Black holes as particle detectors

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(CENTRA/Técnico & Perimeter)

...

Quy Nhon, Vietnam

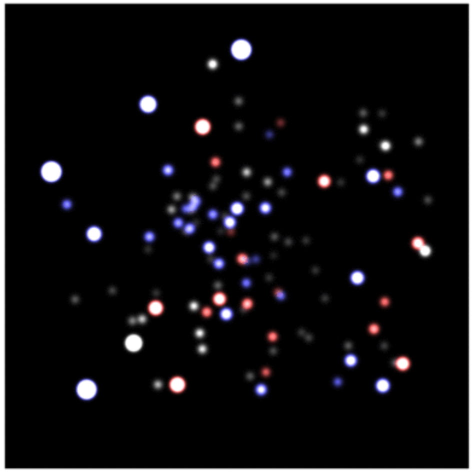
TÉCNICO LISBOA | centra | blackholes.ist.utl.pt | erc supports this project

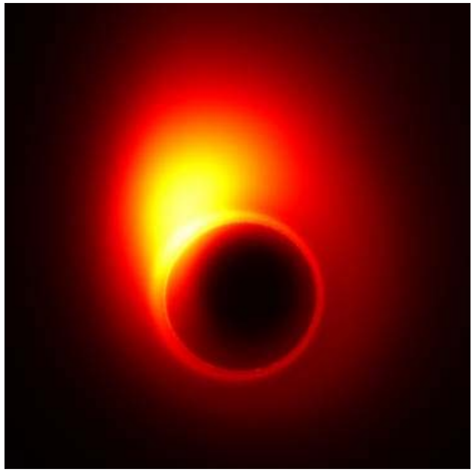
Cardoso, Gualtieri, Herdeiro & Sperhake
Exploring New Physics Frontiers Through Numerical Relativity,
Liv. Rev. Relativity; arXiv:1409.0014

Brito, Cardoso & Pani,
Superradiance,
Springer-Verlag (2015); arXiv:1501.06570

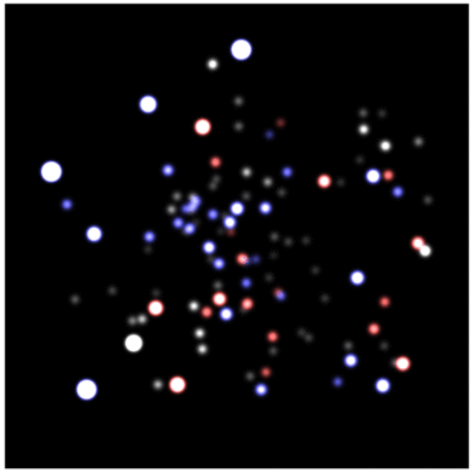
Berti et al,
Testing General Relativity with Present and Future Observations,
arXiV:1501.07274

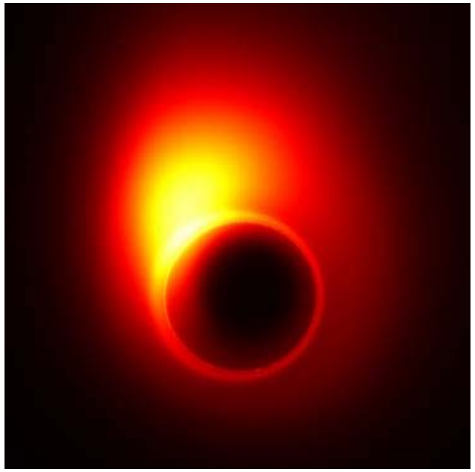
Black holes exist





Black holes exist



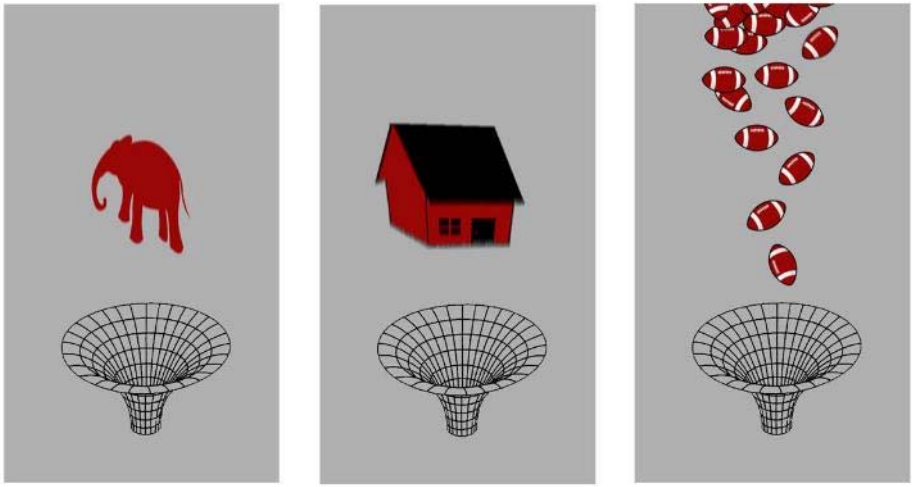


Black holes have no hair

One star made of matter and other of antimatter, produce identical BHs.

A stationary BH is characterized by only three quantities:

