LISA in Copenhagen
August 9th 2023

Tests of the nature of black holes from the WP perspective

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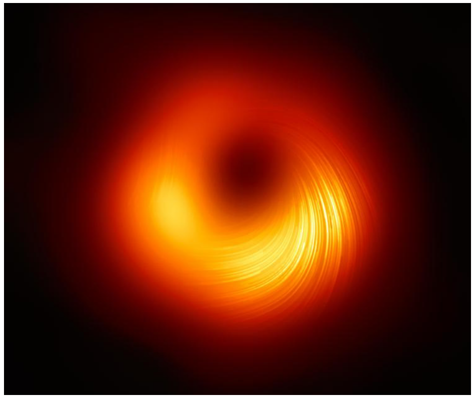
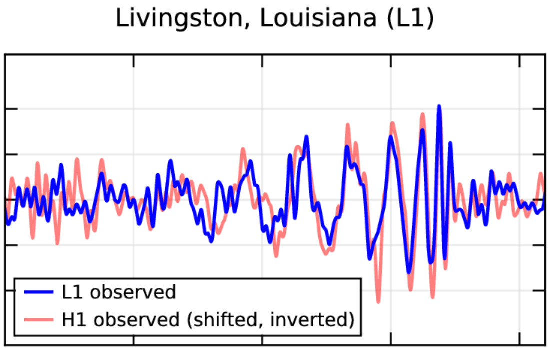
Motivation

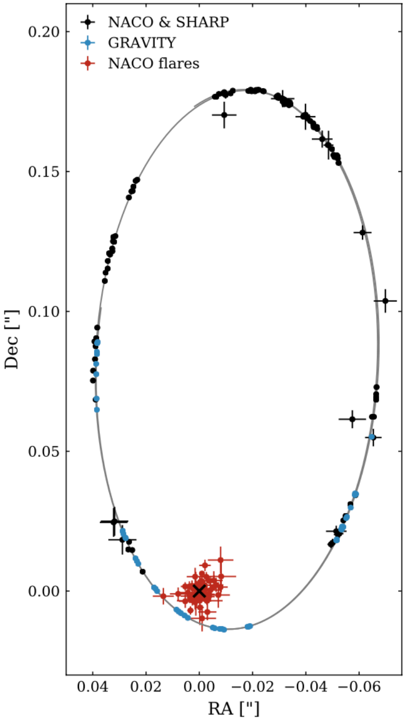
The evidence for black holes is the observation of dark, compact and massive objects.



EHT, ApJL **910**, L12 (2021)



Abbott+, PRL **116** n.6 (2016) 061102



GRAVITY, A&A **636**, L5 (2020)

- Are these compact objects black holes (with horizons)?
- Are they described by general relativity?

Horizonless compact objects

New physics can prevent the formation of the horizon:

- in quantum-gravity extensions of general relativity (e.g. fuzzballs, gravastars)

  Mathur, Fortsch. Phys. **53**, 793-827 (2005); Mazur+, PNAS **101**, 9545-9550 (2004)

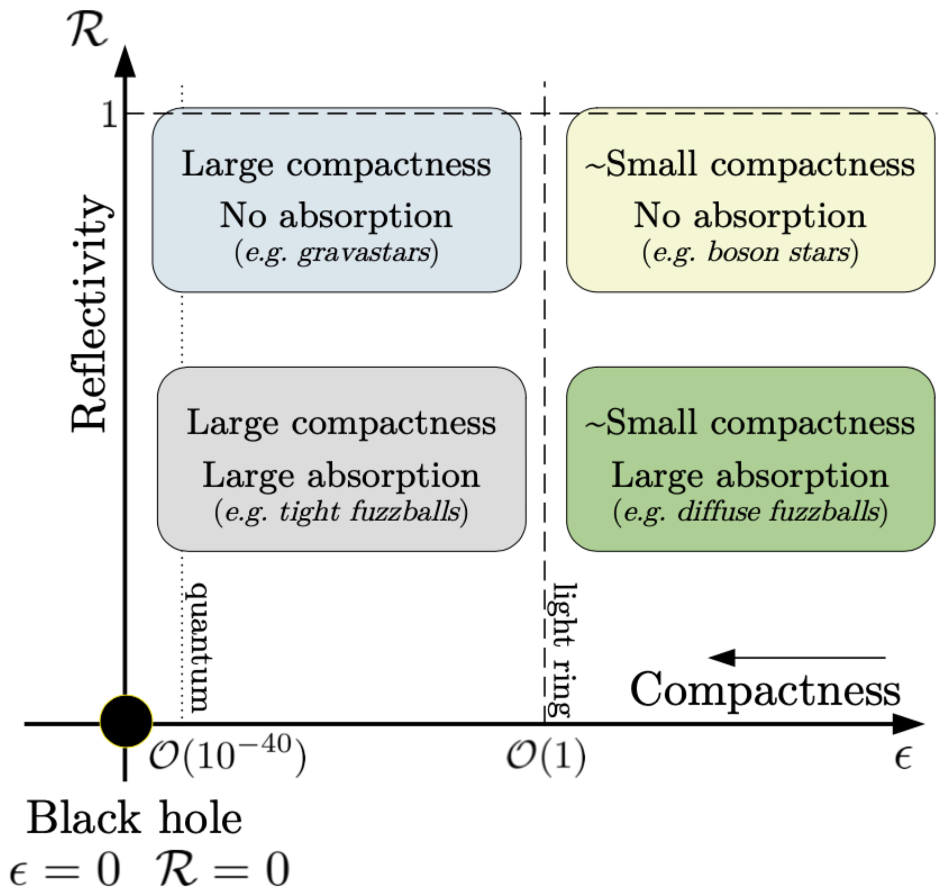
- in general relativity with dark matter or exotic fields (e.g. boson stars, wormholes)

  Liebling+, LRR **20**, 5 (2017); Morris+, Am. J. Phys. **56**, 395-412 (1988)

A parametrized classification

A generic model of horizonless compact object deviates from a BH for its:

- **Compactness**
  since the radius of the object is at $r_0 = r_+(1+\epsilon)$
- **Reflectivity**
  that differs from the totally absorbing black hole case

