MAX PLANCK INSTITUTE
FOR GRAVITATIONAL PHYSICS
(ALBERT EINSTEIN INSTITUTE)

Tests of General Relativity with GW230529

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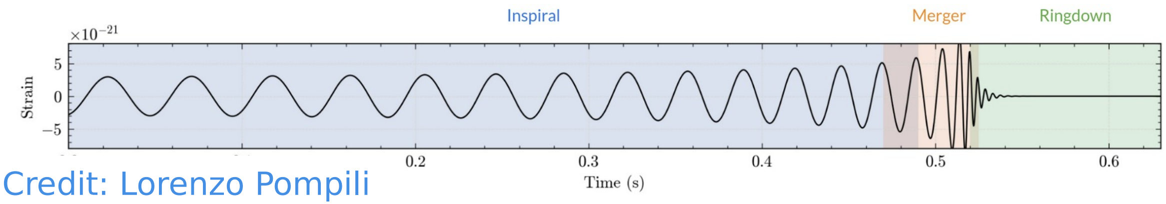
Outline

- Parameterized inspiral tests
- GW230529
- Results
- Challenges
- Theory specific test for EsGB

Based on: Elise M. Sänger, Soumen Roy, et al., arXiv:2406.03568

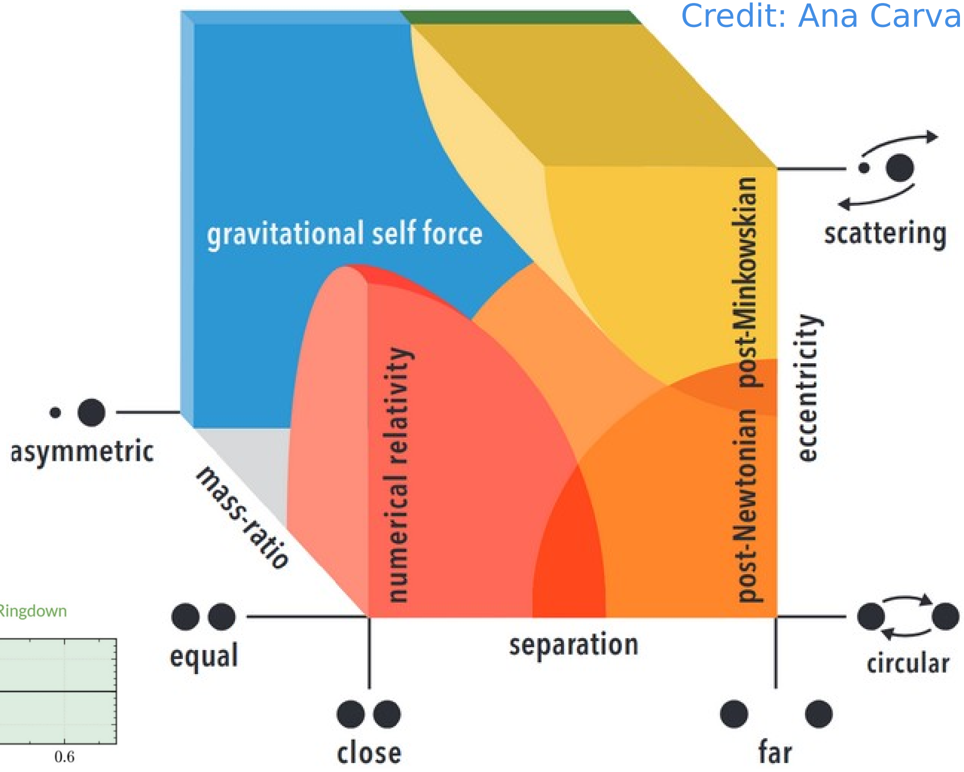
GR waveforms

- Different type of models:
  - Numerical relativity surrogates
  - Effective-one-body
  - Phenomenological
- Inspiral approximated by post-Newtonian expansion



Credit: Lorenzo Pompili

Credit: Ana Carvalho



Parameterized inspiral tests of GR

- Inspiral frequency domain phase in GR:

$$\Psi_{\ell m}^{\mathrm{GR}}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta v^5}\frac{m}{2}\sum_{n=0}^{7}\left(\psi_n^{\mathrm{GR}} + \psi_{n(l)}^{\mathrm{GR}}\log v\right) v^n$$

- Parameterized inspiral tests add a correction of the form

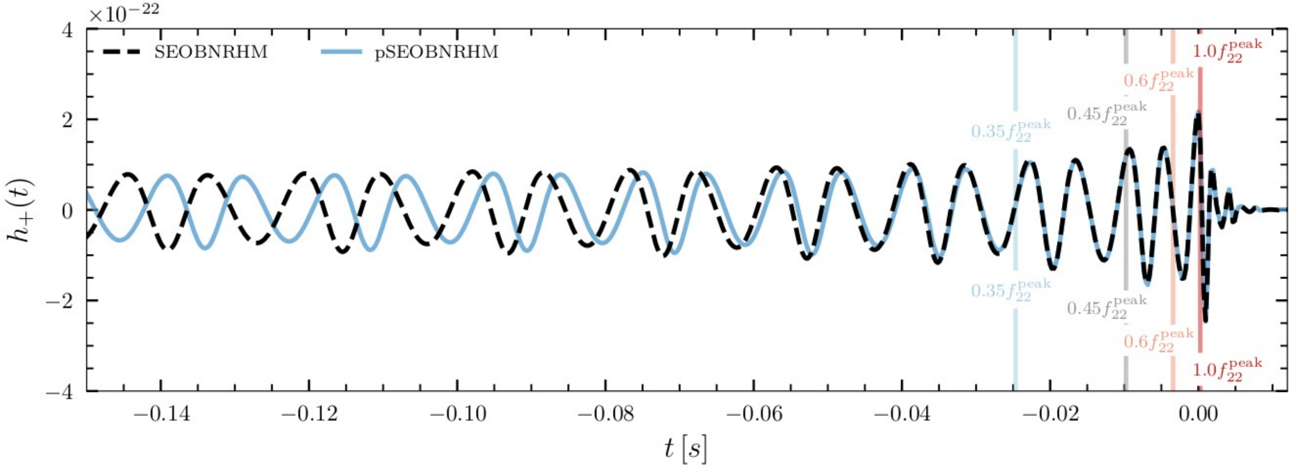
$$\delta\Psi_{\ell m}(f) = \frac{3}{128\eta v^5}\frac{m}{2}\left(\sum_{n=-2}^{7}\boxed{\delta\hat{\varphi}_n}\psi_n^{\mathrm{GR}} v^n + \sum_{n=5}^{6}\boxed{\delta\hat{\varphi}_{n(l)}}\psi_{n(l)}^{\mathrm{GR}} v^n \log v\right)$$

