Echoes *of* Modified Gravity

Vítor Cardoso

[Técnico & CERN]

Image: Einstein and Snoop Dogg in Lisbon, by Ana Carvalho (2018)

TÉCNICO LISBOA

centra

grit gravitation in técnico

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Fundamental questions

a. Is (weak) cosmic censorship preserved?
Sperhake+ PRL103:131102 (2009)

b. What is maximum possible luminosity?
Gibbons & Barrow MNRAS 446:3874 (2015); Cardoso+ PRD97:084013 (2018)

c. What is graviton mass or speed?
See review Barack+ arXiv:1806.05195; ***de Rham's talk, Maselli's talk***

d. Are there extra radiation channels, corrections to gravity?
Barack+arXiv:1806.05195; Barausse+PRL116:241104(2016); ***Kimura's talk***

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

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

g. Is the final - or initial - object really a black hole?
Cardoso & Pani, Nature Astronomy 1: 586 (2017); Carballo-Rubio+ PRD98:124009 (2018)
Maggio's talk

Precision physics

a. Take your favourite theory and work out the consequences

b1. Can we catalogue all theories? When no additional fields, EFT suggests that generic (local) theories are described by EFT action

Endlich+ JHEP1709:122

$$S_{\rm eff} = \int d^4x\sqrt{-g}\,2M_{\rm pl}^2\left(R - \frac{\mathcal{C}^2}{\Lambda^6} - \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} - \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6}\right)$$

$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}\,, \quad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta}\tilde{R}^{\alpha\beta\gamma\delta}\,,$$

Systematic way to search for imprints with precision physics: compute BH solutions, explore dynamics.

Cardoso+ PRL121: 251105 (2018); Cano, Ruipérez arXiv:1901.01315

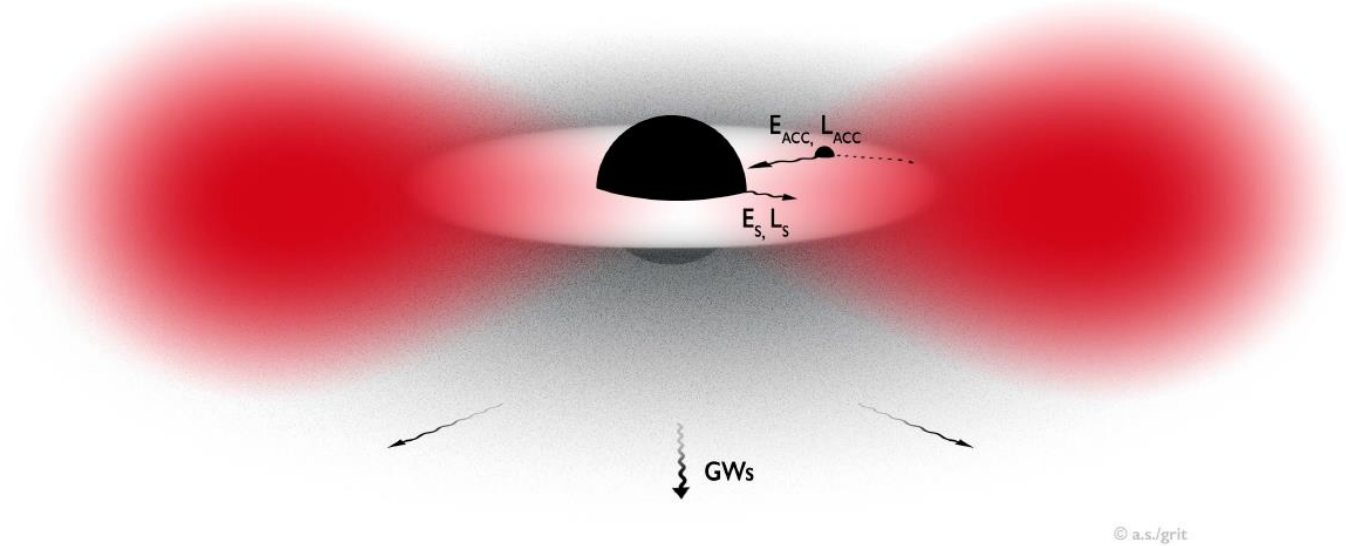
Kimura's talk

b2. Parameterize some theories by their effects on objects, eg. dipolar moments, that lead to (perturbatively small) observational imprints

Barausse + PRL116:241104 (2016); Cardoso + JCAP1605:054 (2016)

Smoking guns: light fields and DM

$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi - \frac{\mu_S^2}{2}\Psi\Psi - \frac{k_{\rm axion}}{2}\Psi\ {}^*F^{\mu\nu}F_{\mu\nu}$$

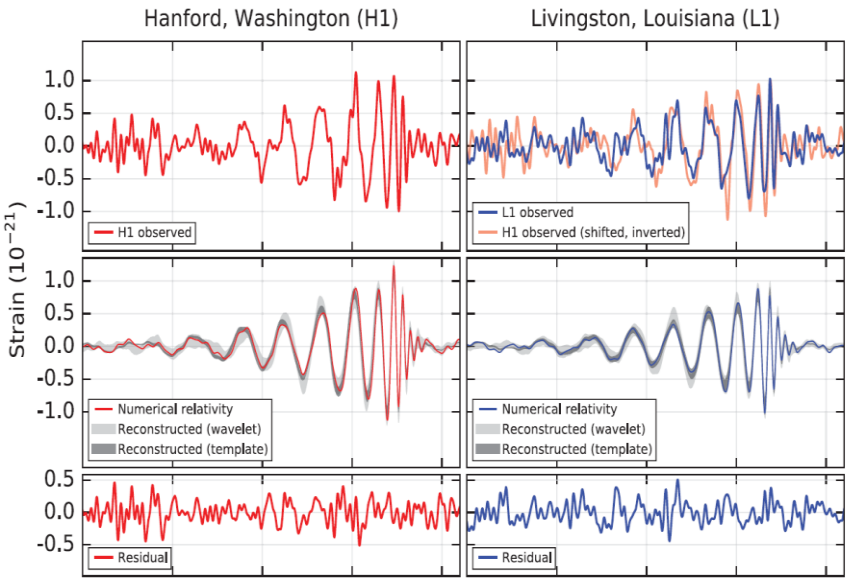


$$\tau \sim 100\left(\frac{10^6 M_\odot}{M}\right)^8\left(\frac{10^{-16}\text{eV}}{\mu}\right)^9 \text{ seconds}$$

Massive “states” around Kerr are linearly unstable

Brito + arXiv:1501.06570; Ikeda + PRL (in press); ***also Ikeda’s poster***

The nature of 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

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

Very, massive compact object indeed!

