Quantum Vacuum and Gravitation: Testing GR in Cosmology @ MITP, March 16, 2017

GW signatures of exotic compact objects and of quantum corrections at the horizon scale

Paolo Pani

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PRL 116 (2016) 171101, PRD94 (2016) 084031 , gr-qc/1701.01116 , gr-qc/1703.03696 + gr-qc/1703.10612

Collaborators: V. Cardoso, V. Ferrari, L. Gualtieri, S. Hopper, C. Macedo, A. Maselli, C. Palenzuela

Students: T. Abdelsalhin, E. Franzin, E. Maggio, G. Raposo

Overview

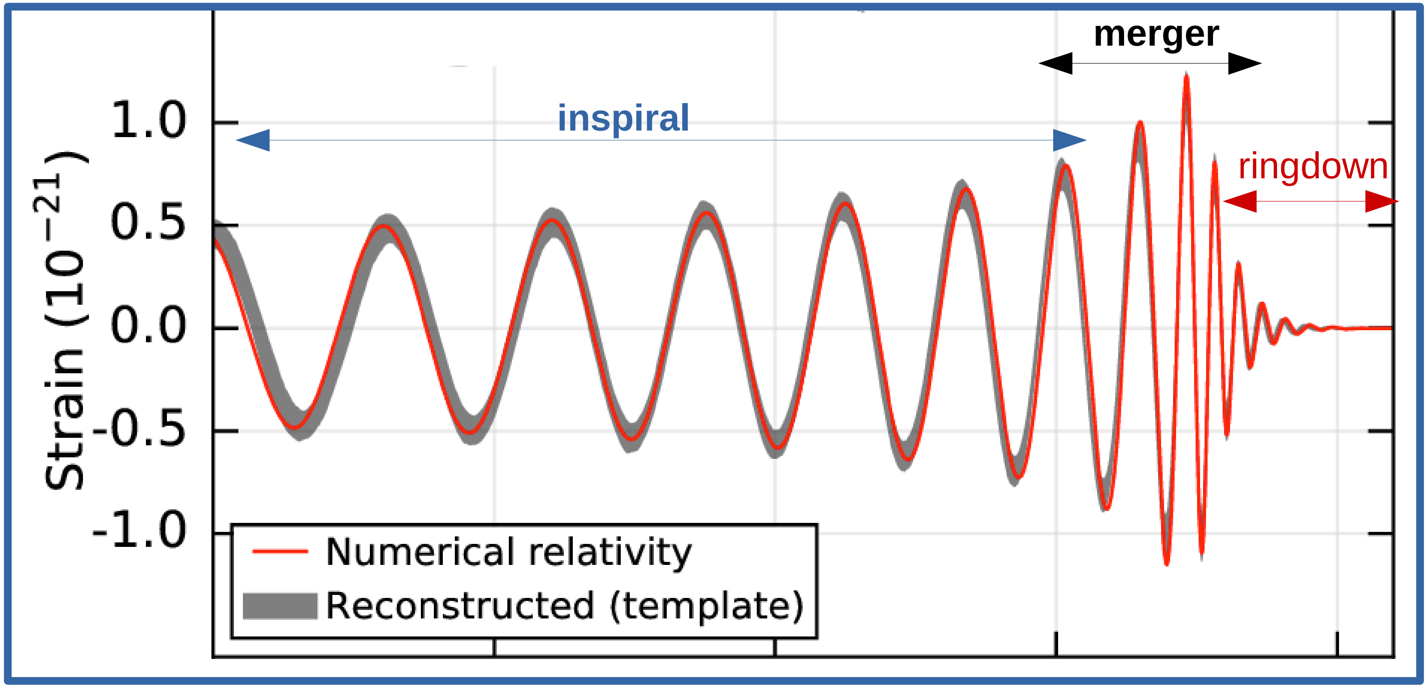
- **Exotic Compact Objects (ECOs)**
  - Motivation
  - Models
- **Gravitational-wave (GW) signatures**
  - GW echoes
  - Different quadrupole moment
  - Absence of tidal heating
  - Nonvanishing tidal Love numbers
- **Ergoregion instability of ECOs**
  - Toy model
  - The role of the reflectivity

GW150914: fact sheet

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

$\mathcal{M} \approx 30 M_\odot$ $\quad m_1 = 36^{+5}_{-4} M_\odot$ $\quad M = 62^{+4}_{-4} M_\odot$

$m_1 + m_2 \gtrsim 70 M_\odot$ $\quad m_2 = 29^{+4}_{-4} M_\odot$ $\quad \chi = 0.67^{+0.05}_{-0.07}$



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

BHs VS exotic compact objects

- **BHs are very economical:**
  - Arbitrary mass
  - Compactness M/R ~ 1
  - Easy to form
  - Consistent with all observations
  - Linearly (mode) stable

[e.g. Dafermos & Rodnianski; Clay Math.Proc. (2013)]

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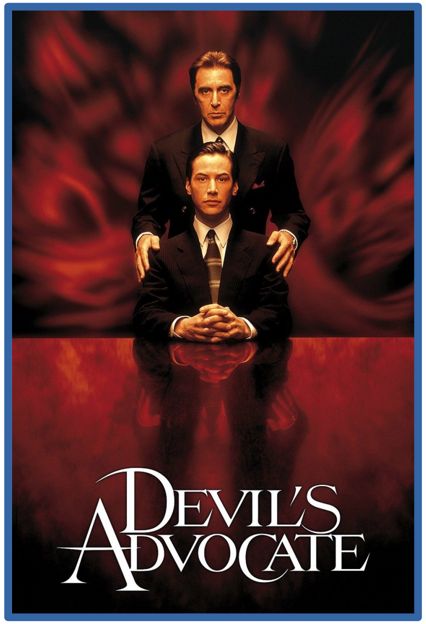
- **However:**
  - Event horizon
  - Curvature singularity
  - Huge entropy $S_{\rm BH} \sim 10^{77} k_B (M/M_\odot)^2$
  - Information loss, unitarity
  - Thermodynamically unstable



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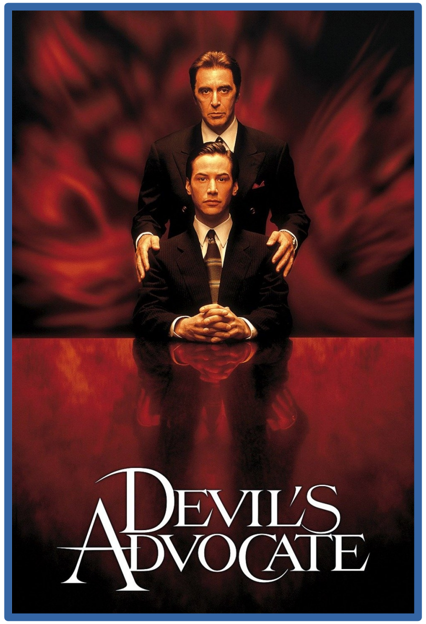
We accept the weird properties of BHs *lightheartedly*… alternatives?



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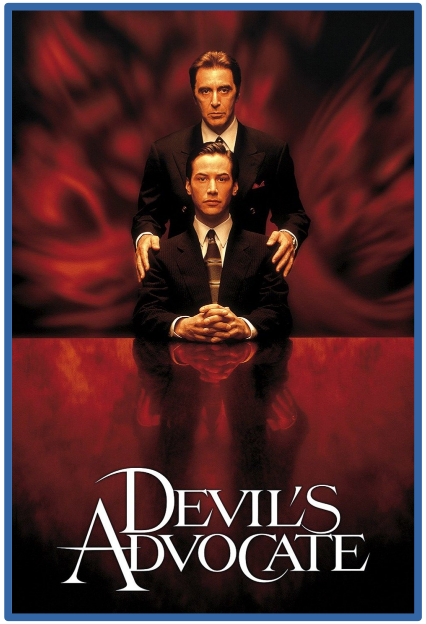

- **Exotic compact objects (ECOs):** [e.g. Cardoso+ (2007), Pani+ (2009), Giudice+ (2016)]
  - Boson stars $\mathcal{L} = \frac{R}{16\pi G} - (\partial\phi)^2 - V(\phi)$ [e.g. Palenzuela & Liebling Liv. Rev. (2012)]
  - Gravastars (de Sitter interior + shell) [Mazur & Mottola, PNAS (2004)]
  - Wormholes [Morris & Thorne (1987), Visser's book (1995)]
  - Quantum effects at the horizon scale → $\langle T_{\mu\nu}\rangle \neq 0$

    [Mathur (2004), Gubser (2014-2016), Almheiri+(2013)]
  - Modified gravity

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[e.g

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GW signatures of exotic compact objects and of quantum corrections at the horizon scale?

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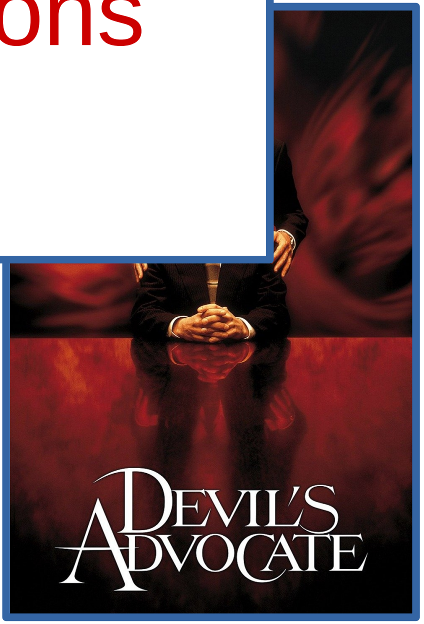
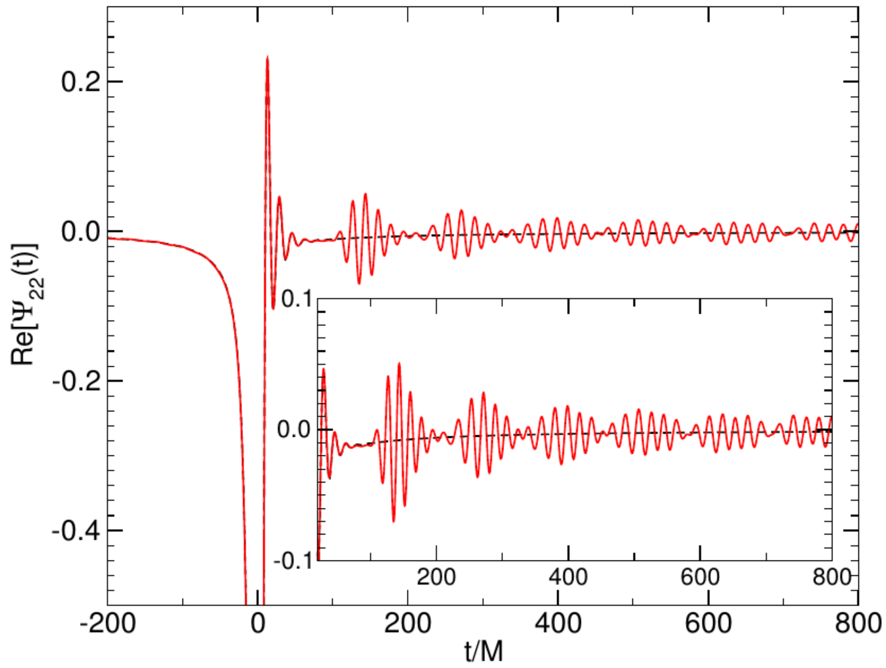


