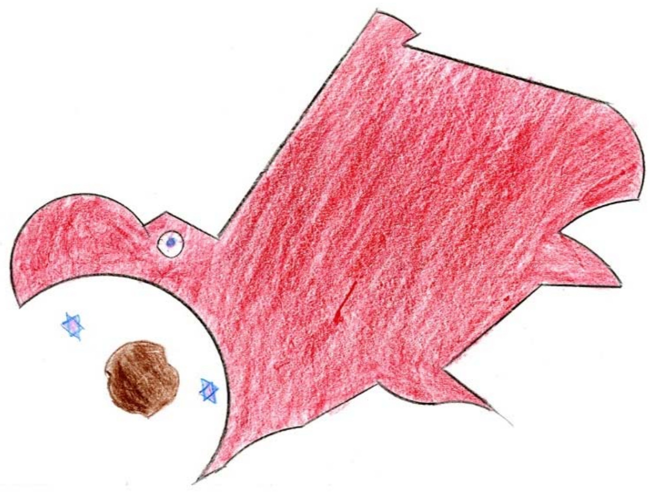
Bumpy black holes



(Drawing depicting a black hole by Clara Vasconcelos, Dr. Horácio Bento de Gouveia Middle School)

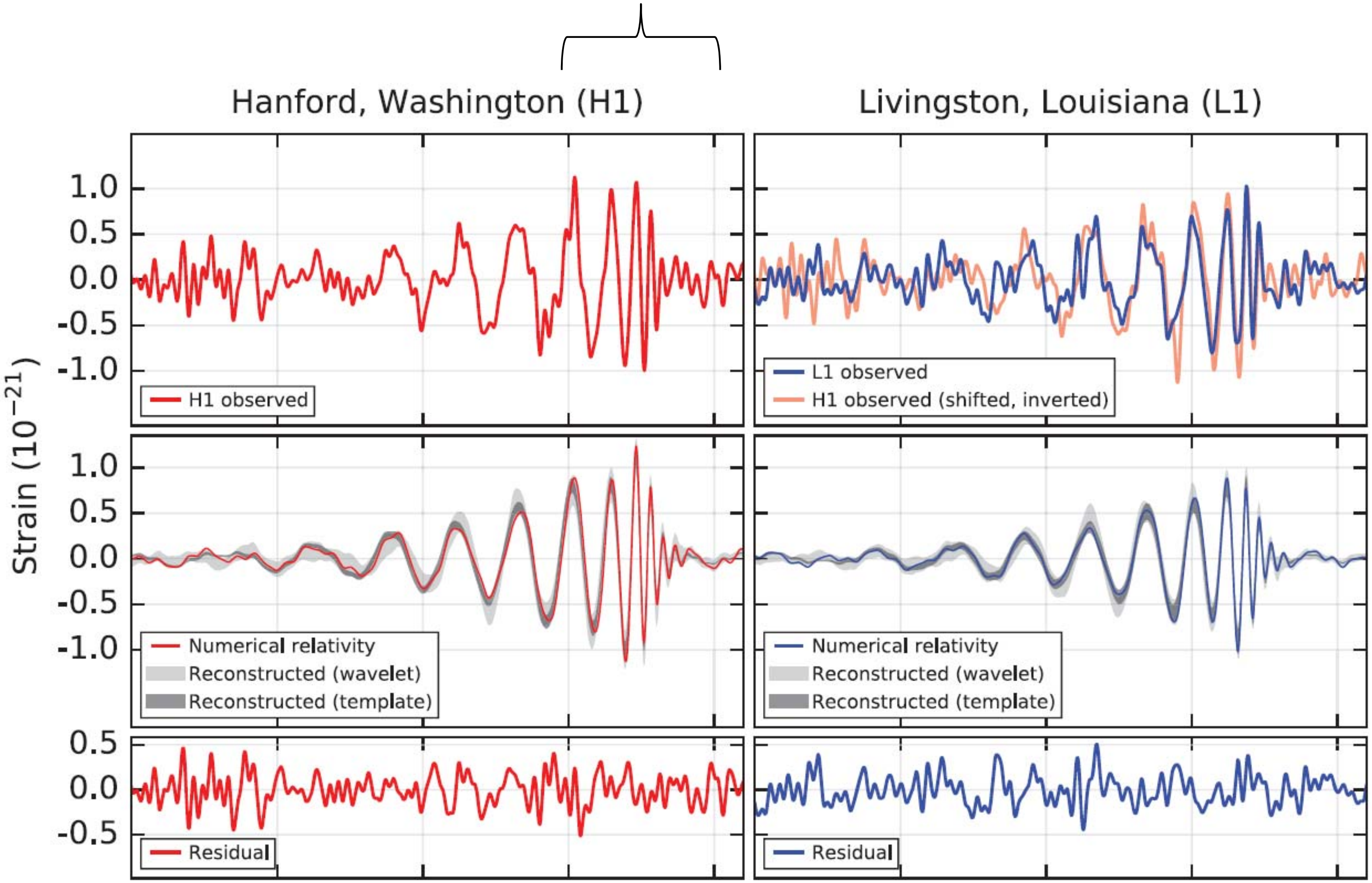
Vítor Cardoso

CENTRA/Técnico & Perimeter

(Caltech 2016)

