Tests of General Relativity Panel Discussion

PAX IX, 23 July, King's College London, UK

Overview

- Swetha Bhagwat: Binary black hole post-merger signals, Test of gravity using ringdown, Application of machine learning towards test of GR, Signal modelling
- Elisa Maggio: False deviations of GR in GW observations
- Félix-Louis Julié: EOB and PN waveforms in modified gravity theories, theory-specific tests of gravity
- Tamara Evstafyeva: Source modelling of exotic compact objects: using NR informed waveforms for testing the nature of compact objects
- Thomas Sotiriou: Semi-agnostic tests of GR

Post-merger tests of GR

Swetha Bhagwat

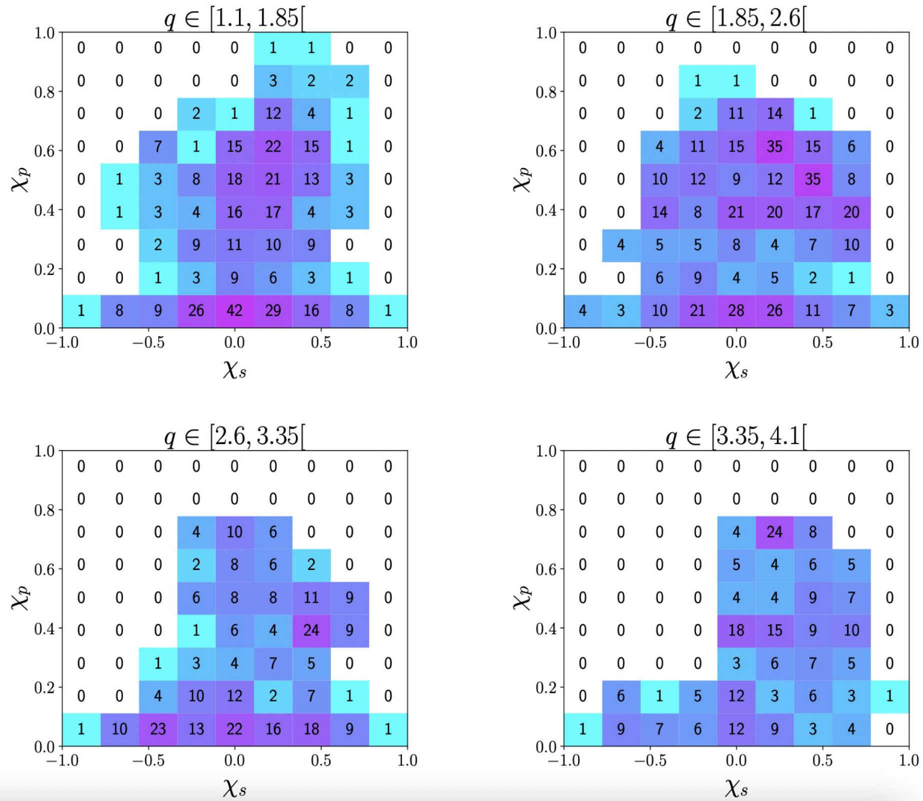
- We will few events of rd snr ~100-200 per year with next generation detector (CE-ET network).
    - This implies we can get sub-percent accuracy in the dominant mode freq, ~4-5 detectable modes with mode freq constrained to ~1-10%. What kind of science can we do with these? What theory will see meaningful constraints with this accuracies, say with stellar mass BHs?
    - Dependence on BBH parameter space?
    - What are the analysis challenges will we face? What developments do we need in -- a) RD modelling and systematics, b) pe setup and c) tests and checks, for performing unbiased precision measurement with these signal?
    - What effects need to be added in modelling the post-merger in GR?

- Can we get merger-ringdown NR waveforms for modified theory?
    - Which theories do we already have some waveforms in?
    - Any Attempts to make a catalogue?

Post-merger tests of GR

- We don't have a good handle precessing and eccentric RD amplitudes and phases but there many interesting features for RD when you have precession.
  - ○ The NR coverage is sparse for calibrating and extracting amplitude patterns (see fig). Can we fill this in?
  - ○ What are the best parametrization? Do we need all 7-d space?

