Testing the nature of compact objects with gravitational waves

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Why?

- **Paradigm:** any compact object heavier than few M_{sun} must be a black hole (BH)
- Observations of exotic compact objects (ECOs) would imply new physics / new matter

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    - ECOs can form in GR with new (dark?) matter fields (e.g. boson/axion stars)

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2. Strong theoretical motivation (singularity and/or information-loss problems):
    - 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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3. At the very least: quantify the "*BH-ness*" of GW sources across mass ranges

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.

- 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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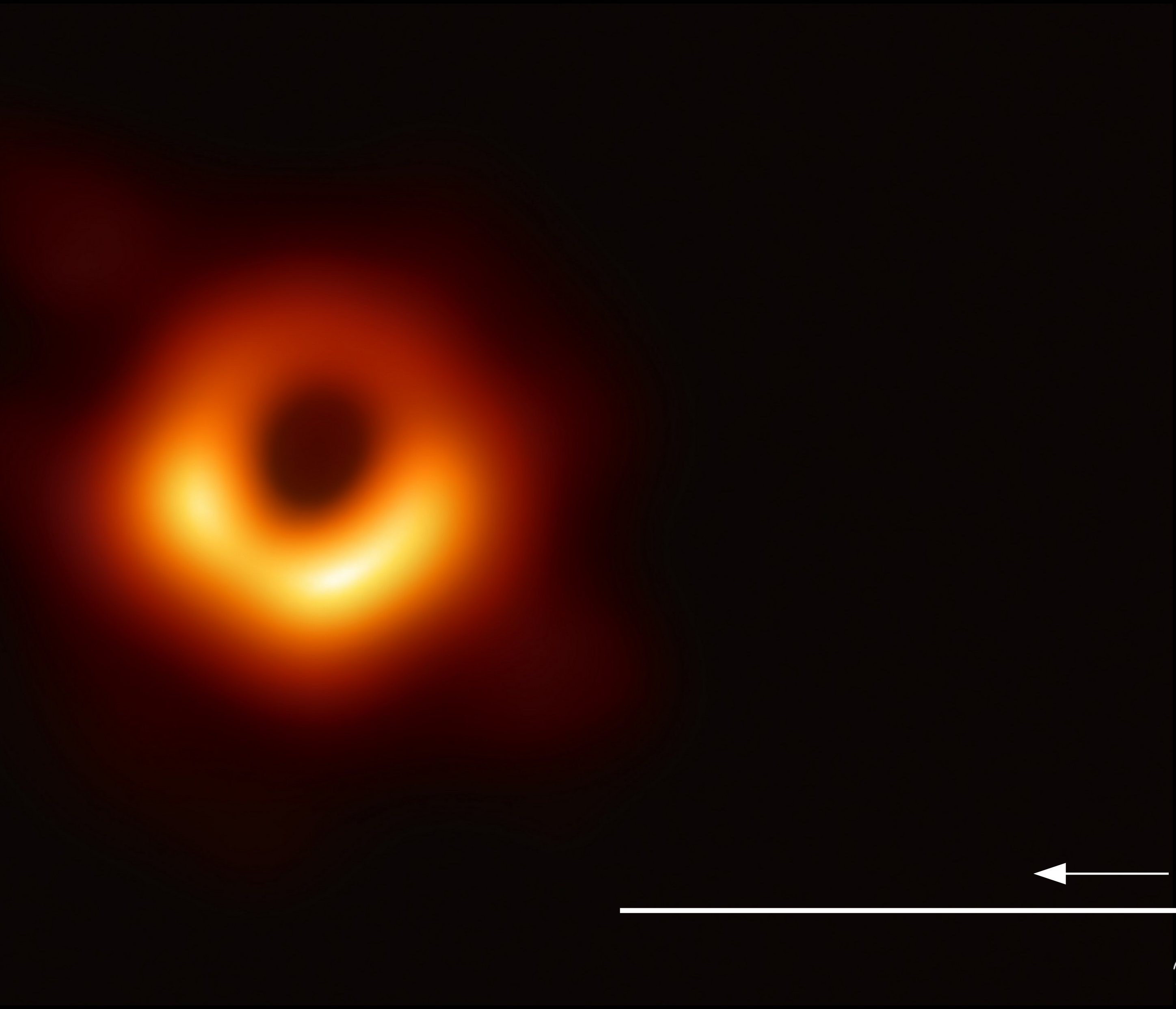
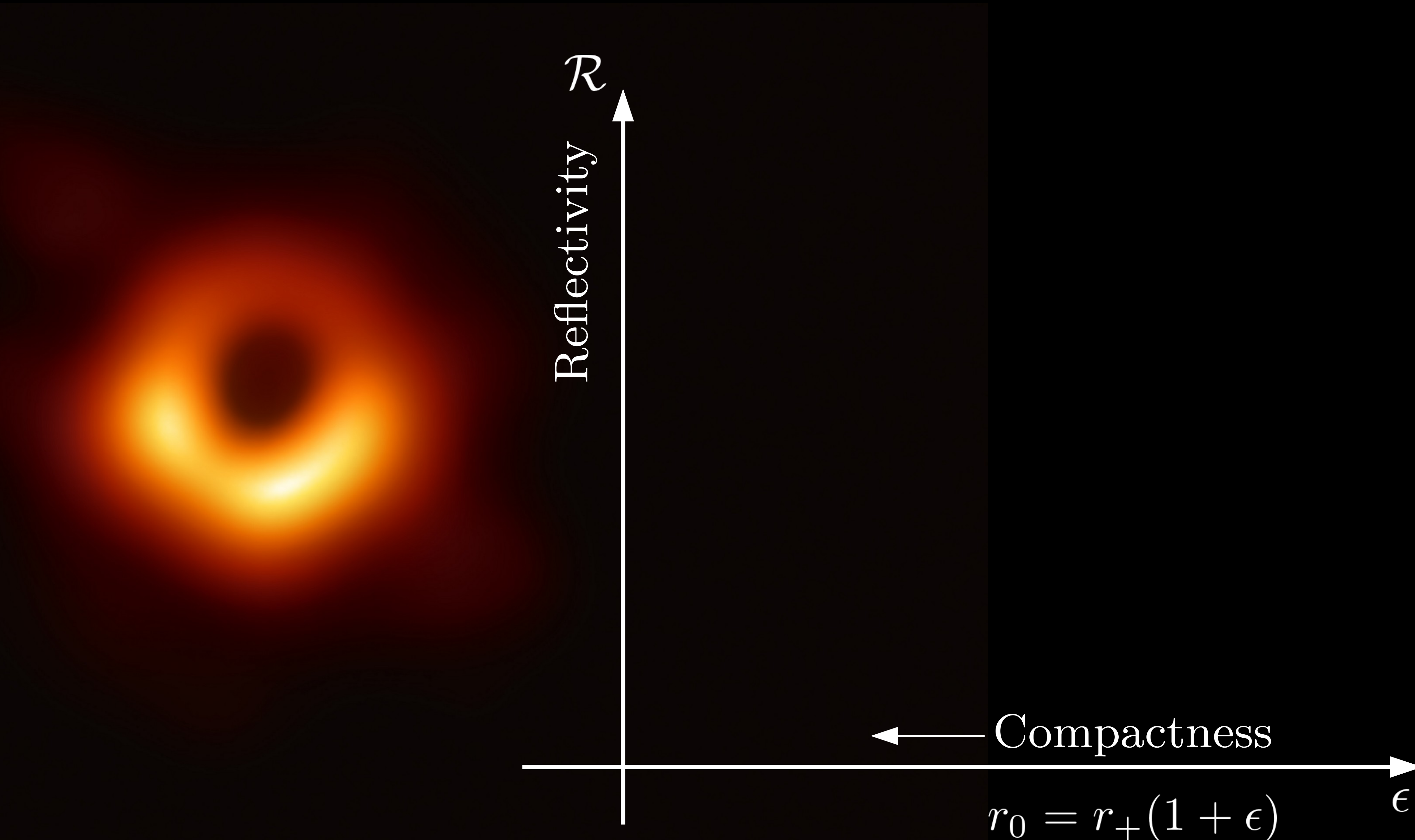


Compactness

ϵ

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

Quantifying the shades of darkness



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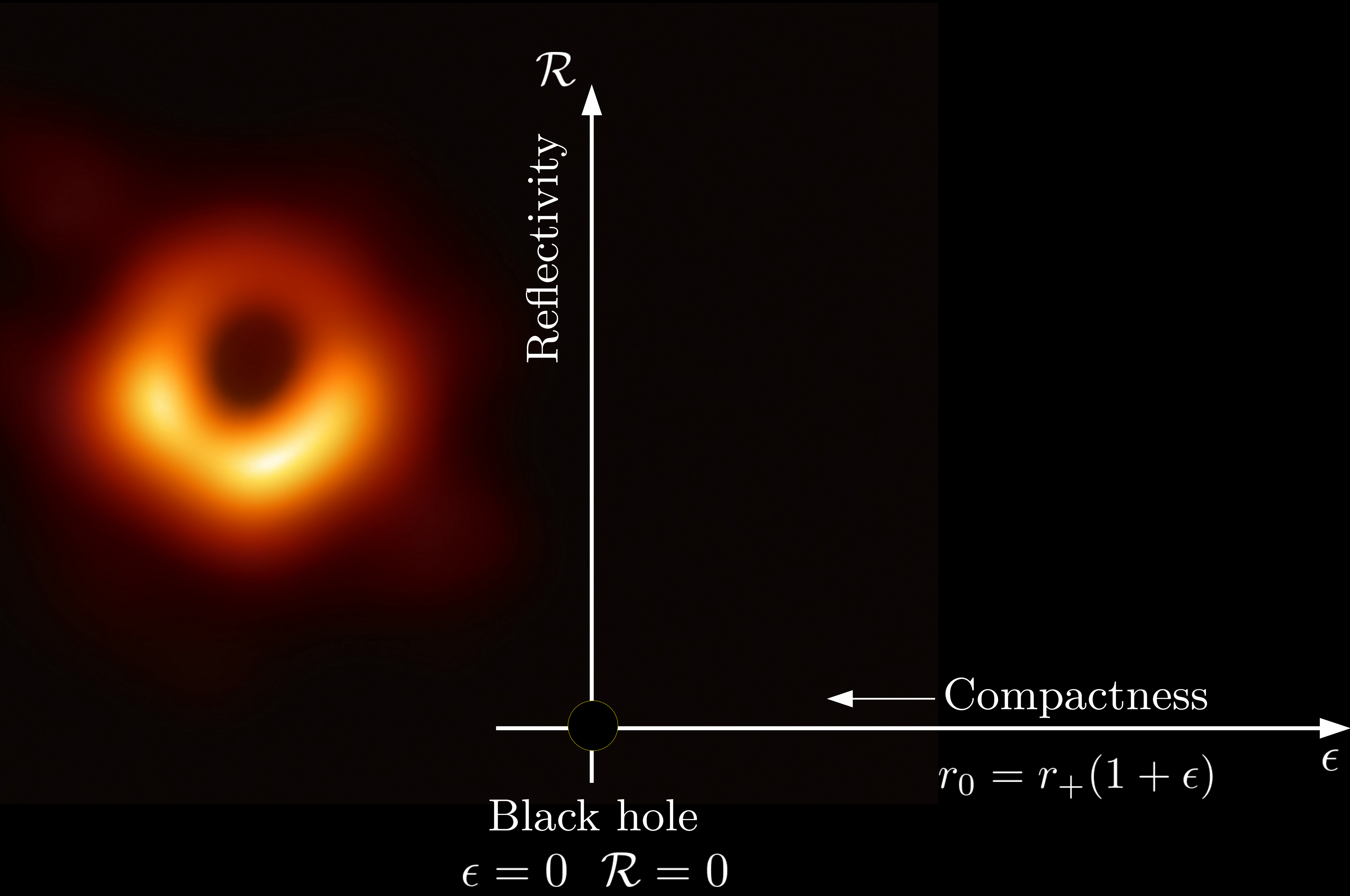

