The Great Impersonation:

towards prototypical black hole microstates and their signatures

Featuring:

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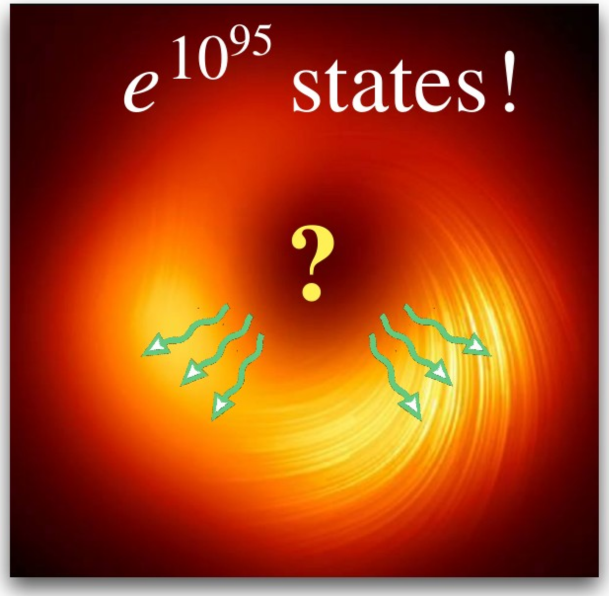
ET-NOW FIS2

Problems on the horizon

1. Entropy problem (largest discrepancy in physics!)

General Relativity: "Black holes have no hair"$\rightarrow$ **one state**

Quantum Mechanics: Entropy $\propto$ horizon area $\rightarrow e^{10^{95}}$ **states**



2. Hawking's Information Paradox (evaporation violates unitarity)

3. Singularities: theory breakdown inside black holes

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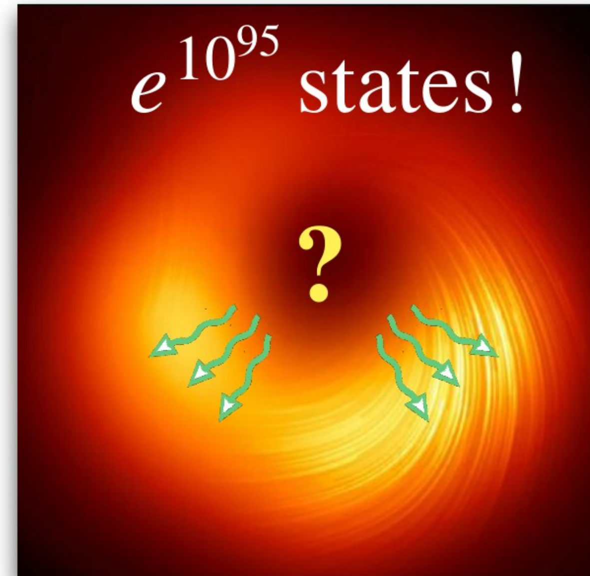
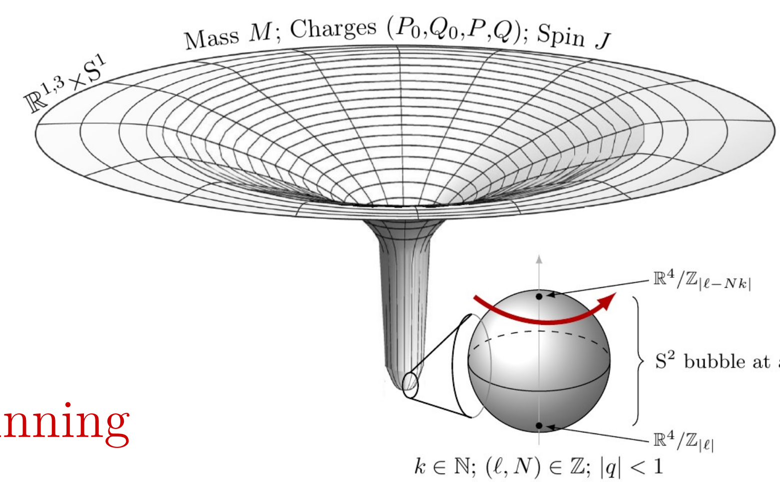


- Fuzzball's goal: solve <u>all</u> these problems with regular, horizonless, microstates

[Lunin 2001, Mathur 2005, Bena+, Warner+, ...]

- Several microstates in string theory, but either **extremal** or **non-spinning**



- Holy Grail:
  - Microstates for *astrophysical BHs:* Neutral & Spinning
  - Confront data with classical BHs

Black Hole Fingerprints

[reviews: Carballo-Rubio+ JCAP 2025; Cardoso & Pani, LLR 2019; Maggio+ 2021; BHIO 24; Princeton BH Mimickers 25]

- Dark
- Compact
- Mass is free parameter
- Size grows with G
- Stable (at least over astro timescales)
- Peculiar properties (multipoles, Love, QNMs...)

Nearly *impossible* within GR and ordinary matter

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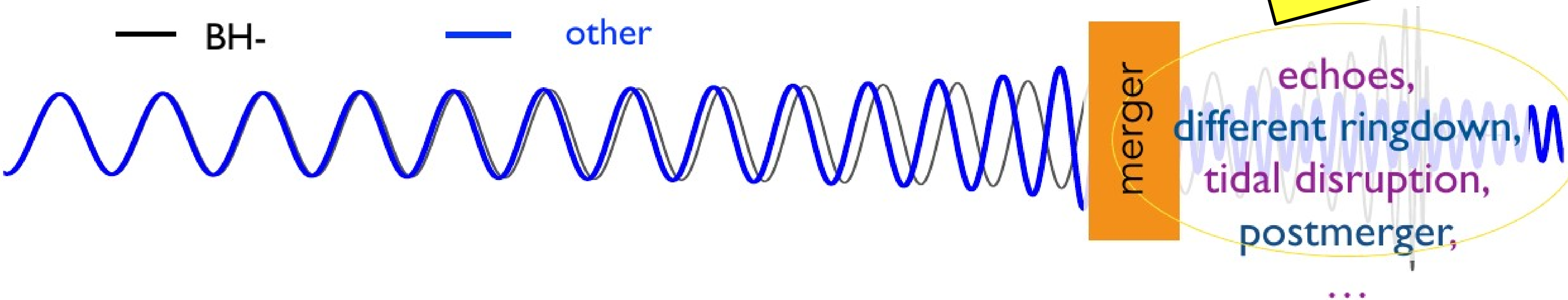
Paradigm shift from top-down approach:

