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Testing general relativity using gravitational waves from colliding compact objects

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19th Recontres du Vietnam – ICISE, Quy Nhon

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Introduction

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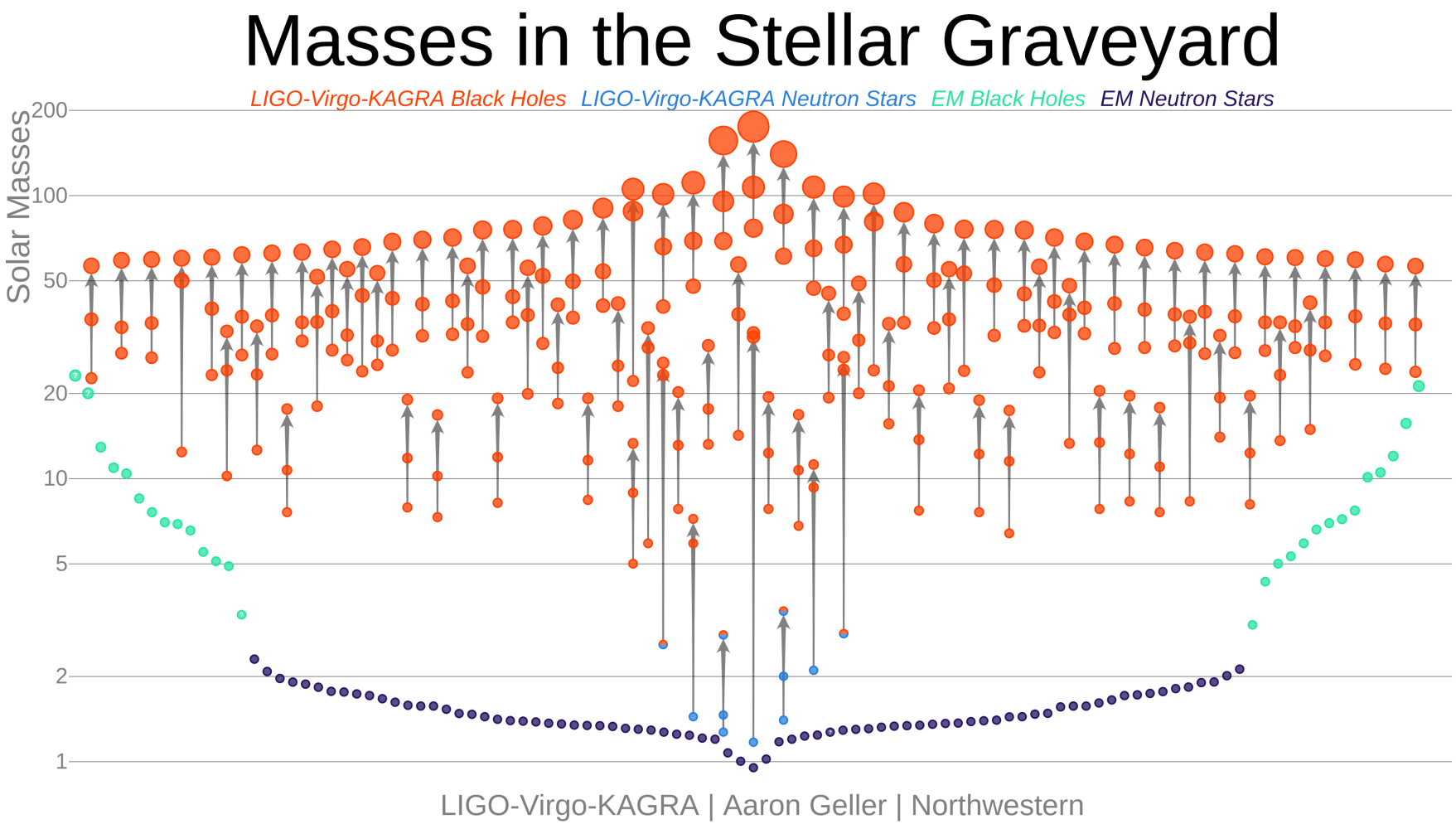
1 Binaries



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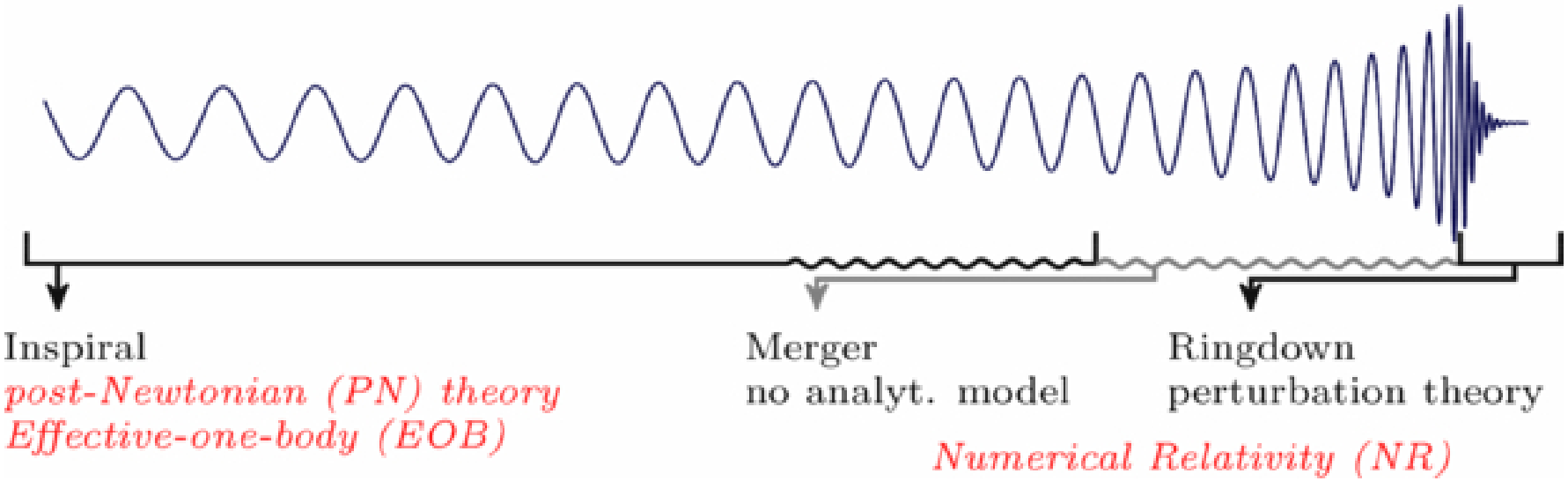
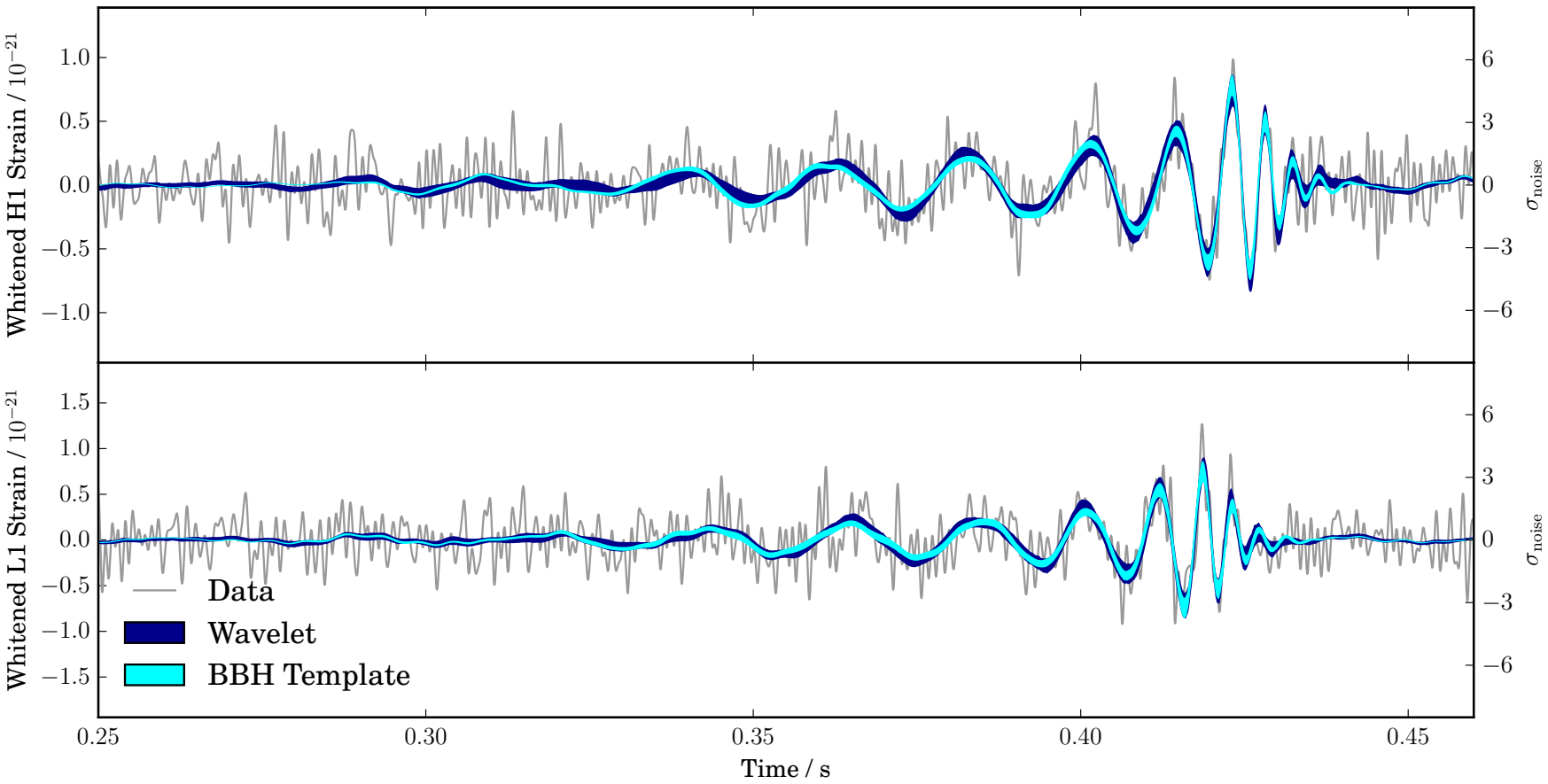
1 Morphology of Colliding Compact Objects

