Black holes as particle detectors

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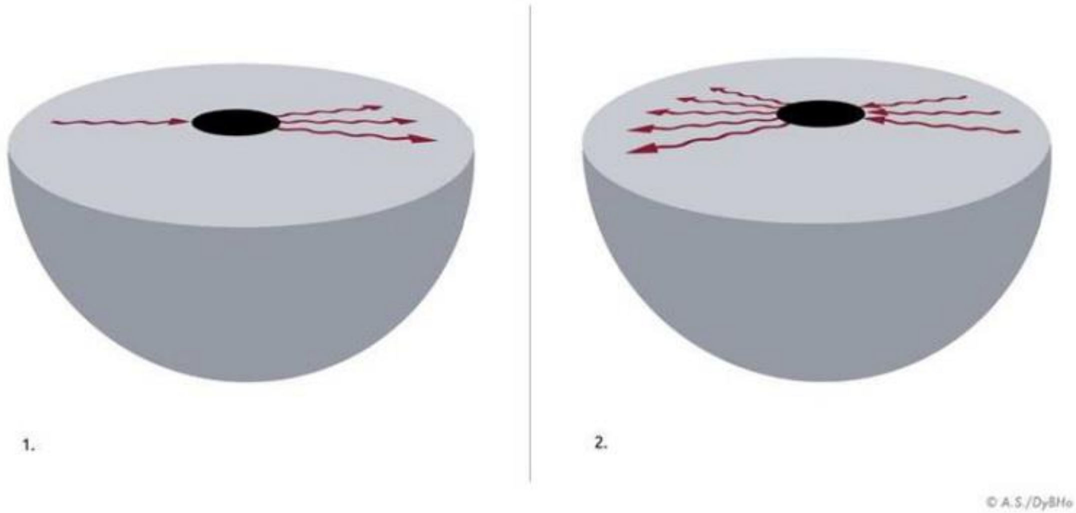
Aveiro, December 18

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

Superradiant instability

Press & Teukolsky, Nature 238 (1972) 211-212
Brito, Cardoso & Pani, Review article in preparation

