David and Goliath: superradiance

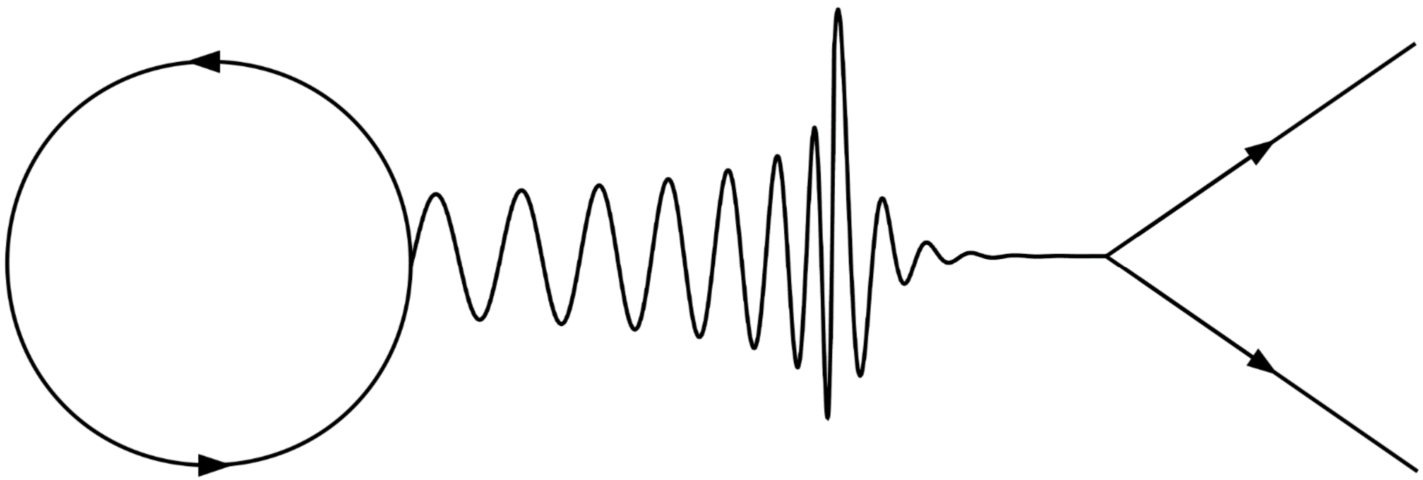
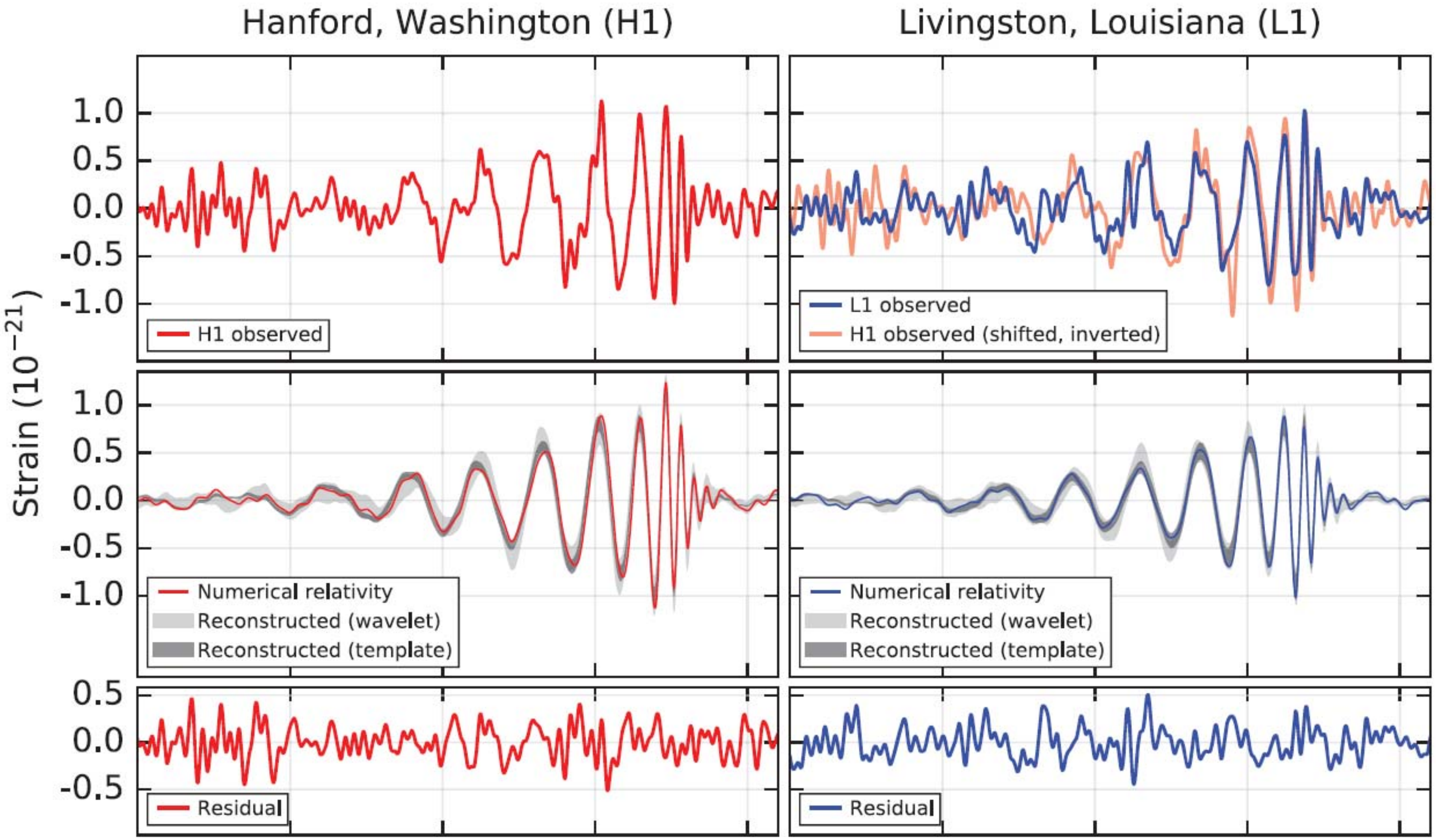


Image: Cardoso & Pani CERN Courier (2016)

Vítor Cardoso

(Técnico & Perimeter)



Masses and spins of initial and final state, localization

Abbott et al, Phys.Rev.Lett.116:061102 (2016)

Fundamental questions

See Barack+ arXiv:1806.05195 for all you need to know about GW science

a. Is cosmic censorship preserved?
Sperhake+ PRL103:131102 (2009)

b. What is maximum possible luminosity?
Gibbons & Barrow MNRAS 446:3874 (2015); Cardoso+ PRD97:084013 (2018)

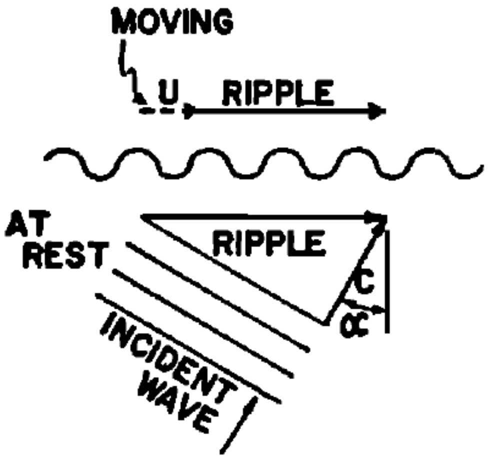
c. What is graviton mass/speed?
Barack+arXiv:1806.05195 (2018)

d. Can GWs from BHs inform us on DM?
Arvanitaki+ PRD95: 043001 (2016); Brito+ PRL119:131101 (2017)

e. Is it a Kerr black hole? Can we constrain alternatives?
Berti+ 2009; 2016; Yang+ 2017; Barausse+2016; Yunes+2016

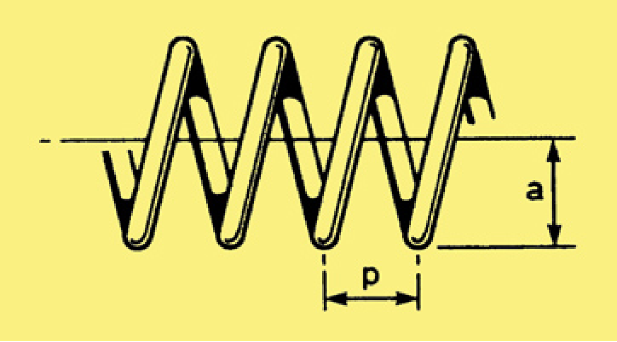
f. Is the final - or initial - object really a black hole?
Cardoso & Pani, Nature Astronomy 1: 586 (2017)

Friction & superradiance

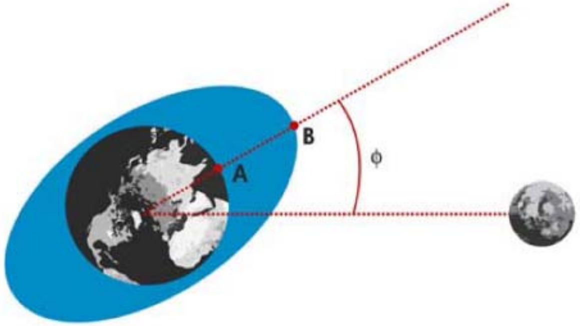


Ribner, J. Acous. Soc. Amer.29 (1957)

