Testing General Relativity

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(CENTRA/Técnico & Perimeter)

...

DESY 2016

blackholes.ist.utl.pt erc supports this project

1900

Derives astronomical bounds
on curvature radius of space:

64 light years if hyperbolic

1600 light years if elliptic

1914

Volunteers for war

Belgium: weather station

France, Russia: artillery trajectories

March 1916

Sent home, ill with pemphigus.

Dies in May.

“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 (not realize solution was the same)

...and others

Are we really observing black holes?

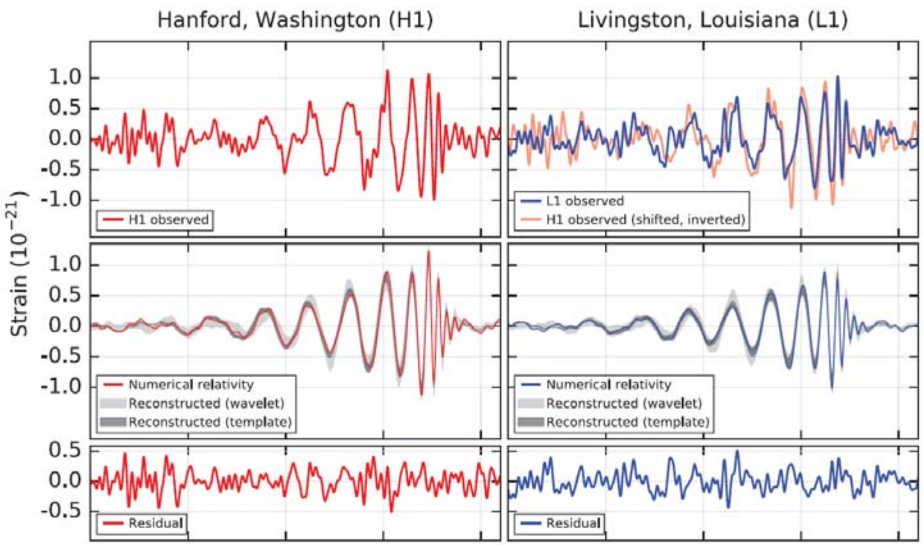
Discovery (1916):	solution written down
Dark ages (1920-1950's):	misinterpreted, misunderstood, dismissed and/or regarded as irrelevant to any observable phenomena
Renaissance (1950-1970's):	theory side- gained solid understanding of true nature of black holes, genericity of singularities and gravitational collapse
	observational side- discovery of quasars, X-ray binaries, pulsars and the CMB
Dark ages^(-1) :	post-renaissance pre-GW150914.
	Notions and predictions of strong-field gravity taken for granted without verification from observation

Strong field intimately connected with some of the deepest mysteries in theoretical physics today such as information loss/firewalls/quantum gravity. It is astonishing that space and time can get so warped to form horizons and singularities;

Must demand a similar "astonishing" level of evidence.

“But a confirmation of the metric of the Kerr spacetime (or some aspect of it) cannot even be contemplated in the foreseeable future.”

S. Chandrasekhar, The Karl Schwarzschild Lecture, Astronomischen Gesellschaft, Hamburg, 18 September 1986



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

Questions to answer

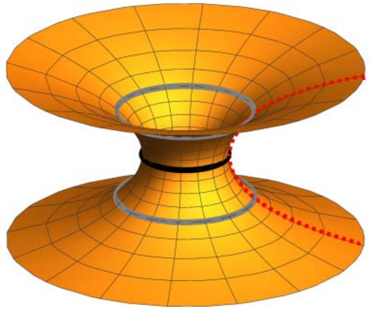
i. Are there alternatives?

ii. Do they form dynamically under reasonable conditions?

iii. Are they stable?

iv. What GW signal do they give rise to?

i. Alternatives



Boson stars, fermion-boson stars, oscillatons
(Kaup 1968; Ruffini, Bonazzolla 1969, Colpi et al 1986, Brito et al 2015)

Wormholes
(Morris, Thorne 1988; Visser 1996)

Gravastars
(Mazur, Mottola 2001)

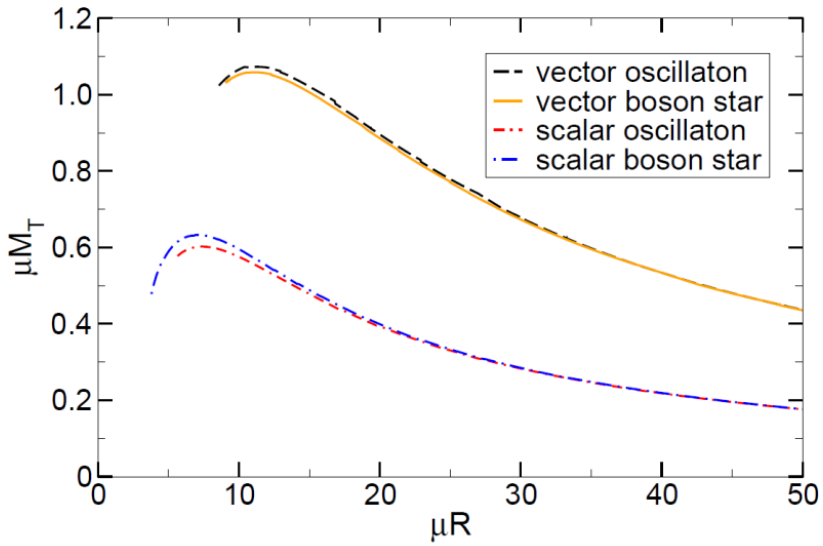
Fuzzballs, Superspinars, Firewalls
(Mathur 2000; Gimon, Horava 2009; Almheiri, Marolf, Polchinski, Sully 2012)

