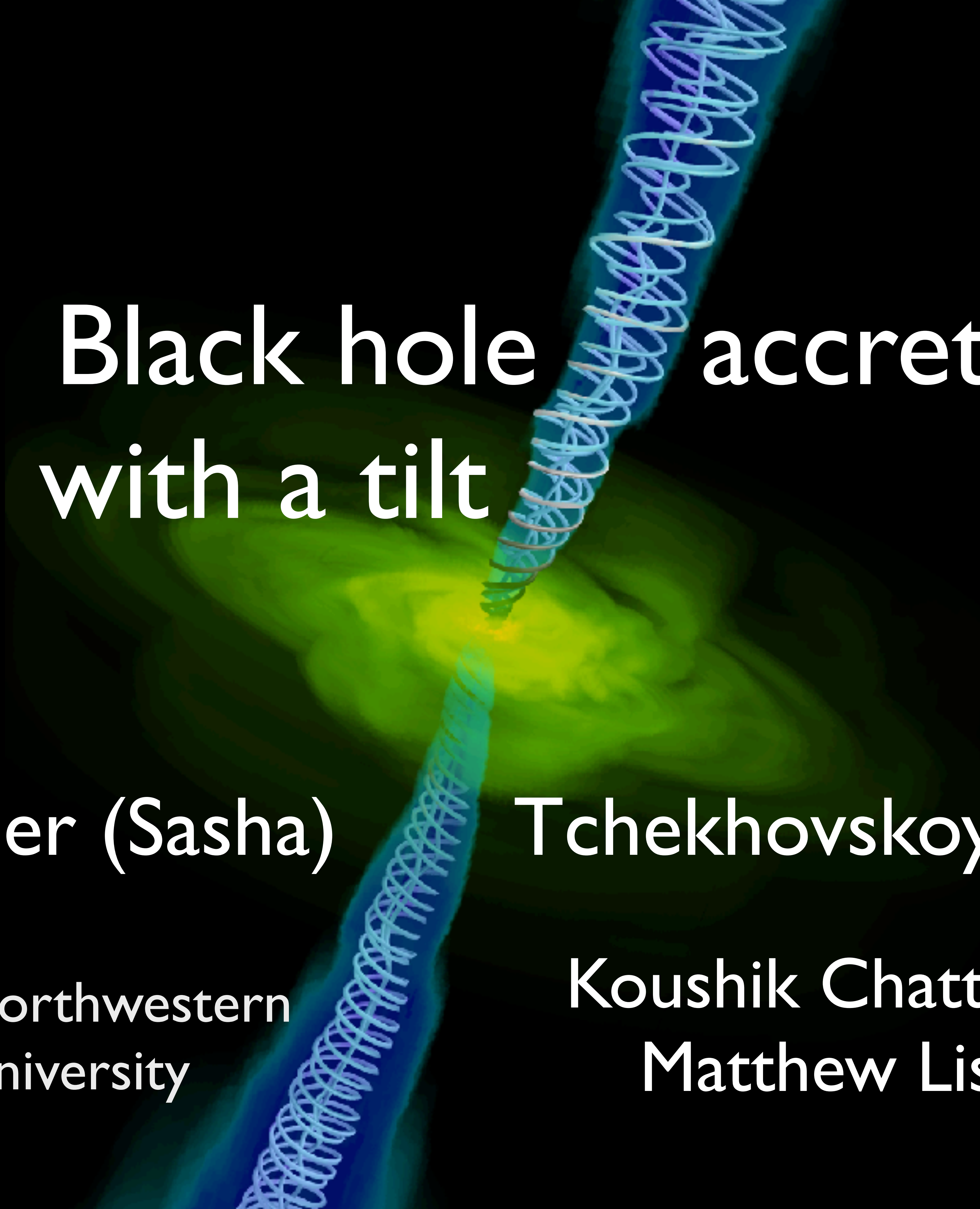
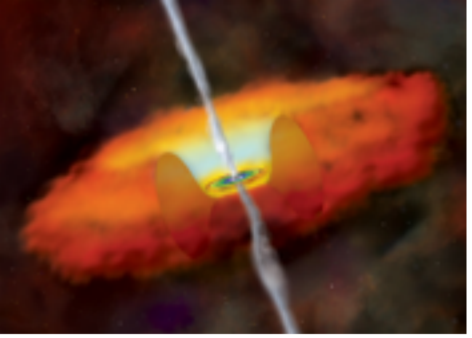


Black hole accretion with a tilt

Alexander (Sasha) Tchekhovskoy

Northwestern University

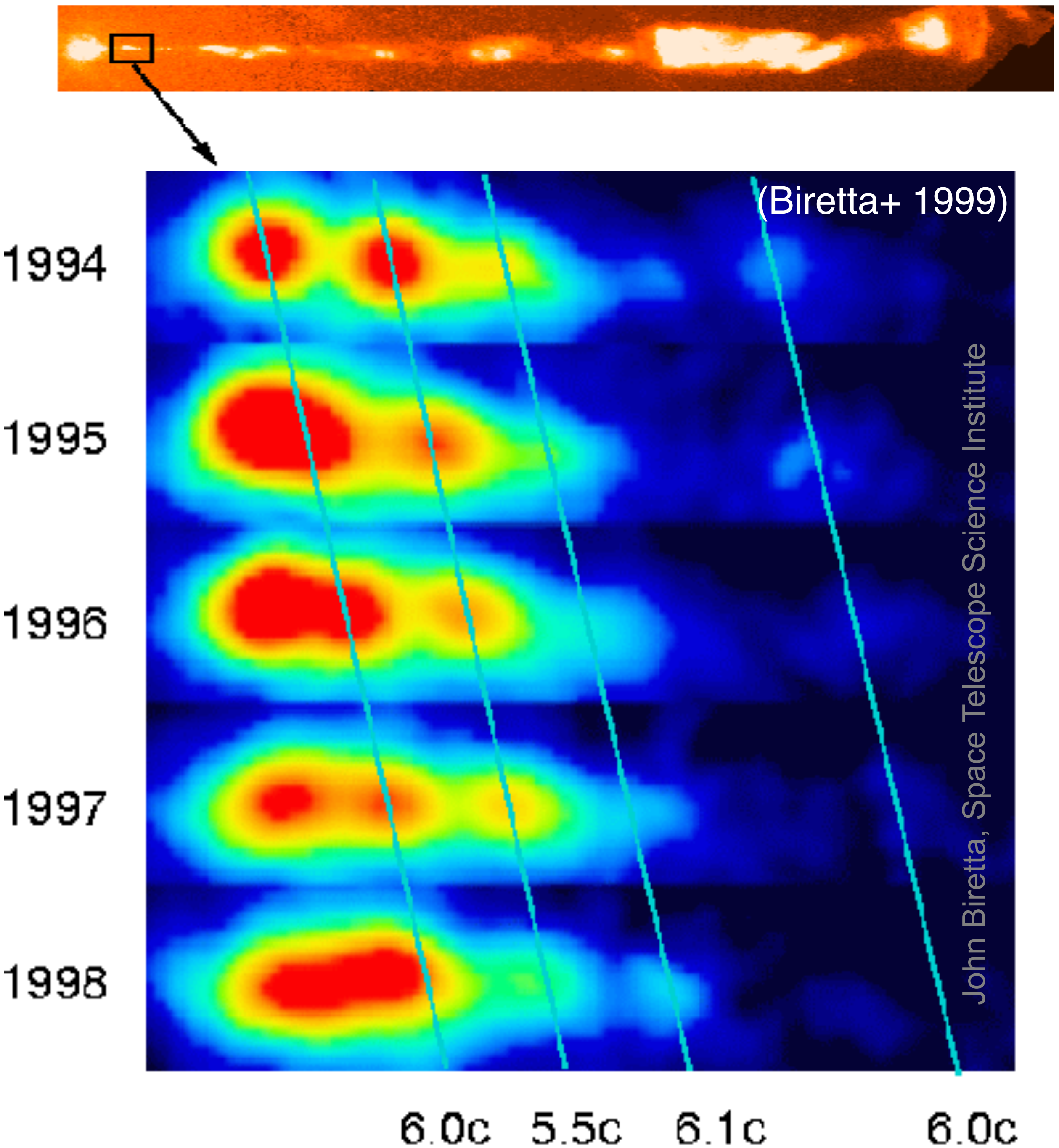
Koushik Chatterjee
Matthew Liska



Chandra XRC

M87 Jet: Acceleration and Collimation over 5 Orders in Distance

Relativistic motions on pc-scales



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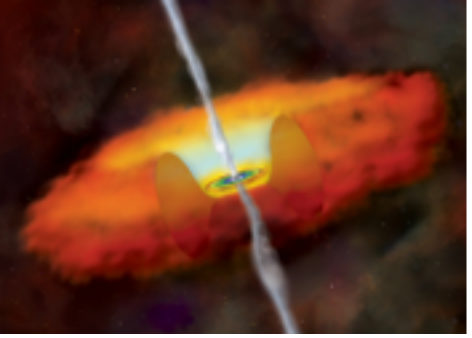

Chandra XRC

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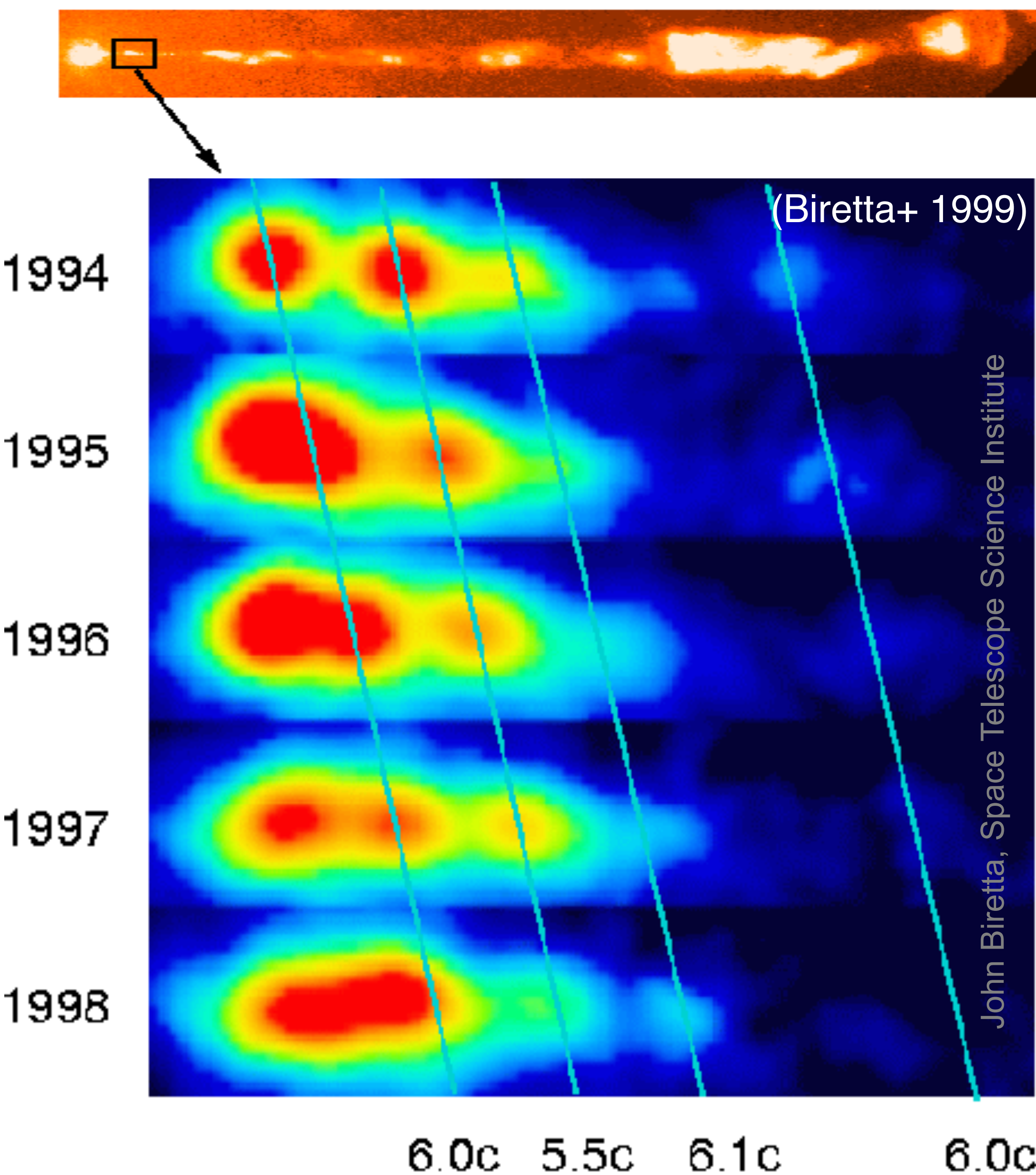
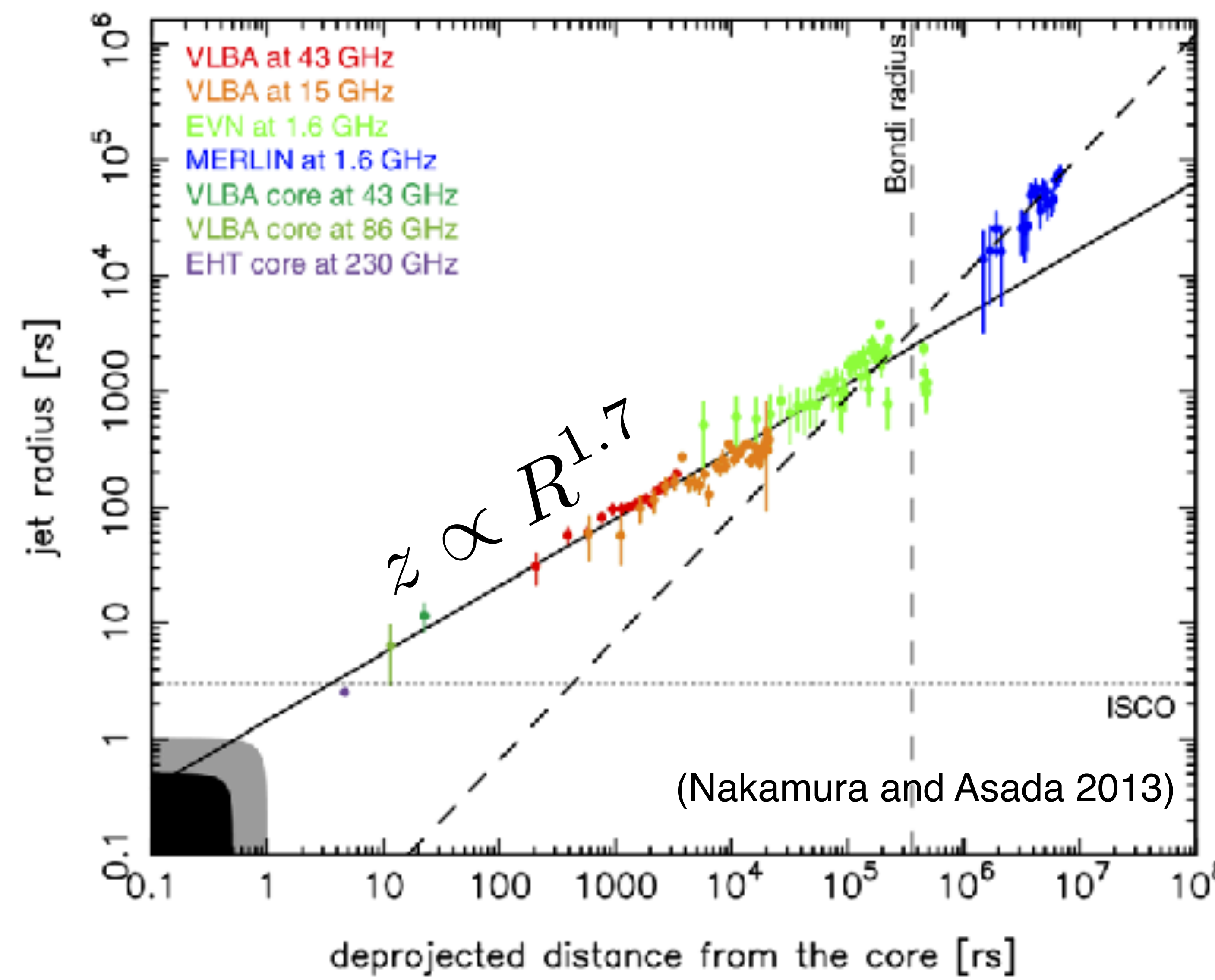
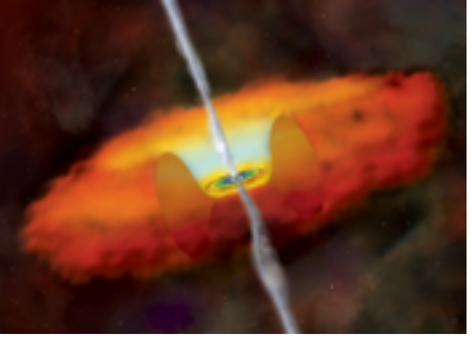


Parabolic Jet over 5 Orders of Magnitude





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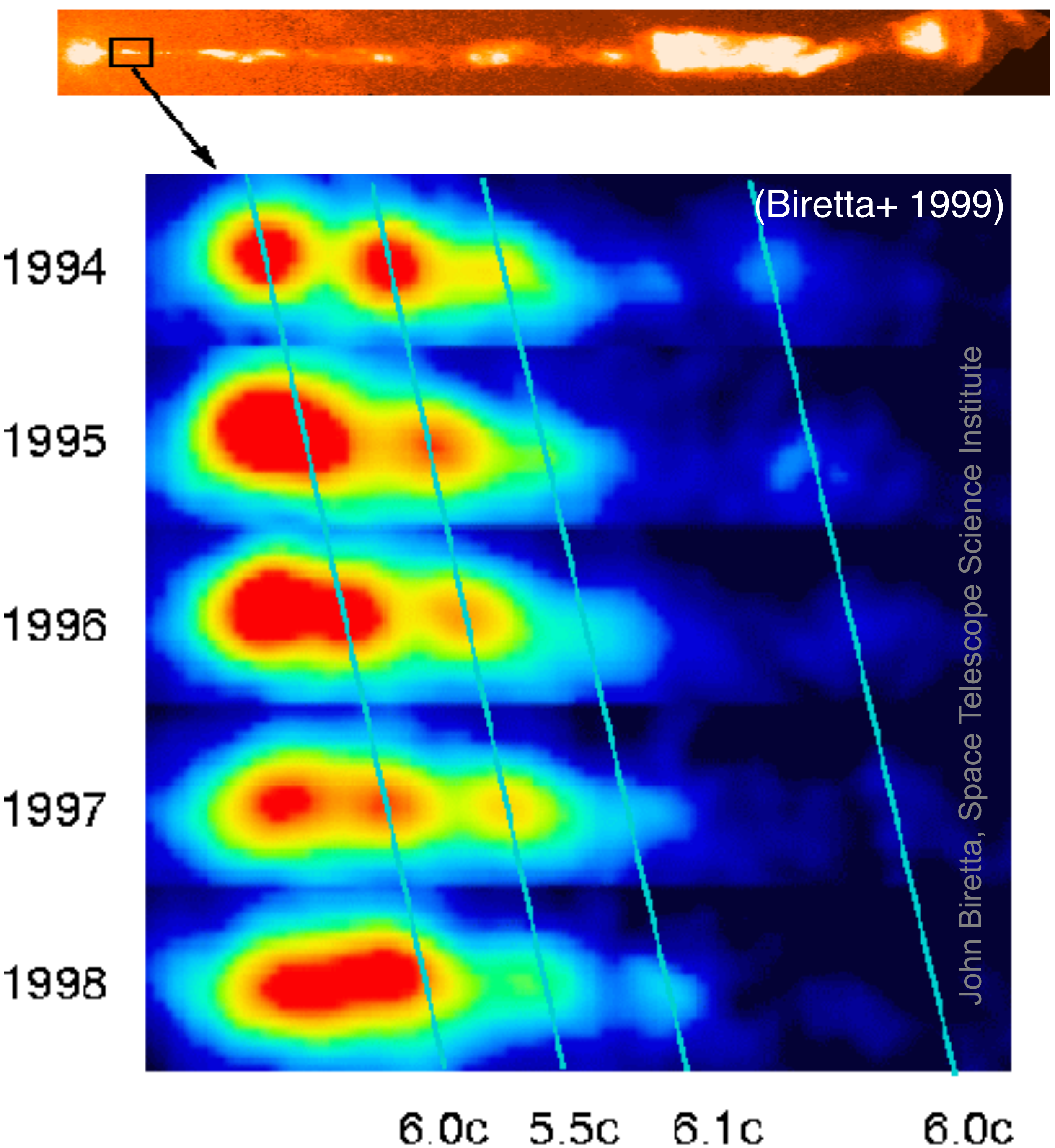

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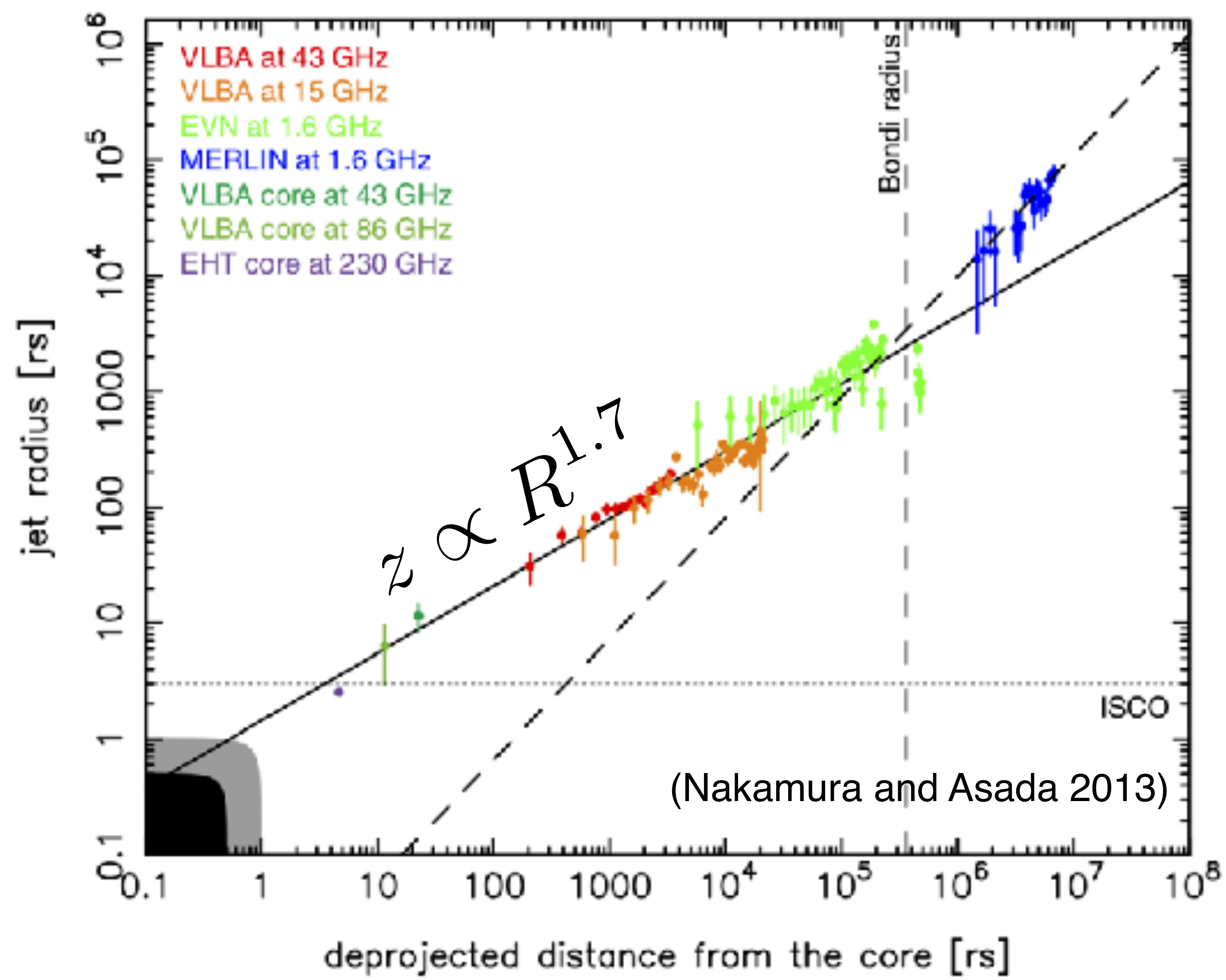
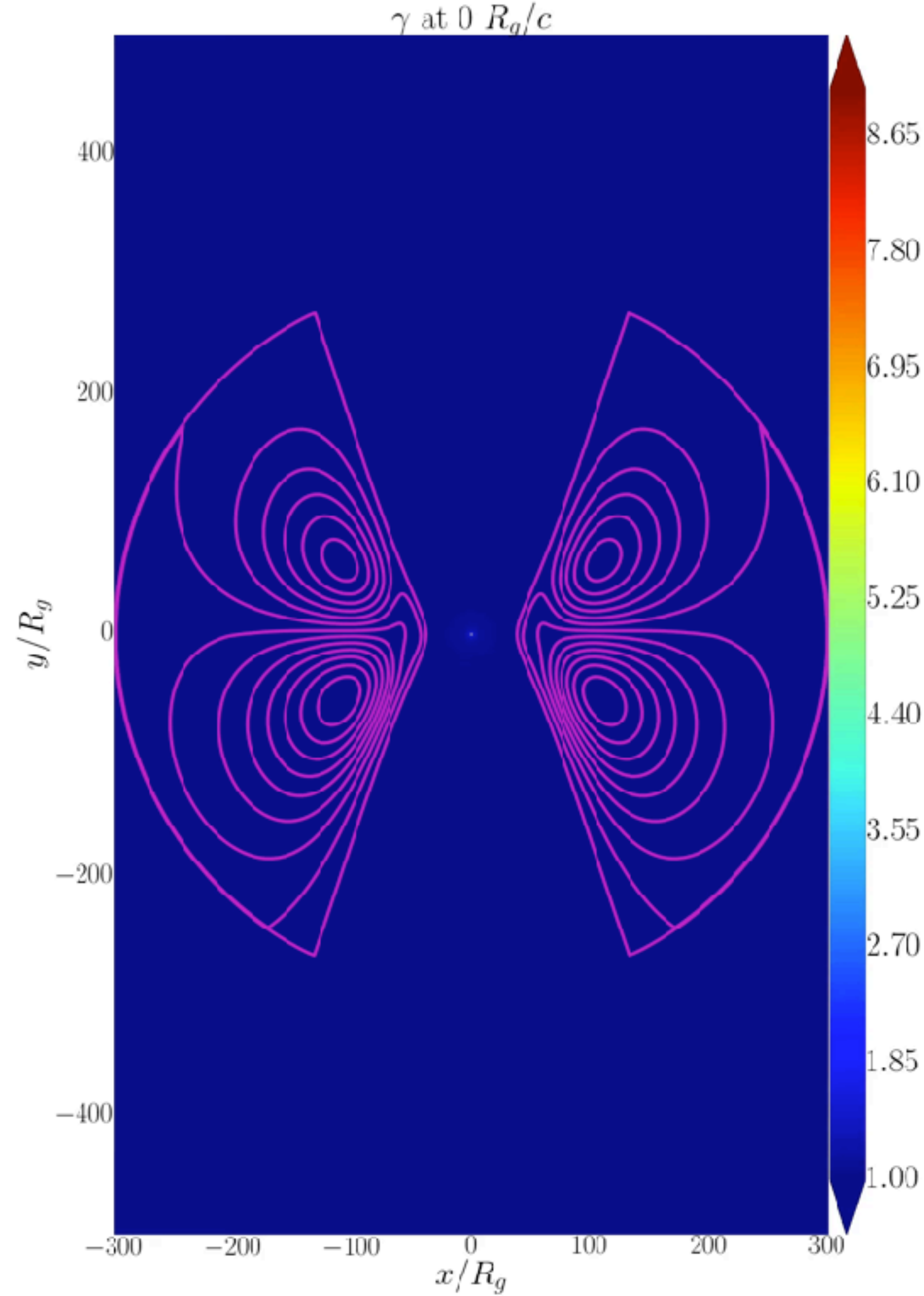


What physics leads to the continuous power-law shape of the jet?