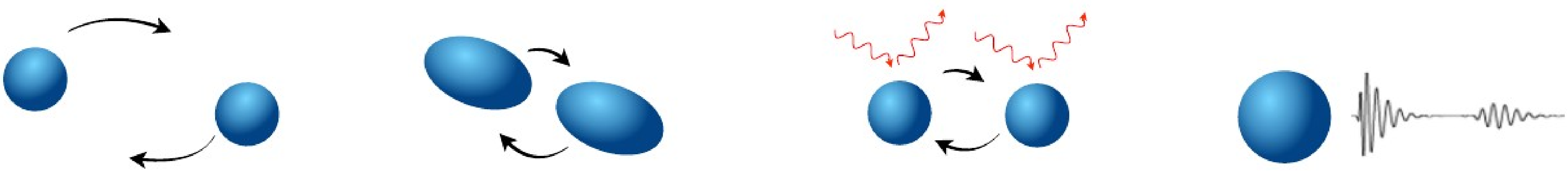
higher dimensions, fluxes, topologies $\rightarrow$ unsual/pathological 4D properties

[reviews: Mayerson 2020; Bena+ Snowmass 2022]

GW-based tests of BHs

See Berti's talk





~point masses: same signal for all objects

tidal effects* + *multipolar structure

absence of horizon ***absorption effects***

echoes

W-solitons

(Soumangsu) Chakraborty-Heidmann; 2503.13589

- 5D minimal supergravity (one small, compact extra dimension)

$$\mathcal{S} = \frac{1}{16\pi G_5}\int \left(R_5 \star_5 1 - \frac{3}{2} F\wedge\star_5 F - F\wedge F\wedge A \right)$$

- 5D metric: Static, non-extremal, smooth

$$ds^2_{\mathcal{W}} = \frac{f_Q(2f_M - f_Q)}{f_M^2}\left(d\psi + \frac{Q\, f_M}{r\, f_Q} dt + Q(\cos\theta+1)\, d\phi\right)^2 - \frac{f_M}{f_Q}\, dt^2 + f_M\left[\frac{dr^2}{2f_M - f_Q} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

$$A = \frac{Q}{r}\, dt + \frac{f_Q - f_M}{f_M}\left(d\psi + Q(\cos\theta+1)\, d\phi\right) - Q(\cos\theta+1)\, d\phi\,,$$

$$f_M \equiv 1 - \frac{2M}{r}, \qquad f_Q \equiv 1 - \frac{2Q^2}{r^2},$$

$$r_\pm \equiv 2M \pm \sqrt{2(2M^2 - Q^2)}$$

coordinate degeneracy

- Compactification → 4D metric apparently "singular"

$$ds^2_{\mathcal{W}} = \sqrt{f_Q(2f_M - f_Q)}\left[-\frac{dt^2}{f_Q} + \frac{dr^2}{2f_M - f_Q} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right],$$

$$A = \frac{Q}{r}\frac{f_M}{f_Q}\, dt - Q(\cos\theta+1)\, d\phi\,, \quad \mathcal{A} = -\frac{Q\, f_M}{r\, f_Q} dt - Q(\cos\theta+1)\, d\phi, \quad z = \underbrace{\frac{f_Q - f_M}{f_M}}_{\text{axion}} + i\, \underbrace{\frac{\sqrt{f_Q(2f_M - f_Q)}}{f_M}}_{\text{dilaton}},$$

W-solitons

(Soumangsu) Chakraborty-Heidmann; 2503.13589

- Same mass and charge of the corresponding BH $\rightarrow$ no tunable parameter!
- Mass is a free parameter
- Neutral case: microstate of Schwarzschild

Schwarzschild redshift

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

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

axion

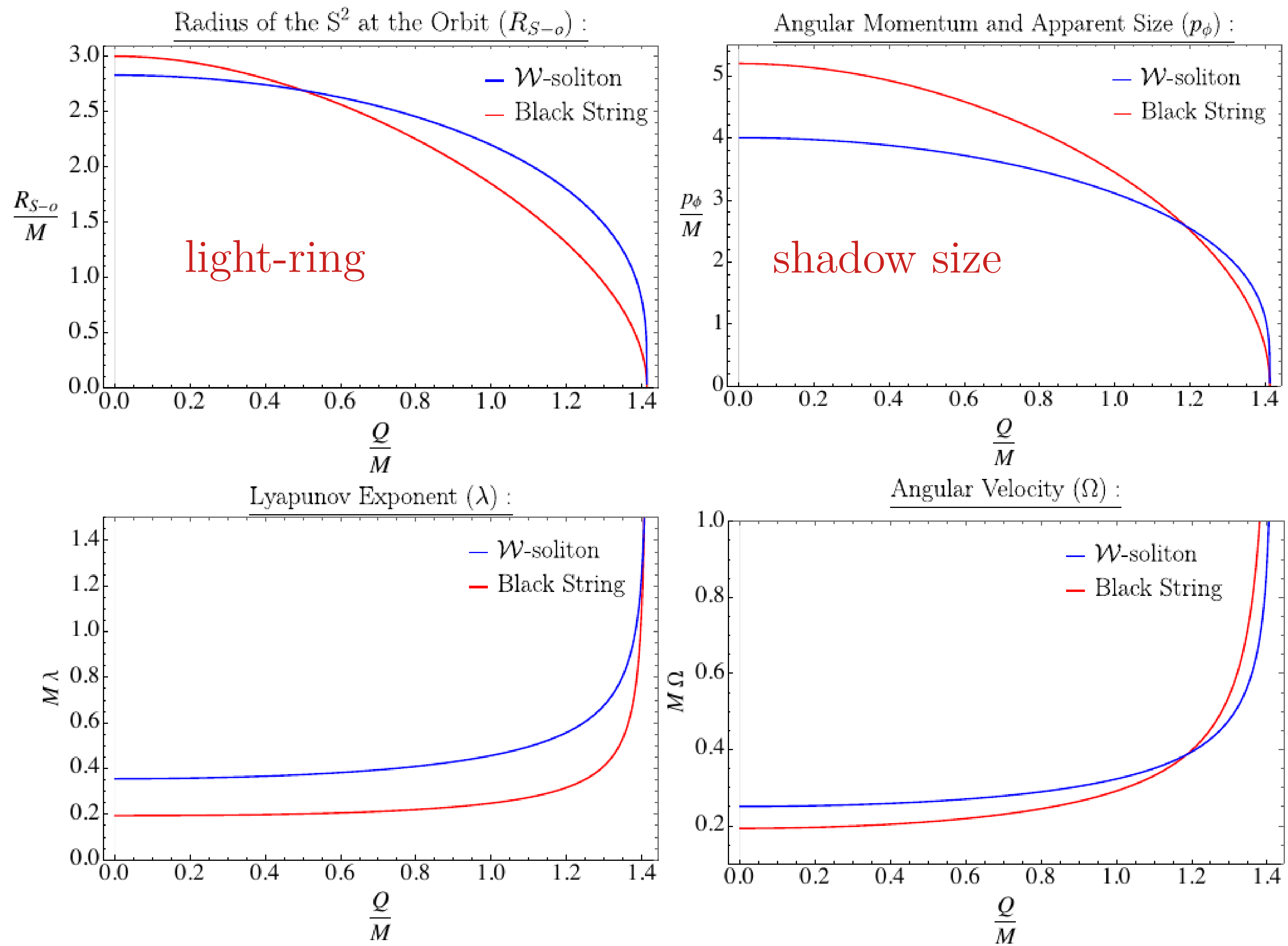
- Effective size:

