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Black holes & Stars as particle detectors

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Belém, May 12

IDPASC

FUNDAÇÃO CALOUSTE GULBENKIAN

More info at http://blackholes.ist.utl.pt

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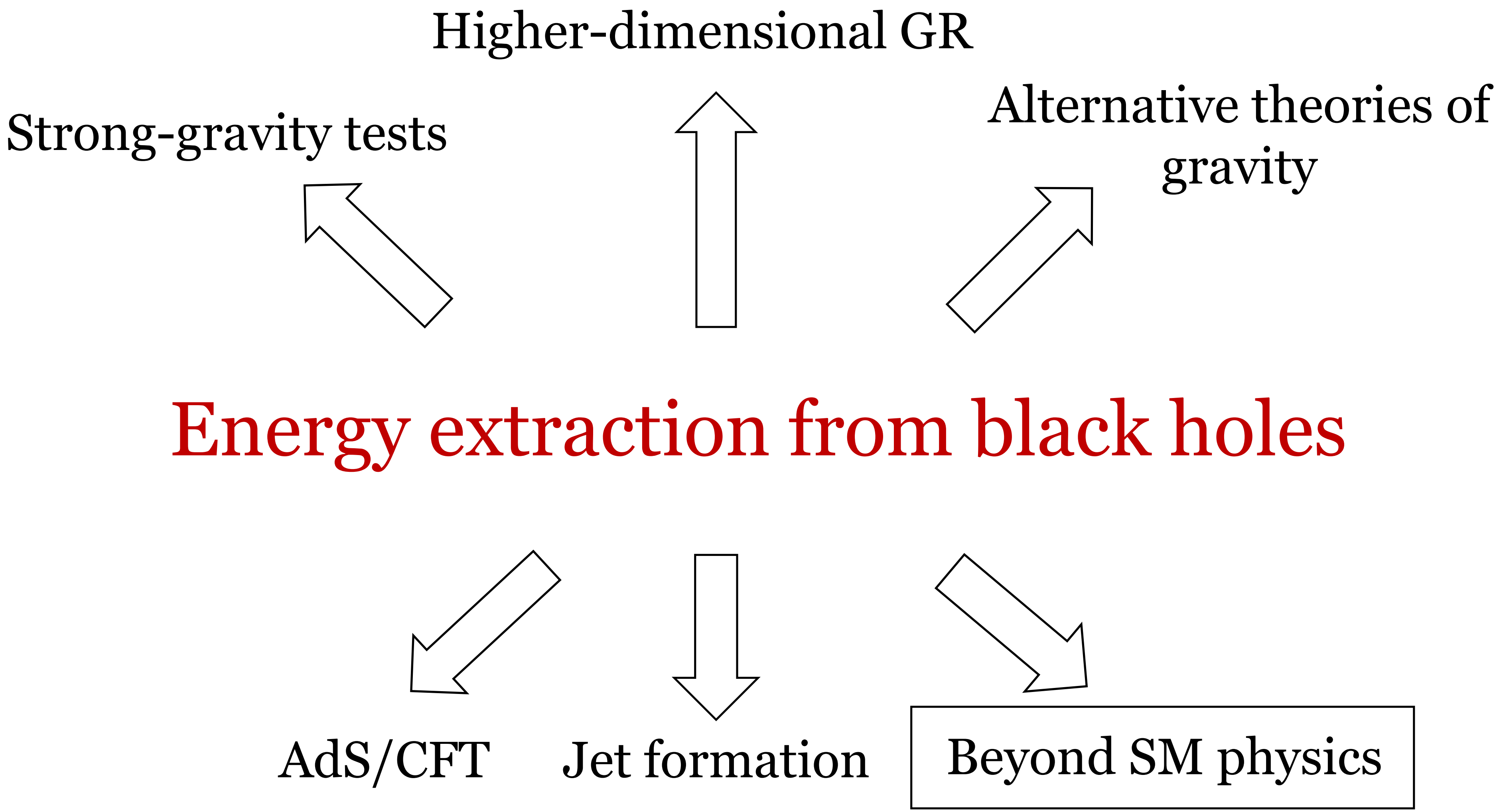
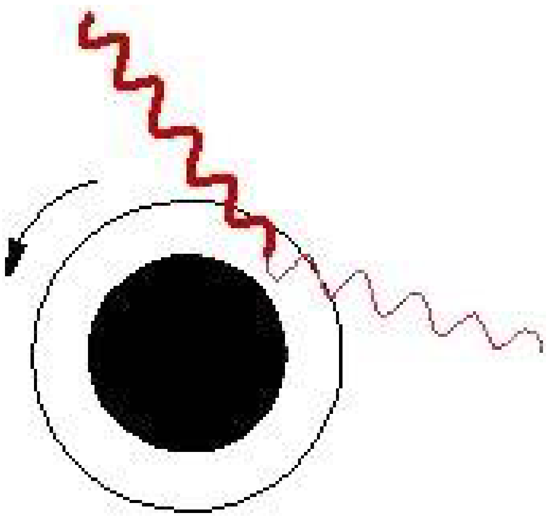


Brito, Cardoso & Pani, Superradiance, “Lecture notes in Physics”,
Springer-Verlag, to be published, arXiv: 1501.06570

Energy extraction from black holes: Superradiance

Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74

$$\Phi = \Psi(r) e^{-i\omega t + im\varphi} S_l(\vartheta)$$



$$\frac{\omega}{m} < \Omega_H$$

$\Downarrow$

amplified scattering of waves

$\Downarrow$

Extraction of energy and angular momentum from the BH

Requires dissipation $\longrightarrow$ Event horizon

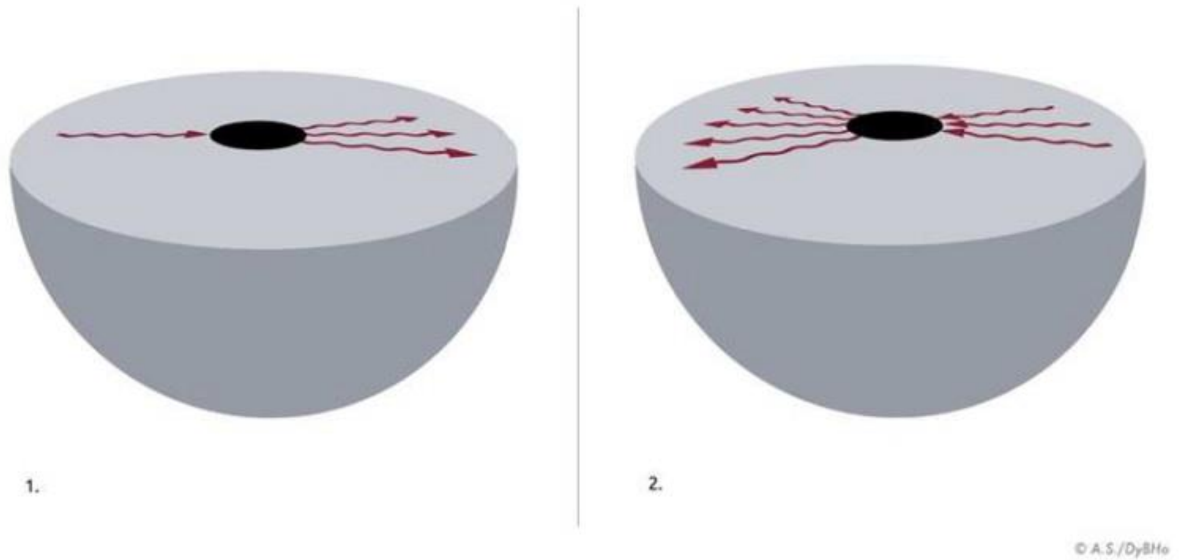
Superradiant instability

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

Confinement + superradiance

↓

Black hole bomb



Credit: Ana Sousa

$$\Phi \sim e^{-i\omega t}$$

$$\omega = \omega_R + i\omega_I$$

Massive bosonic fields

Detweiler , PRD22 (1980) 2323, Pani *et al*, PRD86 (2012) 104017, Witek *et al*, PRD87 (2013) 043513, Brito, Cardoso & Pani, PRD88 (2013) 023514

