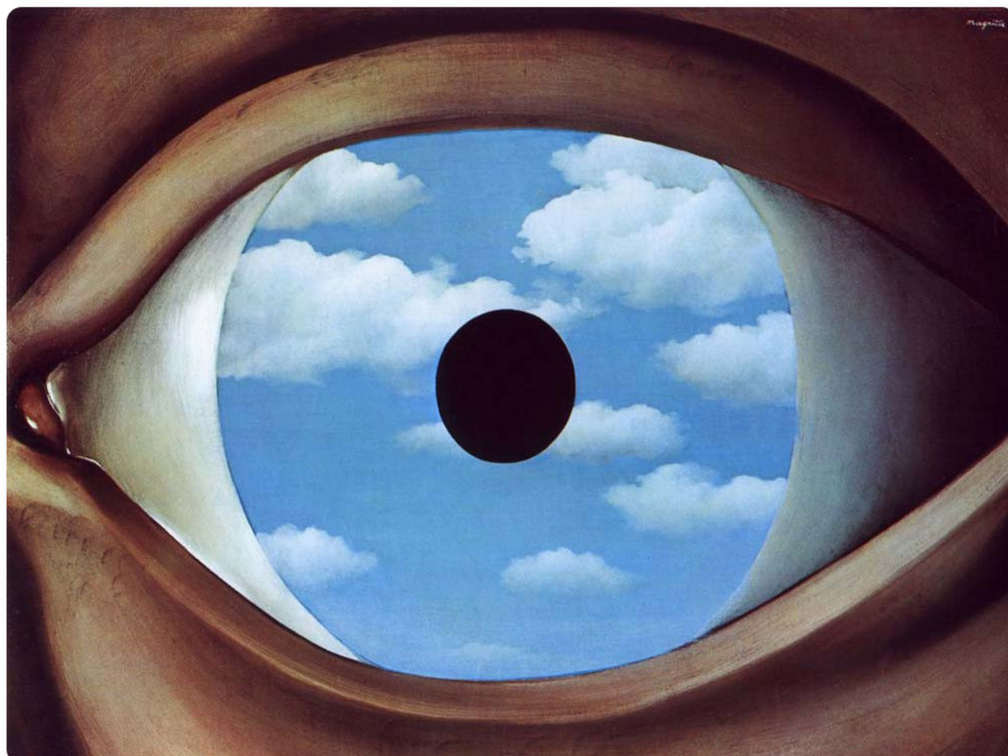
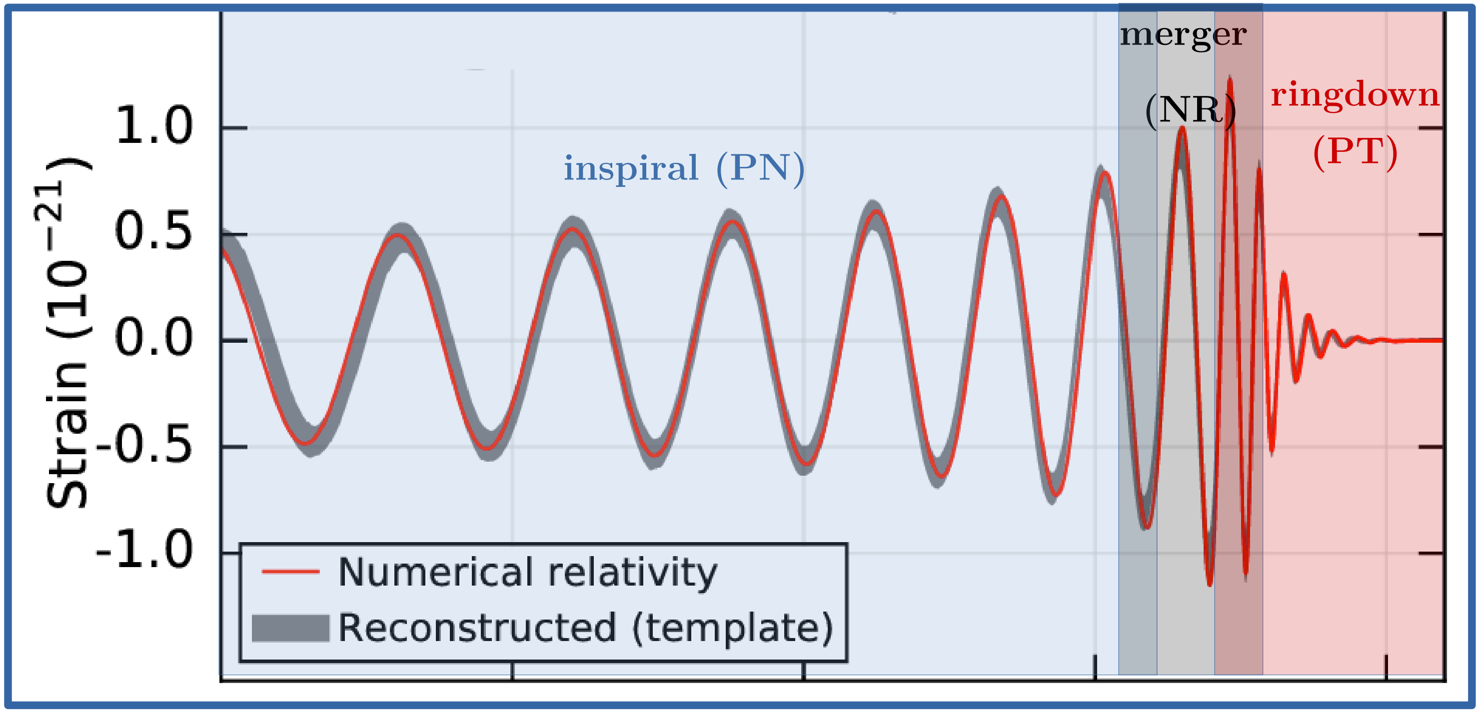
Testing the nature of compact objects with GWs



Paolo Pani
Sapienza University of Rome & INFN Roma1

European Research Council
DarkGRA

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

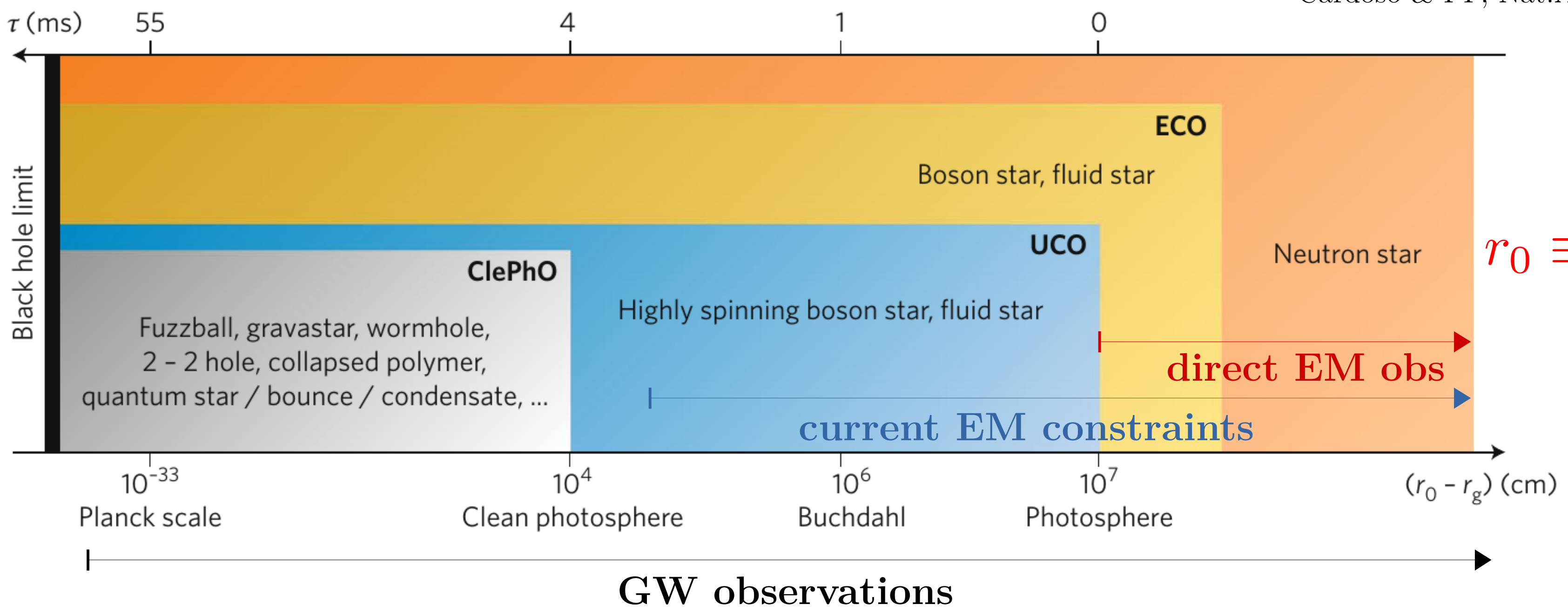
The problem with horizons

(G=c=1 units henceforth)

- BHs are very economical:
  - Arbitrary mass, Compactness M/R ~ 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]

The zoo of Exotic Compact Objects (ECOs)

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



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

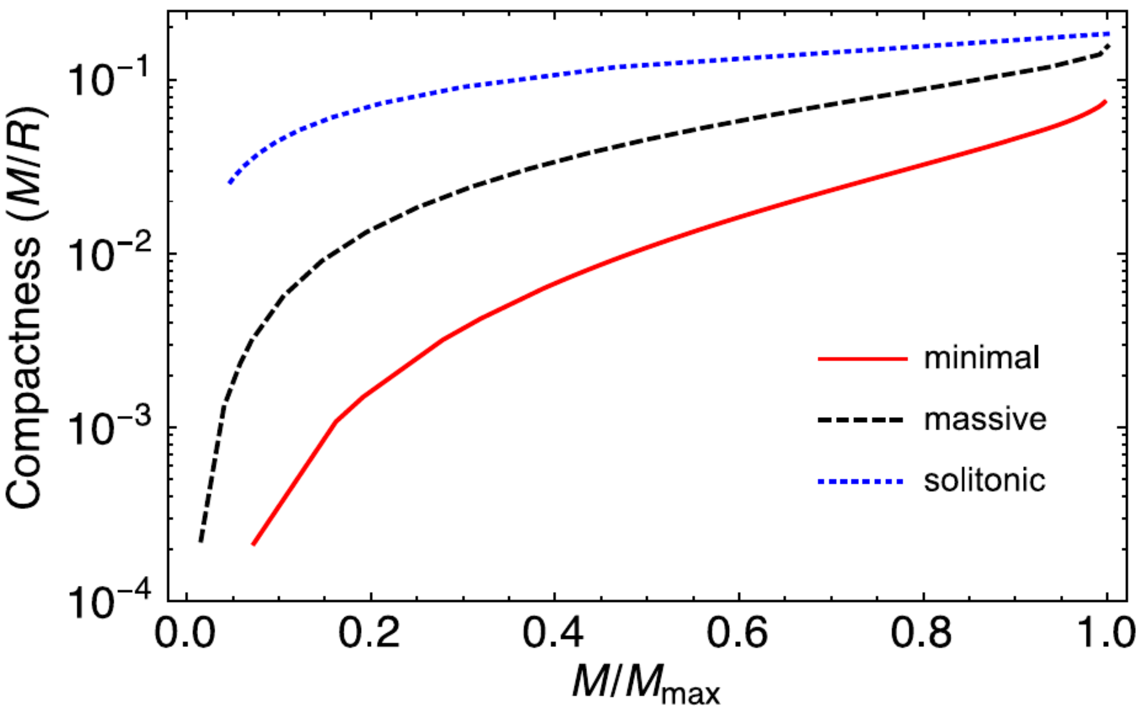
- GW observations can probe regions much closer to the horizon than EM
- Two classes of ECOs:
  - "Neutron-star like" (e.g. boson stars) $\to \epsilon \sim \mathcal{O}(1)$
  - "BH like" (e.g. fuzzballs, "quantum BHs") $\to \epsilon \sim 10^{-39} - 10^{-46}$
- Require a combination of targeted and agnostic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