Confinement + superradiance

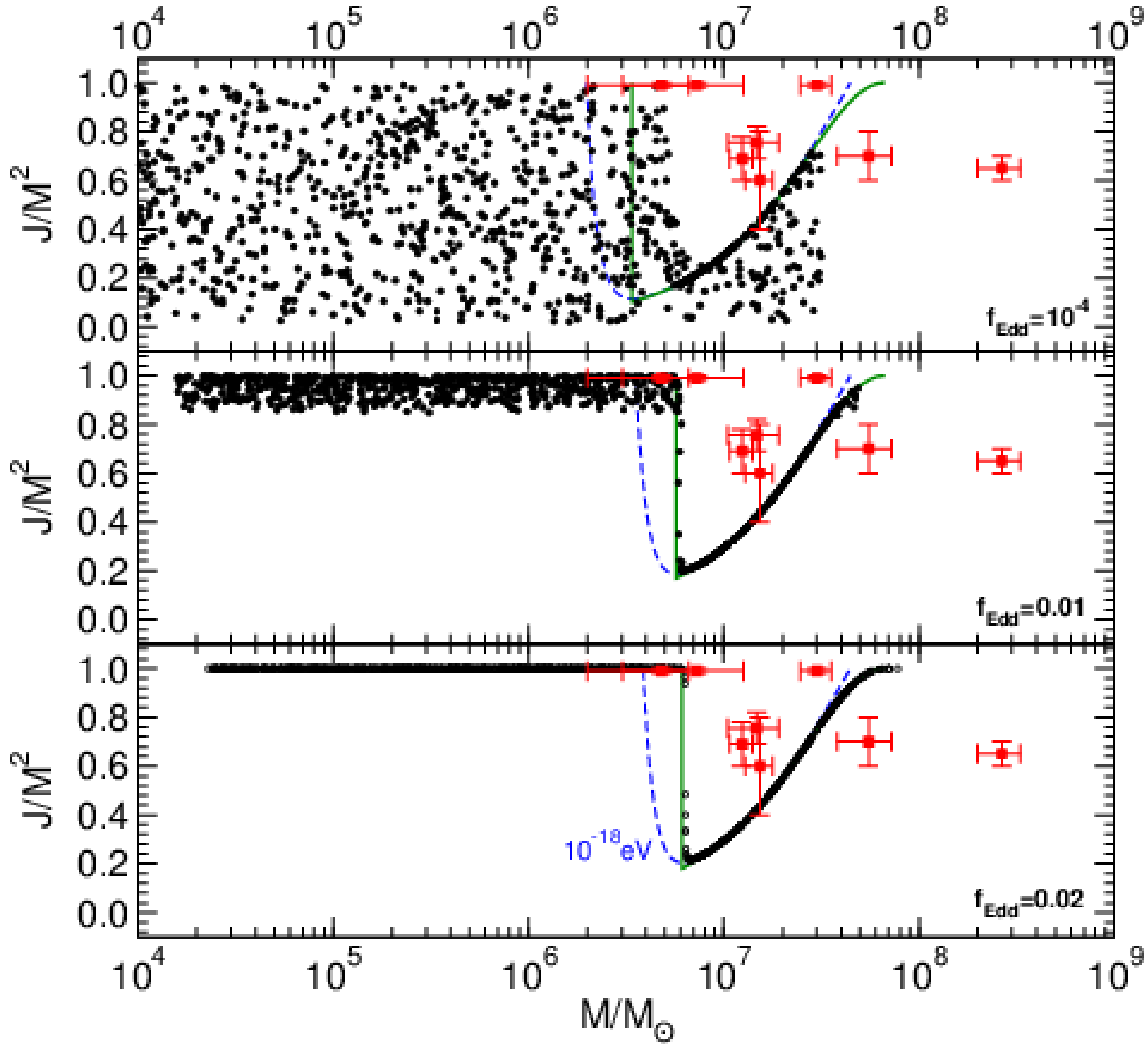


- Massive bosonic fields (Damour et al '76; Zouros & Eardley '79; Detweiler '80; Pani *et al* '12; Witek *et al* '12, Brito, Cardoso & Pani, '13 ; …)
- AdS boundaries (Cardoso & Dias,'04)
- Magnetic fields (Gal'tsov & Pethukov '78; Konoplya '08 , Brito, Cardoso & Pani, '14)
- Plasmas (Pani & Loeb, '13)
- Hairy black holes (Herdeiro & Radu, '14 (see also Herdeiro's and Benone's talk))
- …

Gaps in the ‘Regge’ plane

Brito, Cardoso, Pani, arXiv:1411.0686, 2014

(see also Cardoso’s talk)



Massive bosonic fields

Detweiler , Phys.Rev. D22 (1980) 2323,
Pani *et al*, Phys.Rev.Lett. 109 (2012) 131102, Phys.Rev. D86 (2012) 104017,
Brito, Cardoso & Pani, Phys.Rev. D88 (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
  (see also Volkov's talk) $\begin{cases} \Box h_{\mu\nu} + 2R_{\alpha\mu\beta\nu}h^{\alpha\beta} - \mu_T^2 h_{\mu\nu} = 0\,, \\ \mu_T^2 \nabla^\mu h_{\mu\nu} = 0\,, \\ \left(\mu_T^2 - 2\Lambda/3\right) h = 0\,. \end{cases}$

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

All modes follow:

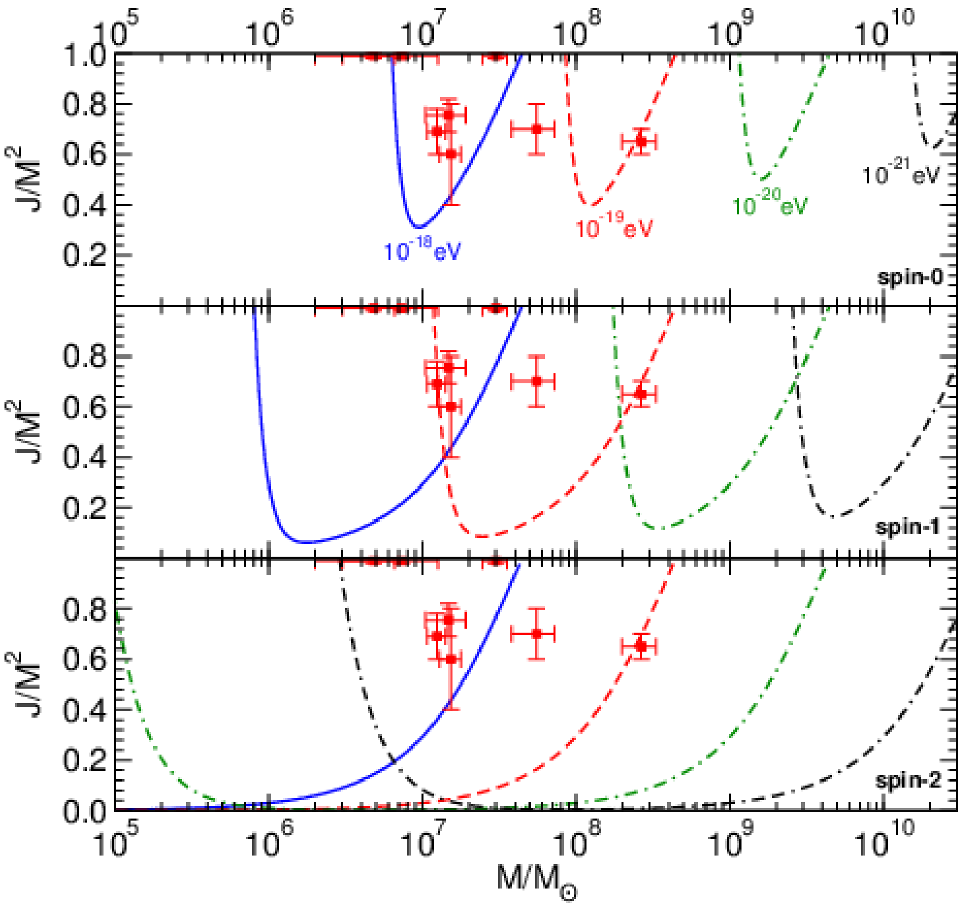
$$\omega_R^2 \sim \;\sim\; \mu^2\left[1-\left(\frac{M\mu}{l+n+S+1}\right)^2\right]$$
$$M\omega_I \;\sim\; \gamma_{Sl}\,(ma/M - 2r_+\mu)\,(M\mu)^{4l+5+2S}$$

