FORMATION OF SUPERMASSIVE BLACK HOLE: DYNAMICS OF HALO GAS COLLAPSE

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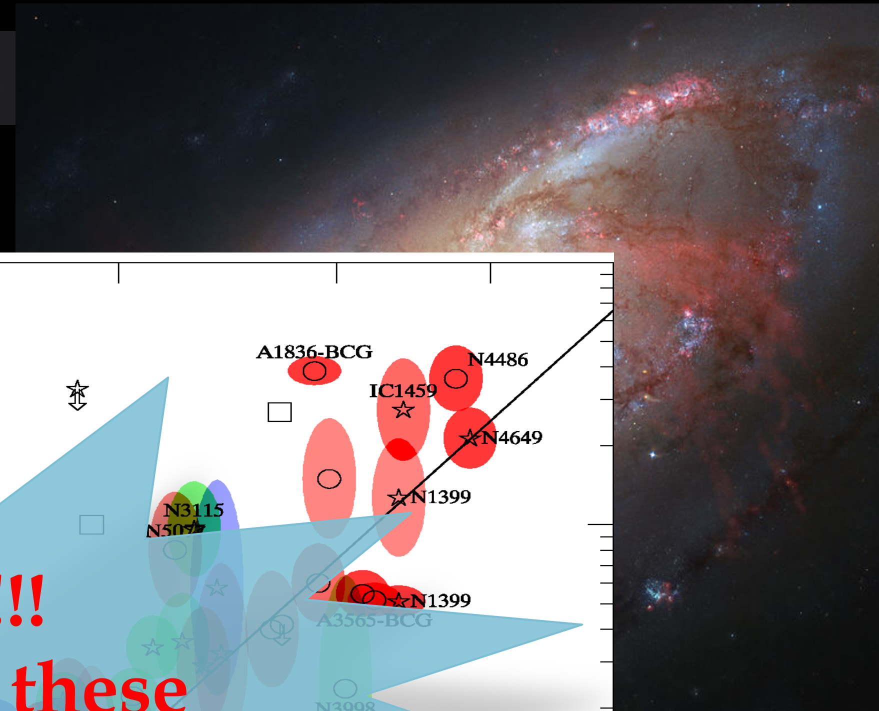
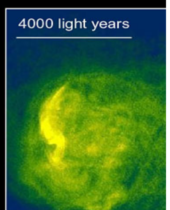
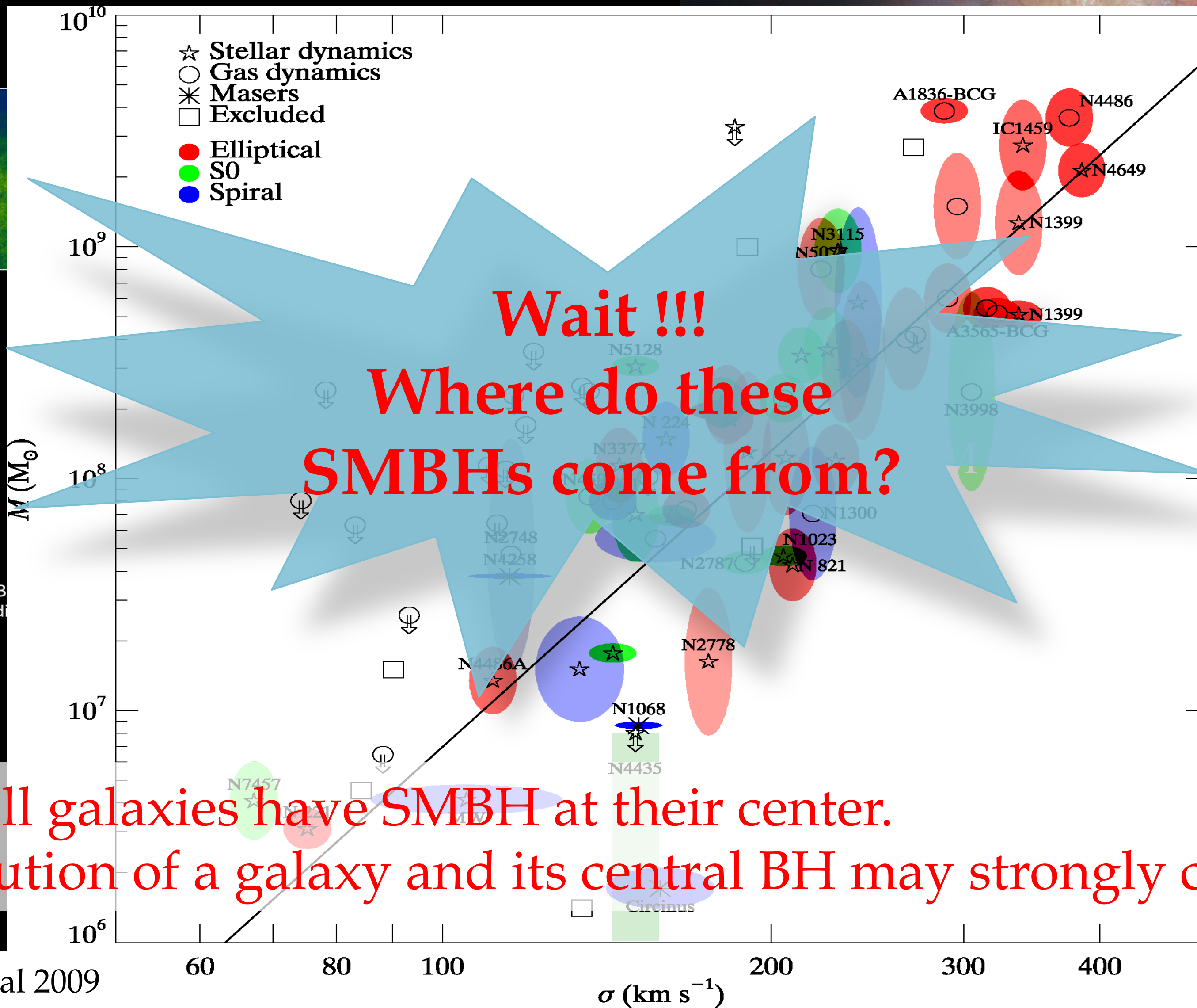
SMBHs are everywhere in Universe





VLA
Radio

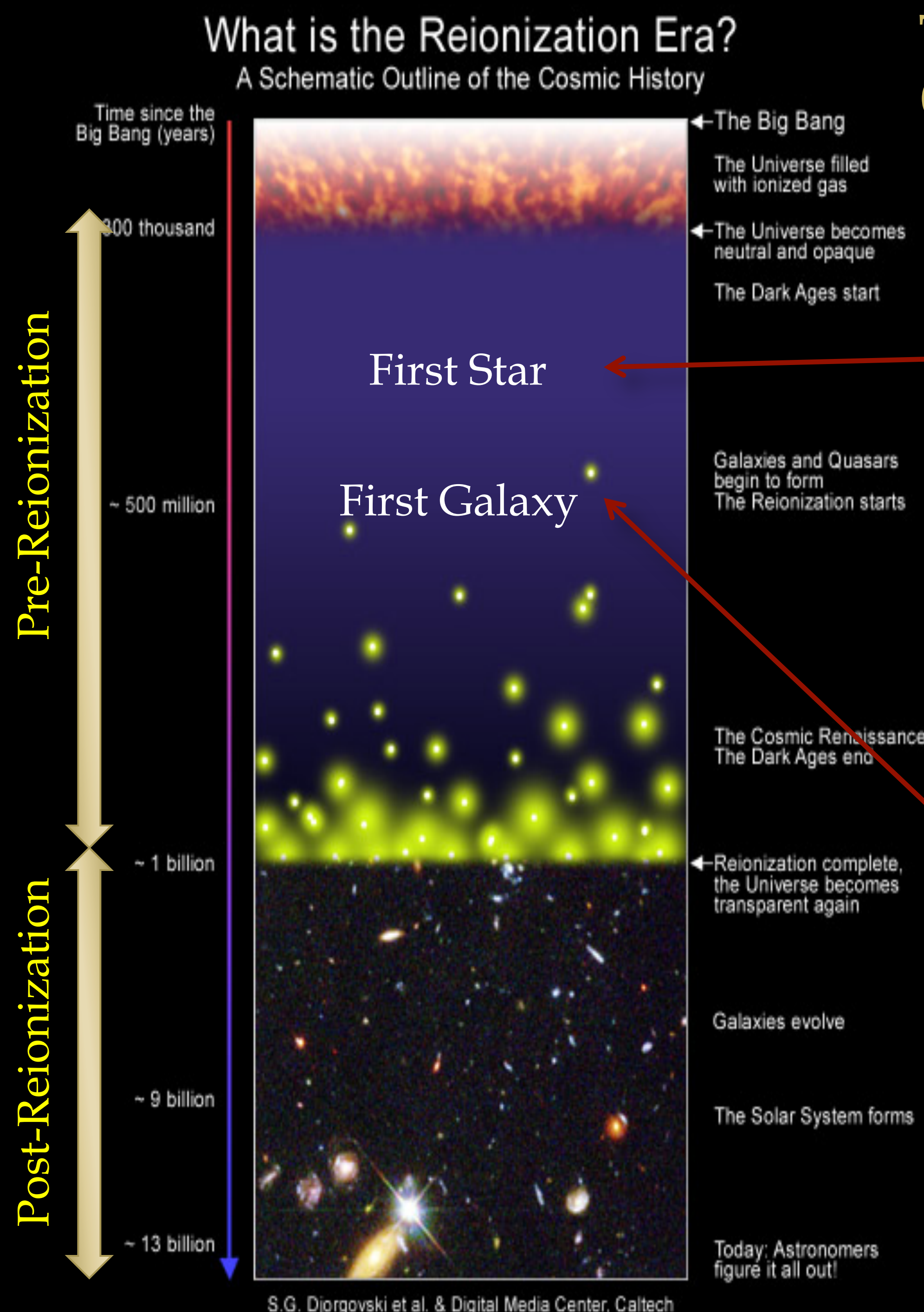
VLB
Radi



Wait !!!
Where do these SMBHs come from?

Almost all galaxies have SMBH at their center.
The evolution of a galaxy and its central BH may strongly connected!

