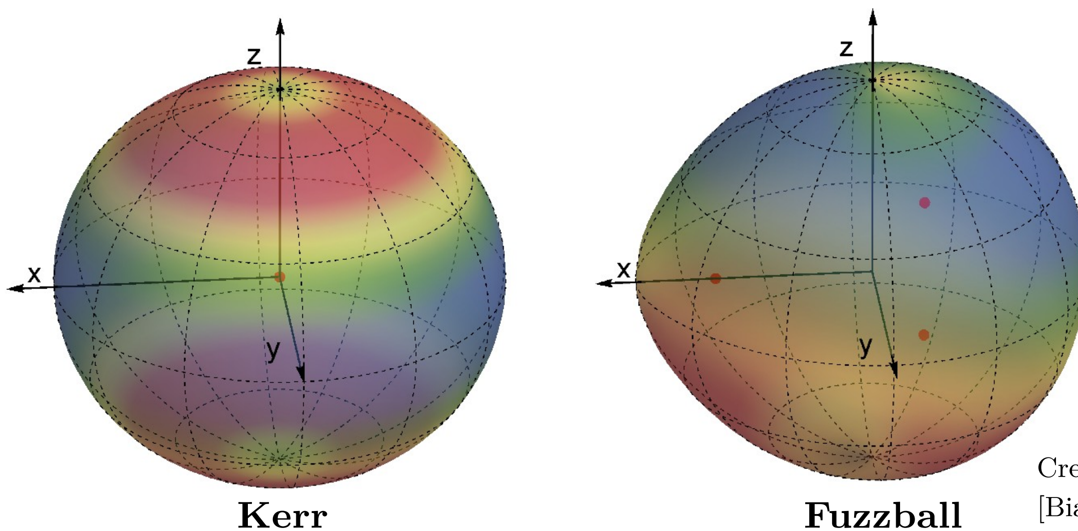
New physics on the horizon?

Testing the nature of dark compact objects

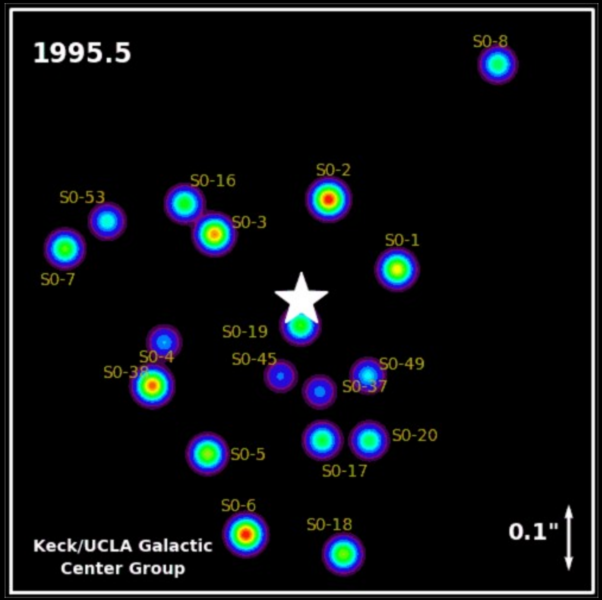


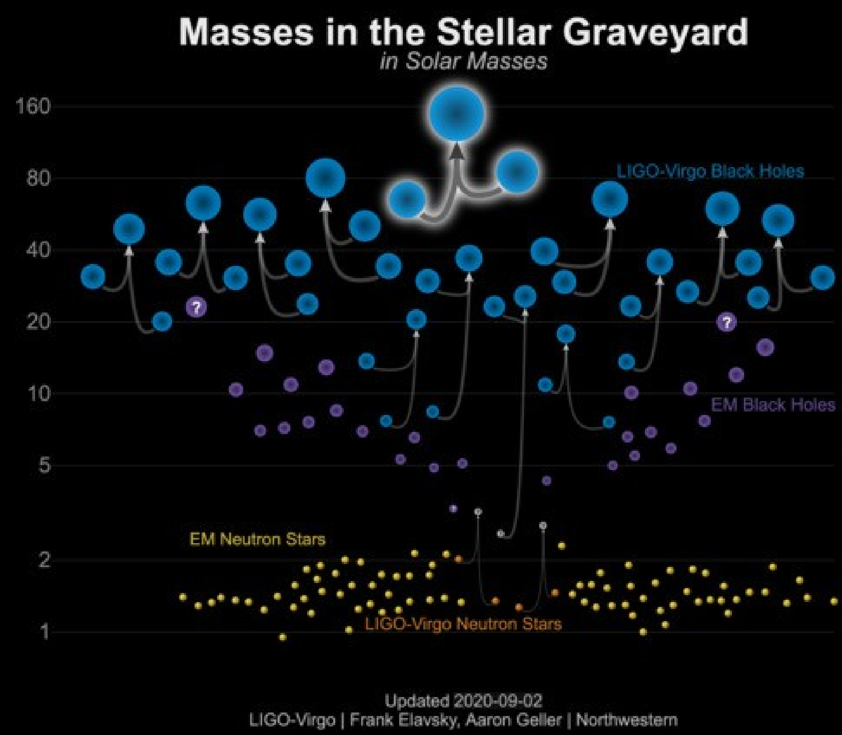
Credits: G. Raposo
[Bianchi+ PRL 2020]

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

European Research Council
DarkGRA

Black holes are now everywhere!





Why testing the BH picture?

Why?

- **Are there compact objects other than black holes and neutron stars?**
  - LIGO/Virgo mass-gap events?
  - Supermassive BH seeds?
  - (Dark) matter compact objects? (e.g. boson/axion stars)

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- **Observational signatures of quantum BHs?** *(if not now, when?)*
  - Information loss, singularities, Cauchy horizons…
  - New physics at the horizon (e.g. firewalls, nonlocality) [Almheri+, Giddings+, 2012-2017]
  - Regular, horizonless compact objects (e.g. fuzzballs) [Mathur+, Bena+, Bianchi+, Giusto+, …]

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Observations of exotic compact objects (ECOs) would imply new physics / new matter

The zoo of ECOs

Solutions to GR with exotic matter sources
(*e.g. anisotropic stars, boson stars, axion stars, gravastars, wormholes*)

Solutions to modified gravity
(*e.g. fuzzballs/microstates, 2-2 holes, superspinars, wormholes*)

- No sharp distinction in some cases

- Some ECOs require modified gravity only in the interior / close to the horizon → assuming GR in the exterior is often a good approx.

- Some models are phenomenological (formation, dynamics, stability?)

- Here we focus on GW phenomenology *agnostically*

[**Cardoso & Pani, Living Rev Relativ (2019) 22:4** for ECO modeling, constraints, and details]

Quantifying the shades of darkness

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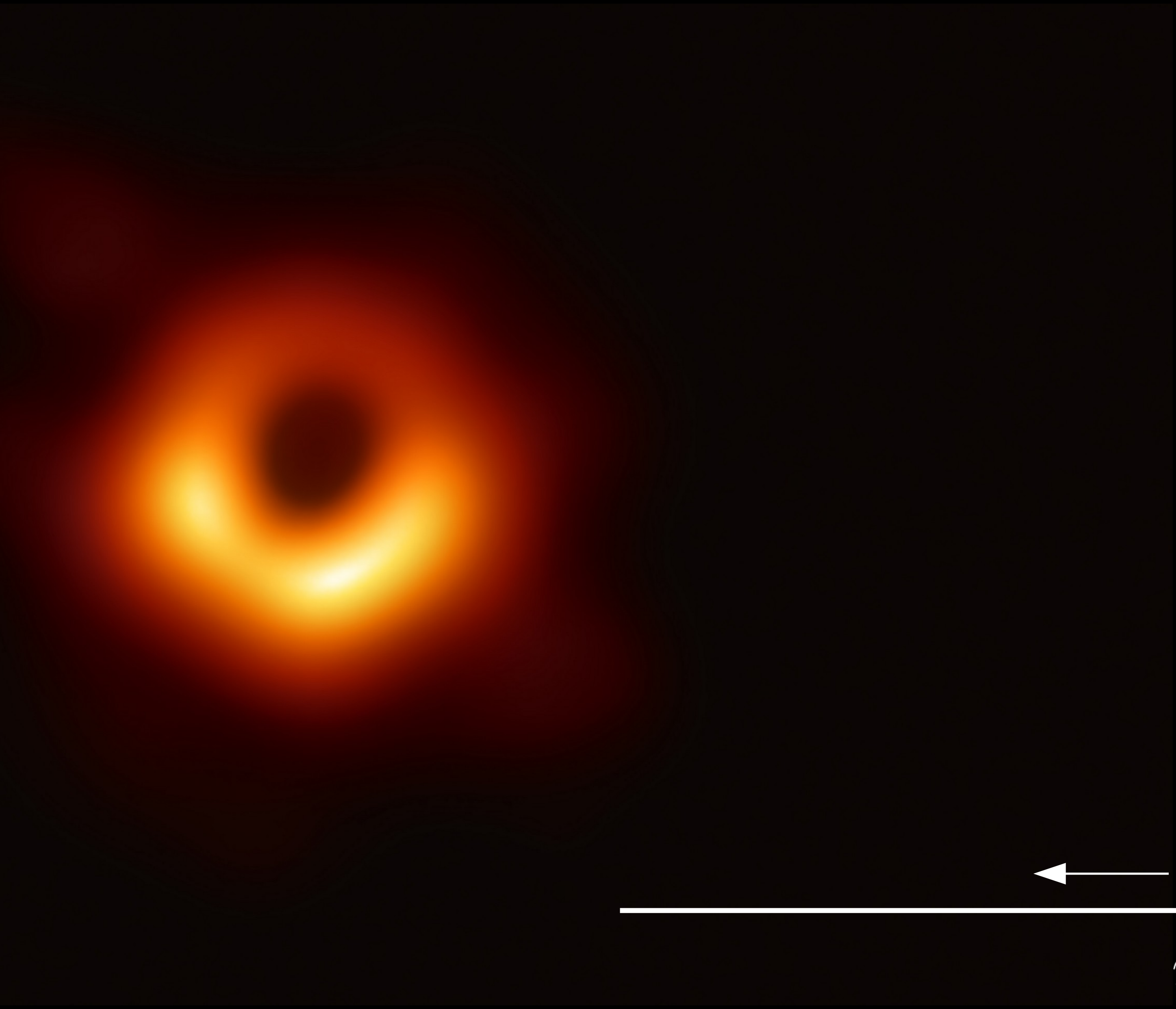

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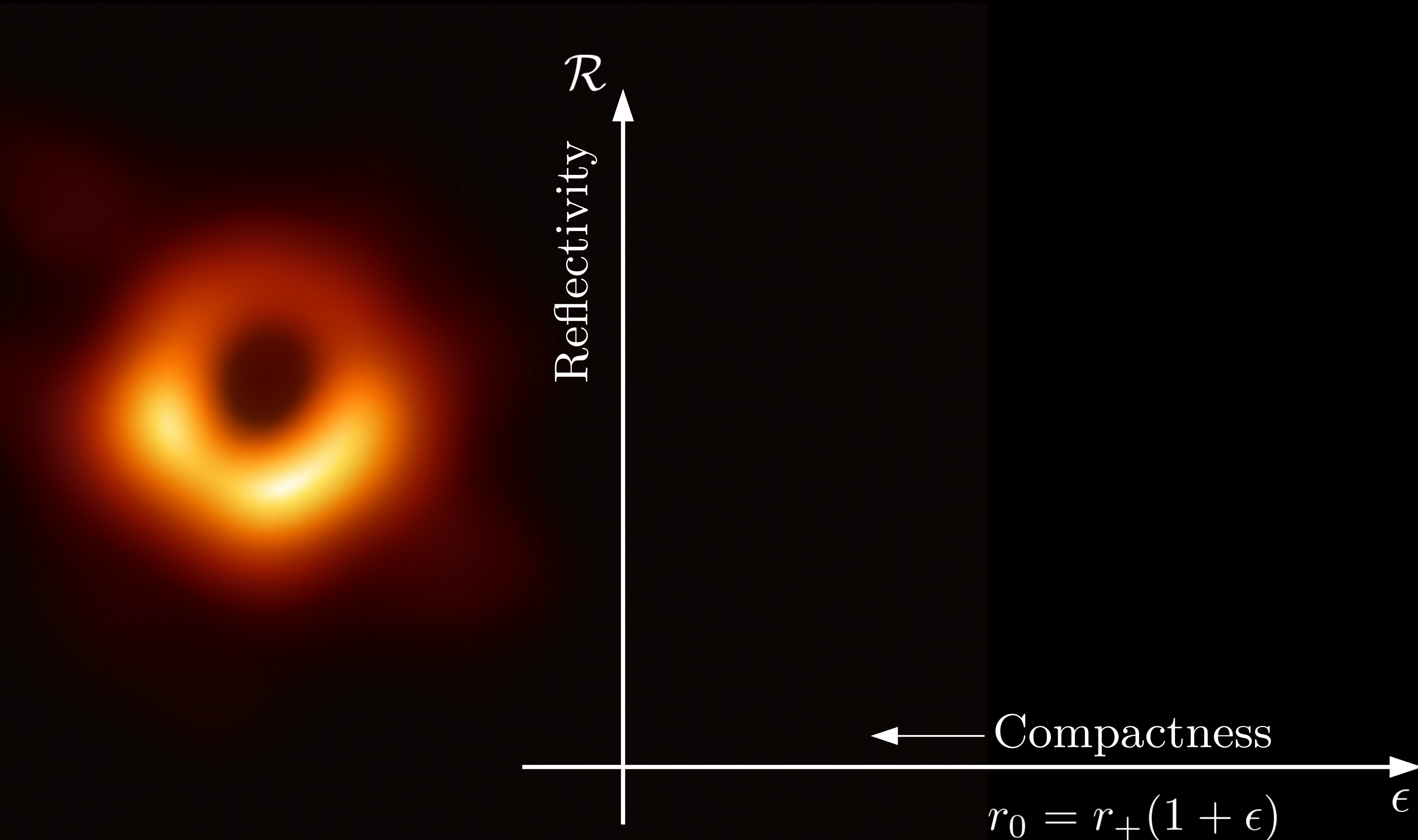

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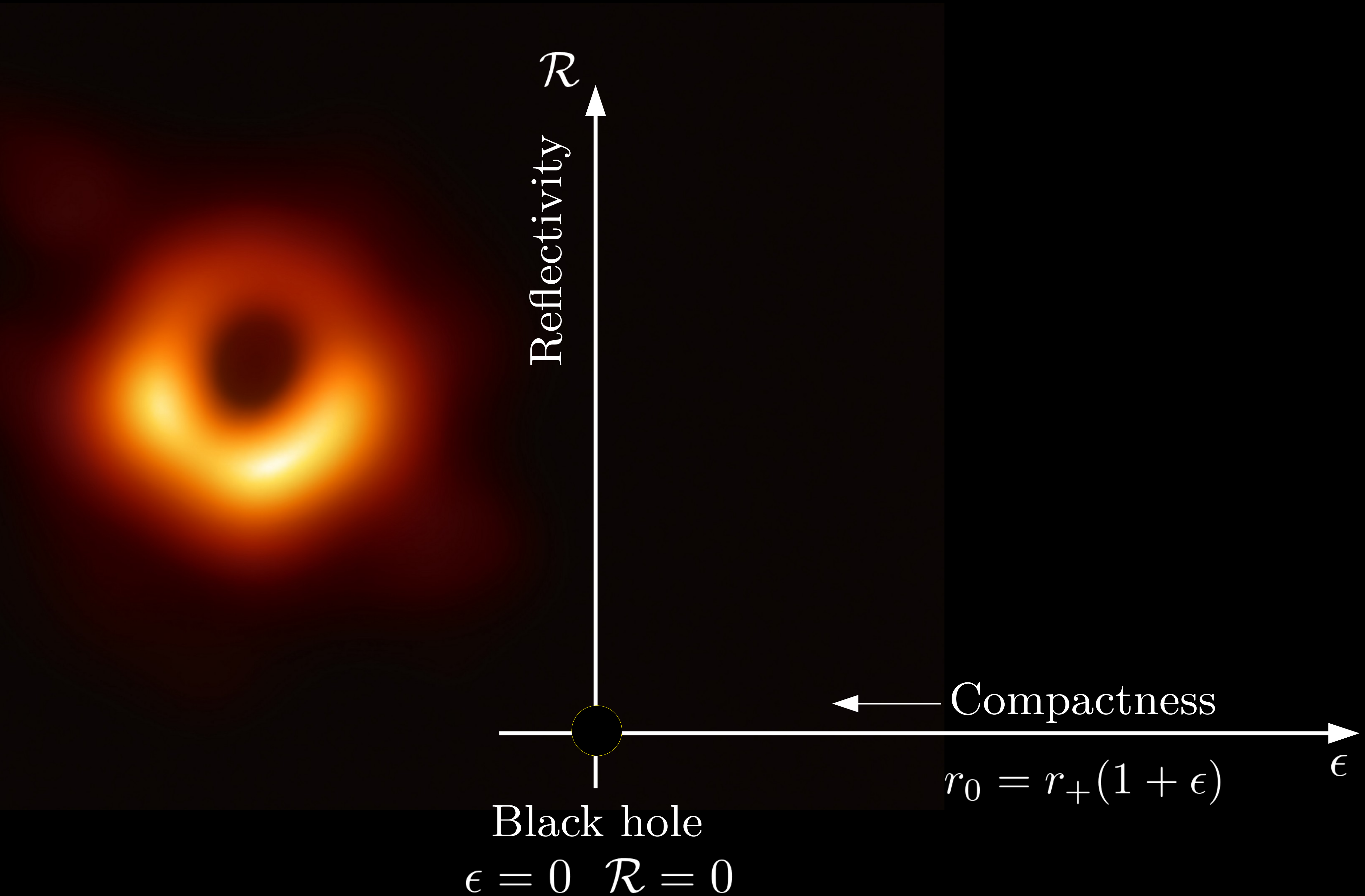

