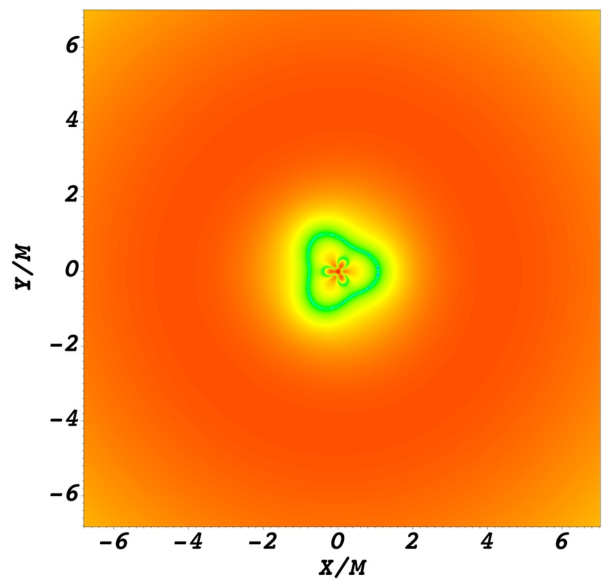
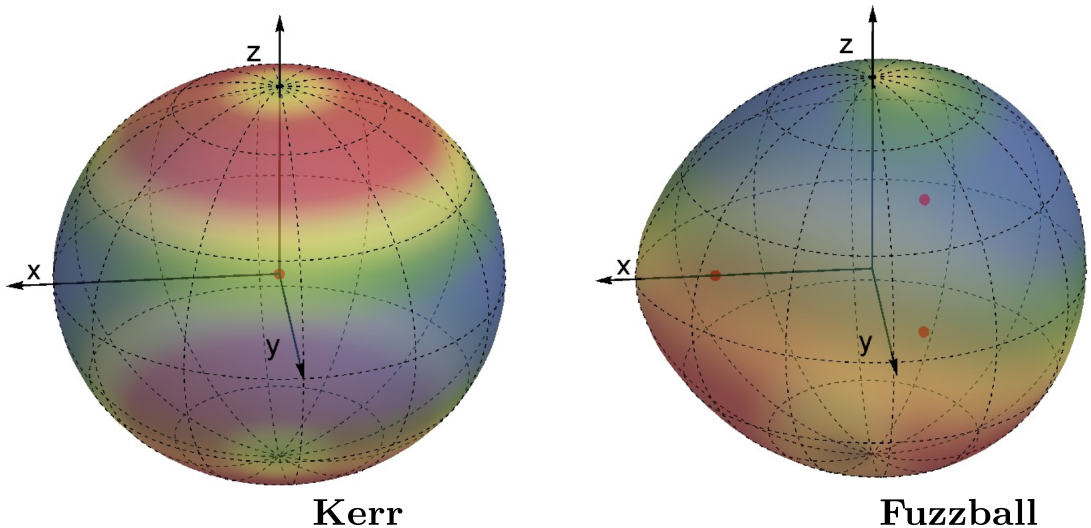
Black Hole Microstates & LISA CONSORTIUM





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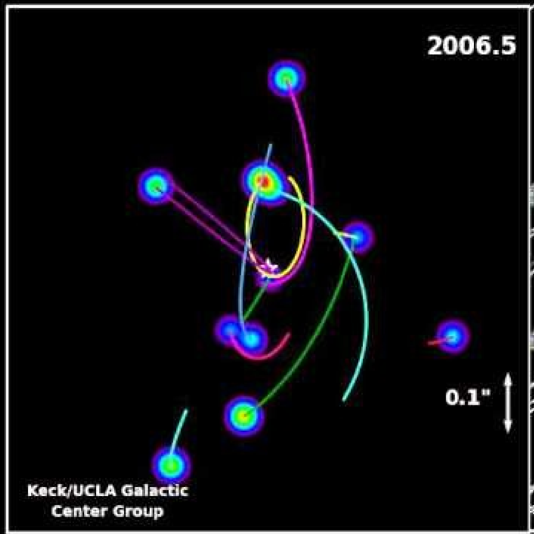
Why did I choose this topic?

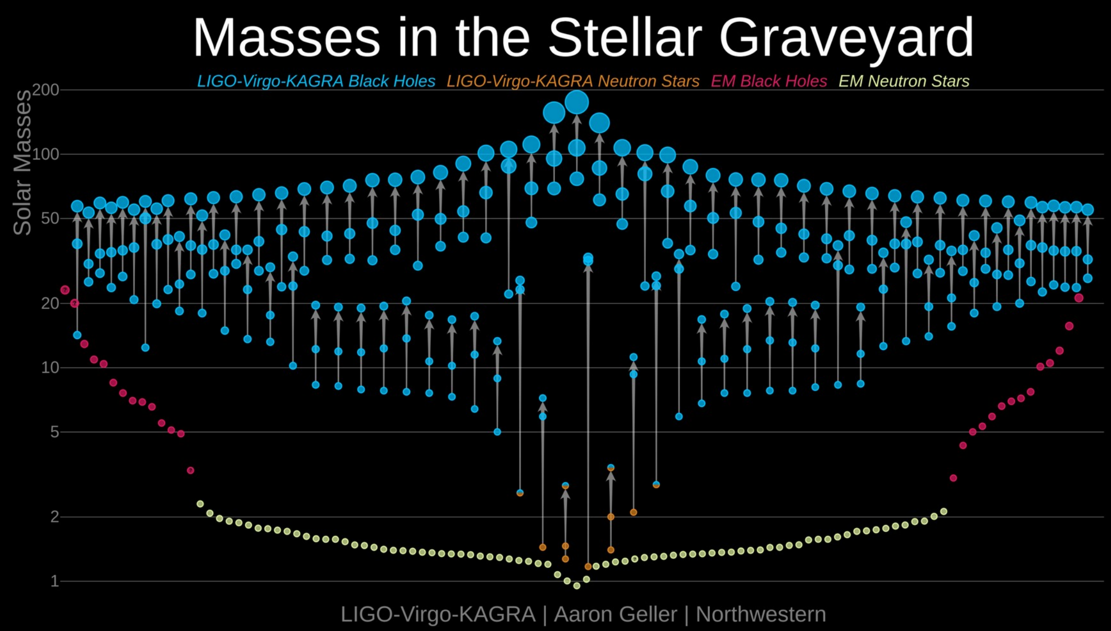
- One of the aims of LISA WGs: connect to other scientific communities

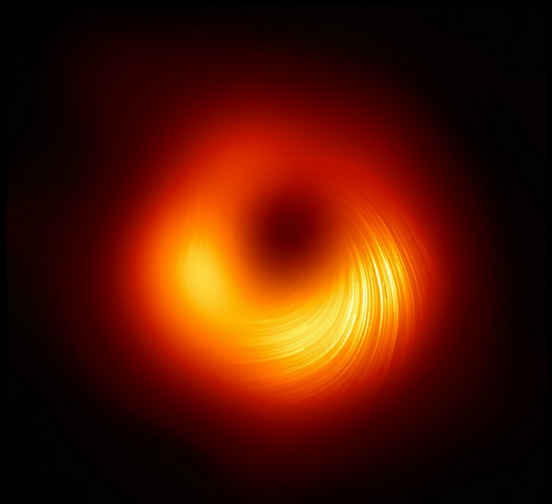
- In many respects complementary to what Carlos Herdeiro just presented

- Lot of progress in the last few years: not totally developed yet, but very promising for the next decade

Black holes are now everywhere!







2017

2020

Why (still) testing the nature of BHs?

Why testing the nature of BHs?

- **Linked to outstanding fundamental physics problems:**
  - **Information loss:** unitarity of BH evaporation inconsistent with locality + "no drama" at the horizon [Hawking, Almheri+ 2013]
  - **Entropy:** Microscopic origin of the huge BH entropy ($\exp[S_{BH}] \sim \exp[G\ M^2]$ states)?
  - **Quantum tunneling:** $\exp[-S_{tunnel}]\ \exp[S_{BH}] \sim 1$ $\rightarrow$ collapsing stars tunnel to quantum-gravity state with O(1) probability [Mathur 2010, Bena+ 2016]
  - **Singularities**, Cauchy horizons, BH interior...
- **New physics ("structure") at the horizon → Observational signatures of quantum BHs?**
- **More conservative / phenomenological motivations:**
  - need concrete models to quantify the "BH-ness" of given sources (e.g. Bayesian model selection)
  - Are there compact objects other than BHs and neutron stars? LIGO/Virgo mass-gap events? Supermassive BH seeds? Dark matter compact objects?
  - 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]

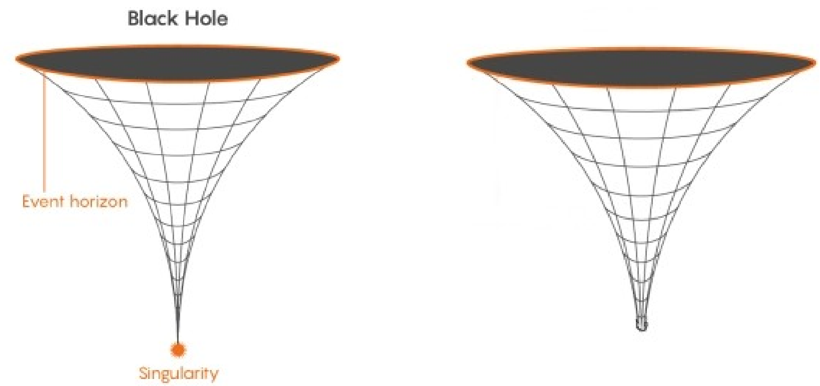
- Tunnelling probability to fuzzball ~ O(1) in specific models
[Bena+ 2016]

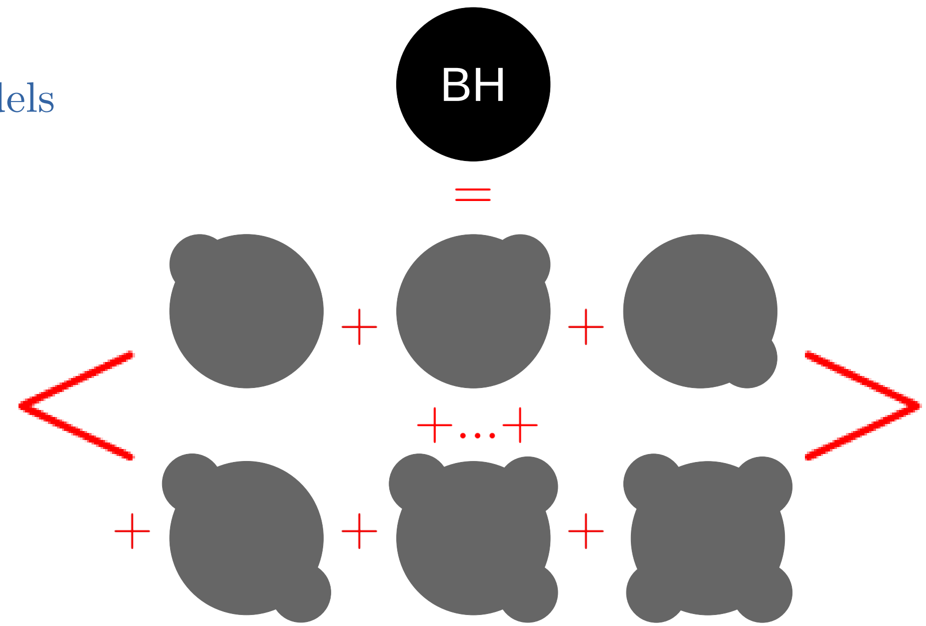
- (Low-energy truncations of) string theory admits huge families of solutions [Bena+ 2007, 2015-2017]

- 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)

- Outlook: measurement problem (typical vs atypical states, averaging?), phenomenology [Mayerson 2020, 2022]





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

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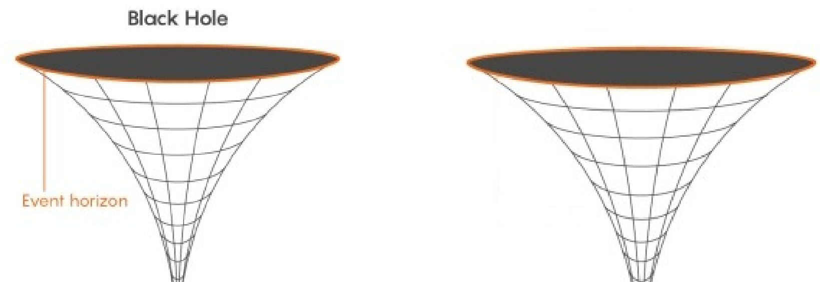

Can we explore the fuzzball picture with LISA?