- Massive scalar field $$\Box\Phi - \mu_S^2\Phi = 0$$
- Massive vector field $$\begin{cases} \Box A_\nu - R_{\nu\mu}A^\mu - \mu_V^2 A_\nu = 0\,, \\ \mu_V^2 \nabla^\mu A_\mu = 0\,. \end{cases}$$
- Massive tensor field $$\begin{cases} \Box h_{\mu\nu} + 2R_{\alpha\mu\beta\nu}h^{\alpha\beta} - \mu_T^2 h_{\mu\nu} = 0\,, \\ \mu_T^2 \nabla^\mu h_{\mu\nu} = 0\,, \\ \left(\mu_T^2 - 2\Lambda/3\right) h = 0\,. \end{cases}$$

$$\Psi \sim e^{-i\omega t} \qquad \omega = \omega_R + i\omega_I$$

All modes follow:

$$\begin{aligned} \omega_R^2 \sim \quad &\sim \quad \mu^2\left[1 - \left(\frac{M\mu}{l+n+S+1}\right)^2\right] \\ M\omega_I \quad &\sim \quad \gamma_{Sl}\,(ma/M - 2r_+\mu)\,(M\mu)^{4l+5+2S} \end{aligned}$$

Except for the massive tensor $l = m = 1$ (polar)

$$\begin{aligned} \omega_R/\mu \quad &\sim \quad 0.72(1 - M\mu) \\ M\omega_I \quad &\sim \quad (ma/M - 2r_+\omega_R)\,(M\mu)^3 \end{aligned}$$

Signatures

- Significant for **primordial BHs** and **SM particles** or **SMBHs** and **ultralight particles**.

- **Complex fields**: stationary hairy BHs with $\frac{\omega}{m} = \Omega_H$ (Hod Phys.Rev. D86 (2012) 104026; Herdeiro & Radu, Phys.Rev.Lett. 112 (2014) 221101)

  Real fields: ultralong-lived states

- "Gravitational wave pulsar" – long-lived scalar and gravitational signals. (Arvanitaki *et al*, Phys.Rev. D81 (2010) 123530 , Arvanitaki & Dubovsky Phys.Rev. D83 (2011) 044026, Okawa, Witek & Cardoso Phys. Rev. D89 (2014) 104032)

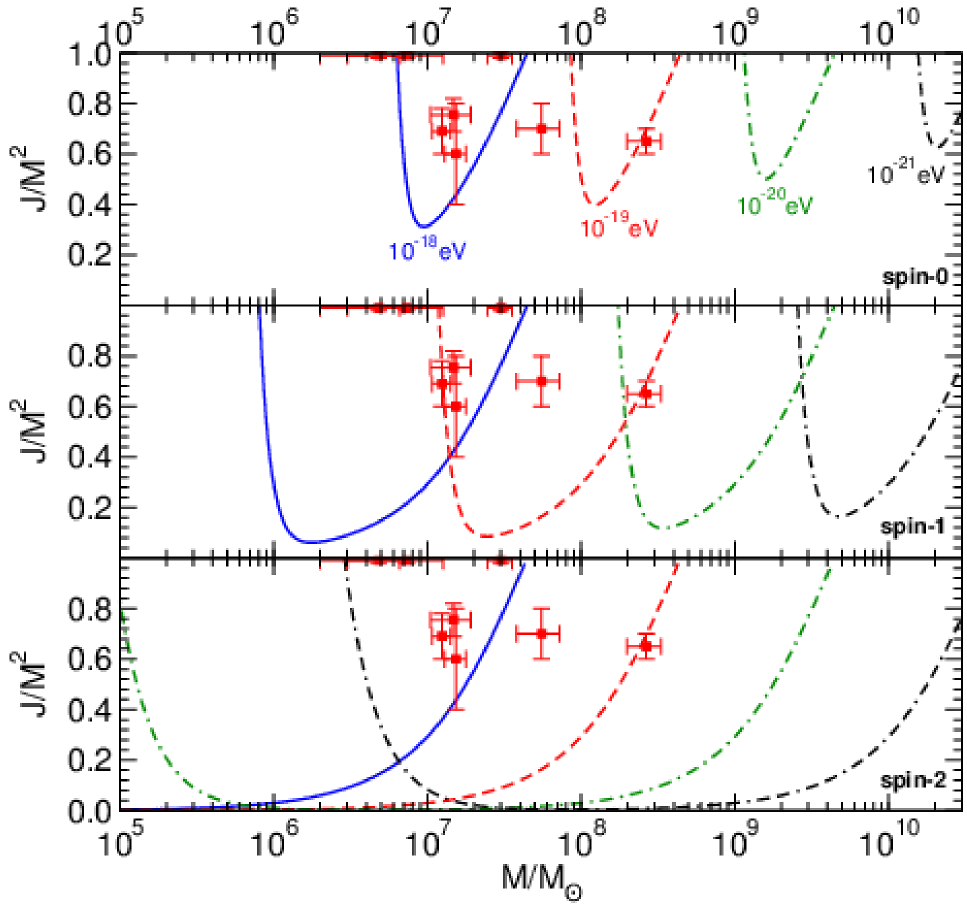
- Gaps in the BH's spin vs mass plane (a.k.a 'Regge' plane) – constraints on the field's mass. (Arvanitaki & Dubovsky Phys.Rev. D83 (2011) 044026, Brito, Cardoso, Pani, arXiv:1411.0686, 2014)

Bounds on light bosons

Arvanitaki & Dubovsky Phys.Rev. D83 (2011) 044026 , Pani *et al*, Phys.Rev.Lett. 109 (2012) 131102, Phys.Rev. D86 (2012) 104017, Brito, Cardoso & Pani, Phys.Rev. D88 (2013) 023514

$$\tau_{\rm ins} \approx \tau_{\rm ACC}$$

$$\tau_{\rm ACC} \sim 4.5 \times 10^7 {\rm yr}/f_{\rm Edd}$$



$$M_\odot \lesssim M \lesssim 10^9 M_\odot \quad \Longrightarrow \quad \begin{array}{lcl} m_S \lesssim 5\times 10^{-20}{\rm eV} & \cup & m_S \gtrsim 10^{-11}{\rm eV} \\ m_V \lesssim 5\times 10^{-21}{\rm eV} & \cup & m_V \gtrsim 10^{-11}{\rm eV} \\ m_T \lesssim 5\times 10^{-23}{\rm eV} & \cup & m_T \gtrsim 10^{-11}{\rm eV} \end{array}$$