- GWs radiates away energy and angular momentum (inspiral)
  - Increasingly higher frequency and bigger amplitude
- At some point, two objects will merge into one (merger)
- Single object radiates as it reaches quiescent state (ringdown)

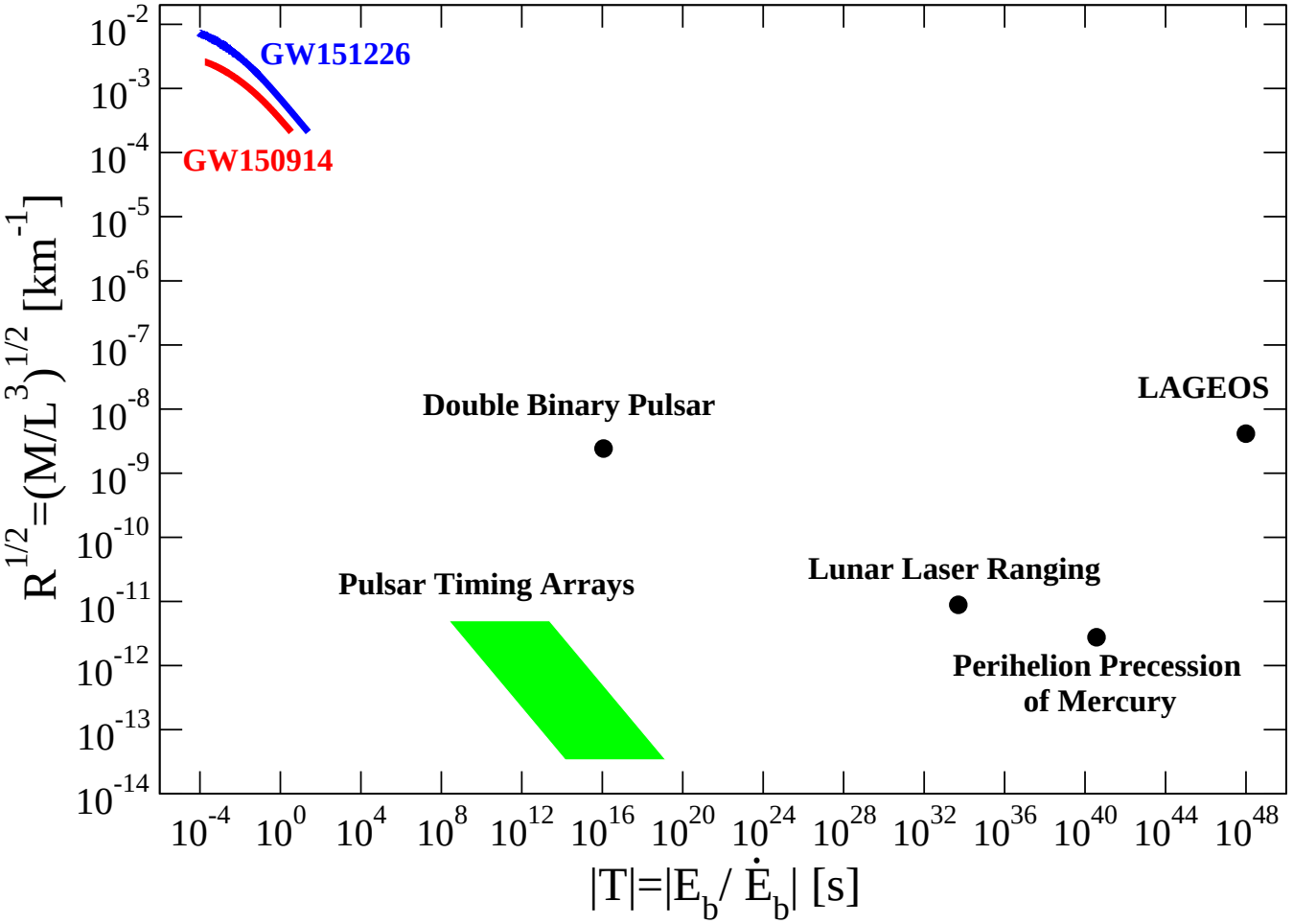


1 Consistent with GR?



Room for small deviations from GR with the uncertainty

1 Testing the Strong-field Dynamics of Gravity



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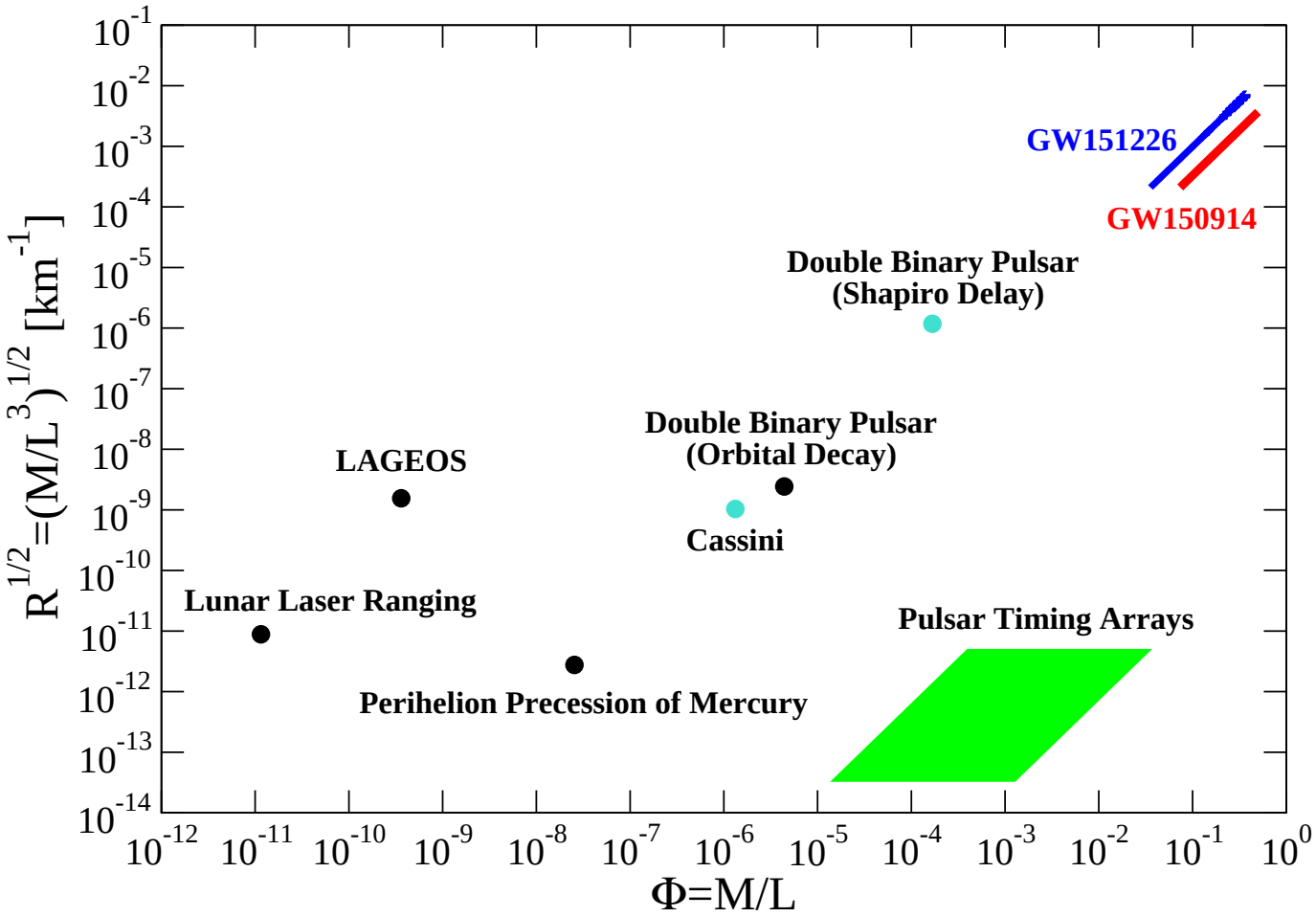
1 Testing the Strong-field Dynamics of Gravity



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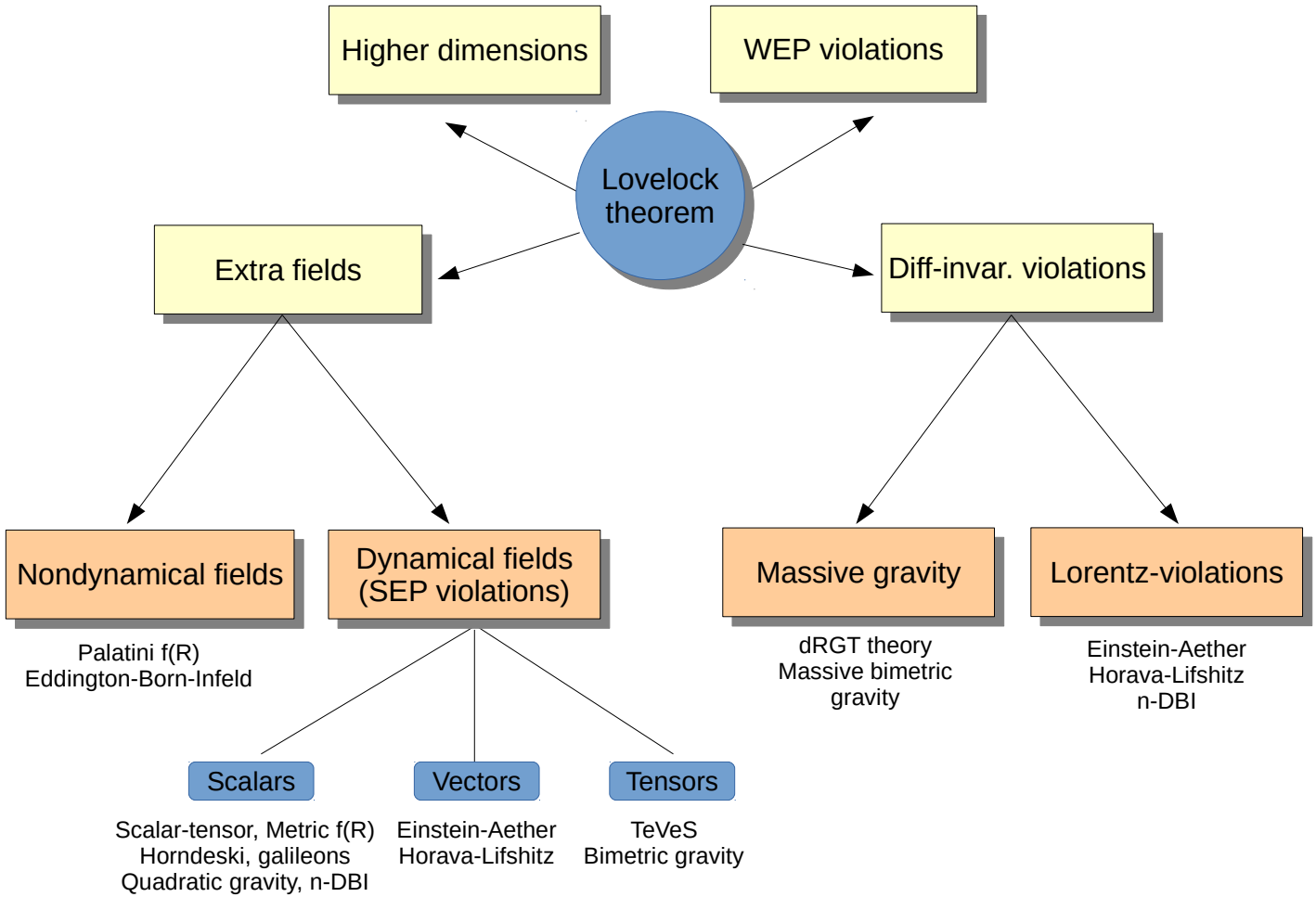
1 A Zoo of Alternative Theories



