Aggressively-Dissipative Dark Dwarfs

Simulating & Modelling Atomic Dark Matter in Dwarf Galaxies

Sandip Roy

Princeton University

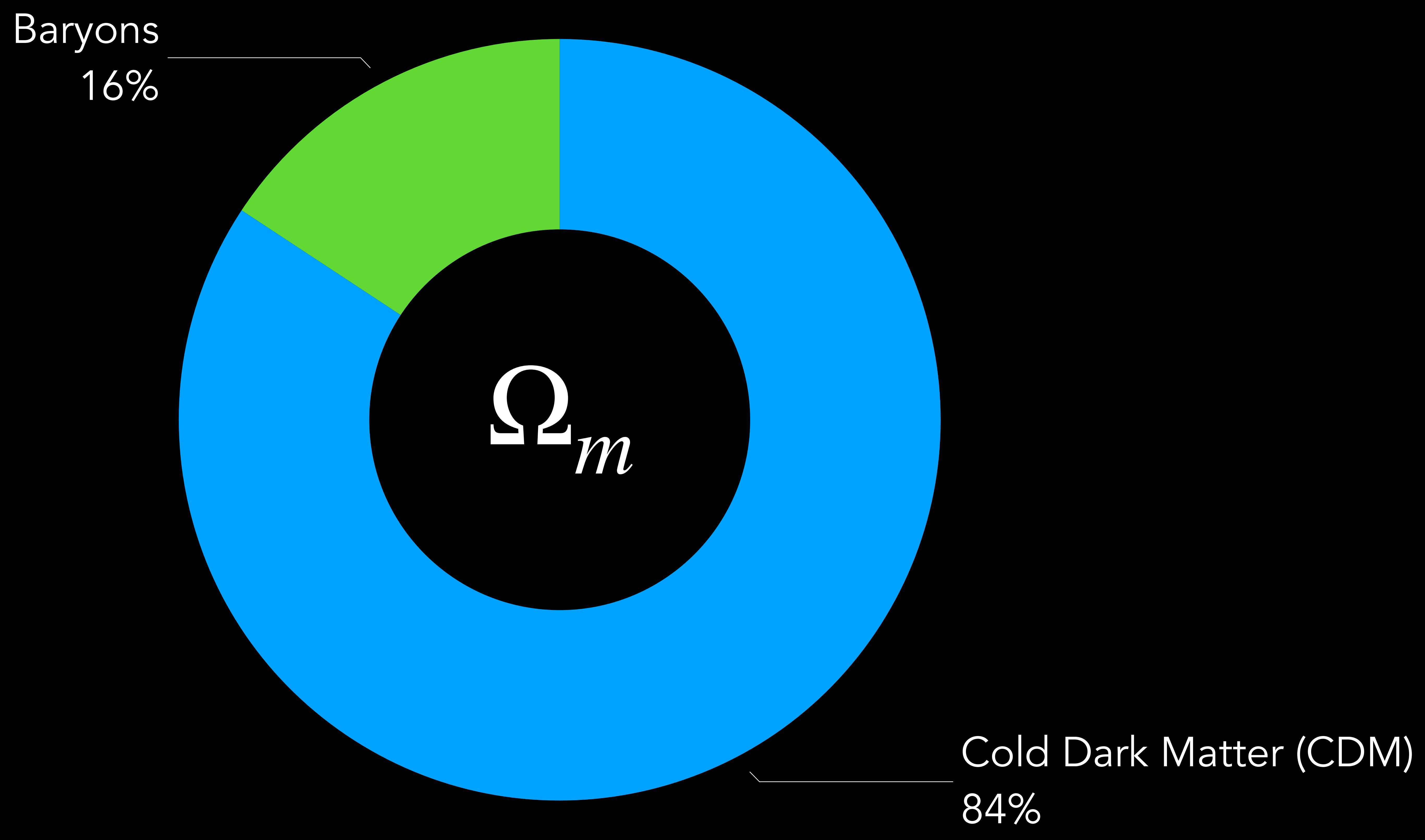
with C. Gemmell, X. Shen, J. Barron, M. Lisanti, D. Curtin, N. Murray, P. F. Hopkins

Arxiv: 2304.09878 (Ap.J. Letters) & 2311.02148 (Ap.J.) & **2408.15317**

TeVPA - University of Chicago - August 2024

Motivation

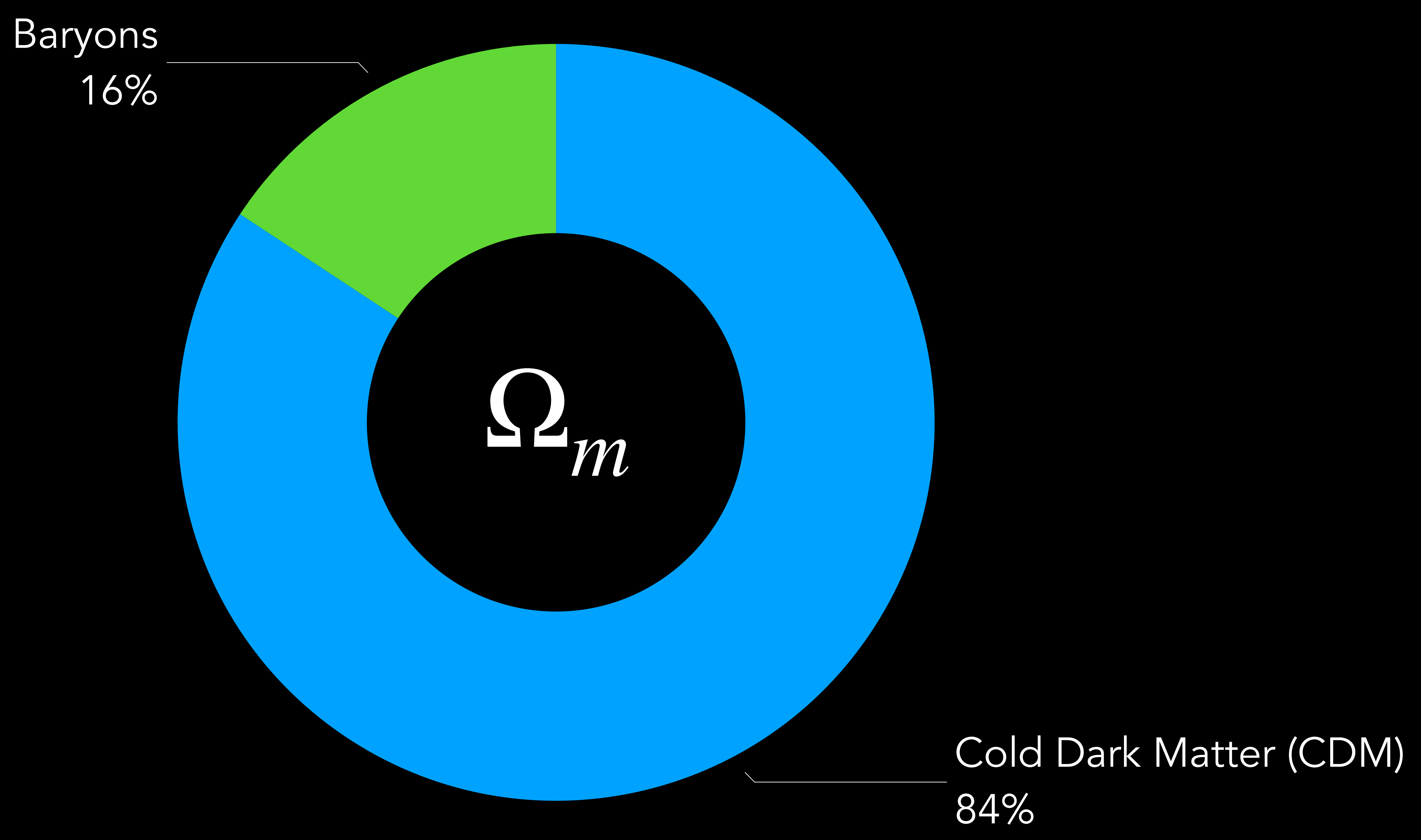
Motivation



Planck Collaboration (1807.06209)

Motivation

Need to test collisionless, CDM paradigm on sub-galactic scales

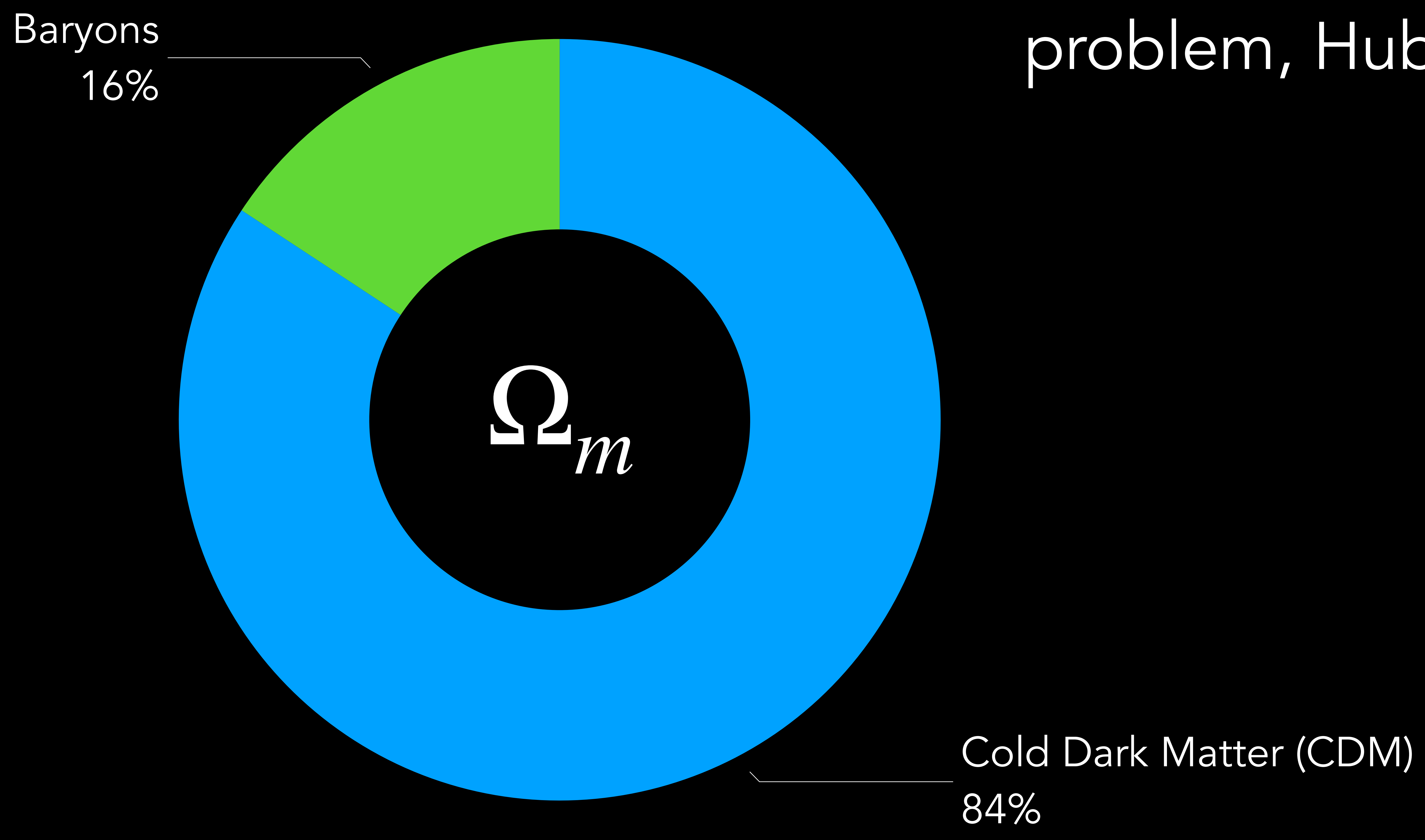


Planck Collaboration (1807.06209)

Motivation

Need to test collisionless, CDM paradigm on sub-galactic scales

Dark sectors are theoretically motivated (hierarchy problem, Hubble tension, etc.)



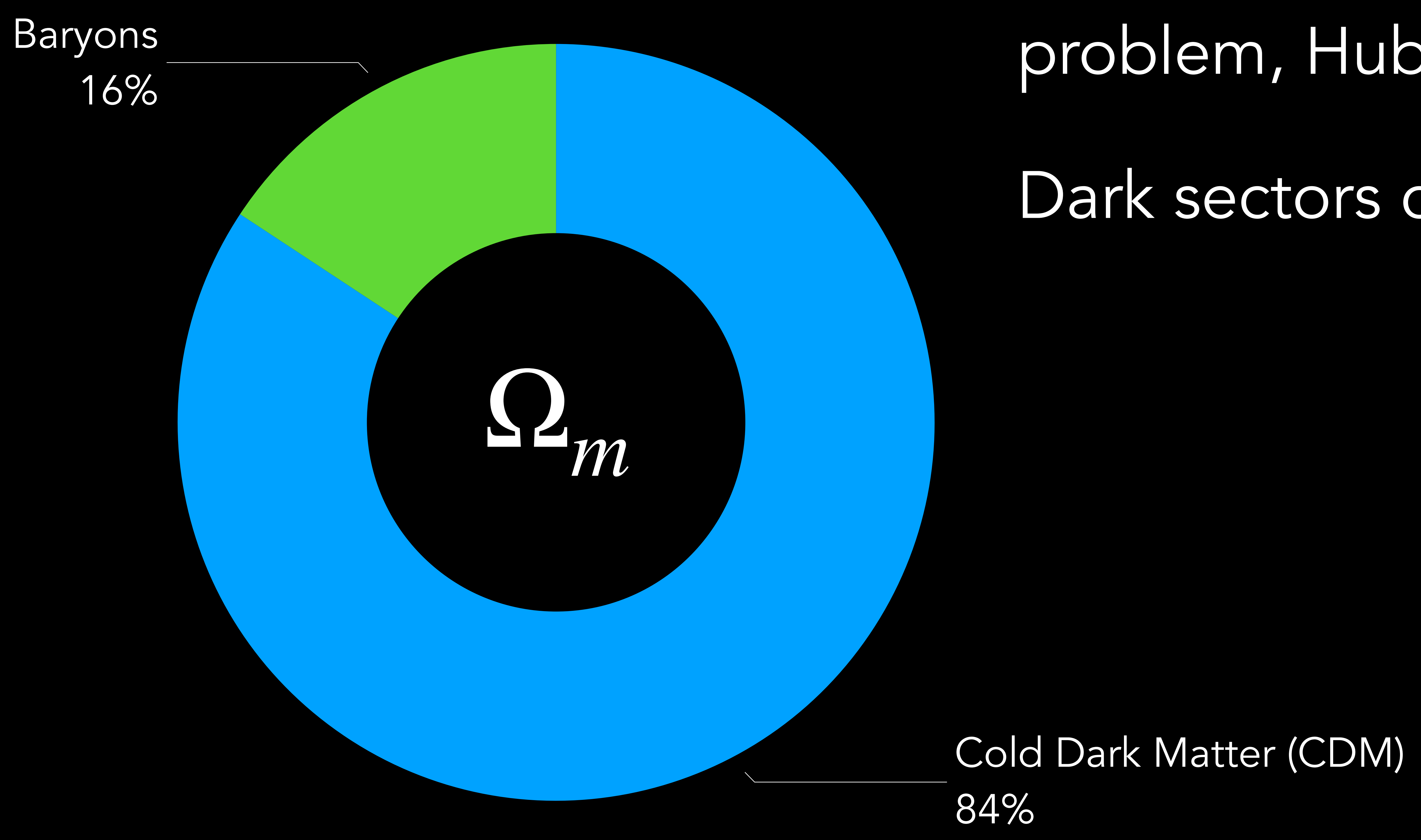
Planck Collaboration (1807.06209)

Motivation

Need to test collisionless, CDM paradigm on sub-galactic scales

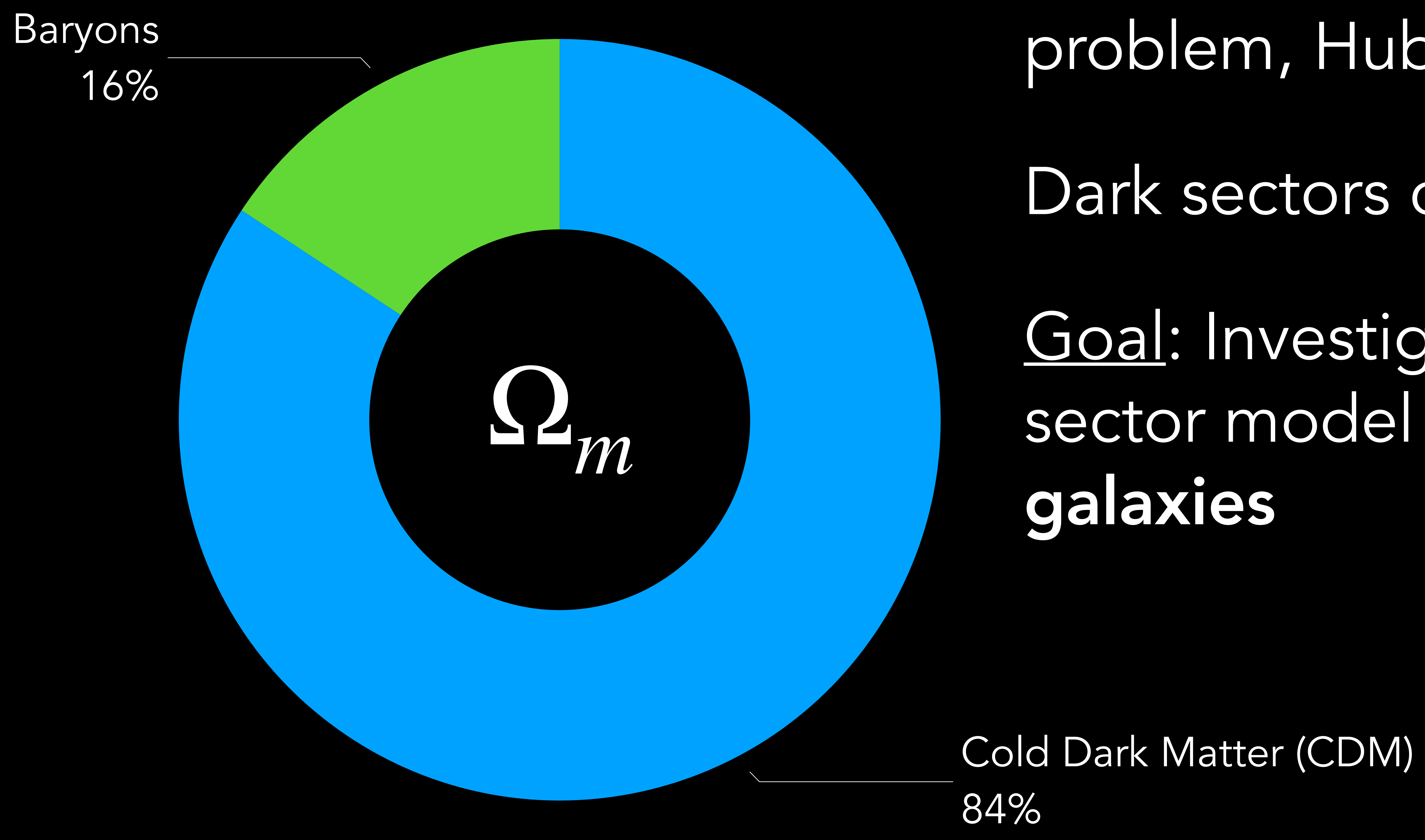
Dark sectors are theoretically motivated (hierarchy problem, Hubble tension, etc.)

Dark sectors can comprise dissipative subfractions



Planck Collaboration (1807.06209)

Motivation



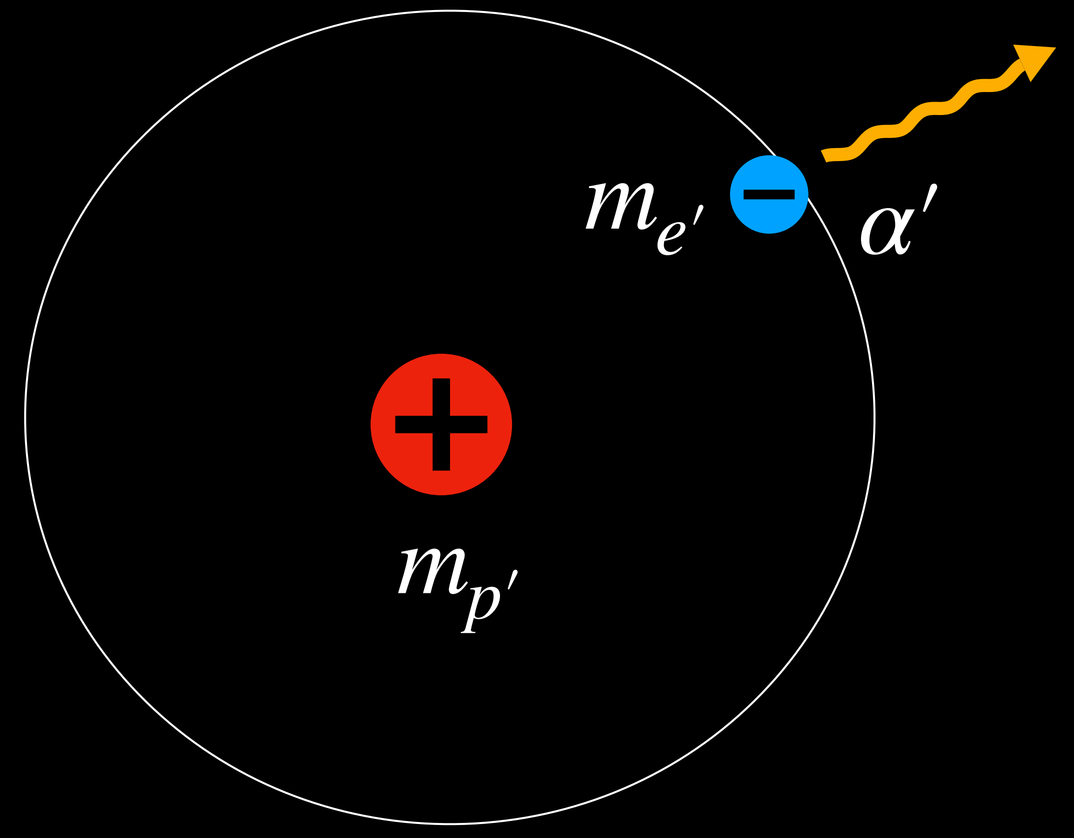
Planck Collaboration (1807.06209)

Need to test collisionless, CDM paradigm on sub-galactic scales

Dark sectors are theoretically motivated (hierarchy problem, Hubble tension, etc.)

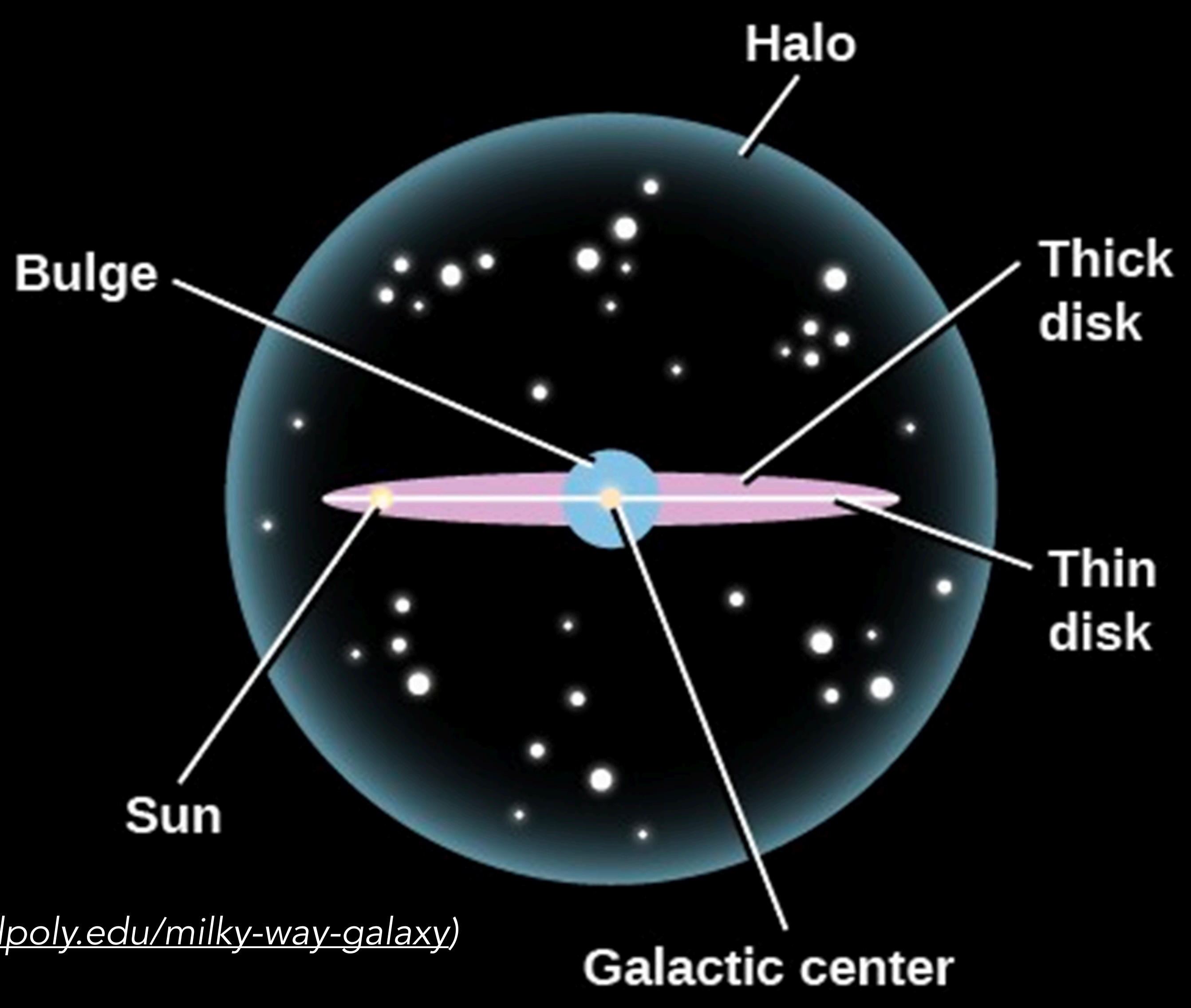
Dark sectors can comprise dissipative subfractions

Goal: Investigate effects of basic, dissipative dark sector model (**atomic dark matter**) in **dwarf galaxies**



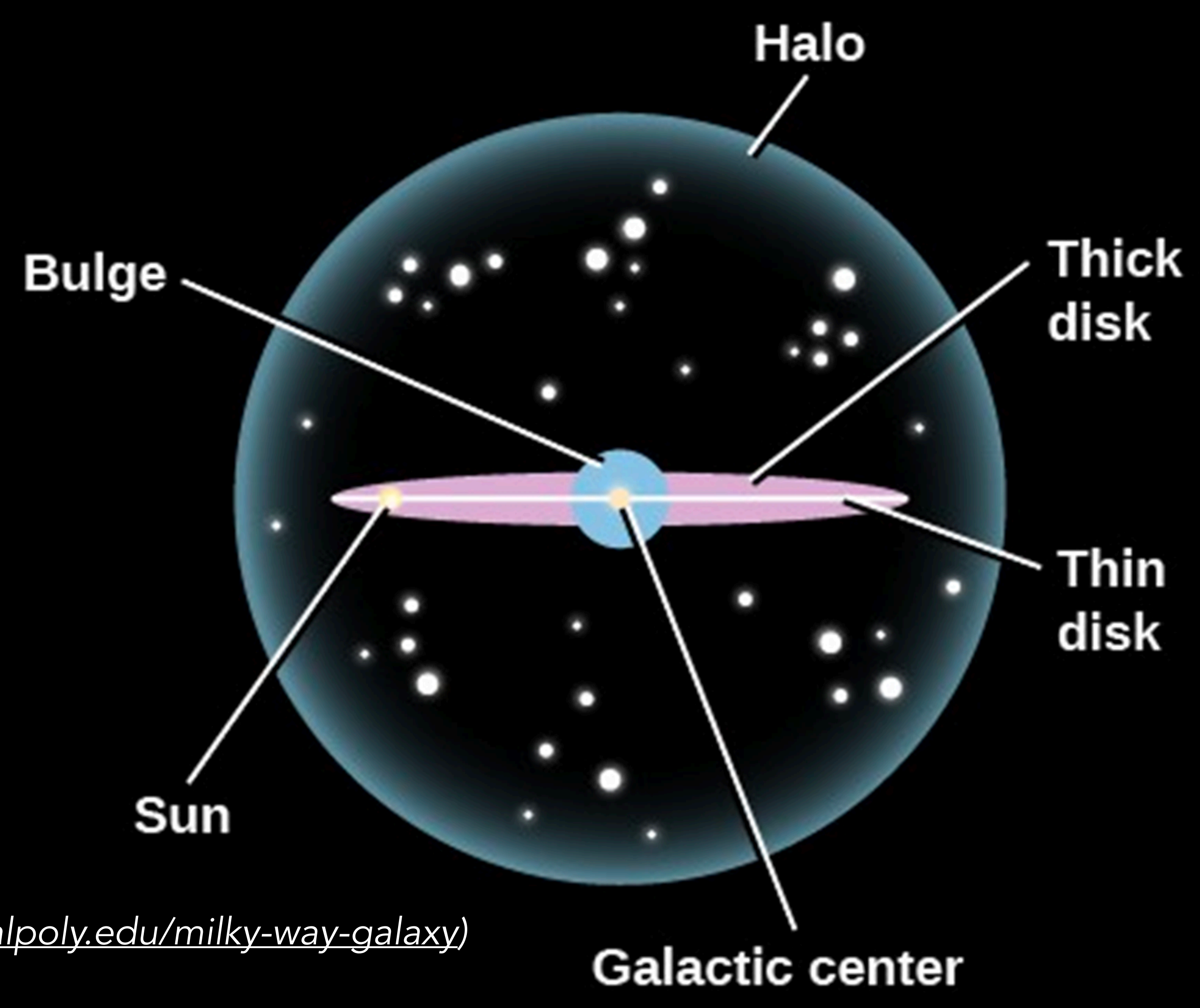
Atomic Dark Matter (aDM) Galactic Morphology

