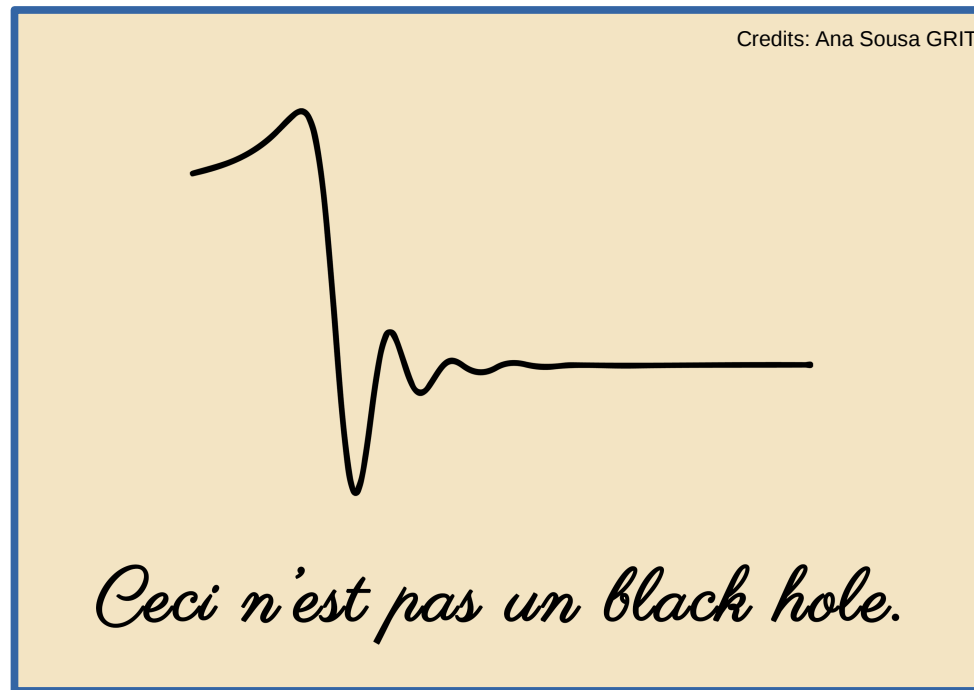


GR21, GW highlight session, July 12, 2016

# *Is the gravitational ringdown a probe of the event horizon?*



Based on Cardoso, Franzin, Pani; Phys.Rev.Lett. 116 (2016) 171101

+ work in progress with V. Cardoso, S. Hopper, C. Macedo, C. Palenzuela

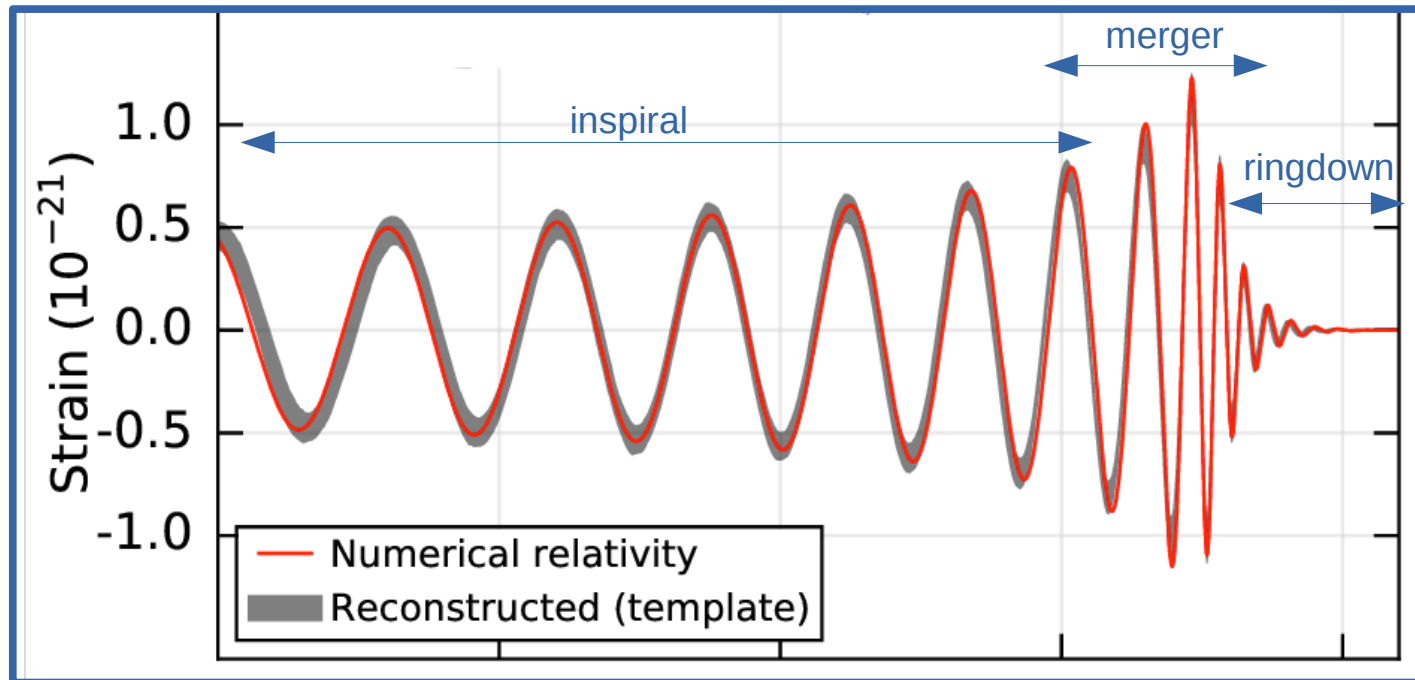
## Paolo Pani

Sapienza University of Rome & INFN Rome1 – IST, Lisbon

# GW150914: fact sheet

[LVC, PRL 116, 061102 (2016), PRL 116, 221101 (2016), PRL 116, 241102 (2016)]

$$\begin{array}{lll} \mathcal{M} \approx 30 M_{\odot} & m_1 = 36_{-4}^{+5} M_{\odot} & M = 62_{-4}^{+4} M_{\odot} \\ m_1 + m_2 \gtrsim 70 M_{\odot} & m_2 = 29_{-4}^{+4} M_{\odot} & \chi = 0.67_{-0.07}^{+0.05} \end{array}$$



- **Cygnus X-1:**  $m \approx 15 M_{\odot}$ ,  $\chi \approx 0.97$  [Orosz+ ApJ (2011)]
- **GW150914:**  $f_{\text{merger}} \approx 75 \text{ Hz} \Rightarrow r_0 \approx 350 \text{ km} \approx 4GM/c^2$
- Coalescence of two **compact** objects with **super-Chandra** masses

# BHs VS exotic compact objects

---

- ▶ **BHs are very economical:**

- ▶ Arbitrary mass
- ▶ Compactness  $M/R \sim 1$
- ▶ Easy to form
- ▶ Consistent with all observations
- ▶ Linearly (mode) stable

[e.g. Dafermos & Rodnianski; Clay Math.Proc. (2013), Holzegel's talk]

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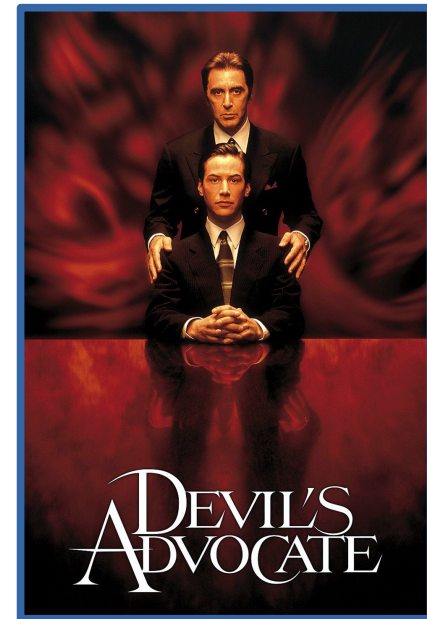
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## ► However:

- Event horizon
- Curvature singularity
- Huge entropy  $S_{\text{BH}} \sim 10^{77} k_B (M/M_\odot)^2$
- Information loss, unitarity
- Thermodynamically unstable



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We accept the weird properties of BHs *lightheartedly*... alternatives?

