Title: David Defeats Goliath: How Ultralight Fields Affect The Dynamics of Massive Black Holes

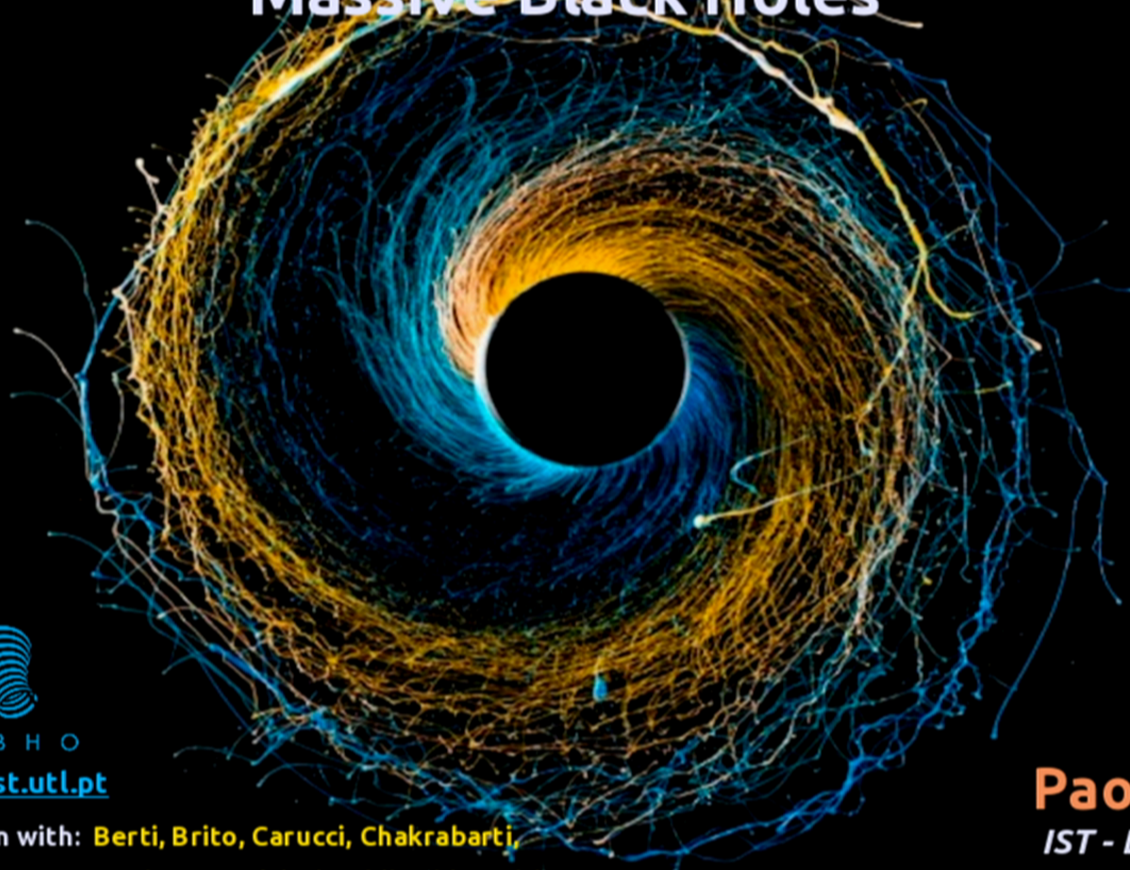
Date: May 09, 2013 01:00 PM

URL: http://pirsa.org/13050001

Abstract: In the last few years several interesting phenomena associated to the interaction between massive black holes and fundamental bosonic fields have been discovered. I present a selection of them, including superradiance instabilities of spin-0, spin-1 and spin-2 fields, floating orbits in extreme-mass ratio inspirals and black-hole spontaneous scalarization. The theoretical potential of these effects
as almost-model-independent smoking guns for exotic particles and modified gravity, as well as their limitations in realistic astrophysical scenarios, are discussed.

David Defeats Goliath

How Ultralight Fields Affect The Dynamics of Massive Black Holes



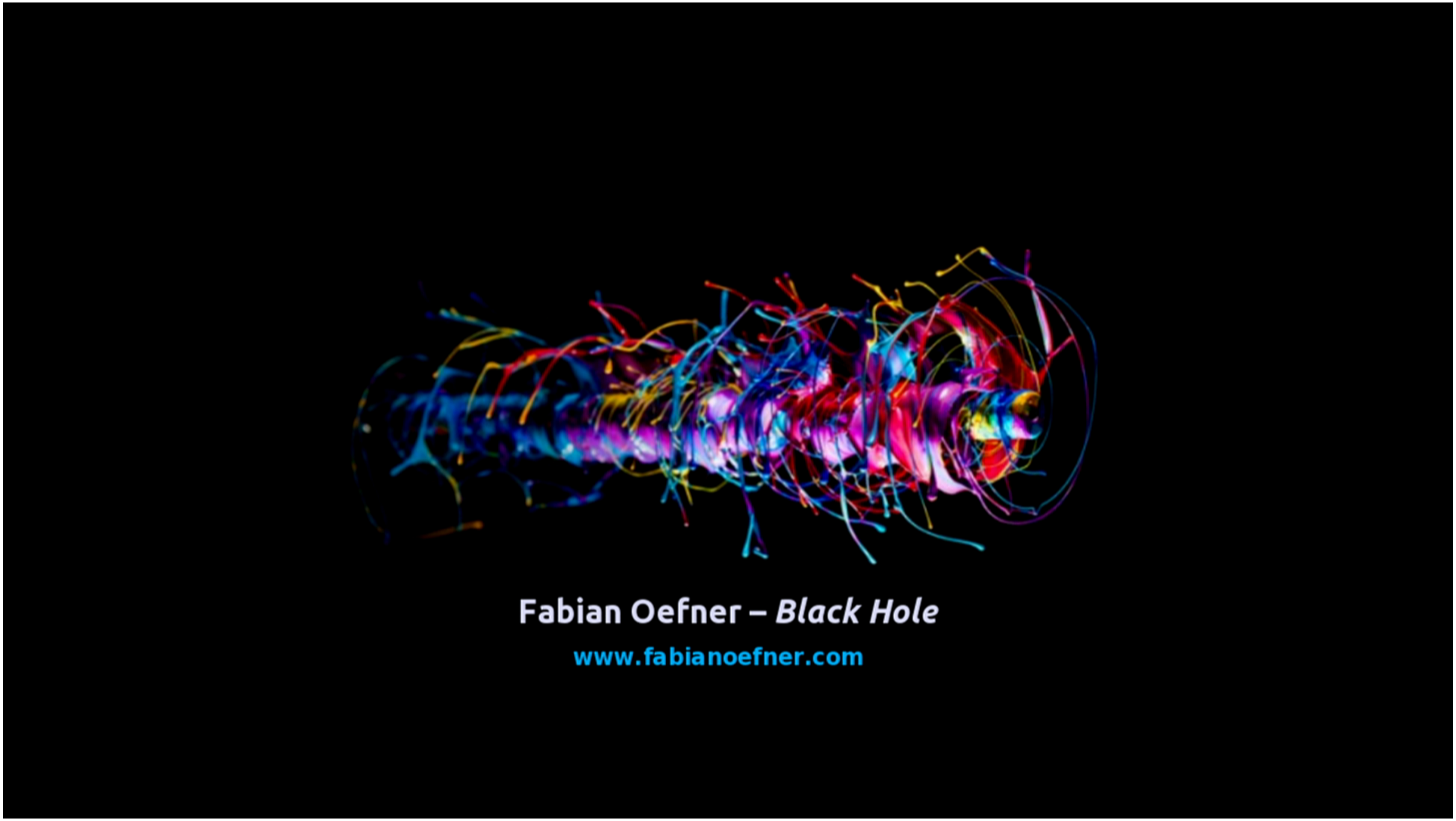
DYBHO

blackholes.ist.utl.pt

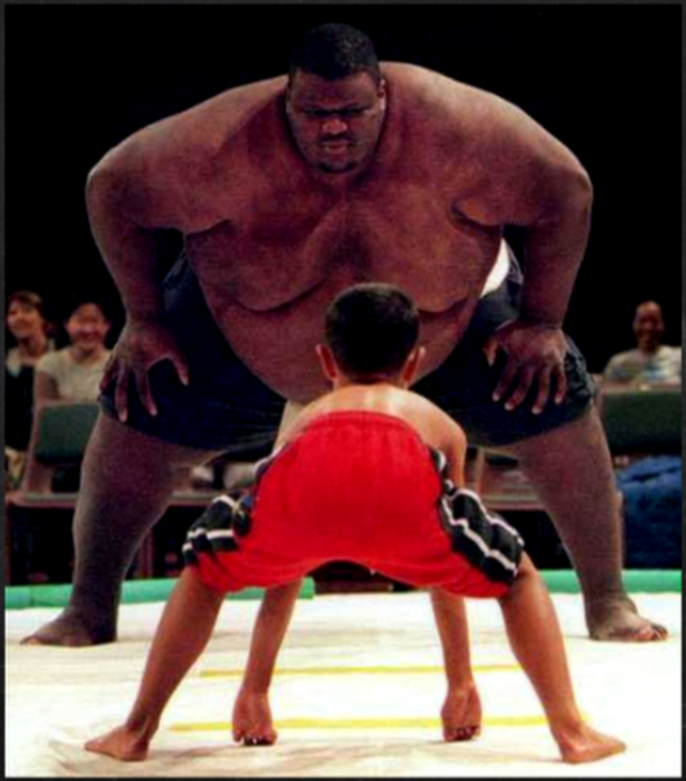
In collaboration with: Berti, Brito, Carucci, Chakrabarti, Cardoso, Gualtieri, Ishibashi, Sotiriou, Yunes

Paolo Pani

IST - Lisbon (PT)


Fabian Oefner – *Black Hole*
www.fabianoefner.com

David VS Goliath



Massive BH

$M_{\rm BH} \in [10, 10^8] M_\odot$

Light field

$m \in [10^{-20}, 10^{-9}]\text{eV}$

Outline

From theory to astrophysics?