$(n/2)$-PN coefficient

- Merger-ringdown the same as in GR

Parameterized inspiral tests of GR

- Two different frameworks:
  - FTI using SEOBNRv4 waveform family
  - TIGER using IMRPhenomX waveform family

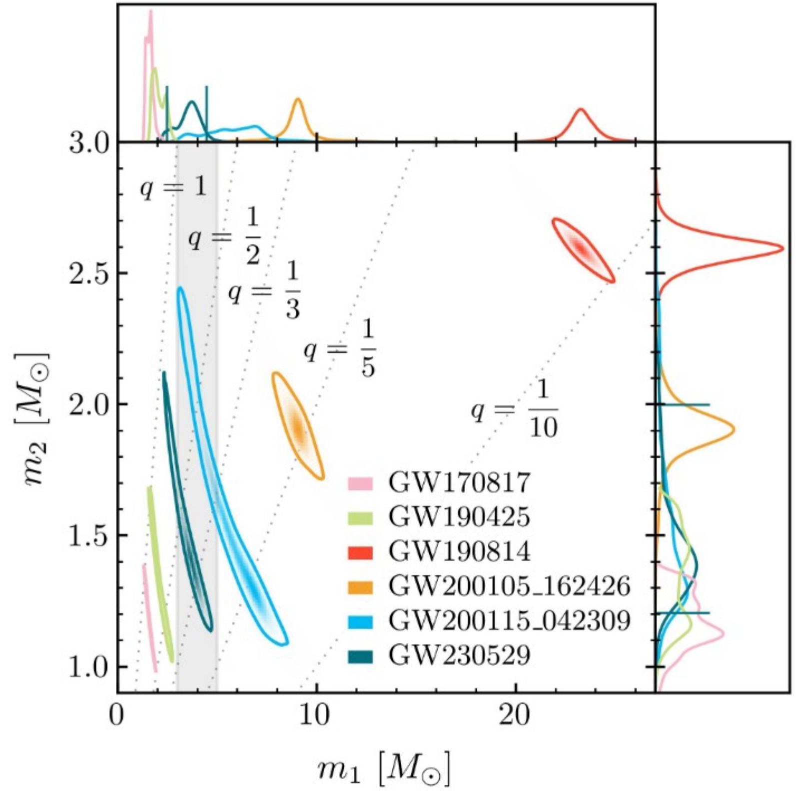


$$\delta\hat{\varphi}_2 = 0.5$$

Ajit Kumar Mehta et al., Phys. Rev. D 107, 044020 (2023), arXiv:2203.13937
Michalis Agathos at al., Phys. Rev. D 89, 082001 (2014), arXiv:1311.0420

GW230529_181500

- Detected on 29 May 2023 by LIGO Livingston only
- SNR 11.6, iFAR > 1000 yr
- Component masses:
  $m_1 = 3.6^{+0.8}_{-1.1}\ \mathrm{M}_\odot, m_2 = 1.4^{+0.6}_{-0.2}\ \mathrm{M}_\odot$
- Most likely a neutron star merging with a black hole in the lower-mass gap