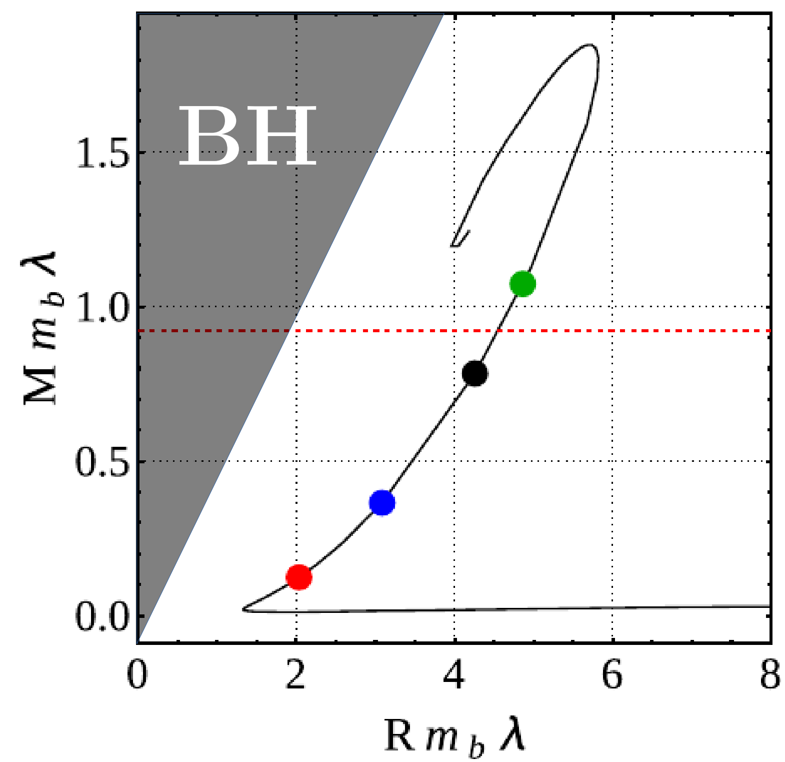
Boson Stars

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

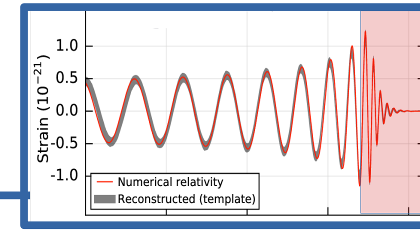
$$\mathcal{L} = \frac{R}{16\pi G} - \partial_\mu \phi\, \partial^\mu \phi^\star - m_b^2|\phi|^2 + \lambda|\phi|^4 + \gamma|\phi|^6 + \ldots$$

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





BH spectroscopy

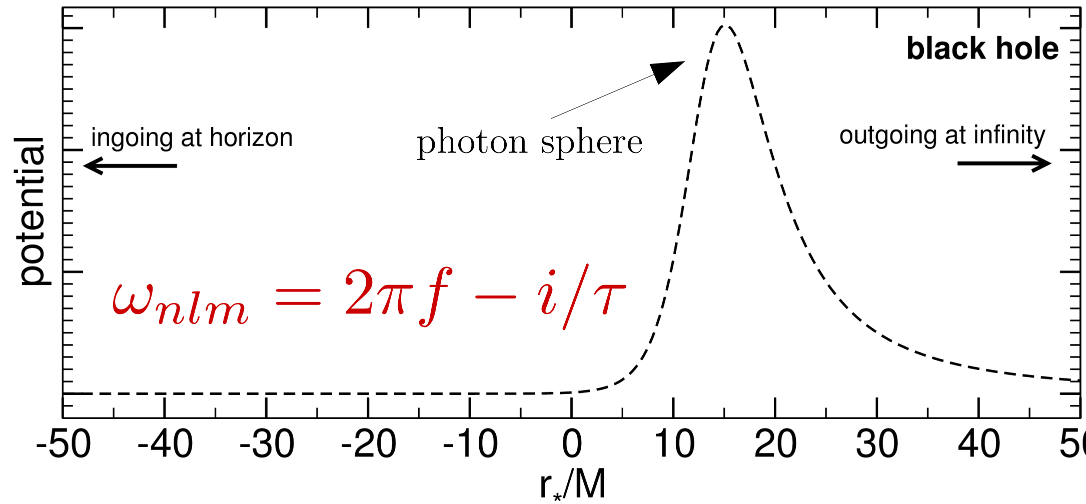


- Post-merger signal → superposition of QNMs [progress in modeling, e.g. Brito+ 1805.00293]

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

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

[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)

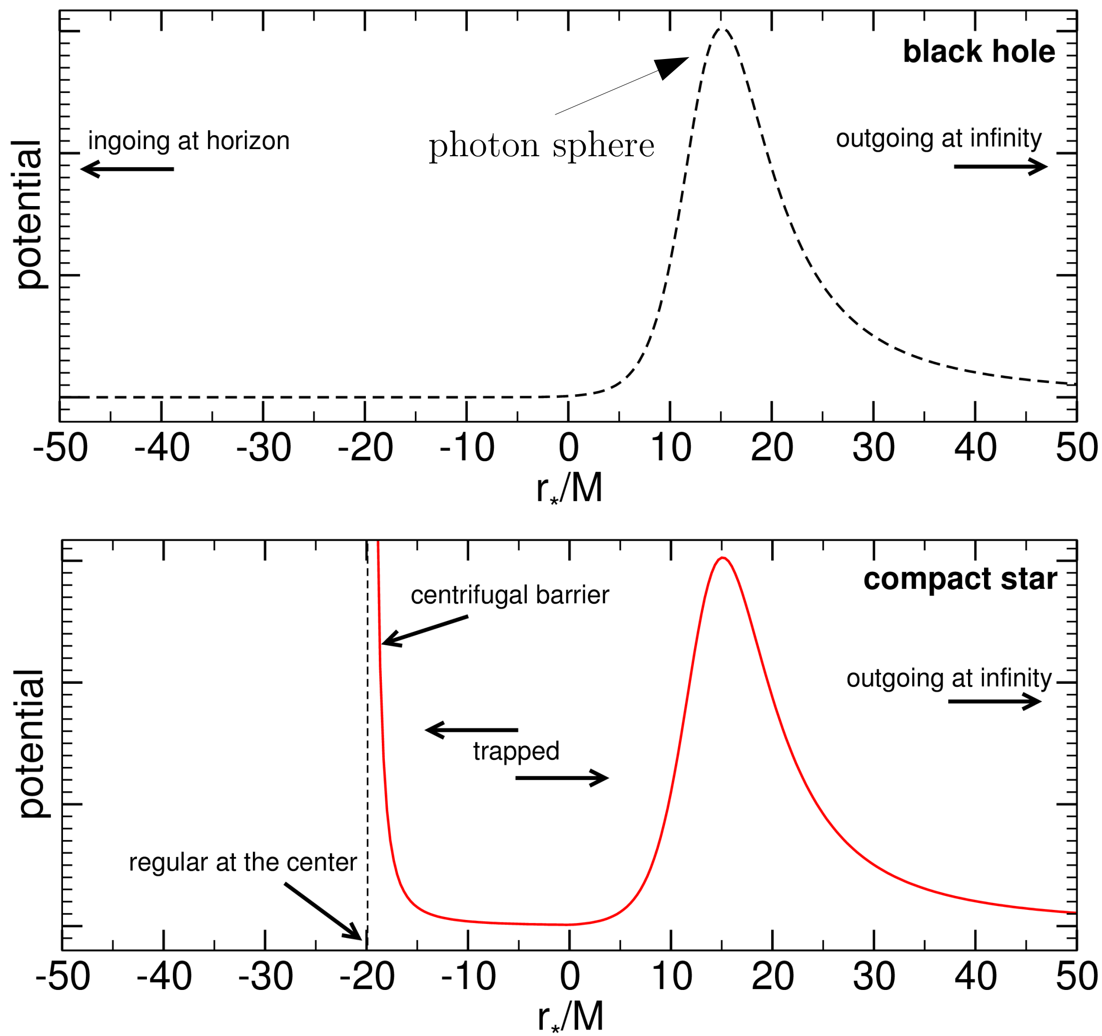
$$\omega_{nlm} = \omega_R^{\rm Kerr}(M,\chi) + \delta\omega_R \qquad \tau_{nlm} = \tau^{\rm Kerr}(M,\chi) + \delta\tau$$