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)

A black hole cartoon

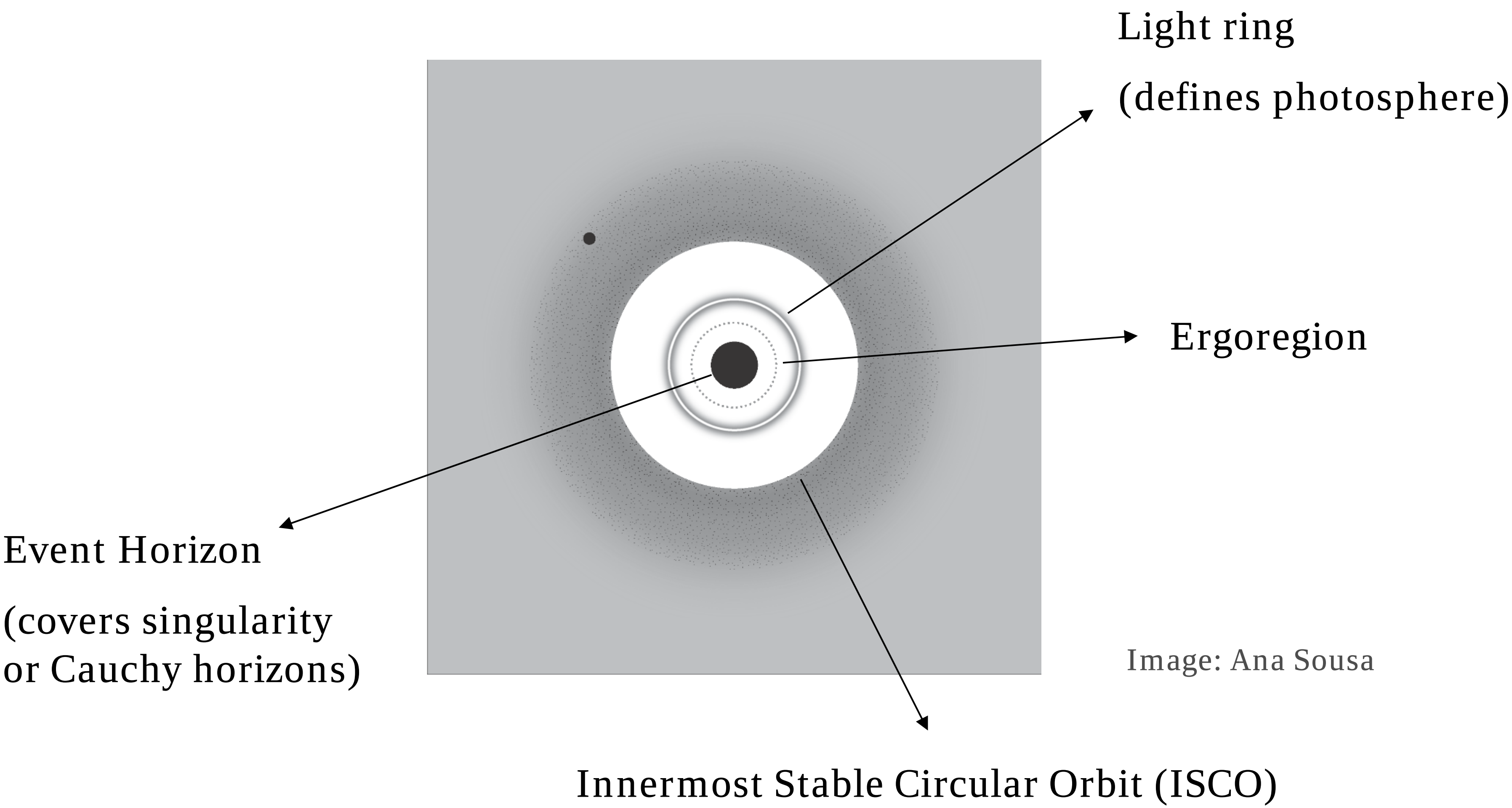
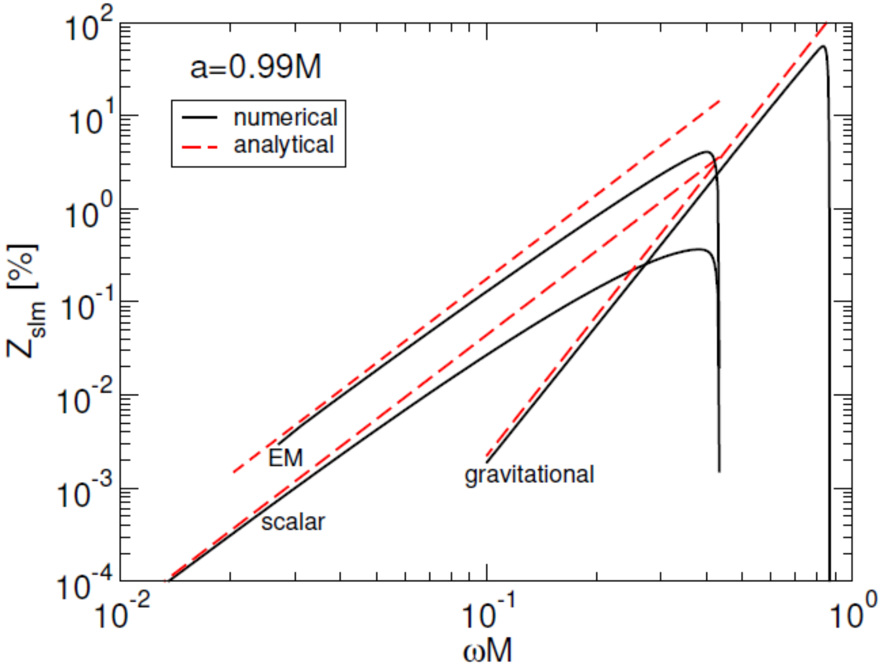
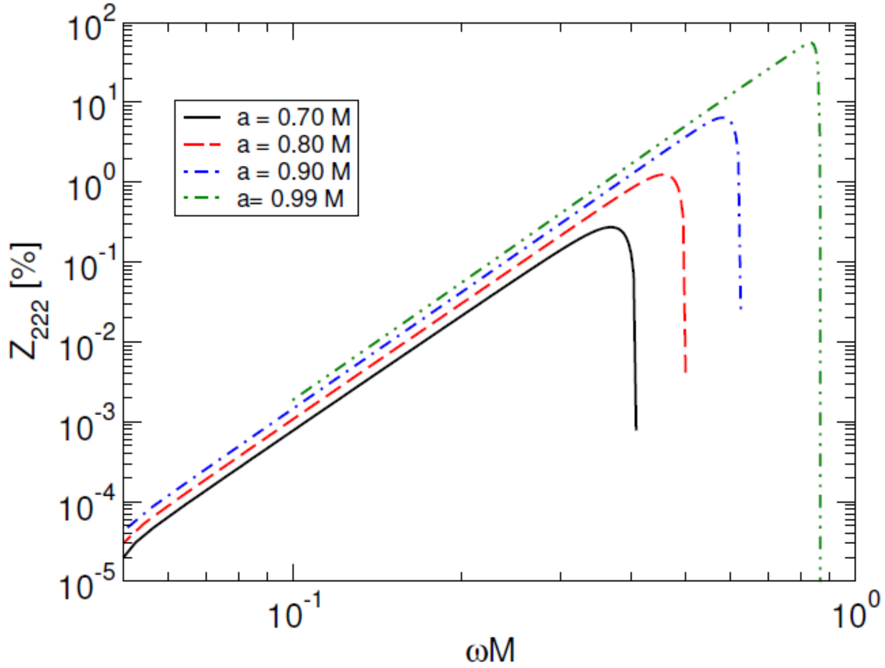


Image: Ana Sousa

Note: ergoregion is at 2M in equator. Outside LR for a>0.7 and outside ISCO for a>0.942