## ► Exotic compact objects (ECOs): [e.g. Cardoso+ (2007), Pani+ (2009), Giudice+ (2016)]

- Boson stars  $\mathcal{L} = \frac{R}{16\pi G} - (\partial\phi)^2 - V(\phi)$  [e.g. Palenzuela & Liebling Liv. Rev. (2012)]
- Gravastars (de Sitter interior + thin shell) [Mazur & Mottola, PNAS (2004)]
- Wormholes [Morris & Thorne (1987), Visser's book (1995)]
- Quantum effects at the horizon scale  $\rightarrow \langle T_{\mu\nu} \rangle \neq 0$
- Modified gravity



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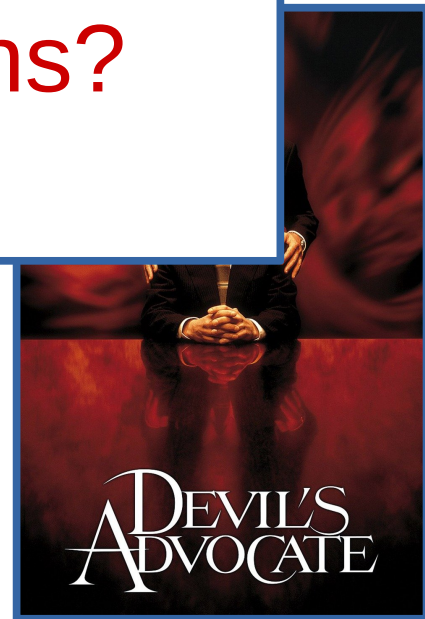
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Can we rule out exotic compact objects with ringdown detections?

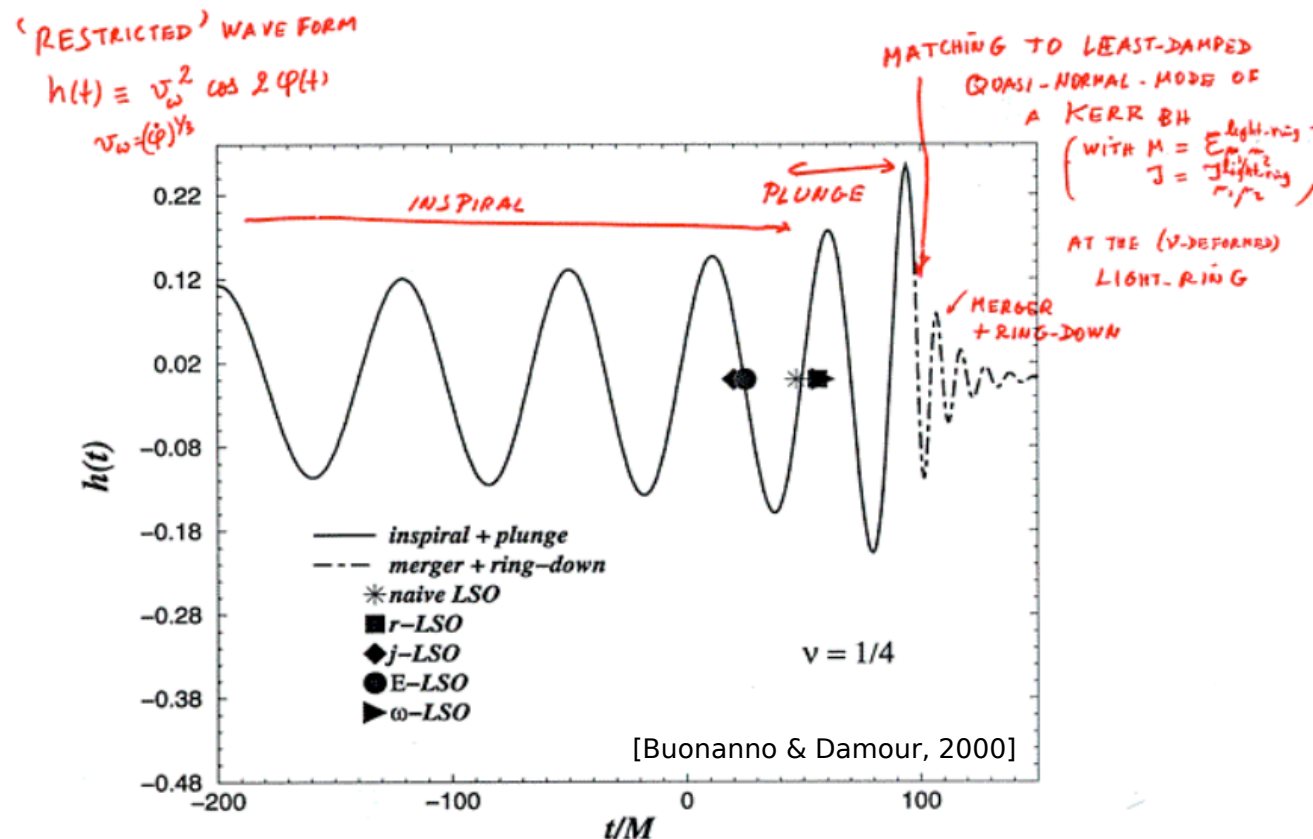
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# Ringdown tests of the event horizon



## Two common assumptions:

- Ringdown originates from the distorted final object and consists of a **superposition of QNMs**
- Accurate measurements of ringdown waveforms can provide **conclusive proof of BHs**

[e.g. Berti, Cardoso, Will; PRD (2006), ...]