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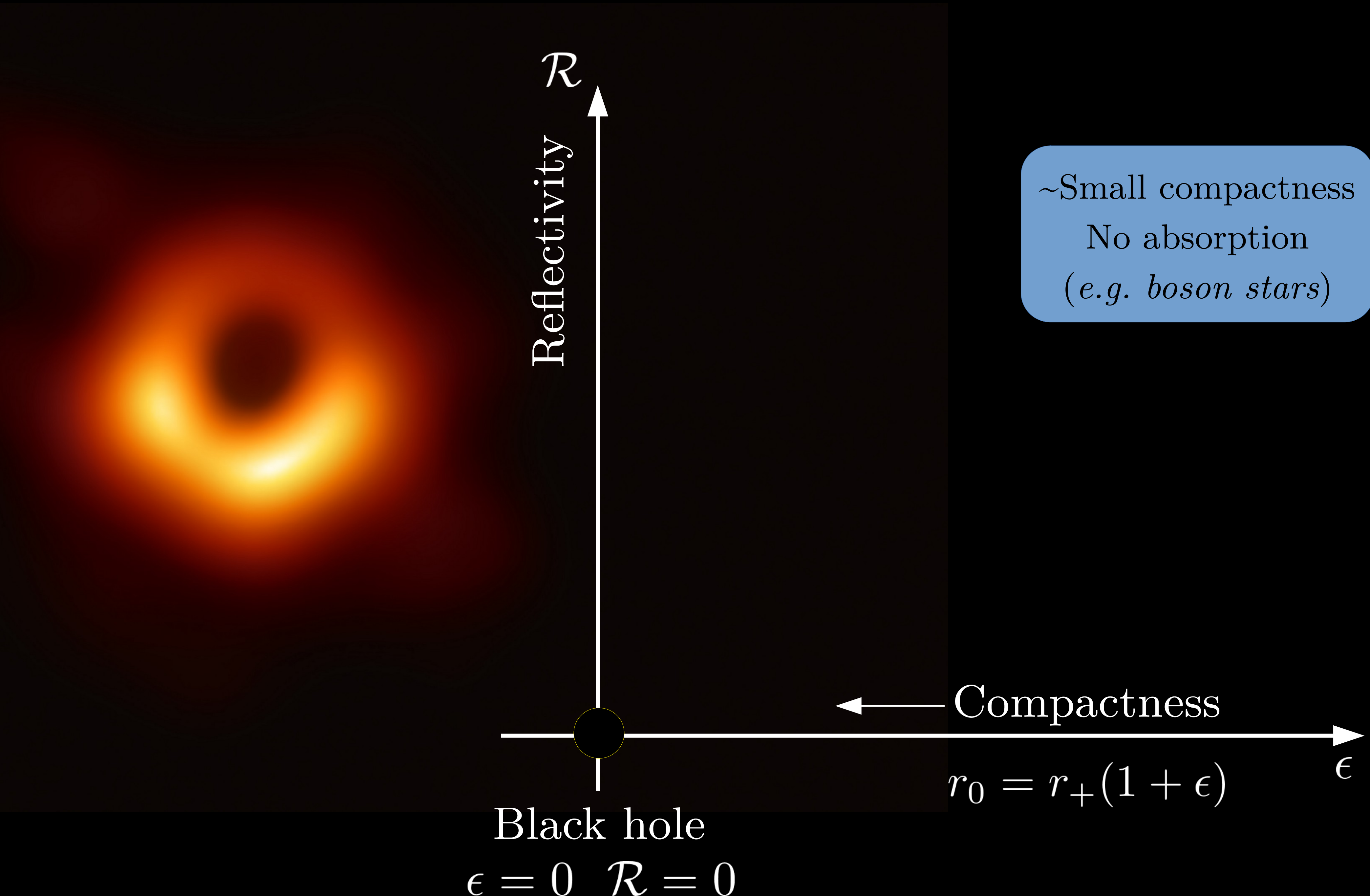

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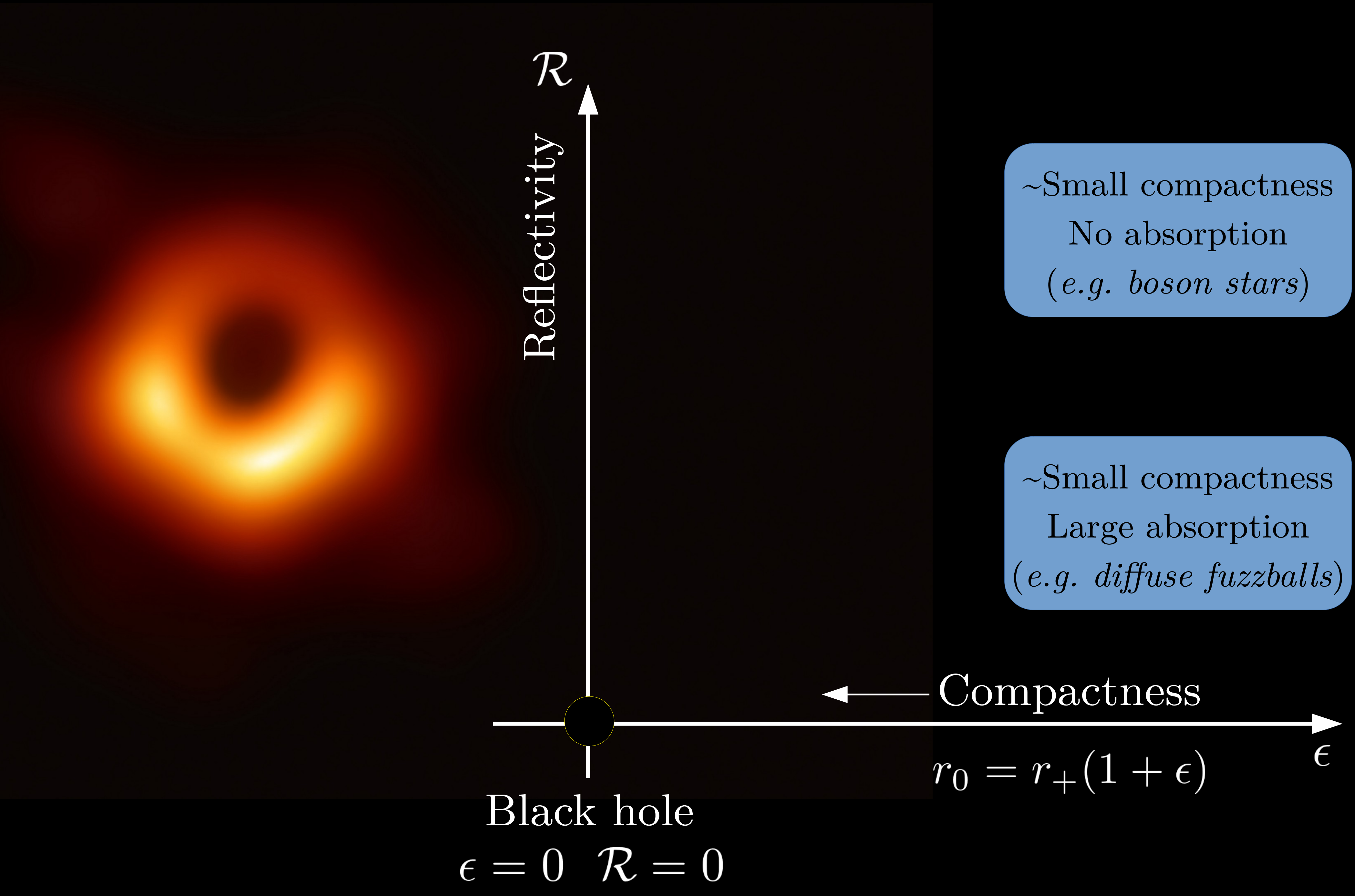