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

0.05 secs (~80 Schwarzschild radius)



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

1. Are we observing black holes (either as initial or final states)?

2. Are these Kerr black holes?

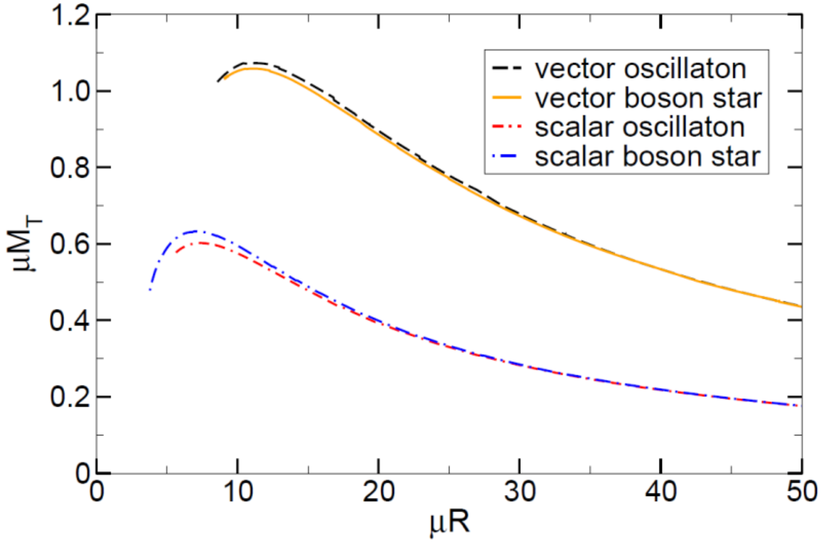
Compact Objects

Boson Stars, oscillatons, etc

(Kaup 1968; Ruffini, Bonazzolla 1969; Colpi et al 1986; Okawa et al 2014; Brito et al 2015)

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{\kappa} - \frac{1}{2}g^{\mu\nu}\bar{\Psi}_{,\mu}\Psi_{,\nu} - \frac{\mu_S^2\bar{\Psi}\Psi}{2}\right)$$

$$\frac{M_{\max}}{M_\odot} = 8\times 10^{-11}\frac{\text{eV}}{m_B c^2}$$



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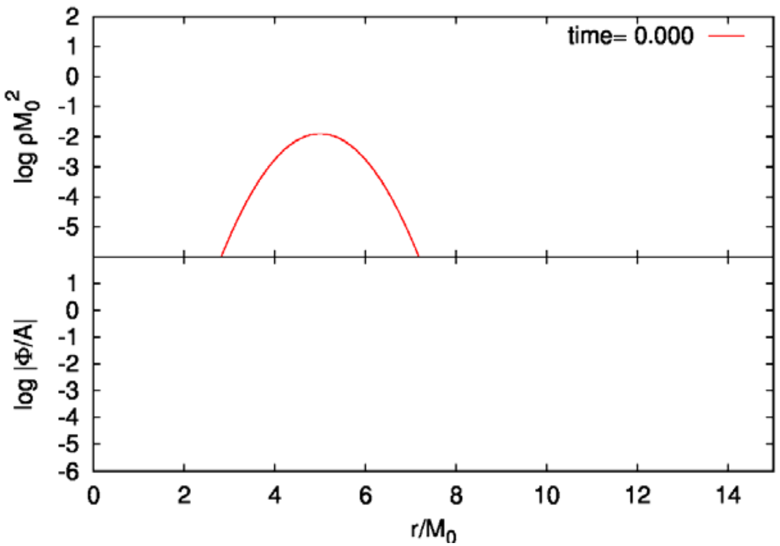
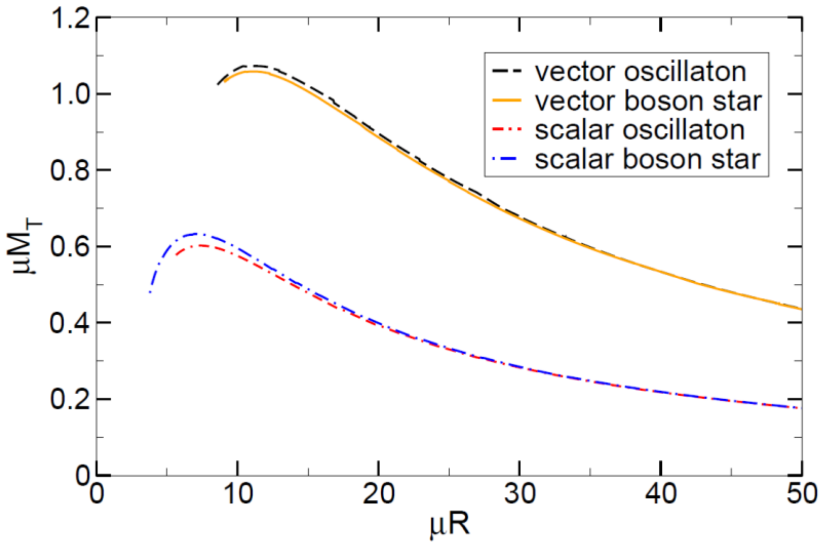




Boson Stars, oscillatons, etc

(Kaup 1968; Ruffini, Bonazzolla 1969; Colpi et al 1986; Okawa et al 2014; Brito et al 2015)

Wormholes

(Morris, Thorne 1988; Visser 1996)

Gravastars

(Mazur, Mottola 2001)

Superspinars (super-extremal Kerr, singularity cut-off)

(Gimon, Horava 2009)

Challenge: Do these objects form?

