Self-interacting Dark Matter and the Early Formation of Supermassive Black Hole

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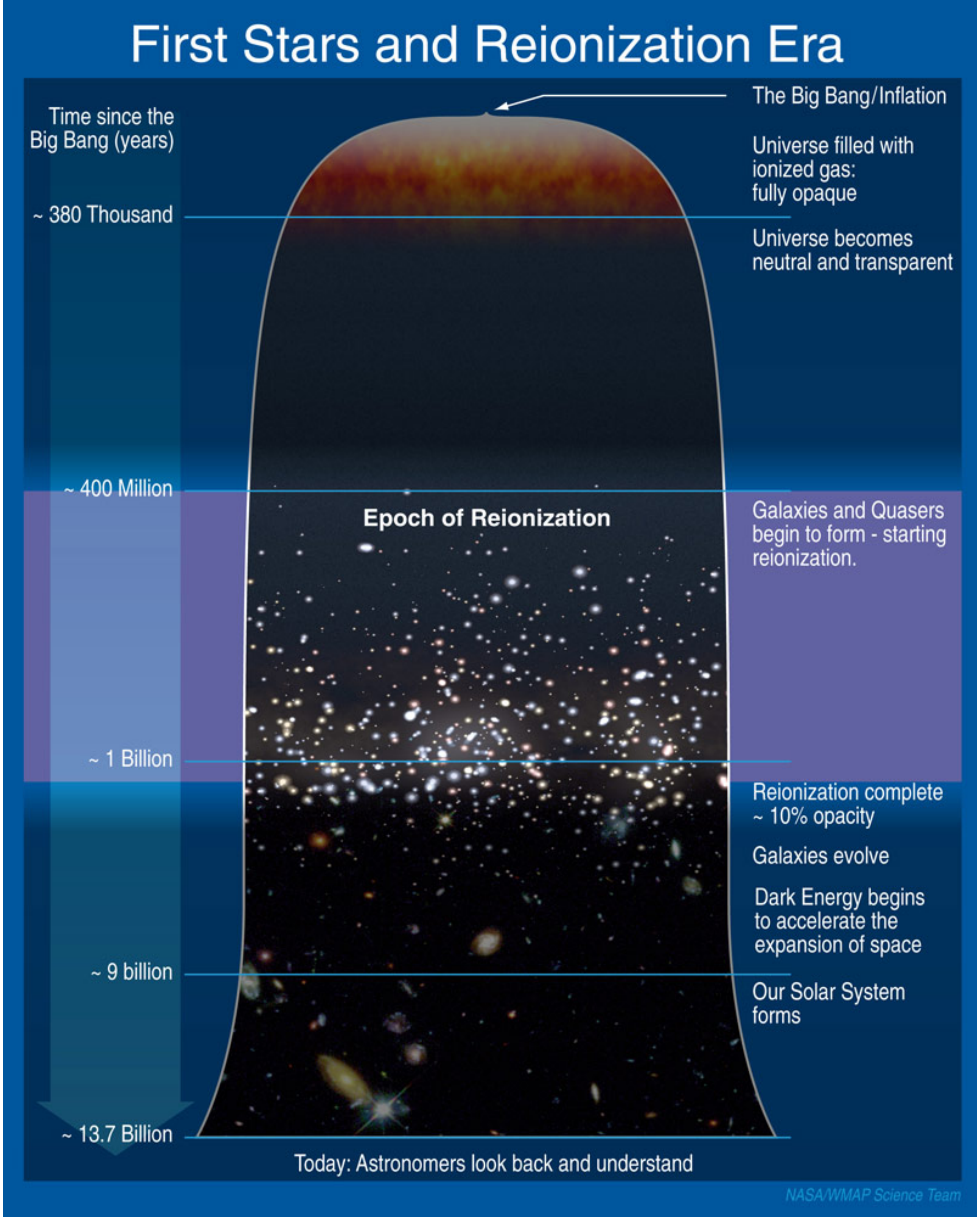
Puzzle: SMBHs in Re-ionization Era

- Most galaxies are found with supermassive black holes (SMBHs) with mass $\gtrsim 10^8 M_\odot$ at their centers.
- The early formation of SMBHs in re-ionization era $(6 < z < 20)$ has puzzled astrophysicists for decades.
- More recently, around a hundred of distant SMBHs are found in $\sim$800 Myr after the creation of our universe (redshift $z \sim 7$).