- Currently we are seeing that the RD analysis seems to be not very robust to setting in analysis e.g., GW150914 overtone analysis or GW190521 higher harmonics detections.
  - ○ What list of checks need to be done?



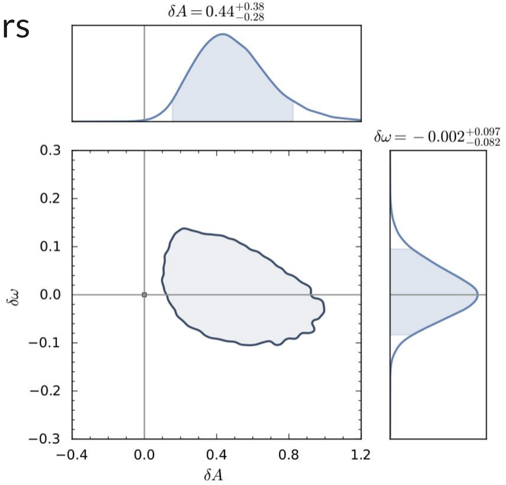
(work in prep.)

False deviations of general relativity in GW observations

- The signal-to-noise ratio of compact binary coalescences is increasing with the improvements in the sensitivity of current detectors and the next-generation detectors. [Abbott et al. 2020, Living Rev. Rel., 23, 3]

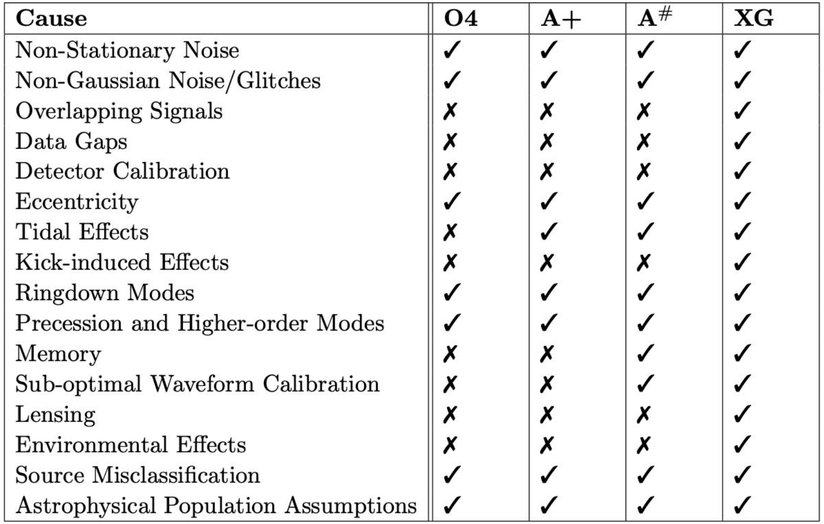
- Tests of general relativity could show false deviations of general relativity due to: [Gupta et al., arXiv:2405.02197]
    - **Noise artifacts**: glitches, detector calibration error, non-stationarity
    - **Waveform systematics**: spin-precession, eccentricity, higher modes, waveform accuracy, numerical errors
    - **Astrophysical aspects**: Environmental effects, black-hole mimickers

- Example of **GW200129**: the peak amplitude is not consistent with general relativity [Maggio et al., PRD 108, 024043 (2023)].
  Possible causes:
    - Spin precession [Hannam et al., Nature 610, 642-655 (2022)]
    - Glitch mitigation [Payne et al., PRD 106, 104017 (2022);
      Macas et al., PRD 109, 062006 (2024)]
    - Eccentricity [Gupte et al., arXiv:2404.14286]



False deviations of general relativity in GW observations

- Which causes of false violations of general relativity are more impactful?
- Which effects should be accounted for in the waveform models or analysis methods (in priority order)?
- If we find a deviation from general relativity, which checklist should we follow? Some ideas:
    - Study of the noise
    - Analysis with different waveform models
    - Injections in zero noise and real noise
    - Comparisons with Bayes factors