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

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

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

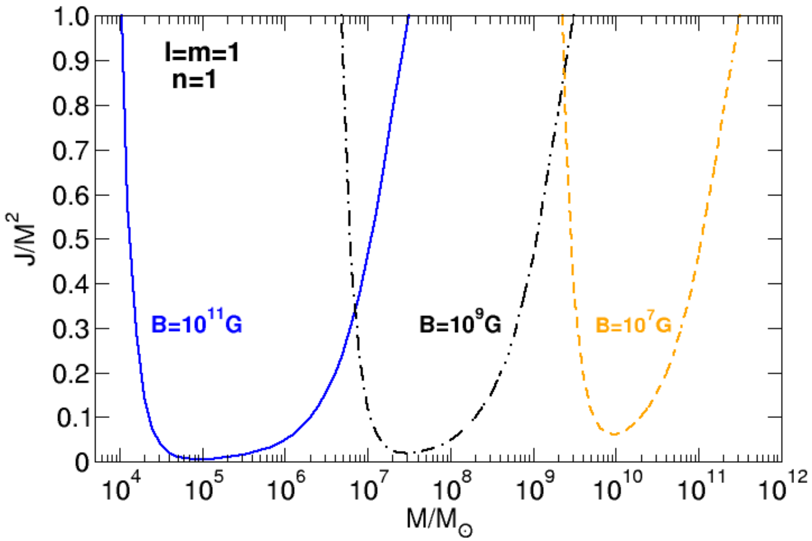


$$10^{-11}\text{eV} \lesssim \quad m_S \quad \lesssim 5\times 10^{-20}\text{eV}$$
$$10^{-11}\text{eV} \lesssim \quad m_V \quad \lesssim 5\times 10^{-21}\text{eV}$$
$$10^{-11}\text{eV} \lesssim \quad m_T \quad \lesssim 5\times 10^{-23}\text{eV}$$

Other constraints

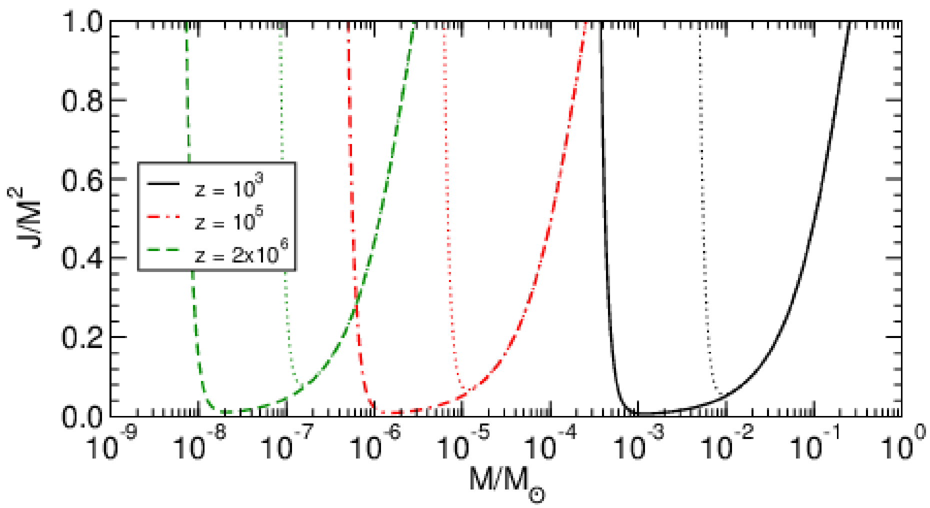
- Magnetized BHs

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



- BHs surronded by plasma

Pani & Loeb, Phys.Rev. D88 (2013) 041301



- Axionic coupling

Brito, Cardoso & Witek, in preparation

$$\nabla_\nu F^{\mu\nu} = -2k_{\rm axion}\, {}^*F^{\mu\nu}\partial_\nu \Phi$$

$$\left(\nabla_\nu \nabla^\nu - \mu_S^2\right)\Phi = \frac{k_{\rm axion}}{2}\, {}^*F^{\mu\nu}F_{\mu\nu} + V'(\Phi)$$