How do such jets become relativistic?

Koushik Chatterjee (U. of Amsterdam)

How Do Jets Form and Accelerate?



(Beskin & Nokhrina 2006, Komissarov+ 07-10, AT 09-10, Lyubarsky 10)

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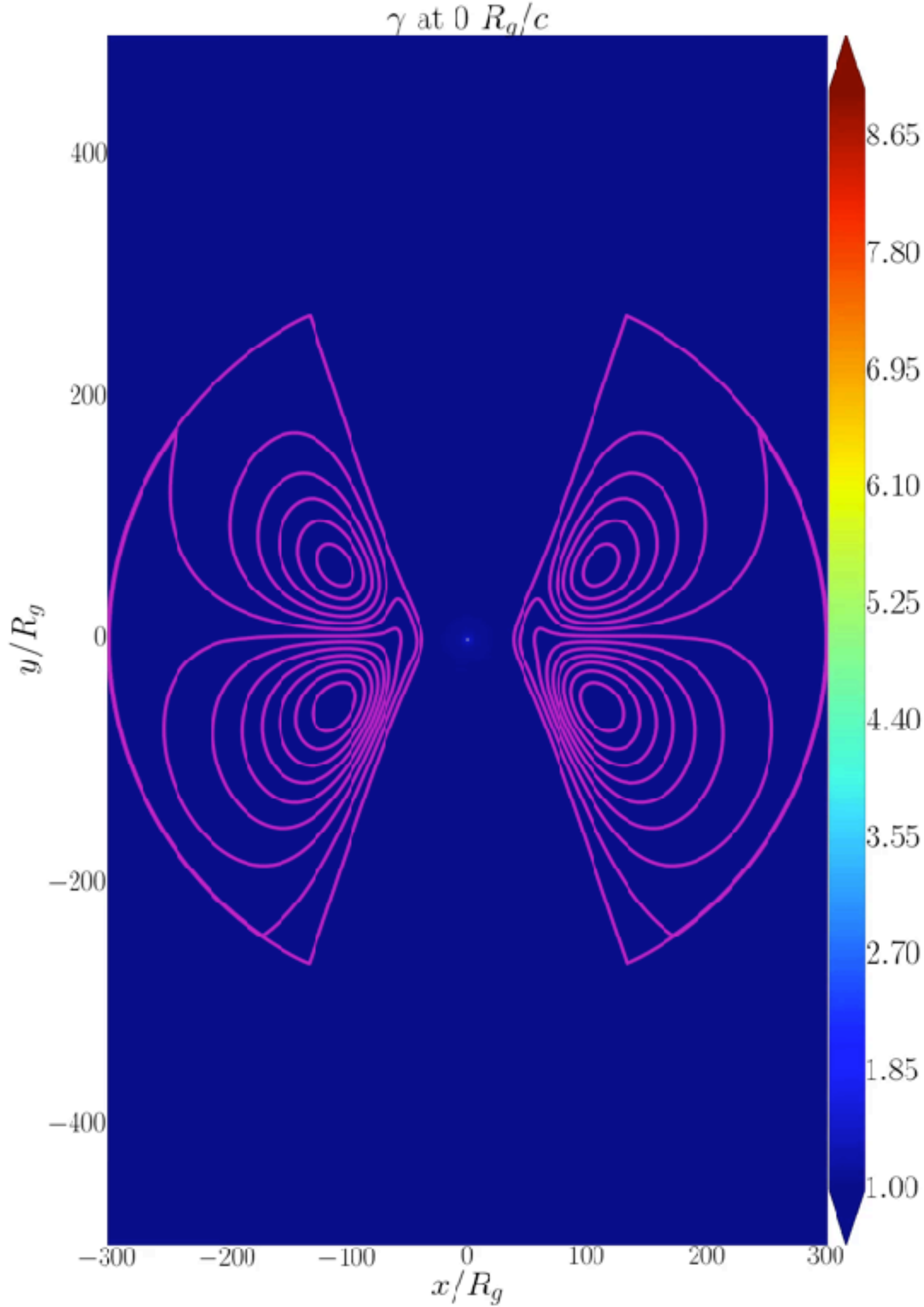
- Black hole + disk = jets + outflows
- Span >5 orders of magnitude in distance:
  - directly compare to observations
  - largest extent disk-jet simulations



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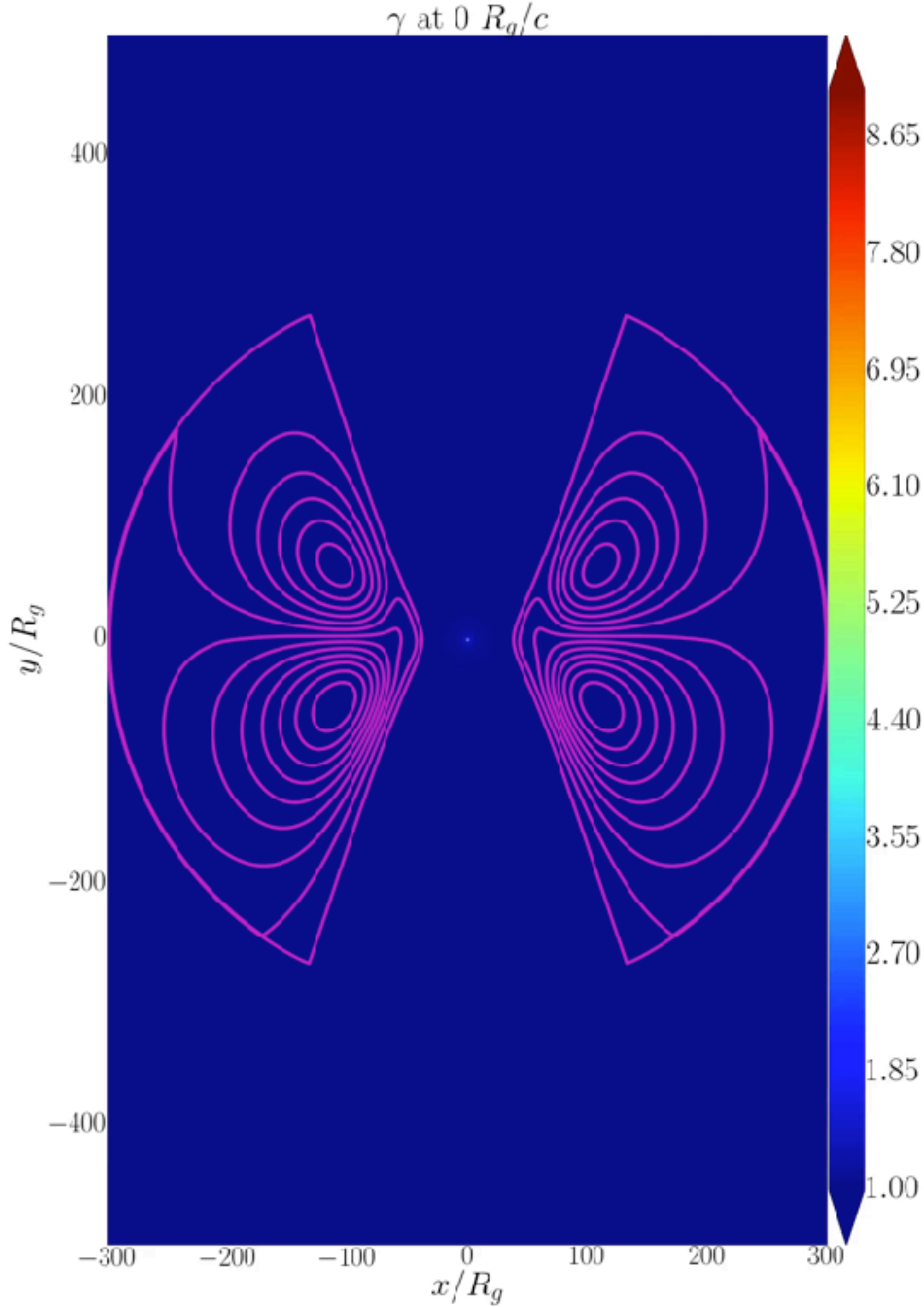

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  - BUT: slow down if collimate too much

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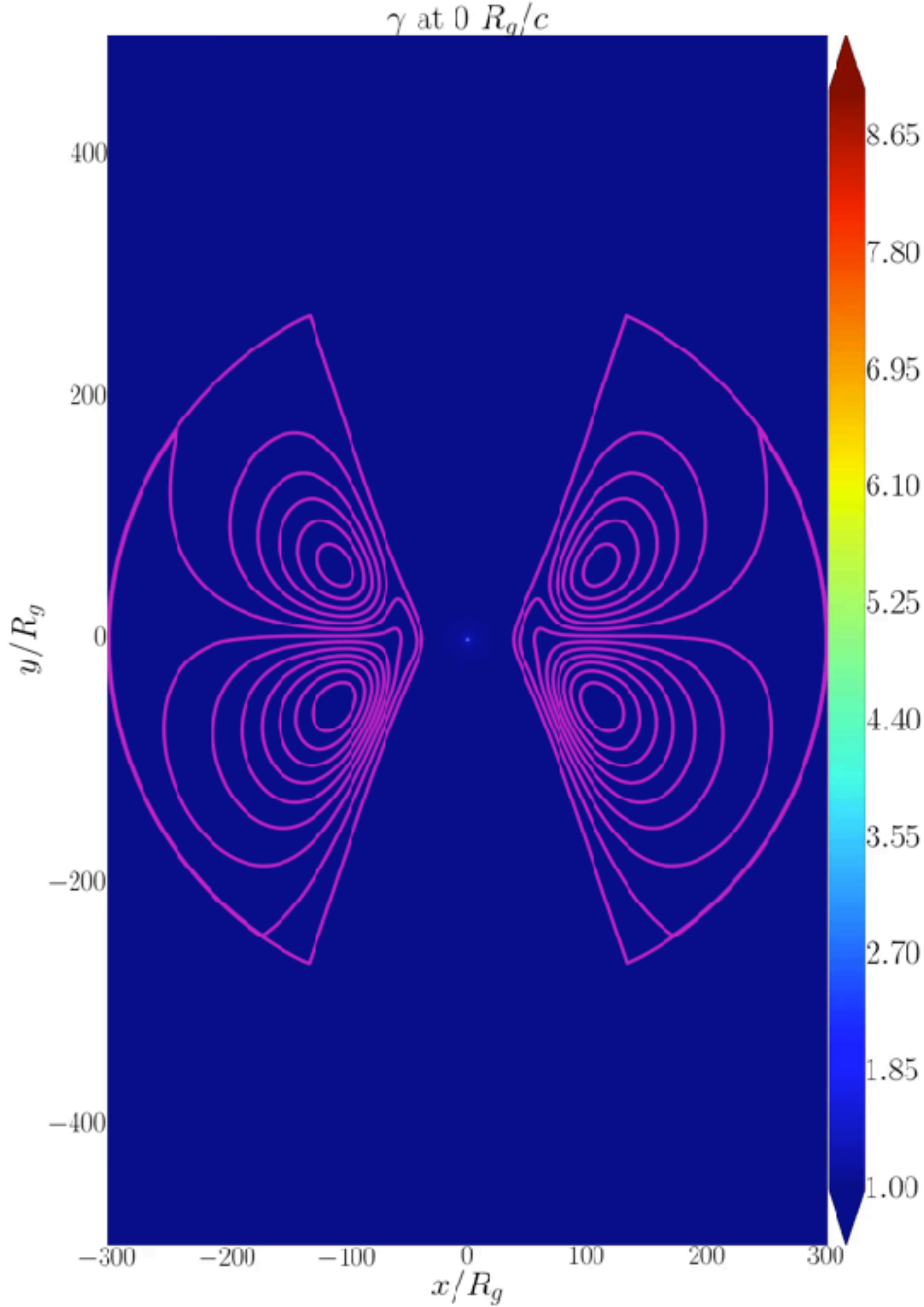

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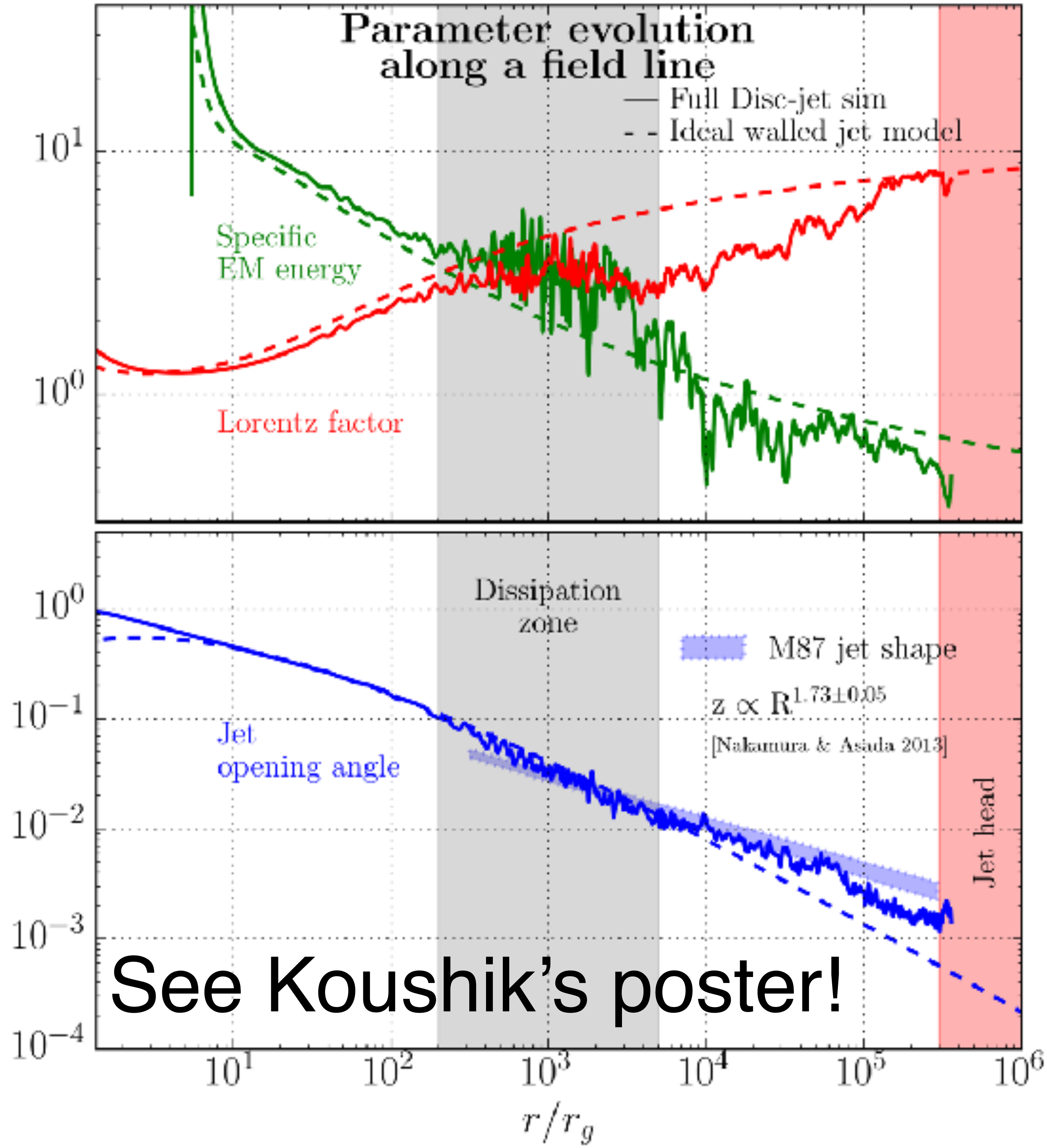

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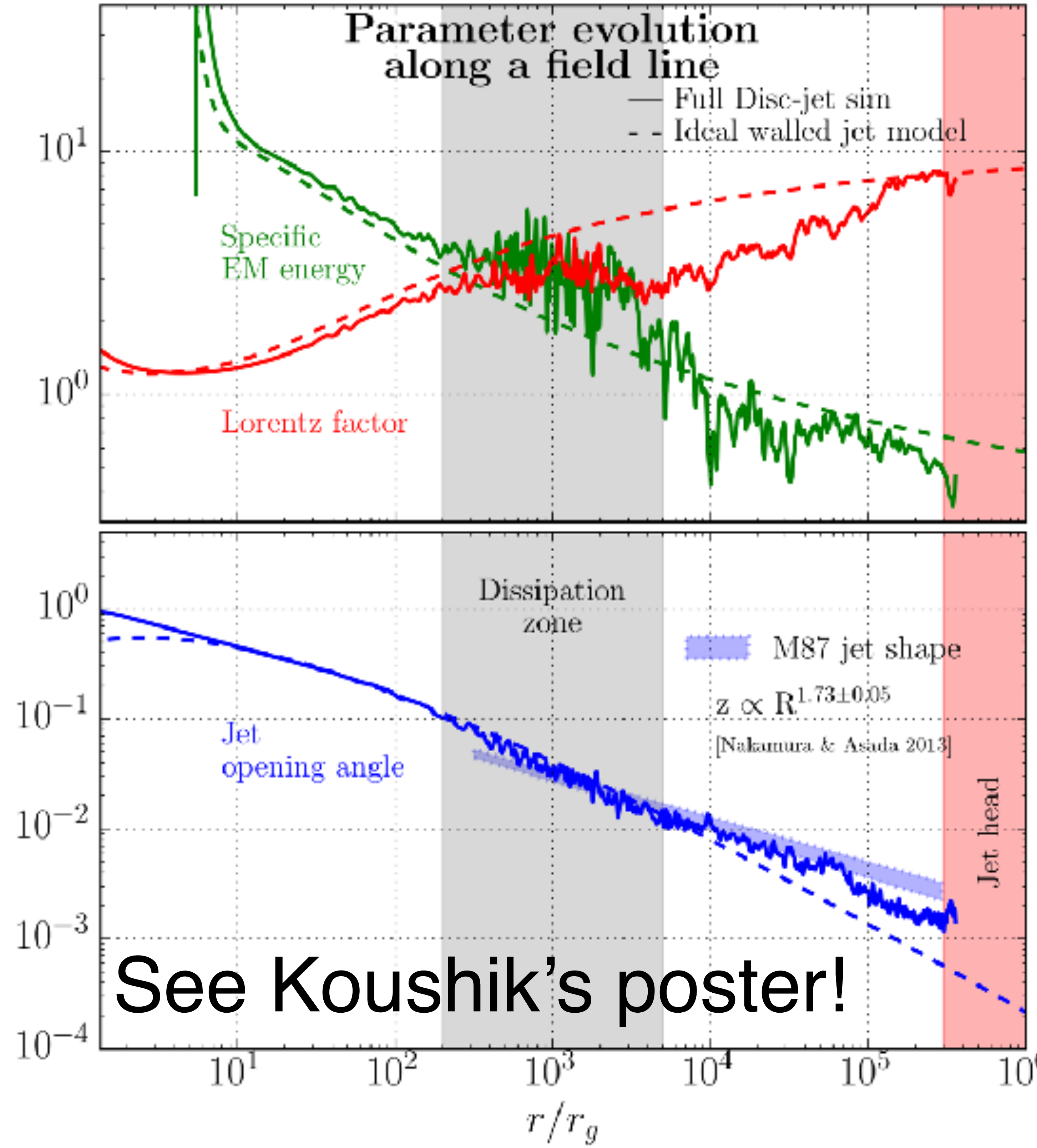
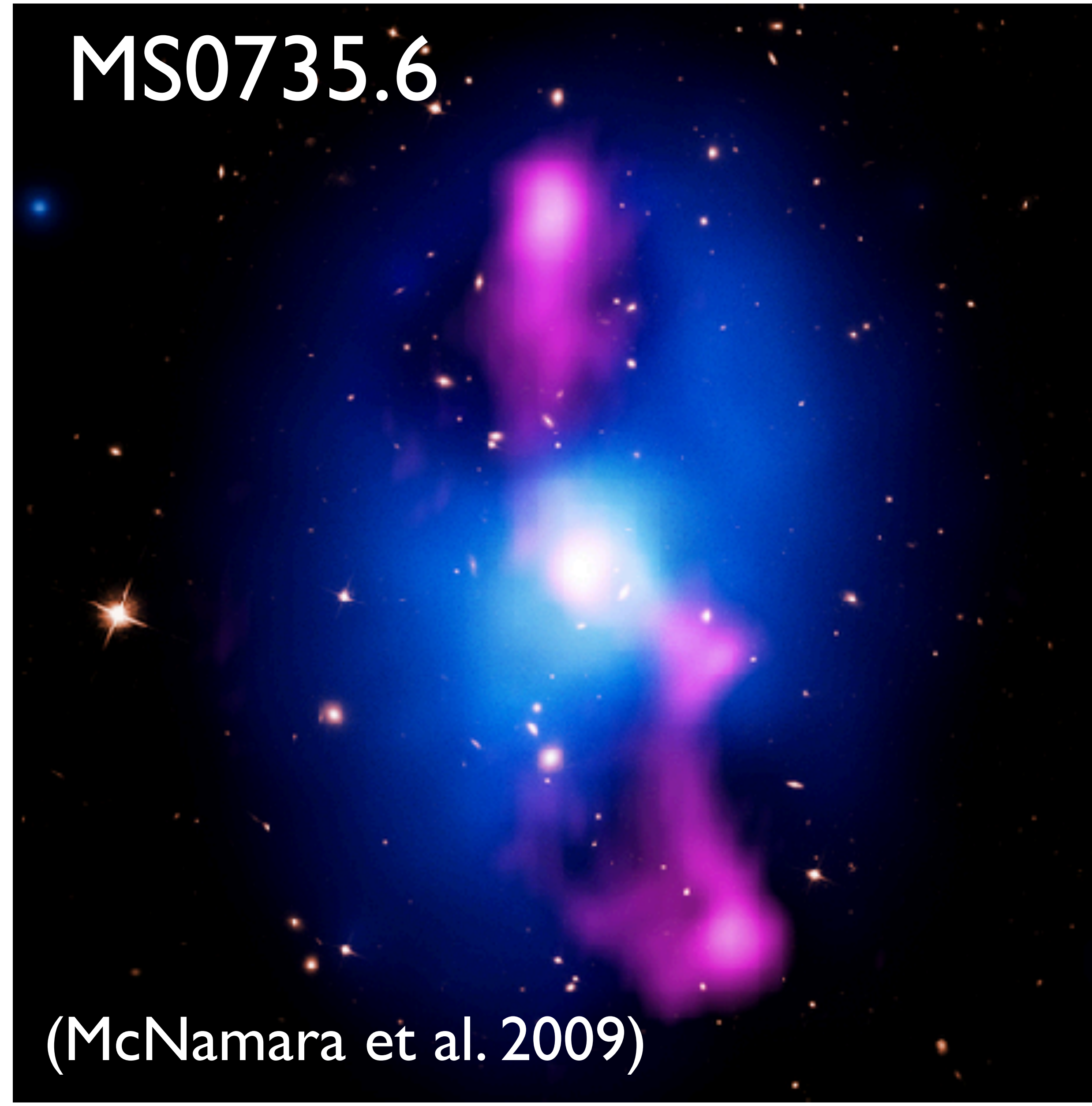
  - BUT: slow down if collimate too much
- Jets efficiently convert magnetic to kinetic energy: reach matter domination

(Beskin & Nokhrina 2006, Komissarov+ 07-10, AT 09-10, Lyubarsky 10)



Are We Missing Anything Important?

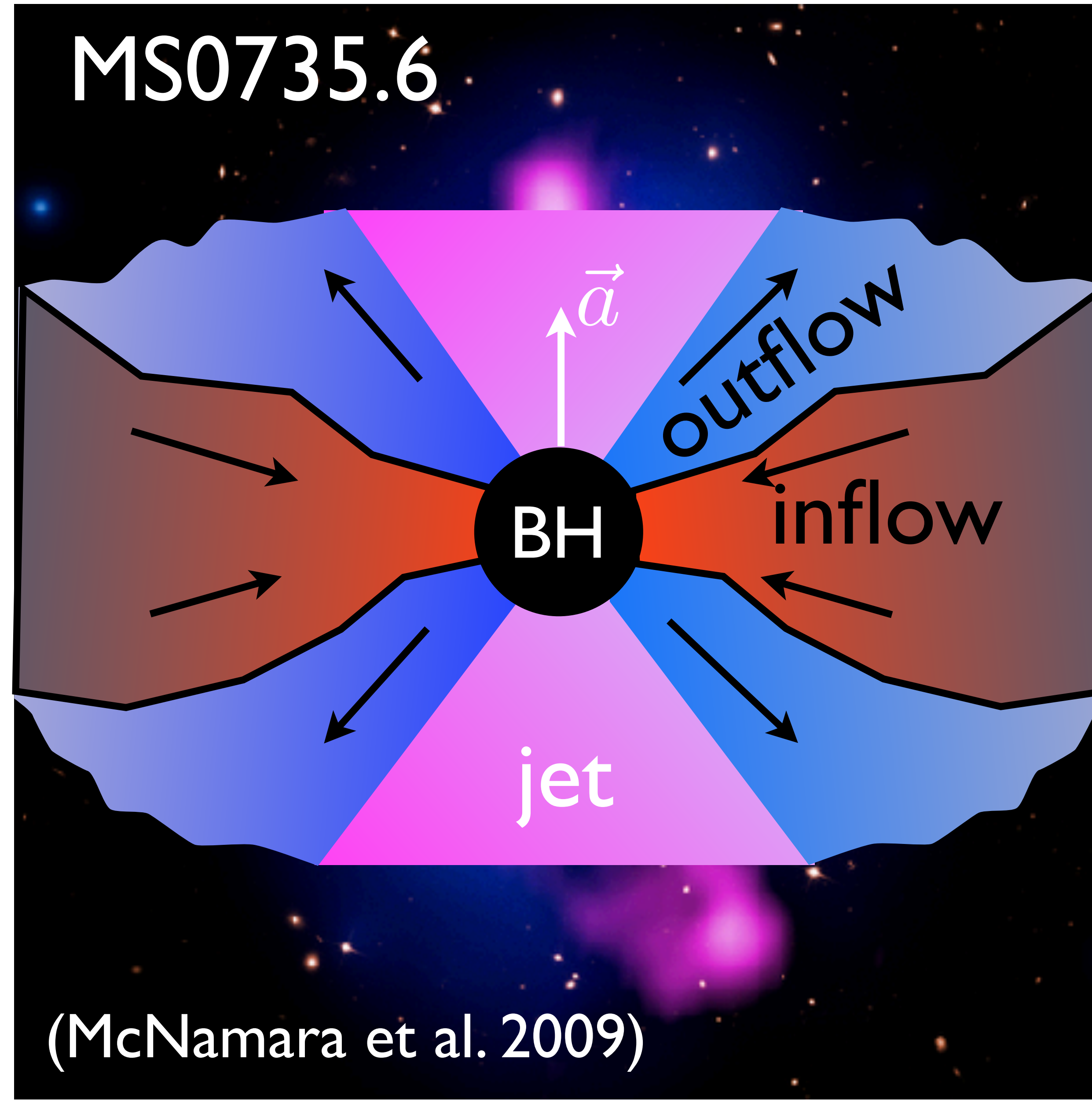
- We already understand the basics of disks and jets



(McNamara et al. 2009)

Are We Missing Anything Important?

