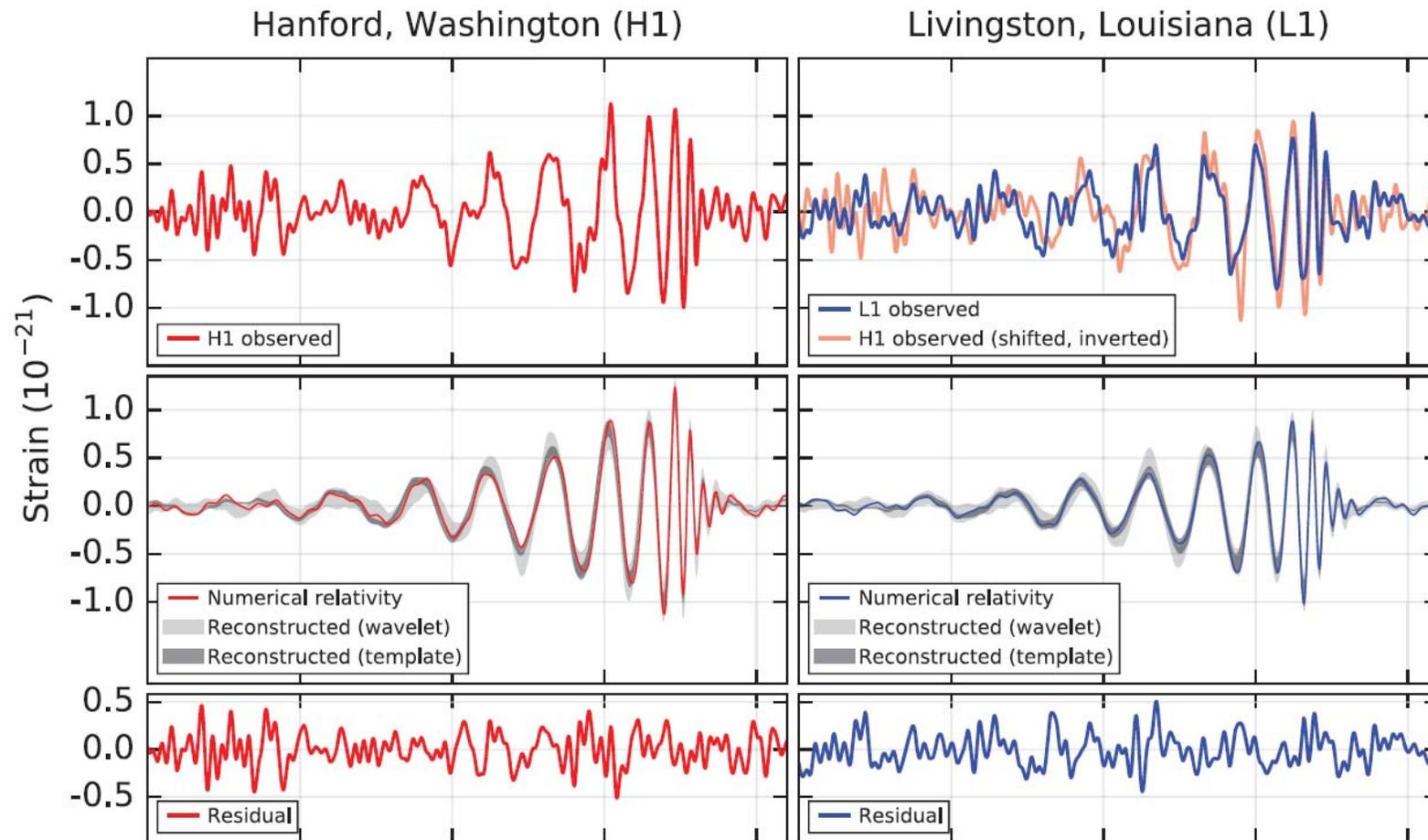


Testing GR with GWs



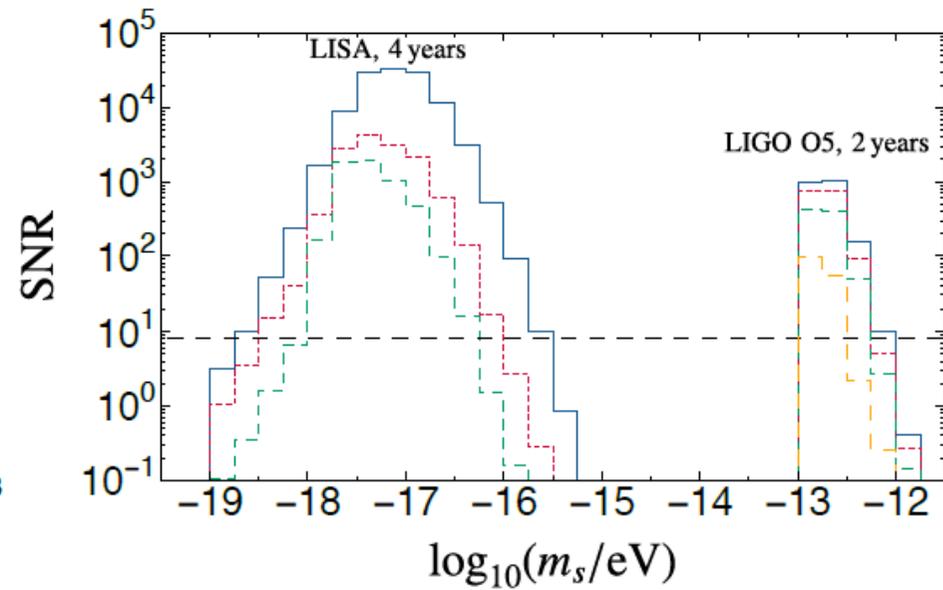
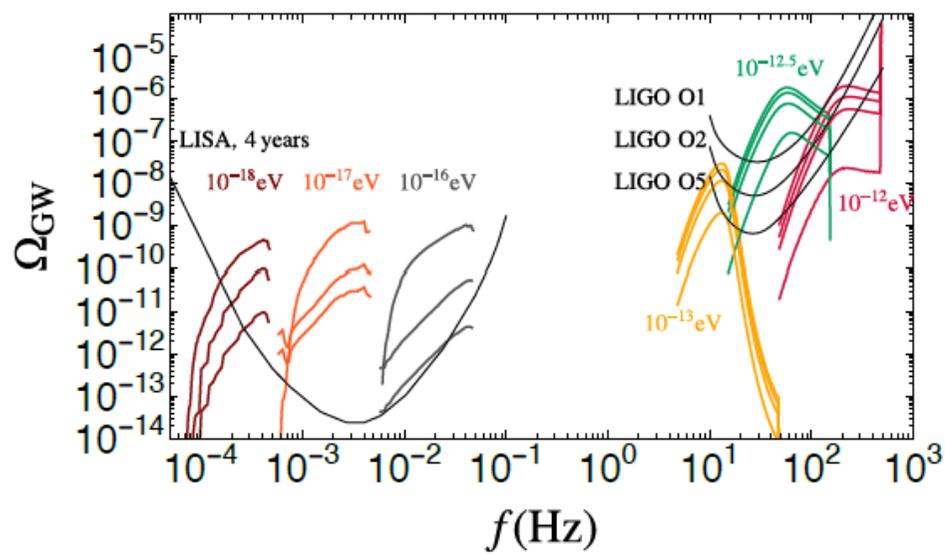
Vítor Cardoso
(Técnico & Perimeter)