Banados et al., Nature, **553**, 473 (2018);
Wang et al., ApJ, **869**, L9 (2018);
Matsuoka et al., ApJ, **883**, 183 (2019); **872**, L2 (2019)



First Stars and Reionization Era
Time since the Big Bang (years)
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
~ 380 Thousand
Universe becomes neutral and transparent
~ 400 Million
Epoch of Reionization
Galaxies and Quasers begin to form - starting reionization.
~ 1 Billion
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
~ 9 billion
Our Solar System forms
~ 13.7 Billion
Today: Astronomers look back and understand
NASA/WMAP Science Team

Self-interacting Dark Matter (SIDM)

- Understanding DM is crucial to unravel the connection of the galaxies to their central holes.
- Rather than cold dark matter (CDM), we consider self-interacting dark matter (SIDM) to model the dark halos.
- Core-cusp, diversity problem…

Kaplinghat et al., PRL, **113**, 021302 (2014);
Kamada et al., PRL, **119**, 111102 (2017)

- Can SIDM halo revolve the puzzle via Direct Collapse scenario ??

Gravothermal Evolution of SIDM Dark Halos

- Long mean free path (LMFP) regime ($\lambda \gg H$).—

$$H = \left(\frac{\nu^2}{4\pi G\rho}\right)^{1/2}$$ (gravitational scale height) is the proper length scale of heat transfer.

The DM particles make several orbits between collisions; the heat conduction is more efficient.

- Short mean free path (SMFP) regime ($\lambda \ll H$).—

$$\lambda = \frac{1}{\sqrt{2}n\sigma}$$ (mean free path) is the proper length scale of heat transfer.

The DM motion is significantly restrained by multiple collisions; the heat conduction is less efficient.

Balberg & Shapiro, PRL, **88**, 101301 (2002);
Balberg, Shapiro & Inagaki, ApJ, **568**, 475 (2002)

Gravothermal Evolution of SIDM Dark Halos

$$\frac{\partial M}{\partial r} = 4\pi r^2(\rho_b + \rho_\chi), \quad \frac{\partial(\rho_\chi \nu_\chi^2)}{\partial r} = -\frac{GM\rho_\chi}{r^2}, \quad \frac{\partial(\rho_b \nu_b^2)}{\partial r} = -\frac{GM\rho_b}{r^2}, \quad \frac{L_\chi}{4\pi r^2} = -\frac{3}{2}\alpha\beta\nu_\chi\sigma_\chi\left(\alpha\sigma_\chi^2 + \frac{\beta}{\gamma}\frac{4\pi G}{\rho_\chi \nu_\chi^2}\right)^{-1}\frac{\partial \nu_\chi^2}{\partial r},$$

$$\frac{L_b}{4\pi r^2} = -\frac{3}{2}\frac{\beta\nu_b}{\sigma_b}\frac{\partial \nu_b^2}{\partial r}, \quad \frac{\partial L_\chi}{\partial r} = -4\pi\rho_\chi r^2 \nu_\chi^2\left(\frac{\partial}{\partial t}\right)_M \ln\frac{\nu_\chi^3}{\rho_\chi}, \quad \frac{\partial L_b}{\partial r} = -4\pi\rho_b r^2 \nu_b^2\left(\frac{\partial}{\partial t}\right)_M \ln\frac{\nu_b^3}{\rho_b},$$

- NFW profile for SIDM as initial condition.

