# FORMATION OF SMBH SEEDS IN COSMOLOGICAL CONTEXT


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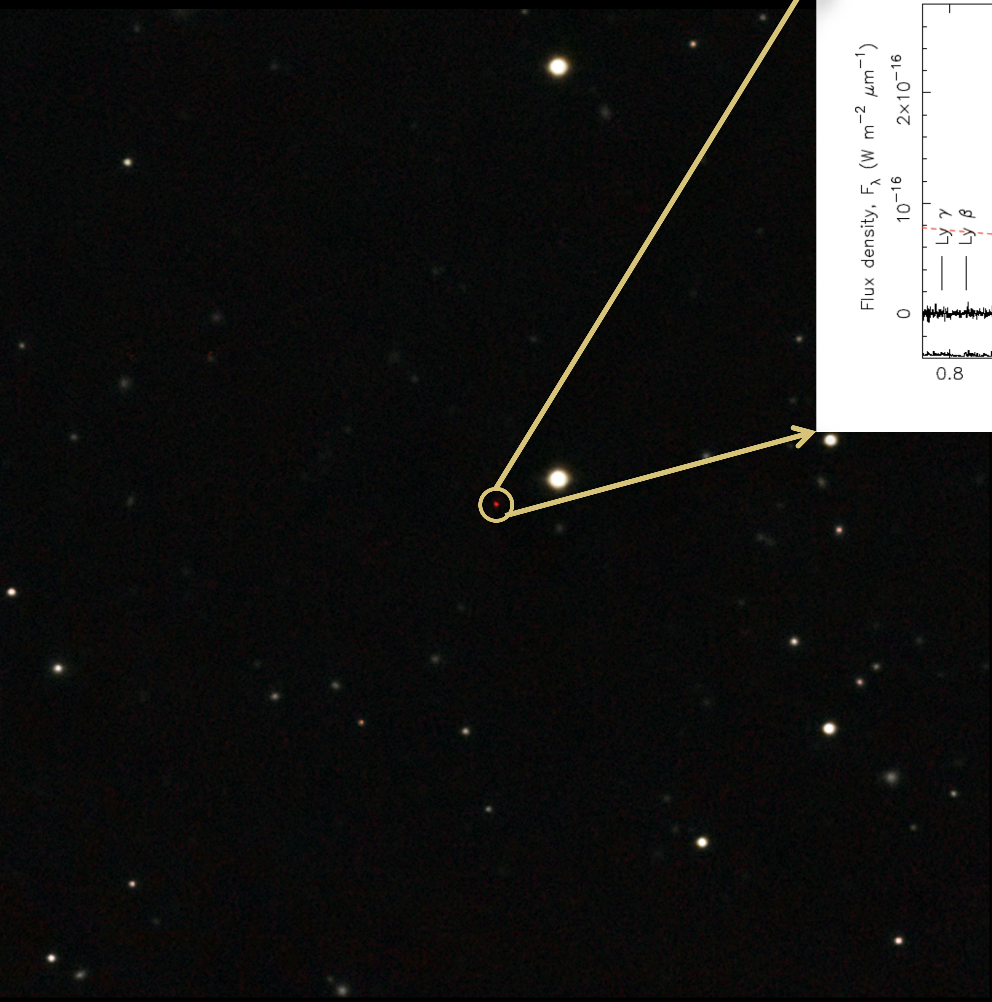
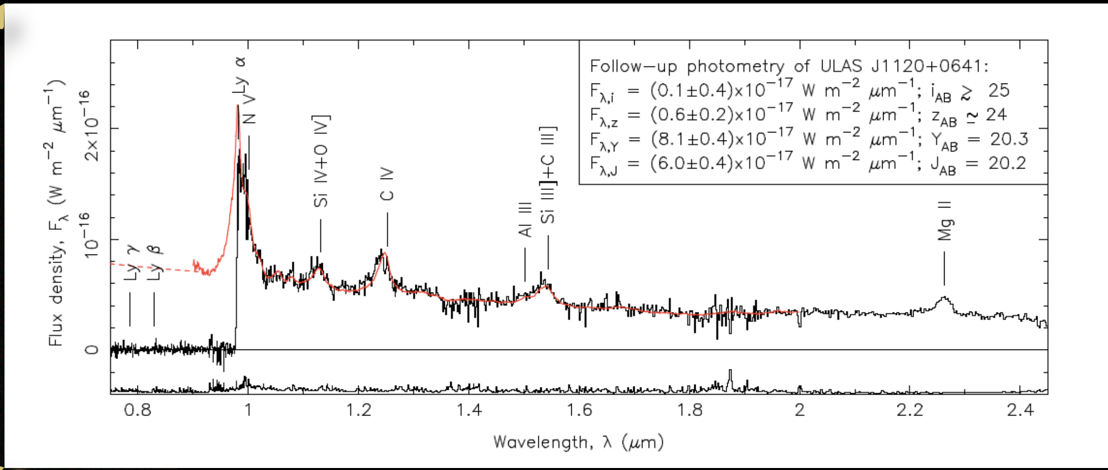
# Most distance quasar





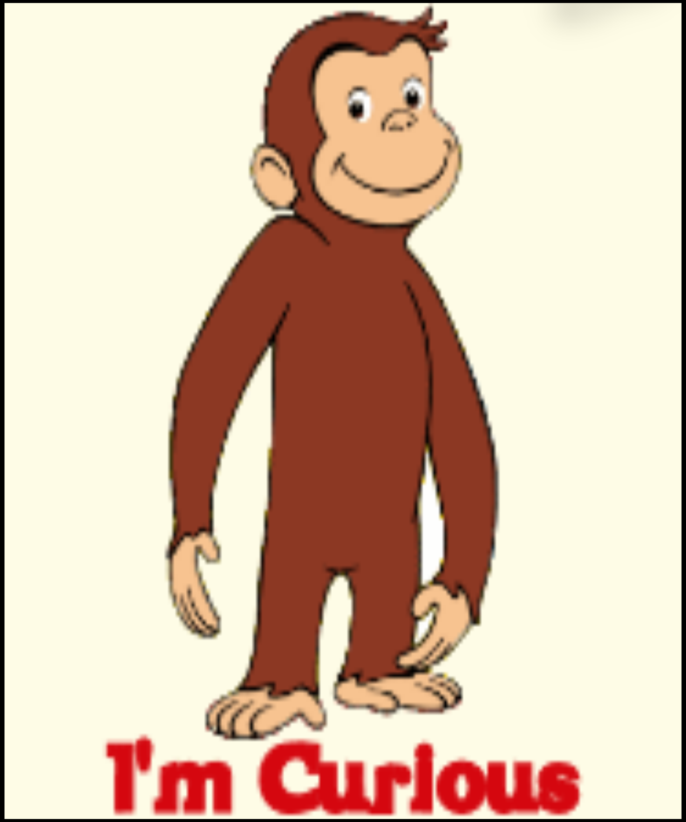

ULAS J112001.48+064124.3
z=7.085; 0.77 Gyr after Big Bag
MBH ~$2\times10^9$ $M_\odot$
First detected by UKIDSS
Spectroscopic observation by FORS2 on VLT : Well evolved quasar

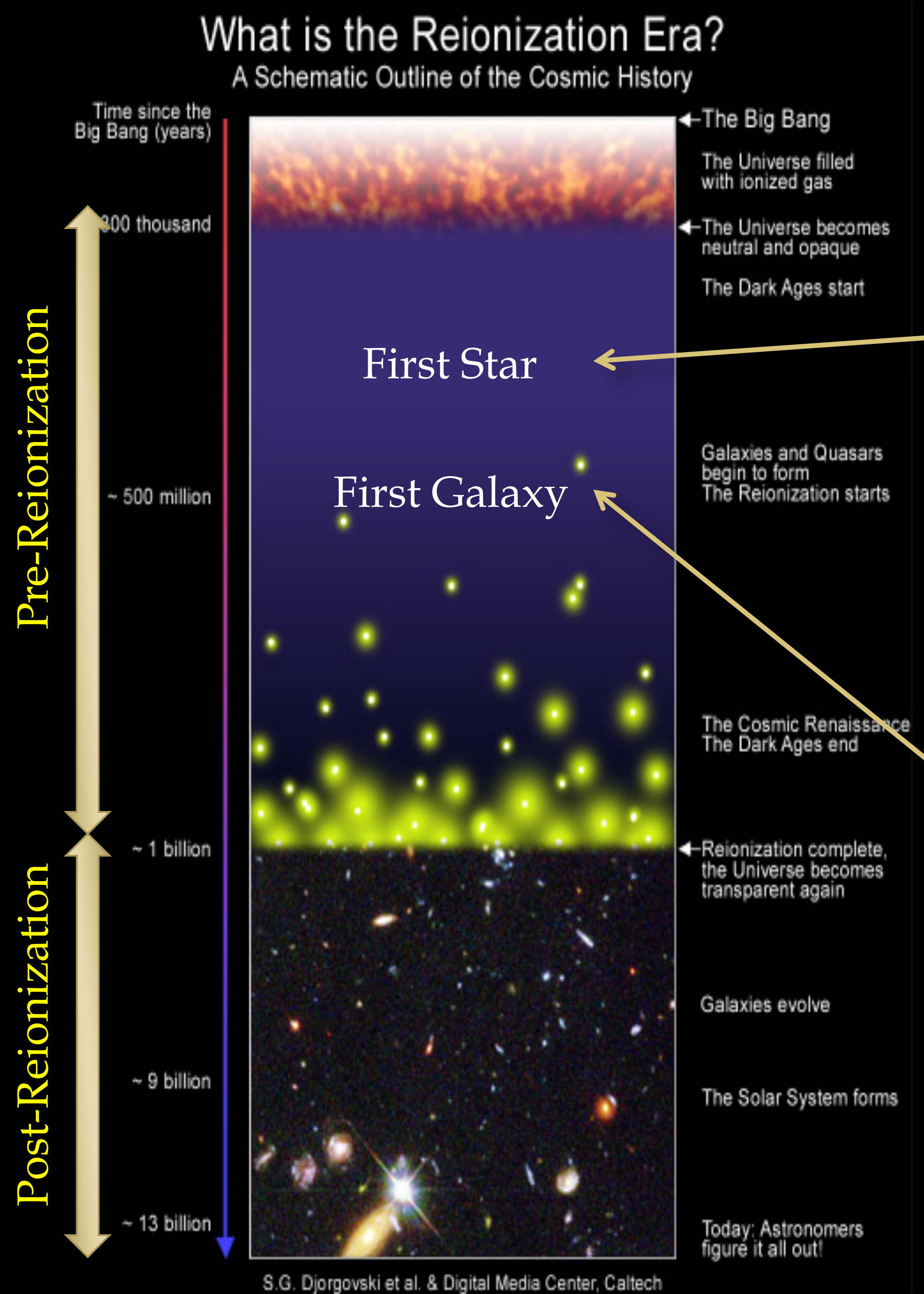
There are significant number of high-z (z>6) quasars.

Mortlock et al. 2011

***Some SMBH seeds should establish their mass very quickly!!***

Wait !!! Where do these SMBHs come from?






