Dynamical extreme black hole horizons

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Extreme black holes: why care?

1. Observationally relevant:

   Astronomers observe many BHs spinning very rapidly

2. Theoretically fascinating:

   - hep-th: Quantum fluctuations in their near-horizon region
   - hep-th: Effective Field Theory breakdown near the horizon
   - math-ph: Non-linear stability with weak instability features

Rapidly spinning black holes

Annual Review of Astronomy and Astrophysics

Observational Constraints on Black Hole Spin

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Keywords

active galactic nuclei, accretion disks, general relativity, gravitational waves, jets

Abstract

The spin of a black hole is an important quantity to study, providing a window into the processes by which a black hole was born and grew. Furthermore, spin can be a potent energy source for powering relativistic jets and energetic particle acceleration. In this review, I describe the techniques currently used to detect and measure the spins of black holes. It is shown that:

- Two well-understood techniques, X-ray reflection spectroscopy and thermal continuum fitting, can be used to measure the spins of black holes that are accreting at moderate rates. There is a rich set of other electromagnetic techniques allowing us to extend spin measurements to lower accretion rates.
- Many accreting supermassive black holes are found to be rapidly spinning, although a population of more slowly spinning black holes emerges at masses above $M > 3 \times 10^7\,M_\odot$ as expected from recent structure formation models.
- Many accreting stellar-mass black holes in X-ray binary systems are rapidly spinning and must have been born in this state.
- The advent of gravitational wave astronomy has enabled the detection of spin effects in merging binary black holes. Most of the premerger

Rapidly spinning black holes

Gravitational wave event GW231123 also rapidly spinning

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GW231123: a Binary Black Hole Merger with Total Mass 190-265 $M_\odot$

THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION

(Compiled: 14 July 2025)

ABSTRACT

On 2023 November 23 the two LIGO observatories both detected GW231123, a gravitational-wave signal consistent with the merger of two black holes with masses $137^{+22}_{-17}\,M_\odot$ and $103^{+20}_{-52}\,M_\odot$ (90% credible intervals), at luminosity distance 0.7–4.1 Gpc and redshift of $0.39^{+0.27}_{-0.24}$, and a network signal-to-noise ratio of ∼22.5. Both black holes exhibit high spins, $0.90^{+0.10}_{-0.19}$ and $0.80^{+0.20}_{-0.51}$ respectively. A massive black hole remnant is supported by an independent ringdown analysis. Some properties of GW231123 are subject to large systematic uncertainties, as indicated by differences in inferred parameters between signal models. The primary black hole lies within or above the theorized mass gap where black holes between 60–130 $M_\odot$ should be rare due to pair instability mechanisms, while the secondary spans the gap. The observation of GW231123 therefore suggests the formation of black holes from channels beyond standard stellar collapse, and that intermediate-mass black holes of mass ∼200 $M_\odot$ form through gravitational-wave driven mergers.

1. INTRODUCTION

From 2015 to 2020 the LIGO-Virgo-KAGRA Collaboration identified 69 gravitational-wave signals from binary black hole mergers with false alarm rates below one per year (Aasi et al. 2015; Acernese et al. 2015;

tal masses (Abbott et al. 2023a; Wadekar et al. 2023), none have false alarm rates less than 1 per year; in addition, GW231123 has both a large signal-to-noise ratio and high statistical significance. Such high masses and spins pose a challenge to our most accurate waveform

Note: Our best shot at observing extreme BH dynamics: EMRIs at LISA

AdS_2 and near-extreme black holes

Near the horizon of (near-)extreme black holes spacetime is AdS_2-like

- Extreme Reissner-Nordstrom; Bertotti-Robinson: [Bertotti, Robinson (1959)]

$$ds^2 = M^2\left[-r^2dt^2 + \frac{dr^2}{r^2} + d\Omega^2\right], \qquad F_{\theta\phi} = M\sin\theta$$

- Extreme Kerr; NHEK: [Bardeen, Horowitz (1999)]