Bounds on the graviton mass

Brito, Cardoso & Pani, Phys.Rev. D88 (2013) 023514
Babichev & Brito, Review article, arXiv: 1503.07529

For some specific BH solutions of massive gravity:

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

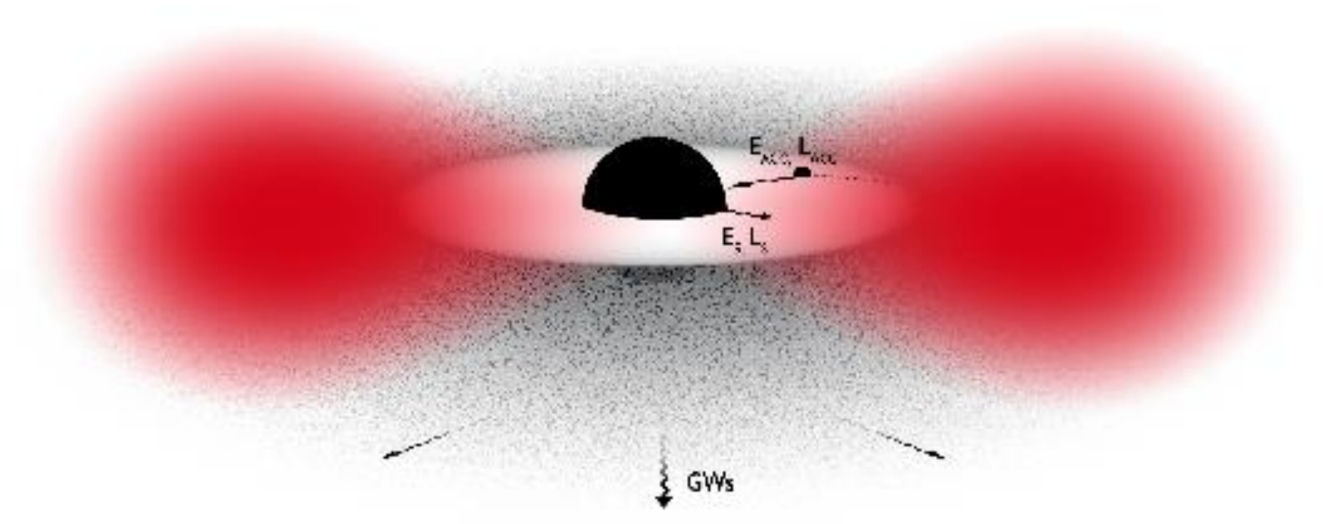
Gravitons interact very weakly.

Review of Particle Physics 2014 (PDG 2014)

VALUE (eV)	*DOCUMENT ID*		*COMMENT*
$<6 \times 10^{-32}$	[1] CHOUDHURY	04	Weak gravitational lensing
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<5 \times 10^{-23}$	[2] BRITO	13	Spinning black holes bounds
$<4 \times 10^{-25}$	[3] BASKARAN	08	Graviton phase velocity fluctuations
$<6 \times 10^{-32}$	[4] GRUZINOV	05	Solar System observations
$>6 \times 10^{-34}$	[5] DVALI	03	Horizon scales
$<8 \times 10^{-20}$	[6,7] FINN	02	Binary pulsar orbital period decrease
	[7,8] DAMOUR	91	Binary pulsar PSR 1913+16
$< 2 \times 10^{-29}\ h_0^{-1}$	GOLDHABER	74	Rich clusters
$<7 \times 10^{-28}$	HARE	73	Galaxy
$<8 \times 10^{4}$	HARE	73	2γ decay

Non-linear effects?
Expected to be negligible

Gravitational-wave emission and accretion?



Credit: Ana Sousa

$$\tau_{\rm ins} \sim M/(M\mu)^9$$

Evolution of the instability

Brito, Cardoso, Pani, arXiv:1411.0686, 2014 (CQG Focus Issue)

- Accretion:

$$\dot{M}_{\rm ACC} \equiv f_{\rm Edd}\dot{M}_{\rm Edd} \sim 0.02 f_{\rm Edd}\frac{M(t)}{10^6 M_\odot} M_\odot {\rm yr}^{-1}$$

$$\dot{J}_{\rm ACC} \equiv \frac{L_{\rm ISCO}(M,J)}{E_{\rm ISCO}(M,J)}\dot{M}_{\rm ACC}$$

- GW emission:

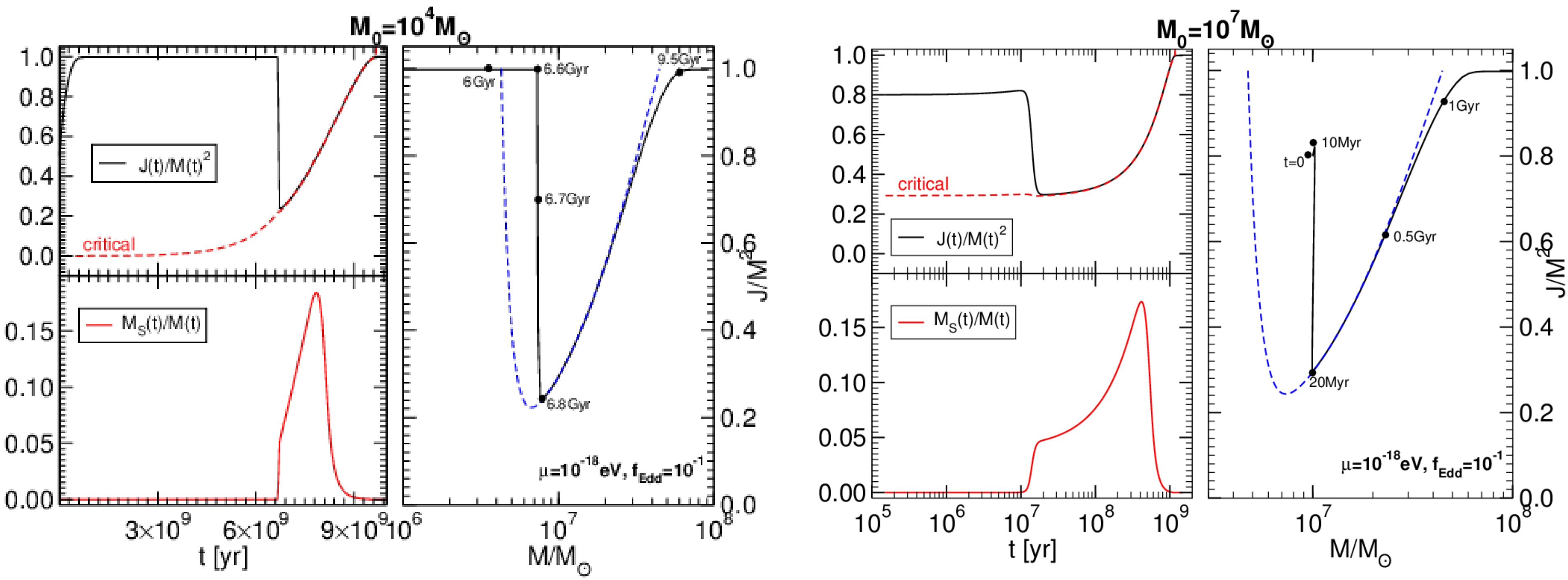
$$\dot{E}_{\rm GW} = \frac{484+9\pi^2}{23040}\left(\frac{M_S^2}{M^2}\right)(M\mu)^{14} \qquad \dot{J}_{\rm GW} = \frac{1}{\omega_R}\dot{E}_{\rm GW}$$