Part I

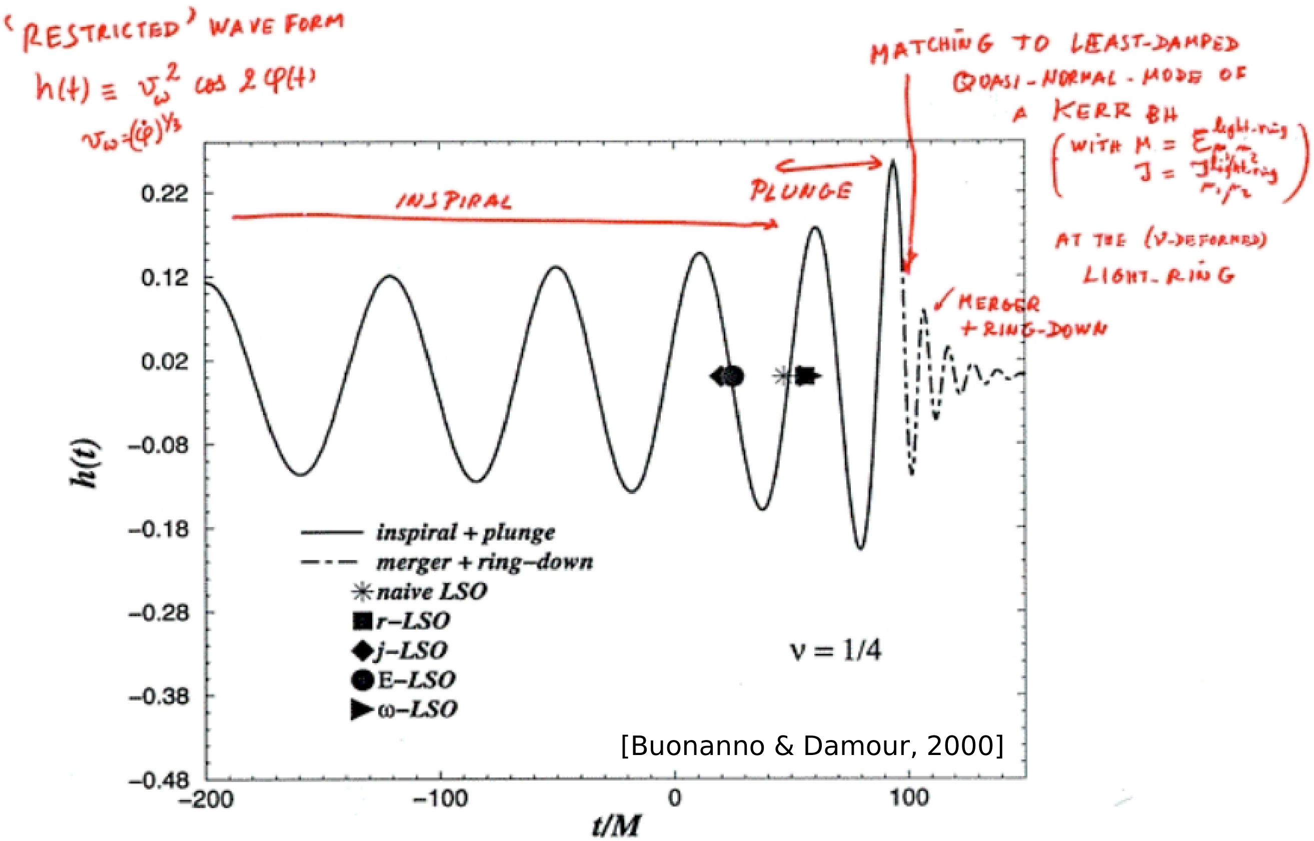
GW "echoes" of exotic compact objects



based on

V. Cardoso, E. Franzin, P. Pani – PRL 116 171101 (2016); Cardoso+, PRD94 084031 (2016) + work in progress

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), ...]

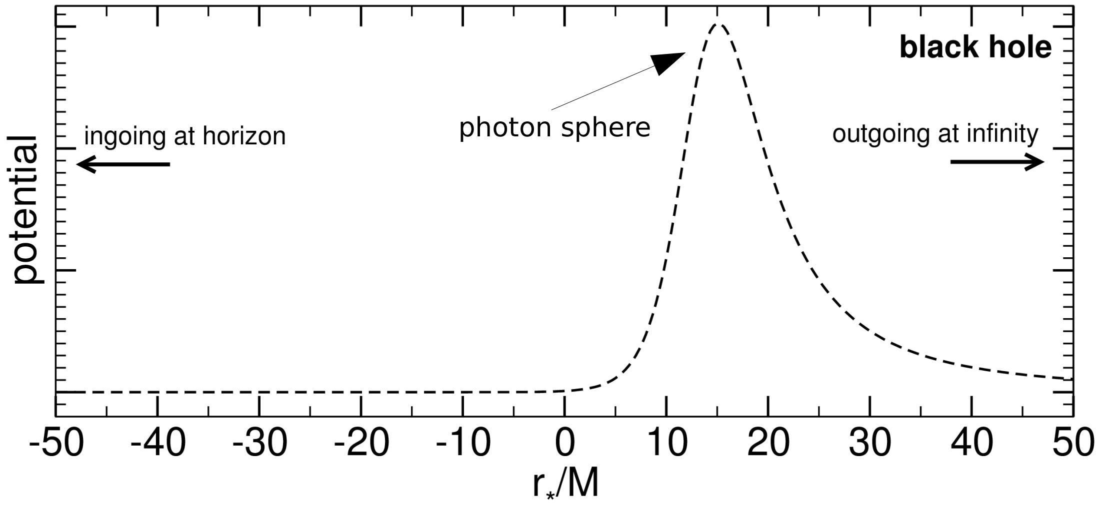
(note of caution: QNMs are not a complete set!)

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



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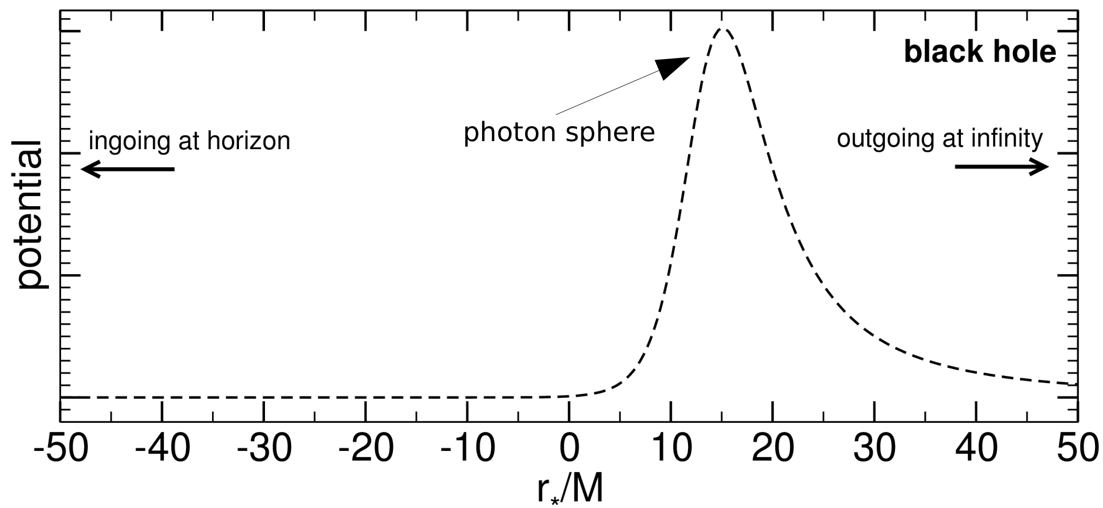
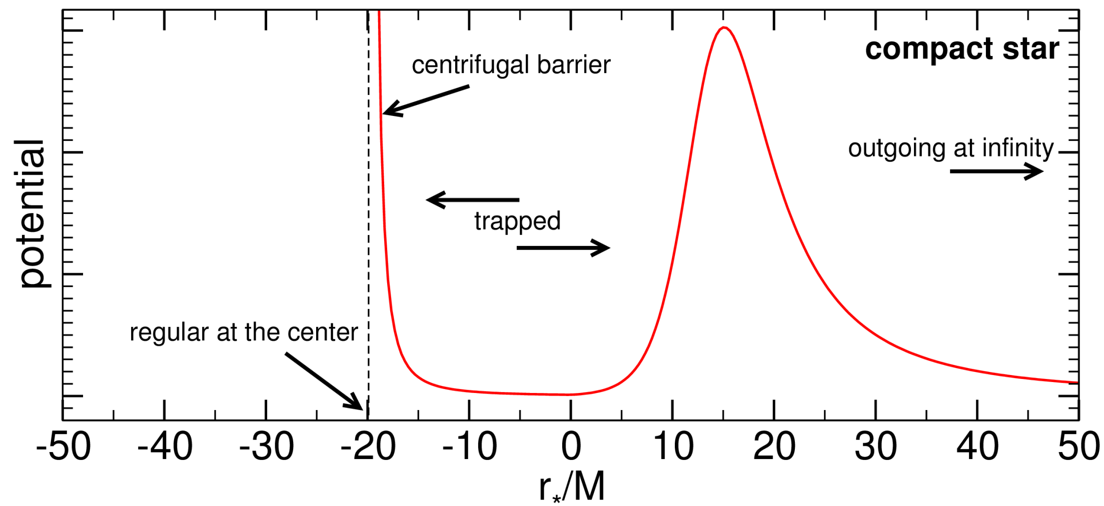


Ultracompact stars generically support trapped modes

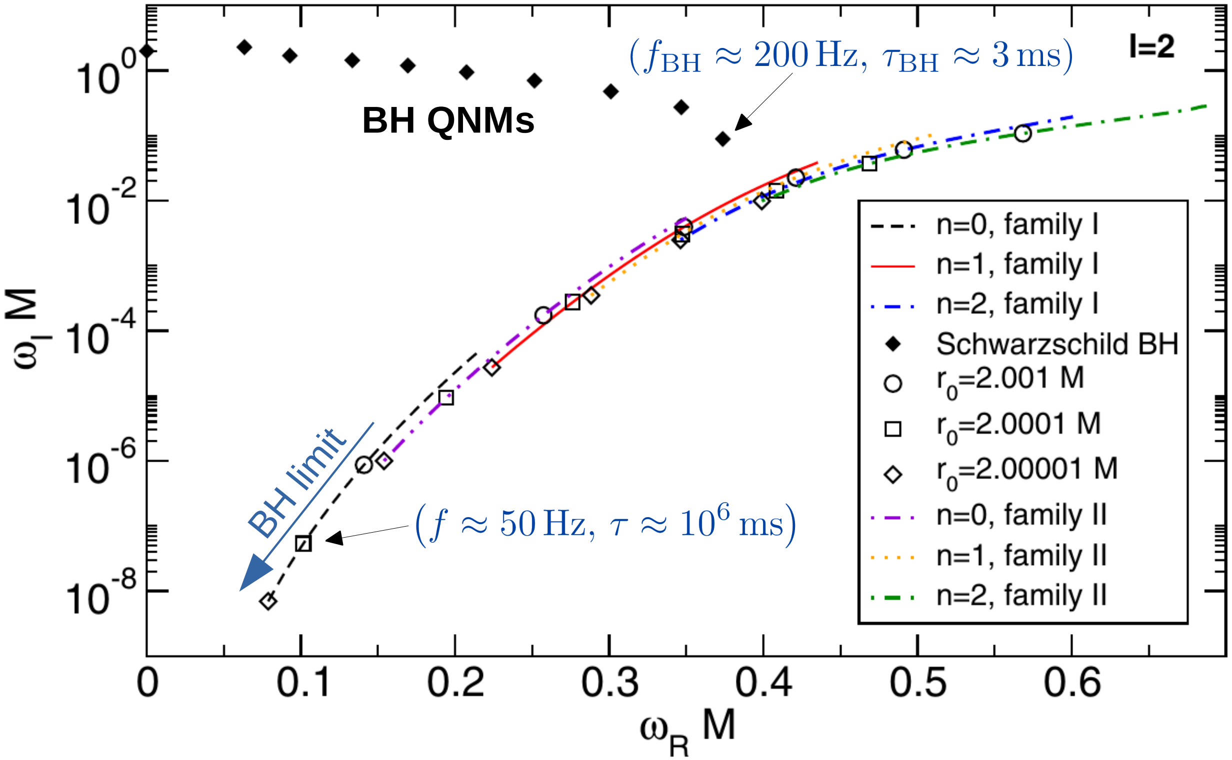
Chandrasekhar & Ferrari PRSLA (1991)



