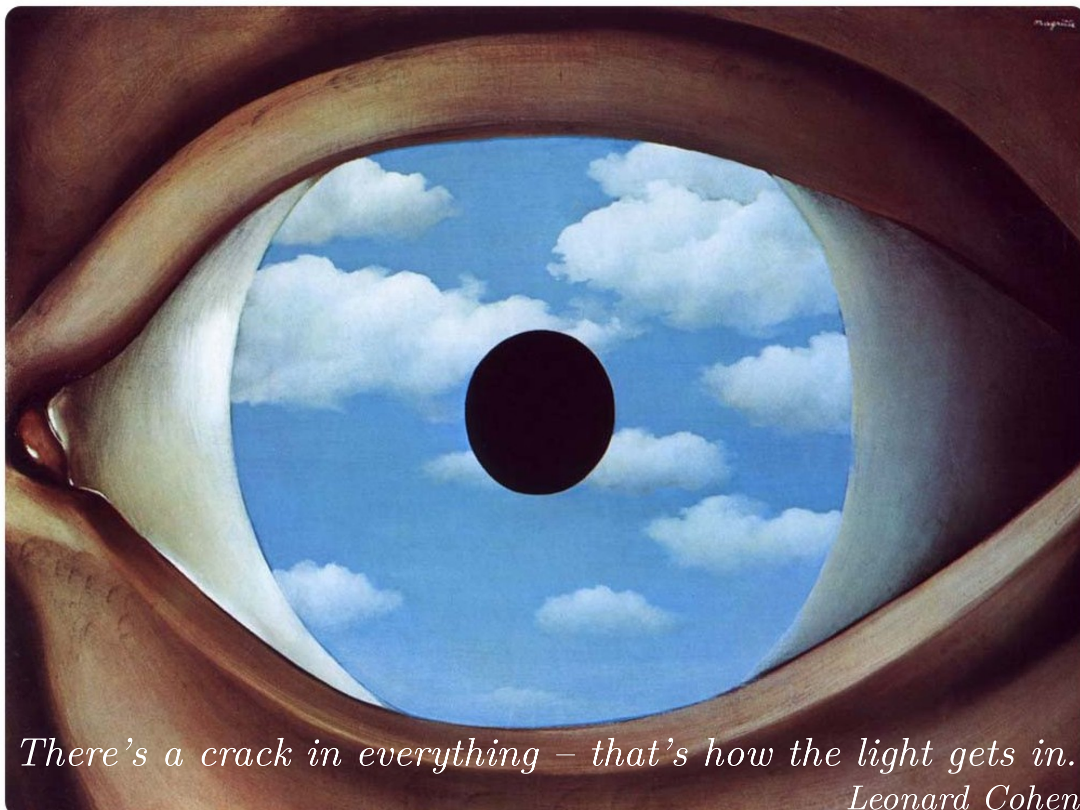
Testing the nature of dark compact objects



Paolo Pani
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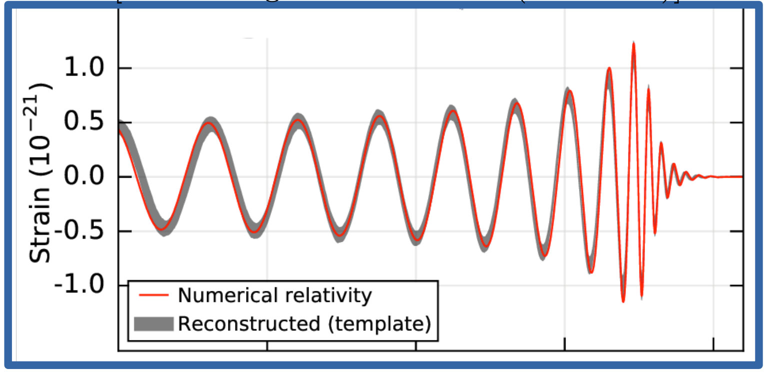
European Research Council
DarkGRA

Disclaimer

- **The observational status of black holes (BHs) is now more solid than ever**
- **(Classical) BHs in GR are very economical:**
  - Arbitrary mass
  - Compactness $M/R \sim 1$ (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 *extreme compact objects* (ECOs)?

Testing BHs, why should we care?

1. Problems on the horizon

- BH exterior is fine, interior is not $\rightarrow$ **singularities**, Cauchy horizons, CTCs...
- BHs are *required* for self consistency of General Relativity (GR) [Cosmic Censorship]
- Drawbacks: Huge entropy, **unitarity loss**, thermodyn. instability [Hawking 1972]

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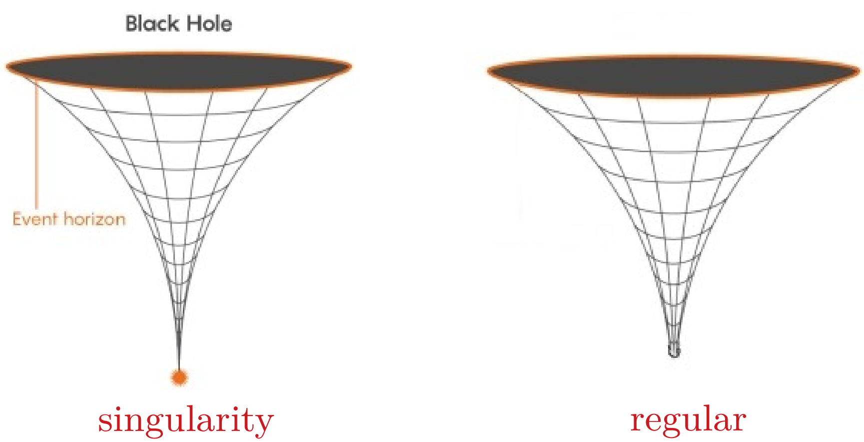
- BHs are *required* for self consistency of General Relativity (GR) [Cosmic Censorship]
- Drawbacks: Huge entropy, **unitarity loss**, thermodyn. instability [Hawking 1972]
- Resolution of Hawking's paradox might require drastic changes at the horizon:
  - New physics at the horizon (e.g. firewalls, nonlocality) [Almheri+, Giddings+, 2012-2017]
  - Regular, horizonless compact objects (e.g. fuzzballs) [Mathur, 2007-now]



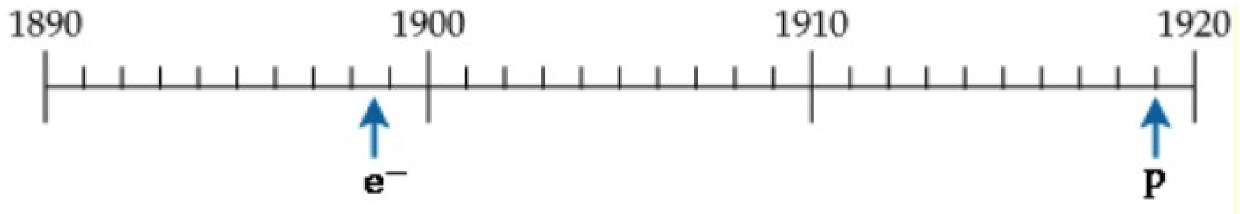
Recent breakthroughs → microstate geometries in SUGRA [Bena+ 2015, Turton, Warner...]

Testing BHs, why should we care?

1. Problems on the horizon

2. New species of compact objects?

Lesson from timeline of particle physics discovery



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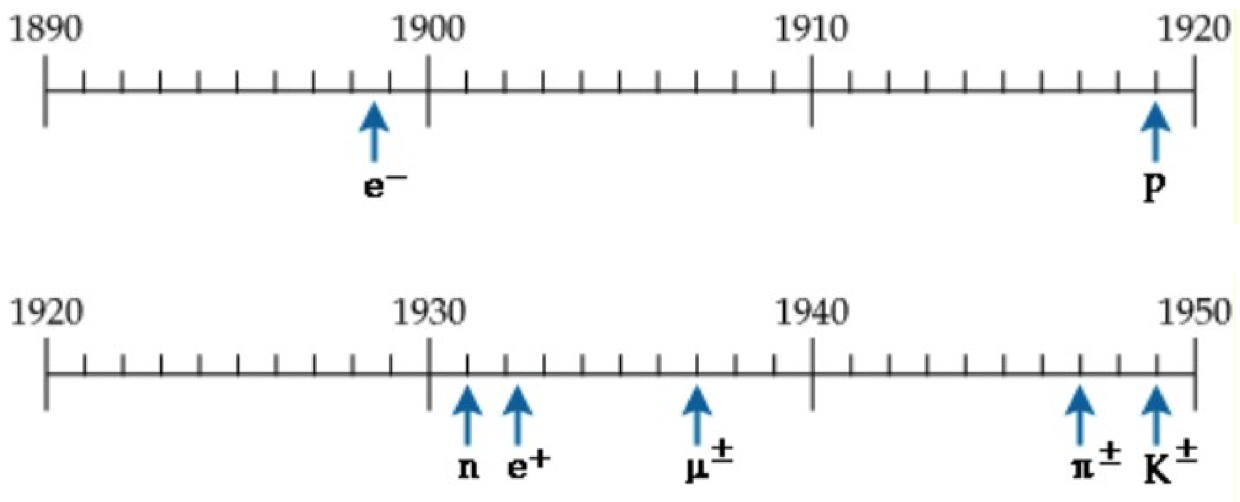

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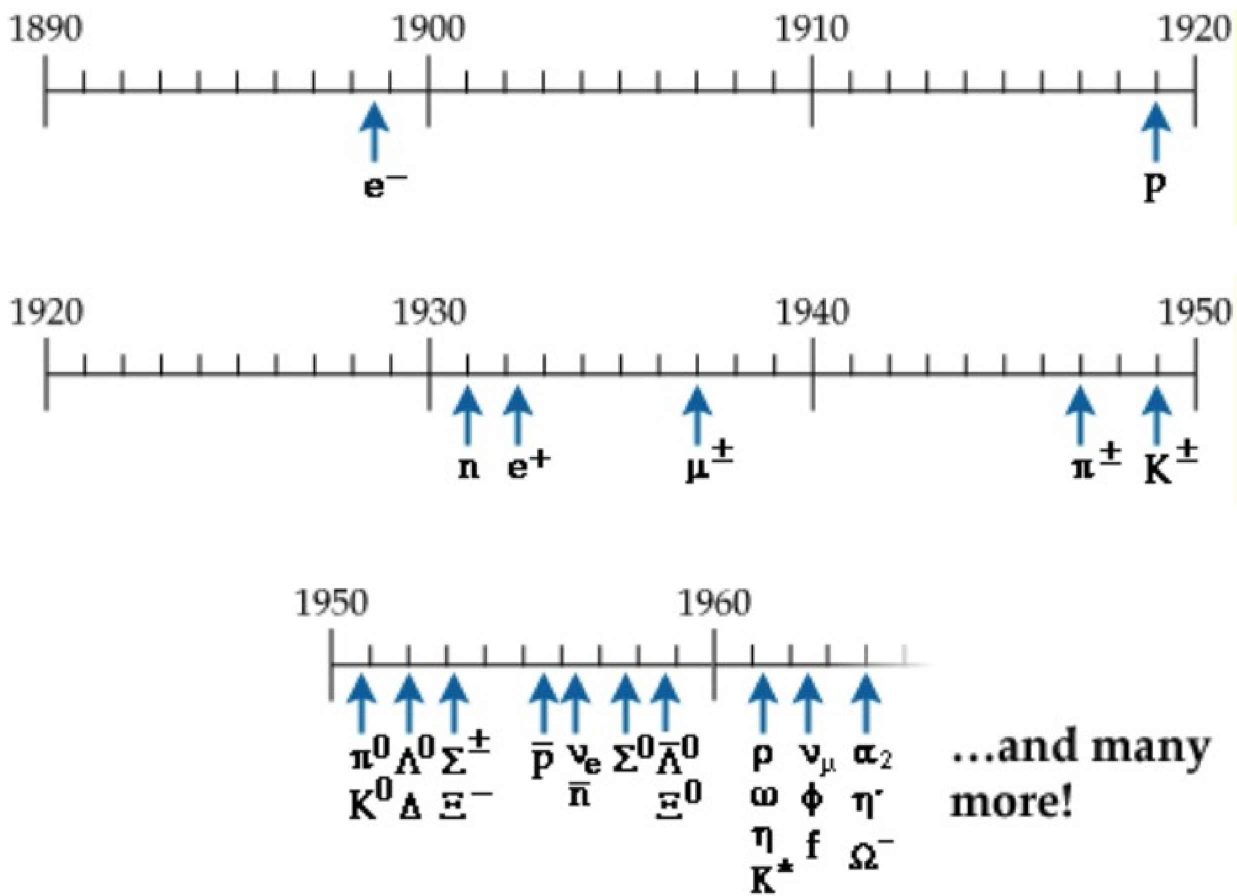

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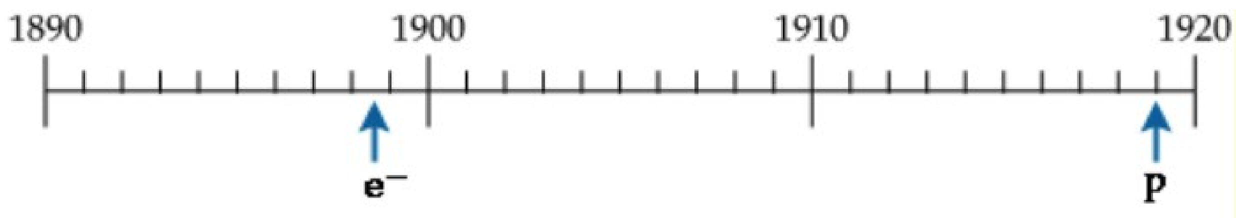
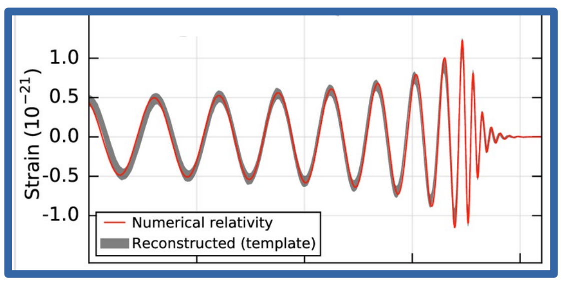
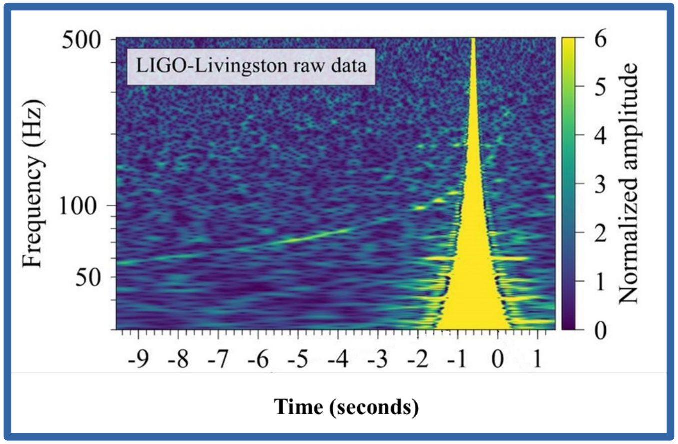




2015: BBHs



2017: BNSs

2020s: BXXs?

Testing BHs, why should we care?

1. Problems on the horizon
   - Singularities, information loss paradox
2. New species of compact objects?
   - Are there other compact objects besides BHs and neutron stars?
3. The dark matter connection
   - *Can ECOs form (part of) the dark matter?*
   - *Example:* boson stars might form if axion-like particles exist in the universe

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   - *Can ECOs form (part of) the dark matter?*
   - *Example:* boson stars might form if axion-like particles exist in the universe
4. Quantifying the evidence for BHs, a fundamental prediction of GR
   - How to even *formulate* the problem?
   - Lessons from tests of the weak equivalence principle, beyond SM physics, etc

