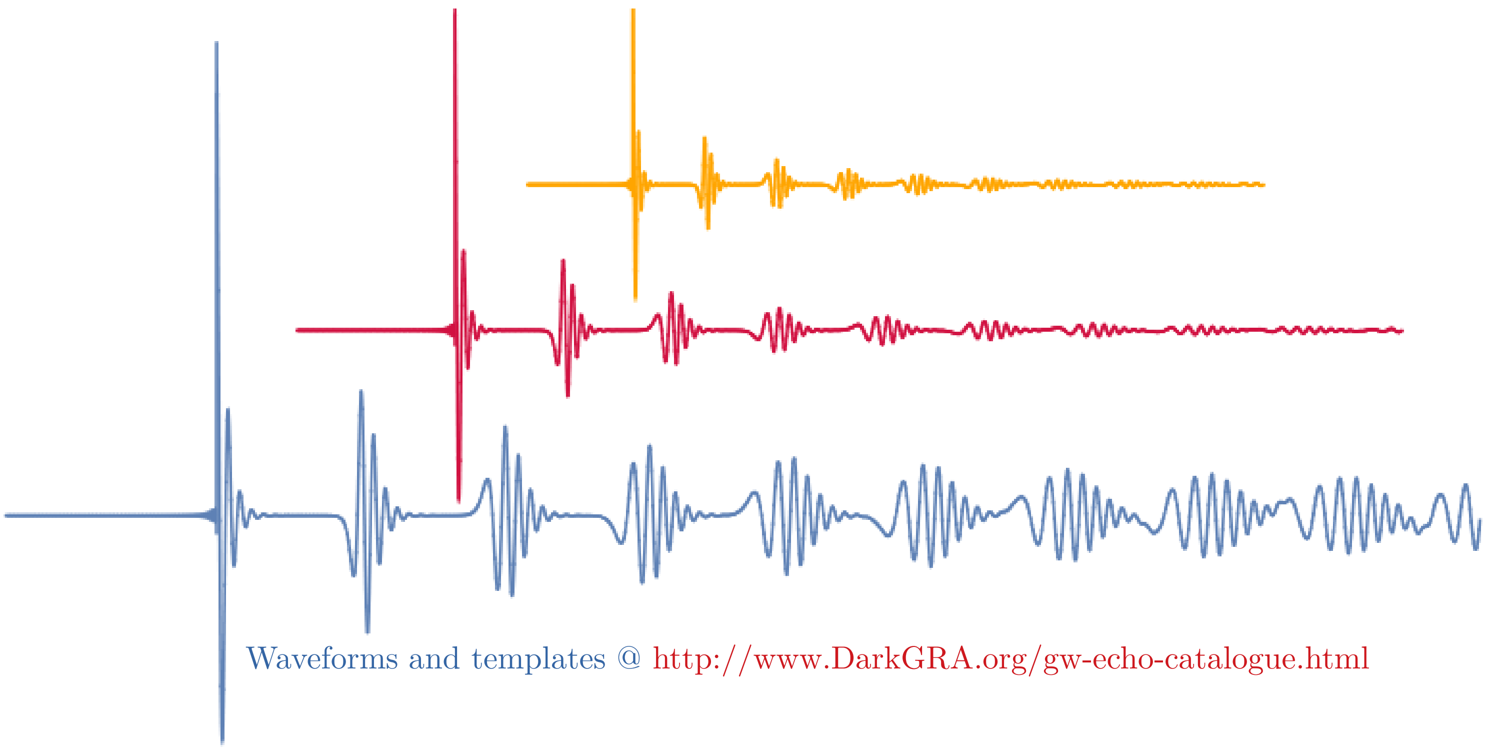
Gravitational-wave echoes



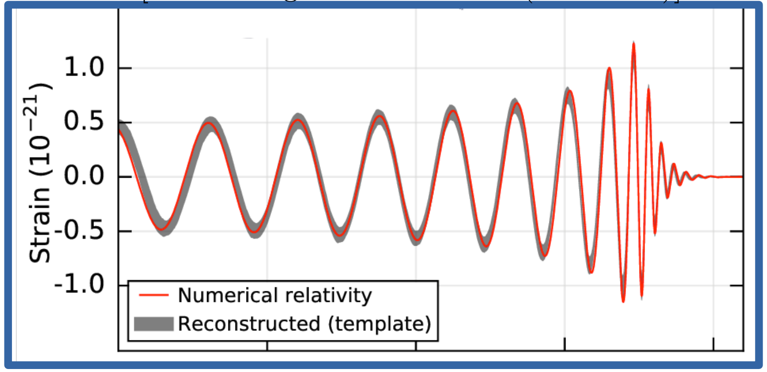
Waveforms and templates @ http://www.DarkGRA.org/gw-echo-catalogue.html

Paolo Pani
Sapienza University of Rome & INFN Roma1
https://web.uniroma1.it/gmunu

Testing BHs, why should we care?

- **The observational status of black holes (BHs) is now more solid than ever**
- **(Classical) BHs in GR are very economical:**
  - Arbitrary mass
  - Compactness M/R ~ 1 (G=c=1 units henceforth)
  - Sound formation mechanism
  - Linearly (at least mode) stable
    [Dafermos & Rodnianski; Clay Math. Proc. (2013)]
  - Consistent with *all* observations

[LIGO-Virgo Collaboration (2016-now)]



[EHT Collaboration. (2019)]

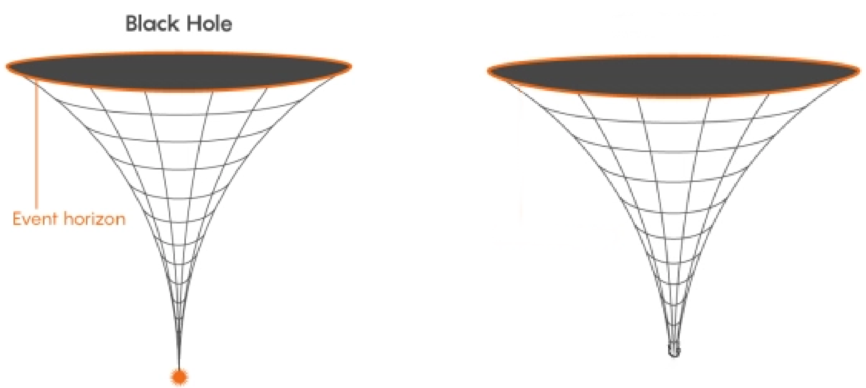
So why questioning the BH picture and testing exotic compact objects (ECOs)?

Testing BHs, why should we care?

- New species of compact objects?
  - Lesson from timeline of particle physics discovery
- The dark matter connection
  - *Can ECOs form (part of) the dark matter?* (es. boson/axion stars)
- Quantifying the evidence for BHs
  - Lessons from tests of the WEP, etc, how to even *formulate* the problem?
- Problems on the horizon
  - BH exterior is fine, interior is not → **singularities**, Cauchy horizons, CTCs...
  - BHs are *required* for self consistency of General Relativity [Cosmic Censorship]
  - Drawbacks: Huge entropy, **unitarity loss**, thermodynamical instability [Hawking 1972]

Testing BHs, why should we care?

- Resolution of Hawking's paradox might require drastic changes at the horizon:
  - New physics at the horizon (e.g. firewalls, nonlocality) [Almheri+, Giddings+, 2012-2017]
  - Regular, horizonless compact objects (e.g. fuzzballs) [Mathur, 2007-, Bena+ 2015, Turton, Warner]



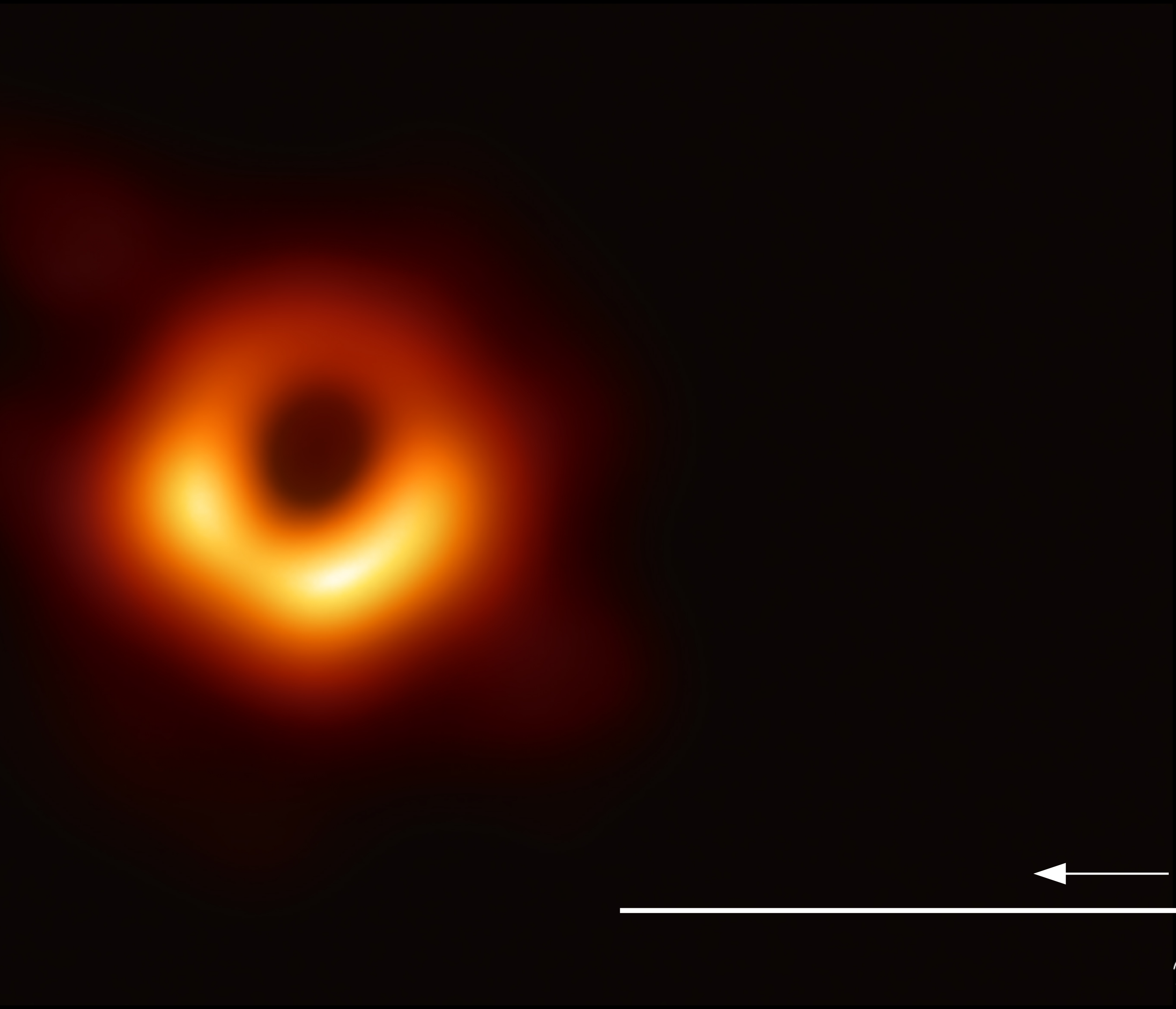
singularity regular

- Tunneling probability to quantum state:
  - small amplitude $\rightarrow$ $\mathcal{A}_{\rm tunneling} \sim e^{-\alpha R_S^2/\ell_P^2} \sim e^{-\alpha M^2/\hbar}$
  - but huge phase space $\rightarrow$ $\mathcal{N}_{\rm states} \sim e^{S_{\rm BH}} \sim e^{4\pi M^2/\hbar}$

$$\mathcal{P}_{\rm tunneling} \sim \mathcal{A}_{\rm tunneling} \times \mathcal{N}_{\rm states} \sim \mathcal{O}(1)$$

How to test the BH picture?