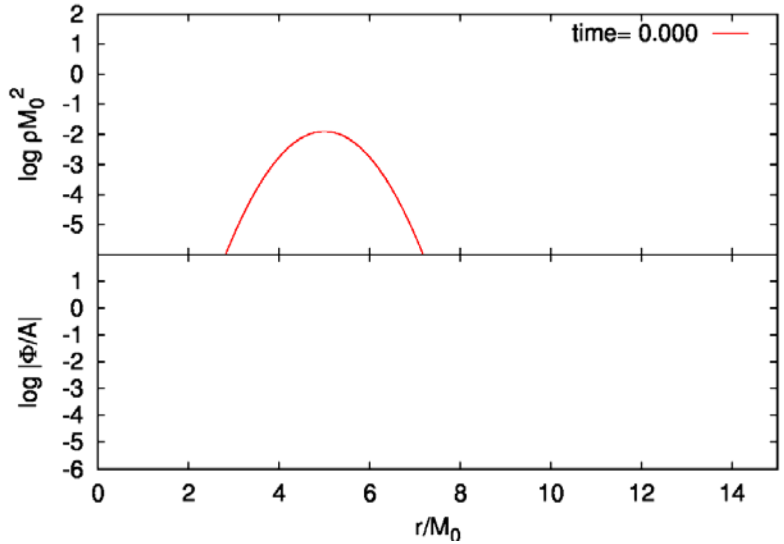
...

ii. Formation

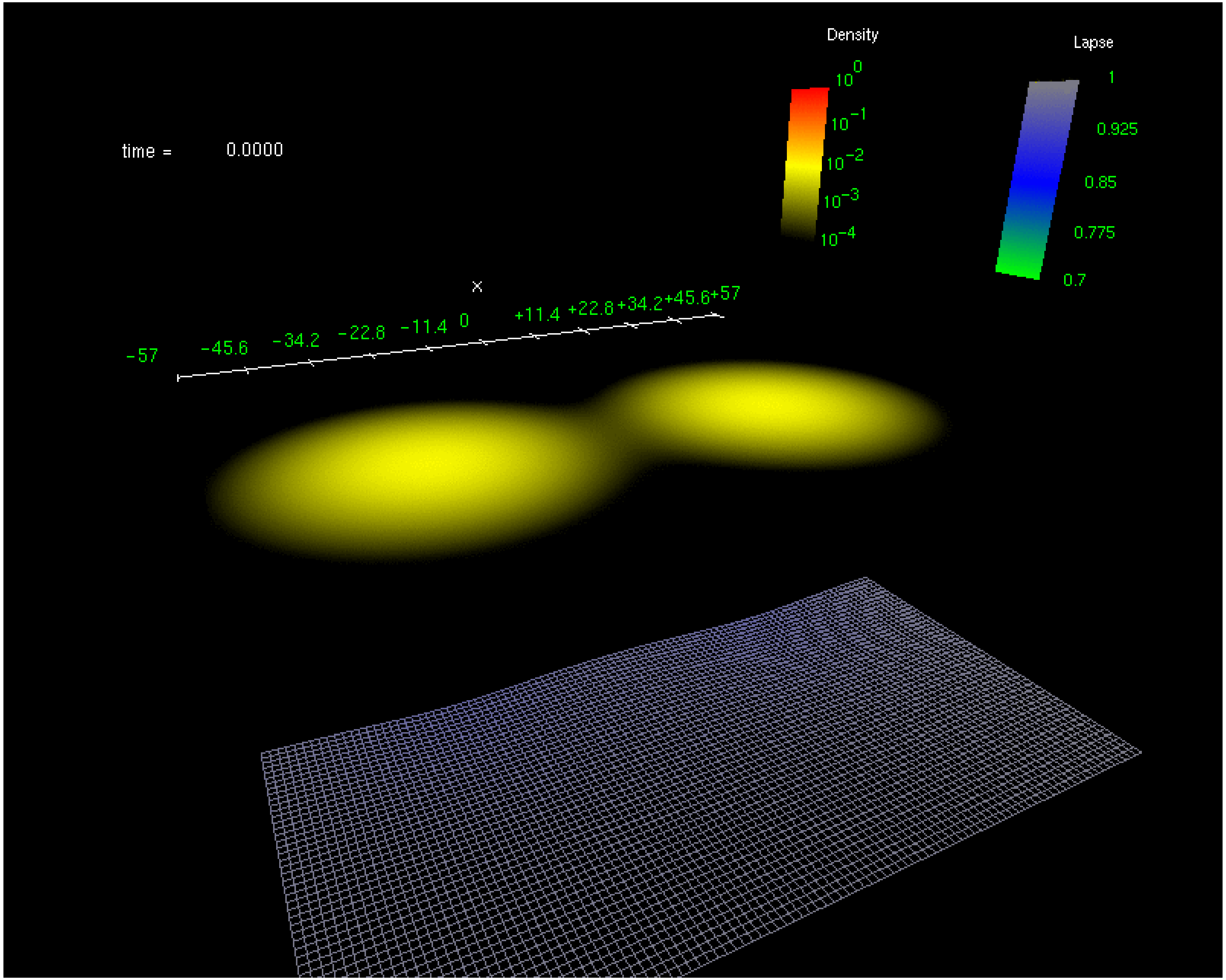
Boson stars, fermion-boson stars, oscillatons

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





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

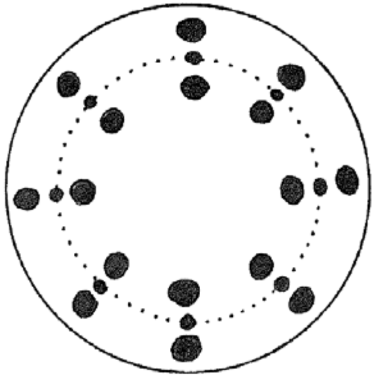


Density and lapse function sub-critical, equal-mass

iii. Stability of objects with photospheres

Keir arXiv:1404.7036; Cardoso et al, PRD90:044069 (2014)

Static objects: *No uniform decay estimate with faster than logarithmic decay can hold for axial perturbations of ultracompact objects.*



In absence of viscosity, Dyson-Chandrasekhar-Fermi mechanism might trigger nonlinear instabilities