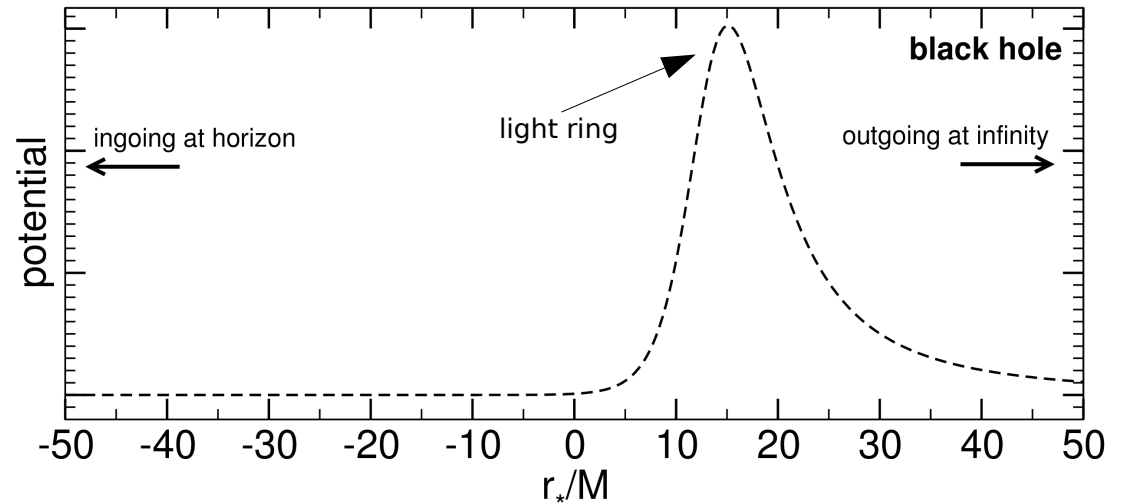
(note of caution: **QNMs are not a complete set!**)

# QNMs of exotic compact objects

$$\frac{\partial^2 \Psi}{\partial t^2} - \frac{\partial^2 \Psi}{\partial r_*^2} + V_{slm}(r_*)\Psi = 0$$

[e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]

QNMs are poles of the Green's function in the complex plane





# QNMs of exotic compact objects

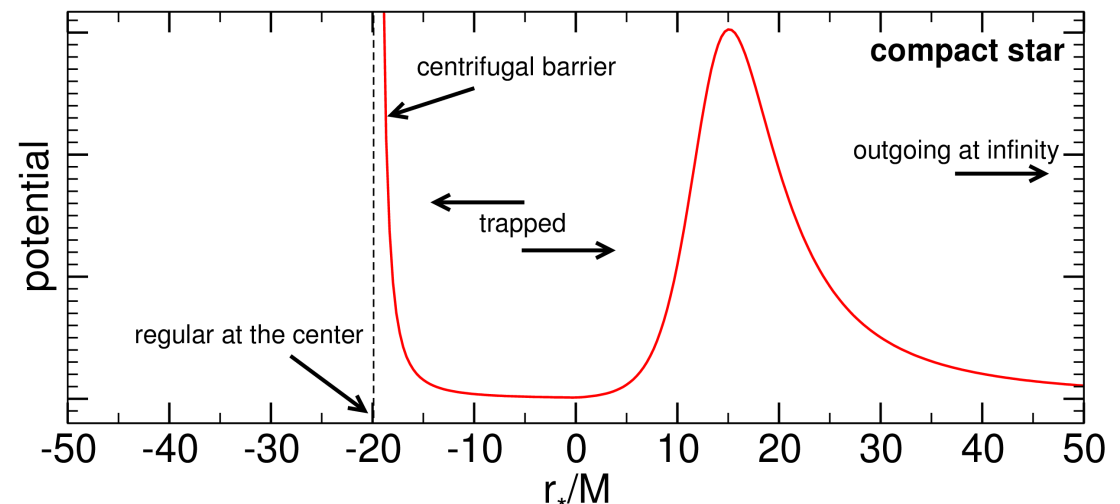
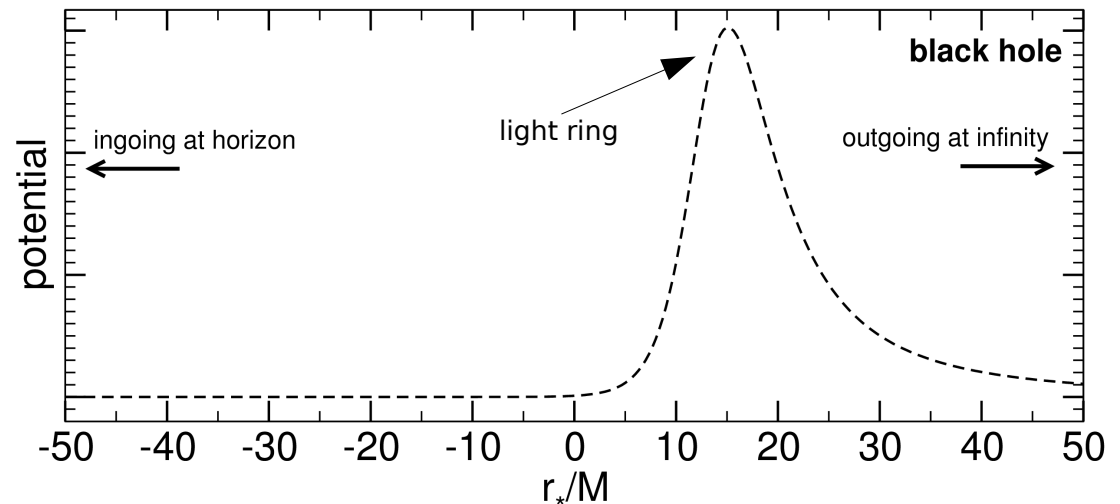
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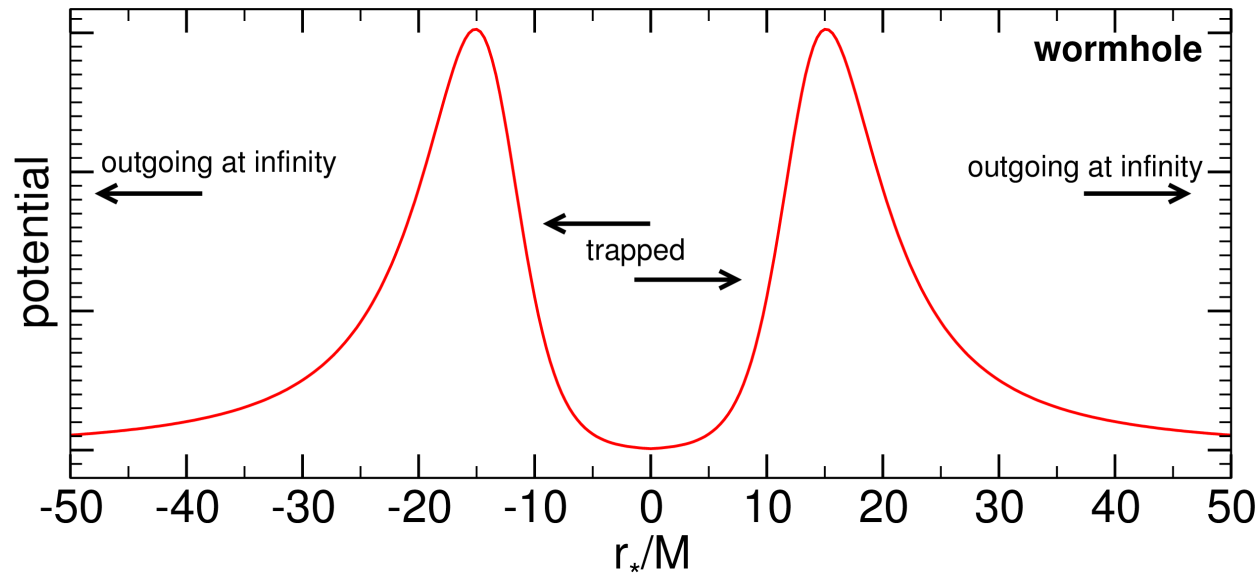
Ultracompact stars generically support **trapped modes**