Cause	**O4**	**A+**	**A$^{\#}$**	**XG**
Non-Stationary Noise	✓	✓	✓	✓
Non-Gaussian Noise/Glitches	✓	✓	✓	✓
Overlapping Signals	✗	✗	✗	✓
Data Gaps	✗	✗	✗	✓
Detector Calibration	✗	✗	✗	✓
Eccentricity	✓	✓	✓	✓
Tidal Effects	✗	✓	✓	✓
Kick-induced Effects	✗	✗	✗	✓
Ringdown Modes	✓	✓	✓	✓
Precession and Higher-order Modes	✓	✓	✓	✓
Memory	✗	✗	✓	✓
Sub-optimal Waveform Calibration	✗	✗	✓	✓
Lensing	✗	✗	✗	✓
Environmental Effects	✗	✗	✗	✓
Source Misclassification	✓	✓	✓	✓
Astrophysical Population Assumptions	✓	✓	✓	✓

[Gupta et al., arXiv:2405.02197]

IMR waveforms in specific modified gravities: status

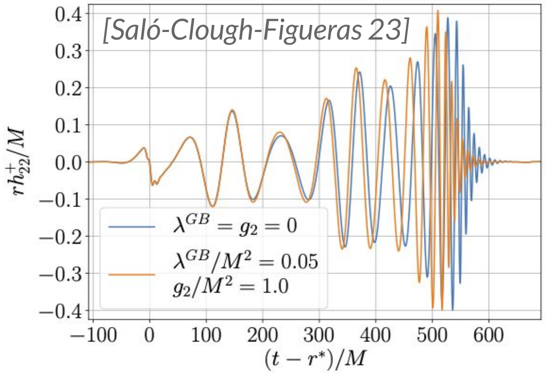
Recent joint efforts of several "schools" in GW modeling beyond GR

Post-Newtonian formalism *[Damour+ 92, Mirshekari+ 13, Lang 15, Sennett+ 16, FLJ 18 & 19, Khalil+ 18, FLJ+ 19 & 22, Bernard+ 19 & 22, Brax+ 21, Shiralilou 22,...]*

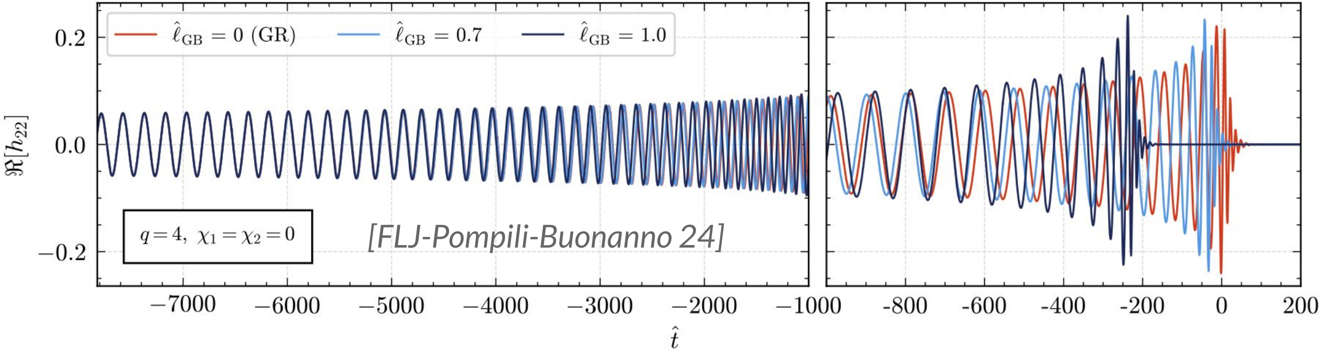
Black hole perturbation theory *[Blázquez-Salcedo+ 17 & 20, Brito+ 18, Pierini+ 21, Langlois+ 22, Chung+ 24,...]*