GULTEKIN et al 2009



Two Models for a SMBH seed
(Rees 1984)

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 $M_\odot$ SMBH 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

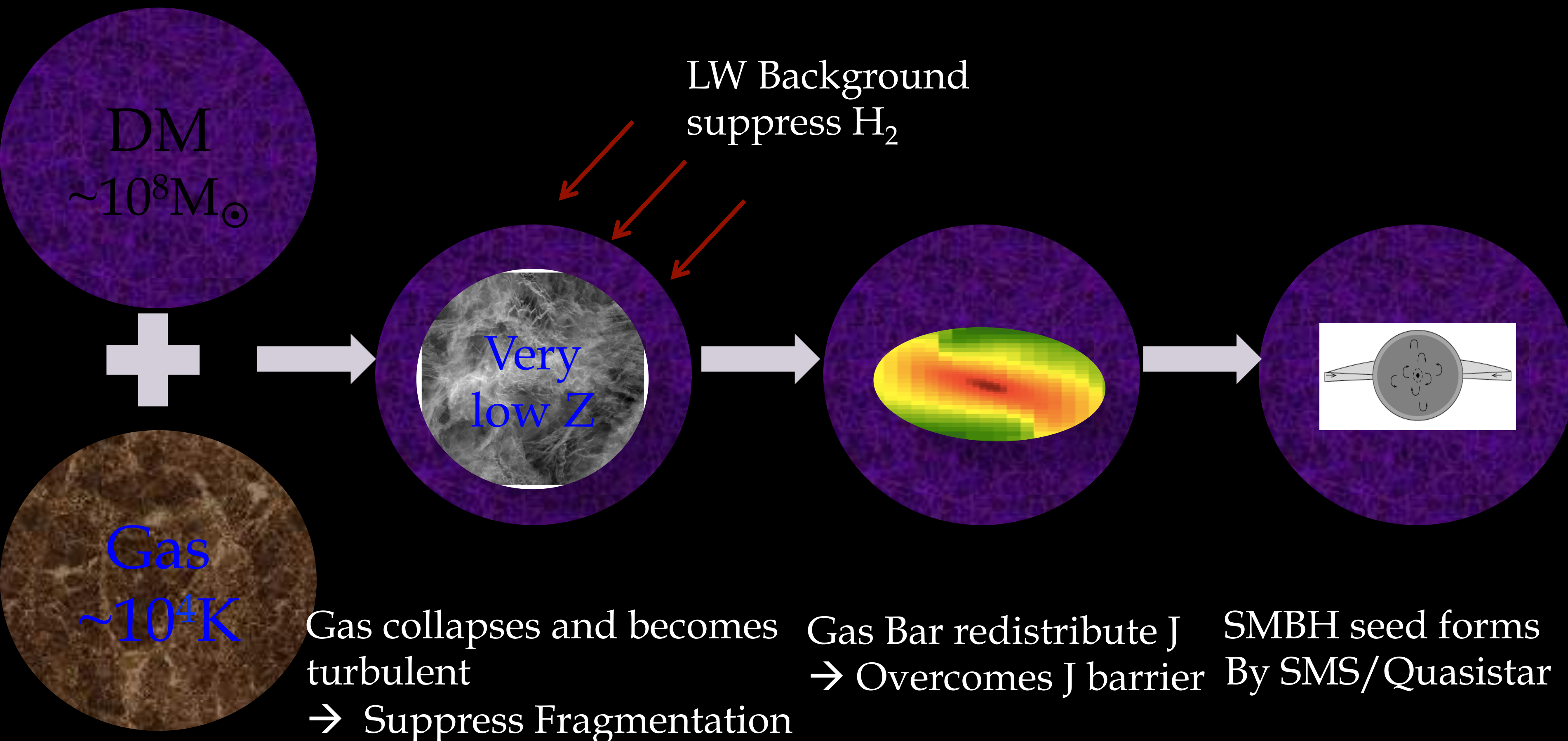
→ ~10^8 $M_\odot$ (T_{vir} ~10^4K) halo gas collapse through the atomic cooling

→ Yield massive SMBH seed at z~15

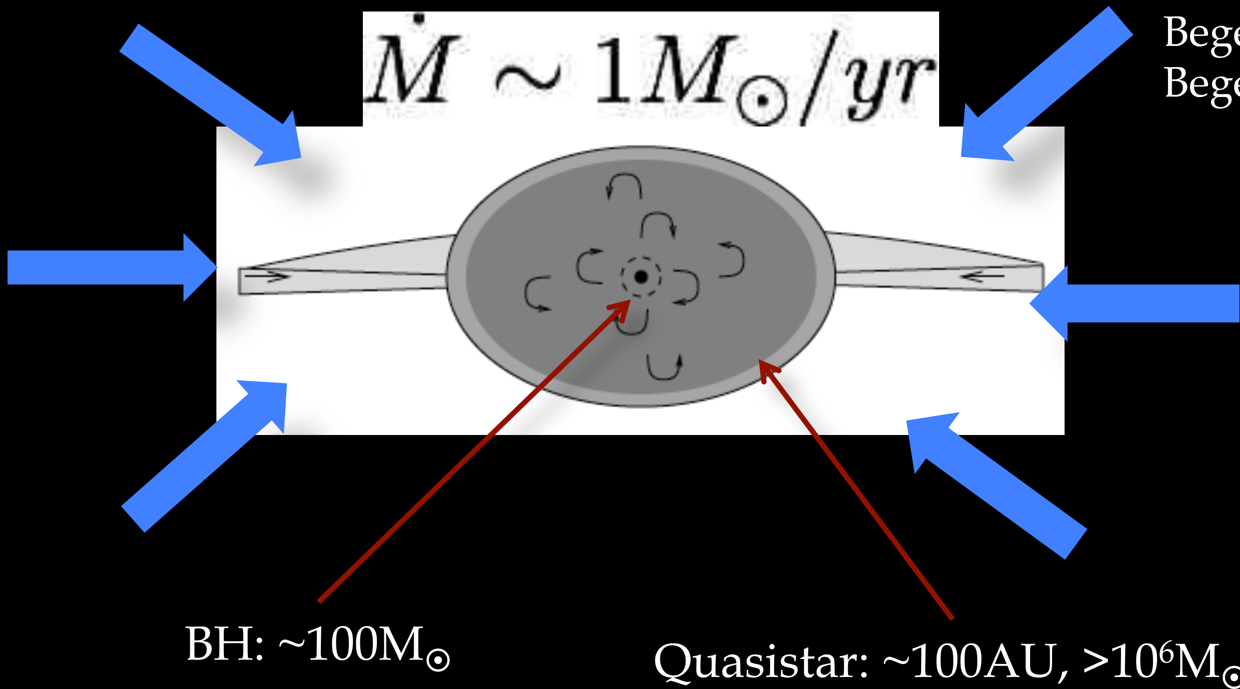
Pros and Cons

- Population III remnant
  - It is natural first candidate: We know how to make seed BH.
  - Time scale (from $z>20$ to $z\sim7$ to $\sim10^9 M_\odot$)
    - Takes $\sim7\times10^8$ yrs to growth $\sim10^9 M_\odot$ close to age of Universe (Mortlock et. al. 2011: $z\sim7.085$ with $M_{BH}\sim2\times10^9 M_\odot$)
  - BH slingshot and ejection from mini-haloes during mergers
  - BH feedback regulates gas accretion
  - New PopIII studies predict lower mass ($\sim50 M_\odot$)
- Direct Gas Collapse
  - Easy to growth by accretion/mergers from $z\sim15$ to $z\sim7$
  - Need an exotic process to make seed BH
  - Dynamical Problems
    - J-barrier prohibit 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 ~100 $M_\odot$BH
- ✓ Quasistar : BH accrete 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

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

(Choi, Shlosman, & Begelman 2013)

Enzo AMR for hydro and gravity solver

- Refined by gas density
- Non-equilibrium atomic cooling (Abel et al. 1997)