- Scalar energy flux:

$$\dot{E}_S = 2M_S\omega_I \qquad M\omega_I = \frac{1}{48}(a/M - 2\mu r_+)(M\mu)^9$$

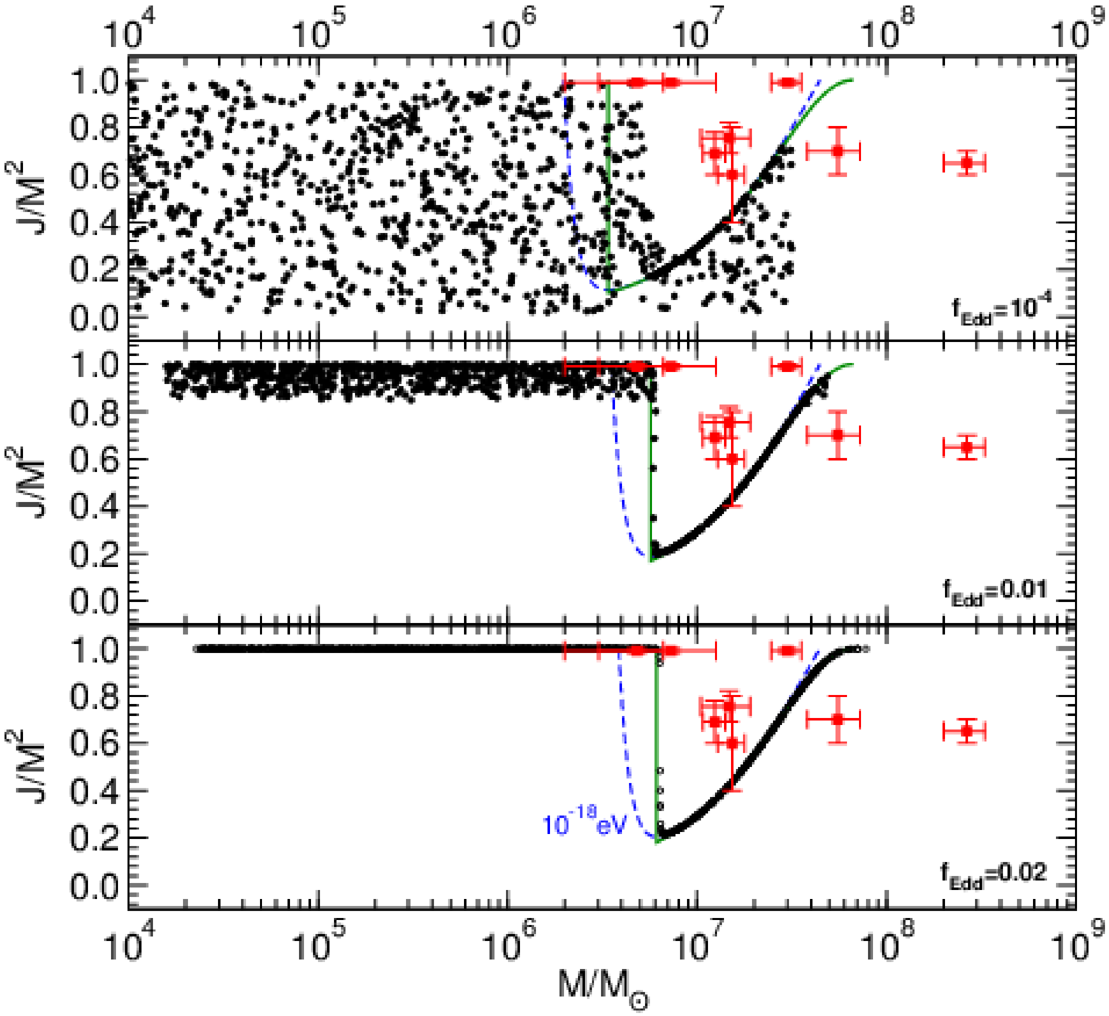
Evolution of the instability

Brito, Cardoso, Pani, arXiv:1411.0686, 2014 (CQG Focus Issue)



Gaps in the 'Regge' plane

Brito, Cardoso, Pani, arXiv:1411.0686, 2014 (CQG Focus Issue)

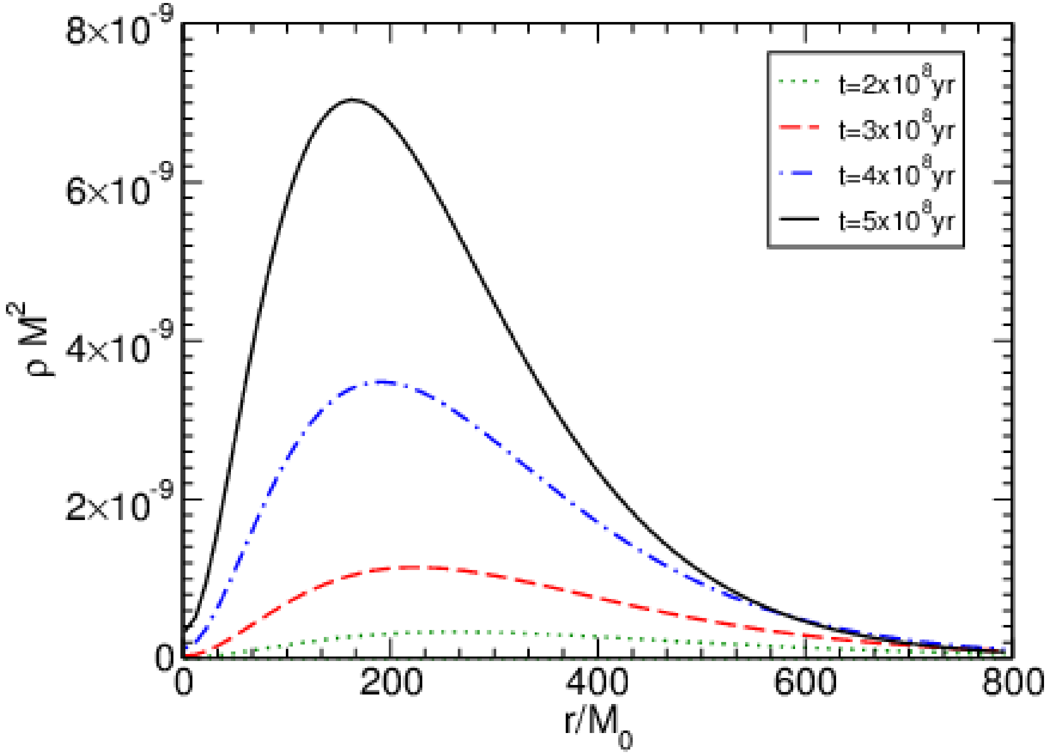


Random distributions of the initial BH mass between $\log_{10} M_0 \in [4, 7.5]$ and $J_0/M_0^2 \in [0.001, 0.99]$ extracted at $t = t_F$, where t_F is distributed on a Gaussian centered at $\bar{t}_F \sim 2 \times 10^9$yr with width $\sigma = 0.1\bar{t}_F$.

