Mechanics and thermodynamics of a near extremal black hole with a moon

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In collaboration with Marc Casals

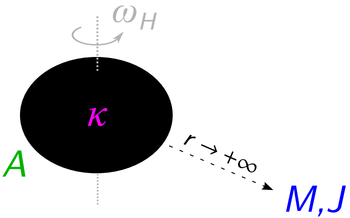
Black hole uniqueness theorem in GR

[Israel 1967, Carter 1971, Hawking 1973, Robinson 1975]

- The only stationary vacuum black hole solution is the Kerr solution of mass M and angular momentum J

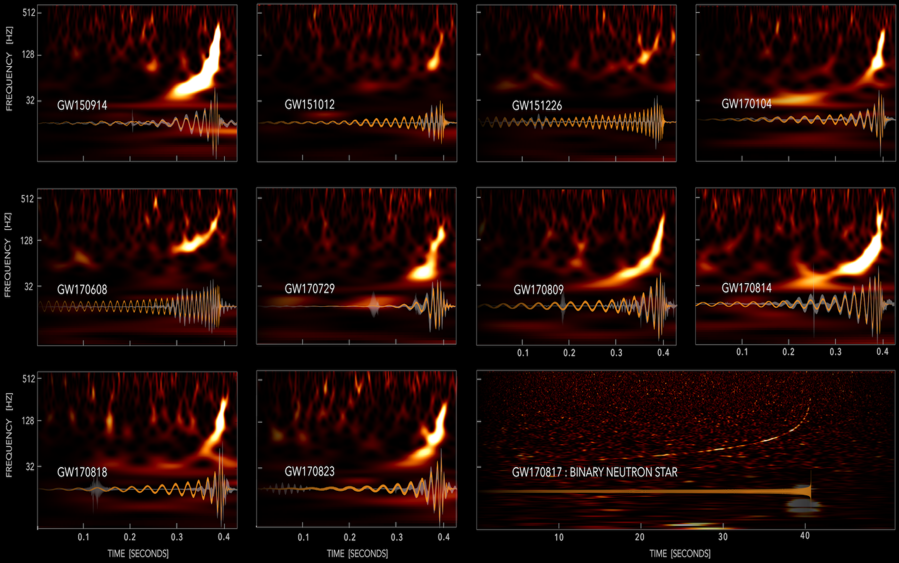
"Black holes have no hair." (J. A. Wheeler)

- Black hole event horizon characterized by:
  - Angular velocity ω_H
  - Surface gravity κ
  - Surface area A



GRAVITATIONAL-WAVE TRANSIENT CATALOG-1

LIGO VIRGO NSF Georgia Tech

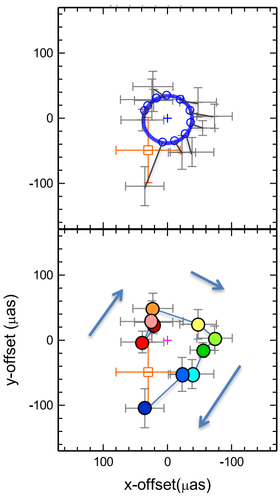


LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

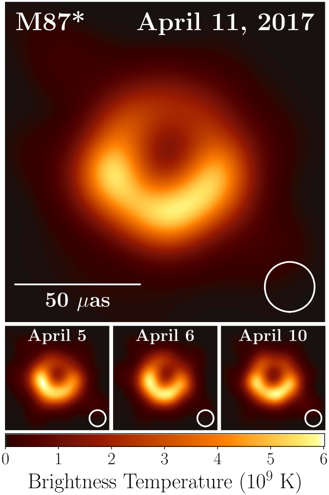
WAVELET (UNMODELED) EINSTEIN'S THEORY

S. GHONGE, K. JANI | GEORGIA TECH

Zooming in on supermassive black holes



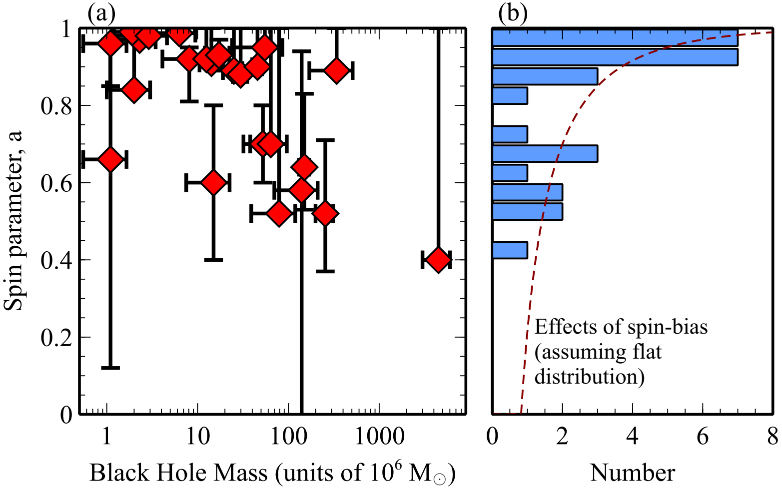
[GRAVITY, A&A 2018]



[EHT, ApJ 2019]

Spin distribution of supermassive BHs

[Reynolds, Nat. Astron. 2019]



Why are (near-)extremal BHs interesting?

Schwarzschild $\boxed{0 \leqslant a \equiv J/M^2 \leqslant 1}$ Extreme Kerr

- Cosmic censorship hypothesis [Penrose, Riv. Nuovo Cim 1969]
- Vanishing surface gravity [Bardeen *et al.*, CMP 1973]
- Enhanced symmetry group [Bardeen & Horowitz, PRD 1999]
- Kerr/CFT correspondance [Guica, Hartman *et al.*, PRD 2009]
- Event horizon instability [Aretakis, Theor. Math. Phys. 2015]
- Unusual dynamics [Yang, Zimmerman & Lehner, PRL 2015]
- Unique GW signature [Gralla, Hughes & Warburton, PRD 2016]

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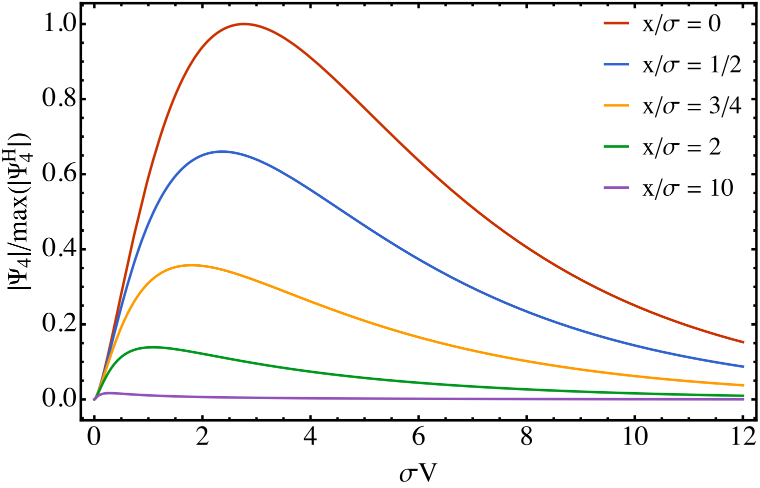
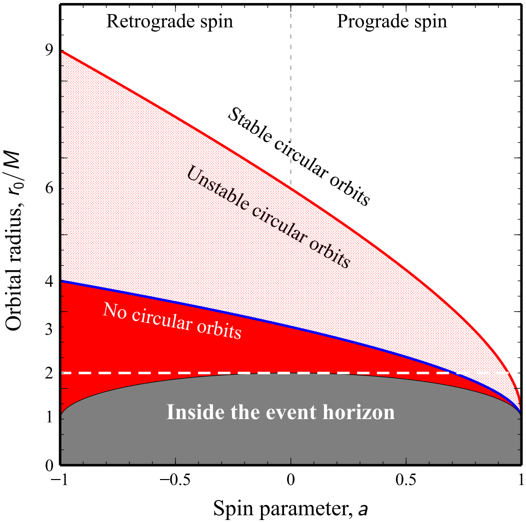
Transient instability of near-extremal BHs

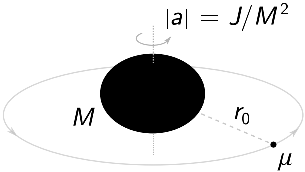
[Gralla, Zimmerman & Zimmerman, PRD 2016]



Circular orbit around a spinning black hole

[Bardeen, Press & Teukolsky, ApJ 1972]





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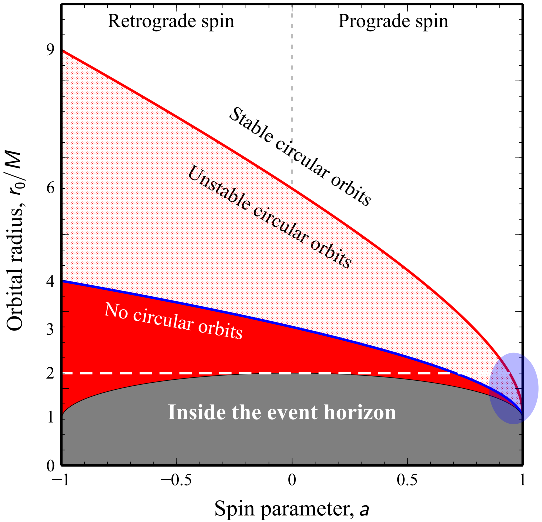
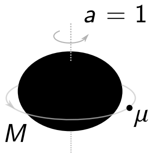
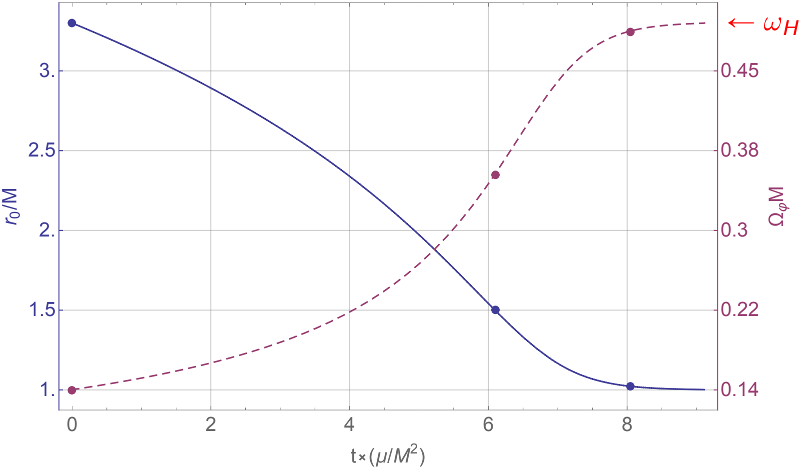


Near-horizon regime of a near-extremal black hole



Inspiral into a near-extremal black hole

[Gralla, Hughes & Warburton, PRD 2016]



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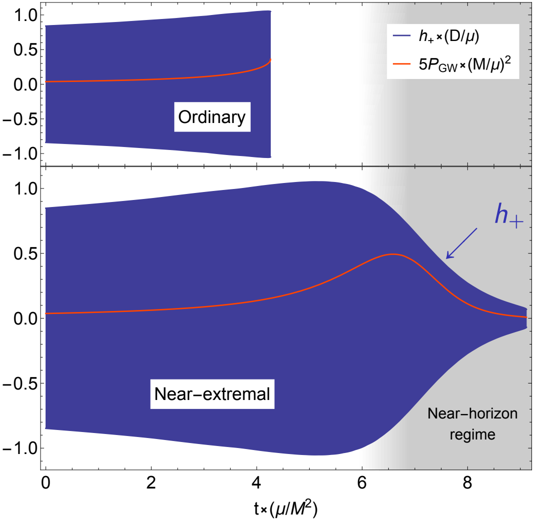
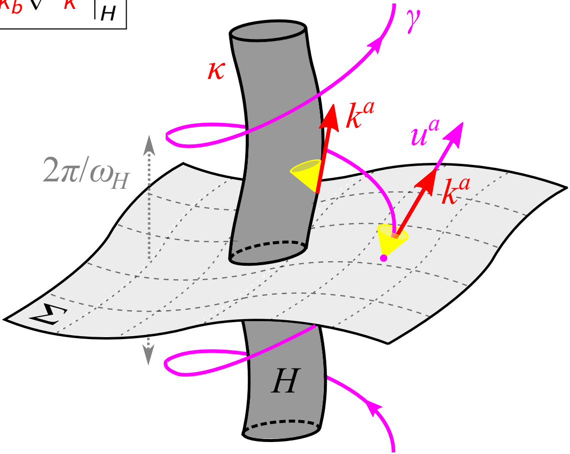


$$h_+ = \frac{\mu}{D} e^{-t/\tau} \sin\left(2\omega_H t\right)$$

Zeroth law for a black hole with moon

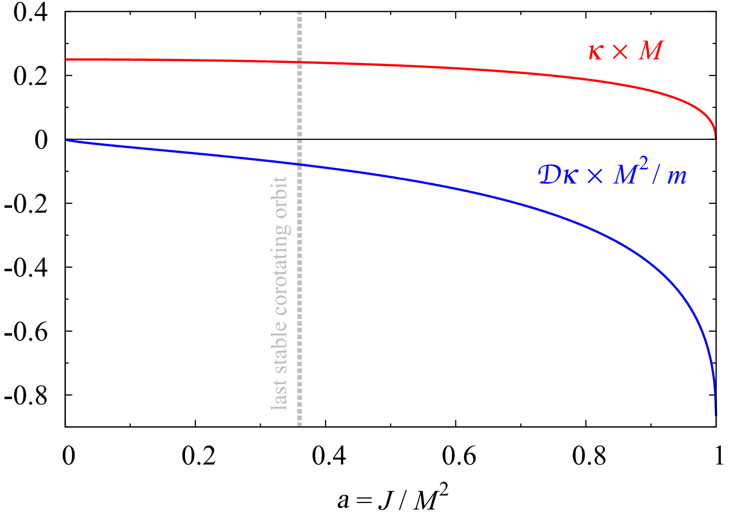
[Gralla & Le Tiec, PRD 2013]

$$\boxed{\kappa^2 = \tfrac{1}{2}\nabla_a k_b \nabla^b k^a\big|_H}$$



Perturbation in horizon surface gravity

[Gralla & Le Tiec, PRD 2013]

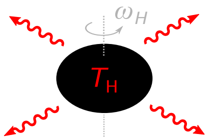


Thermodynamics of stationary black holes

[Hawking, Nature 1975]

- Quantum fields in a classical curved black hole spacetime
- *Stationary* black holes radiate particles at the temperature

$$T_{\mathsf{H}} = \frac{\hbar}{2\pi}\,\kappa$$



- Key result for the search of a quantum theory of gravity: string theory, loop quantum gravity, etc

Cooling a black hole with an orbiting moon

[Casals & Le Tiec, *in progress*]

- The constant surface gravity κ should correspond to the Hawking temperature T_H of the *perturbed* black hole:

$$\mathcal{D}T_\mathsf{H} = \frac{\hbar}{2\pi}\,\mathcal{D}\kappa < 0$$

- The moon has a cooling effect on the rotating black hole!
- Both rotationally-induced and tidally-induced deformations of a BH horizon have a cooling effect $\longrightarrow$ generic result?

Some open questions

[Casals & Le Tiec, *in progress*]

- Could an inspiraling small compact object end up corotating around a near-extremal black hole?
- Compute $\mathcal{D}\kappa$ analytically from a near-horizon analysis of a near-extremal black hole with a corotating moon
- Is the fact that $\kappa < 0$ connected to the Aretakis instability?
- Establish rigorously that $T_{\mathrm{H}} \propto \kappa$ in our physical setup
- What does it mean to have a negative temperature?