Echoes from the Black Hole Microstructure

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@ XVIII BHs Workshop 2025, IST, Lisbon

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Summary

1. **What?** Novel gravitational solitons
2. **Why?** BH mimickers / BH microstate “toy model”
3. **How?** Time domain numerical evolution
4. Conclusion and future prospects

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, P. Heidmann, M. Melis, P. Pani, G. Patashuri, *PRD 112 (2025) , 124056*, arXiv:2509.18245

What?

New viable mimickers

Topological solitons in 5D Einstein-Maxwell:

$$\mathcal{S}_{EM} = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left(R_5 - \frac{1}{4}F_{AB}F^{AB}\right)$$

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

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

Bah & Heidmann (2020; 2021)

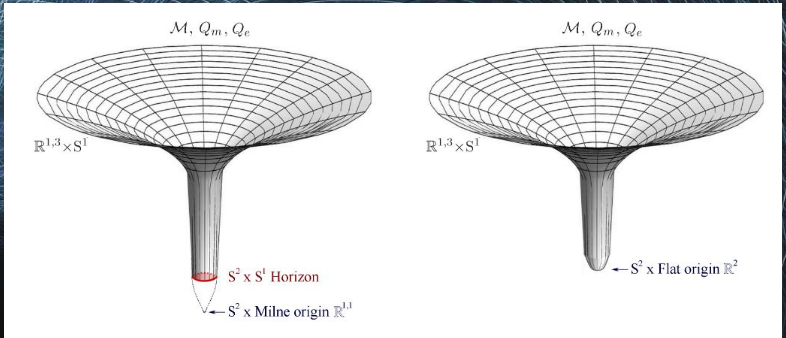
W-solitons in 5D EM + Chern-Simons:

$$\mathcal{S}_{EMCS} = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left(R_5 - \frac{1}{4}F_{AB}F^{AB} - \frac{\lambda}{12}\,\epsilon^{ABCDE}F_{AB}F_{CD}A_E\right)$$

$$ds^2_{\mathcal{W}}|_{Q=0} = -\left(1-\frac{2M}{r}\right)dt^2 + \frac{r-2M}{r-4M}dr^2 + \frac{r(r-4M)}{(r-2M)^2}d\psi^2 + r(r-2M)(d\theta^2 + \sin^2\theta\, d\phi^2)$$

$$A = \frac{2M}{r-2M}d\psi\,,$$

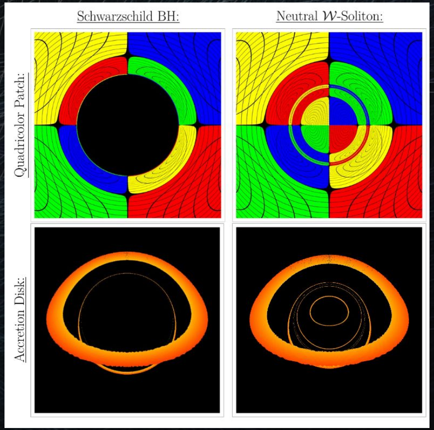
Chakraborty & Heidmann (2025)



(a) Black string. (b) Topological star.

Bah & Heidmann (2021)

- asymptotically R^(1,3) x S_1
- conserved charges as BH
- horizon -> smooth cap
- no singularity
- ultracompact



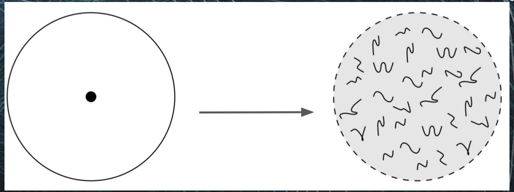
Dima et al. (2025)

Why?
Pheno & UV motivation

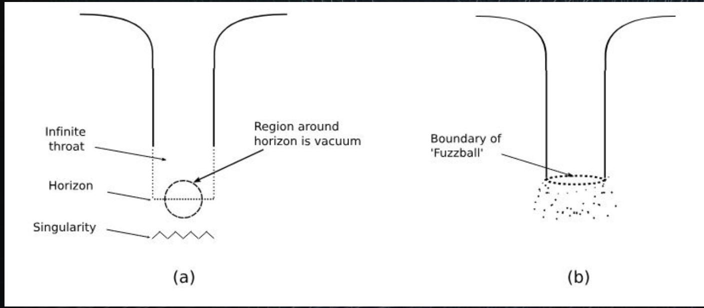
- Consistent **BH mimickers**:
  - ultracompact, regular and horizonless
  - solutions of a consistent theory
  - BH-like compactness
  - 1 or 2 lightrings