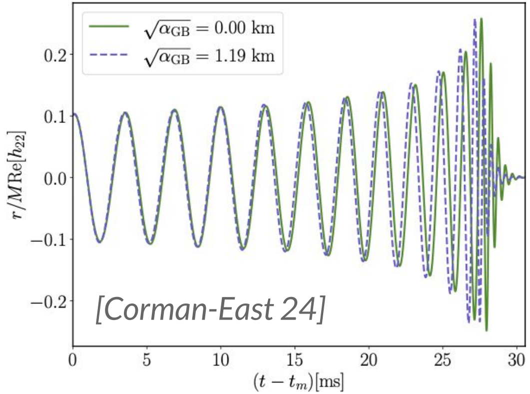
Numerical relativity *[Barausse+ 13, Shibata+ 14, Palenzuela+ 14, Hirschmann+ 17, Okounkova+ 17, Witek+ 19, Silva+ 21, East+ 21, Corman+ 23, Saló+ 22, Doneva+ 22, Corman+ 24, Lara+ 24, Nee+ 24,...]*

Effective-one-body framework *[FLJ+ 17, FLJ 18, Khalil+ 18, Jain+ 23, FLJ+ 23, Jain 23, FLJ-Pompili-Buonanno 24]*


[Saló-Clough-Figueras 23]

Most studied example: **Einstein-scalar-Gauss-Bonnet gravity**


[FLJ-Pompili-Buonanno 24]


[Corman-East 24]

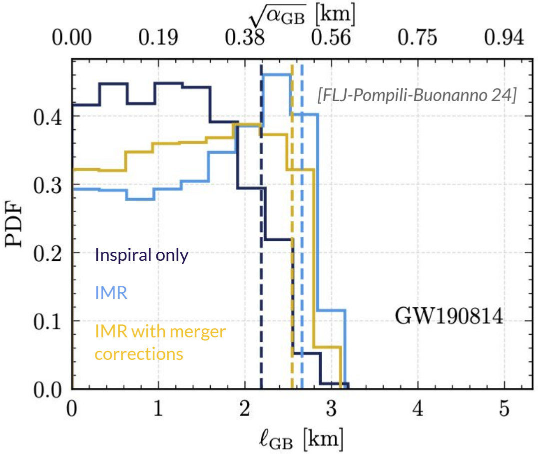
Toward new tests of gravity: four open issues

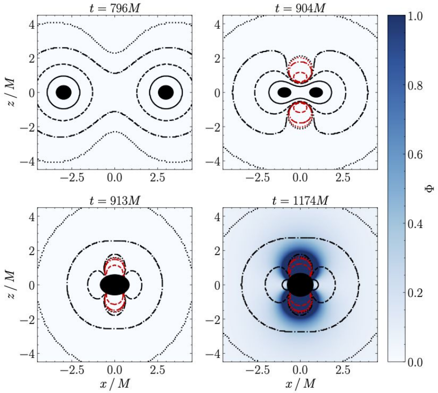
Which modified gravities/effects will be best constrained with IMR waveforms, i.e. that include the ringdown?

We need to (semi-analytically) model the waveform at merger, and predict the remnant’s mass and spin.

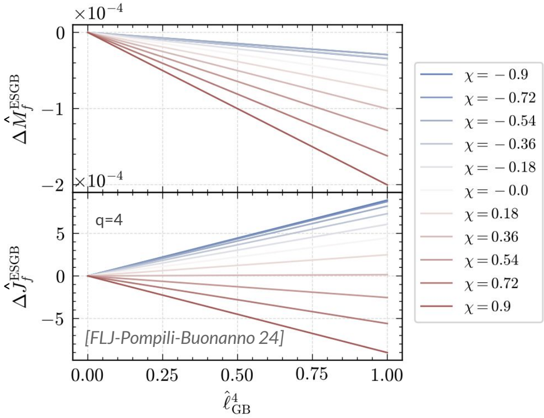
To what extent can we reuse existing PN/EOB/QNM/NR results for other modified gravities?

In a GW signal, how important is including beyond-GR corrections to the bodies’ spins?





