Title: Quantifying the evidence for black holes with GW and EM probes

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Abstract:

SAPIENZA
UNIVERSITÀ DI ROMA

QUANTUM BLACK HOLES IN THE SKY?

*Perimeter Institute – Nov 8-11, 2017*

INFN
Istituto Nazionale di Fisica Nucleare

# Quantifying the evidence for BHs with GW and EM probes

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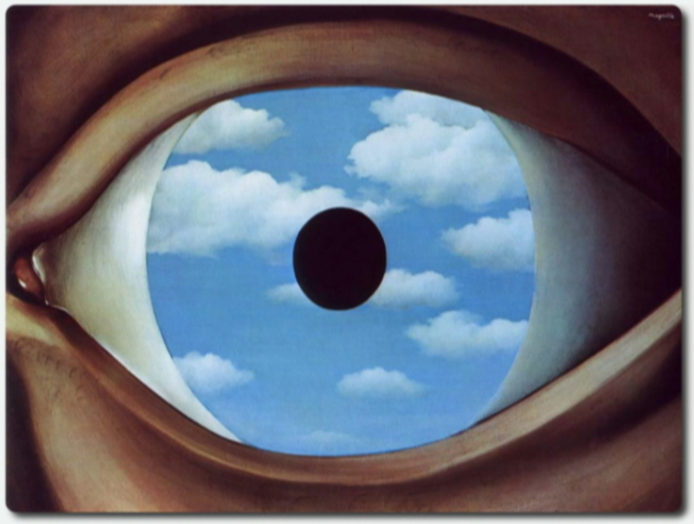
DarkGRA

http://DarkGRA.weebly.com



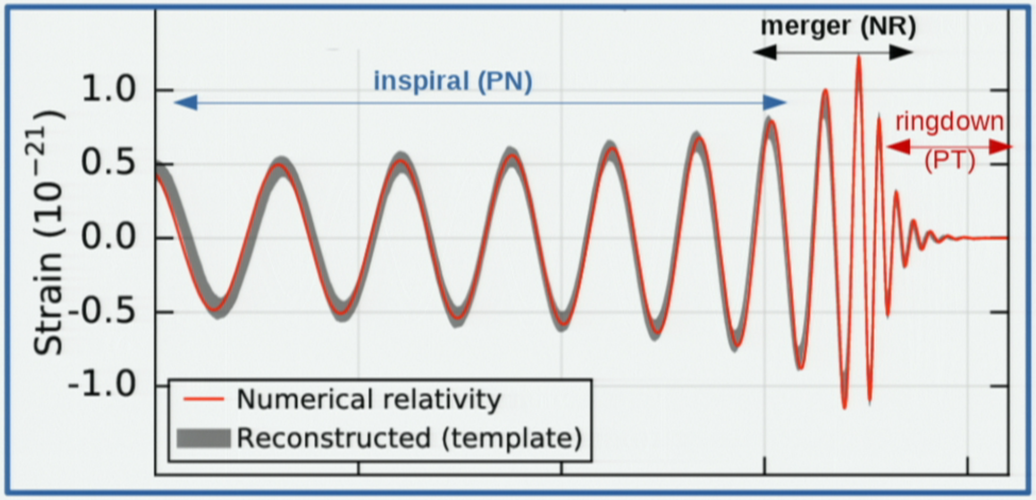
# QUANTUM BLACK HOLES IN THE SKY?

- $\ell_P/R_S \ll 1$
- In the search of a log
- (Event) horizon?
- Dark Compact Objects?
- EM probes
- GW probes

# GW150914: fact sheet

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

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




- Inspiral-merger-ringdown phases can provide complementary diagnostics

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

- Coalescence of two compact objects with super-Chandra masses

# Problems at the horizon

$G = c = 1$
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...
  - Event horizons are ***required*** for self consistency [Cosmic Censorship]
    - *"Extraordinary claims require extraordinary evidence"*
    - Drawbacks: Huge entropy, **unitarity loss**, thermodynamical instability, ...

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- Lesson from (quantum) electrodynamics:
  - Maxwell → E field~$1/r^2$ → QED → new structure near electron
  - GR → Curvature~$1/r^3$ → QG? → new structure near horizon?