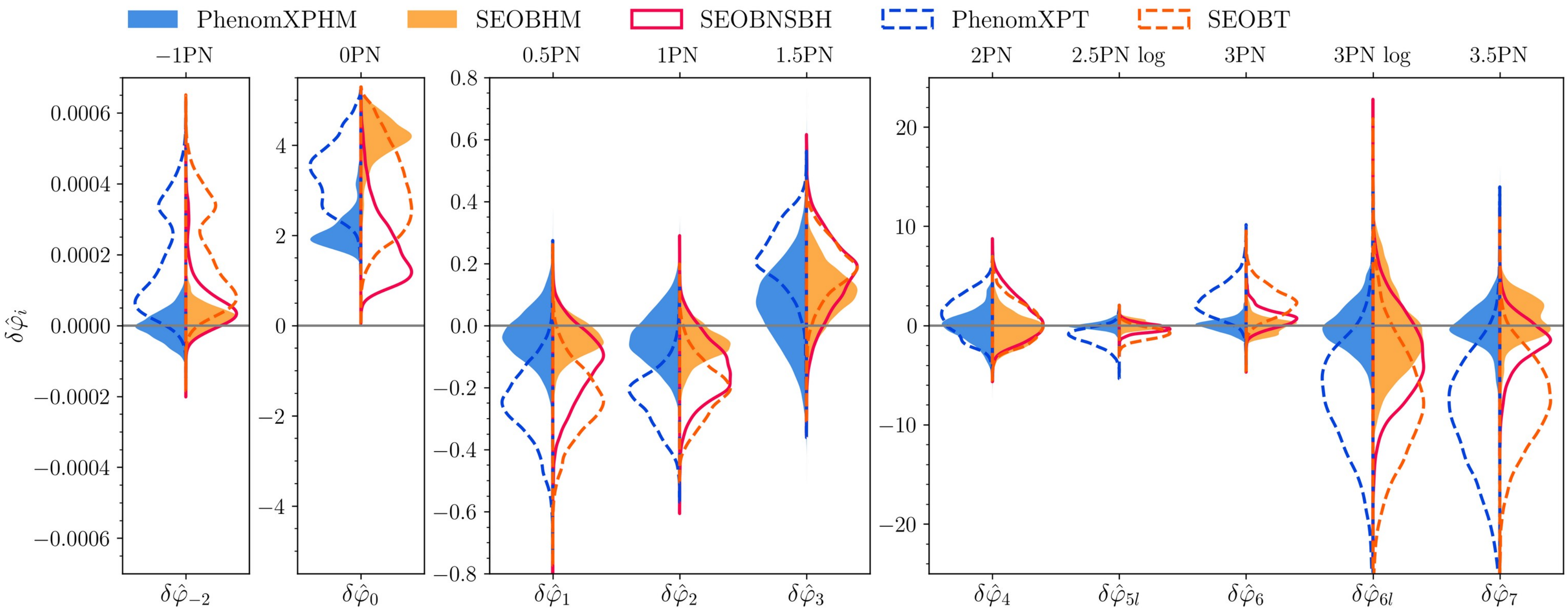


A. G. Abac et al. (LVK), Astrophys. J. Lett. 970, L34 (2024), arXiv:2404.04248

GW230529

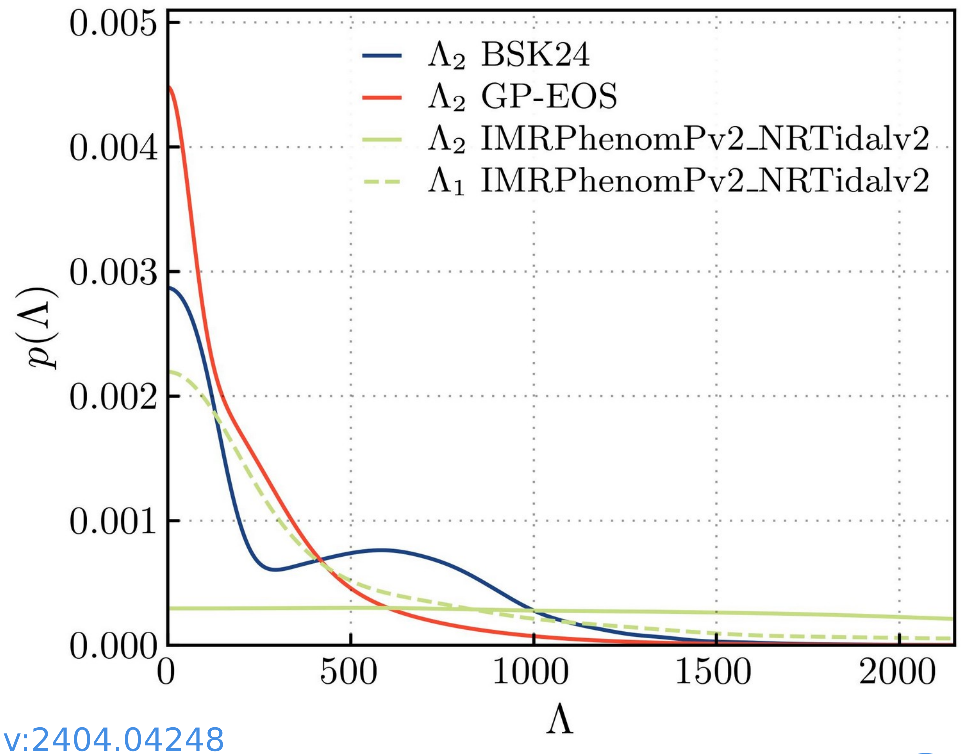
Its long inspiral signal provides a unique opportunity to test GR in a parameter space previously unexplored by strong-field tests

GW230529 results



Tidal effects

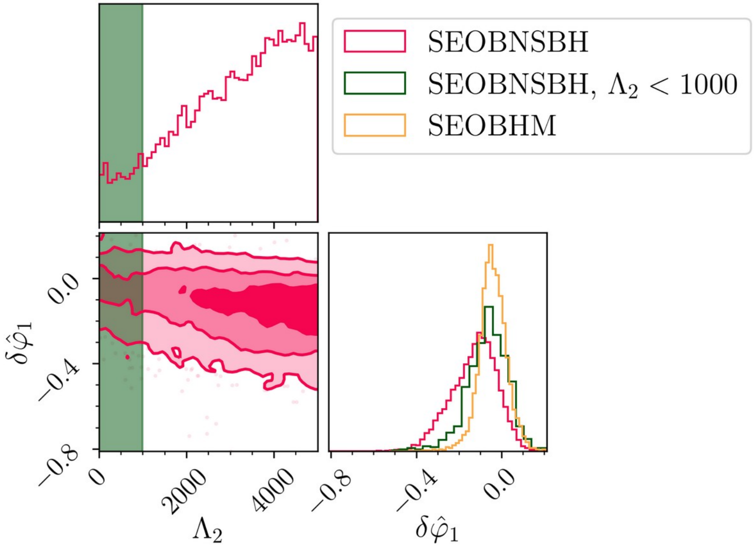
- Tidal effects are not well measured (especially Λ_2)
- Equations of state can inform tides
- Realistically $\Lambda_1 \lesssim 5, \Lambda_2 \lesssim 1000$

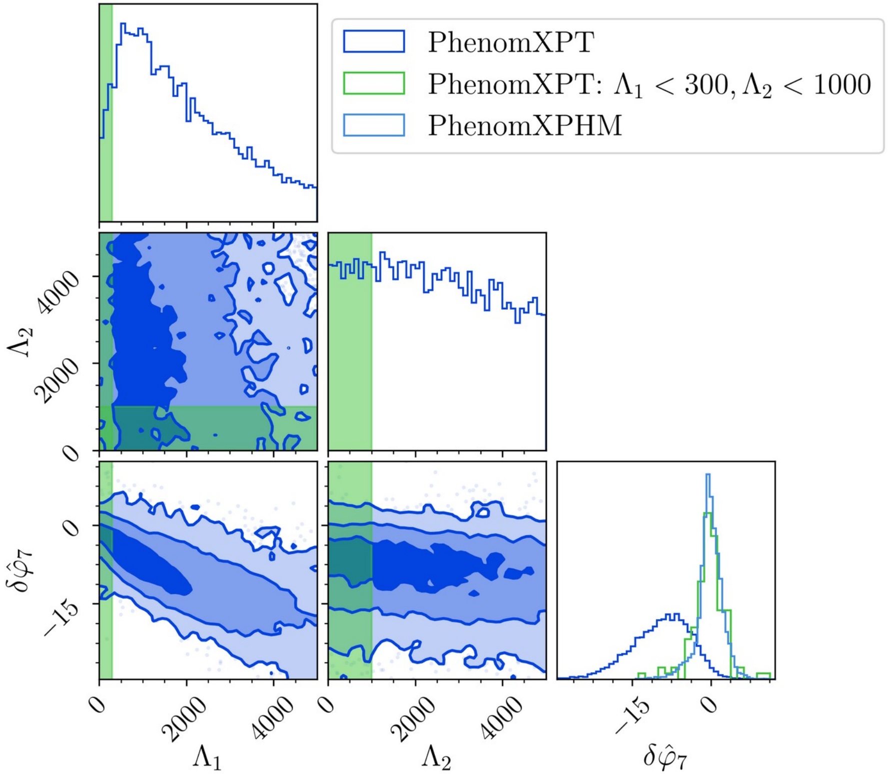


A. G. Abac et al. (LVK), Astrophys. J. Lett. 970, L34 (2024), arXiv:2404.04248
Sabrina Huth et al., Nature 606, 276–280 (2022), arXiv:2107.06229