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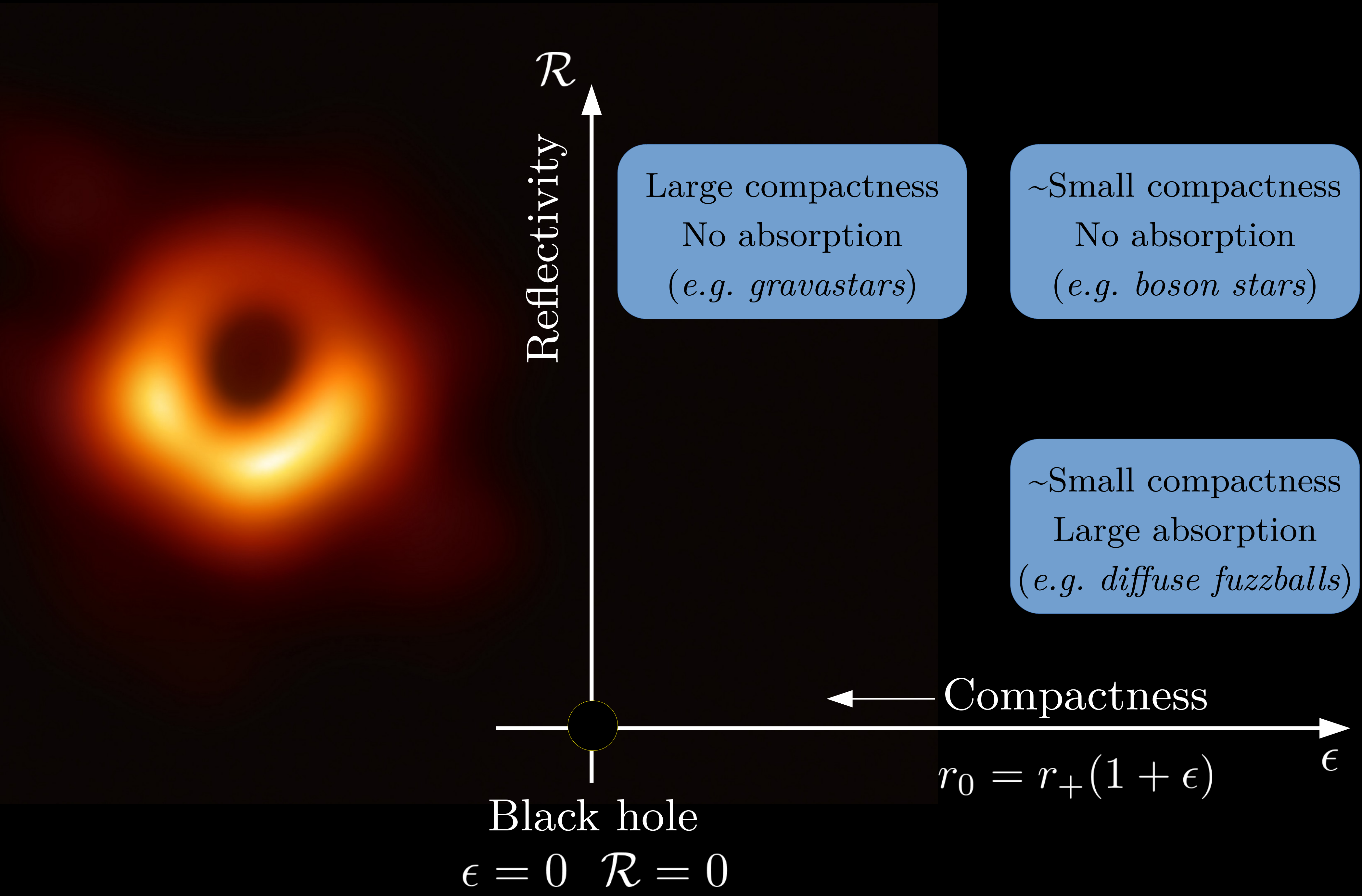

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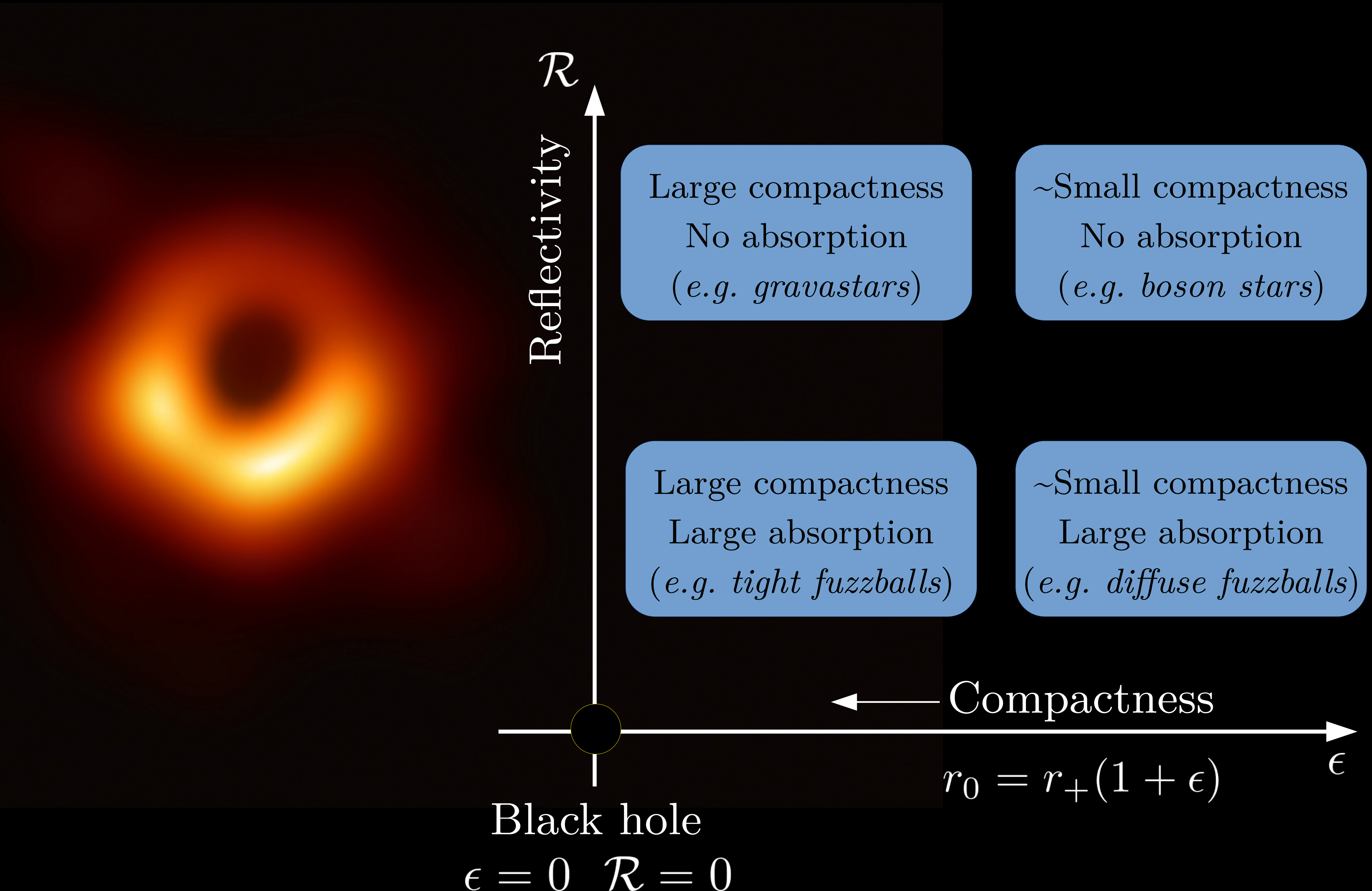