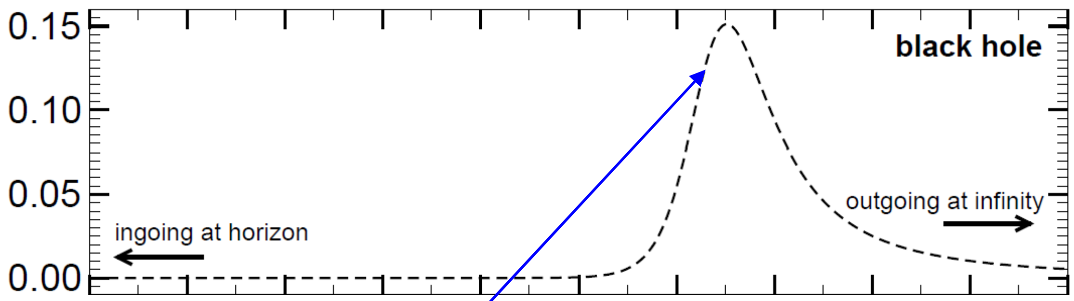
Friedmann Comm. Math.Phys.63:243, 1978

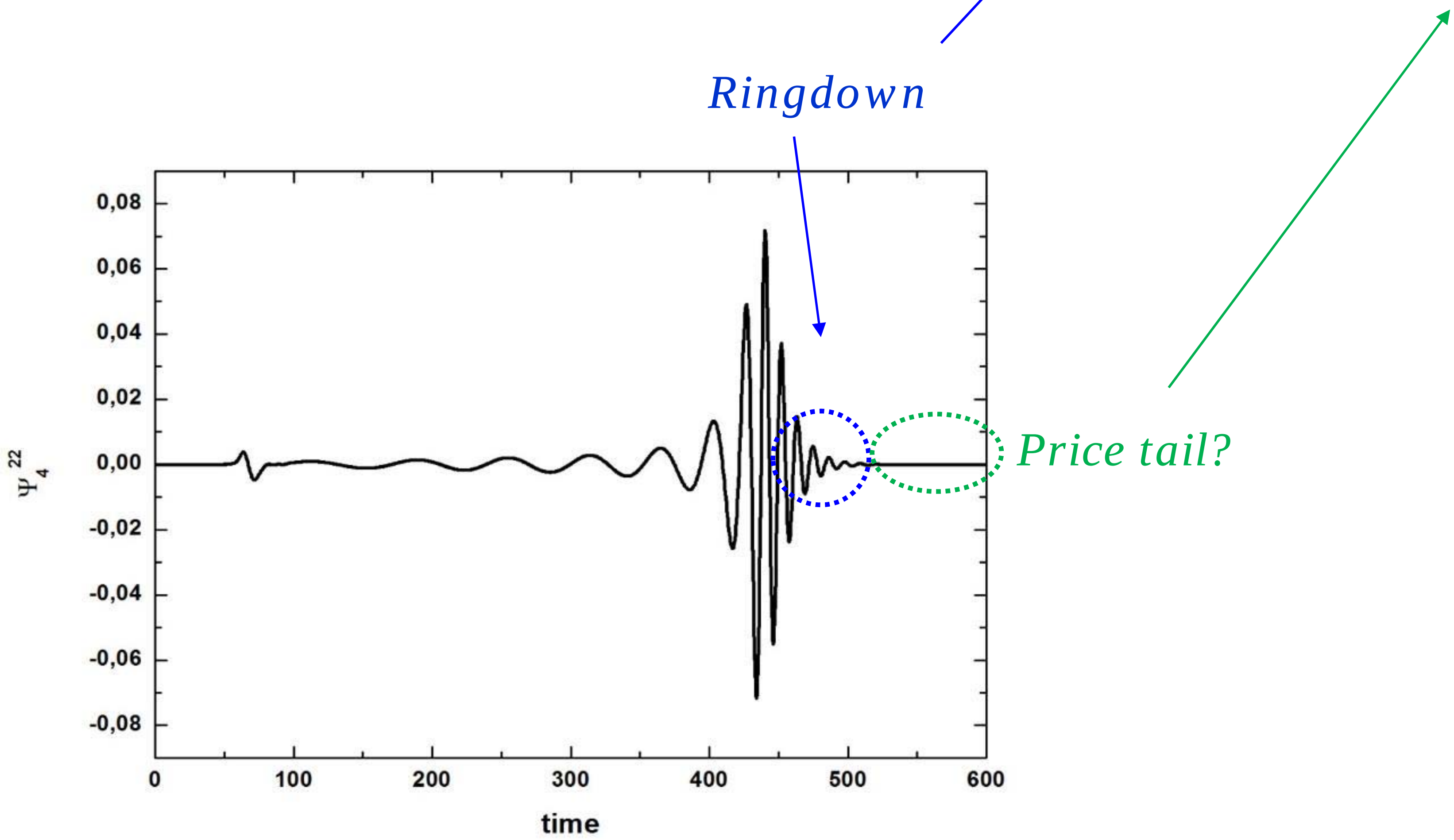
Rotation: *Horizonless objects with ergoregions are linearly unstable*

Most likely objects with photspheres are unstable...but conclusion depends on dissipation mechanisms; decay rates are poorly known.