Conclusions & Outlook

- Black holes are unique labs for beyond-SM physics and extensions of GR;
- Superradiant instabilities provide strong constraints on ultralight bosonic degrees of freedom and can even be used to put bounds on magnetic fields around black holes;
- Does the environment change this picture? (magnetic fields, accretion disks, coupling to other fields, etc…)
- What about stars? Dissipation is a crucial ingredient… (Cardoso, Brito & J.Luis, in preparation)
- Keep following…

Thank you

Backup Slides

Bounds on the graviton mass

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

For some specific BH solutions of bimetric/massive gravity:

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

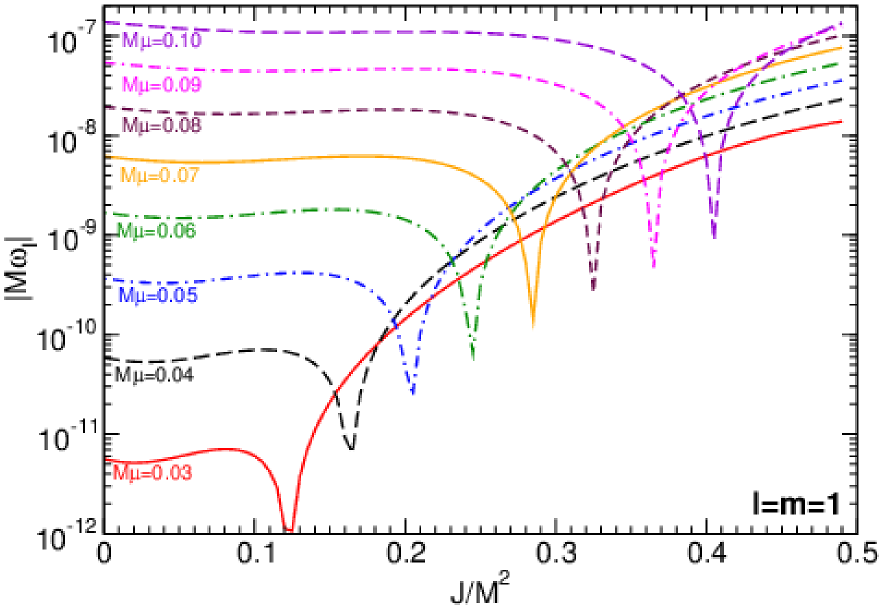
Gravitons interact very weakly, not model-dependent.

Review of Particle Physics 2014 (PDG 2014)

VALUE (eV)	*DOCUMENT ID*		*COMMENT*
$<6\times10^{-32}$	[1] CHOUDHURY	04	Weak gravitational lensing
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<5\times10^{-23}$	[2] BRITO	13	Spinning black holes bounds
$<4\times10^{-25}$	[3] BASKARAN	08	Graviton phase velocity fluctuations
$<6\times10^{-32}$	[4] GRUZINOV	05	Solar System observations
$>6\times10^{-34}$	[5] DVALI	03	Horizon scales
$<8\times10^{-20}$	[6,7] FINN	02	Binary pulsar orbital period decrease
	[7,8] DAMOUR	91	Binary pulsar PSR 1913+16
$<2\times10^{-29}\ h_0^{-1}$	GOLDHABER	74	Rich clusters
$<7\times10^{-28}$	HARE	73	Galaxy
$<8\times10^{4}$	HARE	73	2γ decay