Can we learn generic lessons on BHs and ECOs?

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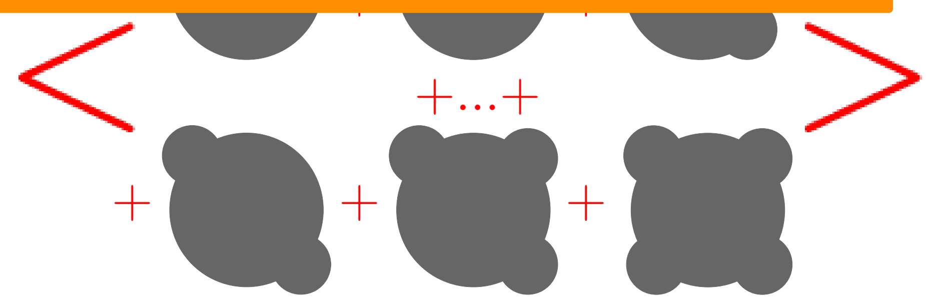
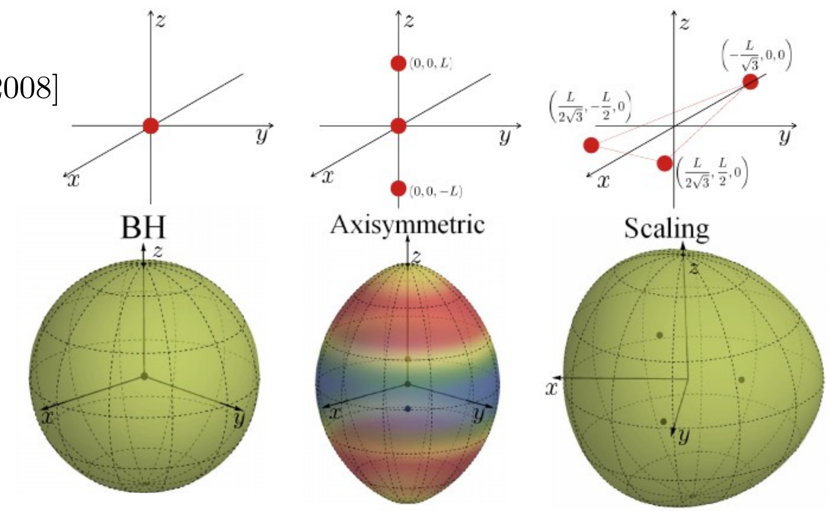


$\sim e^{\frac{M^2}{M_P^2}}$ microstates

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:

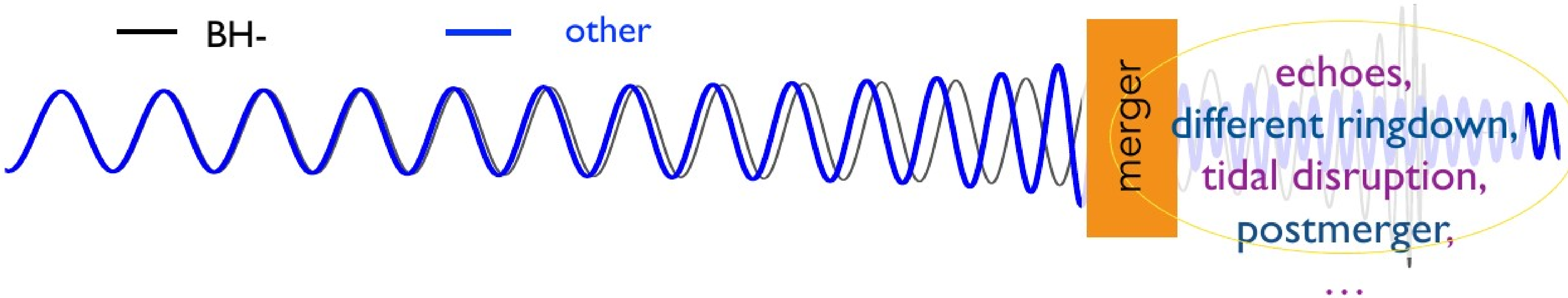
$$V = 1 + \sum_{a=1}^{N}\frac{v_a}{|\vec{x}-\vec{x}_a|}\,, \qquad L_I = 1 + \sum_{a=1}^{N}\frac{\ell_{I,a}}{|\vec{x}-\vec{x}_a|}\,,$$

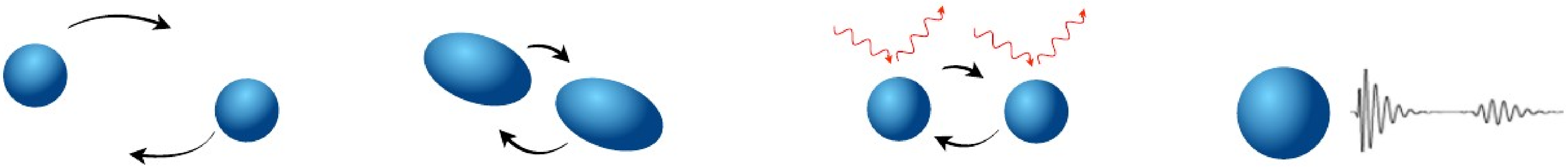
$$K^I = \sum_{a=1}^{N}\frac{k_a^I}{|\vec{x}-\vec{x}_a|}\,, \qquad W = \sum_{a=1}^{N}\frac{m_a}{|\vec{x}-\vec{x}_a|}\,,$$

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

GW-based tests of classical BHs

Slide concept by T. Hinderer + A. Maselli





~point masses: same signal for all objects

Spin measurements

tidal effects

+

multipolar structure

absence of horizon

absorption effects

echoes

+ QNMs

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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- 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 IMR 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?

Post-Newtonian inspiral: BH vs ECO

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

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

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

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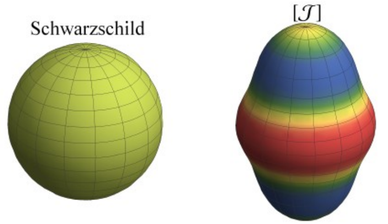
- **2PN:** Point-particle phase depends on **multipole moments** of the bodies
    - Tests of the BH no-hair theorem [Hansen 1974]



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

Mass moments Spin moments

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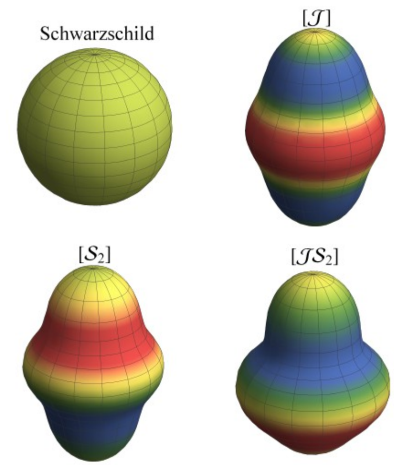
Mass moments — Spin moments



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]

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

(assumes exterior is ~ GR and curvature at $r_0 = r_+(1+\varepsilon)$ is small)

The multipolar structure of ECOs

DarkGRA

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

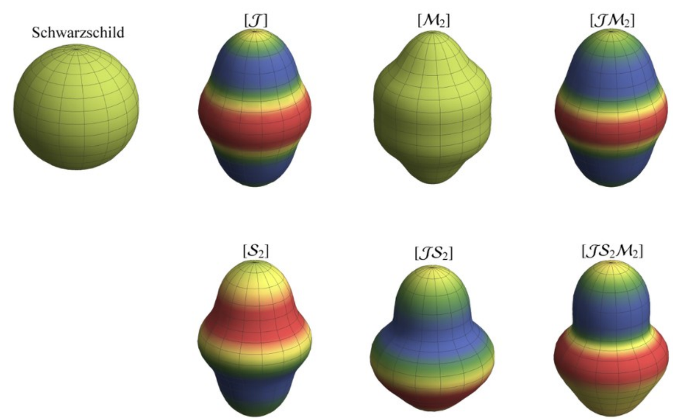
All material is free for use, please make reference to this webpage and to the relevant papers.

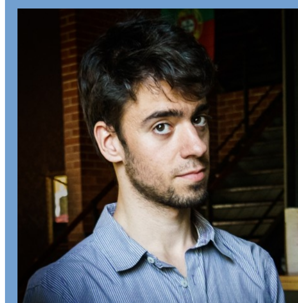
> GW echo catalogue [link to repository]

> 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.





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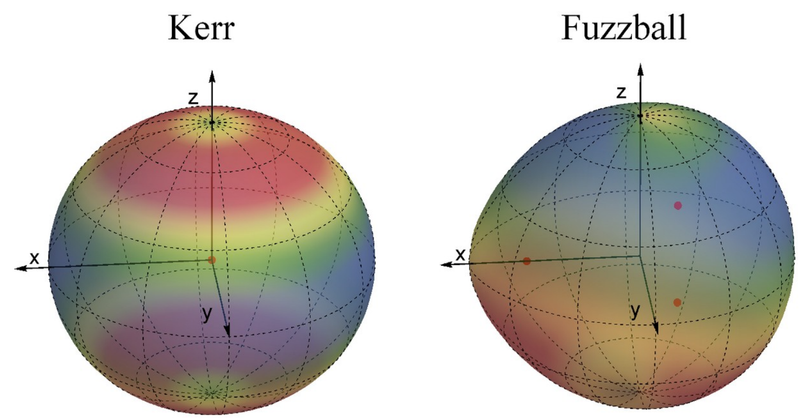
Several families of analytical ECO solutions with soft hair available @ **www.darkgra.org**

The multipolar structure of fuzzballs

- Stationary ECOs can break: [fuzzballs: Bena+ 2020-2021; 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 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]

See R. Brito's talk

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 $\sim$ absent for ECOs $\to$ how about fuzzballs?
  - Small even for 3G for q~1 $\to$ 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]
  - Love $\neq$ 0 for ECOs and BHs in modified gravity [Porto+ Fortsch. Phys. 2016, Cardoso+, PRD 2017]
  - LISA able to distinguish BHs from *any* boson star model [Cardoso+, PRD 2017, Pacilio+ PRD 2021]
  - In several ECO models (including fuzzballs [Bena+, in prep.]) Love scales logarithmically $\rightarrow$ strong constraints with LISA [Maselli+, PRL 2018, CQG 2019; Addazi+ PRL 2019]

Post-Newtonian inspiral: BH vs ECO

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

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

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Beyond-BH tests w. EMRIs/IMRIs

- EMRIs are unique probes of *both* multipolar structure and dynamics

- Non-BH corrections are amplified for small mass-ratio:

  - Spin-induced multipole moments $\rightarrow$ $\delta\bar{M}_2 \sim 10^{-4}$ [Barack-Cutler, PRD 2007, Babak+ 2017]

  - Equatorial symmetry breaking $\rightarrow$ $\delta\bar{S}_2 \sim 10^{-2}$ [Fransen-Mayerson 2022]

