Simulations of tilted black hole accretion

Sasha Tchekhovskoy (Northwestern)

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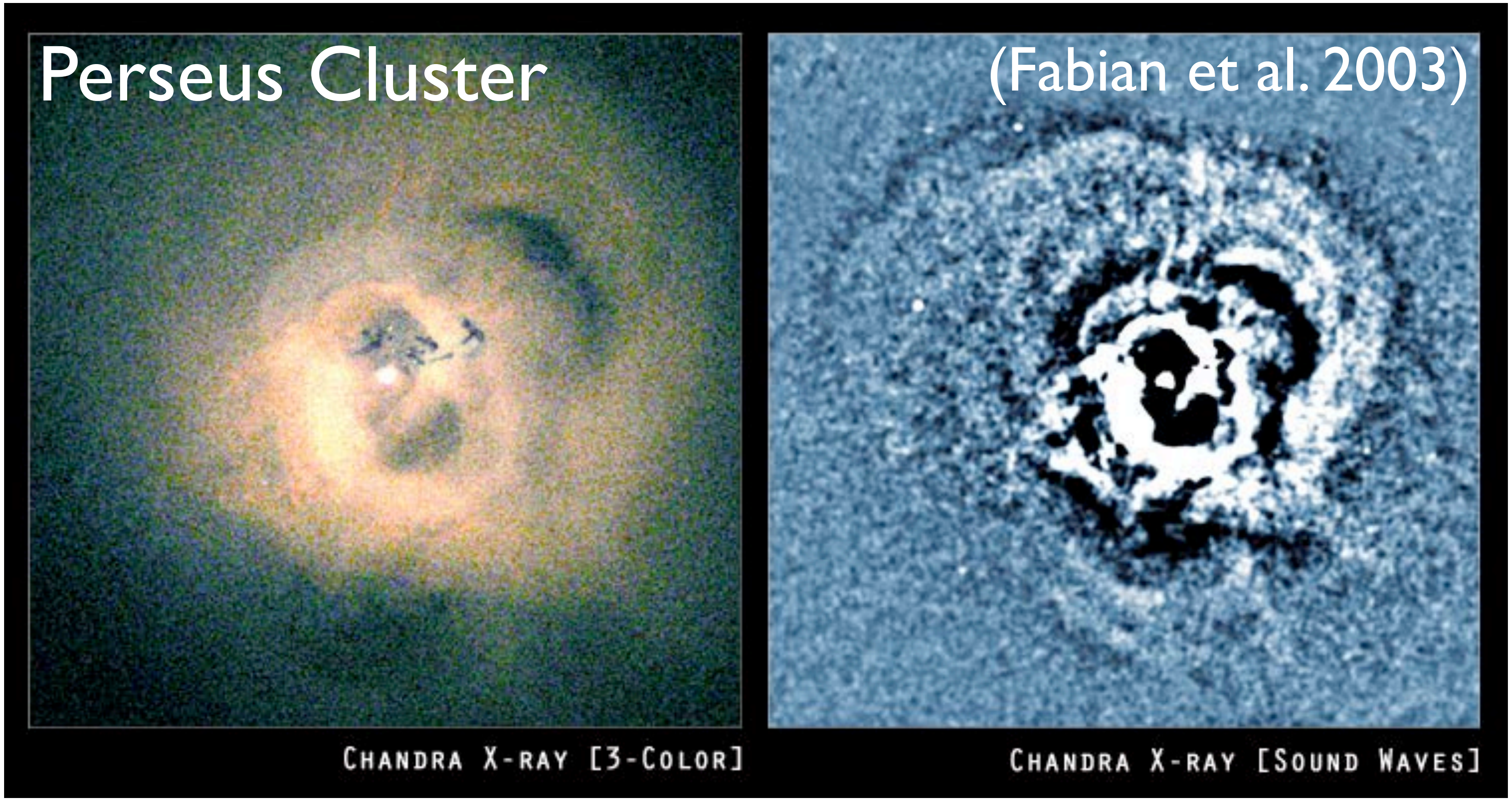
How Do Black Holes Explode Galaxies/Clusters?



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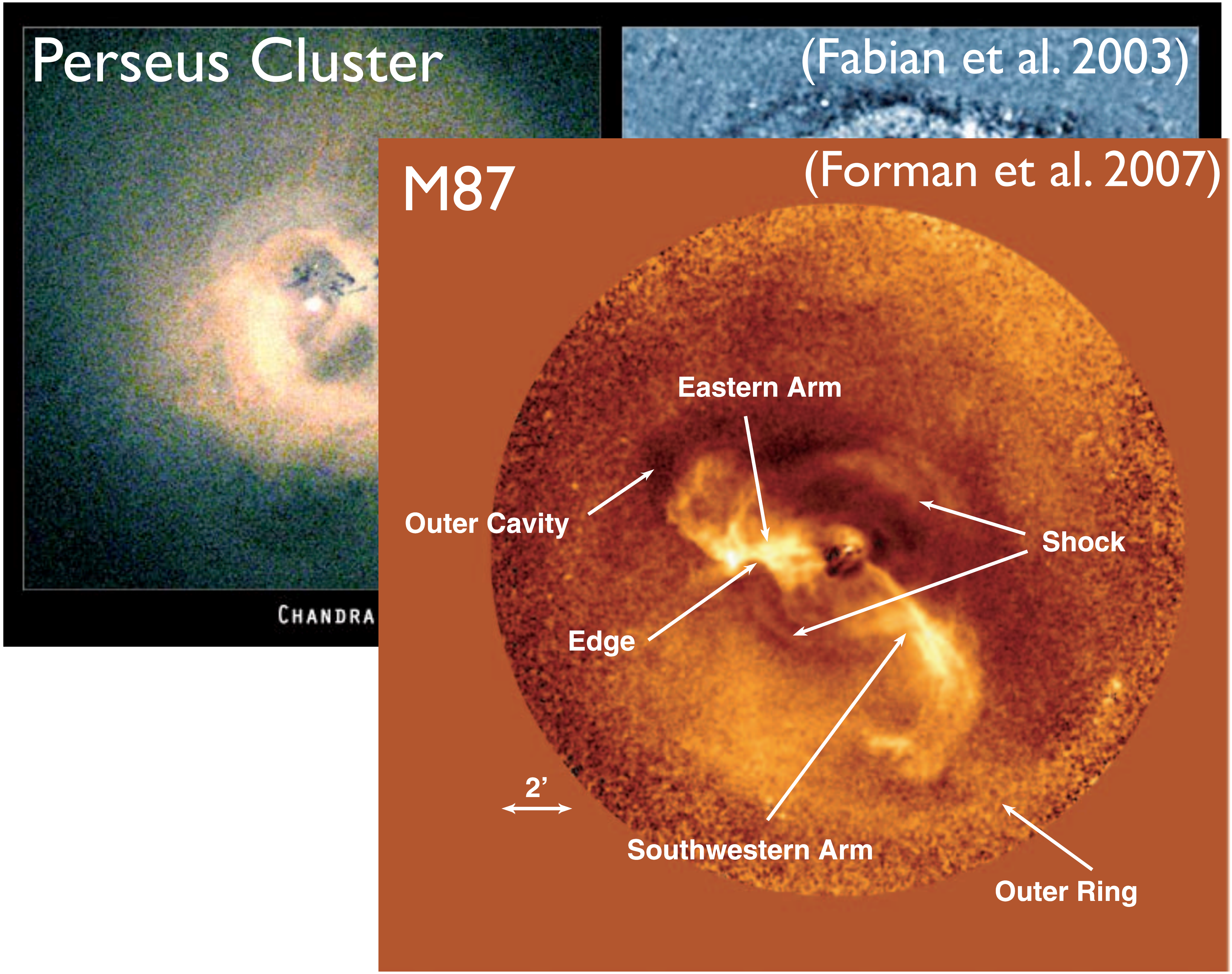

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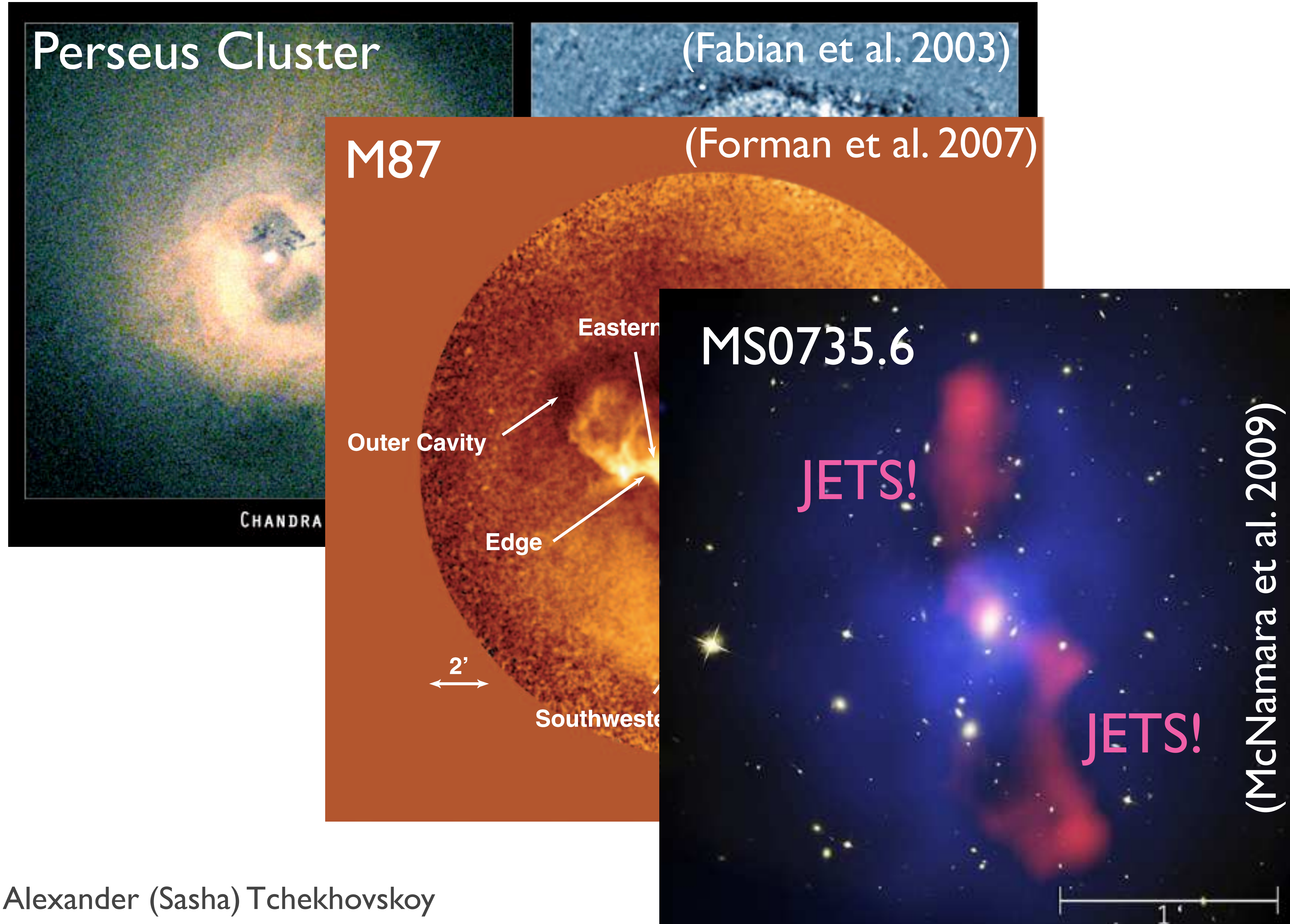
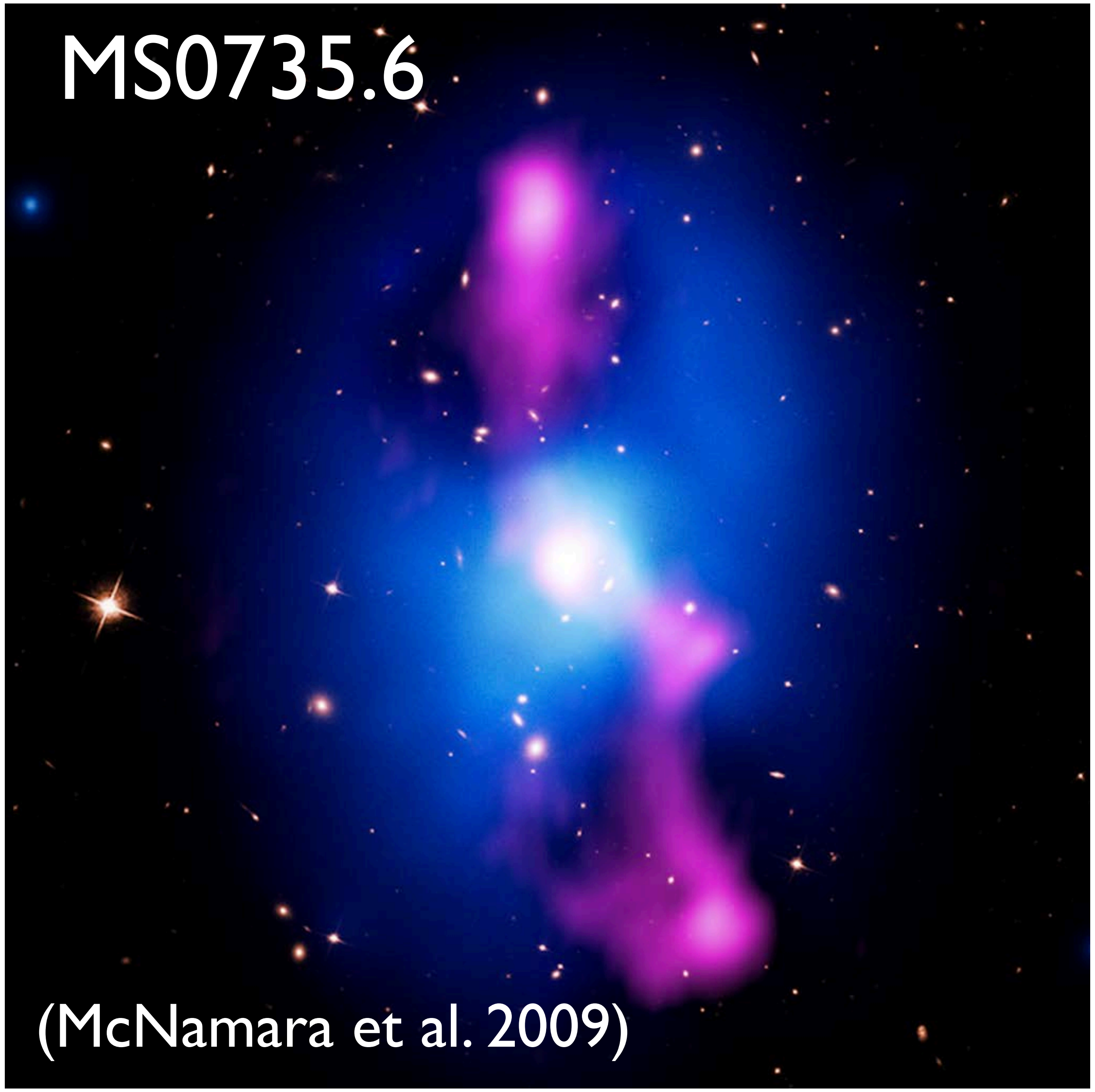