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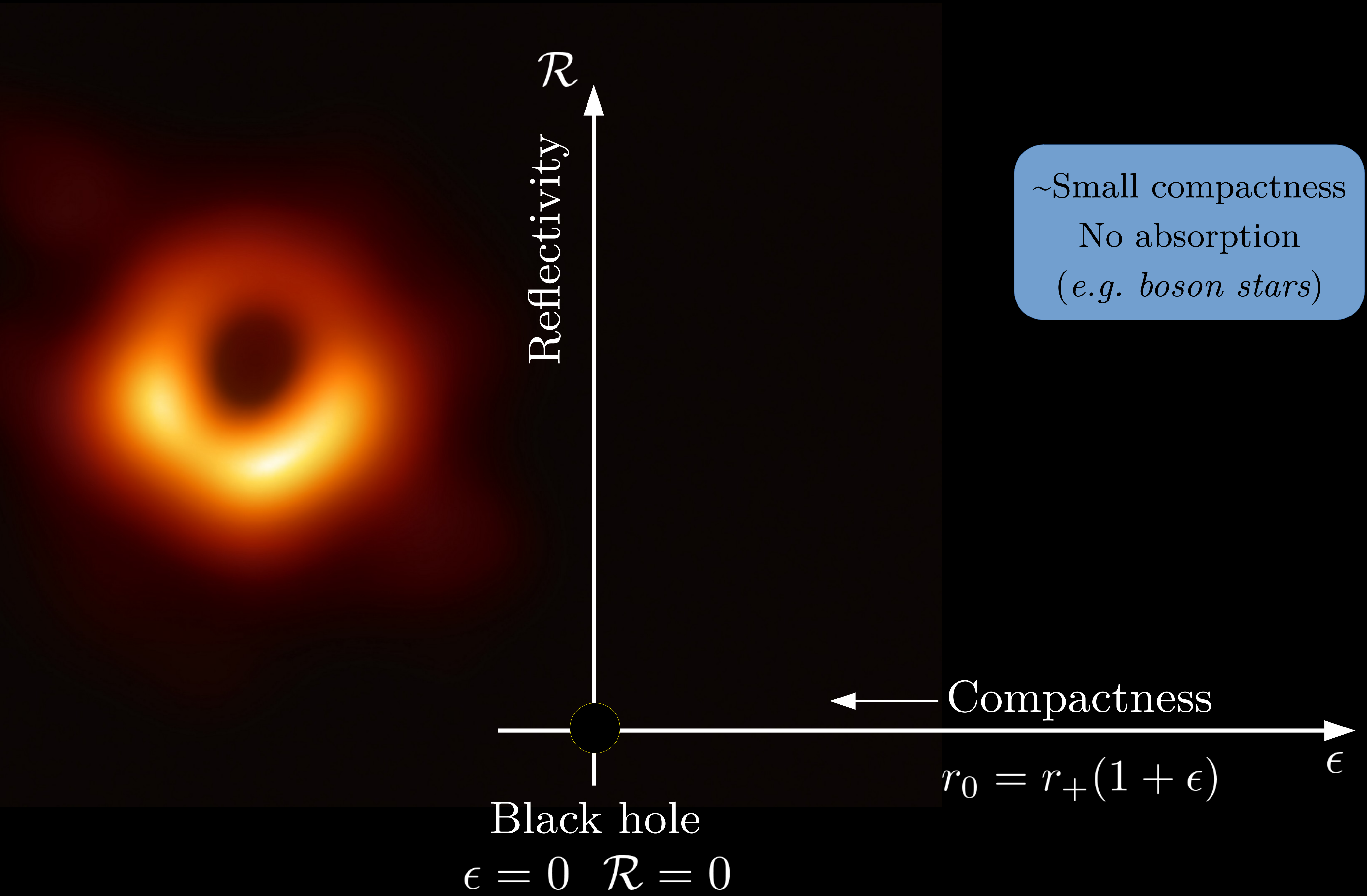

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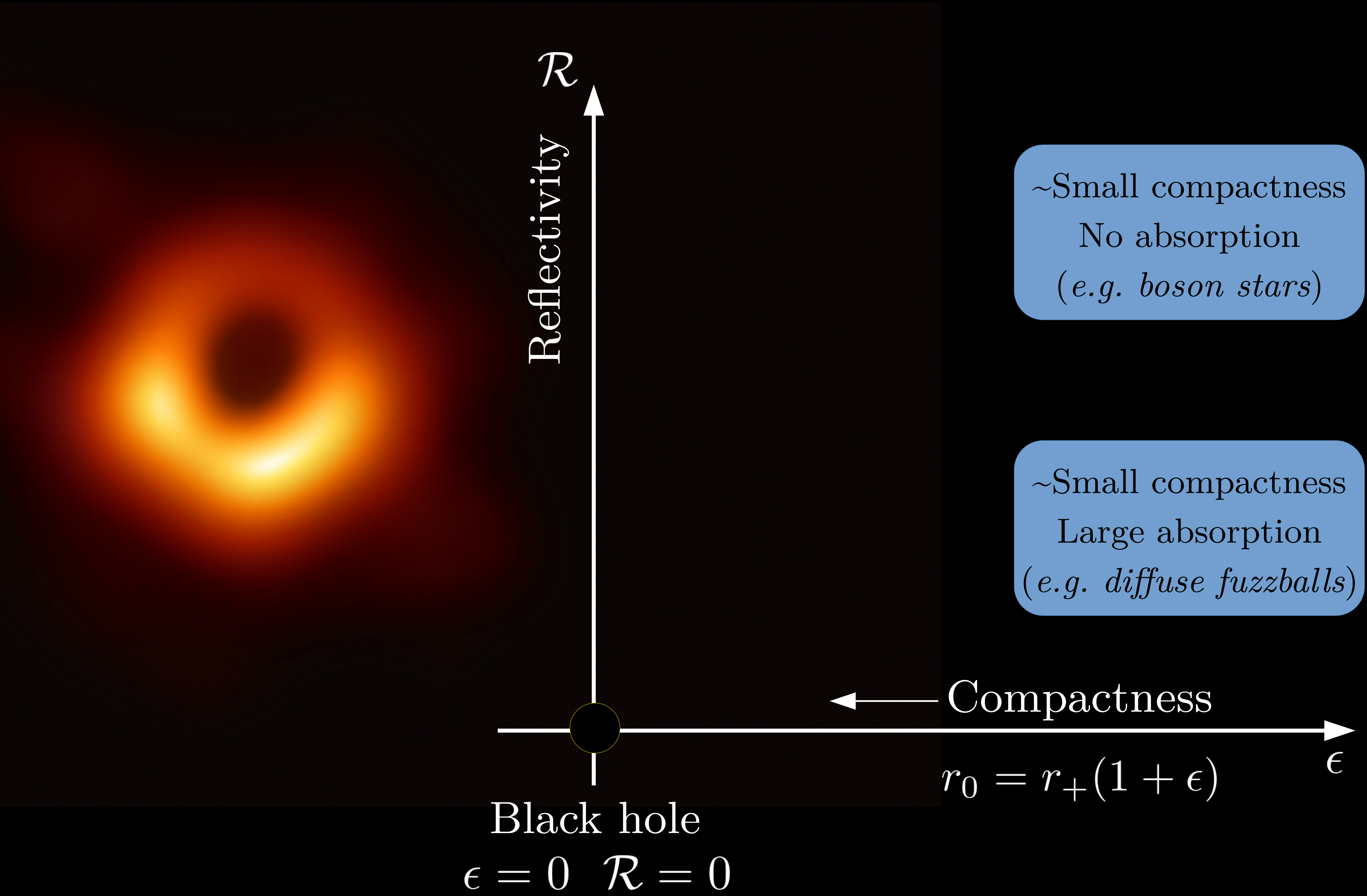

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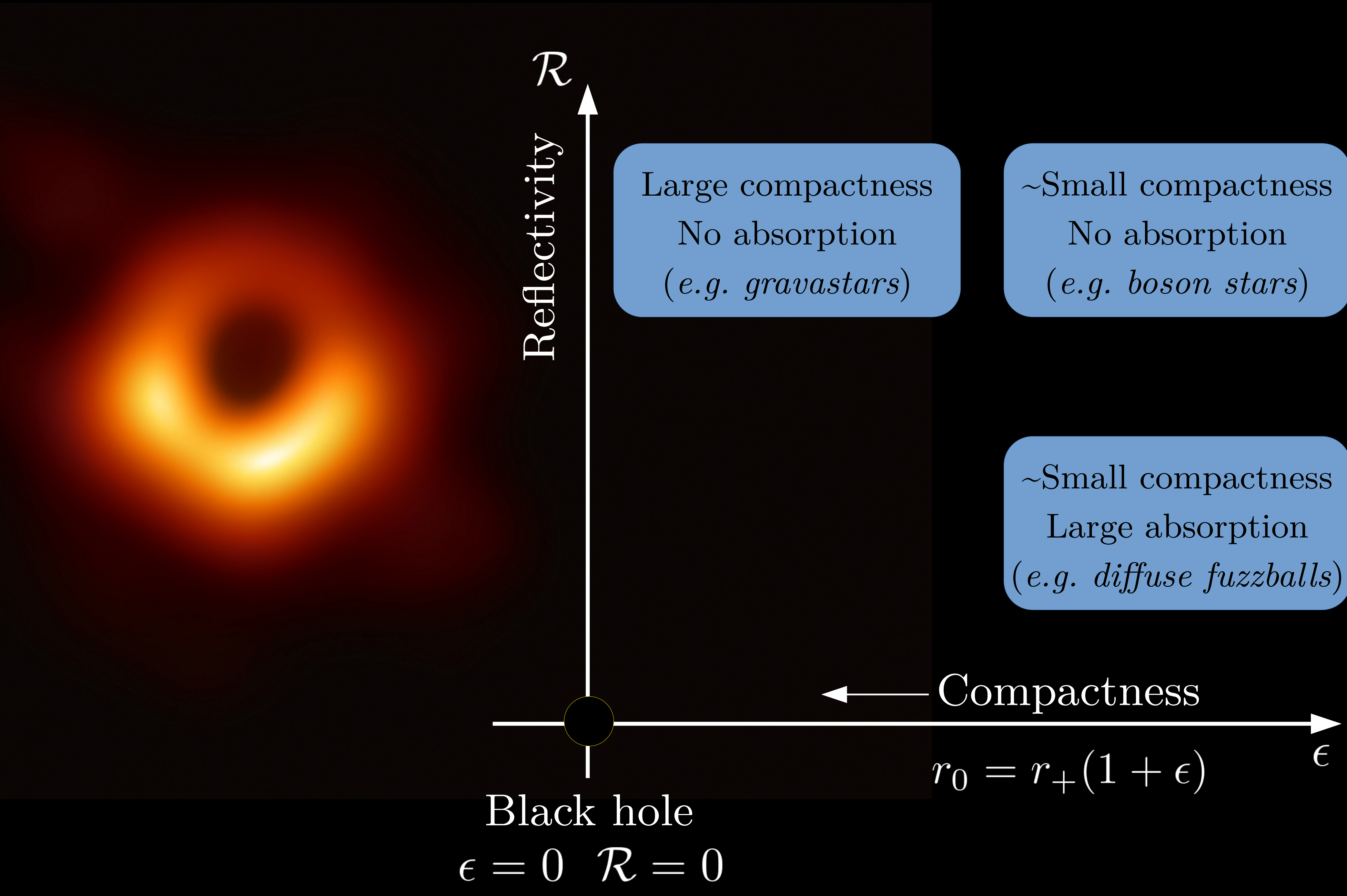

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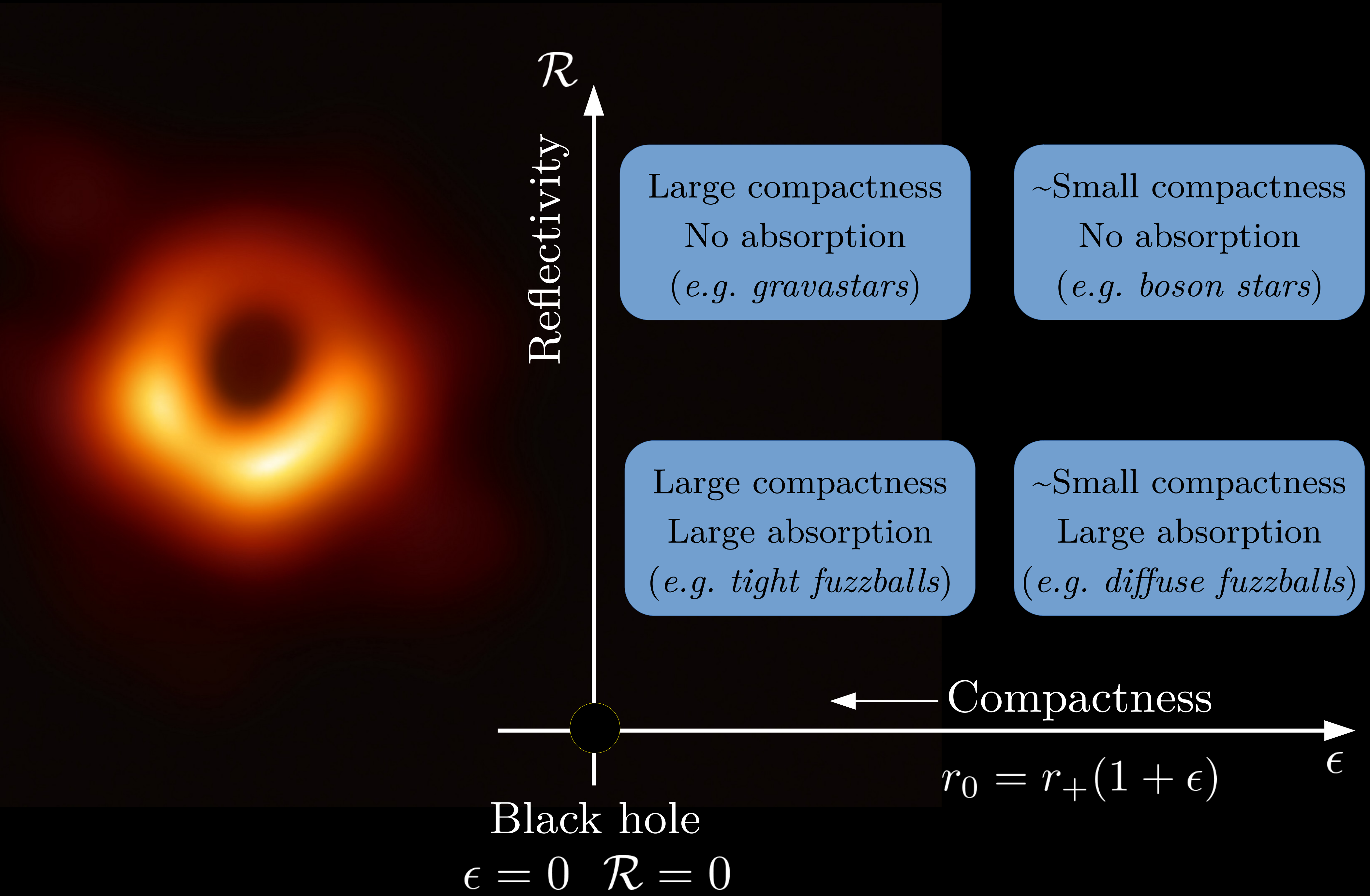