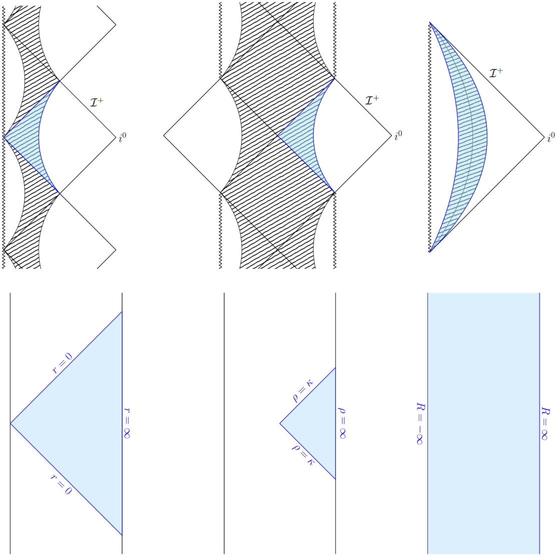
$$ds^2 = 2M^2\Gamma(\theta)\left[-r^2dt^2 + \frac{dr^2}{r^2} + d\theta^2 + \Lambda(\theta)^2(d\phi + r\,dt)^2\right]$$

- Applies for a wide class of theories in any D [Kunduri, Lucietti, Reall (2007)]

  Kinematics of extremal horizon $\rightarrow$ scaling symmetry
  Einstein equations $\rightarrow$ $SL(2)$

- Near-horizon approximations *and* Exact solutions

$AdS_2 \times S^2$ from static RN



Diff and $SL(2)$ invariant characterization of "*anabasis*" perturbations of AdS_2 can tell apart the asymptotically flat solution. [Hadar, Lupsasca, APP (2021)]

Gravitational dynamics of AdS_2 throats

- *Nearly* decoupled from far asymptotic region
- Governed by effective 2D models like Jackiw-Teitelboim (JT) gravity
- Backreaction —classical or quantum— is often solvable

[Review: Mertens, Turiaci (2023)]

Currently in hep-th:

- Large quantum mechanical fluctuations in AdS_2 throats
  $\Rightarrow$ $S_{\rm BH}$ diminishes as $T \to 0$ (non-supersymmetric BHs) [Iliesiu, Turiaci (2021)]
- EFT of General Relativity breaks down near extreme horizons
  $\Rightarrow$ Higher curvature corrections/axions lead to singular horizon

[Horowitz, Kolanowski, Remmen, Santos (2023-2026)]

In this talk: Pure Einstein-Maxwell and $\hbar \to 0$ *first*.

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Extreme BHs in mathematical relativity

- Extreme RN can form in finite time by collapse of a charged scalar

  (in opposition to the Third Law of Black Hole Mechanics) [Kehle, Unger (2022)]

- Extreme RN can lie on the threshold of BH formation/dispersion

  (Einstein-Maxwell-Vlasov theory) [Kehle, Unger (2024)]

- Extreme RN is non-linearly stable: [Angelopoulos, Kehle, Unger (2024, 2026)]

  - Proof in spherical symmetry, Einstein-Maxwell-*neutral* scalar
  - Presence of Aretakis instability *ad infinitum*
  - Lie on the threshold of black hole formation

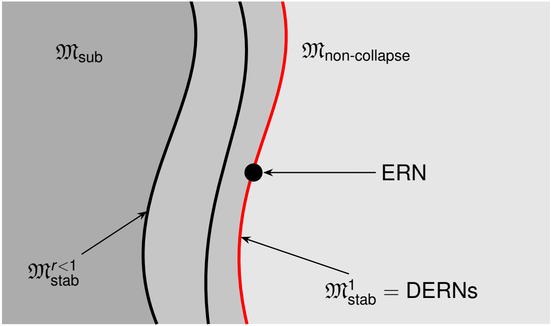
Due to the Aretakis instability these are not static BHs:

Dynamical Extreme Reissner-Nordström (DERN)

First conjectured numerically by: [Murata, Reall, Tanahashi (2013)]

Local picture of moduli space of initial data

[AKU (2024, 2026)]



Note: No more difficult to make a stable DERN ($r = 1$) than any other fixed charge-to-mass ratio ($r < 1$) sub-extreme RN.

