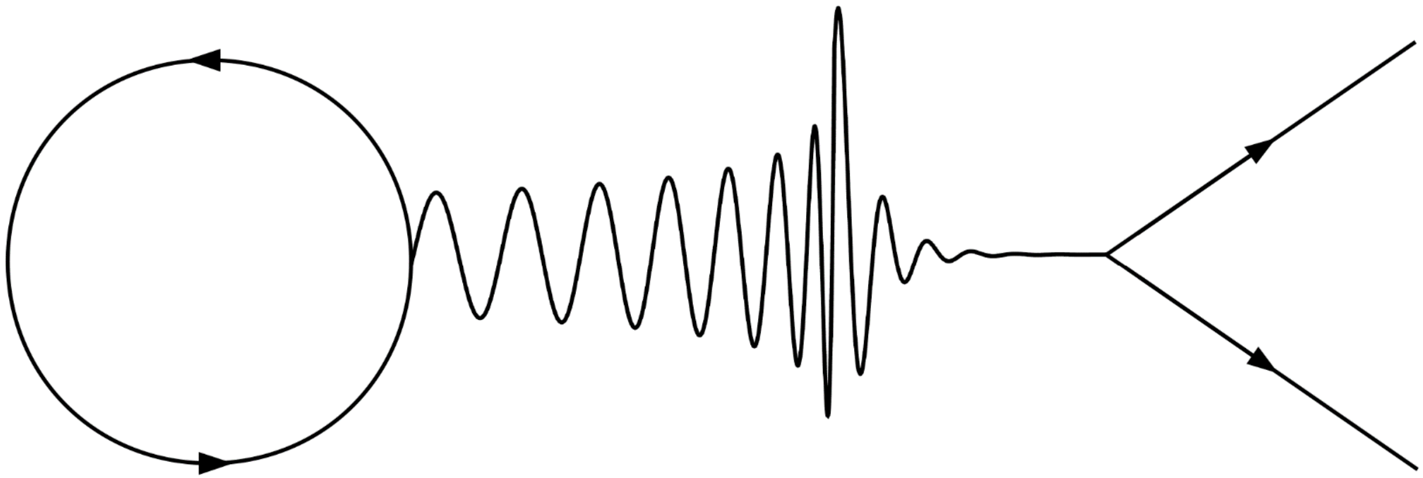
Exotic Compact Objects



Vítor Cardoso • Tanja Hinderer • Carlos Palenzuela • Huan Yang

(Técnico & CERN) (UVA) (Illes Balears) (Guelph/Perimeter)

Image: Cardoso & Pani, CERN Courier (2016)

Why?

a. We don’t know most of the content of the universe (DM, DE). New states of matter invariably lead to new objects.

b. Need to quantify evidence for black holes.

c. Attempt to solve issues with black holes.

Physics is observations: observe and report.

a. dark matter: capture by stars

Accumulation stage, thermalizing on radius $G\rho_{\rm star} r_{\rm th}^2 m_{\rm D} \sim k_B T$

Black hole phase, after DM core becomes self-gravitating

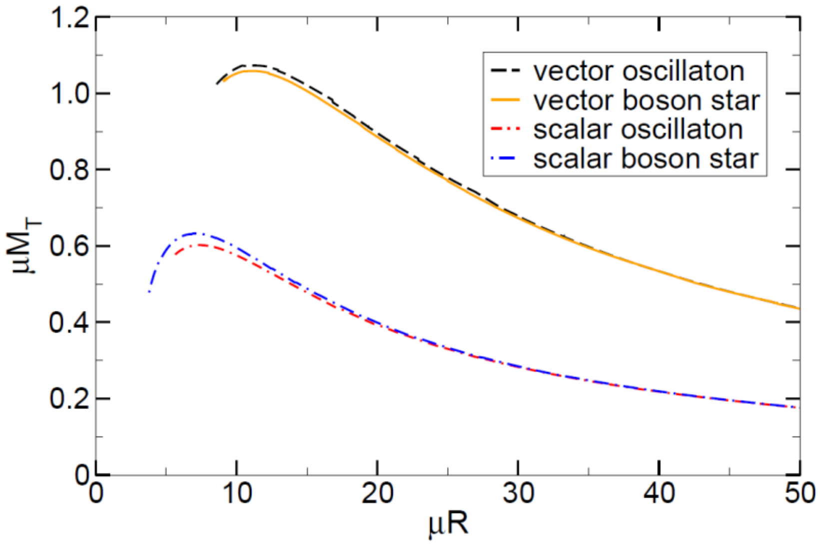
Goldman and Nussinov PRD40: 3221 (1989); Bertone and Fairbairn PRD77: 043515 (2008)

Black hole phase can be avoided by bosonic matter Brito+ PRL115:111301 (2015)

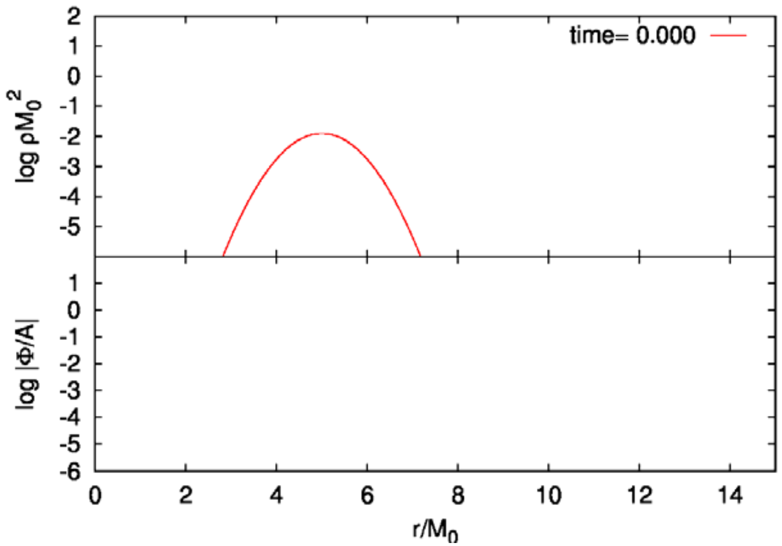
a. dark matter: new stars

Boson stars, fermion-boson stars, oscillatons

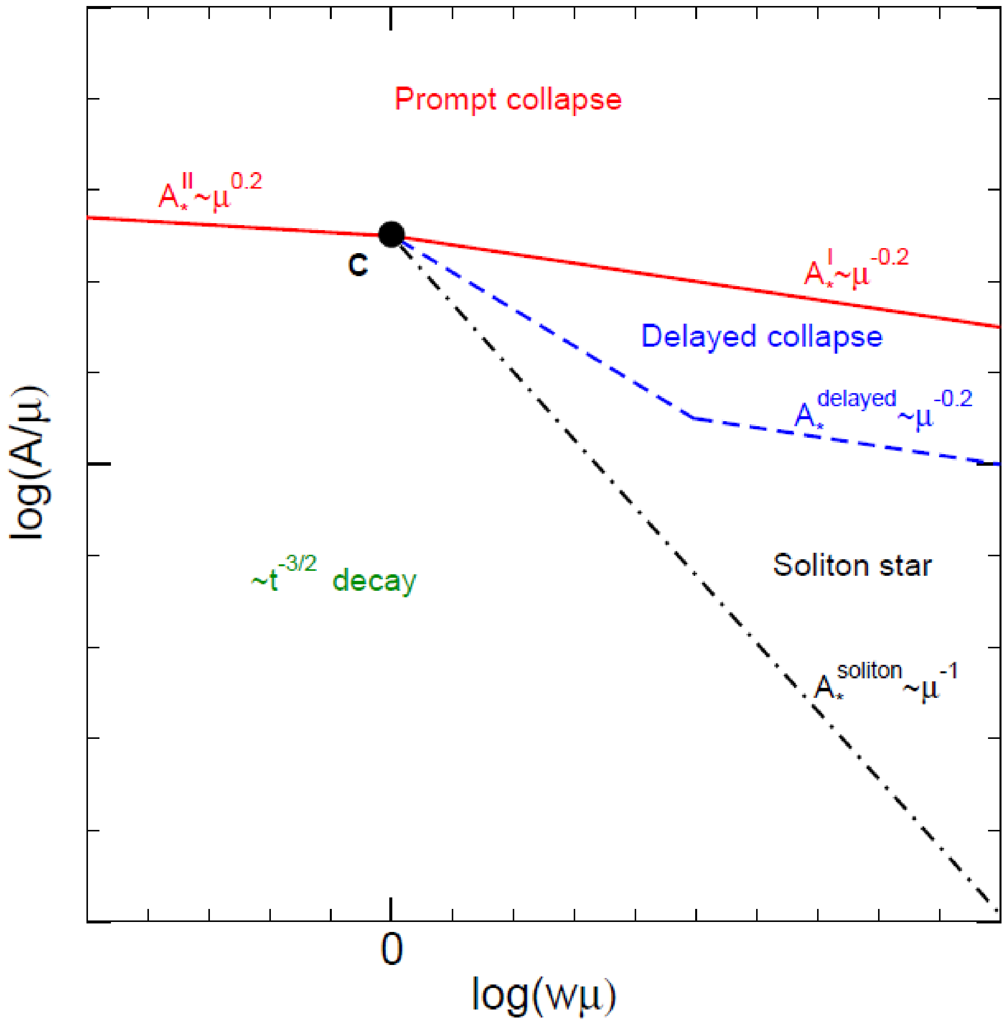
(Kaup 1968; Ruffini, Bonazzolla 1969; Colpi + 1986; Okawa + 2014; Brito + 2015)



