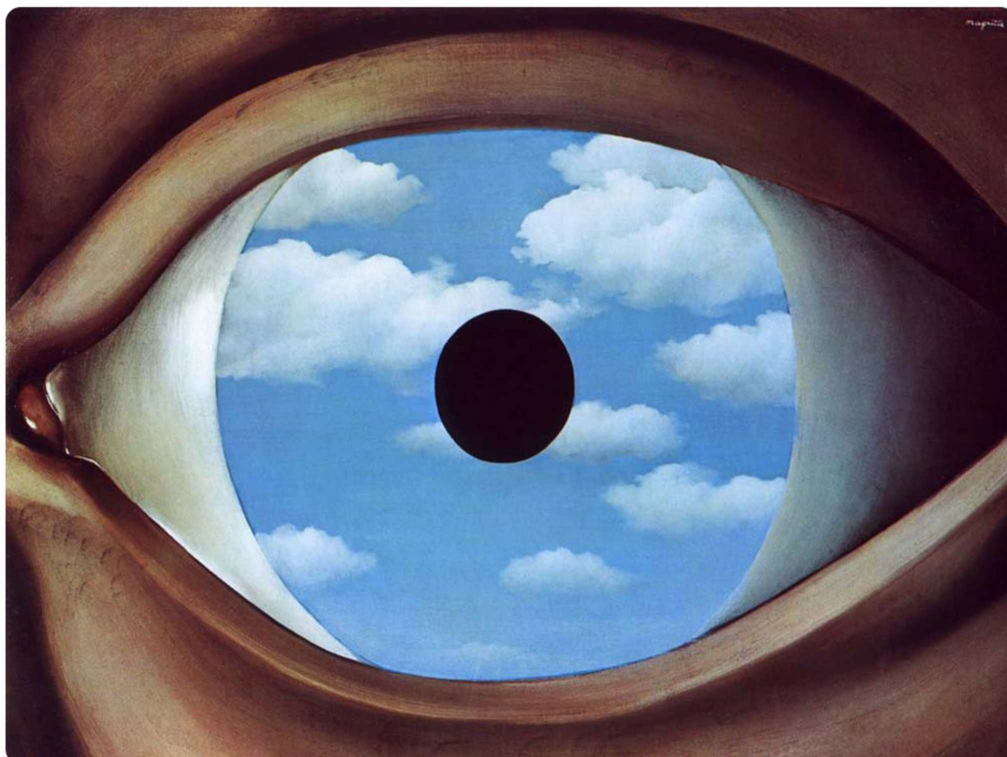
PACTS 2018 – Tallinn 18/06/2018

Testing the nature of compact objects with GWs



Paolo Pani
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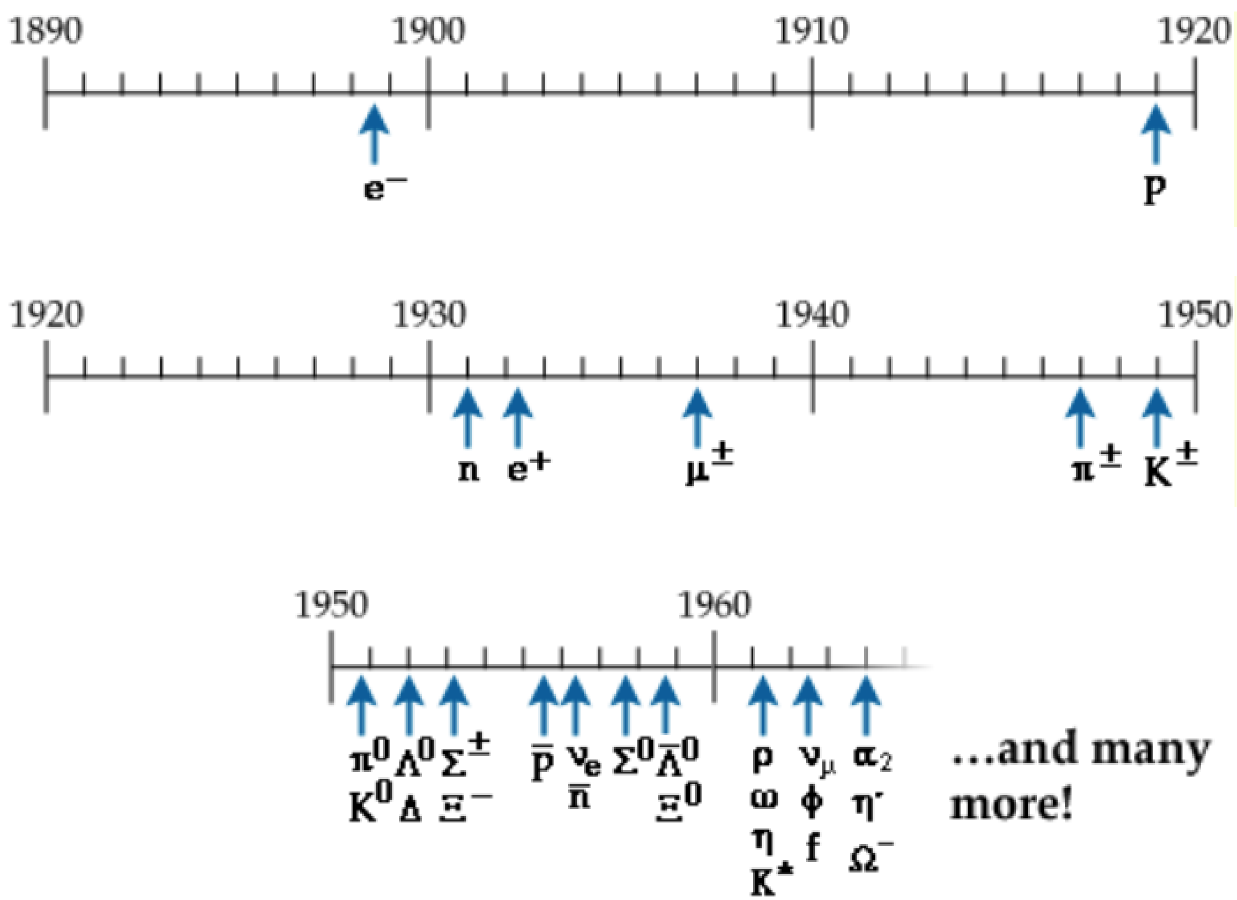
European Research Council erc

DarkGRA

Are exotica out there?

A lesson from particle physics



Are exotica out there?

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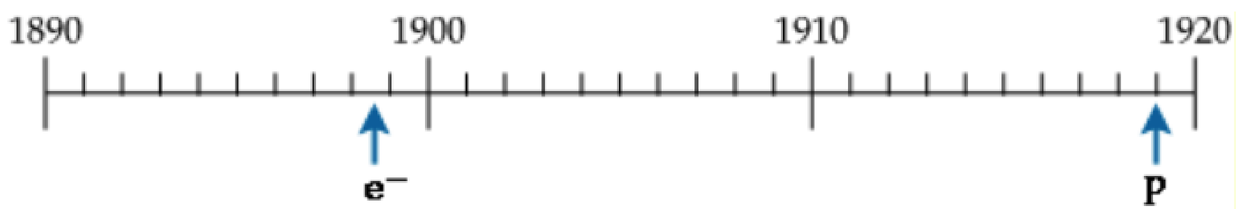
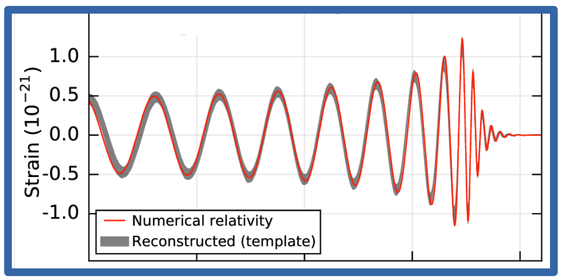
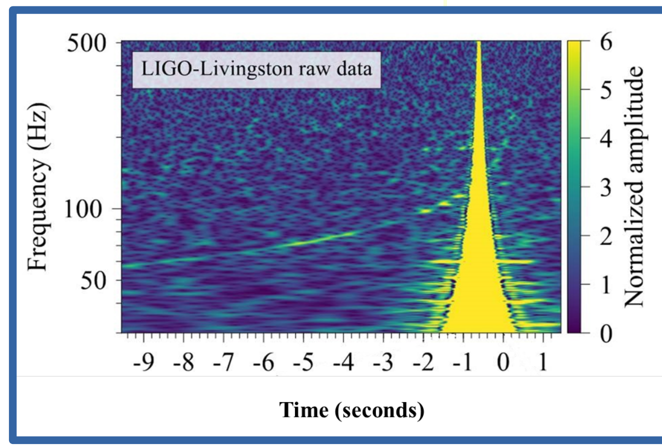




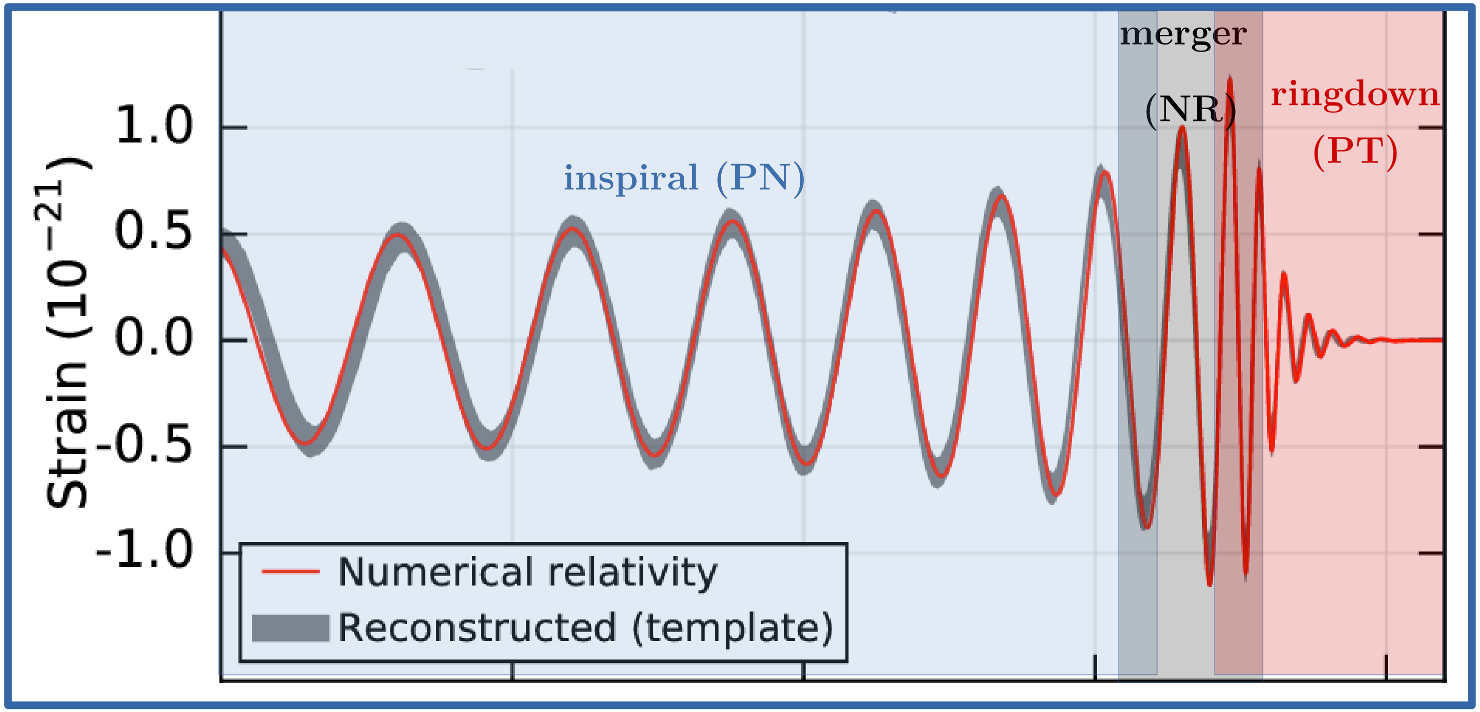
2015: BBHs



2017: BNSs

2020s: *What will the next specie of compact objects?*

The “hydrogen atom” of gravity



[LIGO-Virgo Collaboration, PRL 116, 061102 (2016), PRL 116, 221101 (2016), PRL 116, 241102 (2016), ...]

- Are they *BHs*? Are they *Kerr BHs*? Is *GR* correct @ extreme?
- Do other compact GW sources exist besides BBHs and BNSs?
- Inspiral-merger-ringdown phases can provide complementary diagnostics

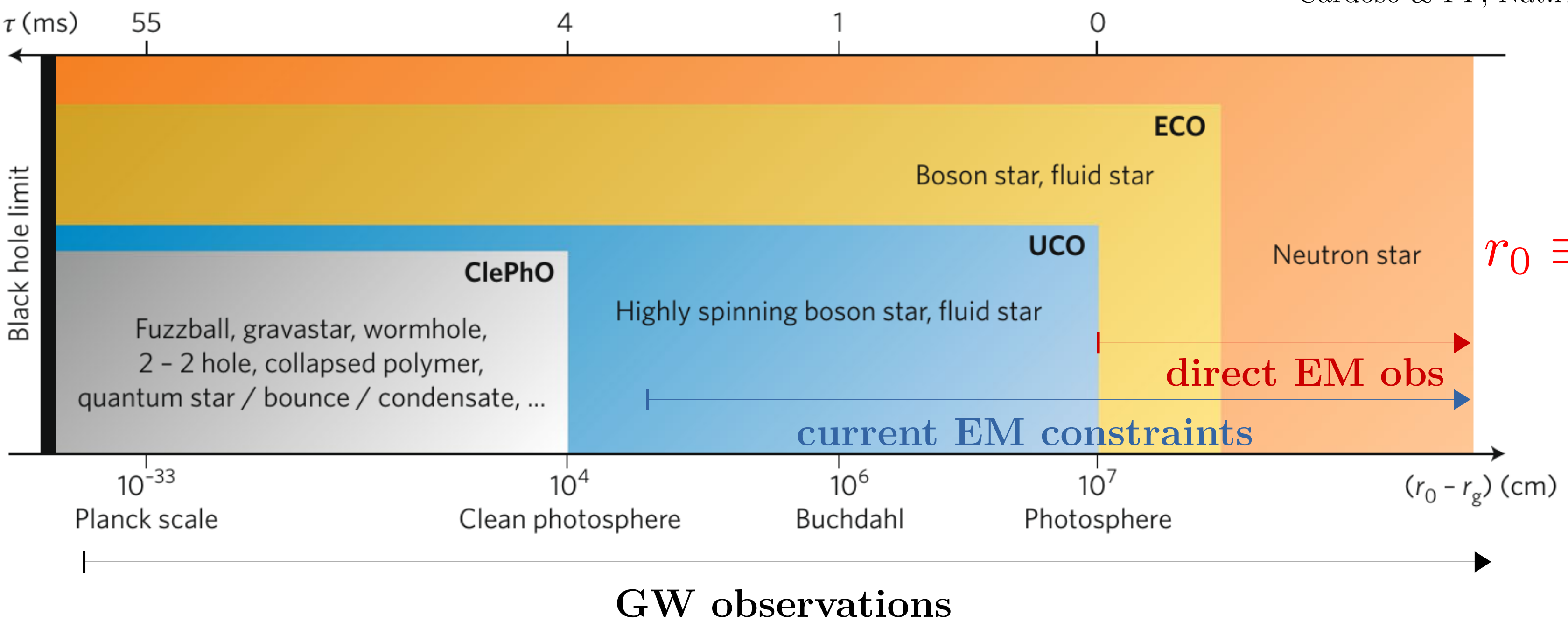
Problems at the horizon?