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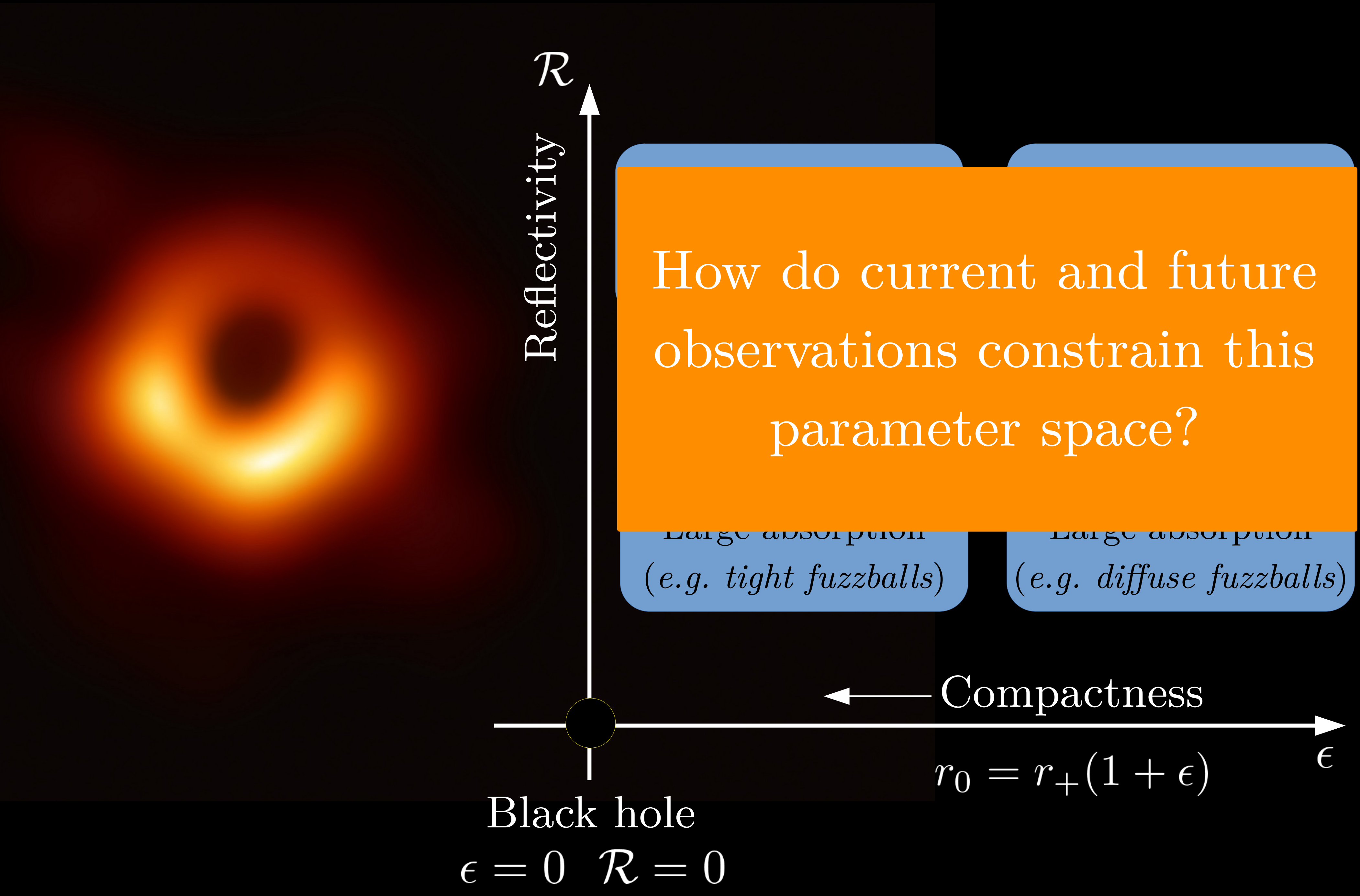
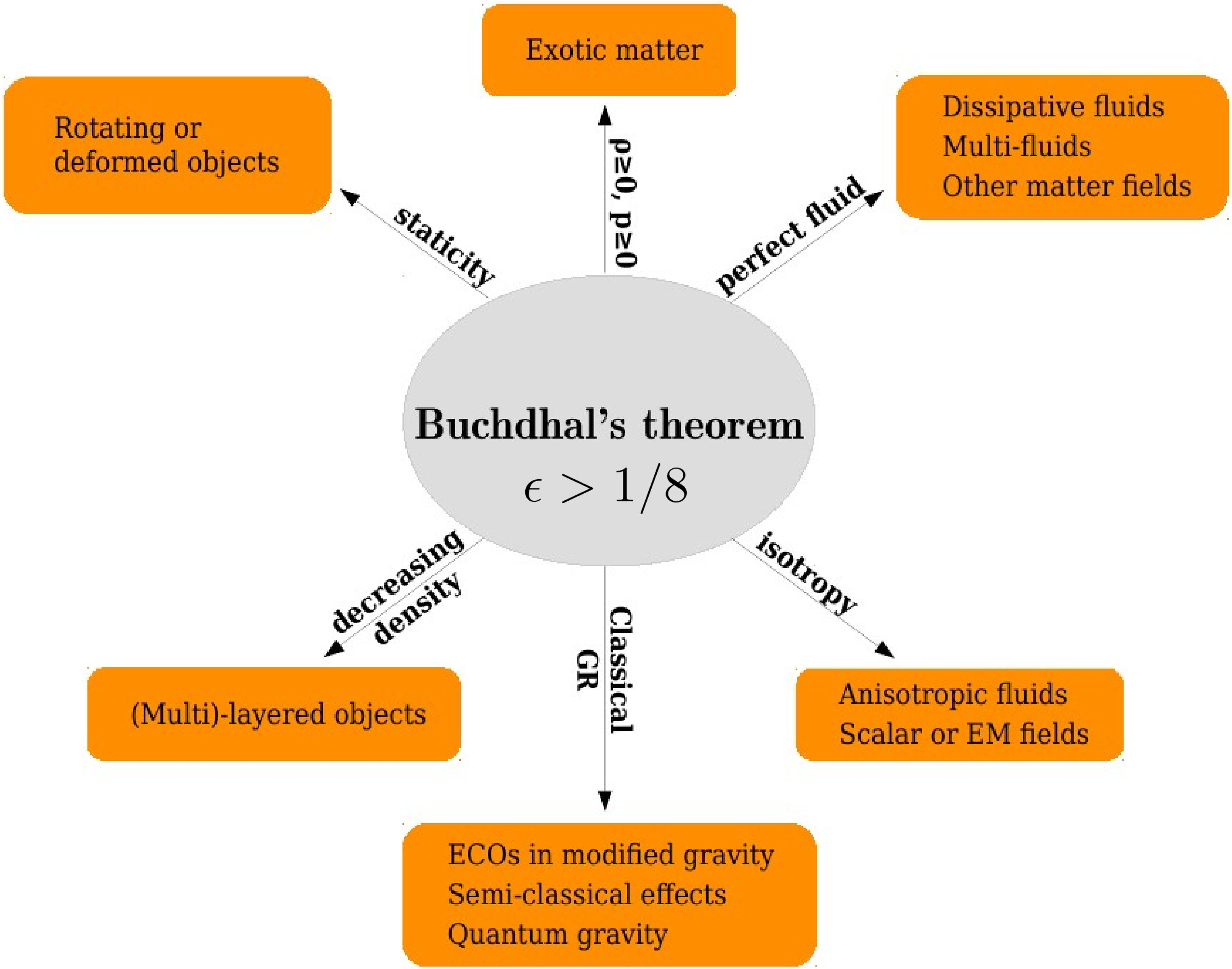


A compass to navigate the ECO atlas

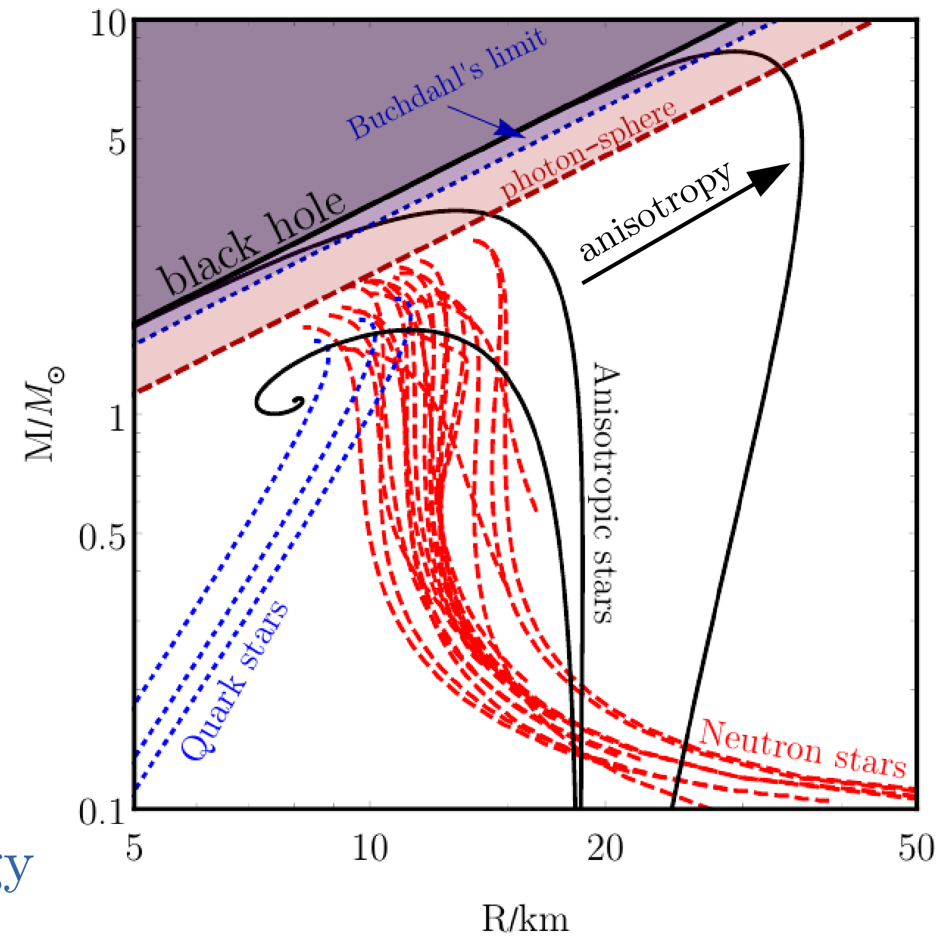


Evading Buchdhal: anisotropic stars

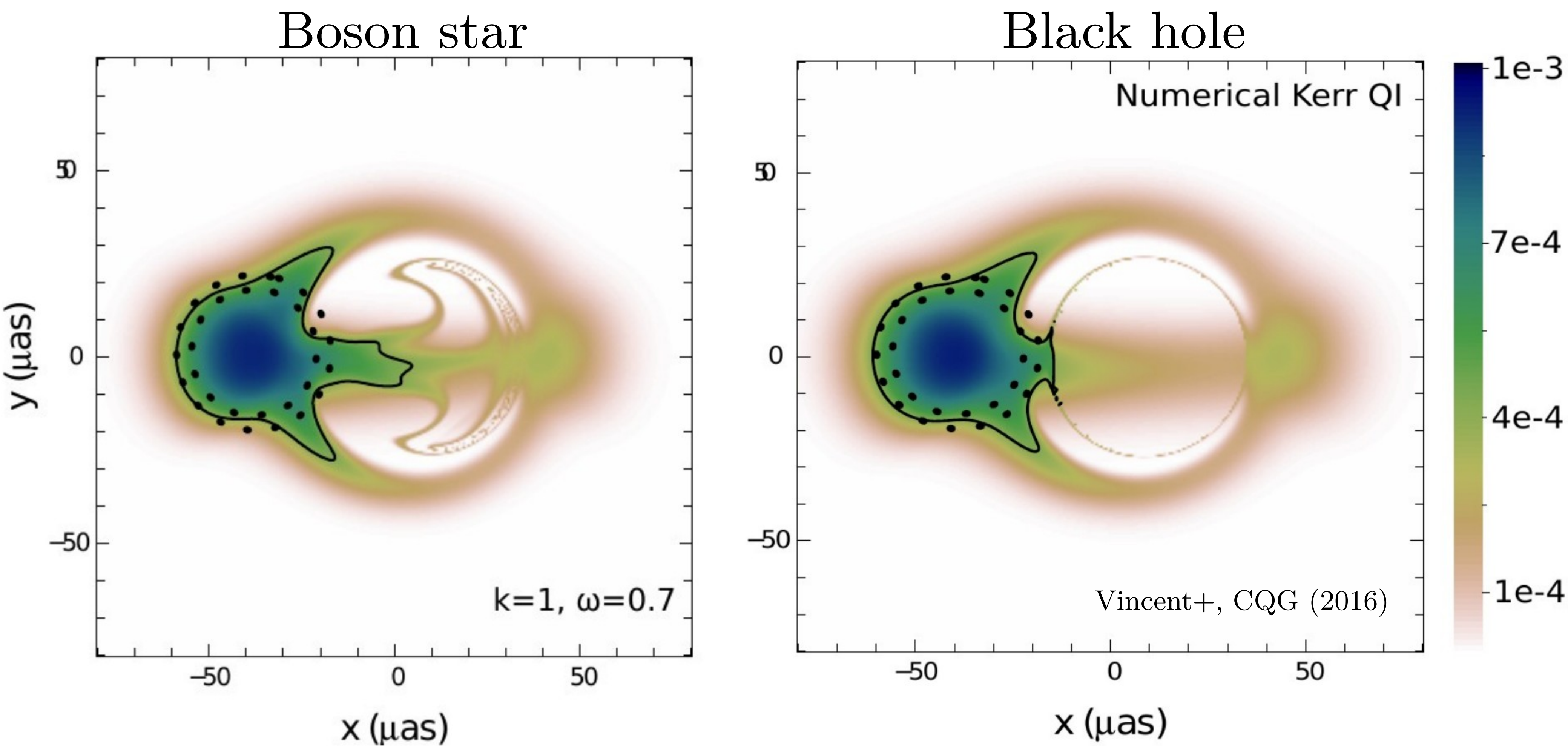
$$T_{\mu\nu} = T^{\rm ISO}_{\mu\nu} + \sigma_1 k_\mu k_\nu + \sigma_2 \xi_\mu \xi_\nu + \sigma_3 \eta_\mu \eta_\nu$$