Why is this enough?

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

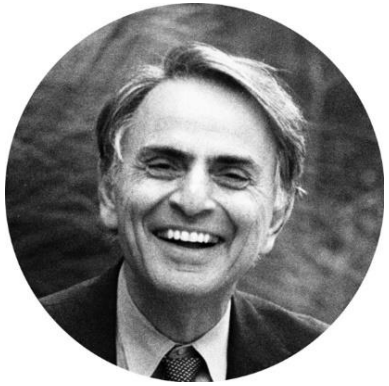
No other massive, dark object has been seen to arise from collapse of known matter.

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. Even if not, many orders of magnitude standing, surprises can hide. *(Arkani-Hamed+ 1998; Giddings & Thomas 2002)*



"*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.

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?

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; Bezares + arXiv:1811.07917

Wormholes
Morris, Thorne 1988; Visser 1996; Damour and Solodukhin 2007

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)

Clean-Photospheres (ClePhOs)

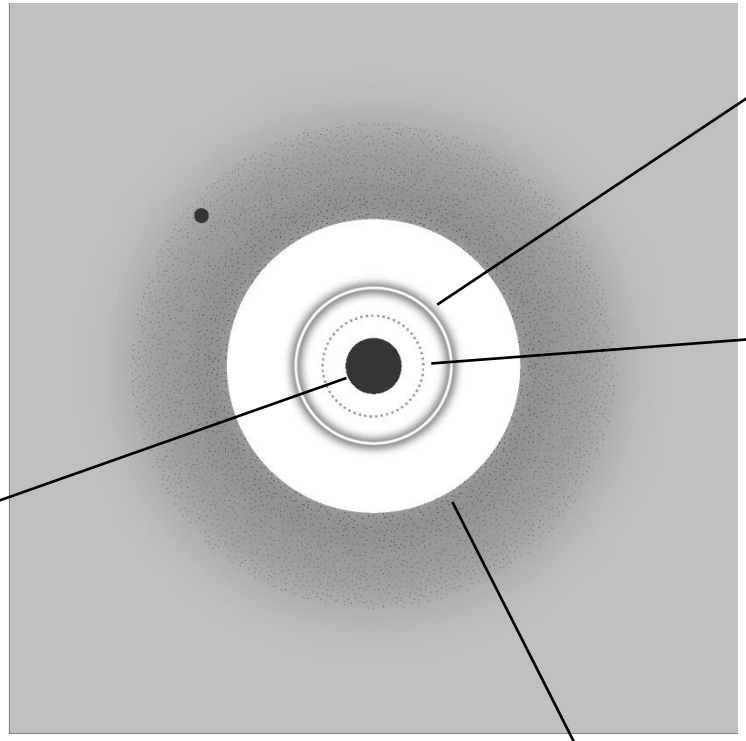


Image: Ana Sousa

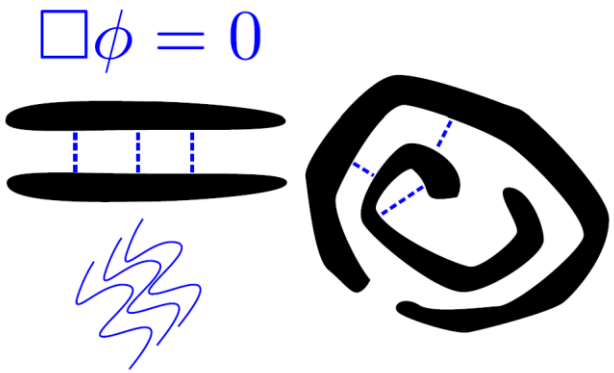
Cardoso & Pani, Nature Astronomy 1: 586 (2017); see also arXiv: 1707.03021[gr-qc]

iiia. 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 CQG 33: 135009 (2016); Cardoso + PRD90:044069 (2014)

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

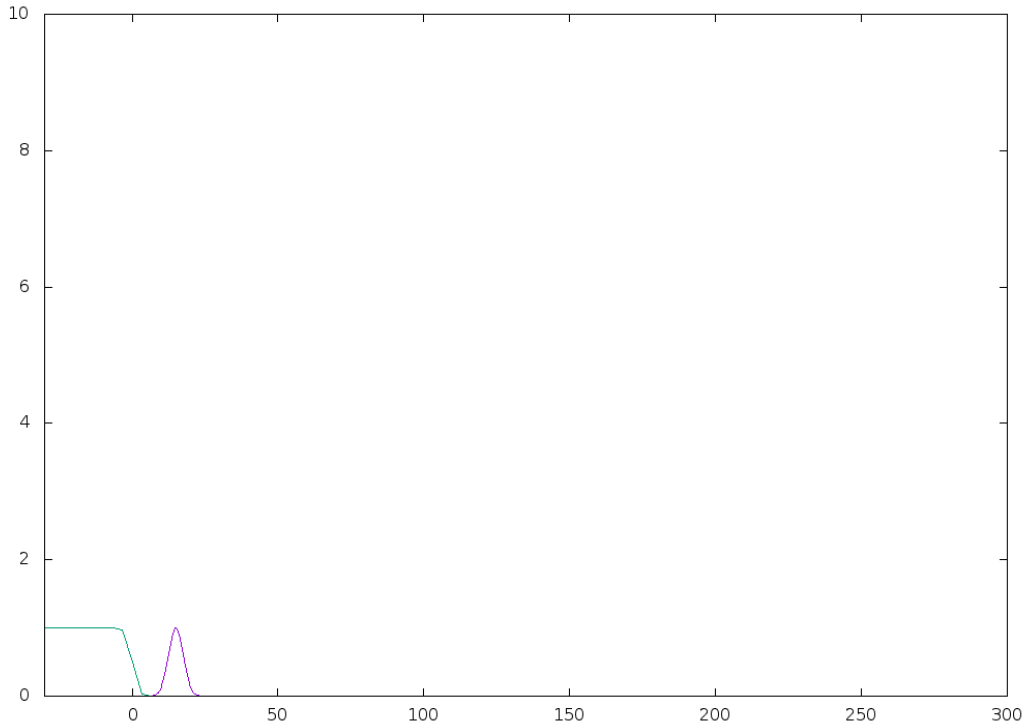


Burq, Acta Mathematica 180: 1 (1998)