(G=c=1 units henceforth)

- BHs are very economical:
  - Arbitrary mass, Compactness $M/R \sim 1$, Easy to form, Linearly (mode) stable [Dafermos & Rodnianski; Clay Math.Proc. (2013)]
  - Consistent with *all* observations
- However:
  - **Singularity**, Cauchy horizon, closed-timelike curves...
  - BHs are *required* for self consistency of General Relativity [Cosmic Censorship]
  - Drawbacks: Huge entropy, **unitarity loss**, thermodyn. instability [Hawking 1972]
- Several models of semiclassical and quantum gravity or GR+exotic matter predict:
  - new physics at the horizon scale (e.g. *firewalls*) [Polchinsky+, Giddings+, 2012-2017]
  - horizonless compact objects (e.g. *fuzzballs*) [Mathur+, 2007-2017]

Exotic Compact Objects (ECOs)

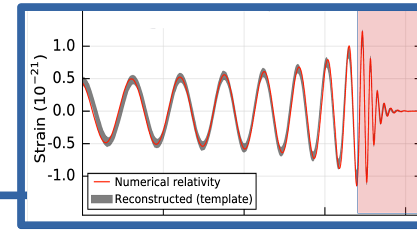
Cardoso & PP, Nat.Astron. 1 (2017) 586-591



$$r_0 \equiv \frac{2GM}{c^2}(1+\epsilon)$$

- GW observations can probe regions much closer to the horizon than EM
- Two classes of ECOs:
  - "Neutron-star like" (e.g. boson stars) $\rightarrow \epsilon \sim \mathcal{O}(1)$
  - "BH like" (e.g. fuzzballs, "quantum BHs") $\rightarrow \epsilon \sim 10^{-39} - 10^{-46}$
- Require a combination of targeted and agnostic searches

BH spectroscopy

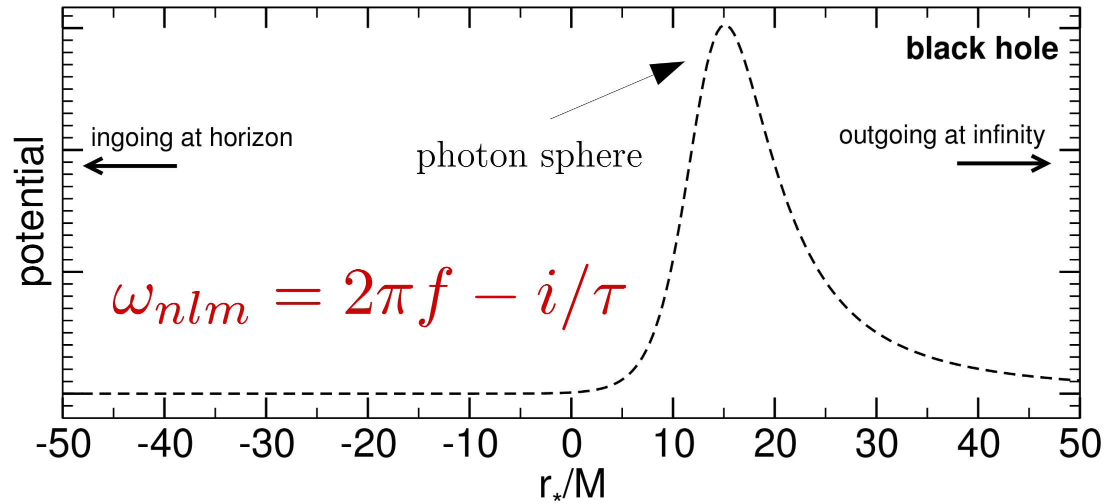


- Post-merger signal → superposition of QNMs [progress in modeling, e.g. Brito+ 1805.00293]

$$h_+ + i h_\times \sim \sum_i A_i \sin(2\pi f_i t + \phi_i) e^{-t/\tau_i}$$

$$\frac{\partial^2 \Psi}{\partial r_*^2} + [\omega^2 - V_{lm}(r_*)]\Psi = 0$$

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



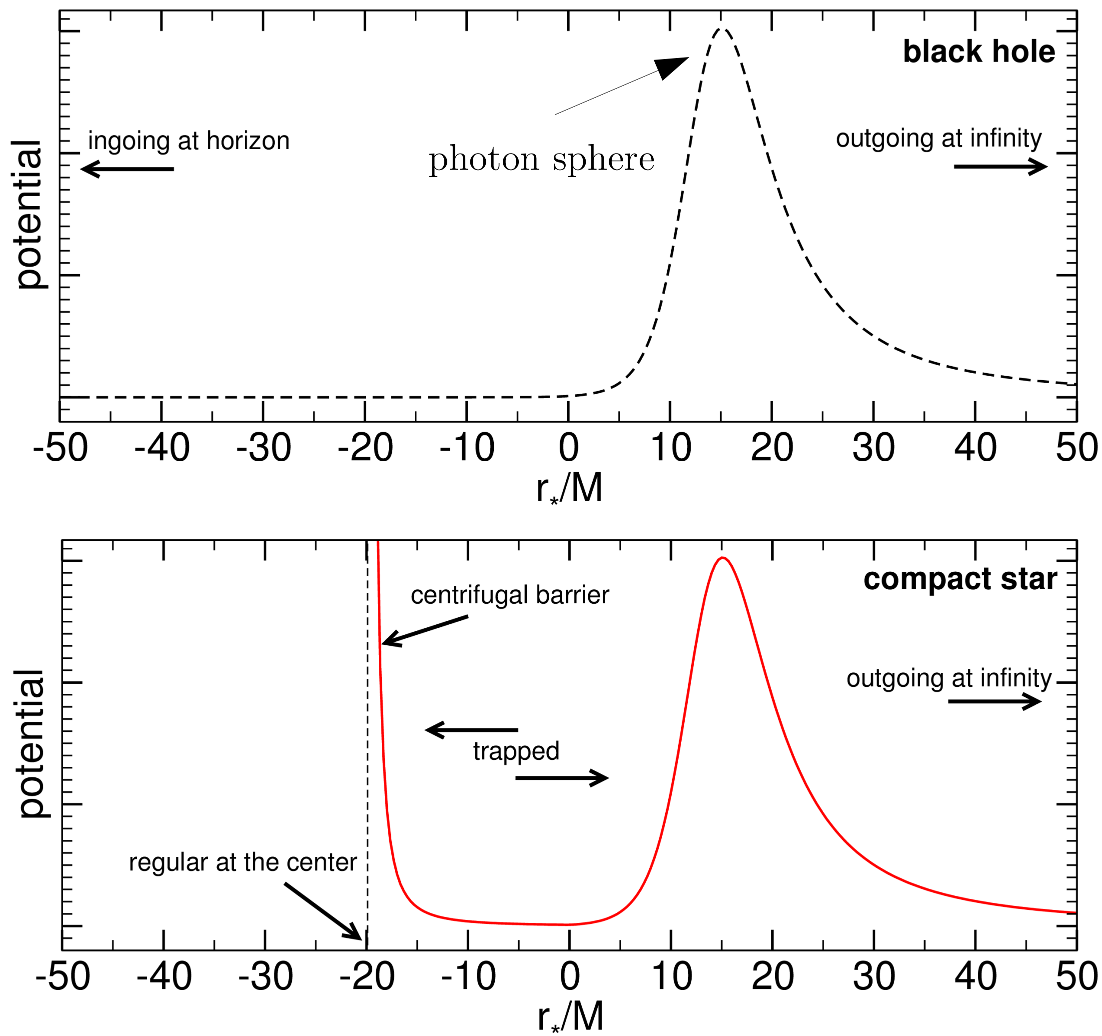
- QNMs of Kerr BH in GR depends only mass and spin [no hair] (**2+** modes needed)

$$\omega_{nlm} = \omega_R^{\rm Kerr}(M,\chi) + \delta\omega_R \qquad \tau_{nlm} = \tau^{\rm Kerr}(M,\chi) + \delta\tau$$

- Mode shift (due to different BH solution, different dynamics, or couplings)
- Extra ringdown modes (e.g., extra polarizations, fields) → amplitudes?

QNMs of exotic compact objects

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

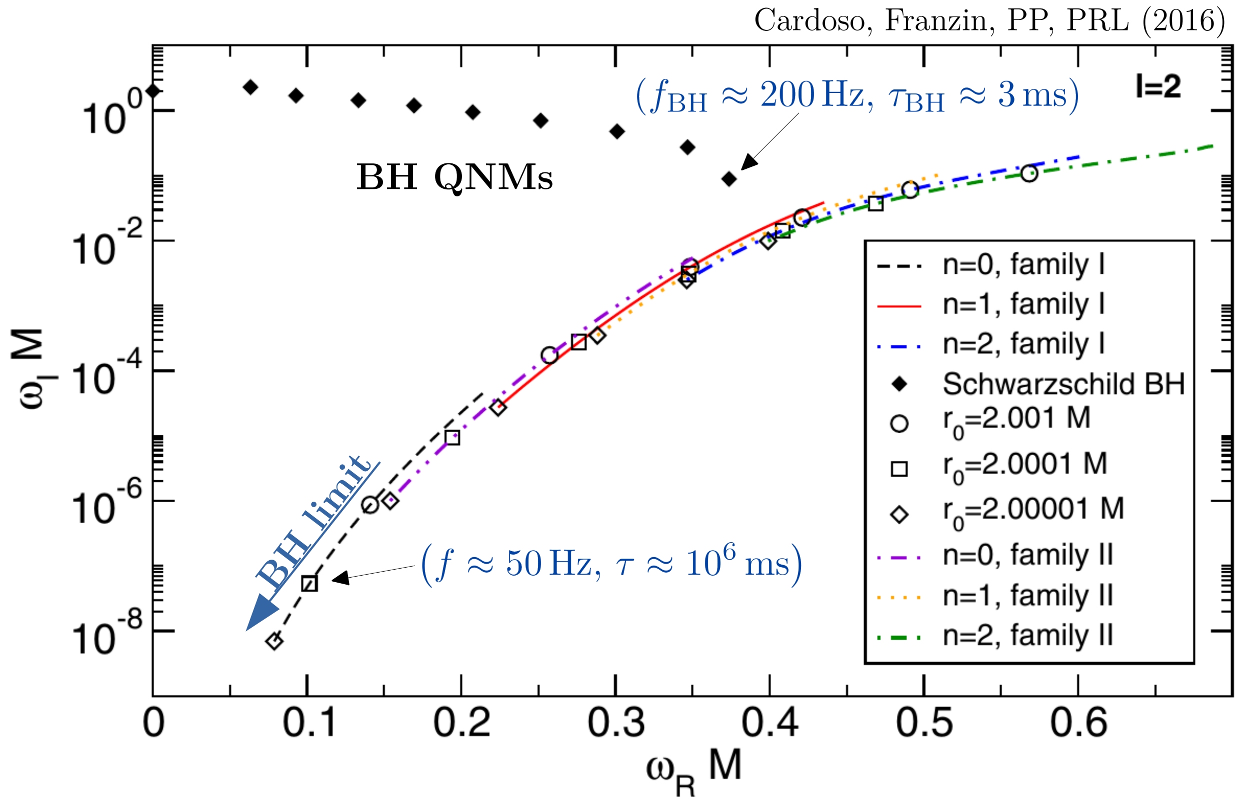


Ultracompact stars generically support trapped modes

Chandrasekhar & Ferrari PRSLA (1991)

No horizon → QNM spectrum dramatically different → ringdown?

QNM spectrum of an UCO



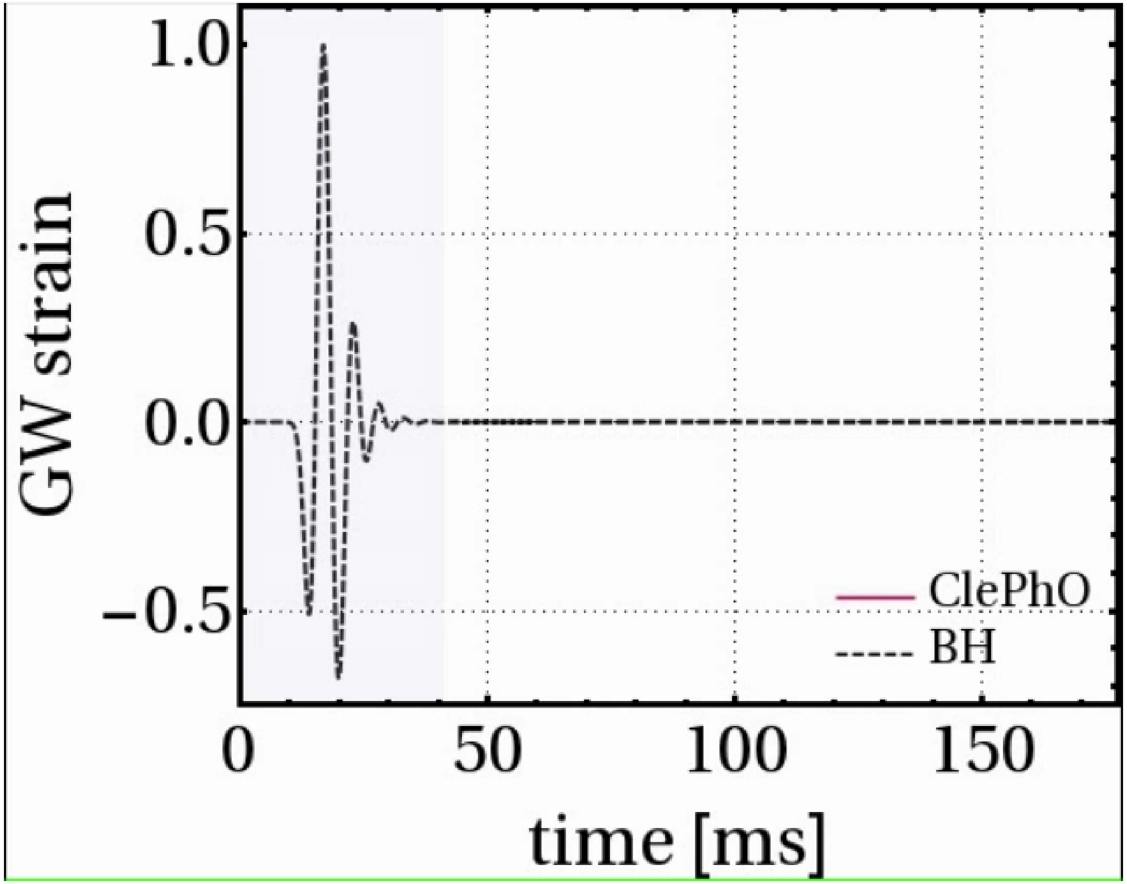
BH limit:

$$f_{\rm QNM} \sim |\log \epsilon|^{-1}$$

$$\tau \sim |\log \epsilon|^{2l+3}$$

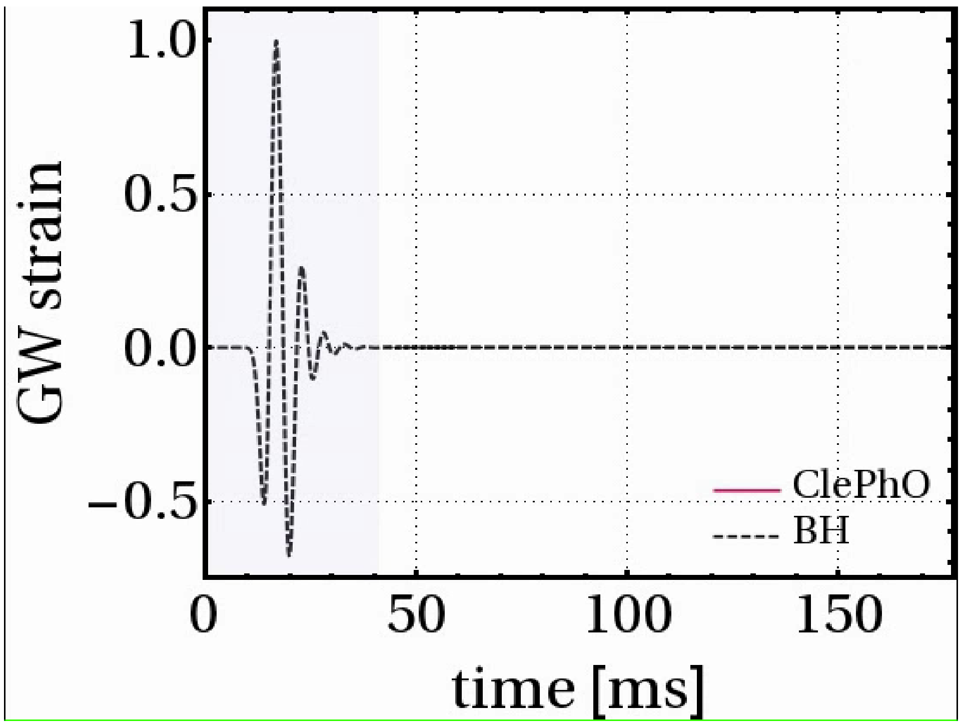
- Generic feature: long-lived QNMs in the BH limit
- QNM spectrum dramatically different → ringdown?