- Hernquist profile for baryons:

$$\Phi_b(r) = -\frac{GM_H}{r + r_H}, \quad M_b(r) = \frac{M_H r^2}{(r + r_H)^2}, \qquad \rho_b(r) = \frac{1}{4\pi G}\nabla^2\Phi_b(r) = \frac{M_H r_H}{2\pi r(r + r_H)^3},$$

$M_0 = 4\pi\rho_s r_s^3$	$(\sigma/m)_0 = (r_s\rho_s)^{-1}$
$\nu_0 = (4\pi G\rho_s)^{1/2} r_s$	$L_0 = (4\pi)^{5/2} G^{3/2} \rho_s^{5/2} r_s^5$
$t_0 = (4\pi G\rho_s)^{-1/2}$	$C_0 = (4\pi G)^{3/2} \rho_s^{5/2} r_s^2$

TABLE I. Fiducial quantities, x_0, and dimensionless variables, $\hat{x}$ for gravothermal evolution

Gravothermal Evolution of SIDM Dark Halos

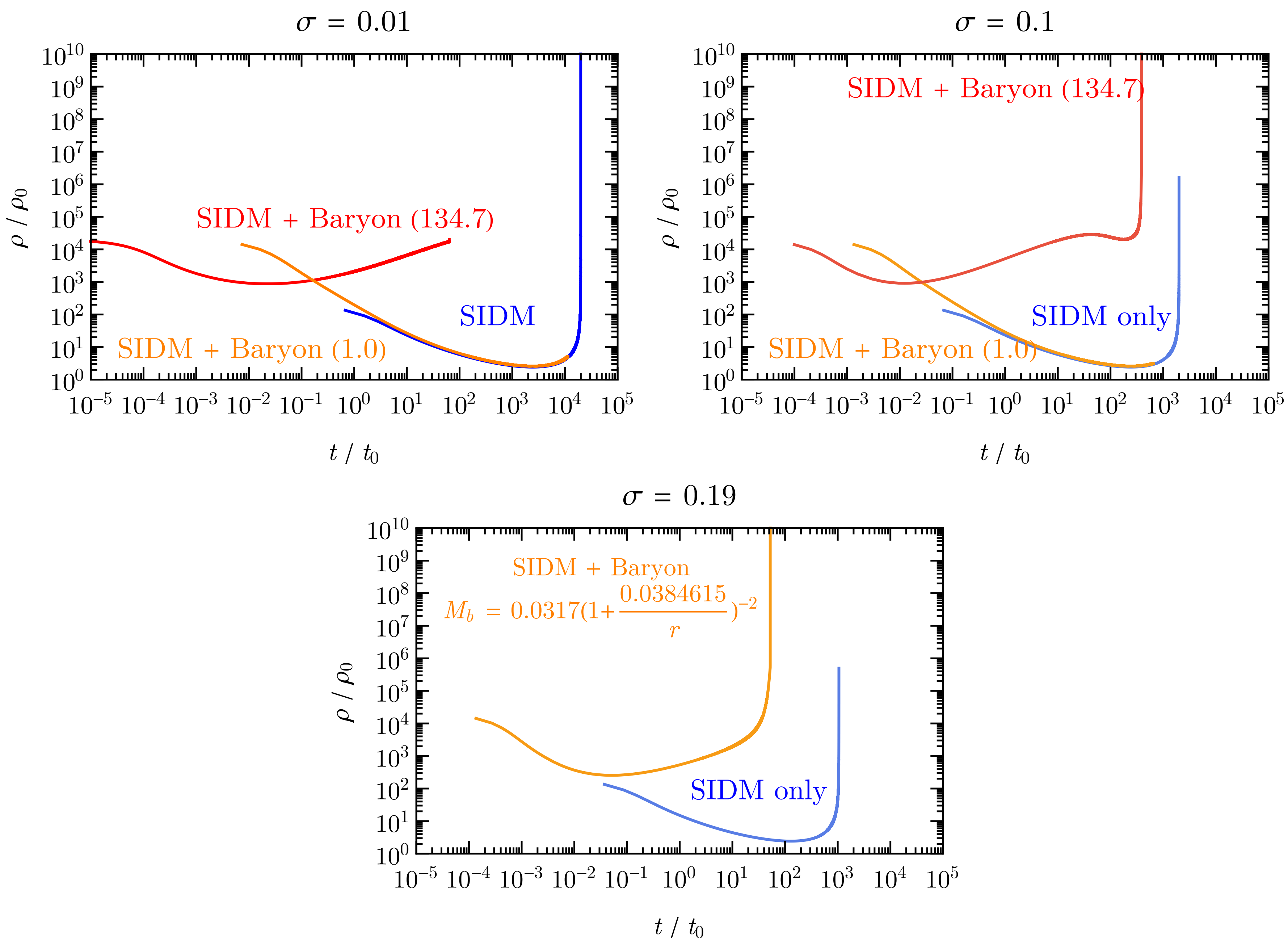


FIG. 1. Evolution of the inner density profiles. Upper left: low-redshift halo, $\sigma/m = 0.82$ cm^2/g ($\hat{\sigma} = 0.01$). Upper right: low-redshift halo, $\sigma/m = 8.2$ cm^2/g. The collapse time is reduced by a factor of 5.2. Bottom: high-redshift halo, $\sigma/m = 0.36$ cm^2/g ($\hat{\sigma} = 0.19$). The collapse time is reduced by a factor of 20.2. Note that the difference in the initial stage of the evolution is due to the fact we start the simulations with $\hat{r}_{\text{inner most}} = 10^{-4}$ (10^{-2}) for SIDM with baryons (pure SIDM).

