Fundamental fields in Strong Gravity

Courtesy of S. Hembrey

Vítor Cardoso (CENTRA/IST & Perimeter) • Kyoto • 2014

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

BH dynamics

Brito, Nerozzi, Okawa, Pani, Rocha

Barausse, Berti, Emparan, Gualtieri, Herdeiro, Ishibashi, Mateos, Pretorius, Sperhake, Witek, Yunes, Zilhão

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Reviews:

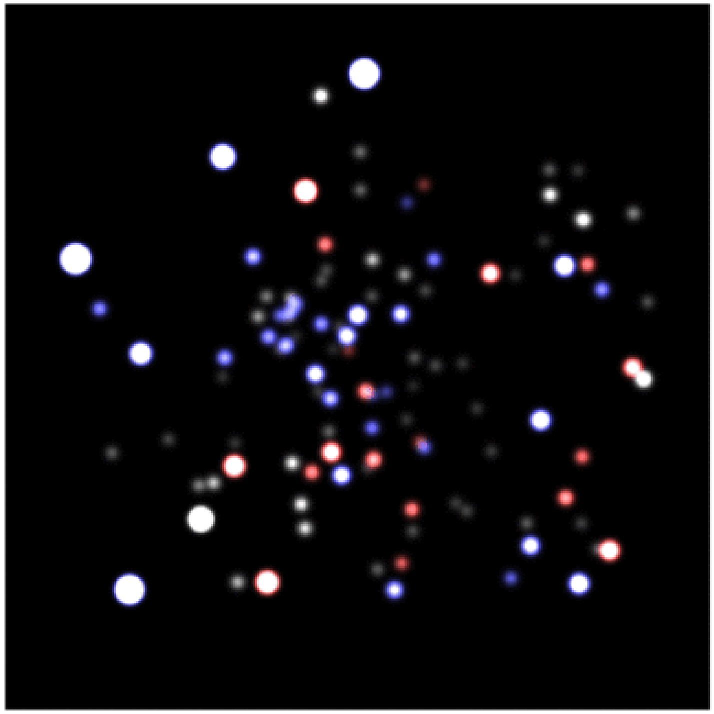
Berti, Cardoso & Starinets CQG (2009)

Pani, Witek, Okawa contributions “NR/HEP Lecture Notes” IJMPA28, 2013

Cardoso, Gualtieri, Herdeiro, Sperhake, Living Reviews in Relativity (2014)

Brito, Cardoso & Pani, in preparation (2014?)

Black holes exist



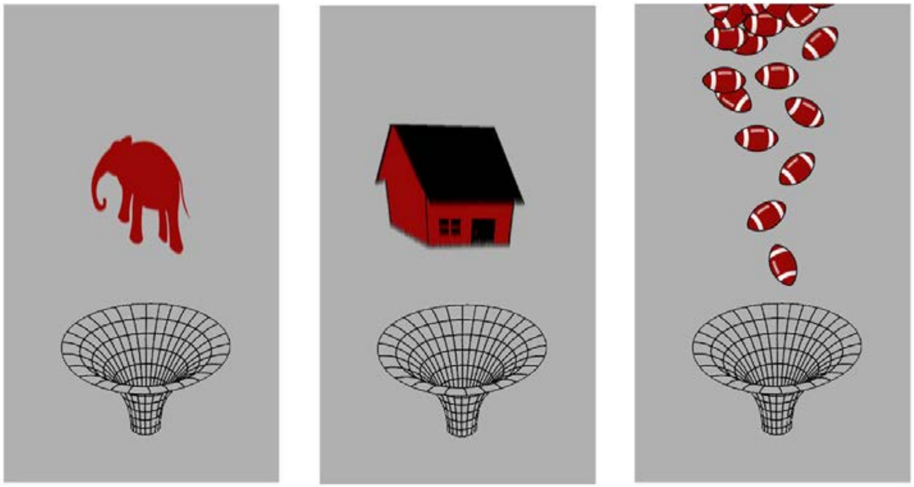
Credit: ESO/MPE (2010)

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



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

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

Why study BH dynamics

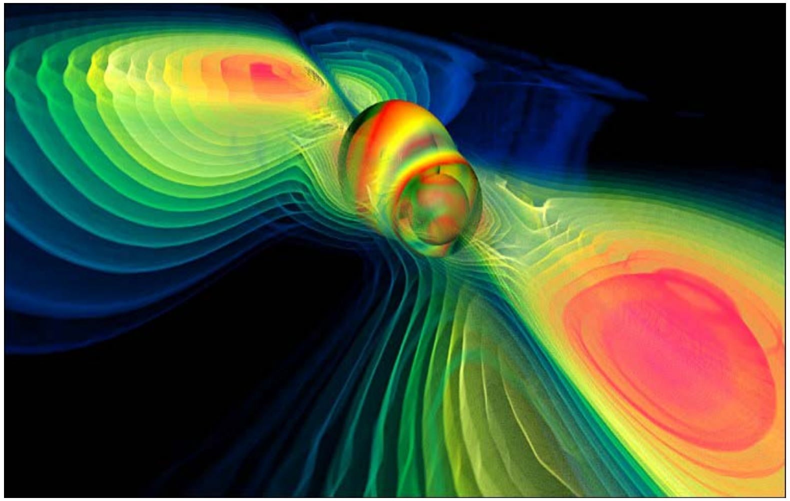
Gravitational-wave detection, GW astrophysics

Mathematical physics

High-energy physics

Particle Physics

Why dynamics: astrophysics and gw physics



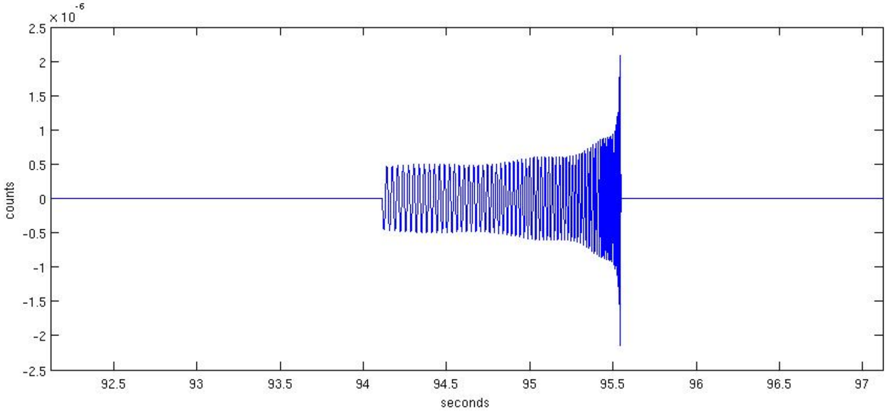
Gravitational-wave emission

Accurate templates for detection, NR/AR

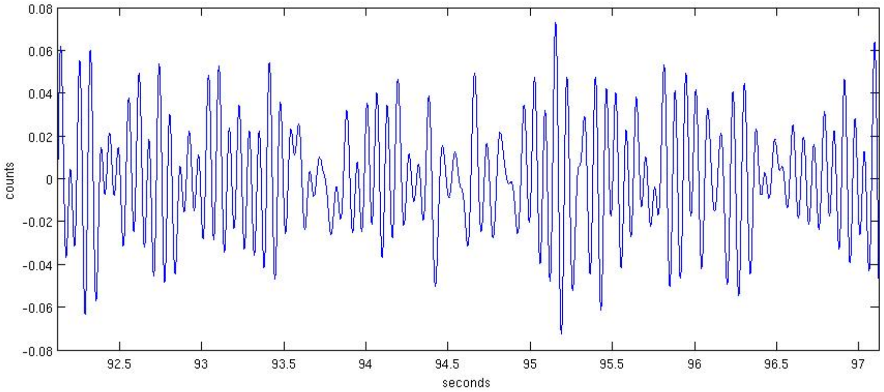
Recoil (structure formation, etc)