# Two Models for SMBH seed

**Pop III remnant (z>20)**

(Haiman & Loeb 2001)

→ Pop III stars are very massive >100 $M_\odot$

→ gas collapse in ~$10^6$ $M_\odot$ halo

→ Yield ~100 $M_\odot$ BH seed at z>20

→ These BH seeds grow to AGN

**Direct halo gas collapse (z~15)**

(Bromm & Loeb 2003, Begelman 2006)

→ From Direct halo gas collapse to form massive BH seeds

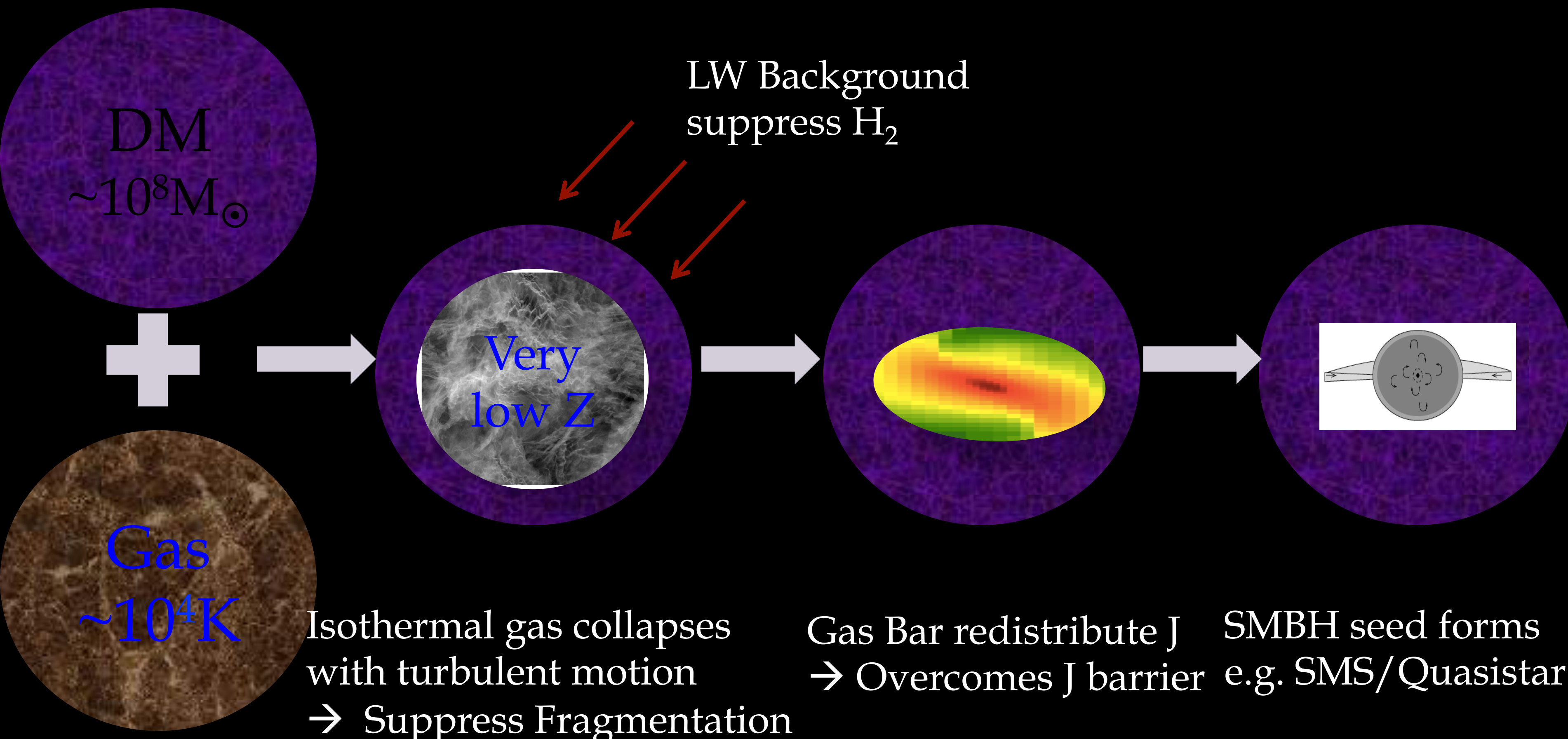
→ ~$10^8$ $M_\odot$ ($T_{vir}$ ~$10^4$K) halo gas collapse through the atomic cooling

→ Yield Massive BH seed at z~15

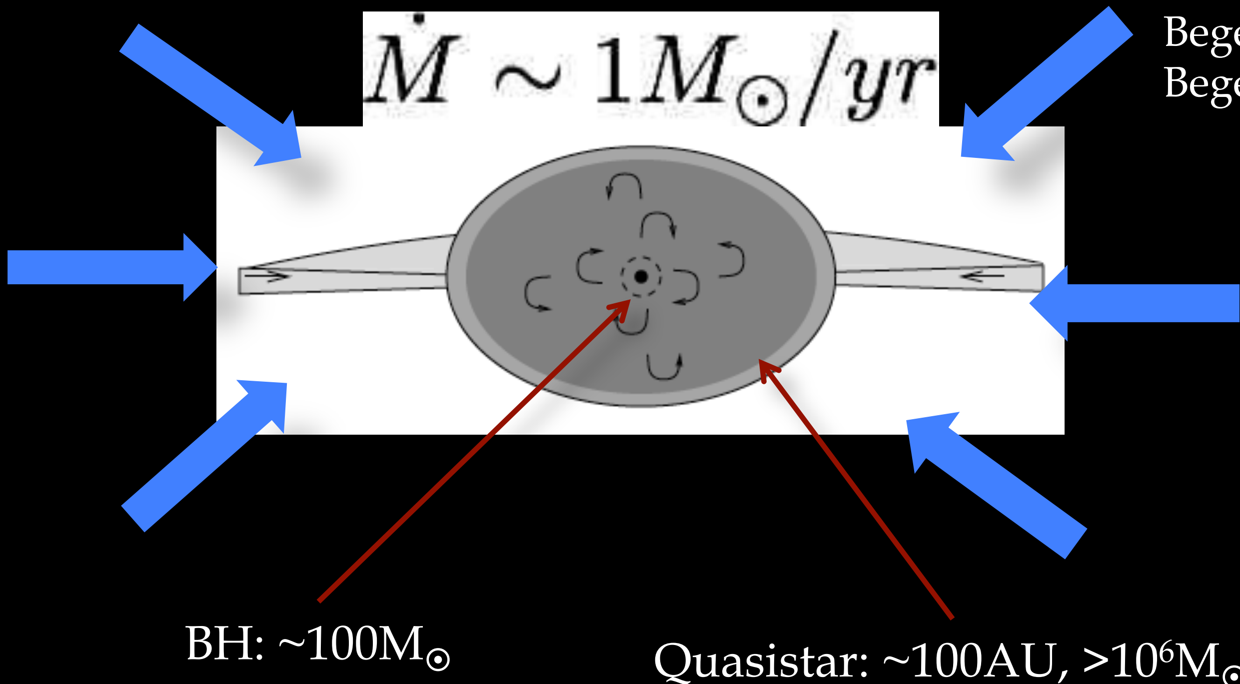
# Pros and Cons

- Population III remnant
  - It is natural first candidate: We know how to make seed BH.
  - Time scale (from z>20 to z~7 to $\sim 10^9 M_\odot$)
    - Takes $\sim 7\times10^8$ yrs to growth $\sim 10^9 M_\odot$ close to age of Universe (Mortlock et. al. 2011: z~7.085 with $M_{BH} \sim 2\times10^9 M_\odot$)
  - BH slingshot and ejection from mini-haloes during mergers
  - BH feedback regulates gas accretion
  - Recent PopIII studies predict lower mass ($\sim 50 M_\odot$)
- Direct Gas Collapse
  - Easy to growth by accretion/mergers from z~15 to z~7
  - Need an exotic process to make seed BH
  - Dynamical Problems
    - J-barrier prohibits gas collapse
    - Fragmentation depletes accreting gas

# Schematic of Direct Collapse Process



# SMS/Quasistar Model




Begelman et al 06 & 08, Begelman 10

- ✓ Very massive object (>>$10^4 M_{\odot}$)
  - ✓ Rapid inflow prohibits relaxation
  - ✓ Inner core burn nuclear fusion and collapse to 1~100 $M_{\odot}$BH
- ✓ Quasistar : BH accretes the mass as the Eddington rate of the whole object
- ✓ Takes a few thousand years from 100 $M_{\odot}$BH to $10^4 M_{\odot}$-$10^6 M_{\odot}$ BH
- ✓ There may be several other exotic processes can be suggested.

# *Outline*

I. Isolated model

II. Cosmological simulation at the early time of the collapse

III. Long-Term sink evolution

# Isolated Halo Gas collapse
## : *Study dynamical processes in direct collapse*

(Choi, Shlosman, & Begelman 2013)

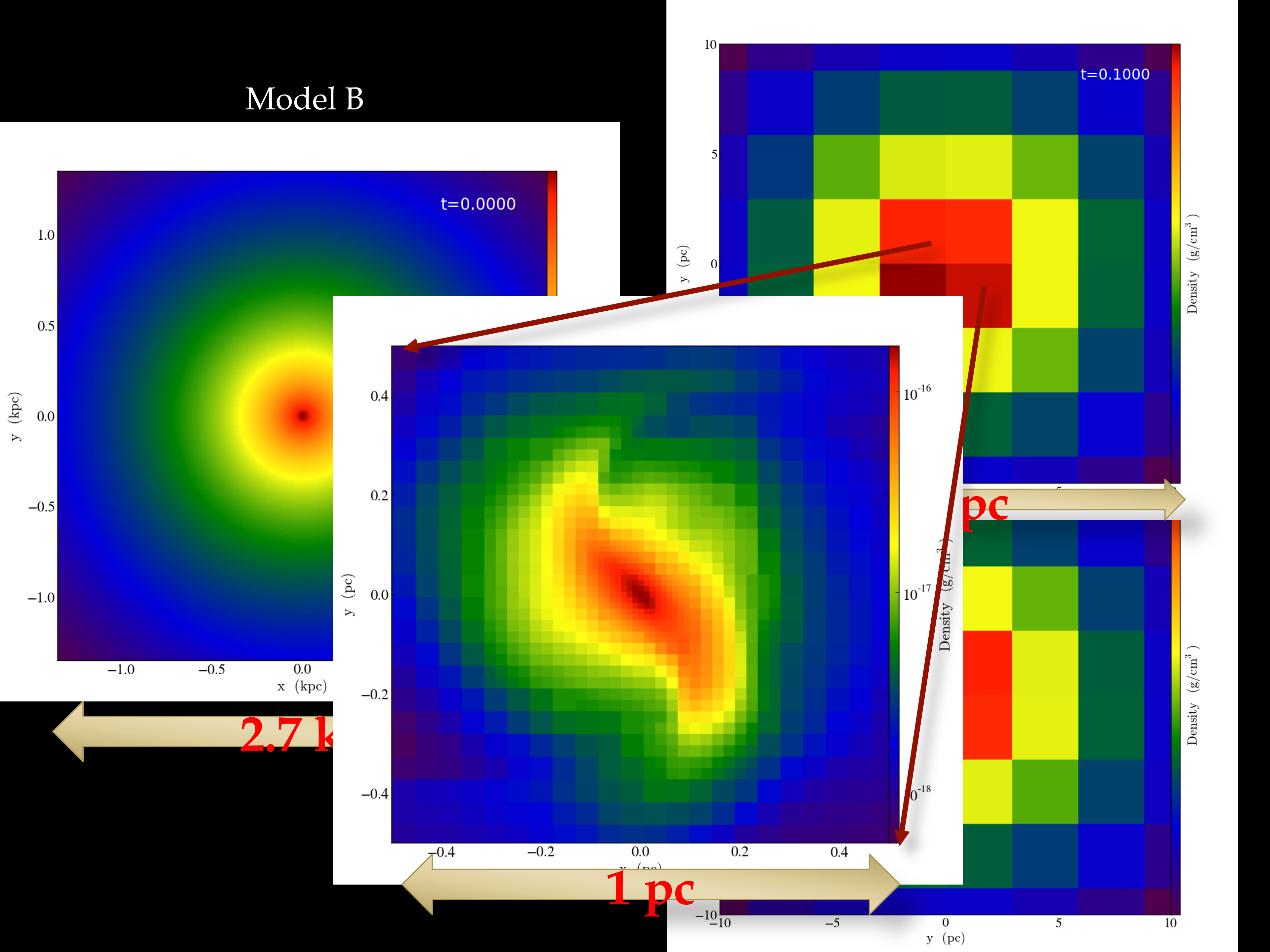
<u>Enzo AMR for hydro and gravity solver</u>

- Non-equilibrium atomic cooling (Abel et al. 1997)