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

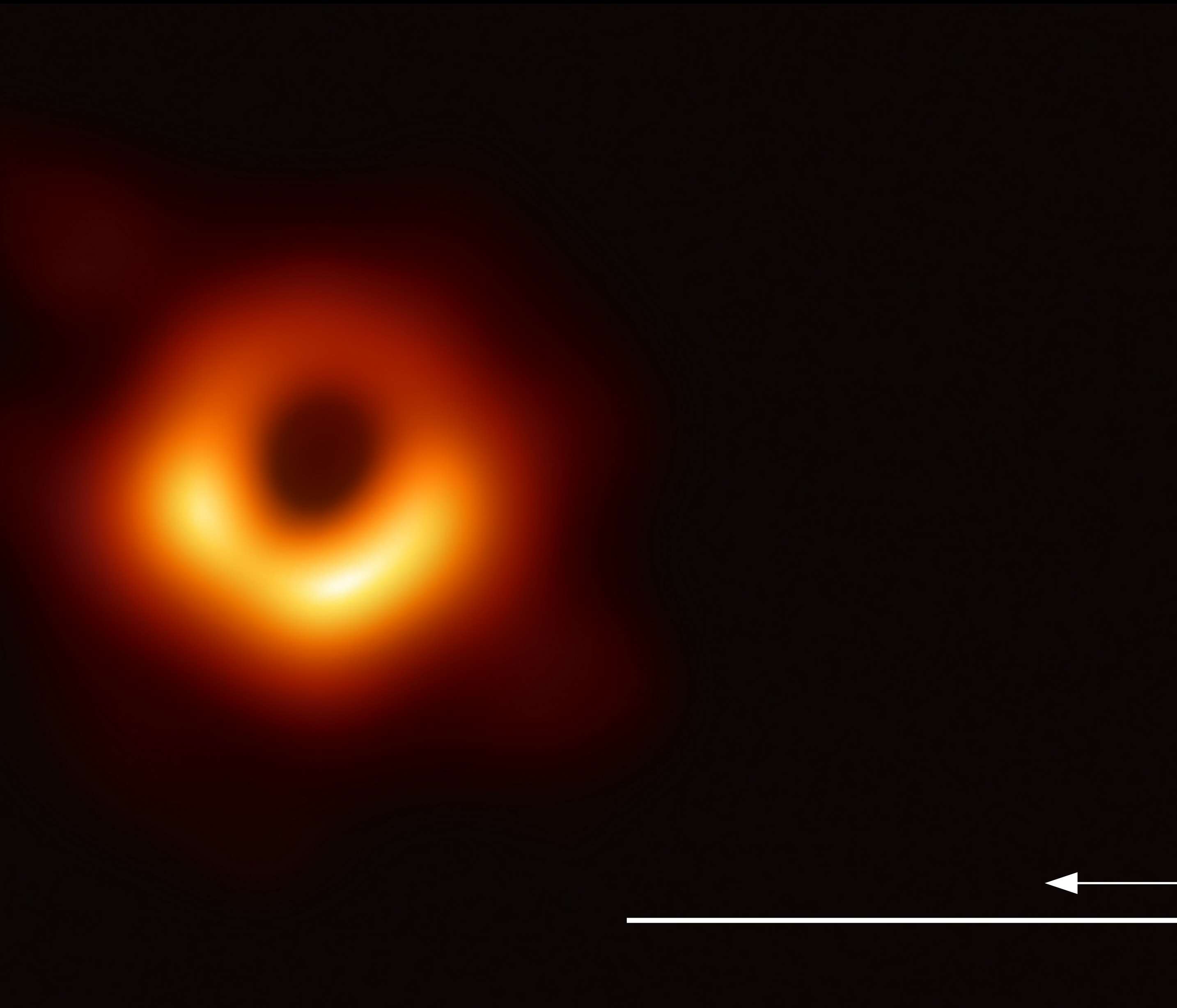
BHs are **unique** yet **simple**

- BHs in GR+SM described by 3 params $\rightarrow$ multiple consistency tests

Need models and framework to go beyond null tests

Quantifying the shades of darkness

Quantifying the shades of darkness

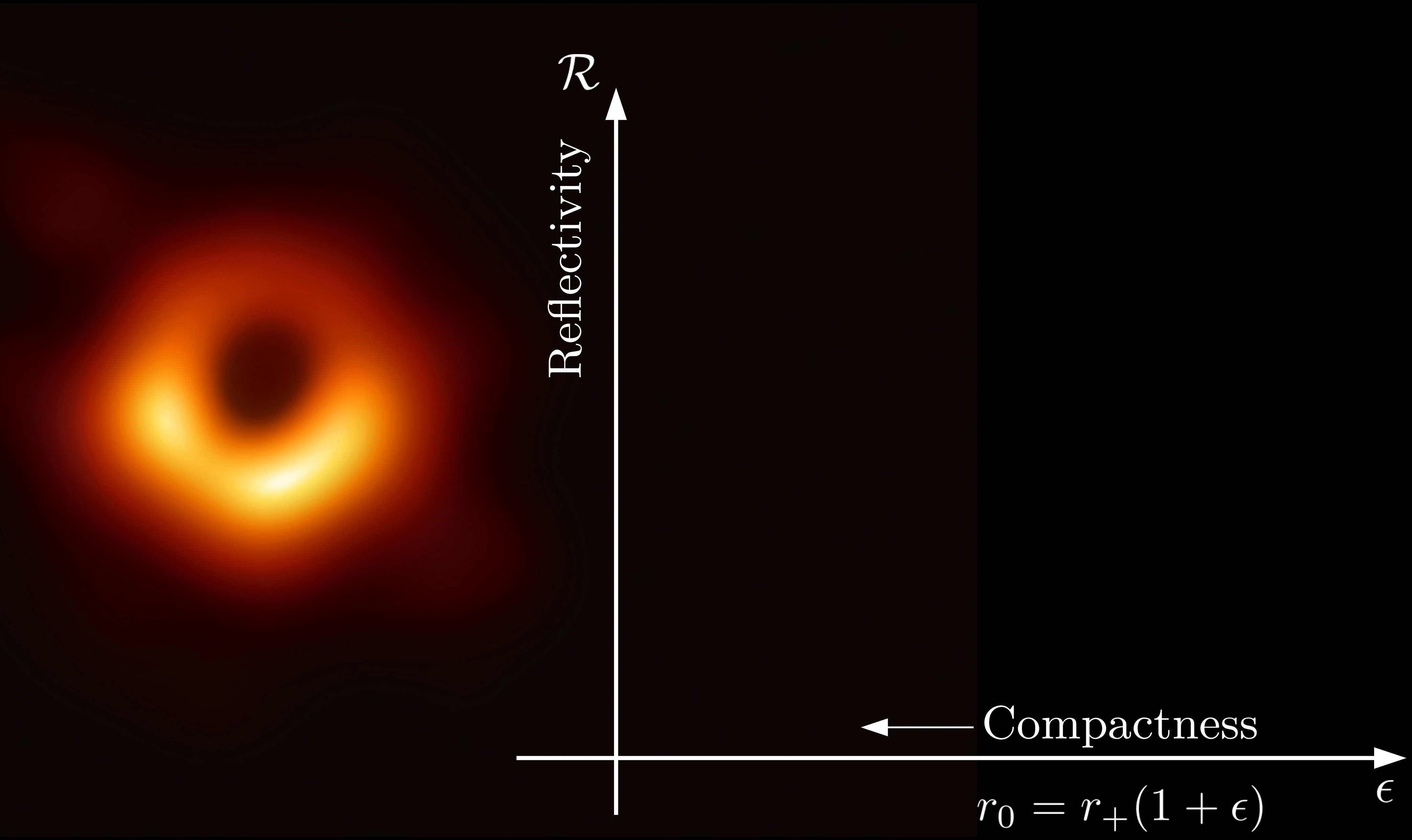


← Compactness

ϵ

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

Quantifying the shades of darkness



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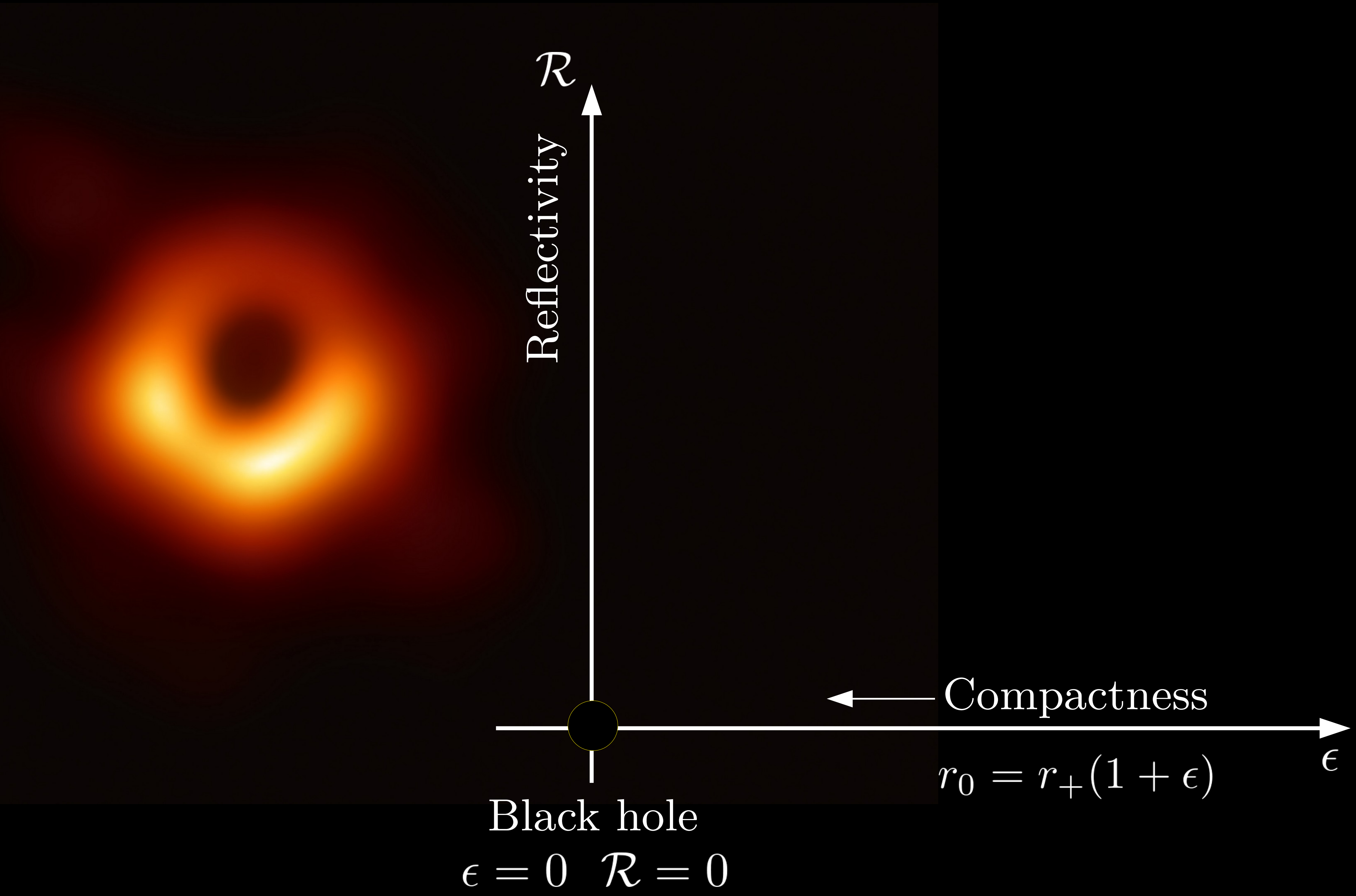

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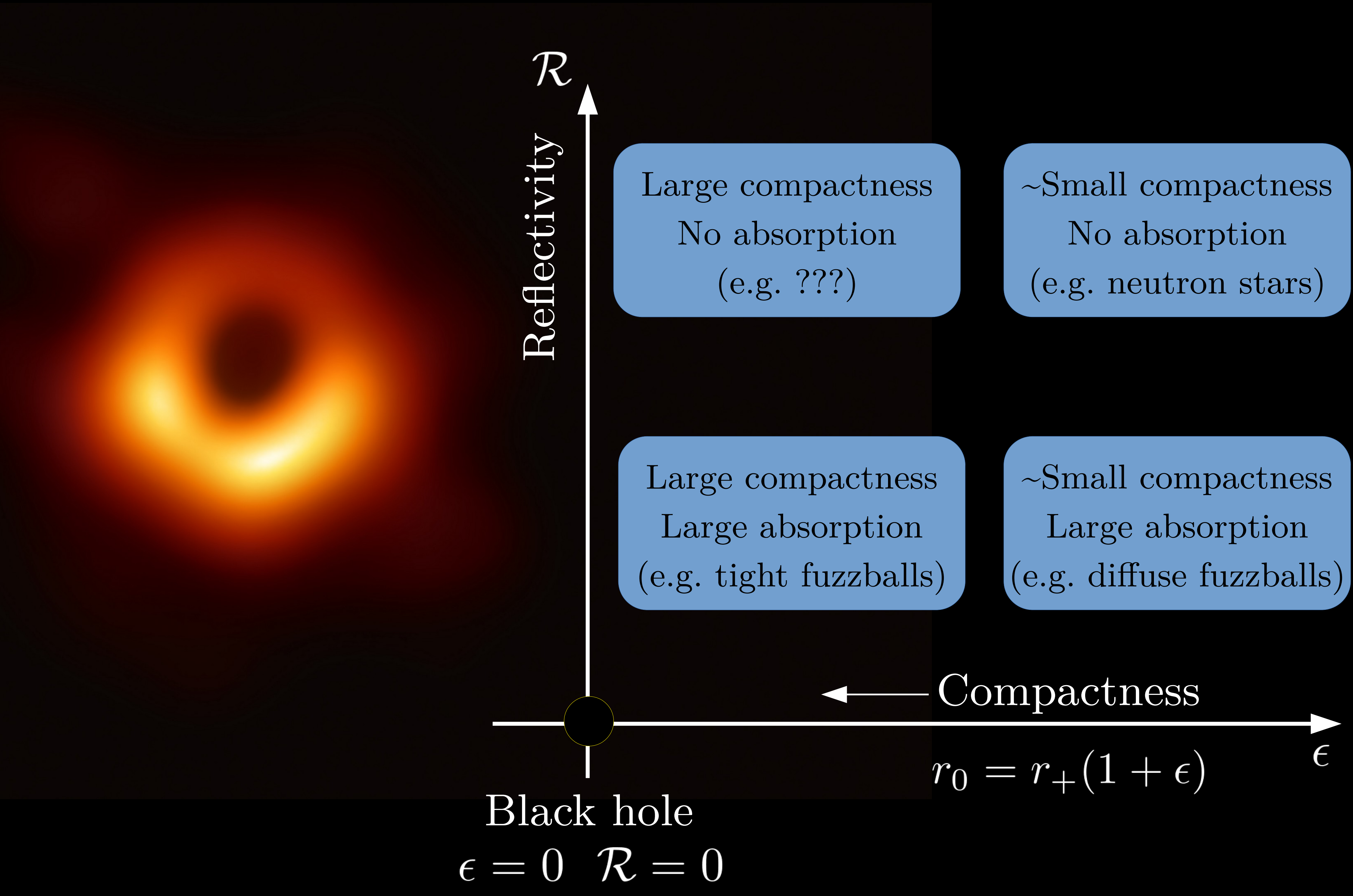


Extreme compact objects (ECOs)

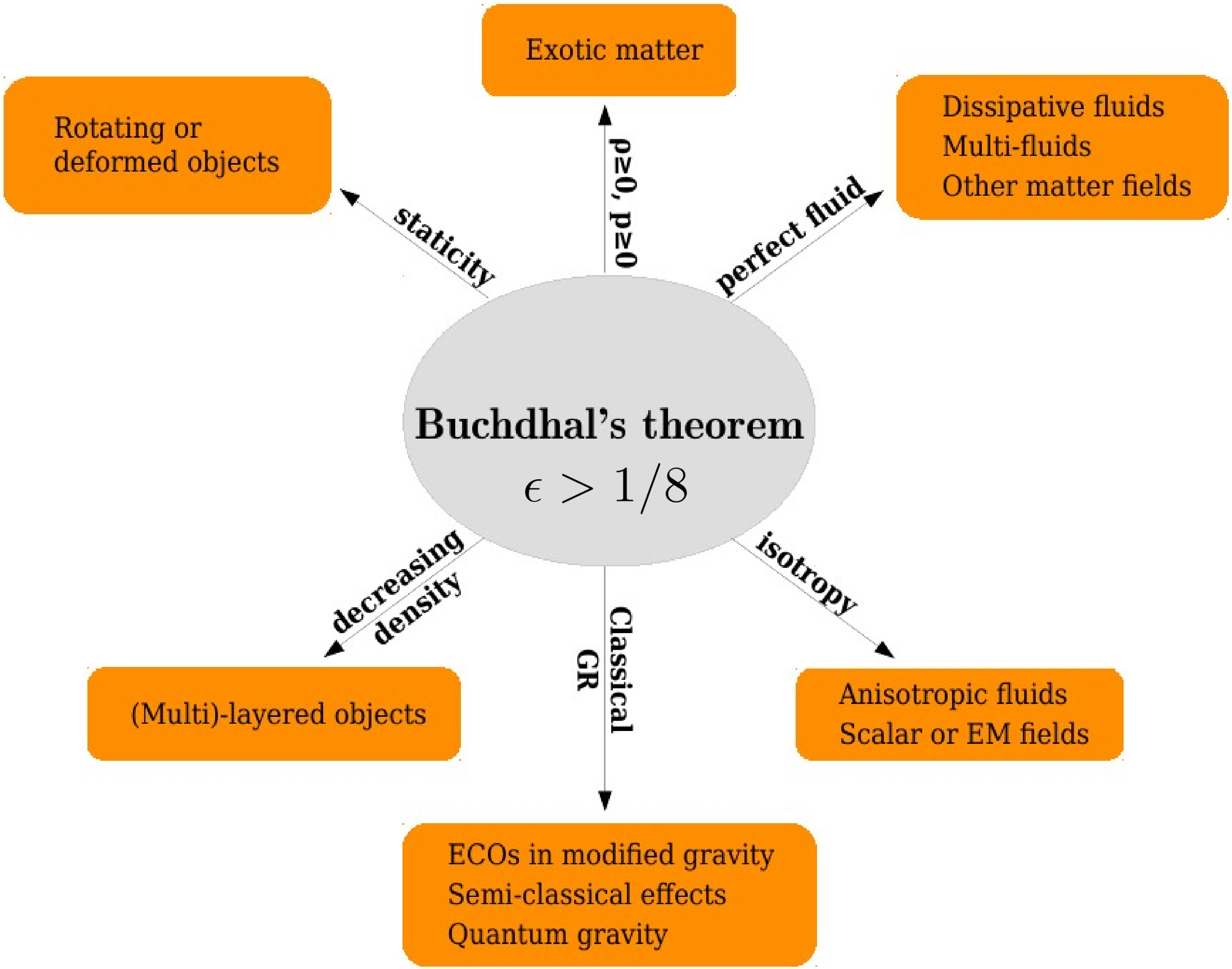
- Several models/proposals
- Different levels of "robustness"
  - Equilibrium sols?
  - Stability?
  - Formation? Coalescence?
- Phenomenologically:
  - "Good" ECOs
  - "Bad" ECOs

Phenomenology can be investigated even in absence of a first-principle framework

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

Model	Formation	Stability	EM signatures	GWs
Fluid stars	✓ 90	✓ 85,88,109–113	✓	✓ 85,109,112,114
Anisotropic stars	✗	✓ 115–117	✓ 118–120	✓ 115,119,120
Boson stars & oscillatons	✓ 53,54,121–123	✓ 86,124–128	✓ 91,129,130	✓ 131–138
Gravastars	✗	✓ 127,139	✓ 140–142	∼ 112,113,135,136,138,142
AdS bubbles	✗	✓ 149	∼ 149	✗
Wormholes	✗	✓ 150–153	✓ 154–157	∼ 136,138,148
Fuzzballs	✗	✗ (but see 158–161)	✗	∼ (but see 135,148,162)
Superspinars	✗	✓ 163,164	✗ (but see 165)	∼ 135,148
2 − 2 holes	✗	✗ (but see 166)	✗ (but see 166)	∼ 135,148
Collapsed polymers	✗ (but see 167,168)	✓ 169	✗ 168	∼
Quantum bounces / Dark stars	✗ (but see 170,171)	✗	✗	∼ 172
Compact quantum objects*	✗ 73,173,174	✗	✗	✓ 38
Firewalls*	✗	✗	✗	∼ 135,175