iiib. 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 and Cardoso PRD97:084032 (2018)

Maggio's talk

EM constraints

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

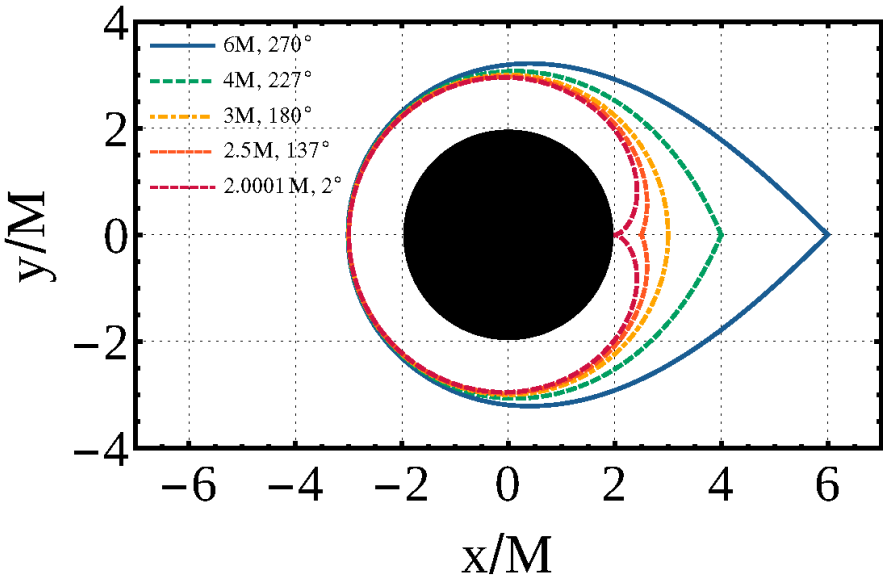
$$\epsilon \lesssim 10^{-5}$$

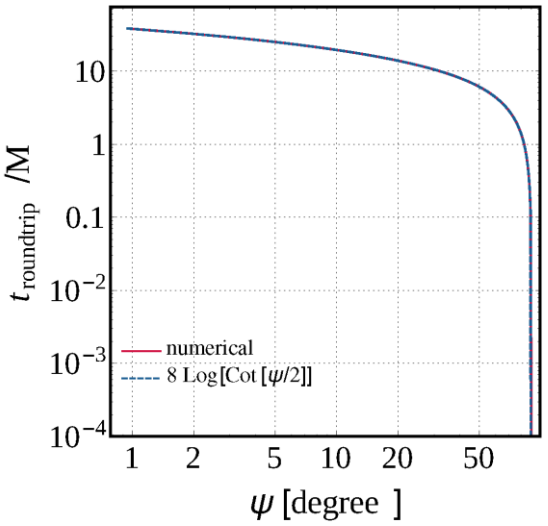
$$\epsilon \lesssim 10^{-35}$$

Absence of transients from tidal disruptions

Dark central spot on SgrA

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

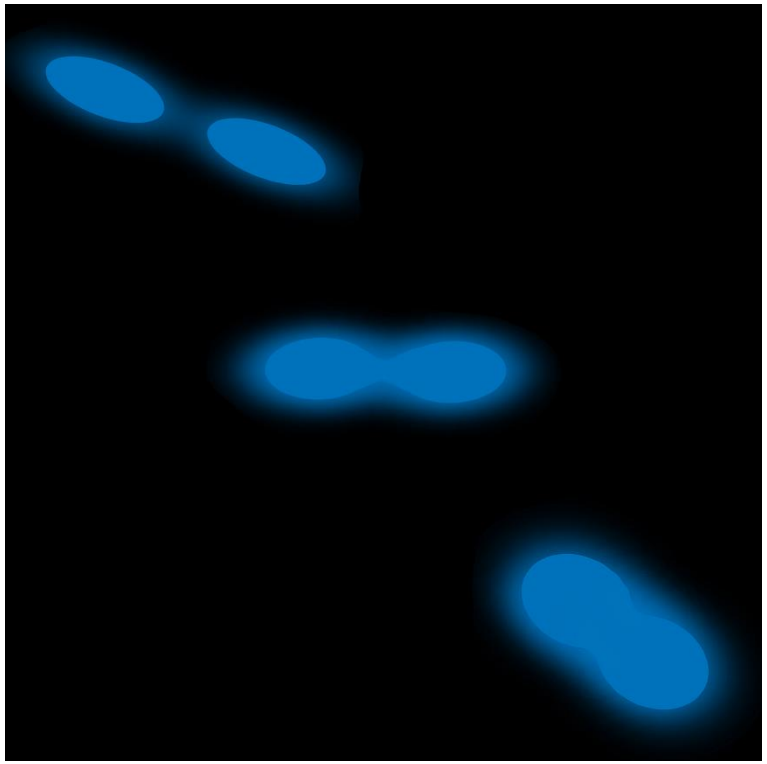