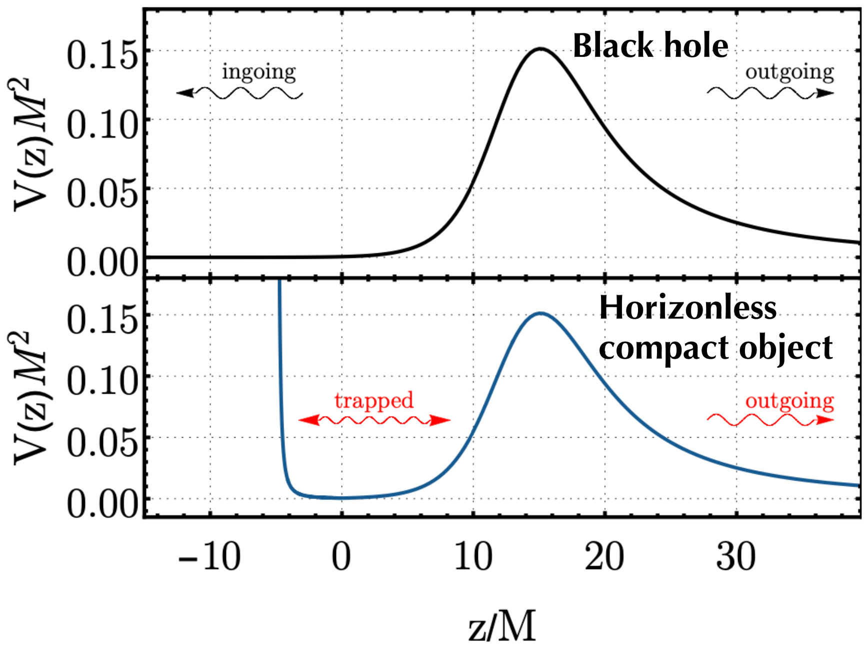


EM, Pani, Raposo, Handbook for GW Astronomy, Springer (2021)

The ringdown

The ringdown stage is dominated by the **quasi-normal modes** of the remnant which describe the response of the compact object to a perturbation.

Cardoso, Pani, LRR **22**:4 (2019)

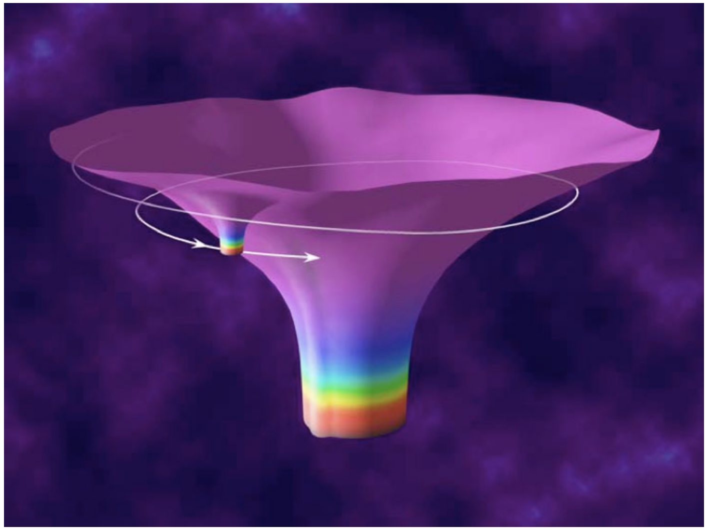


$$\frac{d^2\psi}{dz^2} + \left[\omega^2 - V(z)\right]\psi = 0$$

Teukolsky, Press, ApJ **193** (1974) 443-461

No horizon ⟶ Trapped modes ⟶ Low- frequency and long-lived QNMs

Exotic extreme mass-ratio inspirals



LISA will detect GWs from the inspiral of stellar mass objects around supermassive compact objects at the center of galaxies.

EMRIs are unique probes of the nature of supermassive compact objects:

- Exotic compact objects (ECO)

  Datta+, PRD 101, 044004 (2020); Cardoso+, PRD 100, 084046 (2019); EM+, PRD 104, 104026 (2021)

- Tidal deformability Piovano+, PRD 107, 024021 (2023)
- Boson stars Destounis+, arXiv: 2305.05691 (2023)

EMRIs around an ECO

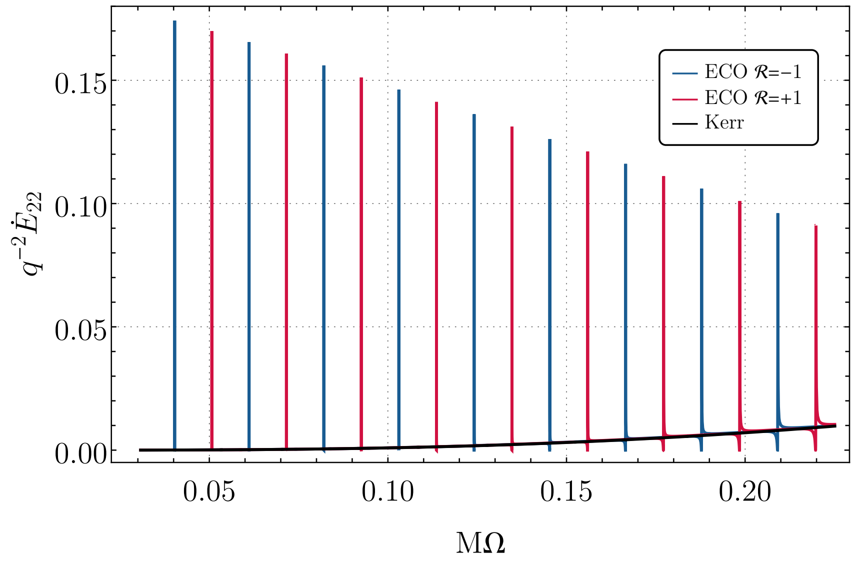
- **Tidal heating** Datta+, PRD 101, 044004 (2020)

  Any evidence of reflectivity is a departure from the classical BH picture:

$$\dot{E}_{\rm ECO} = \left(1 - |\mathcal{R}|^2\right) \dot{E}_{\rm H}$$

- **Resonances**

  Low-frequency resonances are excited when the orbital frequency matches the QNMs of the central ECO.