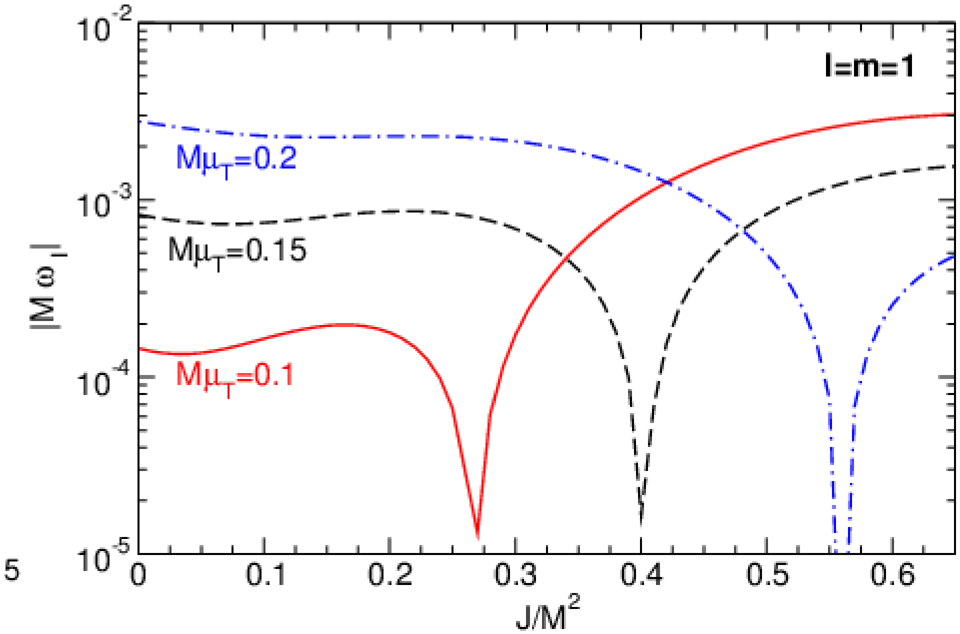
Massive bosonic fields

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:

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

Except for the massive spin 2

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

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

Massive bosonic fields

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

$$\begin{cases} \bar{\Box} A_\nu - \bar{R}_{\nu\mu} A^\mu - \mu_V^2 A_\nu = 0\,, \\ \mu_V^2 \bar{\nabla}^\mu A_\mu = 0\,. \end{cases}$$

- Massive vector field (extensions of the SM)

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

- Massive tensor field (massive gravity, biometric theories of gravity)

$$\delta X_{\mu_1\ldots}(t,r,\vartheta,\varphi) = \delta X_{lm}^{(i)}(r)\mathcal{Y}_{\mu_1\ldots}^{lm\,(i)}(\vartheta)e^{im\varphi}e^{-i\omega t}$$

Non-separable in Kerr $\longrightarrow$ Slow-rotation approximation $(\tilde{a} \equiv J/M^2)$

$$\begin{aligned} \mathcal{A}_{lm} + \tilde{a}m\bar{\mathcal{A}}_{lm} + \tilde{a}(\mathcal{Q}_{lm}\tilde{\mathcal{P}}_{l-1m} + \mathcal{Q}_{l+1m}\tilde{\mathcal{P}}_{l+1m}) &= 0 \\ \mathcal{P}_{lm} + \tilde{a}m\bar{\mathcal{P}}_{lm} + \tilde{a}(\mathcal{Q}_{lm}\tilde{\mathcal{A}}_{l-1m} + \mathcal{Q}_{l+1m}\tilde{\mathcal{A}}_{l+1m}) &= 0 \end{aligned}$$

$\mathcal{A}_{lm}$ – axial functions

$\mathcal{P}_{lm}$ – polar functions

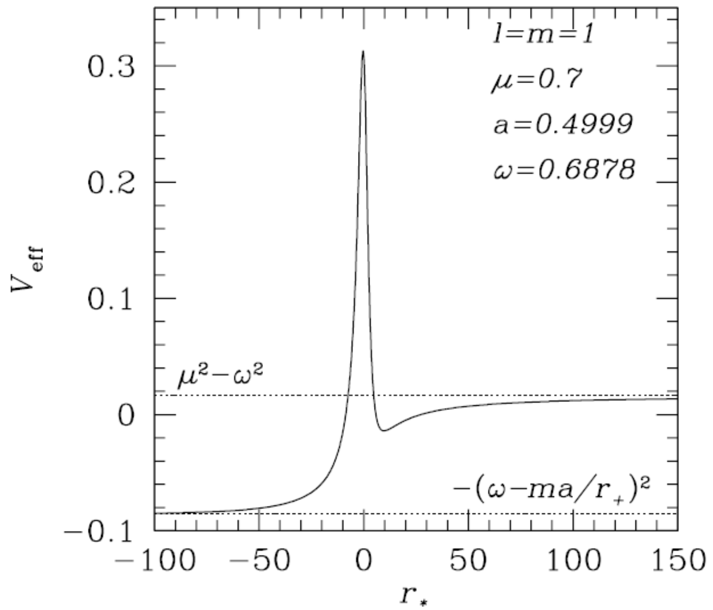
Massive scalar fields

Damour *et al* , Lett. Nuovo Cim 15 (1976) 257

$$\Box\Phi - \mu_S^2\Phi = 0$$

$$\Phi(t,r,\theta,\phi) = \sum_{jm} e^{-i\omega t}\frac{\phi(r)}{r}Y_{jm}(\theta,\phi)$$

$$\frac{d^2\phi}{dr_*^2} + V_{\rm eff}\phi = 0$$



Cardoso & Yoshida, JHEP 0507 (2005) 009

$$\omega \sim \mu_S - \frac{\mu_S}{2}\left(\frac{M\mu_S}{l+n+1}\right)^2 + \frac{i}{\gamma_{nlm}}\left(\frac{am}{M} - 2\mu_S r_+\right)(M\mu_S)^{4l+5}\,, \quad M\mu_S \ll 1$$