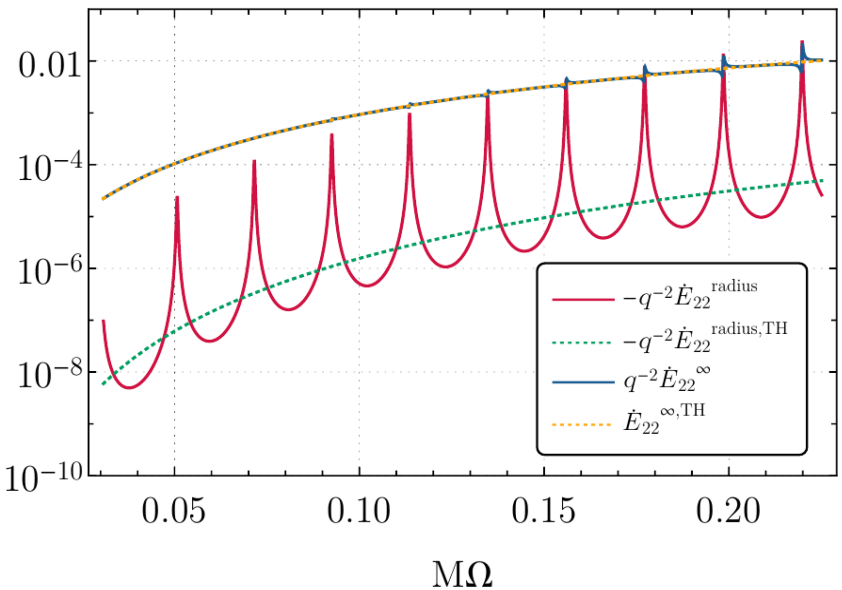
  - Tidal heating $\rightarrow$ $|\mathcal{R}|^2 \lesssim 10^{-8}$ [Datta+ PRD 2020, Maggio+ PRD 2021]

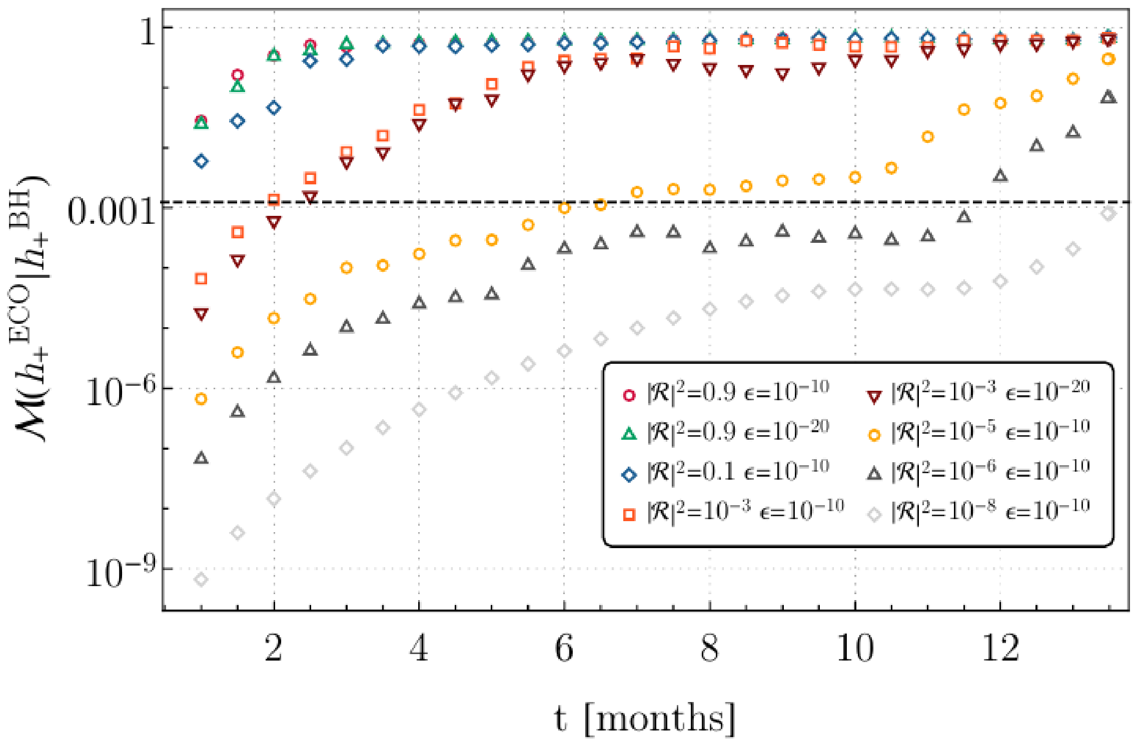
  - Tidal Love numbers $\rightarrow$ $\bar{\Lambda} \sim 10^{-5}$ [Pani-Maselli 2019, Piovano+ in progress]

  - 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+, PRD-PLB 2020, PRD 2021]

- ECO tests with EMRIs/IMRIs $\rightarrow$ many challenges in modeling, parameter estimation, rates, etc... $\rightarrow$ careful with simplistic projected bounds!

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
- However: careful with time scales and “greenhouse” effect [Cardoso-Duque, 2204.05315]

BH microstate ringdown

BH spectroscopy

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

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

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

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

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

  - Extra modes (e.g., polarizations, matter modes) → amplitudes?
  - Isospectrality breaking (probably subdominant, resolvable?)

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- **LIGO/Virgo:** some events where the dominant QNM has been measured, hints of secondary modes in GW150914 and GW190521?

- **LISA:** O(1-100) events/yr allowing for BH spectroscopy at 1-10% level for 3+ QNM quantities [Bhagwat+ PRD 2022]

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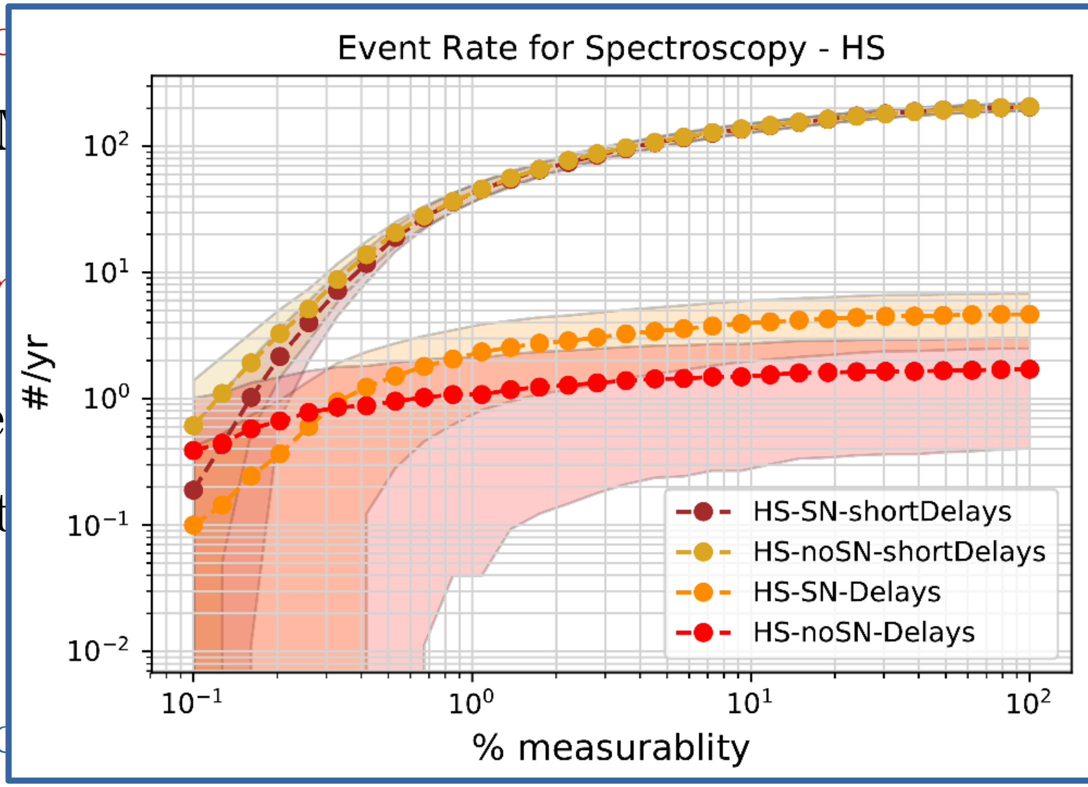
ω_{lm} ... ew)

  - Extra mode ... mplitudes?
  - Isospectralit ... vable?)

- **LIGO/Virgo:** ... as been measured, hints o ... W190521?



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QNMs: BHs vs Rest of the World

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

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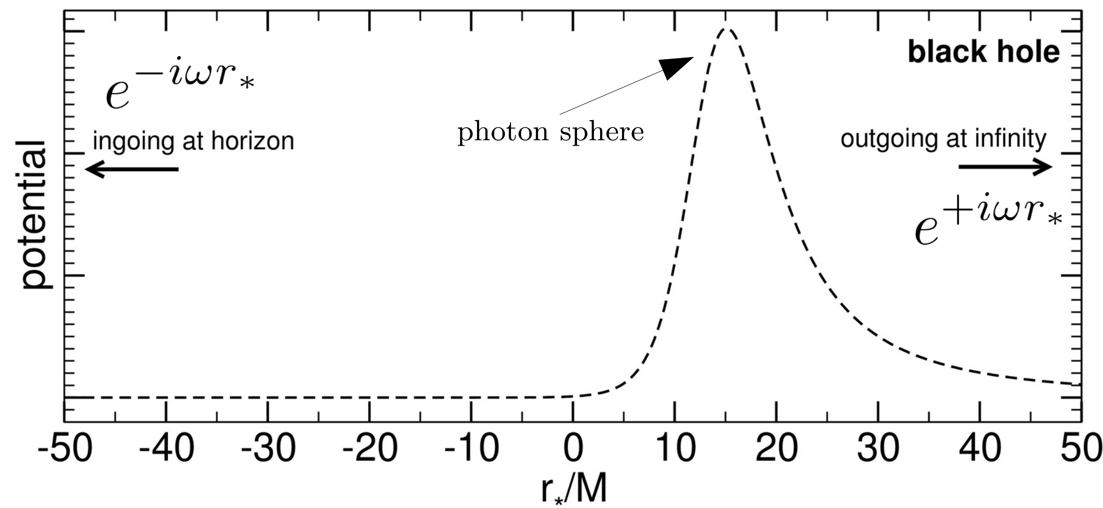

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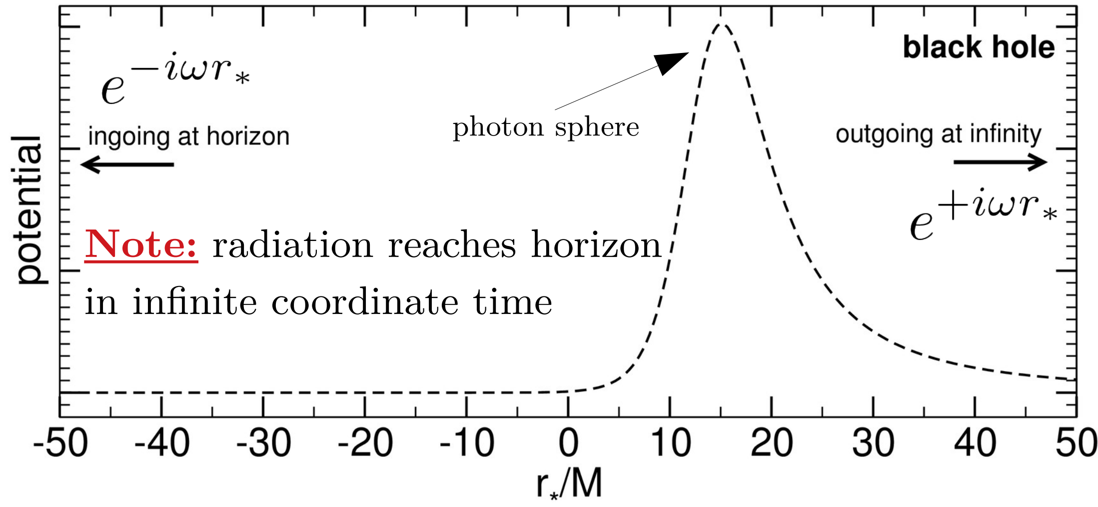

