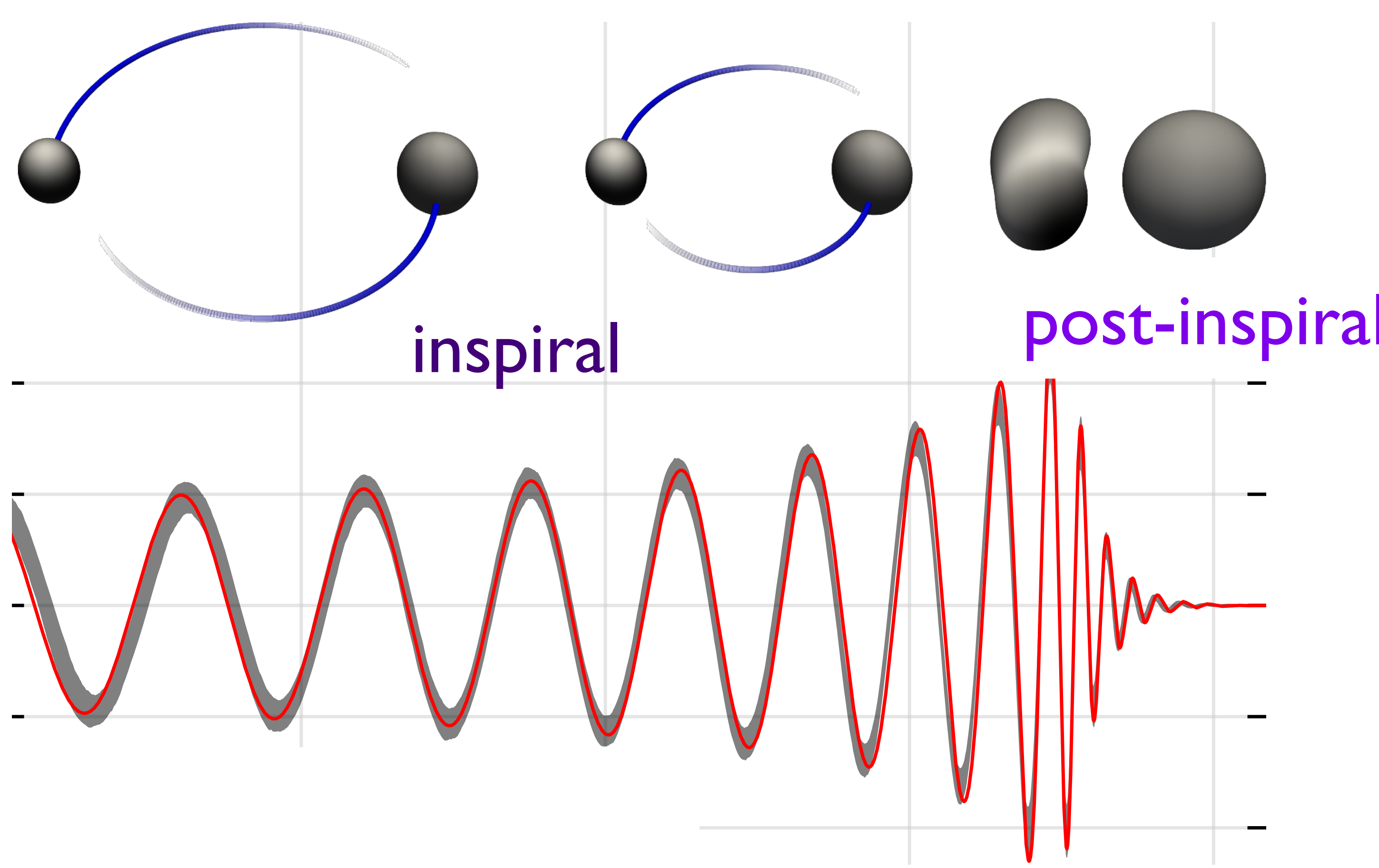
[LVC+ PRD 100, 104036 (2019)]

- Residuals of the data after subtracting the best-fit templates are consistent with noise.

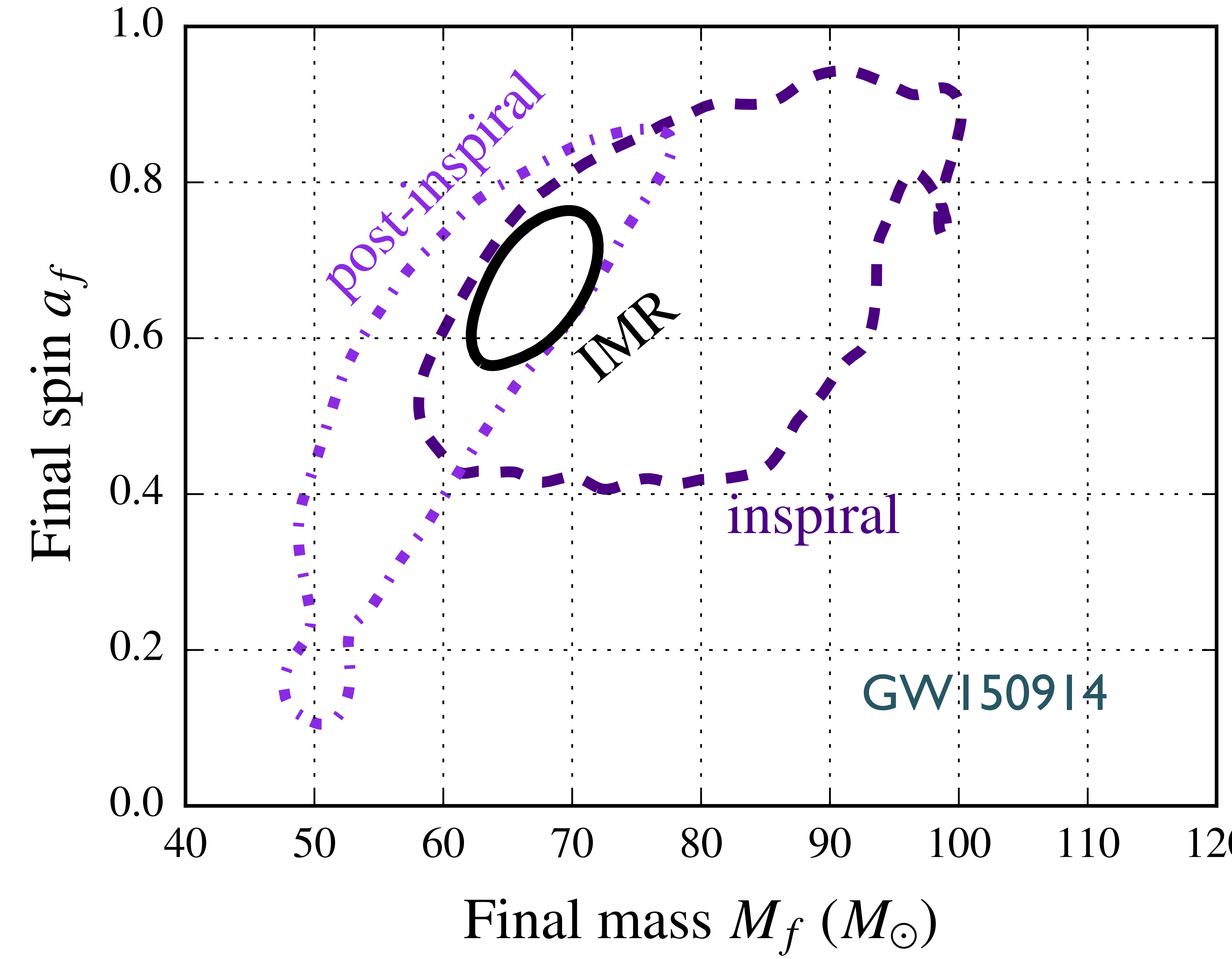


Signal consistency tests: Inspiral-merger-ringdown consistency

- Test the consistency of mass & spin of the final black hole estimated from the inspiral/ post-inspiral parts of the observed signal [Ghosh et al 2016].



[LVC+ PRL 116, 221101 (2016)]