# Exotic Compact Objects (ECOs)

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

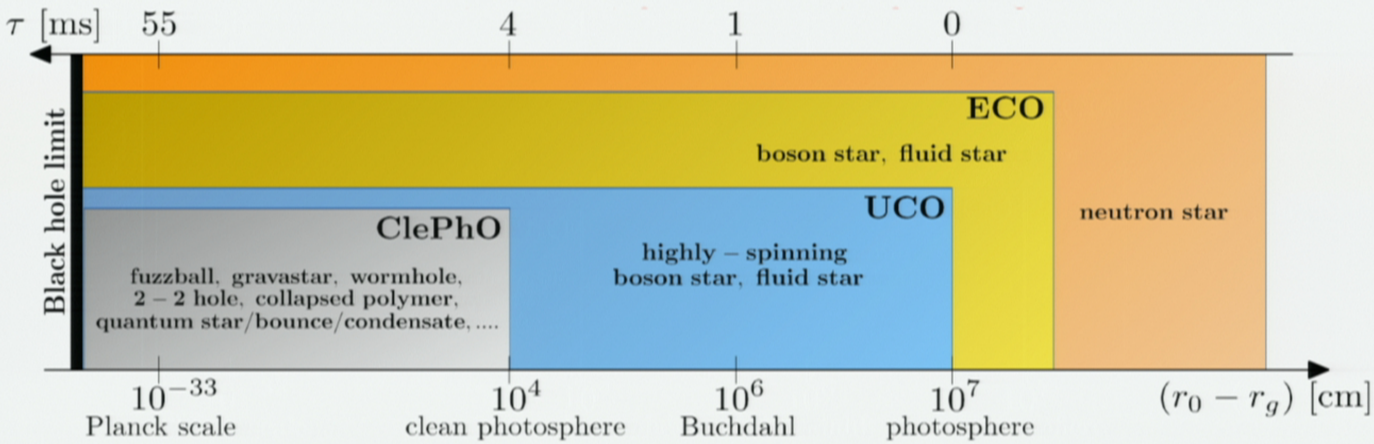
- **Boson stars** → $\mathcal{L} = \frac{R}{16\pi G} - (\partial\phi)^2 - V(\phi)$ [e.g. Palenzuela & Liebling, Liv. Rev. (2012)]
- **Quantum effects at the horizon scale** → $\langle T_{\mu\nu}\rangle \neq 0$ [Gubser (14-16)]
  - **Fuzzballs** (horizonless microstates) [Mathur (2004-)]
  - **Firewalls** (large energy density before the horizon?) [Almheiri+ (2013)]
  - **Gravastars** (de Sitter interior + shell) [Mazur & Mottola, PNAS (2004)]
  - **Wormholes** [Morris & Thorne (1987), Visser's book (1995), Damour & Solodukhin (2007), Lemos+ (2008)]
  - **2-2 holes**, **collapsed polymers**, … [Holdom & Ren (2017), Brusten & Medved (2017)]
  - **Quantum bounces / black stars**, … [Barcelò+ (2008-2017); Rovelli & Vidotto (2014); Baccetti+ (2017)]
- **Modified gravity** → energy conditions might be preserved

# Zoo of Exotic Compact Objects

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

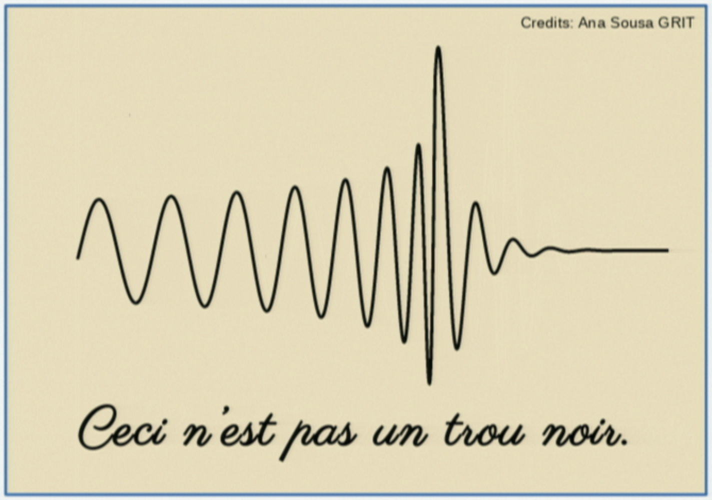
$$r_0 \equiv r_g(1+\epsilon) = \frac{2GM}{c^2}(1+\epsilon)$$

