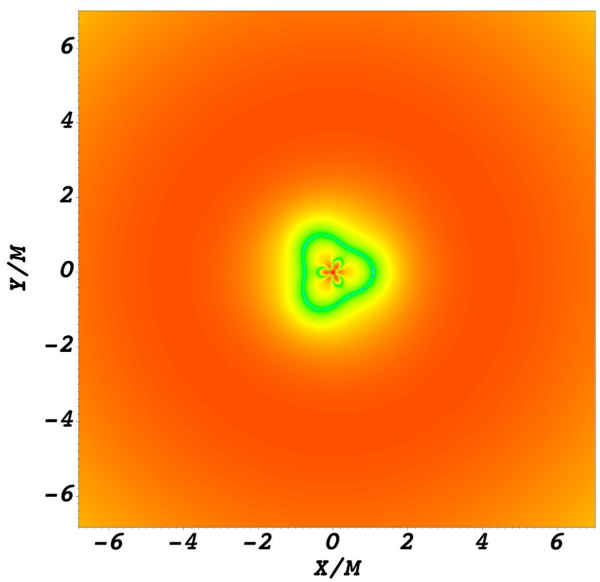
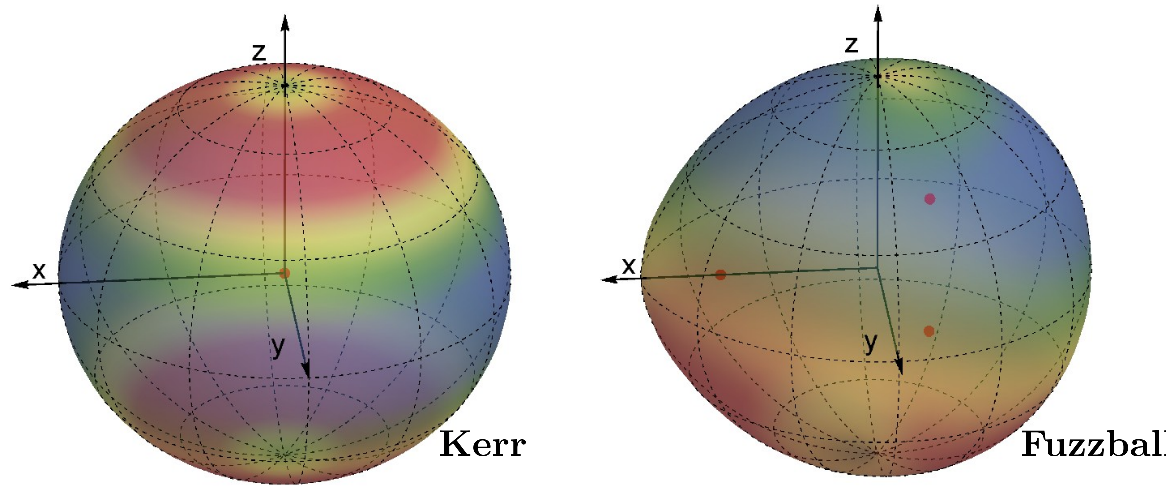
"String Theory as a bridge between Gauge Theories and Quantum Gravity"

Model-agnostic phenomenology of black-hole microstates





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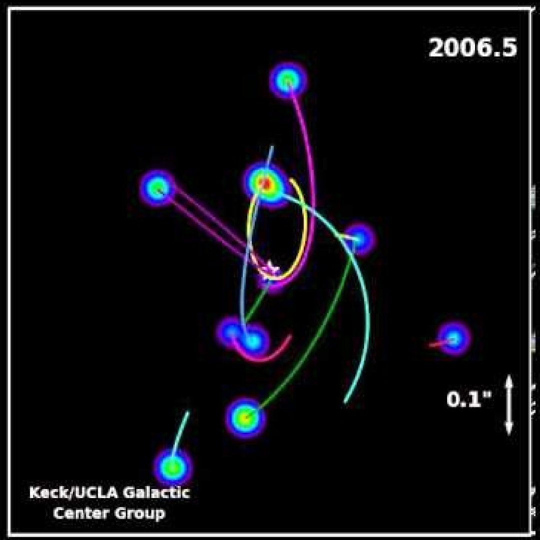
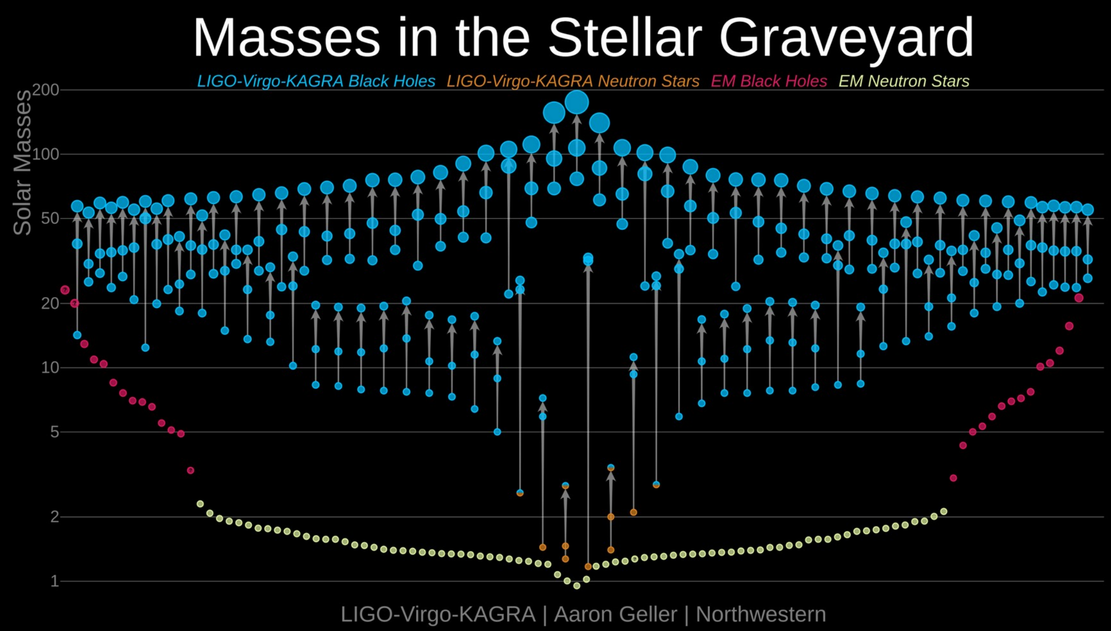
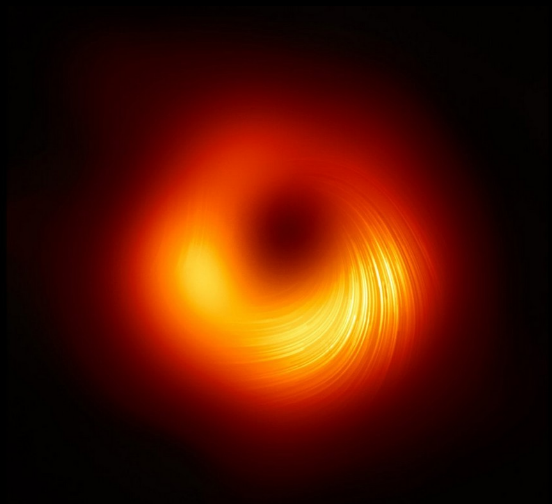
https://web.uniroma1.it/gmunu

Black holes are now everywhere!







2017

2020

Why (still) testing the nature of BHs?

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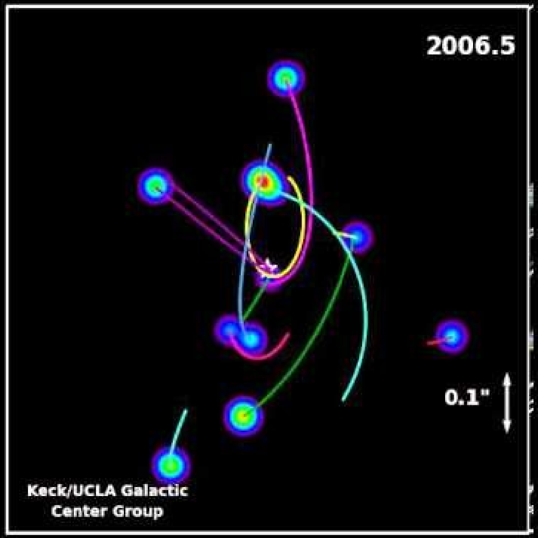

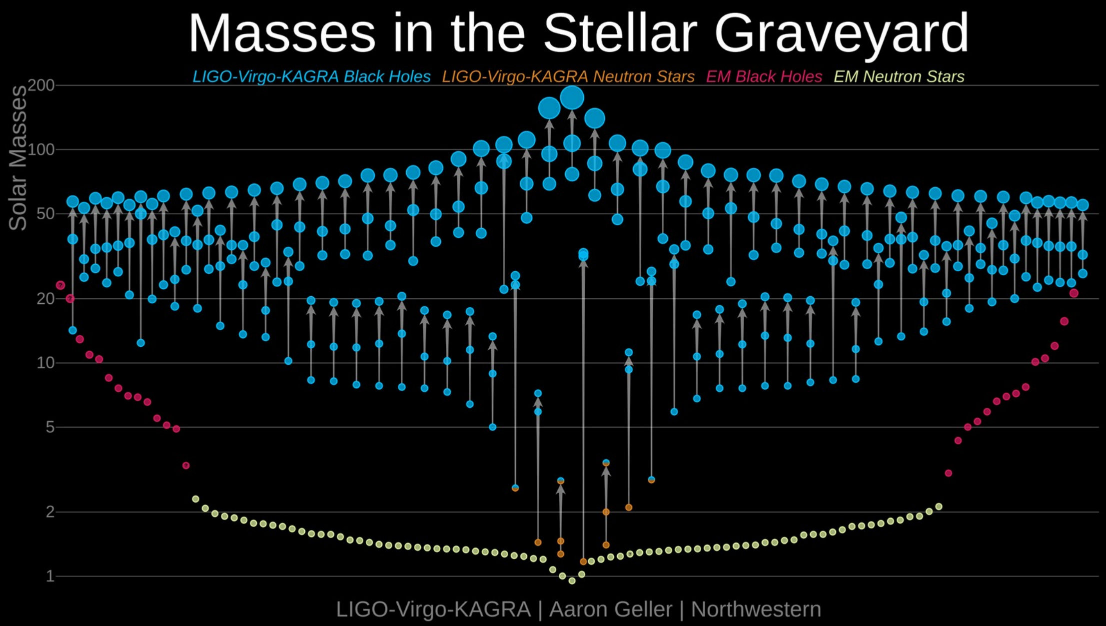

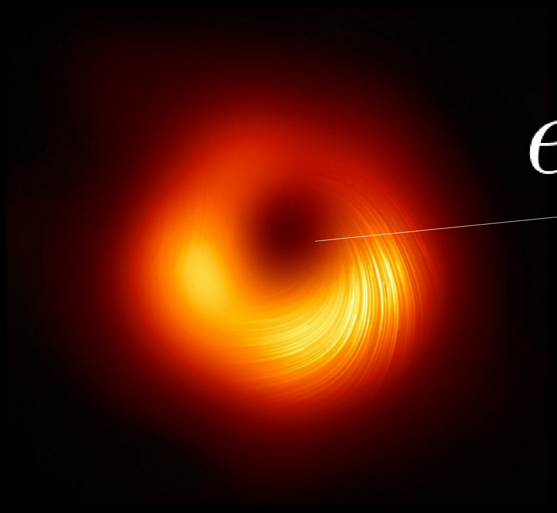

$e^{10^{90}}$ states!