- We already understand the basics of disks and jets
- Most of the work: aligned systems



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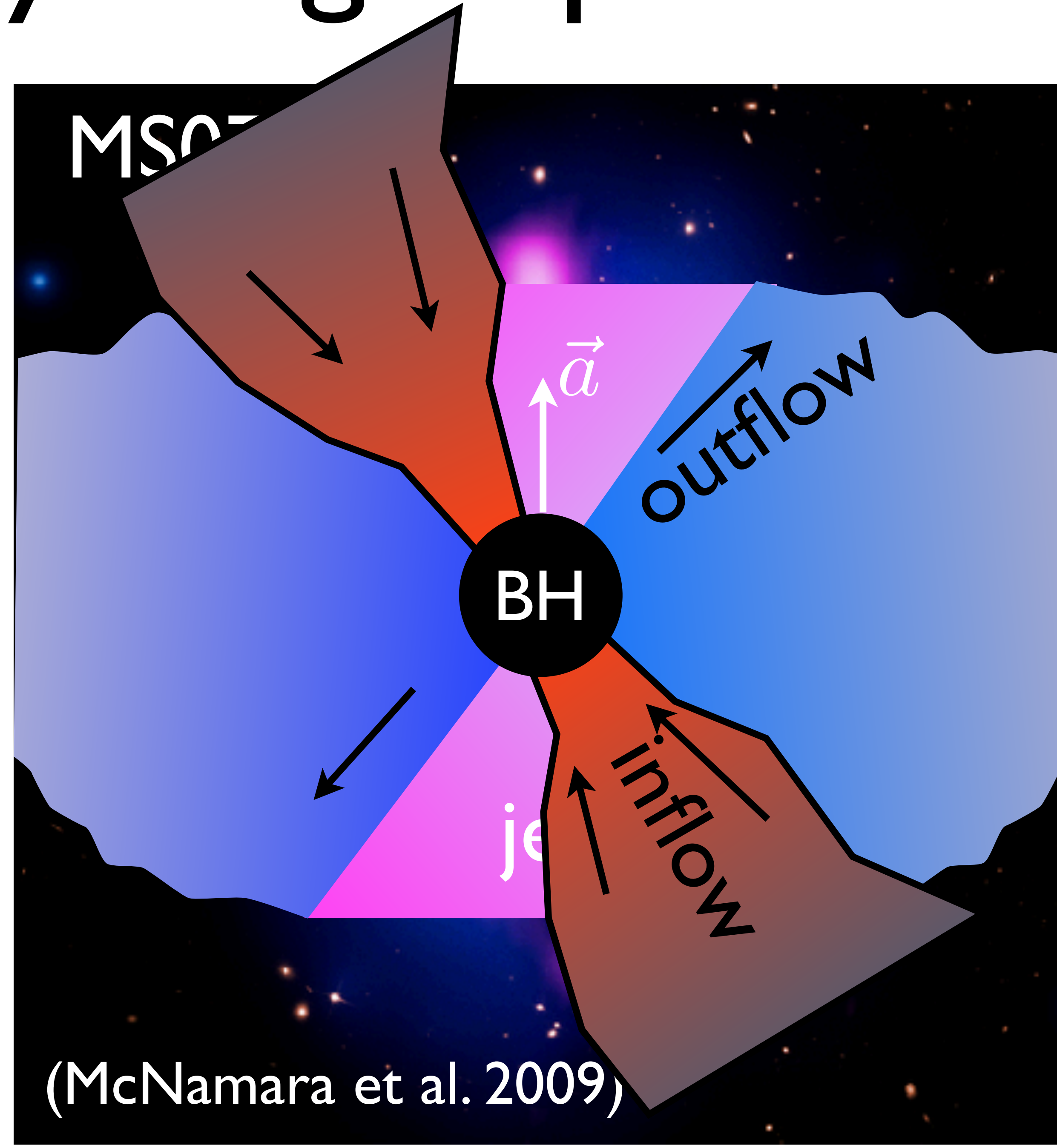
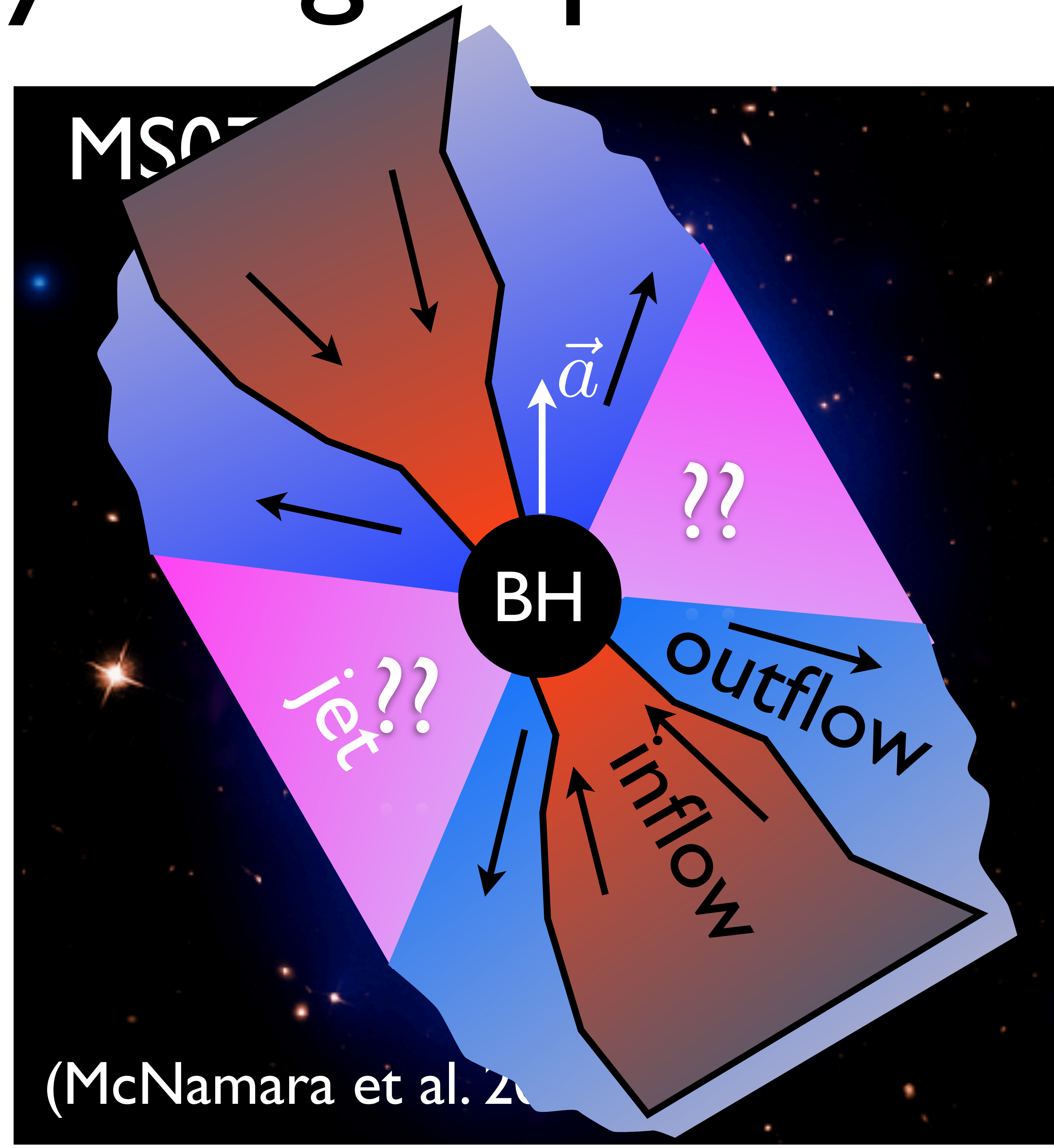


Are We Missing Anything Important?

- We already understand the basics of disks and jets
- Most of the work: aligned systems
- Expectation *(AGN, TDEs, BH-NS mergers)*: *tilted disk*
- Challenge: understand the physics of the *most common*, *tilted*, accretion flows from *first principles*

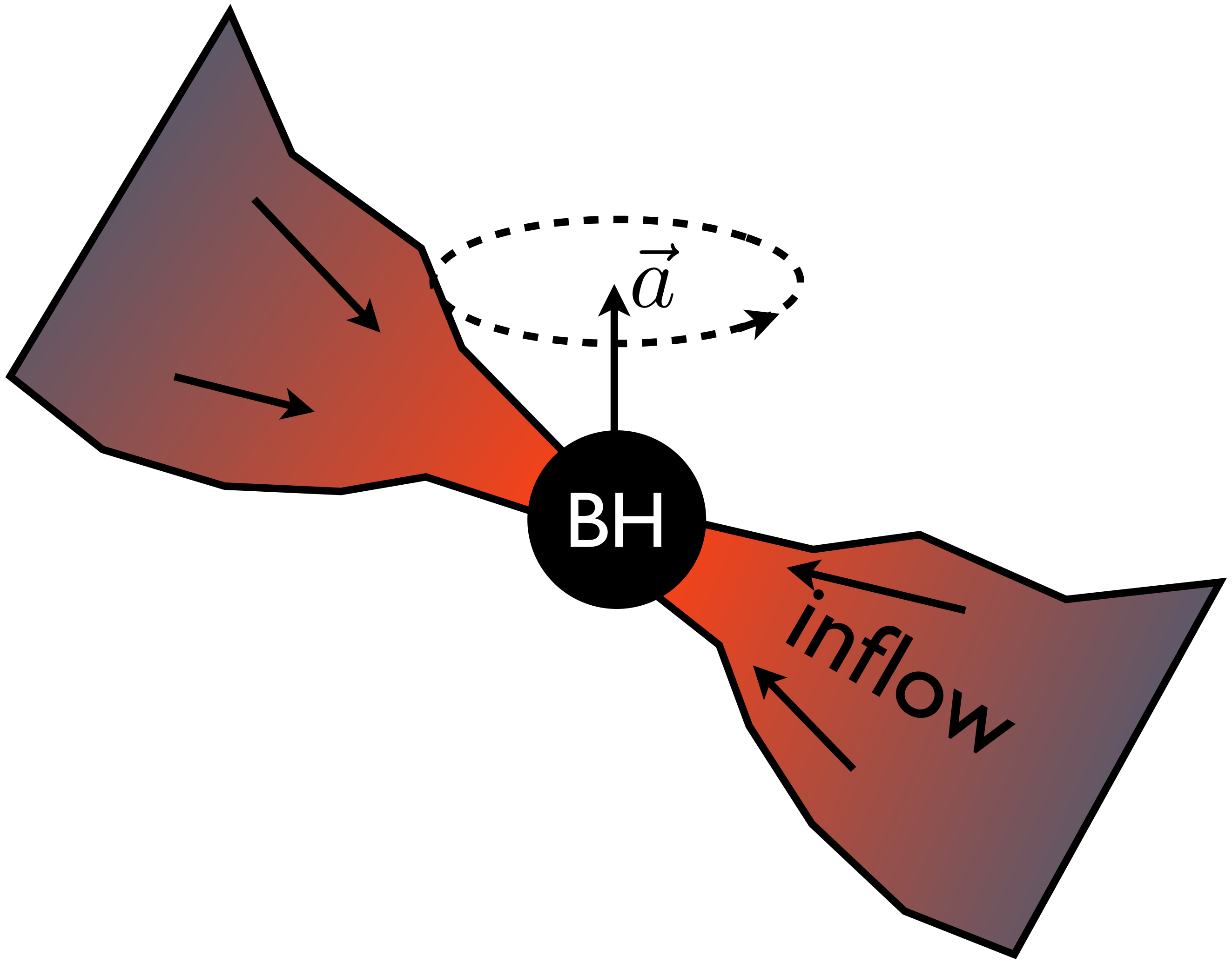


YES: disks are tilted

No: we do not understand them (yet)

Tilted Disk Physics

- **Thick disks** precess due to general relativistic frame dragging by BH spin
  - precessing tilted disk sims could not handle jets (Fragile et al. 2005, 2007)
  - *Do tilted disks produce jets at all? Do jets precess or point along BH spin?* (McKinney, AT+2013)



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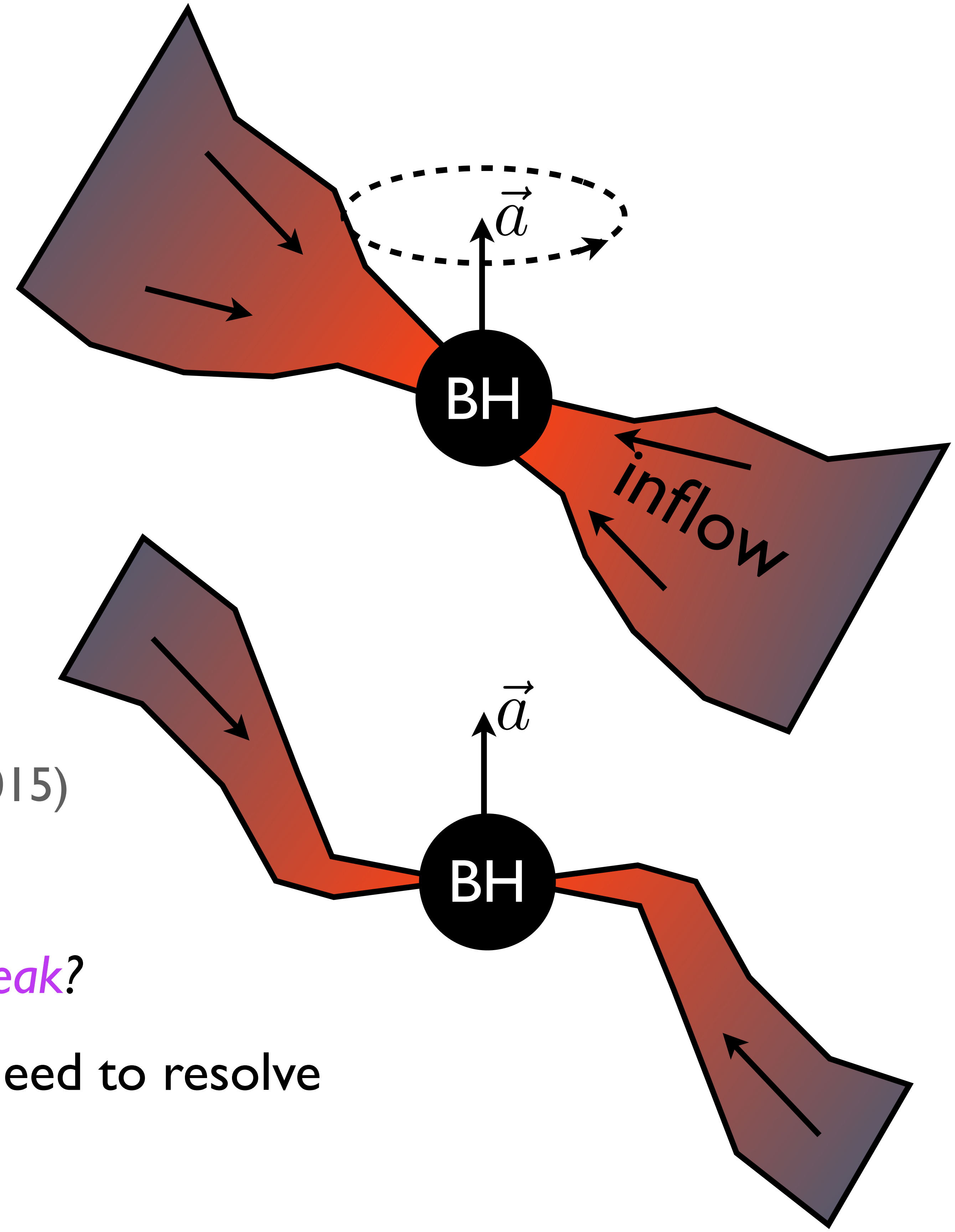
- **Thin disks** can align due to Bardeen-Petterson (1975) effect
  - Seen only in pseudo-Newtonian simulations and at small inclinations (Hawley and Krolik 2015)
  - At larger inclinations disks predicted to break (Nixon et al. 2012)
  - *Do thin disks align in GR? Or do they break?*
- Challenge: enormous dynamical range. Need to resolve thin streams *over* long run times. How?!



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)
  - 100-200x speedup on 1 GPU vs 1 CPU core

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(U of Amsterdam)

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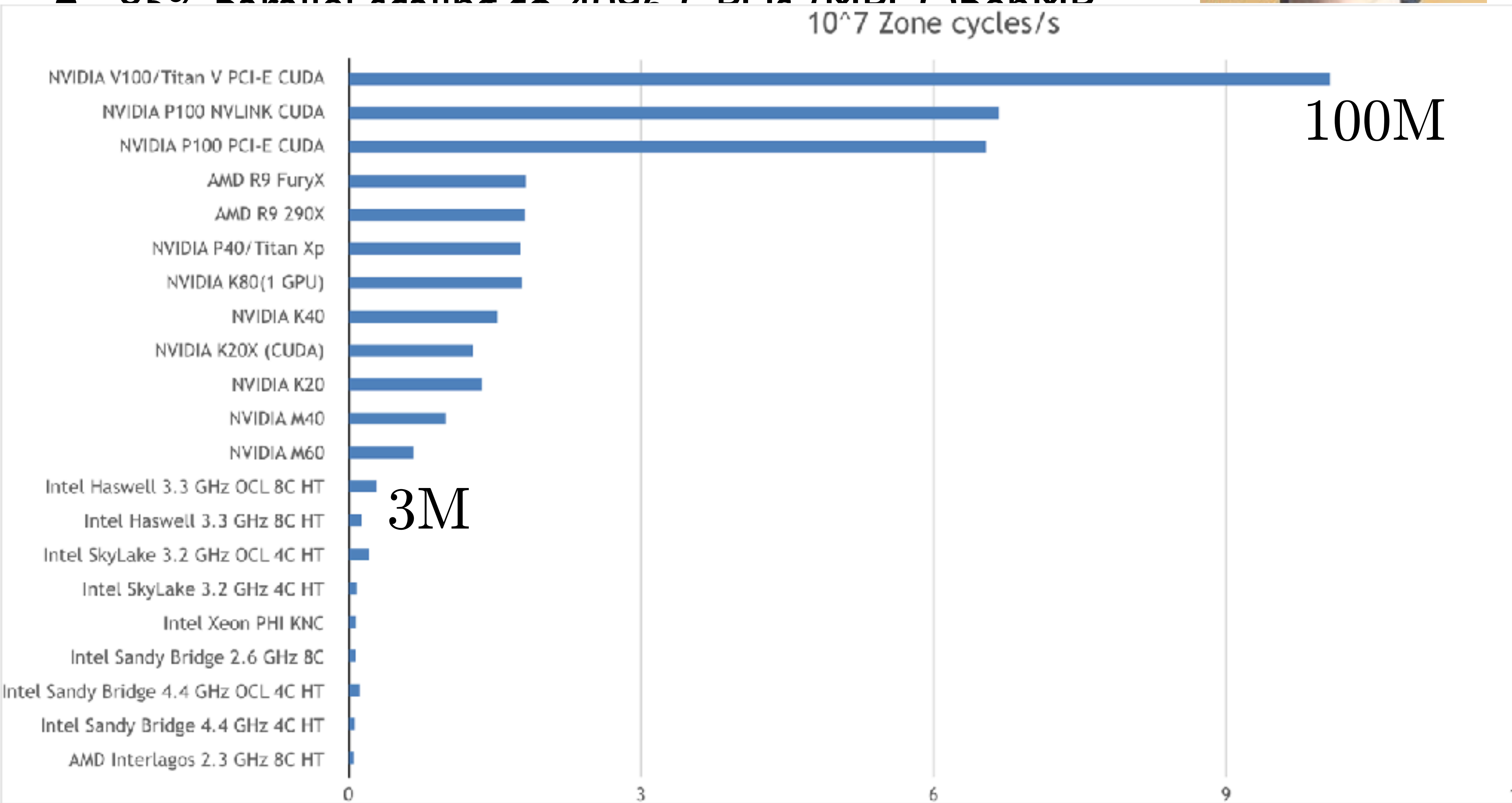

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Matthew Liska
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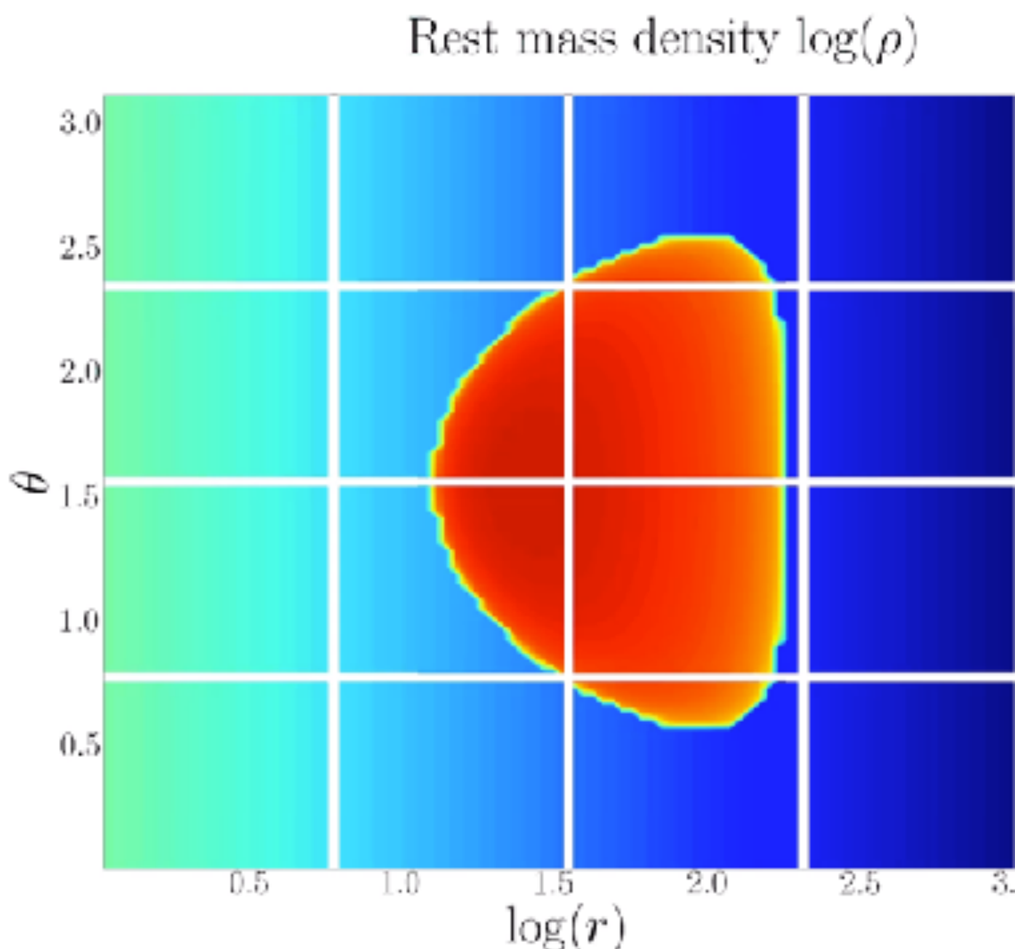

