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 ~ 7 [1,3,6]. This means that SMBHs have already formed ~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 $M_{\rm vir} = 2 \times 10^8\, h^{-1}M_\odot$ and a virial radius $R_{\rm vir} = 945 h^{-1}$pc. The Eulerian equations for our model are given by

ρ : density
v$_b$: baryon velocity
e : fluid energy density
p : thermal pressure,
E : radiation energy density
F$_r$: radiation energy flux
P$_r$: radiation pressure tensor

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\nabla\cdot(\rho \mathbf{v}_b) = 0, \tag{1}$$

$$\frac{\partial \rho \mathbf{v}_b}{\partial t} + \frac{1}{a}\nabla\cdot(\rho\mathbf{v}_b\mathbf{v}_b + \mathbb{I}p) = -\frac{\dot a}{a}\rho\mathbf{v}_b - \frac{1}{a}\rho\nabla\phi + \frac{\kappa_R}{c}\mathbf{F}_r, \tag{2}$$

$$\frac{\partial e}{\partial t} + \frac{1}{a}\cdot\nabla[(e+p)\mathbf{v}_b] = -\frac{2\dot a}{a}e - \frac{\rho}{a}\mathbf{v}_b\cdot\nabla\phi + c\kappa_P E - 4\kappa_P\sigma_{SB}T^4 + \frac{\kappa_R}{c}\mathbf{F}_r\cdot\mathbf{v}_b, \tag{3}$$

$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla\cdot(E\mathbf{v}_b) = -\frac{\dot a}{a}E - \nabla\cdot\mathbf{F}_r - \mathbb{P}_r : \nabla\mathbf{v}_b + 4\kappa_P\sigma_{SB}T^4 - c\kappa_P E - \frac{\kappa_R}{c}\mathbf{F}_r\cdot\mathbf{v}_b, \tag{4}$$

$$e = \frac{p}{\gamma - 1} + \frac{1}{2}\rho v^2, \tag{5}$$

$$\nabla^2\phi = \frac{4\pi G}{a}(\rho + \rho_{dm} - \rho_0), \tag{6}$$

$$\mathbf{F}_r = -\frac{c\lambda}{\kappa_R}\nabla E, \lambda = (9+R^2)^{-1/2}, R = \frac{|\nabla E_r|}{\kappa_R E_r}, \tag{7}$$

$$\mathbb{P}_r = \mathbb{D}E, \mathbb{D} = \frac{1-\chi}{2}\mathbb{I} + \frac{3\chi - 1}{2}\mathbf{nn}, \chi = \lambda + \lambda^2 R^2, \mathbf{n} = \frac{\nabla E_r}{|\nabla E_r|}. \tag{8}$$