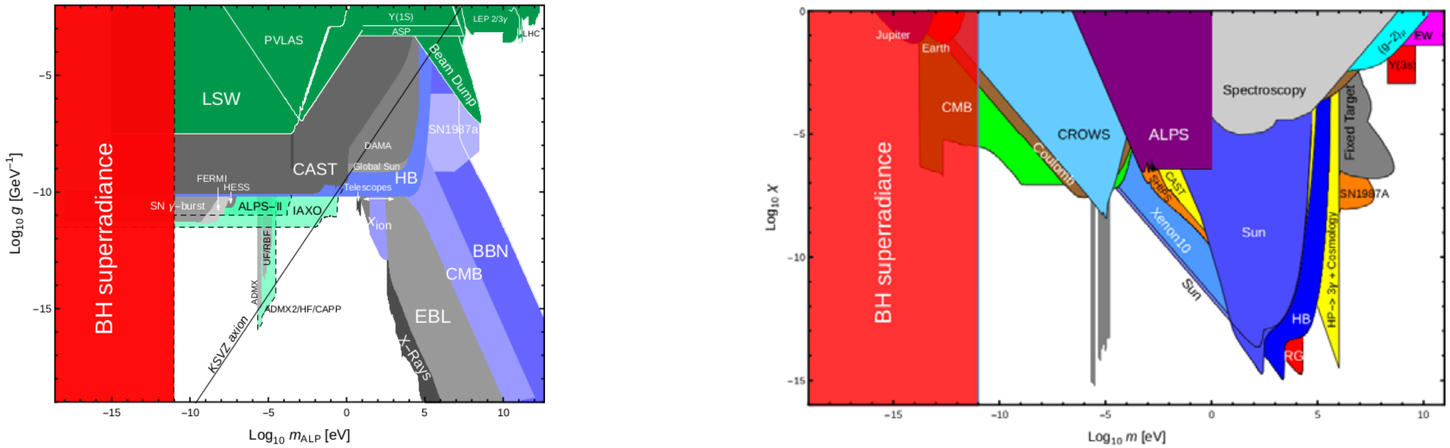


Zel'dovich Pis'ma Zh. Eksp. Teor. Fiz. 14: 270 (*(1971); Press and Teukolsky ApJ193: 443 (1974)*

Brito, Cardoso & Pani, Lect. Notes in Physics 906: 1 (2015); Vicente+ PRD97:084032 (2018)

$$Z = \frac{\text{Flux out} - \text{Flux in}}{\text{Flux out}}$$

Light bosonic fields



Cardoso+ 2018, adapted from Sigl (Atlantis Press 2017) and Jaeckel (Frascati series arXiv:1303.1821)

Interesting as effective description; proxy for more complex interactions

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

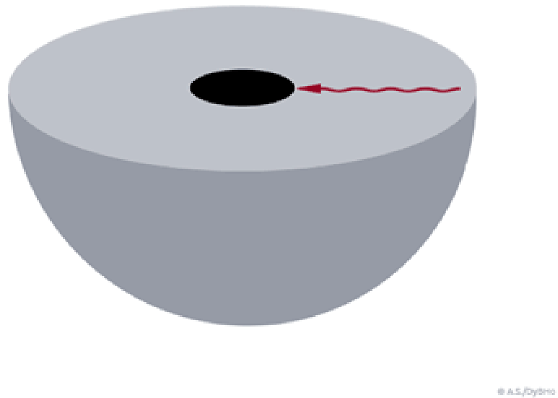
They exist (Higgs) or might exist

Peccei-Quinn (interesting because not invented to solve DM problem)

Axiverse scenarios - moduli and coupling constant in string theory

...and one or more could be a component of DM

Bounding the boson mass



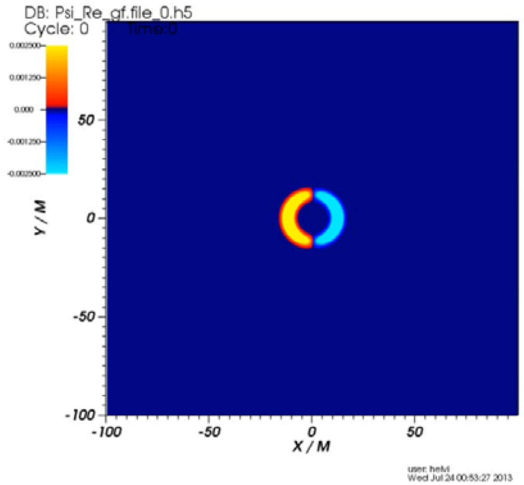
$$\tau \sim 100 \left(\frac{10^6 M_\odot}{M}\right)^8 \left(\frac{10^{-16}\mathrm{eV}}{\mu}\right)^9 \text{ seconds}$$

Massive “states” around Kerr are linearly unstable

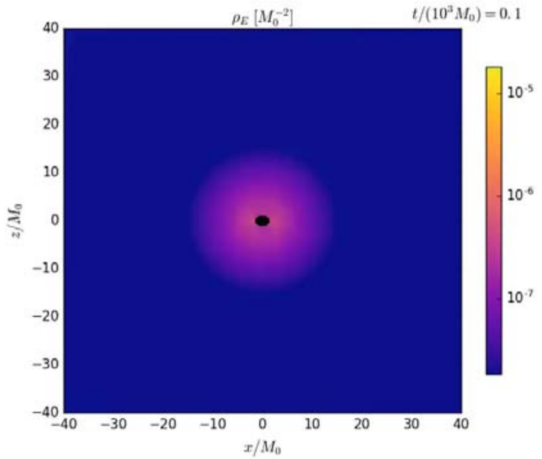
Detweiler PRD22:2323 (1980); Cardoso & Yoshida JHEP0507:009 (2005)

See review Brito + arXiv:1501.06570

Bounding the boson mass



Witek+ PRD87: 043513 2013



East & Pretorius PRL119:041101 2017

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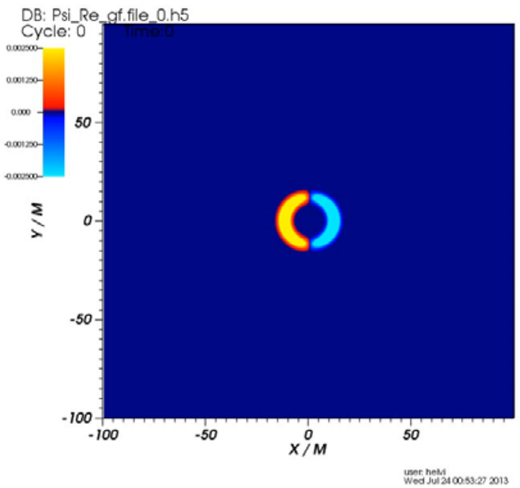
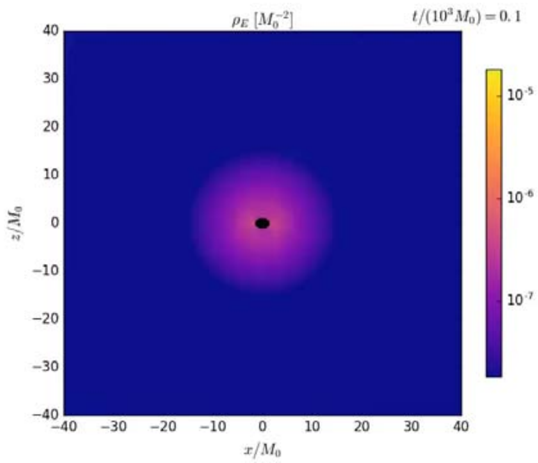