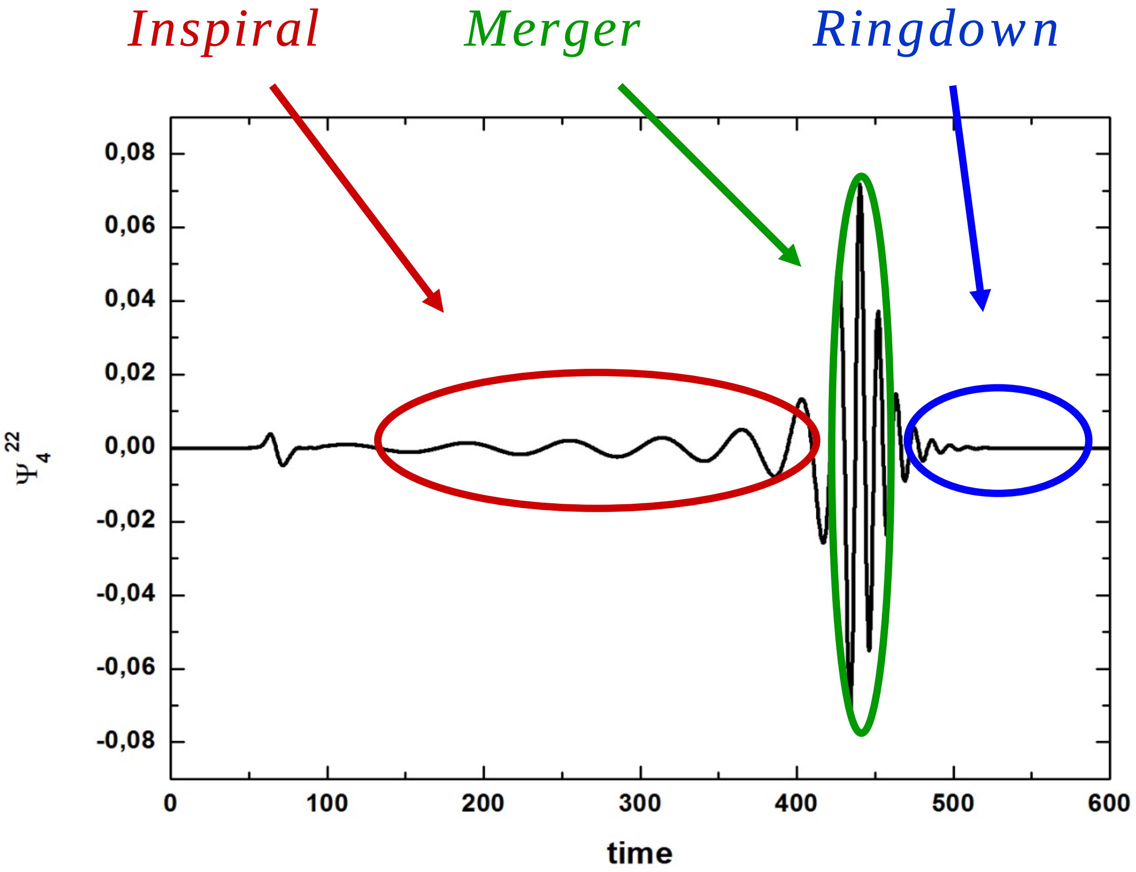
GRBs, accretion disks, etc

Typical signal for coalescing binaries



Typical stretch of data





Inspiral

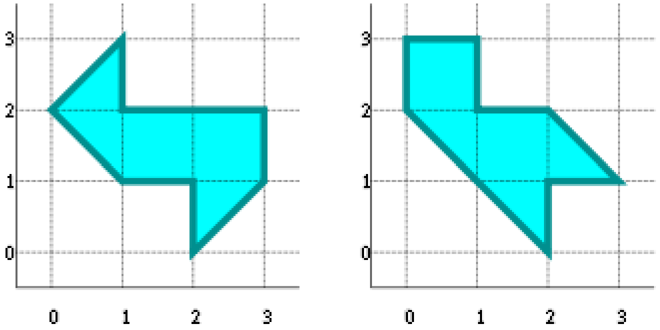
Merger

Ringdown

“Can one hear the shape of a drum?”

Mark Kac, American Mathematical Monthly, *1966*

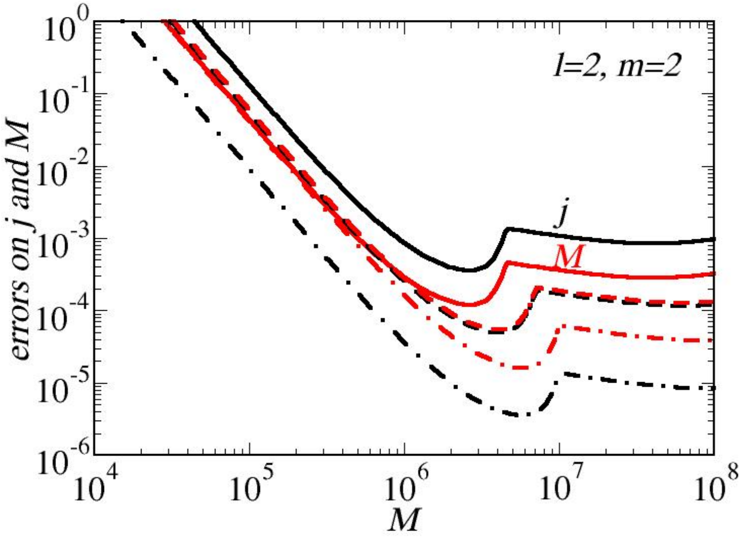
$$A = (2\pi)^d \lim_{R\to\infty} \frac{N(R)}{R^{d/2}}$$



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

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

Berti, Cardoso & Will 2006; Kamaretsos et al 2012

Strong field gravity and fundamental fields

Massive scalars

Interesting as effective description

Simplest extension of field equations

Proxy for more complex interactions (vector or tensor, accretion disks...)

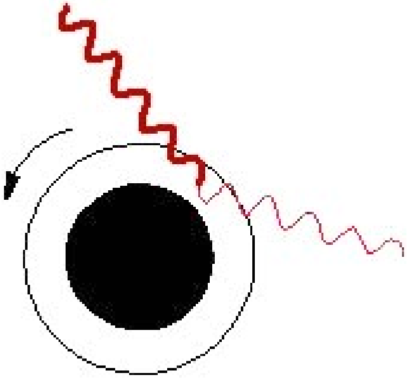
Arise as interesting extensions of GR* (BD or generic ST theories; f(R))

Dark matter candidates I (Boson stars, soliton stars)

Dark matter candidates II (Axiverse scenarios-moduli and coupling constants in string theory, Peccei-Quinn mechanism in QCD)

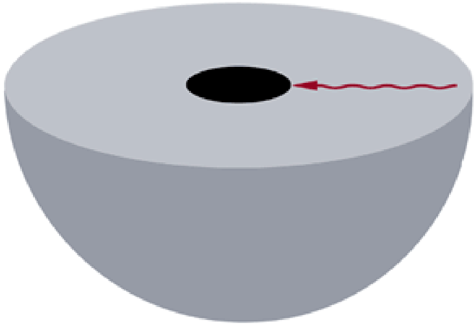
** poorly constrained for massive fields*