Chandrasekhar & Ferrari PRSLA (1991)  
[see also Abramowicz+, CQG (1997)]



No horizon → different boundary conditions → **different eigenvalues**

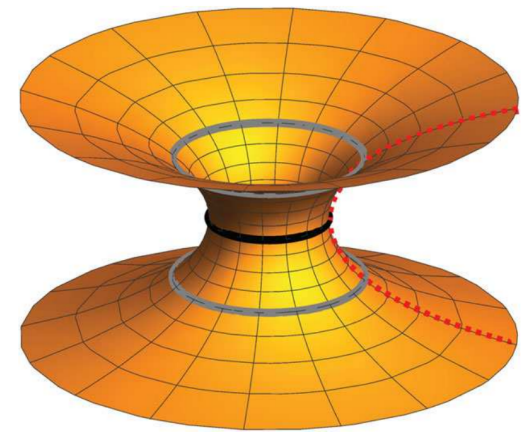
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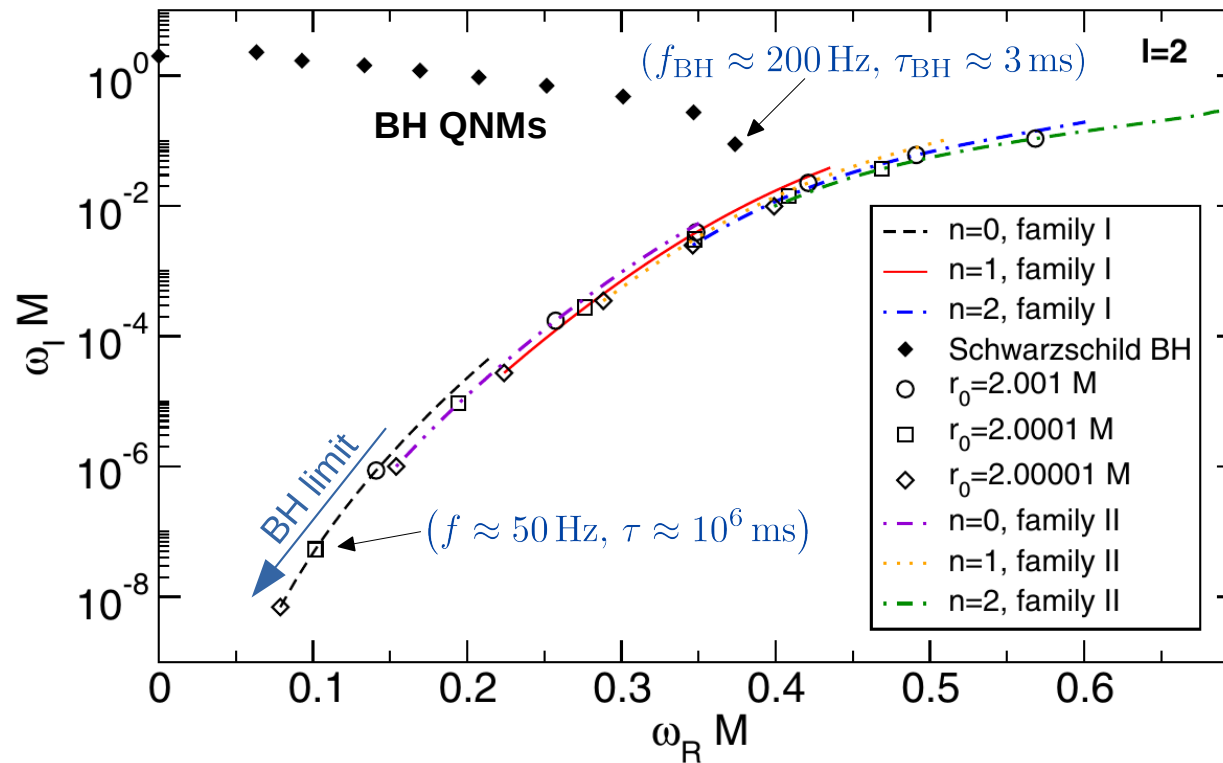
- Two BH metrics matched at the throat  $\rightarrow$  thin shell at  $r=r_0$

$$\sigma = -\frac{\sqrt{1 - 2M/r_0}}{2\pi r_0}, \quad p = \frac{1}{4\pi r_0} \frac{(1 - M/r_0)}{\sqrt{1 - 2M/r_0}}$$

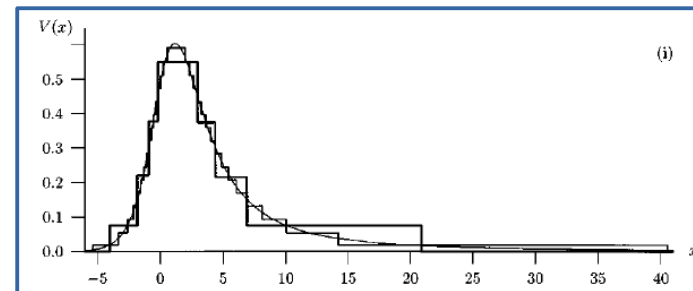
- DEC and WEC violated [Morris & Thorne (1987), Visser's book (1995)]
- SEC and NEC satisfied if  $r_0 < 3M \rightarrow$  light ring



# QNM spectrum of an ECO

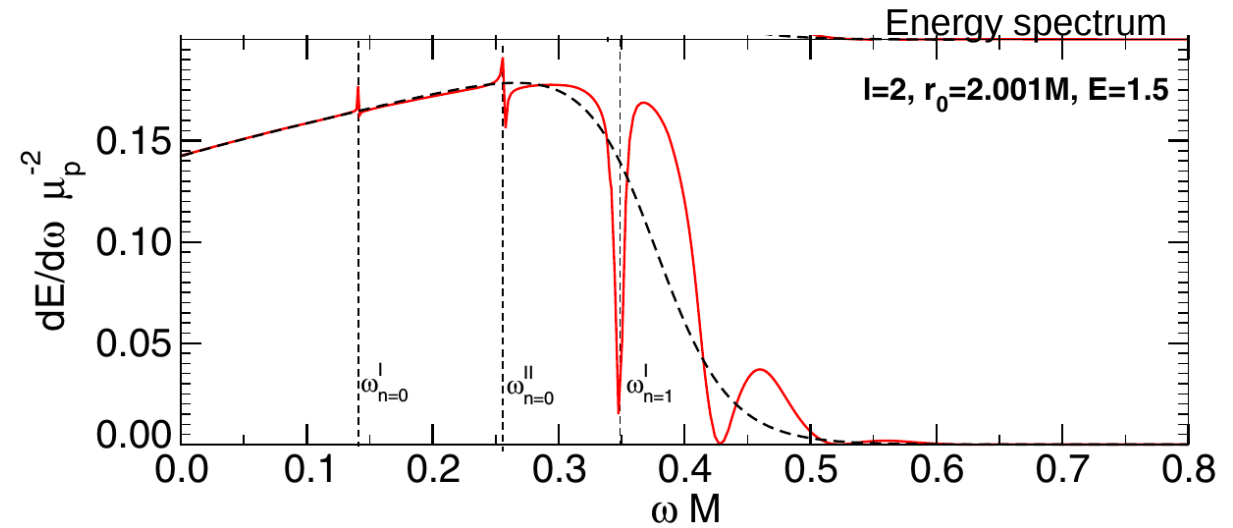
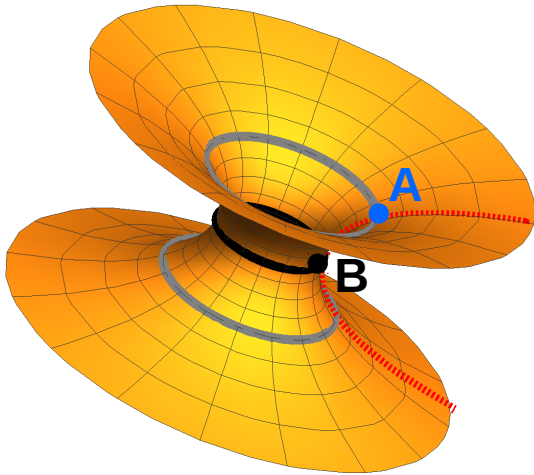


