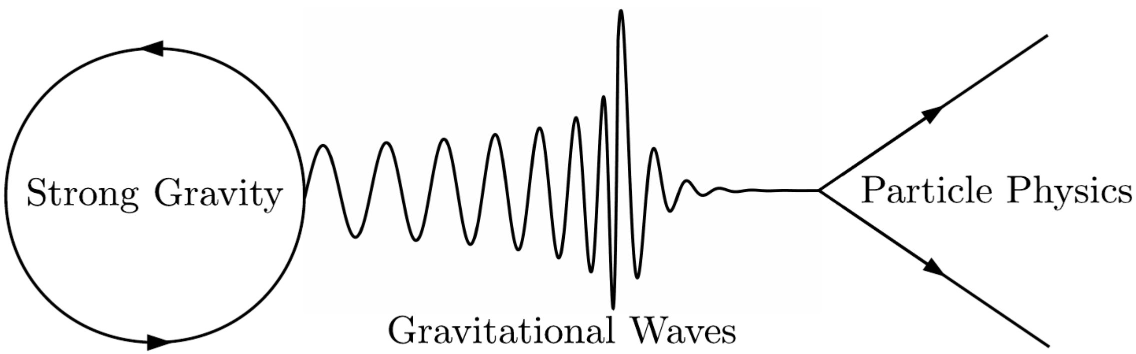
Testing fundamental physics with GWs from compact objects



- GW searches for new physics at the horizon scale
- BHs as GW detectors of ultralight bosons

Paolo Pani
Sapienza University of Rome & INFN Roma1

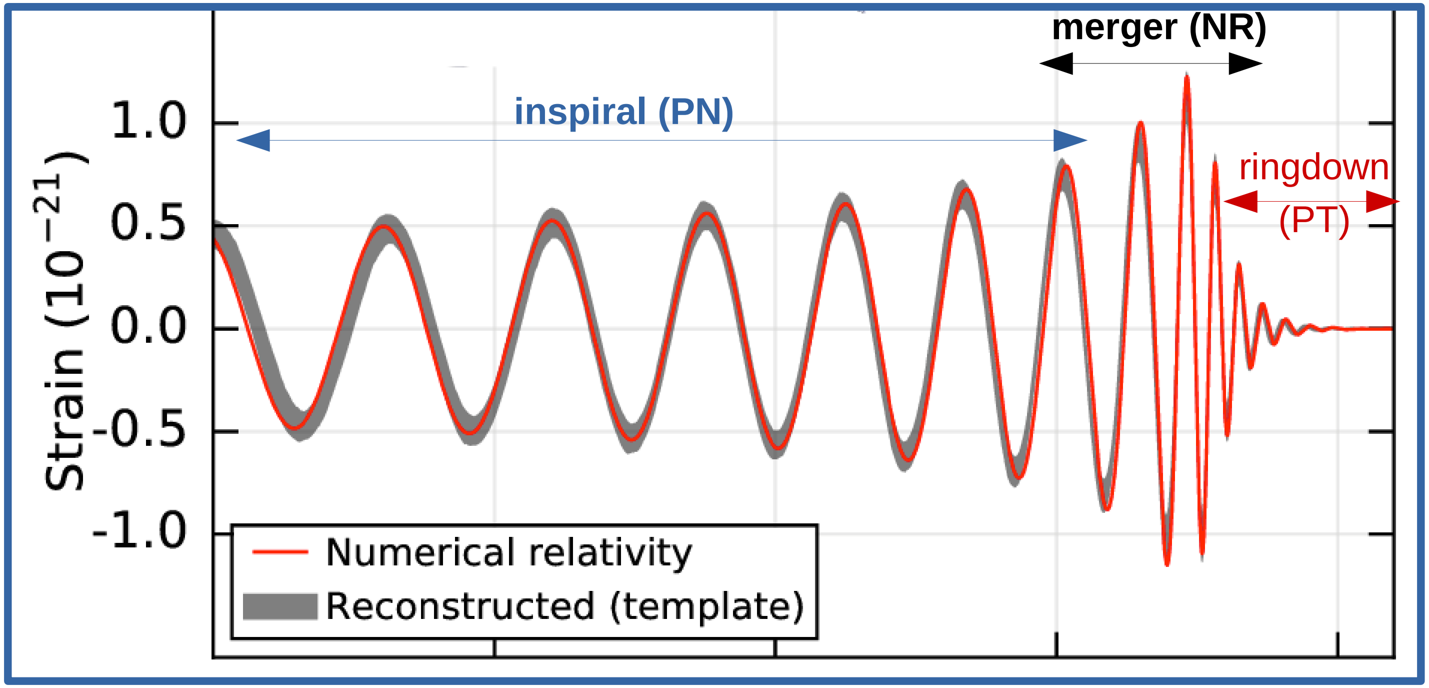
European Research Council

DarkGRA

GW150914: fact sheet

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

$$m_1 = 36^{+5}_{-4} M_\odot \qquad m_2 = 29^{+4}_{-4} M_\odot \qquad M = 62^{+4}_{-4} M_\odot \qquad \chi = 0.67^{+0.05}_{-0.07}$$



$$f_{\rm merger} \approx 75\,{\rm Hz} \quad \Rightarrow \quad {\rm separation}_{\rm merger} \approx 350\,{\rm km} \approx 4GM/c^2$$

- Coalescence of two very massive and compact objects → BHs?
- Inspiral-merger-ringdown provide complementary diagnostics

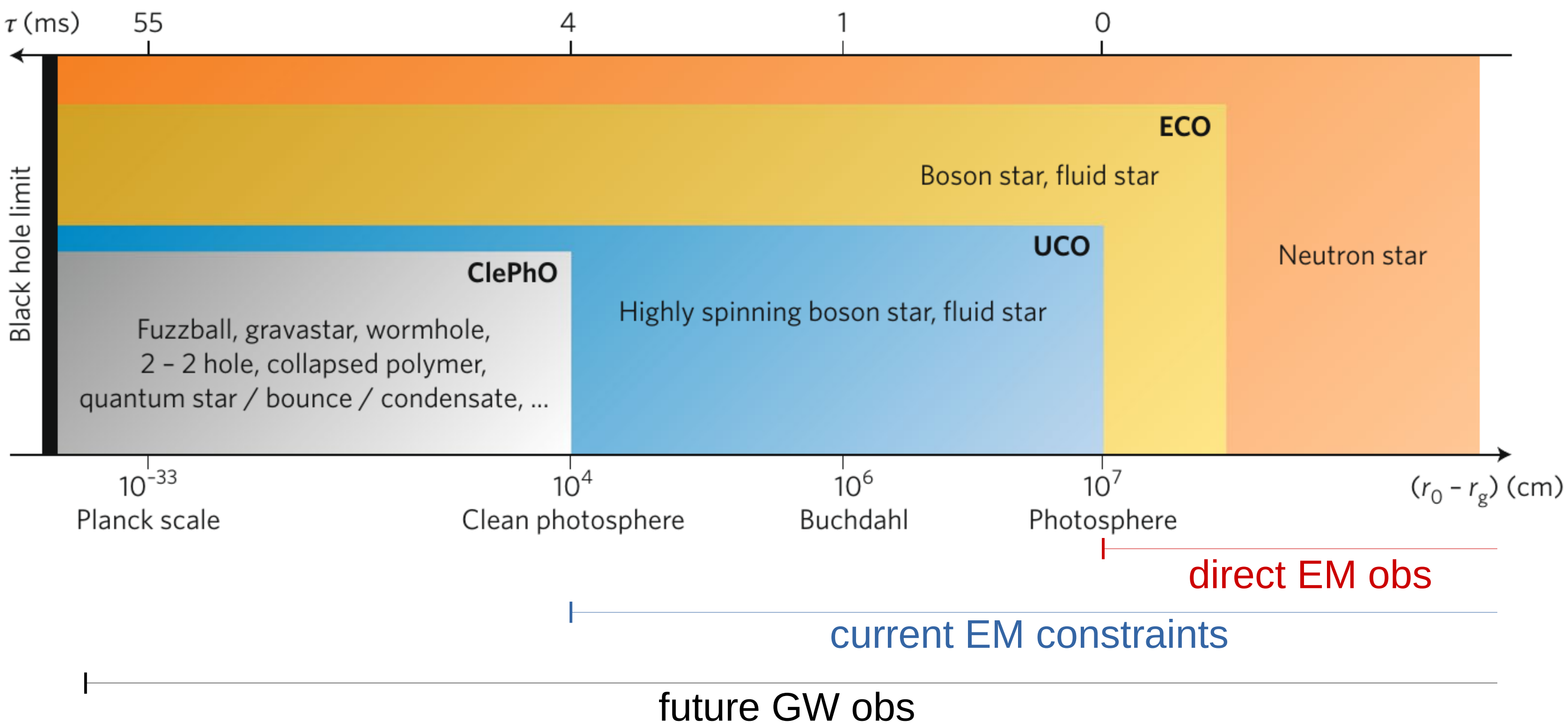
The problem with horizons

$G = c = 1$
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]
    - *“Extraordinary claims require extraordinary evidence”*
    - Drawbacks: Huge entropy, **unitarity loss**, thermodyn. instability [Hawking 1972]
- Several models of semiclassical and quantum gravity or GR+exotic matter predict:
  - horizonless compact objects (e.g. fuzzballs) [Mathur+, 2007-2017]
  - new physics at the horizon scale (e.g. firewalls) [Polchinsky+, Giddings+, 2012-2017]

Exotic Compact Objects (ECOs)

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

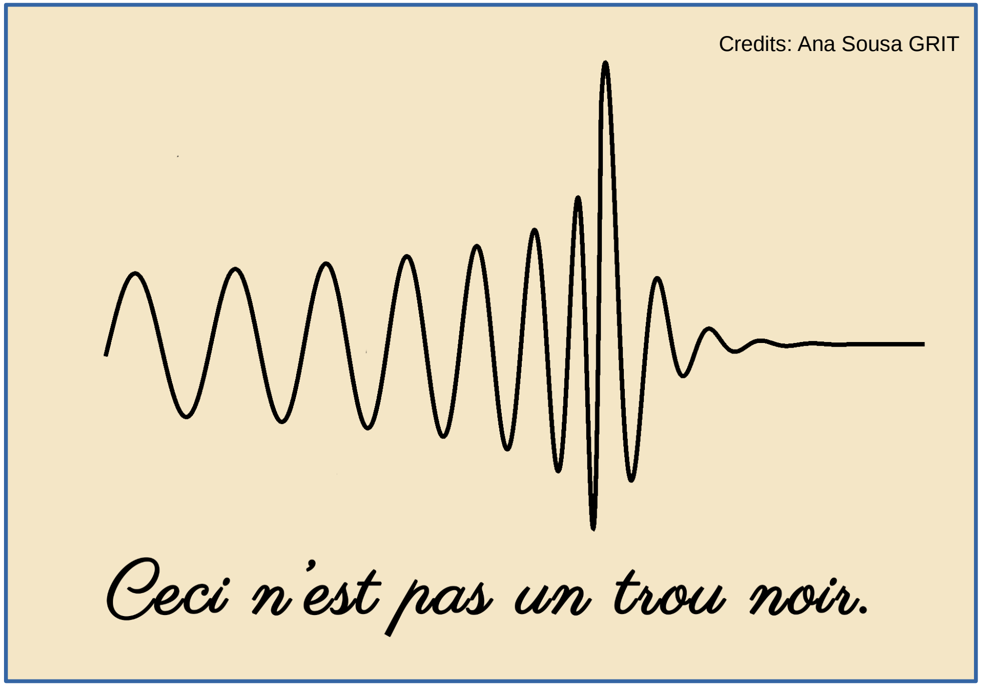


- Goal: probing closer and closer to the horizon (e.g. particle detectors)
- For Planck-scale corrections at the horizon, new physics at:

$$r_0 \equiv \frac{2GM}{c^2}(1+\epsilon) \qquad \epsilon \sim 10^{-39} - 10^{-46}$$

Part I

Searching for new physics at the horizon: *ringdown*



- Two common assumptions:
  - Ringdown from the distorted final object, consists of a superposition of QNMs
  - Accurate measurements of ringdown waveforms → conclusive proof of BHs ?

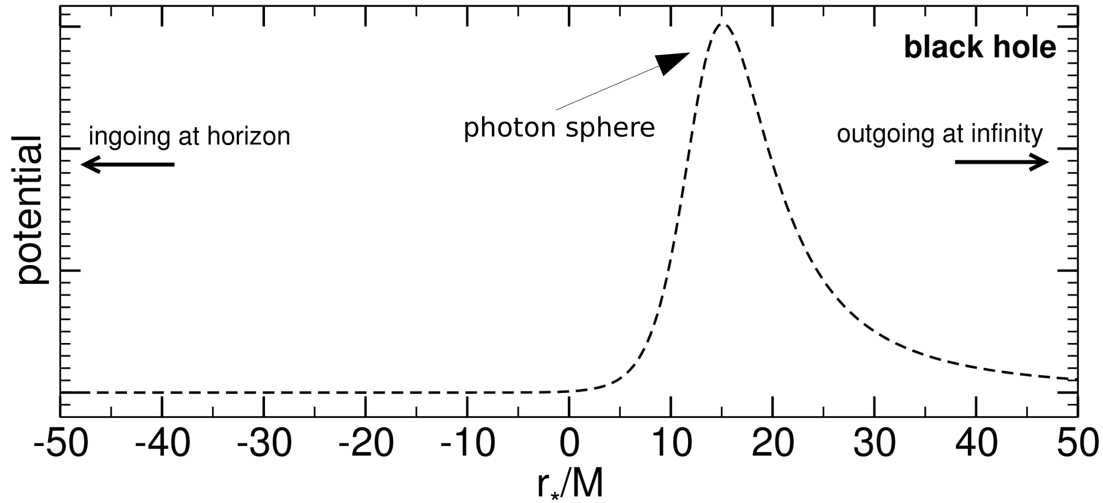
[e.g. Berti, Cardoso, Will; PRD (2006), ...]