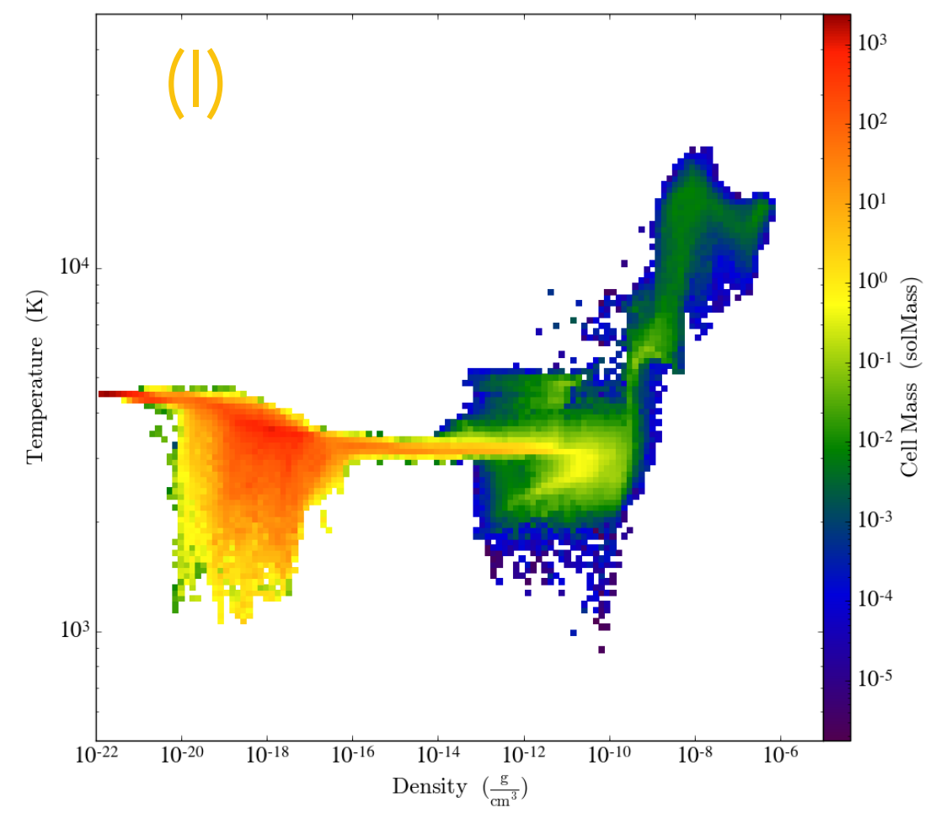
Results

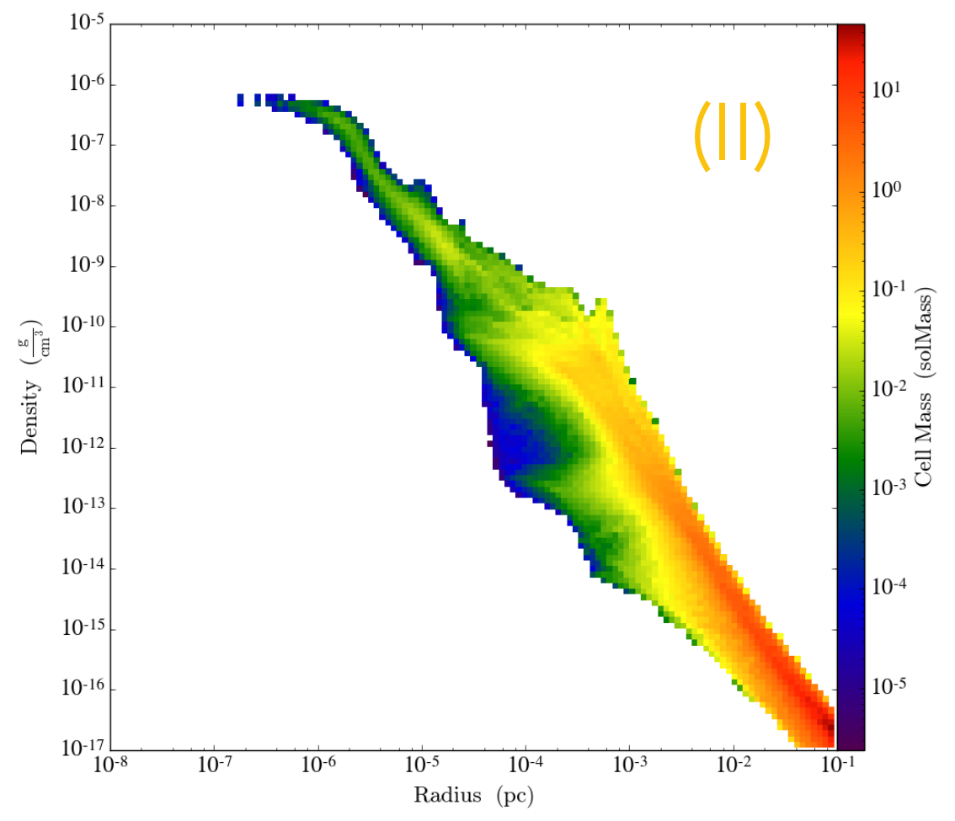
The formation of a central core

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 $\rho < 10^{-13}$ 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} pc).

