Miha Cernetic, Minghao Guo, James M. Stone, Eliot Quataert and Volker Springel

# MULTI-SCALE (GR)MHD MODELLING OF ACCRETION ONTO SUPERMASSIVE BLACK HOLES WITH COSMOLOGICAL INITIAL CONDITIONS

# MOTIVATION

- Accretion on SMBHs are a multi scale problem from the cosmological scale down to Schwarzschild radius ~ 14 orders of magnitude in spatial extent.
- We know halos do exist in the comic web, where they are connected to the environment and continuously accrete and feedback gas.
- There are currently two approaches in the community:
  - Cosmological simulations rely on subgrid models tuned to reproduce observations,
  - small scale GRMHD simulations use idealized setups.

# METHODS

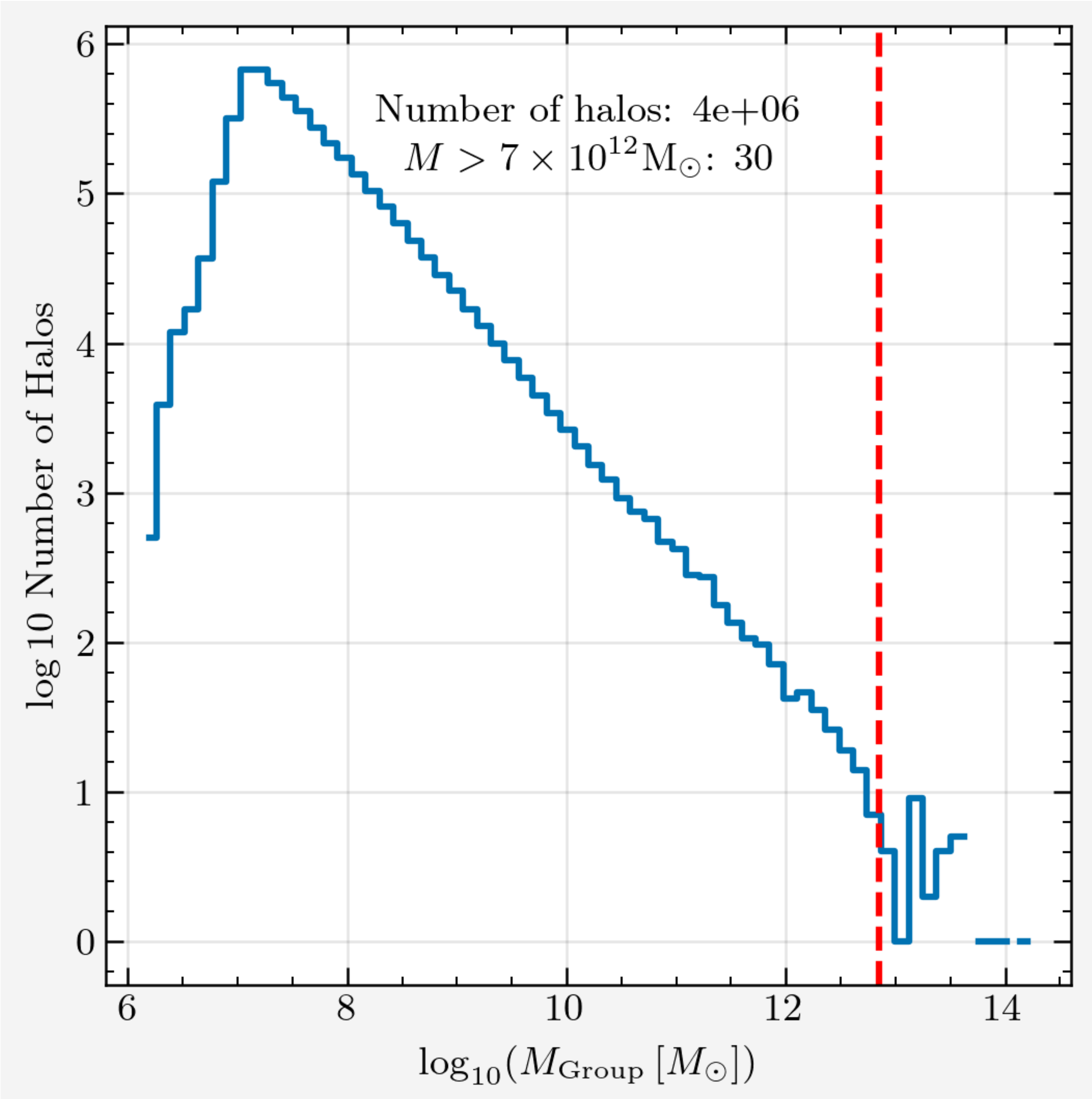
- Make a selection of high mass TNG-50 halos
- Map TNG data to AthenaK's format
- Run at ever increasing zoom levels using Guo+ 2024 isolated M87 setup as baseline

# GLOSSARY

- Illustris TNG - a suite of cosmological MHD simulations.
- Arepo - moving mesh MHD code used to run IllustrisTNG.
- AthenaK - block-based cartesian AMR framework with fluid, particle and numerical relativity solvers in Kokkos (gpu accelerated).

# HALO SELECTION #1

- **Interested in only the most massive halos at high resolution -> TNG-50.**
- **Focusing on halos $M > 7 \times 10^{12}$M$_\odot$limits us to 30 halos.**
- **The halos need to be well resolved at small r.**



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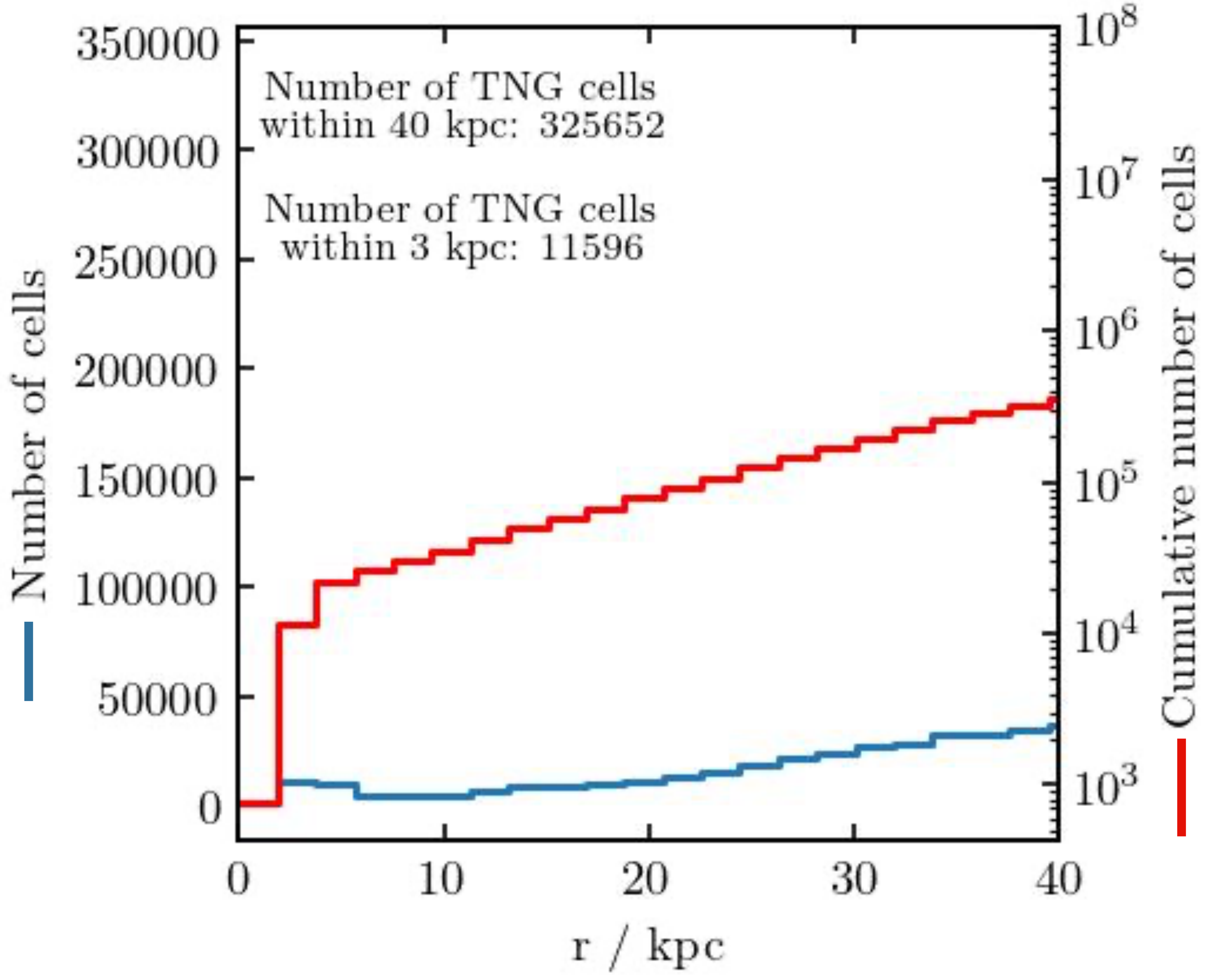

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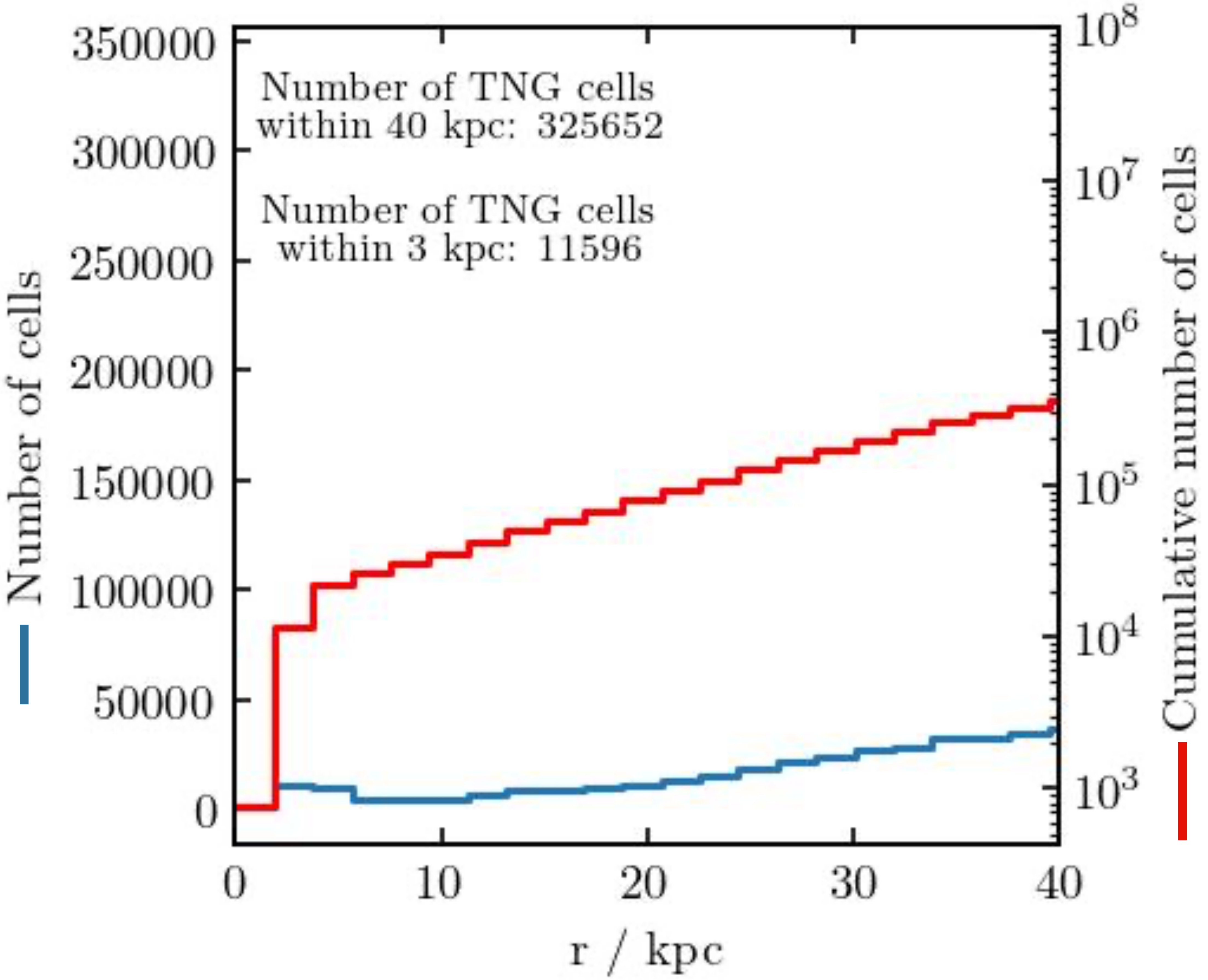
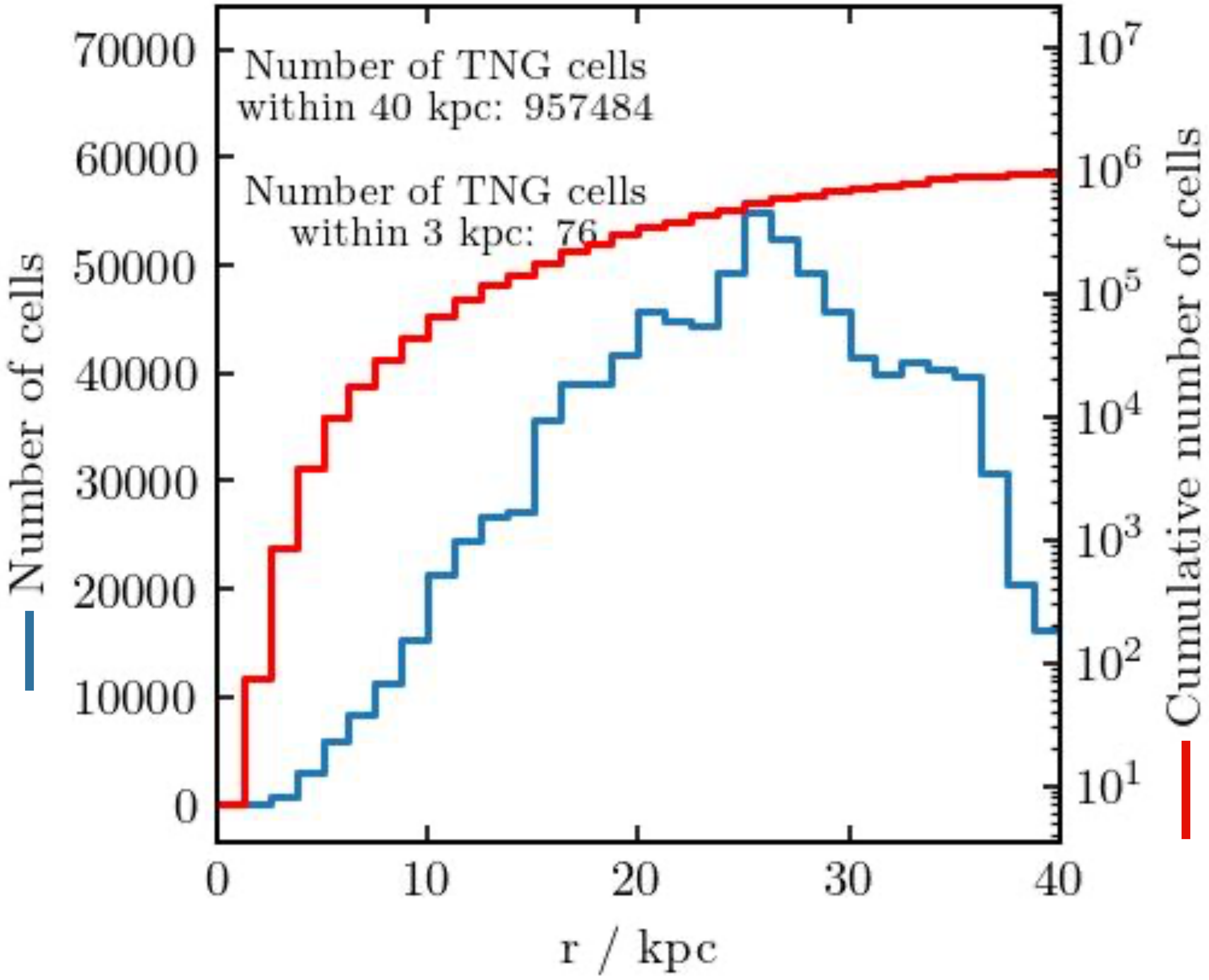
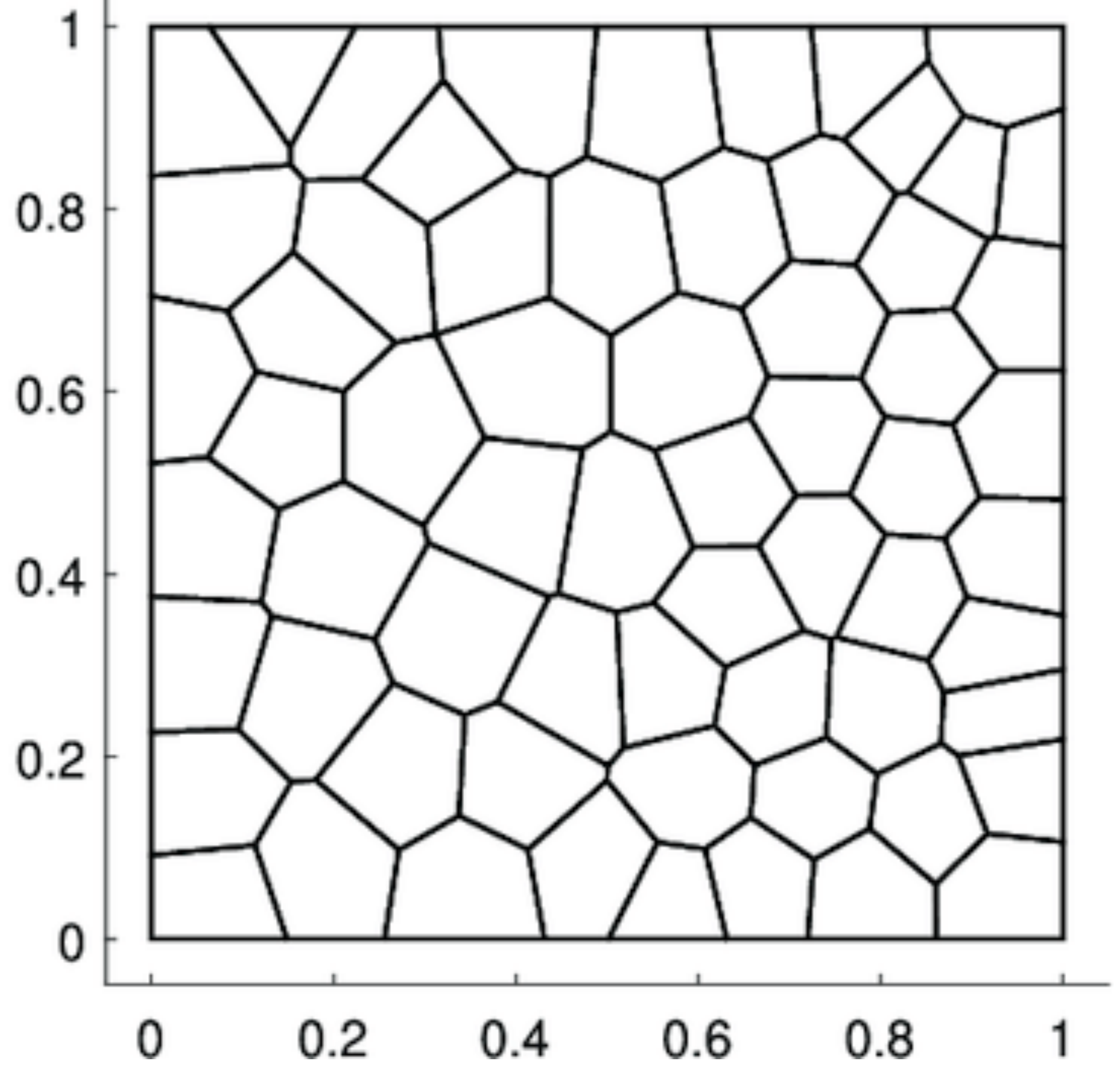