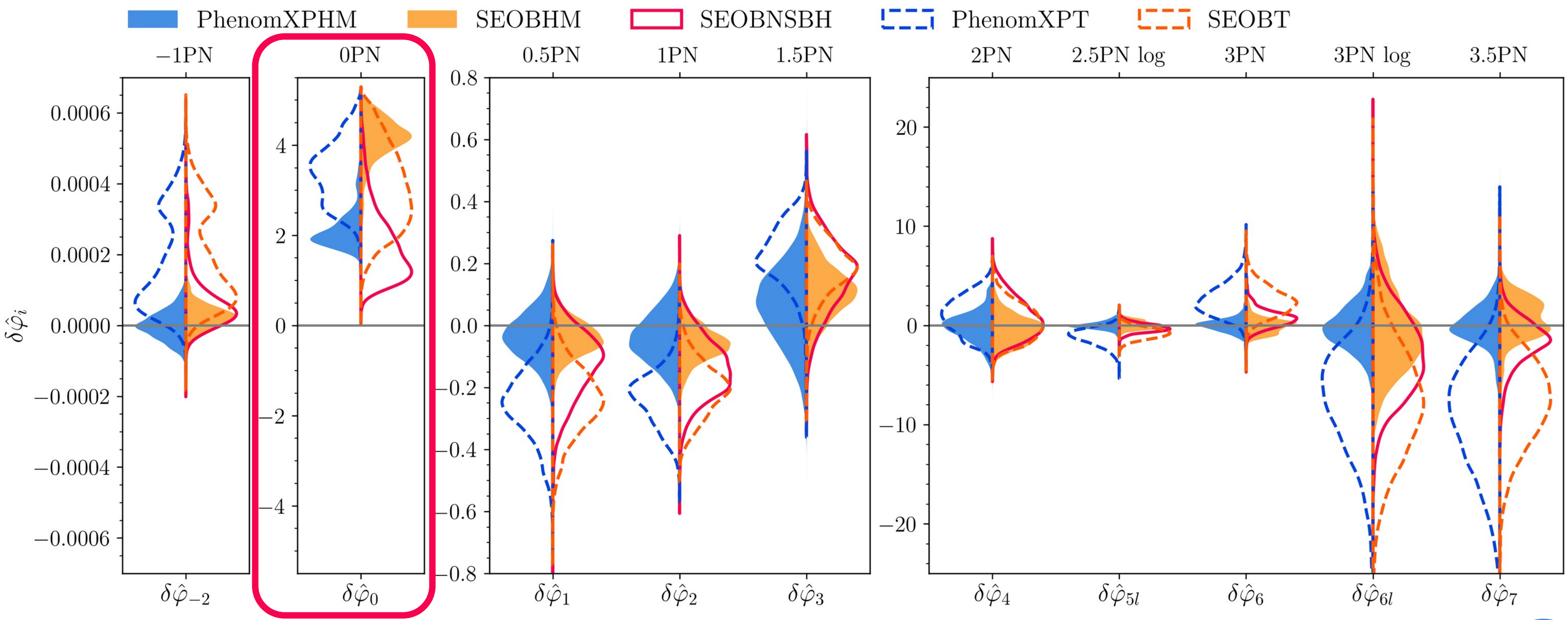
Tidal effects

- Correlations between tides and deviation parameters





GW230529 results

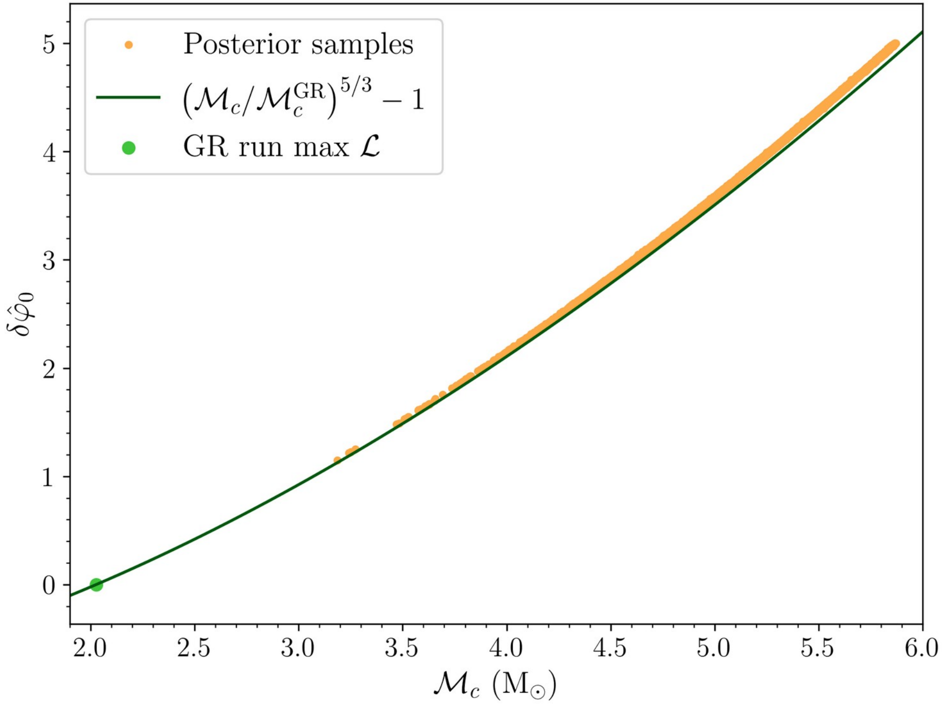


0PN degeneracy

- At Newtonian order:

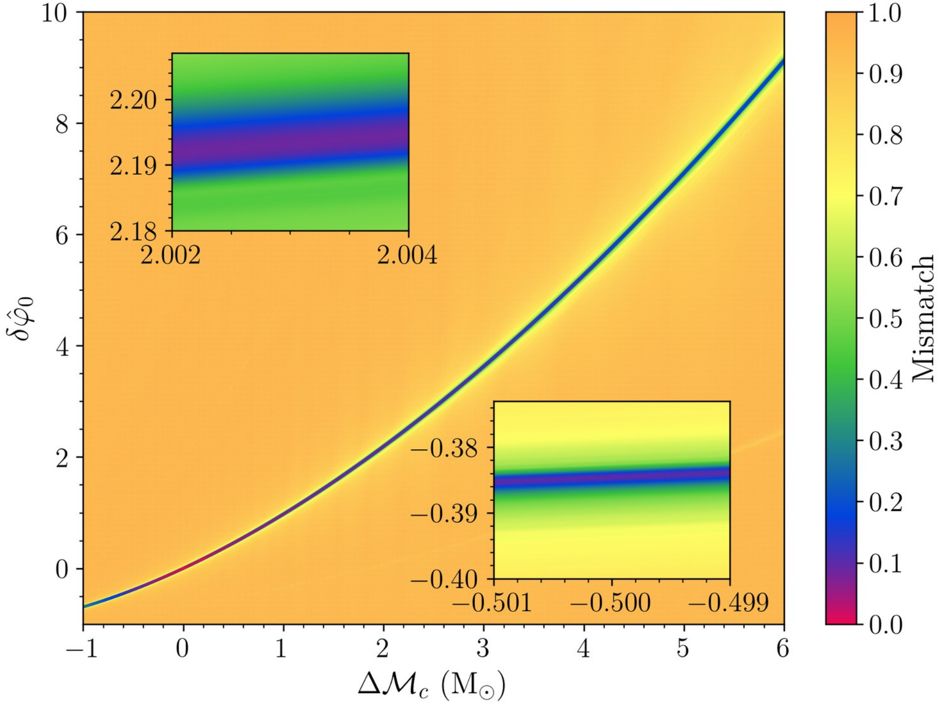
$$\delta\hat{\varphi}_0 = \left(\frac{\mathcal{M}_c}{\mathcal{M}_c^{\mathrm{GR}}}\right)^{5/3} - 1$$

- Degeneracy can be broken by higher PN contributions and by merger-ringdown

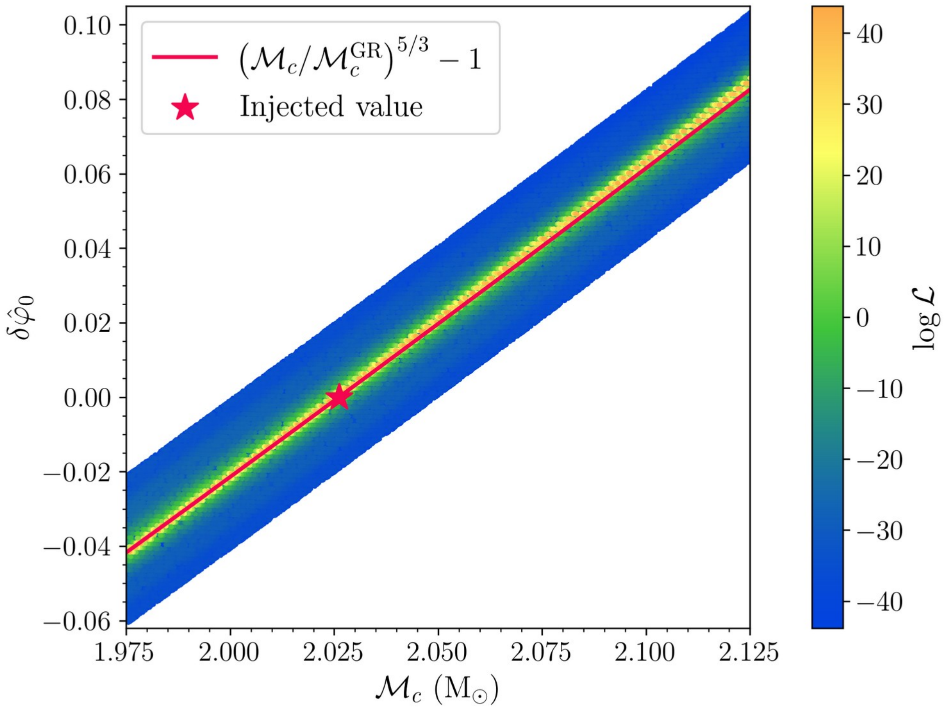


0PN degeneracy: likelihood & sampling issues

Mismatch



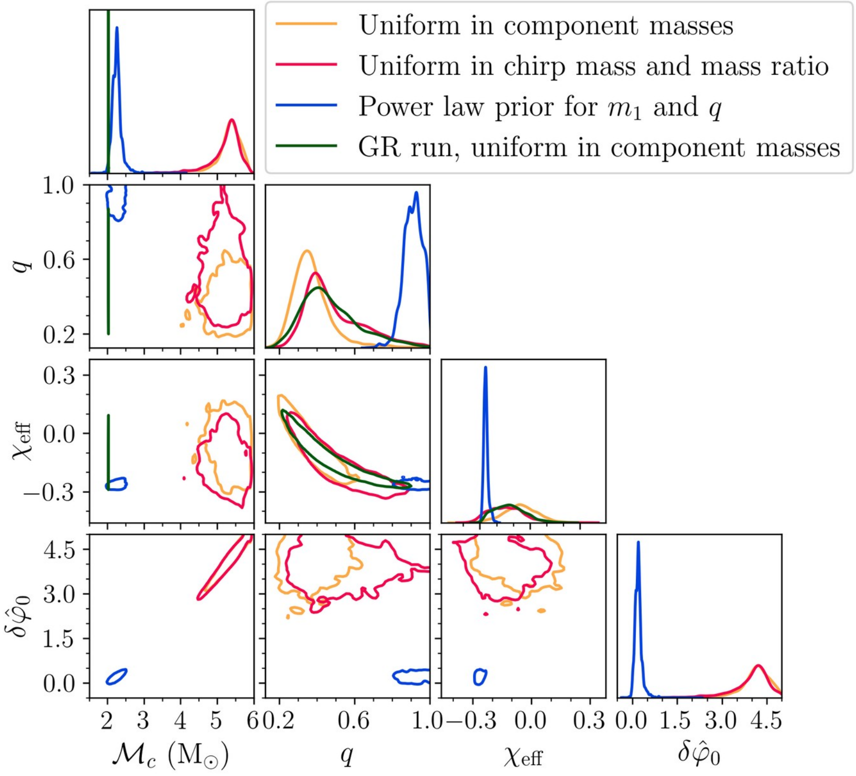
Likelihood



High likelihood region is wider for higher chirp mass → sampling issues?

