Black hole accretion in the era of GPU-accelerated particle-in-cell simulations

John M. Mehlhaff,[†] Alexander Y. Chen, Martin Luepker, Yajie Yuan

Physics Department and McDonnell Center for the Space Sciences, Washington University in St. Louis; MO, 63130, USA

[†] mehlhaff@wustl.edu

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Kinetic accretion modeling and GPUs

- Plasmas accreting onto low-luminosity black holes (BHs) are collisionless
- Ideal general relativistic magnetohydrodynamics (GRMHD) breaks down here, missing nonthermal effects and kinetic instabilities
- General relativistic particle-in-cell (GRPIC) simulations describe the global dynamics self-consistently but at high computational cost
- GRPIC accretion models starting from an orbiting plasma virtually require GPU acceleration

We present the first GRPIC simulations of accretion starting from a finite-angular-momentum plasma

GPUs make otherwise very expensive accretion simulations fairly cheap

A taxing separation of scales

Space:
- Must resolve electron skin depth d_e everywhere: $\Delta r < d_e$
- Box must span whole torus: $r_{\max} = 85 r_g$
- Need to fit MRI wavelength $\lambda_{\rm MRI}$ in between: $d_e \ll \lambda_{\rm MRI} \ll r_{\max}$

$\Rightarrow 4096 \times 4096$ grid.

Time:
- Δt pinned to cell light-crossing time: $\Delta t \lesssim 10^{-3} r_g/c$
- Fully developed accretion state requires $t_{\max} \sim 2500\, r_g/c$

$\Rightarrow$ millions of time steps / run.

Aperture [2]: GPU-accelerated GRPIC

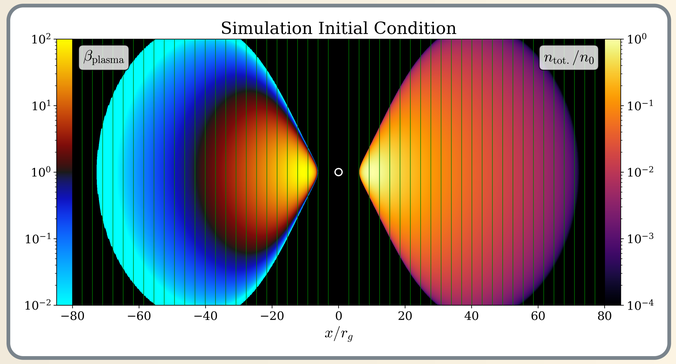
Speed ..... ~ 4 GPU·ns/(ptcl·step)
Per-run cost ..... ~ 400 GPU·hr

Typical CPU-based GRPIC

Speed ..... ~ 4 CPU·μs/(ptcl·step)
Per-run cost ..... $\sim$ 400k CPU·hr

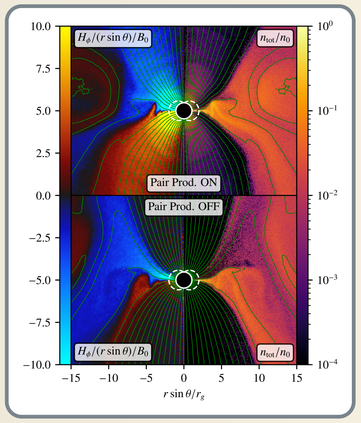
$\Rightarrow$ *$4096^2\times$ millions-of-steps is much more feasible on GPUs.*

Setup: the Luepker torus



- Begin from the *Luepker torus* [1]: a stable, collisionless plasma equilibrium orbiting a Kerr BH.
- Add a weak large-scale vertical (Wald) field to seed the magnetorotational instability (MRI) and provide magnetic flux.
- Pure $e^{\pm}$ plasma torus; vacuum exterior (no density floors in GRPIC).
- Evolved on a 4096^2 logarithmic Kerr-Schild grid, $r_g \leq r \leq 85\, r_g$

Jet launch might require pair creation



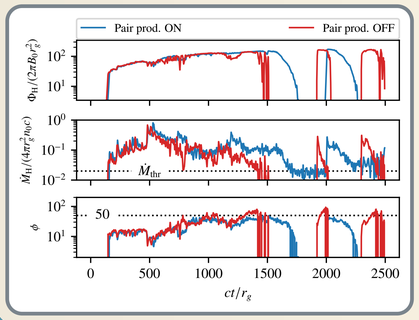
Two runs: identical except $e^{\pm}$ pair production toggled ON-vs-OFF

Pair Prod. ON
- Pairs populate BH-anchored field lines near horizon
- Activates the Blandford-Znajek (BZ) mechanism [3]; jet launches

Pair Prod. OFF
- Funnel remains a vacuum
- Starves the Blandford-Znajek mechanism of charge; no jet

GRPIC captures vacuum regions that are inaccessible to GRMHD, showing jet launch may hinge on the pair supply

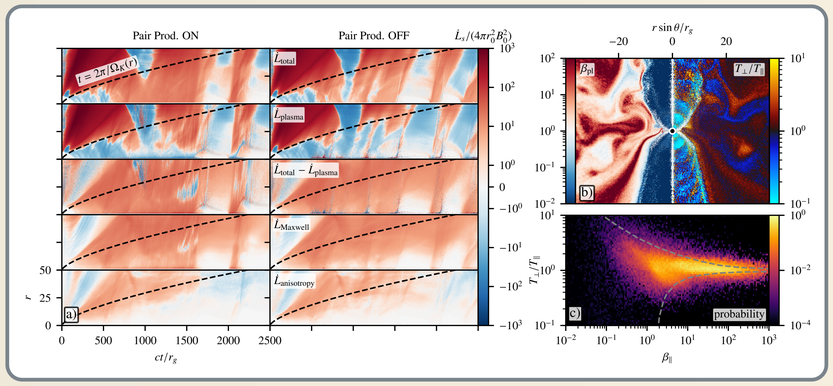
Simulations look like kinetic MADs



Horizon magnetic flux accumulates, saturates, and erupts, reproducing magnetically arrested disk (MAD) cycles observed in GRMHD.

With pair production, eruptions last $\sim 100\, r_g/c$ (equatorial reconnection); in vacuum, flux escapes in a few r_g/c.

Kinetic micro-instabilities keep angular-momentum transport fluid-like



a) Spacetime diagrams of angular-momentum flux decomposed into advective (plasma), magnetic (Maxwell), and pressure-anisotropy contributions

b) High-β (low-field) regions show little temperature/pressure anisotropy, $T_\perp/T_\parallel$

c) Joint probability distribution of temperature anisotropy $T_\perp/T_\parallel$ and $\beta_\parallel$. Anisotropy is pinned near the thresholds of the mirror and firehose instabilities

Micro-instabilities provide an effective collisionality, regulating nonideal stress and keeping fluid torques dominant.

Conclusions and outlook

- First GRPIC accretion model starting from an orbiting plasma thanks to GPU acceleration
- Validated GRMHD: kinetic instabilities $\rightarrow$ fluid-like transport
- Beyond GRMHD: pair creation enables a BZ jet
- Next: 3D plus a nontrivial ion-to-electron mass ratio

GPUs change global kinetic BH accretion from very difficult or impossible to feasible and even routine.

References and acknowledgments

[1] Luepker M., Yuan Y., Chen A. Y., 2026, ApJ, 996, 75
[2] Chen A. Y., Luepker M., Yuan Y., 2025, arXiv:2503.04558 (Aperture)
[3] Blandford R. D., Znajek R. L., 1977, MNRAS, 179, 433

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