QNMs of exotic compact objects

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

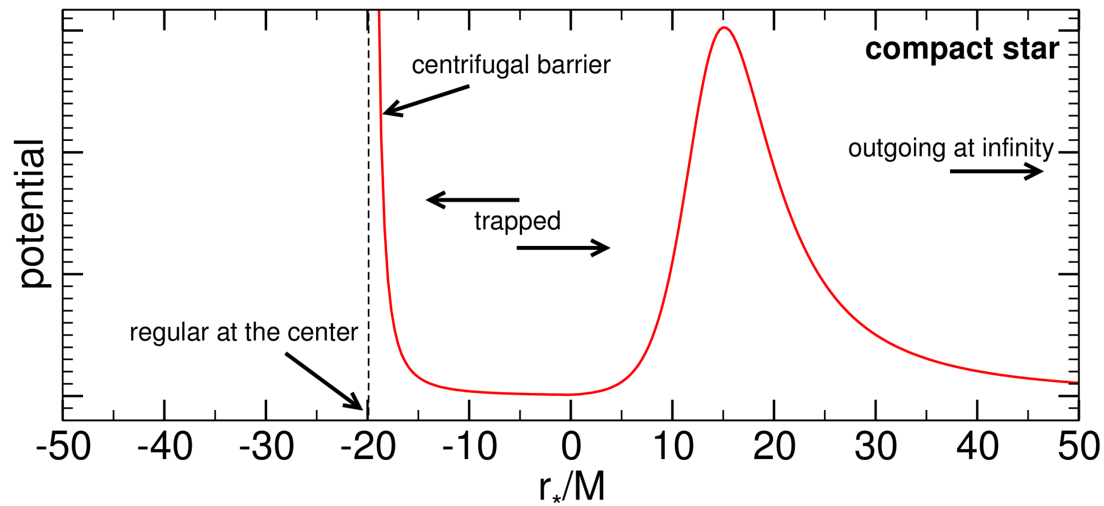
[e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]

QNMs are complex eigenvalues of the linearized problem



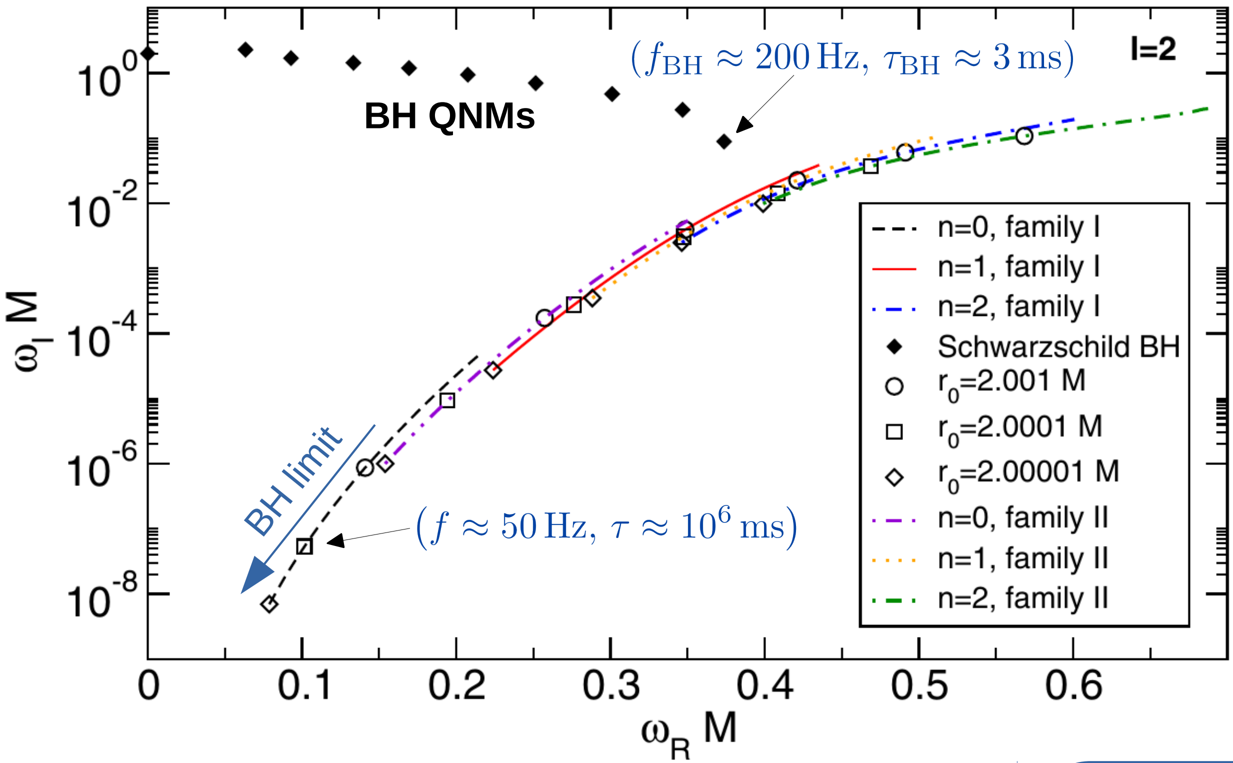
Ultracompact stars generically support trapped modes

Chandrasekhar & Ferrari PRSLA (1991)



No horizon → different boundary conditions → different QNMs

QNM spectrum of an ECO



- Generic feature of *ultracompact horizonless objects*
- Long-lived modes in the BH limit
- QNM spectrum dramatically different → ringdown?

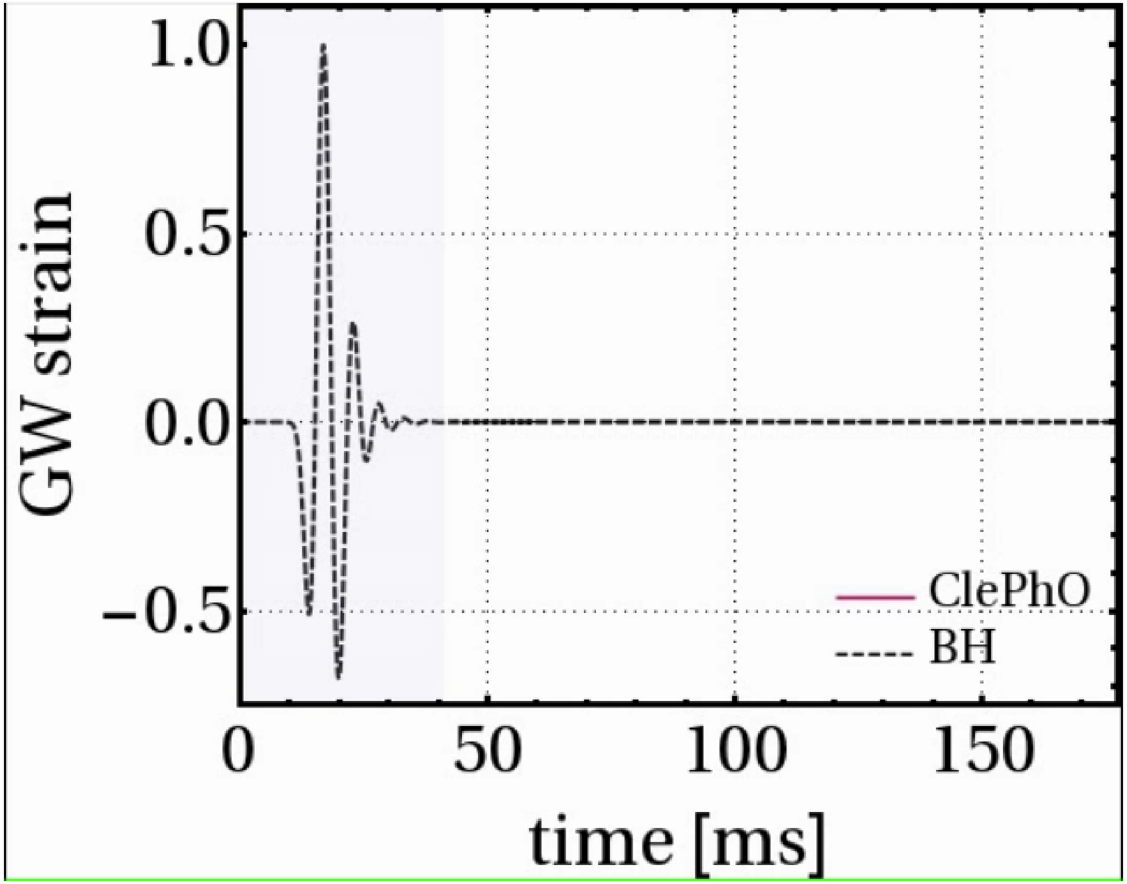
BH limit:

$$r_0 \equiv r_+(1+\epsilon)$$

$$\omega_R \sim |\log \epsilon|^{-1}$$

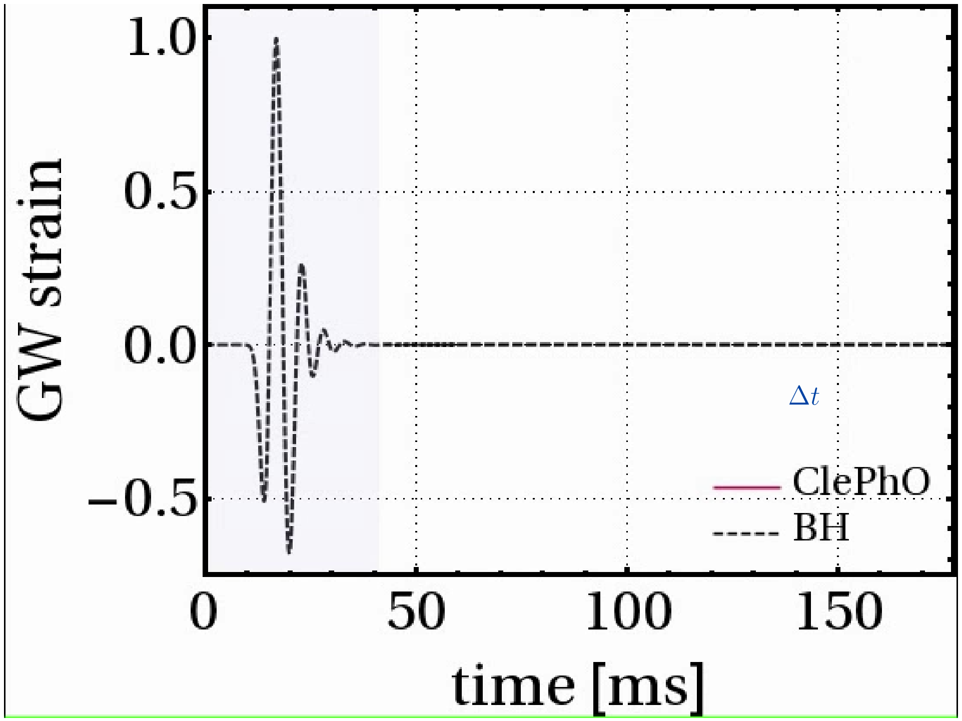
$$\omega_I \sim -|\log \epsilon|^{-(2l+3)}$$

GW echoes



Ringdown of a Schwarzschild BH
(Gaussian perturbation)

GW echoes



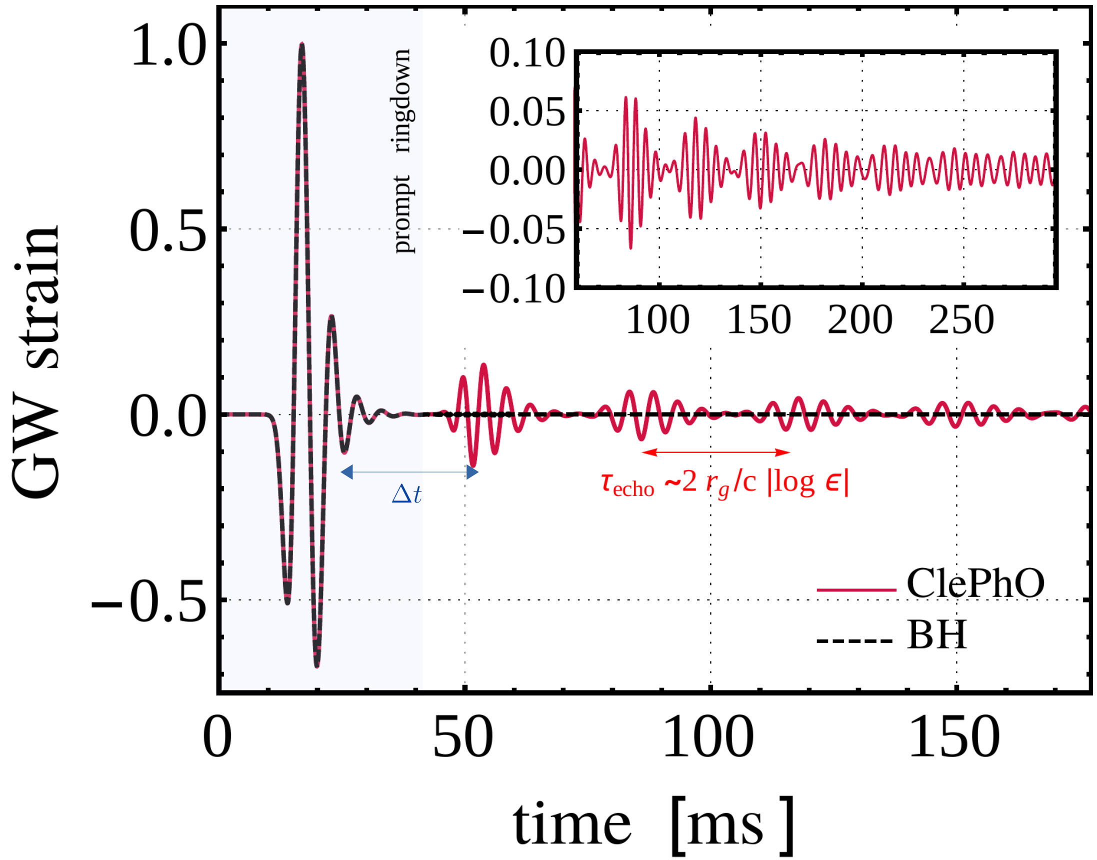
Prompt ringdown is identical, but GW "echoes" at late time

Ferrari & Kokkotas, PRD 2000
Cardoso, Franzin, Pani, PRL (2016)
Cardoso & Pani, 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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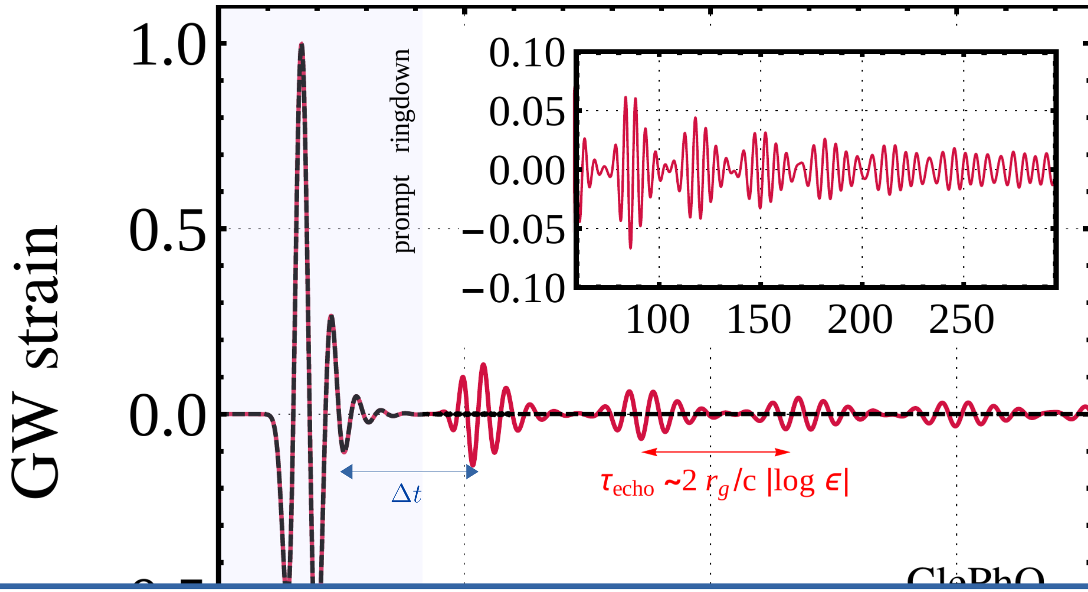
Delay time

