Echoes from the Black Hole Microstructure

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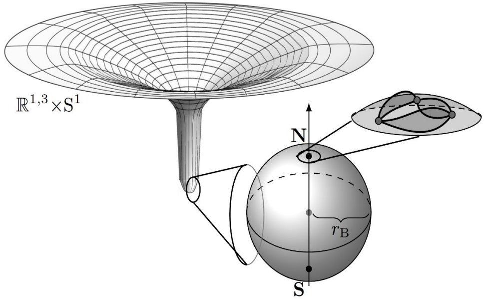

Based on:
-**AD**, M. Melis, P. Pani, *PRD 110 (2024) 8, 084067*, arXiv:2406.19327
-**AD**, M. Melis, P. Pani, *PRD 111 (2025) 10, 104001*, arXiv:2502.04444
-**AD**, F. Corelli, P. Pani, in preparation

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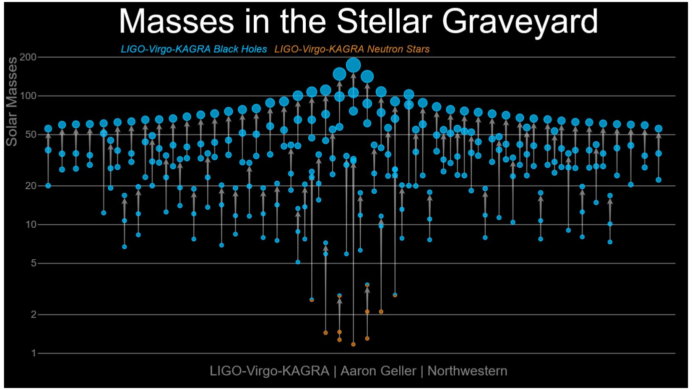
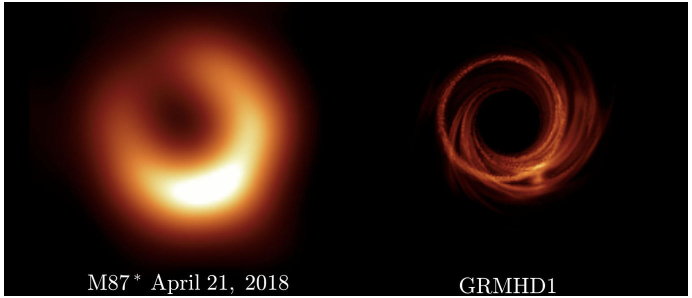
Outline

- A case for the ET: classical BH vs mimickers
- The fuzzball paradigm: a toy model of microstate geometries
- Topological stars: QNMs, echoes and stability
- Conclusions & future prospects

The Kerr paradigm

- Novel observational probes:
  - LVK, ~100 BBH mergers
  - EHT, ~2 SMBH “shadow” images
- What are we observing?
- Classical Black Hole paradigm:
  - Relies on uniqueness and no-hair theorems
  - Extreme astrophysical compact objects can be interpreted as Kerr black holes (or Neutron Stars)
- Open challenges:
  - **Large B-H entropy**
  - **Singularity**
  - **Information Paradox**

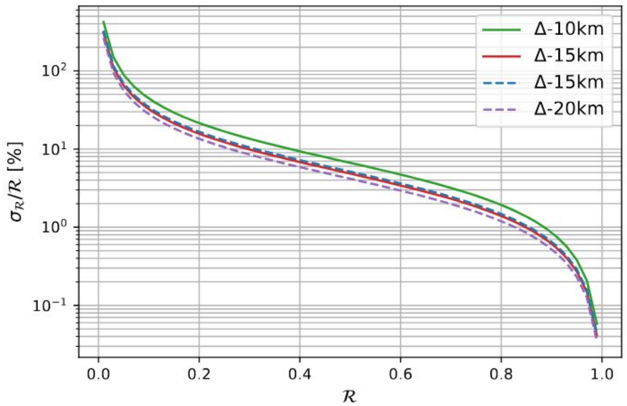




Black Hole mimickers: a target for 3G detectors

- **Black Hole mimickers**: ultra compact, regular and horizonless objects
  Bambi et al. (2025)
- Most are **bottom-up** models (boson stars, gravastars, wormholes)
- Possible signatures:
  - Non-trivial **Tidal deformability**
  - Anomalous **spin-induced quadrupole moment**
  - **Echoes** in the ringdown

