The bright side of black holes

Vítor Cardoso
[Técnico & CERN]

Fundamental questions

a. BH seeds, BH demography, galaxy co-evolution (how many, where, how?)
Barack+ arXiv:1806.05195

b. What is graviton mass or speed?
See review Barack+ arXiv:1806.05195

c. Are there extra radiation channels, corrections to gravity?
Barack+arXiv:1806.05195; Barausse+PRL116:241104(2016);

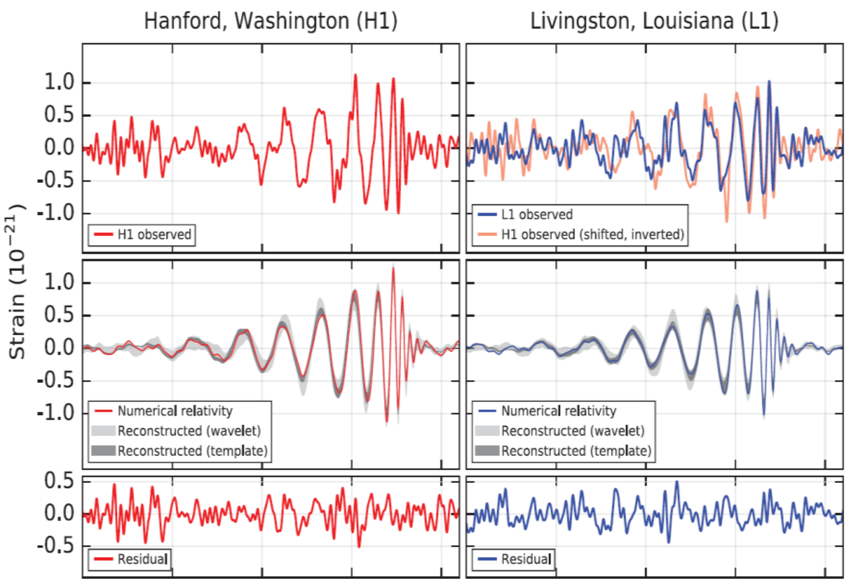
d. Can GWs from BHs inform us on fundamental fields/DM?
Barack+arXiv:1806.05195; Arvanitaki+ PRD95: 043001 (2016); Brito+ PRL119:131101 (2017)

e. Is it a Kerr black hole? Can we constrain alternatives?
Berti+ 2016; Cardoso & Gualtieri 2016; Yang+2017; Yunes+2016

f. Is cosmic censorship preserved?
Sperhake+ PRL103:131102 (2009); Cardoso+ PRL120:031103 (2018)

g. Is the final - or initial - object really a black hole?
Cardoso+ PRL116: 171101 (2016); Cardoso & Pani, Nature Astronomy 1: 586 (2017)

The nature of dark compact objects



$$f_{GW}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3}(t_0 - t)$$

$$\mathcal{M} = (\mu^3 M^2)^{1/5}$$

Two unknowns, need frequency at two instants. Result: M ~ 65 suns

Use Kepler's law, separation at collision is ~ 500 Km… same using ringdown…

Massive, compact object indeed!

Why is this enough?

BHs are end-point of gravitational collapse, using EoS thought to prevail.

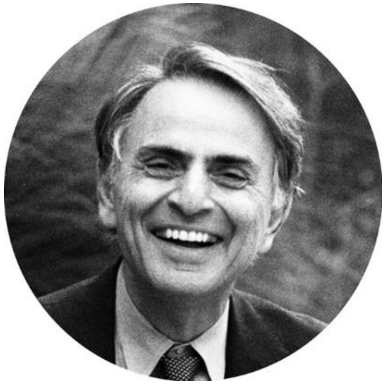
No other massive, dark object has been seen to arise from collapse of known matter.

Why is this not enough?

1. BH exterior is pathology-free, interior is not.

2. Quantum effects not fully understood. Non-locality to solve information paradox? Hard-surface to quantize BH area (Bekenstein & Mukhanov 1995)

3. Tacitly assumed quantum effects at Planck scales. Planck scale could be significantly lower *(Arkani-Hamed+ 1998; Giddings & Thomas 2002)*. Even if not, many orders of magnitude standing, surprises can hide (Bekenstein & Mukhanov 1995).

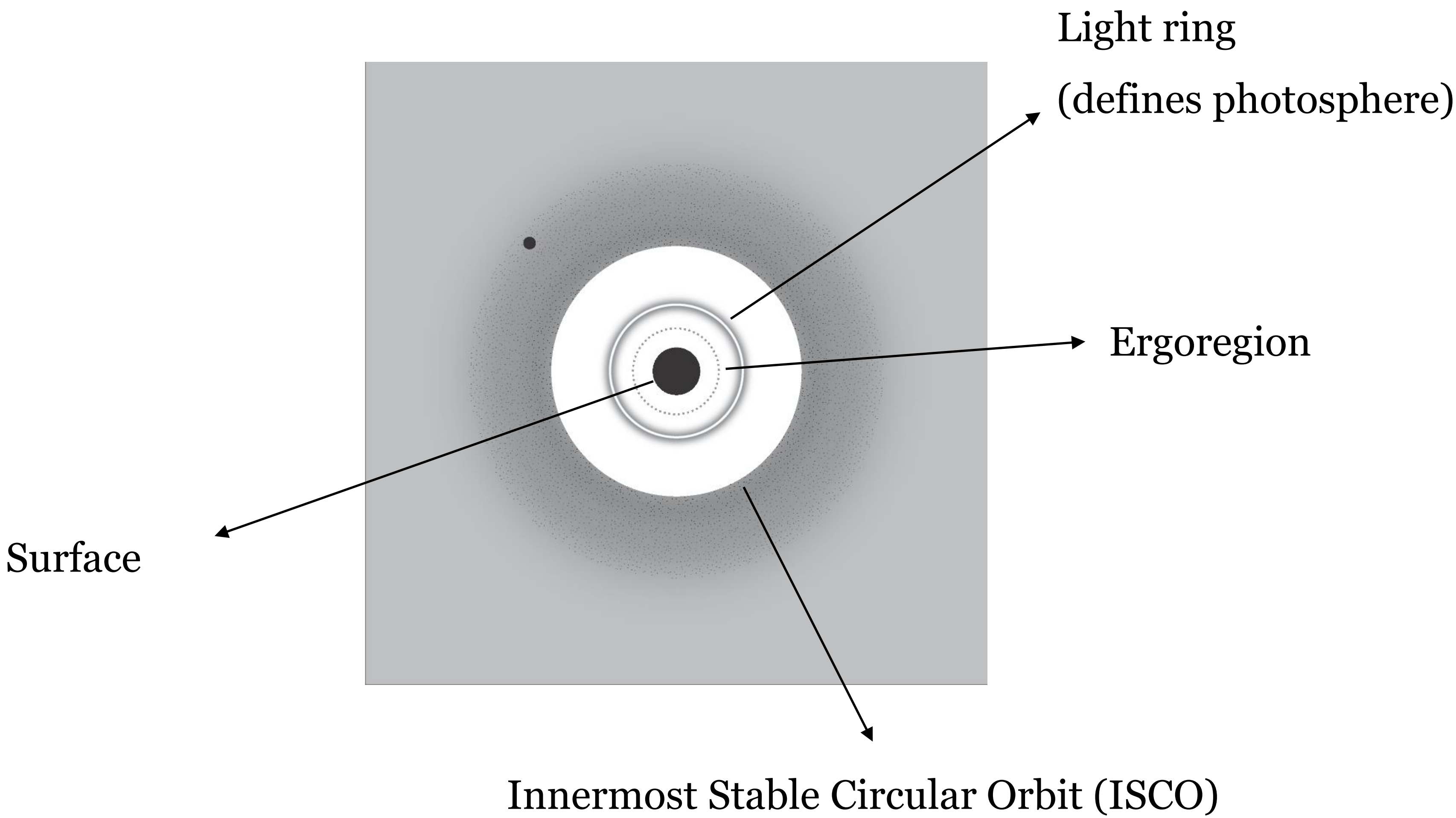


"*Extraordinary claims require extraordinary evidence.*"
Carl Sagan

4. Dark matter exists, and interacts gravitationally. Are there compact DM clumps?

5. Physics is experimental science. We can test exterior. Aim to quantify evidence for horizons. Similar to quantifying equivalence principle.

Black holes are black!



Cardoso & Pani, Nature Astronomy 1: 586 (2017); see also arXiv: 1707.03021[gr-qc]

Image: Ana Carvalho

Some challenges

i. Are there alternatives?

ii. Do they form dynamically under reasonable conditions?

iii. Are they stable?

iv. How do they look like? Is GW or EM signal similar to BHs?

v. Observationally, how close do we get to horizons?

i. Alternatives

Boson stars, fermion-boson stars, oscillatons

Kaup 1968; Ruffini, Bonazzolla 1969; Colpi + 1986; Okawa+ 2014; Brito + 2015

Anisotropic stars

Bowers, Liam 1974; Dev, Gleiser 2000; Raposo + arXiv:1811.07917

Wormholes

Morris, Thorne 1988; Visser 1996; Damour and Solodukhin 2007; Maldacena+ 2017

Gravastars

Mazur, Mottola 2001

Fuzzballs, Superspinars, collapsed polymers, 2-2 holes

Mathur 2000; Gimon, Horava 2009; Brustein, Medved 2016;Holdom, Ren 2016

…

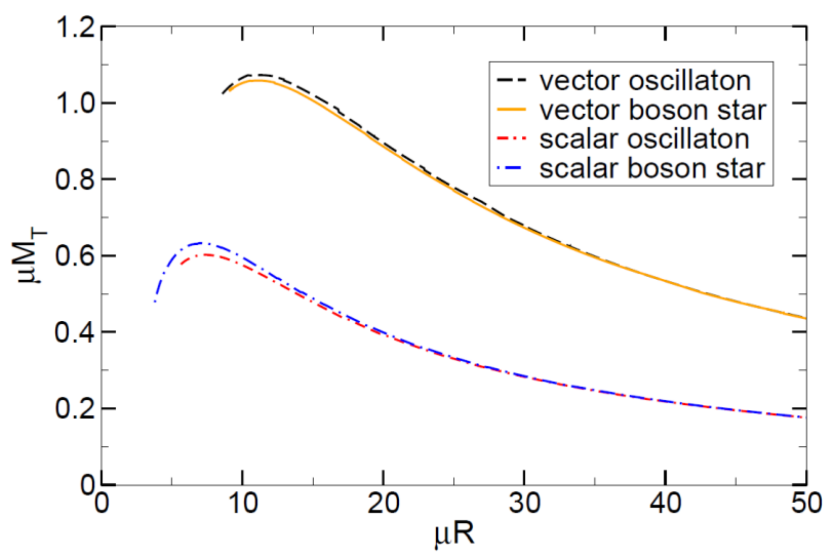
Bekenstein-Mukhanov proposal for BH area quantization