- ▶ Long-lived modes in the BH limit
- ▶ QNM spectrum dramatically different → different ringdown?
- ▶ No BH-like QNM!
- ▶ See also Nollert PRD (1996)



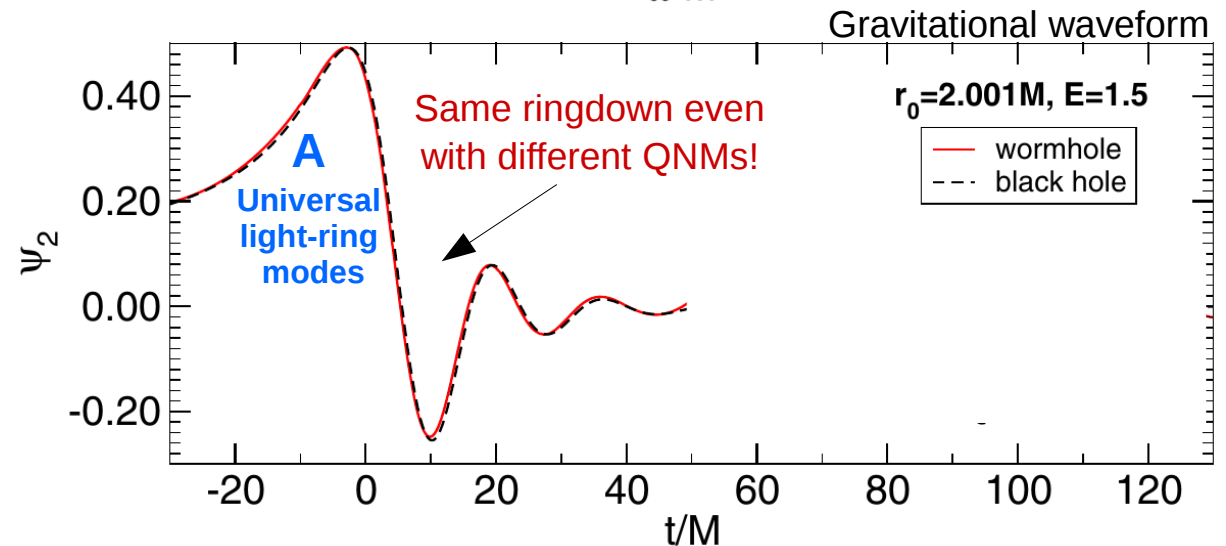
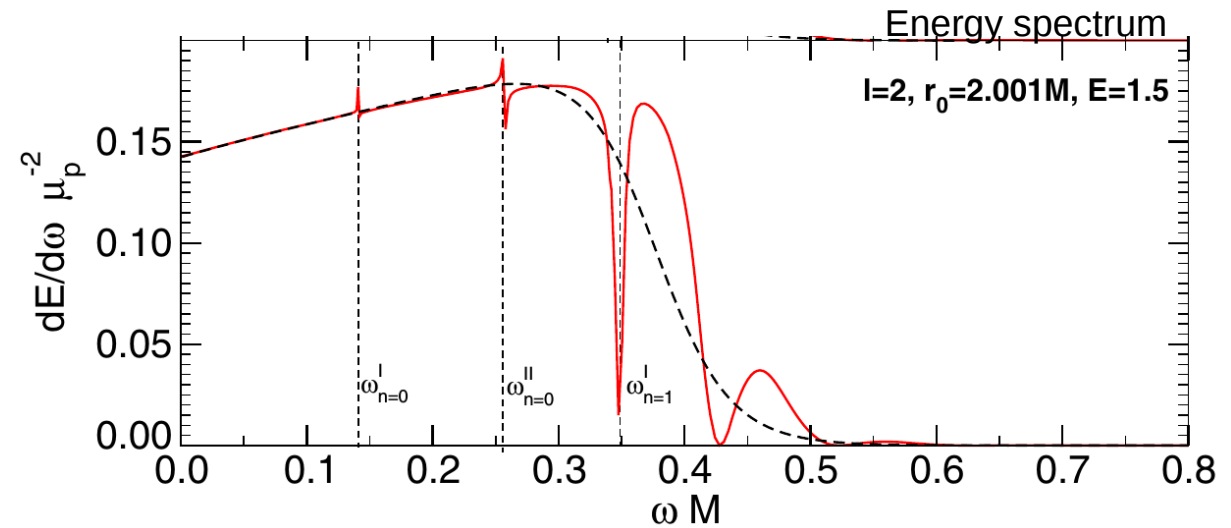
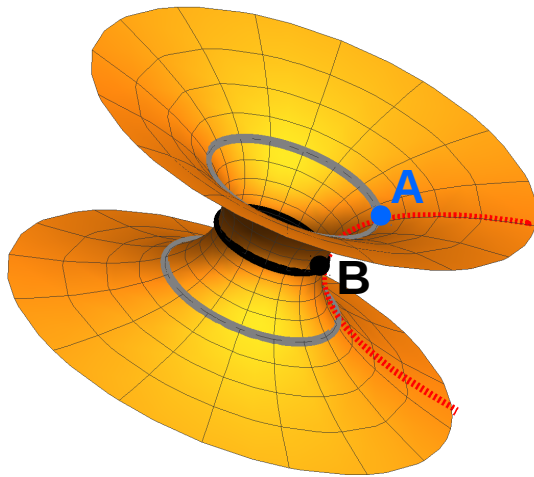
# Radial plunge into a wormhole