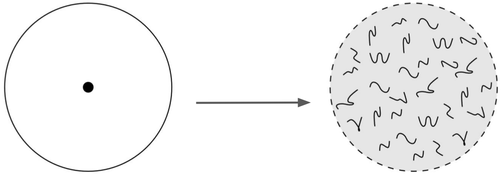
  Cardoso, Franzin, Pani (2016); Cardoso & Pani (2019)



- 2G detectors are limited: SNR ~O(100) required for echoes detection
  Testa & Pani (2017); Maggio et al. (2019); Abbott et al. (2021)
- ET (and other 3G detectors) could make a difference!
  Maggiore et al. (2020); Branchesi et al. (2023)

The fuzzball paradigm

Mathur (2005)



- String Theory's **fuzzballs:** ensembles of **many**, **smooth** and **horizonless** microstates
- Microstate geometries: BH asymptotics, horizon-scale structure

  Lunin & Mathur (2002); Mathur (2005, 2008); Meyerson (2020)
- supported via **higher dimensions** and **non-trivial topology** *Gibbons & Warner (2014)*
- Known microstates: **supersymmetric (or extremal)**, many charges, complex geometries

  Bena, Warner (2008, 2013); Bena et al., (2011); Bena, Shigemori, Warner (2014); Bianchi et al., (2017); ...
- Few brave phenomenological studies

  Bianchi et al. (2018a, 2018b); Bena et al. (2018, 2019); Ikeda et al. (2021).

The 5D Einstein-Maxwell toy model

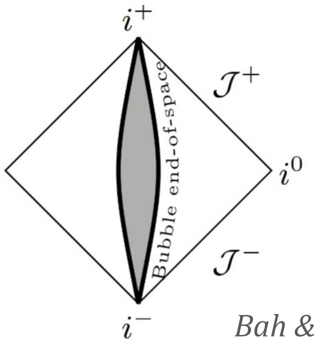
5D Einstein+Maxwell:

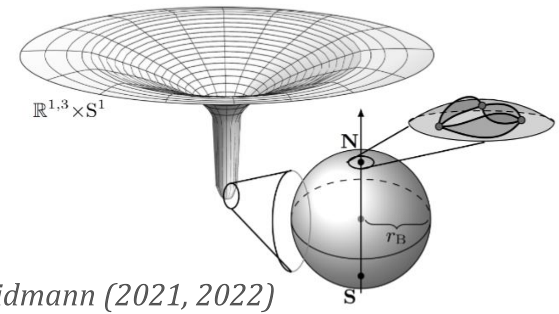
$$S_5 = \int d^5x \sqrt{-\mathbf{g}} \left(\frac{1}{2\kappa_5^2} \mathbf{R} - \frac{1}{4} \mathbf{F}_{AB} \mathbf{F}^{AB} \right)$$

$$ds^2 = -f_S(r) dt^2 + f_B(r) dy^2 + \frac{1}{h(r)} dr^2 + r^2 d\Omega_2^2 \qquad F = P \sin\theta \, d\theta \wedge d\phi$$

$$f_B(r) = 1 - \frac{r_B}{r}, \quad f_S(r) = 1 - \frac{r_S}{r}, \quad h(r) = f_B(r) f_S(r), \quad P = \pm \kappa_5^{-1} \sqrt{\frac{3}{2} r_B r_S}$$

- **Magnetized Black String**: $r_B < r_S$
- **Topological Star**: $r_B > r_S$





Bah & Heidmann (2021, 2022)

Topological Stars

$$M = \frac{2\pi}{\kappa_4^2}(2r_S + r_B)\,, \quad Q_m = \frac{1}{\kappa_4}\sqrt{\frac{3}{2}r_S r_B}$$

- **1st kind TS**: $\frac{3}{2}r_S \leq r_B \leq 2r_S$

  $r_{(ph)} = r_B$

  (unstable)