2017

2020

Why (still) testing the nature of BHs?

Problems on the horizon

- **Information loss:** unitarity of BH evaporation inconsistent with <u>locality</u> + <u>"no drama" at the horizon</u>

[Hawking, Almheri+ 2013]

- **Entropy:** Microscopic origin of the huge BH entropy ($\exp[S_{BH}] \sim \exp[G M^2]$ states)?

- **Quantum tunneling:** $\exp[-S_{tunnel}] \exp[S_{BH}] \sim 1$ $\rightarrow$ tunnel to quantum-gravity state with O(1) probability

[Mathur 2010, Bena+ 2016]

- **Singularities**, Cauchy horizons, BH interior...

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- **Singularities**, Cauchy horizons, BH interior…

- **New physics ("structure") at the horizon solves all these problems**

  → Observational signatures of quantum BHs?

- **More conservative / phenomenological motivations:**

  - need concrete models to quantify the "BH-ness" of source (e.g. Bayesian model selection)

  - BHs are unique: any evidence of deviations from classical BH → new physics / new matter

The fuzzball paradigm

- BHs are quantum objects: ensembles of a huge number of <u>regular</u>, <u>horizonless</u>, microstates
  [Lunin+ 2001, Mathur 2005+, Bena+, Bianchi+, Giusto+, ...]

- BH entropy accounted for by the number of microstates
  [Strominger 1996, Horowitz 1996, Maldacena 1997]

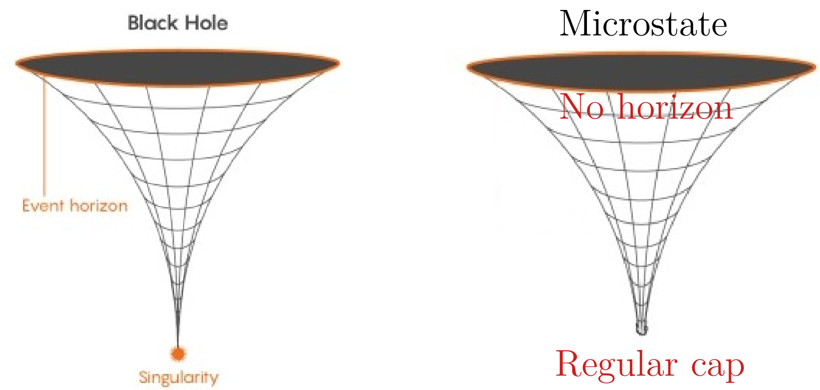
- Tunnelling probability to fuzzball ~ O(1) in specific models
  [Bena+ 2016]

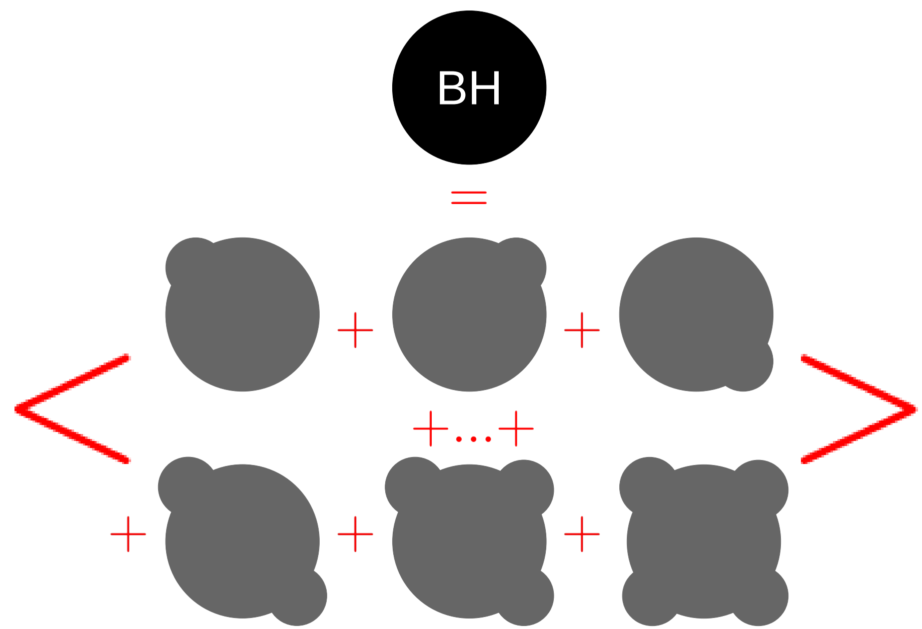
- (Low-energy truncations of) string theory admits huge families of solutions [Bena+ 2007, 2015-2017]

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

- Cons: complicated, mostly extremal charged BHs
  (but see [Bha+ 2021] for non-SUSY extension and [Bha+ 2022] for uncharged case)

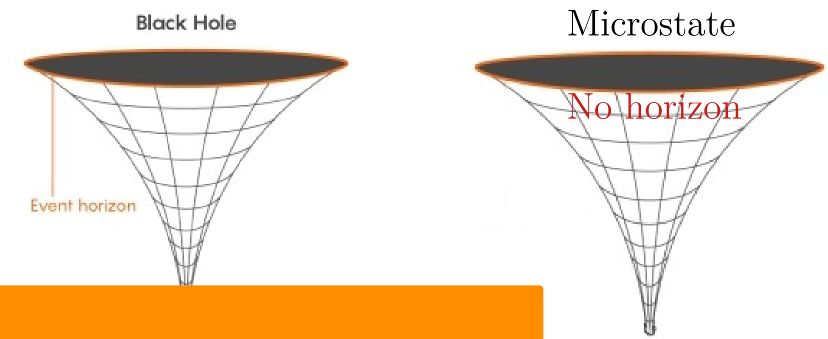
- Growing interest in studying the phenomenology
  [Mayerson 2020, 2022, Bena+ Snowmass 2022]





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

The fuzzball paradigm



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Model-agnostic observational signatures?

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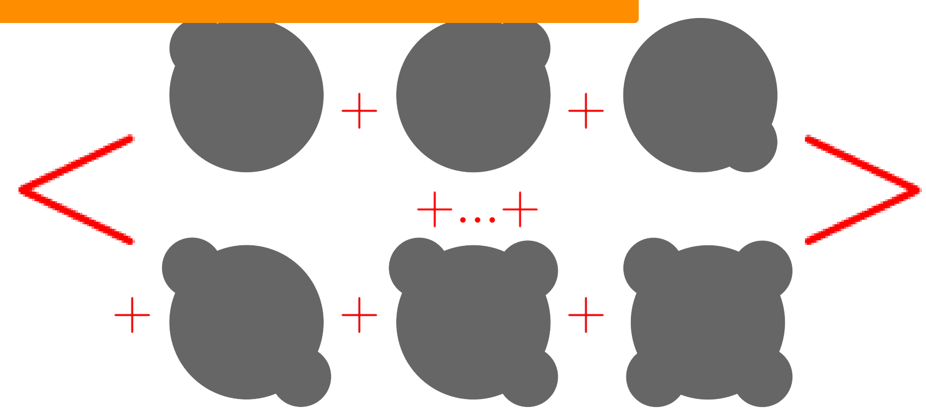
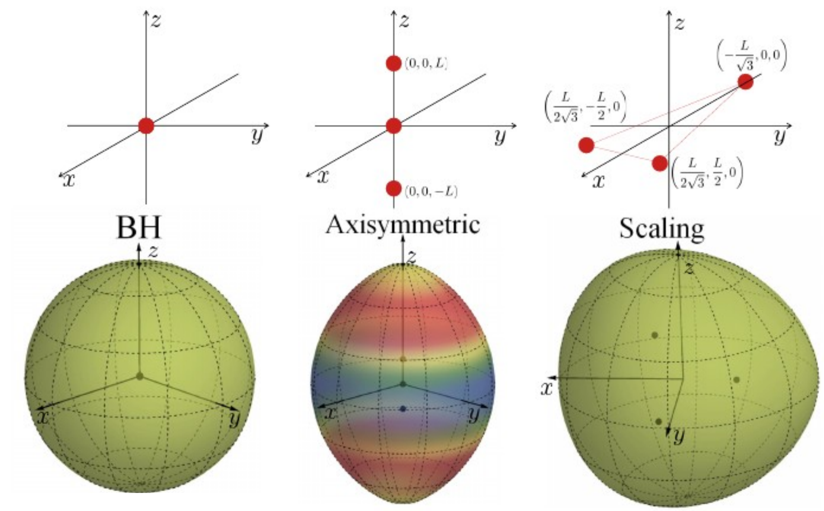


$\sim e^{\frac{M^2}{M_P^2}}$ microstates

A family of microstates

- N=2 supergravity: 4 gauge fields, 3 scalars [Bena-Warner 2008]
- No spatial isometries in general, but closed form!



4D ansatz:

$$ds^2 = -e^{2U}(dt+\omega)^2 + e^{-2U}\sum_{i=1}^{3} dx_i^2,$$

$$Z_I = L_I + \frac{|\epsilon_{IJK}|}{2}\frac{K^J K^K}{V}, \qquad e^{-4U} = Z_1 Z_2 Z_3 V - \mu^2 V^2,$$

$$\mu = \frac{W}{2} + \frac{L_I K^I}{2V} + |\epsilon_{IJK}|\frac{K^I K^J K^K}{6V^2} \qquad *_3 d\omega = \tfrac{1}{2}\left(V dW - W dV + K^I dL_I - L_I dK^I\right)$$

N centers:

$$V = 1 + \sum_{a=1}^{N} \frac{v_a}{|\vec{x}-\vec{x}_a|}, \qquad L_I = 1 + \sum_{a=1}^{N} \frac{\ell_{I,a}}{|\vec{x}-\vec{x}_a|},$$

$$K^I = \sum_{a=1}^{N} \frac{k_a^I}{|\vec{x}-\vec{x}_a|}, \qquad W = \sum_{a=1}^{N} \frac{m_a}{|\vec{x}-\vec{x}_a|},$$

