Title: Black holes as probes of fundamental physics

Date: Apr 03, 2013 02:00 PM

URL: http://pirsa.org/13040109

Abstract: Black holes are the elementary particles of gravity, the final state of sufficiently massive stars and of energetic collisions. With a forty-year long history, black hole physics is a fully-blossomed field which promises to embrace several branches of theoretical physics. Here I review the main developments in highly dynamical black holes with an emphasis on high energy black hole collisions and probes of particle physics via superradiance.

Black holes

as probes of fundamental physics

Courtesy of S. Hembrey

Vítor Cardoso (CENTRA/IST, PI) • Waterloo • 2013

TÉCNICO LISBOA | More at http://blackholes.ist.utl.pt | erc supports this project

Black hole dynamics

Brito, Nerozzi, Okawa, Pani, Rocha, Witek, Zilhão

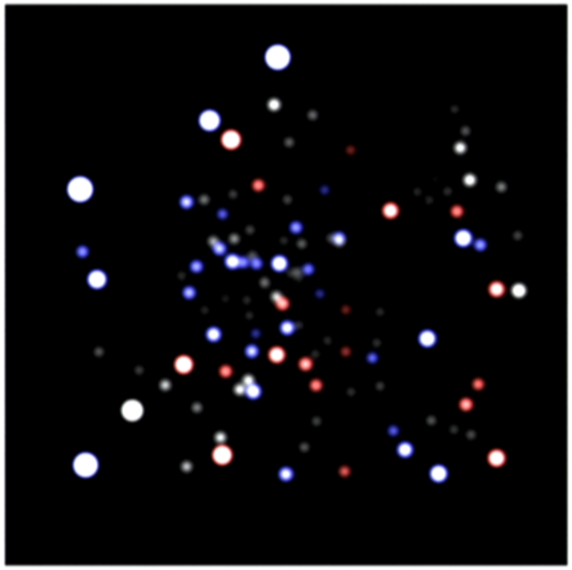
Barausse, Berti, Gualtieri, Herdeiro, Pretorius, Sperhake, Yunes

* * *

PRL 103:131102; 103: 239001 (2009);105:261102 (2010); 107:031101(2011); 109:131102 (2012)

PRD 81:084052; 81:104048; 82:104014 (2010); 83:024037; 83:104048 (2011); 85:124062 (2012)

Black holes exist



Credit: ESO/MPE (2010)

Credit: ESO/MPE/M.Schartmann (2011)

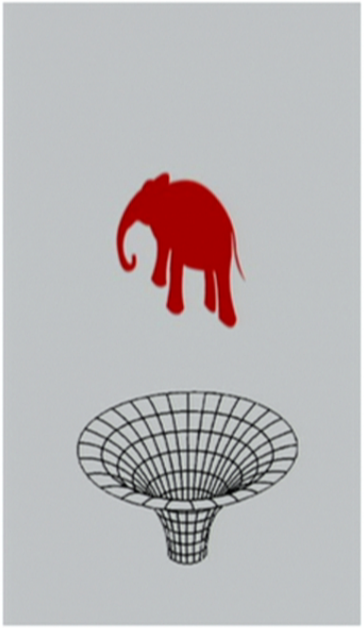
Gillessen et al, Nature 481, 51 (2012)

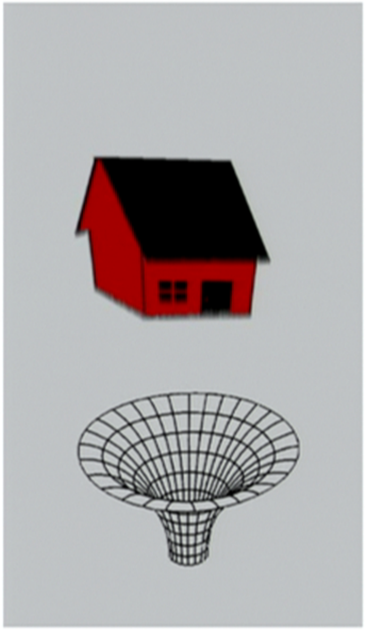
Black holes have no hair

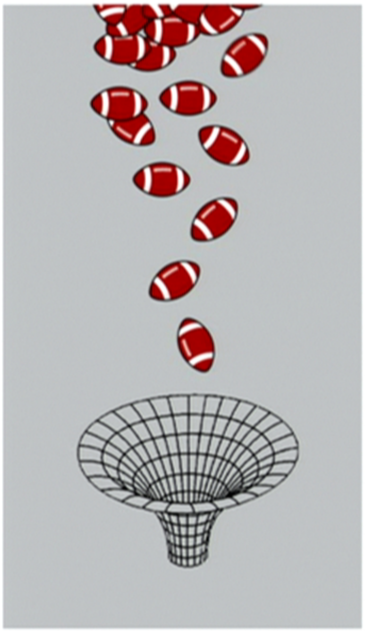
One star made of matter and other of antimatter, produce identical BHs.

A BH has only three quantities in common with the star which created it:

mass, spin and electric charge







Uniqueness: the Kerr solution

(Kerr 1963)

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

(Carter 1971, Robinson 1975)

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

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

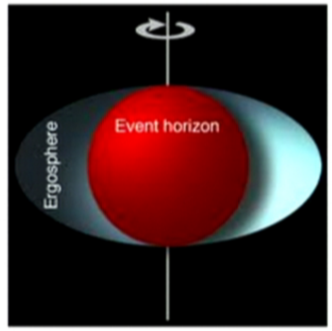
Describes a rotating BH with mass M and angular momentum J=aM

Singularity at r=0, infinite tidal forces, quantum effects are important

...Cosmic Censorship?

Perhaps all collapsing objects do conceal the nakedness of their singularities behind the cloak of an event horizon. But even if they do, according to the work for which Hawking is most famous that cloak may not last forever, and one day the nakedness of the singularity could be exposed to the Universe at large, with all that that implies.

—John Gribbin, Unveiling the Edge of Time



Upper limit on rotation: $j \equiv a/M \leq 1$ in SI units $j = \frac{Jc}{GM^2} \leq 1$

Sun: j=1.12, Earth: j=10^3, spinning top: j=10^19

The sound of black holes: gravitational waves (GWs)

GWs allow us to measure:

radiated energy E_{rad}, momenta P_{rad}, J_{rad}

predicted strain h_+, h_x

Why study BH dynamics

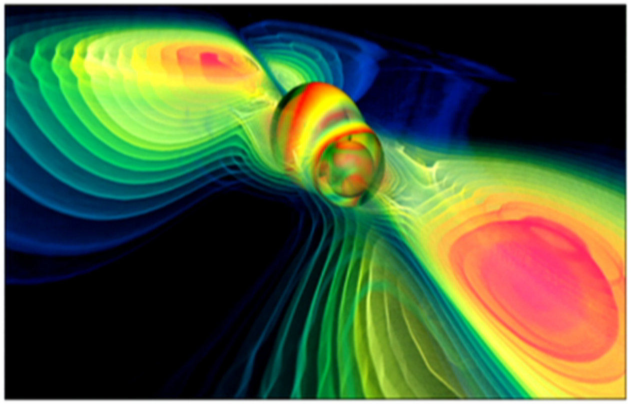
Gravitational-wave detection, GW astrophysics