- BHs as particle physics labs
- Strong-field effects on fundamental fields
- Theoretical challenges in BH physics
  - *BHs & light bosons*
  - *Floating orbits in EMRIs*
  - *Spontaneous scalarizations in BHs*
- Astrophysical consequencies?

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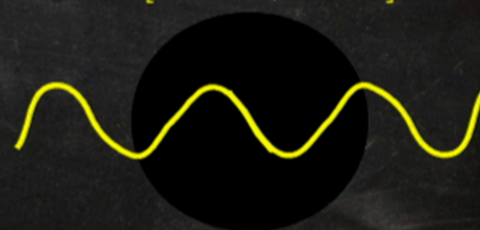

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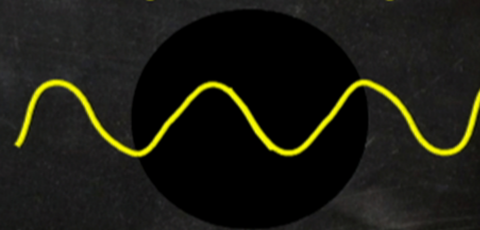

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BH superradiance

[Teukolsky & Press, '70]

- Simple BH- matter interaction
- Kerr BH: Killing vector ∂_t becomes spacelike in the ergoregion:
- Amplification of scattered waves → angular momentum extraction if:

$$\omega < m\Omega_H$$

- Linear effect, but peek to backreaction
- Requires dissipation → event horizon
- ~ tidal heating at the horizon

[Cardoso & Pani, 2012]

[Thorne, Price, Macdonald's book]

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Zel'dovich effect. [Credit: Ana Sousa]

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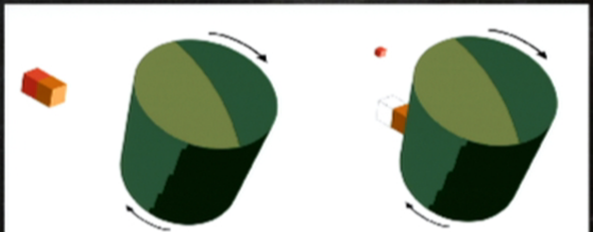
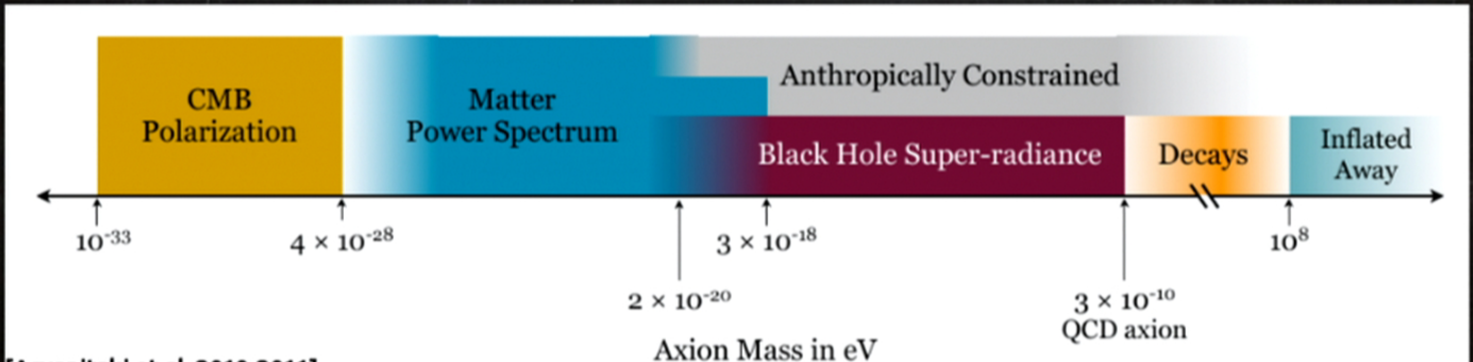


Zel'dovich effect. [Credit: Ana Sousa]

Part I

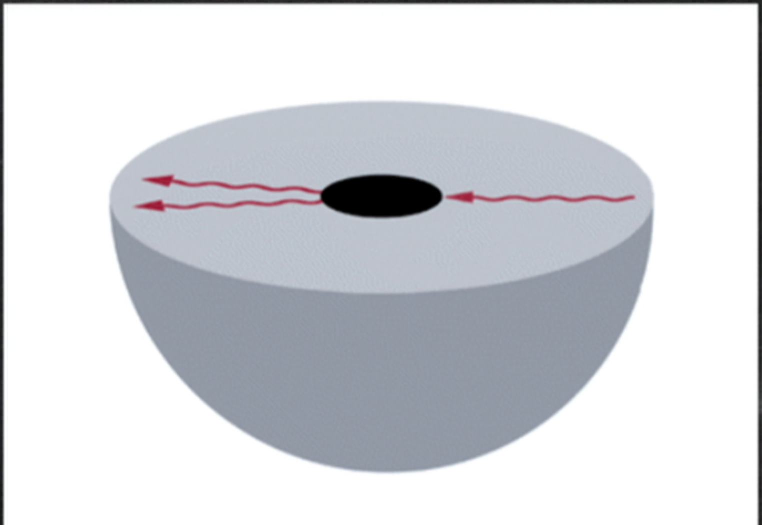
BHs & light bosons



[Arvanitaki et al. 2010-2011]

The BH bomb

[Press & Teukolsky, Nature '72]



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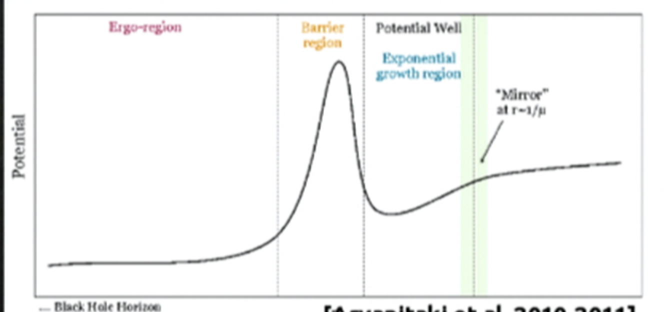
"Nature may provide its own mirrors"

[Cardoso, Dias, Lemos, Yoshida, PRD 2004]

- AdS boundaries
- Massive fields
- Matter interactions



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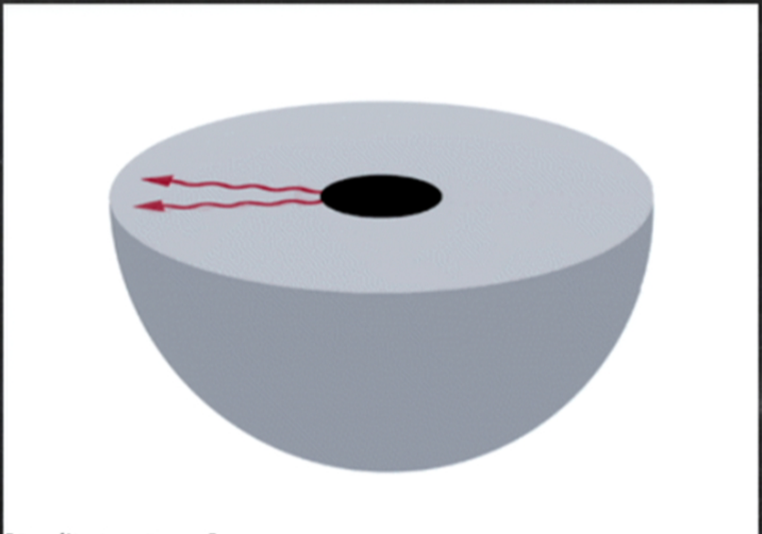

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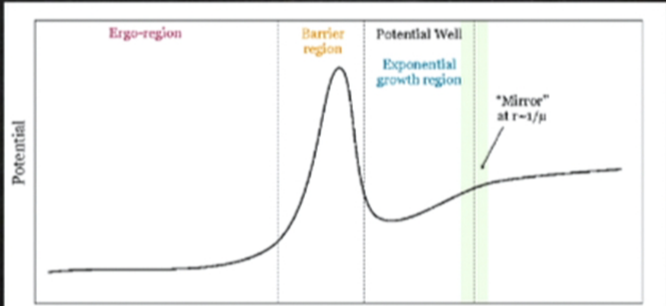