mass, spin and electric charge



Note: B & L numbers are also non-conserved in black hole physics

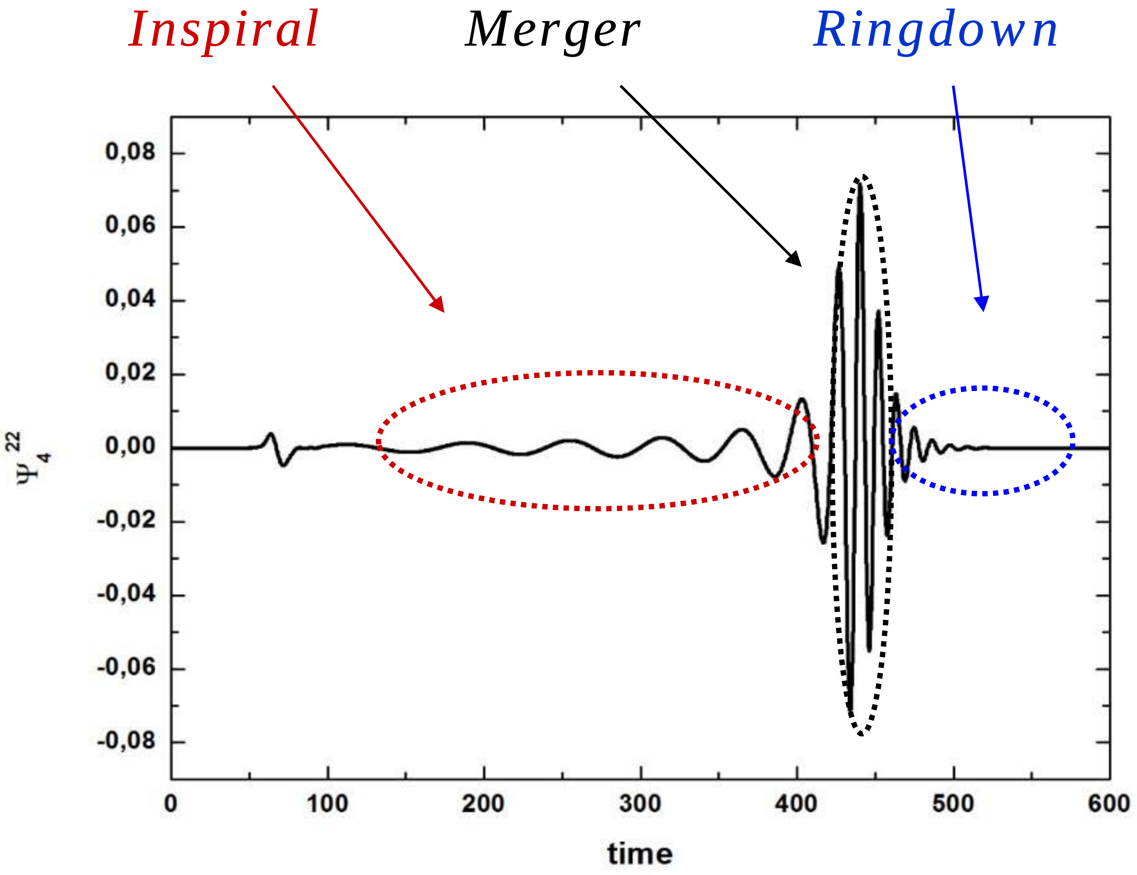
Why study dynamics

Gravitational-wave detection, GW astrophysics

Fundamental physics

High-energy physics

Particle physics



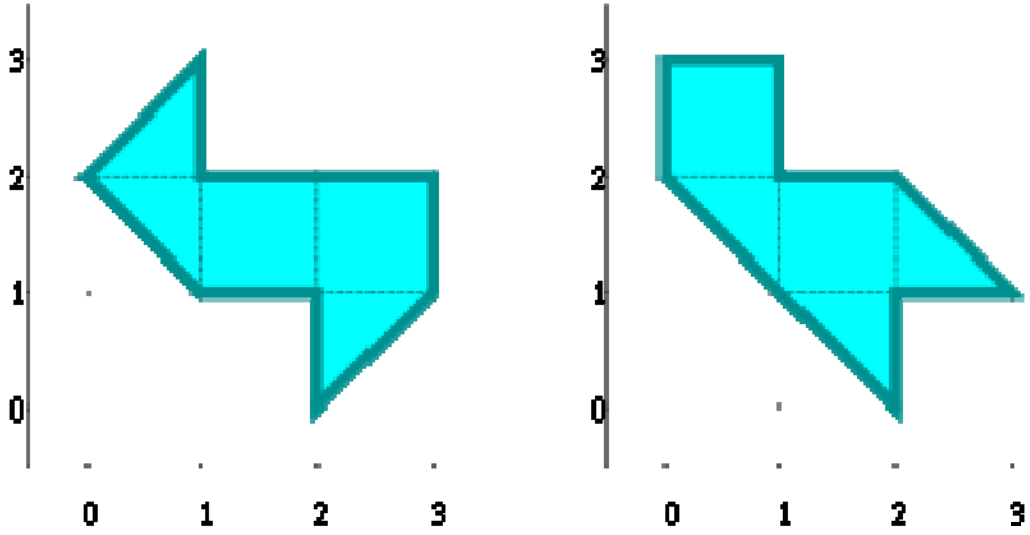
Inspiral *Merger* *Ringdown*

“Can one hear the shape of a drum?”

Mark Kac, American Mathematical Monthly, *1966*

$$A = (2\pi)^d \lim_{R\to\infty} \frac{N(R)}{R^{d/2}}$$

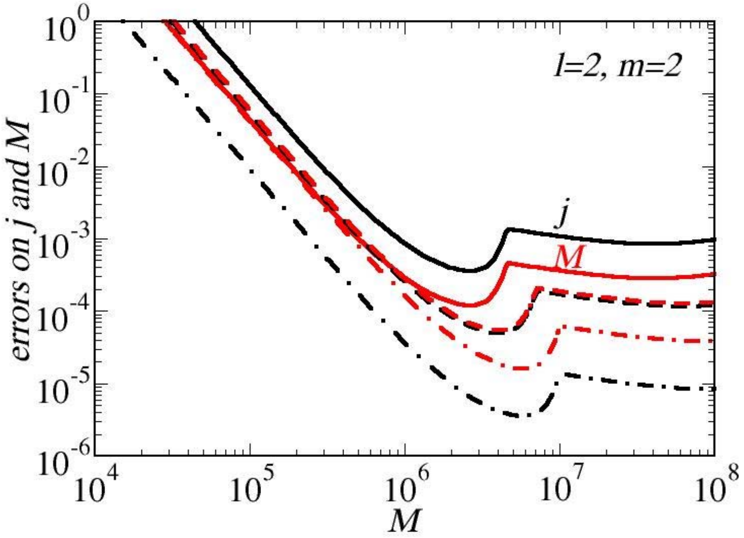
H. Weyl 1911



Gordon, Webb & Wolpert, Inventiones Mathematicae 1992

Can one hear the shape of a BH?

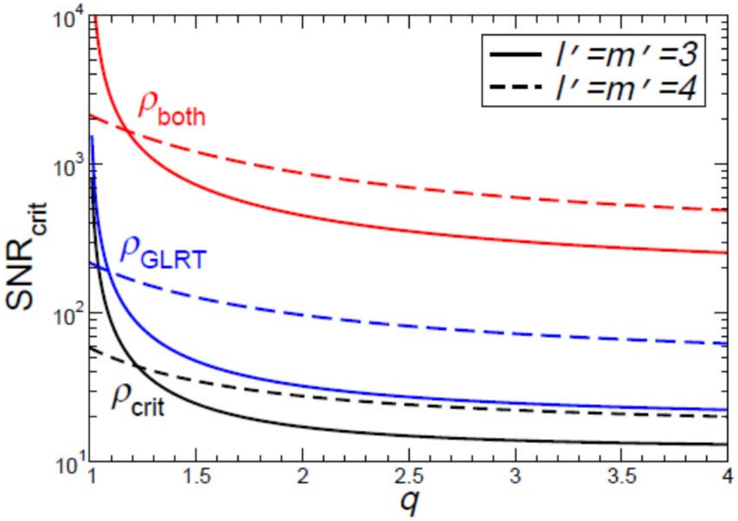
D_L=3Gpc, ε_{rd}=3%



j=0

0.8

0.98



Berti et al PRD76, 104044(2007)

$$\begin{aligned} \epsilon &= 10^{-2}\% \\ M &= 10^6 M_\odot \qquad \sigma_{j,M} = 1\% \\ j &= 0.8 \end{aligned}$$

Berti, Cardoso & Will PRD73, 064030(2005)
Kamaretsos et al PRD85, 024018 (2012)

Stability, spectroscopy?

*

Cosmic Censorship?

*

New dynamical, long-term stable solutions?

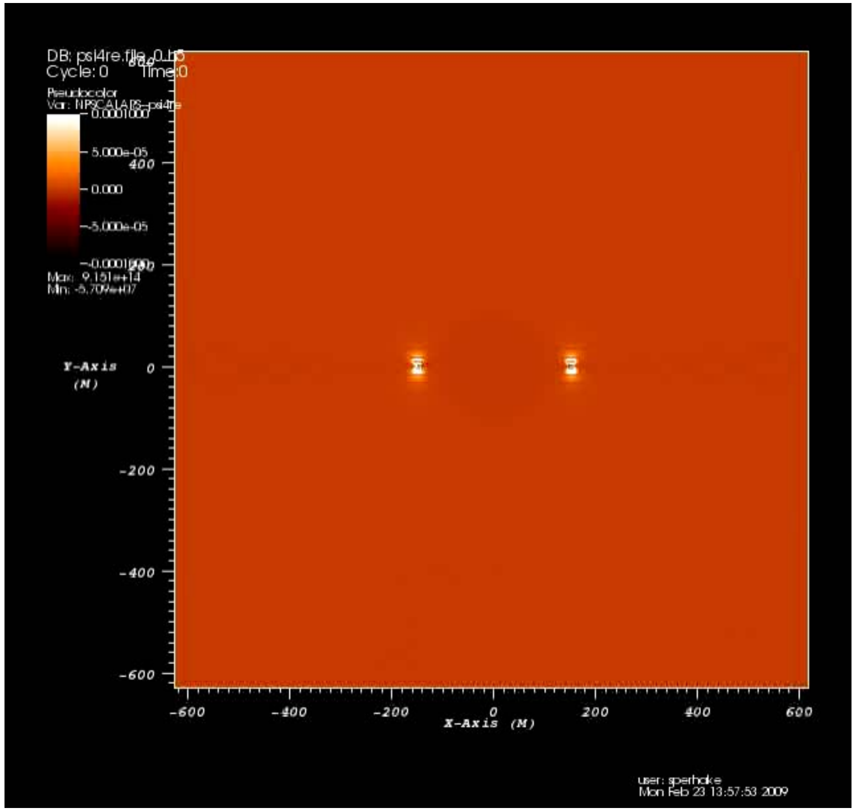
*

Universal limit on maximum luminosity c^5/G (10^59 erg/sec)