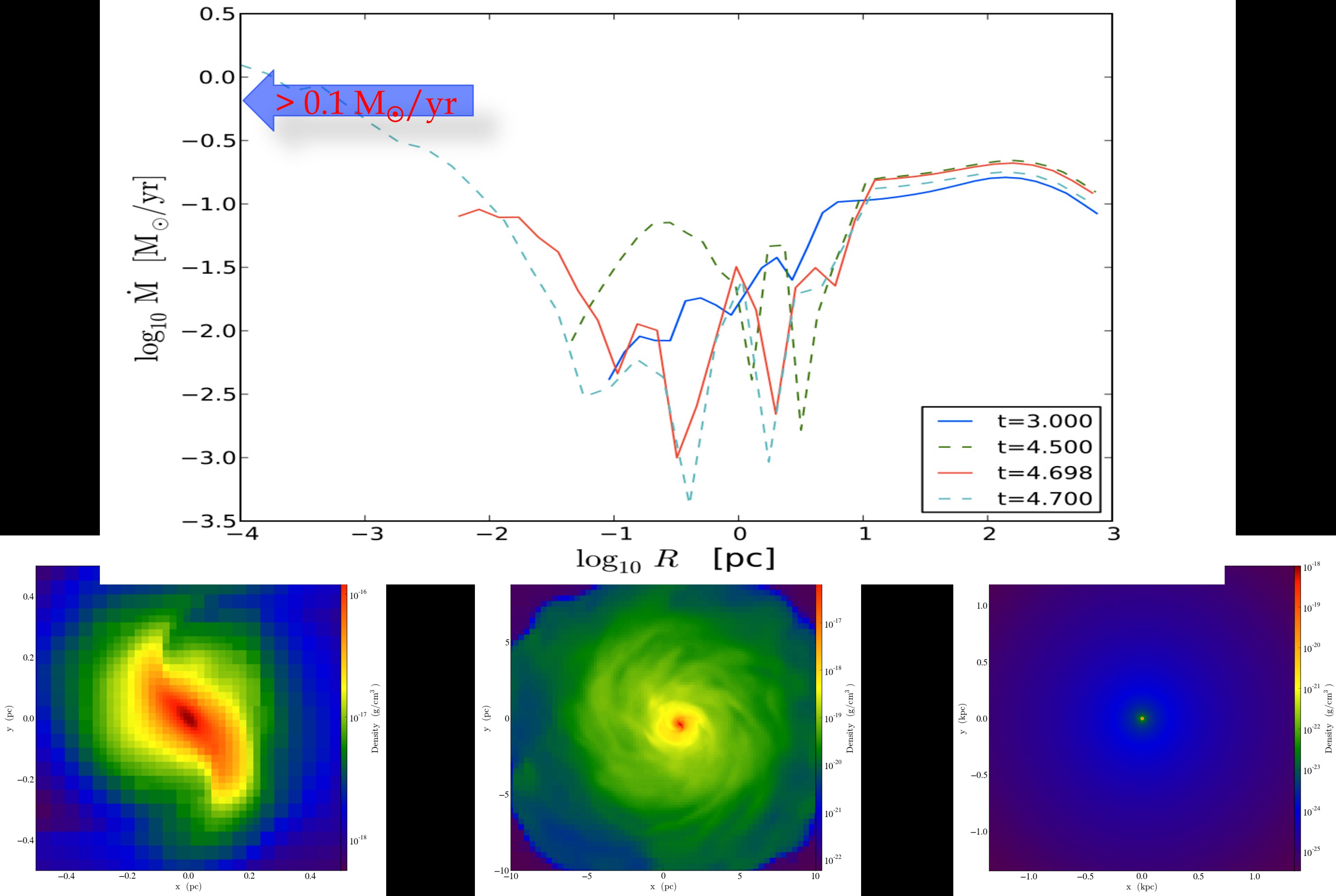
<u>Cosmologically motivated idealized IC</u>

- Isolated isothermal sphere for DM halo (~$10^8 M_\odot$, ~1 kpc)
- Isothermal gas sphere with core in DM halo
  - Cosmological $f_{gas}$ (~0.16) and $\lambda$(~0.05).

# Model B

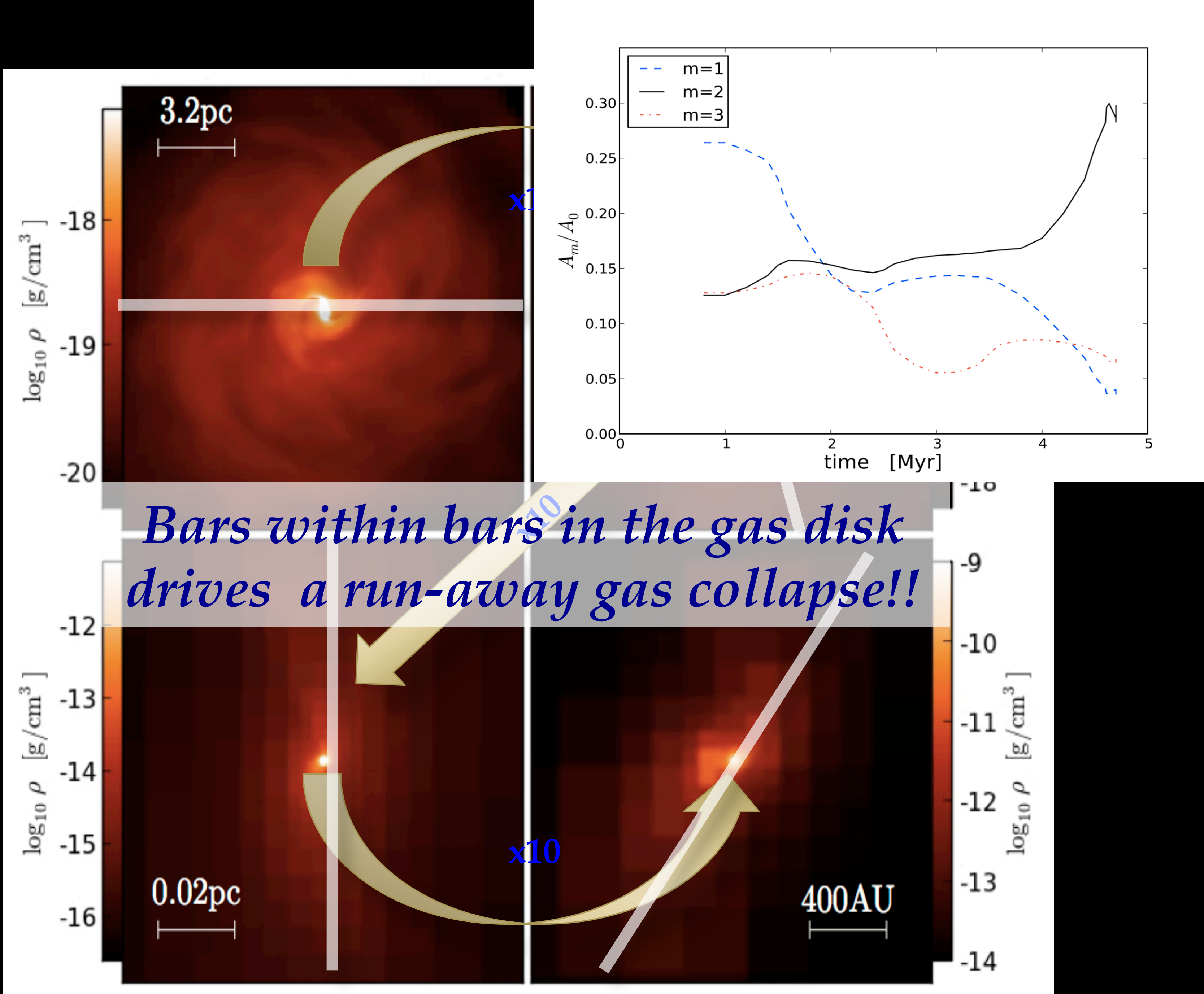


t=0.0000
t=0.1000
y (kpc)
x (kpc)
y (pc)
x (pc)
Density (g/cm$^3$)
$10^{-16}$
$10^{-17}$
$10^{-18}$
2.7 k
1 pc
pc



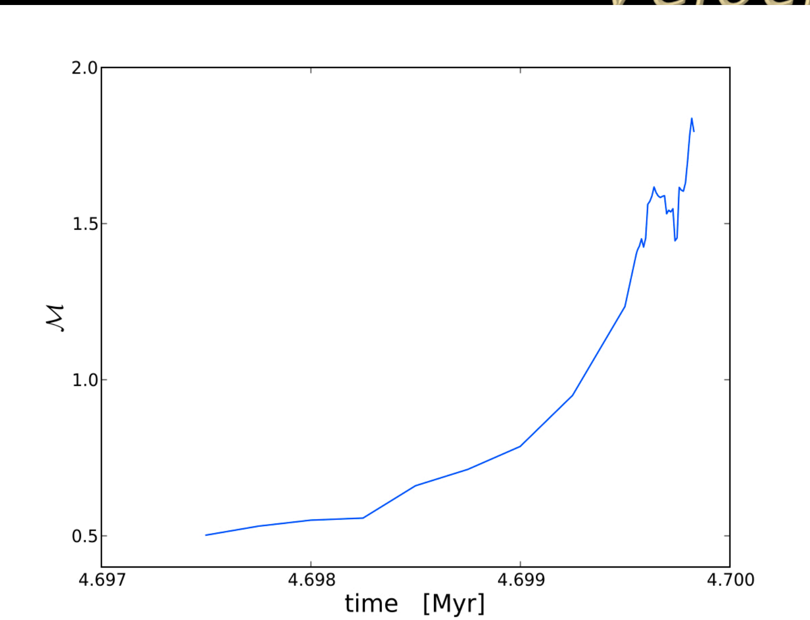
> 0.1 M⊙/yr
log10 Ṁ [M⊙/yr]
log10 R [pc]
t=3.000
t=4.500
t=4.698
t=4.700
x (pc)
y (pc)
Density (g/cm^3)
x (kpc)
y (kpc)

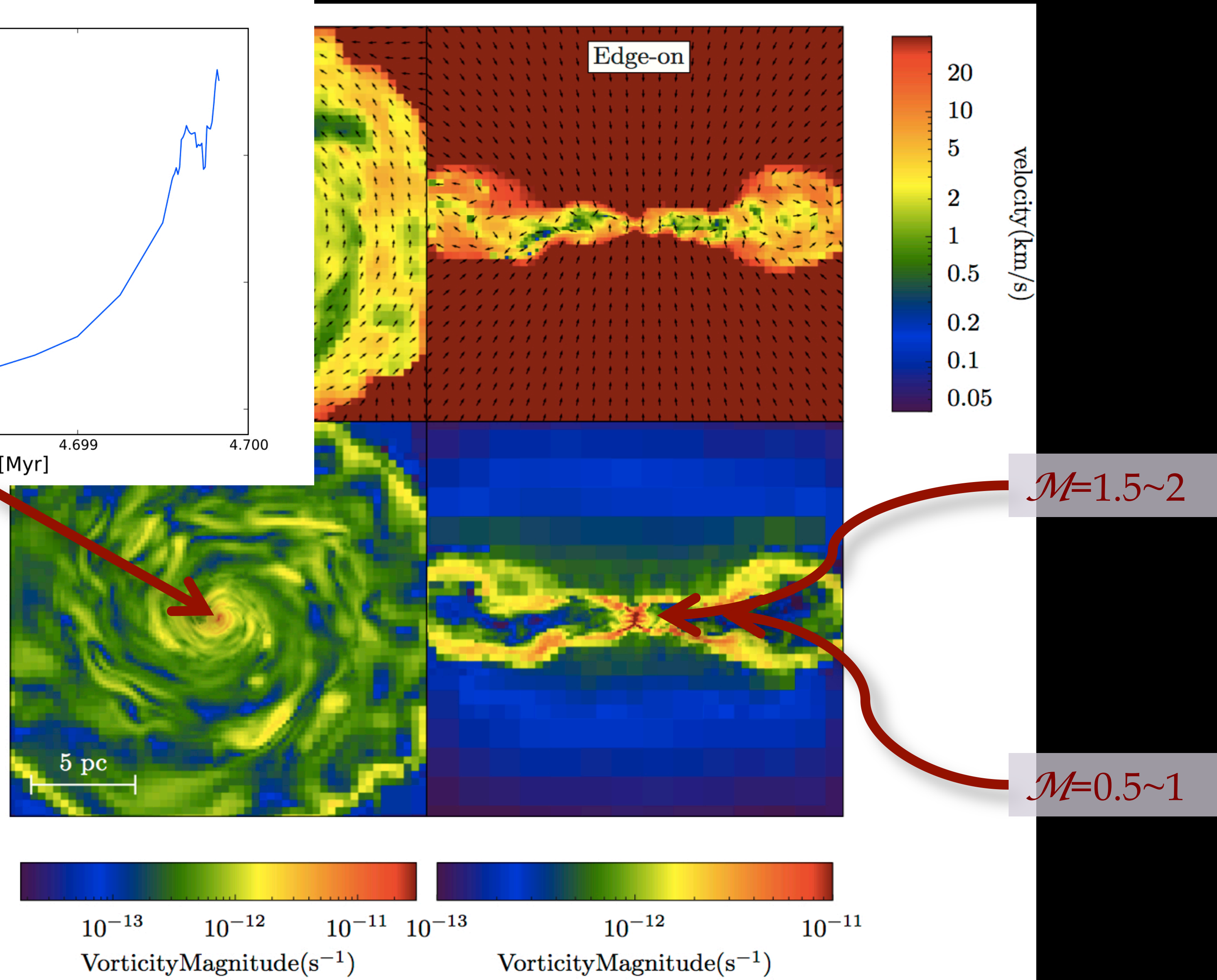
*Bars within bars in the gas disk drives a run-away gas collapse!!*