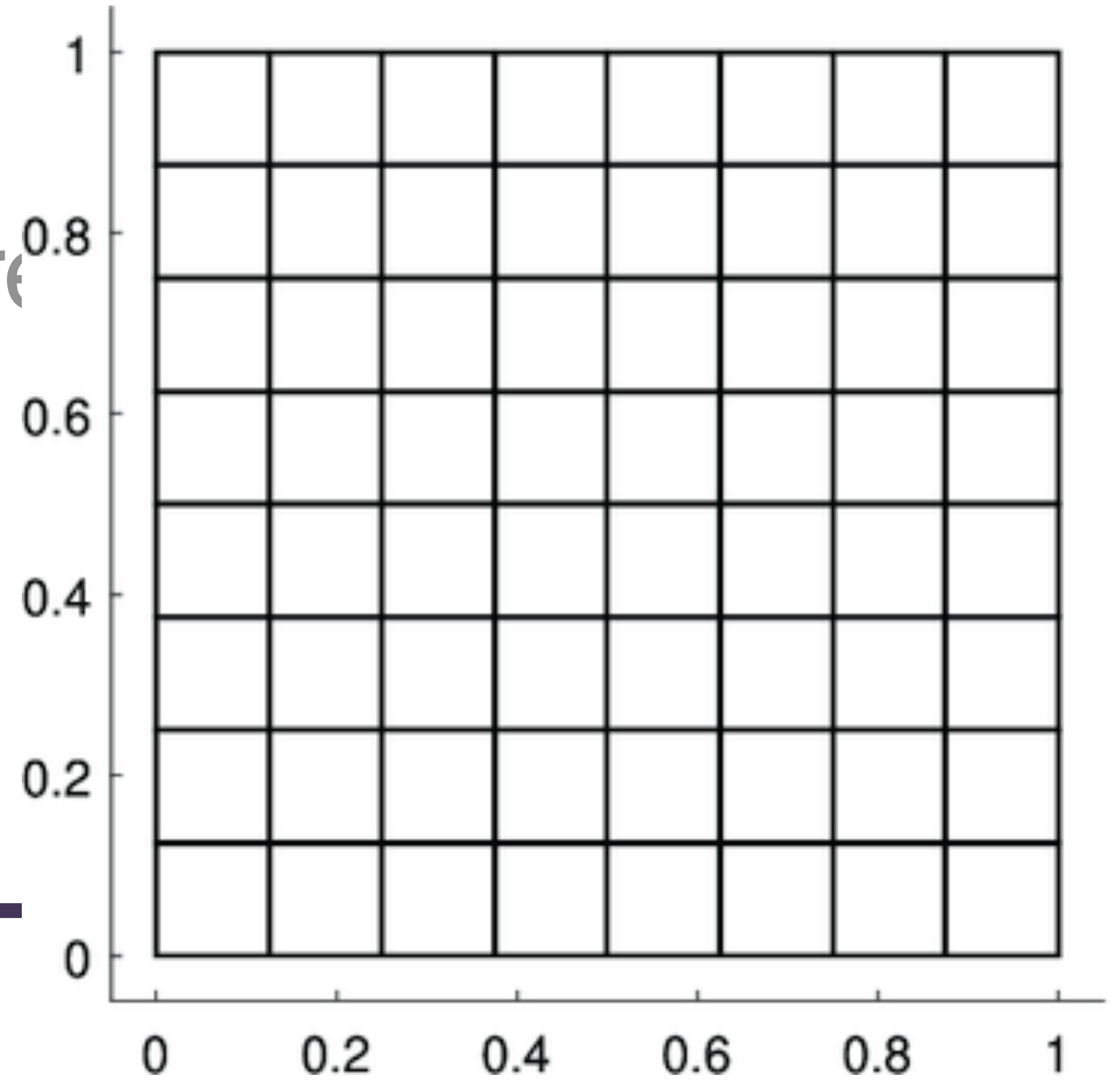



# MAP TNG GALAXIES AS ICS FOR ATHENA RUNS

- IllustrisTNG data is an **unstructured voronoi mesh**
- AthenaK uses a nested **cartesian grid**
- **Procedure:**
  1. Get all particles within ~50 kpc of halo center from TNG snap
  2. Construct a KdTree for fast neighbor search
  3. Query the tree at Athena's grid coords → 16M in ~10 seconds
  4. Do this for density, momenta and total energy

- Note on magnetic field: Athena needs the vector potential A, where B, use PyAMG to get A from B in the Lorentz gauge (future work)



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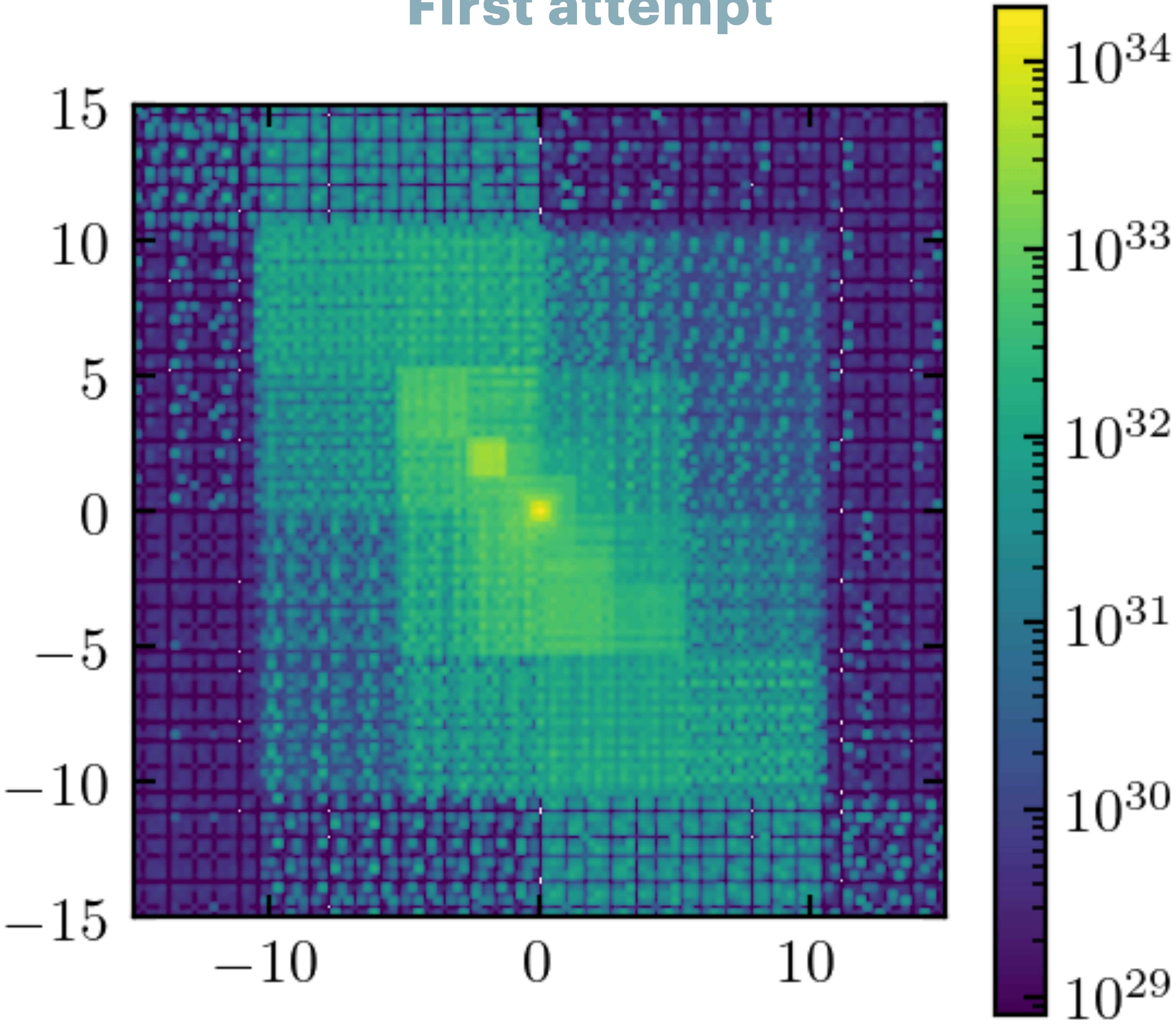
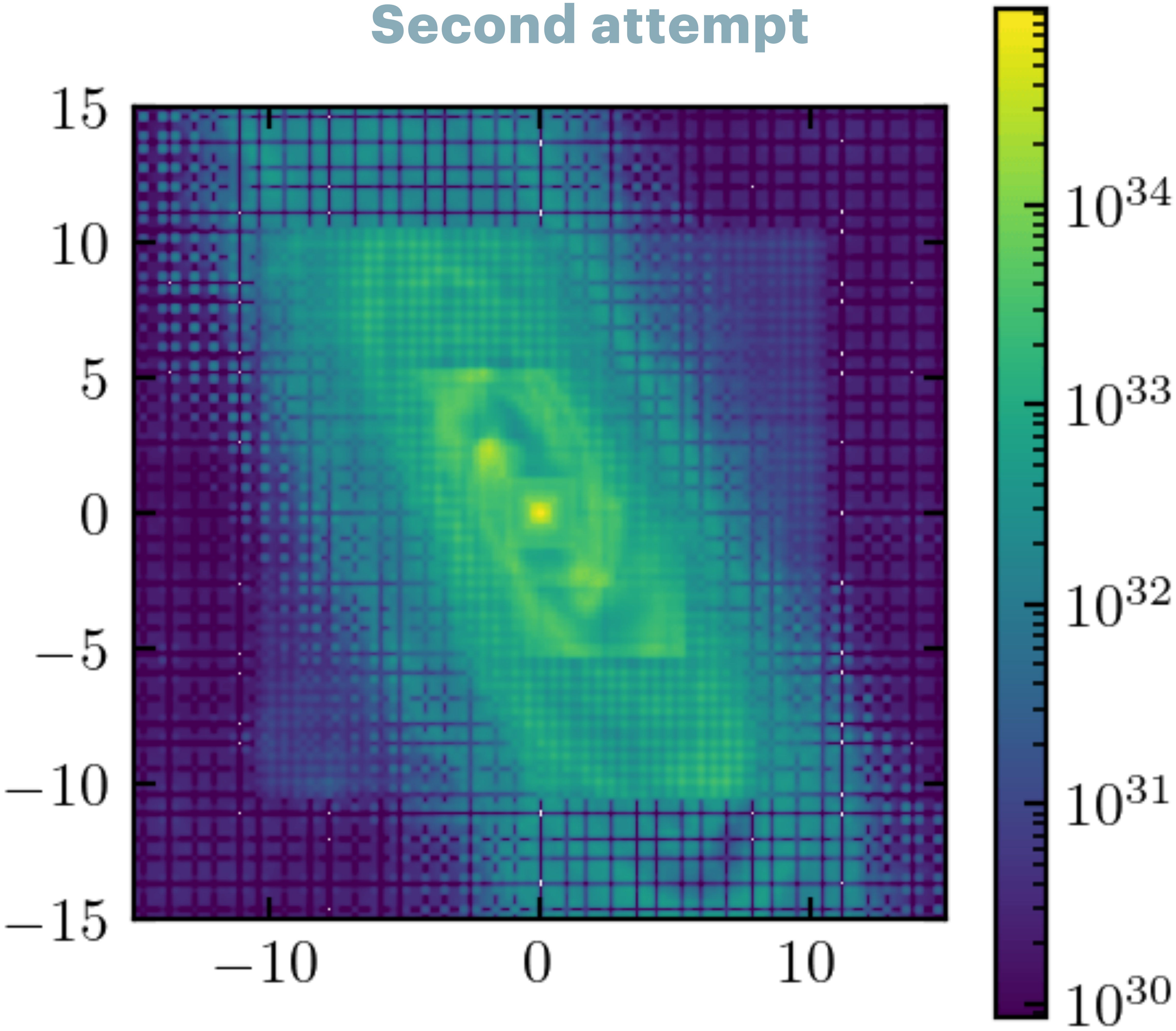
First attempt




Second attempt



# MAPPED DATA


AthenaK data extracted from TNG
Y [kpc]
X [kpc]
40
30
20
10
0
−10
−20
−30
−40
−40
−20
0
20
40
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
AthenaK data extracted from TNG
Y [kpc]
X [kpc]
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
−10
−5
0
5
10
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$10^{-1}$
$10^{-2}$
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- Smooth the ICs with an SPH kernel (the irony!)