Witek+ PRD87: 043513 2013



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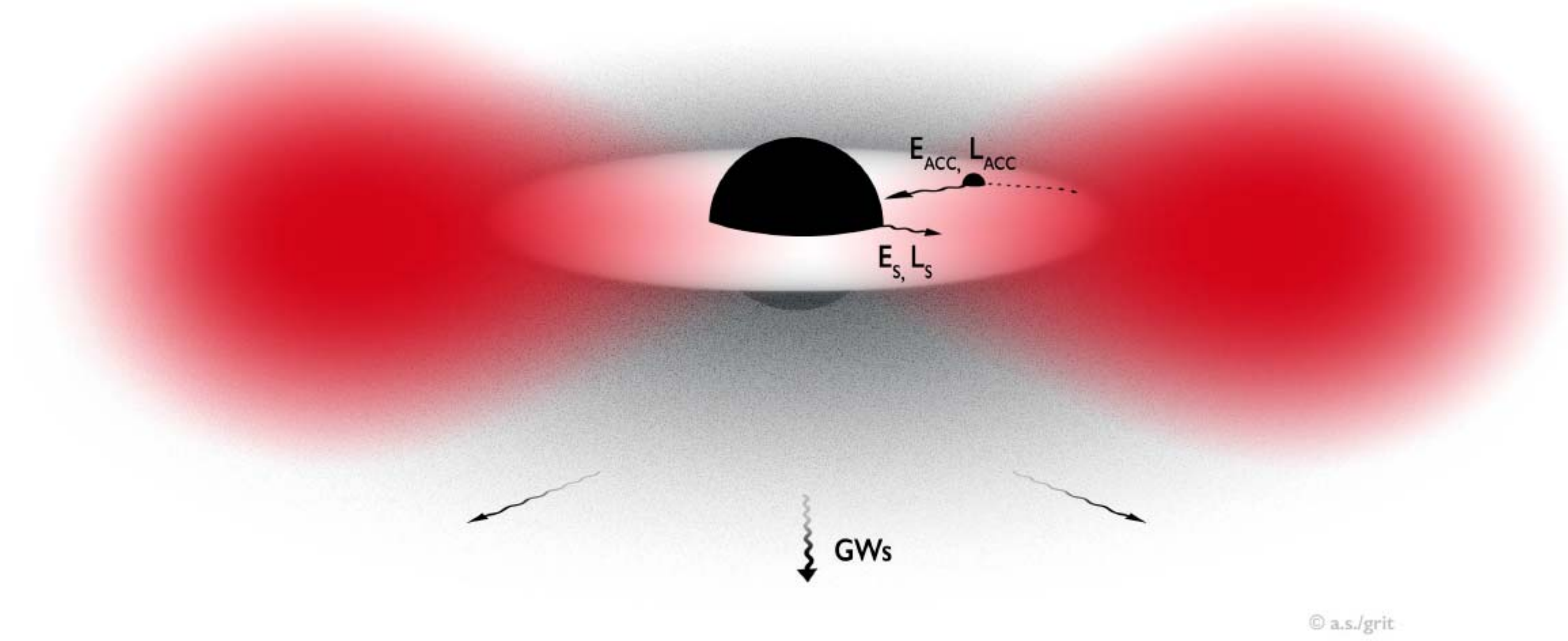
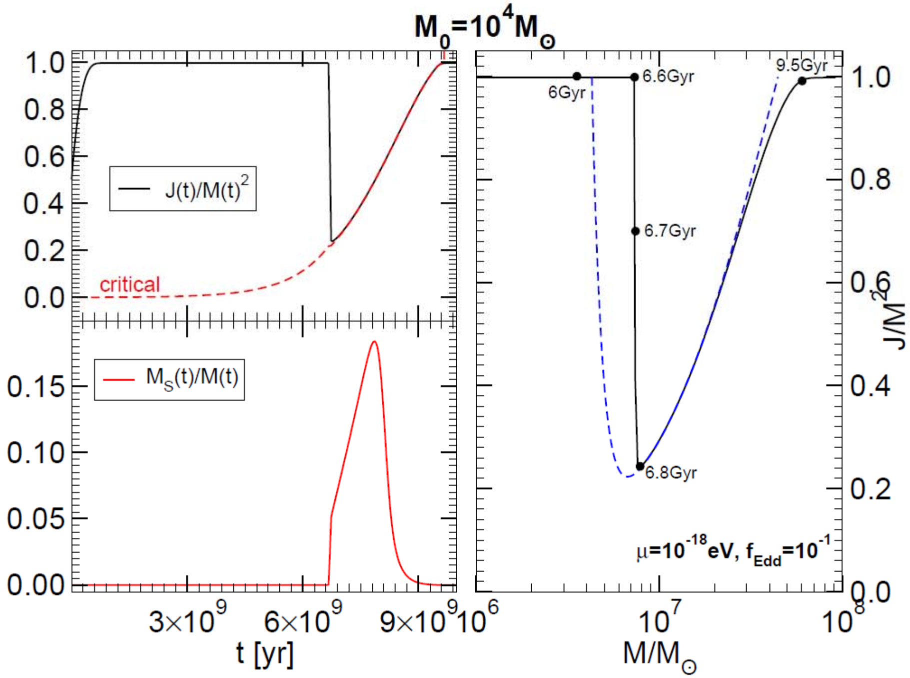
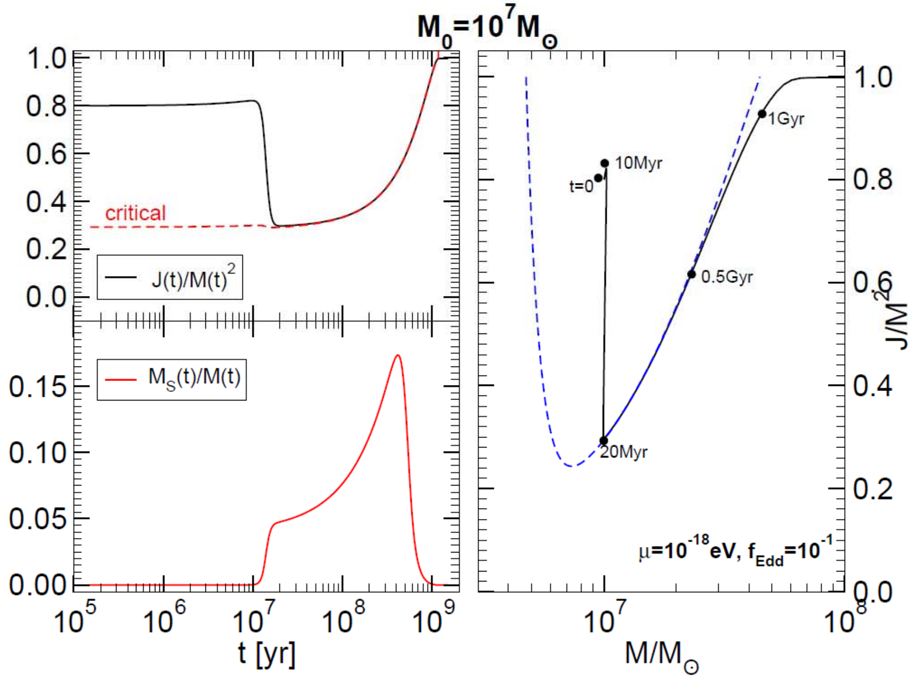


Brito, Cardoso, Pani CQG32:134001 (2015)

Brito, Cardoso & Pani, Lecture Notes Physics 906: 1-237 (2015) j=0.5, μM=0.0001



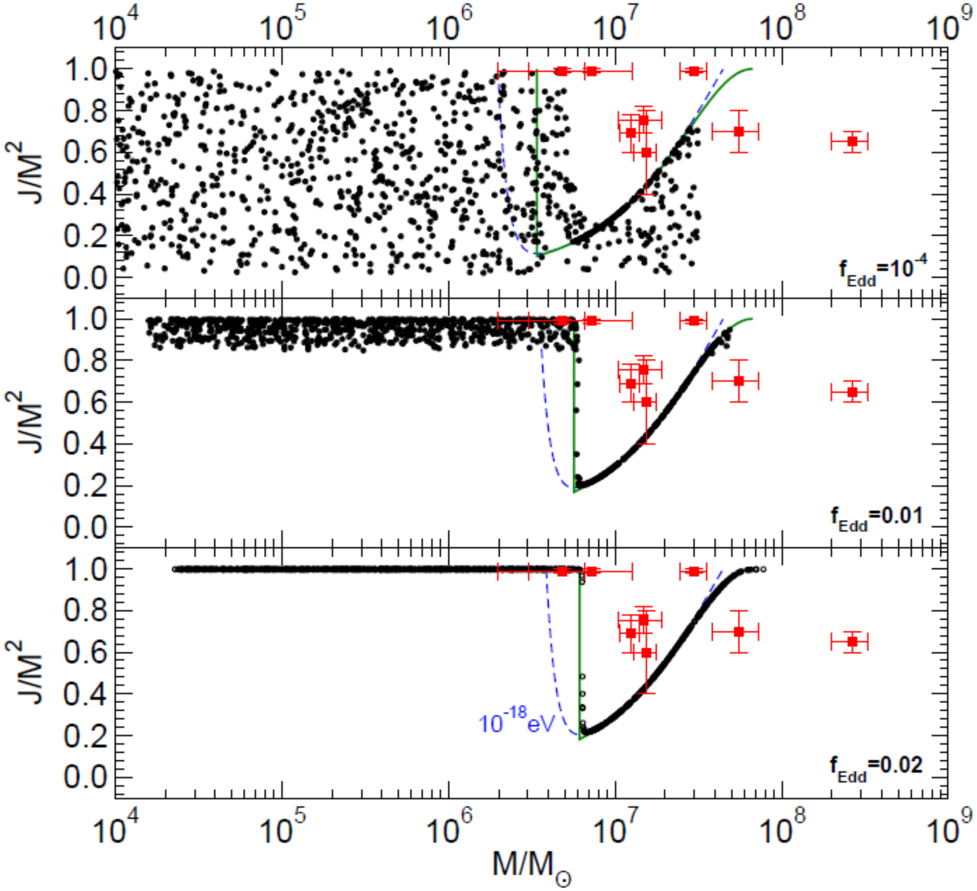
j=0.8, μM=0.1



Brito et al CQG32: 134001 (2015)

Holes in Regge plane

Brito, Cardoso, Pani CQG32: 134001 (2015)

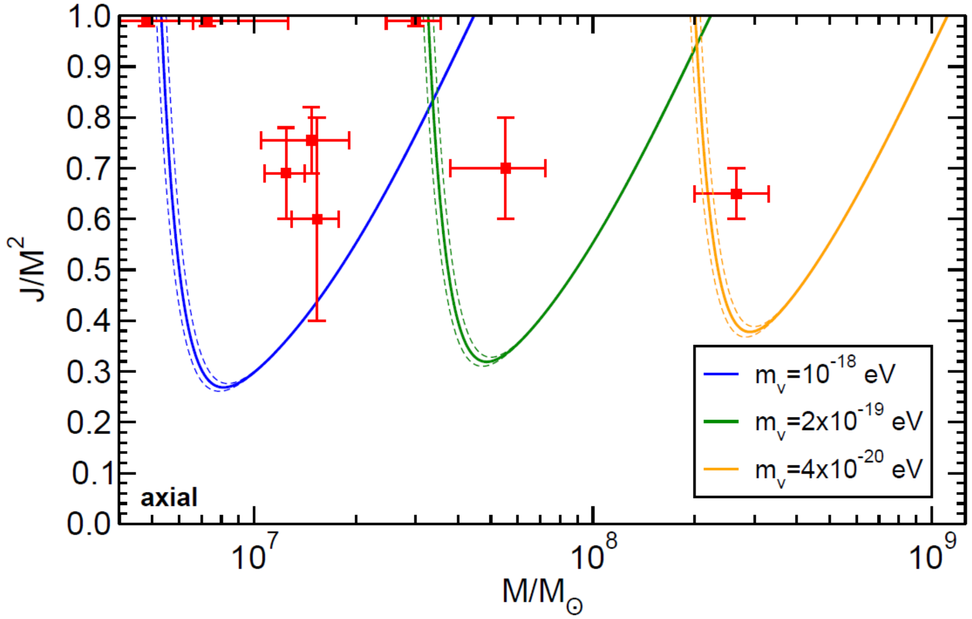


$$\mu = 10^{-18}\text{eV}$$

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 $\bar{t}_F \sim 2 \times 10^9$yr with width $\sigma = 0.1\bar{t}_F$.