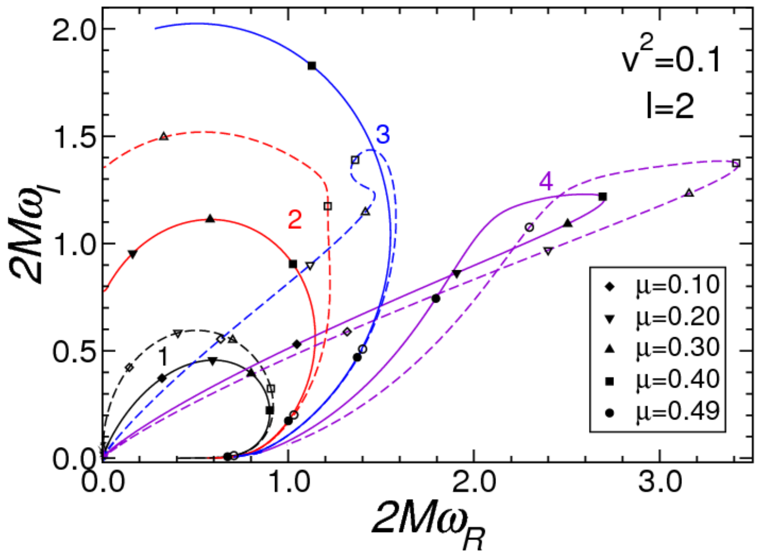
No horizon → different boundary conditions → different eigenvalues

QNM spectrum of an ECO

Wormhole



Gravastar



[e.g. Pani+, PRD80 (2009) 124047]

- Long-lived modes in the BH limit
- QNM spectrum dramatically different → ringdown?
- No BH-like QNM!
- Generic feature of ultracompact objects

BH limit:

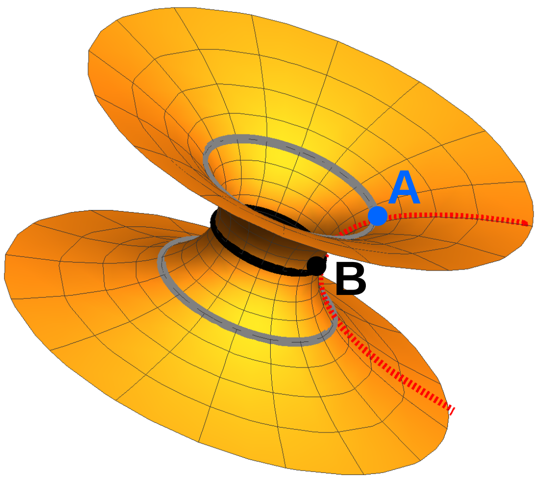
$$r_0 \equiv r_+ + \delta \to r_+$$

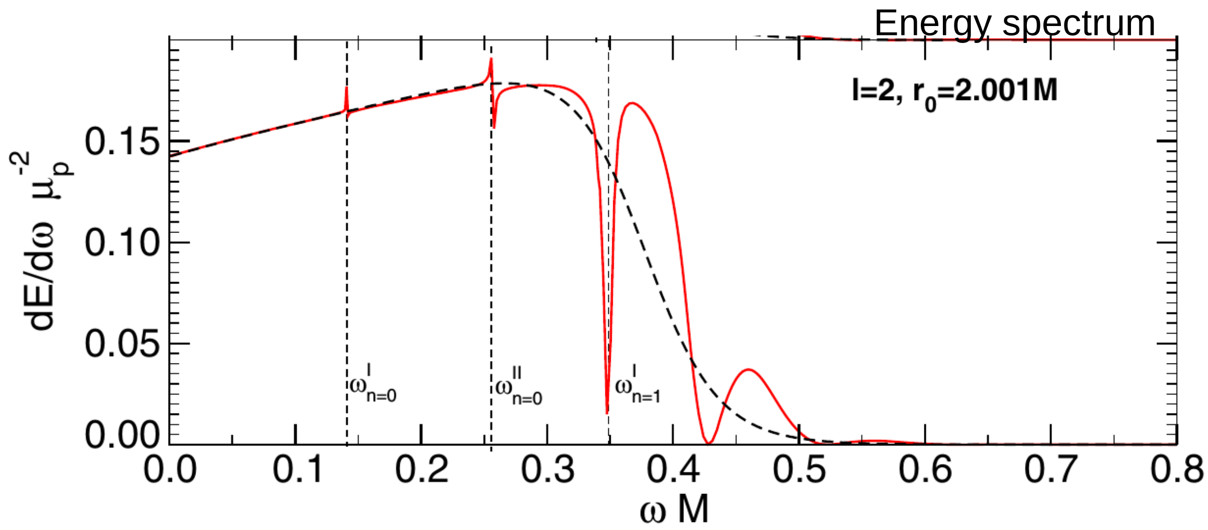
$$\omega_R M \sim -[\log \delta/M]^{-1}$$

$$\omega_I M \sim (\delta/M)^p$$

Radial plunge into a wormhole

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





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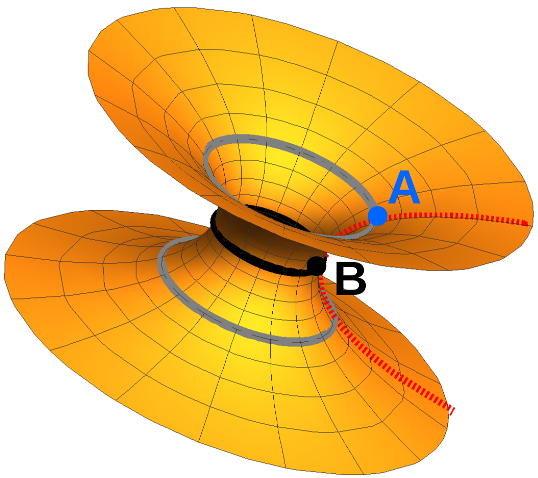
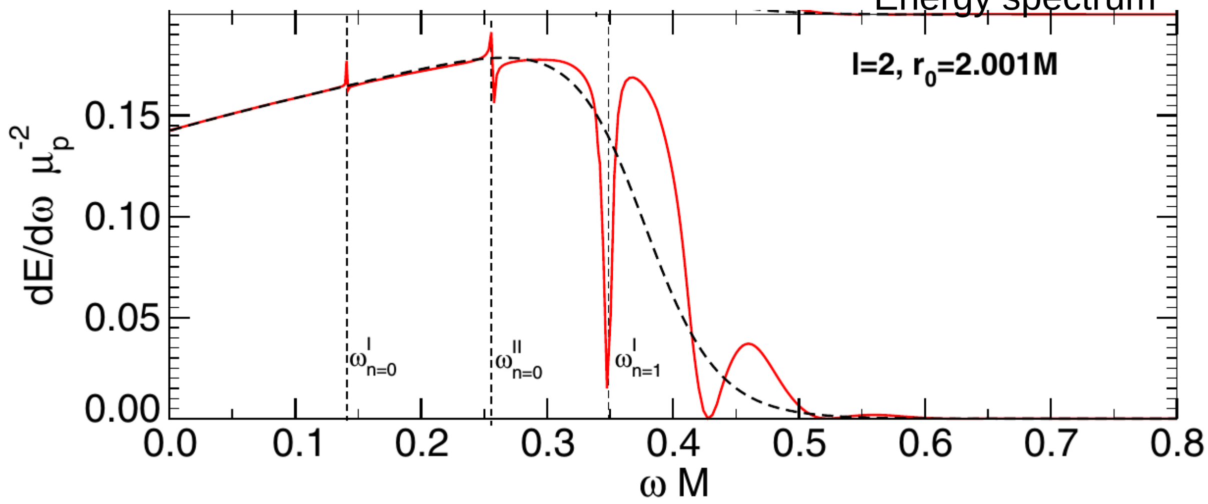
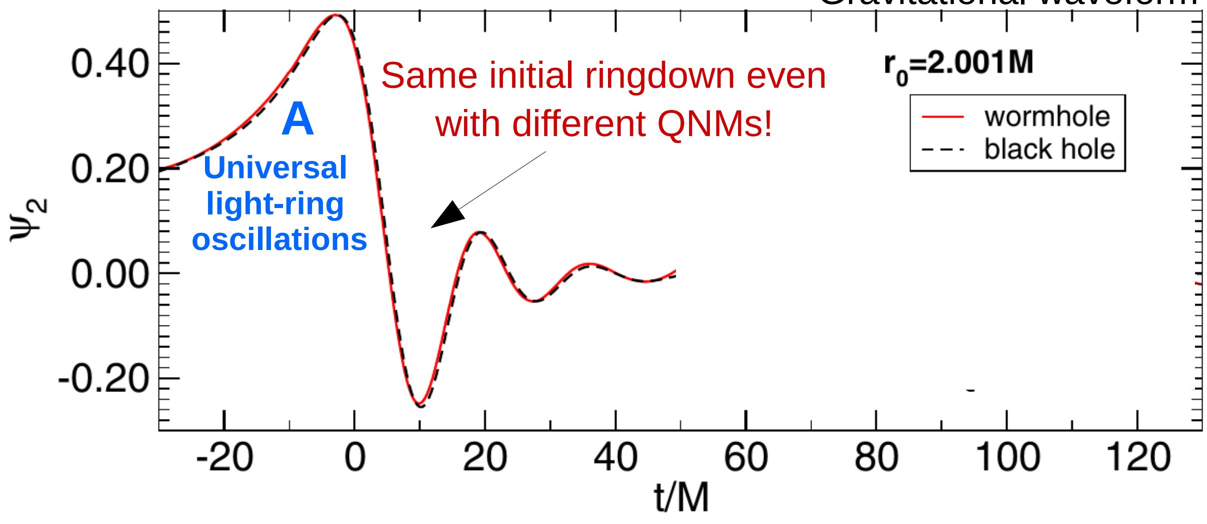


