Black holes?

Vítor Cardoso

(Técnico & Perimeter)

Fundamental questions

a. Is cosmic censorship preserved? (Choptuik+ 2010, Sperhake+ 2013)

b. What is maximum possible luminosity?
(Cardoso 2013, Gibbons+Barrow 2015)

c. Can GWs from BHs inform us on DM? Do fundamental massive bosons exist? (Arvanitaki+2016, Brito+2017)

d. Is it a Kerr black hole? Can we constrain alternatives?
(Berti + 2009; Berti+ 2016; Yang+ 2017; Barausse+2016; Yunes+2016)

e. Is the final - or initial - object really a black hole?

Uniqueness: the Kerr solution

Theorem (Carter 1971; Robinson 1975):
A stationary, asymptotically flat, vacuum solution must be Kerr

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

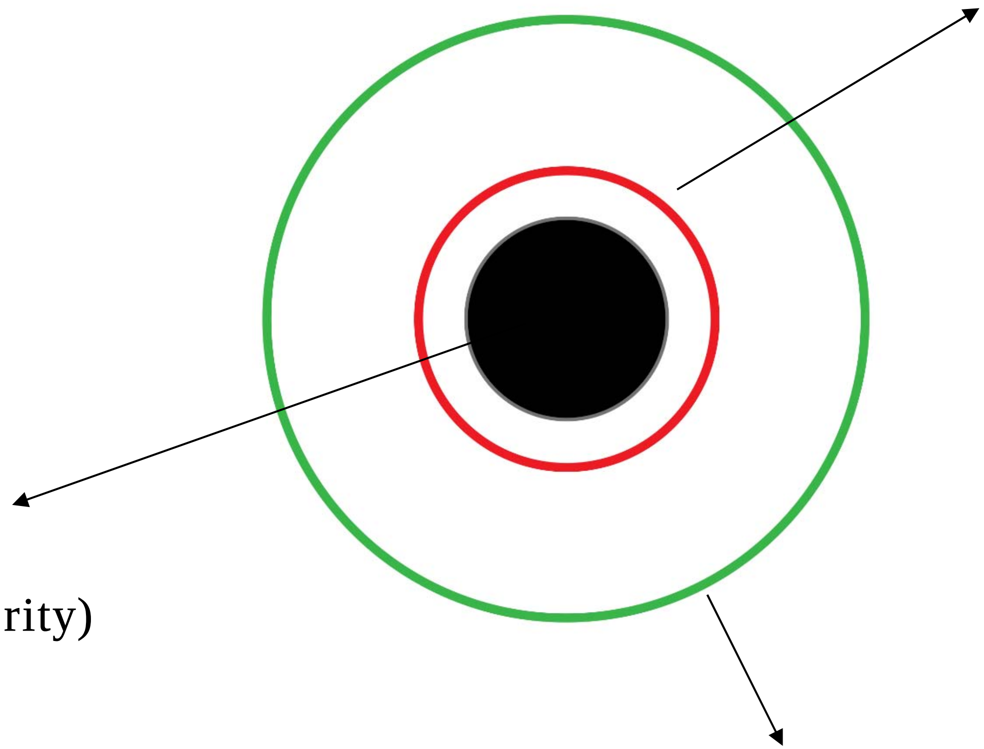
$$\Sigma = r^2 + a^2\cos^2\theta\,, \quad \Delta = r^2 + a^2 - 2Mr$$

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

"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity provides the *absolutely exact representation* of untold numbers of black holes that populate the universe."

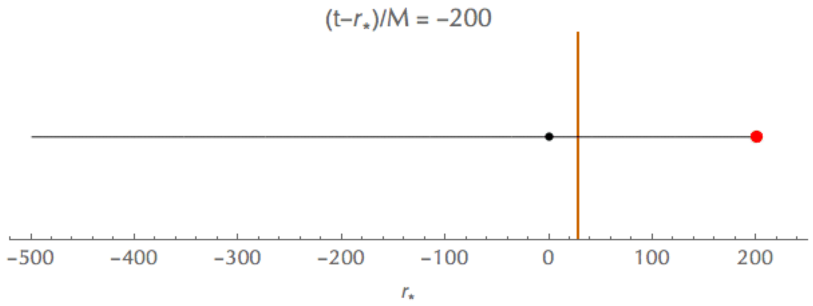
S. Chandrasekhar, The Nora and Edward Ryerson lecture, Chicago April 22 1975

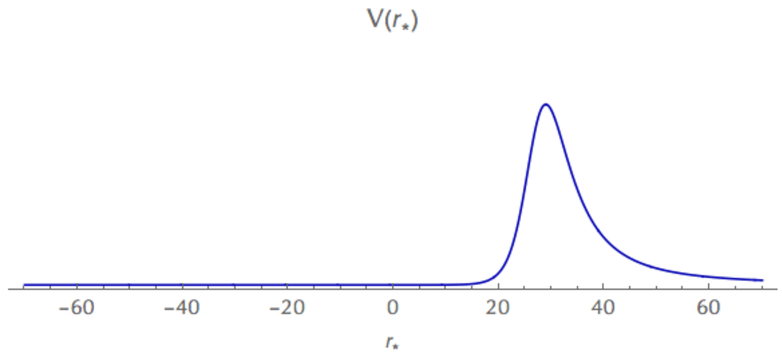
Black holes

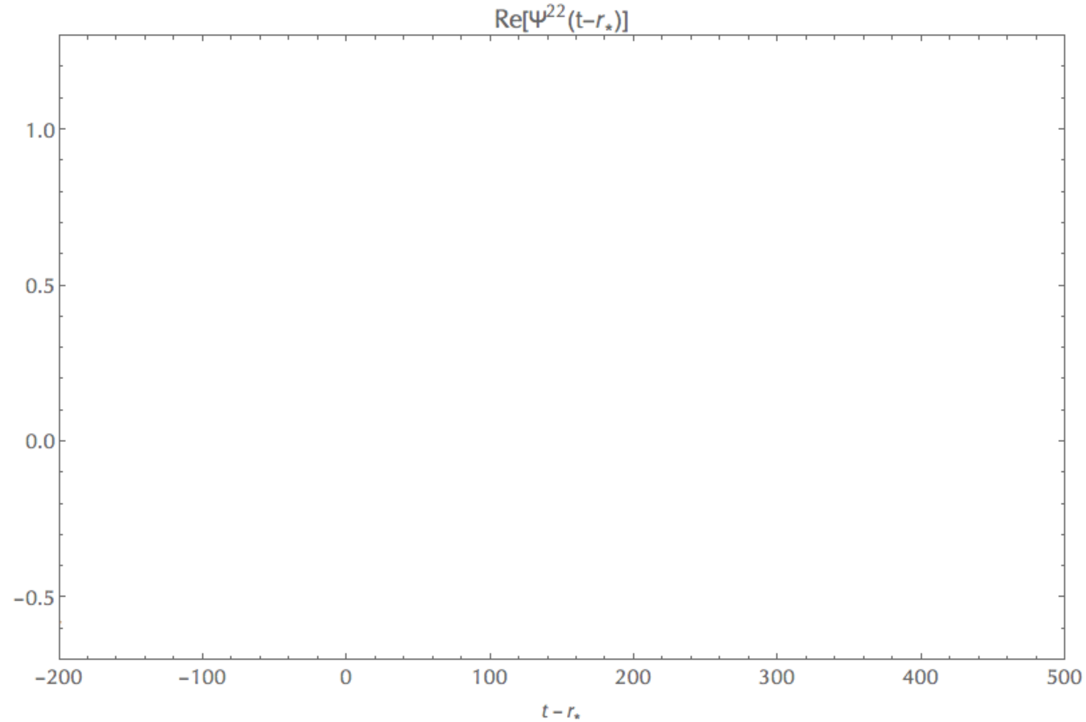


Specific energy=$\frac{2\sqrt{2}}{3} = 0.94$

$\mathcal{E} = 1.5,\ \mathcal{J} = 0$







Are we really observing black holes?