We are Missing Something Important!



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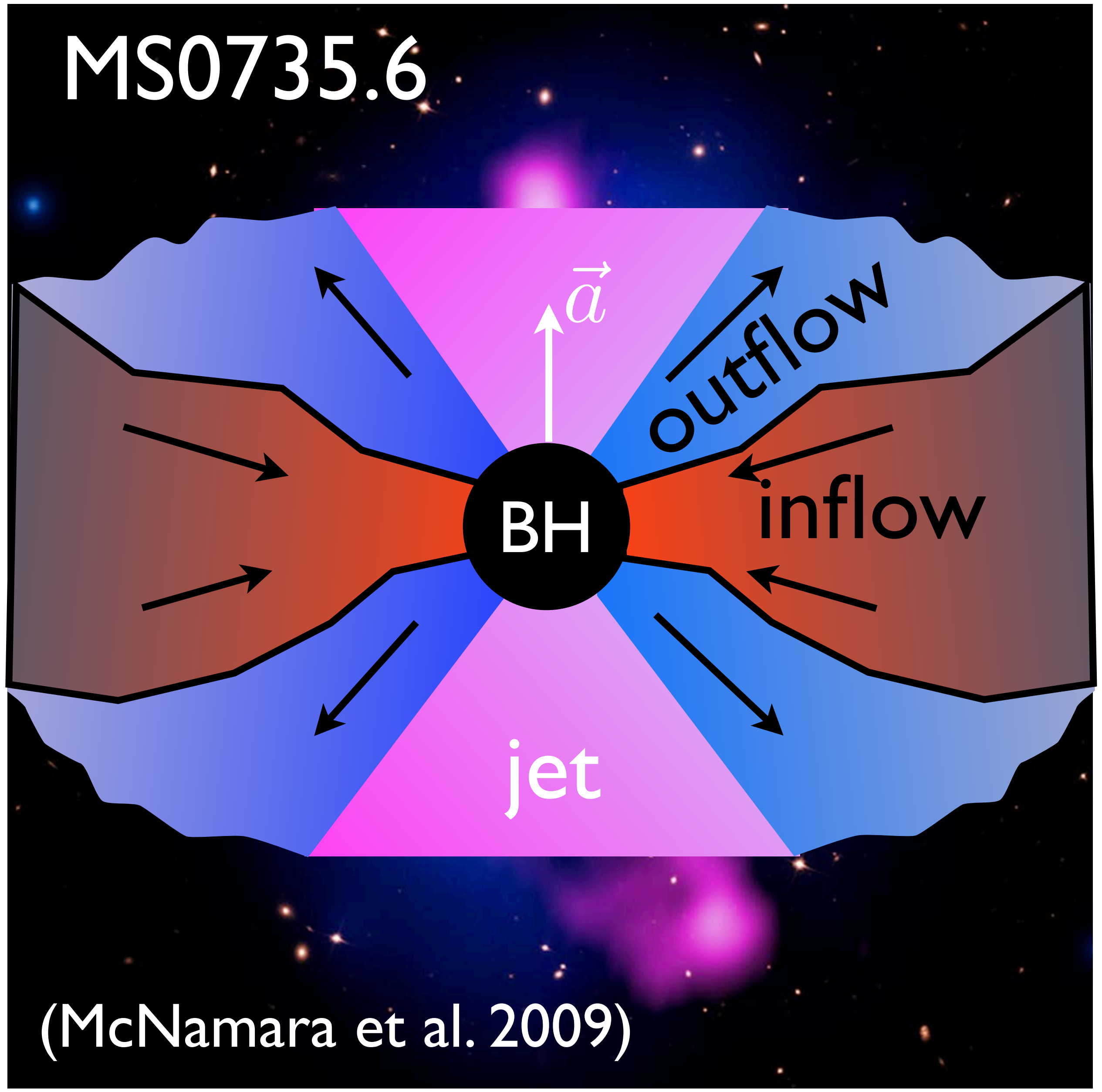

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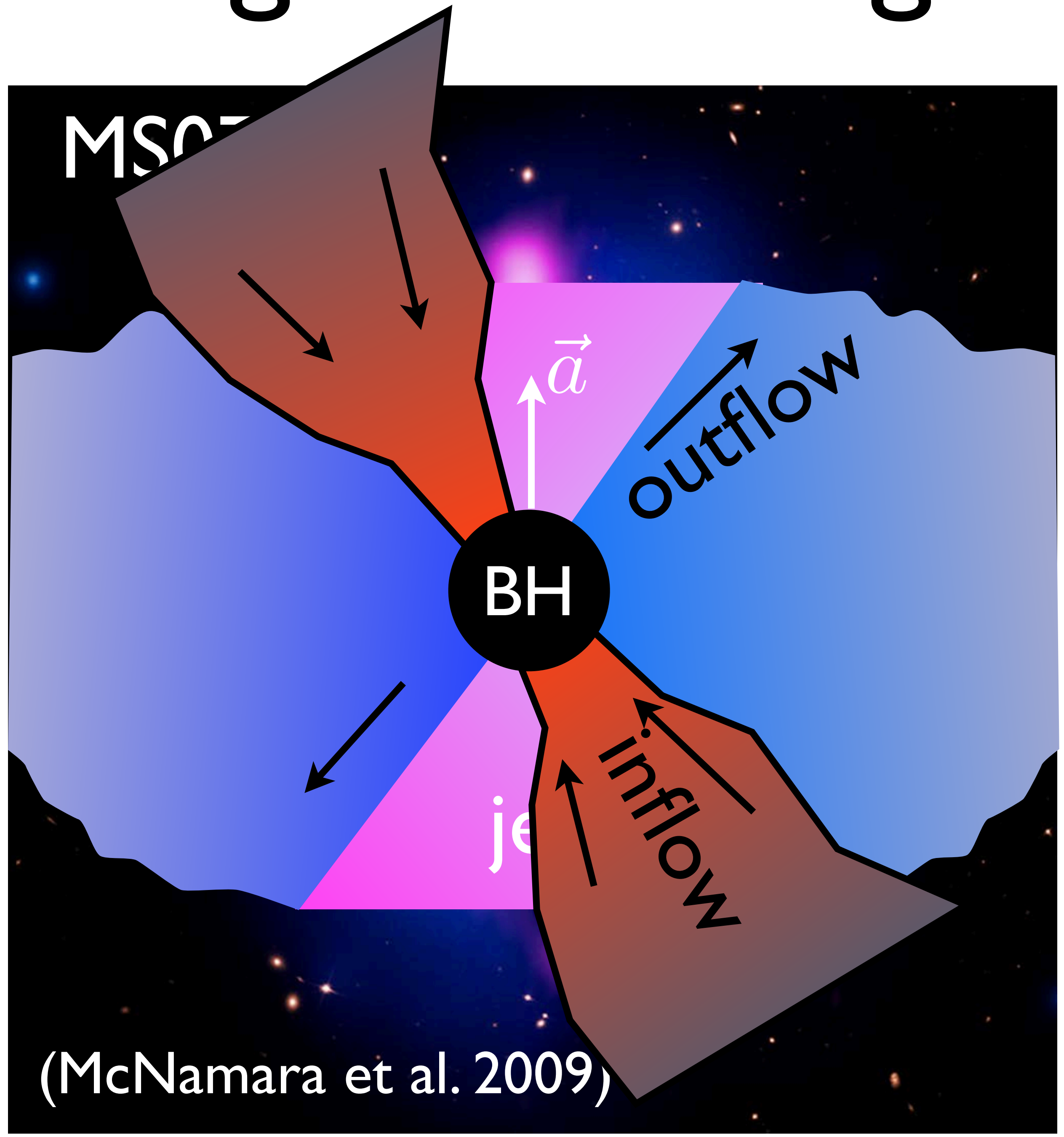