(Long-lived) hairy black holes?

Brito, Cardoso, Pani, arXiv:1411.0686, 2014;
Herdeiro & Radu, Phys.Rev.Lett. 112 (2014) 221101

Cloud is localized at: $r_{\rm cloud} \sim M/(M\mu)^2 \gg 2M$



$$\rho \equiv -T^0_0\,, \qquad T^{\mu\nu} = \Psi^{*,(\mu}\Psi^{,\nu)} - \frac{1}{2}g^{\mu\nu}\left(\Psi^*_{,\alpha}\Psi^{,\alpha} + \mu^2\Psi^*\Psi\right)$$

Kerr geometry is a very good approximation (for BHs grown out of Kerr).

Superradiance in stars

Cardoso, Brito & J.L.Rosa, submitted

$$\Box\Phi + \boxed{\alpha\frac{\partial\Phi}{\partial t}} = \mu^2\Phi$$

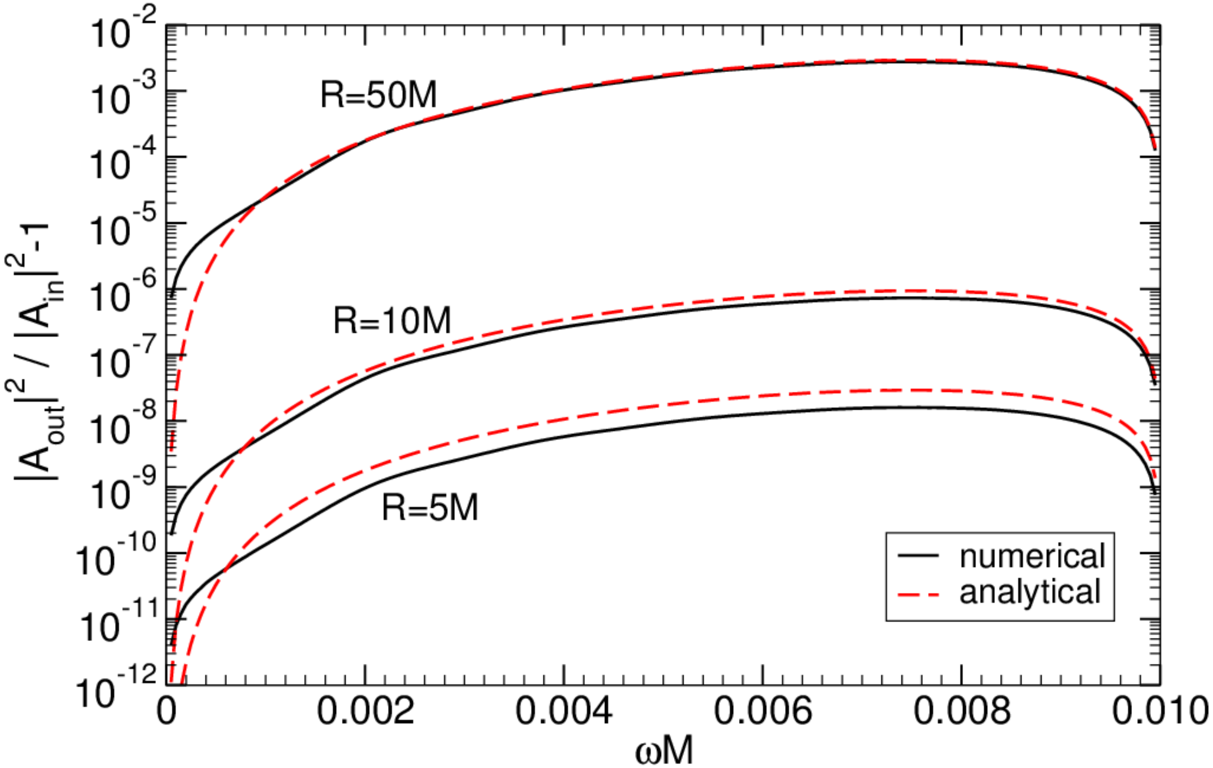
$$\Downarrow$$

Phenomenological approach: Dissipation breaks Lorentz invariance

$$\alpha = \frac{1}{\ell} = n\sigma \qquad M\alpha = \frac{GM}{c^2}\frac{\rho\sigma}{m_N} \sim 0.92\,\frac{\rho}{10^{15}\,\mathrm{Kg\,m}^{-3}}\frac{M}{M_\odot}\frac{\sigma}{10^{-41}\,\mathrm{cm}^2}$$

$$\Phi(t,r,\vartheta,\varphi) = \frac{\Psi(r)}{r}e^{-i\omega t+im\varphi}P_l(\cos\vartheta)$$

$$\varphi_{\rm iner} = \varphi_{\rm corr} - \Omega t \quad \Longrightarrow \quad \omega' = \omega - m\Omega$$

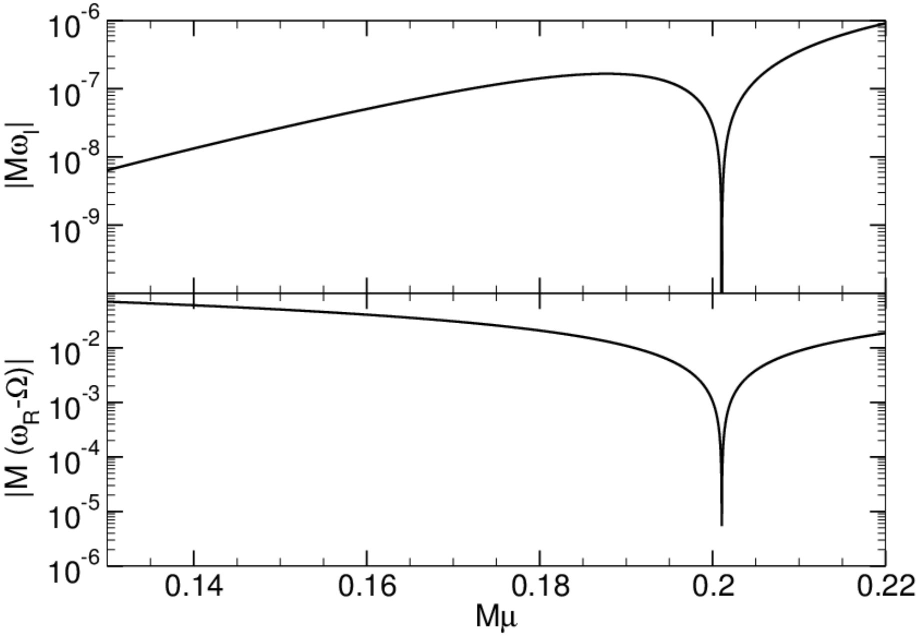


$$\mu = 0$$
$$M\alpha = 0.1$$
$$M\Omega = 0.01$$

$$\Psi = A_{\rm out} e^{i\omega r} + A_{\rm in} e^{-i\omega r}$$

$$\frac{|A_{\rm out}|^2}{|A_{\rm in}|^2} - 1 = \frac{4\alpha R \left(R\Omega - \omega R\right)\left(\omega R\right)^{2l+1}}{(2l+1)!!(2l+3)!!}$$