A compass to navigate ECO atlas

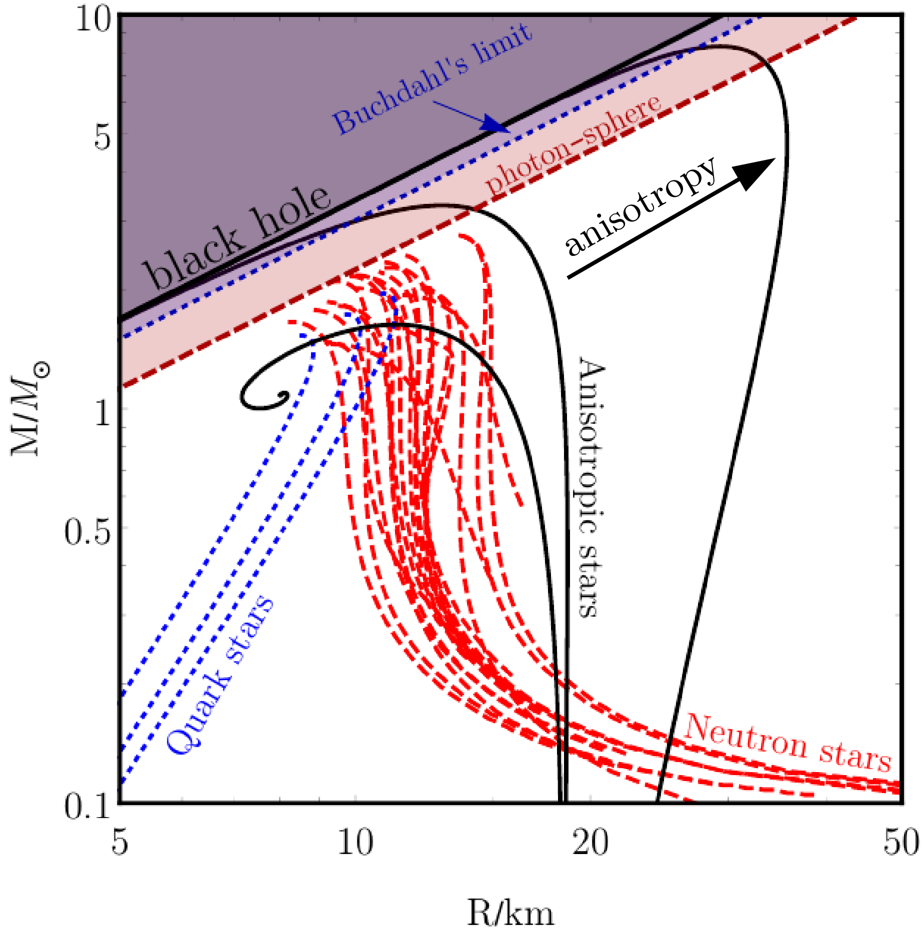


Evading Buchdhal: anisotropic stars

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

- 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

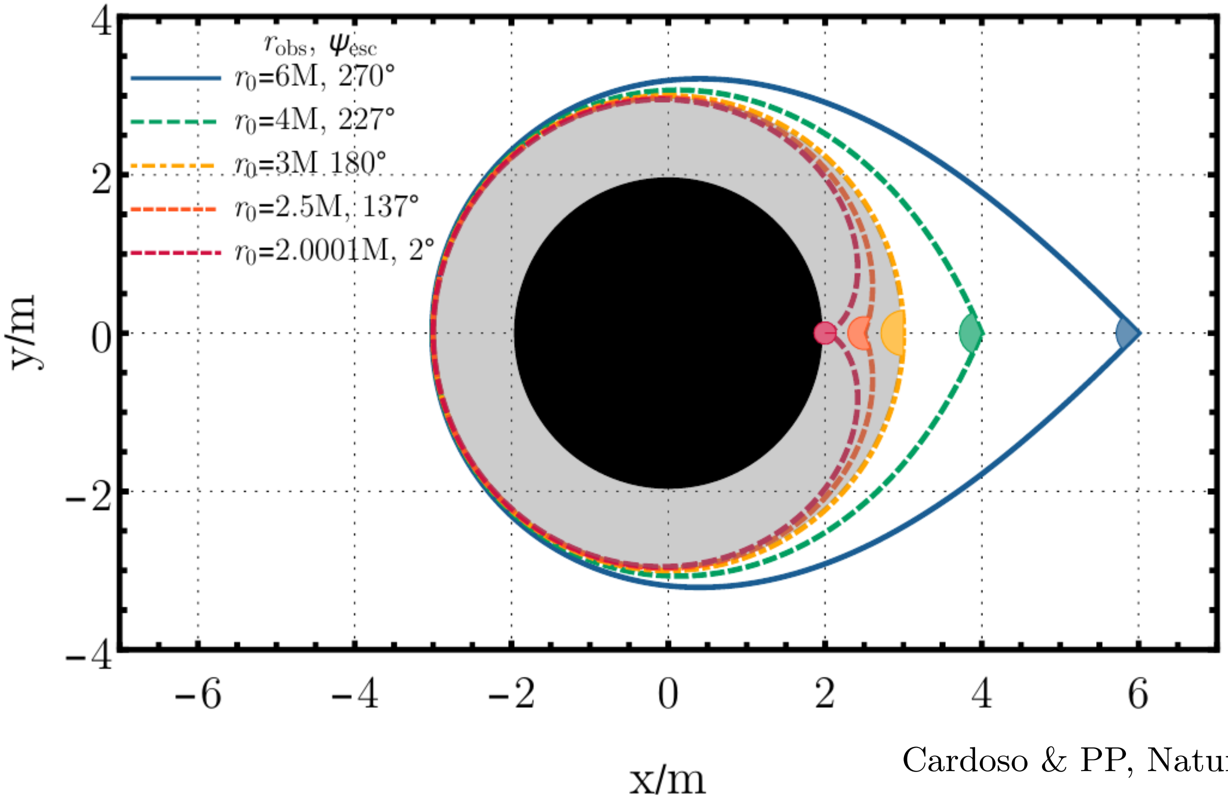
Raposo+, Phys. Rev. D 99, 104050 (2019)



Electromagnetic tests

Are ECOs ruled out by EM obs?

Escape angle ~ O(ε)



Cardoso & PP, Nature Astronomy (2017)

EM tests of the horizon are very challenging, *if possible at all!*

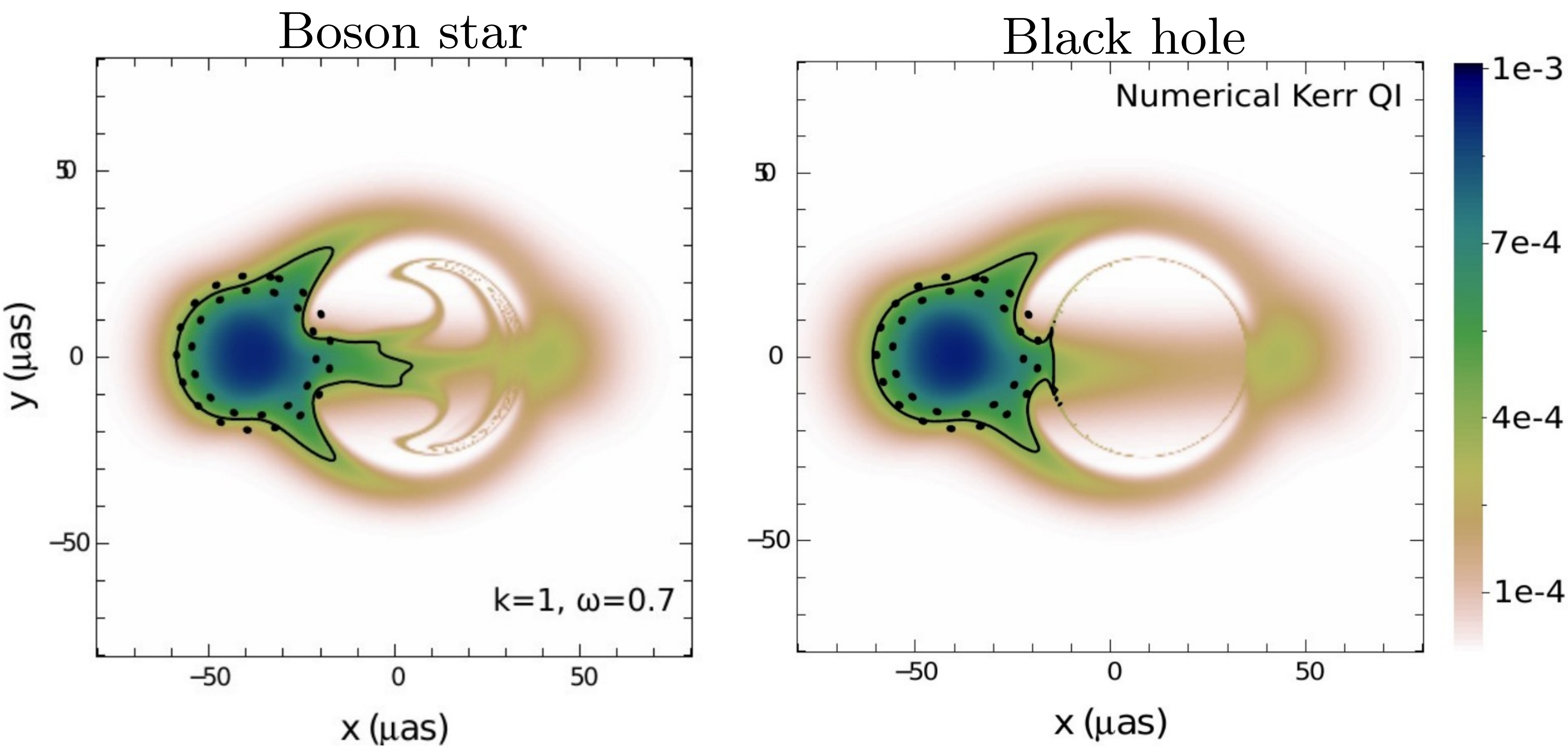
[Abramowicz+ (2012)]

The silhouette of a black hole?

[Event Horizon Collaboration (2019)]

Shadows: BH vs Boson Star

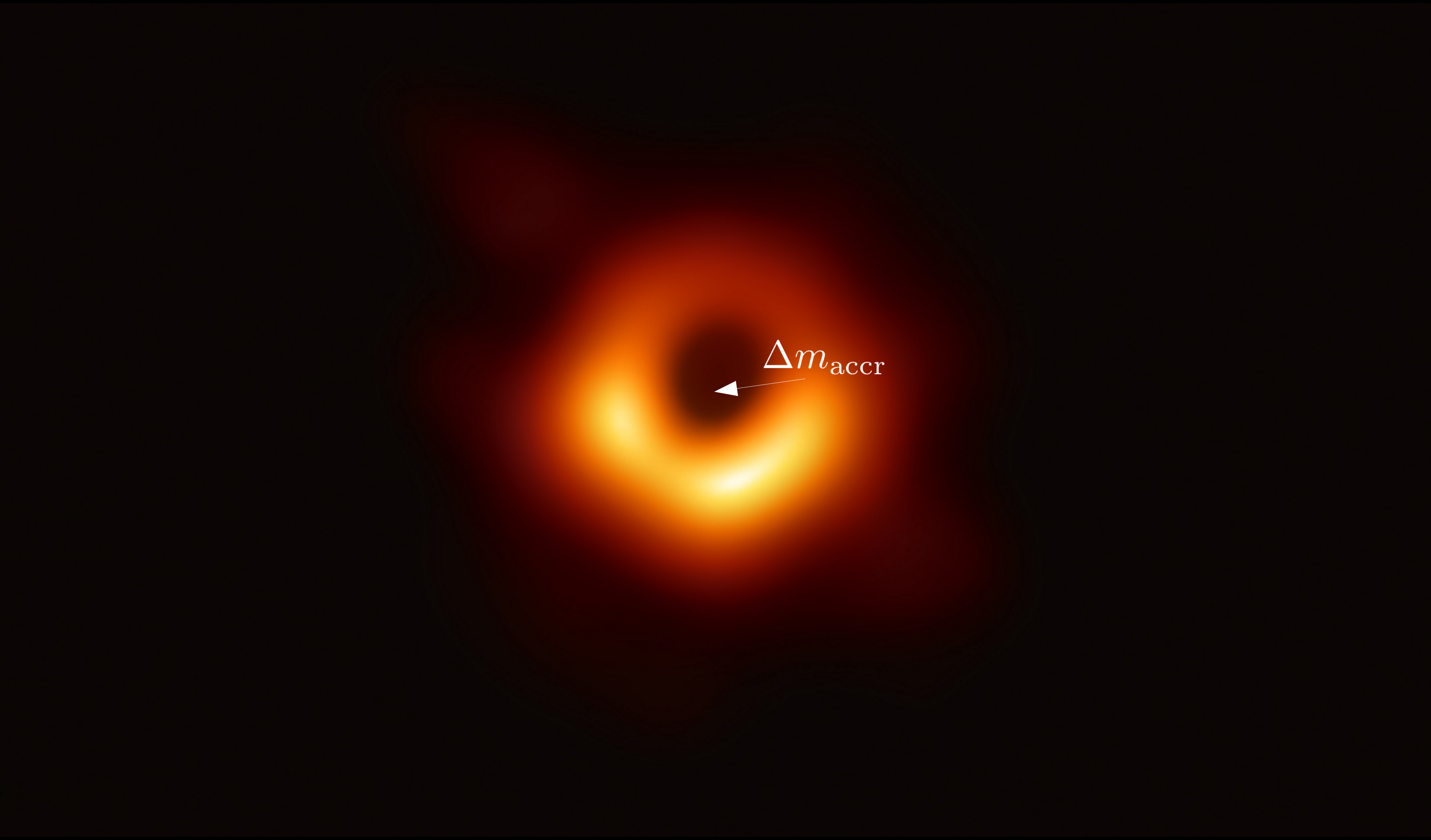
Vincent+, CQG (2016)



- Telling the shadow of a boson star from a Kerr BH is very challenging
- Tests based on shadows can constrain $\rightarrow \epsilon \sim \mathcal{O}(1)$ and $|\mathcal{R}|^2 \sim \mathcal{O}(1)$

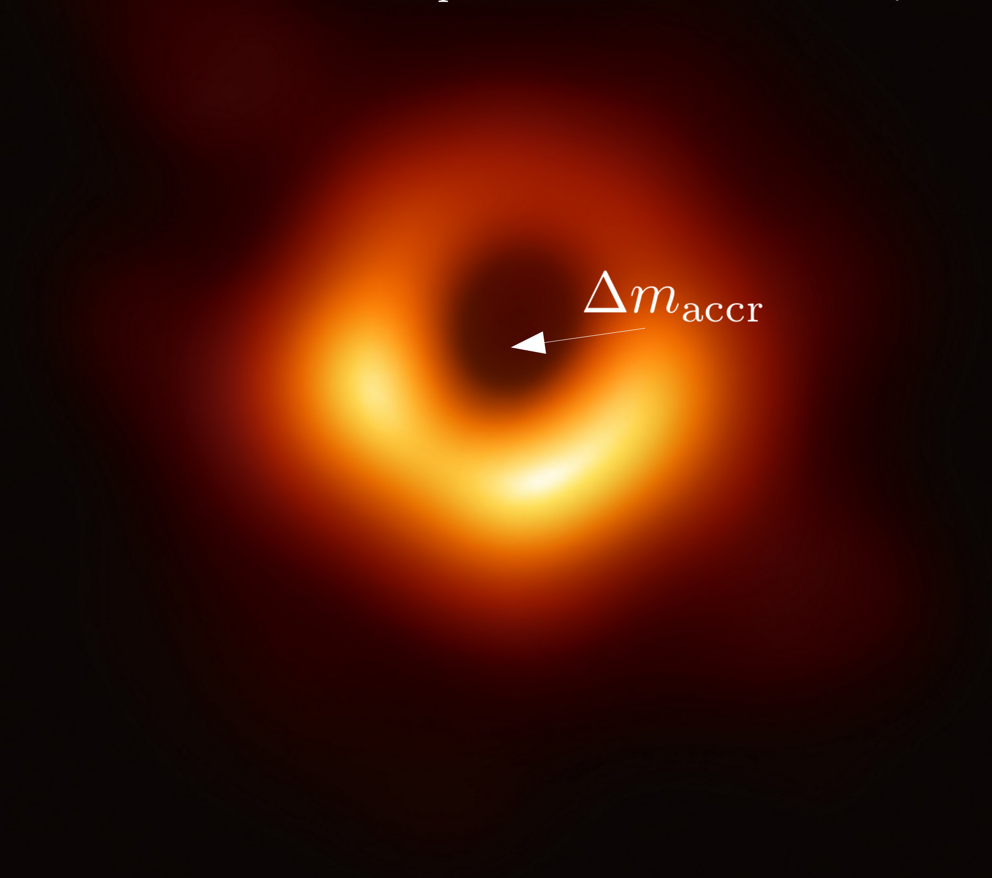
Rummel & Burgess, 2001.00041 (2020)

How about accretion?



