Black holes as laboratories of fundamental physics

Vítor Cardoso

(CENTRA/Técnico & Perimeter)

...

CERN 2015

blackholes.ist.utl.pt

supports this project

BH dynamics

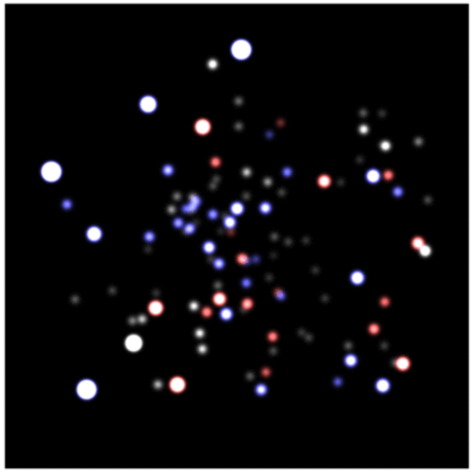
Brito, Nerozzi (Okawa, Pani, Rocha, Witek, Zilhão)

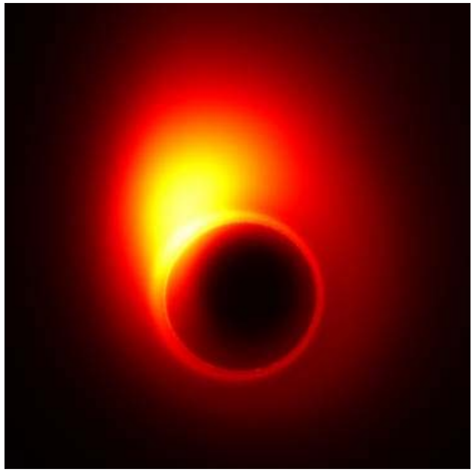
Barausse, Berti, Gualtieri, Herdeiro, Pretorius, Sperhake

Cardoso, Gualtieri, Herdeiro, Sperhake,
Exploring New Physics Frontiers Through Numerical Relativity,
Living Rev. Rel. 18:1 (2015)

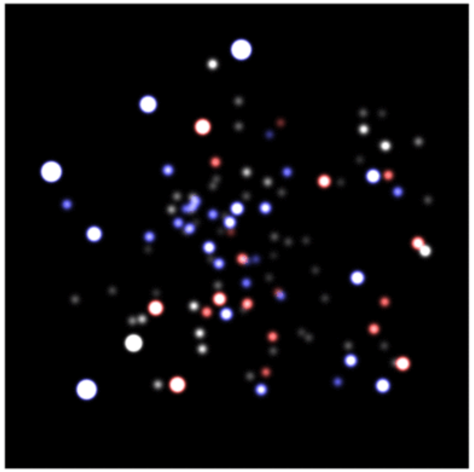
Brito, Cardoso, Pani,
Superradiance,
Lect. Notes Phys.(Springer-Verlag, 2015)

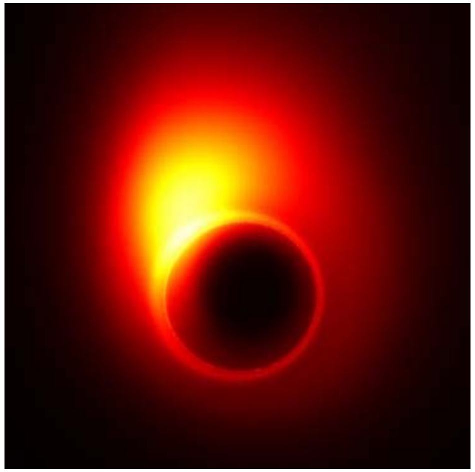
Black holes exist





Black holes exist



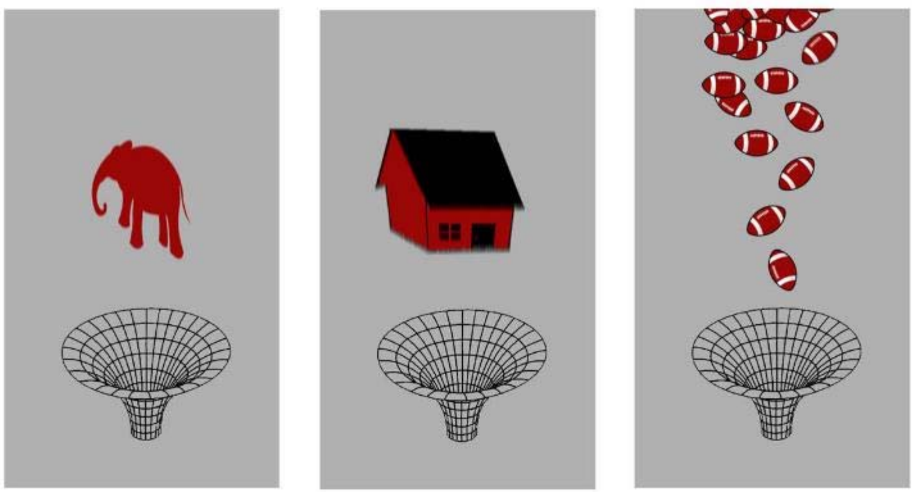


Black holes have no hair

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

A stationary BH is characterized by only three quantities:

mass, spin and electric charge



Note: B & L numbers are also non-conserved in black hole physics

Why study dynamics

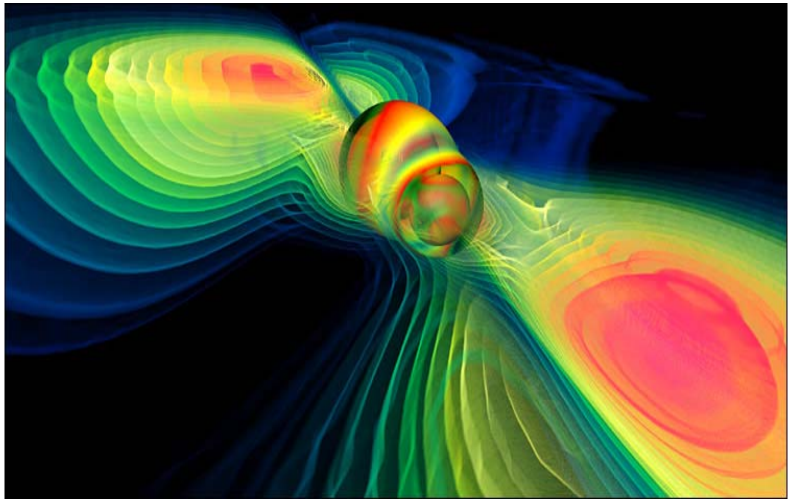
Gravitational-wave detection, GW astrophysics

Fundamental physics

High-energy physics

Particle physics

Why dynamics: astrophysics and gw physics

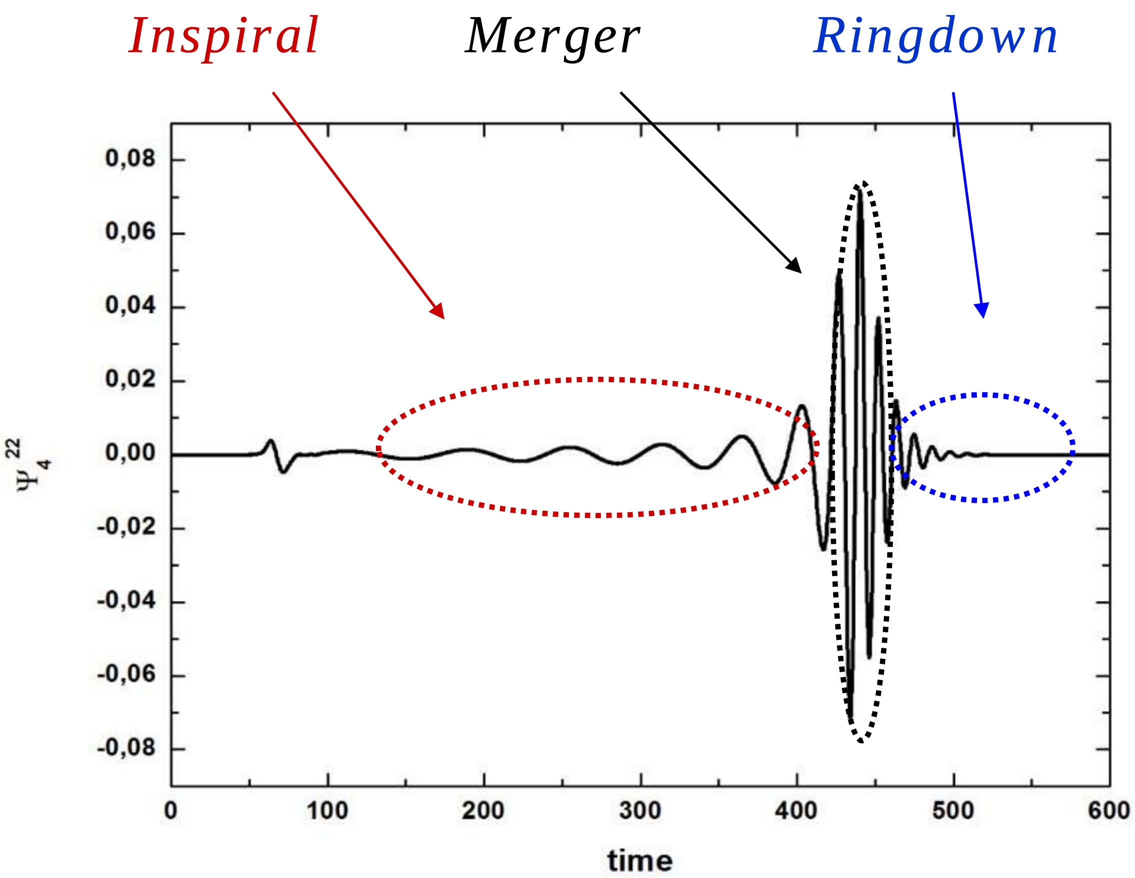


Gravitational-wave emission

Accurate templates for detection, NR/AR

Recoil (structure formation, etc)