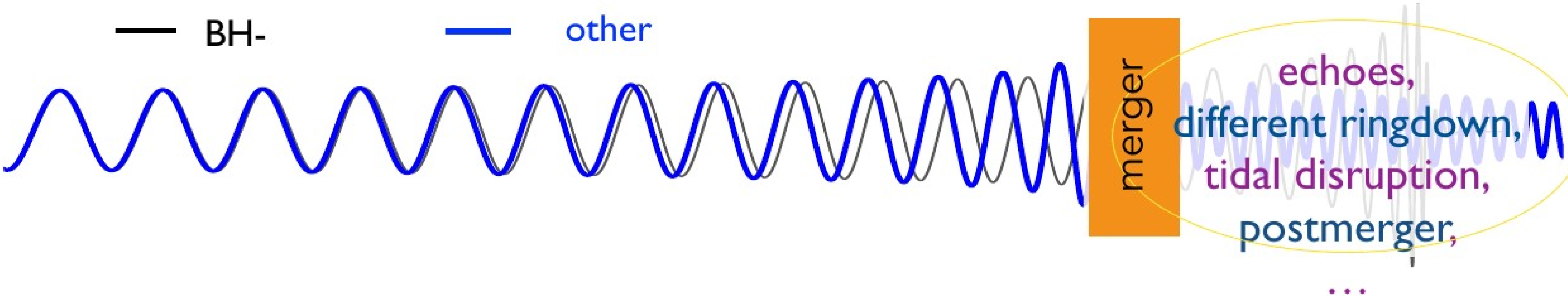
- In D=4 solutions looks singular at the centers, but regular in higher dimensions
- No ergoregion by construction → no ergoregion instability

Model-agnostic properties

- Charges, Dipoles $\rightarrow$ different emission in binaries
- Spin & higher multipoles $\rightarrow$ different structure/emission
- Non-integrable motion and chaos $\rightarrow$ different geodesics
- Tidal Love numbers $\rightarrow$ different tidal properties
- QNMs & echoes $\rightarrow$ different ringdown

GW signatures

Slide concept by T. Hinderer + A. Maselli



~point masses: same signal for all objects

Spin Measurements + extra DOF

tidal effects
+
spins

multipolar structure

absence of horizon
absorption effects

echoes
+ QNMs

Post-Newtonian inspirals

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

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

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

- Dynamics described as point particles endowed with moments:

$$\mathcal{L} = \mathcal{L}_{orb} + \mathcal{L}_2^{int} \qquad \mathcal{L}_{orb} = \mathcal{L}_M + \mathcal{L}_J + \mathcal{L}_{Q2} + \mathcal{L}_{Q3} + \mathcal{L}_{S2} + \mathcal{L}_{S3}$$

$$\mathcal{L}_M = \frac{\mu v^2}{2} + \frac{\mu M}{r} + \frac{\mu}{c^2}\left\{\frac{1-3\nu}{8} v^4 + \frac{M}{2r}\left[(3+\nu) v^2 + \nu \dot{r}^2 - \frac{M}{r}\right]\right\} + O\left(c^{-4}\right)$$

$$\mathcal{L}_J = \frac{\epsilon^{abc}}{c^2} v^b \left[\left(\eta_2 J_1^a + \eta_1 J_2^a\right) \frac{2M}{r^2} n^c + \left(\eta_2^2 J_1^a + \eta_1^2 J_2^a\right) \frac{a^c}{2}\right] + O\left(c^{-4}\right)$$

$$\mathcal{L}_{Q2} = \frac{3\eta_1 M}{2r^3} Q^{ab} n^{ab}$$

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$$\mathcal{L}_{Q2} = \frac{3\eta_1 M}{2r^3} Q^{ab} n^{ab}$$

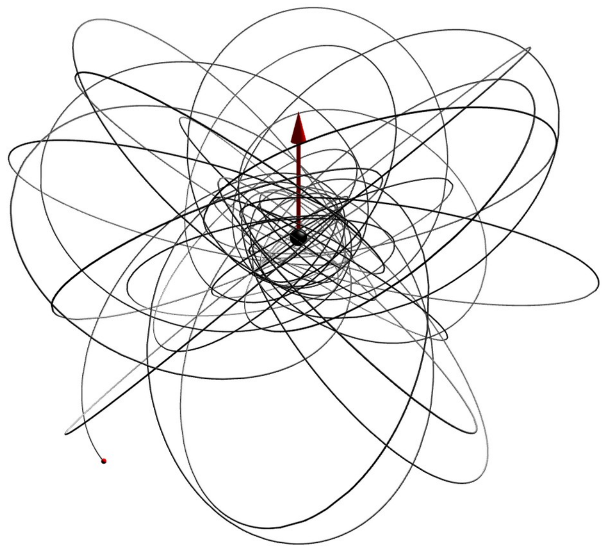
$$\mathcal{L}_2^{int} = -\frac{1}{4\lambda_2} Q^{ab} Q^{ab} - \frac{1}{12\lambda_3} Q^{abc} Q^{abc} - \frac{1}{6\sigma_2} S^{ab} S^{ab} - \frac{1}{16\sigma_3} S^{abc} S^{abc} + \alpha J_2^a Q^{bc} S^{abc} + \beta J_2^a S^{bc} Q^{abc}$$

Finite-size effects (Love numbers)

Extreme mass-ratio inspirals

Review: Barack, CQG 2009

- Point particle moving on primary's spacetime
- + self-force and finite-size effects
- To leading order:
  - (adiabatic) geodesic motion around primary
  - GW fluxes from perturbation theory
  - Any other flux from other fields



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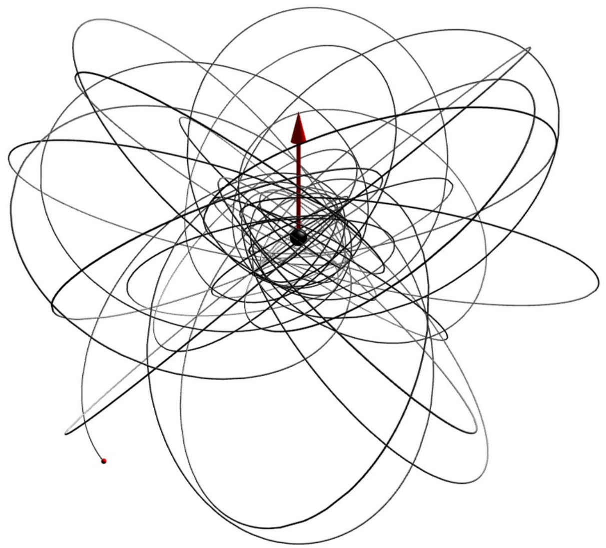

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  - Any other flux from other fields
- In GR:

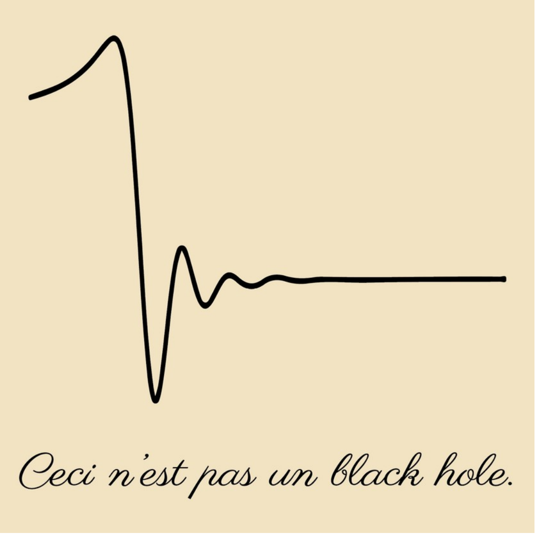
$R_{\mu\nu}^{\rm bkg}=0$ Kerr BH

$\nabla^\mu T_{\mu\nu}^{\rm particle}=0$ Geodesics

$\delta G_{\mu\nu}=8\pi T_{\mu\nu}^{\rm particle}$ Linearized $\rightarrow$ fluxes

Field theory in curved spacetime

Review: Berti, Cardoso, Starinets, CQG 2009



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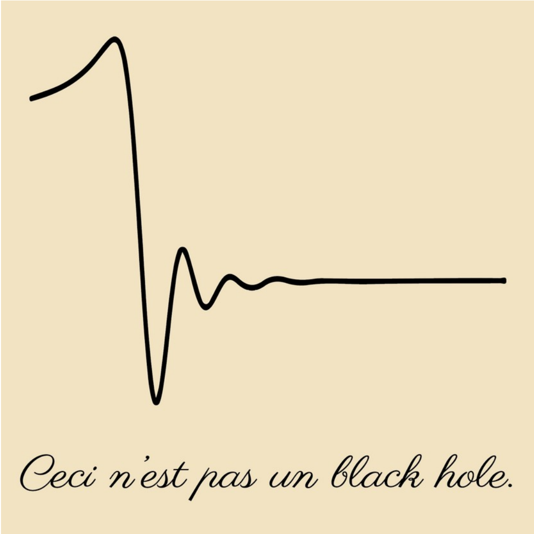

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$$\Box_{\text{bkg}} h_{\mu\nu} = 0 \qquad \text{Linear perturbations + boundary conditions}$$

- Post-merger signal → superposition of quasinormal modes (QNMs)

$$h_+ + i h_\times \sim \sum_{i=(\ell,m,n)} A_i \sin(\omega_i t + \phi_i) e^{-t/\tau_i}$$

- Smoking guns of "new physics":
  - Shift of QNMs (bkg geometry + dynamics + boundary conditions):

$$\omega_{lmn} = \omega_{lmn}^{\text{Kerr}}(M,\chi) + \delta\omega_{lmn}(M,\chi,\ell_{\text{new}})$$

  - Extra modes (e.g., polarizations, matter modes), Isospectrality breaking

Constraining fundamental charges

- PN theory: extra dipolar emission [Barausse-Yunes-Chamberlain PRL 2016]

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

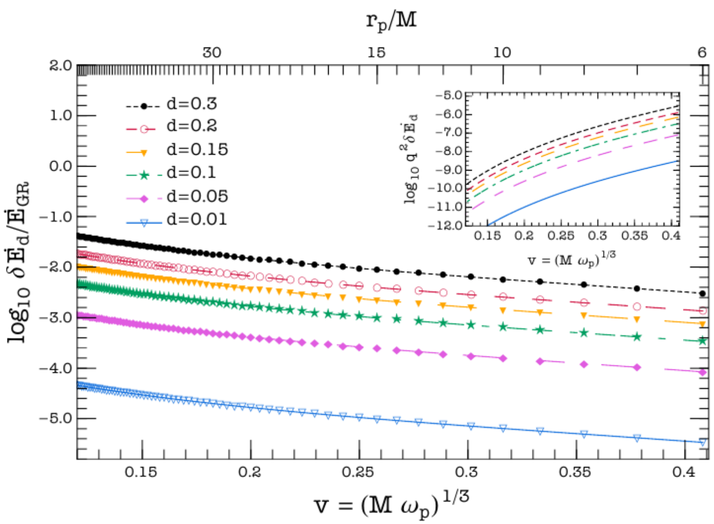
-1PN correction (stronger at large distance)

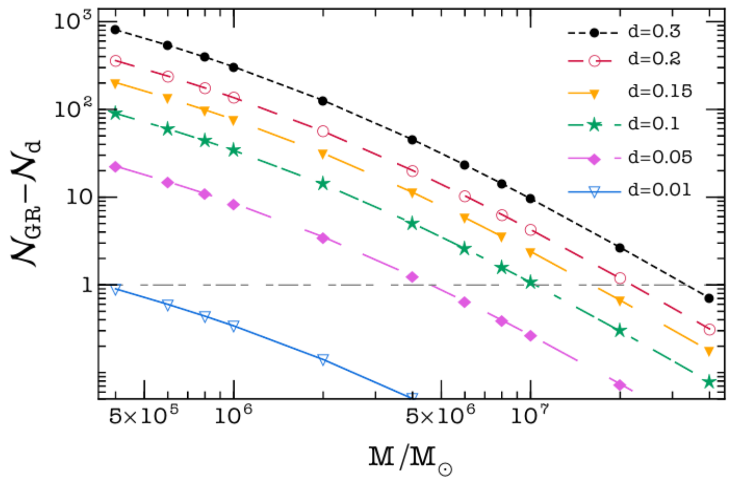
- EMRIs: for high-curvature extensions to GR, supermassive BHs are ~Kerr, but the secondary can be modelled as a point charge:

[Maselli+ PRL 2022-2023, Nature Astronomy 2022]

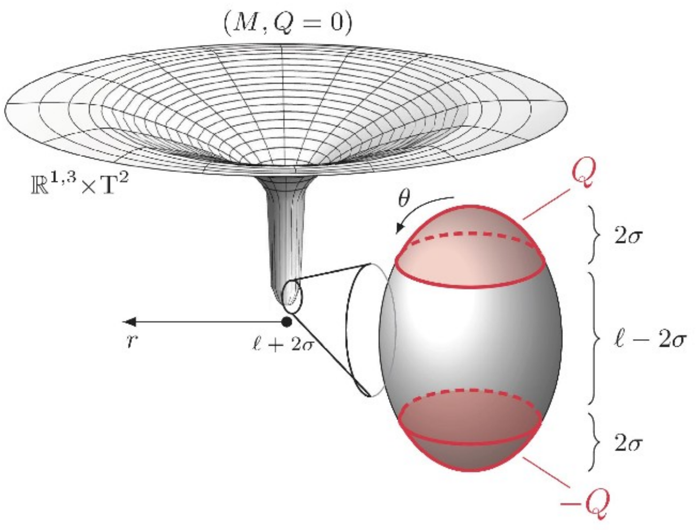
$$\Box_{\rm Kerr}\phi = \text{charge}\,\mathcal{T}_{\rm particle}$$

Constraints: d=Q/M<0.01





Globally neutral solitons



Bah, Heidmann+, PRL 2020, PRD 2022,2023

- Zero net charge, but dipole moment!
- Phenomenology of fundamental dipoles?
  - Precession, extra radiation

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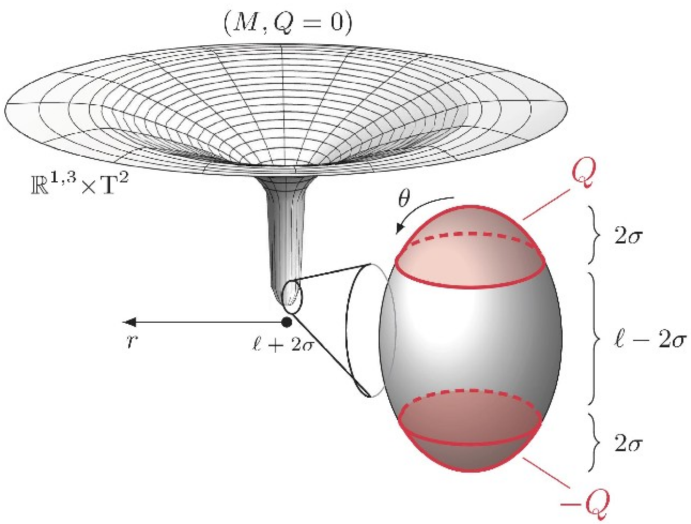

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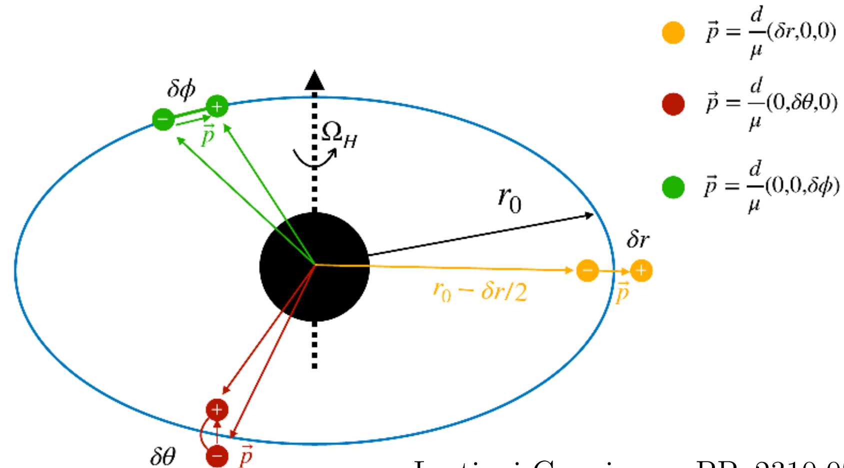
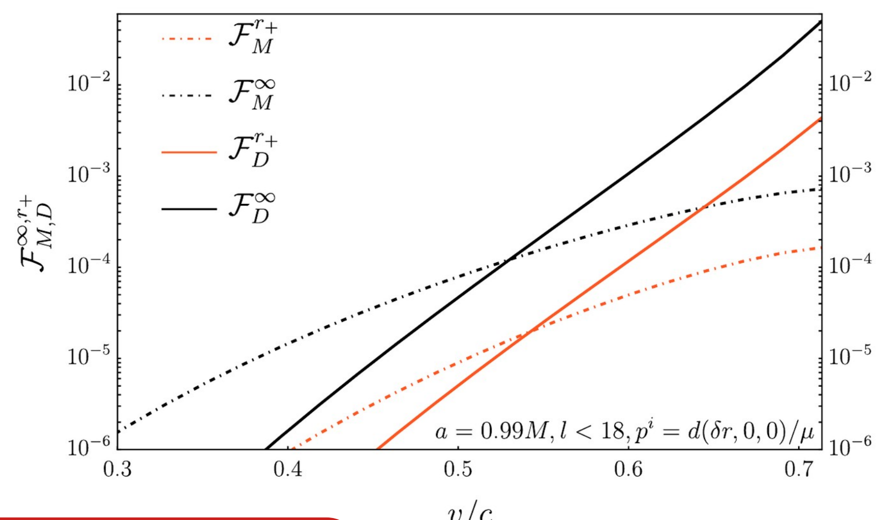


Lestingi-Cannizzaro-PP, 2310.07772

$$F_M=(4\pi)^2 q^2 d^2 \mathcal{F}_M, \qquad F_D=(4\pi)^2 q^4 p^2 \mathcal{F}_D$$



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Emission suppressed in EMRIs
How about comparable binaries?

Testing the Kerr bound

- GR BHs have dimensionless spin $\chi \equiv \frac{J}{M^2} \leq 1$
- Fuzzballs can evade this bound
  - Microstates of *static* BHs are generically (slowly?) spinning
  - Quantum gravity generically admits “superspinars” [Gimon-Horava PRD 2009]

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  - Microstates of *static* BHs are generically (slowly?) spinning
  - Quantum gravity generically admits "superspinars" [Gimon-Horava PRD 2009]
- Kerr bound can be tested in a model-independent way:
  1. Point particle PN phase up to 1.5PN depends only on masses & spins
     - but no consistent PN inspiral or merger waveforms
  2. Measuring secondary spin in an EMRI with LISA? [Piovano+ PLB 2020]
     - but correlated with other parameters! [Piovano+ PRD 2021]
     - can spin precession and generic orbits break degeneracy?

Signatures of multipolar structure

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

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

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

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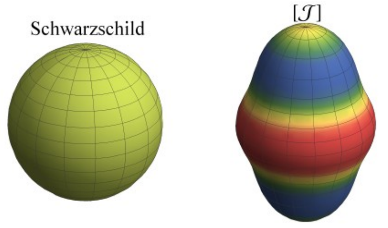
  - Tests of the BH no-hair theorem [Hansen 1974]



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

Mass moments   Spin moments

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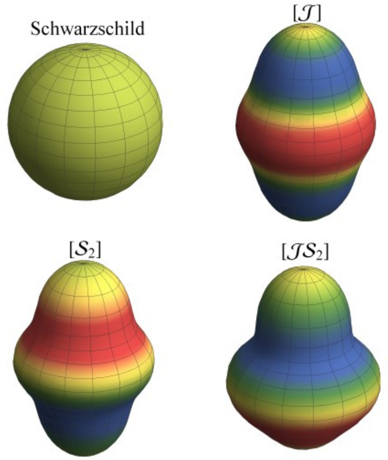

  - **Any non-Kerr object**:

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

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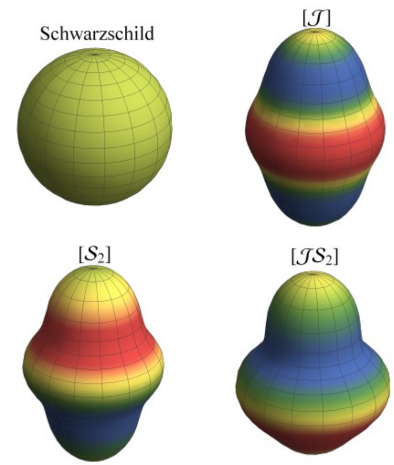

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Mass moments — Spin moments

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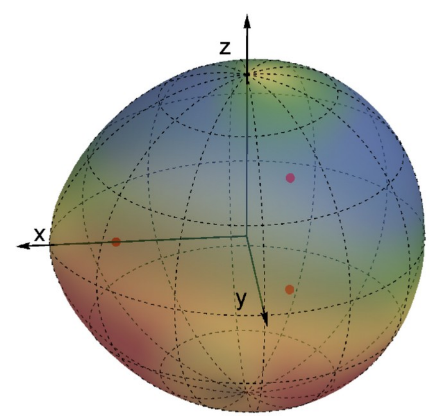
Fuzzball can break: [Bena+ 2020-2021; Bianchi+ PRL-JHEP 2020]

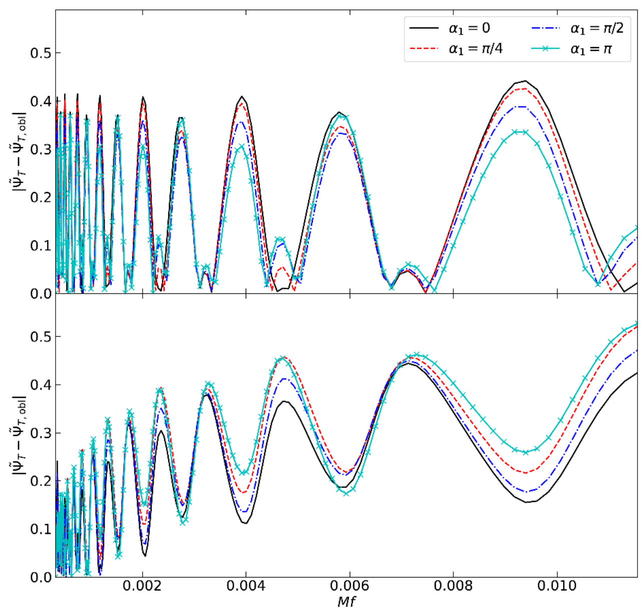
- equatorial symmetry: e.g. $S_2 \neq 0$, $M_3 \neq 0$
- axial symmetry: e.g. $M_{20} \neq 0$, $M_{21} \neq 0$, $M_{22} \neq 0$