Equispaced resonances at $\Omega = \omega_R/m$

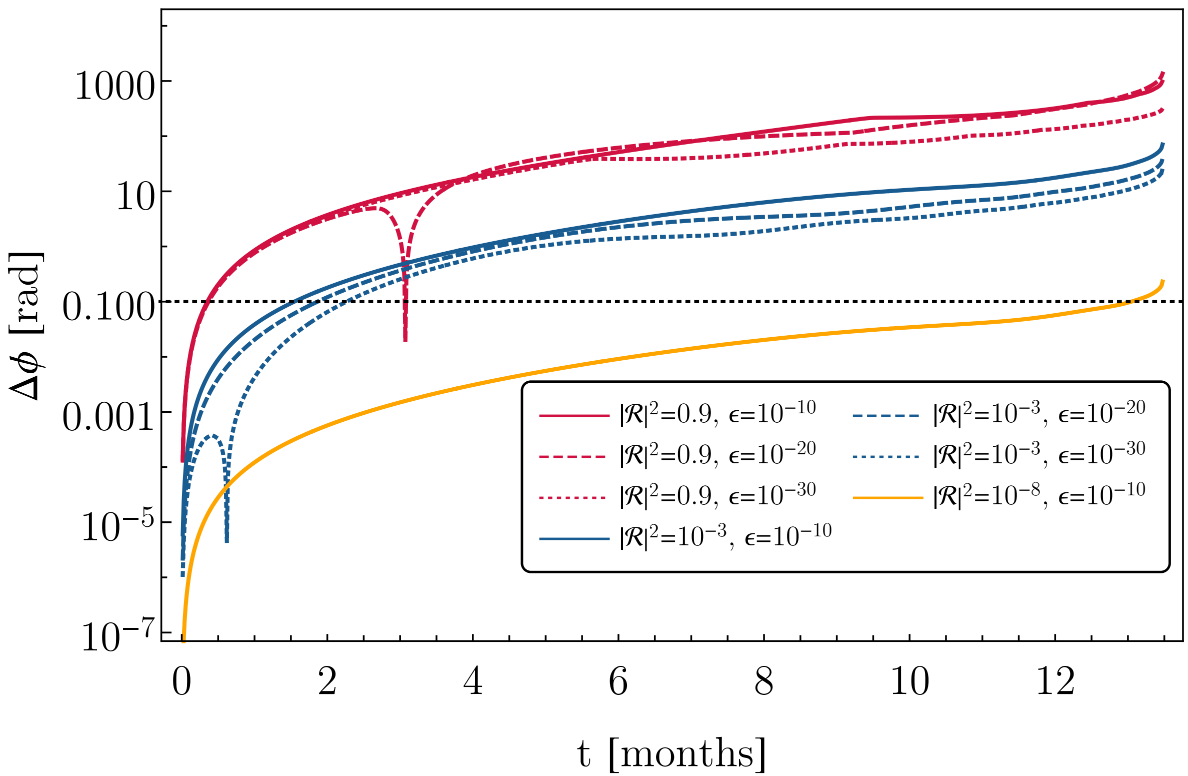
Resonance width: $\delta\Omega \sim \omega_I$

Cardoso+, PRD 100, 084046 (2019); EM+, PRD 104, 104026 (2021)

GW dephasing

The GW dephasing accumulated up to a certain time between the BH and the horizonless case is:

$$\Delta\phi(t) = \phi_{\rm GW}^{\rm BH}(t) - \phi_{\rm GW}^{\rm ECO}(t)$$



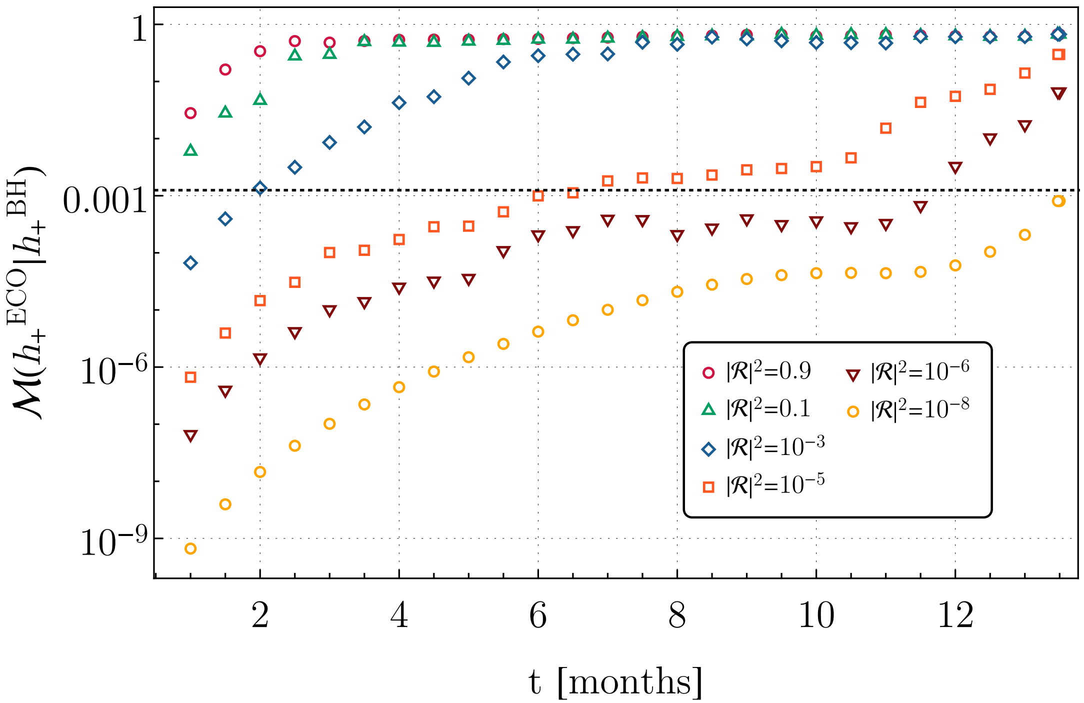
$\chi = 0.8$

$q = 3 \times 10^{-5}$

EM+, PRD 104, 104026 (2021)

Waveform mismatch

The mismatch is computed between the waveforms for a central BH and a central horizonless compact object.