- 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

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

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

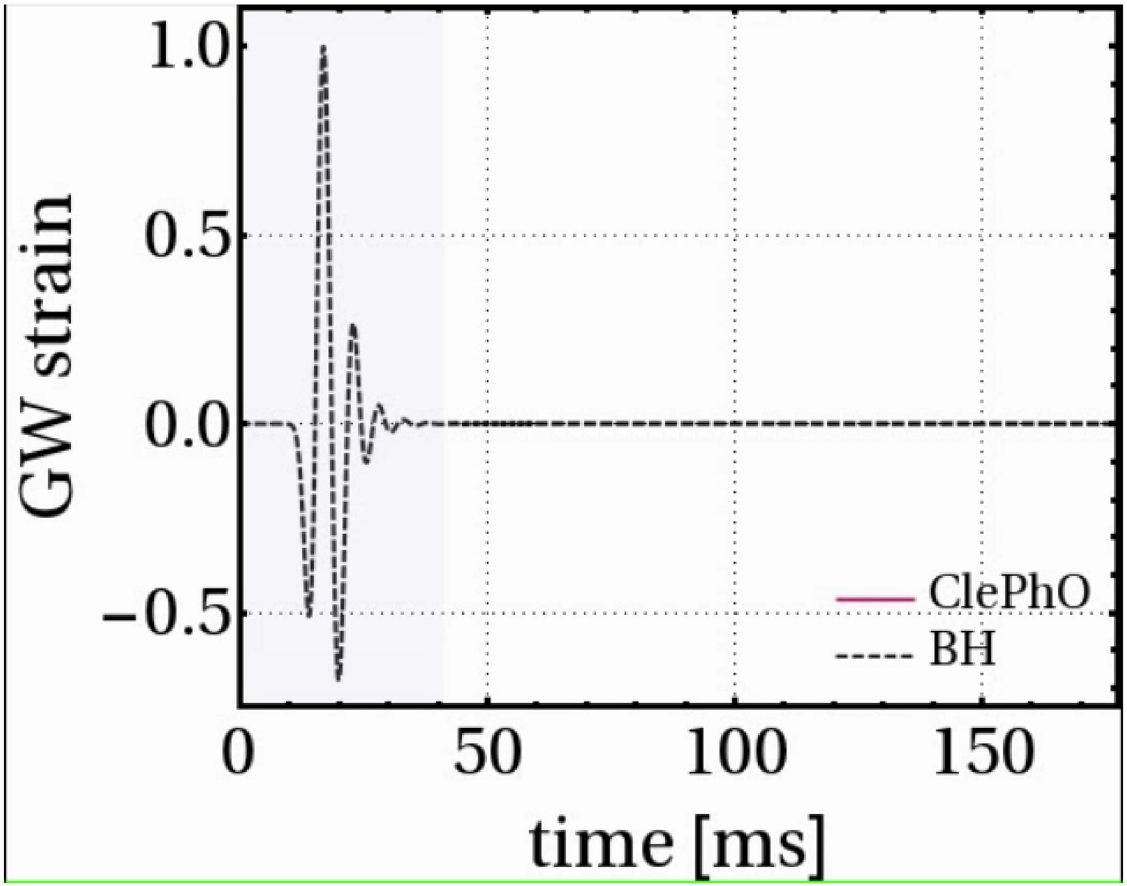


Ultracompact stars generically support trapped modes

Chandrasekhar & Ferrari PRSLA (1991)

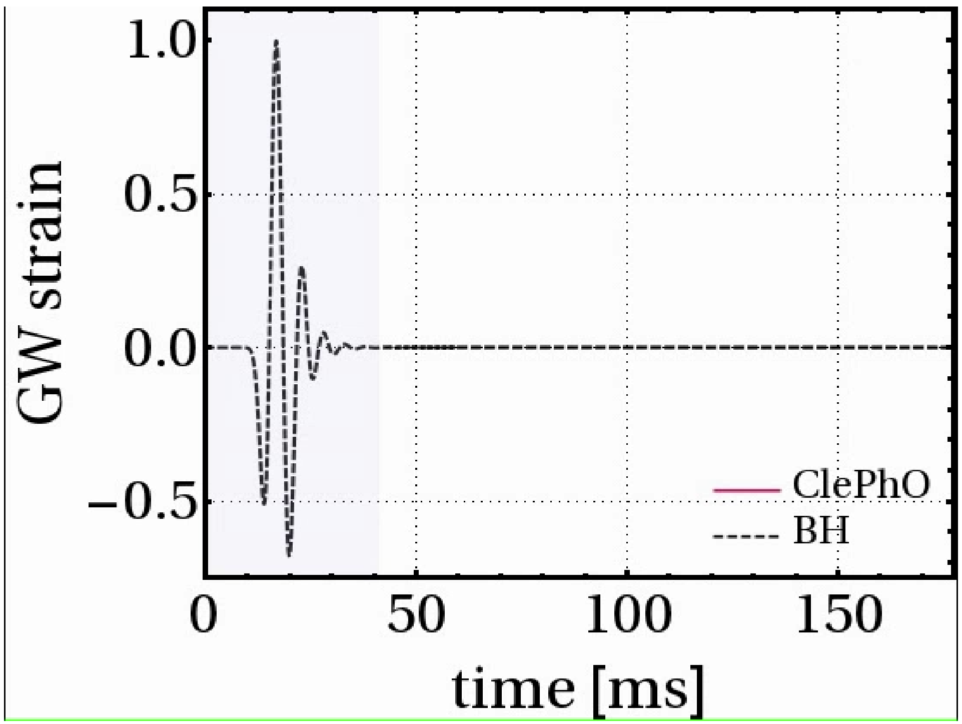
No horizon → QNM spectrum dramatically different → ringdown?

GW echoes



Ringdown of a Schwarzschild BH
(Gaussian perturbation)

GW echoes



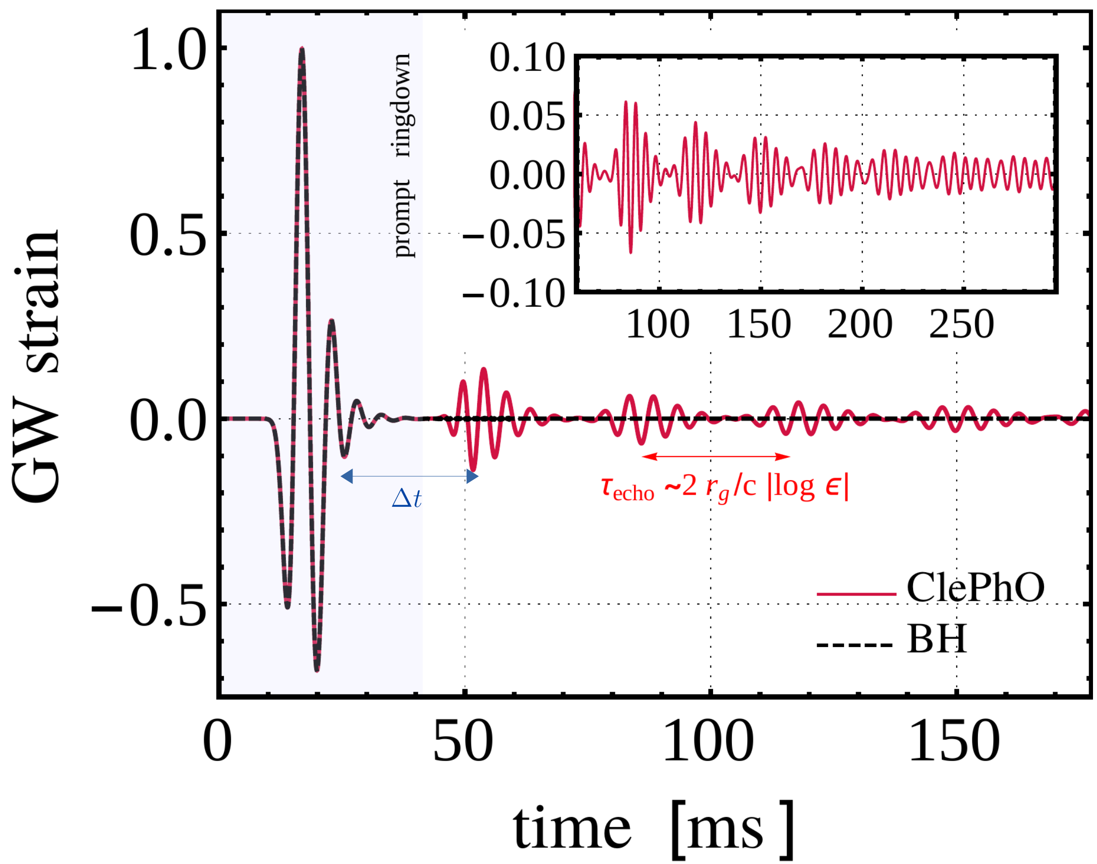
Prompt ringdown is identical, but GW "echoes" at late time

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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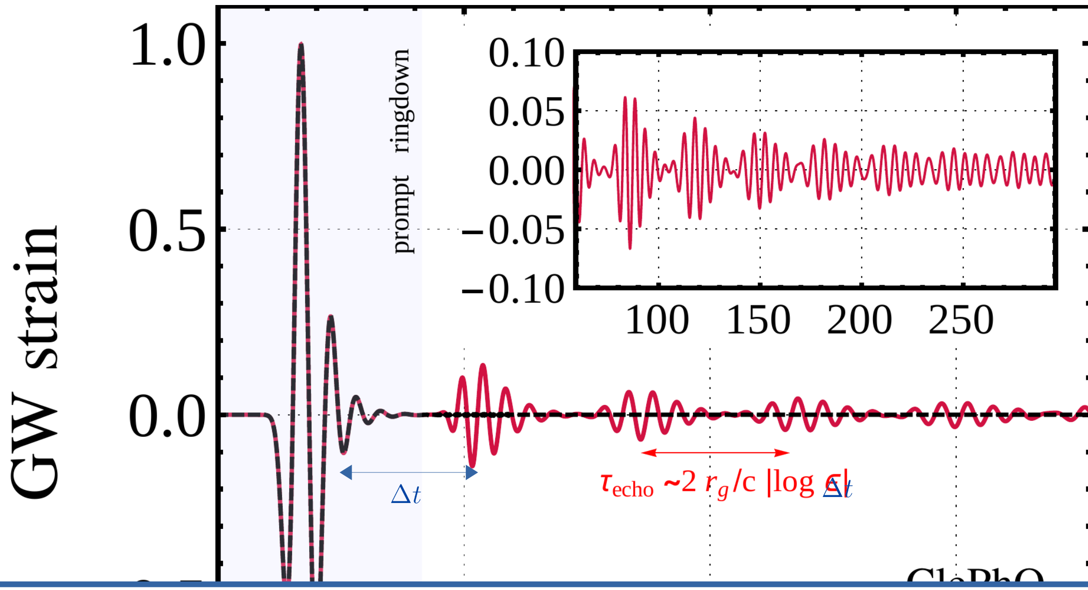
Delay time

- 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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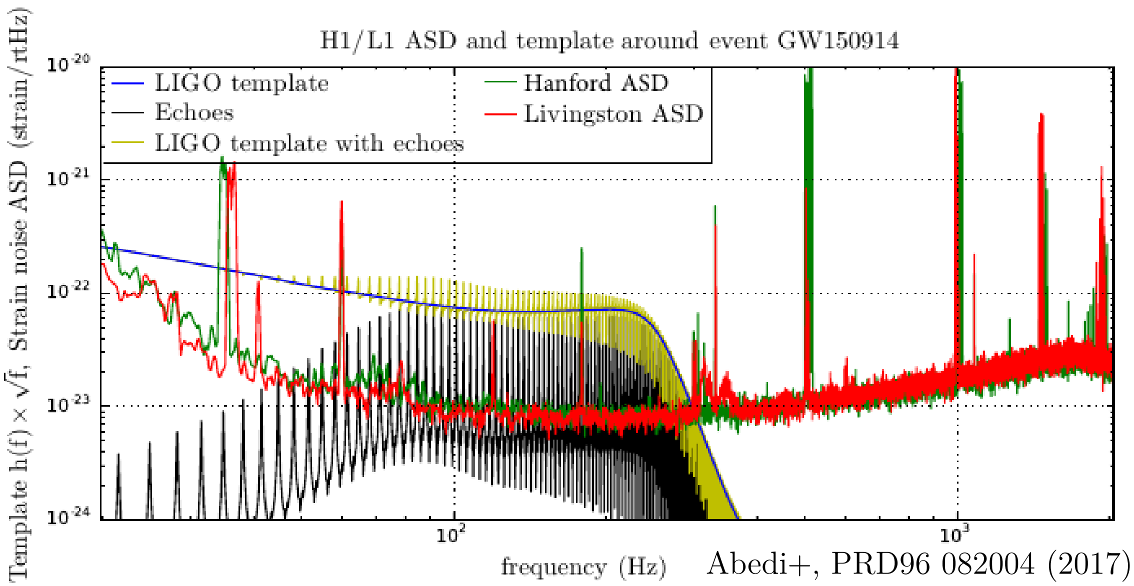
> evolution used by Hawking would be invalidated. The problem is that we need an *order unity* correction to the evolution of these modes, since they have to go from a fully entangled state to a non-entangled state. On the other hand, all quantum gravity effects are expected to be of order (l_p/R) to 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