Mathematical physics

High-energy physics

Particle Physics

Astrophysics and gravitational-wave physics



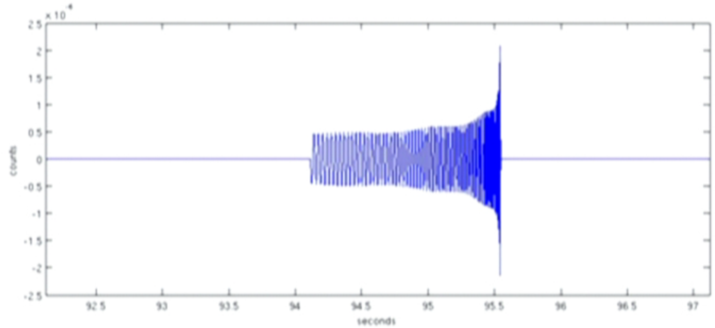
Gravitational-wave emission

Accurate templates for detection, NR/AR

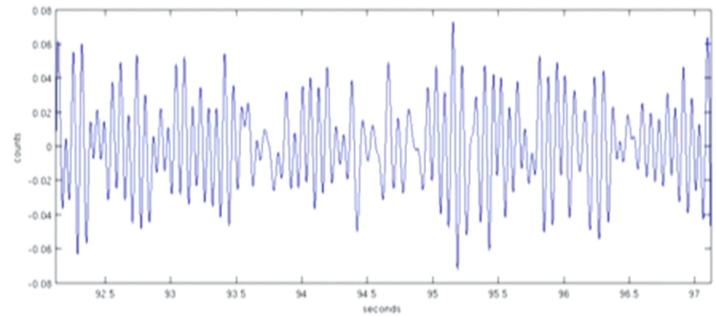
Recoil (structure formation, etc)

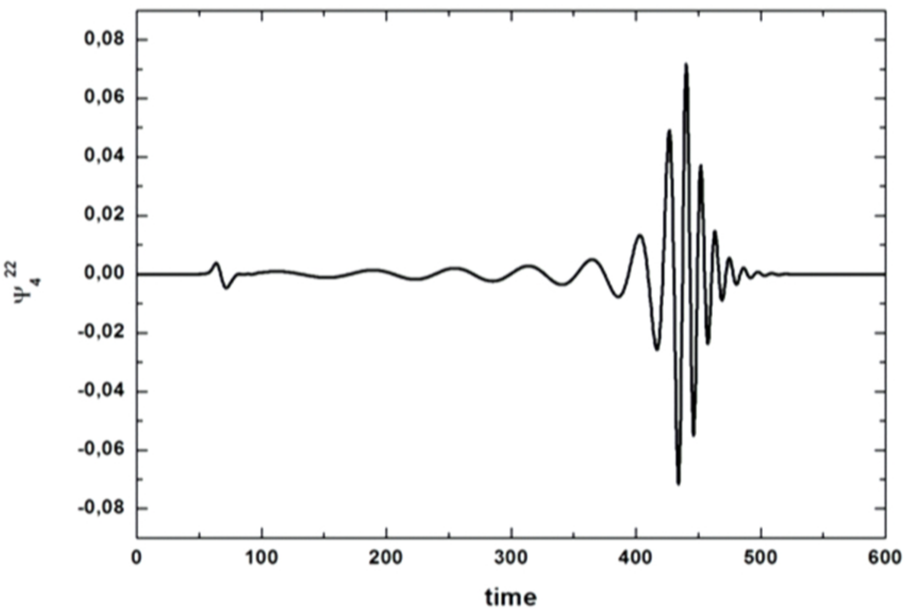
GRBs, accretion disks, etc

Typical signal for coalescing binaries



Typical stretch of data

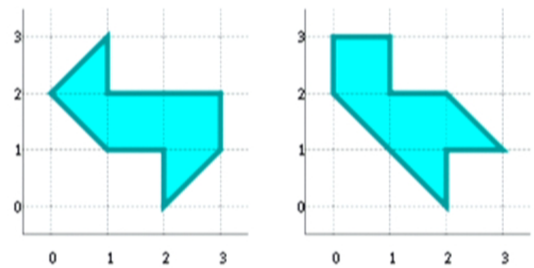



0,08
0,06
0,04
0,02
0,00
-0,02
-0,04
-0,06
-0,08
Ψ_4^{22}
0
100
200
300
400
500
600
time

“Can one hear the shape of a drum?”

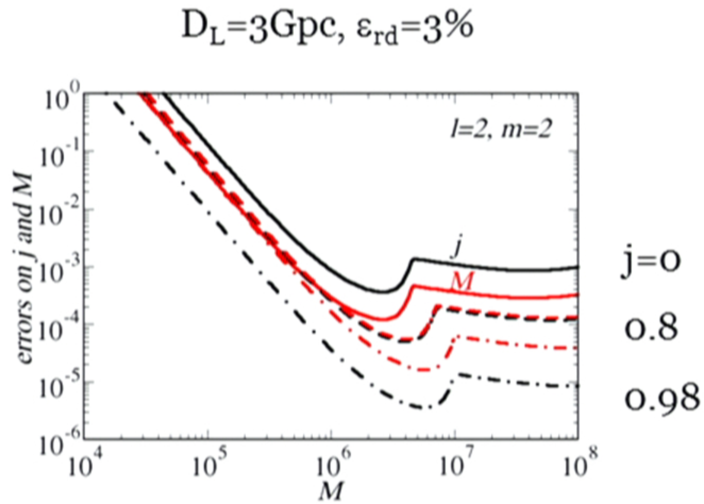
Mark Kac, American Mathematical Monthly, *1966*

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



Gordon, Webb & Wolpert, Inventiones mathematicae, *1992*

Can one hear the shape of a BH?



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

Berti, Cardoso & Will 2006; Kamaretsos et al 2012

Why study dynamics: mathematical physics

Cosmic Censorship: do horizons always form?

*

Are black objects always stable? Phase diagrams...

*

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

*

Critical behavior, resonant excitation of QNMs; analytical tools, etc

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ZFL

(Weinberg '64; Smarr '77)

Take two free particles, changing abruptly at t=0

$$T^{\mu\nu} = \sum_{i=1,2} \frac{P_i^\mu P_i^\nu}{E_i} \delta^3(x - v_i t)\theta(-t) + \frac{P_i^{'\mu} P_i^{'\nu}}{E_i'} \delta^3(x - v_i' t)\theta(-t)$$

$$\frac{dE}{d\omega d\Omega} = \frac{M^2\gamma^2 v^4}{\pi^2} \frac{\sin^4\theta}{(1 - v^2\cos^2\theta)^2}$$

Radiation isotropic in the UR limit, multipole structure $E_l \propto \frac{1}{l^2}$

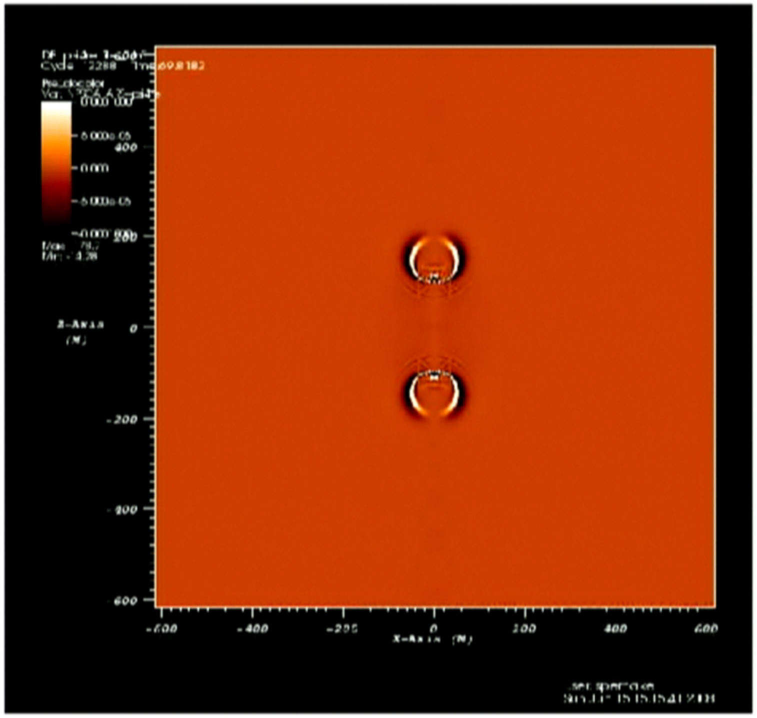
Functional relation $E_{rad}(\gamma)$, flat spectrum