$\chi = 0.8$

$q = 3 \times 10^{-5}$

$\epsilon = 10^{-10}$

Lindblom criteria

SNR = 20

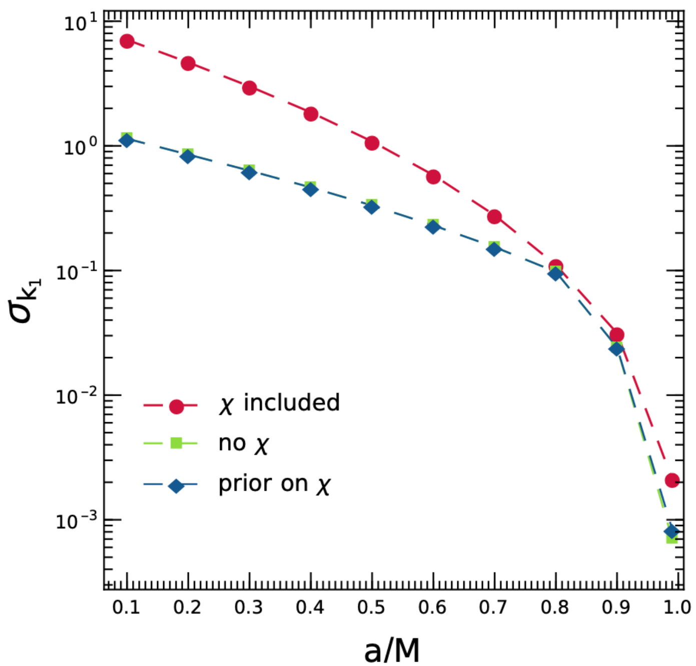
In one year of observation, LISA is sensitive to a reflectivity of the central object $|\mathcal{R}|^2 = \mathcal{O}(10^{-8})$.

EM+, PRD 104, 104026 (2021)

Tidal deformability

Horizonless compact object have nonzero tidal Love numbers (TLNs) and are deformable when immersed in an external tidal field. Cardoso+, PRD 95, 084014 (2017)

A **Fisher matrix analysis** can assess the measurability of the TLN of the central object, k_1.



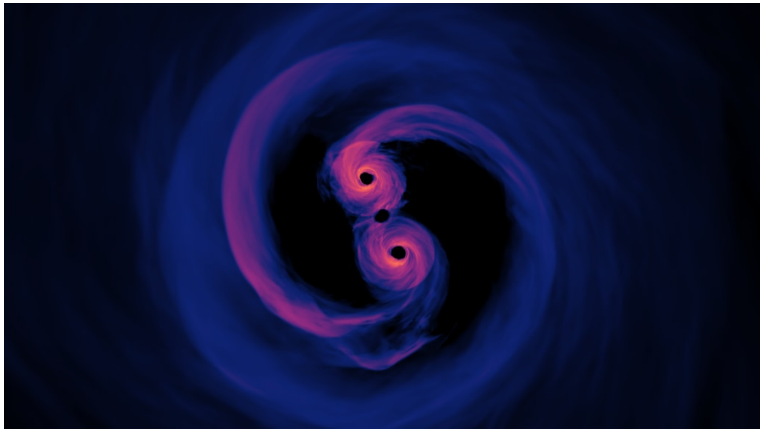
If the central object is highly spinning the TLN can be measured at the level of 10^{-3}.

Current measurement errors from GW170817 are:

$$\sigma_{k_1} < 10^3$$

Piovano+, PRD 107, 024021 (2023)

Ringdown of massive binaries



Kerr BHs are determined uniquely by:
- Mass
- Angular momentum

Carter, PRL **26**, 331 (1971); Robinson, PRL **34**, 905 (1975)

- Detecting **multiple QNMs** in the ringdown would allows us to perform independent tests of the BH paradigm.

Dreyer+, CQG **21**, 787 (2004); Berti+, PRD **73**, 064030 (2006)

- In ECOs and modified theories of gravity, there is a **breaking of isospectrality** between axial and polar QNMs.

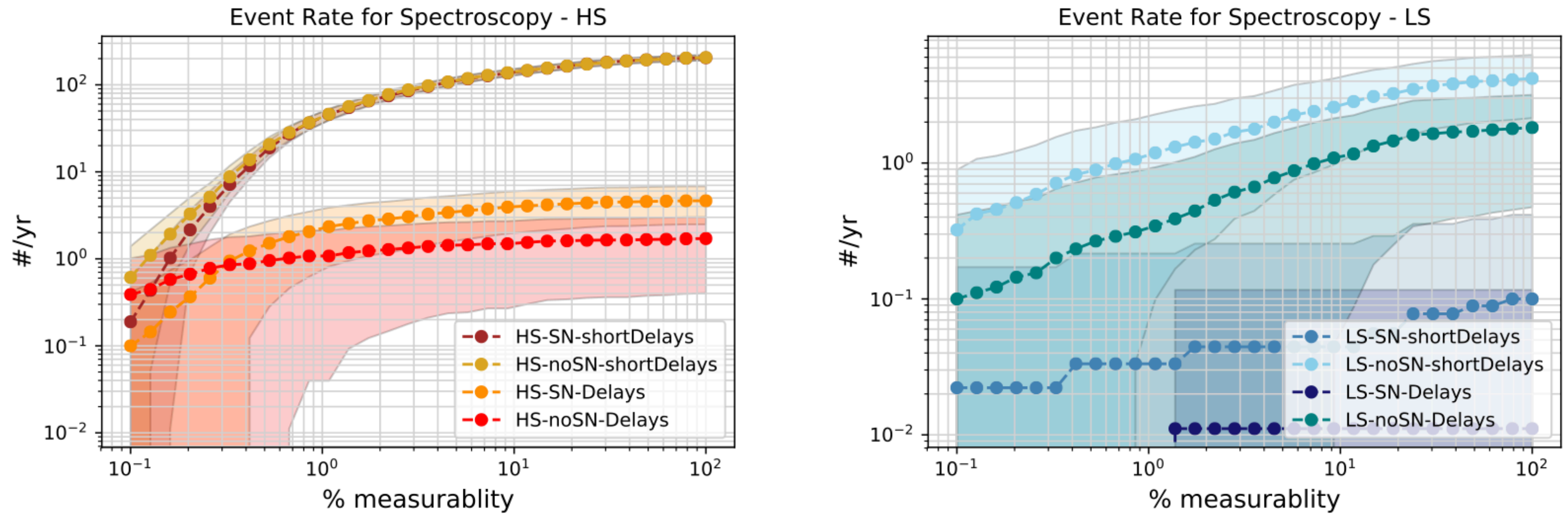
Blázquez-Salcedo+, PRD 94, 104024 (2016); EM+, PRD 102, 064053 (2020)

BH spectroscopy with LISA

The rates of massive BH binaries with mass $\sim 10^5 M_\odot$ depends on the underlying massive BH populations. Bhagwat+, PRD 105, 124063 (2022)

- **Heavy seed scenario:**
  Usign a Fisher-matrix analysis, LISA will measure $\mathcal{O}(100)$ events with at least 3 independent QNMs at 1% error.