$$R_{\mathcal{W}} = r\sqrt{f_M}|_{r=r_+} = \sqrt{r_+(r_+-2M)} = \frac{\sqrt{4k^2-N^2}}{2}\,R_\psi$$

size extra dim

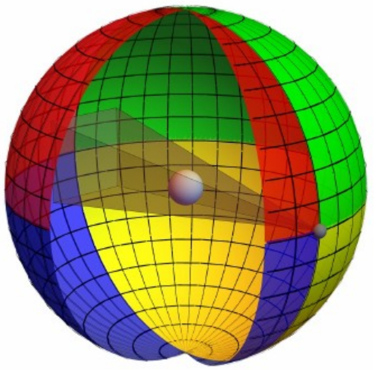
- Geodesics and perturbations are separable

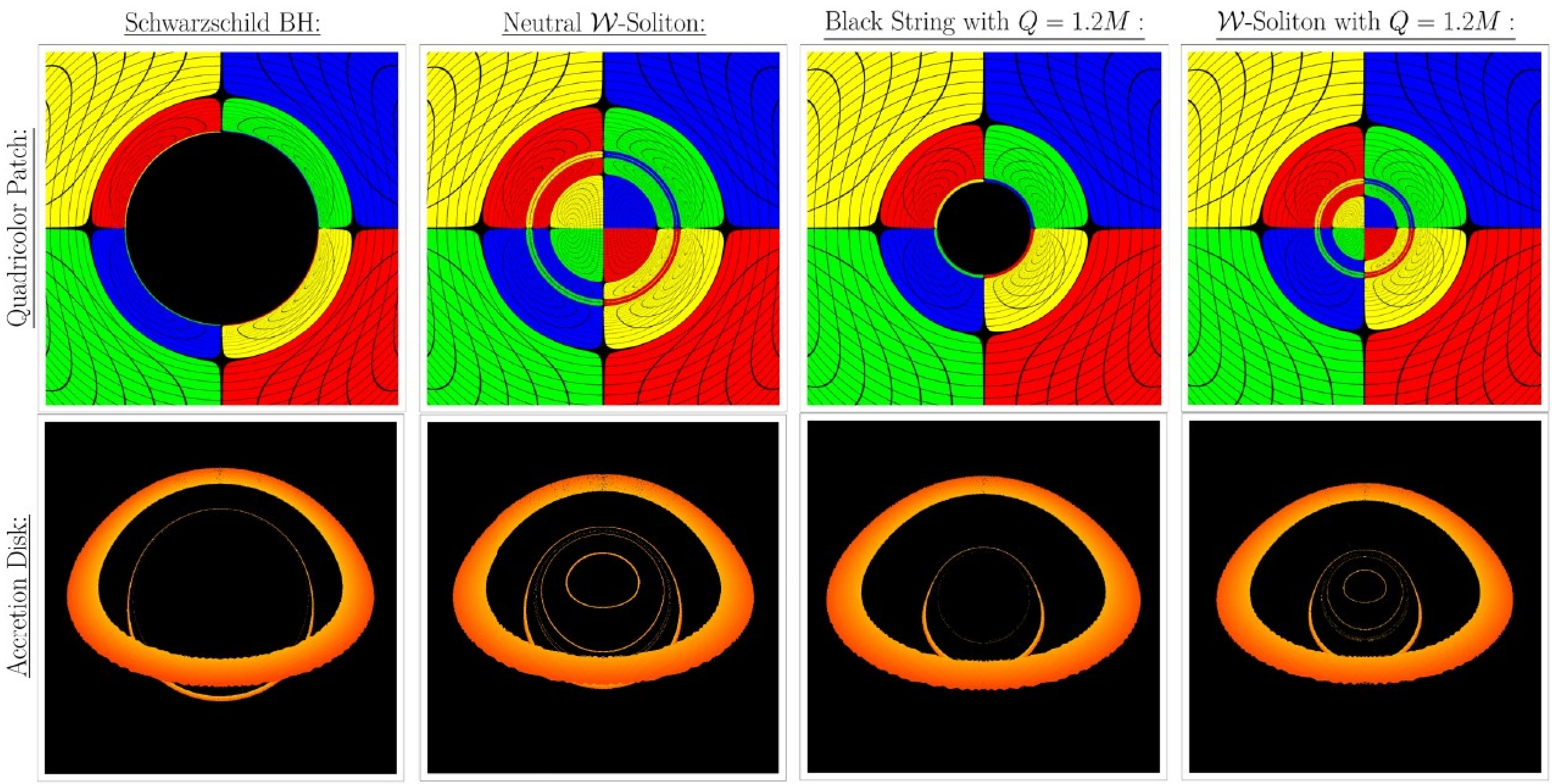
Geodesics properties: microstate vs BH



Qualitatively similar properties, yet O(10%) differences

Imaging: microstate vs BH





Effective absorption? Radiation from inside?