How about accretion?

$$\frac{\Delta m_{\rm accr}}{M} \sim f_{\rm Edd} \frac{T_{\rm age}}{\tau_{\rm Salpeter}} \approx 3 \times 10^{-2} \left(\frac{f_{\rm Edd}}{10^{-4}} \right)$$



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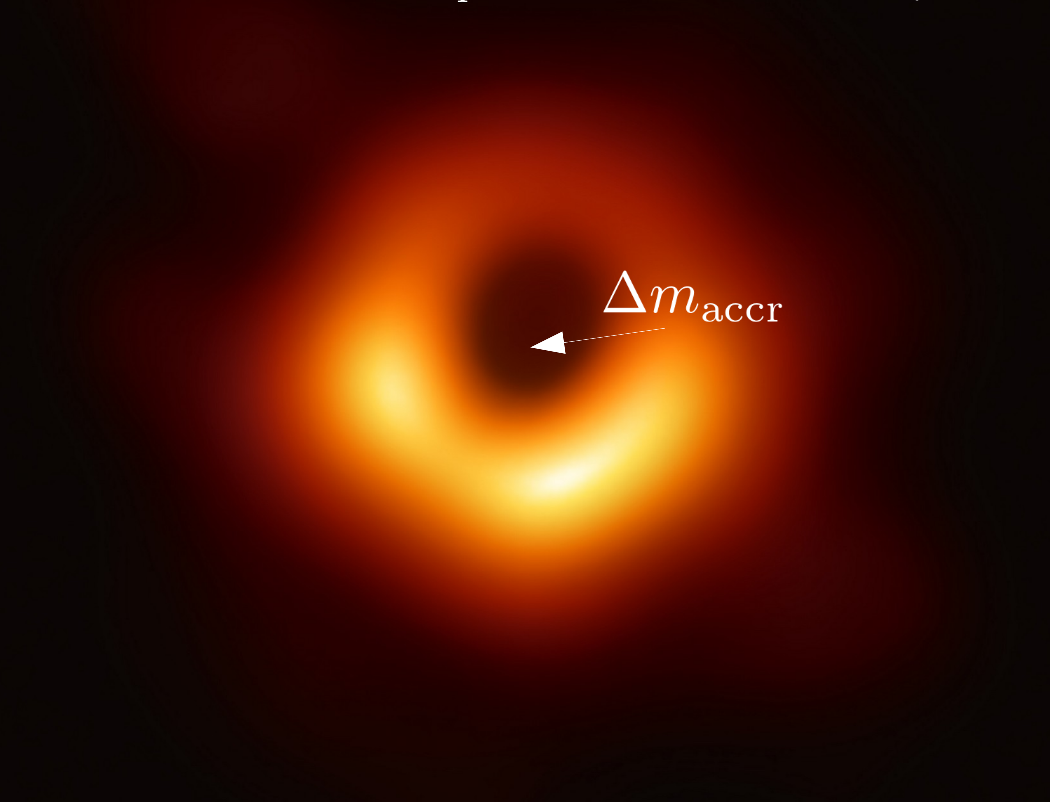


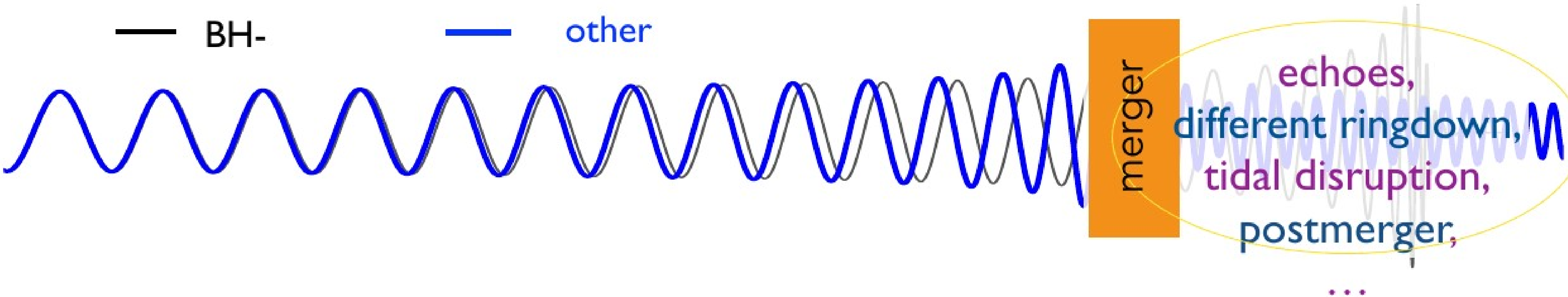
Assuming thermal equilibrium and hard surface yields much tighter constraints

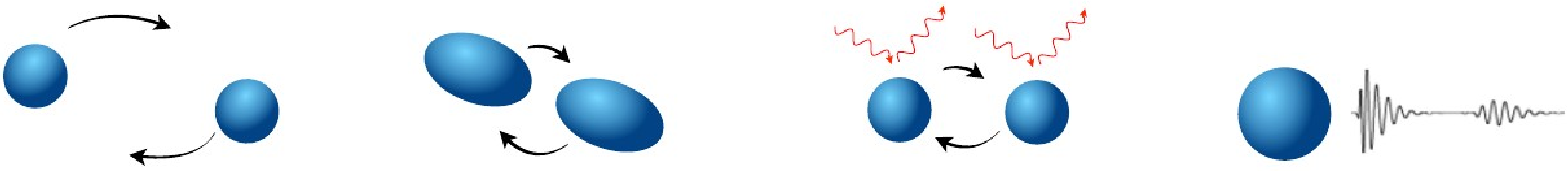
[Broderick-Narayan CQG 2007]

$$\epsilon < 10^{-14}$$

GW-based tests of ECOs

Slide concept by T. Hinderer and A. Maselli



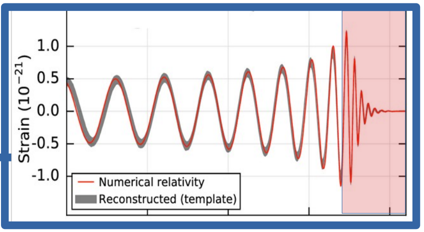


~point masses: same signal for all objects

tidal effects + ***spins deformations***

absence of horizon ***absorption effects***

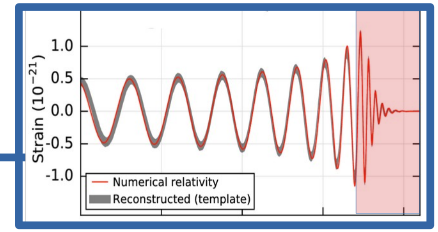
echoes



GW test #1:

Ringdown

GW spectroscopy



- Post-merger signal → superposition of QNMs

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

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

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

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

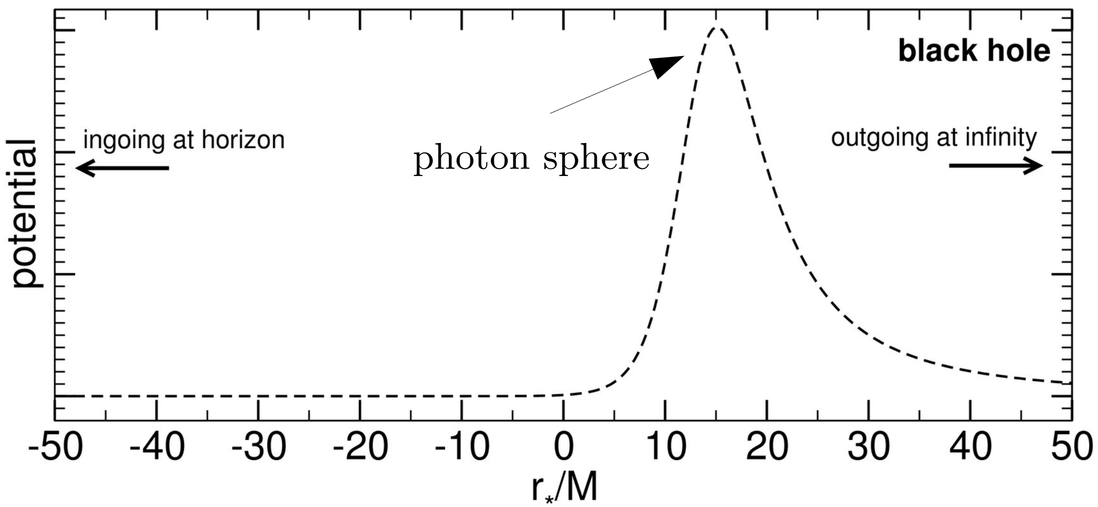
- Mode shift (due to different object, different dynamics, or couplings)
- Extra ringdown modes (e.g., extra polarizations, fields, matter) → amplitudes?
- Overtones might be used [Gieser+, 2019] but careful with resolvability [Bhagwat+, 2020]

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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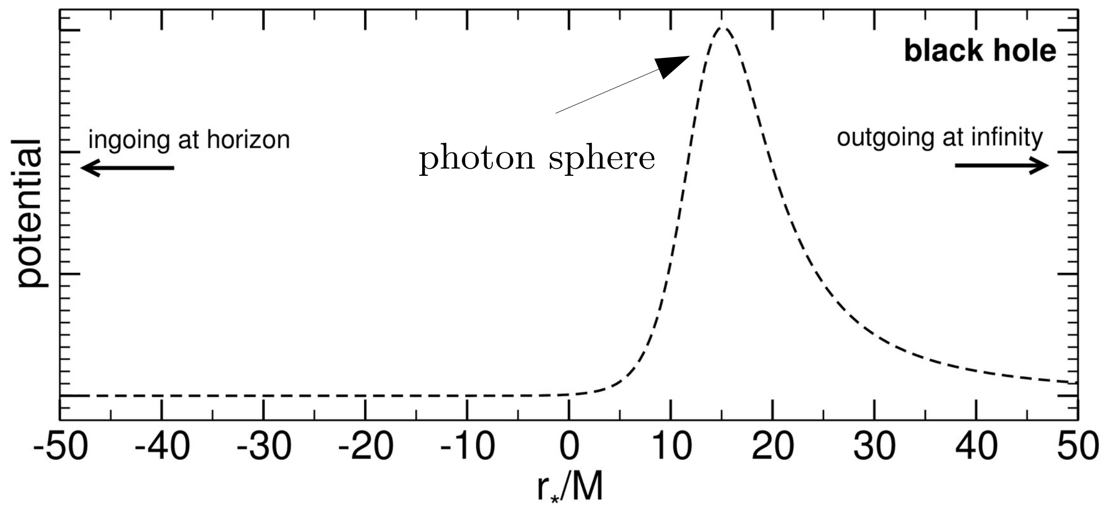
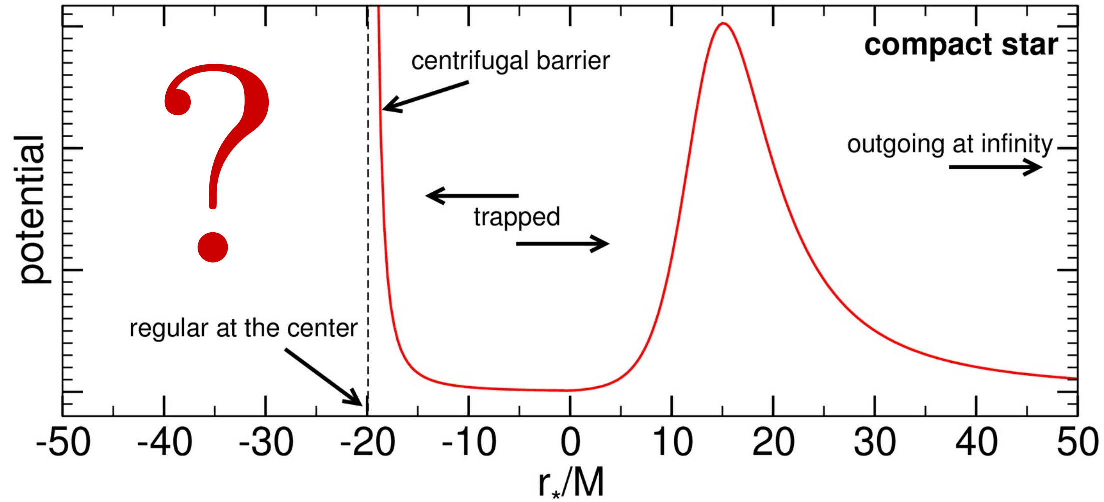


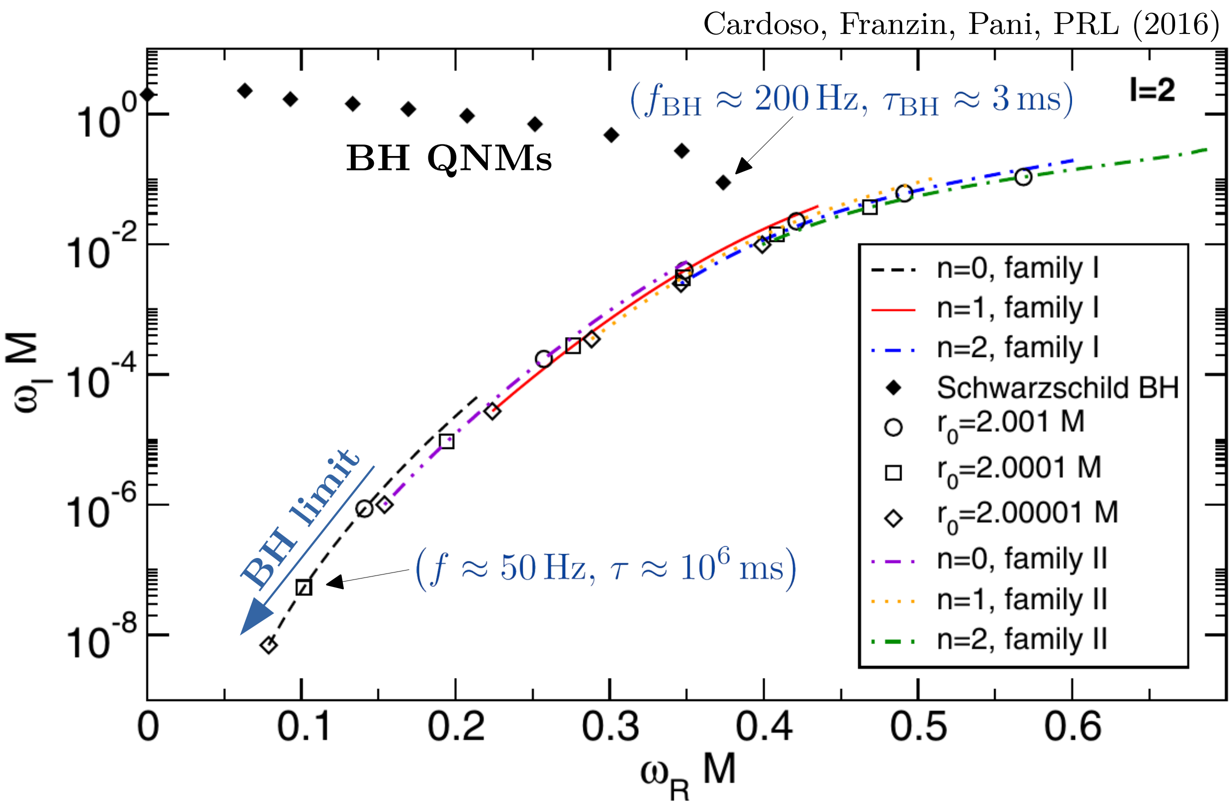
Ultracompact stars generically support trapped modes

Chandrasekhar & Ferrari PRSLA (1991)



No horizon → QNM spectrum dramatically different

QNM spectrum of an UCO

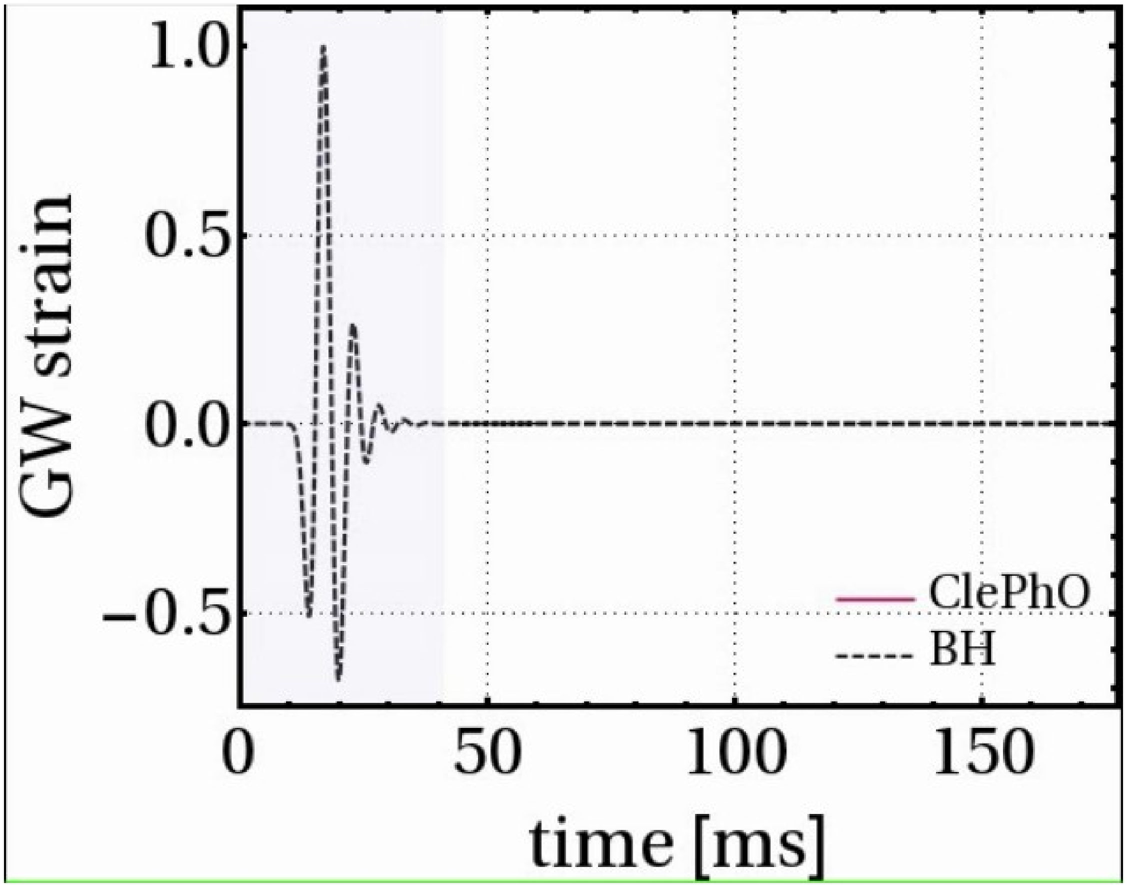


- Generic feature: low-frequency, long-lived QNMs in the BH limit

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

- QNM spectrum dramatically different → ringdown?