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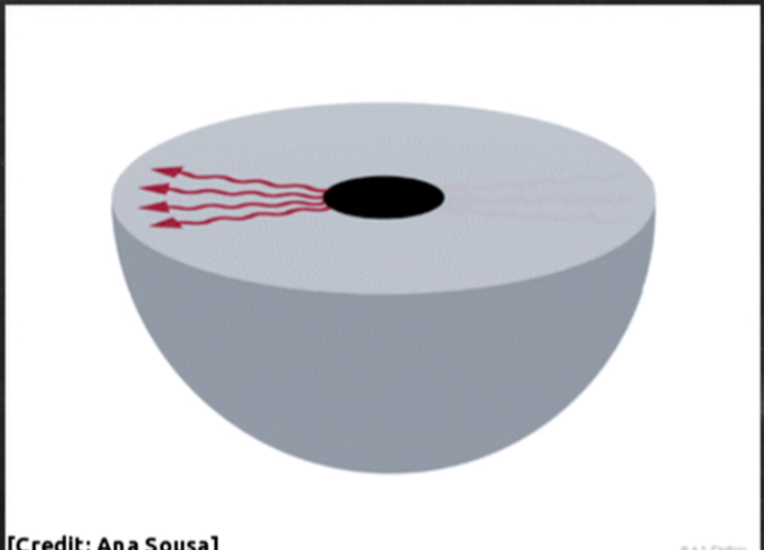

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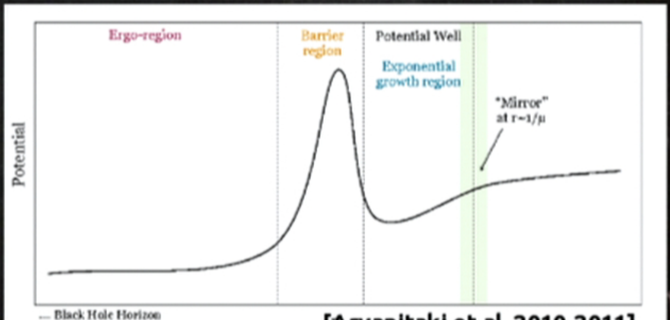


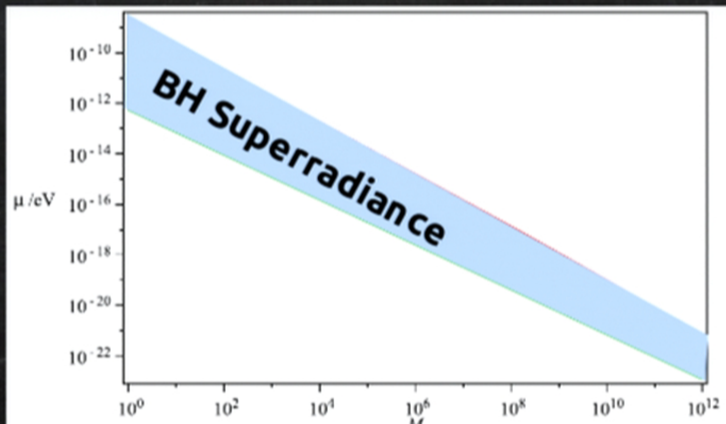
[Arvanitaki et al. 2010-2011]

Scalar fields & superradiance

$$\Box\phi - \mu^2\phi = 0$$

- Massive fields around spinning BHs are unstable
- Strongest instability when $\mu M \sim 1 \rightarrow \tau \sim 10^6\, M$
  - Ultra-light particles ($m \sim 10^{-21}$ - 10^{-9} eV) and (super)massive BHs

[Damour et al. 1976]
[Detweiler, 1980]
[Earley & Zouros 1979]
[Cardoso & Yoshida 2005]
[Dolan 2007]
[Rosa 2010, 2012]

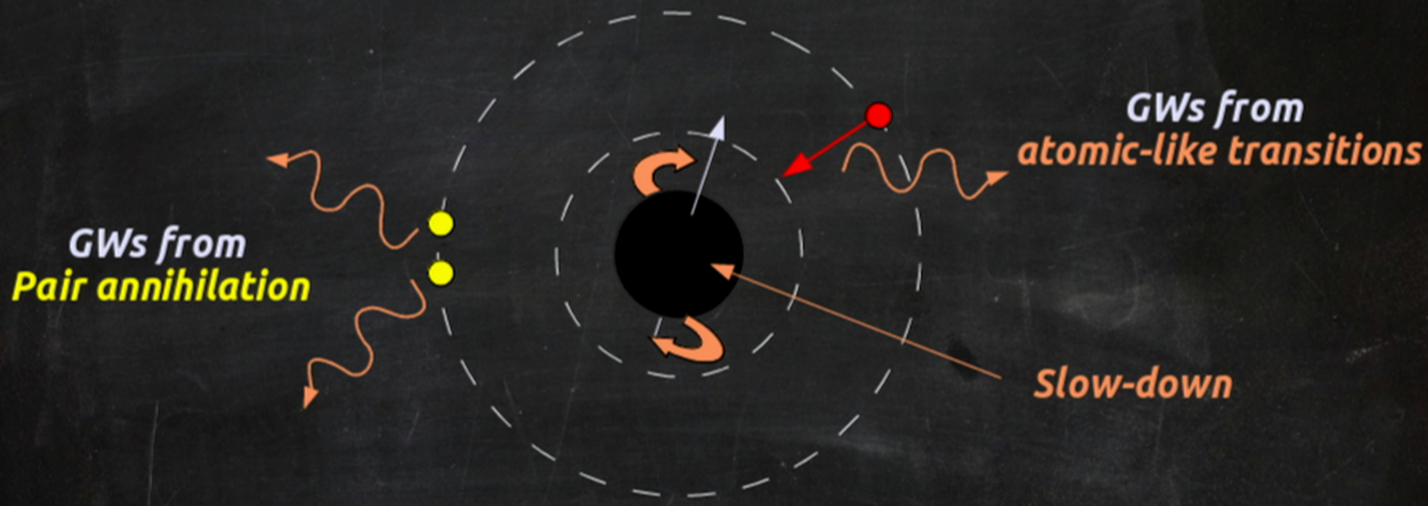


[Arvanitaki et al. 2010-2011]

- Numerical simulation are challenging

[Kodama & Yoshino 2011-2012]
[Witek et al, PRD 2012, Dolan 2012]

Scalar fields & superradiance



- High-frequency GWs
- Optical-trap detectors

[Arvanitaki & Geraci PRL 2013]

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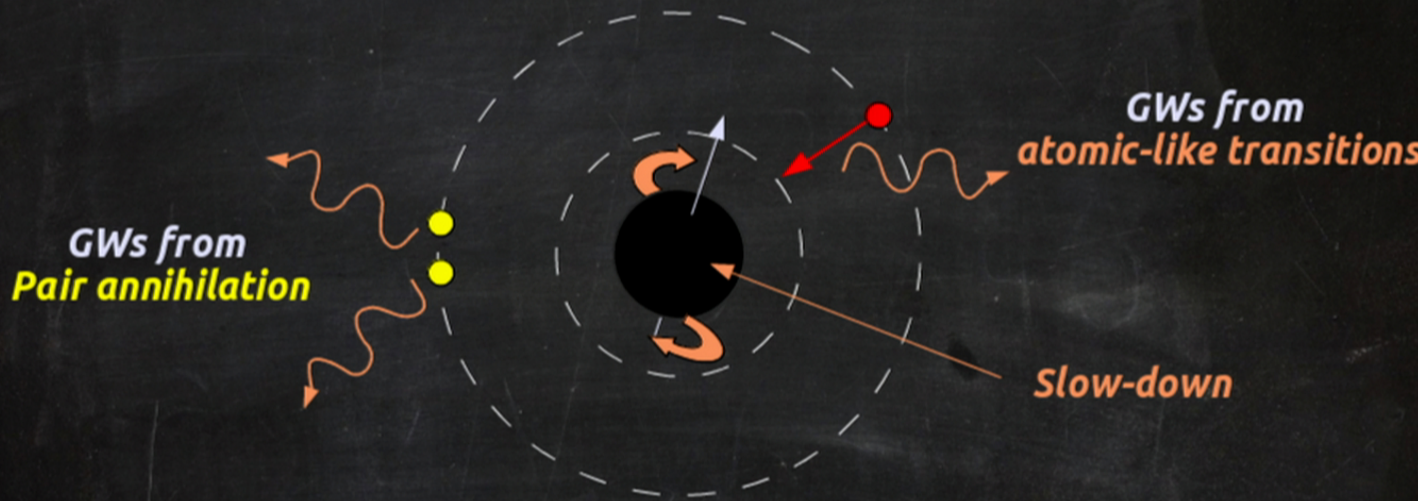