Long-lived scalar states and superradiance



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

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



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Black hole bombs

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

Low-frequency absorption probability

Starobinski 73; Maldacena & Strominger 97

$$|\mathcal{A}|^2 = 4\pi\left(\frac{M\omega_R}{2}\right)^{2+2l}\frac{\Gamma^2[1+l+s]\Gamma^2[1+l-s]}{\Gamma^2[1+2l]\Gamma^2[l+3/2]}$$

$$\sim (M/r_0)^{2l+2} \ll 1$$

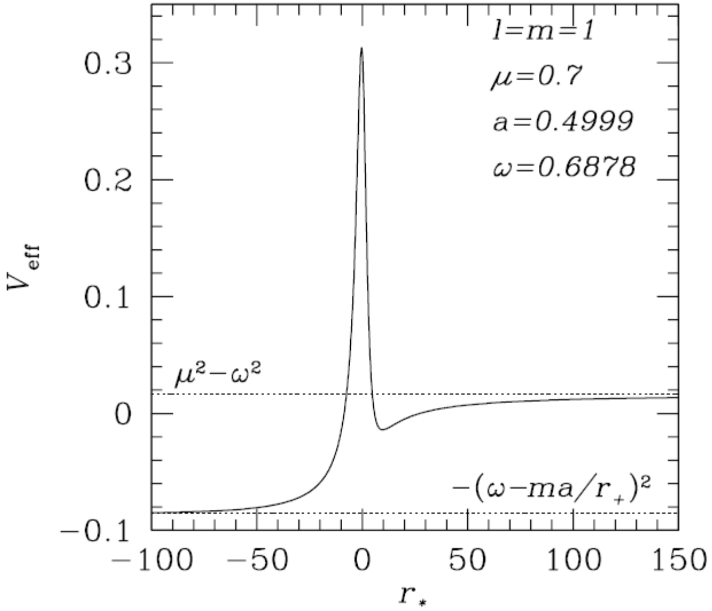
After N reflections

$$A(t) = A_0\left(1-|\mathcal{A}|^2\right)^N \sim A_0\left(1-N|\mathcal{A}|^2\right) = A_0\left(1-t|\mathcal{A}|^2/r_0\right)$$

Thus $M\omega_I \sim -(M/r_0)^{2l+3}$

For any confined geometry (AdS, boxes, Ernst spacetime, etc)

Brito, Cardoso & Pani 2014

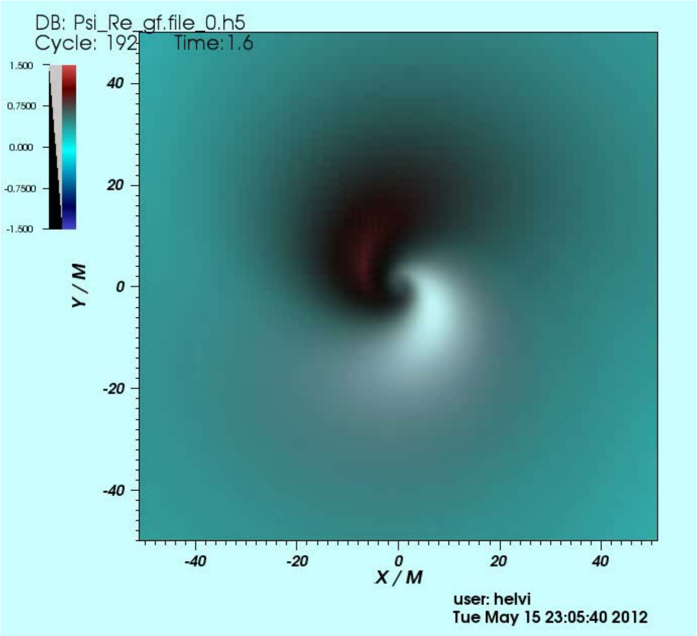


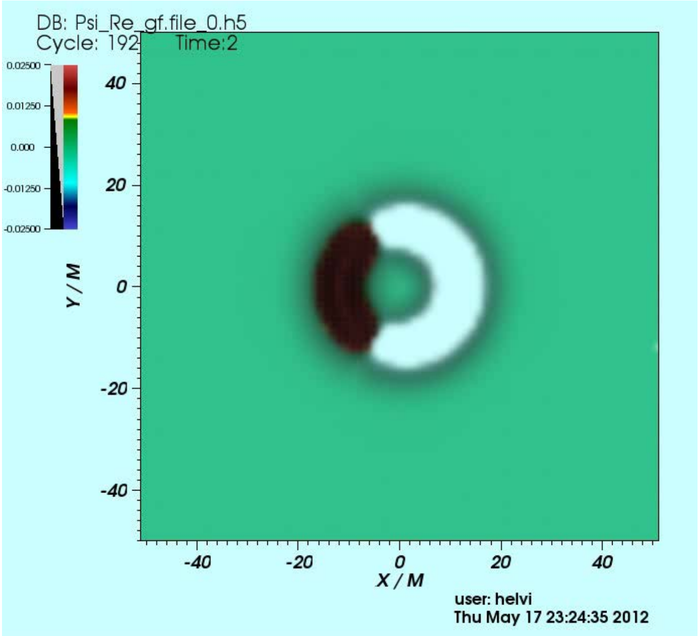
$$\omega_{\rm res}^2 = \mu_s^2 - \mu_s^2\left(\frac{\mu_s M}{l+1+n}\right)^2 \qquad \omega_I = \mu_s\frac{(\mu_s M)^8}{24}\left(a/M - 2\mu_s r_+\right)$$

Massive scalar fields around Kerr linearly are unstable

Damour et al ‘76; Detweiler ’80; Cardoso & Yoshida ’05; Dolan ’07; Witek et al 12

