Title: How does a dark compact object ringdown?

Speakers: Elisa Maggio

Series: Strong Gravity

Date: October 01, 2020 - 1:00 PM

URL: http://pirsa.org/20100005

Abstract: Gravitational waves from the coalescence of compact binaries provide a unique opportunity to test gravity in strong field regime. In particular, the postmerger phase of the gravitational signal is a proxy for the nature of the remnant.

This is of particular interest in view of some quantum-gravity models which predict the existence of horizonless dark compact objects that overcome the paradoxes associated to black holes. Such dark compact objects can emit a modified ringdown with respect to the black hole case and late-time gravitational wave echoes as characteristic fingerprints.

In this talk, I develop a generic framework to the study of the ringdown of dark compact objects and provide a gravitational-wave template for the echo signal. Finally, I assess the detectability of dark compact objects with current and future gravitational-wave detectors.

Strong Gravity Seminar @Perimeter Institute
October 1st, 2020

How does a dark compact object ringdown?

Elisa Maggio
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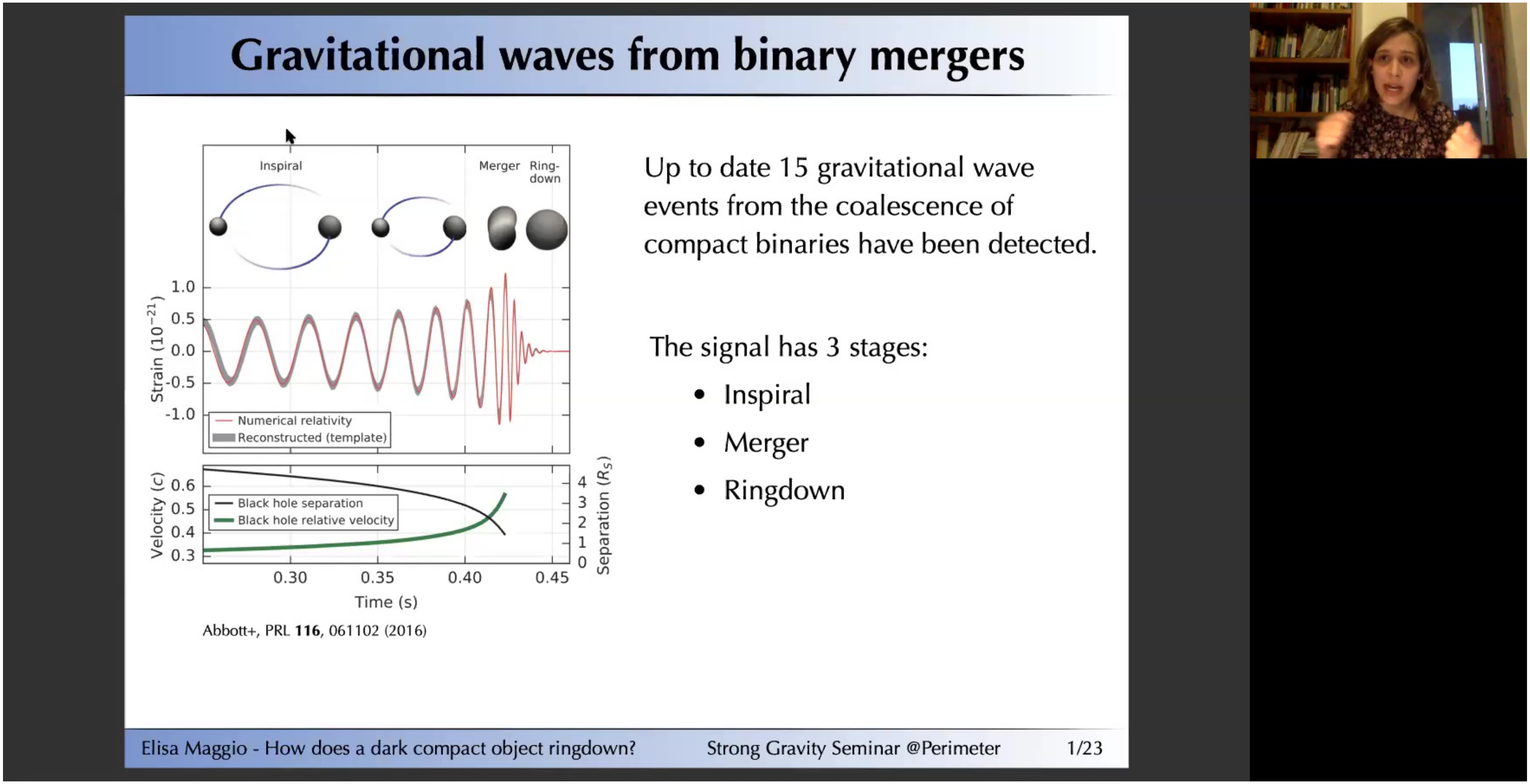


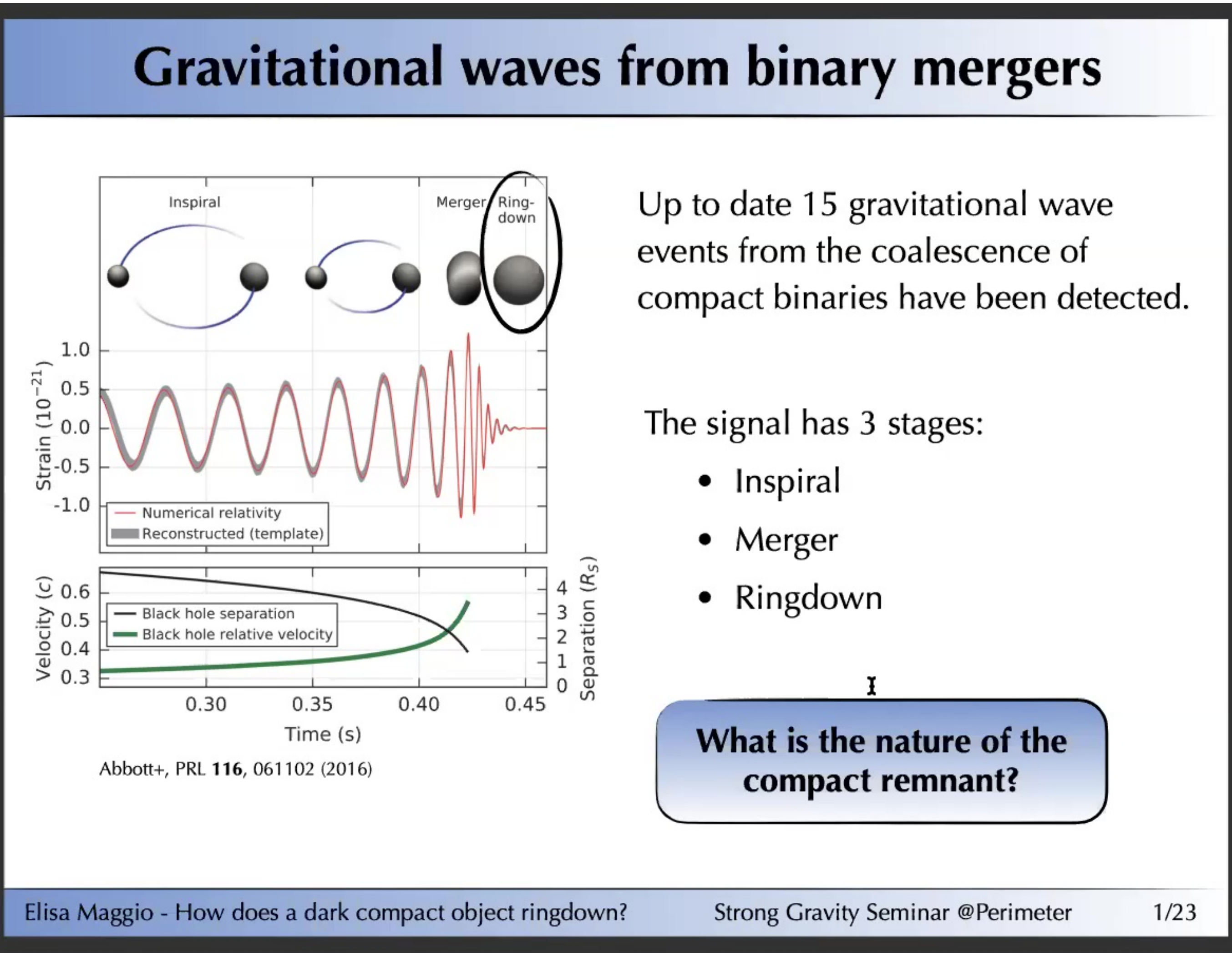
Gravitational waves from binary mergers

Abbott+, PRL **116**, 061102 (2016)

Up to date 15 gravitational wave events from the coalescence of compact binaries have been detected.

The signal has 3 stages:

- Inspiral
- Merger
- Ringdown



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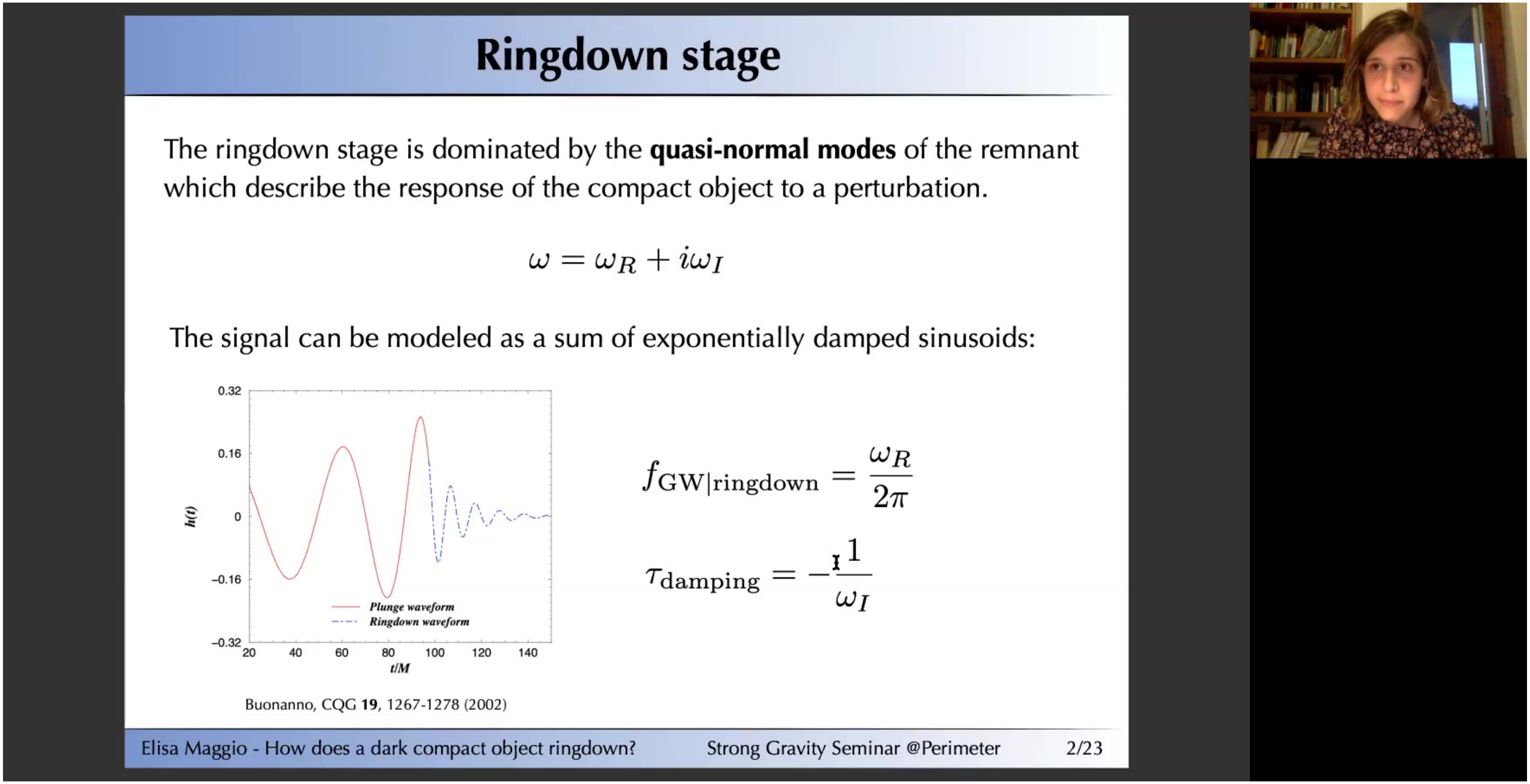
What is the nature of the compact remnant?