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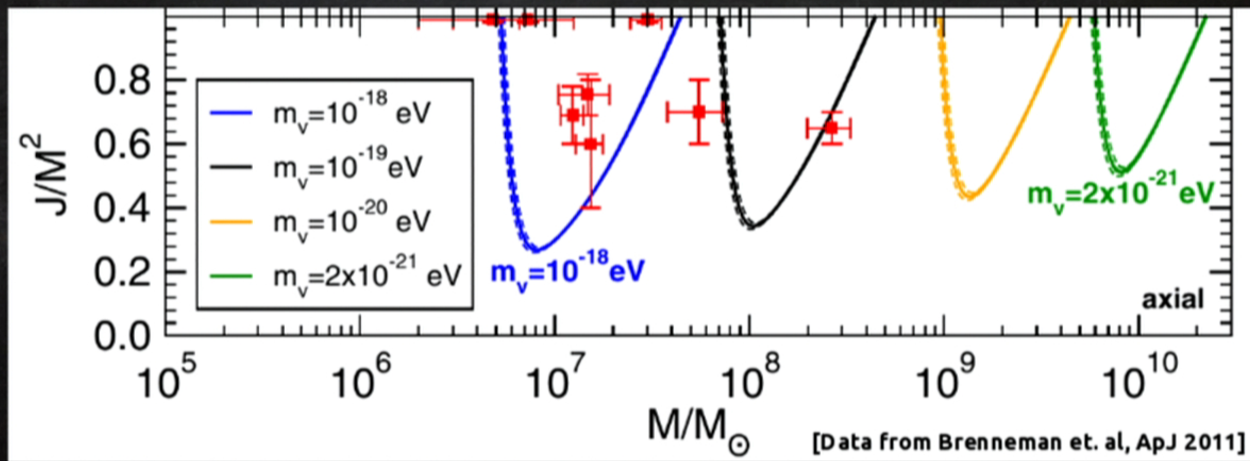
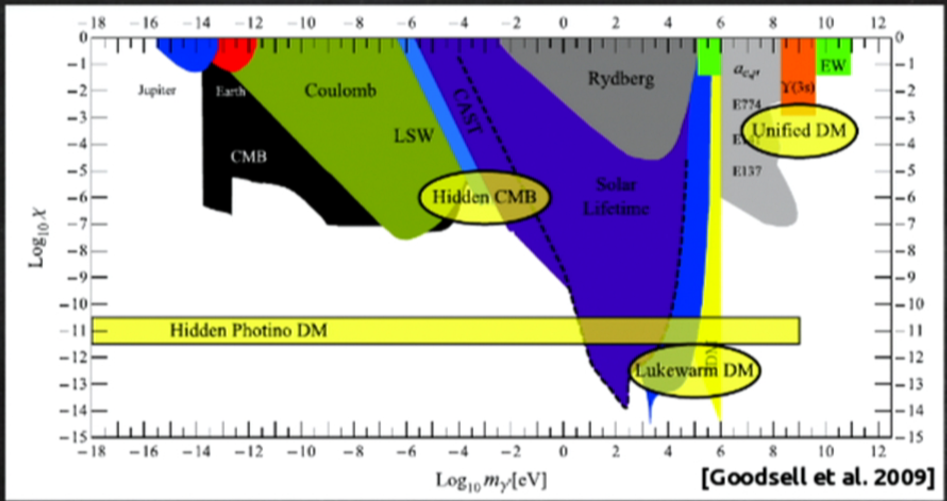
If ultralight scalars exist and they are superradiantly unstable, we shouldn't observe highly-spinning BHs



Constraints on axion parameters from BH observations and future GW detection

What about vector fields?

$$\mathcal{L} = -\frac{1}{4g_a^2}F^{(a)}_{\mu\nu}F^{\mu\nu}_{(a)} - \frac{1}{4g_b^2}F^{(b)}_{\mu\nu}F^{\mu\nu}_{(b)} + \frac{\chi_{ab}}{2g_a g_b}F^{(a)}_{\mu\nu}F^{(b)\mu\nu} + \frac{m^2_{ab}}{g_a g_b}A^{(a)}_{\mu}A^{(b)\mu}$$



[Goodsell et al. 2009]

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

- Proca eq. (apparently) nonseparable in a Kerr background
- Conjecture of a stronger instability?

Alexandru Proca

Slow-rotation approximation

Expansion of any field perturbation in a complete basis of spherical harmonics

$0 = \mathcal{A}_\ell$

Zeroth order: decoupled

$\mathcal{P}_{L+3}$

$\mathcal{A}_{L+2}$

$0 = \mathcal{P}_\ell$

$\mathcal{P}_{L+1}$

$\mathcal{A}_{L}$

$\mathcal{P}_{L-1}$

$\mathcal{A}_{L-2}$

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[Pani et al. PRL, PRD 2012]

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$$+\tilde{a}m\bar{\mathcal{A}}_\ell + \tilde{a}(\mathcal{Q}_\ell\tilde{\mathcal{P}}_{\ell-1} + \mathcal{Q}_{\ell+1}\tilde{\mathcal{P}}_{\ell+1})$$

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First order: polar-axial l±1

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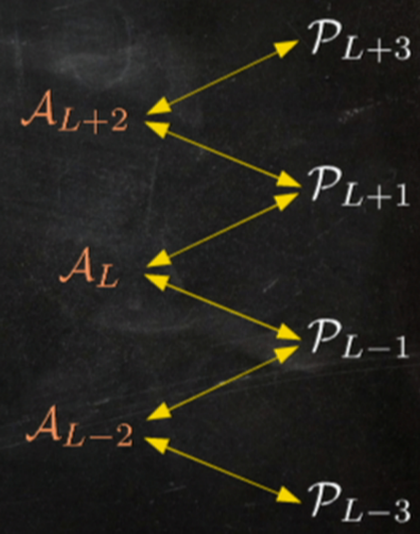

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Slow-rotation approximation

Expansion of any field perturbation in a complete basis of spherical harmonics

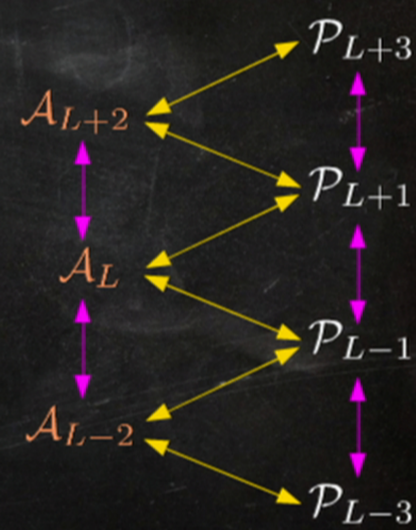
$$0 = \mathcal{A}_\ell + \tilde{a}m\bar{\mathcal{A}}_\ell + \tilde{a}(\mathcal{Q}_\ell\tilde{\mathcal{P}}_{\ell-1} + \mathcal{Q}_{\ell+1}\tilde{\mathcal{P}}_{\ell+1}) + \tilde{a}^2\left[\hat{\mathcal{A}}_\ell + \mathcal{Q}_{\ell-1}\mathcal{Q}_\ell\breve{\mathcal{A}}_{\ell-2} + \mathcal{Q}_{\ell+2}\mathcal{Q}_{\ell+1}\breve{\mathcal{A}}_{\ell+2}\right]$$

Zeroth order: decoupled

First order: polar-axial l±1

Second order: l±2

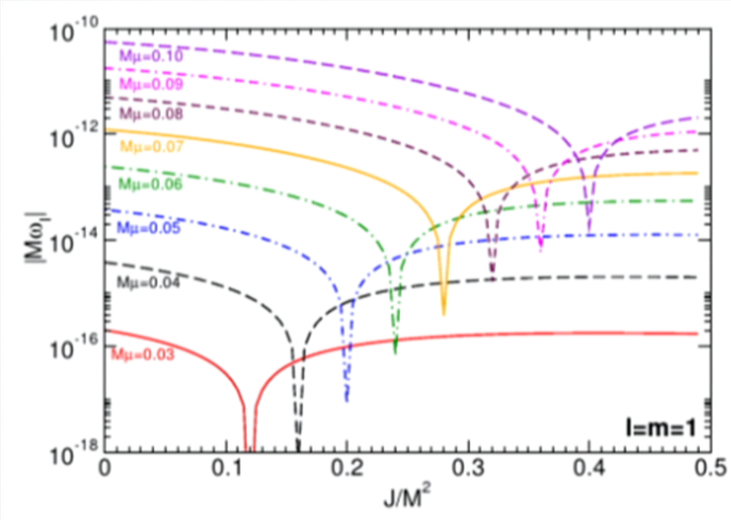
$$0 = \mathcal{P}_\ell + \tilde{a}m\bar{\mathcal{P}}_\ell + \tilde{a}(\mathcal{Q}_\ell\tilde{\mathcal{A}}_{\ell-1} + \mathcal{Q}_{\ell+1}\tilde{\mathcal{A}}_{\ell+1}) + \tilde{a}^2\left[\hat{\mathcal{P}}_\ell + \mathcal{Q}_{\ell-1}\mathcal{Q}_\ell\breve{\mathcal{P}}_{\ell-2} + \mathcal{Q}_{\ell+2}\mathcal{Q}_{\ell+1}\breve{\mathcal{P}}_{\ell+2}\right]$$



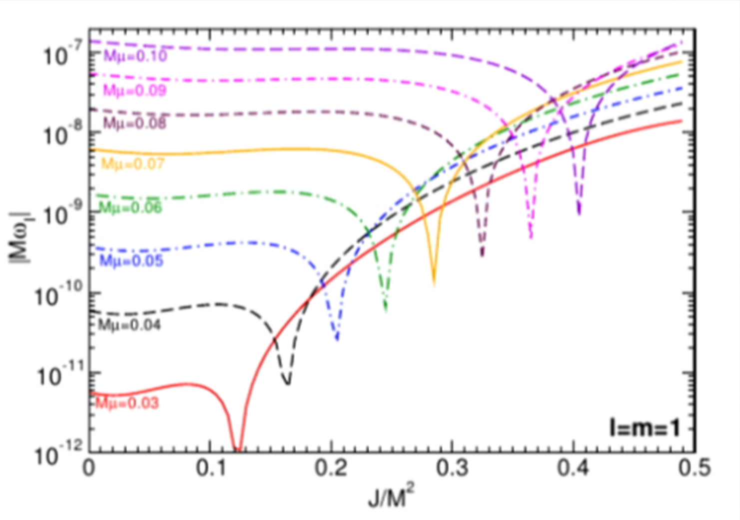
- **Zeeman rule**, **Laporte rule**, **propensity rule**
- **Generic: any metric, any perturbation, any theory, any order** [Pani et al. PRL, PRD 2012]