Lensing has to be properly included, as well as emission into other channels

Abramowicz, Kluzniak, Lasota 2002; Cardoso, Pani 20017

GW signal



Nature of inspiralling objects is encoded

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

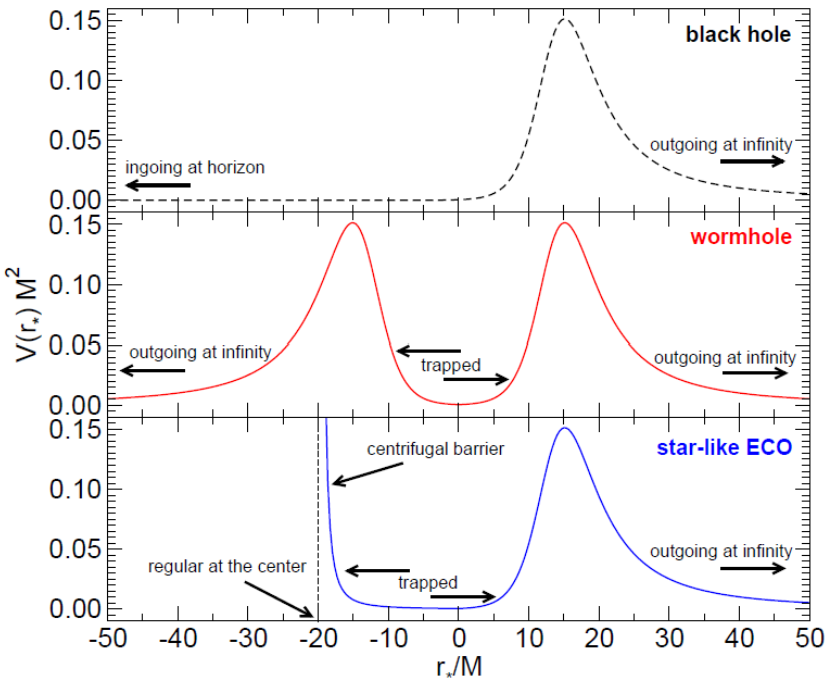
(ii) in way they respond when acted upon by external field of companion – through their tidal Love numbers (TLNs), and

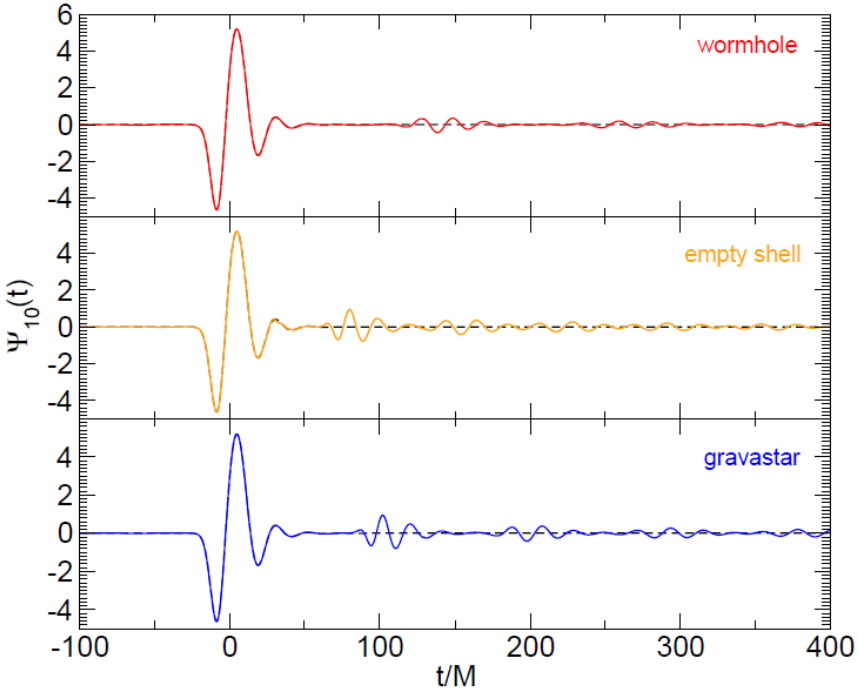
(iii) on amount of radiation absorbed, i.e., tidal heating