Atomic Dark Matter (aDM) Galactic Morphology

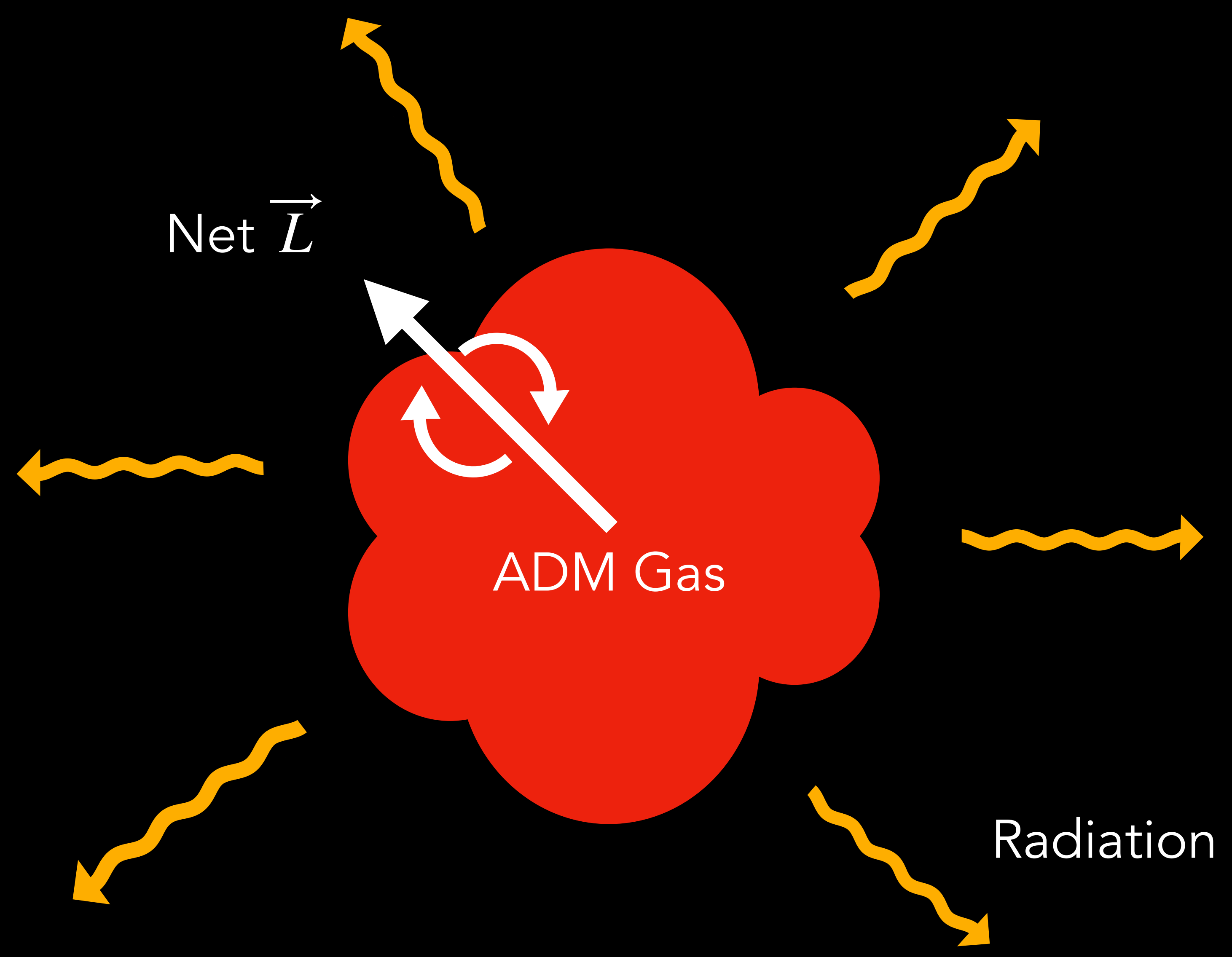


(evolution.calpoly.edu/milky-way-galaxy)

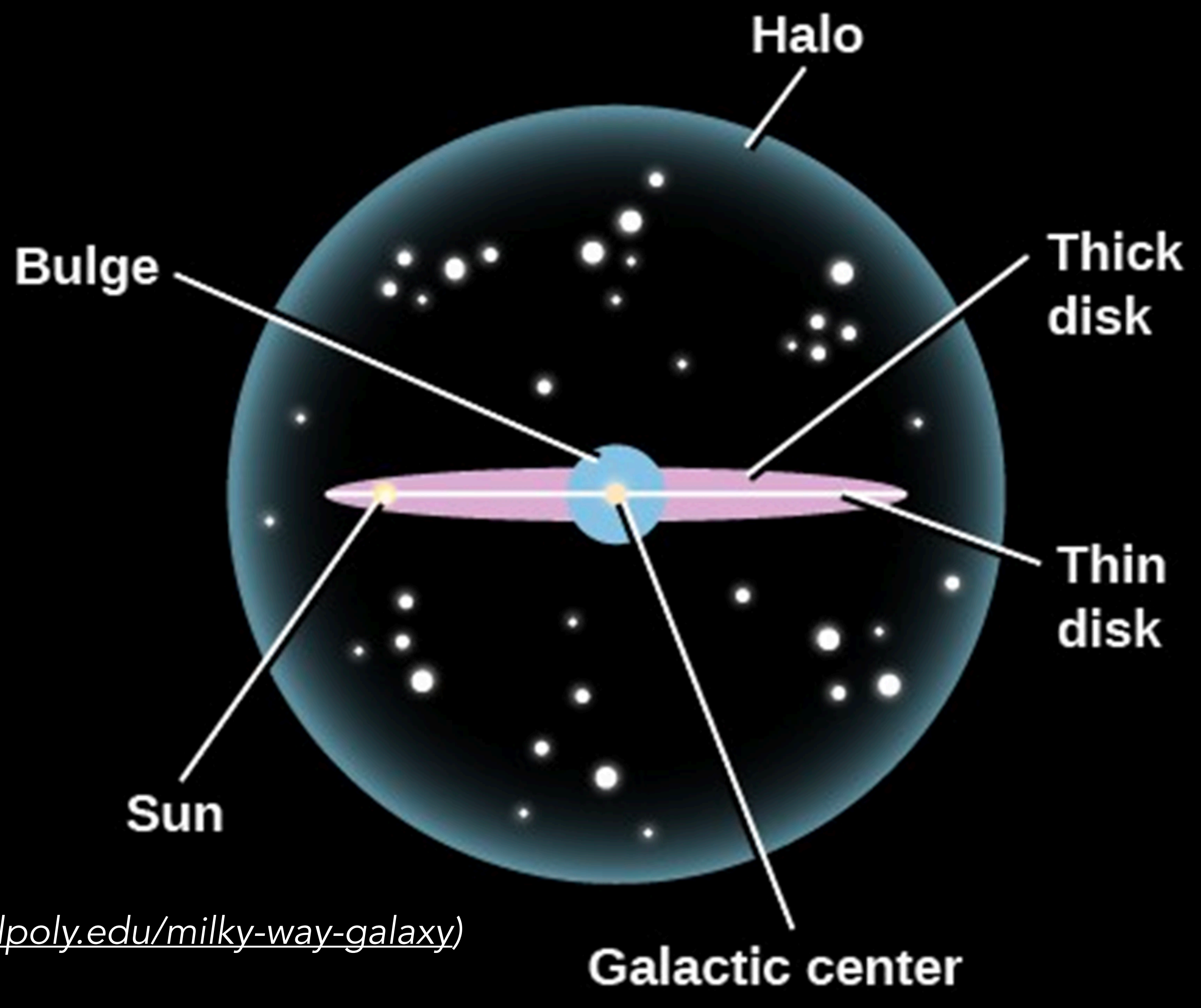
Atomic Dark Matter (aDM) Galactic Morphology



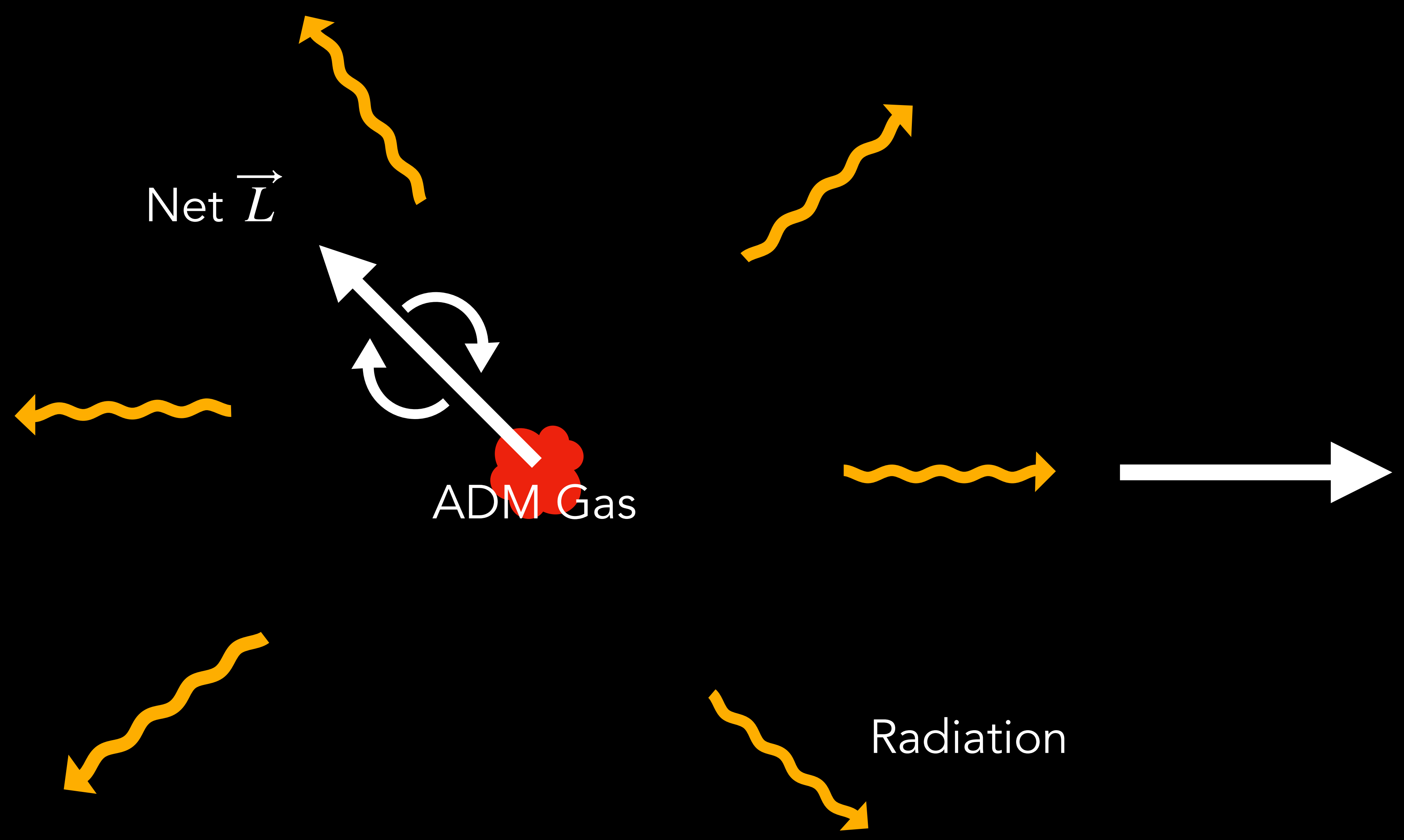
(evolution.calpoly.edu/milky-way-galaxy)

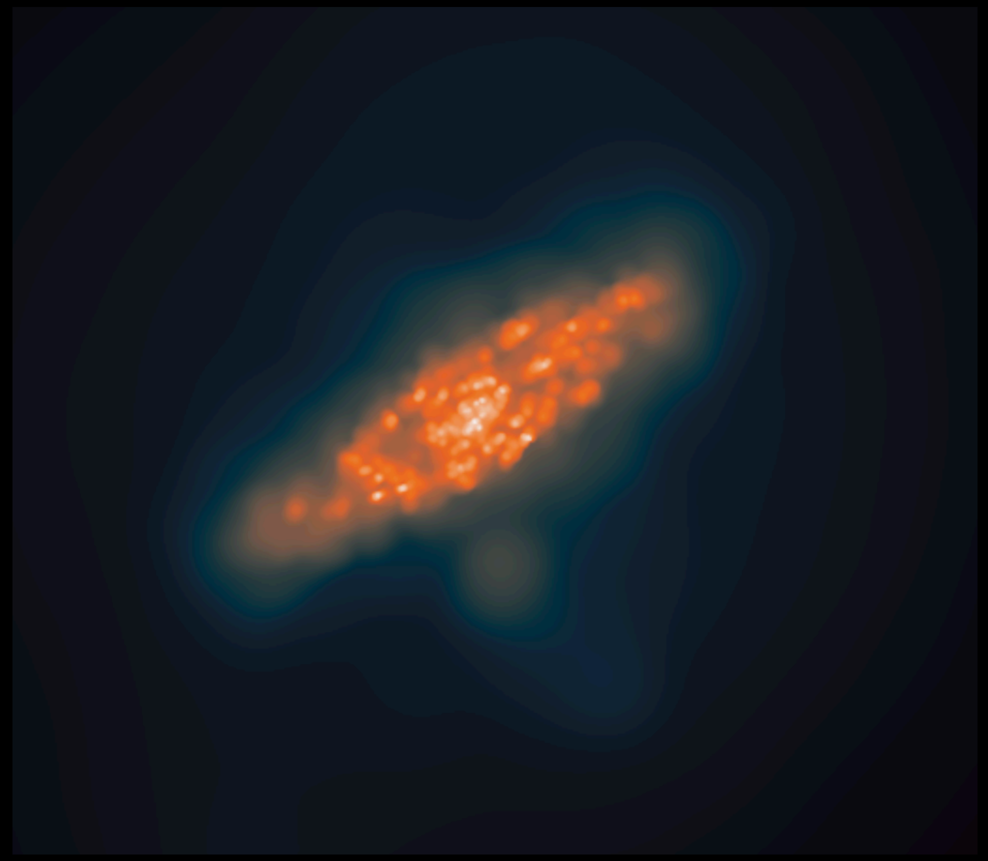


Atomic Dark Matter (aDM) Galactic Morphology



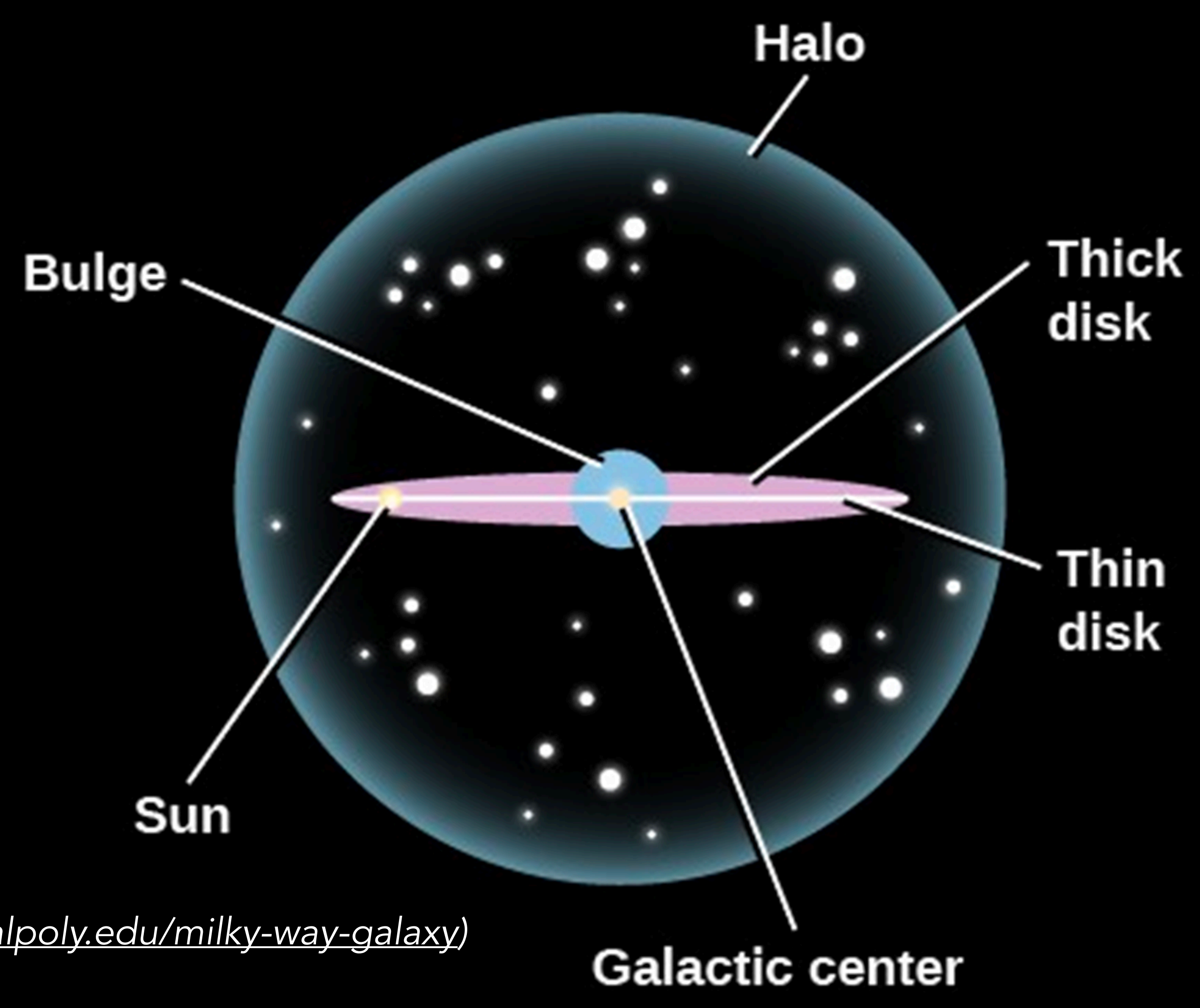
(evolution.calpoly.edu/milky-way-galaxy)



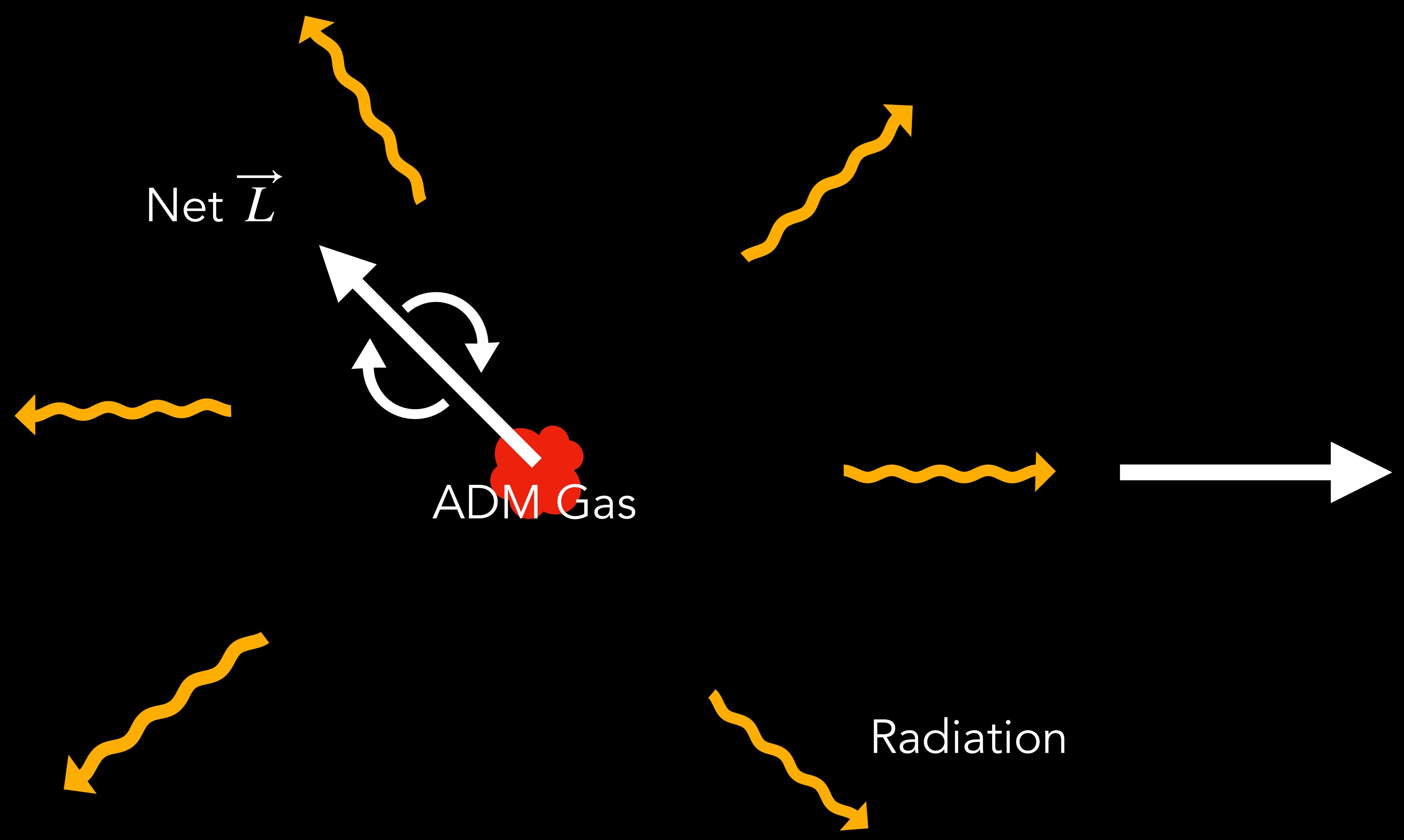


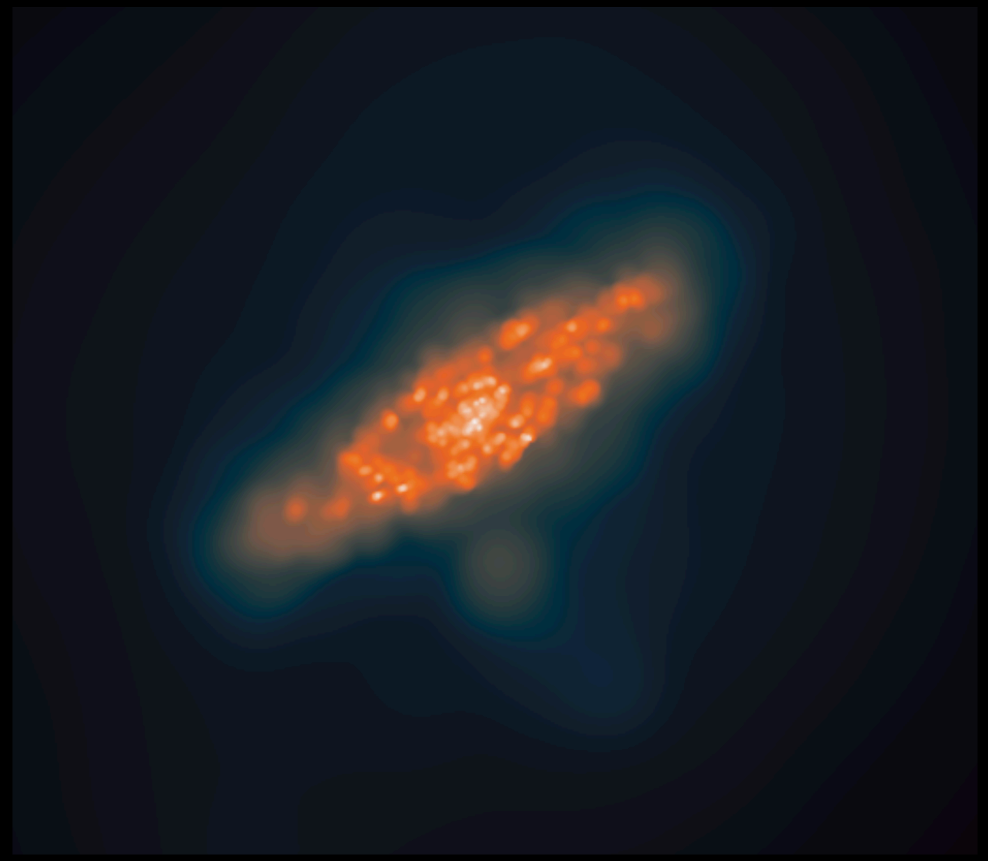
Fan et al. (1303.1521), Ghalsasi et al. (1712.04779), Kramer et al. (1604.01407), Schutz et al. (1711.03103), Buch et al. (1808.05603), Widmark et al. (2105.14030)

Atomic Dark Matter (aDM) Galactic Morphology



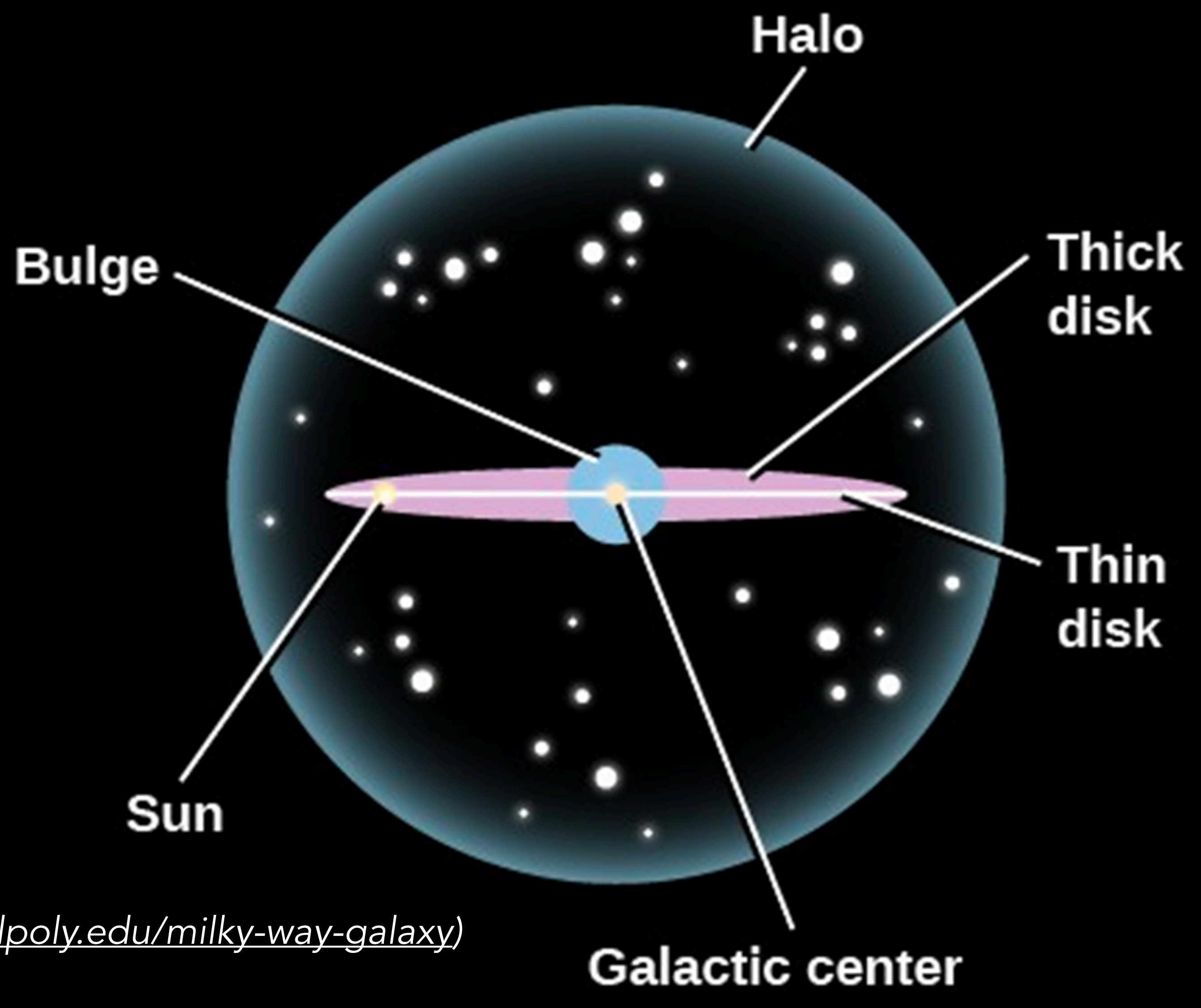
(evolution.calpoly.edu/milky-way-galaxy)