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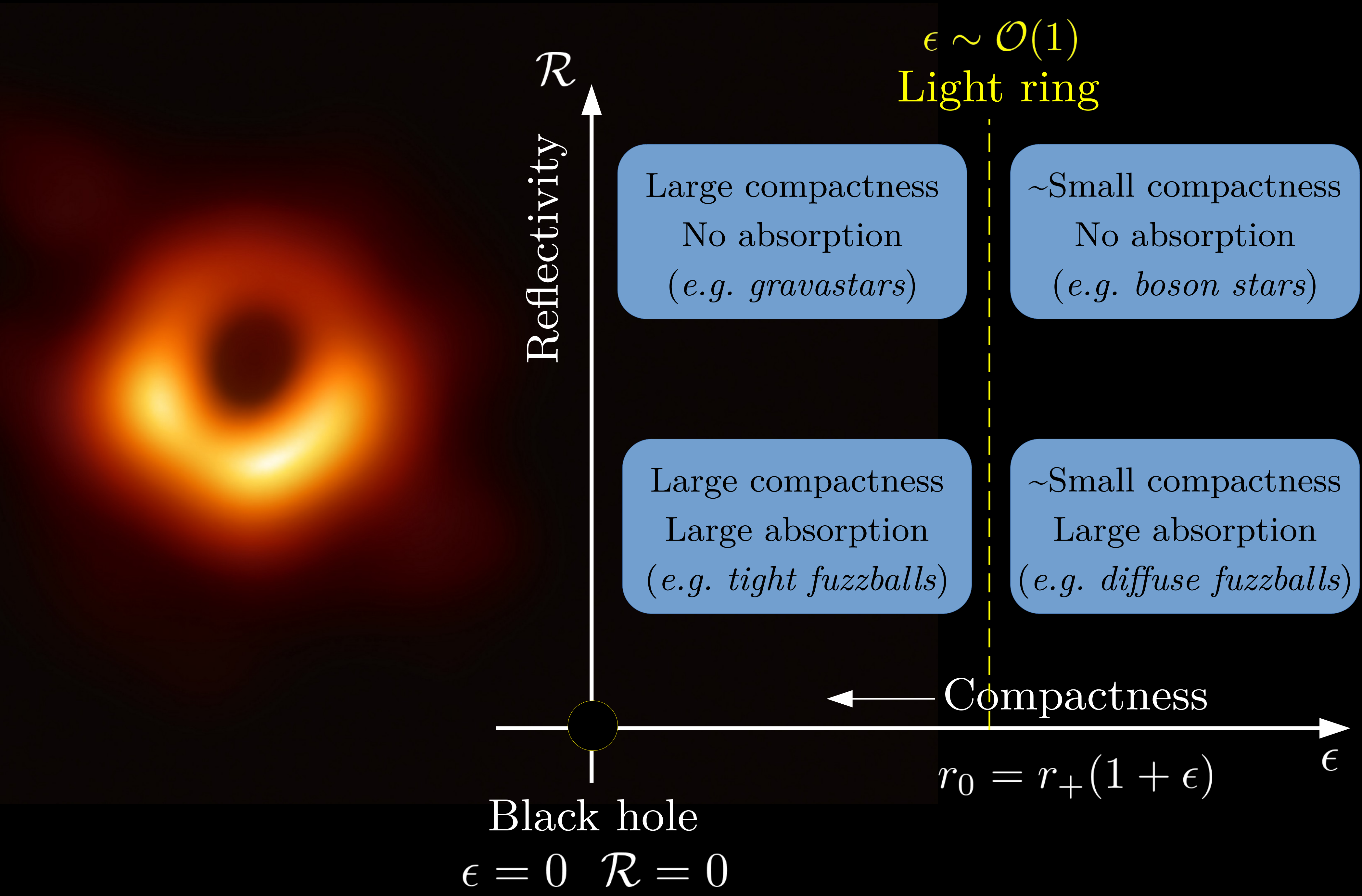

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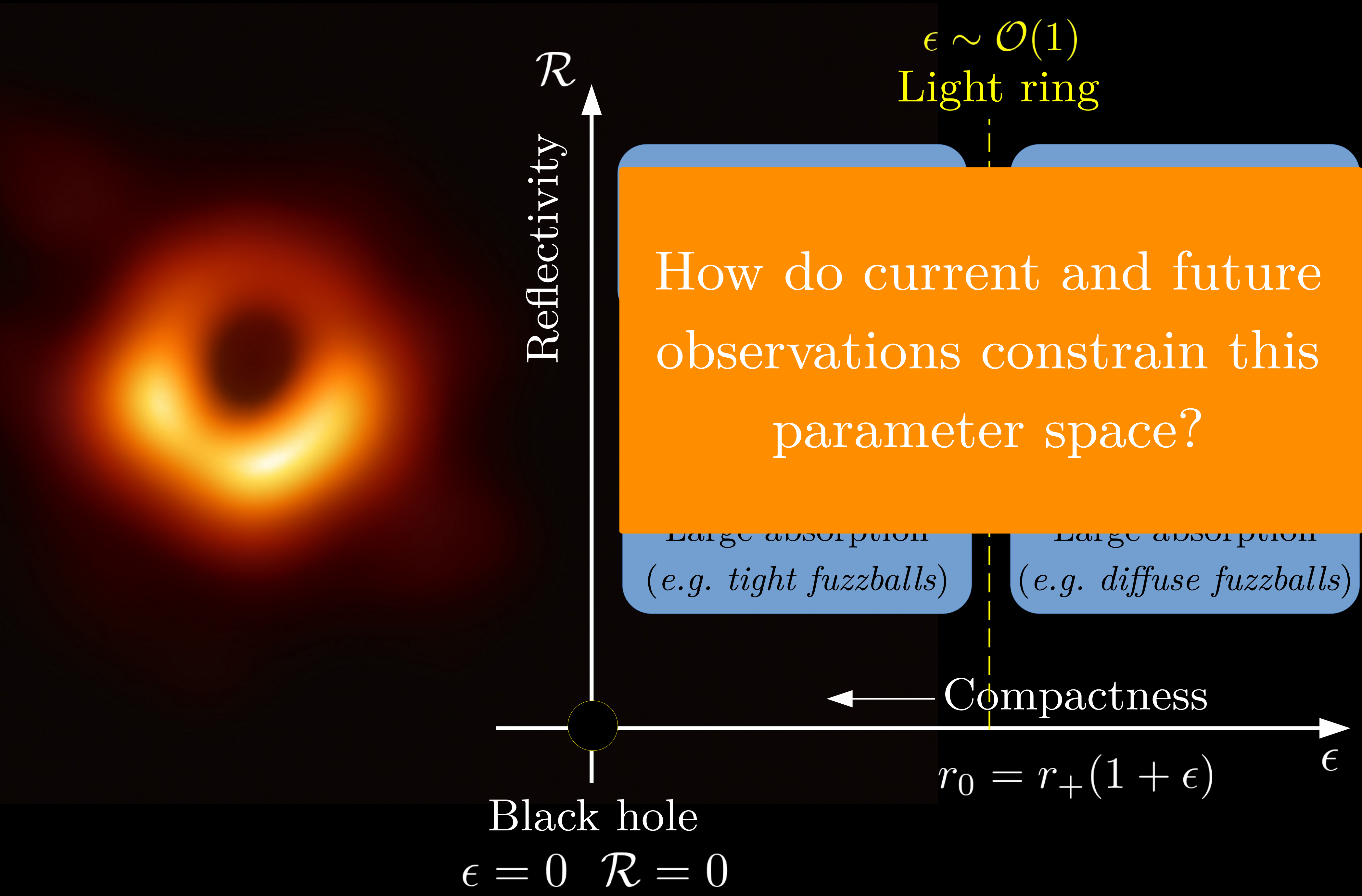
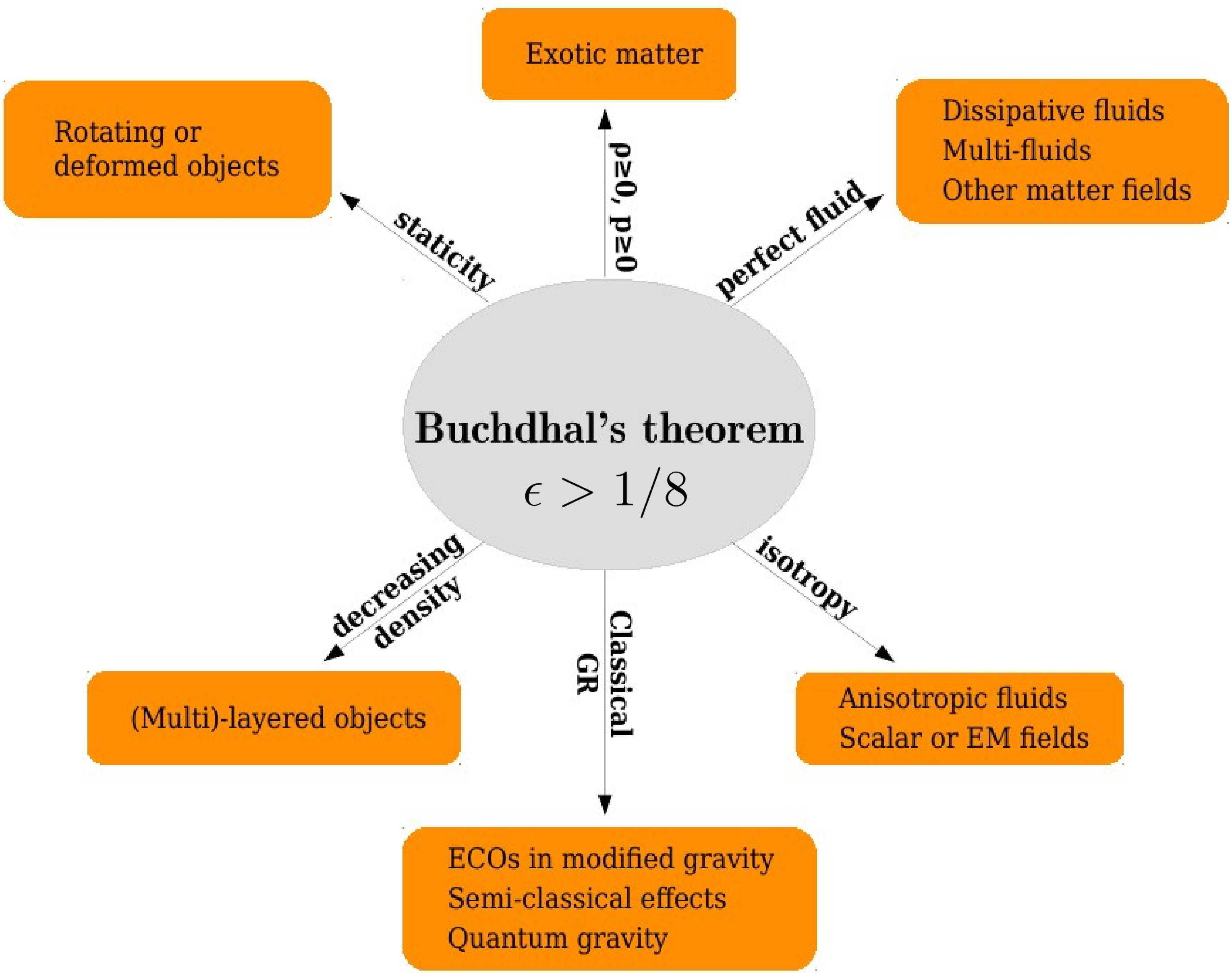


A compass to navigate the ECO atlas



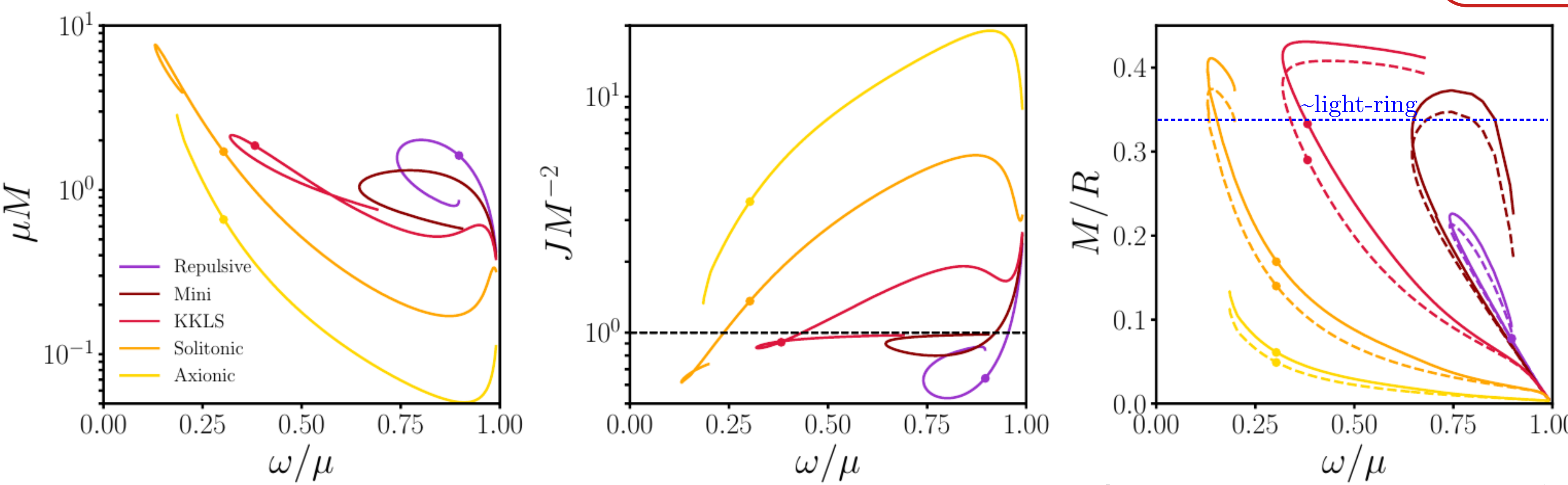
Evading Buchdhal #1:Boson stars

Liebling & Palenzuela Living Rev. Rel. 20, (2017), 5

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

- Well-motivated and consistent: Self-gravitating solutions to GR + (complex) boson
- Max. mass and compactness depend on self-interactions
- Spinning (scalar) boson stars are unstable unless strongly interacting [Sanchis-Gual+ PRL 2019, Siemonsen-East PRD 2021]

Model	Potential $V(\lvert\Phi\rvert^2)$	Maximum mass $M_{\max}/M_\odot$
Minimal	$\mu^2\lvert\Phi\rvert^2$	$8(\frac{10^{-11}\text{ eV}}{m_S})$
Massive	$\mu^2\lvert\Phi\rvert^2 + \frac{\alpha}{4}\lvert\Phi\rvert^4$	$5\sqrt{\alpha\hbar}(\frac{0.1\text{ GeV}}{m_S})^2$
Solitonic	$\mu^2\lvert\Phi\rvert^2[1 - \frac{2\lvert\Phi\rvert^2}{\sigma_0^2}]^2$	$5[\frac{10^{-12}}{\sigma_0}]^2(\frac{500\text{ GeV}}{m_S})$



[Siemonsen & East, Phys. Rev. D 103 (2021)]

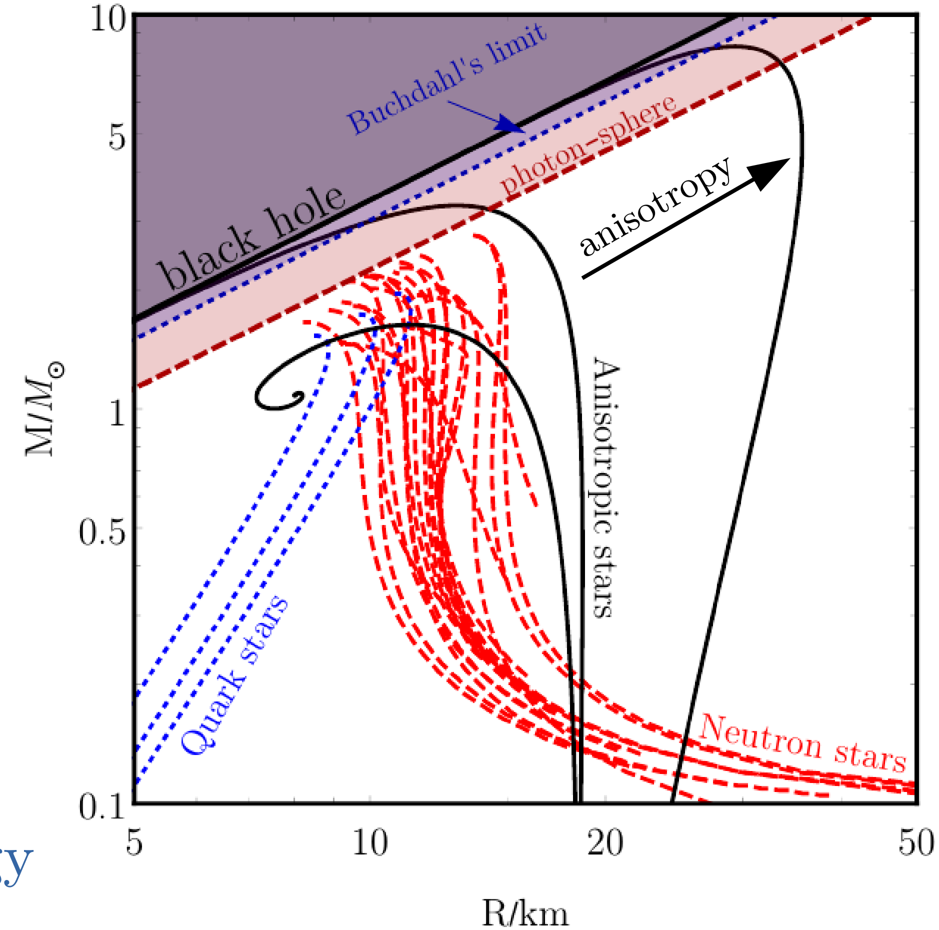
- Strong interactions give rise to multiple stable branches [Guerra, Macedo, PP, JCAP 2019]

Evading Buchdhal #2: 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)



Evading Buchdhal #3: fuzzballs

- Fuzzball paradigm: classical BHs are ensembles of a huge number of regular, horizonless, microstate geometries [Lunin+ 2001, Mathur 2005+, Bena+, Bianchi+, Giusto+, ...]