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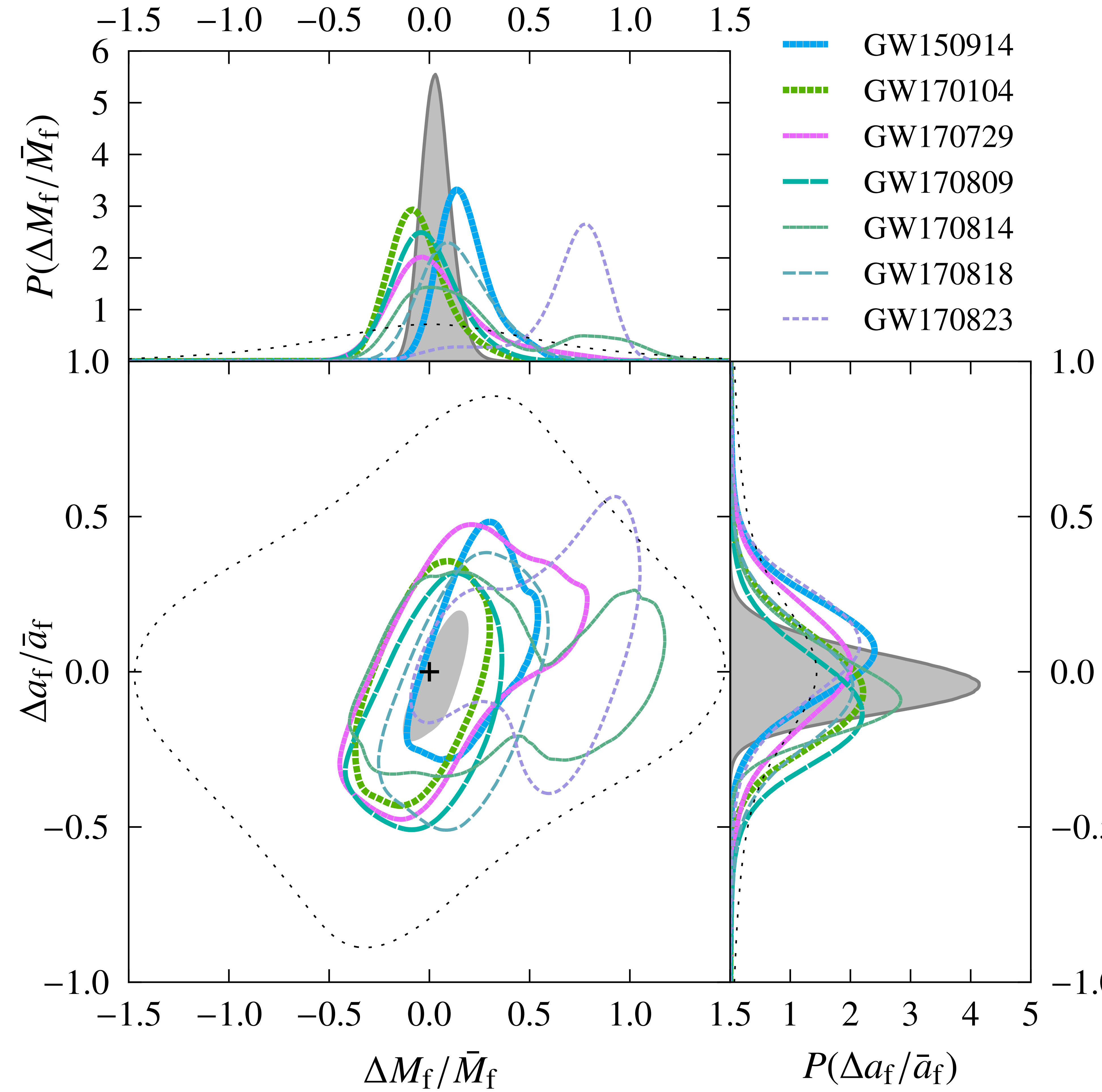

Future Test of black hole area theorem [Cabero et al 2018], measurement of the energy loss [Hughes et al 2004], etc.

Tests of waveform generation: Parameterized tests

- Introduce deviations in the coefficients describing the GR waveform's phase

$$p_i \rightarrow (1 + \delta\hat{p}_i)\; p_i$$

Coefficients are unique functions of the intrinsic parameters

GR waveform phase $\psi(f) = \sum_i p_i\, f^i$

Analogous to binary pulsar tests using the post-Keplerian formalism

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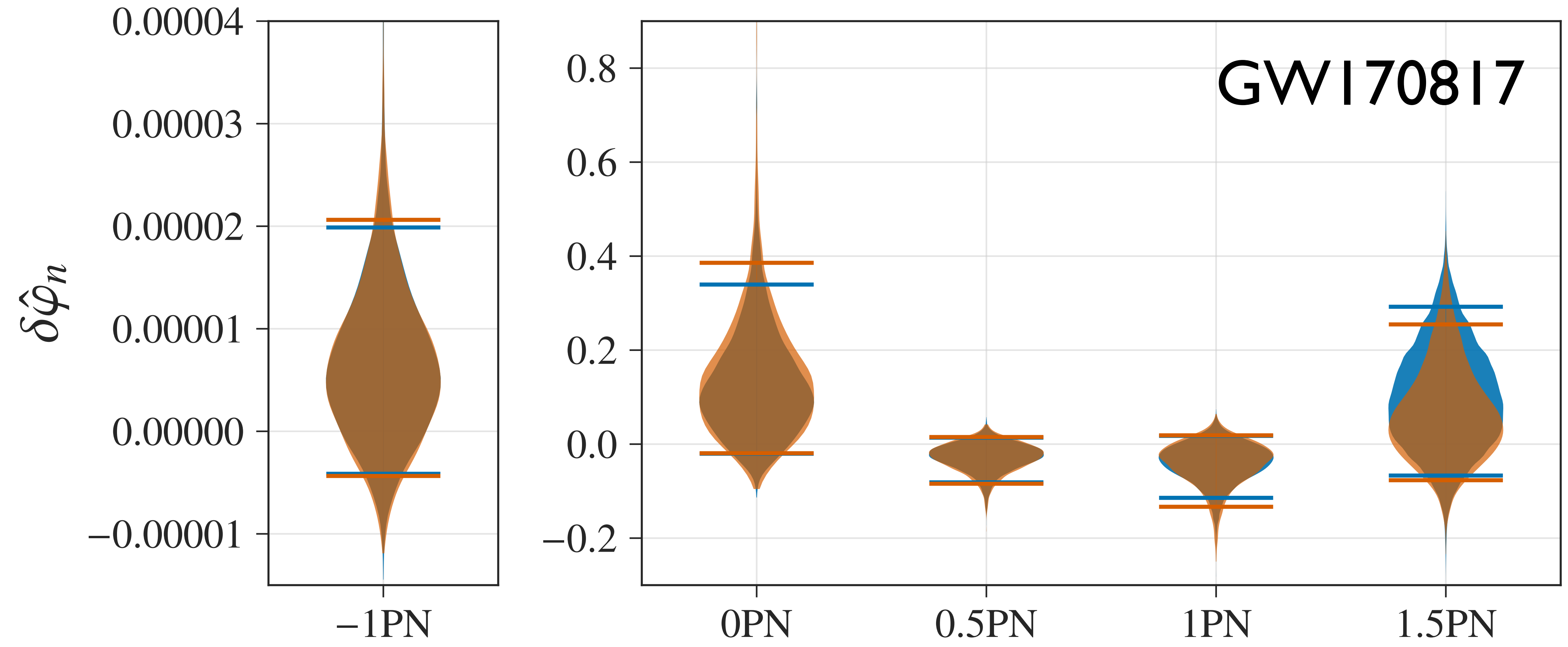
- Estimate posteriors on deviation parameters along with the parameters in GR [Arun et al 2006, Yunes & Pretorius 2009, Li et al 2011, Sennett et al]

[LVC+ PRL 123, 011102 (2019)]



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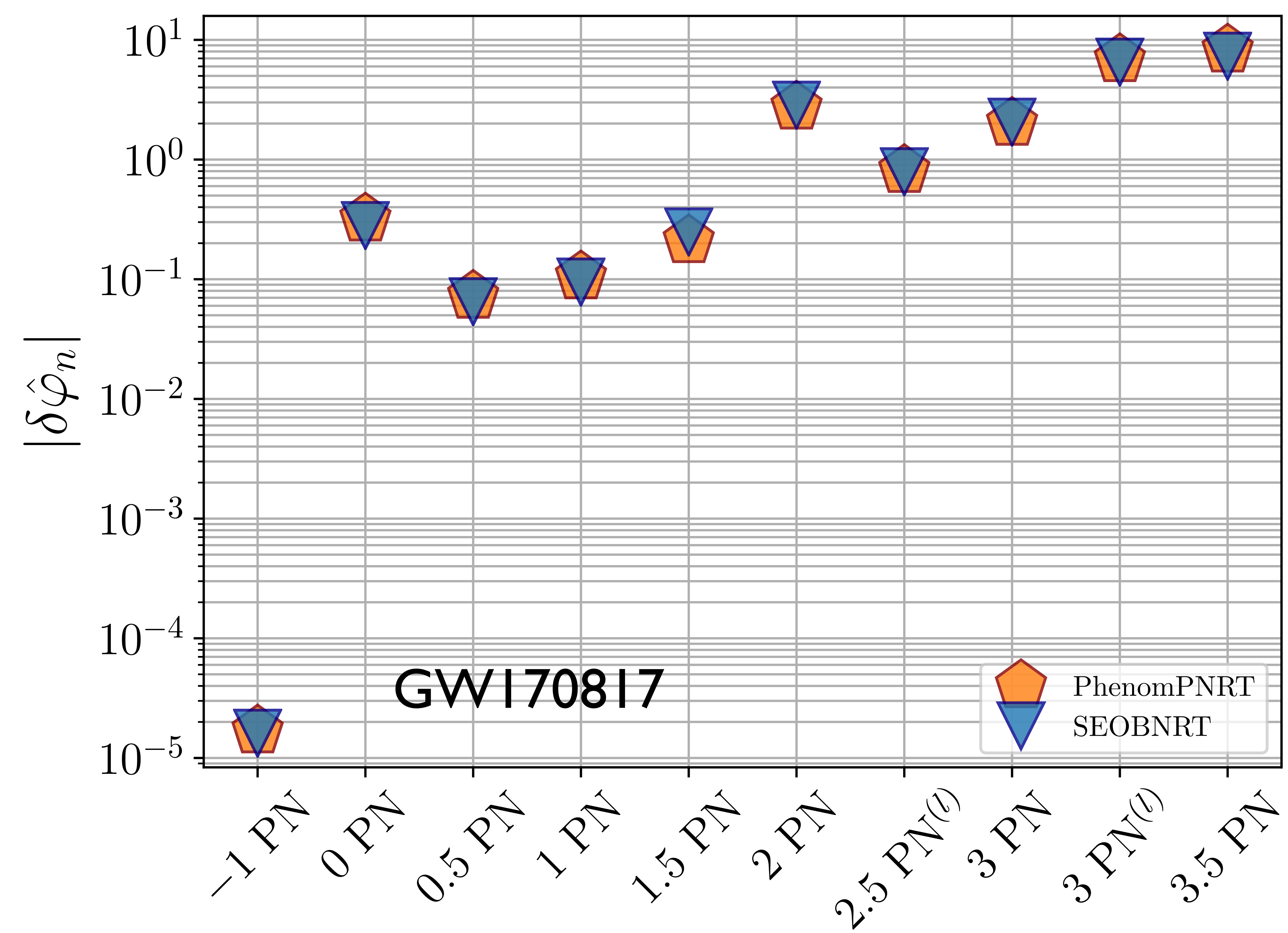
- Bounds on deviation parameters could be interpreted in terms of specific theories [e.g, Nair et al 2019]