$\epsilon \sim 10^{-39} - 10^{-46}$
for Planck-scale corrections




- Light ring is unstable on time scales ~ 5M → clean photon sphere if ε<<1
- Conjecture: ECO → BH as ε→ 0 ...but which scaling?
- Goal: probing closer and closer to the horizon (e.g. particle detectors)

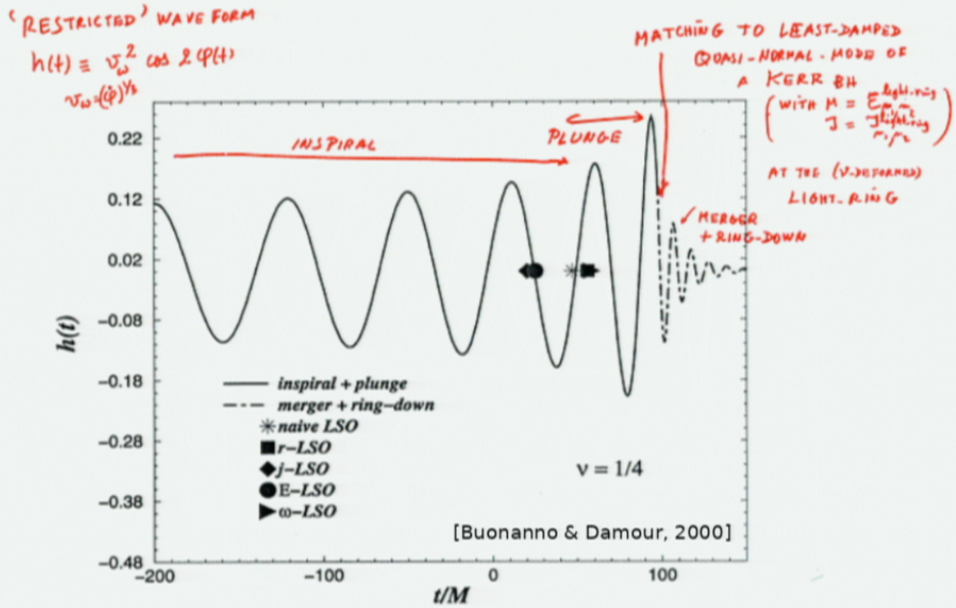
# Part I
# Ringdown tests




based on work with V. Cardoso+

**PRL 116 171101 (2016); PRD94 084031 (2016); arXiv:1707.03021; Nat.Astron. 1 (2017) 586-591**

# Ringdown tests of the event horizon



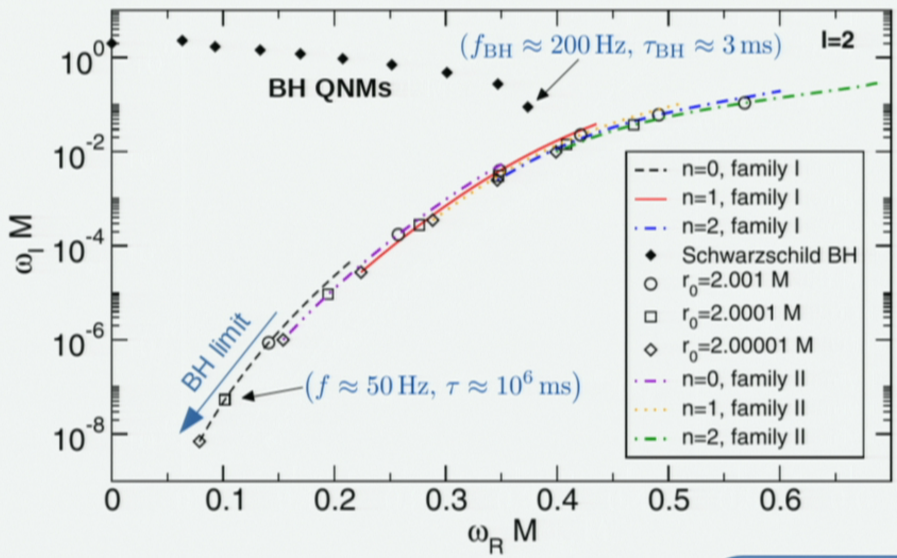

Two common assumptions:

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

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

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

# QNM spectrum of an ECO




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

BH limit:

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

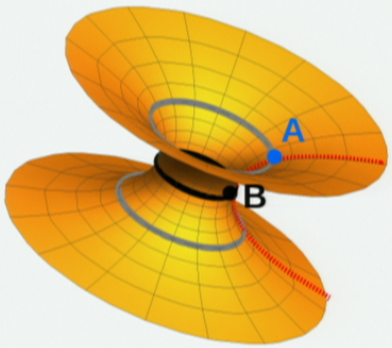
$$\omega_R M \sim |\log\epsilon|^{-1}$$

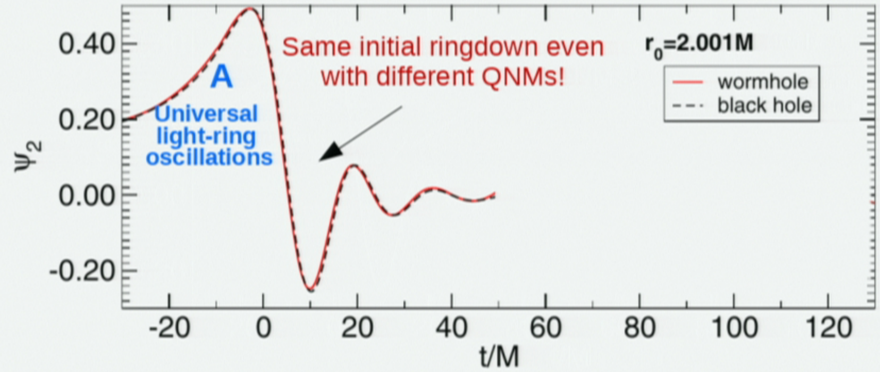
$$\omega_I M \sim -|\log\epsilon|^{-(2l+3)}$$

# GW echoes

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

Cardoso+; PRD94 (2016) 084031



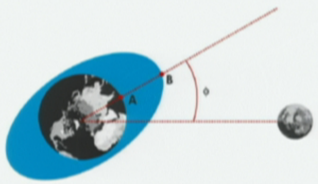
# Post-Newtonian inspiral: BH vs ECO

- Gravitational waveform in the frequency domain:

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

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

- Tidal heating at the horizon:



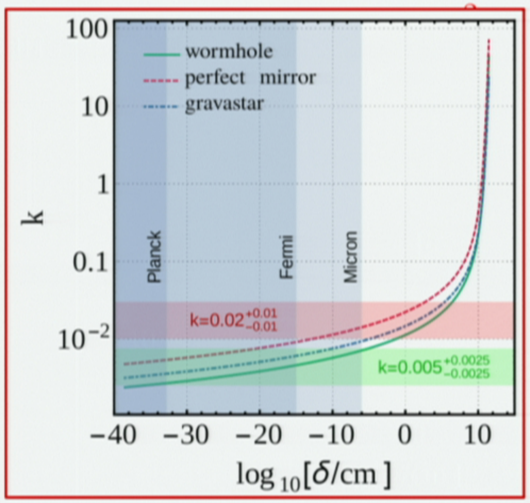
$$\psi_{\rm TH} \sim \underbrace{(\Omega-\Omega_H)}_{\text{superradiance}}\Omega \sim \underbrace{\chi\psi_{\rm TH}^{2.5\rm PN}}_{\text{Linear in spin}} + \underbrace{\psi_{\rm TH}^{4\rm PN}}_{\text{nonspinning}}$$