YES: typical disks are **tilted**

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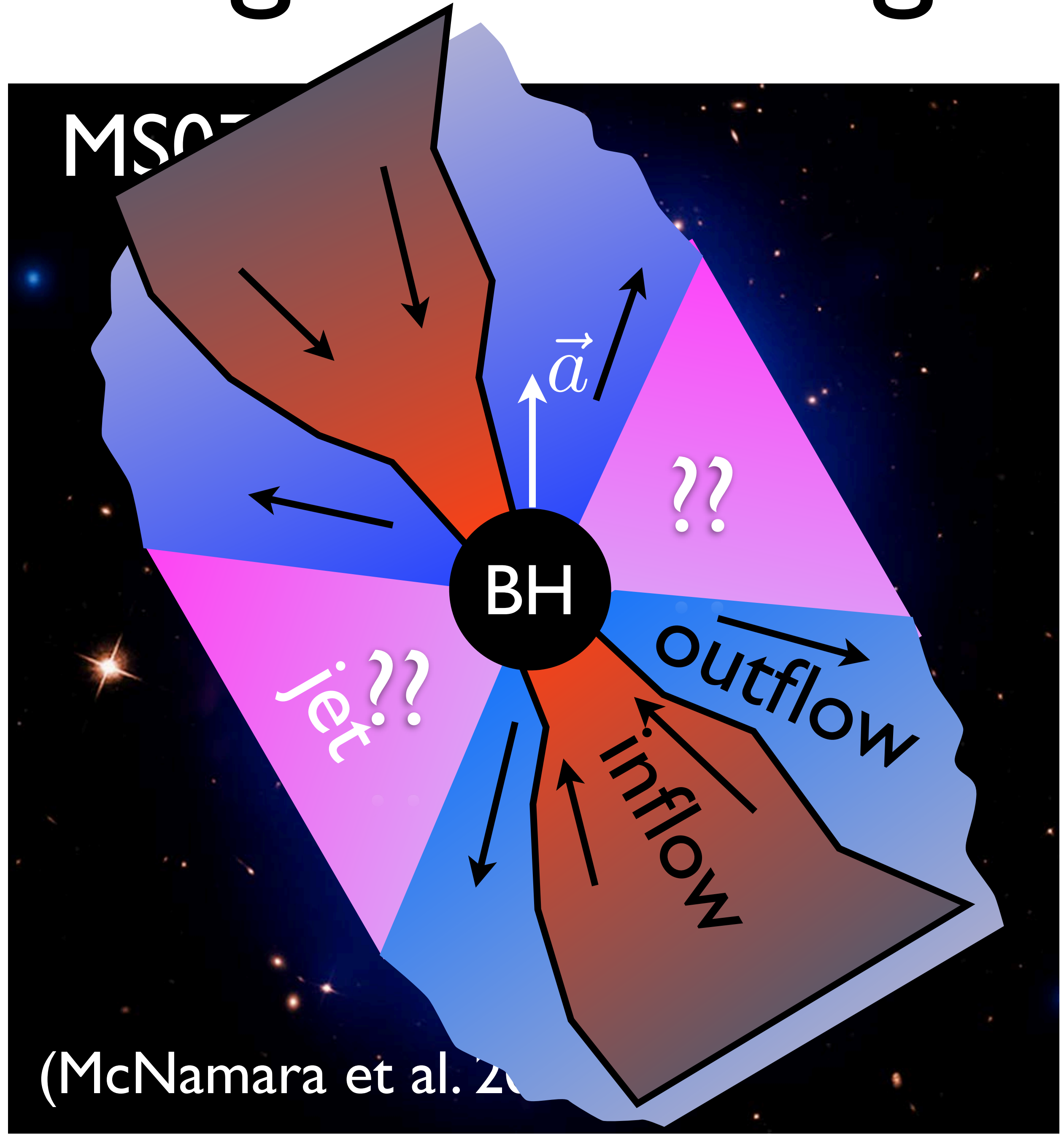
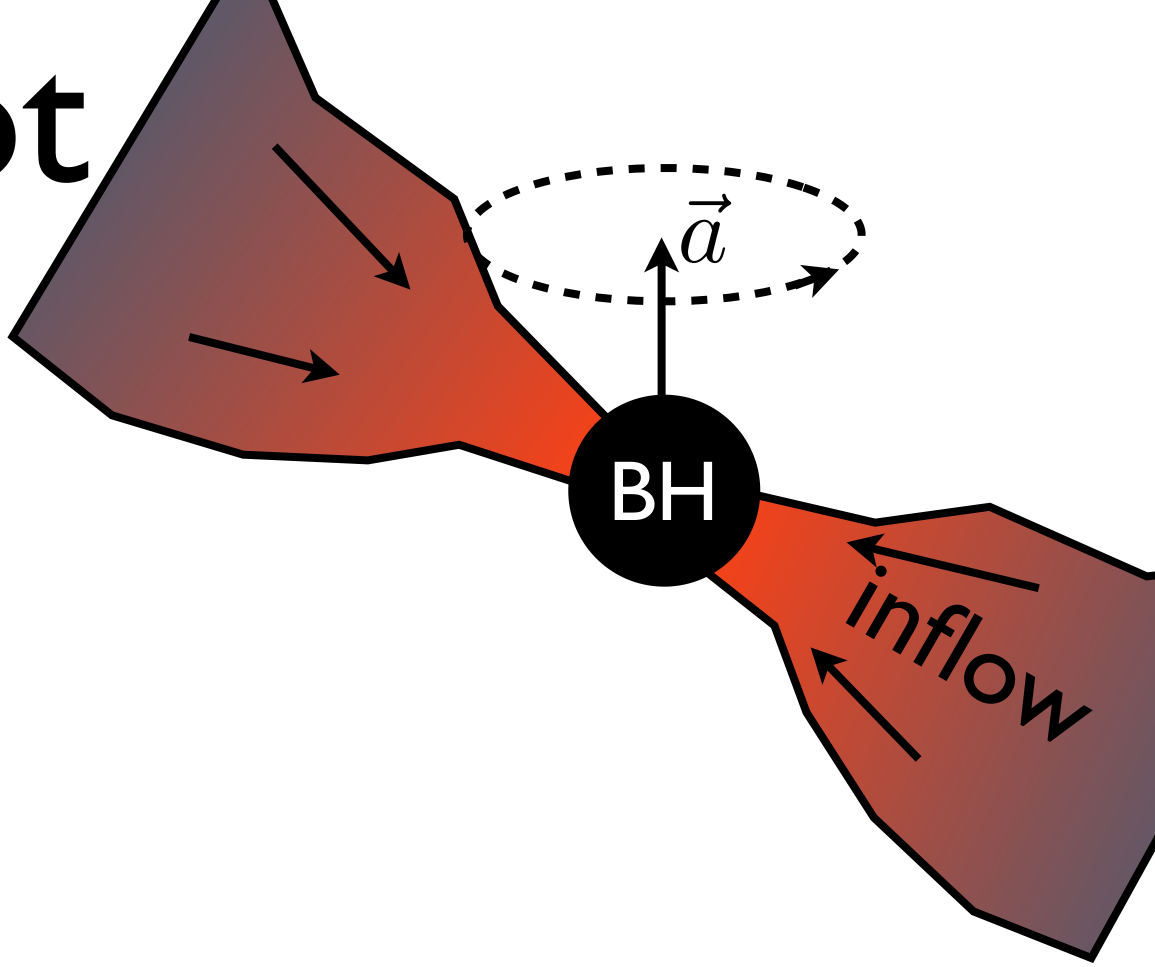


YES: typical disks are **tilted**

No: we do not understand them (yet)

Tilted Disks are Hot

- **Thick disks** precess due to general relativistic frame dragging by BH spin
  (Fragile et al. 2005, 2007, Teixeira 2014)



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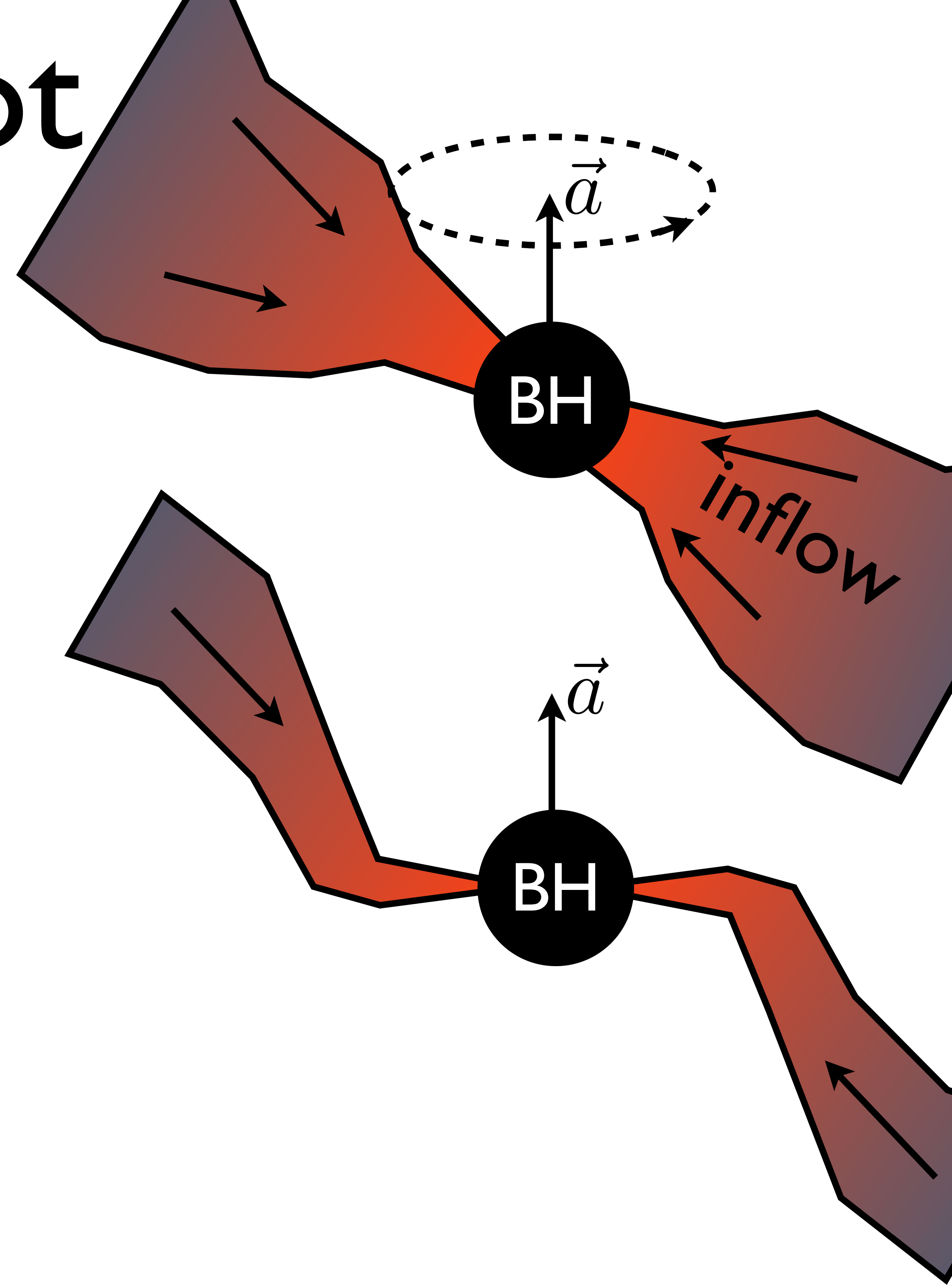
  - *Do thin disks align in GR? Do they form jets?*