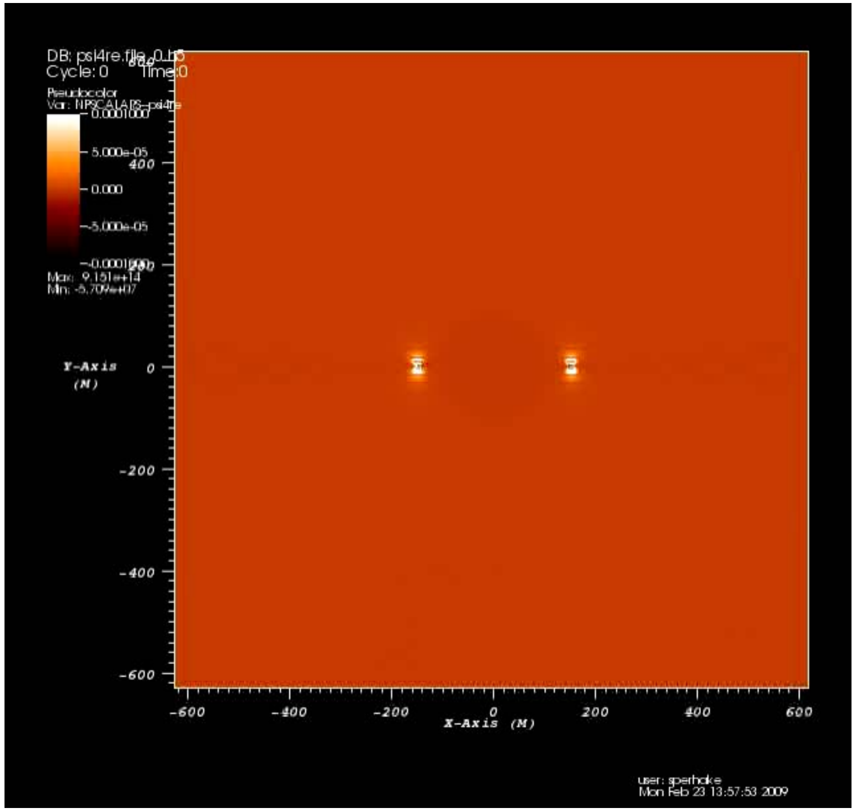
Barrow & Gibbons MNRAS 446, 3874 (2015)

*

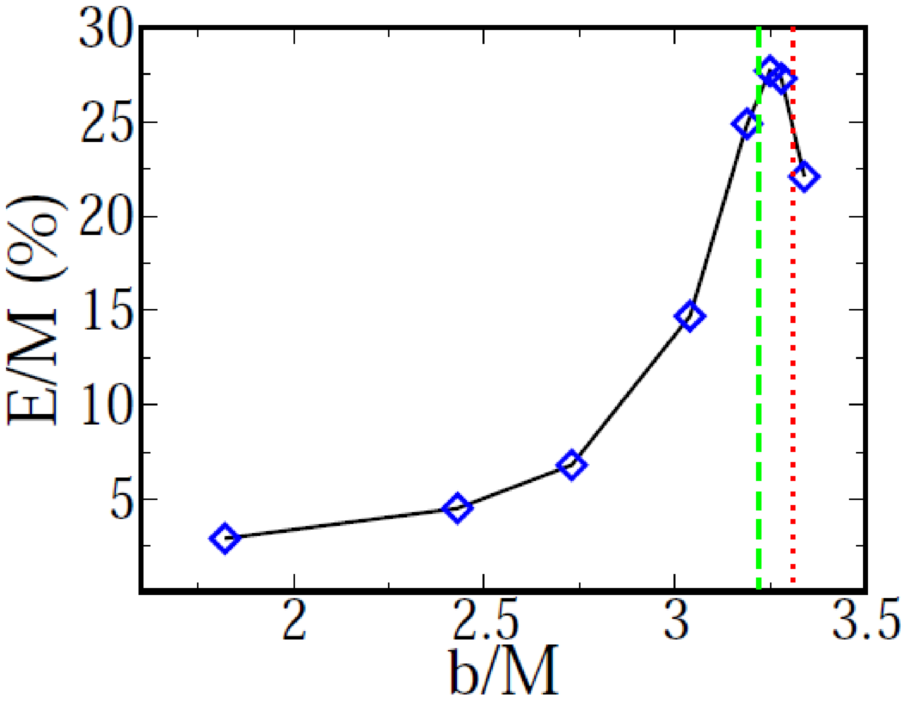
Critical behavior, etc

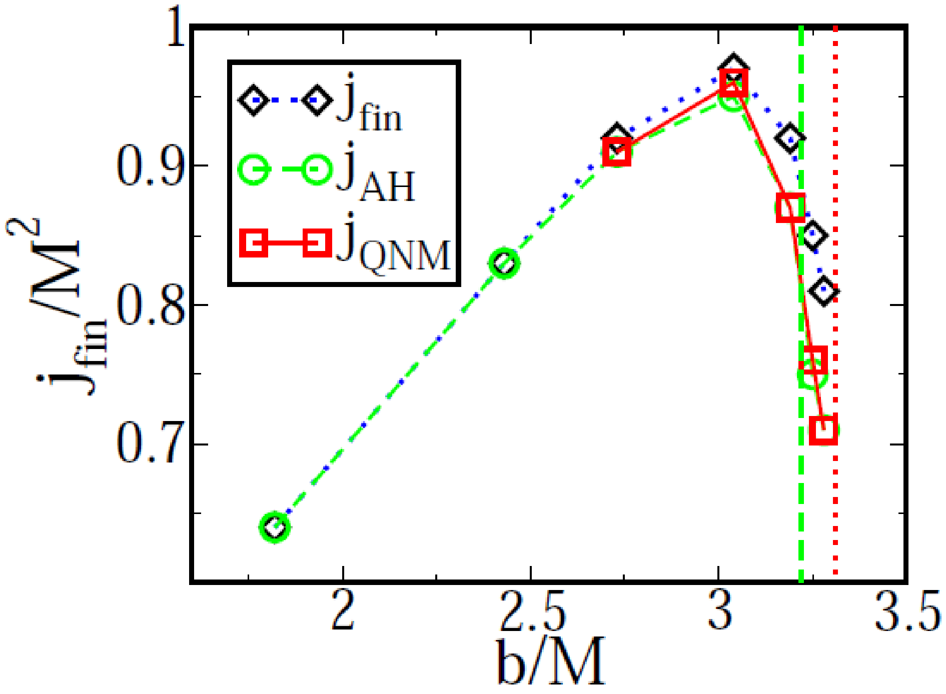


Sperhake et al PRL 2009, 2013



Sperhake et al PRL 2009, 2013





More than 25% (35%) CM energy radiated for v=0.75 c (0.92c)!

Final BH rapidly spinning

Strong field and fundamental fields

Massive scalars

Interesting as effective description; proxy for more complex interactions

Arise as interesting extensions of GR***** *(BD or generic ST theories; f(R))*

DM candidates *(boson and soliton stars, Axiverse scenarios - moduli and coupling constant in string theory, Peccei-Quinn mechanism in QCD)*

Plan

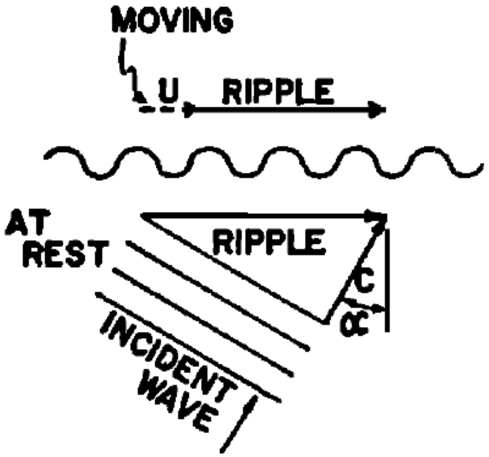
Energy extraction, bound states; evading no-hair theorems

Accretion and gravitational-wave emission

Bounds on ultra-light fields

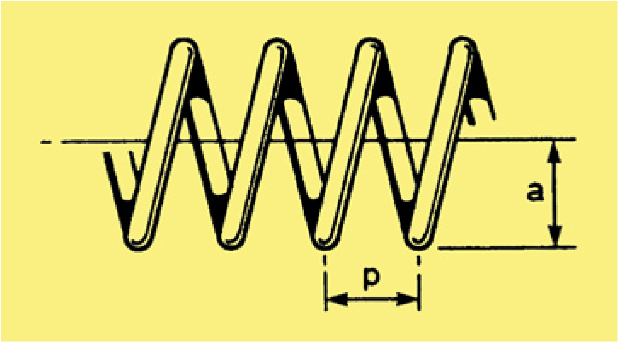
***** *Poorly constrained for massive fields*