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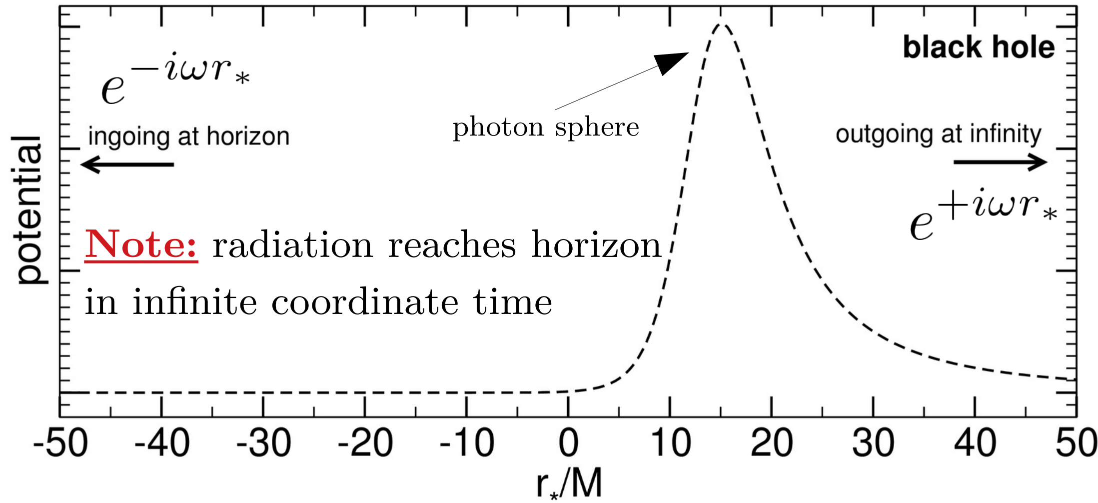

Only (classical) BHs absorb everything!

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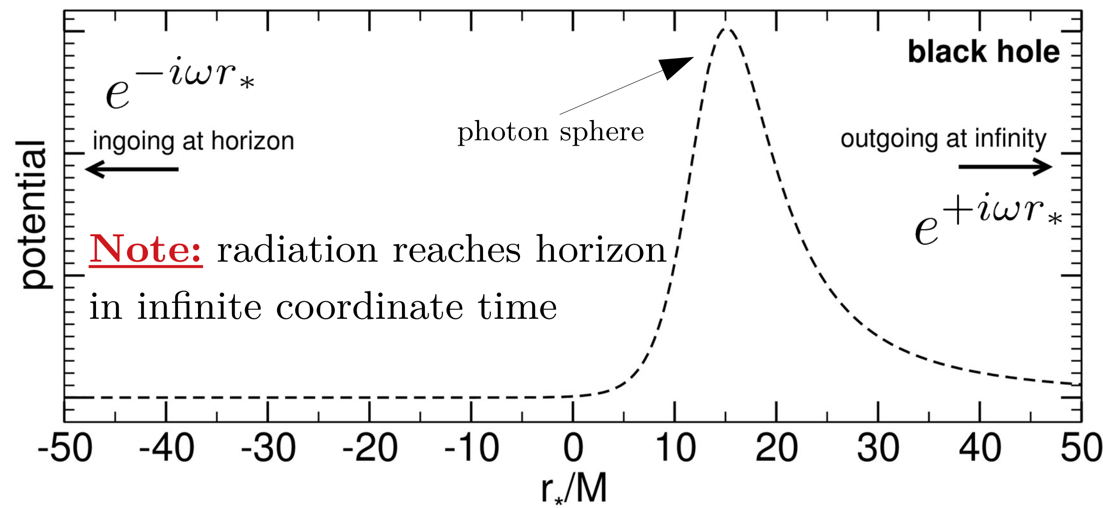
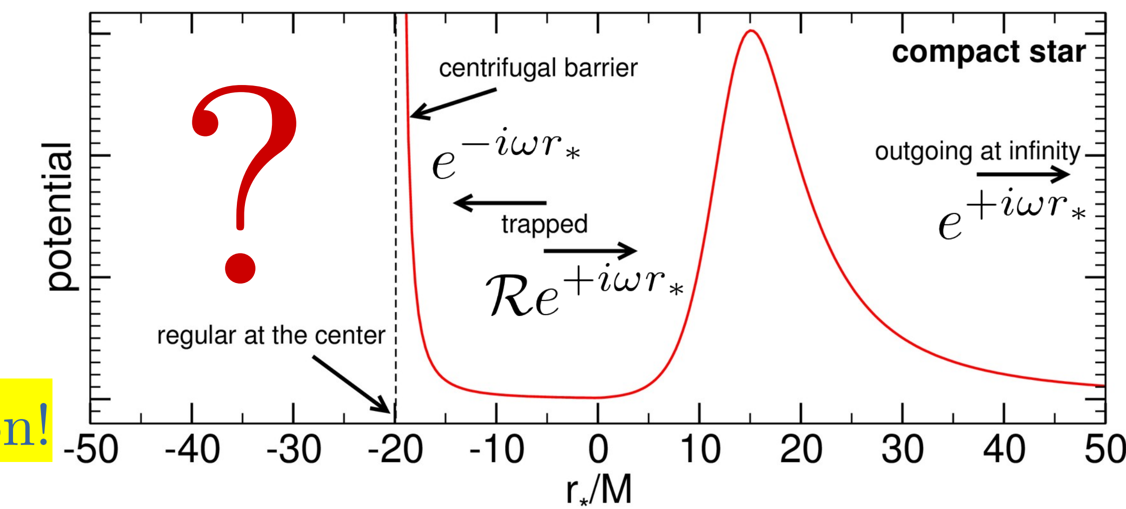


Only (classical) BHs absorb everything!

- 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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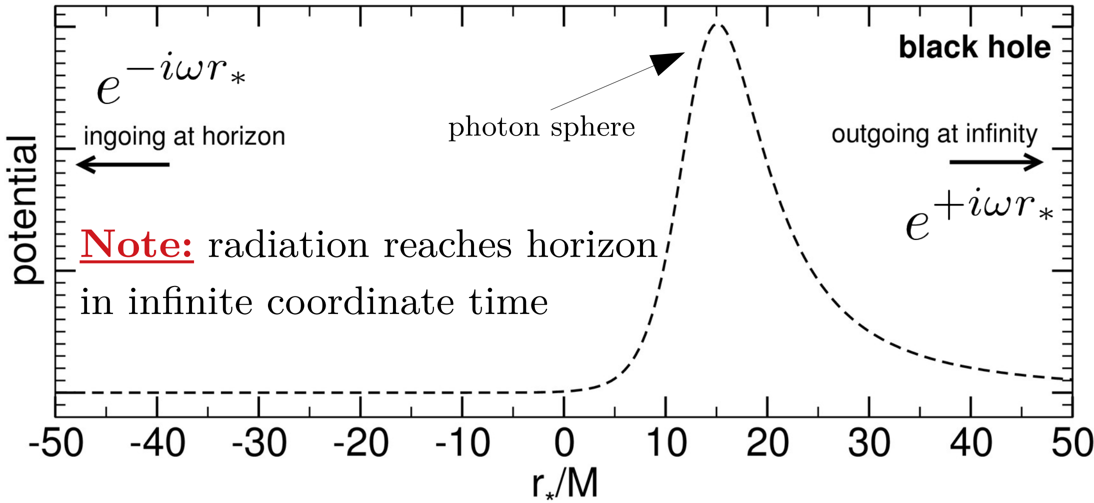
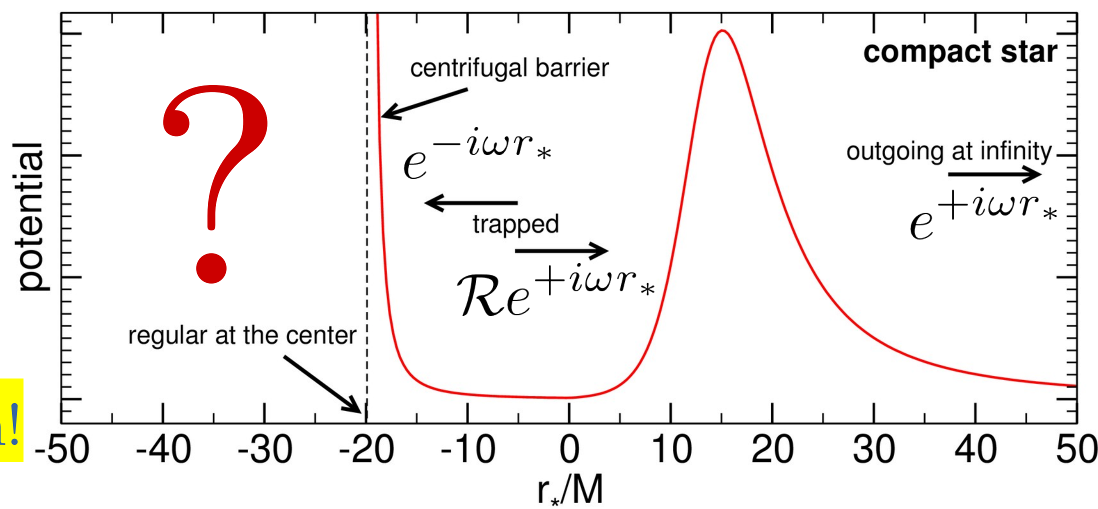


Only (classical) BHs absorb everything!

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

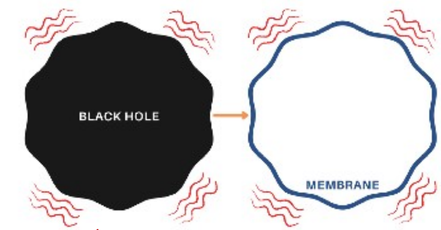


No horizon $\rightarrow$ different ringdown

QNMs: boundaries & metric

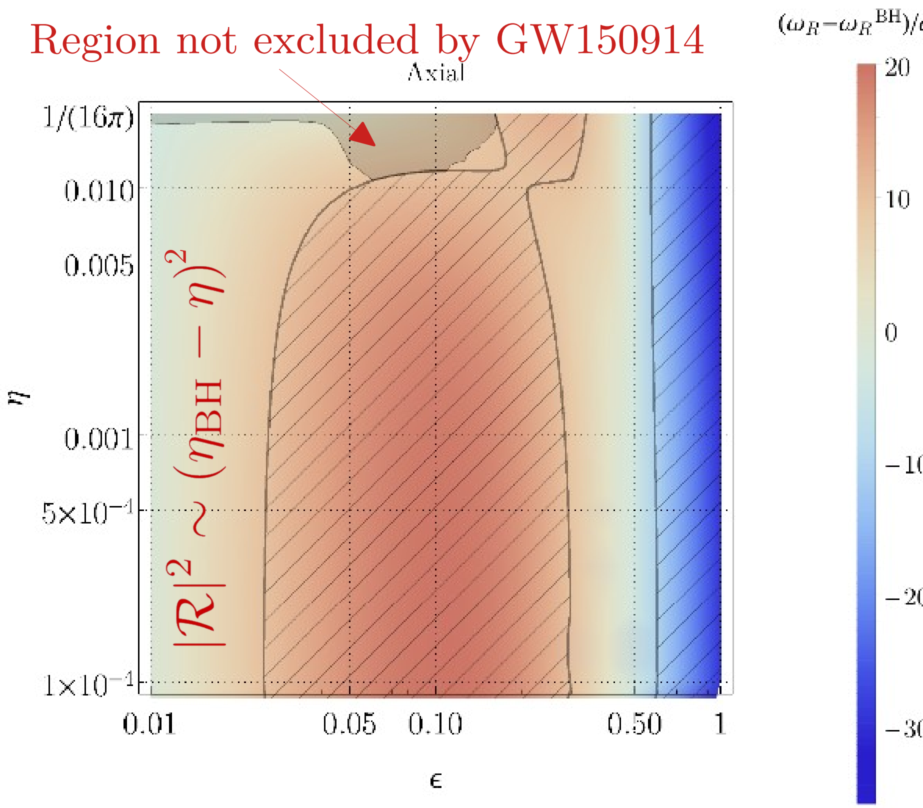
[Oshita+ 2019, Maggio+ PRD 2020]