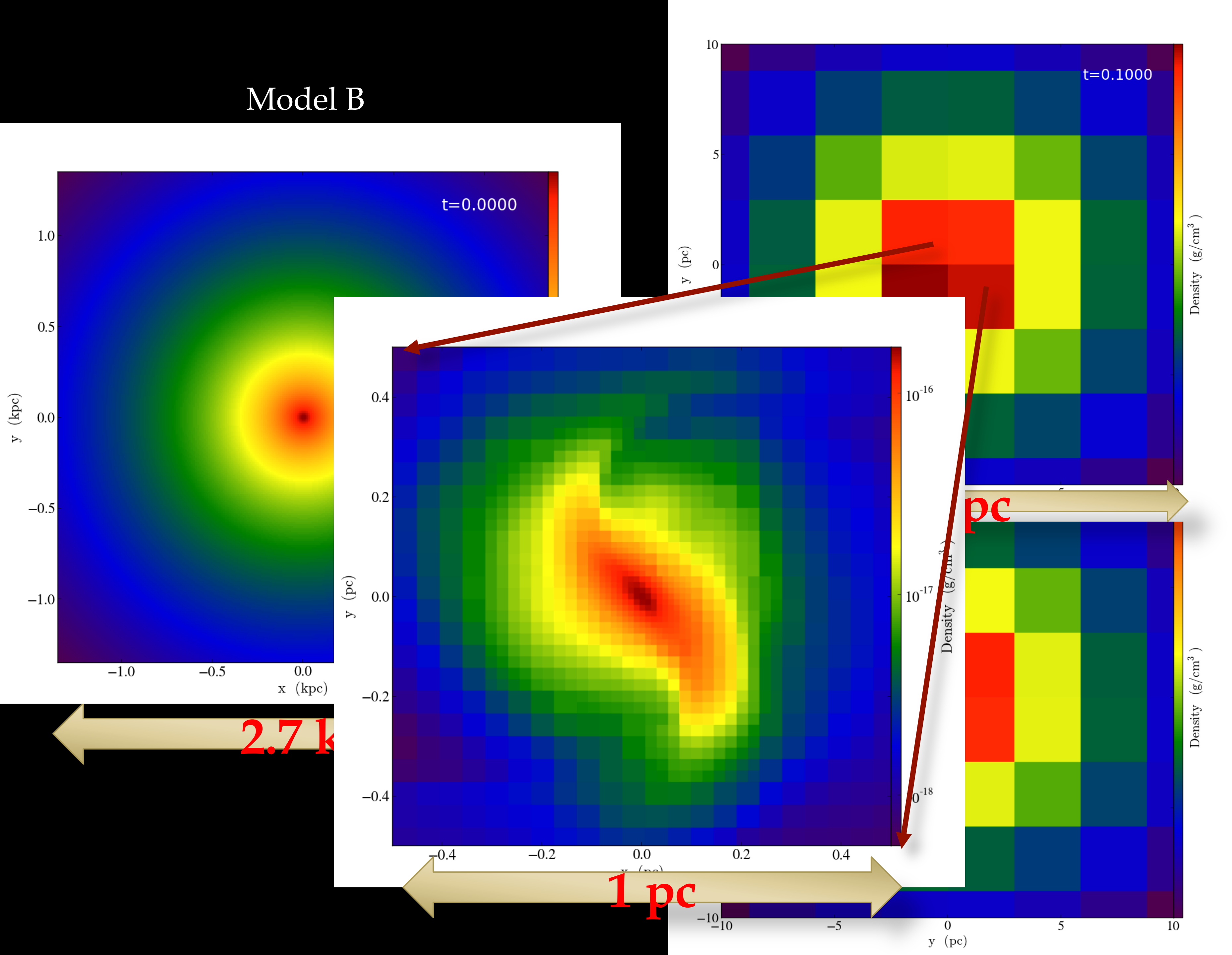
Cosmologically motivated idealized IC

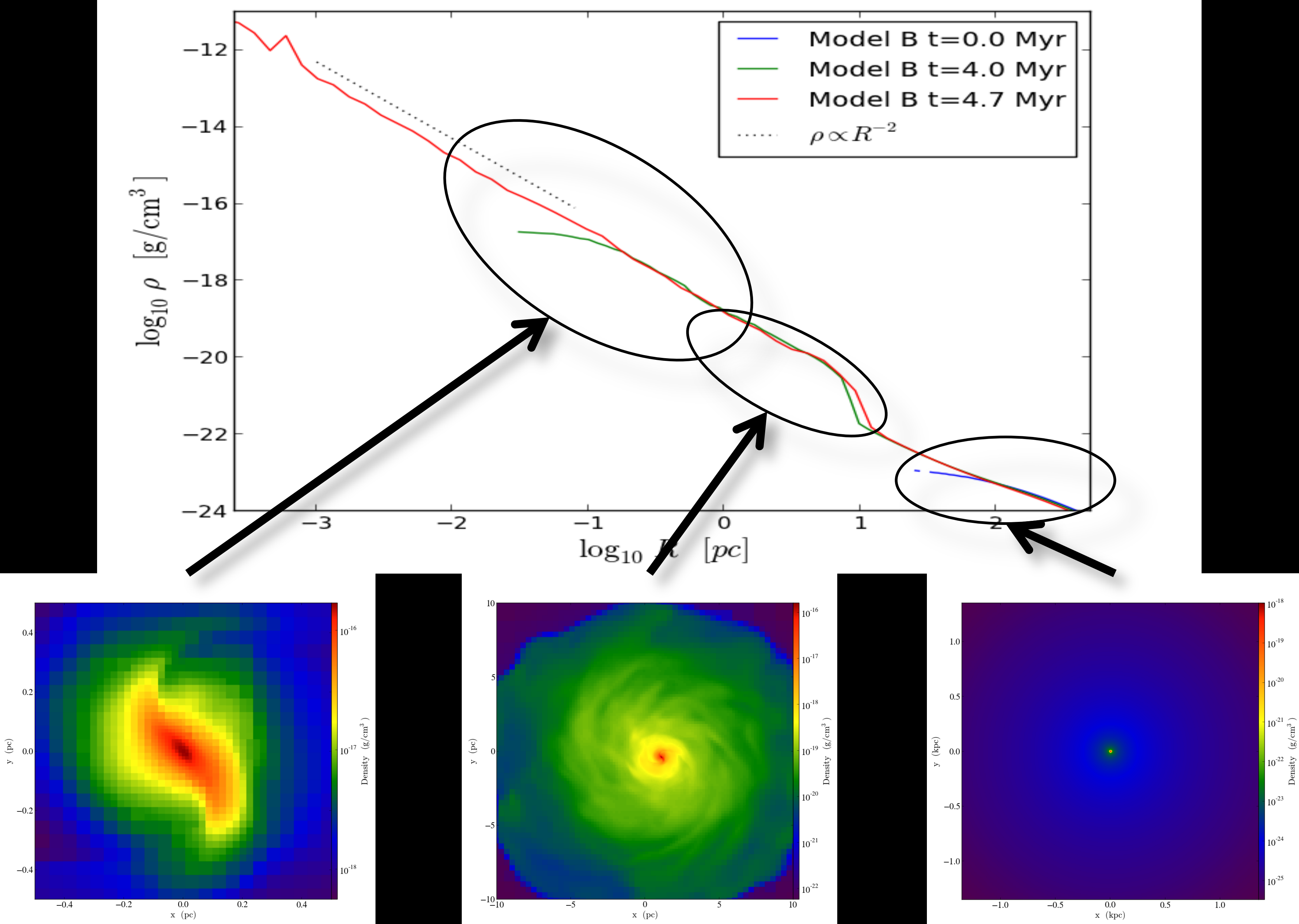
- Isolated isothermal sphere for DM halo (~$10^8 M_\odot$, ~1 kpc)
- Isothermal gas sphere in DM halo
  - f_{gas} ~0.16, r_{core}~100pc,
  - λ~0.05 flat rotation (outside) + solid rotation (inside)

Different DM cores (A→E)

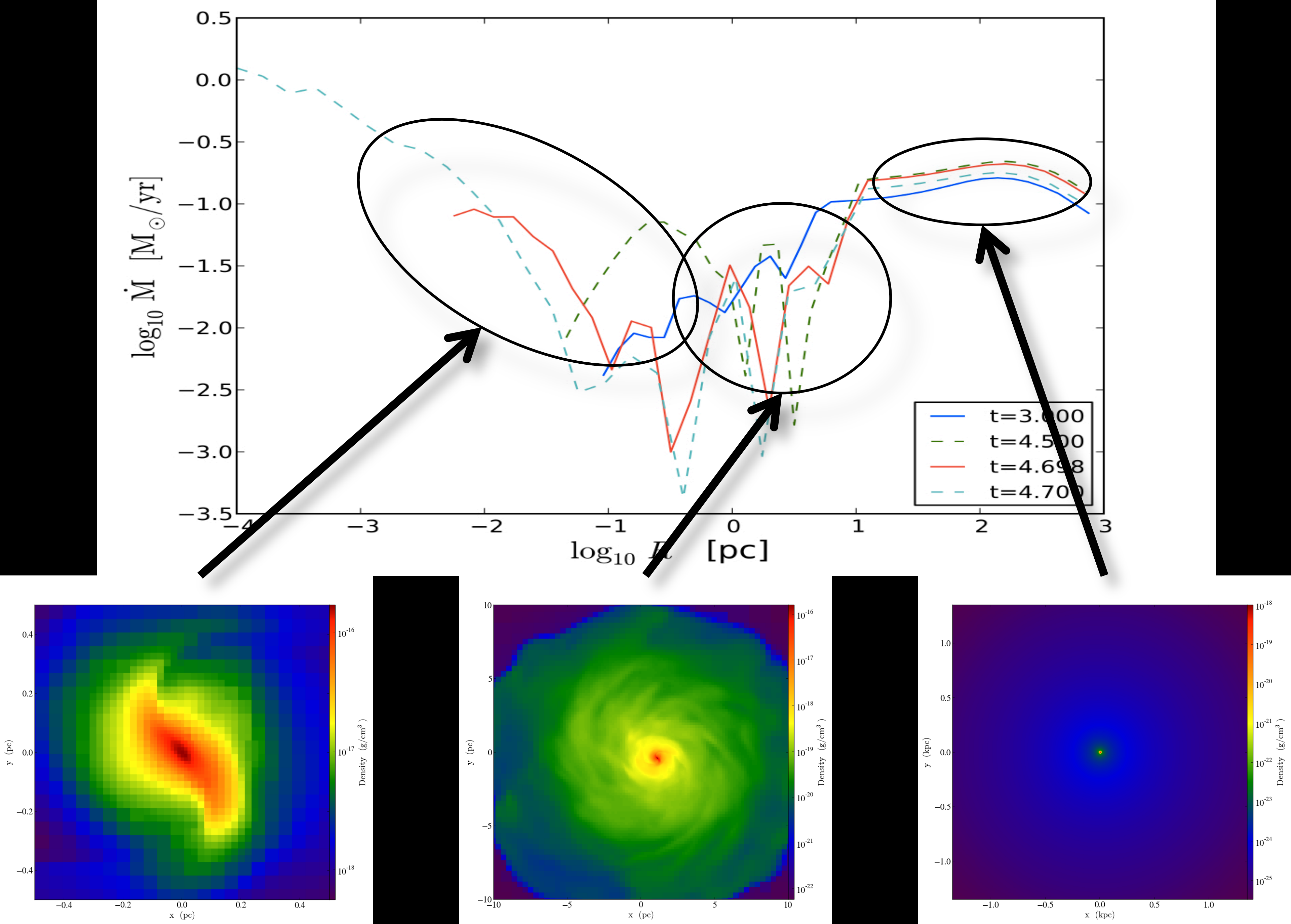
- Small halo core make steep gas disk structure
- Model A, B, and C collapse and Model D and E not