Strong field intimately connected with some of the deepest mysteries in theoretical physics today such as information loss/firewalls/quantum gravity. It is astonishing that space and time can get so warped to form horizons and singularities.

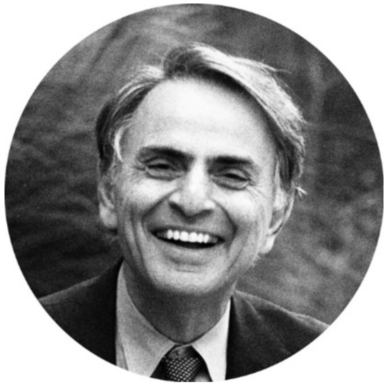
Must demand a similar "astonishing" level of evidence.

“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

a. BH exterior is pathology-free, but interior is not. Singularities and Cauchy horizons, signalling breakdown of predictability.

b. Quantum effects are not fully understood. E.g. information loss, which could lead to new endstates (Wald & Unruh 2017)

c. It is tacitly assumed that quantum effects become important only at Planck scales. Planck scale could be significantly lower. Even if not, many orders of magnitude standing, surprises can hide (Arkani-Hamed+ 1998; Giddings & Thomas 2002)

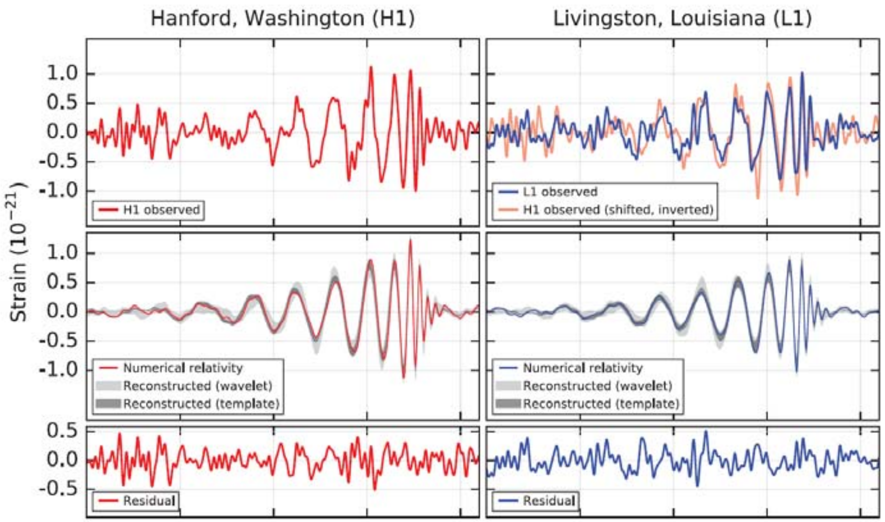
d. We *can* test exterior, *for free*.

e. More sensitive detectors: probing regions closer to horizon. Similar to particle accelerators! Measure compactness of objects.

"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 September 1986

Final state is compact!



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Some questions to answer

i. Are there alternatives?

ii. Do they form dynamically under reasonable conditions?

iii. Are they stable?

iv. What GW signal do they give rise to?

i. Alternatives

Boson stars, fermion-boson stars, oscillatons
(Kaup 1968; Ruffini, Bonazzolla 1969, Colpi et al 1986, Brito et al 2015)

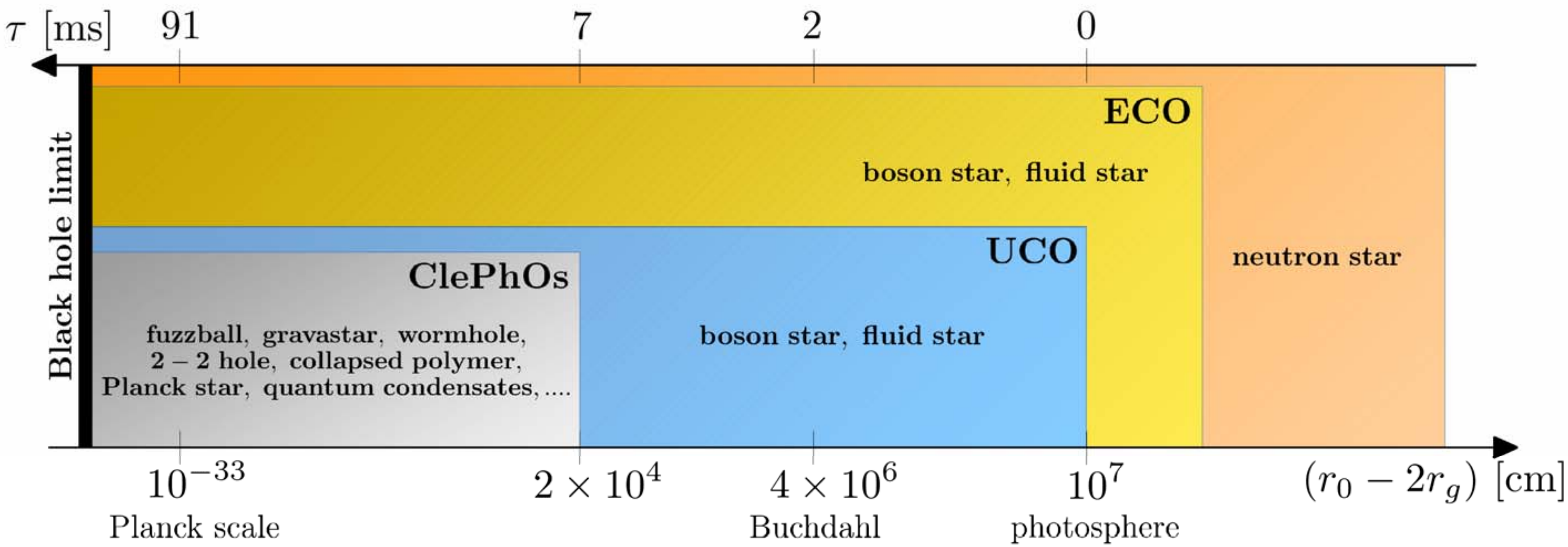
Wormholes
(Morris, Thorne 1988; Visser 1996)

Gravastars
(Mazur, Mottola 2001)

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

...