Alvi PRD 2001, Poisson, PRD 2009

# Post-Newtonian inspiral: BH vs ECO

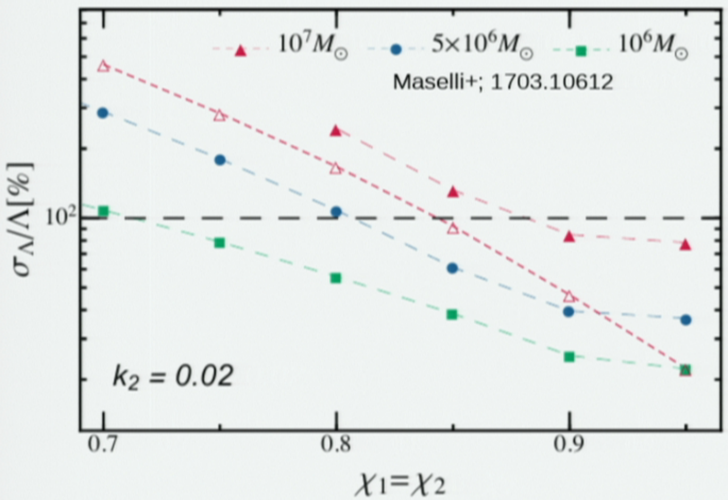
- Gravitational waveform in the frequency domain:

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




- Tidal deformability and tidal Love numbers:

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




- **Love Numbers of a BH are zero**

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

- Love numbers of a ClePhO:

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

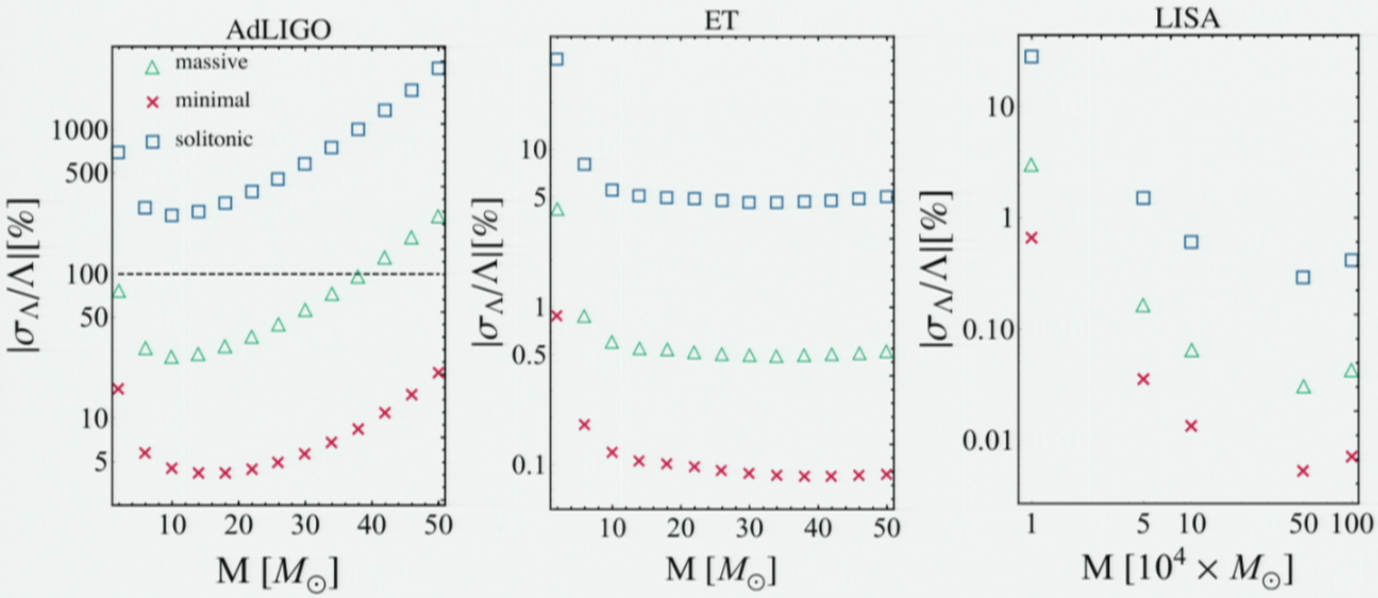
Cardoso, Franzin, Maselli, Pani, Raposo, PRD 2017

k~0.005 in order to probe
Planck corrections → **need LISA**

# 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

- GW astronomy: opportunity to search for new physics at the horizon scale:

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

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

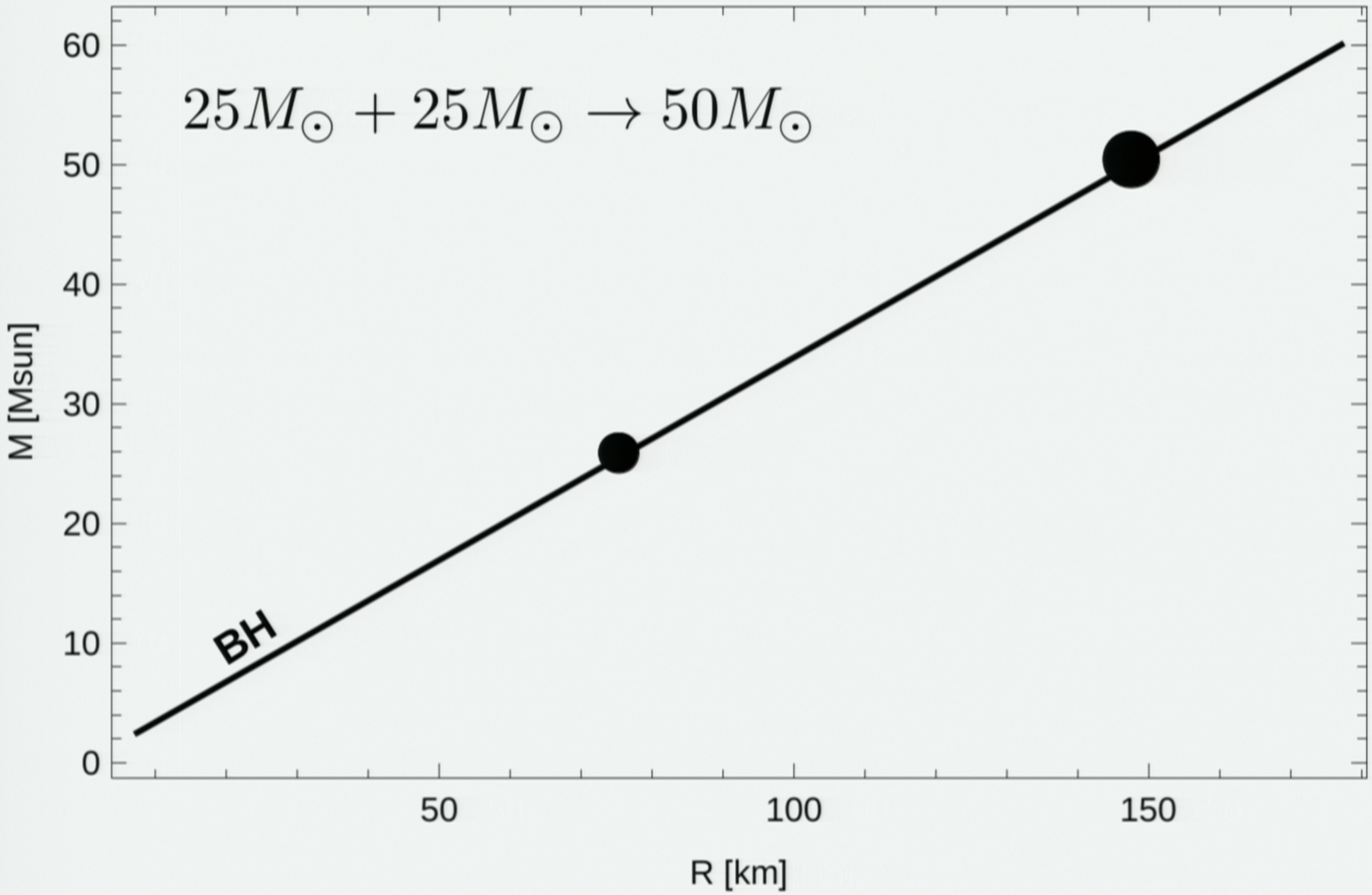
No-hair theorem: for a Kerr BH → $M_l + iS_l = M^{l+1}\,(i\chi)^l$ [Hansen (1974)]

- Inspiral-merger-ringdown phases provide complementary tests
- **Merger:** preliminary results for boson stars [Palenzuela+, PRD95, 124005 (2017), 1710.09432]
- **Future:** highly-spinning supermassive LISA binaries → unparalleled tests of quantum-gravity effects at the horizon scale

# BH vs ECO: Open questions #1

- Isolated equilibrium solutions?
- Formation?
- Coalescence: ClePhO + ClePhO → ClePhO or BH?