Model B

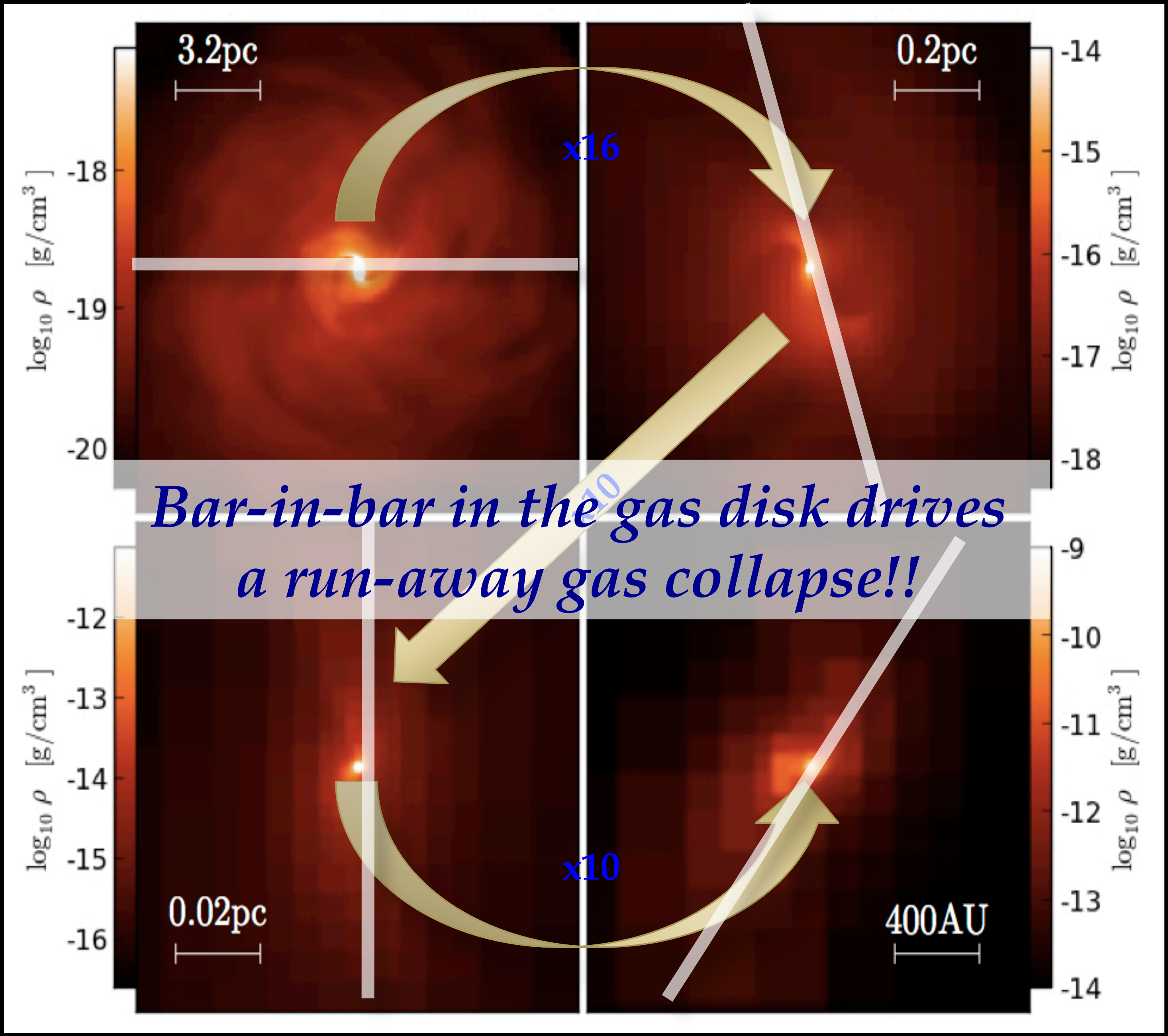




Model B t=0.0 Myr
Model B t=4.0 Myr
Model B t=4.7 Myr
$\rho \propto R^{-2}$
$\log_{10} \rho$ [g/cm^3]
$\log_{10} R$ [pc]
x (pc)
y (pc)
Density (g/cm^3)
x (kpc)
y (kpc)

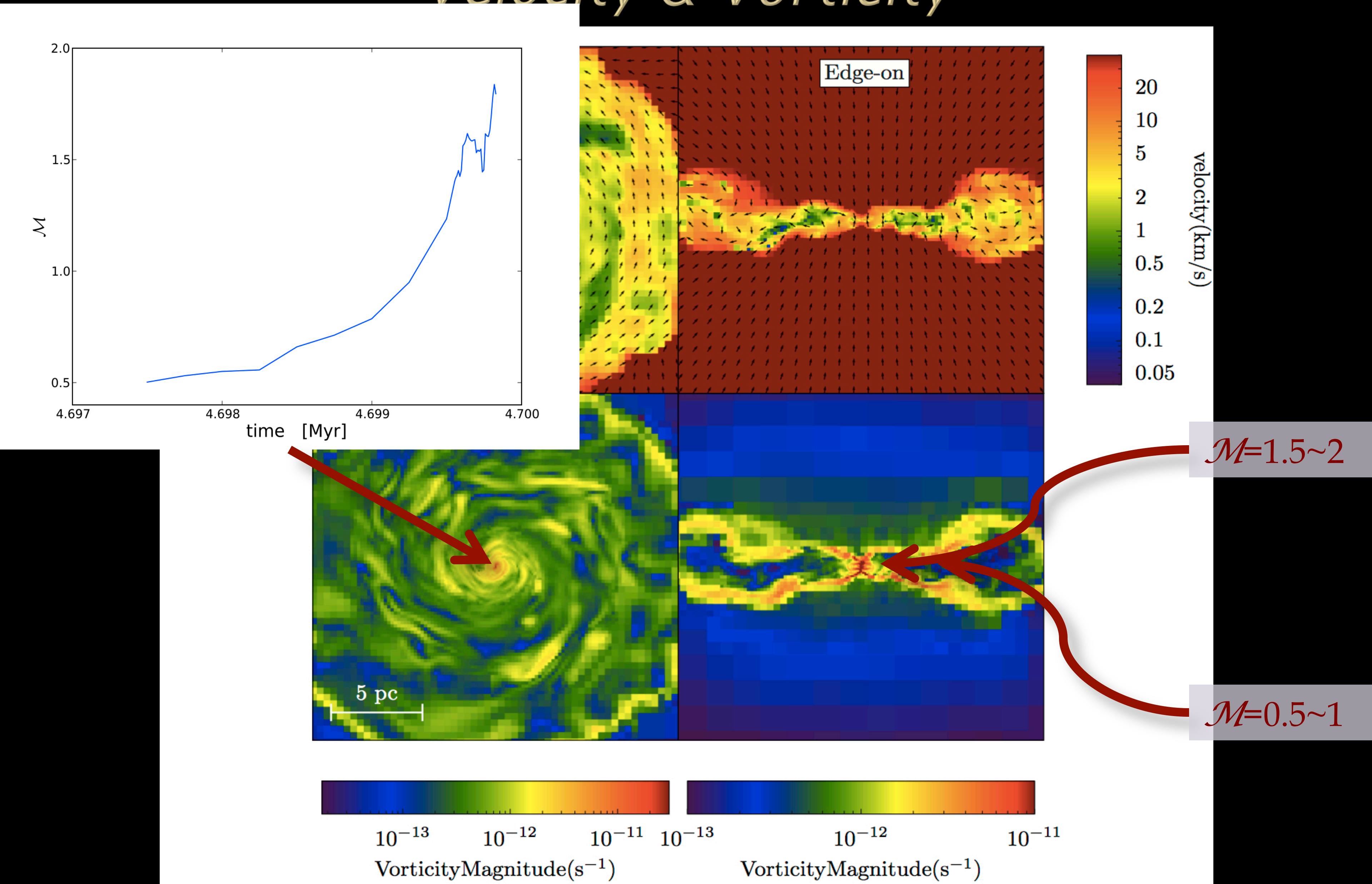


$\log_{10} \dot{M}$ [$M_\odot$/yr]
$\log_{10} R$ [pc]
t=3.000
t=4.500
t=4.698
t=4.700
x (pc)
y (pc)
Density (g/cm^3)
x (kpc)
y (kpc)


Bar-in-bar in the gas disk drives
a run-away gas collapse!!
3.2pc
0.2pc
0.02pc
400AU
x16
x10
x10
log10 ρ [g/cm3]
-18
-19
-20
-14
-15
-16
-17
-18
-12
-13
-14
-15
-16
-9
-10
-11
-12
-13
-14