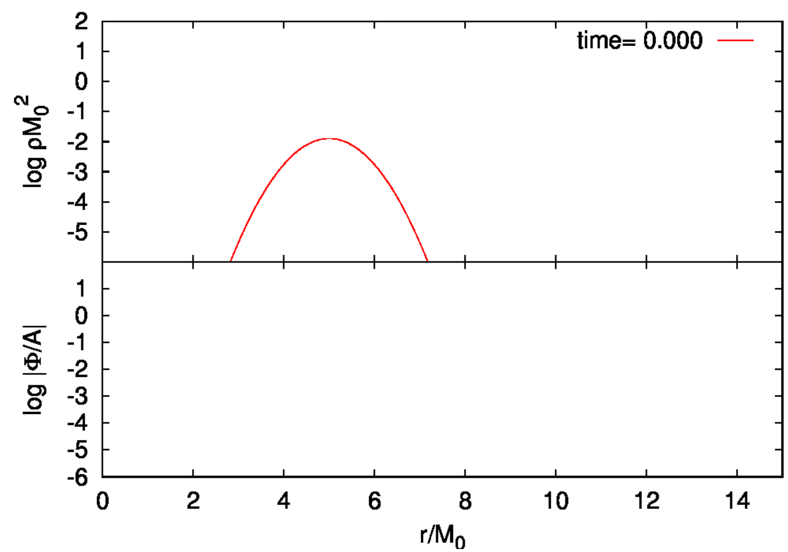
Bekenstein and Mukhanov (1995)

ii. Formation

Boson stars, fermion-boson stars, oscillatons

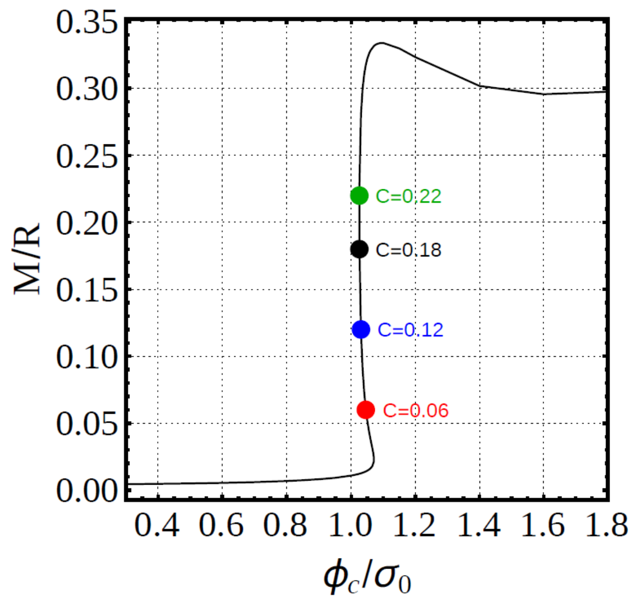
(Kaup '68; Ruffini, Bonazzolla '69; Colpi+ 1986; Tkachev '91; Okawa+ 2014; Brito+ 2015)

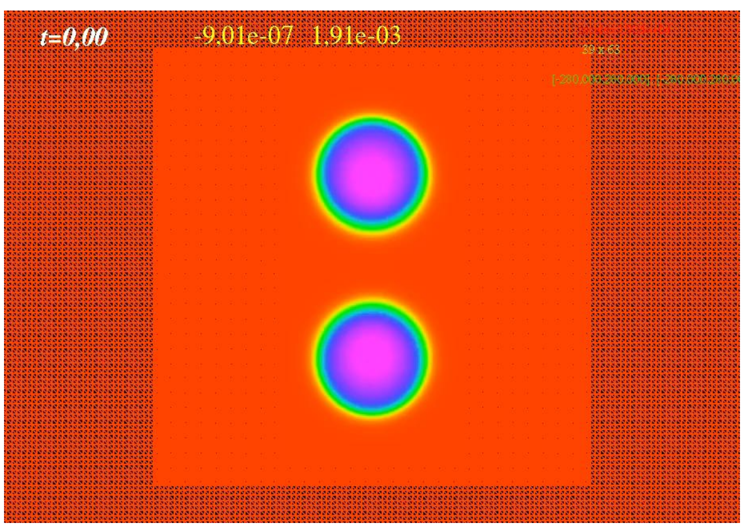


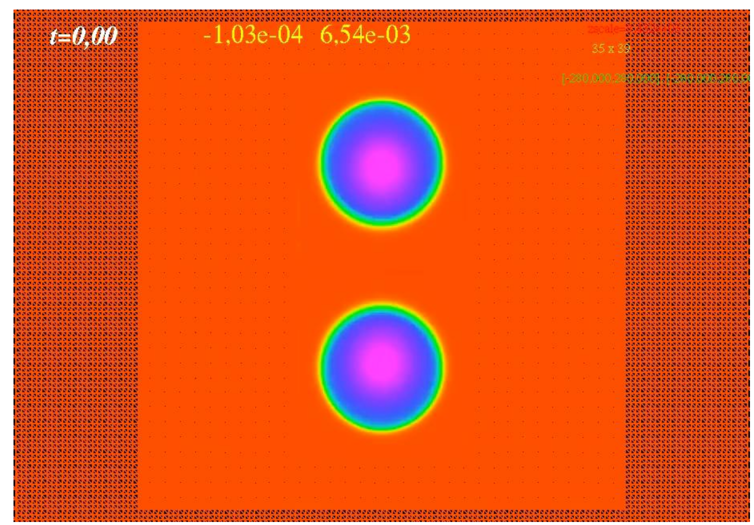


$$\frac{M_{\rm max}}{M_\odot} = 8 \times 10^{-11} \frac{\rm eV}{m_B c^2}$$

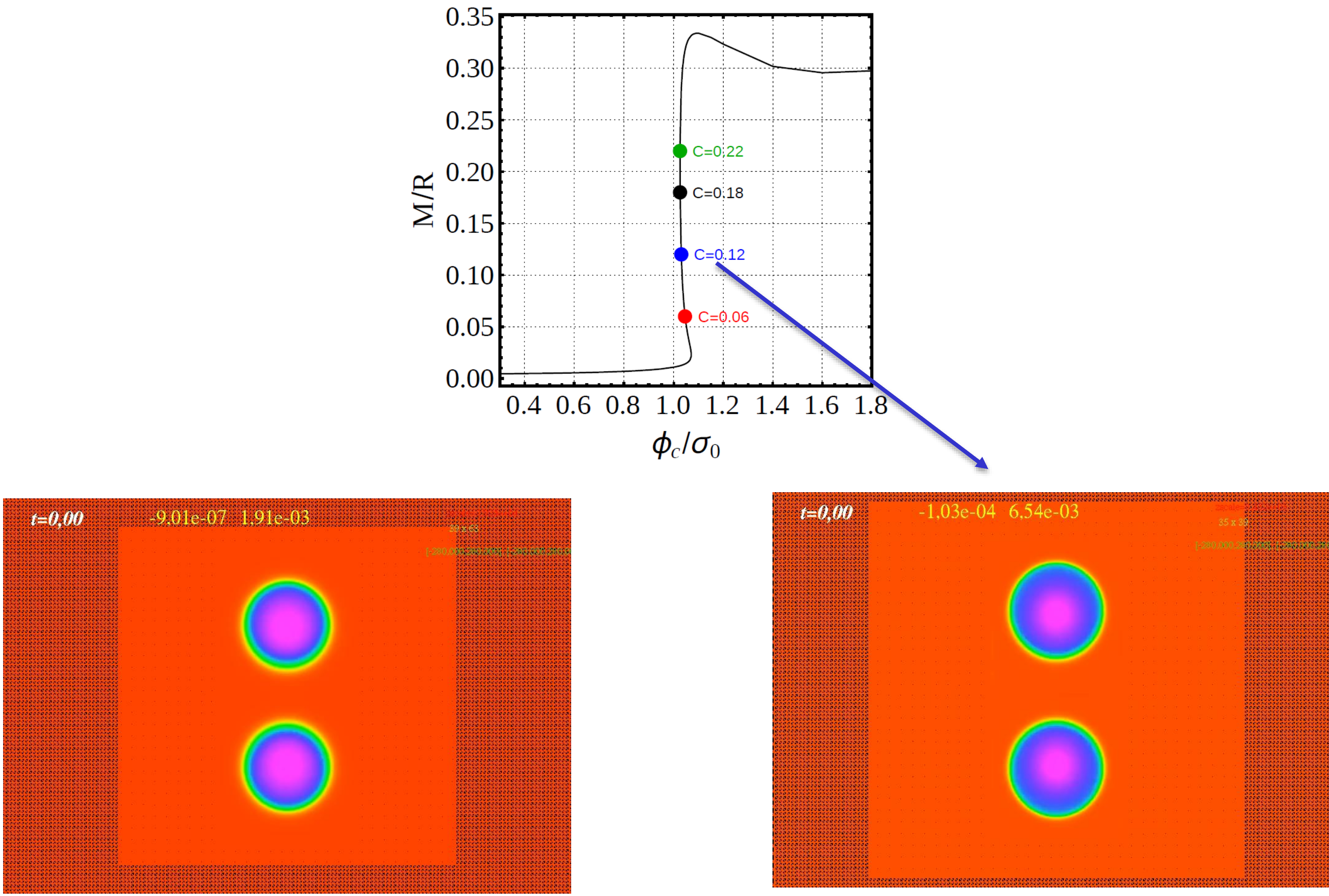
Challenge: repeat for anisotropic stars, wormholes, gravastars, etc