GW echoes



Ringdown of a Schwarzschild BH
(Gaussian perturbation)

GW echoes



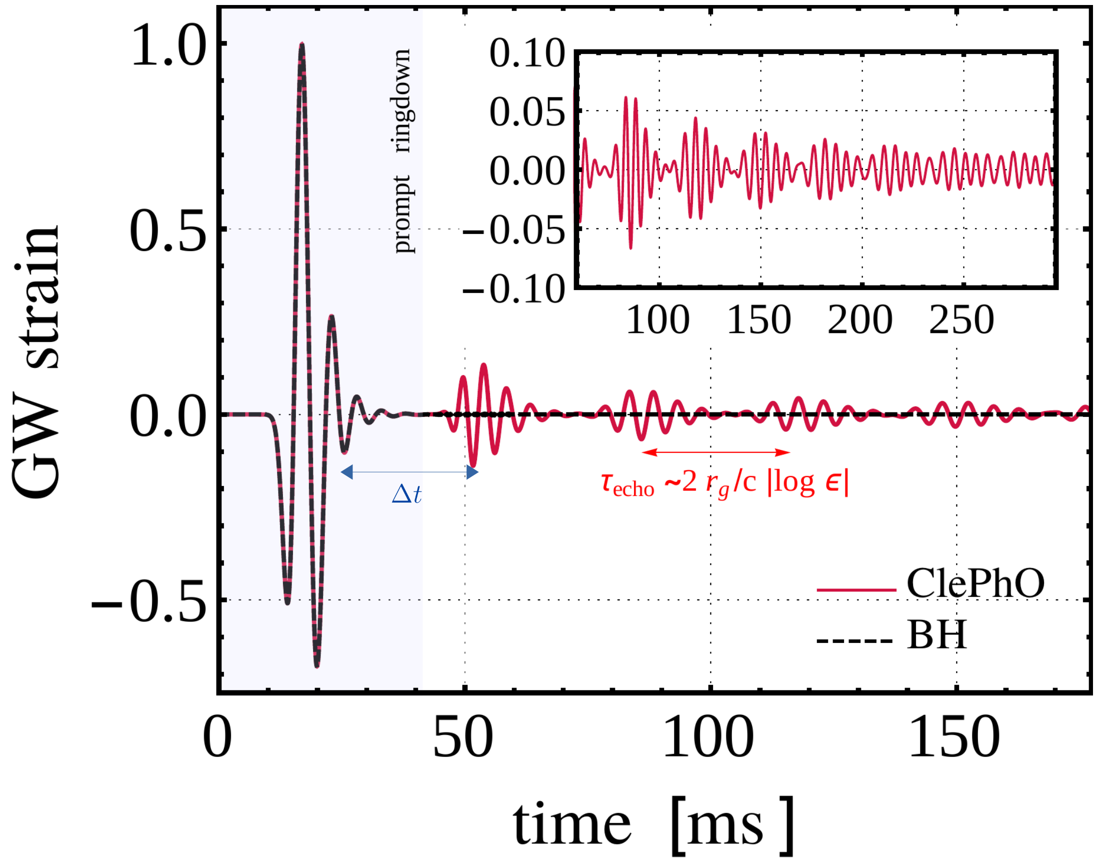
Prompt ringdown is identical,
but GW "echoes" at late time

Ferrari & Kokkotas, PRD 2000
Cardoso, Franzin, PP, PRL (2016)
Cardoso & PP, Nature Astronomy (2017)

$$\tau_{\rm echo} = \int_{r_0}^{3M} \frac{dr}{F} \sim \frac{2GM}{c^3} |\log \epsilon|$$

Delay time

GW echoes



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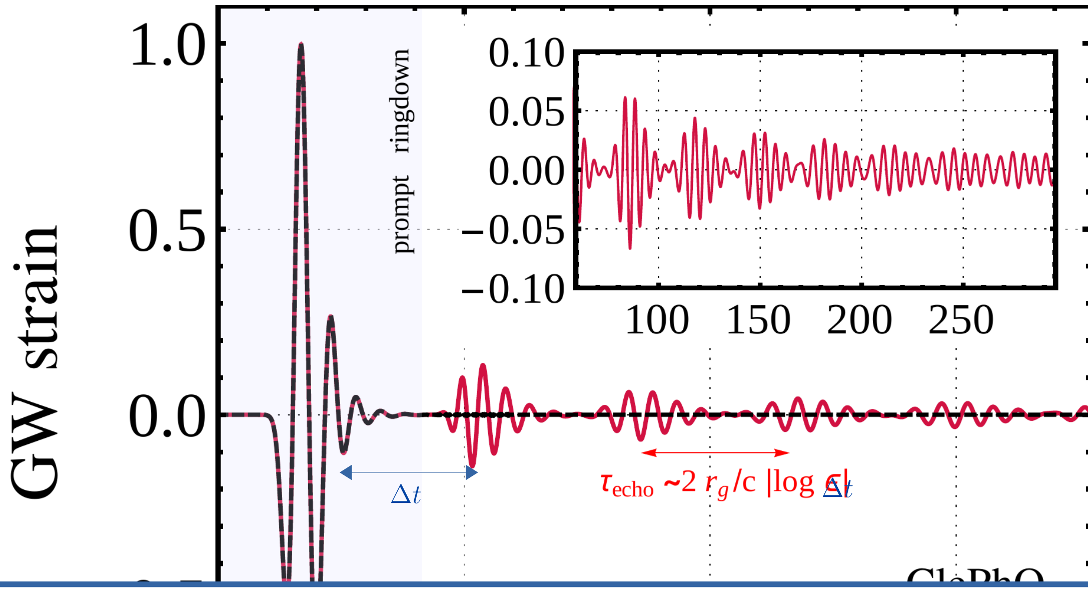
Delay time

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

$$r_0 - 2M \sim L_p \approx 10^{-33}\,{\rm cm} \Rightarrow \tau_{\rm echo} \sim \frac{GM}{c^3} |\log \epsilon| \sim \mathcal{O}(50\,{\rm ms})$$

GW echoes



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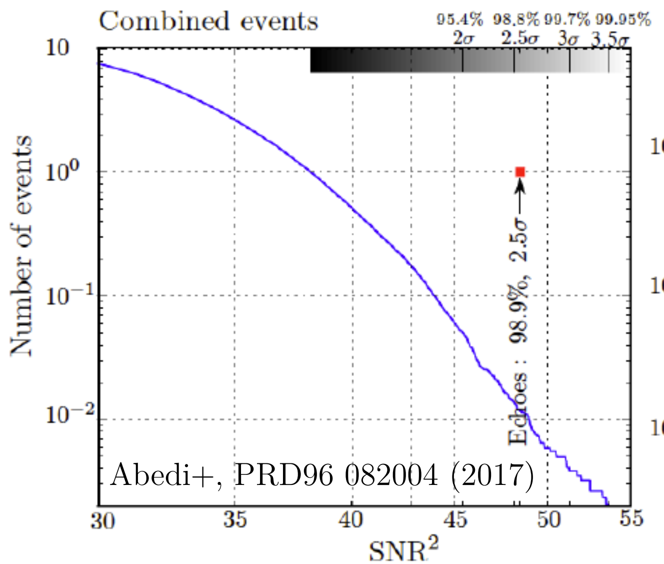
evolution used by Hawking would be invalidated. The problem is that we need an *order unity* correction to the evolution of these modes, since they have to go from a fully entangled state to a non-entangled state. On the other hand, all quantum gravity effects are expected to be of order (l_p/R) to some power, where l_p is planck length and R is the curvature radius. Thus despite a lot of effort in this direction, a resolution could not be found. These attempts

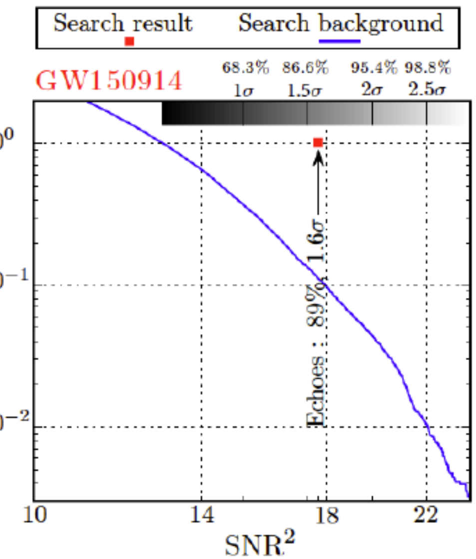
Mathur (2009)

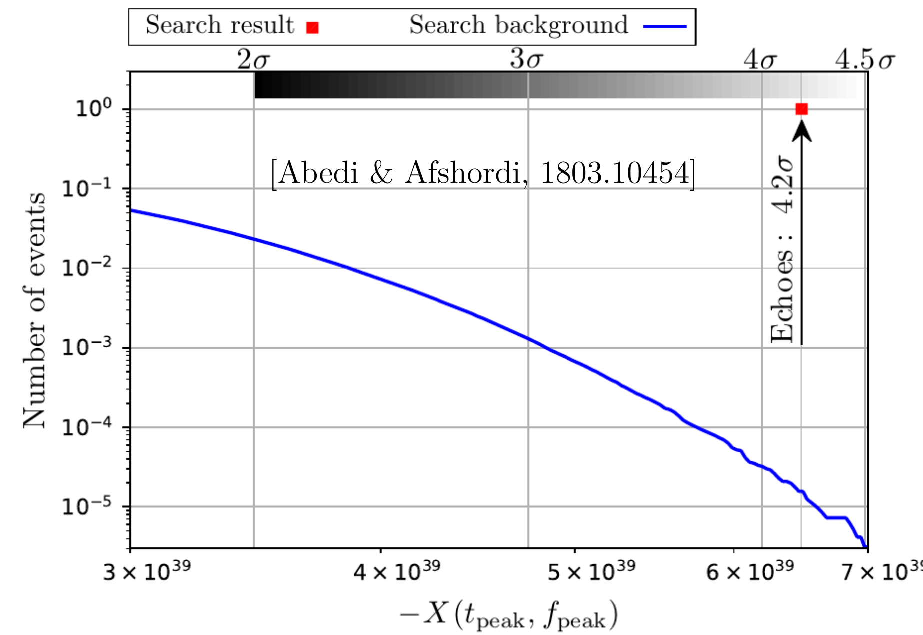
- Even Planck-scale corrections near horizon are within reach!

$$r_0 - 2M \sim L_p \approx 10^{-33}\,{\rm cm} \Rightarrow \tau_{\rm echo} \sim \frac{GM}{c^3} |\log \epsilon| \sim \mathcal{O}(50\,{\rm ms})$$

Searching for GW echoes with LIGO/Virgo





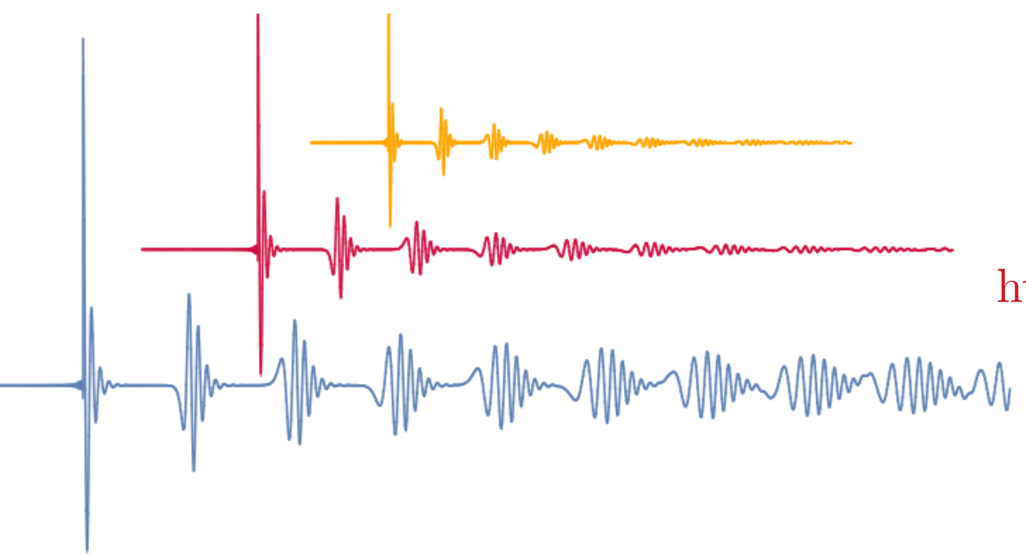


- Tentative detection of ~72 Hz echoes @4.2σ in GW170817 [Abedi & Afshordi 1803.10454]
- Contrasting results [Abedi+ PRD96 082004 (2017), Conklin+ 1712.06517, Ashton+ 1612.05625, Westerweck+ 1712.09966, Abedi+1803.08565]
- Limitation in the templates: frequency/amplitude distortions, spin, ...
- Progress in modeling [Nakano+, PTEP (2017); Mark+ PRD96 084002 (2017); Maselli+ PRD96 064045 (2017), Bueno+ PRD97 024040 (2018), Wang & Afshordi 1803.02845, Correia & Cardoso PRD97 084030 (2018), Tsang+ 1804.04877, Testa & PP, 180604253]

Quantum corrections within reach of current and future detectors!