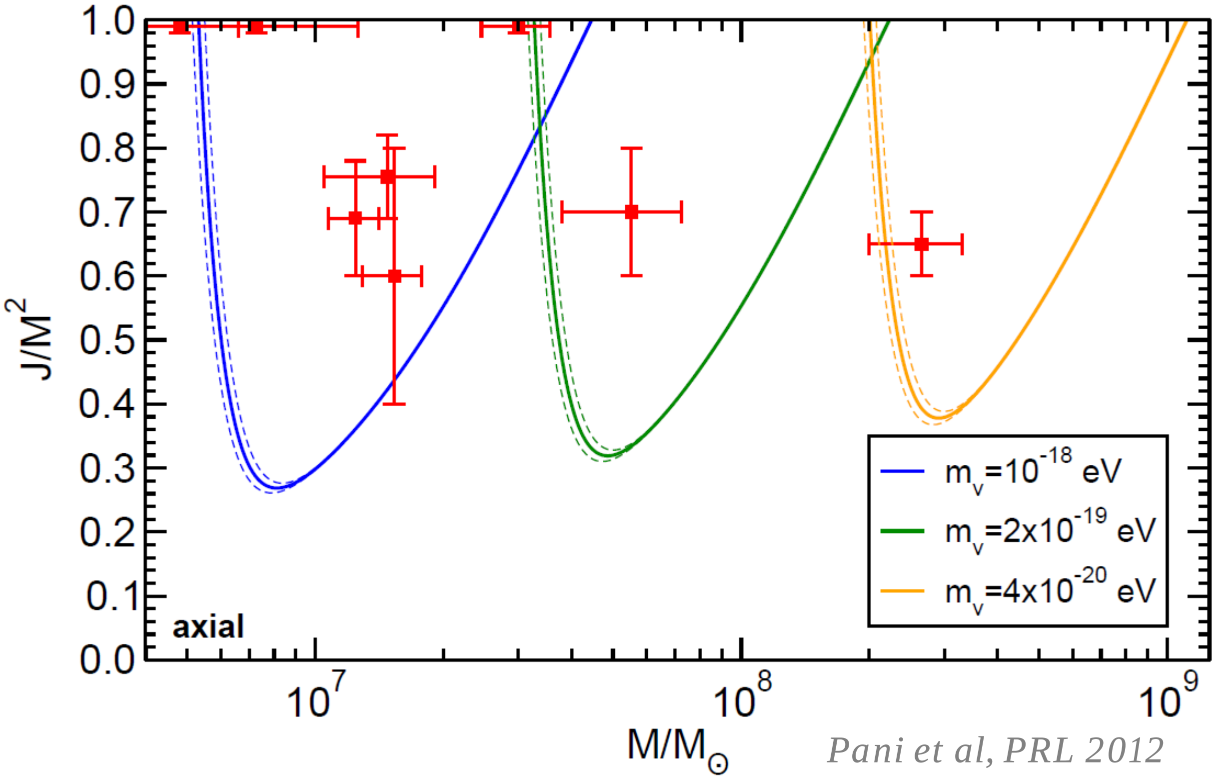
Massive scalars: non-rotating BHs





Witek, Cardoso, Sperhake, Ishibashi 2012; Okawa, Witek, Cardoso 2014

Bounding the photon mass



Pani et al, PRL 2012

Depend very mildly on the fit coefficient and on the threshold

*

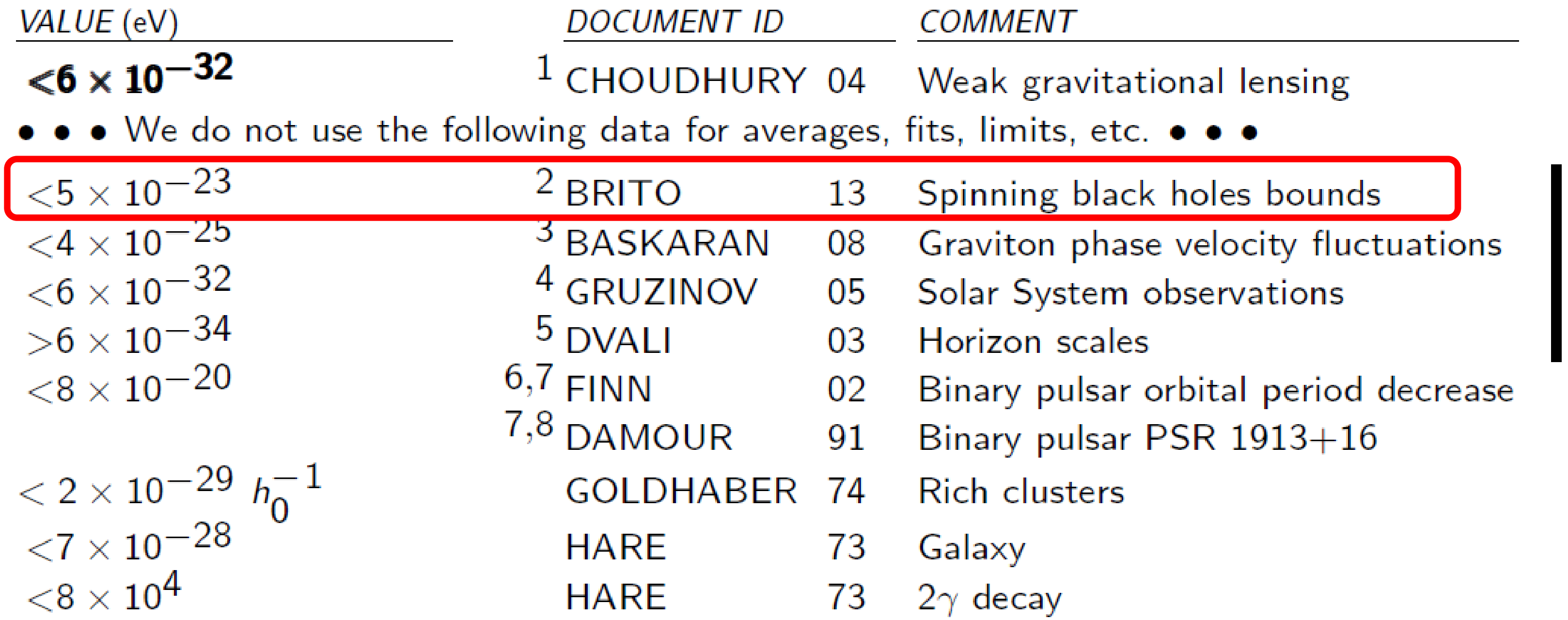
τ_{Salpeter} → timescale for accretion at the Eddington limit

Bounding the graviton mass

Brito, Cardoso & Pani 2013

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

$$\bar{\Box} h_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu} h^{\alpha\beta} - \mu^2 h_{\mu\nu} = 0\,,$$
$$\mu^2 \bar{\nabla}^{\mu} h_{\mu\nu} = 0\,,$$
$$\left(\mu^2 - 2\Lambda/3\right) h = 0\,.$$

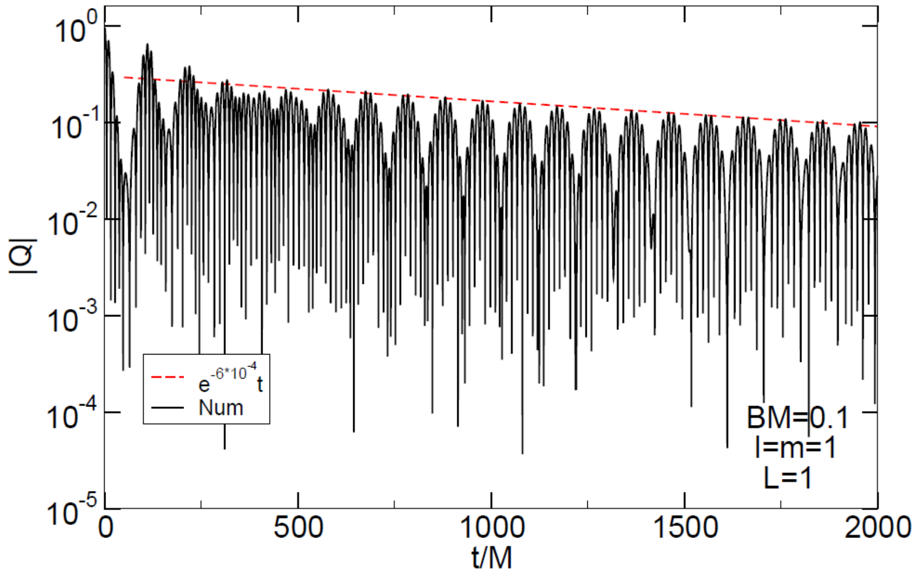


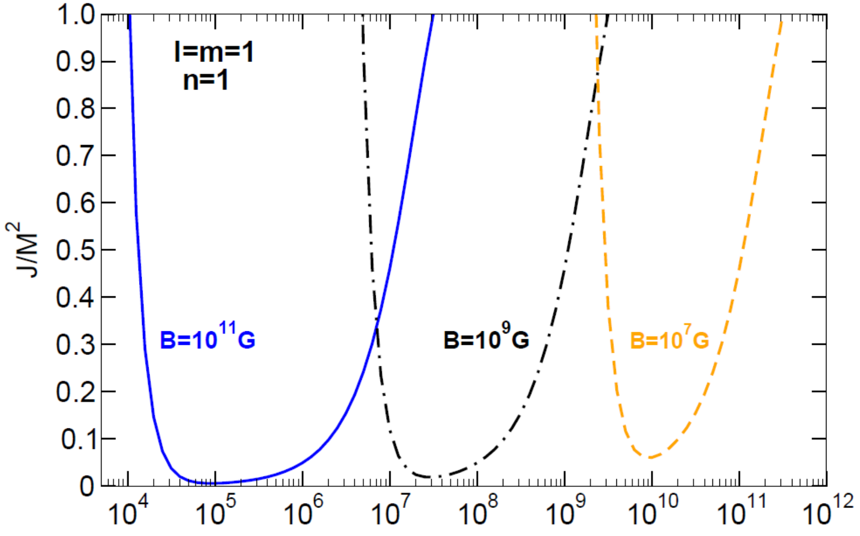
YOUR DATA

VALUE (eV)	*DOCUMENT ID*		*COMMENT*
$<6 \times 10^{-32}$	[1] CHOUDHURY	04	Weak gravitational lensing
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<5 \times 10^{-23}$	[2] BRITO	13	Spinning black holes bounds
$<4 \times 10^{-25}$	[3] BASKARAN	08	Graviton phase velocity fluctuations
$<6 \times 10^{-32}$	[4] GRUZINOV	05	Solar System observations
$>6 \times 10^{-34}$	[5] DVALI	03	Horizon scales
$<8 \times 10^{-20}$	[6,7] FINN	02	Binary pulsar orbital period decrease
	[7,8] DAMOUR	91	Binary pulsar PSR 1913+16
$< 2 \times 10^{-29}\ h_0^{-1}$	GOLDHABER	74	Rich clusters
$<7 \times 10^{-28}$	HARE	73	Galaxy
$<8 \times 10^{4}$	HARE	73	2γ decay