[LVC+ PRL 123, 011102 (2019)]



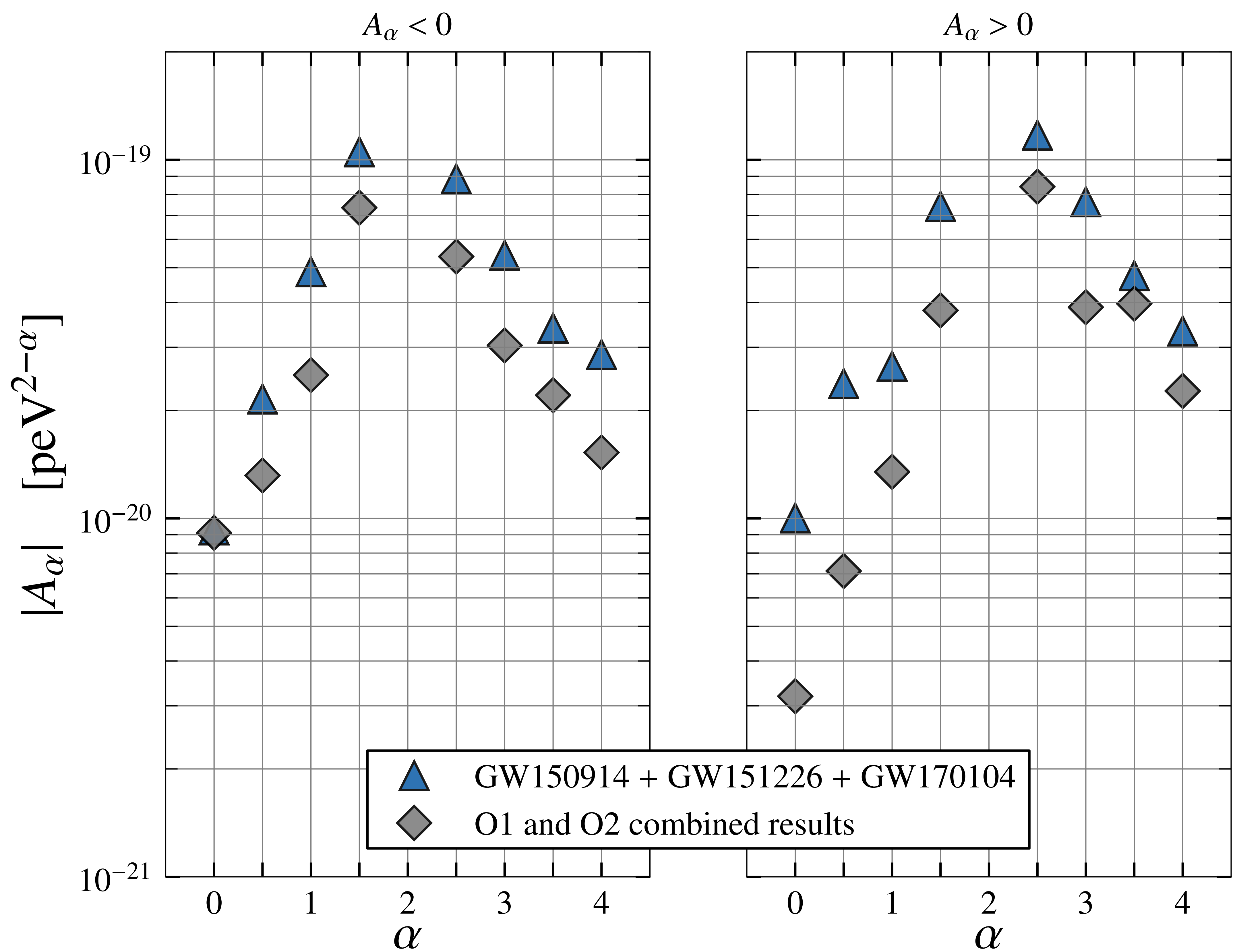
Tests of GW propagation: Modified dispersion relation

[LVC+ PRD 100, 104036 (2019)]

- In GR, GWs propagate at the speed of light and are non-dispersive. However, one can consider a more general dispersion relation…

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

GR part + Phenomenological modification



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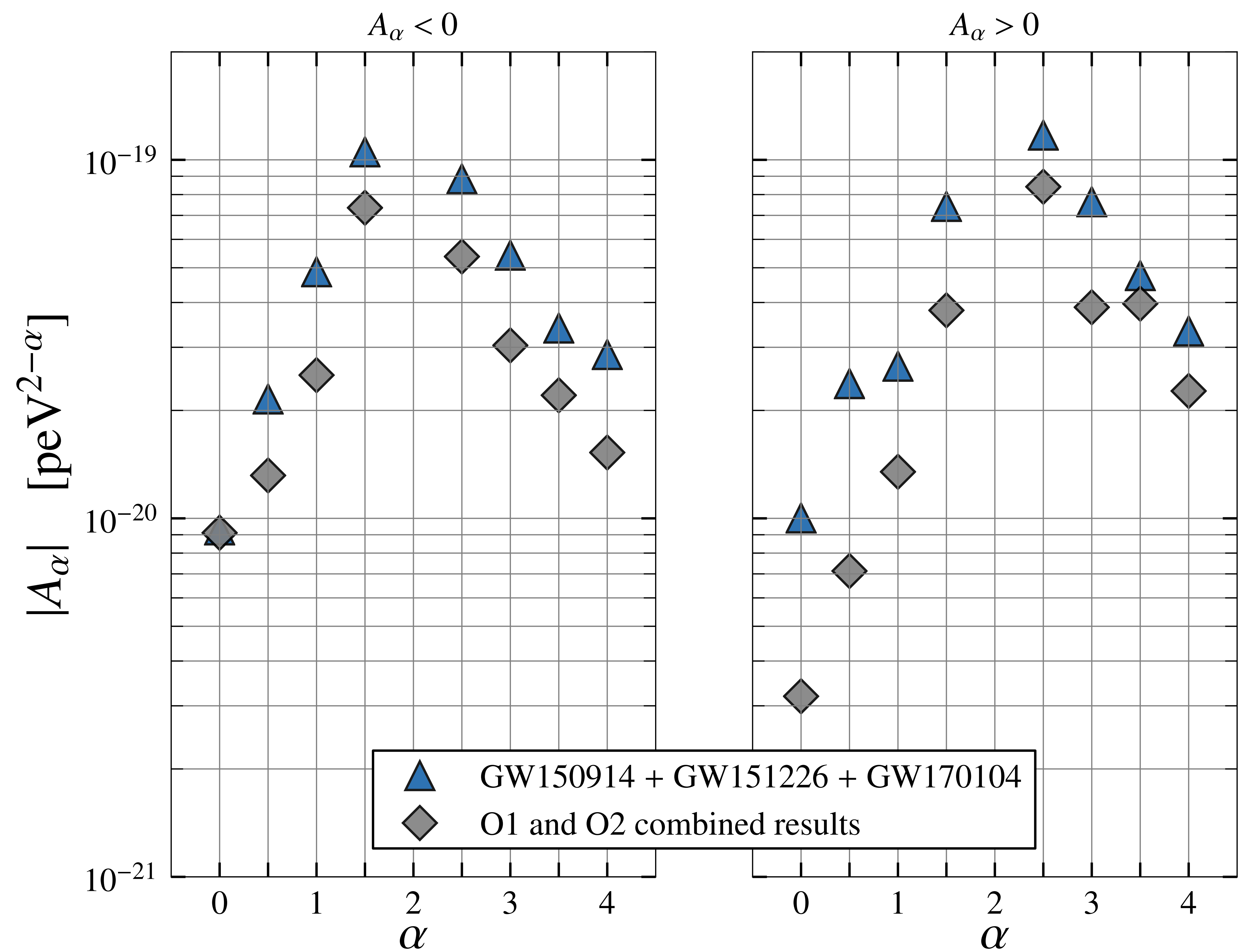
- Special case Massive graviton ($A > 0$, $\alpha = 0$) [Will 1998]. Current constraint $m_g \leq 5 \times 10^{-23}\, \mathrm{eV}/c^2$.
- α = 2.5, 3, 5 correspond to specific theories.

[LVC+ PRD 100, 104036 (2019)]



Tests of GW propagation: EM-GW comparison

- Arrival time difference between GWs & γ-rays.
  - Speed of GWs.
  - Test of the equivalence principle.
  - Tests of Lorentz violation.

[ApJ 848:L13, 27 (2017)]

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

Fractional difference between speed of GWs & light

Tight constraints on $f(R)$/scalar-tensor theories from the speed of GW measurement.

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- Arrival time difference between GWs & ɣ-rays.