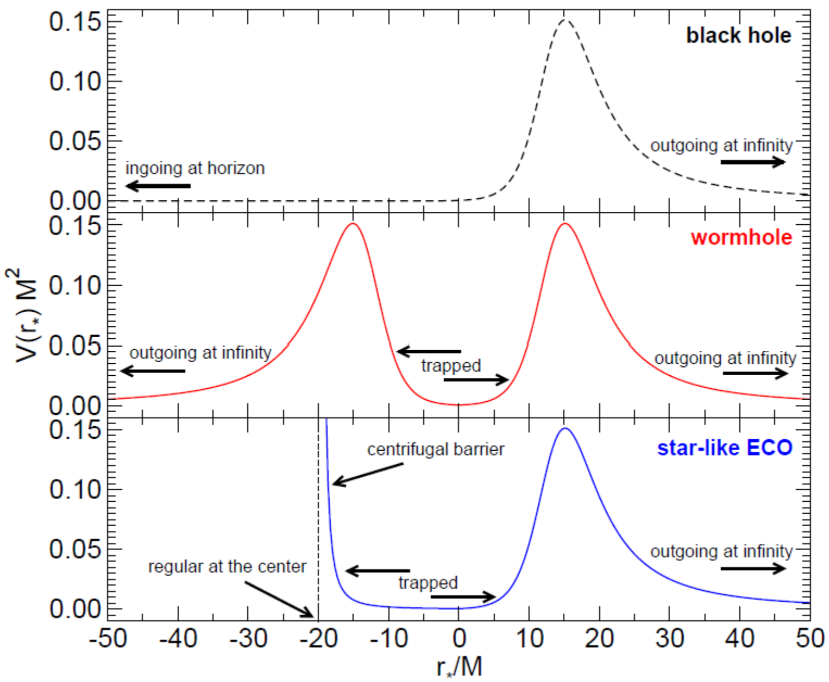
iv. GW-signal

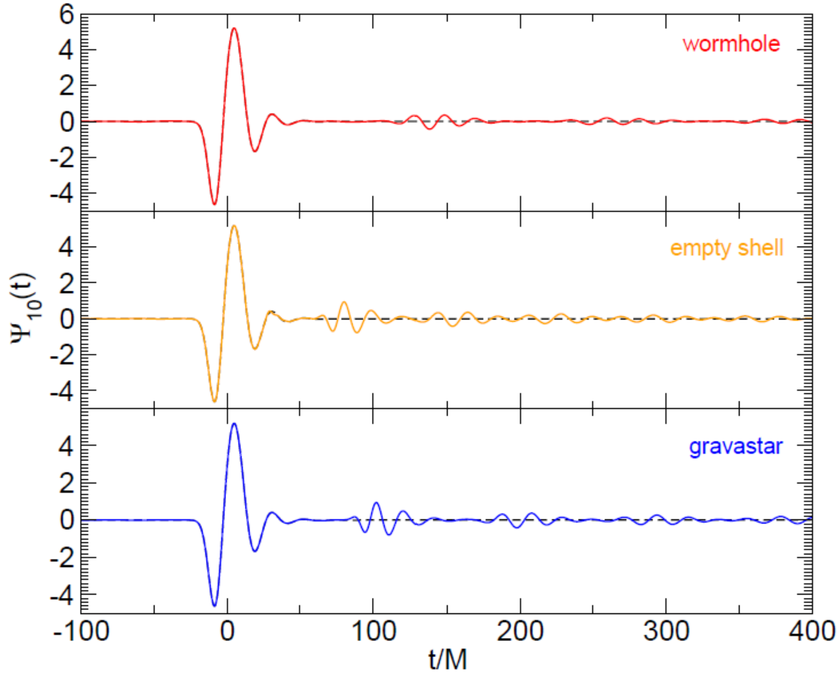
$$\frac{d^2\Psi}{dr_*^2} + \left(\omega^2 - V(r_*)\right)\Psi = 0$$





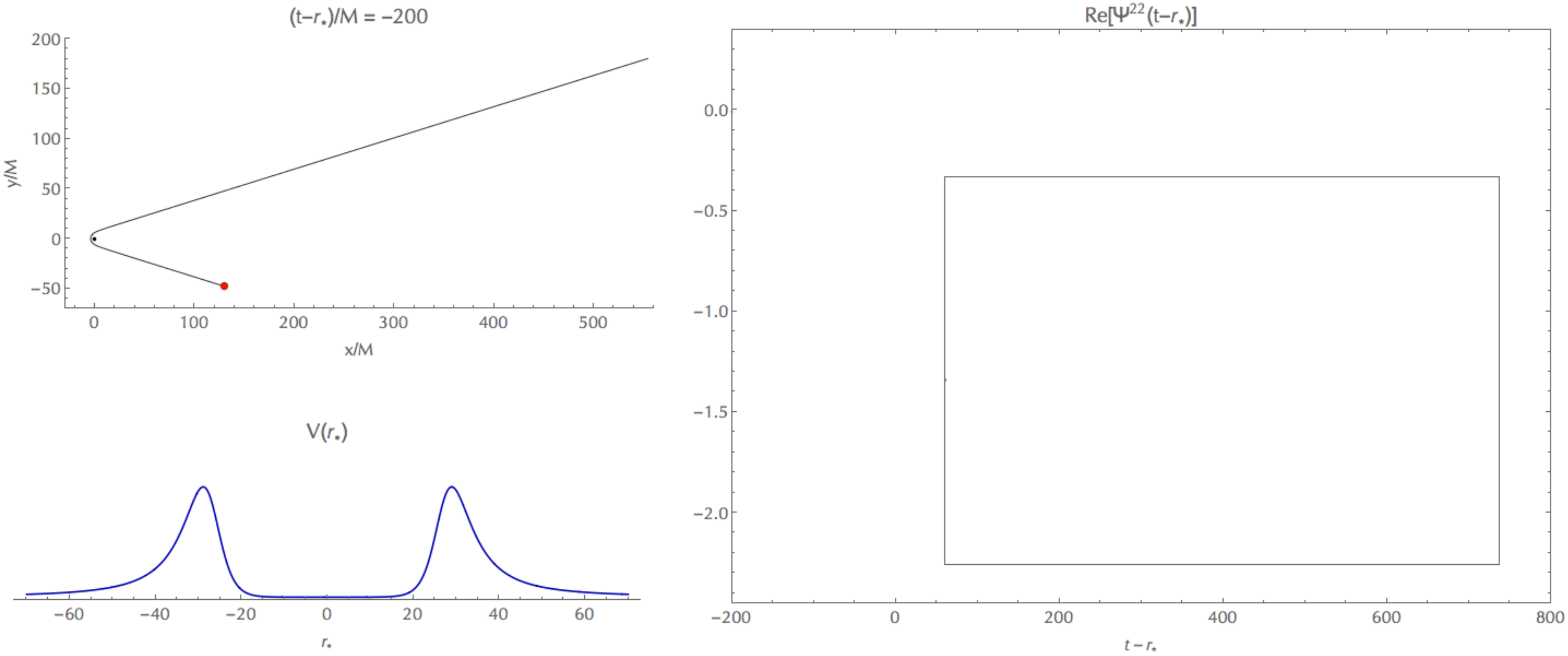
iv. GW-signal





Cardoso, Franzin, Pani, PRL116:171101 (2016)