Bounding the boson mass

Pani et al PRL109, 131102 (2012)

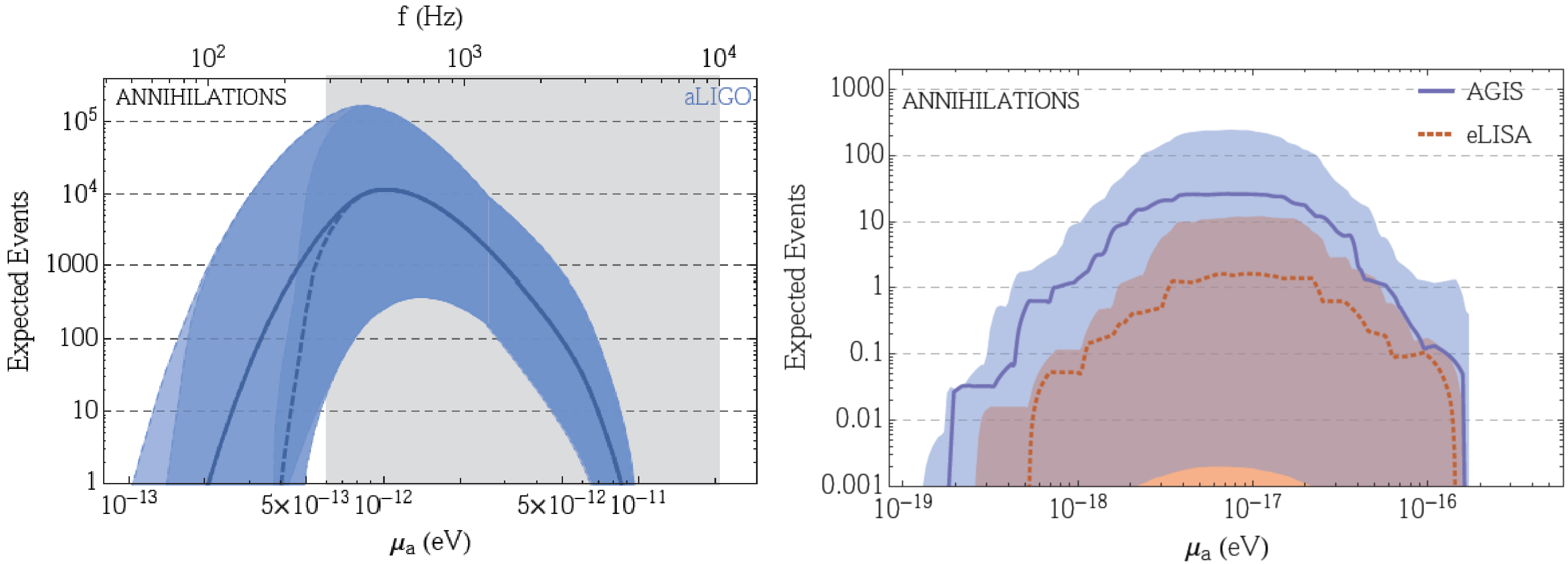


Bound on photon mass is model-dependent: details of accretion disks or intergalactic matter are important… but gravitons interact very weakly!

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

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

Wonderful sources for different GW-detectors!



Arvanitaki+ PRD91:084011 (2015)

Wonderful sources for different GW-detectors!

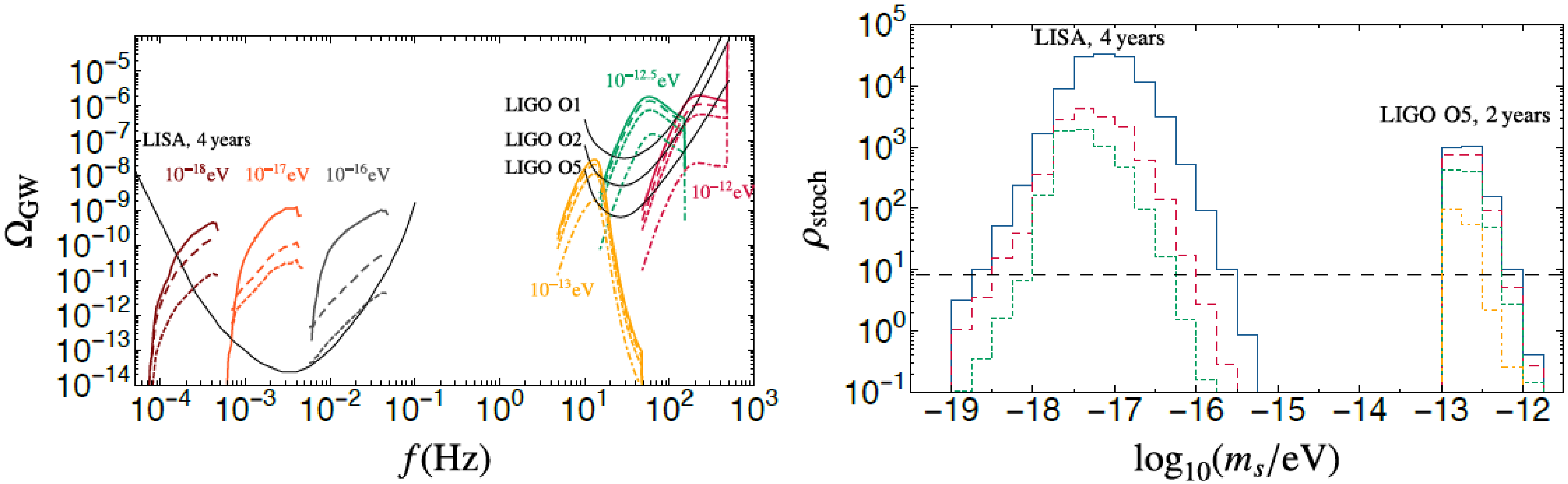
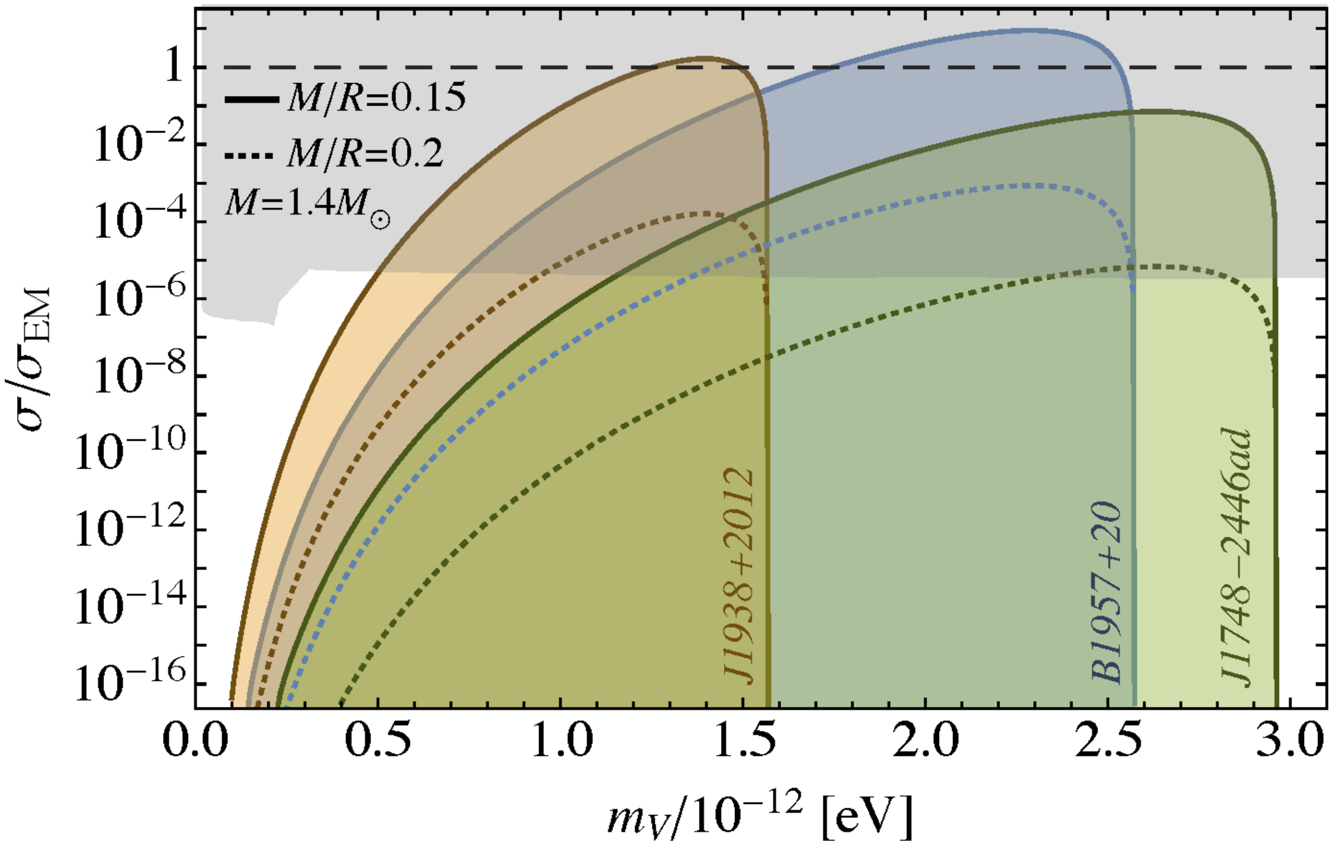