Gravothermal Evolution of SIDM Dark Halos

- Summary of high redshift halo formed at $z = 10$ (473Myr):

$\rho_c(z = 10) \approx 5.71 \times 10^4 M_\odot/\text{kpc}^3$ and $c_{200} = 3.9$

$\rightarrow \rho_s = 2.84 \times 10^8 M_\odot/\text{kpc}^3$, $r_s = 8.9$ kpc

$$\rho_s = \frac{200}{3}\frac{c_{200}^3}{K_{c_{200}}}\rho_c, \quad r_s = \left(\frac{3M_{200}}{800\pi c_{200}^3\rho_c}\right)^{1/3}$$

and we pick $M_H = 8 \times 10^{10} M_\odot$, $r_H = 0.34$ kpc

we find for $\hat{\sigma} = 0.19$ ($\sigma/m = 0.36$ cm^2/g), the collapse time:

- **8.3 Gyr** for pure SIDM halo; **413 Myr** for SIDM with baryons
- A factor of **20** reduction !!

Gravothermal Evolution of SIDM Dark Halos

- Inner/Secondary core emergence

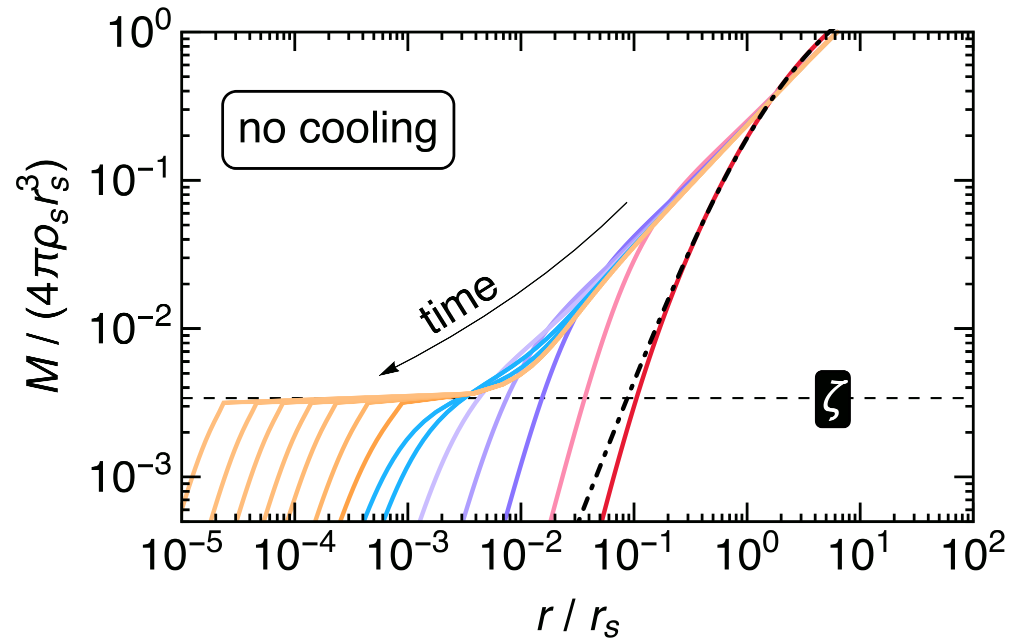
$$\frac{\mathcal{M}}{M_{200}} = \frac{\mathcal{M}}{M_{2\mathrm{nd}}}\frac{M_{2\mathrm{nd}}}{M_0}\frac{M_0}{M_{200}} = \frac{\mathcal{M}}{M_{2\mathrm{nd}}}\zeta\frac{1}{K_{c_{200}}}$$