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

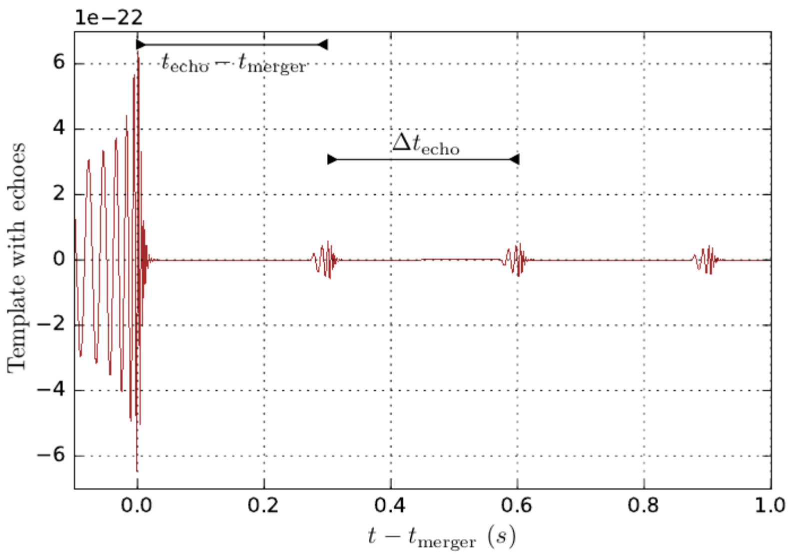
evolution used by Hawking would be invalidated. The problem is that we need an *order unity* correction to the evolution of these modes, since they have to go from a fully entangled state to a non-entangled state. On the other hand, all quantum gravity effects are expected to be of order (l_p/R) to some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

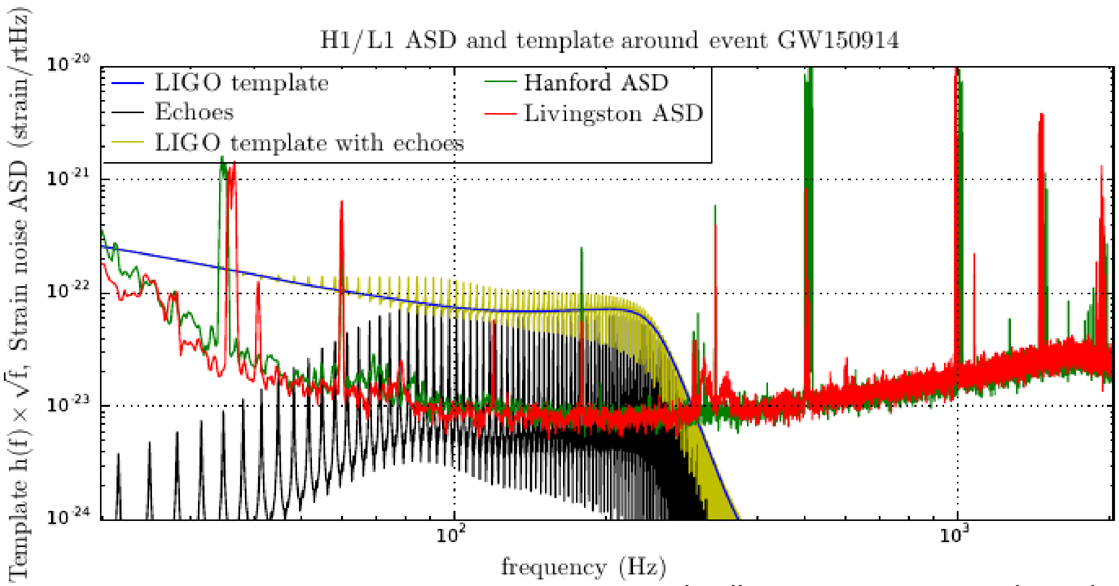
Mathur (2009)

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

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

Searching for GW echoes with LIGO/Virgo



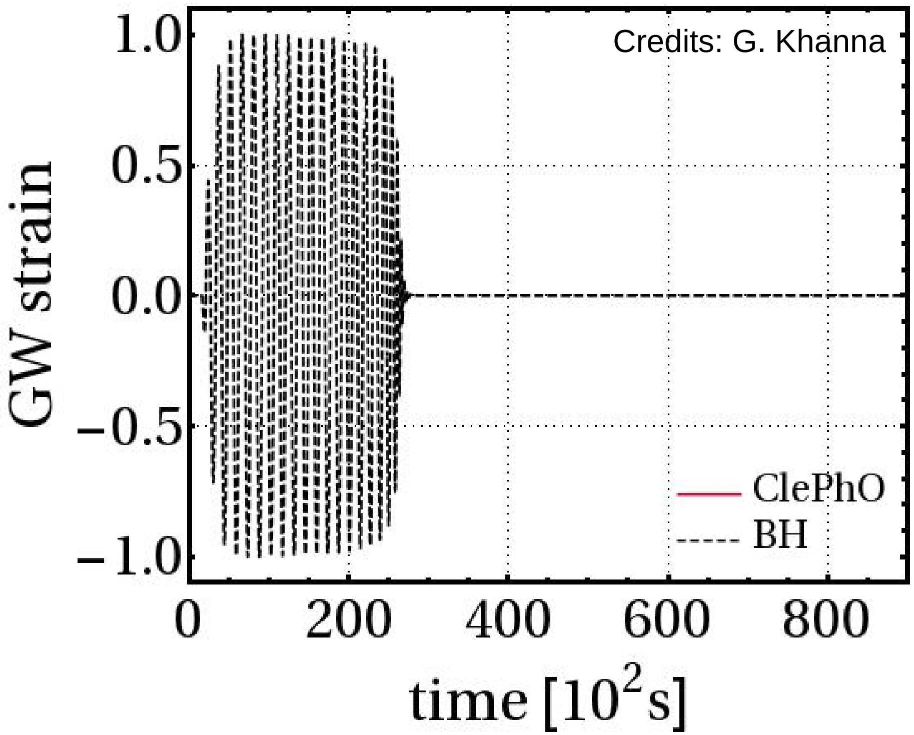


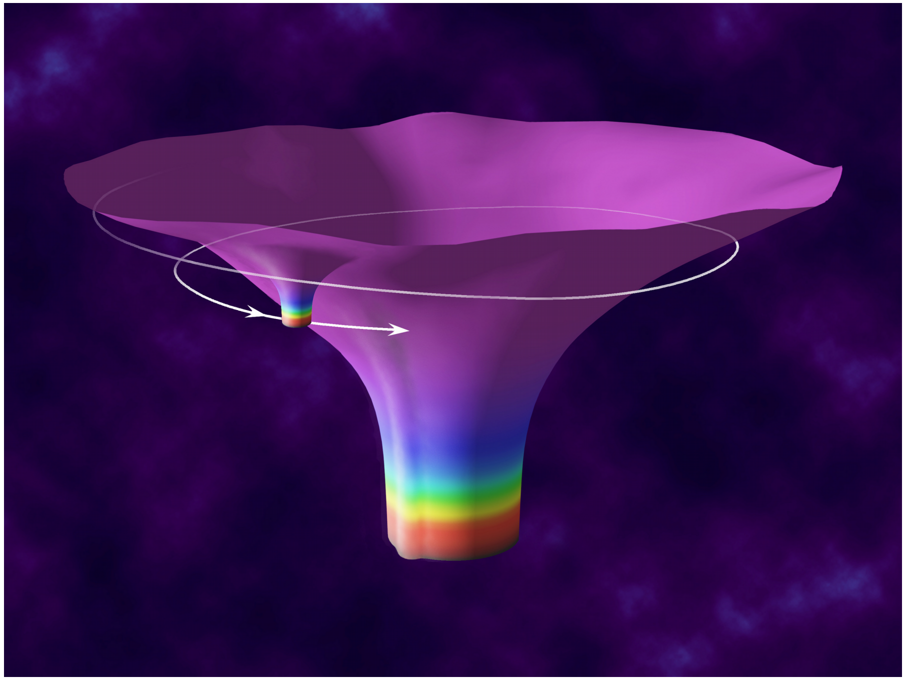
Abedi+, PRD96 082004 (2017)

- Limitation in the templates: distortions, spin, …
- Progress in modelling [Nakano+, 1704.07175; Mark+ 1706.06155; Maselli+ 1708.02217, Bueno+ 1711.00391, A. Testa's thesis]
- Contrasting results [Abedi+, PRD96 082004 (2017), Conklin+, 1712.06517, Ashton+, 1612.05625, Westerweck+, 1712.09966]

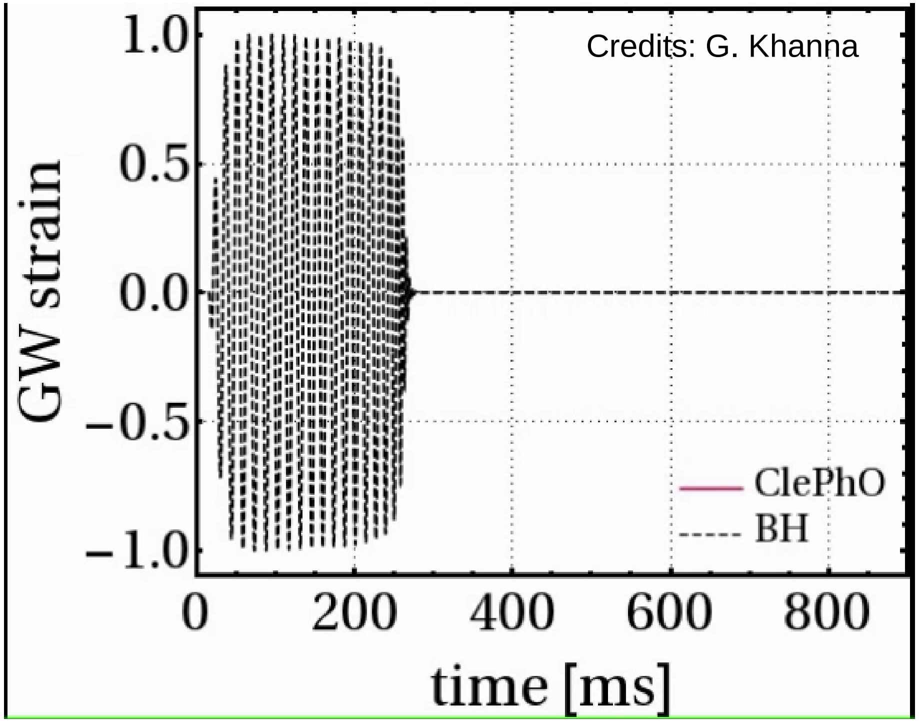
More work needed, but quantum corrections within reach current and future detectors!

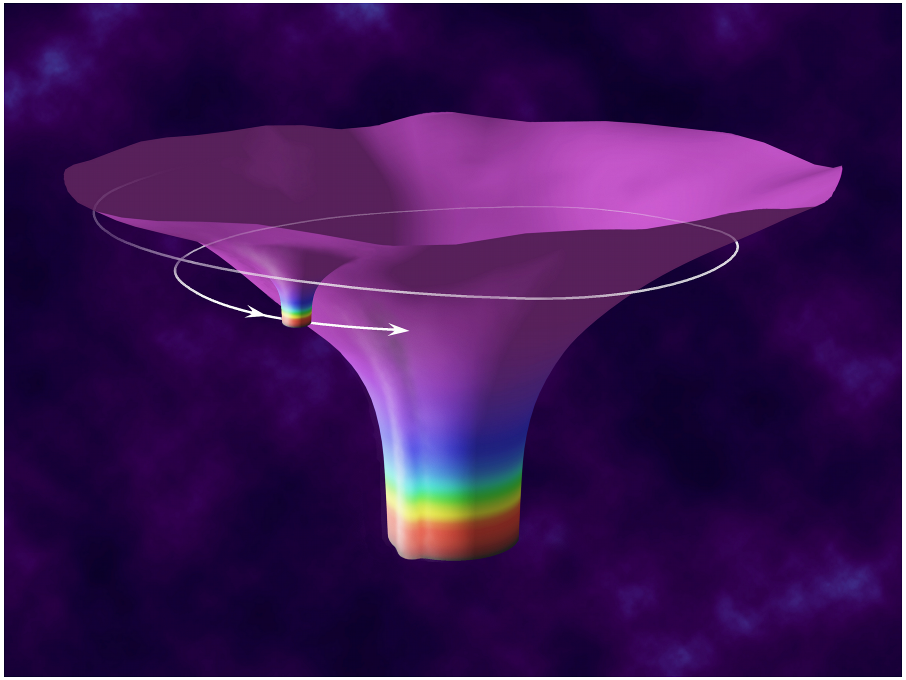
Future: GW echoes in LISA





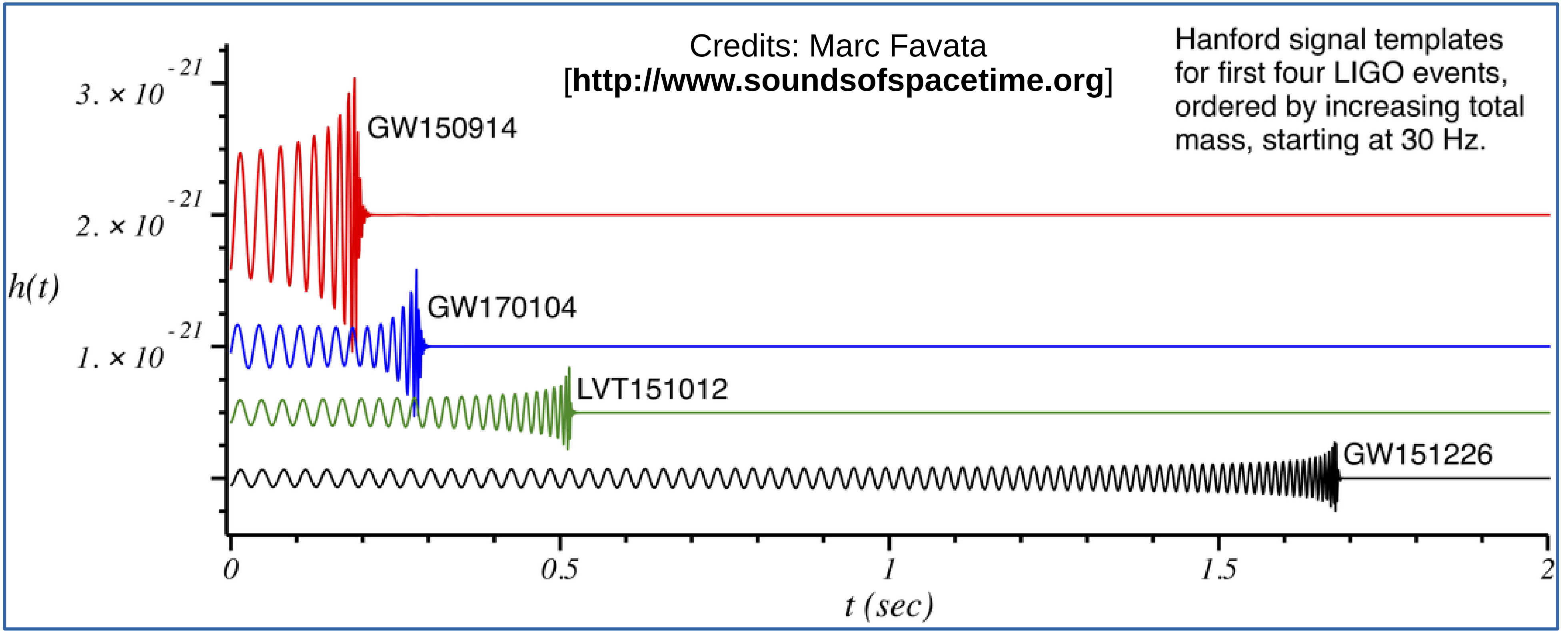
Future: GW echoes in LISA





Part II

Searching for new physics at the horizon: *inspiral*



Testing the nature of BHs with the inspiral signal?