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Strong-field Dynamics of Spacetime

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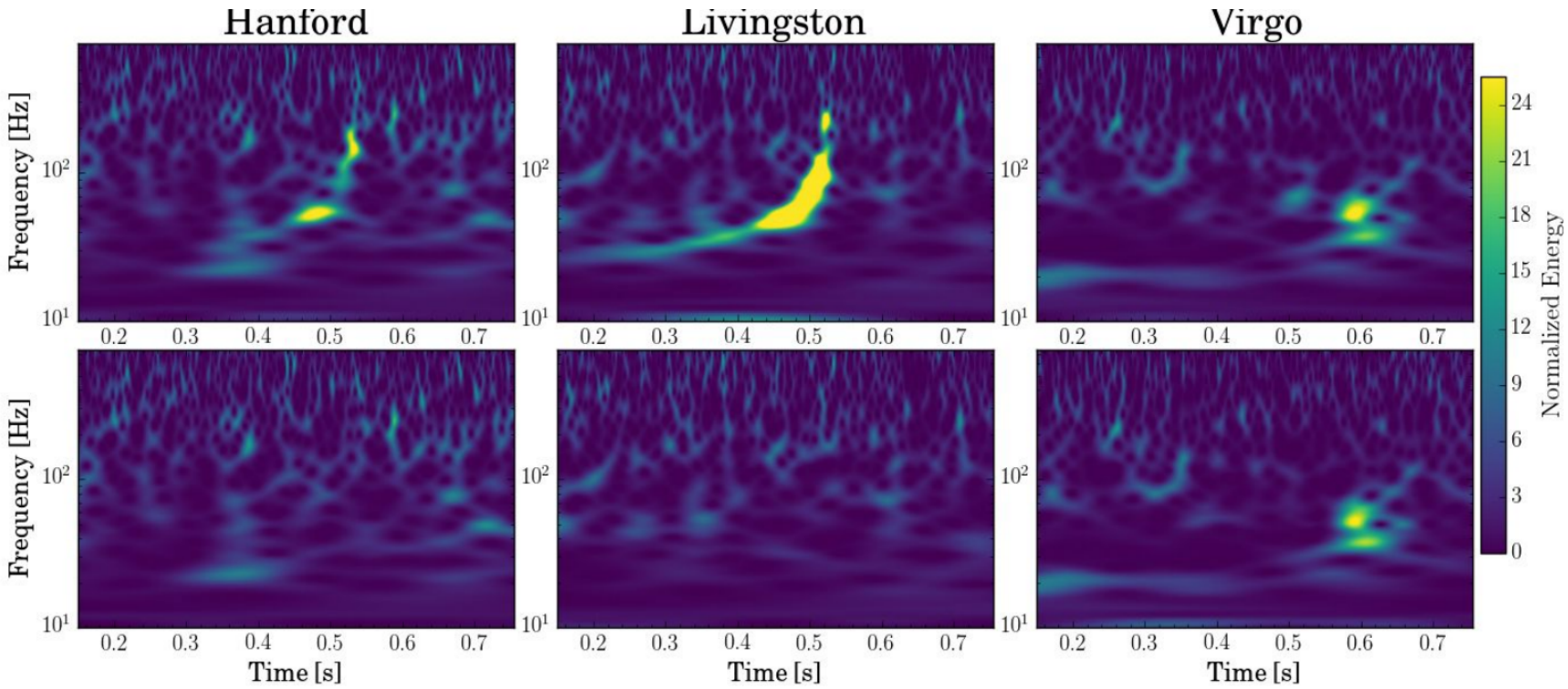
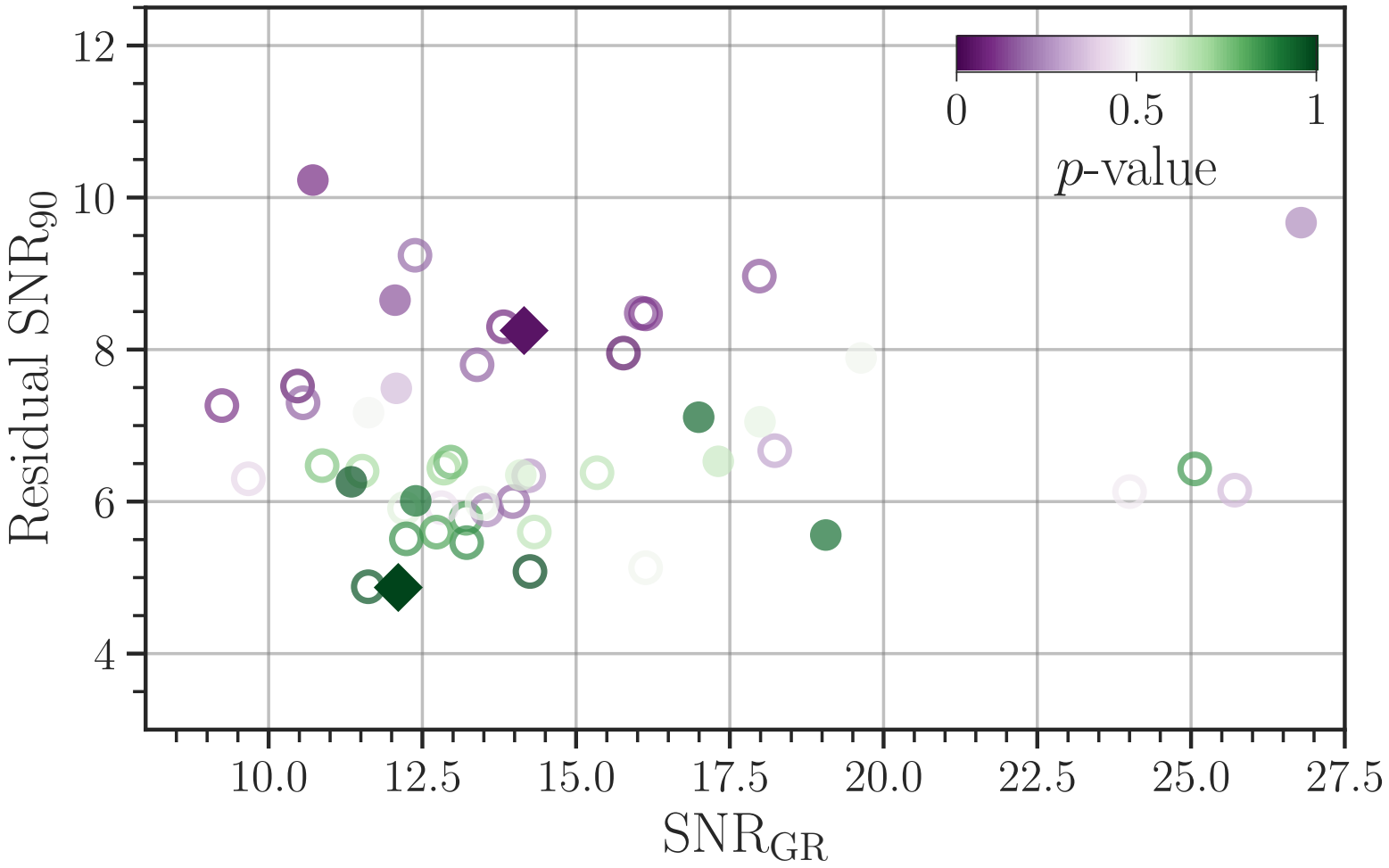
2 Residual Test I



- Subtract best-fit GR template
- Consistent residual in the network after removing the GW indicates an inconsistency between data and GR template