Credits: G. Raposo

Signatures of multipolar structure

- Fuzzballs (in N=2 supergravity):
  - certain multipole ratios are ~ universal [Bena-Mayerson PRL-JHEP 2020]
  - certain multipole invariants are minimum for BPS BHs [Bianchi+ PRL-JHEP 2020] ….but not for non-BPS states [Bena+ 2021]
- Lot of progress: current models should be extended beyond Kerr symmetries:
  - Searching for equatorial-symmetry breaking with LISA EMRIs [Fransen-Mayerson 2022]
  - Axial-symmetry breaking introduces precession & phase modulation [Loutrel+ 2022]



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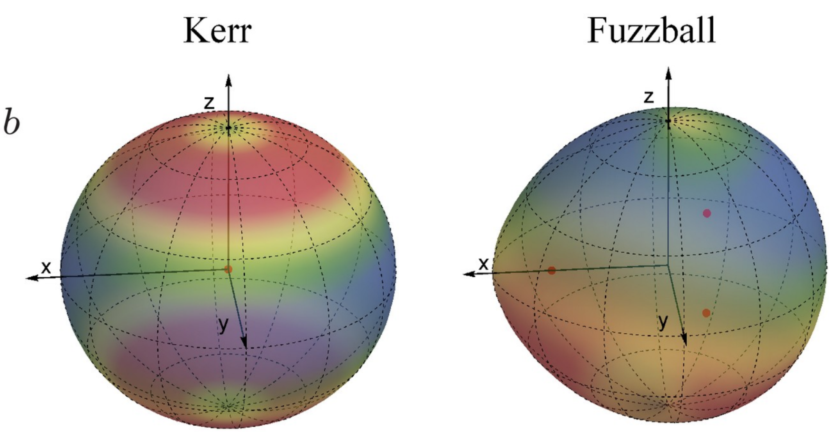


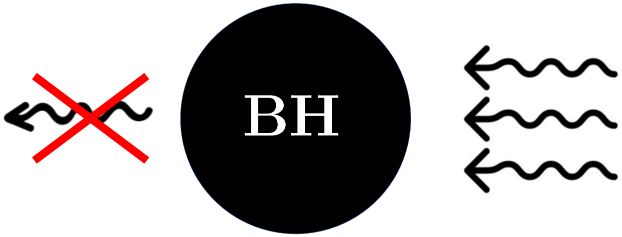
Precession is crucial to measure the effect

[Loutrel+ PRD 2022; Loutrel+ 2309.17404]

Tidal effects beyond Kerr

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

- **2.5log PN: tidal heating** [Alvi PRD 2001, Poisson, PRD 2009]
  - BHs absorb radiation at horizon
  - Tidal heating is ~ absent for ECOs → how about fuzzballs?
  - Important for EMRIs in LISA [Maselli+, 2018, Hughes PRD 2001, Datta+ PRD 2020]



Tidal effects beyond Kerr

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

- **2.5log PN: tidal heating** [Alvi PRD 2001, Poisson, PRD 2009]
  - BHs absorb radiation at horizon
  - Tidal heating is ~ absent for ECOs → how about fuzzballs?
  - Important for EMRIs in LISA [Maselli+, 2018, Hughes PRD 2001, Datta+ PRD 2020]

- **5PN: tidal deformability and Love numbers** [Flanagan & Hinder, PRD77 021502 2008]
  - Love = 0 for an isolated BH in GR [Damour '86; Binnington-Poisson PRD 2009; Damour-Nagar PRD 2009]
  - Love ≠ 0 in any other case [Porto+ Fortsch. Phys. 2016, Cardoso+, PRD 2017]
  - In several ECO models Love scales logarithmically → strong constraints with LISA [Maselli+, PRL 2018, CQG 2019; Addazi+ PRL 2019]

Tidal effects beyond Kerr

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

Any evidence of Love $\neq 0$ in a supermassive object would imply a departure from the standard vacuum GR BH picture

- **5PN: tidal deformability and Love numbers** [Flanagan & Hinder, PRD77 021502 2008]
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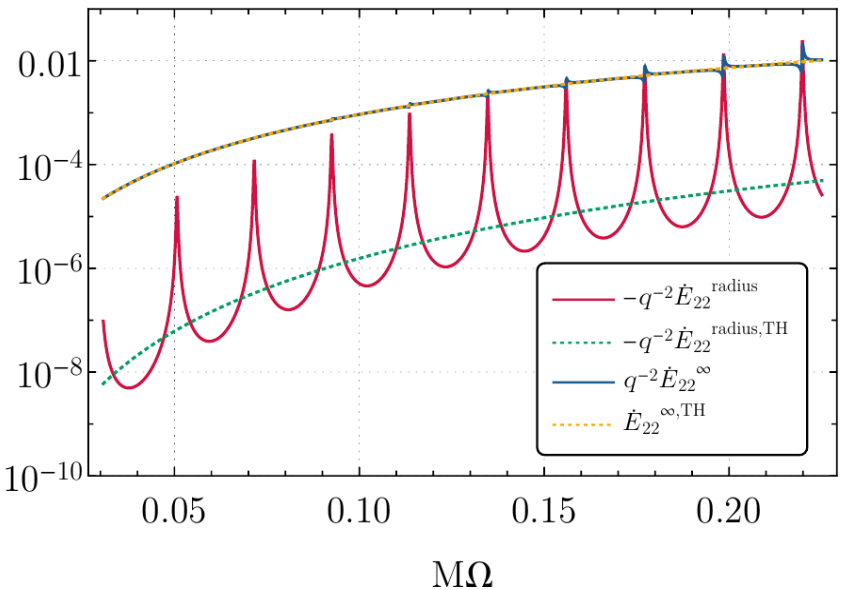
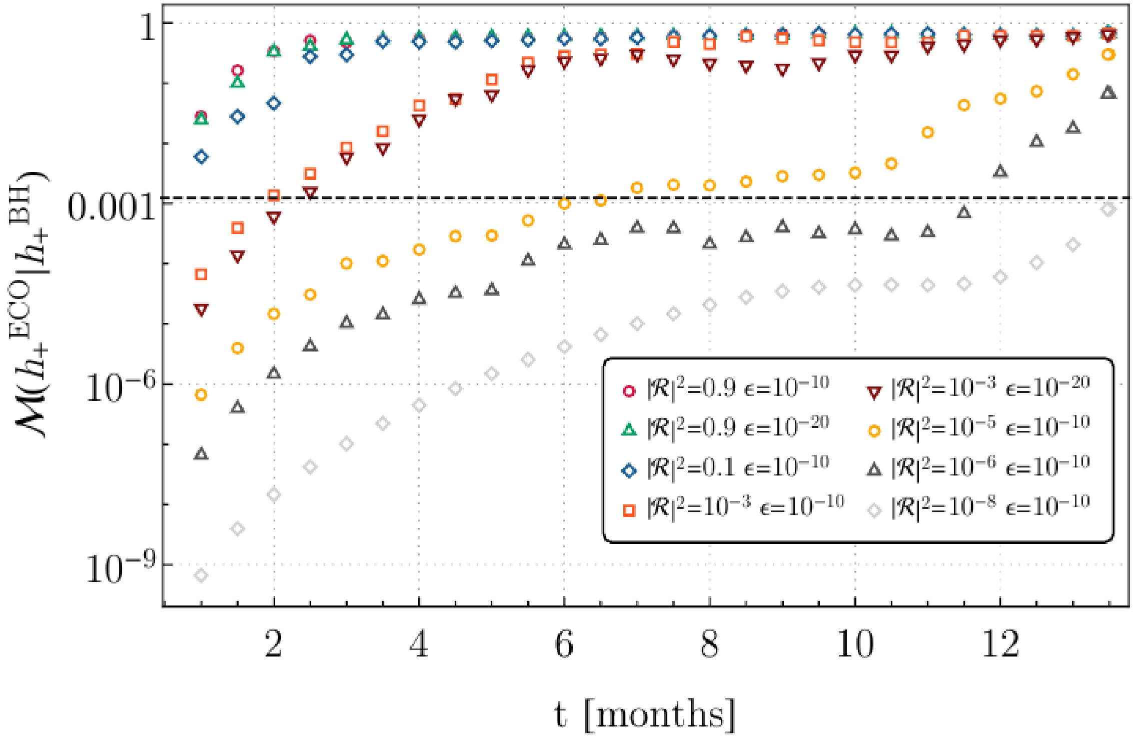
Testing horizon absence with EMRIs





- ECO QNM excitation in fluxes [Maggio, van de Meent, Pani; PRD 2021; see also Sago-Tanaka PRD 2021]
- EMRIs can potentially constrain the reflectivity at the level of $|\mathcal{R}|^2 \lesssim 10^{-8}$
- Specific models (e.g. $\mathcal{R}(\omega) = e^{-\frac{|\omega - m\Omega|}{2T_H}}$) can be confirmed/ruled out

Dynamical Love beyond Kerr

Chakraborty-Maggio-Silvestrini-Pani, 2310.06023

- Teukolsky formalism for Kerr metric + boundary conditions [Chia 2021, Creci+ 2021, Consoli+ 2022, Bonelli+ 2021]

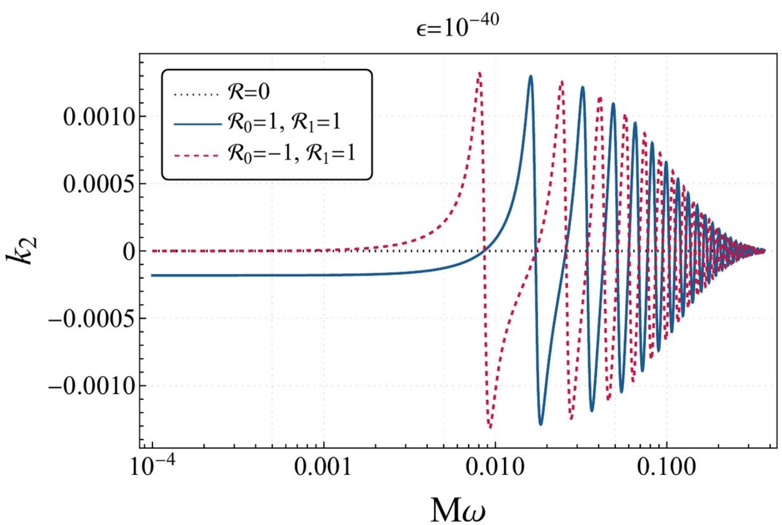
Zero static Love unless $\mathcal{R}(\omega) = 1 + iM\omega\mathcal{R}_1$