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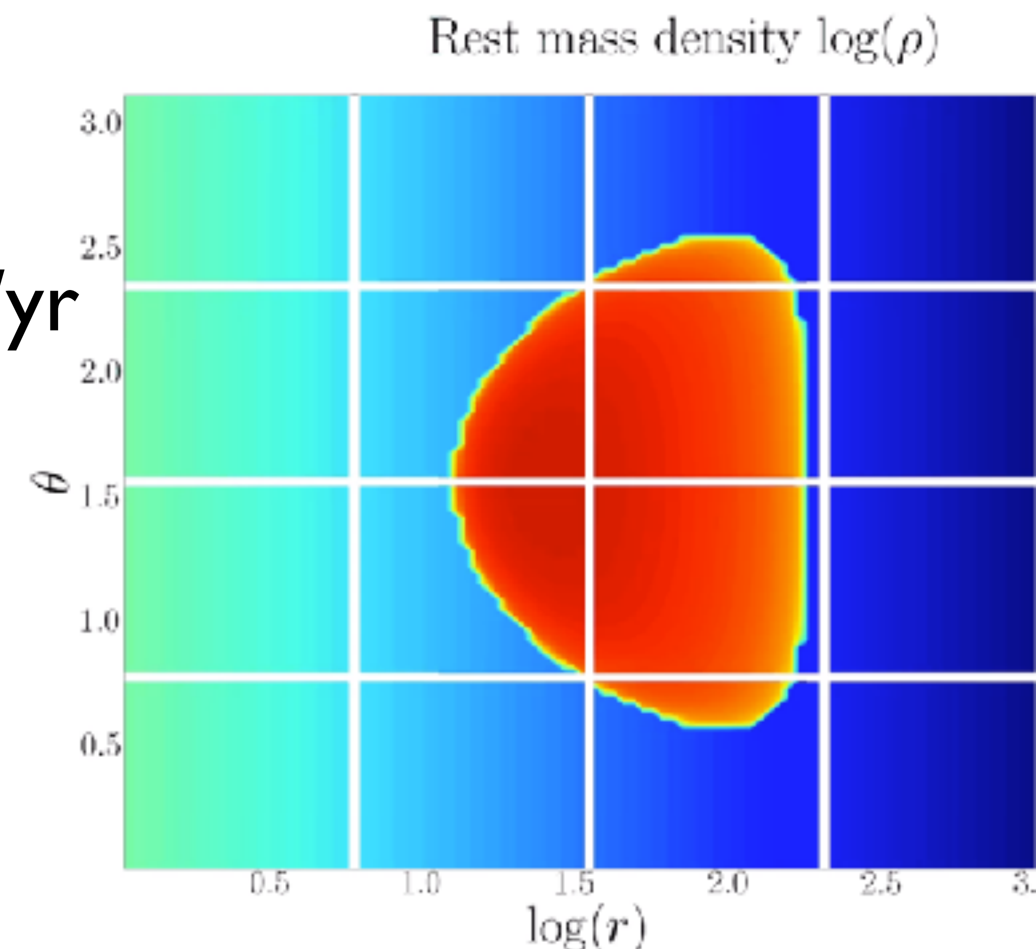
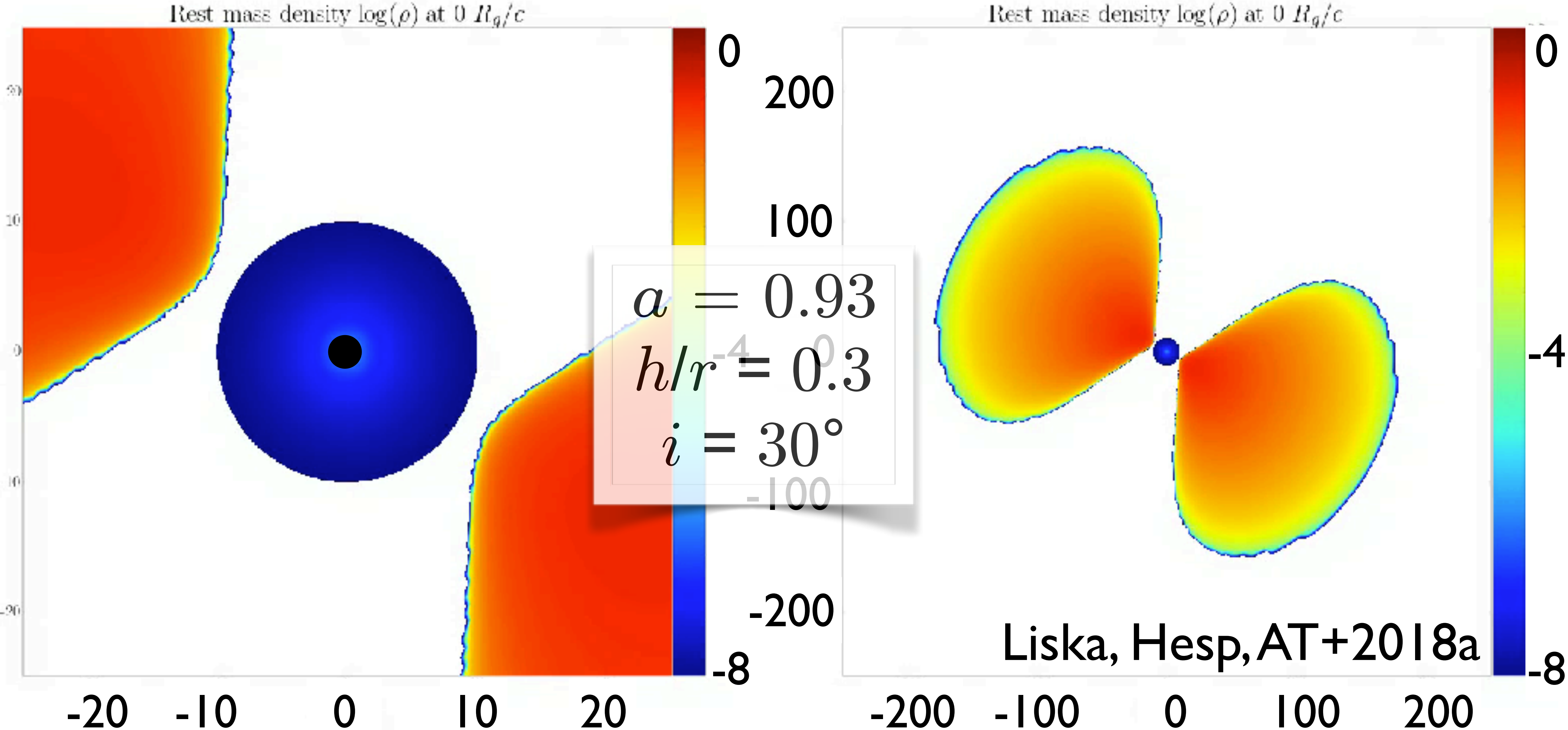
- Advanced features (extra few - 10x speedup):
  - Adaptive Mesh Refinement (AMR)
  - Local adaptive time-stepping
- Ideal for getting computational time:
  - 5M GPU-hours/yr = 5B CPU core-hours/yr on NSF Blue Waters supercomputer
  - Science is no *longer limited by computational resources*!

Matthew Liska
(U of Amsterdam)



Thick Disks Precess



- The first demonstration that
  - tilted thick disks produce tilted jets
  - tilted jets precess
- Longest GRMHD tilted disk simulation, $120{,}000\ r_g/c$
- Highest resolution GRMHD simulations: $896 \times 288 \times 480$
  - convergence verified at 2x resolution: *first ever billion cell run*

(Fragile+07,09; McKinney,AT+13)

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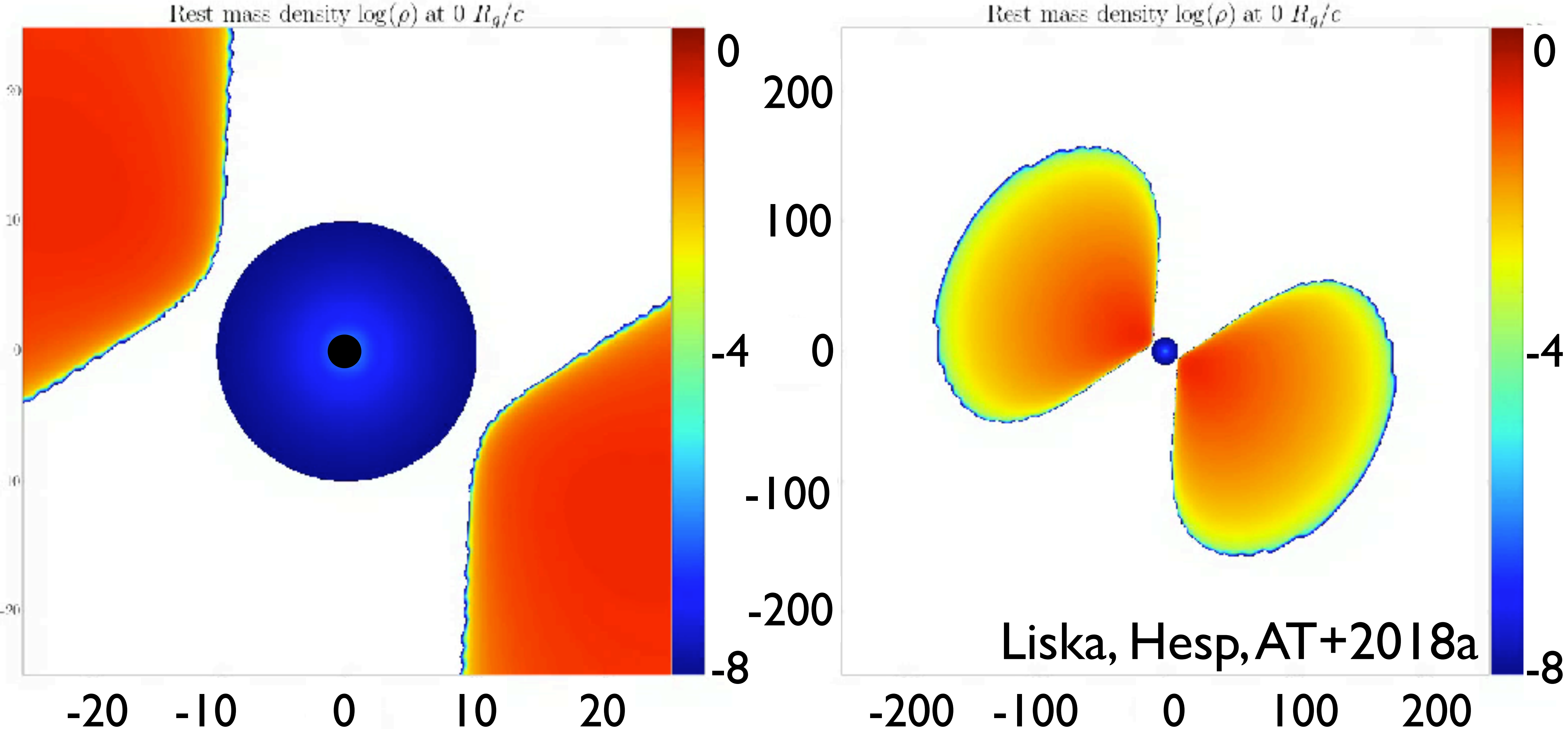

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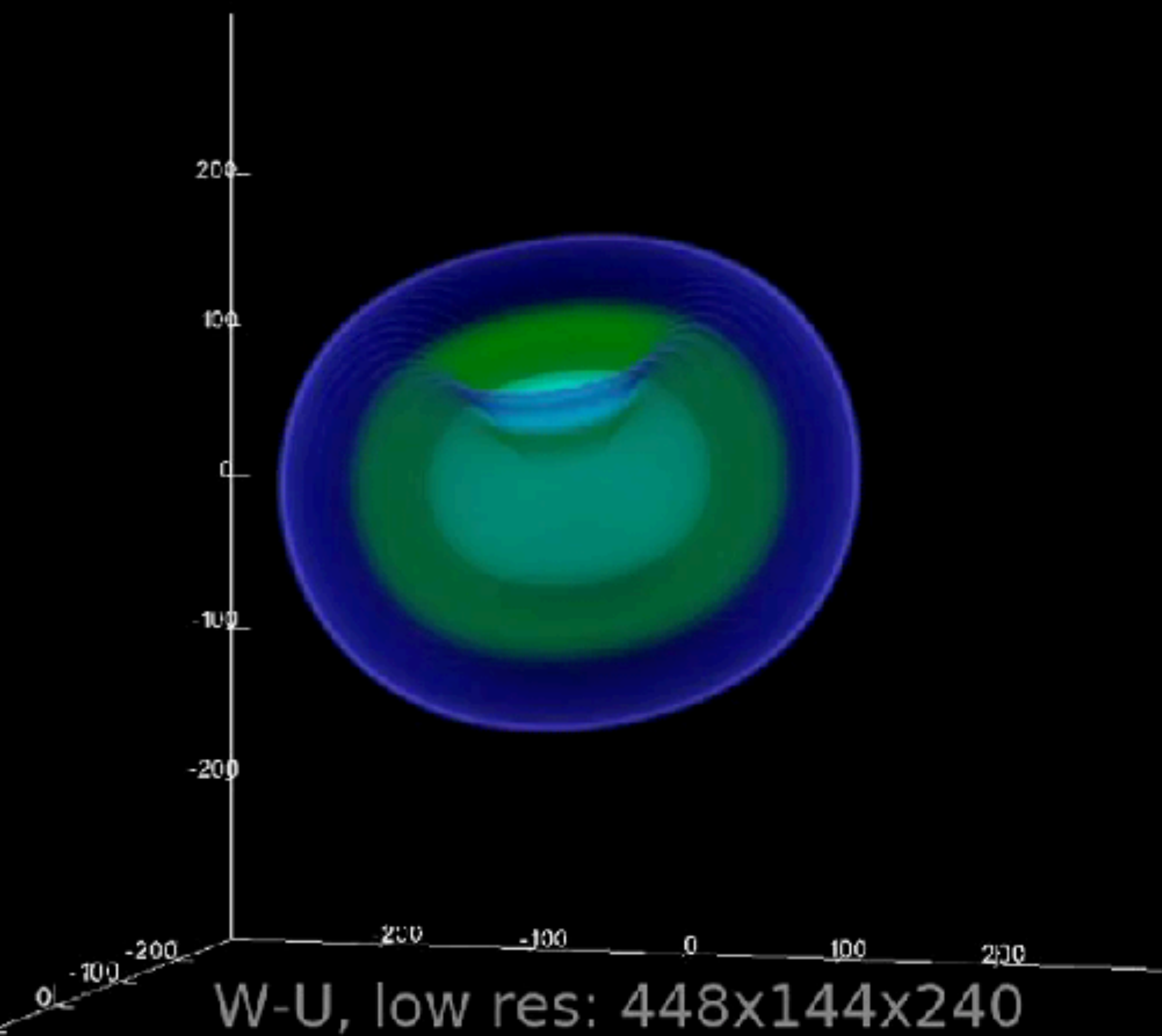
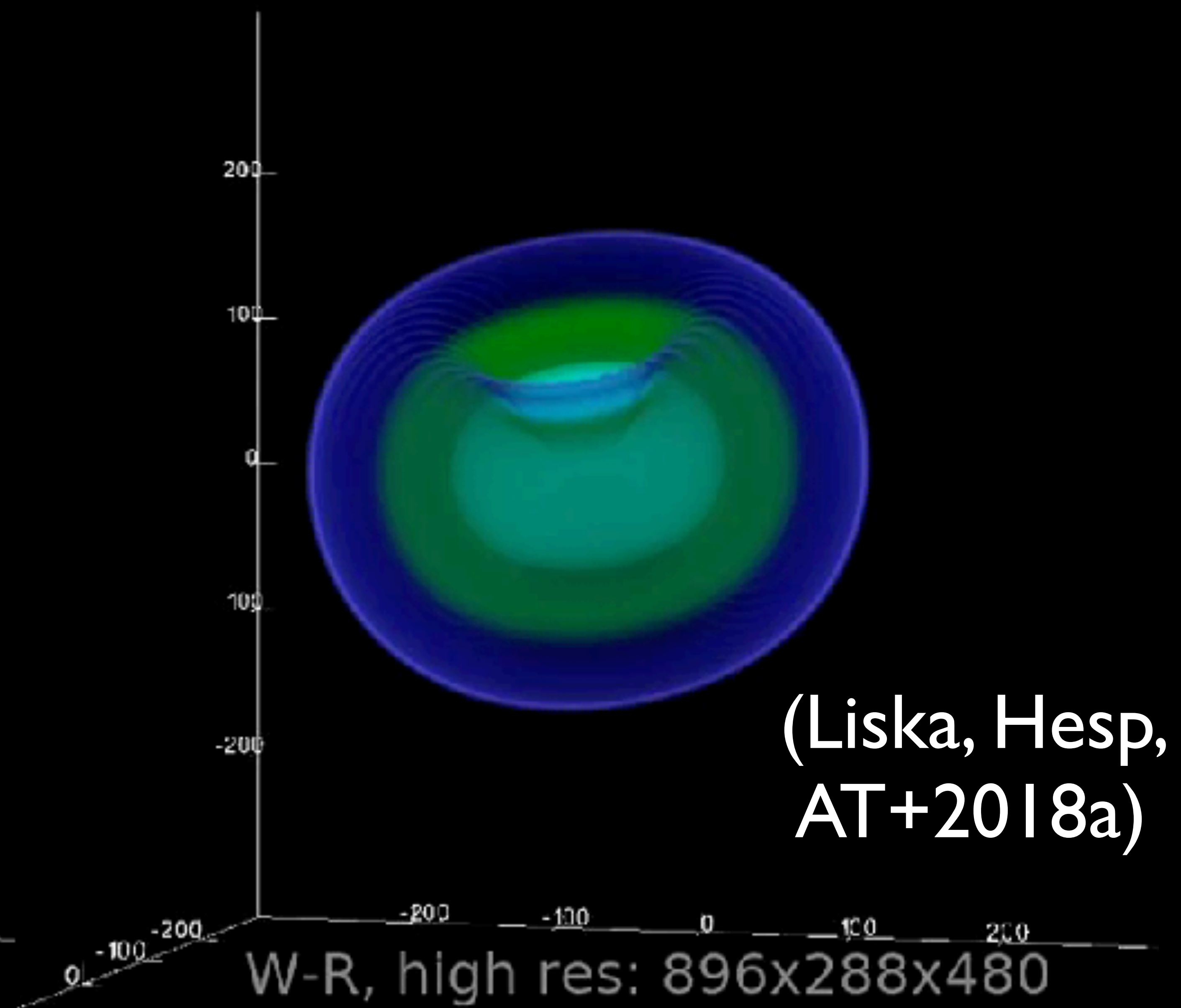
BUT: precession slows down

2x lower resolution



fiducial resolution



(Liska, Hesp, AT+2018a)

At 2x higher resolution:
results are similar -> convergence

BUT: precession slows down

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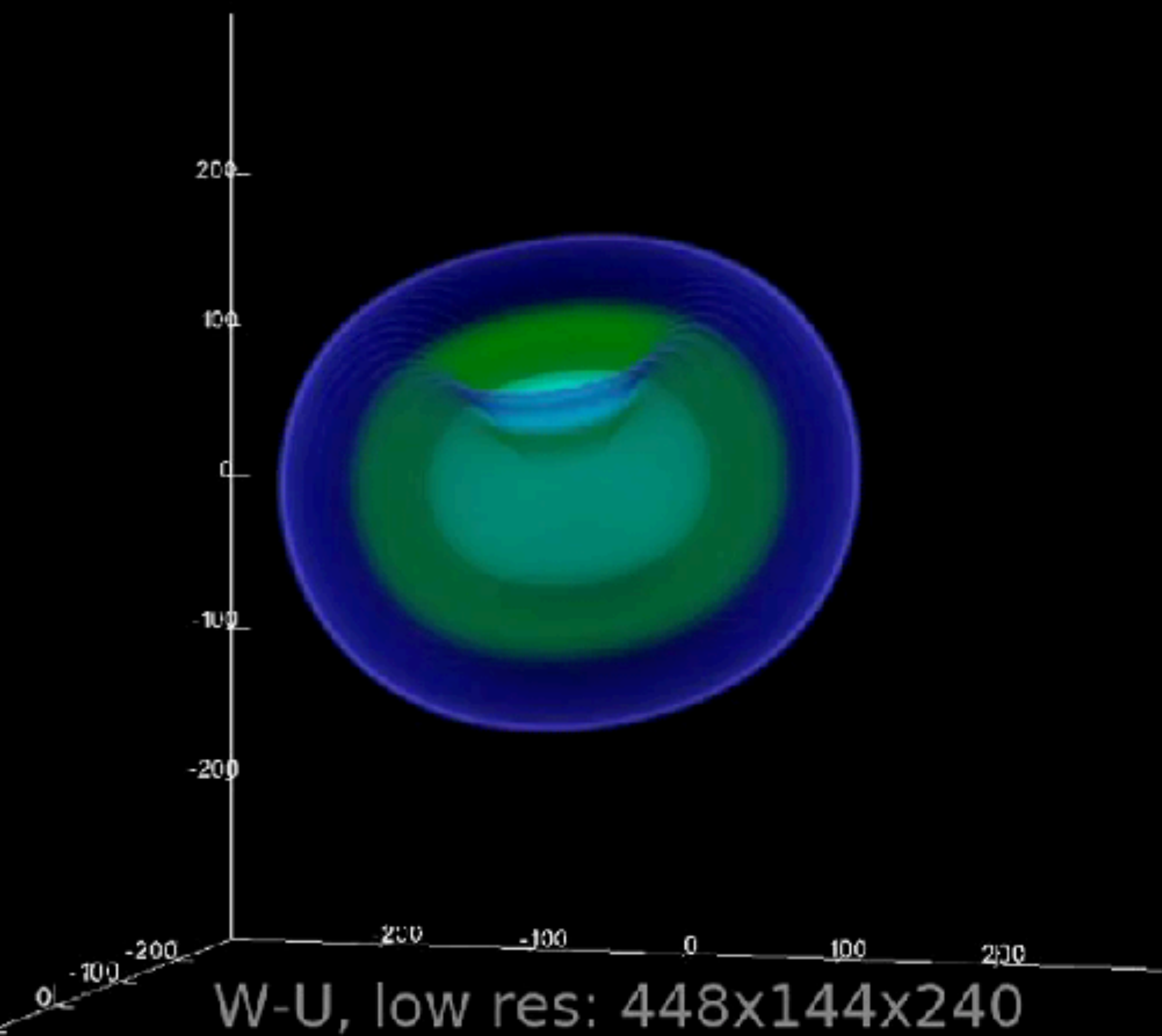

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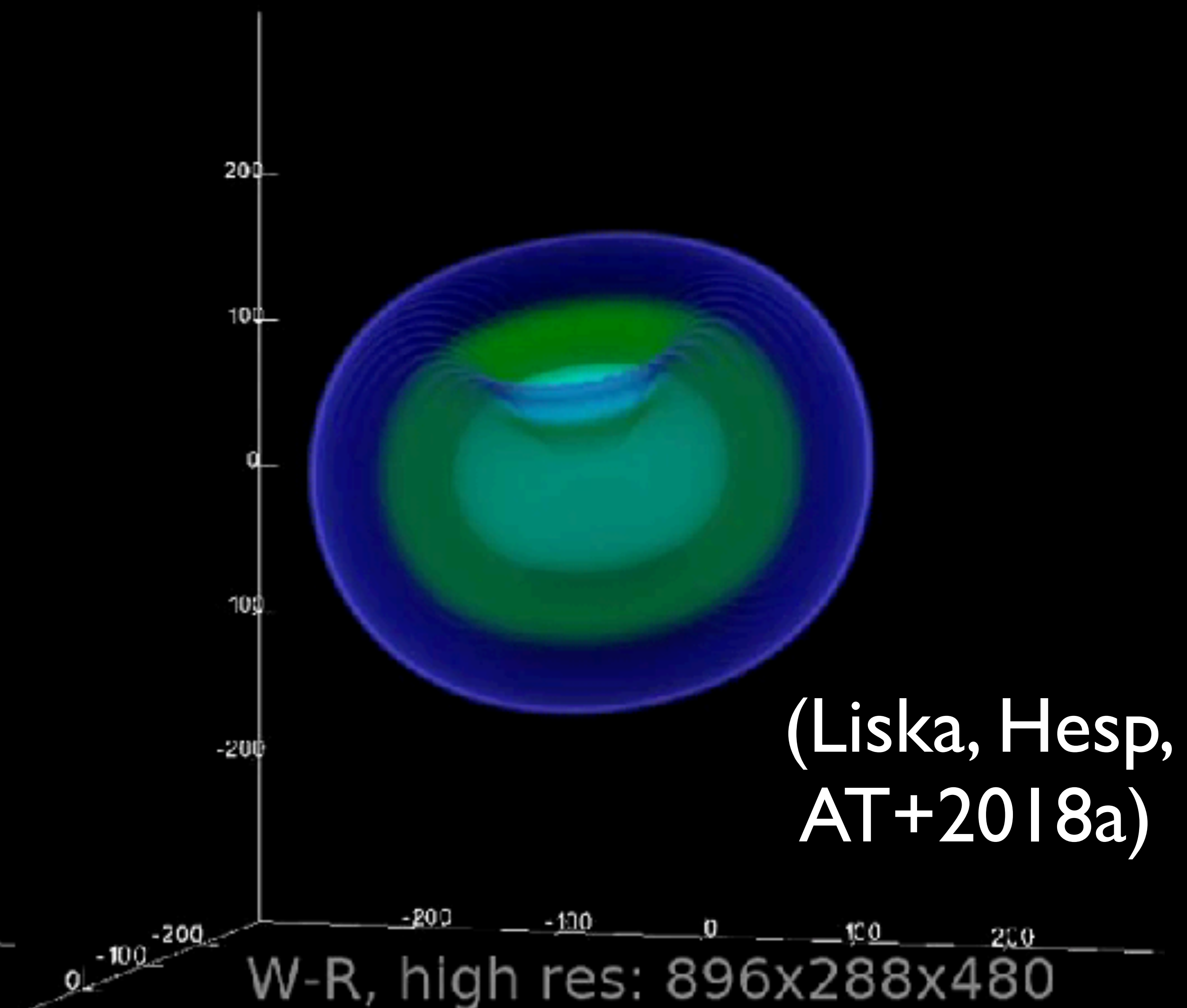

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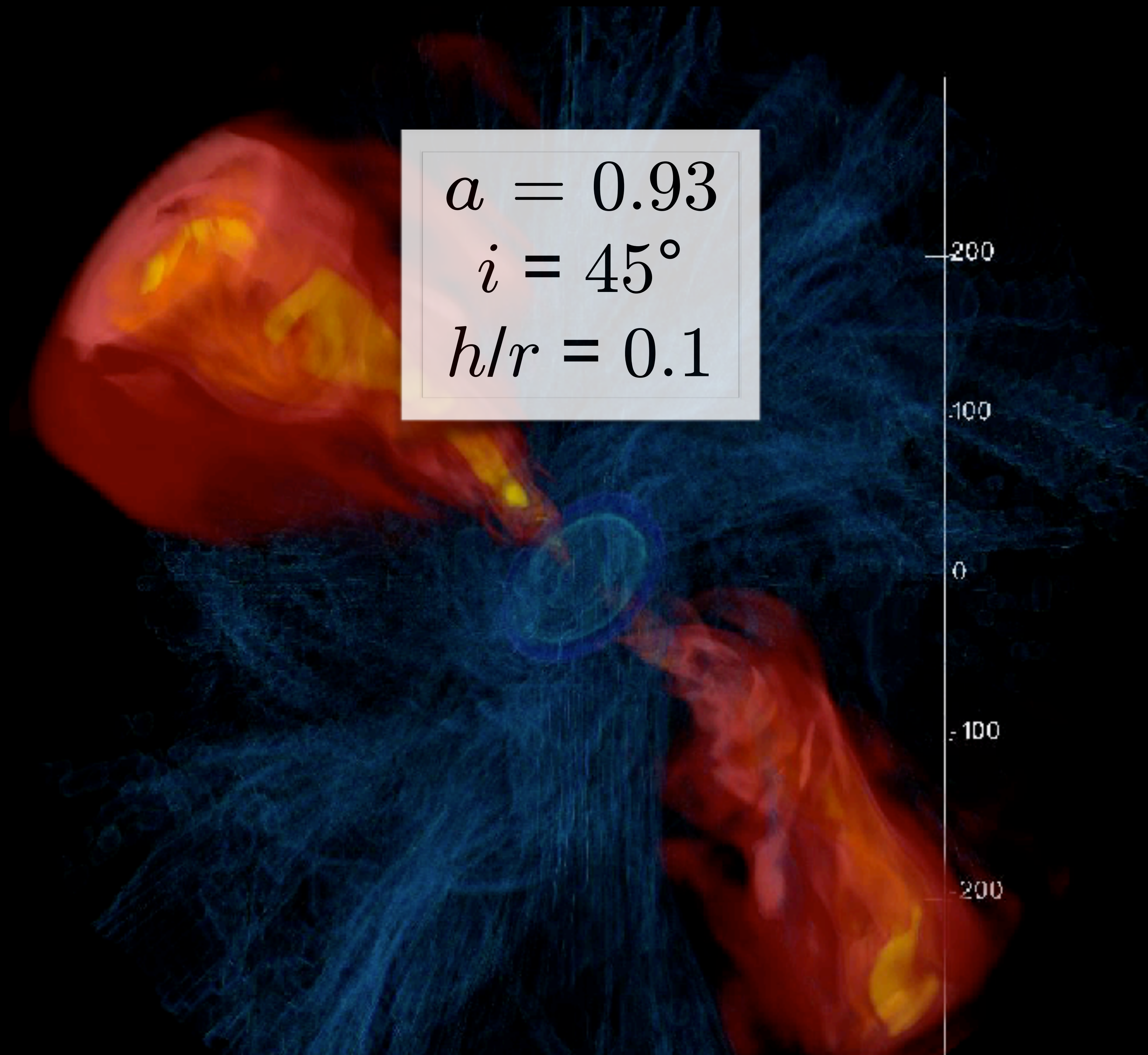
Thick-ish Disks Precess and Align