GW echo modeling

- Signal is rich: amplitude/frequency modulation, spin effects, boundaries, ...
  - Re-processing through a transfer function [Mark+ PRD96 084002 (2017)]
  - Model-agnostic "wavelets" burst searches [Tsang+ 1804.04877]
  - Other approaches [Nakano+, PTEP (2017); Bueno+ PRD (2018), Maselli+ PRD96 064045 (2017), Wang & Afshordi 1803.02845, Correia & Cardoso PRD (2018)]
  - Analytical template with physical ECO properties [Testa & PP 180604253]



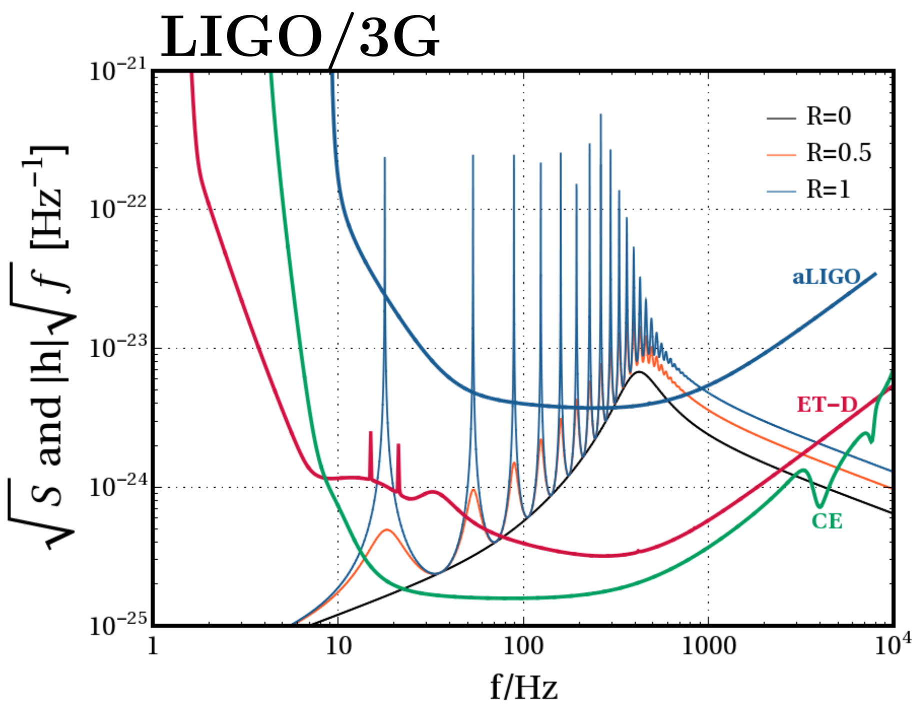
Waveforms, templates, and movies available at:

http://www.DarkGRA.org/gw-echo-catalogue.html

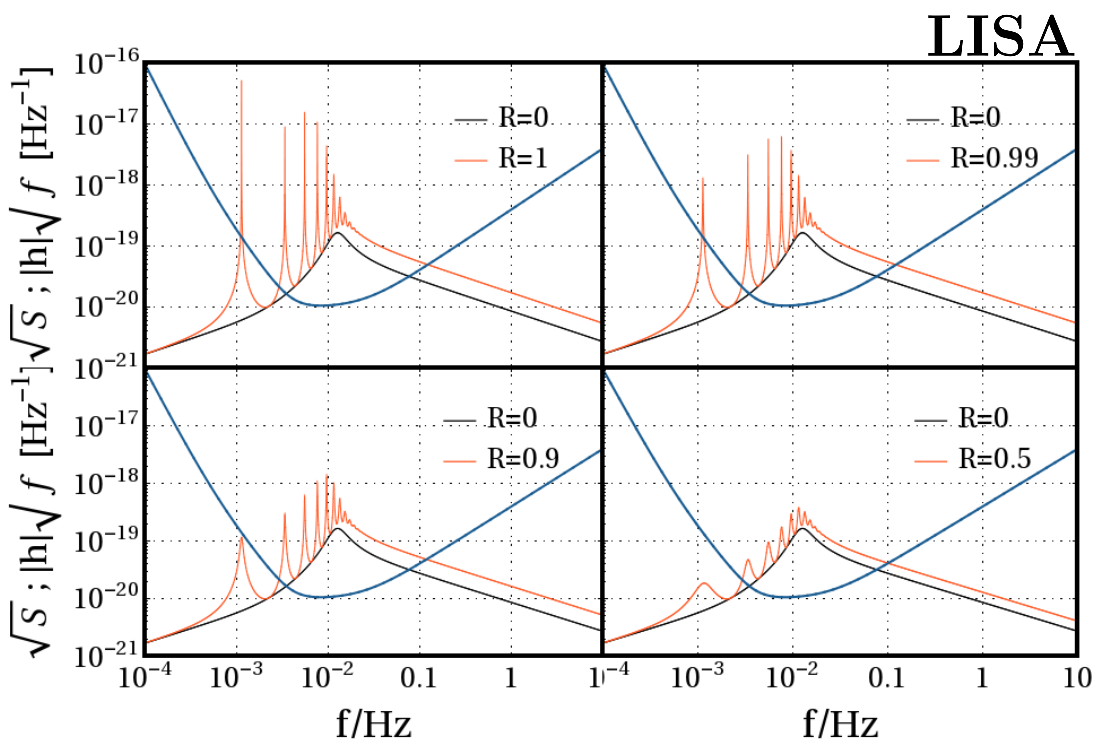
GW echoes: detectability #1

Testa & PP 180604253

- Echoes might be louder than ringdown
- Signal is strongly dependent on reflectivity



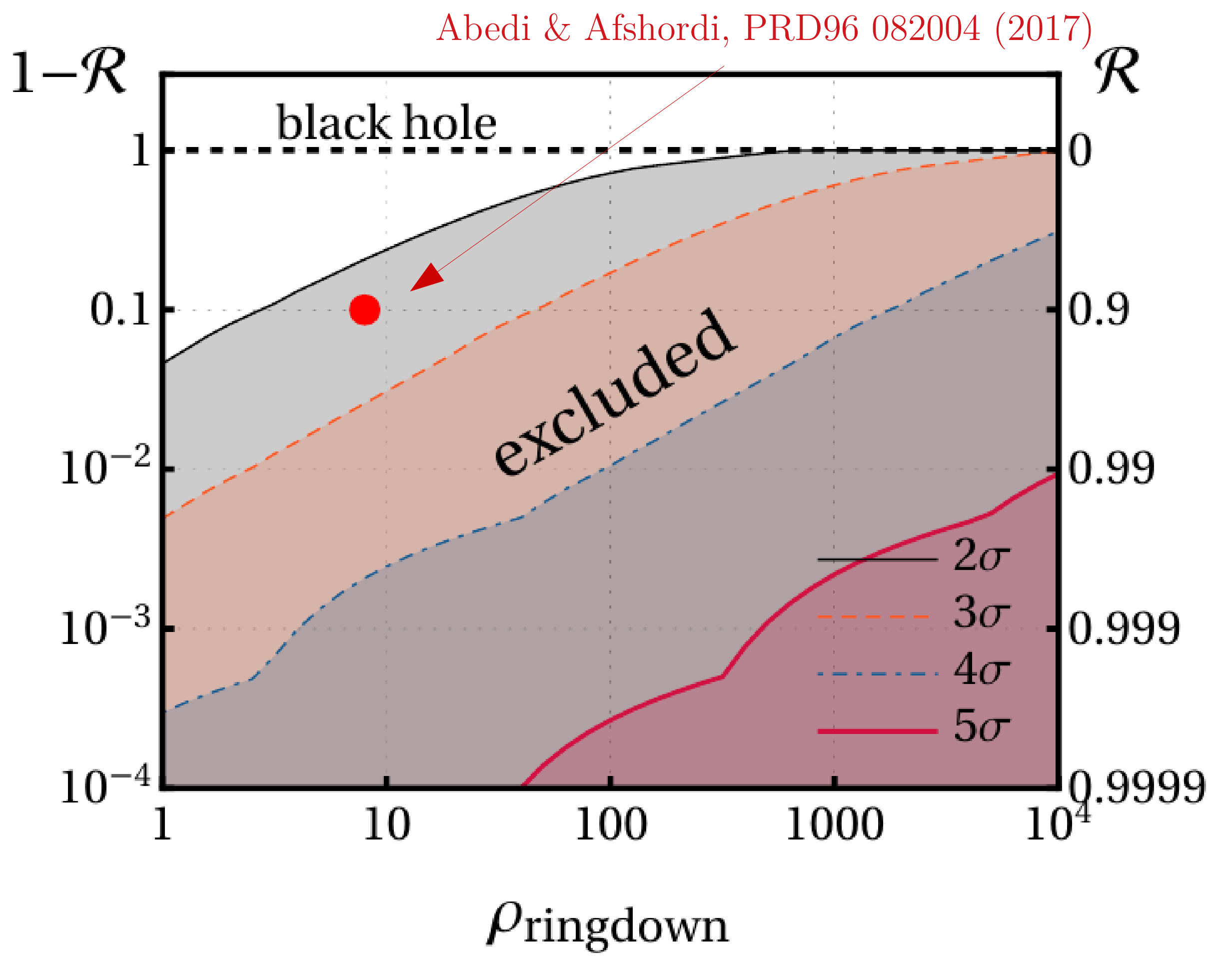
d=100 M, M=30 Msun, D=400 Mpc



d=100 M, M=10^6 Msun, D=100 Gpc

GW echoes: detectability #2

Testa & PP 180604253

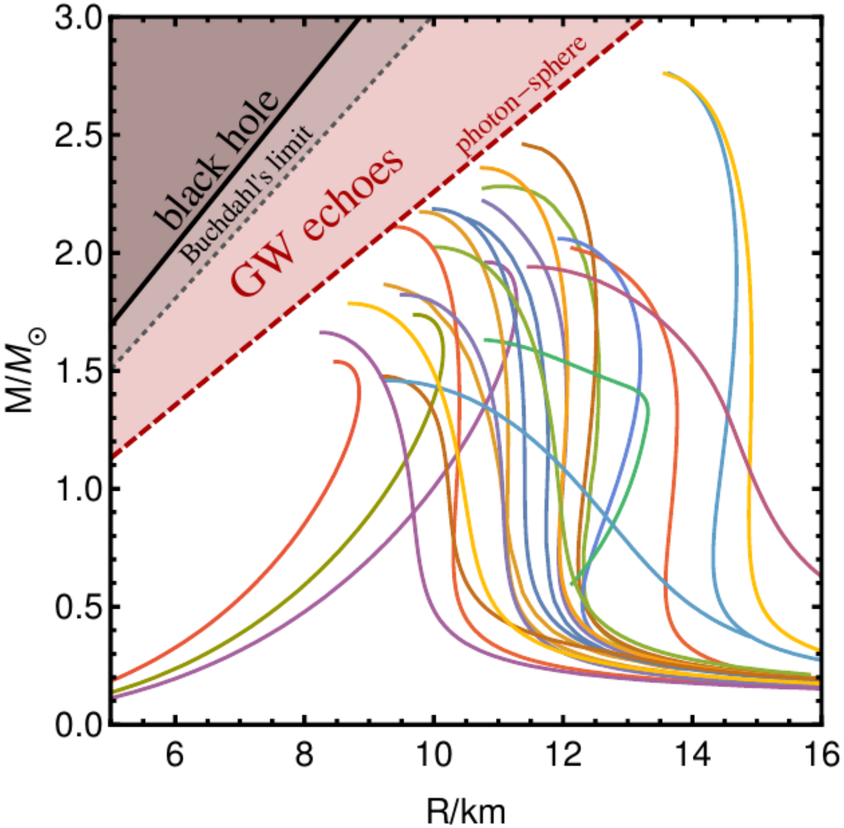


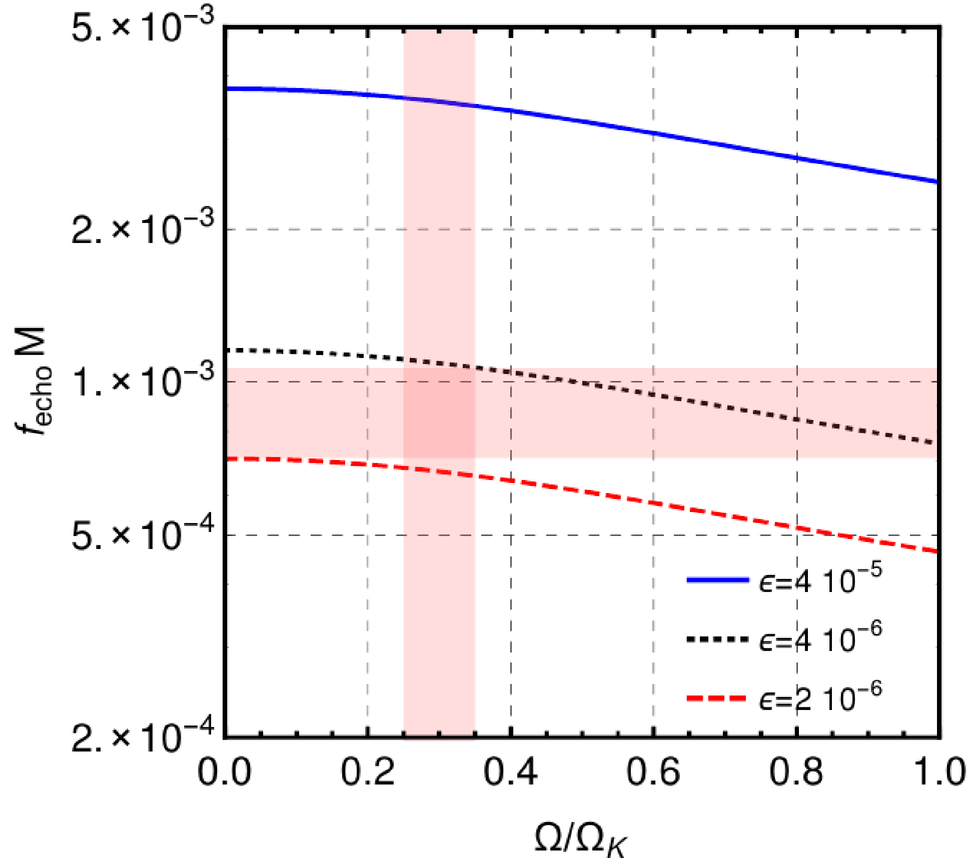
- Ruling out/detecting $\mathcal{R}\sim 1$ → might be feasible with aLIGO/aVirgo even at 5σ
- Ruling out/detecting $\mathcal{R}\sim 0$ → requires SNR>100 → 3G or LISA

Potential inferences from GW echoes

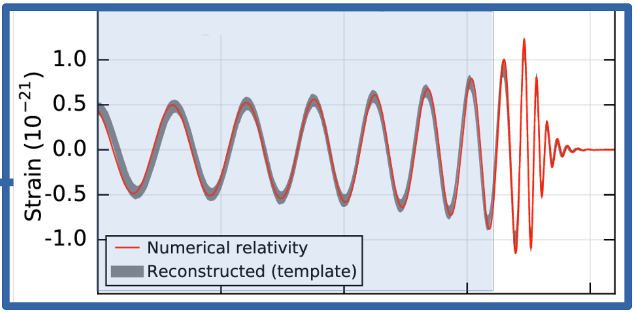
PP & Ferrari, 1804.01444, CQG Letters (in press)