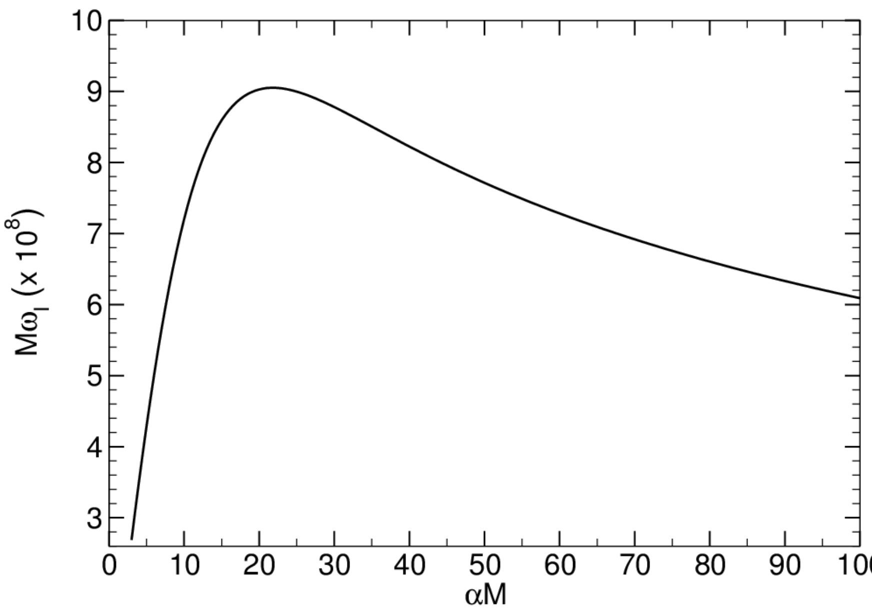
$$R \sim 2M \text{ and } 1/\alpha = M \quad \Longrightarrow \quad \frac{|A_{\rm out}|^2}{|A_{\rm in}|^2} - 1 = \frac{16}{45} M \left(\Omega - \omega\right)\left(2M\omega\right)^3$$



$$M\Omega = 0.2$$
$$R/M = 4$$
$$M\alpha = 20$$

$$\omega_R \sim \mu$$
$$\omega_I \propto (\omega_R - m\Omega)(M\mu)^{9\pm 2}$$

For small $M\alpha$, $\omega_I \propto \alpha$.



$$M\mu = 0.17$$

Conclusions

- Black holes are unique labs for beyond-SM physics and extensions of GR;
- Superradiant instabilities provide strong constraints on ultralight bosonic degrees of freedom;
- Compact stars with dissipative channels may be interesting probes for beyond-SM physics.

Thank you

Backup Slides

Black holes in a box: a simple model

Brito, Cardoso & Pani, Phys.Rev. D89 (2014) 104045

- Modes supported by the box: $\omega_R \sim 1/r_m$
- Absorption probability at the horizon: Starobinski '73

$$|\mathcal{A}|^2 = 4\pi \left(\frac{M\omega_R}{2}\right)^{2+2l} \frac{\Gamma^2[1+l+s]\Gamma^2[1+l-s]}{\Gamma^2[1+2l]\Gamma^2[l+3/2]} \sim (M/r_m)^{2l+2} \ll 1$$

- After N reflections the amplitude of the wave is:

$$A(t) = A_0\left(1-|\mathcal{A}|^2\right)^N \sim A_0\left(1-N|\mathcal{A}|^2\right) = A_0\left(1-t|\mathcal{A}|^2/r_m\right)$$

$$\Updownarrow$$

$$A(t) \sim A_0 e^{-|\omega_I|t} \sim A_0(1-|\omega_I|t) \implies M\omega_I \sim -(M/r_m)^{2l+3}$$

$$\Downarrow \text{ Rotation}$$

$$\omega_R^{2l+2} \to (\omega_R - m\Omega_H)\omega_R^{2l+1}$$

For any confined geometry! (Box, AdS, Ernst, …)

An incomplete list of open issues

- Fundamental bound on superradiant amplification?
- Energy extraction from BH binaries (even if the individual BHs are non-spinning)?
- Induced superradiance for fermions coupled to bosons? Self-interactions? Non-linear couplings?
- Backreaction of superradiant waves on the metric (only recently studied fully non-linearly (East, Ramazanoglu & Pretorius PRD89 (2014) 061503)).
- Superradiance for non-axisymmetric spacetimes.
- Superradiance & accretion disks.
- Energy extraction from BHs (e.g. Blandford-Znajek mechanism) and formation of jets.

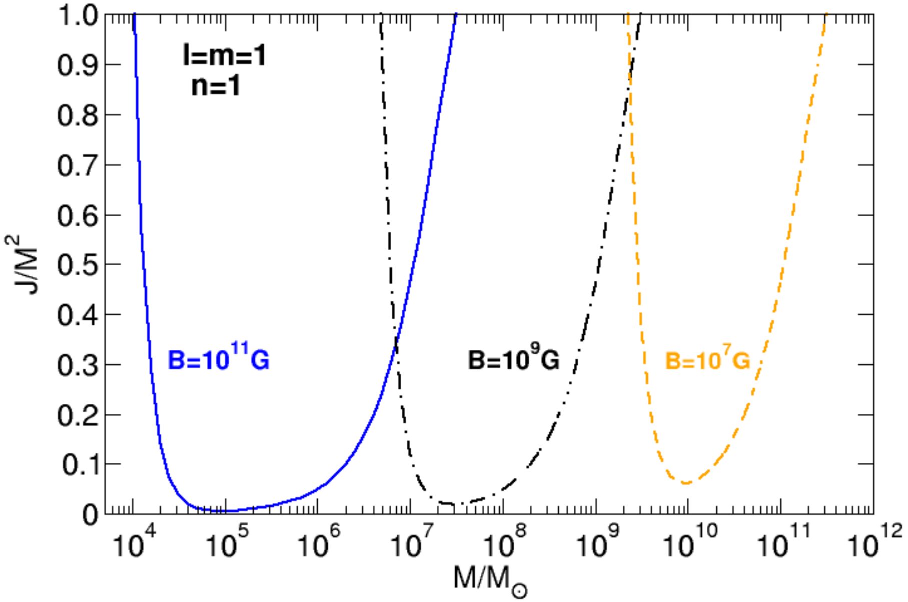
Where do we stand?