# Turbulence

## *Velocity & Vorticity*



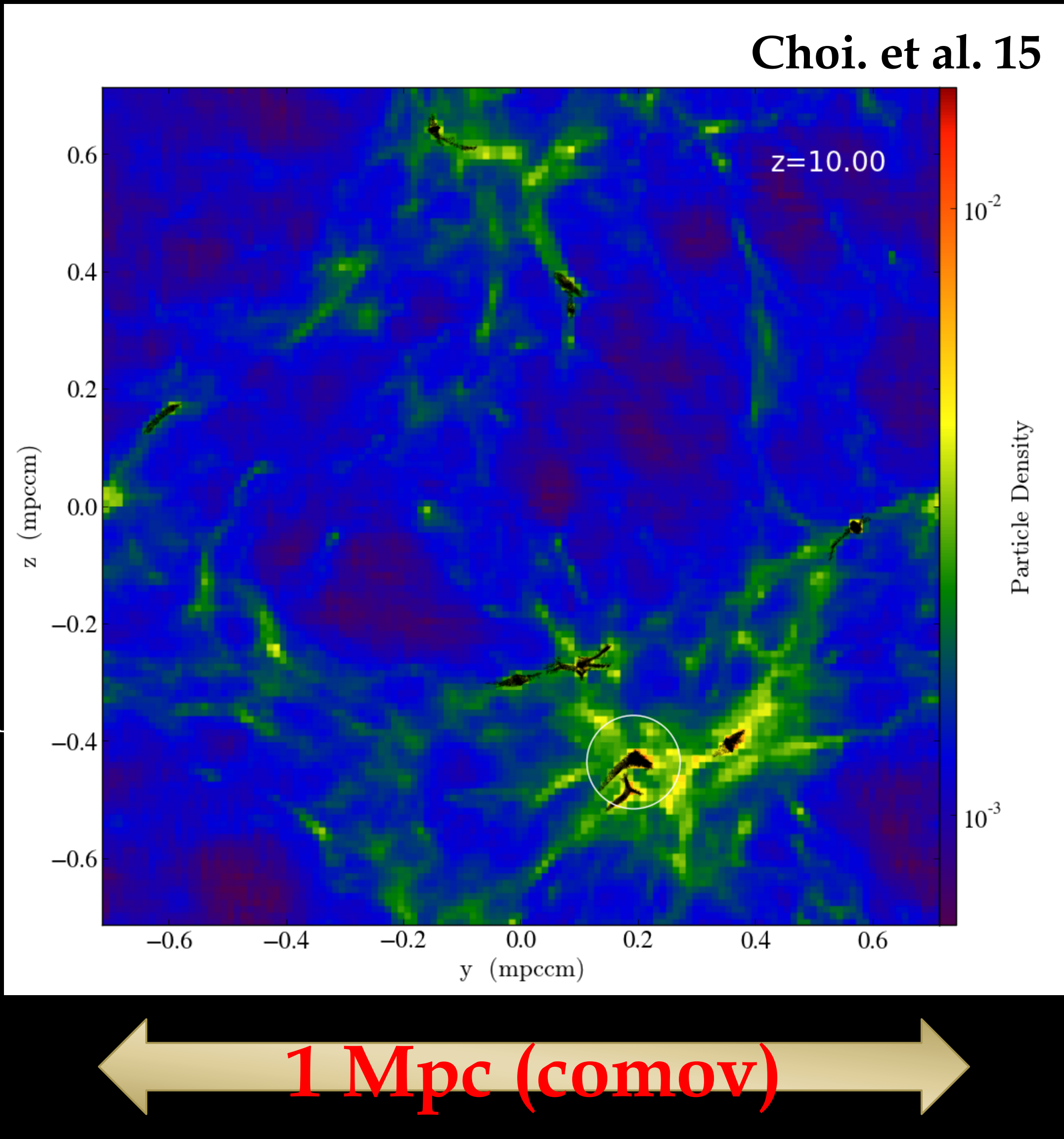
**In the idealized model, gas in an atomic cooling halo experiences the run-away collapse to ~100 AU scale. Collapsing gas overcomes the J-barrier through the J redistribution from gaseous bars and suppresses the fragmentation by turbulent motion.**

*Is the same direct collapse occurs in the ideal model expected in the Universe?*

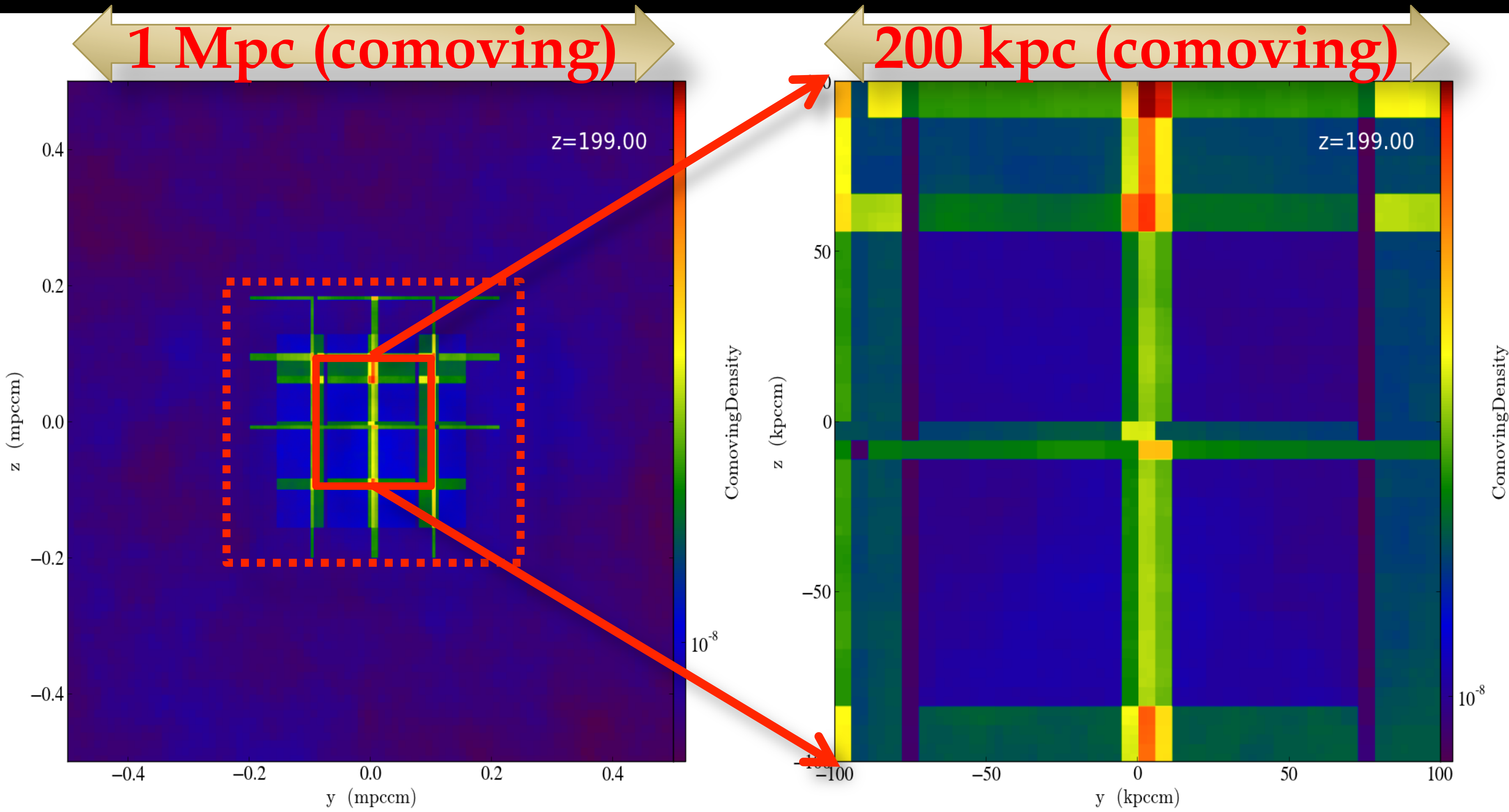
*Need to study in full cosmological context!!!*

# Cosmological Simulation

- MUSIC Cosmological Zoom-in IC generator
  - 2nd-order Lagrangian perturbation theory
  - WMAP7 cosmology
  - DM only (w/ AMR): find massive halo at z~10 ($128^3$ grids)
  - Zoom-in : DM+Baryon ( X4 additional initial refinement and AMR)
- ENZO AMR

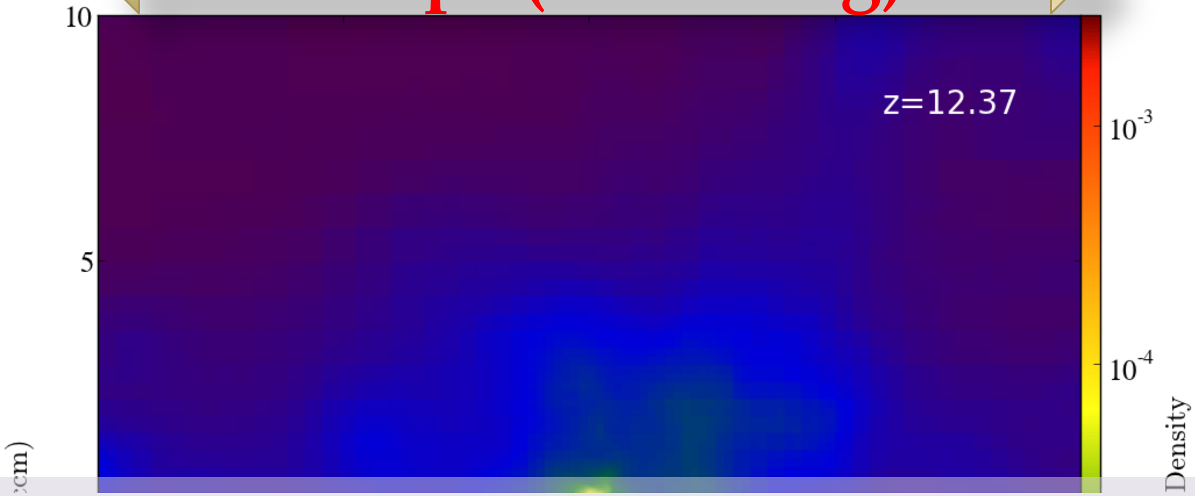


# Cosmological Zoom-In Simulation with ENZO AMR

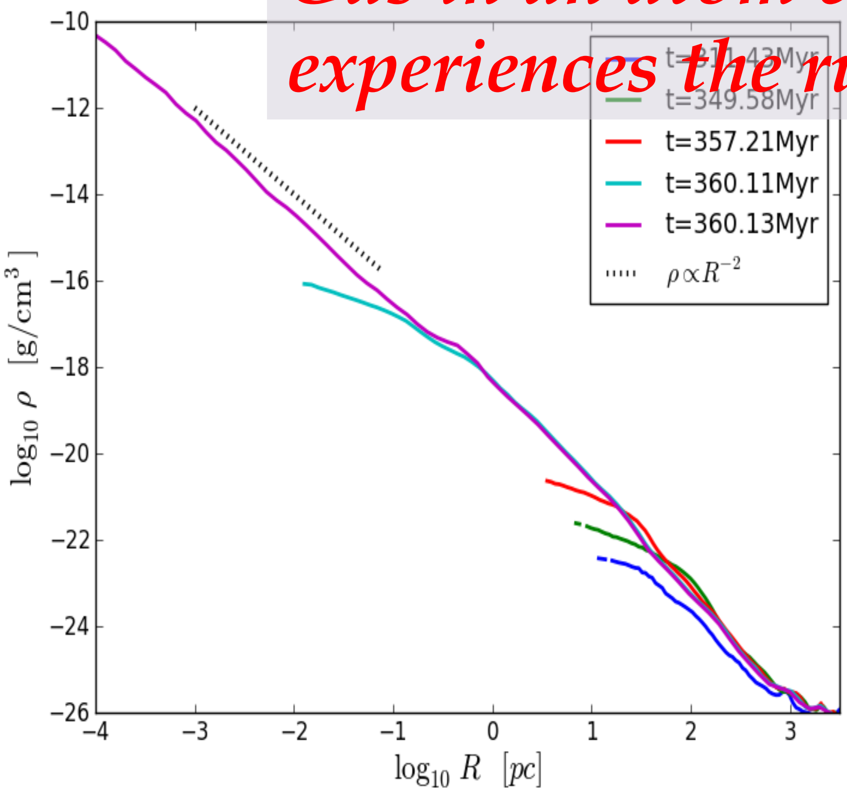


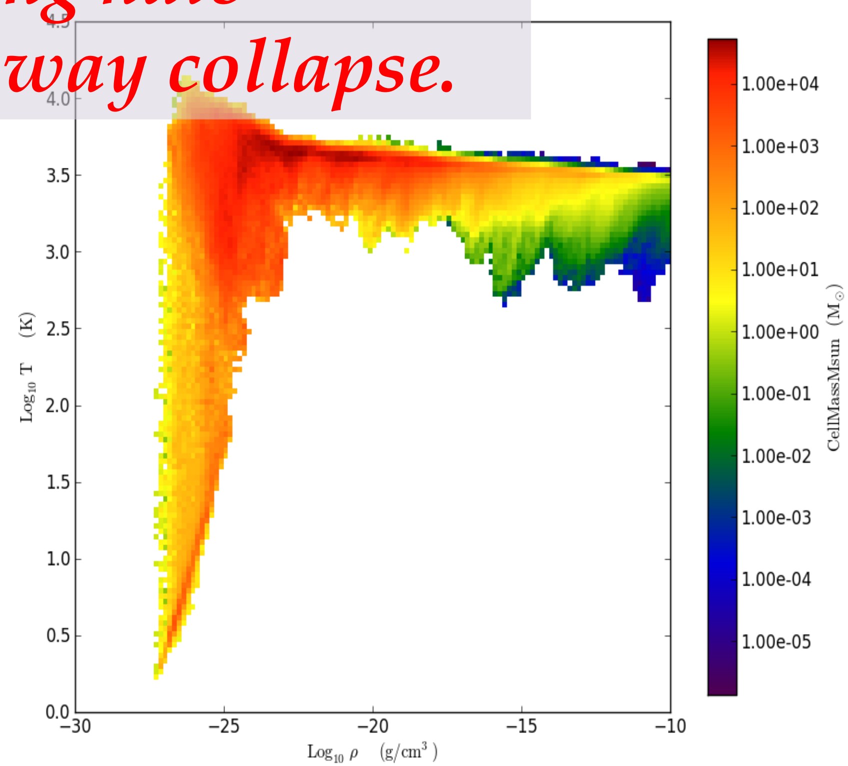

At z~12.37, ~2x$10^7$ $M_\odot$ halo experiences direct gas collapse.