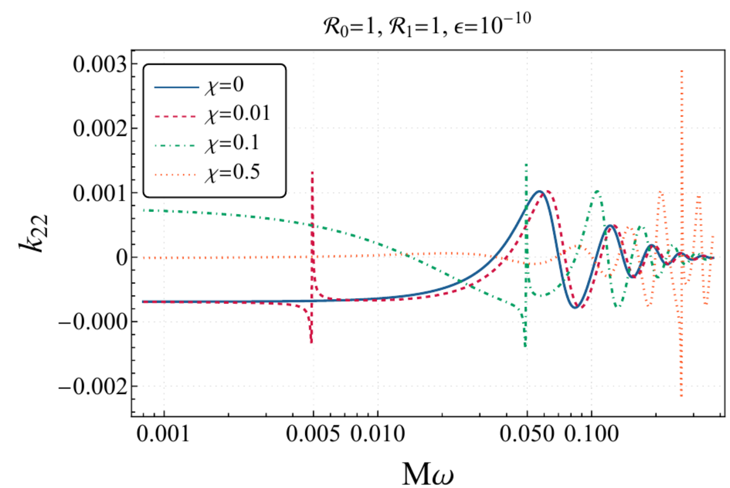
$$\mathcal{R}(\omega) = \mathcal{R}_0 + iM\omega\mathcal{R}_1 + \mathcal{O}(M^2\omega^2)$$

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

$$k_2 = \frac{2}{15}\mathrm{Re}\left[\frac{1}{-2\mathcal{R}_1 + \{7 + 16i\pi + 8(\epsilon + \ln\epsilon)\}}\right]$$

- Generic log dependence, static limit discontinuous, resonances



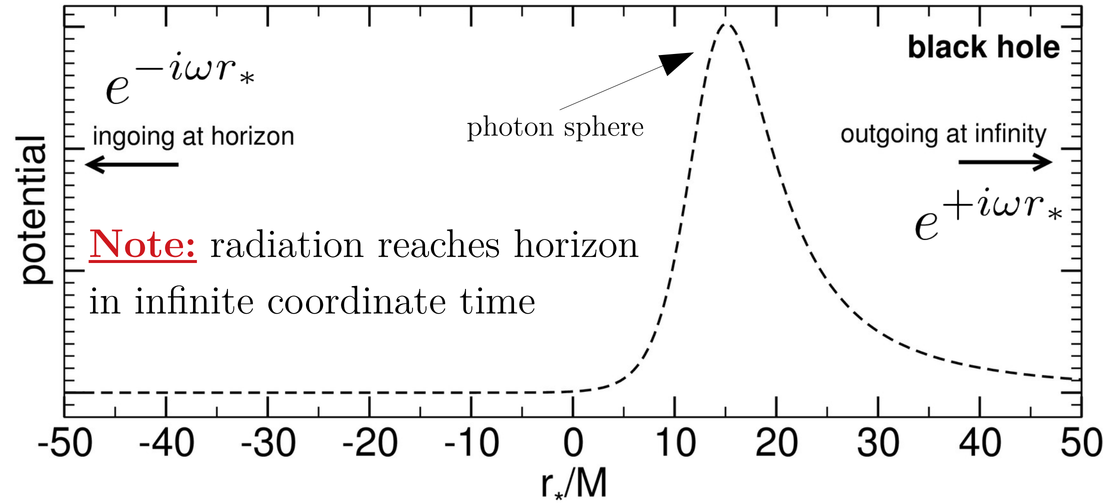


BH microstate ringdown

QNMs: BHs vs Rest of the World

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

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



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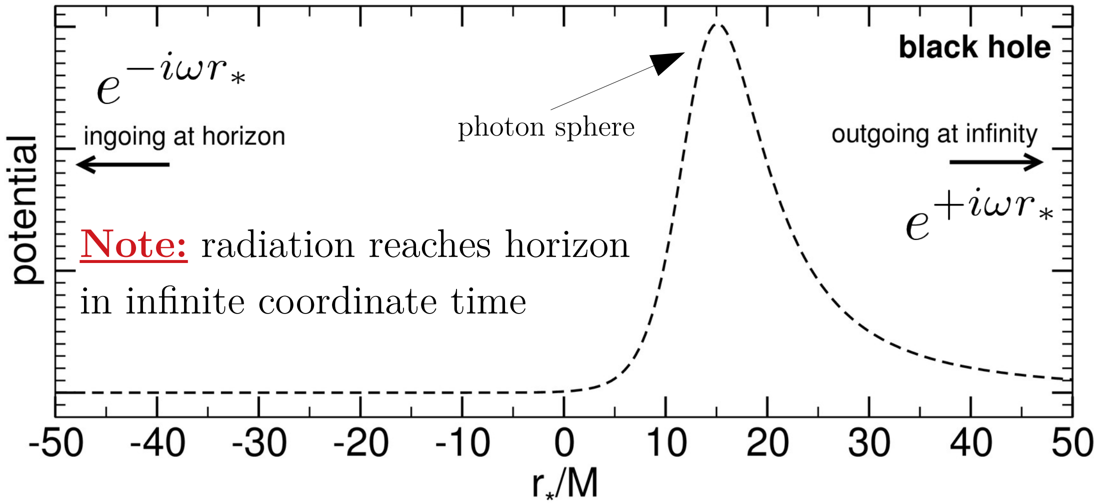

Only (classical) BHs absorb everything!

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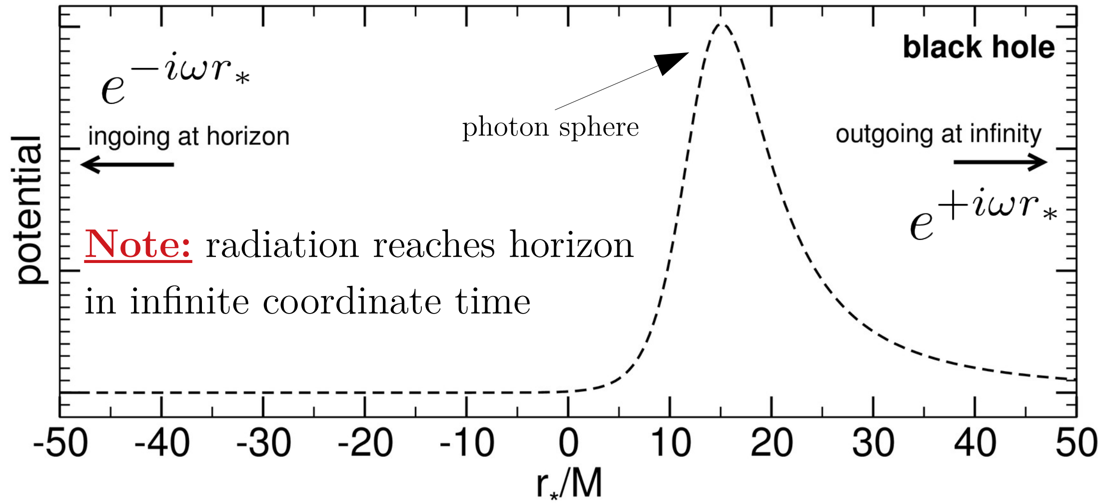
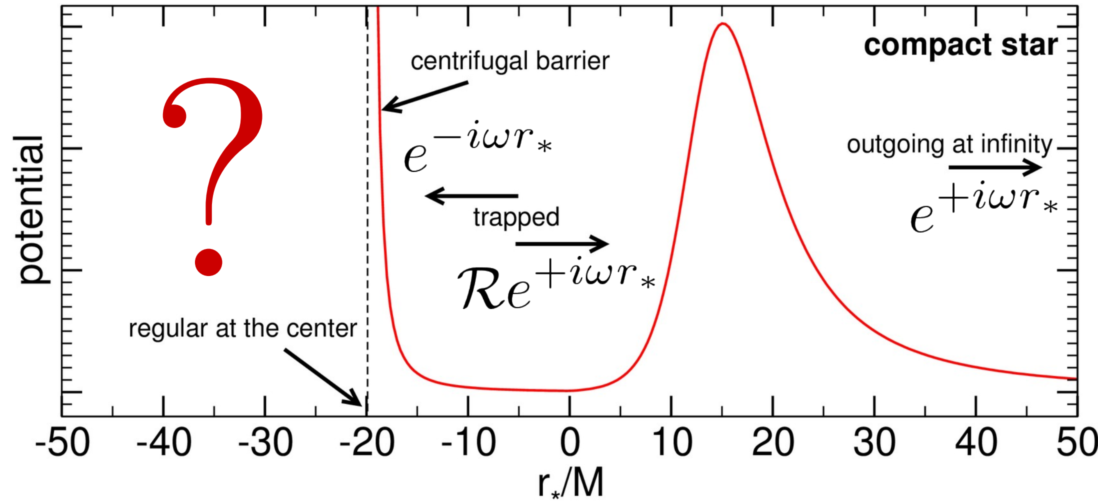


Only (classical) BHs absorb everything!

- Total absorption is the <u>defining</u> property of a BH
- Some reflectivity in any other case
- Reflectivity = weak GW interaction!



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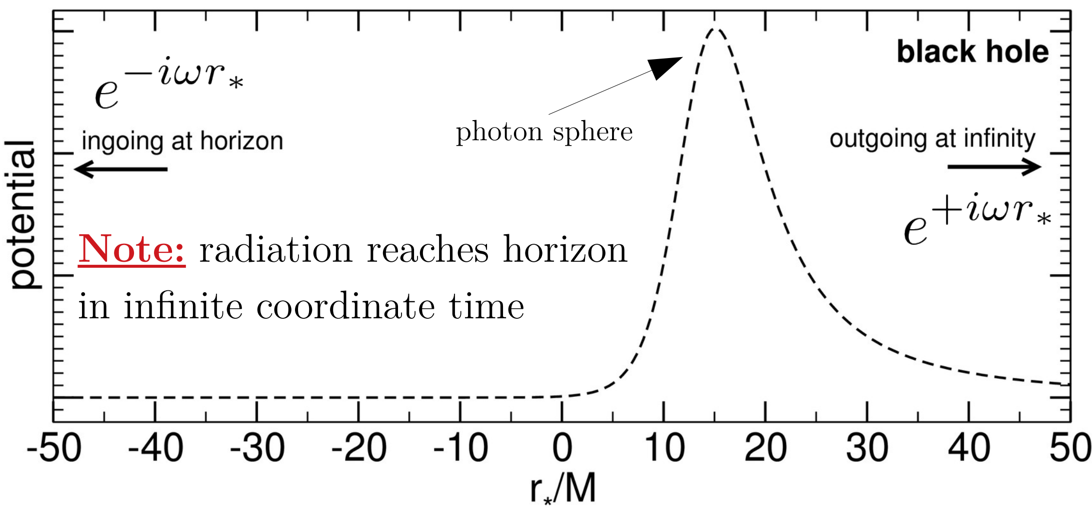