[Elley-Silva-Witek-Yunes 22]

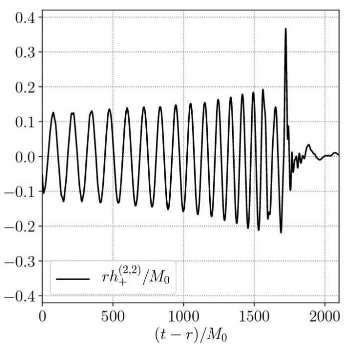


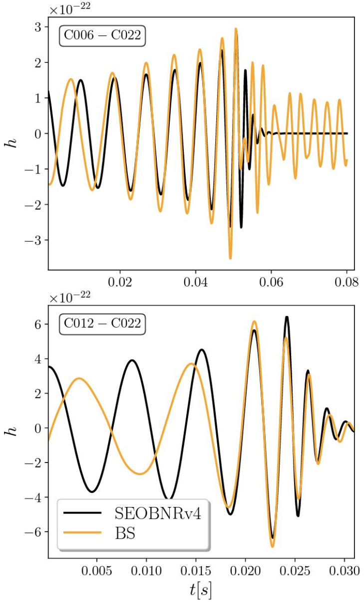
Source modelling of exotic compact objects – status

- **How?** – using NR, PN, perturbation theory to test predictions of exotic compact objects (or modified theories of gravity).
- For example, **boson stars** (BSs) – a complex scalar field minimally coupled to gravity [Kaup ‘68, Palenzuela ‘06, Schunck ‘08, Liebling ‘12, Miguel Alcubierre ’18, Siemonsen ‘20, Helfer ‘21]
- Extensions also include **BSs in modified theories of gravity** [Tores ‘97, Whinnett ‘99, Evstafyeva ‘23, Masó-Ferrando ‘24] and **Proca stars** [Brito ‘15, Sanchis-Gual ‘19, Herdeiro ‘21, Wang ‘24]

GW signal from unequal-mass aligned spin BS binary.

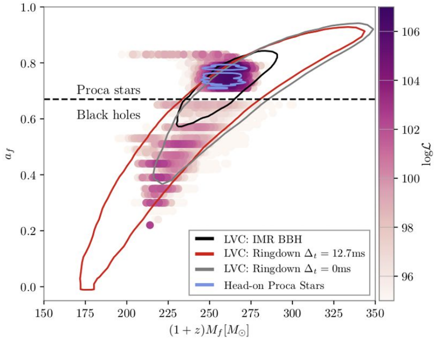
Siemonsen ‘23





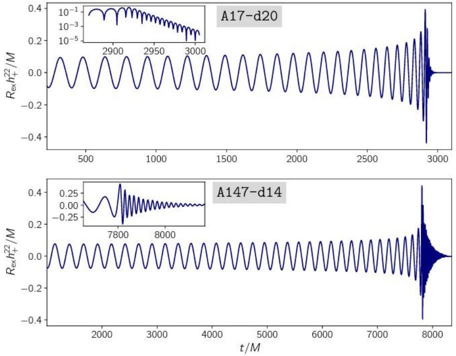
Comparison of BS signals and SEOBNRv4.

Bezares ‘22



GW190521 as a merger of Proca stars.

Bustillo ‘21



Smoking-gun GW signatures as well as degeneracies present in some regions of the parameter space.

Evstafyeva ‘24

Source modelling of exotic compact objects – questions and challenges

*See also **modified gravity** NR simulations: Witek '19, Okounkova '17, Aresté Saló '23, Doneva '24, Corman '24.*

- The source modelling described is theory specific, and therefore slow and resource expensive!
- Requires long + high precision + eccentricity reduced waveforms and constraint satisfying initial data (or complete understanding of uncertainties stemming from approximate initial data).
- Requires full exploration of the parameter space.
- Requires joint efforts from several groups [e.g. NINJA project for BBH waveforms, NRAR comparison].

Zoo of possibilities to explore: what exotic compact objects and/or modified theories of gravity to focus on?

Hybridizing NR waveforms (e.g. with EOB) to construct inspiral-merger-ringdown ECOs waveform banks?