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 environment (DM)? Do fundamental massive bosons exist? (Arvanitaki+2016, Brito+2017)
- d. Is it a Kerr black hole? Can we constrain alternatives? (Berti, Cardoso, Will 2009; Berti+ 2016; Yang+ 2017)
- e. Is the final - or initial - object really a black hole?



Brito et al, to appear (2017)

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Uniqueness: the Kerr solution

Theorem (Carter 1971; Robinson 1975):

A stationary, asymptotically flat, vacuum solution must be Kerr

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

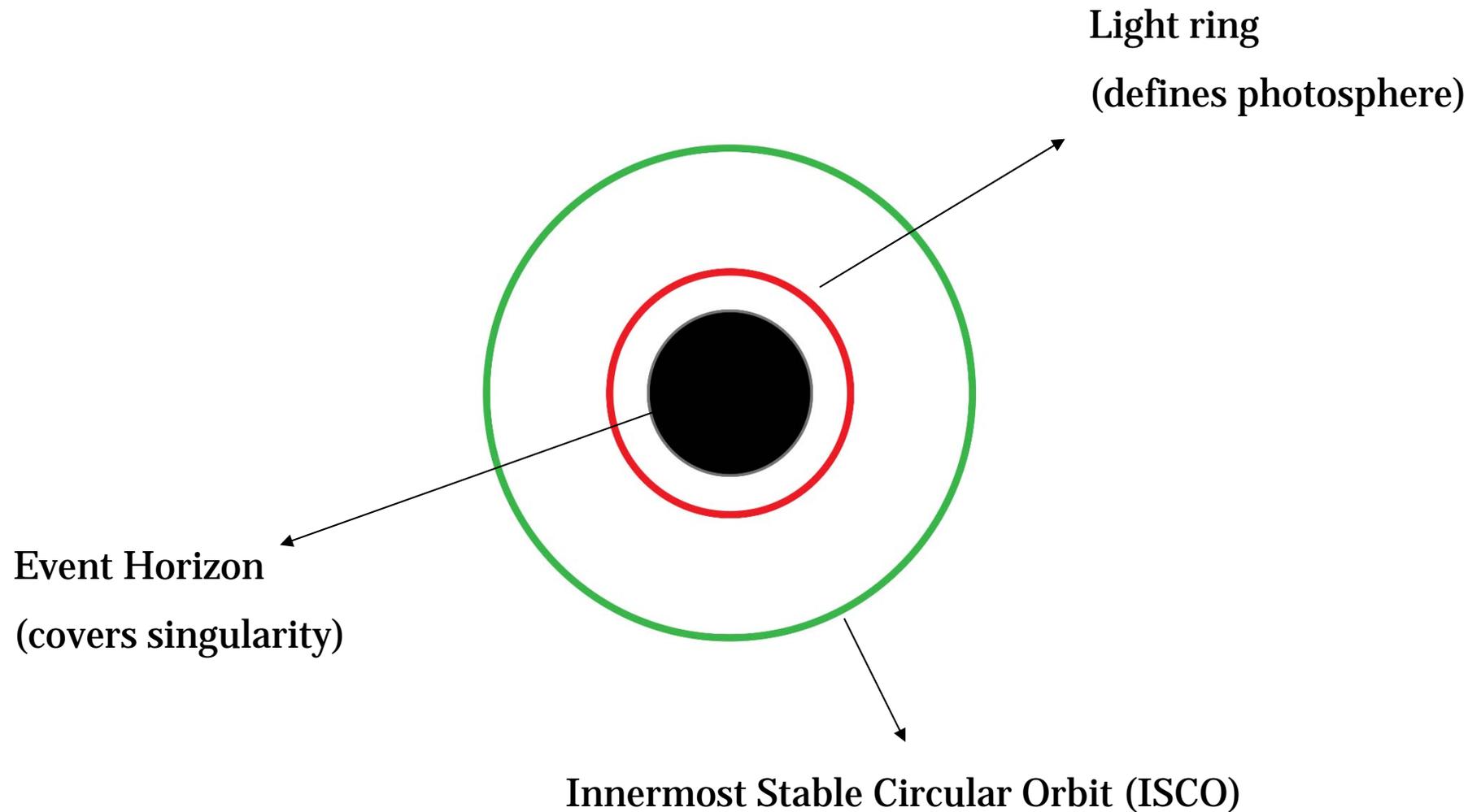
$$\Sigma = r^2 + a^2 \cos^2 \theta, \quad \Delta = r^2 + a^2 - 2Mr$$

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.”

