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Challenging GR
with future detectors:
the case of space based interferometers

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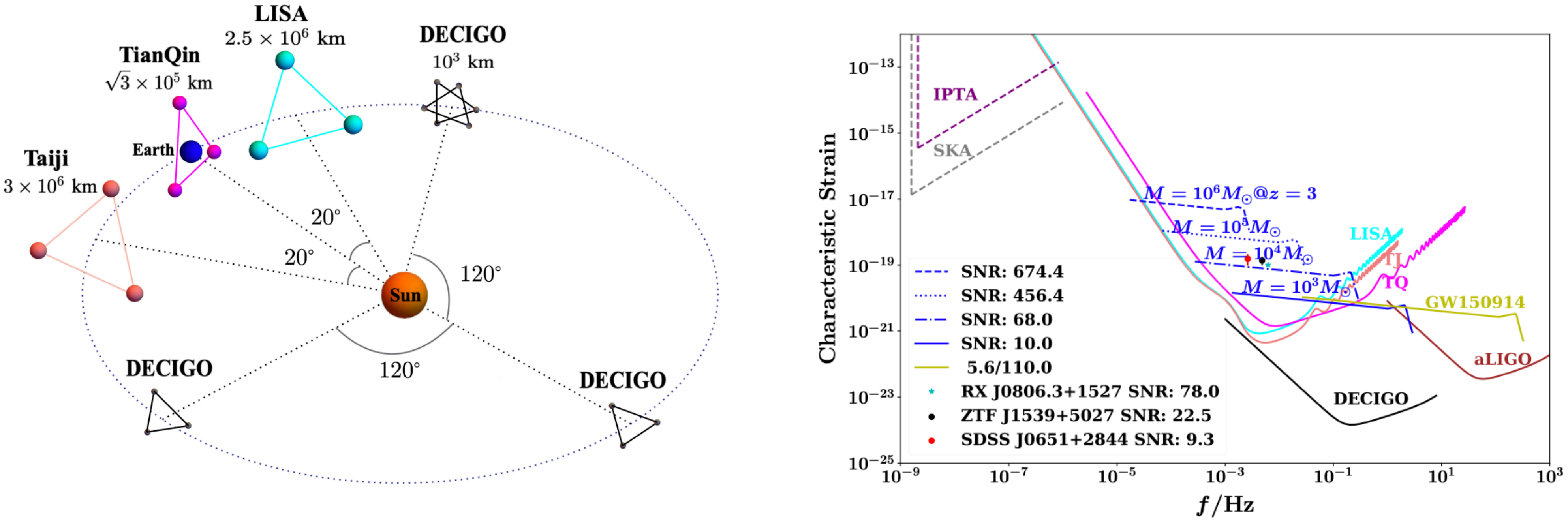
WHITE PAPER

New horizons for fundamental physics with LISA

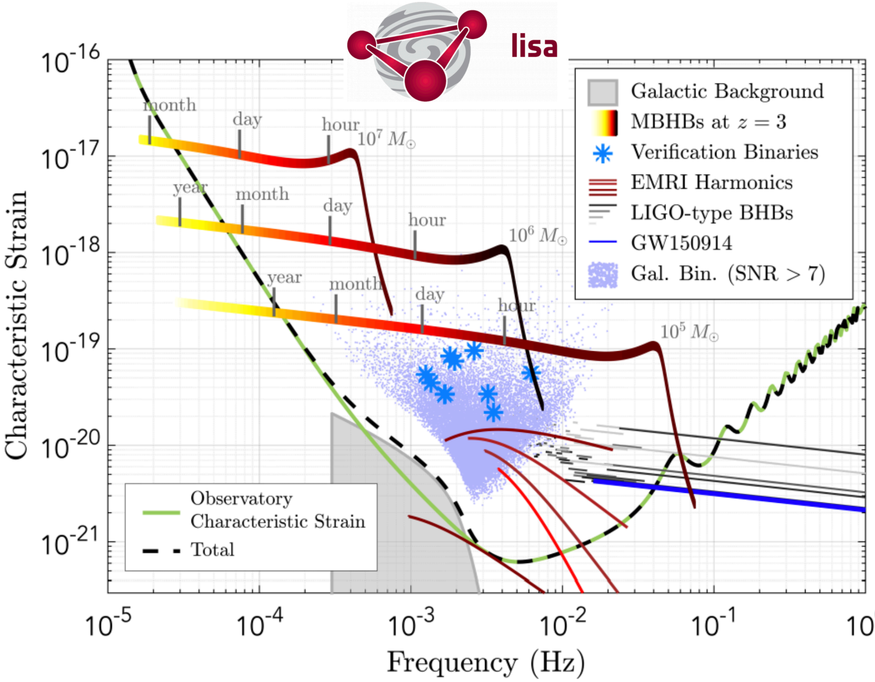
Space-based interferometers



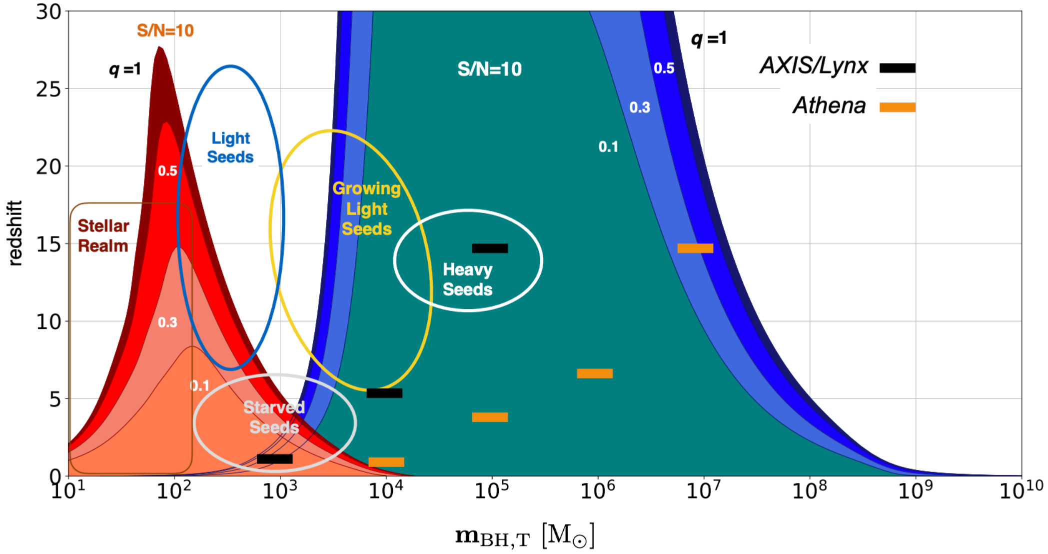
From: Gong+, Nature Astronomy 5, 881 (2021)

Other proposals: Lunar GW Antenna (LGWA) (Harms+ '20); beyond LISA missions (white papers for Astro2020 Decadal Survey & ESA's Voyage 2050 plan); atomic GW interferometric sensor (AGIS) (Dimopoulos+ '09)