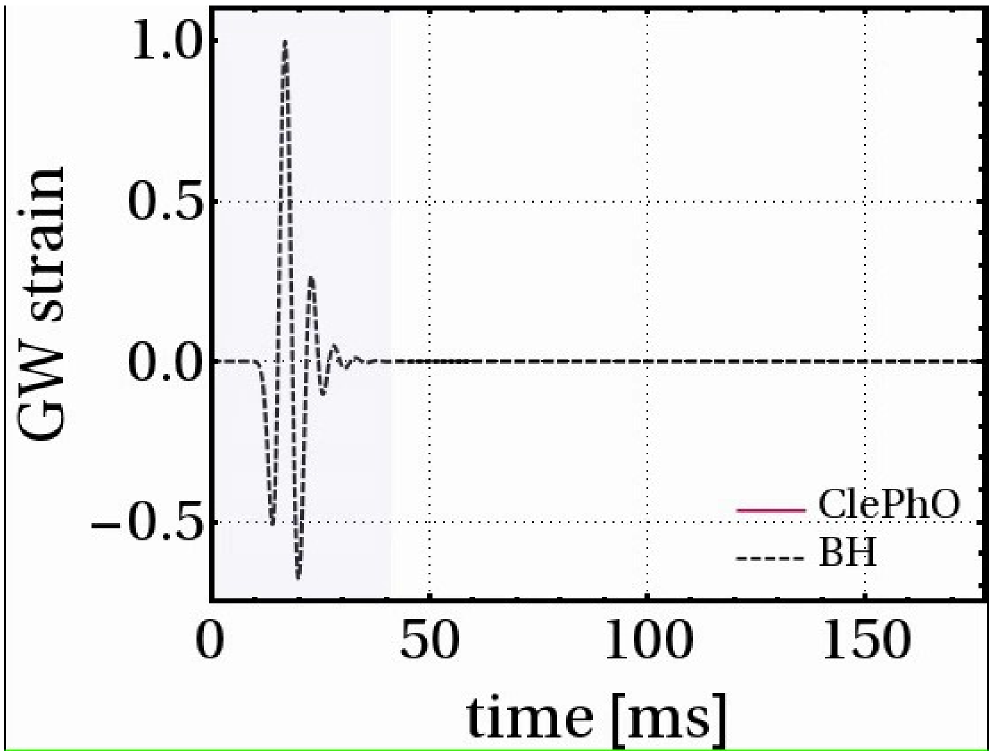
GW echoes



Ringdown of a Schwarzschild BH
(Gaussian perturbation)

GW echoes

Cardoso & PP, Nature Astronomy (2017)



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

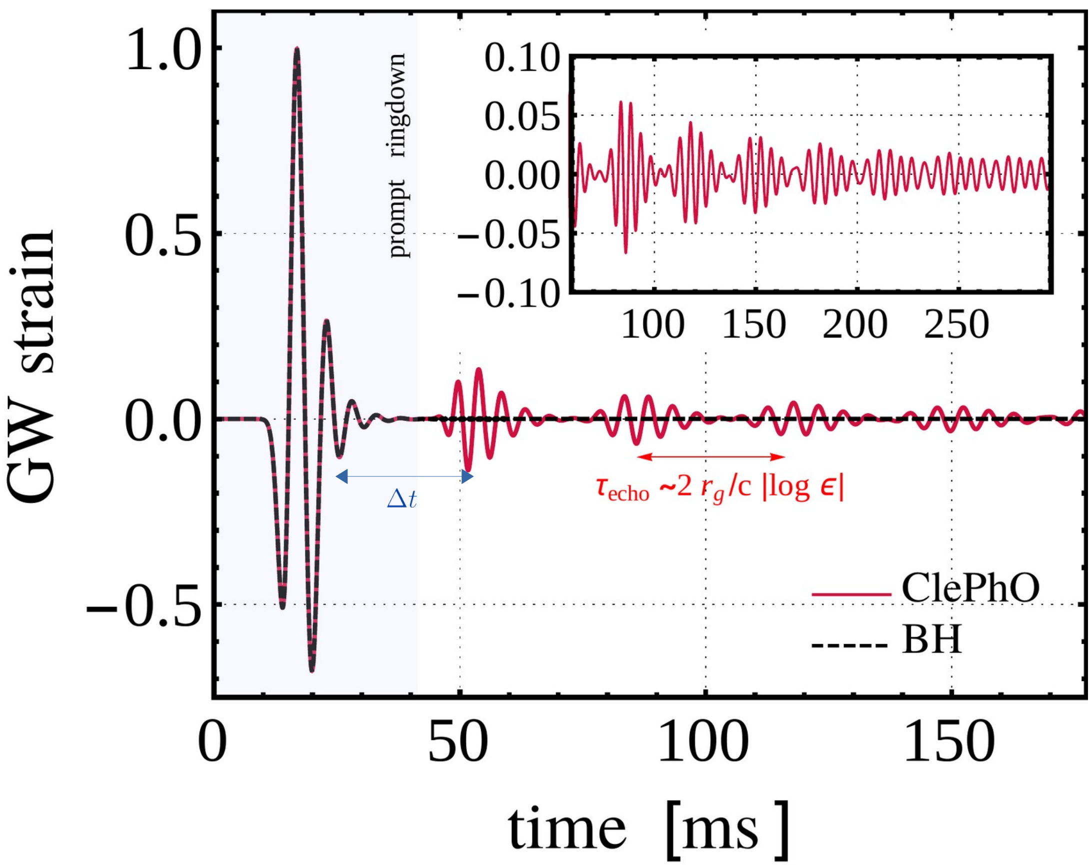
Kokkotas 1996; Ferrari & Kokkotas, PRD 2000
Cardoso, Franzin, PP, PRL (2016), Cardoso+ PRD (2016)

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

Delay time → log dependence

GW echoes

Cardoso & PP, Nature Astronomy (2017)



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

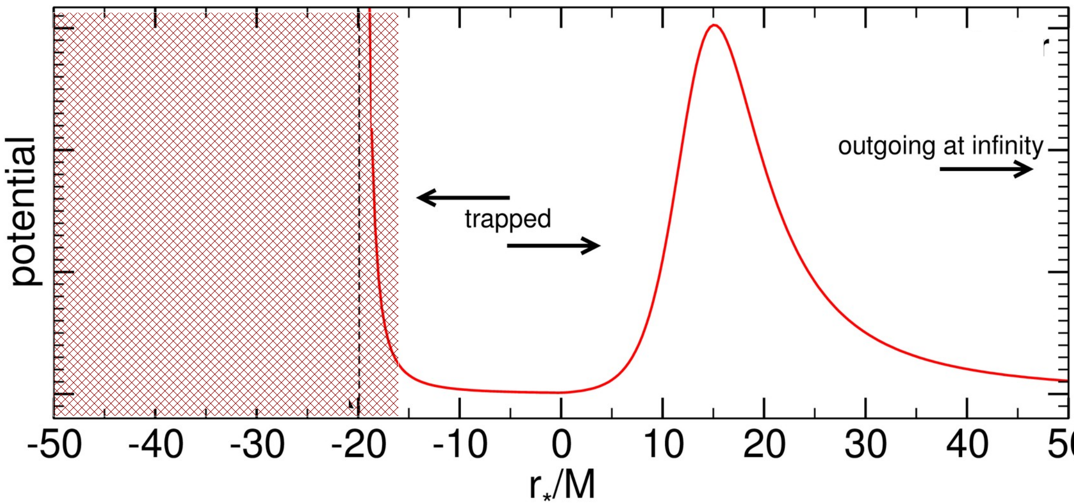
Delay time → log dependence

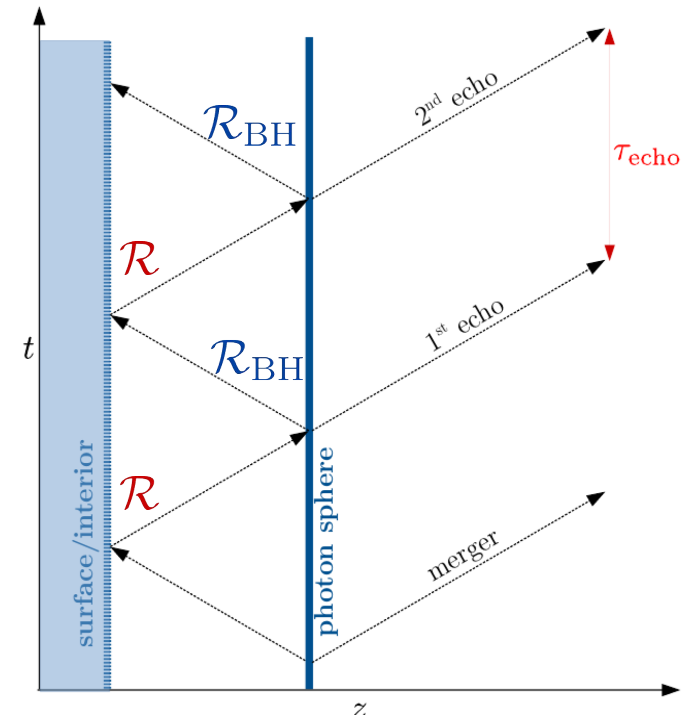
- Even Planck-scale corrections near horizon are within reach!

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

Model-independent signatures

- Only (classical) horizons absorb everything!

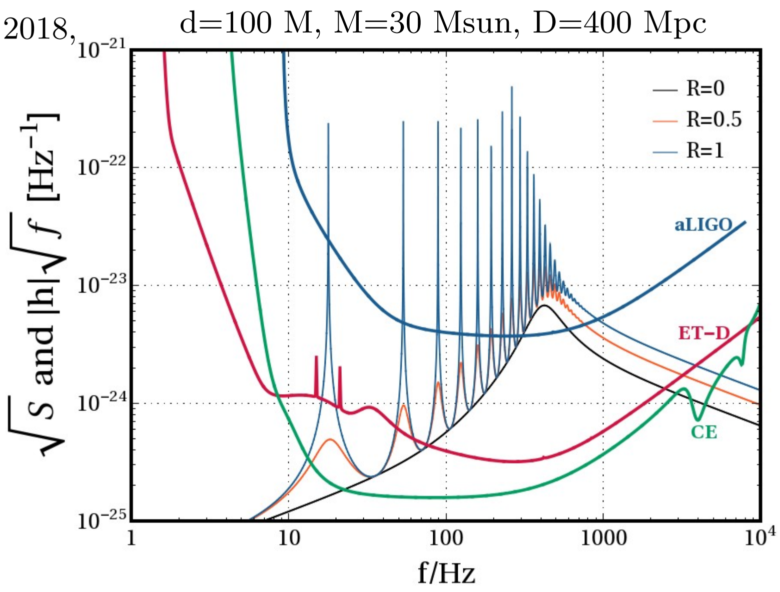




- Reflectivity arises in many contexts:
  - Stellar-like regular interior
  - "Fuzziness"
  - Quantum emission from horizon
- Can be modelled by frequency-dependent reflectivity coefficient

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]



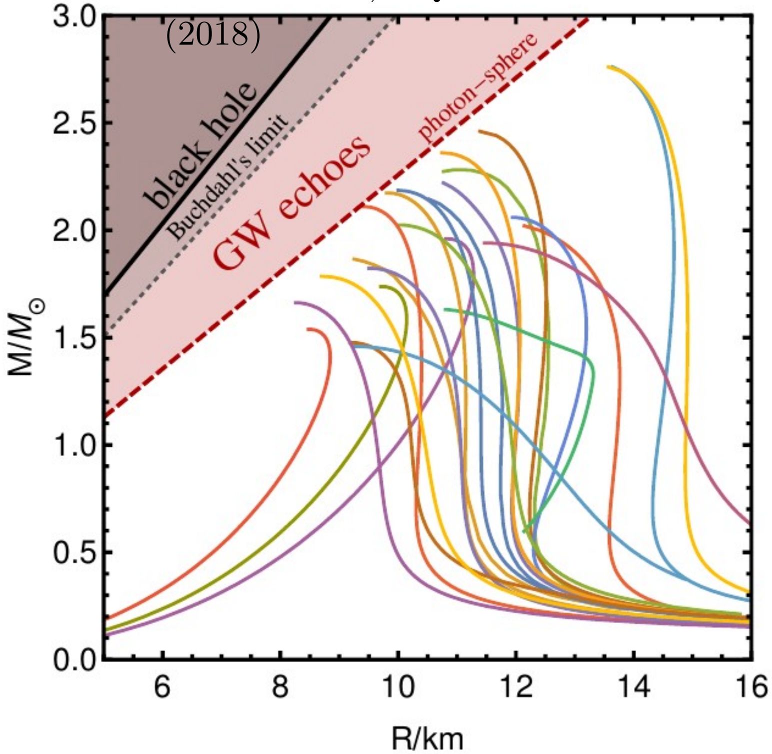
- For a recent account: Abedi+, 2001.00821, 2001.09553 (2020)

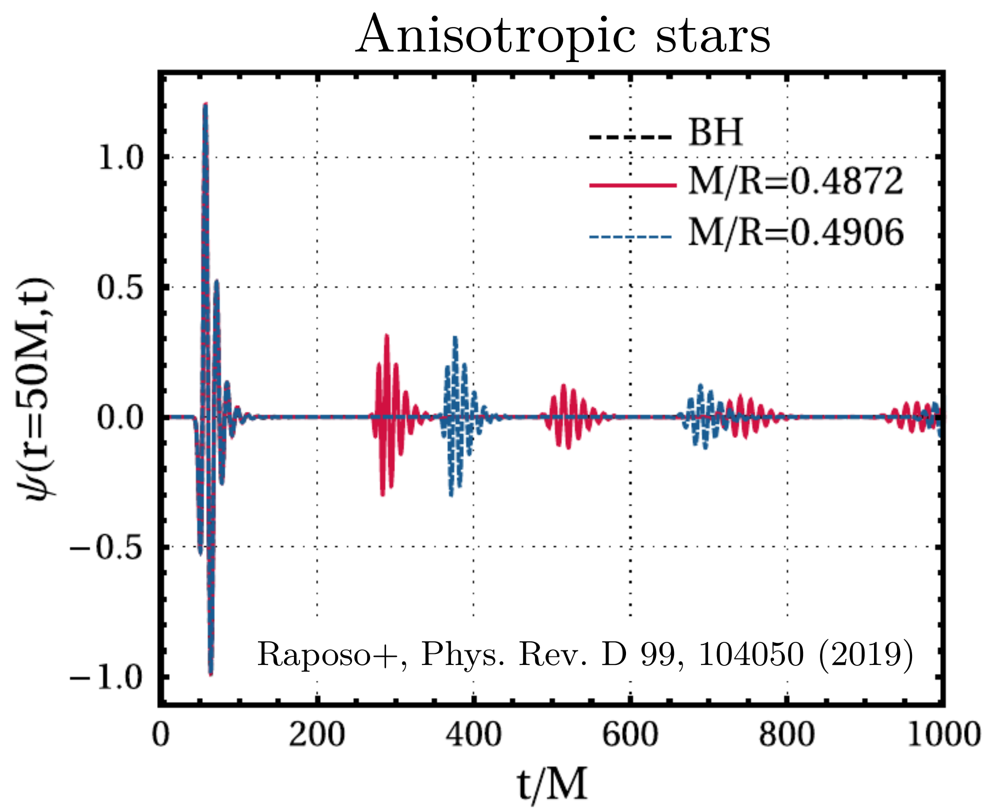
> - Near-horizon quantum (?) structures within reach!
> - Negative searches also important → constrain/rule out ECO models

Potential inferences from echoes

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

PP & Ferrari, CQG Letters (2018)





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+ 2019-2020, Delhom+ 2019]

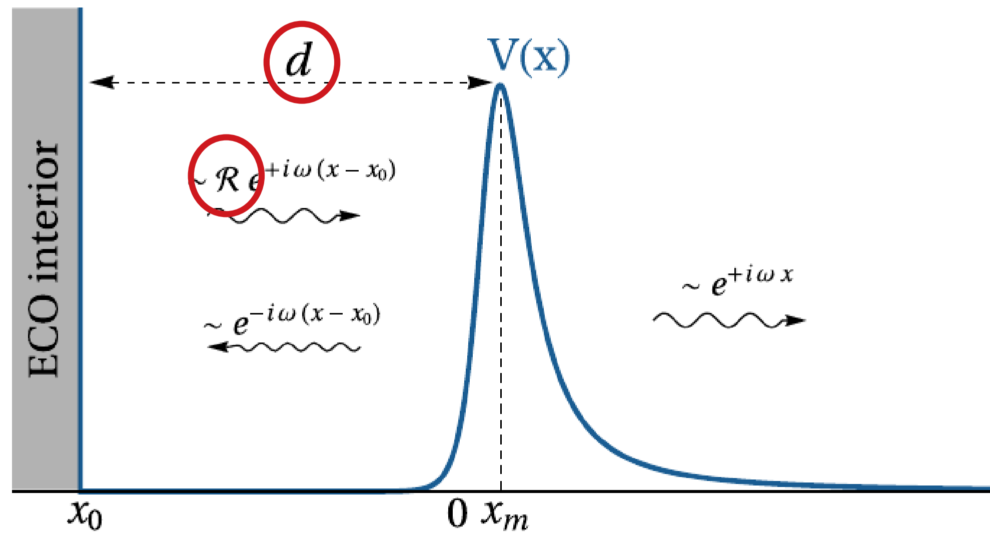
GW echo modeling

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

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

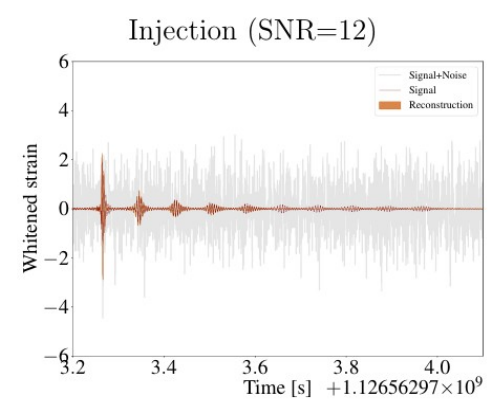
$$\tilde{Z}^{+}(\omega) = \tilde{Z}^{+}_{\rm BH}(\omega) + \mathcal{K}(\omega)\tilde{Z}^{-}_{\rm BH}(\omega)$$

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



- 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]