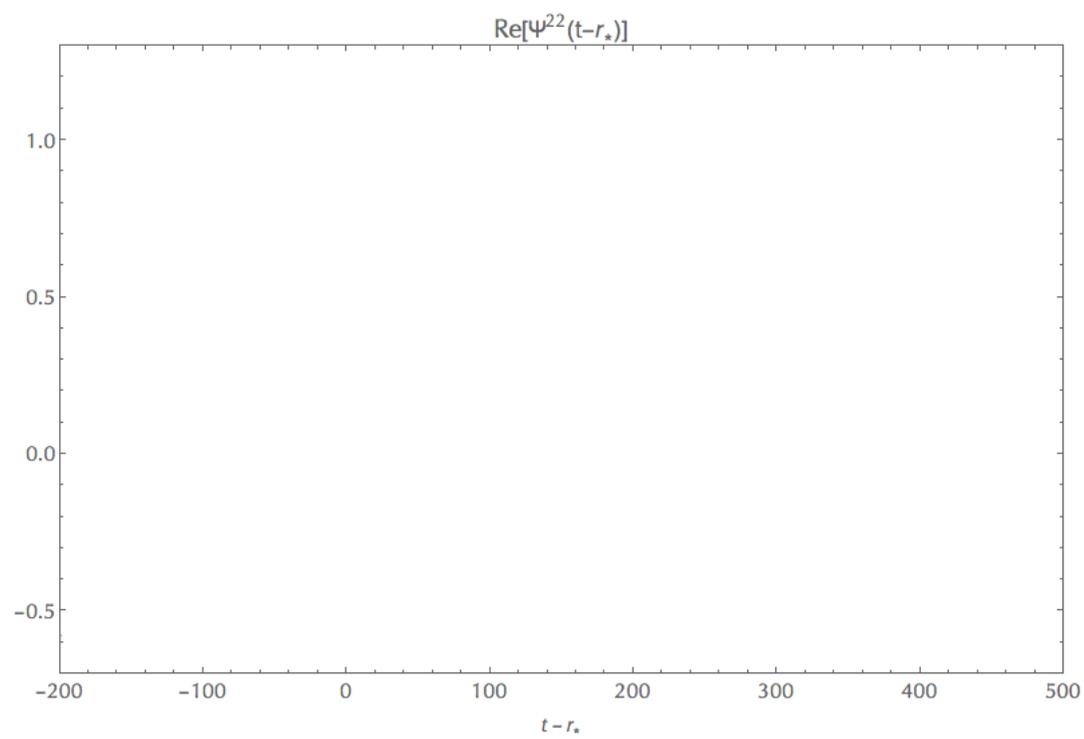
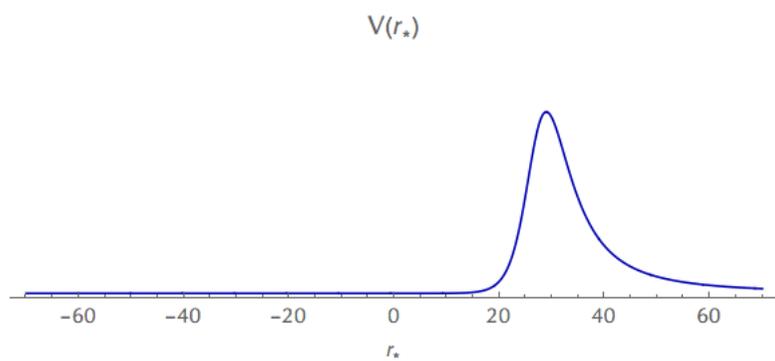
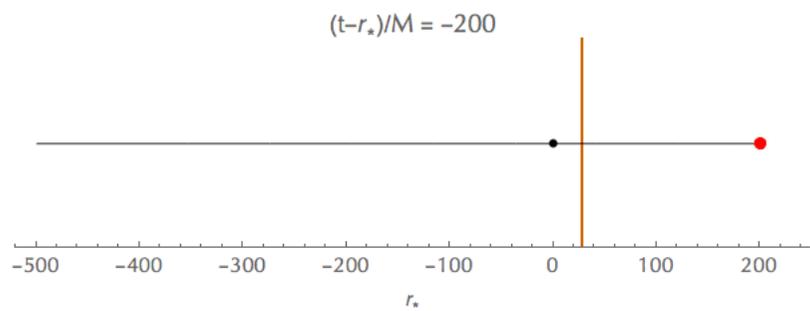
S. Chandrasekhar, The Nora and Edward Ryerson lecture, Chicago April 22 1975

Black holes



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

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



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.



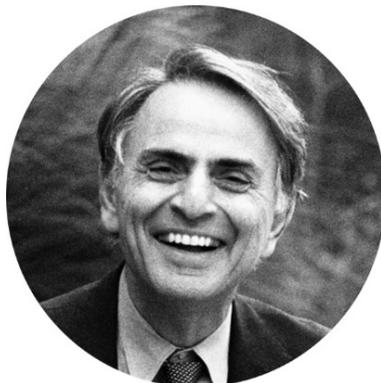
“Plus un fait est extraordinaire, plus il a besoin d’être appuyé de fortes preuves; car, ceux qui l’attestent pouvant ou tromper ou avoir été trompés, ces deux causes son d’autant plus probables que la réalité du fait l’est moins en elle-même...”

Laplace, Essai philosophique sur les probabilités 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.”

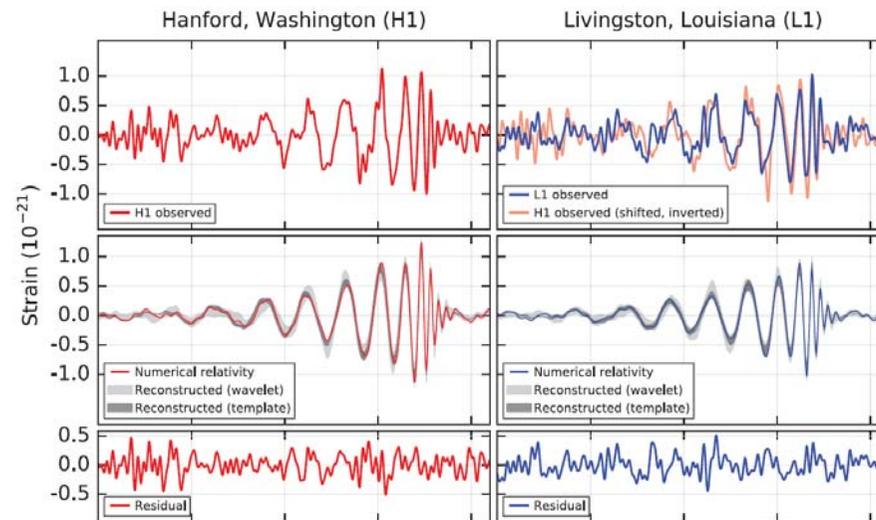
Carl Sagan



“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!