Gravitational-wave sources



From: Amaro-Seoane+, arXiv:1702.00786

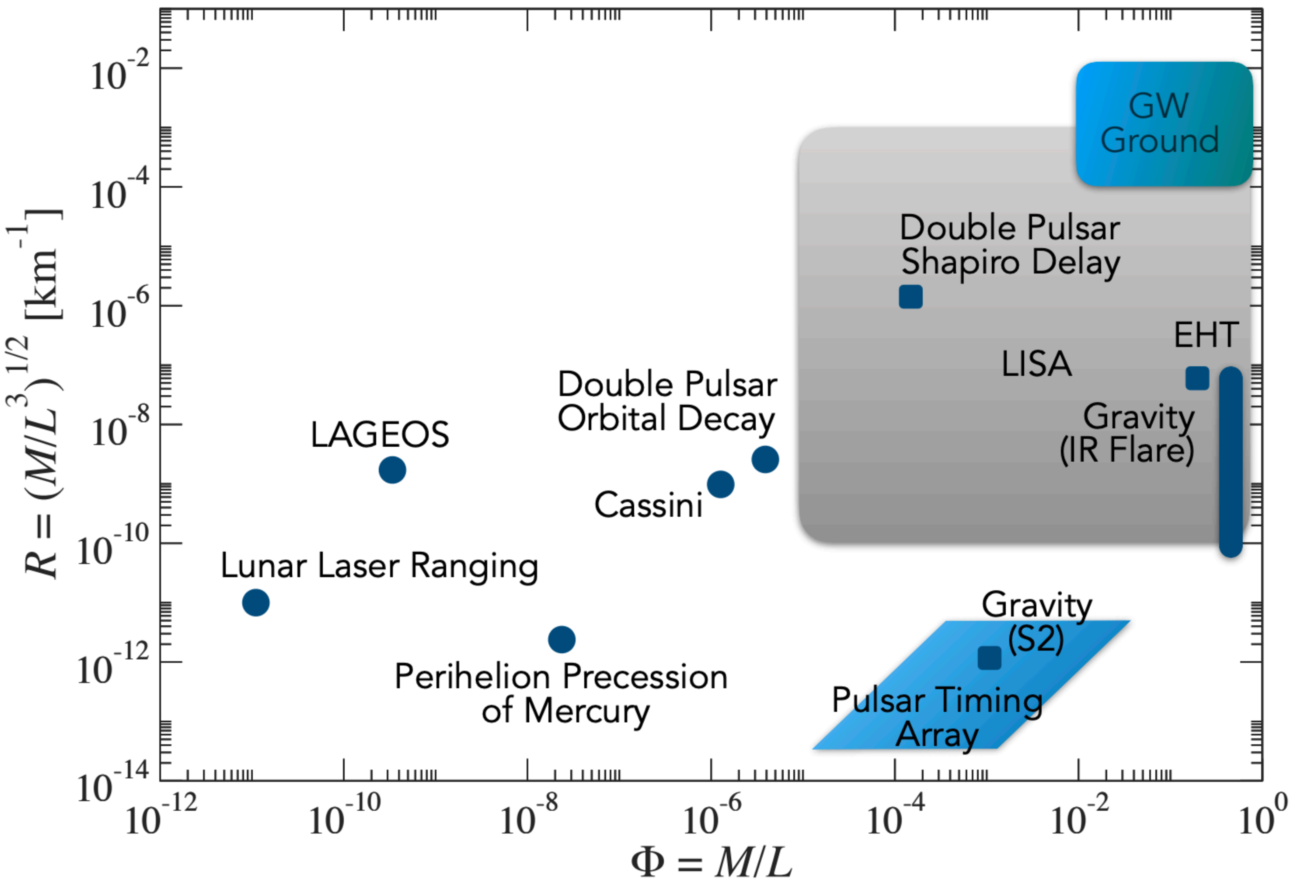


From: Valiante+, MNRAS, 500 (2020) 3

	MBHB	EMRI	IMRI	SOBHB	GB (considering mostly BWDs)
$M_{\rm total}$ ($M_\odot$)	$10^5 - 10^7$	$10^5 - 10^7$	$10^2 - 10^7$	$\lesssim 10^2$	~ 1
q	$1 - 10$	$10^4 - 10^6$	$10^2 - 10^4$	$q > 0.1$	~ 1
J/M^2	$0 - 0.99$	$0 - 0.99$	$0 - 0.99$ (?)	$\lesssim 0.5$	(?)
e_0	$0 - 0.99$	$0 - 0.81$	$0 - 0.99$ (?)	$0 - 0.99$ (?)	< 0.1
SNR	$10 - 10^4$	$20 - 10^2$	$10 - 10^3$ (?)	$\mathcal{O}(10)$ (only LISA)	$5 - 200$
# events	$\mathcal{O}(1) - \mathcal{O}(10^2)$ yr^{-1}	$\mathcal{O}(1) - \mathcal{O}(10^3)$ yr^{-1}	(?)	a few	$\mathcal{O}(10^4)$

Numbers taken from:
LISA's Waveform WG white paper *(in prep)* & Astrophysics WG white paper, arXiv: 2203.06016

Challenging GR in the strong field regime



From: Kalogera+, arXiv:2111.06990

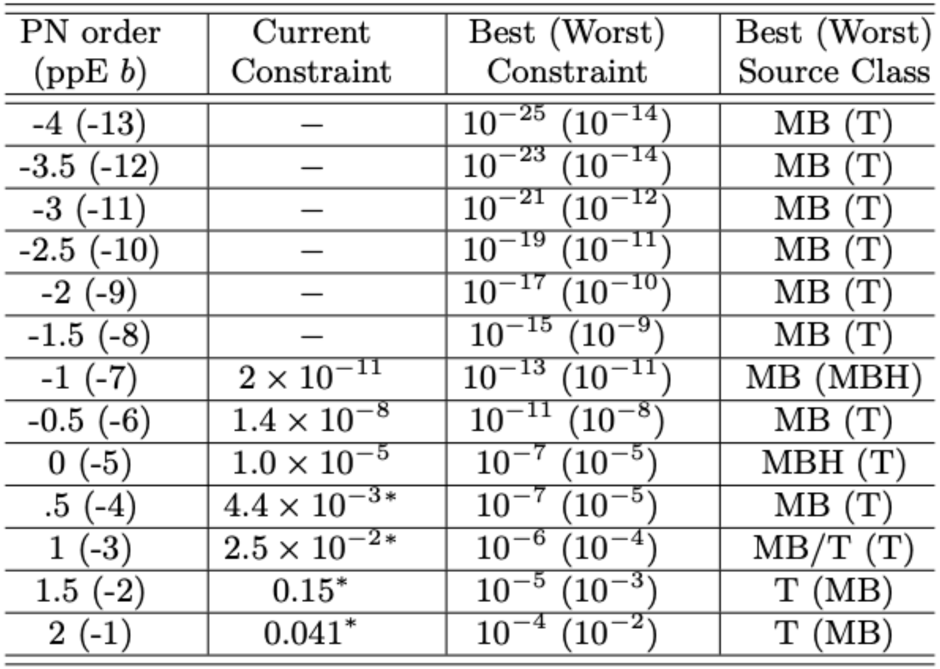
Ground-based detectors **probe higher-curvatures***.

***EMRIs** with a secondary carrying a scalar charge induced by higher-order curvature corrections (e.g. EsGB, dCS) can probe similar curvature scales to SOBHB [see Maselli+ PRL125 (2020) 14, 141101; Nat.Astron. 6 (2022) 4, 464].