- 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)



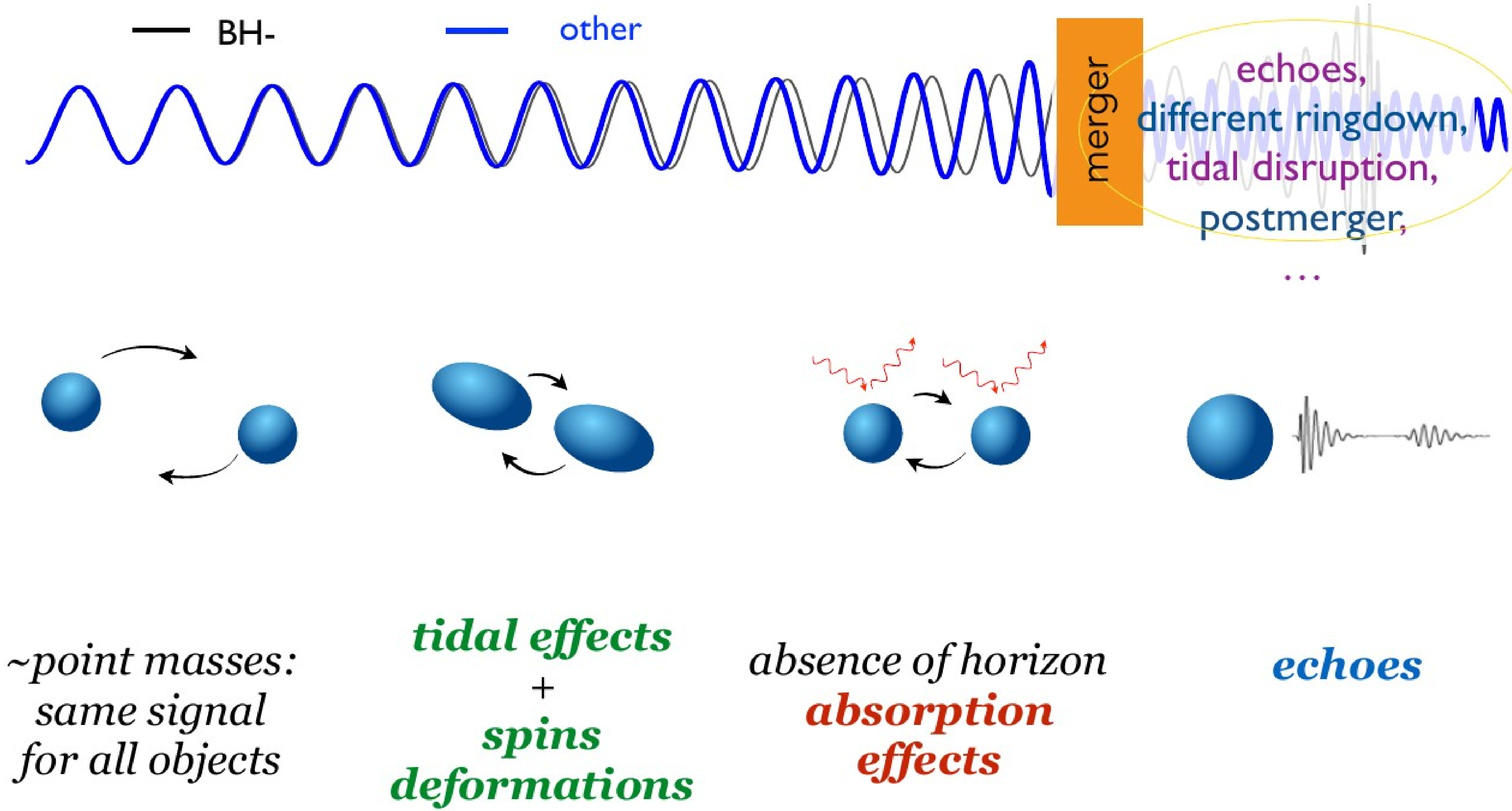
Shadows: BH vs Boson Star



- Telling the shadow of a boson star from a Kerr BH is very challenging
- Lot of dirty astrophysics [Gralla 2019-2020]
- Tests based on shadows can at most constrain $\to \epsilon \sim \mathcal{O}(1)$

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

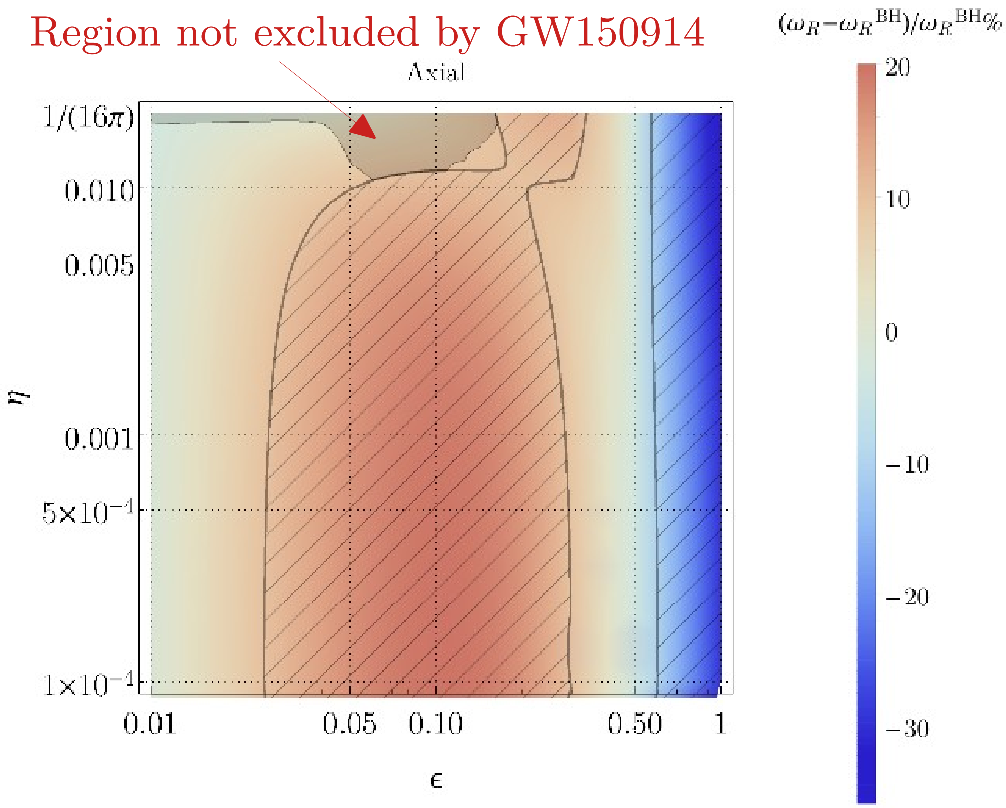
[Meidam+ (2014), Glampedakis+ (2017), Carullo+ (2018), Cardoso+ (2019), McManus+ (2019), Maselli+ (2020)]

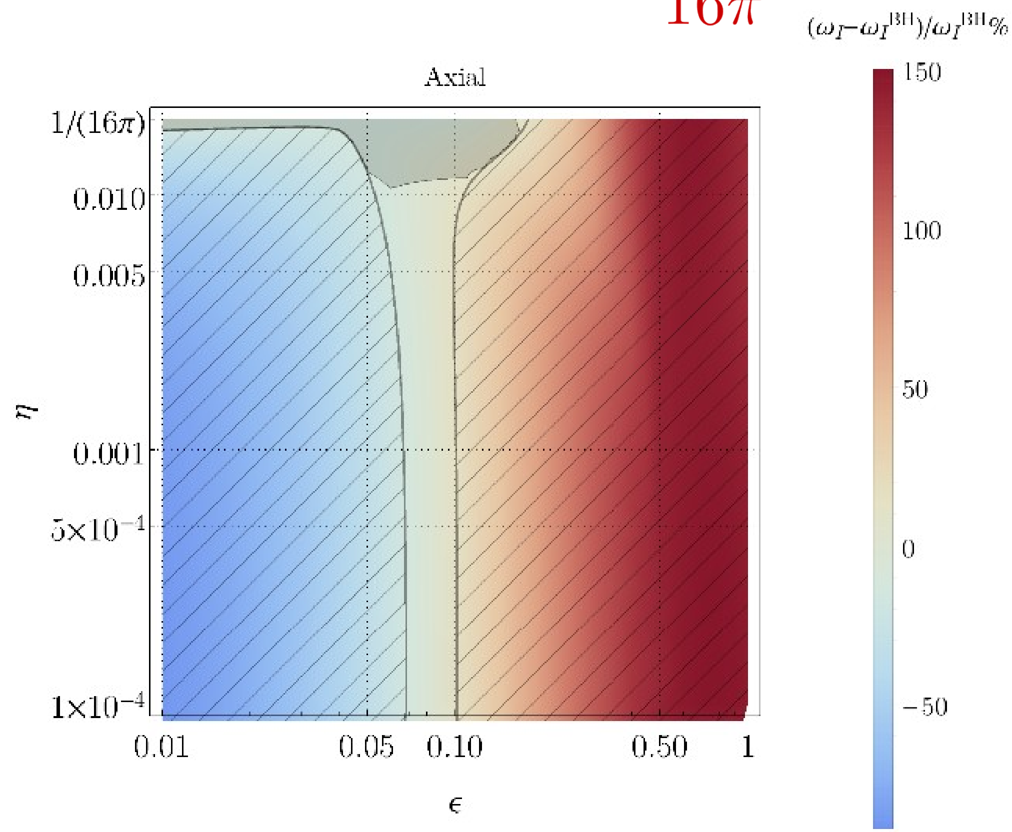
How does an ECO ringdown?