- The mass of the inner core follows

$$\zeta \equiv \frac{M_{2\mathrm{nd}}}{M_0} = 0.075((\sigma/m)r_s\rho_s)^{2/3}$$

(**empirical fitting**)

- Direct Collapse of the inner core ??



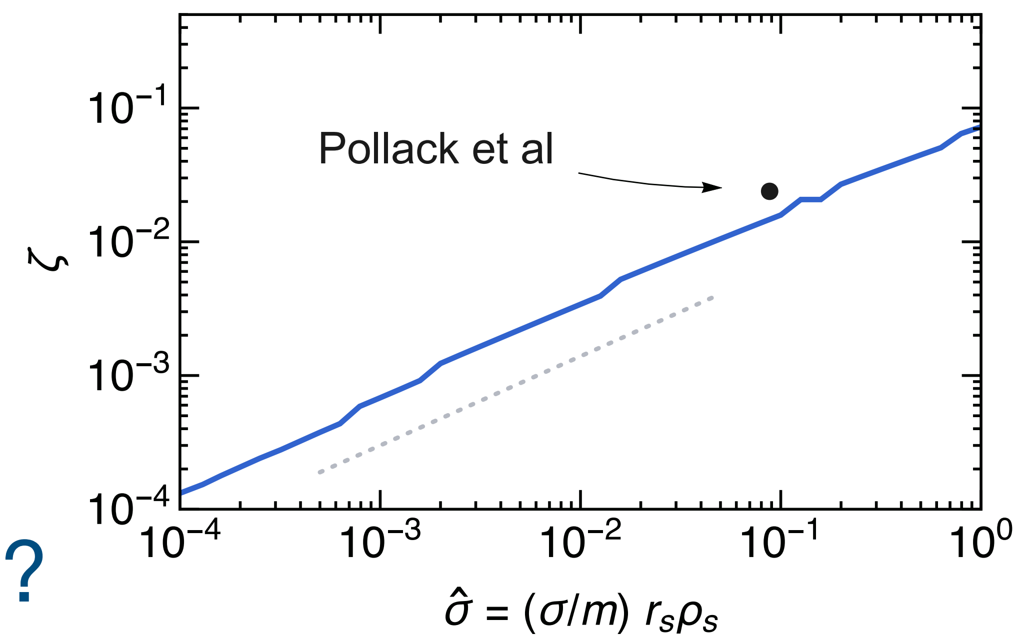


FIG. 3. $M_{2\mathrm{nd}}/M_0$ as a function of $(\sigma/m)r_s\rho_s$

Pollack, Spergel & Steinhardt , ApJ, **804**, 131 (2015)

Dynamical Instabilities

- The dynamical instability in Newtonian gravity requires the (pressure-averaged) adiabatic index of the core $\langle\Gamma\rangle \leq \Gamma_{\textbf{cr.}} = 4/3$, whereas $4/3 \leq \Gamma \leq 5/3$ for ideal gas.