FIG. 2. Left panel: stochastic background in the LIGO and LISA bands. For LISA, the three different signals correspond to the "optimistic" (top), "less optimistic" (middle) and "pessimistic" (bottom) astrophysical models. For LIGO, the different spectra for each scalar field mass correspond to a uniform spin distribution with (from top to bottom) $\chi_i \in [0.8, 1]$, $[0.5, 1]$, $[0, 1]$ and $[0, 0.5]$. The black lines are the power-law integrated curves of Ref. [61], computed using noise PSDs for LISA [9], LIGO's first two observing runs (O1 and O2), and LIGO at design sensitivity (O5) [62]. By definition, $\rho_{\rm stoch} \geq 1$ when a power-law spectrum intersects one of the power-law integrated curves. Right panel: $\rho_{\rm stoch}$ for the backgrounds shown in the left panel. We assumed $T_{\rm obs} = 2$ yr for LIGO and $T_{\rm obs} = 4$ yr for LISA.

Brito + PRL119: 131101 (2017); arXiv:1706.05097

PRD96:064050 (2017); arXiv:1706.06311

Stars?



Exclusion plots for known pulsars, based on measured spin-down rates. M is assumed to be M=1.4 $M_{\rm sun}$. Grey is excluded region from CMB distortion (photon->X depletion)

V. Cardoso, P. Pani and T-t Yu PRD95: 124056 (2017); arXiv:1704.06151

Couplings and lasers

$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi - \frac{\mu_S^2}{2}\Psi\Psi - \frac{k_{\rm axion}}{2}\Psi\,{}^*F^{\mu\nu}F_{\mu\nu}$$

Blasts of EM radiation for

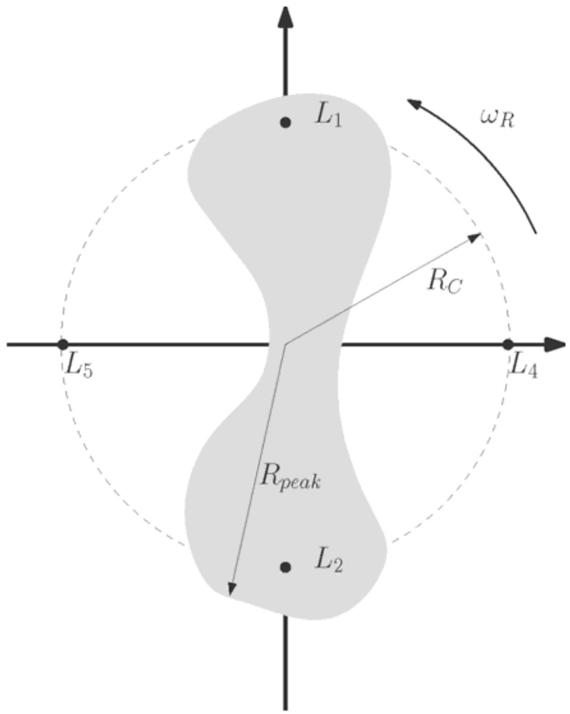
$\mu > 10^{-8}$eV, M<0.01 $M_{\rm sun}$

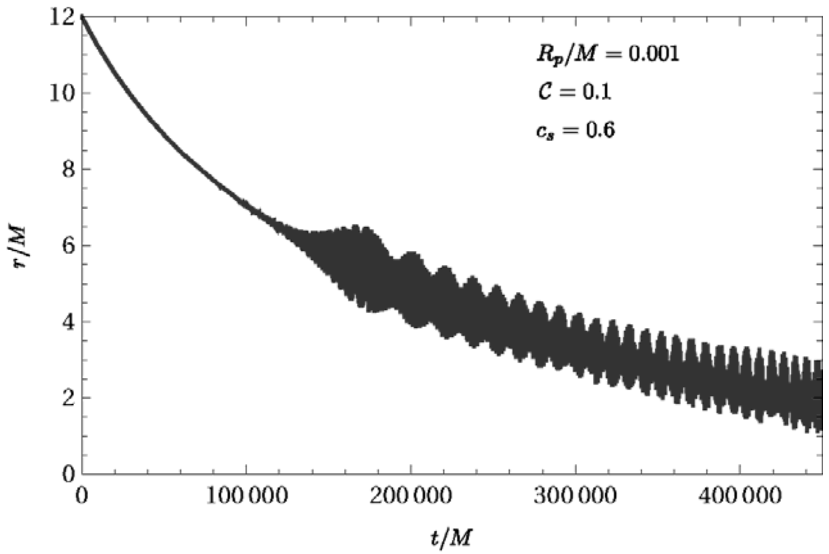
See João Rosa's talk

J. G. Rosa and T. W. Kephart arXiv:1709.06581

S. Sen arXiv:1805.06471

Orbital motion of stars and planets





C. Macedo+ PRD96:083017 (2017)

M. Boskovic+, to appear (2018)

Phenomenology and open questions

Can we measure (rotational) superradiance? T. Torres+ 2017

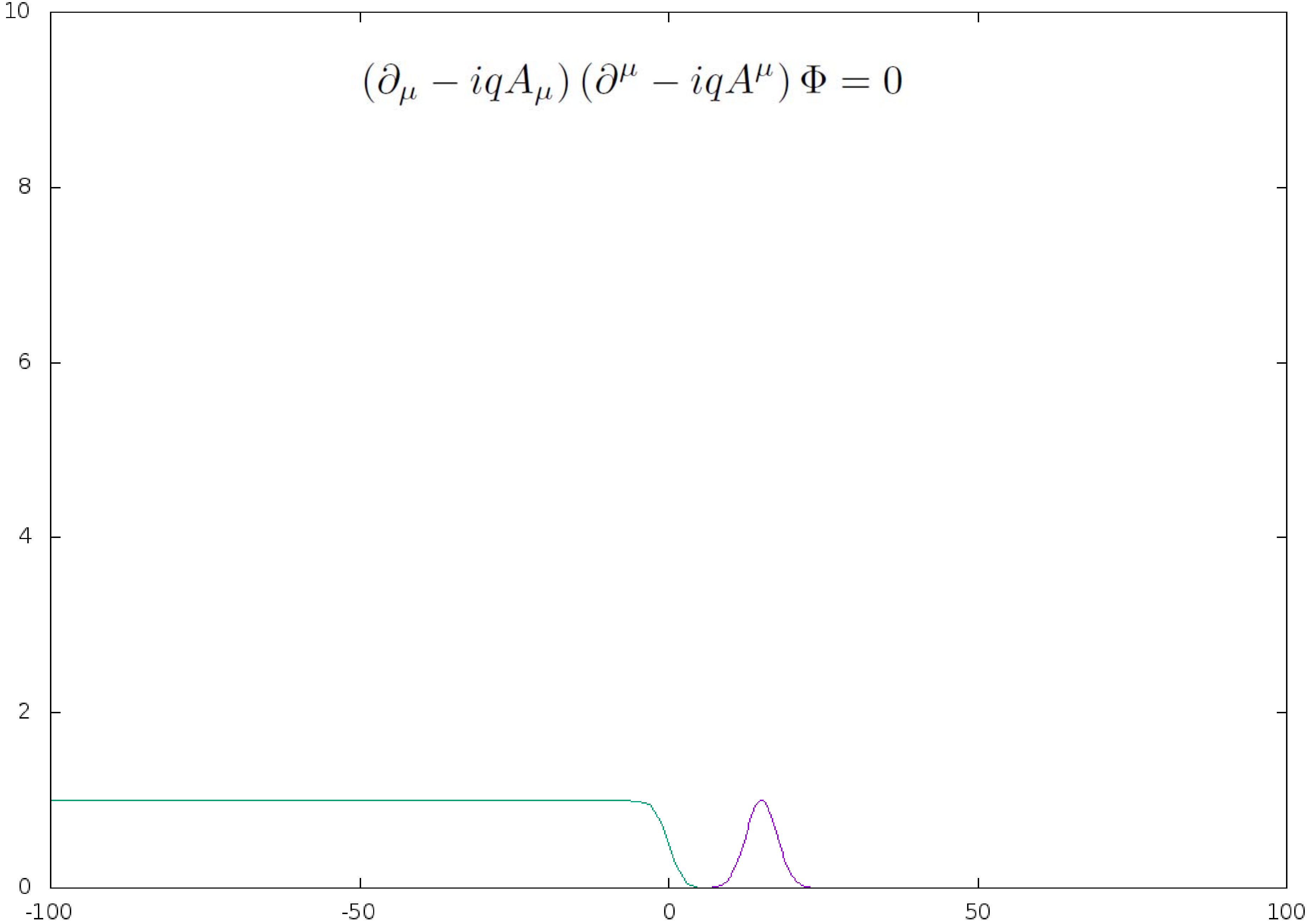
Is there a maximum amplification factor?