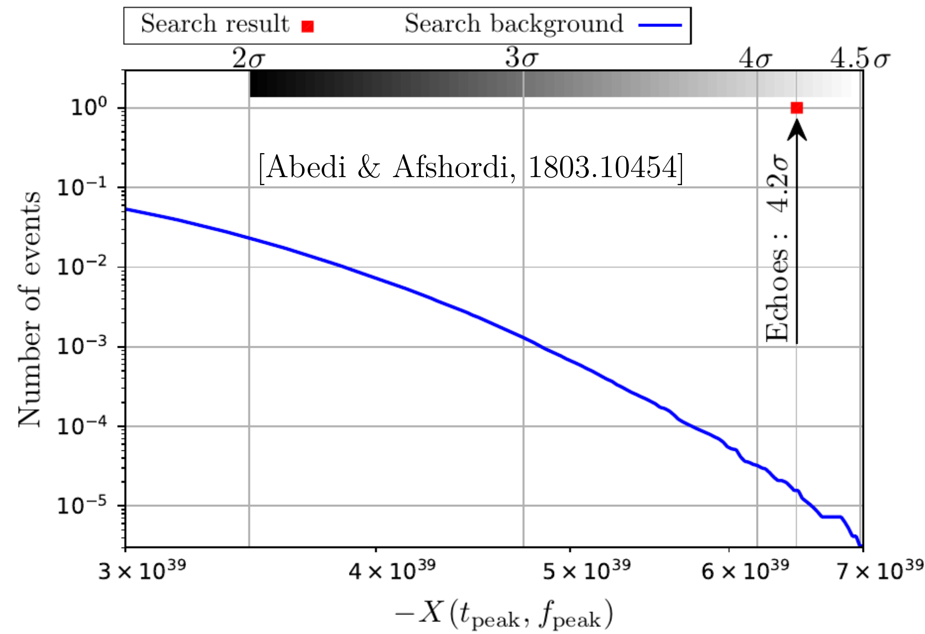
Mathur (2009)

- 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





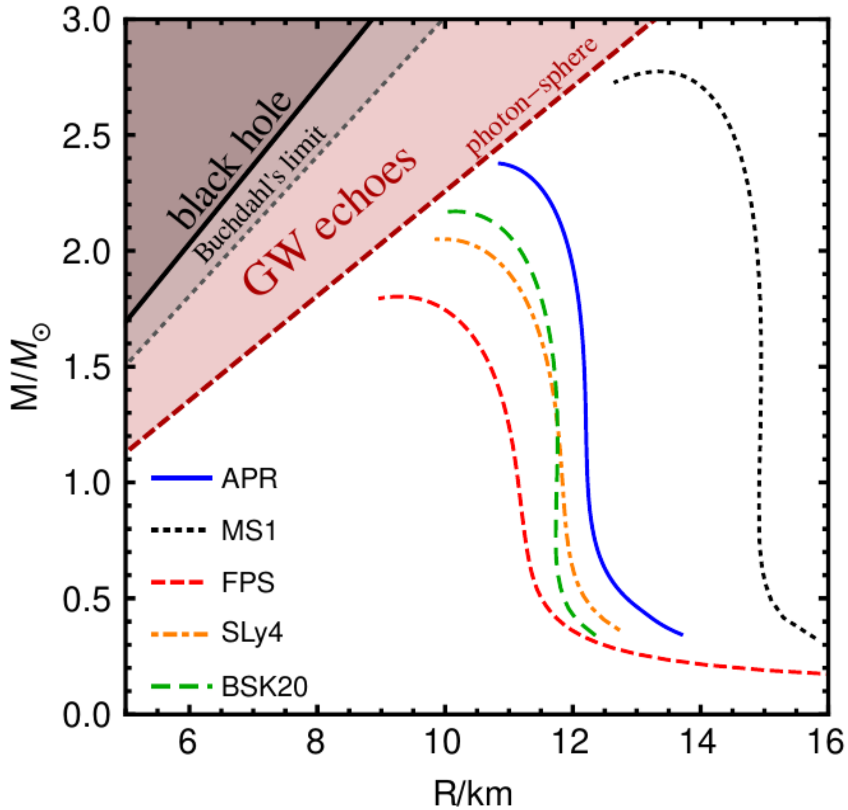
- Tentative detection of ~72 Hz echoes @4.2 σ in GW170817 [Abedi & Afshordi 1803.10454]
- Contrasting results [Abedi+ PRD96 082004 (2017), Conklin+ 1712.06517, Ashton+ 1612.05625, Westerweck+ 1712.09966, Abedi+1803.08565]
- Limitation in the templates: frequency/amplitude distortions, spin, ...
- Progress 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 (to appear)]

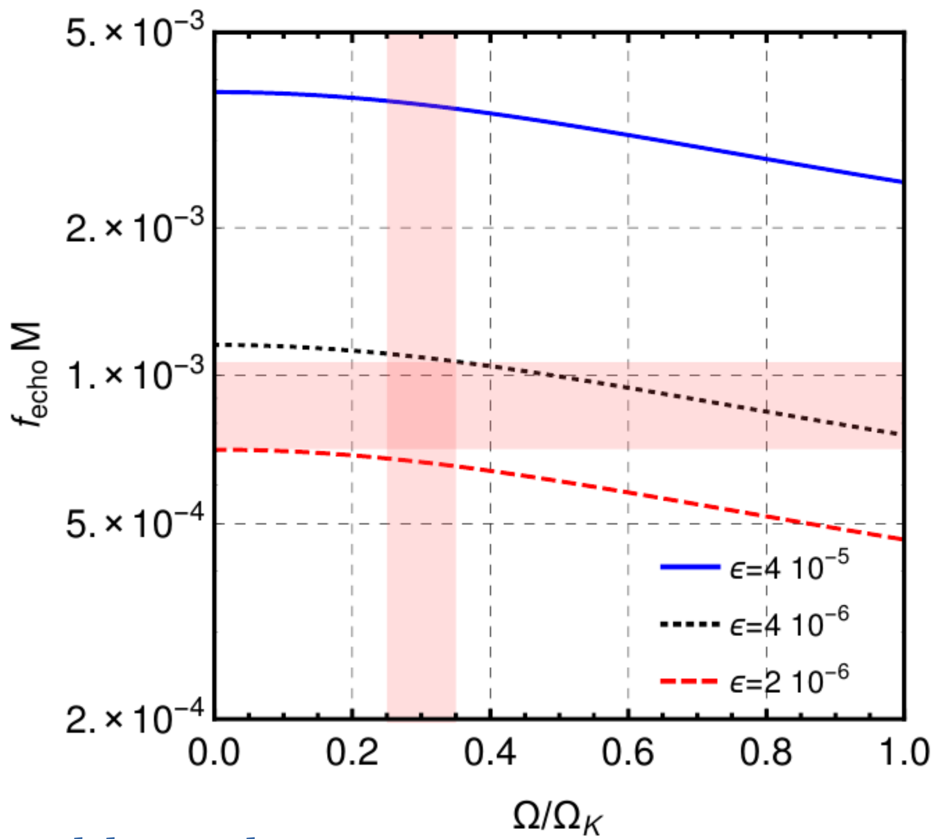
Quantum corrections within reach of current and future detectors!

Potential inferences from GW echoes

PP & Ferrari, 1804.01444

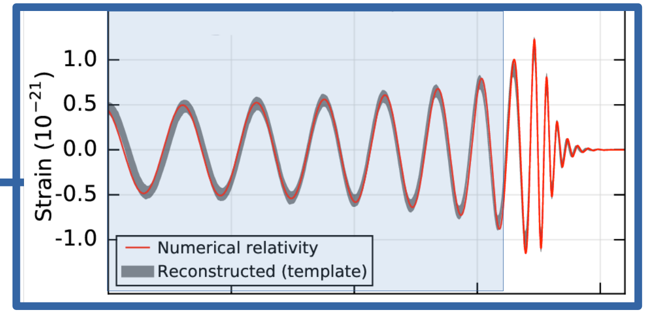
- Merger remnant has photon sphere but no horizon → neither BH *nor* ordinary NS



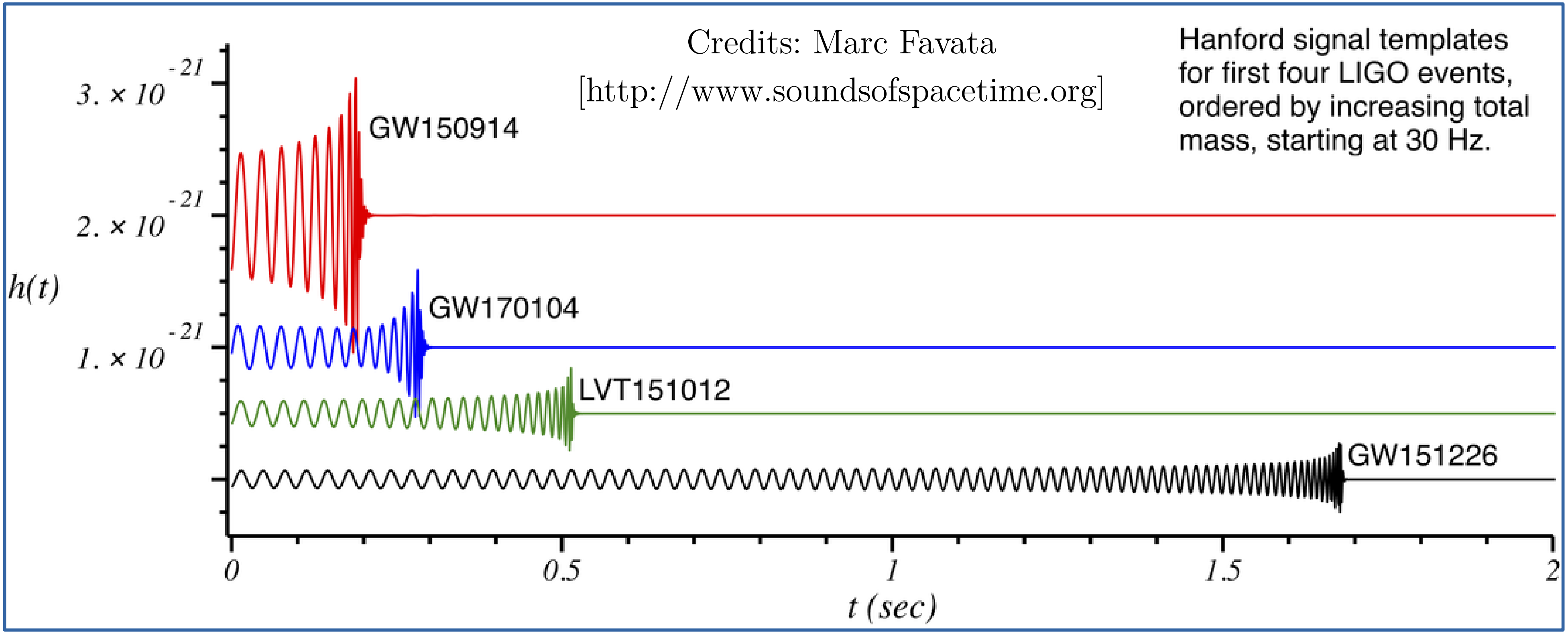


- Echoes in GW170817 at ~72 Hz compatible with
  - Near-horizon quantum structures
  - NS with very exotic matter