20 kpc (comoving)

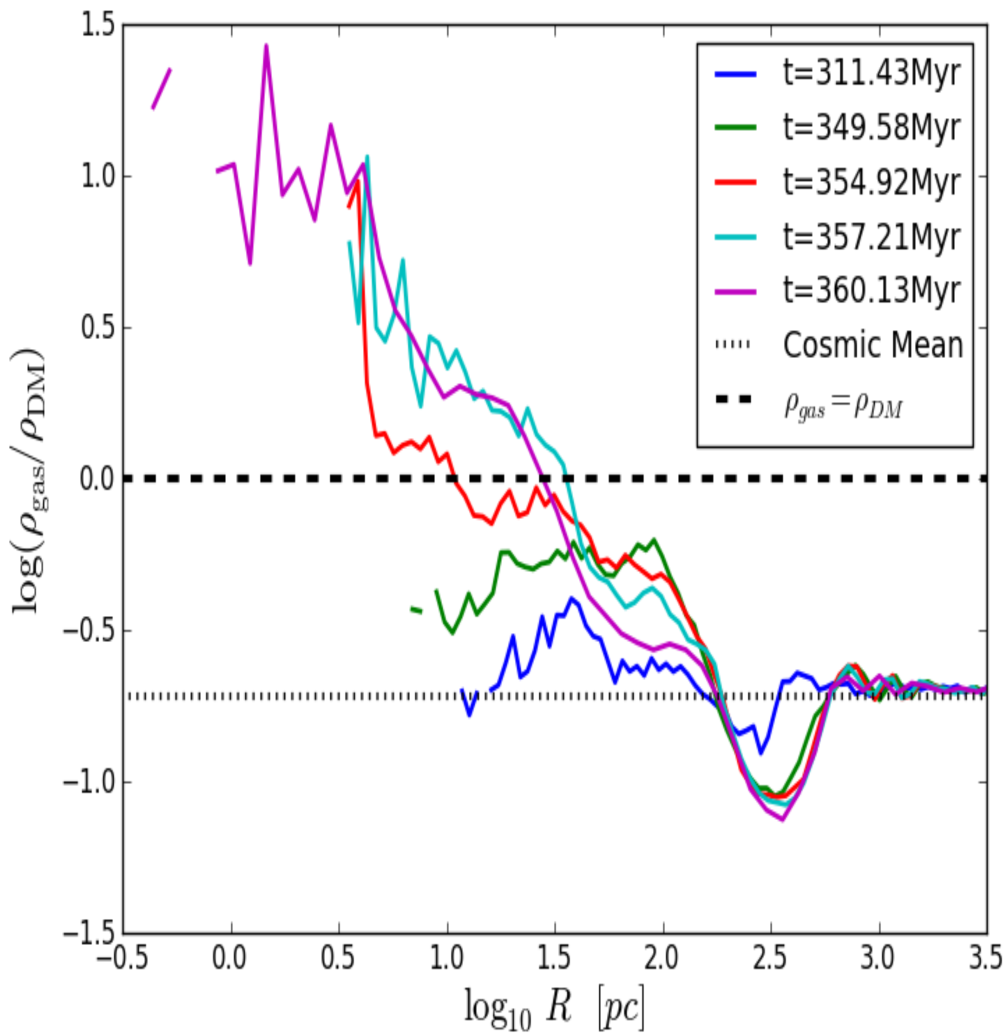



*Gas in an atom cooling halo experiences the run-away collapse.*

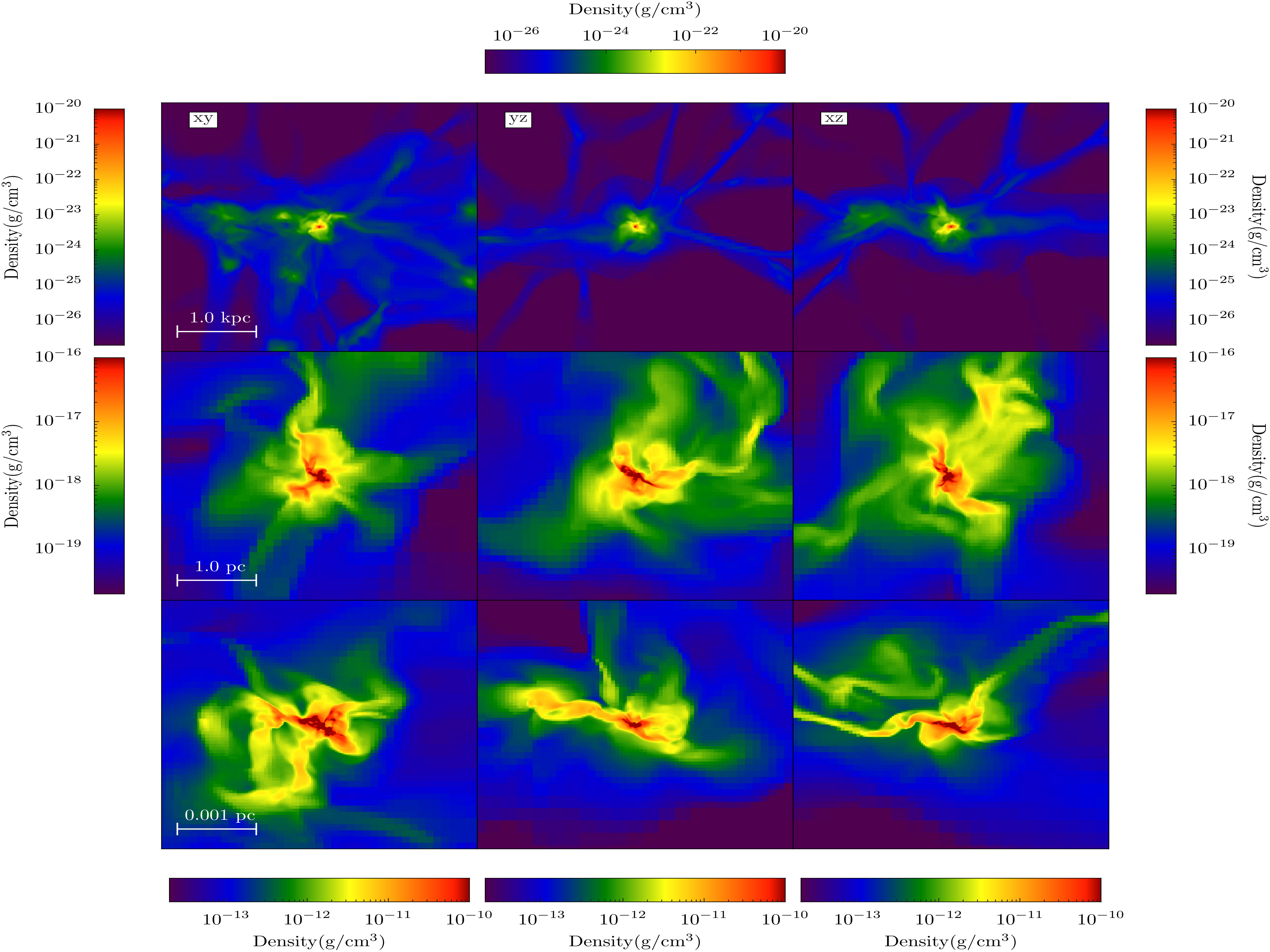


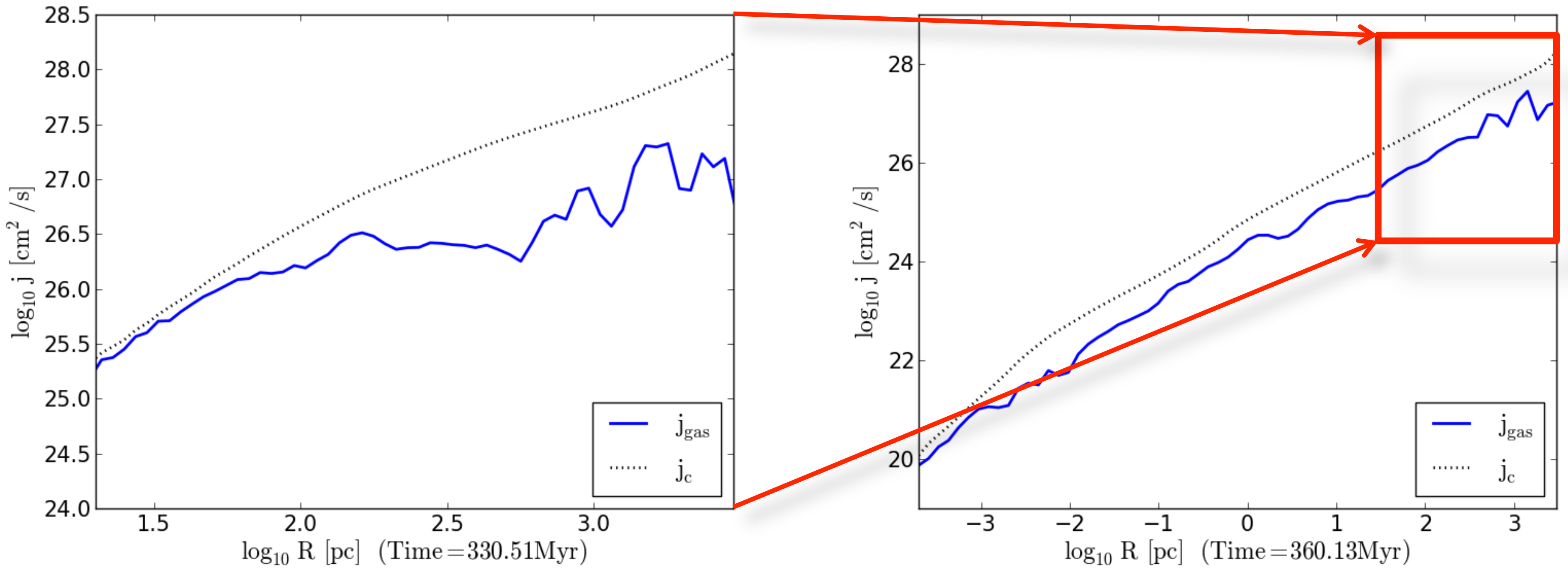



# Run-away collapse condition



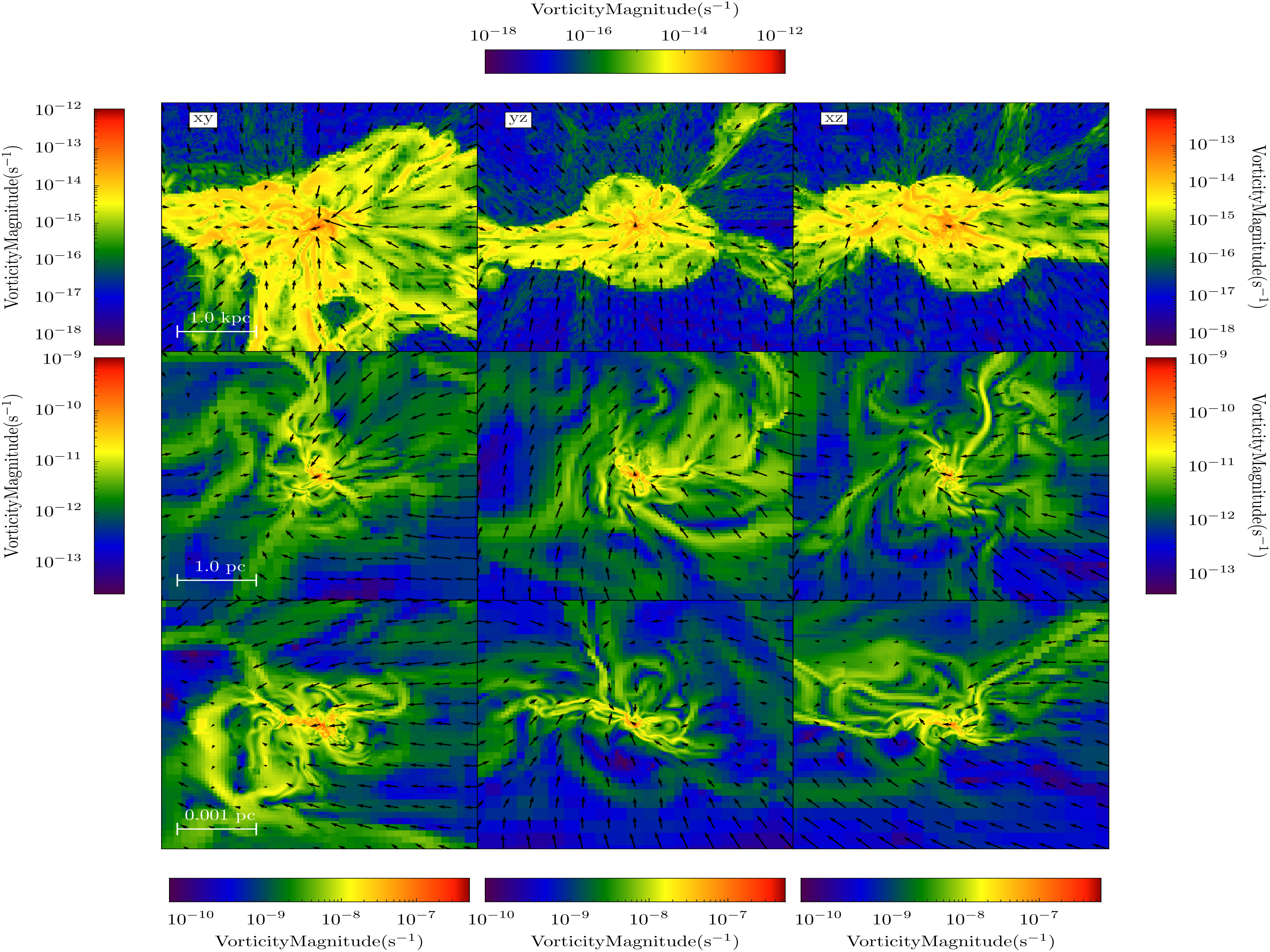

- Outer halo : $\rho_{dm} > \rho_{gas}$
- Inner halo : $\rho_{dm} < \rho_{gas}$
- r ~ 20pc
  - $\rho_{dm} \sim \rho_{gas}$
  - Run-away collapse starts
- Gas cooling contracts the halo gas and the run-away collapse start at $\rho_{dm} \sim \rho_{gas}$


Density(g/cm$^3$)
$10^{-26}$
$10^{-24}$
$10^{-22}$
$10^{-20}$
xy
yz
xz
1.0 kpc
1.0 pc
0.001 pc
$10^{-20}$
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
$10^{-16}$
$10^{-17}$
$10^{-18}$
$10^{-19}$
$10^{-13}$
$10^{-12}$