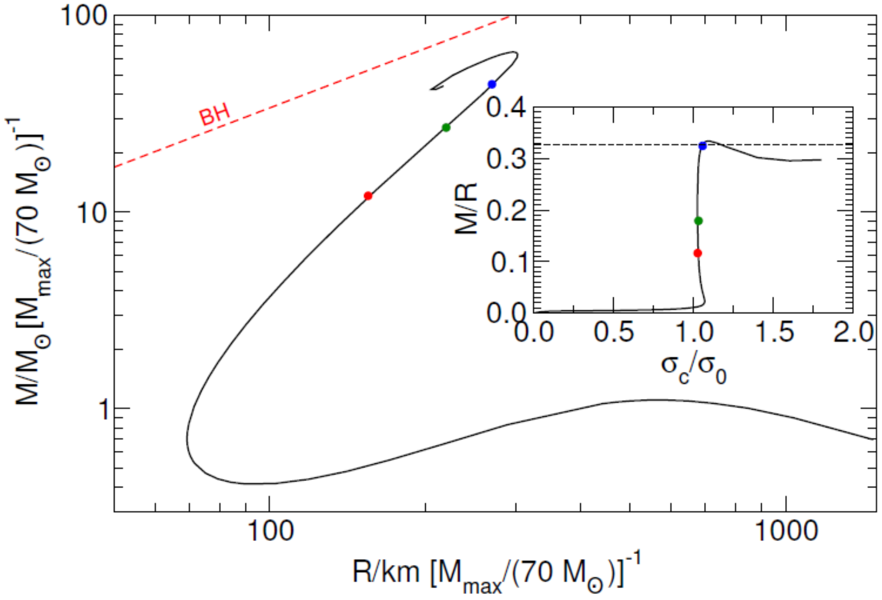
$\mathcal{E} = 1.5$, $r_{min}=4.3M$, $r_0-2M = 10^{-6}M$



Cardoso, Hopper, Macedo, Palenzuela, Pani 2016

$$t \sim 54(n/4)\, M_{30} \left[1 - 0.01 \log\left(\frac{\ell/L_P}{M_{30}}\right)\right] \text{ ms}$$

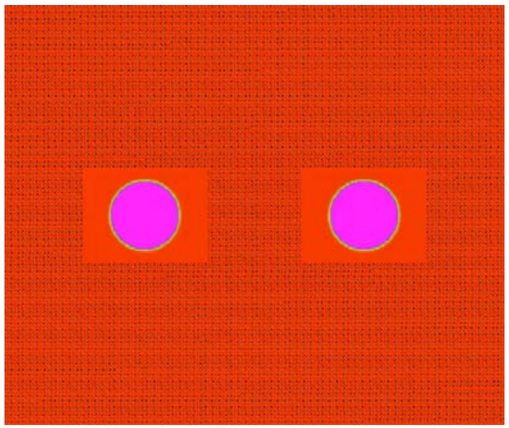
$$\rho_{\text{tot}} \sim \frac{80}{\sqrt{E_{\text{echo}}(\%)}}$$

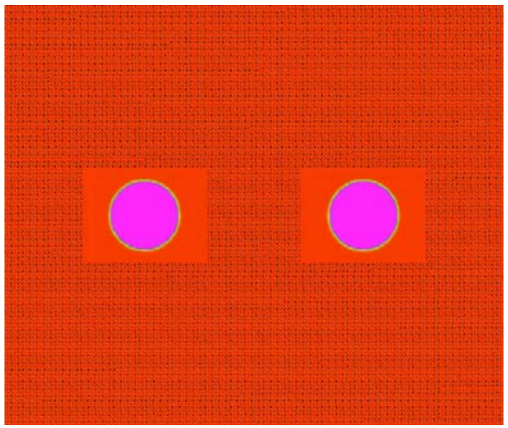


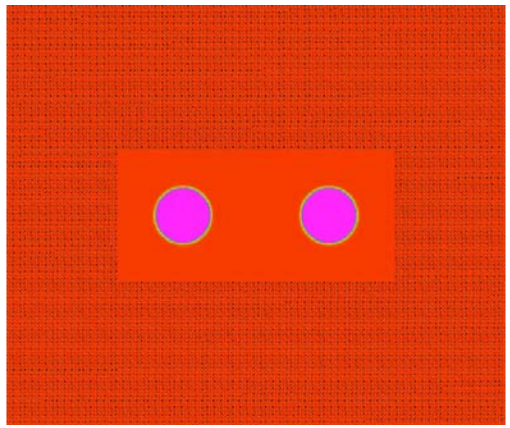
BS/BS

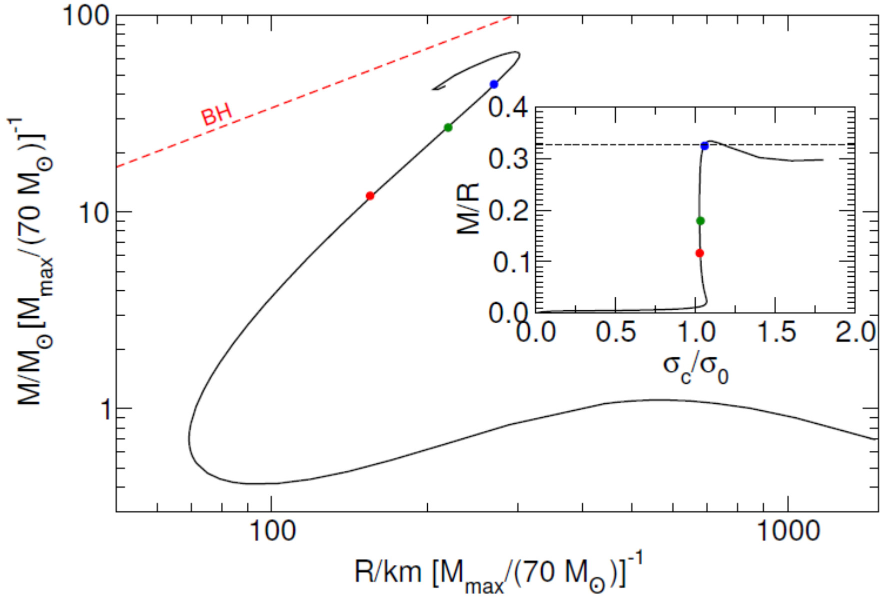
BS-BS (OP)