Phys. Rev. D 95, 084014 (2017); 1703.03696 (PRD 2017); 1703.10612; + work in progress

Post-Newtonian inspiral: BH vs ECO

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

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

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

Post-Newtonian inspiral: BH vs ECO

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

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

- **2PN:** Point-particle contribution depends on the **multipole moments** of the objects
  - For a (Kerr) BH all multipoles depend only on mass and spin [Hansen (1974)]
  - E.g., quadrupole moment:

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

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

  - Tests of the BH no-hair theorem [Krishnendu, Arun, Mishra, PRL 2017]
  - Conjecture: multipole moments of an ECO tends to those of a BH

Pani, Phys.Rev. D92 (2015) 124030, G. Raposo's PhD work

Post-Newtonian inspiral: BH vs ECO

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

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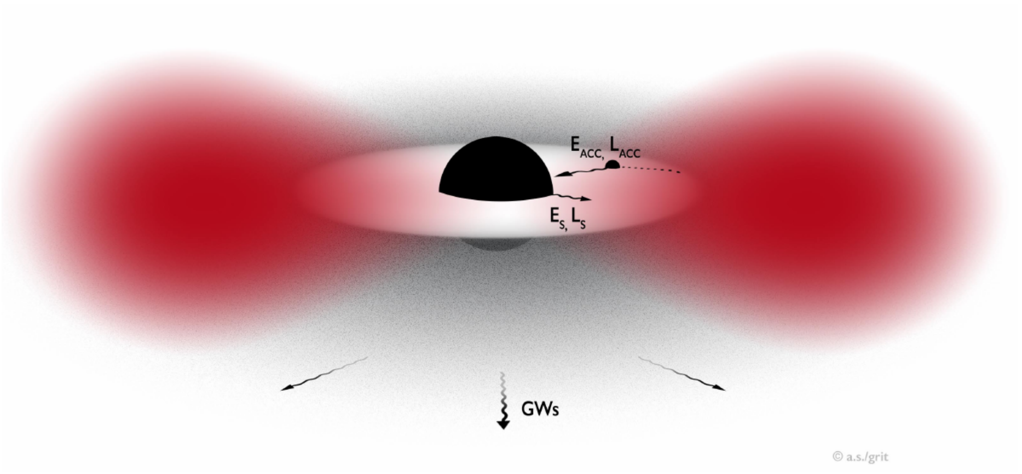
Blanchet, Living Rev. Relativity 17, 2 (2014)

- **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** [Alvi PRD 2001, Poisson, PRD 2009]
  - Love Numbers of a BH are zero [Binnington & Poisson, 2009; Damour & Nagar 2009; Pani+, 2015]
  - Love numbers of an ECO: $k_l \sim [\log \epsilon]^{-1}$ [Cardoso, Franzin, Maselli, Pani, Raposo, PRD 2017]
- Small corrections → requires **LISA**
- Spinning supermassive binaries →golden sources to probe Planckian corrections!

Maselli+; 1703.10612

Part III

Probing ultralight dark matter with BHs and GWs



[**overview:** Brito, Cardoso, Pani - Springer Lect.Notes Phys. 906 (2015) - **1501.06570**]

Ultralight fields in the dark universe?

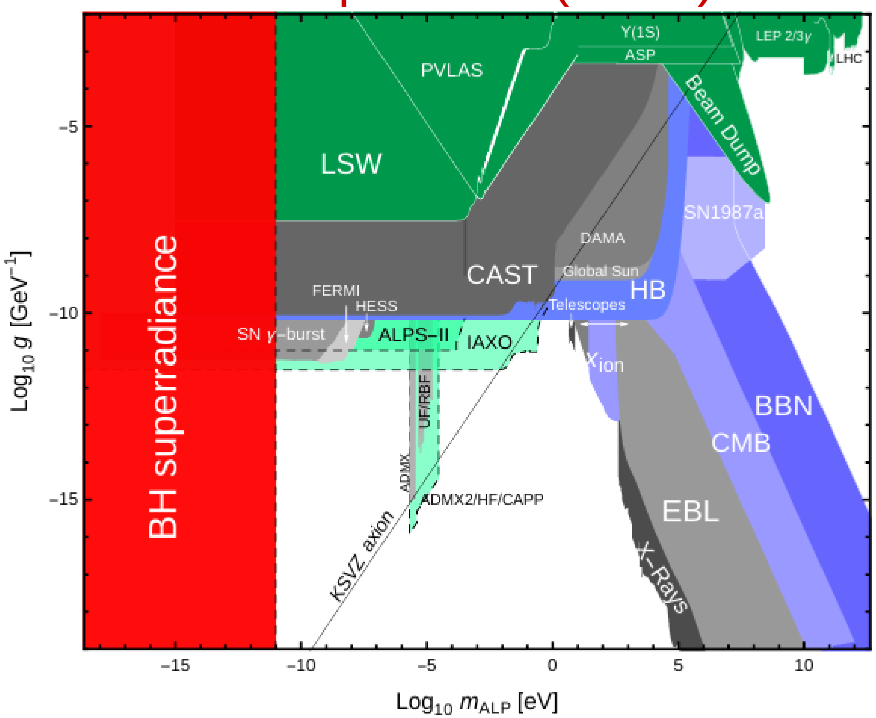
- Compelling dark-matter candidates alternative to WIMPs
  - Fuzzy DM: mass~10^{-22} eV → may solve sub-kpc problems
    Hui, Ostriker, Tremaine, Witten, PRD95 043541 (2017)
  - Plethora of sub-eV DM particles in the dark sector:
    Jaeckel+, Redondo+, Ringwald+, Essig+….
    - QCD axion, stringy axion-like particles (ALPs)
    - Dark photons & hidden sectors, massive gravitons …
- Common properties:
  - Bosonic fields
  - Small-mass landscape (from sub-eV down to 10^{-33} eV)
  - Weakly coupled to SM (*or not coupled at all!*)

Dark sectors and ultralight particles

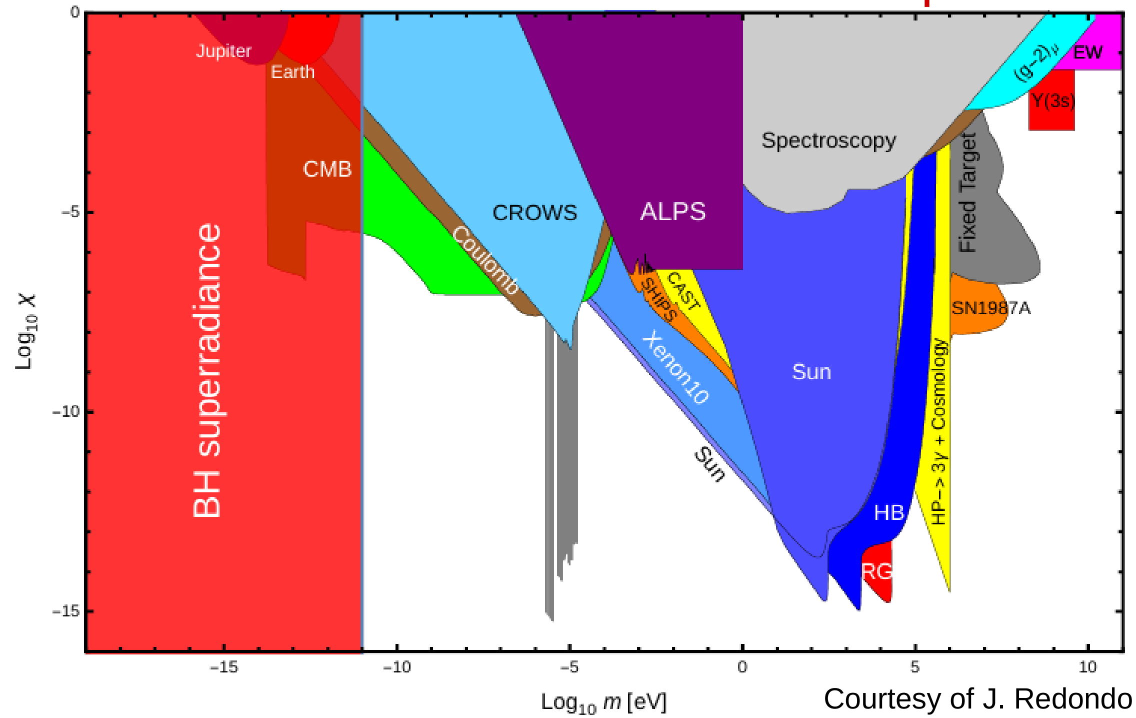
Essig+, 1311.0029

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}(\partial_\mu\Phi\partial^\mu\Phi + \mu_a^2\Phi^2) + \frac{g_{a\gamma\gamma}}{4}\Phi\, F_{\mu\nu}{}^*F^{\mu\nu} + \frac{\gamma}{2}F_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\mu_\gamma^2 B_\mu B^\mu\right)$$

Axion-like particles (ALPs)



Dark photons



Courtesy of J. Redondo

Looking for ultralight fields in strongly-gravitating systems

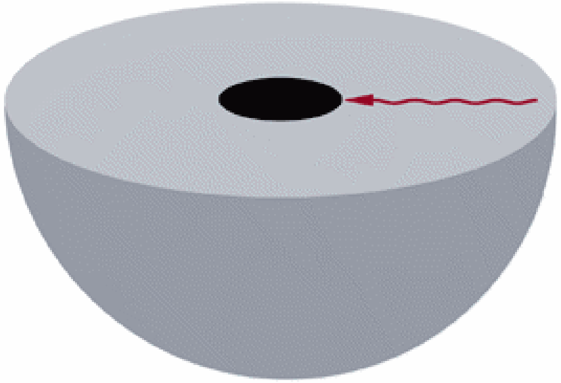
BH superradiant instability

Damour, Deruelle & Ruffini; Detweiler; Zouros & Eardley 1980s;…, Shlapentokh-Rothman, 2015

- Spinning BHs are unstable against massive bosons

  (amplification of low-frequency waves + Yukawa effective potential)

$$\Box\phi - \frac{\mu^2 c^2}{\hbar^2}\phi = 0 \quad \Rightarrow \quad \phi \sim e^{t/\tau}$$



Press & Teukolsky, Nature 238 (1972) 211-212

- Instability effective only for ultralight bosonic fields [Arvanitaki+ 2010-2016]

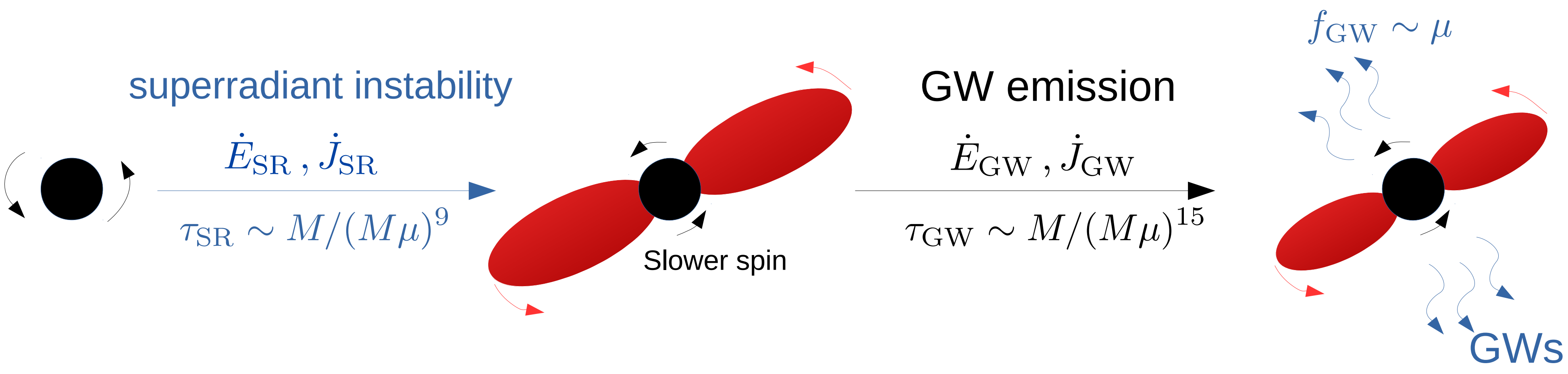
$$\frac{G}{\hbar c} M\mu \sim \left(\frac{M}{10 M_\odot}\right)\left(\frac{\mu c^2}{10^{-11}\,\mathrm{eV}}\right) \sim \mathcal{O}(1)$$

Coupling parameter

- Stronger instability for dark photons and massive gravitons [Pani+, 2012-2018]

$$\omega_R \sim \mu \qquad\qquad \omega_I \sim -\left(\omega_R - m\Omega_H\right)(M\mu)^{4\ell+4+2S}$$