Scalar perturbations are separable

$$\boxed{\frac{1}{\sqrt{-g}}\partial_\mu(g^{\mu\nu}\sqrt{-g}\,\partial_\nu\Phi)=0}$$

$$\Phi=\sum_{p,m}\int d\omega\;\Psi(r)\,S(\theta)\,e^{i\left(\frac{p}{R_\psi}\psi+m\phi-\omega t\right)}$$

- Angular equation

$$\frac{1}{\sin\theta}\partial_\theta\left(\sin\theta\,\partial_\theta S\right)-\left[\frac{1}{\sin^2\theta}\left(m-\frac{pN}{2}(1+\cos\theta)\right)^2-\lambda\right]S=0,$$

- Radial equation (W-soliton)

$$\partial_r\left(r^2(2f_M-f_Q)\,\partial_r\Psi\right)-\left[\frac{r^2 f_M^3}{f_Q(2f_M-f_Q)}\frac{p^2}{R_\psi^2}-r^2 f_Q\left(\omega+\frac{f_M}{2rf_Q}Np\right)^2+\lambda\right]\Psi=0$$

- Radial equation (black hole)

$$\partial_r\left(r^2 f_- f_M\,\partial_r\Psi\right)-\left[\frac{r^2}{f_+}\frac{p^2}{R_\psi^2}-\frac{r^2 f_-^2 f_+}{f_M}\left(\omega+\frac{1}{2rf_+}Np\right)^2+\lambda\right]\Psi=0$$

Scalar perturbations are separable

$$\frac{1}{\sin\theta}\partial_\theta\left(\sin\theta\,\partial_\theta S\right) - \left[\frac{1}{\sin^2\theta}\left(m - \frac{pN}{2}(1+\cos\theta)\right)^2 - \lambda\right]S = 0,$$

- Spin-weighted spherical harmonics with half-integer spin s=-pN/2

$$\lambda = \ell(\ell+1) + s(1+2\ell) = \ell(\ell+1) - \frac{pN}{2}(1+2\ell), \qquad \ell \in \mathbb{N}, \qquad \ell \geq \frac{|pN| + pN}{2}, \qquad \ell \geq |m|$$

angular eigenvalue quantization

Scalar perturbations are separable

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angular eigenvalue quantization

- **Bonus:** Fermionic Love numbers of a black hole in GR are nonzero!!

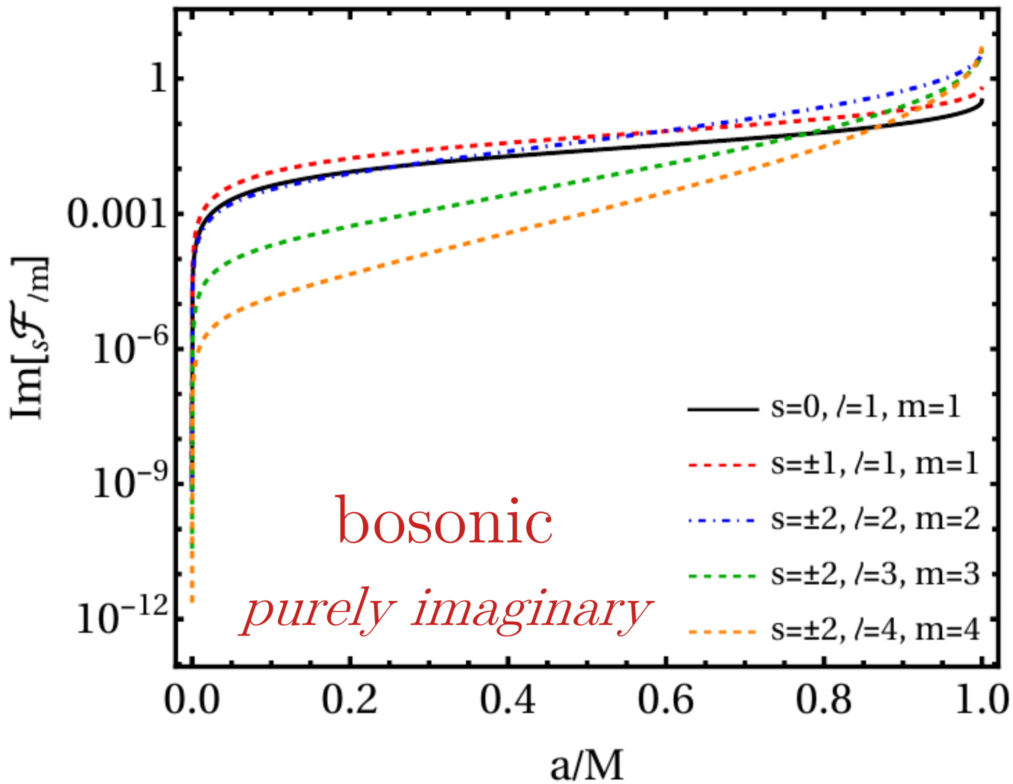
(Sumanta) Chakraborty-Heidmann-PP 2508.20155

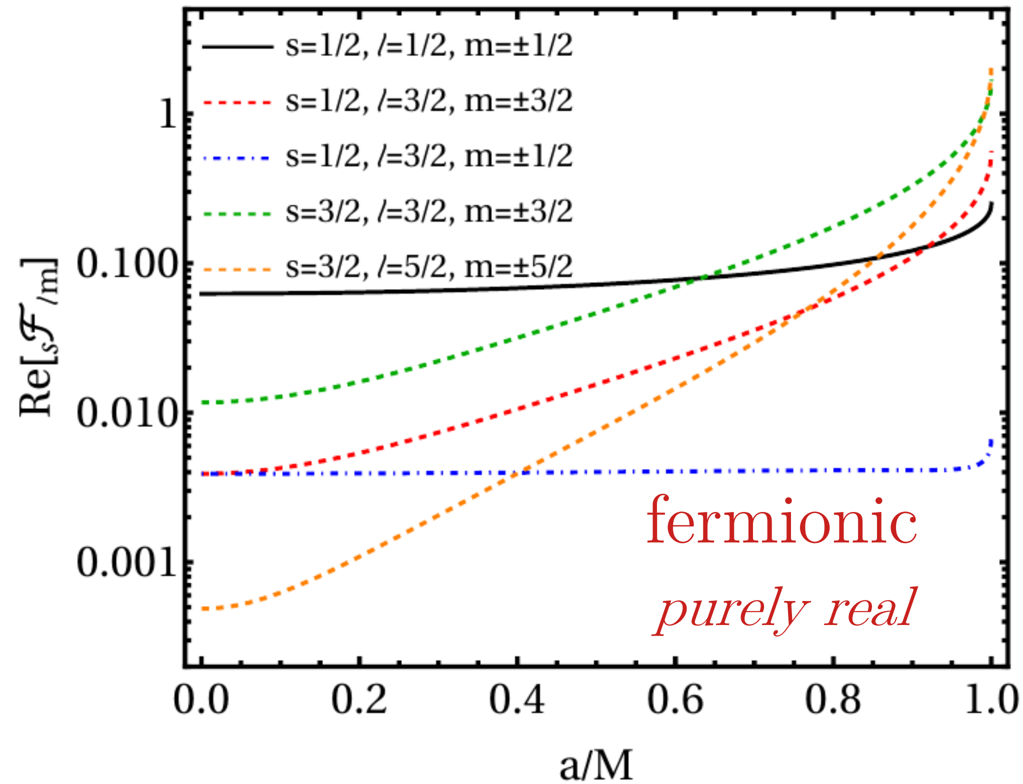
$$R_s \underset{r\to\infty}{=} \mathcal{E}_{s\ell m}\, r^{\ell-s}\left[(1+\cdots) + \mathcal{F}_{s\ell m}\left(\frac{r_+}{r}\right)^{2\ell+1}(1+\cdots)\right]$$