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

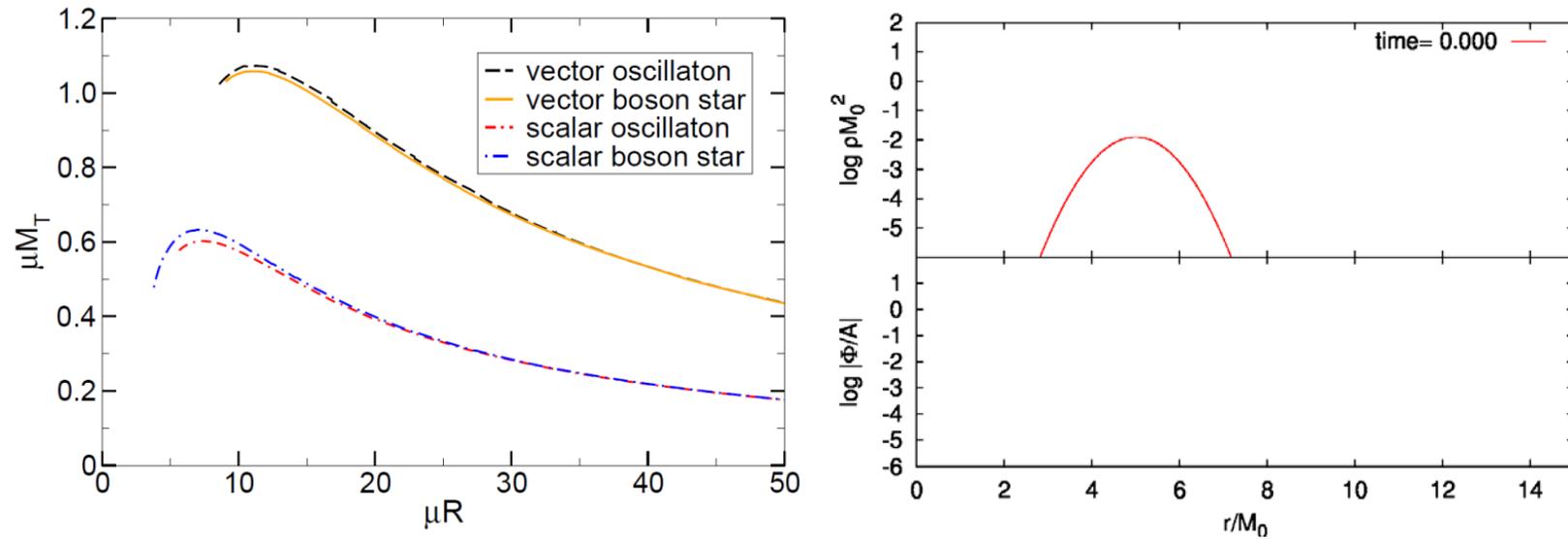
(Mathur 2000; Gimon, Horava 2009; Brustein, Medved 2016; Holdom, Ren 2016)

...

ii. Formation

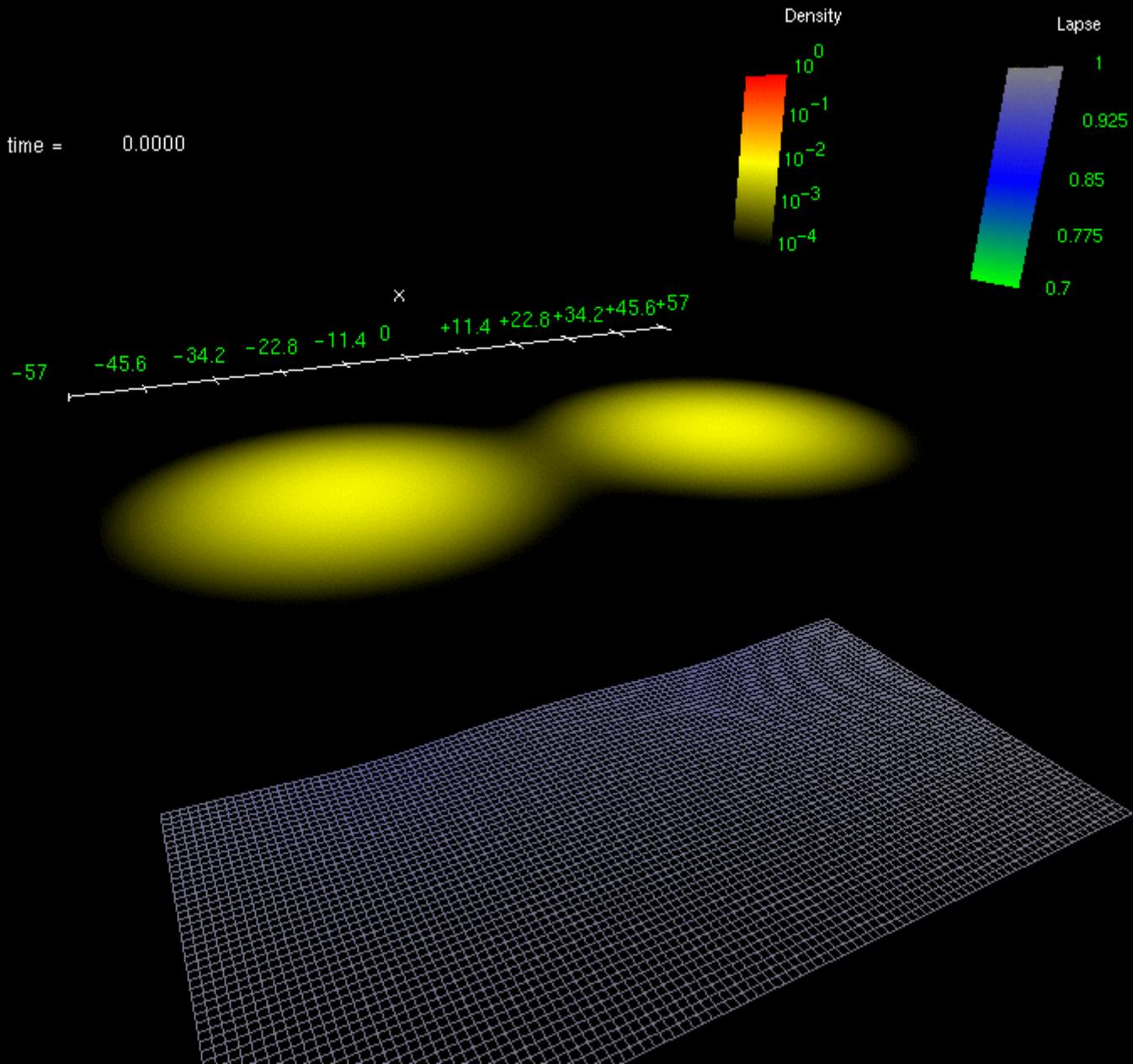
Boson stars, fermion-boson stars, oscillatons