How to test the BH picture?

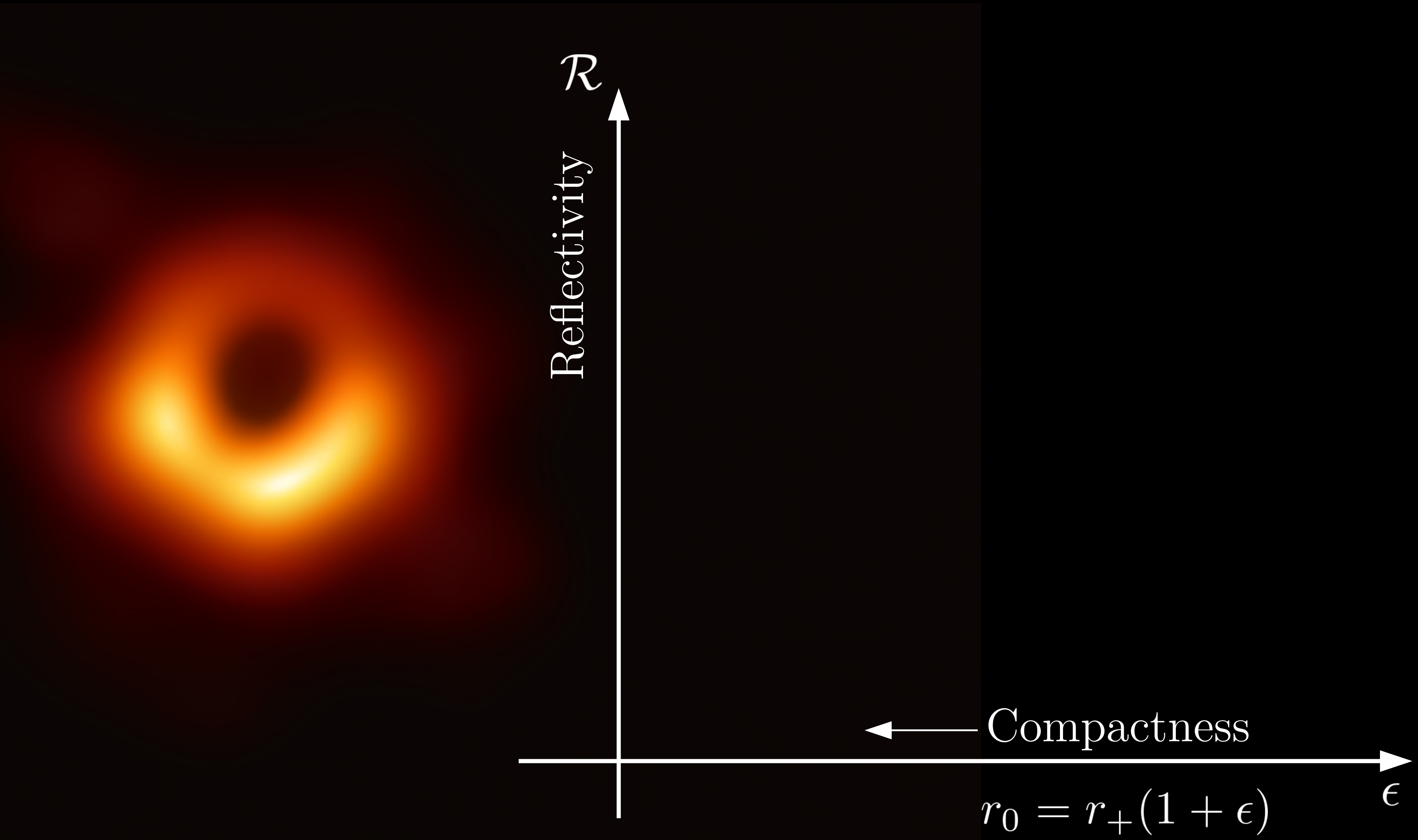


← Compactness

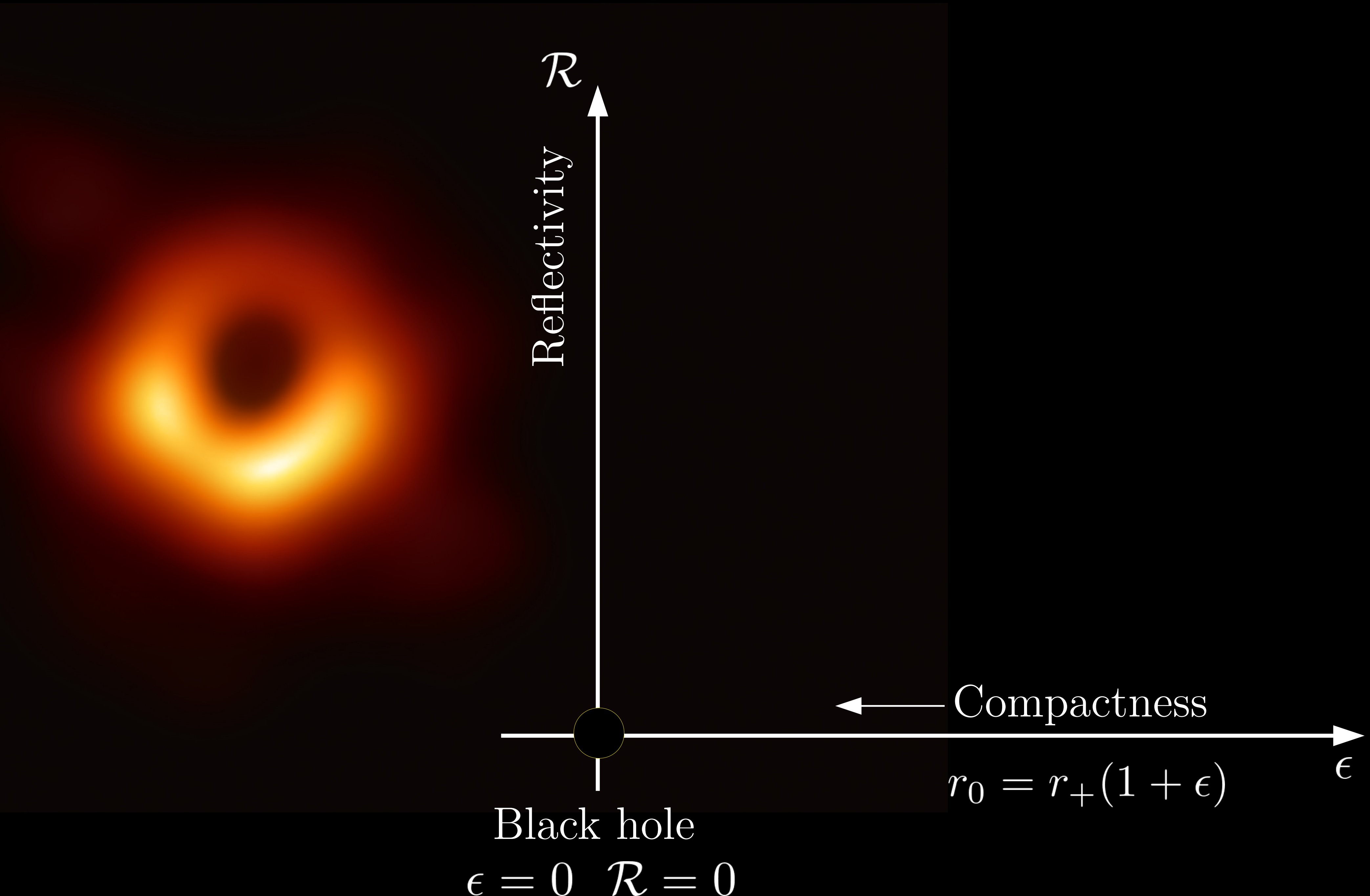
ϵ →

$r_0 = r_+(1+\epsilon)$

How to test the BH picture?



How to test the BH picture?