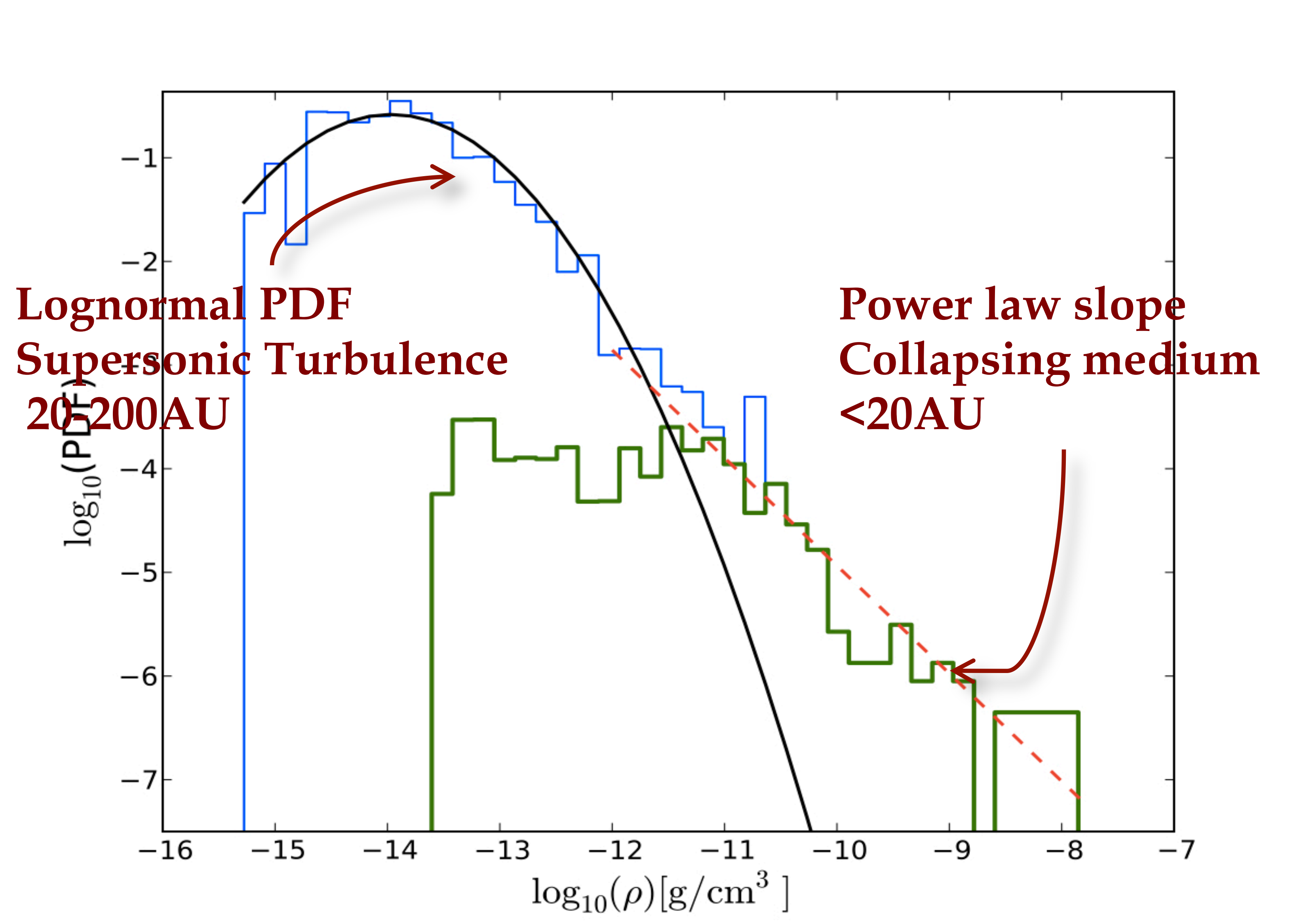
Turbulence

Velocity & Vorticity

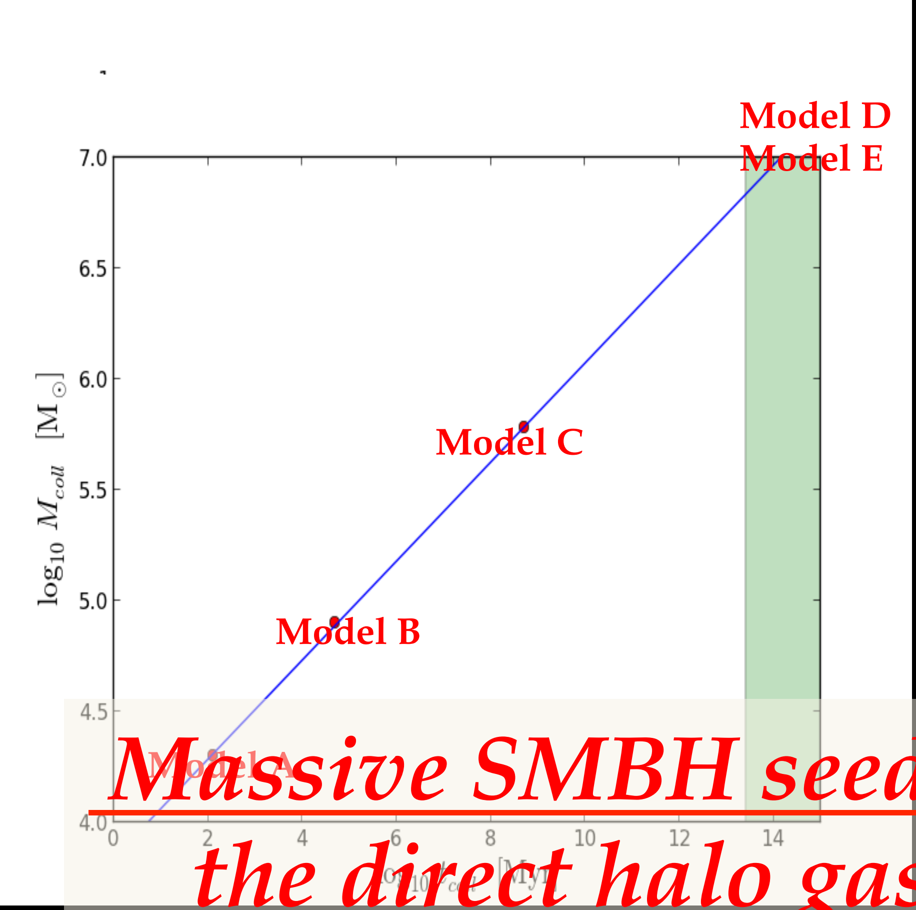


Turbulence (II)

Gas Density PDF (Inner collapse region)



Speculate BH seed mass



- Different core halo result in different initial disk profiles
  - Larger core → Shallower disk
- Off-center disk fragmentation occurs ~13.4 Myr
- Shallow gas disk collapses late
  → larger collapsing radius (R_{coll})
  → larger collapsing mass
  → $\log M_{coll} \sim \log t_{coll}$
- Assuming the all mass in R_{coll} collapse to BH seed
- BH seed mass
  $2\times10^4 M_\odot - 2\times10^6 M_\odot$

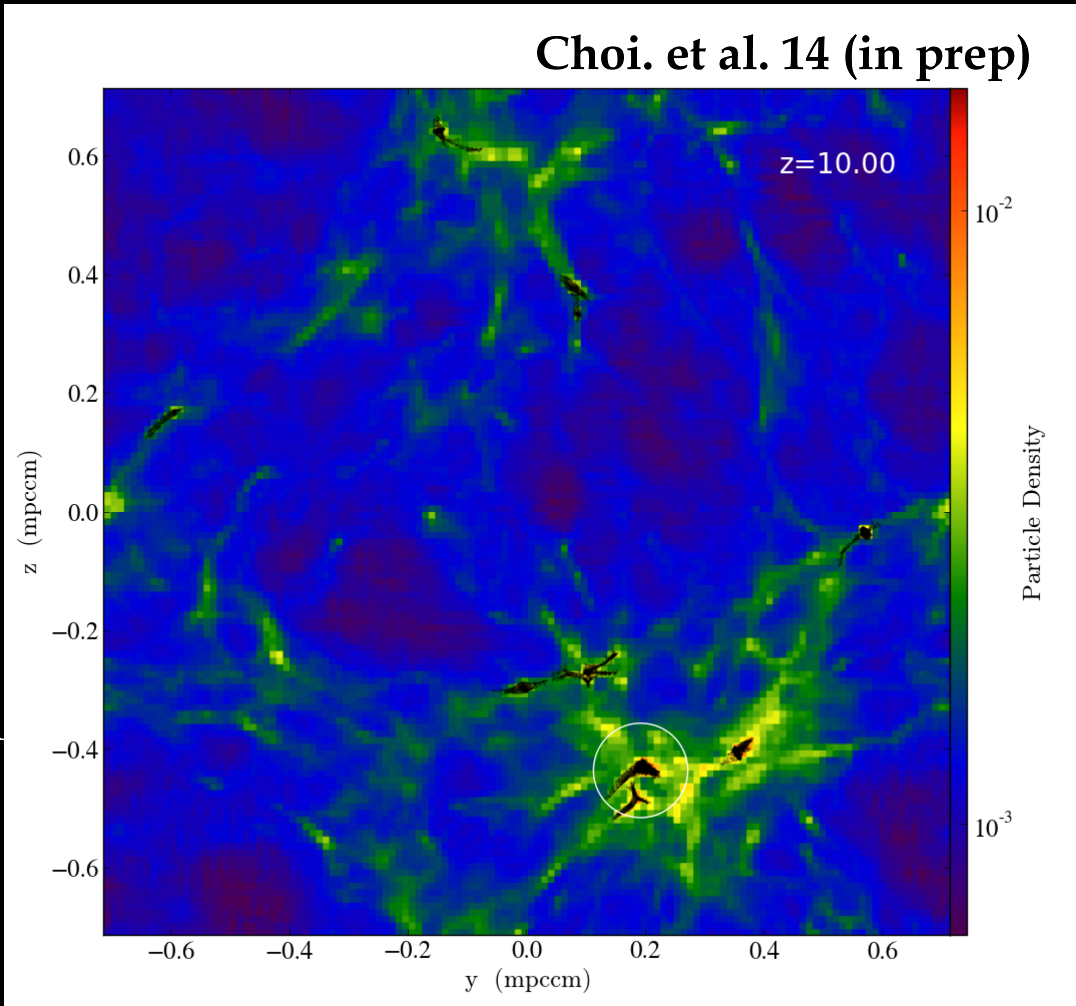
Massive SMBH seeds can be form through the direct halo gas collapse at high-z.

Does the direct collapse occur in the ideal model expected in the Universe?