- “Toy” models of coherent **fuzzball microstates:**
  - smooth horizon-scale structure
  - extra compact dimensions + non-trivial topology
  - Non-extremal BH microstates
  - Reduced dimensionality
  - Spherical symmetry

Mathur (2005)



Classical BH   Fuzzball

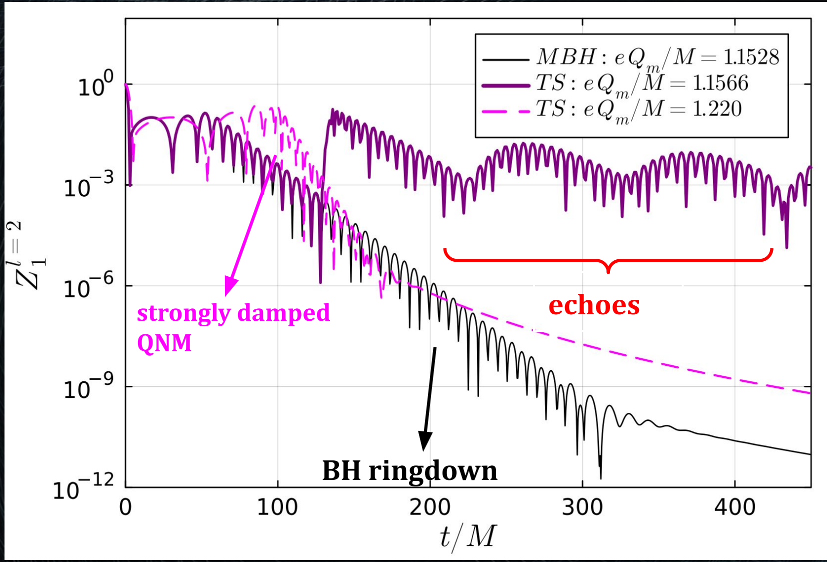


Mathur (2008)

How?

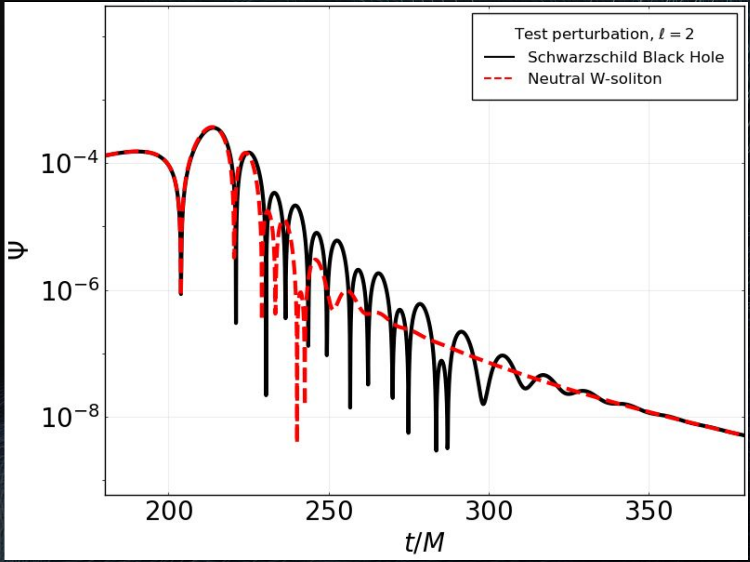
Time domain simulations

Gravitational perturbations of Topological Solitons vs Magnetized BH



Dima, Melis, Pani (2024; 2025)

Test perturbations of W-soliton vs Schwarzschild BH



Dima et al. (2025)

Conclusions

Results:

- Geodesics and Lensing on W-soliton spacetime
- Linear stability of topological solitons
- Linear spectrum: QNMs & Echoes

What's next?