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

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

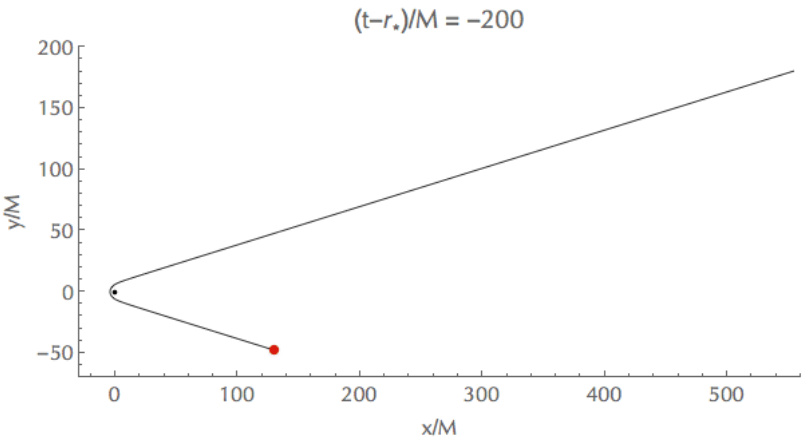
Echoes

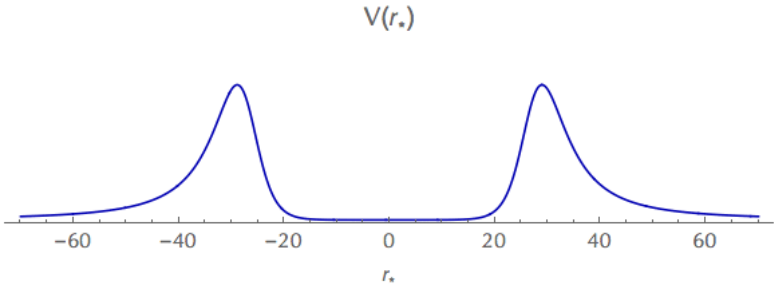


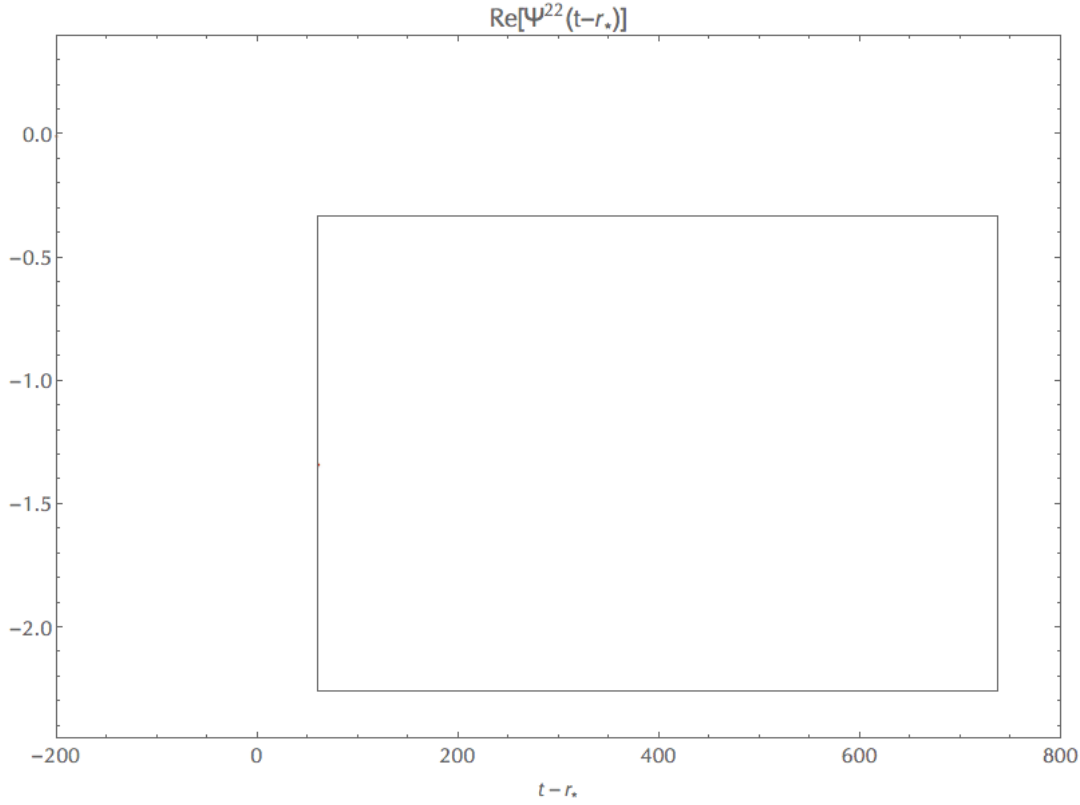


Cardoso + PRL116:171101 (2016); Cardoso+ Nature Astronomy 1: 2017

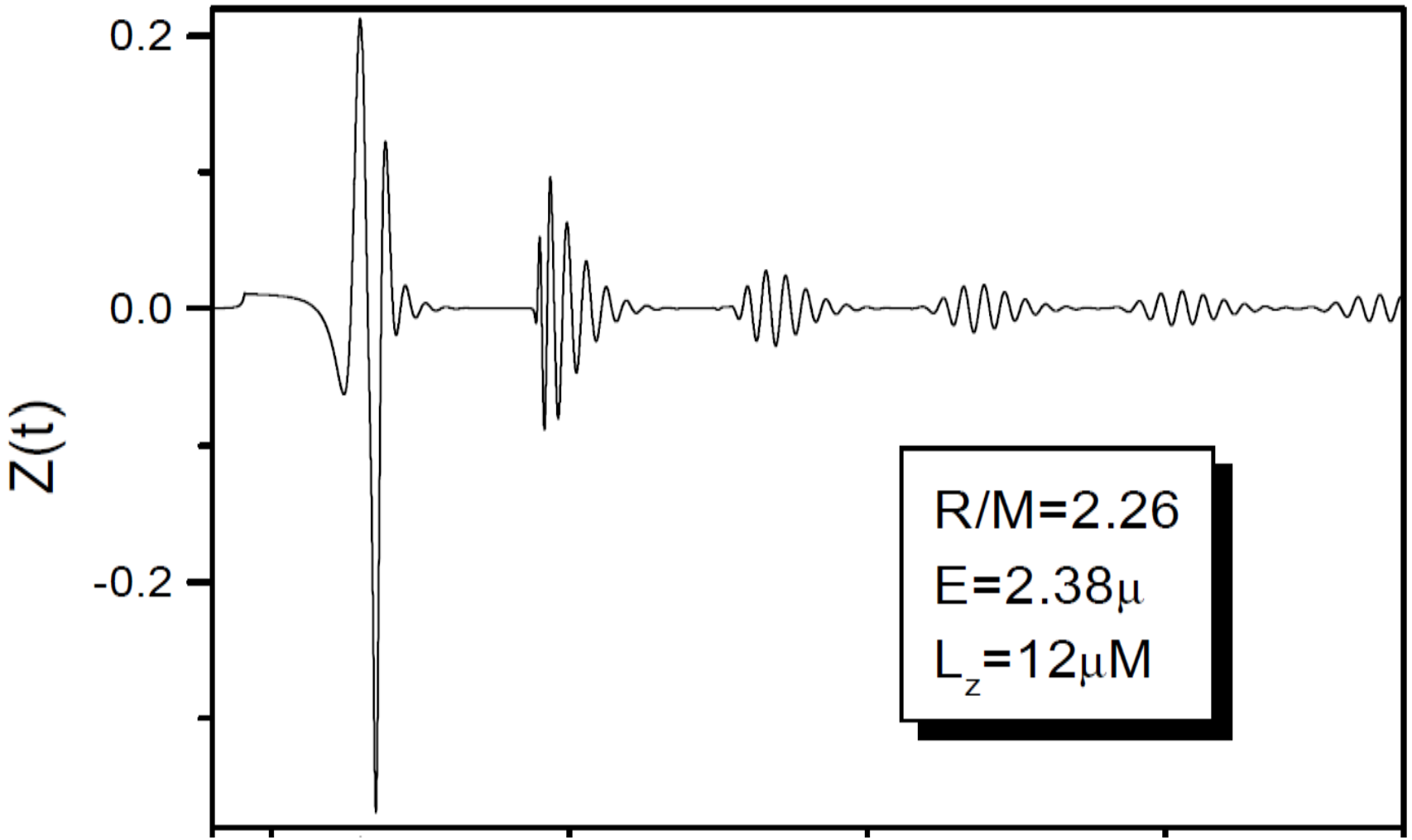
$\mathcal{E}$ = 1.5, r_{min}=4.3M, r_0−2M = 10^{-6}M