Conjecture: For complete initial data $\mathfrak{M}_{\text{non-collapse}} = \mathfrak{M}_{\text{dispersion}}$
"**extremal critical collapse**"

The linear Aretakis instability and its non-linear fate

A weak linear instability

[Aretakis (2011)]

$$\Box\sigma = 0$$

- **Decay:** The field σ decays on and outside $\mathcal{H}^+$.
- **Non-Decay:** Transverse derivatives $\partial_\perp^k \sigma$ do **not** all decay on $\mathcal{H}^+$.

Lots of followup $\to$ it's a robust feature of all perturbed extreme BH horizons.

The *generic* non-linear fate

[MRT (2013), AKU (2024,2026)]

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 2\left(F_{\mu\rho}F_\nu{}^\rho - \frac{1}{4} g_{\mu\nu} F^2\right) + \nabla_\mu\sigma\nabla_\nu\sigma - \frac{1}{2} g_{\mu\nu}(\nabla\sigma)^2$$

$$\mathrm{d}F = \mathrm{d}\star F = 0\,, \qquad \Box\sigma = 0$$

For a neutral scalar $\sigma \sim \mathcal{O}(\epsilon)$ gravitational backreaction regulates instability:

- BH settles to **sub-extreme RN** with $\kappa = O(\epsilon)$
- **Instability survives transiently** for $\mathcal{O}(1/\epsilon)$ time

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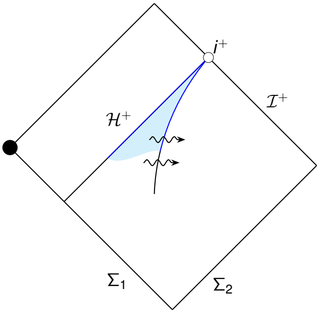
Dynamical Extreme Reissner-Nordström (DERN)

- Initial data on $\Sigma_1 \cup \Sigma_2$ close to ERN,

$$M_i(\epsilon) = Q + \mathcal{O}(\epsilon^2) \qquad \text{and} \qquad \sigma \sim \mathcal{O}(\epsilon)$$

- There is data given by $M_\star(\epsilon)$ such that
  for $M_i > M_\star(\epsilon) \longrightarrow$ sub-extreme RN
  for $M_i < M_\star(\epsilon) \longrightarrow$ super-extreme RN
  for $M_i = M_\star(\epsilon) \longrightarrow$ **DERN**
- DERN features:
  (i) The metric tends to static ERN
  (ii) The scalar field exhibits the linear Aretakis instability *ad infinitum*.



$\Longrightarrow$ DERN at late times = dynamical extreme horizon + static ERN exterior

Our Result [APP, Rosen, Tsaraktsidis (2026)] : Explicit closed-form description of the late-time near-horizon approach to DERN. Obtained using JT gravity and identifying the **the correct boundary conditions** for (i) and (ii).

JT gravity

$$S_{JT} = \frac{1}{2}\int d^2x\sqrt{-g}\,\Phi\,(R+2) - \frac{1}{2}\int d^2x\sqrt{-g}\,(\nabla\sigma)^2$$

- Describes s-wave dynamics of 4D Einstein-Maxwell-neutral scalar near an $AdS_2 \times S^2$ black hole throat close to extremality. ($L_{AdS_2} \equiv 1$)
- Scalar σ: direct descendant of the 4D spherically symmetric scalar
- Dilaton Φ: variation in the area of S^2 as one climbs out of the throat.
- EOMs

$$R[g] = -2\,, \qquad \Box\sigma = 0\,,$$

$$g_{\mu\nu}\Box\Phi - \nabla_\mu\nabla_\nu\Phi - g_{\mu\nu}\Phi = \mathcal{T}_{\mu\nu}[\sigma]$$

$\Longrightarrow$ Metric is fixed to AdS_2: $ds^2 = -r^2dt^2 + \frac{dr^2}{r^2} = \frac{-4dUdV}{\sin^2(U-V)}$