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

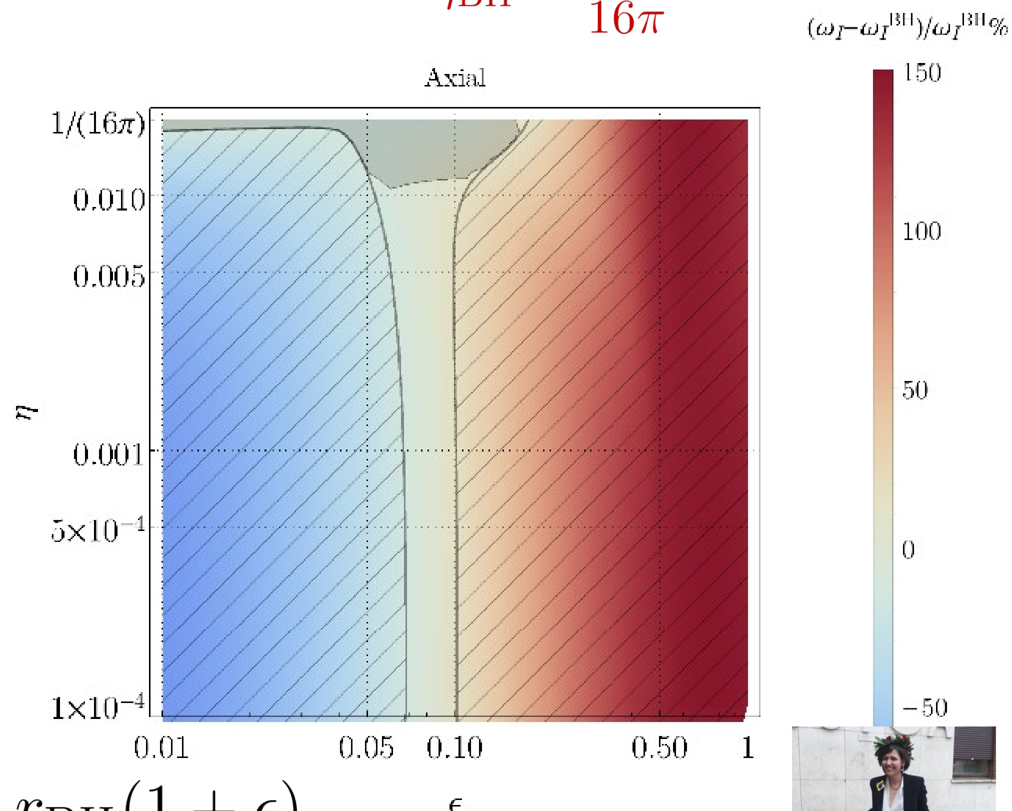


$$\eta_{\rm BH} = \frac{1}{16\pi}$$

Region not excluded by GW150914



$$r_0 = r_{\rm BH}(1+\epsilon)$$



Credits:
Elisa Maggio

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

QNMs: boundaries & metric

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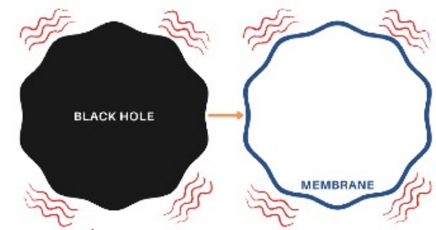

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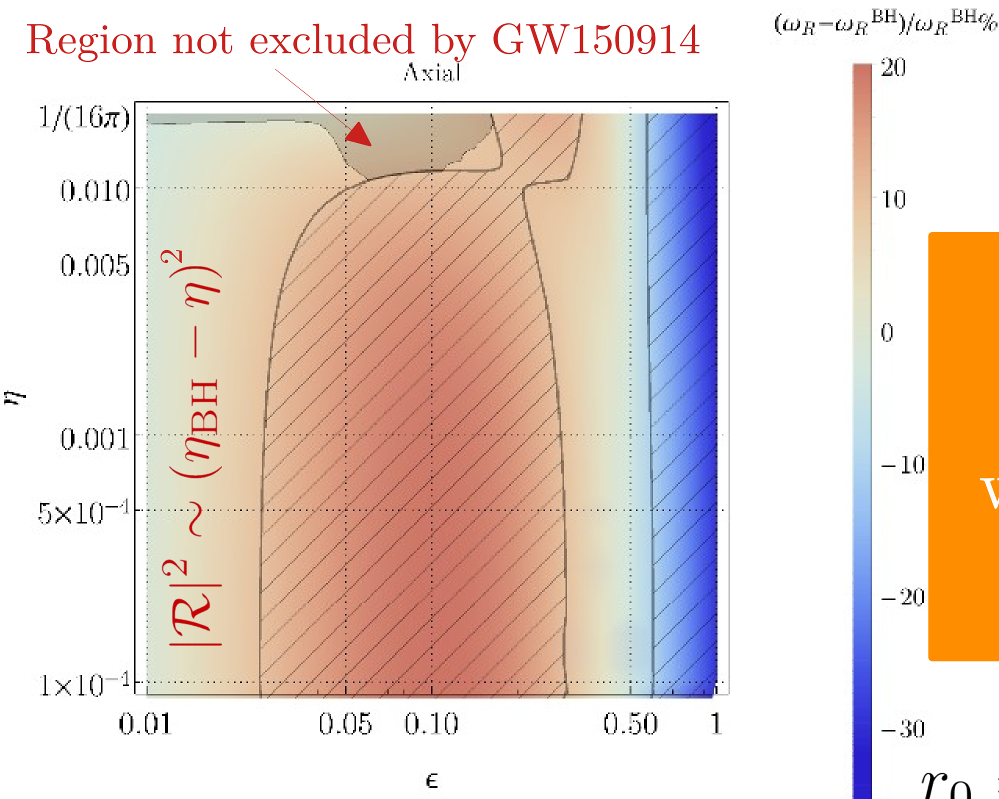
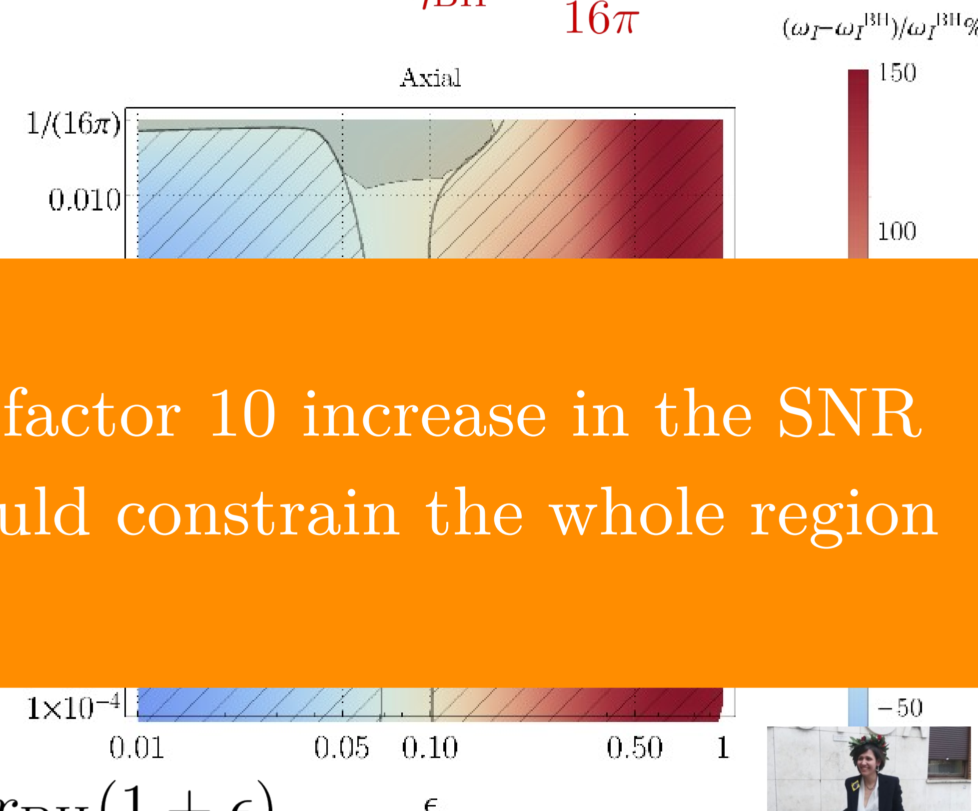