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

[Ezquiaga & Zumalacarregui, PRL 119, 251304 (2017)]

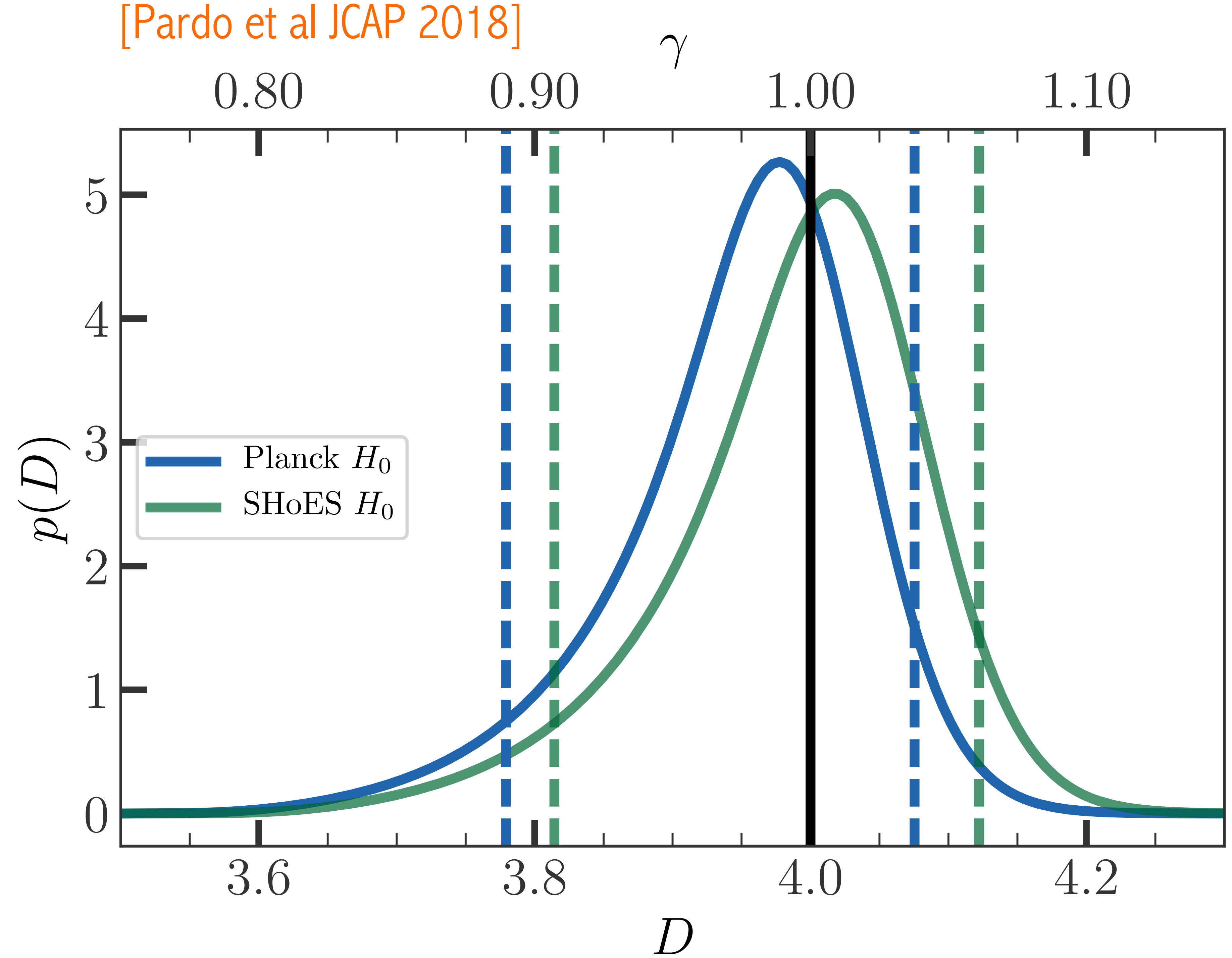
	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity	quartic/quintic Galileons [13, 14]
	quintessence/k-essence [46]	Fab Four [15]
	Brans-Dicke/$f(R)$ [47, 48]	de Sitter Horndeski [49]
	Kinetic Gravity Braiding [50]	$G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [51], $f(\phi)\cdot$Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17]	quartic/quintic GLPV [18]
	Disformal Tuning (21)	quadratic DHOST [20] with $A_1 \neq 0$
	quadratic DHOST with $A_1 = 0$	cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

Tight constraints on *f*(*R*)/scalar-tensor theories from the speed of GW measurement.

Tests of GW propagation: EM-GW comparison

- Comparison of distance estimates from GW & EM observations.
  - If non-compact extra dimensions exist, GWs could leak into them, producing a systematic bias in the luminosity distance estimated from GW observations.

[Pardo et al JCAP 2018]



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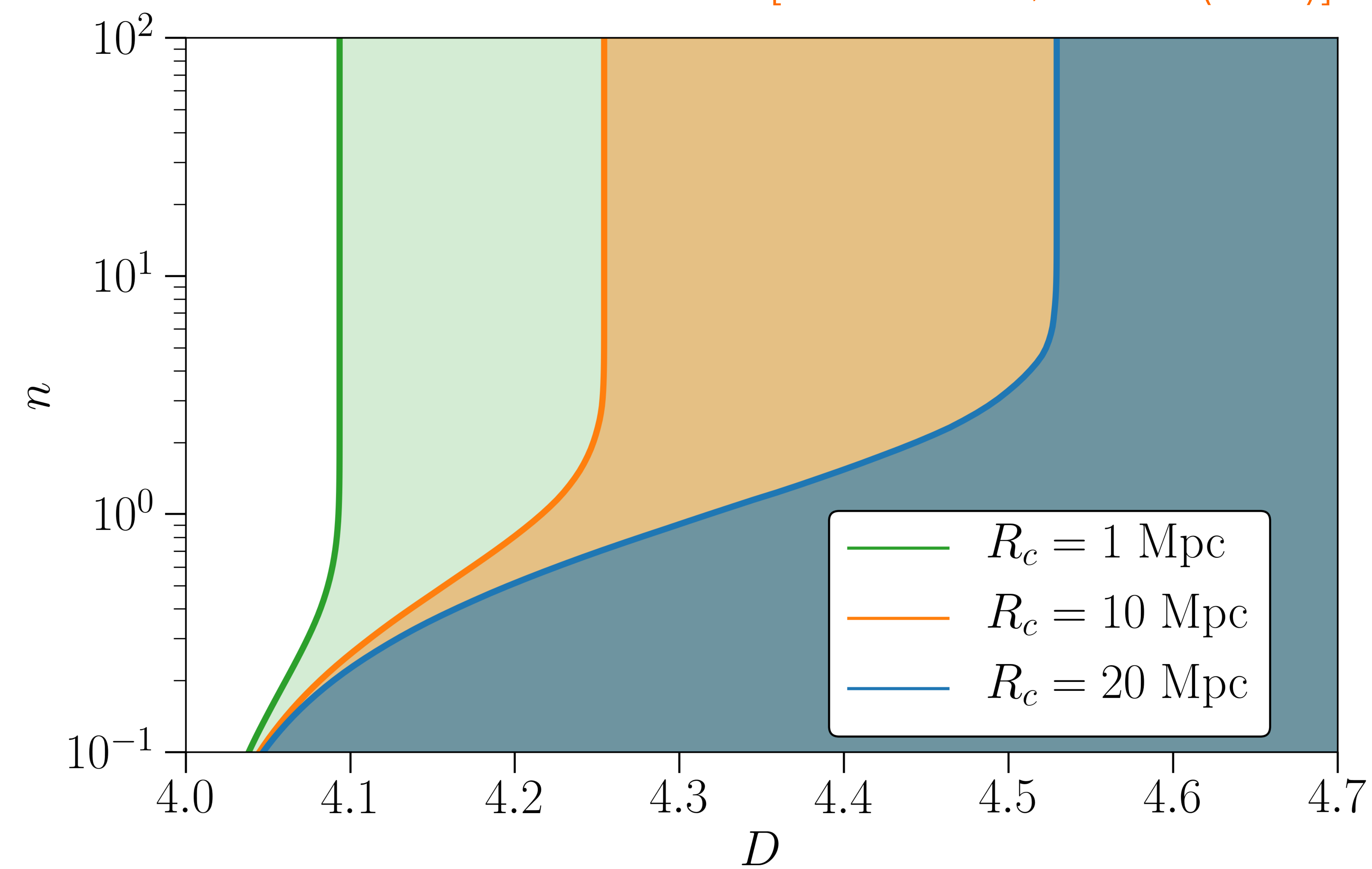