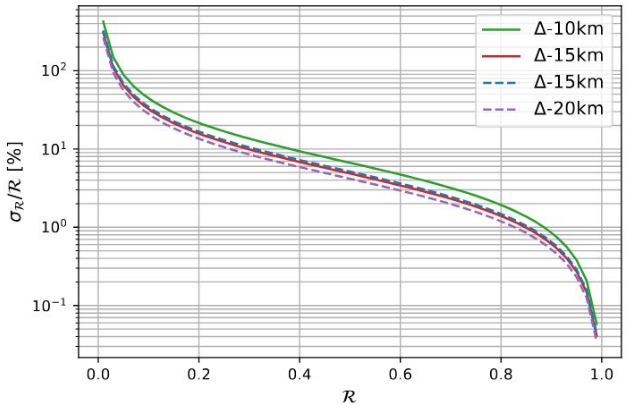
- Full linear stability analysis of W-solitons*
- Linear perturbations of rotating/axisymmetric solitons
- 1+1 nonlinear evolution of topological solitons (AD, F. Corelli, P. Pani, in preparation)
- Full NR 3+1 simulations of isolated + binary soliton systems
- Numerical waveform model of coalescing microstate geometries

Backup slides

Black Hole mimickers: a target for GW 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

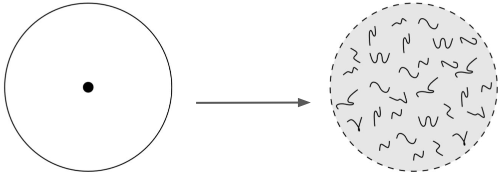
  Cardoso, Franzin, Pani (2016); Cardoso & Pani (2019)



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

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**: $\frac{3}{2}r_S \leq r_B \leq 2r_S$

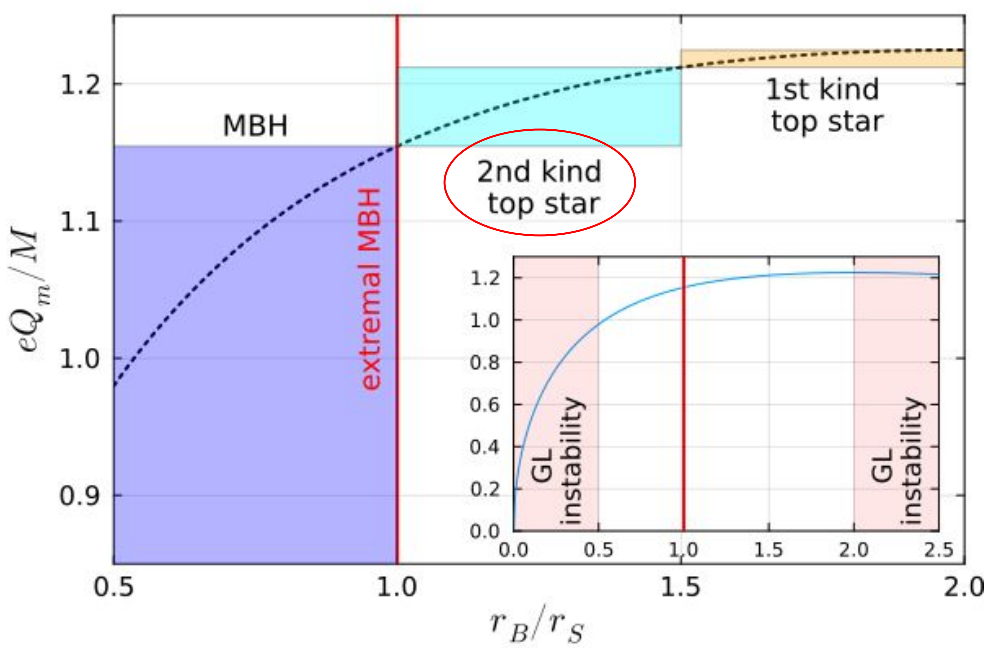
  $r_{(ph)} = r_B$
  (unstable)

- **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:

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



Regge-Wheeler-Zerilli perturbation scheme (5D)

Type-I

axial gravitational + polar EM (l≥1)

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

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

Type-II

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

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

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

Perturbed equations in canonical form:

Reduction to 4D, $\sigma = 0$ →

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

→ F-domain: matrix-based QNM solver

→ T-domain: 1+1 pde solver

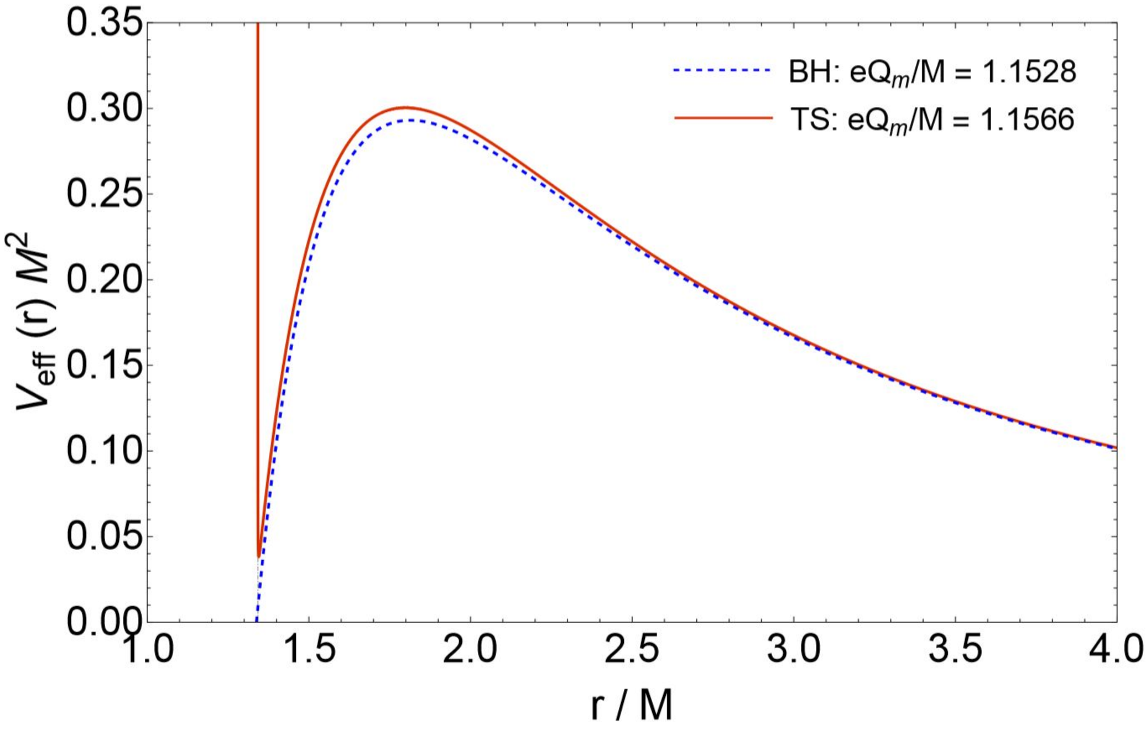
Where do the echoes come from?

Near-extremal MBH:

- Effective potential barrier
- Potential vanishes asymptotically

2nd kind Top Star:

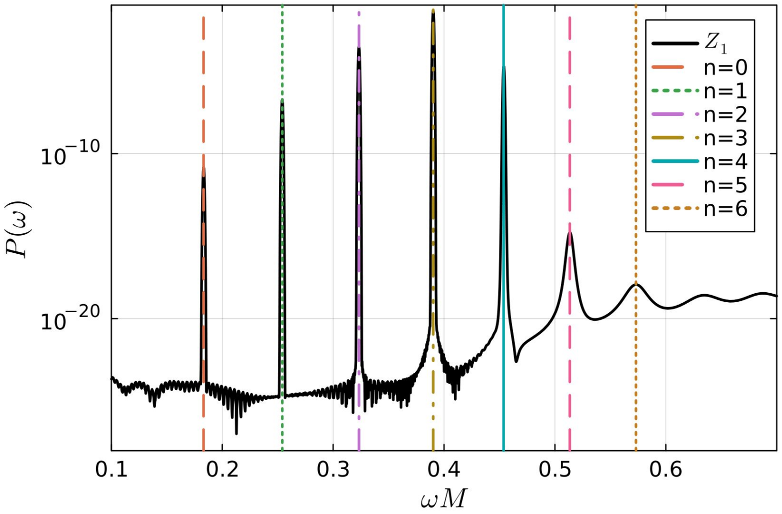
- Same BH asymptotics at large distances
- "Small" corrections at the potential peak
- Reflective "surface"!
- Potential well leads to trapped modes!