- **Light seed scenario:** favoured in the ET band



BH spectroscopy with LISA

Parametrized deviations to the frequency and damping time of the fundamental QNMs are introduced in the inspiral-merger-ringdown `pSEOBNRv5HM` waveform:

Ghosh+, PRD 103, 124041 (2021); Brito+, PRD 98, 084038 (2018); Pompili+, 2303.18039 (2023)

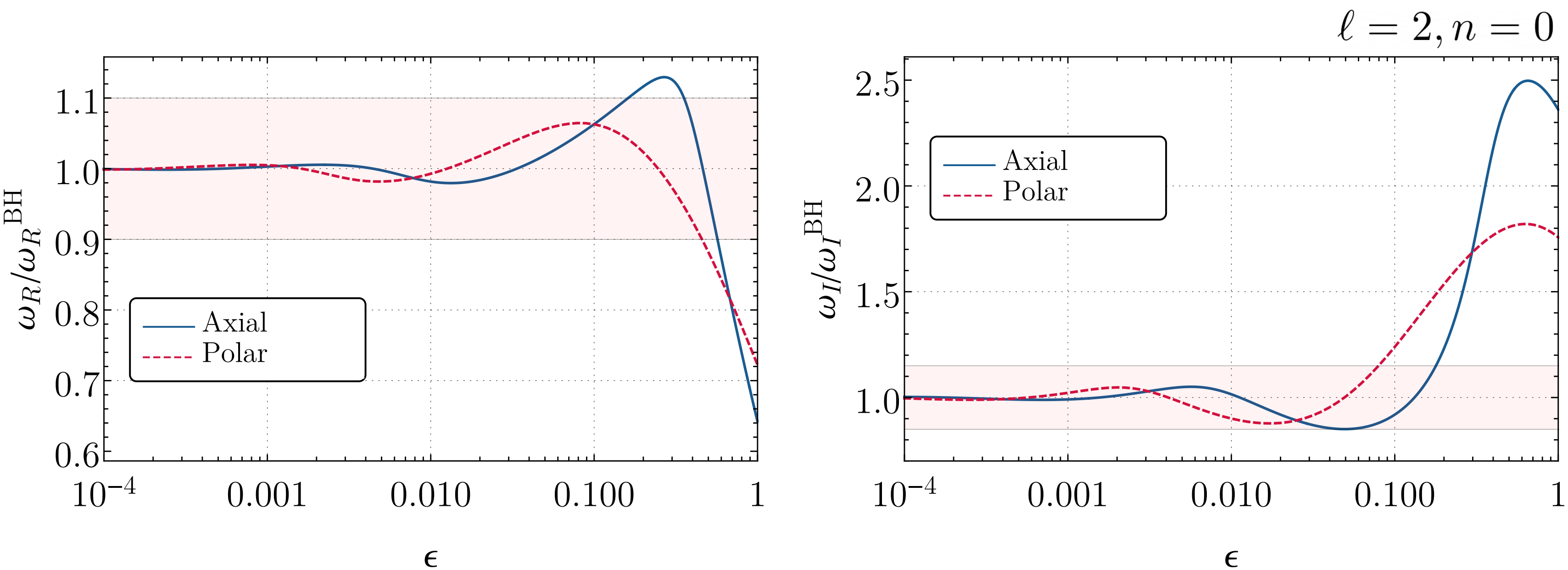
$$f_{\ell m0} = f_{\ell m0}^{\rm GR}(1 + \delta f_{\ell m0})$$
$$\tau_{\ell m0} = \tau_{\ell m0}^{\rm GR}(1 + \delta \tau_{\ell m0})$$

Bayesian analyses estimate that deviations of the $(2,2), (3,3), (4,4), (5,5)$ QNMs can be constrained down to 1% for systems with mass $\sim 10^7 M_\odot$.

Toubiana+, arXiv:2307.15086 (2023)

QNM doublet

- In Schwarzschild BHs, axial and polar QNMs are isospectral.
- In ECOs, axial and polar modes are not isospectral and form a doublet.



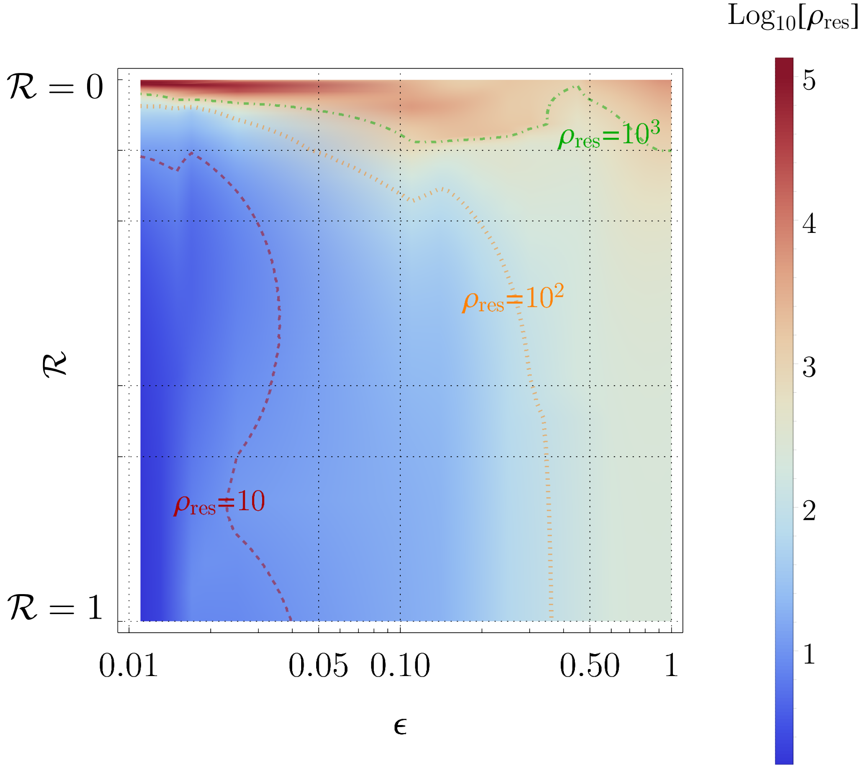
EM+, PRD **102**, 064053 (2020)

QNM doublet

- In Schwarzschild BHs, axial and polar QNMs are isospectral.
- In ECOs, axial and polar modes are not isospectral and form a doublet.