Nature of GW polarizations

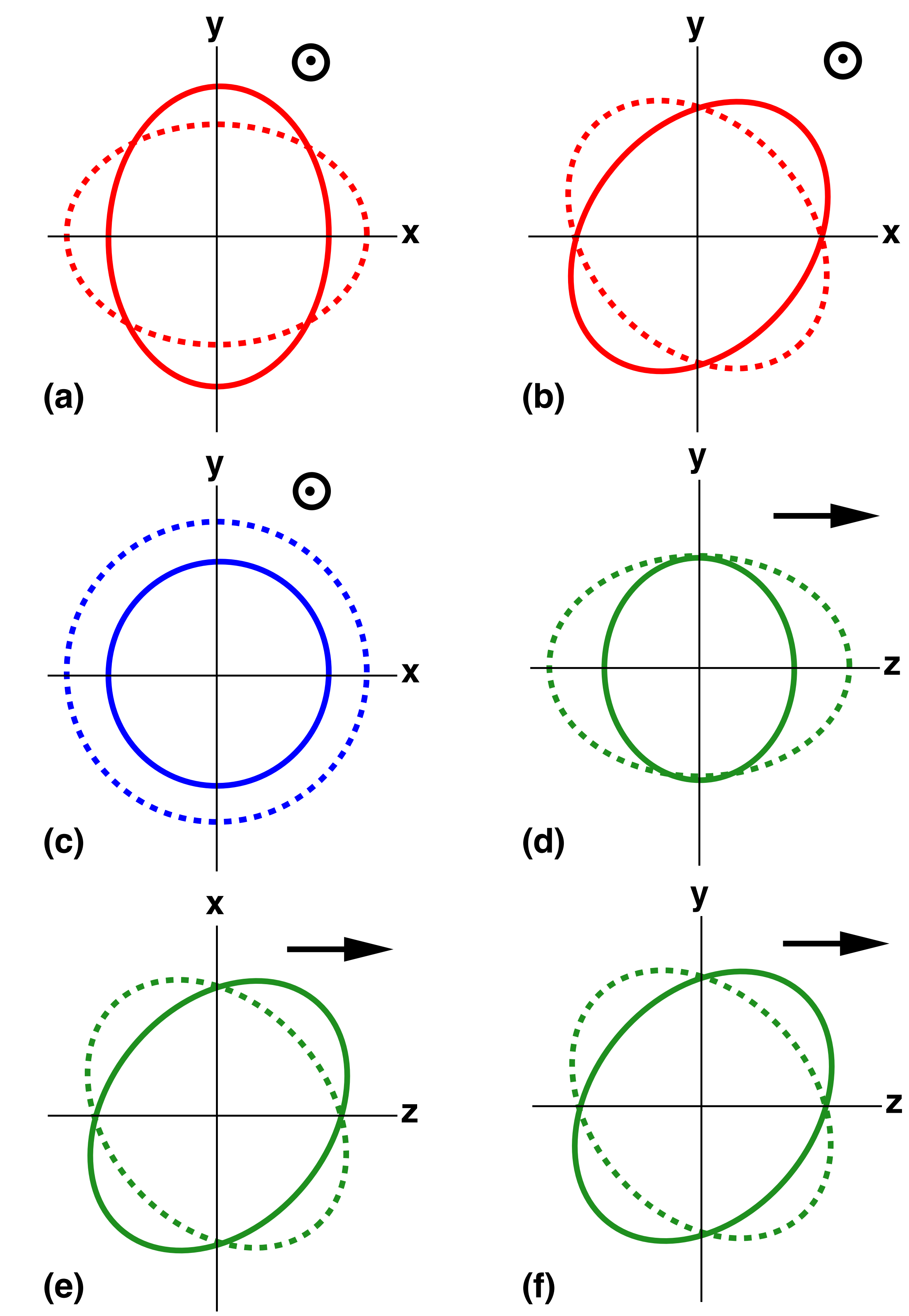
[Will, Living Rev (2014)]

- Generic metric theories of gravity allow up to six GW polarizations. Only two tensor modes are permitted in GR.

Tensor modes

Scalar modes

Vector modes

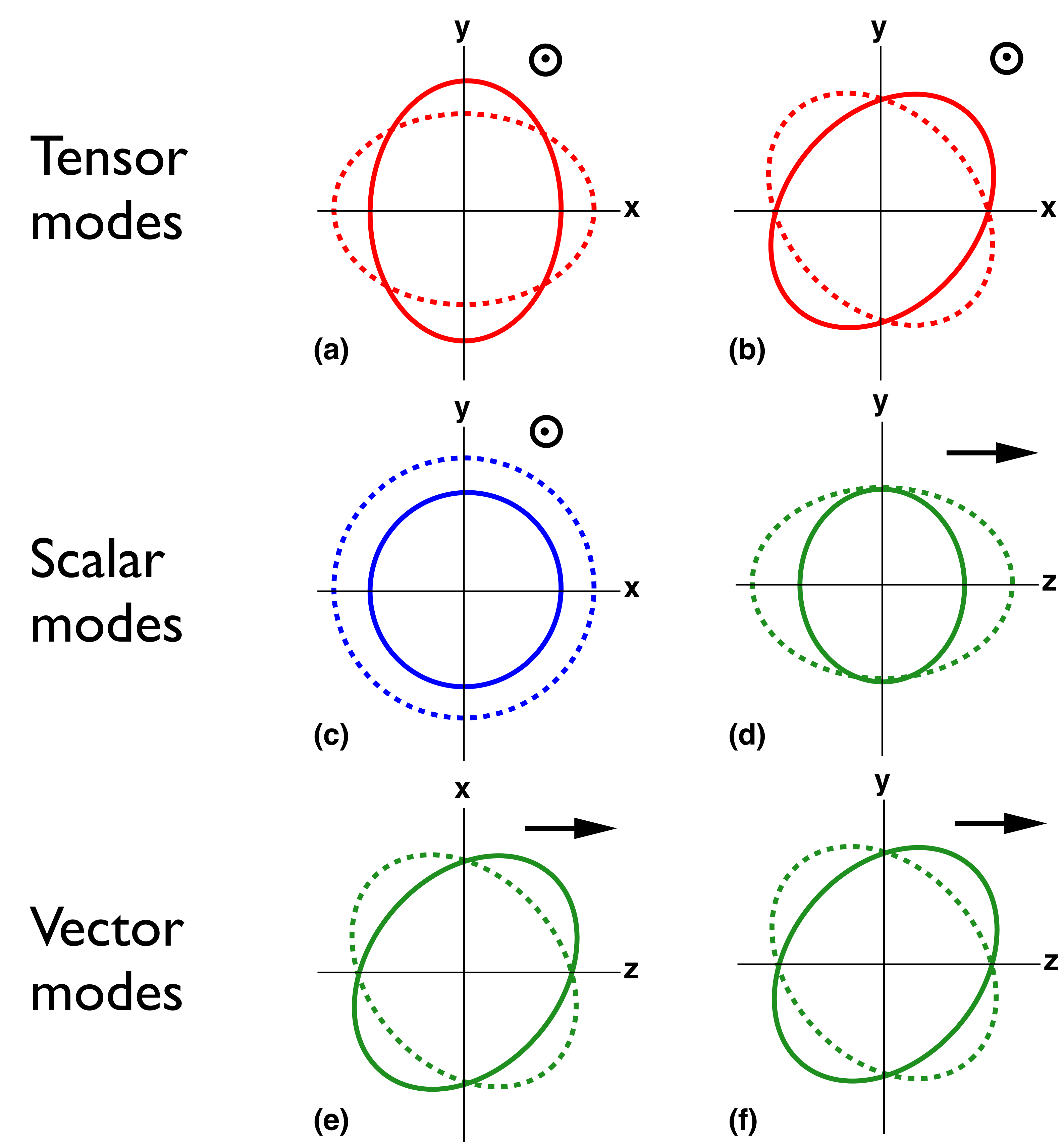


Nature of GW polarizations

- Generic metric theories of gravity allow up to six GW polarizations. Only two tensor modes are permitted in GR.
  - Current tests using CBC signals: A tensor-only model is preferred over scalar-only or vector-only model.
  - Similar possible constraints from CWs [Isi et al 2014] and stochastic background [Nishizawa 2009]

Future Better constraints with 5-detector advanced network?

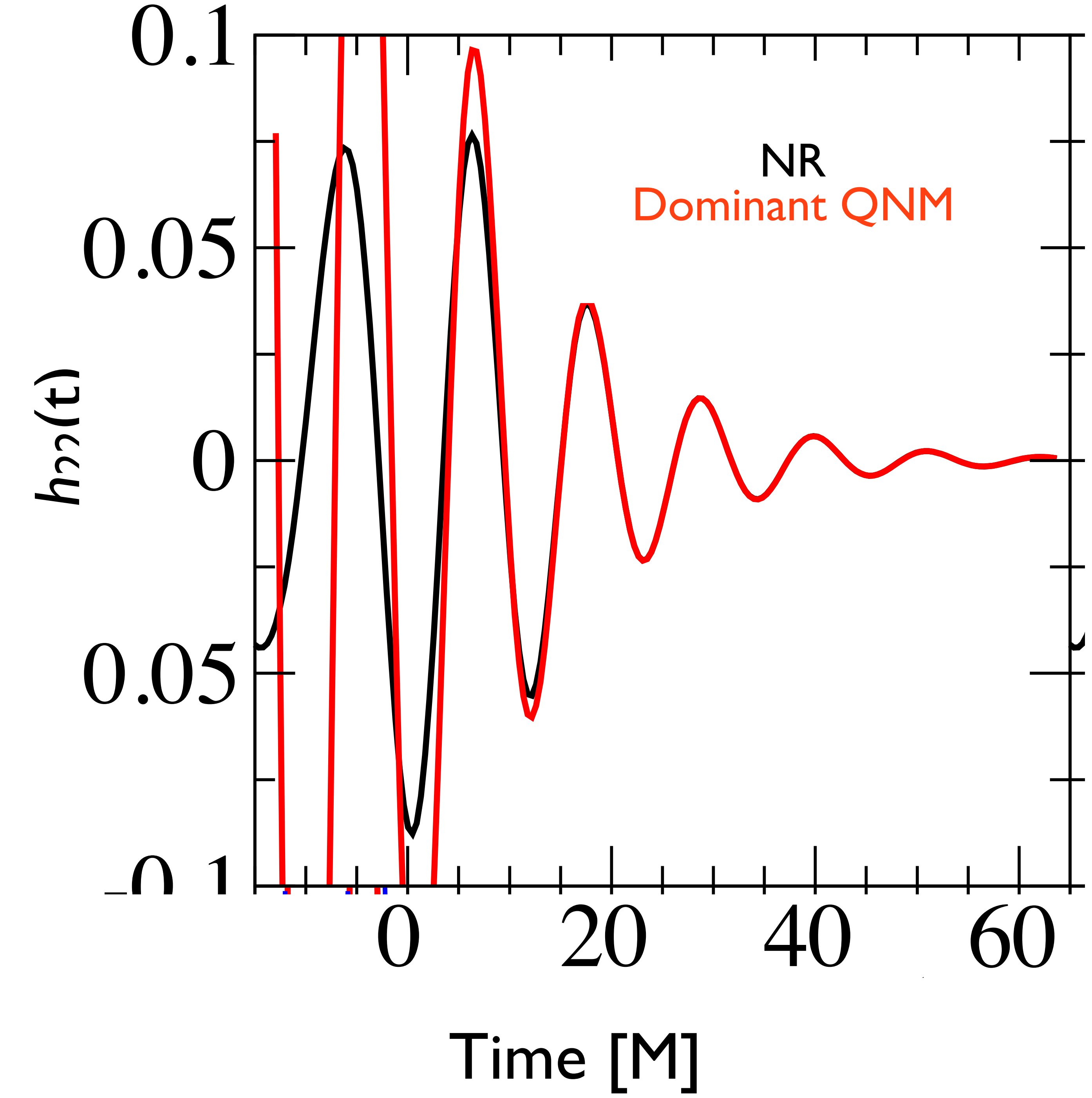
[Will, Living Rev (2014)]



Evidence of quasi-normal modes

- Late stages of the post-merger signal from a BBH coalescence should be described by a QNM spectrum.