Energy spectrum



Gravitational waveform



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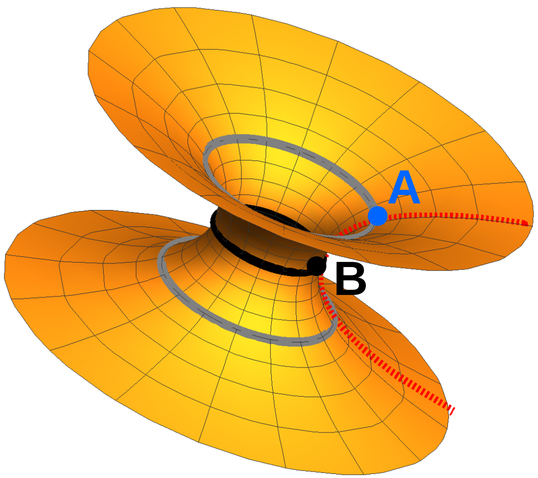
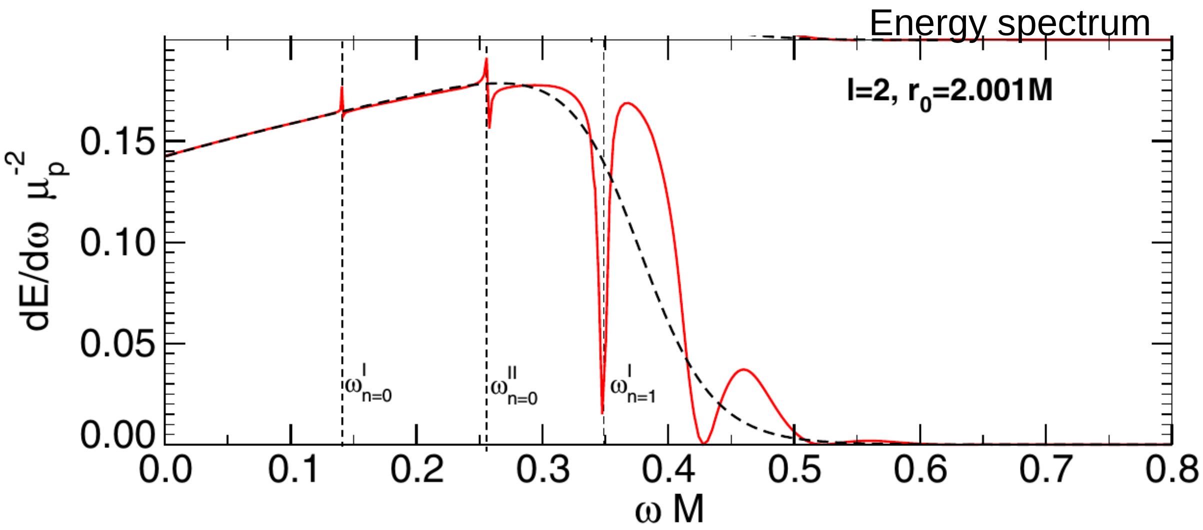
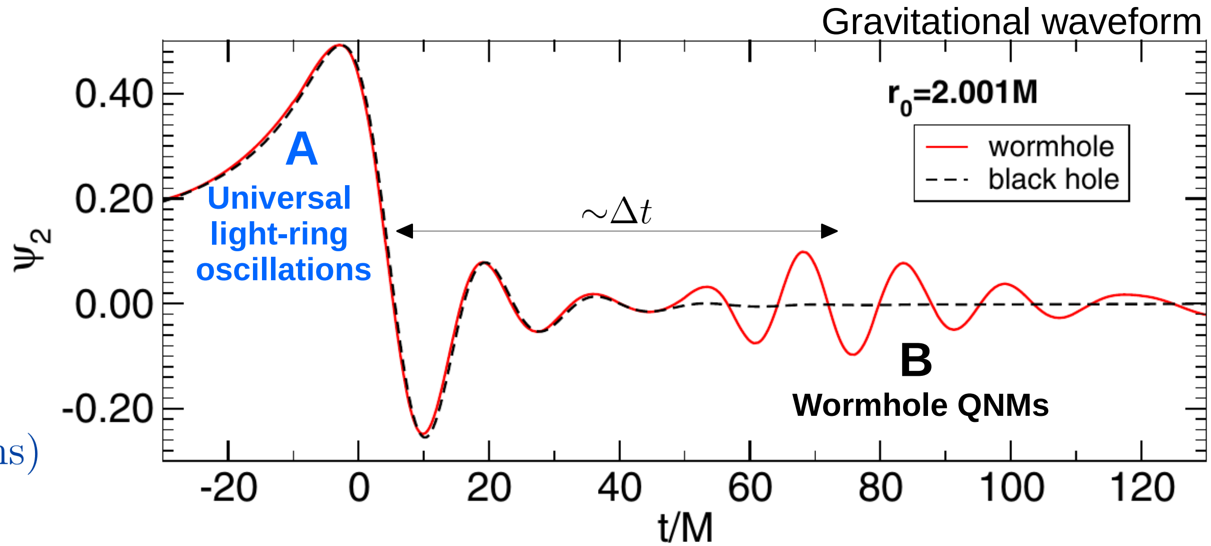




$$\Delta t = \int_{r_0}^{3M} \frac{dr}{F} \sim 2M \log\left(\frac{r_0}{M} - 2\right)$$

Delay time

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



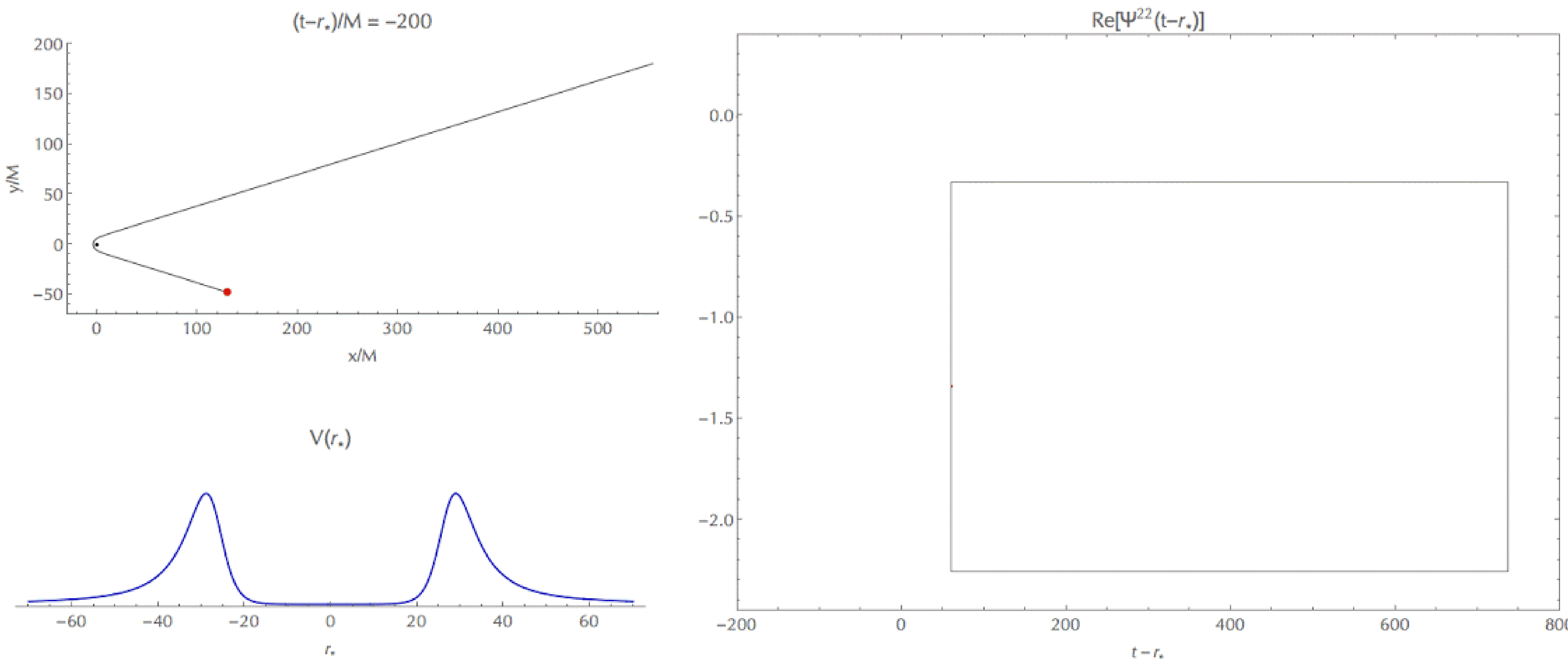
Even Planck-scale corrections near horizon are within reach!

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

The role of the photon sphere

V. Cardoso, S. Hopper, C. Macedo, C. Palenzuela, P. Pani; PRD94 084031 (2016)

$\mathcal{E} = 1.5$, r_{min}=4.3M, $r_0 - 2M = 10^{-6}M$

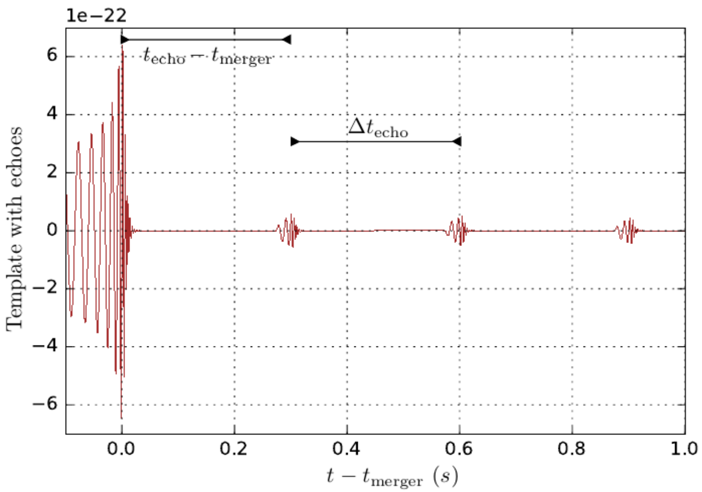


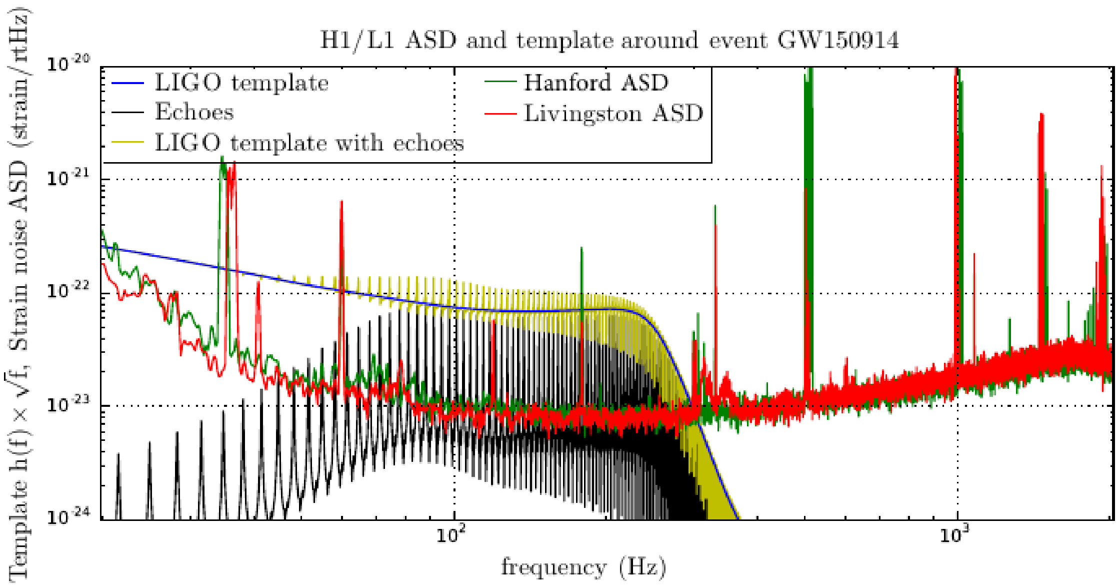
[Credits: Seth Hopper]