Cardoso + PRD94:084031 (2016)



Ferrari and Kokkotas PRD62: 107504 (2000)

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

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

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

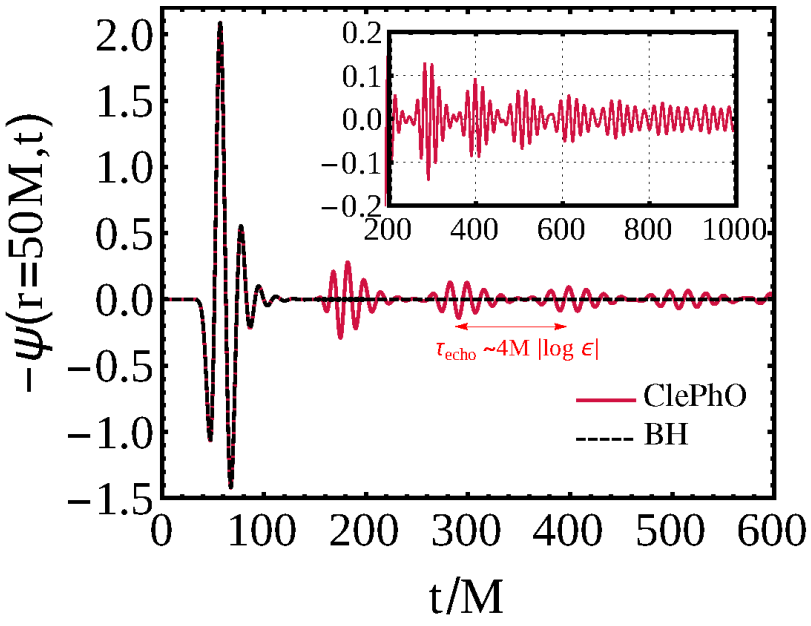
$$\psi = \sum_{k=1}^{\infty} \int_{z_0}^{\infty} g(z,z_1)\cdots g(z_{k-1},z_k) V(z_1)\cdots V(z_{k-1})\mathcal{S}(z_k) dz_1 \cdots dz_k$$

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

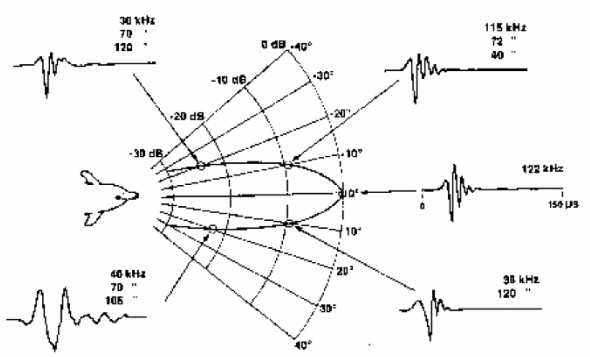
$$\psi = \psi_o + \sum_{n=1}^{\infty} \psi_n$$

Correia, Cardoso PRD97: 084030 (2018)

Echoes



$$M\omega_R \sim |\log\epsilon|^{-1}$$
$$M\omega_I \sim |\log\epsilon|^{-(2l+3)}$$