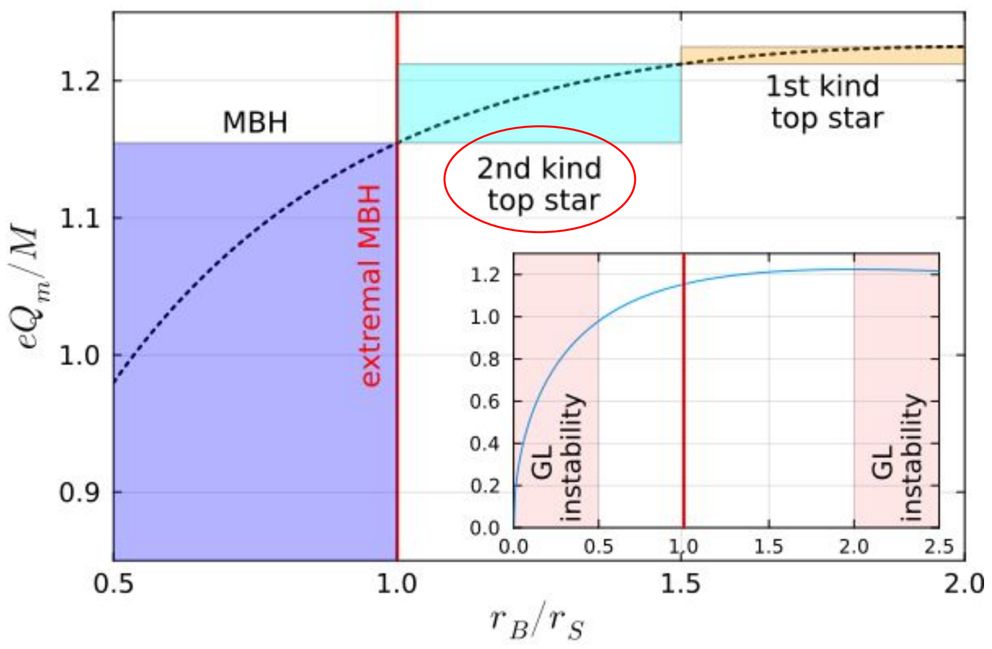
- **2nd kind TS** : $r_S < r_B < \frac{3}{2}r_S$

  $r_{(ph)} = \frac{3}{2}r_S\,, \quad r_{(ph)} = r_B$

  (stable) (unstable)

Gregory-Laflamme instability:

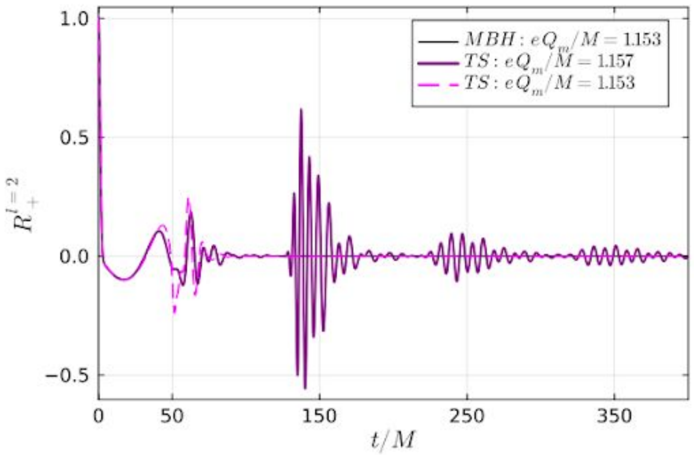
$$r_B < \frac{1}{2}r_S\,, \quad r_B > 2r_S$$



Top Star Phenomenology

- **Test field probes**: Heidemann, Speeney, Berti (2023); Bianchi et al. (2023)
- **Geodesic motion:** Bini, Di Russo (2025)
- **EMRIs (test point scalar charge):** Di Russo, Bianchi, Bini (2024a, 2024b); Melis, Brito, Pani (2025)
- **Shadow Imaging:** Heidemann, Bah, Berti (2022)
- **Linear Perturbations:** **Dima**, Melis, Pani (2024, 2025); Bena et al. (2024); Bianchi, Bini, Di Russo (2024); Cipriani et al. (2024)

Spoiler: echoes!



Regge-Wheeler-Zerilli perturbation scheme (5D)

Type-I

axial gravitational + polar EM (l≥1)

$$h_{AB}^{\rm odd} = \sum_{l,m} \begin{pmatrix} 0 & 0 & 0 & -h_0(t,y,r)/\sin\theta\partial_\phi & h_0(t,y,r)\sin\theta\partial_\theta \\ 0 & 0 & 0 & -h_2(t,y,r)/\sin\theta\partial_\phi & h_2(t,y,r)\sin\theta\partial_\theta \\ 0 & 0 & 0 & -h_1(t,y,r)/\sin\theta\partial_\phi & h_1(t,y,r)\sin\theta\partial_\theta \\ -h_0(t,y,r)/\sin\theta\partial_\phi & -h_2(t,y,r)/\sin\theta\partial_\phi & -h_1(t,y,r)/\sin\theta\partial_\phi & 0 & 0 \\ h_0(t,y,r)\sin\theta\partial_\theta & h_2(t,y,r)\sin\theta\partial_\theta & h_1(t,y,r)\sin\theta\partial_\theta & 0 & 0 \end{pmatrix} Y_{lm}(\theta,\phi)$$