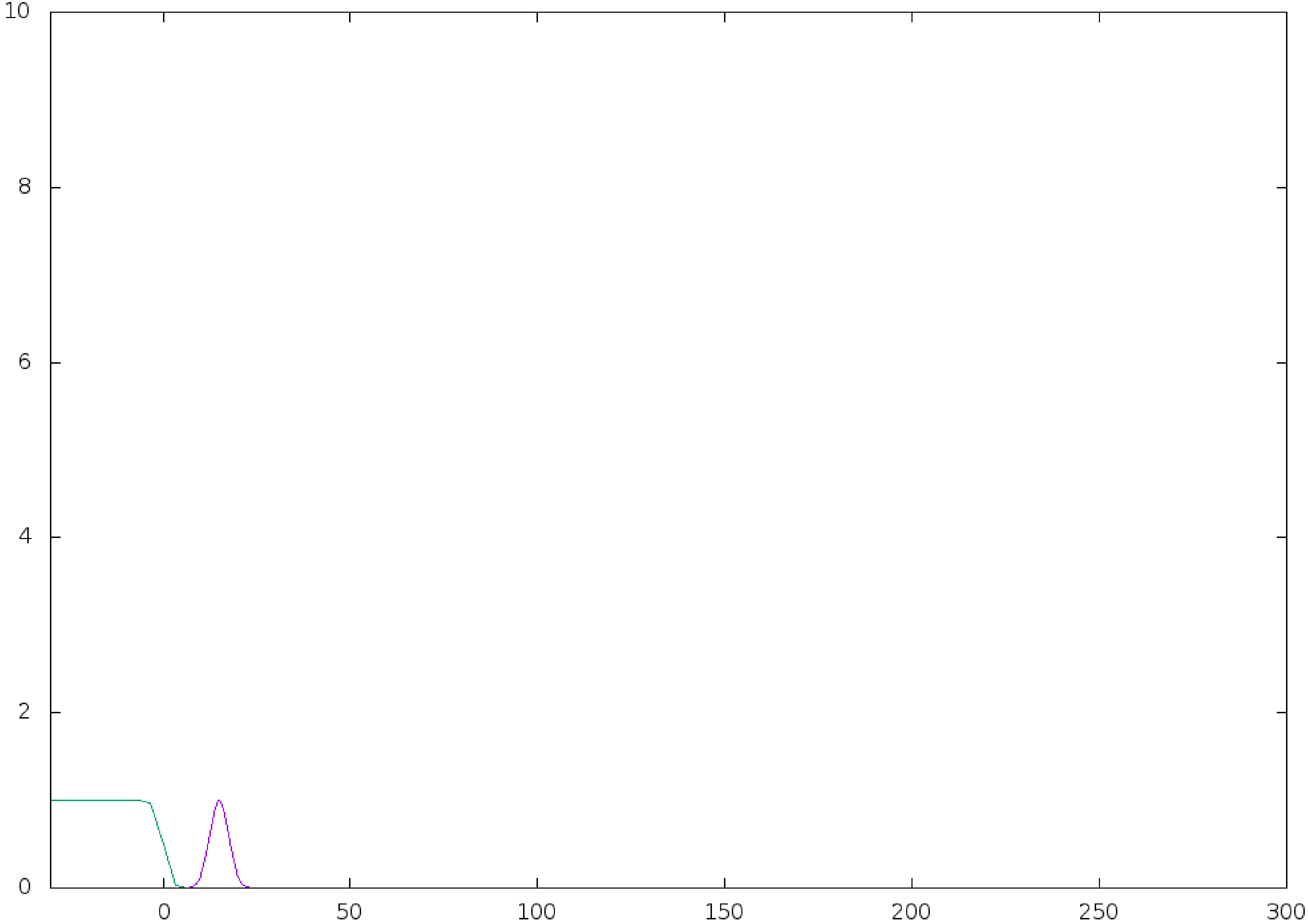
Do BH binaries superradiate?

End-state of superradiant instabilities?

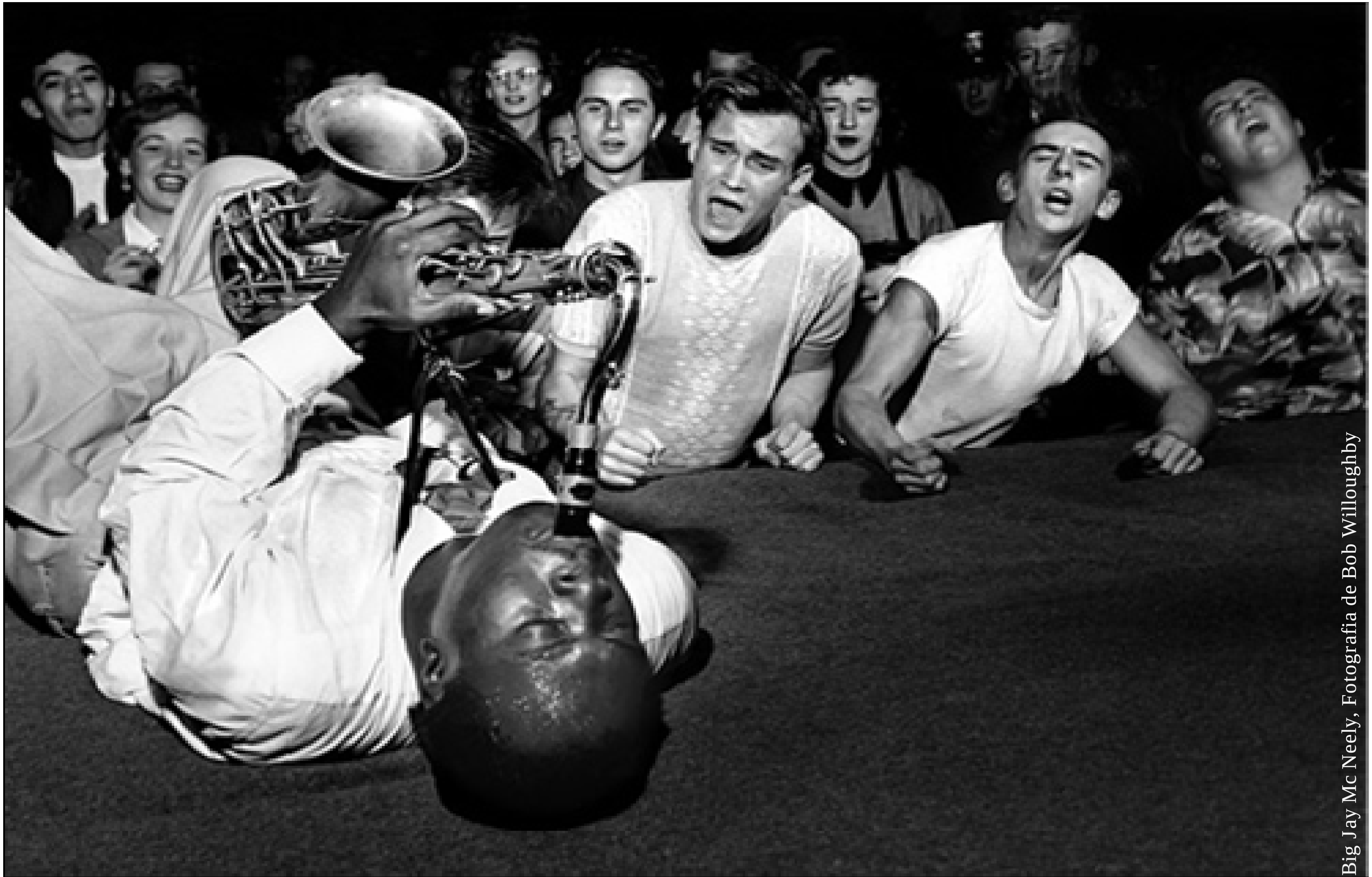
Penrose process & superradiance & fermions-bosons R.Vicente+ 2018

Coupling to disks and/or magnetic fields?