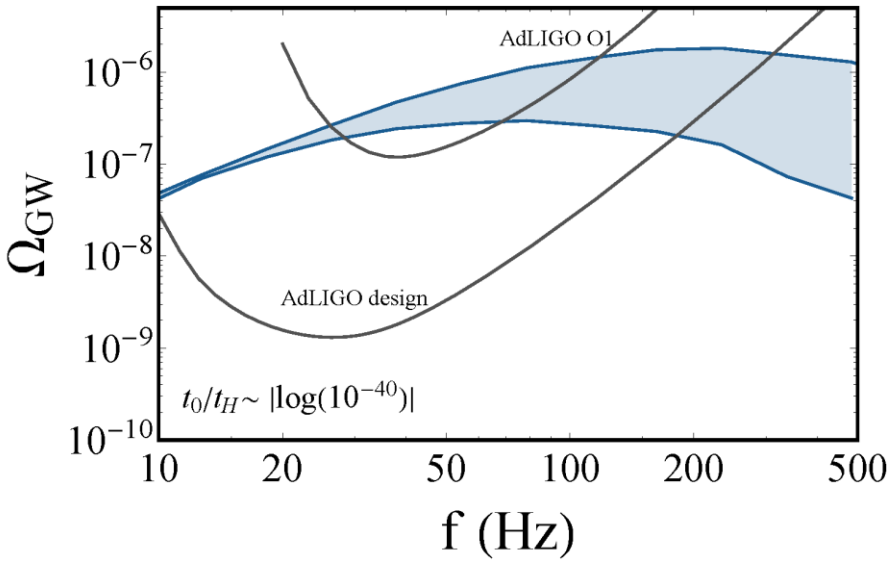


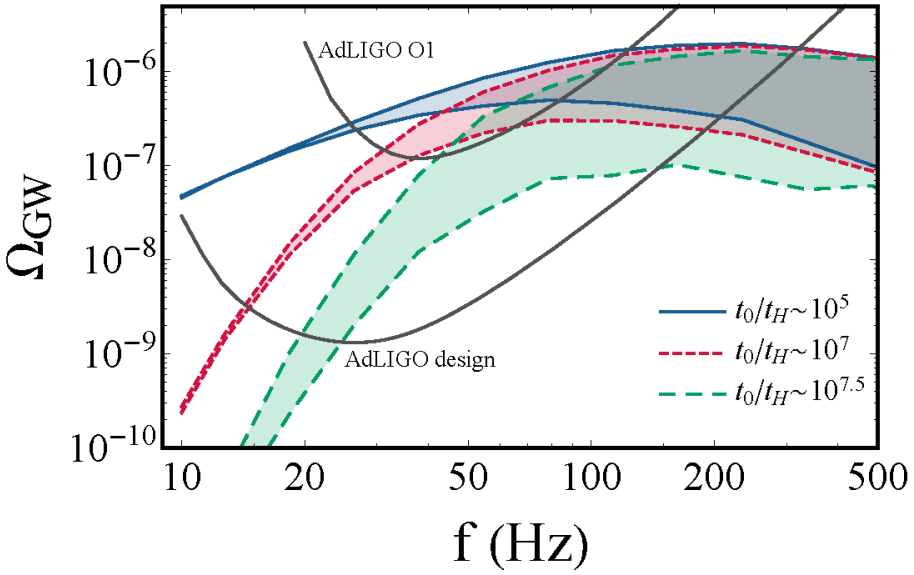
Target echo in reverberation at the dolphin's threshold of detection (from Au [8]).

Cardoso, Pani, Nature Astronomy 1: 2017

Au+ (J. Acoust. Soc. Am. 1992)

Stochastic background of GWs





Barausse+ CQG35:20LT01 (2018)

Exciting times!

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

Do ultralight scalars exist?

…do black holes exist?

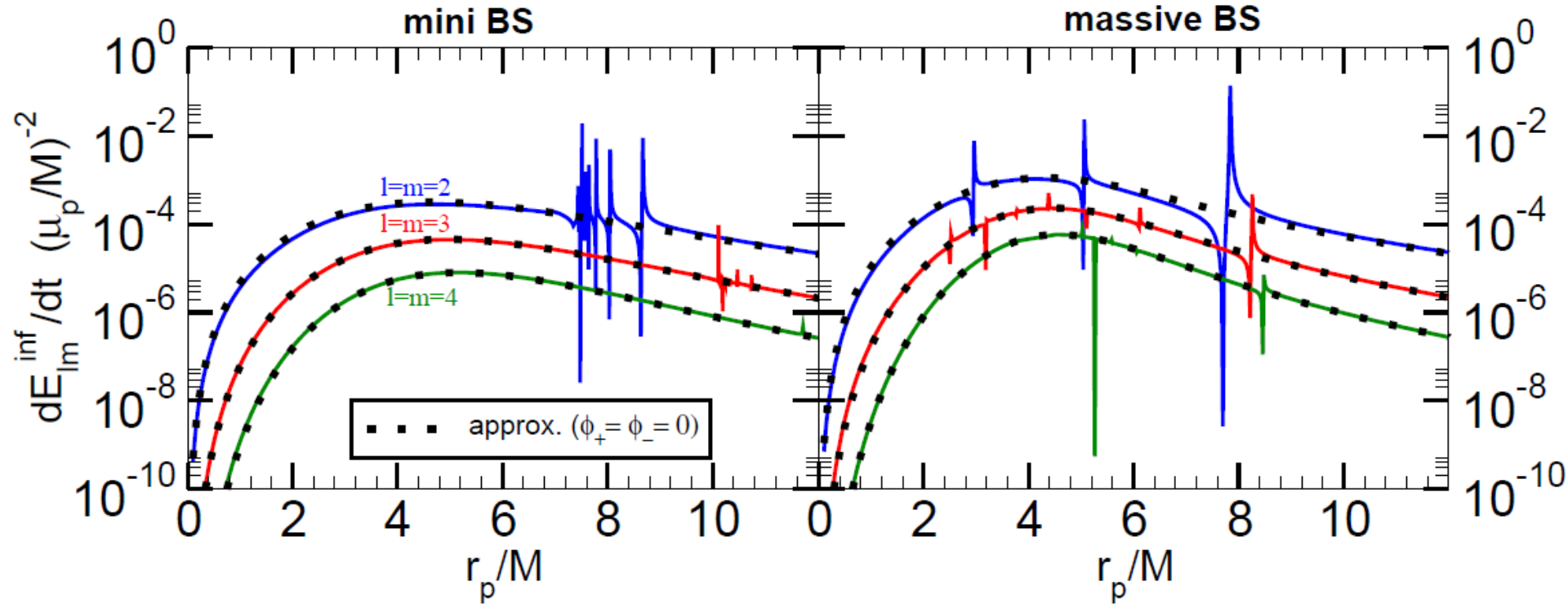
Tools missing (where in spectra are LR modes, nonlinear evolutions etc)

Searches for echoes ongoing…need modelling efforts too
(Abedi+ 2017; Ashton+ 2017; Tsang+ 2018; Westerweck+ 2018; Lo+ 2019; Nielsel + 2019; Oshita+ 2019)