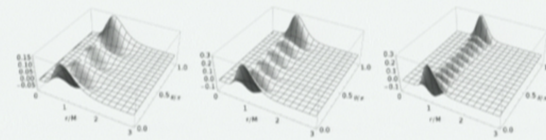
# Short-blancket problem?

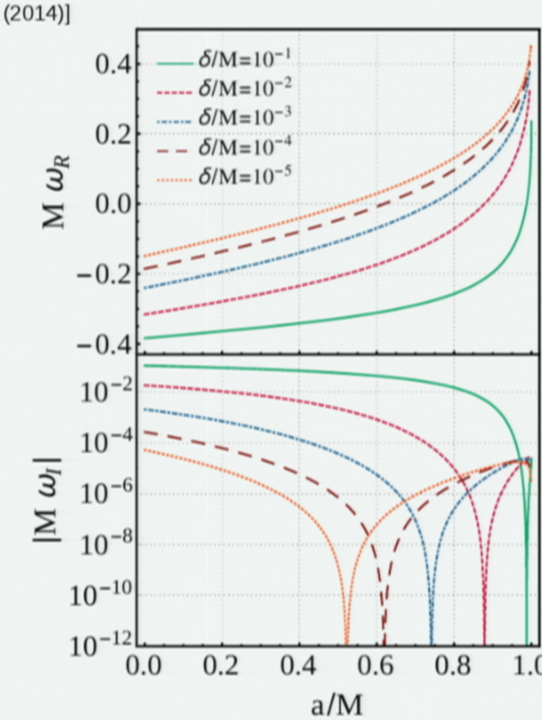



P. Pani @ Quantum Black Holes in the Sky? - PI Nov 2017

# BH vs ECO: Open questions #2

- Stability? (long-lived modes turn unstable!)
  - Ergoregion instability [Friedman (1976), Cardoso+ (2008), Pani+ (2010-2012)]
  - Nonlinear instability? (turbulence, fragmentation) [Keir (2014), Cardoso+ (2014)]






[Maggio, Pani, Ferrari, 1703.03696 (PRD 2017)]

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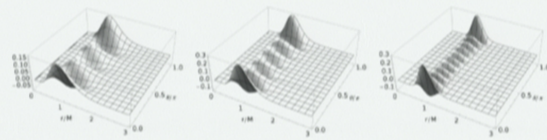
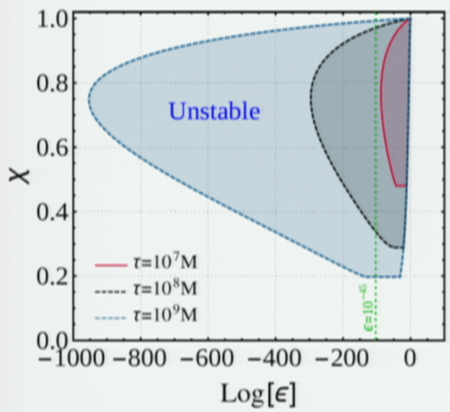
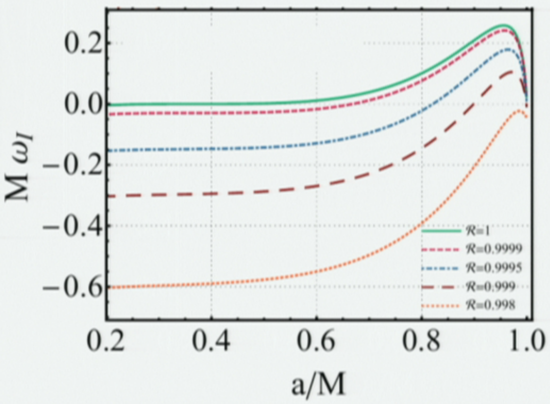
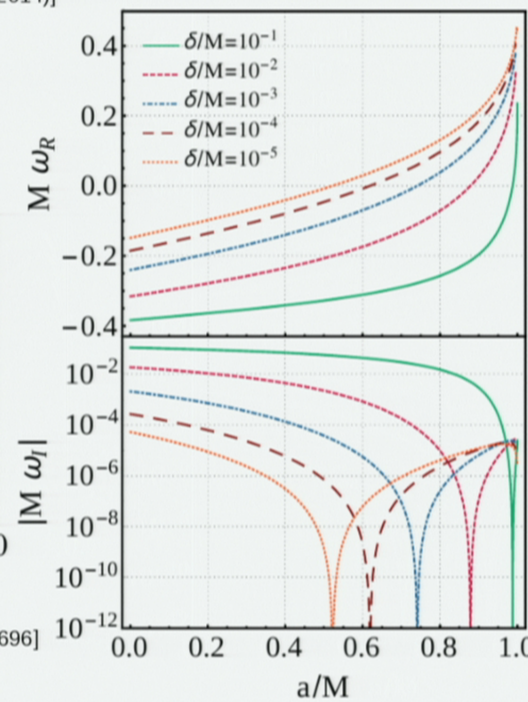