2 Residual Test II



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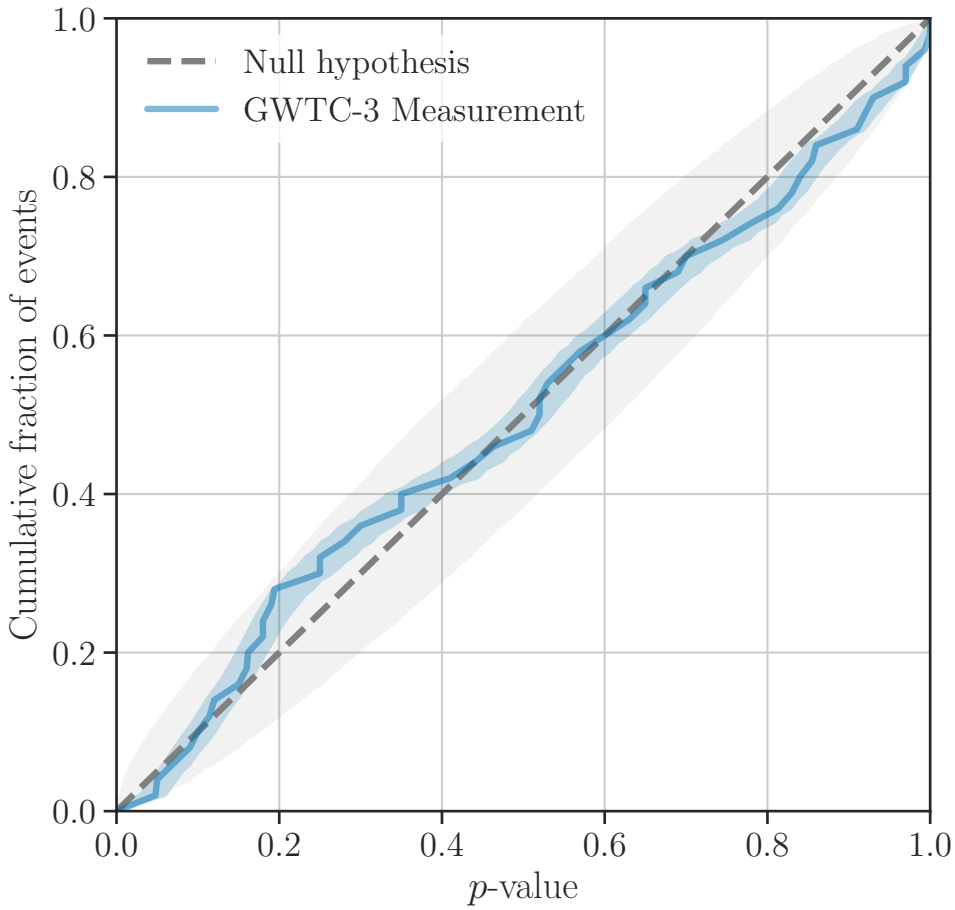
2 Residual Test III

- If left-over SNR from detector noise

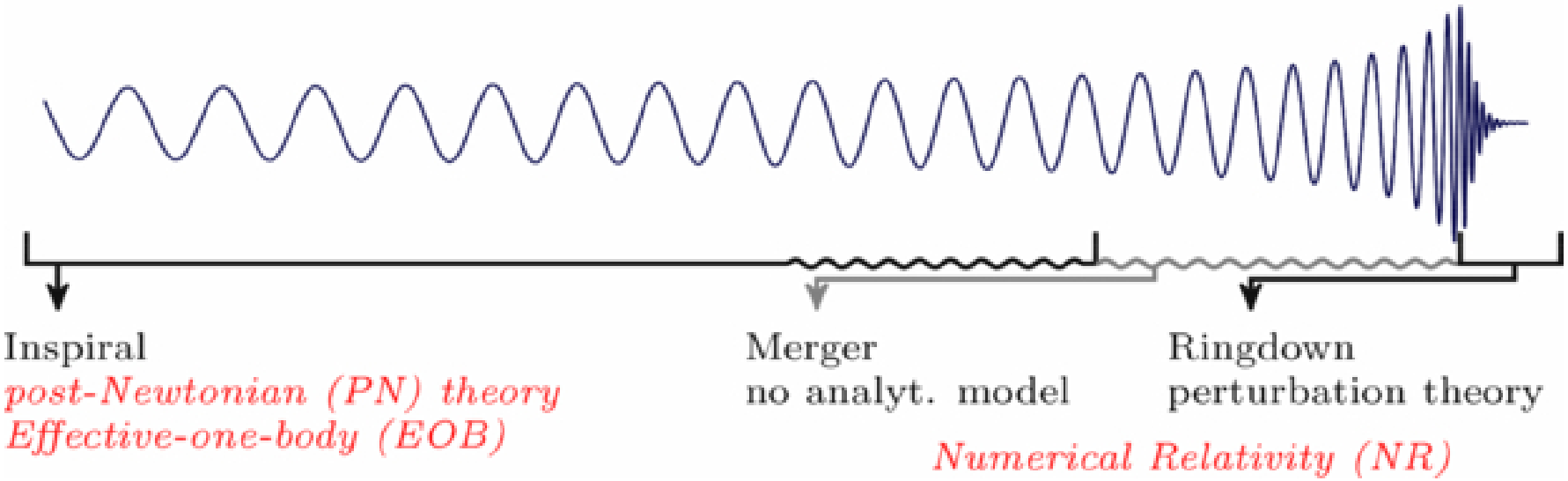
$$p \in [0, 1]$$

- All events from GWTC-3
- PP plot is within 90% credible region of null hypothesis

No significant deviation in the residual data



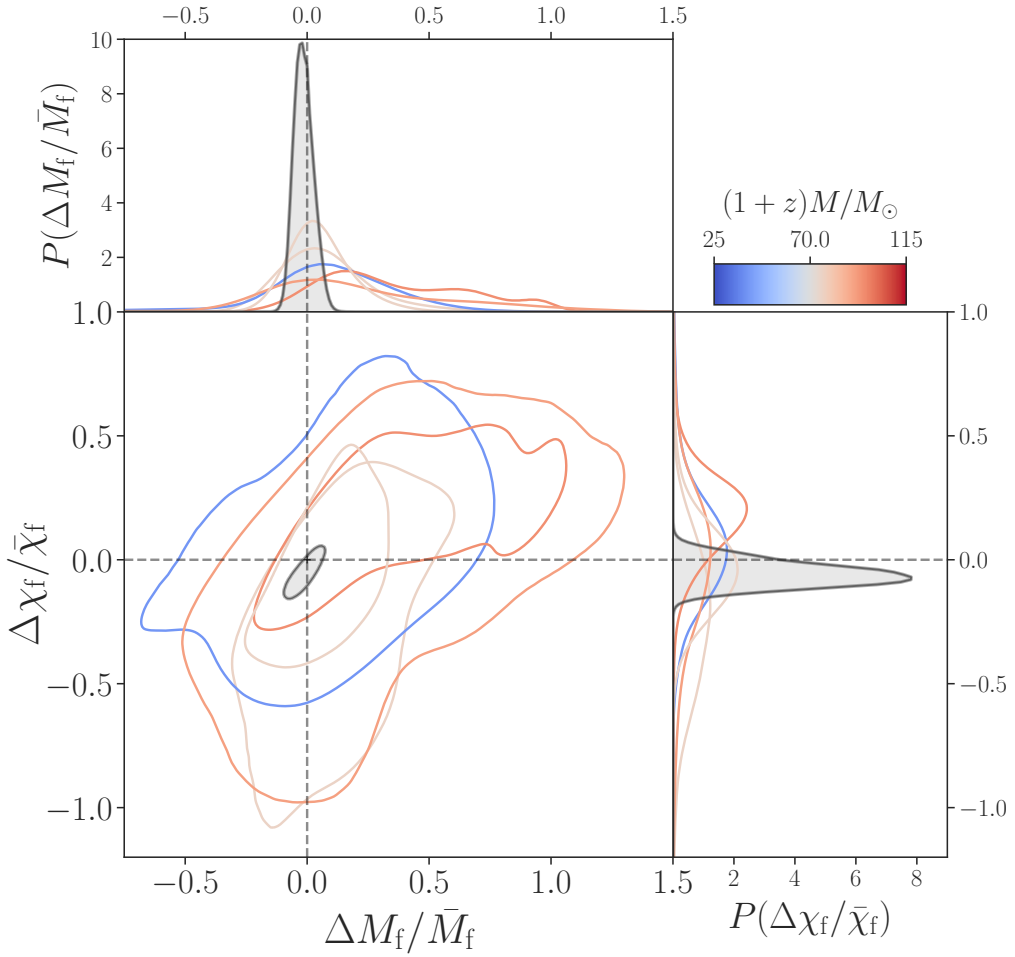
2 Consistency Check I



- Check consistency of mass/spin of remnant BH inferred from low- and high-frequency parts of signal
- Divide signal in two parts at some cutoff frequency
- Mass/spin of remnant BH estimated from NR-calibrated fits.

2 Consistency Check II

- Fractional difference in final mass/spin
- 90% confidence intervals
- $(0, 0)$ expected for GR