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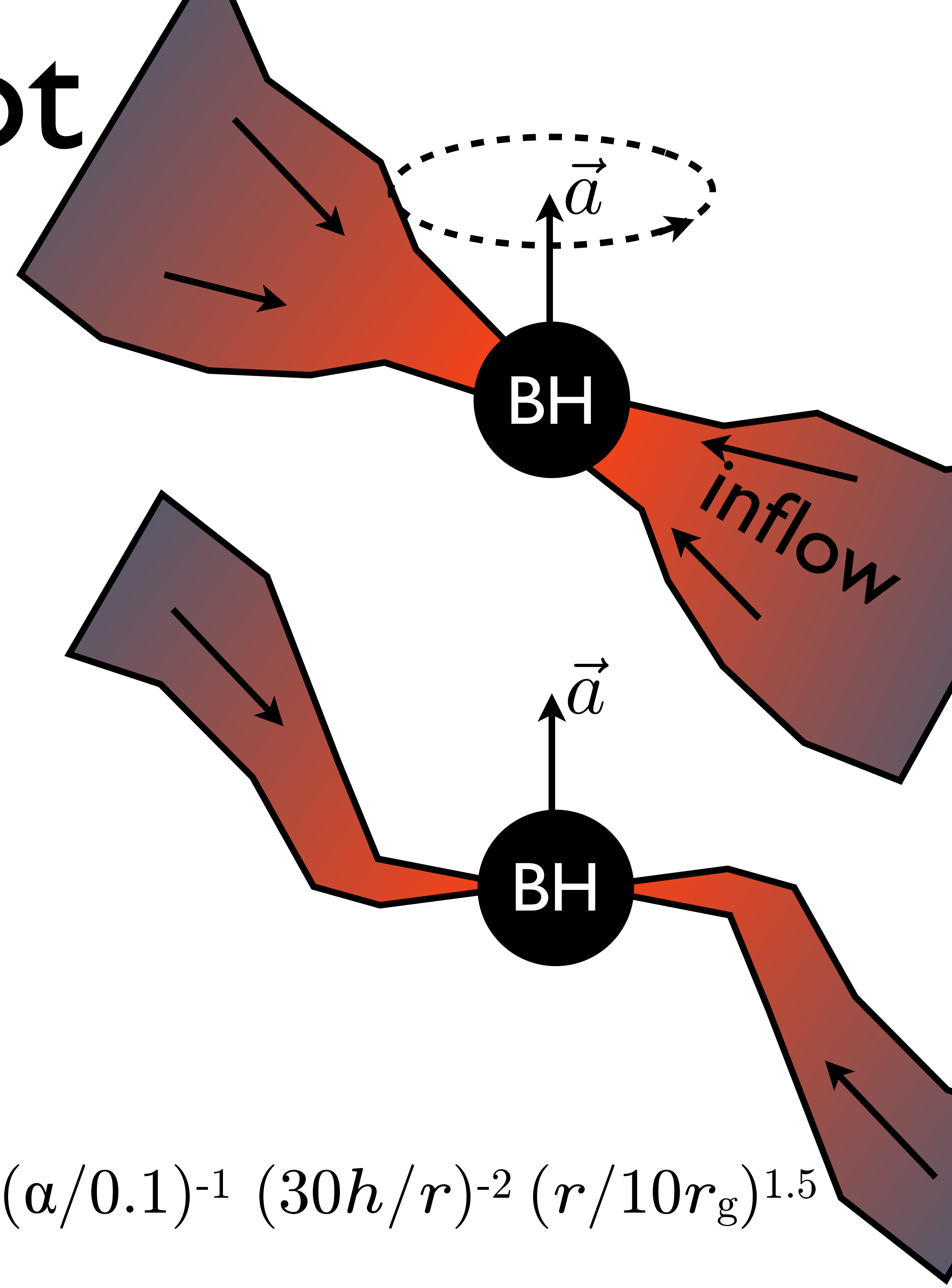
- Challenge: **enormous dynamical range**. Need to resolve thin disk *over* long run times:
  - prohibitive cost $\propto (h/r)^{-5}$
  - very long accretion time: $t = 4\times10^5\, r_g/c\ (\alpha/0.1)^{-1}\ (30h/r)^{-2}\ (r/10r_g)^{1.5}$
- How could one possibly pull this off??!



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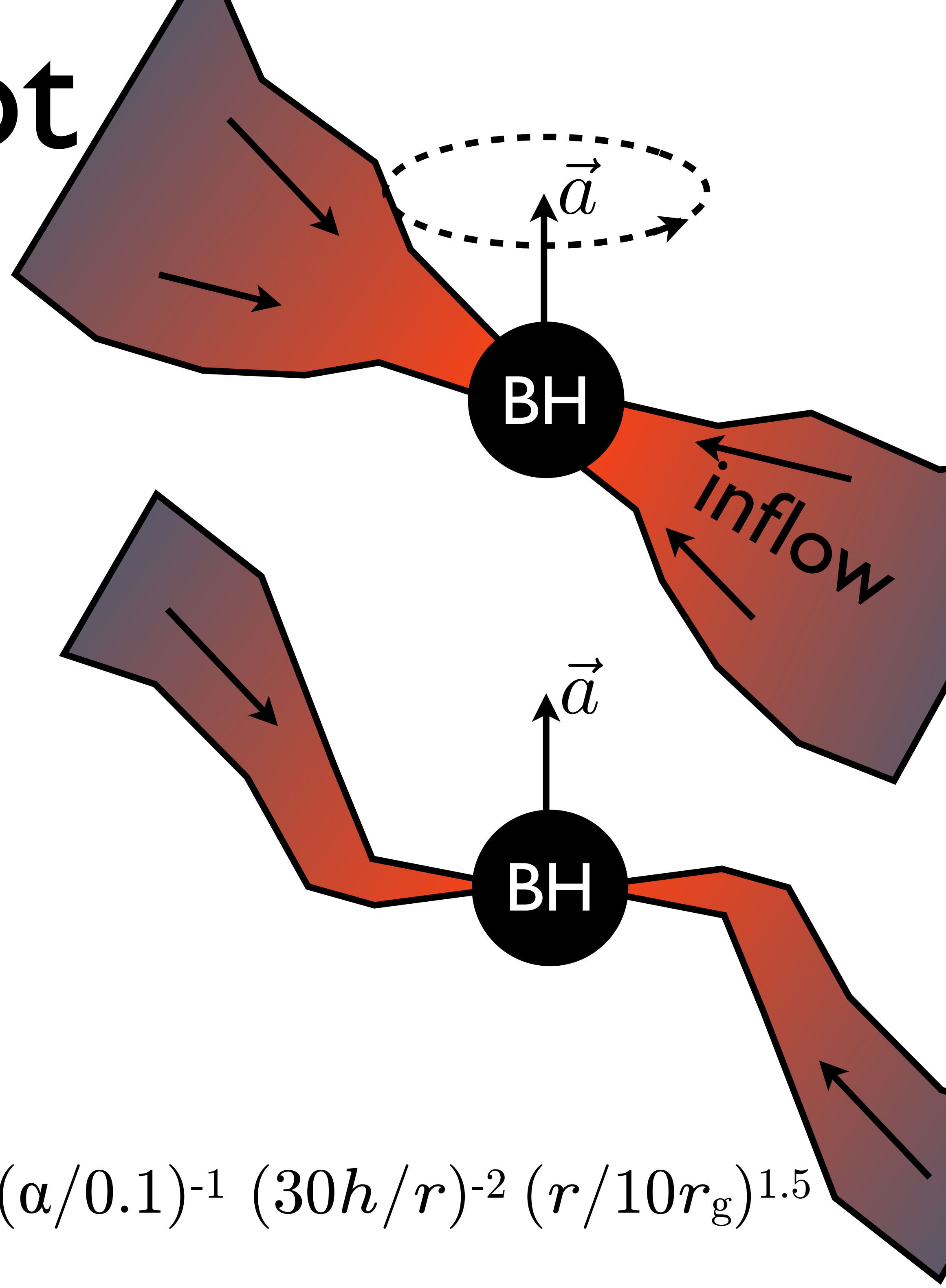

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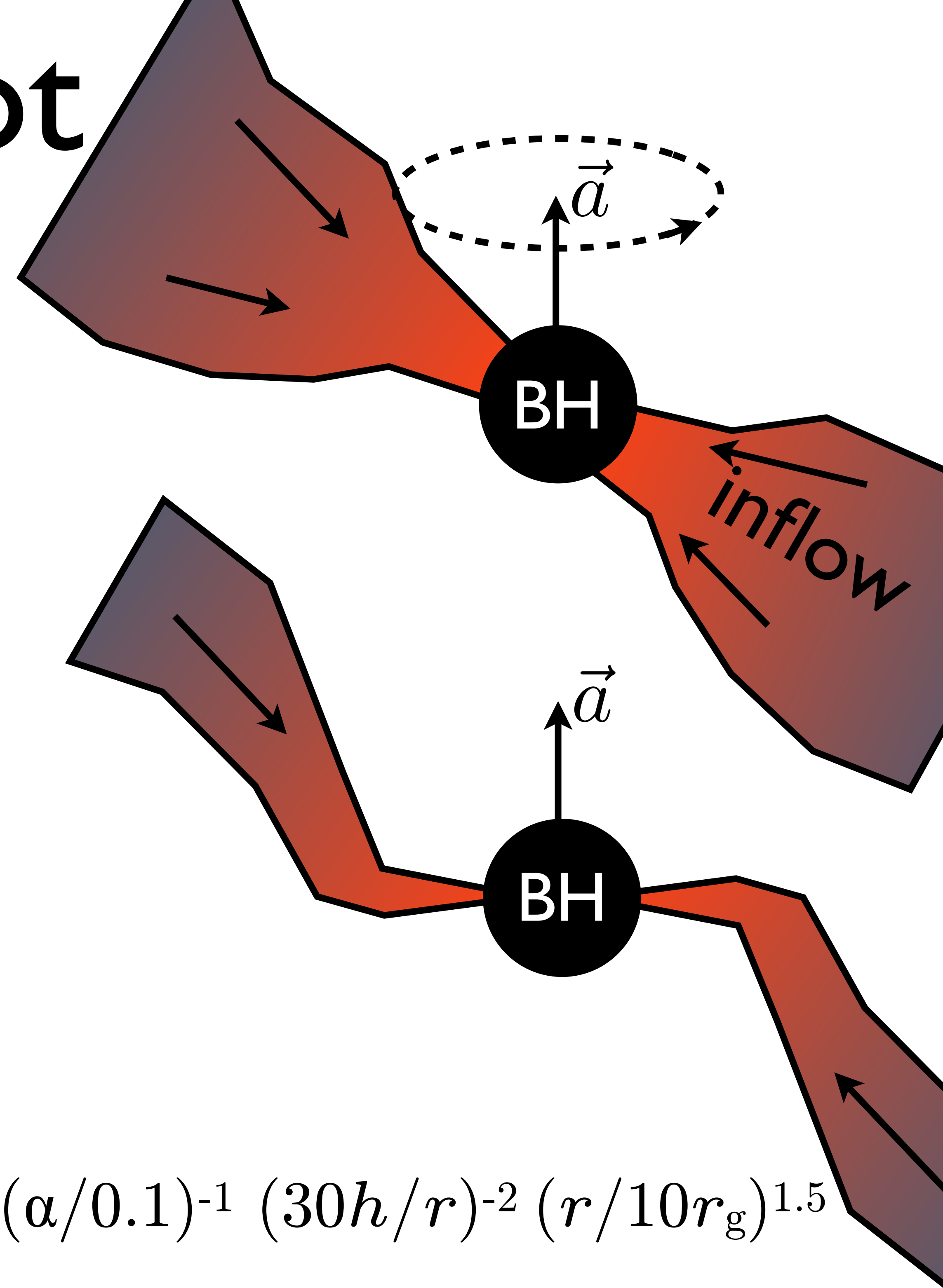

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  - is it even possible to attack the full problem?
  - this would require hundreds of millions of CPU core-hours!

H-AMR: What's Your Nail?

- Multi-GPU 3D H-AMR ("hammer", Liska, AT, et al. 2018):
  - Based on HARMPI
  - 85% parallel scaling to 4096 GPUs (MPI, OpenMP, OpenCL, CUDA, NVLINK, GPUDIRECT)
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Matthew Liska
(U of Amsterdam)