- Merger remnant has photon sphere but no horizon → neither BH *nor* ordinary NS

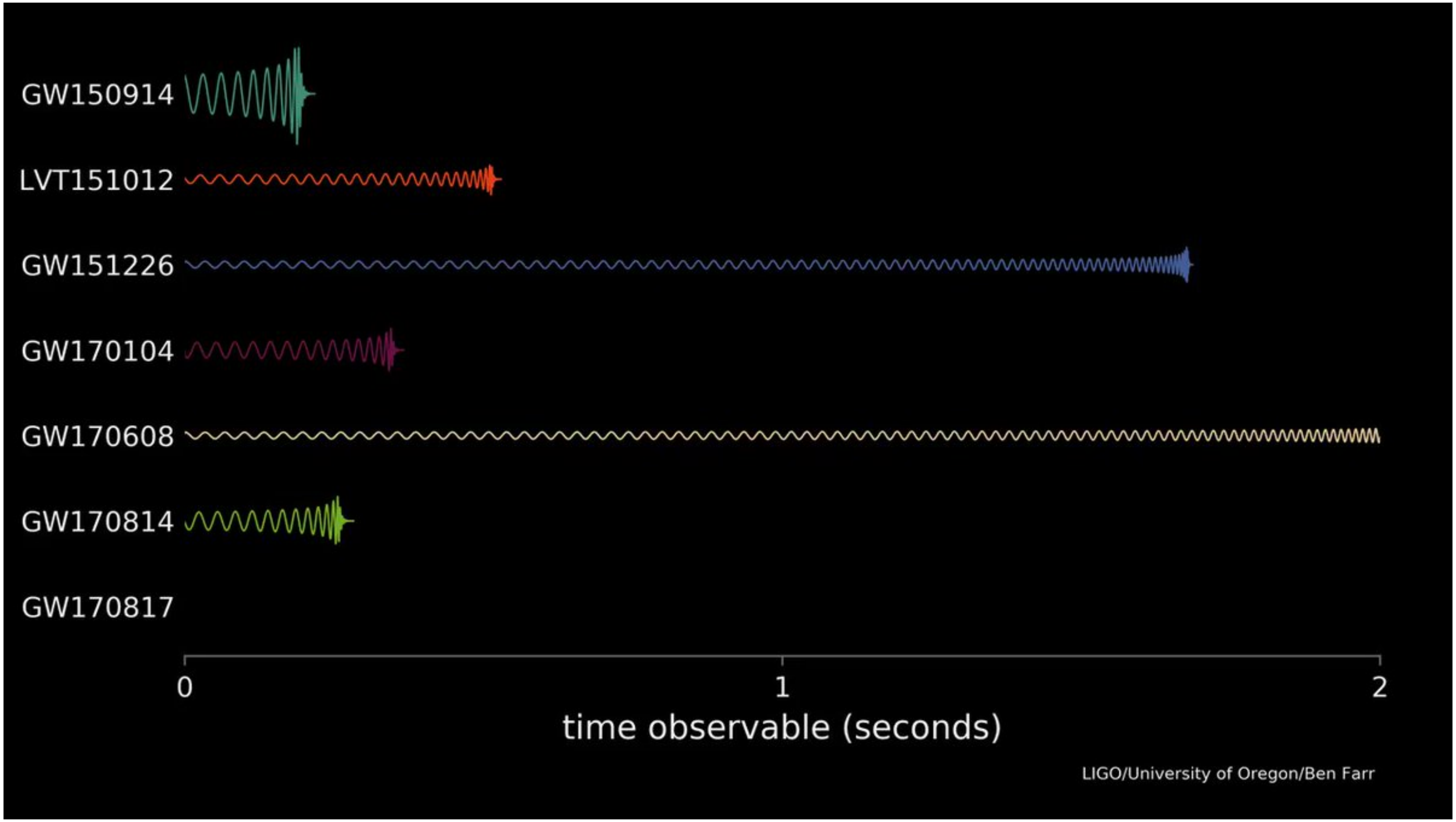




- Echoes in GW170817 @72 Hz compatible with
  - Near-horizon quantum structures
  - NS with very exotic matter (strange stars not enough compact [Mannarelli & Tonelli, PRD 2018])



Inspiral-based tests of exotic compact objects



Post-Newtonian inspiral: BH vs ECO

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

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

Blanchet, Living Rev. Relativity 17, 2 (2014), see Blanchet's talk

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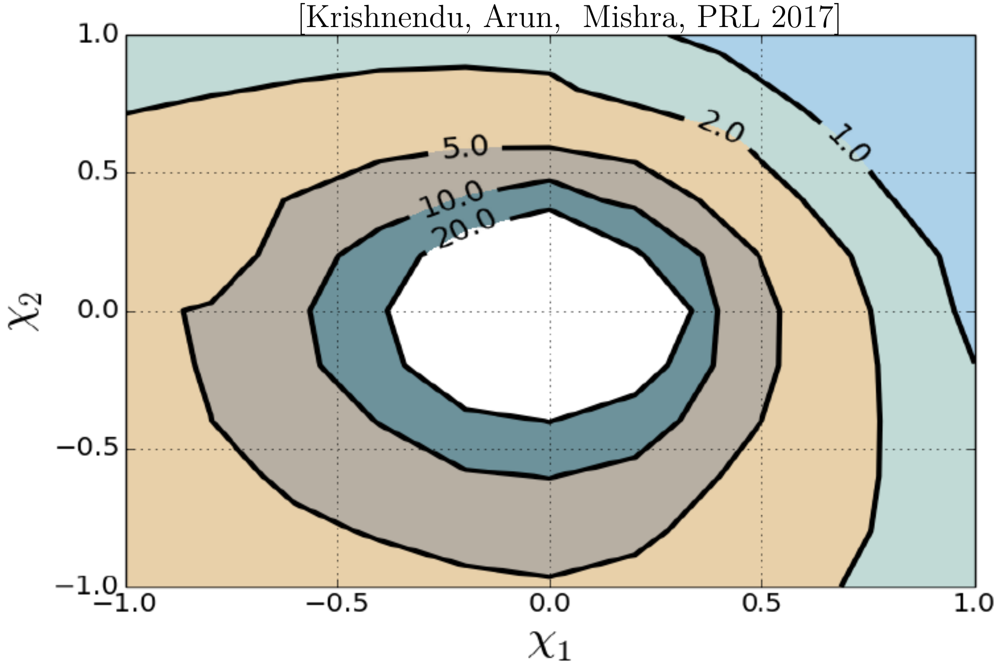
Blanchet, Living Rev. Relativity 17, 2 (2014), see Blanchet's talk

- **2PN:** Point-particle terms depend on the **multipole moments** of the bodies
  - Tests of the BH no-hair theorem

[Krishnendu, Arun, Mishra, PRL 2017]



$$M_2^{\rm Kerr}(m,\chi) = -m^3\chi^2$$

$$M_2^{\rm ECO}(m,\chi,\epsilon) = -m^3\chi^2 + \delta M_2$$

- Limitations:
  - Requires high spin
  - Multipole moments of an ECO approach those of a BH [PP, Phys.Rev. D92 (2015) 124030, Raposo, PP, Emparan (in preparation)]

Post-Newtonian inspiral: BH vs ECO

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Blanchet, Living Rev. Relativity 17, 2 (2014), see Blanchet's talk

- **2.5PN: tidal heating** [Alvi PRD 2001, Poisson, PRD 2009]
  - BHs absorb radiation at horizon
  - Tidal heating is ~ absent for ECOs

Post-Newtonian inspiral: BH vs ECO

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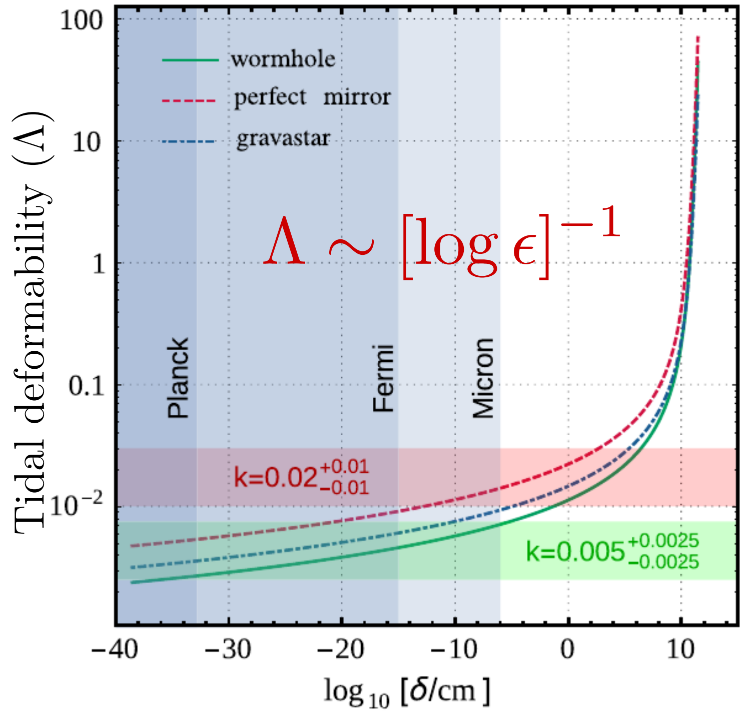
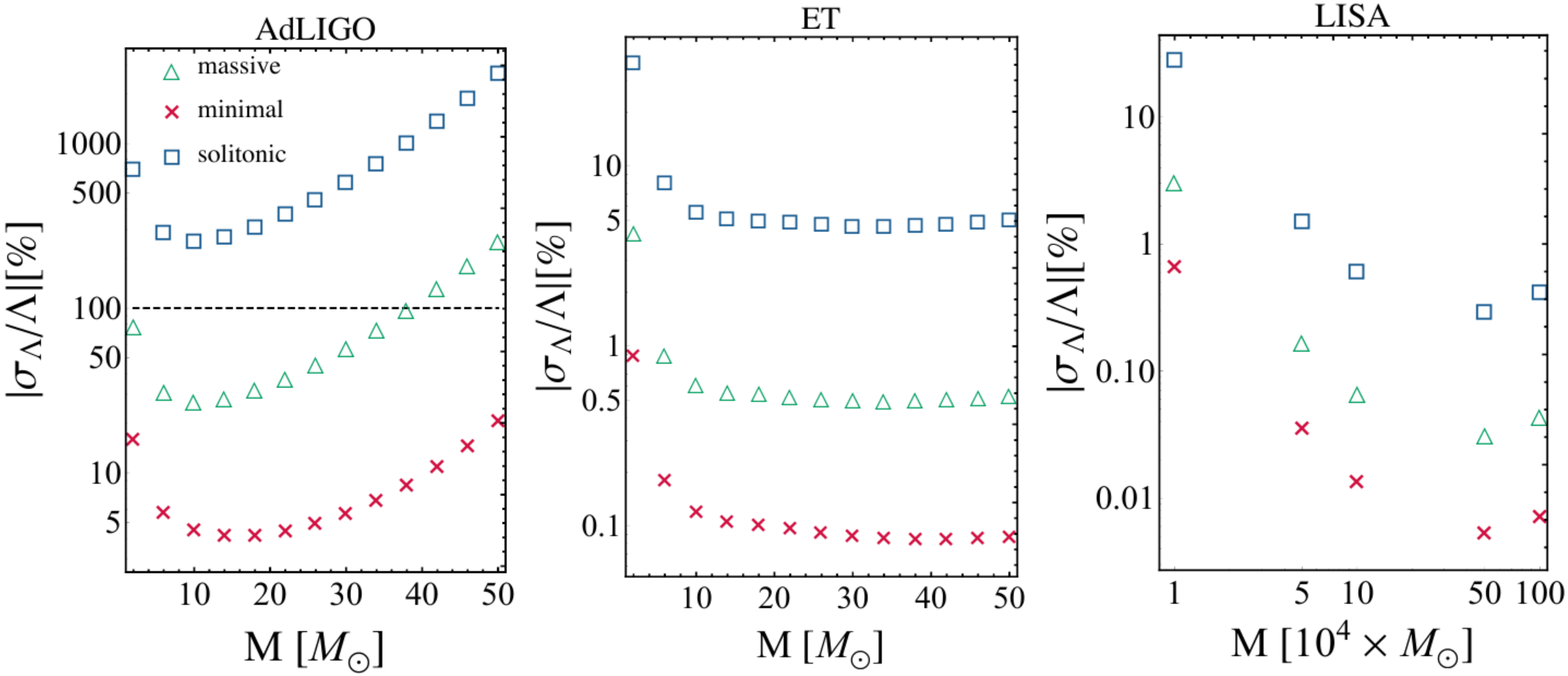


- **5PN: tidal deformability and Love numbers** [Flanagan & Hinder, PRD77 021502 2008]
  - Love numbers of a BH are zero [Binnington & Poisson, 2009; Damour & Nagar 2009; PP+, 2015] (but see PP+ 1509.02171 & Gralla, 1710.11096)
  - ECOs have nonzero Love numbers [Cardoso, Franzin, Maselli, PP, Raposo, PRD 2017]

BH/NS vs Boson Stars: Love numbers

Cardoso, Franzin, Maselli, PP, Raposo, PRD95 (2017) 084014

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



- aLIGO can exclude only BS vs BH models with relatively small compactness

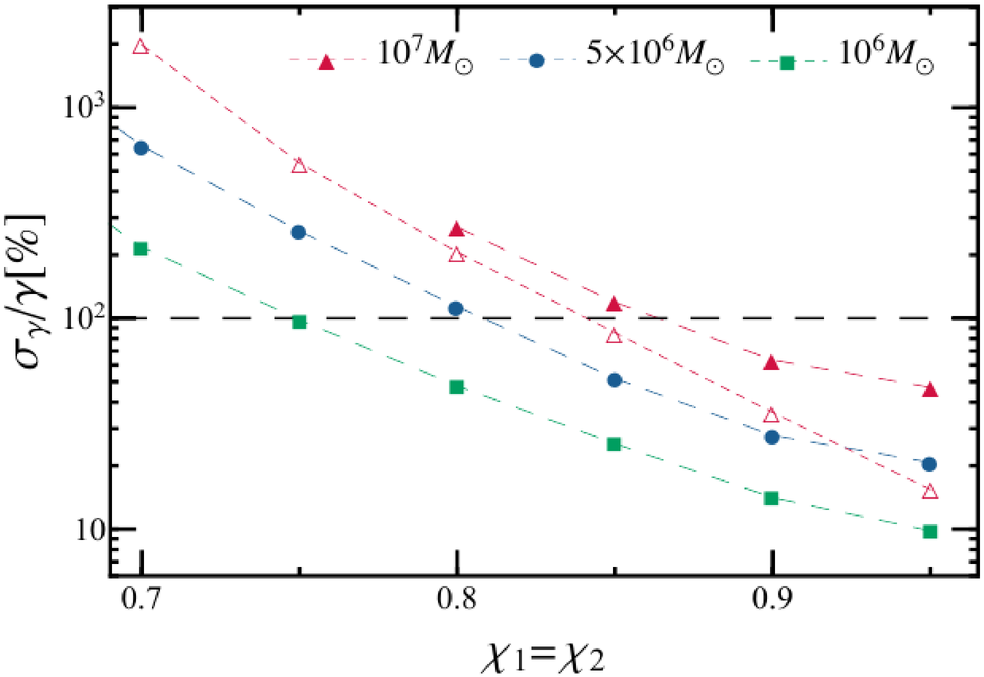
[Cardoso+ (2017), Sennet+ PRD 96 024002 (2017), Johnson-McDaniel+, 1804.08026]

- aLIGO can also distinguish NS vs BS [Sennet+ PRD 96 024002 (2017)]
- 3G & LISA will be able to distinguish BHs vs *any* BS model

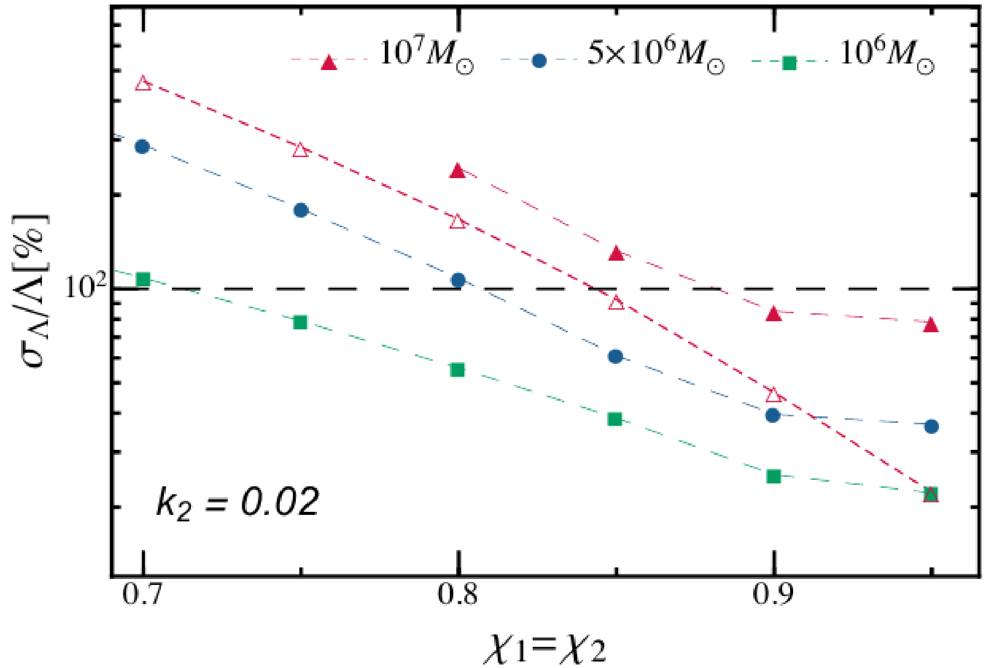
Probing BH quantum structures with LISA

Maselli, PP+; PRL 120 081101 (2018)