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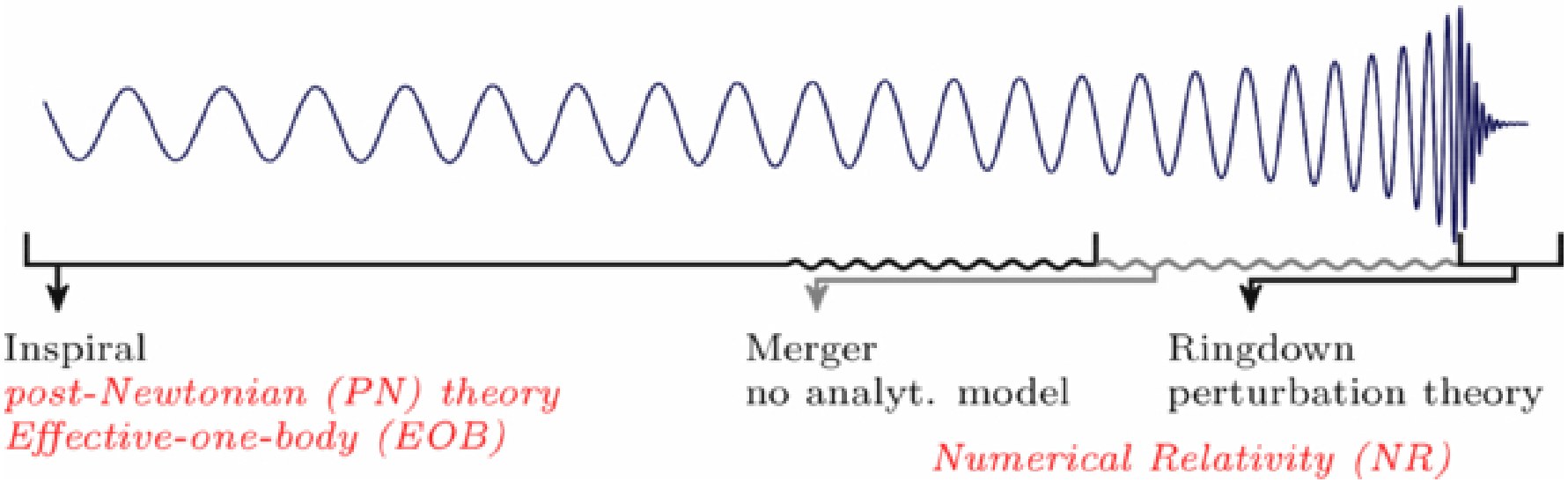
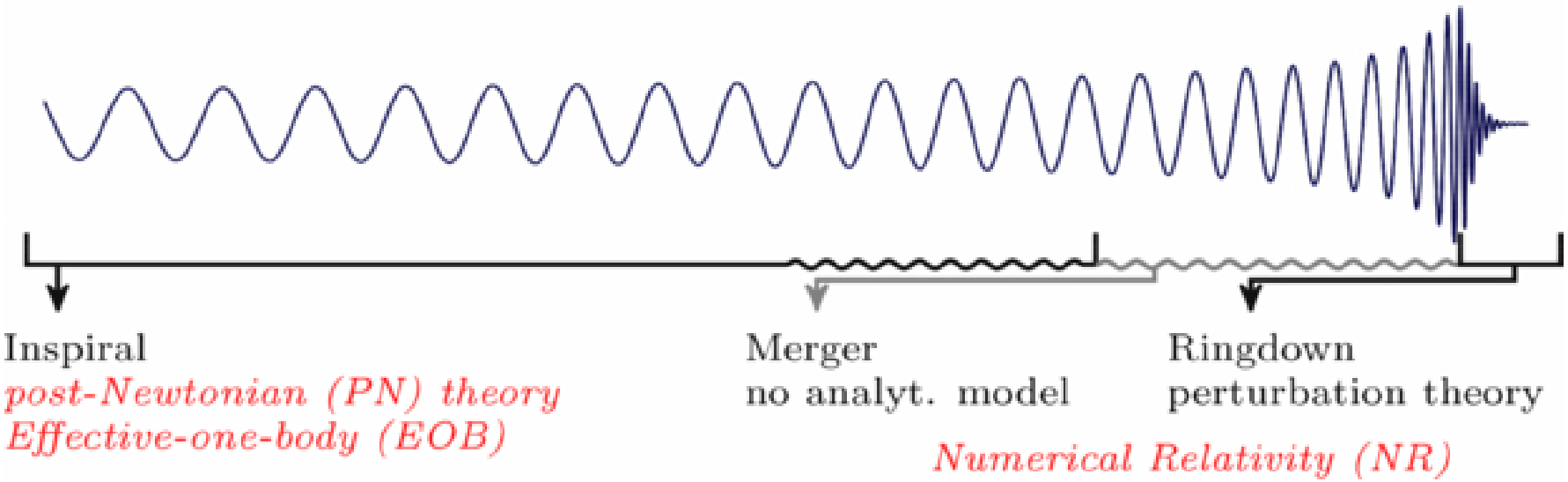
2 Parameterised Tests



- Consider phase in PN theory

$$\varphi_{\mathrm{PN}}(f) = \ldots + \frac{3}{128\eta}\left(\pi\tilde{f}\right)^{-5/3}\sum_{i=0}^{7}\left[\varphi_i + \varphi_{i\,l}\log(\pi\tilde{f})\right]\left(\pi\tilde{f}\right)^{i/3}$$

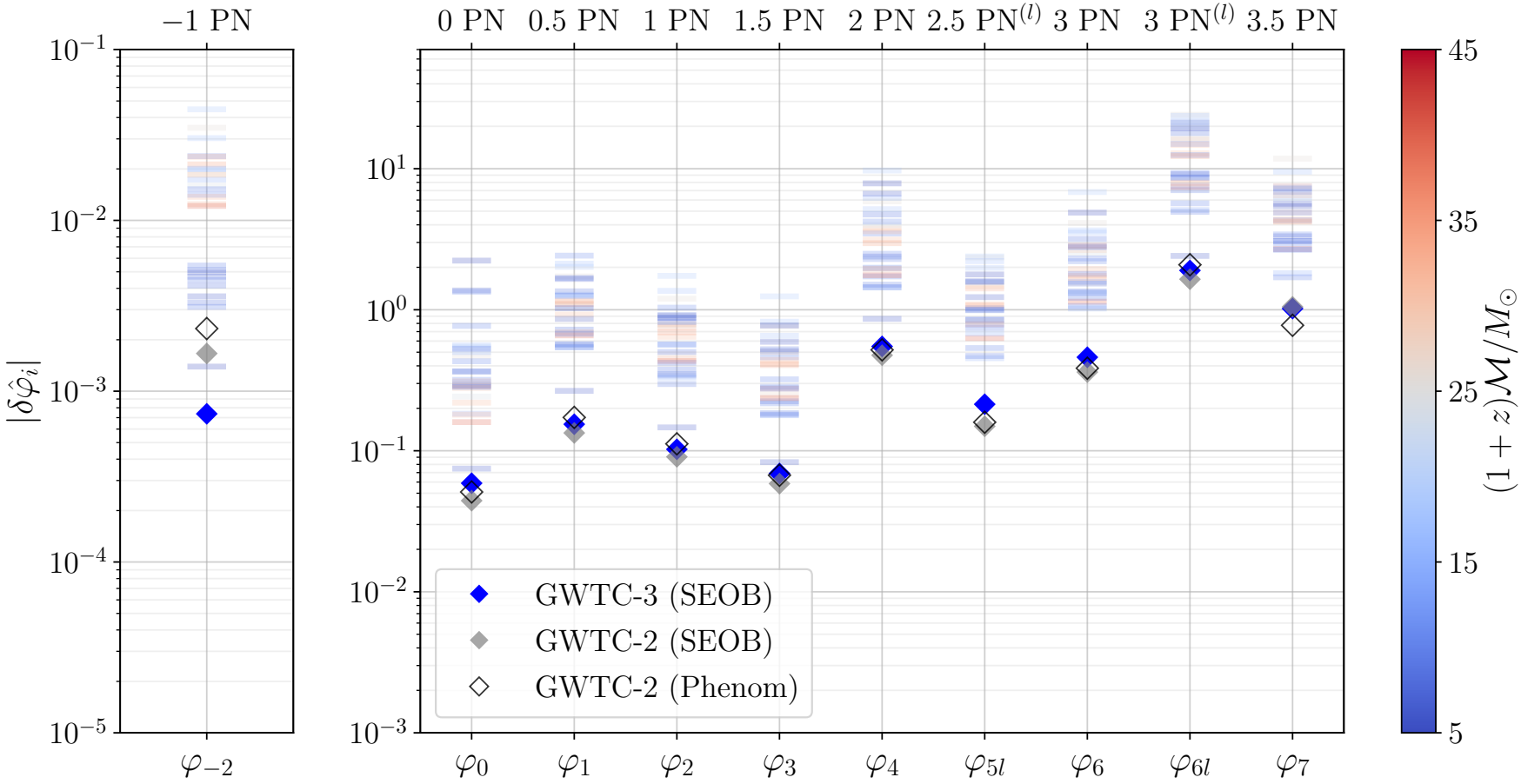
2 Parameterised Tests



- Allow for fractional changes with respect to the GR value

$$\varphi_i \to (1 + \delta\hat{\varphi}_i)\,\varphi_i$$

2 Parameterised Tests: Results



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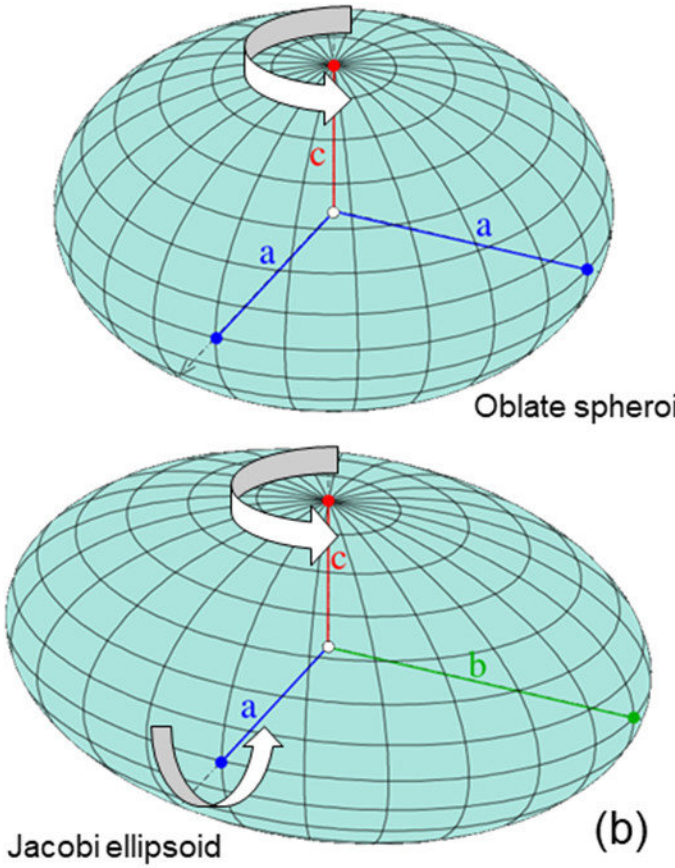
2 Spin-induced Quadrupole Moment

- Spinning objects have quadrupole (and higher) contributions due to their rotational deformations.
- The leading order term can be schematically represented as,

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

- κ has different values types of stars
  - Kerr black hole: $\kappa = 1$
  - Neutron stars: $\kappa \in [\sim 2, \sim 14]$
  - Boson stars: $\kappa \in [\sim 10, \sim 150]$