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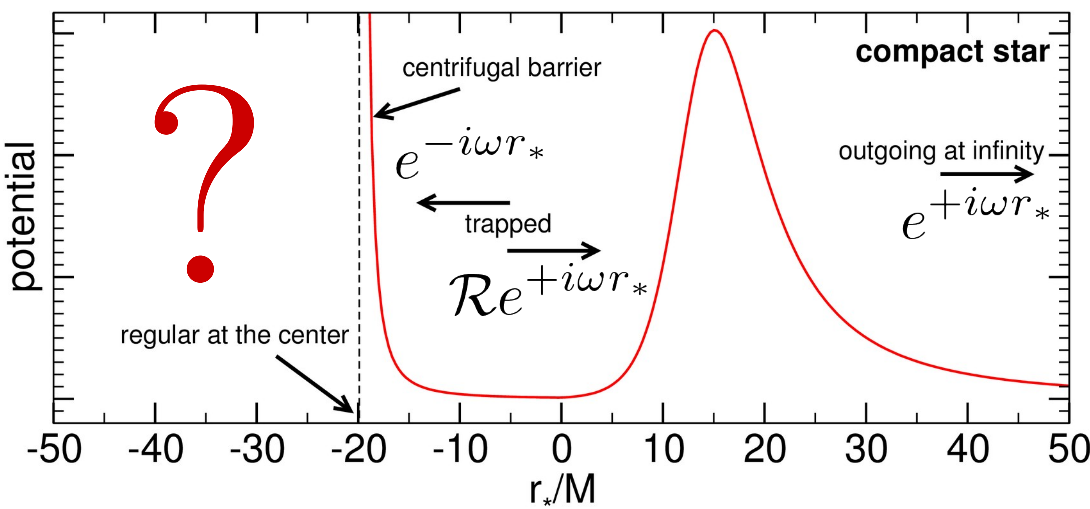
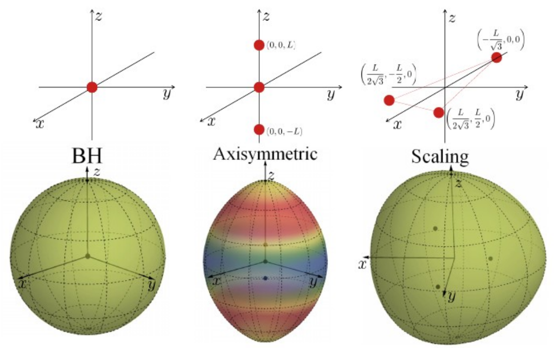


No horizon $\rightarrow$ different ringdown

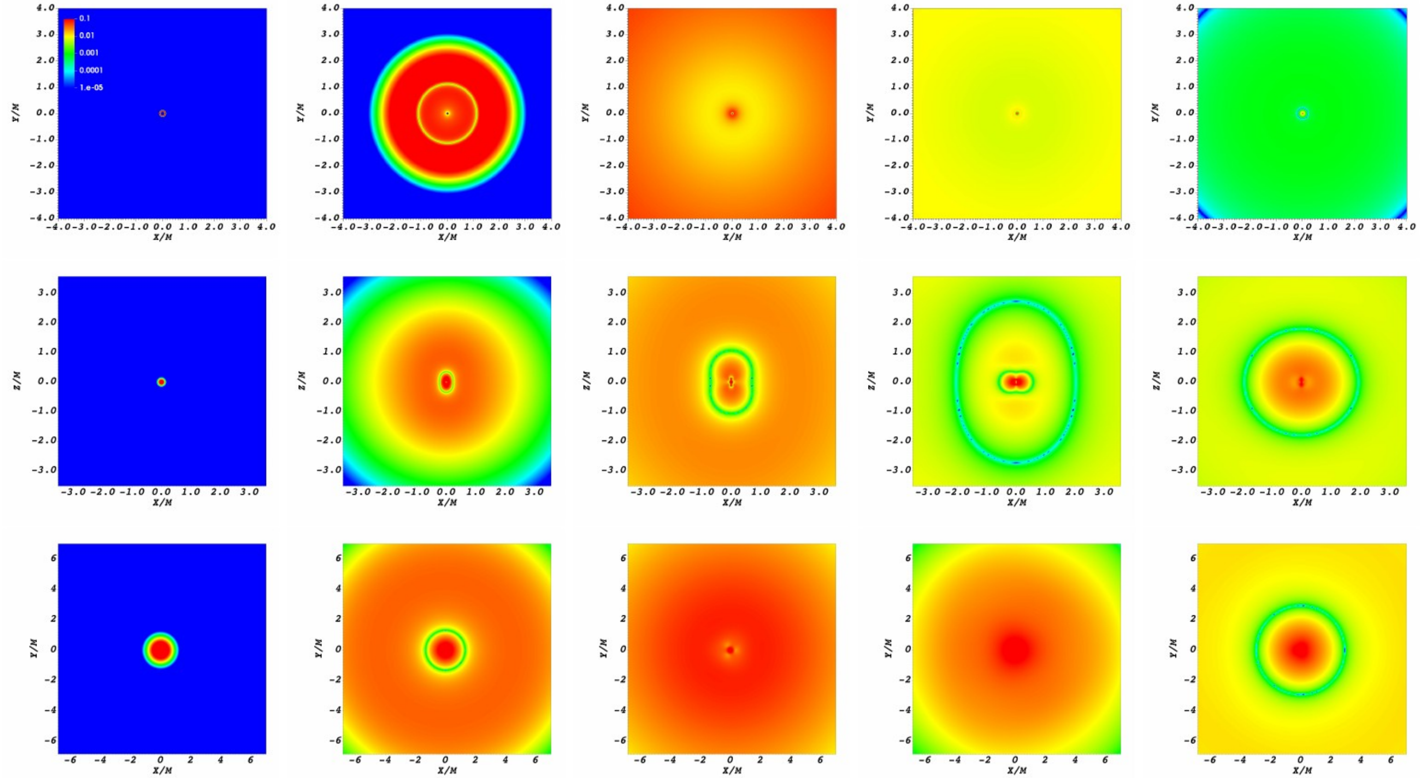
BH microstate spectroscopy

Ikeda+, PRD 2021



Bianchi+ 2020

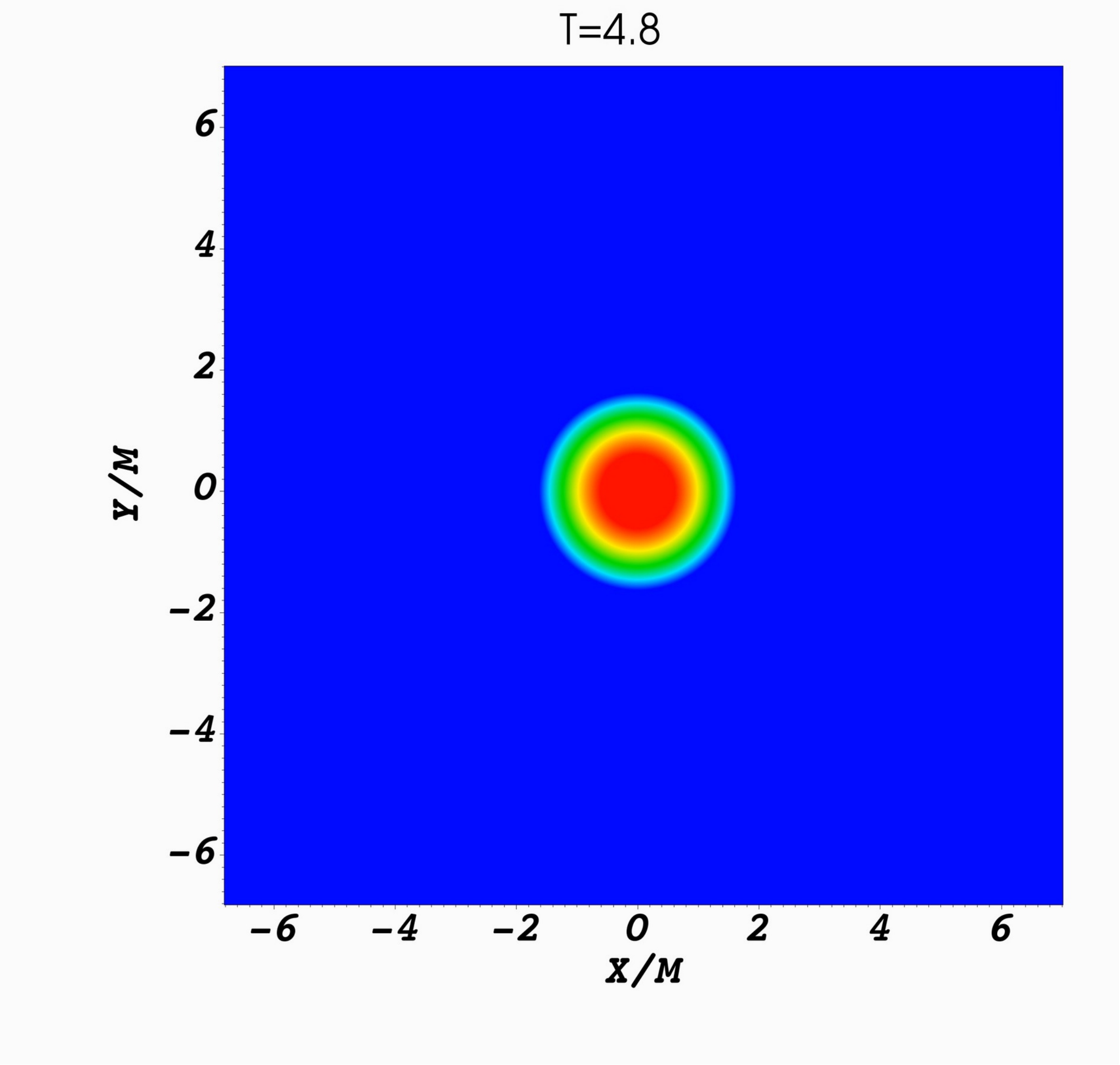
- Background: family of sols to N=2 supergravity [Bena-Warner 2008]
- 3+1 evolution of Klein-Gordon equation on generic microstate
- No spatial isometries in general



- Qualitatively similar results also for neutral topological solitons [Heidmann+ 2023; Bianchi-Di Russo 2023]