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



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

time = 0.0000



Density and lapse function sub-critical, equal-mass

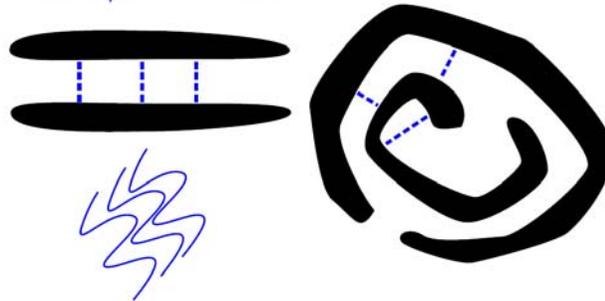
iii. Stability of objects with photospheres

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)

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

$$\square \phi = 0$$

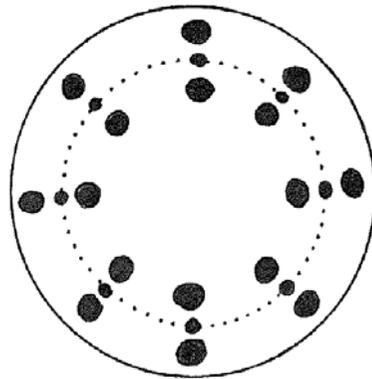


Burq, Acta Mathematica 180: 1 (1998)

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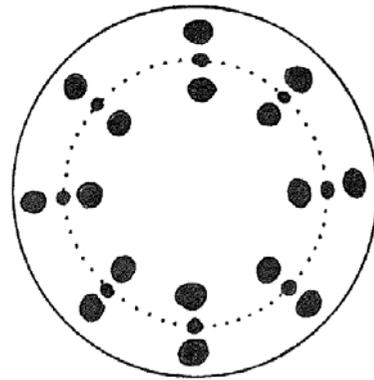


In absence of viscosity,
Dyson-Chandrasekhar-Fermi
mechanism might trigger
nonlinear instabilities

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Rotation: *Horizonless objects with ergoregions are linearly unstable*

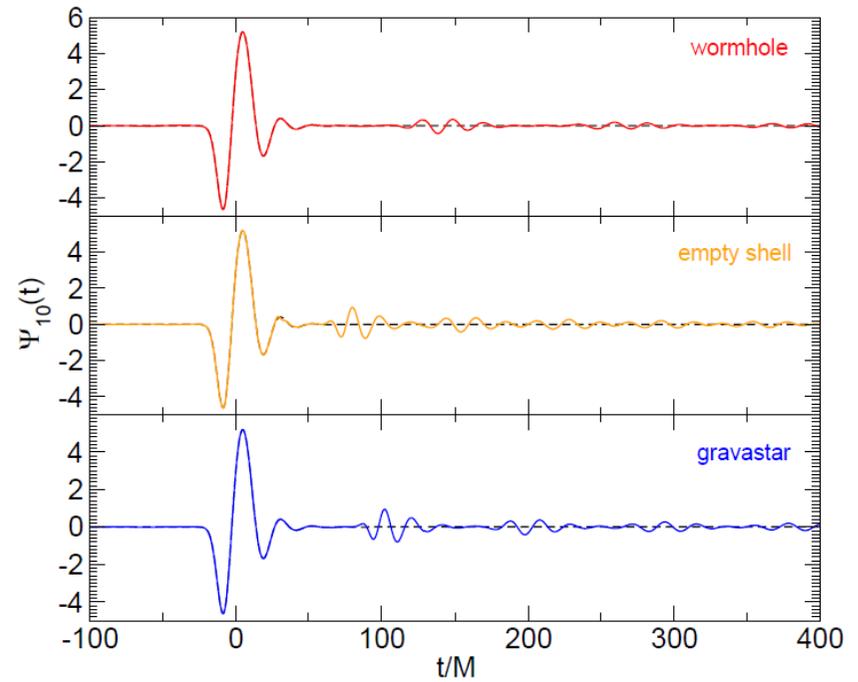
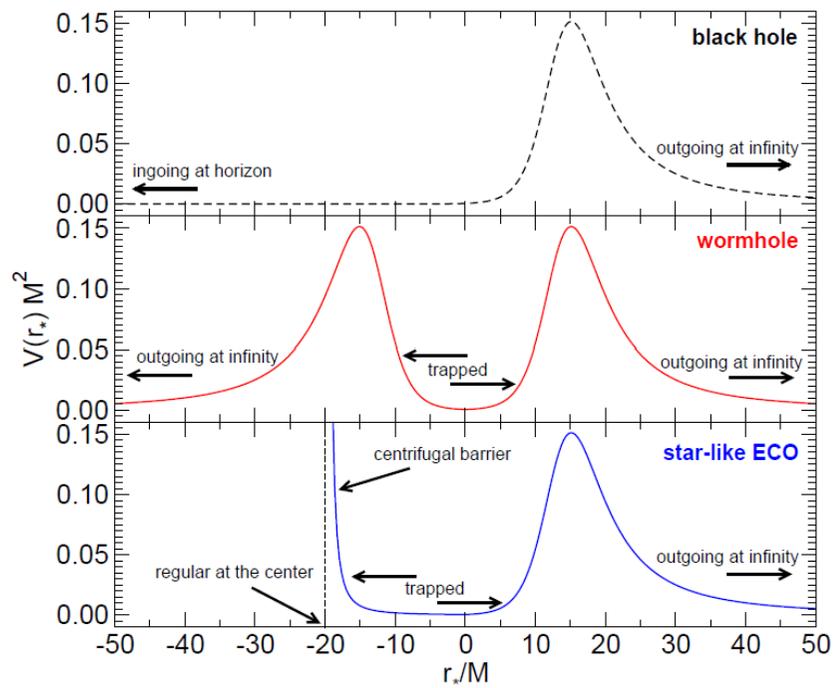
Friedmann Comm. Math.Phys.63:243, 1978; Brito, Cardoso, Pani 2015; Moschidis 2016