Black holes

Theorem (Carter 1971; Robinson 1975):

A stationary, asymptotically flat, vacuum regular solution must be Kerr

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

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

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

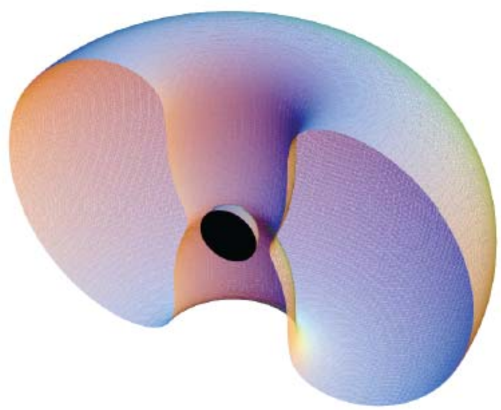
Hairy Kerr in minimally coupled KG theory (BS with BH at center)

(Herdeiro, Radu 2014)

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{\kappa} - \frac{1}{2} g^{\mu\nu} \bar{\Psi}_{,\mu} \Psi_{,\nu} - \frac{\mu_S^2 \bar{\Psi}\Psi}{2} \right)$$

Evade no-hair theorems with complex, time-dependent scalars but time-independent stress-tensor (prevents hair from falling *out*)

Superradiance prevents hair from falling *in* (Herdeiro and Radu 2014)



Challenge: are these solutions linearly stable?

Anisotropic fluid hair

(Brown, Hussain 1997)

Black holes in EYM theory (with SU(2) gauge group, “colored BHs”)

(Bizon 1990)

Einstein-dilaton-Gauss-Bonnet

(Zwiebach 1985; Berti et al 2015)

$$S = \int d^4x\sqrt{-g}\left(R - \frac{1}{2}\partial_a\phi\partial^a\phi + \frac{\alpha}{4}e^{\phi}\mathcal{R}^2\right)$$

$$\mathcal{R} = {R_{abcd}}^2 - 4{R_{ab}}^2 + R^2$$

Dynamical-Chern-Simons

(Alexander, Yunes 2009)

$$S = \int d^4x\sqrt{-g}\,\kappa R + \frac{\alpha}{4}\vartheta\,{}^*RR - \frac{\beta}{2}g^{ab}\nabla_a\vartheta\nabla_b\vartheta$$

$$*\,RR = \frac{1}{2}R_{abcd}\epsilon^{baef}R^{cd}_{ef}$$

Models of mini-charged DM predict heavy, fractional “electrons”

(Rujula, Glashow, Sarid 1990; Perl, Lee 1997; Holdom 1986; Sigurdson et al 2004)

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + 4\pi e j^{\mu}_{\rm em}A_{\mu} + 4\pi e_h j^{\mu}_{h}B_{\mu} + 4\pi\epsilon e j^{\mu}_{h}A_{\mu}\right)$$

Models of DM predict other couplings, axionic or scalar-type

(Klasen 2015; Marsh 2015)

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

Massive gravity theories

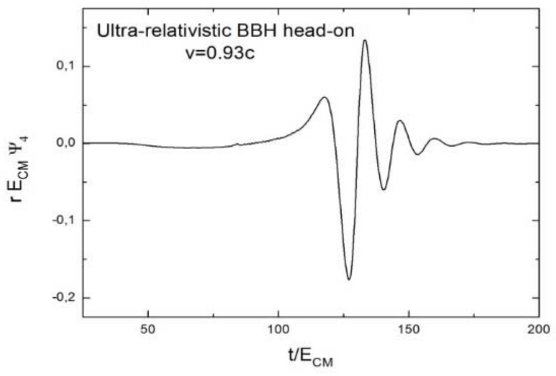
(Rham, Gabadadze, Tolley 2011; Hassan and Rosen 2012)

$$\mathcal{L} = \sqrt{|g|}\left[m_g^2 R_g + m_f^2\sqrt{f/g}\,R_f - 2m_v^4 V\left(g, f\right)\right]$$

Schwarzschild is solution, but can be unstable...new solutions with hairy graviton cloud (Brito, Cardoso, Pani 2013)

Tests of the ‘no-hair’ and BH hypothesis

Gravitational waves and ringdown modes



$$e^{-0.0898\, t/M_{BH}} \sin\left(0.374\, t/M_{BH}\right)$$

Followed by power-law decay

Multipolar structure: motion of stars and pulsars

Accretion disks

Black hole shadows

Challenge: Can we test Kerr nature?

Need to measure two or modes: disentangle frequencies, damping times and amplitudes

$$\rho_{\rm GLRT}^{l=2,3} = 17.687 + \frac{15.4597}{q-1} - \frac{1.65242}{q}$$

$$\rho_{\rm GLRT}^{l=2,4} = 37.9181 + \frac{83.5778}{q} + \frac{44.1125}{q^2} + \frac{50.1316}{q^3}$$

Berti et al, PRD76,104044 (2007); 2016

Challenge: Can we estimate extra couplings?