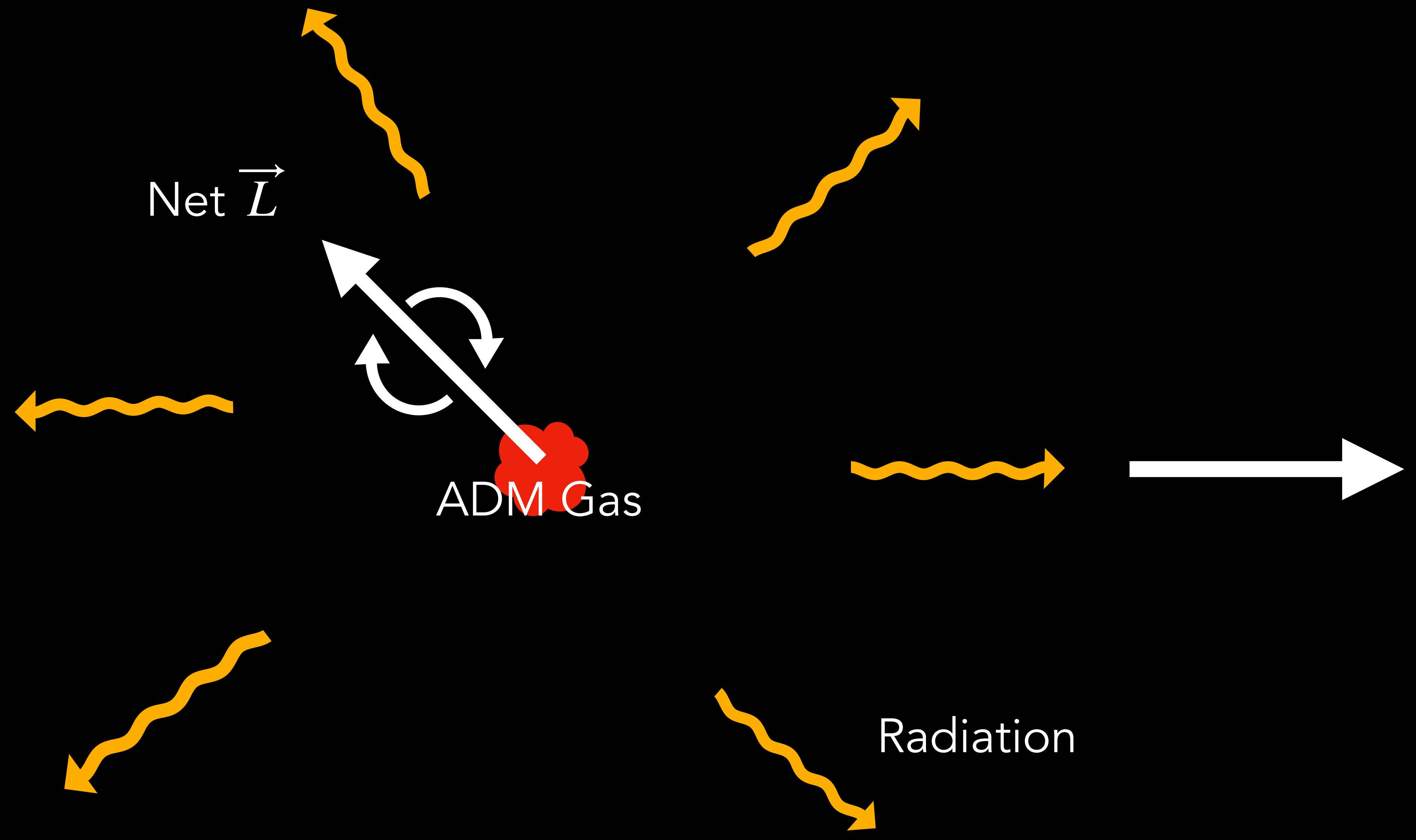


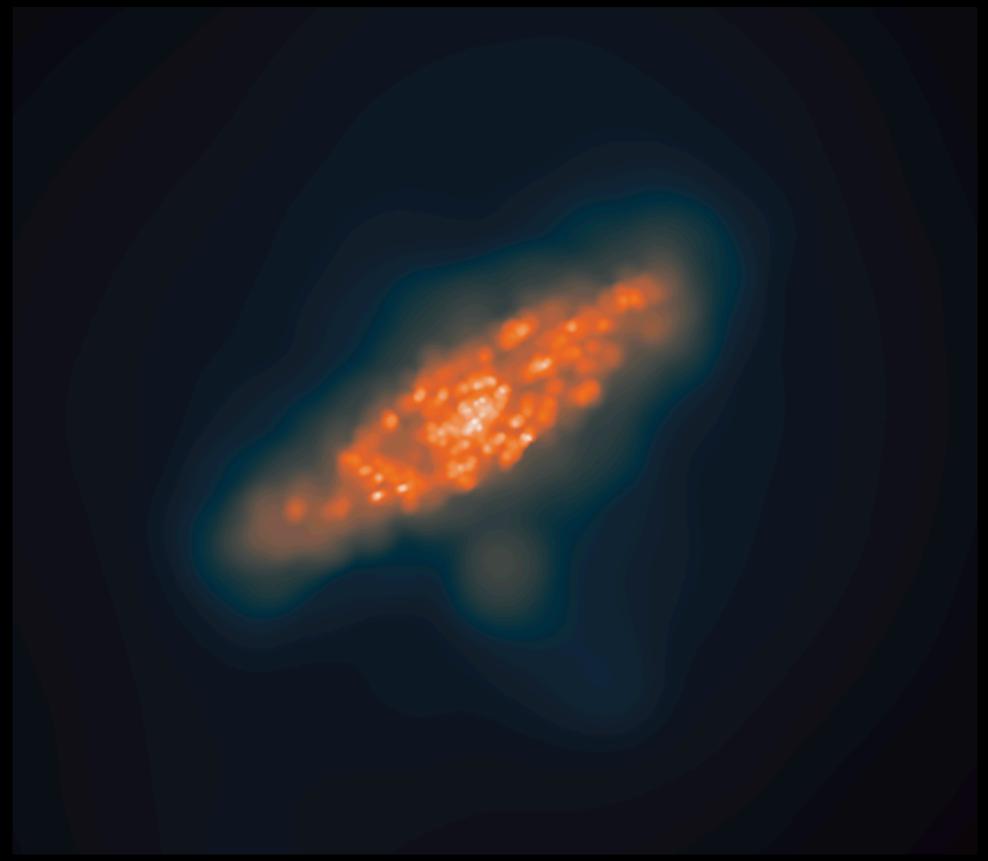
We simulated aDM in dwarf galaxies

Atomic Dark Matter (aDM) Galactic Morphology



(evolution.calpoly.edu/milky-way-galaxy)





We simulated aDM in dwarf galaxies

Fairly complicated? Aggressively-cooling is actually simple!

Talk Outline

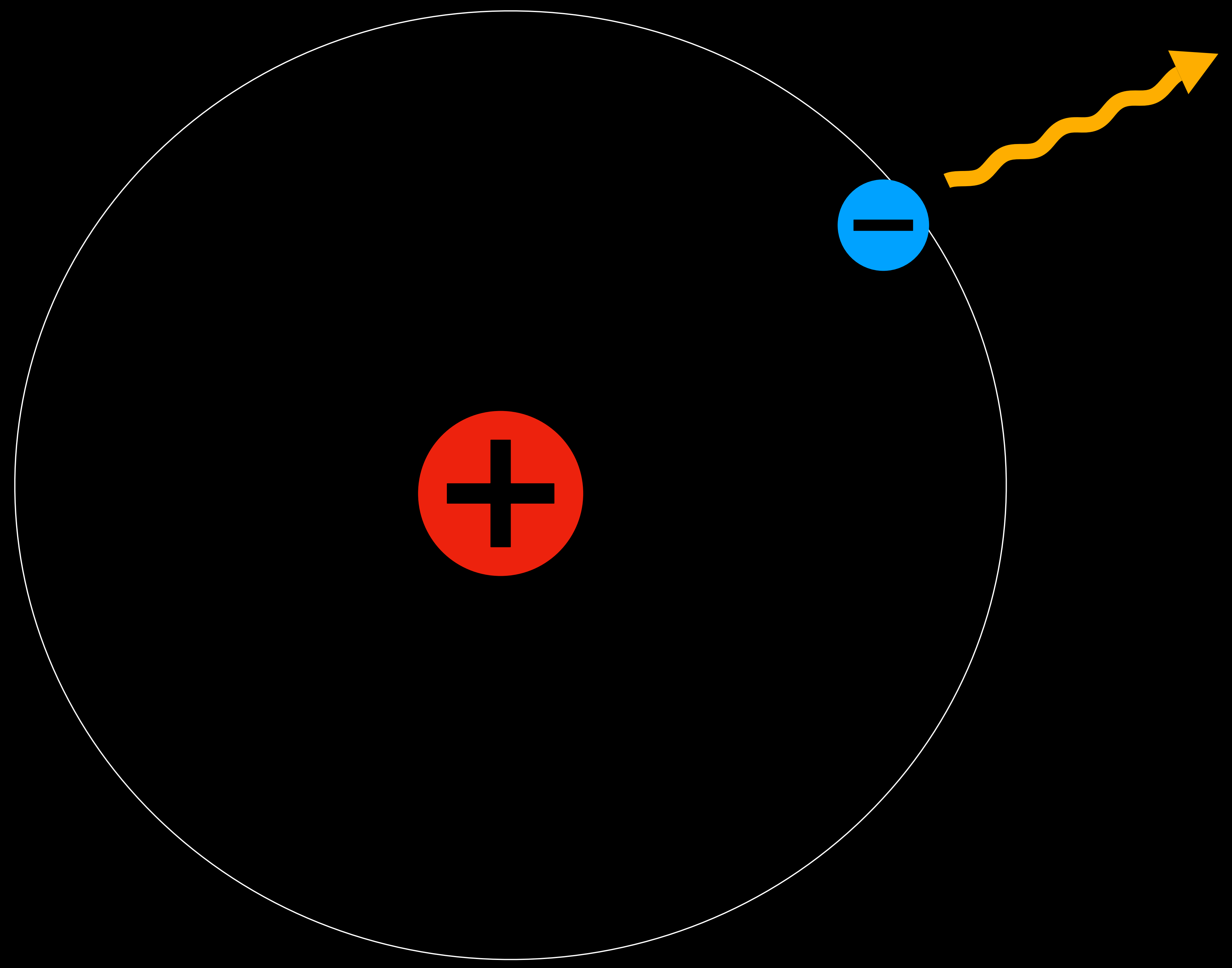
Overview of aDM physics

aDM parameter space explored

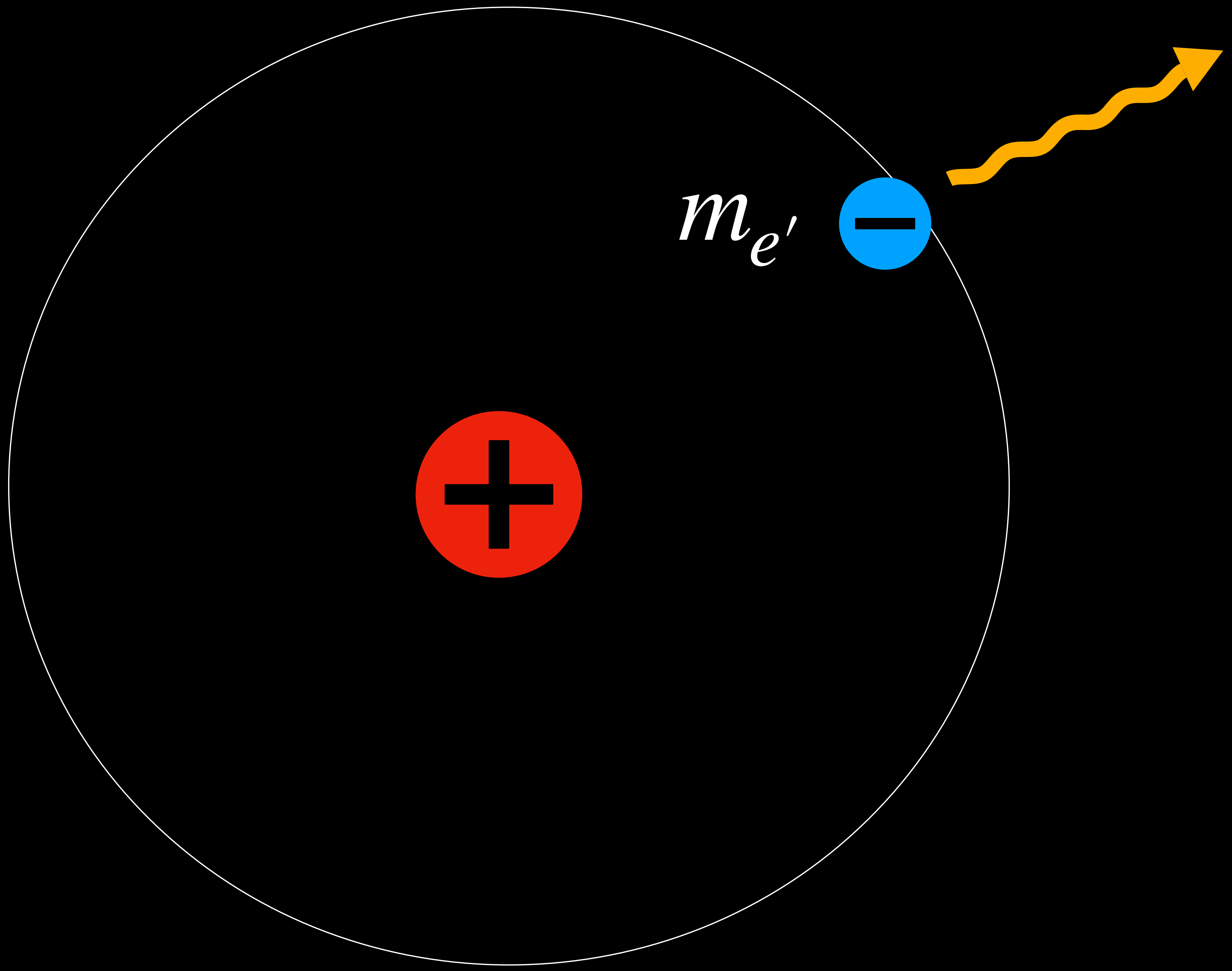
Final results

Atomic Dark Matter Intro & Simulation Setup

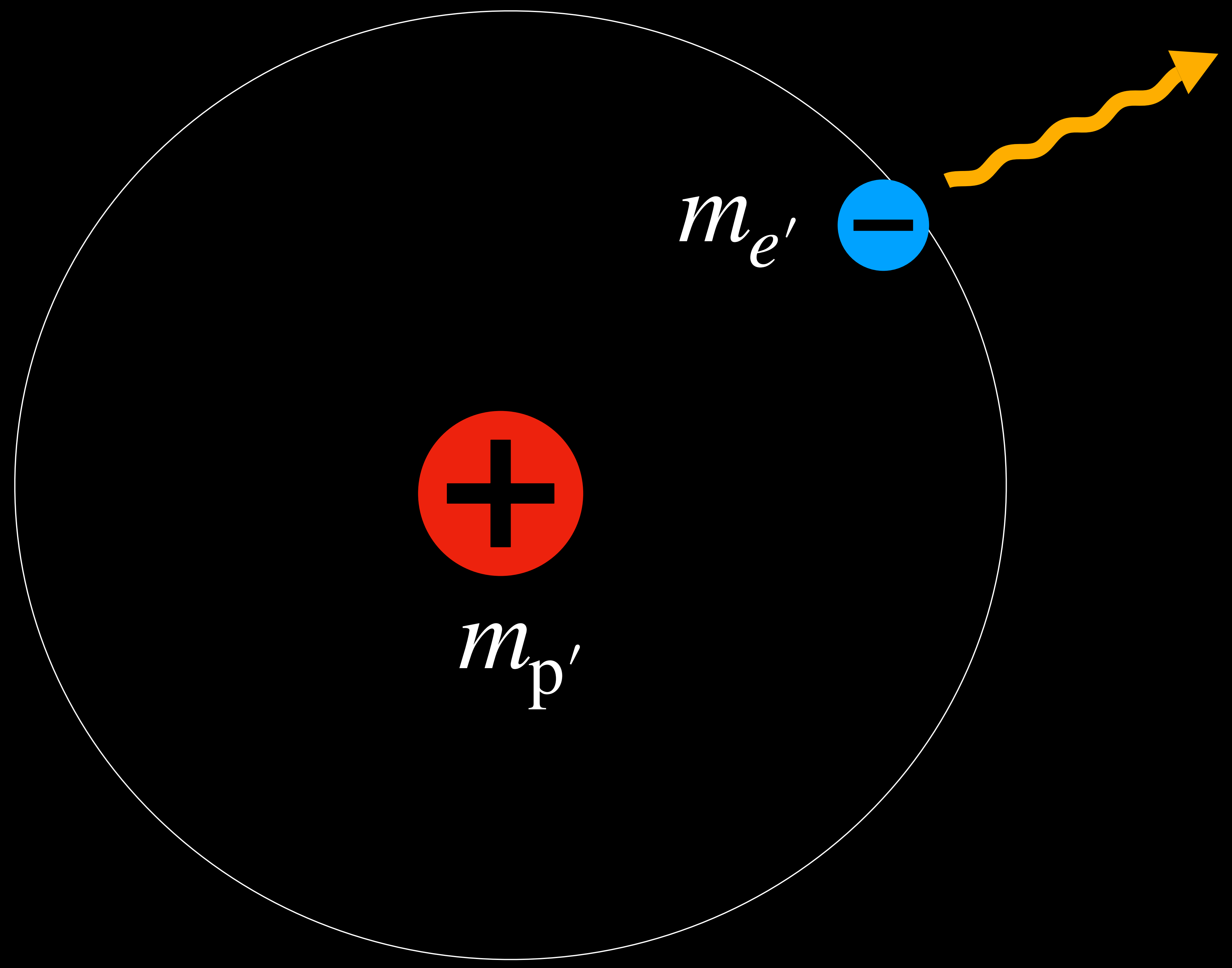
aDM Parameters (Five Numbers…)



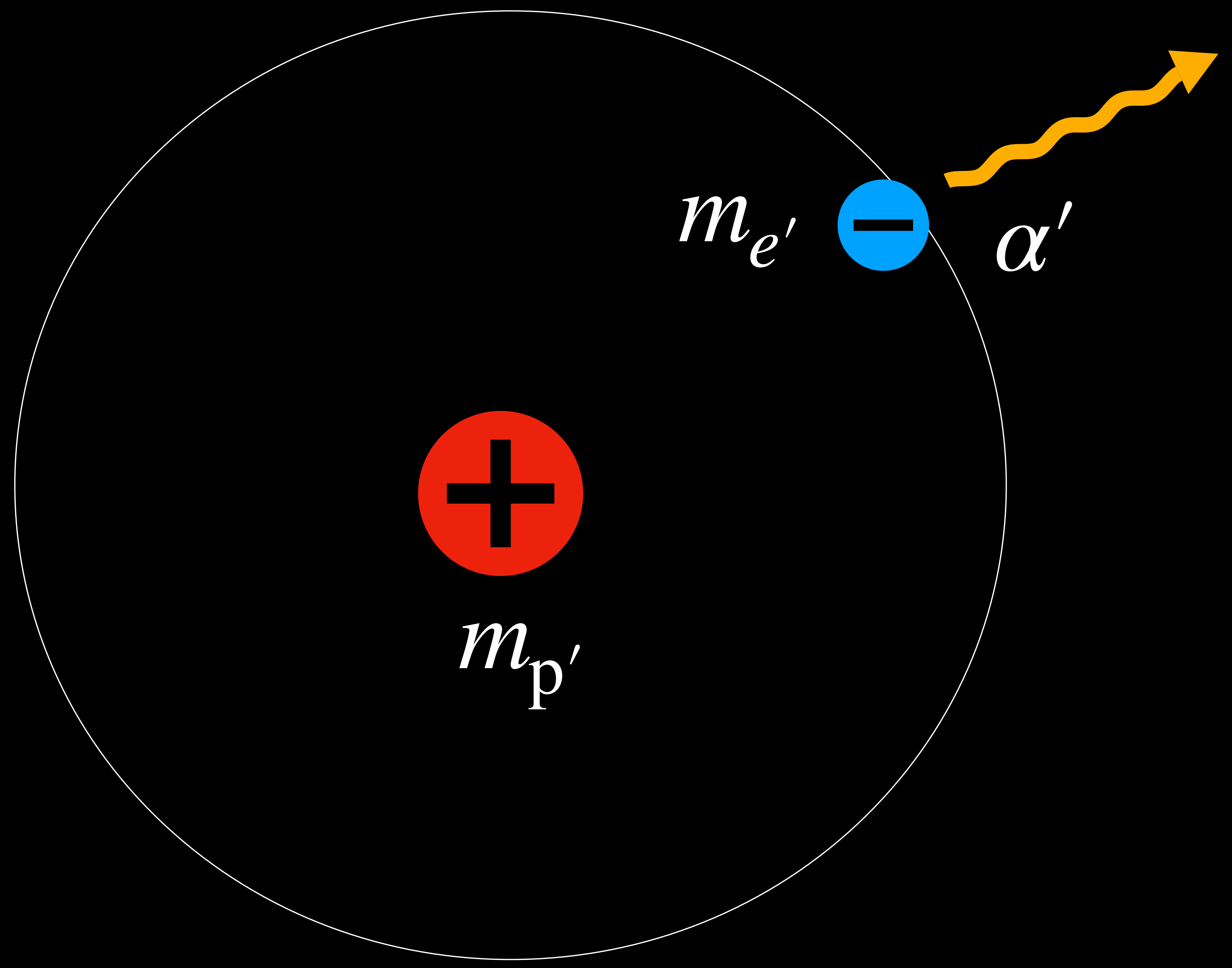
aDM Parameters (Five Numbers...)



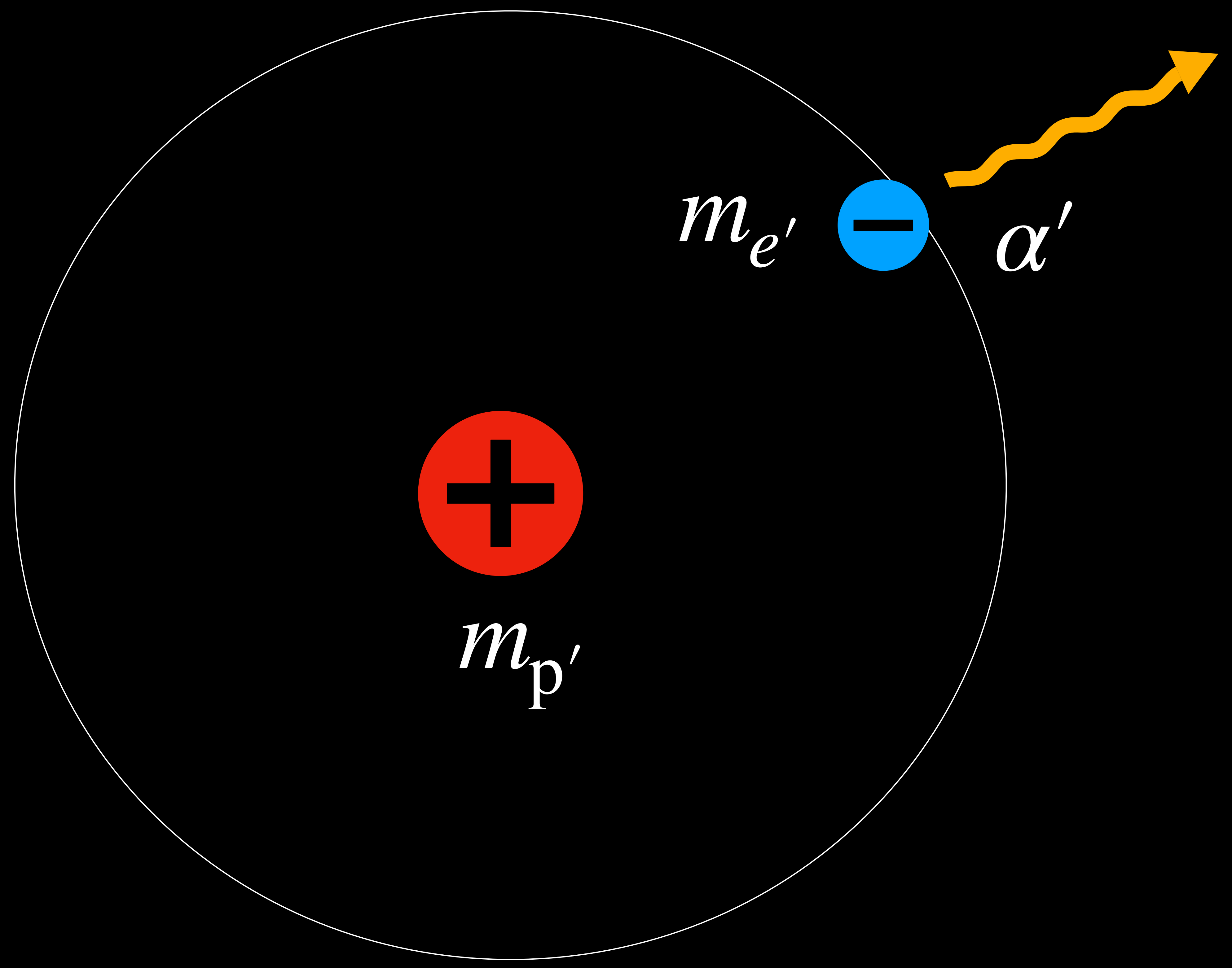
aDM Parameters (Five Numbers…)



aDM Parameters (Five Numbers...)