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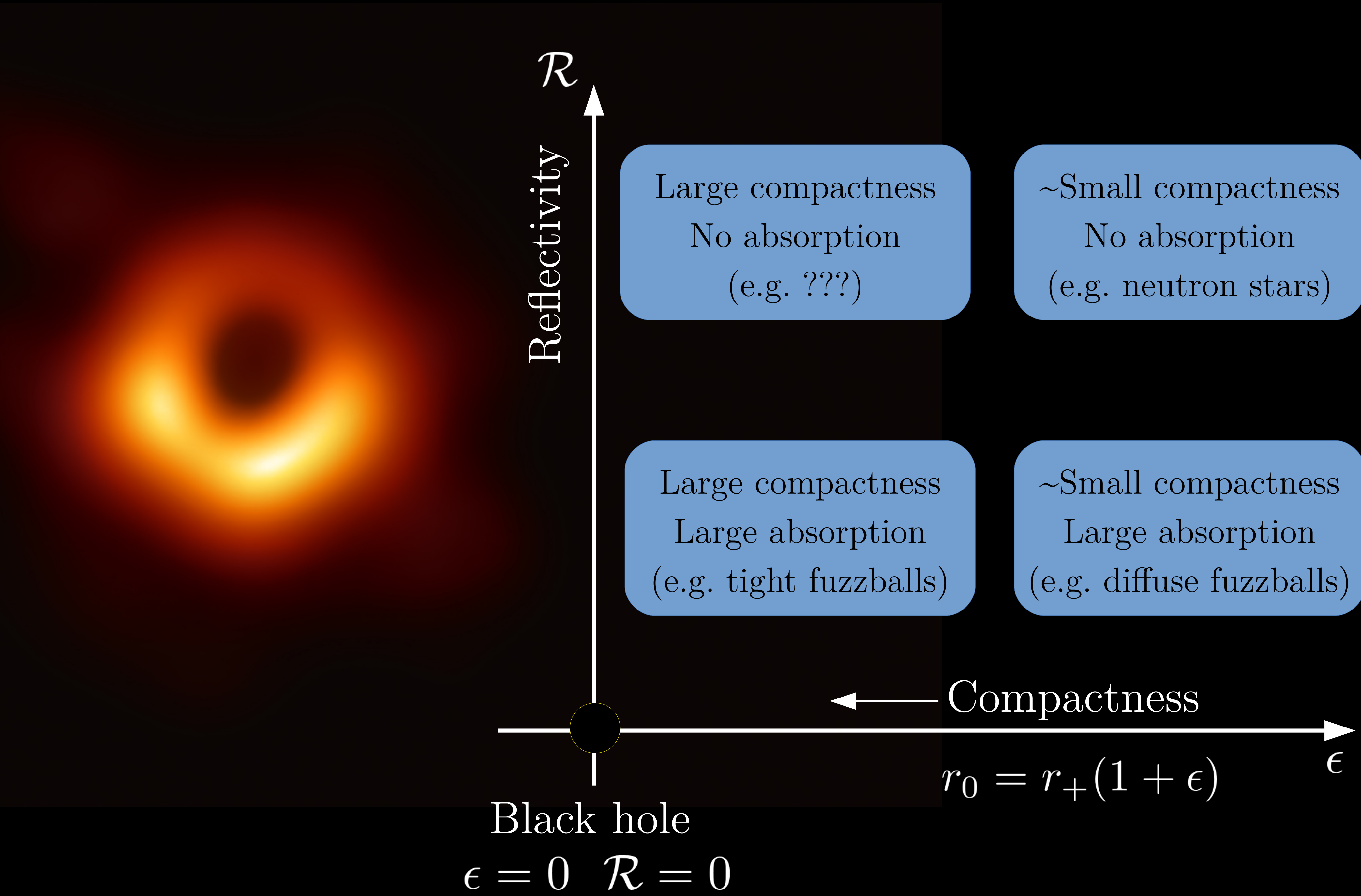
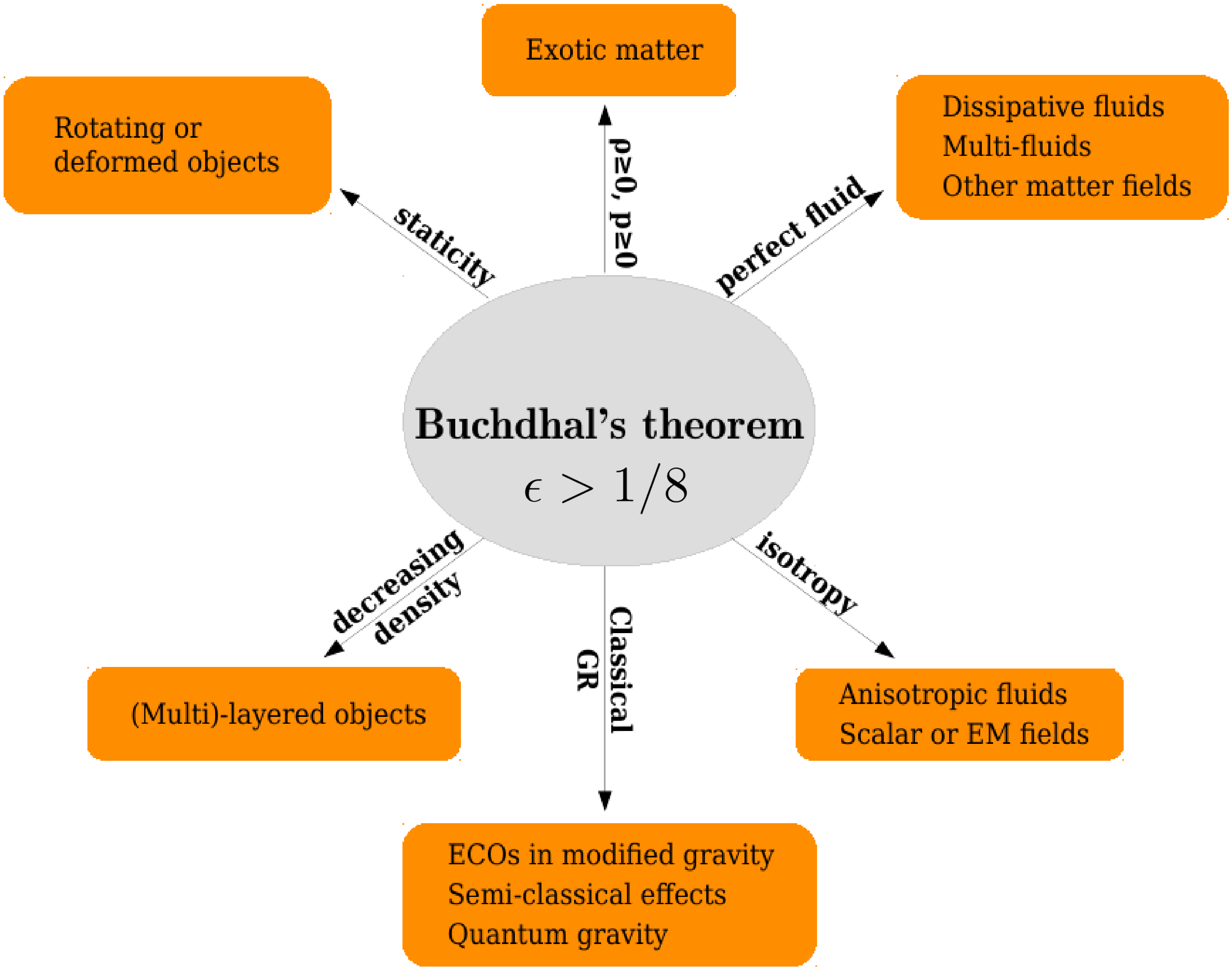


Exotic compact objects (ECOs)

Cardoso & Pani, Living Rev Relativ (2019) 22:4

- Several models/proposals
- Different levels of "robustness" and open problems
    - Equilibrium sols? Stability? Formation? Coalescence?
- Phenomenologically:
    - "Good" ECOs [fluid stars, anisotropic stars, boson stars, oscillatons, ...]
    - "Bad" ECOs [fuzzballs, gravastars, wormholes, firewalls...]
- Two approaches:
    - Model-dependent and from first principles
    - Phenomenological and agnostic on the model

A compass to navigate the ECO atlas

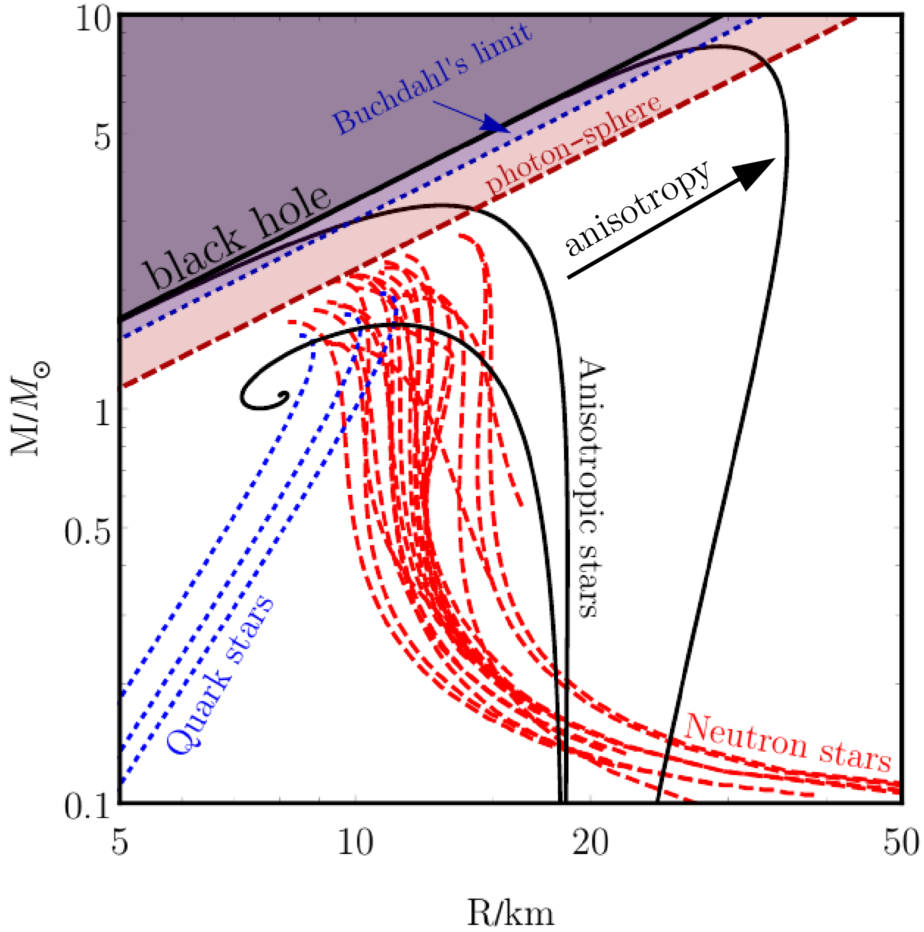


Evading Buchdhal: anisotropic stars

$$T_{\mu\nu} = T^{\mathrm{ISO}}_{\mu\nu} + \sigma_1 k_\mu k_\nu + \sigma_2 \xi_\mu \xi_\nu + \sigma_3 \eta_\mu \eta_\nu$$

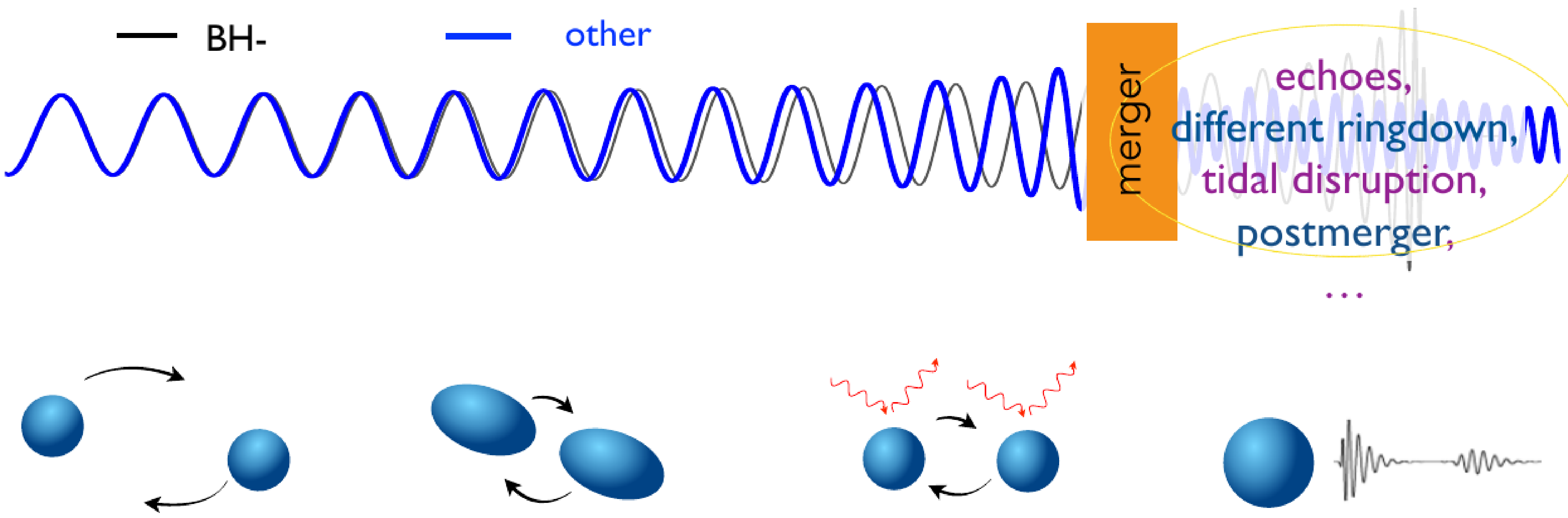
- Covariant framework for anisotropic fluids in GR, ready for 3+1 simulations
- Consistent proxy for ultracompact objects
- Satisfy WEC and SEC; highly-anisotropic configurations violate DEC
- Display all ECO typical phenomenology