Roughly 65% of maximum possible at γ=3

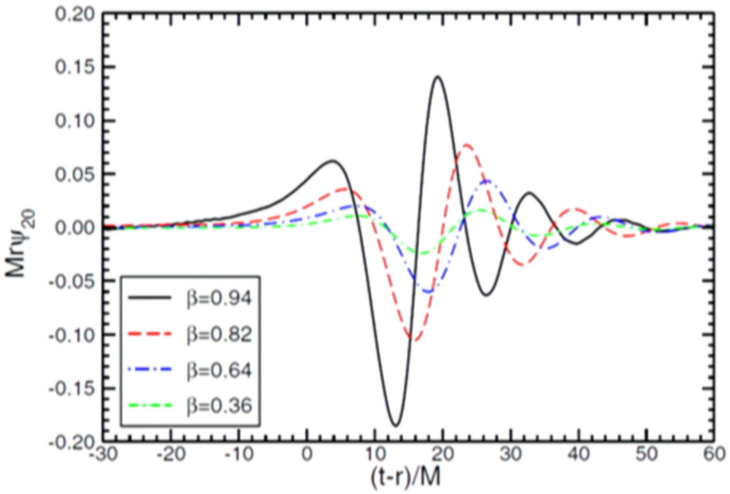
With cutoff M $\omega \approx 0.4$ we get 25% efficiency for conversion of gws

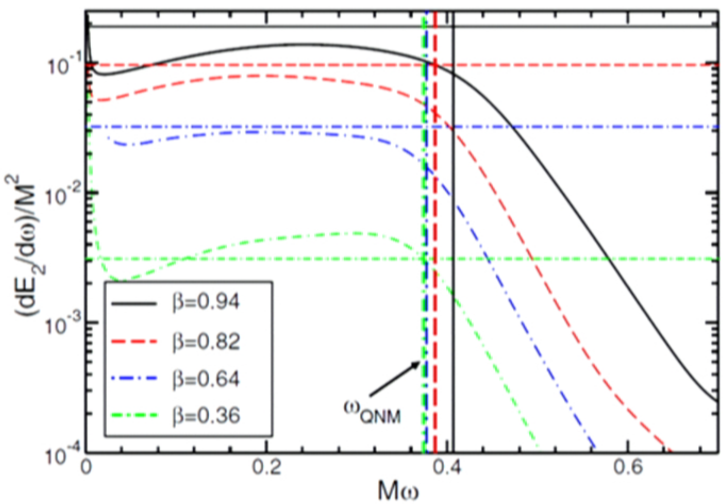
High energy head-ons

β=0.93



Sperhake, Cardoso, Pretorius, Berti and Gonzalez '08

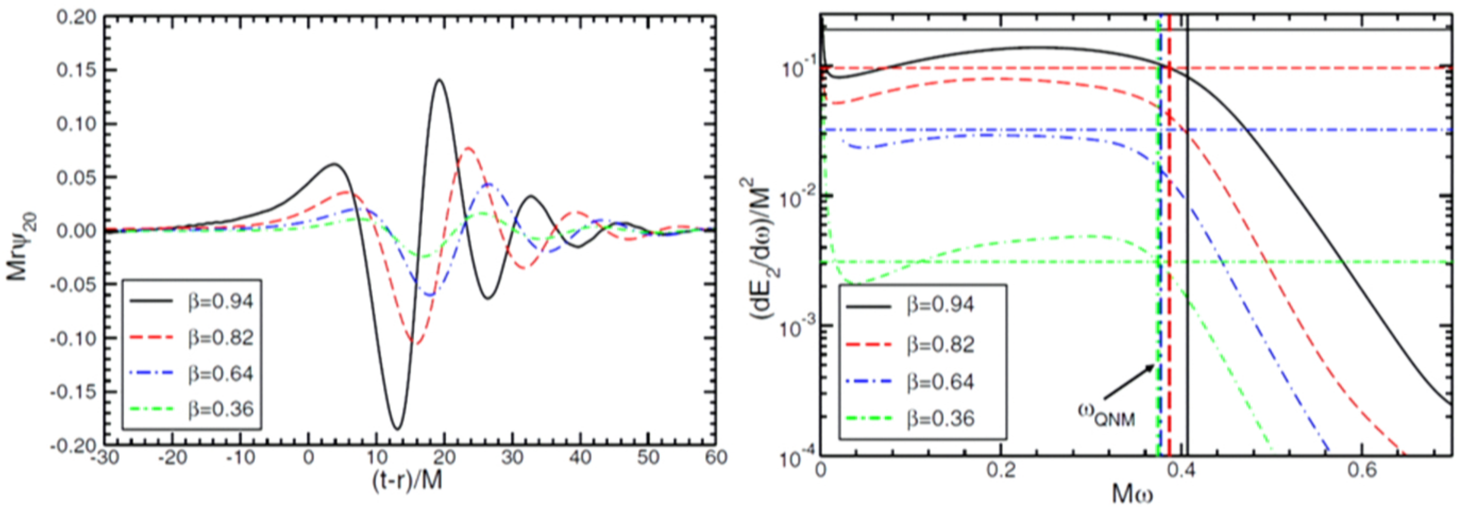




Waveform is almost just ringdown

The unreasonable effectiveness of approximations

Cutoff frequency at the lowest quasinormal frequency



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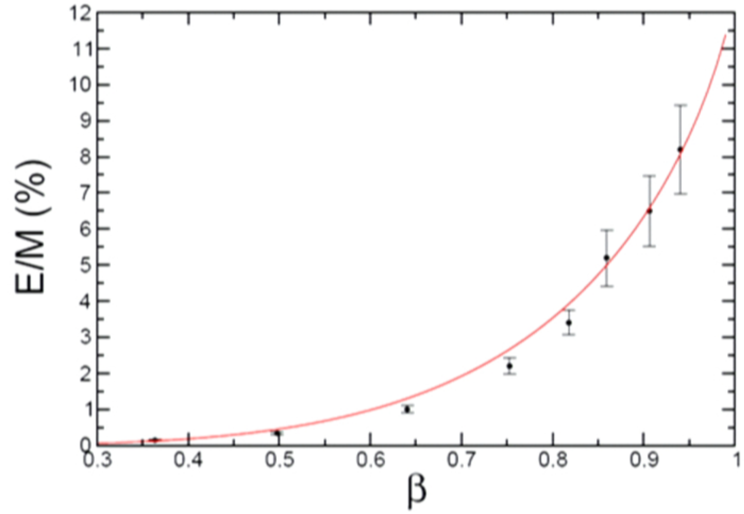