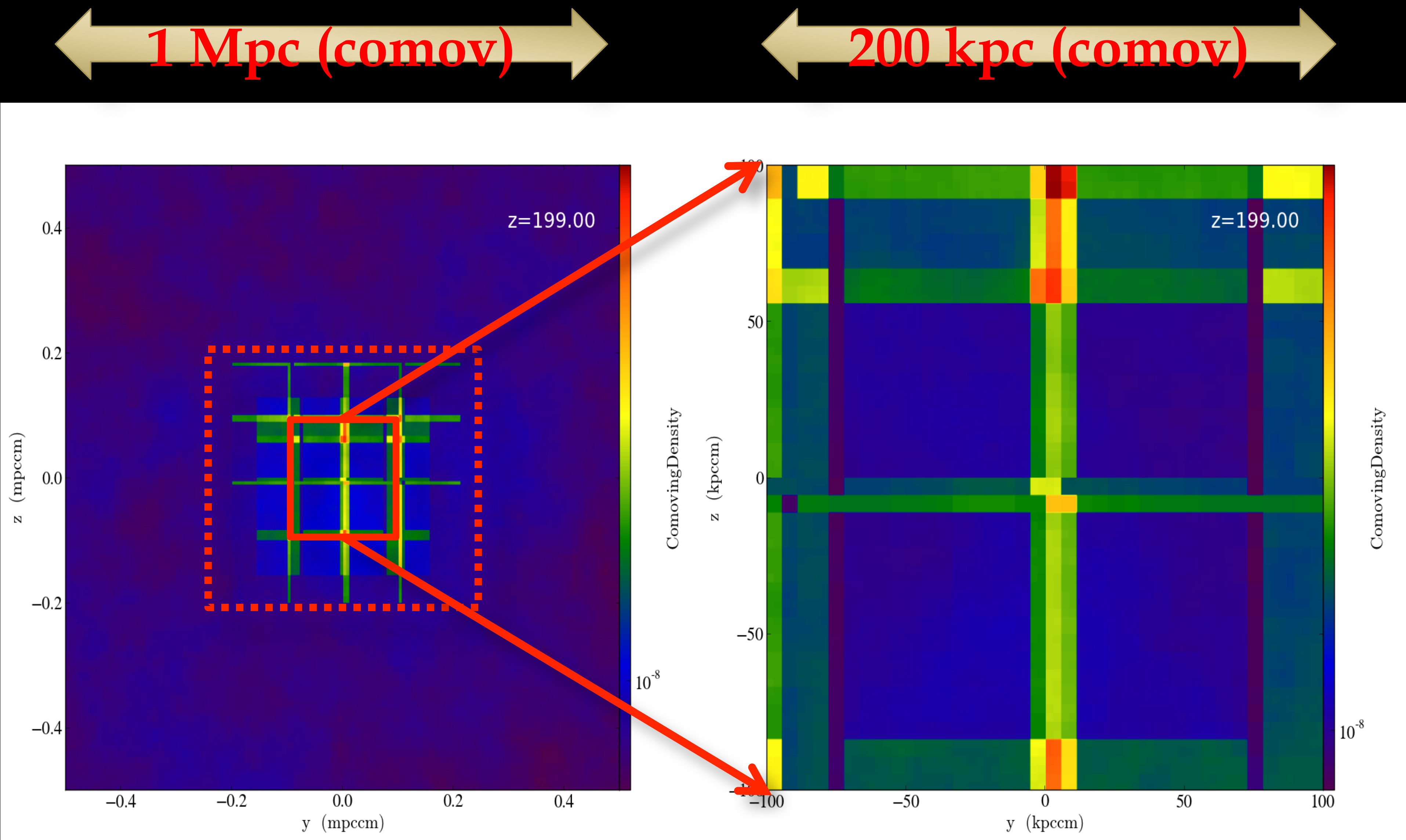
Need to study cosmological simulations!!!

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

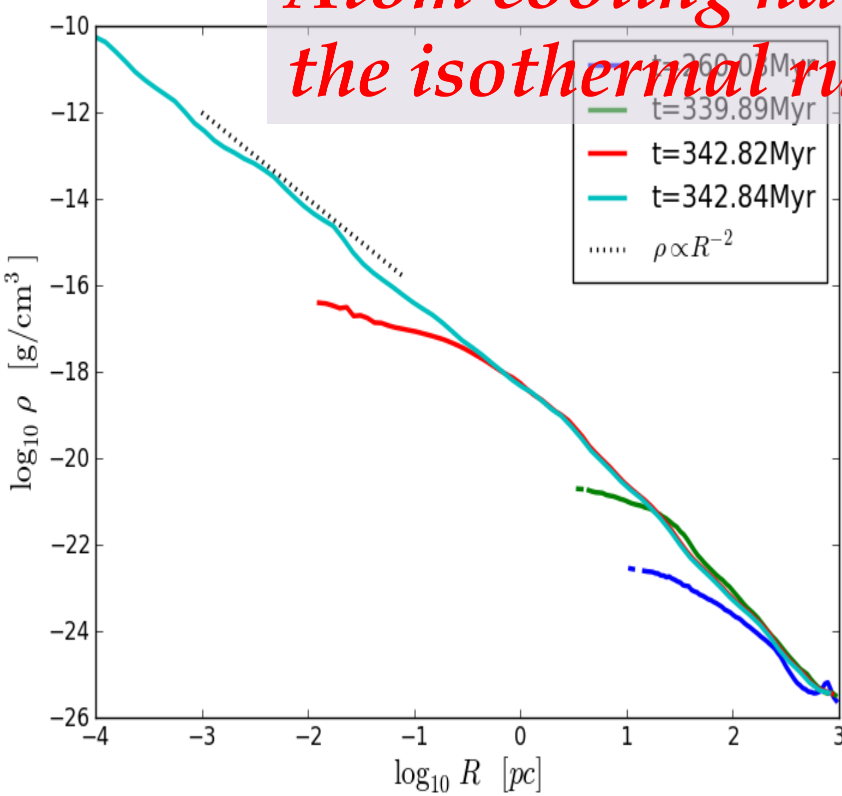


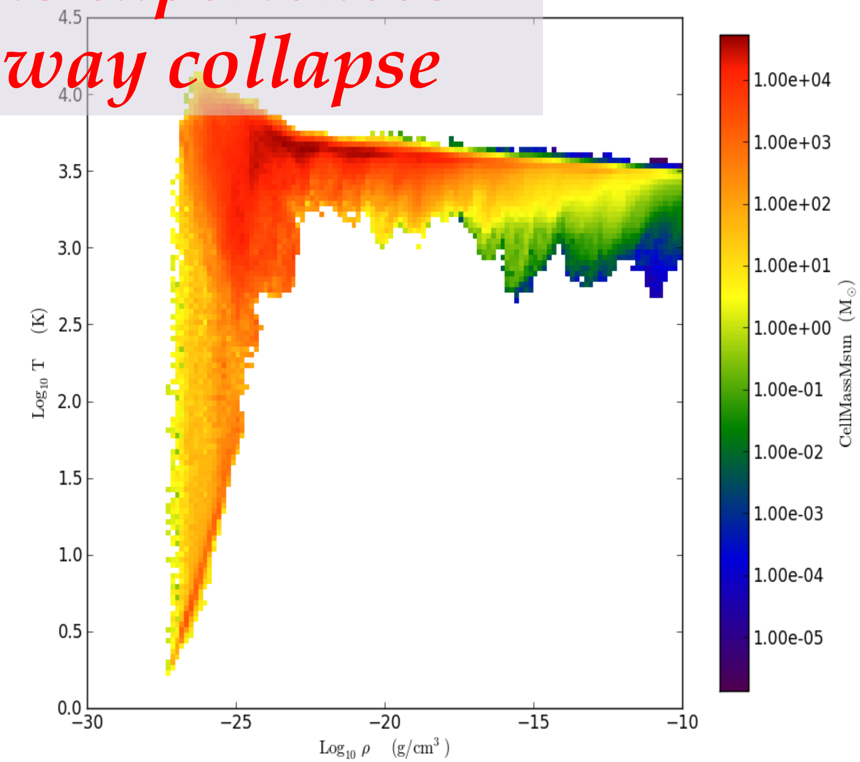
1 Mpc (comov)



At z~12.37, ~5x10^7 M$_\odot$ DM halo experiences direct gas collapse.

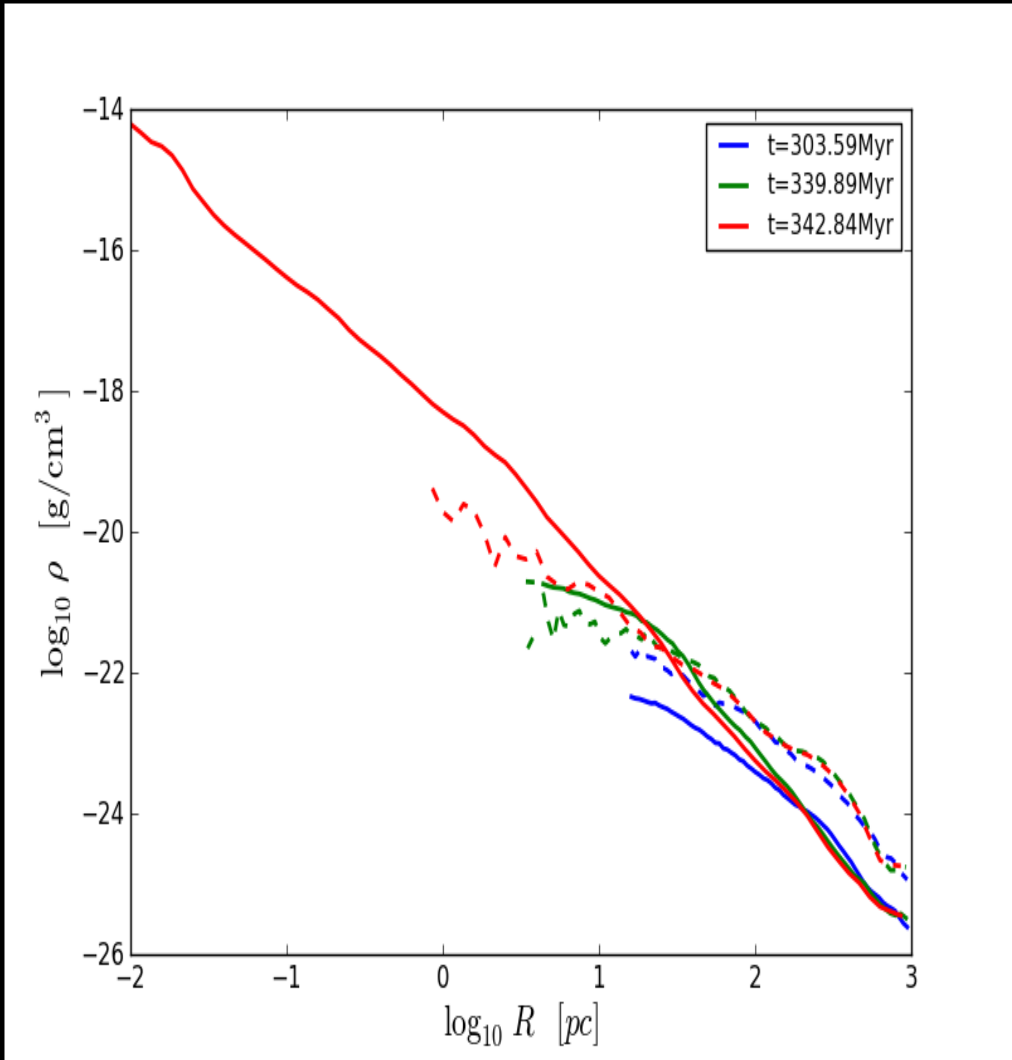
Atom cooling halo gas experiences the isothermal run-away collapse