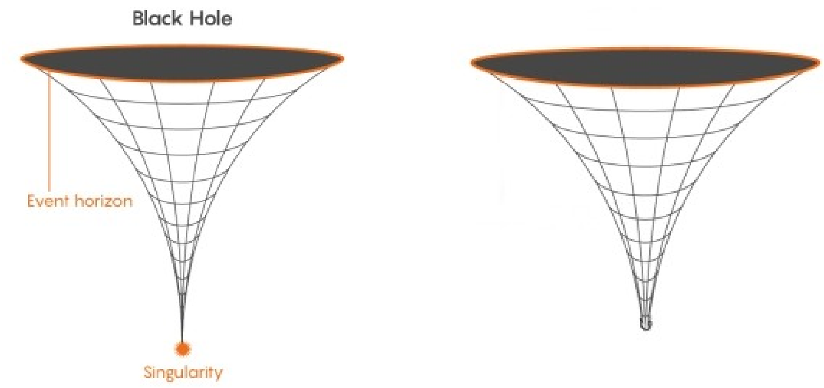
- BH entropy explained by the number of microstates. BH entropy accounted for in special cases [Strominger 1996, Horowitz 1996, Maldacena 1997]

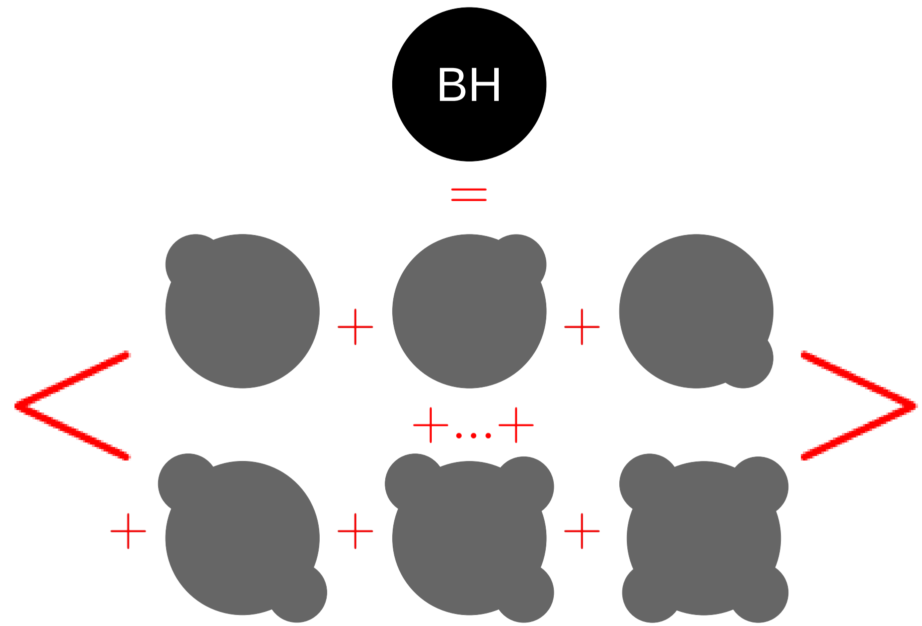
- (Low-energy truncations of) string theory admits huge families of solutions [Bena+ 2007, 2015-2017]

- Pros: well motivated, <u>mass is free parameter</u>

- Cons: only nearly extremal charged BHs so far, complicated

- Open issues: measurement problem (typical vs atypical states, averaging?), phenomenology [Mayerson 2020]

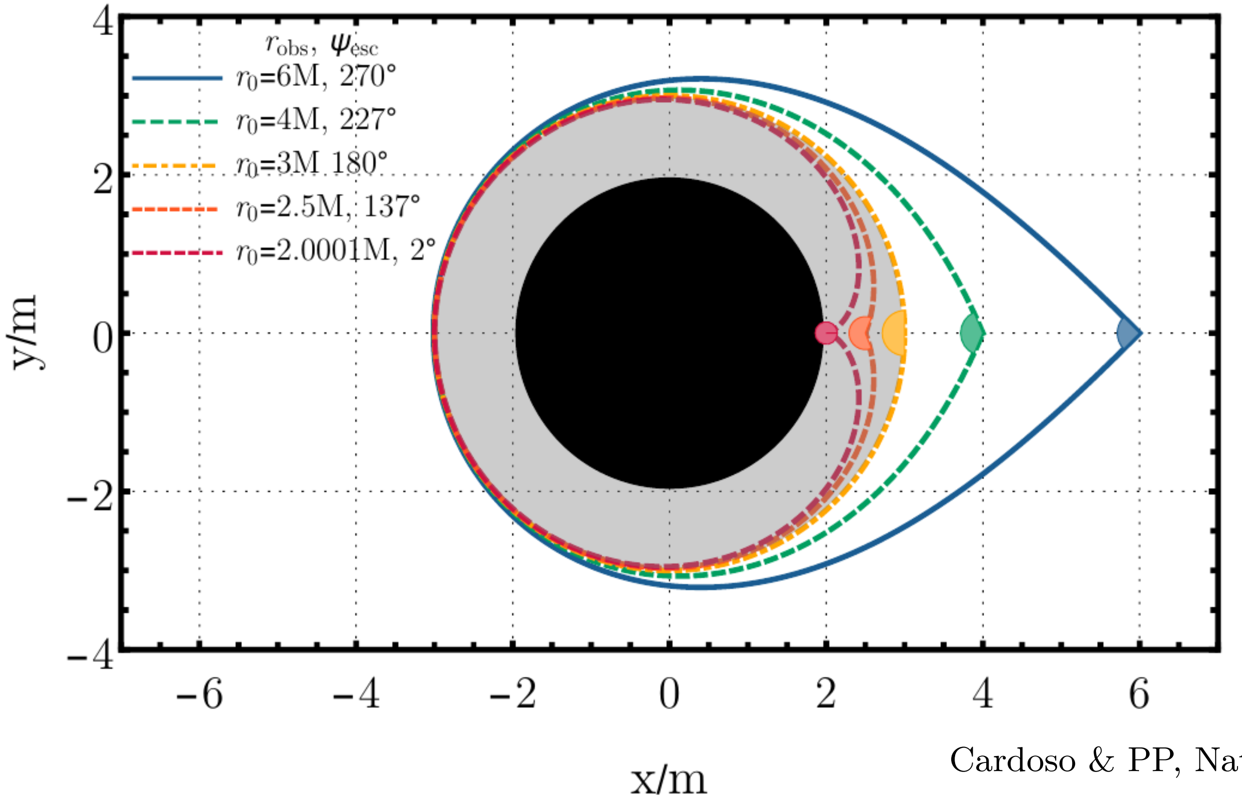




$\sim e^{\frac{M^2}{M_P^2}}$ microstates

Imaging the horizon?

Escape angle ~ O(ε)

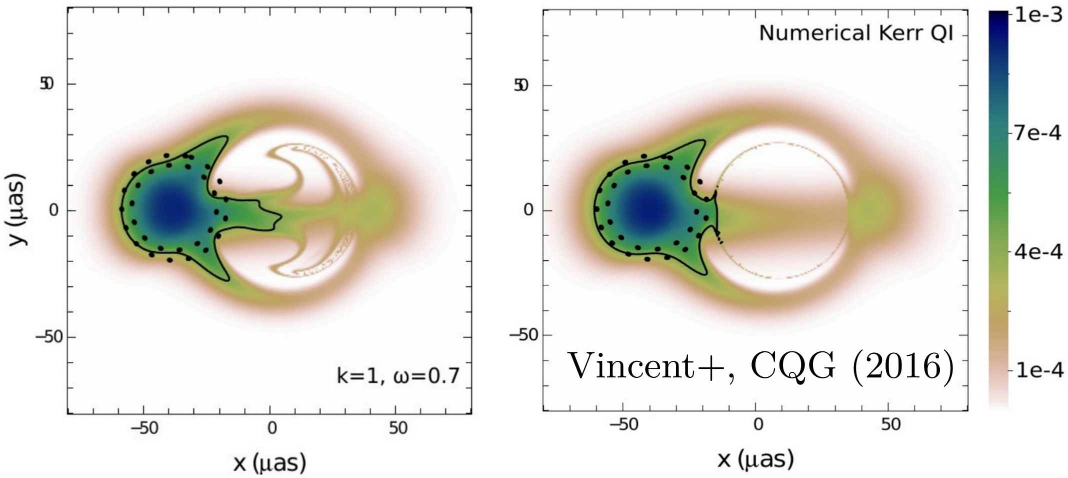


Cardoso & PP, Nature Astronomy (2017)

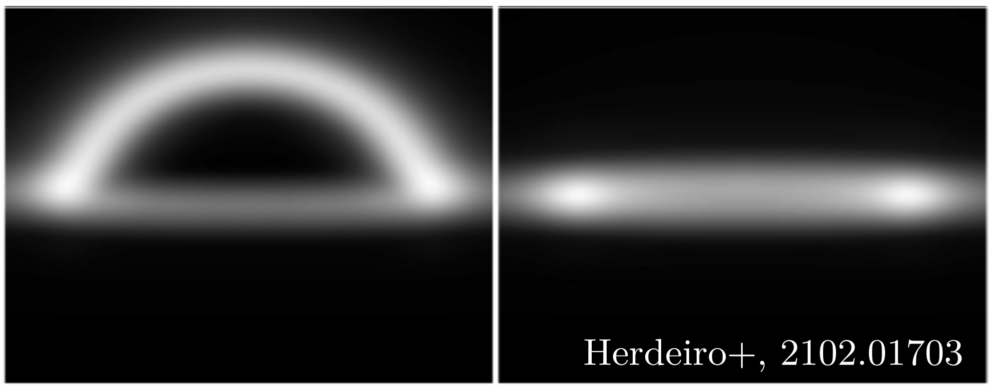
- EM tests when ε→0 are very challenging [Abramowicz+ (2012)]
- Existence of a light ring is a strong discriminator