Brito + PRL115:111301 (2015)



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



Okawa + PRD89, 041502 (2014)

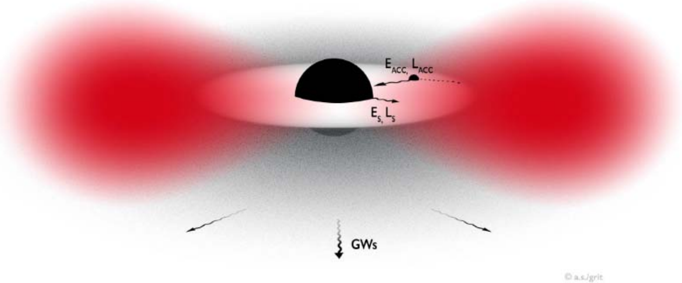
a. dark matter: notes

DM is likely composed of variety of fields and particles, from axions to MACHOs

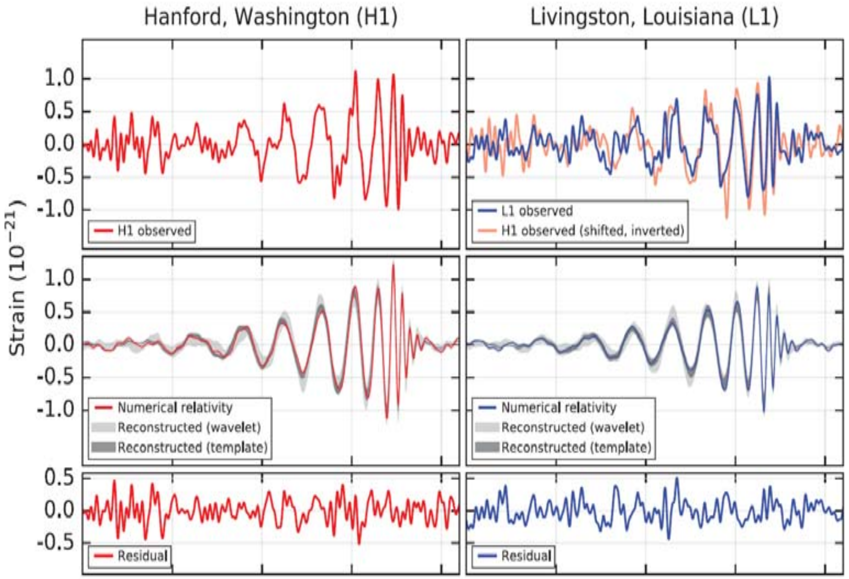
Can be very compact, evolution drives to large compactness

Compactness > 90% that of black hole not “natural” (fine-tuning required)

Hairy BHs not included in this description...comments?



b. Quantifying evidence for black holes



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

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

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

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

Very compact massive object indeed!

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.

b. Quantifying evidence for black holes

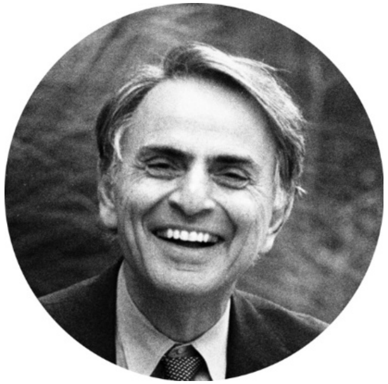
By definition, it is impossible to prove existence of black holes.
In finite time-span, can only gather evidence that supports paradigm.

Black holes are very special: harbour singularities, have huge entropy and give rise to infinite redshift...can we take these properties lightly?

To quantify evidence it is useful to understand ECOs as BH strawmen.
Unlike DM-inspired objects, BH mimickers are not “natural”:

Don’t require fine tuning,
can and should have compactness as close to that of BHs as possible.

c. Issues with black holes



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

“*Extraordinary claims require extraordinary evidence.*”
Carl Sagan

2. Quantum effects not fully understood (Monday panel).

3. Tacitly assumed quantum effects at Planck scales. Planck scale could be significantly lower. Even if not, many orders of magnitude standing, surprises can hide.
(Antoniadis 1990, 1998; Arkani-Hamed+ 1998; Giddings & Thomas 2002)

Physics is experimental science. We *can* test exterior.
Similar to quantifying equivalence principle.

Clean and dirty Photospheres (ClePhOs)

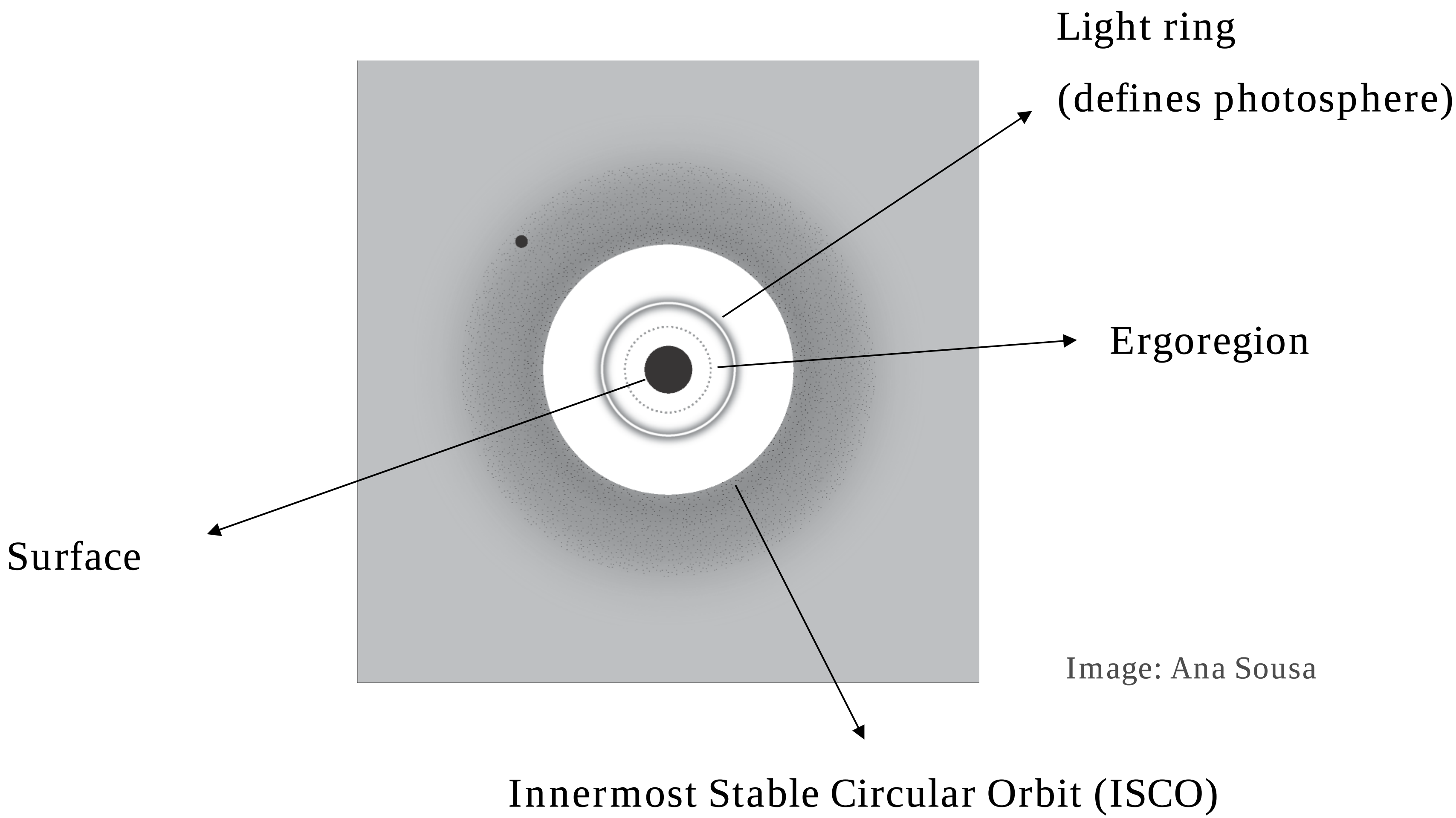


Image: Ana Sousa

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

Some questions to answer

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?

i. Alternatives

Boson stars, fermion-boson stars, oscillatons
Kaup 1968; Ruffini, Bonazzolla 1969, Colpi + 1986, Brito + 2015

Anisotropic stars
Bowers, Liam 1974; Dev, Gleiser 2000; Yagi, Yunes 2015; Bezares + 2018 (to appear)

Wormholes
Morris, Thorne 1988; Visser 1996

Gravastars
Mazur, Mottola 2001

Fuzzballs, Superspinars, collapsed polymers, 2-2 holes
Mathur 2000; Gimon, Horava 2009; Brustein, Medved 2016; Holdom, Ren 2016

...

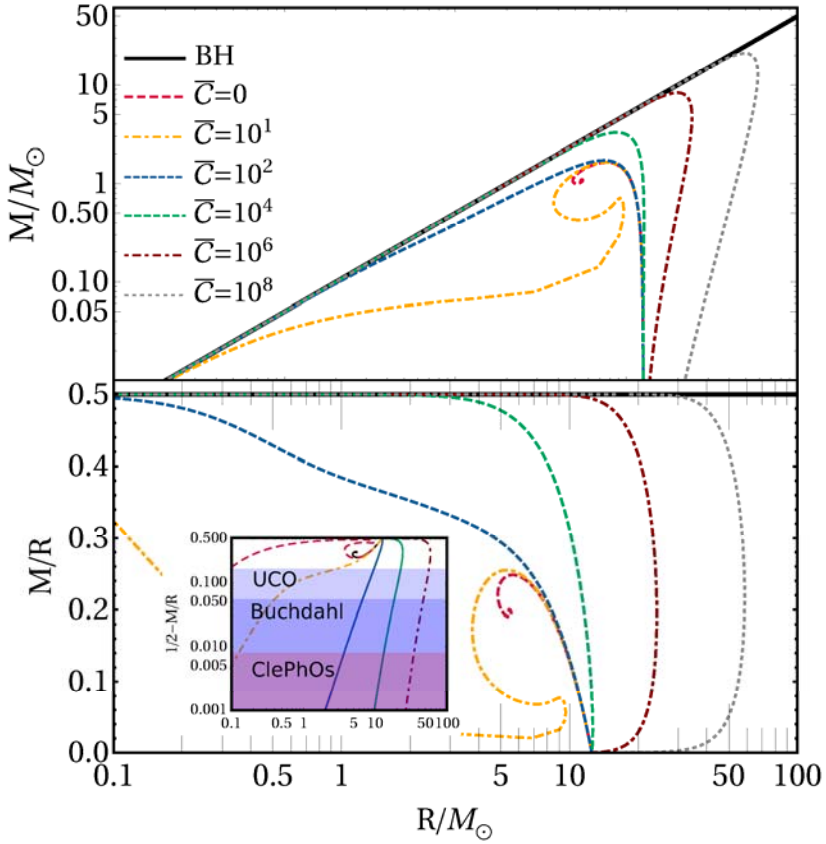
$$T_{\mu\nu} = \rho u_\mu u_\nu + P_r k_\mu k_\nu + P_t \Pi_{\mu\nu}$$

$$\Pi_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu - k_\mu k_\nu$$

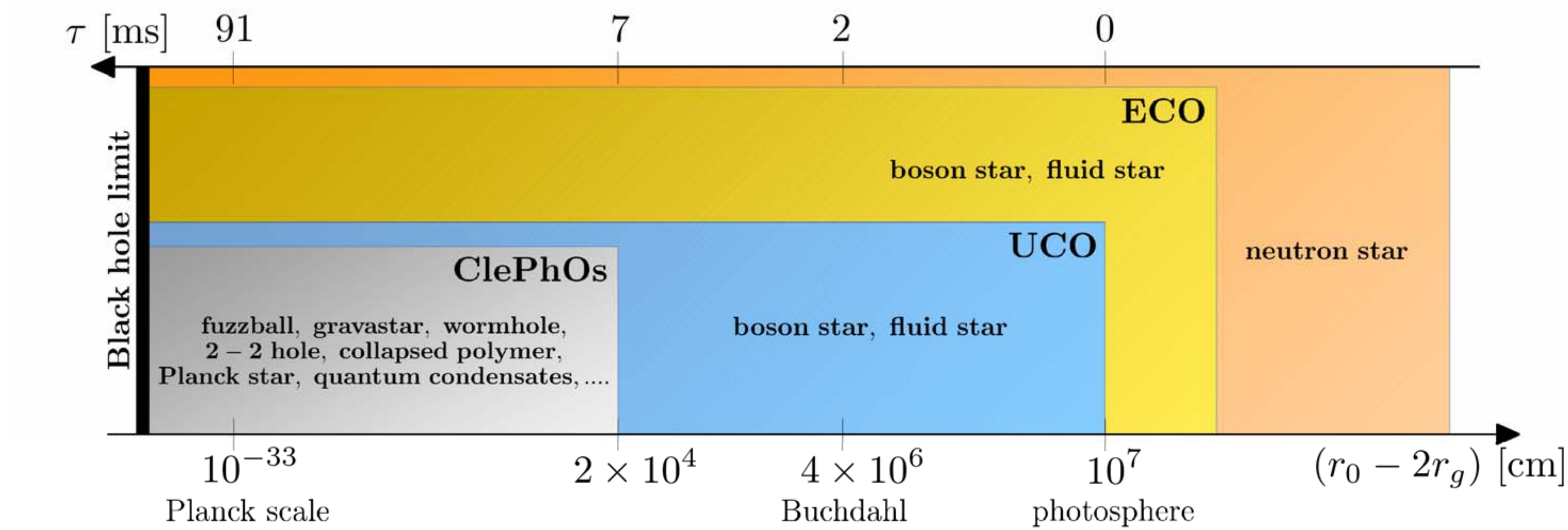
$$k^\mu k_\mu = 1 = -u^\mu u_\mu$$

$$u^\mu k_\mu = 0$$

$$P_t = P_r - \mathcal{C} f(\rho) k^\mu \nabla_\mu P_r$$



Bezares + (2018, to appear)



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

ii. Formation

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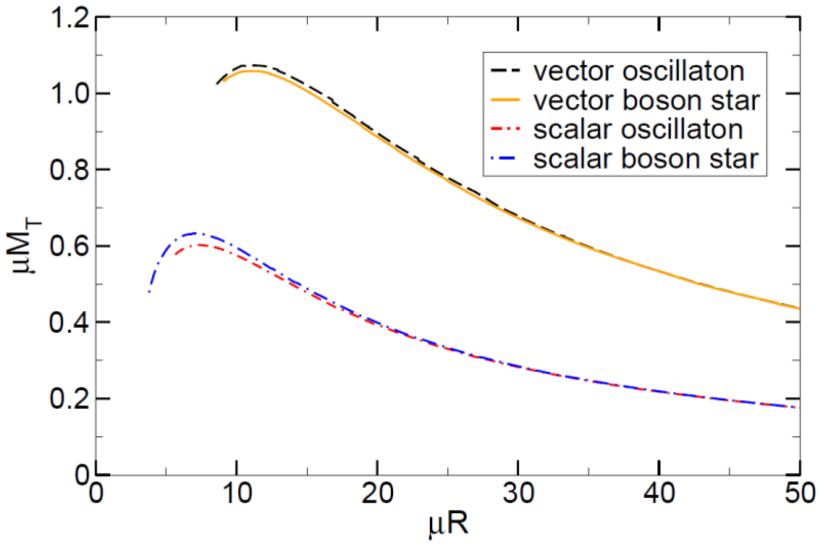
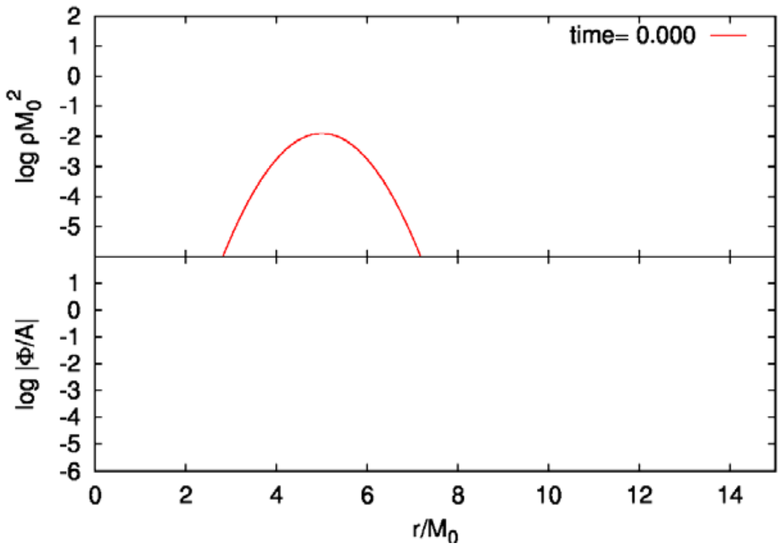
(Kaup 1968; Ruffini, Bonazzolla 1969; Colpi et al 1986; Okawa et al 2014; Brito et al 2015)





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

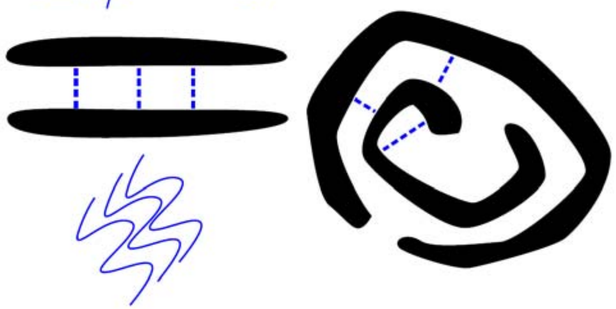
iii. Stability of objects with photospheres

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

Keir 2014, CQG 33: 135009 (2016); Cardoso et al, 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)

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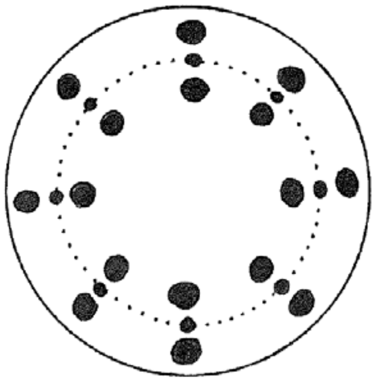

In absence of viscosity, Dyson-Chandrasekhar-Fermi mechanism might trigger nonlinear instabilities

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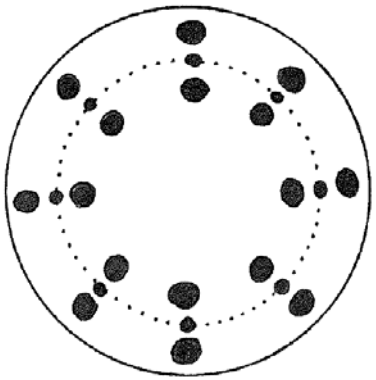


In absence of viscosity, Dyson-Chandrasekhar-Fermi mechanism might trigger nonlinear instabilities

Rotation: *Horizonless objects with ergoregions are linearly unstable*

Friedmann Comm. Math.Phys.63:243, 1978; Brito, Cardoso, Pani 2015; Moschidis 2016

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

EM & GW signal

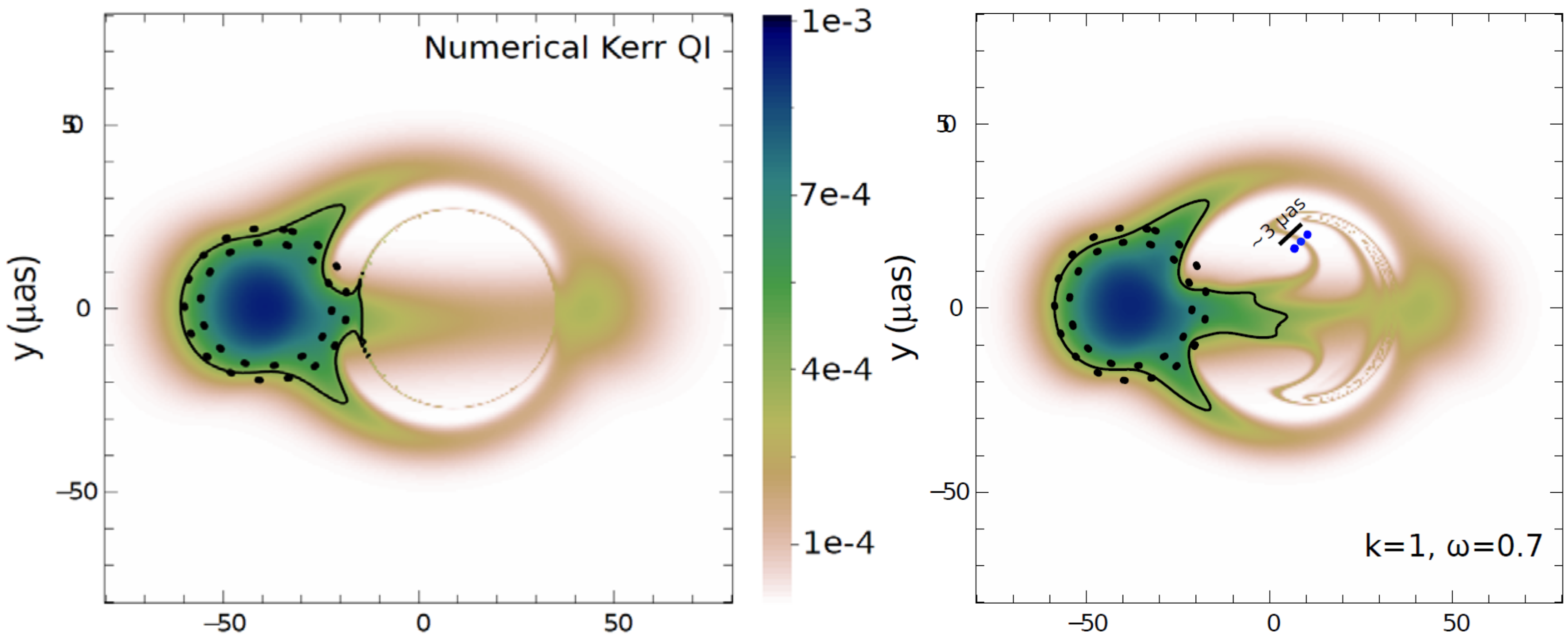
Hawking radiation

It is a distinctive feature of event horizons, but not exclusive

Almost any notion of trapping horizon or dynamic horizonless object radiates

A. Paranjape + PRD80: 044011 (2009)
Barcelo + JHEP1102:003 (2011)
Harada + (to appear, 2018)

Shadows



Vincent+ CQG 33:105015 (2016)

EM signals from ECOs (DM-inspired)

Axionic couplings leading to EM signals

DM cores in stars changes structure of star - > new post-merger signals

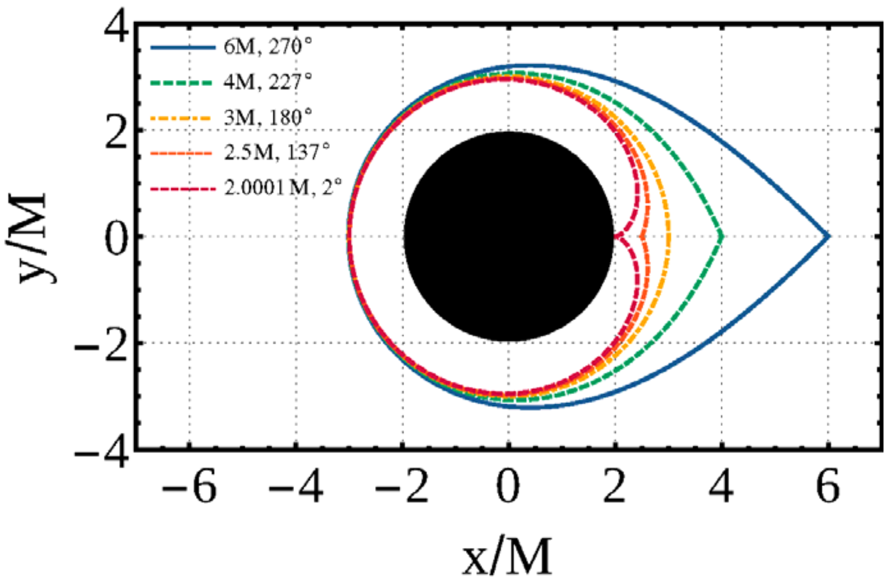
EM constraints

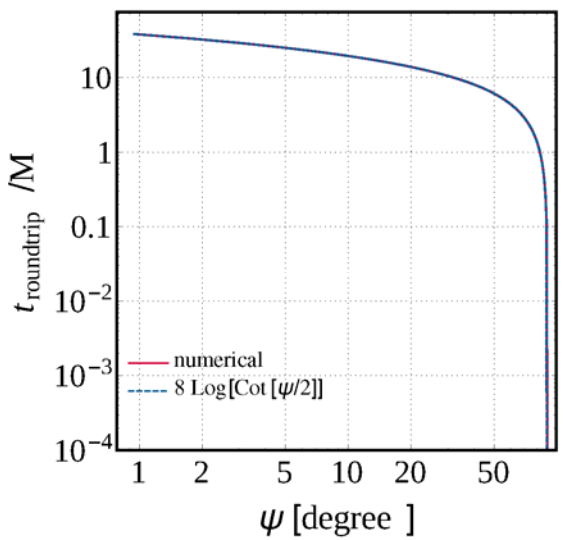
$$r = 2M\,(1+\epsilon)$$

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

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

The Pan-STARRS1 Surveys arXiv:1612.05560
Broderick, Narayan CQG24:659 (2007)



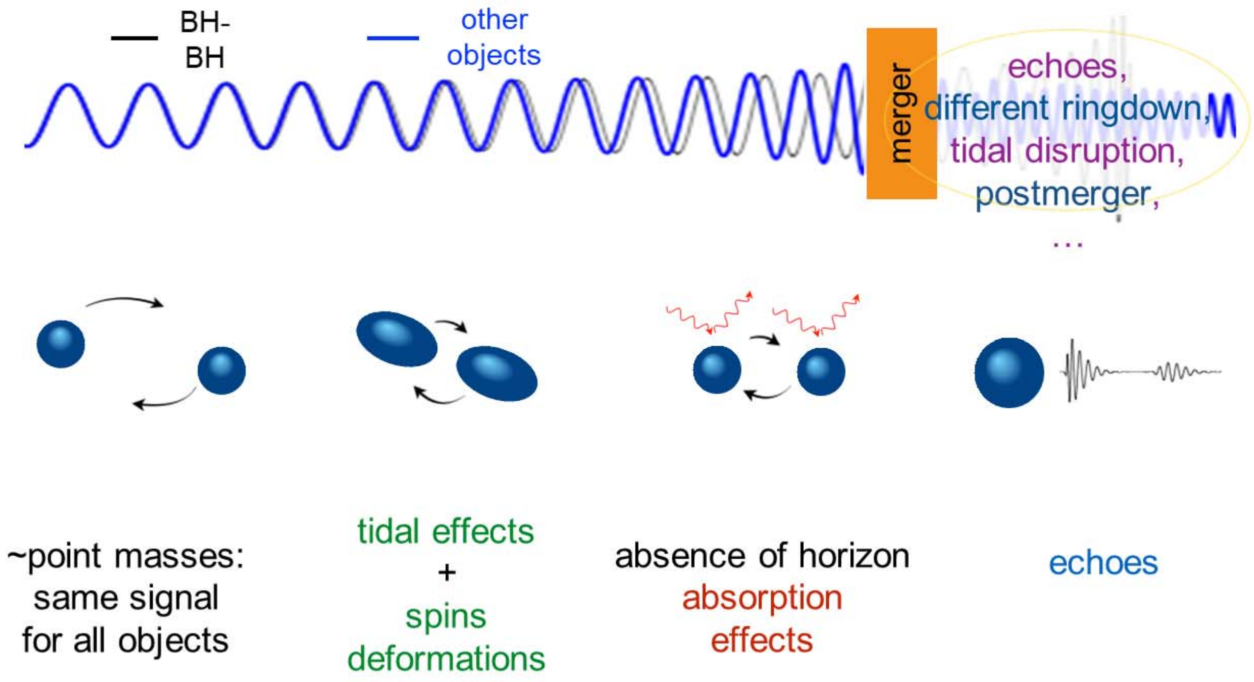


Lensing has to be properly included, as well as emission into other channels

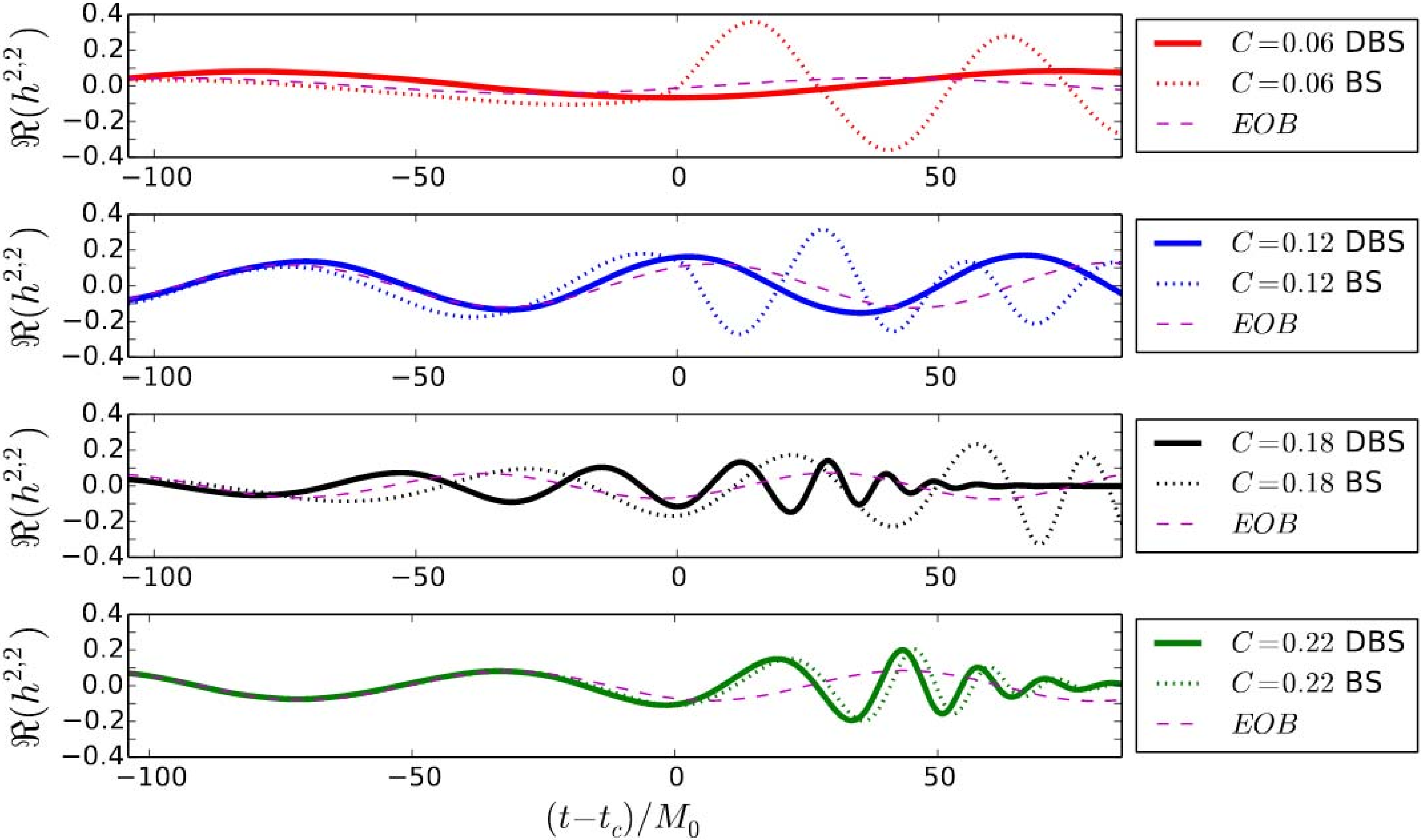
Cardoso, Pani Nature Astronomy 1 2017; *arXiv:1707.03021*

GW signal

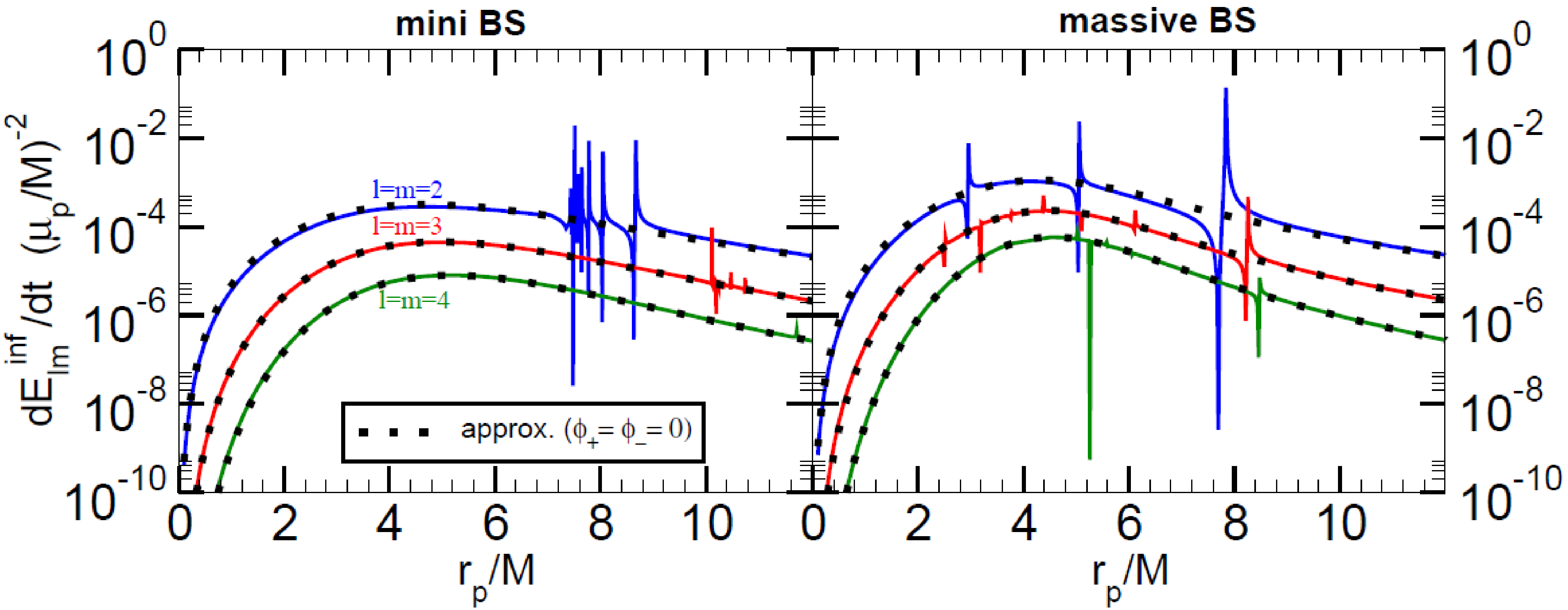
(Figure courtesy of Andrea Maselli)



Cardoso + PRD95:084014 (2017); Cardoso+ PRL116:171101 (2016)
Cardoso+ Nature Astronomy 1: 2017; Sennett + PRD96:024002 (2017)
Maselli+ PRL120:081101 (2018); Johnson-McDaniel+arXiv:1804.08026



Bezares + arXiv:1808.10732; Palenzuela + PRD96: 104058 (2017)



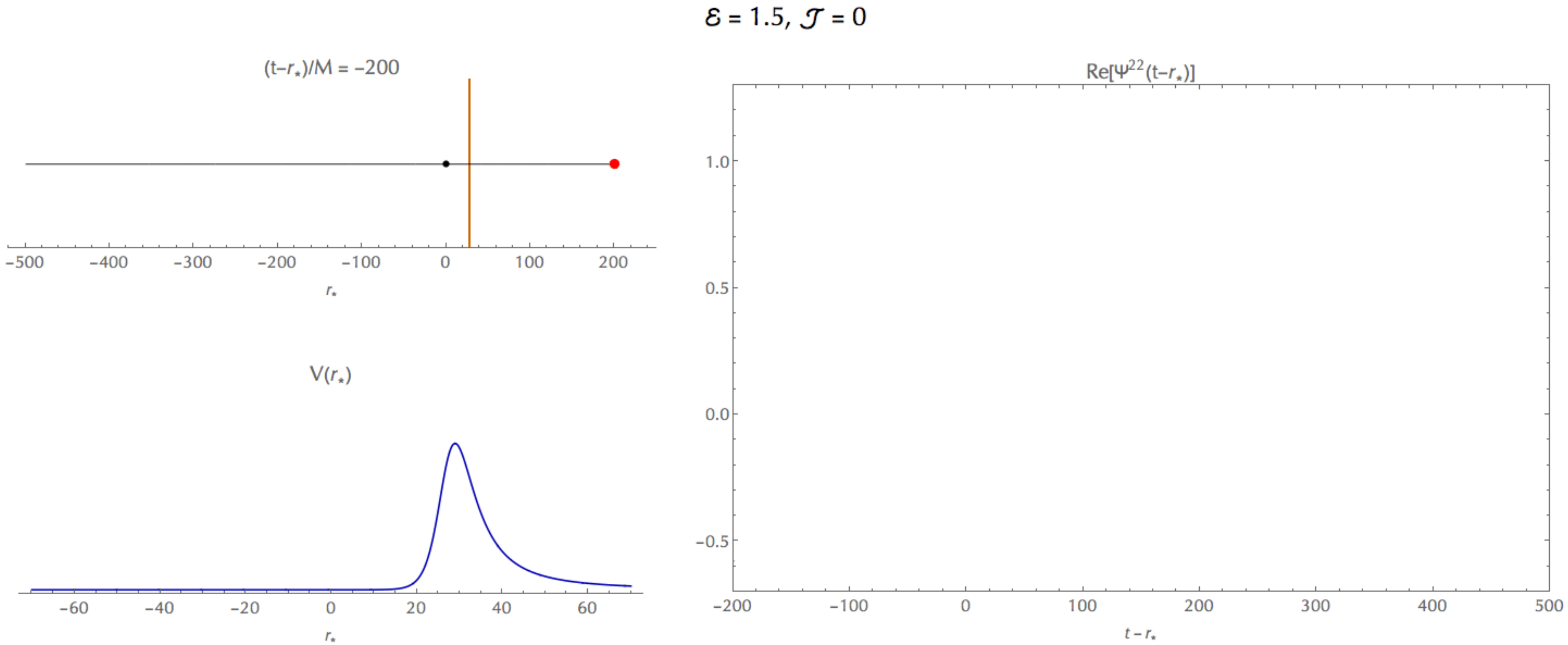
Macedo+ ApJ 774: 48 (2013); PRD 88: 064046 (2013)

TABLE I. Tidal Love numbers of some ECOs and BHs. For comparison, TLNs of NS with compactness $C \approx 0.2$ is provided (precise number depends on EoS). For BSs, the table provides the lowest value of the corresponding TLNs among different models. For ECOs, surface r_0 sits at $r_0 = 2M(1+\epsilon)$. TLNs for Einstein-Maxwell and Chern-Simons gravity were obtained under the assumption of vanishing electromagnetic and scalar tides.

		k_2^E
NSs		210
ECOs	Massive Boson star	444
	Solitonic Boson star	2.06
	Wormhole	$\frac{4}{5(8+3\log\epsilon)}$
	Perfect mirror	$\frac{8}{5(7+3\log\epsilon)}$
	Gravastar	$\frac{16}{5(23-6\log 2+9\log\epsilon)}$
BHs	Einstein-Maxwell	0
	Scalar-tensor	0
	Chern-Simons	0

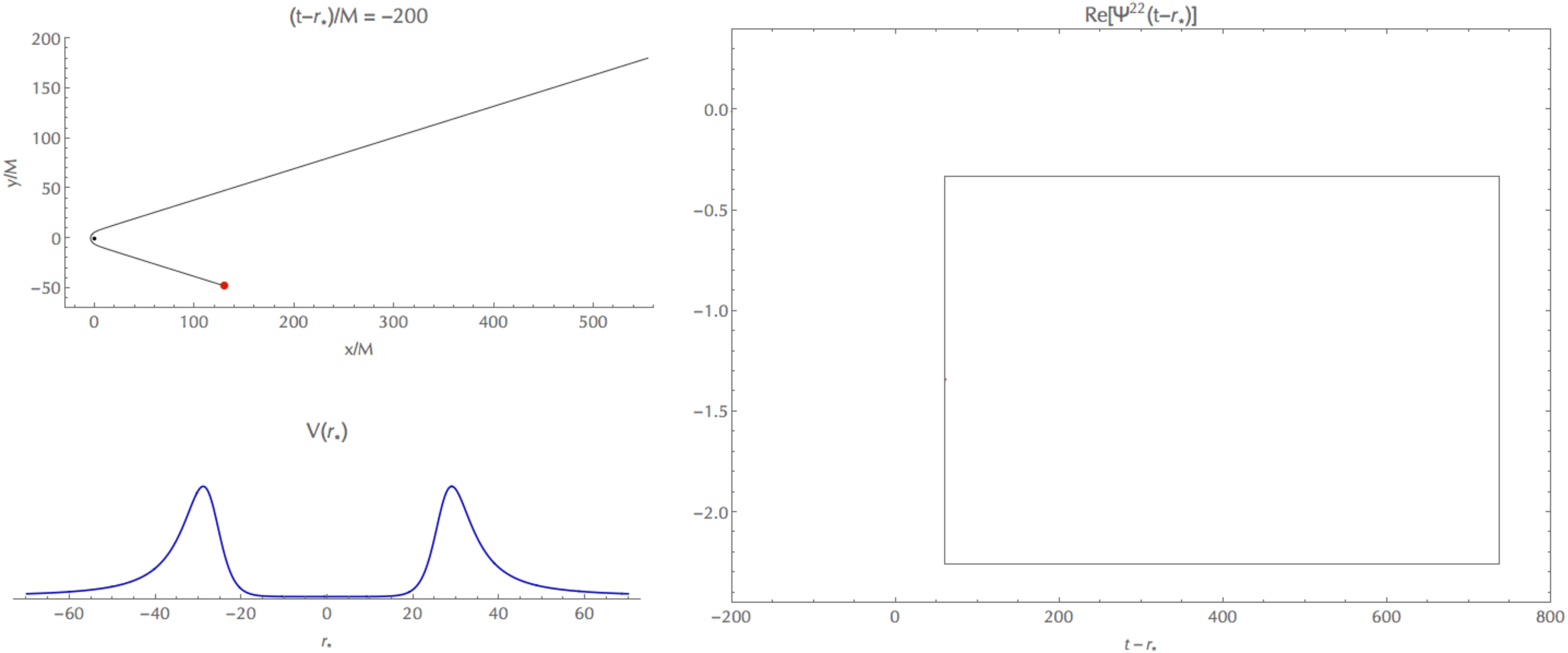
Adapted from Cardoso + PRD95:084014 (2017) and Sennett PRD96: 024002 (2017)

Echoes



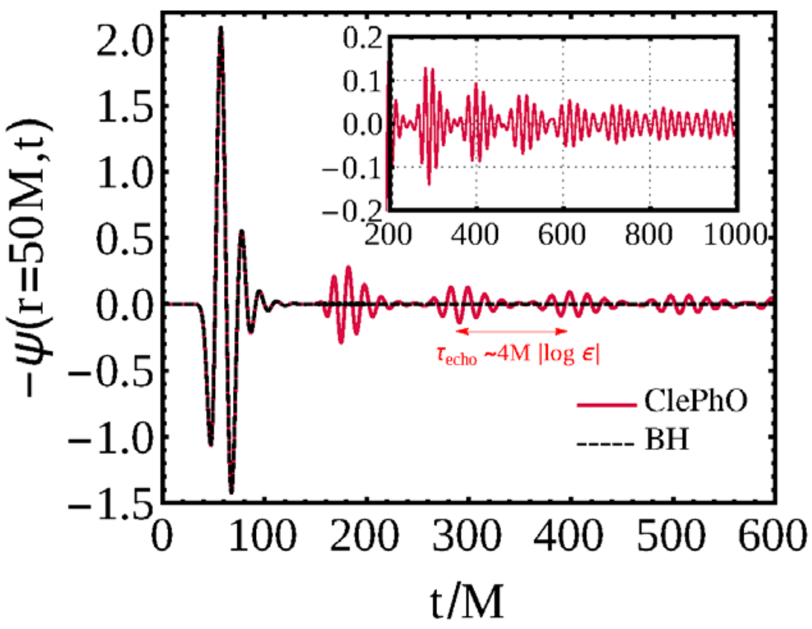
V. Ferrari, K. Kokkotas, PRD 62 (2000)
Cardoso+PRL116:171101 (2016); PRD94:084031 (2016)
Cardoso, Pani arXiv:1707.03021 (Nature Astronomy 1: 2017)

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



Cardoso, Hopper, Macedo, Palenzuela, Pani, PRD94:084031 (2016)
V. Ferrari, K. Kokkotas, PRD 62 (2000)

Echoes



$$M\omega_R \sim |\log\epsilon|^{-1}$$

$$M\omega_I \sim |\log\epsilon|^{-(2l+3)}$$

Cardoso, Pani arXiv:1707.03021 (Nature Astronomy 1: 2017)

Looking for echoes

$$\rho_{\text{prompt ringdown}} \gtrsim \frac{80}{\sqrt{\gamma_{\text{echo}}(\%)}}$$

For 20% energy in first echo, it should be detectable with only ringdown templates.
Will be seen by LISA, Einstein or Voyager like, at least 1/yr (using rates in Berti+ 2016)

More sophisticated searches either use unmodelled sequence of echoes, or model the echo structure, e.g. as BH response convoluted with known transfer function at the barrier

Mark+ PRD96: 084002 (2017)
Volkel+ CQG 34:125006 (2017)
Correia+ PRD97:084030 (2018)
K. W. Tsang + PRD 98: 024023 (2018)
Testa, Pani PRD98: 044018 (2018)

Some questions to answer

i. Devise independent search techniques

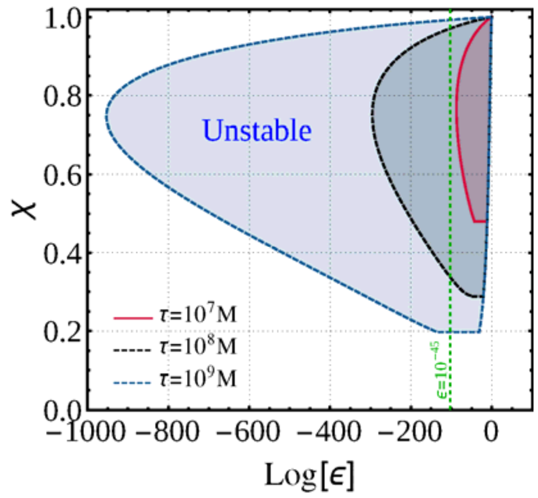
ii. (Nearly) Model-independent evidence of horizons

(iii. Measure spins accurately!)

iv. Do EM observations provide interesting constraints?

(serious redoing of astrophysics)

v. If no echoes?



Cardoso & Pani, 2017

i. Are there alternatives?

ii. Do they form dynamically under reasonable conditions?

iii. Are they stable? Timescales for instability?

iv. What GW signal do they give rise to?

Conclusions: exciting times!

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

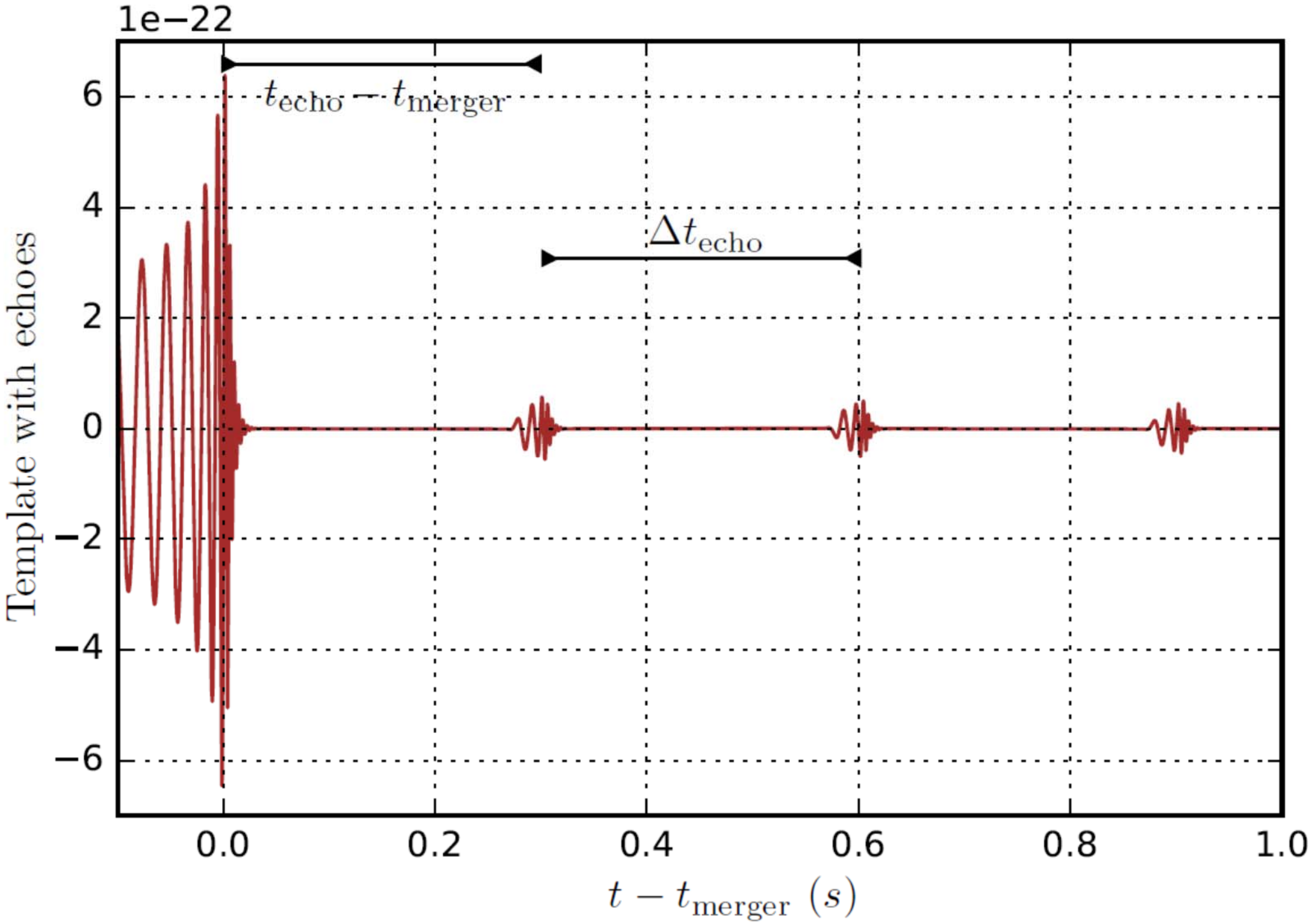
Black holes remain the simplest explanation for the observations of dark, massive and compact objects...but one can now test the BH hypothesis... improved sensitivity pushes putative surface closer to horizon... like probing short-distance structure with accelerators.

“*The excitement of the next generation of astronomical facilities is not in the old questions which will be answered, but in the new questions that they will raise.*“

K. I. Kellermann + “The exploration of the unknown”

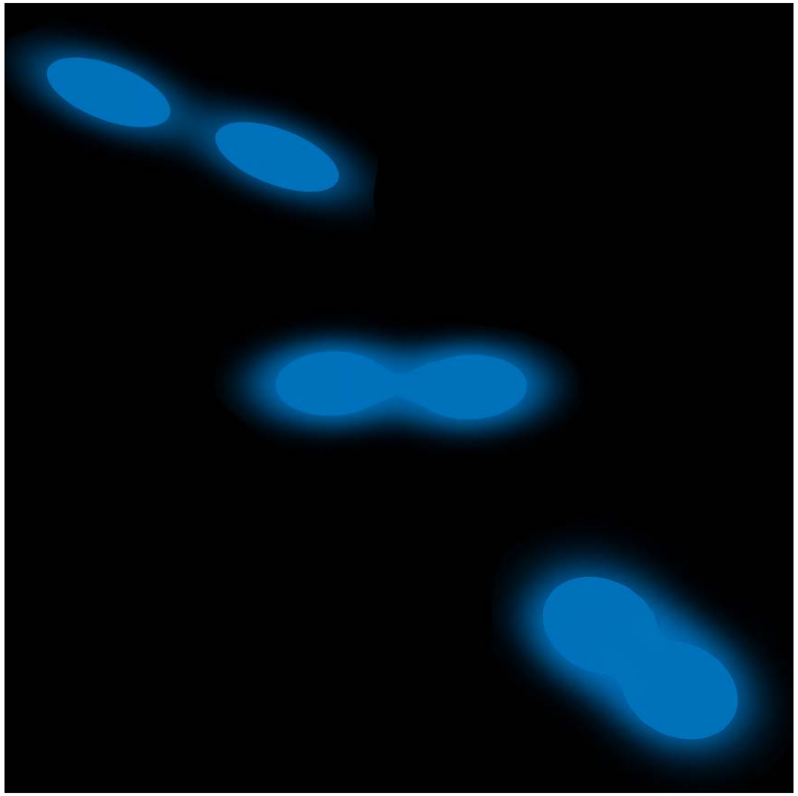
Thank you

Have we seen echoes ?!



Abedi, Dykaar, Afshordi 2016;
Ashton et al 2016

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