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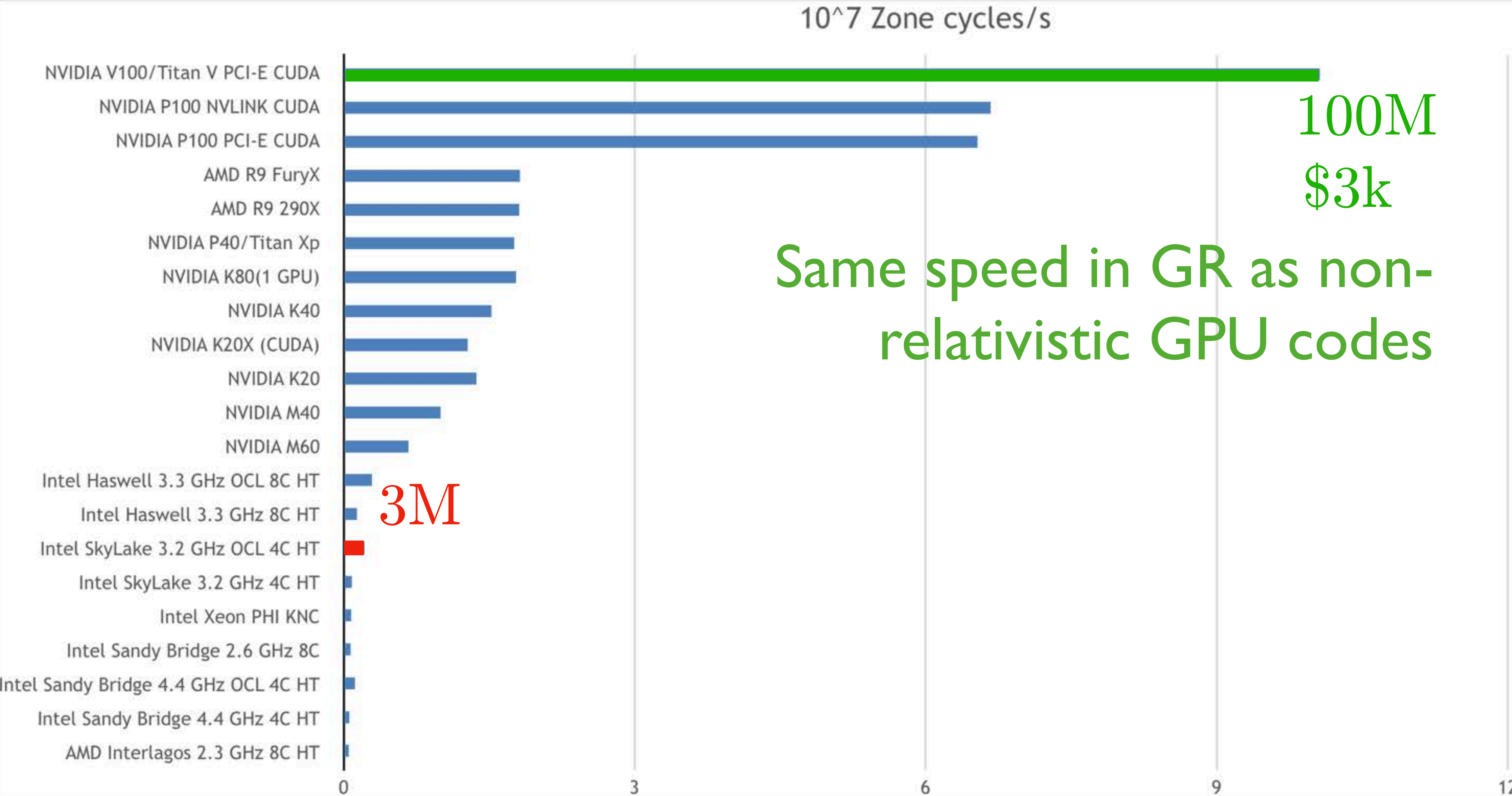

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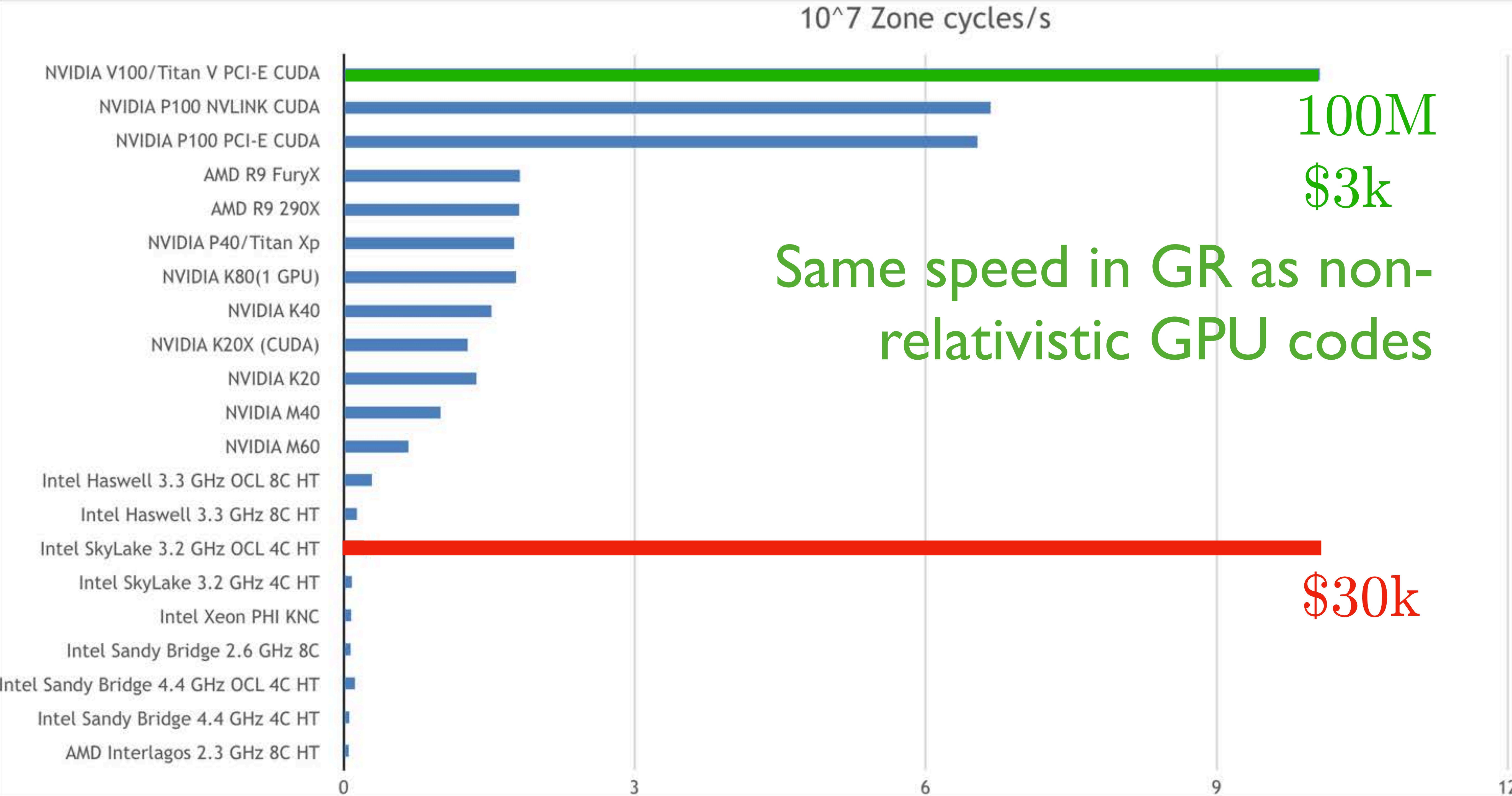

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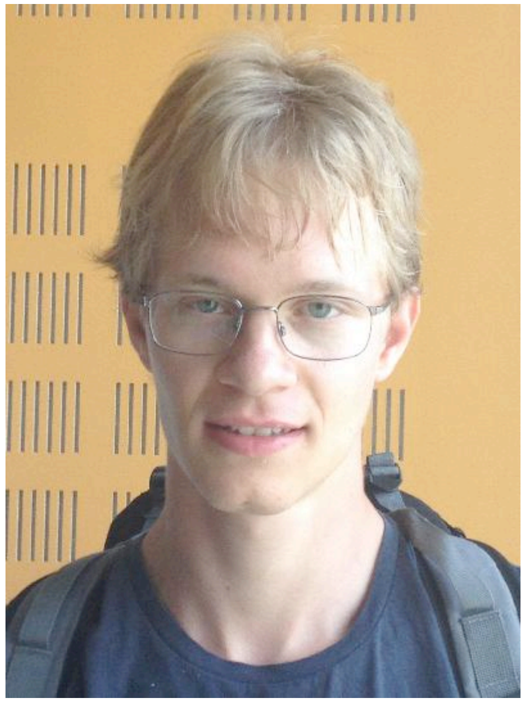
  - Adaptive Mesh Refinement (AMR)
  - Local adaptive time-stepping



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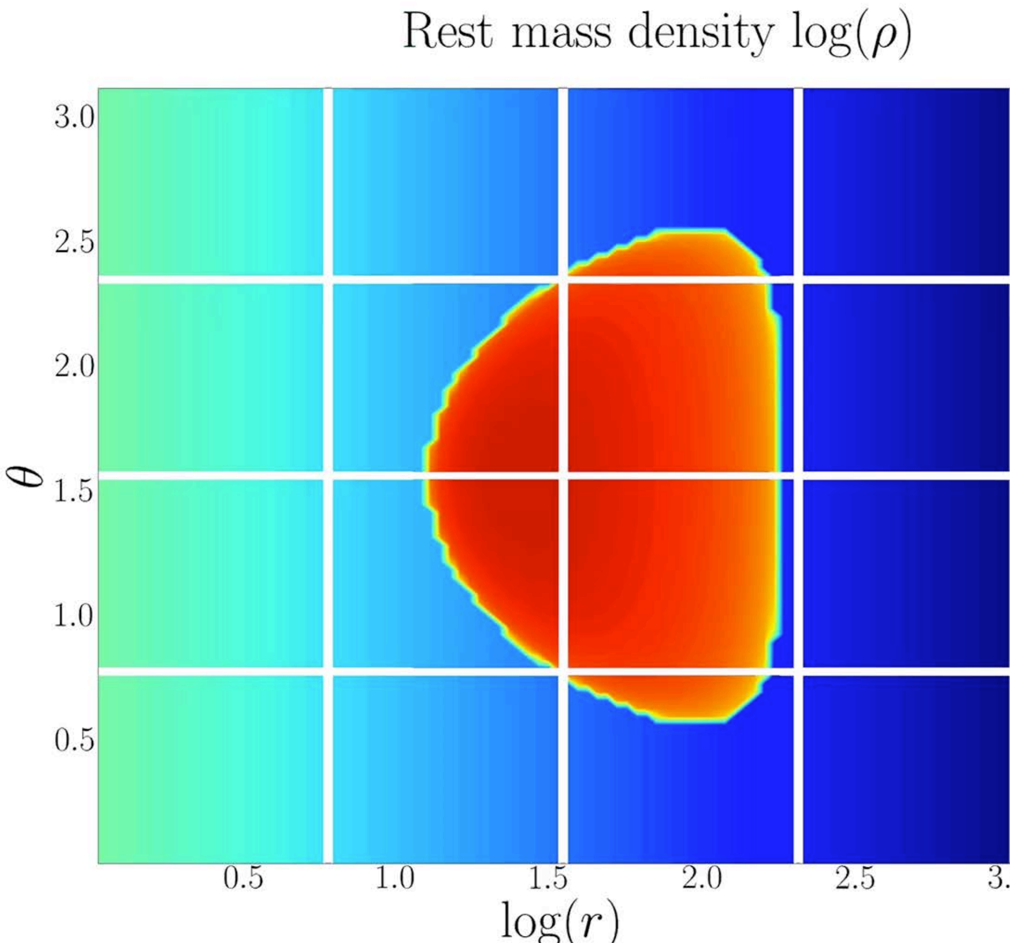

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- Advanced features (extra few - 10x speedup):
  - Adaptive Mesh Refinement (AMR)
  - Local adaptive time-stepping
- These advances are crucial for enabling next-generation research:
  - 5M K20x GPU-hours/yr = effectively 5B CPU core-hours/yr on Blue Waters
  - Science is no *longer limited by computational resources*!