Proca instability of Kerr BHs

Axial modes (S=0)



Polar modes (S=+1,-1)

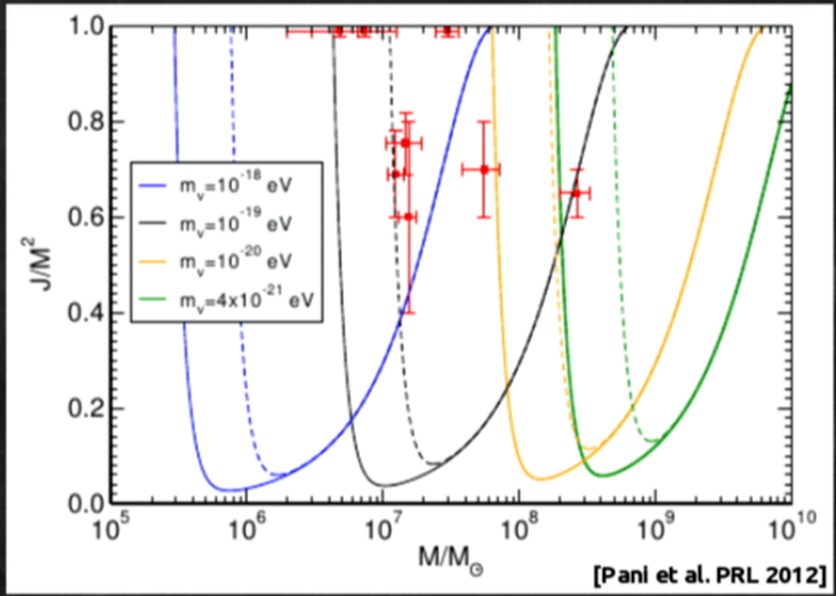


$$\omega_R \sim \mu - \frac{\mu(M\mu)^2}{2(\ell+n+S+1)} \qquad M\omega_I \sim \gamma_{S\ell}\,(\tilde{a}m - 2r_+\mu)\,(M\mu)^{4\ell+5+2S}$$

- **Instability timescale for polar vector modes is 10^3 times shorter**
- **Confirmed by simulations in the near-extremal limit** [Witek et al, PRD 2012]

Proca instability. Regge plane

- Instability is effective roughly for **any non-vanishing spin**!



- Depend **very mildly** on the fit coefficient and on the threshold
- $\tau_{Salpater}$ → timescale for accretion at the **Eddington limit**

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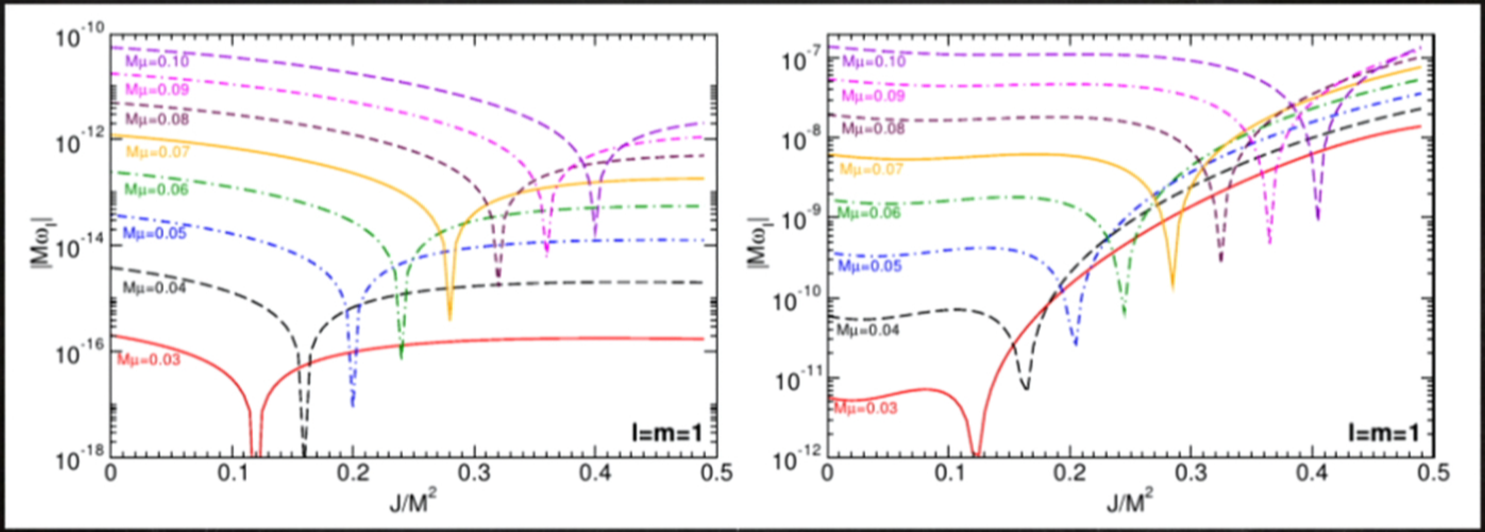

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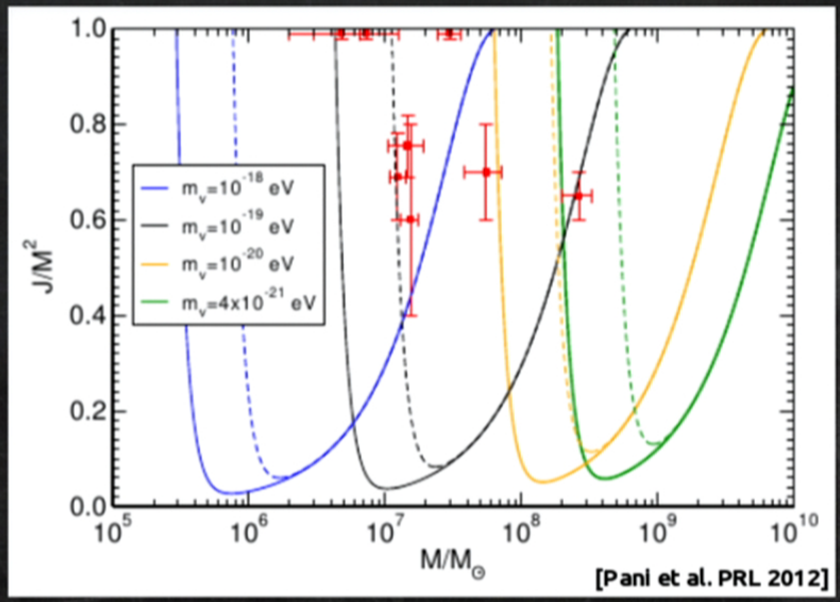

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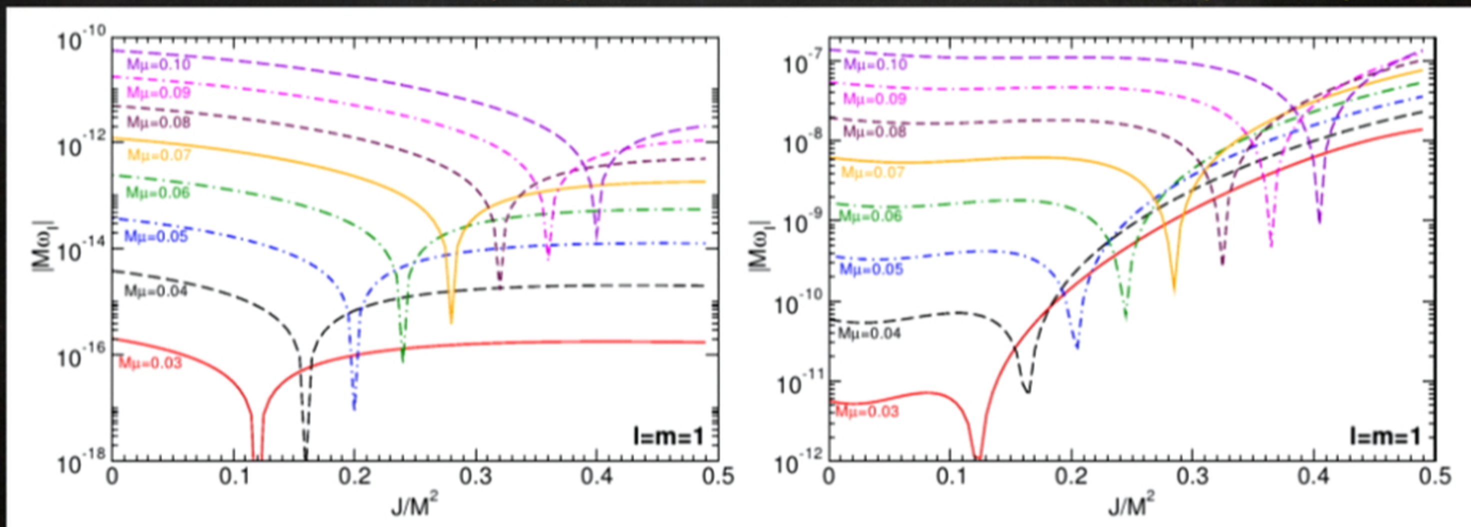