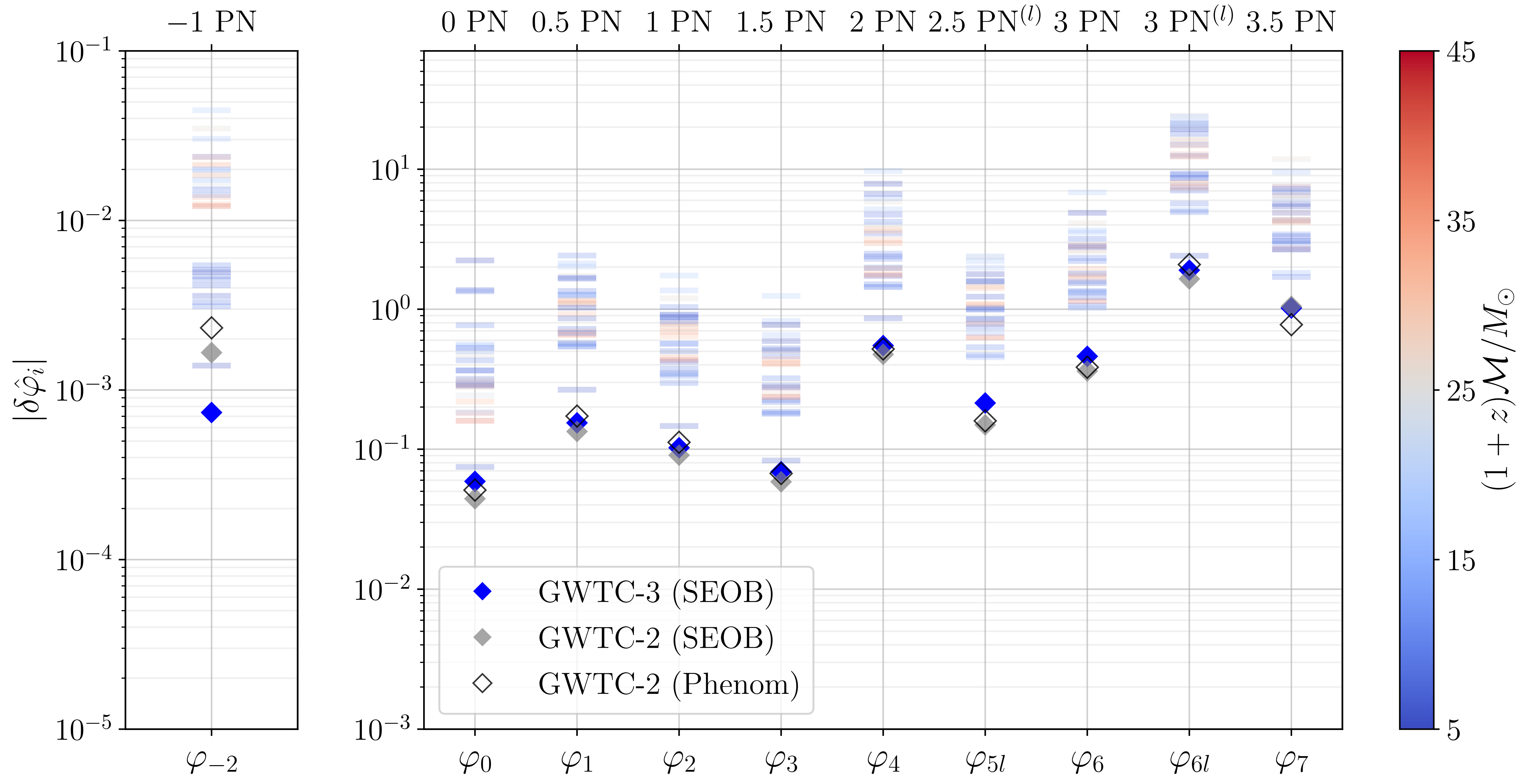
Are the current tests good enough?

How do we anticipate to break potential degeneracies that may arise in certain regimes of the parameter space?

What smoking gun features we should be looking for?

How feasible is the synergy between ML and NR techniques in helping us to explore the parameter space more efficiently? [e.g. **Luna '24, Freitas '22**]

Parametrized Tests of GR



LVK, arXiv:2112.06861 [gr-qc]

But $\delta\phi_i$ is not universal!

Common problem with parametrizations.