i. Alternatives

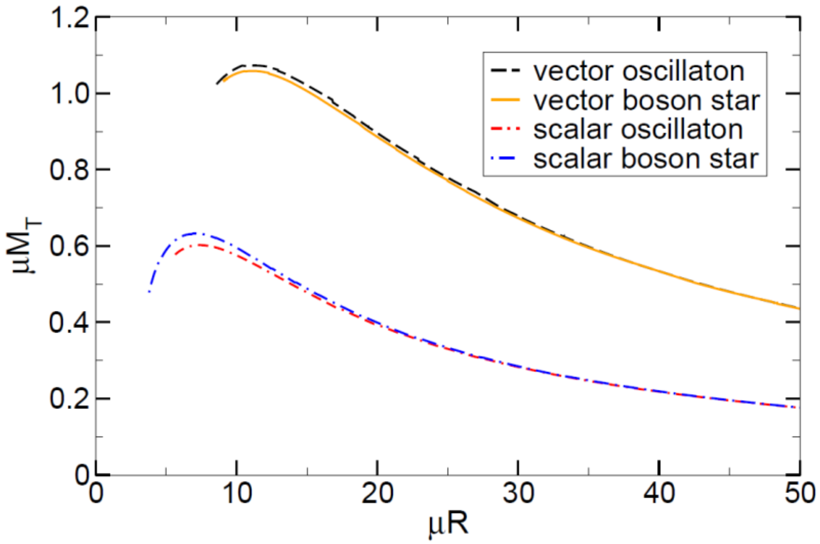


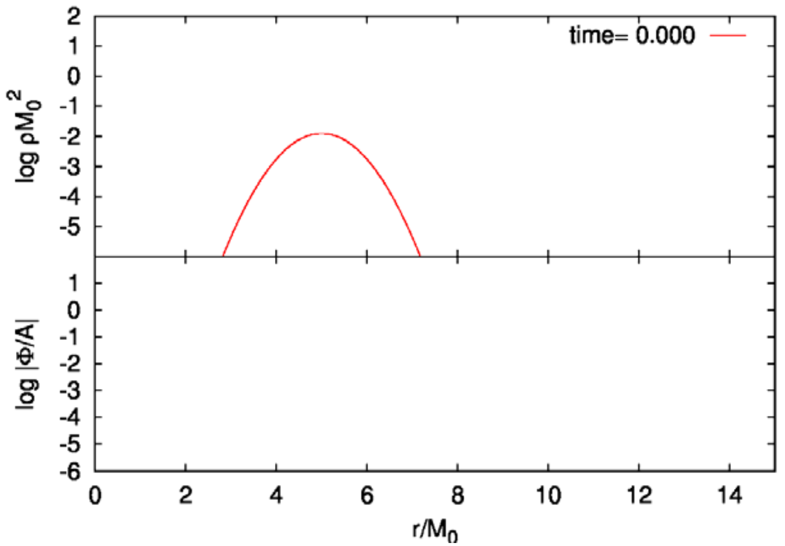
Cardoso & Pani (to appear, 2017)

ii. Formation

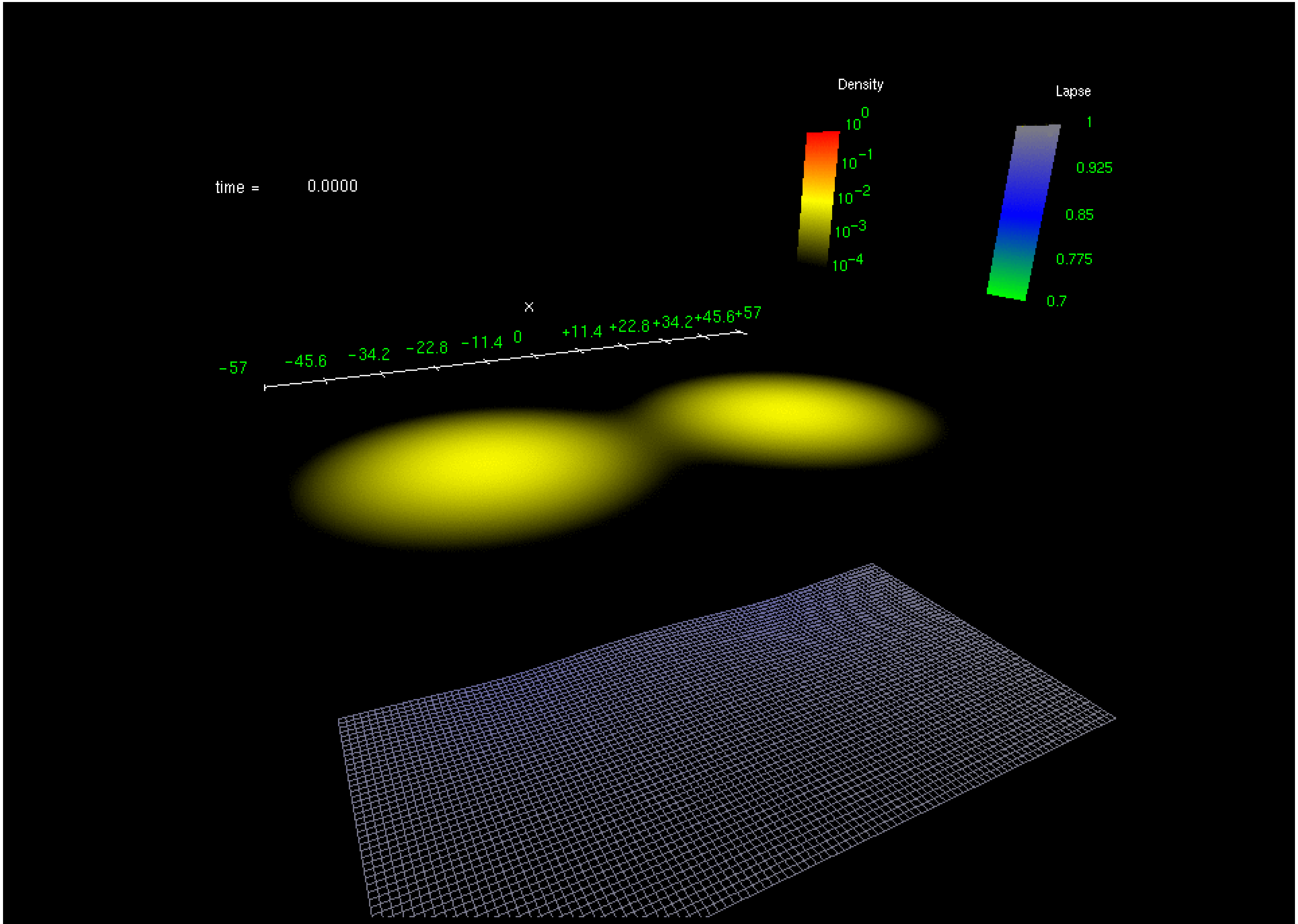
Boson stars, fermion-boson stars, oscillatons

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





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



Density and lapse function sub-critical, equal-mass

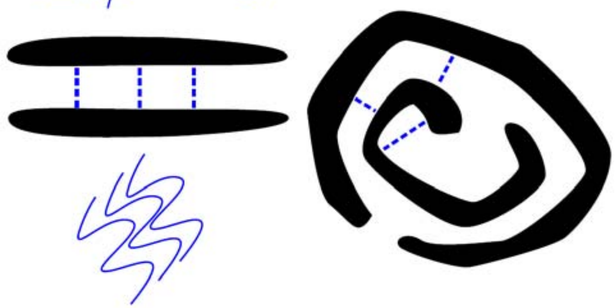
iii. Stability of objects with photospheres

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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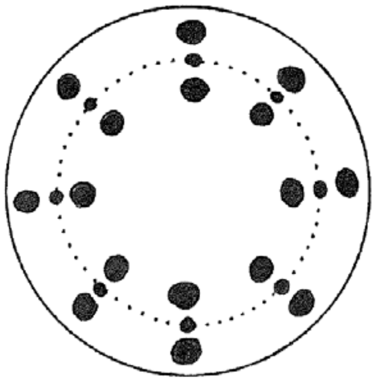