Absence of tidal heating



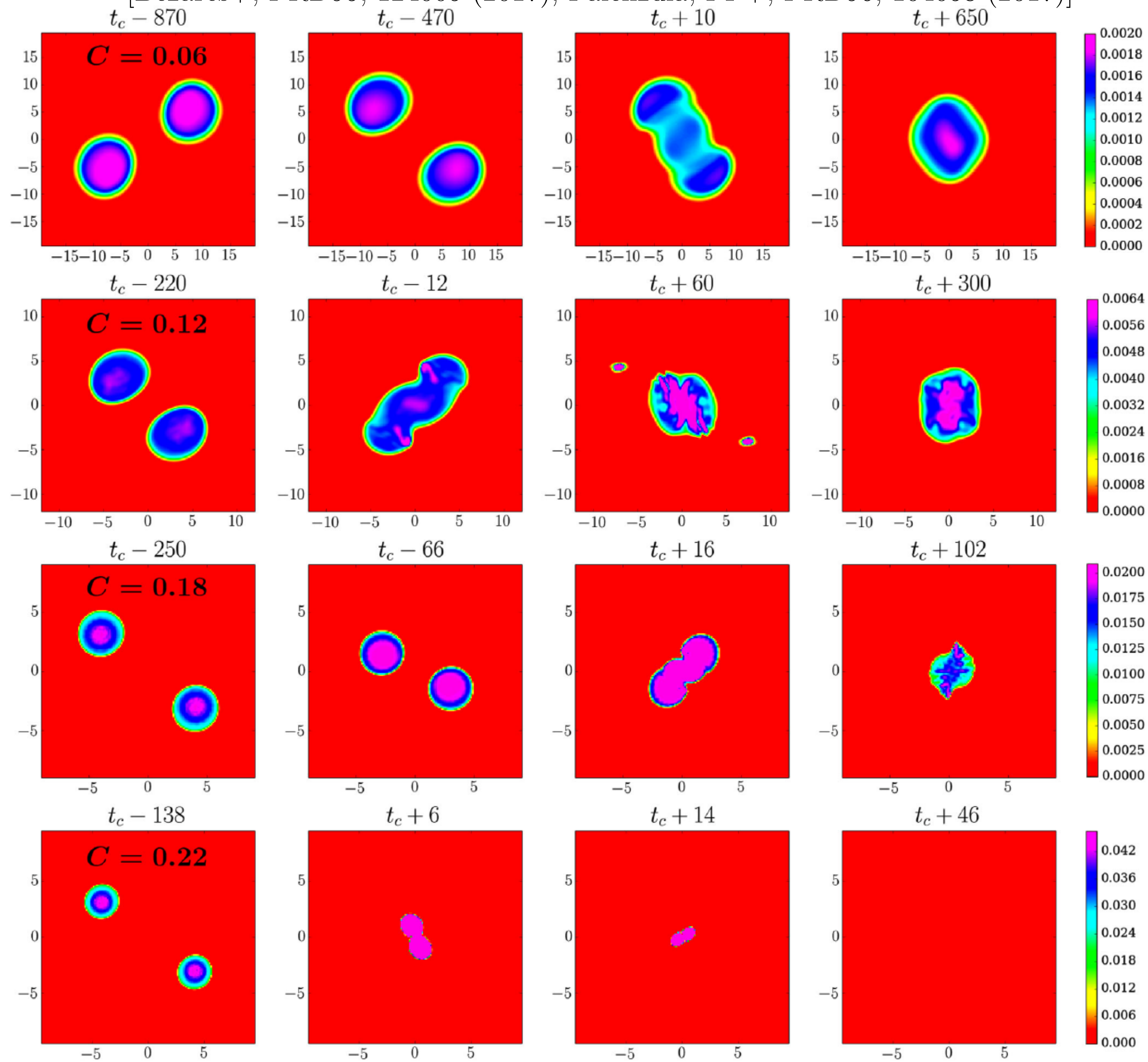
Tidal deformability



- Small corrections $\to$ requires spinning supermassive binaries @ 2-20 Gpc
- LISA binaries are golden sources to probe Planckian corrections!
- Tidal terms recently computed to 6.5PN [Abdelsalhin, Gualtieri, PP; 1805.01487]

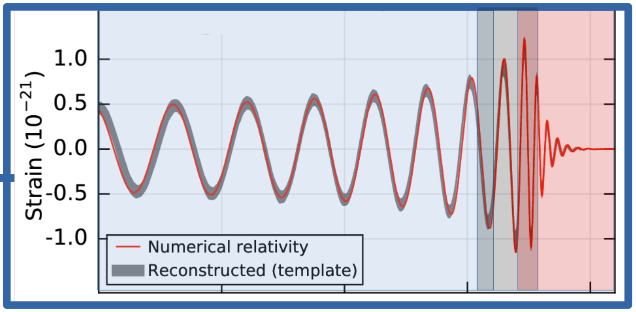
Binary Boson Stars (BBSs)

[Bezares+, PRD95, 124005 (2017); Palenzula, PP+, PRD96, 104058 (2017)]

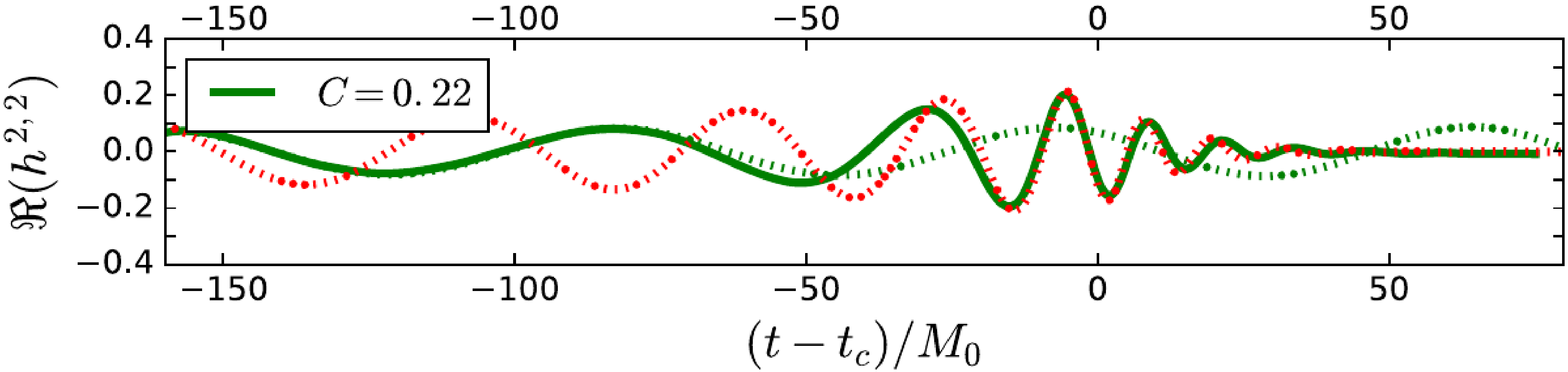


- Boson stars have quantized spin, J=nQ
- Final state → either BH or nonspinning BS?

BBSs or BBHs?



Can BBSs mimick the full signal from BBH coalescence?



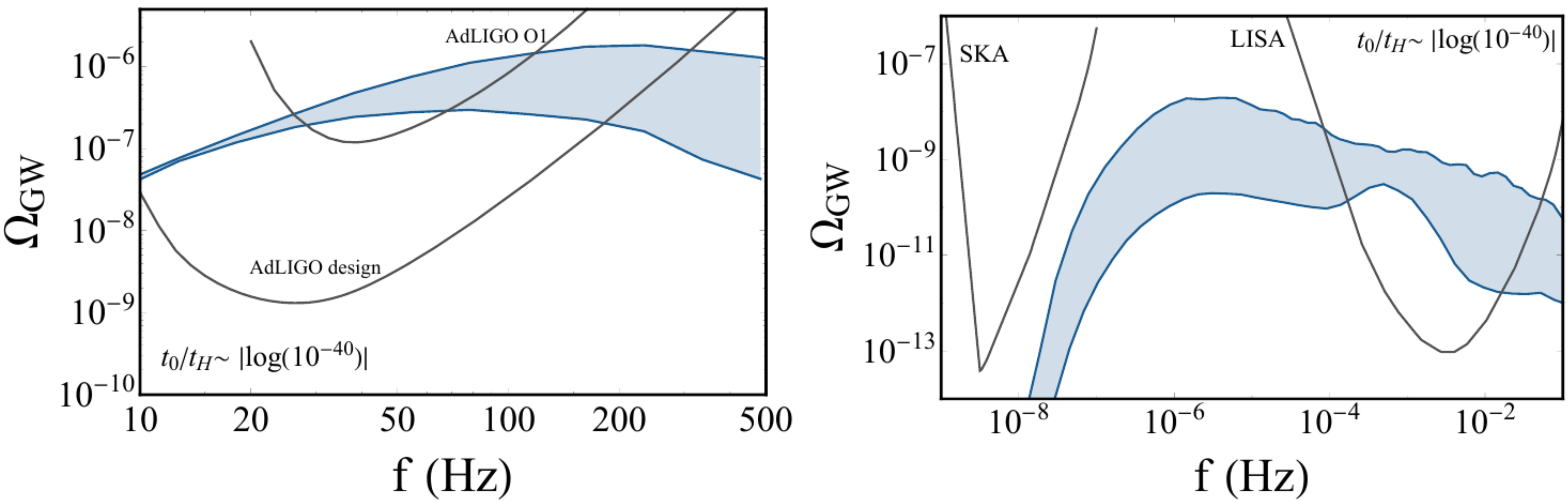
[Palenzula, PP+, PRD96, 104058 (2017)]

"Short-blancket" problem: mimicking IMR signal of BBHs is hard

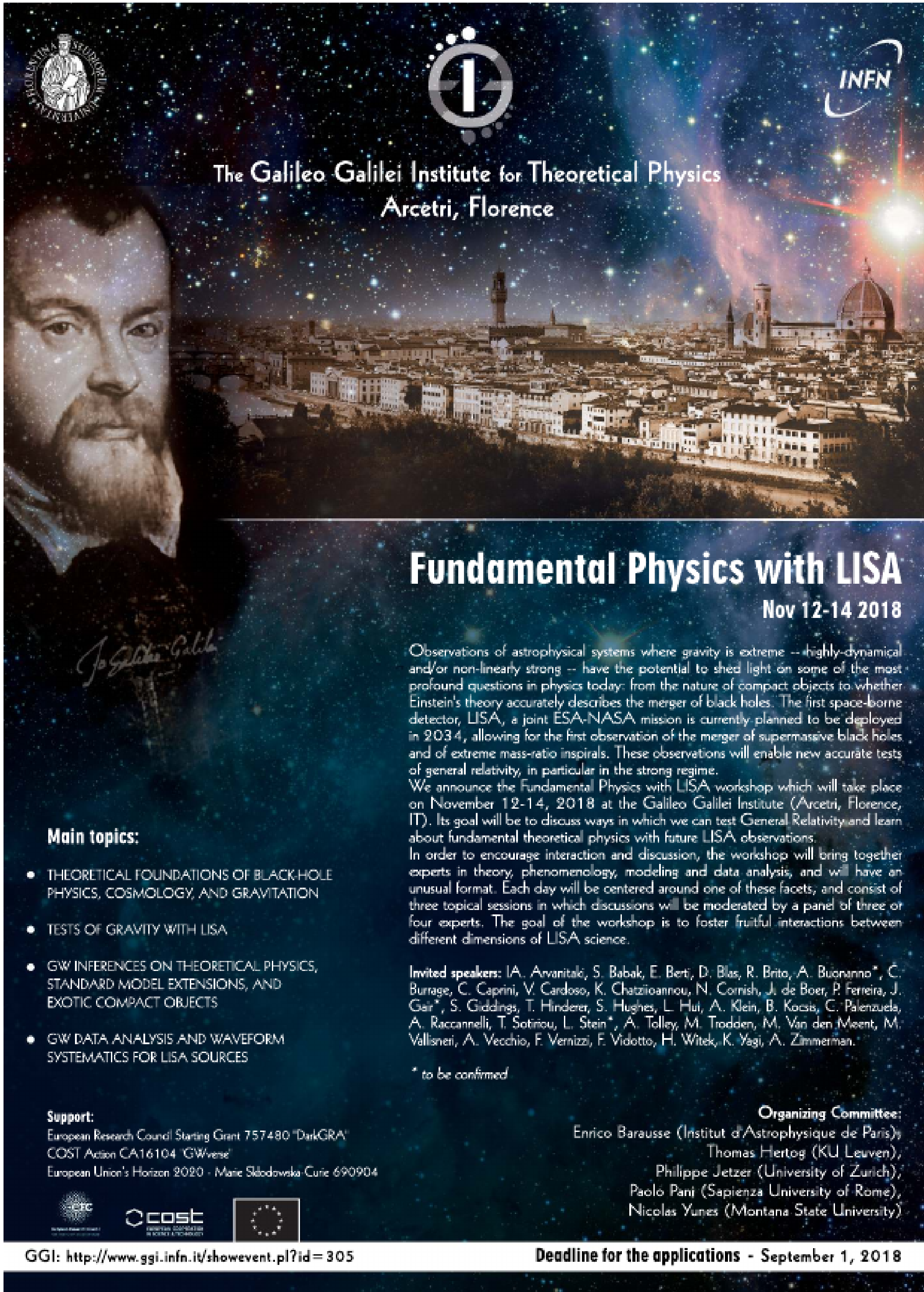
Stochastic GW background from ECOs

Barausse, Brito, Dvorkin, Cardoso, PP (1805.08229, 2018)

- Spinning ECOs are unstable → GW spin-down [Friedman (1976), Cardoso+ (2008)]
- ECOs must be either slowly spinning or partly absorbing [Maggio, PP, Ferrari, (PRD 2017)]



- LIGO O1 bounds on stochastic background rule out perfectly reflecting ECOs
- Stochastic background of echoes is smaller but detectable [Du & Yanbei, 1803.10947]



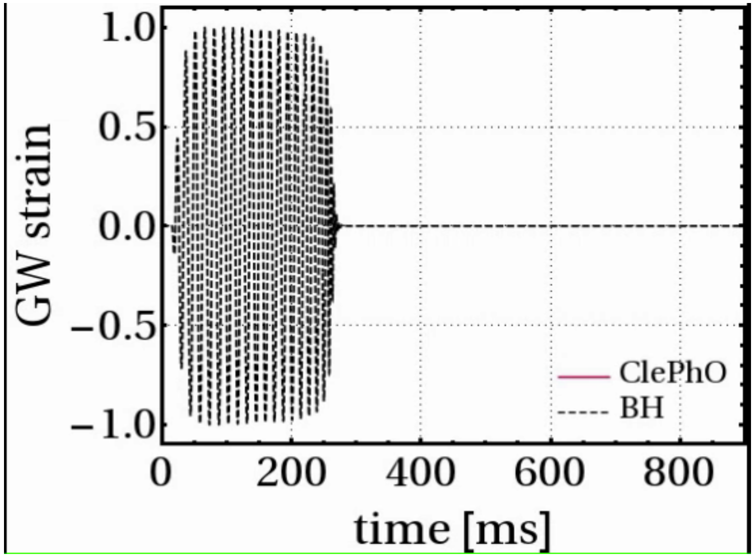
www.darkgra.org/lisa-workshop.html

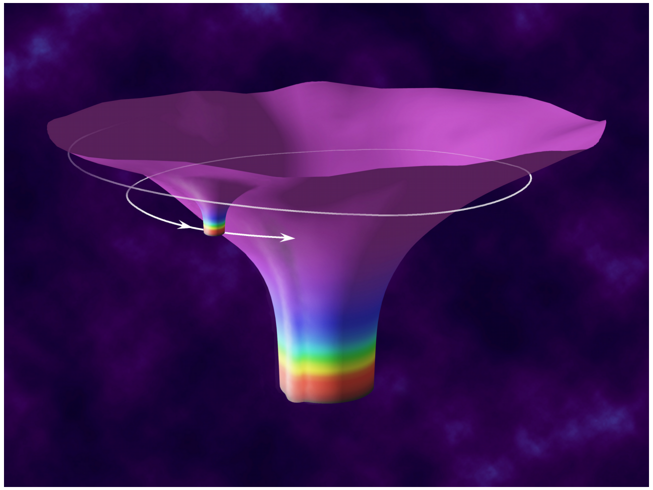
- 12-14 Nov 2018 @ GGI (Arcetri, FI)
- 1st meeting of the LISA Working Group on Fundamental Physics
- Deadline for applications: Sept 1st

What will the next specie of compact objects?