$\Longrightarrow$ Matter propagates freely on it: $\sigma = f(U) + g(V)$

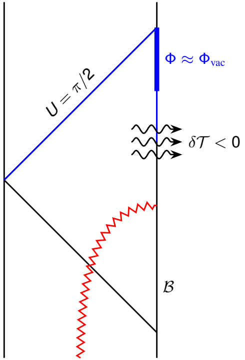
The non-linear gravitational dynamics is encoded in the solution for Φ:

JT gravity

$$\Phi = \Phi_{\text{vac}} + \Phi_{\text{bal}} - \frac{1}{\sin(U-V)} \int_V^{\pi/2} \mathrm{d}X \sin(U-X) \sin(X-V)\, \delta\mathcal{T}(X)\,,$$

Measures the size of the transverse S^2 as one moves outwards from $AdS_2 \times S^2$

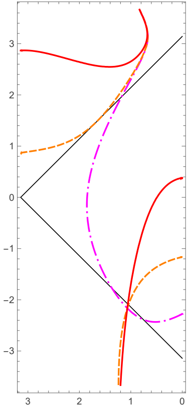
- Φ_{vac} vacuum soln corresp. to a static RN
- $\Phi_{\text{bal}} \propto \int_V^U \mathrm{d}X\, f'(X)^2 \ldots$ solution with vanishing net matter flux along $\mathcal{B}\,(U = V)$
- $\delta\mathcal{T}(U) \equiv (\mathcal{T}_{VV} - \mathcal{T}_{UU})\,|_{\mathcal{B}} = g'(U)^2 - f'(U)^2$ the net matter flux through $\mathcal{B}$
- **DERN in JT gravity via boundary conditions at late times on $\mathcal{B}$:**
  - (i) Metric glues onto ERN in the exterior: $\implies \Phi \approx \Phi_{\text{vac}}^{\text{ERN}}$
  - (ii) Scalar exhibits linear Aretakis: $\implies \delta\mathcal{T}(\pi/2) = 0,\ \delta\mathcal{T}'(\pi/2) = 0$



DERN in JT gravity: singularity avoidance

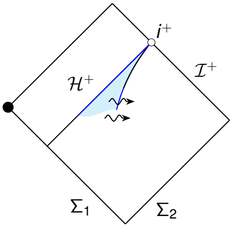
- Singularity locus: $1 + \Phi = 0$
  (corresponds to $r = 0$ in 4D)
- Need a singularity-free horizon $U = \pi/2$
- Requires **sufficiently leaky** $\delta\mathcal{T} < 0$
- Example: an explicit DERN via
  $\Phi^{\mathrm{ERN}}_{\mathrm{vac}} = \frac{4\cos U \cos V}{\sin(U-V)}$, $f(U) = -2U$
  $\delta\mathcal{T}(U) = -A(\pi/2 - U)^2$ with $A > A_{\mathrm{min}} \approx 2.76$

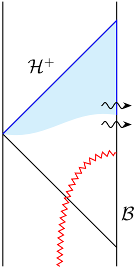
  On the right: $A = A_{\mathrm{min}}/10$, $A = A_{\mathrm{min}}$, $A = 10A_{\mathrm{min}}$



$$\Phi^{\mathrm{DERN}} = \frac{4\cos U \cos V}{\sin(U-V)} + \cot(U-V)\left[2(U-V) - \frac{A}{6}\left(\frac{\pi}{2} - V\right)^3 + \frac{A}{4}\left(\frac{\pi}{2} - V\right)\right] - \frac{A}{4}\frac{\sin(U)\cos(V)}{\sin(U-V)} + \frac{A}{4}\left(\frac{\pi}{2} - V\right)^2 - 2$$

Summary





- **DERN exists:** Provided explicit closed-form description of the late-time near-horizon approach. Requires final burst of outgoing matter flux.
- **JT gravity:** Exact solutions with boundary conditions at AdS_2 boundary, matching linear Aretakis for matter and critical dilaton for the geometry
- **To do list:**
  - $\rightarrow$ Charged matter; numerically: [Gelles, Pretorius (2026)]
  - $\rightarrow$ Pure gravity; Dynamical Extreme Kerr?
  - $\rightarrow$ 3[rd] Law of BH *thermodynamics*? QM must intervene!
  - $\rightarrow$ ...

Thank you