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

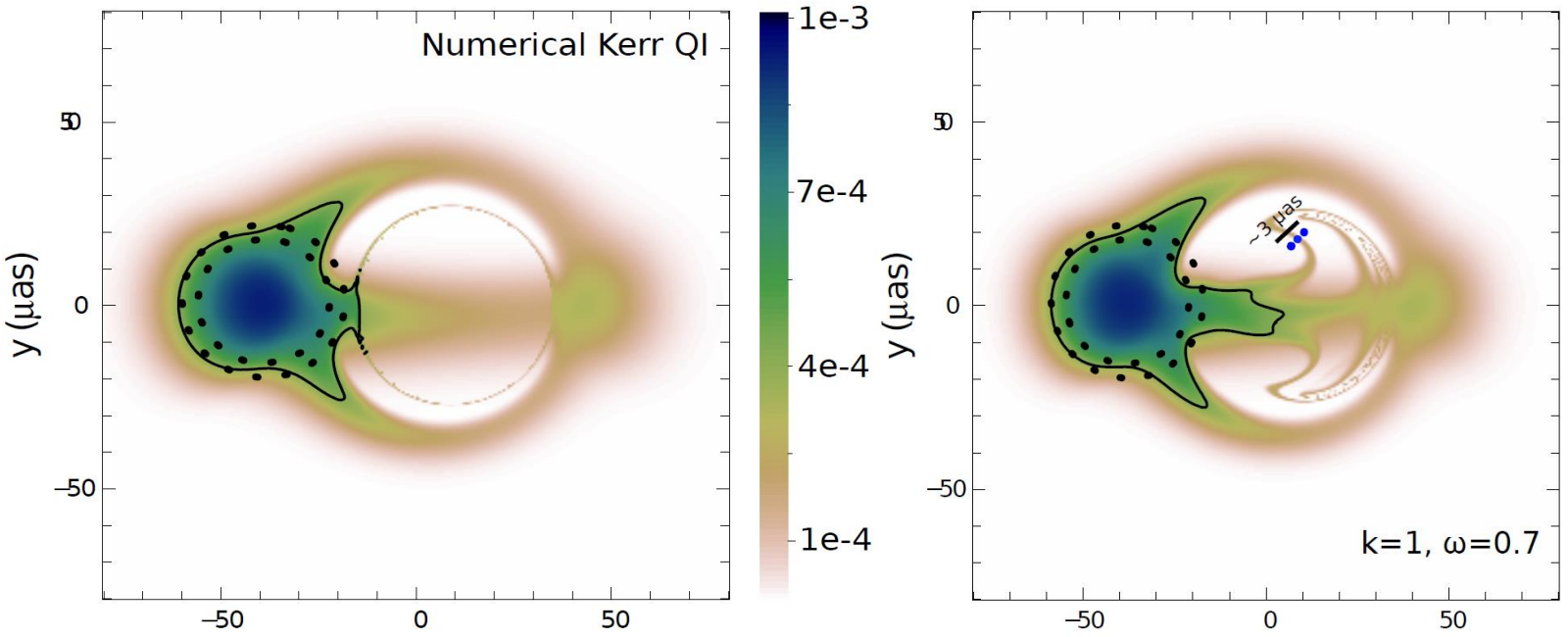
S. Chandrasekhar, The Karl Schwarzschild Lecture, Astronomischen Gesellschaft, Hamburg, 18 Sept. 1986

Thank you



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

Shadows



Vincent+ CQG 33:105015 (2016)

Hawking radiation

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

Almost any notion of trapping horizon or dynamic horizonless objects radiates

Paranjape, Padmanabhan PRD80:044011 (2009)
Barcelo, Liberati, Sonego, Visser JHEP1102:003 (2011)
Harada+ arXiv:1811.05179

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

K-W Tsang+ PRD98:024023 (2018)
Mark+ PRD96:084002 (2017)

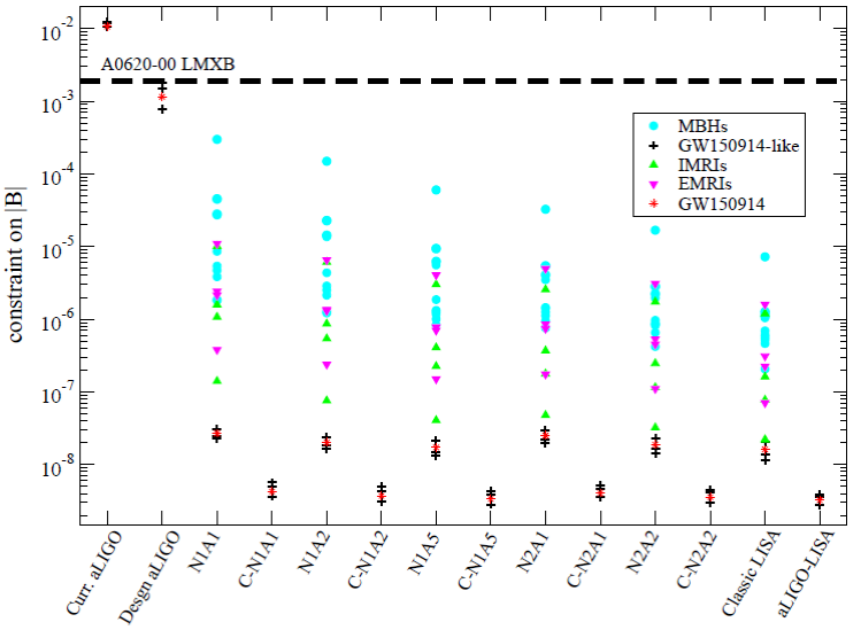
Have we seen echoes (at 2.9-4.2 sigma)?!

Abedi + PRD96: 082004 (2017)
Ashton et al 2016
Abedi+ (2018)

Extra fields, bounding dipolar radiation from inspiral

Barausse + PRL116:241104 (2016), Cardoso + JCAP1605:054 (2016)

$$\dot{E}_{\rm GW} = \dot{E}_{\rm GR}\left[1 + B\left(\frac{Gm}{r_{12}c^2}\right)^{-1}\right]$$



For EM charge or hidden vectors $B = \frac{5}{24}\left(\frac{Q_1}{M_1} - \frac{Q_2}{M_2}\right)^2$

Cardoso + JCAP1605:054 (2016)

Phenomenology for precision physics

Can we catalogue all theories? When no additional fields, EFT suggests that generic (local) theories are described by EFT action

Endlich+ JHEP1709:122

$$S_{\rm eff} = \int d^4x\sqrt{-g}\, 2M_{\rm pl}^2 \left(R - \frac{\mathcal{C}^2}{\Lambda^6} - \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} - \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6} \right)$$

$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta} R^{\alpha\beta\gamma\delta}\,, \quad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta} \tilde{R}^{\alpha\beta\gamma\delta}\,,$$

Systematic way to search for imprints with precision physics: compute BH solutions, explore dynamics.

Cardoso+ PRL121: 251105 (2018); Cano, Ruipérez arXiv:1901.01315

Are GR effects and degeneracies sufficiently understood (spin, spin-precession, eccentricity)?

Are tidal Love numbers measurable when small?

Can we catalogue all possible ringdown frequencies?