- Generic features for ultracompact ECOs (wormholes, gravastars,ultracompact stars, ...)
- The ringdown of ECOs without light ring is *qualitatively* different [Ferrari & Kokkotas, PRD 2000]
- GW observations can rule out less compact ECOs without light ring [Chirenti & Rezzolla, PRD 2016]

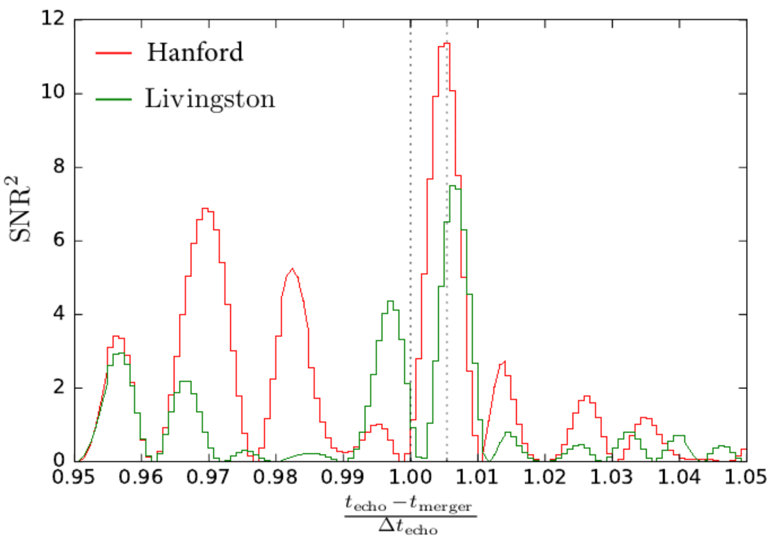
GW echo in aLIGO data?

Abedi, Dykaar, Afshordi, 1612.00266



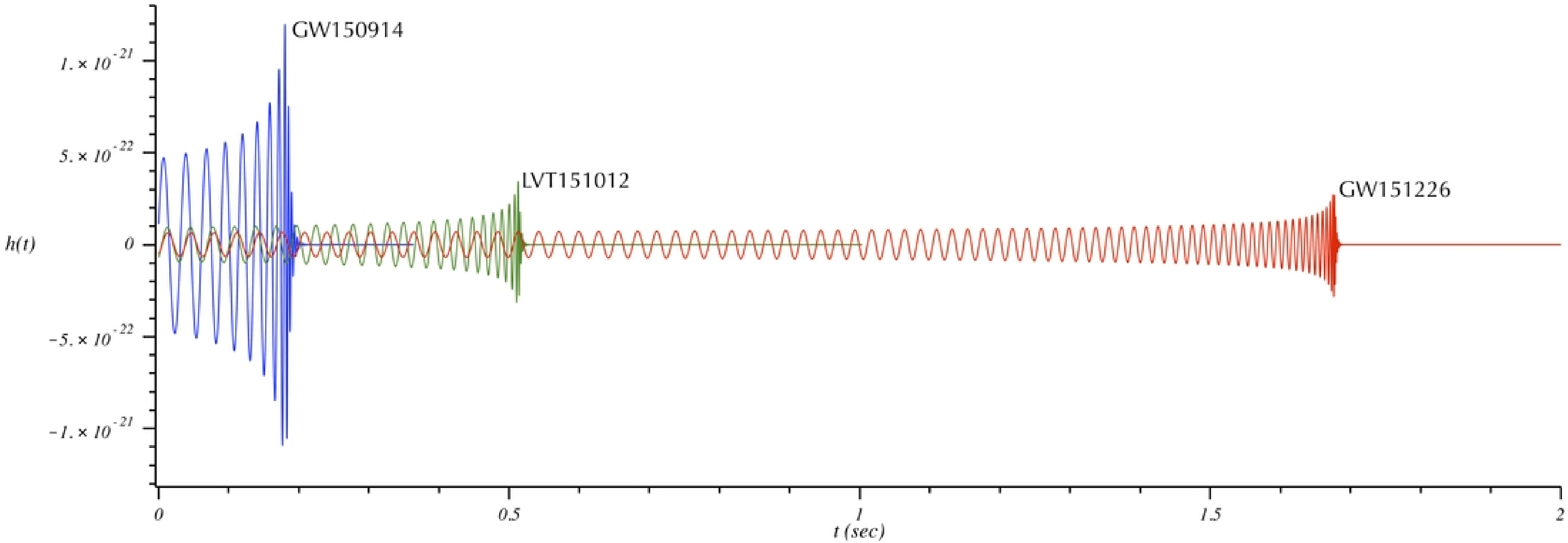


- Claimed significance at ~(2.6-2.9)σ
- Limitations in the analysis Ashton+, 1612.05625
- Limitation in the model: distortions, spin, ...



More work is required, but quantum corrections are within reach

Part II
GW signatures of ECOs in the inspiral phase



based on

gr-qc/1701.01116 (PRD in press) + work in progress

Post-Newtonian inspiral: BH VS ECO

- Gravitational waveform in the frequency domain:

$$1\mathrm{PN} = \frac{v^2}{c^2}$$

$$\tilde{h}(f) = \mathcal{A}(f) e^{i(\psi_{\rm PP} + \psi_{\rm TH} + \psi_{\rm TD})}$$

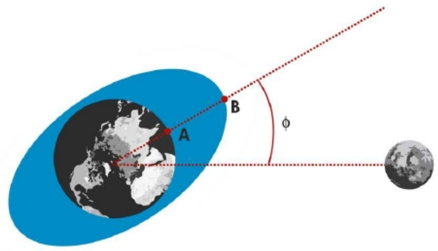
- Point particle contribution:

$$\psi_{\rm PP} \sim \psi_{\rm Newtonian} + \underbrace{\chi_i \psi^{1.5\rm PN}_{\rm spin-orbit}}_{\text{Linear in spin}} + \underbrace{\chi_i \chi_j \psi^{2\rm PN}_{\rm spin-spin}}_{\text{Quadratic in spin → include quadrupole}} + \cdots$$

- Tidal heating at the horizon: $\dot{E}^{\rm heating}_{\rm BH} \sim \dot{E}_{\rm GW} v^8$

$$\psi_{\rm TH} \sim \underbrace{(\Omega - \Omega_H)}_{\text{superradiance}}\Omega \sim \underbrace{\chi \psi^{2.5\rm PN}_{\rm TH}}_{\text{Linear in spin}} + \underbrace{\psi^{4\rm PN}_{\rm TH}}_{\text{nonspinning}}$$

Alvi PRD 2001, Poisson, PRD 2009



Cardoso & Pani 2013
Brito, Cardoso, Pani “Superradiance” (2015)

- Tidal deformability and tidal Love numbers:

$$\psi_{\rm TD} \sim \frac{2}{3} m_i^5 k_i \psi^{5\rm PN}_{\rm TLN}$$

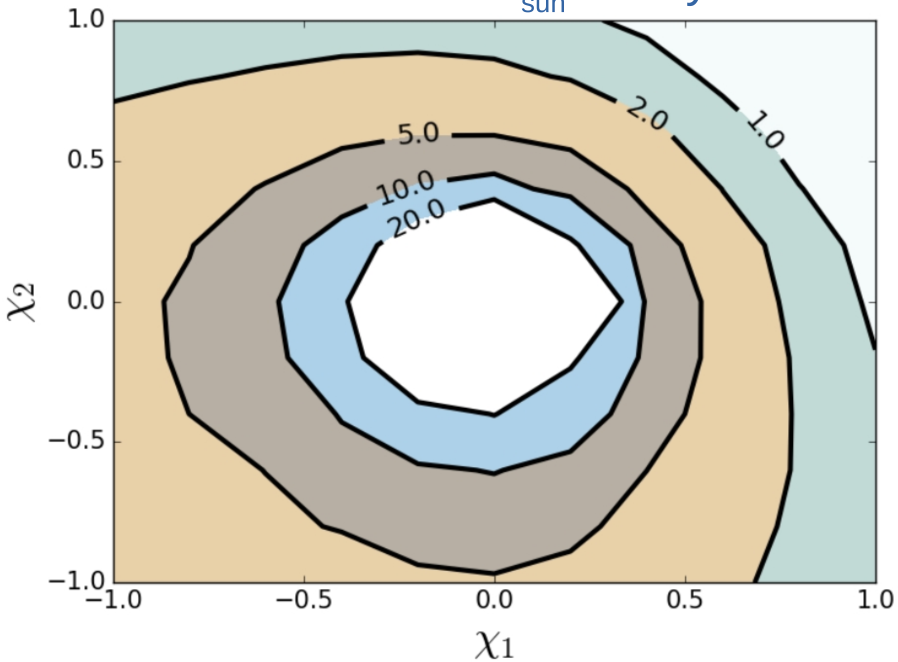
$$\underbrace{k_i = \frac{\text{induced quadrupole moment}}{\text{external tidal field}}}_{\text{tidal Love Number}}$$

BH vs ECO: quadrupole moment

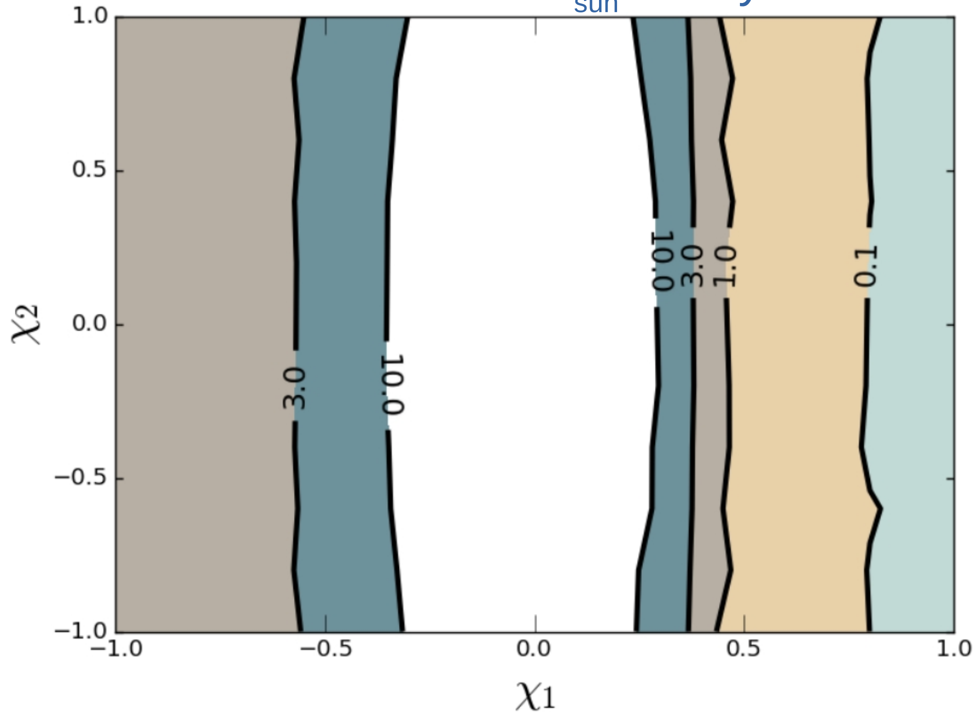
Krishnendu, Arun, Mishra, 1701.06318

$$Q = -\kappa m^3 \chi^2$$

aLIGO: 10 M_{sun} binary



LISA: 10^6 M_{sun} binary



- Analysis valid only for small spin
- Ultracompact gravastars and other ECOs have the same Q as Kerr!