Cardoso, Franzin, Pani; Phys.Rev.Lett. 116 (2016) 171101



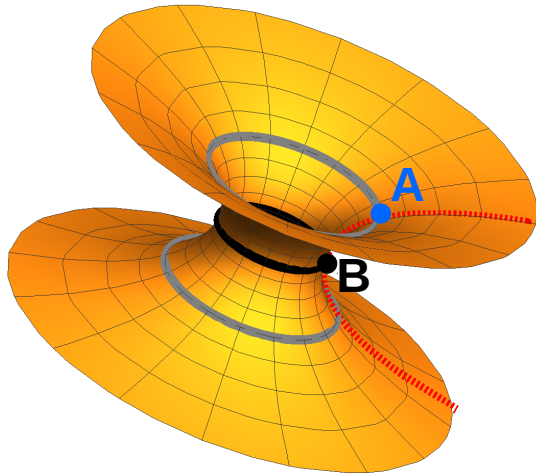
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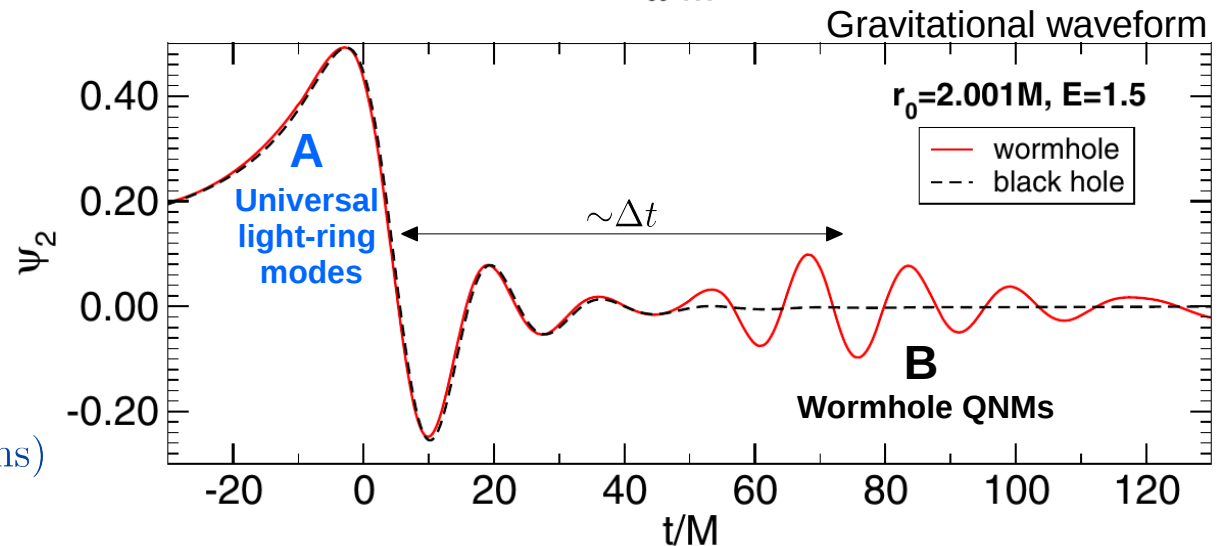
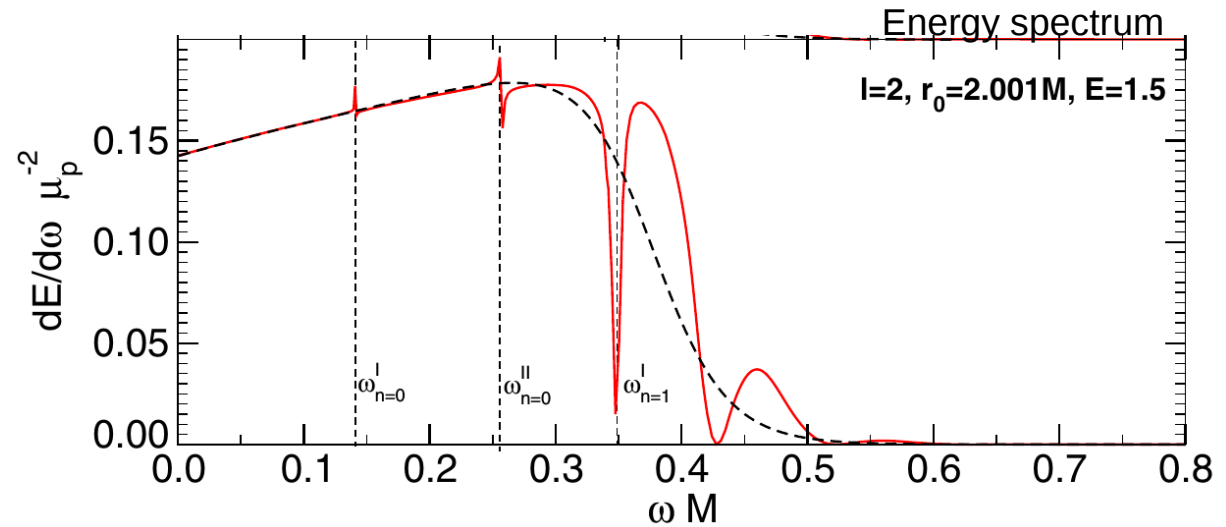
Cardoso, Franzin, Pani; Phys.Rev.Lett. 116 (2016) 171101



$$\Delta t = \int_{r_0}^{3M} \frac{dr}{F} \sim 2M \log \left( \frac{r_0}{M} - 1 \right)$$

Delay time

$$r_0 - 2M \sim L_p \approx \times 10^{-33} \text{ cm} \Rightarrow \Delta t \sim \mathcal{O}(50 \text{ ms})$$