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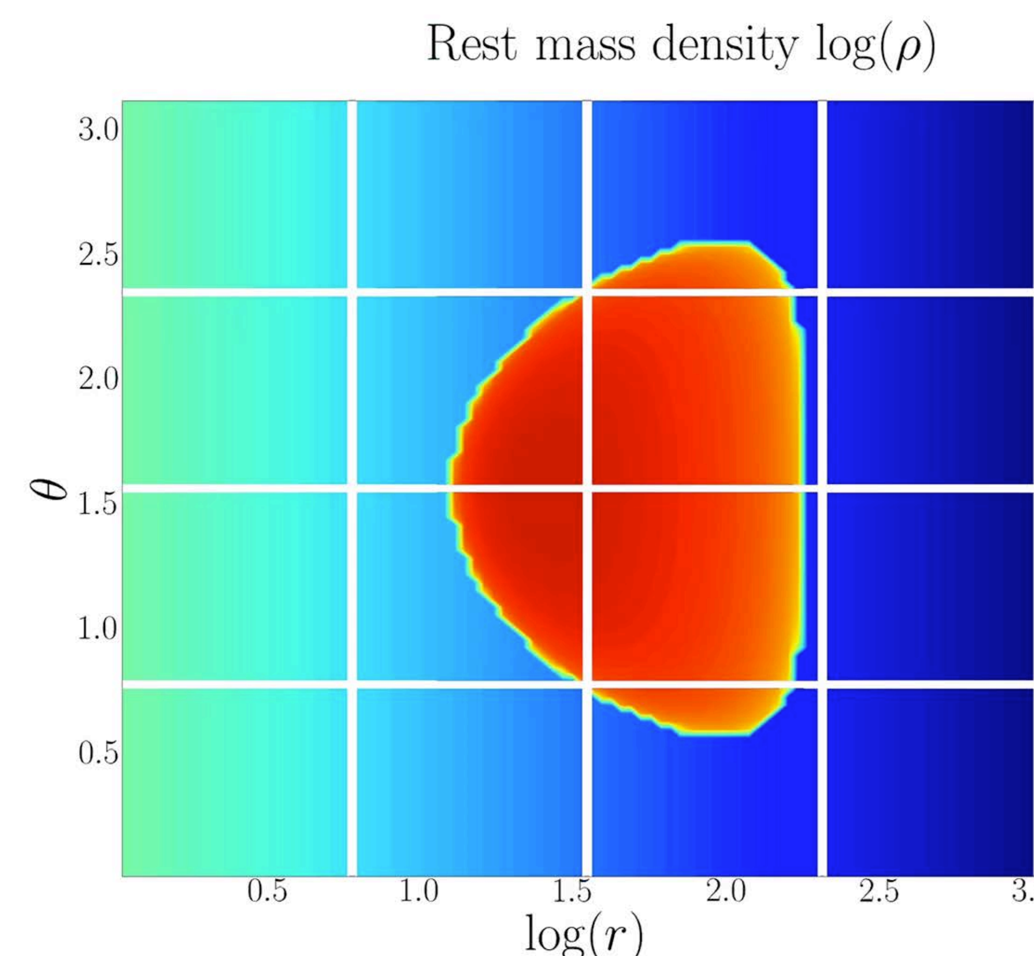
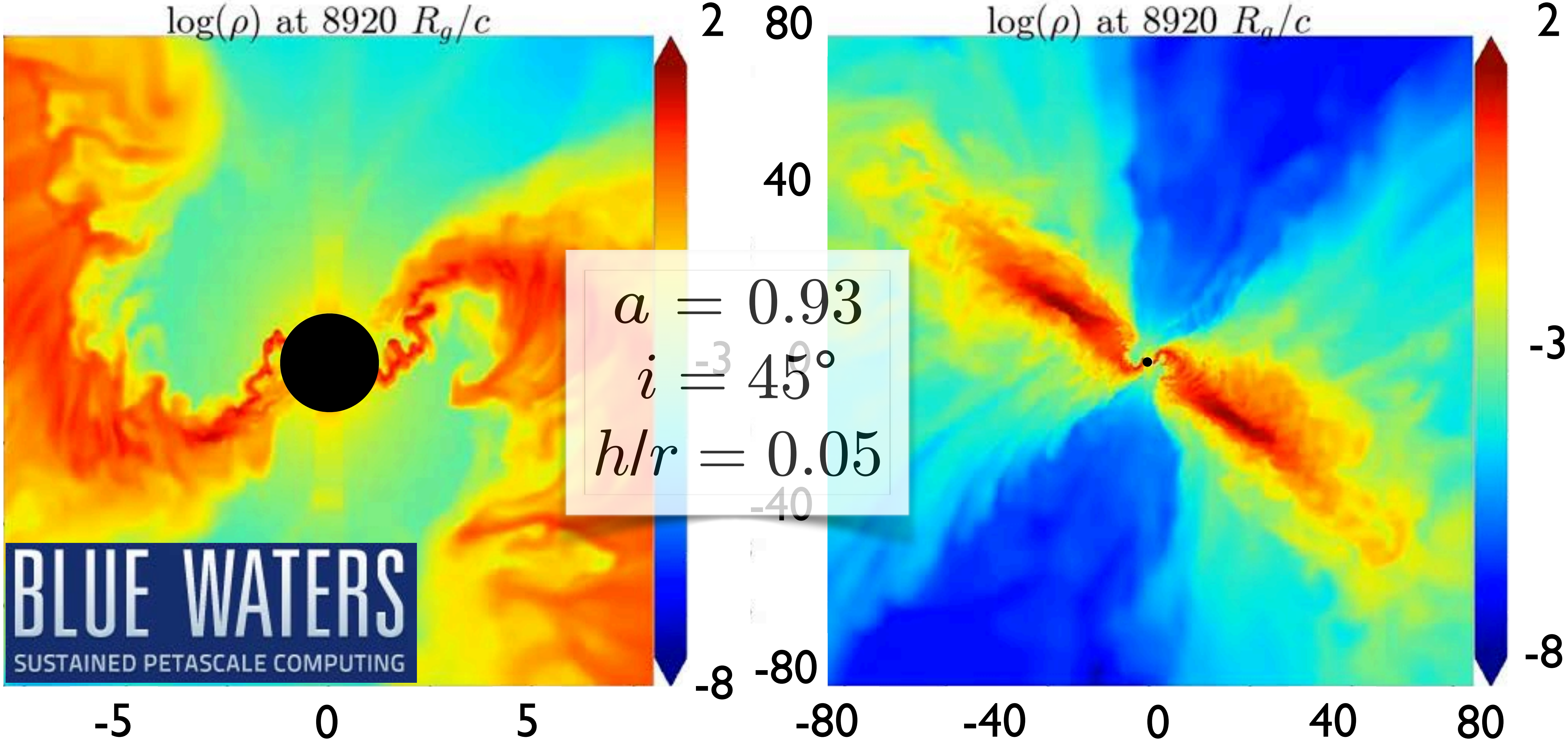


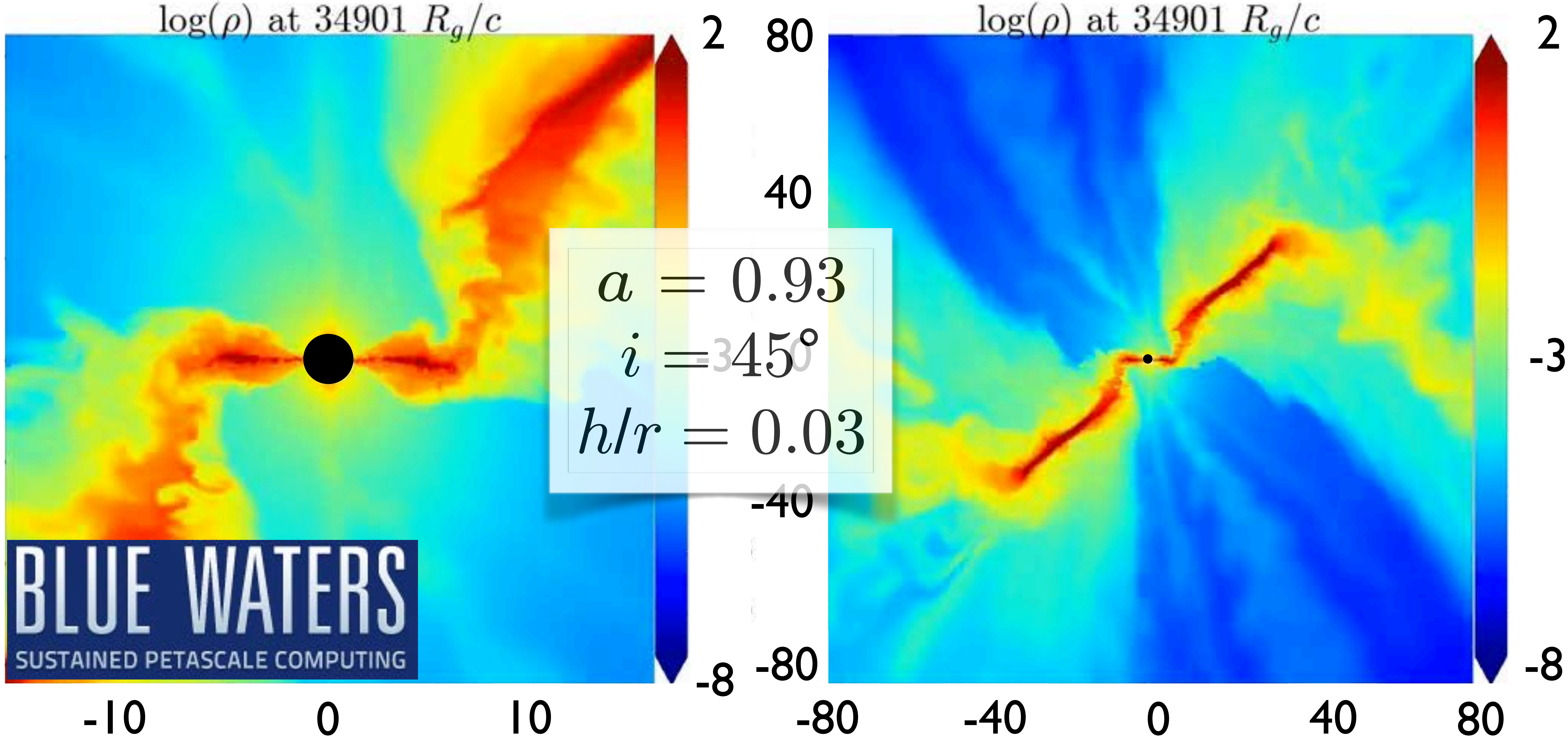
No signs of alignment…



- No sign of alignment at this thickness, h/r = $0.05\ldots$
- Effective resolution $2880{\times}860{\times}1200$, 3 AMR levels

Liska, Hesp, AT+ 2019, MNRAS, submitted, arXiv:1904.08428

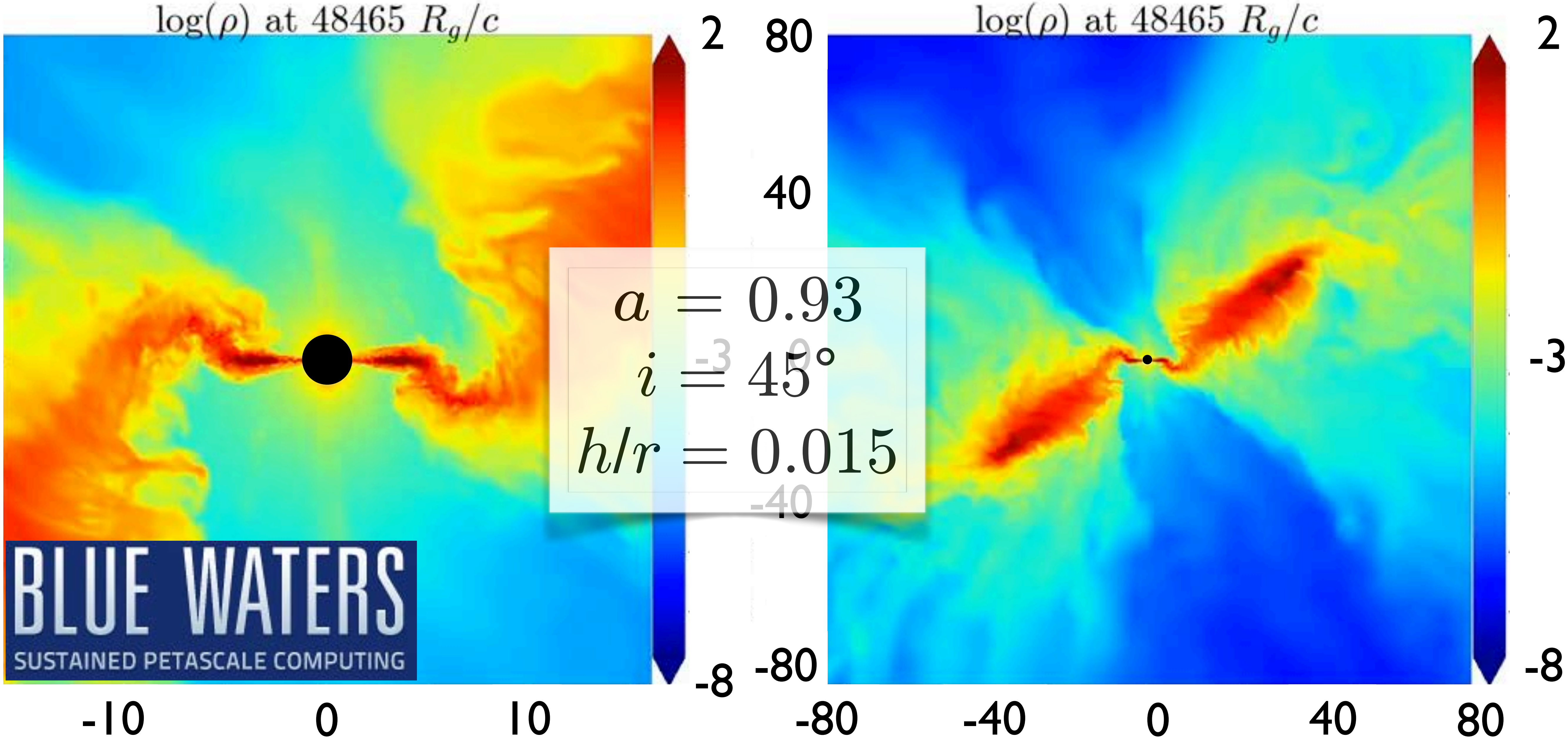
Thin Misaligned Disks **Align** and **Break**