BH microstate spectroscopy

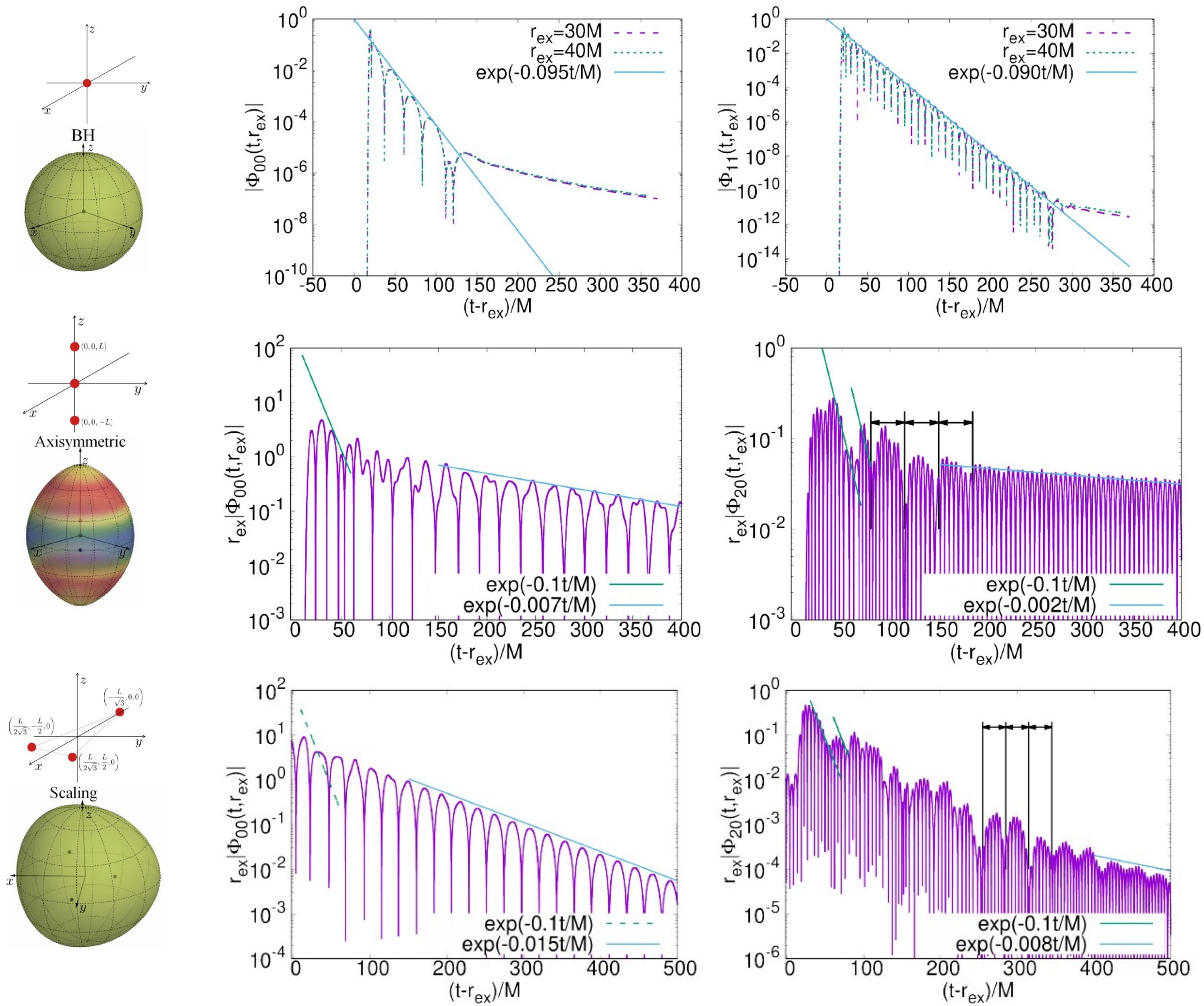
Ikeda+, PRD 2021



Movies @ https://web.uniroma1.it/gmunu/fuzzballs-multipole-moments-and-ringdown

BH microstate spectroscopy

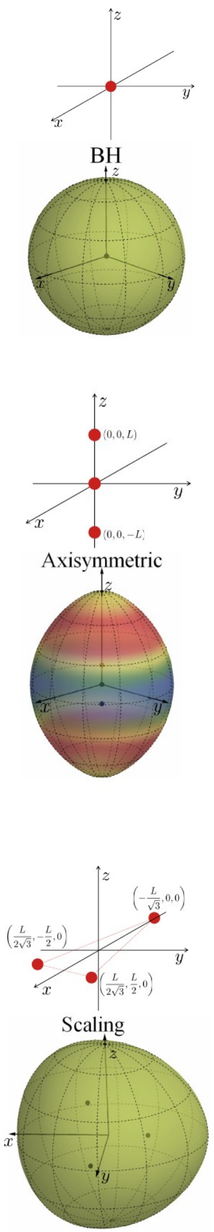
Ikeda+, PRD 2021

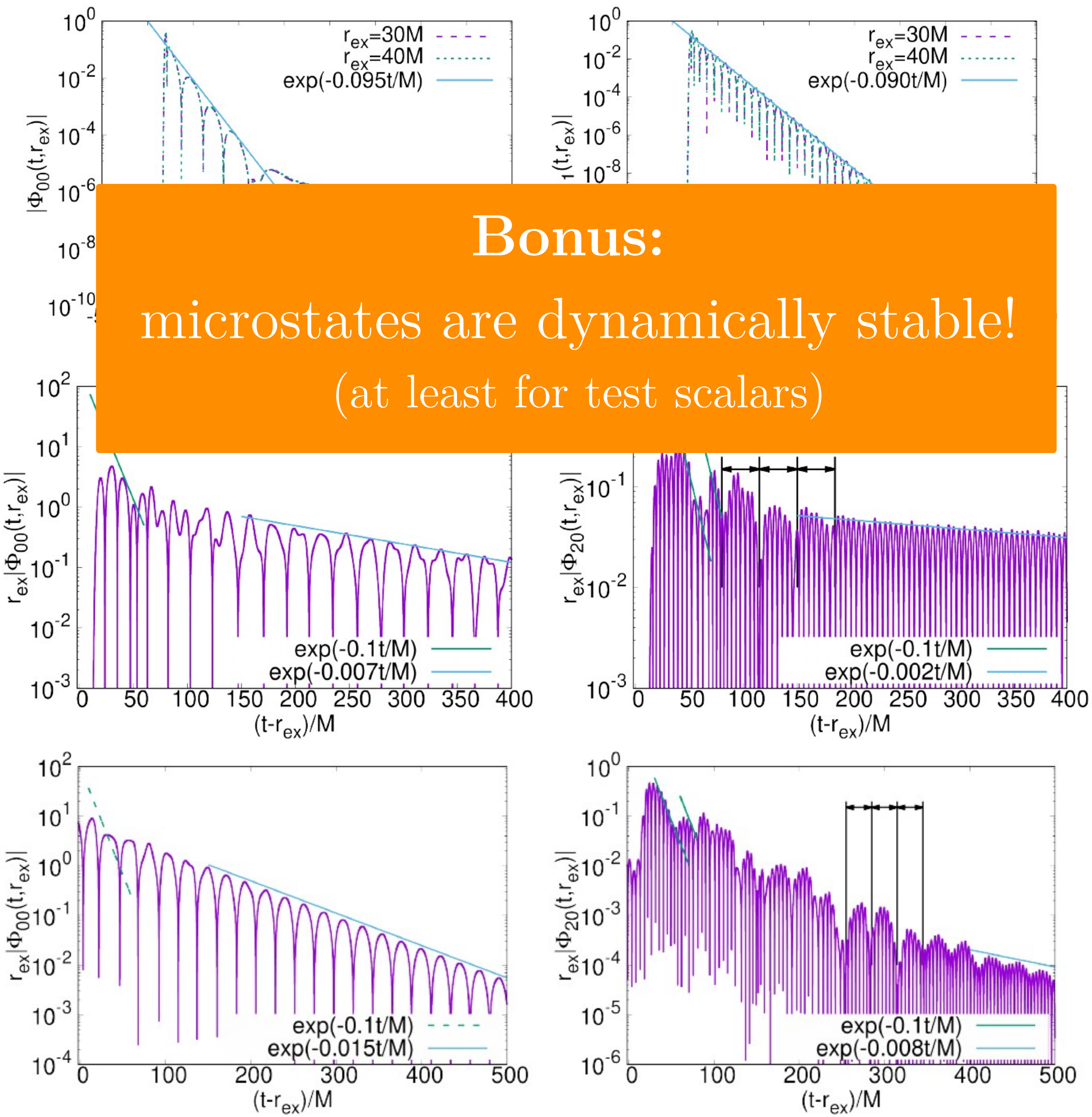


Overall structure qualitatively clear but mode mixing complicates the signal

BH microstate spectroscopy

Ikeda+, PRD 2021





Bonus:

microstates are dynamically stable!

(at least for test scalars)

Overall structure qualitatively clear but mode mixing complicates the signal

Conclusion & Outlook

- *Living the BH era*: discovery opportunities for new physics!
- BH microstate phenomenology is now in full blossom
  - consistent quantum gravity model to quantify beyond-BH effects
  - unveiled way more complex/messy phenom than ECO toy models
- BHs are unique: portal to observable quantum gravity effects?
- **If Not Now, When?** (LISA/ET constraints will be unparalleled)
- Long way and open issues before confronting fuzzballs with the data:
  - **Uncharged/non-SUSY** (is an issue? Maybe not... see modified gravity)
  - **Dynamical simulations** (e.g. microstate vs BH dynamical formation)
  - **Measurement problem** (typical vs atypical states, averaging?)

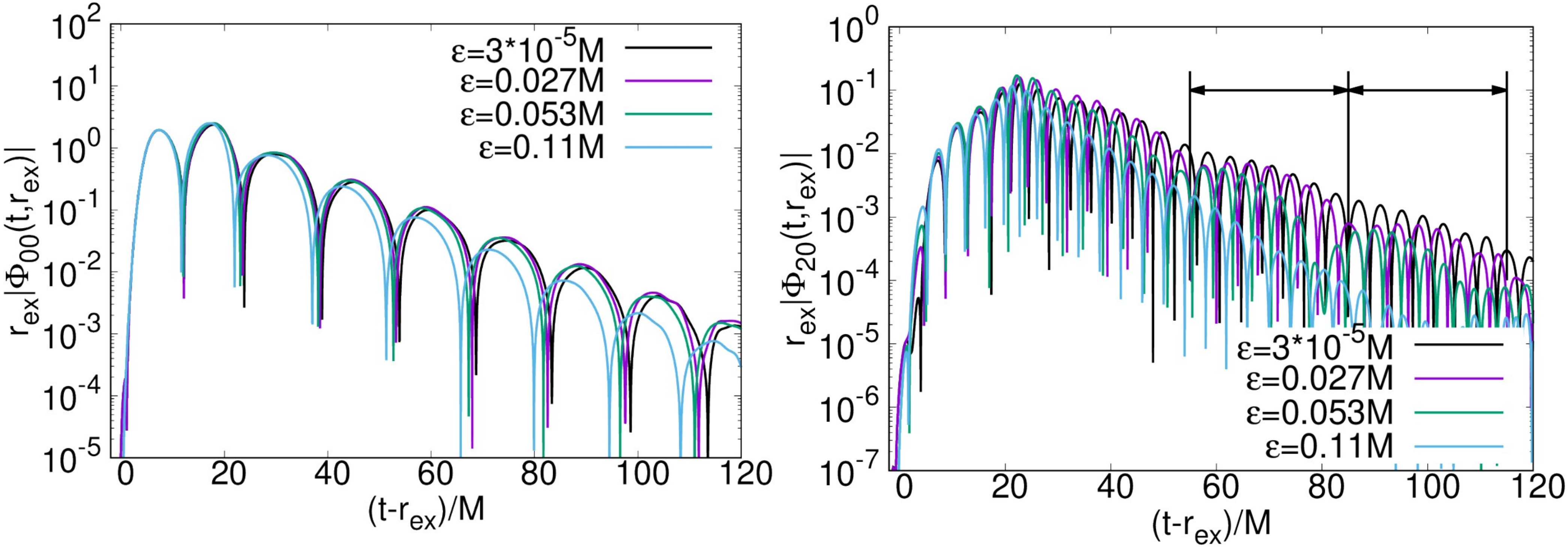
Backup slides

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

Dealing with the singularities

Ikeda+, PRD 2021

$$\frac{1}{|\vec{x}-\vec{x}_a|} \to \frac{\mathrm{erf}(|\vec{x}-\vec{x}_a|/\epsilon)}{|\vec{x}-\vec{x}_a|}$$



- Careful with the resolution and numerical convergence!
- 4D boundary conditions from 5D regularity? (might be hard to implement)
- Numerical simulations in D=5?