Friction & superradiance

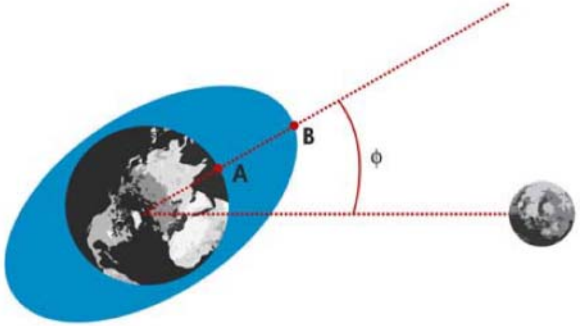


Ribner, J. Acous. Soc. Amer.29 (1957)

Tamm & Frank, Doklady AN SSSR 14 (1937)

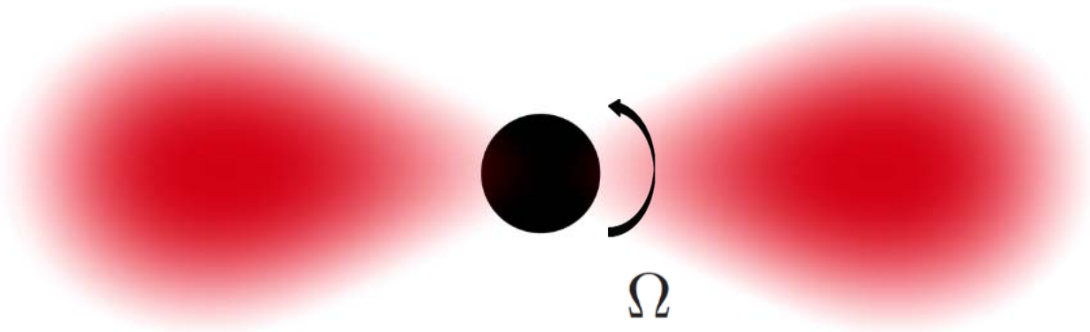


Pierce (& Kompfner), Bell Lab Series (1947)
Ginzburg, anomalous Doppler year



G. H. Darwin, Philos. Trans.
R. Soc. London 171 (1880)

$$\Phi \sim e^{-i\omega t + im\phi} \;\rightarrow\; (Angular)\, phase\, velocity = \frac{\omega}{m}$$

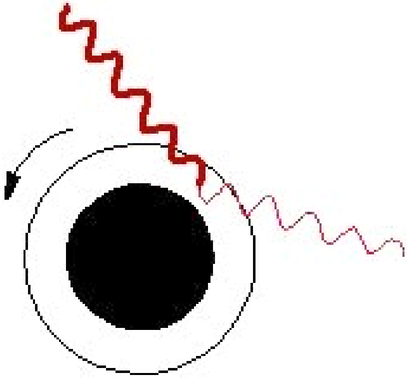


$$\omega < m\Omega$$

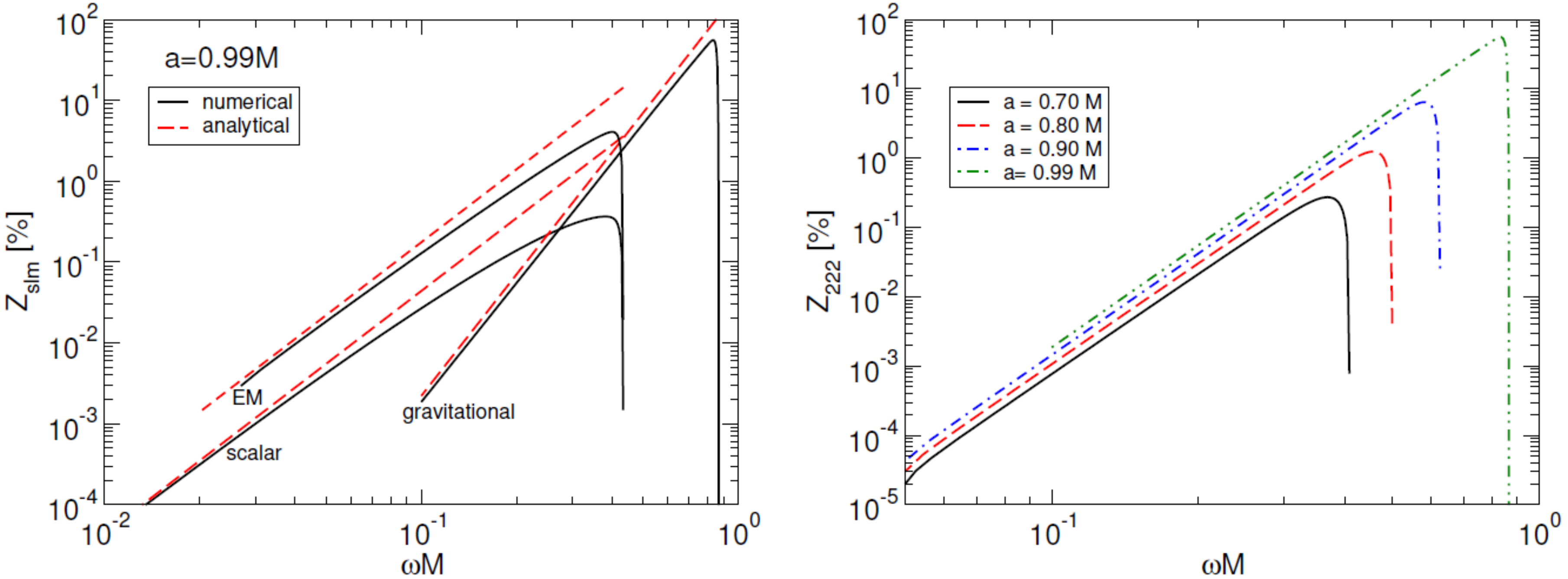
Zel'dovich, Pis'ma Zh. Eksp. Teor. Fiz. 14 (1971)

Black holes and superradiance

Friction built-in through one-way membrane (horizon)



Zel’dovich, Pis’ma Zh. Eksp. Teor. Fiz. 14 (1971), Brito et al, arXiv:1501.06570

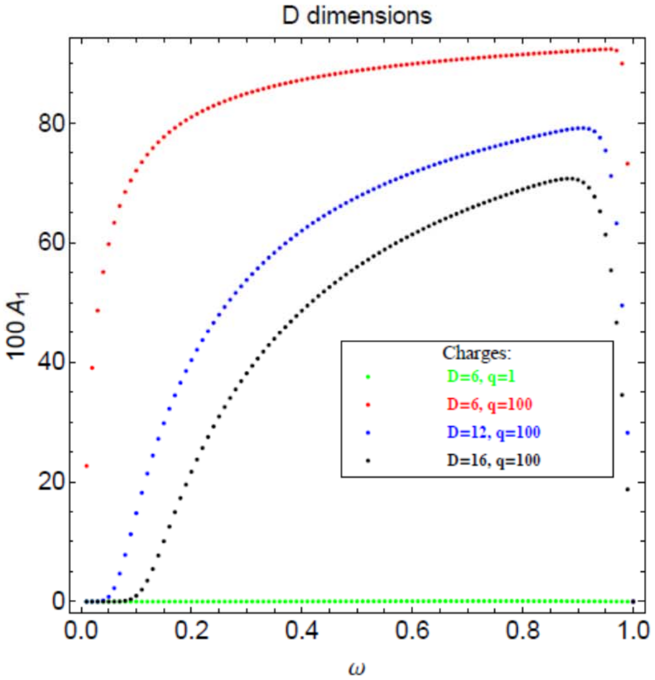


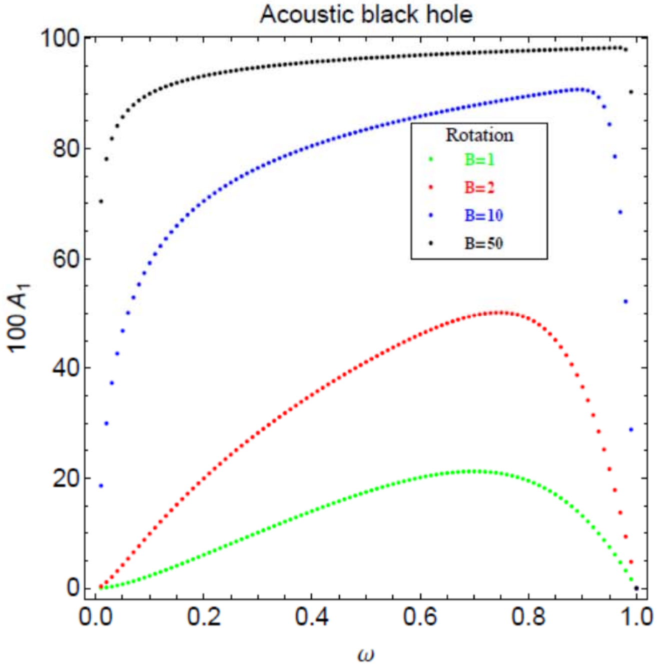
Brito, Cardoso & Pani , arXiv:1501.06570

(Rotational) superradiance in the lab?