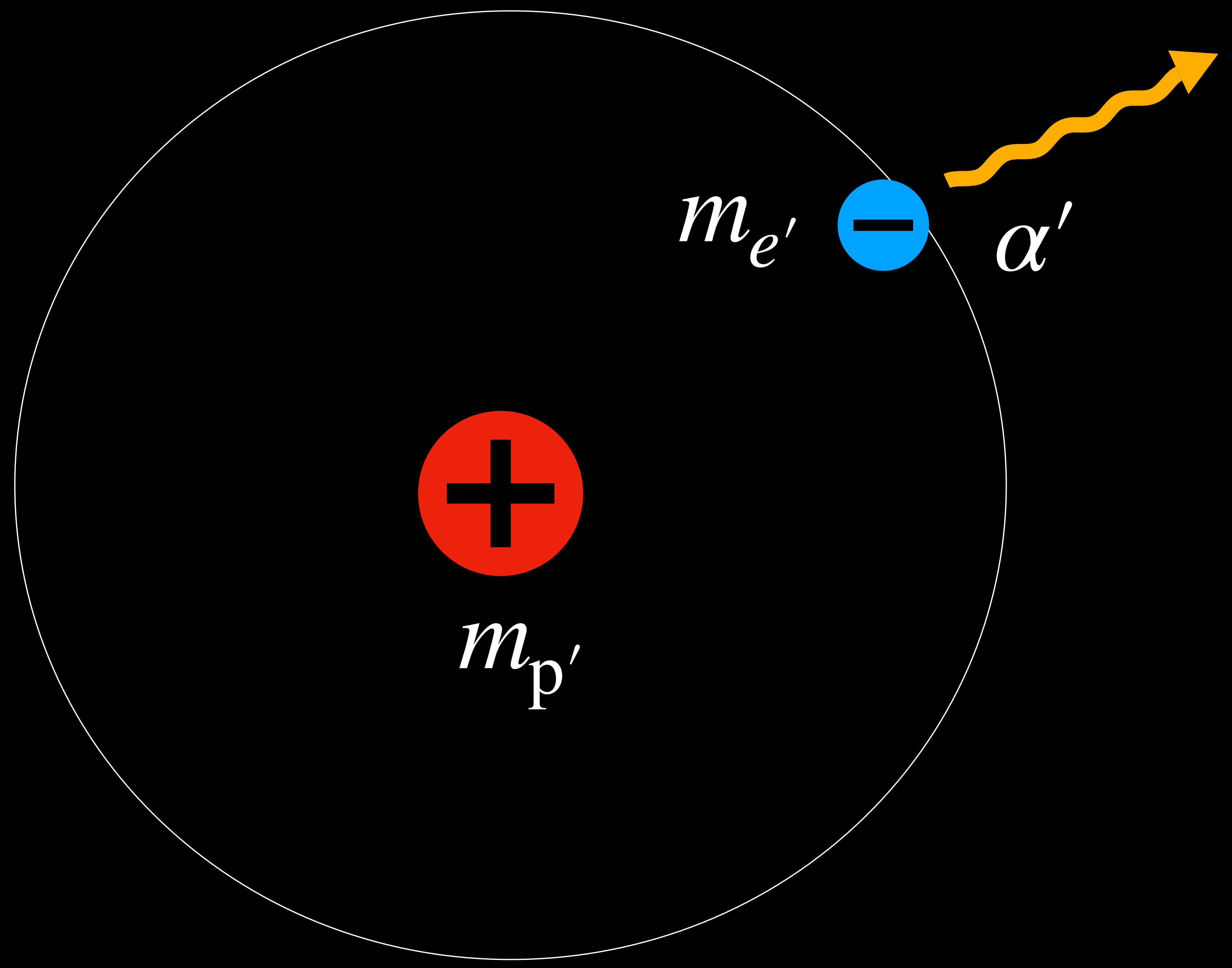


aDM Parameters (Five Numbers…)



$$\xi' = \frac{T'}{T_{\mathrm{CMB}}}$$

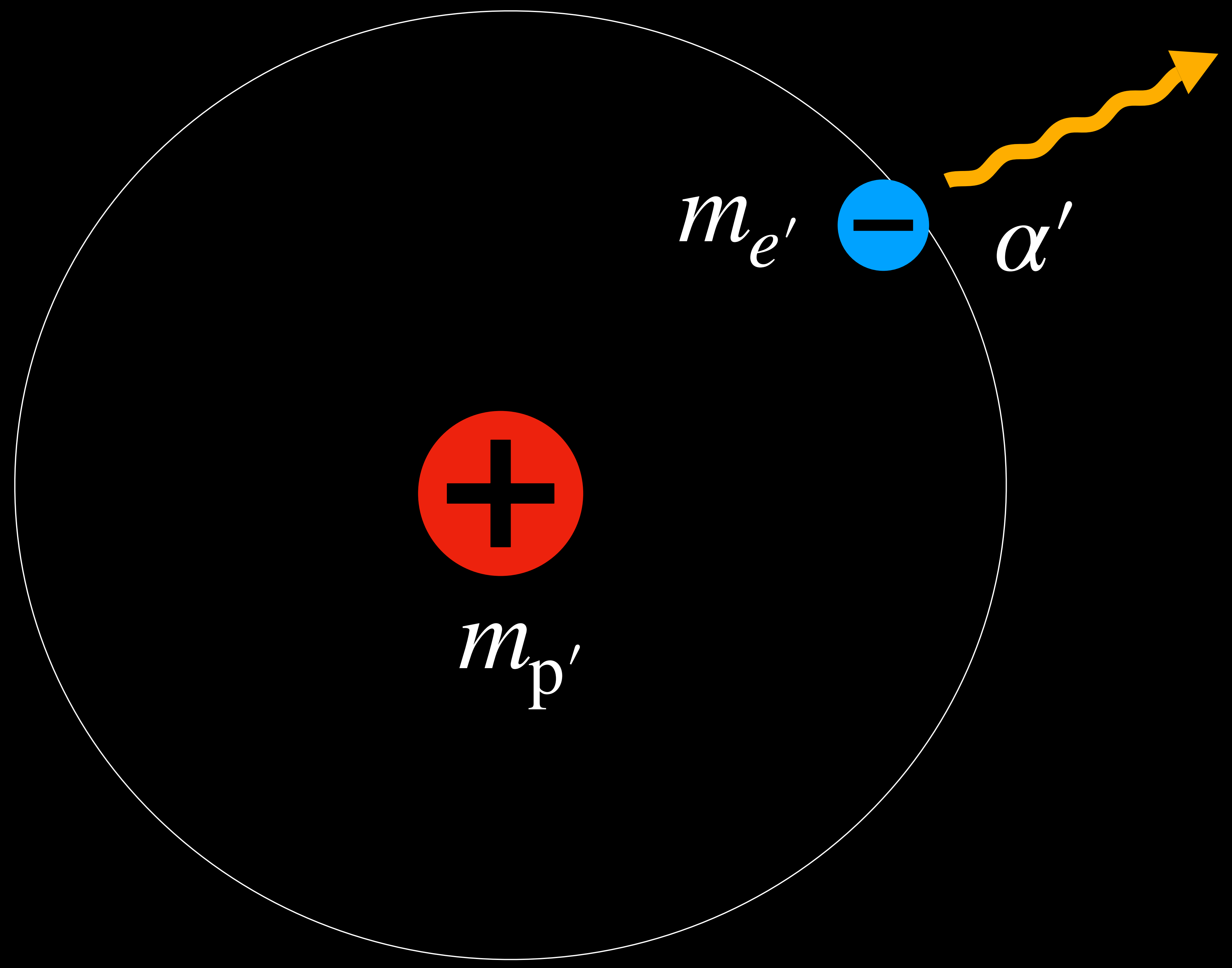
aDM Parameters (Five Numbers…)



$$\xi' = \frac{T'}{T_{\rm CMB}}$$

$$f' = \frac{\Omega_{\rm aDM}}{\Omega_{\rm DM}}$$

aDM Parameters (Five Numbers…)



$$\xi' = \frac{T'}{T_{\rm CMB}}$$

$$f' = \frac{\Omega_{\rm aDM}}{\Omega_{\rm DM}}$$

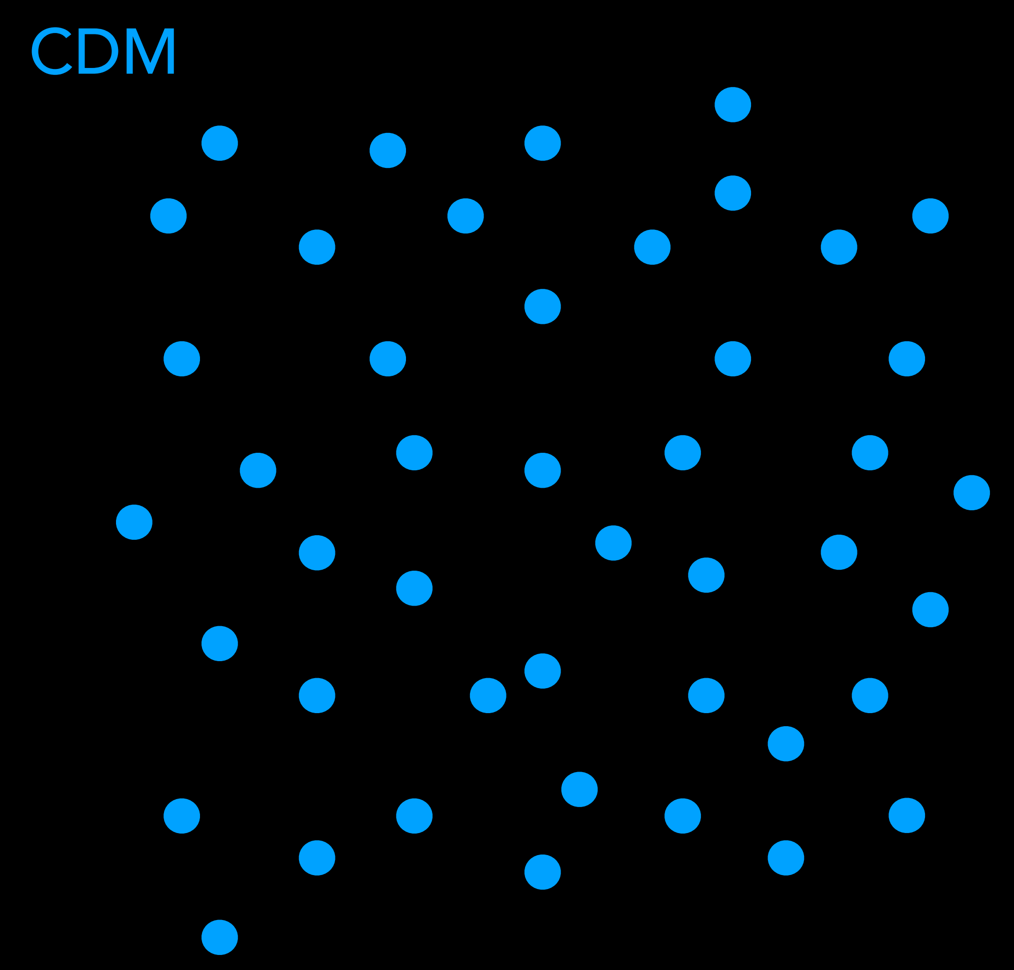
No dark nuclear physics→No dark stars→No dark supernovae (SN)→No dark feedback