The SNR required for the resolvability of the axial-polar QNM doublet is $\mathrm{SNR} \sim 10^3$.

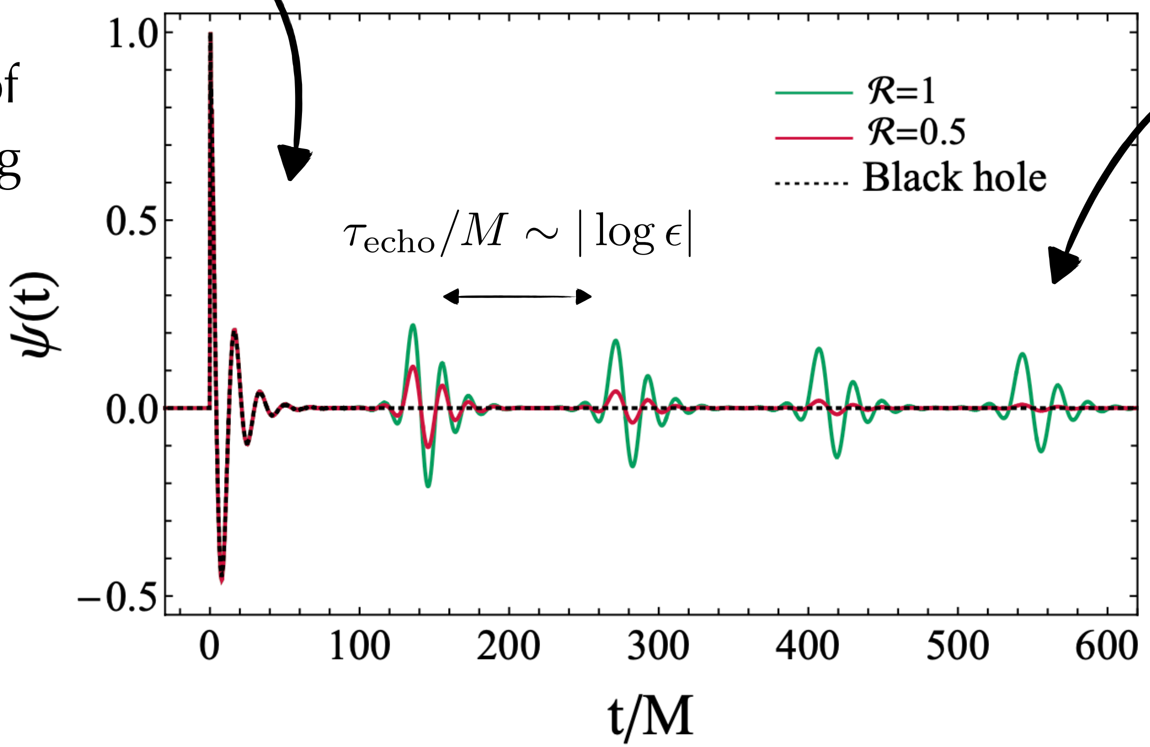
EM+, PRD **102**, 064053 (2020)



Ringdown of horizonless ultracompact objects

Same prompt ringdown

due to the excitation of the light ring



GW echoes

due to trapped modes

Cardoso+, PRL 116, 171101 (2016); EM+, Handbook for GW Astronomy, Springer (2021)

Matched-filtered searches for GW echoes

- Time-domain template based on standard GR templates with additional parameters: Abedi+, PRD 96 (2017) 082004; Nakano+, PTEP no. 7 071E01 (2017); Wang+, PRD 97 (2018) 124044

$$h(t) \equiv A \sum_{n=0}^{\infty} (-1)^{n+1} \gamma^n \mathcal{M}(t + t_{\rm merger} - t_{\rm echo} - n\Delta t_{\rm echo}, t_0)$$

- Time-domain template based on the superposition of sine Gaussians

  Maselli+, PRD 96 (2017) 064045

- Frequency-domain templates depending on the physical parameters of ECOs (radius and reflectivity): Mark+, PRD 96 (2017) 084002; Testa+, PRD 98 (2018) 044018; Maggio+, PRD 100 (2019) 064056

$$\tilde{Z}^{\infty}_{\rm ECO}(\omega) = \tilde{Z}^{\infty}_{\rm BH}(\omega) + \mathcal{K} \tilde{Z}^{\rm H}_{\rm BH}(\omega)$$

$\mathcal{K}$ ↓ Transfer function

Unmodelled searches for GW echoes

- Superposition of generalised wavelets adapted from burst searches

  Tsang+, PRD 98 (2018) 024023; Tsang+, PRD 101 (2020) 064012

- Searches with Fourier windows using the fact that GW echoes should pile up at specific frequencies

  Conklin+, PRD 98 (2018) 044021; Conklin+, PRD 100 (2019) 124030

- Coherent wave burst pipeline

  Miani+, arXiv: 2302.12158 (2023)

Searches for GW echoes

- A tentative evidence for echoes in GWTC-1 data has been reported

  Abedi+, PRD 96, 082004 (2017); Conklin+, PRD 98, 044021 (2018); Abedi+, JCAP 11, 010 (2019)

- Independent searches argued that the statistical significance of echoes is consistent with noise