- In GR, the pressure (thermal energy) plays a role in gravitational energy such that

$$\Gamma_{\textbf{cr.}} = 4/3 + (\textbf{pressure contribution})$$

Chandrasekhar, PRL, **12**, 114; ApJ, **140**, 417 (1964)

Dynamical Instabilities

- Truncated Maxwell-Boltzmann model

  (Merafina & Ruffini, A&A, **221**, 4 (1989))
- The critical compactness $\sim 10^{-2}$
- The critical central velocity dispersion

$$v_d(0) \simeq 0.55 \sim 0.57c$$

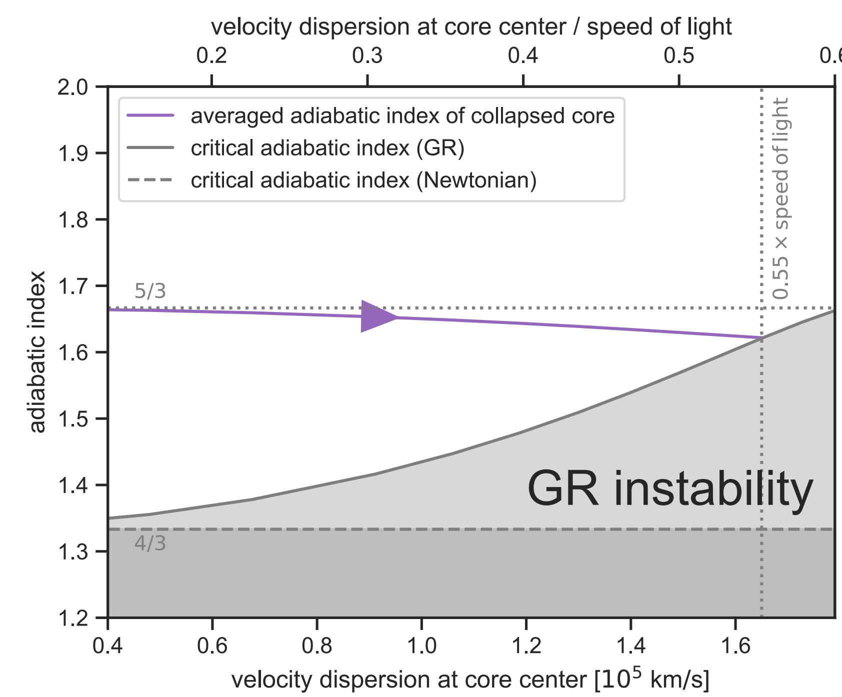


FIG. 4. Adiabatic indices as functions of $v_d(0)$ (truncated MB model) at $b = 0.1$

TABLE III. Marginal stable points corresponding to different temperature parameters $b = k_B T_R/mc^2$. We find it hard to achieve the GR dynamical instability for $b \lesssim 10^{-2}$. For $b \gtrsim 1.0$ pair production effects of SIDM need to be taken into account and the results should be modified.