Palenzuela+ PRD96:104058(2017)

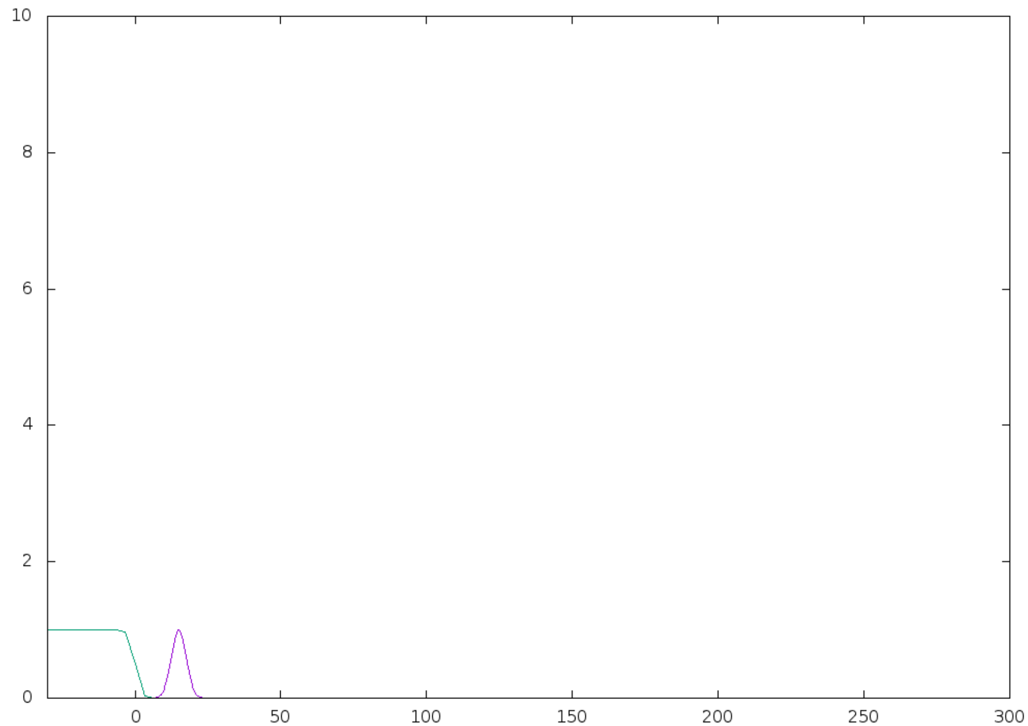


Palenzuela+ PRD96:104058(2017)

iiia. Stability of objects with ergoregions

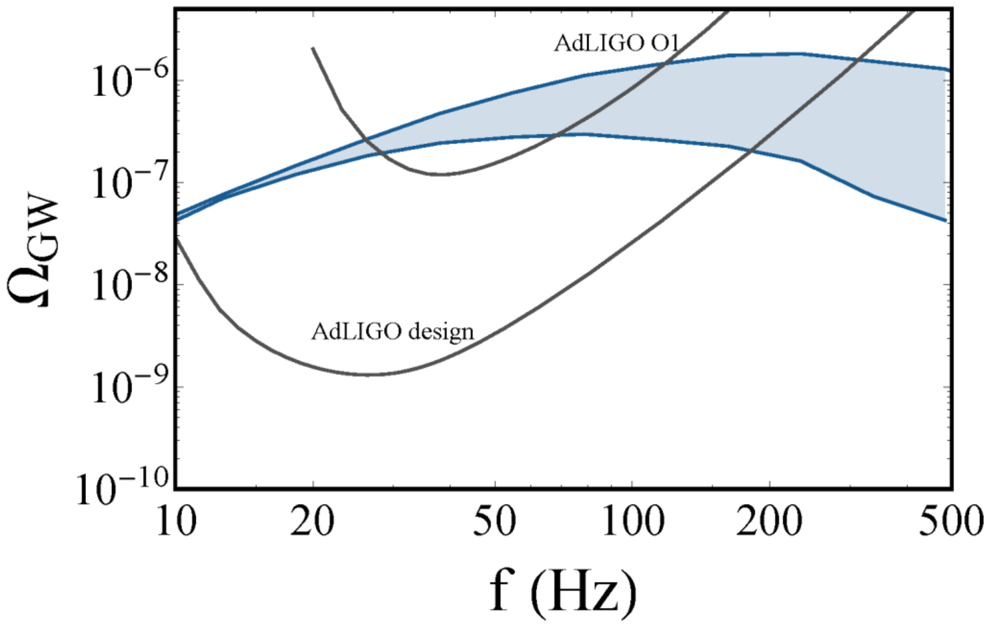
AS flat, horizonless spacetimes with ergoregions are linearly unstable

Friedmann Comm. Math.Phys.63:243 (1978); Moschidis Comm. Math. Phys. 358: 437 (2016)



Vicente & Cardoso PRD97:084032 (2018); Brito+ Lect. Notes Phys 906 (2015)

Stochastic background of GWs



Blue bands bracket population models, from optimistic to pessimistic

Barausse+ CQG35:20LT01 (2018)

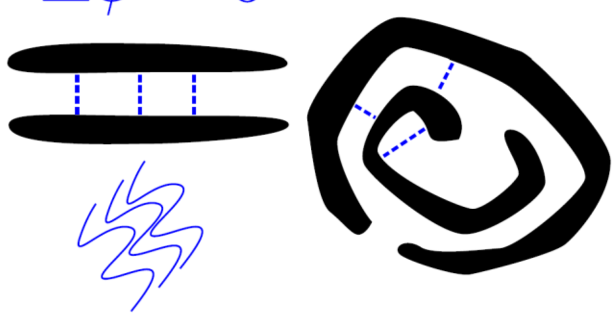
iiib. Stability of objects with photospheres

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

Keir CQG33: 135009 (2016); Cardoso + PRD90:044069 (2014)

$$\mathcal{E}^{(N)}_{\mathrm{local}}(t) \lesssim \frac{1}{(\log(2+t))^2}\mathcal{E}^{(N)}_{(2)}(0)$$

$$\Box\phi = 0$$



Burq, Acta Mathematica 180: 1 (1998)

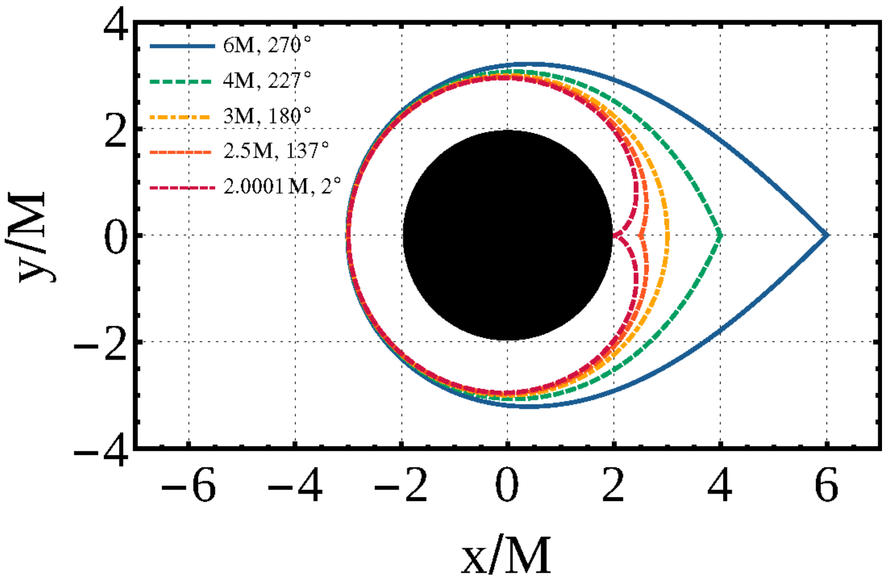
iv. EM constraints

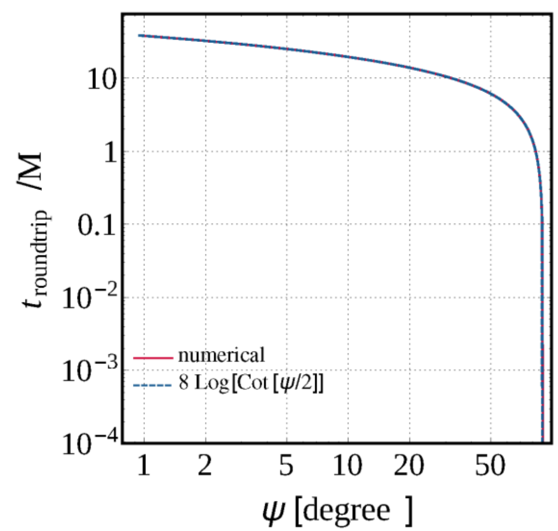
$$r = 2M\,(1+\epsilon)$$

$\epsilon \lesssim 10^{-5}$ Absence of transients from tidal disruptions

$\epsilon \lesssim 10^{-35}$ Dark central spot on SgrA

Carballo-Rúbio, Kumar, PRD97:123012 (2018)
Broderick, Narayan CQG24:659 (2007)

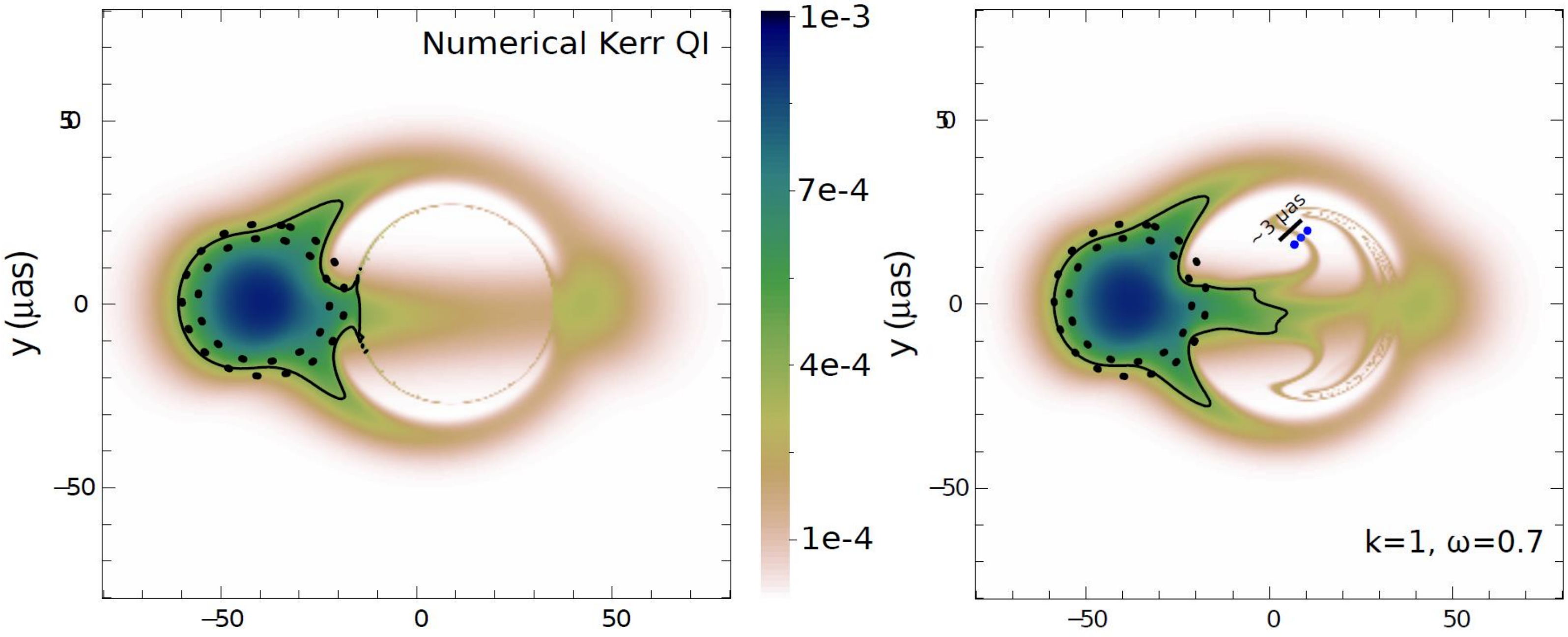




Lensing has to be properly included, as well as emission into other channels

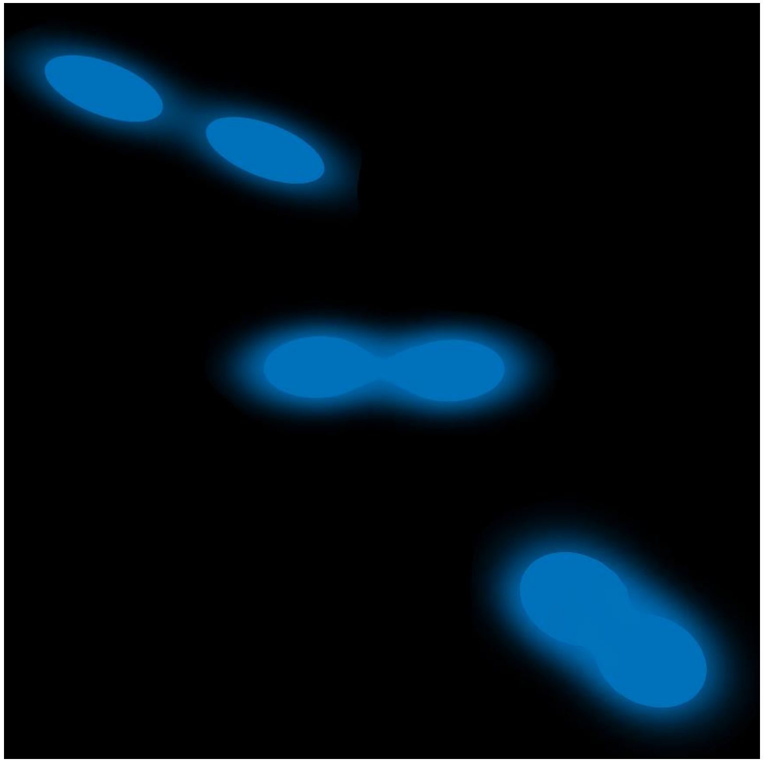
Abramowicz, Kluzniak, Lasota 2002; Cardoso, Pani Nature Astronomy 1 (2017)

Shadows



Vincent+ CQG 33:105015 (2016)

iv. GW signal



Nature of inspiralling objects is encoded

(i) in way they respond to own field (multipolar structure)

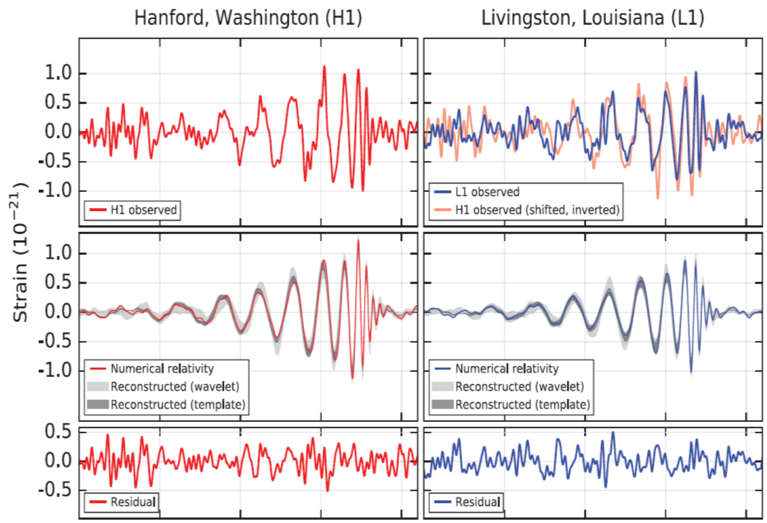
(ii) in way they respond when acted upon by external field of companion – through their tidal Love numbers (TLNs), and

(iii) on amount of radiation absorbed, i.e., tidal heating

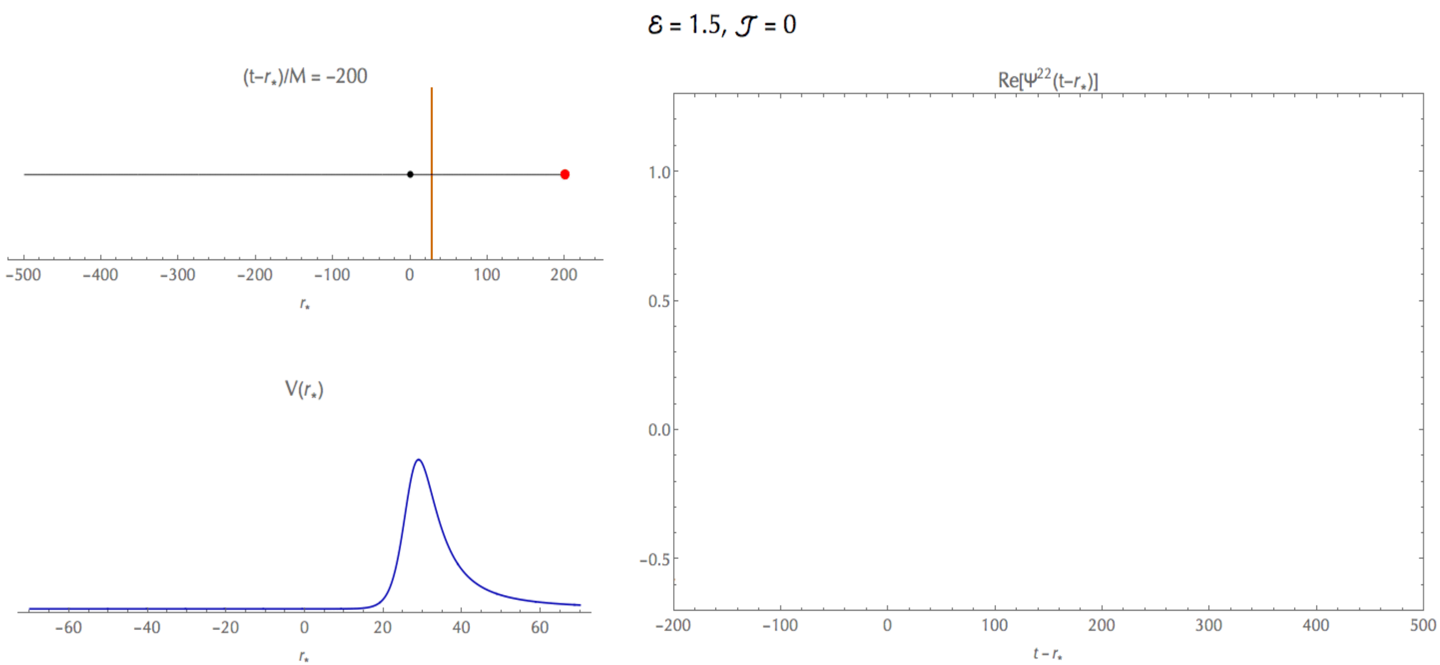
$$\tilde{h}(f) = \mathcal{A}(f) e^{i(\psi_{\rm PP} + \psi_{\rm TH} + \psi_{\rm TD})}$$

Cardoso + PRD95:084014 (2017); Sennett + PRD96:024002 (2017)
Maselli+ PRL120:081101 (2018); Johnson-McDaniel+arXiv:1804.08026

Post-merger

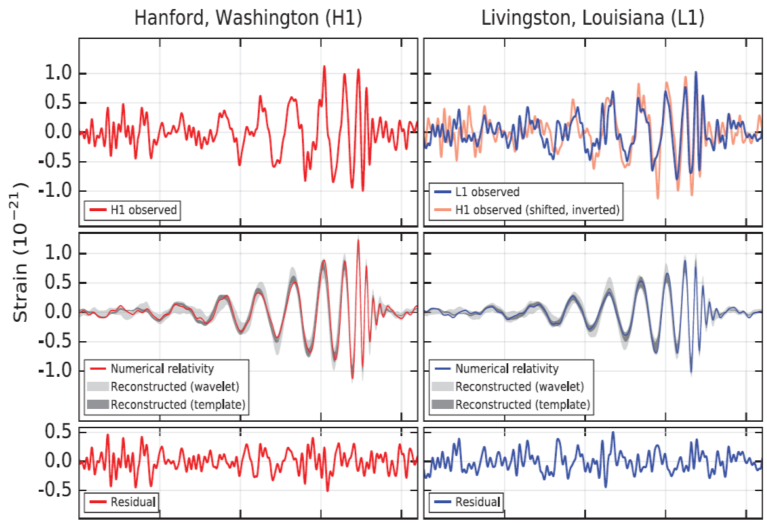


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
1.0
0.5
0.0
-0.5
-1.0

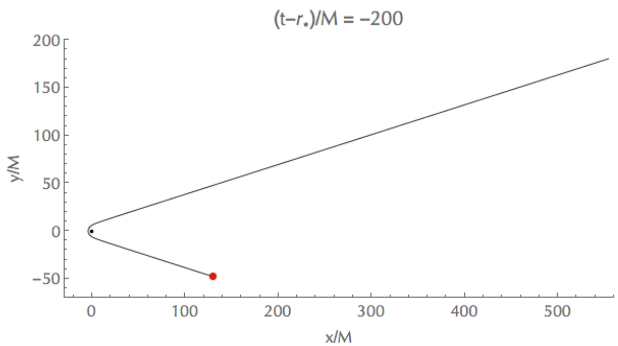


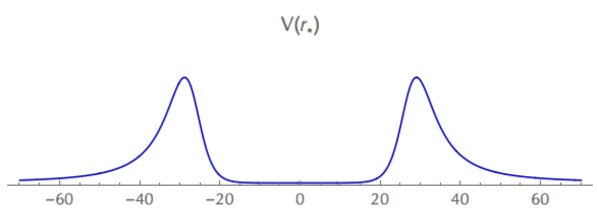
$\mathcal{E} = 1.5$, $\mathcal{J} = 0$
$(t-r_*)/M = -200$
r_*
$V(r_*)$
$\mathrm{Re}[\Psi^{22}(t-r_*)]$
$t - r_*$

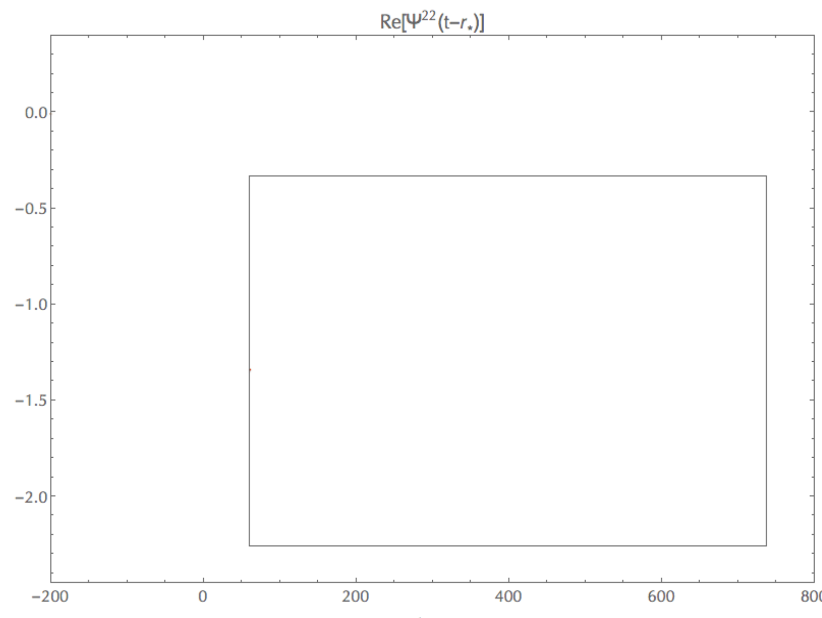
Post-merger



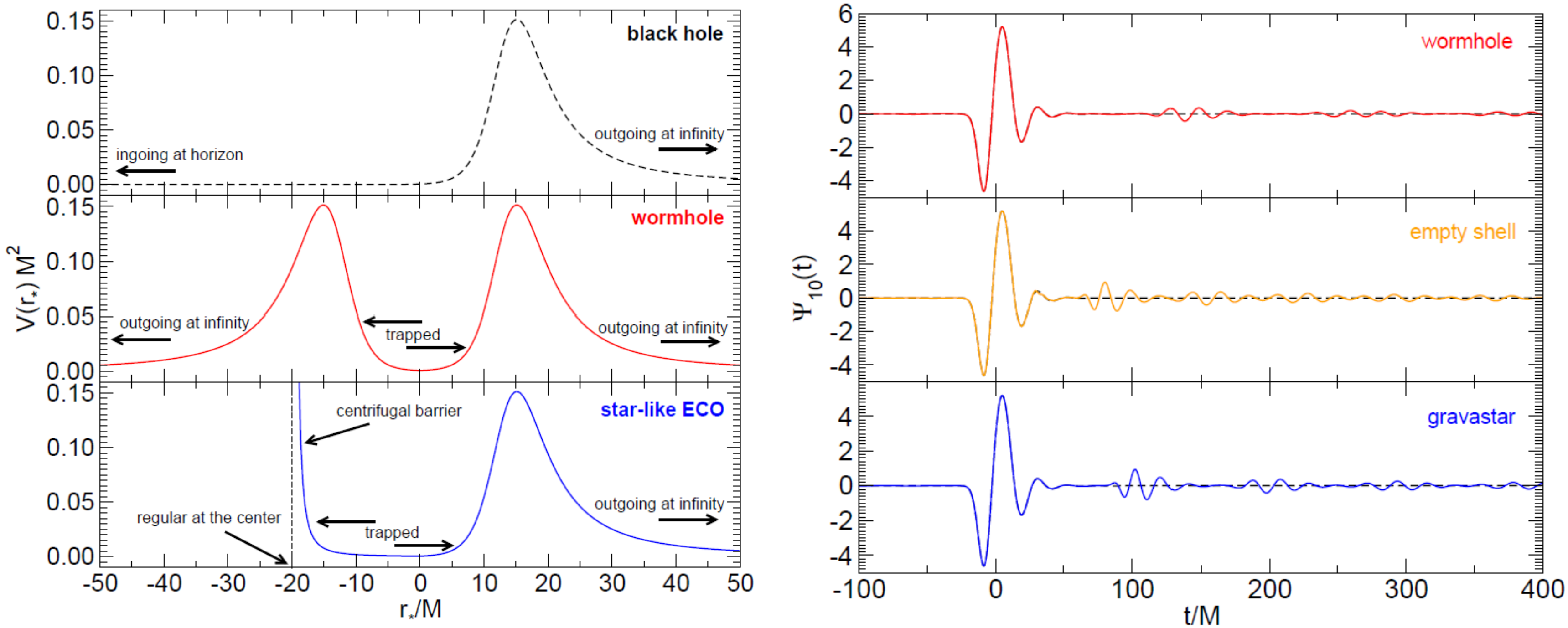
$\mathcal{E} = 1.5$, $r_{min}=4.3M$, $r_0-2M = 10^{-6}M$





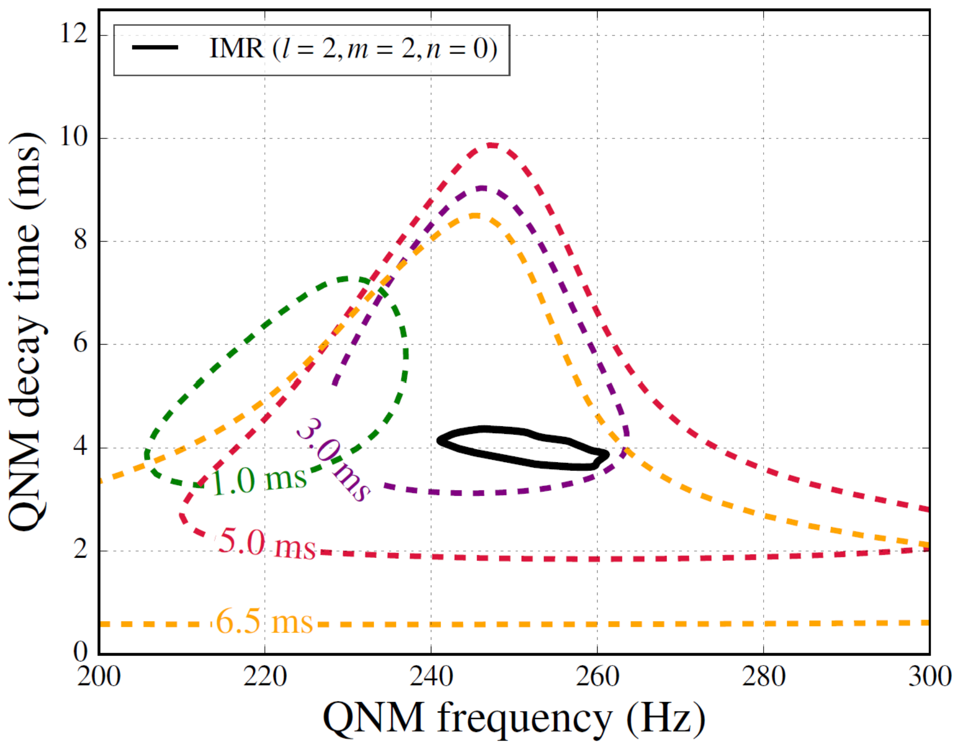


Echoes



Cardoso + PRL116:171101 (2016); Cardoso and Pani, Nature Astronomy 1: 2017
Cardoso and Pani, Living Reviews in Relativity, to appear

One and two-mode estimates



90% posterior distributions.