$$f_{AB}^{\rm even} = \sum_{l,m} \begin{pmatrix} 0 & f^+_{ty}(t,r) & f^+_{tr}(t,r) & f^+_{t\theta}(t,r)\partial_\theta & f^+_{t\theta}(t,r)\partial_\phi \\ -f^+_{ty}(t,r) & 0 & f^+_{yr}(t,r) & f^+_{y\theta}(t,r)\partial_\theta & f^+_{y\theta}(t,r)\partial_\phi \\ -f^+_{tr}(t,r) & -f^+_{yr}(t,r) & 0 & f^+_{r\theta}(t,r)\partial_\theta & f^+_{r\theta}(t,r)\partial_\phi \\ -f^+_{t\theta}(t,r)\partial_\theta & -f^+_{y\theta}(t,r)\partial_\theta & -f^+_{r\theta}(t,r)\partial_\theta & 0 & 0 \\ -f^+_{t\theta}(t,r)\partial_\phi & -f^+_{y\theta}(t,r)\partial_\phi & -f^+_{r\theta}(t,r)\partial_\phi & 0 & 0 \end{pmatrix} Y_{lm}(\theta,\phi)$$

Type-II

polar gravitational + polar scalar + axial EM (l≥0)

$$h_{AB}^{\rm even} = \sum_{l,m} \begin{pmatrix} f_S H_0(t,y,r) & H_4(t,y,r) & H_1(t,y,r) & 0 & 0 \\ H_4(t,y,r) & f_B H_3(t,y,r) & H_5(t,y,r) & 0 & 0 \\ H_1(t,y,r) & H_5(t,y,r) & (f_S f_B)^{-1} H_2(t,y,r) & 0 & 0 \\ 0 & 0 & 0 & r^2 K(t,y,r) & 0 \\ 0 & 0 & 0 & 0 & r^2\sin\theta^2 K(t,y,r) \end{pmatrix} Y_{lm}(\theta,\phi)$$

$$f_{AB}^{\rm odd} = \sum_{l,m} \begin{pmatrix} 0 & 0 & 0 & f^-_{t\theta}(t,r)/\sin\theta\partial_\phi & -f^-_{t\theta}(t,r)\sin\theta\partial_\theta \\ 0 & 0 & 0 & f^-_{y\theta}(t,r)/\sin\theta\partial_\phi & -f^-_{y\theta}(t,r)\sin\theta\partial_\theta \\ 0 & 0 & 0 & f^-_{r\theta}(t,r)/\sin\theta\partial_\phi & -f^-_{r\theta}(t,r)\sin\theta\partial_\theta \\ -f^-_{t\theta}(t,r)/\sin\theta\partial_\phi & -f^-_{y\theta}(t,r)/\sin\theta\partial_\phi & -f^-_{r\theta}(t,r)/\sin\theta\partial_\phi & 0 & \Lambda f^-_{\theta\phi}(t,r)\sin\theta \\ f^-_{t\theta}(t,r)\sin\theta\partial_\theta & f^-_{y\theta}(t,r)\sin\theta\partial_\theta & f^-_{r\theta}(t,r)\sin\theta\partial_\theta & -\Lambda f^-_{\theta\phi}(t,r)\sin\theta & 0 \end{pmatrix} Y_{lm}(\theta,\phi)$$

Perturbed equations in canonical form:

Reduction to 4D, $\sigma = 0$ $\longrightarrow$

$$\left[\frac{d^2}{dt^2} - \frac{d^2}{d\rho^2} + V_{\rm eff}\right]\Psi(t,\rho) = 0$$

F-domain: matrix-based QNM solver

T-domain: 1+1 pde solver

Linear response in t-domain

Near-extremal MBH:

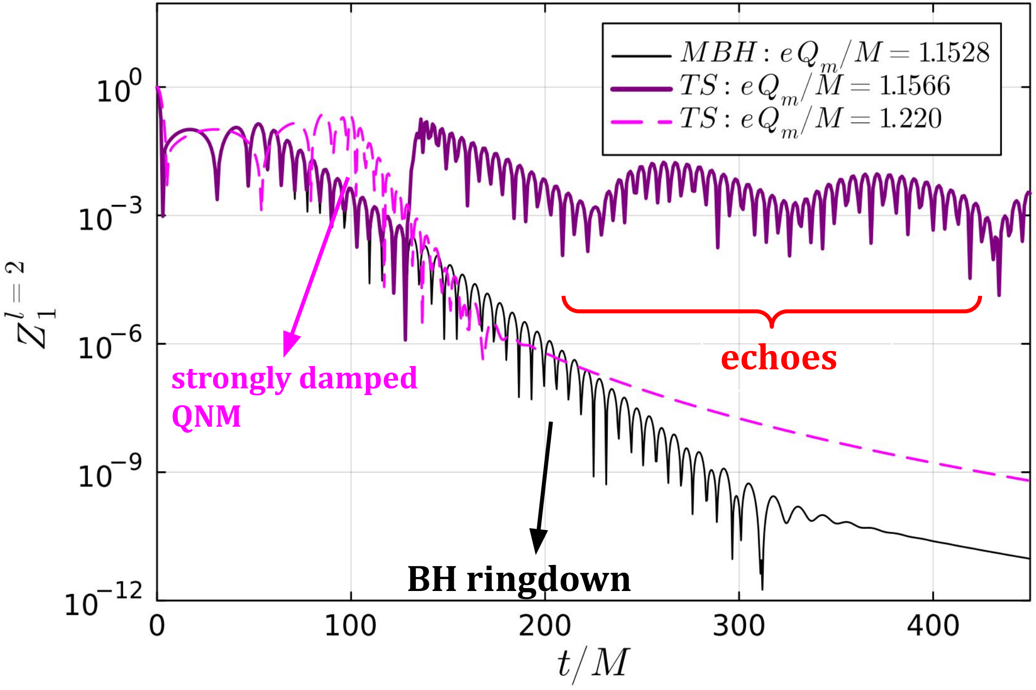
- fixed mass (M=1)
- Config w/ 99.7% of extremal charge
- ringdown + tail

2nd kind Top Star:

- Config w/ 100.3% of extremal charge
- initial **BH-like ringdown**
- long-lived modes: **echoes**!

1st kind Top Star:

- fixed mass (M=1)
- less compact
- higher frequencies QNMs, BH-like timescale of damping



Type-I, l=2, metric perturbation

Linear response in t-domain

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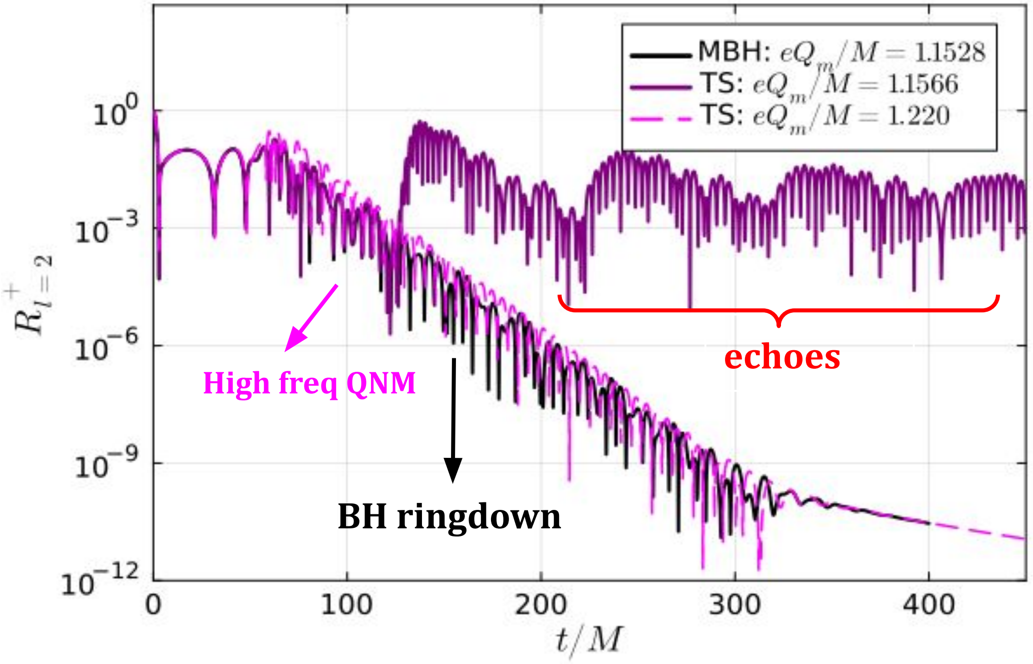

Type-II, l=2, metric perturbation

Summary & Follow-up

Topological Stars: a fun playground for investigating the type of horizon-scale effects the ET will be looking for!