Ringdown stage

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

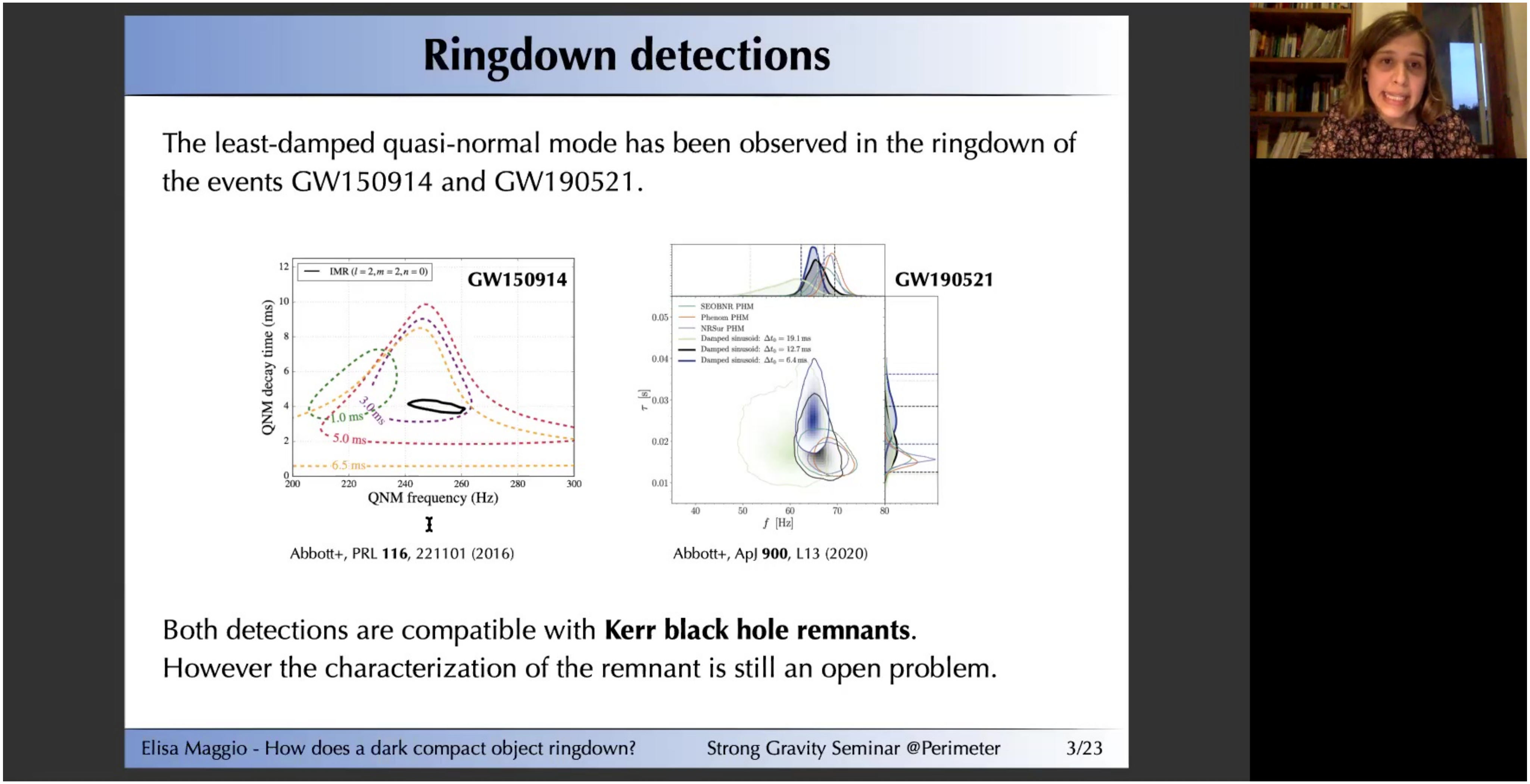
$$\omega = \omega_R + i\omega_I$$

The signal can be modeled as a sum of exponentially damped sinusoids:

$$f_{\mathrm{GW|ringdown}} = \frac{\omega_R}{2\pi}$$

$$\tau_{\mathrm{damping}} = -\frac{1}{\omega_I}$$

Buonanno, CQG **19**, 1267-1278 (2002)



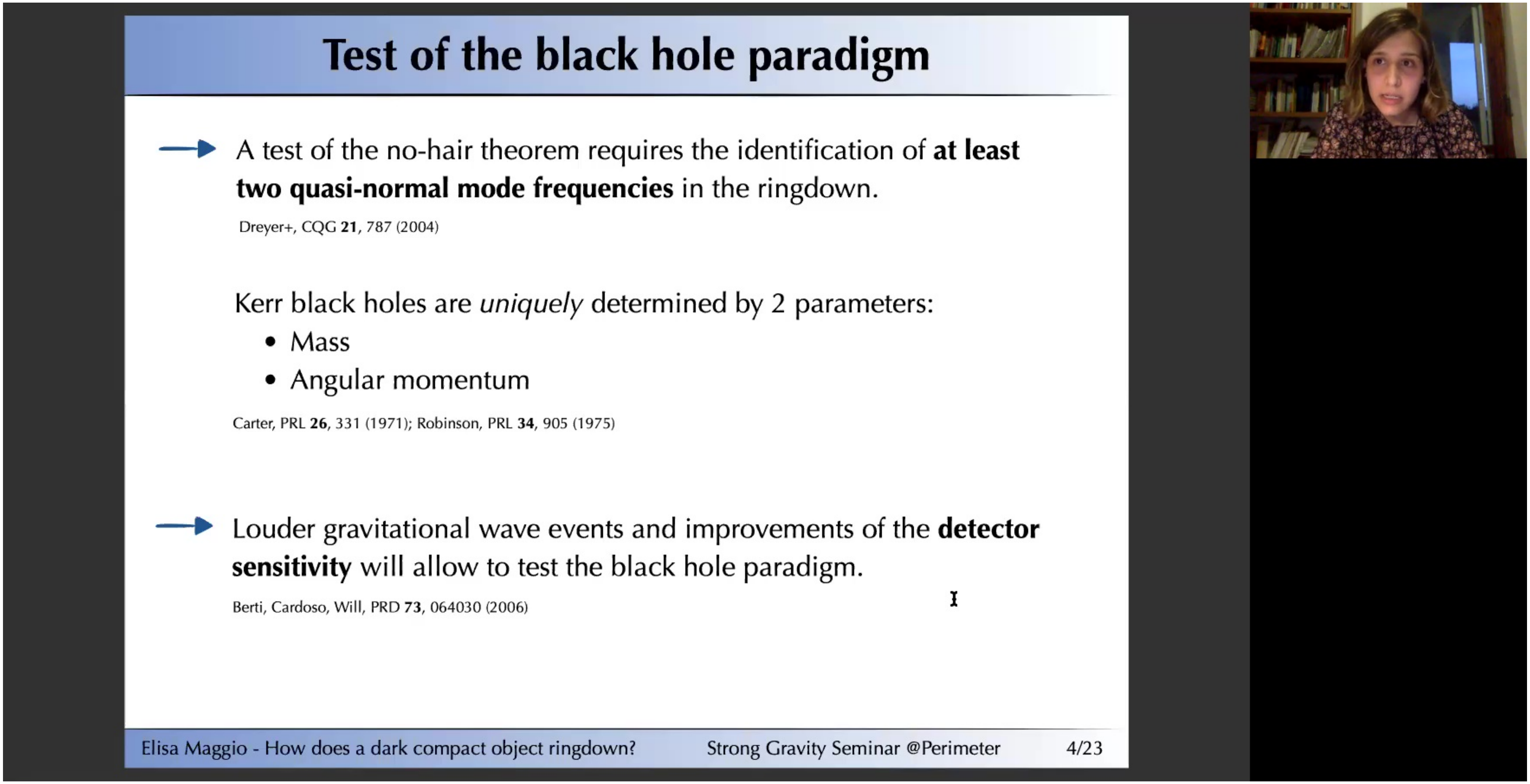
Ringdown detections

The least-damped quasi-normal mode has been observed in the ringdown of the events GW150914 and GW190521.

Abbott+, PRL **116**, 221101 (2016)

Abbott+, ApJ **900**, L13 (2020)

Both detections are compatible with **Kerr black hole remnants**.
However the characterization of the remnant is still an open problem.



Test of the black hole paradigm

- A test of the no-hair theorem requires the identification of **at least two quasi-normal mode frequencies** in the ringdown.

Dreyer+, CQG **21**, 787 (2004)

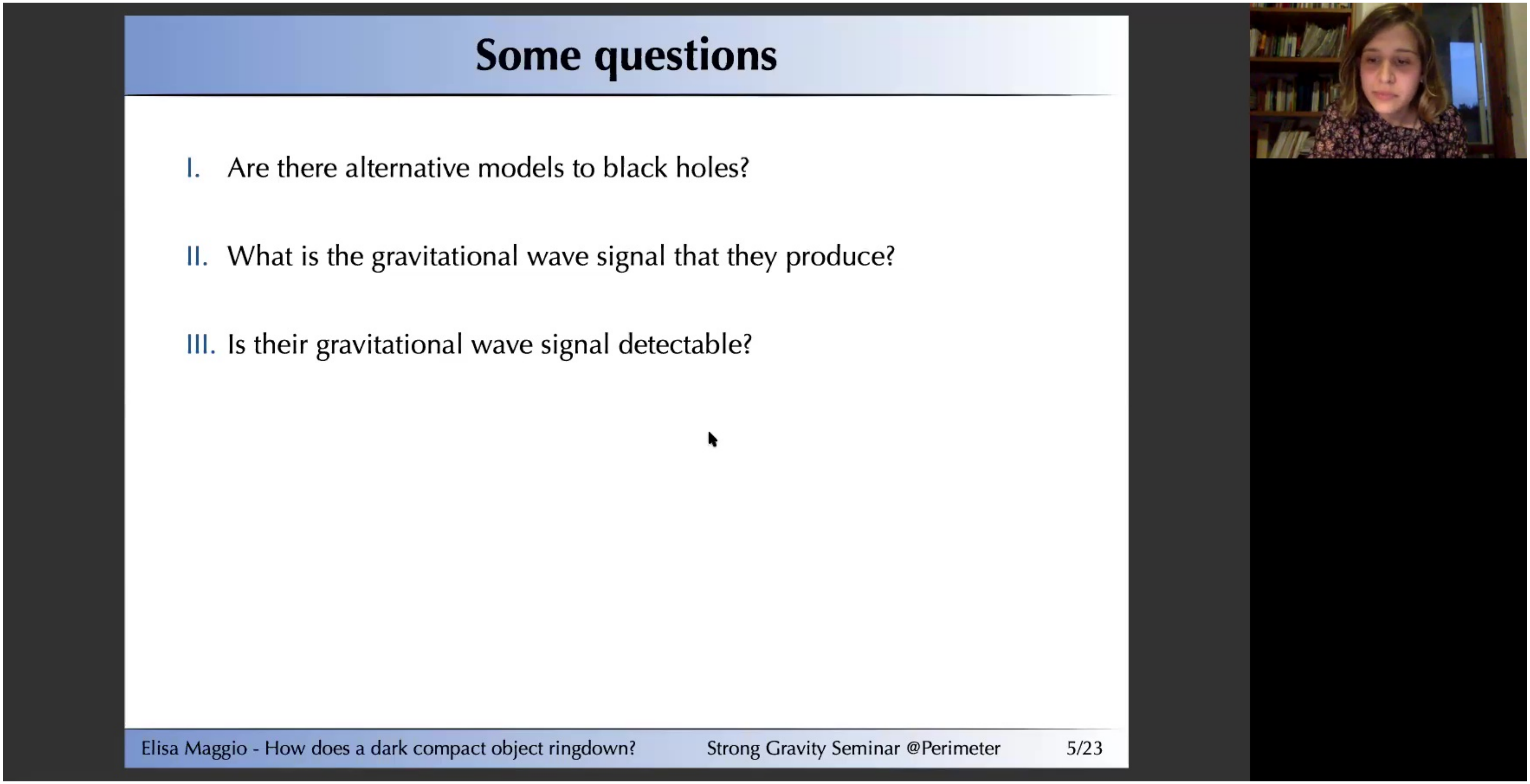
Kerr black holes are *uniquely* determined by 2 parameters:

- Mass
- Angular momentum

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

- Louder gravitational wave events and improvements of the **detector sensitivity** will allow to test the black hole paradigm.

Berti, Cardoso, Will, PRD **73**, 064030 (2006)