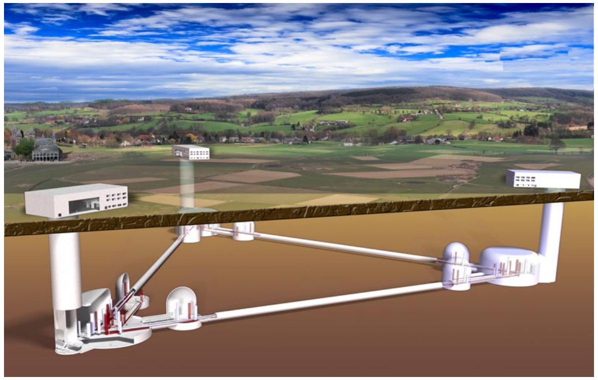
2020s: BXXs?

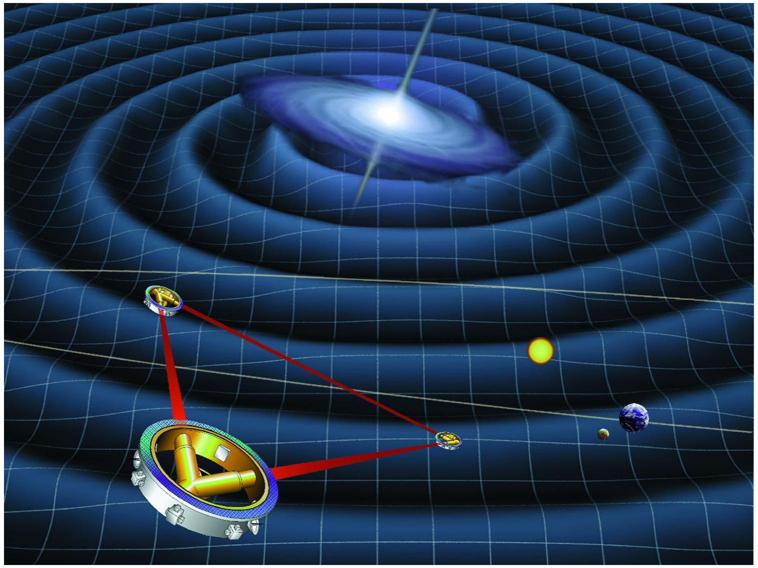
Credits: G. Khanna





Echoes in Extreme-Mass-Ratio Inspiral for LISA





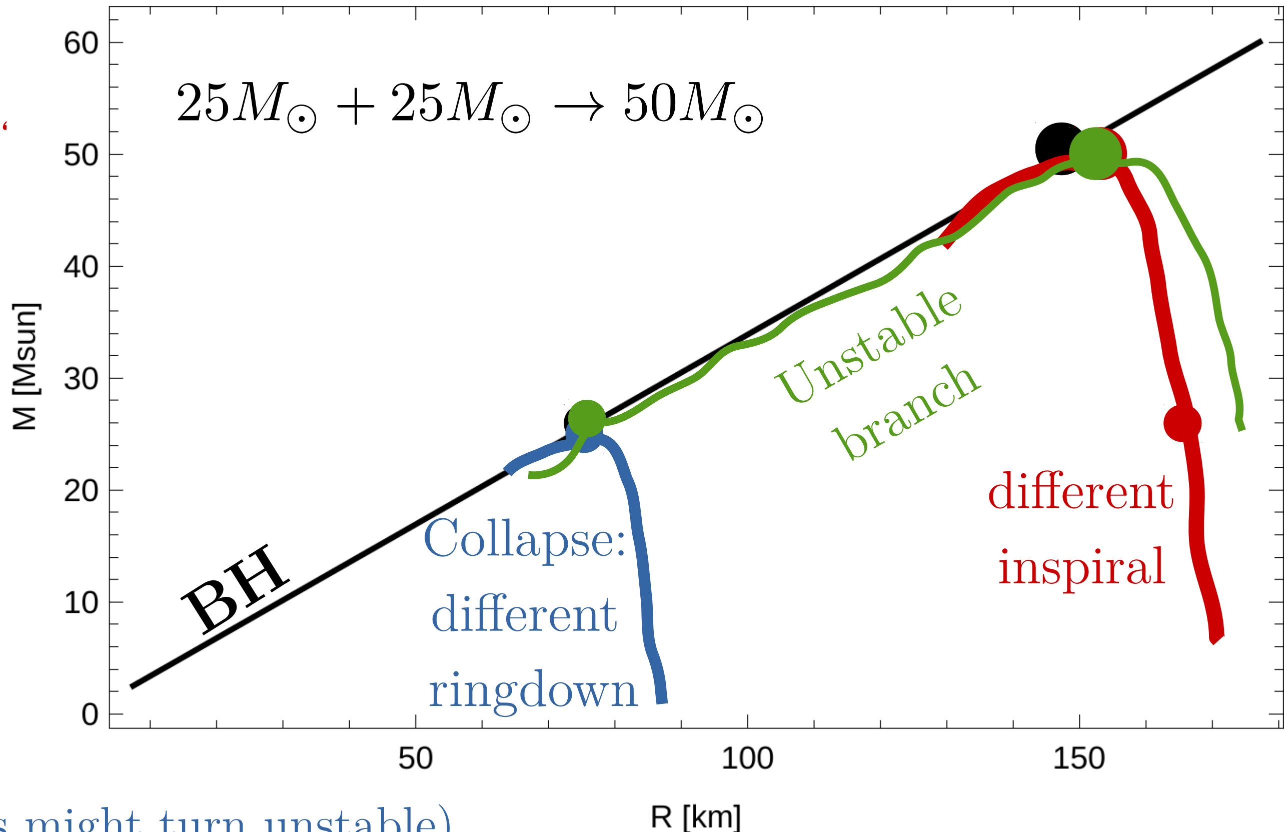
Backup slides

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

BH vs ECO: theoretical challenges

"Short-blanket" problem: **ECO + ECO → ECO or BH?**

- Equilibrium solutions‘
- Formation?
- Coalescence?



- Stability? (long-lived modes might turn unstable)
  - Ergoregion instability [Friedman (1976), Cardoso+ (2008), Pani+ (2010-2012)]
  - Nonlinear instability? [Keir (CQG 2014), Cardoso+ (PRD 2014), Cunha, Berti Herdeiro (PRL 2017)]
- ECOs must be either slowly spinning or partly absorbing [Maggio, Pani, Ferrari, (PRD 2017)]

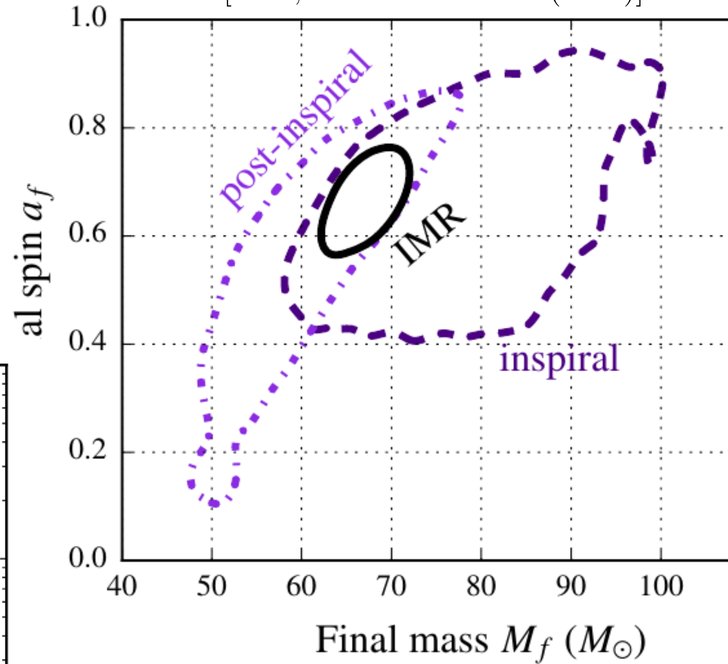
Ringdown and GW spectroscopy

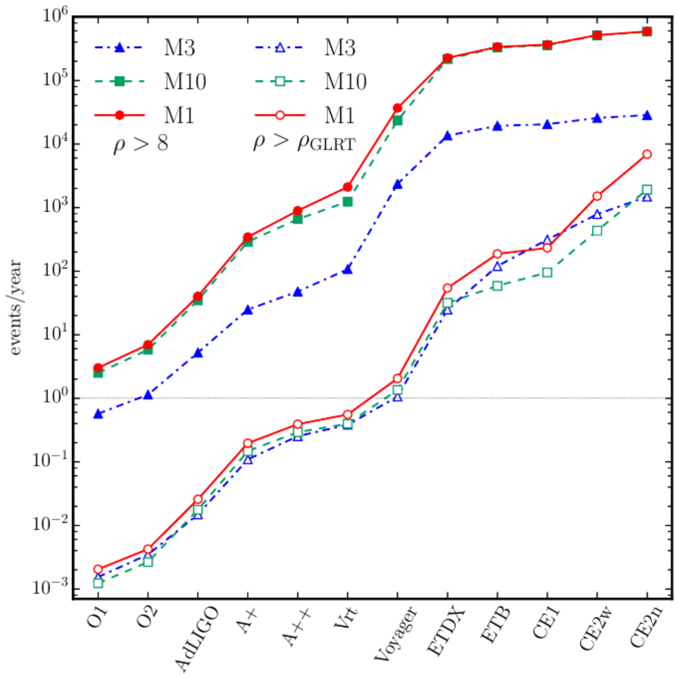
- Current detections consistent with Kerr, but low SNR in the ringdown (~1cycle/damping time)
- Ringdown tests possible with **3G** and **LISA** [Berti+, PRL. 117 101102 (2016)]

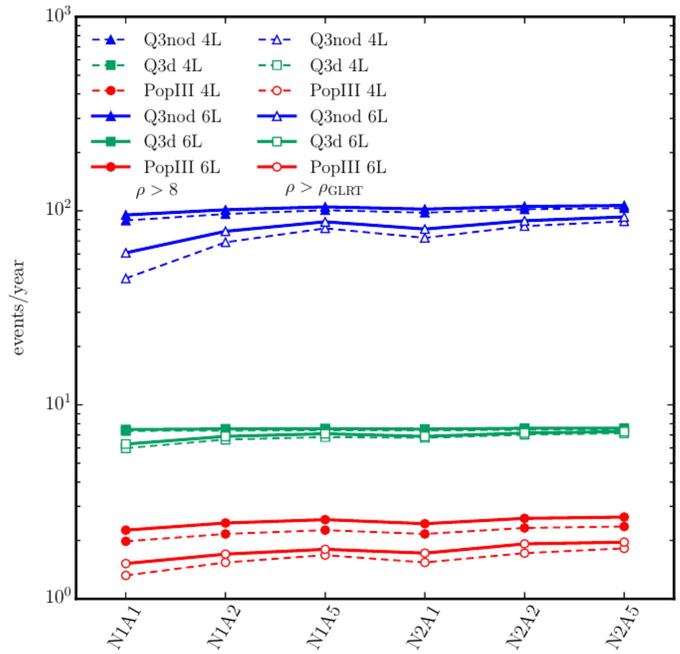
$$\mathrm{SNR}_{\mathrm{ringdown}} \propto \frac{M_{\mathrm{BH}}^{3/2}}{\sqrt{S_h(f)}}$$

Supermassive sources more than compensate
for smaller detector sensitivity

[LVC, PRL 116 221101 (2016)]







Conclusion & Outlook

- GW astronomy: opportunity to search for exotic GW sources and signatures of new physics at the horizon scale:
  - **GW echoes** in the post-merger ringdown signal
  - Finite-size corrections to the inspiral $\rightarrow$ **precision GW physics**
  - **Much better modeling is required** (especially of IMR signal)
- Mimicking BHs is extremely challenging $\rightarrow$ observational & theoretical issues:
  - Formation? Instabilities? Full coalescence?