$$\mathcal{F}_{s\ell m} = \begin{cases} i\,(-1)^{1-s}\,\dfrac{am}{r_+}\,\dfrac{(\ell-s)!\,(\ell+s)!}{(2\ell+1)!\,(2\ell)!}\displaystyle\prod_{k=1}^{\ell}\left[k^2\left(1-\frac{r_-}{r_+}\right)^2 + \left(\frac{2am}{r_+}\right)^2\right] & \text{for bosons, } (s,\ell,m) \text{ integers,} \\ \dfrac{(-1)^{\frac{1}{2}-s}}{2}\,\dfrac{(\ell-s)!\,(\ell+s)!}{(2\ell+1)!\,(2\ell)!}\displaystyle\prod_{k=1}^{\ell+\frac{1}{2}}\left[(k-\tfrac{1}{2})^2\left(1-\frac{r_-}{r_+}\right)^2 + \left(\frac{2am}{r_+}\right)^2\right] & \text{for fermions, } (s,\ell,m) \text{ half-integers,} \end{cases}$$

Love numbers of Kerr

(Sumanta) Chakraborty-Heidmann-PP 2508.20155





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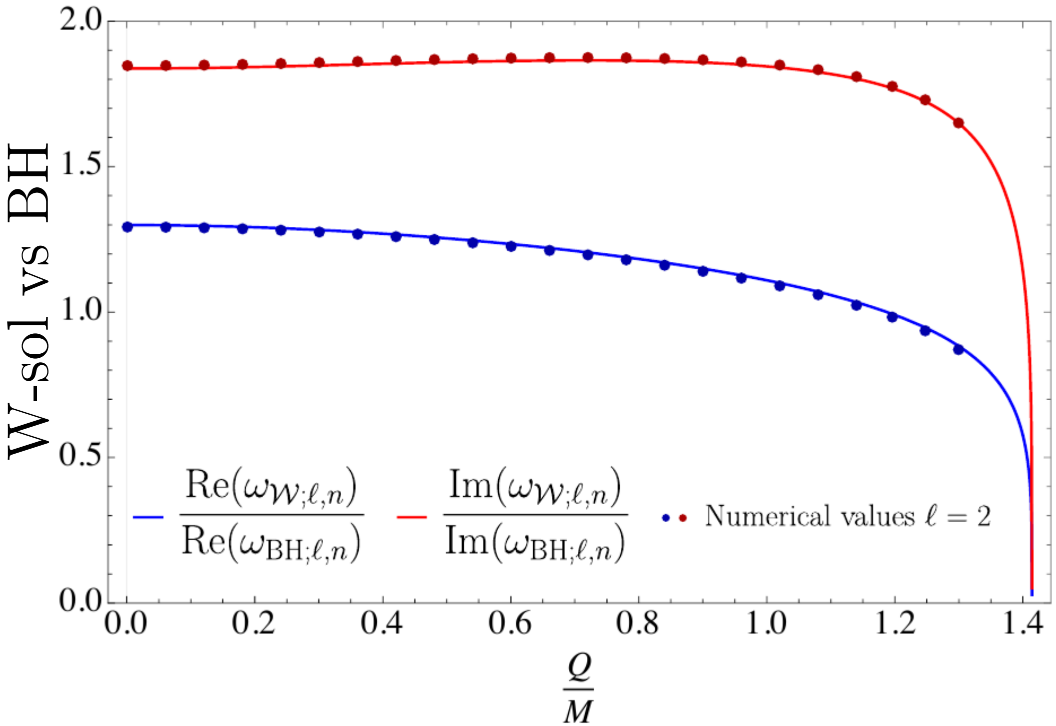
Scalar perturbations