Example: massless scalar

Massless $\leftrightarrow$ shift-symmetry $\Rightarrow$ $\alpha\phi\mathcal{G}$ only interaction that leads to hair

T.P.S. and S.-Y. Zhou, PRL 112, 251102 (2014)

For shift-symmetric scalars

$$P \propto \alpha \int_{\mathcal{H}} n_a \mathcal{G}^a \qquad \mathcal{G} = \nabla_a \mathcal{G}^a$$

M. Saravani & T.P.S., Phys. Rev. D 99, 12, 124004 (2019)

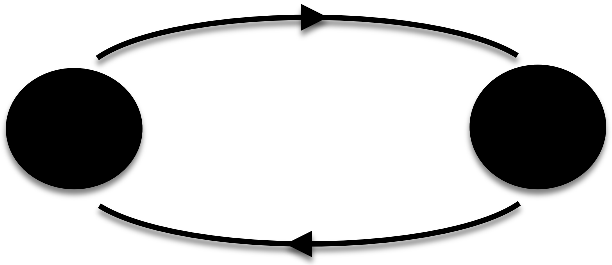
which implies that charge per unit mass

$$d = \frac{P}{M} \approx \frac{\alpha}{M^2}$$

and large (enough) BHs are effectively Kerr BHs!

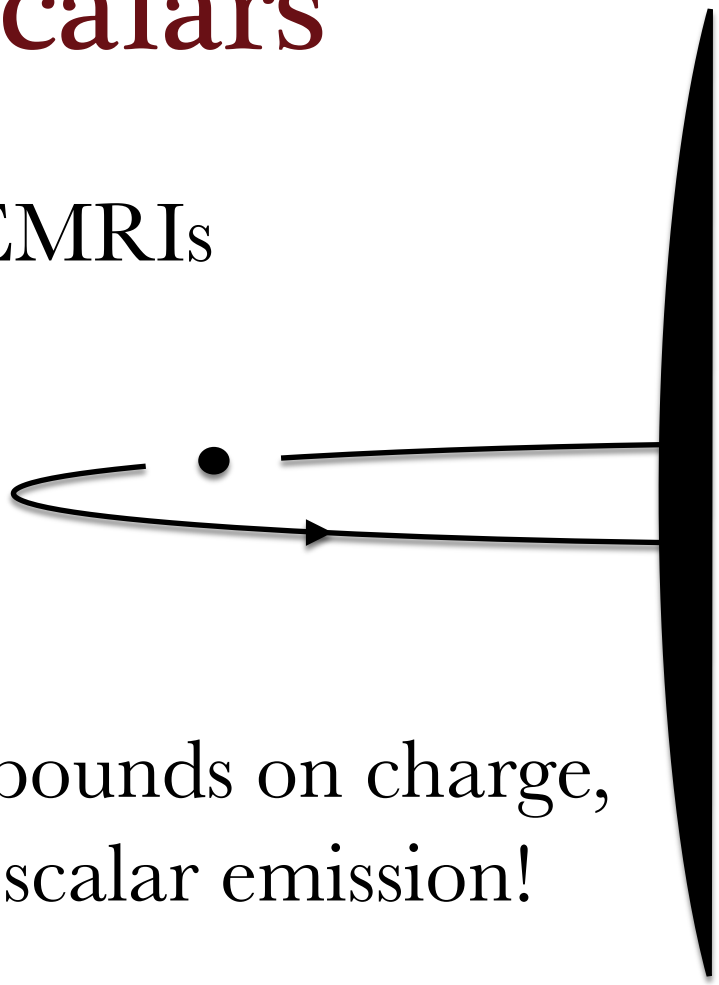
Probes for massless scalars

BH Binaries



weaker bounds on charge
for larger masses

EMRIs



stronger bounds on charge,
but from scalar emission!