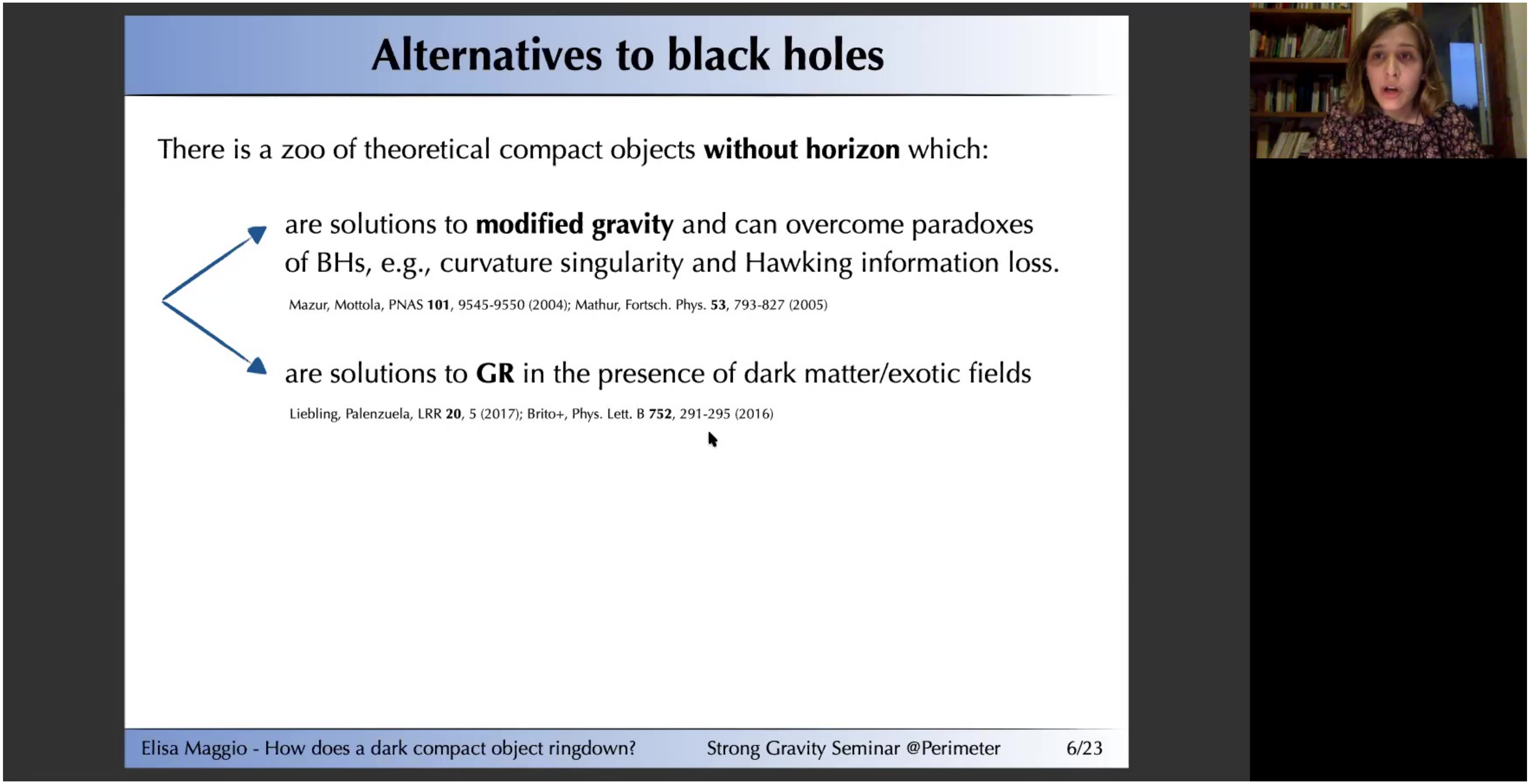


Some questions

I. Are there alternative models to black holes?

II. What is the gravitational wave signal that they produce?

III. Is their gravitational wave signal detectable?



Alternatives to black holes

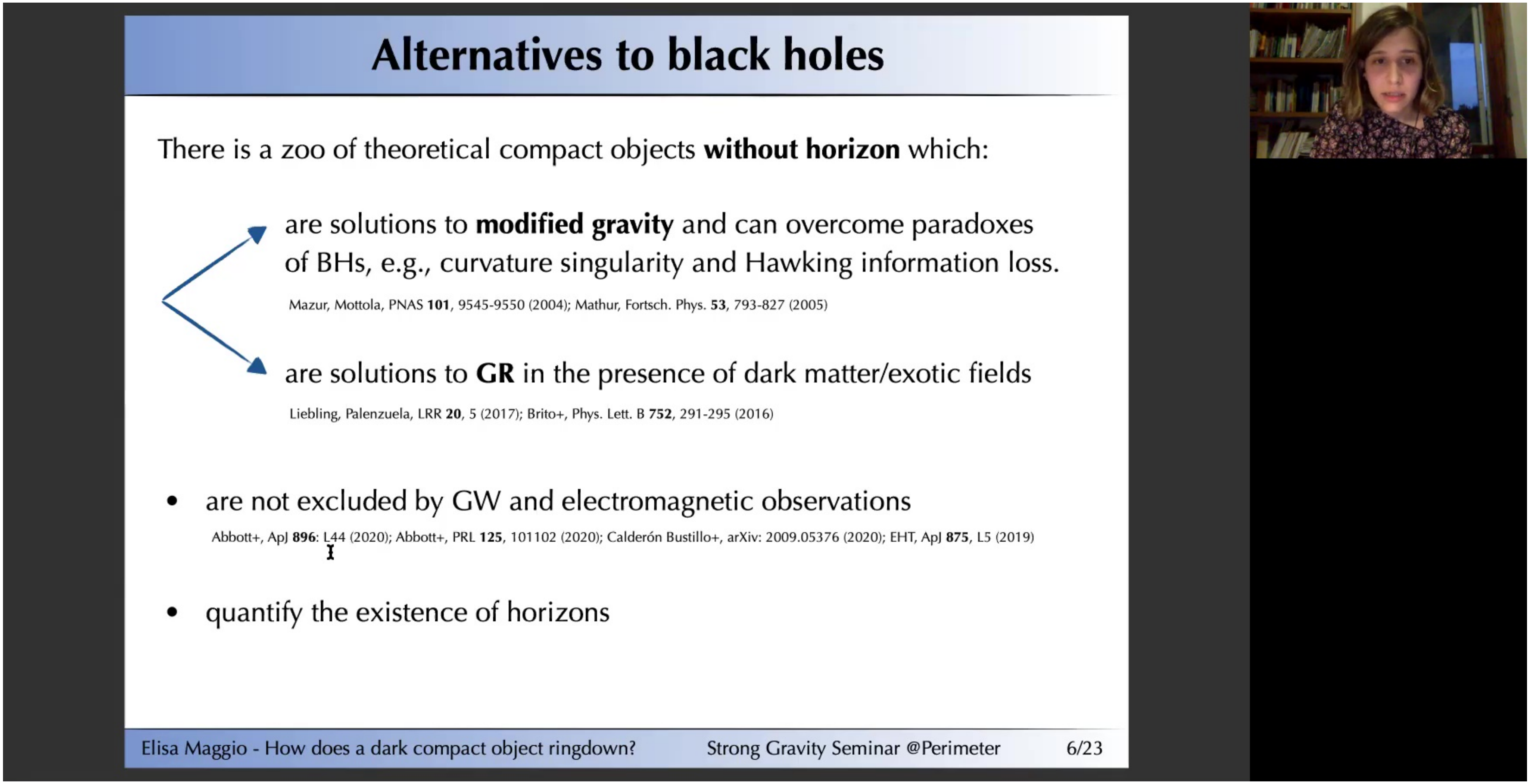
There is a zoo of theoretical compact objects **without horizon** which:

- are solutions to **modified gravity** and can overcome paradoxes of BHs, e.g., curvature singularity and Hawking information loss.

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

- are solutions to **GR** in the presence of dark matter/exotic fields

  Liebling, Palenzuela, LRR **20**, 5 (2017); Brito+, Phys. Lett. B **752**, 291-295 (2016)



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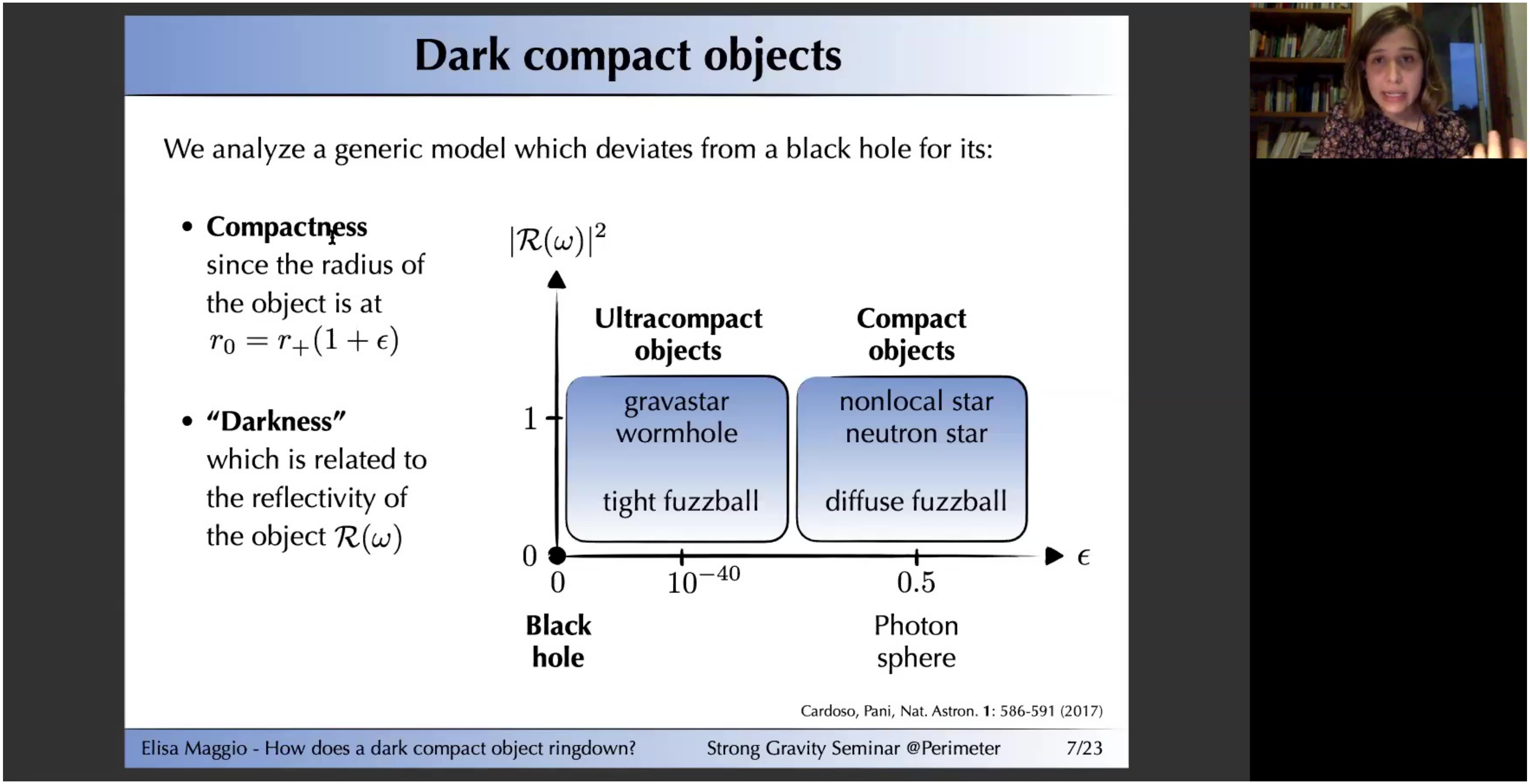
- are solutions to **GR** in the presence of dark matter/exotic fields

  Liebling, Palenzuela, LRR **20**, 5 (2017); Brito+, Phys. Lett. B **752**, 291-295 (2016)

- are not excluded by GW and electromagnetic observations

  Abbott+, ApJ **896**: L44 (2020); Abbott+, PRL **125**, 101102 (2020); Calderón Bustillo+, arXiv: 2009.05376 (2020); EHT, ApJ **875**, L5 (2019)

- quantify the existence of horizons

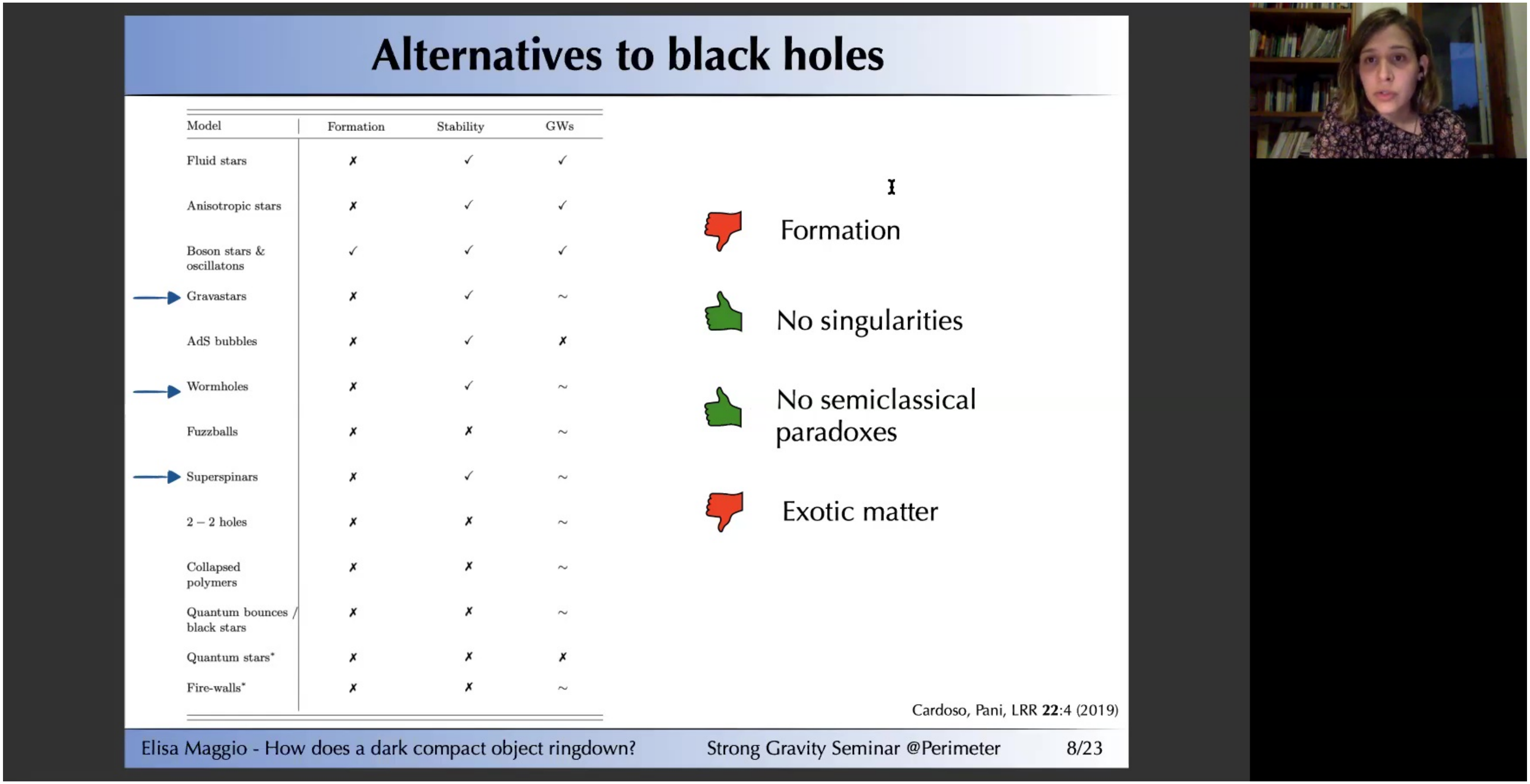


Dark compact objects

We analyze a generic model which deviates from a black hole for its:

- **Compactness** since the radius of the object is at $r_0 = r_+(1+\epsilon)$
- **“Darkness”** which is related to the reflectivity of the object $\mathcal{R}(\omega)$

Cardoso, Pani, Nat. Astron. **1**: 586-591 (2017)