$|\mathcal{R}|^2 \sim (\eta_{\rm BH} - \eta)^2$



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

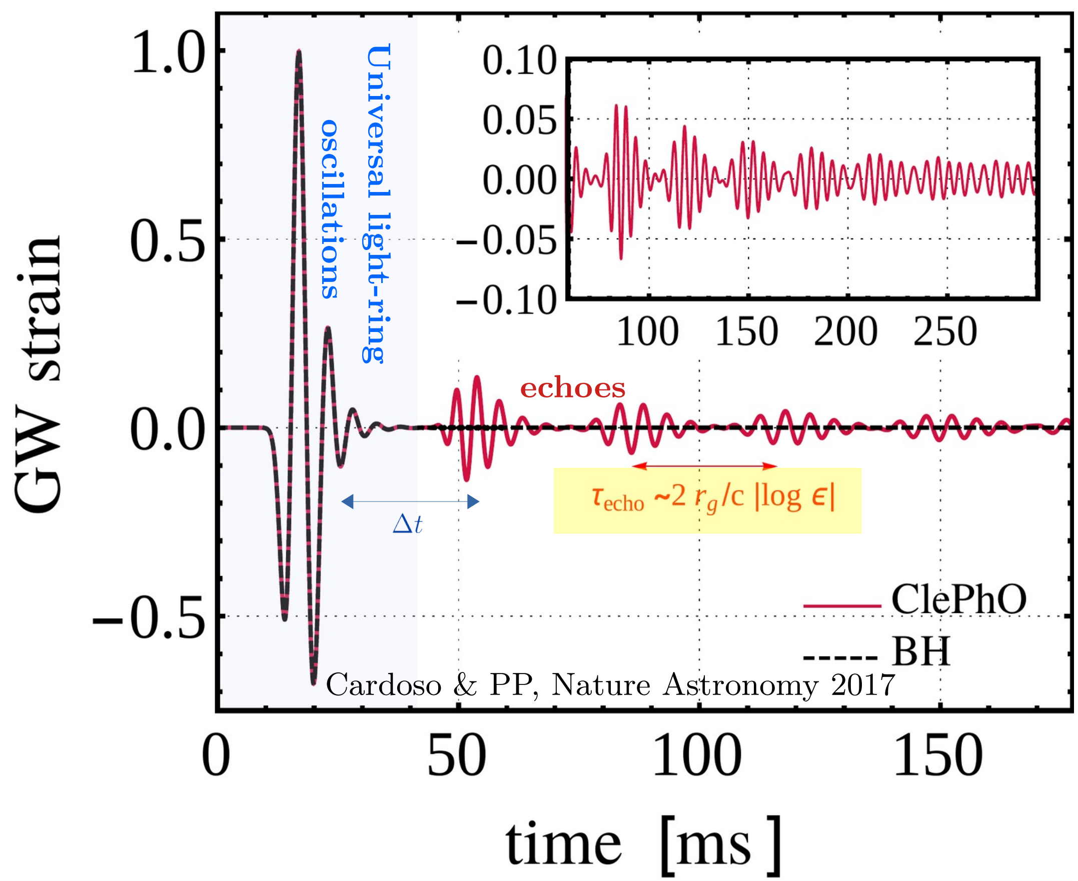
$$r_0 = r_{\rm BH}(1+\epsilon)$$

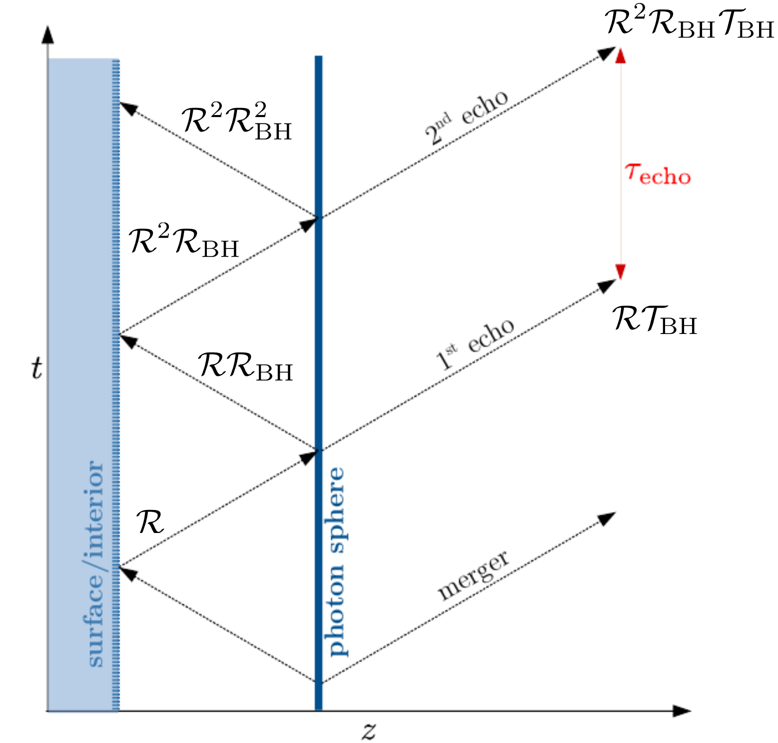
- Axial and polar modes are not isospectral but harder to resolve

Credits:
Elisa Maggio

GW echoes

- For ultracompact objects (ε<0.01) prompt ringdown is identical to BHs but **GW "echoes"** appear at later times [Cardoso+ PRL-PRD 2016...]

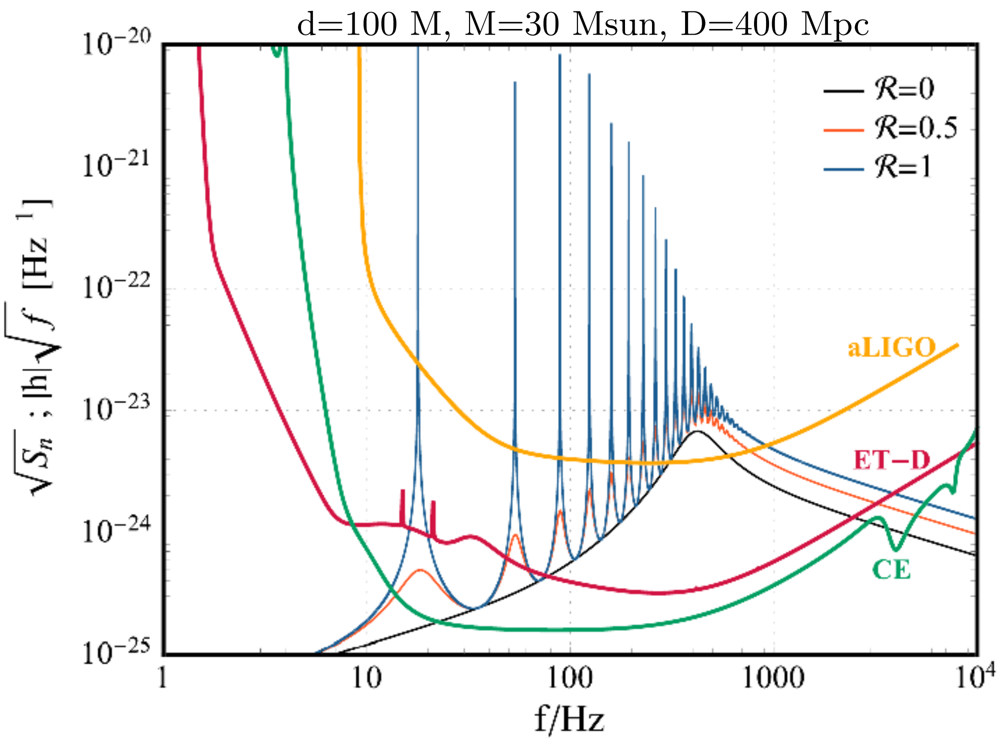




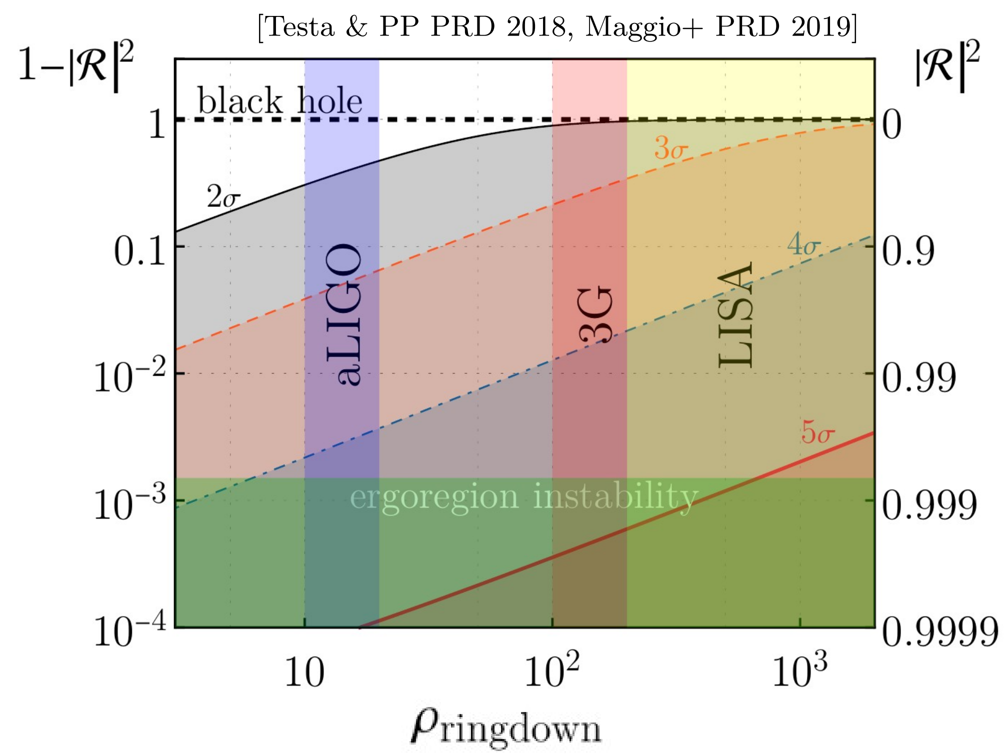
Vilenkin PLB 1978, Mark+ PRD 2017, Abedi+ PRD 2017

- Echo delay time scales logarithmically with compactness
- Echoes would imply either exotic matter or beyond GR [Alho+ 2022; Alho+ in progress]

Echo detectability



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



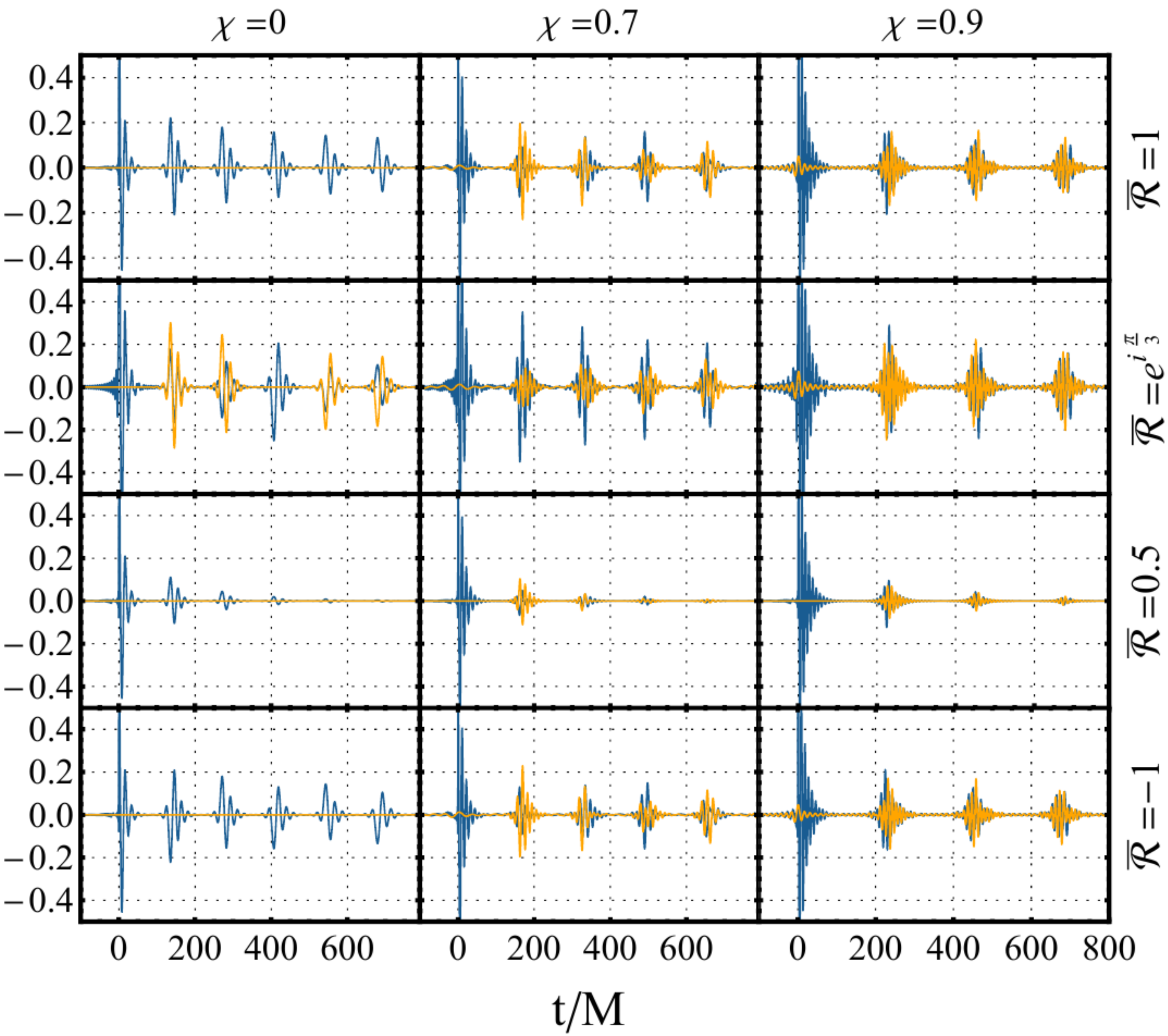
- Contrasting results with LIGO data [Abedi+, 2017/18, Conklin+ 2018/19, Ashton+ 2017, Westerweck+ 2018]

but no statistical evidence in LVKC searches [Uchikata+ 2019, Tsang+ 2019, GWTC-3 2021]

- Recent “measurement” claims in GW190521 [Abedi+ 2022]
- Near-horizon corrections are within reach! Echo search pipelines now routine in LVKC
  - LIGO/Virgo can probe only large reflectivity, much better prospects with LISA!
- Lot of progress on echo waveform modeling, pipelines, and searches [Abedi+, Universe (2020)]

GW echo slideshow

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



Coherent, analytical template in the FD:

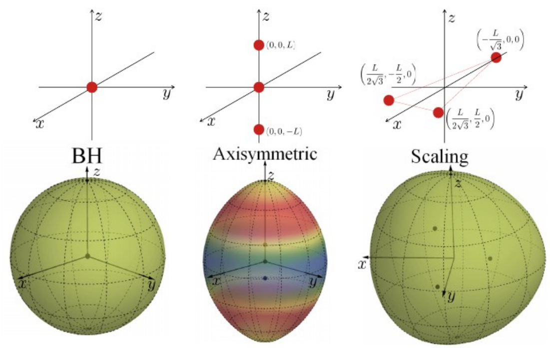
- complex reflectivity
- mixing of polarizations
- spin-dependent modulation
- This complexity absent in current searches

..and still a toy model!