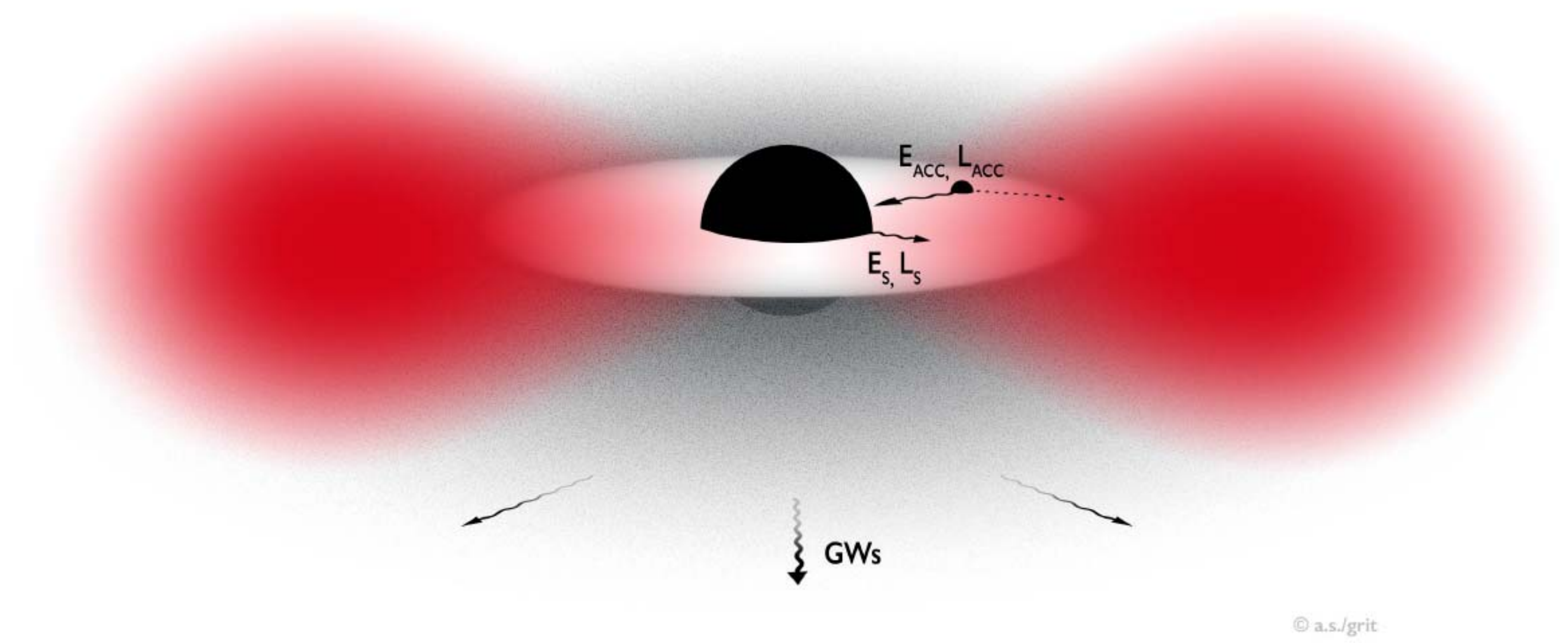
$$\omega^R_{lm} = \omega^R_{\mathrm{Kerr}\,lm}\left(1 + R_{lm}\alpha^2\right)$$
$$\omega^I_{lm} = \omega^I_{\mathrm{Kerr}\,lm}\left(1 + I_{lm}\alpha^2\right)$$

$$\alpha \lesssim \sqrt{\frac{1}{\rho}}\sqrt{\frac{0.190R_{33} - 1.064I_{22}}{(R_{33} - 5.595I_{22})(R_{33} - 0.986R_{22} - 0.0143I_{22})}}$$

$$\frac{Q}{M} \lesssim 0.1\sqrt{\frac{100}{\rho}} \qquad \frac{\alpha}{M^2} \lesssim 0.4\sqrt{\frac{100}{\rho}} \qquad \alpha_{\mathrm{DCS}} \lesssim 0.1\sqrt{\frac{100}{\rho}}$$