$10^{-11}$
$10^{-10}$

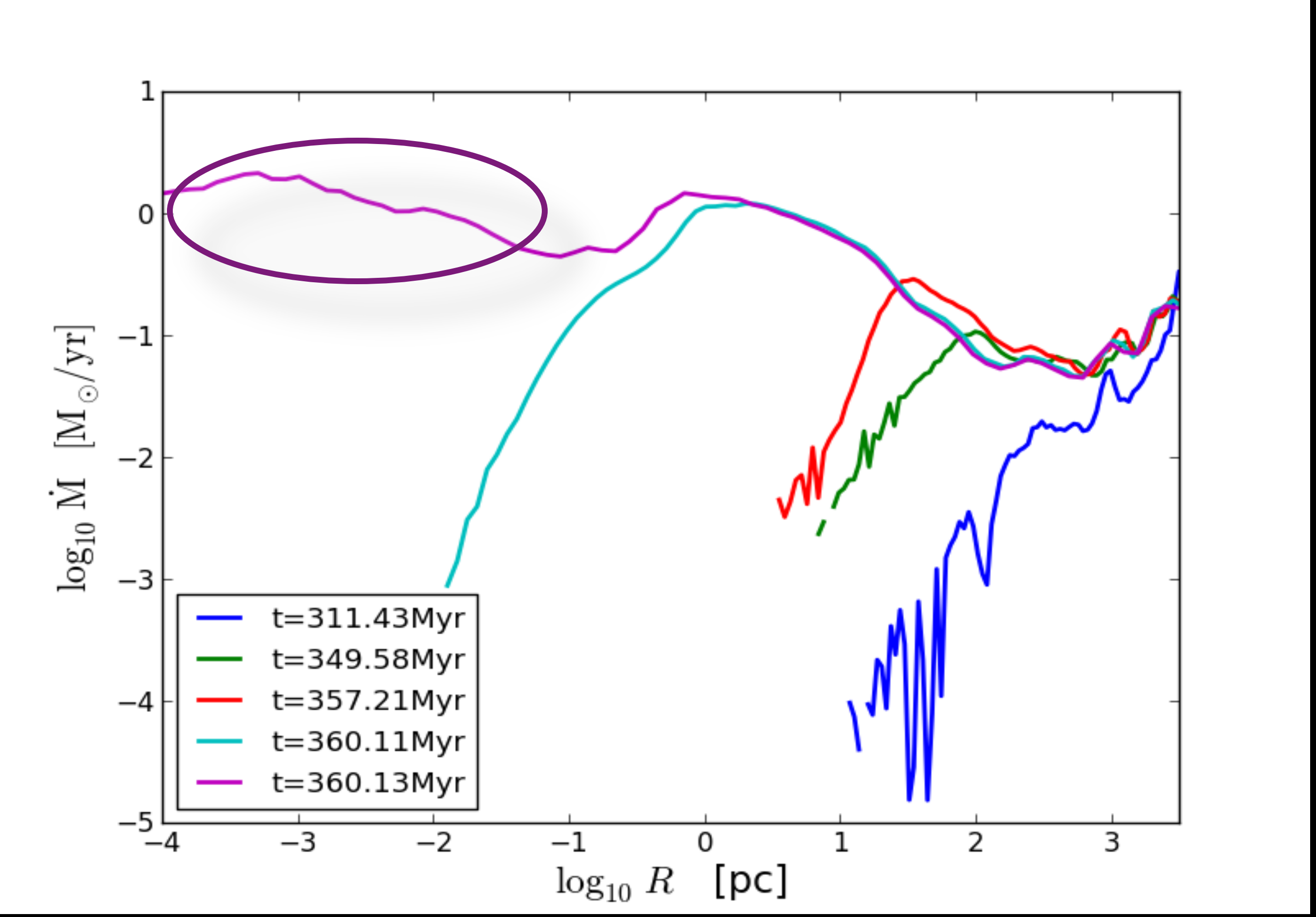



# J-Evolution

- Inner region $J_{gas}$ is slightly lower than $J_c$.
- $J_{gas}$ gets close to $J_c$ and lose → Angular momentum transfer → Continue to collapse
- Collapsing gas should be closely rotationally support. → Maintaining disky/rotational feature



VorticityMagnitude(s$^{-1}$)
$10^{-18}$
$10^{-16}$
$10^{-14}$
$10^{-12}$
xy
yz
xz
1.0 kpc
1.0 pc
0.001 pc
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-7}$
$10^{-8}$




Gas accretion in the collapse region reaches up to ~$1M_\odot$/ yr.

Outer : DM potential dominant

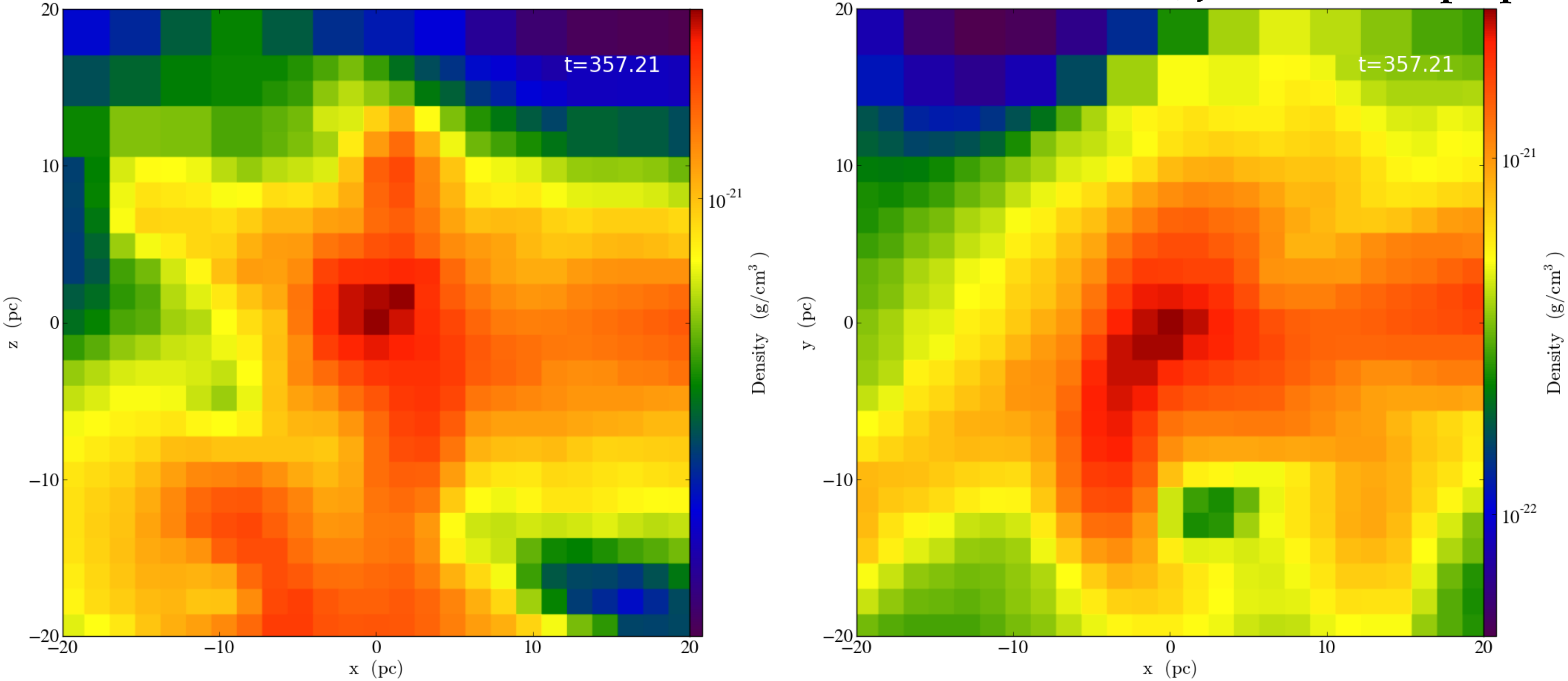
Inner : Gas potential dominant

Strong mass accretion is an important ingredient to form SMBH seeds from the direct collapse.