14%

$$\frac{E}{M} = E_\infty \left(\frac{1+2\gamma^2}{2\gamma^2} + \frac{(1-4\gamma^2)\log\left(\gamma + \sqrt{\gamma^2-1}\right)}{2\gamma^3\sqrt{\gamma^2-1}} \right)$$

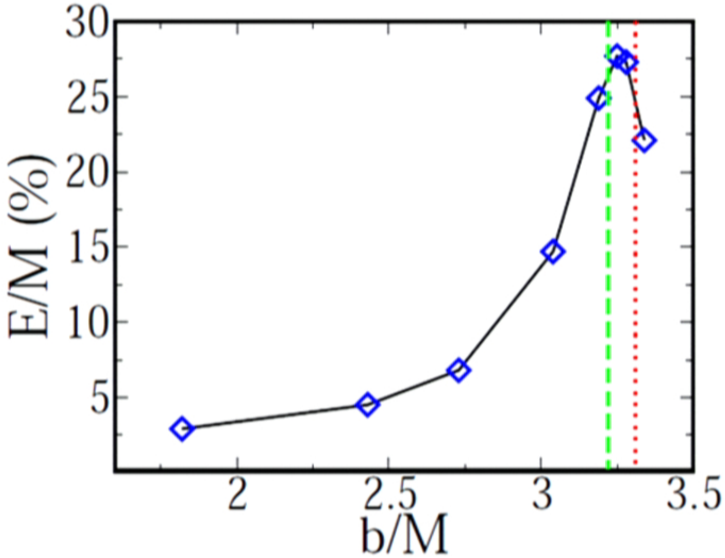
$$\dot{E}_{\rm peak} \sim 10^{-2}$$

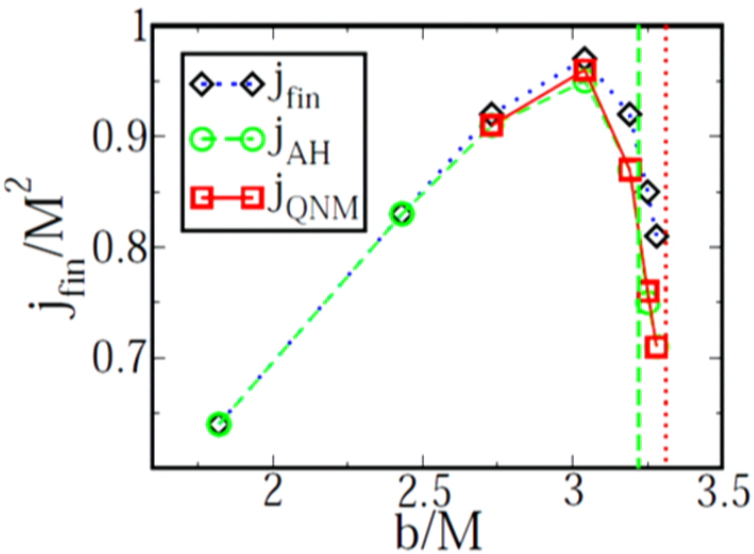
Grazing collisions

Plunge, zoom-whirl and scattering

Sperhake, Cardoso, Pretorius, Berti, Hinderer, Yunes PRL 2009

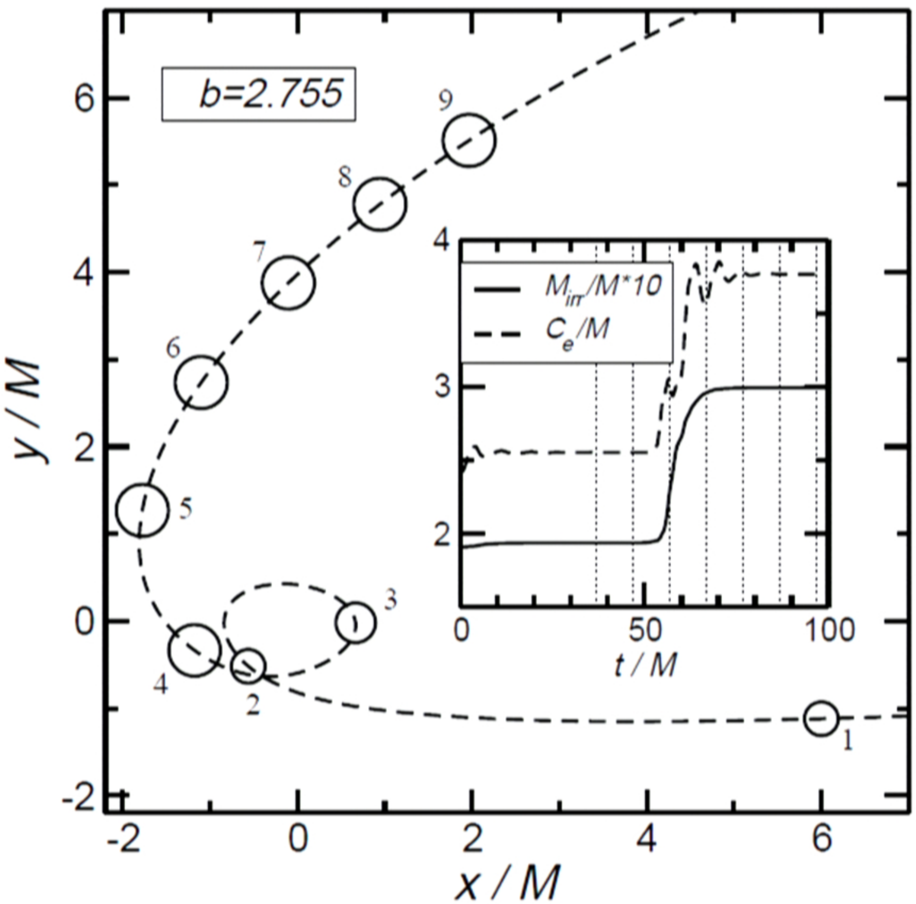
Sperhake, Berti, Cardoso and Pretorius, submitted 2013



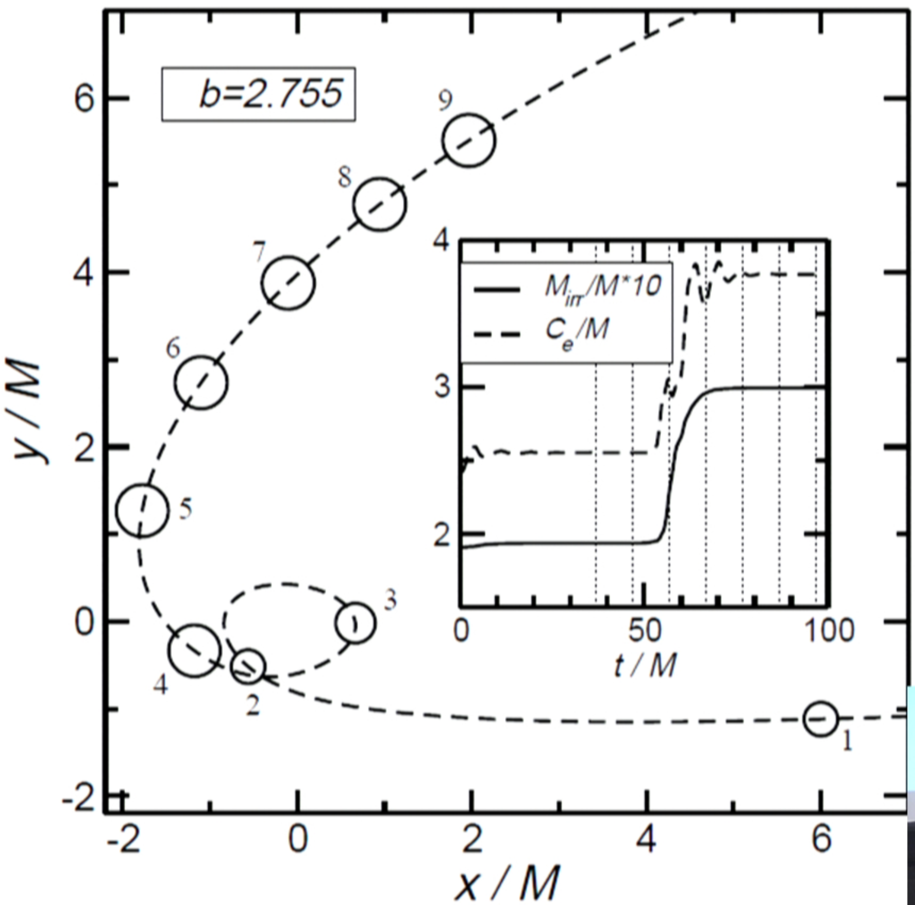


More than 25% CM energy radiated for v=0.75 c!