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”

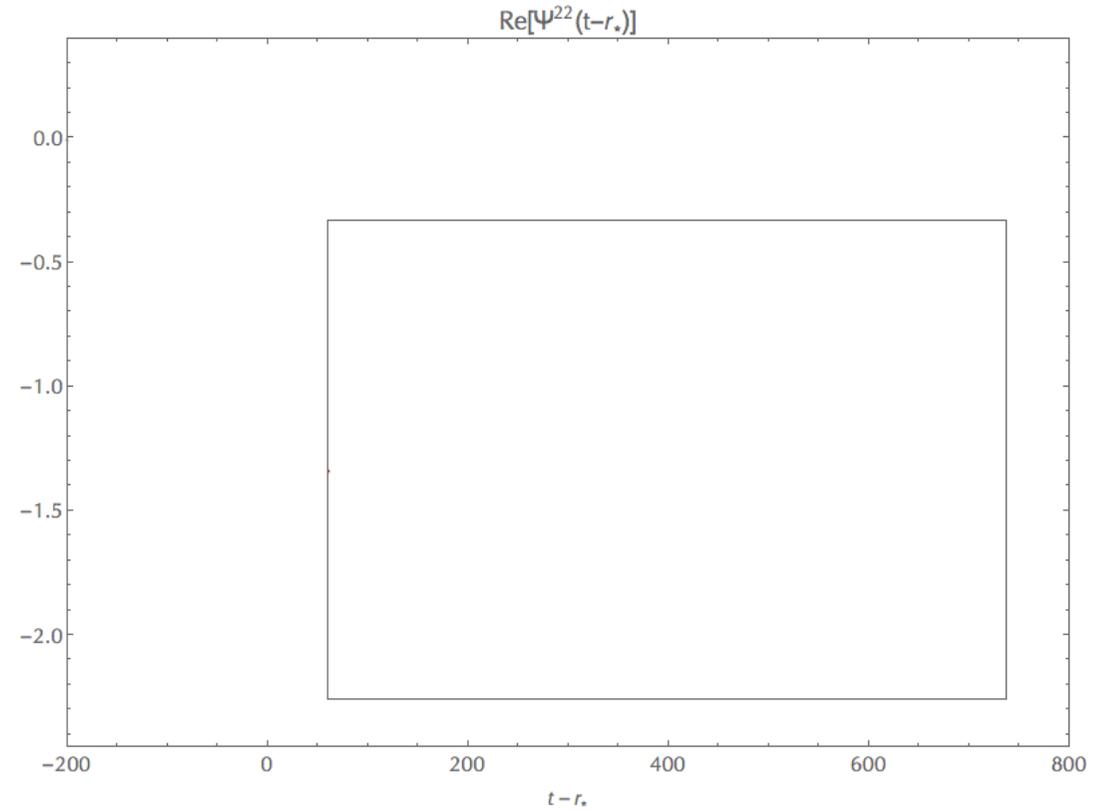
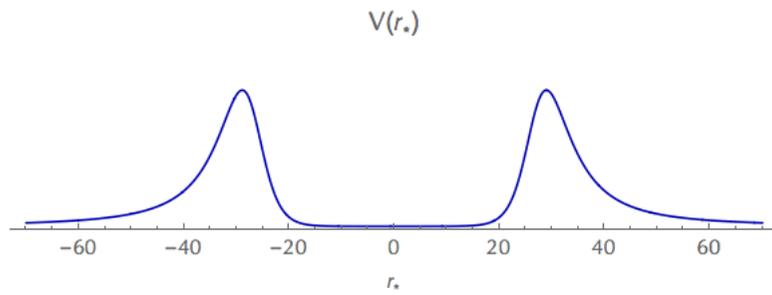
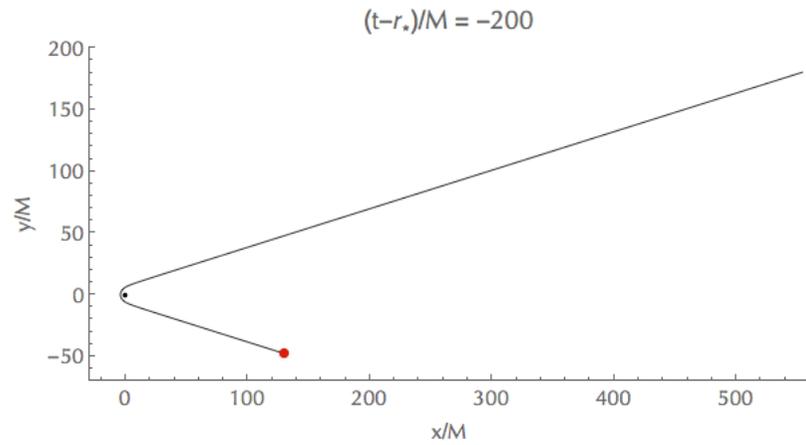
John Keats