b	W_0	$\bar{\mathcal{M}}$	$\bar{R}$	$\mathcal{C} = G\mathcal{M}/c^2R$	$\epsilon_c(0)/mc^2$	$\bar{\rho}(0)$	$\bar{p}(0)$	$v_d(0)/c$	$\langle\Gamma\rangle = \Gamma_{\rm cr.}$
5.0	6.46760×10^{-2}	2.06291×10^{-1}	2.59300×10^{0}	7.95569×10^{-2}	4.77940×10^{-1}	1.59029×10^{-1}	1.69197×10^{-2}	5.64962×10^{-1}	1.62360
3.0	1.07885×10^{-1}	1.58848×10^{-1}	2.00200×10^{0}	7.93447×10^{-2}	4.78539×10^{-1}	2.68968×10^{-1}	2.85863×10^{-2}	5.64662×10^{-1}	1.62359
1.0	3.25432×10^{-1}	8.89055×10^{-2}	1.13900×10^{0}	7.80557×10^{-2}	4.82454×10^{-1}	8.73831×10^{-1}	9.24768×10^{-2}	5.63460×10^{-1}	1.62352
0.5	6.57400×10^{-1}	5.98030×10^{-2}	7.88001×10^{-1}	7.58920×10^{-2}	4.89672×10^{-1}	1.99392×10^{0}	2.09844×10^{-1}	5.61895×10^{-1}	1.62234
0.3	1.11294×10^{0}	4.30745×10^{-2}	5.94001×10^{-1}	7.25159×10^{-2}	5.01296×10^{-1}	4.04500×10^{0}	4.22622×10^{-1}	5.59857×10^{-1}	1.62321
0.1	3.82510×10^{0}	1.47252×10^{-2}	3.36001×10^{-1}	4.38247×10^{-2}	6.19961×10^{-1}	5.81339×10^{1}	5.87858×10^{0}	5.50785×10^{-1}	1.62163

Angular Momentum of the Dark Halos

- Universal angular momentum profile of dark halo?

Bullock et al., ApJ, **555**, 240 (2001)

- To reach the direct collapse into a BH without fragmentation, the angular momentum of the inner core must satisfy $\mathcal{J} < (G/c)\mathcal{M}^2$

- For halo mass $M_{200} = 10^{12} M_\odot$ with concentration $c_{200} = 4$; the core radius starts to form around $0.1 r_s$, by using NFW profile and the fitting function from N-body simulations

Liao, Chen & Chu, ApJ, **844**, 86 (2017)

$$\mathcal{M} = 5.44 \times 10^9 M_\odot$$

$$\mathcal{J} = 7.29 \times 10^7 M_\odot \cdot \mathrm{Mpc} \cdot \mathrm{km/s} \simeq 10^2 (G/c)\mathcal{M}^2 \gg$$

$$(G/c)\mathcal{M}^2 = 4.24 \times 10^5 M_\odot \cdot \mathrm{Mpc} \cdot \mathrm{km/s}.$$

Angular Momentum of the Dark Halos

- The dissipation of angular momentum due to viscosity (SMFP)

$$\mathcal{J}(t) = \mathcal{J}(t_i)\exp\left(-\frac{20\pi}{3\sqrt{6}}\int_{t_i}^{t}\frac{\sqrt{b(t')}R(t')}{\mathcal{M}(\sigma/m)}cdt'\right)$$

- To estimate, we take

$\mathscr{M} = 10^{10}M_{\odot}, R = 0.1r_s \simeq 1$kpc, $\sigma/m = 3$cm^2/g and $b = k_B T_R/mc^2 = 10^{-6}$

The time Δt for $\mathcal{J}(t) \simeq 10^{-4}\mathcal{J}(t_i)$ is around 2×10^{15} s $\simeq$ 64 Myr, which can be less or *around* the collapse time $10^1 \sim 10^2$ Myr, as the viscosity and conductivity share the same microscopic nature of "collisional" SIDM.

Summary

- For pure SIDM, the inner core mass follows $\zeta \equiv \frac{M_{\mathrm{2nd}}}{M_0} = 0.075((\sigma/m)r_s\rho_s)^{2/3}$
- With baryons, a larger r_H leads to larger M_{2nd} than pure SIDM case; M_{2nd} is always smaller than M_H but insensitive to the change of M_H when r_H is very small compare to r_s.
- Qualitatively, for SIDM halo with baryons: larger M_H ; smaller r_H will lead to a faster collapse.
- The sufficient condition for the inner core to collapse into a BH: $v_d(0) \simeq 0.55 \sim 0.57c$.
- The angular momentum of SIDM halo can be transported out within the collapse time, and a Direct Collapse of a BH $\sim 10^9 - 10^{10} M_\odot$ before redshift $z = 7$ is possible !!

Thanks for your attention !