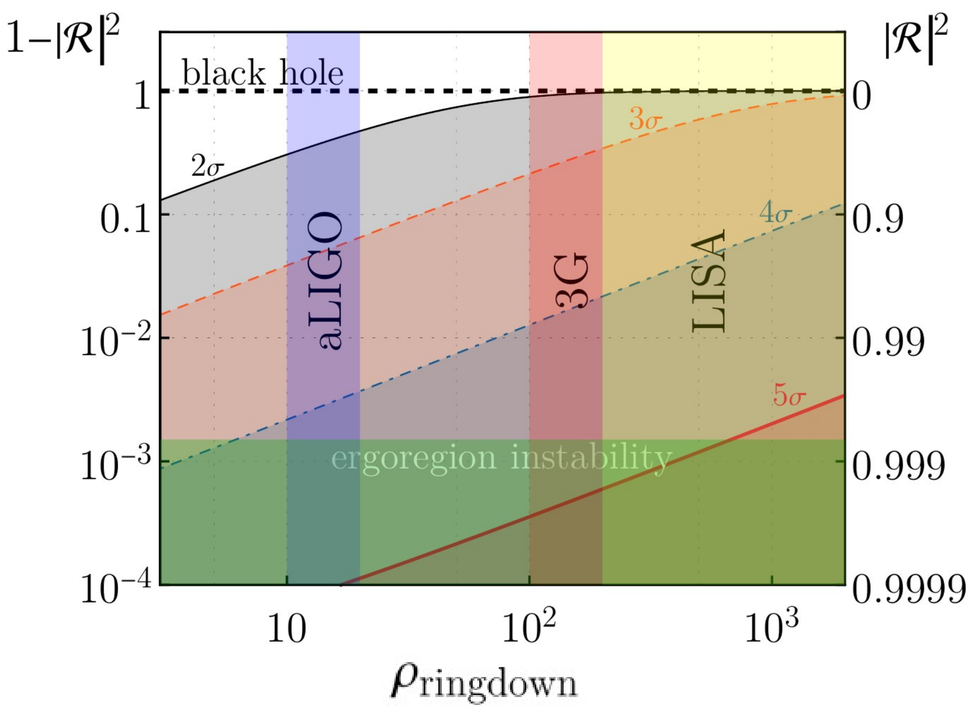


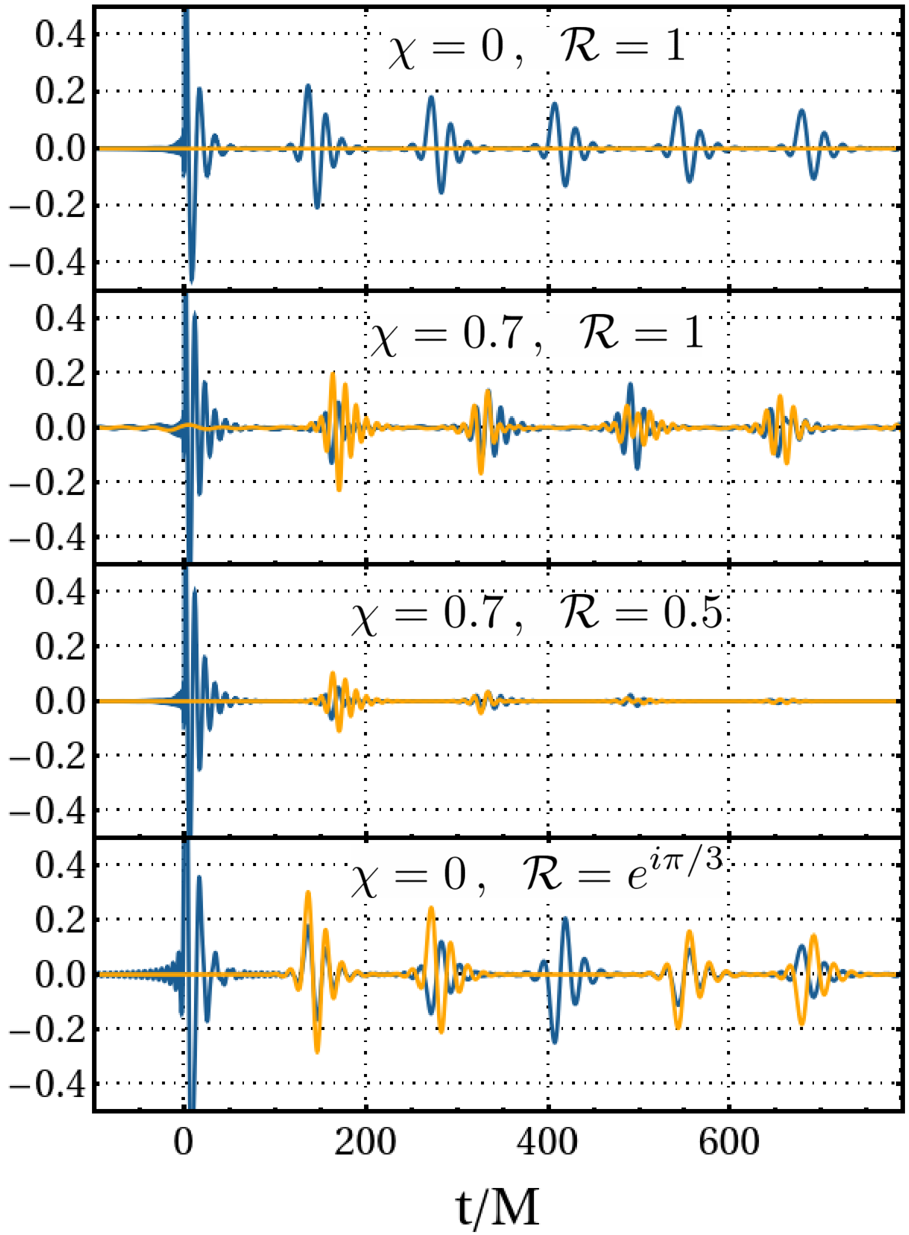
Echo modeling & detectability

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

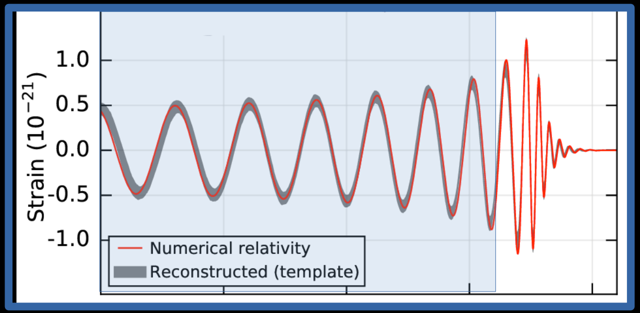
Physically-motivated, analytical template:

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



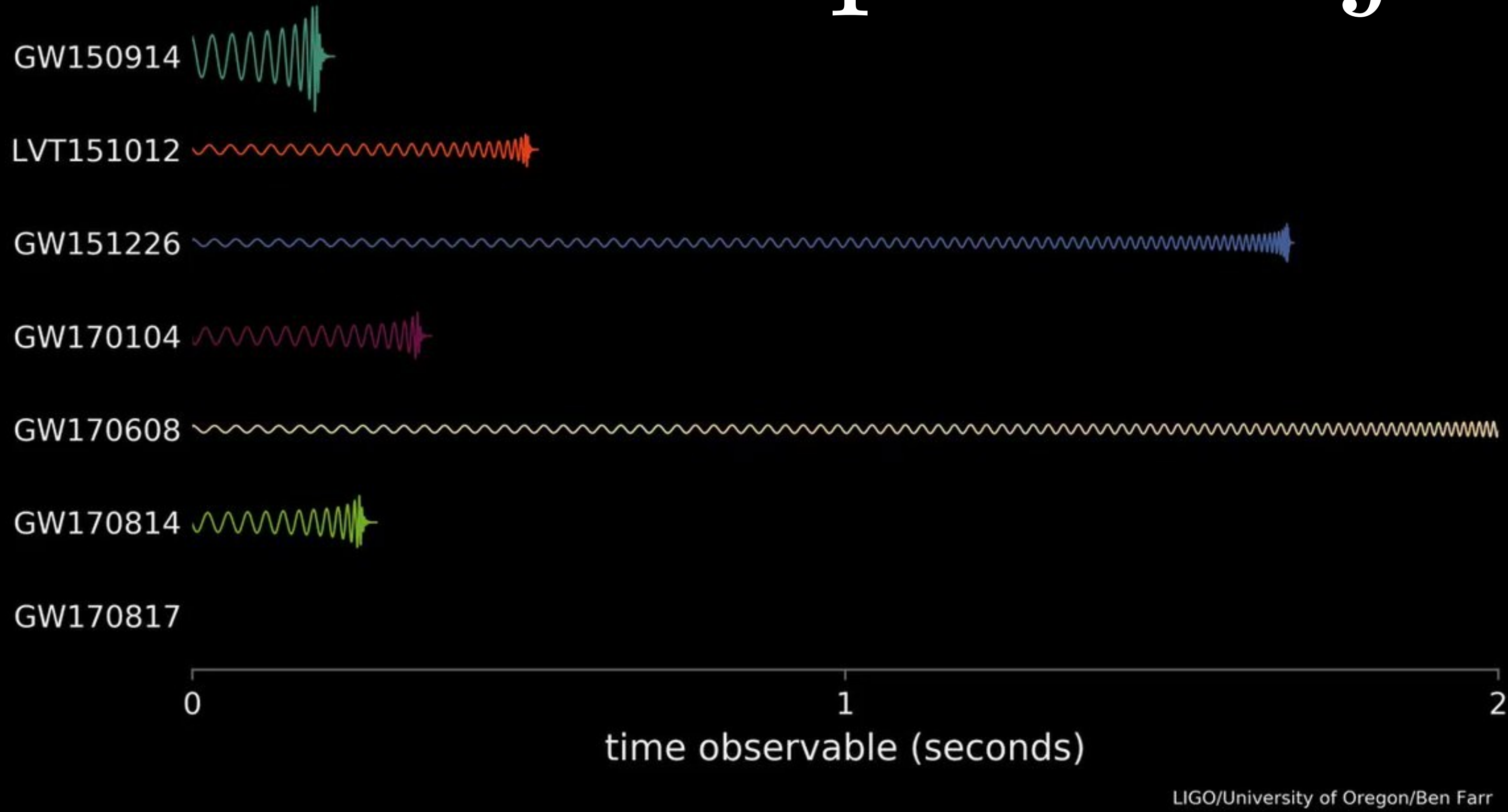


Waveforms, templates, and movies available @ http://www.DarkGRA.org/gw-echo-catalogue.html



GW tests #II:

Inspiral-based tests of exotic compact objects



Post-Newtonian inspiral: BH vs ECO

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

$$1\text{PN} = \frac{v^2}{c^2}$$

Blanchet, Living Rev. Relativity 17, 2 (2014)

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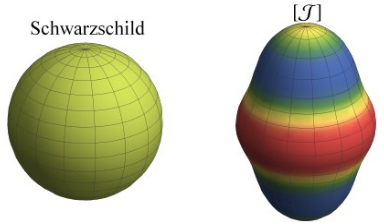
- **2PN:** Point-particle terms depend on **multipole moments** of the bodies
  - Tests of the BH no-hair theorem [Hansen 1974]



$$M_\ell^{\rm Kerr} + i S_\ell^{\rm Kerr} = M^{\ell+1} (i\chi)^\ell$$

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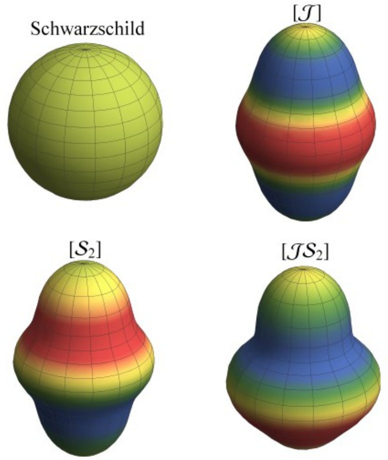

$$M_\ell^{\rm Kerr} + i S_\ell^{\rm Kerr} = M^{\ell+1} (i\chi)^\ell$$

  - **ECOs:** [2+ hair, might break equatorial symmetry]

$$M_\ell = M_\ell^{\rm Kerr} + \delta M_\ell \qquad S_\ell = S_\ell^{\rm Kerr} + \delta S_\ell$$

  - In the BH limit → hair conditioner! [Raposo, PP, Emparan, PRD 2019]

$$\frac{\delta M_\ell}{M^{\ell+1}} \to a_\ell \frac{\chi^\ell}{\log\epsilon} + b_\ell\,\epsilon + \dots \qquad \frac{\delta S_\ell}{M^{\ell+1}} \to c_\ell \frac{\chi^\ell}{\log\epsilon} + d_\ell\,\epsilon + \dots$$

(if exterior is ~ GR and curvature near the surface is small)

Post-Newtonian inspiral: BH vs ECO

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

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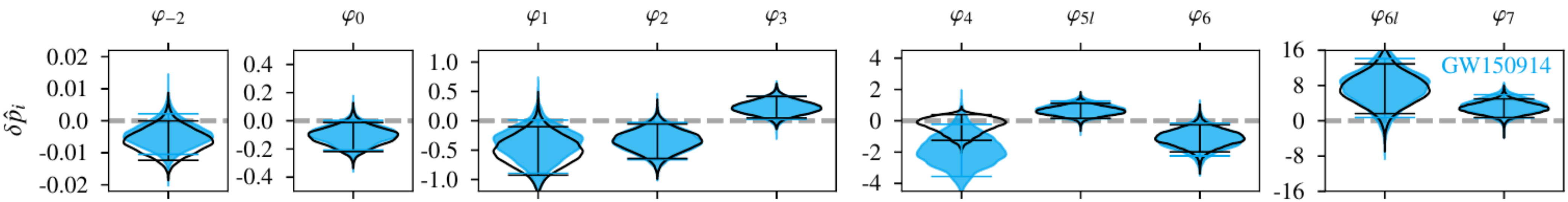
- **2PN:** Point-particle terms depend on the **multipole moments** of the

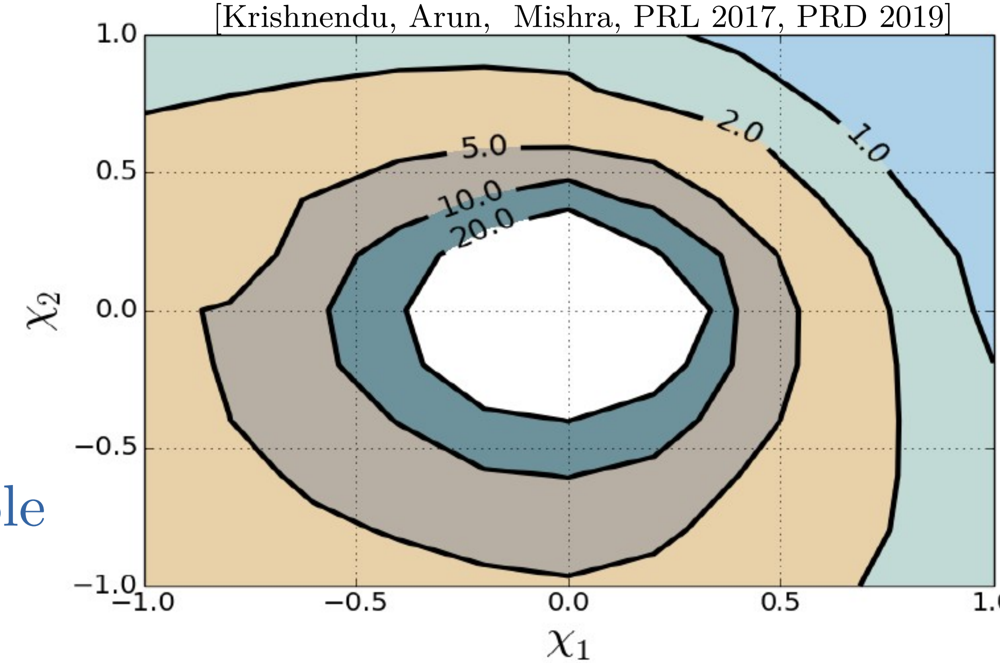


LIGO-Virgo Collaboration, tests of GR with GWTC-1; 1903.04467

$$M_2^{\rm Kerr}(m,\chi) = -m^3\chi^2$$

$$M_2^{\rm ECO}(m,\chi,\kappa) = -\kappa m^3\chi^2$$

[Krishnendu, Arun, Mishra, PRL 2017, PRD 2019]



- Requires highly-spinning binaries
- 3G/LISA can measure also octupole

Post-Newtonian inspiral: BH vs ECO

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

- **2.5log PN: tidal heating** [Alvi PRD 2001, Poisson, PRD 2009]
  - BHs absorb radiation at horizon
  - Tidal heating is ~ absent for ECOs
  - Small even for 3G, requires LISA
    - Highly-spinning MBBHs @ 2-20 Gpc [Maselli+ PRL 2018]
    - Very large effect in EMRIs [Hughes PRD 2001, Datta+ PRD 2020]

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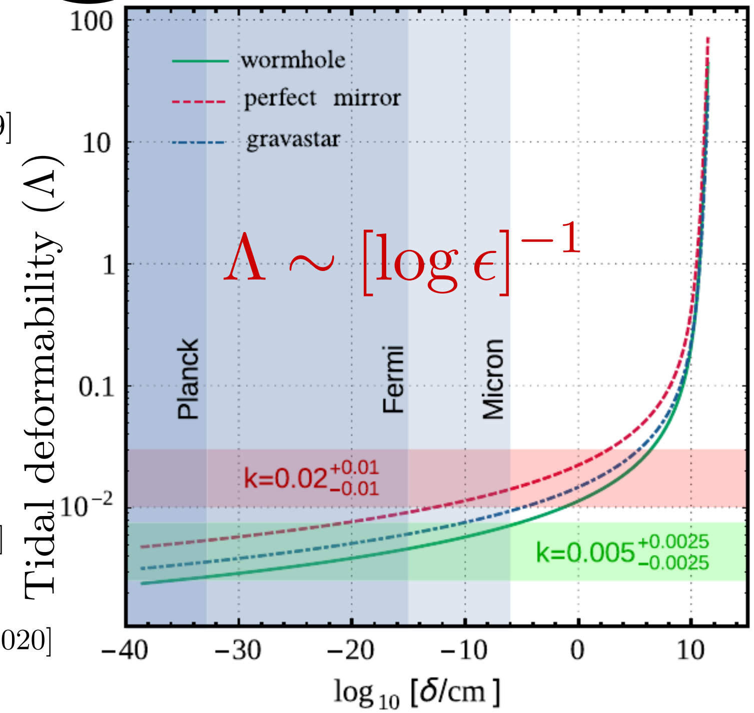