- Massive scalar fields around BHs (Damour et al '76; Zouros & Eardley '79; Detweiler '80; Cardoso & Yoshida '05; Dolan '07; Berti et al '09; Konoplya et al '06; Pani et al '12; Hod '12; Barranco et al '13; Strafuss & Khanna '05; Kodama & Yoshino '12; Barranco et al '12; Dolan '12; Witek et al '12; ...*)*
- Proca fields around BHs (Rosa & Dolan '11; Pani *et al* '12; Witek *et al* '12*)*
- Massive gravitons (Brito, Cardoso & Pani, '13, Babichev & Fabbri, '13*)*
- BHs surronded by plasma – constraints on primoridal BHs as dark matter candidates (Pani & Loeb '13*)*
- Charged scalar in a RN BH background (Degollado & Herdeiro '13; Degollado, Herdeiro & Runarsson '13; Hod '13, Degollado & Herdeiro '13)
- Non-linear self-interactions ("Bosenova" particle bursts) (Yoshino & Kodama '14*)*
- Non-linear evolution of massive scalar fields around BHs (Okawa *et al* '14*)*
- Full non-linear study of gravitational BH superradiance (East '14*)*
- Magnetic fields around BHs (Gal'tsov & Pethukov '78; Konoplya '08; Brito, Cardoso & Pani, '14*)*
- BHs in Ads (Hawking & Reall '00; Cardoso & Dias '04; Dias *et al* '12; Cardoso *et al* '13*)*
- Kerr BHs with scalar hair (Hod '12; Herdeiro & Radu '14*)*

Other constraints

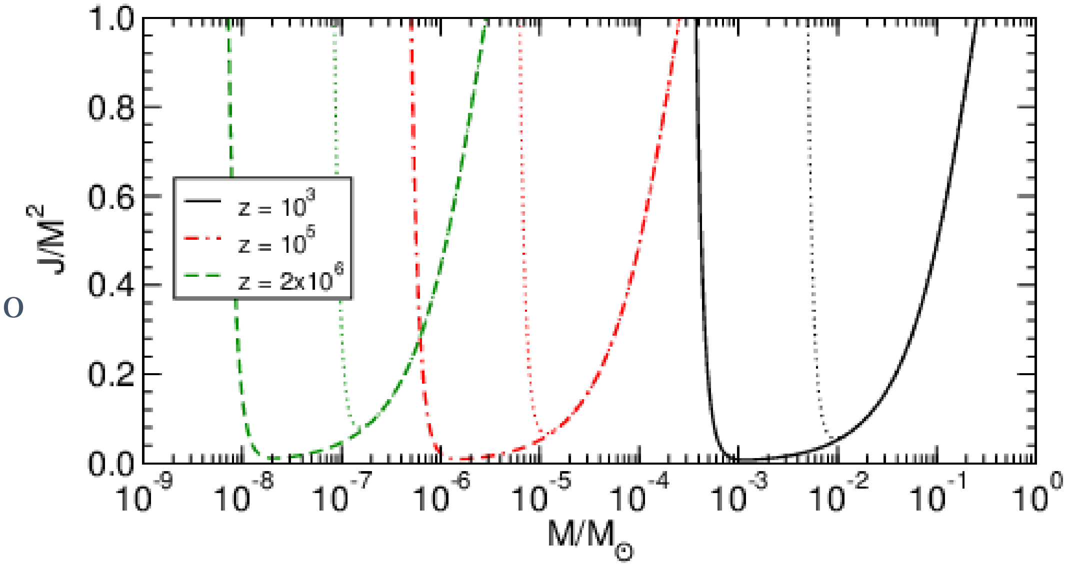
Magnetized BHs

Brito, Cardoso & Pani, Phys.Rev. D89 (2014) 104045



Primordial BHs surrounded by plasma

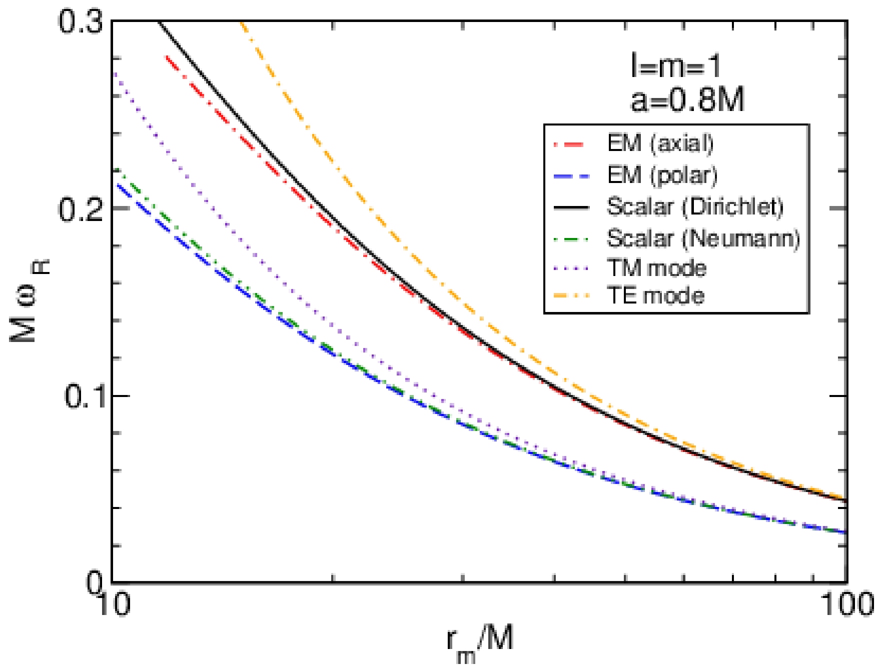
Pani & Loeb, Phys.Rev. D88 (2013) 04130

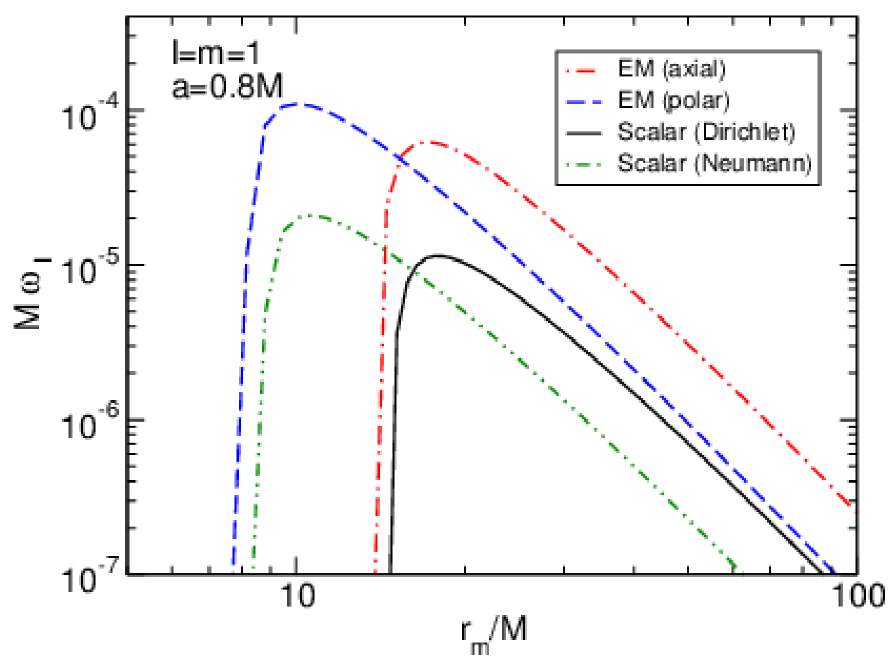


Black hole in a box

Cardoso *et al*, Phys.Rev. D70 (2004) 049903
Brito, Cardoso & Pani, Superradiance, Springer-Verlag, arXiv: 1501.06570

BH + perfectly reflecting spherical mirror





$$\omega_R \propto 1/r_m\,, \qquad M\omega_I \propto -(\omega_R - m\Omega_H)(M\omega_R)^{2l+2}$$

Evolution of the instability

Brito, Cardoso, Pani, arXiv:1411.0686, 2014

- Separation of scales allow us to use an adiabatic approximation (for $\mu M \ll 1$)
- Use linearized analysis for the superradiant instability (for a dipolar cloud localized at $r_{\rm cloud} \sim M/(M\mu)^2$)
- GW emission for a *stationary dipolar* cloud with frequency $\tilde{\omega} \sim 2\mu$
- Consider accretion at the Eddington rate for a disk extending up to the ISCO.