Detweiler , Phys.Rev. D22 (1980) 2323

$$a \sim M\,,\ \mu_S \sim 0.42M^{-1} \sim 5.6\times10^{-17}\left(\frac{10^6 M_\odot}{M}\right)\mathrm{eV}\,,\ \tau \sim 6.7\times10^6 M \sim \left(\frac{M}{10^6 M_\odot}\right)\mathrm{yr}$$

Dolan, Phys.Rev. D76 (2007) 084001

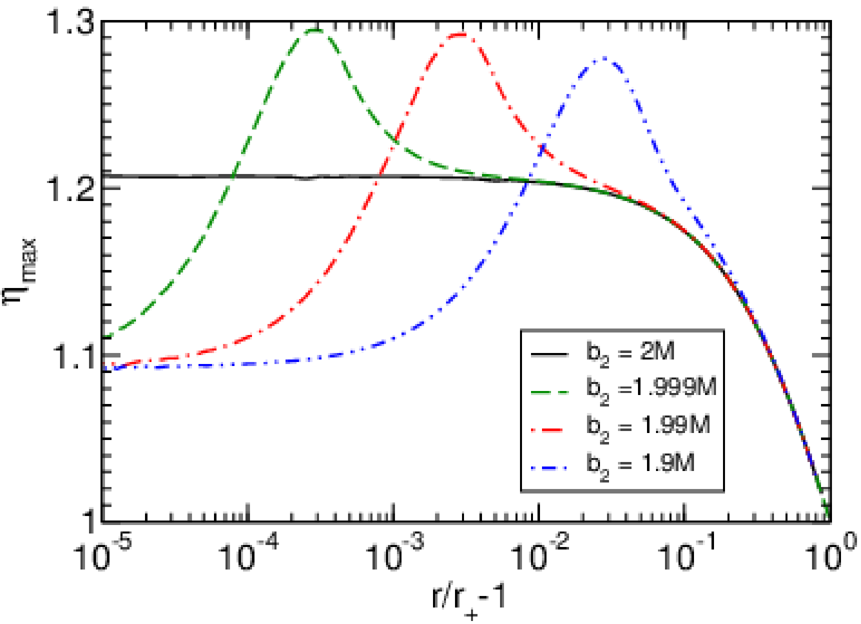
Where do we stand?

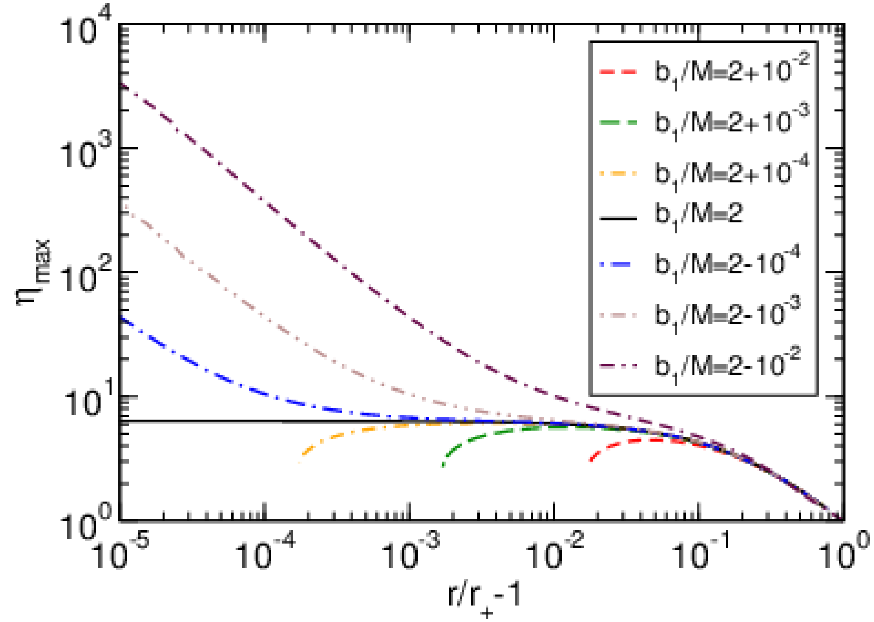
- Massive scalar fields around BHs (Damour et al '76; Zouros & Eardley '79; Detweiler '80; Cardoso & Yoshida '05; Dolan '07; Berti et al '09; Konoplya et al '06; Pani et al '12; Hod '12; Barranco et al '13; Strafuss & Khanna '05; Kodama & Yoshino '12; Barranco et al '12; Dolan '12; Witek et al '12; *...)*
- 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*)*