GRBs, accretion disks, etc



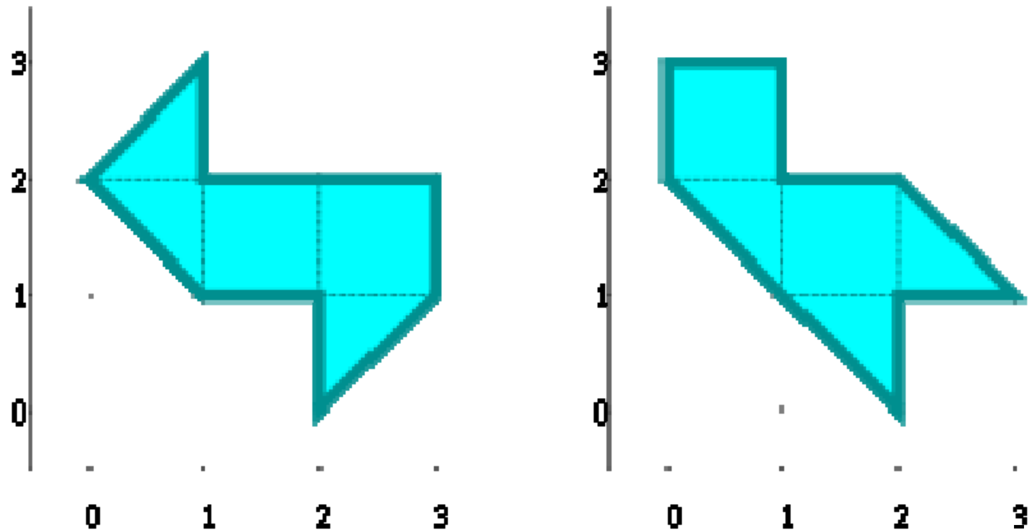
Inspiral
Merger
Ringdown
0,08
0,06
0,04
0,02
0,00
-0,02
-0,04
-0,06
-0,08
Ψ_4^{22}
0
100
200
300
400
500
600
time

“Can one hear the shape of a drum?”

Mark Kac, American Mathematical Monthly, *1966*

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

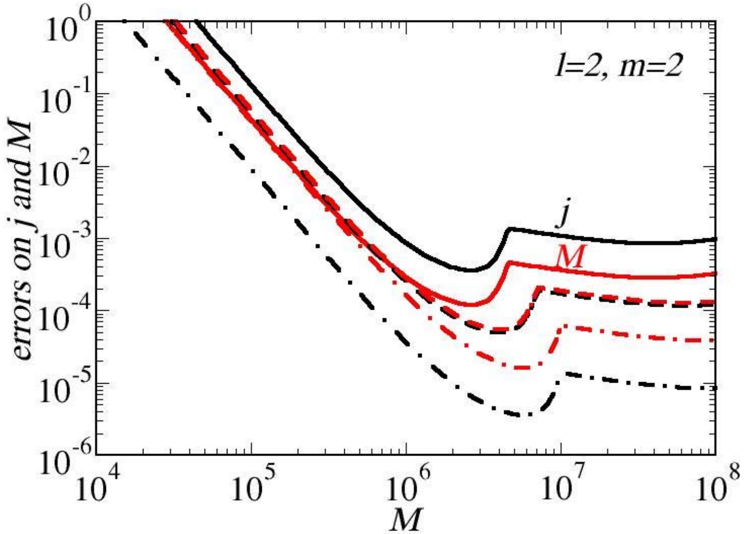
H. Weyl 1911



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

Berti, Cardoso & Will PRD73, 064030(2005)
Kamaretsos et al PRD85, 024018 (2012)

Stability, spectroscopy?

Cosmic Censorship?

New dynamical, long-term stable solutions?

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

Barrow & Gibbons MNRAS 446, 3874 (2015)

Critical behavior, etc

ZFL

(Weinberg '64; Smarr '77)

Take two free particles, changing abruptly at t=0

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

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}\,, \qquad h_{\mu\nu} = 4 \int \frac{T_{\mu\nu}(t_r, x') - 1/2\eta_{\mu\nu}(t_r, x')}{|x' - x|} d^3x'$$

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

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

LEAN code (*Sperhake '07)*

Based on the Cactus computational toolkit

BSSN formulation (ADM-like, but strongly hyperbolic)

Puncture initial data (*Brandt & Brügmann 1996)*

Elliptic solver: TwoPunctures (*Ansorg 2005)*

Mesh refinement: Carpet (*Schnetter '04)*

Numerically very challenging!

Length scales: $M_{ADM} \propto \gamma\, M_0$

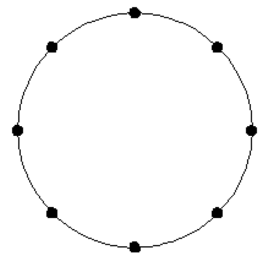
Horizon Lorentz-contracted "Pancake"

Mergers extremely violent

Substantial amounts of unphysical "junk" radiation

Most important result: Emitted gravitational waves (GWs)

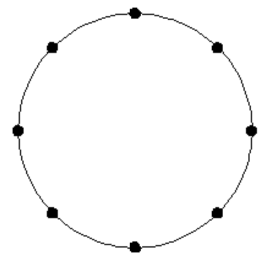
Newman-Penrose scalar:



$$\Psi_4 = C_{\alpha\beta\gamma\delta}\, n^{\alpha}\, m^{\beta}\, n^{\gamma}\, m^{\delta}$$

Complex $\longrightarrow$ 2 free functions

GWs allow us to measure:



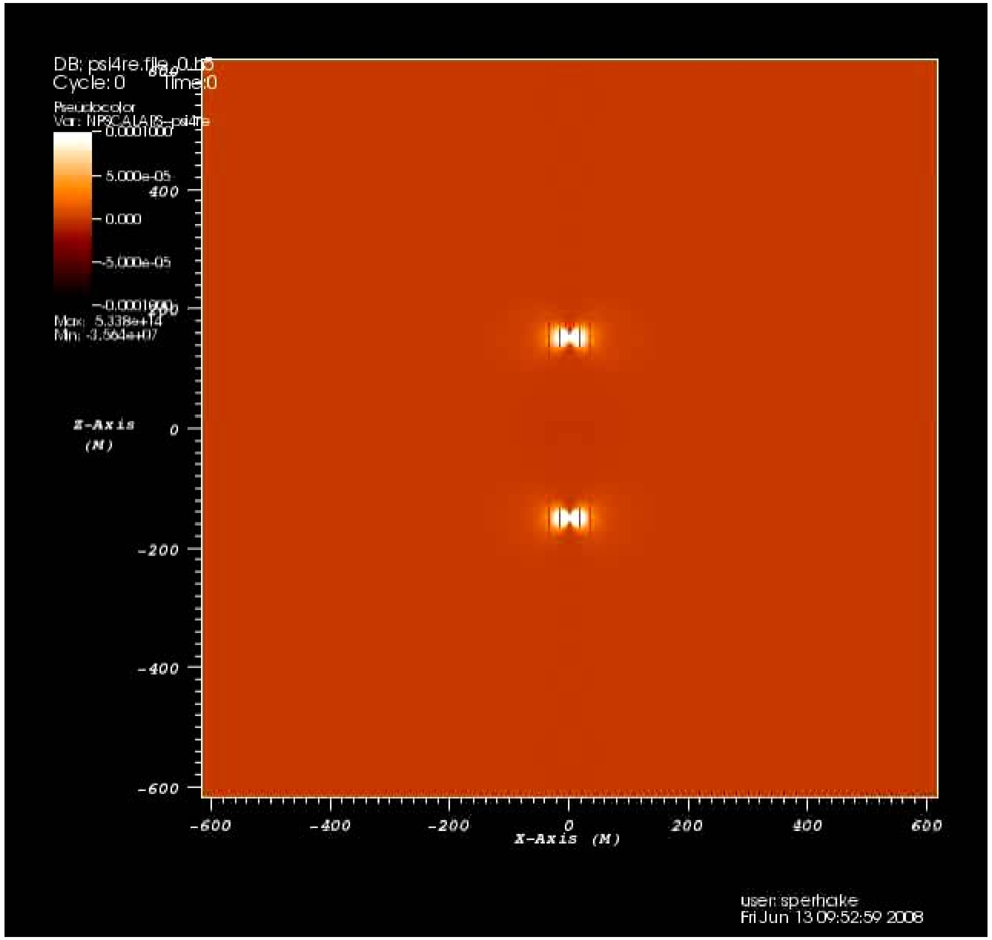
Radiated energy E_{rad}

Radiated momenta P_{rad}, J_{rad}

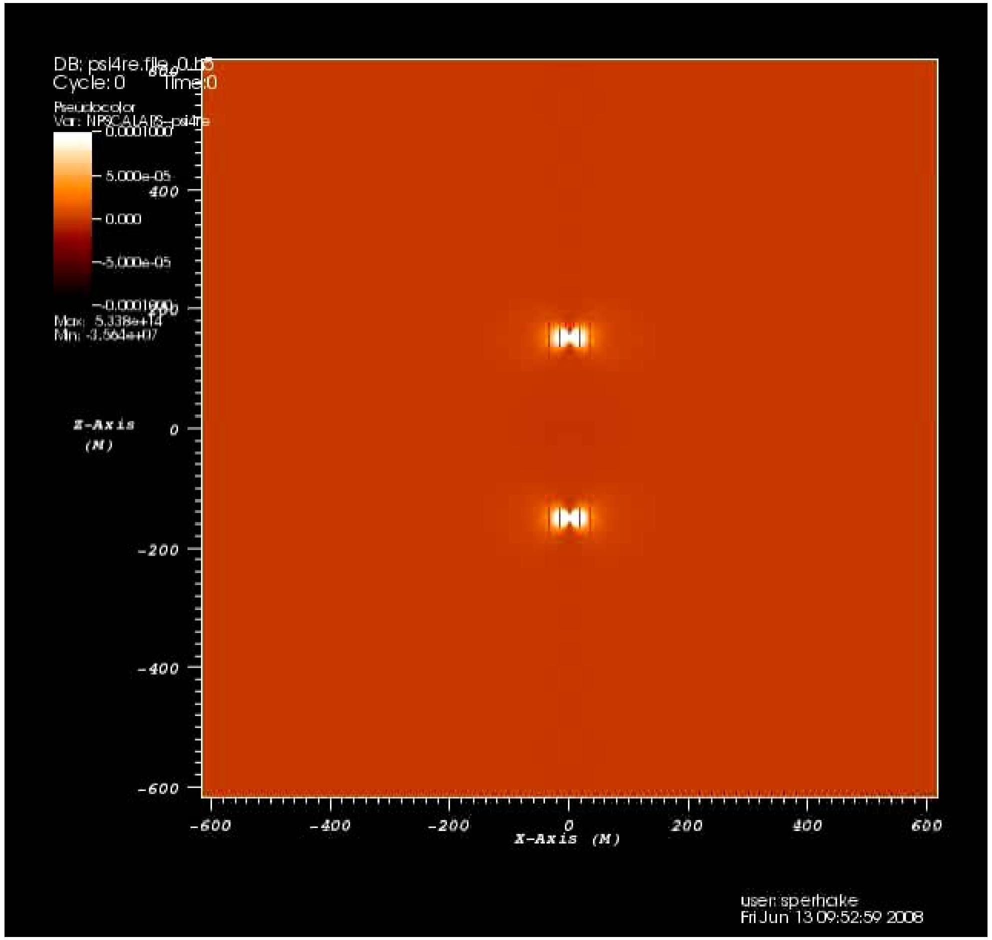
Angular dependence of radiation

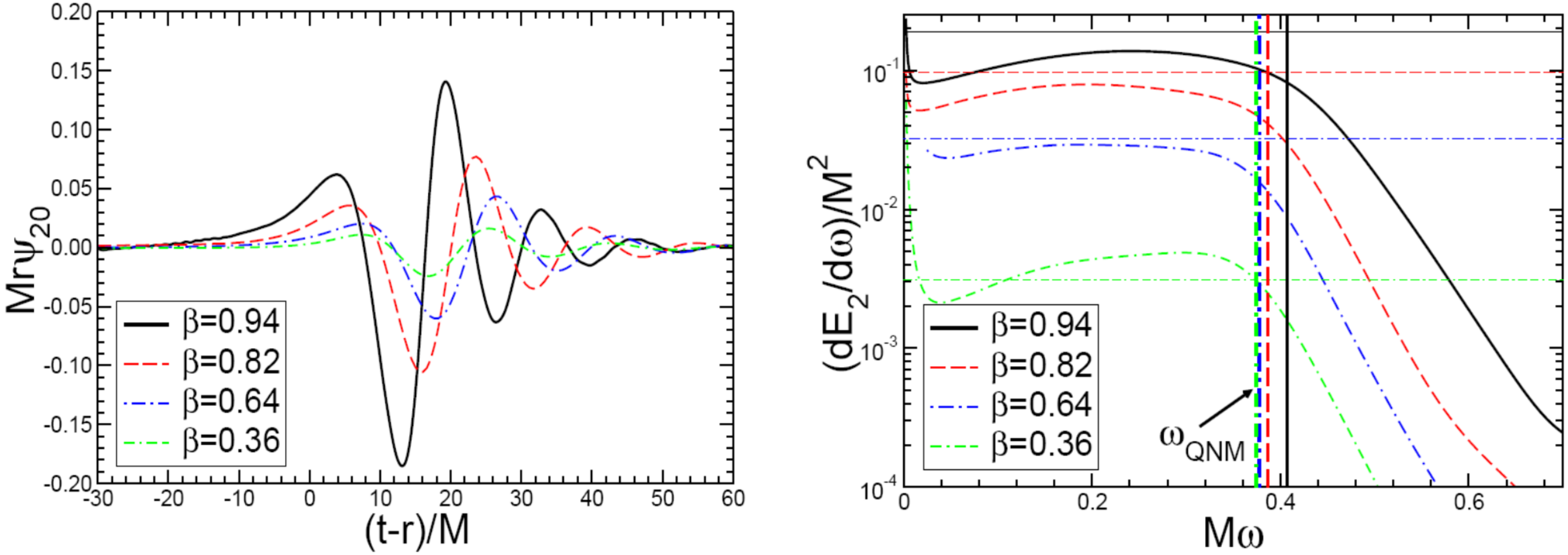
Predicted strain h_{+}, h_{x}

High energy head-ons



High energy head-ons

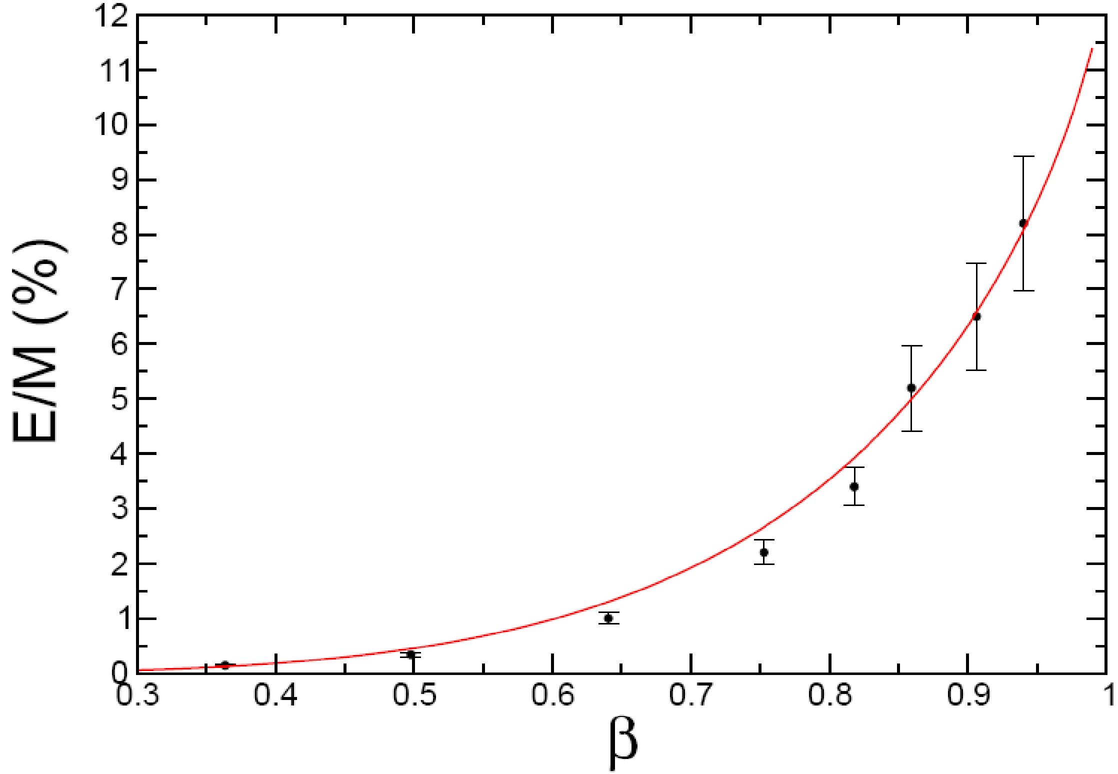




Waveform is almost just ringdown

Spectrum is flat, in good agreement with ZFL

Cutoff frequency at the lowest quasinormal frequency



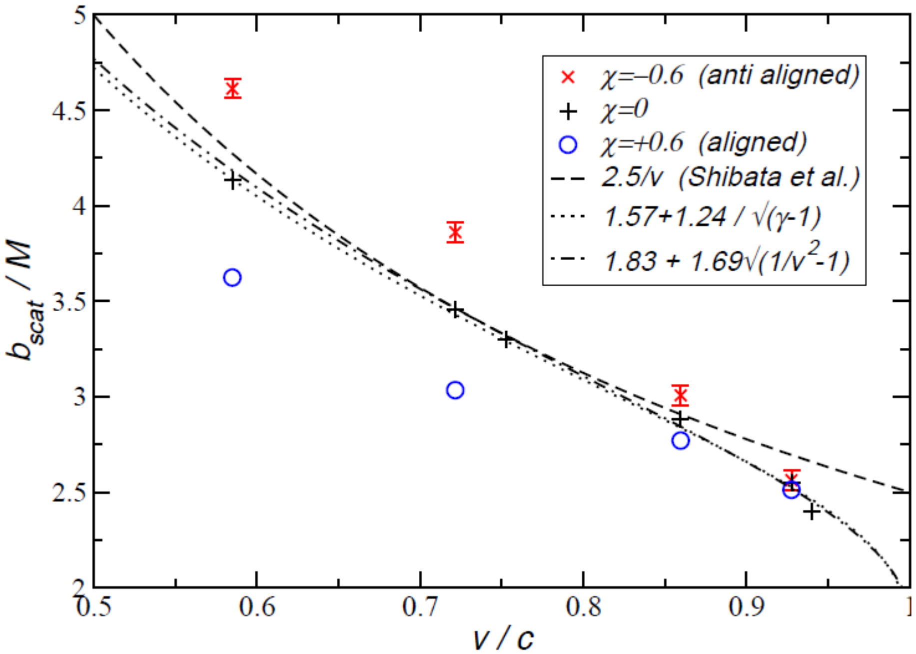
13%

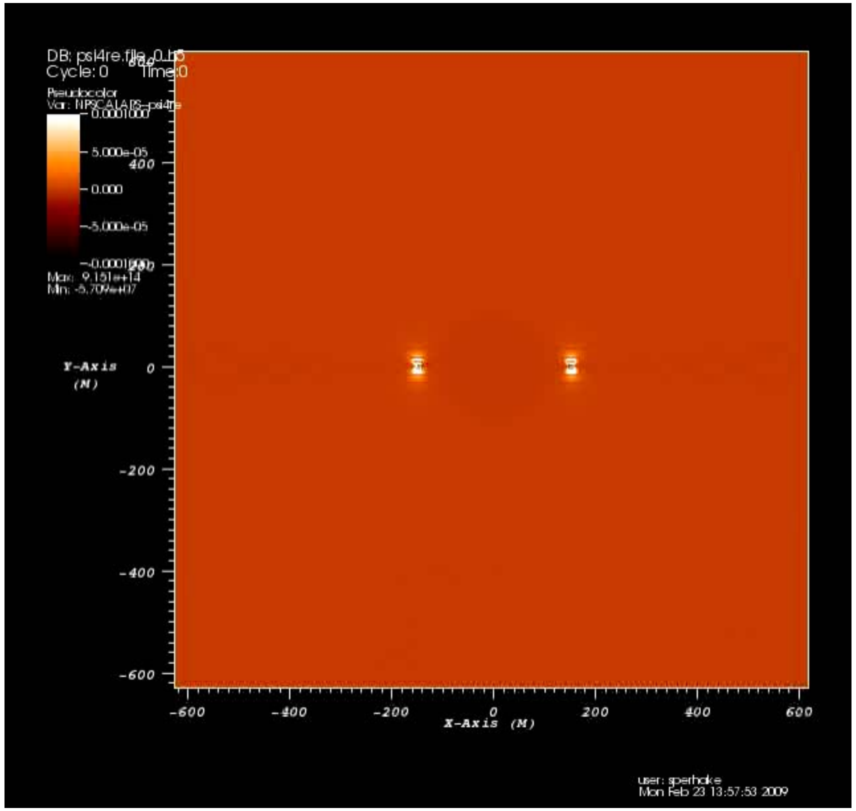
$$\frac{E}{M} = E_\infty \left(\frac{1+2\gamma^2}{2\gamma^2} + \frac{(1-4\gamma^2)\log\left(\gamma + \sqrt{\gamma^2-1}\right)}{2\gamma^3\sqrt{\gamma^2-1}} \right)$$