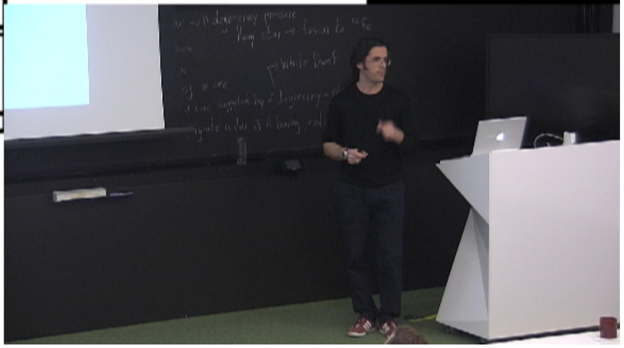
Final BH rapidly spinning



Sperhake, Berti, Cardoso and Pretorius 2013

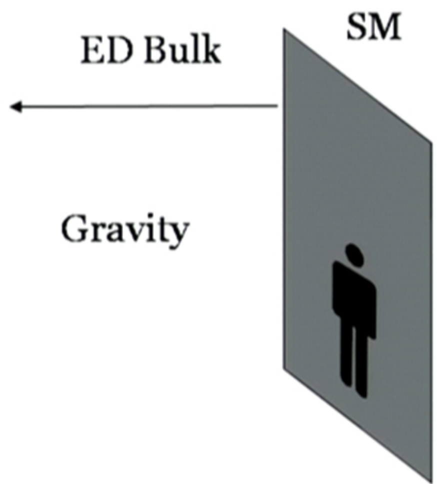


Sperhake, Berti, Cardoso and Pretorius 2013



High energy physics

Hierarchy problem or UV instability of the ratio $\frac{M_W^2}{M_P^2} \approx 10^{-32}$



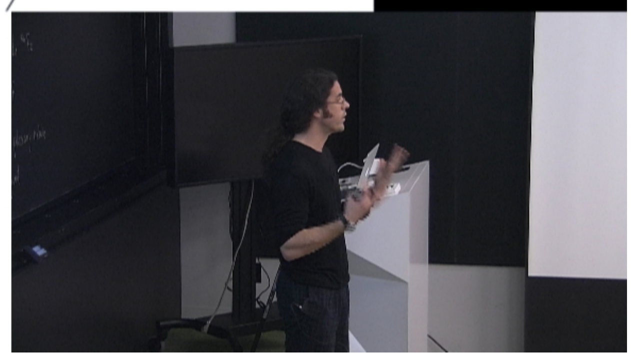
Hoop Conjecture

(Thorne 1972)

"An imploding object forms a BH when, and only when, a circular hoop with circumference 2π the Schwarzschild radius of the object can be made that encloses the object in all directions."

Large amount of energy in small region

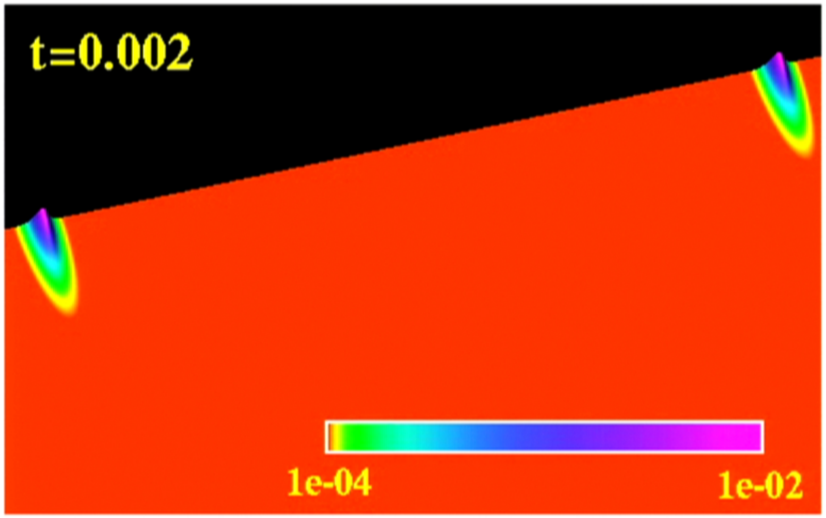
Hoop $R=2GM/c^2$



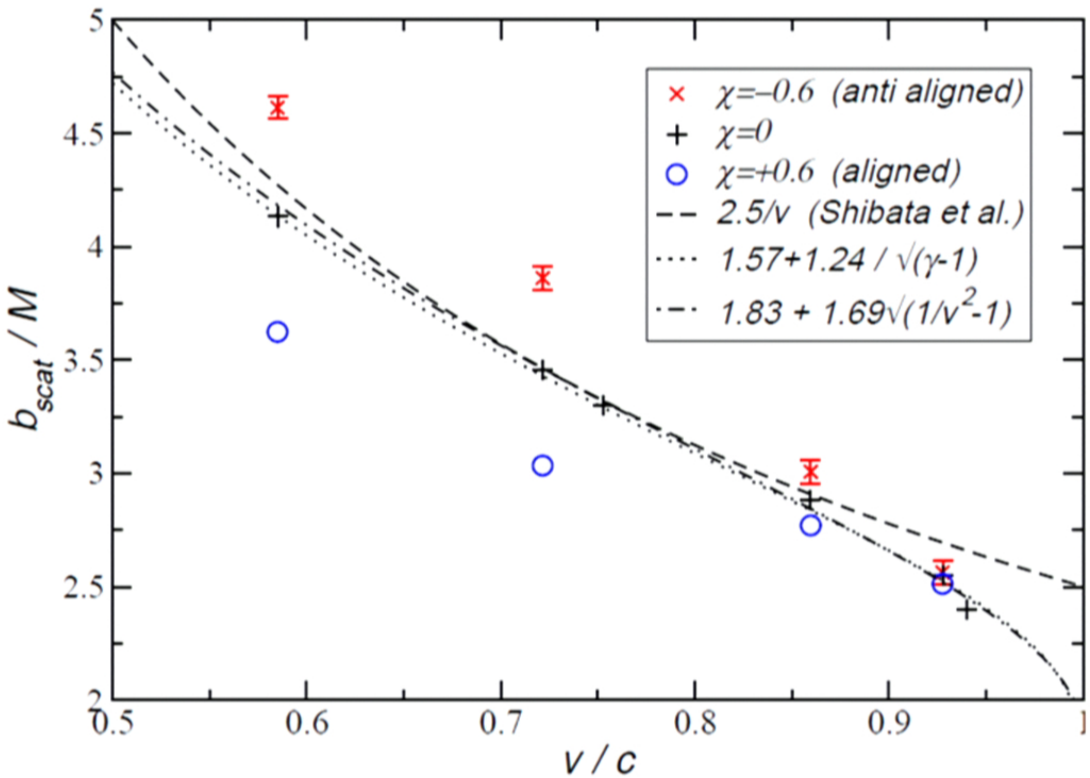
Size of electron: 10^(-17) cm

Schwarzschild radius: 10^(-55) cm

$$2M/R = 1/20 \Longrightarrow \gamma_{\rm crit} \sim 10$$



(Choptuik & Pretorius 2010; Sperhake et al 2012)

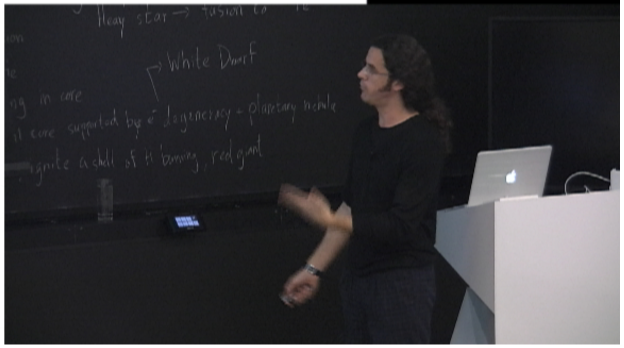


Sperhake, Berti, Cardoso & Pretorius 2013

Black holes do form in high energy collisions

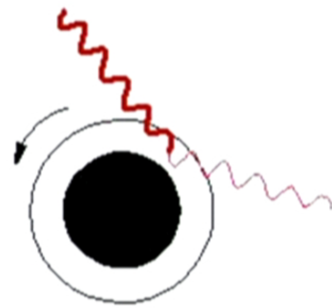
Transplanckian scattering well described by BH collisions...

Matter does not matter



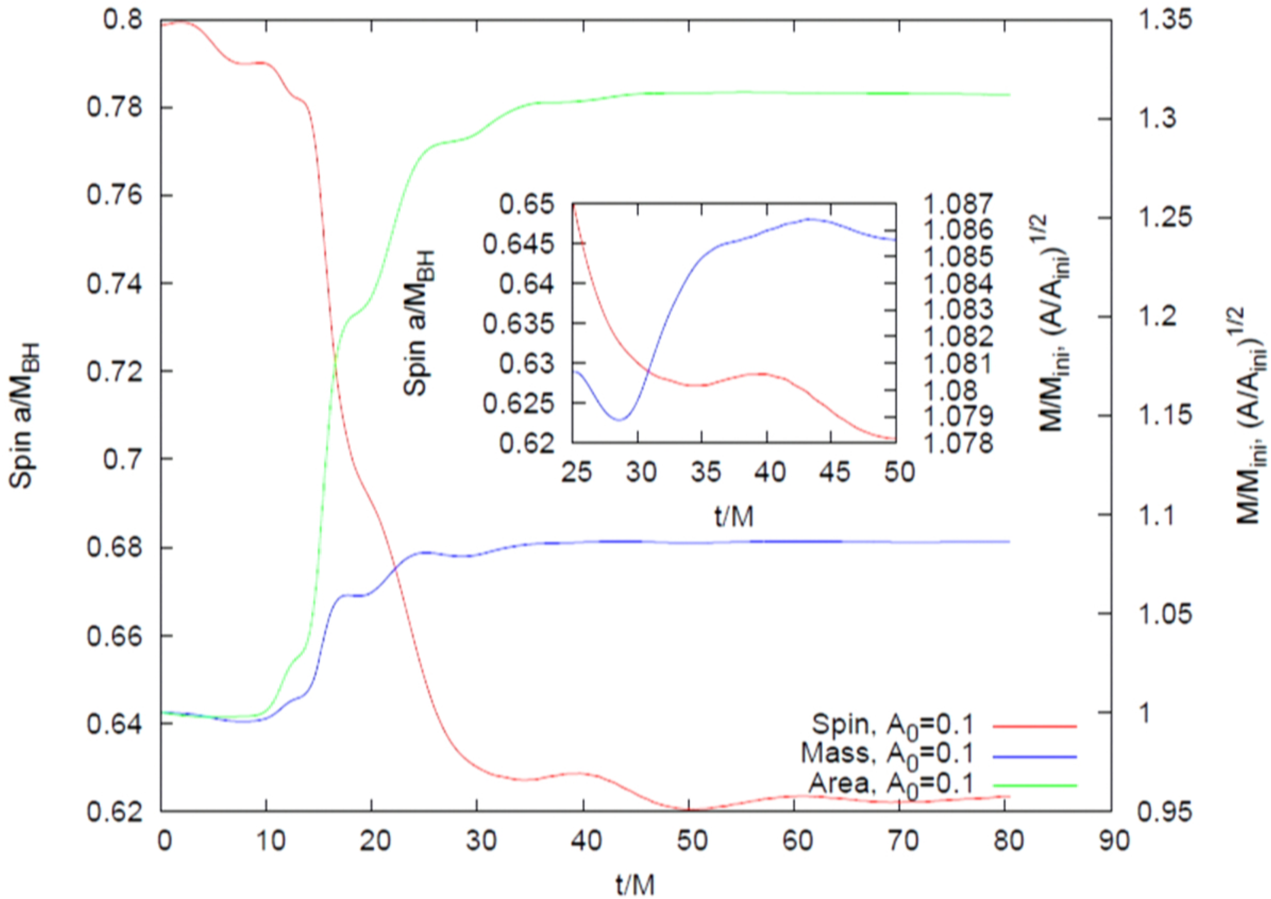
Why study dynamics: particle physics

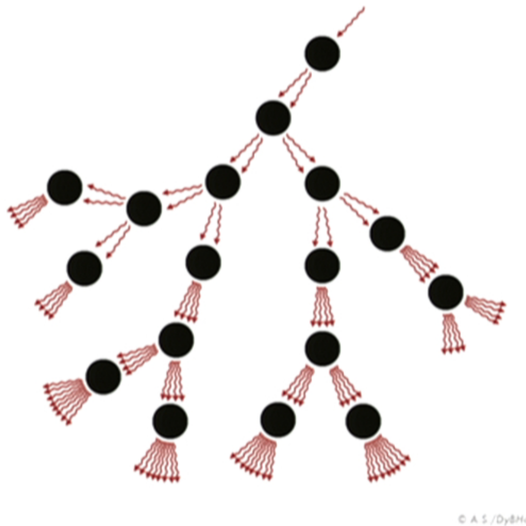
Black holes and matter fields: superradiance