[Maggio+ PRD 2020]

- Neglecting spin and assuming GR in the exterior → Schwarzschild
- Interior modeled extending the BH *membrane paradigm* [Damour, Thorne, ...]
- Boundary conditions → 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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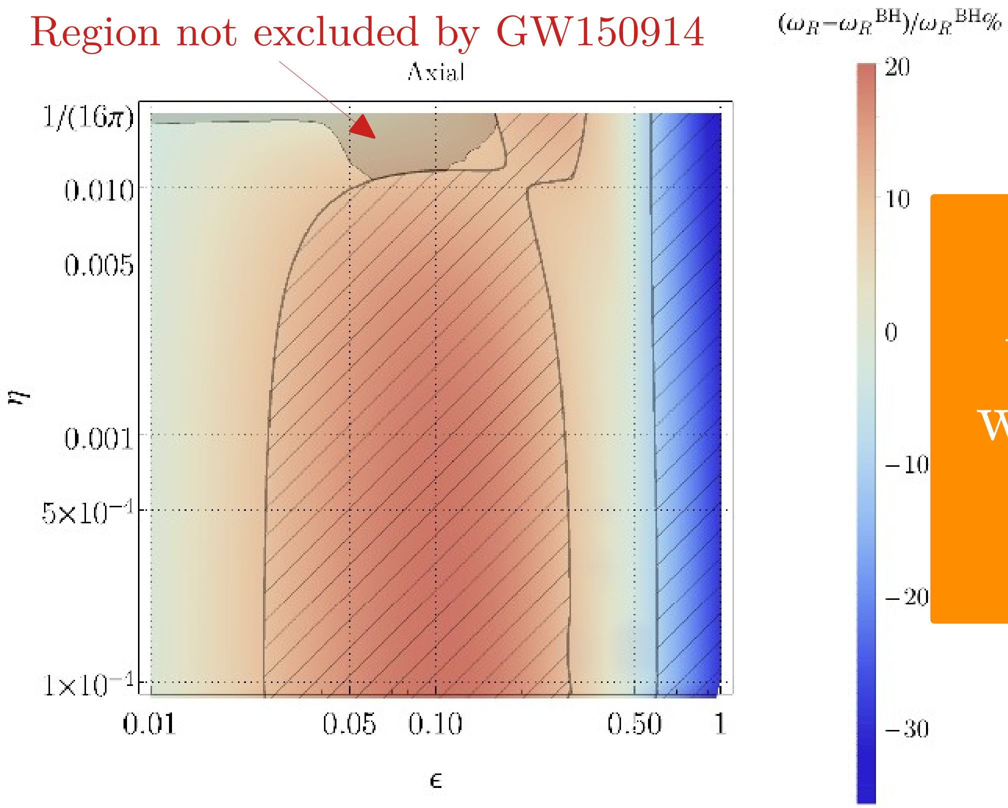
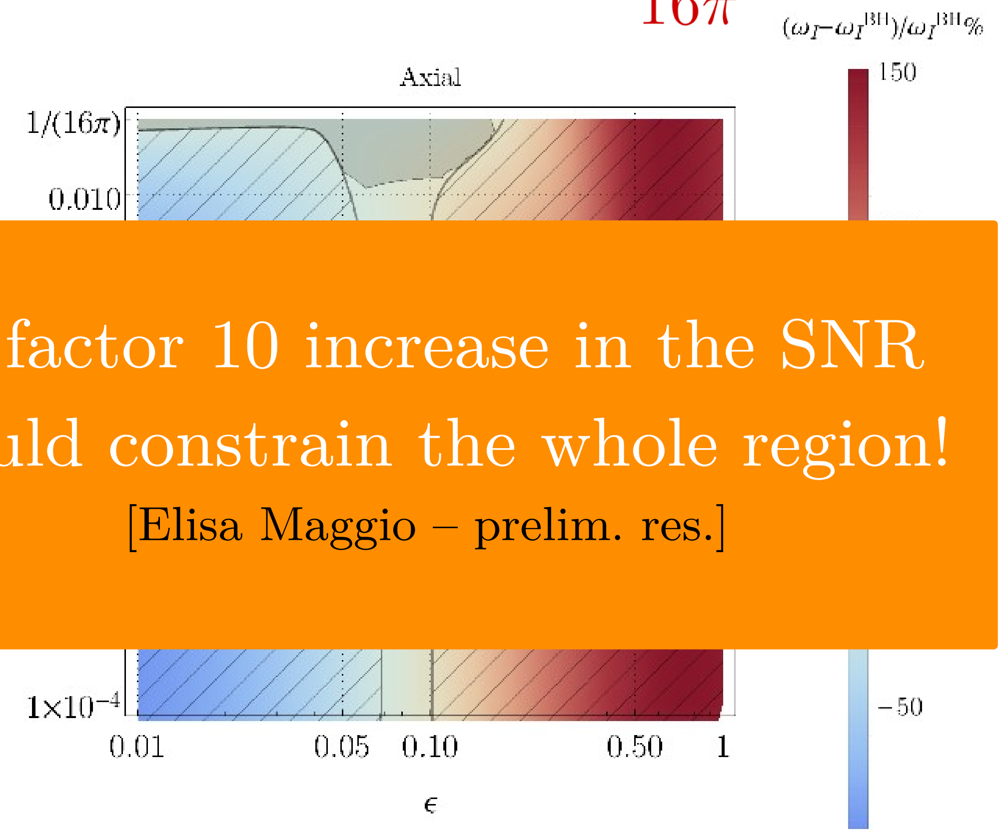




A factor 10 increase in the SNR would constrain the whole region!

[Elisa Maggio – prelim. res.]

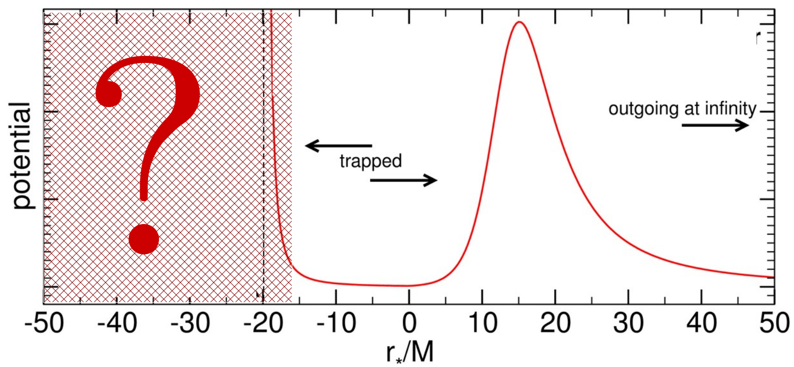
- Axial and polar modes are not isospectral but harder to resolve

GW echoes

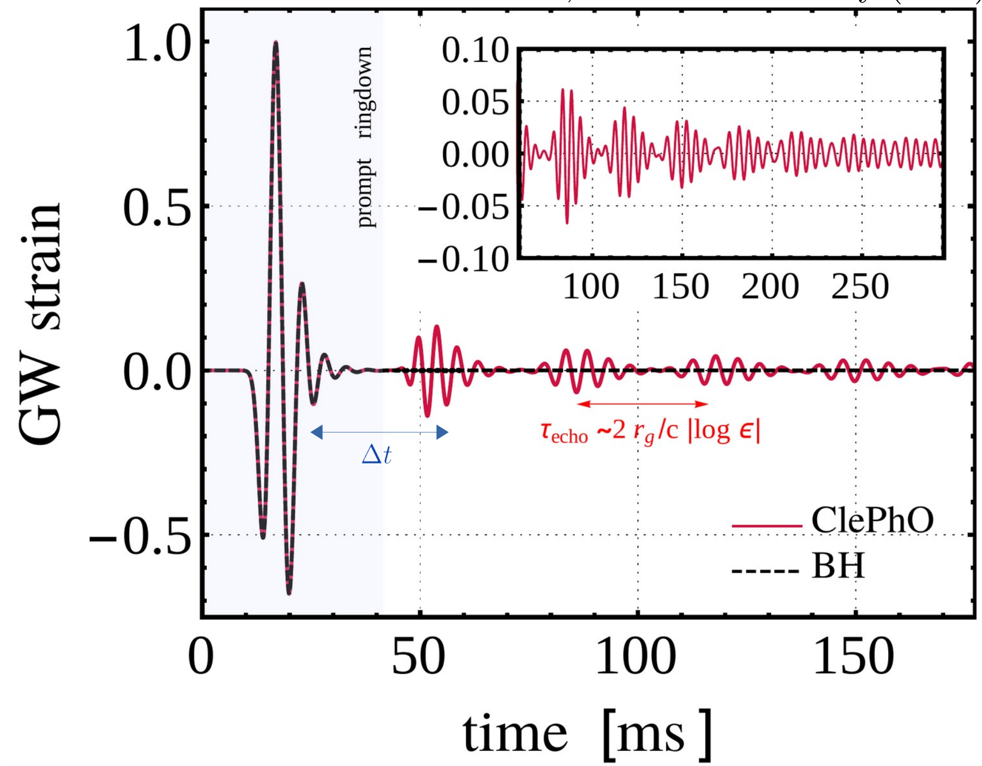
- For ultracompact ECOs (ε<0.01) prompt ringdown is identical to BHs but **GW "echoes"** at later times

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

- Only (classical) horizons absorb everything!