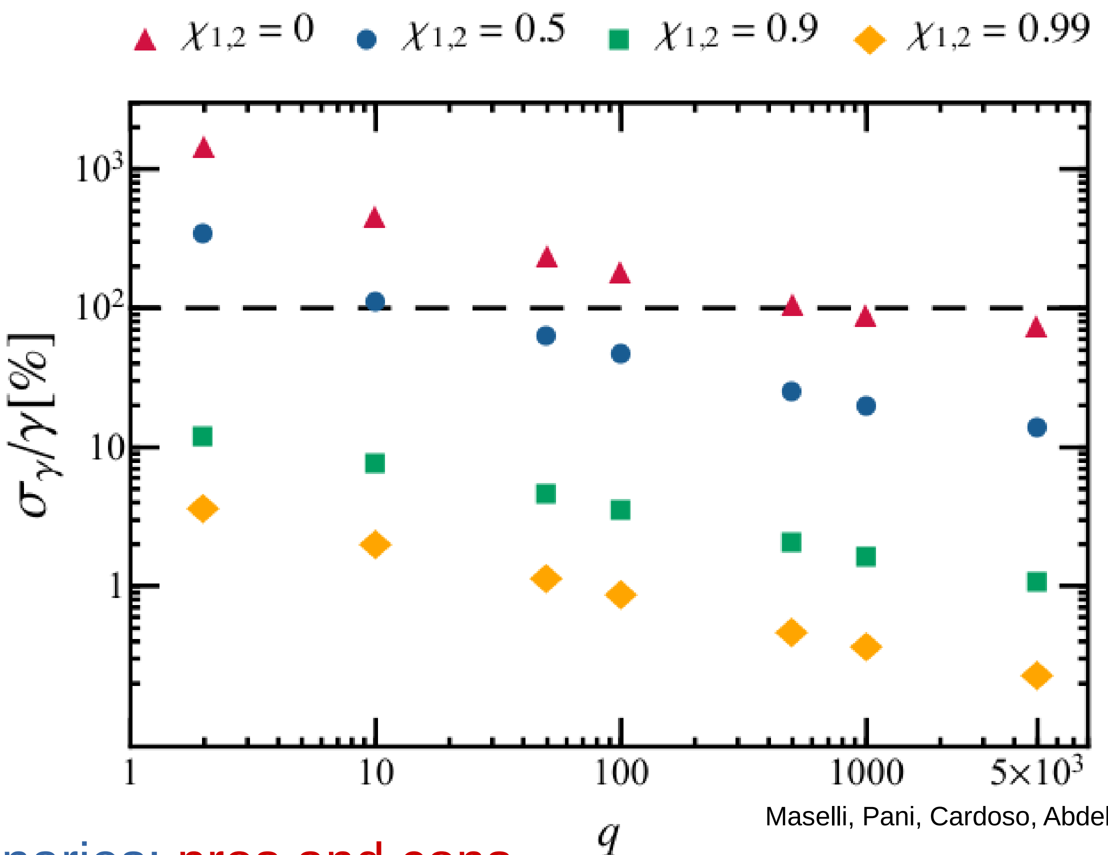
Pani, Phys.Rev. D92 (2015) 124030

BH VS ECO PN inspiral: heating

- BHs can absorb/amplify radiation at the horizon

$$\psi_{\rm TH}^{\rm BH} = \frac{5\left(1+q^4\right)}{48q(1+q)^2}(\pi f m)[1-\log(\pi f m)]$$

- Tidal heating is absent for ECOs



Maselli, Pani, Cardoso, Abdelsalhin, Gualtieri, Ferrari, 1703.10612

- Spinning binaries: pros and cons

BH vs ECO: Love numbers

Cardoso, Franzin, Maselli, Pani, Raposo, 1701.01116 (PRD in press)

- Love Numbers (TLNs) of a BH are zero

Binnington & Poisson, 2009; Damour & Nagar 2009; Gürlebeck 2015; Pani+, 2015

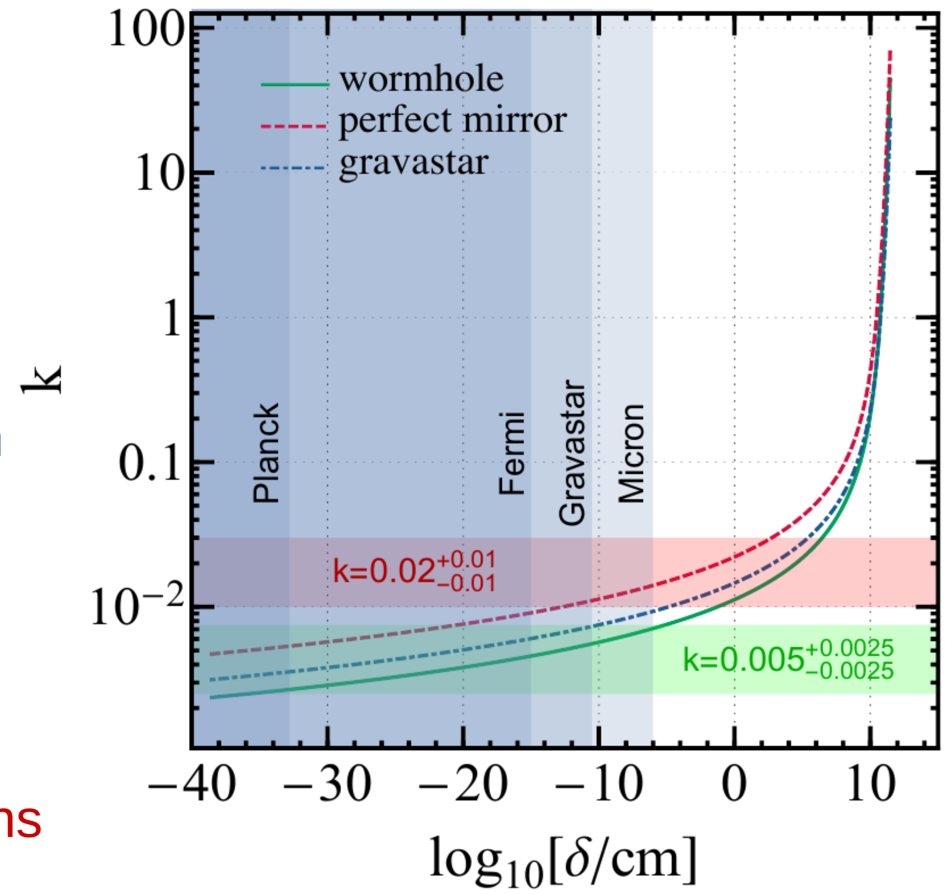
- Love numbers of an ultracompact object:

$$k_l \sim [\log \delta/M]^{-1}$$

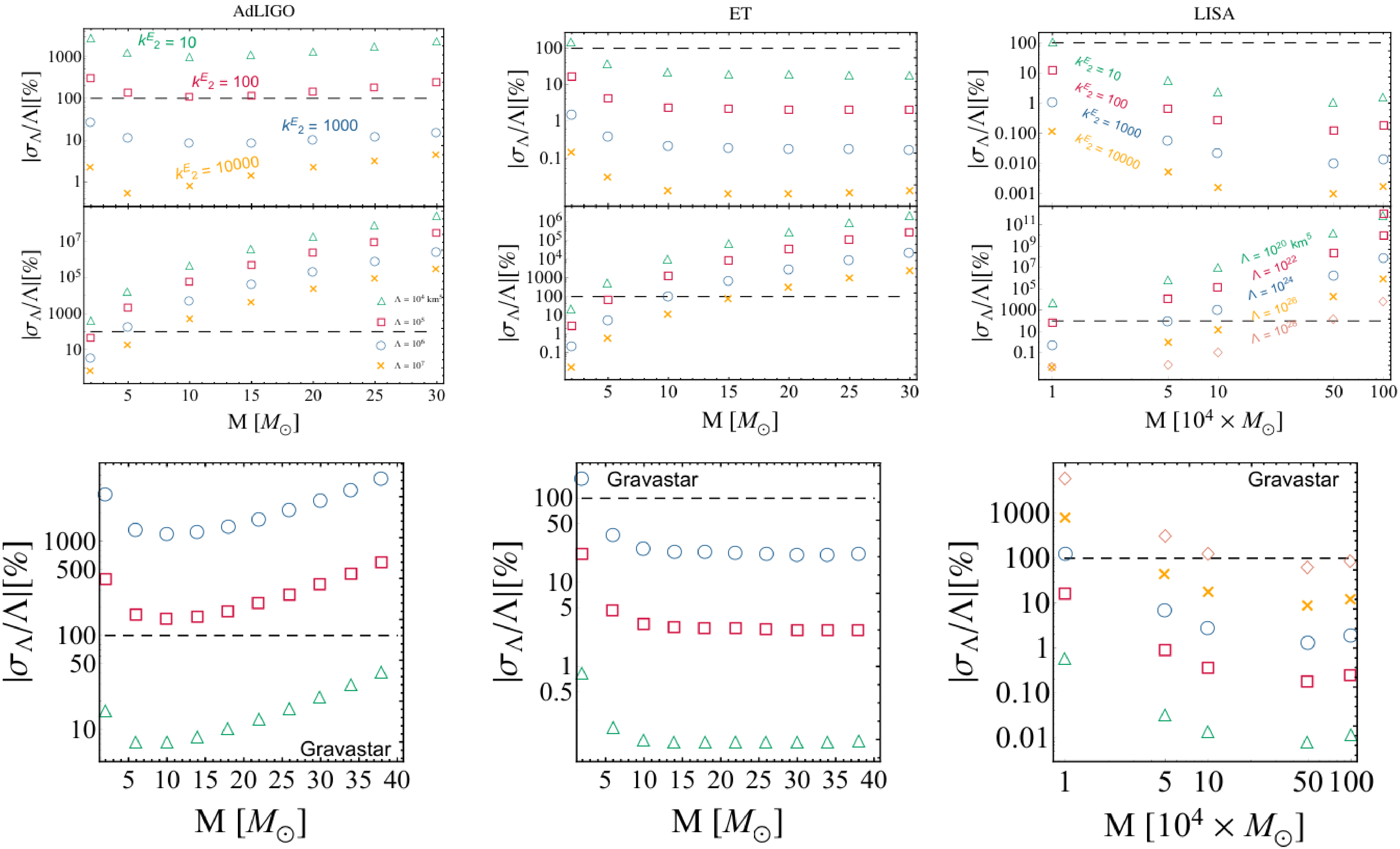
- Measurement of the TLN translates into an estimate of the distance of the ECO surface:

$$\delta \sim 2Me^{-1/k}$$

- k~0.005 in order to probe Planck corrections

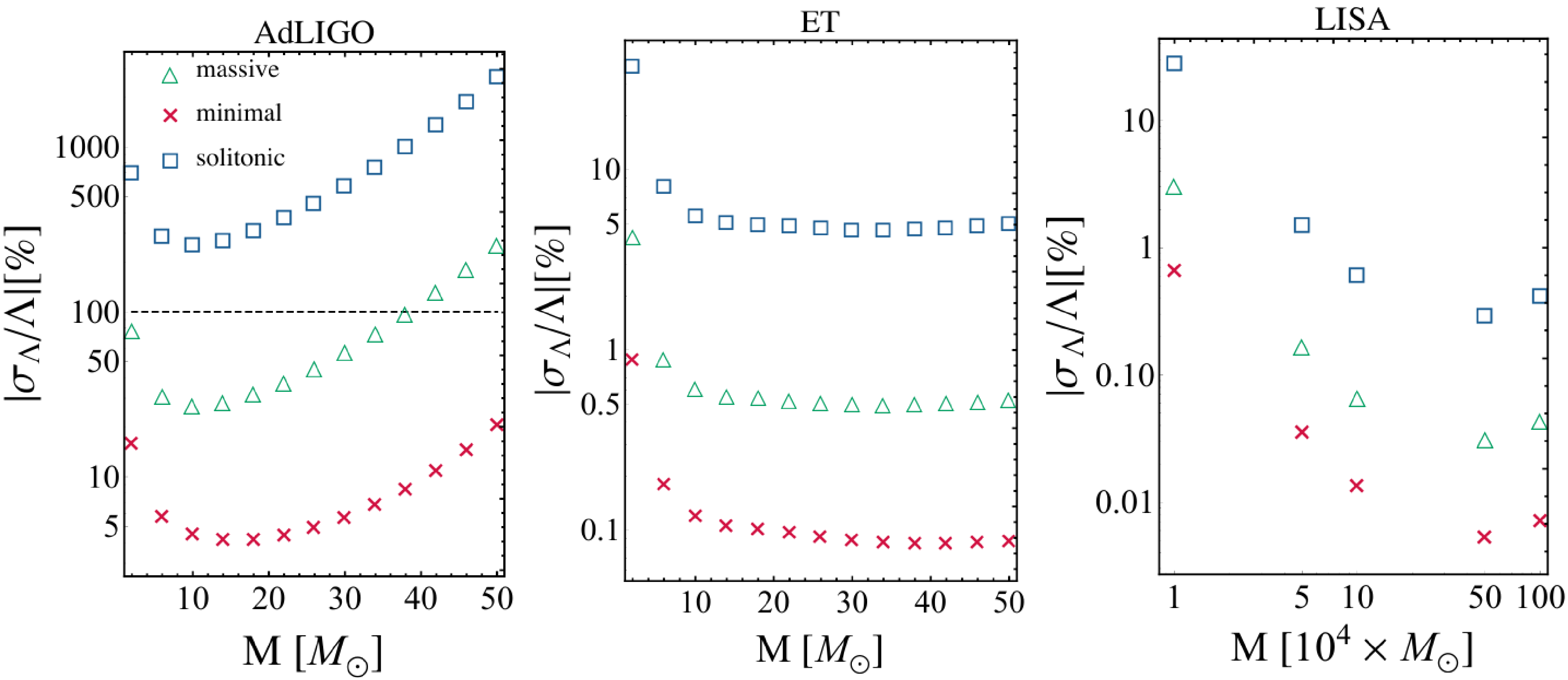


BH vs ECO: Love numbers



BH vs Boson Stars: Love numbers

$$\mathcal{L} = \frac{R}{16\pi G} - \partial_\mu \phi^\mu \phi^\star - m^2|\phi|^2 + \lambda|\phi|^4 + \gamma|\phi|^6 + \ldots$$



- aLIGO can exclude only BS models with small compactness
- LISA will be able to distinguish between BHs and any BS model

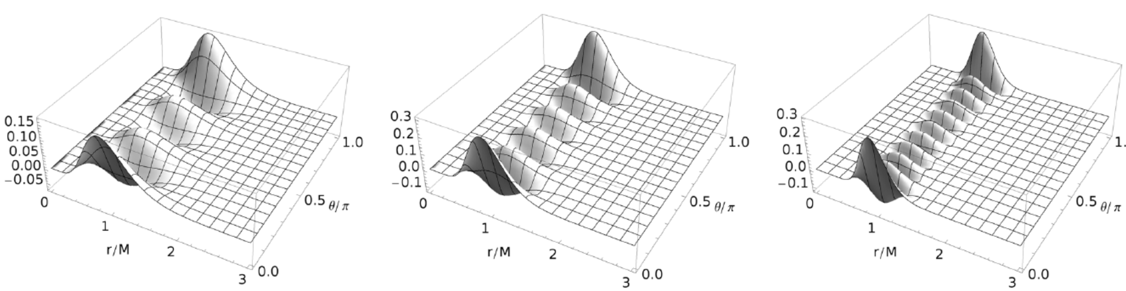
Part III
Ergoregion instability of ECOs and How to Quench It

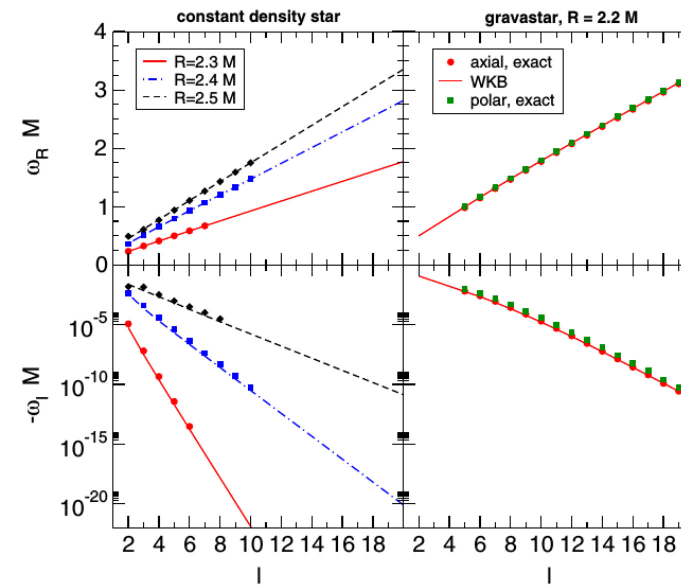
based on

E. Maggio, P. Pani, V. Ferrari, gr-qc/1703.03696

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)]



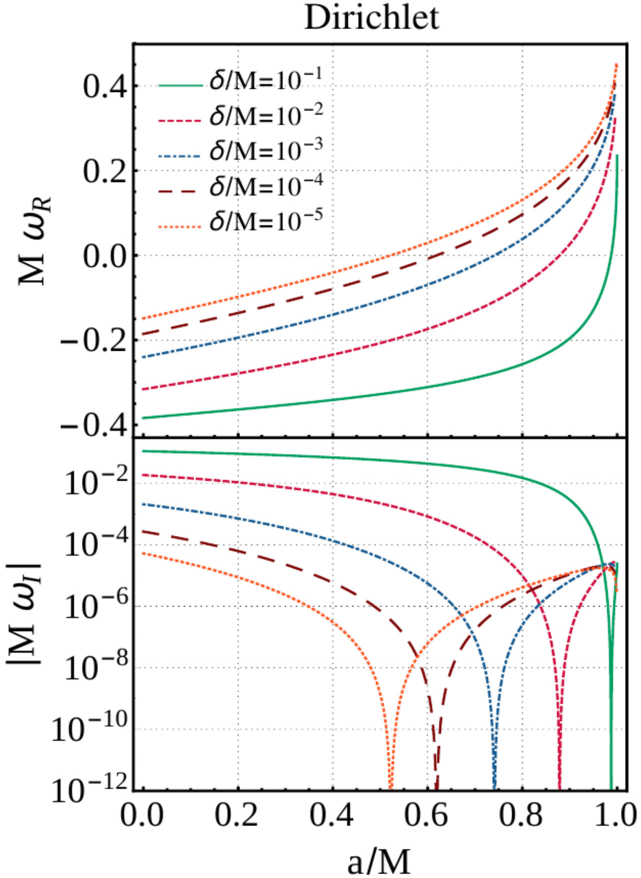


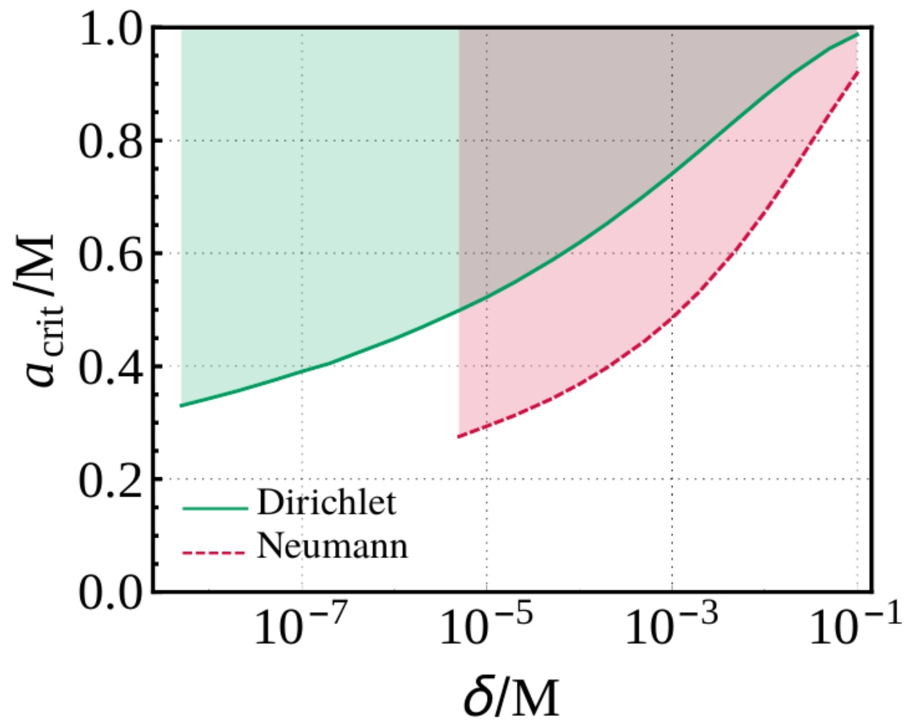
- matter oscillations? [Yunes, Yagi, Pretorius; Phys.Rev. D94 (2016) 084002]
- Maximum mass: ECO + ECO → ECO or BH?