0PN degeneracy: prior effects

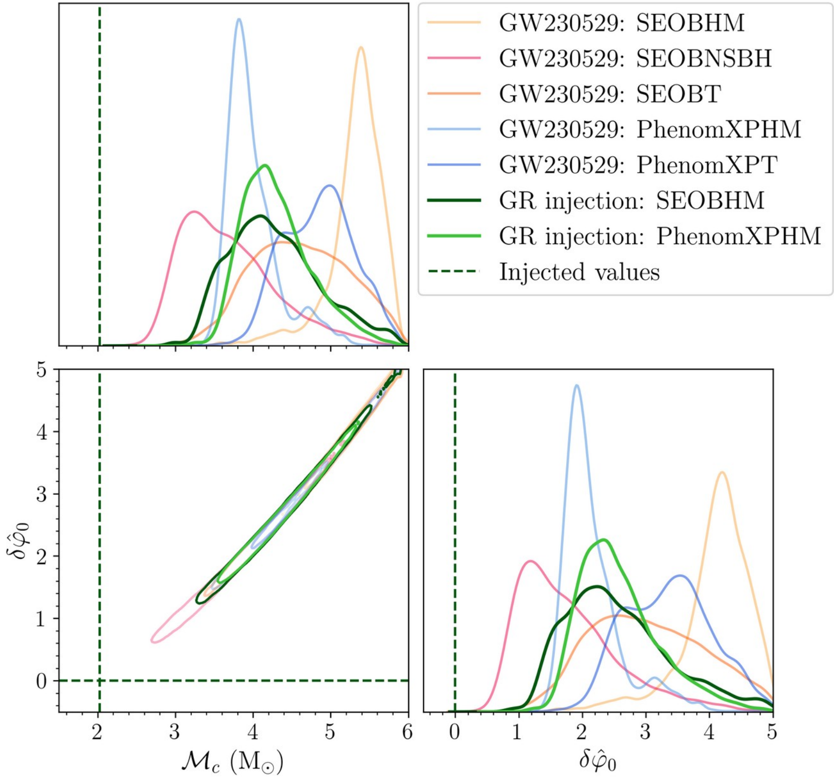
- Default prior: uniform in component masses
- Vary mass priors:
  - Uniform in M_c and q
  - Power law for m_1 and q
- Results are prior dependent



Ethan Payne et al., Phys. Rev. D 108, 124060 (2023), arXiv:2309.04528

0PN degeneracy: injections

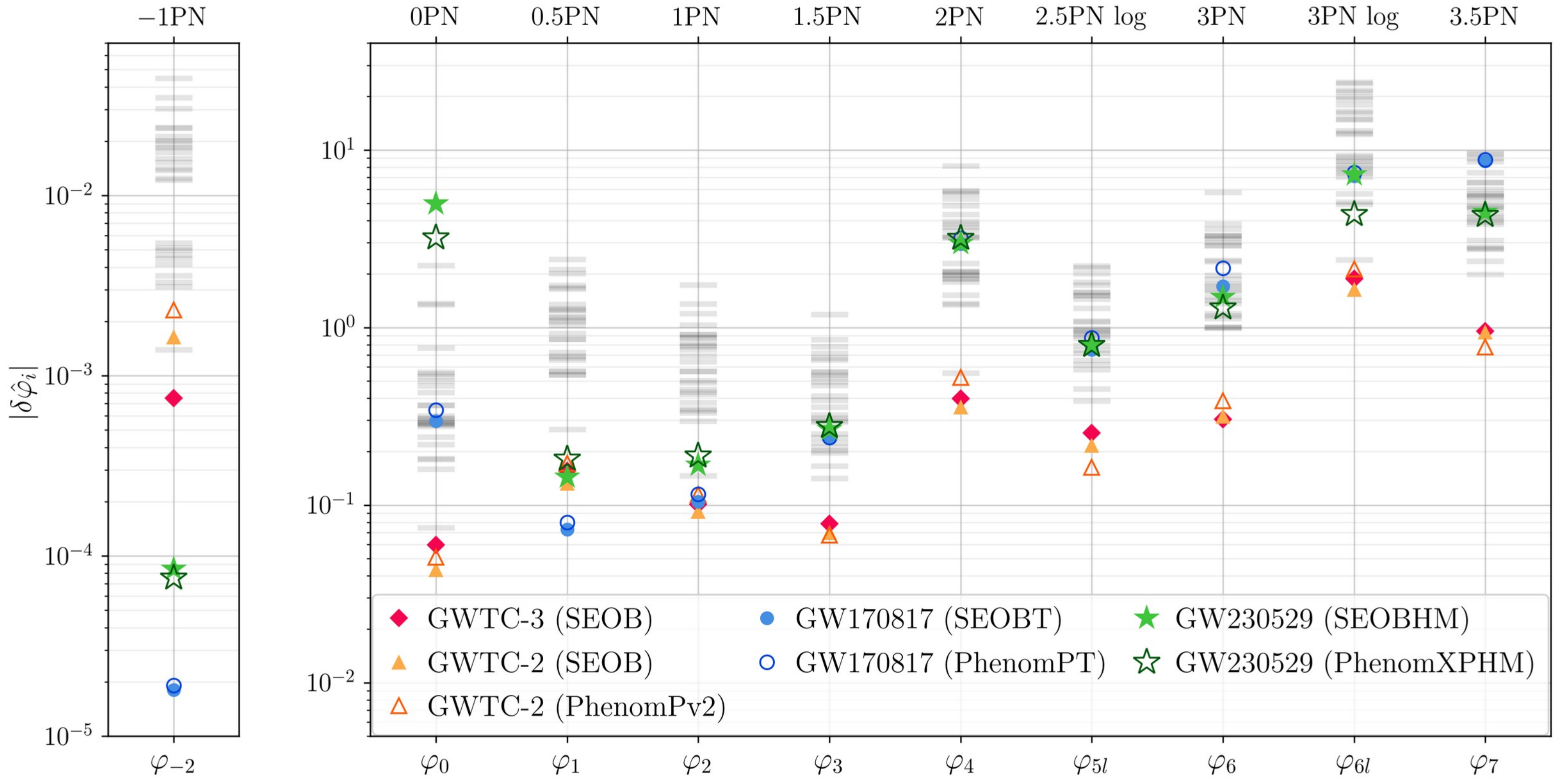
- Inject GR waveform in zero-noise
- See similar shift away from GR
- Noise is unlikely to explain deviation



0PN degeneracy

False violation of GR!