Raposo+, Phys. Rev. D 99, 104050 (2019)



GW-based tests of ECOs

Slide concept by T. Hinderer and A. Maselli



~point masses:
same signal
for all objects

tidal effects
+
spins
deformations

absence of horizon
absorption
effects

echoes

GW spectroscopy

- Post-merger signal → superposition of QNMs

[e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]

$$h_+ + ih_\times \sim \sum_i A_i \sin(\omega_i t + \phi_i) e^{-t/\tau_i} \mathcal{Y}_i$$

- QNMs of Kerr BH in GR depends only mass and spin [no hair] (**2+** modes needed)

$$\omega_{nlm} = \omega_R^{\mathrm{Kerr}}(M,\chi) + \delta\omega_R \qquad \tau_{nlm} = \tau^{\mathrm{Kerr}}(M,\chi) + \delta\tau$$

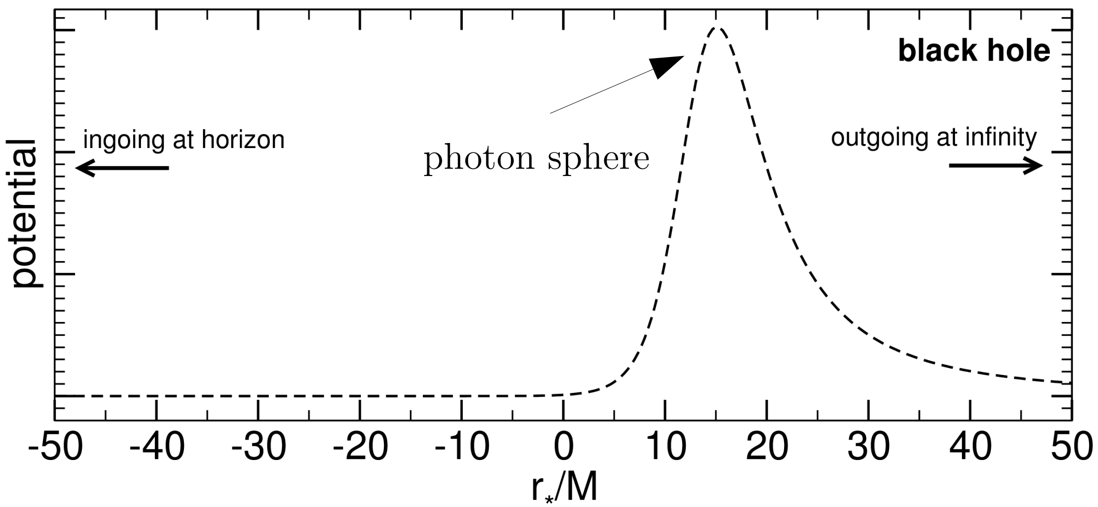
- Mode shift (due to different object, different dynamics, or couplings)
- Extra ringdown modes (e.g., extra polarizations, fields, matter) → amplitudes?
- Overtones might be used [Gieser+, 2019] but careful with resolvability [Bhagwat+, 1910.08708]

QNMs of exotic compact objects

$$\frac{\partial^2 \Psi}{\partial t^2} - \frac{\partial^2 \Psi}{\partial r_*^2} + V_{slm}(r_*)\Psi = 0$$

[e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]

QNMs exponentially sensitive to boundary conditions



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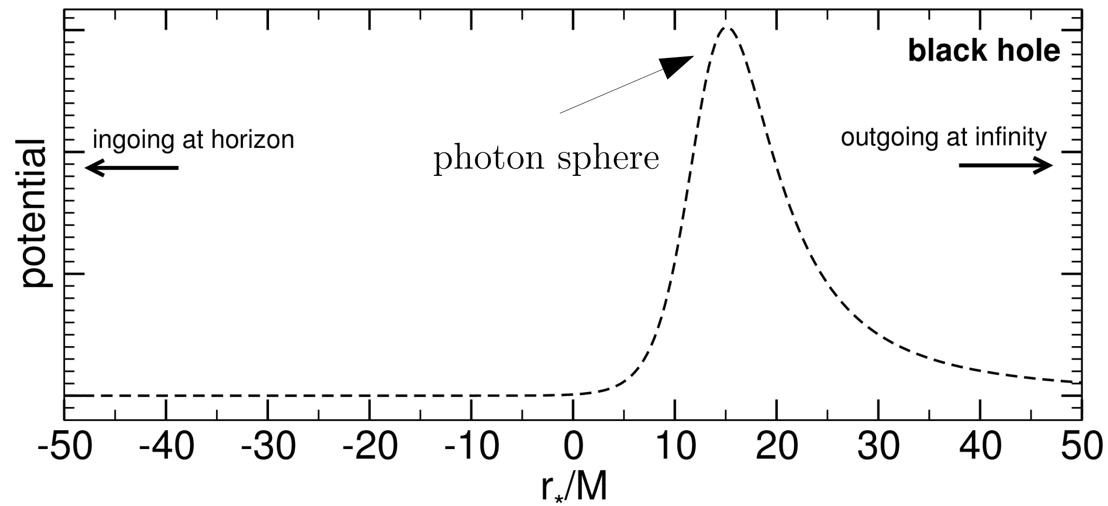
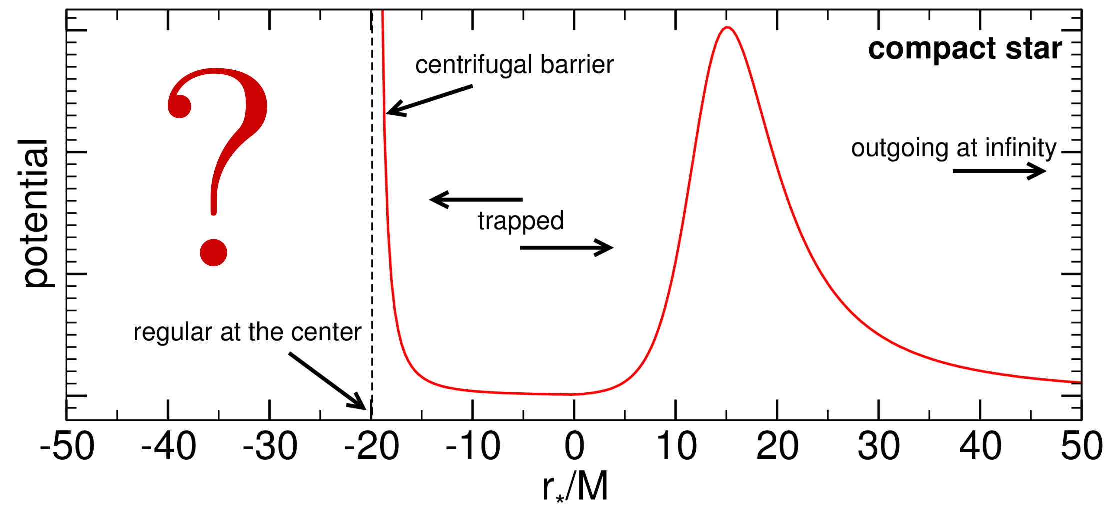


Ultracompact stars generically support trapped modes

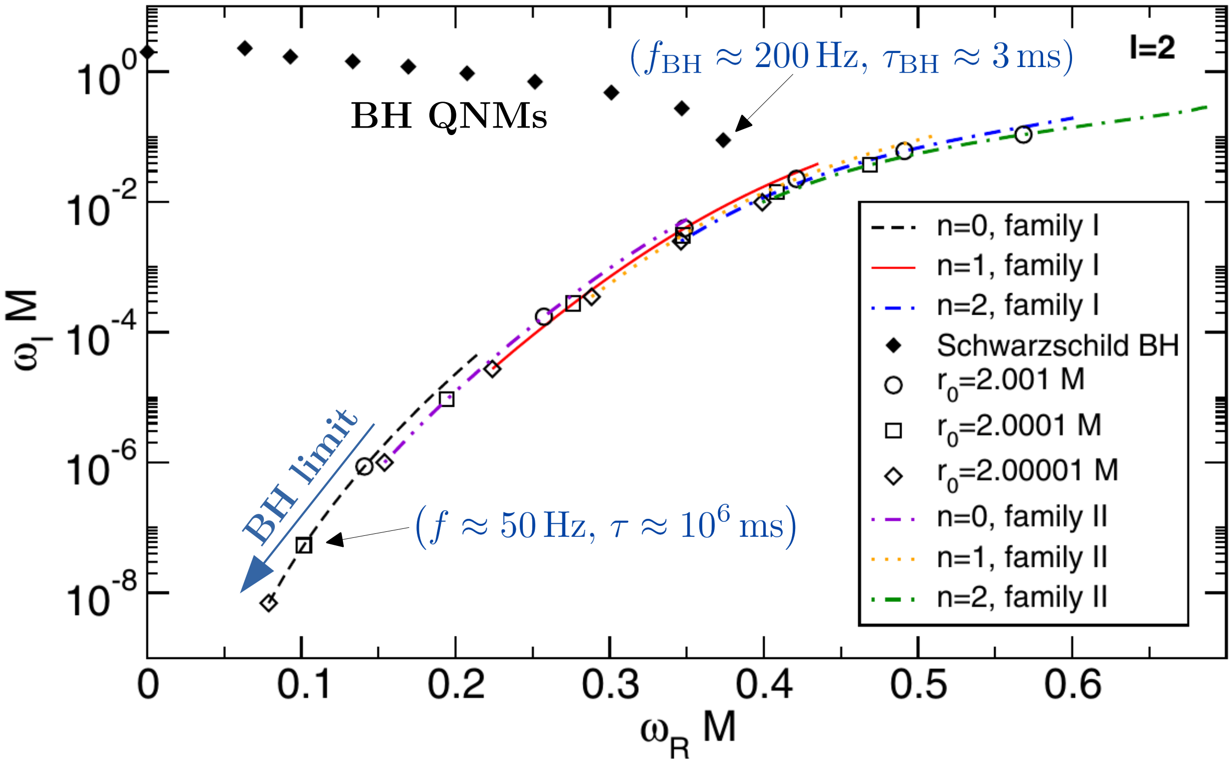
Chandrasekhar & Ferrari PRSLA (1991)



No horizon $\rightarrow$ QNM spectrum dramatically different

QNM spectrum of an UCO

Cardoso, Franzin, Pani, PRL (2016)