Need absorbing surface, characterized by complex acoustic impedance Z

Cardoso, Coutant , Richartz & Weinfurtner, in progress





Amplification < 100%...fundamental bound on superradiance?

$$(\nabla_\mu - iqA_\mu)(\nabla^\mu - iqA^\mu)\Psi = 0$$

$$\frac{d^2X}{dx^2} + \left[(\omega - qA_0)^2 - V\right]X = 0$$

Baibhav, Cardoso and Emparan, in progress

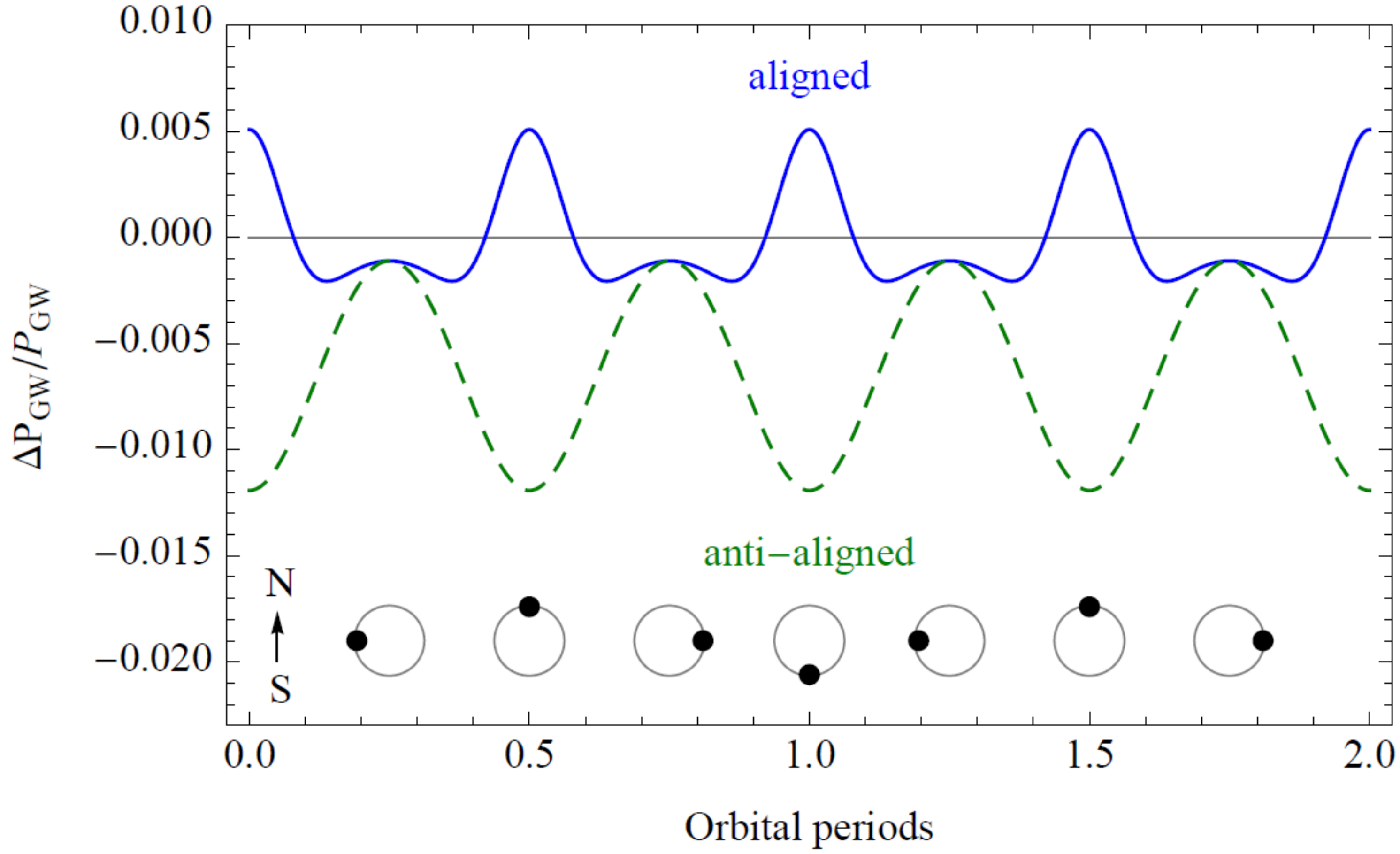
Binaries?

Backreaction?

Superradiance in stars?

Direct observational effects?

VC1



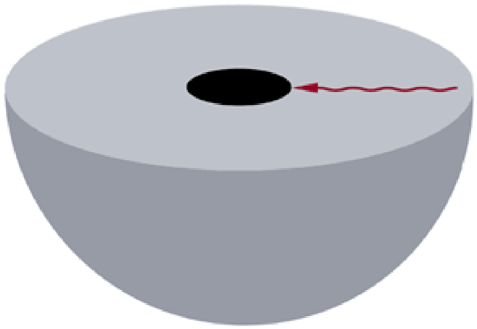
Rosa, arXiv:1501.07605

Slide 22

VC1 Vitor Cardoso, 10/08/2015

Superradiant instabilities

Can construct unstable states by forcing wave to bounce back



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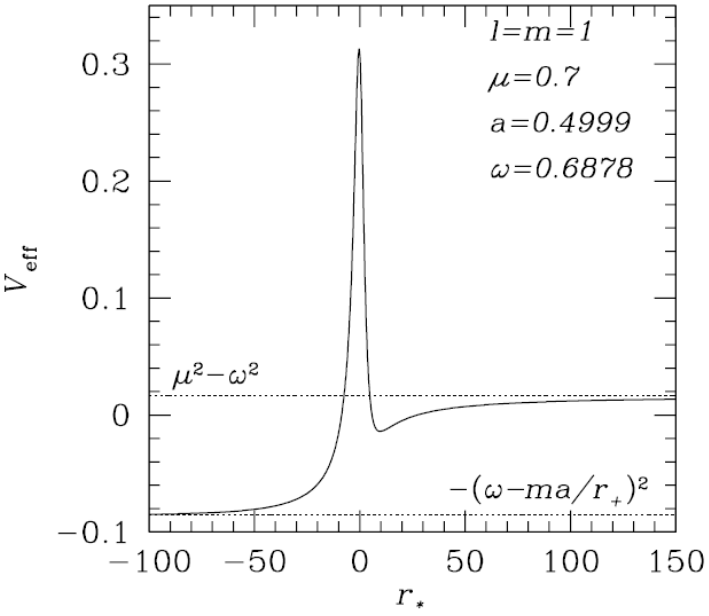
Zel’dovich, Pis’ma Zh. Eksp. Teor. Fiz. 14 (1971);

Cardoso & Dias, PRD70 (2004) ; Brito, Cardoso & Pani, arXiv:1501.06570



$$\omega_{\mathrm{res}}^2 = \mu_s^2 - \mu_s^2 \left(\frac{\mu_s M}{l+1+n}\right)^2 \qquad \omega_I = \mu_s \frac{(\mu_s M)^8}{24}\left(a/M - 2\mu_s r_+\right)$$