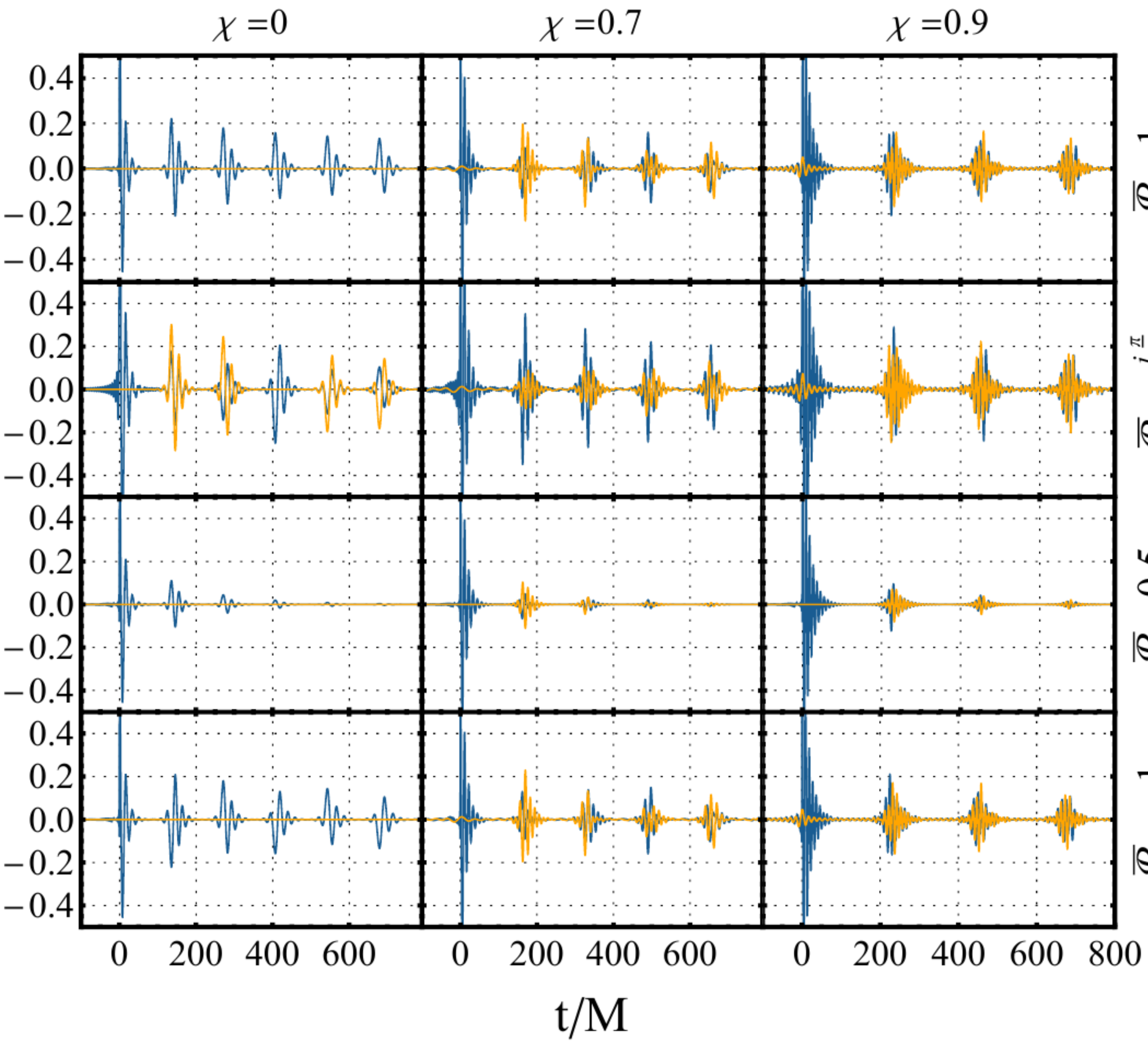
Cardoso & PP, Nature Astronomy (2017)



- 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)]

GW echo slideshow

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

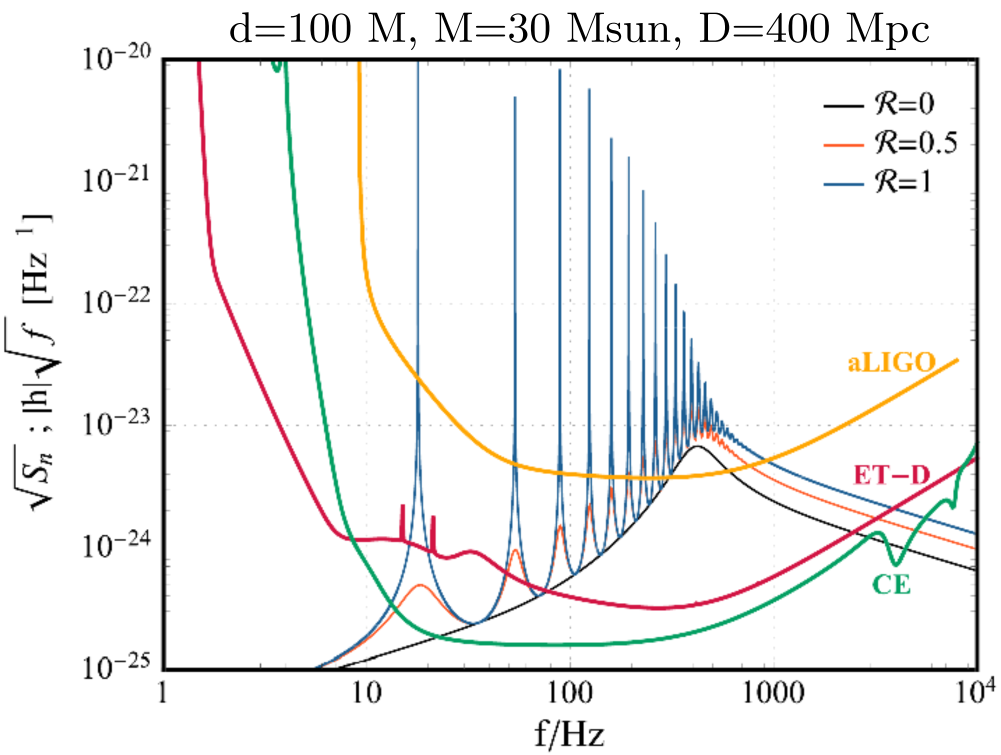


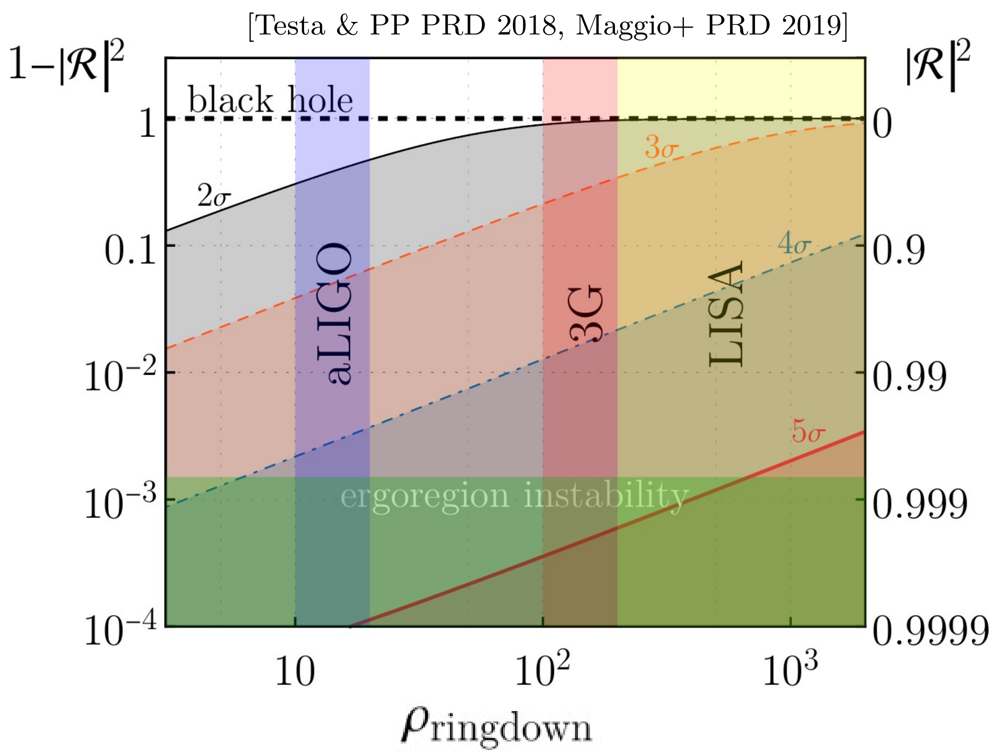
Coherent, analytical template in the FD:

- 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

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

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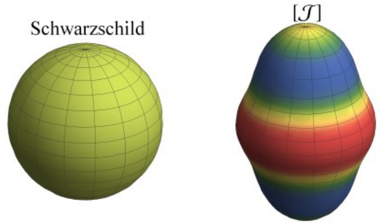
- **2PN:** Point-particle phase depends on **multipole moments** of the bodies
  - Tests of the BH no-hair theorem [Hansen 1974]



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

Mass moments — Spin moments

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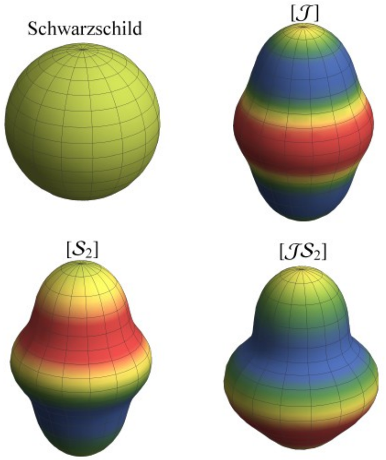

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Mass moments   Spin moments

  - **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"** [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)

Post-Newtonian inspiral: BH vs ECO

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- (Stationary) ECOs can break: [fuzzballs: Bianchi+ 2007.01743, 2008.01445; boson stars: Herdeiro+ 2008.10608]
  - equatorial symm.: e.g. $S_2 \neq 0$, $M_3 \neq 0$
  - axial symm.: e.g. $M_{20} \neq 0$, $M_{21} \neq 0$, $M_{22} \neq 0$