BS-BS (OP)





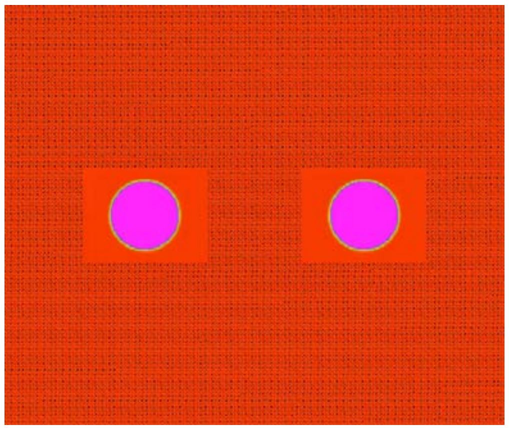


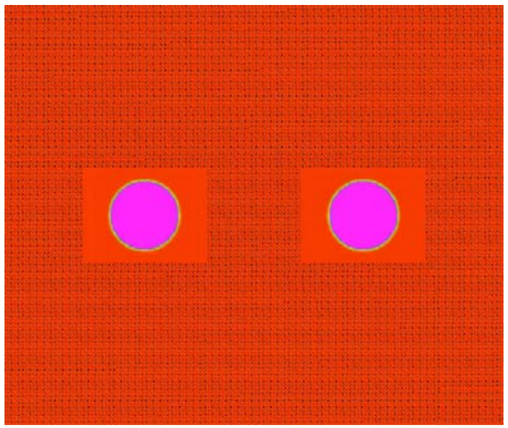


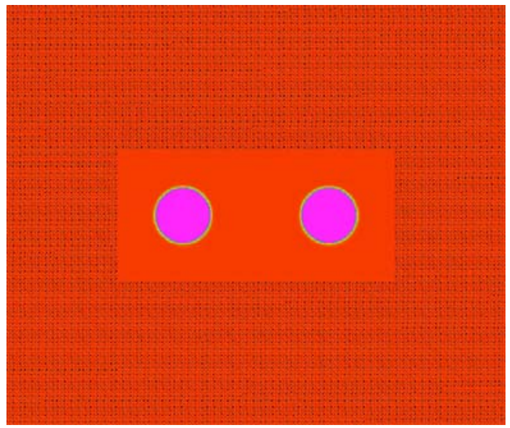
BS/BS

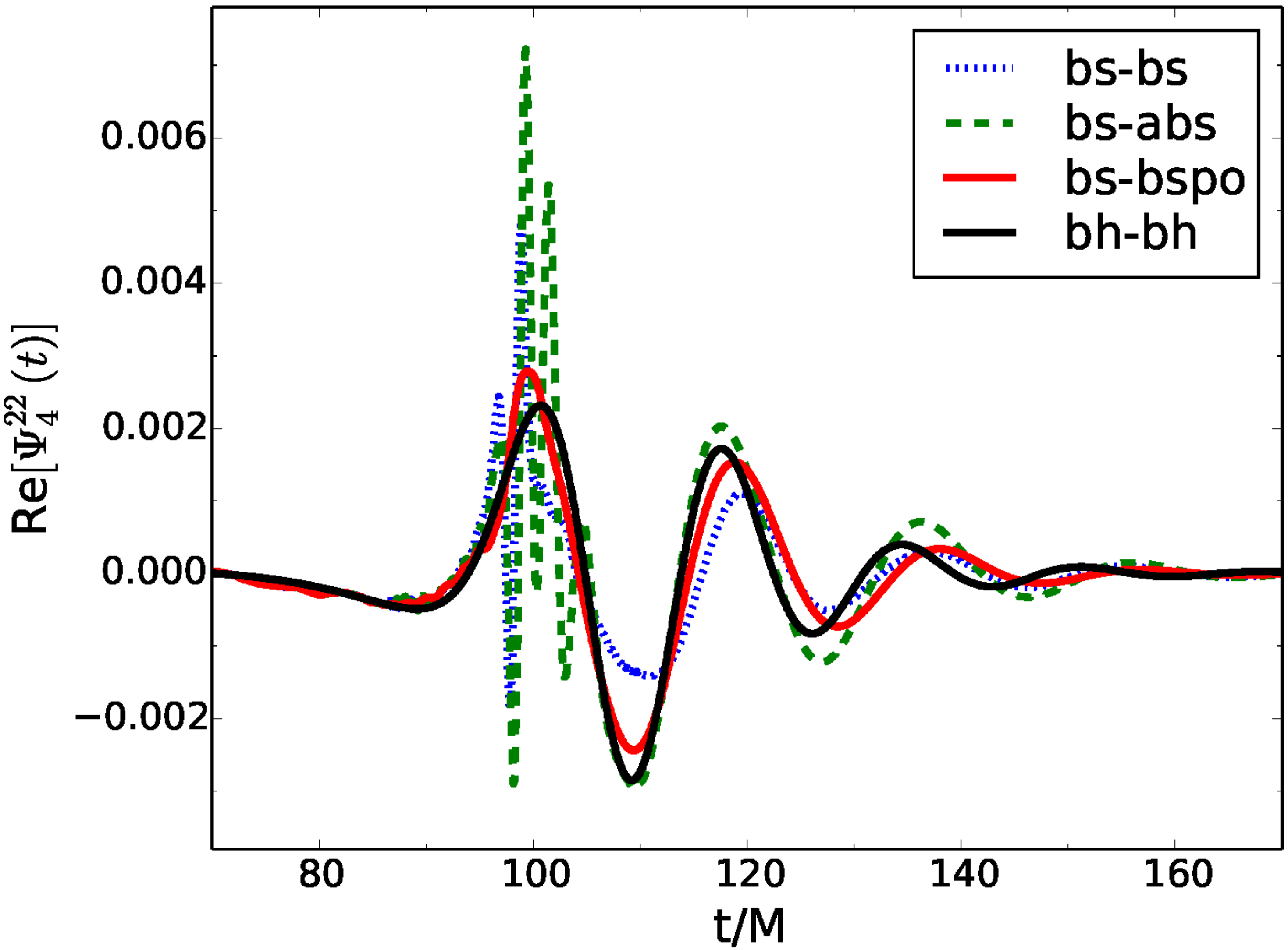
BS-BS (OP)