Review of Particle Physics 2014 (PDG, in preparation)

Bounding magnetic fields





Melvin magnetic universe:

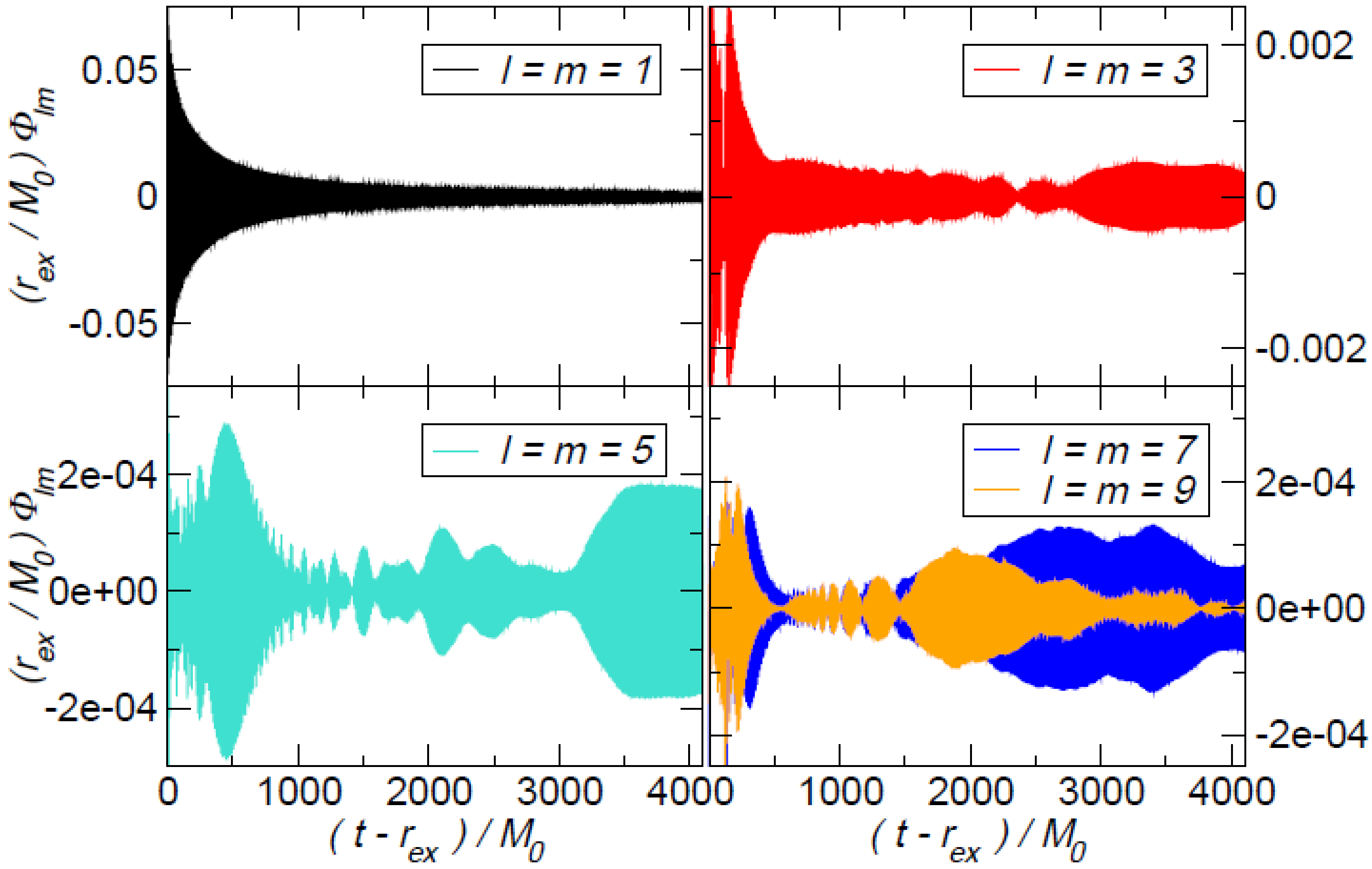
$$ds^2 = \Lambda^2\left(-dt^2 + d\rho^2 + dz^2\right) + \frac{\rho^2}{\Lambda^2}d\phi^2$$

$$\Lambda = 1 + B^2\rho^2/4$$

Confining geometry:
add BH+rotation...

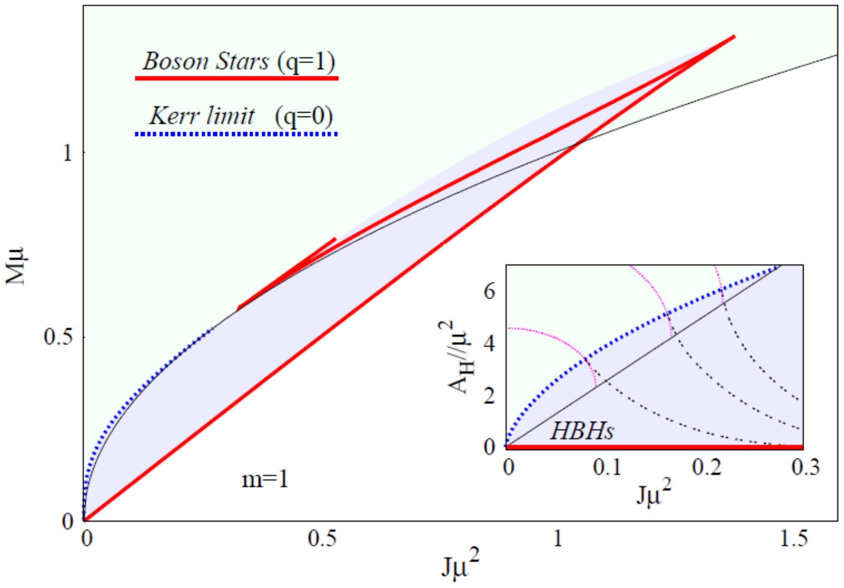
Brito, Cardoso & Pani 2014

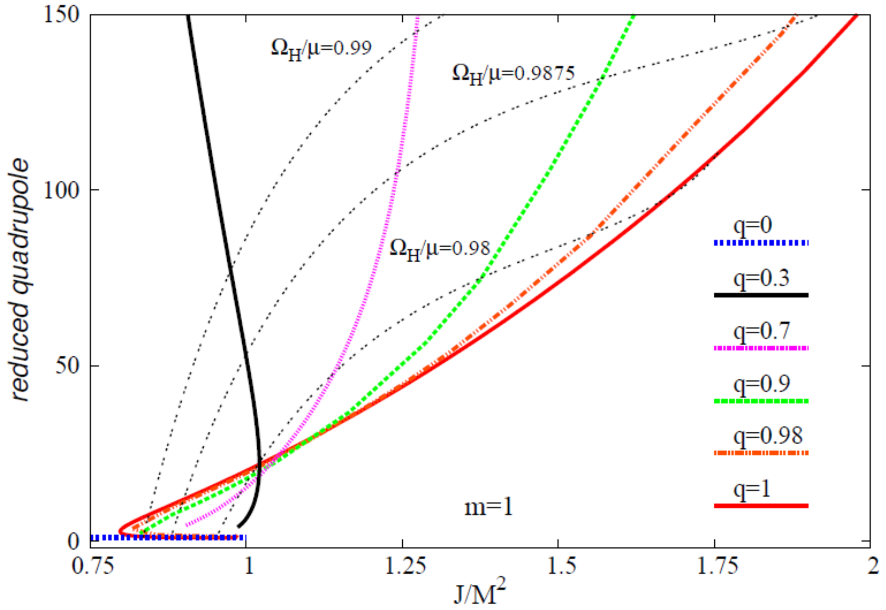
Final state I: turbulence and collapse?