iv. GW signal: Echoes



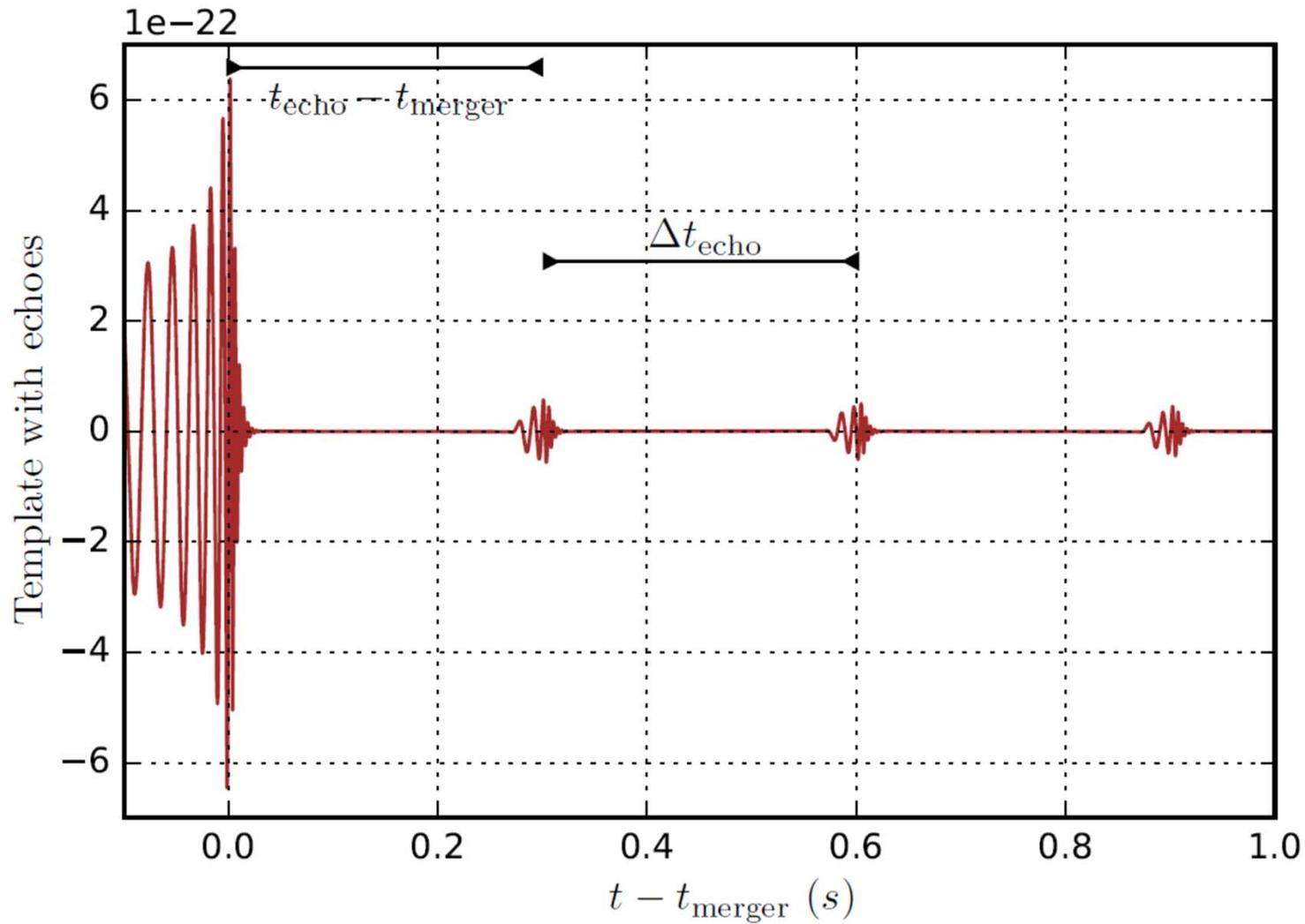
Cardoso, Franzin, Pani, PRL116:171101 (2016)

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



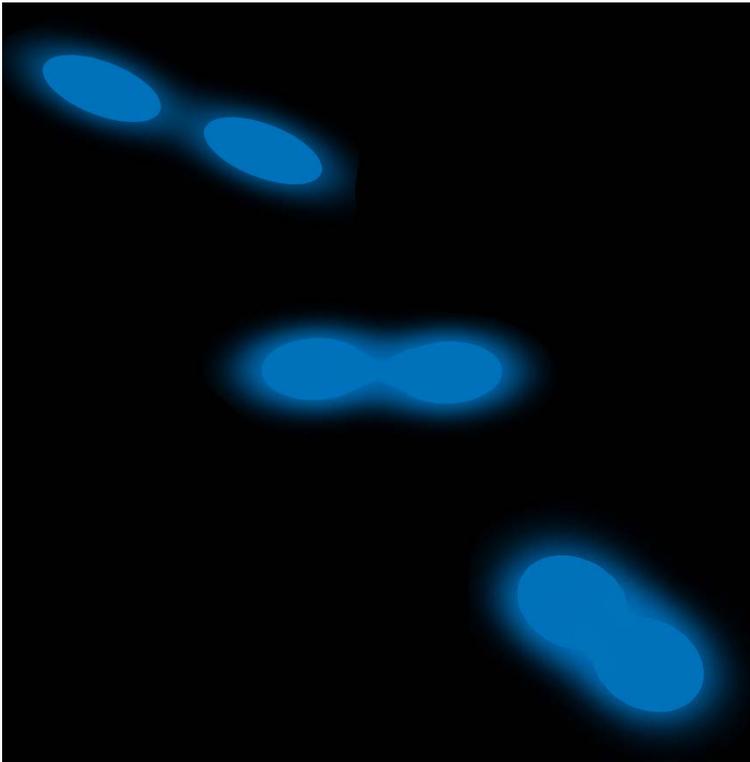
Cardoso, Hopper, Macedo, Palenzuela, Pani, PRD94:084031 (2016)