- Simple and viable **UCOs**
- **Toy models** for "quantum gravity" objects (microstate geometries/fuzzballs)
- **Linear response** of **Topological Stars:**
  - **stability** under **linear** perturbations (verified numerically)
  - compact (2nd kind) Topological Stars can produce **echoes!**
- Next steps:
  - Response of rotating Top Stars
  - Nonlinear stability (1+1D)
  - 3+1D dynamics, binaries and mergers
  - Complex microstate geometries

Thank you!

Bonus slides

Black Hole mimickers: a target for 3G detectors

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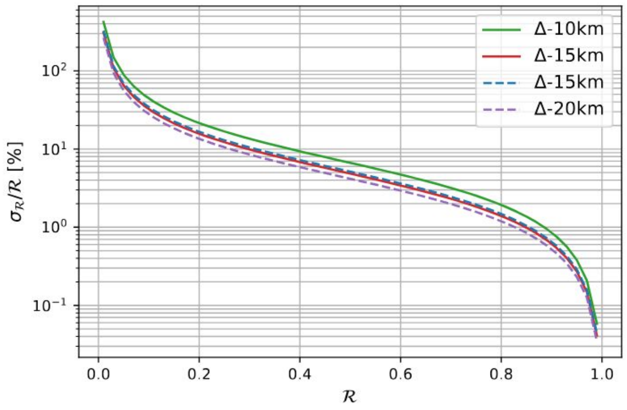

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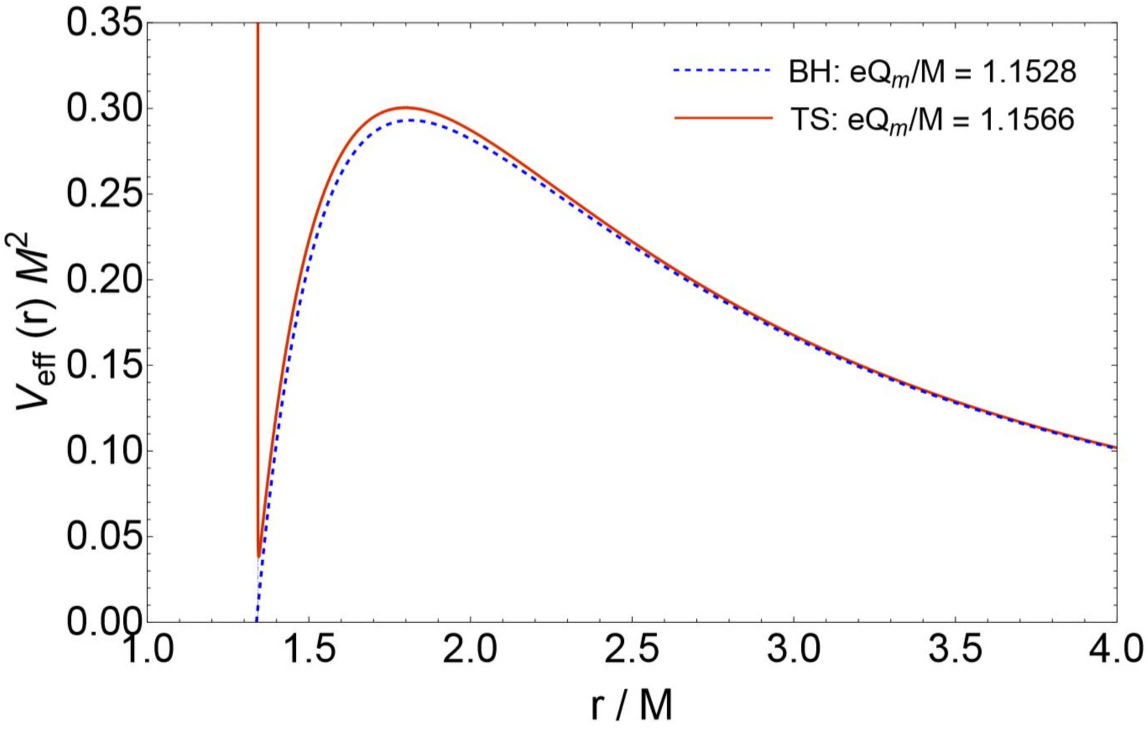
Where do the echoes come from?

Near-extremal MBH:

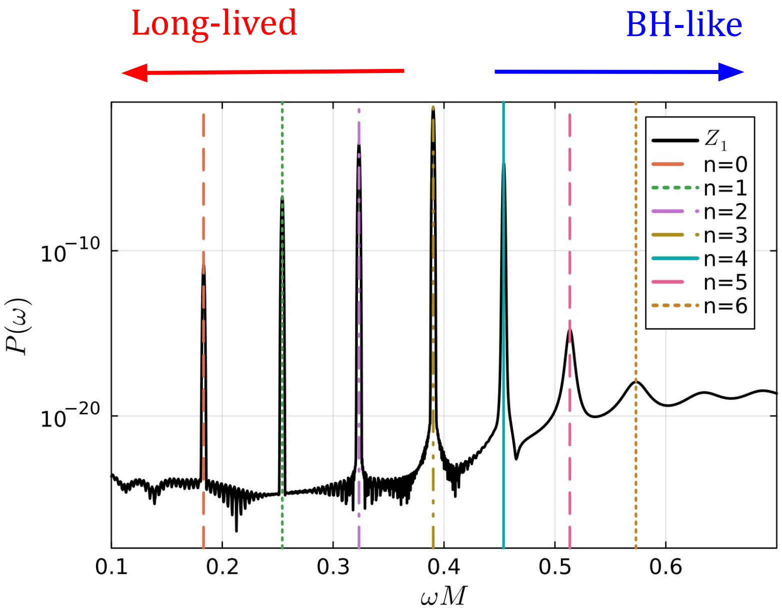
- Effective potential barrier
- Potential vanishes asymptotically

2nd kind Top Star:

- Same BH asymptotics at large distances
- "Small" corrections at the potential peak
- Reflective "surface"!
- Potential well leads to trapped modes!



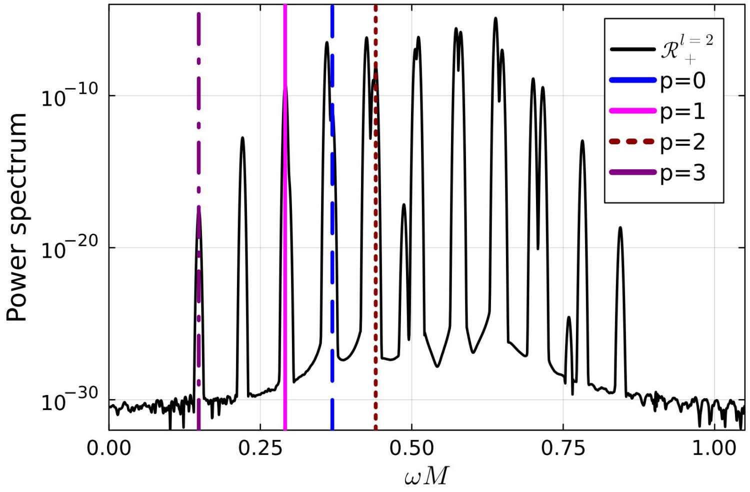
Type-I QNMs: QNM Spectrum



		Magnetized BH	TS, second kind	TS, first kind
$n=0$	f-domain	$0.489568 - i\,7.972\times10^{-2}$	$0.183217 - i\,4.674\times10^{-10}$	$0.644348 - i\,0.1551$
	t-domain	$0.489600 - i\,7.978\times10^{-2}$	$0.183219 - i\,3.349\times10^{-10}$	$0.643938 - i\,0.1665$
$n=1$	f-domain	-	$0.254071 - i\,6.001\times10^{-8}$	-
	t-domain	-	$0.254084 - i\,6.008\times10^{-8}$	-
$n=2$	f-domain	-	$0.323219 - i\,2.615\times10^{-6}$	-
	t-domain	-	$0.323263 - i\,2.622\times10^{-6}$	-
$n=3$	f-domain	-	$0.390169 - i\,6.116\times10^{-5}$	-
	t-domain	-	$0.390256 - i\,6.142\times10^{-5}$	-
$n=4$	f-domain	-	$0.453786 - i\,8.348\times10^{-4}$	-
	t-domain	-	$0.453832 - i\,8.340\times10^{-4}$	-
$n=5$	f-domain	-	$0.513765 - i\,5.463\times10^{-3}$	-
	t-domain	-	$0.513375 - i\,2.754\times10^{-3}$	-
$n=6$	f-domain	-	$0.574947 - i\,1.658\times10^{-2}$	-
	t-domain	-	$0.572869 - i\,1.140\times10^{-2}$	-