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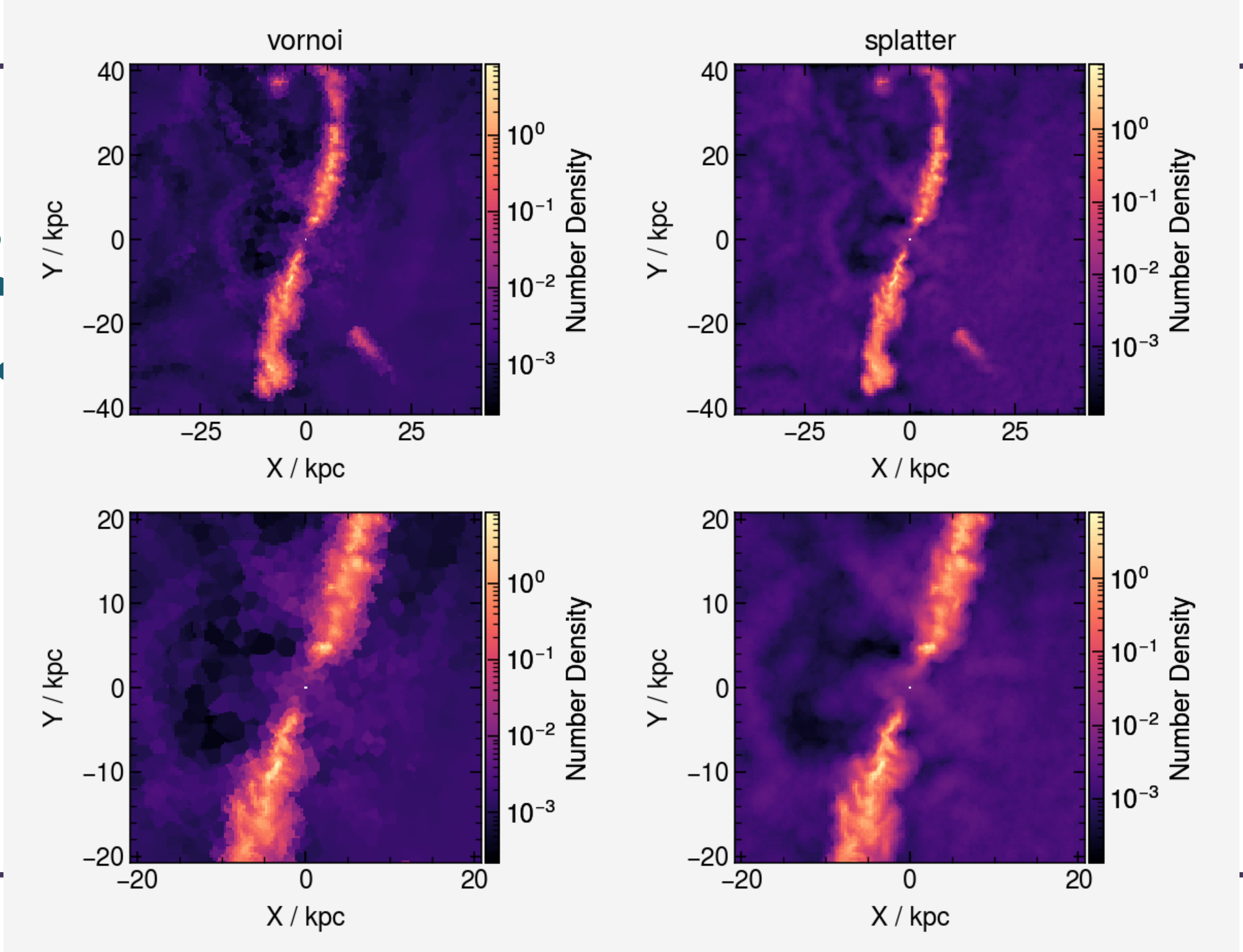
- **Smoo**



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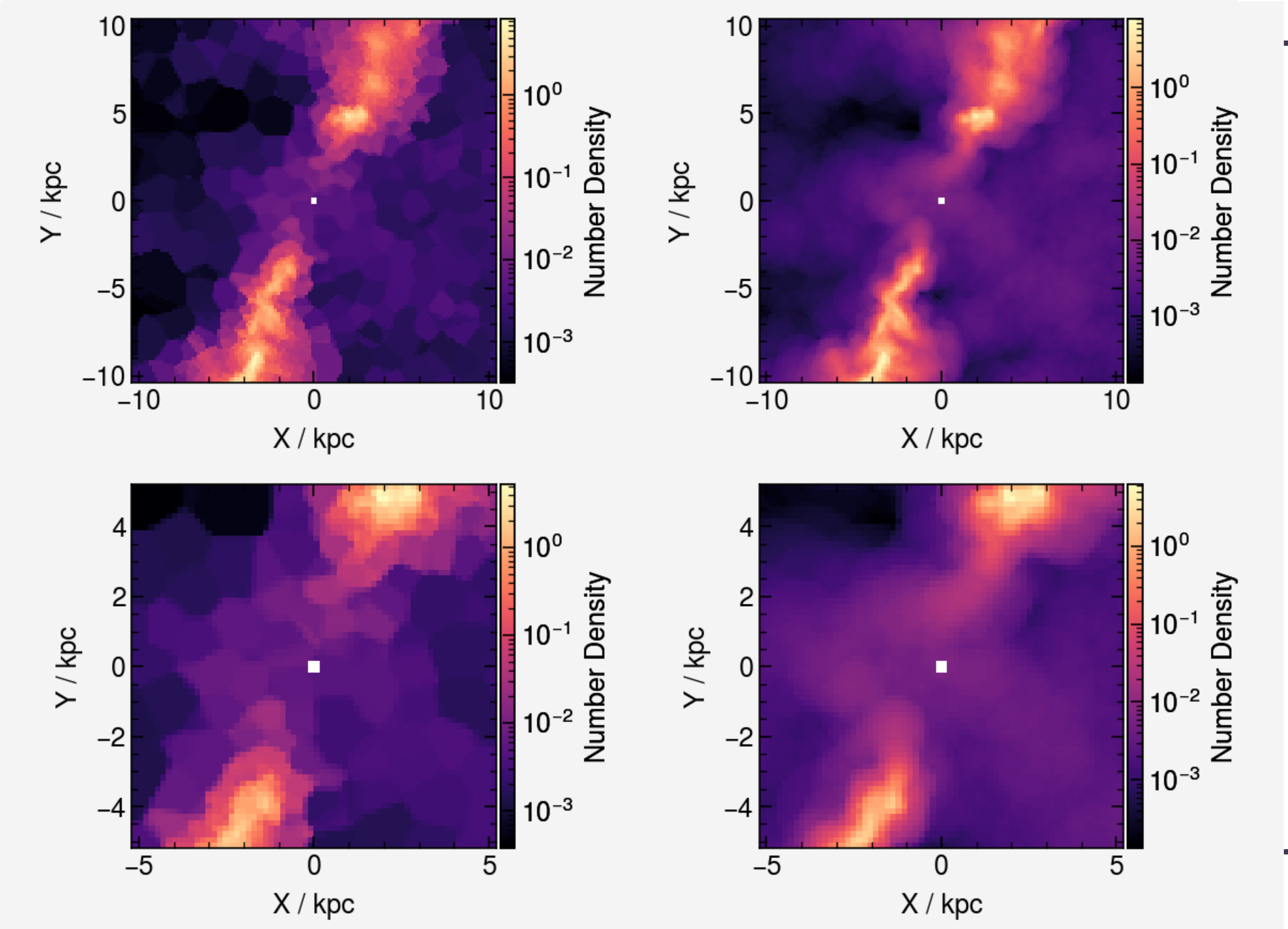

# SETUP

- **Halo in "hydrostatic equilibrium".**
- **Gravitational potential defined by TNG's:**
  1. **Central black hole,**
  2. **NFW for dark matter, and**
  3. **NFW for stars.**
- **Magnetic fields are initialized with a Gaussian random vector potential at large scales with $\beta = 100$.**

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- Numerical details
  - piecewise linear (PLM) reconstruction method,
  - HLLC Riemann solver,
  - the 2nd order Runge-Kutta time integration,
  - gravity, cooling, and heating included via operator splitting,
    - cooling by Schure et al. (2009) for solar metallicity, and
    - idealized phenomenological heating which balances the global but not local cooling rates.

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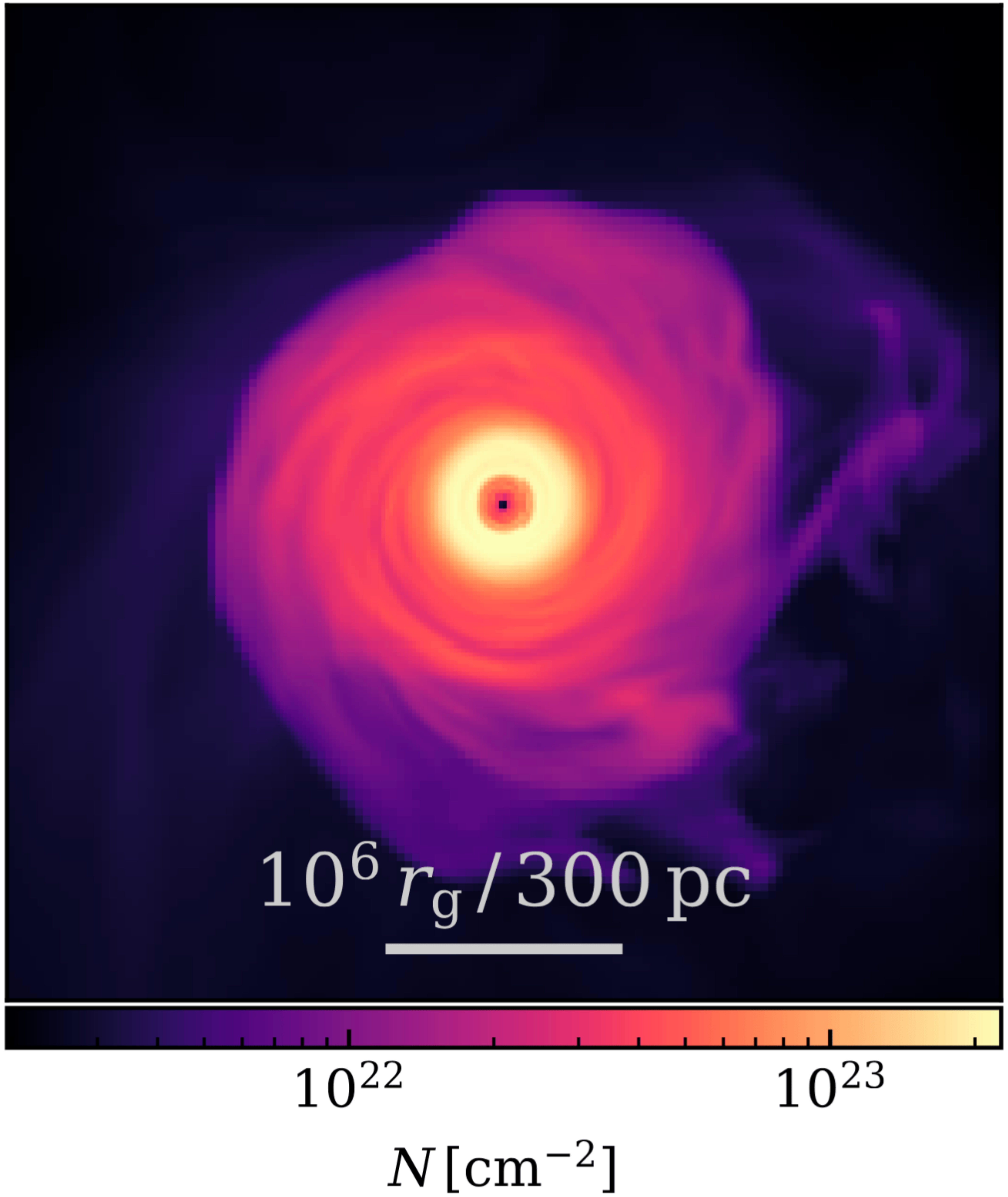