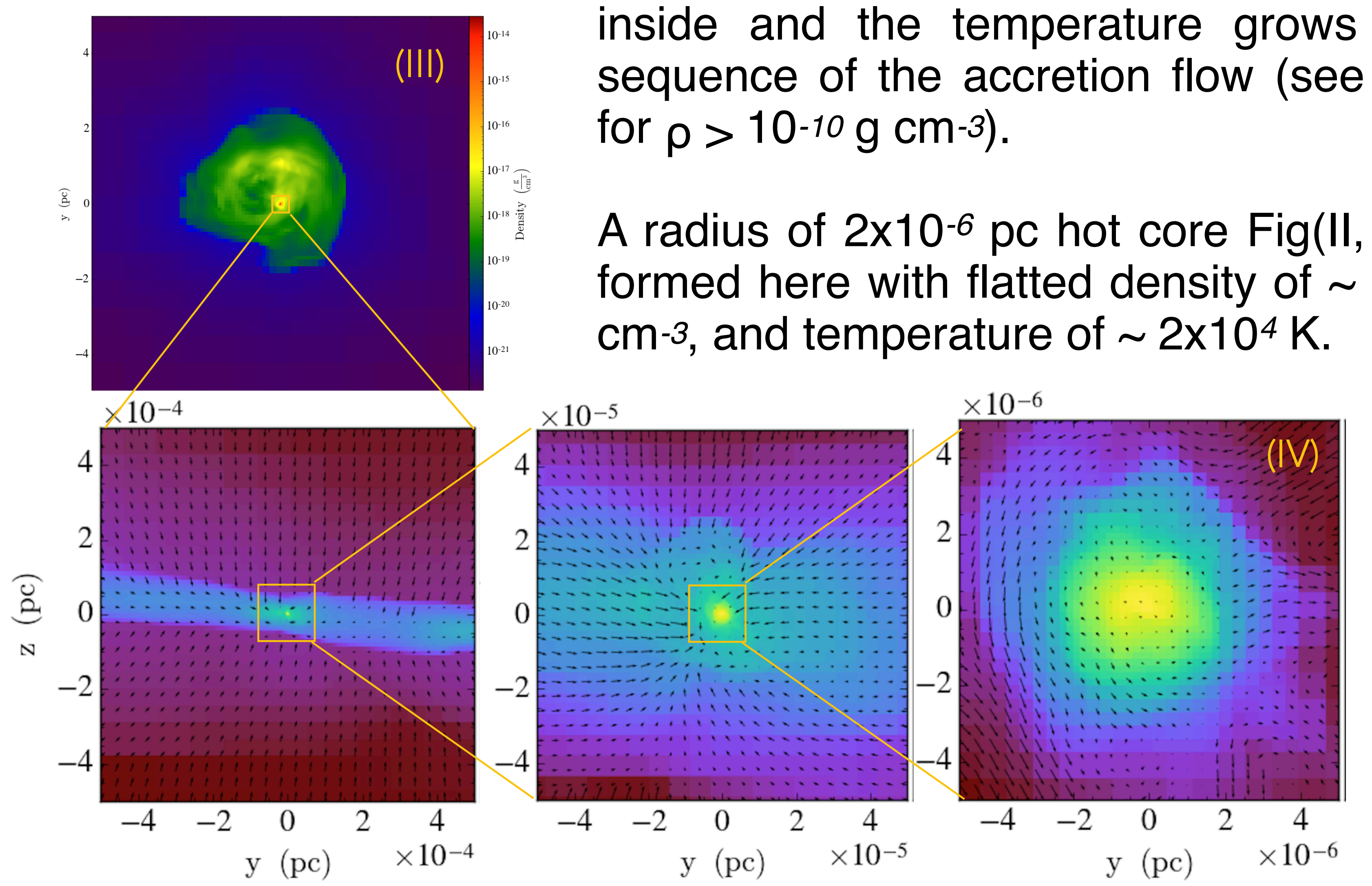
When collapsing gas reaches the centrifugal barrier, a shock forms Fig (III). Most of the gas behind the shock collapses and accumulates into the center.





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

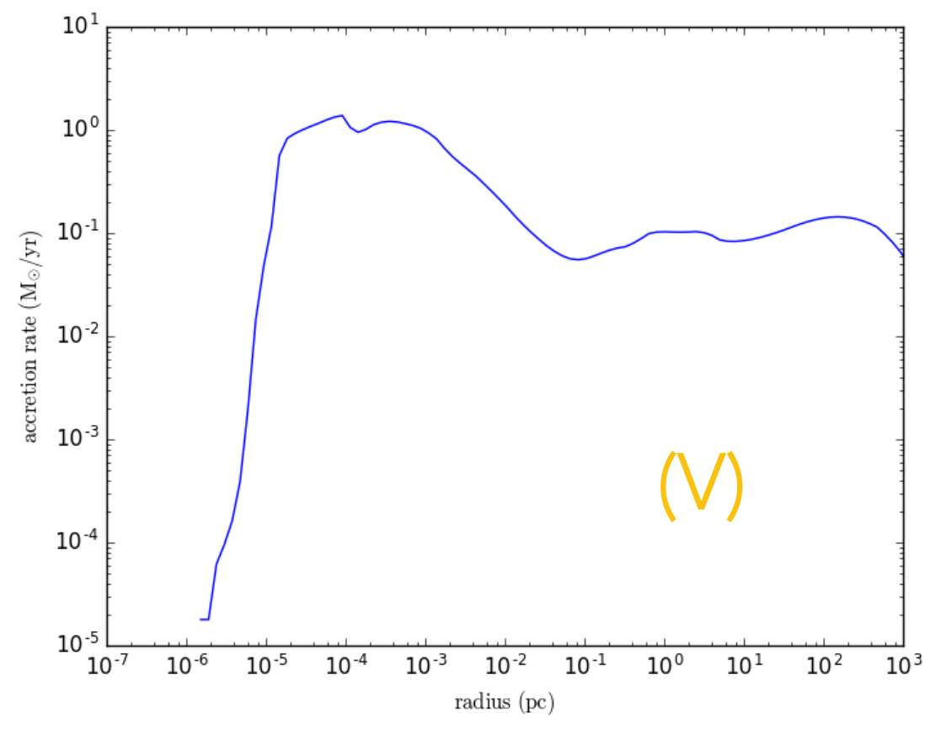
A radius of 2x10^{-6} pc hot core Fig(II, IV) is formed here with flatted density of ~ 10^{-6} g cm^{-3}, and temperature of ~ 2x10^4 K.

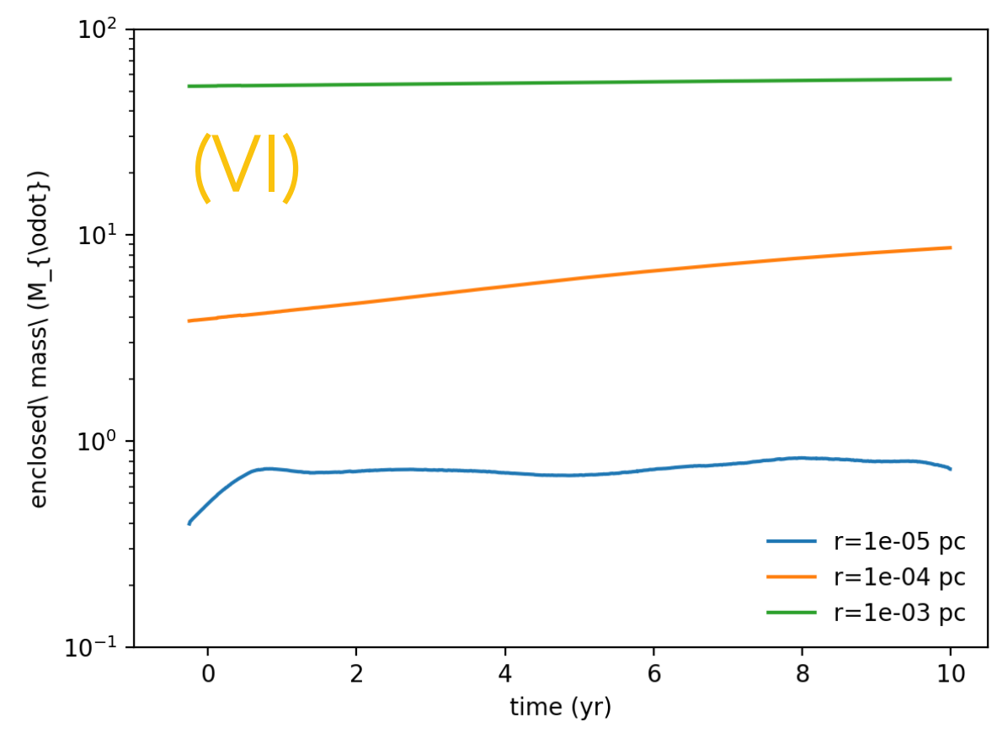


During the run away collapse of the gas, the gas flow along with a filament until the rotation of the core stops the accretion. The core is supported by radiation and gas pressure and rotation.

The growth of the core

At radius ~ 10^{-4} 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} 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} cm^{-3}, the optical depth traps the radiation and temperature grows, around 1 AU to few x 10^4 K.
- The accretion rate to the center is a few solar mass per year, and we have formed a central core with radius of 2x10^{-6} pc and mass of ~ 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

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