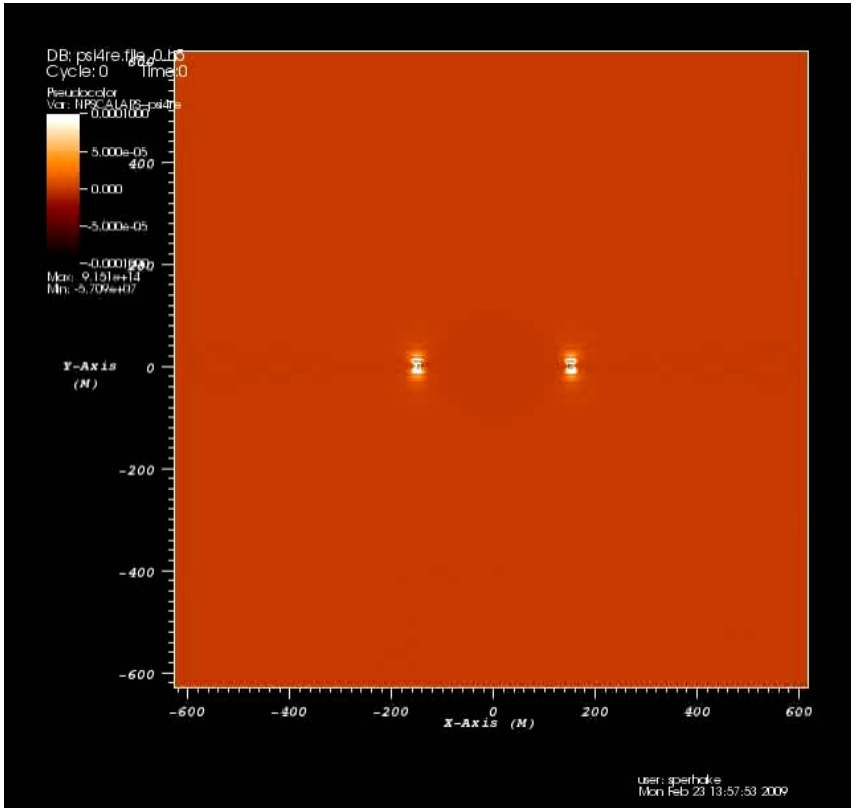
Black holes do form in high energy collisions

(Choptuik & Pretorius 2010; East & Pretorius 2013; Rezzolla & Takami 2013)

Structure of colliding object is irrelevant




DB: psi4re.file_0.h5
Cycle: 0 Time:0
Pseudocolor
Var: NPSCALARS-psi4re
0.0001000
5.000e-05
0.000
-5.000e-05
-0.0001000
Max: 9.151e+14
Min: -5.709e+07
Y-Axis (M)
X-Axis (M)
user: sperhake
Mon Feb 23 13:57:53 2009



DB: psi4re.file_0.h5
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Var: NPSCALARS-psi4re
0.0001000
5.000e-05
0.000
-5.000e-05
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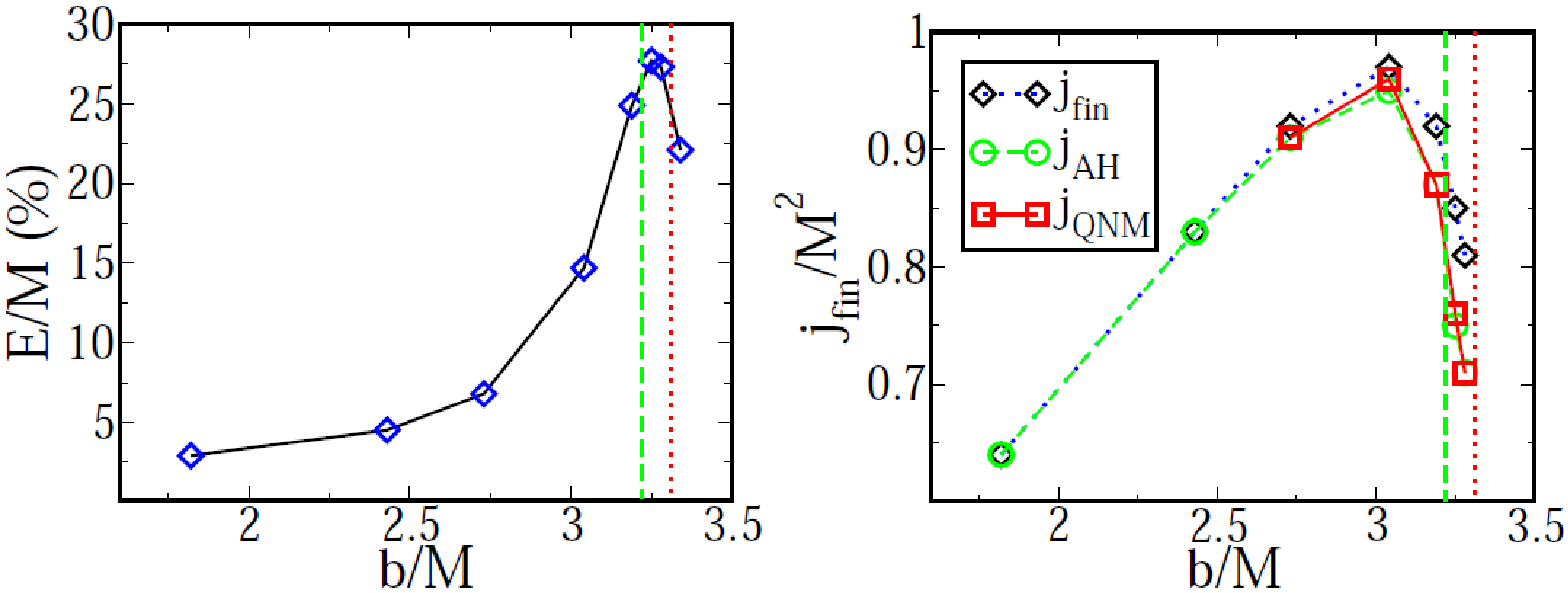


More than 25% (35%) CM energy radiated for v=0.75 c (0.92c)!