Casper Hesp
(University of Amsterdam)

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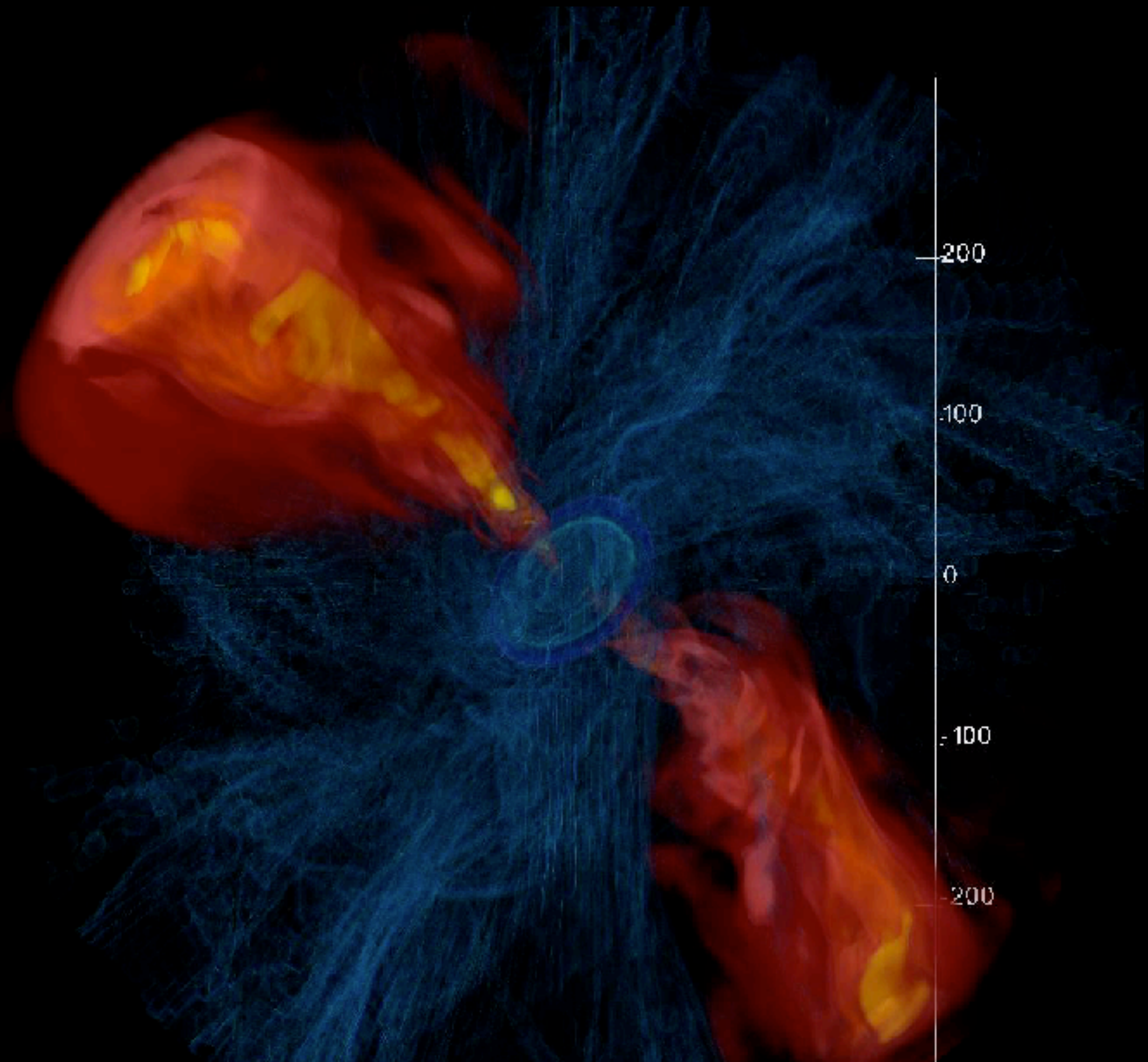
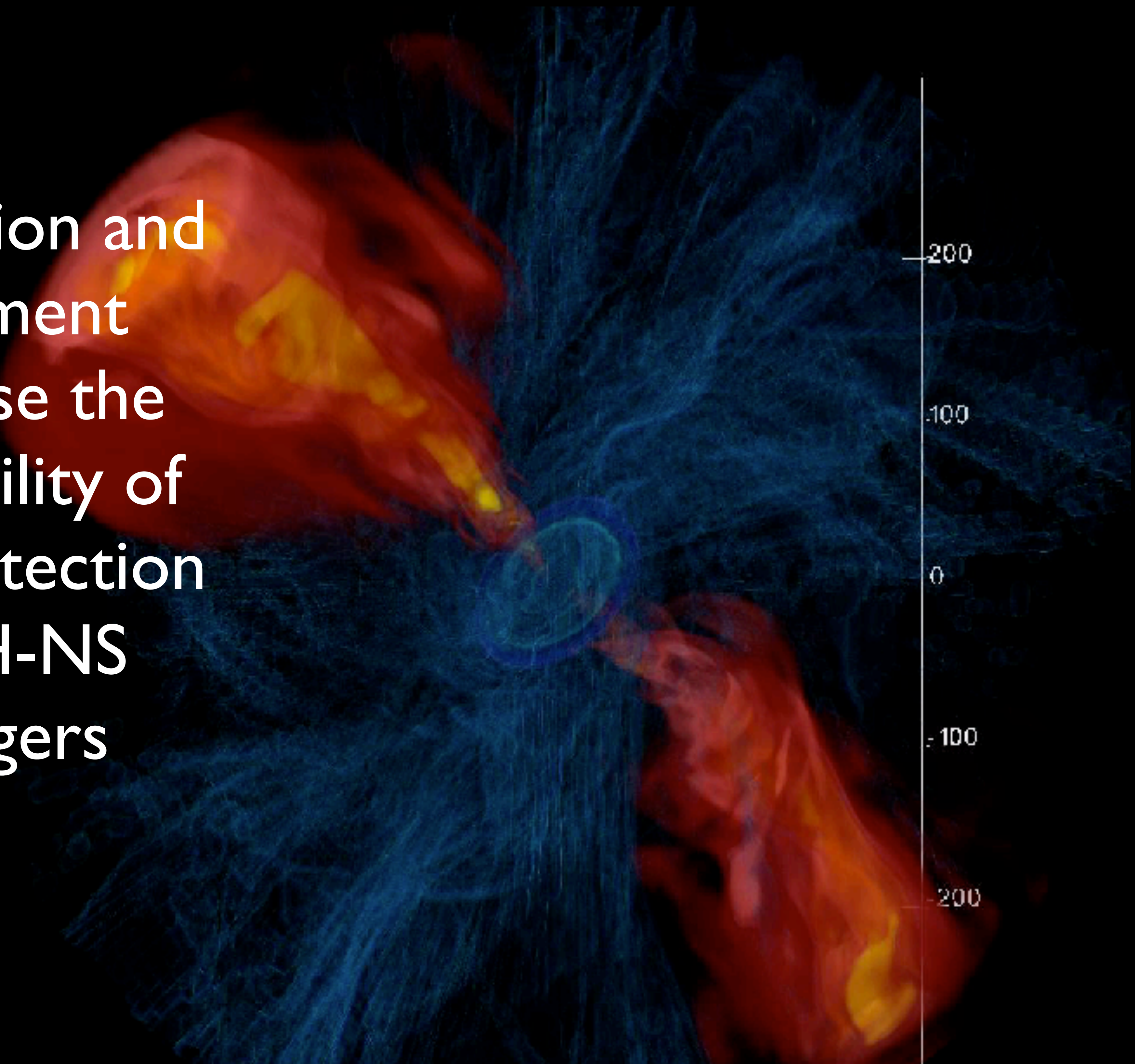


Casper Hesp (University of Amsterdam)

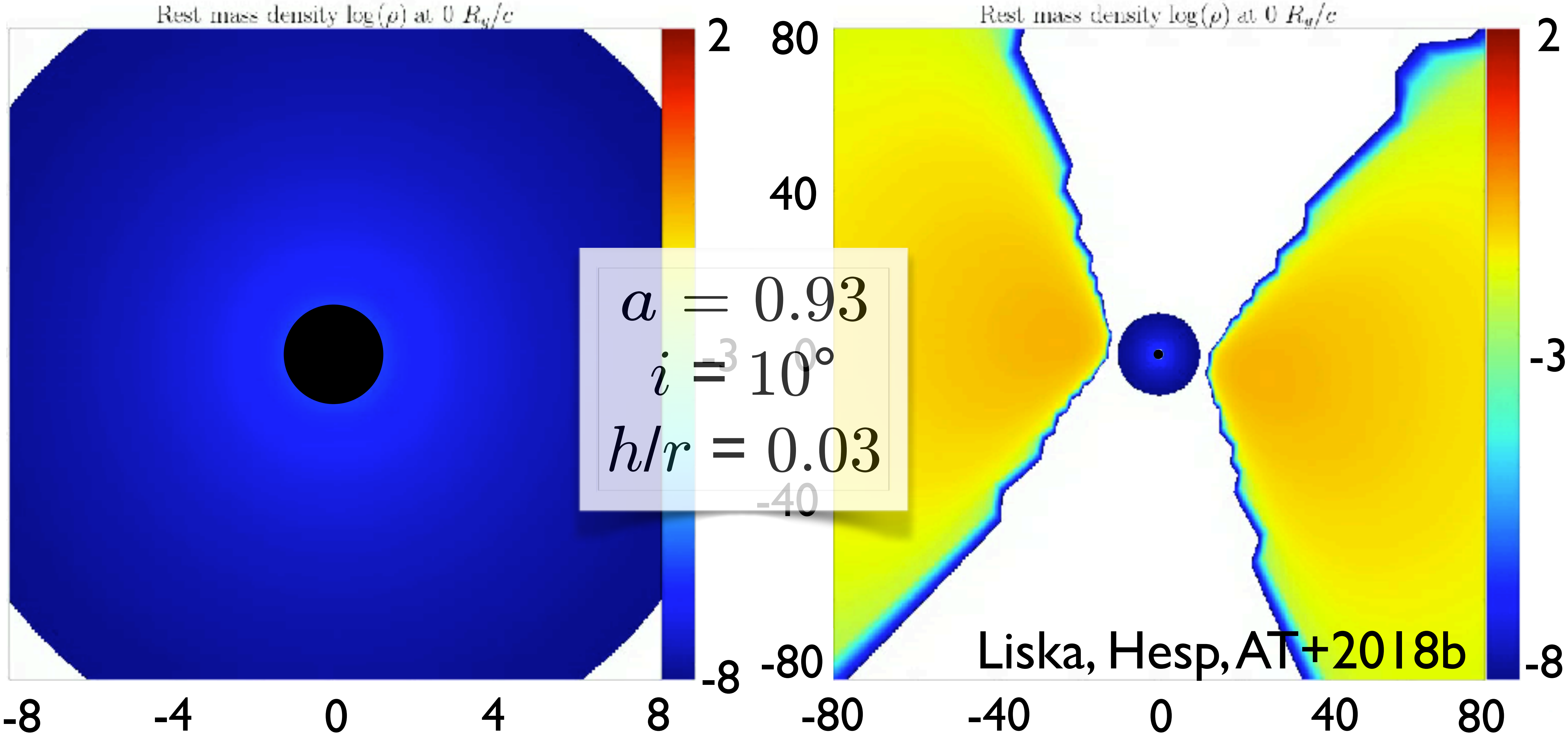
Thick-ish Disks Precess and Align

Precession and alignment increase the probability of GRB detection in BH-NS mergers



Casper Hesp (University of Amsterdam)

Thin **Weakly** Misaligned Disks **Align**



- Thinnest disk simulations to date: $h/r = 0.03$
- First demonstration of (Bardeen-Petterson?) alignment in a general relativistic MHD simulation of a thin disk
- Effective resolution $1792{\times}860{\times}1200$, 3 AMR levels

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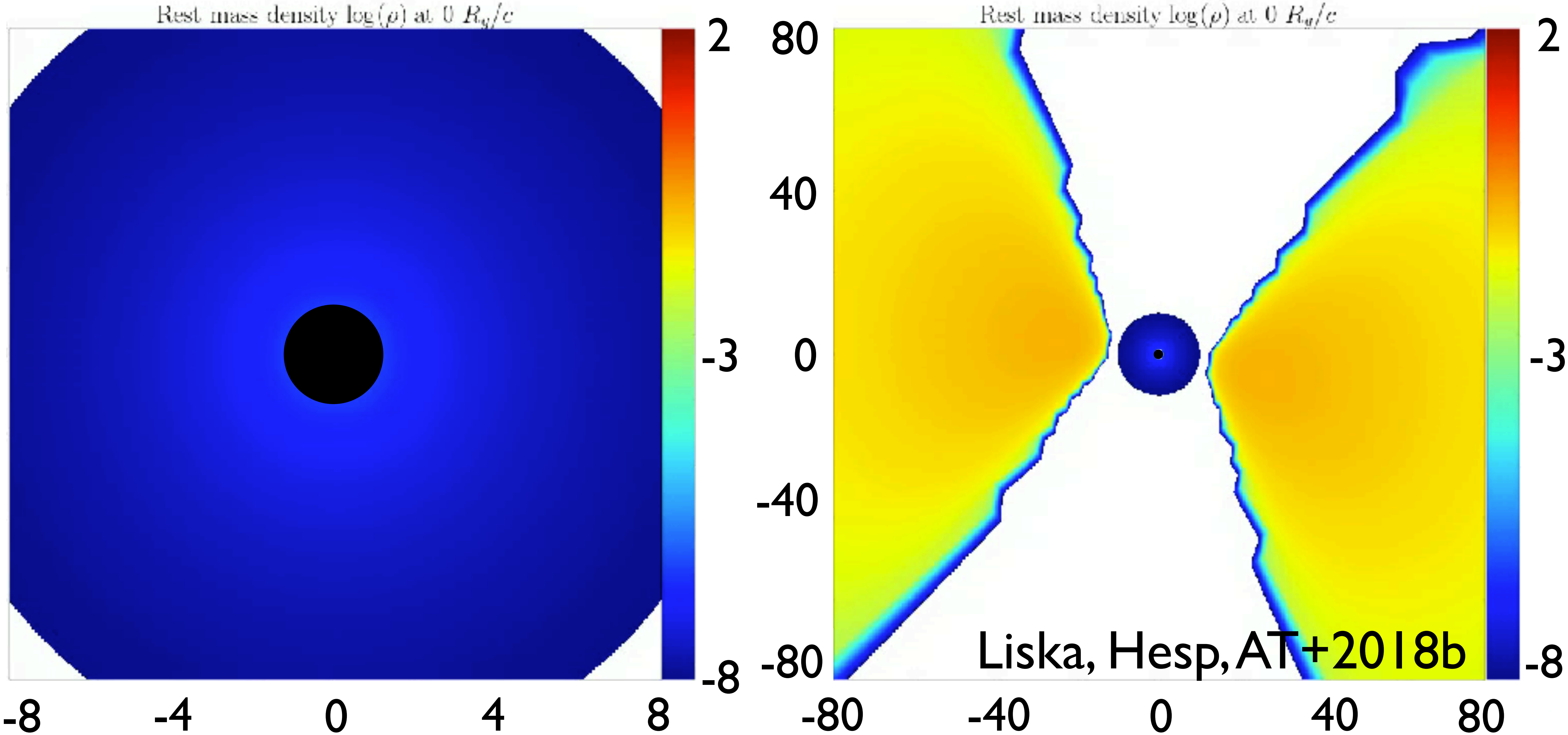

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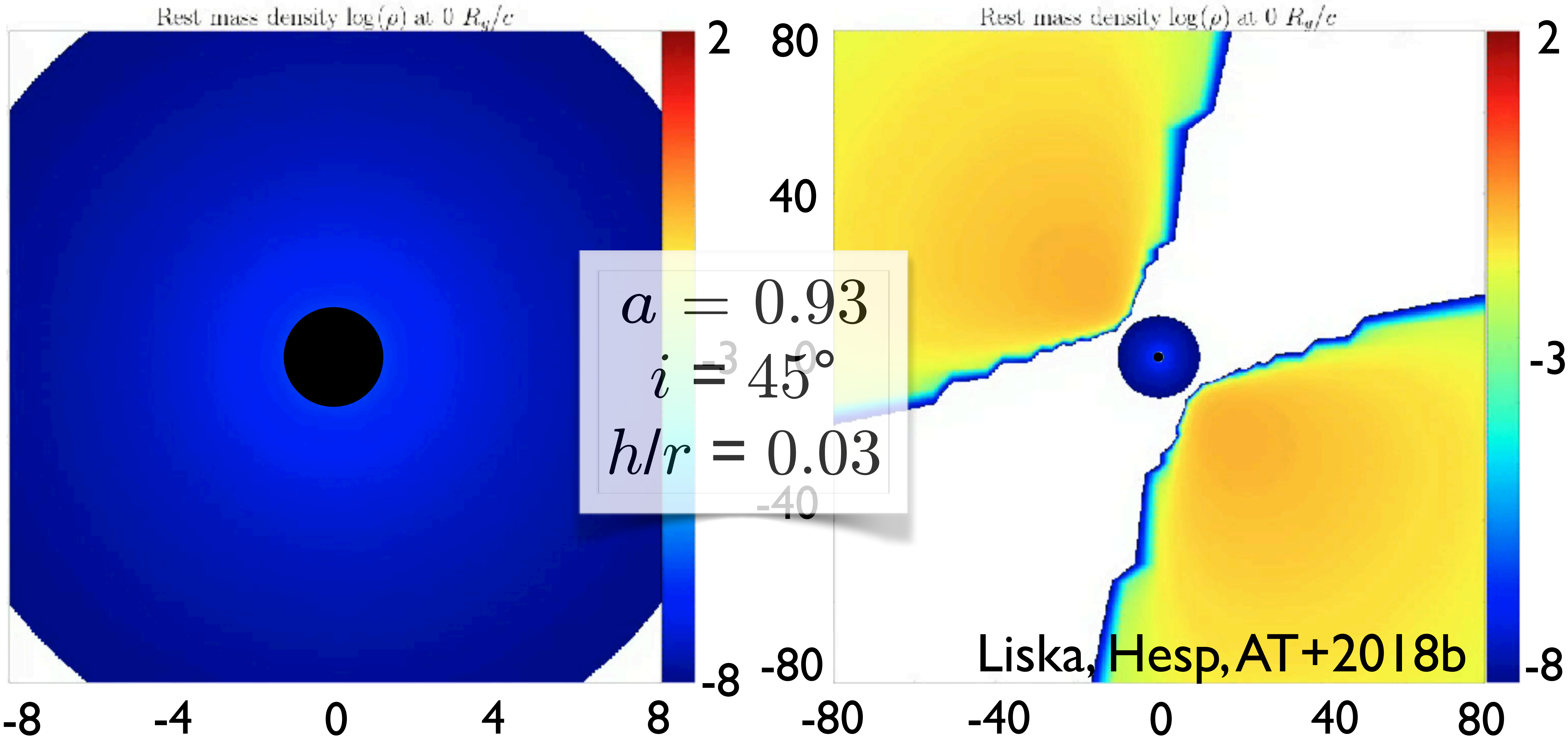

- First demonstration of (Bardeen-Petterson?) alignment and disk breaking in GRMHD!
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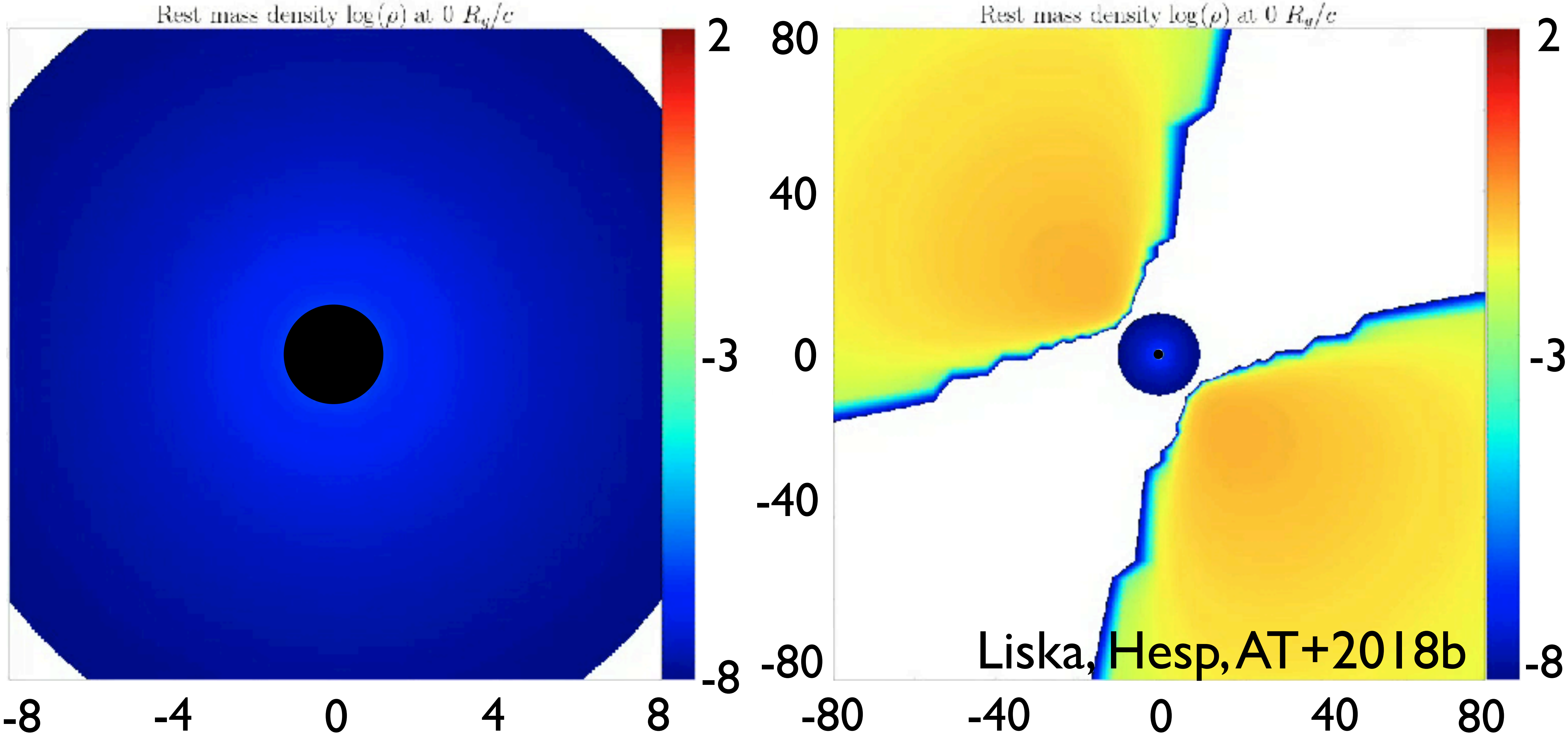
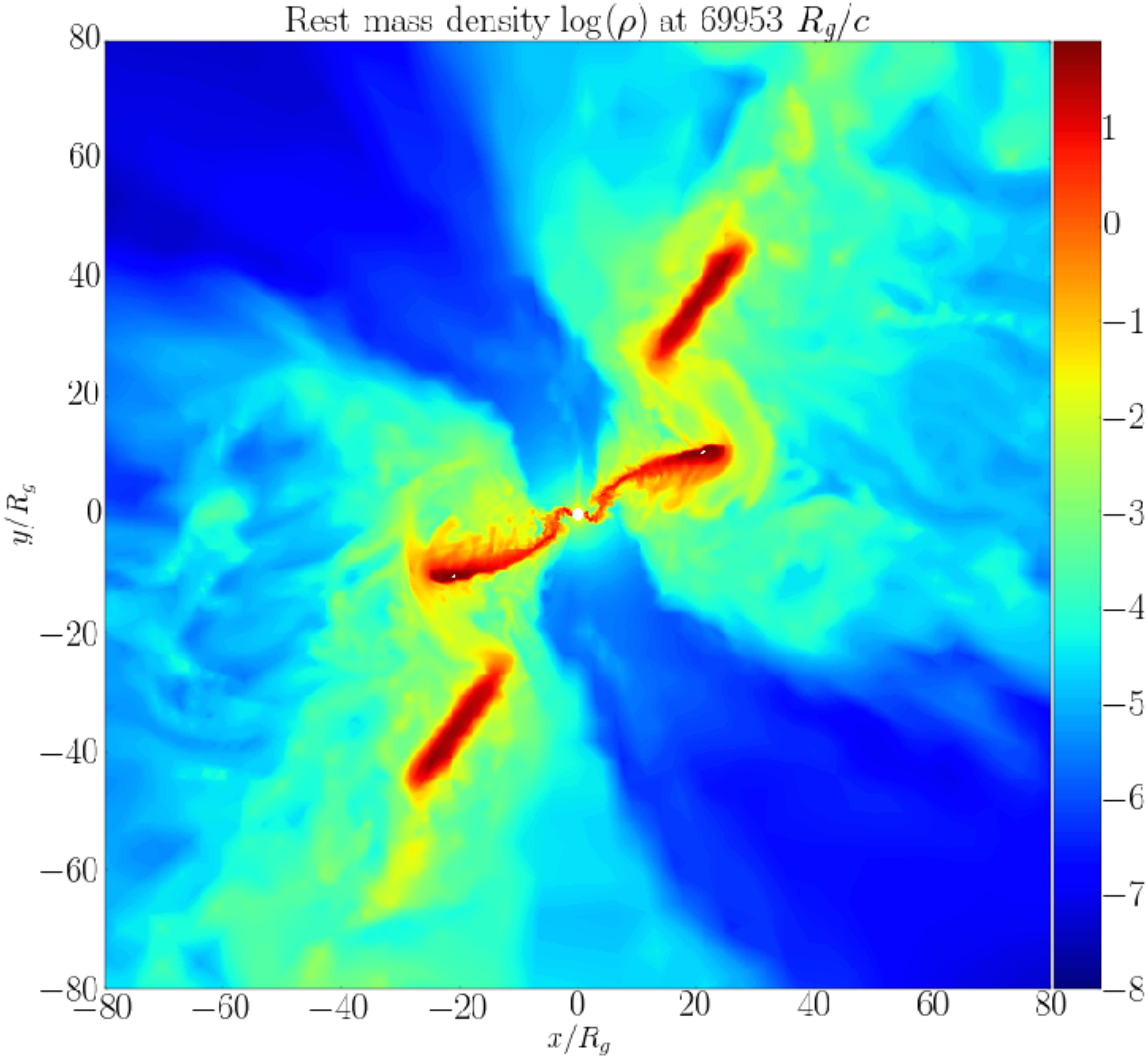


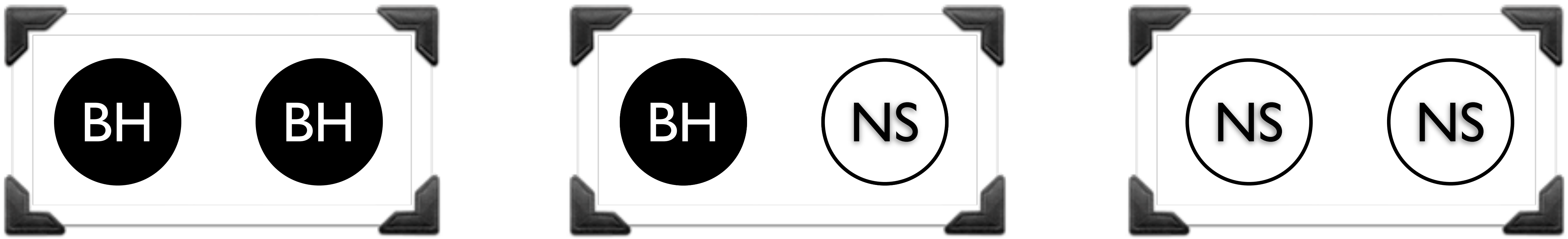
- First demonstration of (Bardeen-Petterson?) alignment and disk breaking in GRMHD!
- Effective resolution $1792 \times 860 \times 1200$, 3 AMR levels

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

- Disks can tear up into individual segments
- Extra dissipation and luminosity
- Completely different luminosity profile
- Larger observed disk size than expected? (Blackburn+2011)



EM Counterparts to Binary Mergers



detected! — detected as well!