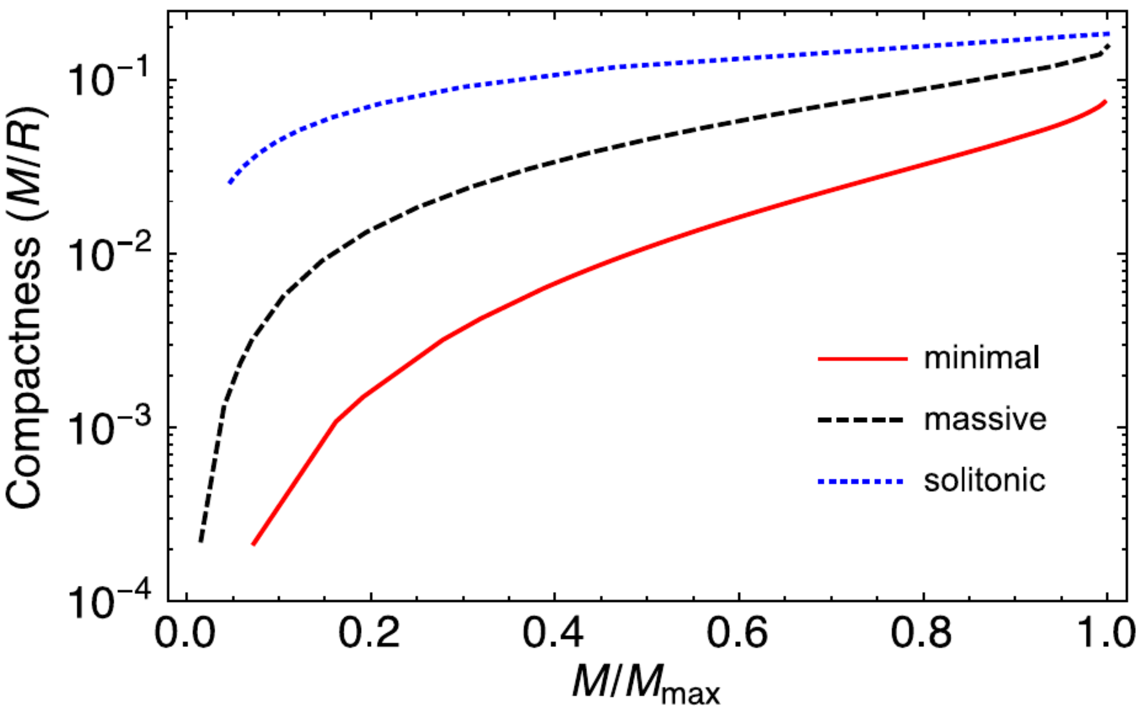
GW astronomy: expect the unexpected

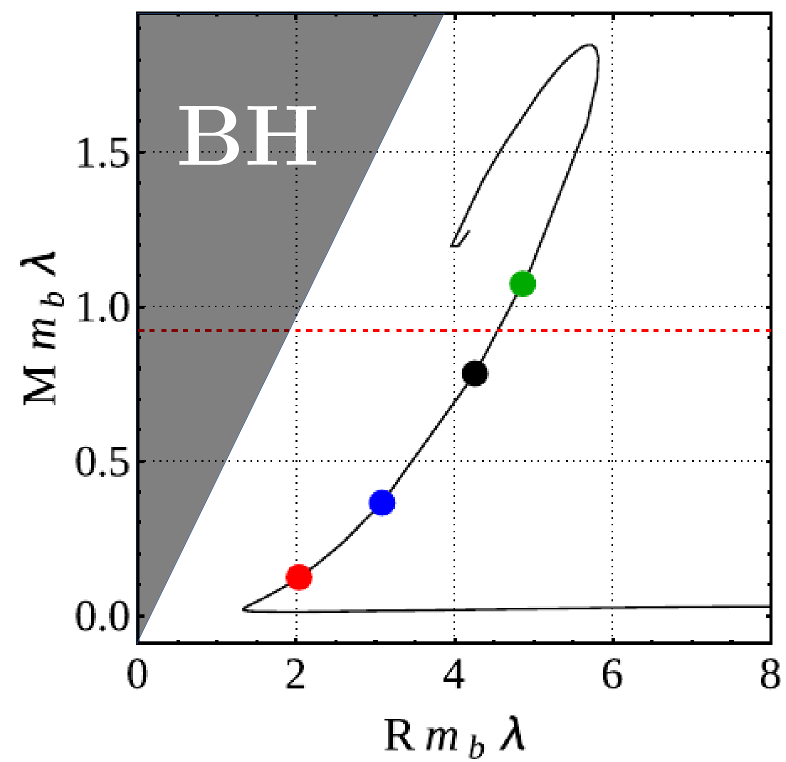
Boson Stars

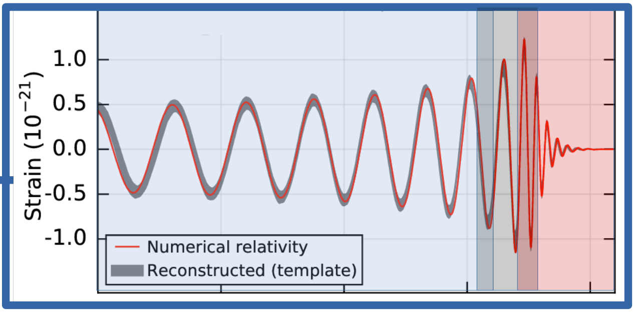
Palenzuela & Liebling, Liv. Rev. Rel. (2017)

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

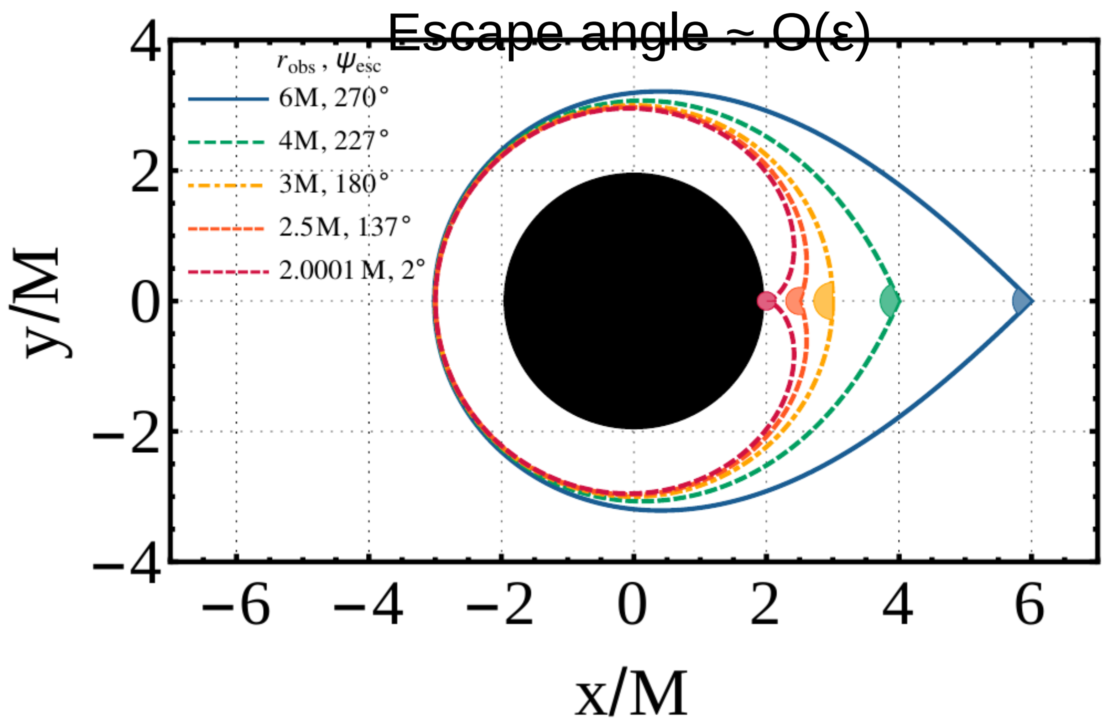
- Non-interacting field $\rightarrow$ diluted configurations (e.g. fuzzy DM) [Hui+ PRD 2017]
- Self-interactions can support compact configurations $r_0 \approx 3M \rightarrow \epsilon \sim \mathcal{O}(1)$
- Maximum mass set by the interaction $\rightarrow$ $M_{\rm max} \gg 1.4 M_\odot$

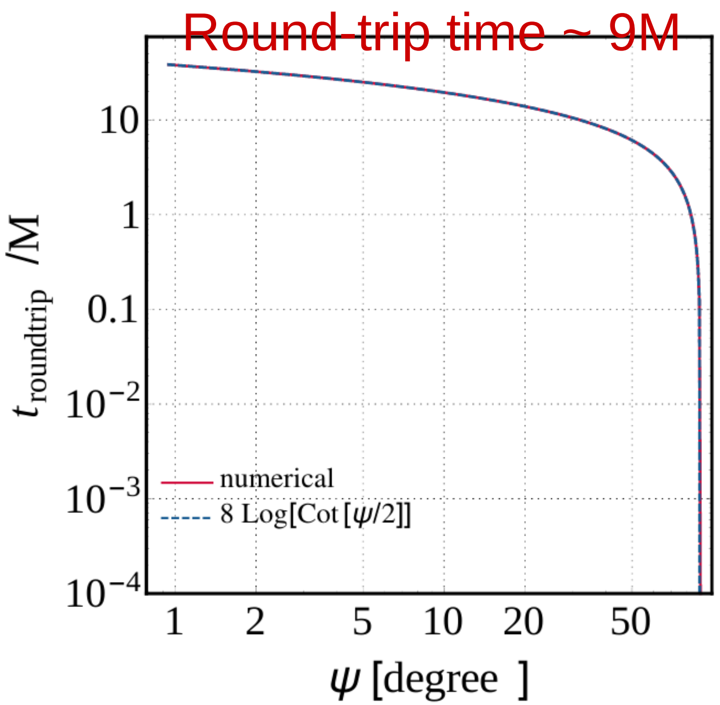





Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)

Are ECOs ruled out by EM observations?





- Energy dissipated over time scale → $\tau_{\rm dissipation} \sim \frac{10M}{\epsilon} \gg \tau_{\rm Hubble}$
- EM tests of the horizon are very challenging, *if possible at all!* [Abramowicz, Kluzniak, Lasota (2012)]

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

Part III

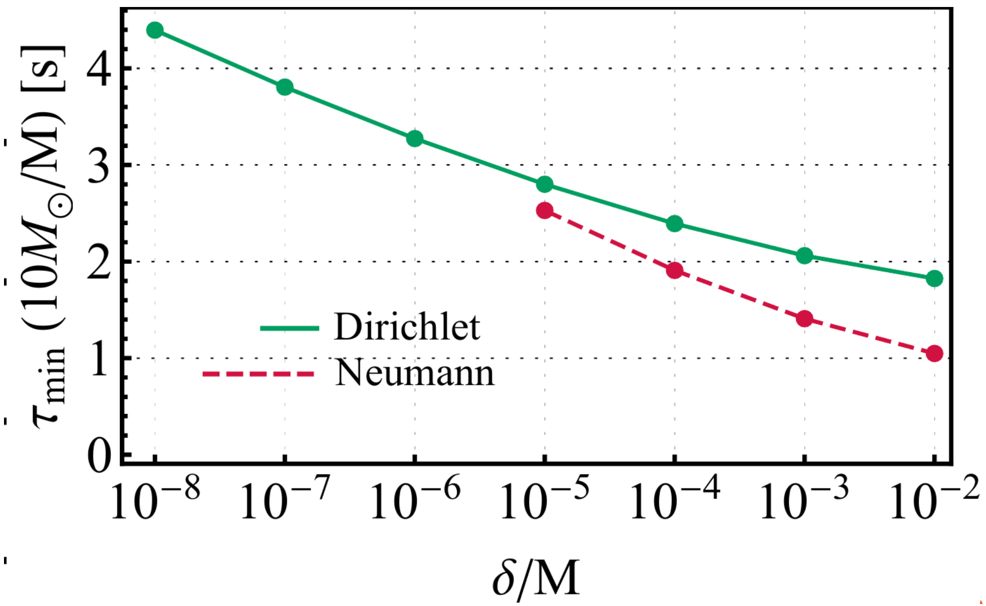
Ergoregion instability of ECOs and How to Quench It

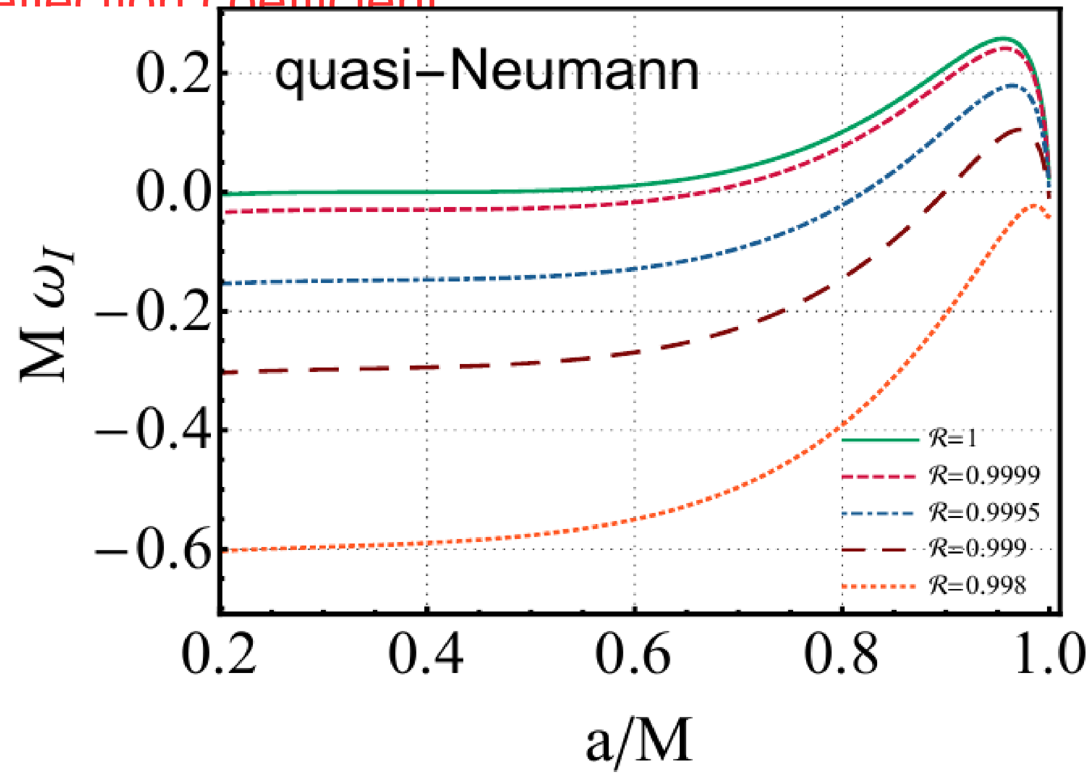
based on

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

Ergoregion instability is fragile

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





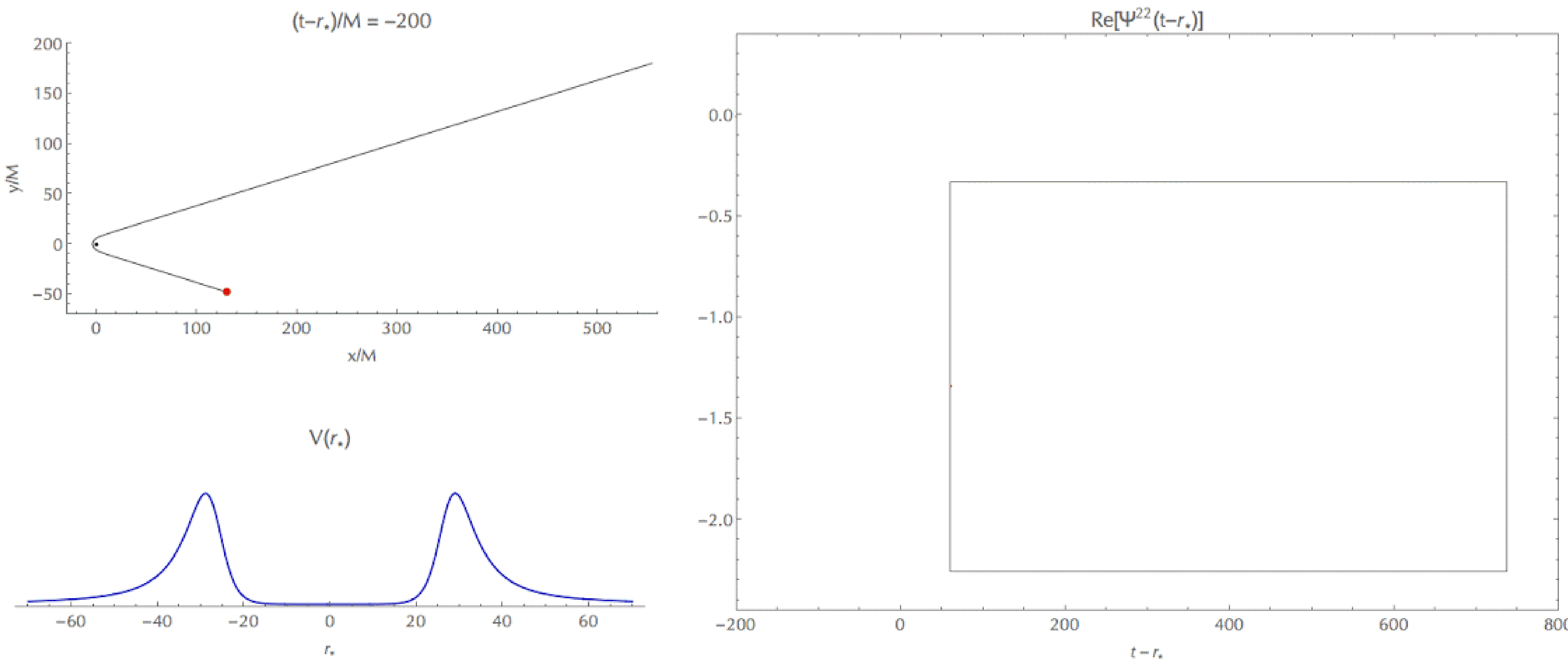
- Matter viscosity introduces absorption [Esposito, 1972]

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

The role of the photon sphere

Cardoso, Hopper, Macedo, Palenzuela, 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, ...)
  [Ferrari & Kokkotas, PRD 2000]
- The ringdown of ECOs without light ring is *qualitatively* different
  [Chirenti & Rezzolla, PRD 2016]
- GW observations can rule out less compact ECOs without light ring