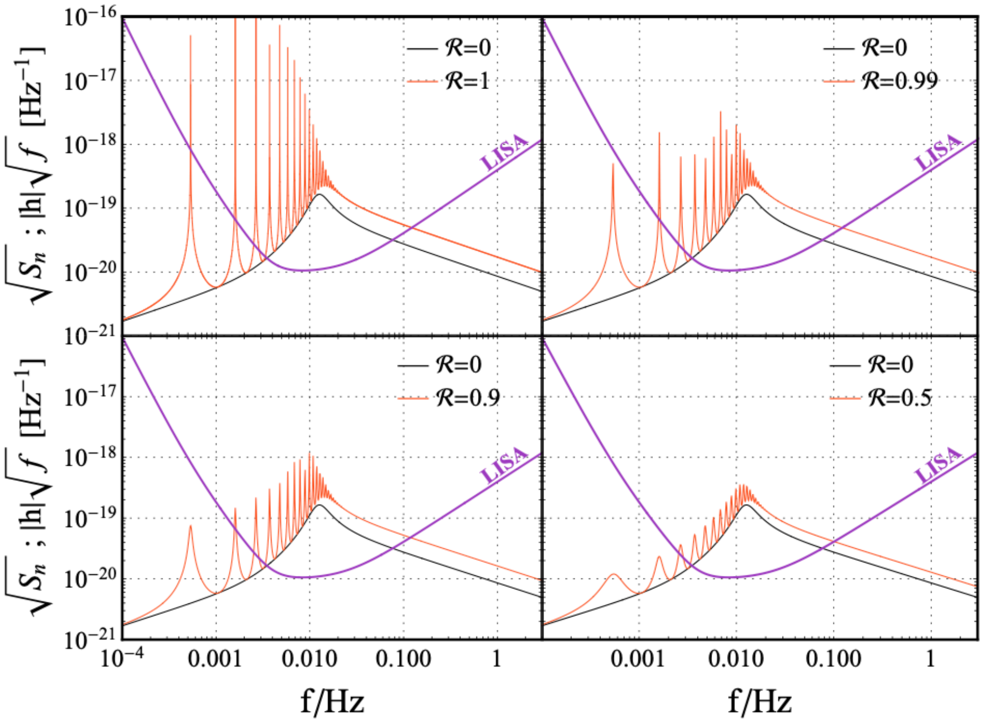
  Westerweck+, PRD 97, 124037 (2018); Nielsen+, PRD 99, 104012 (2019); Uchikata+, PRD 100, 062006 (2019); Lo+, PRD 99, 084052 (2019); Tsang+, PRD 101, 064012 (2020)

- No evidence for echoes in GWTC-2 and GWTC-3 data

  Abbott+, PRD 103 (2021) 12, 122002; Abbott+, arXiv:2112.06861 (2021)

Prospects with LISA

In the frequency domain, **low-frequency resonances** are excited at the QNMs of the horizonless compact object.



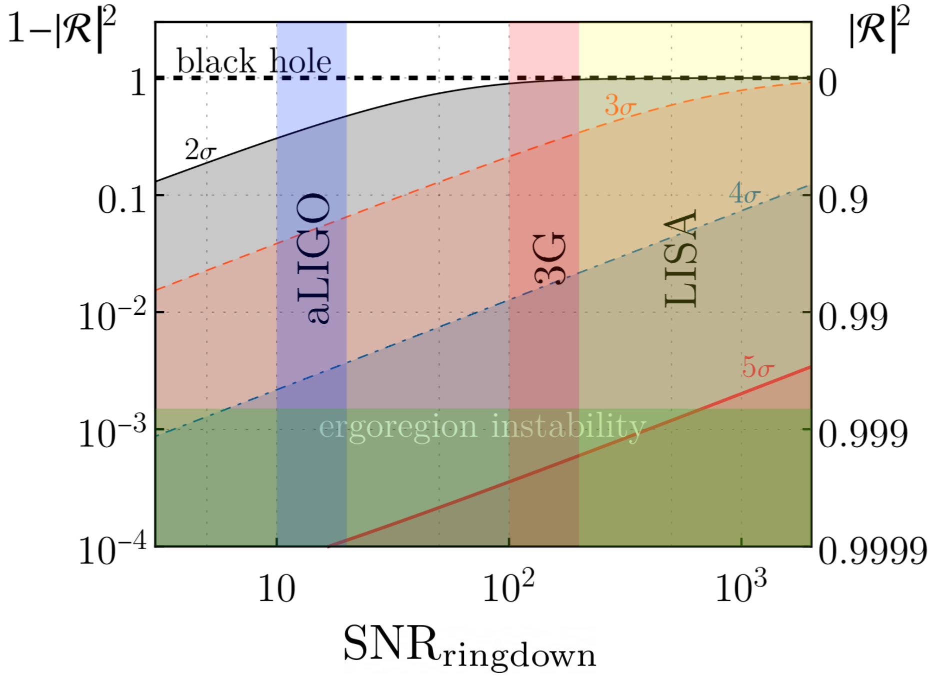
$M = 10^6 M_\odot$
$D = 100$ Gpc

The detectability of GW echoes depends on the reflectivity of the ECO.

Testa+, PRD 98, 044018 (2018)

Prospects with LISA

With a Fisher analysis we can assess the **detectability of the reflectivity** of compact objects as a function of the signal-to-noise ratio in the ringdown.



EM+ PRD 100, 064056 (2019)

Excluding or detecting echoes for models with $|\mathcal{R}|^2 < 1$ requires:

$$\mathrm{SNR_{ringdown}} \gtrsim 100$$

which will be achieved by LISA.

WP science goals

Waveforms:

- Numerical relativity simulations of ECO coalescences
- EOB/Phenom-like inspiral-merger-ringdown waveforms for ECO mergers
- Accurate waveforms in general relativity (systematics)

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Outputs:

- Data-analysis pipeline yielding Bayes factors for the hypotheses of deviation from GR, environmental effects, near-horizon physics
- Estimation of the corresponding parameters based on individual or stacked sources
- Framework to translate parametrized constraints to specific beyond GR theories/models