Final BH rapidly spinning

CC is preserved

Strong gravity and fundamental fields: (massive) scalars

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)

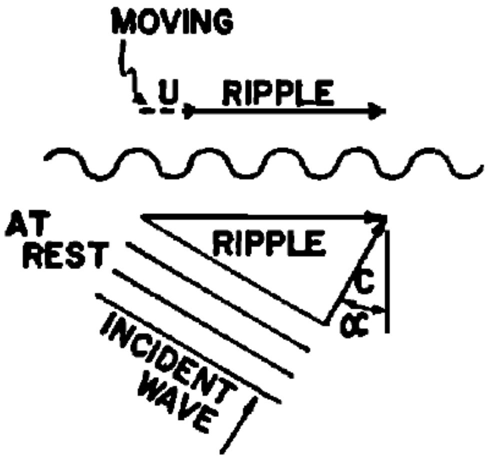
They might exist *Peccei-Quinn (interesting because not invented to solve DM problem)*

Axiverse scenarios - moduli and coupling constant in string theory

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

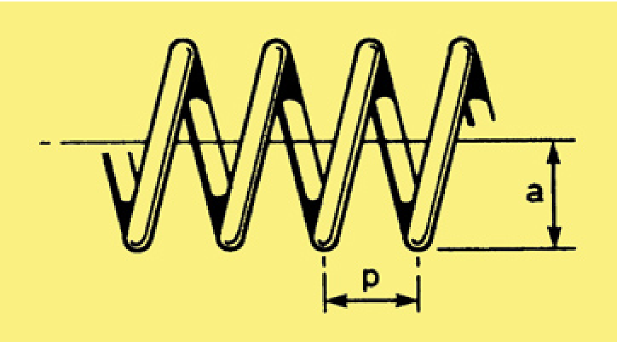
** Poorly constrained for massive fields*

Friction & superradiance

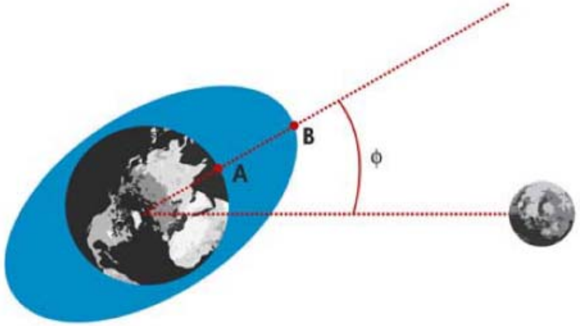


Ribner, J. Acous. Soc. Amer.29 (1957)

Tamm & Frank, Doklady AN SSSR 14 (1937)

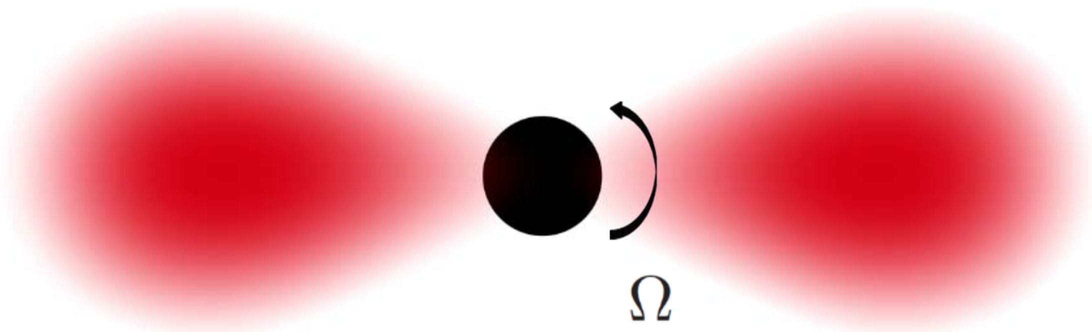


Pierce (& Kompfner), Bell Lab Series (1947)
Ginzburg, anomalous Doppler year



G. H. Darwin, Philos. Trans.
R. Soc. London 171 (1880)

$$\Phi \sim e^{-i\omega t + im\phi} \;\rightarrow\; (Angular)\, phase\, velocity = \frac{\omega}{m}$$

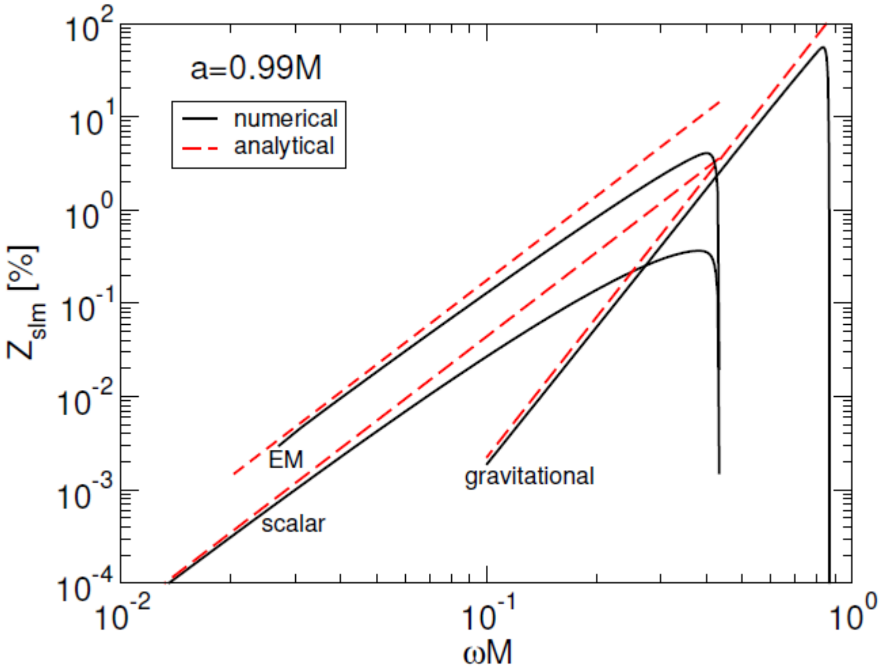


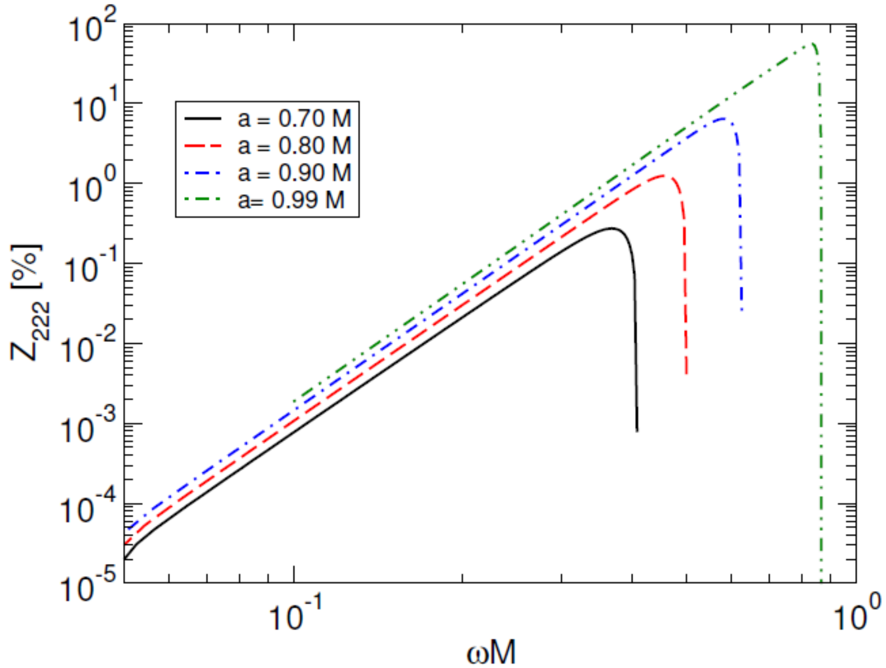
$$\omega < m\Omega$$

Zel'dovich, Pis'ma Zh. Eksp. Teor. Fiz. 14 (1971)

Black holes and superradiance

Friction built-in through one-way membrane (horizon)





Brito, Cardoso & Pani , arXiv:1501.06570

(Rotational) superradiance in the lab?

Need absorbing surface, characterized by complex acoustic impedance Z

Cardoso, Coutant , Richartz & Weinfurtner, in progress

Binaries?

Backreaction?

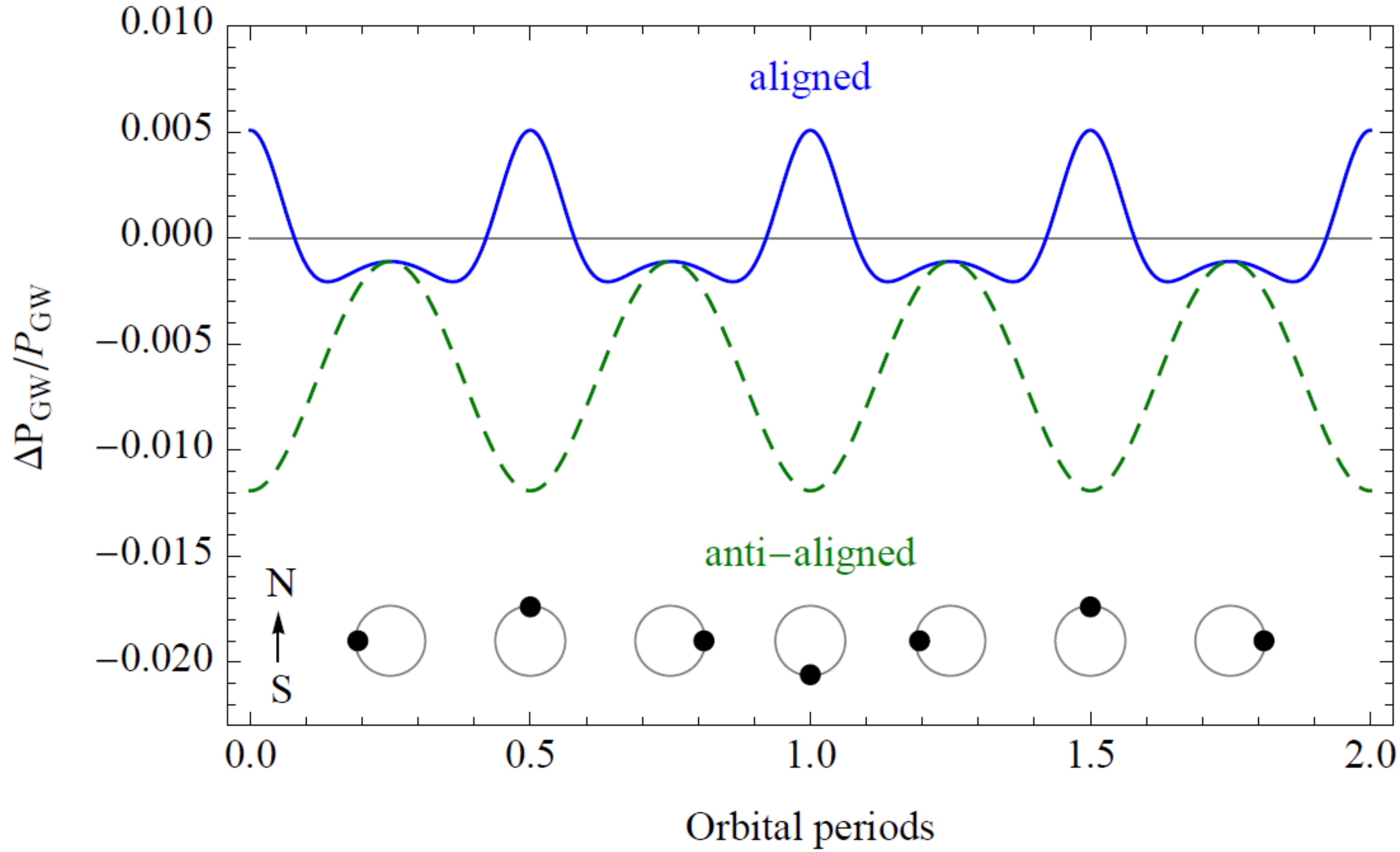
Superradiance in stars?