$(\partial_\mu - iqA_\mu)(\partial^\mu - iqA^\mu)\Phi = 0$
10
8
6
4
2
0
-100
-50
0
50
100



10
8
6
4
2
0
0
50
100
150
200
250
300



Big Jay Mc Neely, Fotografia de Bob Willoughby

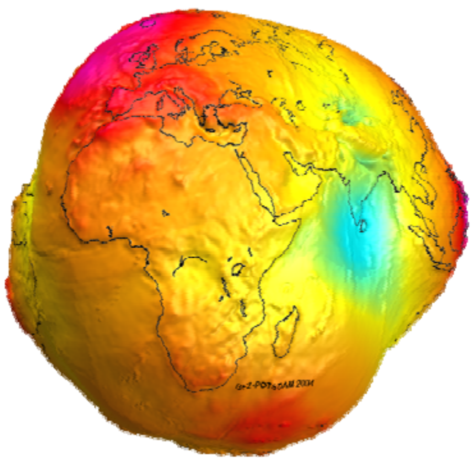
“Imagine being able to see the world but you are deaf, and then suddenly someone gives you the ability to hear things as well - you get an extra dimension of perception” B. Schutz, BBC

Thank you

Black holes have no hair

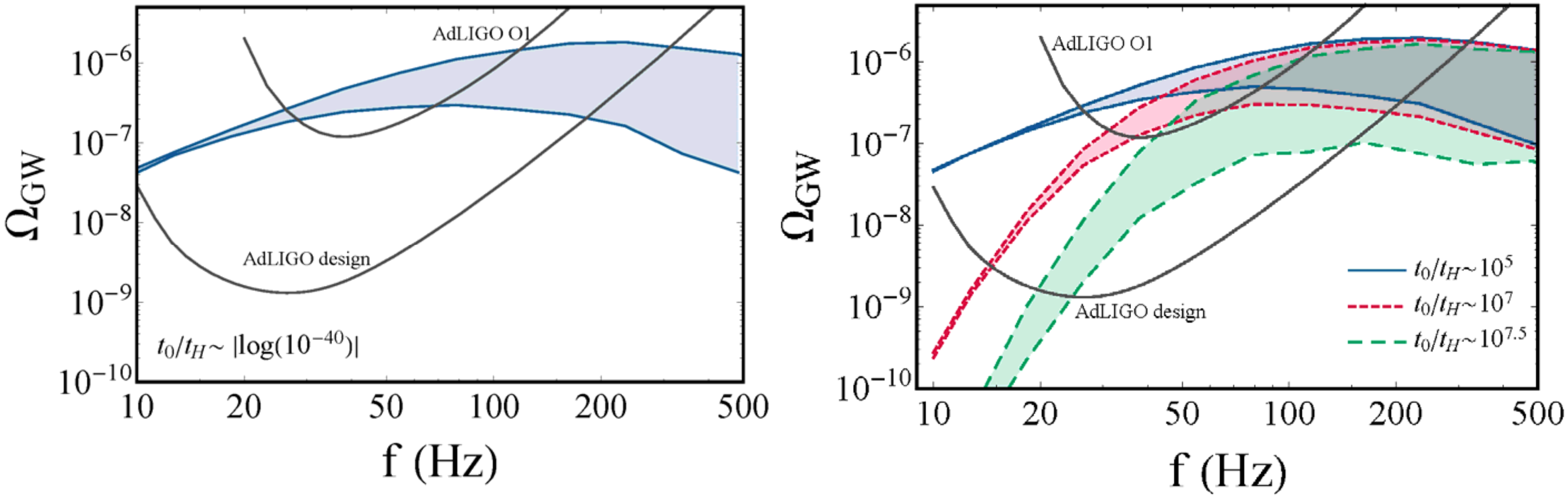
Theorem 1: Isolated, stationary, regular BHs in the Einstein-Klein-Gordon with a *time-independent boson* are described by Kerr family (impossible to hold the hair)

Theorem 2: Isolated, stationary, regular BHs in the Einstein-Klein-Gordon theory with *one real scalar* are described by Kerr family (impossible not to radiate GWs)



A stationary BH in vacuum is characterized by **mass and spin**

BHs are super-absorbers too!
stochastic background of GWs



Brito+ (2018)

"I made at once by good luck a search for a full solution. A not too difficult calculation gave the following result: ..."

K. Schwarzschild to A. Einstein
(Letter dated 22 December 1915)

Solution re-discovered by many others:

J. Droste, May 1916 (part of PhD thesis under Lorentz):
Same coordinates, more elegant

P. Painlevé, 1921, A. Gullstrand, 1922: P-G coordinates
(did not realize solution was the same)

...and others

Uniqueness: the Kerr solution

Theorem (Carter 1971; Robinson 1975):
A stationary, asymptotically flat, regular vacuum solution must be Kerr

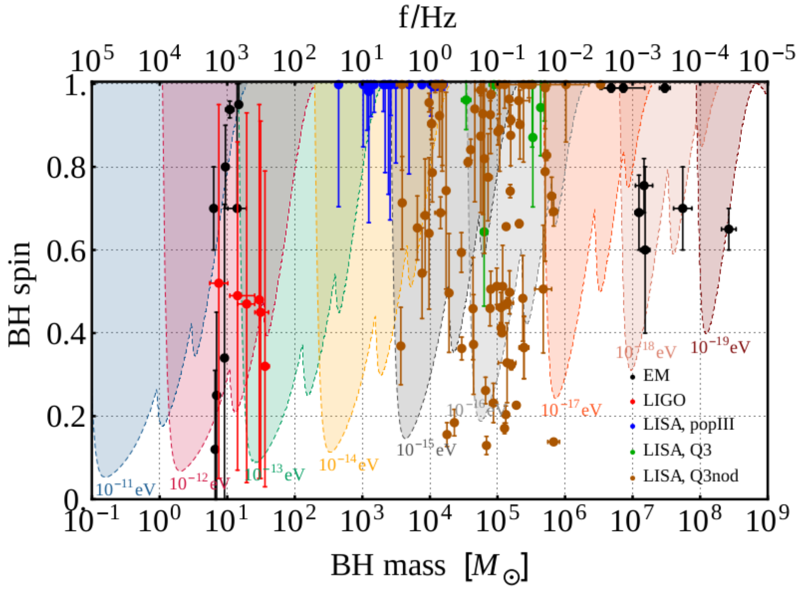
$$\begin{aligned} ds^2 &= \frac{\Delta - a^2 \sin^2\theta}{\Sigma} dt^2 + \frac{2a(r^2+a^2-\Delta)\sin^2\theta}{\Sigma} dt d\phi \\ &- \frac{(r^2+a^2)^2 - \Delta a^2 \sin^2\theta}{\Sigma} \sin^2\theta d\phi^2 - \frac{\Sigma}{\Delta} dr^2 - \Sigma d\theta^2 \end{aligned}$$

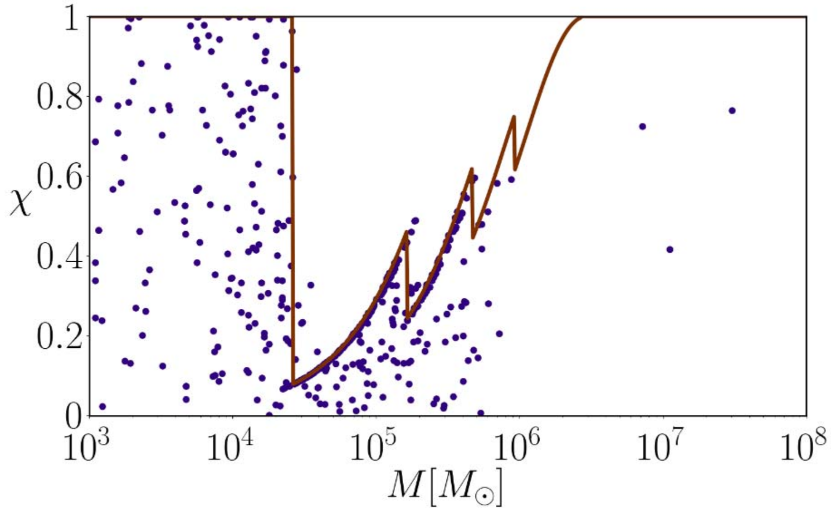
$$\Sigma = r^2 + a^2 \cos^2\theta\,, \quad \Delta = r^2 + a^2 - 2Mr$$

Describes a rotating BH with mass M and angular momentum J=aM

“In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein’s equations of general relativity provides the *absolutely exact representation* of untold numbers of black holes that populate the universe.”

S. Chandrasekhar, The Nora and Edward Ryerson lecture, Chicago April 22 1975





Two-year simulation for LISA and a boson with 10^{-16} eV. Final estimate from LISA: $(0.88 - 1.35) \times 10^{-16}$ eV

Brito +, PRL119: 131101 (2017); arXiv: 1706:05097

PRD96:064050 (2017); arXiv: 1706.06311

Between electron (0.5 MeV) & Hubble scale (10^-33 eV):

40 orders of magnitude.

New fundamental scales could set in and populate seemingly forlorn arena.

$$\nabla_\gamma \nabla^\gamma \Phi = \boxed{\mu_{\mathrm{S}}^2} \Phi$$
$$\nabla_\gamma F^{\gamma\nu} = \boxed{\mu_{\mathrm{V}}^2} A^\nu$$
$$\nabla_\gamma \nabla^\gamma h_{\mu\nu} = \boxed{\mu_{\mathrm{T}}^2} h_{\mu\nu}$$

Superradiance

Vítor Cardoso

(Técnico & Perimeter)