Inspiral tests with LISA

From: Perkins, Yunes & Berti, PRD103, 044024 (2021)

$$\tilde{h}(f) = \tilde{A}_{\rm GR} e^{i\Psi_{\rm GR}(f) + i\beta_{\rm ppE} v(f)^b}$$

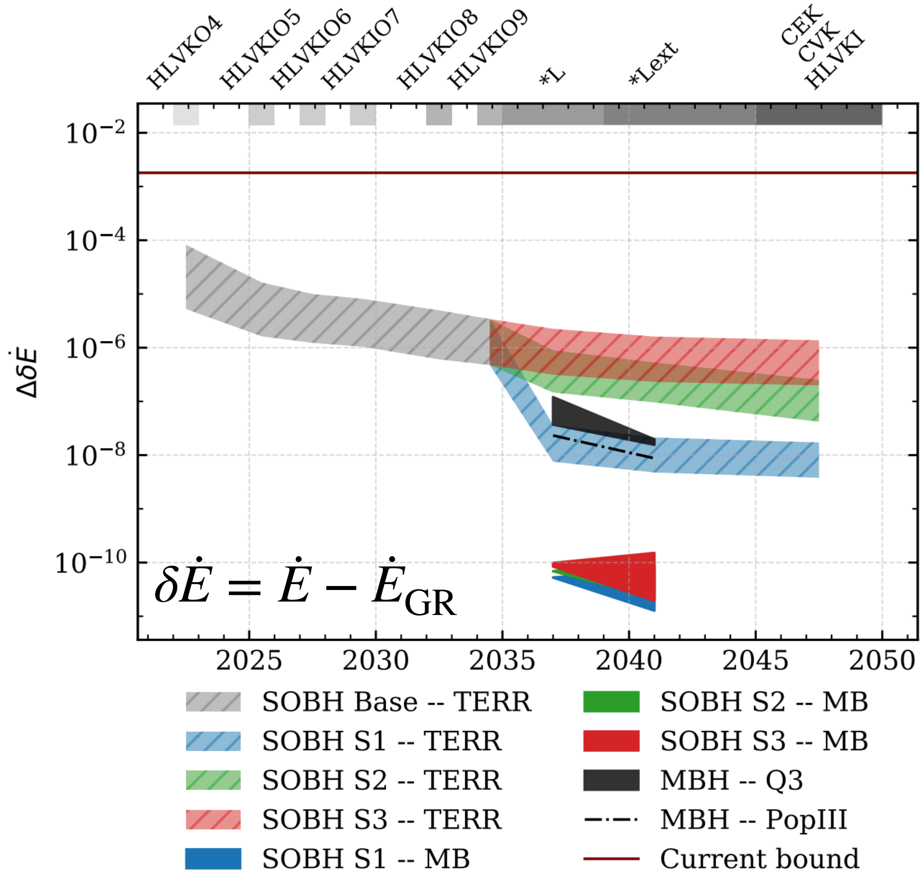


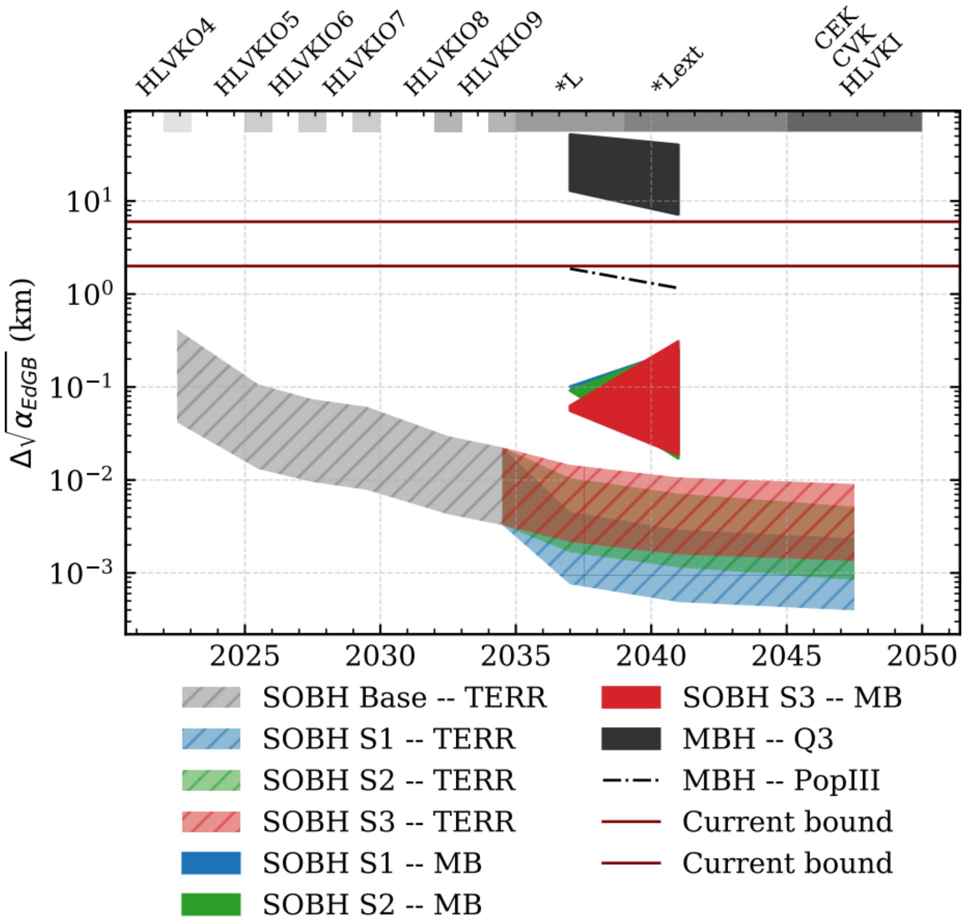
PN order (ppE b)	Current Constraint	Best (Worst) Constraint	Best (Worst) Source Class
-4 (-13)	–	10^{-25} (10^{-14})	MB (T)
-3.5 (-12)	–	10^{-23} (10^{-14})	MB (T)
-3 (-11)	–	10^{-21} (10^{-12})	MB (T)
-2.5 (-10)	–	10^{-19} (10^{-11})	MB (T)
-2 (-9)	–	10^{-17} (10^{-10})	MB (T)
-1.5 (-8)	–	10^{-15} (10^{-9})	MB (T)
-1 (-7)	2×10^{-11}	10^{-13} (10^{-11})	MB (MBH)
-0.5 (-6)	1.4×10^{-8}	10^{-11} (10^{-8})	MB (T)
0 (-5)	1.0×10^{-5}	10^{-7} (10^{-5})	MBH (T)
.5 (-4)	$4.4 \times 10^{-3*}$	10^{-7} (10^{-5})	MB (T)
1 (-3)	$2.5 \times 10^{-2*}$	10^{-6} (10^{-4})	MB/T (T)
1.5 (-2)	0.15^*	10^{-5} (10^{-3})	T (MB)
2 (-1)	0.041^*	10^{-4} (10^{-2})	T (MB)

- **Multiband (MB)** observations particularly good to constrain negative PN orders
- Even in the absence of multiband detections, LISA MBHB detections, in general, better to constrain **negative PN orders** when compared to terrestrial-only (T) SOBHB detections

Inspiral tests with LISA: beyond GR

From: Perkins, Yunes & Berti, PRD103, 044024 (2021)