BS-BS (OP)









bs-bs
bs-abs
bs-bspo
bh-bh
0.006
0.004
0.002
0.000
−0.002
$\mathrm{Re}[\Psi_4^{22}(t)]$
80
100
120
140
160
t/M

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**

"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

The no-hair hypothesis *must* be wrong

Anisotropic fluid hair

(Brown, Hussain 1997)

$$ds^2 = -f dt^2 + \frac{dr^2}{f} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$

$$f = 1 - \frac{2M}{r} + \frac{Q^{2k}}{r^{2k}}, \qquad \rho = \frac{Q^{2k}(2k-1)}{8\pi r^{2k+2}}, \quad P = k\rho$$

Einstein-dilaton-Gauss-Bonnet

(Mignemi, Stewart 1993; Kanti et al 1995)

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{2}g^{\mu\nu}\Psi_{,\mu}\Psi_{,\nu} + \frac{\alpha}{4}\mathcal{R}^2\right), \qquad \mathcal{R}^2 = R^2_{abcd} - 4R^2_{ab} + R^2$$

The no-hair hypothesis *must* be wrong

Models of mini-charged DM predict heavy, fractional "electrons"
(Rujula, Glashow, Sarid 1990; Perl, Lee 1997; Holdom 1986; Sigurdson et al 2004)

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

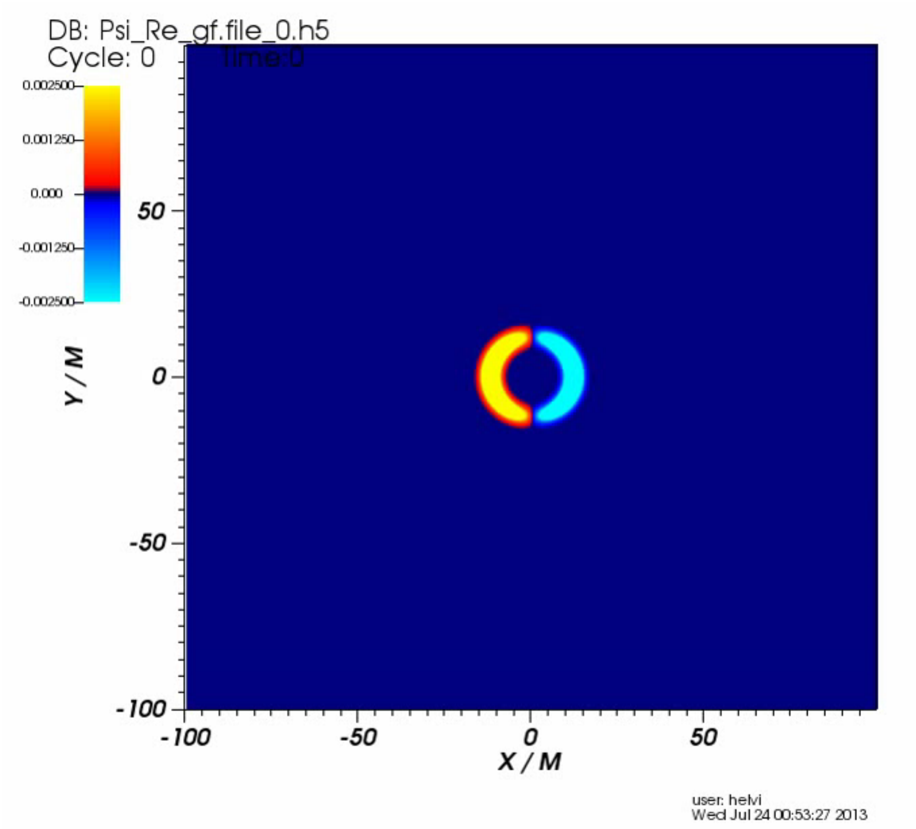
Discharge mechanisms can be suppressed (Cardoso et al JCAP1605: 054, 2016)

Hairy Kerr in minimally coupled KG theory (BS with BH at center)
(Herdeiro, Radu 2014)

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{2}g^{\mu\nu}\Psi^{*}_{,\mu}\Psi_{,\nu} - \frac{\mu_S^2}{2}\Psi^{*}\Psi\right)$$

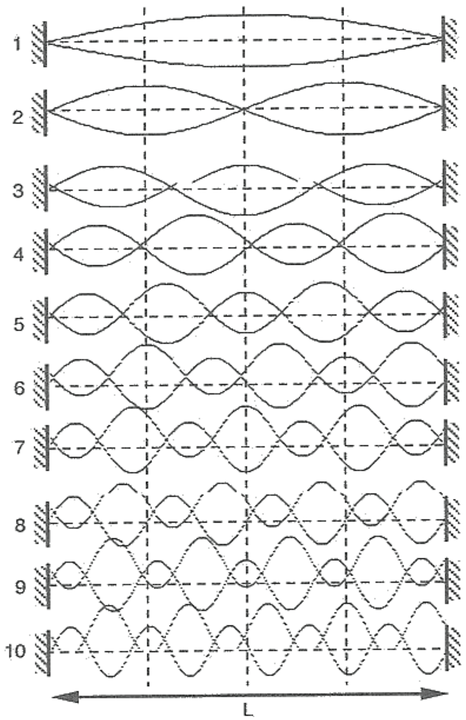
Evades theorems with complex, time-dependent scalar but time-independent stress-tensor (no GWs). Superradiance prevents hair from falling *in* (Brito, Cardoso, Pani 2015)

Even real scalars or vectors...