Accurate templates are needed to discriminate different models



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)

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

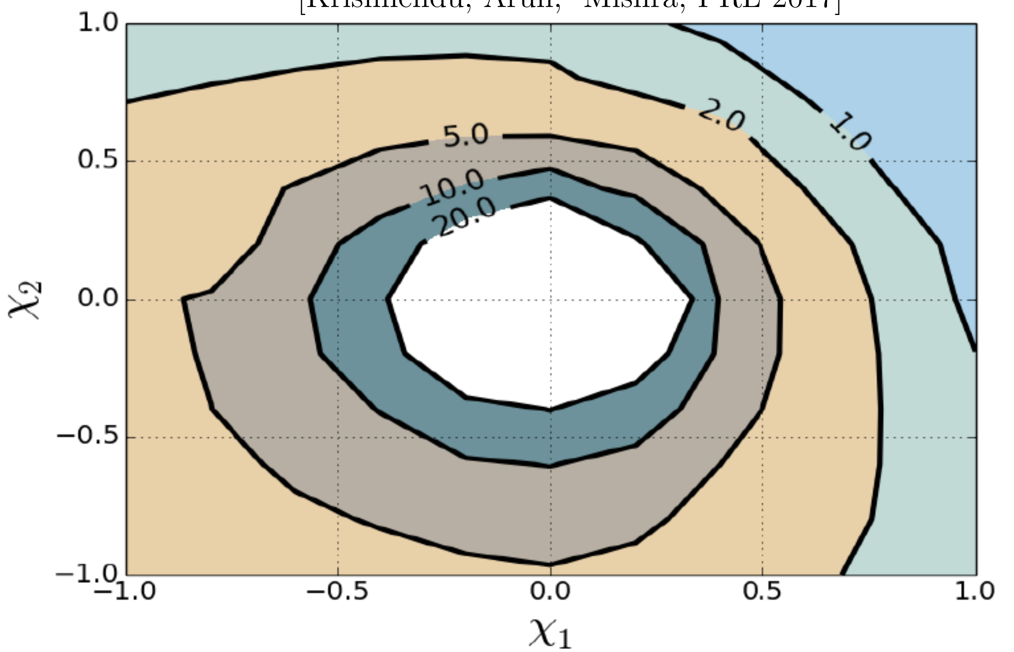
Blanchet, Living Rev. Relativity 17, 2 (2014)

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

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

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

[Krishnendu, Arun, Mishra, PRL 2017]



- 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

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

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Blanchet, Living Rev. Relativity 17, 2 (2014)

- **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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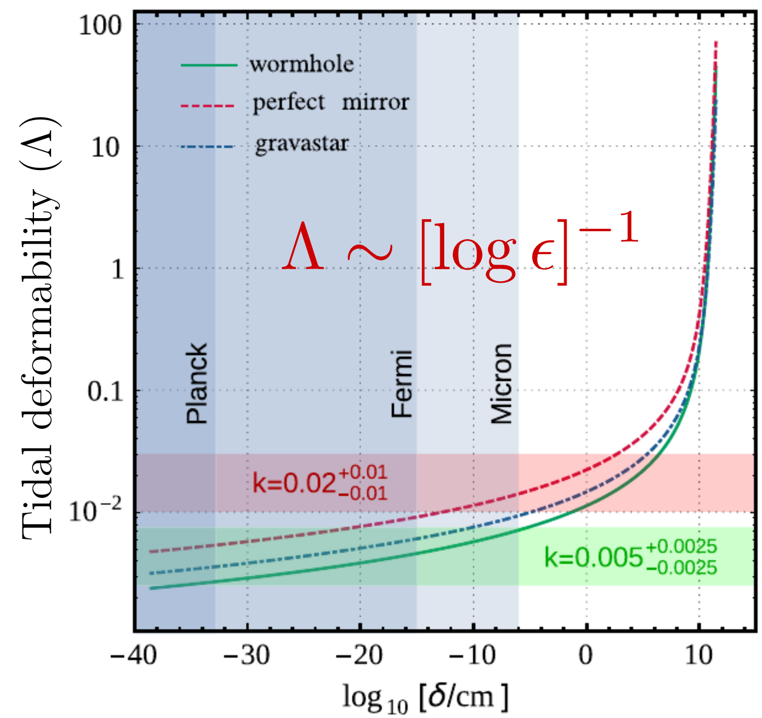
Blanchet, Living Rev. Relativity 17, 2 (2014)

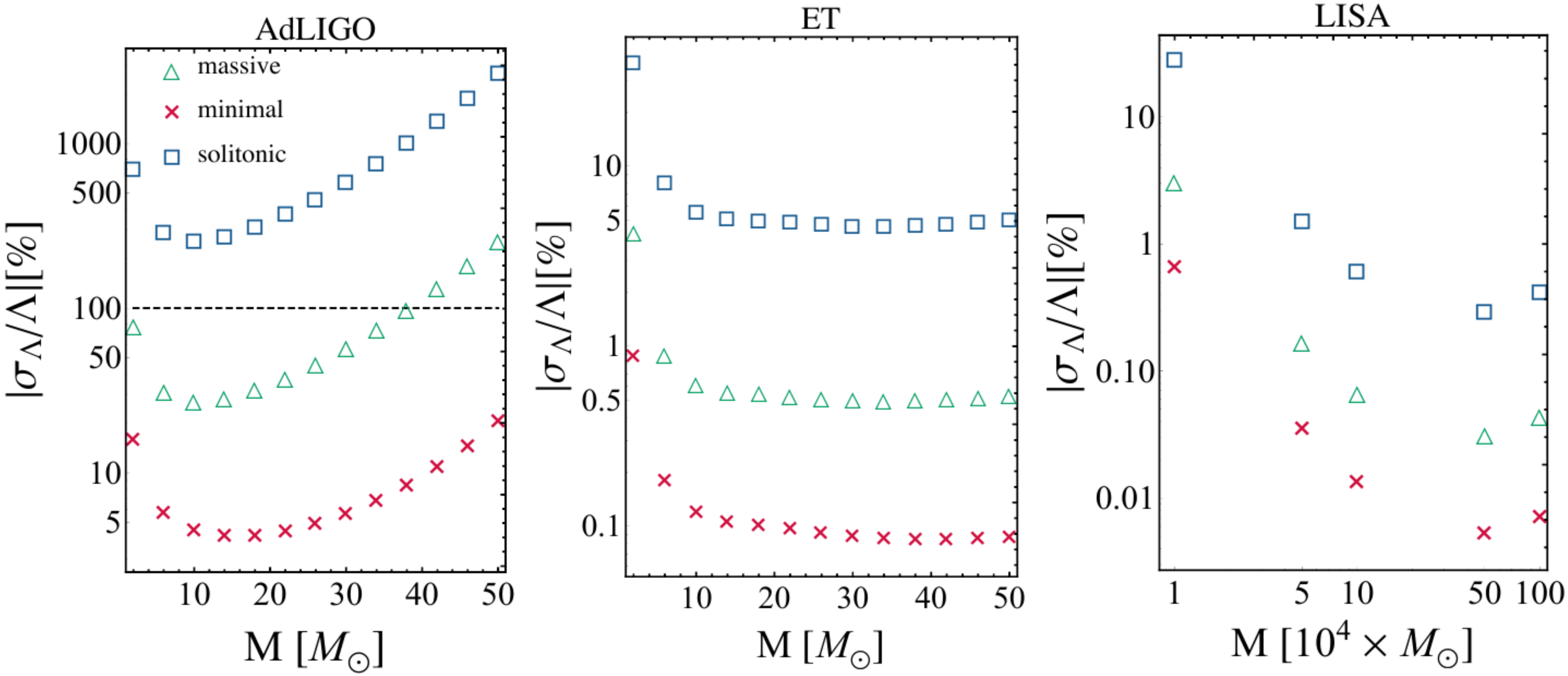


- **2.5PN: tidal heating** [Alvi PRD 2001, Poisson, PRD 2009]
  - BHs absorb radiation at horizon
  - Tidal heating is ~ absent for ECOs
- **5PN: tidal deformability and Love numbers** [Flanagan & Hinder, PRD77 021502 2008]
  - Love numbers of a BH are zero [Binnington & Poisson, 2009; Damour & Nagar 2009; PP+, 2015]
  - 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

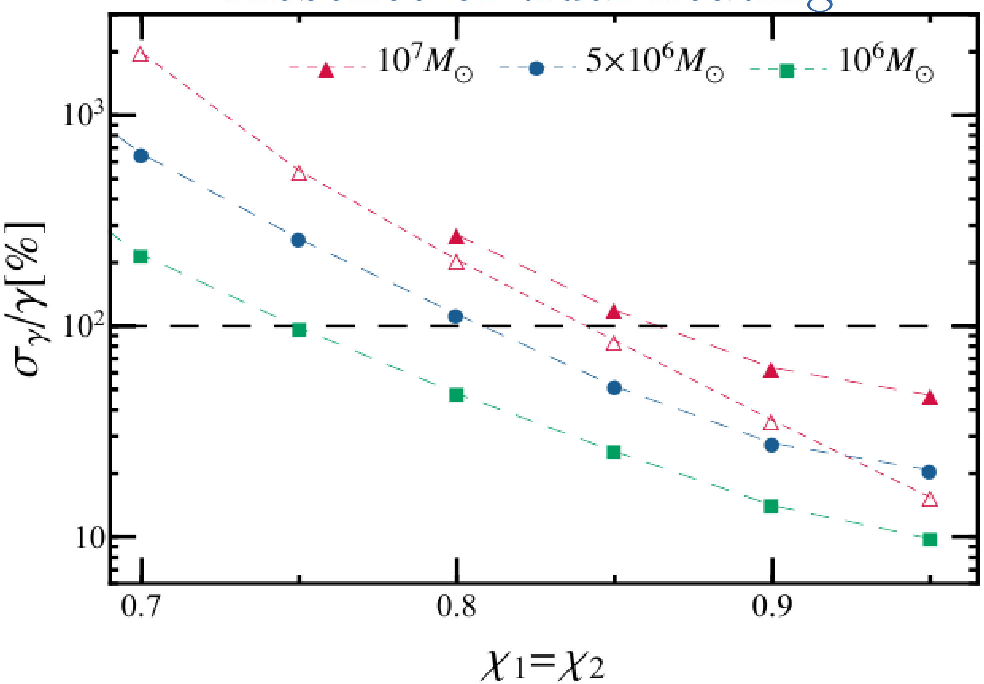
[Cardoso+ (2017), Sennet+ PRD 96 024002 (2017), Johnson-McDaniel+, 1804.08026]