Okawa, Witek, Cardoso, in preparation

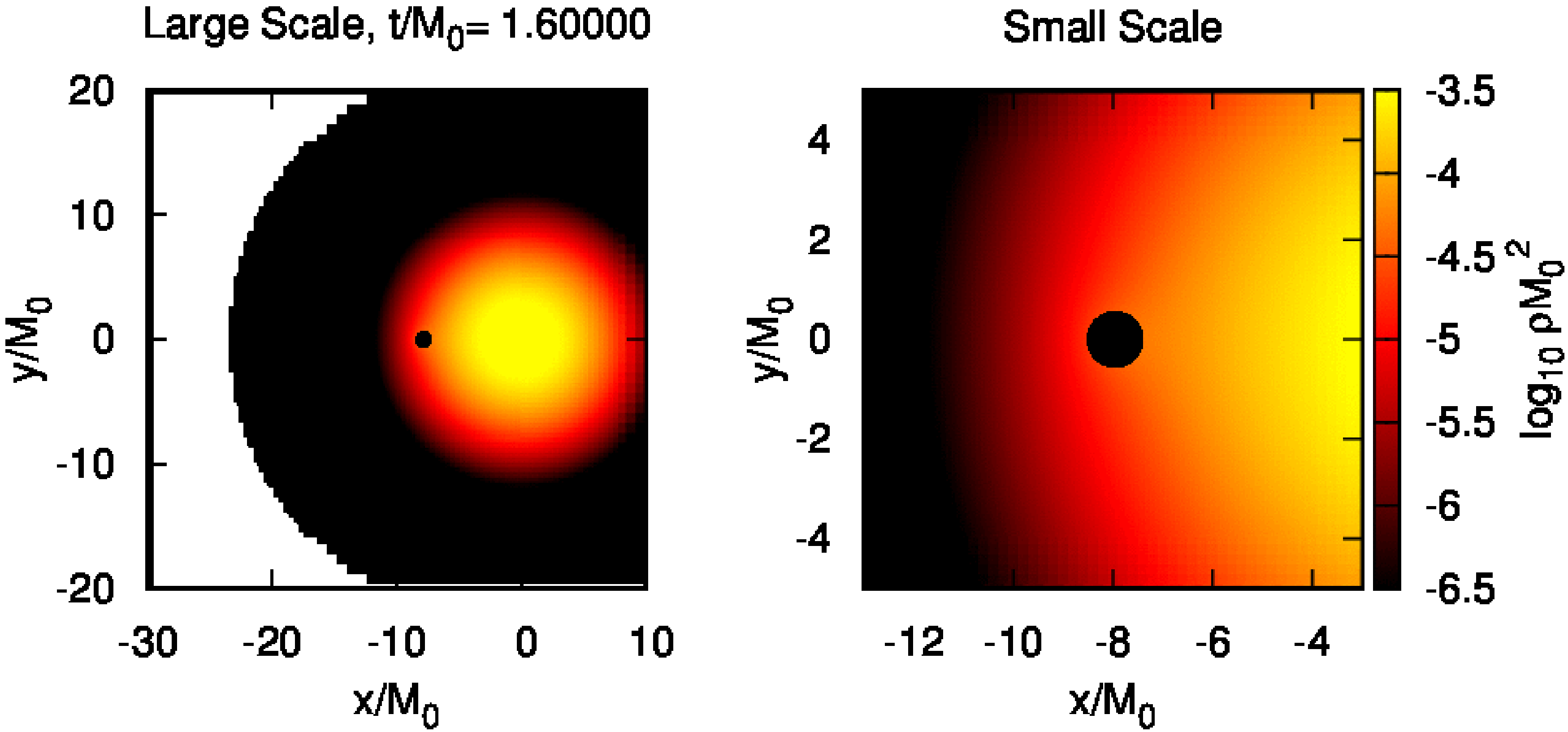
Final state II: hairy black holes?





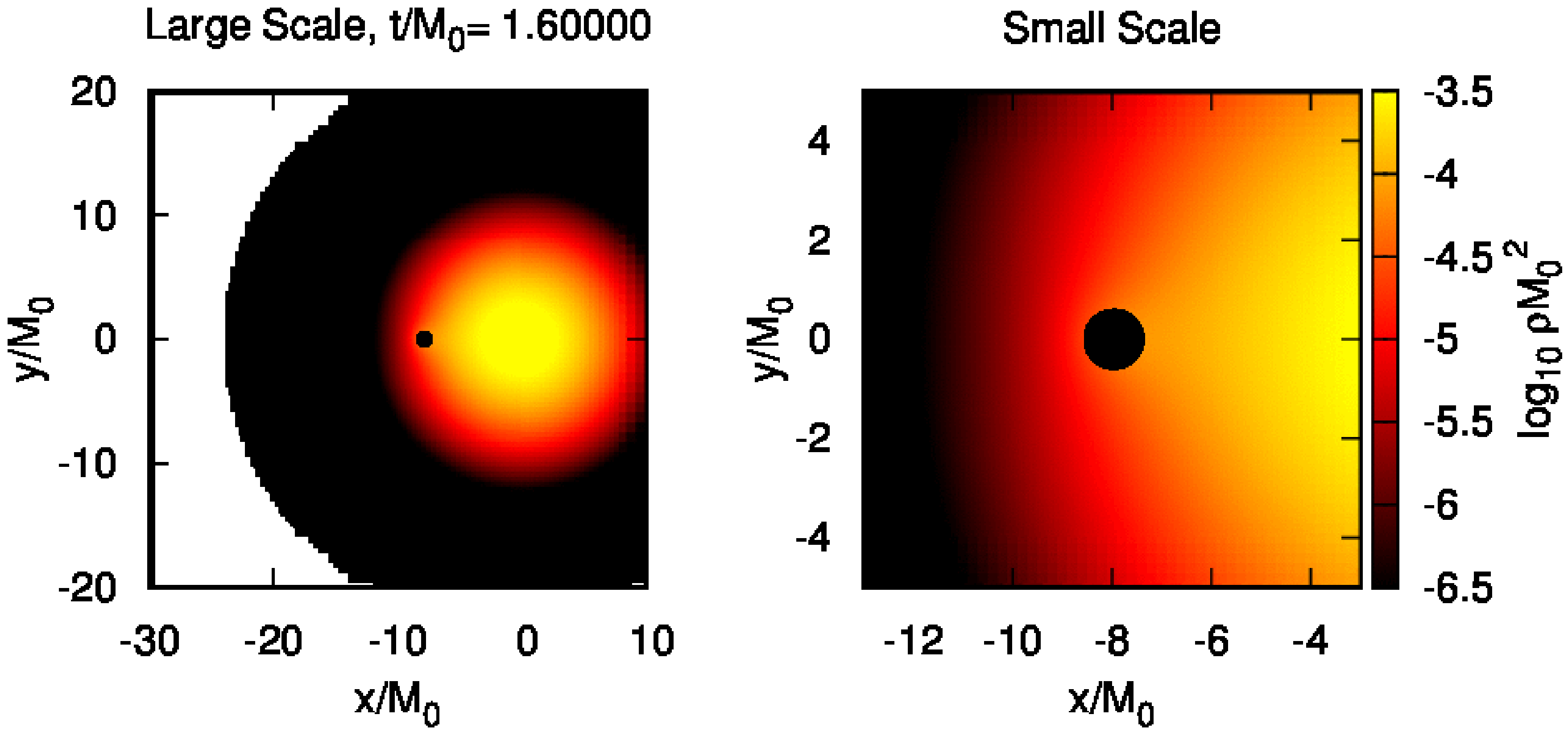
Dias et al 2012; Herdeiro & Radu arXiv: 1403.2757