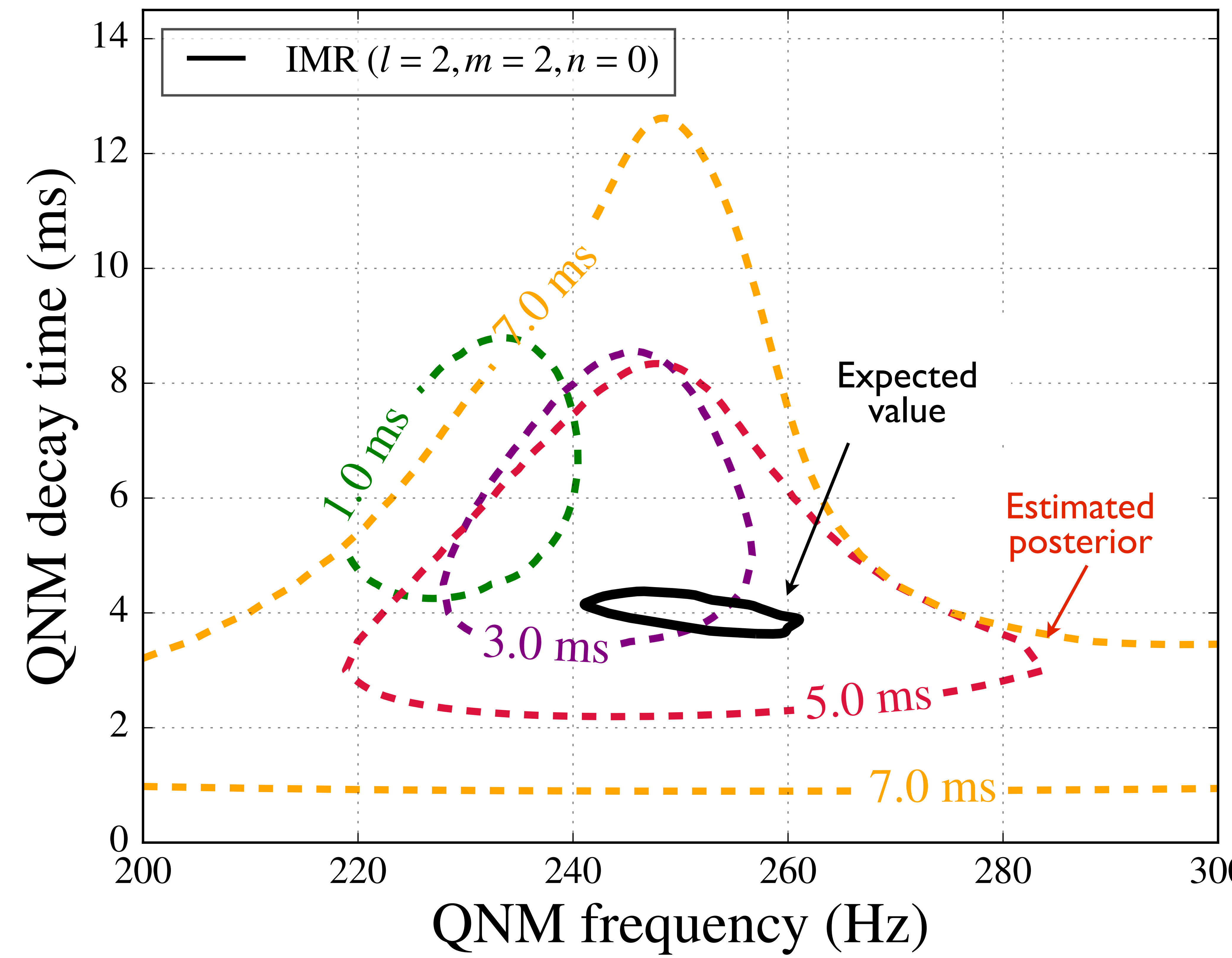
[Buonanno et al 2006]



Evidence of quasi-normal modes

- Late stages of the post-merger signal from a BBH coalescence should be described by a QNM spectrum.
- Data following the peak of GW150914 consistent with the least-damped QNM inferred from the mass & spin of the remnant BH.

[PRL 116, 221101 (2016)]



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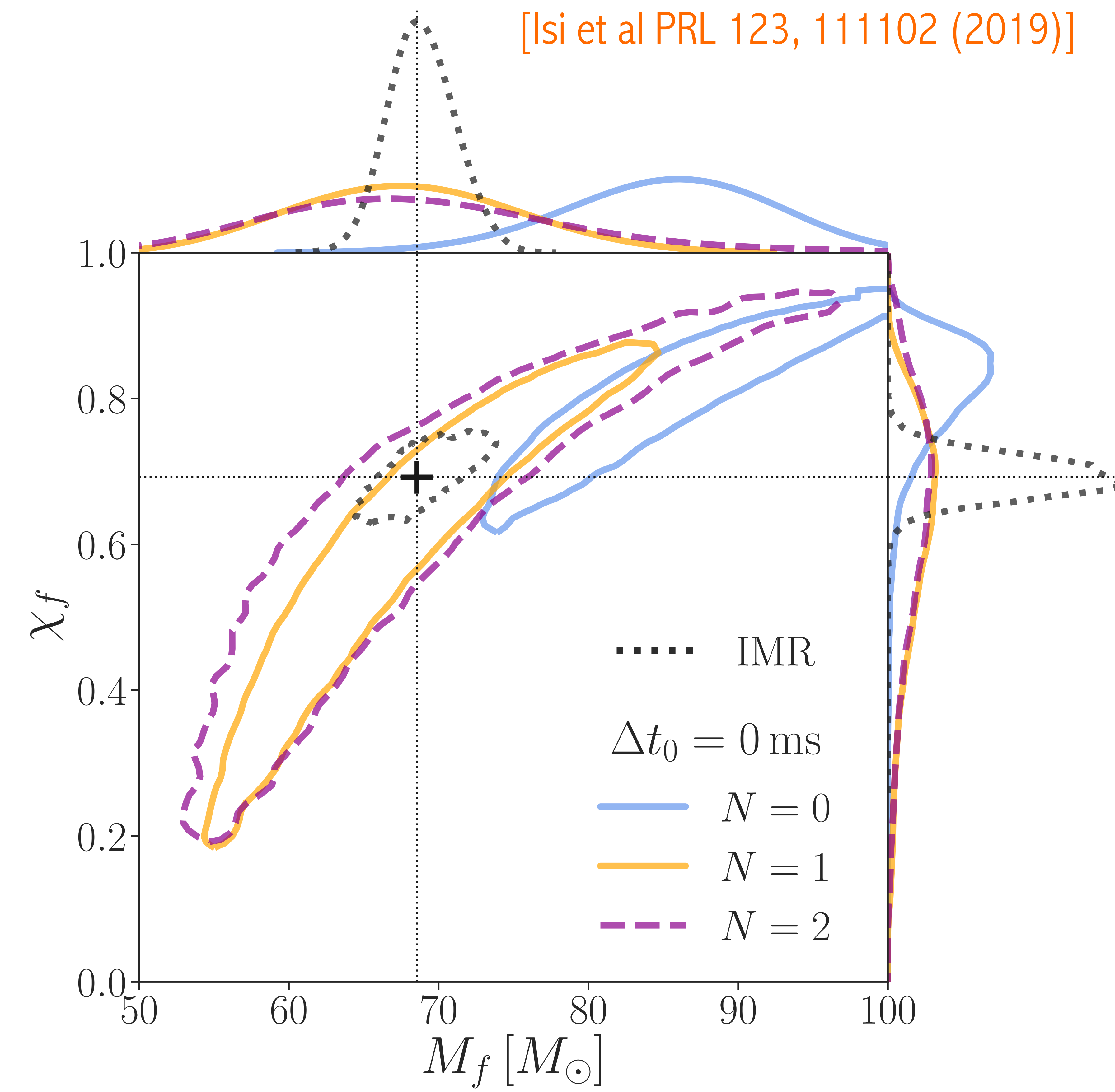
- Late stages of the post-merger signal from a BBH coalescence should be described by a QNM spectrum.
- Data following the peak of GW150914 consistent with the least-damped QNM inferred from the mass & spin of the remnant BH.
- Claims of a confident QNM detection considering multiple "overtones."