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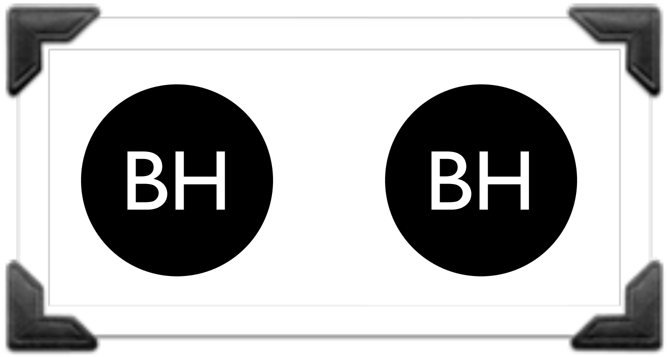

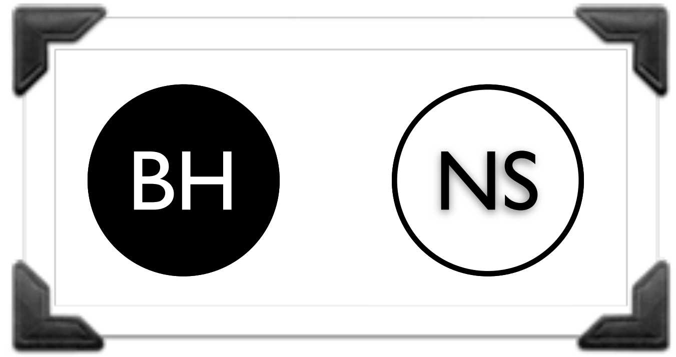

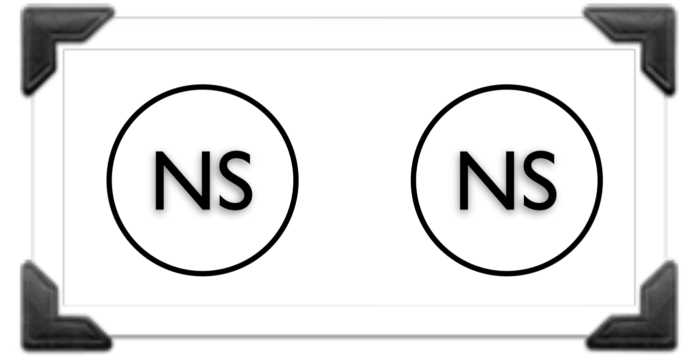

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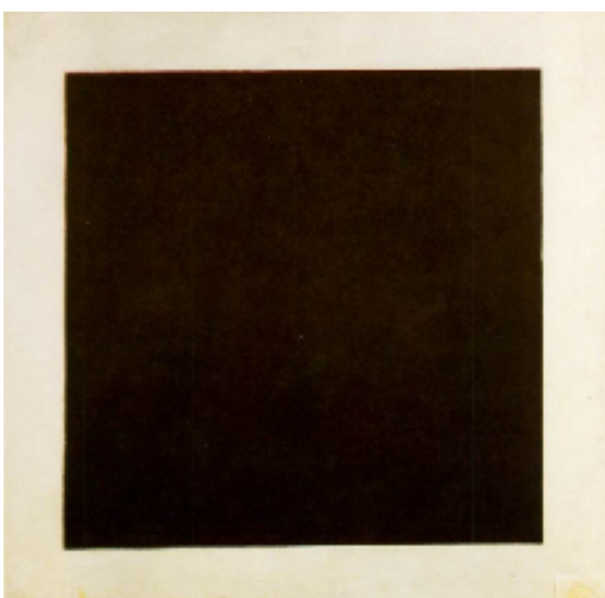
but:



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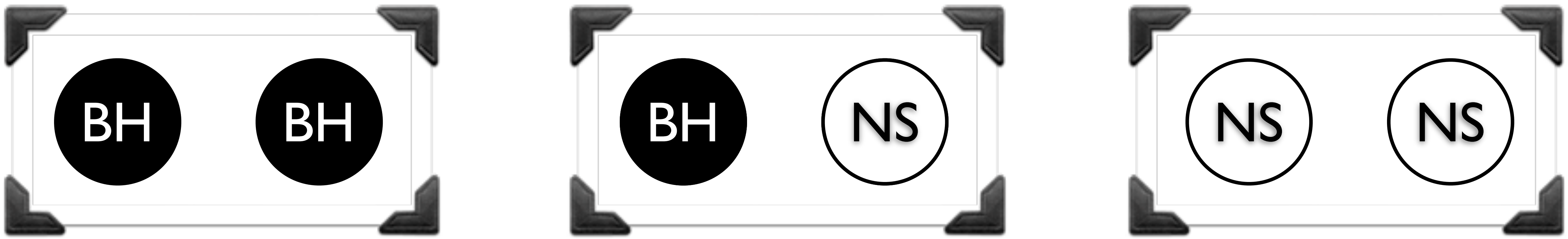
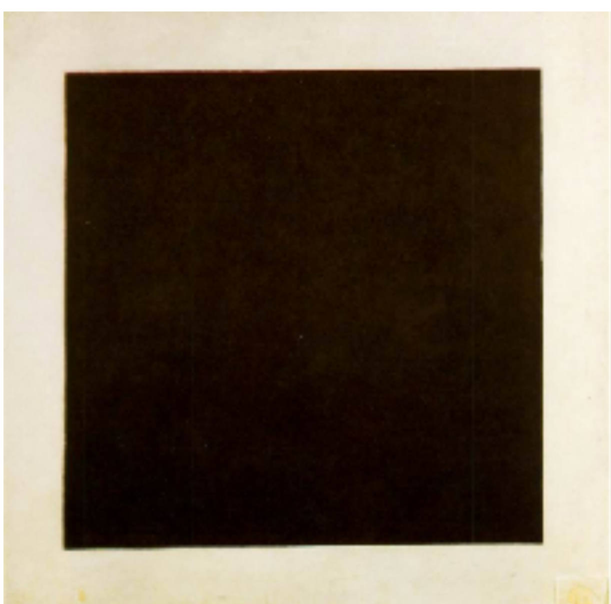
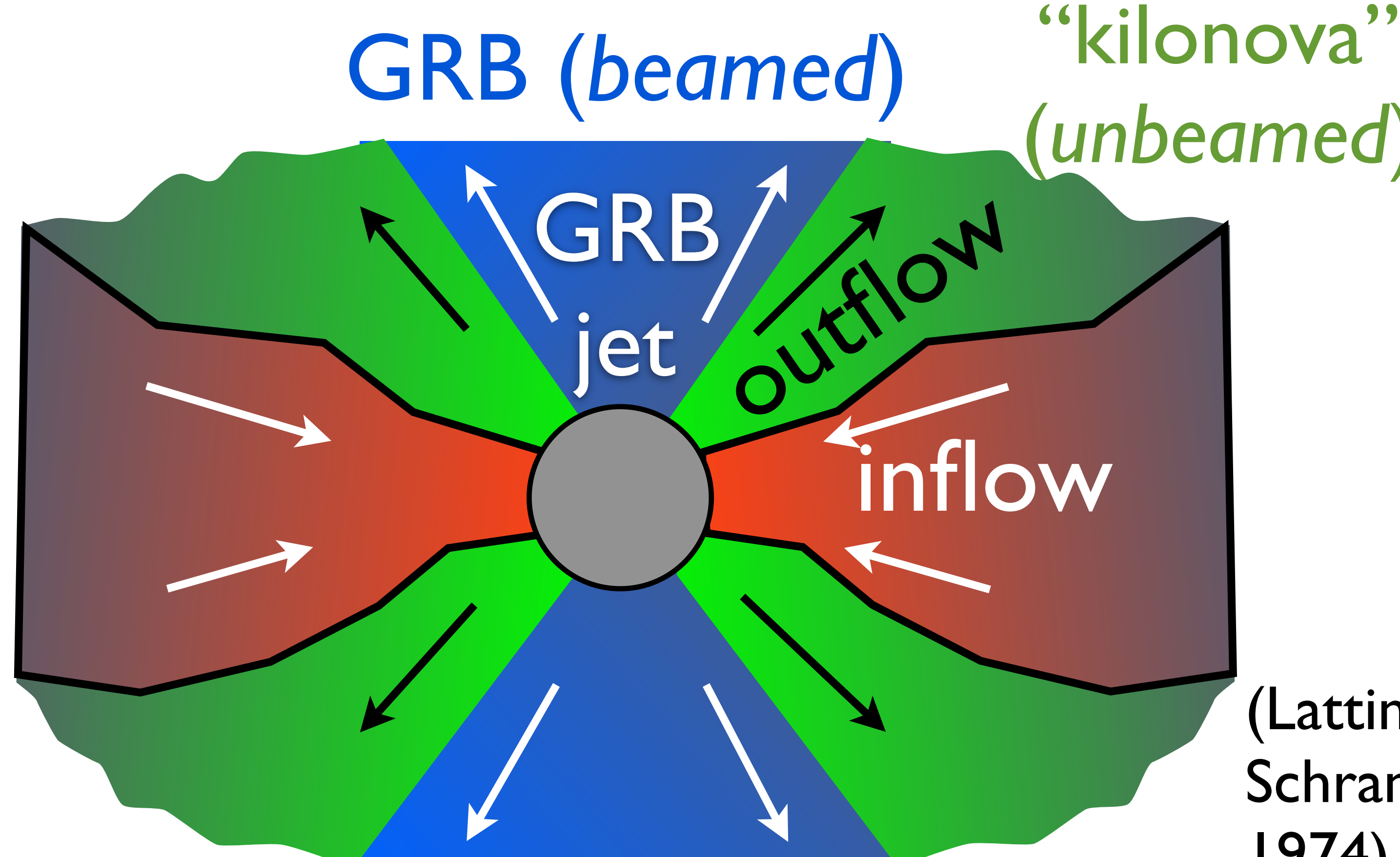


— detected! —   —— detected as well! ——

but: and have EM counterparts:



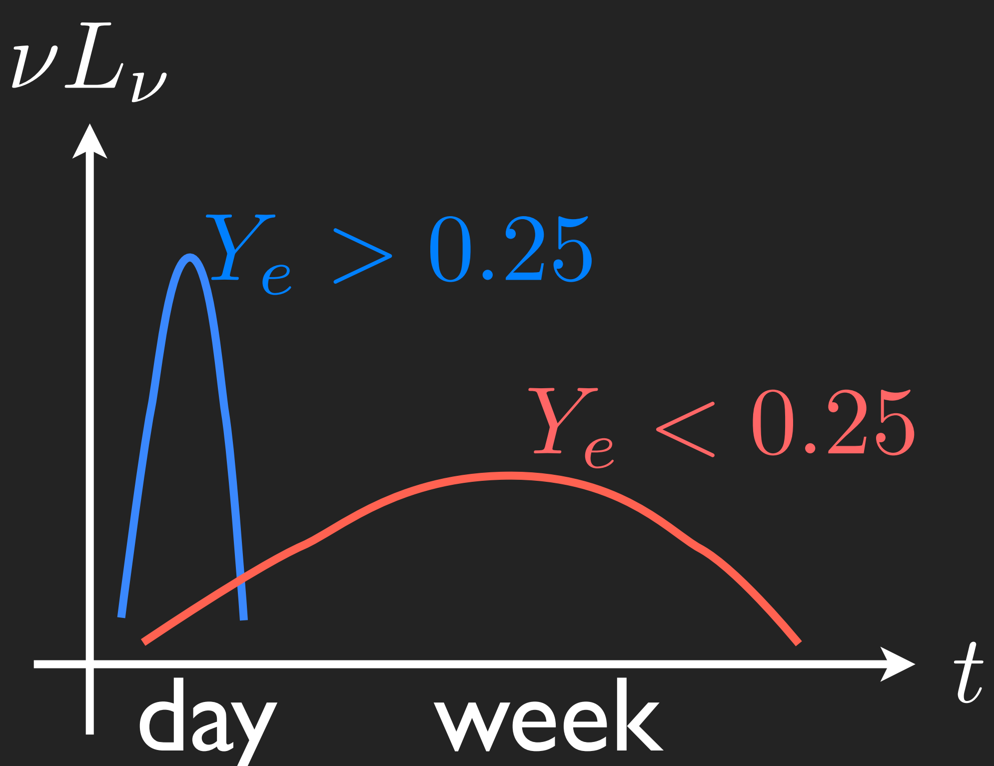


(Lattimer & Schramm 1974)

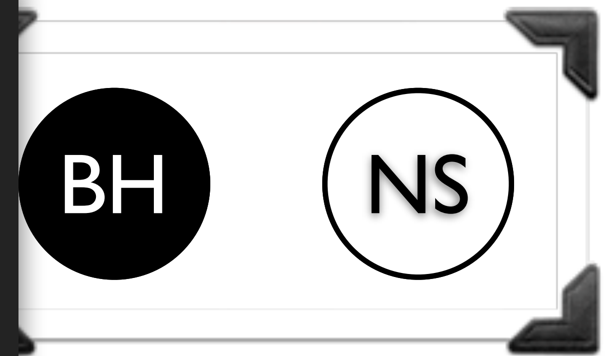
EM Counterparts to Binary Mergers

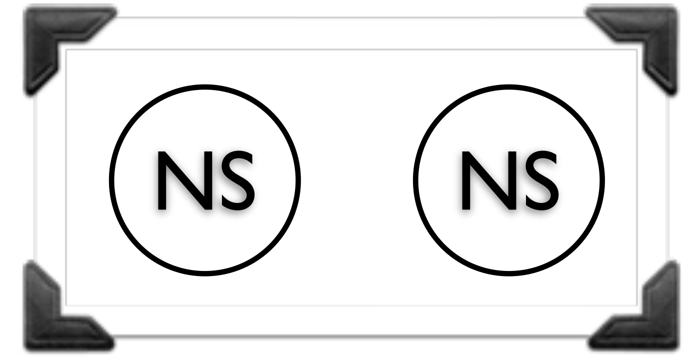
Effect of composition on kilonova light curves

Electron fraction $Y_e = \frac{n_e}{n_B}$



high Y_e = short blue luminous transient



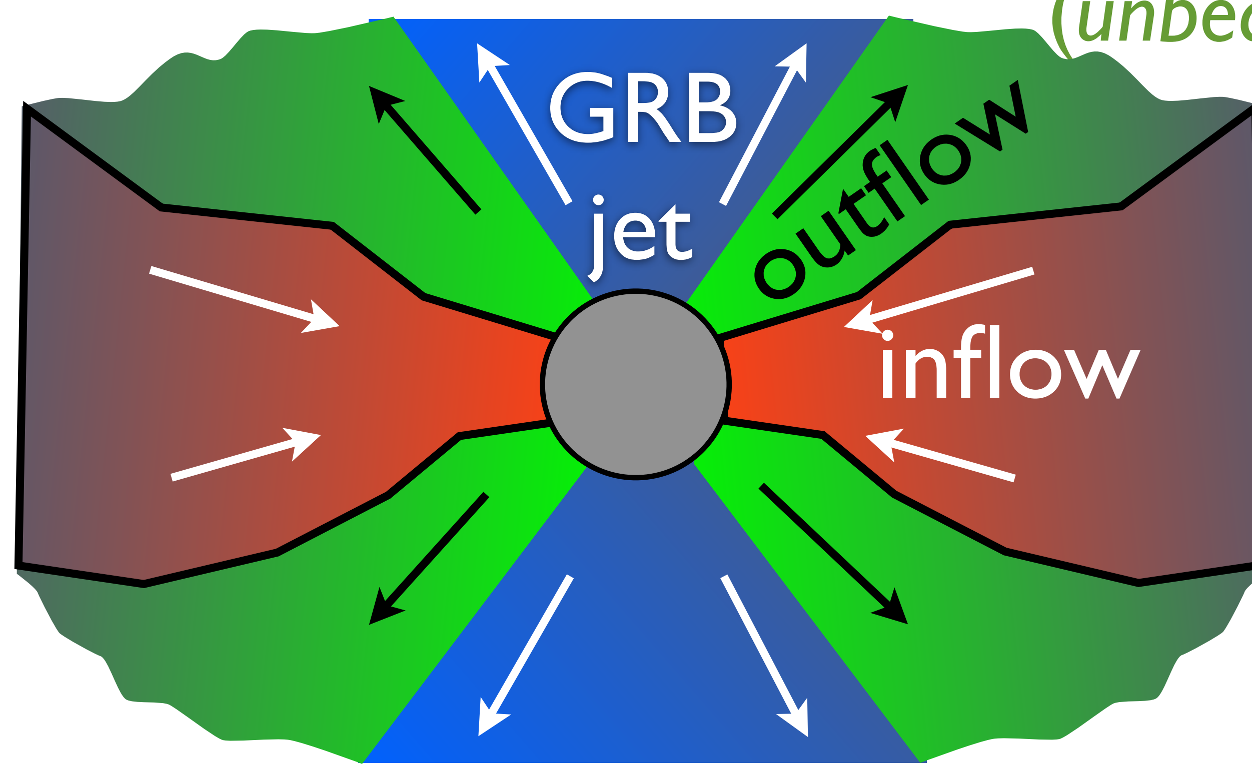


detected as well!

and have EM counterparts:

GRB (*beamed*)

"kilonova" (*unbeamed*)



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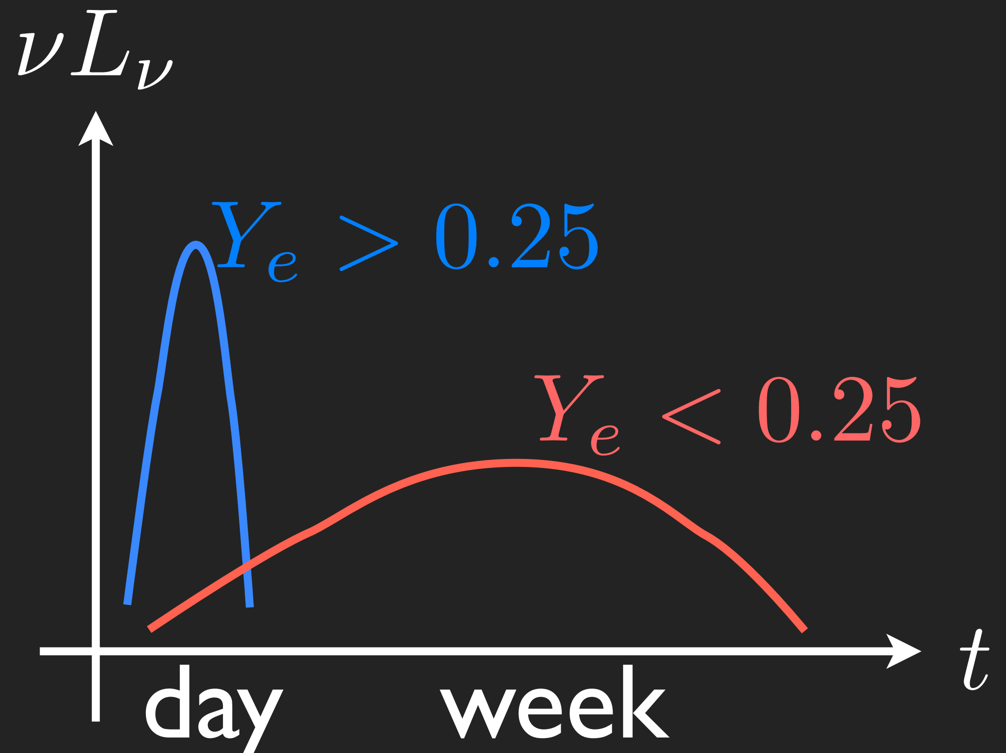
EM Counterparts to Binary Mergers

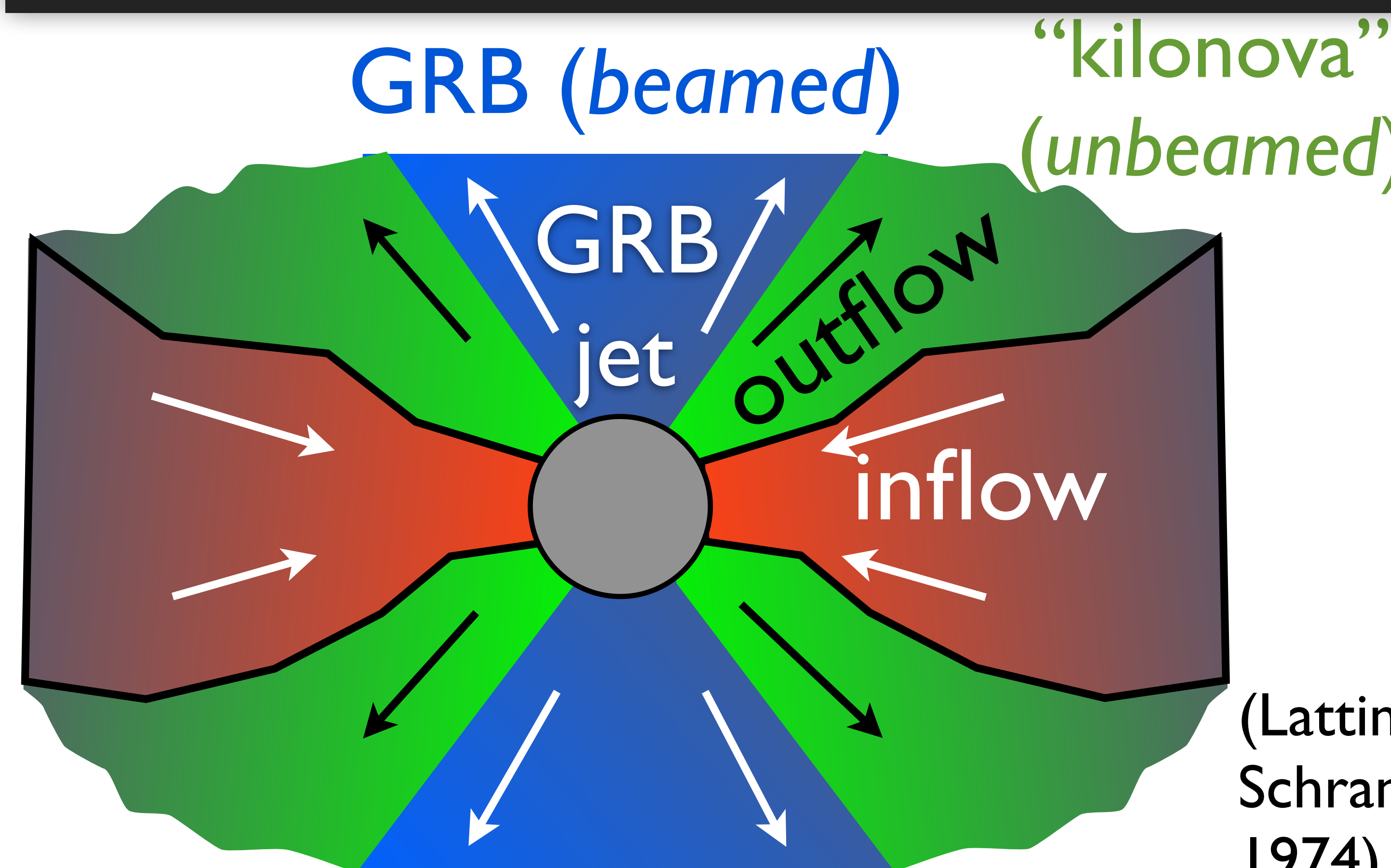
Effect of composition on kilonova light curves

Electron fraction $Y_e = \frac{n_e}{n_B}$



high Y_e = short blue luminous transient

- *Merger disk mass outflow*:
  - fully forms in ~5 seconds
  - over this time, studied in 2D, neglecting GR and magnetic fields (Fernandez+15; but see Siegel & Metzger 17)
- Crucial to include both in 3D