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**M87:**

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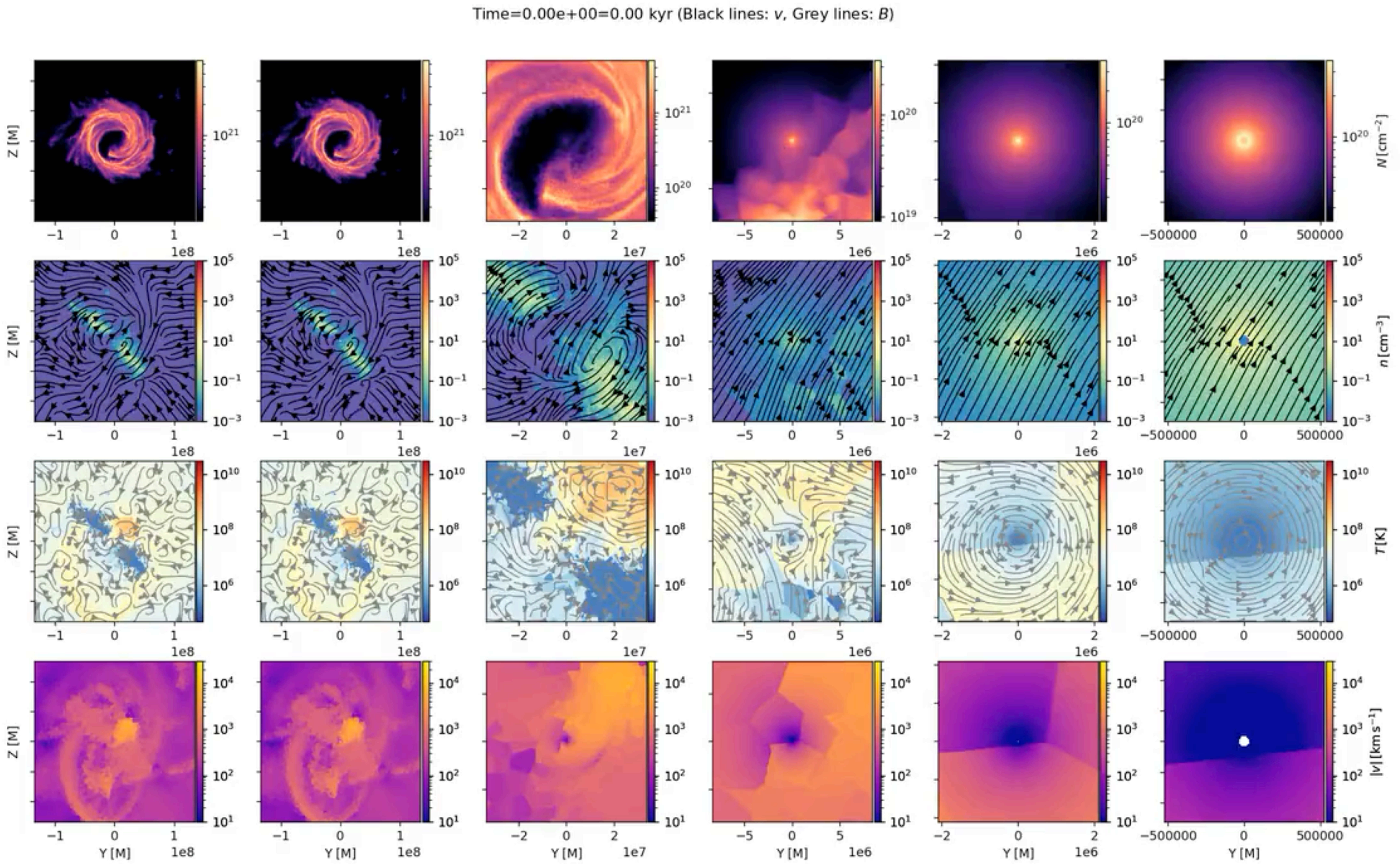
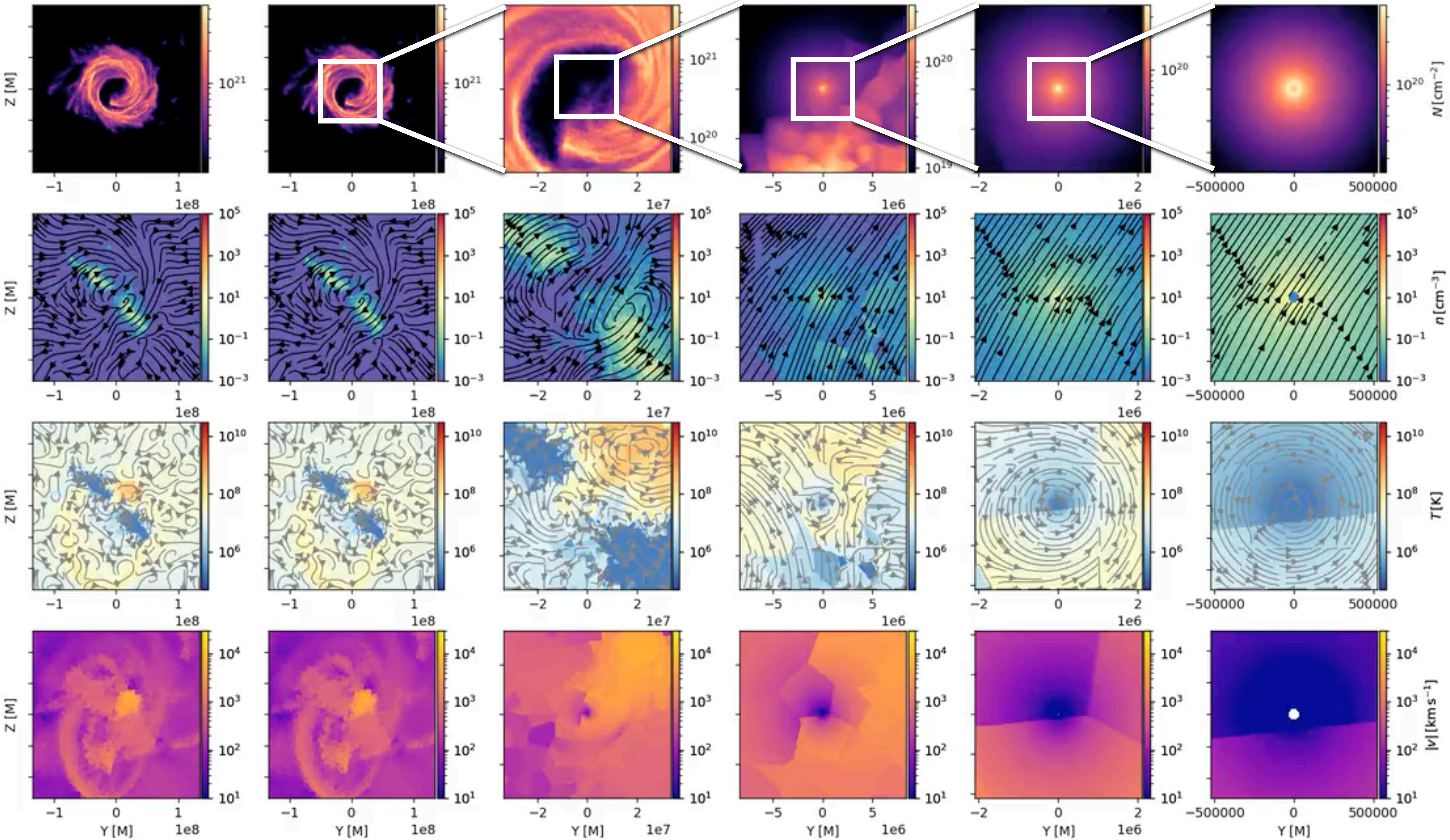
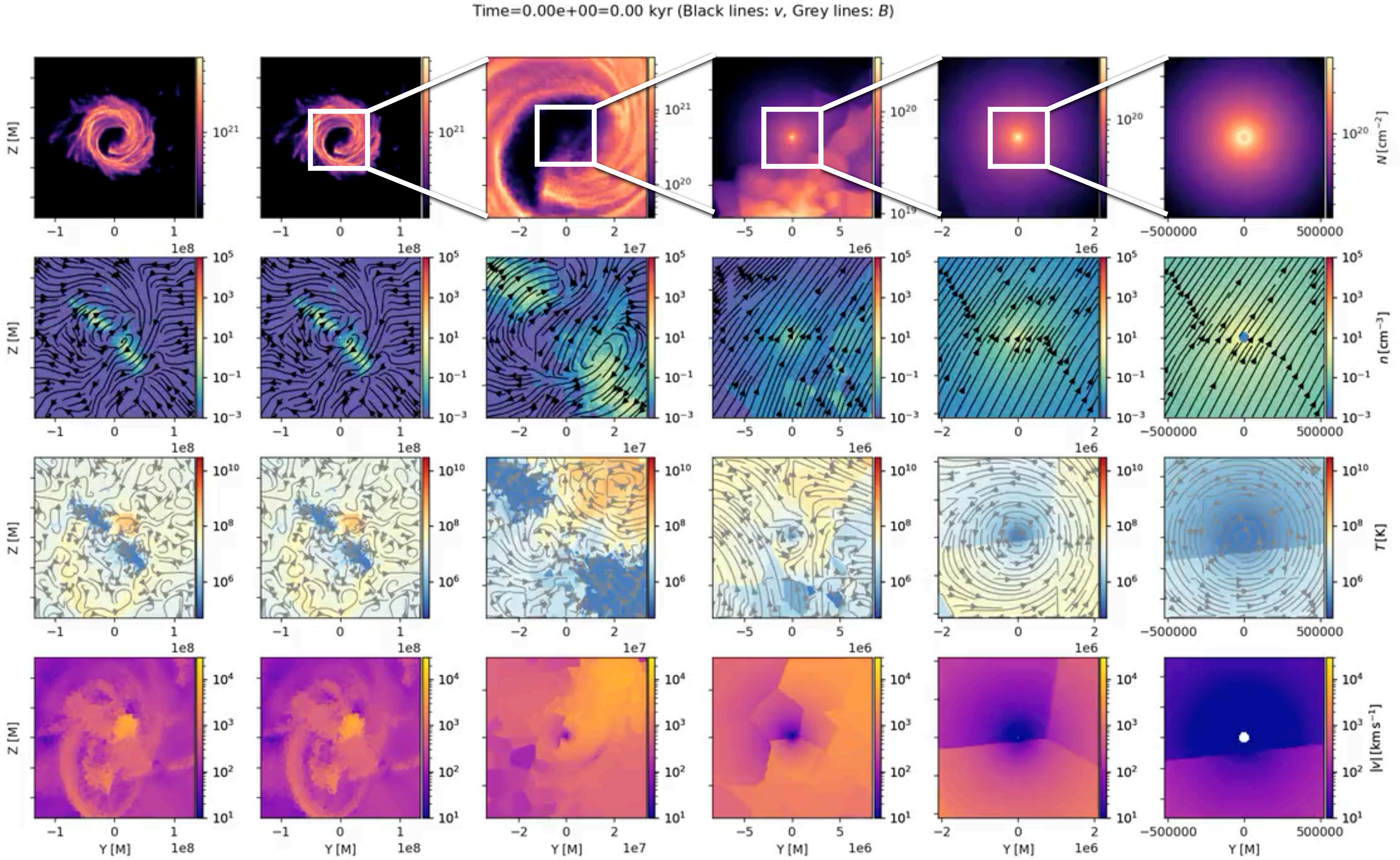
# NOW FOR SOME MOVIES!


Time=0.00e+00=0.00 kyr (Black lines: v, Grey lines: B)
Z [M]
Y [M]
1e8
1e7
1e6
N [cm⁻²]
n [cm⁻³]
T [K]
|v| [km s⁻¹]

Time=0.00e+00=0.00 kyr (Black lines: $v$, Grey lines: $B$)





Time=0.00e+00=0.00 kyr (Black lines: v, Grey lines: B)
Z [M]
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1e8
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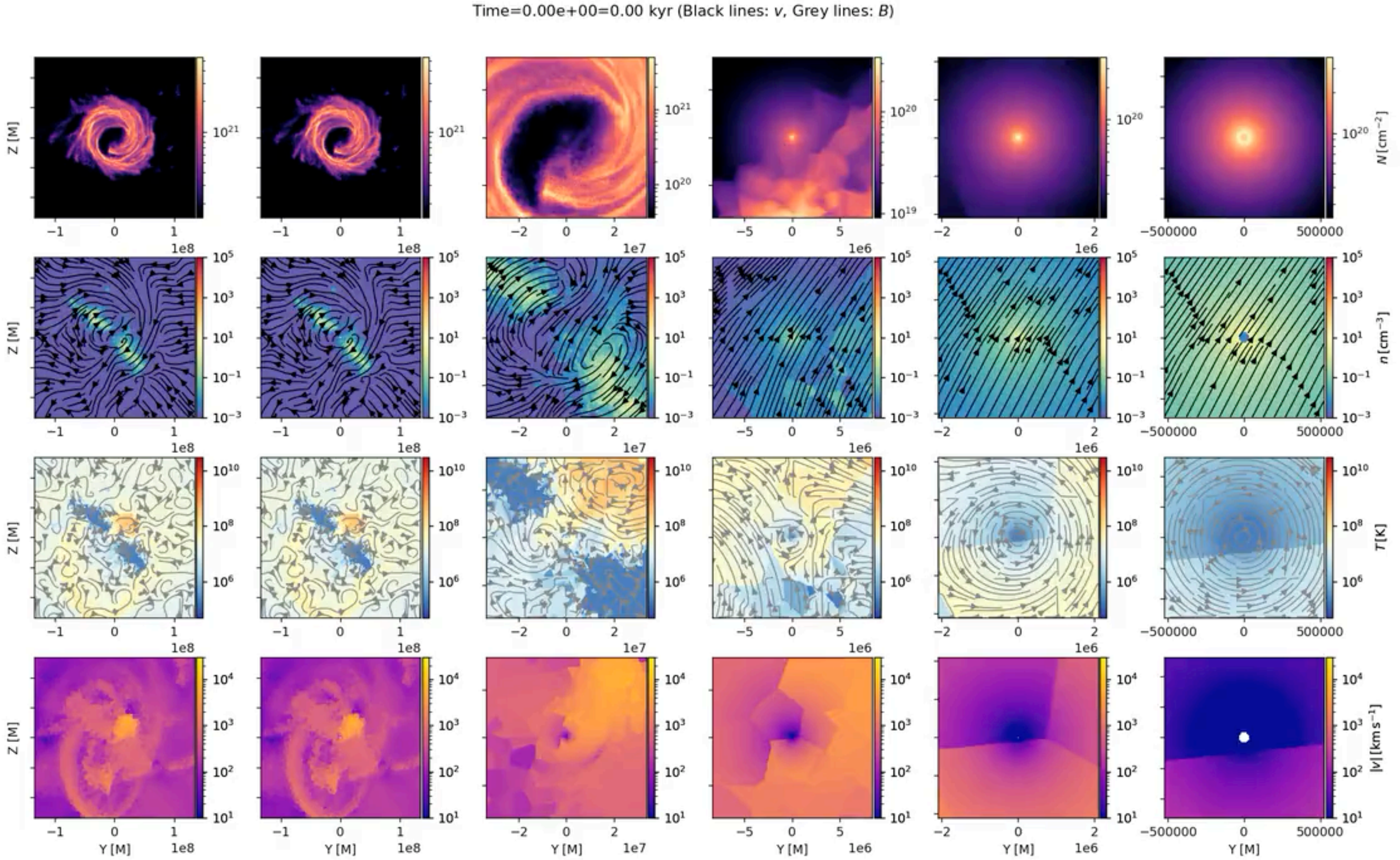