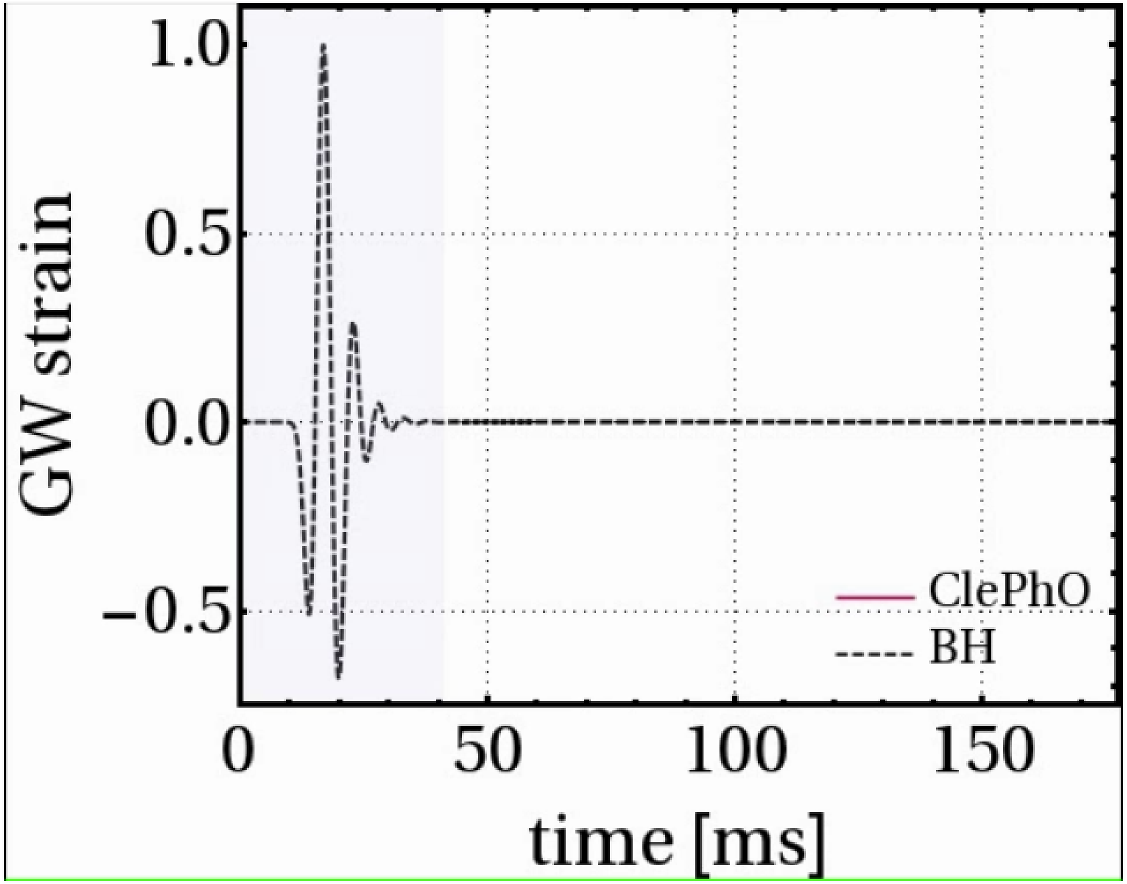


- Generic feature: low-frequency, long-lived QNMs in the BH limit

$$f_{\rm QNM} \sim |\log \epsilon|^{-1} \qquad \tau \sim |\log \epsilon|^{2l+3} \qquad r_0 = r_+(1+\epsilon)$$

- QNM spectrum dramatically different → ringdown?

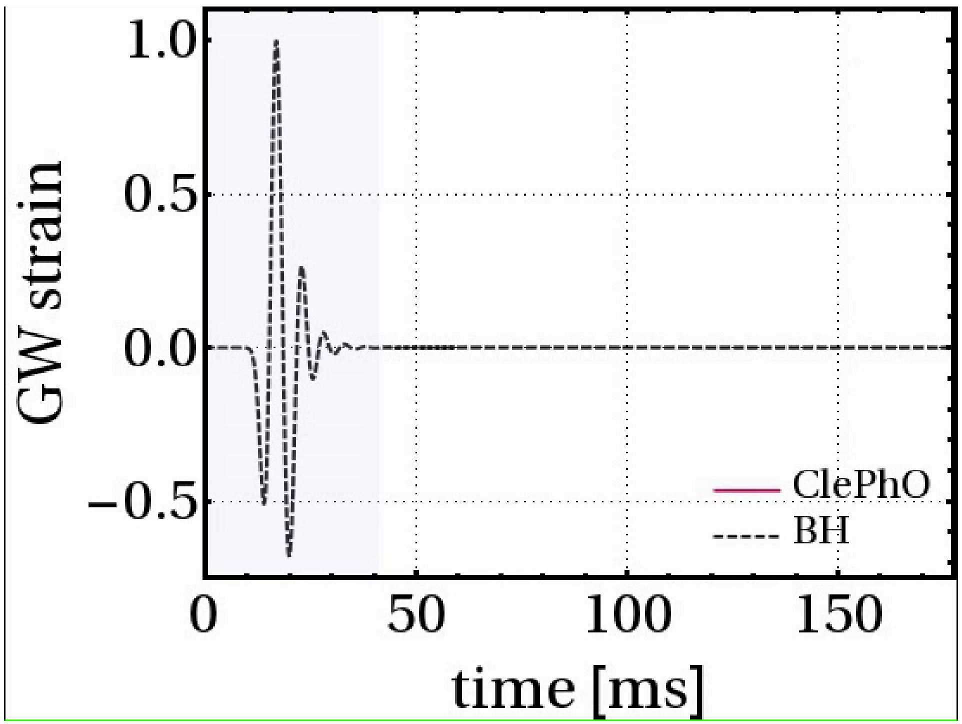
GW echoes



Ringdown of a Schwarzschild BH
(Gaussian perturbation)

GW echoes

Cardoso & PP, Nature Astronomy (2017)



Prompt ringdown is identical, but GW "echoes" at late time

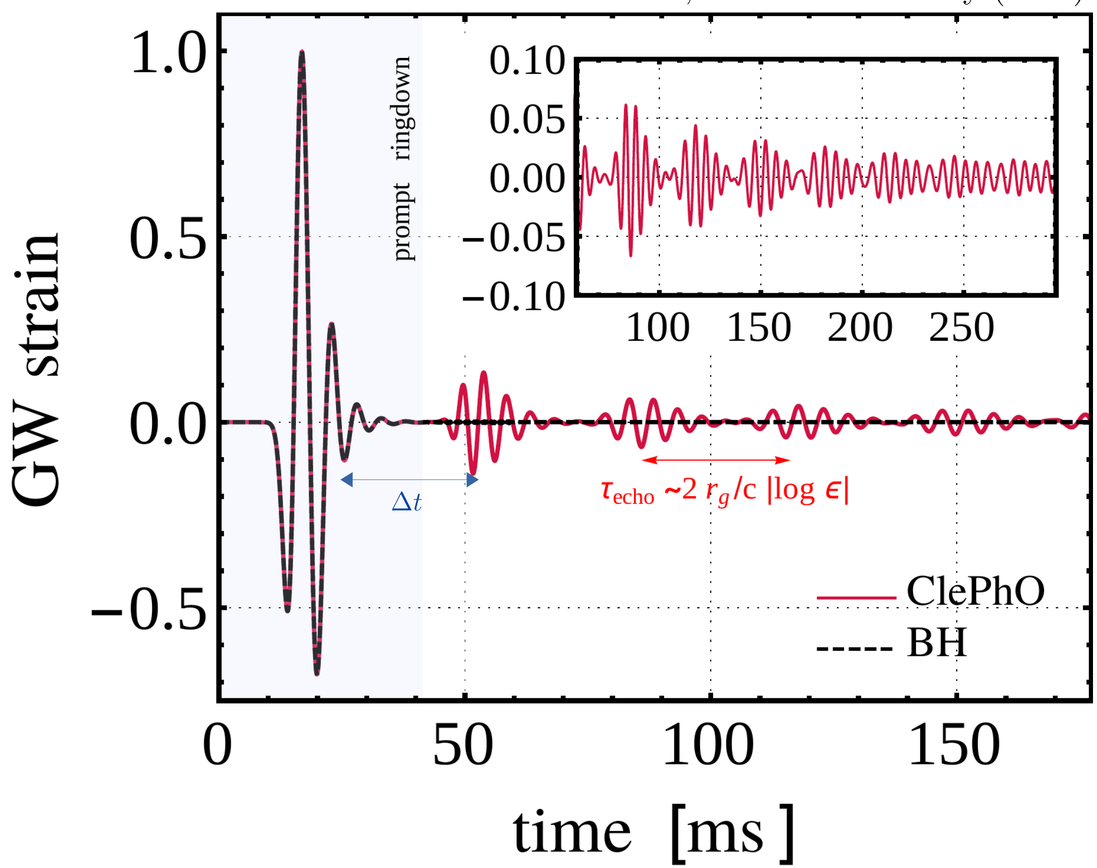
Kokkotas 1996; Ferrari & Kokkotas, PRD 2000
Cardoso, Franzin, PP, PRL (2016), Cardoso+ PRD (2016)

$$\tau_{\rm echo} = \int_{r_0}^{3M} \frac{dr}{F} \sim \frac{2GM}{c^3} |\log \epsilon|$$

Delay time → log dependence

GW echoes

Cardoso & PP, Nature Astronomy (2017)



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$$\tau_{\rm echo} = \int_{r_0}^{3M} \frac{dr}{F} \sim \frac{2GM}{c^3}|\log\epsilon|$$