The imitation game

BH Boson star

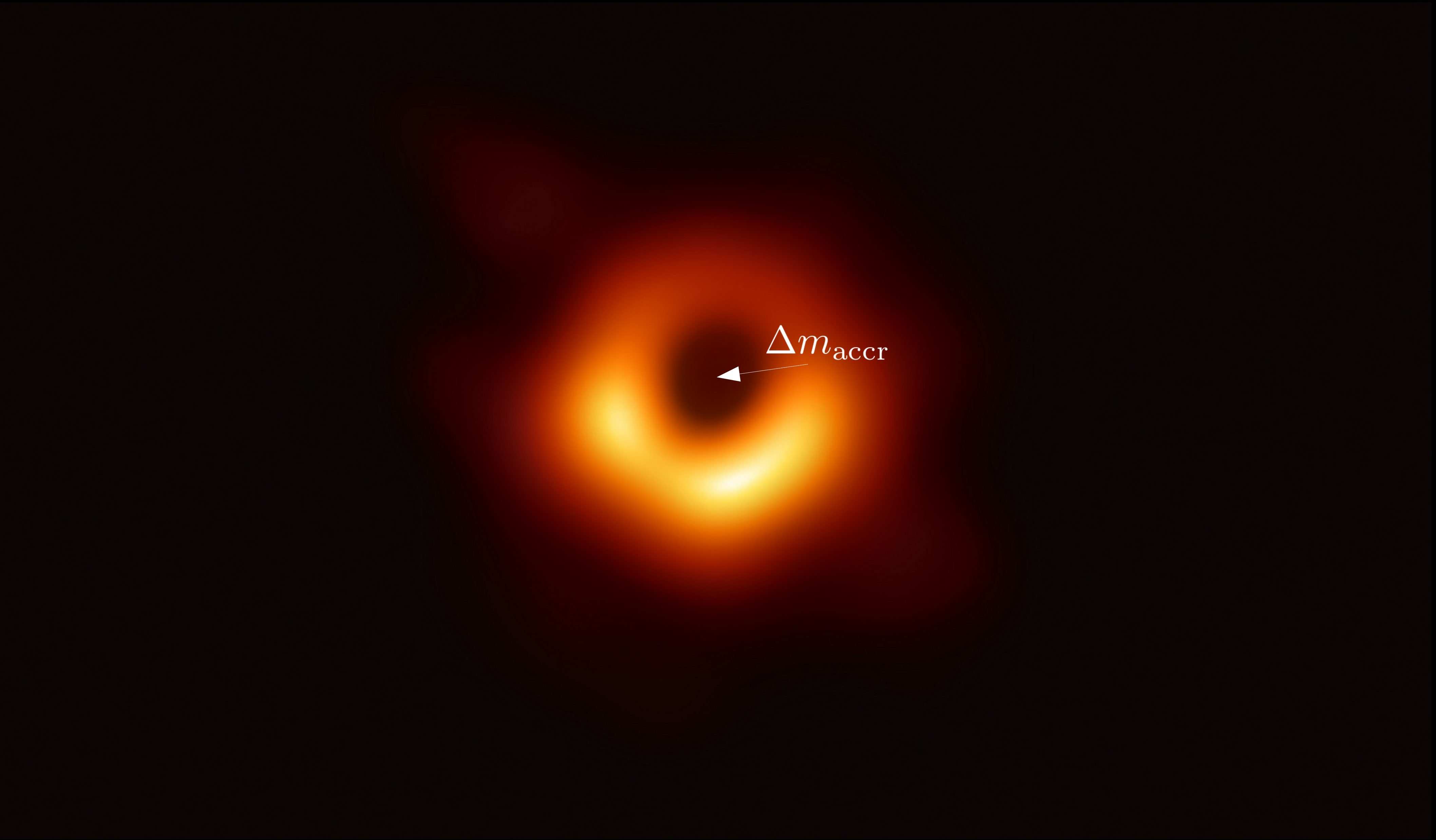


BH Proca star



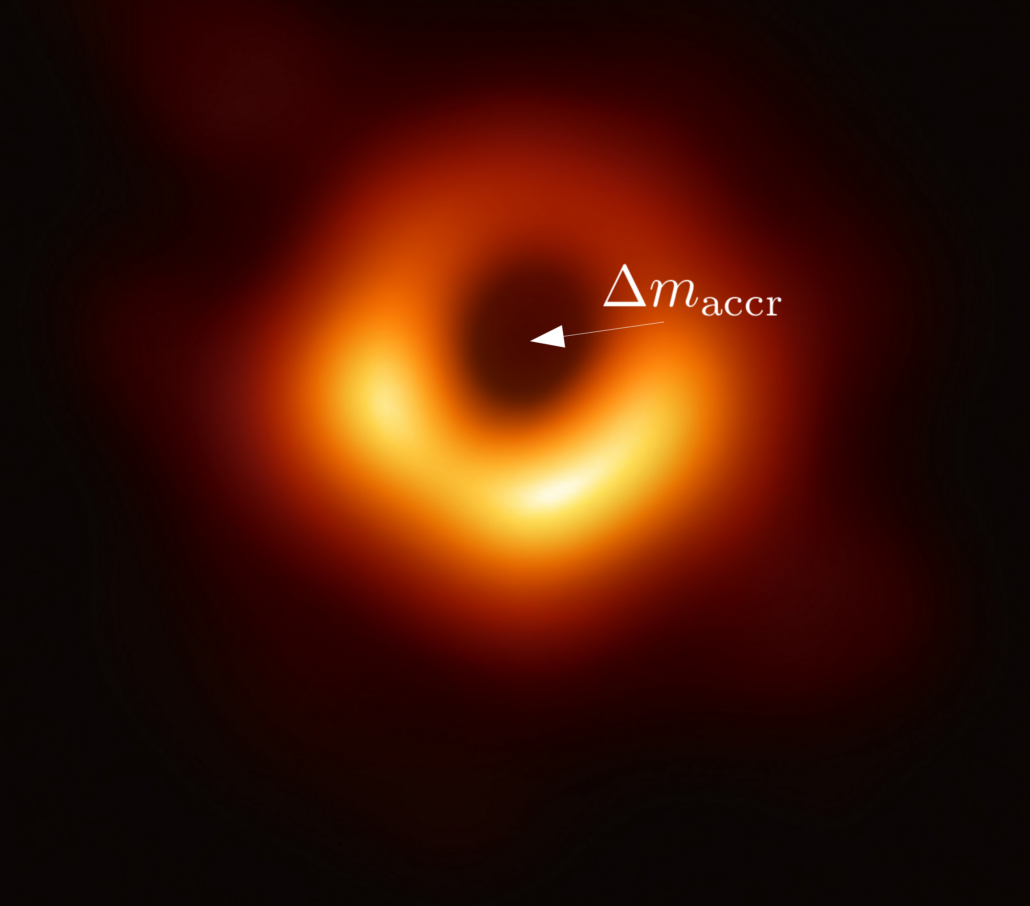
- Degeneracy with spin, distance, accretion model, emissivity?
- More compact ECOs would imitate the BH better
- Tests based on shadows can constrain $\epsilon \sim \mathcal{O}(1)$ [EHT 2019, Cardoso-Pani 2019, Volkel+ 2020]

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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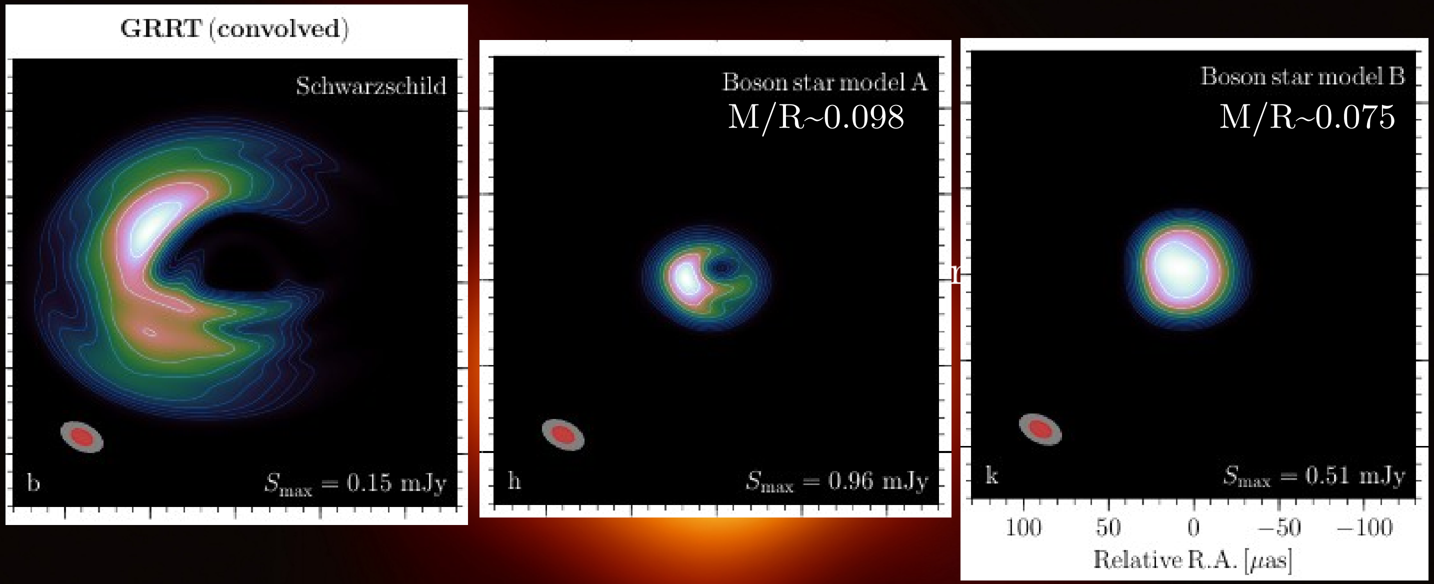

Quantitative differences due to matter accumulating in the interior

[Olivares+ MNRAS 2020]

More compact objects with light rings might be harder to distinguish

[Cardoso, Duque, Foschi (2021)]

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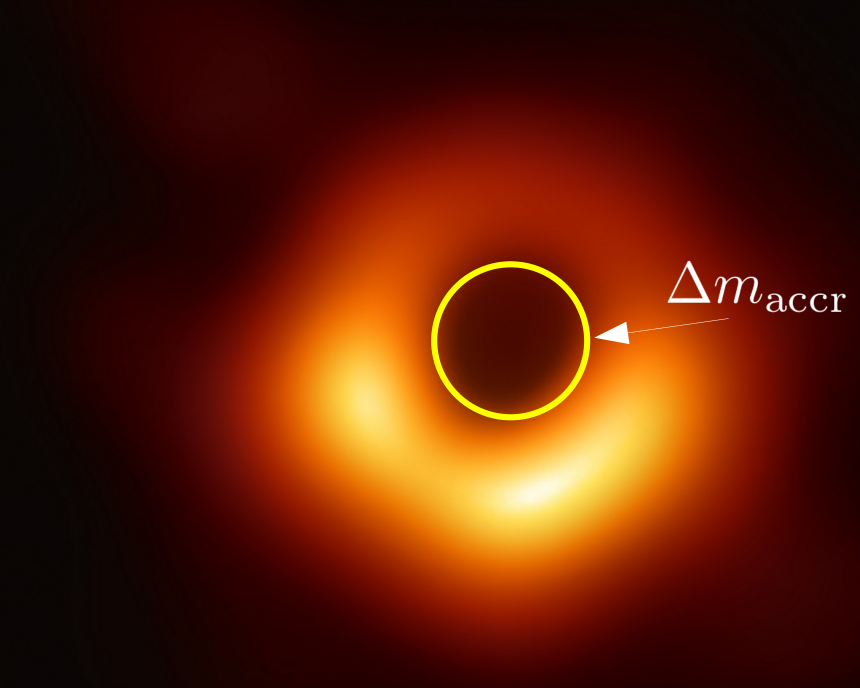


Assuming thermal equilibrium and hard surface yields much tighter constraints [Broderick-Narayan CQG 2007]

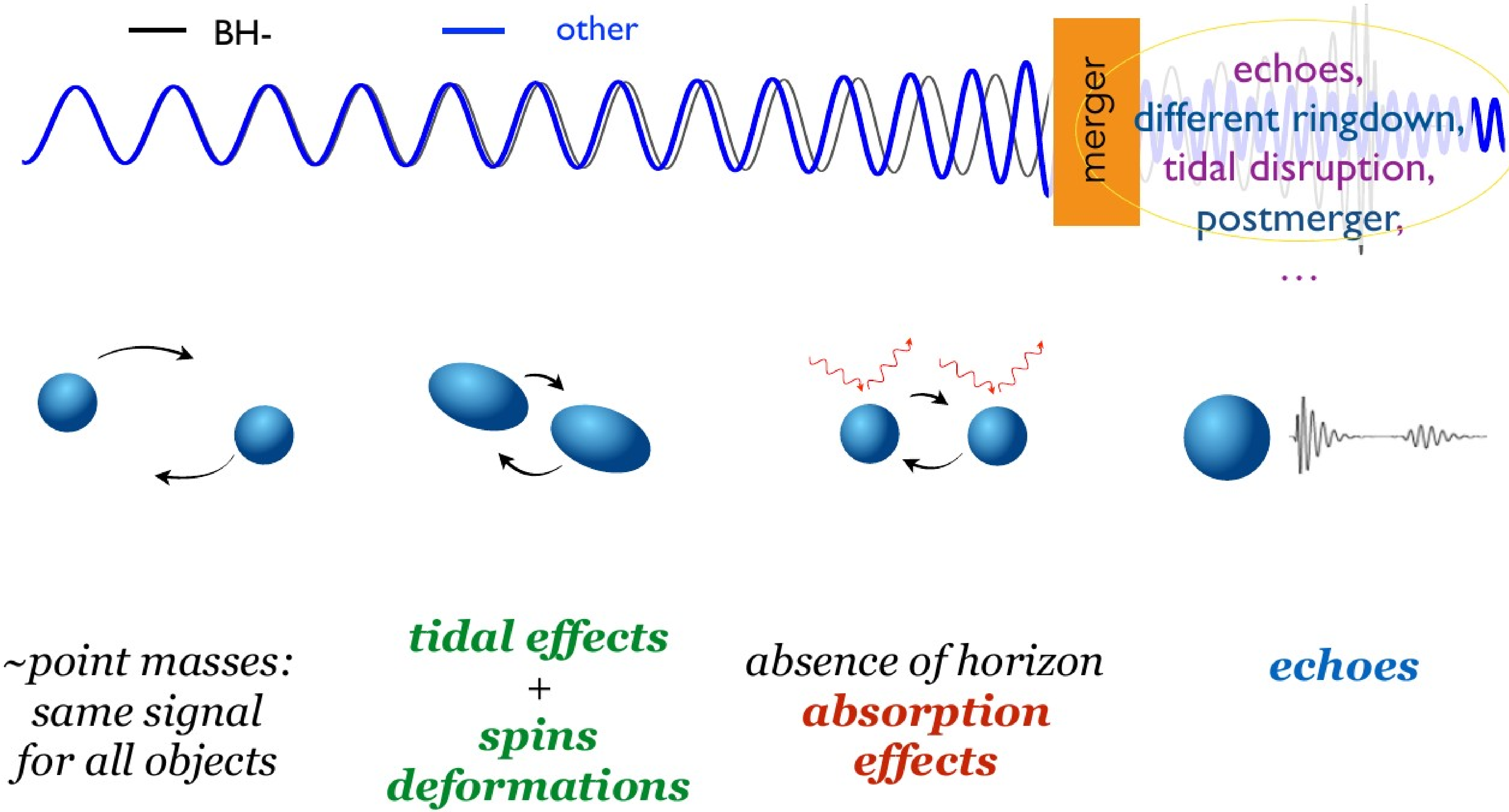
$$\epsilon < 10^{-14}$$

This stringent constraint is evaded if the object has just a tiny absorption

[Carballo-Rubio+, Phys.Rev.D 98 12 124009 (2018)]

GW-based tests of ECOs

Slide concept by T. Hinderer and A. Maselli



ECO spectroscopy

- **Prompt ringdown**: superposition of quasinormal modes (QNMs)

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

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

- 3G/LISA → O(100-1000) events/yr allowing for BH spectroscopy [Berti+ (2016)]
- Overtones also important → multimode/multitone analysis?

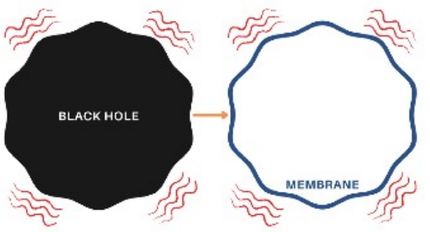
[Gieser+ 2019, Isi+ 2019, Bhagwat+ 2020, Ota-Chirenti 2020, Forteza+ 2020]

- ECO smoking guns in the prompt ringdown (shared with modified gravity):
  - Shift of the entire QNM spectrum
  - Extra ringdown modes (e.g., extra polarizations, matter modes) → amplitudes?
  - Isospectrality breaking
- Ringdown parametrizations sufficient for null-hypothesis tests

[Meidam+ (2014), Glampedakis+ (2017), Carullo+ (2018), Cardoso+ (2019), McManus+ (2019), Maselli+ (2020), Carullo 2021]

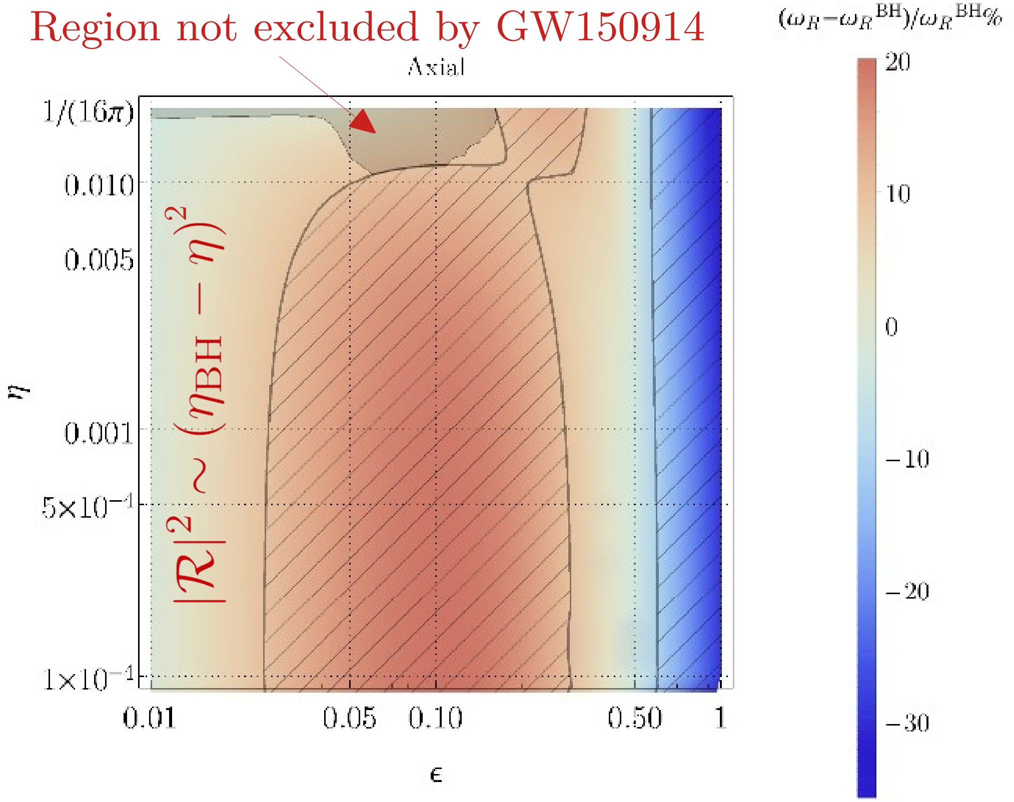
How does an ECO ringdown?