Direct observational effects?

Bounds on amplification?

Baibhav, Cardoso and Emparan, in progress

VC1



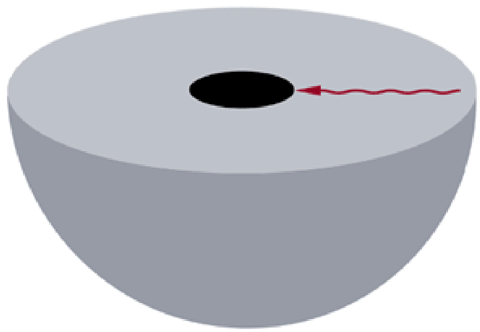
Rosa, arXiv:1501.07605

Slide 29

VC1 Vitor Cardoso, 10/08/2015

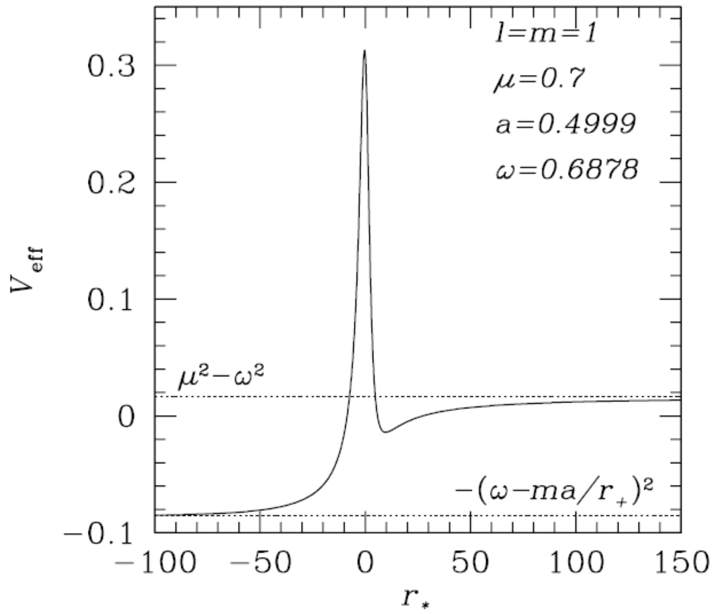
Superradiant instabilities

Can construct unstable states by forcing wave to bounce back



Zel'dovich, Pis'ma Zh. Eksp. Teor. Fiz. 14 (1971);

Cardoso & Dias, PRD70 (2004) ; Brito, Cardoso & Pani, arXiv:1501.06570

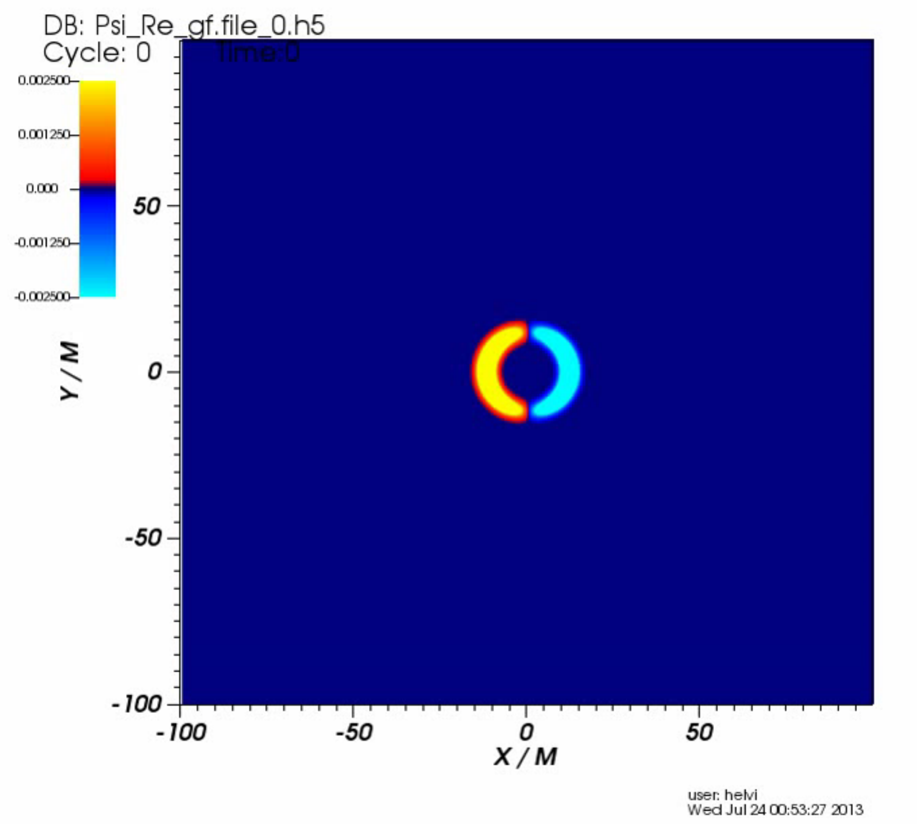


$$\tau \sim 100 \left(\frac{10^6 M_\odot}{M} \right)^8 \left(\frac{10^{-16}\mathrm{eV}}{\mu} \right)^9 \text{ seconds}$$

Massive "states" around Kerr are linearly unstable

Damour et al '76; Detweiler PRD; See reviews Brito et al arXiv:1501.06570

Final state I: almost-hairy BHs

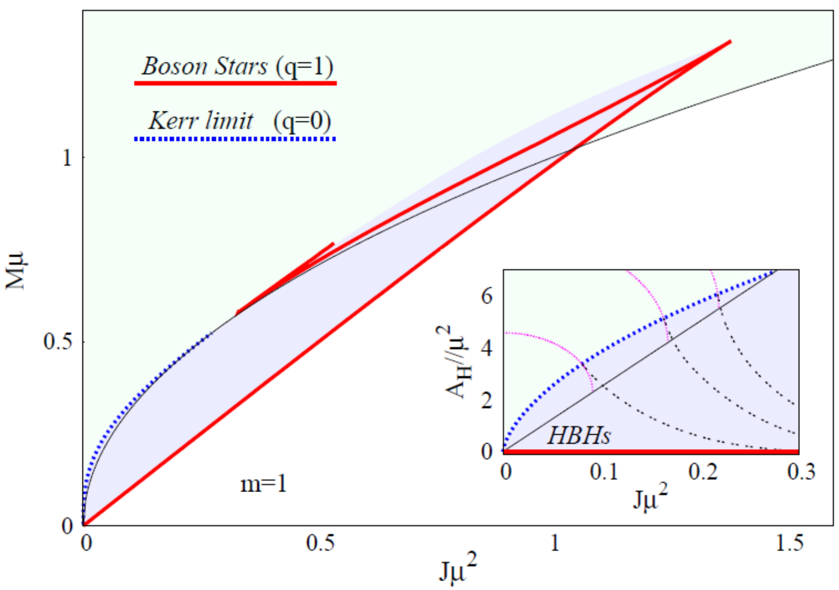


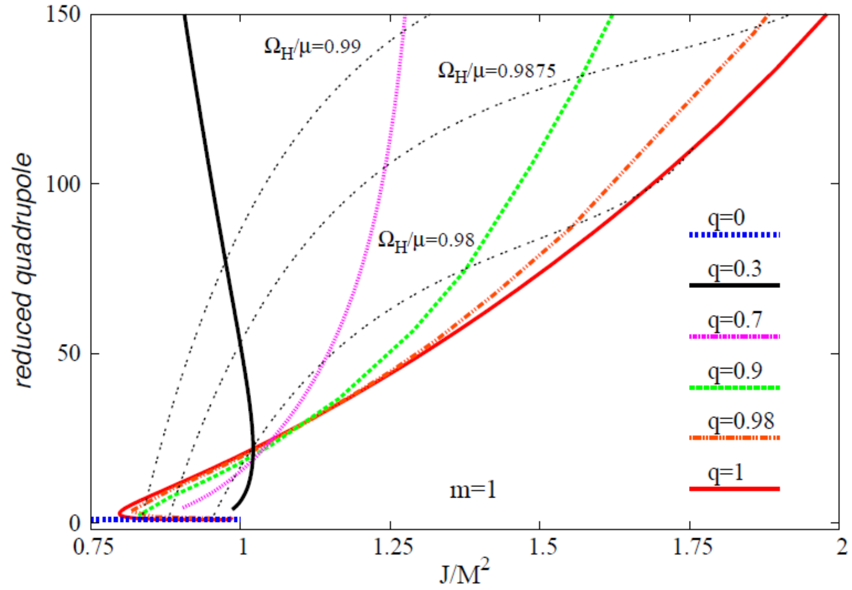
$$\Psi = e^{-i\omega t} Y_{lm}(\theta,\, \phi)\psi(r)$$

$$T^{\mu\nu} = -g^{\mu\nu}\left(\Psi^*_{,\alpha}\Psi^{,\alpha} + \mu^2\Psi^*\Psi\right) + \Psi^{*,\mu}\Psi^{,\nu} + \Psi^{,\mu}\Psi^{*,\nu}$$

Okawa et al PRD89, 104032 (2014)

Final state II: hairy black holes?