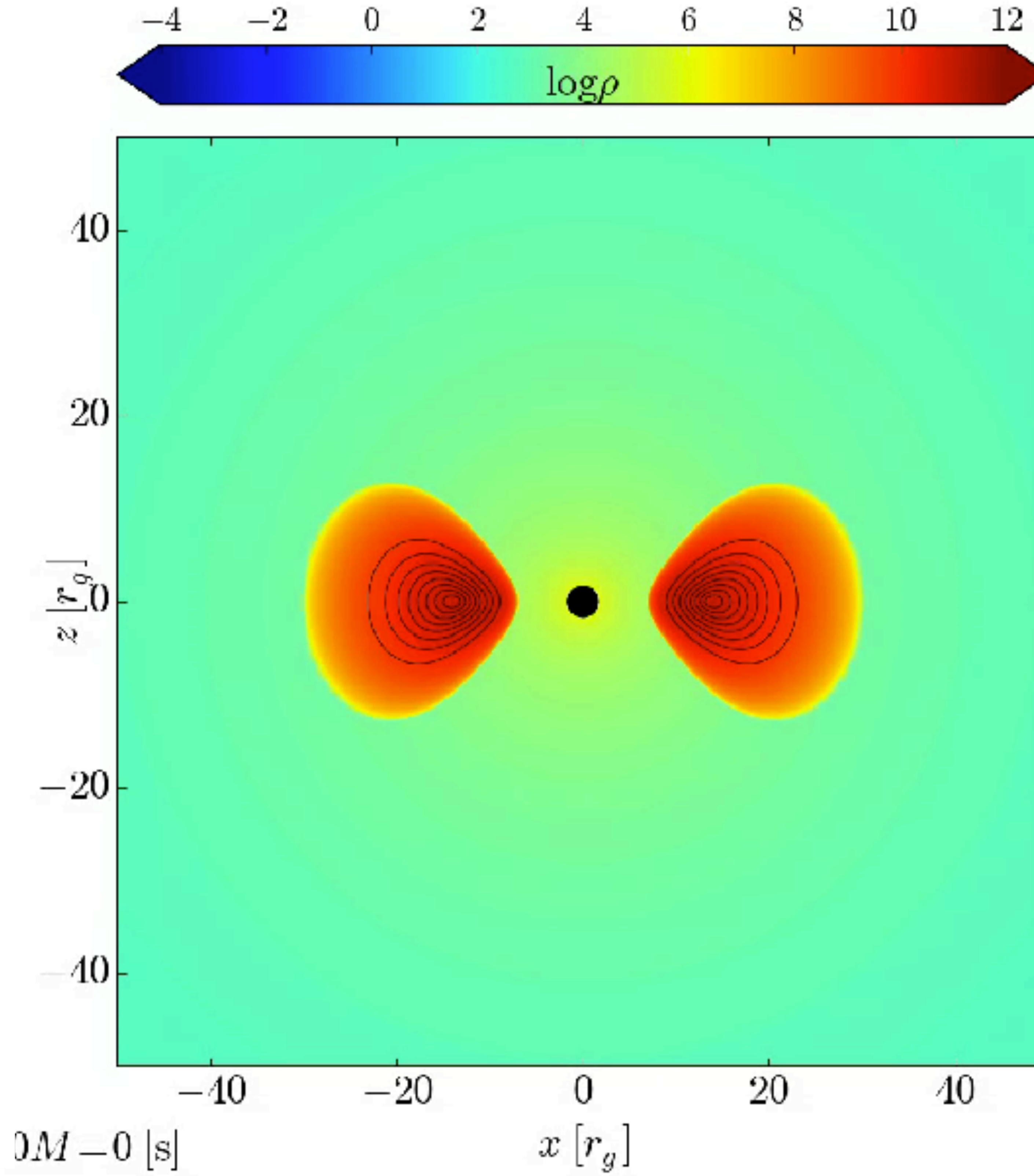
(Lattimer & Schramm 1974)

Magnetic Fields Double Mass Outflow

(AT, Fernandez+ 2018, in prep)

$$M_{\rm BH} = 3\ M_{\rm sun}$$
$$M_{\rm disk} = 0.03\ M_{\rm sun}$$
$$a = 0.8$$
$$B_p = 10^{15}\ G$$

- Implemented into HARMPI:
  - neutrino emission
  - nuclear recombination



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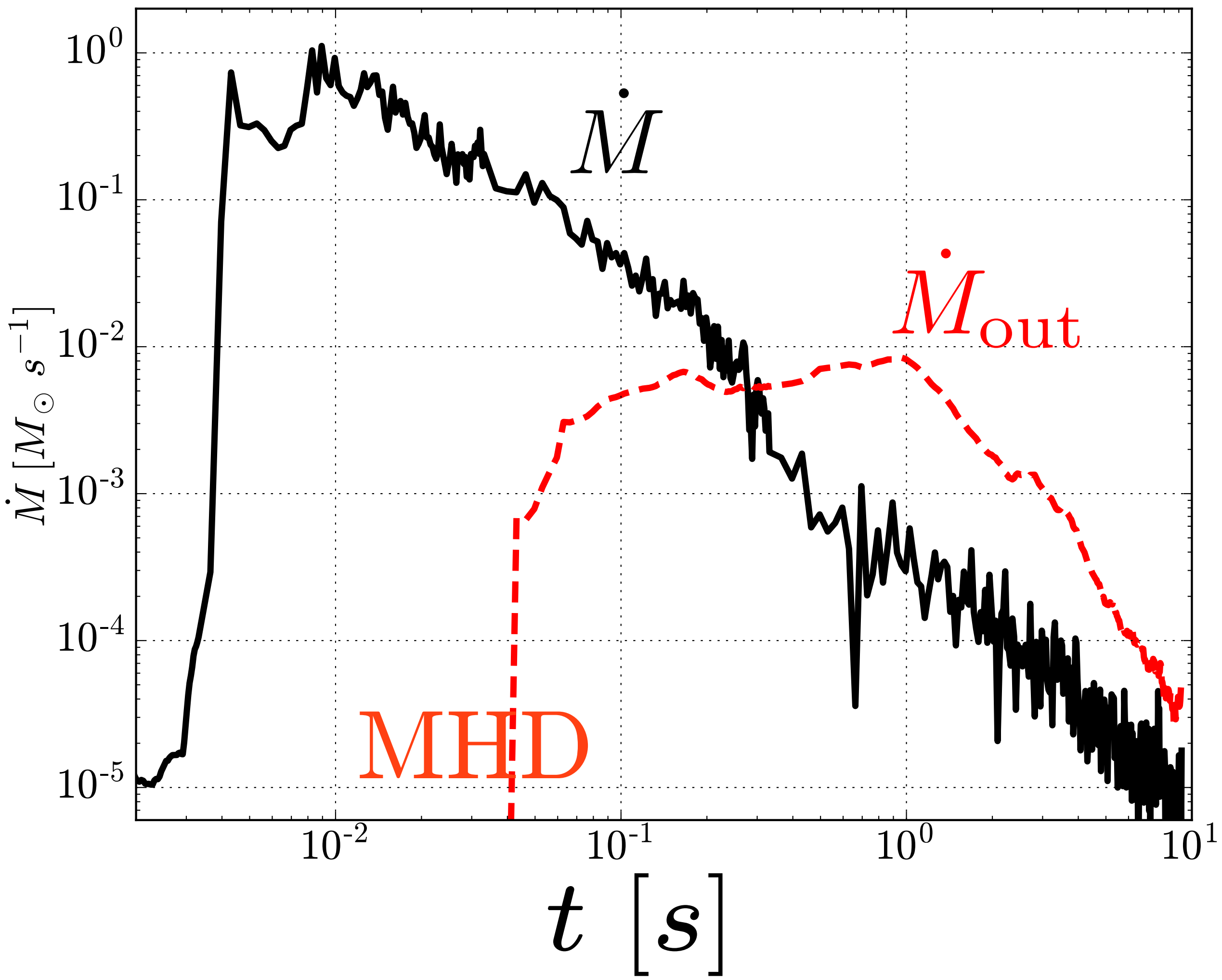

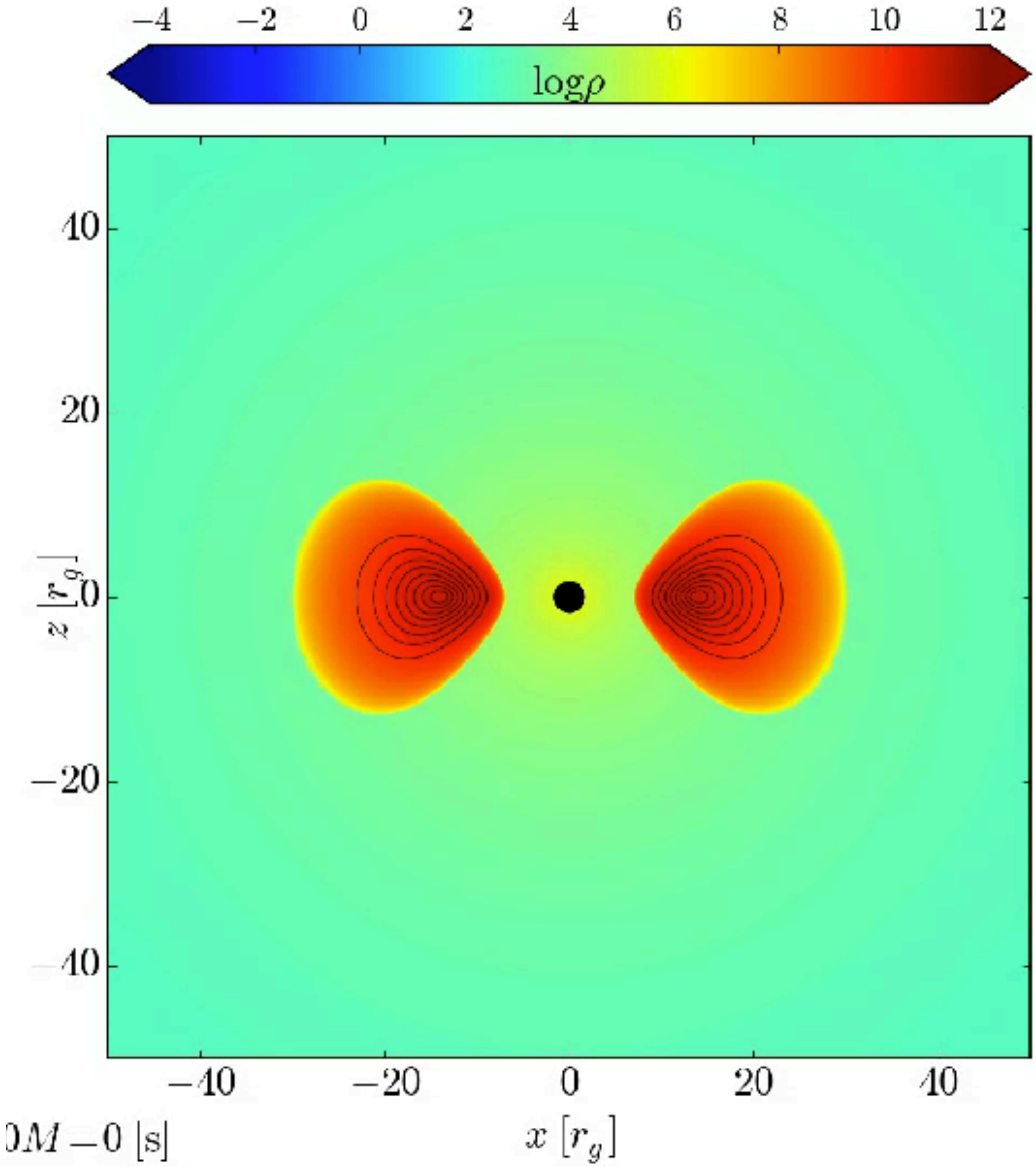

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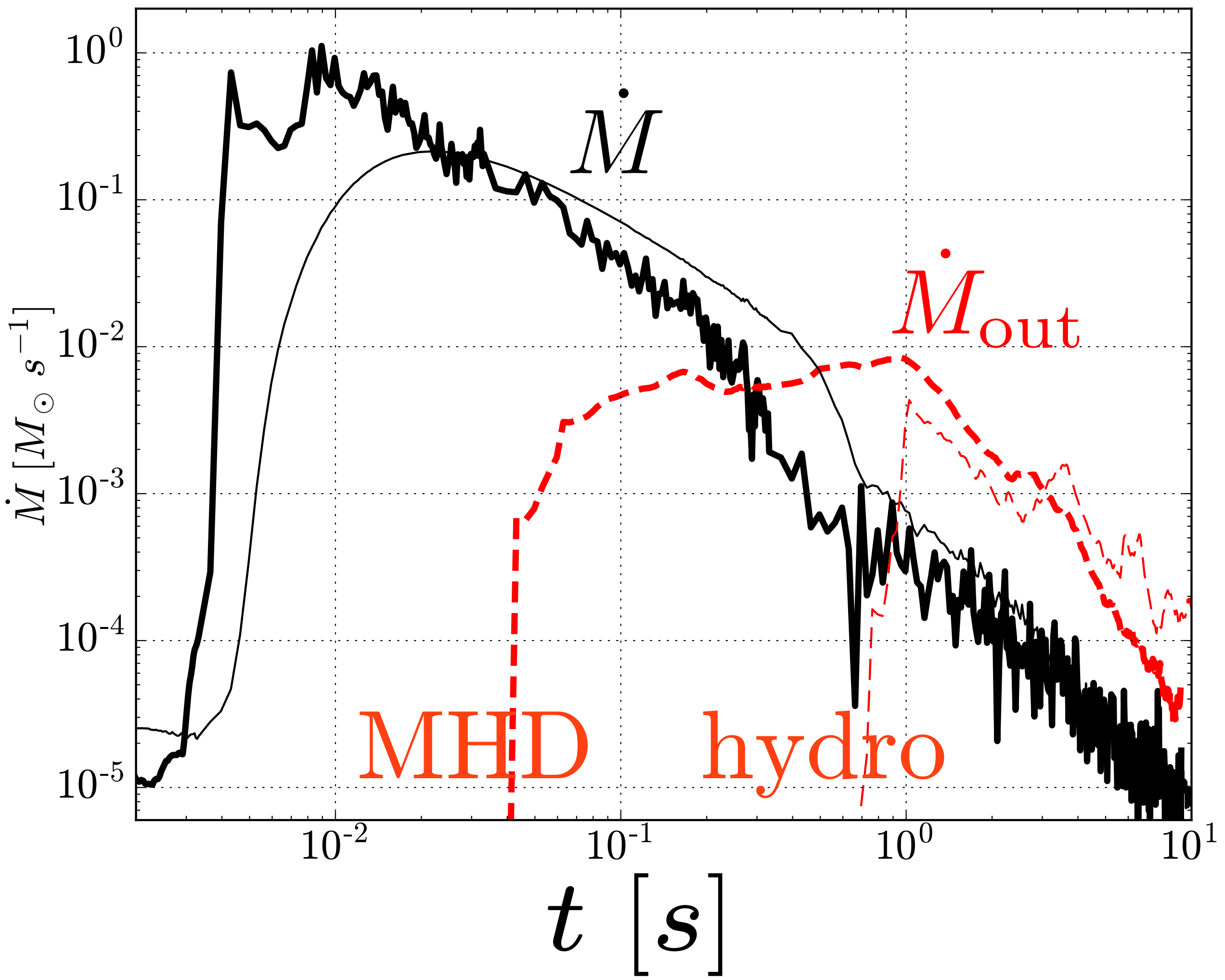

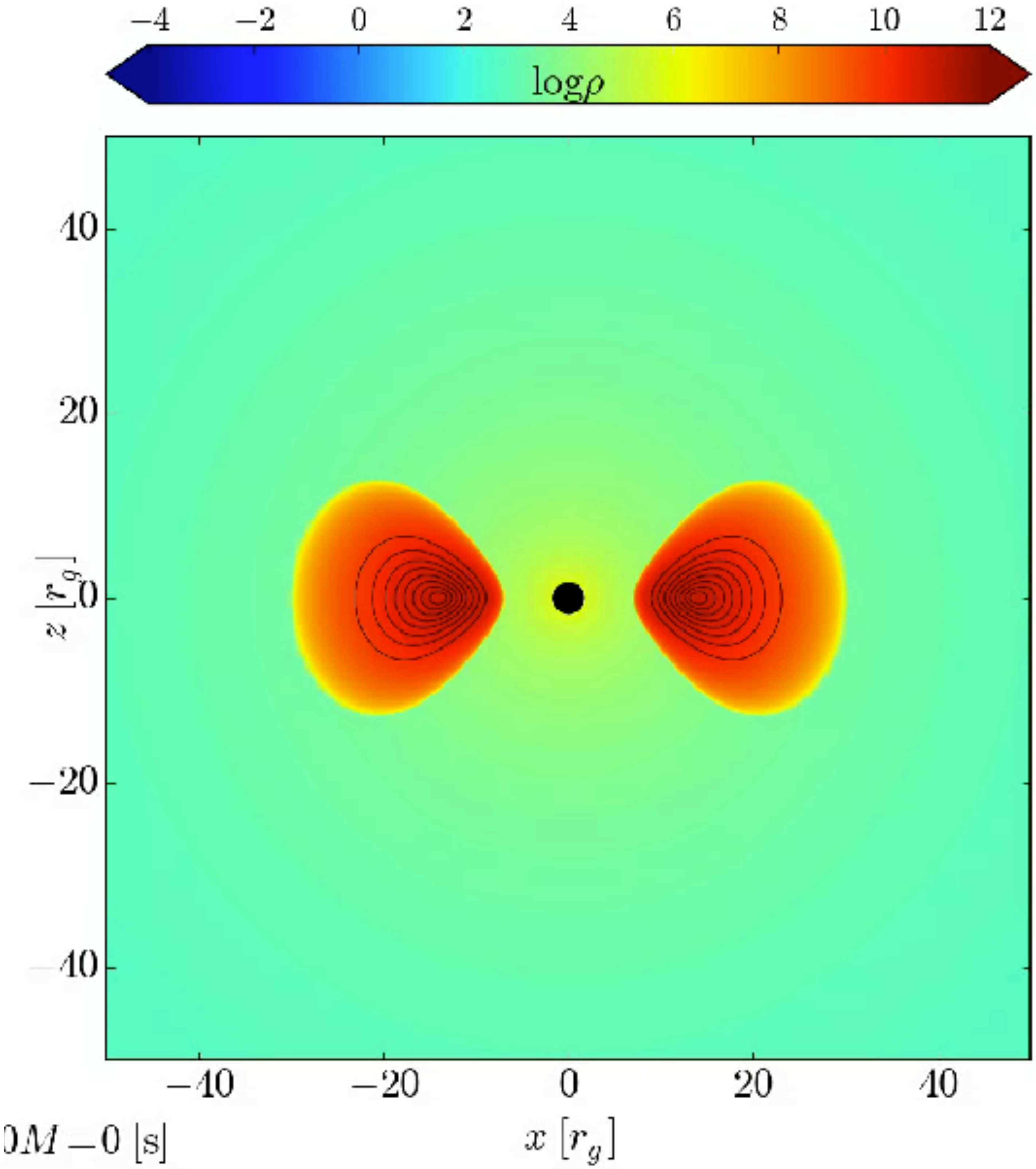

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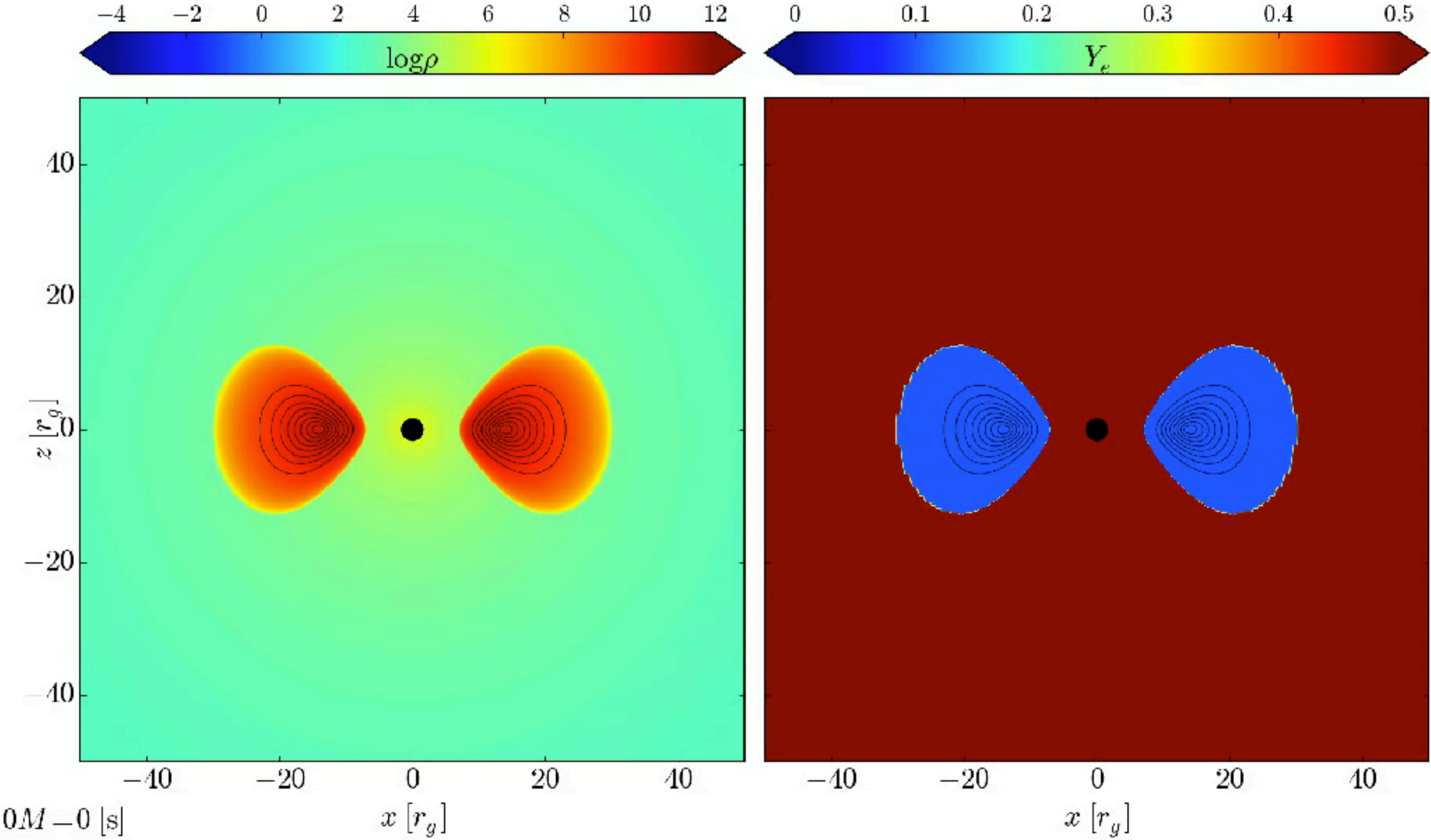
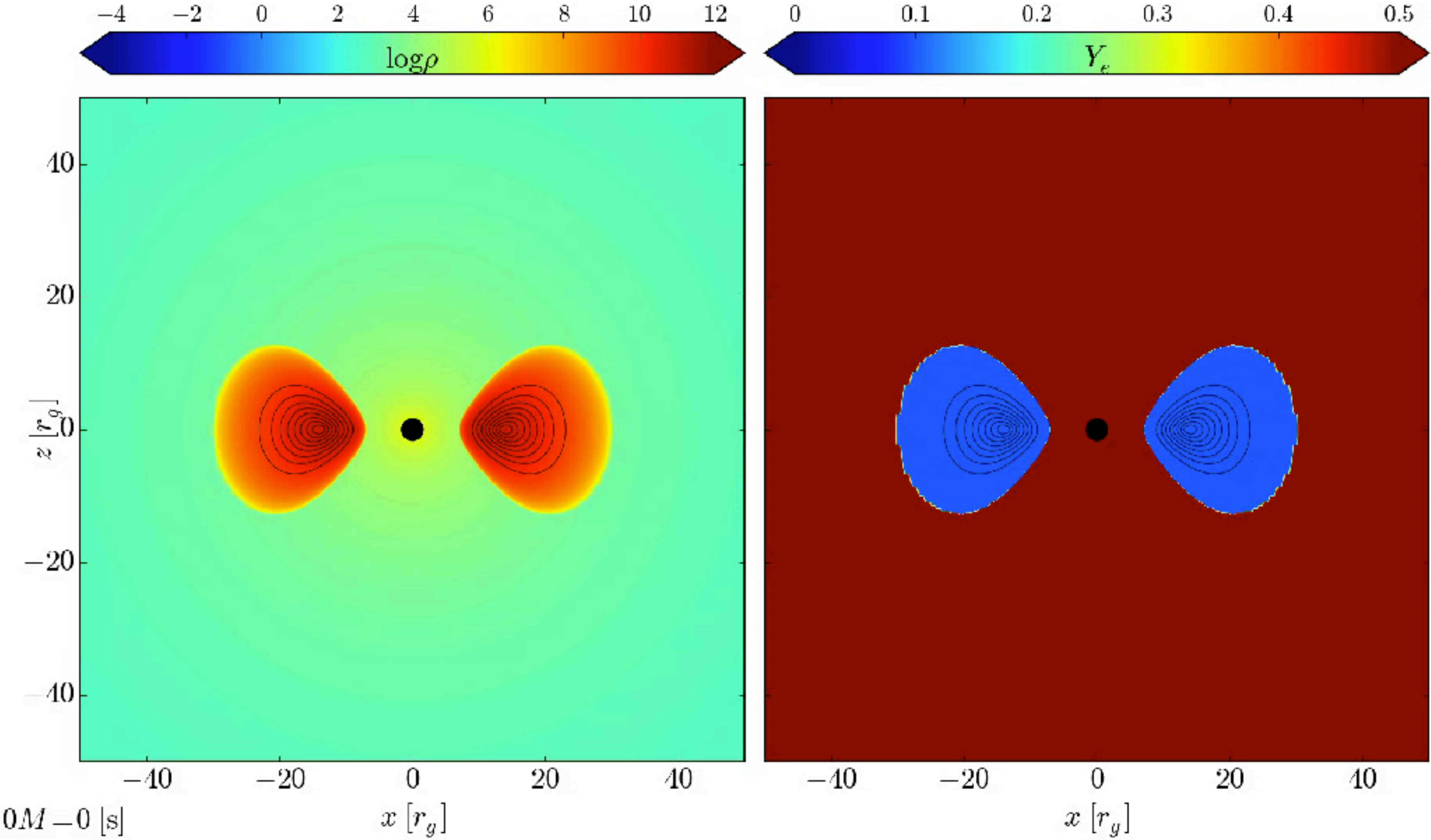