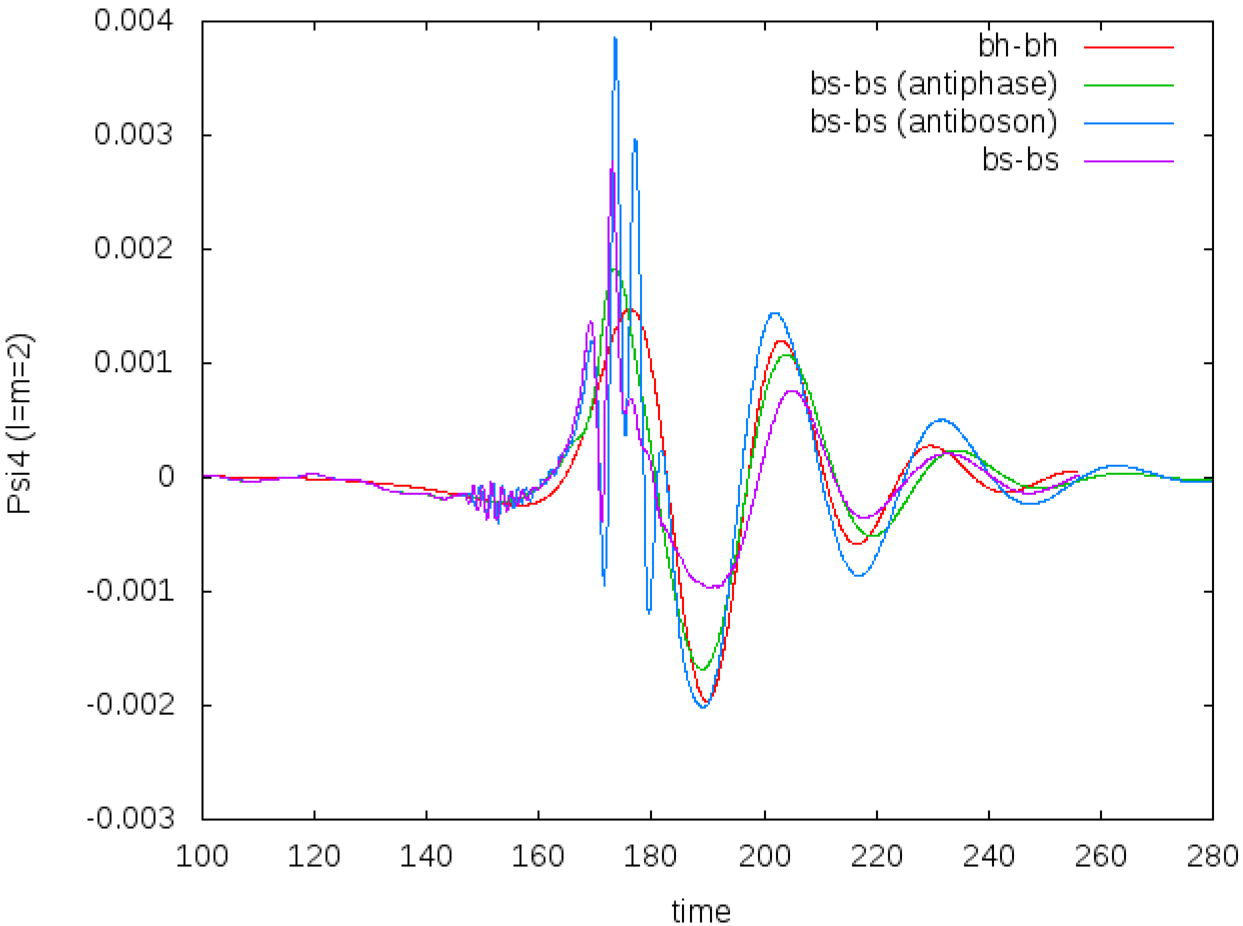
Cardoso et al, JCAP 1605: 054 (2016); In preparation (2016)

Is this always possible?



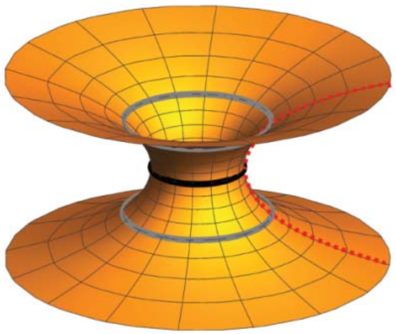
Challenge: When do QNMs dominate the first ringdown stage?

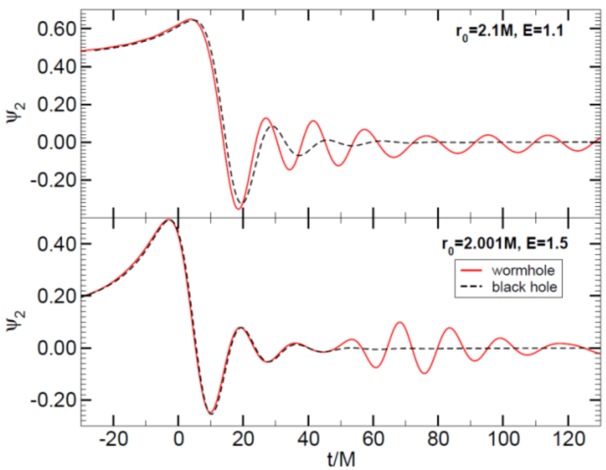
Challenge: Are we dealing with black holes?