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

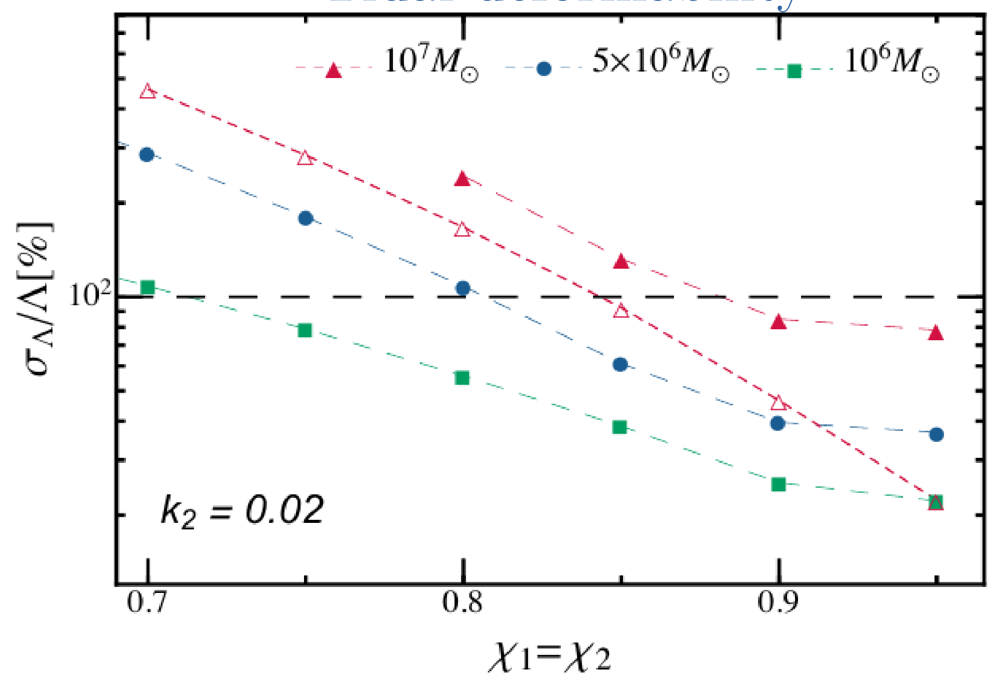
Probing BH quantum structures with LISA

Maselli, PP+; PRL 120 081101 (2018)

Absence of tidal heating



Tidal deformability

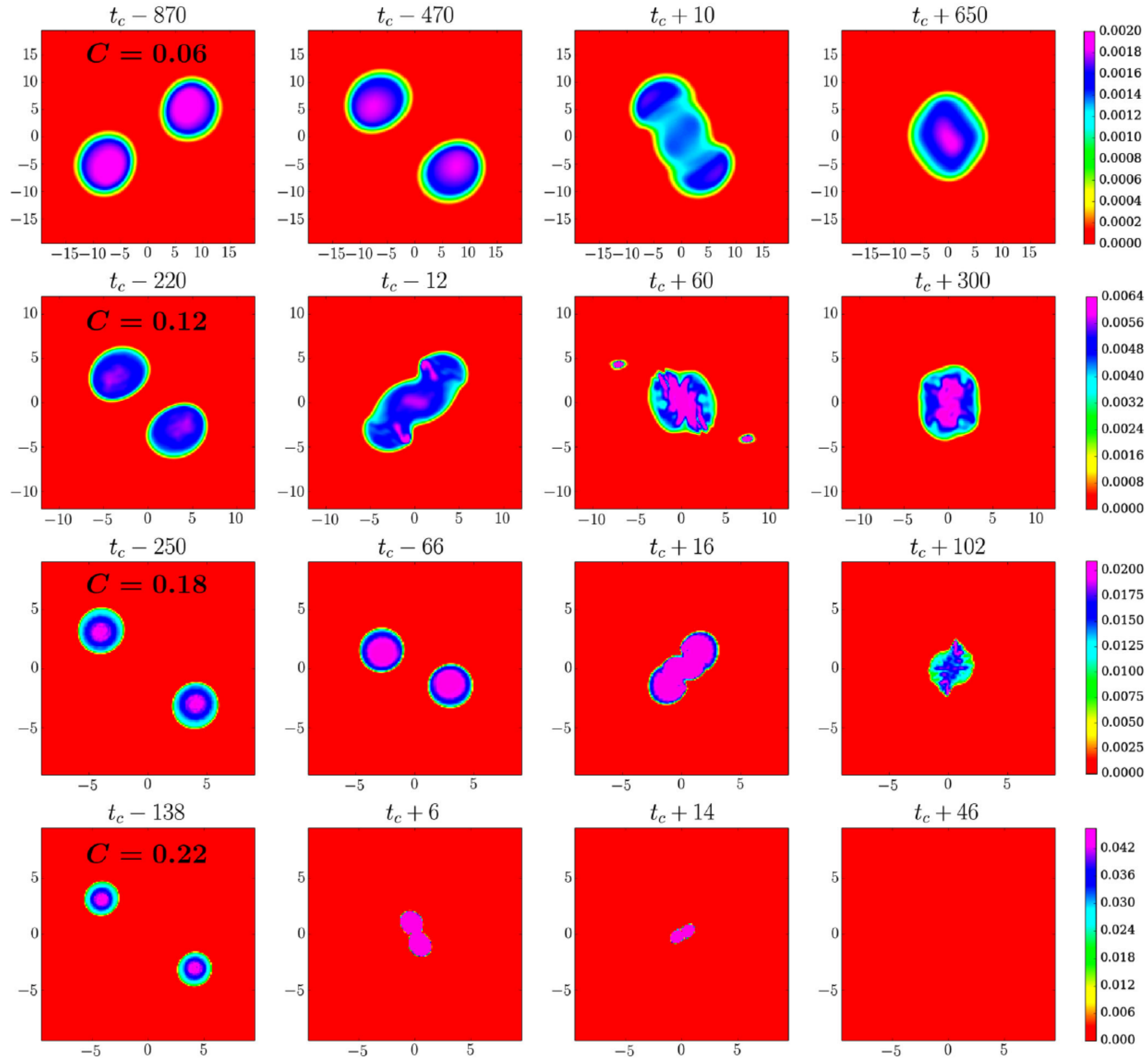


- Small corrections → requires spinning supermassive binaries @ 2-20 Gpc
- LISA binaries are golden sources to probe Planckian corrections!
- Tidal terms recently computed to 6.5PN [Abdelsalhin, Gualtieri, PP; 1805.01487]

Binary Boson Stars (BBSs)

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

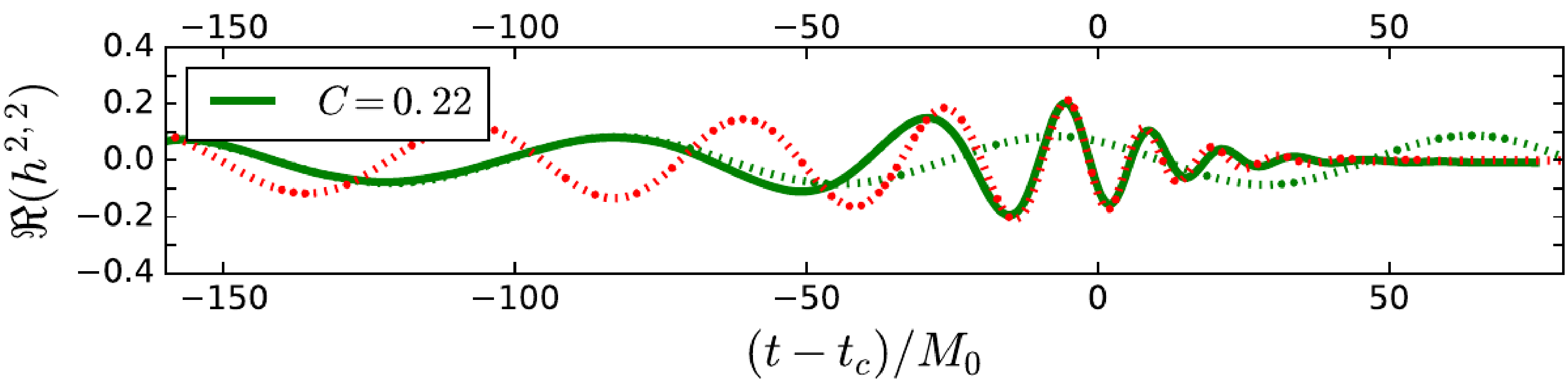
- Boson stars have quantized spin, J=nQ
- Final state → either BH or nonspinning BS?



BBSs or BBHs?

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

Can BBSs mimick the full signal from BBH coalescence?