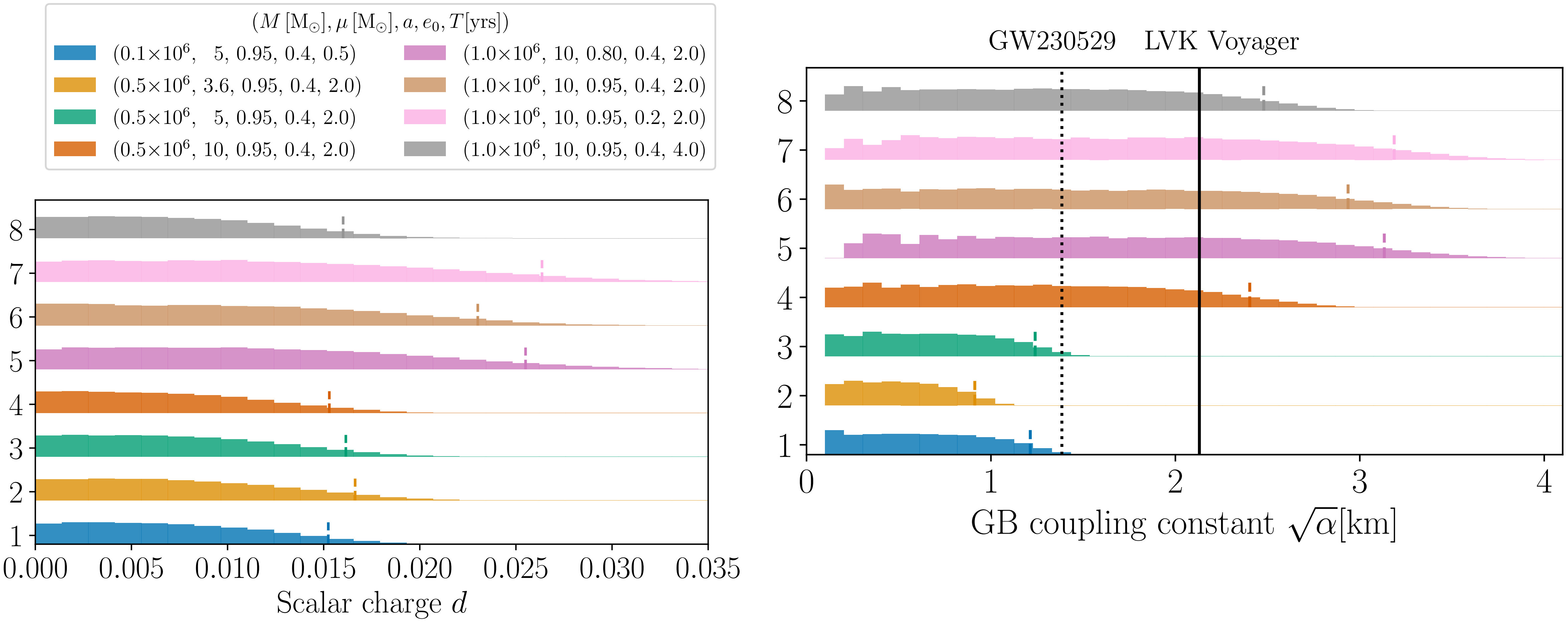
A. Maselli, N. Franchini, L. Gualtieri, and T.P.S, PRL 125, 14, 141101 (2020)

$$S=\int d^4x\frac{\sqrt{-g}}{16\pi}\left(R-\frac{1}{2}\partial^\mu\phi\partial_\mu\phi\right)+\alpha S_c$$

Define dimensionless $\zeta\equiv\frac{\alpha}{M^n}=q^n\frac{\alpha}{m_p^n}$ $\qquad\frac{\alpha}{m_p^n}\leq 1$

Scalar Charge

A. Maselli, N. Franchini, L. Gualtieri, T.P.S, S. Barsanti, P. Pani, Nature Astronomy (2022)
L. Speri et al., arXiv:2406.07607 [gr-qc]



Only one more parameter a 1PA

A. Spiers, A. Maselli, T.P.S., Phys. Rev. D 109, 6, 064022 (2024)

QNMs for large BHs with the same approach

G. D'Addario, A. Padilla, P. Saffin, T.P.S., and A. Spiers, Phys. Rev. D 109, 8, 084046 (2024)

Are semi-agnostic test the new frontier?

Discussion

Slido.com with the code **#1771162**

https://app.sli.do/event/hErqQzFdMYk1eEkmJTvJXf