- First demonstration of (Bardeen-Petterson?) alignment and disk breaking in GRMHD!
- Formation of powerful precessing jets → can this explain jets from quasars?
- Inflow equilibrium out to 15-20 $r_{\rm g}$
- Effective resolution $2880 \times 860 \times 1200$, 3 AMR levels

Liska, AT+ 2019, MNRAS, doi:10.1093/mnras/stz834
Liska, Hesp, AT+ 2019, MNRAS, submitted, arXiv:1904.08428

Even Thinner Disks **Align** to Larger Distance

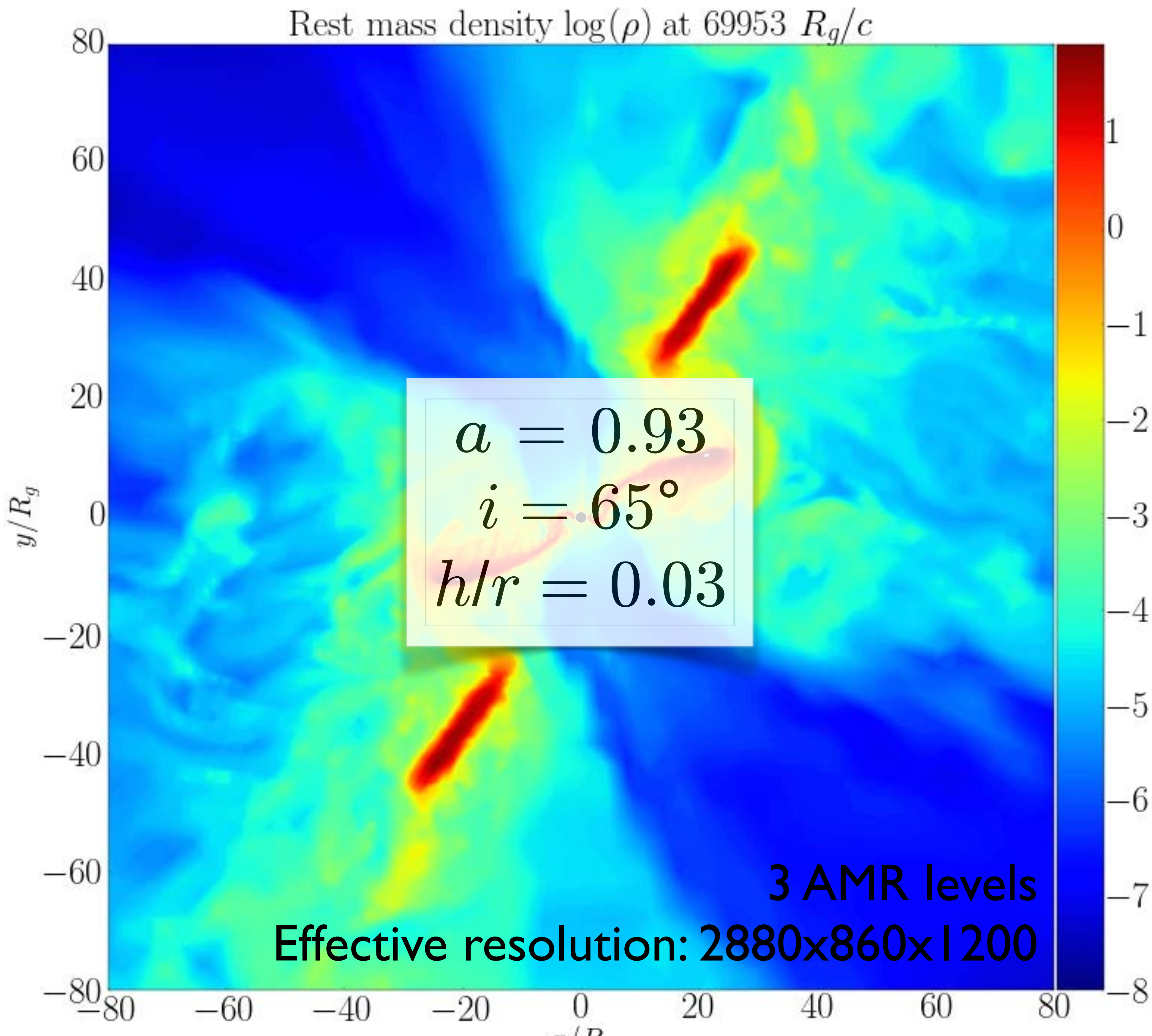


- Start with $h/r = 0.03$, cool down to $h/r = 0.015$
- Alignment radius is larger for smaller h/r
- Inflow equilibrium out to $10\ r_{\rm g}$
- Effective resolution $5760 \text{x} 1720 \text{x} 2400$, 4 AMR levels

Liska, Hesp, AT+ 2019, MNRAS, submitted, arXiv:1904.08428

Thin **Strongly** Misaligned Disks **Tear**

- Disks can tear up into individual segments
- Extra dissipation and luminosity
- Completely different luminosity profile
- Can affect BH spin measurements
- Can this explain larger observed disk size than expected? (Blackburne+2011)



BLUE WATERS SUSTAINED PETASCALE COMPUTING

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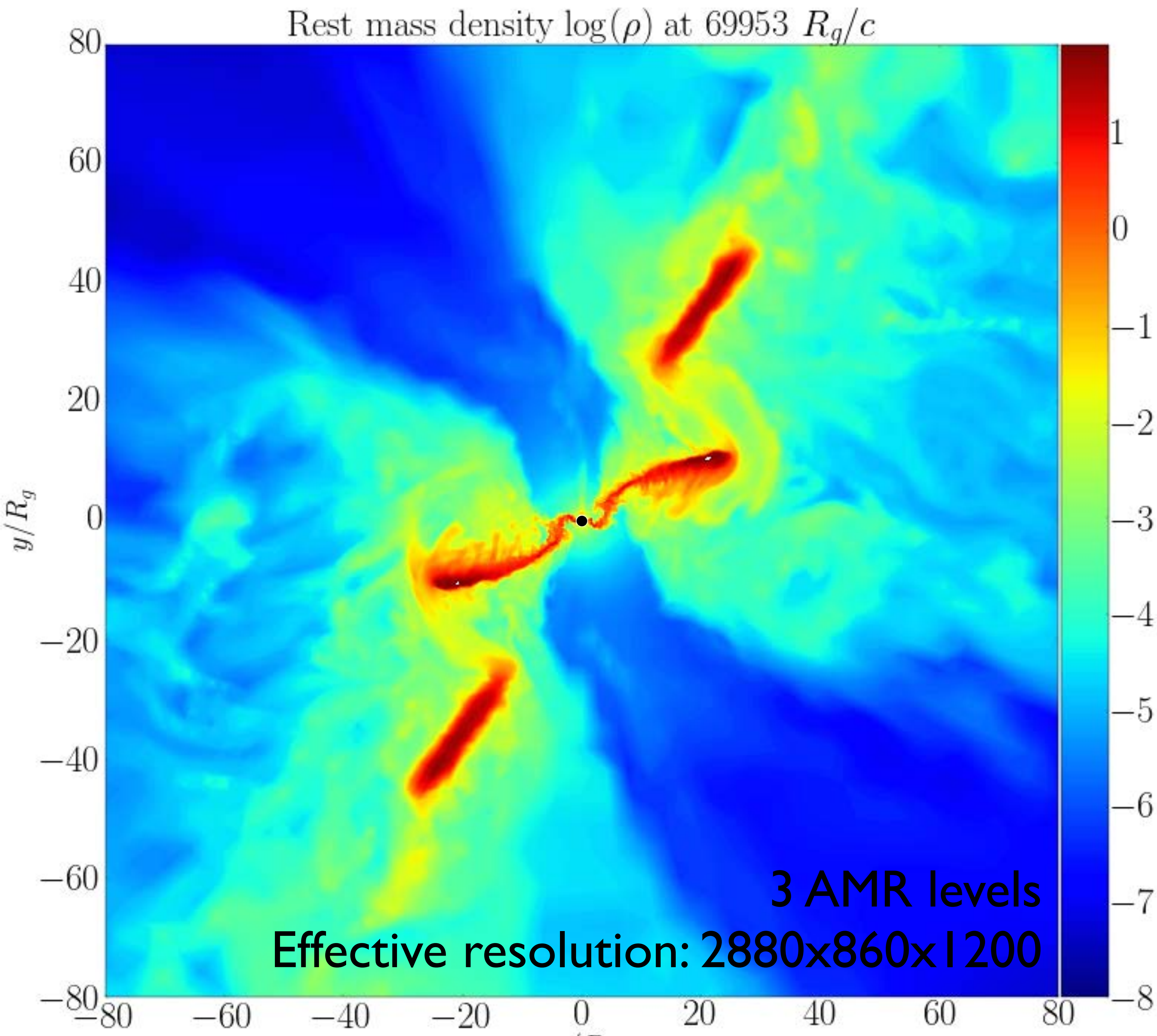

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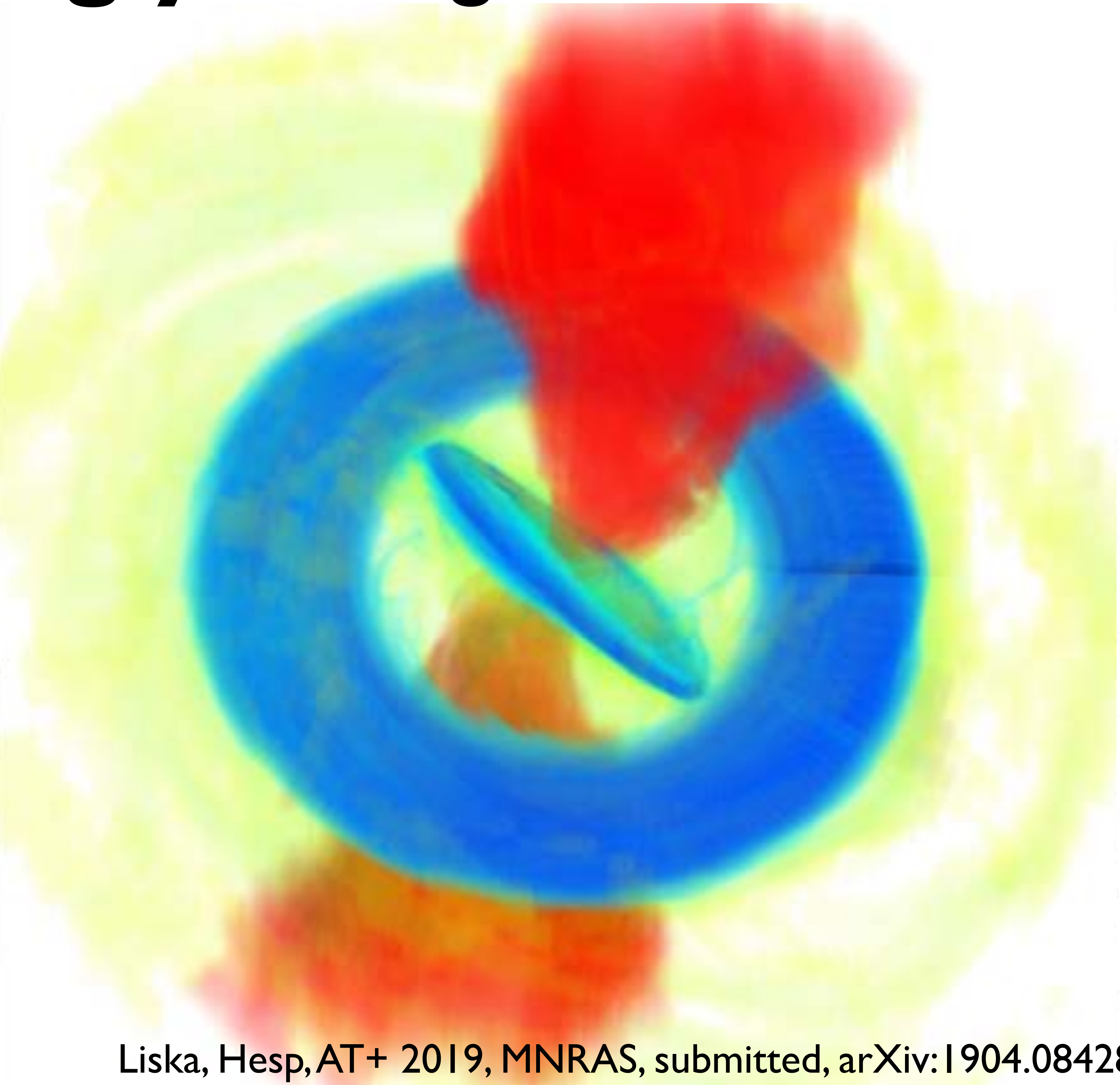