$$\frac{d^2\overline{\Psi}}{d{r_*}^2} - V\,\overline{\Psi} = 0,$$



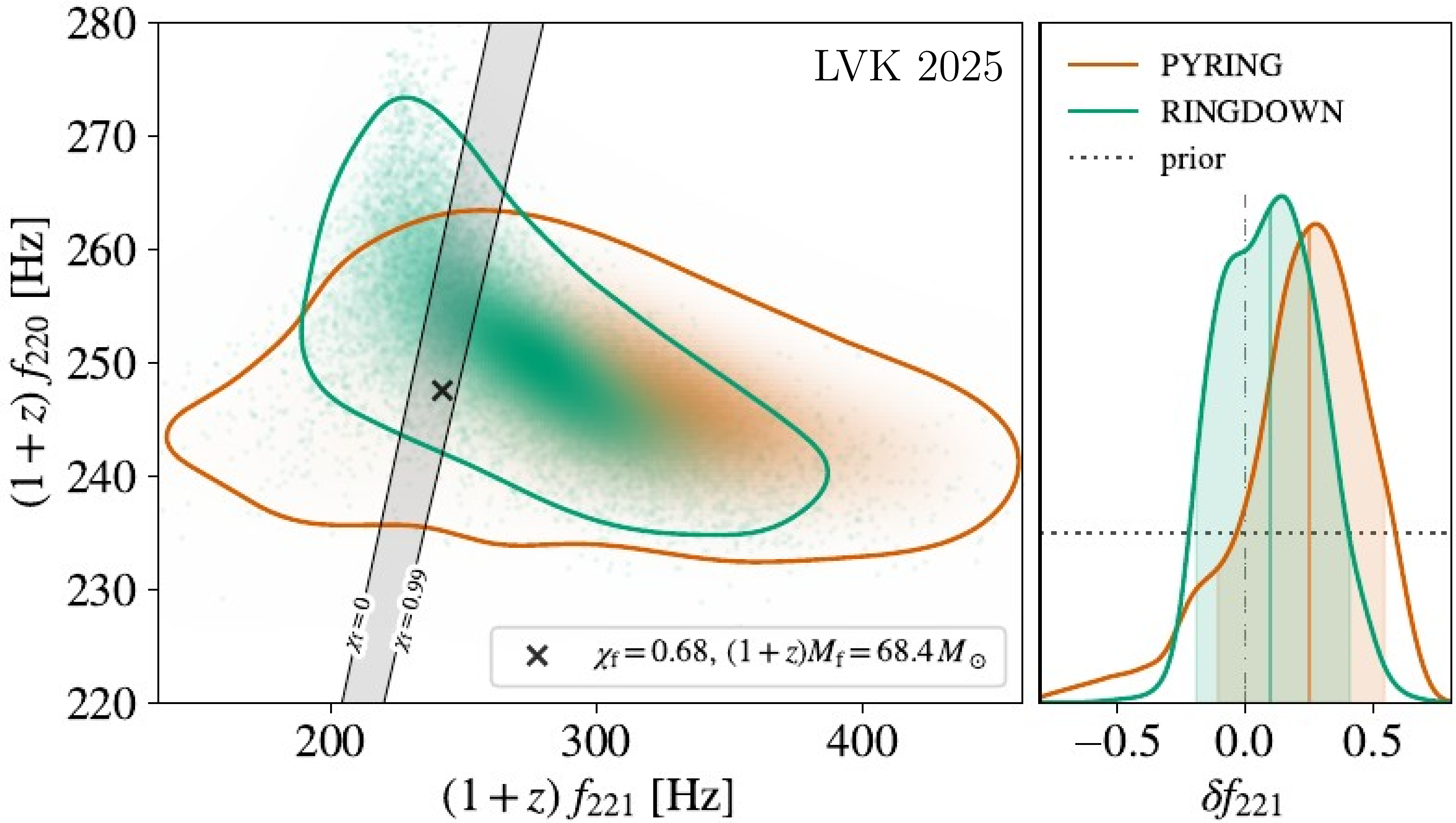
ℓ	Neutral $\mathcal{W}$-soliton		Schwarzschild BH	
	continued fraction	WKB	continued fraction	WKB
0	$0.13669 - i\,0.20545$	$0.125 - i\,0.17678$	$0.11046 - i\,0.10490$	$0.09623 - i\,0.09623$
1	$0.37542 - i\,0.18194$	$0.375 - i\,0.17678$	$0.29294 - i\,0.09766$	$0.28868 - i\,0.09623$
2	$0.62508 - i\,0.17872$	$0.625 - i\,0.17678$	$0.48364 - i\,0.09676$	$0.48113 - i\,0.09623$
3	$0.87503 - i\,0.17778$	$0.875 - i\,0.17678$	$0.67537 - i\,0.09650$	$0.67358 - i\,0.09623$
5	$1.37501 - i\,0.17719$	$1.375 - i\,0.17678$	$1.05961 - i\,0.09634$	$1.05848 - i\,0.09623$
10	$2.62500 - i\,0.17689$	$2.625 - i\,0.17678$	$2.02132 - i\,0.09626$	$2.0207 - i\,0.09623$
30	$7.62500 - i\,0.17679$	$7.625 - i\,0.17678$	$5.86993 - i\,0.09623$	$5.8697 - i\,0.09623$

n	Neutral $\mathcal{W}$-soliton		Schwarzschild BH	
	$\ell = 1$	$\ell = 5$	$\ell = 1$	$\ell = 5$
0	$0.37542 - i\,0.18194$	$1.37501 - i\,0.17719$	$0.29294 - i\,0.09766$	$1.05961 - i\,0.09634$
1	$0.28371 - i\,0.60411$	$1.34139 - i\,0.53626$	$0.26445 - i\,0.30626$	$1.05004 - i\,0.29015$
2	$0.20907 - i\,1.10779$	$1.27631 - i\,0.90978$	$0.22954 - i\,0.54013$	$1.03150 - i\,0.48735$
3	$0.17171 - i\,1.62472$	$1.18556 - i\,1.30773$	$0.20326 - i\,0.78830$	$1.00520 - i\,0.68993$
4	$0.15050 - i\,2.13882$	$1.08008 - i\,1.73772$	$0.18511 - i\,1.04076$	$0.97297 - i\,0.89948$

$$\omega_{\mathrm{BH};\ell,n} = \Omega_{\mathrm{BH}}\left(\ell + \frac{1}{2}\right) - i\,\lambda_{\mathrm{BH}}\left(n + \frac{1}{2}\right)$$

- WKB in excellent agreement with numerics
- V>0 → W-solitons are stable!
- O(10%) differences → measurable and falsifible