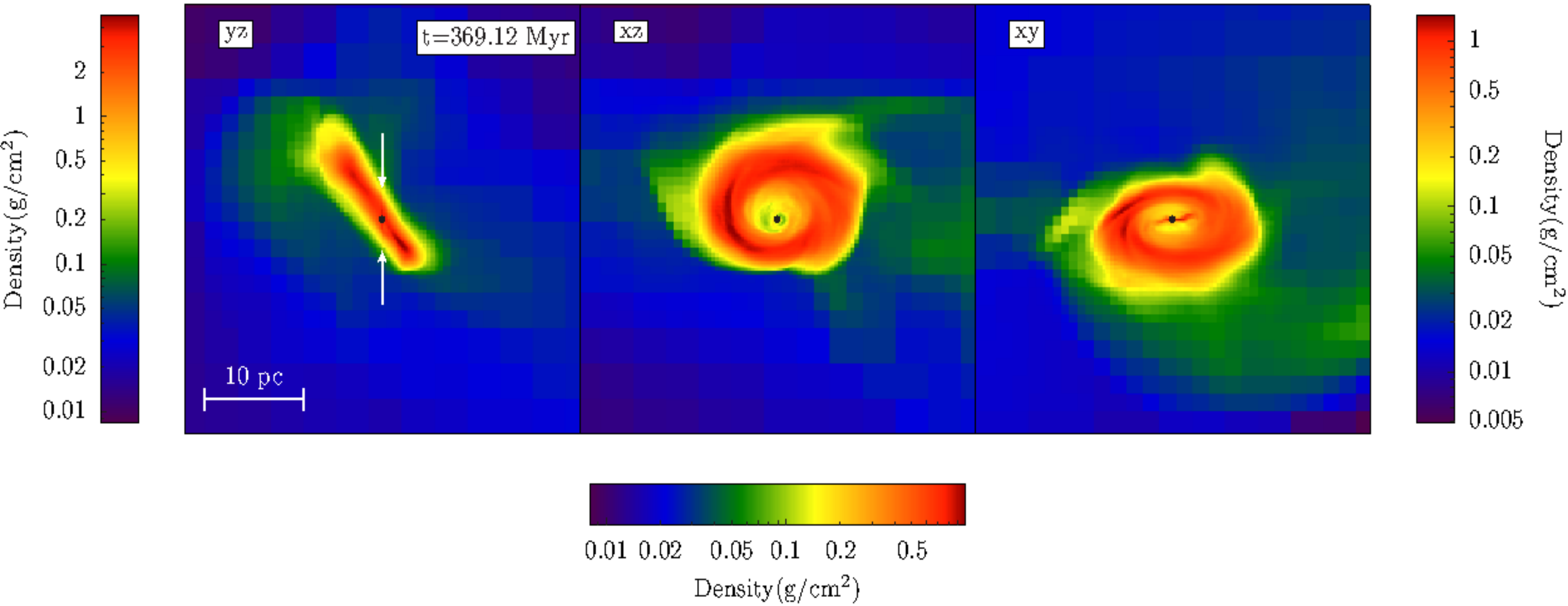
# Long-term evolution of collapsing gas and central object

- Numerically, run-away gas collapsing can reach the maximum refinement and open halts and/or significantly slows down the simulation.
- Sink Method in Enzo (Wang et. al. 2010)
  - Exceeding gas above the maximum density allowed at the maximum refinement level coverts to the sink
  - Mass accretion : Bondi-Hoyle formula
  - Sink merger : two sinks come closer to ~5 cells distance
- Three sink resolutions
  - Level 10 (7.63 pc/h in comoving)
  - Level 12 (1.91 pc/h in comoving)
  - Level 15 (0.24 pc/h in comoving)

Shlosman, JHC ++ 15 in prep.




- The AMR level 12 simulation
- Disk feature as well as gaseous bar are clearly observed.
- Central sink forms and continuously accretes gas and merge other sinks.
- Central sink forms first, resides at the center of potential, and is always >99% of total sink mass.



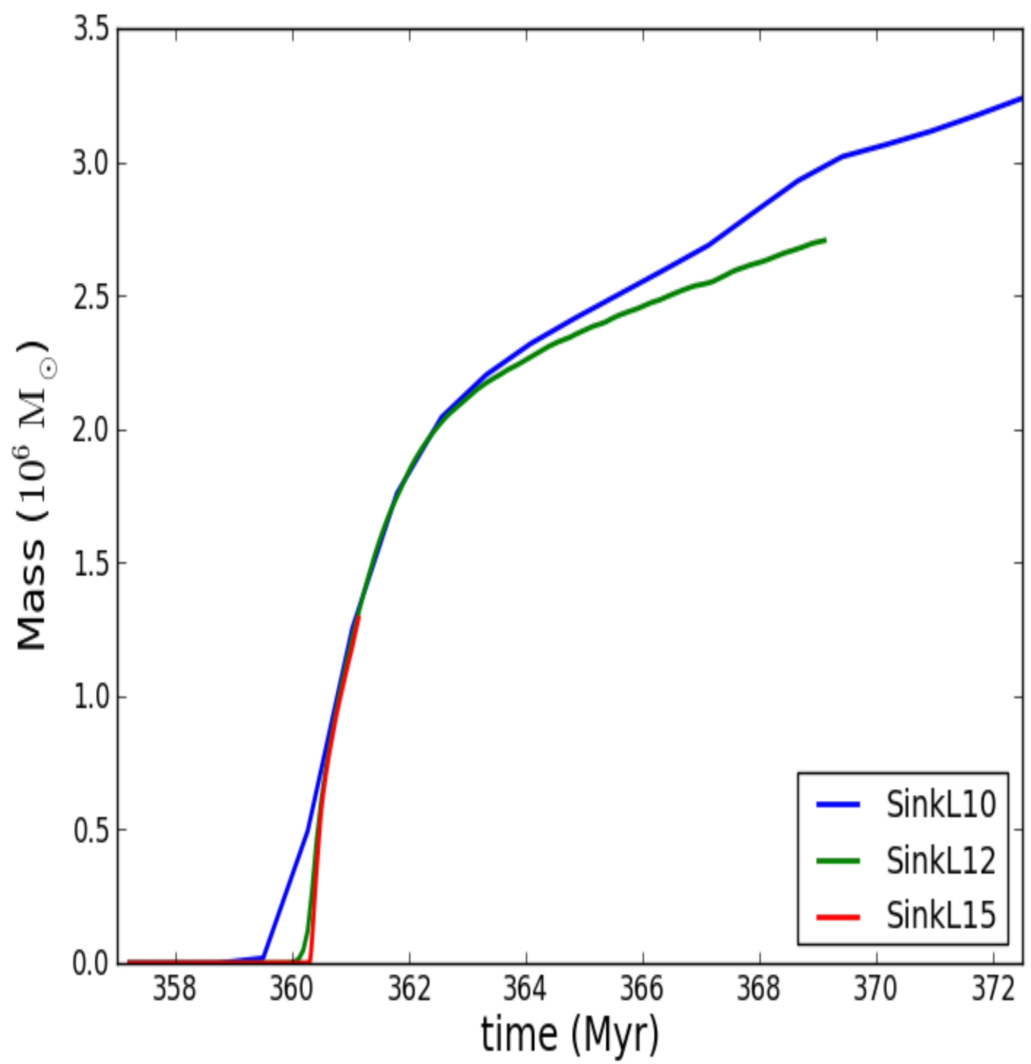

- Density projection
- Thick outer disk and thin inner disk
- Two disks are misaligned
  - Initial J(r) distribution in halo
- Accreted gas accumulated in outer disk!!

# Sink Evolution

Three resolution runs show a good convergence of the central sink masses.

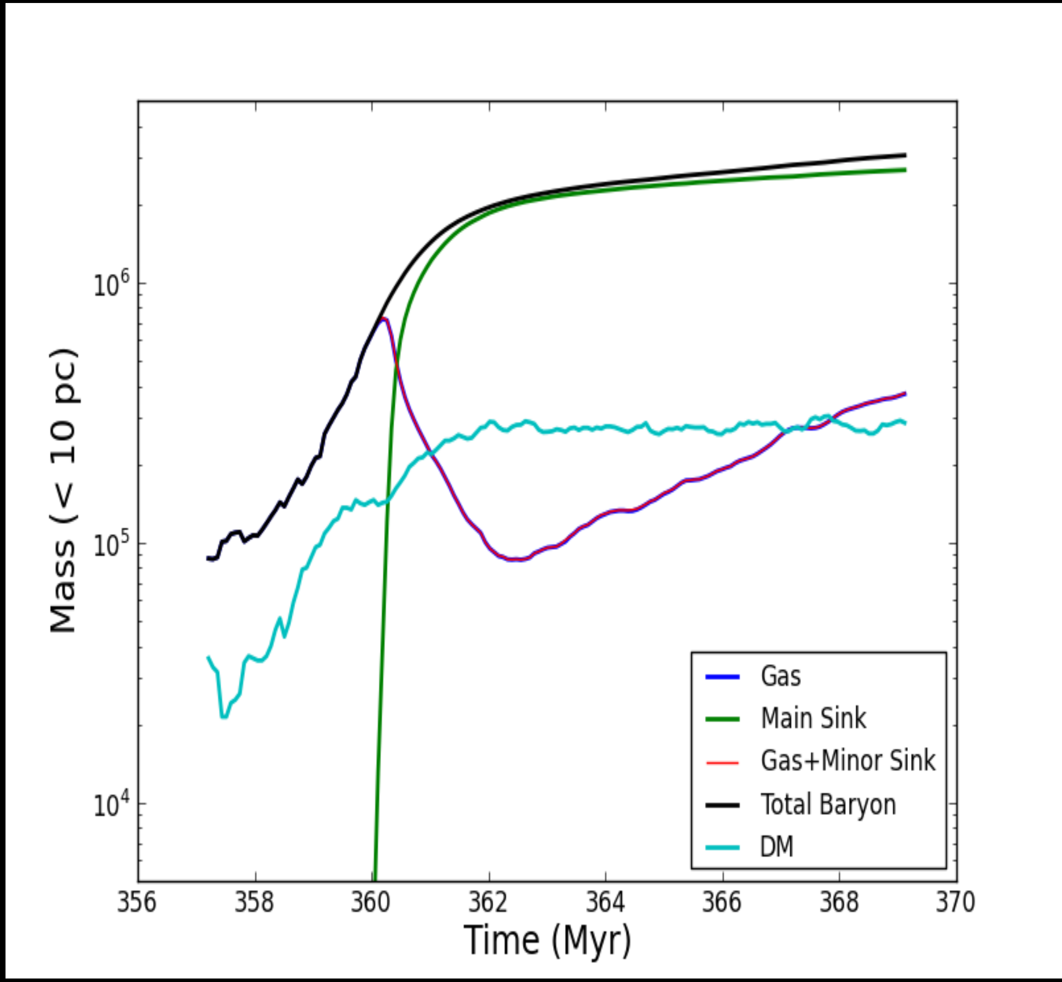
The central sink reaches ~$10^6$ $M_\odot$ in ~$10^6$ yrs after the sink forms.

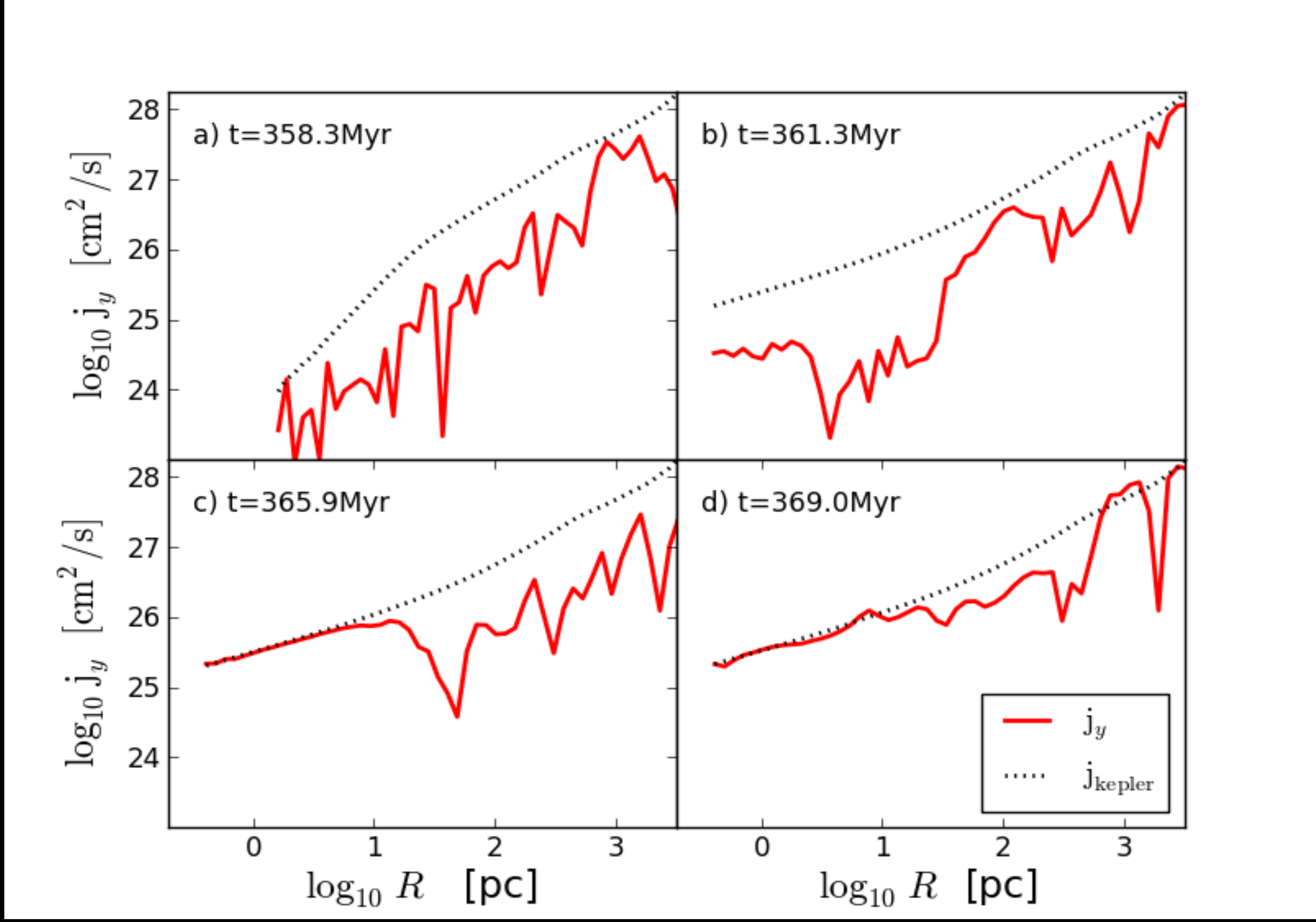
Continuous gas accretion and minor sink merger of the central sink is large enough and fast enough to makes a massive SMBH seed.