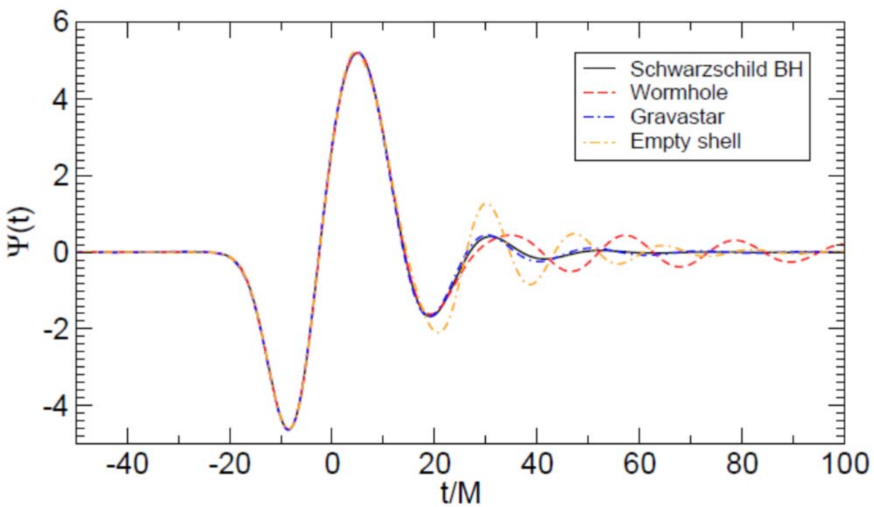


Preliminary

Challenge: Are we dealing with black holes?







Cardoso, Franzin, Pani
PRL116 (2016), 171101

Challenge: Environmental effects?

However, inasmuch as the goal of the gravitational wave observatories is to obtain astrophysical information of our universe (...), there is no doubt that we will eventually have to face this problem of the QNM spectra of dirty black holes.

- Leung et al 1999

Correction	$\lvert\delta_R\rvert[\%]$	$\lvert\delta_I\rvert[\%]$
spherical near-horizon distribution	0.05	0.03
ring at ISCO	0.01	0.01
electric charge	10^{-5}	10^{-6}
magnetic field	10^{-8}	10^{-7}
gas accretion	10^{-11}	10^{-11}
DM halos	$10^{-21}\rho_3^{\rm DM}$	$10^{-21}\rho_3^{\rm DM}$
cosmological effects	10^{-32}	10^{-32}

Barausse, Cardoso, Pani 2014

Thank you

Theorem:

Isolated, stationary, regular BHs in the Einstein-Klein-Gordon or Einstein-Proca theory with a *time-independent boson* are described by Kerr family

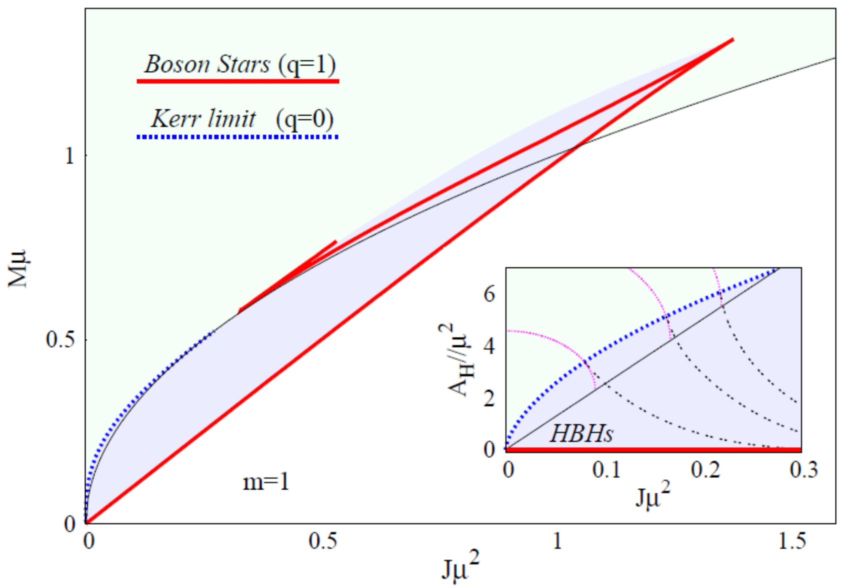
(impossible to hold the hair)

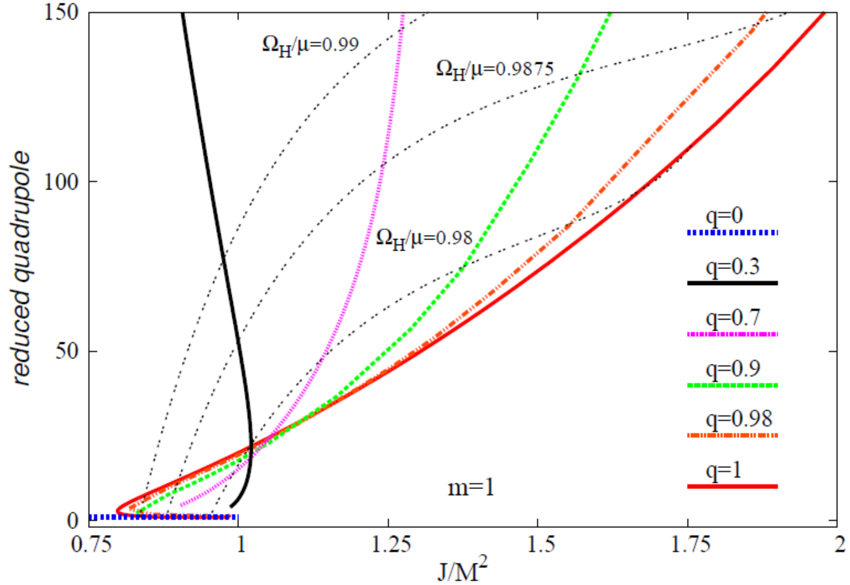
Theorem 3:

Isolated, stationary, regular BHs in the Einstein-Klein-Gordon theory with *one real scalar* are described by the Kerr family

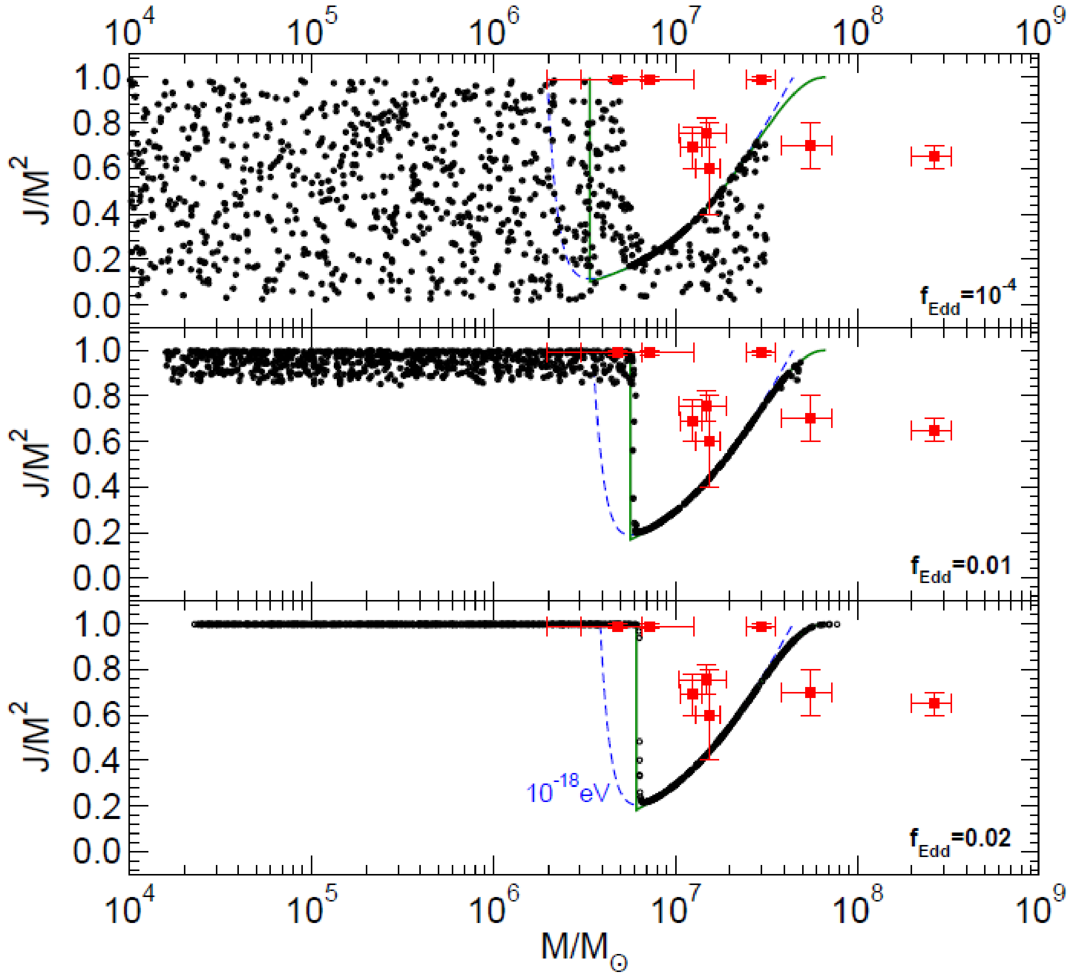
(impossible not to radiate GWs)

Hairy black holes?





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



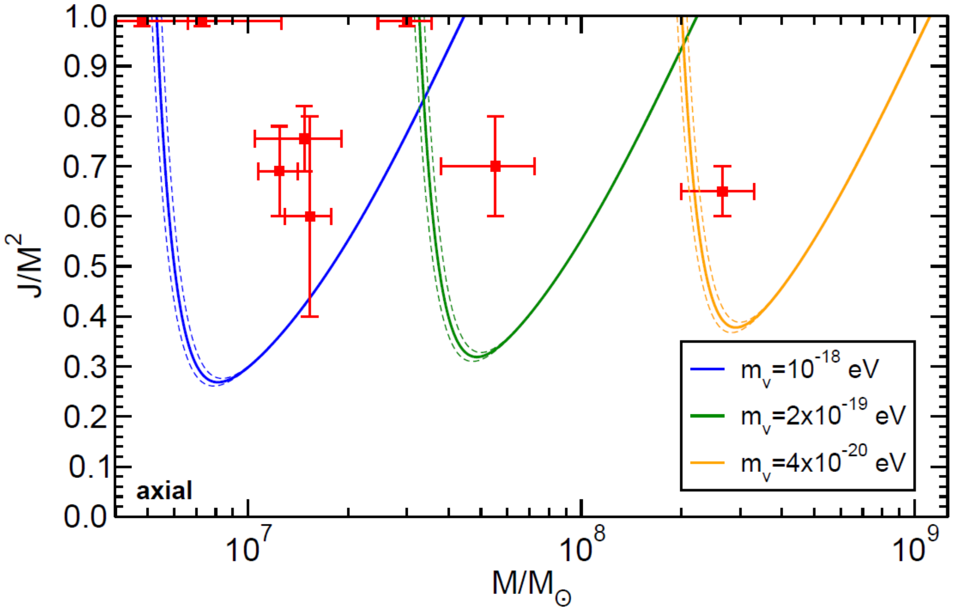
$$\mu = 10^{-18}\mathrm{eV}$$

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 $\sigma = 0.1\bar{t}_F$.