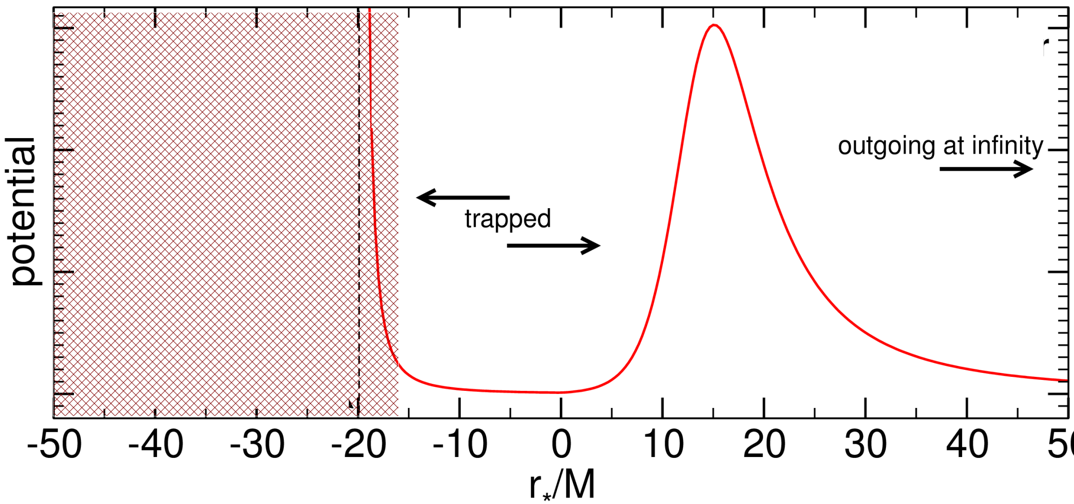
Delay time → log dependence

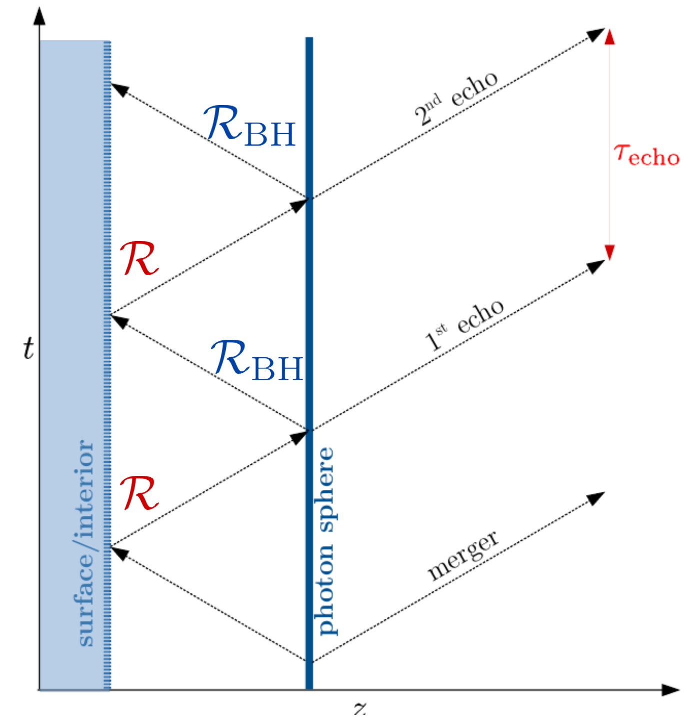
- Even Planck-scale corrections near horizon are within reach!

$$r_0 - 2M \sim L_p \approx 10^{-33}\,{\rm cm} \Rightarrow \tau_{\rm echo} \sim \frac{GM}{c^3}|\log\epsilon| \sim \mathcal{O}(50\,{\rm ms})$$

Model-independent signatures

- Only a (classical) horizon absorbs everything!





- Reflectivity arises in many contexts:
  - Stellar-like regular interior
  - "Fuzziness"
  - Quantum emission from horizon
- Can be modelled by frequency-dependent reflectivity coefficient

GW searches for echoes with LIGO/Virgo

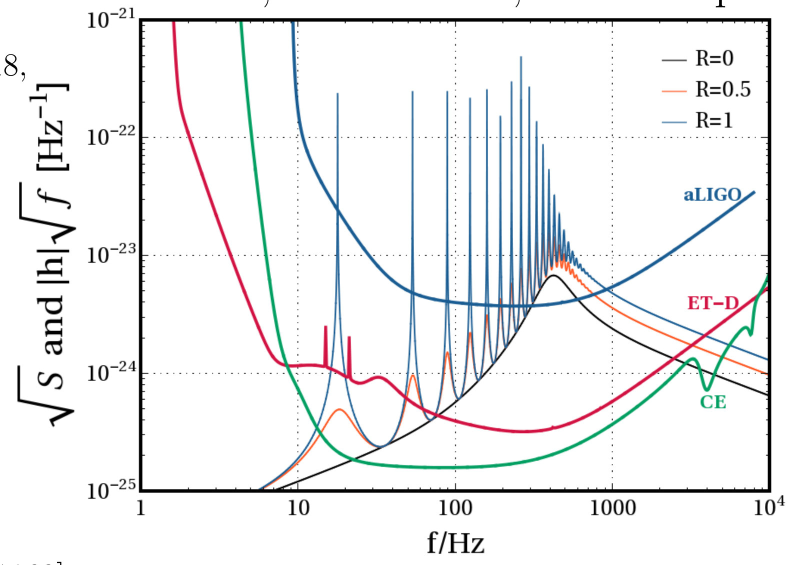
- Tentative evidence in LIGO O1 [Abedi+, 2017, Conklin+ 2018]

- Contrasting results [Abedi+ 2017-2018, Ashton+ 2017, Westerweck+ 2018, Conklin+ 2019]

- Tentative detection of ~72 Hz echoes @4.2σ in GW170817 [Abedi & Afshordi JCAP 2019]

- Absence of statistical evidence in O1 and O2 confirmed by recent analyses [Uchikata+ PRD 2019, Tsang+ 1906.11168]

d=100 M, M=30 Msun, D=400 Mpc

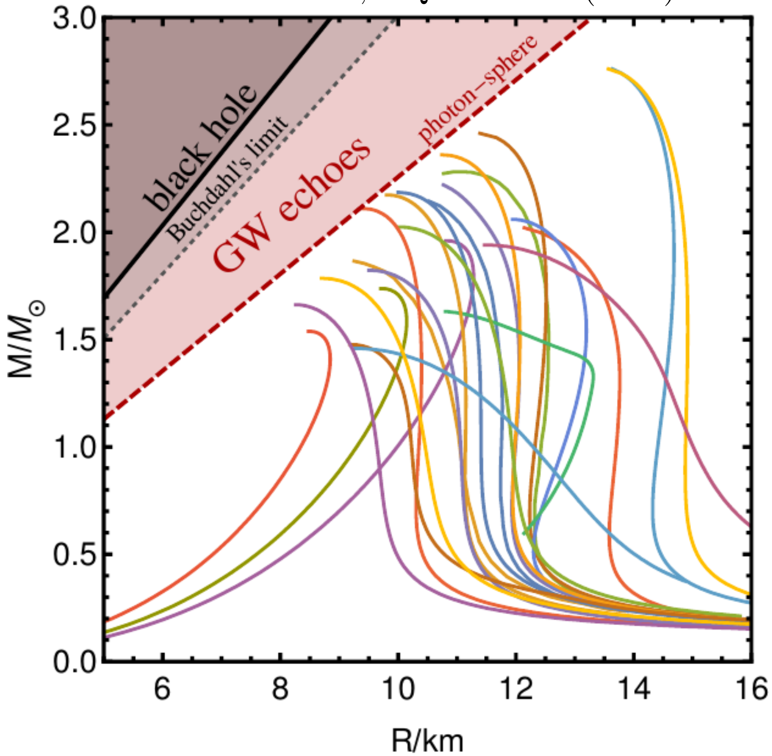


- Near-horizon quantum (?) structures within reach!
- Negative searches also important → constrain/rule out ECO models

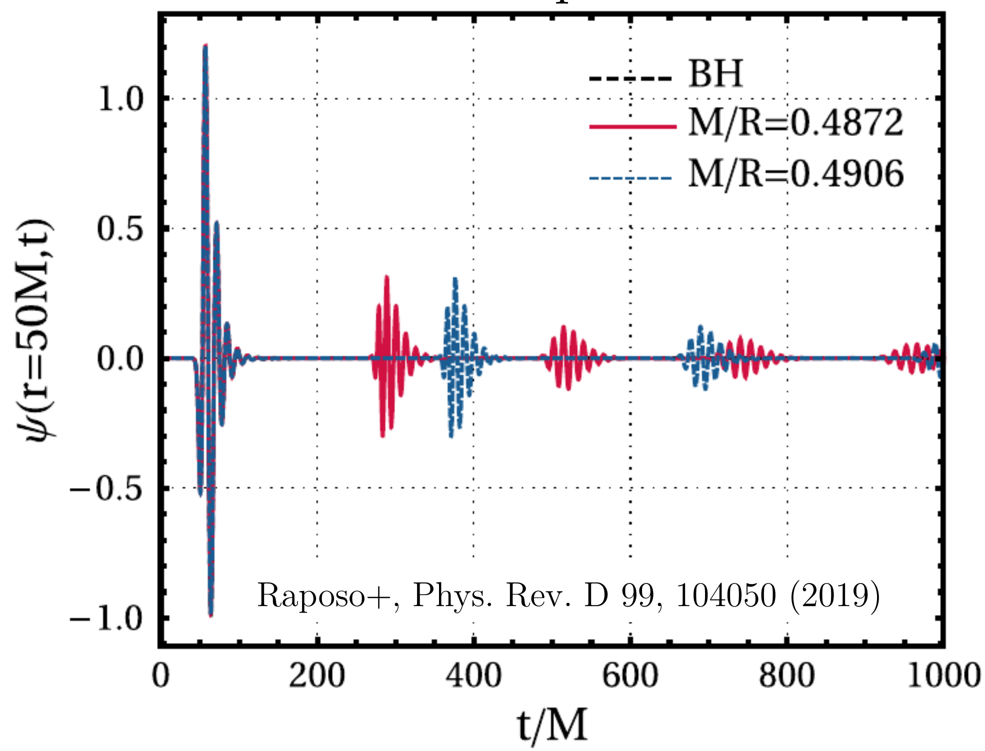
Potential inferences from echoes

→ Remnant has photon sphere but ∼ no horizon → neither GR BH *nor* ordinary NS

PP & Ferrari, CQG Letters (2018)



Anisotropic stars



Echoes in GW170817-like system would be compatible with

- Near-horizon quantum structures [Cardoso+ 2016, Abedi+ 2017, Wang+ 2019, ...]
- NS with very exotic matter [Pani-Ferrari 2018, Mannarelli & Tonelli, PRD 2018])
- Modified theories of gravity [Conklin+ 2017, Buoninfante+ 2019, Delhom+ 2019]

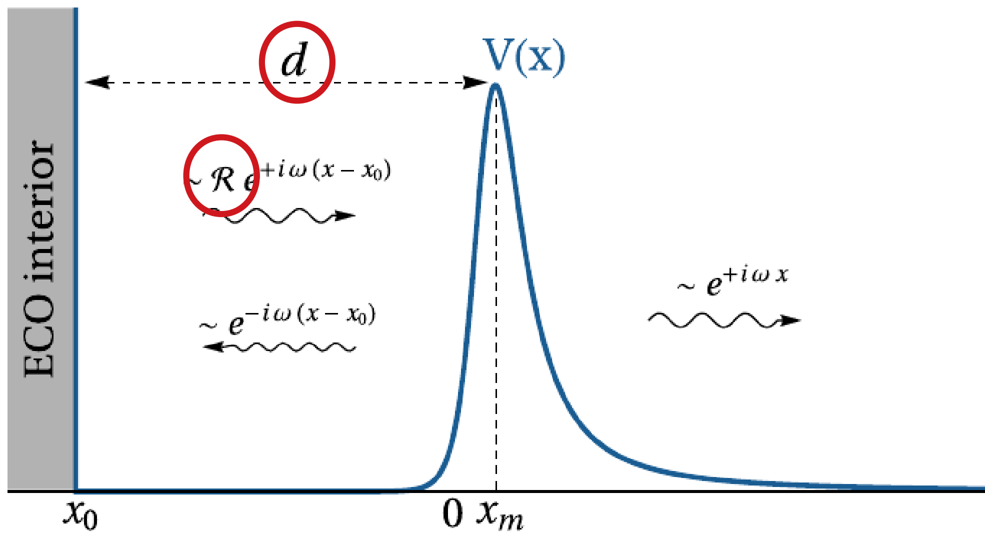
GW echo modeling

Signal is rich: amplitude/frequency modulation, spin effects, reflectivity...