Type-I QNMs: QNM Spectrum

Long-lived

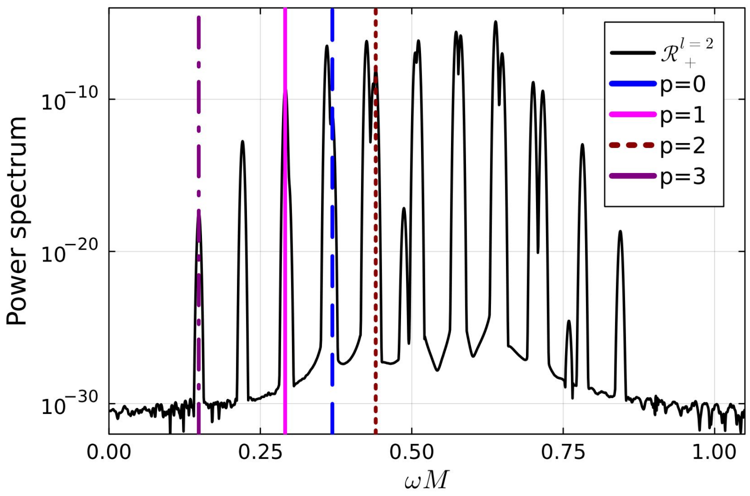
BH-like



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

Type-II QNMs: QNM Spectrum

Gravity-induced perturbations (l=2)

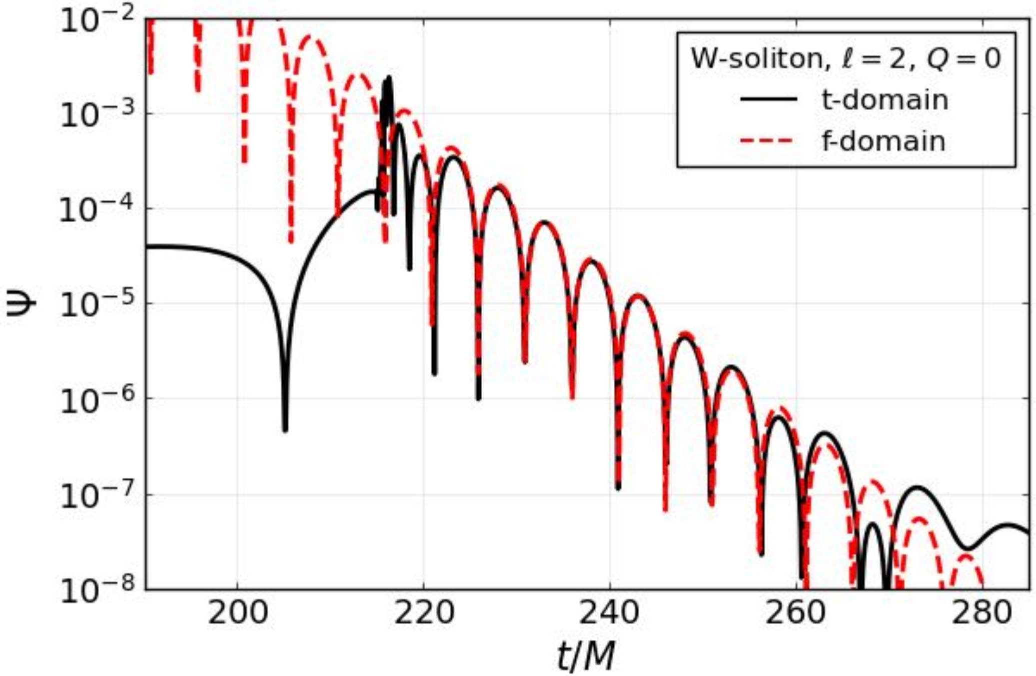


$r_S/r_B =$			7/10	9/10	19/20	99/100
$l=1$	$p=0$	f-domain	$0.725735 - i\,9.739 \times 10^{-2}$	$0.594653 - i\,3.979 \times 10^{-3}$	$0.463193 - i\,2.163 \times 10^{-5}$	$0.221521 - i\,1.967 \times 10^{-11}$
		t-domain	$0.725753 - i\,9.735 \times 10^{-2}$	$0.594636 - i\,3.978 \times 10^{-3}$	$0.463183 - i\,2.160 \times 10^{-5}$	$0.221438 - i\,2.110 \times 10^{-11}$
	$p=1$	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.

W-soliton: t-domain vs f-domain

Neutral soliton
test field
ringdown



W-soliton: test field perturbation

Charged W-soliton vs charged black string, test field response: