

# Formation of Supermassive Black Holes in the Early Universe: High-Resolution Numerical Simulations of Radiation Transfer Inside Collapsing Gas

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## Introduction

Observations of high-redshift quasars reveal that super massive black holes (SMBHs) with masses exceeding  $10^9 M_\odot$  formed as early as redshift  $z \sim 7$  [1,3,6]. This means that SMBHs have already formed  $\sim 700$  million years after the Big Bang. How did such SMBHs could grow so quickly?

In this work, we use a modified and improved version of the block-structured adaptive mesh refinement (AMR) code ENZO [2] to provide high spatial and temporal resolution for modeling the formation of SMBHs via direct collapse within dark matter (DM) halos at high redshifts. The radiation hydrodynamics equations are solved in the flux-limited diffusion (FLD) approximation in the full cosmological background [5]. The chemical species are assumed to be in local thermodynamic equilibrium (LTE). We follow the evolution of the collapsing gas from a kilo-parsec scale down to 0.001 AU --- 11 decades in radius.

## Numerical setup

We simulate the gas evolution within DM haloes of a virial mass of  $M_{\text{vir}} = 2 \times 10^8 h^{-1} M_\odot$  and a virial radius  $R_{\text{vir}} = 945 h^{-1} \text{pc}$ . The Eulerian equations for our model are given by

$$\begin{aligned} \rho : \text{density} & \quad \frac{\partial \rho}{\partial t} + \frac{1}{a} \nabla \cdot (\rho \mathbf{v}_b) = 0, & (1) \\ \mathbf{v}_b : \text{baryon velocity} & \quad \frac{\partial \rho \mathbf{v}_b}{\partial t} + \frac{1}{a} \nabla \cdot (\rho \mathbf{v}_b \mathbf{v}_b + \mathbb{I}p) = -\frac{\dot{a}}{a} \rho \mathbf{v}_b - \frac{1}{a} \rho \nabla \phi + \frac{\kappa_R}{c} \mathbf{F}_r, & (2) \\ e : \text{fluid energy density} & \quad \frac{\partial e}{\partial t} + \frac{1}{a} \nabla \cdot [(e+p)\mathbf{v}_b] = -\frac{2\dot{a}}{a} e - \frac{\rho}{a} \mathbf{v}_b \cdot \nabla \phi + c\kappa_p E - 4\kappa_p \sigma_{SB} T^4 + \frac{\kappa_R}{c} \mathbf{F}_r \cdot \mathbf{v}_b, & (3) \\ p : \text{thermal pressure,} & \quad e = \frac{p}{\gamma - 1} + \frac{1}{2} \rho v^2, & (5) \\ E : \text{radiation energy density} & \quad \nabla^2 \phi = \frac{4\pi G}{a} (\rho + \rho_{\text{dm}} - \rho_0), & (6) \\ \mathbf{F}_r : \text{radiation energy flux} & \quad \mathbf{F}_r = -\frac{c\lambda}{\kappa_R} \nabla E, \lambda = (9 + R^2)^{-1/2}, R = \frac{|\nabla E_r|}{\kappa_R E_r}, & (7) \\ \mathbb{P}_r : \text{radiation pressure tensor} & \quad \mathbb{P}_r = \mathbb{D}E, \mathbb{D} = \frac{1-\chi}{2} \mathbb{I} + \frac{3\chi-1}{2} \mathbf{nn}, \chi = \lambda + \lambda^2 R^2, \mathbf{n} = \frac{\nabla E_r}{|\nabla E_r|}. & (8) \end{aligned}$$

## The formation of a central core

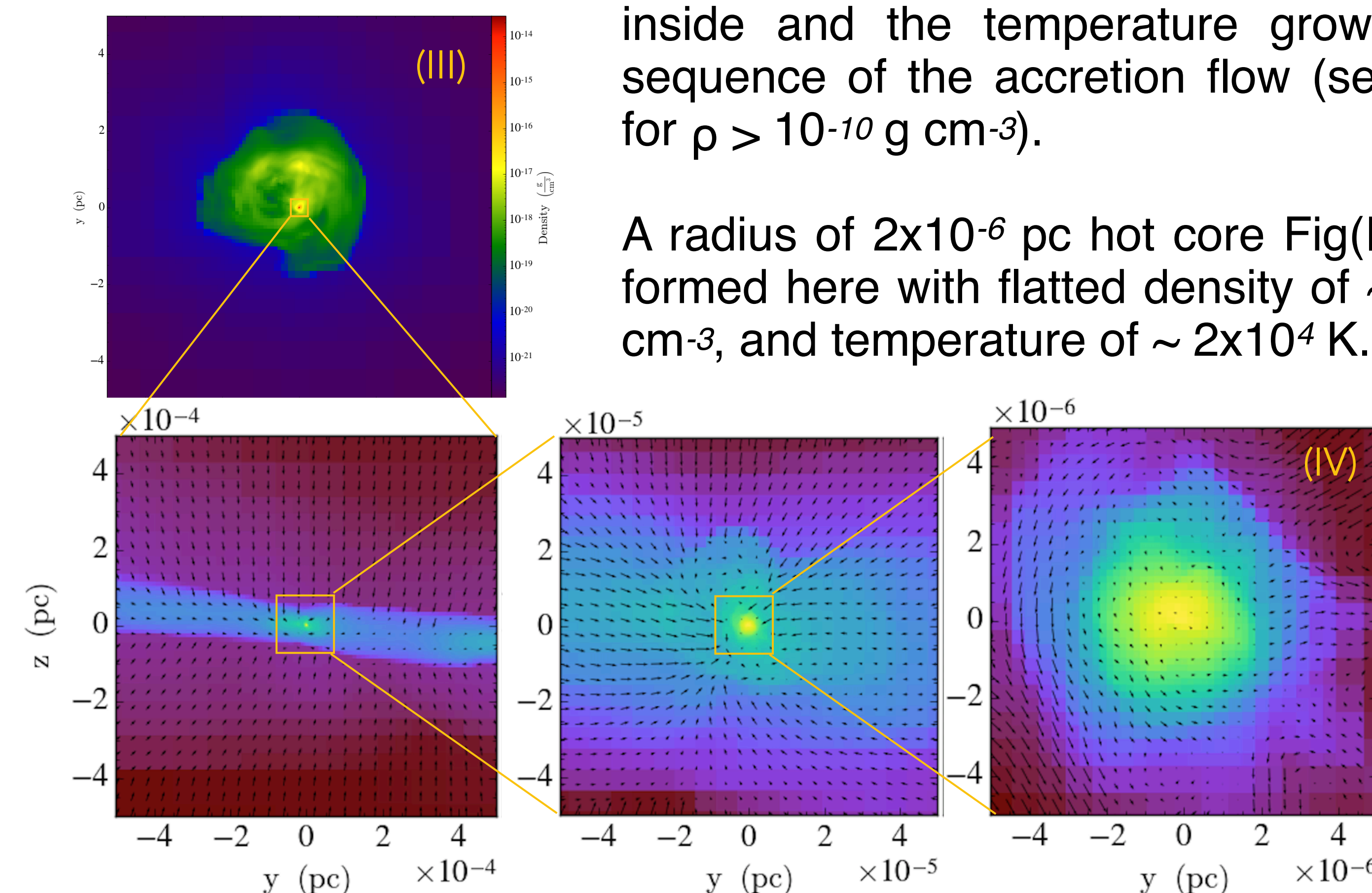
The initial collapse is optically-thin and isothermal [3,4,6].

First, the gas cools down to the cooling floor of atomic gas (Fig (I), for  $\rho < 10^{-13} \text{ g cm}^{-3}$ ), then collapses following a self-similar isothermal solution,  $\rho \propto R^{-2}$  (Larson 1969; Penston 1969), with some modifications by the present angular momentum (Fig (II), for  $R > 10^{-5} \text{ pc}$ ).

When collapsing gas reaches the centrifugal barrier, a shock forms Fig (III). Most of the gas behind the shock collapses and accumulates into the center.

As the gas collapses, the gas density increases, as well as the opacities. At  $\rho \sim 10^{-10} \text{ g cm}^{-3}$ , the radiation is trapped inside and the temperature grows as a sequence of the accretion flow (see Fig(I) for  $\rho > 10^{-10} \text{ g cm}^{-3}$ ).

A radius of  $2 \times 10^{-6} \text{ pc}$  hot core Fig(II, IV) is formed here with flatted density of  $\sim 10^{-6} \text{ g cm}^{-3}$ , and temperature of  $\sim 2 \times 10^4 \text{ K}$ .

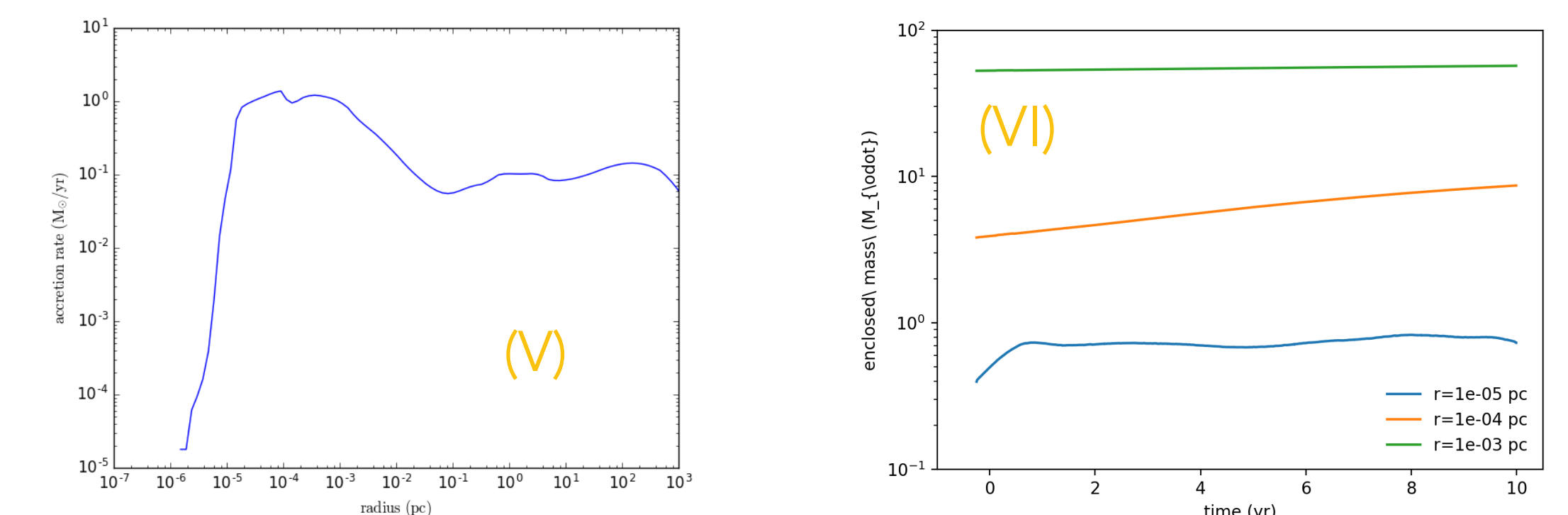
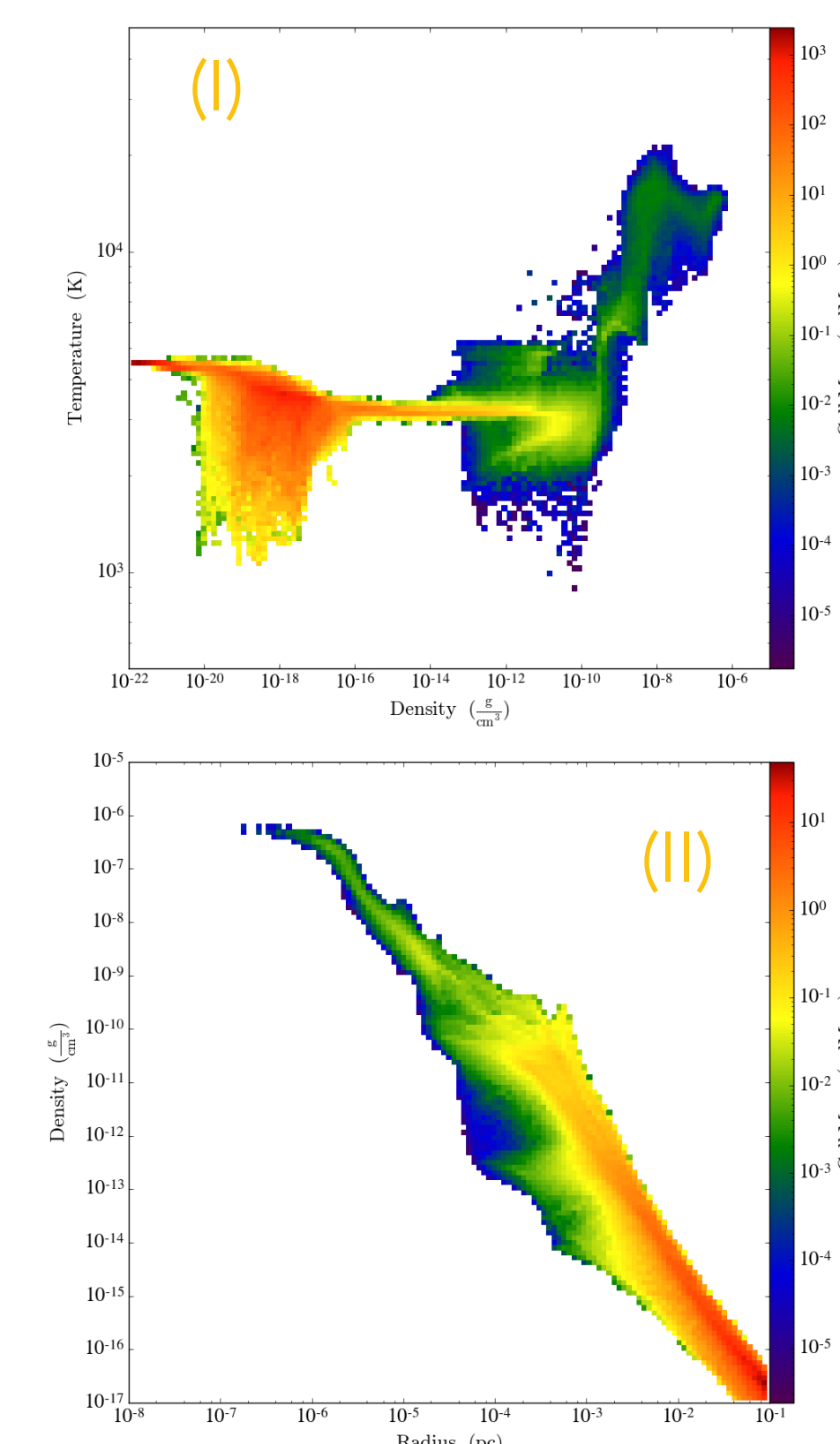