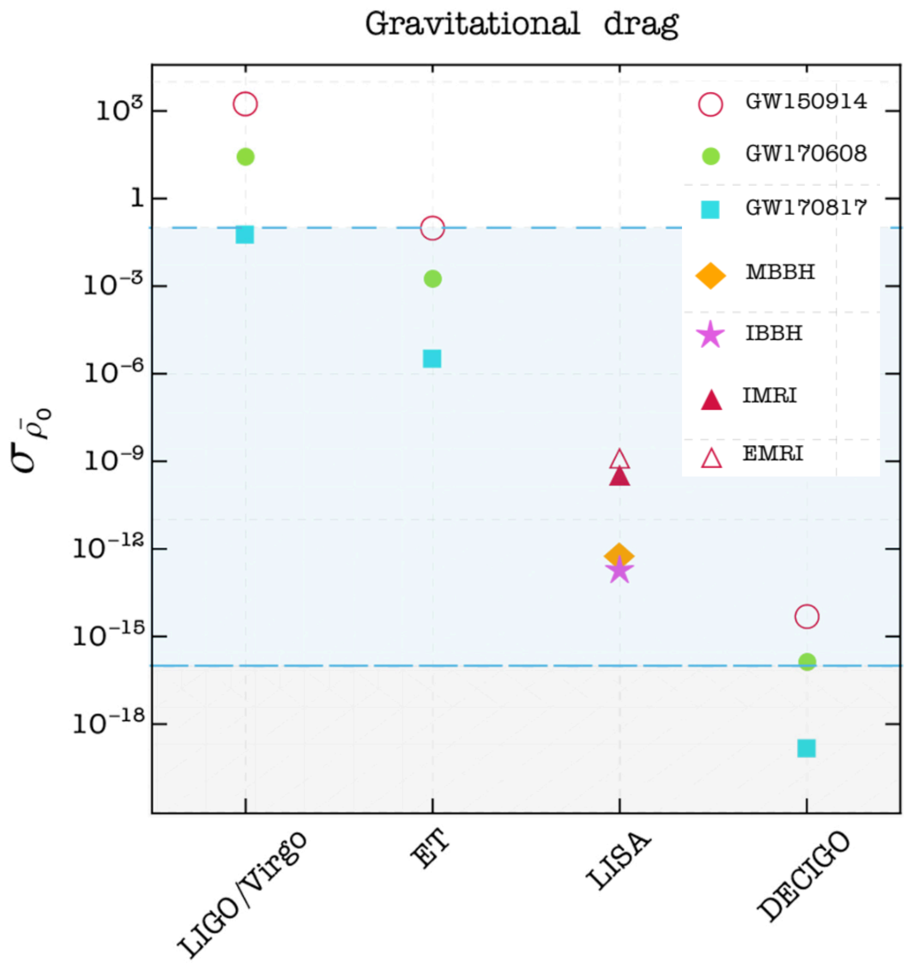




Examples of negative PN: dipole radiation (-1PN); BH evaporation (-4PN); time-varying G (-4PN)

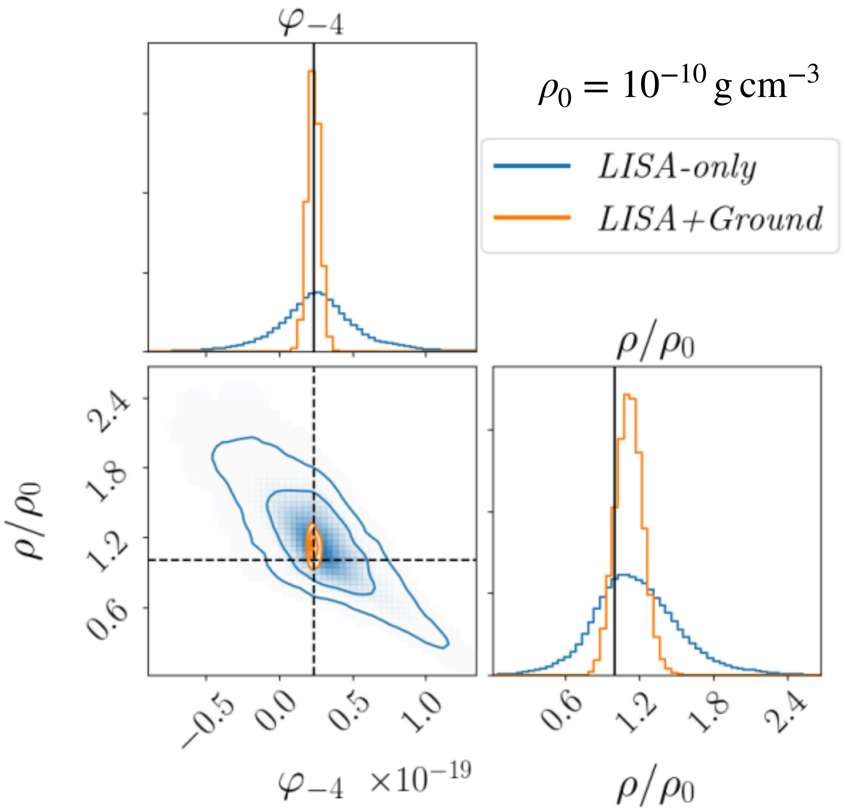
Challenges: go beyond leading-order PN corrections; waveform systematics under control? distinguish beyond GR vs environmental effects?…

Inspiral tests with LISA: environment



From: Cardoso & Maselli, A&A 644, A147 (2020)

GW190521-like event



From: Toubiana+, PRL126, 101105 (2021)

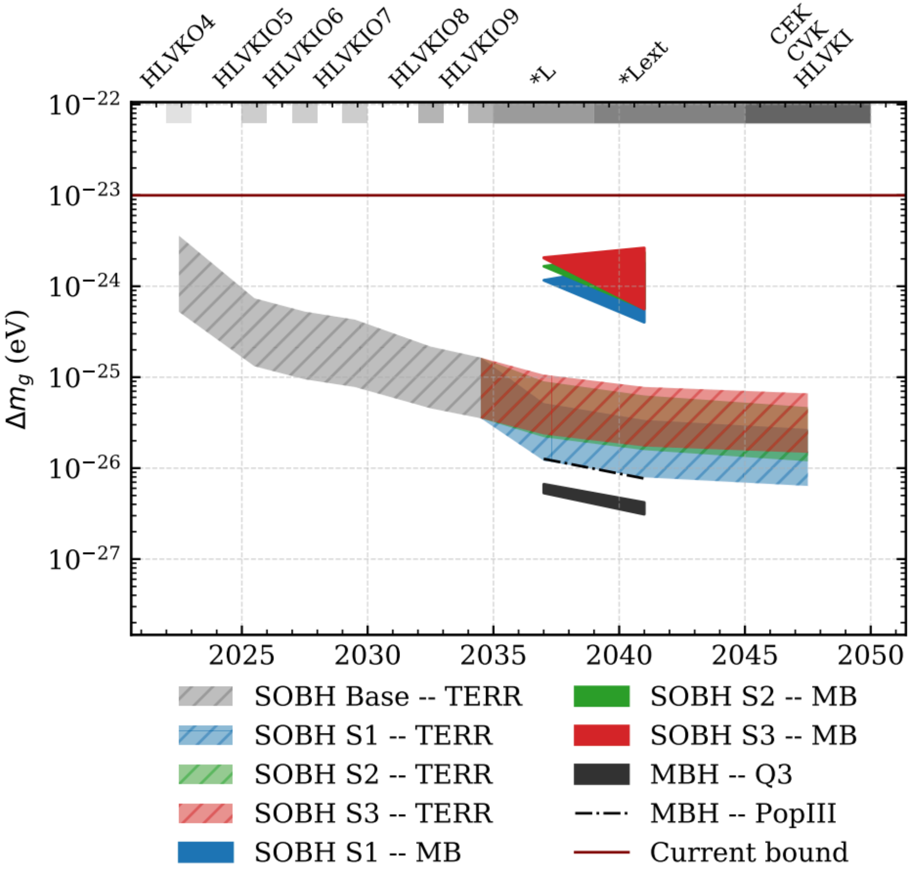
Examples of negative PN: environmental effects such as dynamical friction (-5.5PN for a constant density medium) and accretion (-4PN for accretion disks)

Testing GW propagation

$$h_A'' + 2\left[1-\delta(\eta,k)\right]\mathcal{H}h_A' + \left[c_T^2(\eta,k)k^2 + m_T^2(\eta,k)\right]h_A = \Pi_A$$

[see LISA CosWG WP,
arXiv: 2204.05434]

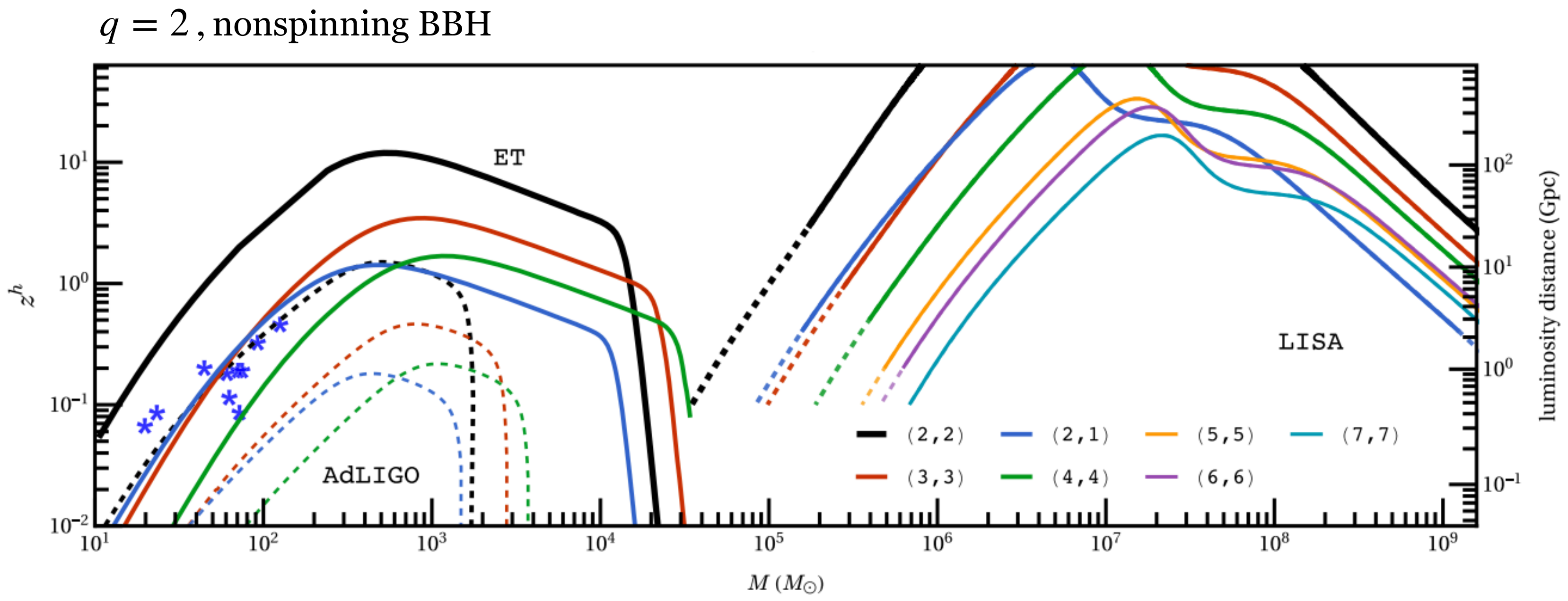
- ❖ Some theories predict modifications in GW **propagation** (e.g. massive gravity; Lorentz symmetry violations in gravity sector; dark energy models)
- ❖ Propagation effects build up over large distances: **orders of magnitude** improvement expected over current constraints
- ❖ **Challenges:** most works assume GW generation is the same as in GR and only the propagation is modified. Is that always good assumption?



[From: Perkins+, PRD103, 044024 (2021)]

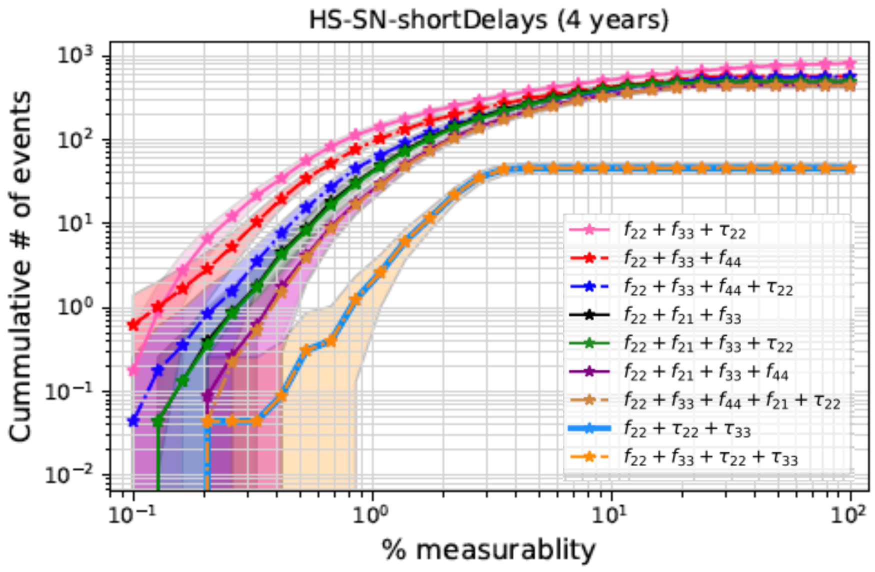
Error scaling: $\Delta m_g \propto \sqrt{(1+z)\pi f_{\rm low}/(\rho D_0)}$

Black hole spectroscopy with LISA



From: Baibhav & Berti PRD99, 024005 (2019)

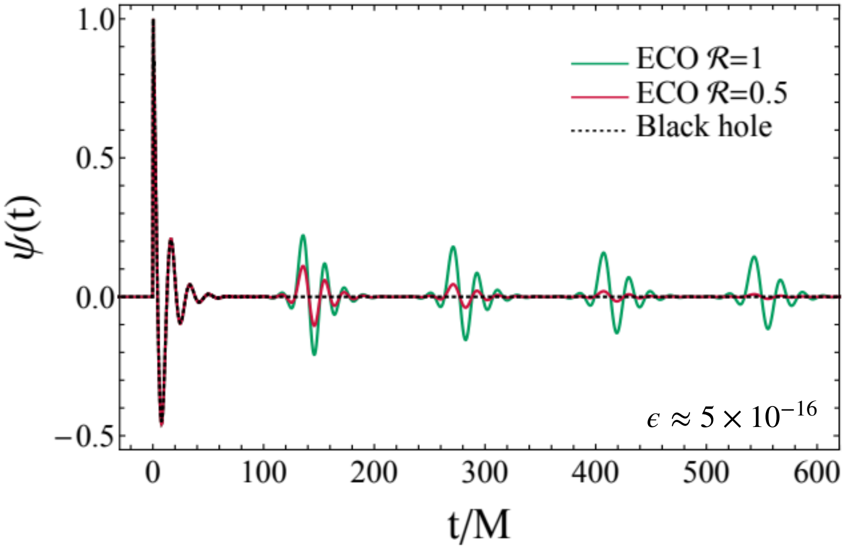
- **Opportunity:** many ringdown modes detectable by LISA
- Most optimistic scenarios predict $\mathcal{O}(100)$ **events** with 1% measurability for 3 or more QNM quantities.
- **Challenges:** Nonlinear modes? Overtones? Environment? For which theories can LISA do better than ground-based detectors?



From: Bhagwat *et al* PRD105, 124063 (2022)

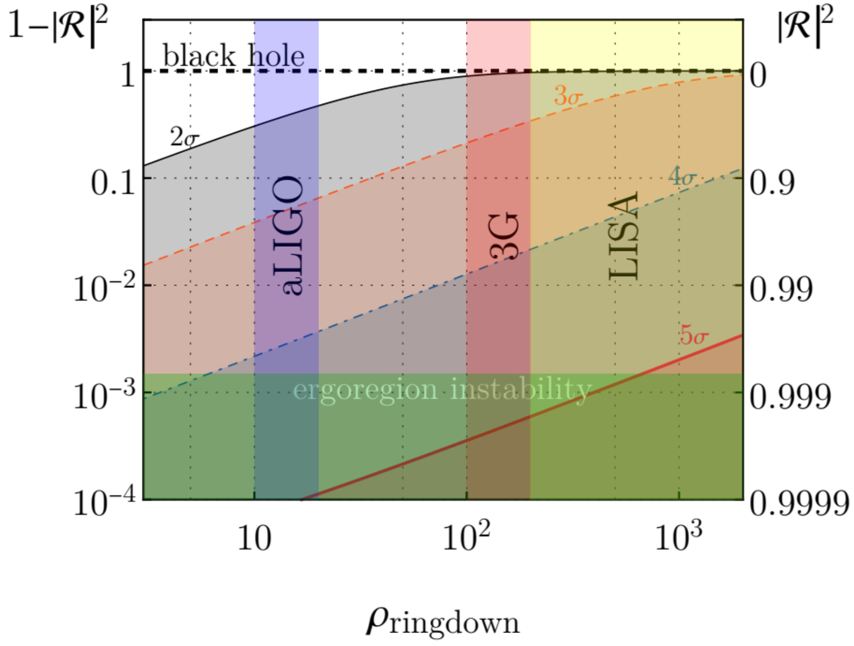
Testing the presence of an horizon: echoes

surface of exotic compact object (ECO) at
$r_0 = 2M(1+\epsilon)$



From: Maggio, Raposo & Pani, arXiv:2105.06410

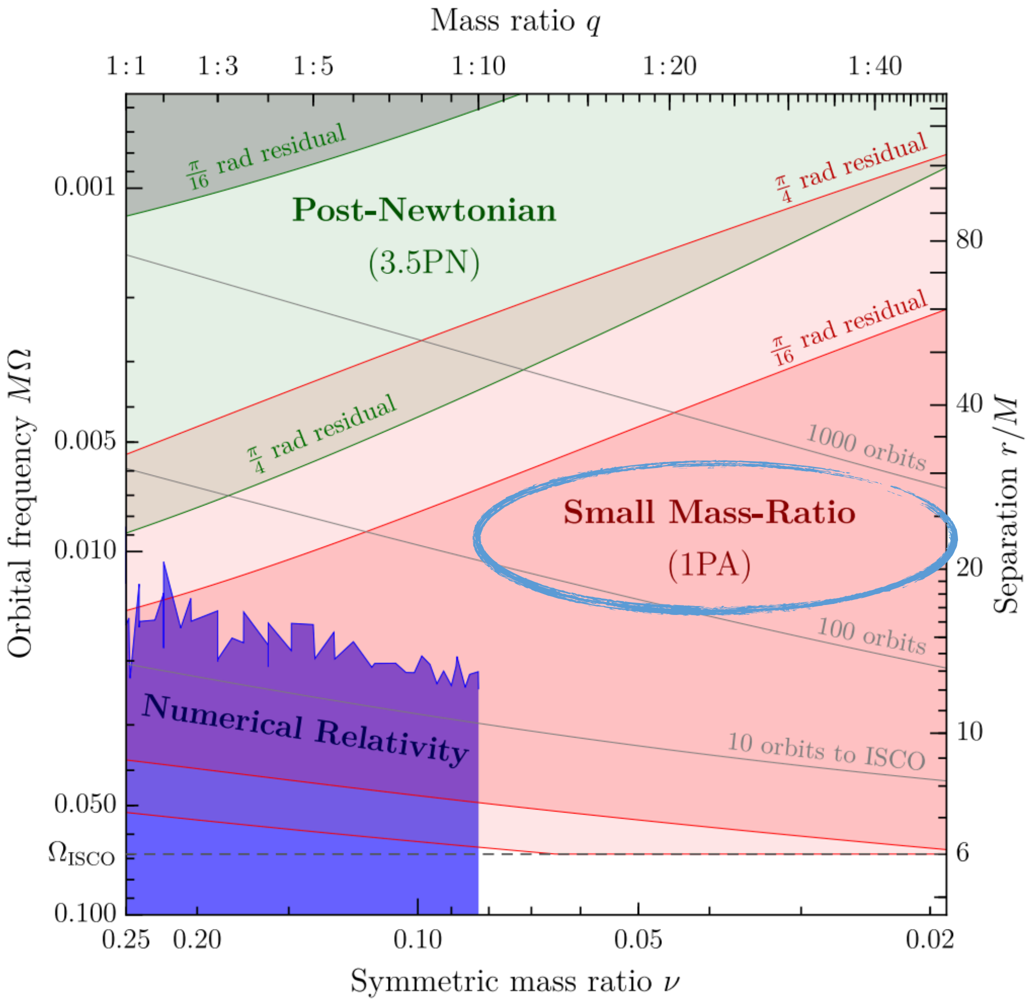
$|\mathscr{R}|^2$ — "Reflectivity" of the object's surface



From: Maggio *et al* PRD100 (2019) 6, 064056

- Typical **high post-merger SNR** in LISA allows to probe much smaller reflectivities than currently probed
- **Challenges:** numerical simulations of realistic extremely compact ECOs (are these even theoretically possible?)

Extreme-mass-ratio-inspirals



From: van de Meent & Pfeiffer, PRL125, 181101 (2020)

Large number of GW cycles in band $\sim \mathcal{O}(q)$ allows to measure waveform parameters with very **high precision**.

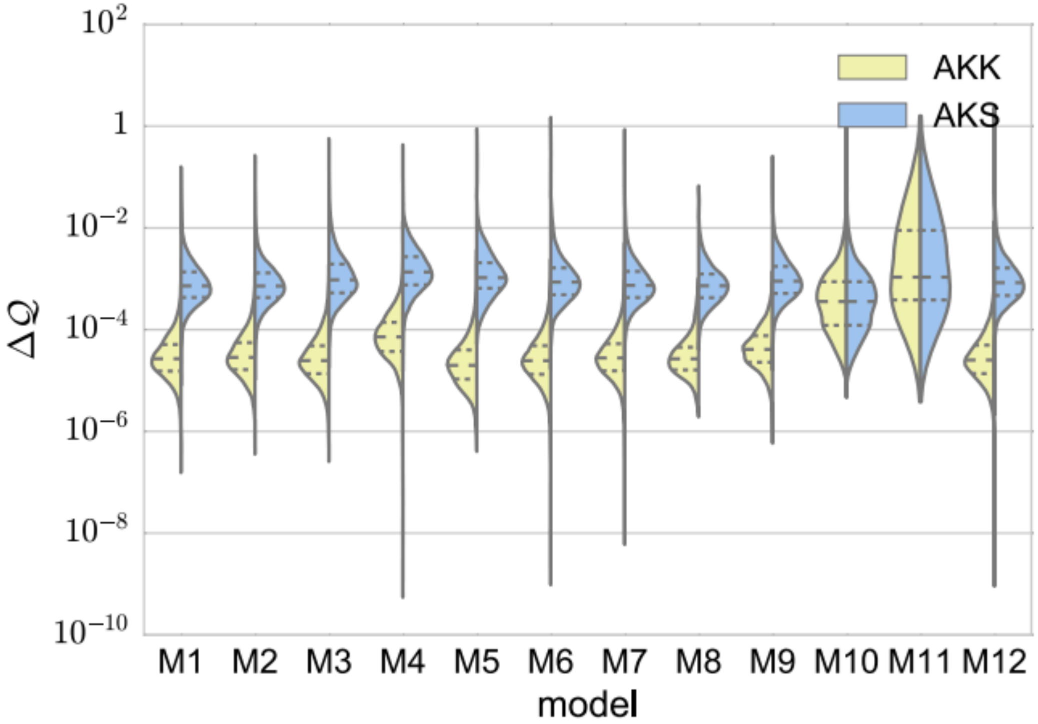
Challenge: Still "work in progress" even in vacuum GR.