Black solid is 90% posterior of QNM as derived from the posterior mass and spin of remnant

LIGO Collaboration PRL116:221101 (2016)

Echoes and BH transfer functions

$$\frac{d^2\psi}{dz^2} + \left(\omega^2 - V\right)\psi = \mathcal{S}$$
$$\psi_{\rm ECO} \sim e^{-i\omega z} + \mathcal{R}e^{i\omega z - 2i\omega z_0}$$

The signal can be expressed as the one which would arise from a BH, with an appropriate transfer function K

$$\psi_{\rm ECO}^{\infty} = \psi_{\rm BH}^{\infty} + \mathcal{K}e^{2i\omega z}\psi_{\rm BH}^{r_+}$$
$$\mathcal{K} = \frac{\mathcal{R}e^{-2i\omega z_0}}{B_{\rm out} - B_{\rm in}\mathcal{R}e^{-2i\omega z_0}}$$

The expansion as a geometric series yields a series of echoes!

$$\mathcal{K} = \frac{\mathcal{R}e^{-2i\omega z_0}}{B_{\rm out}} \sum_{n=1}^{\infty} \left(\frac{B_{\rm in}\mathcal{R}}{B_{\rm out}}\right)^{n-1} e^{-2i\omega(n-1)z_0}$$

Mark+ PRD96: 084002 (2017)

Echoes and Dyson series

Express instead the problem in a flat spacetime background, treating the potential V as a perturbation

$$\psi = \psi_0 + \int_{z_0}^{\infty} g(z,z')\, V(z')\psi(z')\, dz'$$

$$g(z,z') = \frac{e^{i\omega|z-z'|} + \mathcal{R}e^{-2i\omega z_0}\, e^{i\omega(z+z')}}{2i\omega}$$

g is Green function for free wave operator, with previous BCs, and psi_0 is free wave amplitude. Solution is Dyson series

$$\psi = \sum_{k=1}^{\infty}\int_{z_0}^{\infty} g(z,z_1)\cdots g(z_{k-1},z_k)V(z_1)\cdots V(z_{k-1})\mathcal{S}(z_k)dz_1\cdots dz_k$$

The expansion as a geometric series yields a series of echoes!

$$\psi = \psi_o + \sum_{n=1}^{\infty}\psi_n$$

Correia, Cardoso PRD97: 084030 (2018)

v. The evidence for black holes

Cardoso and Pani, Living Reviews in Relativity *(to appear)*

	Constraints		Source
	$\epsilon(\lesssim)$	$\frac{\nu}{\nu_\infty}(\gtrsim)$	
1.	$\mathcal{O}(1)$	1.4	Sgr A* & M87
2.	$\mathcal{O}(0.01)$	10	GW140915
3.	$10^{-4.4}$	158	All with $M > 10^{7.5} M_\odot$
4.	10^{-14}	10^7	Sgr A*
5.	10^{-40}	10^{20}	All with $M < 100 M_\odot$

	Effect and caveats
1.	Uses detected structure in "shadow" of SgrA and M87.
	Spin effects are poorly understood; systematic uncertainties not quantified.
2.	Uses same ringdown as BH and lack of echoes.
	?
3.	Lack of optical/UV transients from tidal disruption events.
	Assumes: all objects are horizonless, have a hard surface, spherical symmetry, and isotropy.
4.	Uses absence of relative low luminosity from Sgr A*, compared to disk.
	Spin effects and interaction of radiation with matter poorly understood; assumes spherical symmetry.
5.	Uses absence of GW stochastic background (from ergoregion instability).
	Assumes: hard surface (perfect reflection); exterior Kerr; all objects are horizonless.

Exciting times!

We can test GR in strong field... are BHs described by Kerr family?

...do black holes exist?

Tools missing (where in spectra are LR modes, nonlinear evolutions etc)

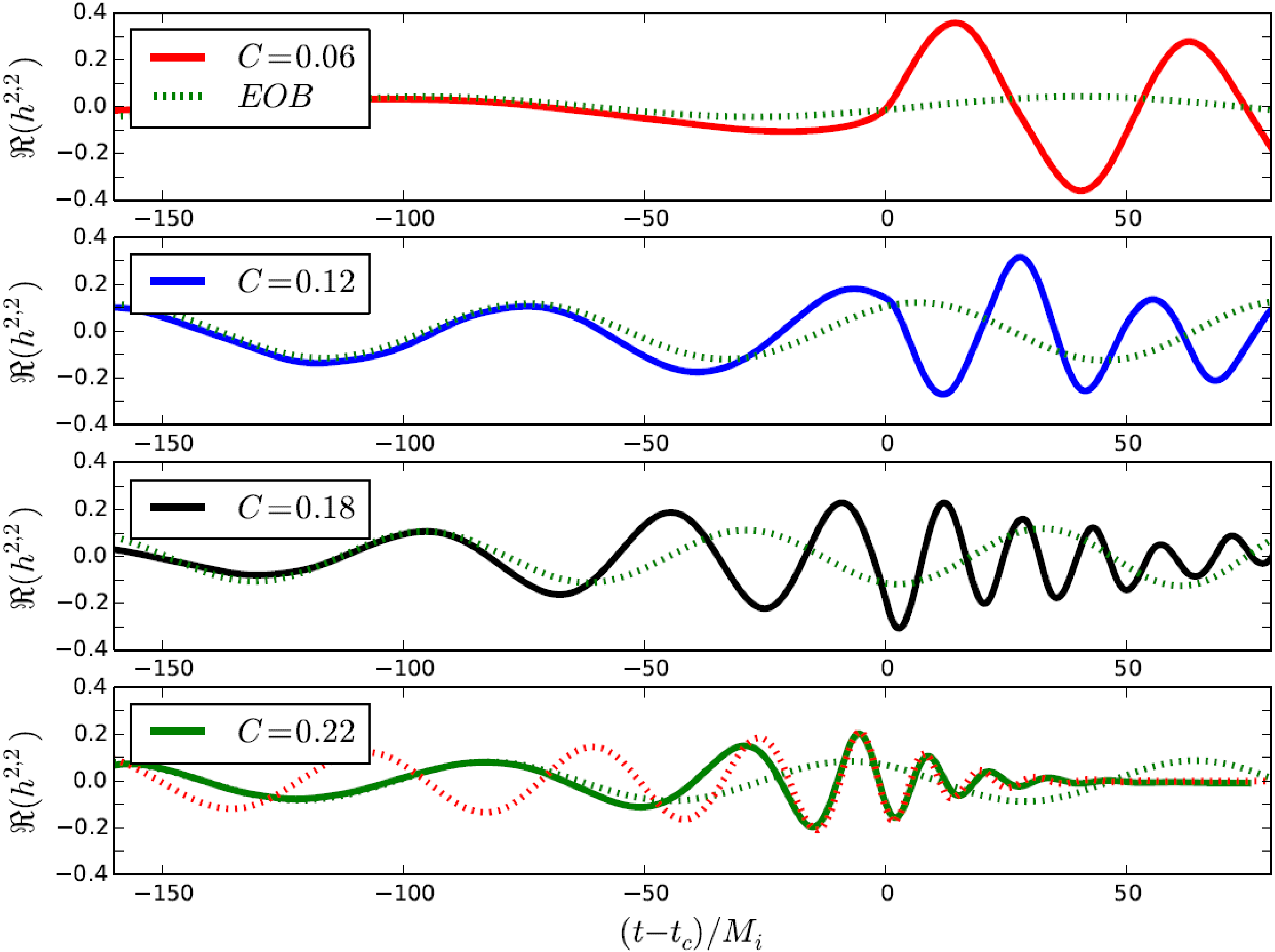
Searches for echoes ongoing...need modelling efforts too

Cardoso, Pani, Living Reviews in Relativity (2019)