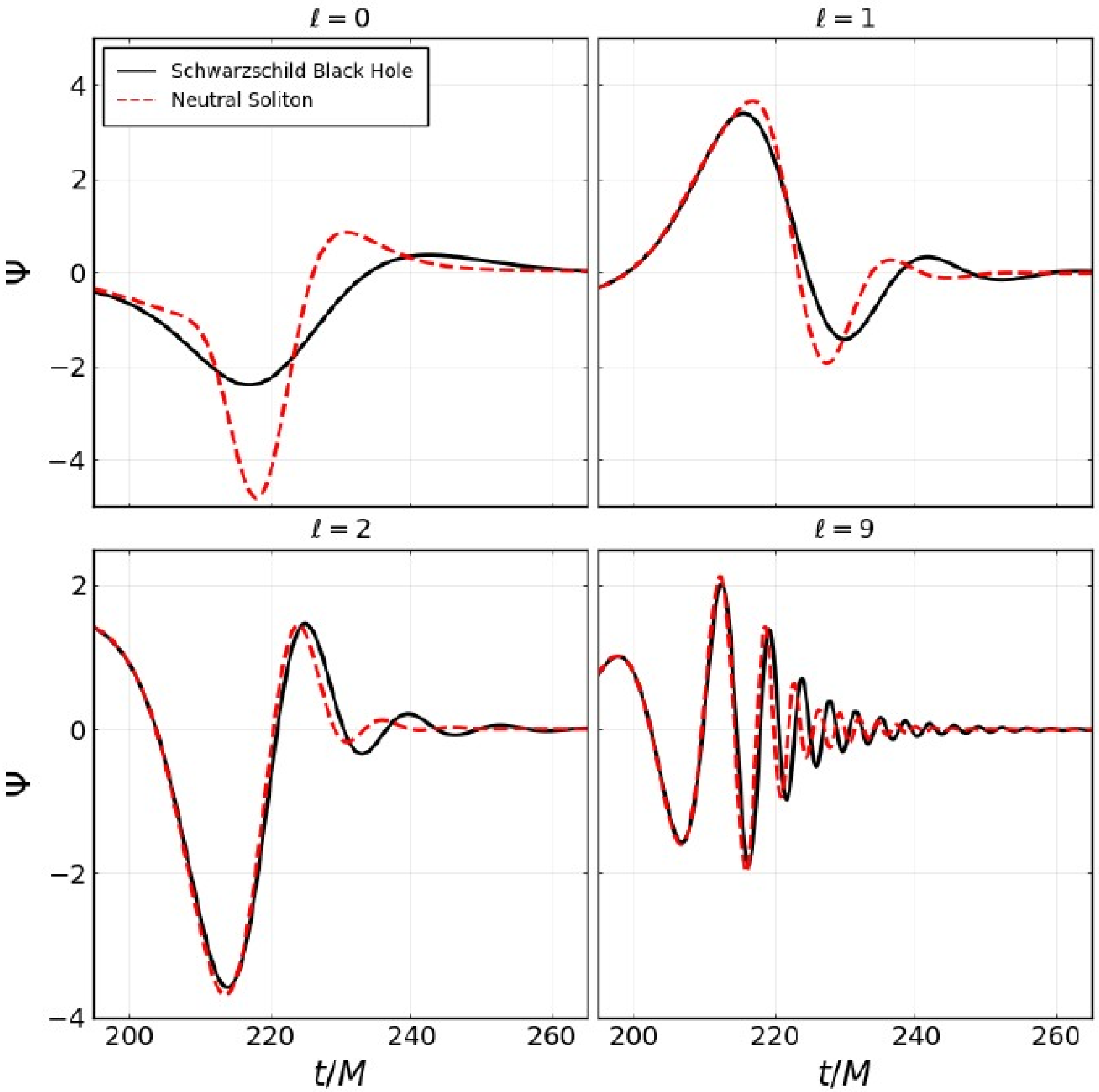
Confronting with GW250114

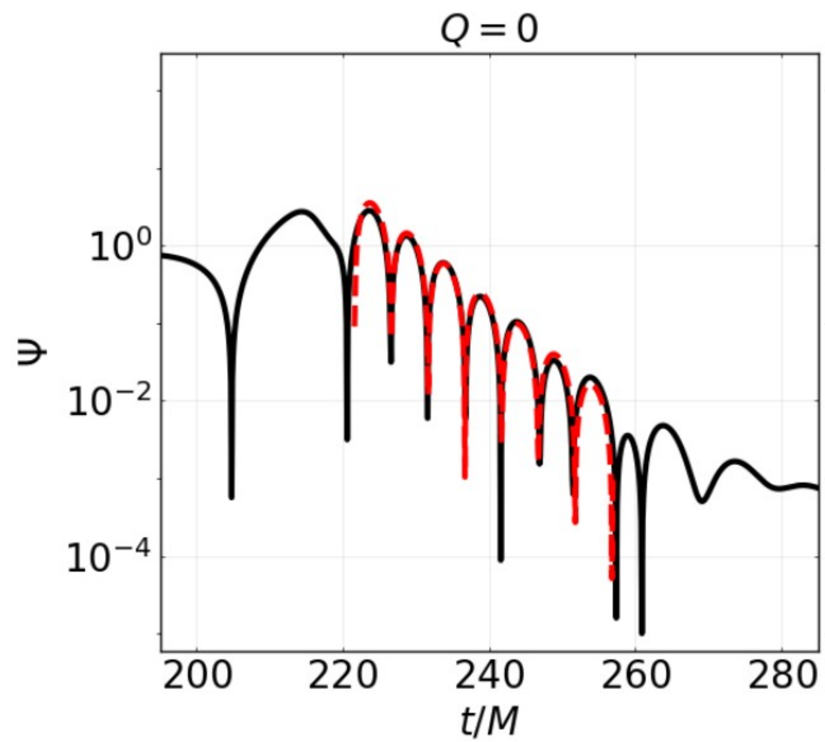


- ~30% deviations in overtone frequency are (still) allowed
- Mass and spin (fundamental mode) more accurate (<10%)

Time-domain response: microstate vs BH

$$-\Psi_{tt} + \Psi_{xx} = V\Psi \qquad \Psi(0,r) = A(r) \qquad \Psi_t(0,r) = B(r)$$





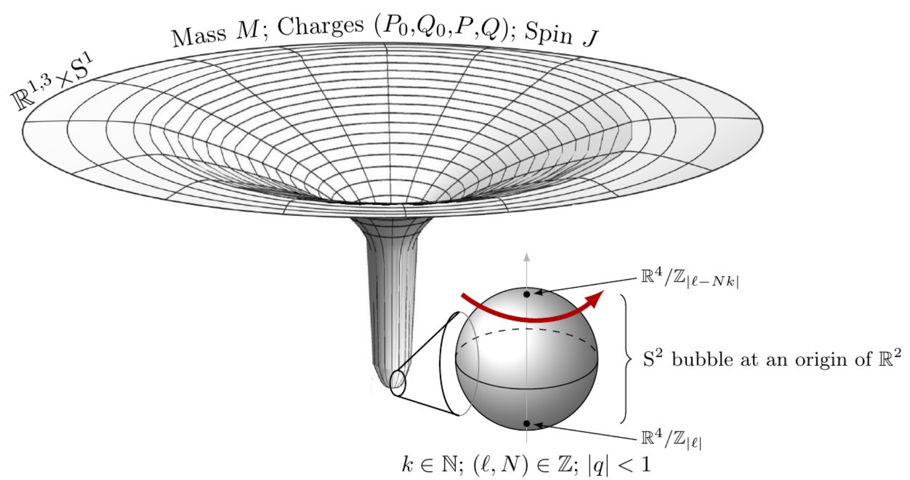
No stable light ring
→ **no echoes**!