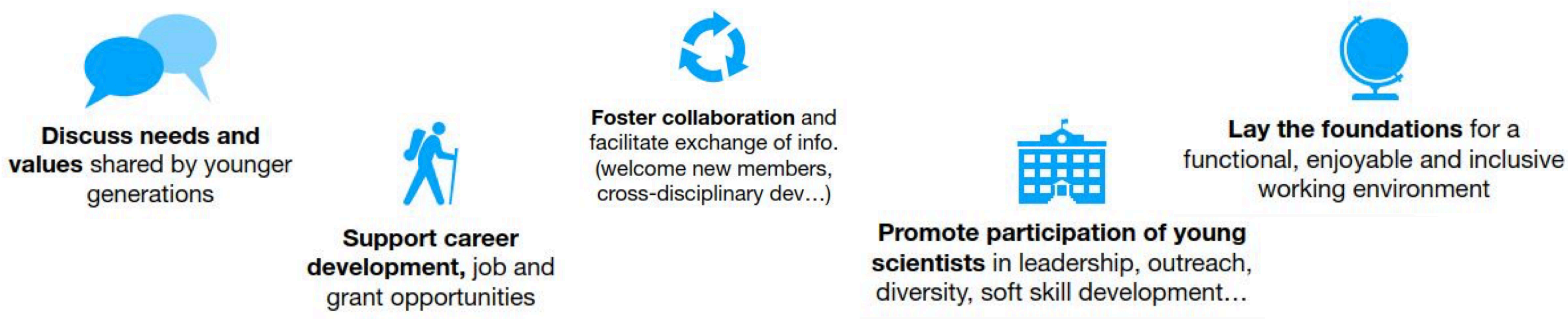
Conclusions

- We can look for new physics at the horizon scale with LISA.
- EMRIs and massive binaries are promising sources to test general relativity.
- EMRIs around an ECO: tidal deformability, tidal heating, resonances, chaos.
- Ringdown tests: spectroscopy, QNM doublet, GW echoes.

LISA Early Career Scientists (LECS) working group

LECS working group

Scope of the group:



Chairs: Elisa Maggio, Martina Muratore, Michael Katz

The chairs are elected democratically by the group:

- for a 2 year long mandate
- via online elections
- diversity rule applies (career, gender)
- new elections will be in October 2023!

Mentorship program

The mentorship program aims to provide help and guidance for junior LISA scientists at the beginning of their careers.

The **objectives** are:

- Provide personal mentorship for junior LISA scientists
- Connect and provide a support network for junior scientists
- Create a generally open and inclusive environment

Mentors are willing to share their career path and expertise, and discuss non-academic topics such as challenges in academia, work/life balance.

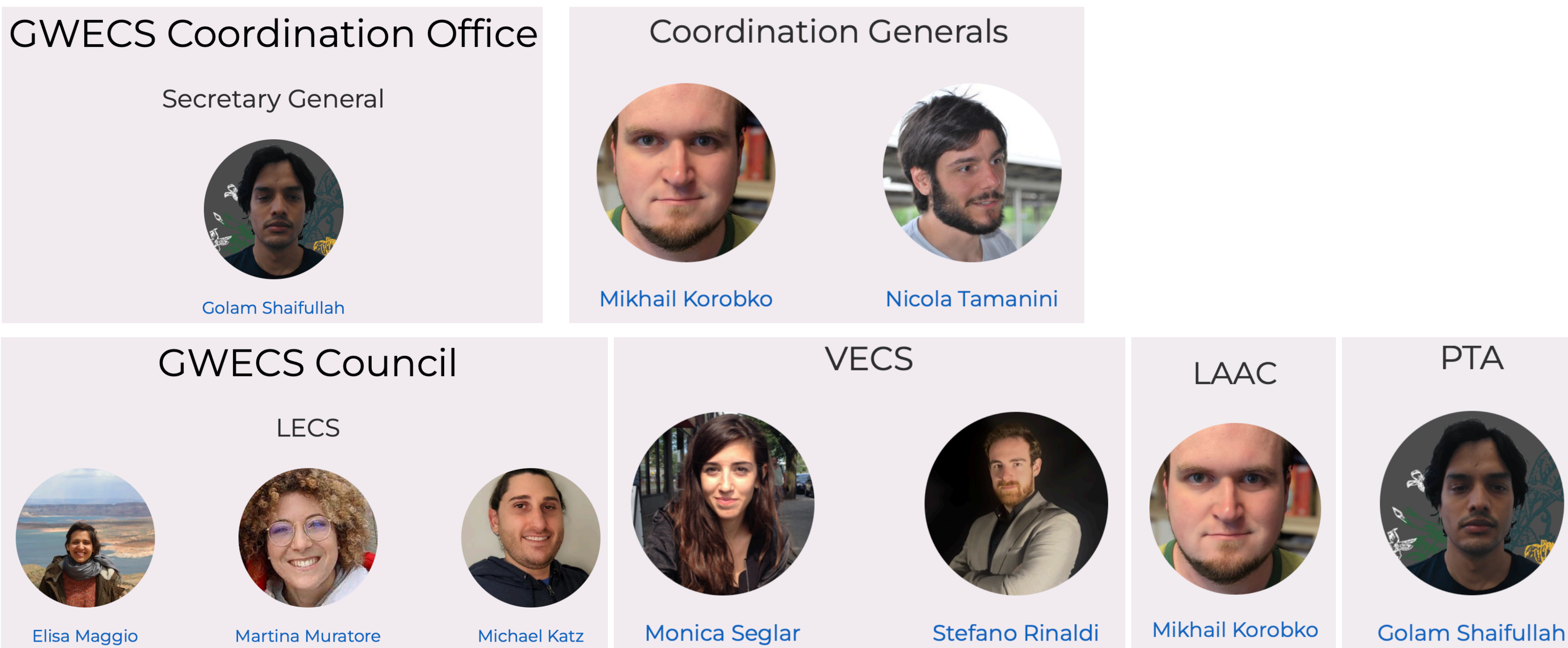
To sign up as a mentee: https://forms.gle/bQckjGSDFe84CuVXA
To sign up as a mentor: https://forms.gle/BPQqLq4Xe9BQmuLk9

By September 8th!

GWECS

www.gwecs.org

The gravitational wave early career scientists (GWECS) organisation is designed to unite and coordinate different communities of early career scientists working on GWs.



GWECS Offices

Well being & mental health
Career opportunities
Science & research
Media & outreach

DEI & social welfare
Education & skill development
Funding & sustainability
Tech support & membership management

- **Well-being and mental health talks**

  A series of talks dedicated to PhDs and Postdocs in the academic field, covering topics such as preventing burnout, improving resilience at work or healthy leadership.

- **Job fairs in Fall**
  - We collect job offers
  - Each recruiter has the chance to talk about their group and available positions
  - The early career scientists have the chance to introduce themselves

- **Shared resources**

  We maintain 2 spreadsheets about **Fellowships for ECSs** and **LISA Host Institutes**.

How to join LECS

The LECS group is open to any full or associate LISA member who consider themselves an early career scientist.

If you would like to become a member, please contact the LECS chairs: lecs-chairs@lisamission.org

Early career scientists are invited to subscribe to the GWECS mailing list in www.gwecs.org to receive news.