aDM Implementation in GIZMO

GIZMO: N-Body Hydrodynamics Code

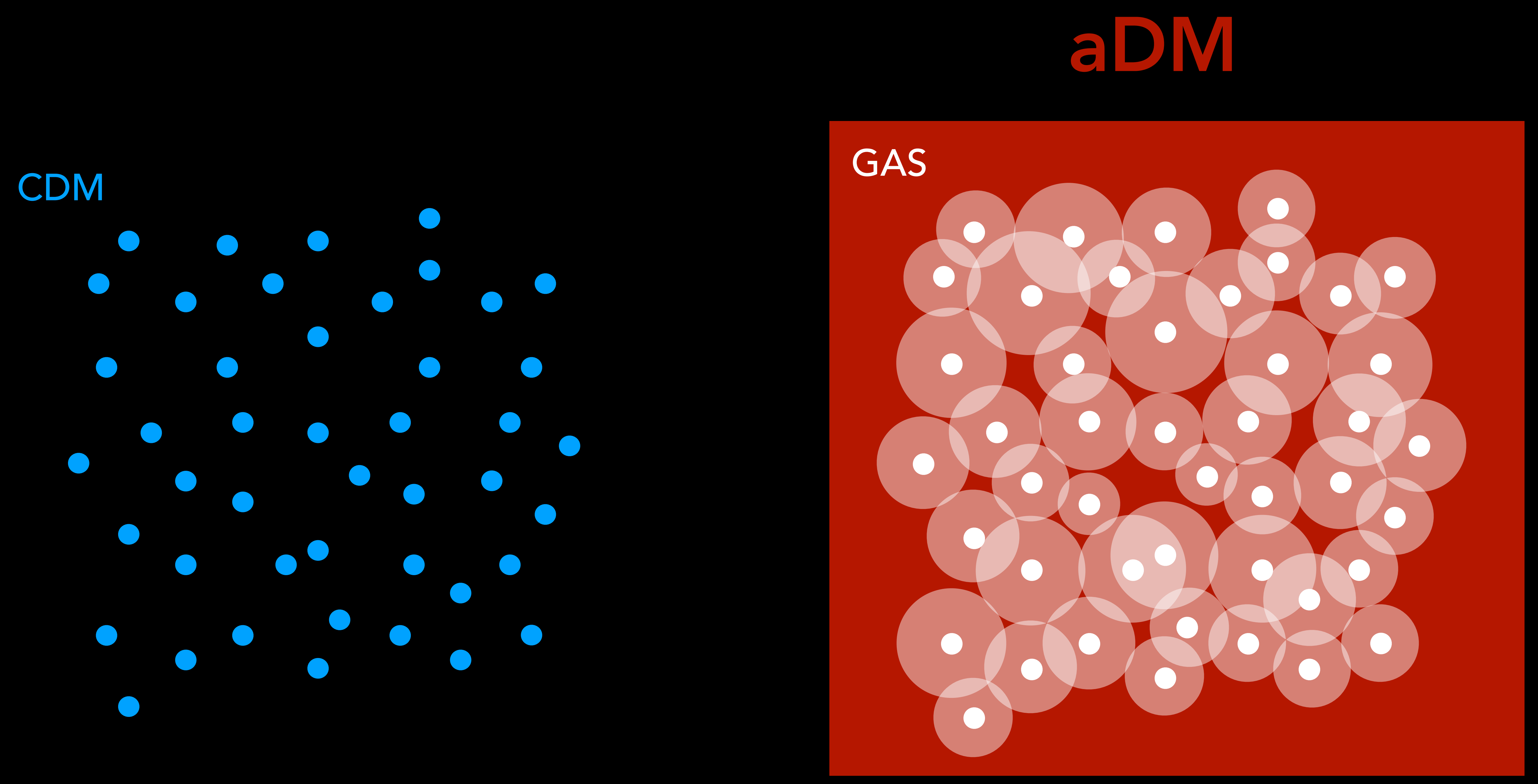
aDM Implementation in GIZMO

GIZMO: N-Body Hydrodynamics Code



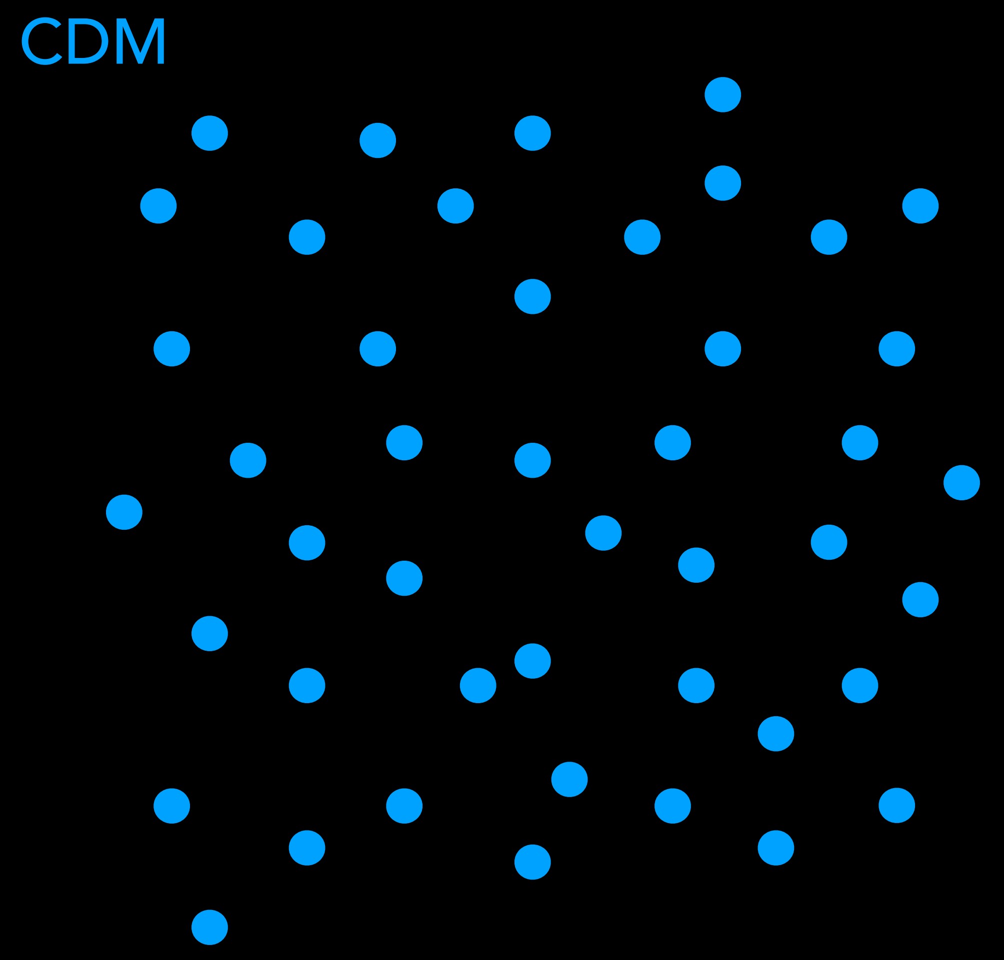
aDM Implementation in GIZMO

GIZMO: N-Body Hydrodynamics Code

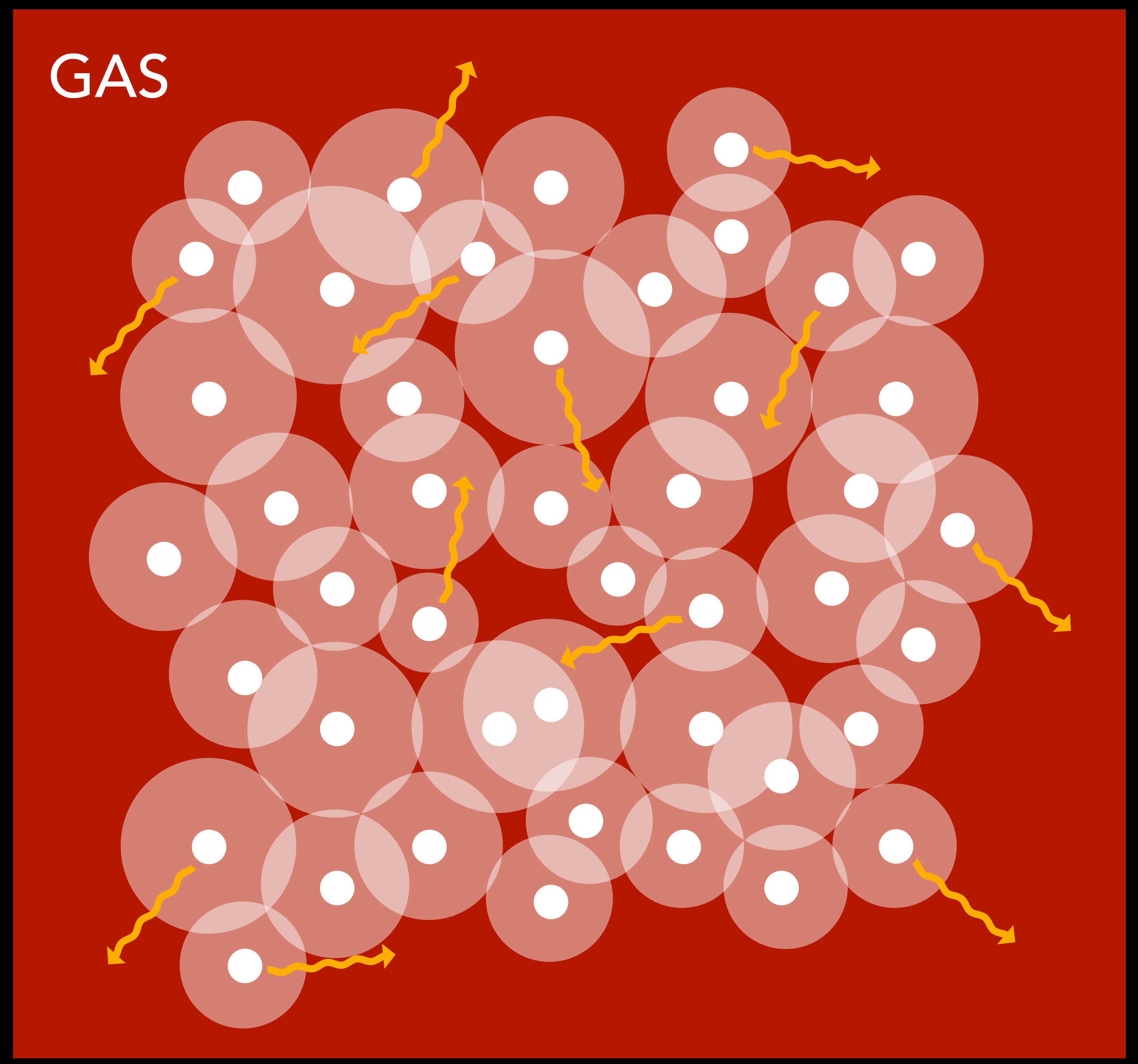


aDM Implementation in GIZMO

GIZMO: N-Body Hydrodynamics Code

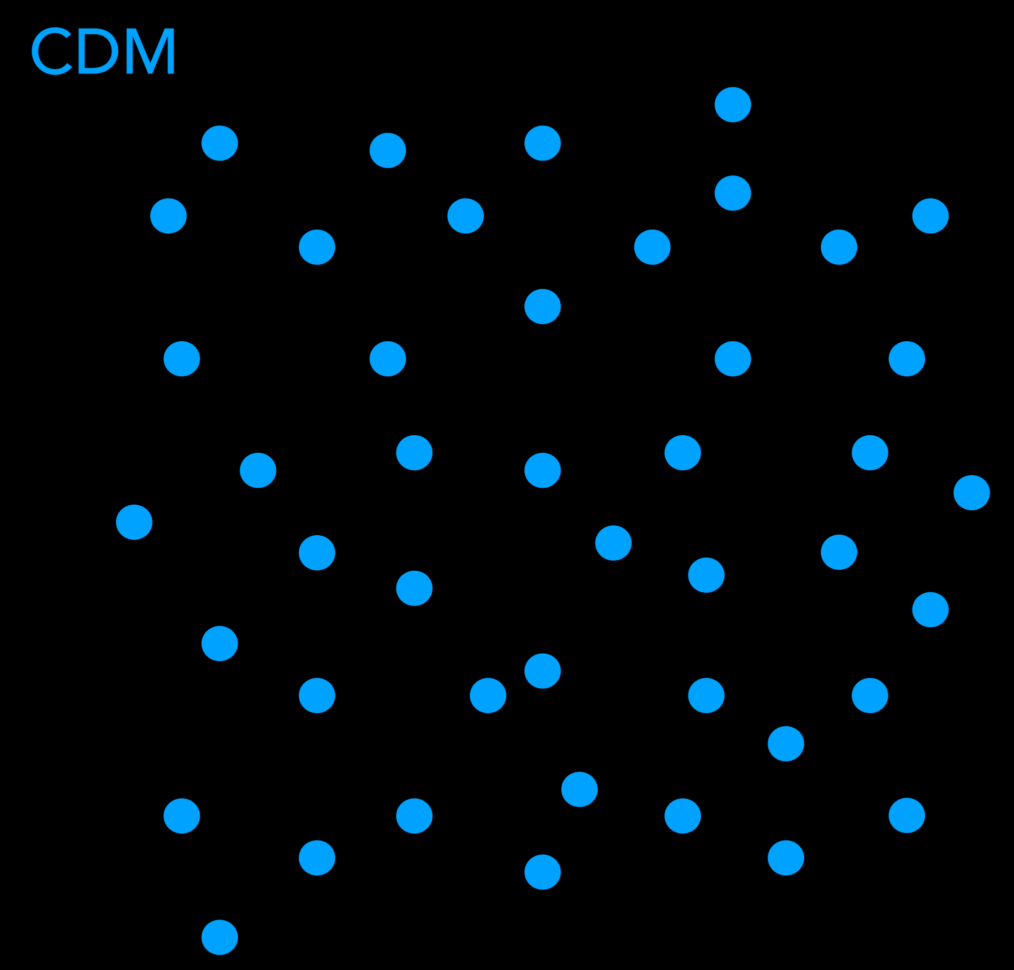


aDM

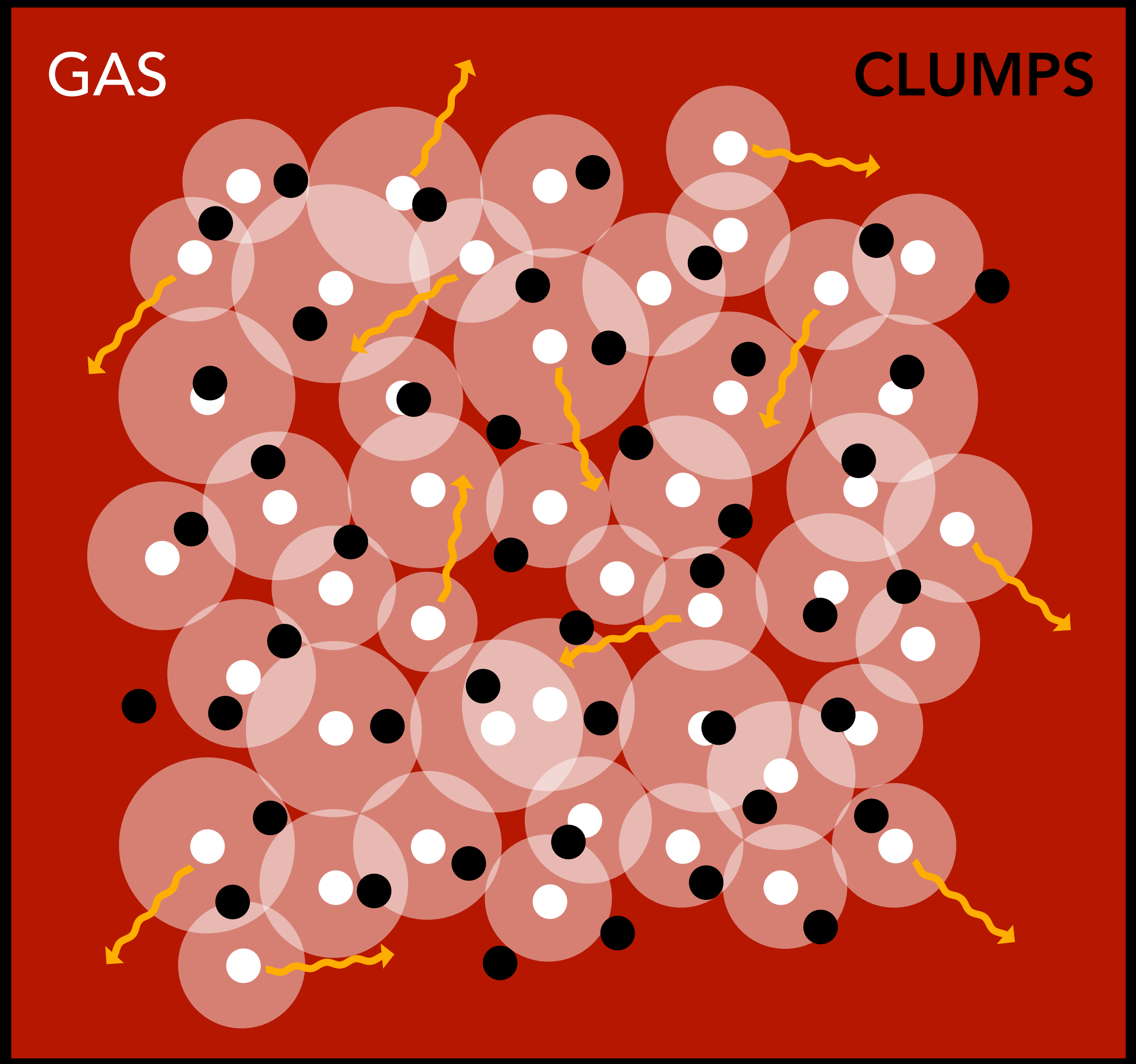


aDM Implementation in GIZMO

GIZMO: N-Body Hydrodynamics Code

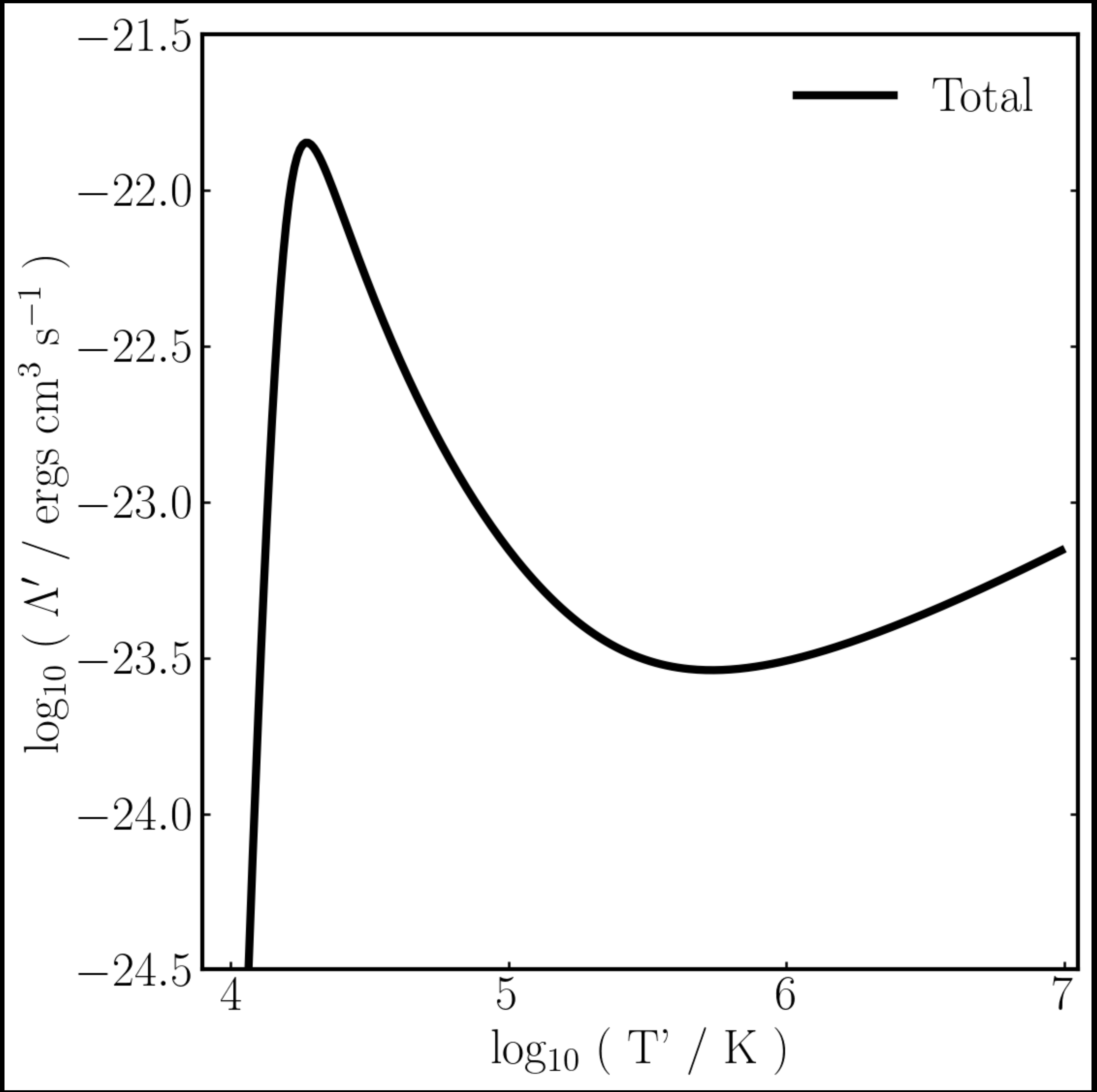


aDM

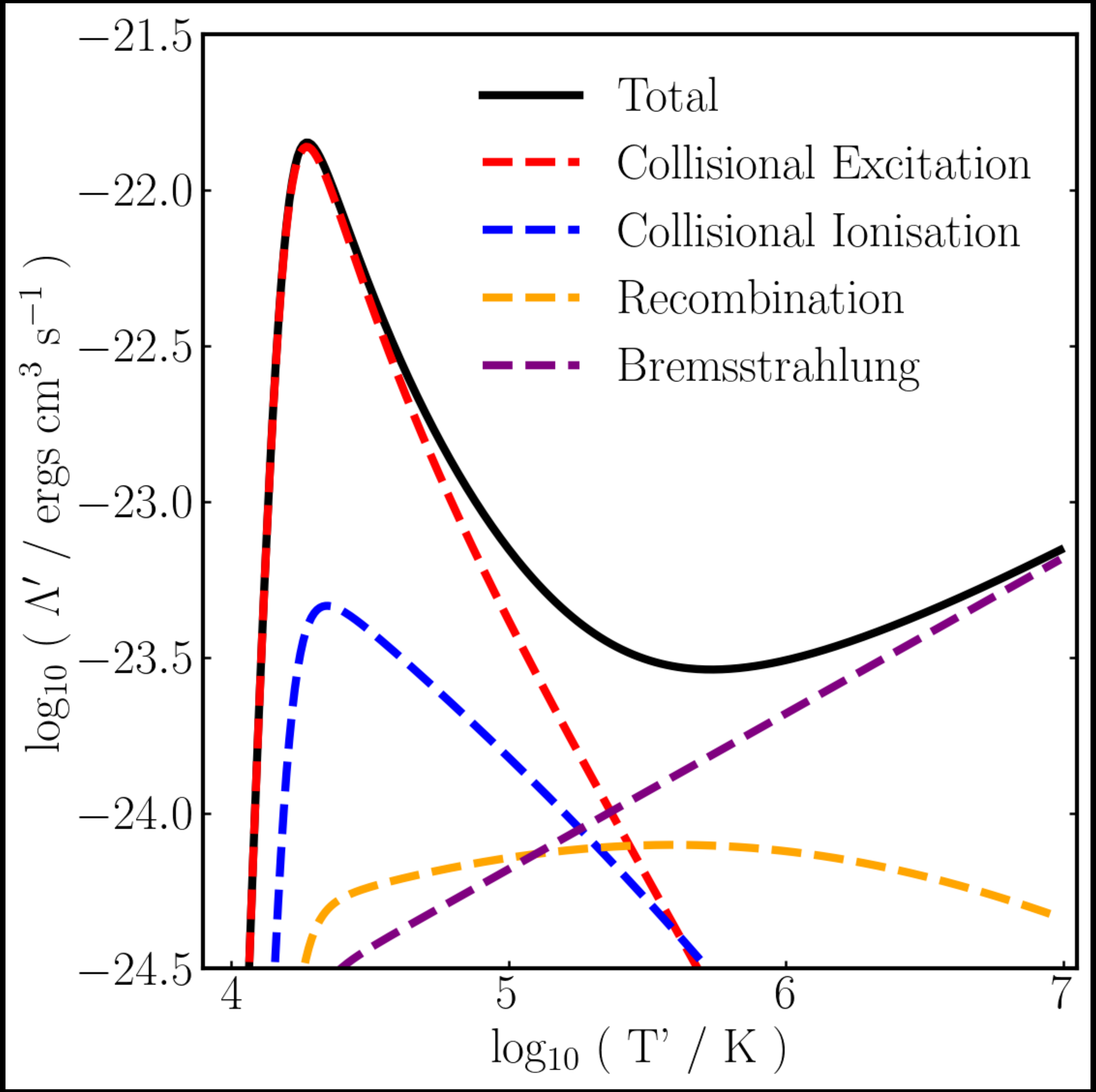


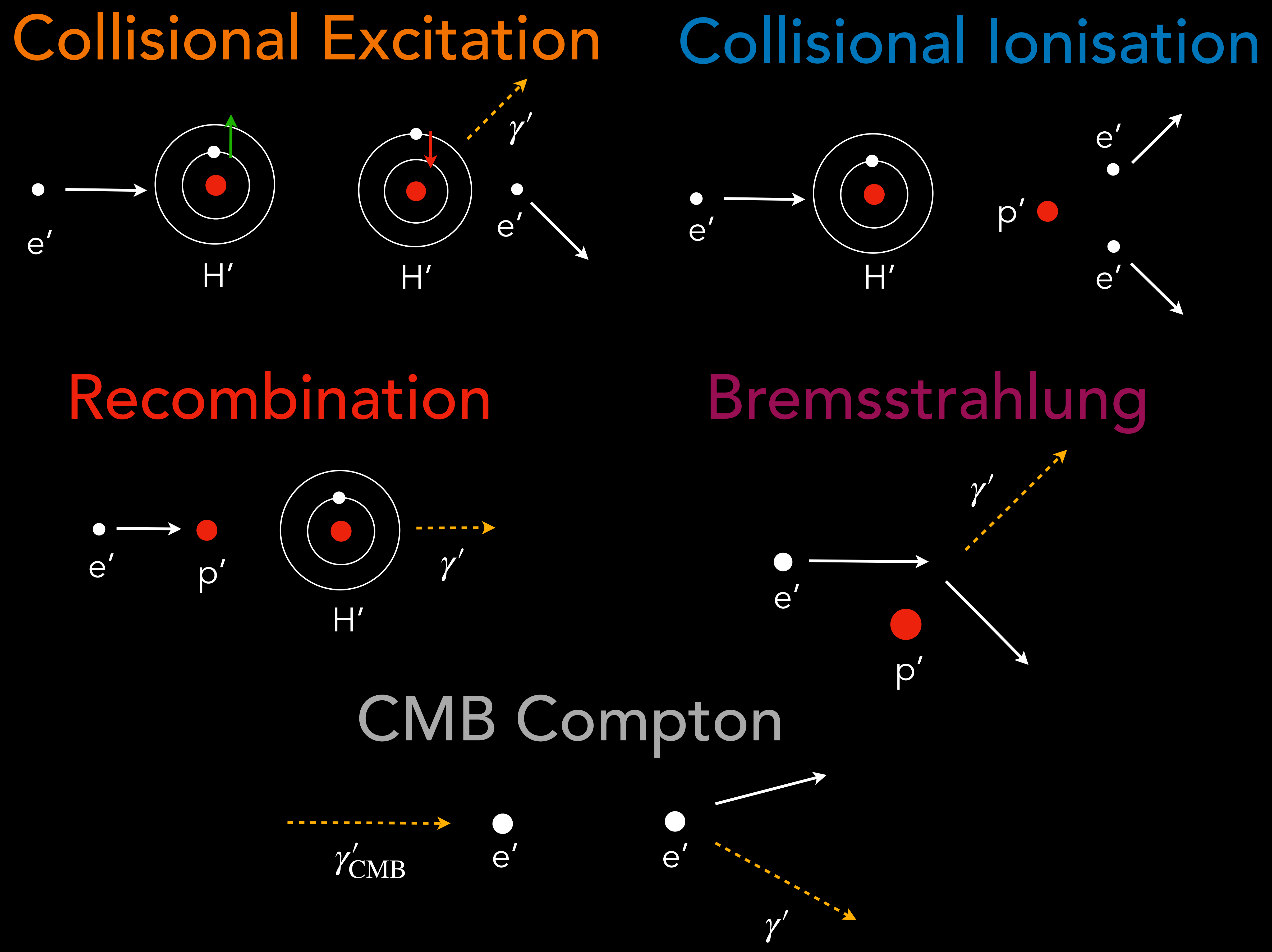
aDM Cooling Processes

aDM Cooling Processes

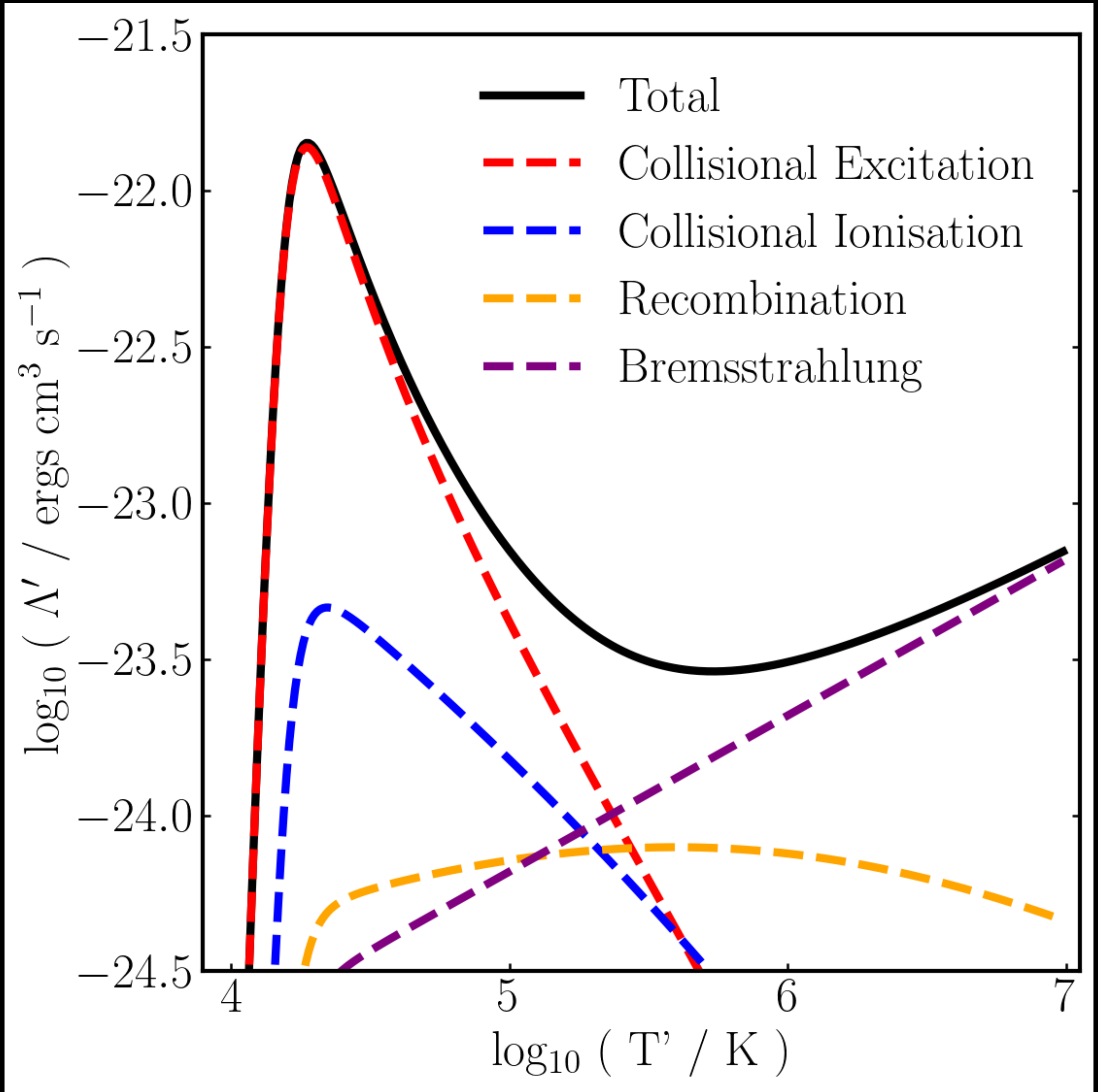


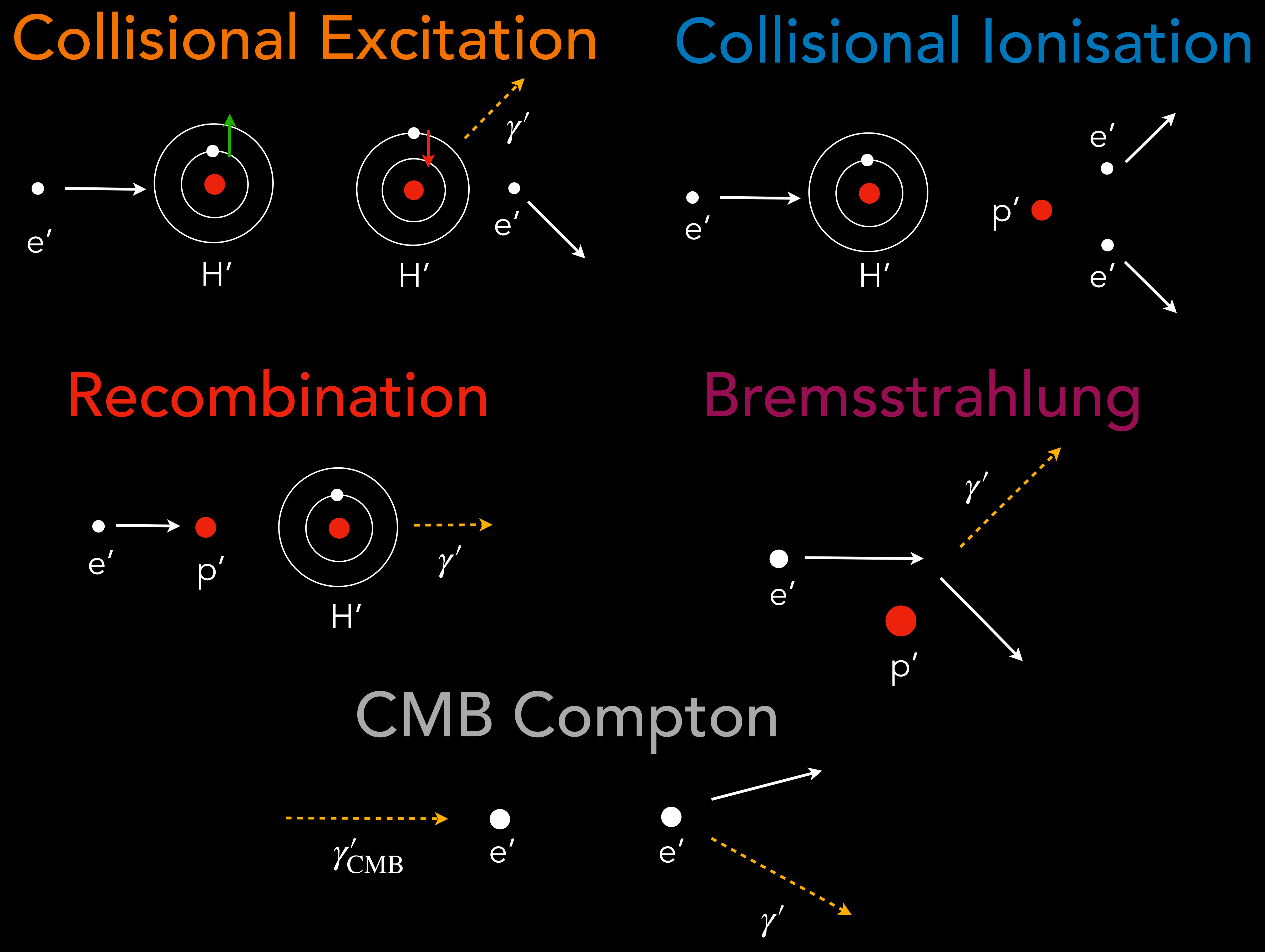
aDM Cooling Processes





aDM Cooling Processes



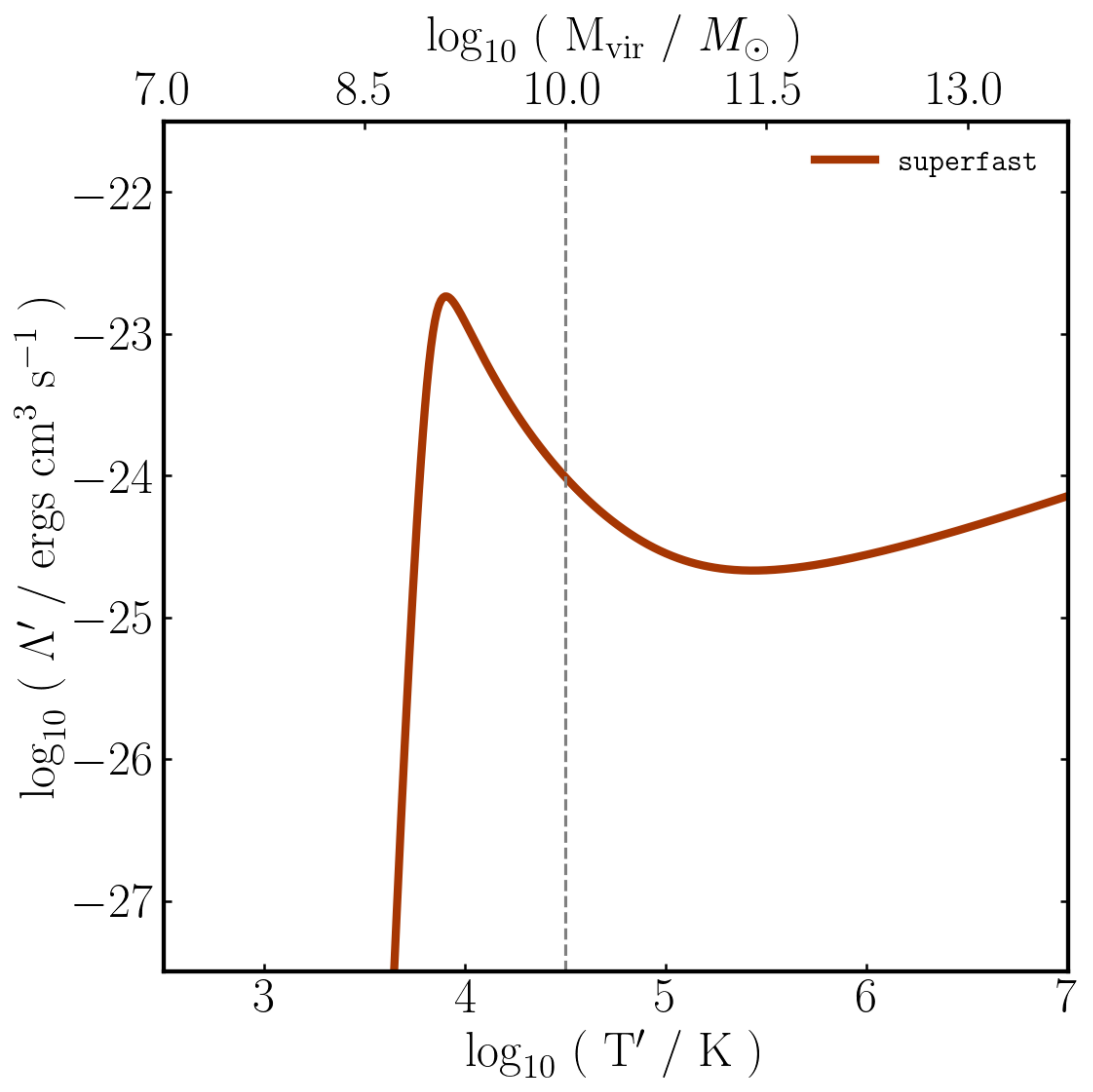


$$T'_{\text{cut-off}} \propto E_{b'} = \frac{1}{2} m_{e'} (\alpha')^2$$

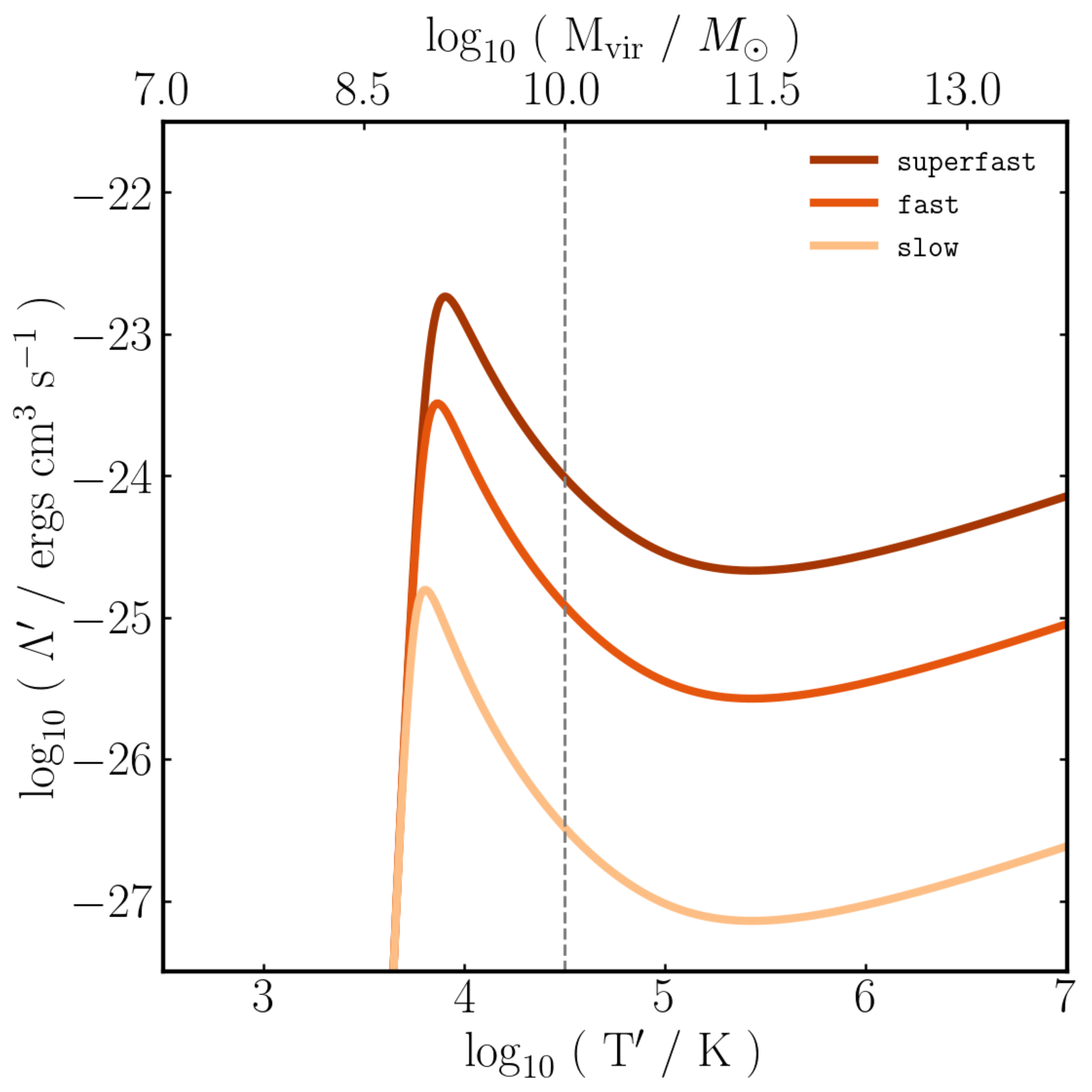
Simulation Parameters

Varying Cooling Strength & Binding Energy

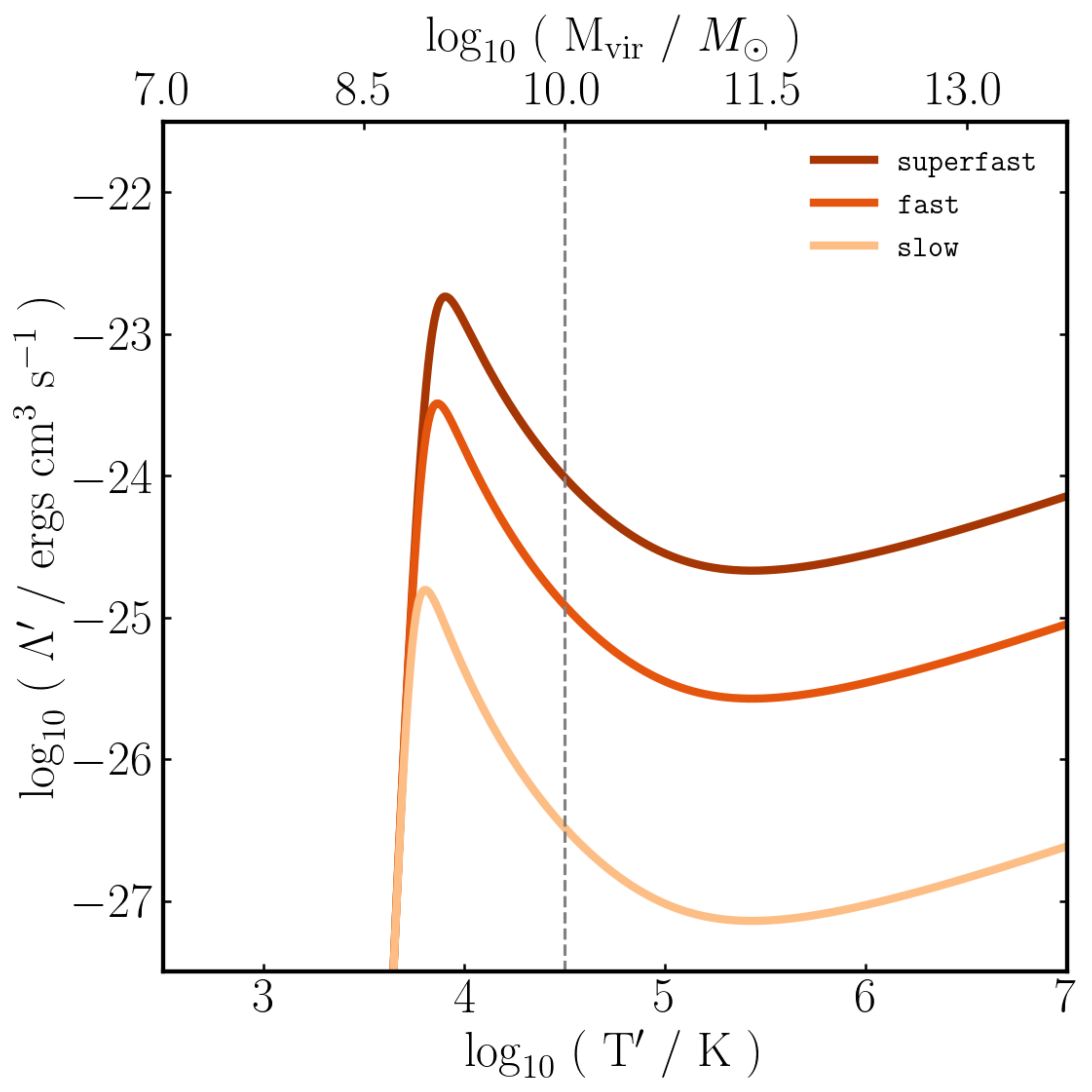
Varying Cooling Strength & Binding Energy