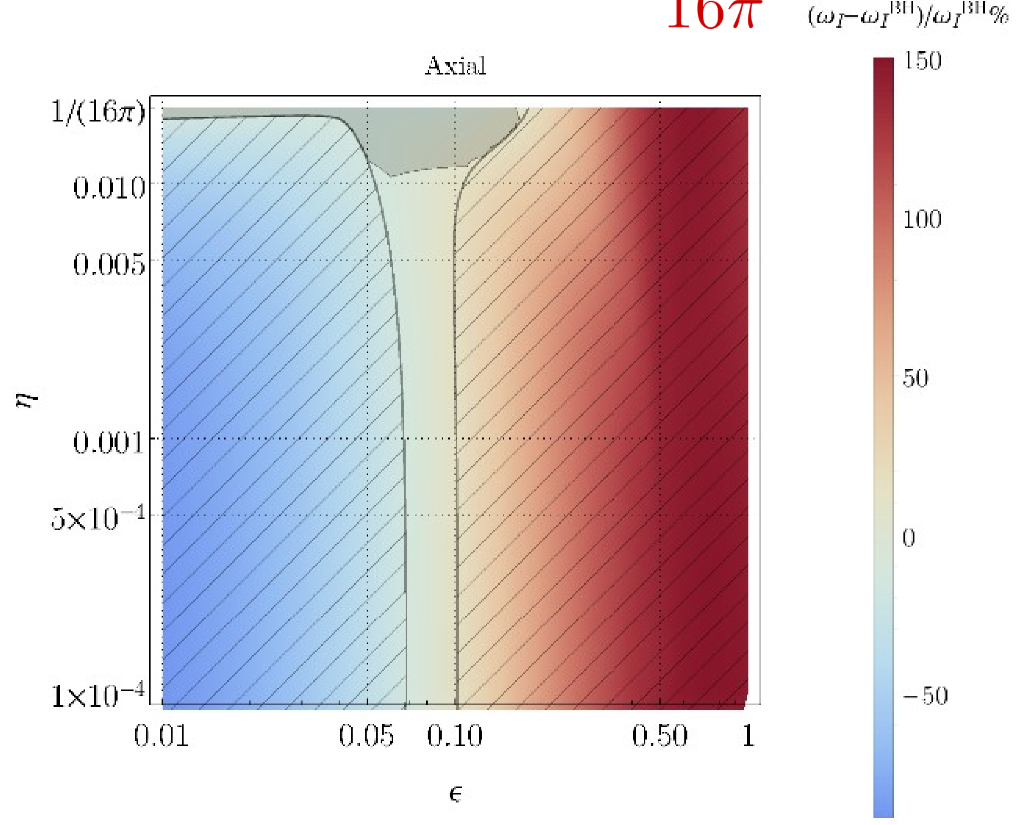
[Maggio+ PRD 2020]



- Neglecting spin and assuming GR in the exterior
- Interior modeled by the *membrane paradigm* [Damour, Thorne, ...]
- Boundary conditions $\to$ viscosity of a *fictitious* fluid

$$\eta_{\rm BH} = \frac{1}{16\pi}$$





- Axial and polar modes are not isospectral but harder to resolve

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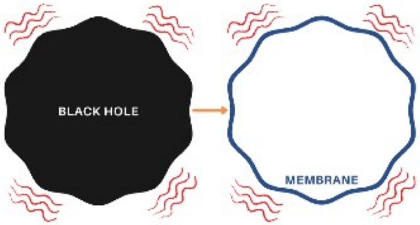

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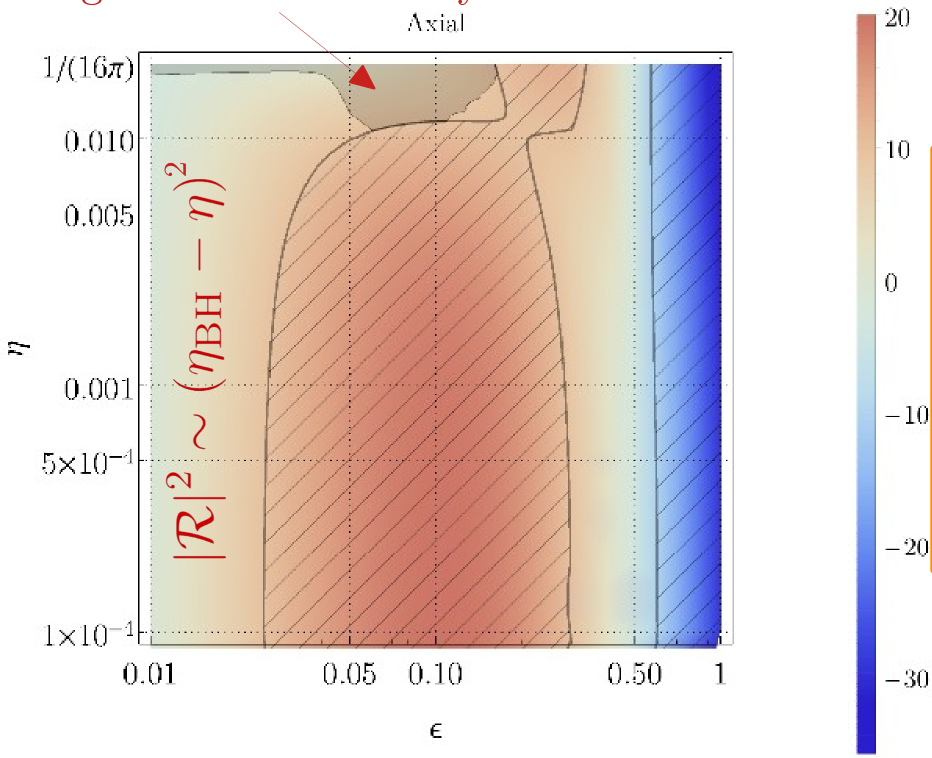
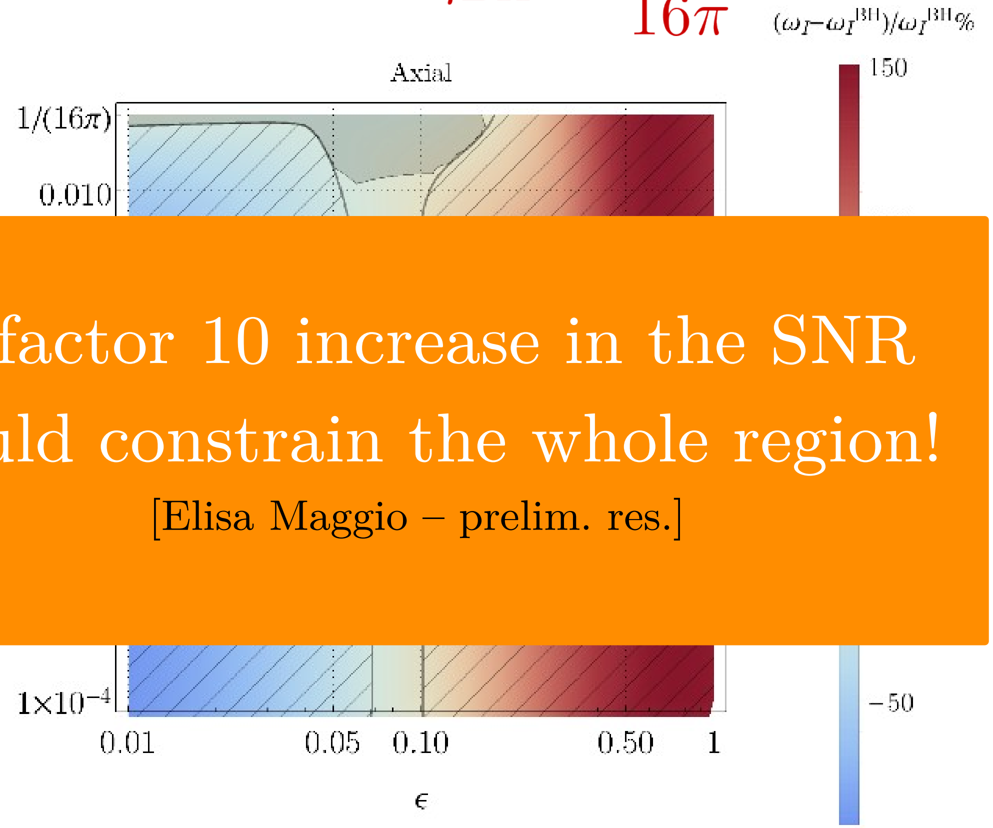
Region not excluded by GW150914





A factor 10 increase in the SNR would constrain the whole region!

[Elisa Maggio – prelim. res.]

- Axial and polar modes are not isospectral but harder to resolve

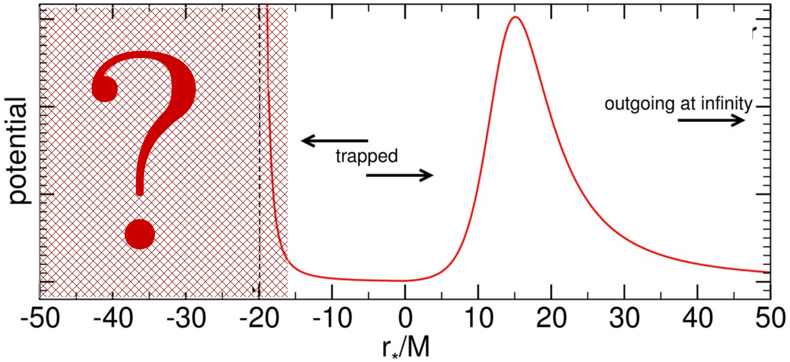
GW echoes

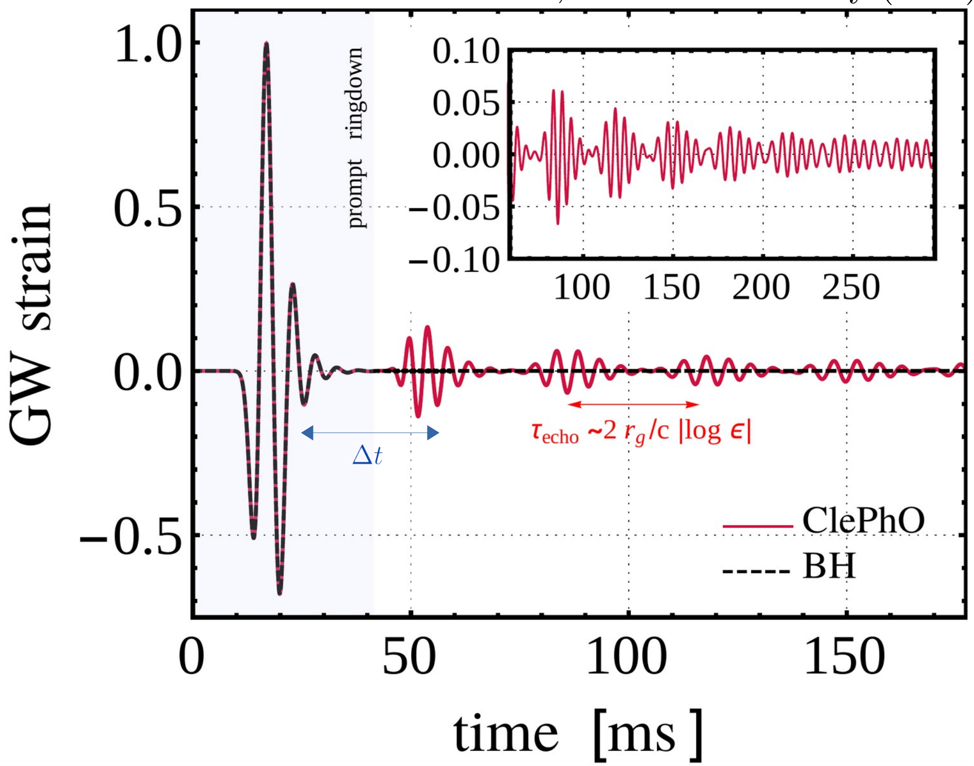
- For ultracompact ECOs (ε<0.01) prompt ringdown is identical to BHs but **GW "echoes"** at later times

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

- Only (classical) horizons absorb everything!

Cardoso & PP, Nature Astronomy (2017)

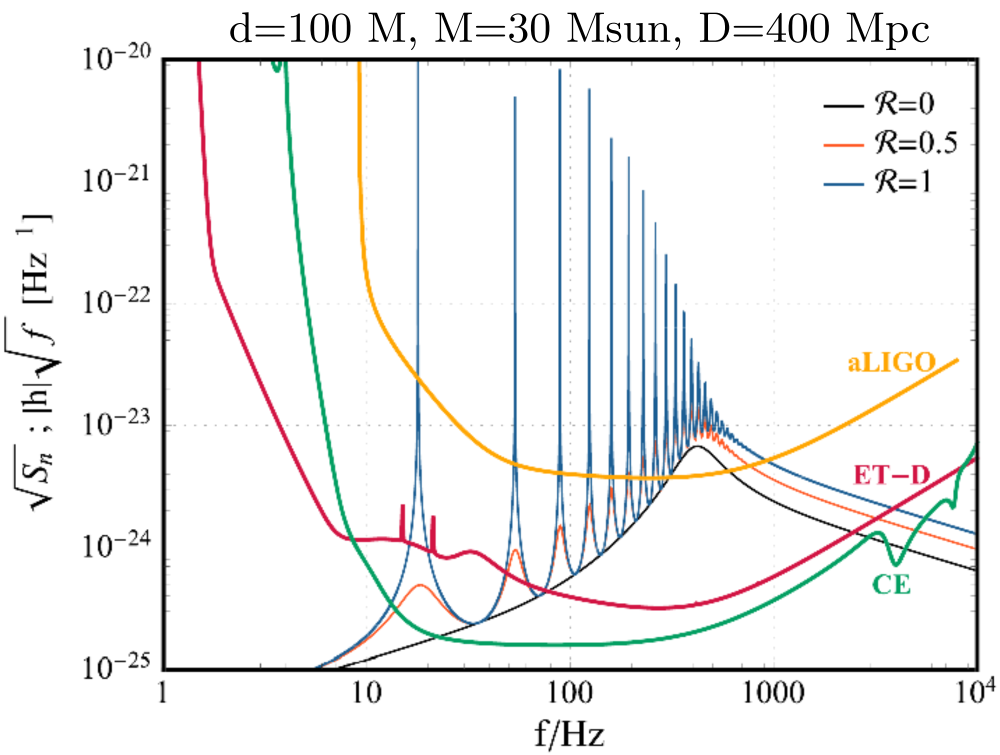


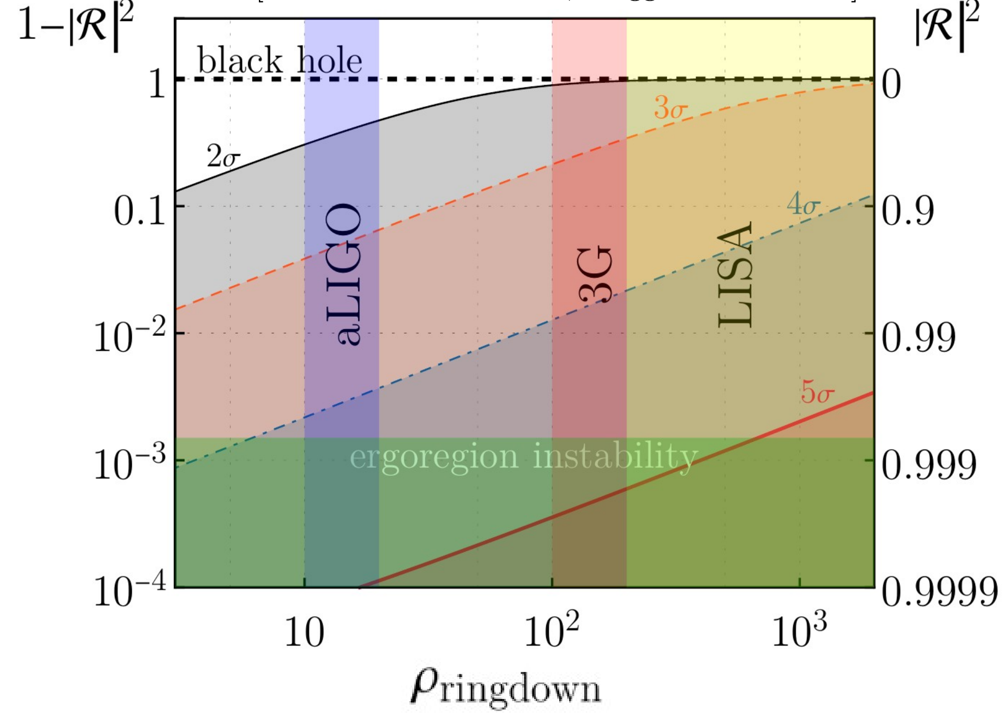


- Reflectivity arises in many contexts:
    - Stellar-like regular interior
    - "Fuzziness"
    - Quantum emission from horizon

- Lot of progress on echo waveform modeling and searches [Abedi+, Universe (2020)]