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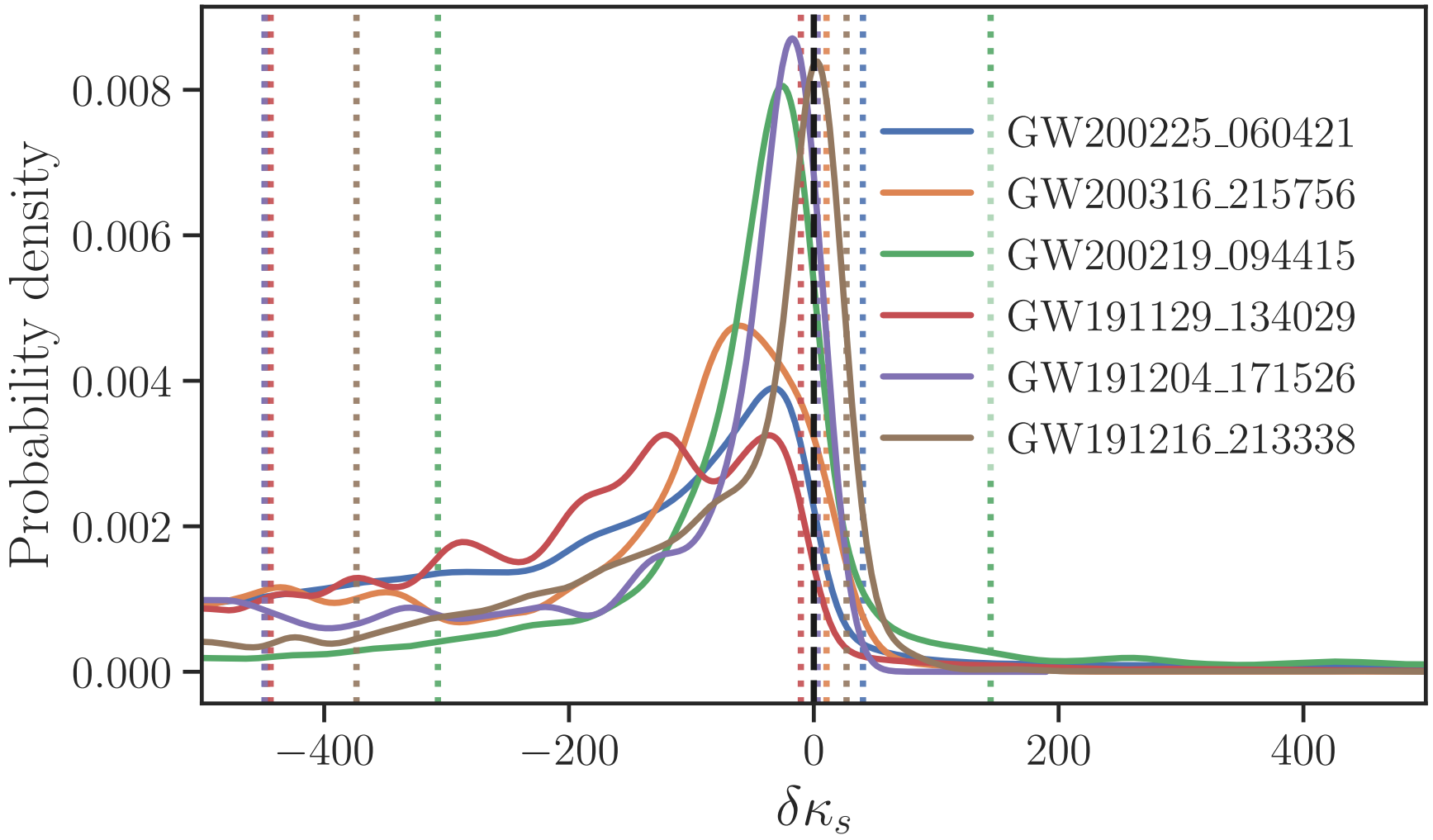

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Nature of Gravitational Waves

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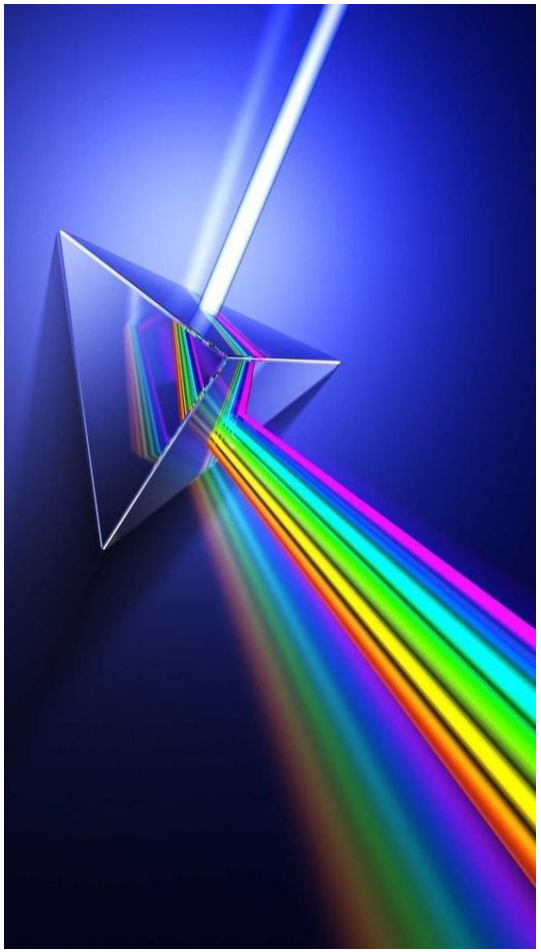
3 Wave Propagation

- GR predicts that GWs propagate nondispersively
- Parameterise dispersion relation

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

- Captures various dispersion relationships
  - Massive graviton: $\alpha = 0$ with $A_\alpha > 0$



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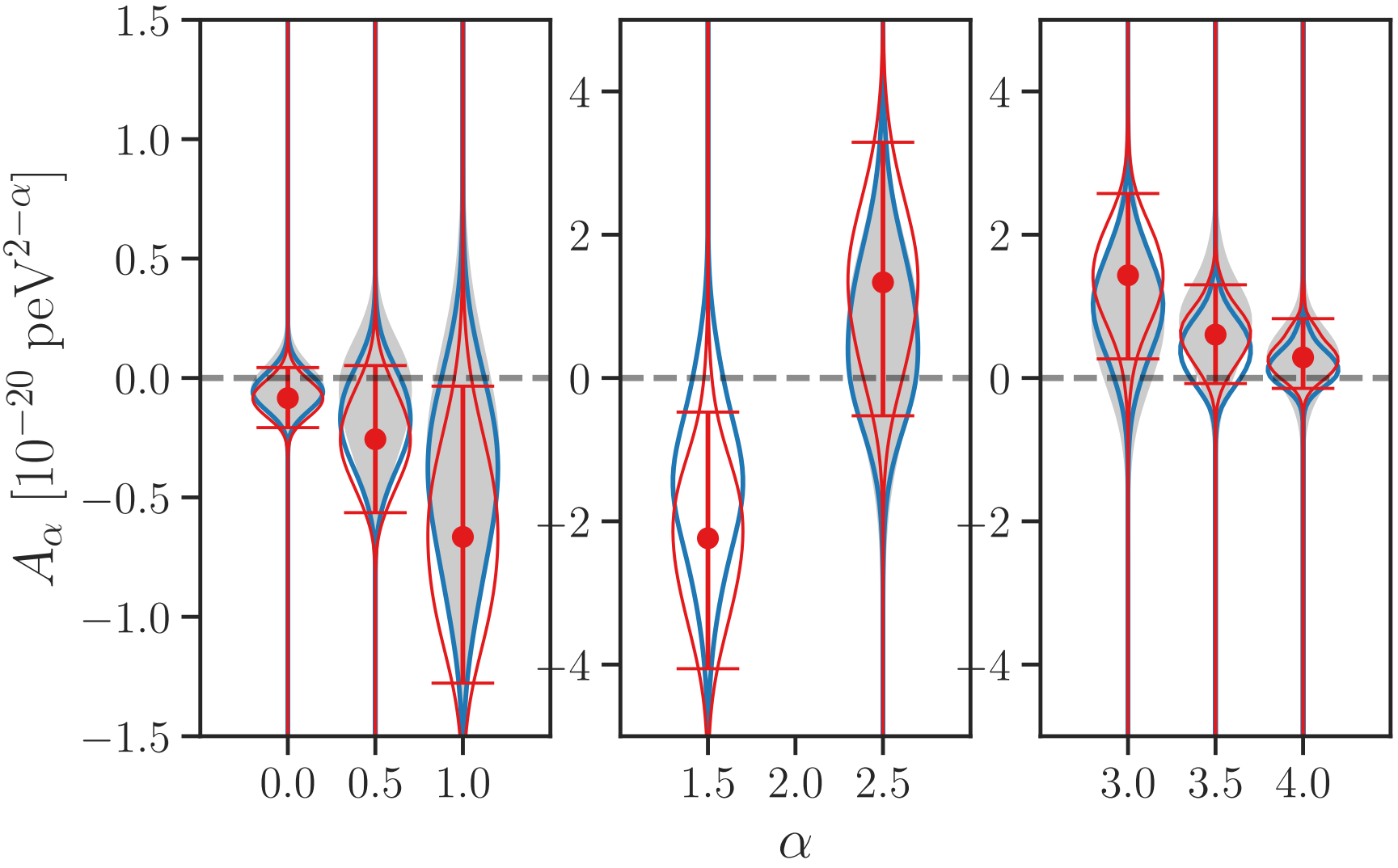