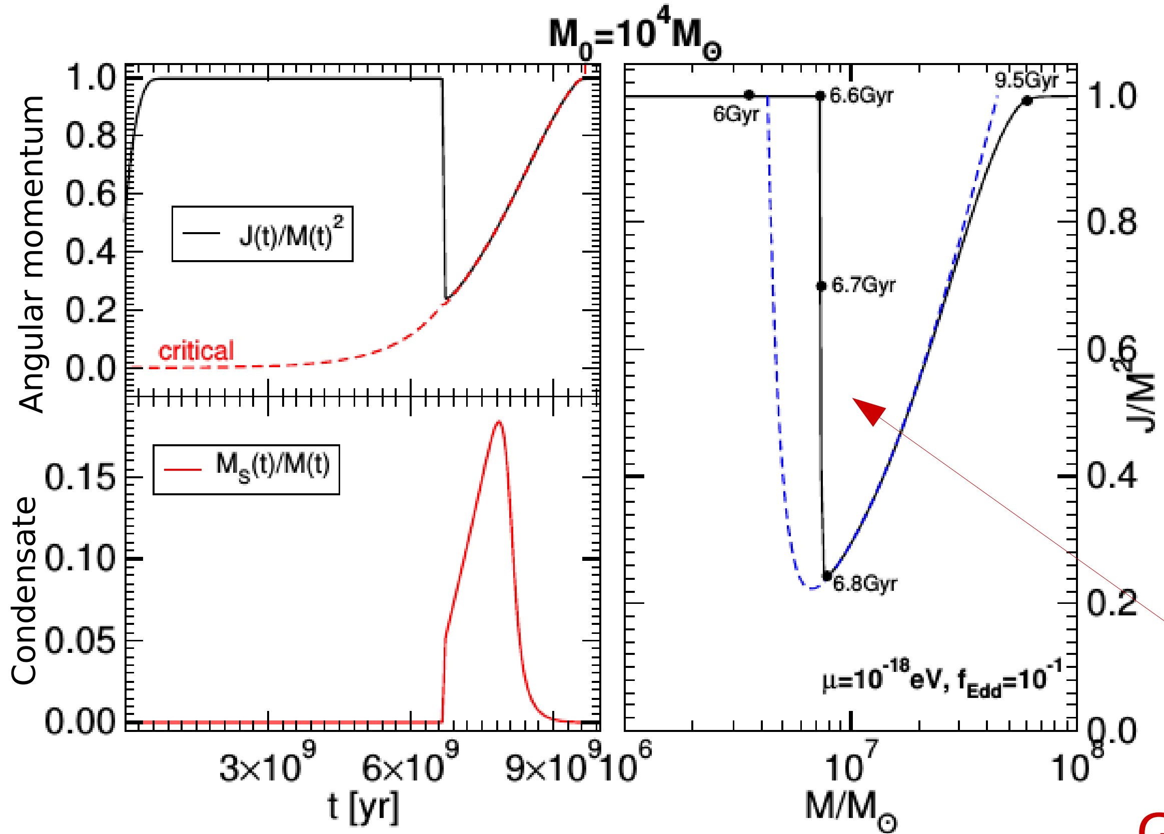
BH superradiant instability

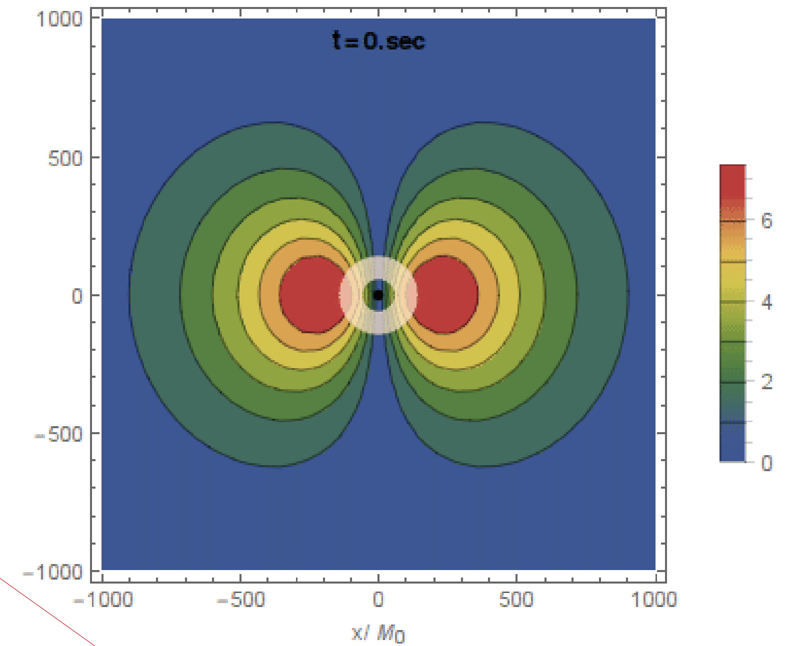


- Confirmed by numerical simulations of Einstein equations [East & Pretorius PRL 2017]
- **Two generic predictions:** [Arvanitaki+ 2014-2016; Pani+ 2012; Baryakhtar+ 2017; Brito+ 2015-2017]
  - BHs should NOT spin fast in the presence of ultralight bosons
  - Periodic GW signal → continuous sources for LIGO/Virgo/LISA

Evolution of superradiant instability

[Brito, Cardoso, PP, 2015 Class. Quantum Grav. 32 134001, G. Ficarra's thesis]

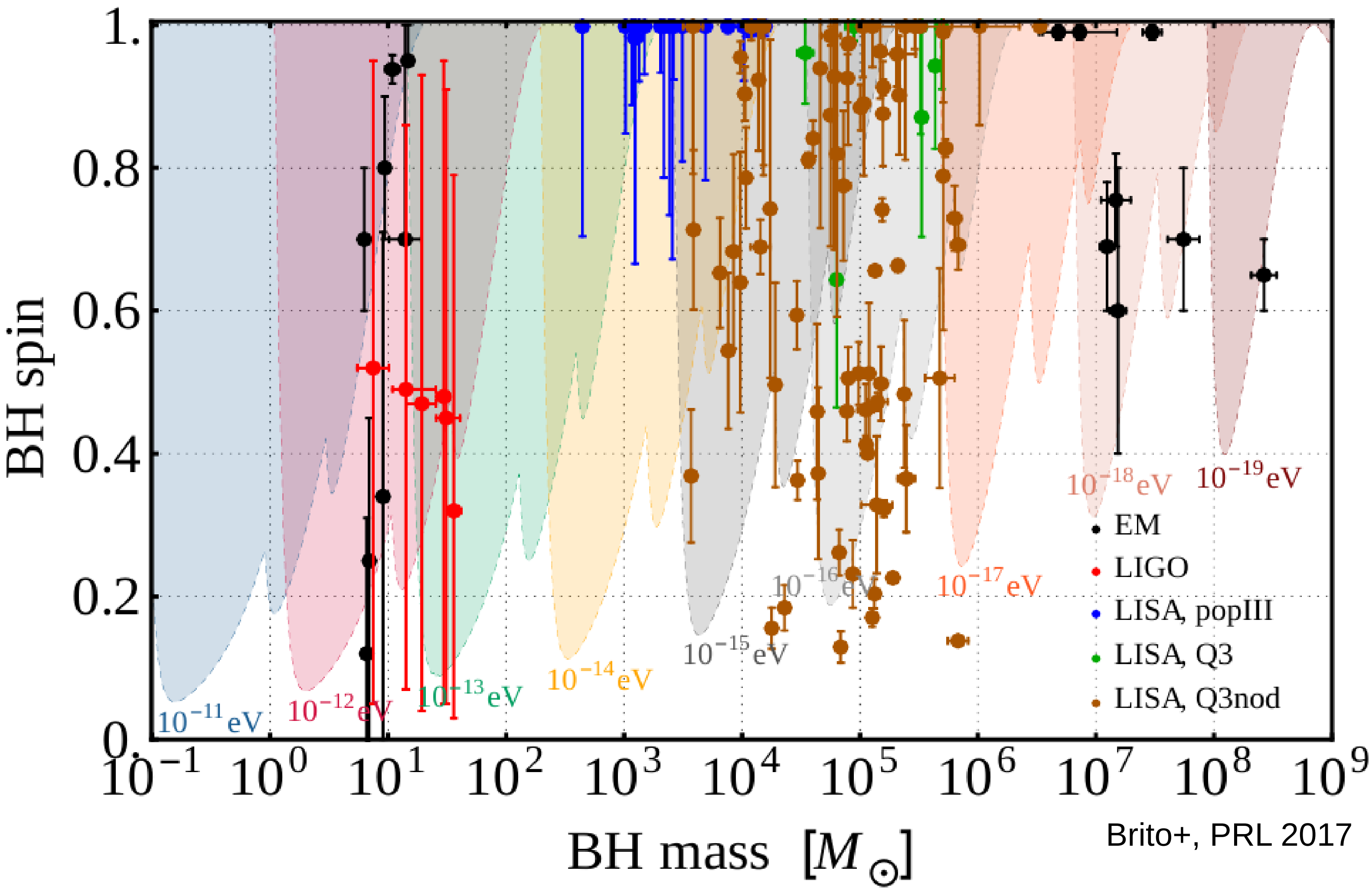




Gaps in BH "Regge" plane

- Observations of highly-spinning BHs → bounds on ultralight DM

BH “Regge” plane



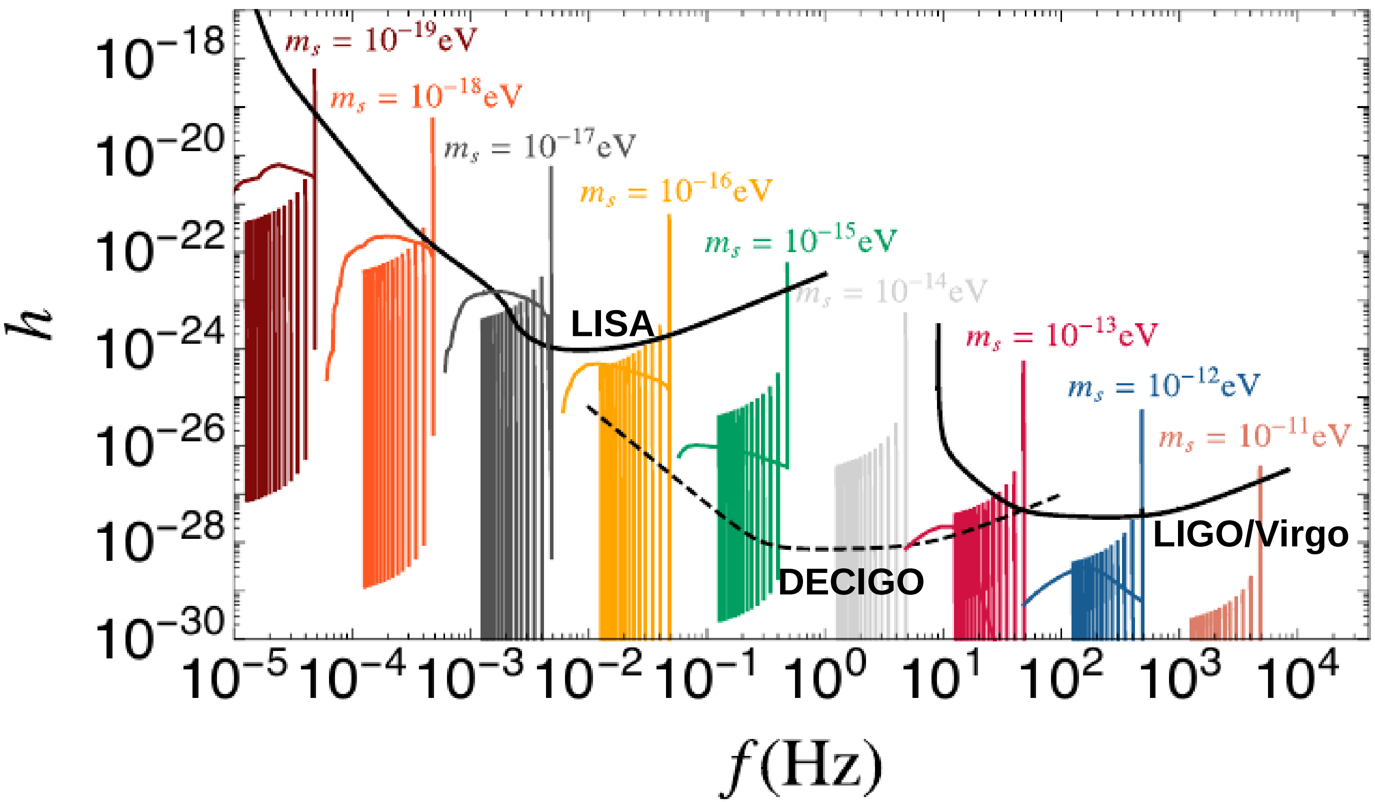
Brito+, PRL 2017

- LISA will fill the mass gap by detecting intermediate-mass BHs
- Stronger constraints for dark photons and massive spin-2 fields

GW periodic signal from axions

Brito+, PRL 2017, PRD 2017

- Monochromatic signal → $\mathrm{SNR} \approx \frac{h\sqrt{T_{\rm obs}}}{\sqrt{S_h(f_0)}}$ → Continuous GW source



Future → multiband GW constraints on ultralight fields

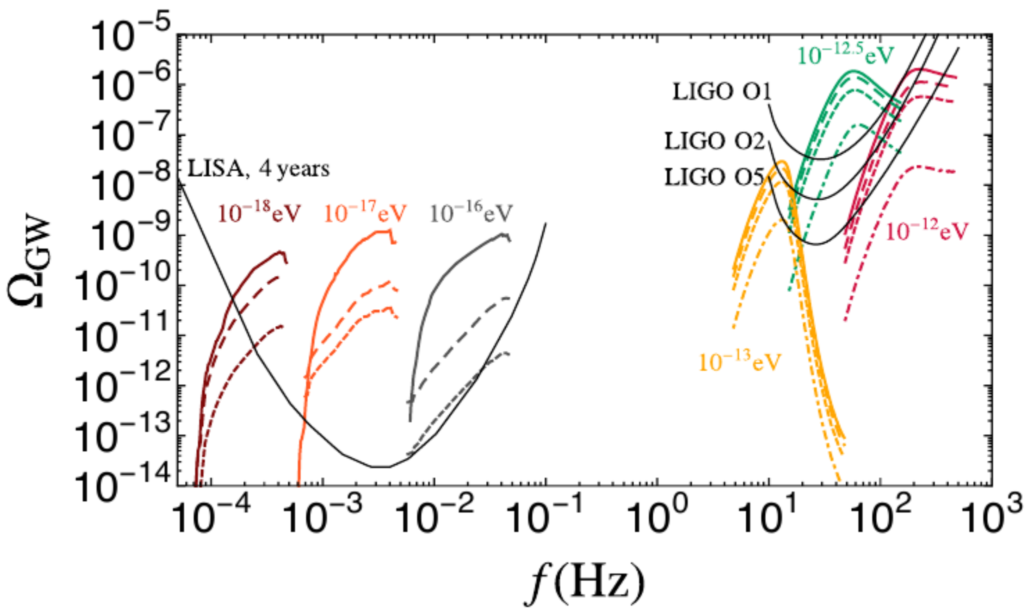
GW stochastic bkg from axions

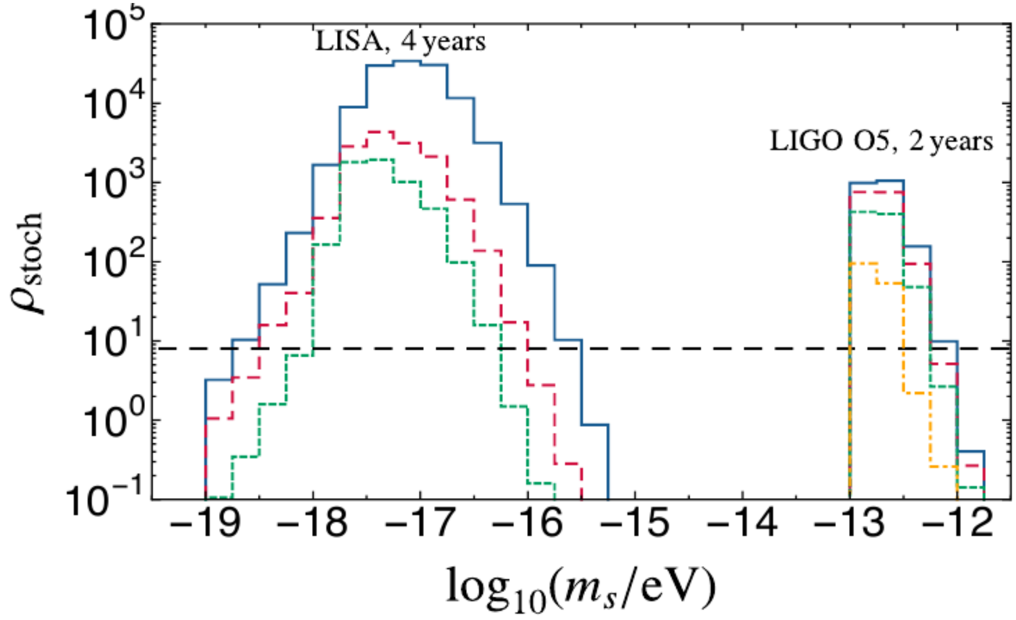
Brito+, PRL 2017, PRD 2017

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_{\rm crit}} \int_{\rho<8} dz \frac{dt}{dz} \dot{n}(M,\chi,z) \frac{dE_s}{df_s}$$

Formation rate density per comoving volume

Energy spectrum

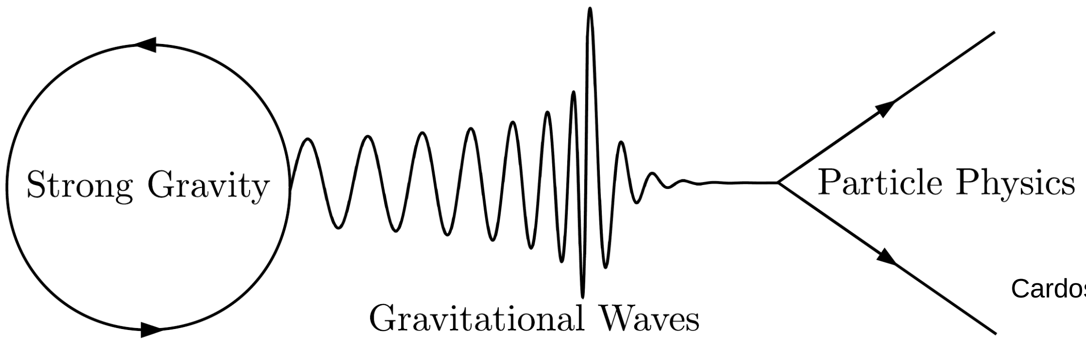




Preliminary constraints on axions from absence of stochastic bkg in LIGO O1

To Recap

- GW astronomy: searches for new physics @ strong gravity



Cardoso, Pani – CERN Courier (2017)

- GW echoes in the post-merger ringdown waveform
- GW searches for ultralight dark matter via BH superradiance in LIGO/Virgo
- **Future:** constraints on Planck-scale corrections at horizon with 3G and LISA
- **ECO vs BHs:** Formation? Stability? [Maggio, Pani, Ferrari, PRD 2017] Full coalescence?