The longest 3D GRMHD simulation ever: cost ~5M CPU-hours

Magnetic Fields Double Mass Outflow



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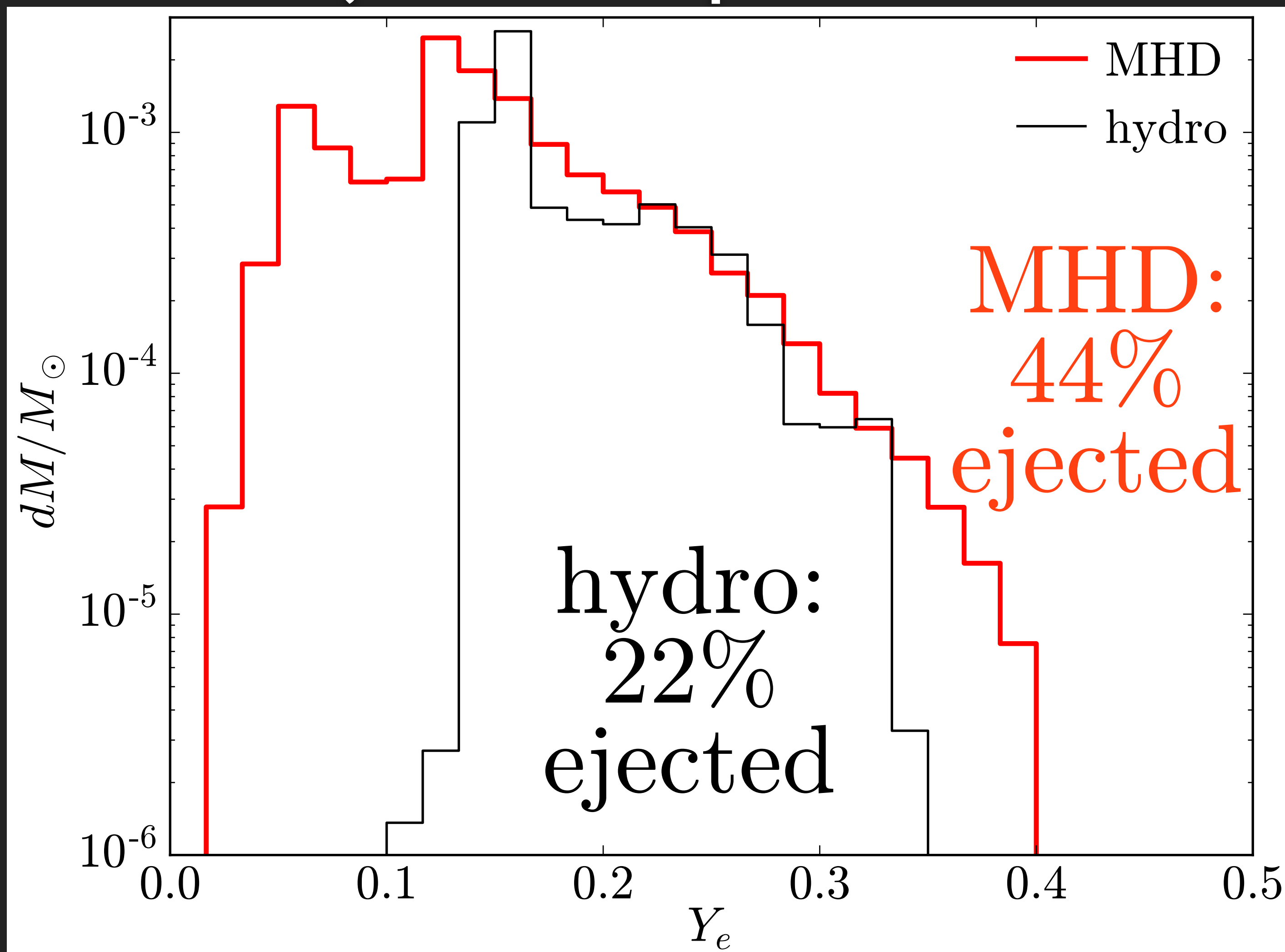
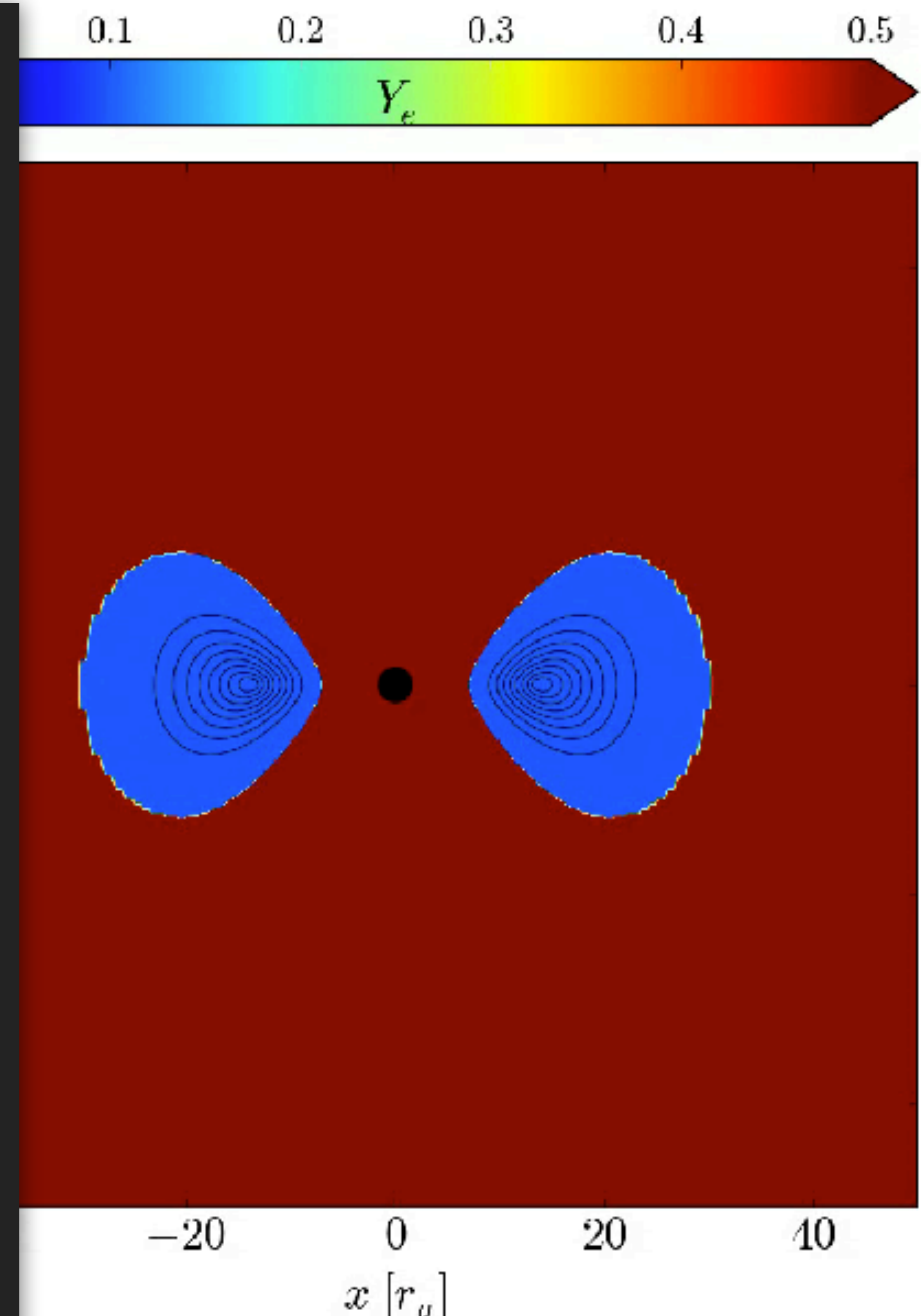
Magnetic Fields Double Mass Outflow

Ejecta composition



Magnetic effects lead to:

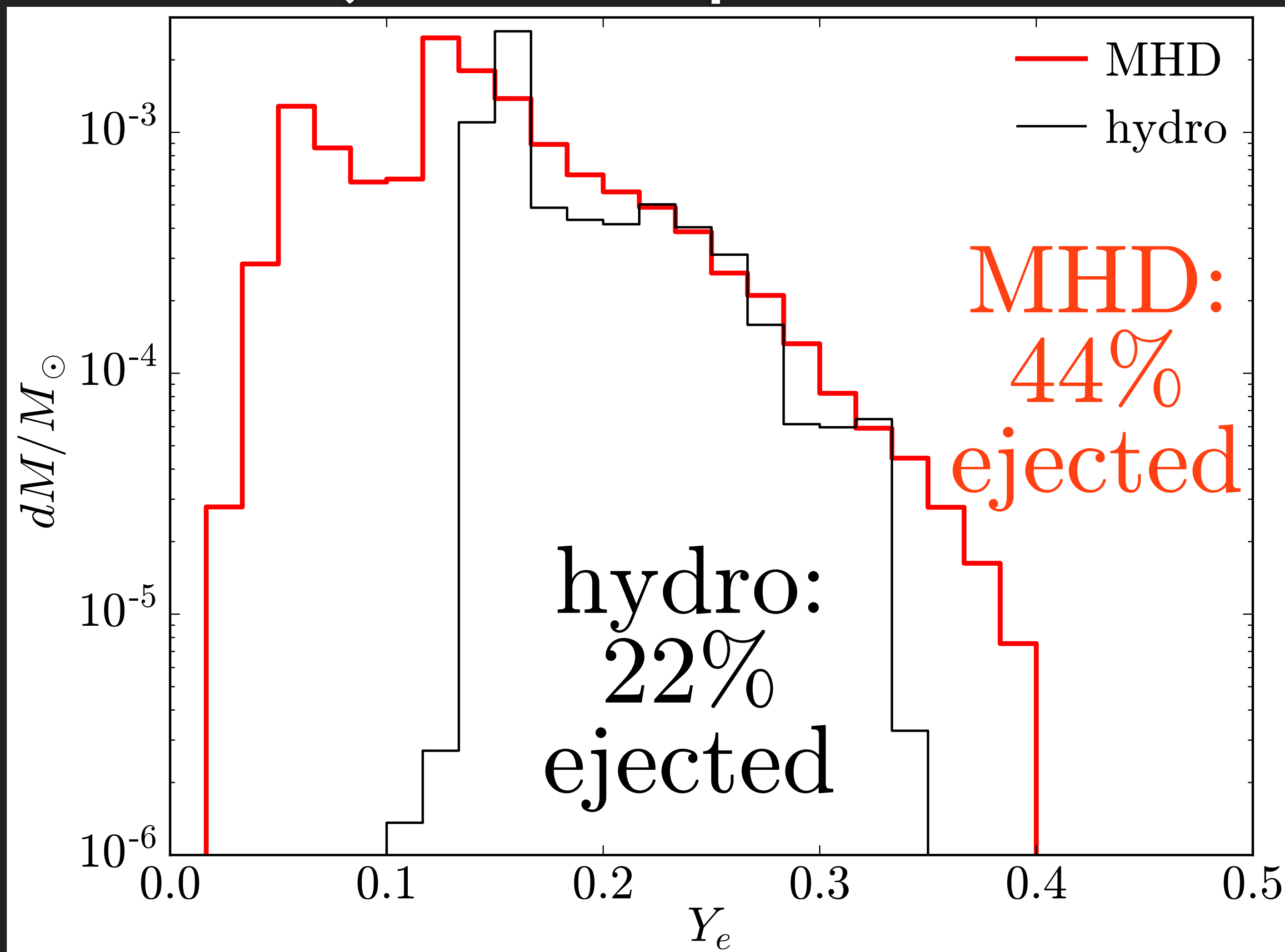
- 2x increase in ejecta mass
  - *brighter kilonova*
- broader ejecta composition
  - *more heavy element enrichment*



...ever: cost ~5M CPU-hours (see also Siegel+17)

Magnetic Fields Double Mass Outflow

Ejecta composition



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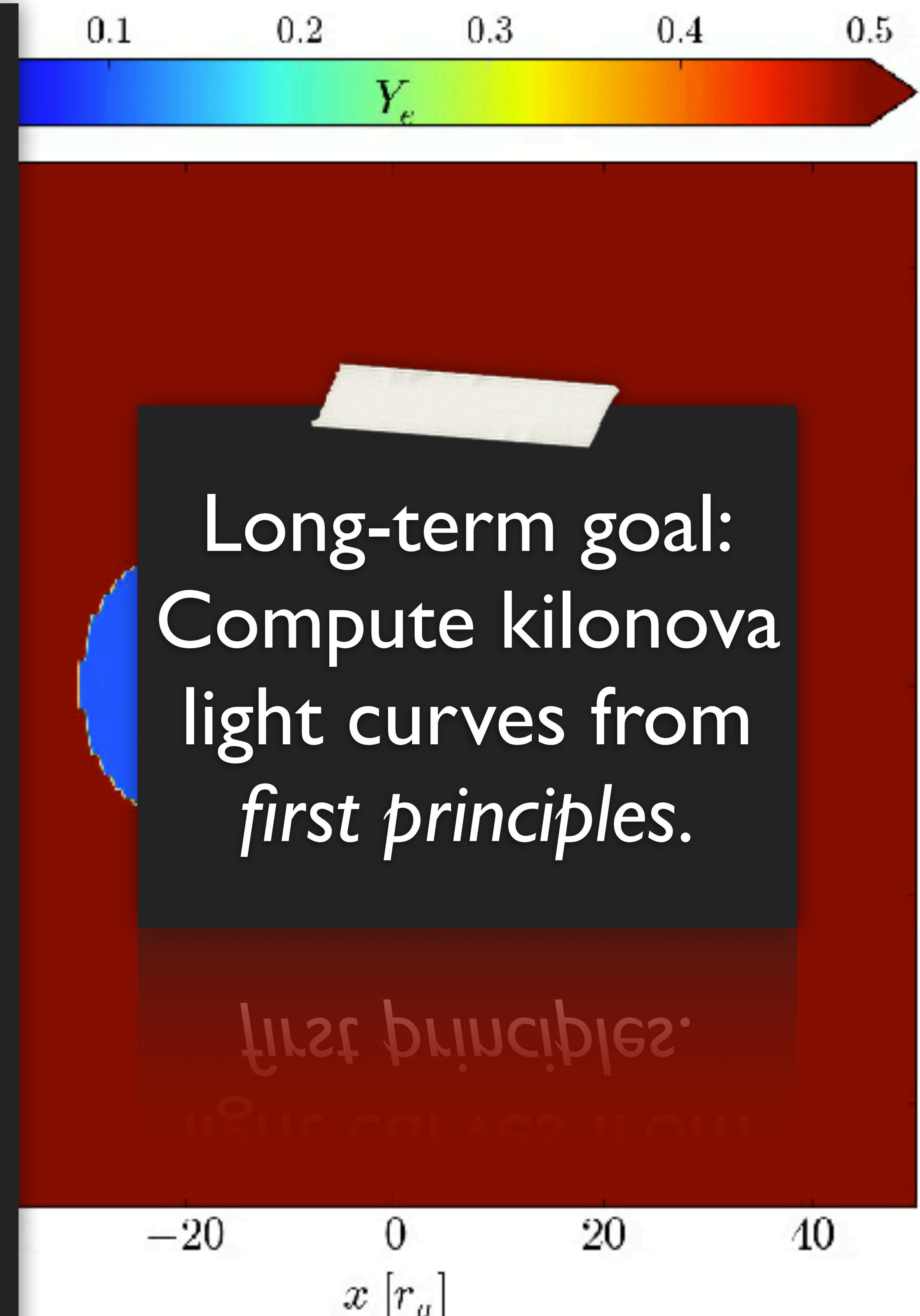
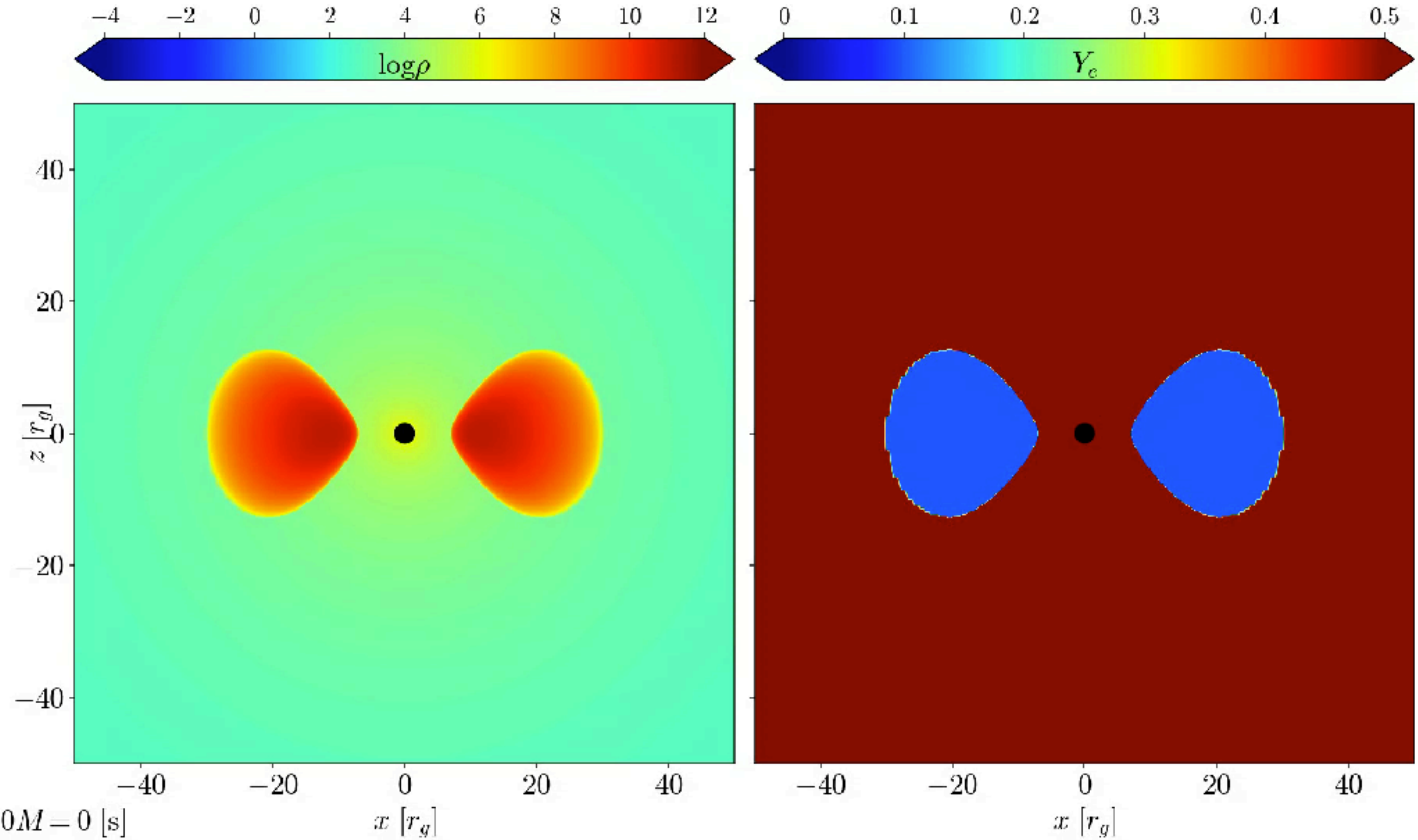


Long-term goal: Compute kilonova light curves from *first principles.*

ever: cost ~5M CPU-hours (see also Siegel+17)

Alexander (Sasha) Tchekhovskoy

Jets without Poloidal Fields?



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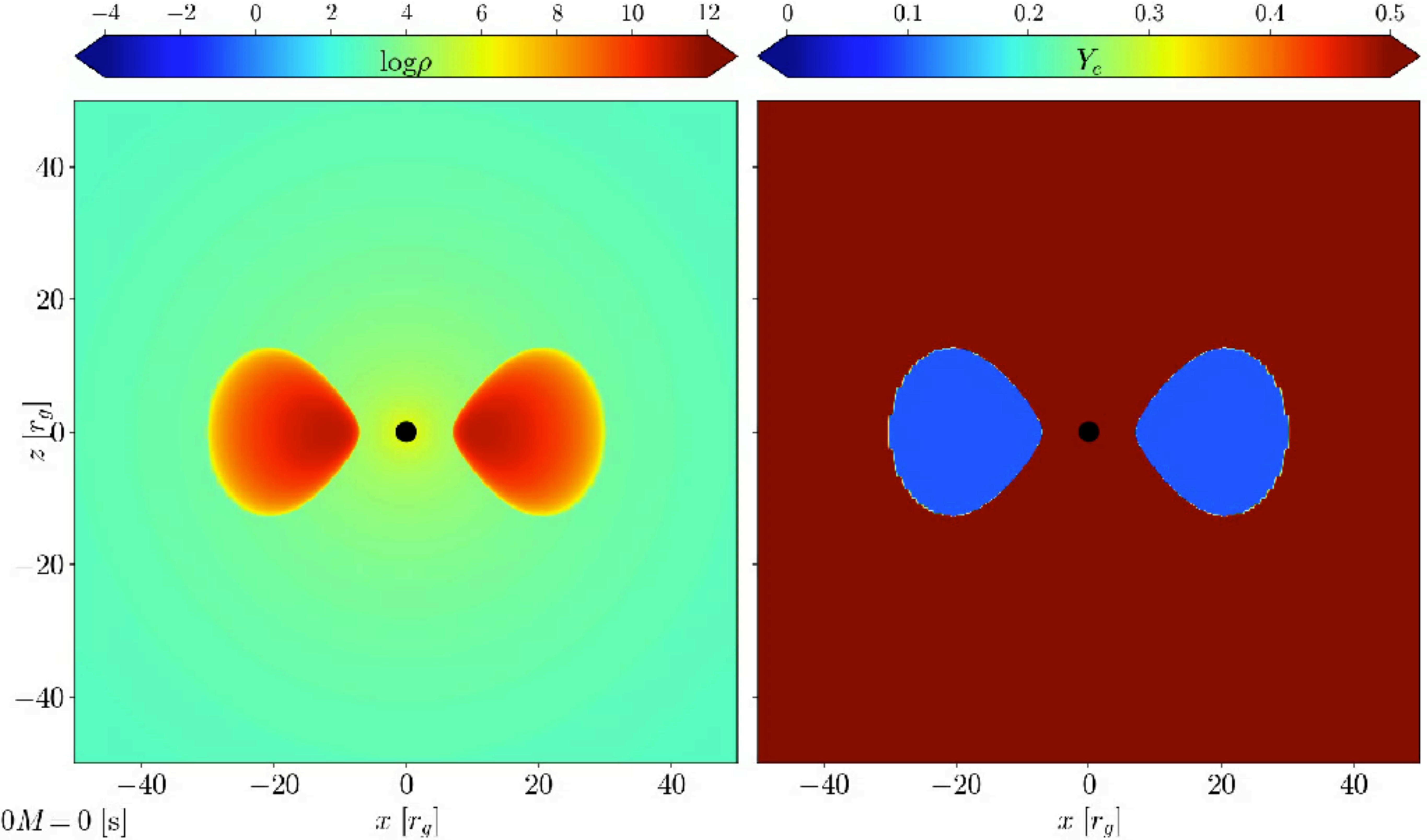

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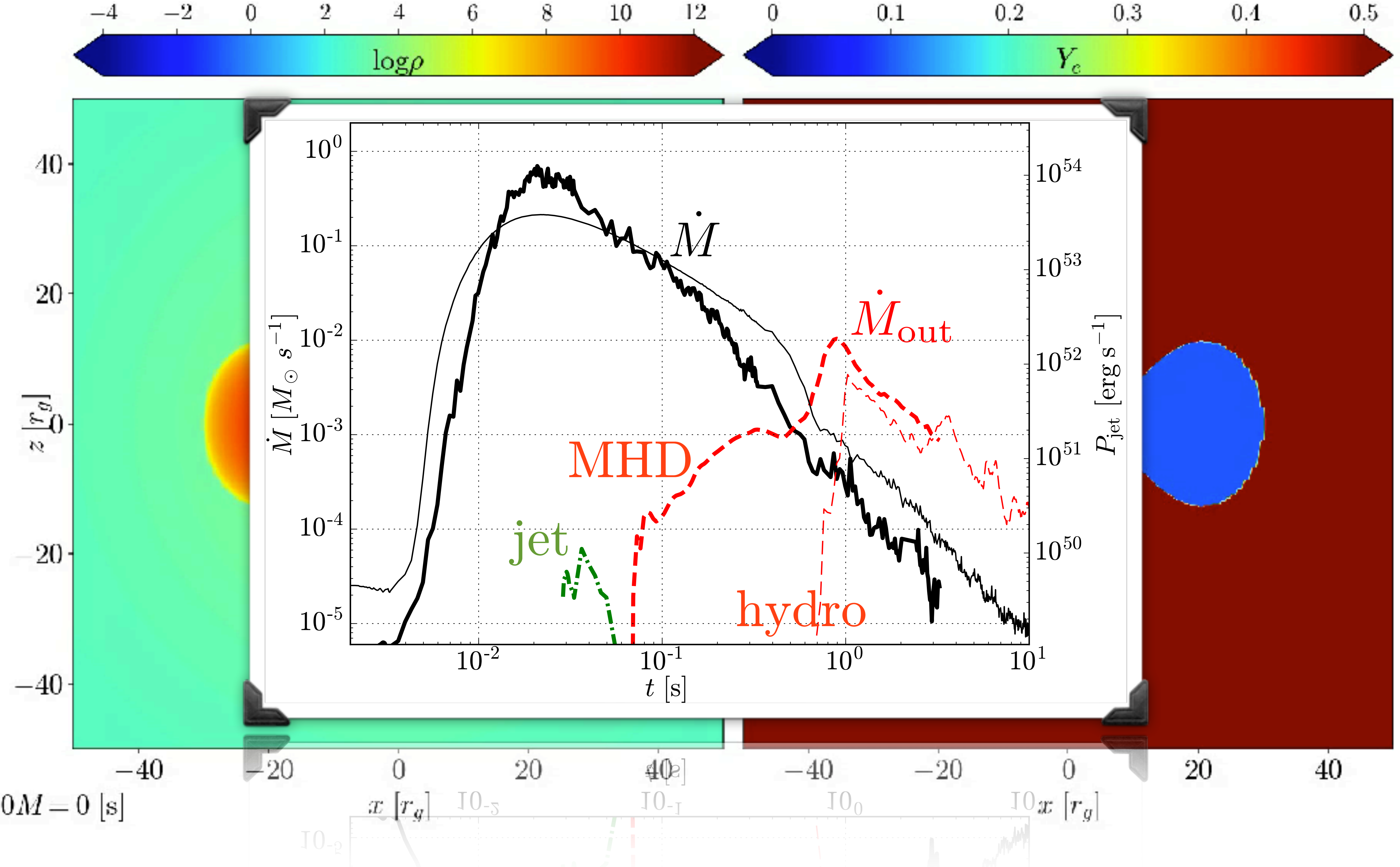

Black Hole Disk Wrap-up

Koushik Chatterjee (University of Amsterdam)

- ***Jets precess*** together with tilted disks ➛ higher likelihood of GRB detection from a nearby BH-NS merger
- Bardeen-Petterson-like ***alignment*** and ***breaking*** of thin disks first seen in GRMHD ➛ essentially unexplored observational manifestations
- ***Longest*** simulations of ***binary merger remnant*** disks: universe enrichment w/heavy elements

Matthew Liska (University of Amsterdam)

Casper Hesp (University of Amsterdam)

NCSA

NSF

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

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