$$\Phi \sim e^{-i\omega t}$$

$$\omega < \Omega_{BH}$$


Spin a/M_BH
M/M_ini, (A/A_ini)^1/2
t/M
Spin, A0=0.1
Mass, A0=0.1
Area, A0=0.1

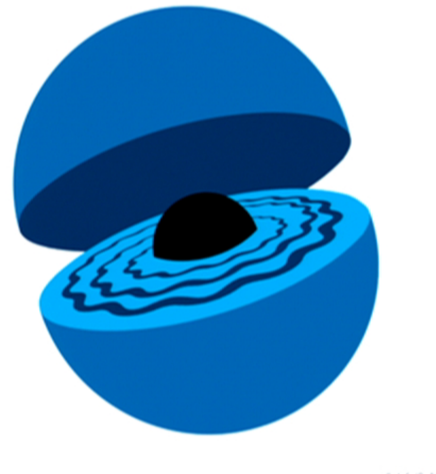


No fission-like process

$$\sigma \sim r_+^2 < 0$$

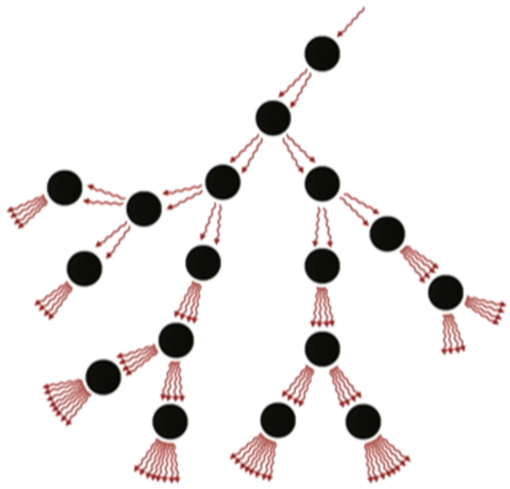
$$\ell_{\text{free path}} \sim \frac{1}{\sigma n}$$

$$\ell_{\text{free path}} \leq R \rightsquigarrow \frac{NM}{R} \gtrsim N^{\frac{1}{2}}$$



Black hole bombs

Zel'dovich '71; Press and Teukolsky '72; Cardoso et al '04



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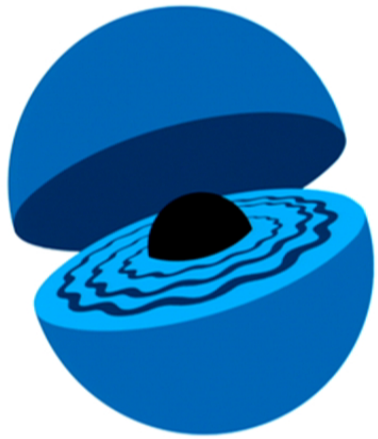

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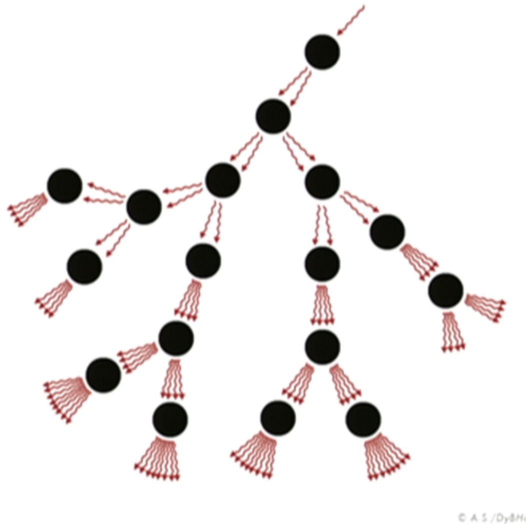

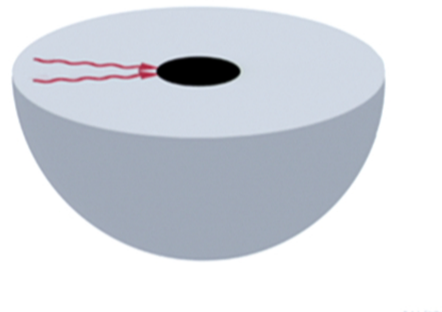

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Black hole bombs

Zel'dovich '71; Press and Teukolsky '72; Cardoso et al '04

Nature may provide its own mirrors:

AdS boundaries **("covariant box")** *Cardoso & Dias '04; Jorge & Oscar's talk*

Massive scalars *Detweiler '80; Cardoso & Yoshida '05; Dolan '07*

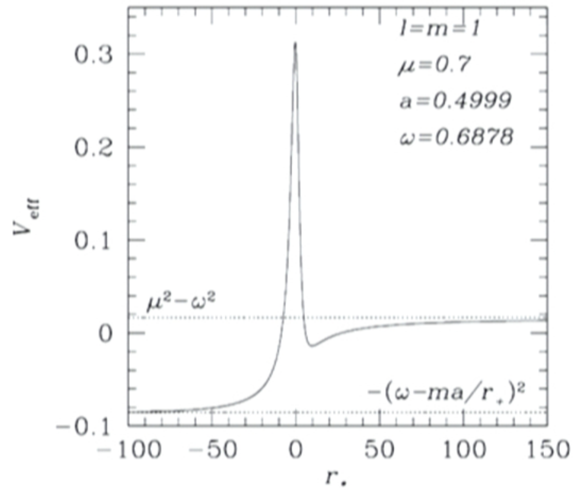
Interesting as effective description

Proxy for more complex interactions

Arise as interesting extensions of GR

(Brans-Dicke or generic scalar-tensor theories; quadratic f(R))

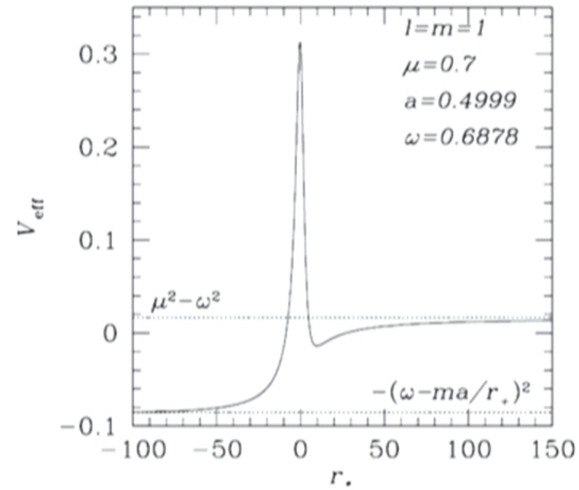
Axiverse scenarios (moduli and coupling constants in string theory, Peccei-Quinn mechanism in QCD, etc) *Arvanitaki et al '10*



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

Massive scalar fields around Kerr are unstable

Damour et al '76; Detweiler '80; Cardoso & Yoshida '05; Dolan '07



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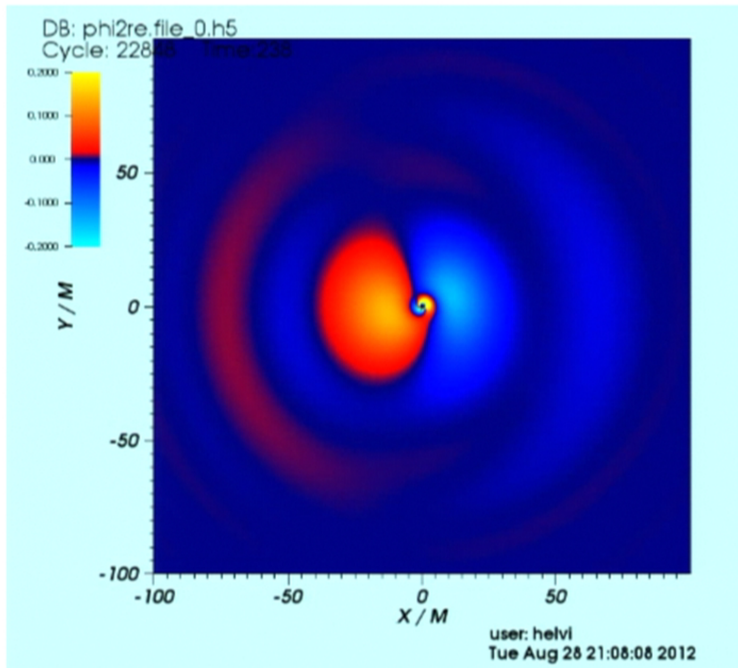