GW astronomy: expect the unexpected!

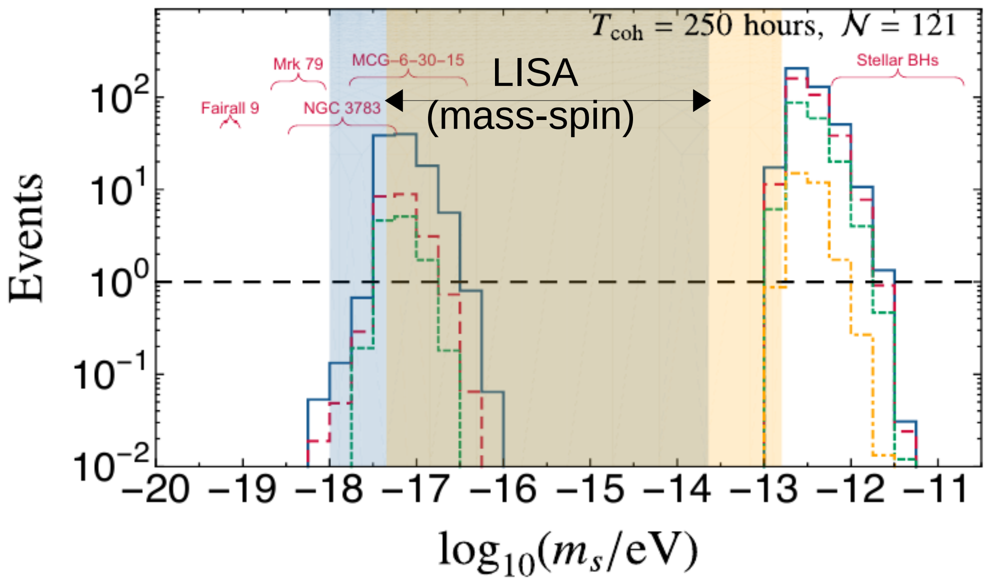
Backup slides

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

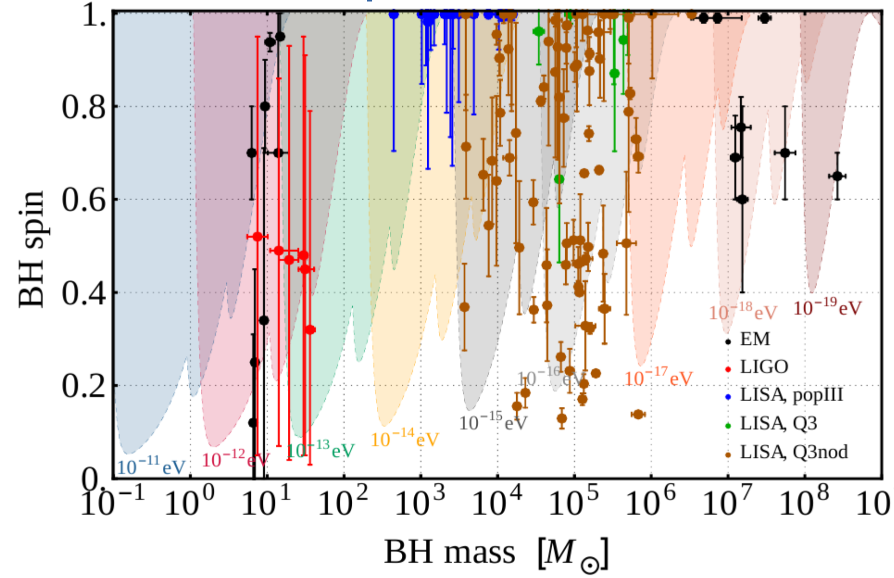
GW signatures of axions

Brito+, PRL 2017

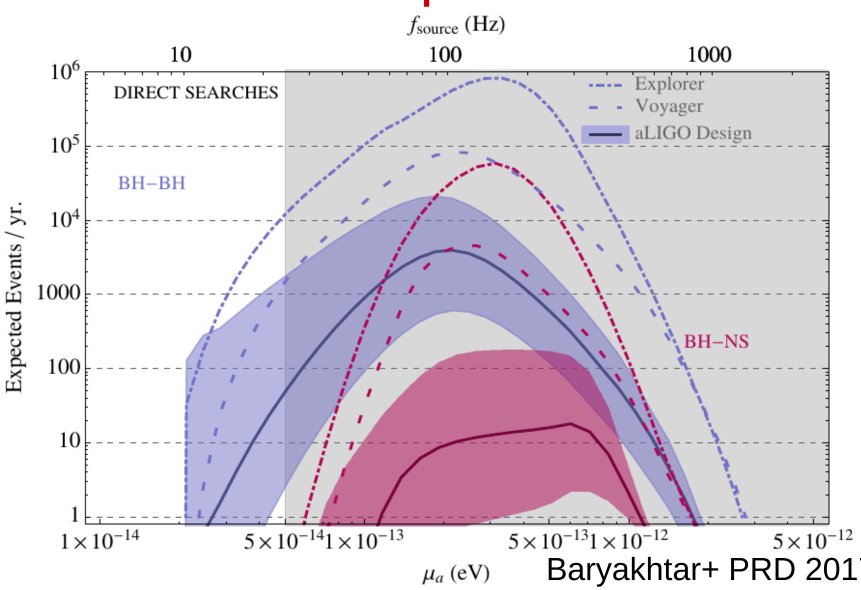
Direct detection



Mass-spin measurements

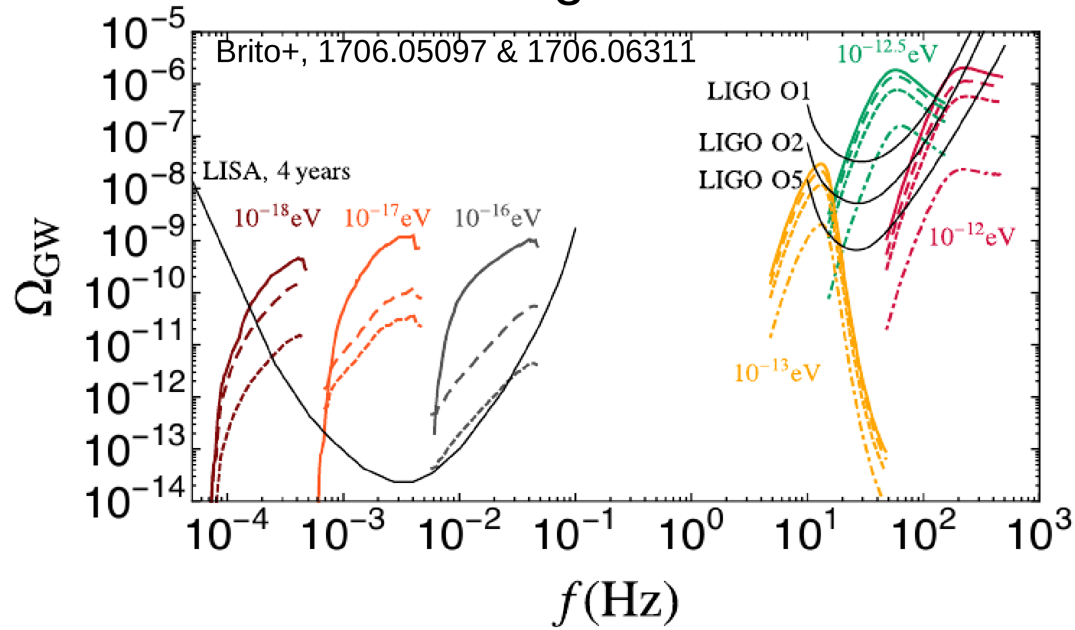


Follow-up searches

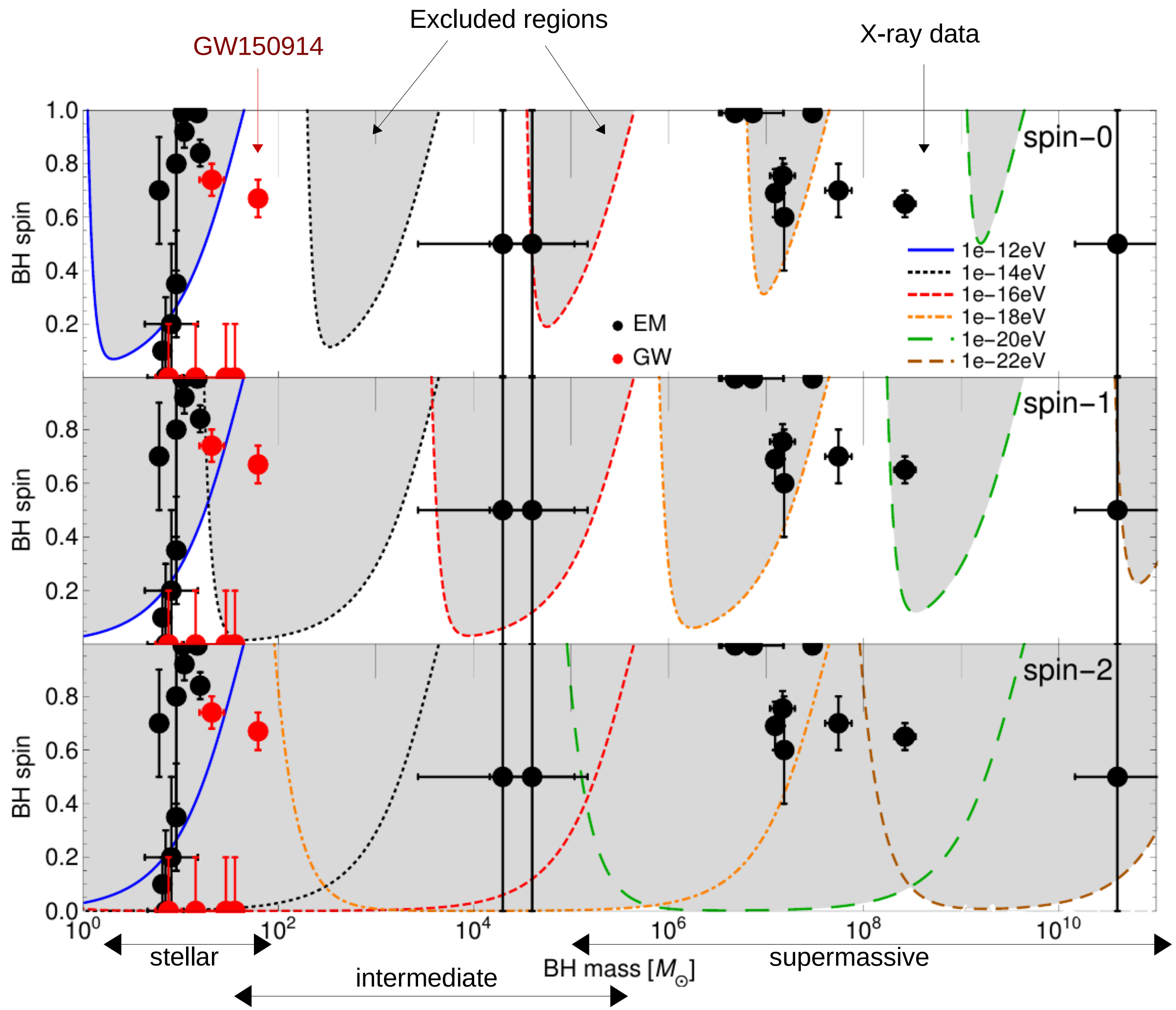


Baryakhtar+ PRD 2017

Stochastic background from ALPs



Bounds on light bosons



QCD axion
Axion-like particles
String axiverse

Dark photons
Mirror DM
Massive photon

Massive spin-2
Massive graviton

Observations of highly-spinning BHs → bounds on ultralight DM

Exotic Compact Objects (ECOs)

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

[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)]
- Quantum effects at the horizon scale → $\langle T_{\mu\nu} \rangle \neq 0$
  - Fuzzballs (horizonless microstates) [Mathur (2004)]; Firewalls [Almheiri+(2013)] ... [Gubser (14-16)]
  - Gravastars (de Sitter interior + shell) [Mazur & Mottola, PNAS (2004)]; Womrholes, ...
  - 2-2 holes, collapsed polymers, ... [Holdom & Ren (2017), Brustein & Medved (2017)]
  - Quantum bounces / black stars, … [Barcelò+ (2008-2017); Rovelli & Vidotto (2014); Baccetti+ (2017)]
- Modified gravity → energy conditions might be preserved

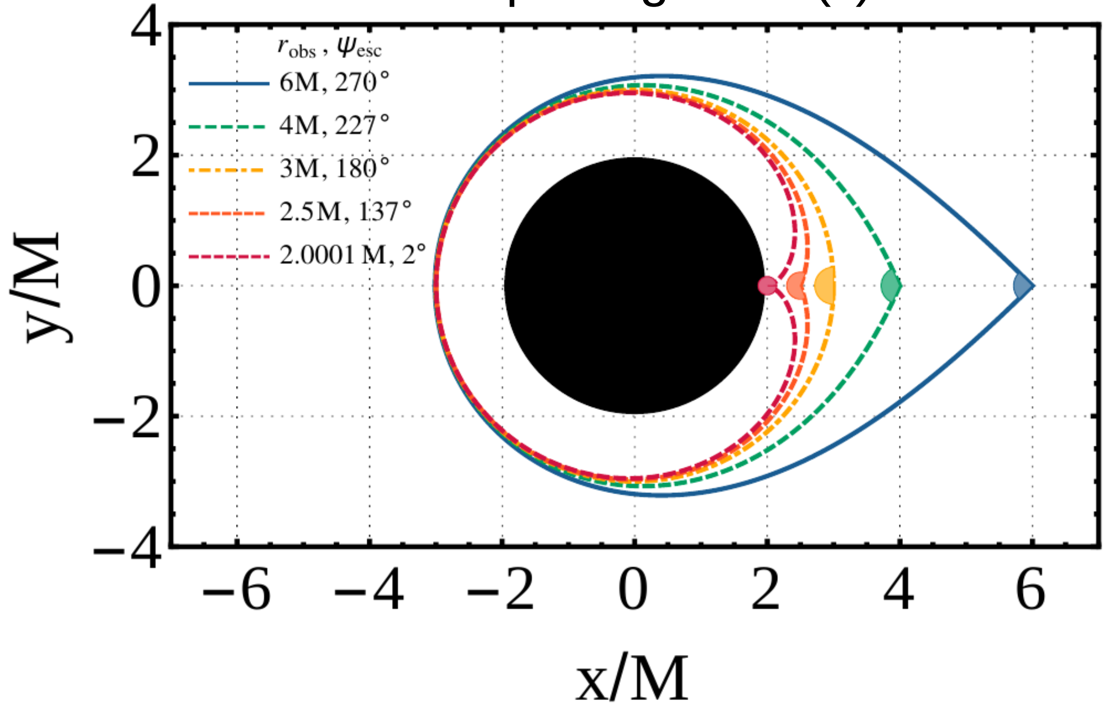
- Tunneling probability to quantum state:
  - small amplitude → $\mathcal{A}_{\rm tunneling} \sim e^{-\alpha R_S^2/\ell_P^2} \sim e^{-\alpha M^2/\hbar}$
  - but huge phase space → $\mathcal{N}_{\rm states} \sim e^{S_{\rm BH}} \sim e^{4\pi M^2/\hbar}$

$$\mathcal{P}_{\rm tunneling} \sim \mathcal{A}_{\rm tunneling} \times \mathcal{N}_{\rm states} \sim \mathcal{O}(1)$$