Extreme-mass-ratio-inspirals

EMRIs excellent to probe **nature of massive compact objects**

Measure central body
multipolar structure:

$$M^{\mathrm{Kerr}}_{\ell=2n\, m=0} = (-1)^n M \left(\frac{J}{M}\right)^{2n} , \quad S^{\mathrm{Kerr}}_{\ell=2n+1\, m=0} = (-1)^n M \left(\frac{J}{M}\right)^{2n+1} , \quad n = 0,1,\ldots$$



From: Babak+, PRD95, 103012 (2017)

Constraints on deviations away from Kerr mass quadrupole $\Delta\mathcal{Q} \equiv (M_{20} - M^{\mathrm{Kerr}}_{20})/M^3 \lesssim 10^{-4}$

[Barack & Cutler, '06; Babak+, 2017]

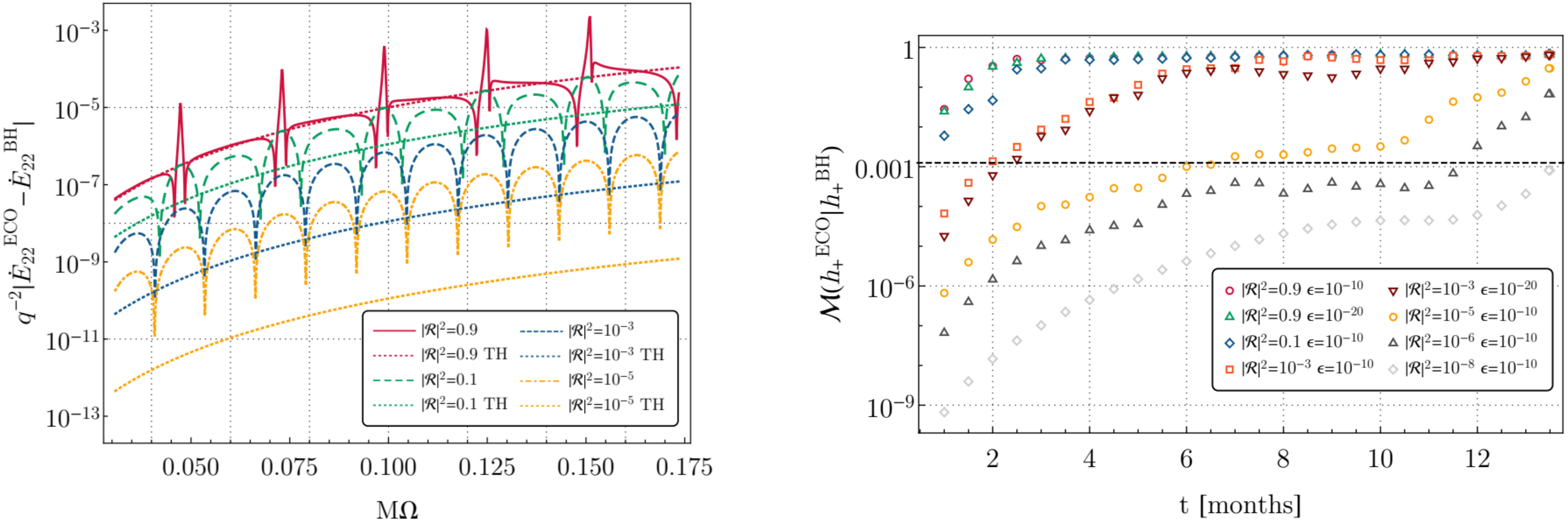
Test **spacetime symmetries**: constrain deviations away from equatorial symmetry with accuracies $\mathcal{O}(1\%)$

[Fransen&Mayerson, '22;
Loutrel, RB, Maselli & Pani '22]

Extreme-mass-ratio-inspirals

EMRIs excellent to probe **nature of massive compact objects**

Measure central body
reflectivity:



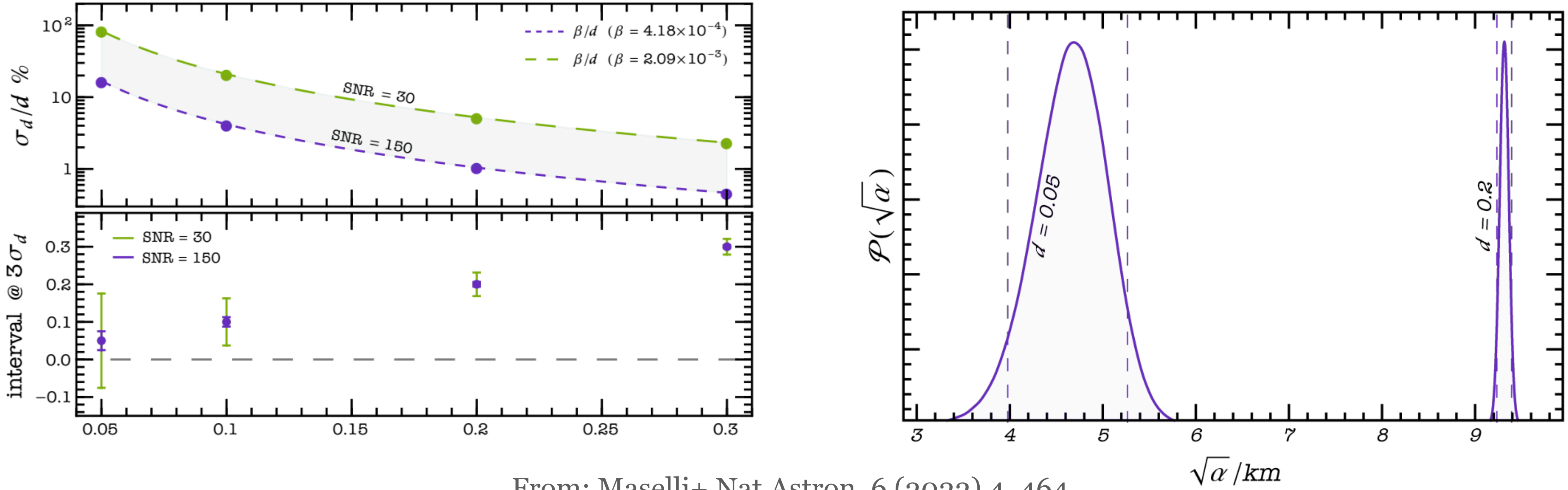
From: Maggio+, PRD104, 104026 (2021)

Potential **constraints on reflectivity** at the level $|\mathscr{R}|^2 \lesssim 10^{-8}$. Orders of magnitude better than what is achievable though "echoes".