During the run away collapse of the gas, the gas flow along with a filament until the rotation of the core stops the accretion. The core is supported by radiation and gas pressure and rotation.

## Results

### The growth of the core

At radius  $\sim 10^{-4} \text{ pc}$ , the accretion rate is close to a few solar mass per year Fig (V). From the evolution of the enclosed mass at different radius Fig (VI), the mass is accumulating at  $10^{-4} \text{ pc}$ . The enclosed mass of our newly formed core is around  $0.7 M_\odot$ .



## Summary

- We have performed a high resolution 3D numerical simulation of the formation and evolution of a SMBH seed in an atomic cooling halo.
- The initial collapse of the gas is optically-thin and isothermal.
- For densities above  $10^{14} \text{ cm}^{-3}$ , the optical depth traps the radiation and temperature grows, around 1 AU to few  $\times 10^4 \text{ K}$ .
- The accretion rate to the center is a few solar mass per year, and we have formed a central core with radius of  $2 \times 10^{-6} \text{ pc}$  and mass of  $\sim 0.7 M_\odot$ .
- This newly formed object --- a supermassive star, is supported by radiation and gas pressure and rotation. Collapse of such object to the SMBH is anticipated and under investigation.

## Reference

- [1].Begelman, M. C., Volonteri, M. & Rees, M. J. Formation of supermassive black holes by direct collapse in pre-galactic haloes. *Monthly Notices of the Royal Astronomical Society* **370**, 289–298 (2006).
- [2]. Bryan, G. L. et al. ENZO: An Adaptive Mesh Refinement Code for Astrophysics. *The Astrophysical Journal Supplement Series* **211**, 19 (2014).
- [3].Choi, J.-H., Shlosman, I. & Begelman, M. C. Supermassive Black Hole Formation at High Redshifts via Direct Collapse: Physical Processes in the Early Stage. *ApJ* **774**, 149 (2013).
- [4].Luo, Y., Nagamine, K. & Shlosman, I. Direct collapse to supermassive black hole seeds: comparing the AMR and SPH approaches. *Monthly Notices of the Royal Astronomical Society* **459**, 3217–3233 (2016).
- [5].Reynolds, D. R., Hayes, J. C., Paschos, P. & Norman, M. L. Self-consistent solution of cosmological radiation-hydrodynamics and chemical ionization. *Journal of Computational Physics* **228**, 6833–6854 (2009).
- [6].Shlosman, I., Choi, J.-H., Begelman, M. C. & Nagamine, K. Supermassive black hole seed formation at high redshifts: long-term evolution of the direct collapse. *Monthly Notices of the Royal Astronomical Society* **456**, 500–511 (2016).