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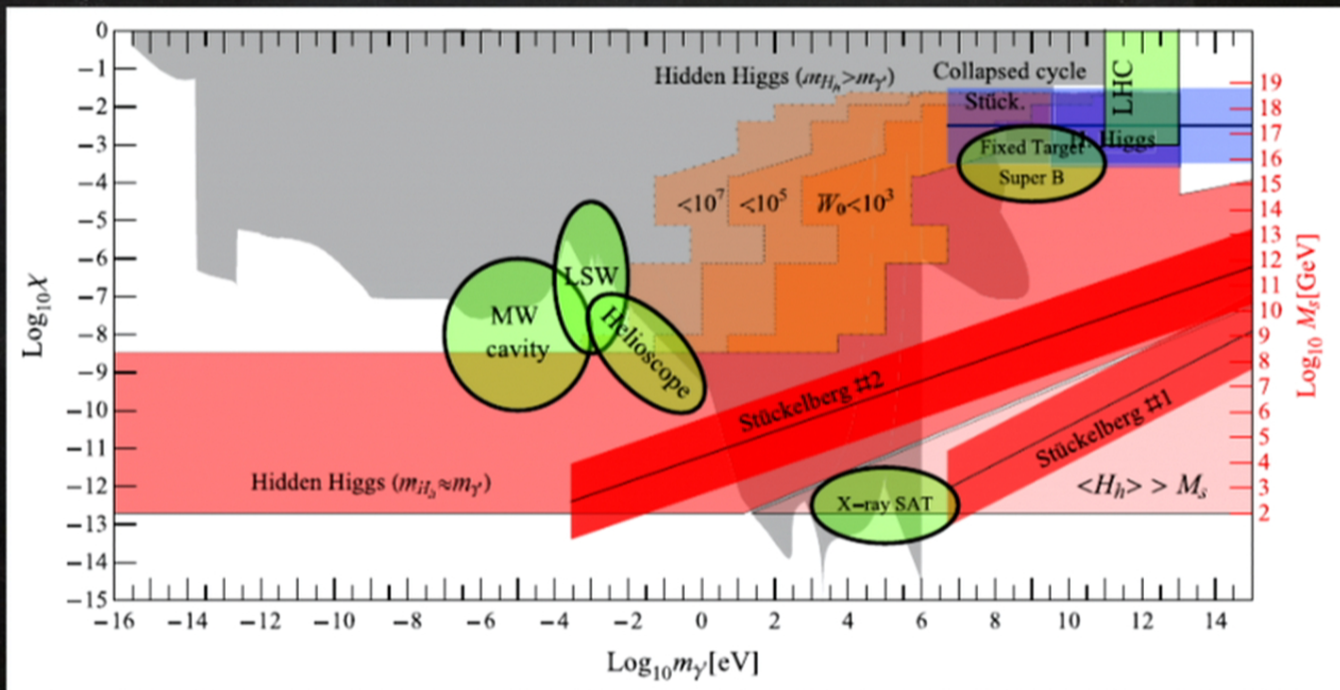

[Goodsell et al. 2009]

BH Bomb. *Limitations*

- **Nonlinear effects:**
  - Self-interaction → gradual slow down or bosenova?

[Kodama & Yoshino 2011-2012]

- **Accretion disks:**
  - Hidden bosons are weakly coupled to matter
  - Might be relevant for massive photons → plasma frequency
  - Superradiant mode are coherent and $\lambda \sim$ BH size
  - Disks are charge neutral and matter coupling incoherent
  - Equatorial disks can at most quench some unstable modes

Spin-2 and GL instability

[Babichev & Fabbri 2013]
[Brito, Cardoso, PP 2013]

$$\begin{cases} \bar{\Box} h_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu} h^{\alpha\beta} - \mu^2 h_{\mu\nu} = 0\,, \\ \mu^2 \bar{\nabla}^\mu h_{\mu\nu} = 0\,, \\ \left(\mu^2 - 2\Lambda/3\right) h = 0\,, \end{cases}$$

Extension of the Fierz-Pauli theory in curved background

[Hinterbichler' review 2012]

If Λ=0, equivalent to 5D black string where mass~ KK momentum

Gregory-Laflamme instability [Gregory & Laflamme 1993]

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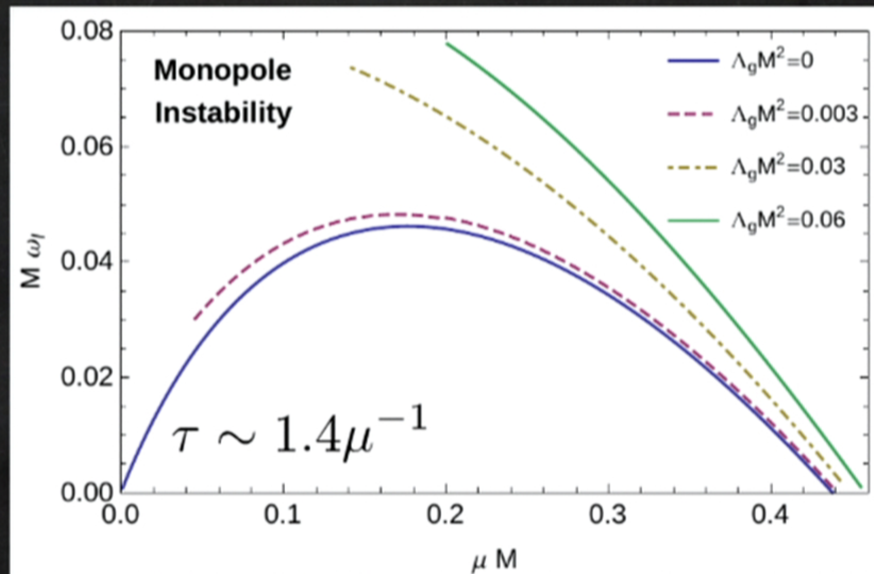


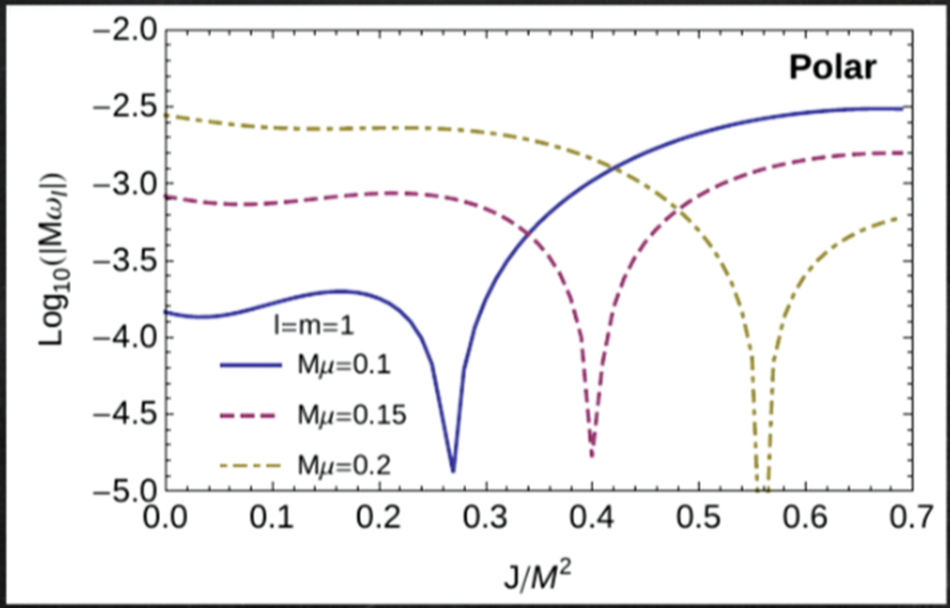
Nonlinear massive gravity, bimetric theories — De Rham et al. 2011; Hassan et al. 2011-2012

Any theory propagating a massive spin-2 field on a GR BH

GR BHs in Partially Massless gravity seem stable — Deser et al. '80-2013

BHs and massive gravitons

[Brito, Cardoso, PP 2013]

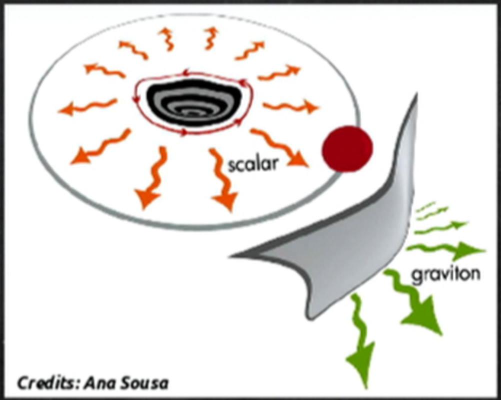


$$\tau_{\text{graviton}} = \omega_I^{-1} \sim \frac{M(M\mu)^{-3}}{\gamma_{\text{polar}}(\tilde{a} - 2r_+\omega_R)}$$

Reliable for large spin? Nonlinear effects?