How good is GW230529 for testing GR?



R. Abbott et al. (LVK), (2021), arXiv:2112.06861

Einstein-scalar-Gauss-Bonnet

- Modified gravity theory where a scalar field is coupled to the Gauss-Bonnet density:

$$S = \frac{1}{16\pi}\int \mathrm{d}x^4 \sqrt{-g}\left(R - 2(\partial\phi)^2 + \ell_{\mathrm{GB}}^2 f(\phi)\mathcal{G}\right)$$

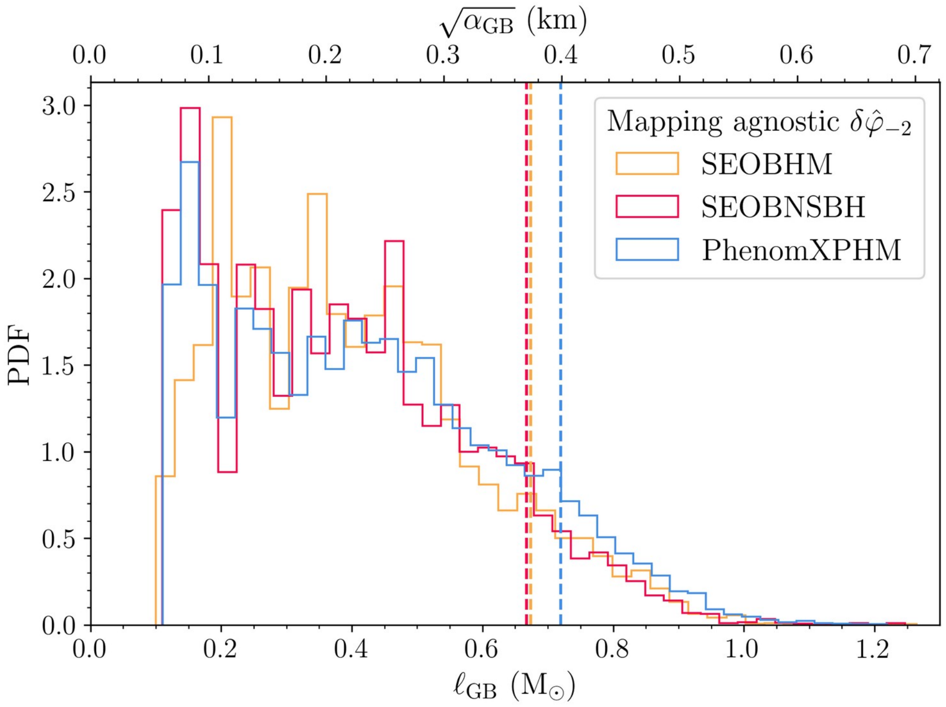
- Leading-order correction at -1PN due to scalar dipole radiation:

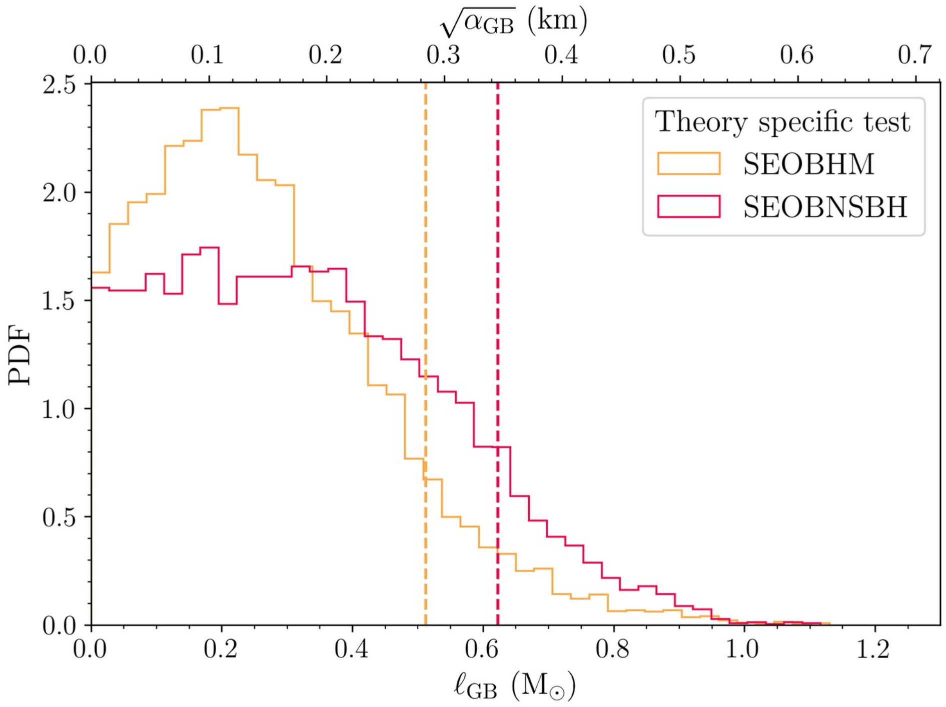
$$\delta\hat{\varphi}_{-2} = -5\ell_{\mathrm{GB}}^4 \frac{\left(m_1^2 s_2 - m_2^2 s_1\right)^2}{168 m_1^4 m_2^4}$$

- Can map -1PN results to EsGB

Zhenwei Lyu, Nan Jiang, and Kent Yagi, Phys. Rev. D 105, 064001 (2022), arXiv:2201.02543

EsGB results





Best bound on EsGB to date!