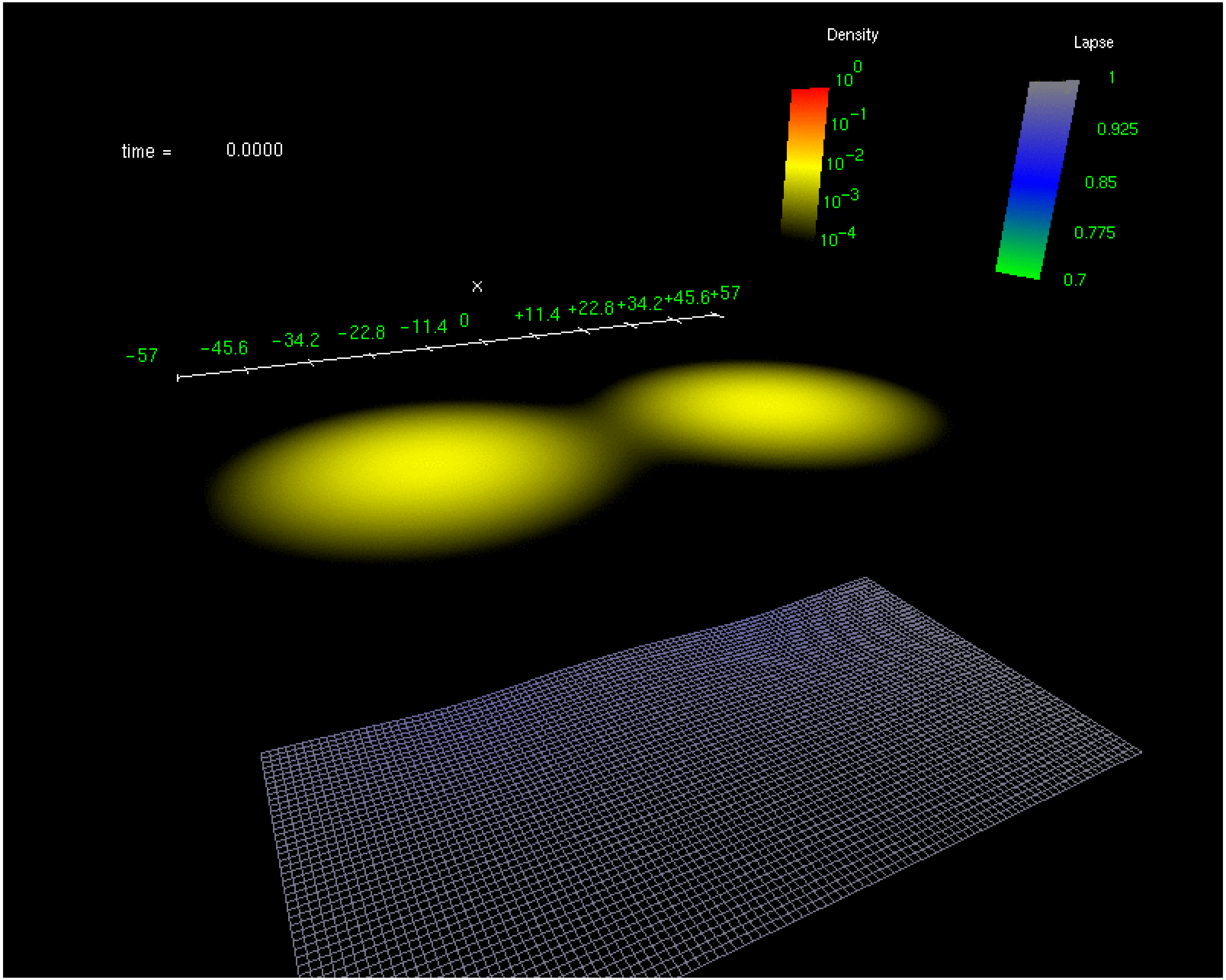
"But a confirmation of the metric of the Kerr spacetime (or some aspect of it) cannot even be contemplated in the foreseeable future."

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

Thank you



$C=0.06$
EOB
$C=0.12$
$C=0.18$
$C=0.22$
$\Re(h^{2,2})$
$(t-t_c)/M_i$
0.4
0.2
0.0
−0.2
−0.4
−150
−100
−50
0
50

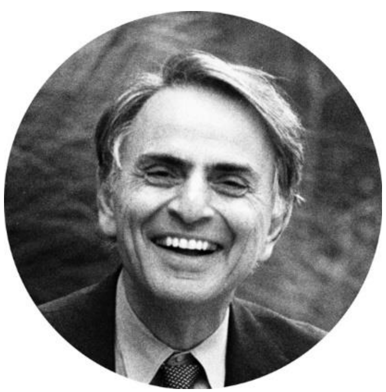

Density
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Lapse
1
0.925
0.85
0.775
0.7
time = 0.0000
x
-57
-45.6
-34.2
-22.8
-11.4
0
+11.4
+22.8
+34.2
+45.6
+57

“Plus un fait est extraordinaire, plus il a besoin d'être appuyé de fortes preuves; car, ceux qui l'attestent pouvant ou tromper ou avoir été trompés, ces deux causes son d'autant plus probables que la réalité du fait l'est moins en elle-même.…”

Laplace, Essai philosophique sur les probabilities 1812

“No testimony is sufficient to establish a miracle, unless the testimony be of such a kind, that its falsehood would be more miraculous than the fact which it endeavors to establish.”

David Hume, An Enquiry concerning
Human Understanding 1748



“Extraordinary claims require extraordinary evidence.”