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

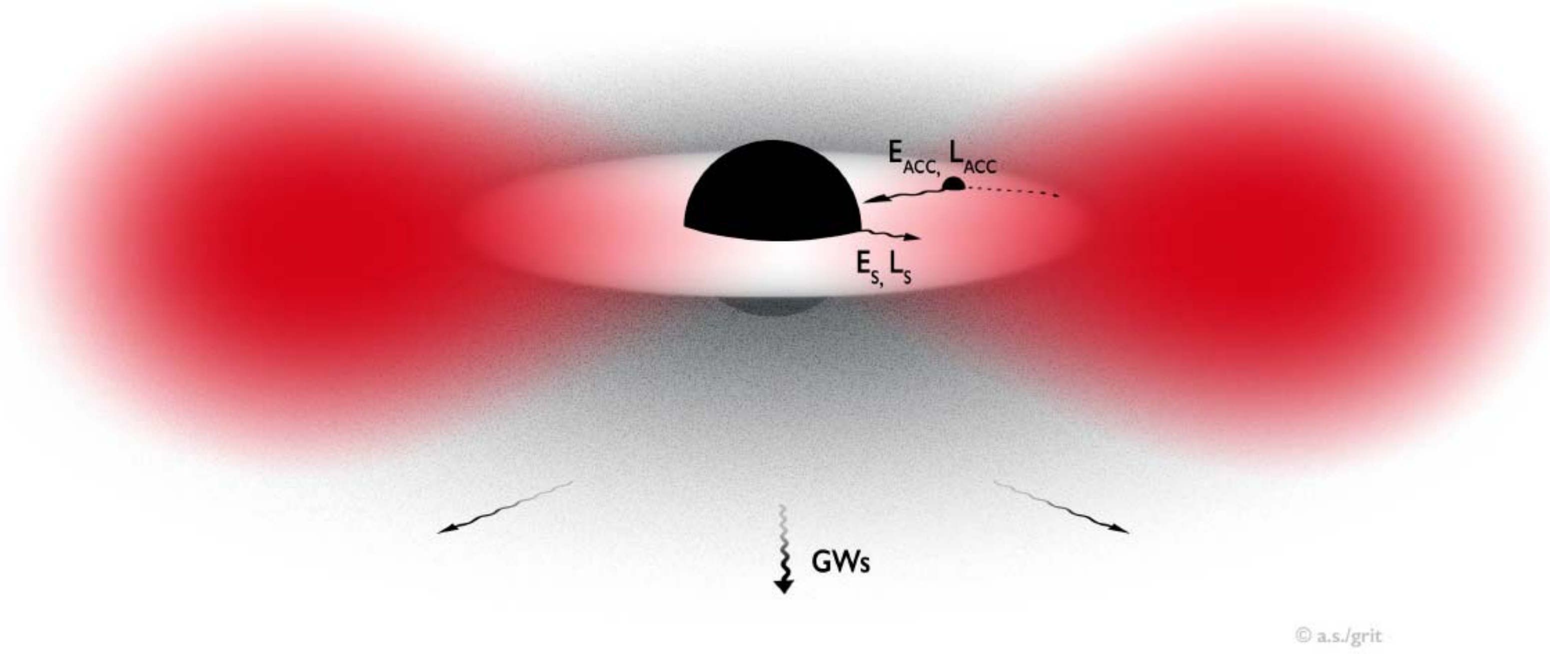
Are themselves unstable in parts of the parameter space

Brito, Cardoso & Pani, arXiv:1501.06570

End-state of linear instability?

Gravitational-wave emission and accretion?

Are hairy solutions formed?



E_{ACC}, L_{ACC}
E_S, L_S
GWs
© a.s./grit

Accretion:

$$\dot{M}_{\mathrm{ACC}} \equiv f_{\mathrm{Edd}} \dot{M}_{\mathrm{Edd}} \sim 0.02 f_{\mathrm{Edd}} \frac{M(t)}{10^6 M_\odot} M_\odot \mathrm{yr}^{-1}$$

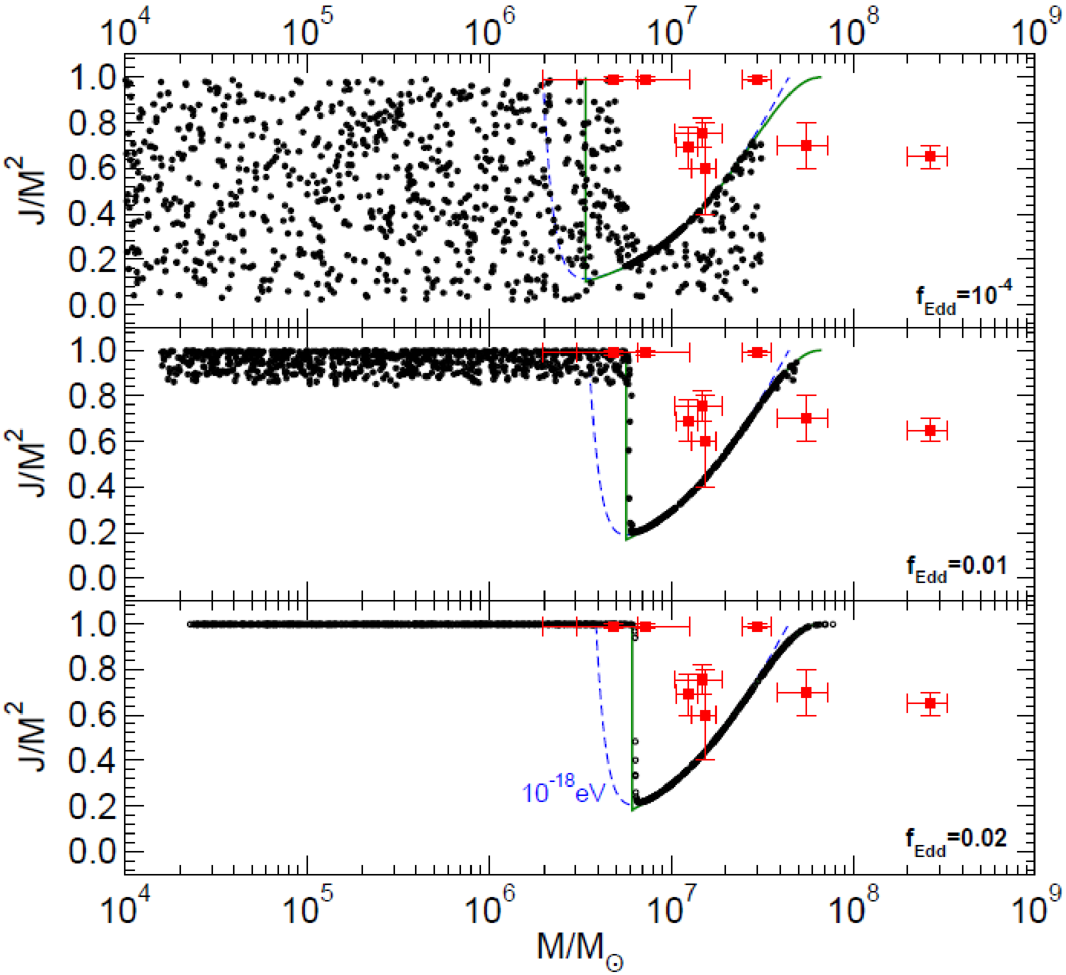
$$\dot{J}_{\mathrm{ACC}} \equiv \frac{L(M,J)}{E(M,J)} \dot{M}_{\mathrm{ACC}}$$

Gravitational-wave emission:

$$\dot{E}_{\mathrm{GW}} = \frac{484 + 9\pi^2}{23040} \left(\frac{M_S^2}{M^2}\right) (M\mu)^{14}$$

$$\dot{J}_{\mathrm{GW}} = \frac{1}{\omega_R} \dot{E}_{\mathrm{GW}}$$

Yoshino & Kodama PTEP 2014 (043E02); Brito et al CQG32 (2015) 13, 134001

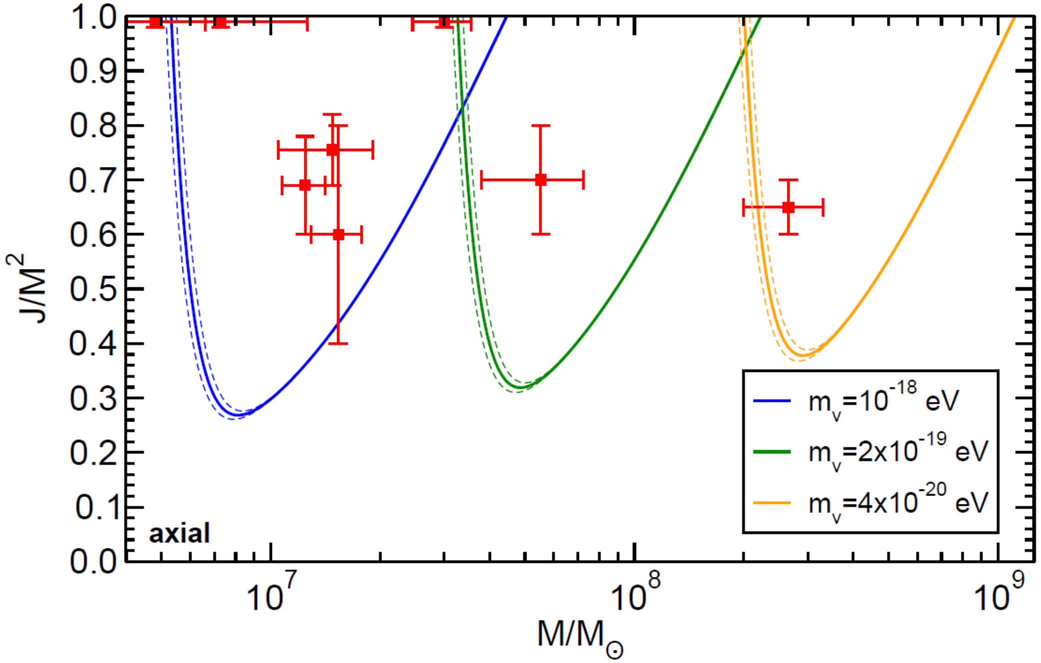


$$\mu = 10^{-18}\text{eV}$$

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

Strong field gravity is a fascinating topic

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.

Thank you

Numerical evolution

GR: "Space and time exist together as Spacetime"

Numerical relativity: reverse this process!

ADM 3+1 decomposition

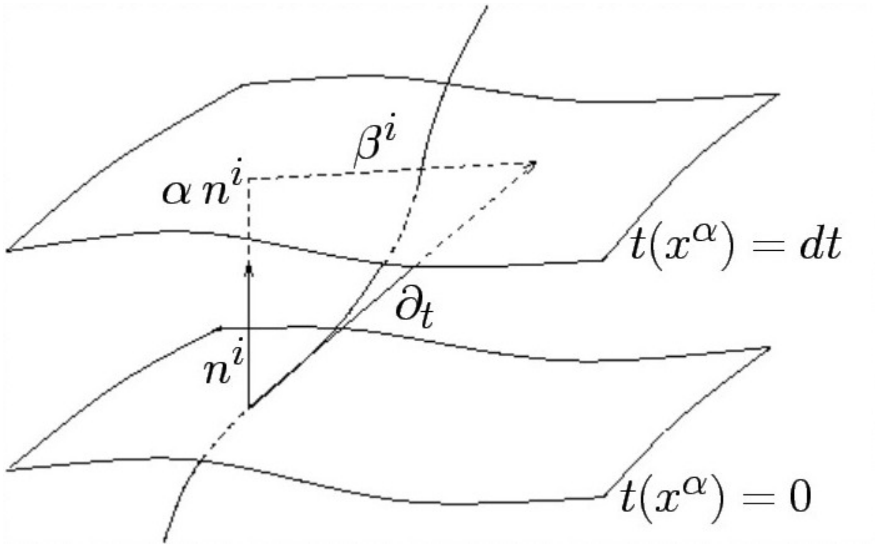
Arnowitt, Deser, Misner (1962); York (1979); Choquet-Bruh)at, York (1980)

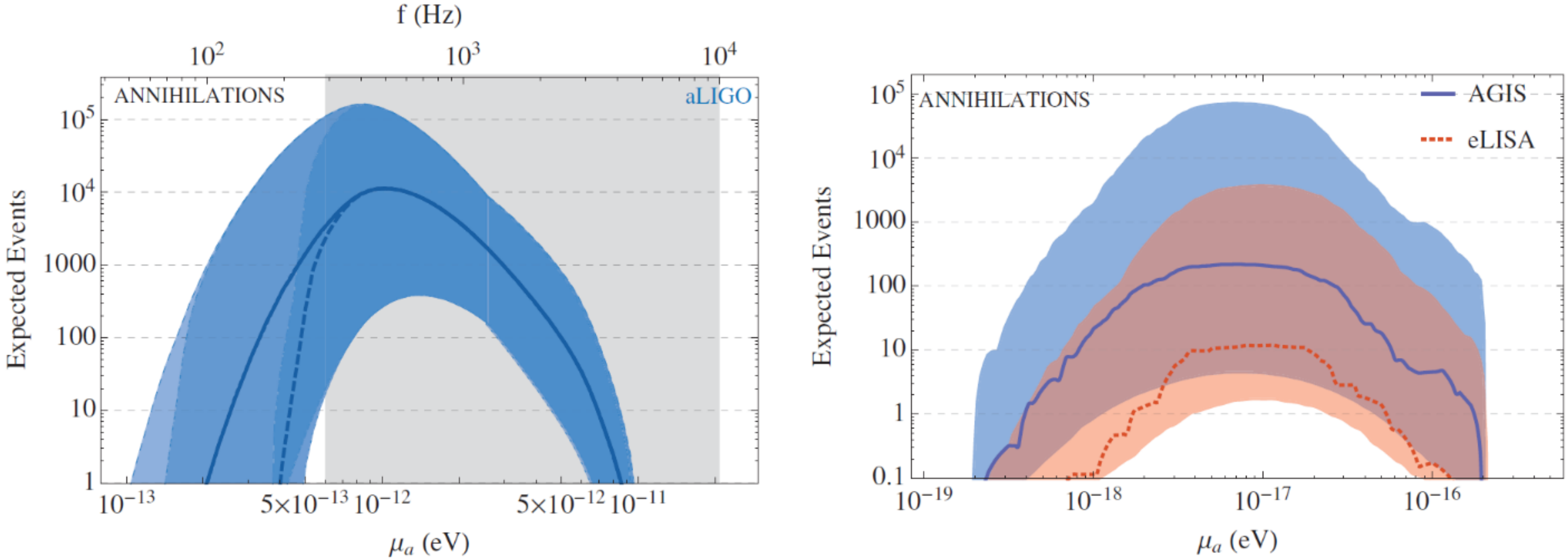
3-metric γ_{ij}

lapse α

shift β^i

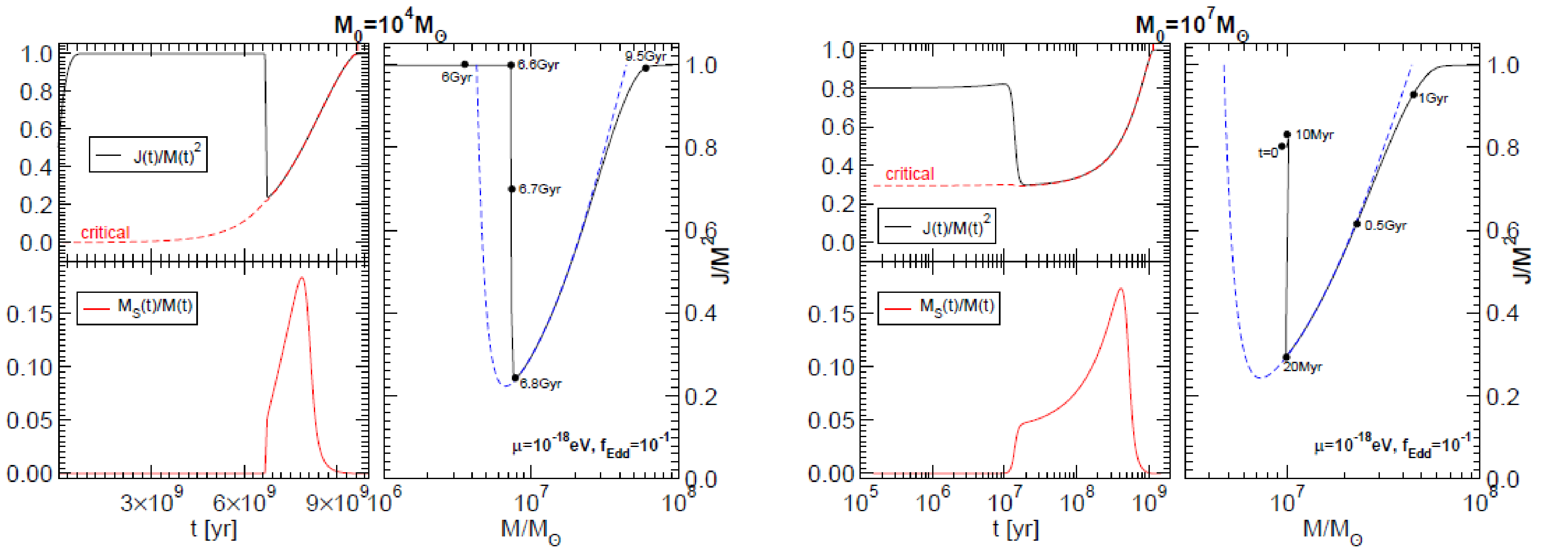
lapse, shift $\Rightarrow$ Gauge





Arvanitaki, Baryakhtar, Huang arXiv:1411.2263

(rates may be overly optimistic)



Brito, Cardoso, Pani arXiv:1411.0686