Interaction with scalar clouds I. Dynamics of hairy solutions



Okawa, Cardoso arXiv:1405.4861

Interaction with scalar clouds I. Dynamics of hairy solutions



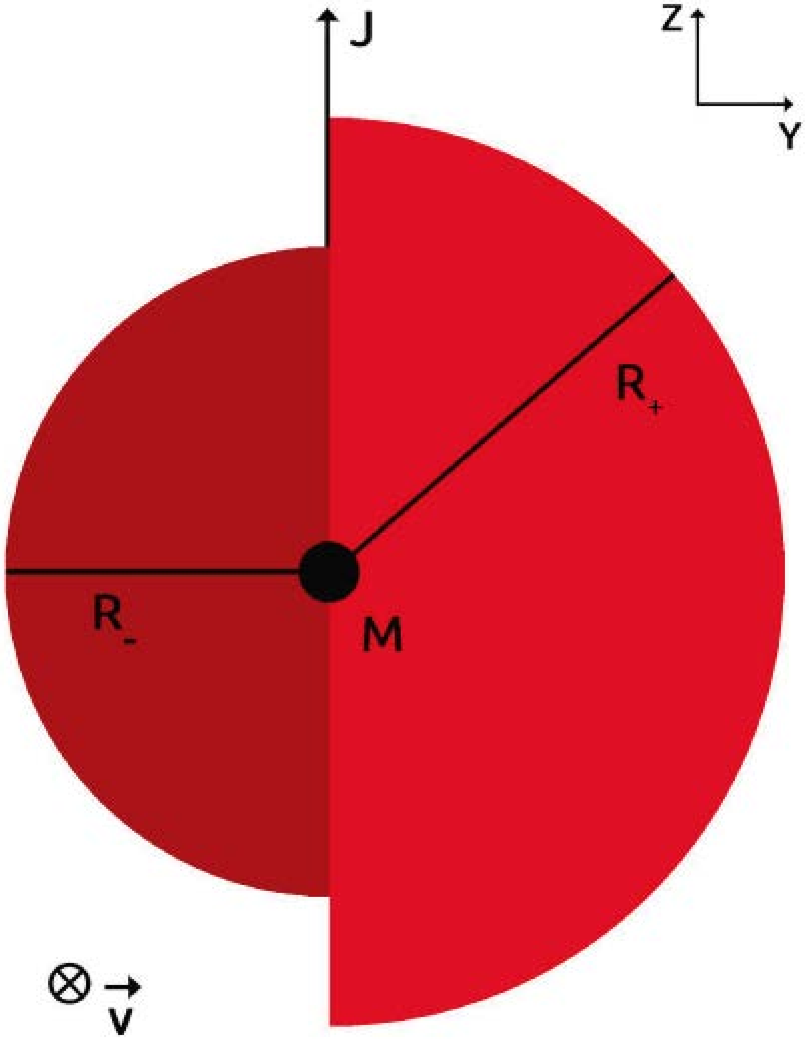
Okawa, Cardoso arXiv:1405.4861

Interaction with scalar clouds II. BH (anti-) Magnus effect

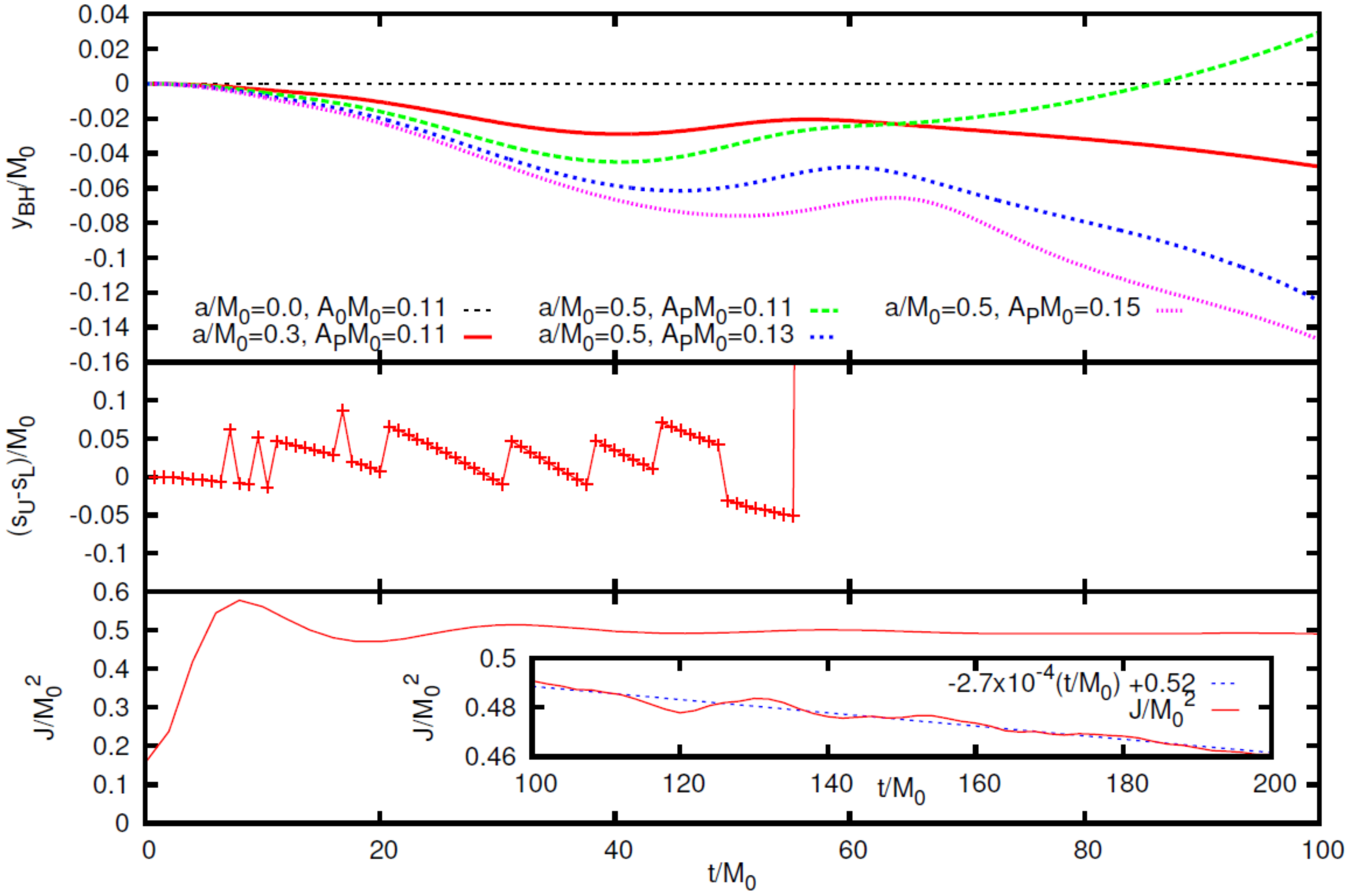
“Everything I know about morality and the obligations of men, I owe it to football”

Albert Camus

Interaction with scalar clouds II. BH (anti-) Magnus effect



Interaction with scalar clouds II. BH (anti-) Magnus effect



Strong field gravity is a fascinating topic

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From precise maps of our Universe to tests of Cosmic Censorship, and constraints on dark matter candidates, the possibilities are exciting.

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 *(more in Yoshino's talk)*

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Strong field gravity and fundamental fields

End-state of superradiant instability, turbulence, hairy sols?