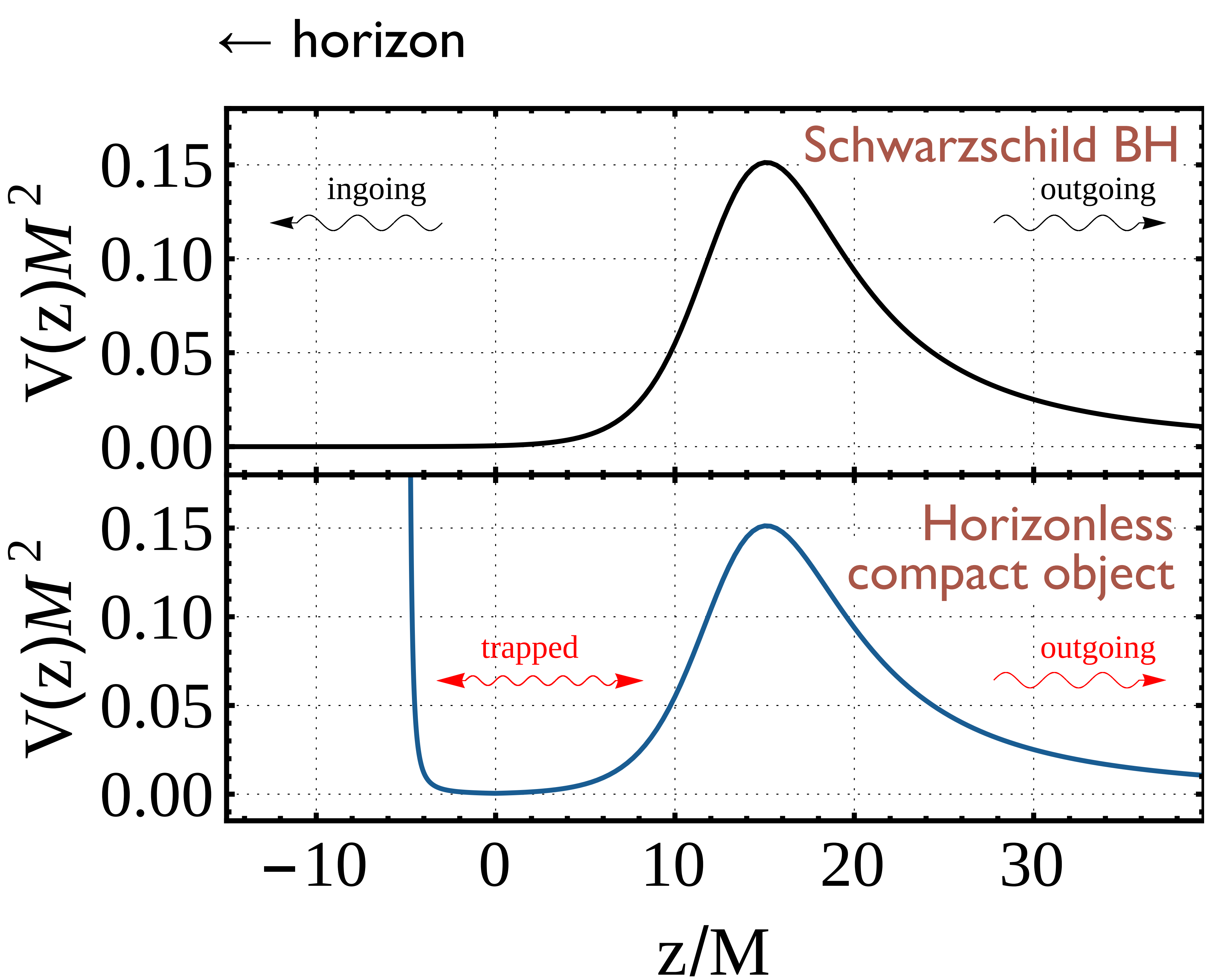
Future Tests of no-hair theorem based on the consistency of multiple QNMs [Dreyer et al 2003, Carullo et al 2018].

[Isi et al PRL 123, 111102 (2019)]



Evidence of (lack of) horizons: Echoes

- For an ultra compact object, BH horizon is replaced by a partly outgoing boundary condition.



[Cardoso & Pani (2017)]

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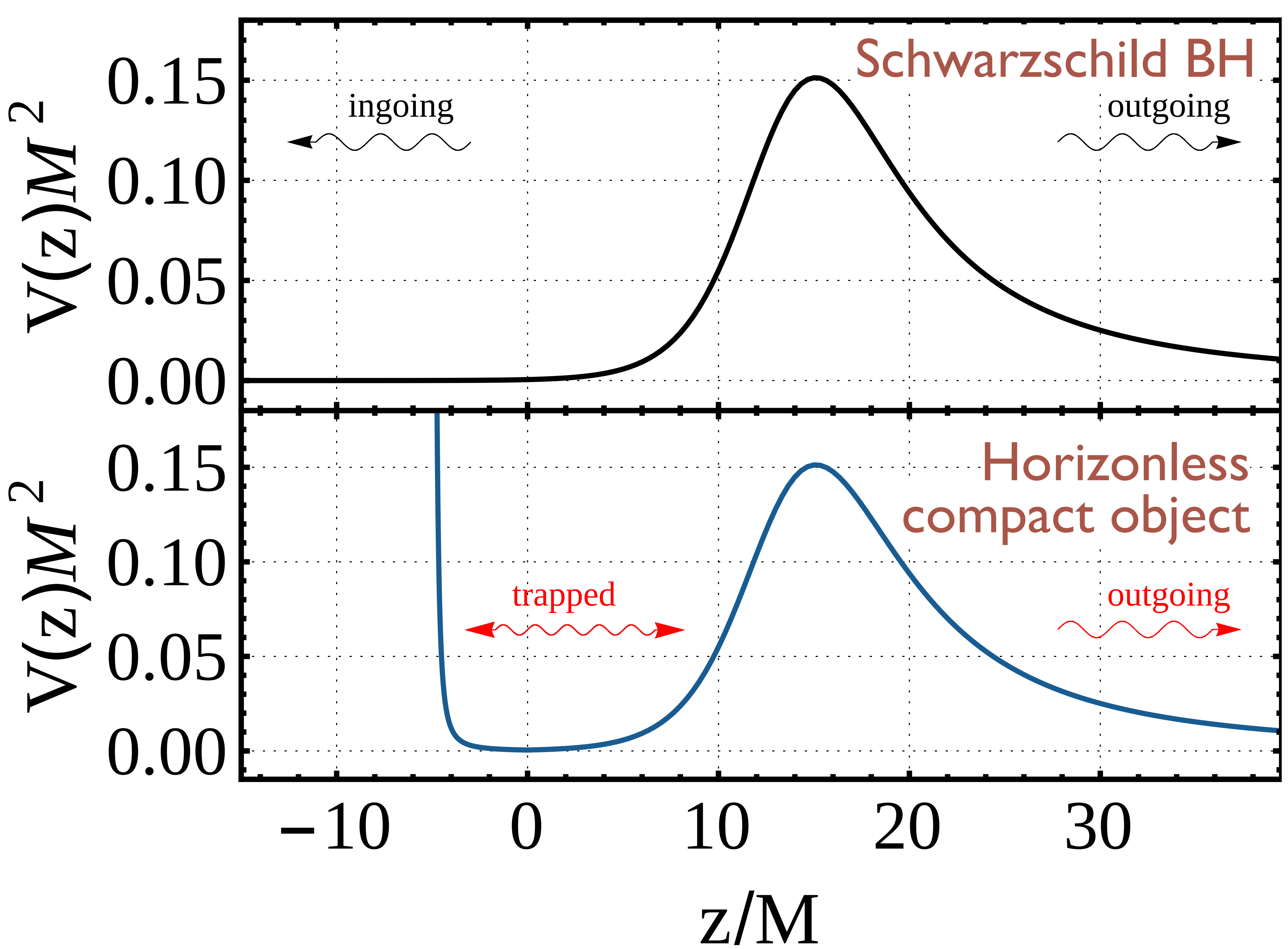
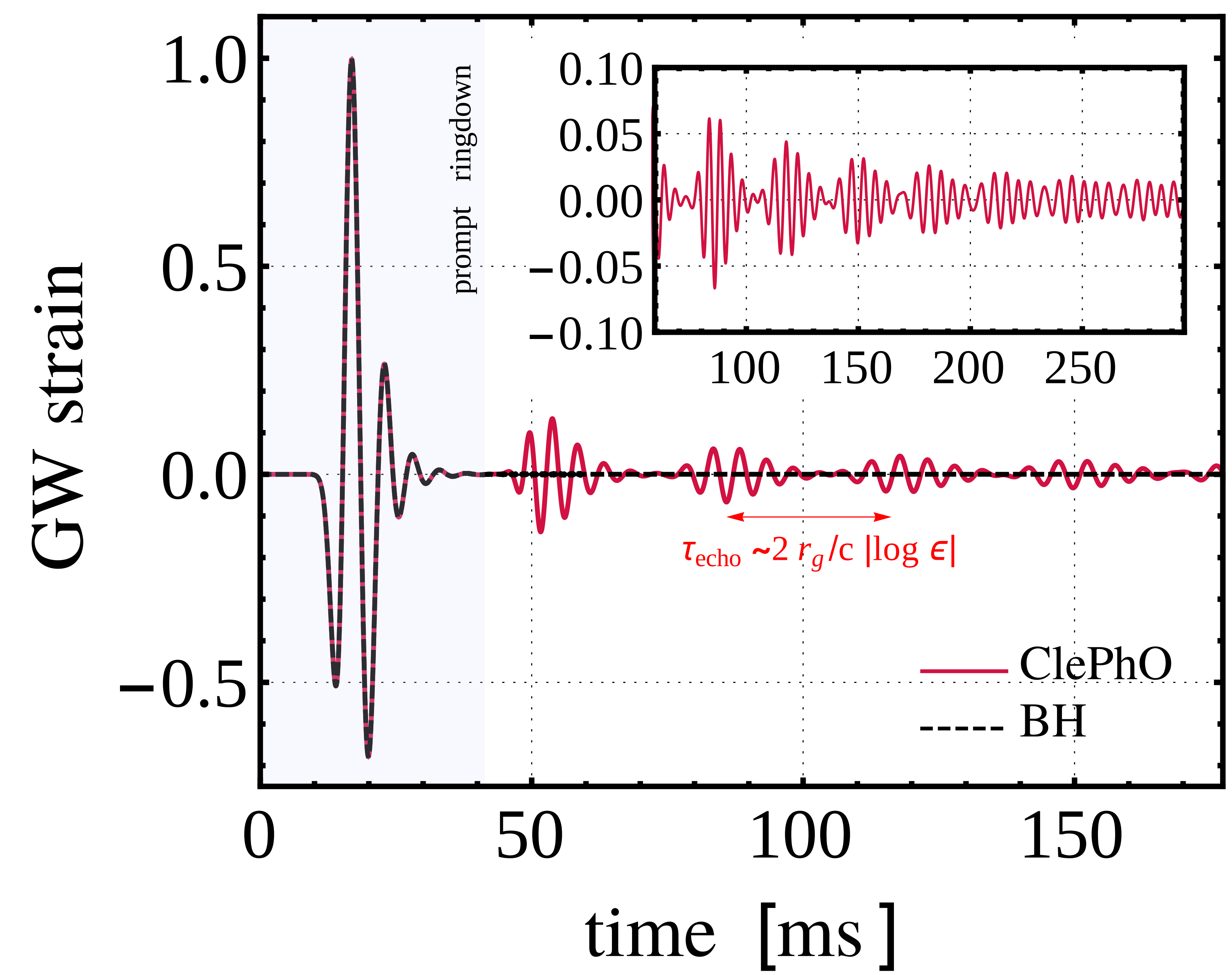
  - Modes (semi) trapped between the photon ring and the boundary can reach the outside observer, producing a series of echoes.