In absence of viscosity, Dyson-Chandrasekhar-Fermi mechanism might trigger nonlinear instabilities

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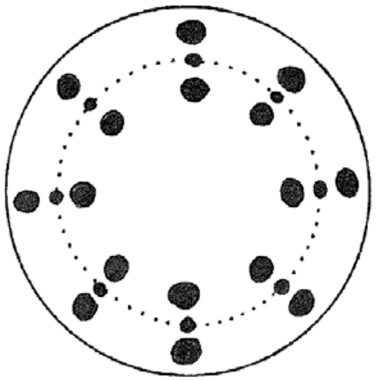


In absence of viscosity, Dyson-Chandrasekhar-Fermi mechanism might trigger nonlinear instabilities

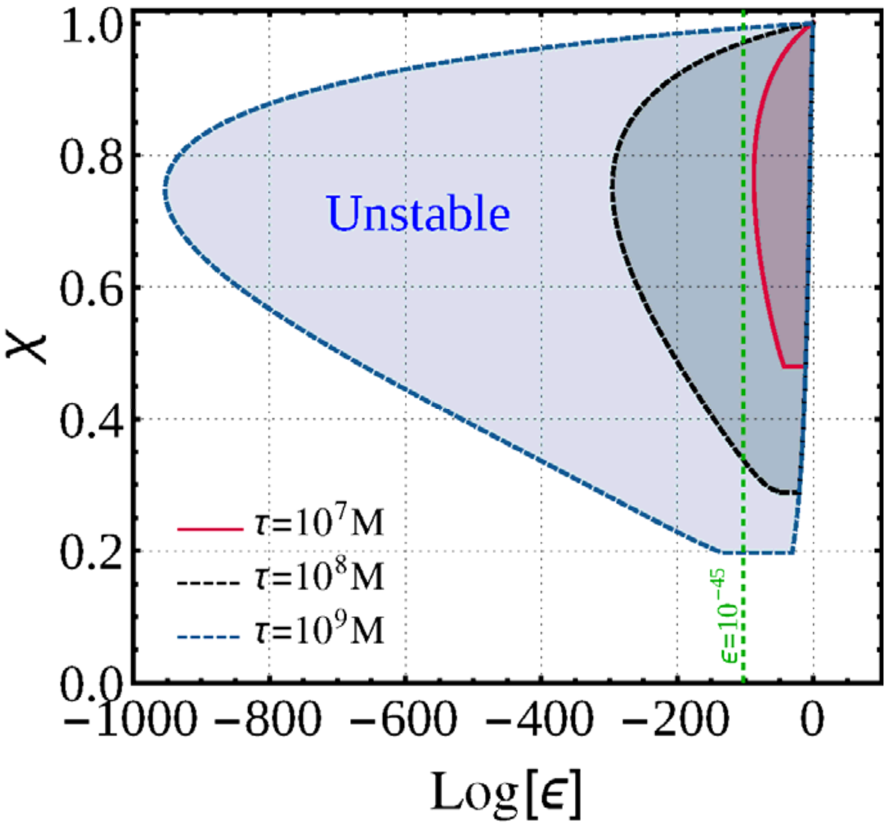
Rotation: *Horizonless objects with ergoregions are linearly unstable*

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.

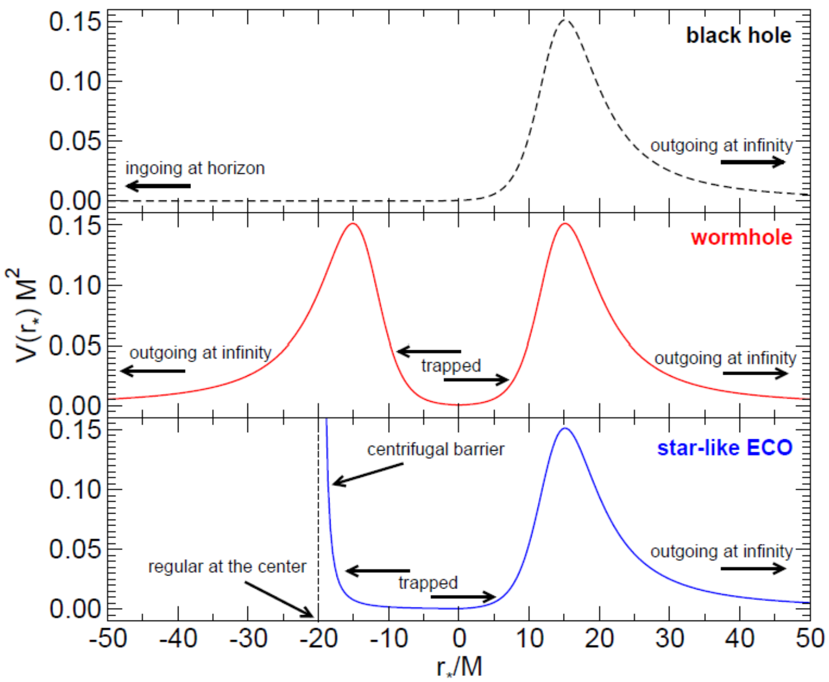
“There is nothing stable in the world; uproar’s your only music”

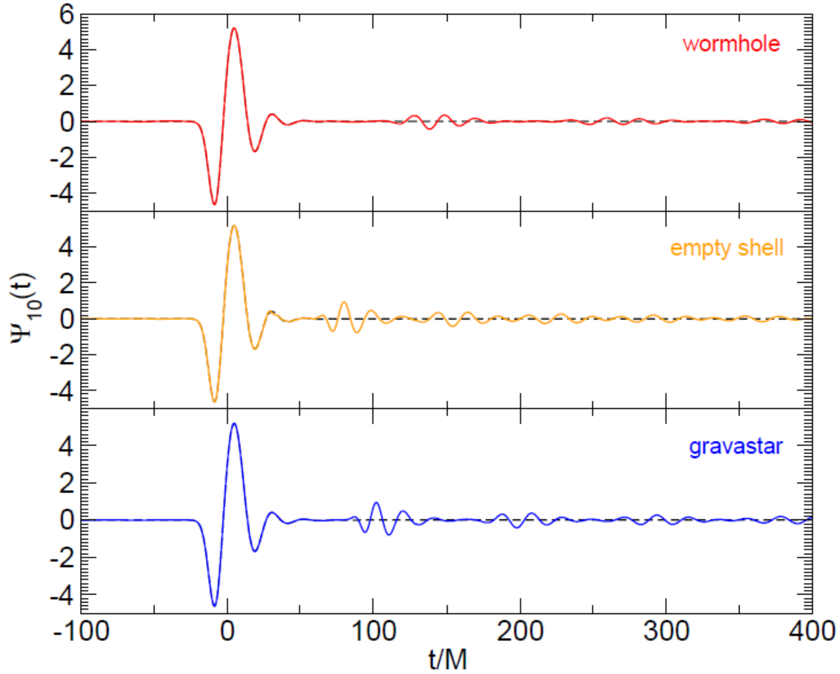
John Keats



Cardoso & Pani, 2017, to appear (also Vilenkin 1978)

iv. GW signal: Echoes





Cardoso, Franzin, Pani, PRL116:171101 (2016)

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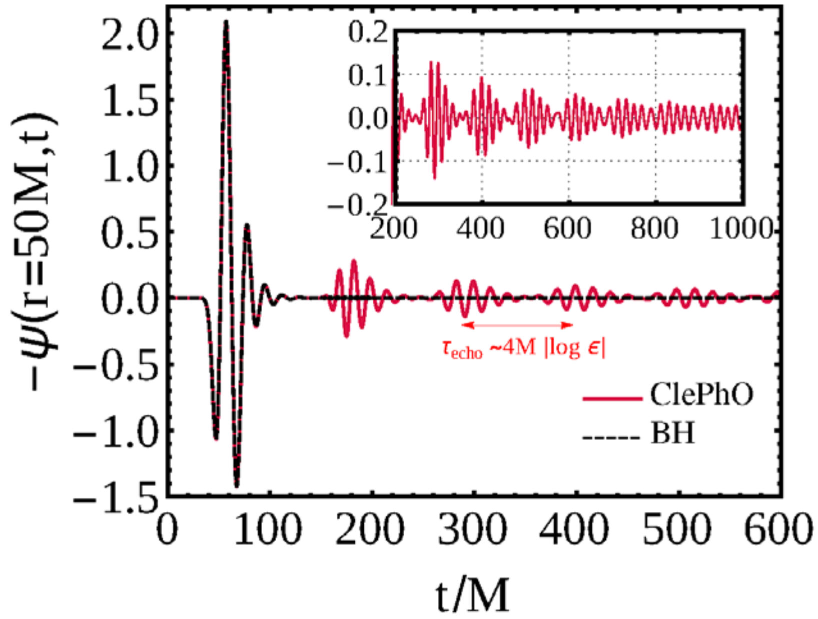
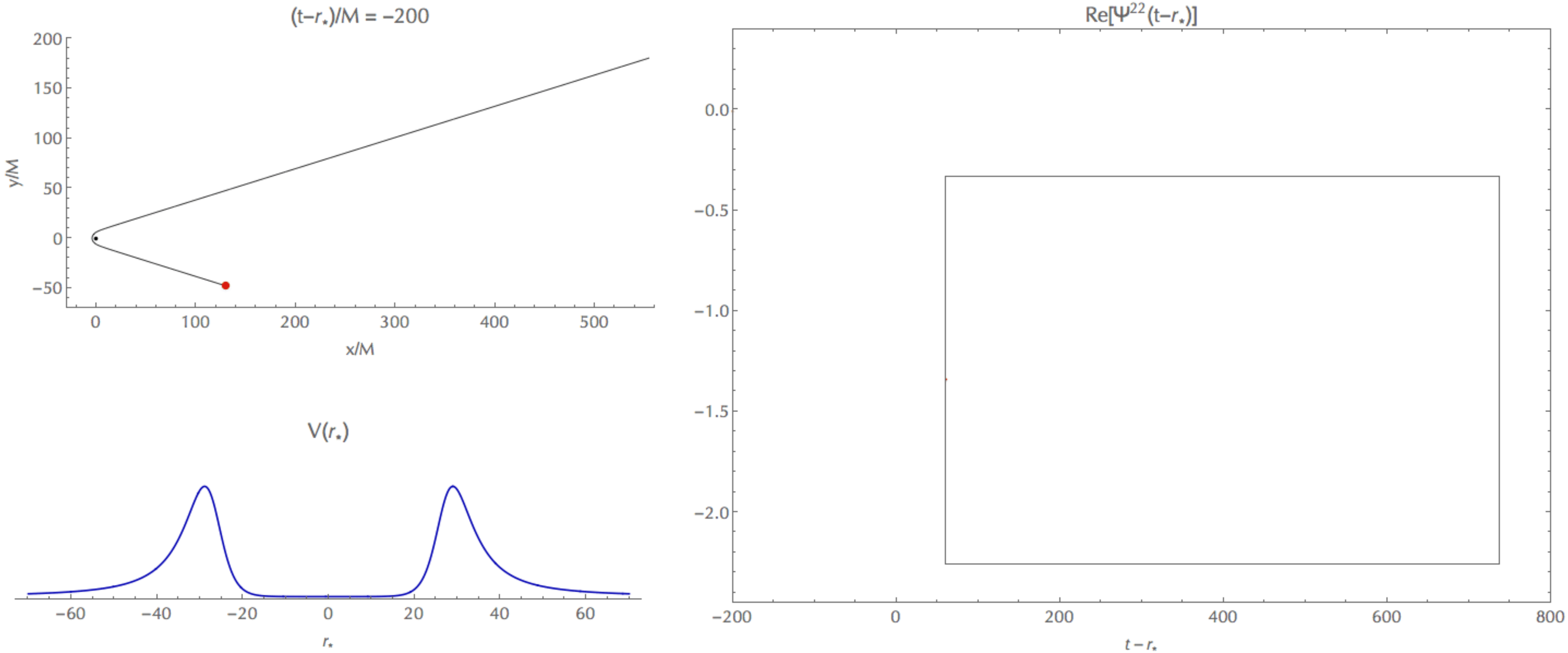


$$M\omega_R \sim |\log\epsilon|^{-1}$$

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

Cardoso, Pani (2017, to appear)

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



Cardoso, Hopper, Macedo, Palenzuela, Pani, PRD94:084031 (2016)

Looking for echoes

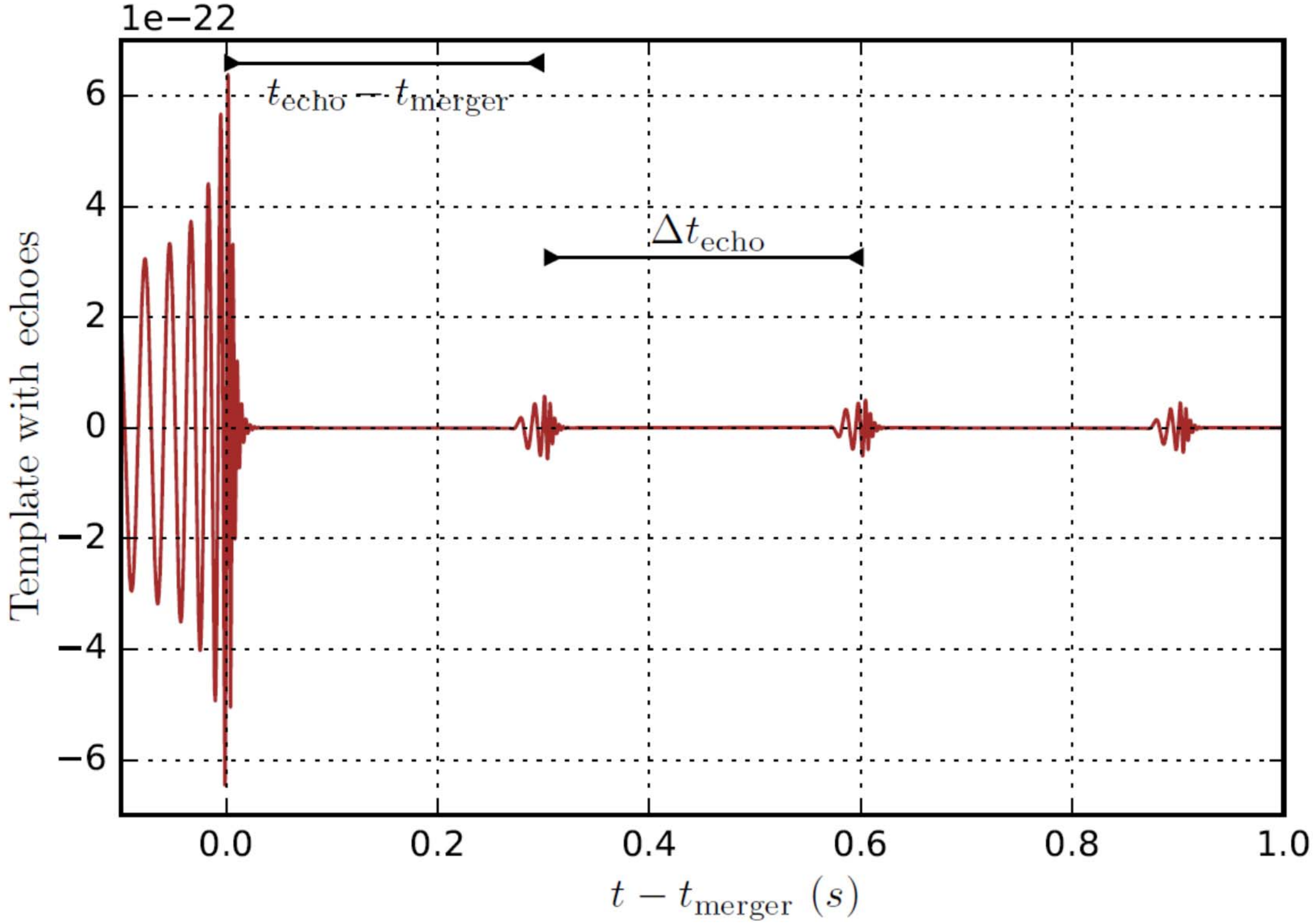
$$\rho_{\text{prompt ringdown}} \gtrsim \frac{80}{\sqrt{\gamma_{\text{echo}}(\%)}}$$