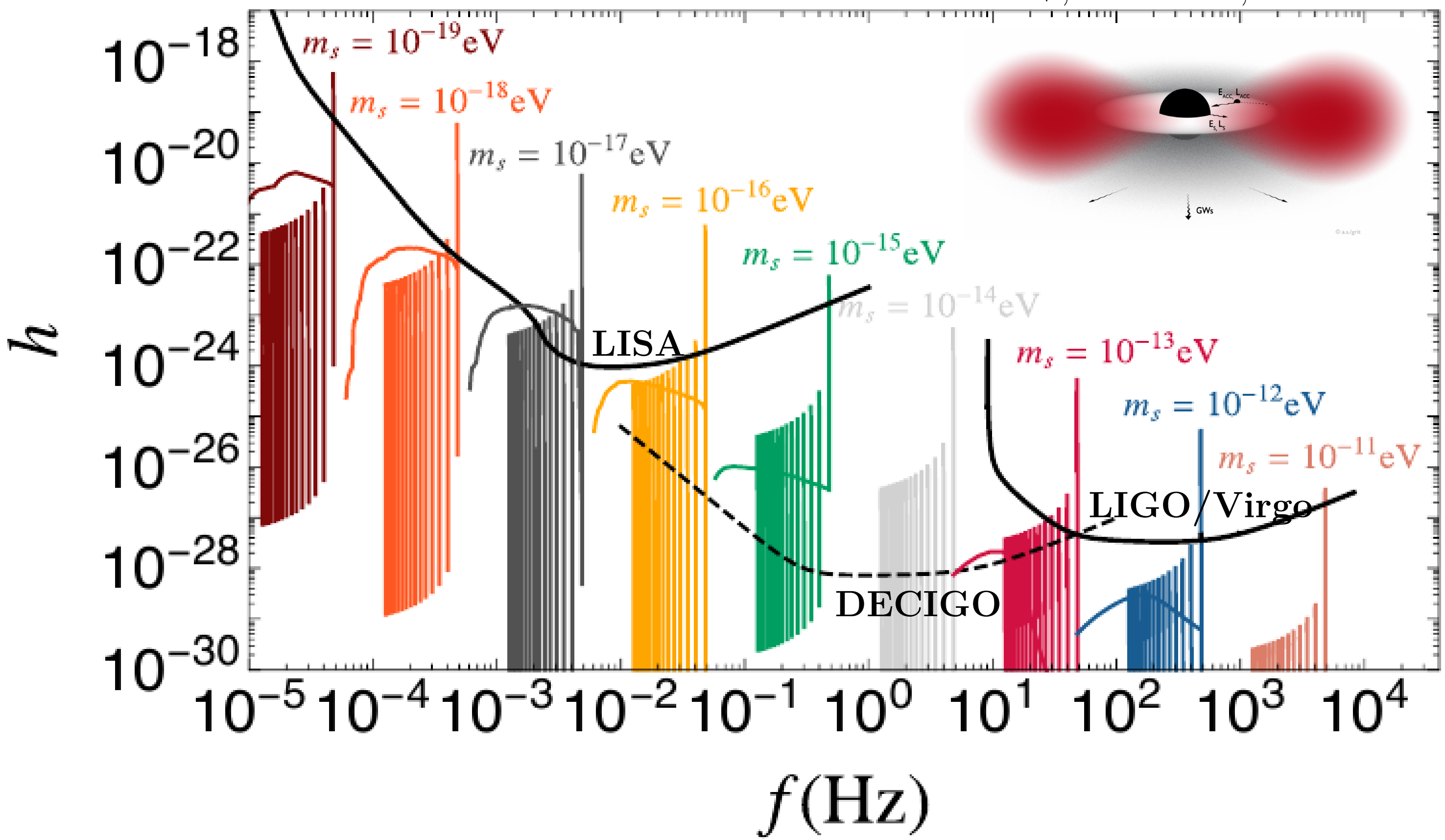


"Short-blancket" problem: mimicking IMR signal of BBHs is hard

GW periodic signal from axions

- Spinning BHs are unstable against ultralight boson fields [Arvanitaki+, 2012, Cardoso+ 2015]
- Continuous GW source at a frequency given by the axion mass

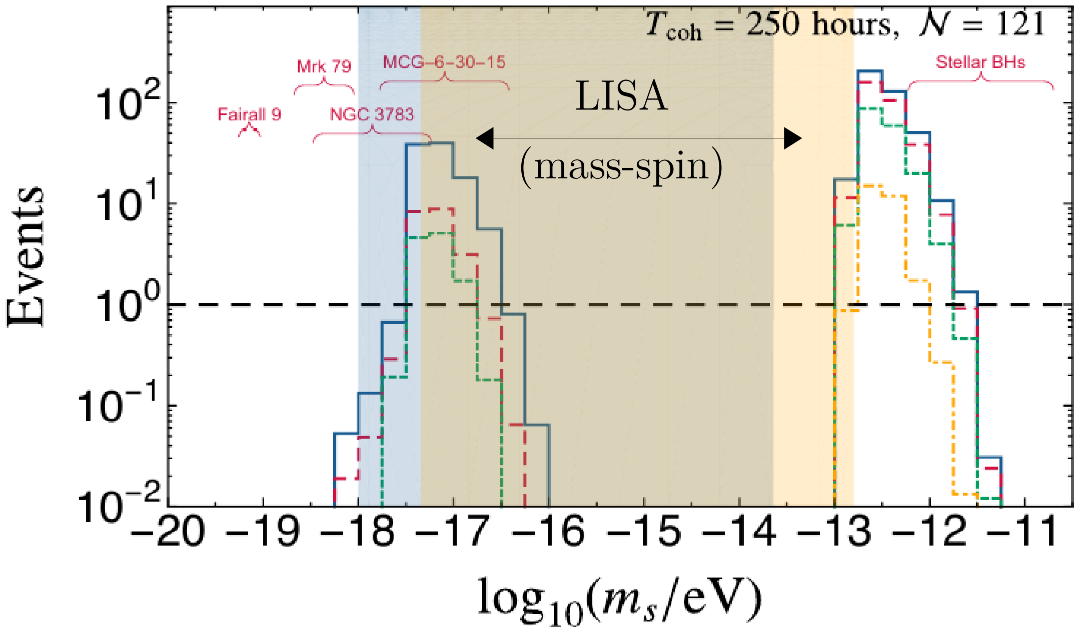
Brito+, PRL 2017, PRD 2017



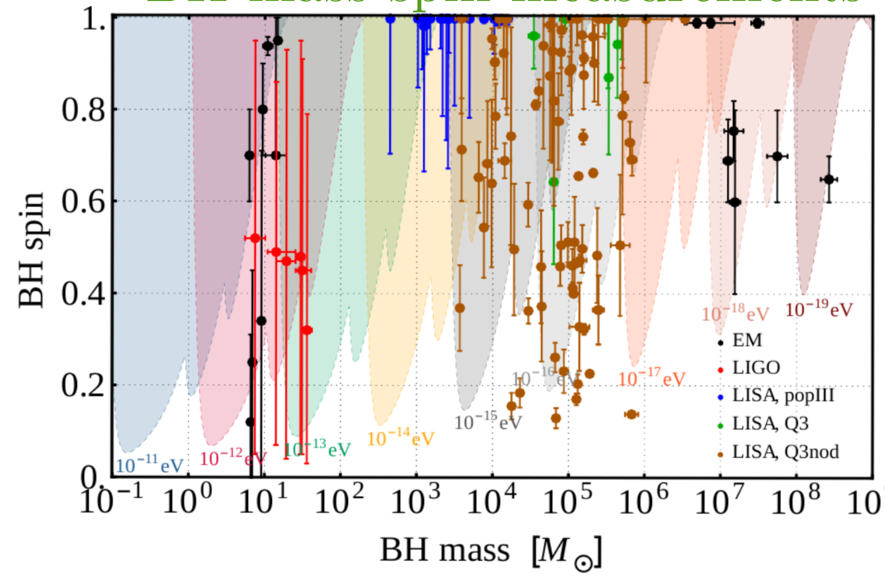
GWs from BH-axion condensates

Arvanitaki+ PRD (2016), Baryakhtar+ PRD (2017), Brito+, PRL 2017, PRD 2017, Hannuksela, 2018