Rotating Top Stars: main features

Heidmann-PP-Santos, 2510.05200

- 1 continuous param (q) and 3 integers (k,l,N)
- Both mass and angular momentum are quantized
- No 4D ergoregion, BUT **5D ergoregion near the cap**

  $\rightarrow$ *ergoregion instability for modes with KK momentum?*
- Geodesics and scalar perturbations are separable

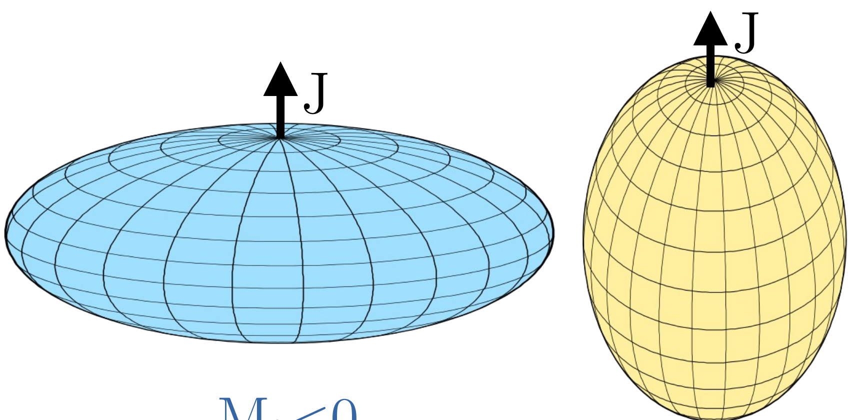


Rotating Top Stars: quadrupole

$$M_2 = \frac{a^2(M^2 - \overline{M}^2)}{M}, \qquad S_2 = -\frac{2aJ\overline{M}}{M},$$

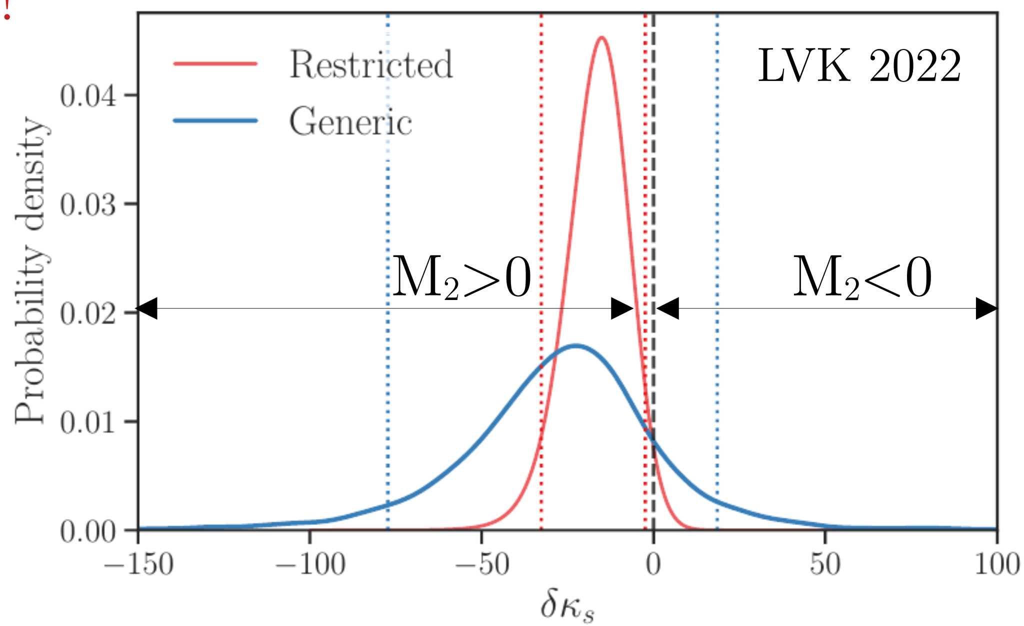
$$M_2^{\rm BH} = -\frac{a^2(M^2 + \overline{M}^2)}{M}, \quad S_2^{\rm BH} = -\frac{2aJ\overline{M}}{M}.$$

- Sign of M_2 for Top Star is not fixed!



$M_2<0$
oblate

$M_2>0$
prolate



Positive M_2 exotic, but
not excluded by GW observations

Conclusion & Outlook

- New microstates of neutral or spinning black holes
- Short blanket: sizable deviations from BHs $\rightarrow$ model can be ruled out!
- Many extensions ahead:
  - Grav. perturbations of W-solitons
  - Stability of neutral solutions
  - Quadrupole, Love numbers, etc...
  - Two-body problem and waveforms
  - Neutral and rotating solitons?

Backup slides

"Nothing is More Necessary than the Unnecessary" [cit.]

Full W-soliton

$$ds_5^2 = \frac{\Delta}{(H_1H_2H_3)^{\frac{2}{3}}}(d\psi + P_0\cos\theta\, d\phi + \chi\, dt)^2 + \frac{(H_1H_2H_3)^{\frac{1}{3}}}{\sqrt{\Delta}}\left[-\sqrt{\Delta}\, dt^2 + \frac{1}{\sqrt{\Delta}}\, ds_3^2\right],$$

$$X^I = \frac{(H_1H_2H_3)^{\frac{1}{3}}}{H_I}, \qquad A^I = A^I_\psi\,(d\psi + P_0\cos\theta\, d\phi + \chi dt) + A^I_t\, dt - P_I\cos\theta\, d\phi\,,$$

$$\Delta = 1 - \frac{2(mr-n^2)}{r^2-n^2}, \quad H_I = 1 - \frac{2(mr-n^2)\sin^2\alpha_I}{r^2-n^2}, \quad \chi = \frac{2n(r-m)\prod_{I=1}^3\sin\alpha_I}{r^2-n^2},$$

$$A^I_\psi = \frac{(mr-n^2)\sin 2\alpha_I}{(r^2-n^2)H_I}, \quad A^I_t = \frac{2n(r-m)}{r^2-n^2}\frac{|\epsilon_{IJK}|}{2}\cos\alpha_I\sin\alpha_J\sin\alpha_K$$

- 4 magnetic + 4 electric charges, 3+2 independent parameters:

$$P_0 = 2n\prod_{I=1}^3\cos\alpha_I\,, \qquad P_I = 2n\frac{|\epsilon_{IJK}|}{2}\sin\alpha_I\cos\alpha_J\cos\alpha_K\,,$$

$$Q_0 = 2n\prod_{I=1}^3\sin\alpha_I\,, \qquad Q_I = -2n\frac{|\epsilon_{IJK}|}{2}\cos\alpha_I\sin\alpha_J\sin\alpha_K\,.$$