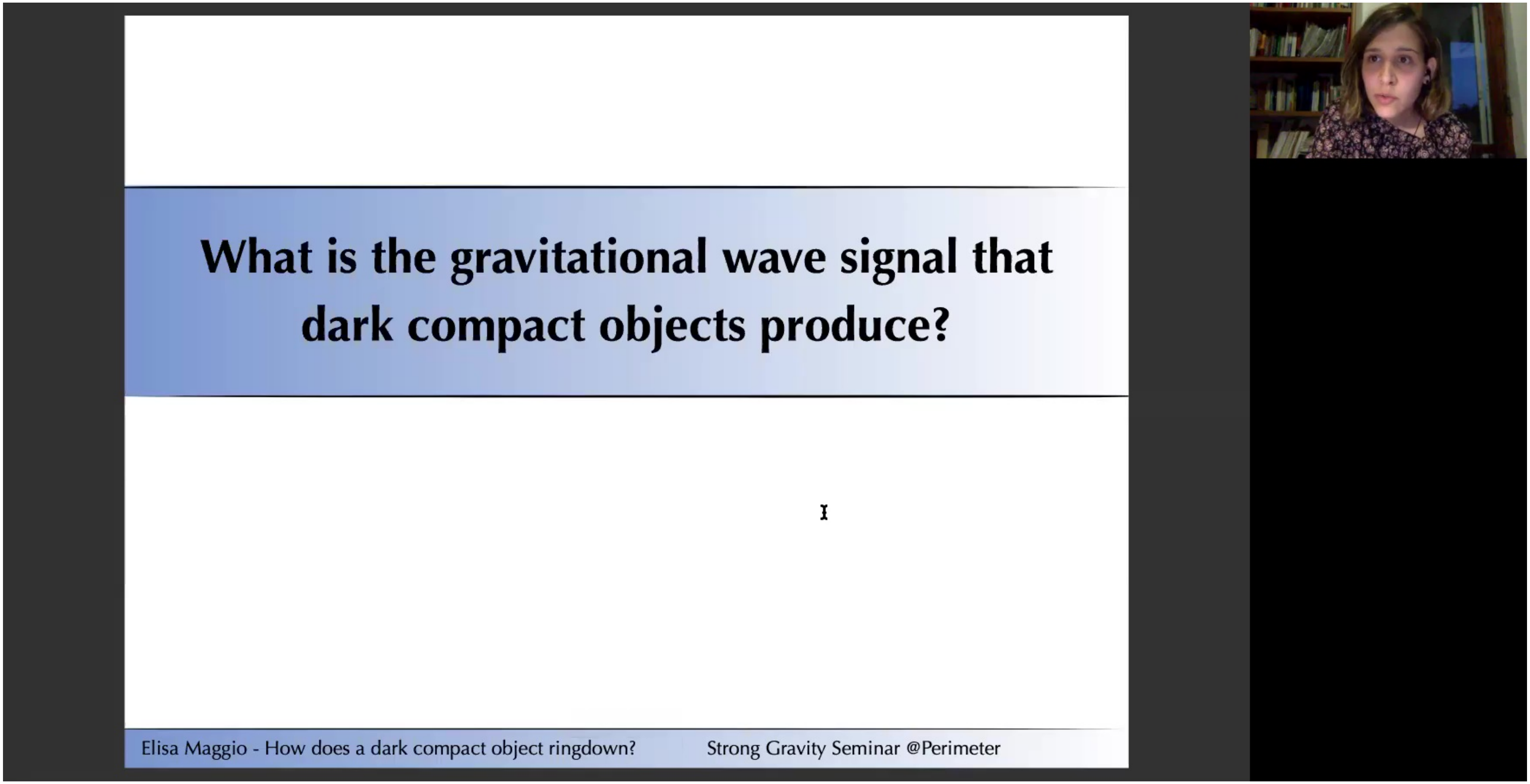


Alternatives to black holes

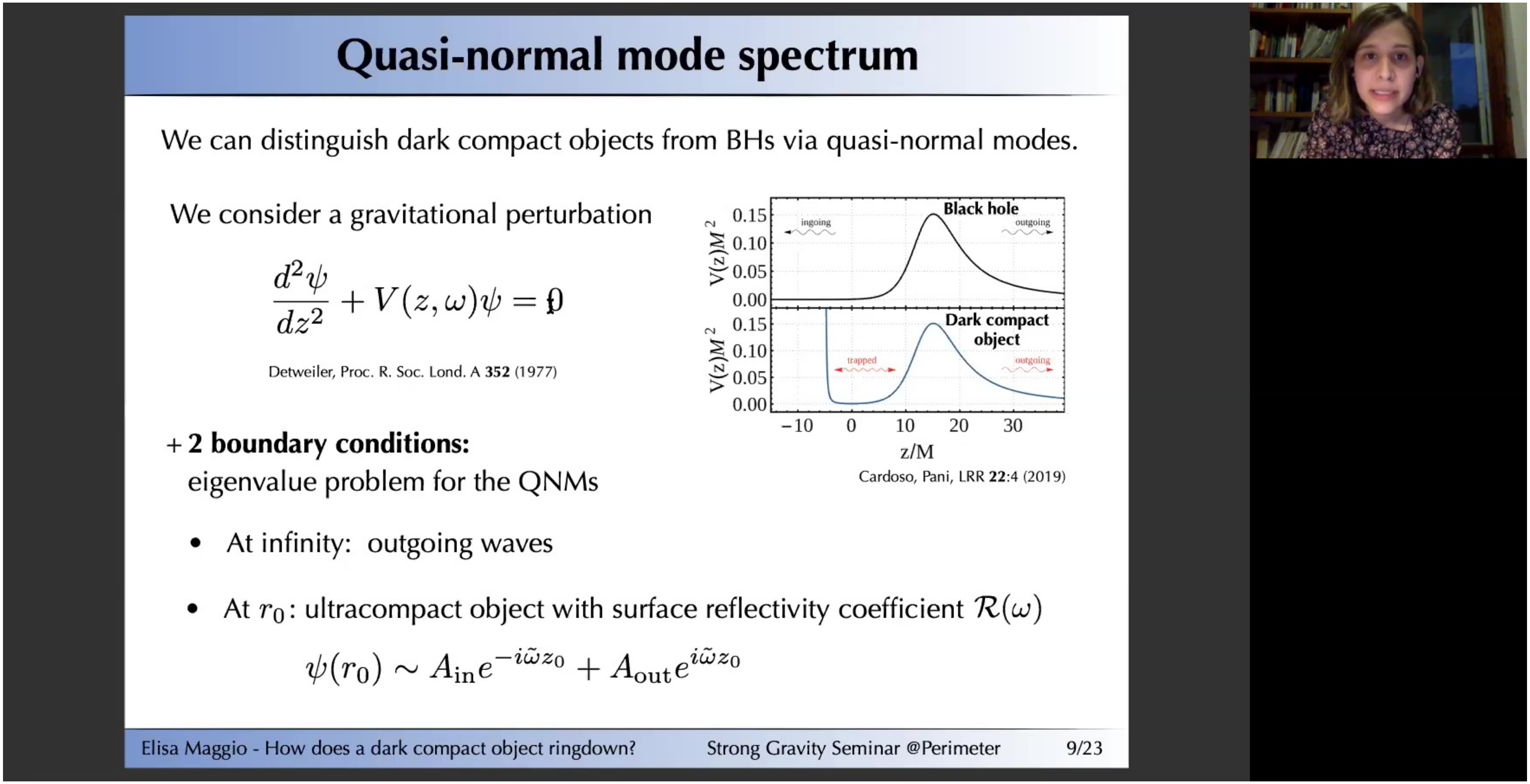
Model	Formation	Stability	GWs
Fluid stars	✗	✓	✓
Anisotropic stars	✗	✓	✓
Boson stars & oscillatons	✓	✓	✓
→ Gravastars	✗	✓	~
AdS bubbles	✗	✓	✗
→ Wormholes	✗	✓	~
Fuzzballs	✗	✗	~
→ Superspinars	✗	✓	~
$2-2$ holes	✗	✗	~
Collapsed polymers	✗	✗	~
Quantum bounces / black stars	✗	✗	~
Quantum stars*	✗	✗	✗
Fire-walls*	✗	✗	~

- 👎 Formation
- 👍 No singularities
- 👍 No semiclassical paradoxes
- 👎 Exotic matter

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



What is the gravitational wave signal that dark compact objects produce?



Quasi-normal mode spectrum

We can distinguish dark compact objects from BHs via quasi-normal modes.

We consider a gravitational perturbation

$$\frac{d^2\psi}{dz^2} + V(z,\omega)\psi = 0$$

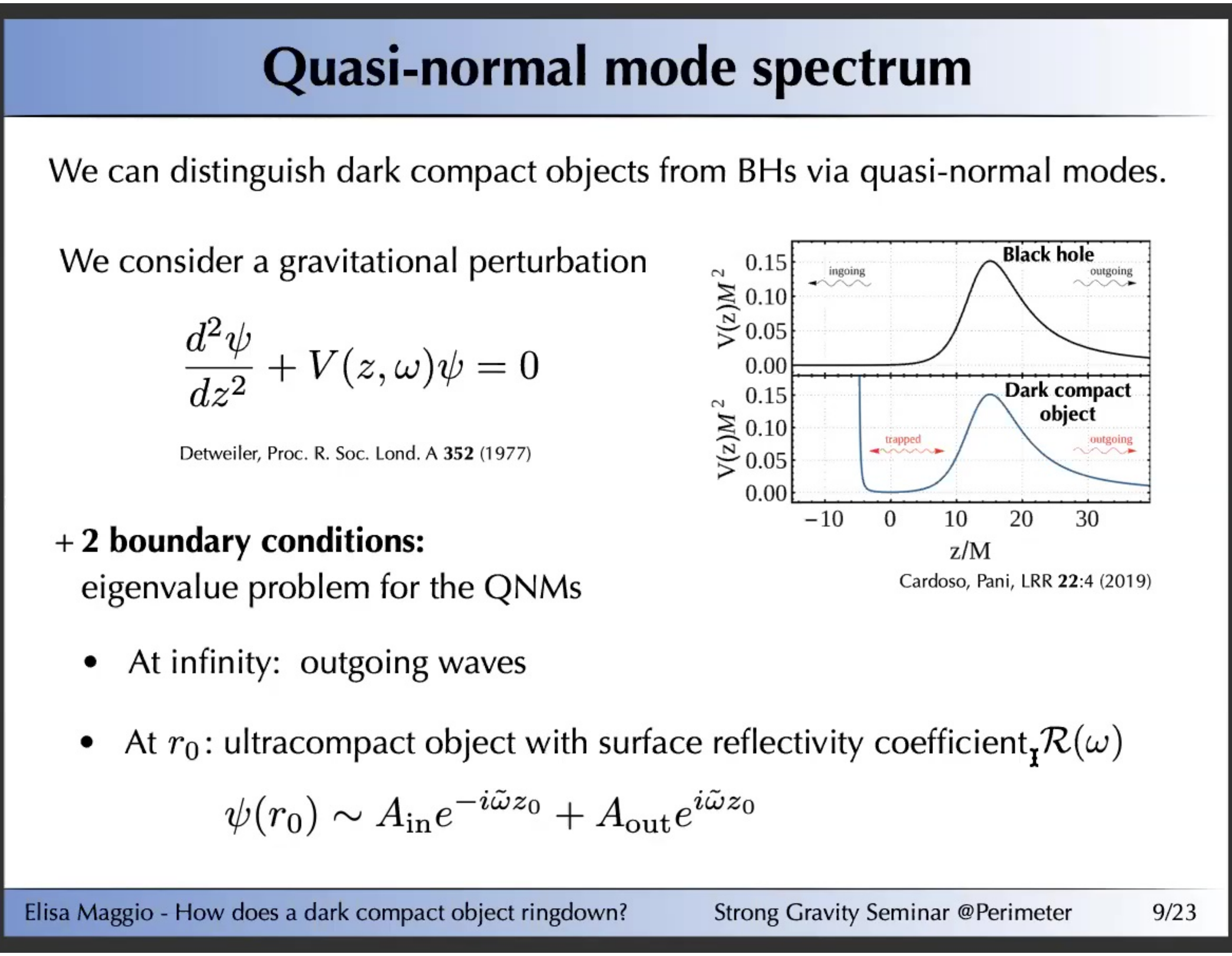
Detweiler, Proc. R. Soc. Lond. A **352** (1977)

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

+ **2 boundary conditions:**
eigenvalue problem for the QNMs

- At infinity: outgoing waves
- At r_0: ultracompact object with surface reflectivity coefficient $\mathcal{R}(\omega)$

$$\psi(r_0) \sim A_{\rm in} e^{-i\tilde{\omega} z_0} + A_{\rm out} e^{i\tilde{\omega} z_0}$$



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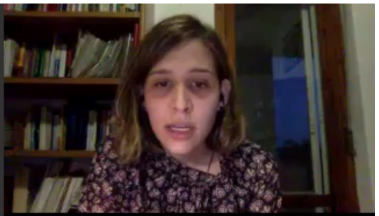
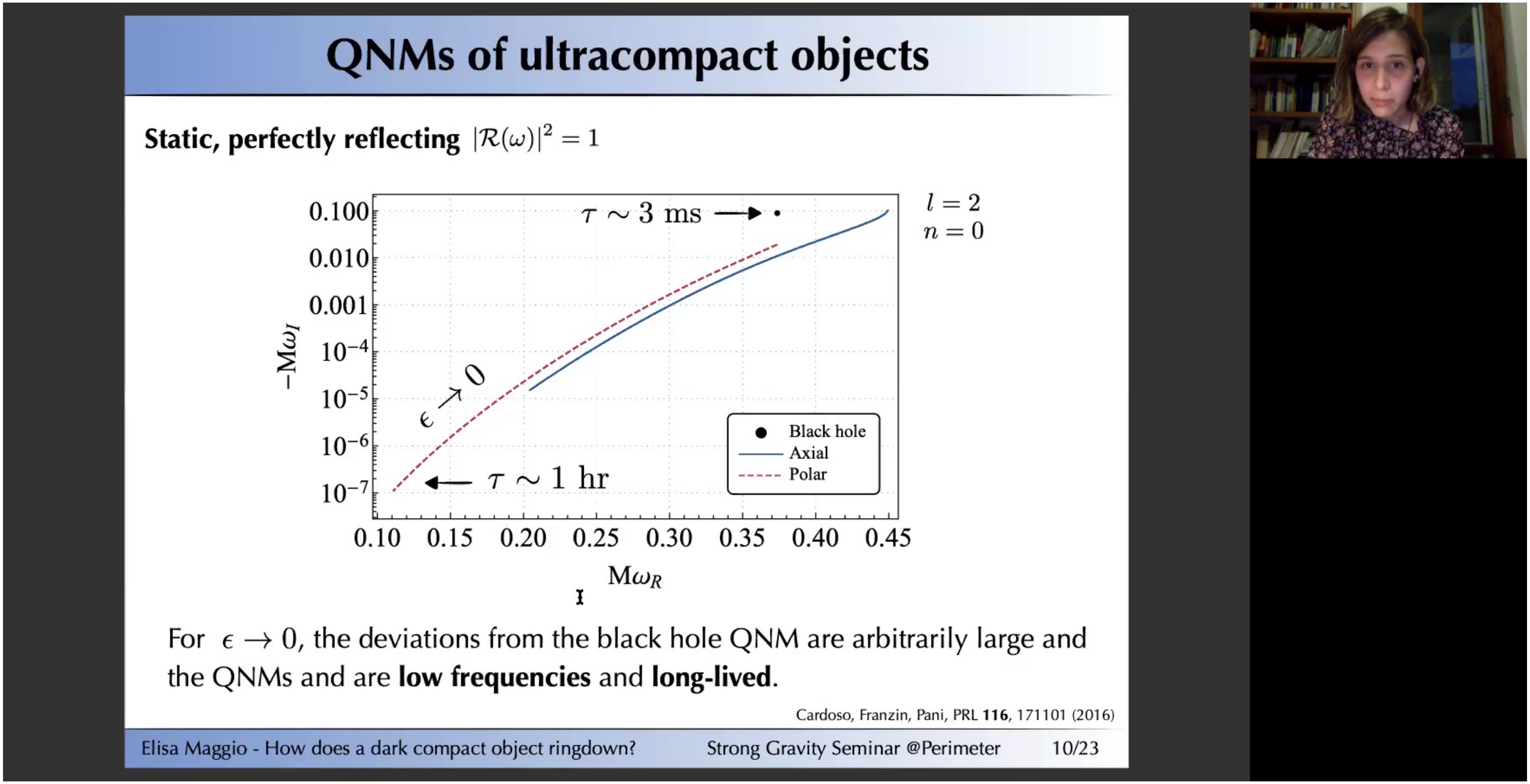


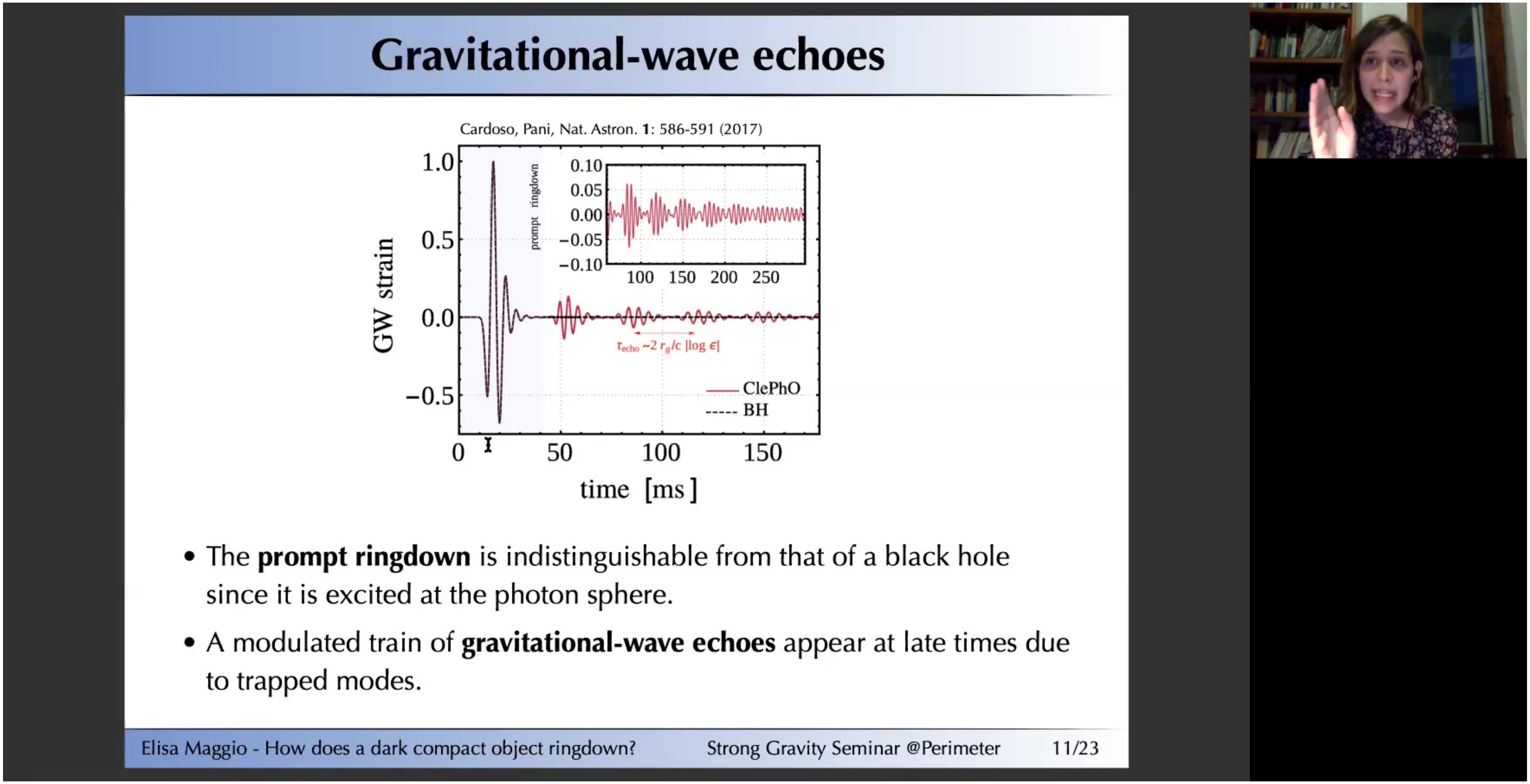


QNMs of ultracompact objects

Static, perfectly reflecting $|\mathcal{R}(\omega)|^2 = 1$

For $\epsilon \to 0$, the deviations from the black hole QNM are arbitrarily large and the QNMs and are **low frequencies** and **long-lived**.

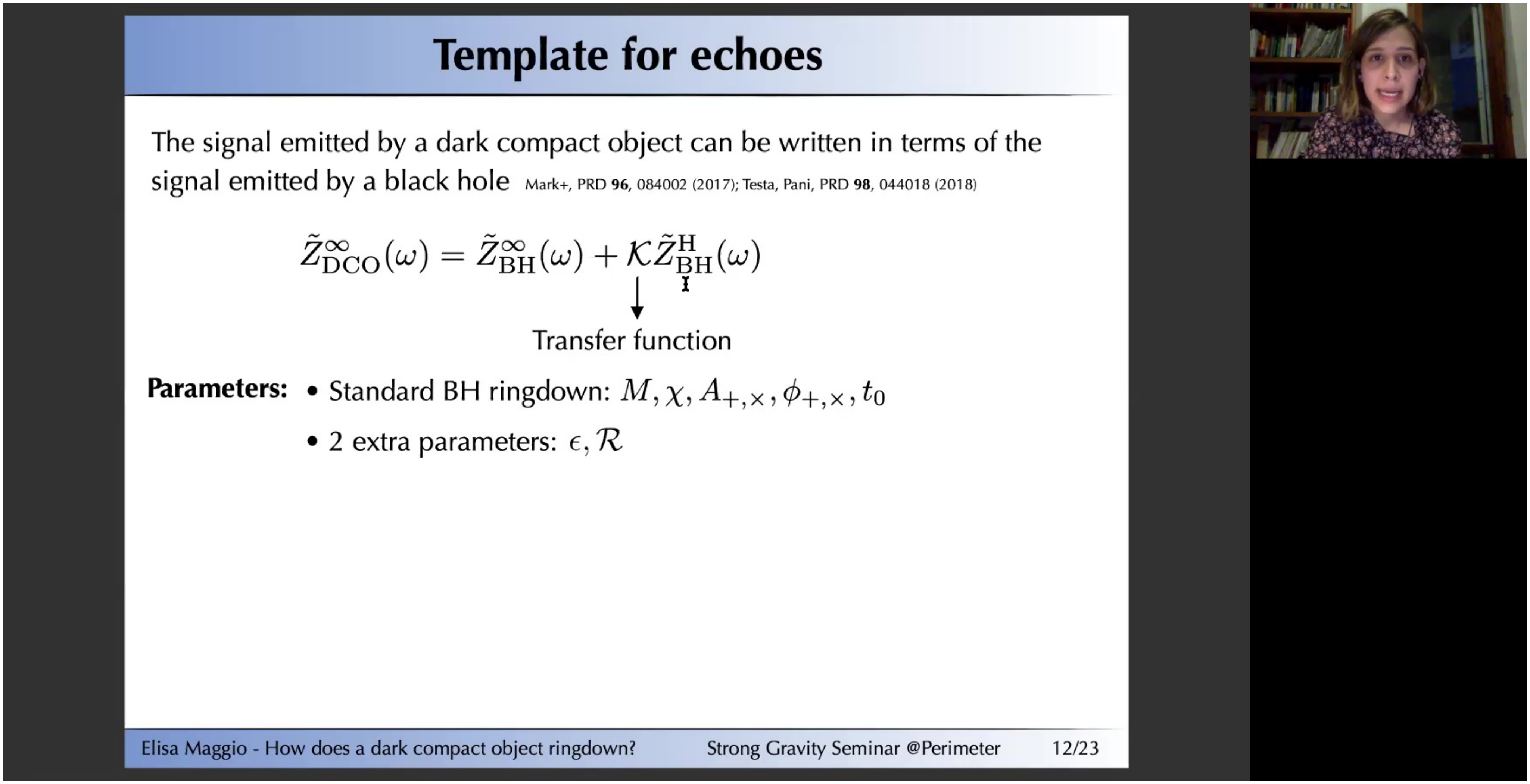
Cardoso, Franzin, Pani, PRL **116**, 171101 (2016)



Gravitational-wave echoes

Cardoso, Pani, Nat. Astron. **1**: 586-591 (2017)

- The **prompt ringdown** is indistinguishable from that of a black hole since it is excited at the photon sphere.
- A modulated train of **gravitational-wave echoes** appear at late times due to trapped modes.

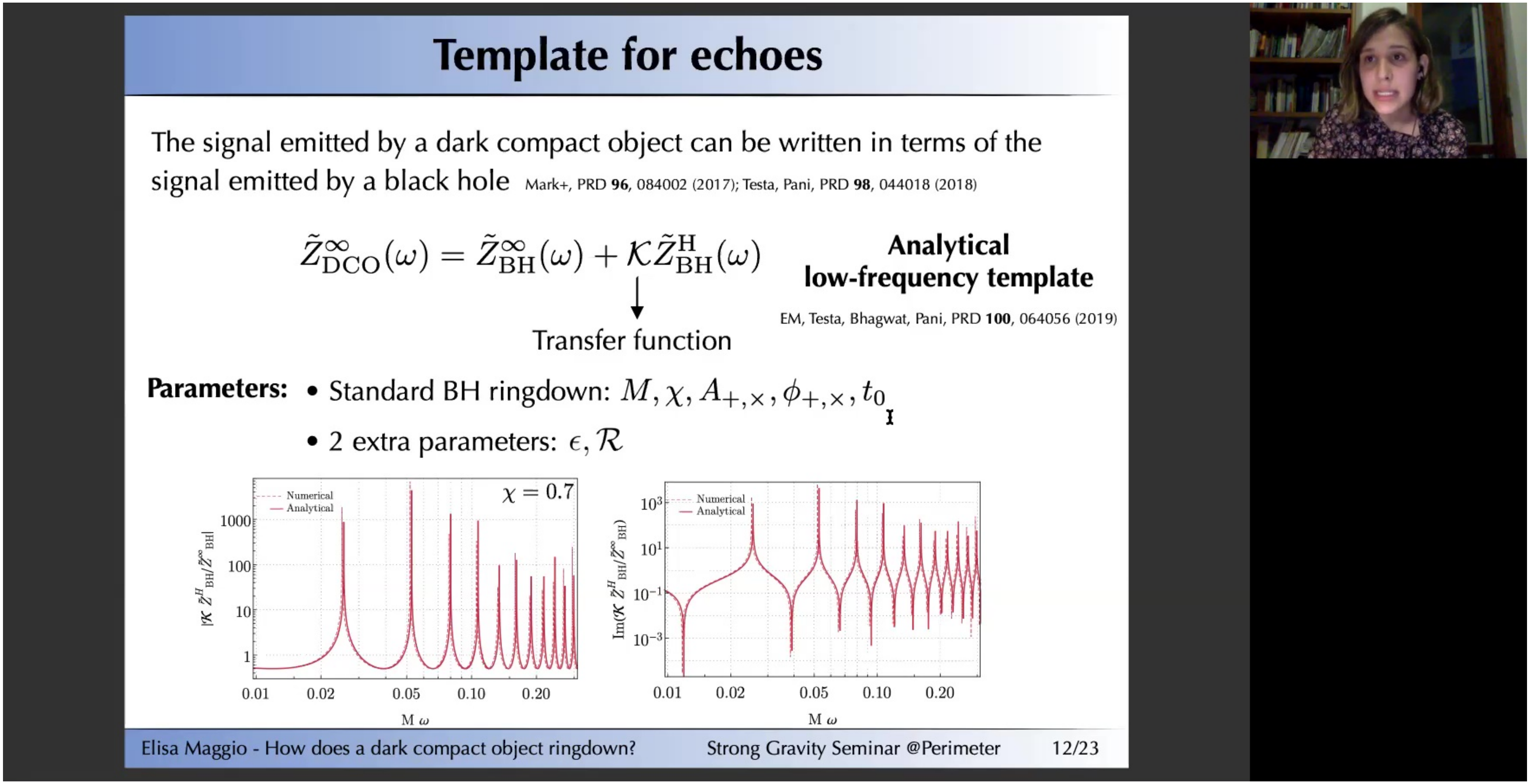


Template for echoes

The signal emitted by a dark compact object can be written in terms of the signal emitted by a black hole Mark+, PRD **96**, 084002 (2017); Testa, Pani, PRD **98**, 044018 (2018)

$$\tilde{Z}^{\infty}_{\rm DCO}(\omega) = \tilde{Z}^{\infty}_{\rm BH}(\omega) + \underset{\substack{\downarrow \\ \text{Transfer function}}}{\mathcal{K}}\tilde{Z}^{\rm H}_{\rm BH}(\omega)$$

Parameters:
- Standard BH ringdown: $M, \chi, A_{+,\times}, \phi_{+,\times}, t_0$
- 2 extra parameters: $\epsilon, \mathcal{R}$



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Analytical low-frequency template

EM, Testa, Bhagwat, Pani, PRD **100**, 064056 (2019)

Parameters:
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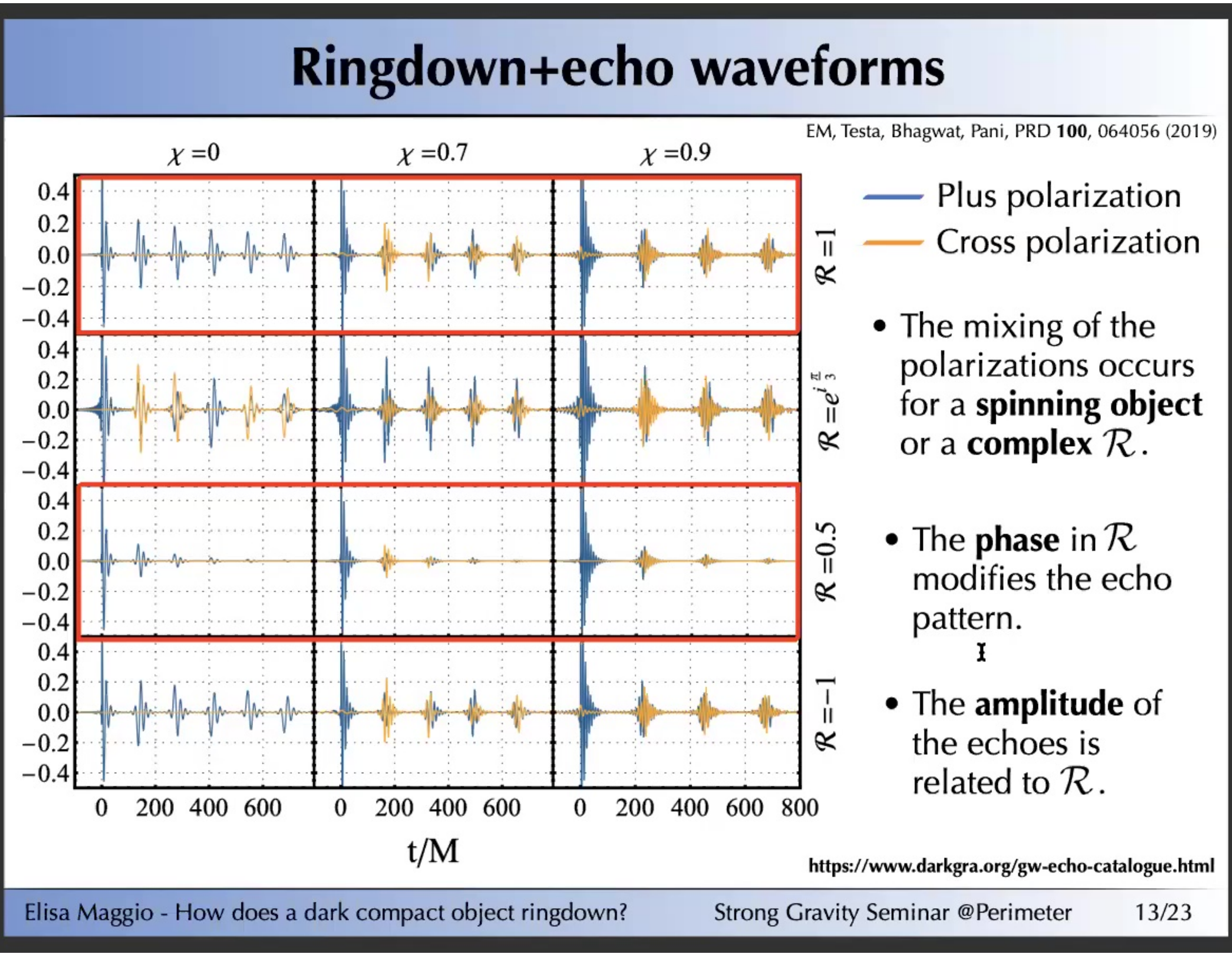
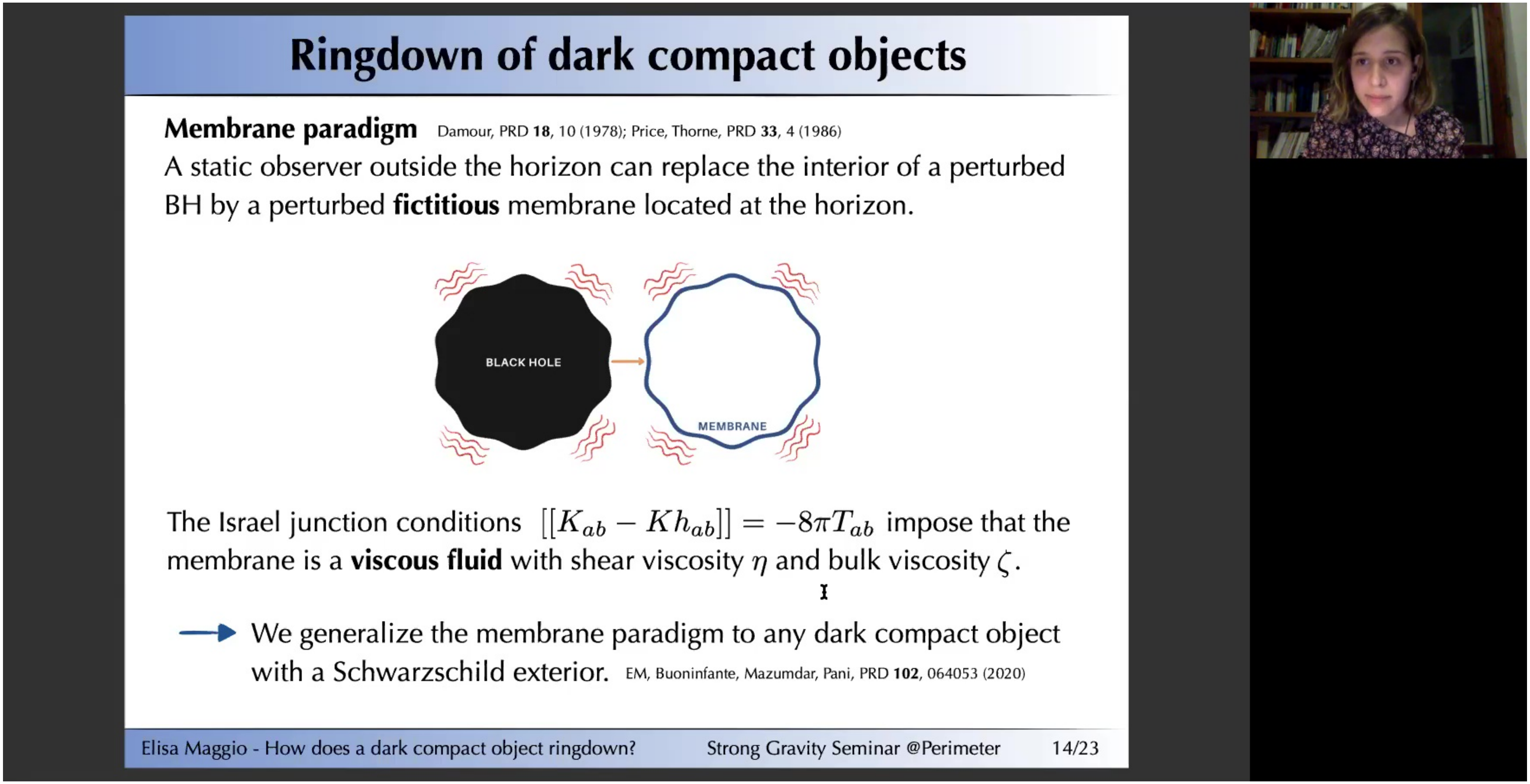


Ringdown+echo waveforms

EM, Testa, Bhagwat, Pani, PRD **100**, 064056 (2019)

- The mixing of the polarizations occurs for a **spinning object** or a **complex** $\mathcal{R}$.
- The **phase** in $\mathcal{R}$ modifies the echo pattern.
- The **amplitude** of the echoes is related to $\mathcal{R}$.

https://www.darkgra.org/gw-echo-catalogue.html



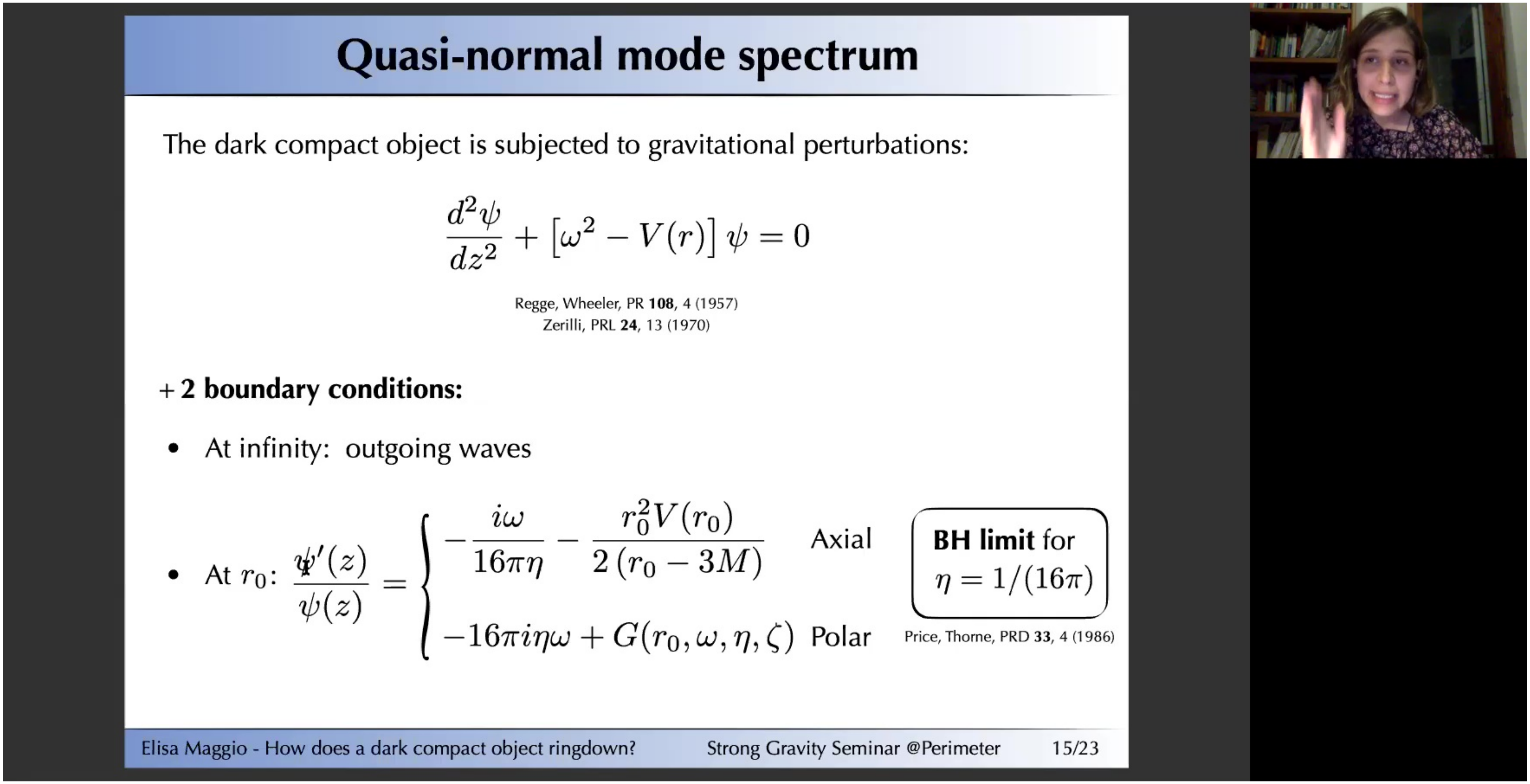
Ringdown of dark compact objects

Membrane paradigm Damour, PRD **18**, 10 (1978); Price, Thorne, PRD **33**, 4 (1986)

A static observer outside the horizon can replace the interior of a perturbed BH by a perturbed **fictitious** membrane located at the horizon.

The Israel junction conditions $[[K_{ab} - Kh_{ab}]] = -8\pi T_{ab}$ impose that the membrane is a **viscous fluid** with shear viscosity η and bulk viscosity ζ.

→ We generalize the membrane paradigm to any dark compact object with a Schwarzschild exterior. EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)



Quasi-normal mode spectrum

The dark compact object is subjected to gravitational perturbations:

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

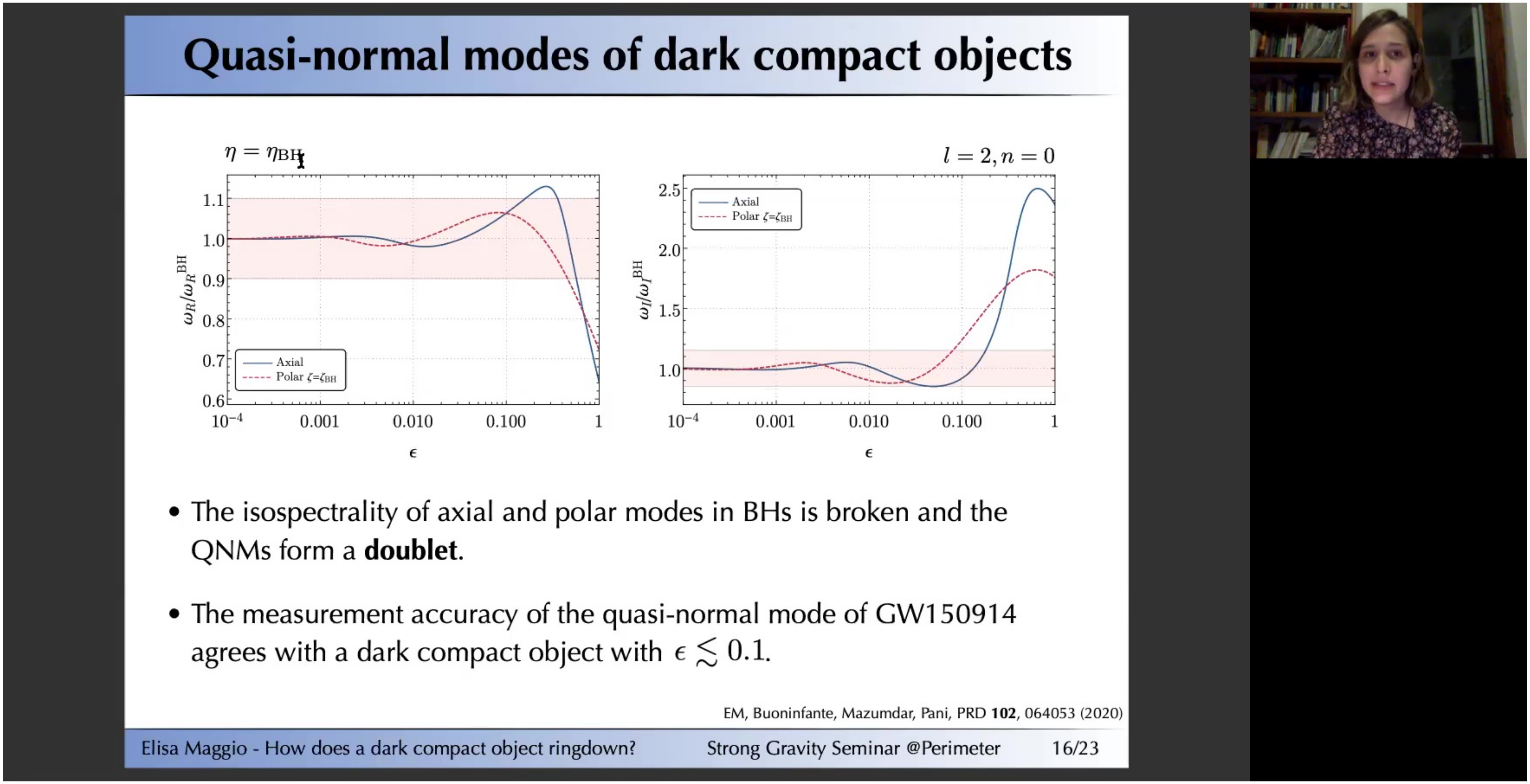
Regge, Wheeler, PR **108**, 4 (1957)
Zerilli, PRL **24**, 13 (1970)

+ **2 boundary conditions:**

- At infinity: outgoing waves
- At r_0: $$\frac{\psi'(z)}{\psi(z)} = \begin{cases} -\dfrac{i\omega}{16\pi\eta} - \dfrac{r_0^2 V(r_0)}{2\,(r_0 - 3M)} & \text{Axial} \\ -16\pi i\eta\omega + G(r_0,\omega,\eta,\zeta) & \text{Polar} \end{cases}$$

BH limit for
$\eta = 1/(16\pi)$

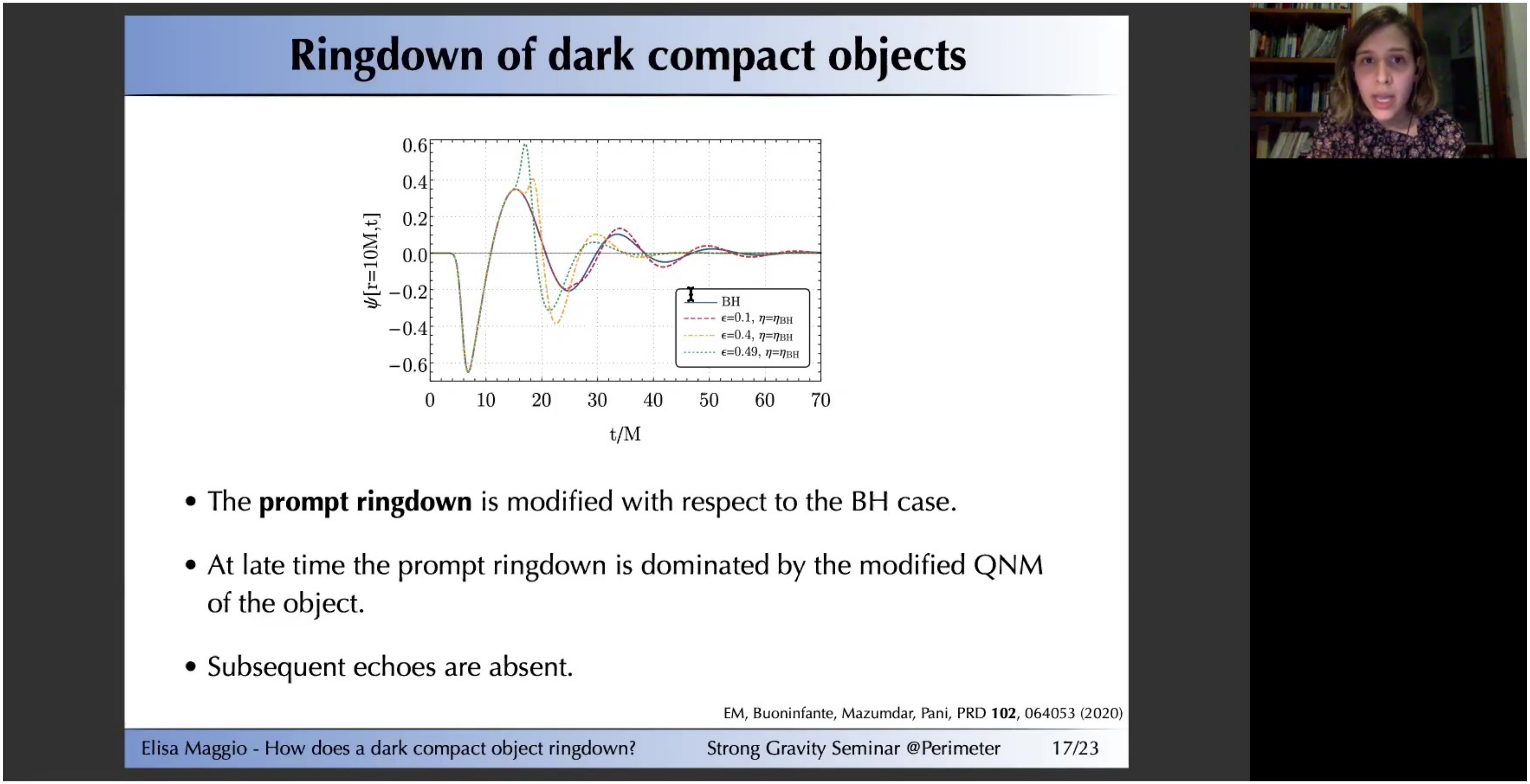
Price, Thorne, PRD **33**, 4 (1986)



Quasi-normal modes of dark compact objects

- The isospectrality of axial and polar modes in BHs is broken and the QNMs form a **doublet**.
- The measurement accuracy of the quasi-normal mode of GW150914 agrees with a dark compact object with $\epsilon \lesssim 0.1$.

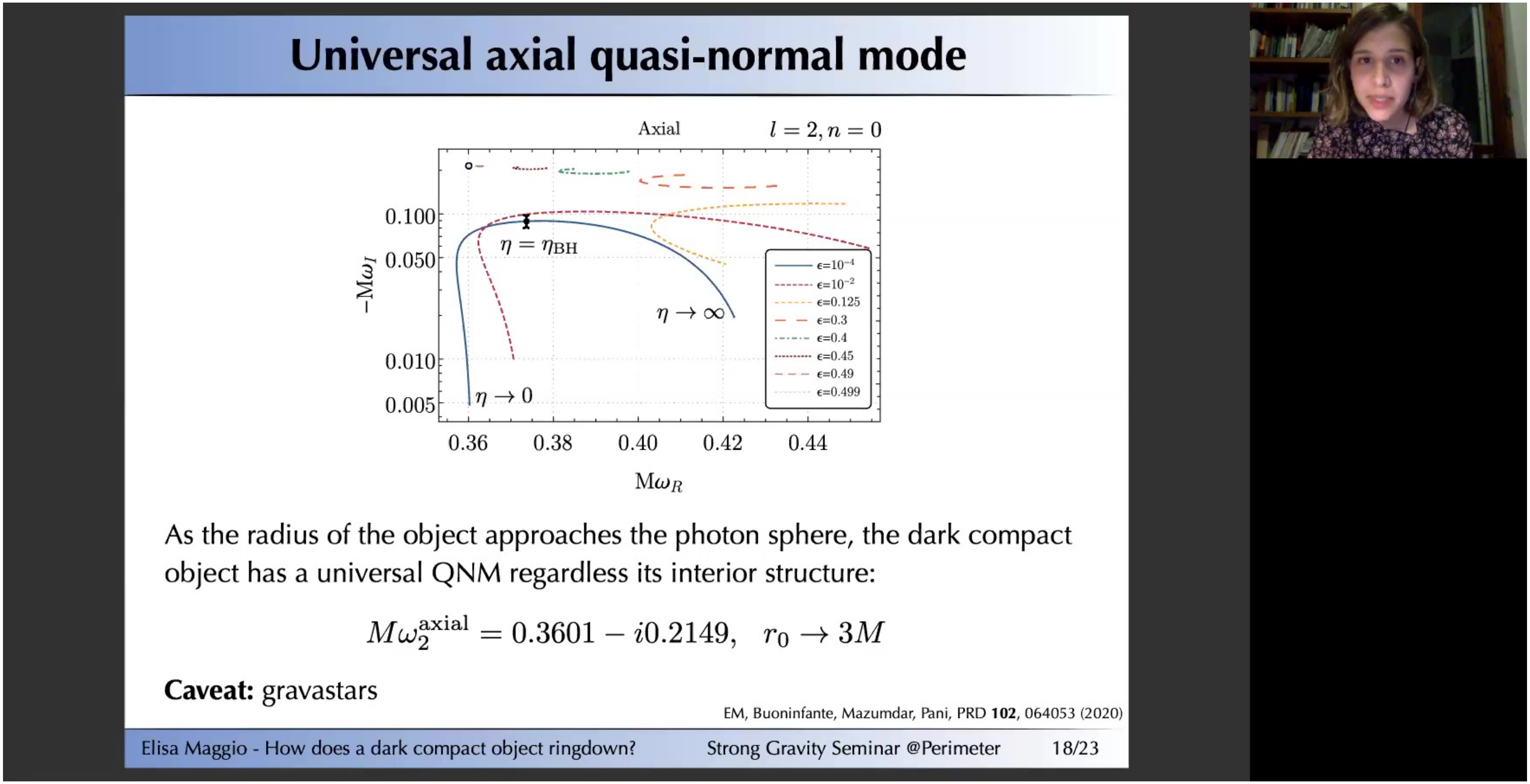
EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)



Ringdown of dark compact objects

- The **prompt ringdown** is modified with respect to the BH case.
- At late time the prompt ringdown is dominated by the modified QNM of the object.
- Subsequent echoes are absent.

EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)



Universal axial quasi-normal mode

As the radius of the object approaches the photon sphere, the dark compact object has a universal QNM regardless its interior structure:

$$M\omega_2^{\rm axial} = 0.3601 - i0.2149, \quad r_0 \to 3M$$

Caveat: gravastars

EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

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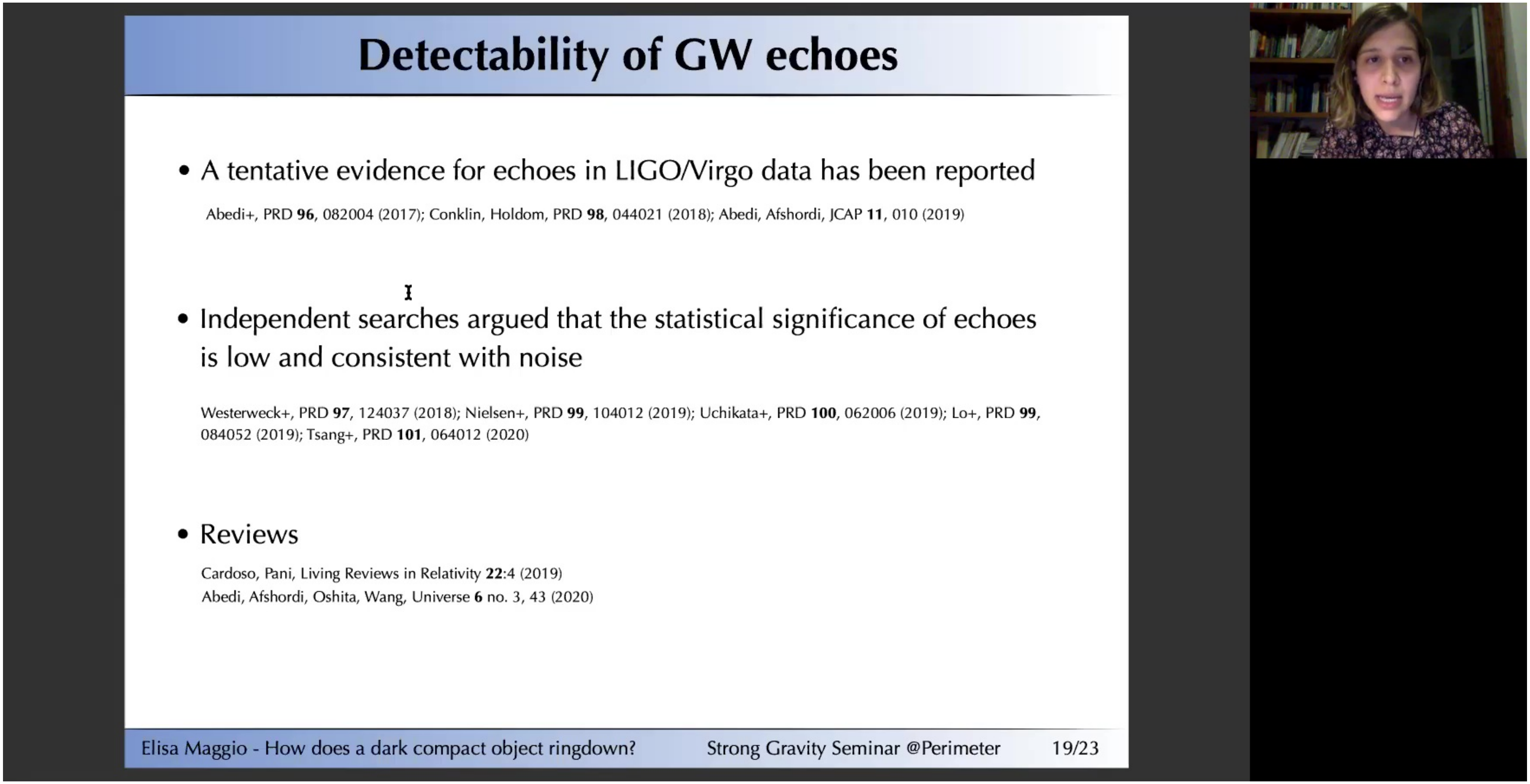


Detectability of GW echoes

- A tentative evidence for echoes in LIGO/Virgo data has been reported

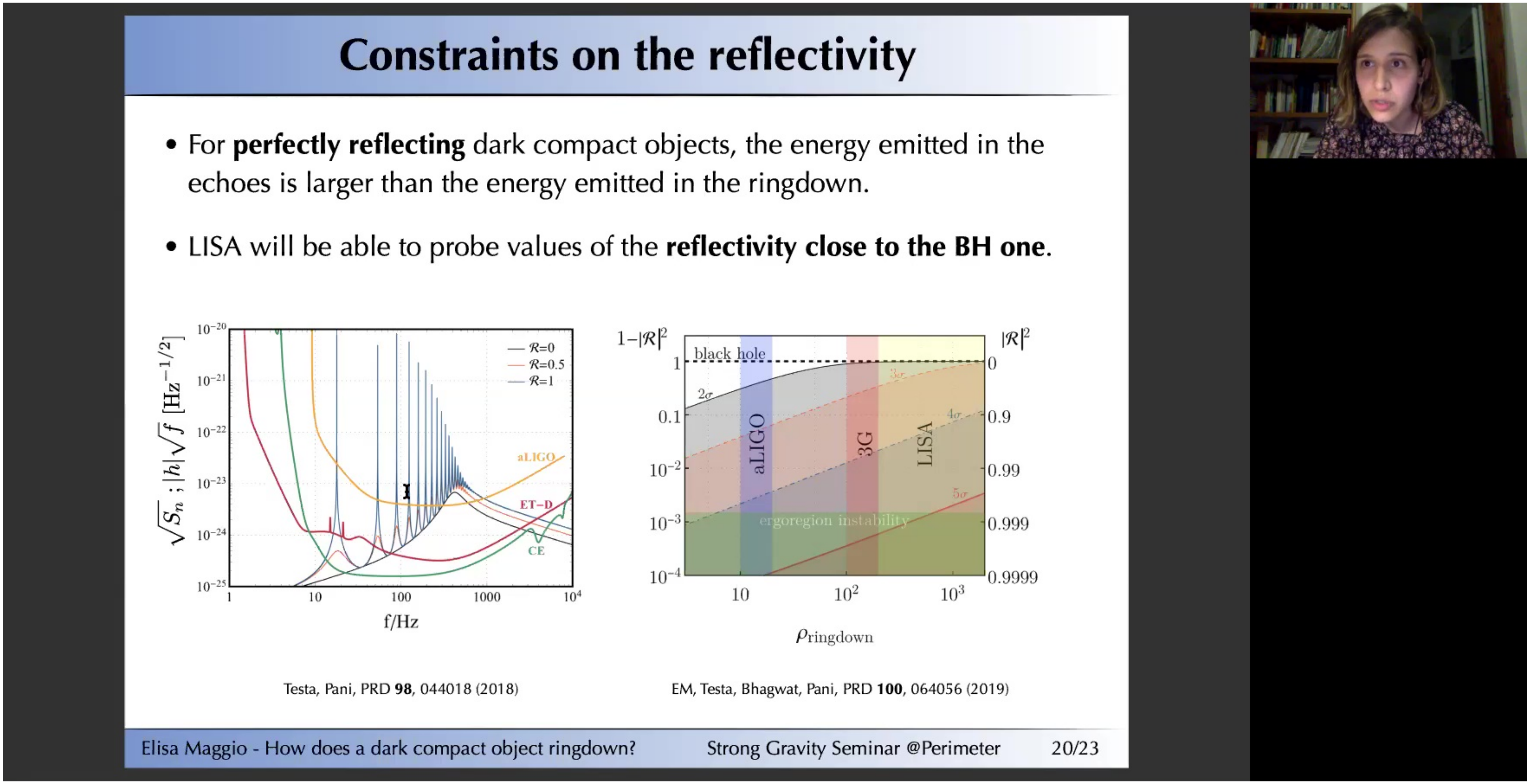
  Abedi+, PRD **96**, 082004 (2017); Conklin, Holdom, PRD **98**, 044021 (2018); Abedi, Afshordi, JCAP **11**, 010 (2019)

- Independent searches argued that the statistical significance of echoes is low and 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)

- Reviews

  Cardoso, Pani, Living Reviews in Relativity **22**:4 (2019)
  Abedi, Afshordi, Oshita, Wang, Universe **6** no. 3, 43 (2020)

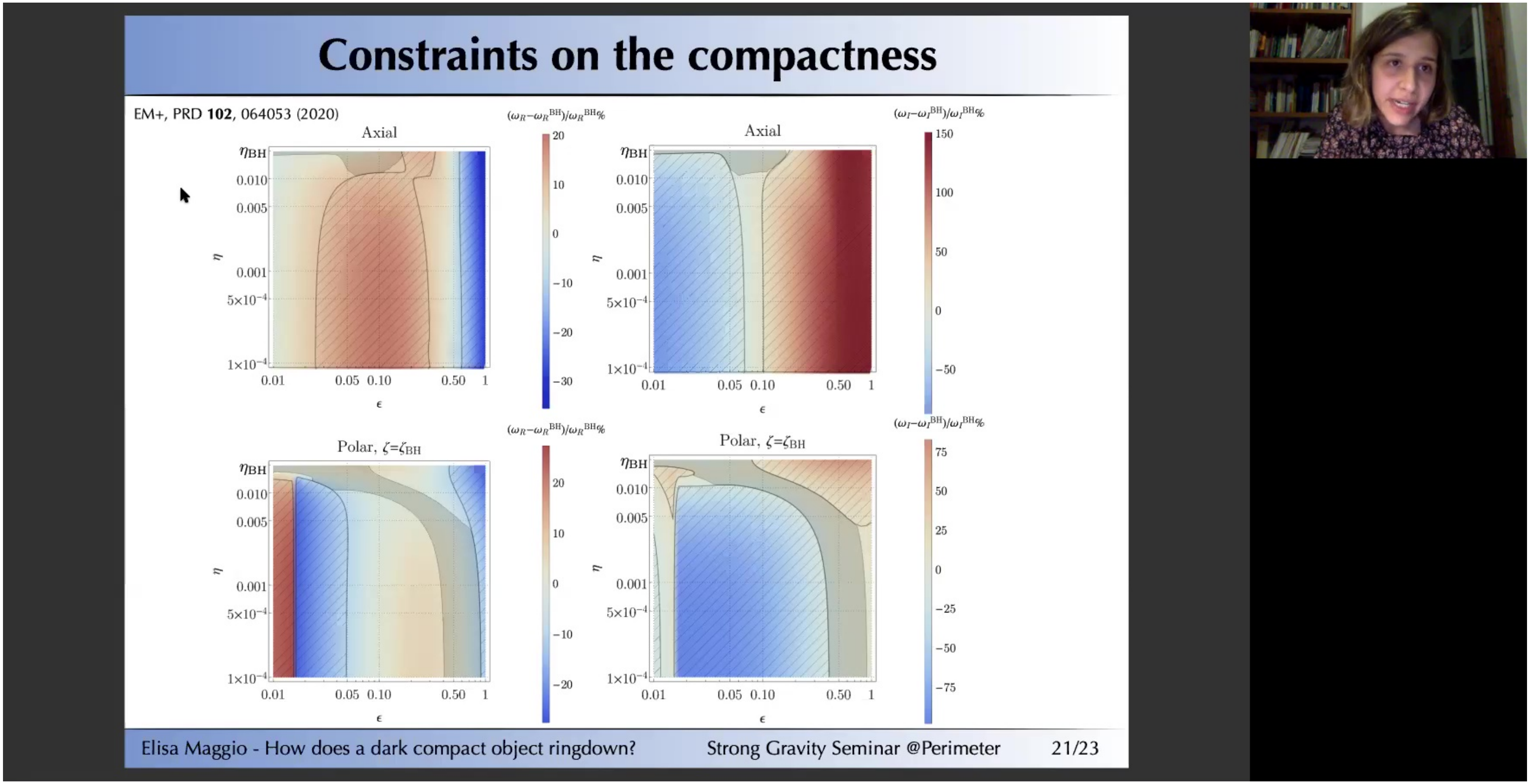


Constraints on the reflectivity

- For **perfectly reflecting** dark compact objects, the energy emitted in the echoes is larger than the energy emitted in the ringdown.
- LISA will be able to probe values of the **reflectivity close to the BH one**.

Testa, Pani, PRD **98**, 044018 (2018)

EM, Testa, Bhagwat, Pani, PRD **100**, 064056 (2019)



Constraints on the compactness

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

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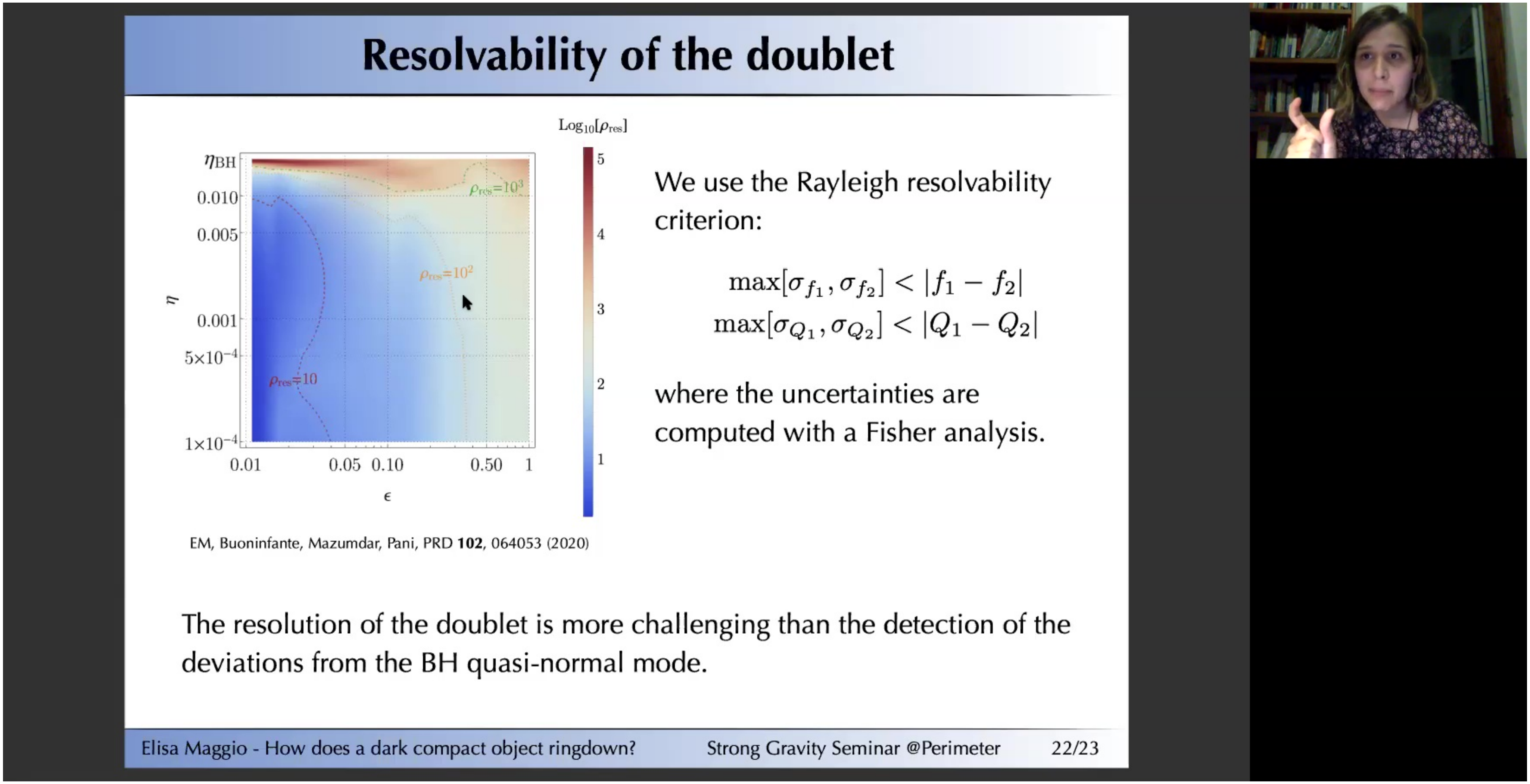


Resolvability of the doublet

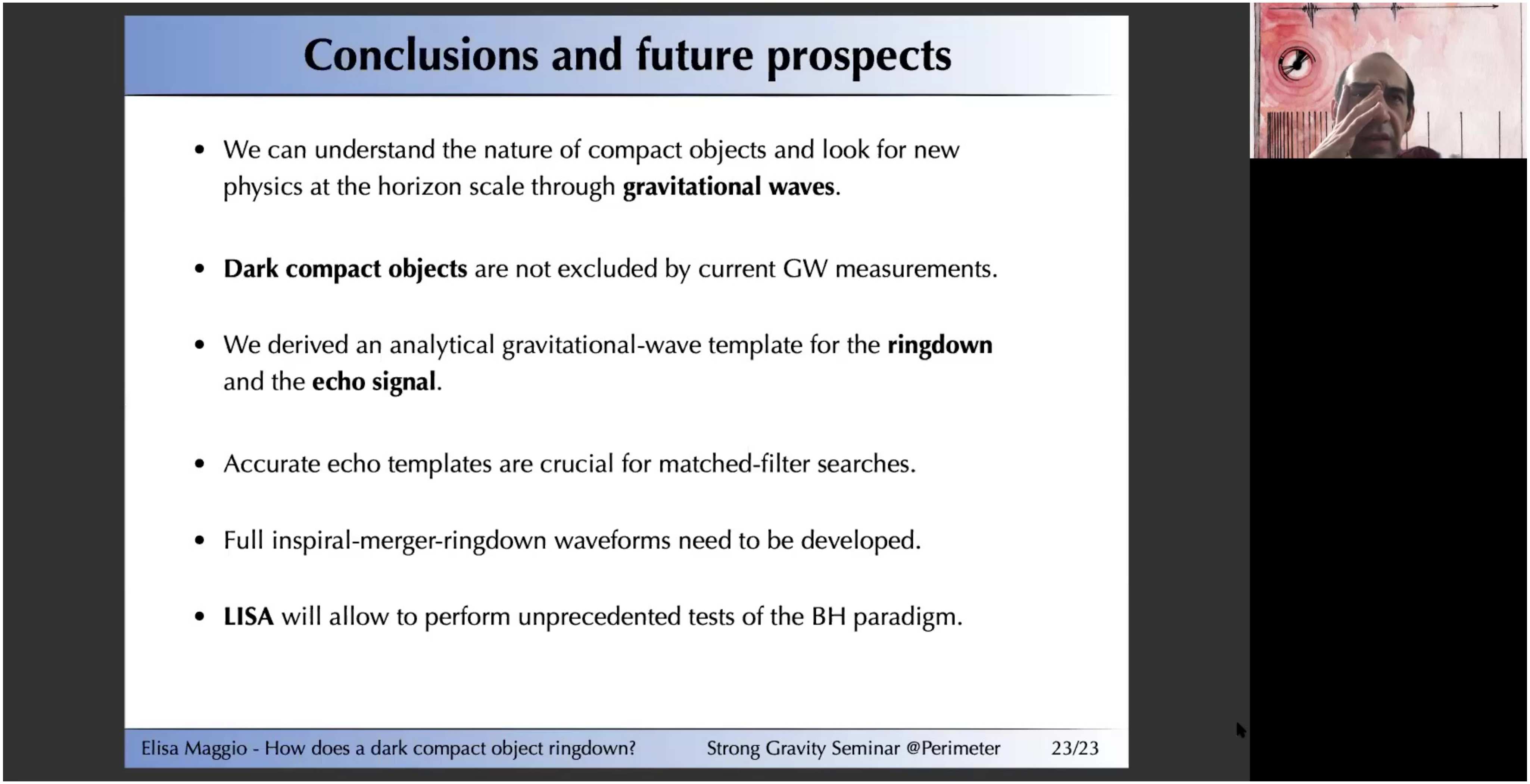
EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

We use the Rayleigh resolvability criterion:

$$\max[\sigma_{f_1}, \sigma_{f_2}] < |f_1 - f_2|$$
$$\max[\sigma_{Q_1}, \sigma_{Q_2}] < |Q_1 - Q_2|$$

where the uncertainties are computed with a Fisher analysis.

The resolution of the doublet is more challenging than the detection of the deviations from the BH quasi-normal mode.



Conclusions and future prospects

- We can understand the nature of compact objects and look for new physics at the horizon scale through **gravitational waves**.
- **Dark compact objects** are not excluded by current GW measurements.
- We derived an analytical gravitational-wave template for the **ringdown** and the **echo signal**.
- Accurate echo templates are crucial for matched-filter searches.
- Full inspiral-merger-ringdown waveforms need to be developed.
- **LISA** will allow to perform unprecedented tests of the BH paradigm.