Extreme-mass-ratio-inspirals

EMRIs excellent to probe **modifications in dissipative sector**

Probe additional dissipation due to
small body scalar charge:
[see Maselli+’20-22; Barsanti+ ’22]



From: Maselli+ Nat.Astron. 6 (2022) 4, 464

- EMRIs can probe scalar charges as small as $d \sim 10^{-2}$. When translated to constraints on EdGB corresponds to probing $\alpha_{\rm EdGB} \sim \mathcal{O}$(km): similar to ground-based detectors.
- **Caveat:** if scalar field is massive, constraints only effective when $m_s M_{\rm BH}/M_{\rm pl}^2 \lesssim 1$

[Barsanti+ ’22]

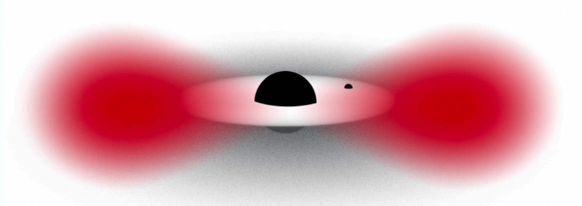
Extreme-mass-ratio-inspirals

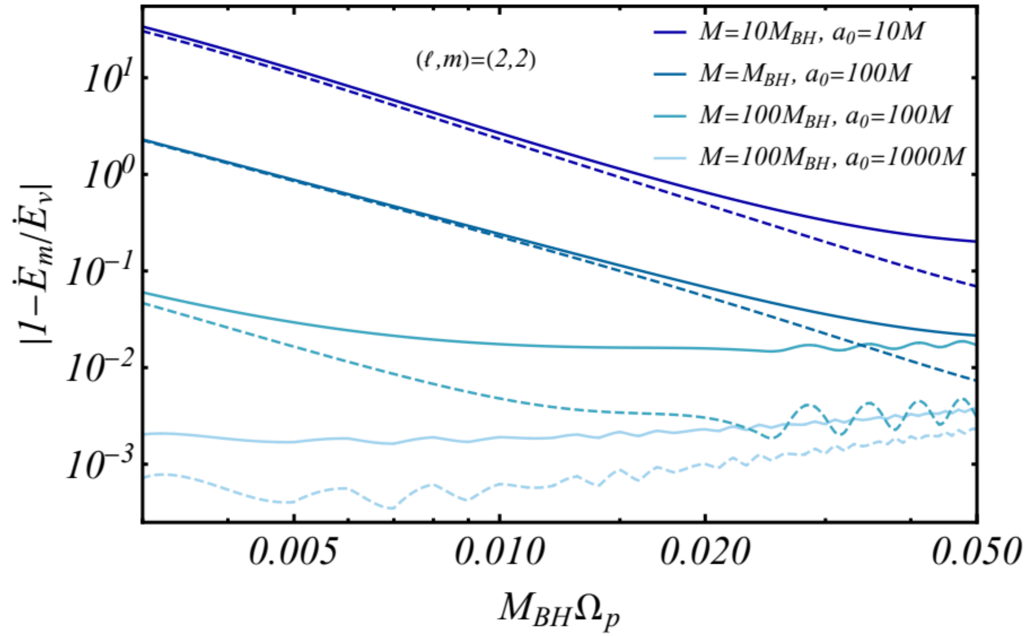
EMRIs excellent to probe **modifications in dissipative sector**

Probe the **environment** (accretion disks, dark matter spikes, boson clouds):

$$ds^2 = a(r)dt^2 + b(r)^{-1}dr^2 + r^2 d\Omega^2$$

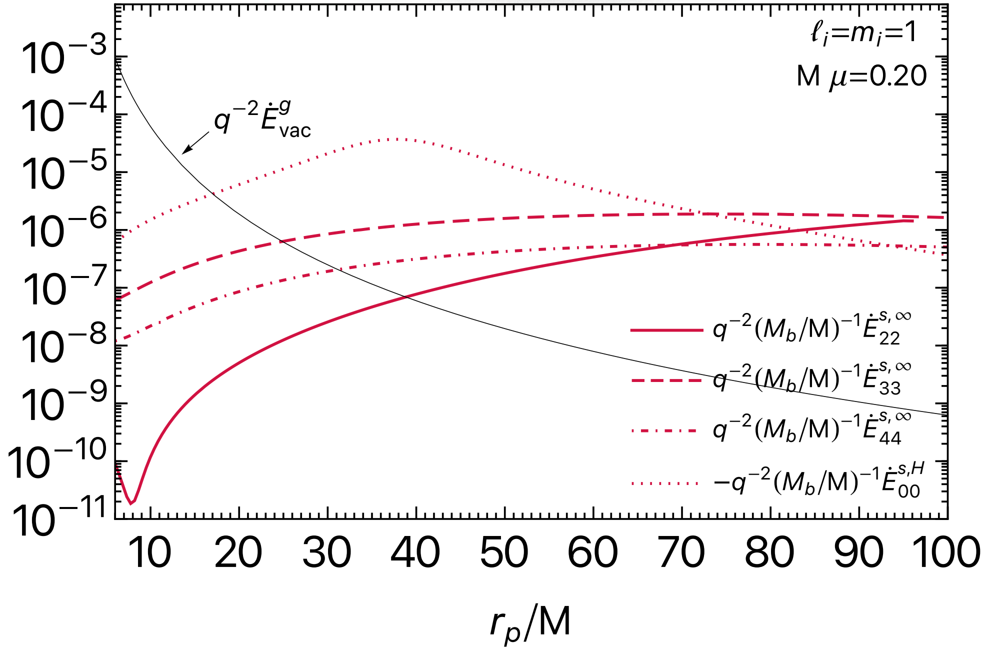
$$T^{\rm env}_{\mu\nu} = \rho u_\mu u_\nu + p_r k_\mu k_\nu + p_t \Pi_{\mu\nu}$$





[From: Cardoso+, PRL129, 241103 (2022)]

[See Cardoso+ ’21-22; Figueiredo+ ‘23]

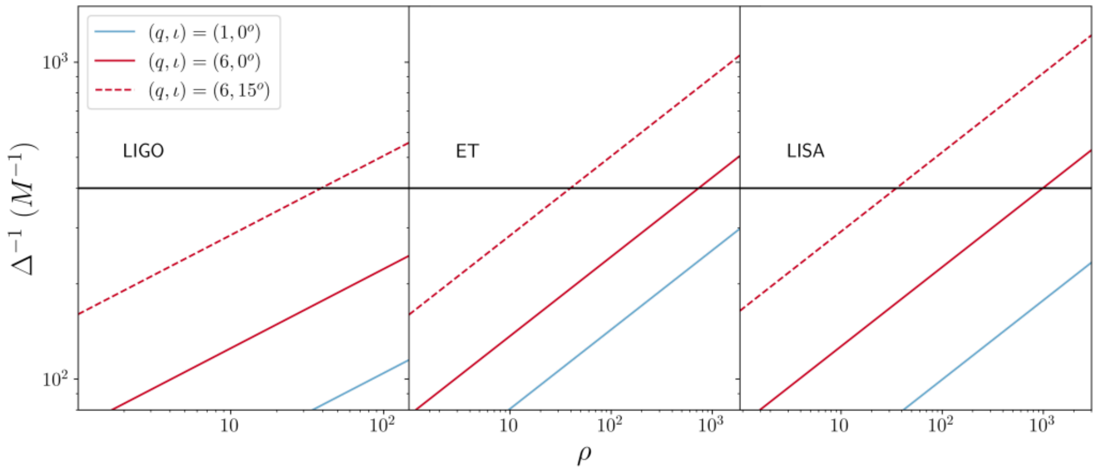


[From: RB & S. Shah, work in progress]

[See Baumann+’18-’21; Cole+ ’22; Tomaselli ’23]

Final remarks

Minimum required resolution for a NR simulation



From: Ferguson *et al*, PR104 (2021) 4 ,044037

Current highest resolution in NR catalog produced with MAYA code (formerly Georgia Tech code)

❖ **Challenges**:

- What is the **accuracy level** that NR simulations much reach? Is the required accuracy achievable (especially for high spins, high mass ratios, large eccentricities)?
- What PN accuracy is required for comparable-mass BH binaries so that we can perform **precision tests** of GR with LISA?
- **Second-order self-force** waveforms in vacuum still in development: we need them before we can even think about using EMRIs to do precision tests with EMRIs
- Development of full *usable* waveforms in beyond-GR theories and/or environments, still a **long way to go** in most cases: how far should we go? is it worth the effort?
- **Global fit** problem: how much can it affect precision tests?
- How do **instrumental systematics** affect precision tests (calibration errors, data gaps, glitches,…)?

Thank you!