# Sink Evolution Cont.

- $M_{Brayon} >> M_{DM}$ : run-away collapse
- $M_{\text{main sink}} >> M_{\text{minor sinks}}$
- r < 10pc : $M_{\text{main sink}} \sim M_{\text{Baryon}}$
- After $M_{\text{main sink}} \sim 10^6 M_\odot$ sink growth slowed down and gas mass start increase
- Dynamics will be dictated by main sink mass

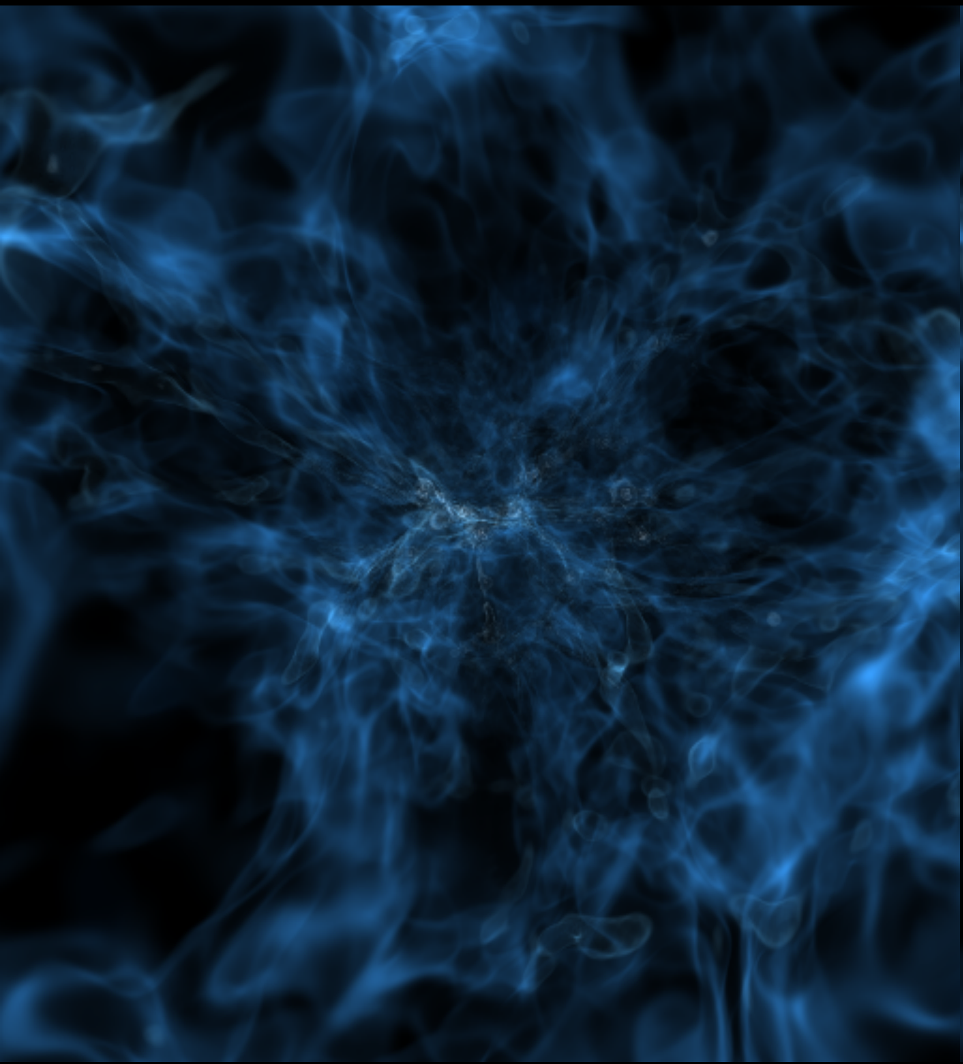


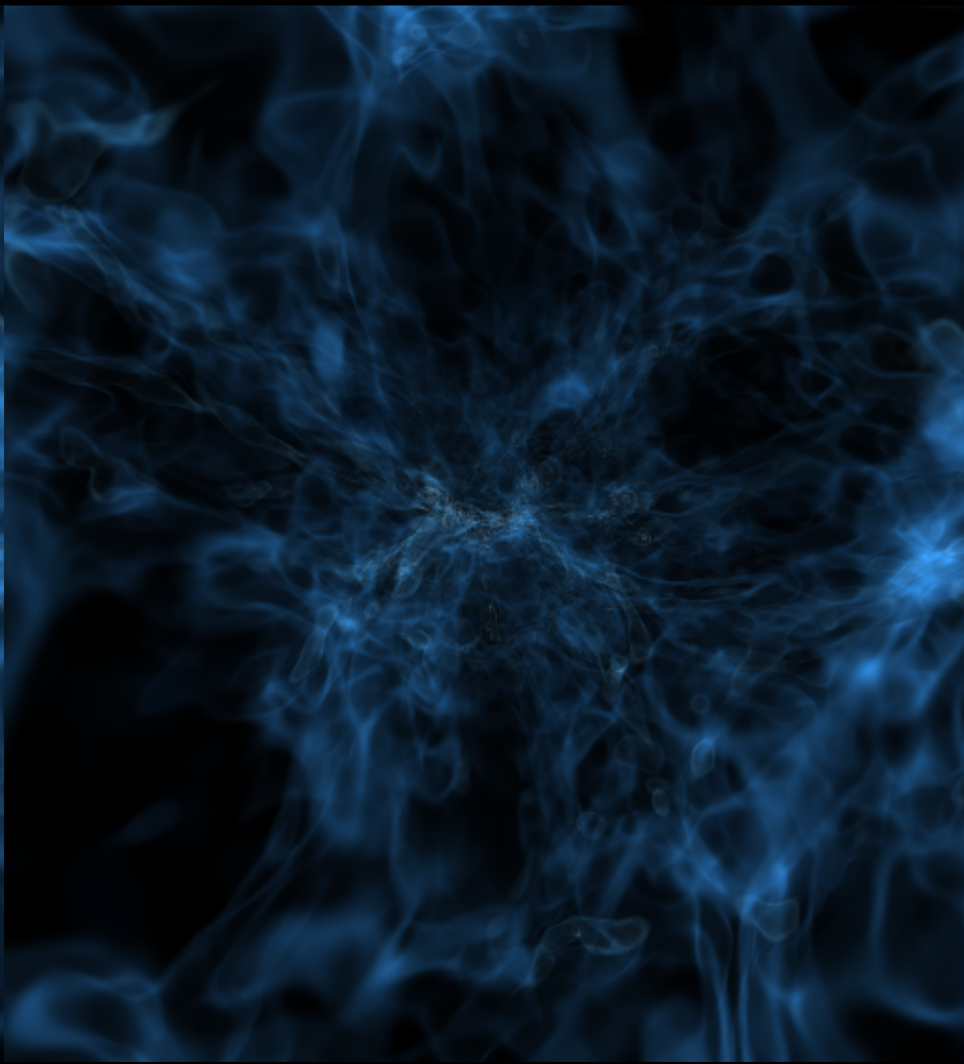



- After sink form the gas disk becomes rotationally supported
- The disk growth with a time and gas accretion.

T = 359 Myr
Just before Sink Forms

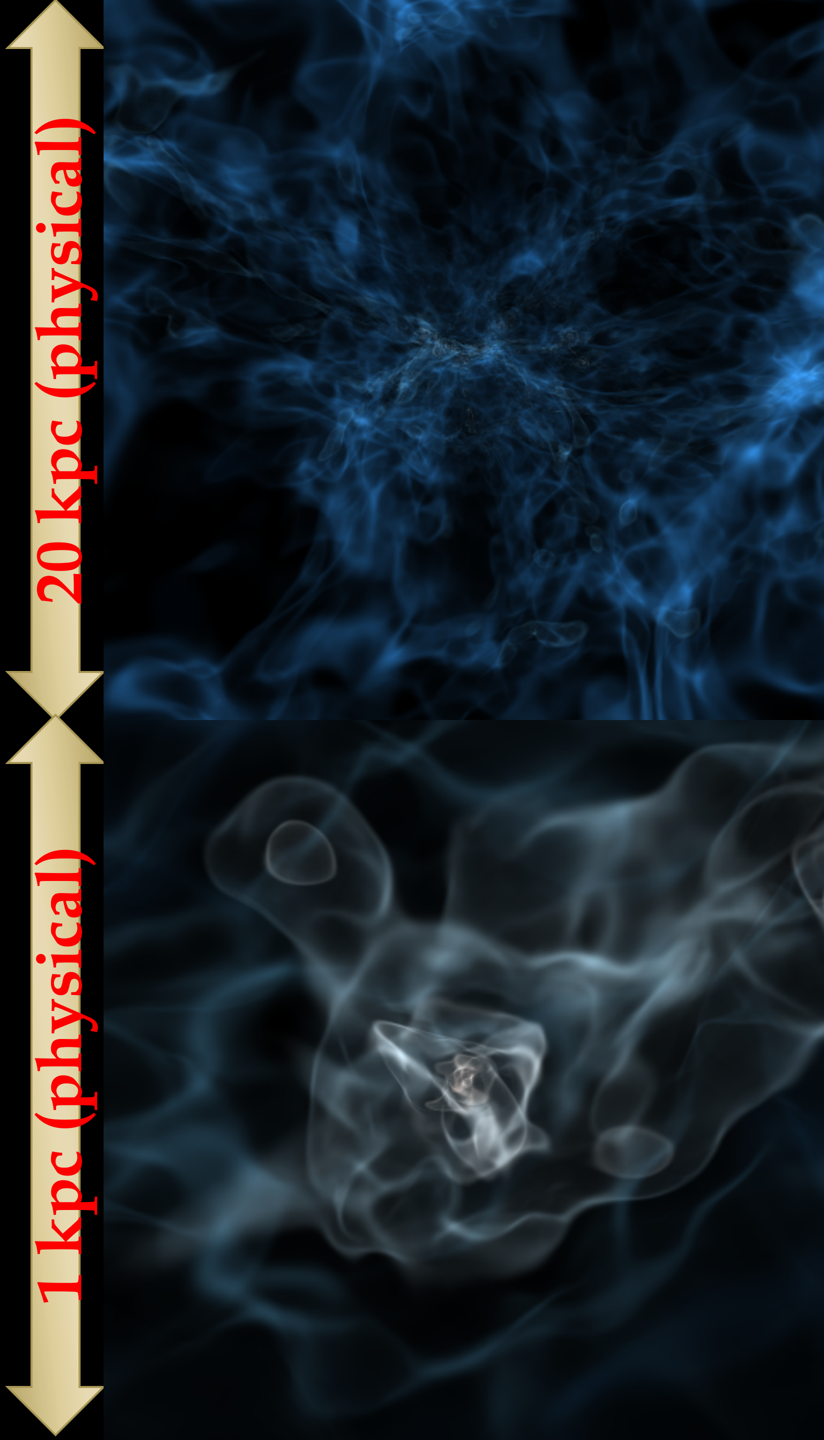
T = 369 Myr
Sink mass reaches ~$10^6$ $M_{sun}$





# Large-scale gas dynamics

- The turbulence motions are seen in global (in two different, x20, scales)
- Cosmic scale: filamentary gas accretion with turbulence and clumps
- Halo Scale: Strong turbulent gas motion
- Turbulence is everywhere.



# Take Home Message

- ✓ Both the idealized and cosmological simulation we see the run-away collapse in an atomic cooling halo ($\sim 10^8 M_\odot$) aided by angular momentum transfer and turbulence flow.
- ✓ Run-away collapse leads rapid gas accretion and forms massive central object ($\sim 10^6 M_\odot$).
- ✓ There will be many interesting new features for first galaxy/SMBH formation
  - ✓ Dynamical effect of the massive central object.
  - ✓ New source for the reionization the Universe
  - ✓ Initial condition of the local M-σ relationship.