Massive “states” around Kerr are linearly unstable

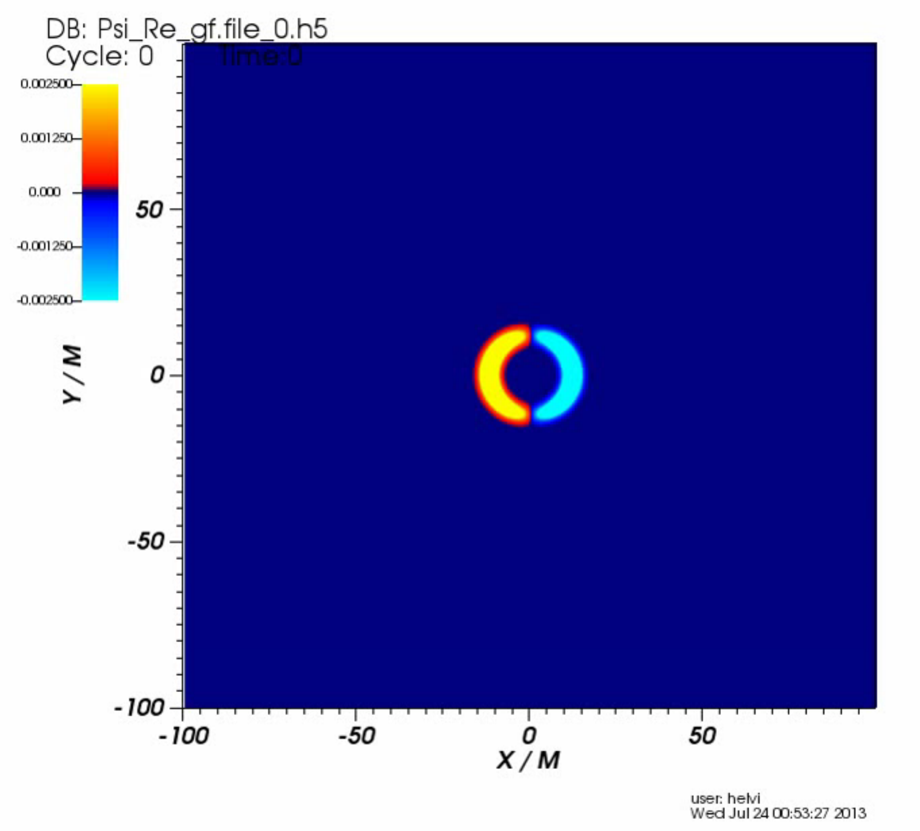
Damour et al ‘76; Detweiler PRD; Cardoso & Yoshida JHEP0507 (2005) 009

Dolan PRD76 (2007) 084001; Witek et al, PRD87 (2013) 4, 043513;

Cardoso, Carucci, Pani, Sotiriou PRL111 (2013) 111101

See reviews Brito et al arXiv:1501.06570 *and Yoshino and Kodama arXiv:1505:00714*

Final state I: almost-hairy BHs

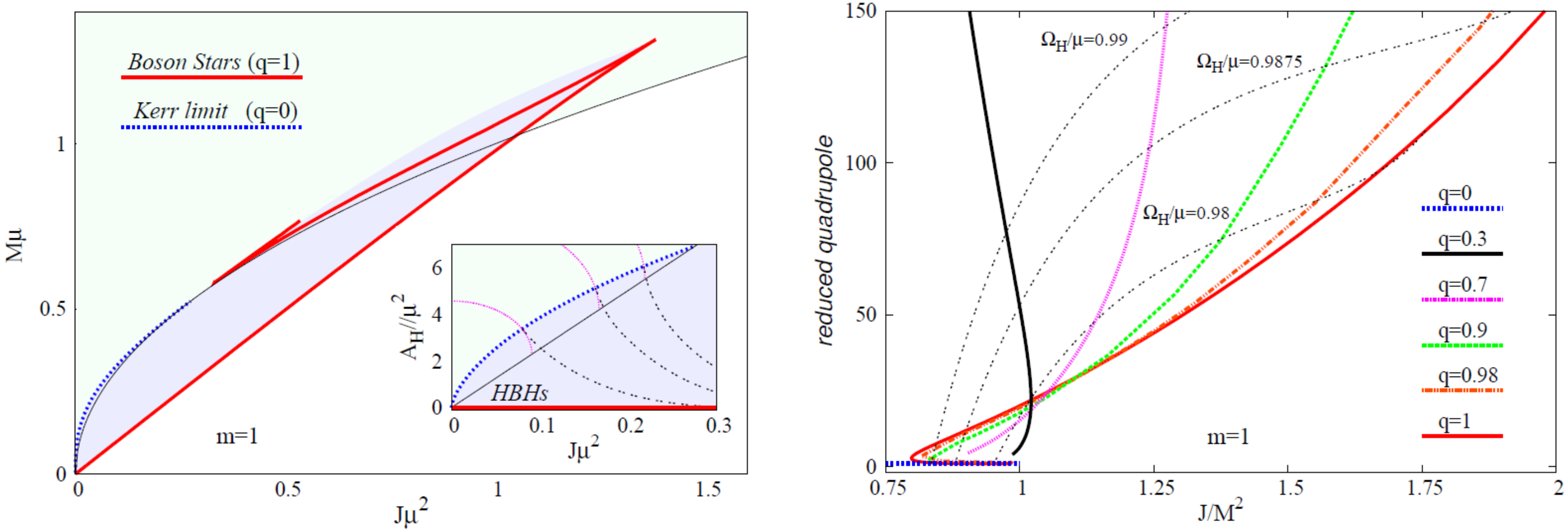


$$\Psi = e^{-i\omega t} Y_{lm}(\theta,\, \phi)\psi(r)$$

$$T^{\mu\nu} = -g^{\mu\nu}\left(\Psi^{*}_{,\alpha}\Psi^{,\alpha} + \mu^{2}\Psi^{*}\Psi\right) + \Psi^{*,\mu}\Psi^{,\nu} + \Psi^{,\mu}\Psi^{*,\nu}$$

Okawa et al PRD89, 104032 (2014)

Final state II: hairy black holes?



Herdeiro & Radu, *PRL112, 221101 (2014)*

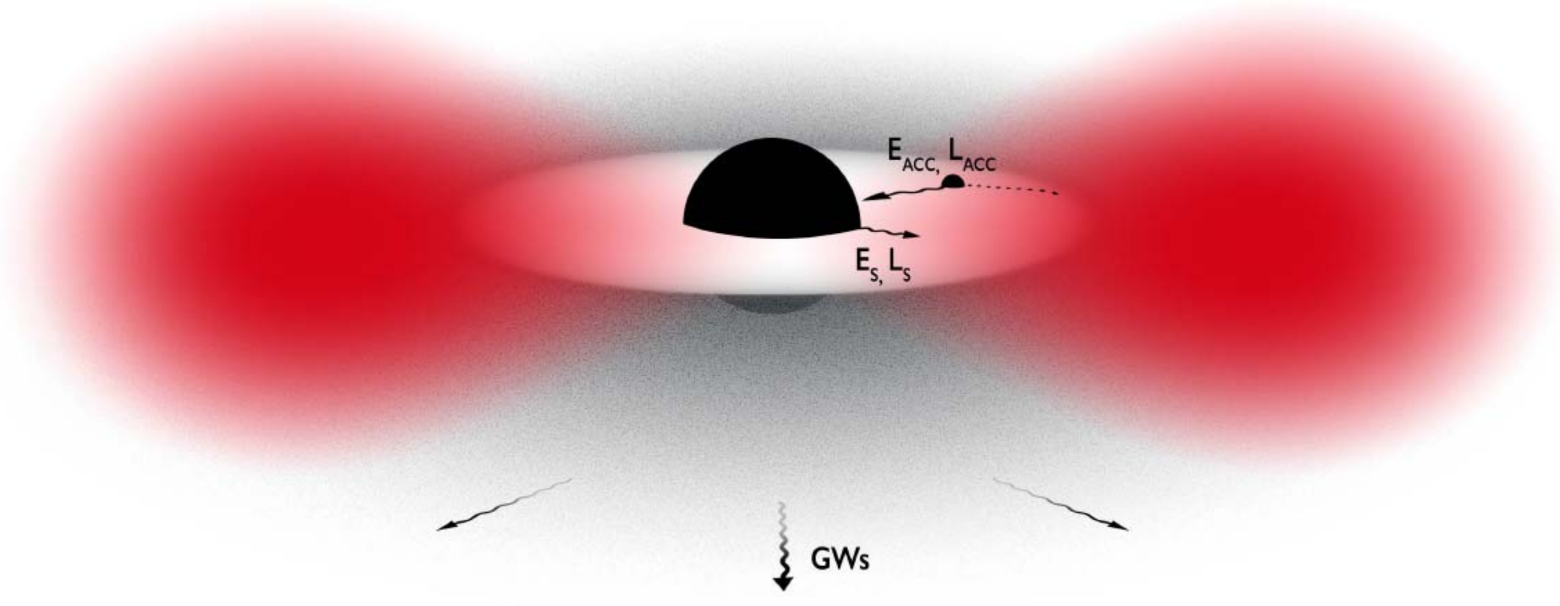
Are themselves unstable in parts of the parameter space

Brito, Cardoso & Pani, arXiv:1501.06570

End-state of linear instability?