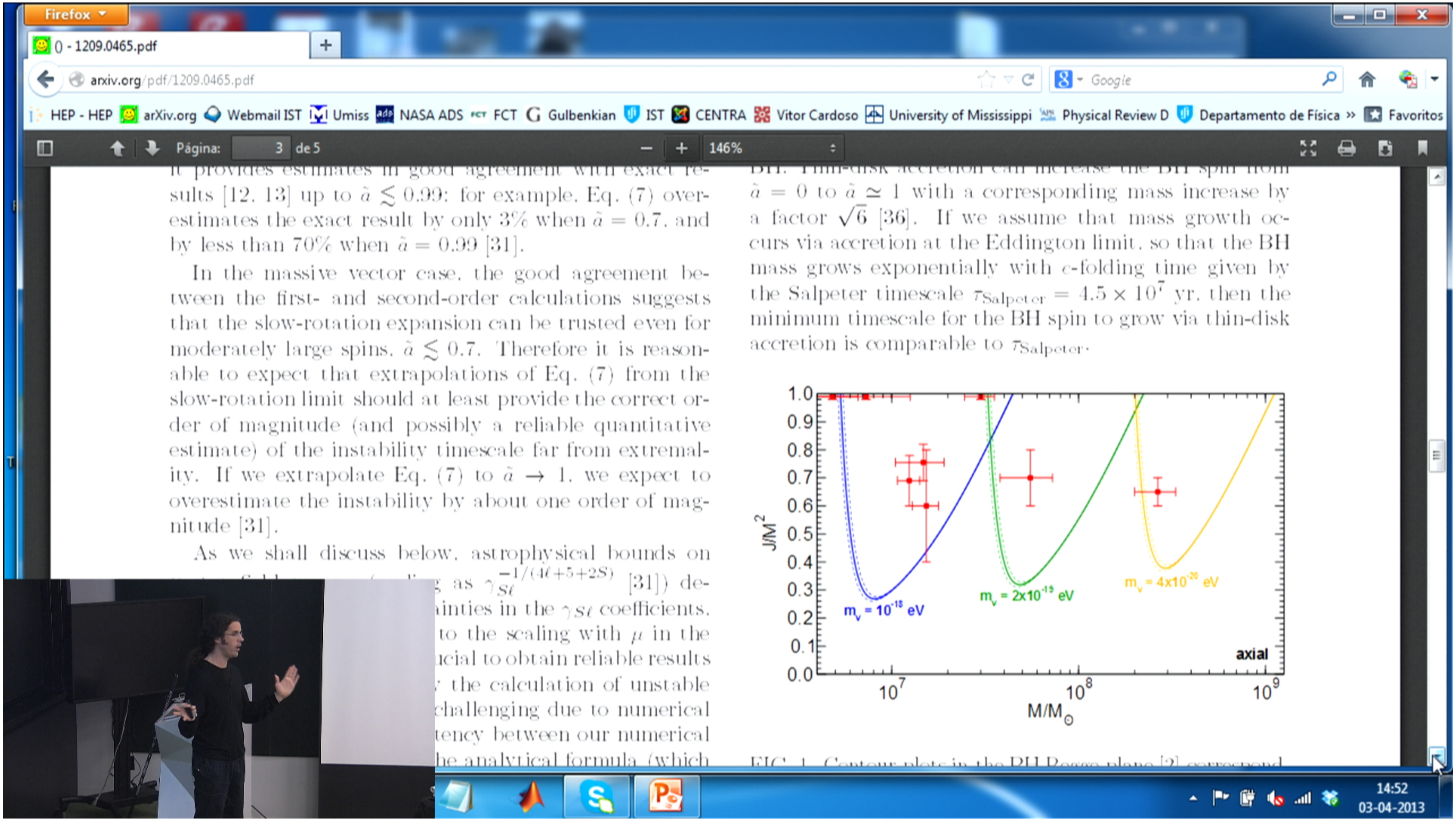
Witek, Cardoso, Ishibashi, Sperhake 2012; Okawa, Witek, Cardoso, in preparation (2013)

Bounding the photon mass

Depend very mildly on the fit coefficient and on the threshold

*

$\tau_{\text{Salpeter}} \rightarrow$ timescale for accretion at the Eddington limit



it provides estimates in good agreement with exact results [12, 13] up to $\tilde{a} \lesssim 0.99$: for example, Eq. (7) overestimates the exact result by only 3% when $\tilde{a} = 0.7$, and by less than 70% when $\tilde{a} = 0.99$ [31].

In the massive vector case, the good agreement between the first- and second-order calculations suggests that the slow-rotation expansion can be trusted even for moderately large spins, $\tilde{a} \lesssim 0.7$. Therefore it is reasonable to expect that extrapolations of Eq. (7) from the slow-rotation limit should at least provide the correct order of magnitude (and possibly a reliable quantitative estimate) of the instability timescale far from extremality. If we extrapolate Eq. (7) to $\tilde{a} \to 1$, we expect to overestimate the instability by about one order of magnitude [31].

As we shall discuss below, astrophysical bounds on ... (scaling as $\gamma_{S\ell}^{-1/(4\ell+5+2S)}$ [31]) de- ... inties in the $\gamma_{S\ell}$ coefficients. ... to the scaling with μ in the ... ucial to obtain reliable results ... the calculation of unstable ... challenging due to numerical ... tency between our numerical ... he analytical formula (which

BH. Thin-disk accretion can increase the BH spin from $\tilde{a} = 0$ to $\tilde{a} \simeq 1$ with a corresponding mass increase by a factor $\sqrt{6}$ [36]. If we assume that mass growth occurs via accretion at the Eddington limit, so that the BH mass grows exponentially with e-folding time given by the Salpeter timescale $\tau_{\rm Salpeter} = 4.5 \times 10^7$ yr, then the minimum timescale for the BH spin to grow via thin-disk accretion is comparable to $\tau_{\rm Salpeter}$.

FIG. 1. Contour plots in the BH Regge plane [2] correspond...

Bounding the photon mass

Depend very mildly on the fit coefficient and on the threshold

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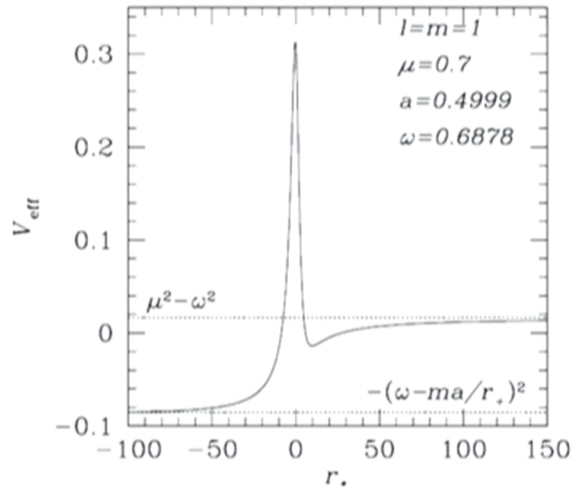

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Massive scalar fields around Kerr are unstable

Damour et al '76; Detweiler '80; Cardoso & Yoshida '05; Dolan '07

BH physics is a fascinating topic in GR

Much remains to be done:

Understand initial data, add charge, higher boosts,

higher dimensional spacetimes, compactified EDs, anti-de Sitter

End-state of superradiant instabilities, dirty effects, etc