Time=0.00e+00=0.00 kyr (Black lines: v, Grey lines: B)
Z [M]
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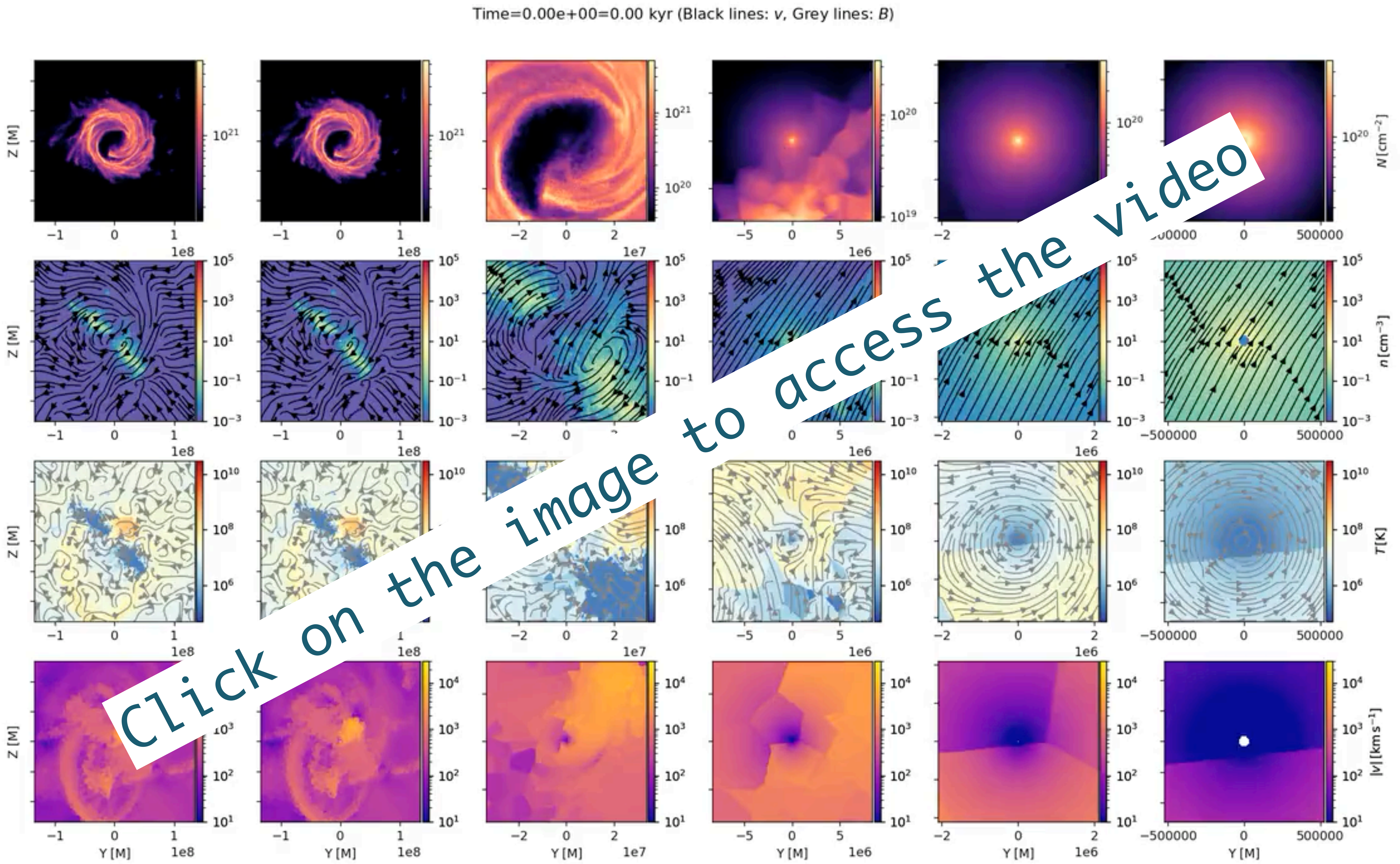
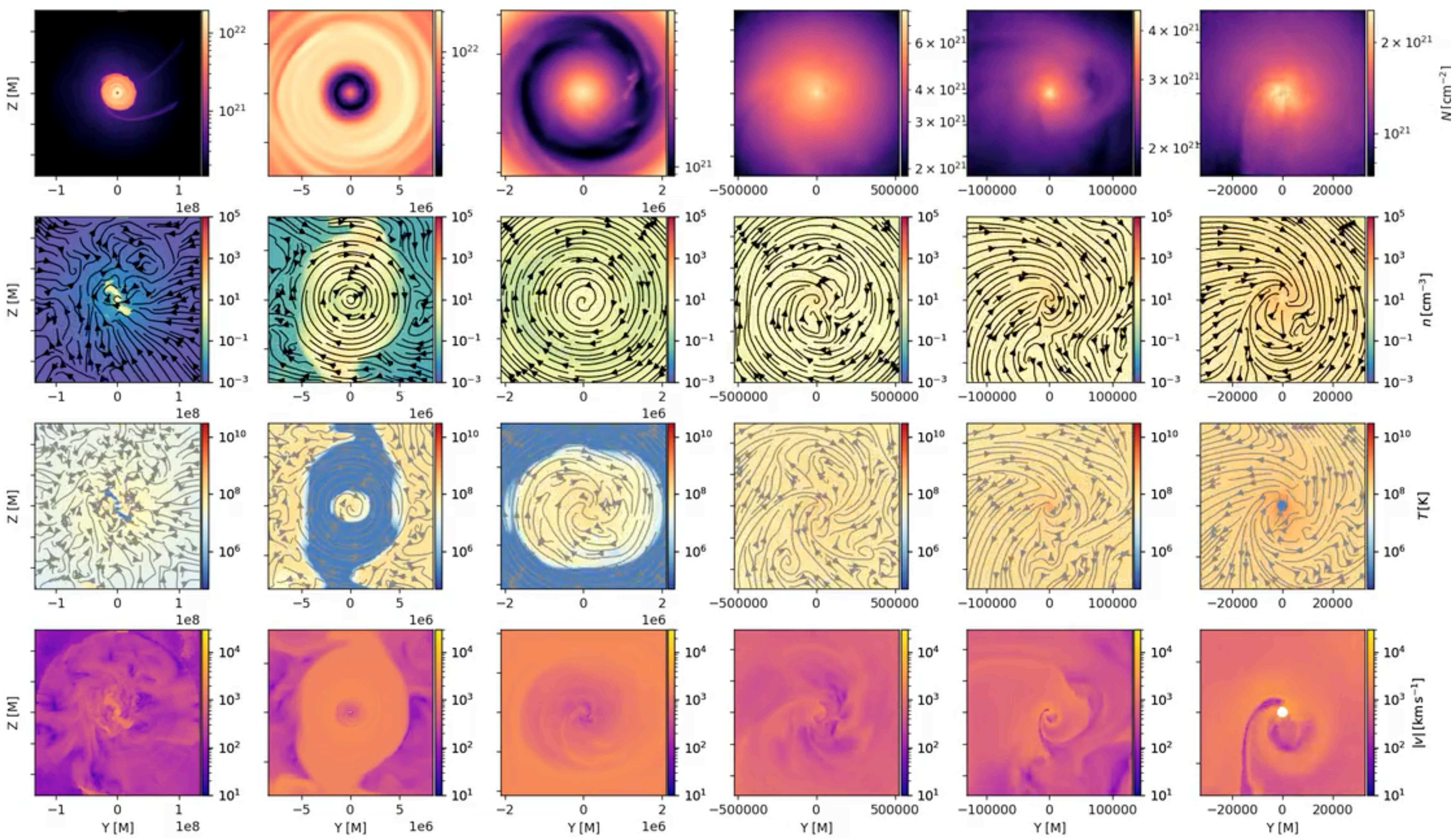
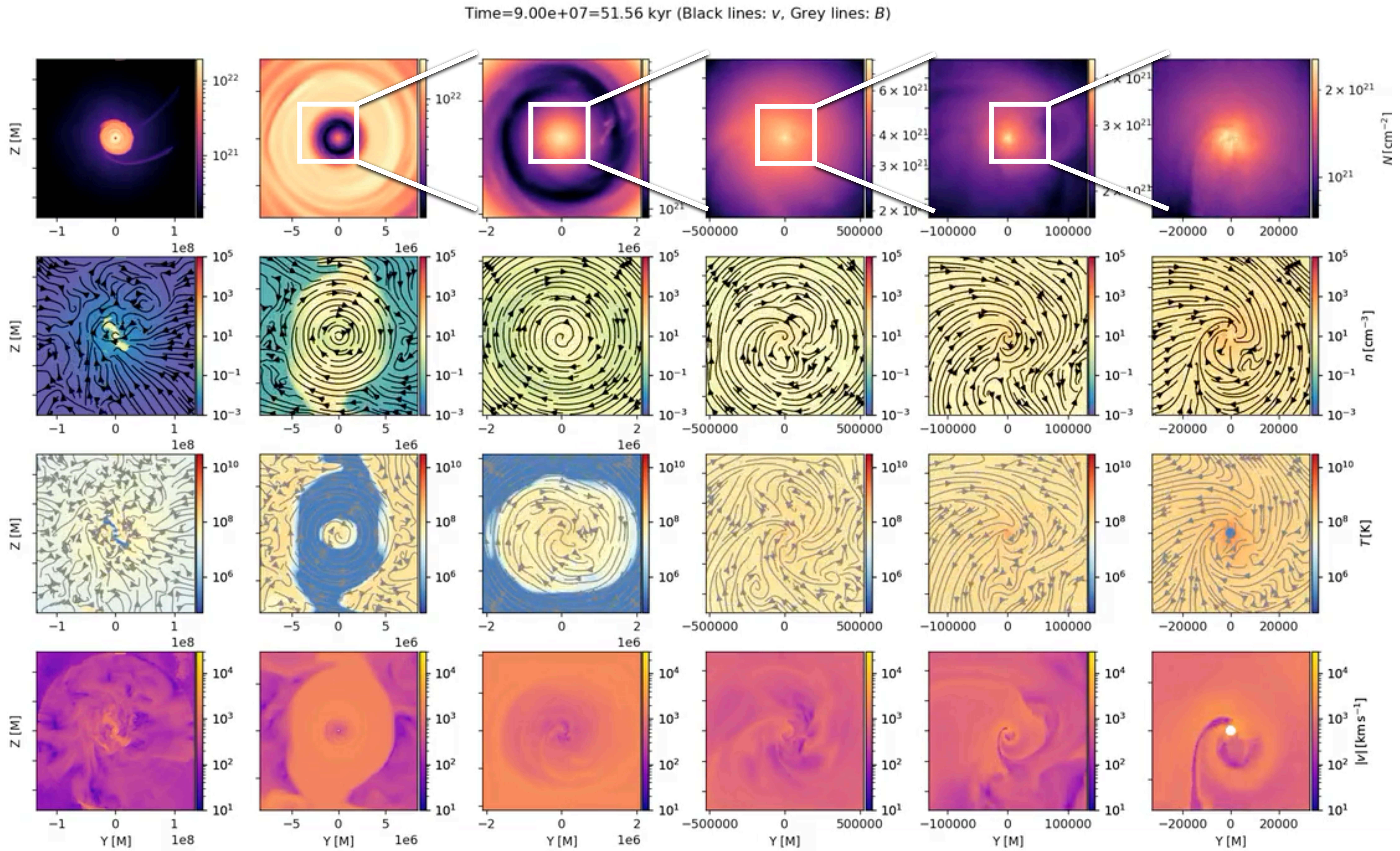


Time=0.00e+00=0.00 kyr (Black lines: v, Grey lines: B)
Click on the image to access the video
Z [M]
Y [M]
N [cm$^{-2}$]
n [cm$^{-3}$]
T [K]
|v| [km s$^{-1}$]
1e8
1e7
1e6

Time=9.00e+07=51.56 kyr (Black lines: $v$, Grey lines: $B$)