Varying Cooling Strength & Binding Energy

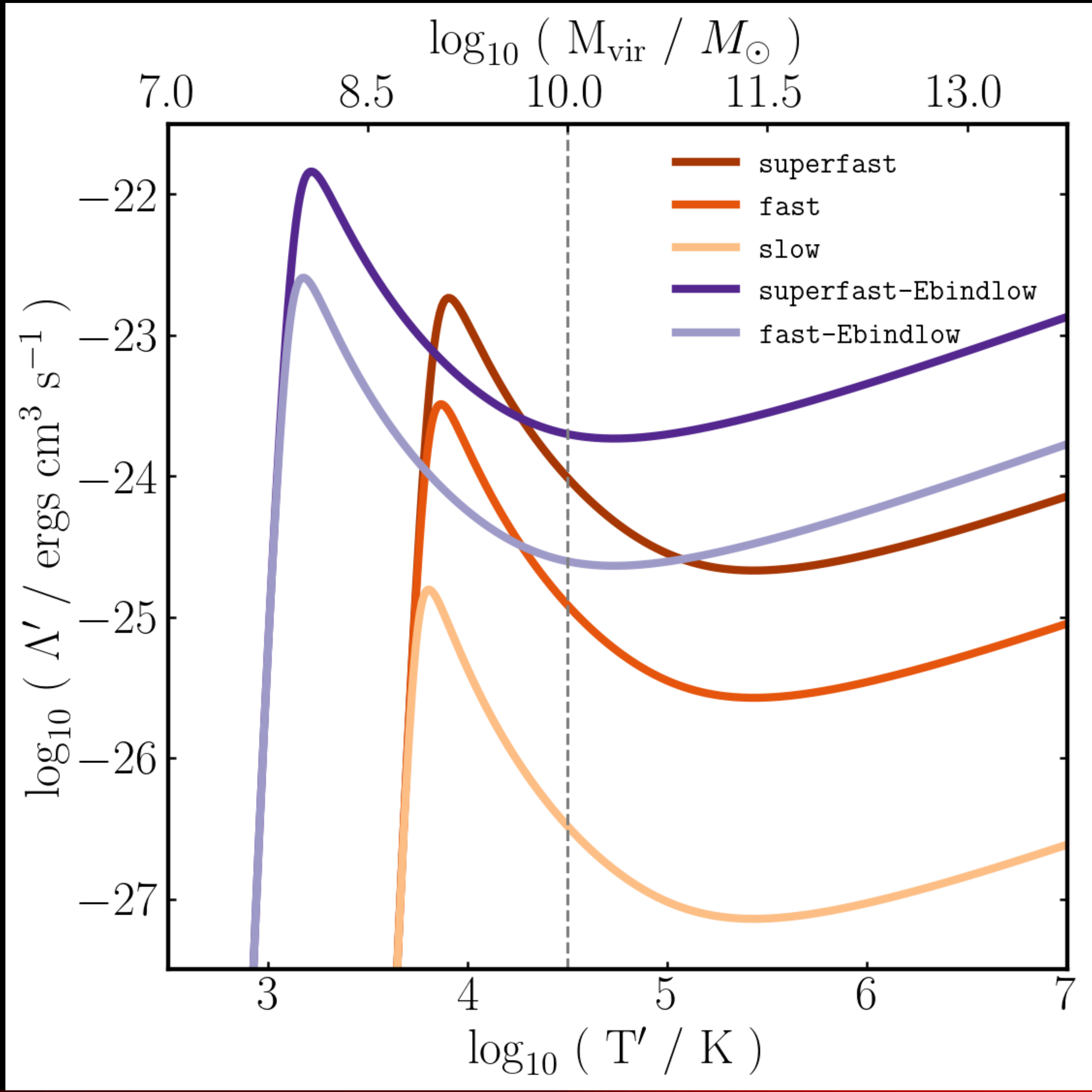


Varying Cooling Strength & Binding Energy



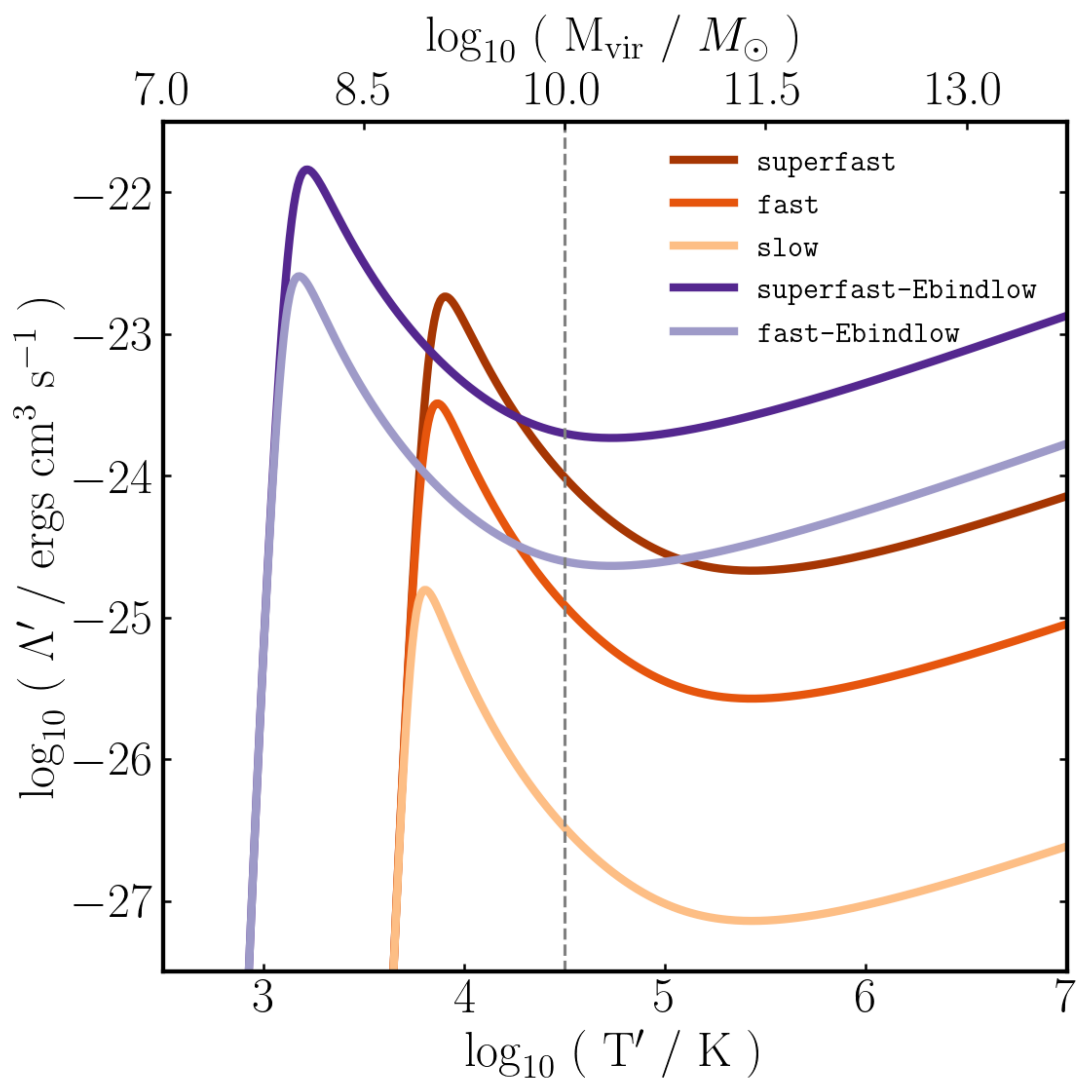
Varied cooling rate over several orders of magnitude, E_b' kept constant

Varying Cooling Strength & Binding Energy



Varied cooling rate over several orders of magnitude, E_b' kept constant

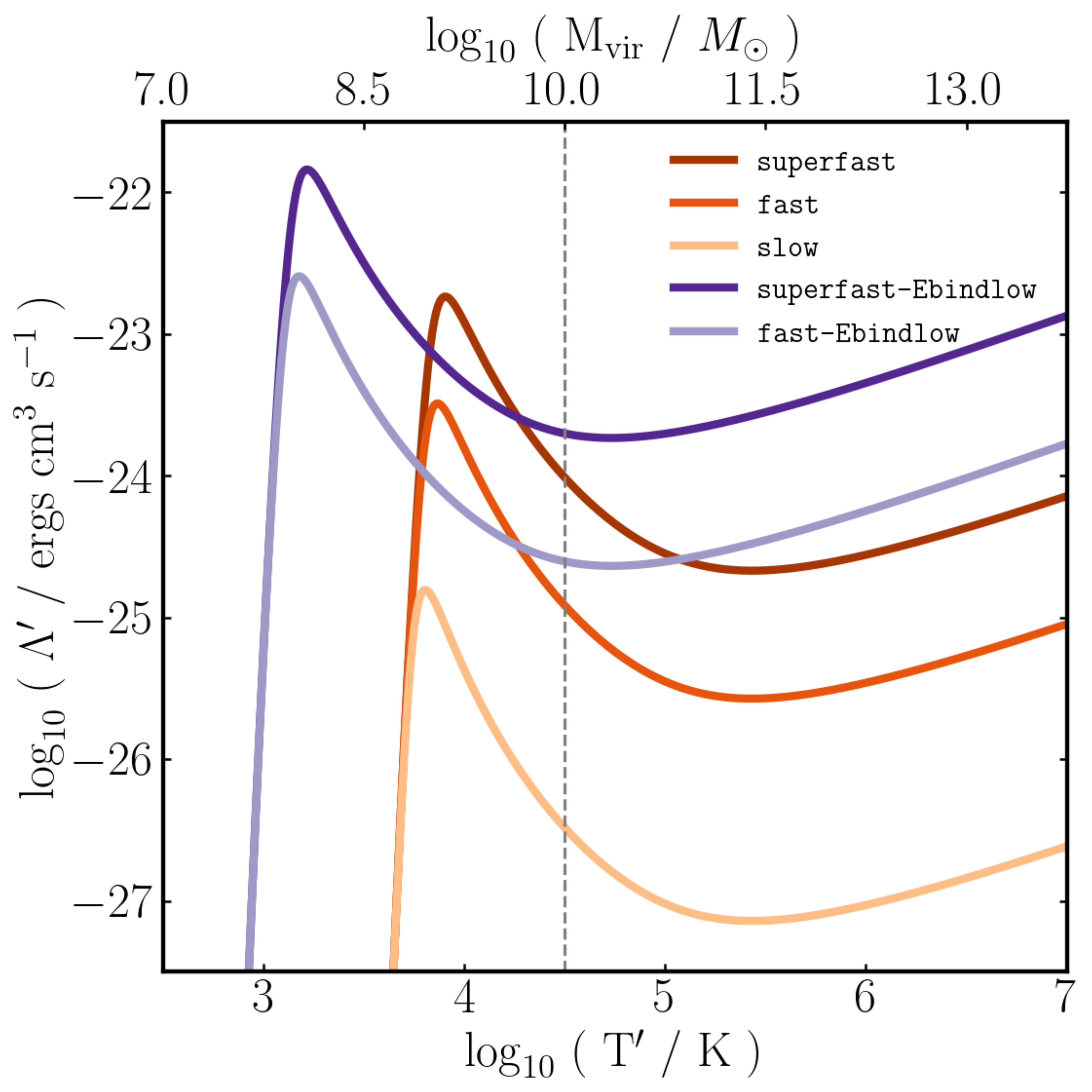
Varying Cooling Strength & Binding Energy