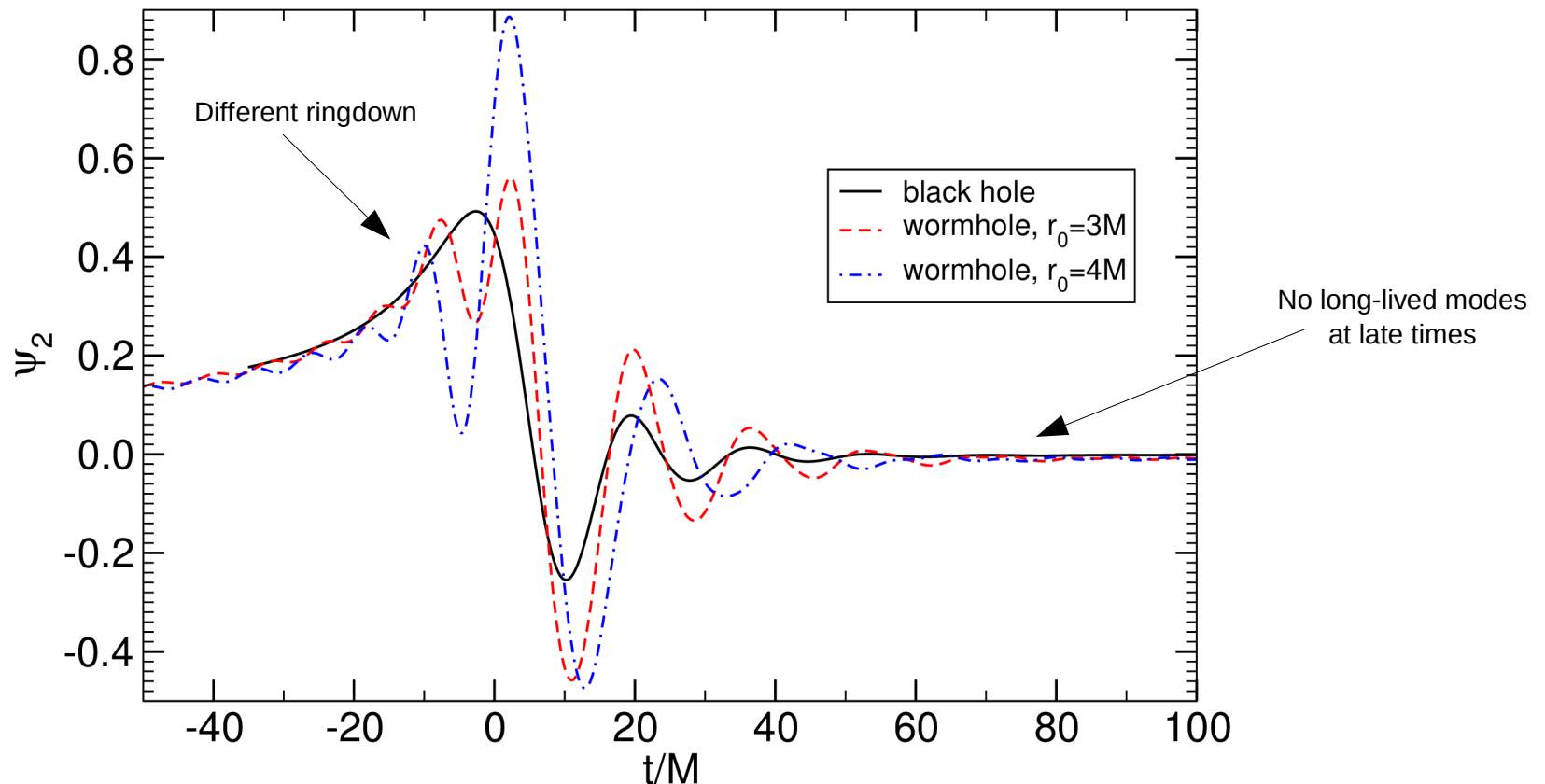


Even **Planck-scale corrections** near horizon are within reach!

Gravastars:  $r_0 - 2M \sim \sqrt{L_p M} \approx \times 10^{-13} \text{ cm} \Rightarrow \Delta t \sim \mathcal{O}(25 \text{ ms})$  [Mazur & Mottola, PNAS (2004)]

# The importance of the light ring

- ▶ The ringdown of ultracompact objects *can* be arbitrarily close to that of a BH
- ▶ The converse is *not* necessarily true!



- ▶ The ringdown of ECOs without light ring is *qualitatively* different
- ▶ GW observations can rule out less compact ECOs without light ring

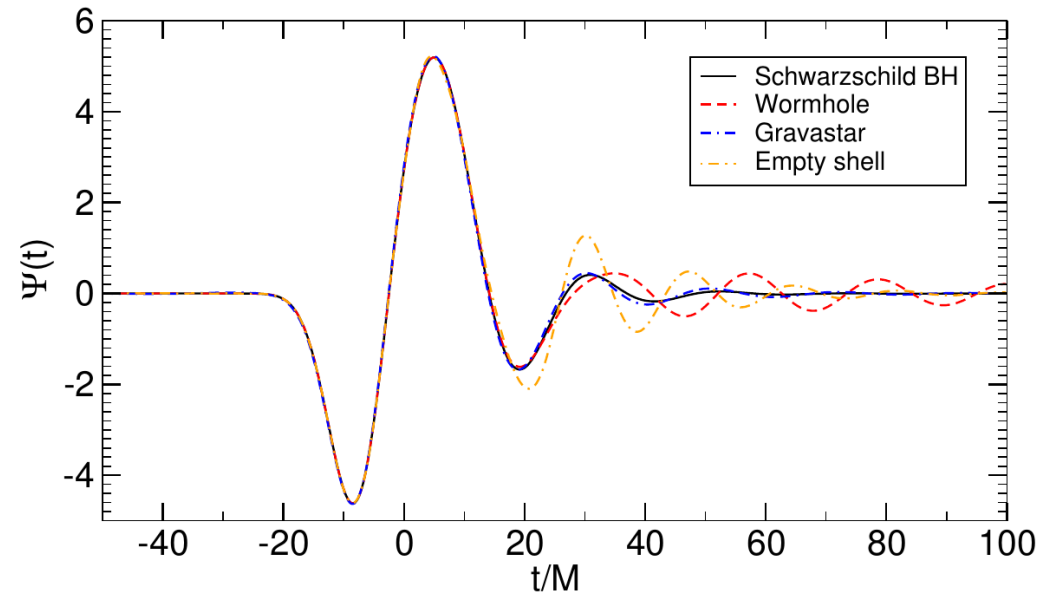
[Chirenti & Rezzolla, arXiv:1602.08759, cf. Chirenti's poster; Palenzuela's talk]

# Extensions

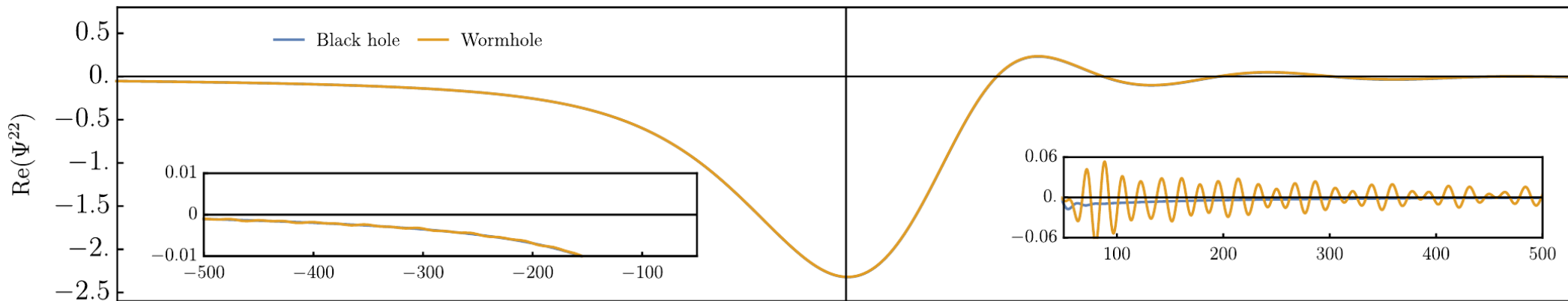


work in progress with V. Cardoso, S. Hopper, C. Macedo, C. Palenzuela

- ▶ Valid for any ECO with light ring
- ▶ Valid for generic orbits
- ▶ Full waveform? [Palenzuela's talk]