Time=9.00e+07=51.56 kyr (Black lines: v, Grey lines: B)
Z [M]
Y [M]
1e8
1e6
N [cm⁻²]
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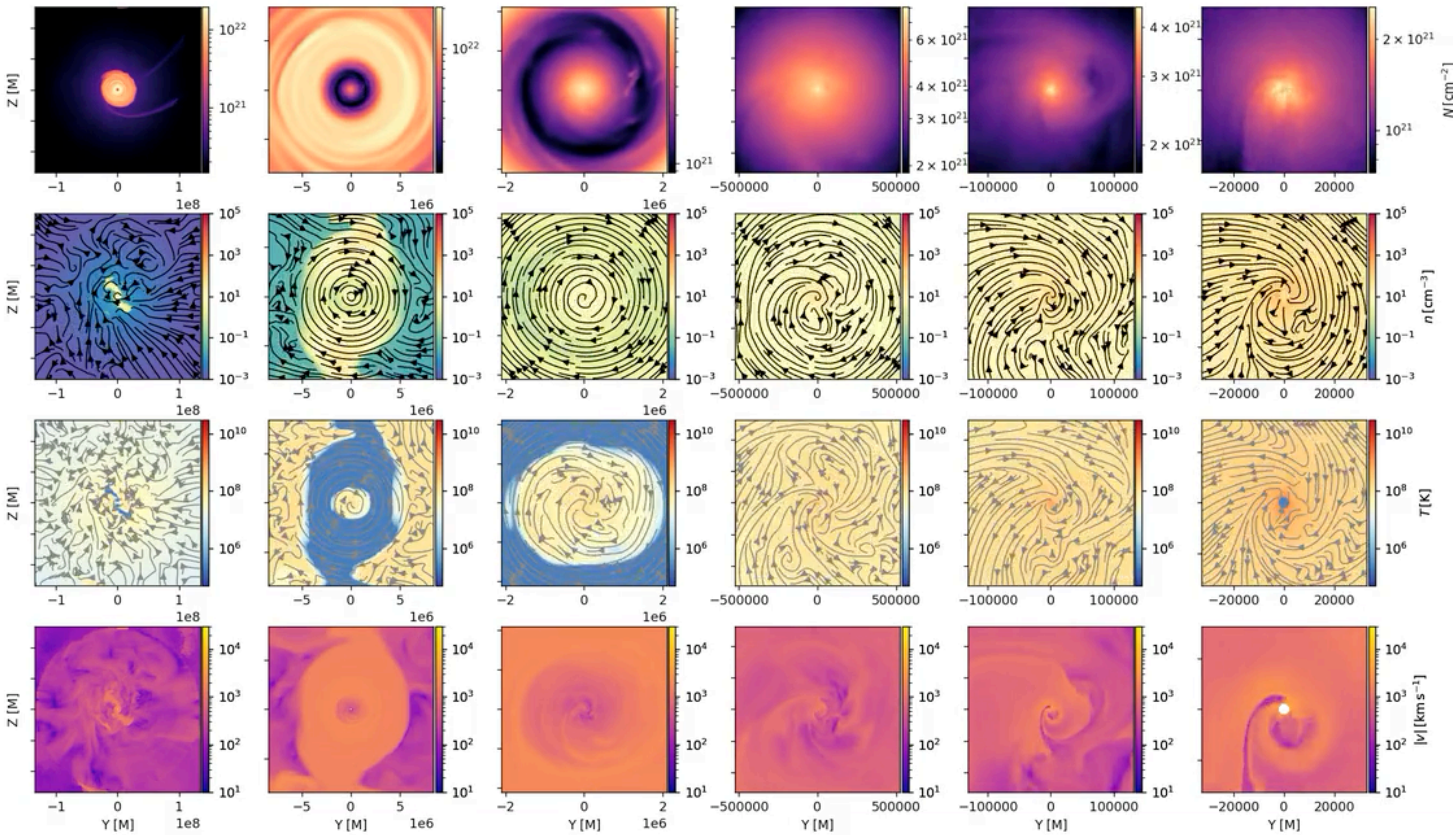
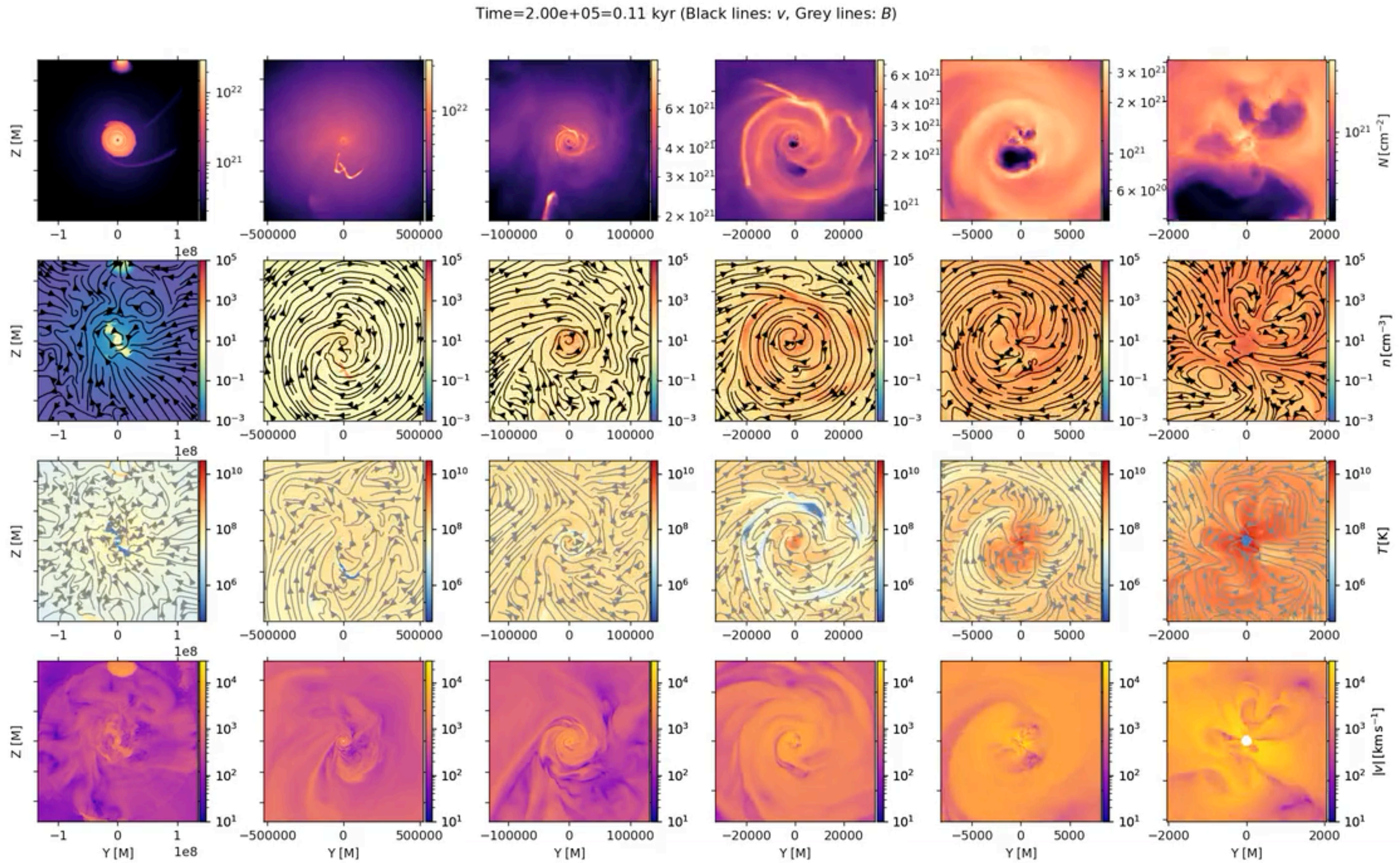
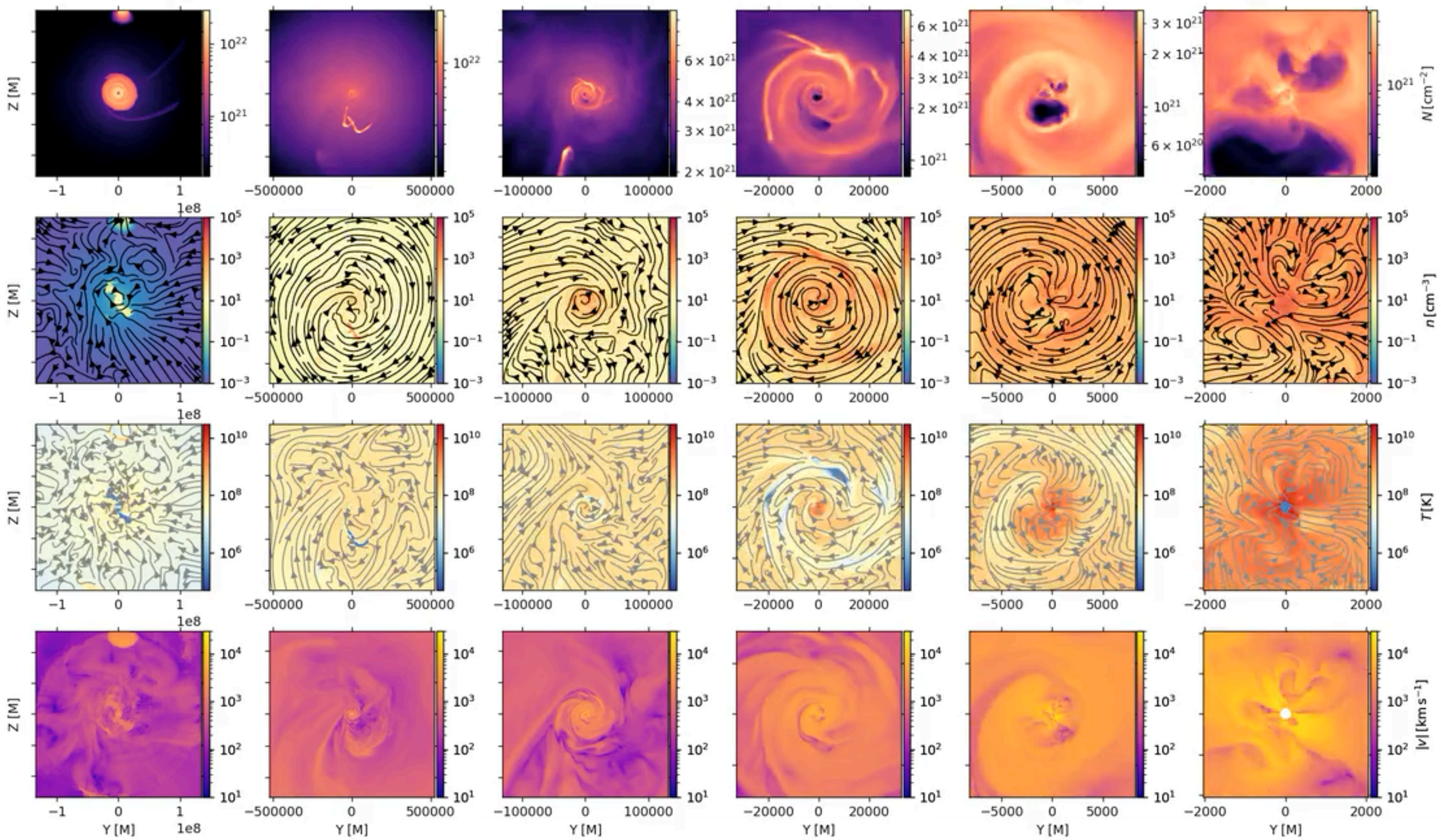



Time=2.00e+05=0.11 kyr (Black lines: v, Grey lines: B)
Z [M]
Y [M]
1e8
N [cm⁻²]
n [cm⁻³]
T [K]
|v| [km s⁻¹]

Time=2.00e+05=0.11 kyr (Black lines: $v$, Grey lines: $B$)



# ACCRETION RATE VS TIME

- Mostly quick relaxation at low zoom level (blue)
- Stable accretion at higher zoom levels
- Halos 2 and 4 follow the "classic" decreasing accretion with increasing zoom level
- Halos 0 and 3 don't
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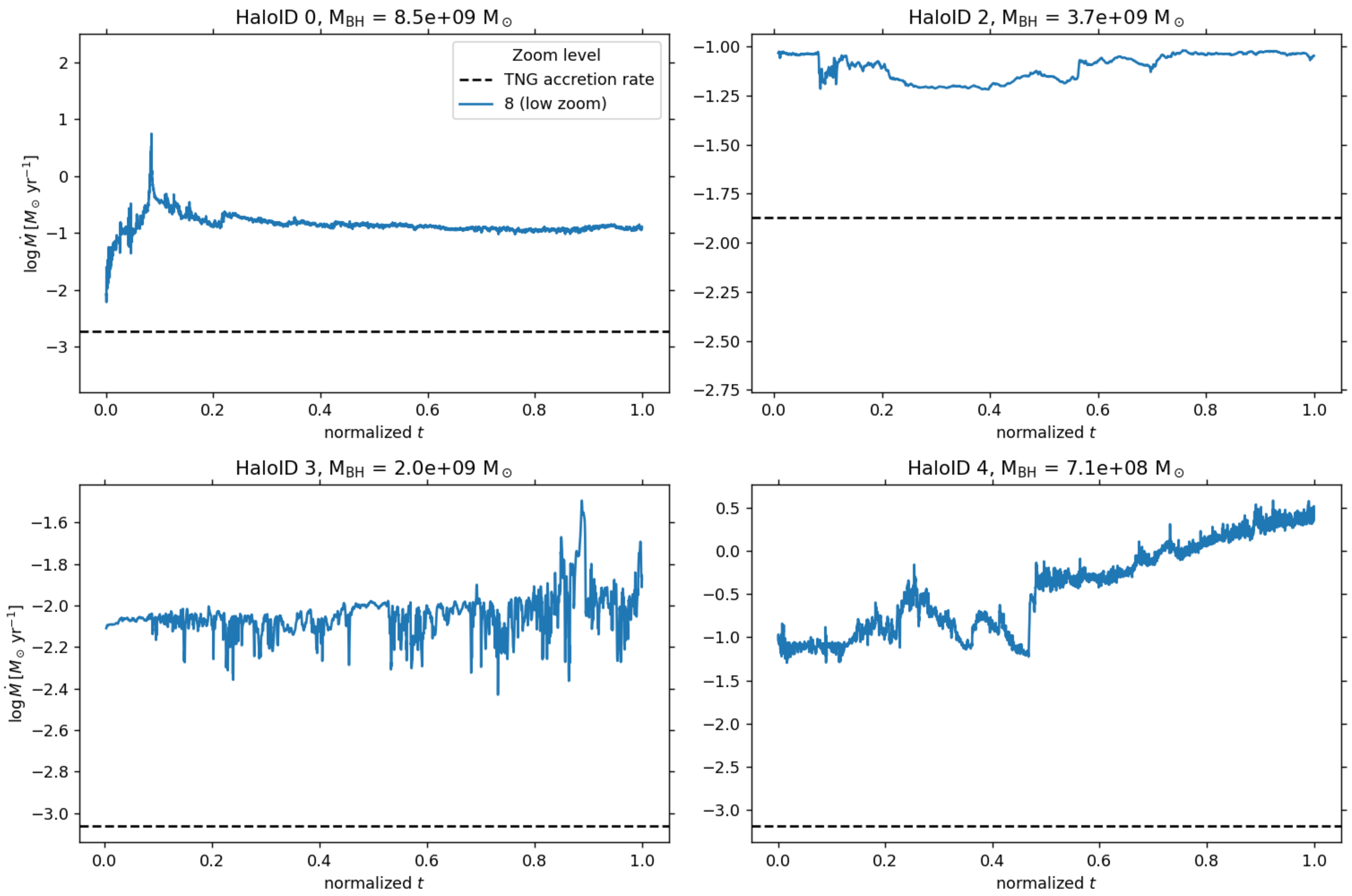

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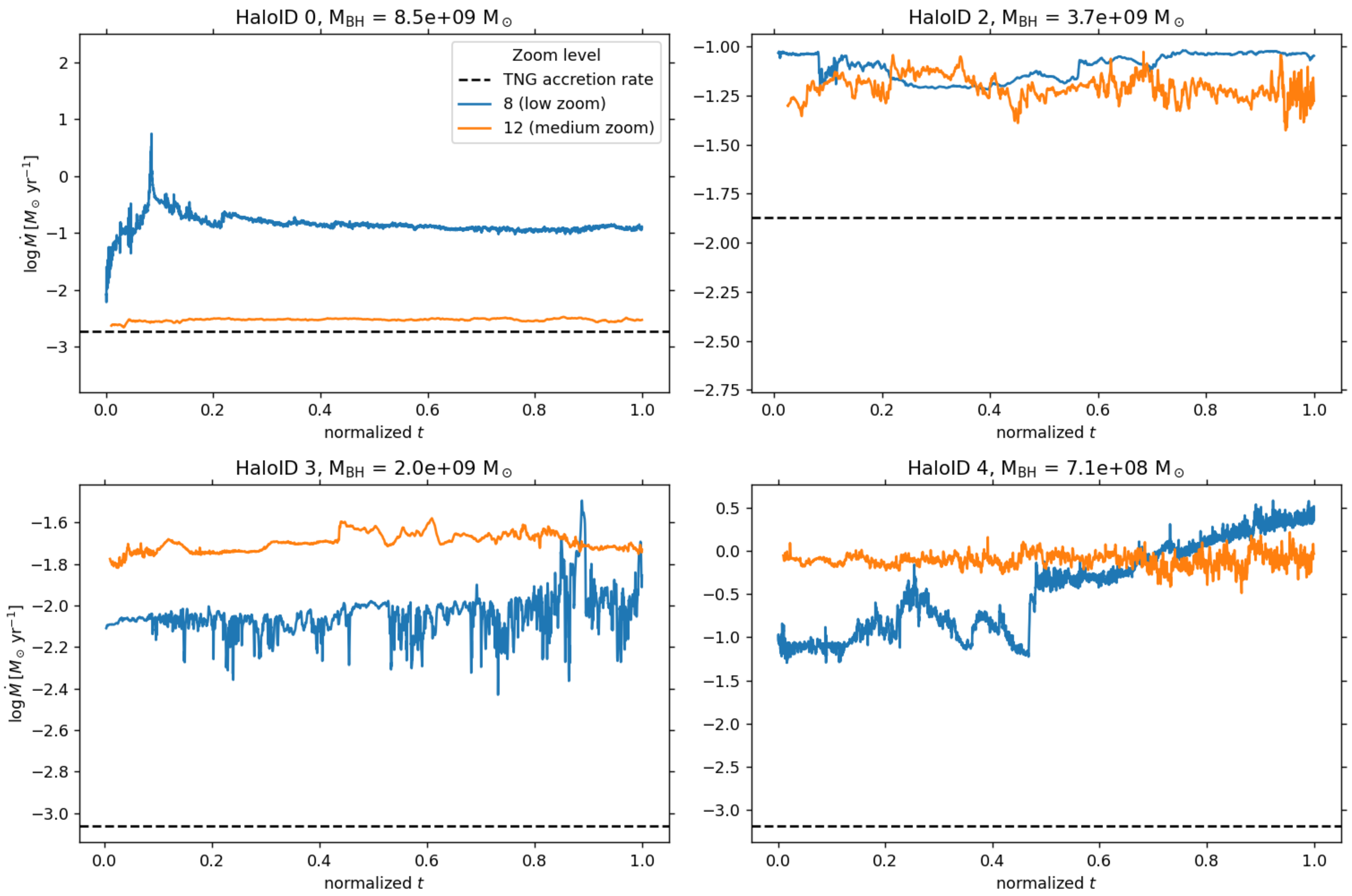