Gravitational-wave emission and accretion?

Are hairy solutions formed?



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Accretion:

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

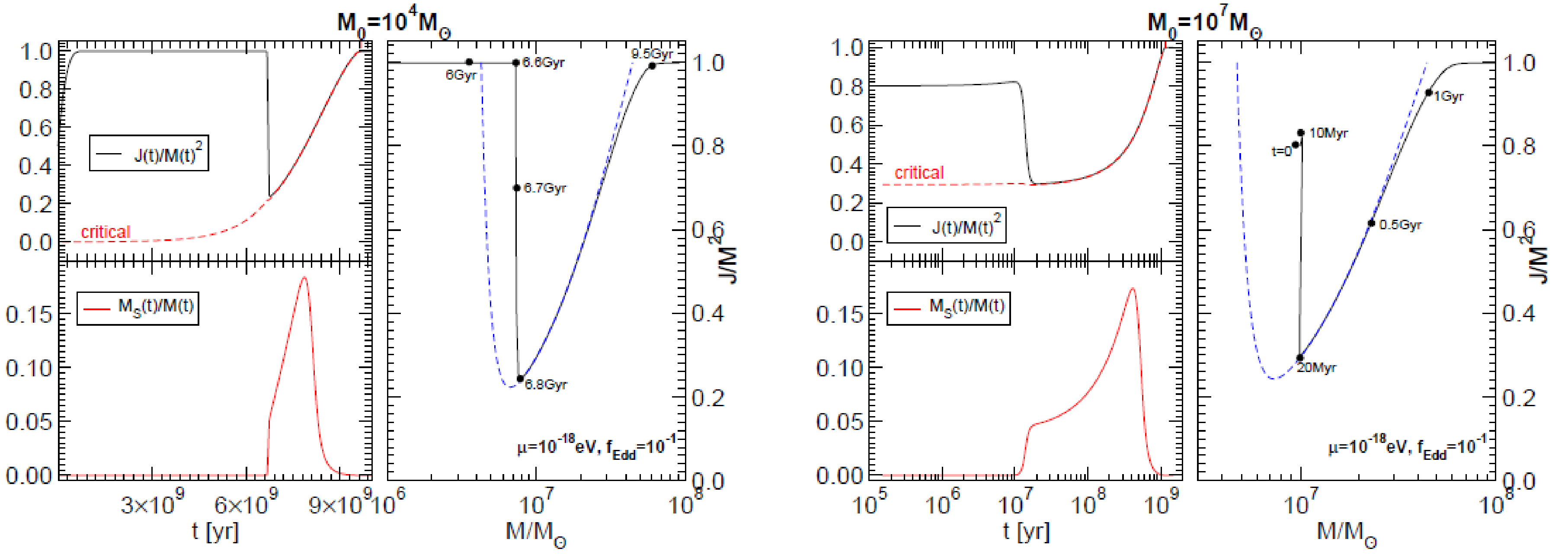
$$\dot{J}_{\rm ACC} \equiv \frac{L(M,J)}{E(M,J)} \dot{M}_{\rm ACC}$$

Gravitational-wave emission:

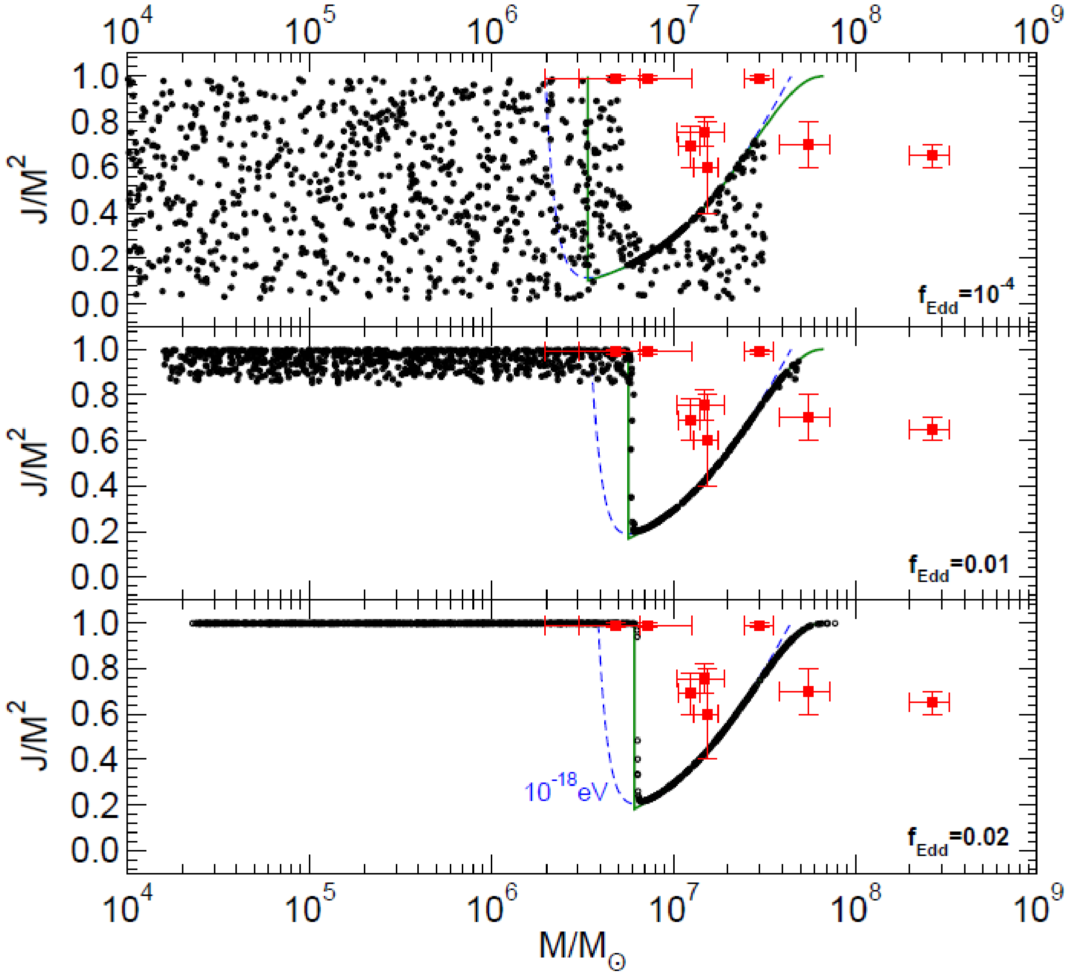
$$\dot{E}_{\rm GW} = \frac{484+9\pi^2}{23040} \left(\frac{M_S^2}{M^2}\right) (M\mu)^{14}$$