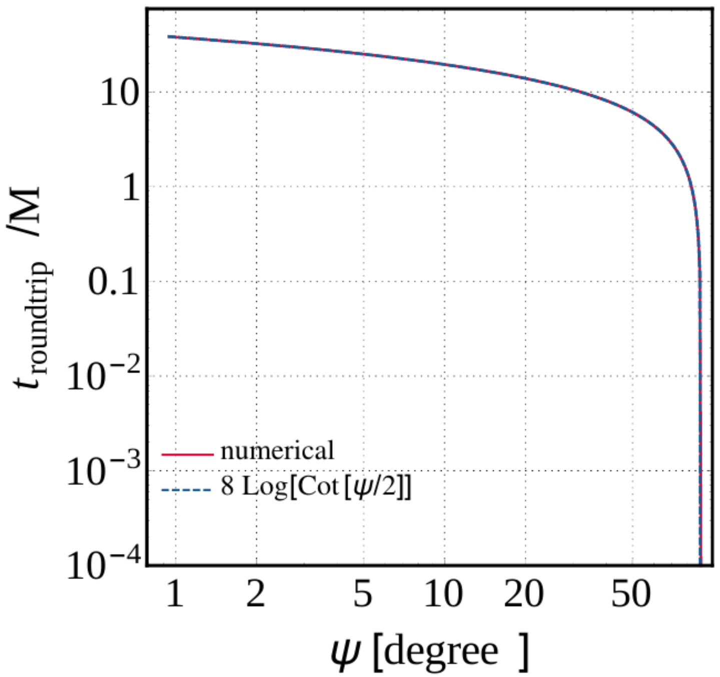
Mathur 2008

Are ECOs ruled out by EM observations?

Escape angle ~ O(ε)



Round-trip time ~ 9M



- Energy dissipated over time scale → $\tau_{\text{dissipation}} \sim \frac{10M}{\epsilon} \gg \tau_{\text{Hubble}}$
- EM tests of the horizon are very challenging, *if possible at all!*

[Abramowicz, Kluzniak, Lasota (2012)]

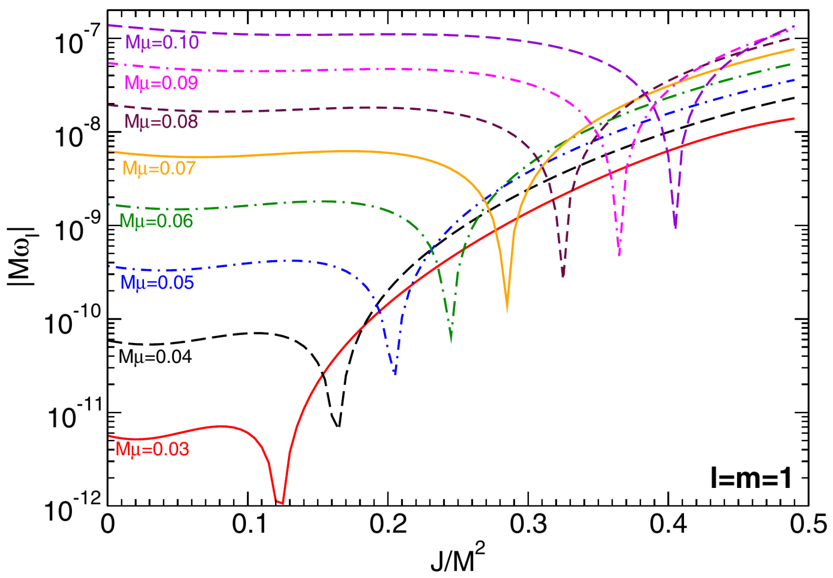
GW signatures of exotic compact objects and of quantum corrections at the horizon scale?

BH instability for bosonic fields

Proca field (massive spin-1)

Pani+, Phys.Rev.Lett. 109 (2012) 131102

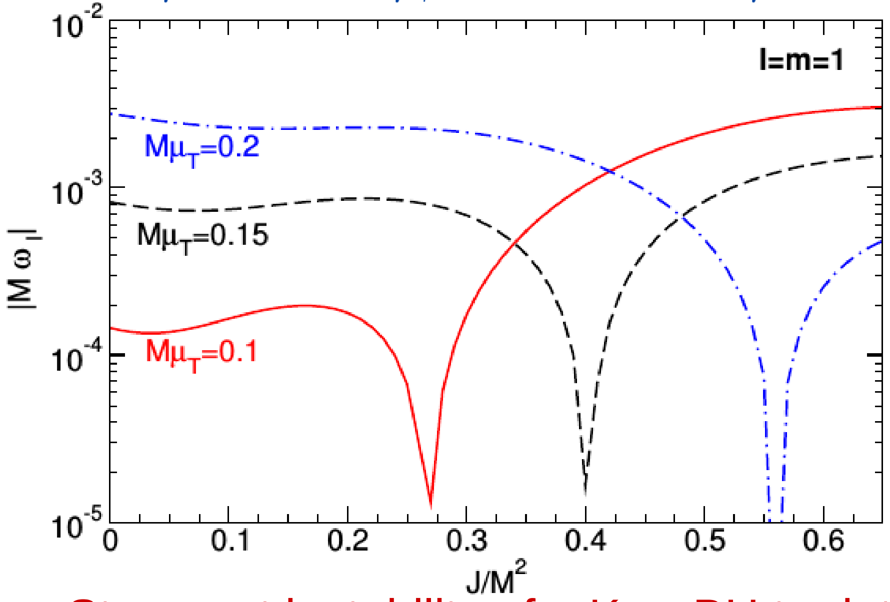
$$\nabla_\sigma F^{\sigma\nu} - \mu^2 A^\nu = 0$$



Massive spin-2

Brito, Cardoso, Pani, Phys.Rev. D88 (2013) 023514

$$\bar{\Box} h_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu} h^{\alpha\beta} - \mu_T^2 h_{\mu\nu} = 0$$



Strongest instability of a Kerr BH to date

- Instability depends on BH & particle spin:

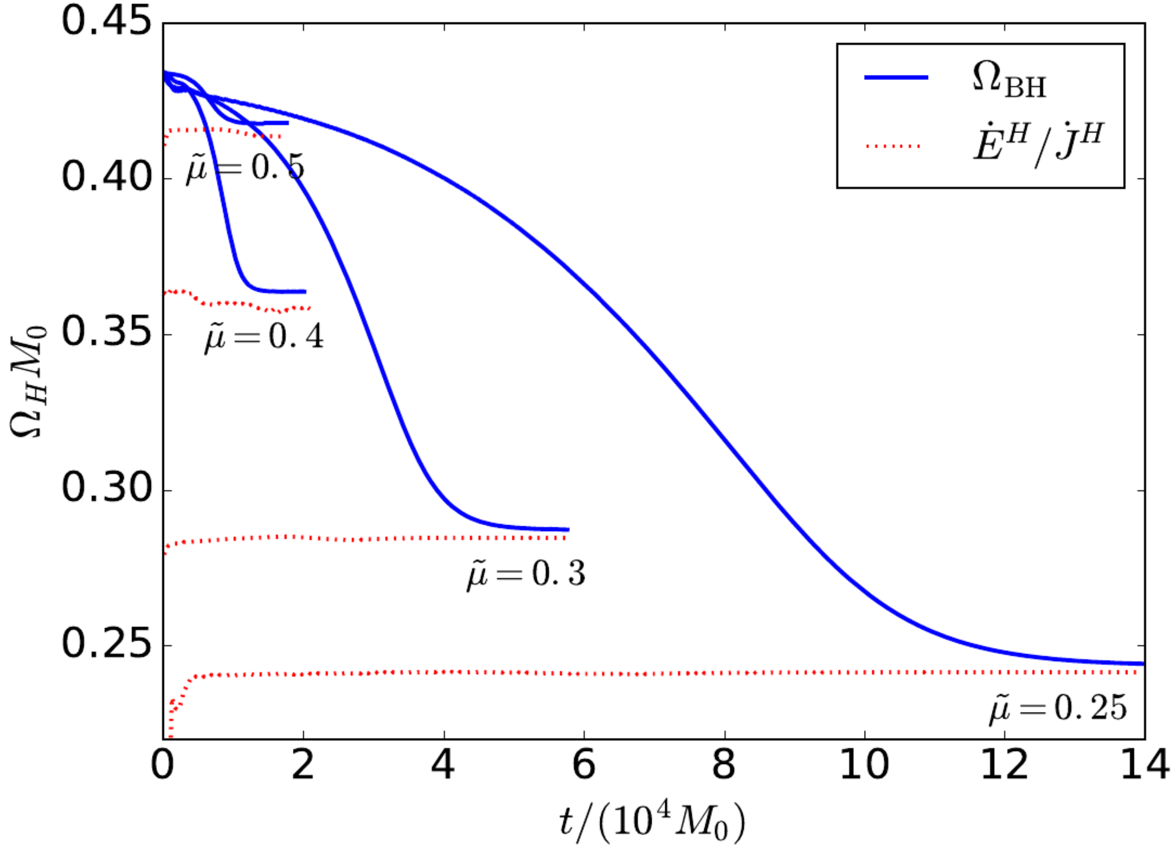
$$\omega_R \sim \mu \qquad \omega_I \sim -(\omega_R - m\Omega_H)(M\mu)^{4\ell+4+2S}$$

Dolan 2007; Rosa & Dolan, 2012; Pani+, Phys.Rev.Lett. 109 (2012) 131102; Witek+, Phys.Rev. D87 (2013) 043513; …
Brito, Cardoso, Pani, Phys.Rev. D88 (2013) 023514; Endlich & Penco, JHEP 1705 (2017) 052; Baryakhtar+ 2017

Evolution of superradiant instability

East & Pretorius, PRL (2017)

$$\omega_R \to m\Omega_H$$



- Confirms linear analysis
- Similar results charged BHs in AdS

Sanchis-Gual+, PRL116 141101 (2016)
Bosh+, PRL2016 141102 (2016)

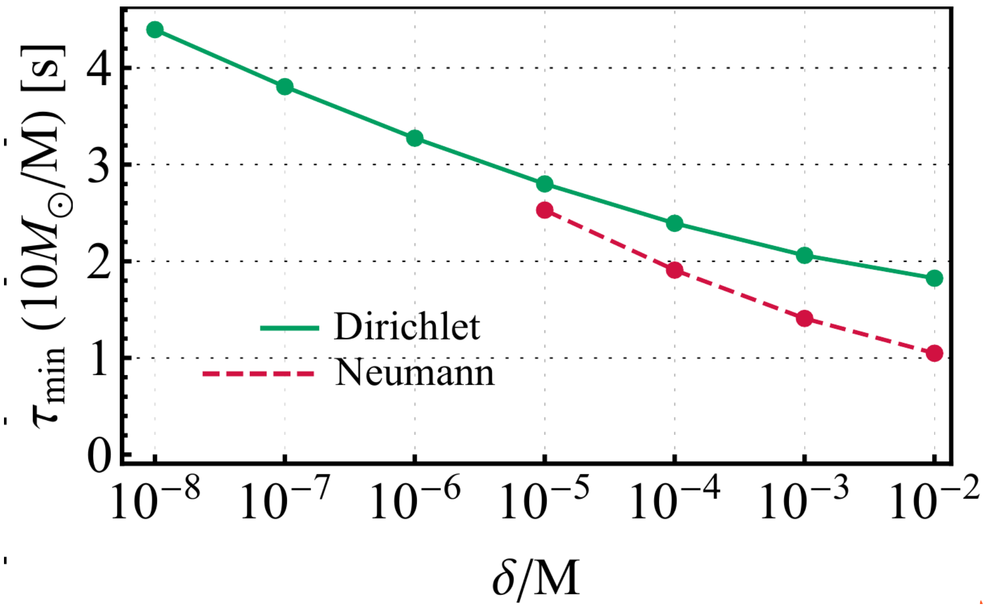
Part III
Ergoregion instability of ECOs and How to Quench It

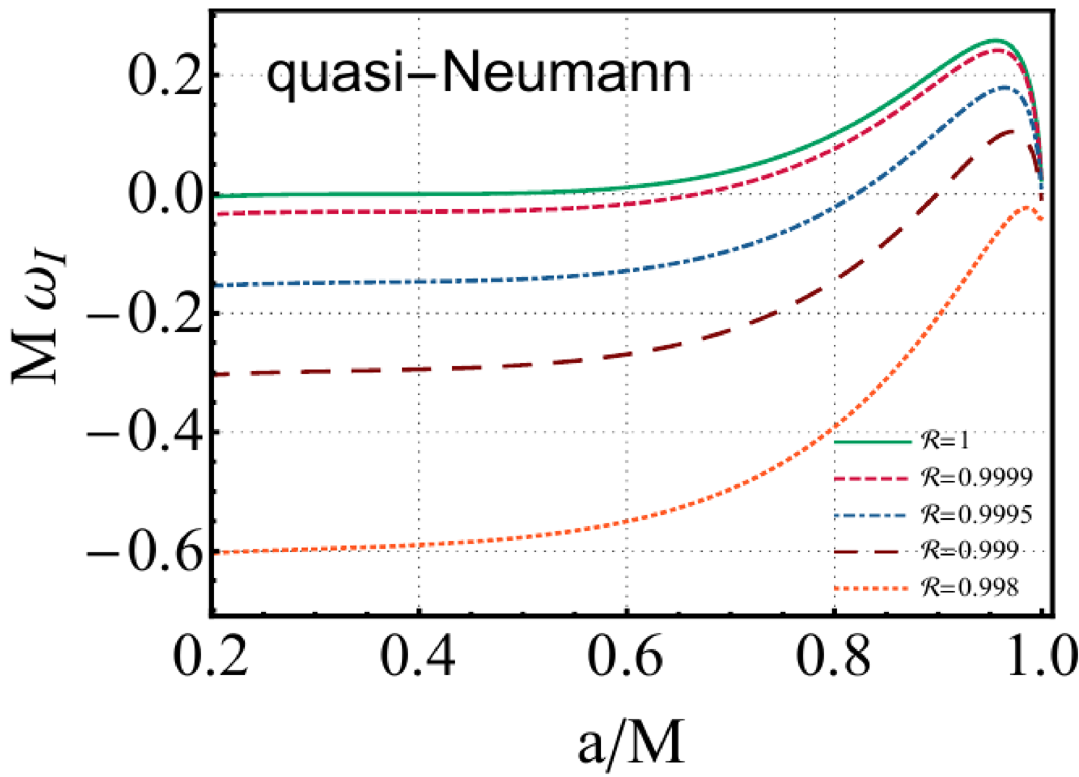
based on

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: $\mathcal{R}\rightarrow$ reflection coefficient