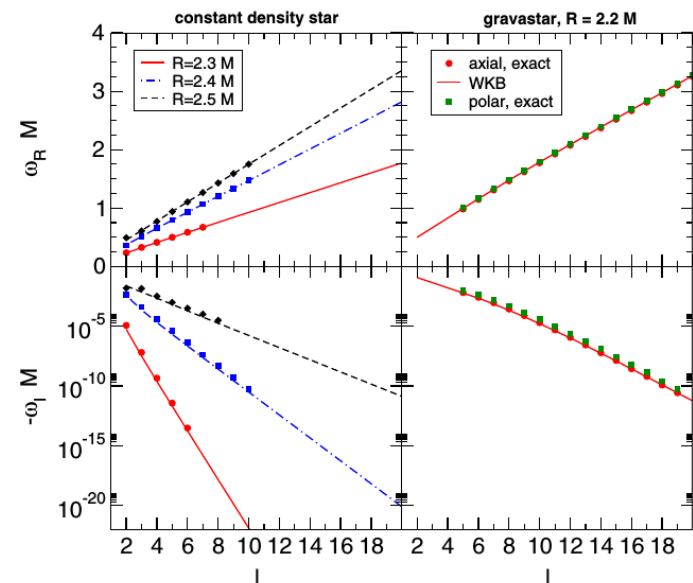
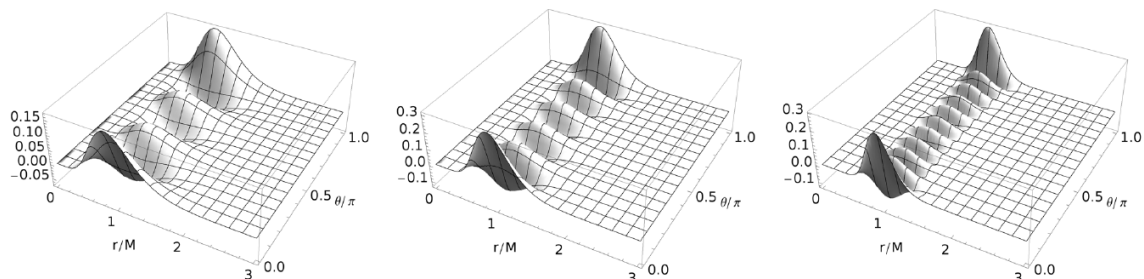
$$E = 1.5, r_{\min} = 4.3M, r_0 = 2.001M, (\ell, m) = (2, 2)$$





# Viable ECOs with a light ring?

- **Existence** (hard to obtain viable solutions with light ring)
- **Formation?**
- **Long-lived modes can become unstable**
- **Ergoregion instability** [Friedman (1976), Cardoso+ (2008), Pani+ (2010, 2012)]
- **Nonlinear instability? (turbulence, fragmentation)**  
[Keir (2014), Cardoso+ (2014)]



- **matter oscillations?** [Yunes, Yagi, Pretorius; arXiv:1603.08955, cf. Yagi's talk]
- **Maximum mass: ECO + ECO  $\rightarrow$  ECO or BH?**

Ultracompact exotic objects are very fragile

# Conclusion & Open Issues

---

- ▶ Ringdown  $\neq$  quasinormal modes
- ▶ GW15xxxx prove the existence of light rings  $\rightarrow$  enough?
- ▶ Two-mode ringdown searches are crucial [Yagi's talk]
- ▶ Viable ECOs with a light ring?
- ▶ Mimic the full coalescence without BHs? [Palenzuela's talk]
- ▶ Large SNR in ringdown  $\rightarrow$  probe horizon scale
- ▶ Is it *philosophically* possible to “hear” the horizon?

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- ▶ Is it *philosophically* possible to “hear” the horizon?

Nevertheless, the case for the existence of black holes in the Universe is very strong and the evidence very convincing. We think, however, that a shadow of doubt will always cast its pall on our certainty in this matter. But it is a fertile doubt: it has already inspired new ideas and will surely continue to do so.

[Abramowicz, Kluzniak, Lasota, A&A (2002)]

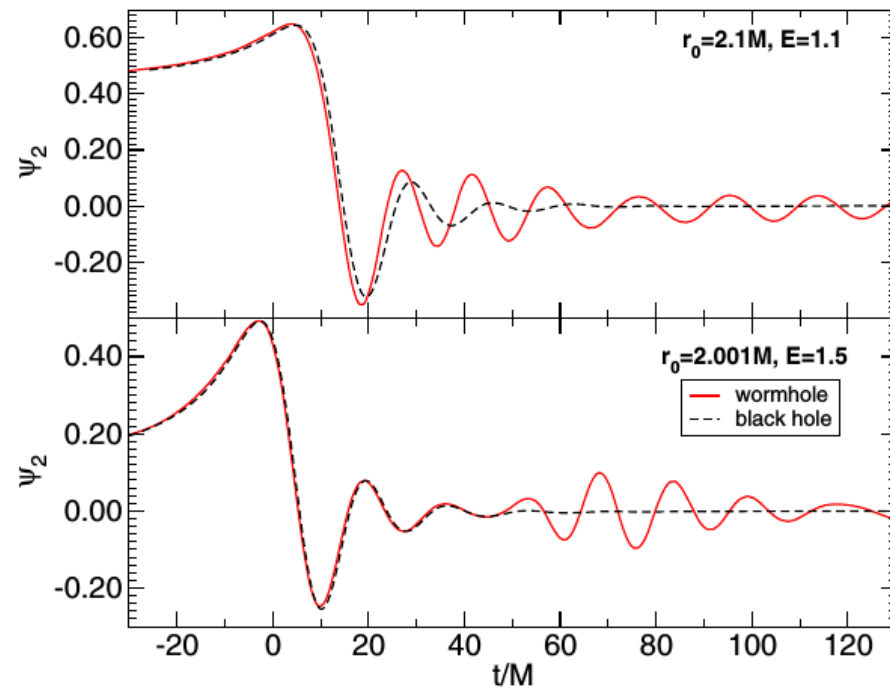
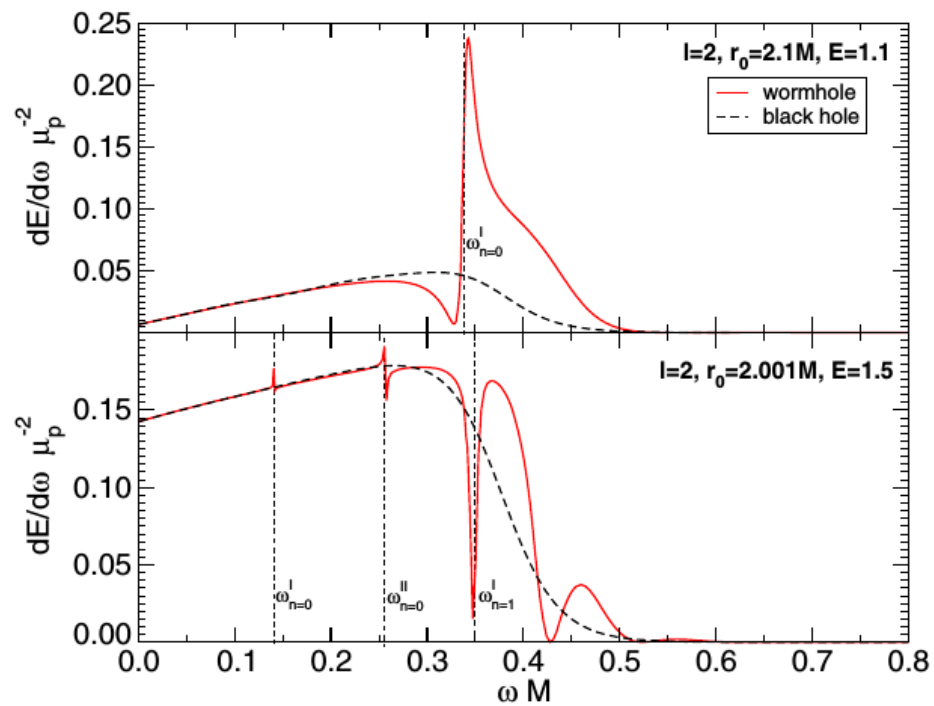


GW astronomy: expect the unexpected?

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# Backup slides

*“Nothing is More Necessary than  
the Unnecessary” [cit.]*



# XXXXX

▶ XXXX

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▶ XXXX

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