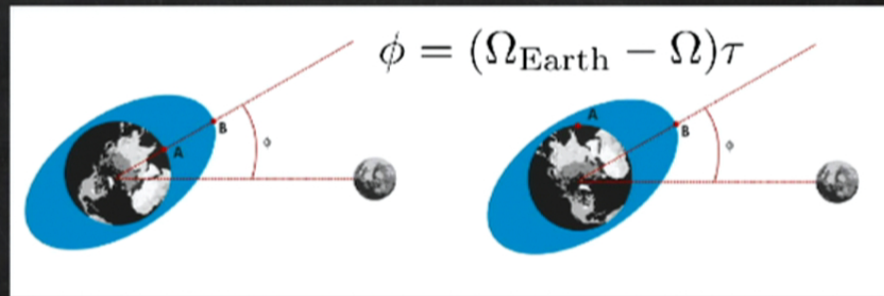
Part II

Light bosons & EMRIs



Tidal acceleration

[Cardoso & Pani, 2012]



$$\dot{E}_{\rm orbital} = 3G\kappa m_p^2 \frac{R^5}{r_0^6}\Omega(\Omega_{\rm Earth} - \Omega)\tau$$

[review: Hut , 1981 - Verbunt, 2007]

Dissipation at the BH horizon is much simpler (one-way membrane)

$$\tau \sim R/c \sim GM/c^2 \longrightarrow \dot{E}_{\rm H} \sim \frac{G^7}{c^{13}}\frac{M^6 m_p^2}{r_0^6}\Omega(\Omega - \Omega_{\rm BH}) < 0$$

Light-crossing time

Agrees with BH perturbations

Hartle, [1973-1974]
Poisson [1998]

Tidal acceleration ↔ BH superradiance

BHs can be spun down → small companion spirals outwards?

Tidal acceleration

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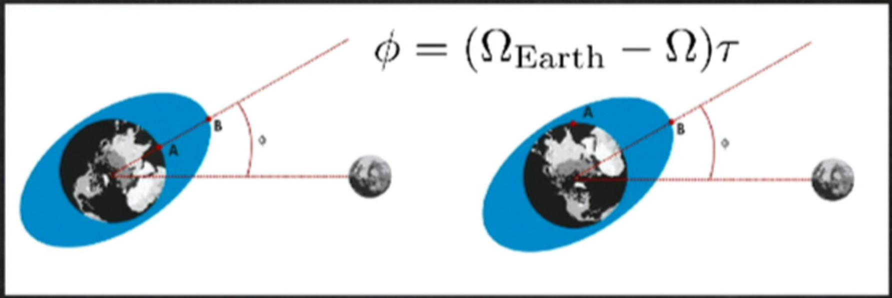

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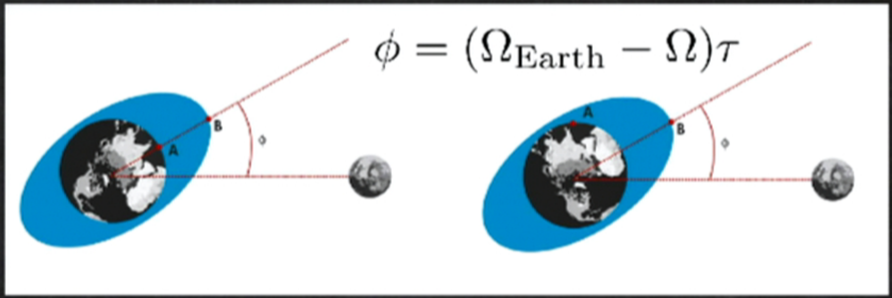

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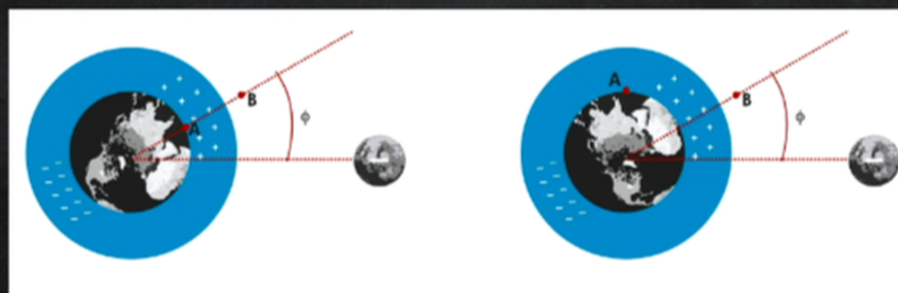
Tidal acceleration

[Cardoso & Pani, 2012]

GW emission to infinity dominates

$$\frac{\dot{E}_{\rm H}}{\dot{E}_\infty} = \left(\frac{GM}{c^2 r_0}\right)^3 \frac{r_0^2\Omega}{c^2}(\Omega - \Omega_{\rm BH}) \sim (v/c)^5 \ll 1$$

For scalar or EM fields: "Dipolar tidal acceleration"



However, still emission at infinity (Larmor's formula) dominates:

$$\frac{\dot{E}_{\rm H}}{\dot{E}_\infty} = \frac{3\pi\epsilon_0 G^4}{c^6}\frac{M^4}{r_0^6\Omega^3}(\Omega - \Omega_{\rm BH}) \sim (v/c)^3$$

Can BHs dissipate more than they emit?

YES, in two cases:

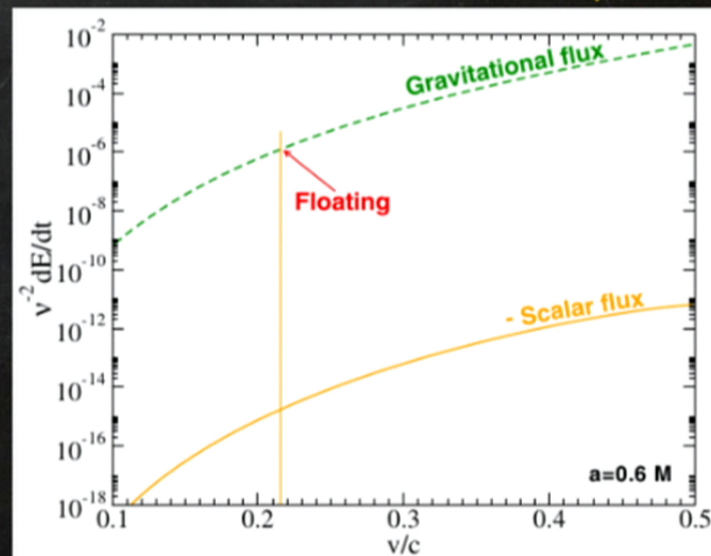
- D>5 → even in pure GR — Brito, Cardoso, Pani, PRD 2012
- D=4, if matter has sufficient structure: $\left[\Box - \mu_s^2\right]\varphi = \alpha \mathcal{T}$
  - Massive light bosons
  - Resonances at $\Omega_p \sim \mu_s$
  - Tiny resonance width $\sim \mu_s^9$

$$\dot{E}_S^{\rm resonance} \sim -\mu_s^{1-4l/3} \sim -v^{-4l+3}$$

$$dE_p/dt = -\dot{E}_{\rm total} = -(\dot{E}_S + \dot{E}_G)$$

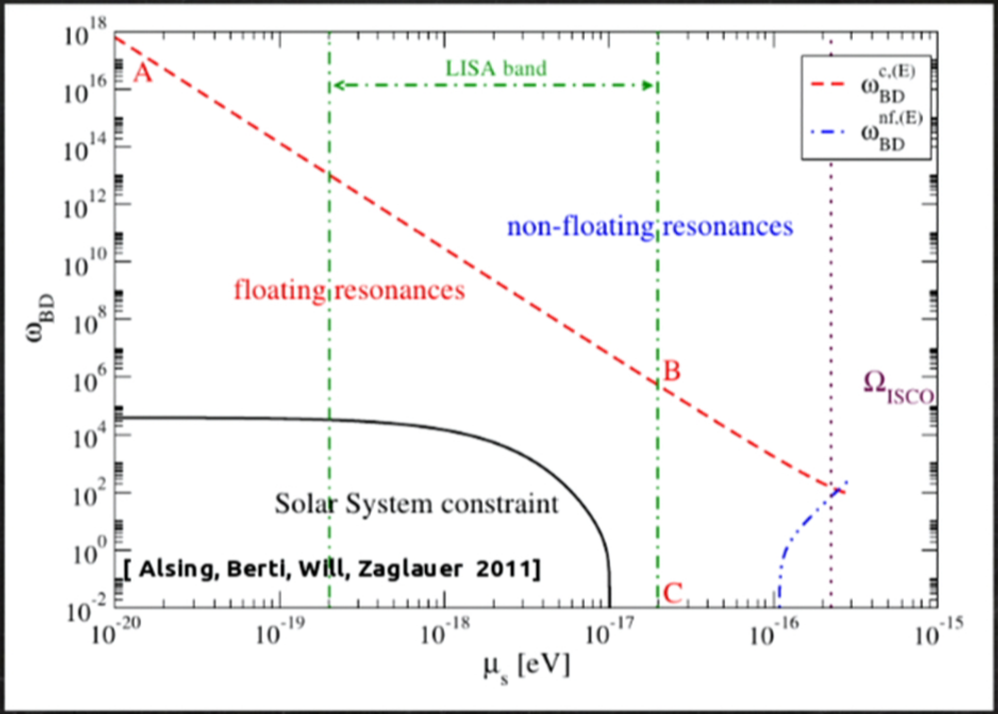
$$\text{if } \dot{E}_S = -\dot{E}_G \Longrightarrow \dot{E}_p = 0$$

Cardoso et al., PRL 2011



Resonances in generic scalar-tensor theories

Observing floating orbits?