- Energy/angular momentum conservation:

$$\begin{aligned} \dot{M} + \dot{M}_S &= -\dot{E}_{\rm GW} + \dot{M}_{\rm ACC} \\ \dot{J} + \dot{J}_S &= -\frac{1}{\mu}\dot{E}_{\rm GW} + \dot{J}_{\rm ACC} \end{aligned}$$

- Superradiant extraction and accretion:

$$\begin{aligned} \dot{M} &= -\dot{E}_S + \dot{M}_{\rm ACC} \\ \dot{J} &= -\frac{1}{\mu}\dot{E}_S + \dot{J}_{\rm ACC} \end{aligned}$$

$$\dot{E}_S = 2M_S\omega_I$$

$$M\omega_I = \frac{1}{48}(a/M - 2\mu r_+)(M\mu)^9$$

$$\dot{E}_{\rm GW} \propto \left(\frac{M_S^2}{M^2}\right)(M\mu)^{14}$$

(Yoshino & Kodama, PTEP 2014 (2014) 043E02)

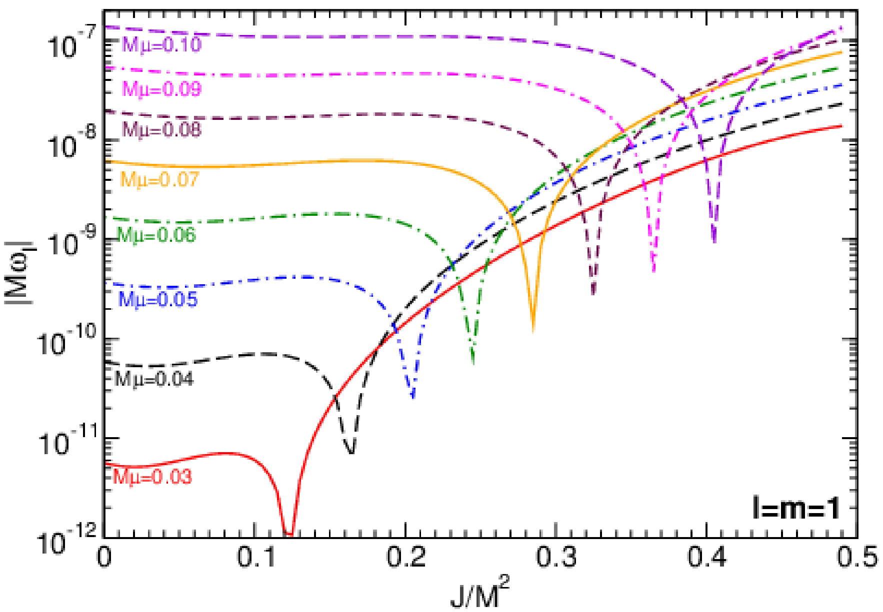
$$\dot{M}_{\rm ACC} \sim 0.02 f_{\rm Edd}\frac{M(t)}{10^6 M_\odot} M_\odot {\rm yr}^{-1}$$

$$\dot{J}_{\rm ACC} \equiv \frac{L(M,J)}{E(M,J)}\dot{M}_{\rm ACC}$$

(Bardeen, Nature (1970) Vol 226 pp 64)

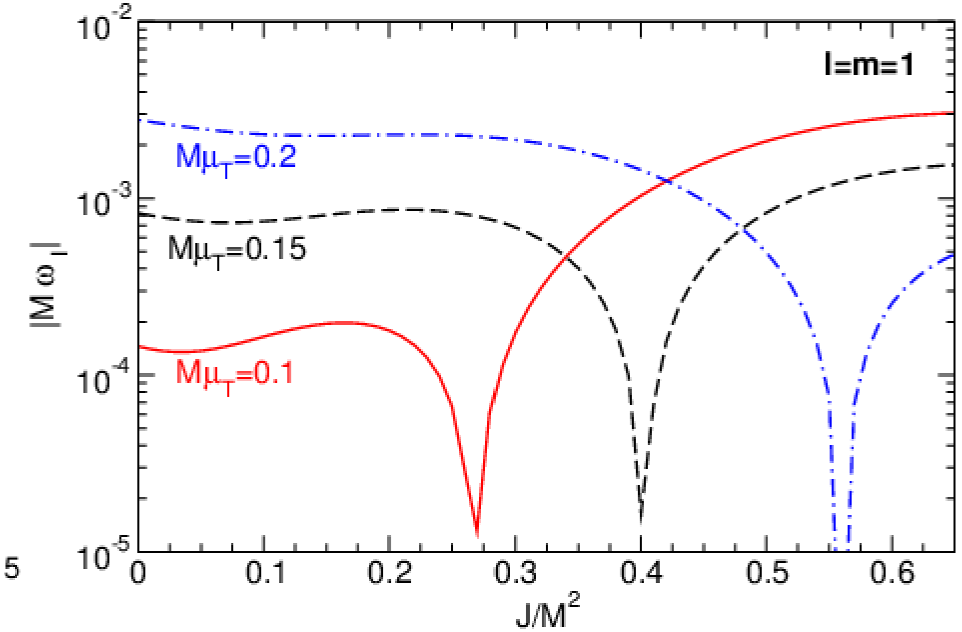
Massive bosonic fields

spin 1 (polar)



Pani *et al*, Phys.Rev. D86 (2012) 104017

spin 2 (polar)



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

All modes follow:

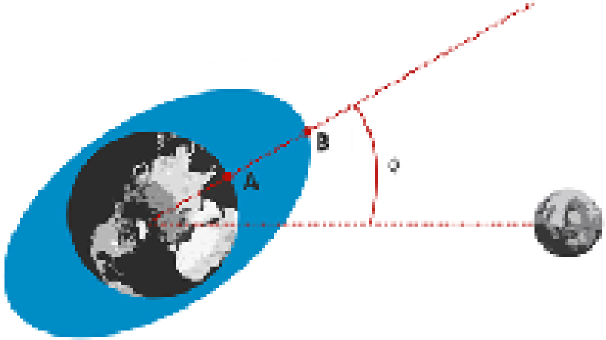
$$\omega_R^2 \sim \; \sim \; \mu^2 \left[1 - \left(\frac{M\mu}{l+n+S+1} \right)^2 \right]$$
$$M\omega_I \; \sim \; \gamma_{Sl} \left(ma/M - 2r_+\mu \right) (M\mu)^{4l+5+2S}$$

Except for the massive spin 2

$$l = m = 1 \quad \text{(polar)}$$

$$\omega_R/\mu \; \sim \; 0.72(1 - M\mu)$$
$$M\omega_I \; \sim \; (ma/M - 2r_+\omega_R)\,(M\mu)^3$$

Energy extraction and dissipation



$$c_s < v \cos\theta$$

$$\Omega_{\rm orbit} < \Omega_{\rm Earth}$$

Internal degrees of freedom where energy can be dumped into.