Ultra-high-energy debris

$$p_1^\mu + p_2^\mu = p_3^\mu + p_4^\mu$$

$b_1 \equiv L/E = 2M$





$p_1^r < 0 \qquad p_2^r < 0$

$p_1^r > 0 \qquad p_2^r < 0$

$$\eta_{\max} \sim 1.3$$

$$\eta_{\max} \sim 0.5\sqrt{(2-b_1)(2-b_2)/(r-r_+)}$$

Energy extraction from black holes

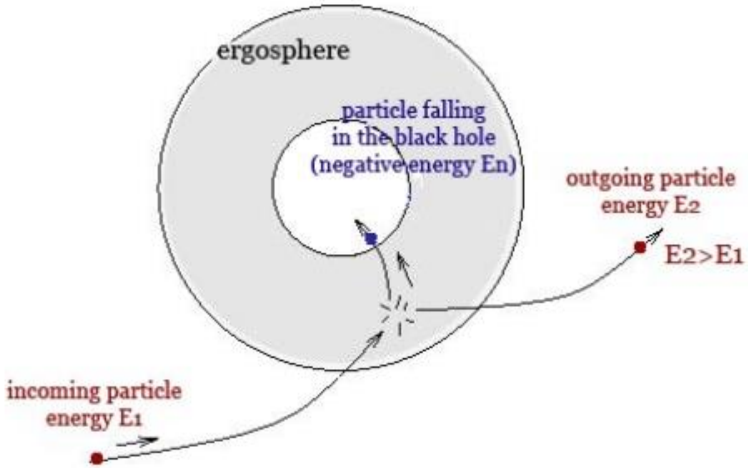
- Penrose process

(Penrose '69 Rev. Nuovo Cimento)

$$E_{\rm out} > E_{\rm in}$$

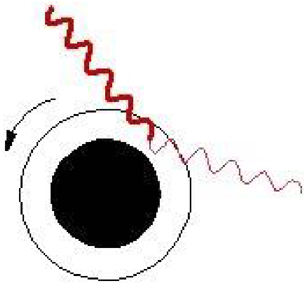
$$\Downarrow$$

Extraction of energy and angular momentum from the BH



- Superradiance

(Zel'dovich, JETPL '71; Misner '72; Press and Teukolsky , ApJ'74)



$$\omega < m\Omega_H$$

$$\Downarrow$$

amplified scattering of waves

$$\Downarrow$$

Extraction of energy and angular momentum from the BH

Realistic?

$$\frac{GB_M^2}{c^4} \sim \frac{1}{r_g^2} \implies B_M \sim 2.4 \times 10^{19} \left(\frac{M_\odot}{M}\right) \text{Gauss}$$

- Magnetars: $M \sim M_\odot\,, \qquad B \sim 10^{13}\text{–}10^{15}\text{Gauss} \implies B/B_M \sim 10^{-6}\text{–}10^{-4}$

- Supermassive BHs: $M \sim 10^9 M_\odot\,, \quad B \sim 10^4\text{Gauss} \implies B/B_M \sim 10^{-6}$

- Ernst metric is not asymptotically flat. Can be trusted up to matter distribution where magnetic field is supported:

$$r_0 \sim 1/B \lesssim r_M \sim M, \quad BM \gtrsim 0.1$$

Massive bosonic fields around BHs

- Massive scalar fields

$$M\mu \ll 1\,,\;\; \tau_{\rm scalar} \sim \frac{48M(M\mu)^{-9}}{(\tilde{a}-2r_+\mu)}$$ (Detweiler '80)

$$M\mu \gg 1\,,\;\; \tau_{\rm scalar} \sim 10^7 e^{1.84M\mu}$$ (Zouros & Eardley '79)

$$a \sim M\,,\;\; \mu_S \sim 0.42M^{-1} \sim 5.6\times10^{-17}\left(\frac{10^6 M_\odot}{M}\right){\rm eV}\,,\;\; \tau \sim 6.7\times10^6 M \sim \left(\frac{M}{10^6 M_\odot}\right){\rm yr}$$

(Dolan '07)

- Massive vector fields

$$M\mu \ll 1\,,\;\; \tau_{\rm vector} \sim \frac{M(M\mu)^{-7}}{\gamma_{-11}(\tilde{a}-2r_+\mu)}$$ (Pani *et al* '13, Witek *et al* '13)

- Massive tensor fields

$$M\mu \ll 1\,,\;\; \tau_{\rm tensor} \sim \frac{M(M\mu)^{-3}}{\gamma_{\rm polar}(\tilde{a}-1.4r_+\mu)}$$ (Brito, Cardoso & Pani '13)