Yunes, PP, Cardoso, PRD 2012

$M=10^5\ M_\odot$

Spin~0.6

ST theories other than BD theory are poorly constrained by current observations

Massive BD, generic ST, quadratic f(R), ...

Floating orbits. *Limitations*

- Eccentric orbits
- Nonequatorial orbits
- Finite-size effects
- Spin effects

Part III

BH scalarization in scalar-tensor theories

BHs in scalar-tensor gravity

In **electrovacuum**, stationary, asymptotically flat BHs in ST theories of gravity are described by the **Kerr-Newman family, just as in GR**.

Hawking, 1972

Sotiriou & Faraoni, PRL 2012

$$S = \int d^4x\sqrt{-g^E}\left(\frac{R^E}{16\pi} - \frac{1}{2}g^E_{\mu\nu}\partial^\mu\Phi\partial^\nu\Phi - \frac{V(\Phi)}{16\pi}\right) + S_m(\Psi_m; A(\Phi)^2 g^E_{\mu\nu})$$

BHs surrounded by matter are forced to develop scalar hairs

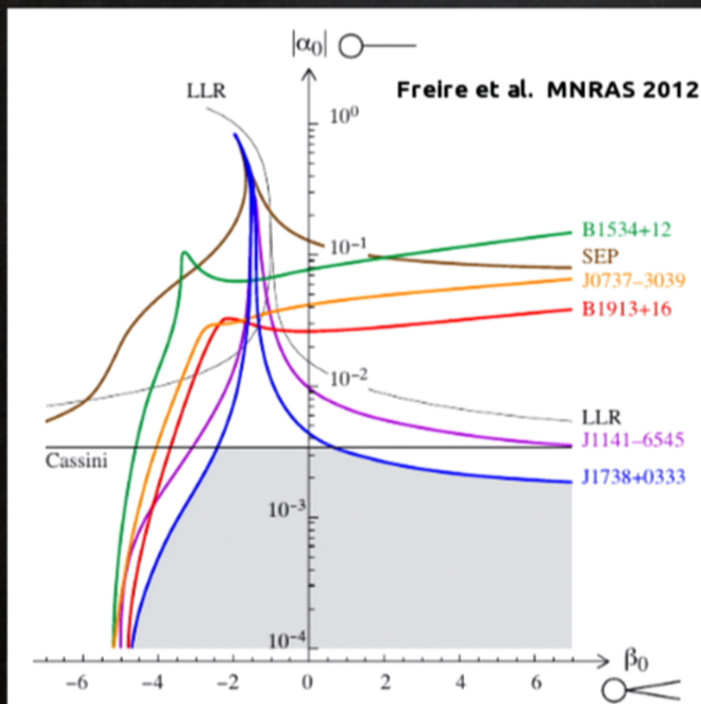
$$\Box^E\Phi = -\frac{A'(\Phi)}{A(\Phi)}T^E + \frac{V'(\Phi)}{16\pi}$$

Exception: if A' = 0 → GR solutions persist in ST gravities

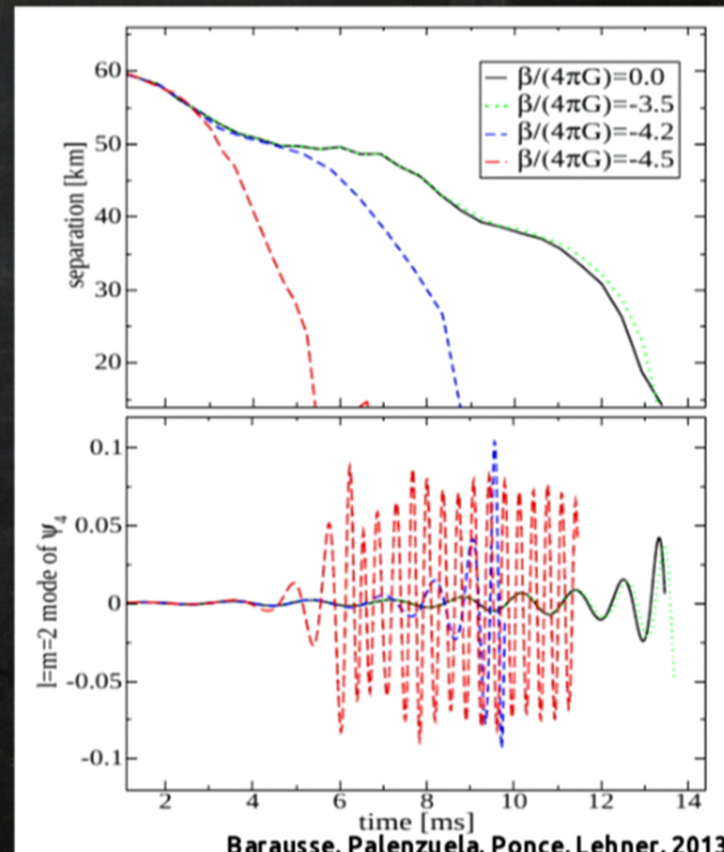
Spontaneous scalarization in NSs

Damour & Esposito-Farese '90

GR solutions are not always entropically favored



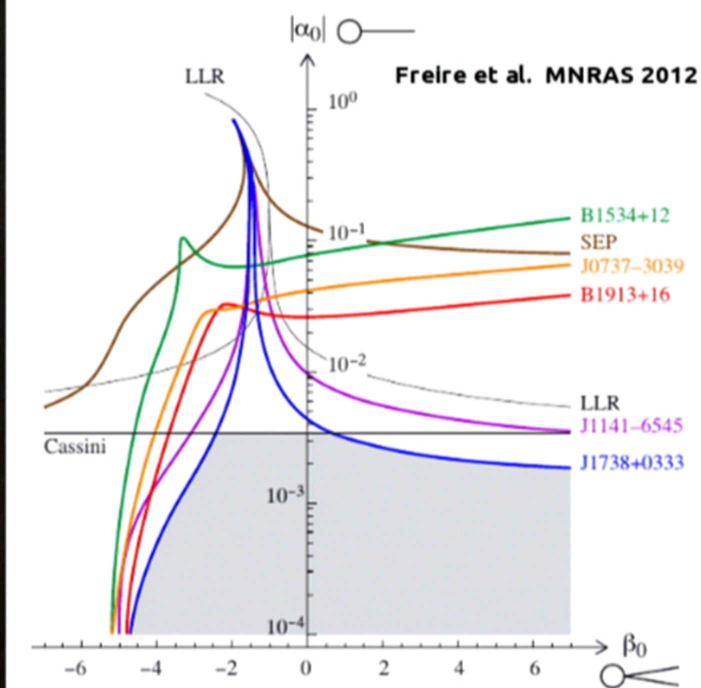
NS-NS binaries



Spontaneous scalarization in NSs

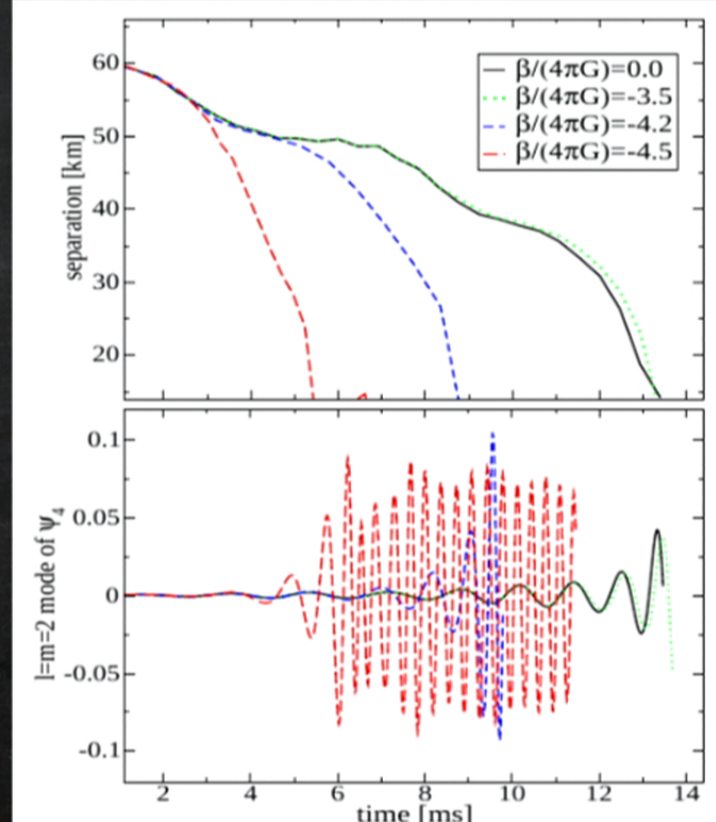
Damour & Esposito-Farese '90

GR solutions are not always entropically favored



Freire et al. MNRAS 2012

NS-NS binaries



Barausse, Palenzuela, Ponce, Lehner, 2013

Summary

- **Spinning BHs as labs** for exotic particles and modified gravity
- Perturbation theory of rotating objects is **challenging**
- **Instability of light massive bosons around Kerr BHs in GR**
  - Bounds on the boson mass and on extensions to the standard model
  - Bounds on massive gravitons and insights on massive gravity theories
- **Smoking guns of weakly-interacting scalar fields:**
  - Gap in the spin-mass plane → **lack of highly spinning BHs?**
  - Floating orbits around supermassive BHs → **monocromatic GW sources?**
  - Spontaneous scalarization of BH surrounded by matter → **dipole moments?**
  - Huge superradiant amplification → **observational effects?**