- Re-processing through a transfer function [Mark+ PRD96 084002 (2017)]

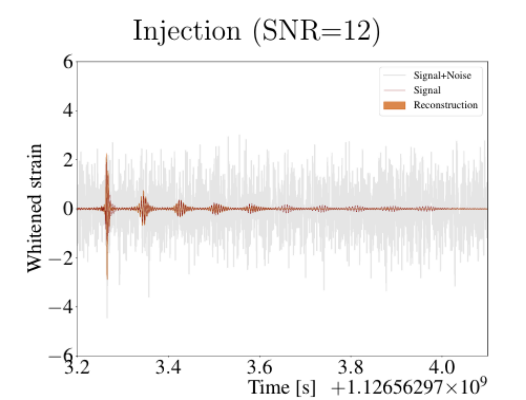
$$\tilde{Z}^{+}(\omega) = \tilde{Z}^{+}_{\rm BH}(\omega) + \mathcal{K}(\omega)\tilde{Z}^{-}_{\rm BH}(\omega)$$

$$\mathcal{K}(\omega) = \frac{\mathcal{T}_{\rm BH}\mathcal{R}}{1-\mathcal{R}_{\rm BH}\mathcal{R}}$$



- Progress in modeling [Nakano+ 2017; Mark+ 2017; Maselli+ 2017, Bueno+ 2018, Wang & Afshordi PRD 2018, Tsang+ 2018-2019, Testa & PP 2018, Wang+ 2019, Uchikata+ 2019, Maggio+ 2019...]

- Other strategies:
  - Dyson series (potential as a perturbation) [Correia & Cardoso PRD 2018]
  - Resonances (in the transfer function) [Conklin+ 2018-2019]
  - Model-agnostic "wavelets" burst searches [Tsang+ PRD 2018, 1906.11168]

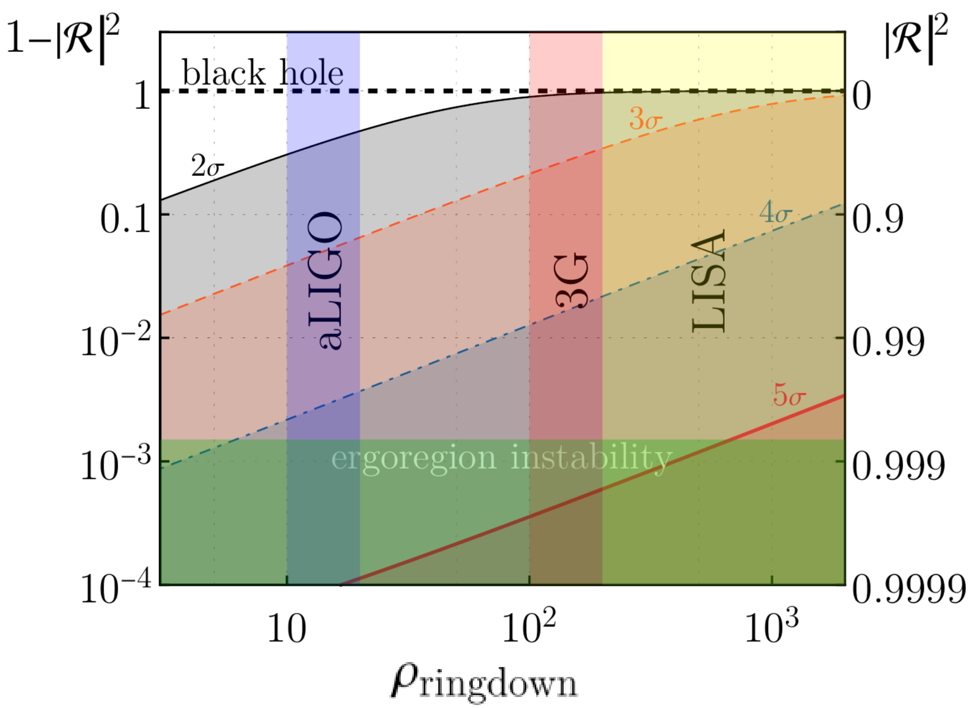


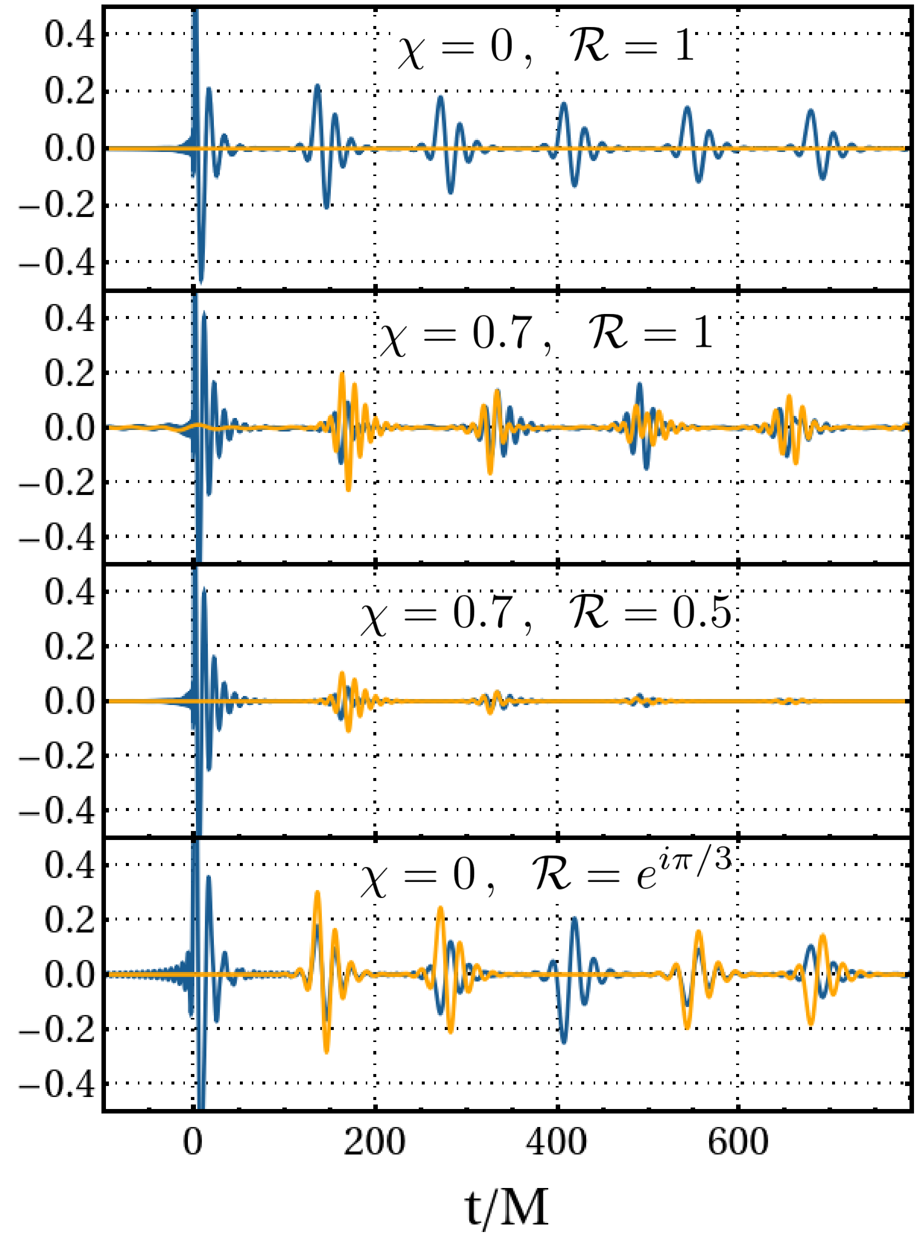
Echo modeling & detectability

[Testa & PP PRD 2018, Maggio+ PRD 2019]

Physically-motivated, analytical template:

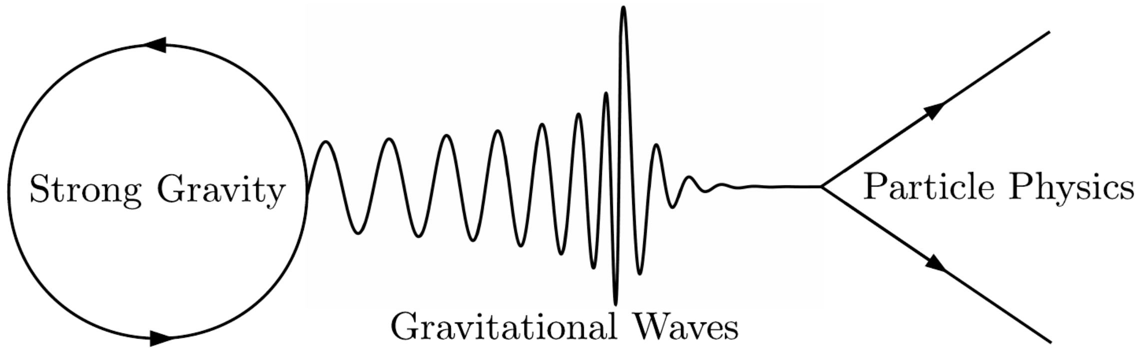
- Reflectivity can be complex!
- Mixing of polarizations
- Spin-dependent modulation
- Large reflectivity crucial for detection





Waveforms, templates, and movies available @ http://www.DarkGRA.org/gw-echo-catalogue.html