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

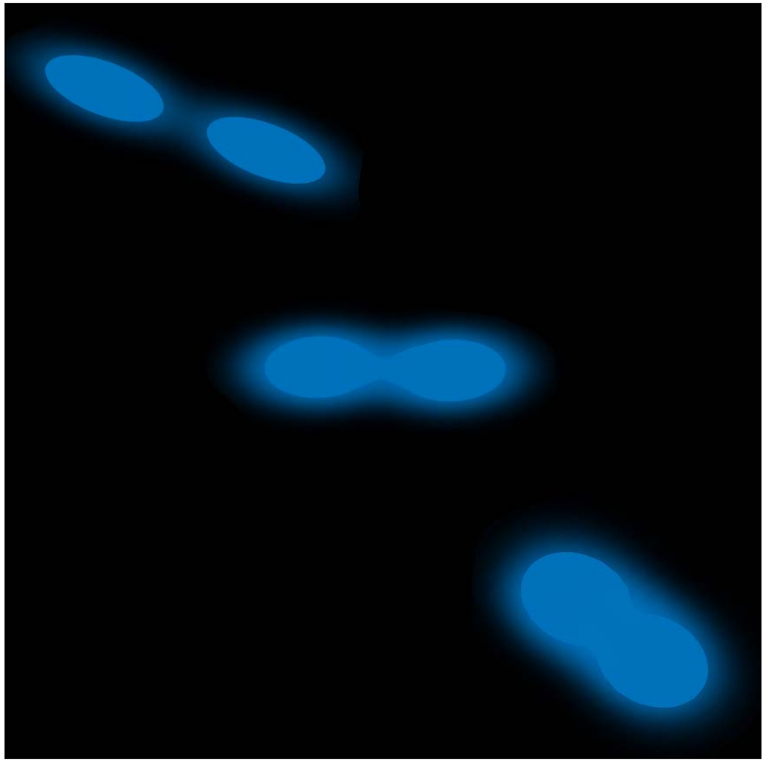
(Mark+ arXiv:1706.06155)

Have we seen echoes (at 2.9 sigma)?!



Abedi, Dykaar, Afshordi 2016;
Ashton et al 2016

iv. GW signal: inspiral



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

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

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 + (2017)

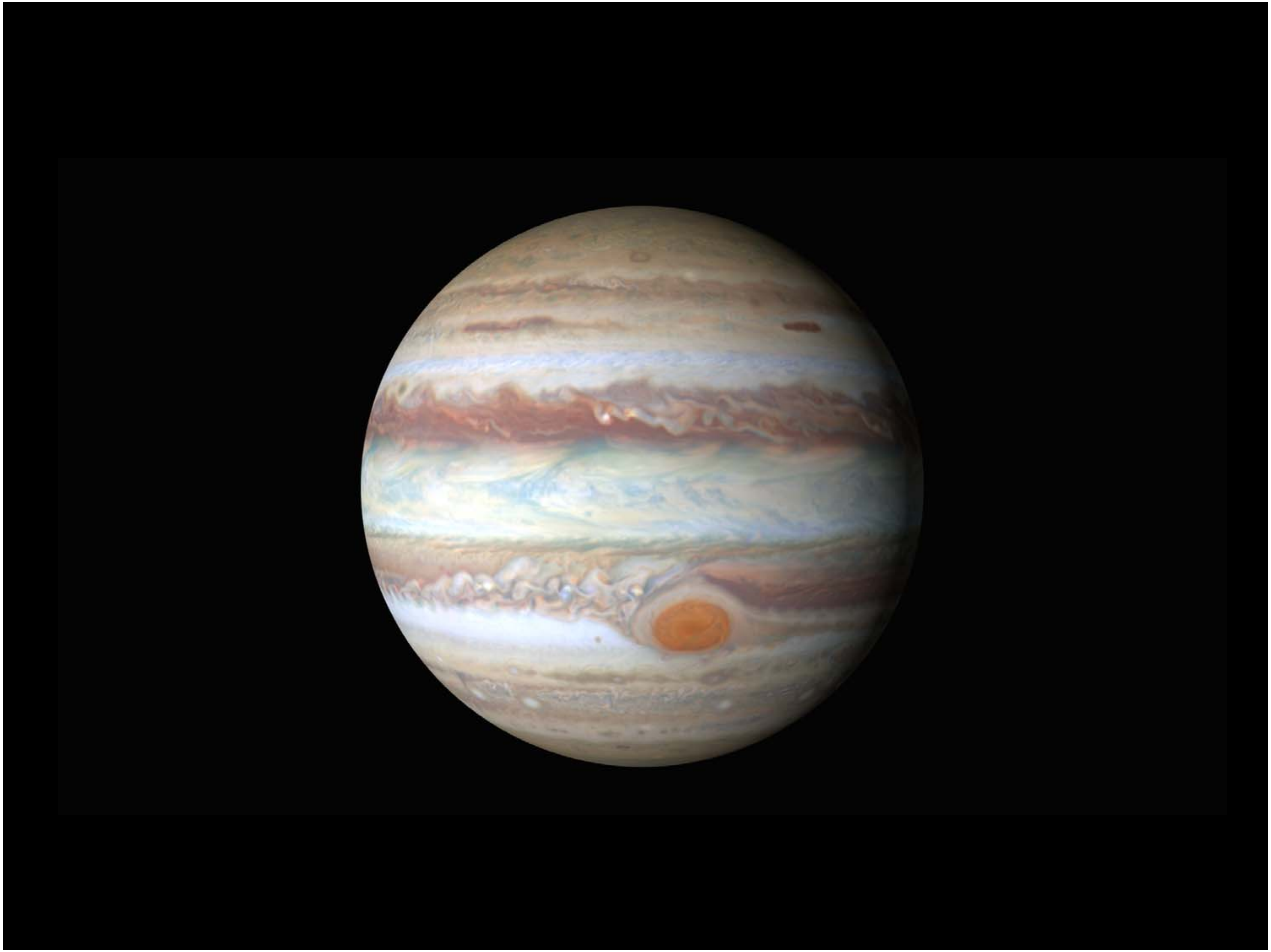
Conclusions: exciting times!