Brito, Cardoso, Pani, CQG32 (2015) 13, 134001; Arvanitaki et al (2016)

Bounding the boson mass

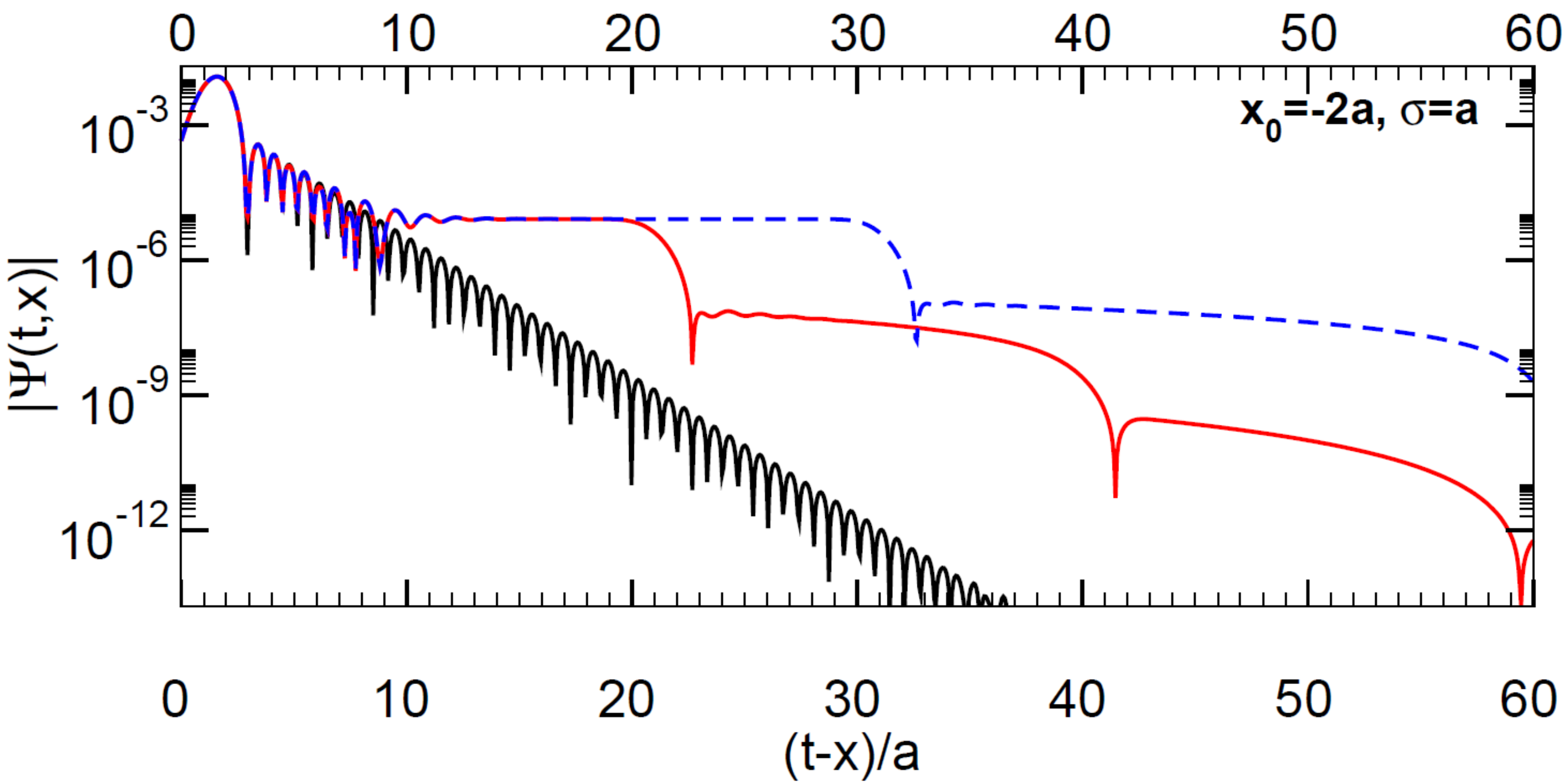
Pani et al PRL109, 131102 (2012)



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


x0=-2a, σ=a
|Ψ(t,x)|
10-3
10-6
10-9
10-12
0
10
20
30
40
50
60
(t-x)/a

Exciting times for gravitational physics!

Hundreds of ringdown observations, tests of GR and Kerr hypothesis will be done routinely.

"*After the advent of gravitational wave astronomy, the observation of these resonant frequencies might finally provide direct evidence of BHs with the same certainty as, say, the 21 cm line identifies interstellar hydrogen*" (S.Detweiler)

Many challenges ahead…for exemple, time-response of BH is dominated by light-ring ringdown at early times, and shared by all horizonless compact objects. These vibrations modes do *not* show up as poles of the corresponding Green function…