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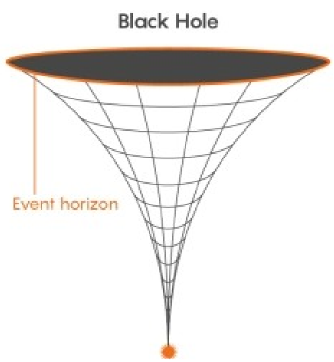
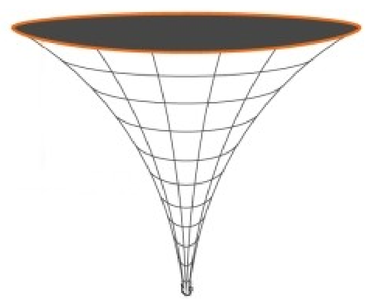
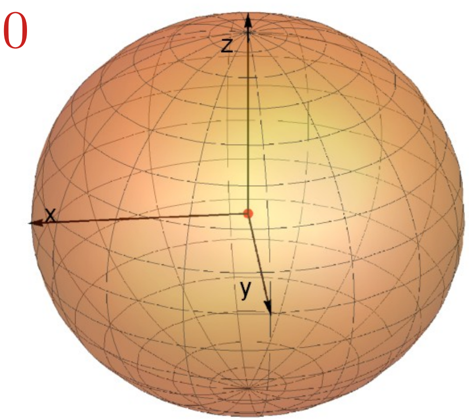


singularity

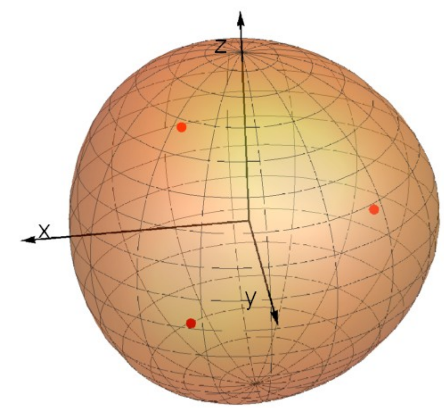


regular

Kerr



Fuzzball



Embedding diagrams by G. Raposo

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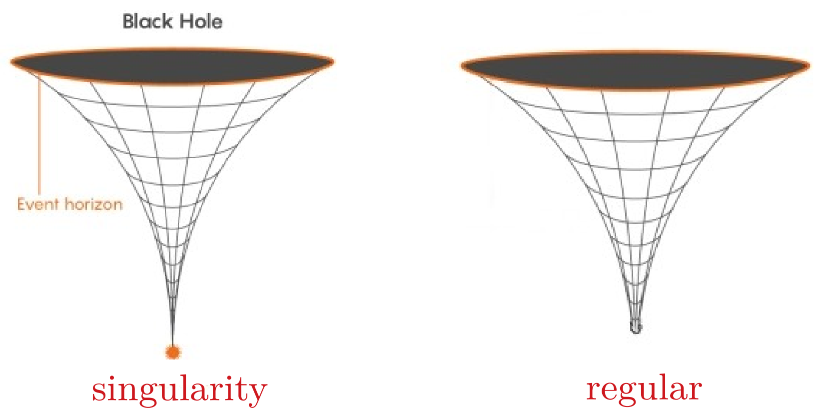

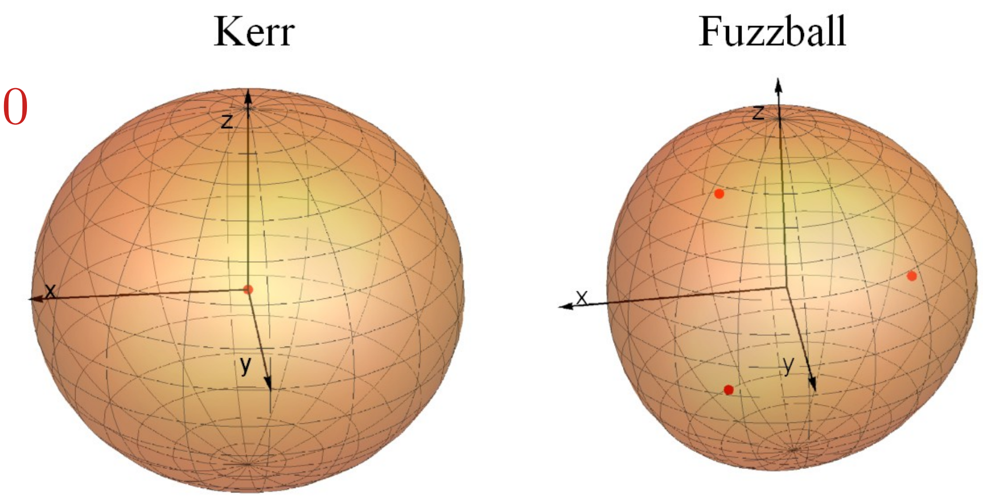

Embedding diagrams by G. Raposo

- Fuzzballs (in N=2 supergravity):
  - certain multipole ratios are ~ universal [Bena-Mayerson PRL 2006.10750, 2007.09152]
  - certain multipole invariants are minimum for BHs [Bianchi+ PRL 2007.01743, 2008.01445]
- Lot of progress: current waveforms should be extended beyond Kerr symmetries

Post-Newtonian inspiral: BH vs ECO

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- **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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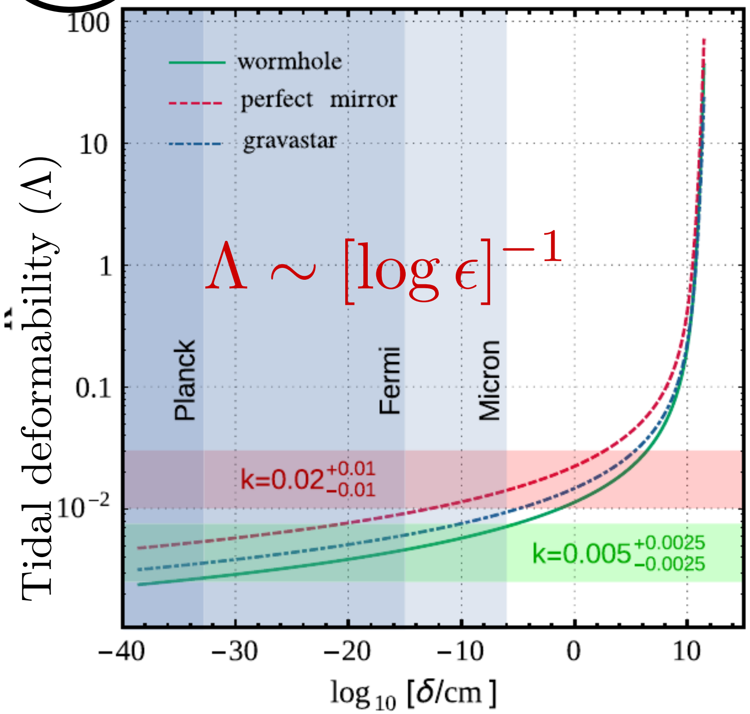


- **5PN: tidal deformability and Love numbers** [Flanagan & Hinder, PRD77 021502 2008]
  - Love = 0 for a BH in GR [Damour '86, Binnington-Poisson PRD 2009; Damour-Nagar PRD 2009; PP+, PRD 2015]
  (but see Le Tiec-Casal 2007.00214 and Chia 2010.07300 for spinning BHs!)
  - Love ≠ 0 for ECOs and BHs in 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]

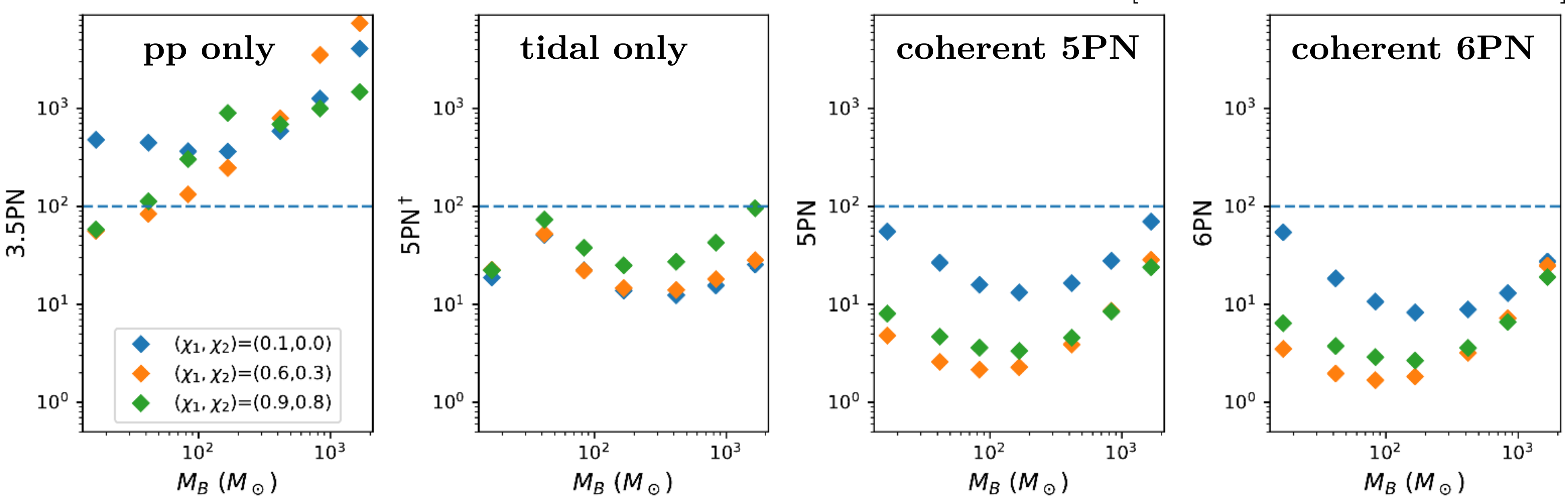
BH vs Boson Stars: coherent model

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

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: merger detections in 3G/LISA are required to constrain boson-star couplings

[Pacilio+ 2007.05264 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 (χ<1) could be much simpler and accurate with EMRIs if one can measure the spin of the secondary [Piovano, Maselli, PP, 2003.08448, 2004.02654]
- ECO tests with EMRIs/IMRIs → many challenges in modeling, parameter estimation, rates, etc...

Conclusion & Open problems

- Future detectors have superior potential to search for departures from classical BHs $\rightarrow$ discovery opportunity for new physics

- Very least: orders of magnitude improvements on current constraints

- Dramatic improvements on ECOs on all fronts in the last few years

- **Better understanding/modeling is needed** (simulations, coalescence, inspiral-merger-ringdown waveforms, and theoretical issues)

- **Testing quantum gravity? In the search of a log...**

Comprehensive living review: Cardoso & Pani, 1904.05363
for description of the effects, caveats, constraints, and references