Ultracompact exotic objects seem very fragile

Ergoregion instability of an ECO

- Toy model: Kerr metric + reflective surface at $r = r_0 = r_+ + \delta$
- Scalar perturbations $\Box\Psi = 0 \Rightarrow \frac{d^2Y}{dz^2} + VY = 0$
- Near the surface: ingoing and outgoing waves $Y(r_0) \sim A_{\rm out} e^{ikz} + A_{\rm in} e^{-ikz}$
- Different boundary conditions at the surface: $Y(r_0) = 0$ Dirichlet $\quad dY(r_0)/dz = 0$ Neumann

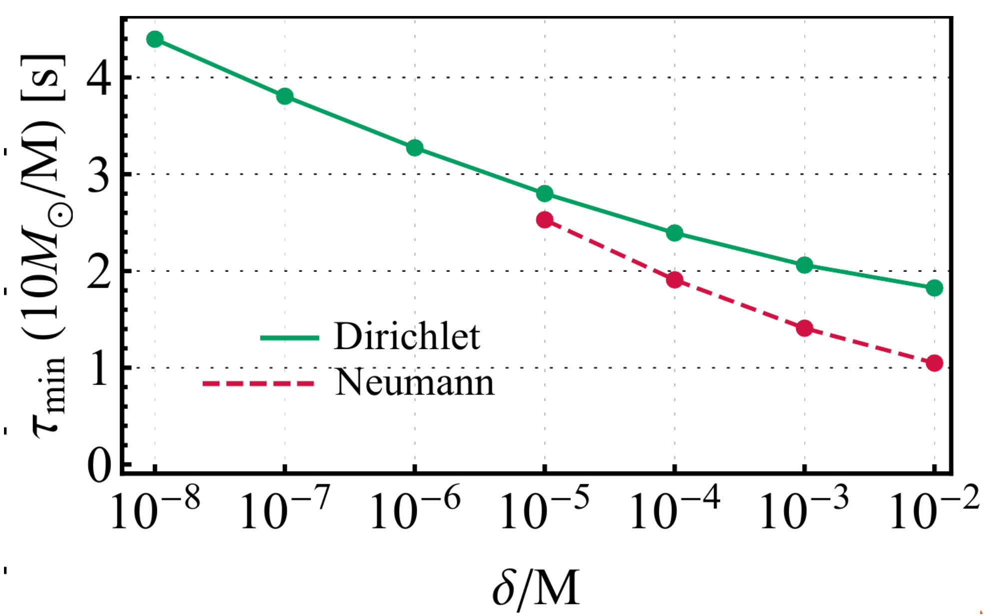


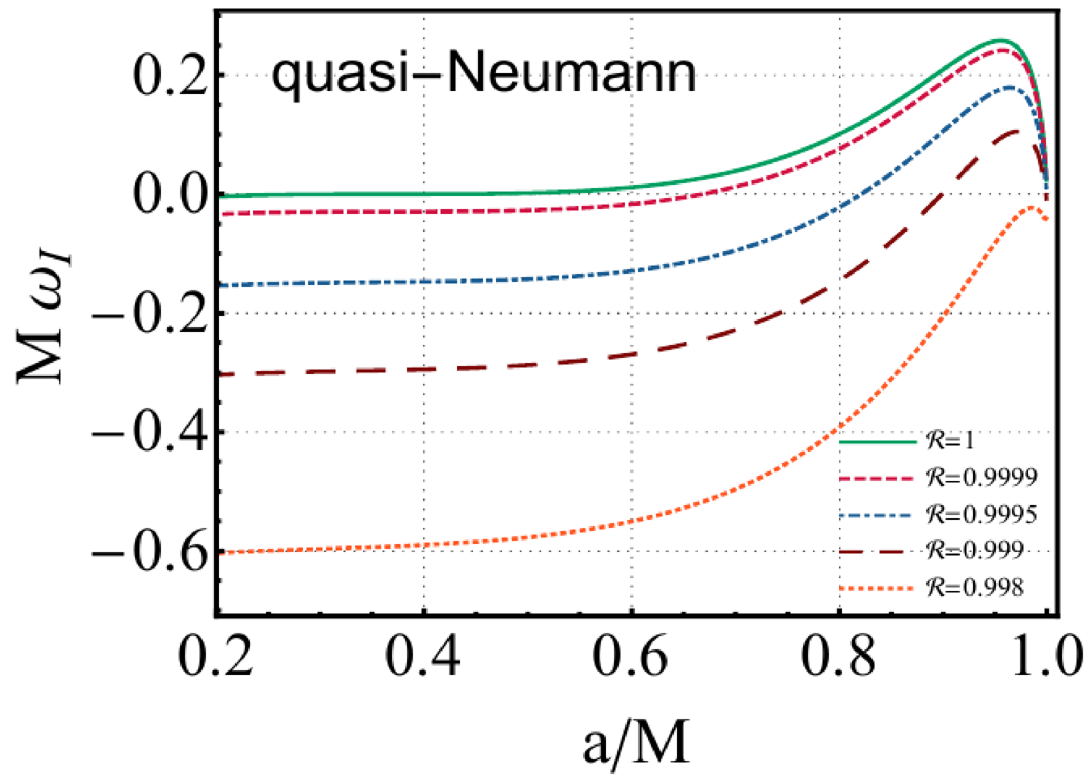


$\tau_{\rm instability} \sim 10^5 M \sim 5\,(M/10M_\odot)$ s

Ergoregion instability is fragile

- Time scale (slightly) increases with compactness
- Partial reflection at the surface: $\mathcal{R} \rightarrow$ reflection coefficient





- Matter viscosity introduces absorption [Esposito, 1972]

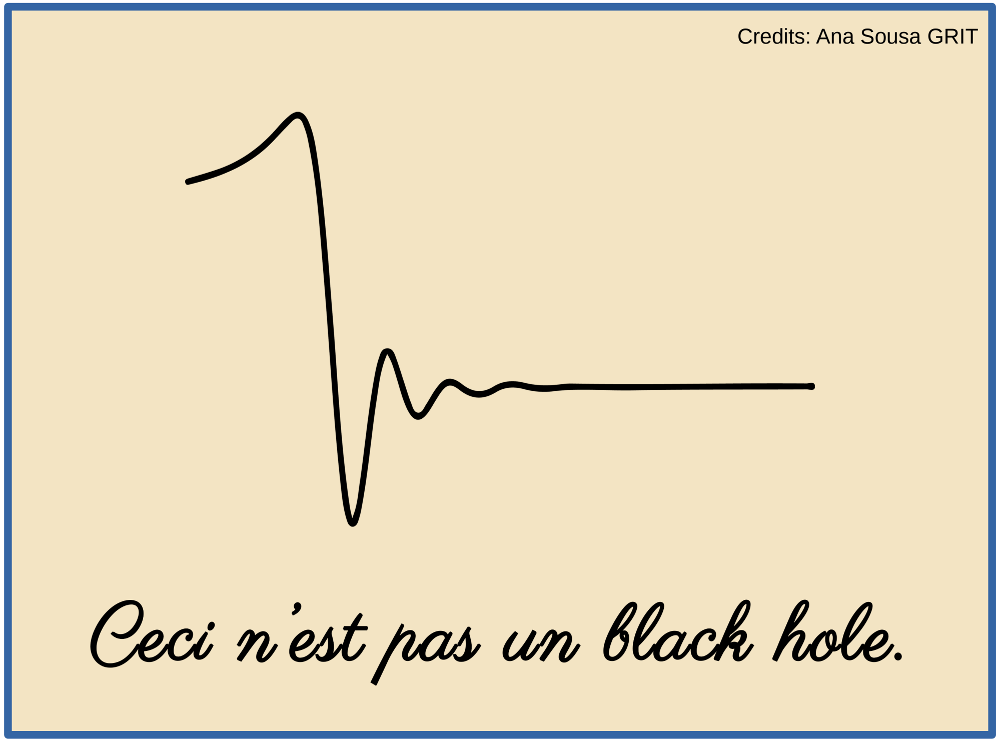
$$e \approx 0.004 \left(\frac{M}{r_0}\right)^{27/4} \left[\frac{10^3\,K}{T}\right]^3 \sqrt{\frac{0.01}{\omega M}} \left(\frac{20 M_\odot}{M}\right)^4$$

Conclusion & Outlook

- GW astronomy: first opportunity to look for new physics at the horizon scale
- Generic features of exotic compact objects:
  - GW echoes in the post-merger ringdown waveform
  - Early-time ringdown ≠ quasinormal modes
- Absence of tidal heating
- Logarithmically small tidal Love numbers
- GW15xxxx prove the existence of light rings → enough?
  - Ergoregion instability might be quenched by small absorption
- Open problems: Formation? Other instabilities? Full coalescence?

GW astronomy: expect the unexpected?

Thank you!

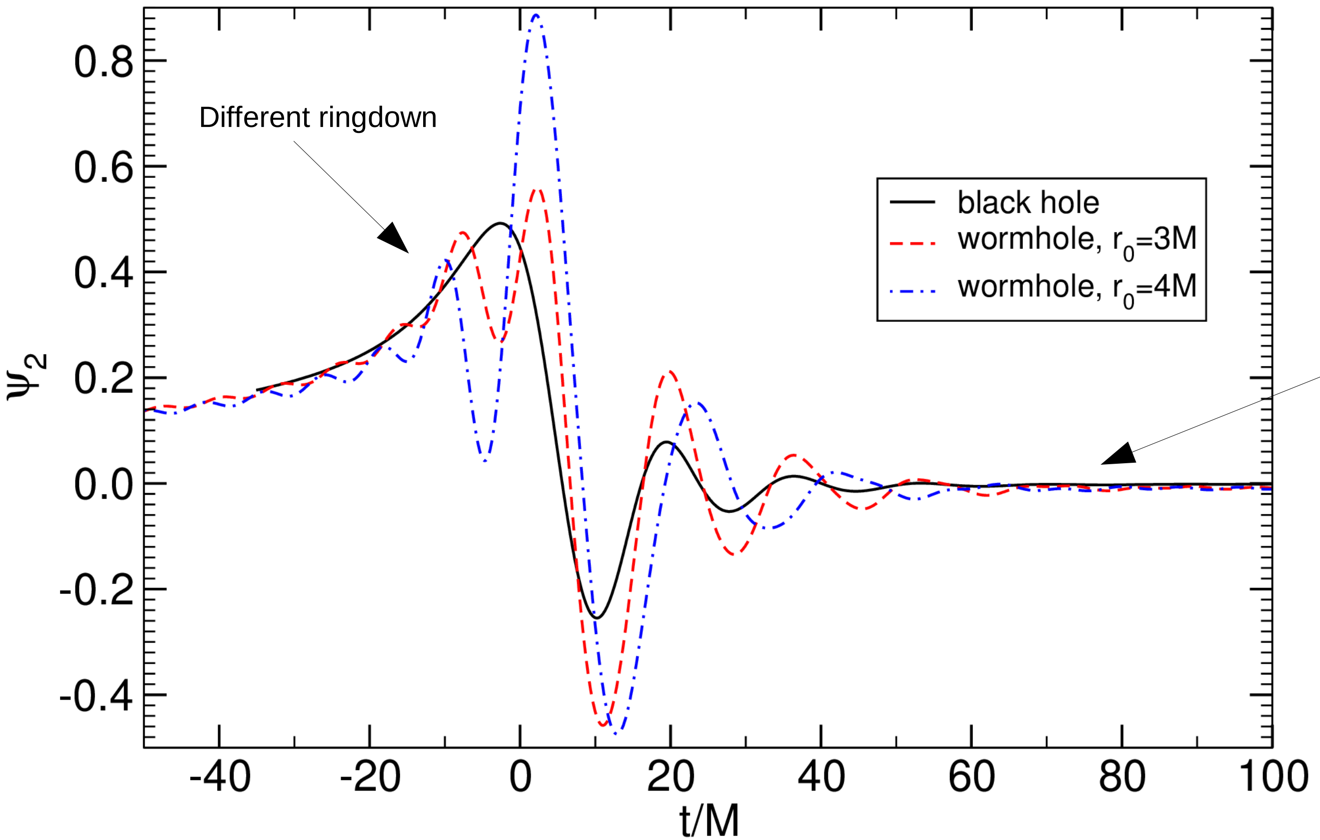


Backup slides

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

The importance of the photon sphere

- 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]