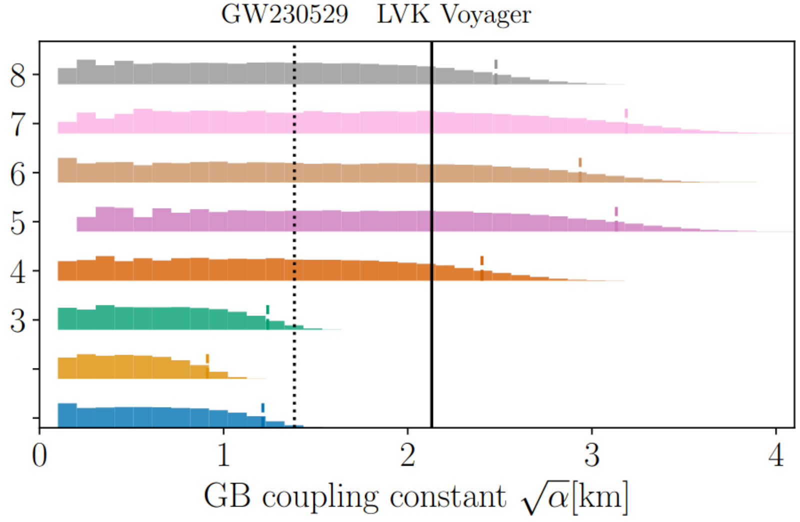
See also: Bo Gao et al., Phys. Rev. D 110, 044022 (2024), arXiv:2405.13279

Conclusion and outlook

- No evidence for deviations from GR for GW230529
- Particularly tight constraints at low-PN orders and on Einstein-scalar-Gauss-Bonnet gravity
- Challenges when analyzing GW230529:
  - Tidal effects
  - Degeneracy at 0PN
- Need to find better ways to account for these effects

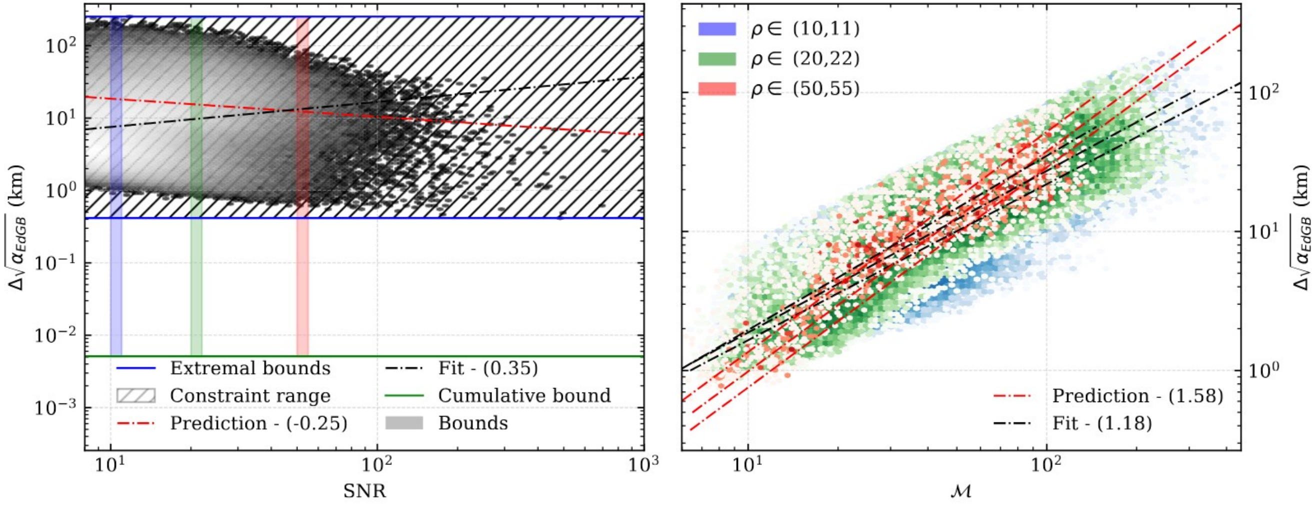
Back-up slides

EsGB: projections for future detectors



LVK Voyager

Scott E. Perkins, Nicolás Yunes, and Emanuele Berti,
Phys. Rev. D 103, 044024 (2021), arXiv:2406.07607



EMRIs

See also Susanna Barsanti’s talk
Lorenzo Speri et al., (2024), arXiv:2406.07607

Full EsGB corrections

$$\delta\hat{\varphi}_{-2} = -5\ell_{\rm GB}^4 \frac{\left(m_1^2 s_2 - m_2^2 s_1\right)^2}{168 m_1^4 m_2^4},$$

$$\delta\hat{\varphi}_0 = -5\ell_{\rm GB}^4 \frac{659 m_1^4 s_2^2 + 1370 m_1^2 m_2^2 s_1 s_2 + 659 m_2^4 s_1^2 + 728\eta \left(m_1^2 s_2 - m_2^2 s_1\right)^2}{16128 m_1^4 m_2^4},$$

$$\delta\hat{\varphi}_1 = 25\pi\ell_{\rm GB}^4 \frac{\left(m_1^2 s_2 - m_2^2 s_1\right)^2}{56 m_1^4 m_2^4},$$

$$\delta\hat{\varphi}_2 = \ell_{\rm GB}^4 \left\{ \frac{5 m_1^4 s_2^2 \left[-13792267 + 5588352\delta - 17640\eta(743 + 594\eta)\right]}{290304 m_1^4 m_2^4 (743 + 924\eta)} - \frac{5 m_2^4 s_1^2 \left[13792267 + 5588352\delta + 17640\eta(743 + 594\eta)\right]}{290304 m_1^4 m_2^4 (743 + 924\eta)} \right.$$
$$\left. + \frac{2 m_1^2 m_2^2 s_1 s_2 \left[56018615 + 3528\eta(12239 + 14850\eta)\right]}{290304 m_1^4 m_2^4 (743 + 924\eta)} \right\},$$

$$\delta\hat{\varphi}_3 = \ell_{\rm GB}^4 \frac{m_1^4 s_2^2(-14363 + 1792\delta - 4564\eta) + 2 m_1^2 m_2^2 s_1 s_2(-3557 + 4564\eta) - m_2^4 s_1^2(14363 + 1792\delta + 4564\eta)}{43008 m_1^4 m_2^4}$$

1.5PN correction newly completed by Félix-Louis Julié

Waveforms used

Waveform model	Short name	Color	Higher modes	Spin precession	Tides
SEOBNRv4HM_ROM [77–79]	SEOBHM	●	✓	-	-
SEOBNRv4_ROM [77]	SEOB		-	-	-
SEOBNRv4_ROM_NRTidalv2_NSBH [80, 81]	SEOBNSBH	●	-	-	✓(NSBH)
SEOBNRv4_ROM_NRTidalv2 [79, 80]	SEOBT	●	-	-	✓(BNS)
IMRPhenomXPHM [82]	PhenomXPHM	●	✓	✓	-
IMRPhenomXHM [83]	PhenomXHM		✓	-	-
IMRPhenomXP [82]	PhenomXP		-	✓	-
IMRPhenomXP_NRTidalv2 [80, 84]	PhenomXPT	●	-	✓	✓(BNS)