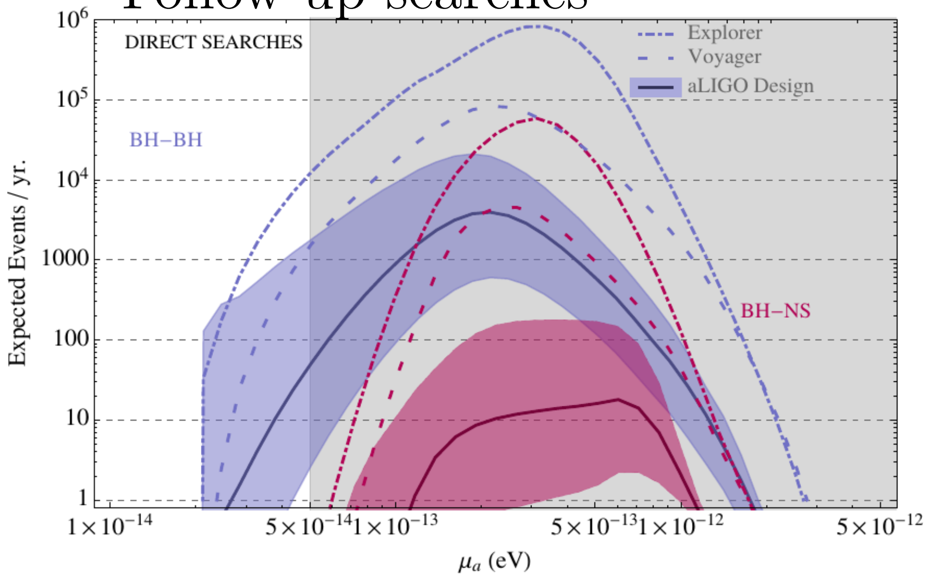
Direct detection



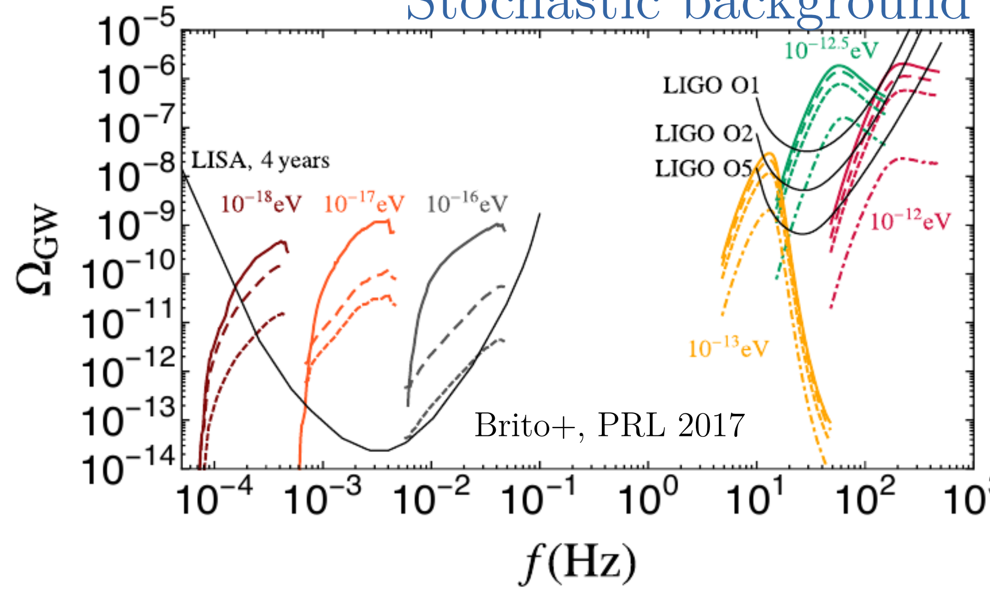
BH mass-spin measurements



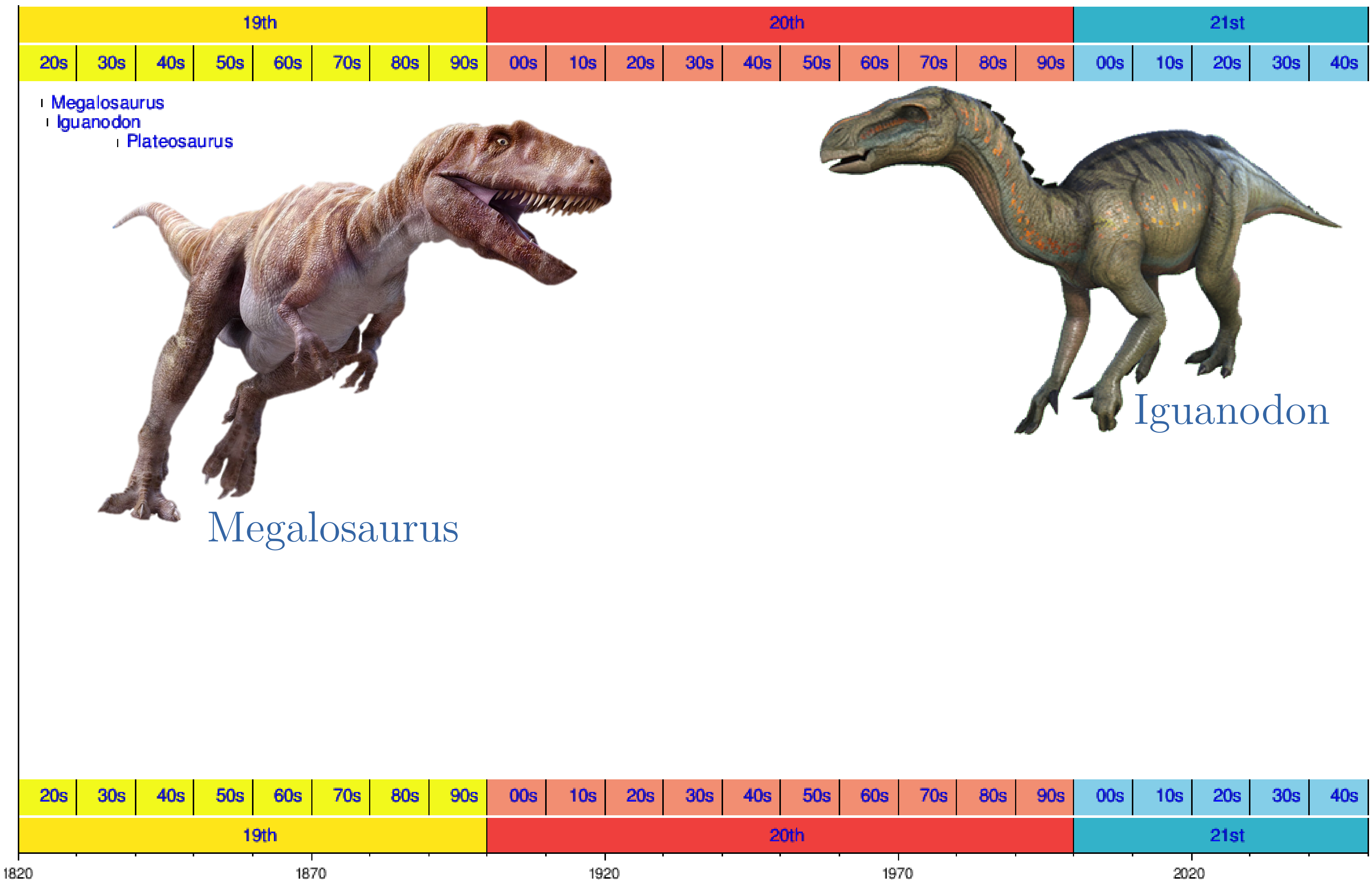
Follow-up searches



Stochastic background



Are exotica out there?



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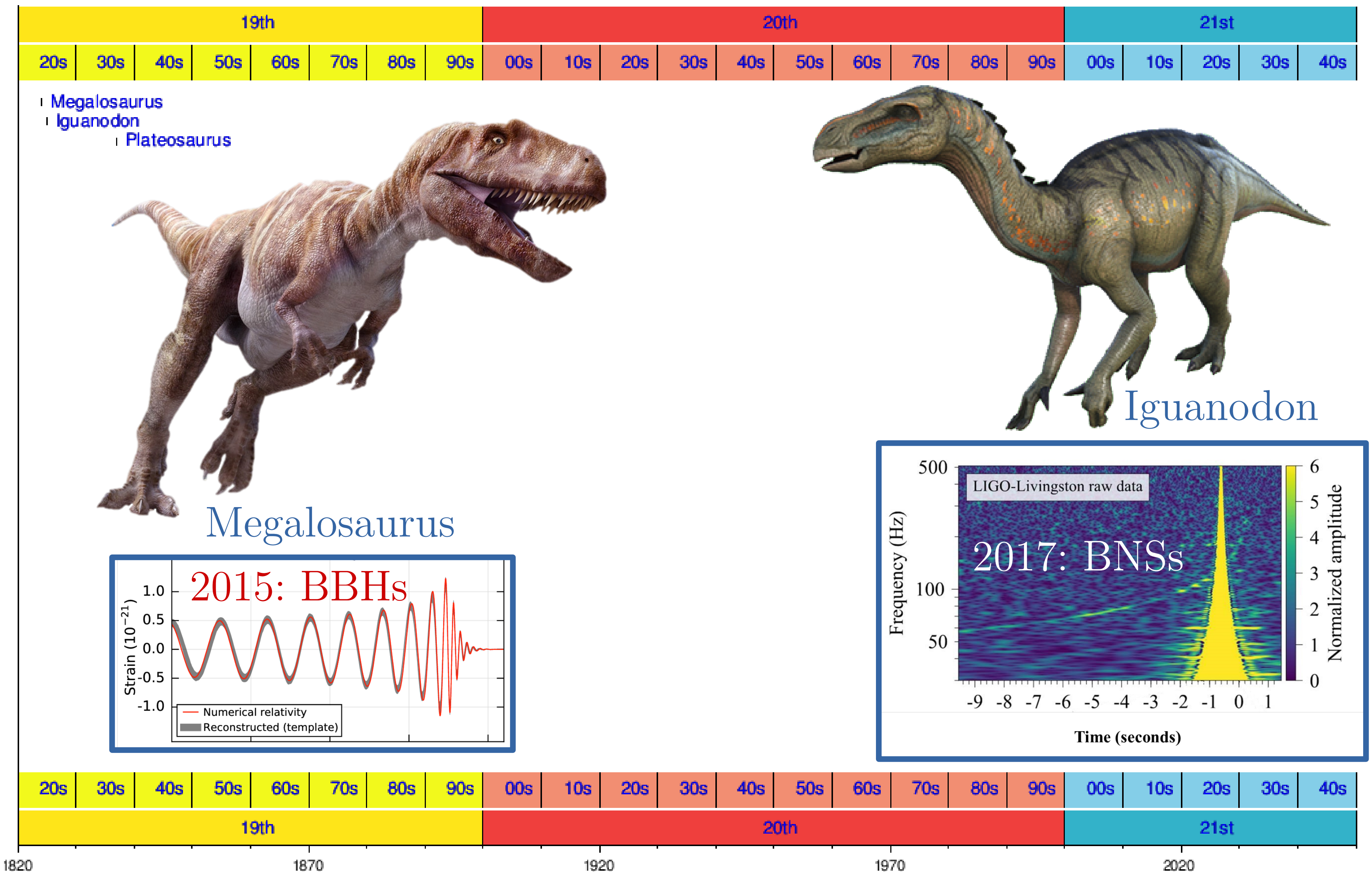
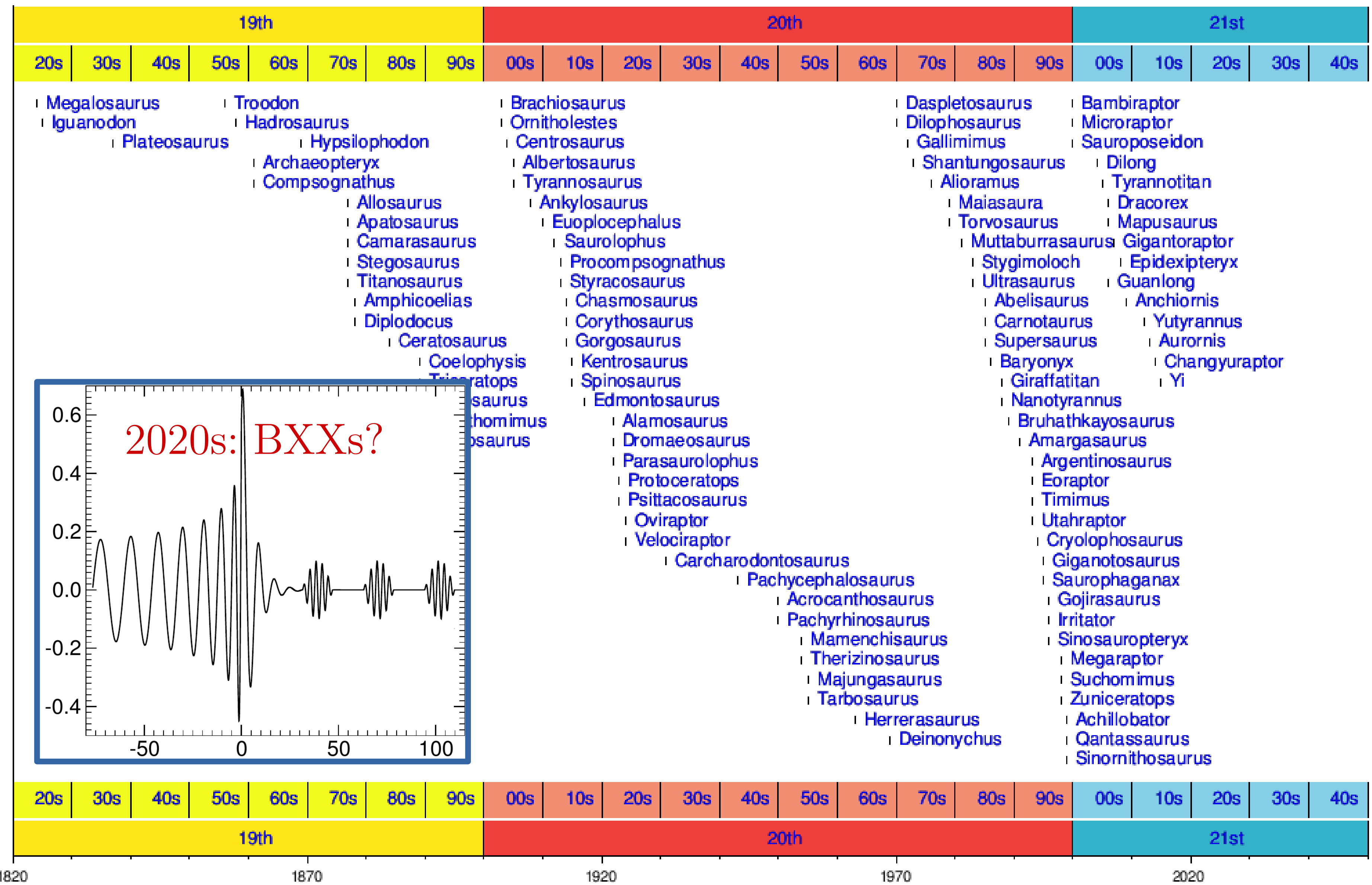


GW astronomy: expect the unexpected



What will the next specie of compact objects?