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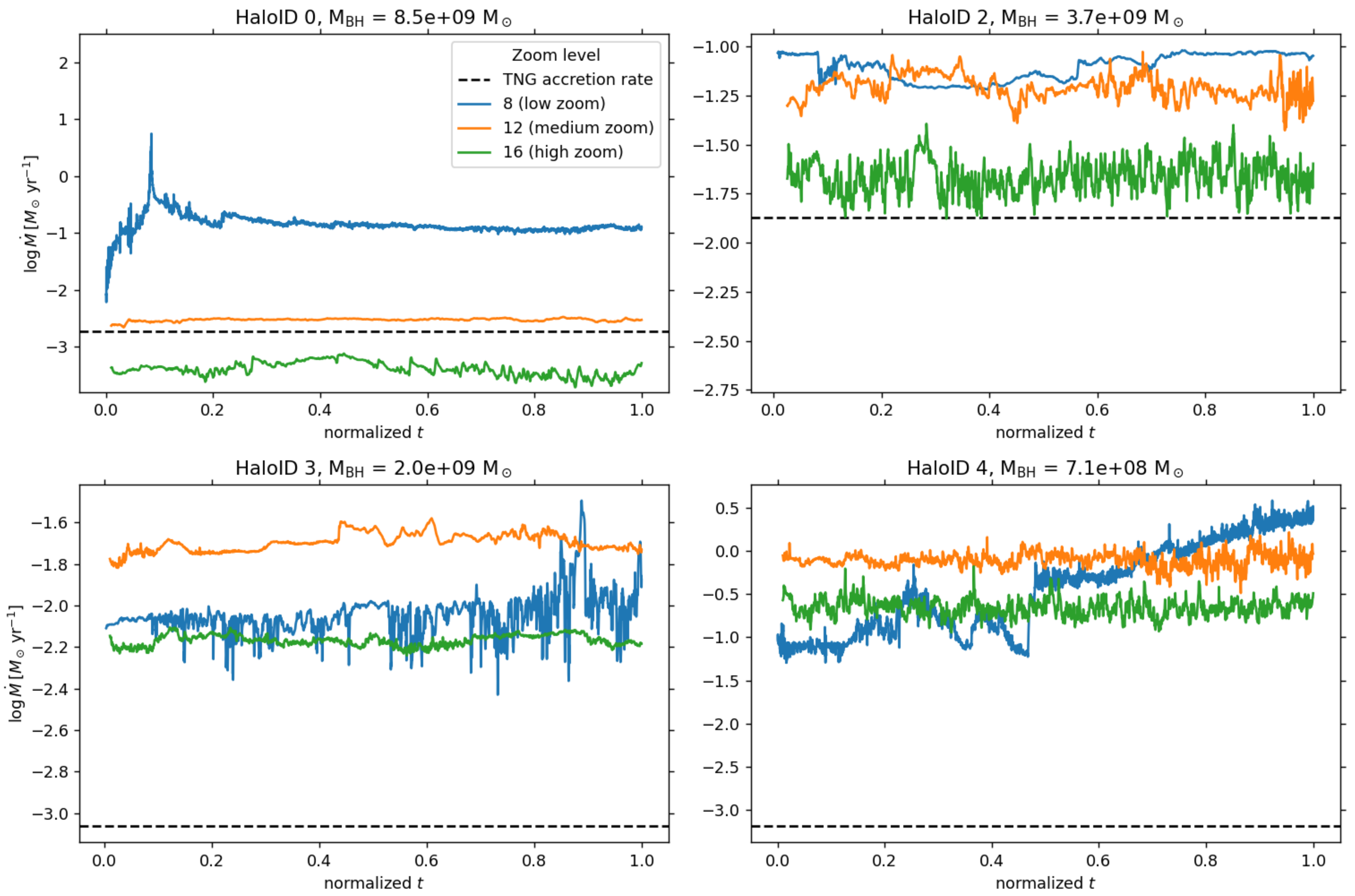

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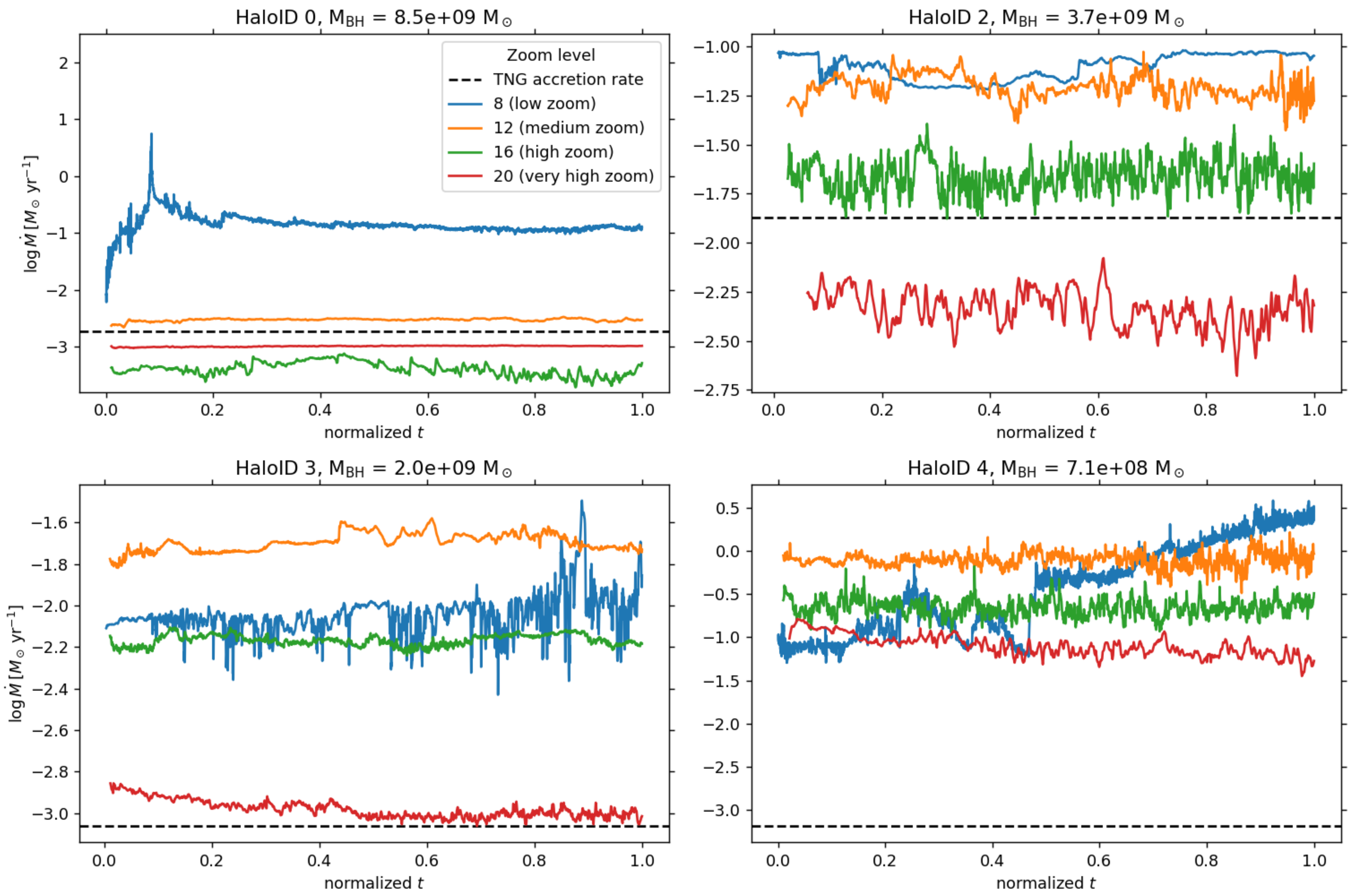
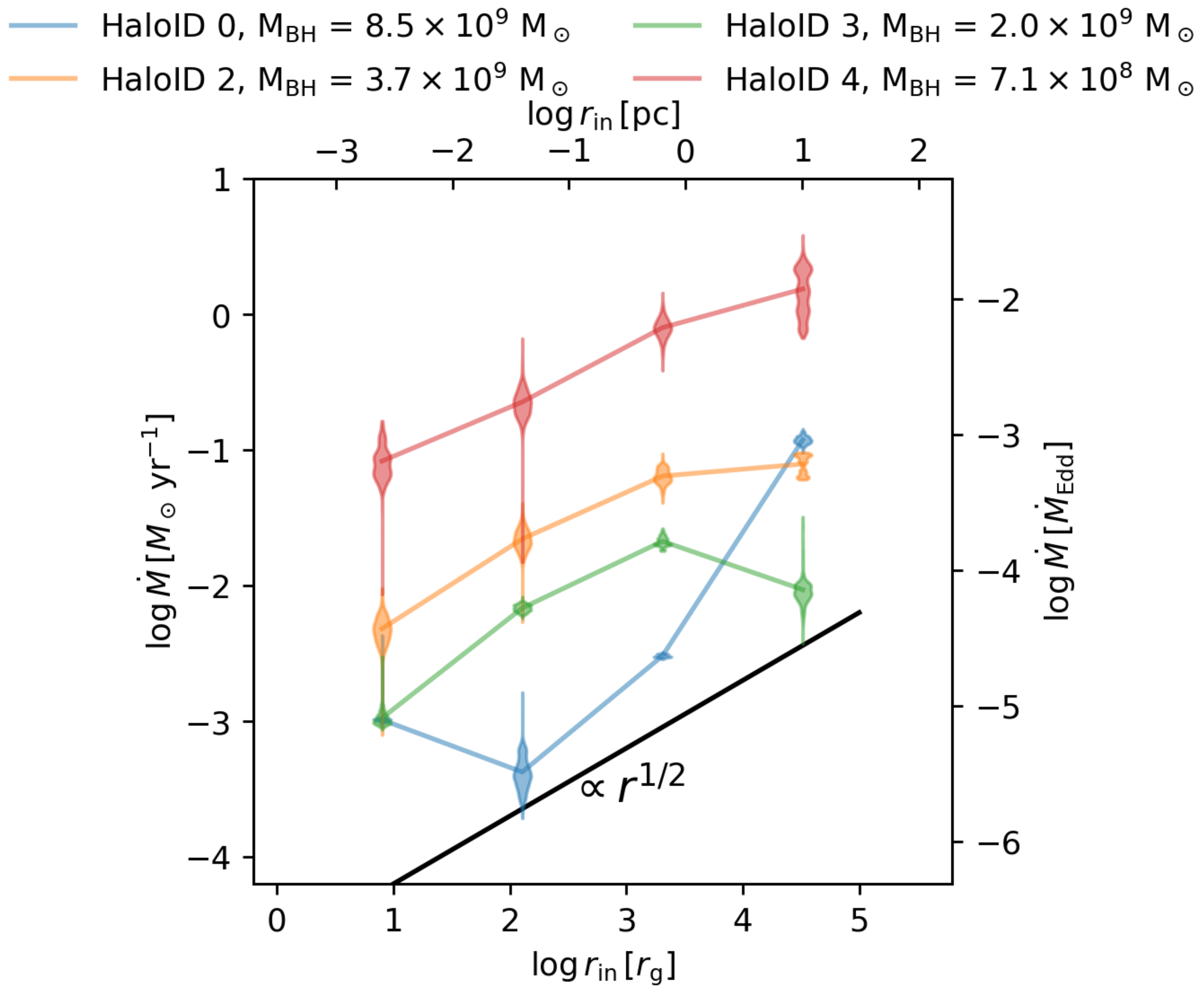


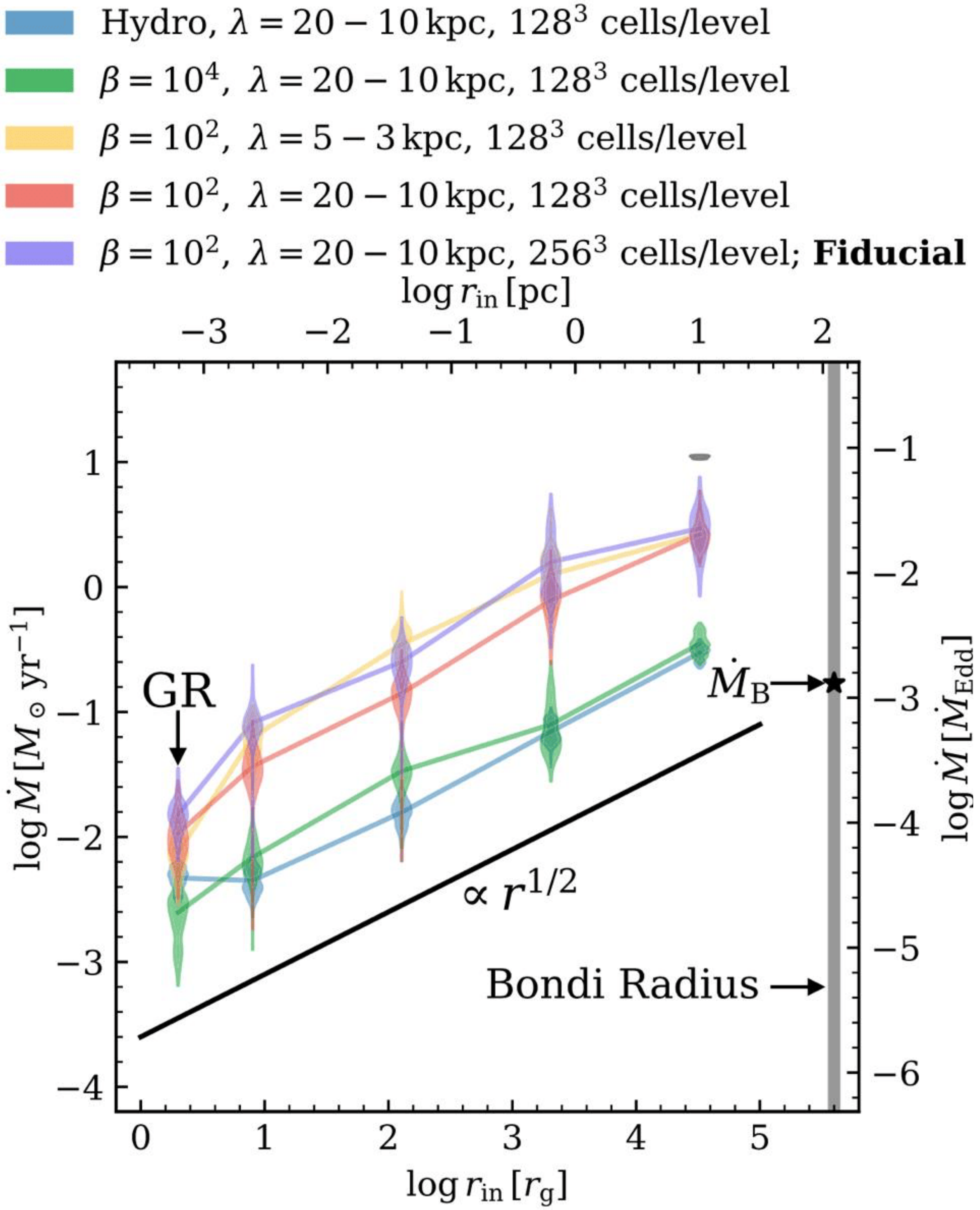
# ACCRETION RATE VS INNER RADIUS

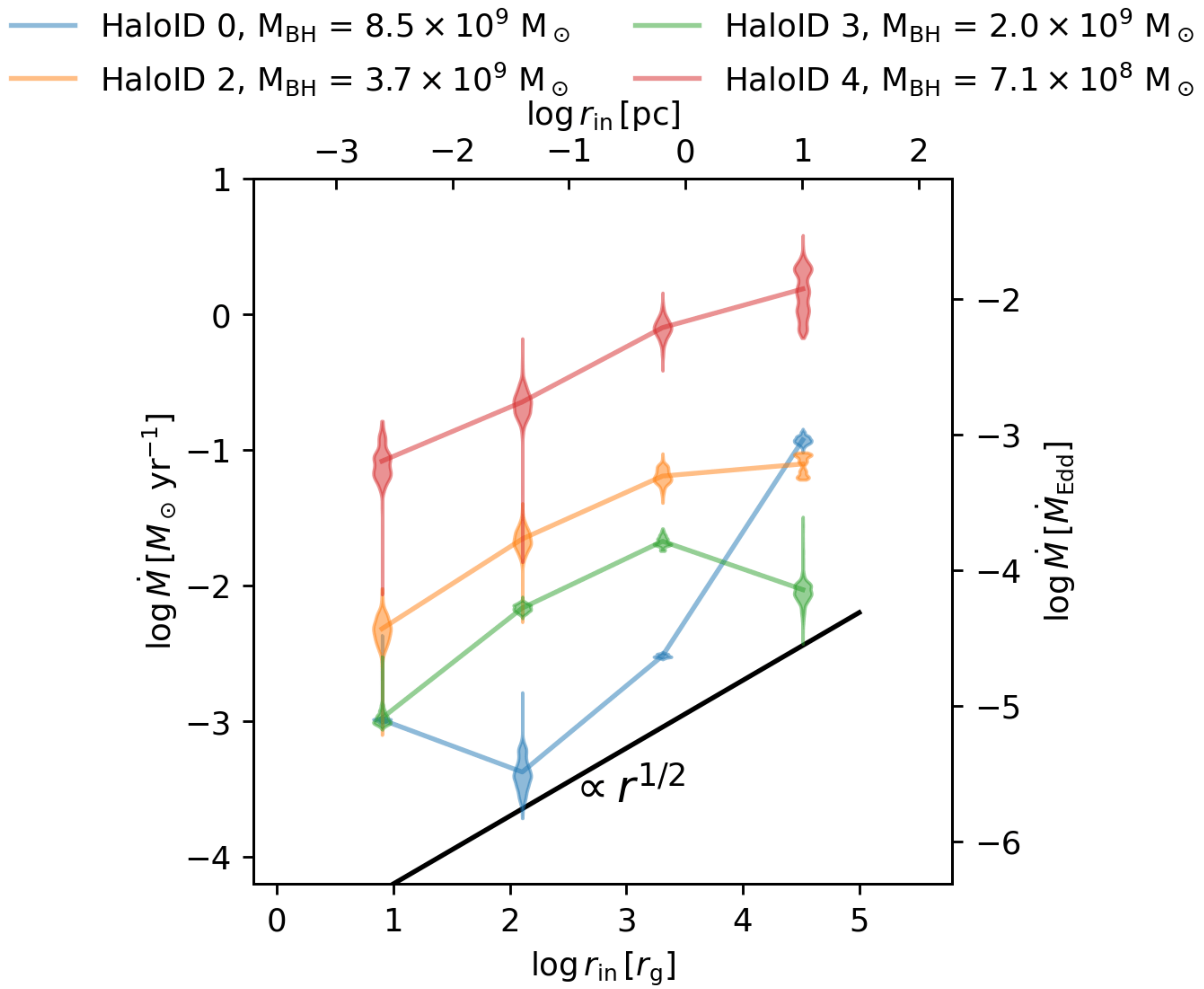
- **Relationship between mass accretion rate and inner radius for various runs.**
- **Guo 2024 find a universal scaling of $\dot{M} \propto r_{in}^{1/2}$**
- **Cosmological ICs result in more complex halos do not follow the scaling at certain zoom levels**