Type-II QNMs: QNM Spectrum

Gravity-induced perturbations (l=2)



$r_S/r_B =$			7/10	9/10	19/20	99/100
$l=1$	$p=0$	f-domain	$0.725735 - i\,9.739 \times 10^{-2}$	$0.594653 - i\,3.979 \times 10^{-3}$	$0.463193 - i\,2.163 \times 10^{-5}$	$0.221521 - i\,1.967 \times 10^{-11}$
		t-domain	$0.725753 - i\,9.735 \times 10^{-2}$	$0.594636 - i\,3.978 \times 10^{-3}$	$0.463183 - i\,2.160 \times 10^{-5}$	$0.221438 - i\,2.110 \times 10^{-11}$
	$p=1$	f-domain	-	$0.543775 - i\,4.233 \times 10^{-2}$	$0.581303 - i\,4.013 \times 10^{-3}$	$0.293106 - i\,4.147 \times 10^{-9}$
		t-domain	–	$0.549296 - i\,3.719 \times 10^{-2}$	$0.581265 - i\,4.006 \times 10^{-3}$	$0.292507 - i\,4.089 \times 10^{-9}$
	$p=2$	f-domain	-	$0.708010 - i\,6.095 \times 10^{-2}$	$0.441270 - i\,3.926 \times 10^{-3}$	$0.220050 - i\,1.896 \times 10^{-7}$
		t-domain	–	$0.709243 - i\,5.997 \times 10^{-2}$	$0.441245 - i\,3.910 \times 10^{-3}$	$0.220049 - i\,1.875 \times 10^{-7}$
	$p=3$	f-domain	-	-	$0.681979 - i\,3.779 \times 10^{-2}$	$0.362912 - i\,2.424 \times 10^{-7}$
		t-domain	–	–	$0.682161 - i\,3.173 \times 10^{-2}$	$0.362168 - i\,2.329 \times 10^{-7}$

$r_S/r_B =$			7/10	9/10	19/20	99/100
$l=2$	$p=0$	f-domain	$0.569028 - i\,4.955 \times 10^{-2}$	$0.834579 - i\,1.619 \times 10^{-4}$	$0.630961 - i\,2.895 \times 10^{-8}$	$0.368629 - i\,3.221 \times 10^{-14}$
		t-domain	$0.569024 - i\,4.981 \times 10^{-2}$	$0.834486 - i\,1.865 \times 10^{-4}$	$0.630844 - i\,3.245 \times 10^{-8}$	$0.368733 - i\,(*)$
	$p=1$	f-domain	$1.085261 - i\,7.599 \times 10^{-2}$	$0.422771 - i\,6.856 \times 10^{-4}$	$0.317783 - i\,5.510 \times 10^{-6}$	$0.295274 - i\,3.206 \times 10^{-12}$
		t-domain	$1.085059 - i\,7.557 \times 10^{-2}$	$0.424131 - i\,7.271 \times 10^{-4}$	$0.317827 - i\,5.551 \times 10^{-6}$	$0.295660 - i\,(*)$
	$p=2$	f-domain	-	$0.782183 - i\,1.144 \times 10^{-2}$	$0.764893 - i\,2.534 \times 10^{-5}$	$0.439992 - i\,3.944 \times 10^{-12}$
		t-domain	-	$0.782285 - i\,1.146 \times 10^{-2}$	$0.765489 - i\,3.821 \times 10^{-5}$	$0.440391 - i\,(*)$
	$p=3$	f-domain	-	$0.960878 - i\,1.792 \times 10^{-2}$	$0.616095 - i\,4.239 \times 10^{-5}$	$0.148446 - i\,6.337 \times 10^{-11}$
		t-domain	-	$0.961672 - i\,1.825 \times 10^{-2}$	$0.616099 - i\,4.103 \times 10^{-5}$	$0.148477 - i\,6.262 \times 10^{-11}$

TABLE II. Same as in Table I but for TSs with $eQ_m/M \approx \{1.208, 1.174, 1.164, 1.157\}$ (equivalently, $r_S/r_B = \{0.70, 0.90, 0.95, 0.99\}$). The asterisk indicates QNMs with a characteristic damping time that is too large for the spectral analysis to retrieve an accurate fit thereof.

Type-II QNMs: MBH vs TS