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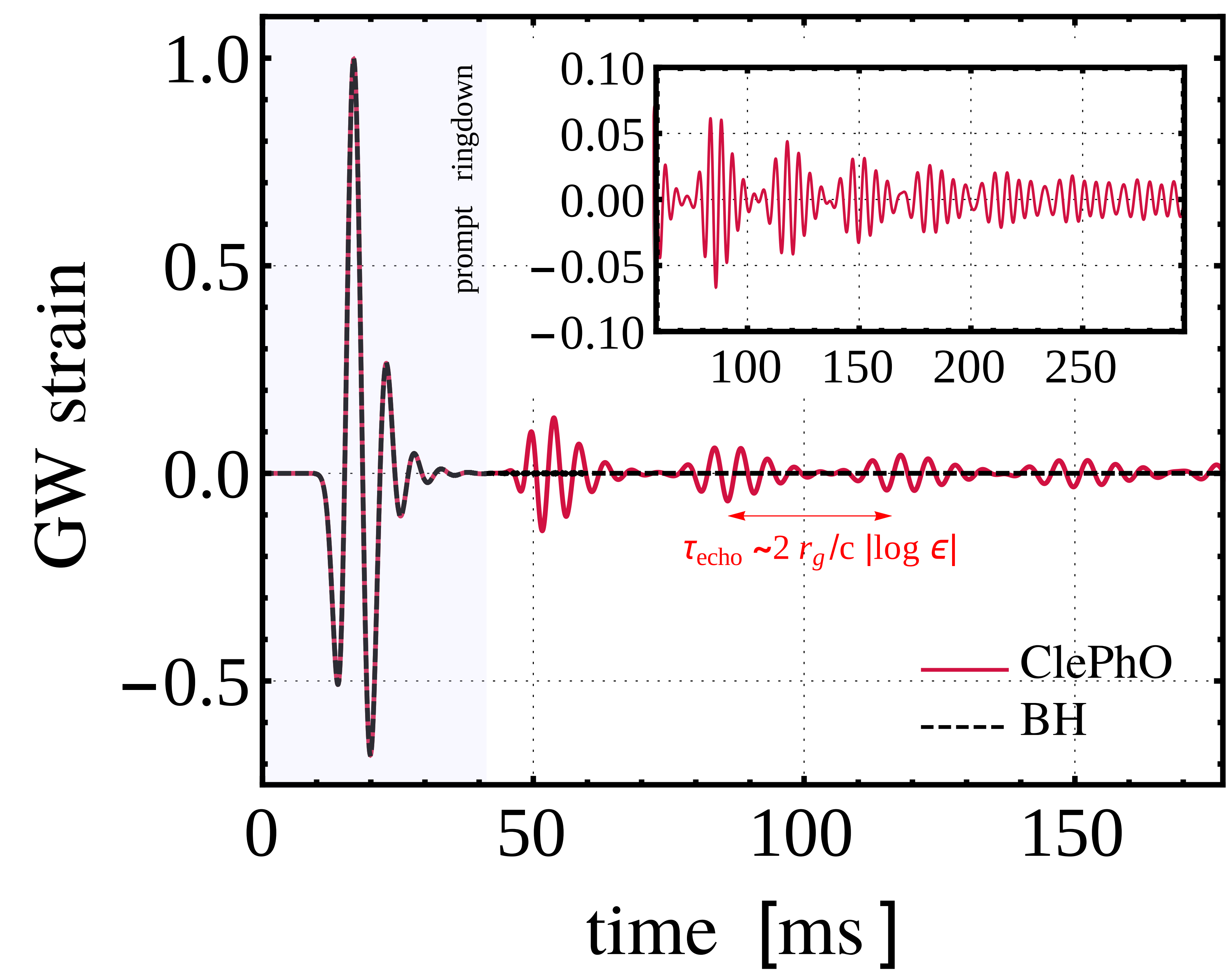
- Claims of weak evidence in LIGO-Virgo events [Abedi et al 2016, Conklin et al 2017]. Contested by other groups [Westerweck et al 2018, Nielsen et al 2019]



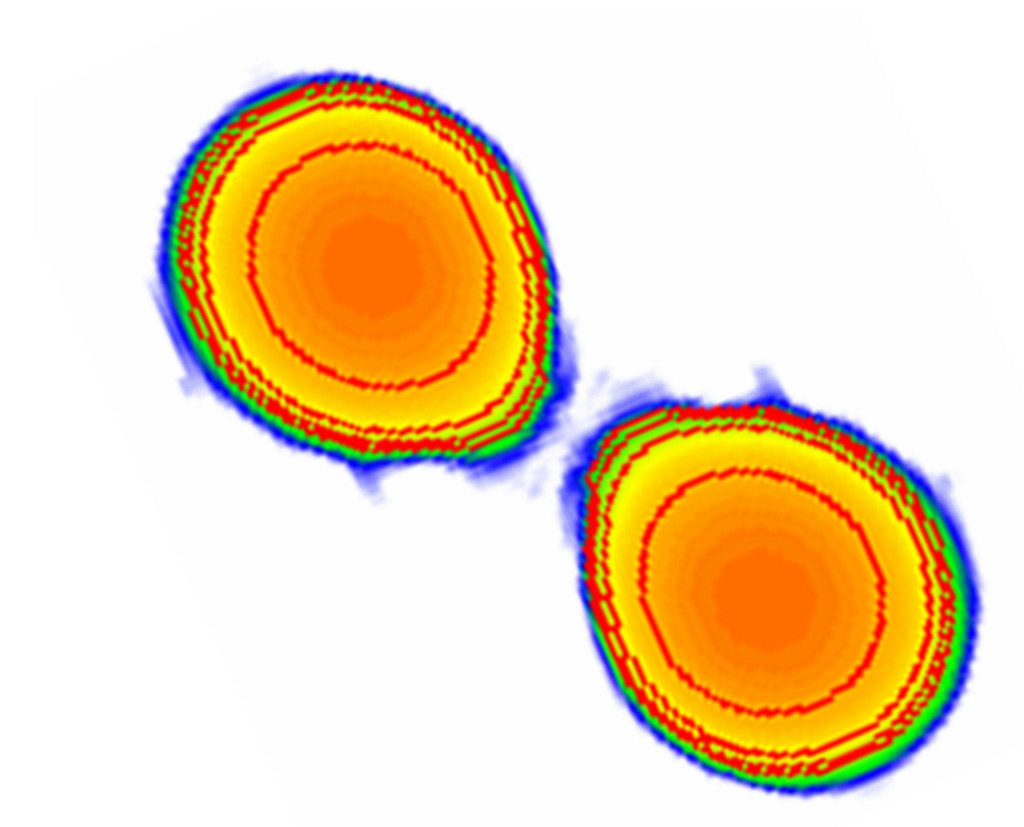
[Cardoso & Pani (2017)]

Exotic compact objects: Tidal/spin-induced deformations

- Possible imprints of black-hole mimickers
  - **Tidal deformability Λ**: Ratio of the induced quadruple moment to the external tidal field. [Cardoso et al 2017, Sennett et al 2017, Johnson-McDaniel et al 2017]

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

= 0 for black holes



  - **Spin-induced quadruple moment** [Krishnendu et al 2017]

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

κ =1 for Kerr BHs. For other objects, depends on the EoS

Accurate modeling of GW signals in alternative theories

- If accurate GW signal predictions are available in alternative theories, straightforward to do Bayesian model selection.

$$\frac{P(\mathscr{H}_{\mathrm{alt}} \,|\, d)}{P(\mathscr{H}_{\mathrm{GR}} \,|\, d)}$$

- Several challenges (e.g. well-posedness of the initial value problem). Interesting new approaches in solving the problem, e.g., [Okounkova et al 2017]

Summary

- GW observations have enabled the first tests of GR in the highly relativistic, strong-field regime.
- In the absence of accurate signals predictions in alternative theories, current tests only probe the consistency of the data with GR.
- Interesting theoretical work in predicting GW signals from alternative theories and exotic objects.
- Considerable reduction statistical errors can be expected in near future. Soon, we will reach a regime where the error budget is dominated by systematic errors!