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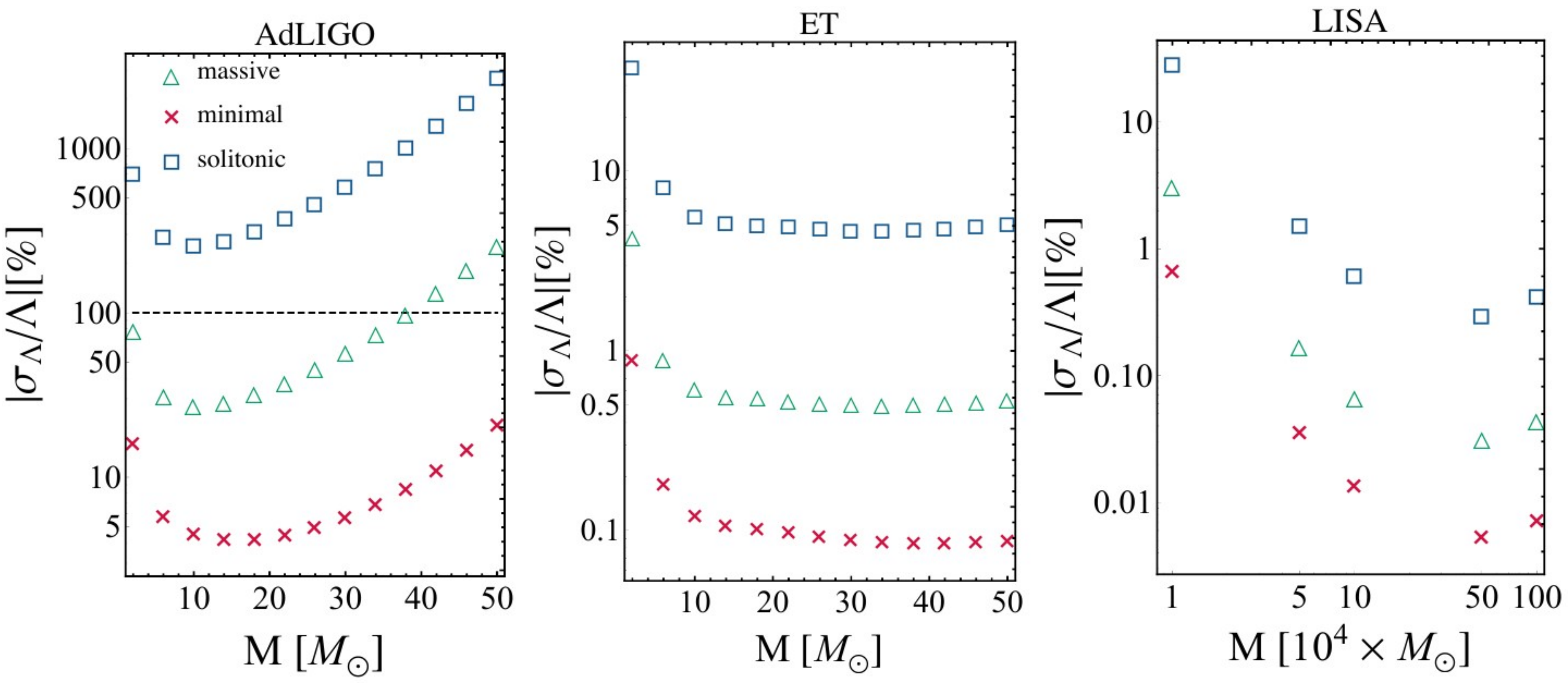
- **5PN: tidal deformability and Love numbers** [Flanagan & Hinder, PRD77 021502 2008]
  - Love = 0 for a BH in GR zero [Damour '86, Binnington-Poisson, PRD 2009; Damour-Nagar PRD 2009; PP+, PRD 2015]
  - Love ≠ 0 for ECOs and BHs in modified gravity [Porto+ Fortsch. Phys. 2016, Cardoso+, PRD 2017]
  - In several ECO models Love scales logarithmically → probing Planck physics?

[Maselli+, 2018-2019, Addazi+ 2019]

BH vs Boson Stars: Love numbers

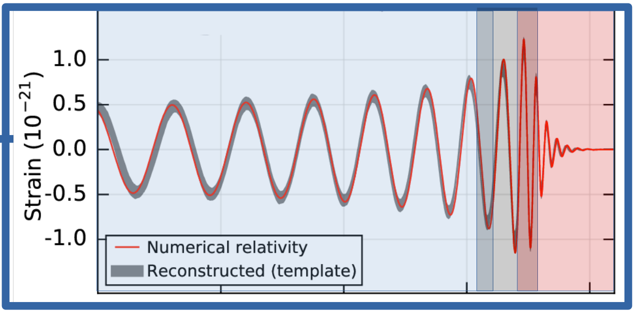
$$\mathcal{L} = \frac{R}{16\pi G} - \partial_\mu \phi \, \partial^\mu \phi^\star - m^2|\phi|^2 + \lambda|\phi|^4 + \gamma|\phi|^6 + \ldots$$



- aLIGO can exclude only BS vs BH models with relatively small compactness [Cardoso+ PRD (2017), Sennet+ PRD 96 024002 (2017), Johnson-McDaniel+, 1804.08026]
- 3G & LISA will be able to distinguish BHs vs *any* BS model
- LISA will constrain Λ for supermassive ECOs like LIGO does for NSs

ECO tests with EMRIs

- EMRIs are unique probes the spacetime near supermassive objects
  - Sentitive to both the multipolar structure and they dynamics (fluxes)
- ECO features are amplified in the extreme-mass ratio limit
  - Spin-induced multipole moments $\rightarrow \delta \bar{M}_2 \sim 10^{-4}$ [Barack-Cutler, PRD 2007, Babak+ 2017]
  - Tidal heating $\rightarrow$ large for highly-spinning objects $\rightarrow |\mathcal{R}|^2 \lesssim 10^{-4}$ [Datta+ PRD 2020]
  - Tidal Love numbers $\rightarrow \bar{\Lambda} \sim 10^{-5}$ [Pani & Maselli 2019]
- Challenges in modeling, parameter estimation, etc...
- LISA has huge potential to constrain supermassive ECO models



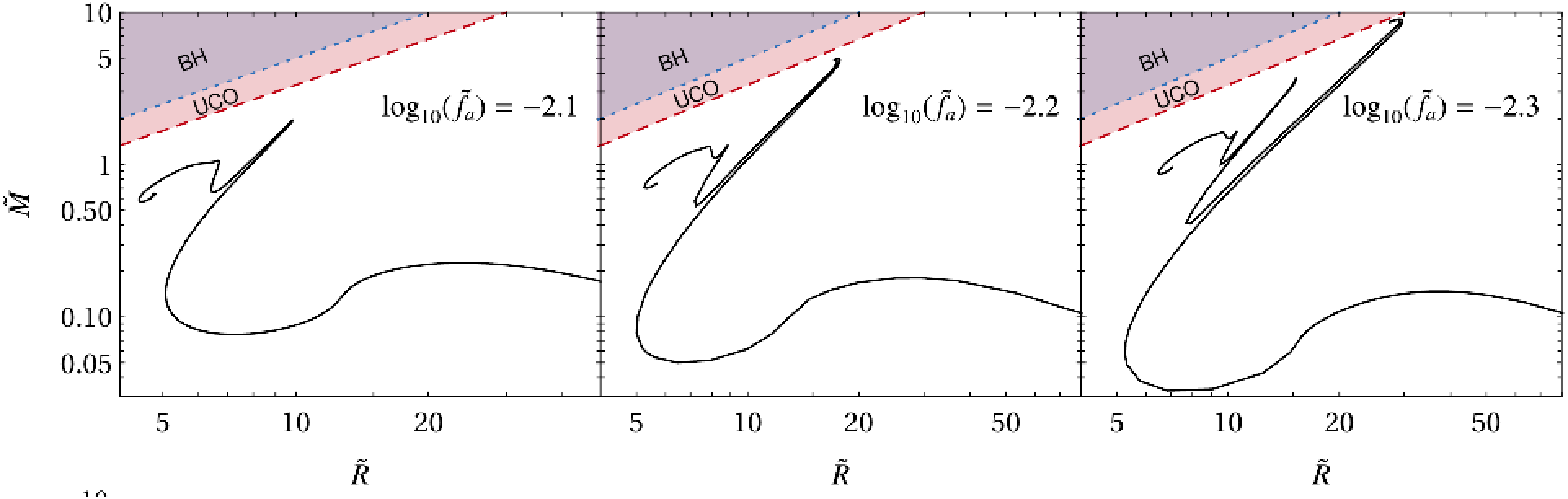
GW tests #3:

Inspiral-merger-rindown consistency

Boson star M-R diagram

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{2\kappa} - g^{\alpha\beta}\partial_\alpha\psi^*\partial_\beta\psi - V(|\psi|^2)\right]$$

$$V(\phi) = \frac{2\mu_a^2 f_a^2}{\hbar B}\left(1 - \sqrt{1 - 4\,B\,\sin^2\left(\frac{\phi\sqrt{\hbar}}{2\,f_a}\right)}\right)$$

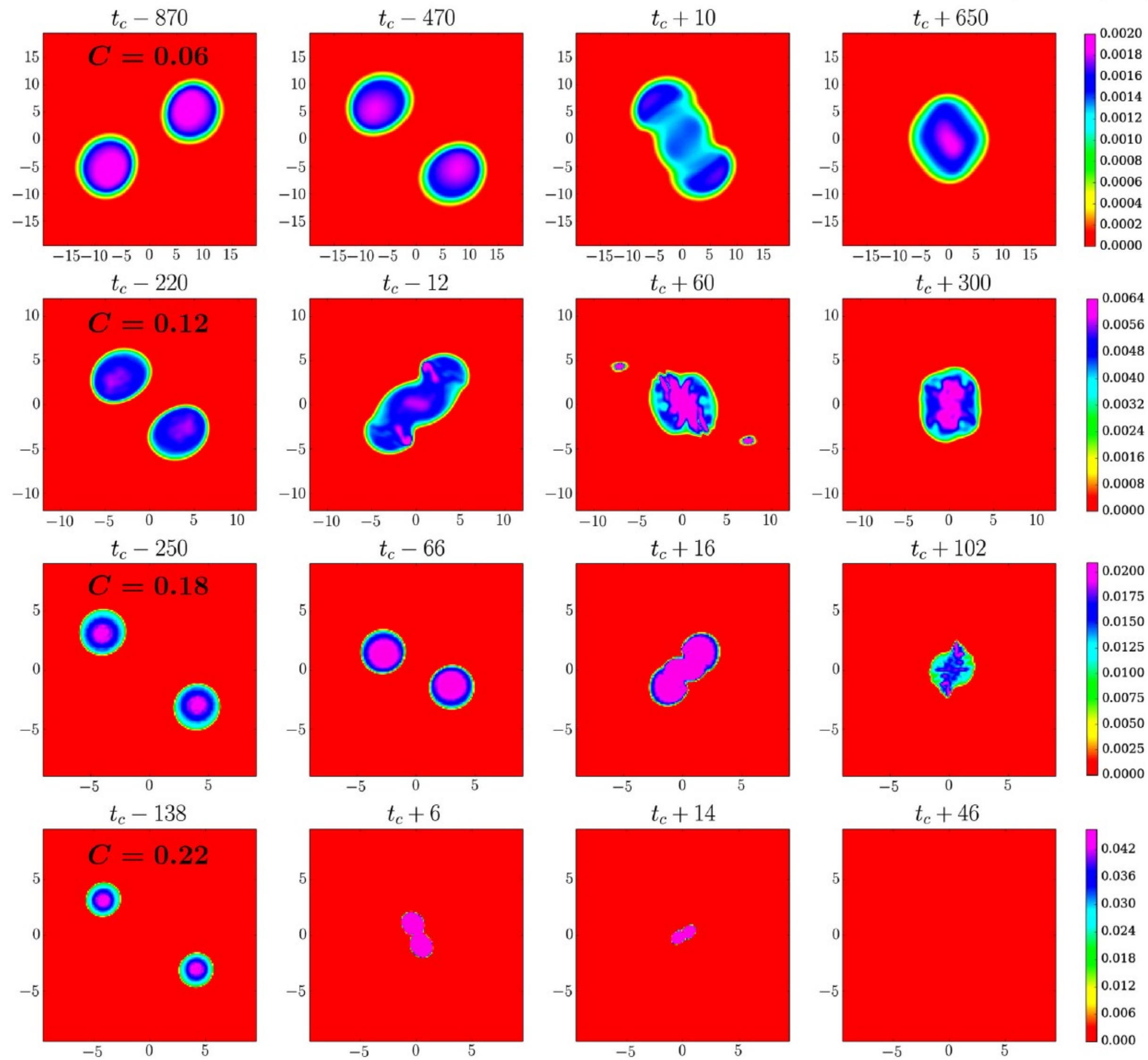


Binary Boson Stars (BBSs)

[Bezares+, PRD95, 124005 (2017); Palenzula+, PRD96, 104058 (2017)]

$$\mathcal{L} = \frac{R}{16\pi G} - \partial_\mu \phi \, \partial^\mu \phi^\star - m_b^2 |\phi|^2 + \lambda |\phi|^4 + \gamma |\phi|^6 + \ldots$$

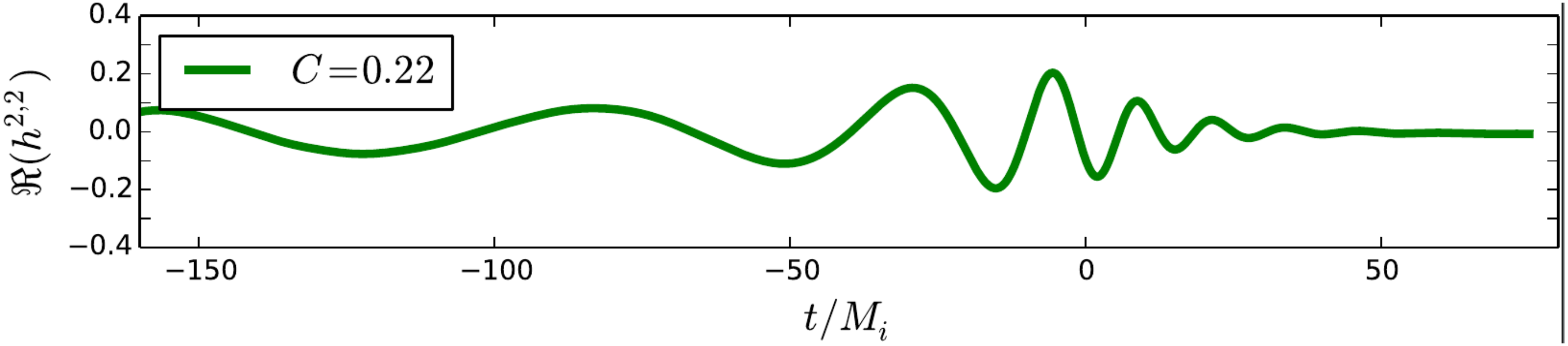
- Simulations of very compact BS binaries can be performed
- Boson stars have quantized spin, J=nQ
- Final state → either BH or nonspinning BS → instability
[Sanchis-Gual+ PRL 2019]
- High-frequency regime is important to distinguish



BBSs or BBHs?

Can BBSs mimic the full signal from BBH coalescence?

[Palenzula+, PRD96, 104058 (2017)]



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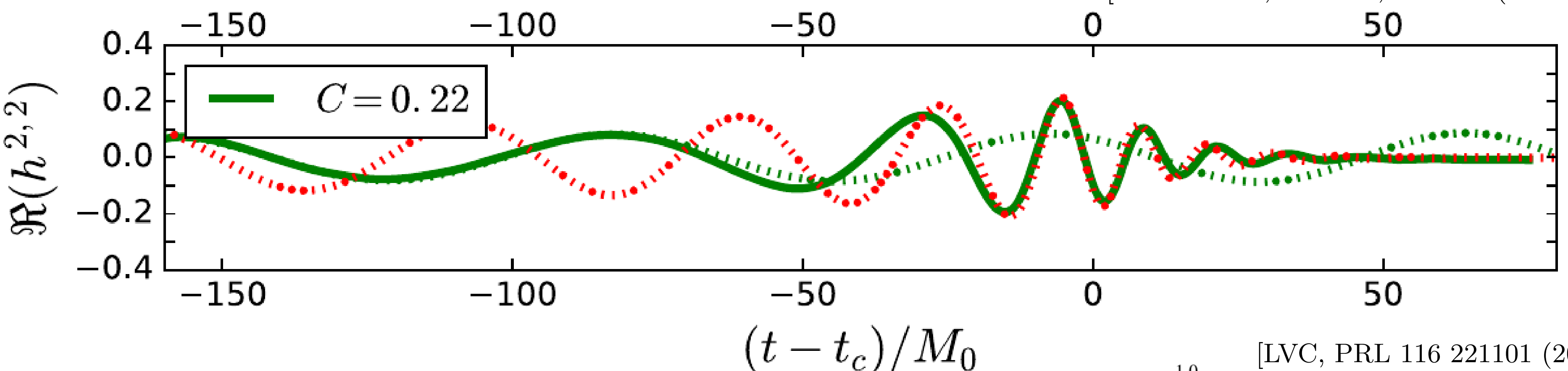
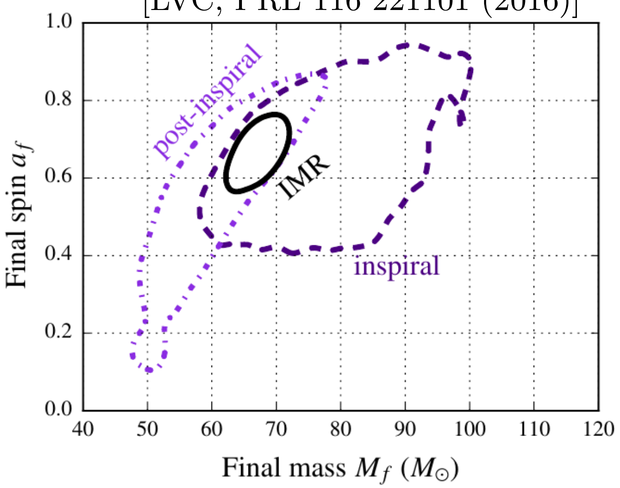


[LVC, PRL 116 221101 (2016)]



“Short-blanket” problem:

mimicking full IMR signal of BBHs is hard

BH vs ECO: theoretical challenges

- Equilibrium solutions with arbitrary mass and compactness?
- Stability?
  - Ergoregion instability: *spinning horizonless compact objects are unstable* [Friedman (1976), Cardoso+ 2008, Pani+ 2010-2012, Moschidis (2018), Barausse+ CQGL 2018]
  - Nonlinear (*photon-sphere*) instability? [Keir CQG 2014, Cardoso+ PRD 2014, Cunha+ PRL 2017]

ECOs either slowly spinning or partly absorbing [Maggio+ PRD 2017-2018]

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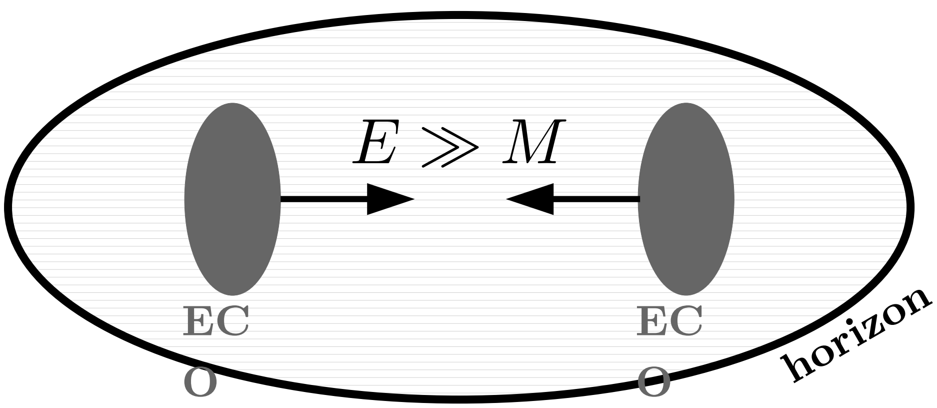
- Formation? Coalescence? **(ECO + ECO → ECO or BH?)**
- Nonlinear instability: causality, hoop conjecture, and BH formation

[Carballo-Rubio+ PRD 2018, Chen+ 1902.08180, Addazi+, 1905.08734, Cardoso-Pani Liv. Rev. Rel. (2019)]



- Horizons are inevitable in *classical* GR
- Do not prevent existence of ECOs

Conclusion & Outlook

- Gravity community underwent a revolution in the last decade
- Opportunity to search for exotic GW sources and signatures of new physics
  - **GW echoes** in the post-merger ringdown signal
  - Finite-size corrections to the inspiral → **precision GW astronomy**
  - **Testing quantum gravity? In the search of a log...**
  - **Better understanding/modeling is needed** (esp. of IMR signal)
- Mimicking BHs is very challenging → observational & theoretical issues:

Being (almost) a BH is (almost) unbearable

Quantifying the "unbearableness"

How well does the BH geometry describe the dark compact objects in our universe?