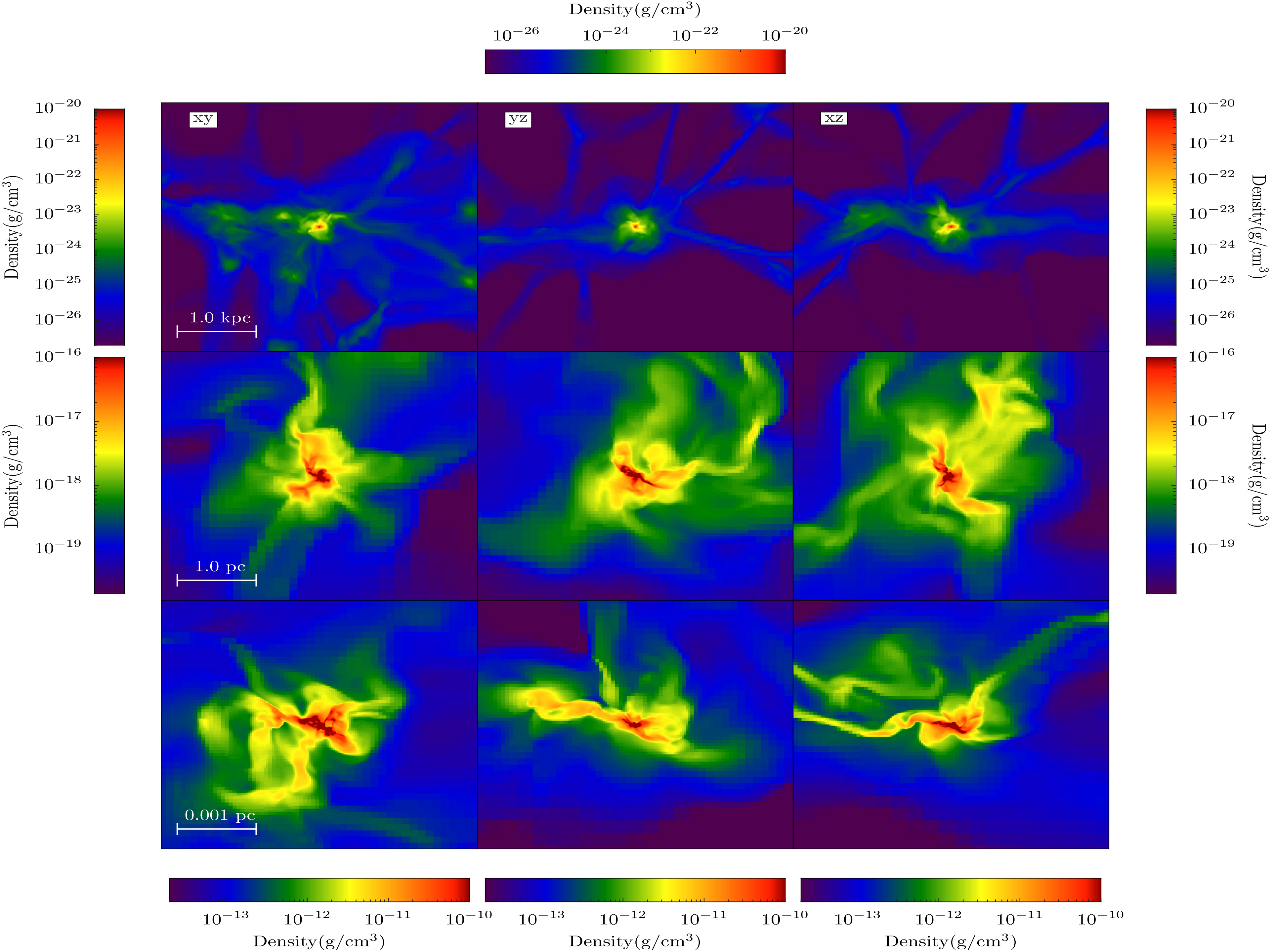




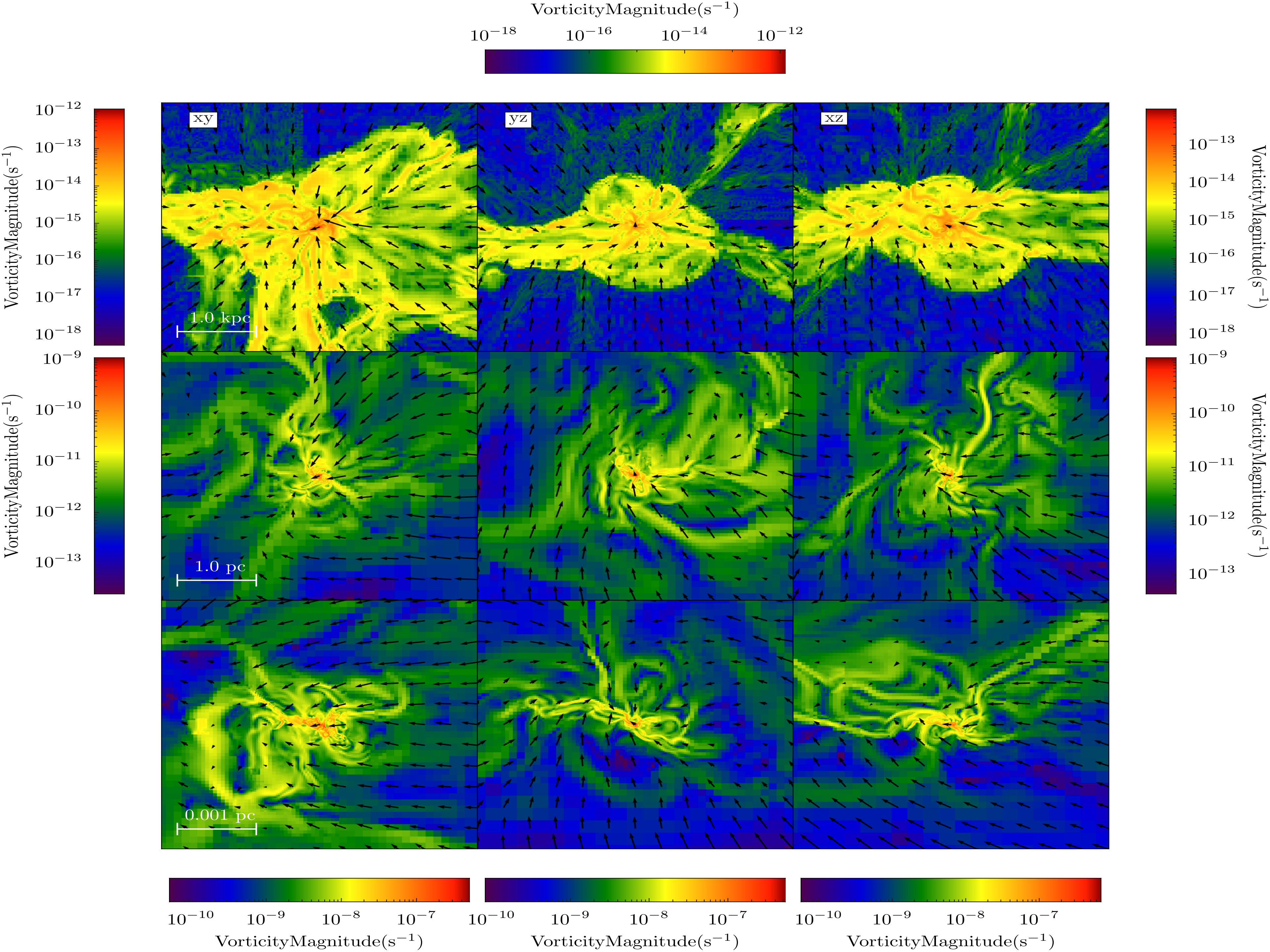
Run-away collapse condition

- Outer halo
  - $\rho_{dm} > \rho_{gas}$
- Inner halo
  - $\rho_{dm} < \rho_{gas}$
- $r \sim 20pc$
  - $\rho_{dm} \sim \rho_{gas}$
  - Run-away collapse start
- Gas cooling contract the halo gas and when $\rho_{dm} \sim \rho_{gas}$ the run-away collapse start