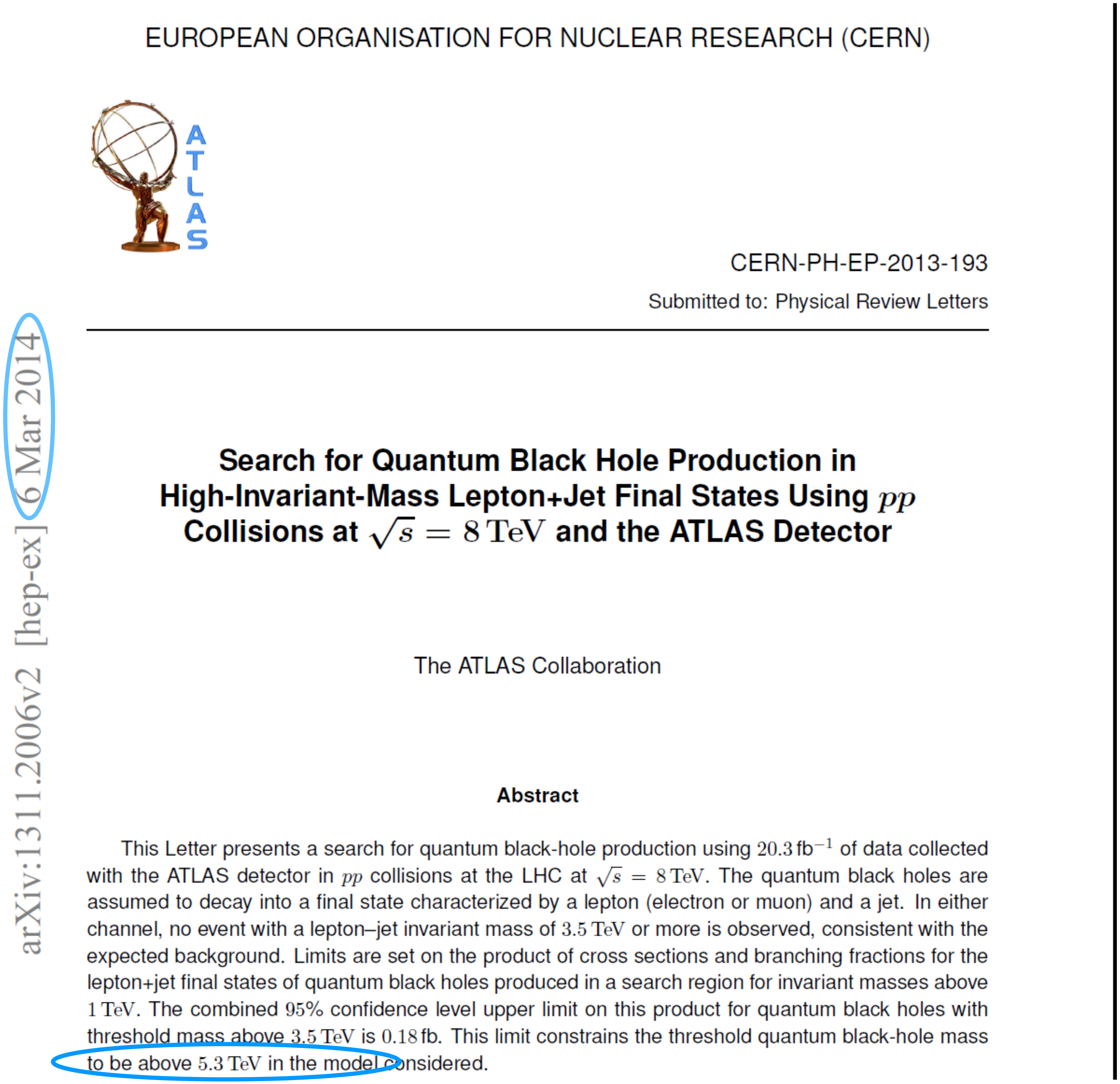
(need very long-term stable simulations)

Role of accretion disks on development of instability?

Accretion, “Magnus-effect,” interaction of scalarized BHs...

Collapse...

Thank you



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2013-193

Submitted to: Physical Review Letters

arXiv:1311.2006v2 [hep-ex] 6 Mar 2014

Search for Quantum Black Hole Production in High-Invariant-Mass Lepton+Jet Final States Using pp Collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ and the ATLAS Detector

The ATLAS Collaboration

Abstract

This Letter presents a search for quantum black-hole production using $20.3\,\mathrm{fb}^{-1}$ of data collected with the ATLAS detector in pp collisions at the LHC at $\sqrt{s} = 8\,\mathrm{TeV}$. The quantum black holes are assumed to decay into a final state characterized by a lepton (electron or muon) and a jet. In either channel, no event with a lepton–jet invariant mass of $3.5\,\mathrm{TeV}$ or more is observed, consistent with the expected background. Limits are set on the product of cross sections and branching fractions for the lepton+jet final states of quantum black holes produced in a search region for invariant masses above $1\,\mathrm{TeV}$. The combined 95% confidence level upper limit on this product for quantum black holes with threshold mass above $3.5\,\mathrm{TeV}$ is $0.18\,\mathrm{fb}$. This limit constrains the threshold quantum black-hole mass to be above $5.3\,\mathrm{TeV}$ in the model considered.

Why dynamics: mathematical physics

Cosmic Censorship: do horizons always form?

* * *

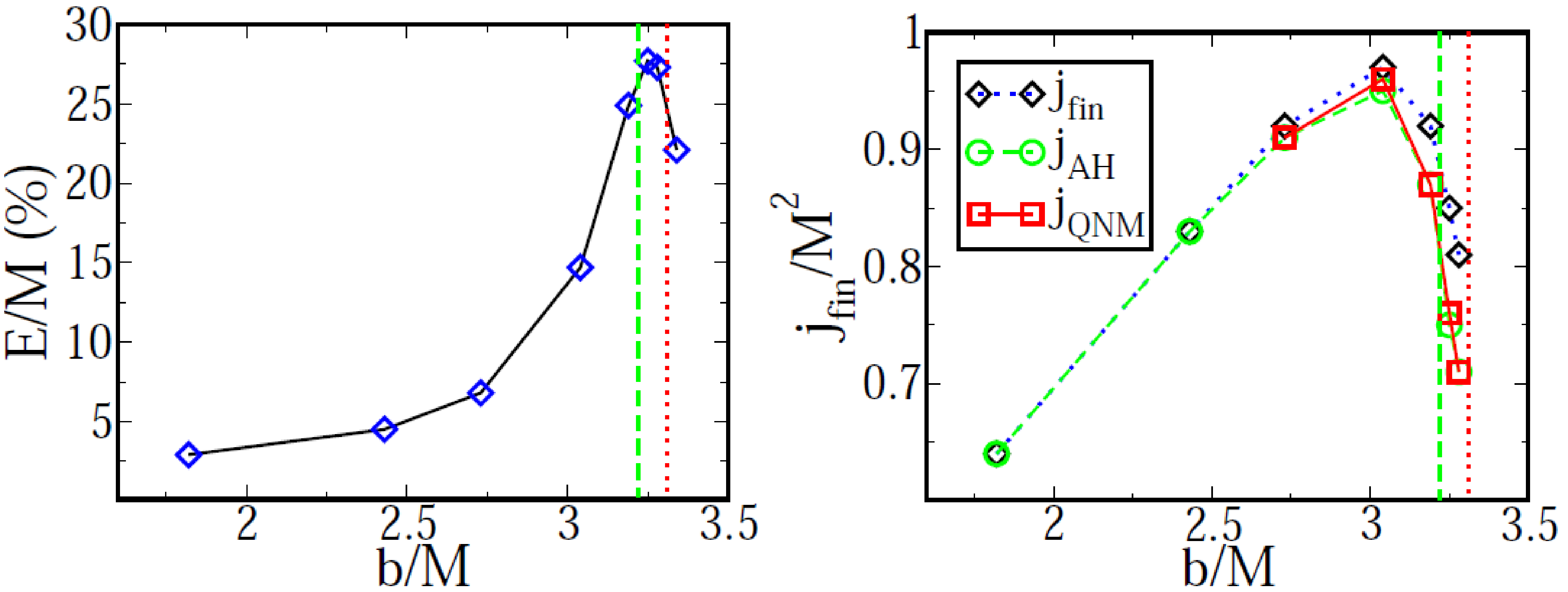
Are black objects always stable? Phase diagrams...

* * *

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

* * *

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



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

Final BH rapidly spinning

More in Sperhake's talk