$$\dot{J}_{\rm GW} = \frac{1}{\omega_R} \dot{E}_{\rm GW}$$

Yoshino & Kodama PTEP 2014 (043E02); Brito et al CQG32 (2015) 13, 134001



Brito, Cardoso, Pani arXiv:1411.0686

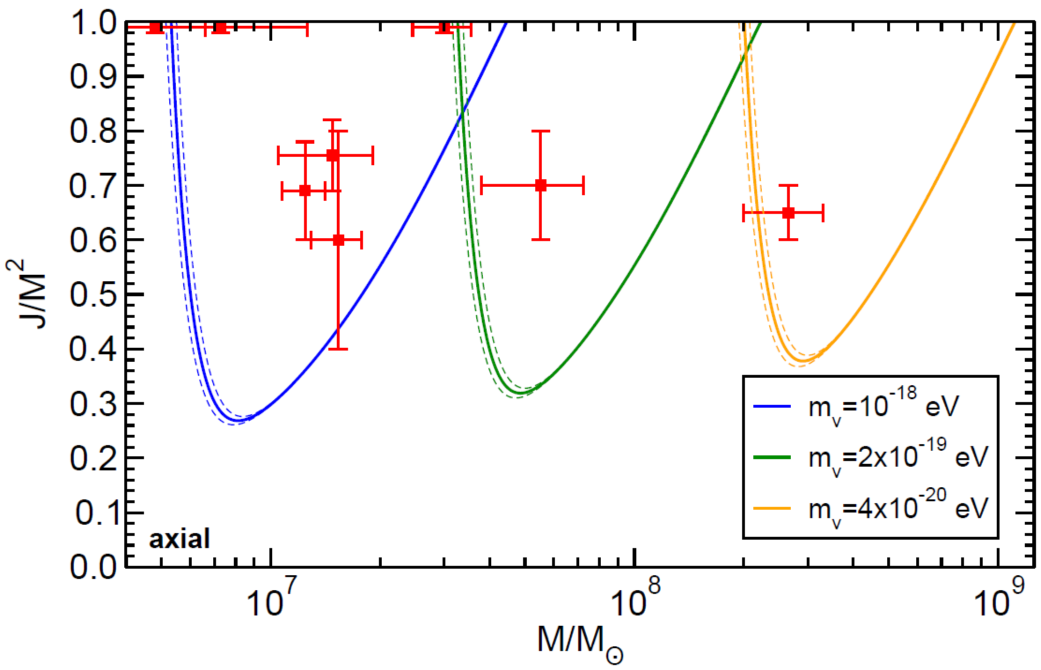


$\mu = 10^{-18}\text{eV}$

Random distributions 1000 BHs, with initial mass between $\log_{10} M_0 \in [4, 7.5]$ and $J_0/M_0^2 \in [0.001, 0.99]$ extracted at $t = t_F$, with t_F distributed on a Gaussian centered at $\bar{t}_F \sim 2 \times 10^9\text{yr}$ with width $\sigma = 0.1\bar{t}_F$.

Bounding the boson mass

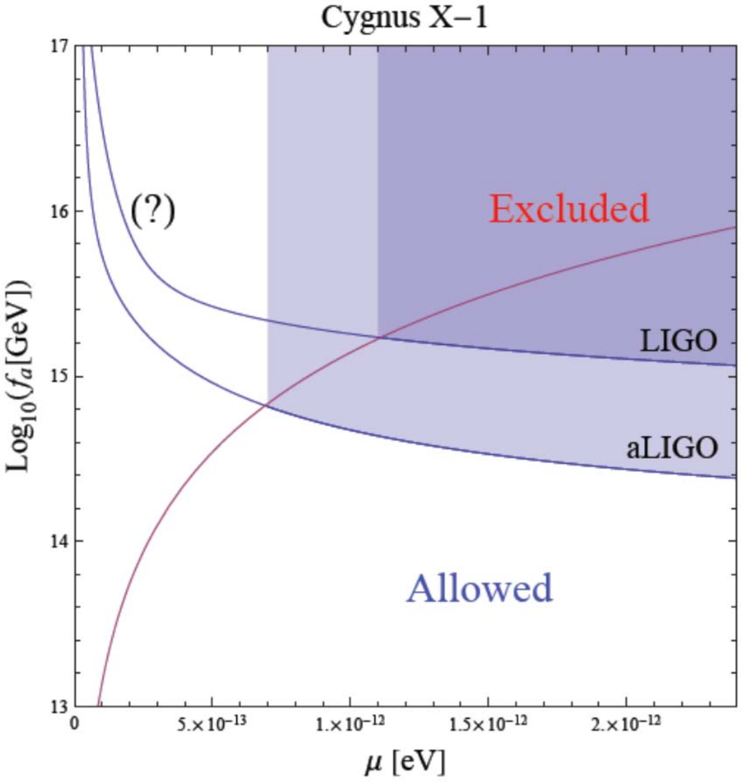
Pani et al PRL109, 131102 (2012)



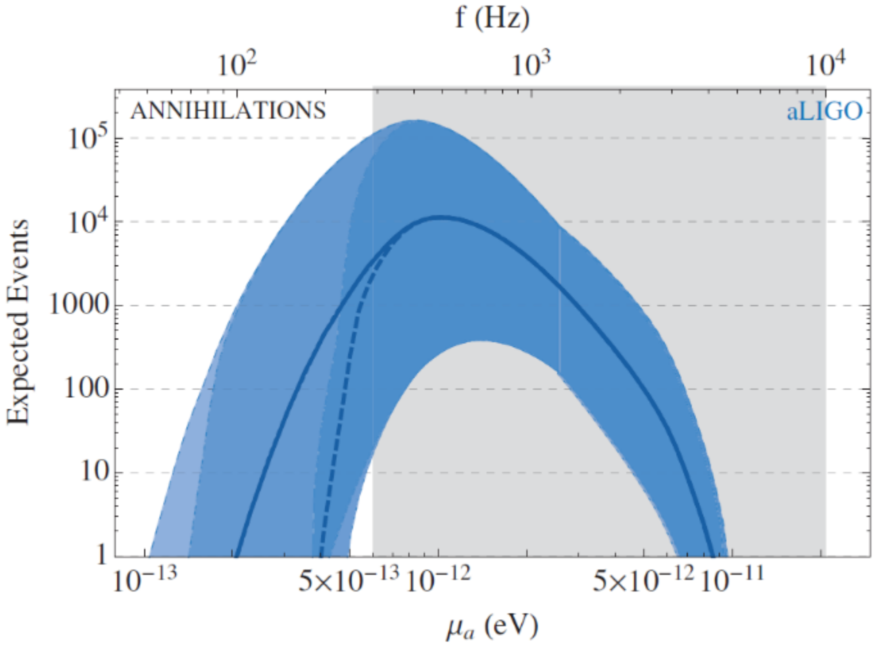
Bound on photon mass is model-dependent: details of accretion disks or intergalactic matter are important...but gravitons interact very weakly!

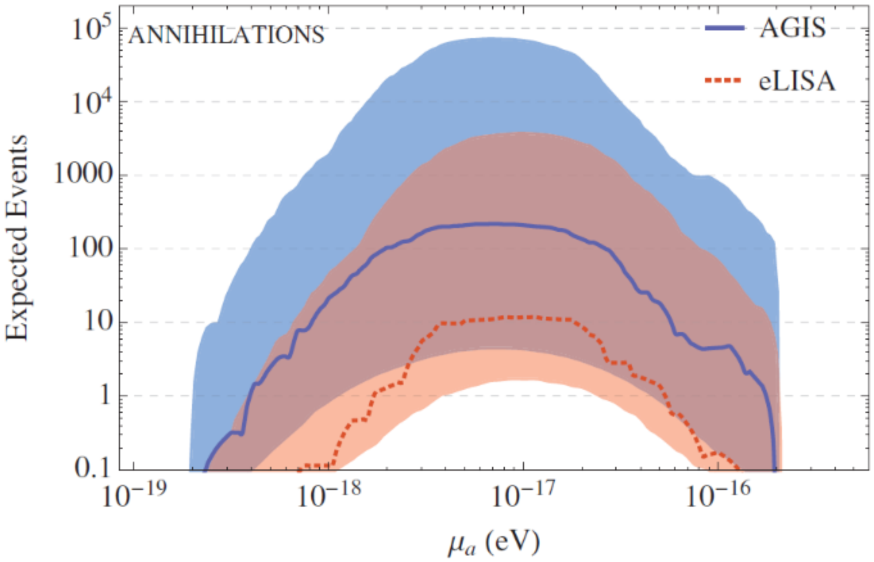
$$m_g < 5 \times 10^{-23}\,\mathrm{eV}$$

Brito et al PRD88:023514 (2013); Review of Particle Physics 2014



Yoshino and Kodama PTEP 2015 6, 061E01





Arvanitaki, Baryakhtar, Huang arXiv:1411.2263

(rates may be overly optimistic)

Strong field gravity is a fascinating topic

* * *

Fundamental fields, either in form of minimally coupled fields or under curvature couplings have a very rich and unexplored phenomenology: condensates outside BHs and compact stars act as gravitational-wave lighthouses, but can also act as dark matter.

* * *

Superradiant instabilities can provide strong constraints on masses of ultra-light bosons, turning black holes into effective particle detectors.

Thank you