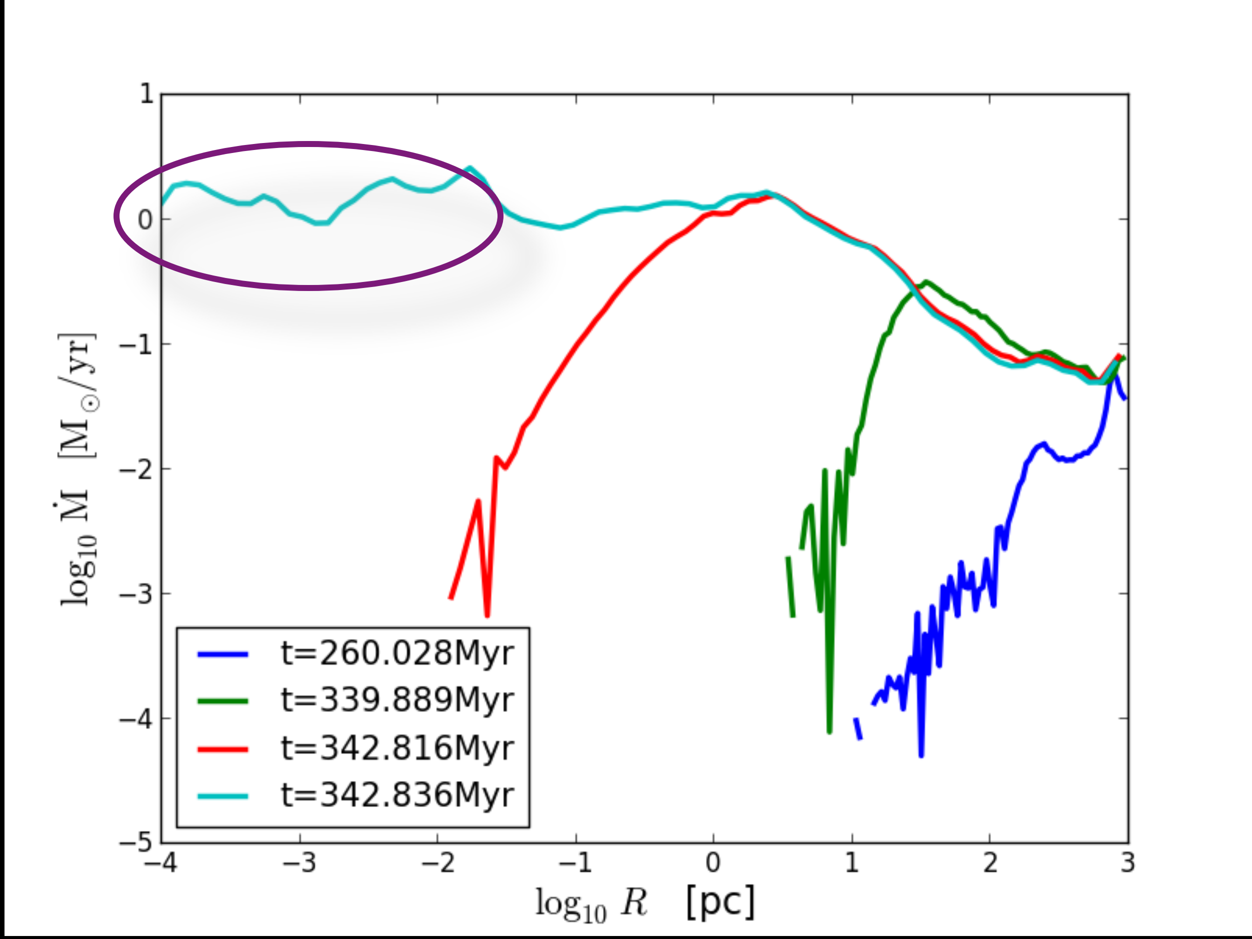




Density(g/cm^3)
10^{-26} 10^{-24} 10^{-22} 10^{-20}
xy
yz
xz
1.0 kpc
1.0 pc
0.001 pc
10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26}
10^{-16} 10^{-17} 10^{-18} 10^{-19}
10^{-13} 10^{-12} 10^{-11} 10^{-10}
Density(g/cm^3)



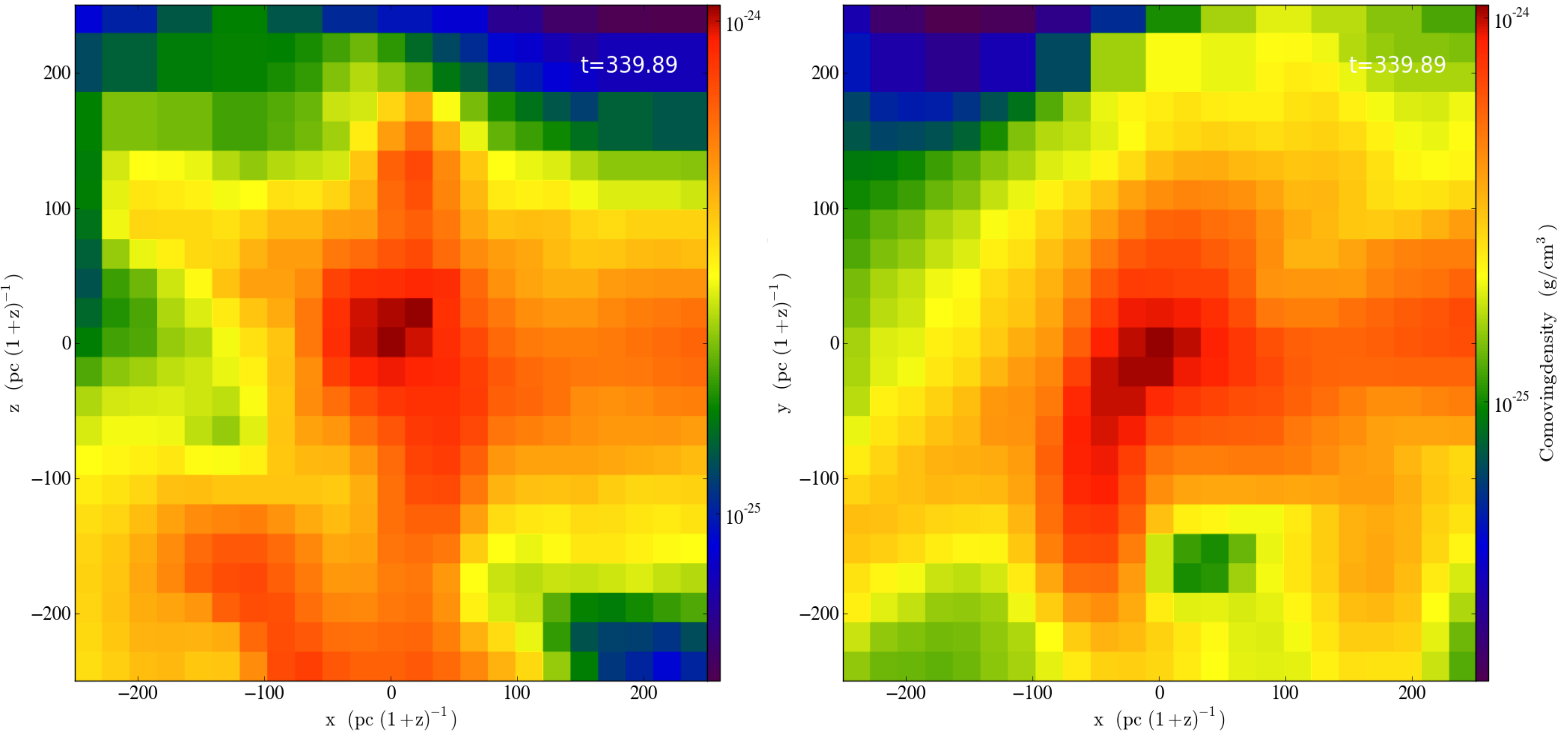
VorticityMagnitude(s^{-1})
10^{-18}
10^{-16}
10^{-14}
10^{-12}
xy
yz
xz
1.0 kpc
1.0 pc
0.001 pc
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-10}
10^{-9}
10^{-8}
10^{-7}



- Gas accretion in the collapse region reaches up to ~$1M_\odot$/yr
- Two phases
  - Outer : DM potential dominant
  - Inner : Gas potential dominant
- <u>Strong mass accretion is an important ingredient to form SMBH seed from direct collapse</u>

Long-term evolution of collapsing gas and central object

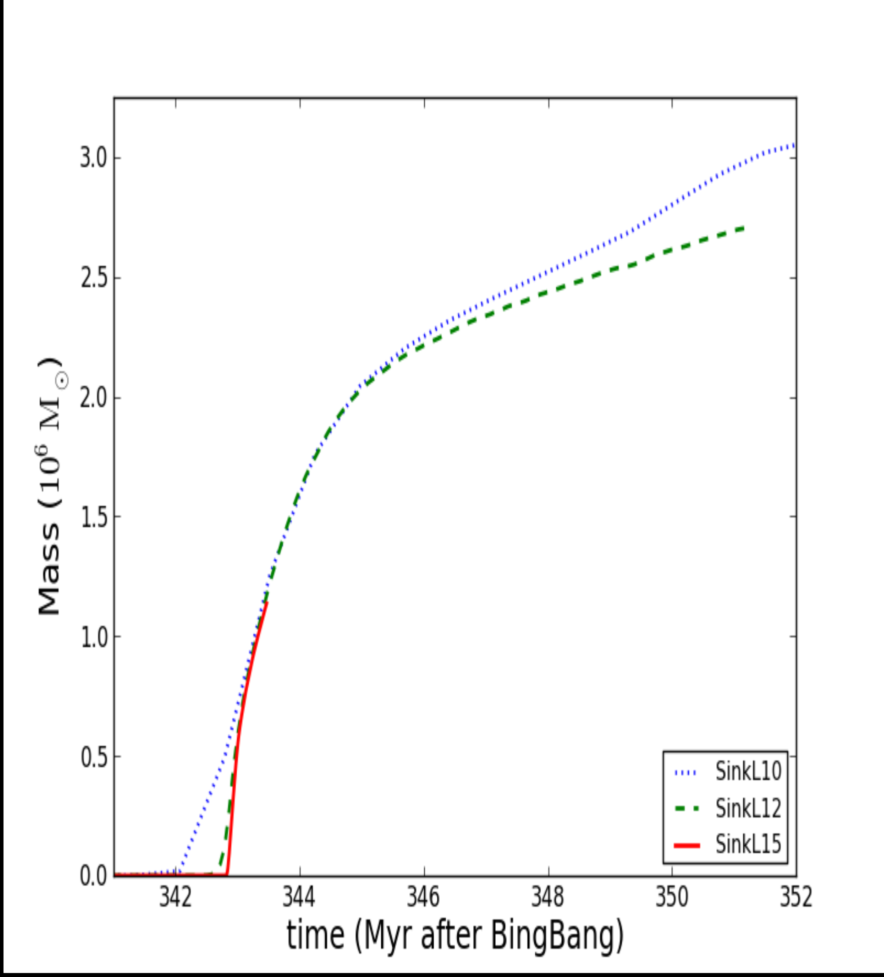
- Numerically, run-away gas collapsing can reach the maximum refinement and open halts and/or significantly slows down the simulation.
- Sink Method in Enzo (Wang et. al. 2010)
  - Jean criterion : Gas above the Jean resolution coverts to the sink
  - Mass accretion : Bondi-Hoyle formula
  - Sink merger : two sinks come closer to ~10 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)



- Level 12 Simulation 500pc(Comov)
- Central sink forms and continuously accrete gas and merge other sinks
- Central sink forms first, resides at the center of potential, and dominant total sink mas (>99%)
- Disk feature as well as gaseous bar are clearly observed.

Sink Mass evolution

- Sink particle mass reaches ~10^6 $M_\odot$ only few Myr after the sink forms.
- Three different resolution of simulations show good convergence of the sink mass
- Amount of continuous gas accretion is large enough and fast enough to make SMBH seed configuration



Summary & Future

- Both the idealized and cosmological simulation we see the run-away collapse in the atomic cooling DM halo aided by angular momentum transfer and turbulence flow.
- Run-away collapse leads rapid gas accretion and forms massive central object in very short period of time
- More detail study for the gas dynamics in cosmological simulation w/ and w/o sink : J-transfer and Turbulence
- Additional physics for in small scale evolution : Chemistry (H_2 and metals), Radiation, MHD
- Cosmological time scale simulation
  - Toward M-σ relationship