Varied cooling rate over several orders of magnitude, E_b' kept constant

Varied $E_{b'}/E_b$ between 0.1 and 0.5

Varying Cooling Strength & Binding Energy



Varied cooling rate over several orders of magnitude, E_b' kept constant

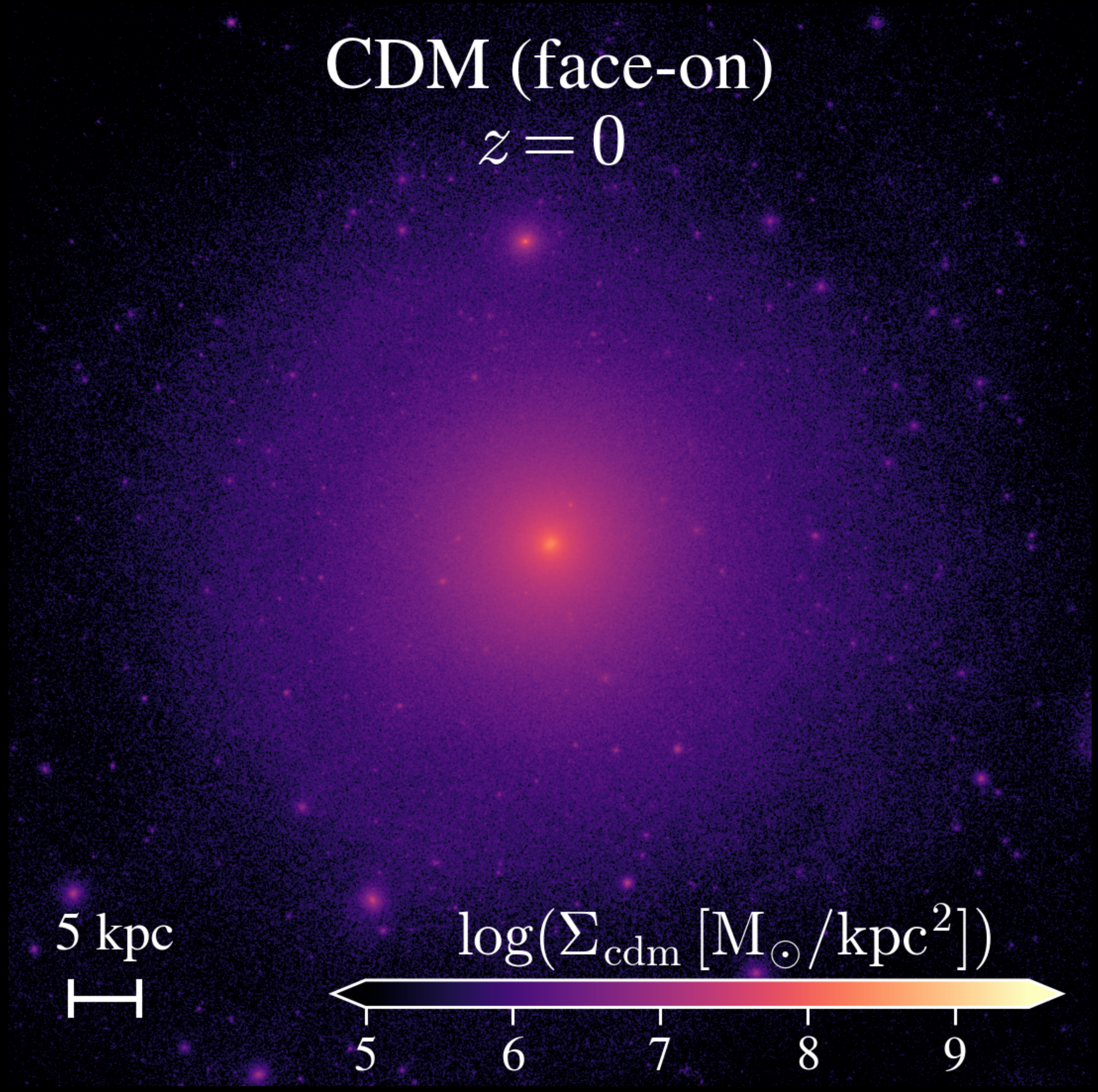
Varied $E_{b'}/E_b$ between 0.1 and 0.5

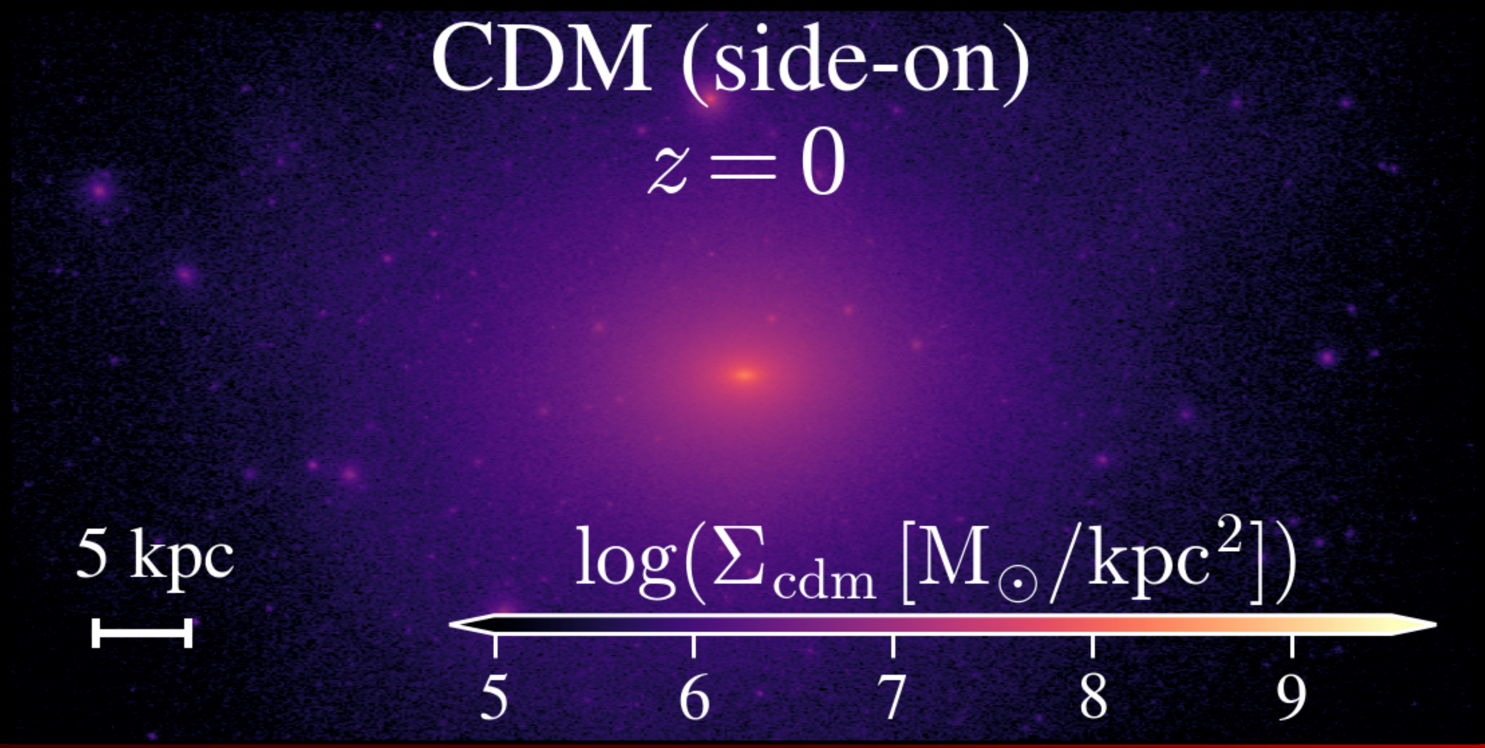
Kept $f' = 6\,\%$ and $m_{p'} = m_p$

Final Results

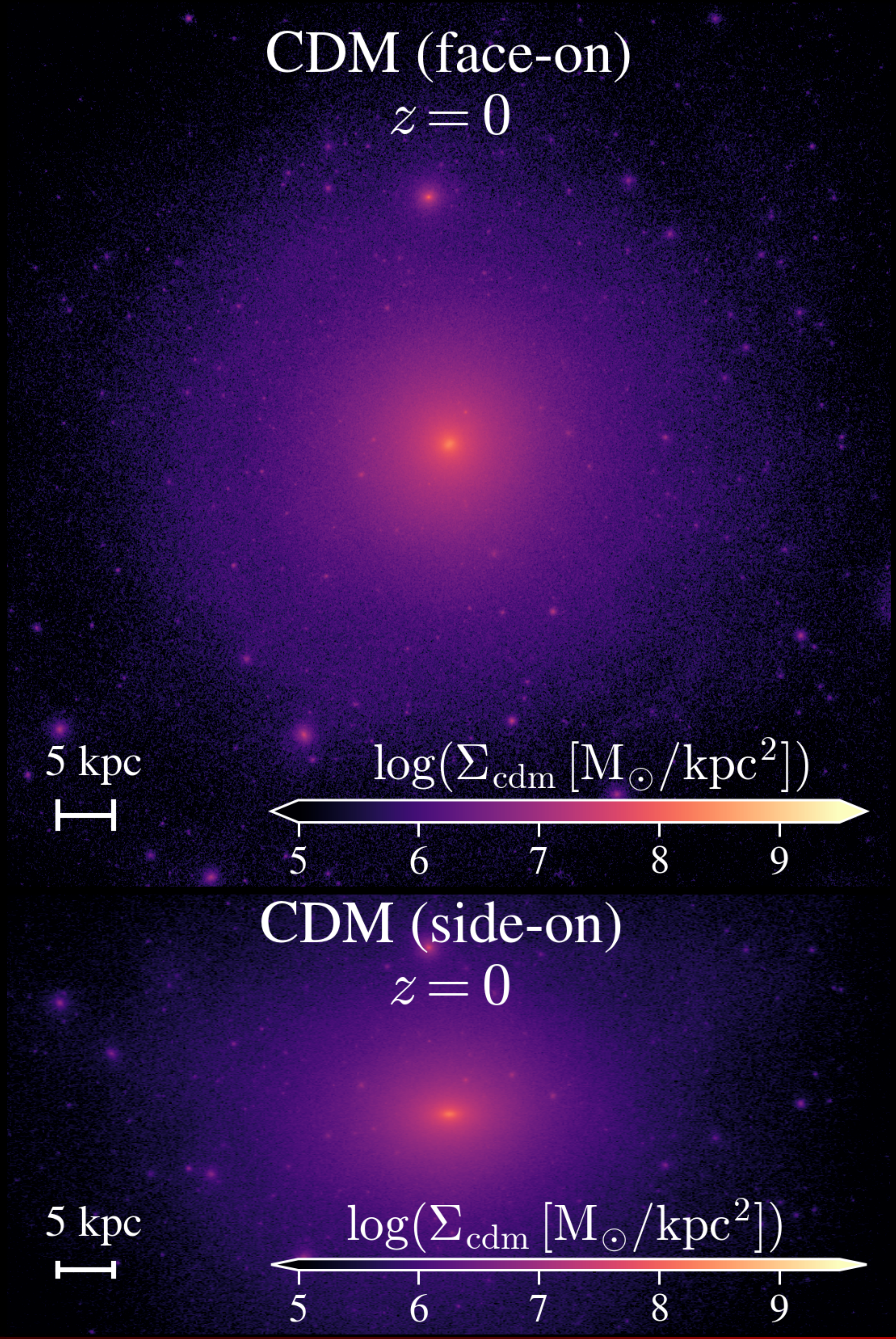
Fiducial CDM and aDM Morphology

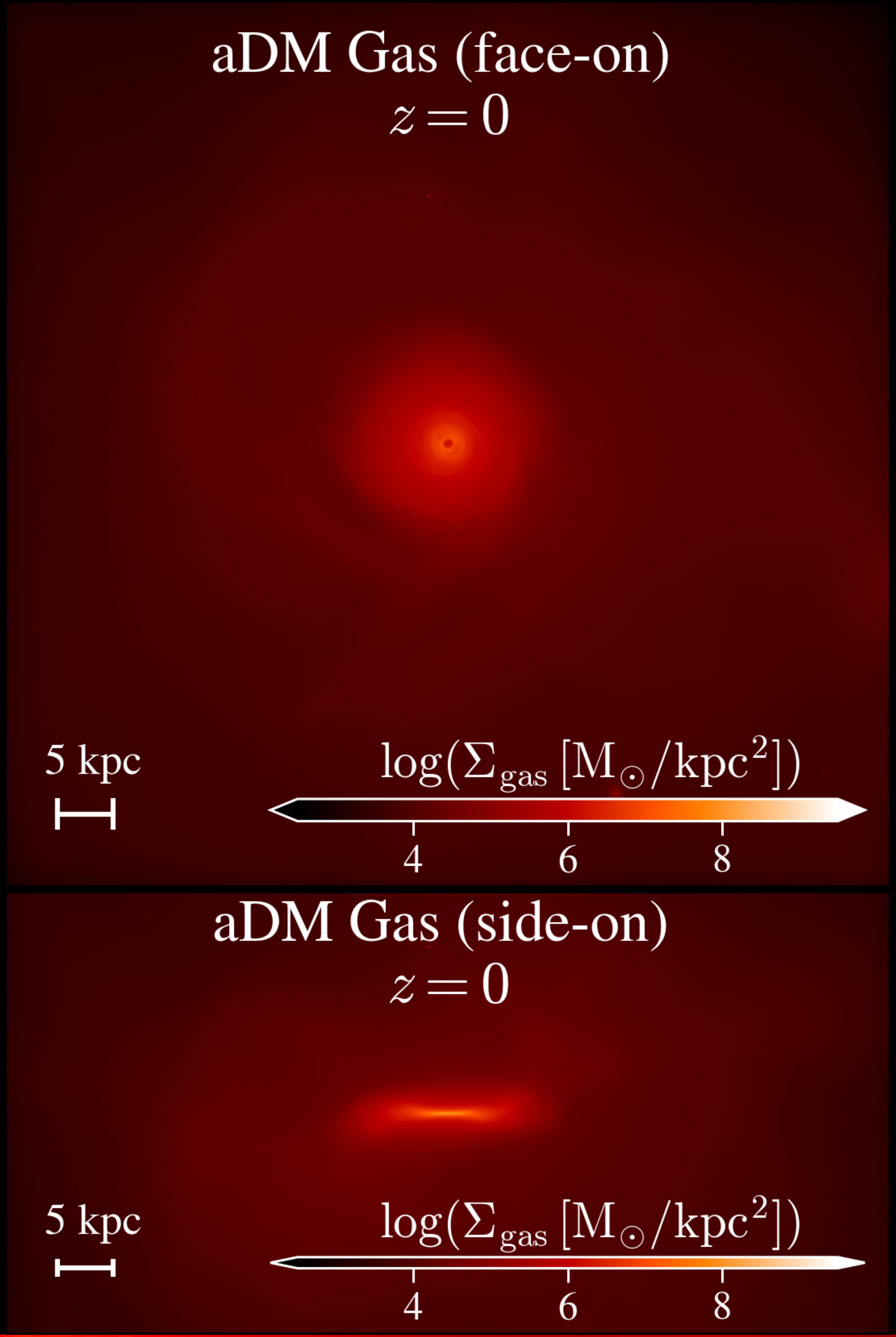
Fiducial CDM and aDM Morphology



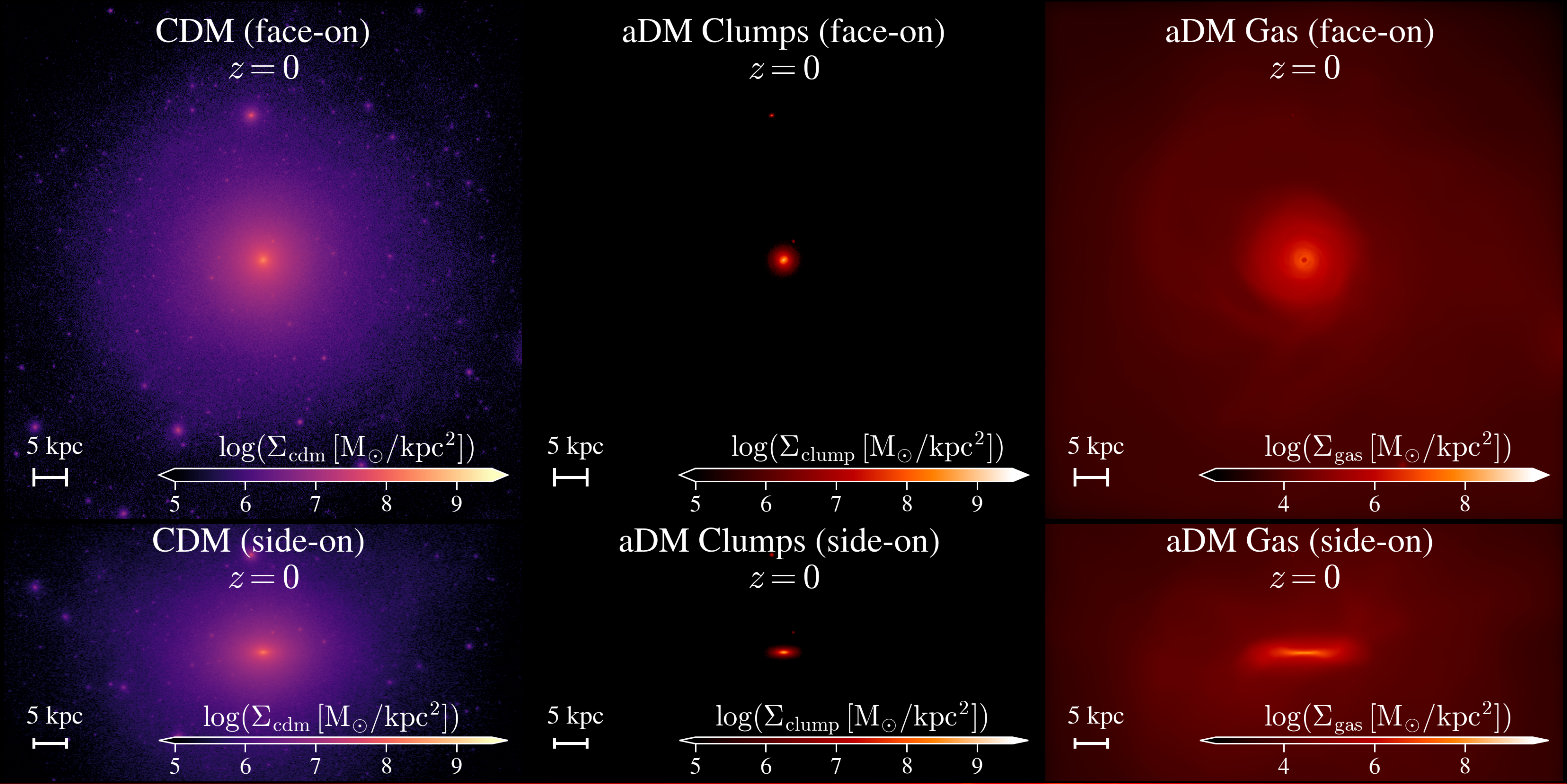


Fiducial CDM and aDM Morphology

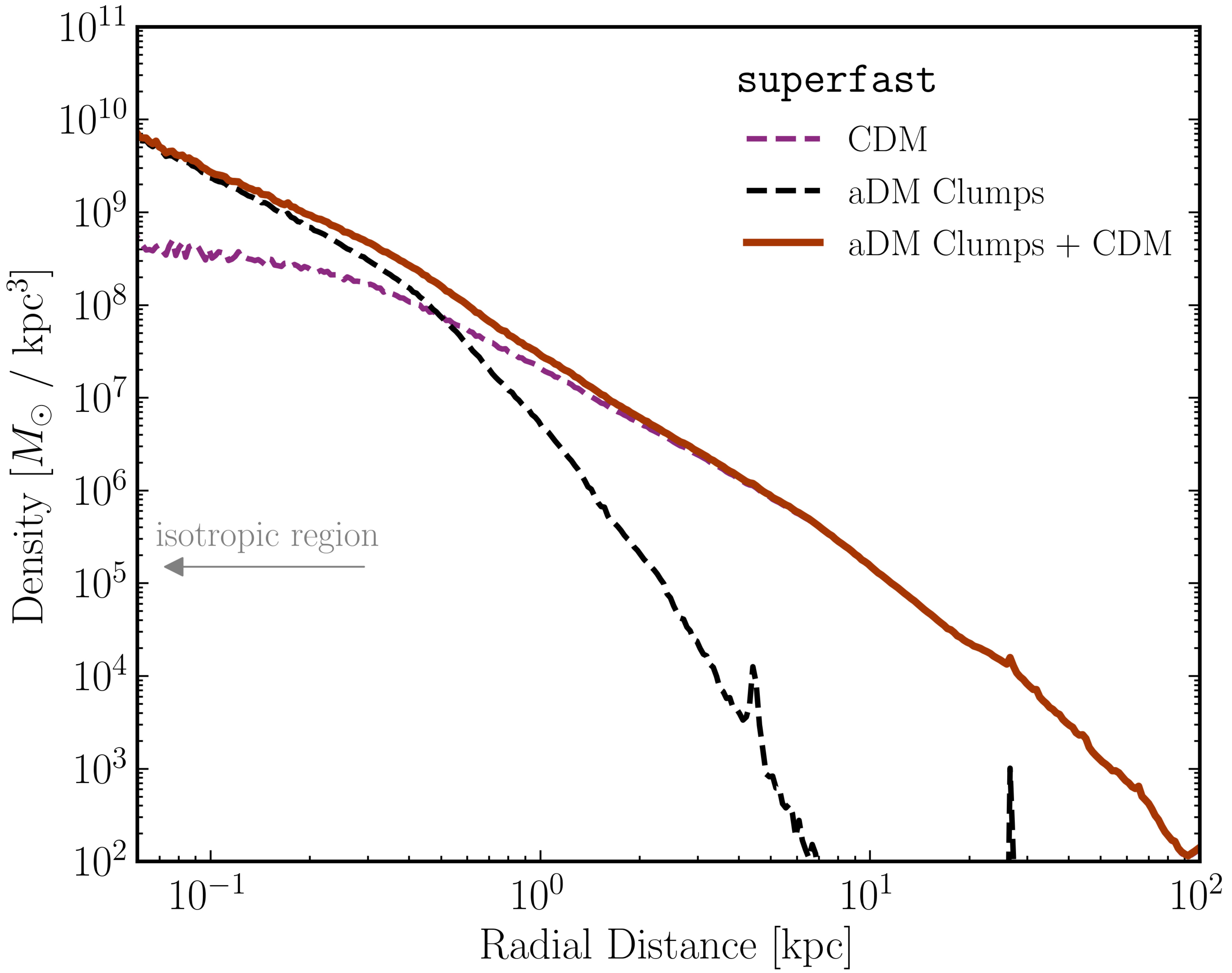




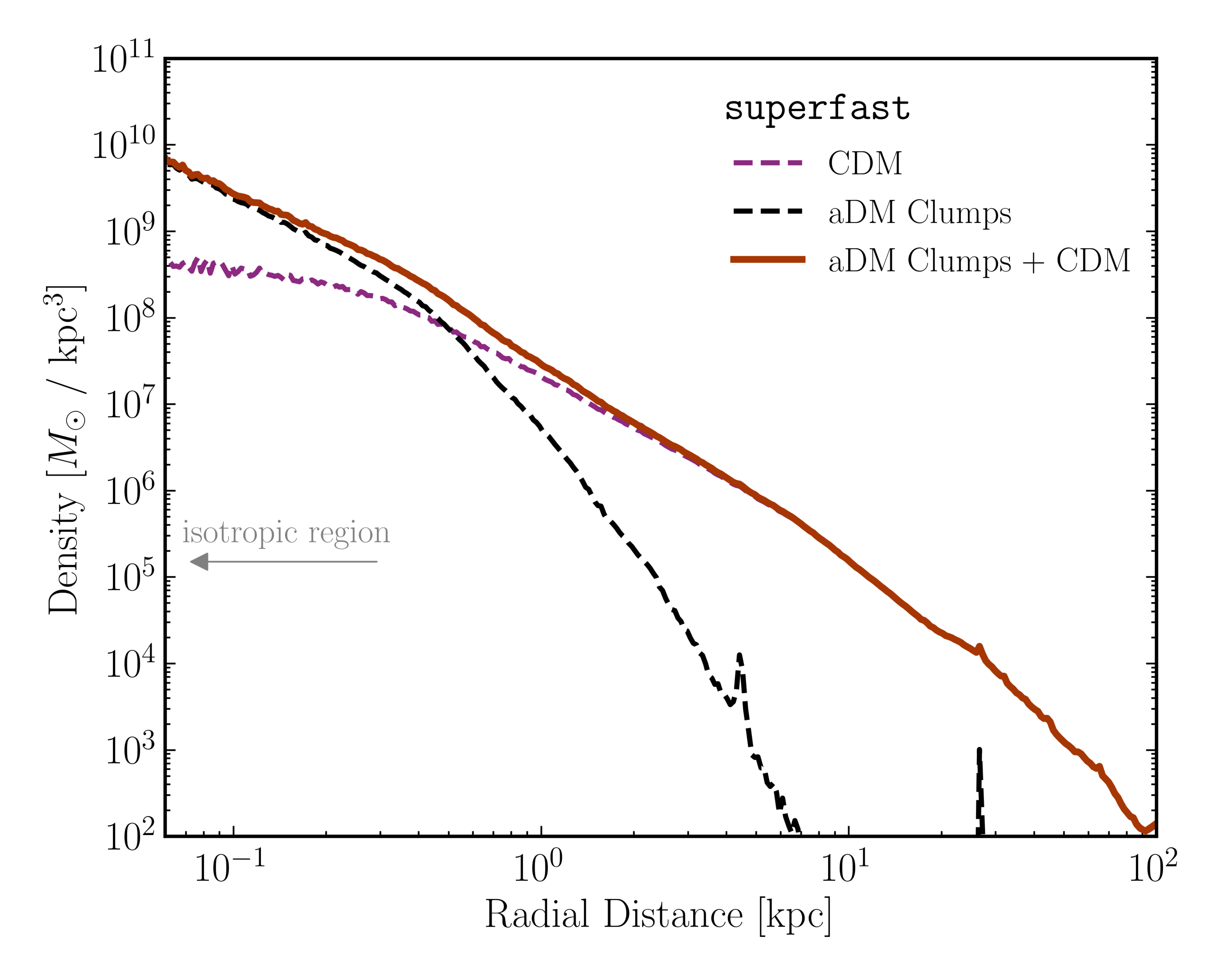
Fiducial CDM and aDM Morphology



Fiducial Simulation Density Profile



Fiducial Simulation Density Profile

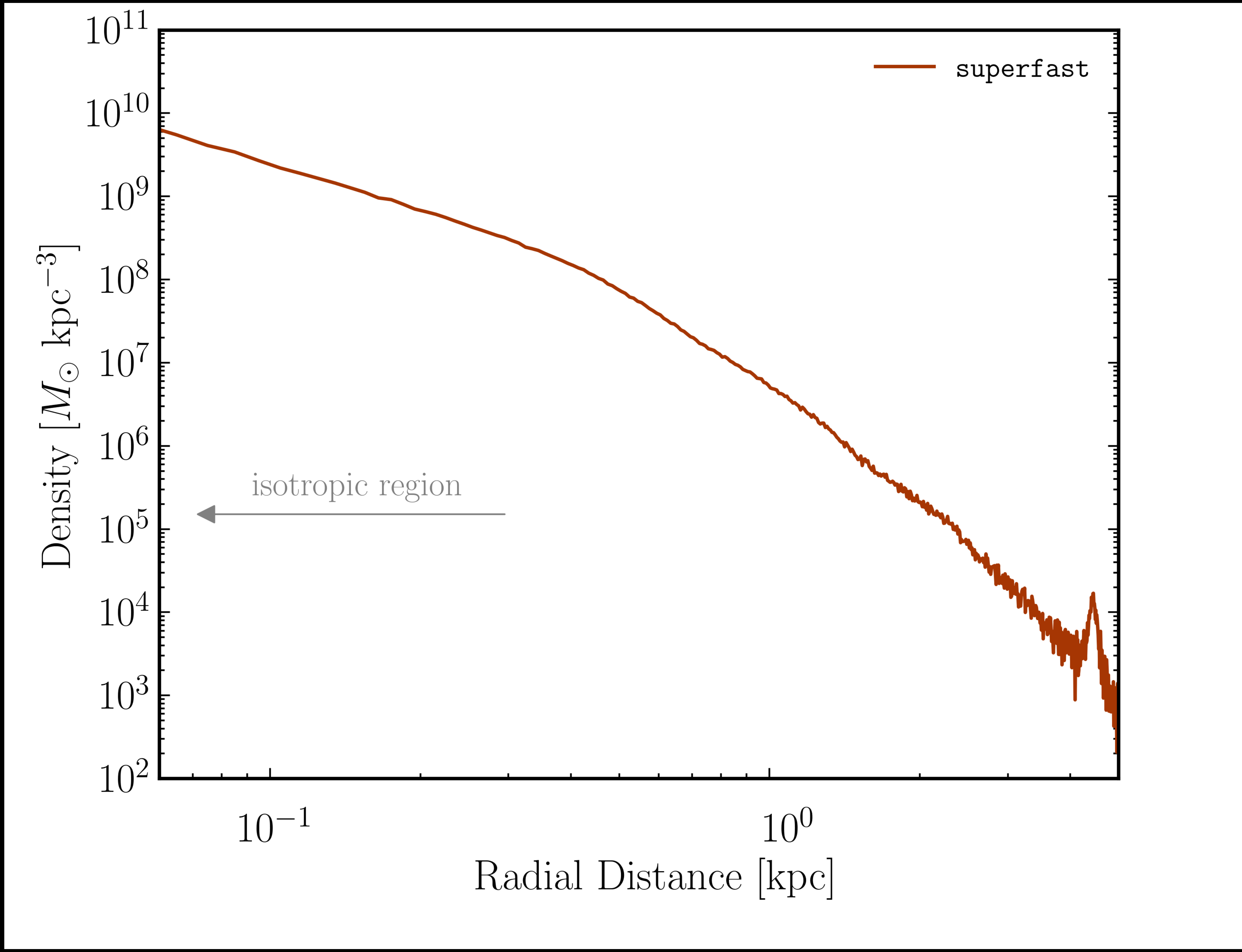


aDM clumps dominate inner halo

CDM dominates outer halo

aDM Clump Densities

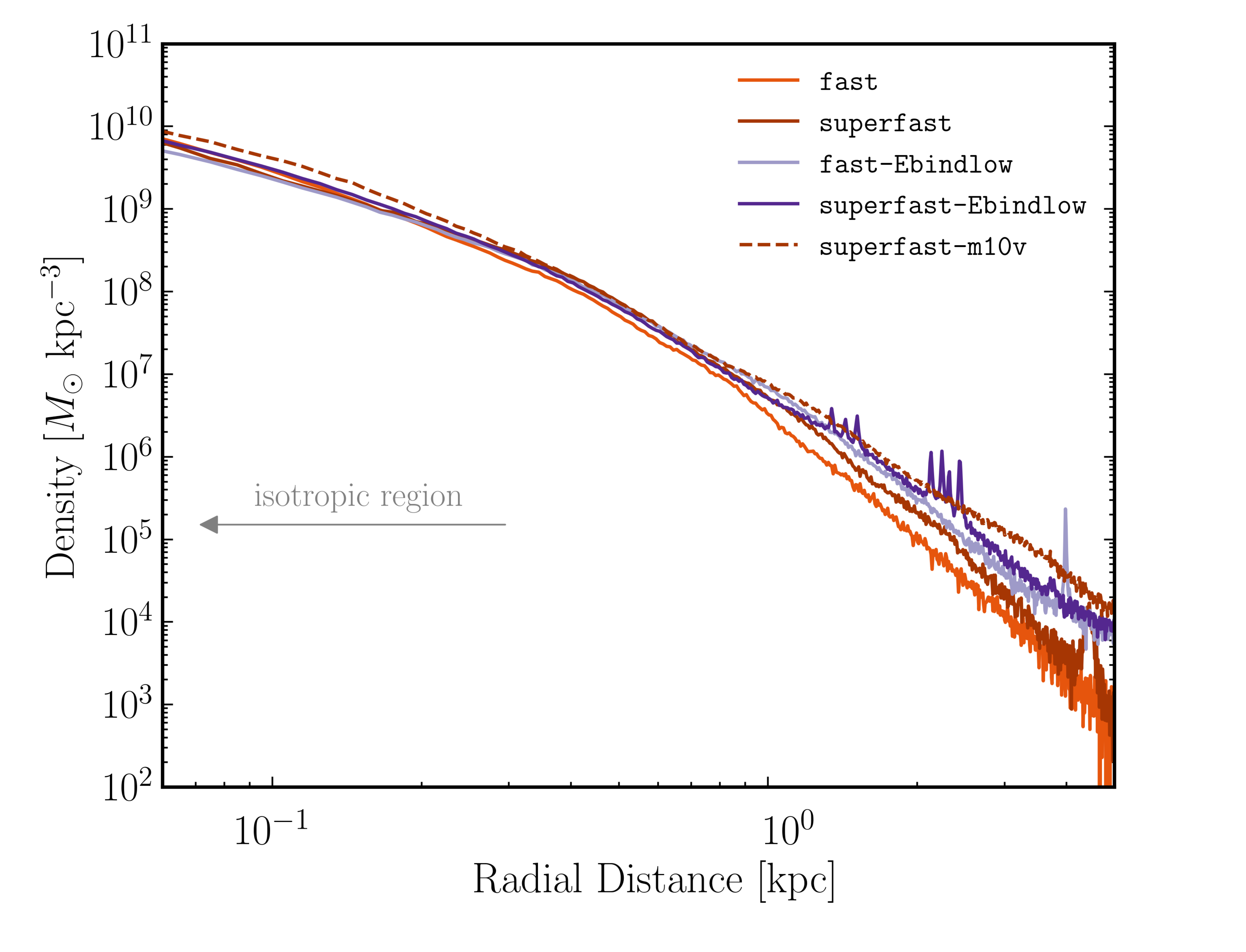
aDM Clump Densities



aDM Clump Densities

They agree to a factor $\lesssim 2$

Almost identical inner slope

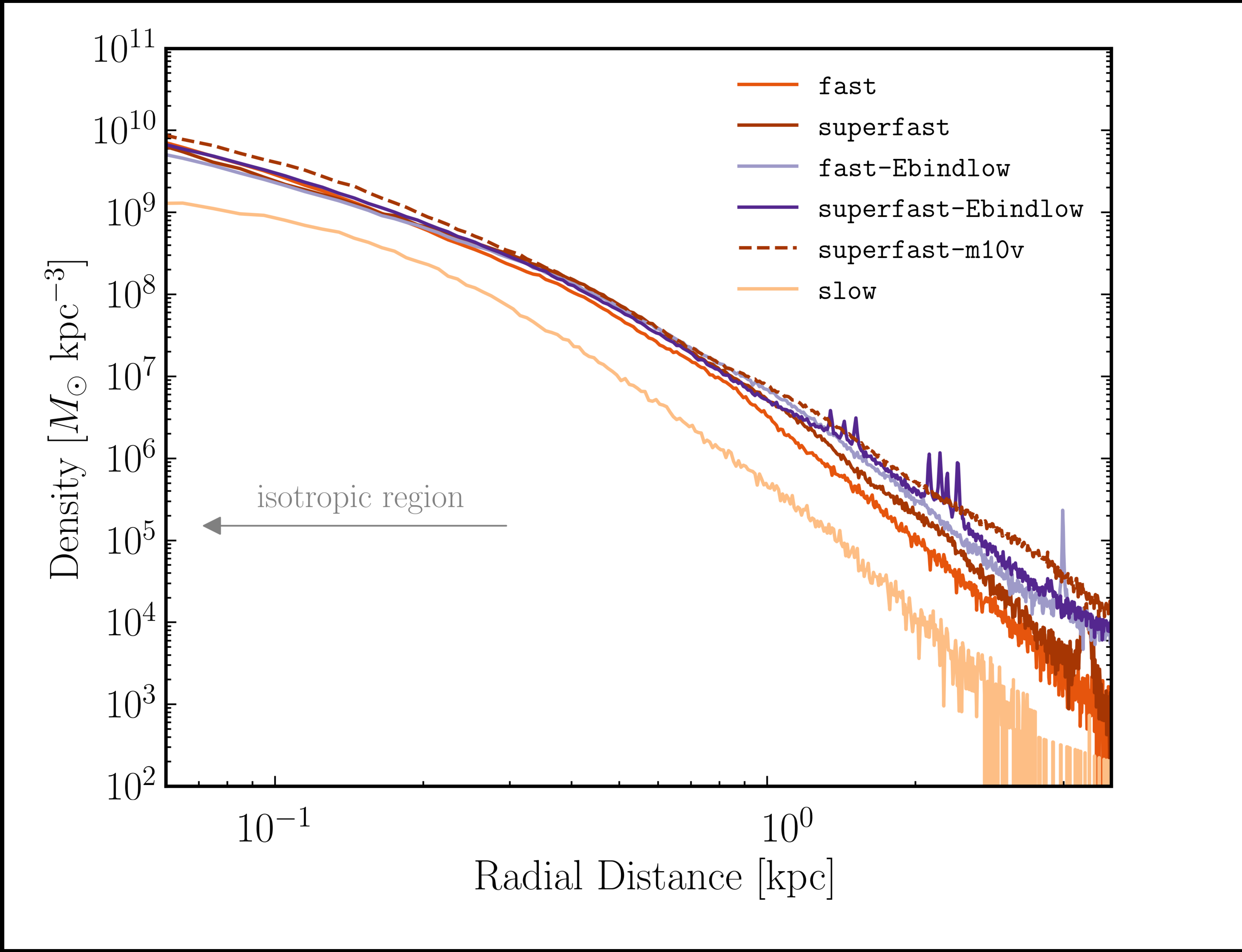


aDM Clump Densities

They agree to a factor $\lesssim 2$

Almost identical inner slope

Slower cooling aDM is less dense



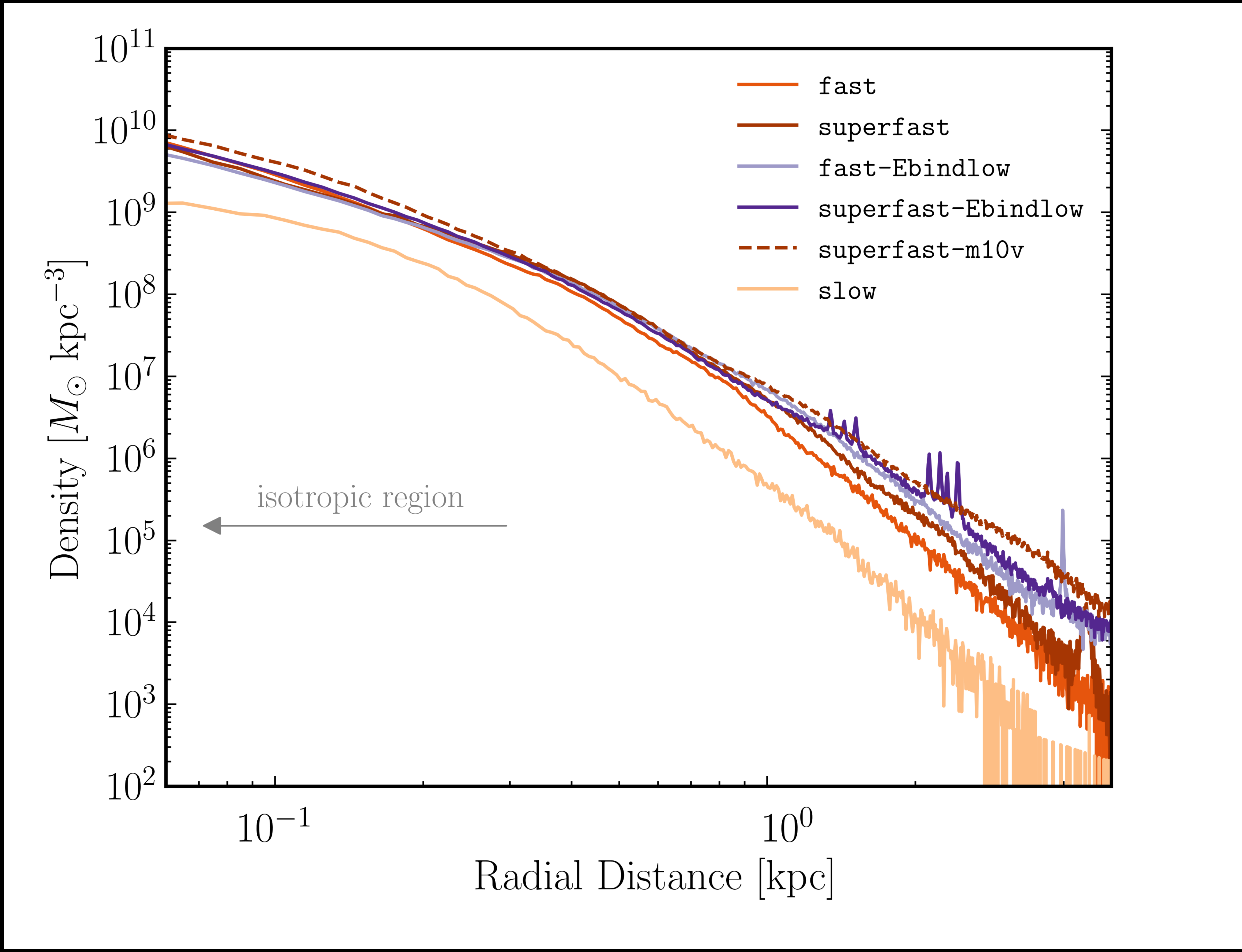
aDM Clump Densities

They agree to a factor $\lesssim 2$

Almost identical inner slope

Slower cooling aDM is less dense

Aggressive cooling -> inner equilibrium

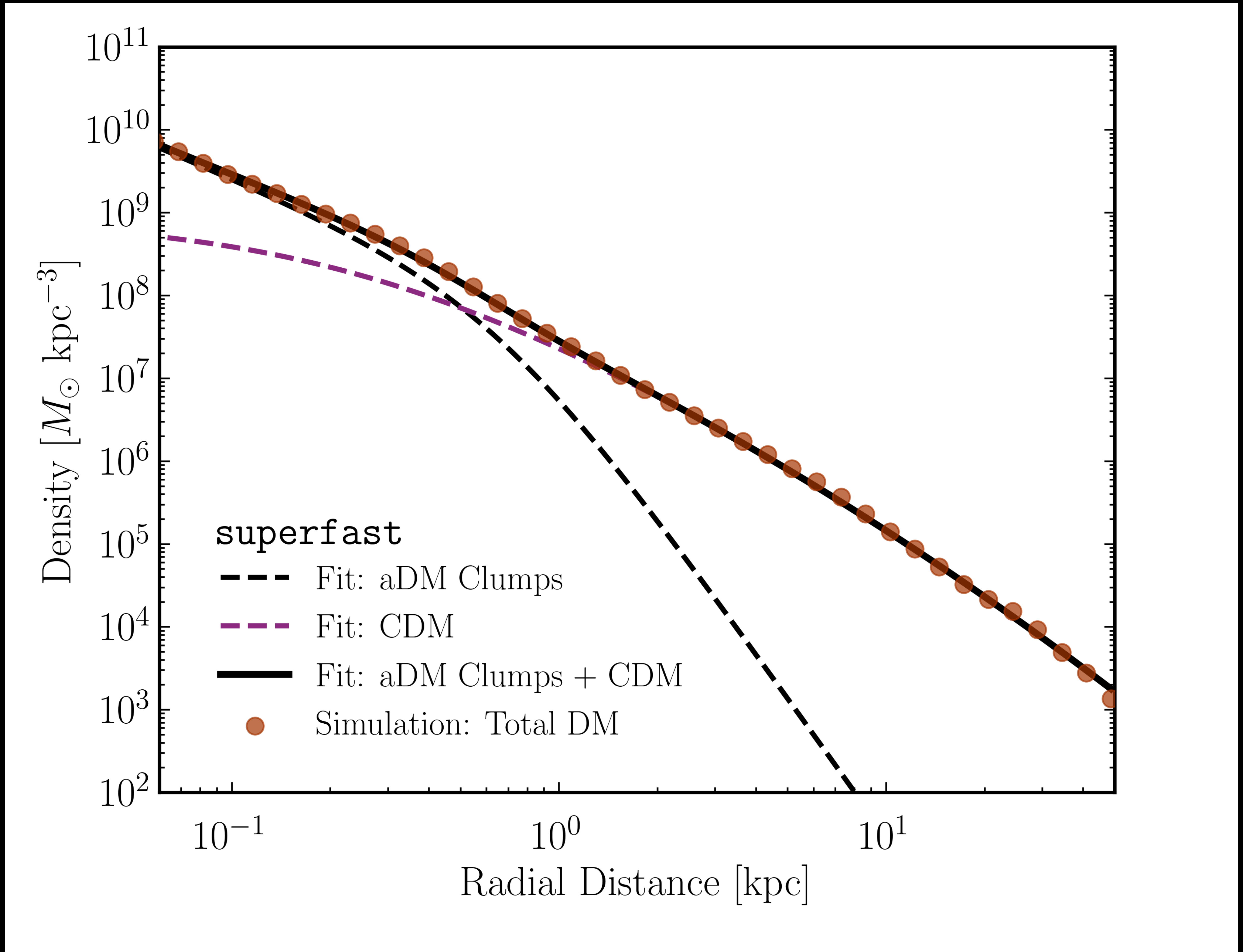


Fitting Functions and Scaling Laws

Fitting Functions and Scaling Laws

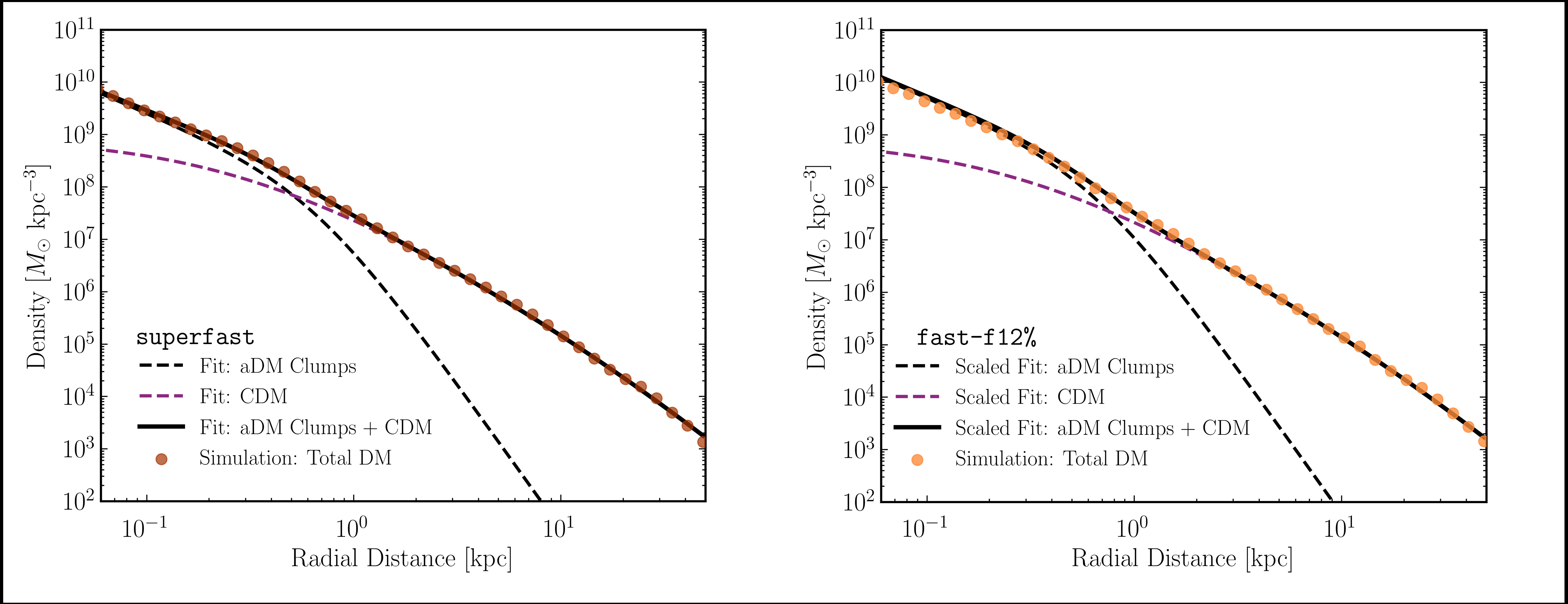
$$\rho_{\rm dm}(r) = \rho'_{\rm adm\,clump}(r) + \rho_{\rm cdm}(r)$$

Fitting Functions and Scaling Laws



$$\rho_{\mathrm{dm}}(r) = \rho'_{\mathrm{adm\,clump}}(r) + \rho_{\mathrm{cdm}}(r)$$

Fitting Functions and Scaling Laws



$$\rho_{\rm dm}(r) = \rho'_{\rm adm\,clump}(r) + \rho_{\rm cdm}(r)$$

Summary and Implications

Summary and Implications

6% aDM: the inner densities increase a lot!