- Prediction: slowly spinning compact objects:



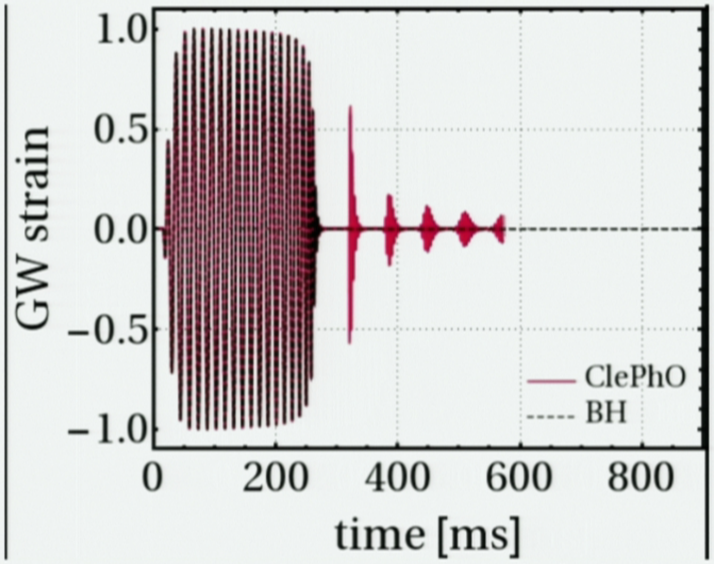




- Small absorption (<0.5%) quench instability [Maggio+, 1703.03696]
- ECO interior? [Bueno+ 1711.00391, Guo+, 1711.01617]

[Maggio, Pani, Ferrari, 1703.03696 (PRD 2017)]

# GW astronomy: expect the unexpected?




Credits: G. Khanna

Echoes in Extreme-Mass-Ratio Inspiral

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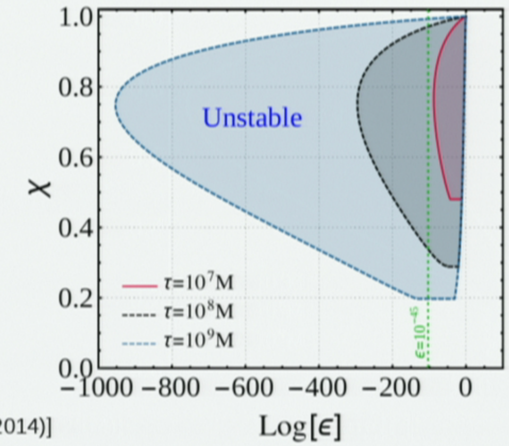
# BH vs ECO: Open questions

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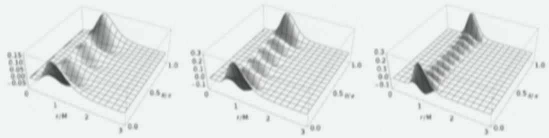

- Instability can be a feature!
  - Prediction: slowly spinning compact objects
  - Matches Hawking radiation [Chowdhury & Mathur, 2008] (Q: how about D=4, zero spin?)
- Detectability? [Abedi+, PRD96 082004 (2017), Ashton+, 1612.05625]
  - Progress in modelling [Nakano+, 1704.07175; Mark+ 1706.06155; Maselli+ 1708.02217, Bueno+ 1711.00391]