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

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

4D ansatz:

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

$$e^{-4U} = Z_1 Z_2 Z_3 V - \mu^2 V^2\,,$$

$$*_3 d\omega = \tfrac{1}{2}\left(V dW - W dV + K^I dL_I - L_I dK^I\right)$$

$$Z_I = L_I + \frac{|\epsilon_{IJK}|}{2}\frac{K^J K^K}{V}\,,$$

$$\mu = \frac{W}{2} + \frac{L_I K^I}{2V} + |\epsilon_{IJK}|\frac{K^I K^J K^K}{6V^2}$$

N centers:

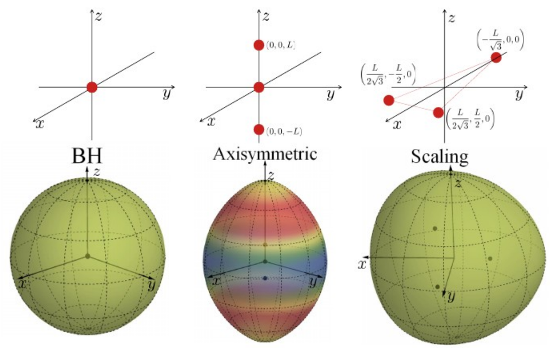
$$V = 1 + \sum_{a=1}^{N} \frac{v_a}{|\vec{x}-\vec{x}_a|}\,, \quad L_I = 1 + \sum_{a=1}^{N} \frac{\ell_{I,a}}{|\vec{x}-\vec{x}_a|}\,,$$

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

- Note: no ergoregion by construction $\rightarrow$ no ergoregion instability
- Works for any stationary 4D geometry (e.g., also non-SUSY, neutral) [Bah+ 2021-2022]

BH microstate spectroscopy

Ikeda+, PRD 2021



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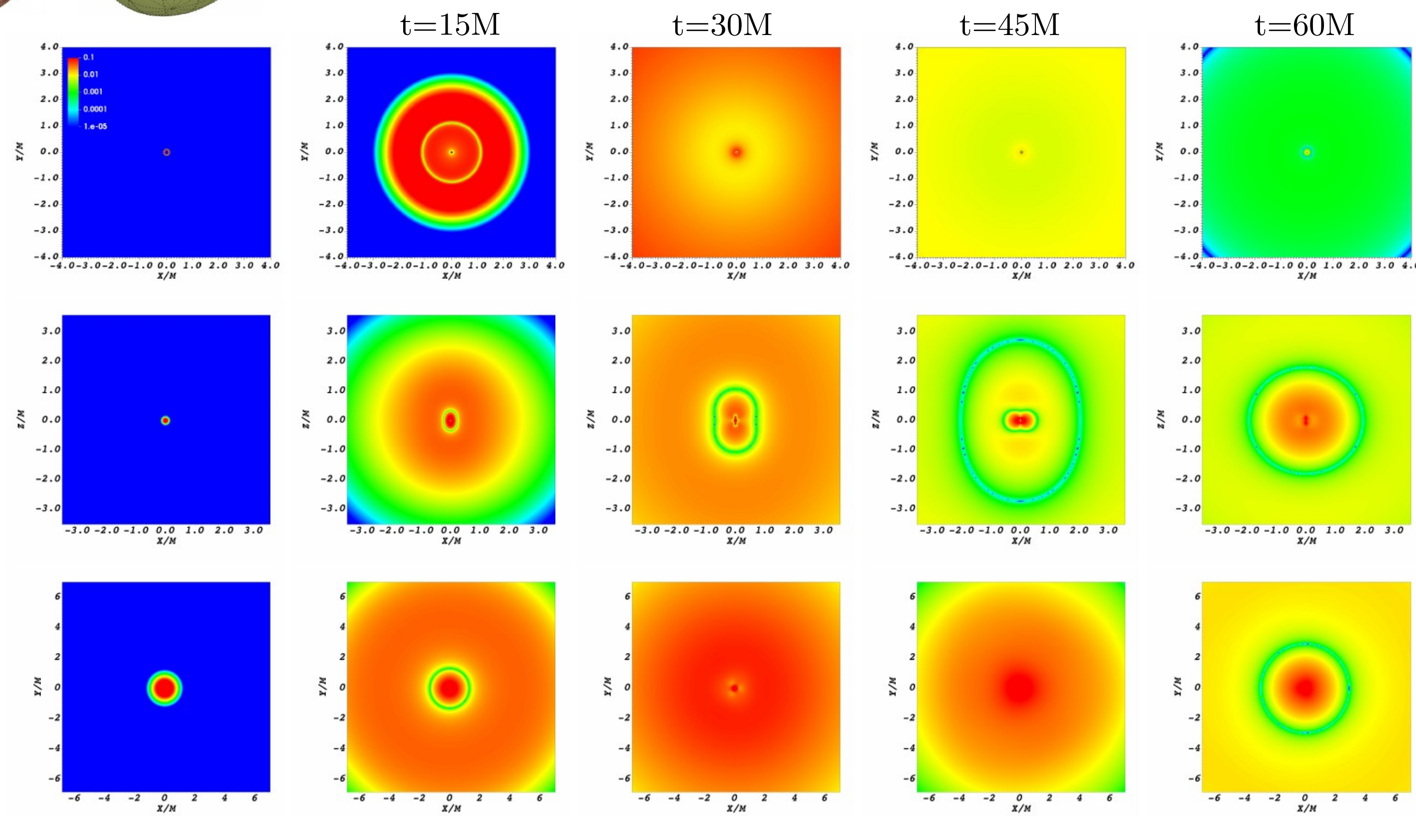
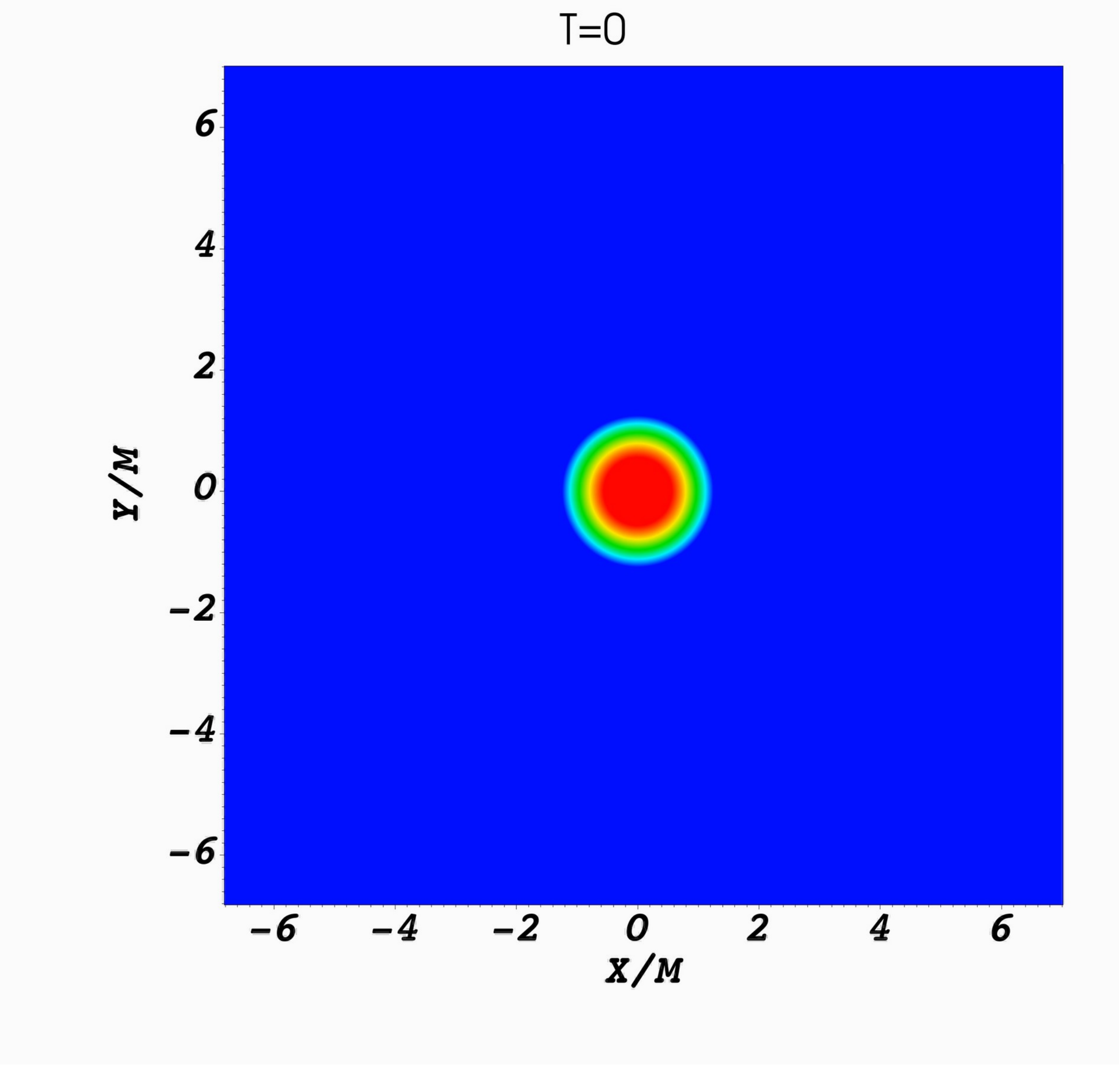