Okawa et al PRD89, 104032 (2014)

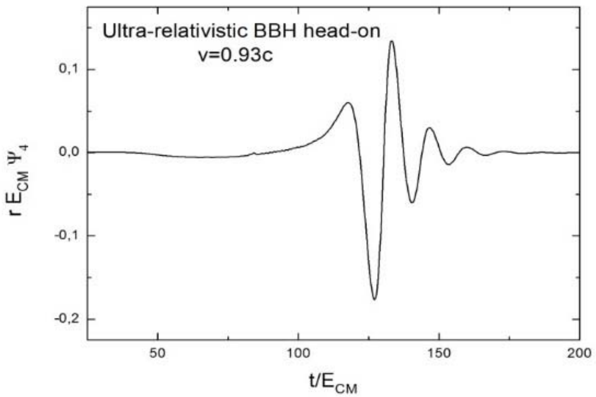
Tests of the no-hair hypothesis



$$f = \frac{nv}{2L}\,, \quad n = 1,\, 2,\, 3...$$

Measure fundamental mode, determine length L.
Measure first overtone, test if it's a string...

Tests of the no-hair hypothesis



$$M\omega_{22} = 1.5251 - 1.1568\,(1-j)^{0.1292}$$
$$Q_{22} = 0.7 + 1.4187\,(1-j)^{-0.499}$$

Measure dominant mode, measure mass and spin. Measure second mode, test GR...

Berti, Cardoso, Will PRD73:064030 (2006)

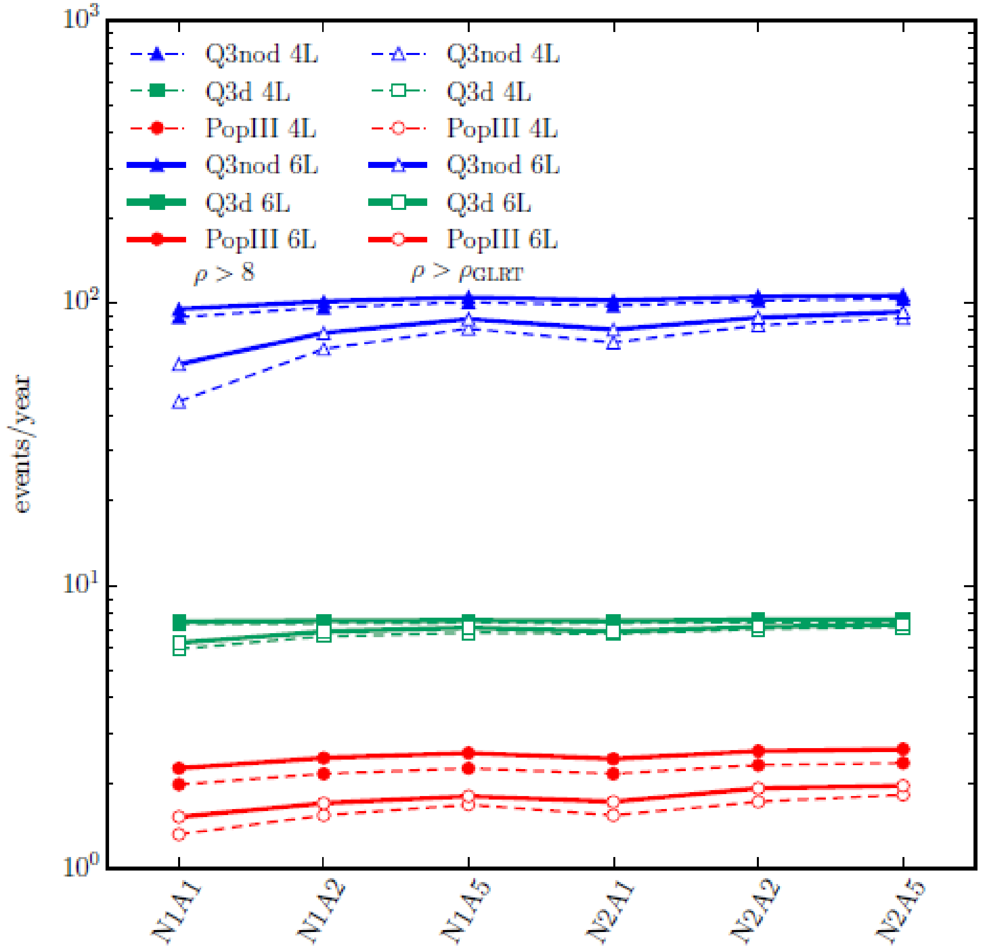
Challenge: Can we “hear” the Kerr nature?

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

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

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

Berti et al PRD76:104044 (2007)
Berti et al PRL117:101102 (2016)



Rates of binary BH mergers that yield detectable ringdown signals (filled symbols) and allow for spectroscopical tests (hollow symbols) with LISA (6-link (solid) and 4-link (dashed)) configurations with varying armlength and acceleration noise.

Berti et al PRL117:101102 (2016)

Challenge: Estimate extra couplings from ringdown

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

Cardoso, Macedo, Pani & Ferrari, JCAP 1605: 054 (2016)

Blázquez-Salcedo et al, arXiv:1609.01286

Conclusions: exciting times!

Gravitational wave astronomy *can* become a precision discipline, mapping compact objects throughout the entire visible universe.

Black holes remain the simplest explanation for the observations of dark, massive and compact objects...but one can now test the BH hypothesis...improved sensitivity pushes putative surface closer to horizon...like probing short-distance structure with accelerators.

“*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 ApJ239:292 1980)

Thank you