Echo detectability





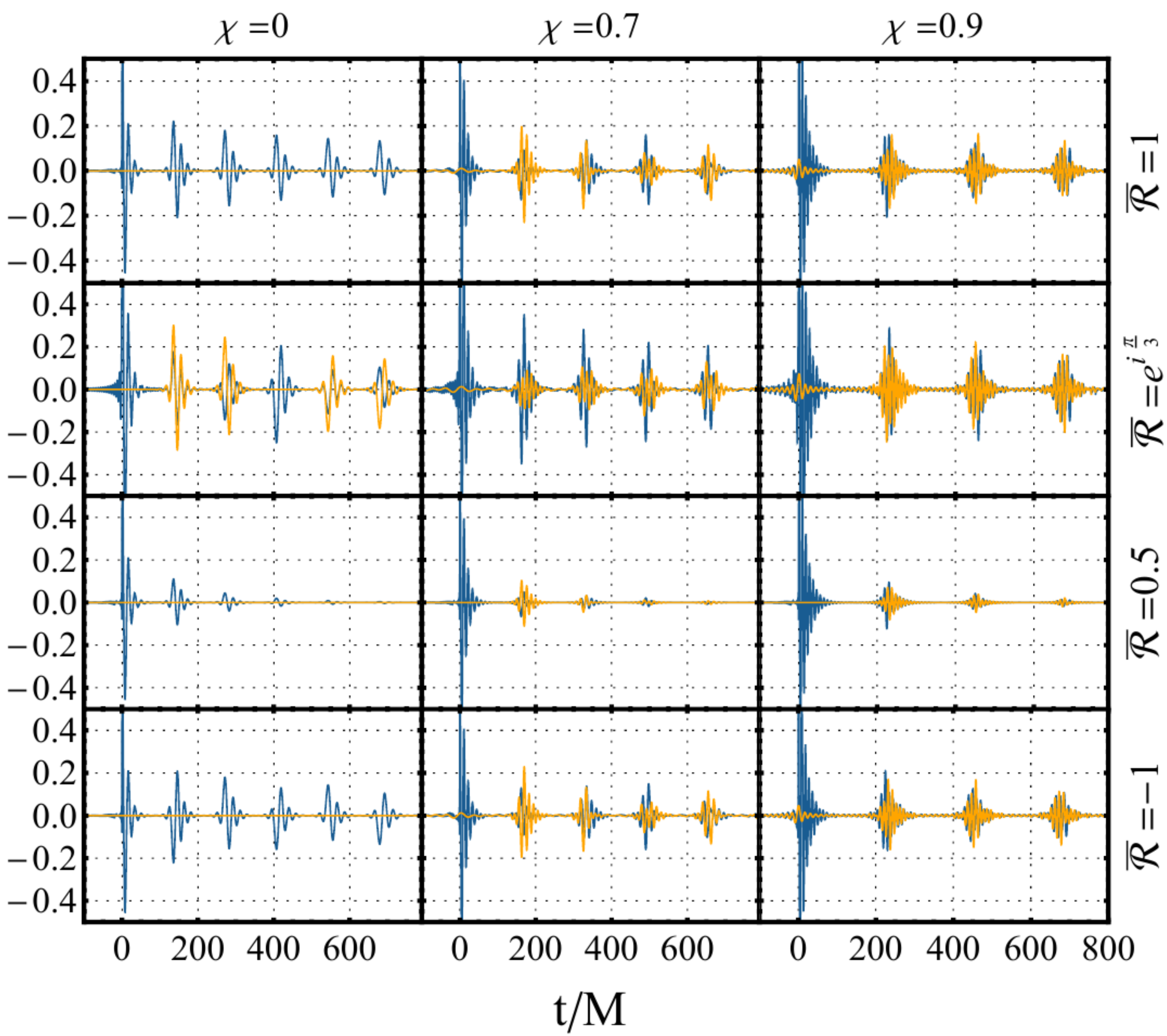
- Contrasting results with LIGO data [Abedi+, 2017/18, Conklin+ 2018/19, Ashton+ 2017, Westerweck+ 2018]

but no statistical evidence in O1-O2 [Uchikata+ 2019, Tsang+ 2019] and in O3a [GWTC-2, Oct 2020]

- Near-horizon corrections are within reach!
  - Large reflectivity crucial for detection with LIGO/Virgo
  - Much better prospects with 3G and LISA

GW echo slideshow

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



Coherent, analytical template in the FD:

- complex reflectivity
- mixing of polarizations
- spin-dependent modulation
- Many more features than templates used in current searches

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

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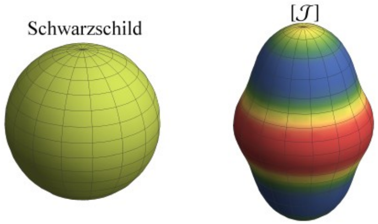
- **2PN:** Point-particle phase depends on **multipole moments** of the bodies
  - Tests of the BH no-hair theorem [Hansen 1974]



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

Mass moments — Spin moments

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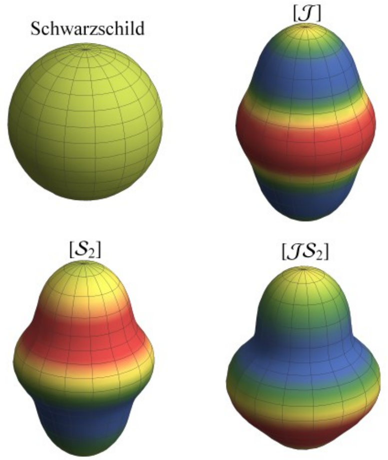


Credits: G. Raposo

  - **ECOs** (axisymmetric case):

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

- 3G/LISA can constrain mass quadrupole (M_2) and spin octupole (S_3) [Krishnendu+ 2018]
- In the BH limit → **"hair conditioner" theorem** [Raposo, PP, Emparan, PRD 2019]

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

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

The multipolar structure of ECOs

DarkGRA

Home Team Publications GW Echoes Projects Talks Events Outreach more...

All material is free for use, please make reference to this webpage and to the relevant papers.

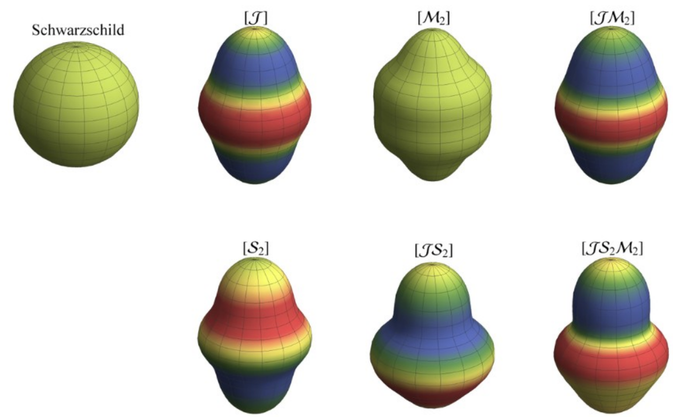
> GW echo catalogue [link to repository]

> Exotic compact objects with soft hair
[reference: Raposo, Pani, Emparan, "Exotic compact objects with soft hair", arXiv:1812.07615]:

- **ReadMe.txt**
- **Equatorially symmetric solutions**
  - [J]^(5) [notebook]
  - [M_2]^(3) [notebook]
  - [J M_2]^(2) [notebook]
- **Nonequatorially symmetric solutions**
  - [S_2]^(3) [notebook]
  - [J S_2]^(2) [notebook]
  - [J M_2 S_2]^(2) [notebook]

The superscript is the order at which the perturbative solution has been truncated, e.g.

[J]^(5) is a purely spin-induced solution up to order five in the spin.

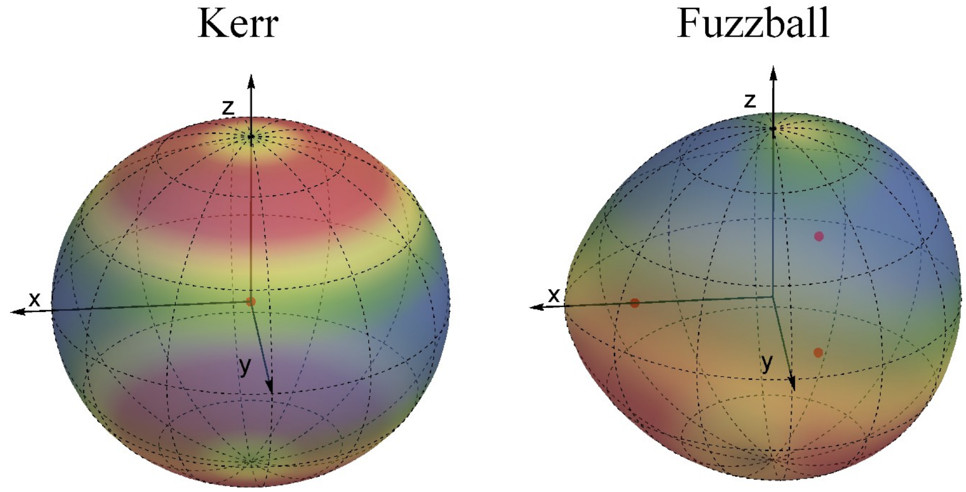


Credits: G. Raposo

Several families of analytical ECO solutions with soft hair available at **www.darkgra.org**

The multipolar structure of ECOs #2

- (Stationary) ECOs can break: [fuzzballs: Bianchi+ PRL-JHEP 2020; boson stars: Herdeiro+ PLB 2020]
  - equatorial symmetry: e.g. $S_2 \neq 0$, $M_3 \neq 0$
  - axial symmetry: e.g. $M_{20} \neq 0$, $M_{21} \neq 0$, $M_{22} \neq 0$



Credits: G. Raposo

- Fuzzballs (in N=2 supergravity):
  - certain multipole ratios are ~ universal [Bena-Mayerson PRL-JHEP 2020]
  - certain multipole invariants are minimum for BHs [Bianchi+ PRL-JHEP 2020]
- Lot of progress: current models should be extended beyond Kerr symmetries

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 for q~1 → IMRIs or LISA

[Maselli+, 2018, Hughes PRD 2001, Datta+ PRD 2020]

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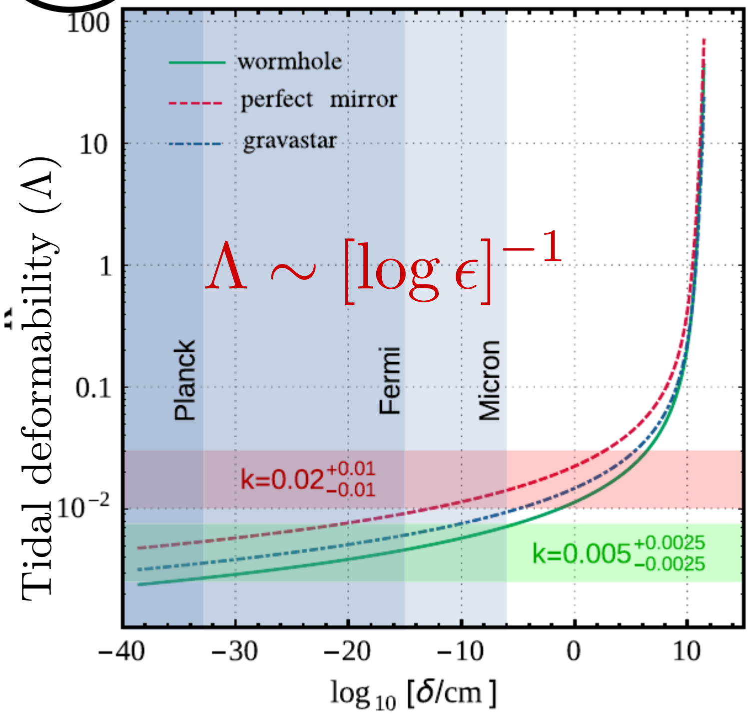


- **5PN: tidal deformability and Love numbers** [Flanagan & Hinder, PRD77 021502 2008]
  - Love = 0 for a BH in GR [Damour '86, Binnington-Poisson PRD 2009; Damour-Nagar PRD 2009; PP+, PRD 2015]

(see Le Tiec-Casal 2007.00214 and Chia 2010.07300 for spinning BHs)

  - Love ≠ 0 for ECOs and BHs in modified gravity [Porto+ Fortsch. Phys. 2016, Cardoso+, PRD 2017]
  - 3G/LISA will be able to distinguish BHs from *any* boson star model [Cardoso+, PRD 2017]
  - In several ECO models Love scales logarithmically → strong constraints [Maselli+, 2018-2019]

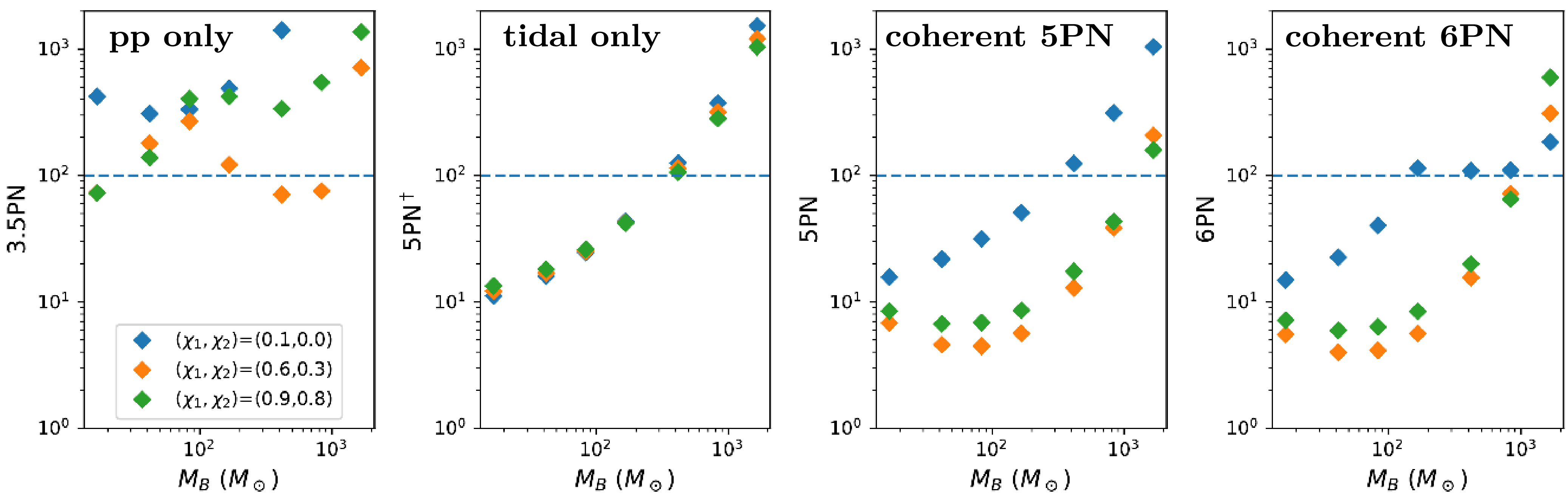
BH vs Boson Stars: coherent model

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

Coherent inspiral waveform → all deviations from Kerr (multipoles, tidal, etc)
depend only on masses & spins and on the theory's coupling constants

- Tidal deformability strongest, but coherent model significantly improves the constraints
- Constraining power of current detectors is marginal: 3G/LISA required to constrain boson-star couplings

[Pacilio+ PRD 2020]



ECO tests with EMRIs/IMRIs

- EMRIs are unique probes of *both* multipolar structure and dynamics
- ECO corrections are amplified for small mass-ratio, lessons form EMRIs:
  - Spin-induced multipole moments → $\delta \bar{M}_2 \sim 10^{-4}$ [Barack-Cutler, PRD 2007, Babak+ 2017]
  - Tidal heating → large for highly-spinning objects → $|\mathcal{R}|^2 \lesssim 10^{-4}$ [Datta+ PRD 2020]
  - Tidal Love numbers → $\bar{\Lambda} \sim 10^{-5}$ [Pani & Maselli 2019]
  - Tests of the Kerr bound ($\chi<1$) could be much simpler and accurate with EMRIs if one can measure the spin of the secondary [Piovano, Maselli, PP, PRD-PLB 2020]
- ECO tests with EMRIs/IMRIs → many challenges in modeling, parameter estimation, rates, etc...

Conclusion

- *Living the BH era*: new discovery opportunities for new physics!
- Dramatic improvements on ECOs on all fronts in the last few years
- Any signature of beyond-Kerrness would shake physics to its grounds
- Strong evidence for light rings coming from GWs & EM
- Existence of (event) horizons is conceptually impossible to prove, but strong constraints $\rightarrow$ perfect reflectivity and less compact models already ruled out
- Horizons are special: portal to observables quantum gravity effects?