	Constraints $\epsilon(\lesssim)$	$\frac{\nu}{\nu_\infty}(\gtrsim)$	Source
1a.	$\mathcal{O}(1)$	$\mathcal{O}(1)$	Sgr A* & M87
1b.	0.74	1.5	GW150914
2.	$\mathcal{O}(0.01)$	$\mathcal{O}(10)$	GW150914
3.	$10^{-4.4}$	158	All with $M > 10^{7.5} M_\odot$
4.	10^{-14}	10^7	Sgr A*
5.	10^{-40}	10^{20}	All with $M < 100 M_\odot$
6.	10^{-47}	10^{23}	GW150914
7*.	$e^{-10^4/\zeta}$	$e^{5000/\zeta}$	EMRIs

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

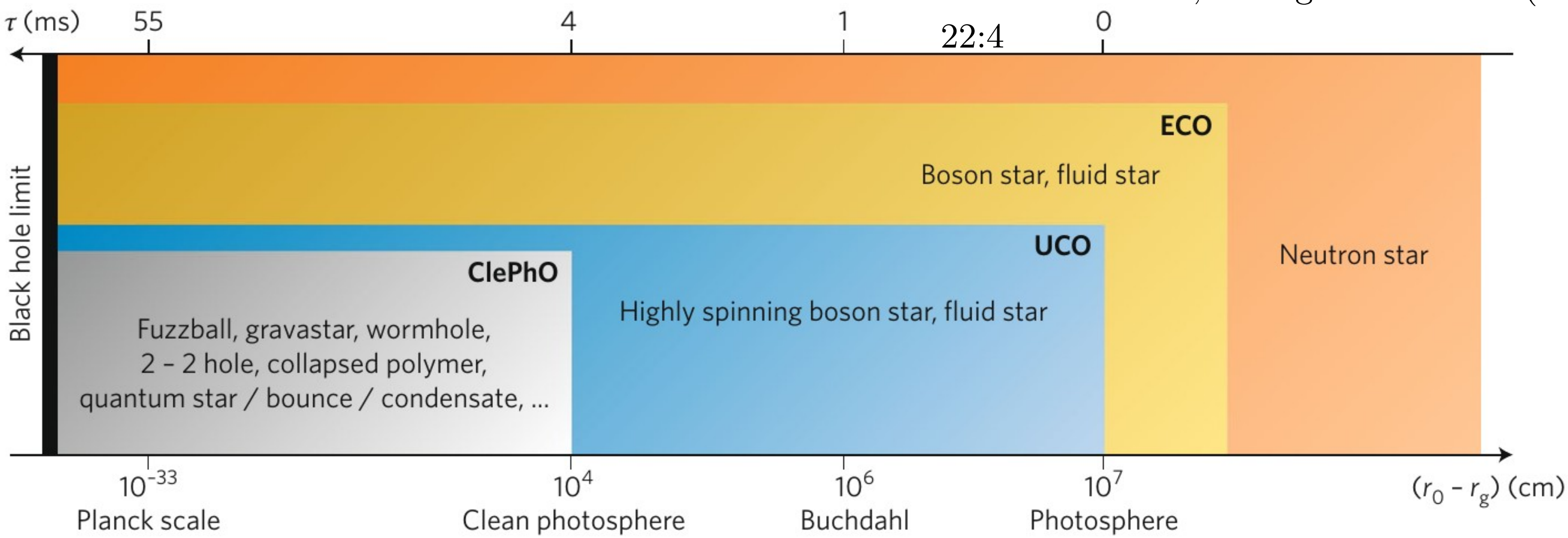
for description of the effects, caveats, and references

Backup slides

“Nothing is More Necessary than the Unnecessary” [cit.]

Quantifying the shade of darkness

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



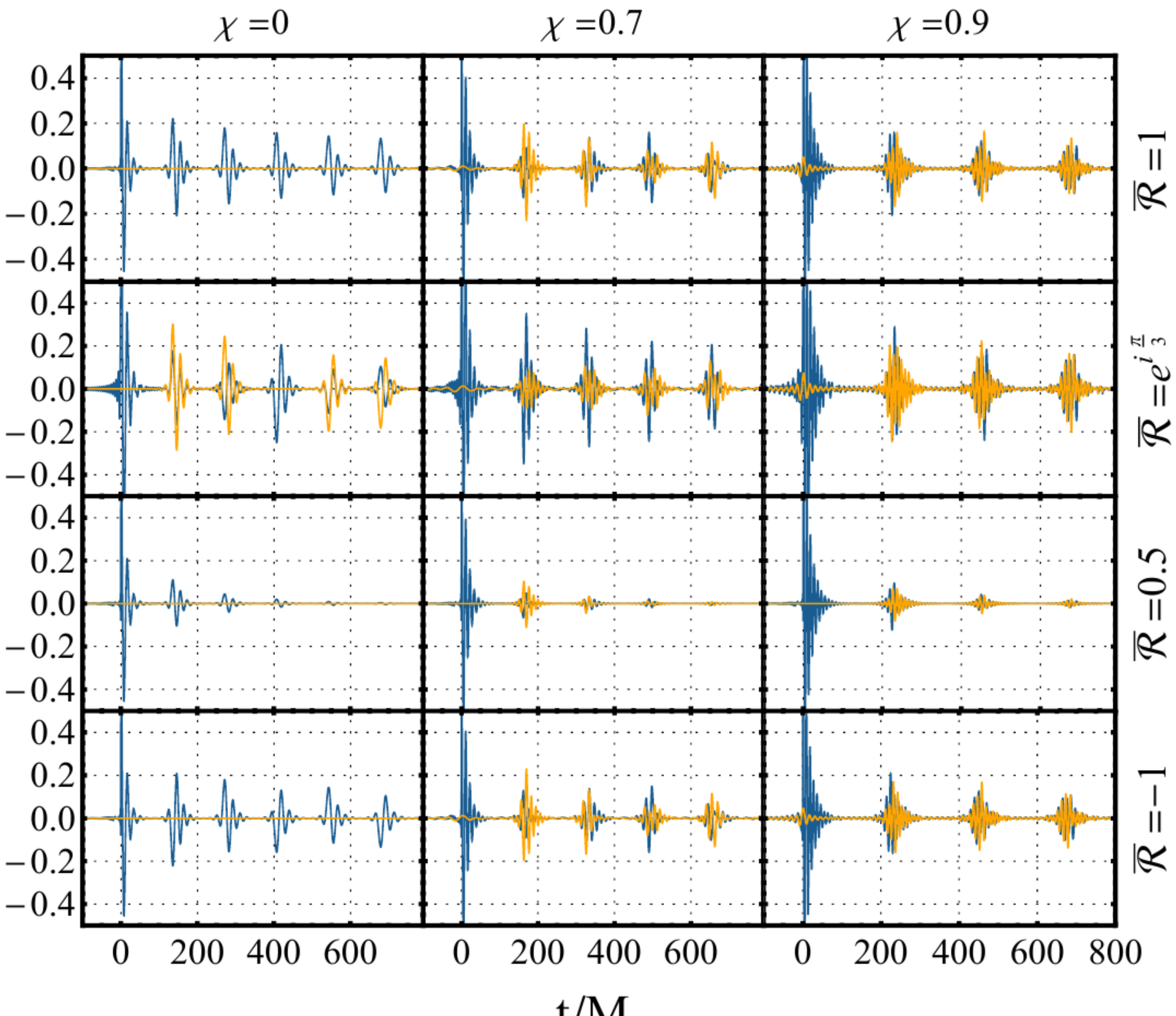
Two classes of ECOs (depending on the "*closeness*" parameter) $r_0 \equiv \frac{2GM}{c^2}(1+\epsilon)$

- "Neutron-star like" (e.g. boson stars) $\rightarrow \epsilon \sim \mathcal{O}(1)$
- "BH like" (e.g. fuzzballs, "quantum BHs") $\rightarrow \epsilon \sim 10^{-39} - 10^{-46}$

Goal: probe smaller and smaller values of ϵ

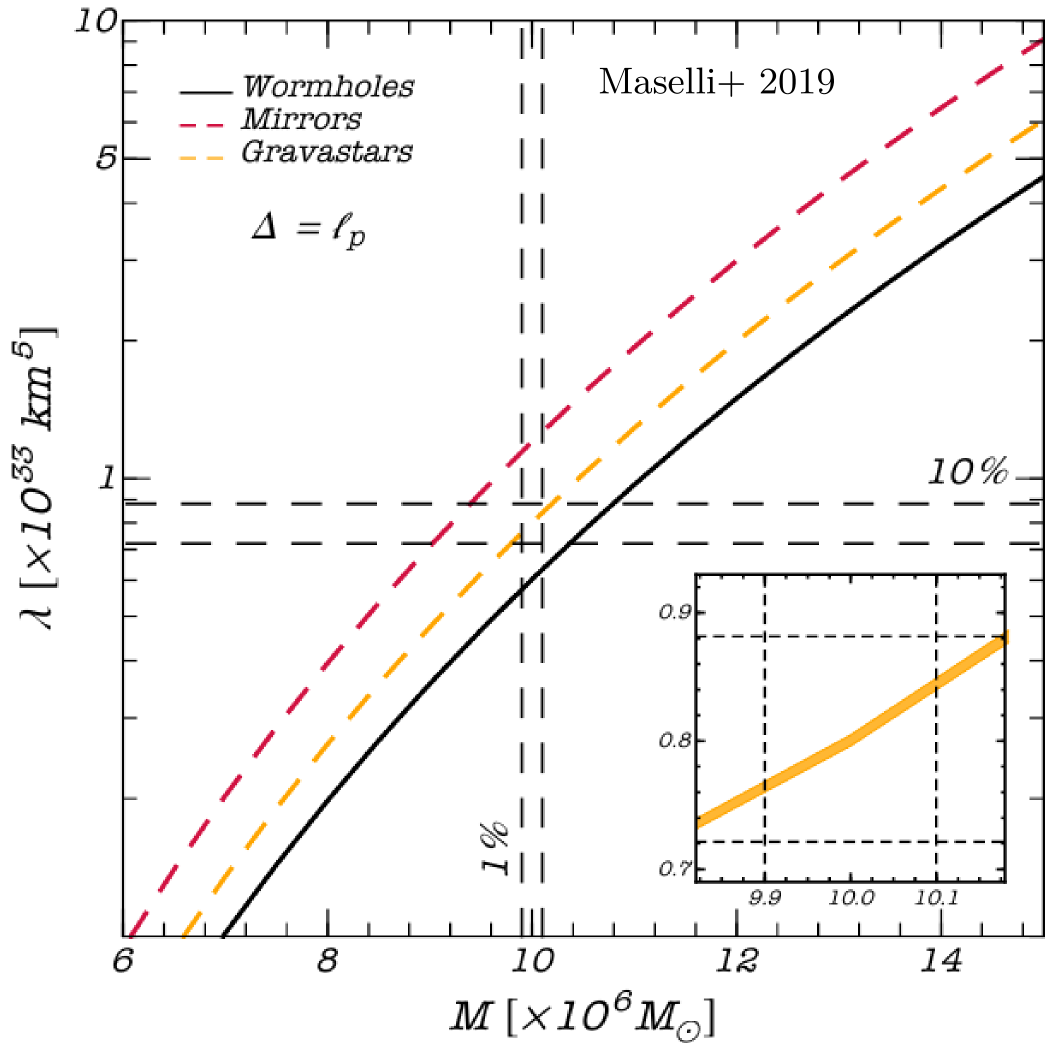
$\rightarrow$ requires combination of targeted and agnostic searches

GW echo slideshow



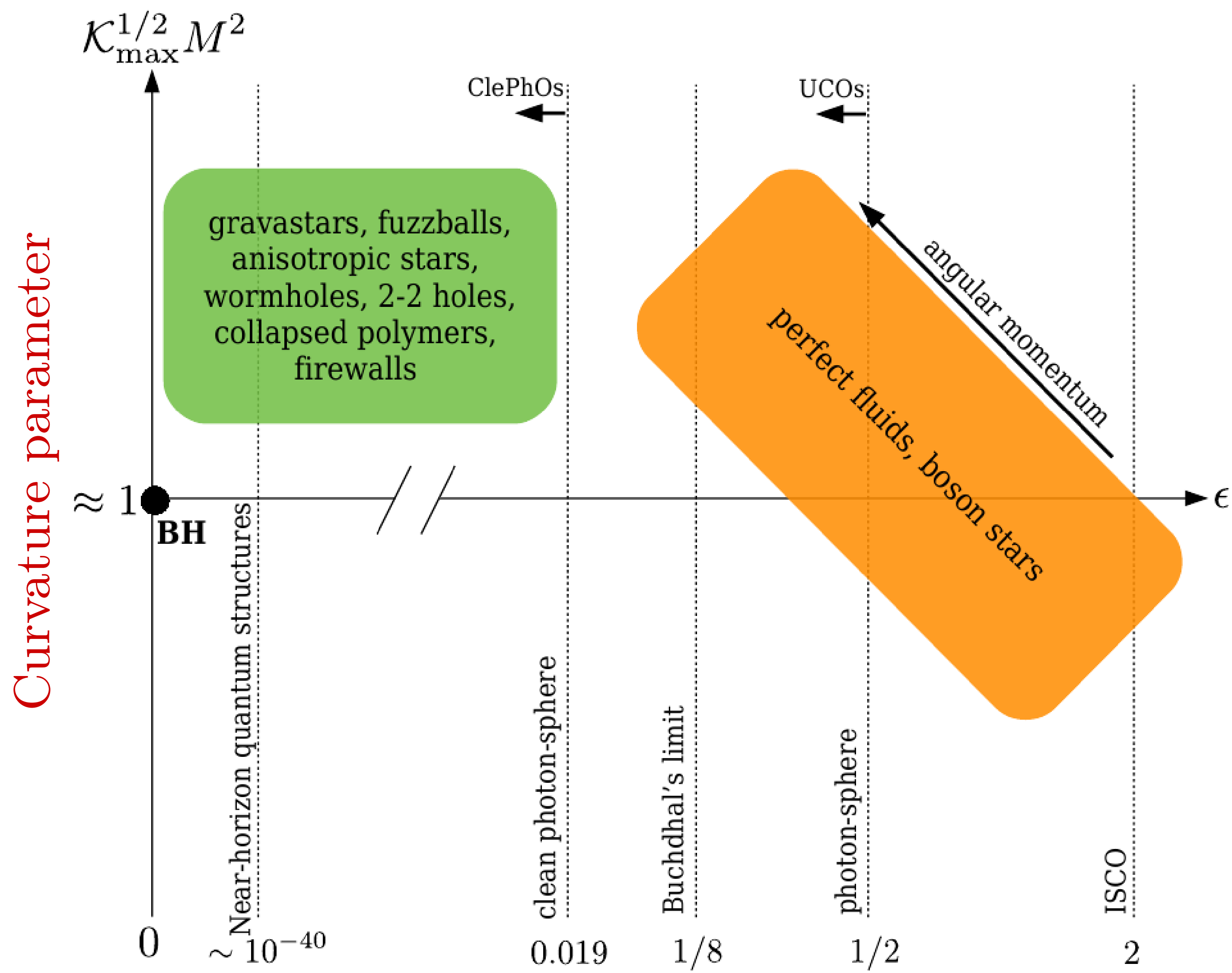
[Testa & PP 180604253, Maggio+ 1907-today, (see **E. Maggio's talk on Friday**)]

Probing Planckian corrections?



Different Planck-inspired models can be distinguished through tidal Love number measurements → lesson from NSs!

Quantifying the shade of darkness



“Closeness” parameter $r_0 \equiv r_g(1+\epsilon) = \frac{2GM}{c^2}(1+\epsilon)$