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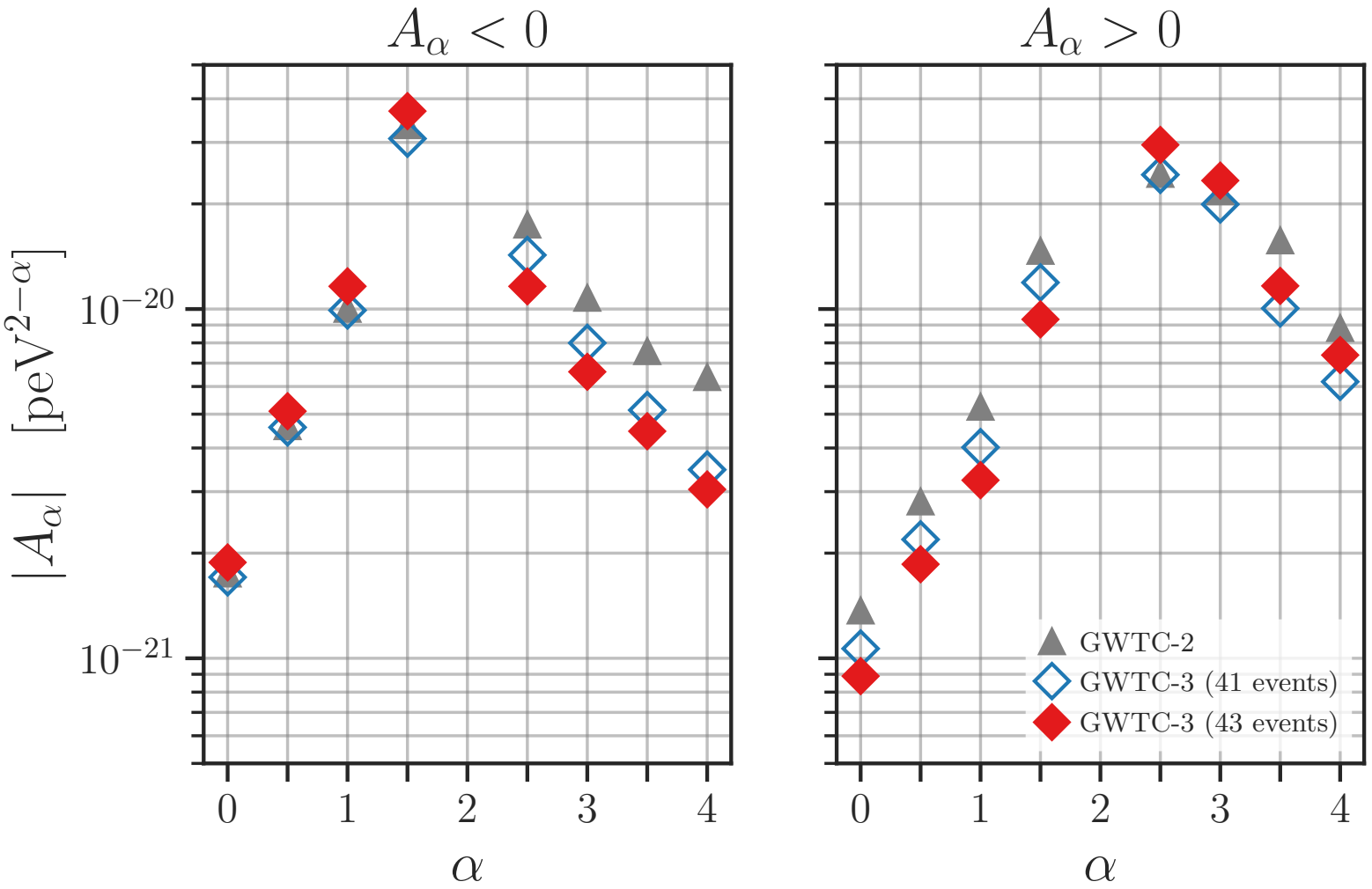

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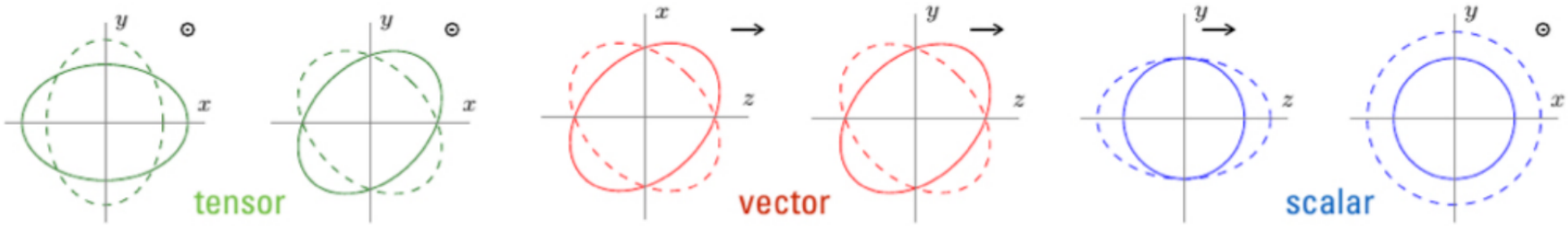
3 Polarisation Modes I



- Metric theories of gravity allow up to 6 polarizations
- Distinct antenna patterns: six distinct antenna patterns
- In GR: GW are transverse, traceless
- In the case of GW170817, sky position known from EM counterpart
  - Pure tensor / pure vector $= 10^{21}/1$
  - Pure tensor / pure scalar $= 10^{23}/1$

3 Polarisation Modes

Events	$\log_{10}\mathcal{B}^{\mathrm{S}}_{\mathrm{T}}$	$\log_{10}\mathcal{B}^{\mathrm{V}}_{\mathrm{T}}$	$\log_{10}\mathcal{B}^{\mathrm{TS}}_{\mathrm{T}}$	$\log_{10}\mathcal{B}^{\mathrm{TV}}_{\mathrm{T}}$	$\log_{10}\mathcal{B}^{\mathrm{VS}}_{\mathrm{T}}$	$\log_{10}\mathcal{B}^{\mathrm{TVS}}_{\mathrm{T}}$
O1	-0.04 ± 0.07	0.09 ± 0.07	0.04 ± 0.07	0.09 ± 0.07	0.09 ± 0.07	0.07 ± 0.07
O2	-0.42 ± 0.12	0.04 ± 0.12	0.08 ± 0.12	0.22 ± 0.12	0.09 ± 0.12	0.35 ± 0.12
O3a	-1.85 ± 0.21	-1.04 ± 0.20	0.25 ± 0.20	0.07 ± 0.20	-1.05 ± 0.20	-0.18 ± 0.20
O3b	-1.93 ± 0.17	-0.79 ± 0.17	-0.17 ± 0.17	-0.07 ± 0.17	-0.86 ± 0.17	-0.32 ± 0.17
Combined	-4.24 ± 0.30	-1.70 ± 0.30	0.20 ± 0.30	0.31 ± 0.30	-1.73 ± 0.30	-0.08 ± 0.30

Combined $\log_{10}$ Bayes factors $\mathcal{B}$ for various polarization hypotheses

against the tensor hypothesis, using both 2-detector and 3-detector events.

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Nature of Compact Objects

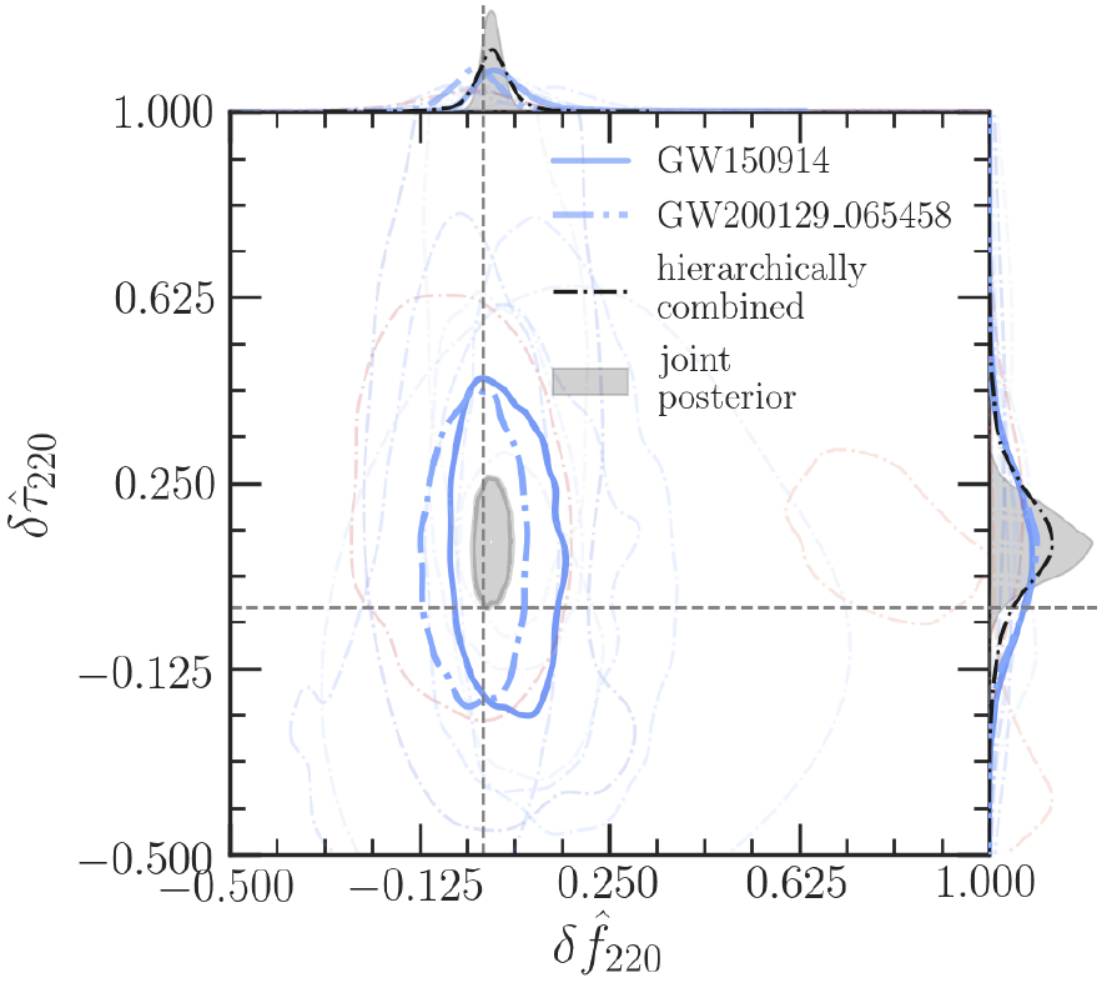
4 Ringdown I

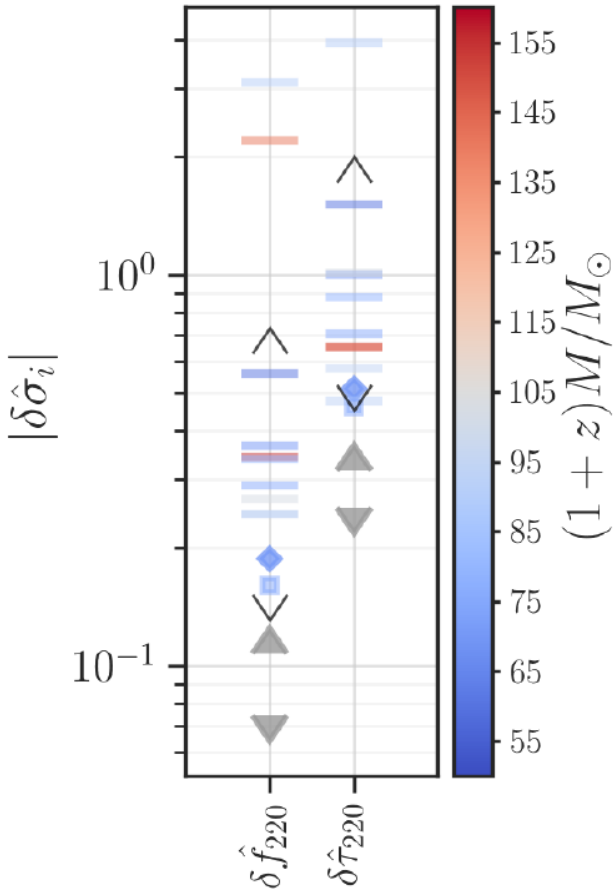
- Ringdown regime: Kerr metric + linear perturbations
  - Superposition of quasi-normal modes