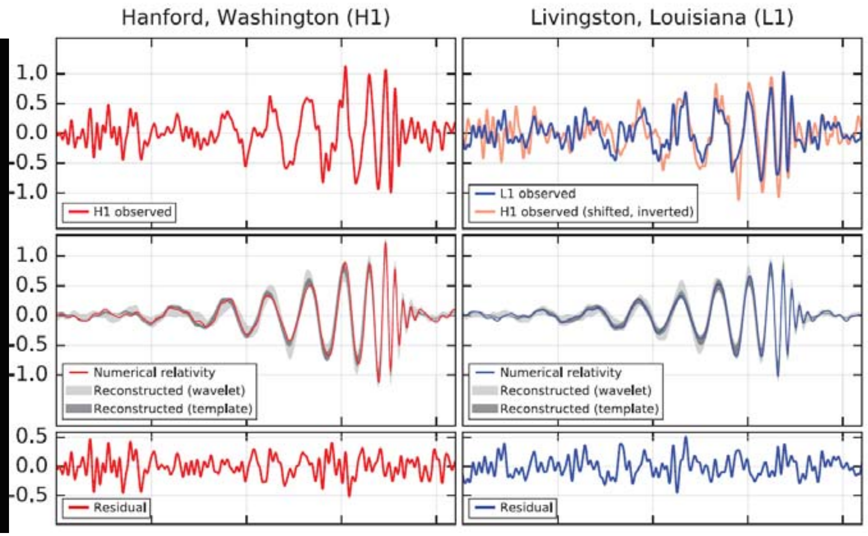
Gravitational wave astronomy *can* become a precision discipline, mapping compact objects throughout the entire visible universe.

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.

"*After the advent of gravitational wave astronomy, the observation of these resonant frequencies might finally provide direct evidence of BHs with the same certainty as, say, the 21 cm line identifies interstellar hydrogen*"

(S. Detweiler ApJ239:292 1980)





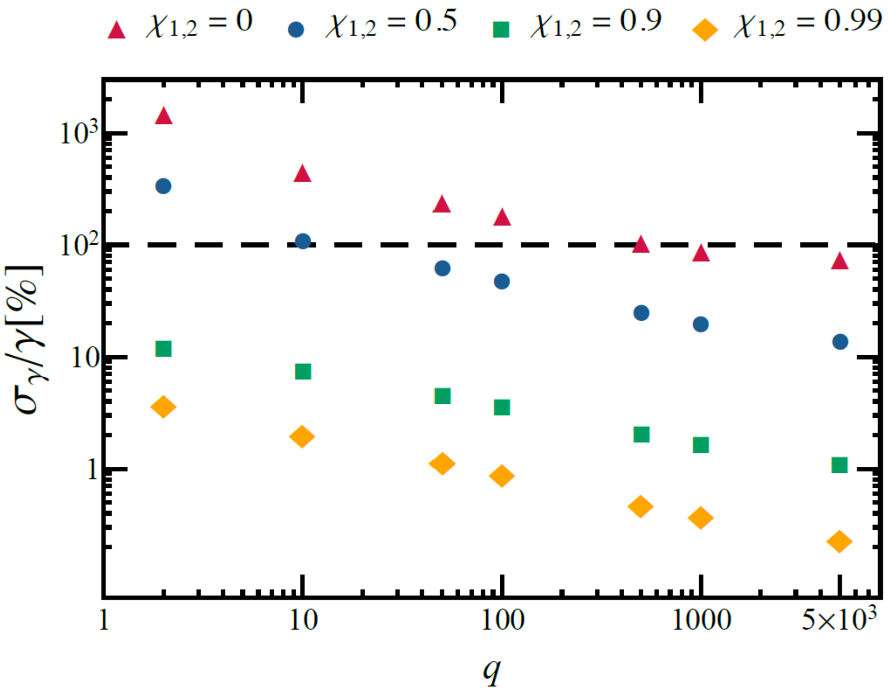
Abbott et al, Phys.Rev.Lett.116:061102 (2016)

Thank you

iv. GW signal: inspiral (precision measurements)

Absorption:

2.5 PN for BHs, vanishes for ECOs

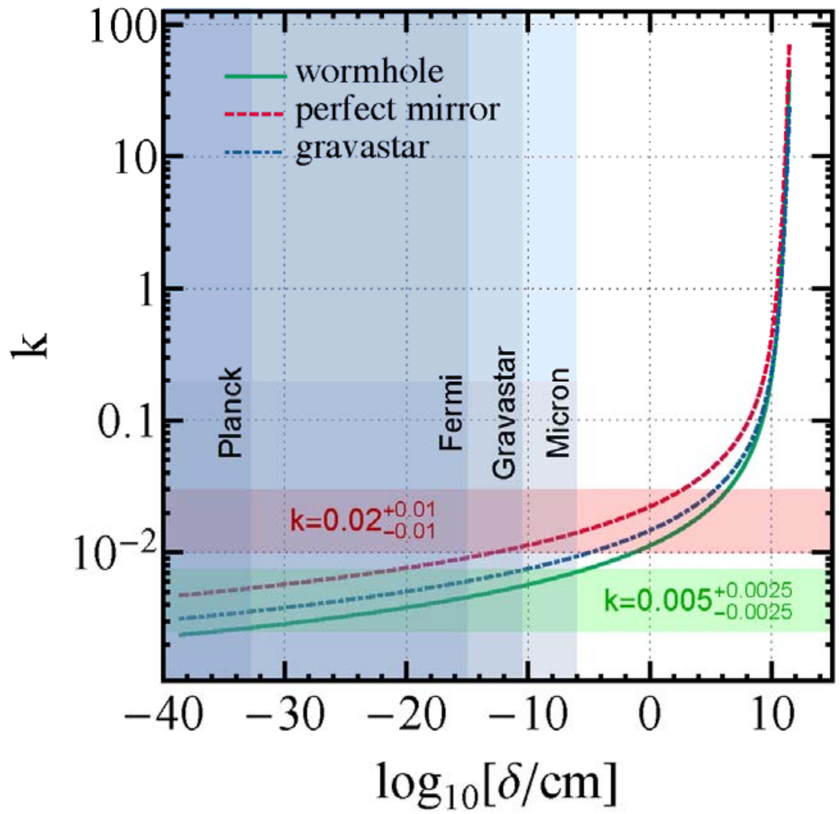


2 Gpc, central mass 10^6 solar masses

Maselli et al, arXiv:1703.10612

iv. GW signal: inspiral (precision measurements)

TLNs: Vanishes for BHs, 5PN and logarithmic for ECOS



Cardoso et al PRD95:084014(2017); Maselli et al, arXiv:1703.10612;
Sennett et al, arXiv:1704.08651