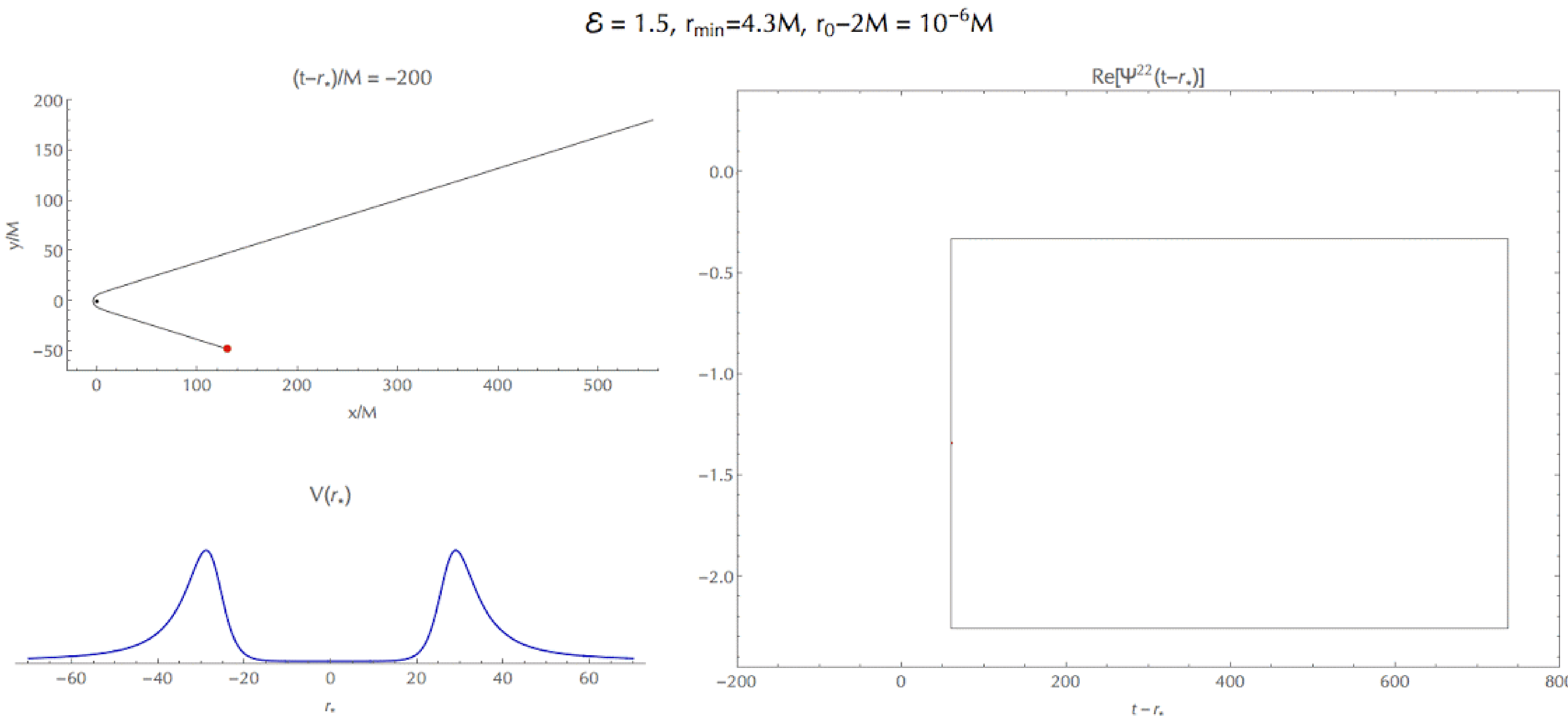


- Matter viscosity introduces absorption [Esposito, 1972]

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

The role of the photon sphere

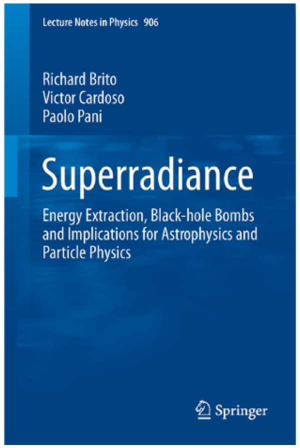
Cardoso, Hopper, Macedo, Palenzuela, Pani; PRD94 084031 (2016)

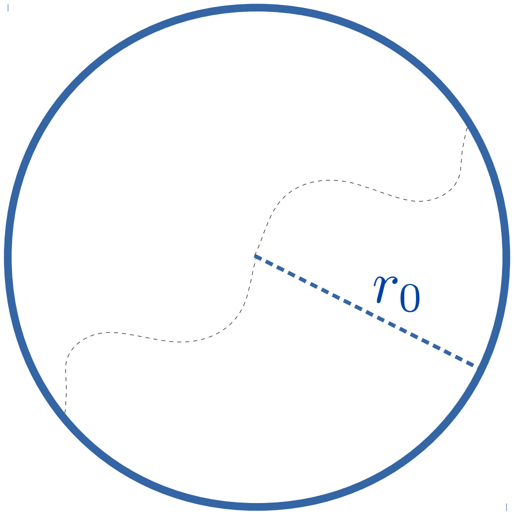


[Credits: Seth Hopper]

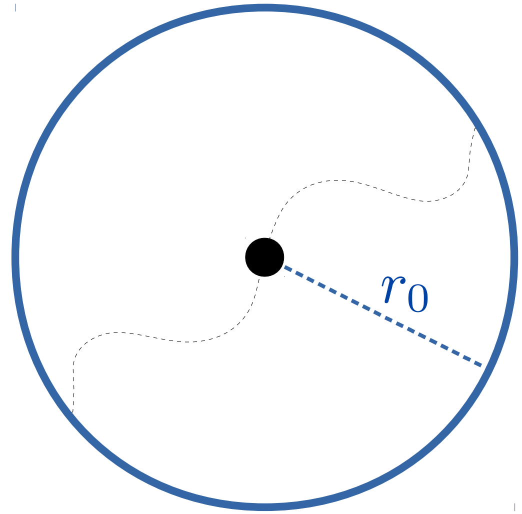
- Generic features for ultracompact ECOs (wormholes, gravastars,ultracompact stars, ...)
- The ringdown of ECOs without light ring is *qualitatively* different [Ferrari & Kokkotas, PRD 2000]
- GW observations can rule out less compact ECOs without light ring [Chirenti & Rezzolla, PRD 2016]

Confined BHs are unstable





$$\omega_R \sim 1/r_0$$



$$\omega \sim 1/r_0 + i\,\omega_I$$

- Amplitude after N reflections $A = A_0(1-|\mathcal{A}|^2)^N \sim A_0(1-N|\mathcal{A}|^2)$

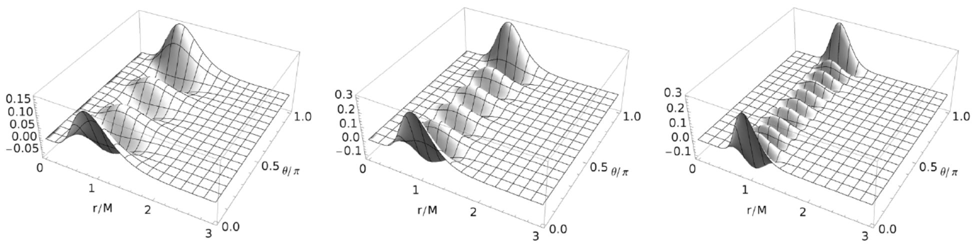
→ - On the other hand →$A(t) = A_0 e^{-|\omega_I|t} \sim A_0(1-|\omega_I|t)$

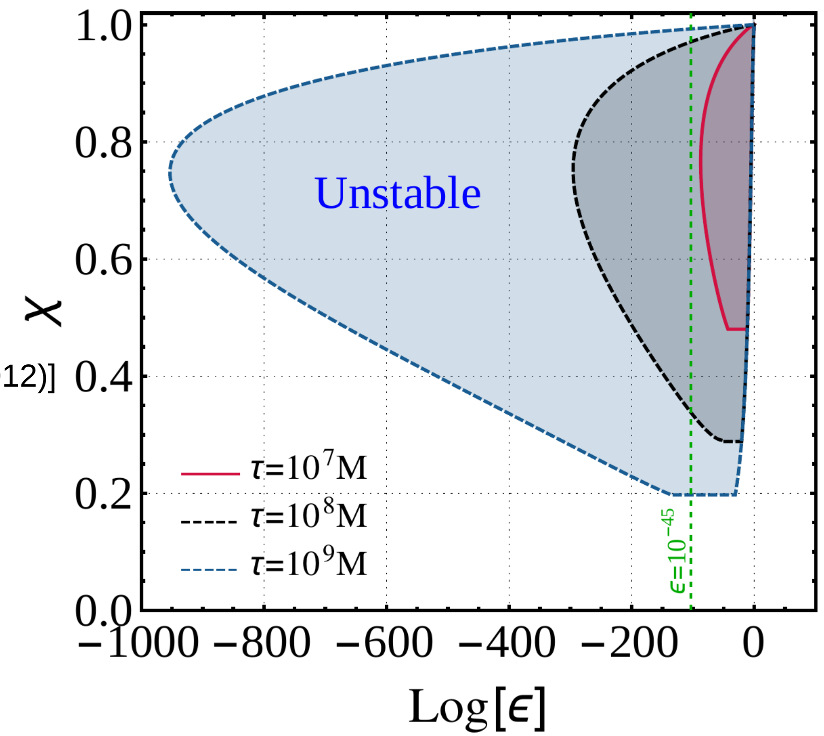
$$\omega_I = |\mathcal{A}|^2/r_0 \sim M^{-1}(M/r_0)^{2l+3}$$

- Correct time scale for cavity, AdS, magnetic fields...

BH vs ECO: Open questions

- Formation? Coalescence?
- ECO + ECO → ECO or BH?
- Stability?
  - Ergoregion instability [Friedman (1976), Cardoso+ (2008), Pani+ (2010-2012)]
  - Nonlinear instability? (turbulence, fragmentation) [Keir (2014), Cardoso+ (2014)]



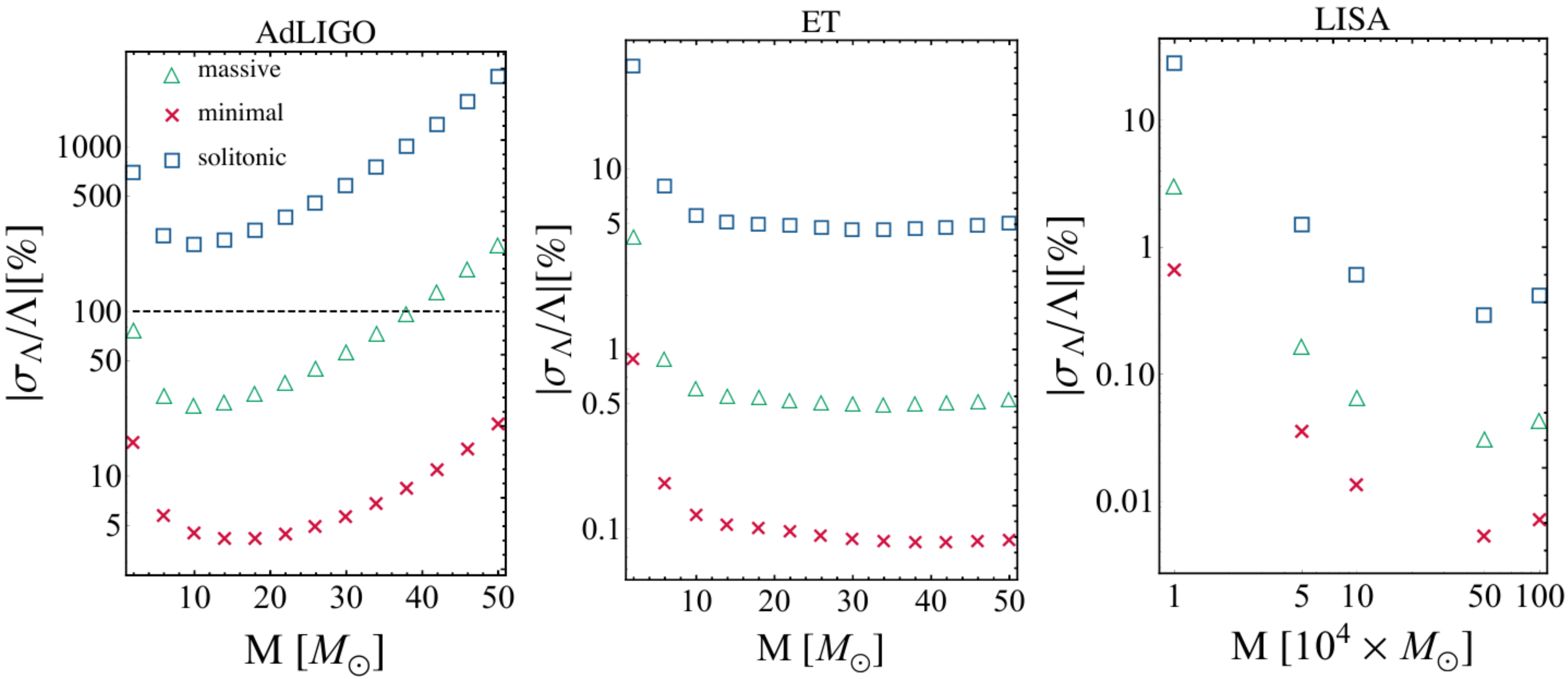


- Small absorption (<0.5%) can quench the instability efficiently [Maggio, Pani, Ferrari, PRD 2017]
- ECO interior?
- Instability can be a feature!
  - Prediction: slowly spinning compact objects
  - Matches Hawking radiation [Chowdhury & Mathur, 2008]

BH vs Boson Stars: Love numbers

Cardoso, Franzin, Maselli, Pani, 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 models with small compactness [Sennet+ (2017)]
- LISA will be able to distinguish between BHs and *any* boson-star model

Summary: testing horizons with GWs

		BH	ECO	ClePhO
ringdown	GW echoes Modified prompt ringdown Extra modes	✗ ✗ ✗	✓(only UCOs) ✓ ✓	✓($\tau_{\rm echo} \sim M\|\log\epsilon\|$) ✗ ✓
inspiral	Multipolar structure (2PN) Tidal heating (2.5 – 4PN) Tidal Love number (5PN) Resonances	$\delta M_l = \delta S_l = 0$ ✓ $k = 0$ ✗	$\delta M_l \neq 0,\ \delta S_l \neq 0$ ✗ $k \lesssim \mathcal{O}(k_{\rm NS})$ [80,96]	$\delta M_l \simeq 0,\ \delta S_l \simeq 0$ ✗ $k \sim [\log\epsilon]^{-1}$ $\omega M \sim [\log\epsilon]^{-1}$

Cardoso & Pani, arXiv:1707.03021; Nat.Astron. 1 (2017) 586-591

- Inspiral-merger-ringdown phases provide complementary tests
- **Merger:** preliminary results for boson stars [Palenzuela+, PRD95, 124005 (2017); PRD96, 104058 (2017)]
- **Future:** 3G and LISA → unparalleled tests of quantum-gravity effects at the horizon scale
- Ergoregion instability [Maggio, Pani, Ferrari, PRD 2017]