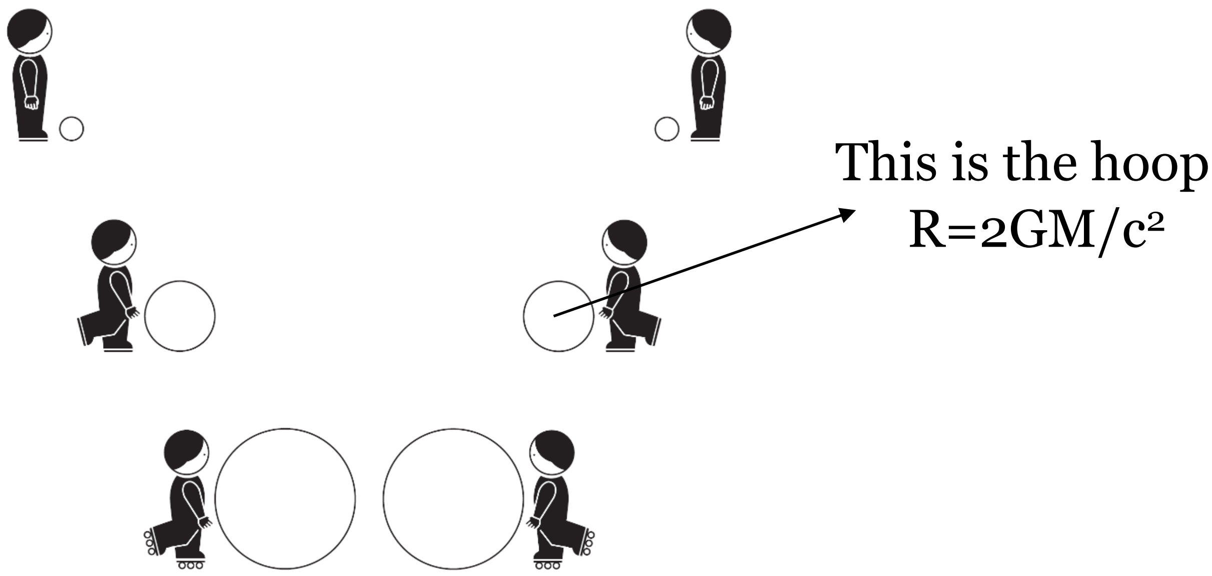
Carl Sagan

iiic. The Hoop and nonlinear stability

Thorne 1972

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

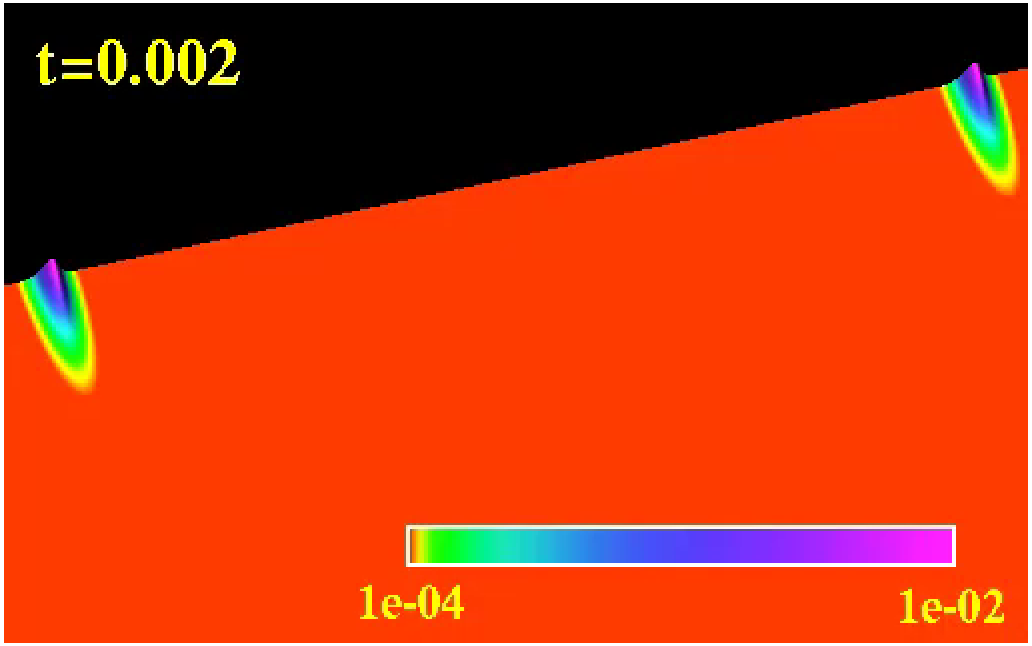
Large amount of energy in small region



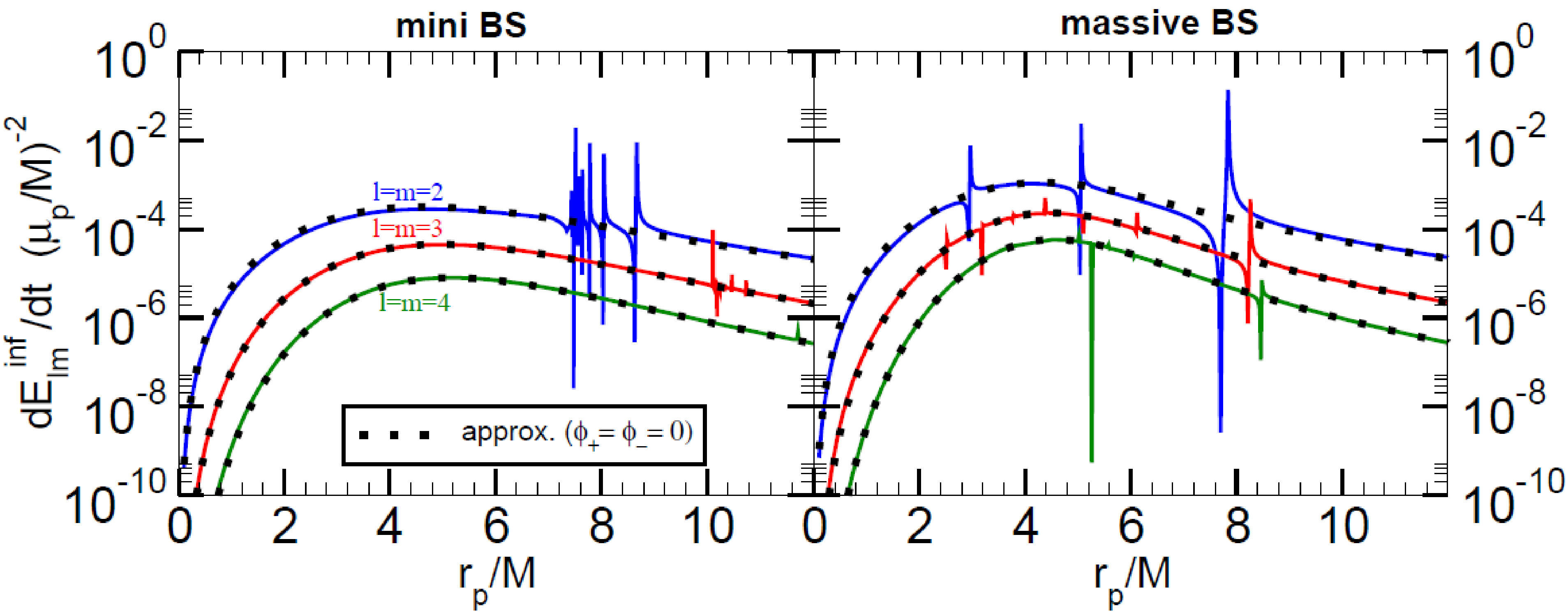
Size of electron: 10^(-17) cm
Schwarzschild radius: 10^(-55) cm

The end of short-distance physics

Lorentz boost = 4



Choptuik & Pretorius PRL 104:111101 (2010)



Macedo+ ApJ 774: 48 (2013); PRD 88: 064046 (2013)

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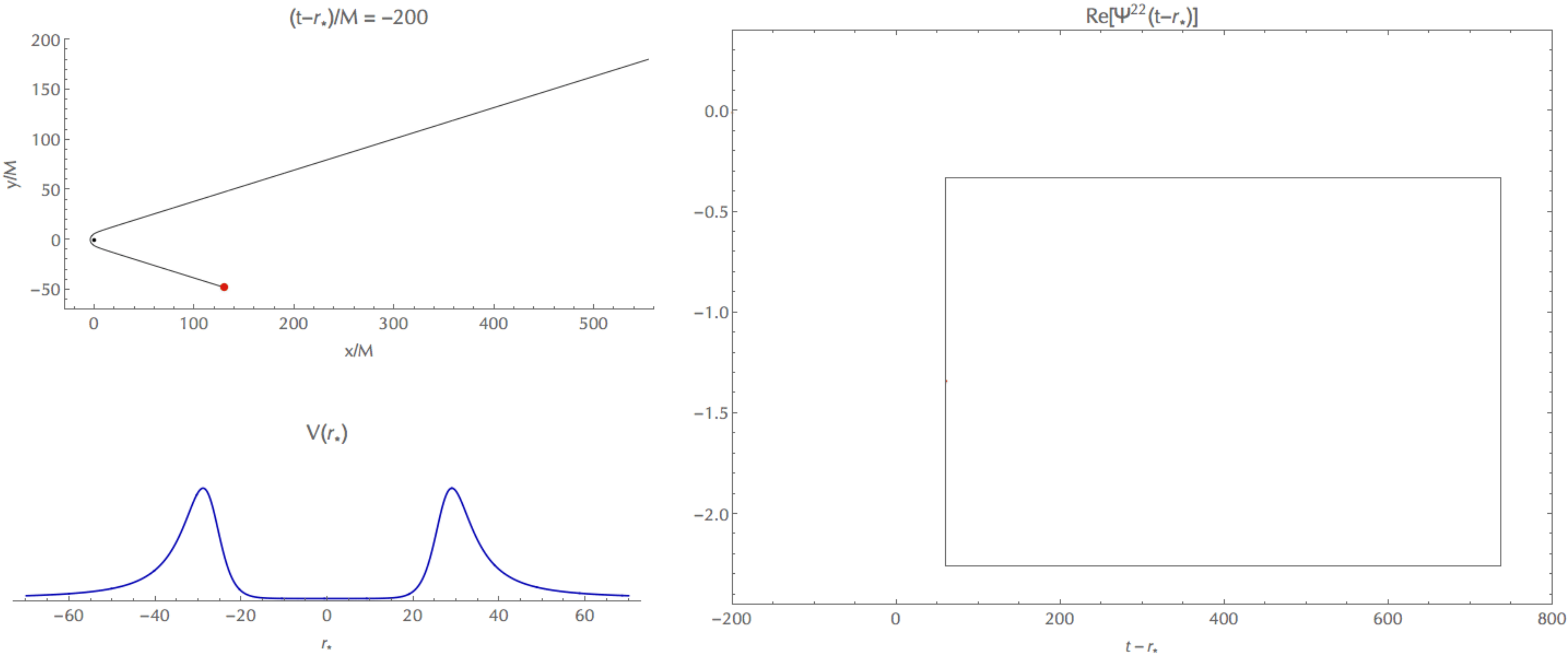
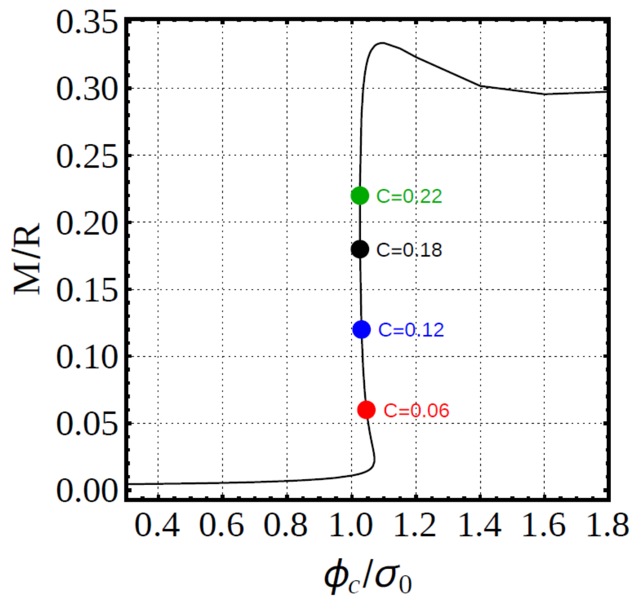
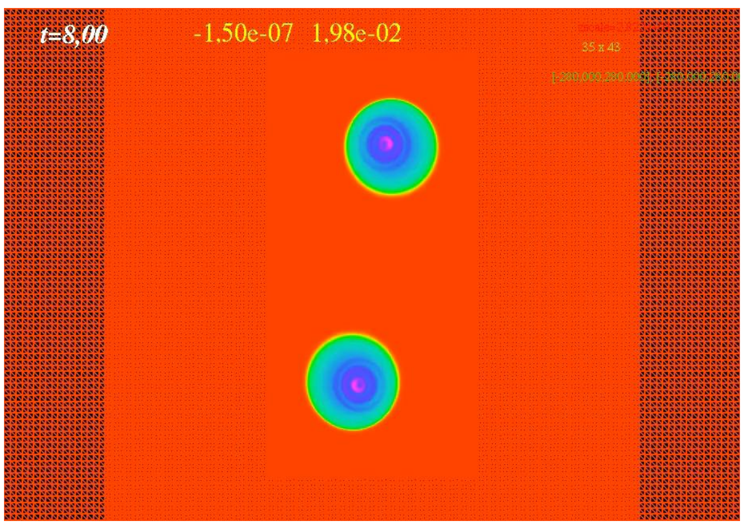
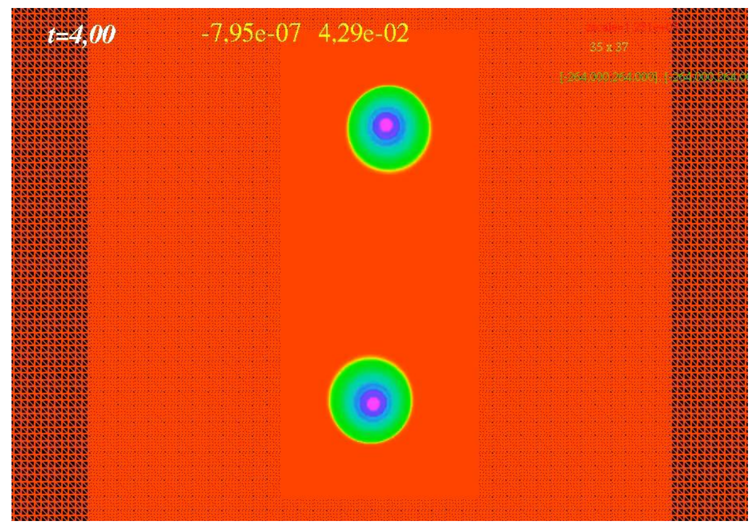


Cardoso + PRD94:084031 (2016)







Palenzuela+ PRD96:104058(2017)