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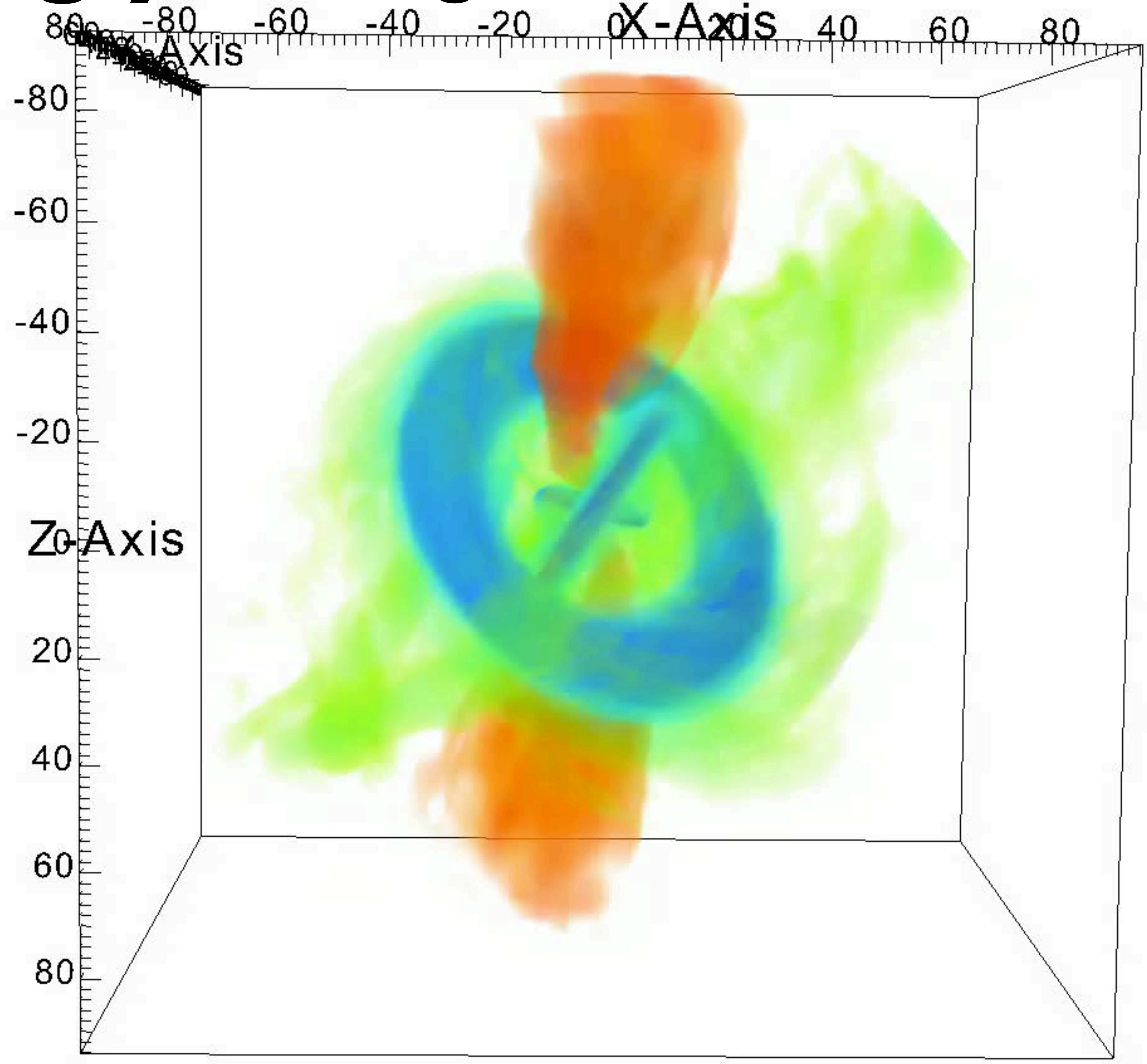

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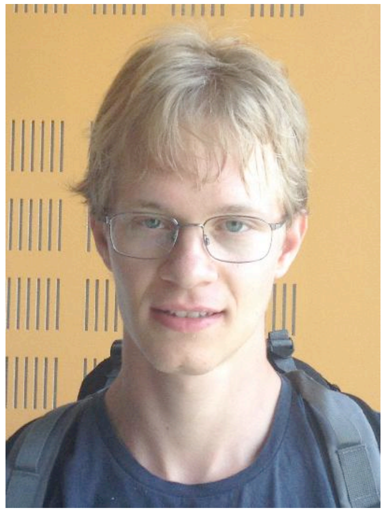
BW enabled training of young scientists presenting posters:

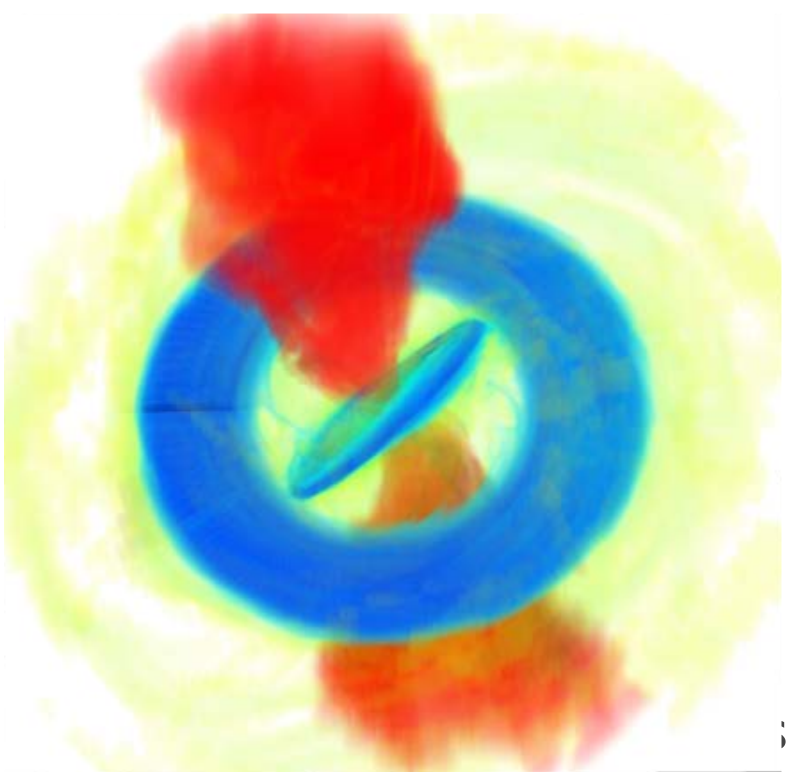


Matthew Liska
(Amsterdam → Harvard)

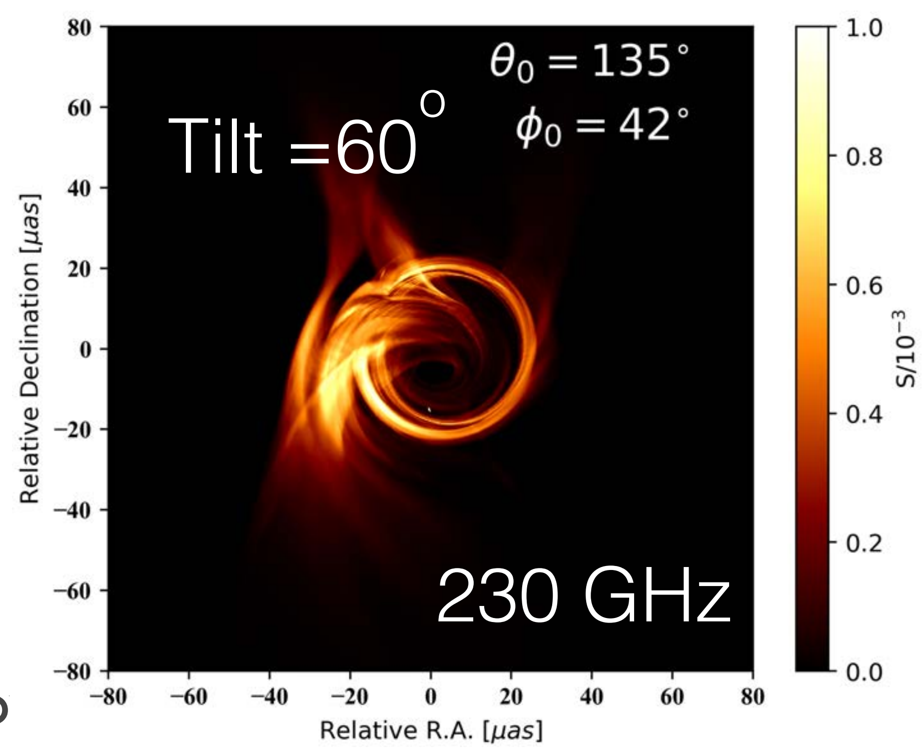
Koushik Chatterjee
(Amsterdam)

Zack Andalman
(Evanston Township High School, Northwestern → Yale)

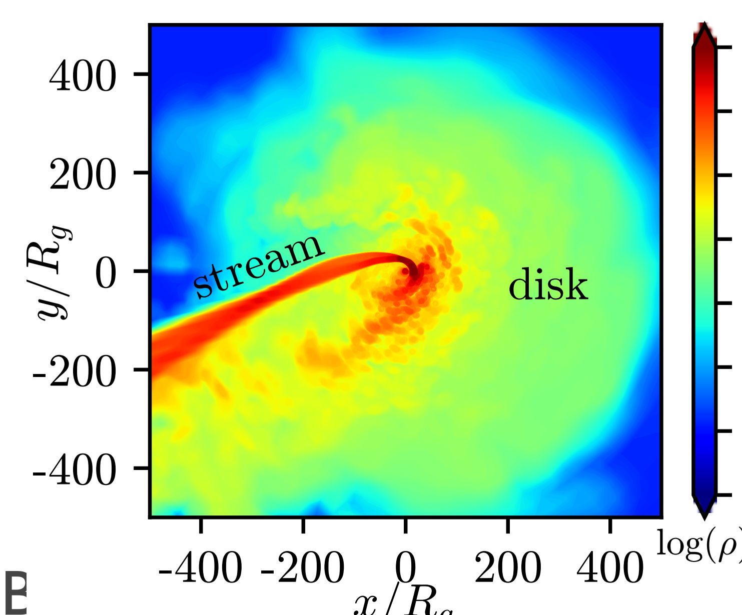
H-AMR + tilted disks



Event horizon images of tilted disks



Formation of disks in tidal disruptions



Summary

- Blue Waters enabled us to begin to understand the typical **tilted** black hole accretion
- Bardeen-Petterson-like ***alignment, breaking, and tearing* of thin disks** first seen for magnetized black hole accretion disks ➛ essentially unexplored observational manifestations
- We thank the Blue Waters team who ensured smooth running and helped us to create 3D visualizations

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