# A INNER RADIUS

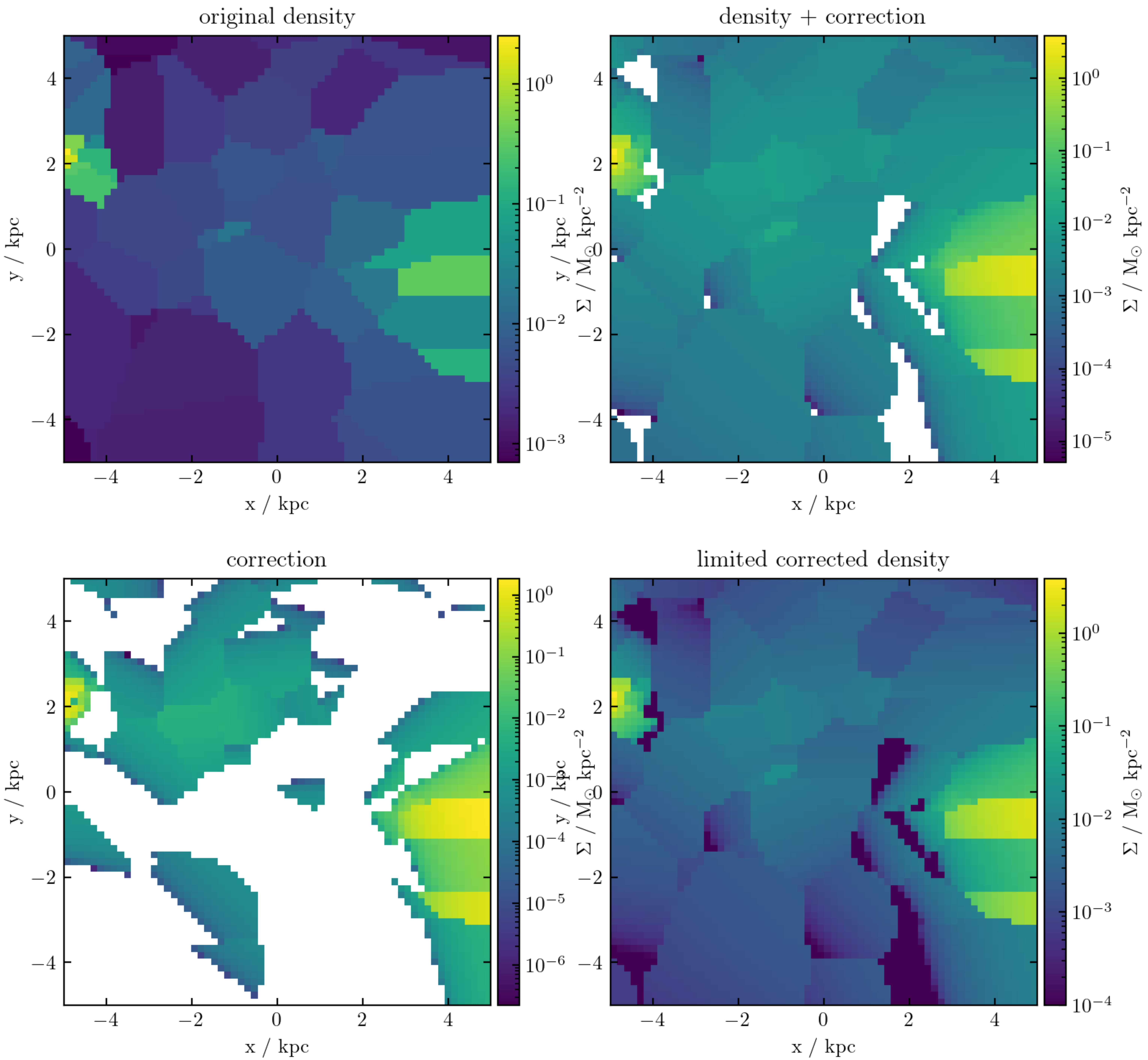
- Rela
  inne
- Guo
- Cosr
  not f



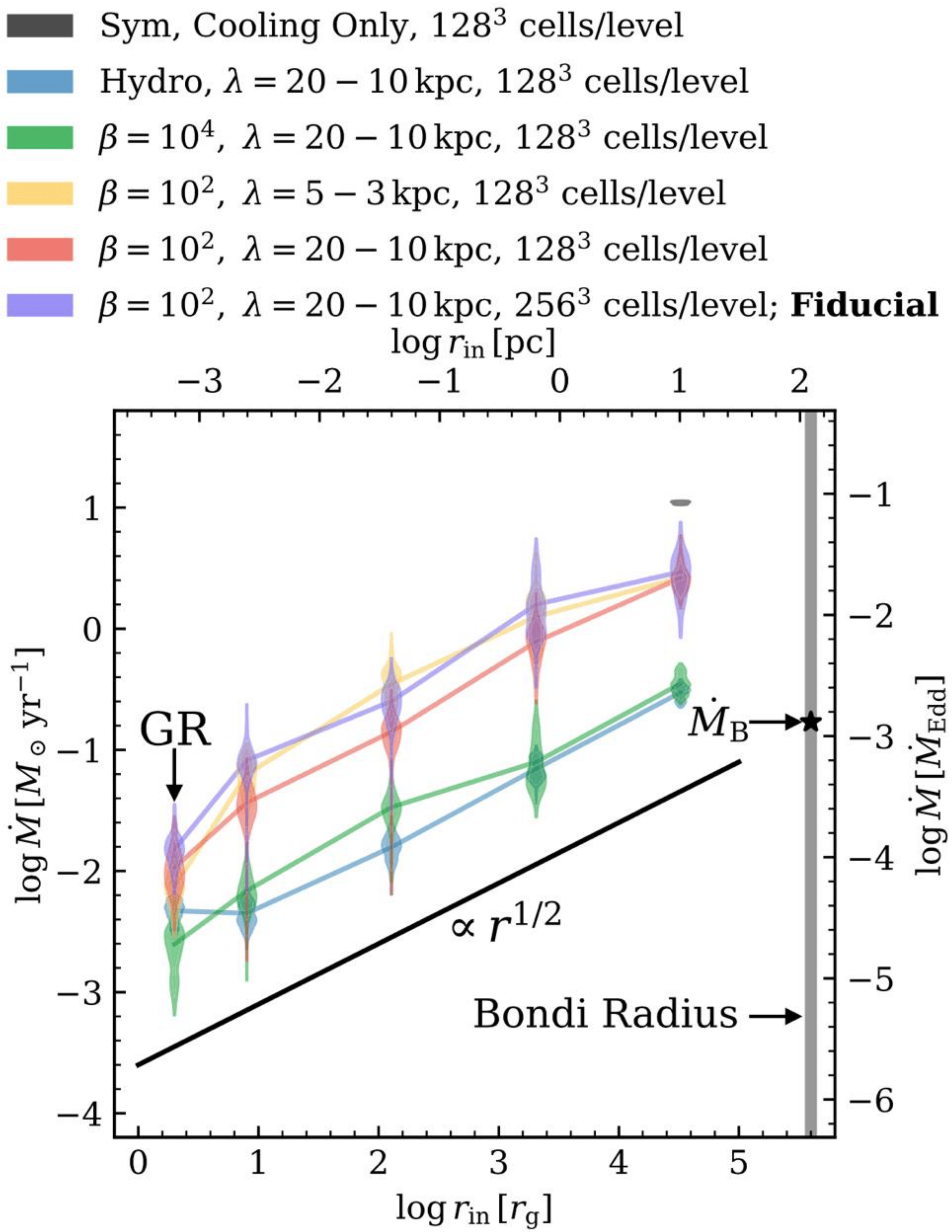



# FUTURE PLANS

- Extract magnetic fields from TNG,
- use the actual star distribution instead of the NFW,
- study the major accretion pathways of the “misbehaving” halos,
- identify the main source of torque on the gas,
- use Guo+ 2025b cyclic zoom approach to periodically zoom-in-zoom-out - connect small scales to large ones and vice versa.



original density
density + correction
correction
limited corrected density
x / kpc
y / kpc
Σ / M⊙ kpc⁻²



Sym, Cooling Only, $128^3$ cells/level
Hydro, $\lambda = 20 - 10\,\mathrm{kpc}$, $128^3$ cells/level
$\beta = 10^4$, $\lambda = 20 - 10\,\mathrm{kpc}$, $128^3$ cells/level
$\beta = 10^2$, $\lambda = 5 - 3\,\mathrm{kpc}$, $128^3$ cells/level
$\beta = 10^2$, $\lambda = 20 - 10\,\mathrm{kpc}$, $128^3$ cells/level
$\beta = 10^2$, $\lambda = 20 - 10\,\mathrm{kpc}$, $256^3$ cells/level; **Fiducial**
$\log r_{\mathrm{in}}\,[\mathrm{pc}]$
$\log \dot{M}\,[M_\odot\,\mathrm{yr}^{-1}]$
$\log \dot{M}\,[\dot{M}_{\mathrm{Edd}}]$
$\log r_{\mathrm{in}}\,[r_{\mathrm{g}}]$
GR
$\dot{M}_{\mathrm{B}}$
$\propto r^{1/2}$
Bondi Radius

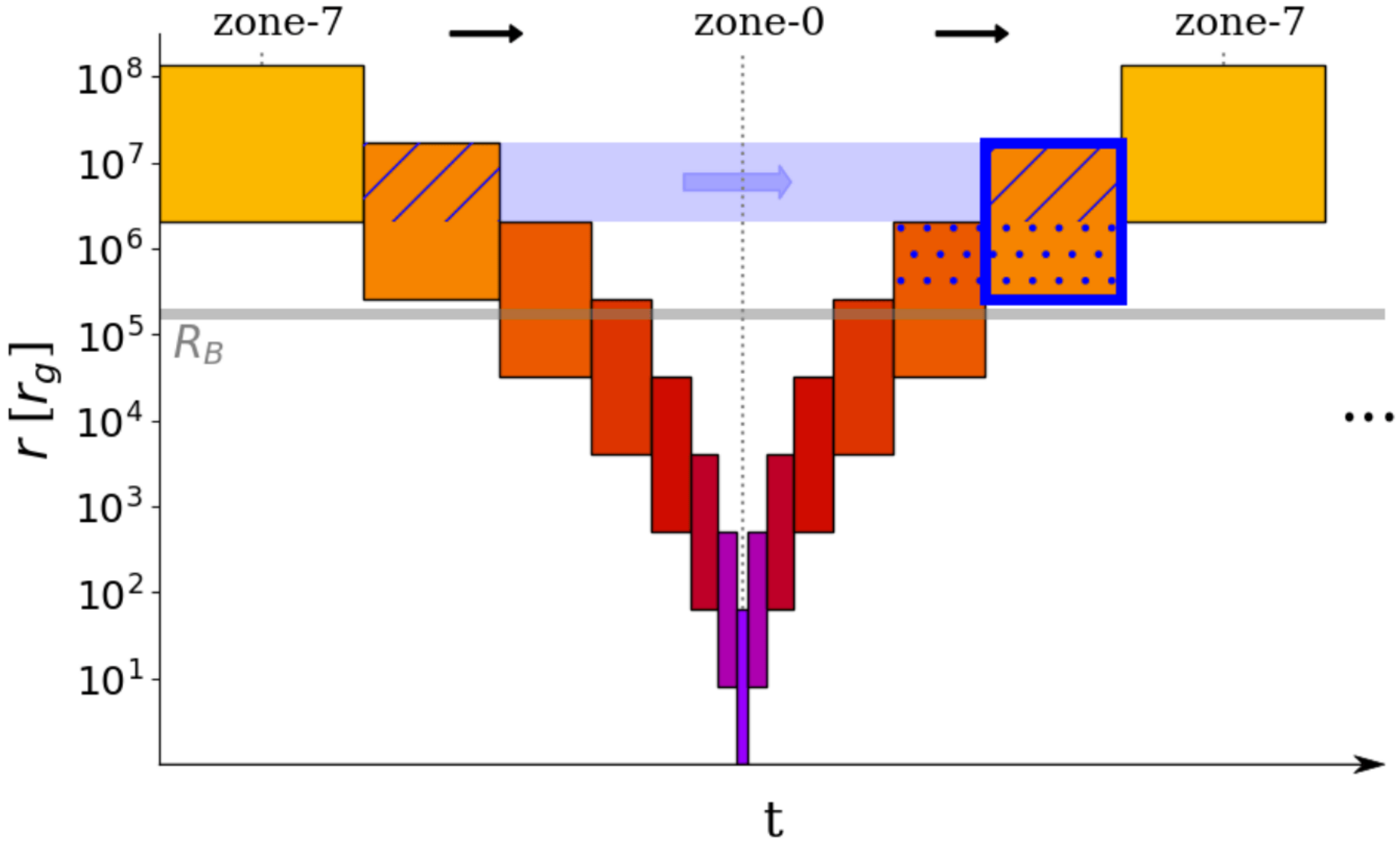



**Figure 1.** Schematics of the multi-zone method: the different colors represent the different zones being simulated. Radii are shown along the $y$-axis, with zone $i$ extending from an inner radius of $8^i\,r_g$ to an outer radius of $8^{i+2}\,r_g$, where $r_g = GM_\bullet/c^2$ is the gravitational radius. Runtime is shown along the $x$-axis (not to scale). The plot here corresponds to one "V-cycle," advancing the entire domain forward by some time. A complete simulation consists of hundreds of V-cycles to allow full information exchange between the smallest and largest scales.