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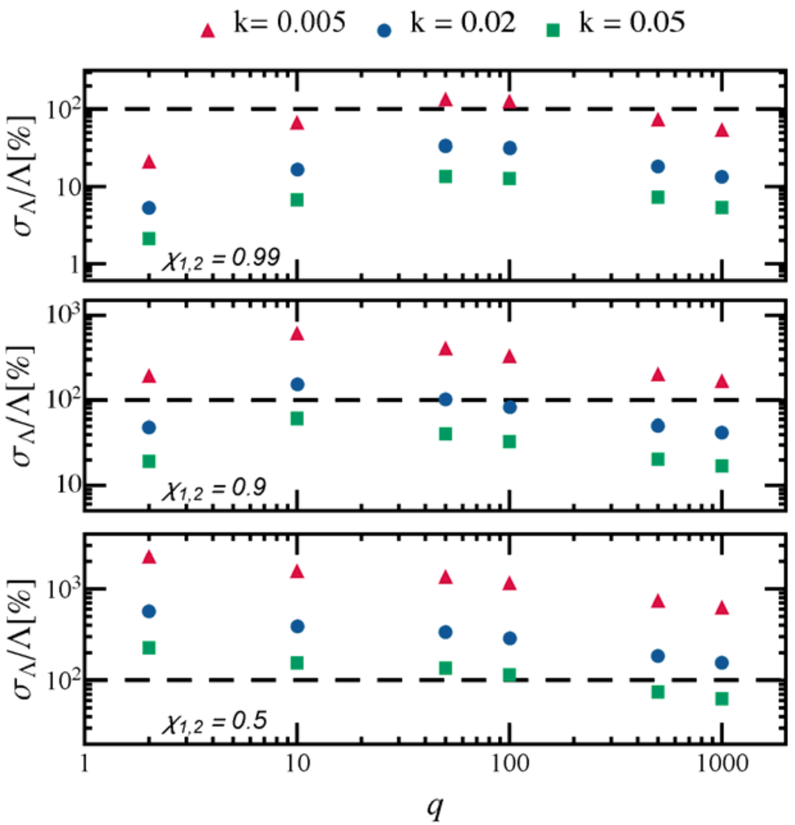
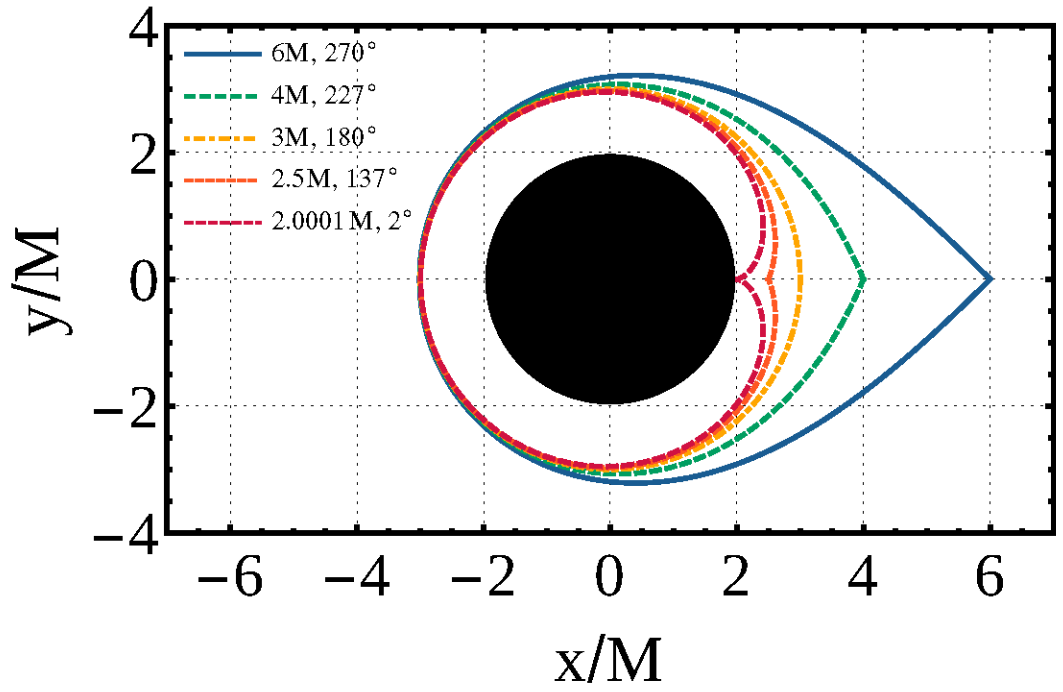
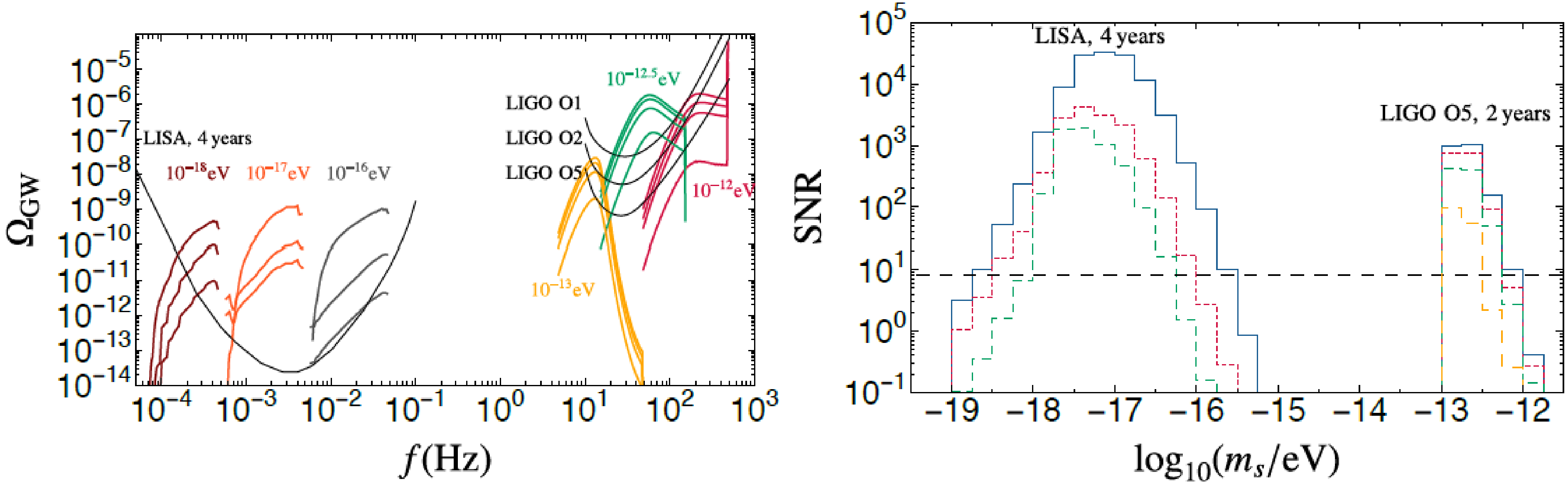


Cardoso et al PRD95:084014(2017); Maselli et al, arXiv:1703.10612;
Sennett et al 2017



6M, 270°
4M, 227°
3M, 180°
2.5M, 137°
2.0001 M, 2°
y/M
x/M
4
2
0
−2
−4
−6
−4
−2
0
2
4
6



Brito et al, to appear (2017)