Backup slides

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

Quantifying the "unbearableness"

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

	Constraints		Source
	$\epsilon(\lesssim)$	$\frac{\nu}{\nu_\infty}(\gtrsim)$	
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 $M < 100M_\odot$
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

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

Extreme compact objects (ECOs)

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

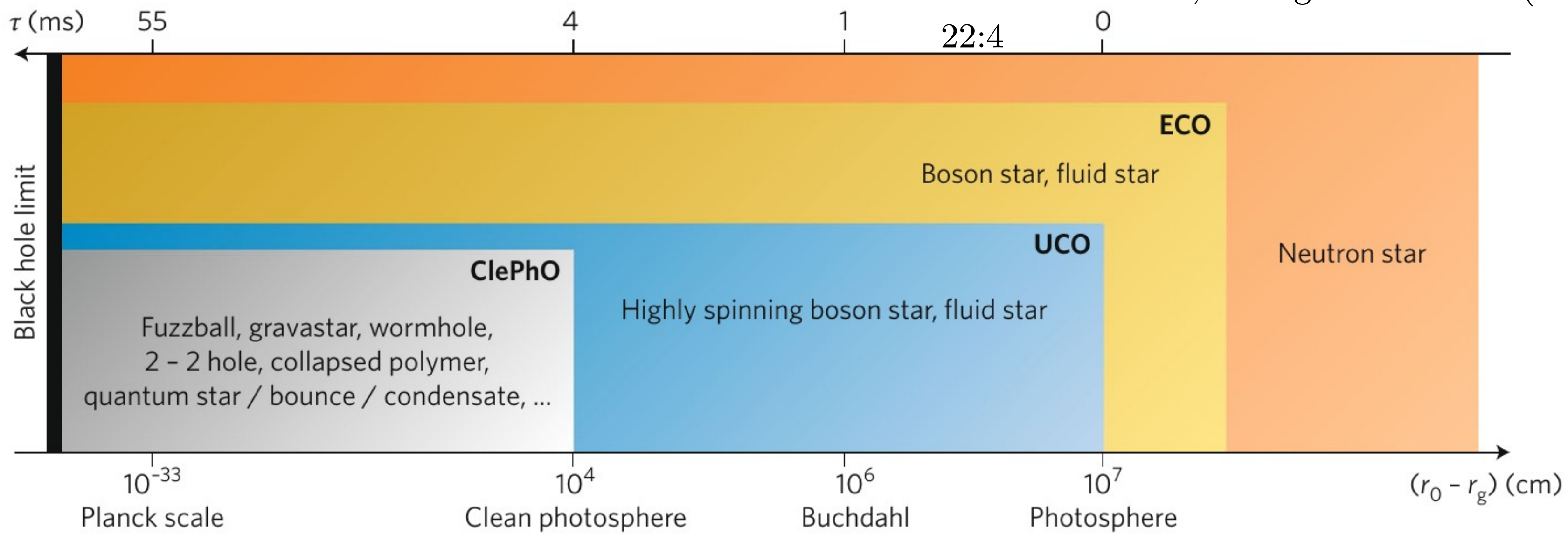
Phenomenology can be investigated even in absence of a first-principle framework

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

Quantifying the shade of darkness

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



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

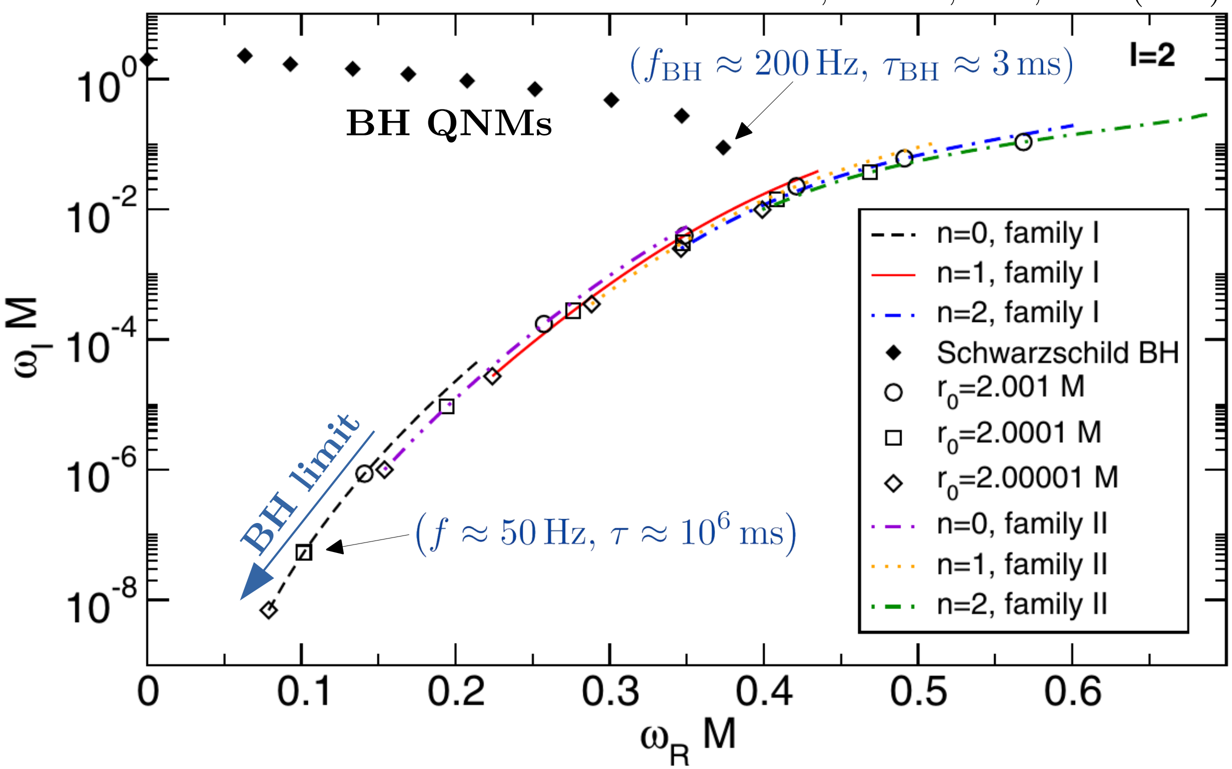
- "Neutron-star like" (e.g. boson stars) $\to \epsilon \sim \mathcal{O}(1)$
- "BH like" (e.g. fuzzballs, "quantum BHs") $\to \epsilon \sim 10^{-39} - 10^{-46}$

Goal: probe smaller and smaller values of ϵ

$\rightarrow$ requires combination of targeted and agnostic searches

QNM spectrum of an UCO

Cardoso, Franzin, Pani, PRL (2016)



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

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

- QNM spectrum dramatically different → ringdown?

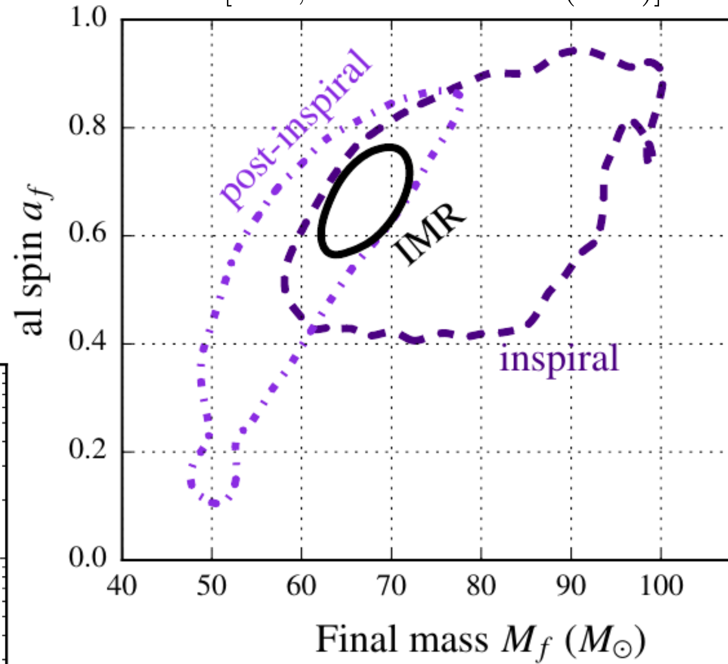
Ringdown and GW spectroscopy

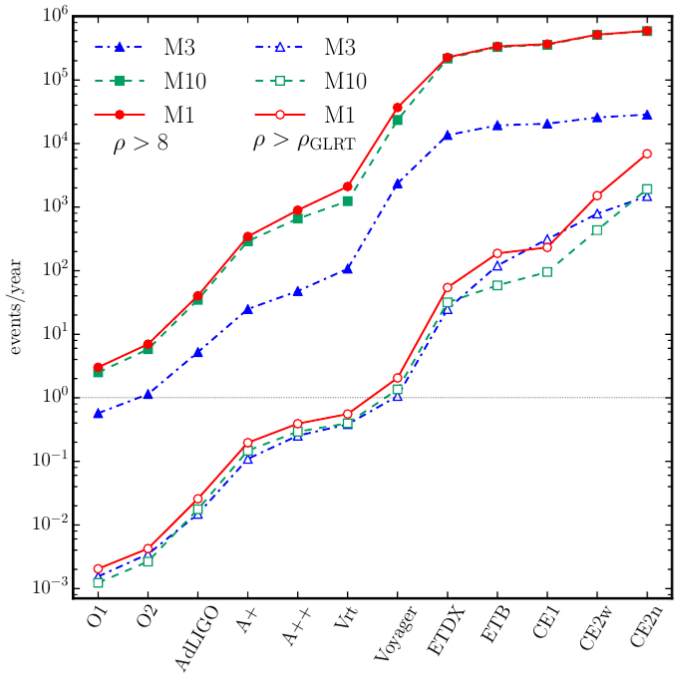
- Current detections consistent with Kerr, but low SNR in the ringdown (~1cycle/damping time)
- Ringdown tests possible with **3G** and **LISA** [Berti+, PRL. 117 101102 (2016)]

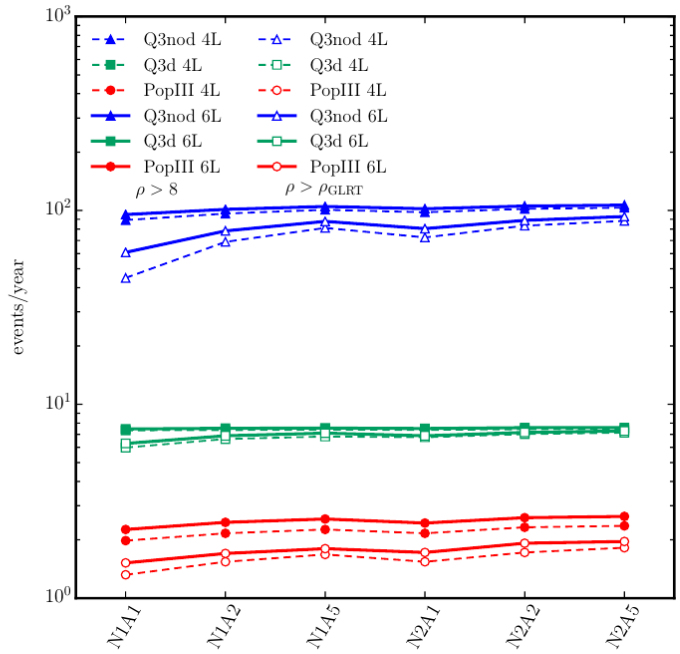
$$\mathrm{SNR}_{\mathrm{ringdown}} \propto \frac{M_{\mathrm{BH}}^{3/2}}{\sqrt{S_h(f)}}$$

Supermassive sources more than compensate for smaller detector sensitivity

[LVC, PRL 116 221101 (2016)]



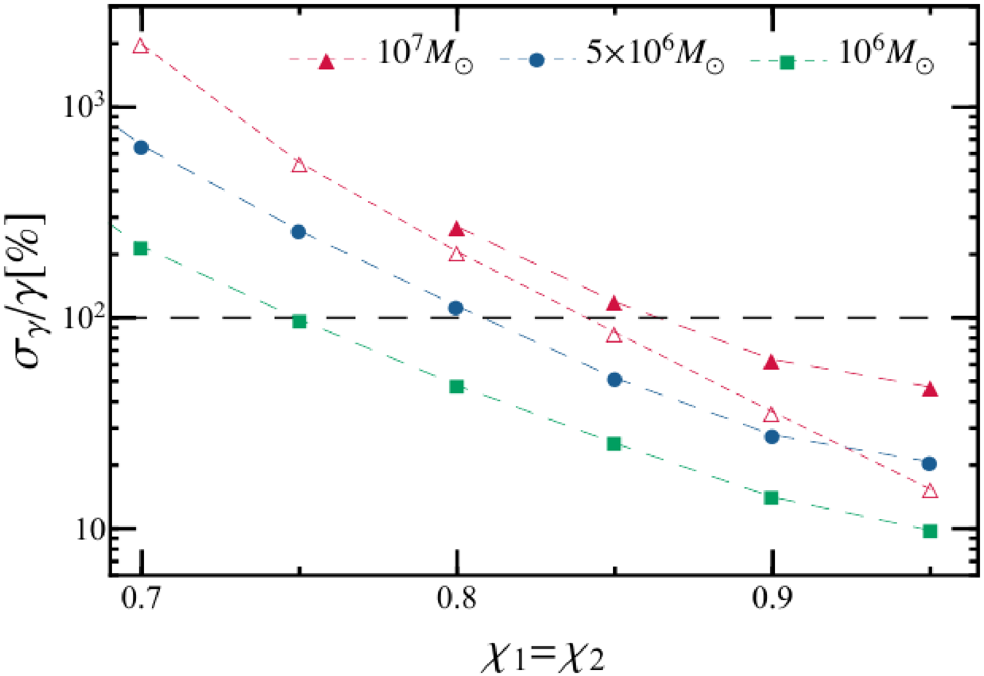




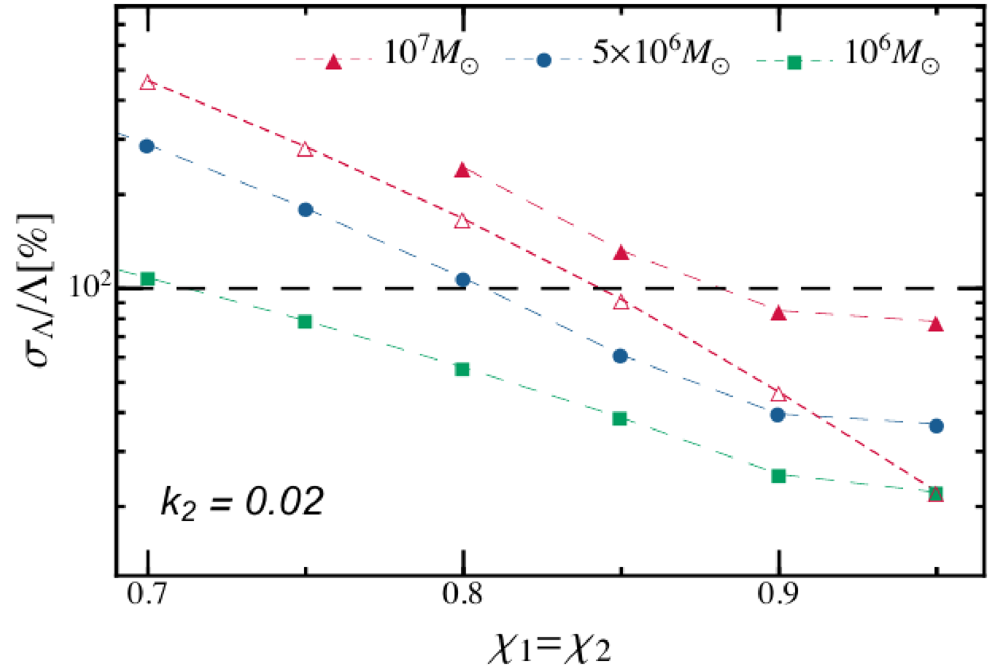
Probing BH quantum structures with LISA

Maselli, PP+; PRL 120 081101 (2018)

Absence of tidal heating



Tidal deformability



- Small corrections → requires spinning supermassive binaries @ 2-20 Gpc
- LISA binaries are golden sources to probe Planckian corrections!
- Tidal terms recently computed to 6.5PN [Abdelsalhin, Gualtieri, PP; 1805.01487]