Credits:
Taishi Ikeda

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

BH microstate spectroscopy

Ikeda+, PRD 2021



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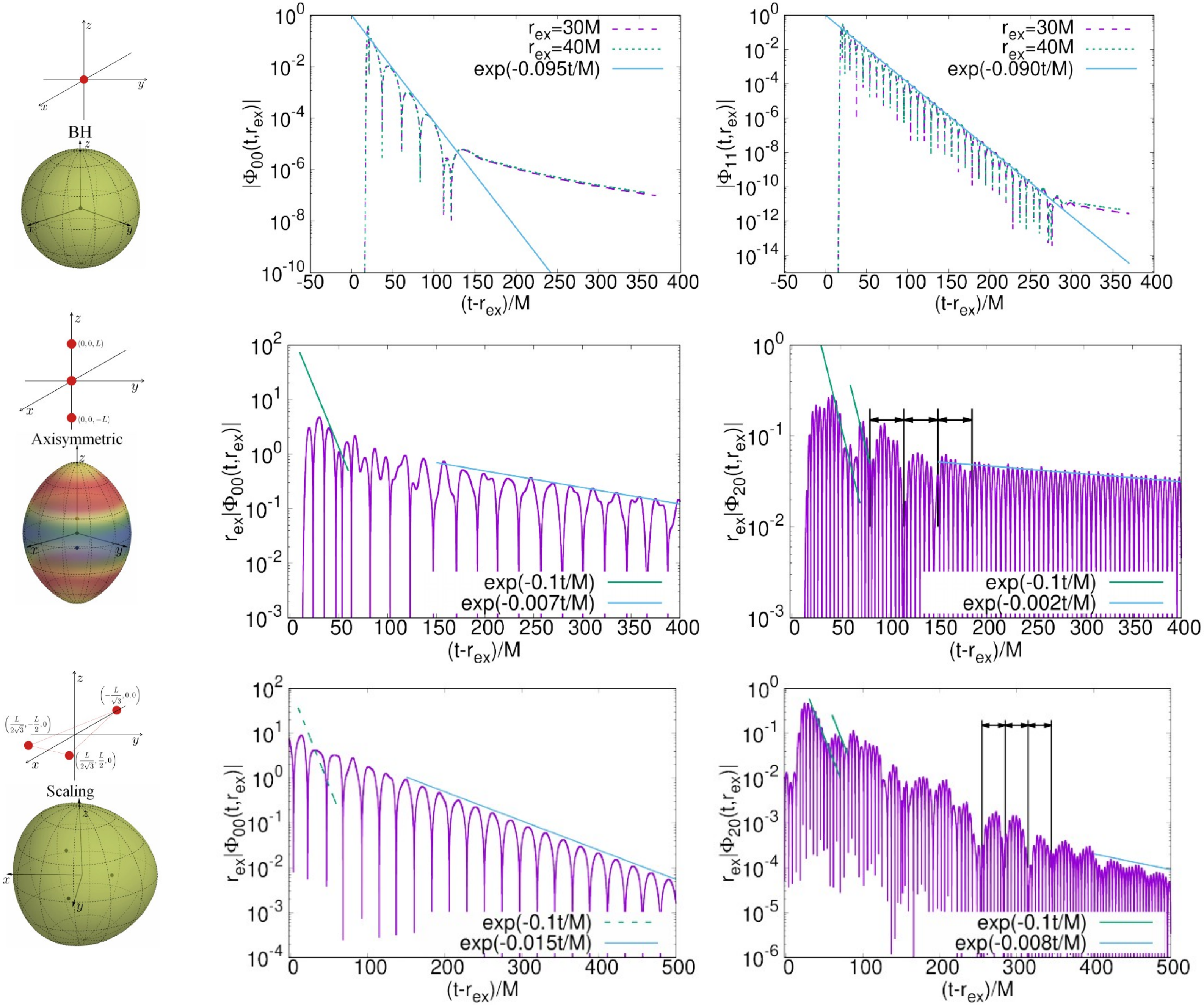
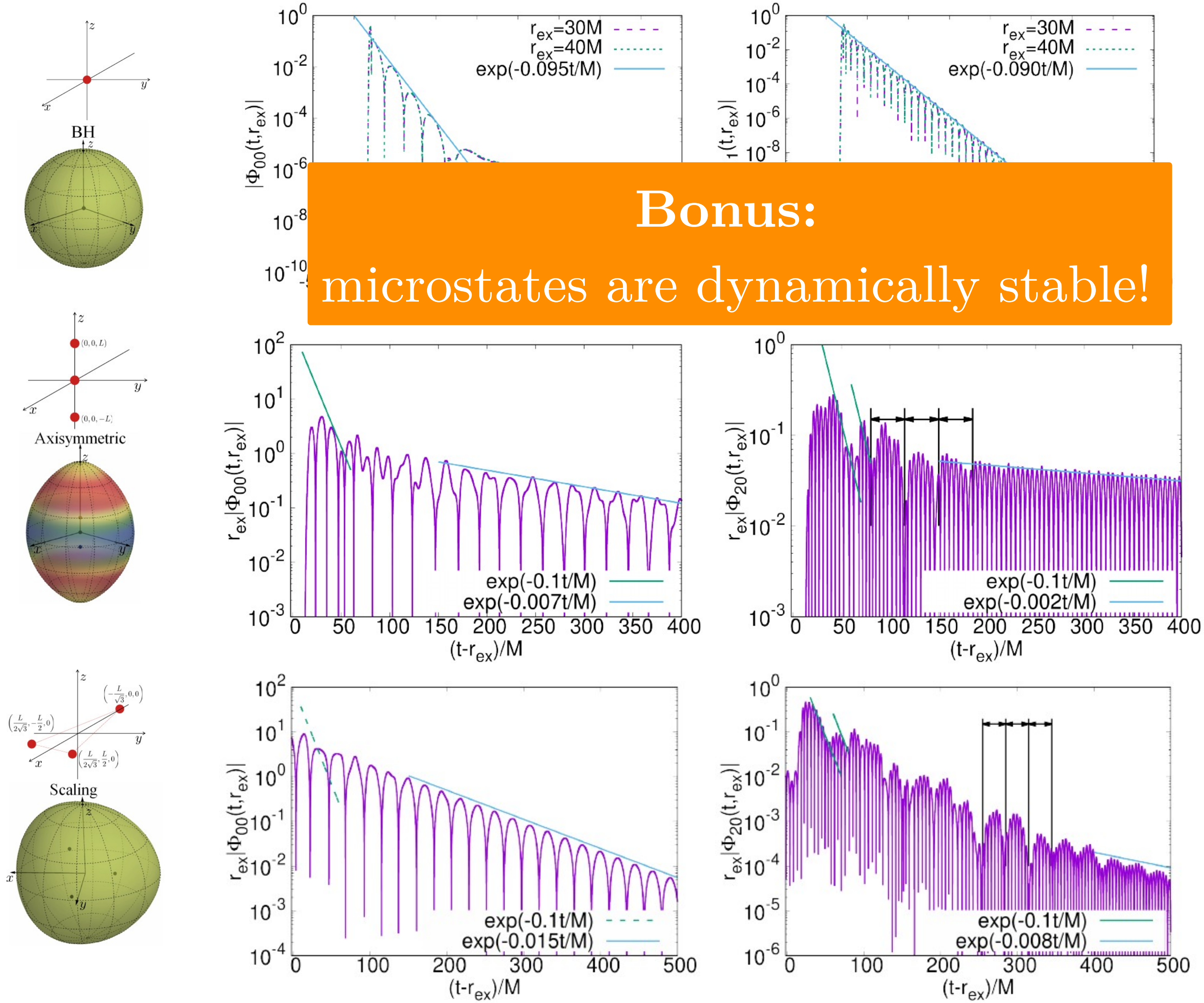
Ikeda+, PRD 2021



Overall structure qualitatively clear but mode mixing complicates the signal

BH microstate spectroscopy

Ikeda+, PRD 2021



Bonus:
microstates are dynamically stable!

Overall structure qualitatively clear but mode mixing complicates the signal

Prompt ringdown: fuzzballs vs BHs

κ	M	L/M	J/M^2	r_+/M	r_-/M	$M\omega^{\rm fuzzball}_{\rm QNM,+}$	$M\omega^{\rm fuzzball}_{\rm QNM,-}$	$M\omega^{\rm BH}_{\rm QNM}$	$\Delta t_+/M$	$\Delta t_-/M$
3	13.75	0.1091	0.0714	0.7314	0.6759	$0.6827 - 0.0767i$	$0.7324 - 0.0878i$	$0.6996 - 0.0871i$	40.7	40.1
4	24.25	0.0508	0.0544	0.7596	0.6490	$0.6860 - 0.0841i$	$0.7372 - 0.0855i$	$0.7083 - 0.0859i$	63.8	62.7
5	37.75	0.0301	0.0439	0.7493	0.6379	$0.6919 - 0.0852i$	$0.7380 - 0.0839i$	$0.7128 - 0.0851i$	84.9	83.7
6	54.25	0.0201	0.0367	0.7378	0.6345	$0.6966 - 0.0854i$	$0.7373 - 0.0831i$	$0.7154 - 0.0847i$	105.1	104.1
7	73.75	0.0144	0.0315	0.7283	0.6343	$0.7001 - 0.0853i$	$0.7362 - 0.0827i$	$0.7170 - 0.0844i$	125.0	124.0
8	96.25	0.0109	0.0276	0.7207	0.6352	$0.7028 - 0.0852i$	$0.7351 - 0.0825i$	$0.7180 - 0.0841i$	144.6	143.7
9	121.75	0.0085	0.0246	0.7146	0.6367	$0.7050 - 0.0851i$	$0.7341 - 0.0825i$	$0.7188 - 0.0840i$	164.0	163.2
10	150.25	0.0069	0.0221	0.7097	0.6383	$0.7067 - 0.0849i$	$0.7332 - 0.0824i$	$0.7193 - 0.0839i$	183.3	182.6
50	3750	0.0003	0.0044	0.6746	0.6593	$0.7188 - 0.0837i$	$0.7244 - 0.0830i$	$0.7216 - 0.0834i$	942.2	942.1
100	15000	0.0001	0.0022	0.6706	0.6629	$0.7103 - 0.0835i$	$0.7231 - 0.0832i$	$0.7217 - 0.0833i$	1887.3	1887.2

Ikeda+, PRD 2021

- If fuzzball sufficiently close to BH $\rightarrow$ prompt ringdown identical!
- Need to search for late-ringdown features $\rightarrow$ high SNR needed!

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/3G 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?)

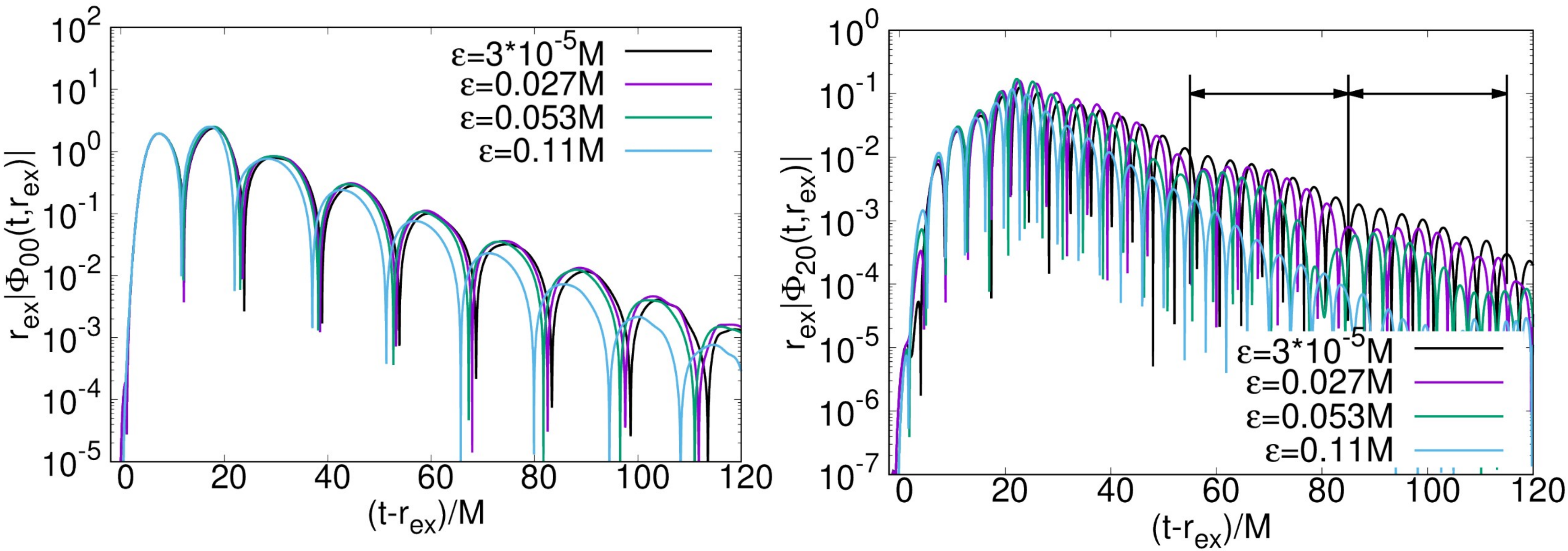
Backup slides

“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?