$$h(t) = \sum_{nlm} A_{nlm} e^{-t/\tau_{nlm}} \cos\left(\omega_{nlm} t + \phi_{nlm}\right) \tag{1}$$

  - Characteristic frequencies and damping times
- No-hair conjecture: BH characterised by mass/spin
- Look for deviations from frequencies and damping times

4 Ringdown II





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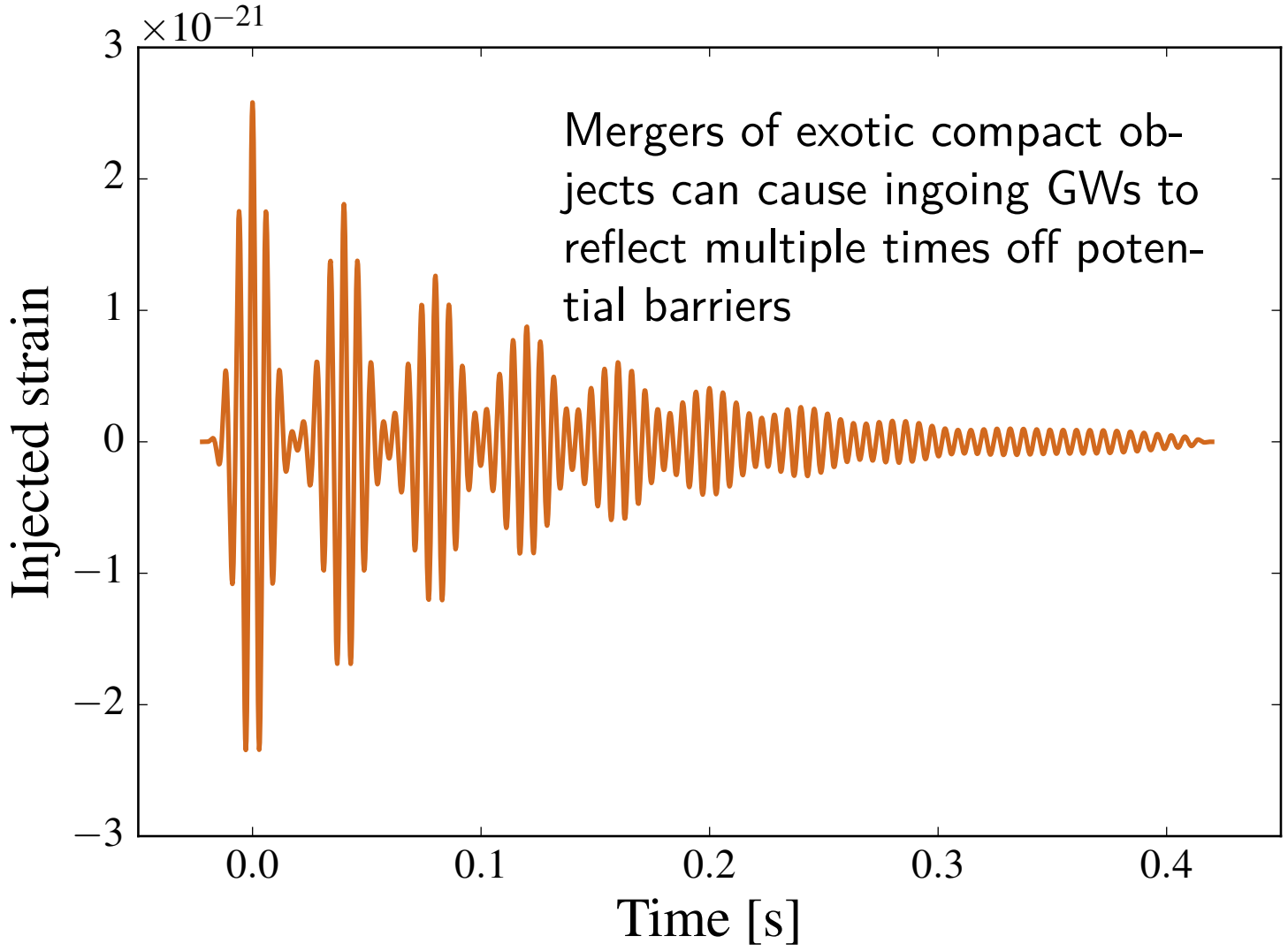
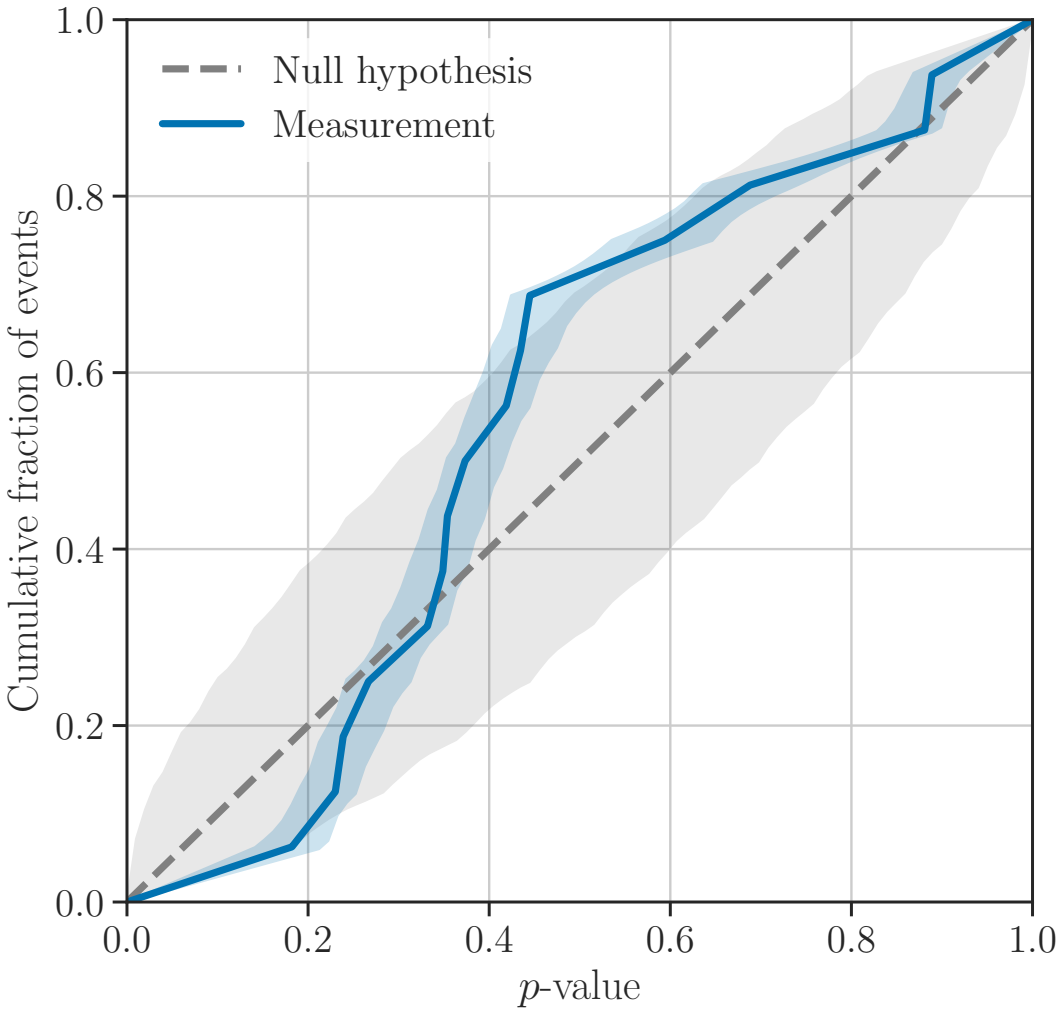
4 Echoes


$\times 10^{-21}$
3
2
1
0
−1
−2
−3
Injected strain
0.0
0.1
0.2
0.3
0.4
Time [s]
Mergers of exotic compact objects can cause ingoing GWs to reflect multiple times off potential barriers

4 Echoes

Event	p-value
GW191109_010717	0.35
GW191129_134029	0.35
GW191204_171526	0.37
GW191215_223052	0.23
GW191216_213338	0.88
GW191222_033537	0.89
GW200115_042309	0.44
GW200129_065458	0.33
GW200202_154313	0.43
GW200208_130117	0.24
GW200219_094415	0.18
GW200224_222234	0.59
GW200225_060421	0.69
GW200311_115853	0.42
GW200316_215756	0.27



Conclusion

5 Concluding Remarks

- Gravitational-wave observations provide a unique tool to test fundamental physics
- Binary black holes and binary neutron star mergers set limits on possible deviations from GR

- Battery of tests performed
  - Strong-field dynamics of spacetime
  - Nature of gravitational waves
  - Nature of compact objects
- No significant devitations from GR found

- Future observing runs with larger catalog of compact binary observations will enable us to carry out more stringent tests of GR