Conclusion & Outlook



Cardoso, Pani - CERN Courier, Jan 2017

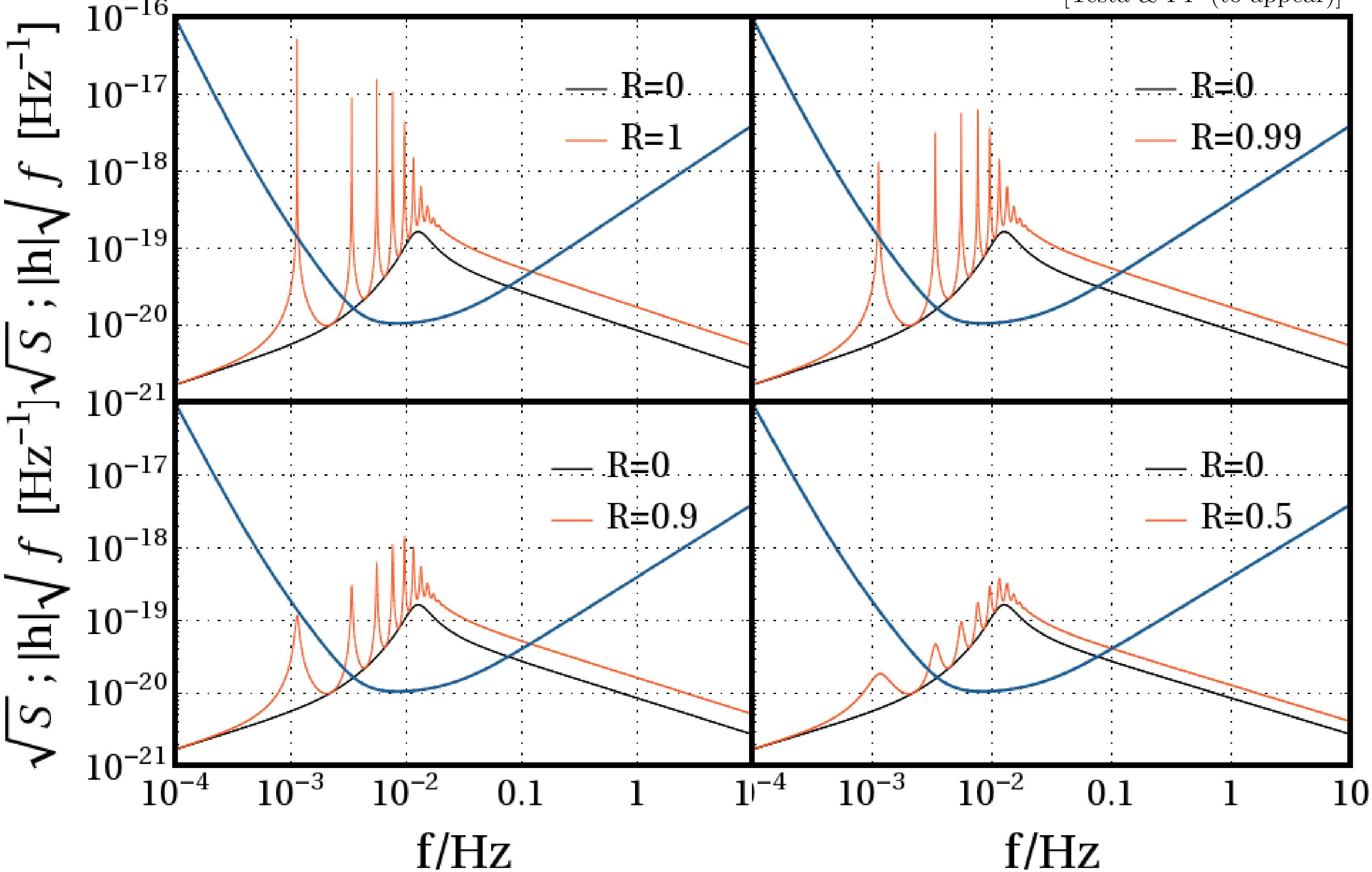
- Gravity community is undergoing a revolution
- Probing fundamental physics with gravitational observations
  - **Testing quantum gravity? In the search of a log...**
  - **Better understanding/modeling is needed** (especially of IMR signal)
  - Current observations put new constraints on ECO models
- Mimicking BHs is extremely challenging $\rightarrow$ observational & theoretical issues

Backup slides

"Nothing is More Necessary than the Unnecessary" [cit.]

Echoes VS LISA noise curve

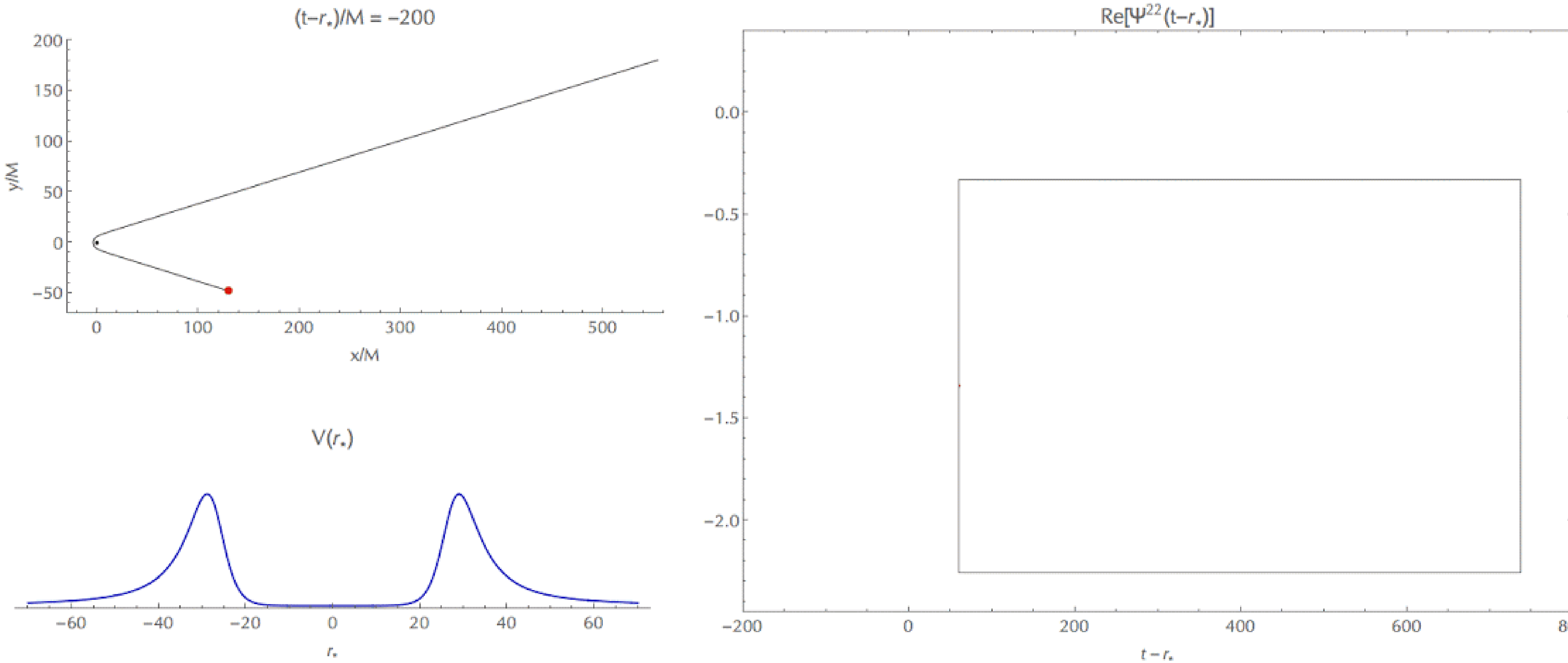
[Testa & PP (to appear)]



The role of the photon sphere

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

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



[Credits: Seth Hopper]

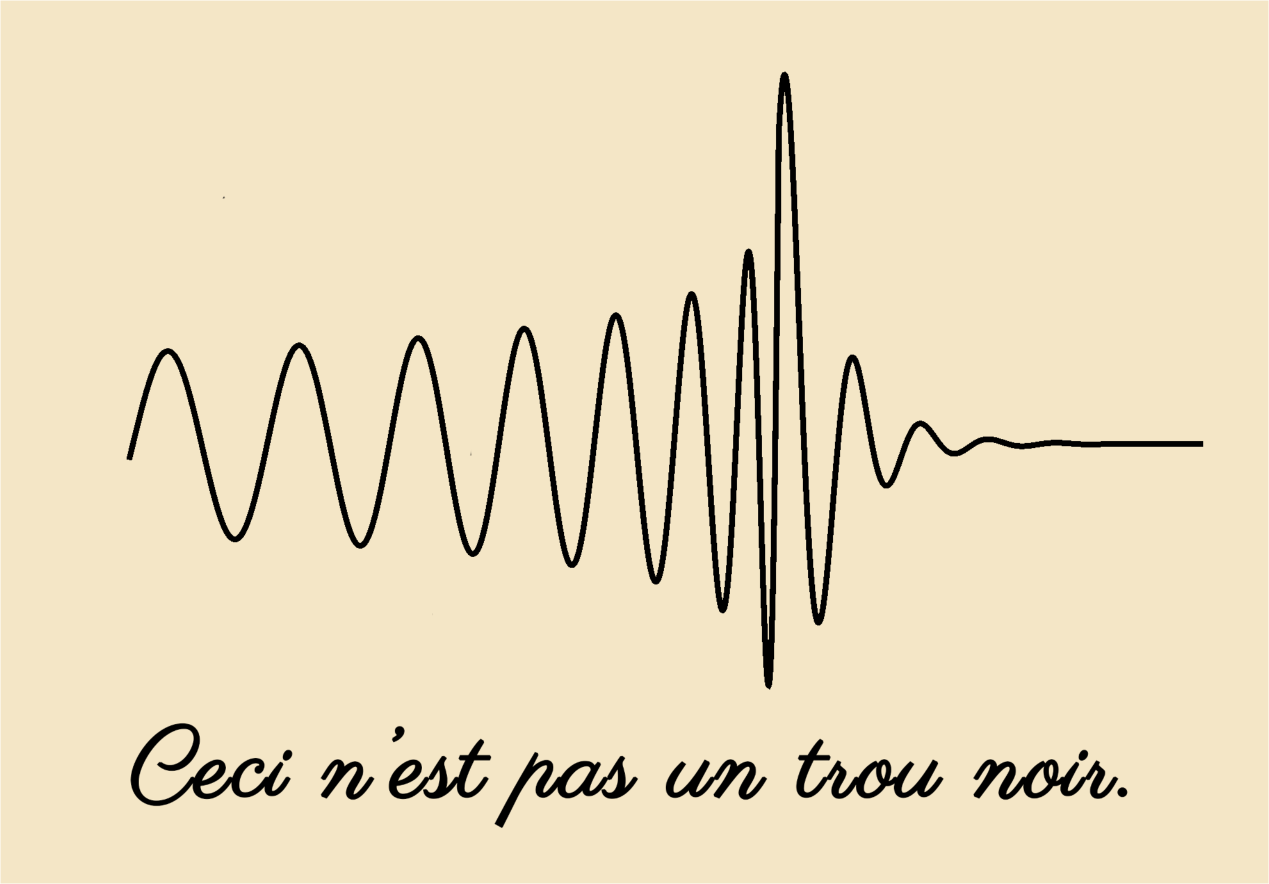
- Generic features for ultracompact ECOs (wormholes, gravastars,ultracompact stars, ...)

[Ferrari & Kokkotas, PRD 2000]

- The ringdown of ECOs without light ring is *qualitatively* different

[Chirenti & Rezzolla, PRD 2016]

- GW observations can rule out less compact ECOs without light ring


Ceci n'est pas un trou noir.

Searching for the absence

When testing *BHs we don't look for something, but for the* ***absence*** *thereof*

- Surface / internal structure
- Radiation *from* the object
- Hair / multipolar structure
- Tidal Love numbers

BHs are **unique** yet **simple**

- BHs in GR+SM described by 3 parameters → multiple consistency tests

Need models and framework to go beyond null tests