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

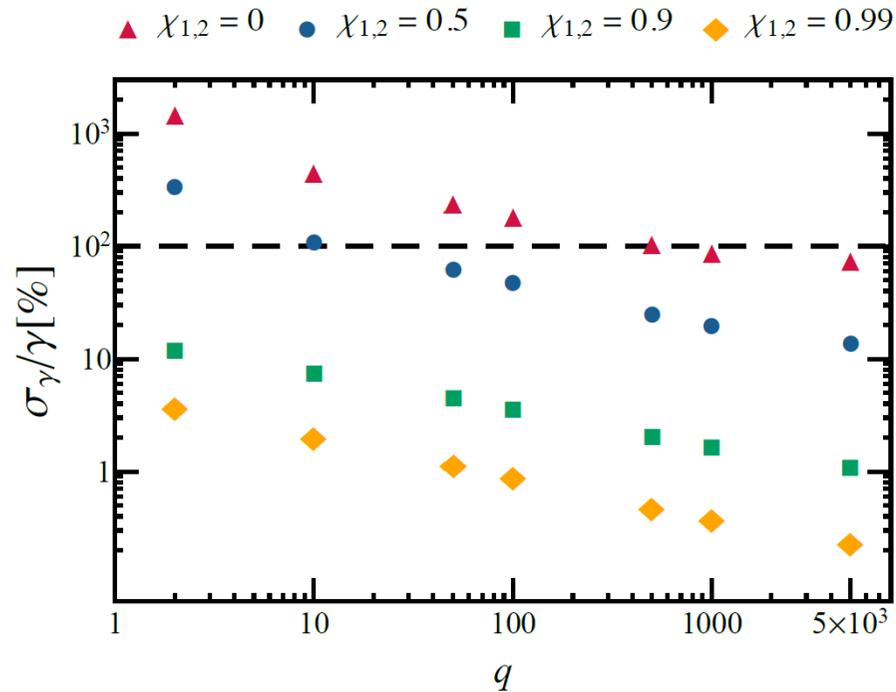
(iii) on amount of radiation absorbed, i.e.,
tidal heating

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

iv. GW signal: inspiral (precision measurements)

Absorption:

2.5 PN for BHs, vanishes for ECOs

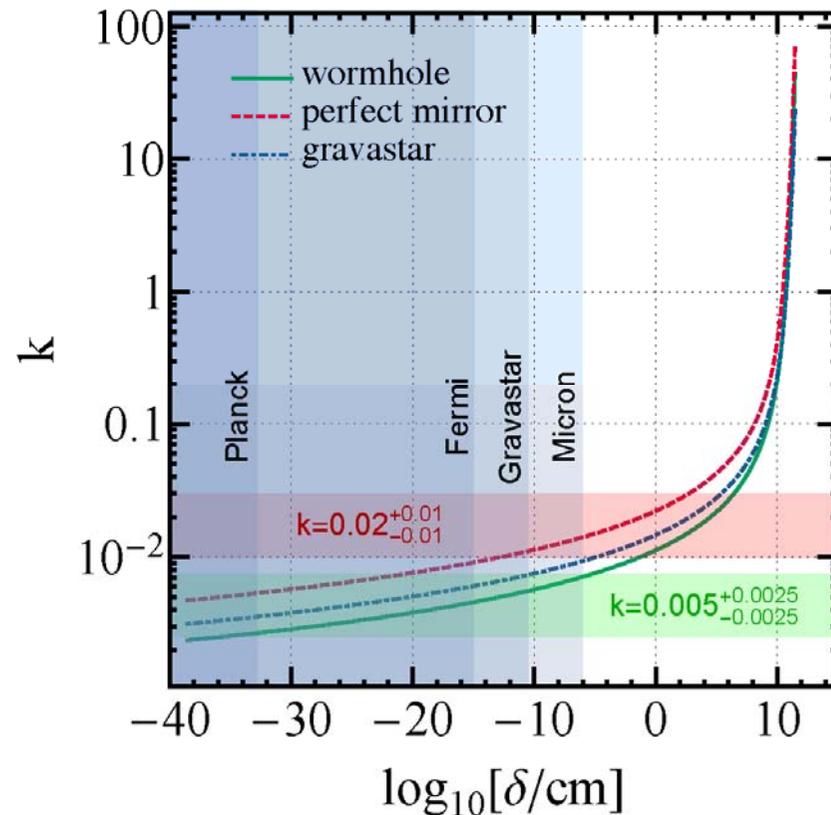


2 Gpc, central mass 10^6 solar masses

Maselli et al, arXiv:1703.10612

iv. GW signal: inspiral (precision measurements)

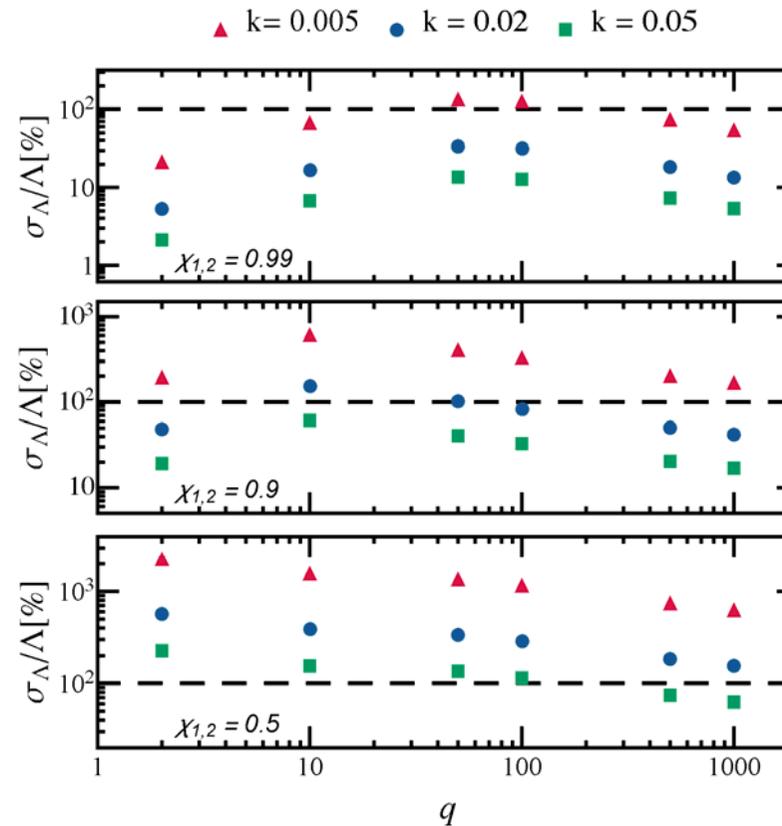
TLNs: Vanishes for BHs, 5PN and logarithmic for ECOS



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

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Sennett et al 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)

Thank you