Magnetized Kerr-Newman black hole

(Ernst, '76; Hiscock, '81; Aliev & Galtsov, '89)

$$ds^2 = H\left[-F dt^2 + \Sigma\left(\frac{dr^2}{\Delta} + d\theta^2\right)\right] + \frac{A\sin^2\theta}{\Sigma H}\left(H_0 d\phi - \varpi dt\right)^2$$

$$r_+ = 2M - \tilde{a}^2\left(\frac{M}{2} + 2B^2M^3\right)$$

- Wald's charge: (Wald '74, Gibbons *et al* '14)

$$q_{\rm neutral}/M = -2\tilde{a}BM + \mathcal{O}\left[\tilde{a}^3(BM)^5\right] \implies Q_{\rm physical} = 0$$

- Angular momentum: (Gibbons *et al* '14)

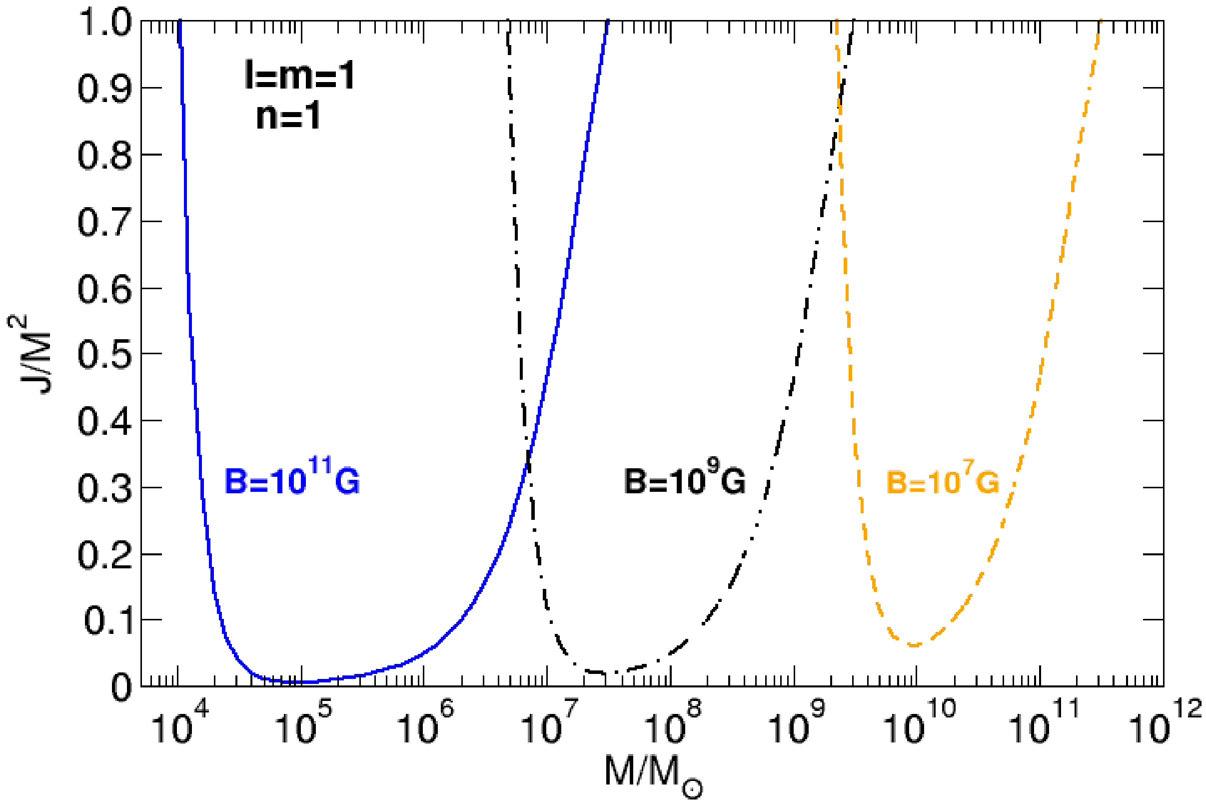
$$J_{\rm physical} = \tilde{a}M^2 + \mathcal{O}\left(\tilde{a}^3\right)$$

- Angular velocity of the horizon:

$$\Omega_H = \frac{\tilde{a}}{4M} + 2\tilde{a}MB^2\left(1 - 2B^2M^2\right) + \mathcal{O}\left(\tilde{a}^3\right)$$

Intrinsic limits on magnetic fields

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



$$10^{-4} \lesssim BM \lesssim 1$$

$$BM \sim 10^{-4} \implies r_M \sim 10^4 M \sim 0.5[M/(10^9 M_\odot)]\mathrm{pc}$$