Summary and Implications

6% aDM: the inner densities increase a lot!

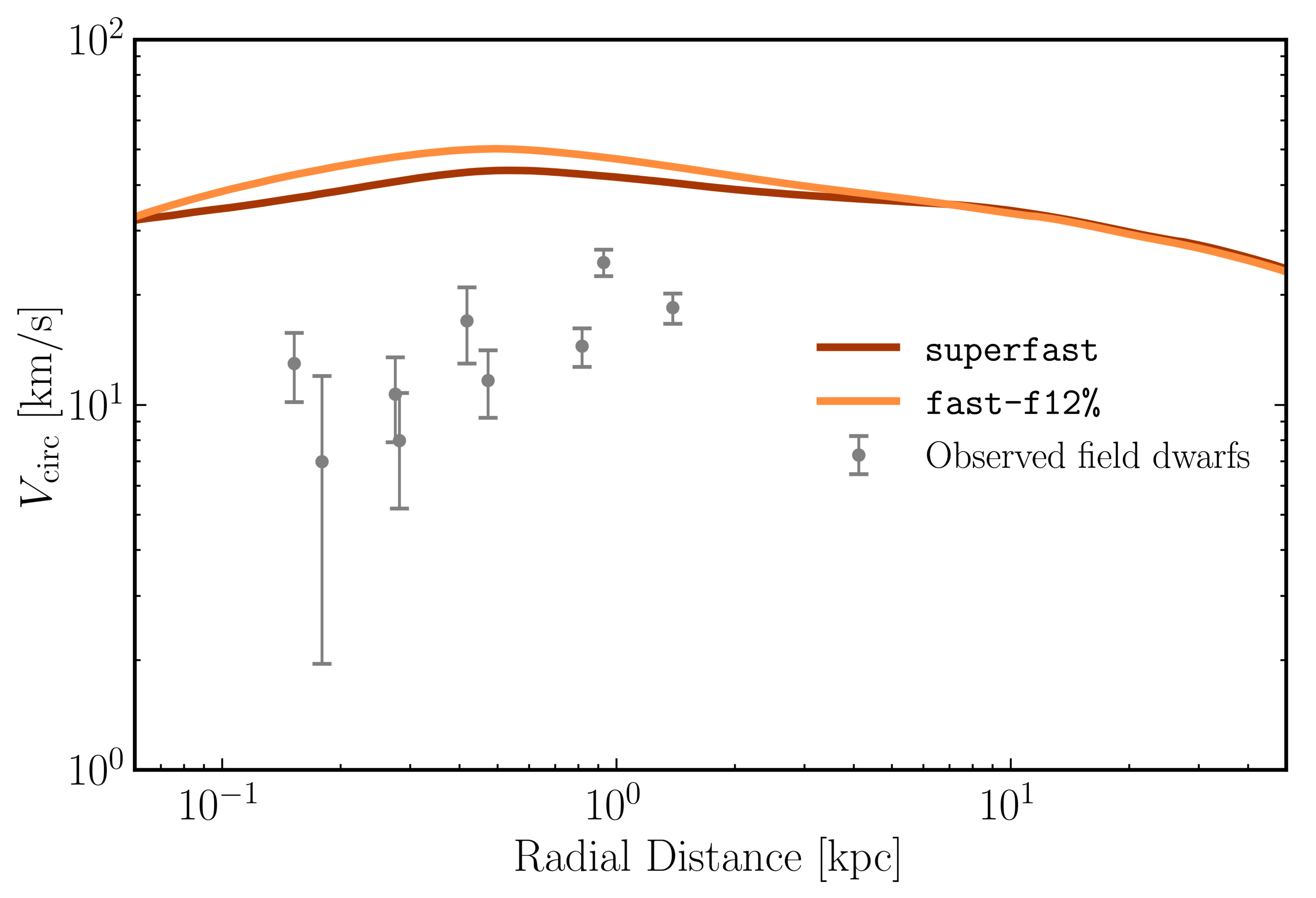
Aggressive-cooling: universal density profiles

Summary and Implications

6% aDM: the inner densities increase a lot!

Aggressive-cooling: universal density profiles

Will constrain aDM w/ dwarf velocities



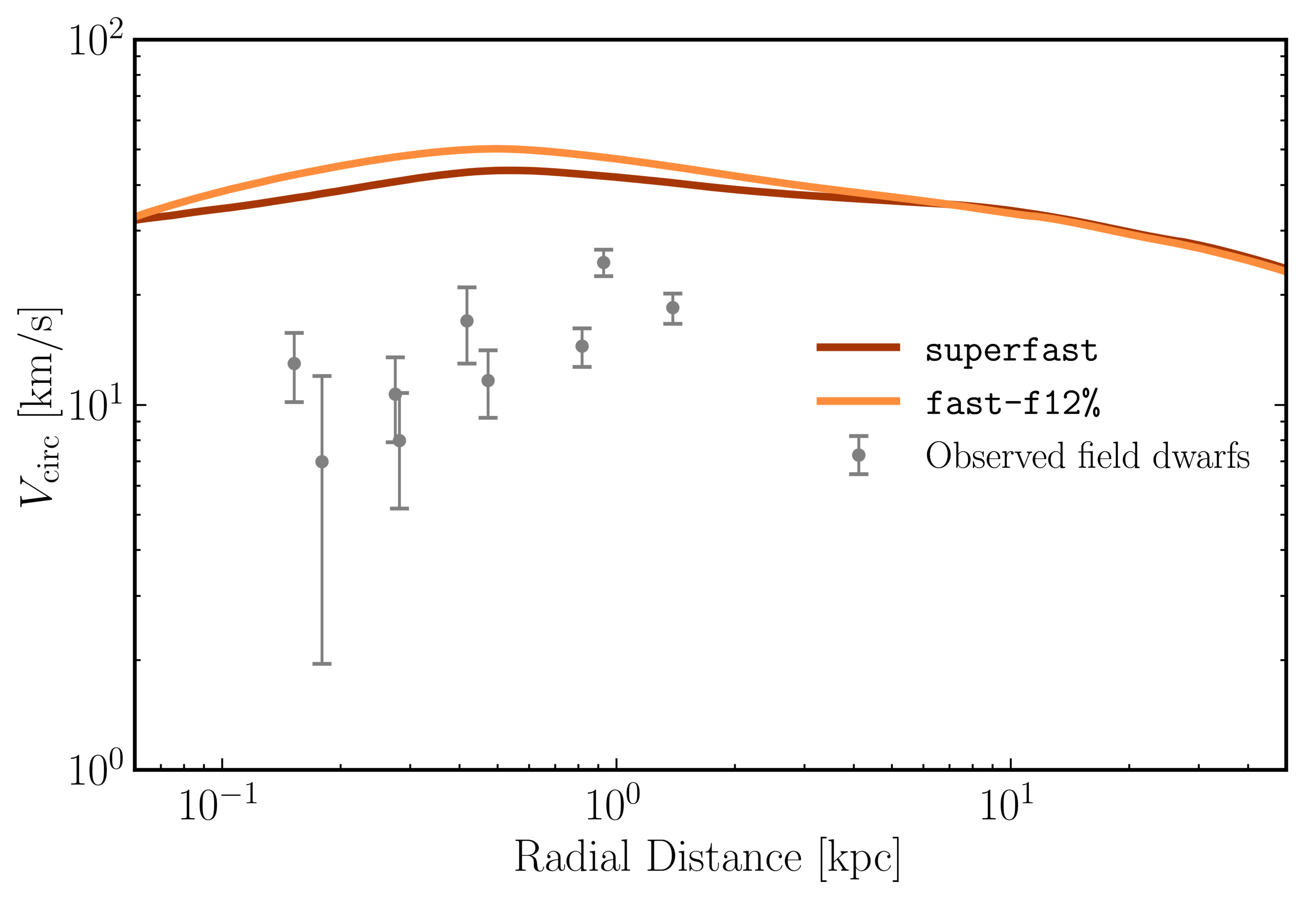
Summary and Implications

6% aDM: the inner densities increase a lot!

Aggressive-cooling: universal density profiles

Will constrain aDM w/ dwarf velocities

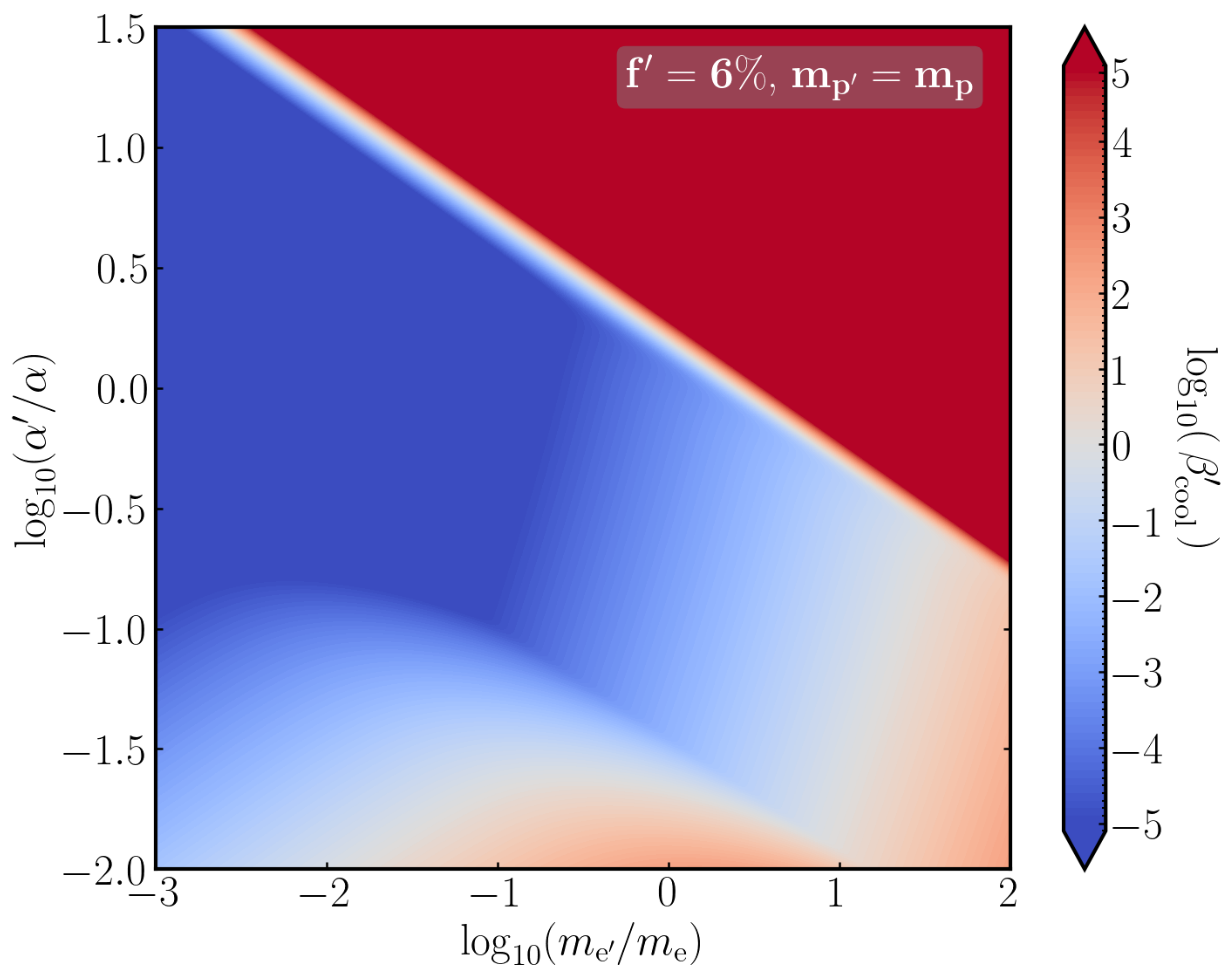
Other interesting observables are welcome! (21-cm, see Jared's talk! Lyman-Alpha, see Caleb's talk!)



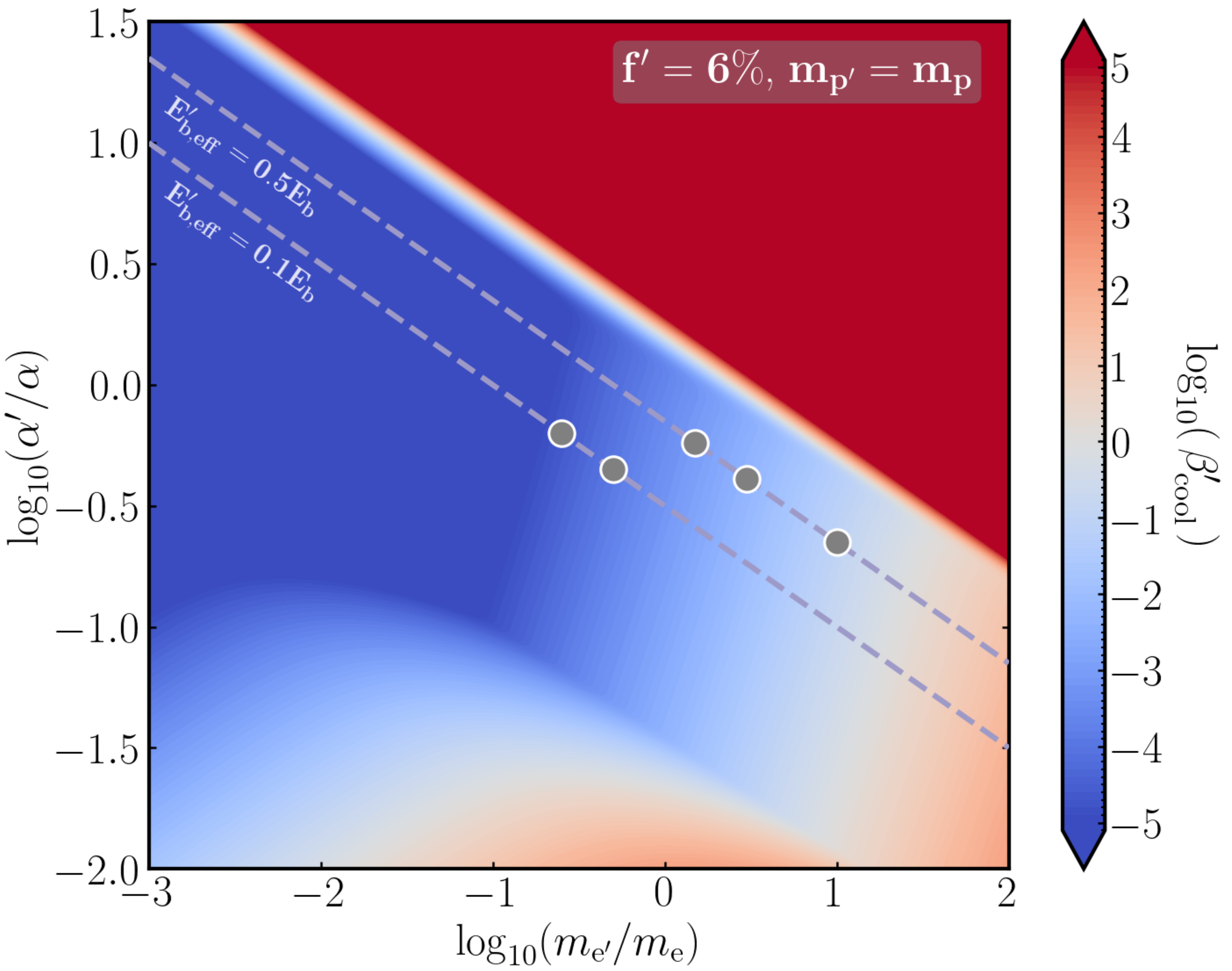
Supplementary Slides

Parameter Space

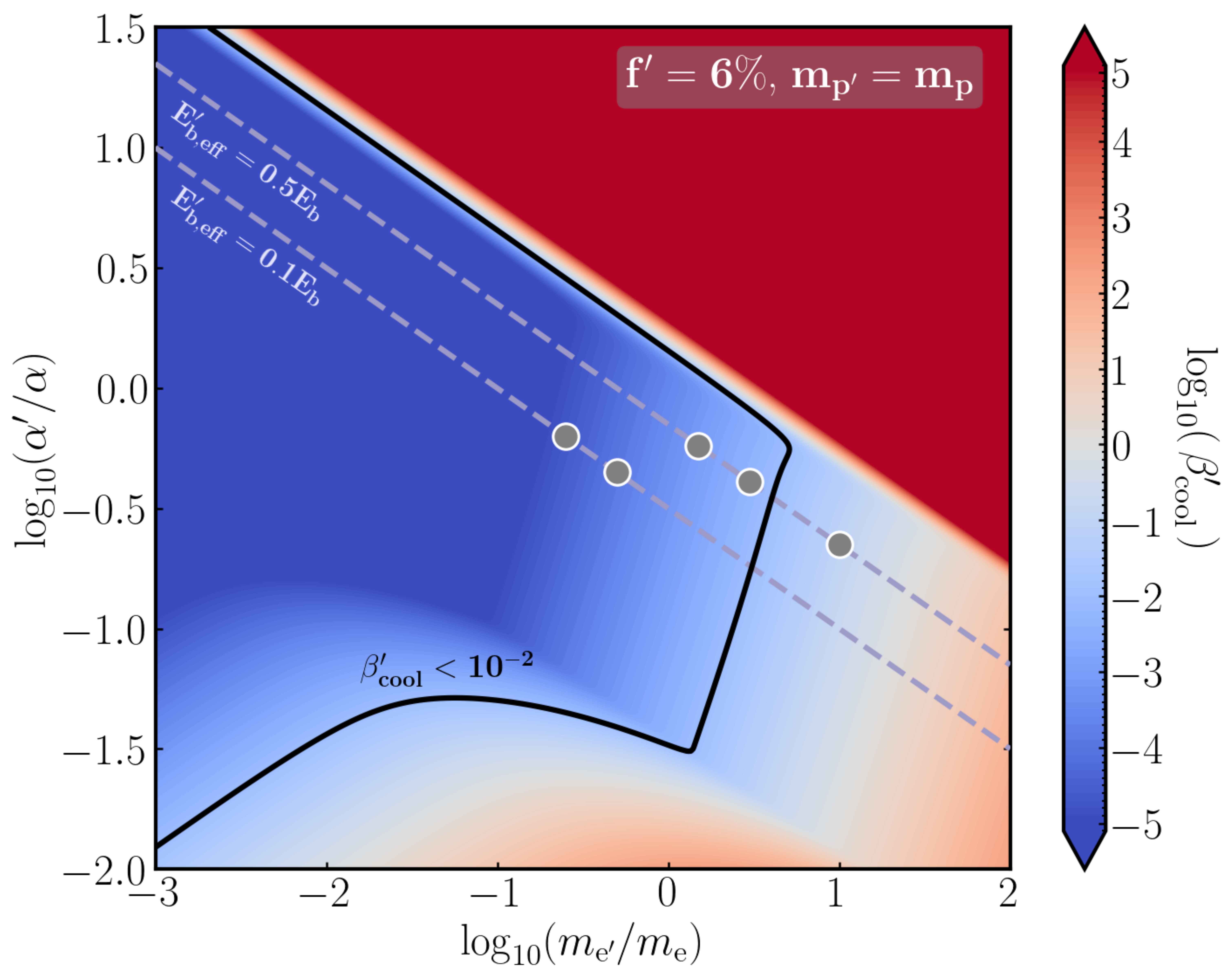
Parameter Space



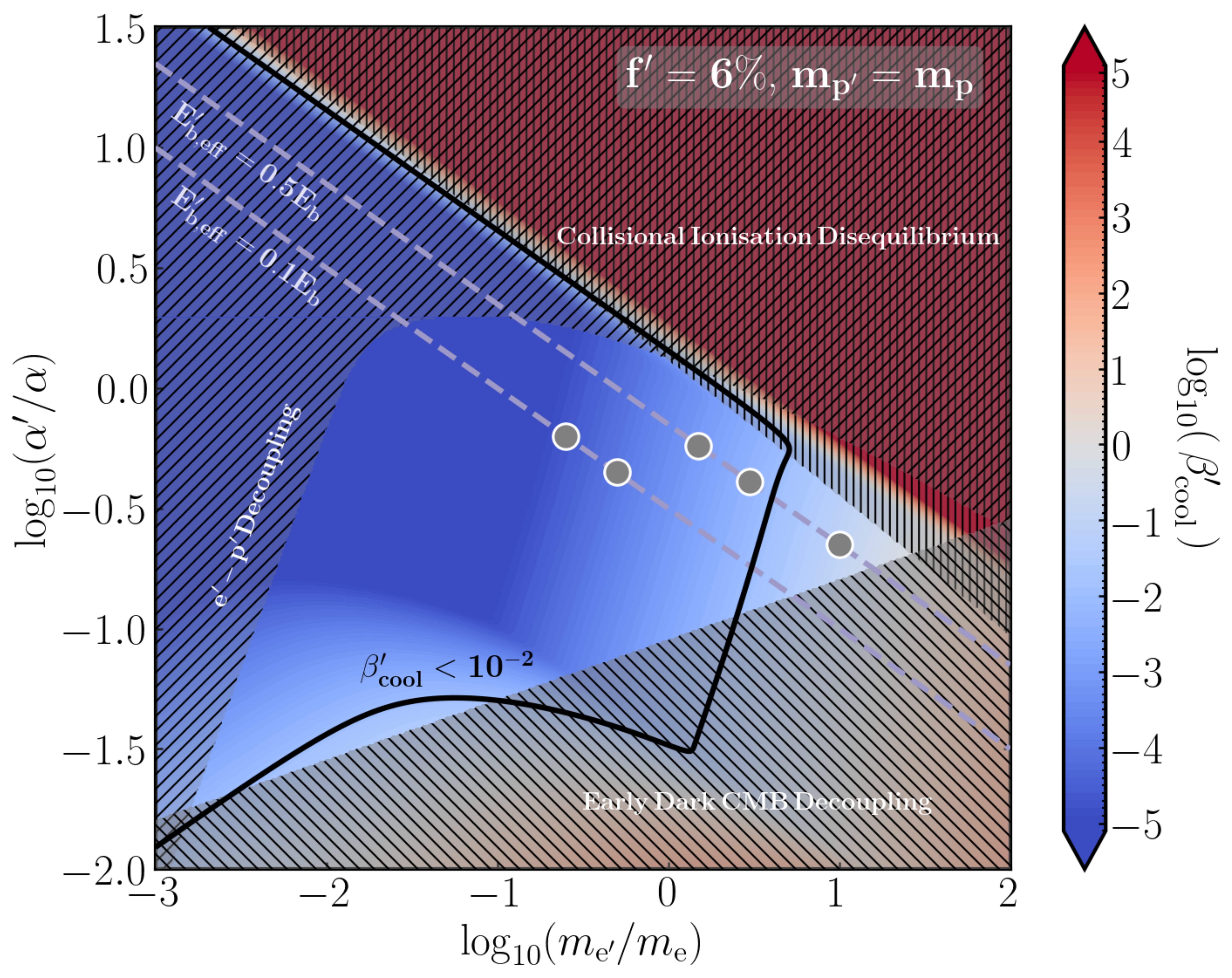
Parameter Space



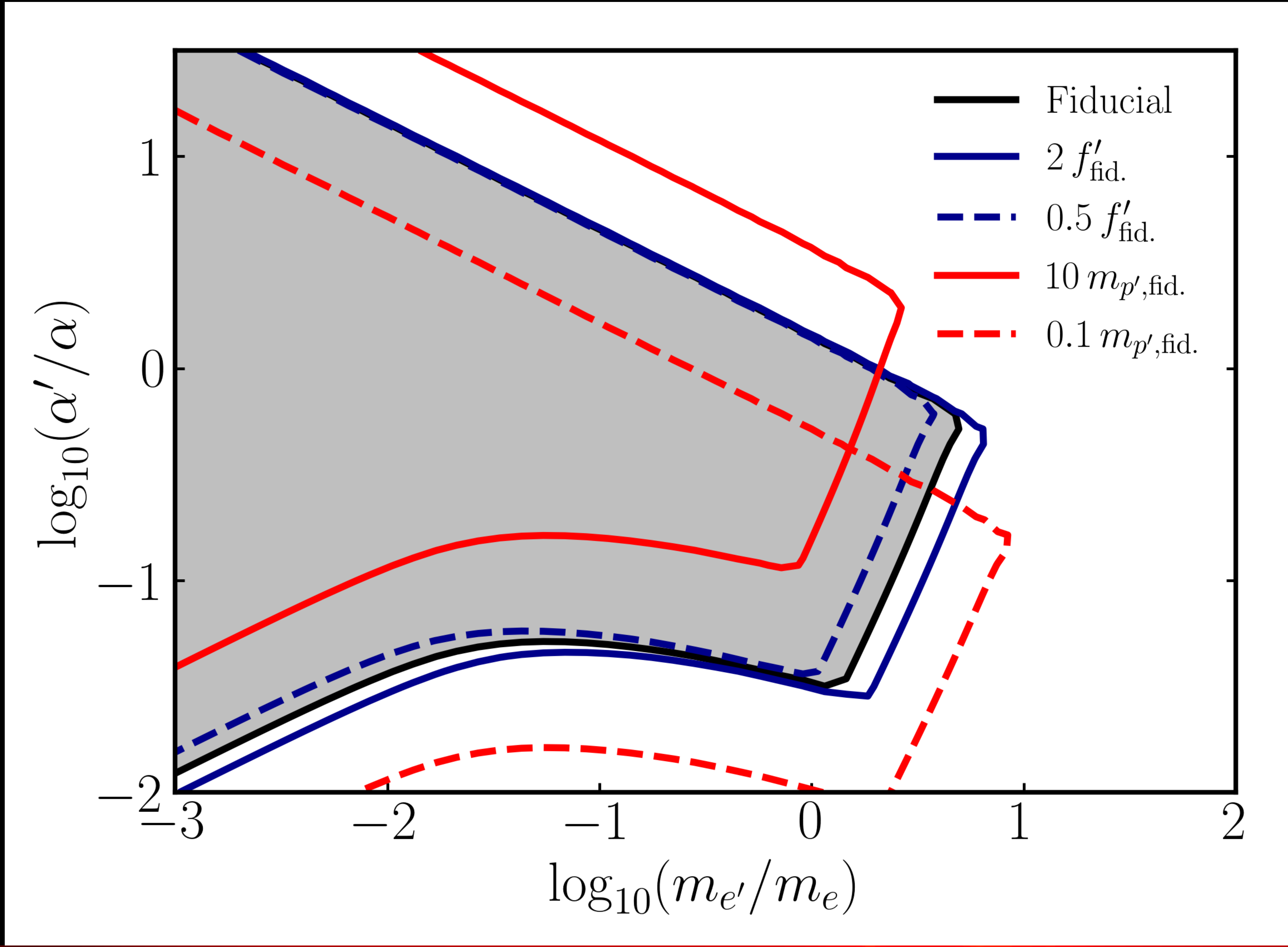
Parameter Space



Parameter Space

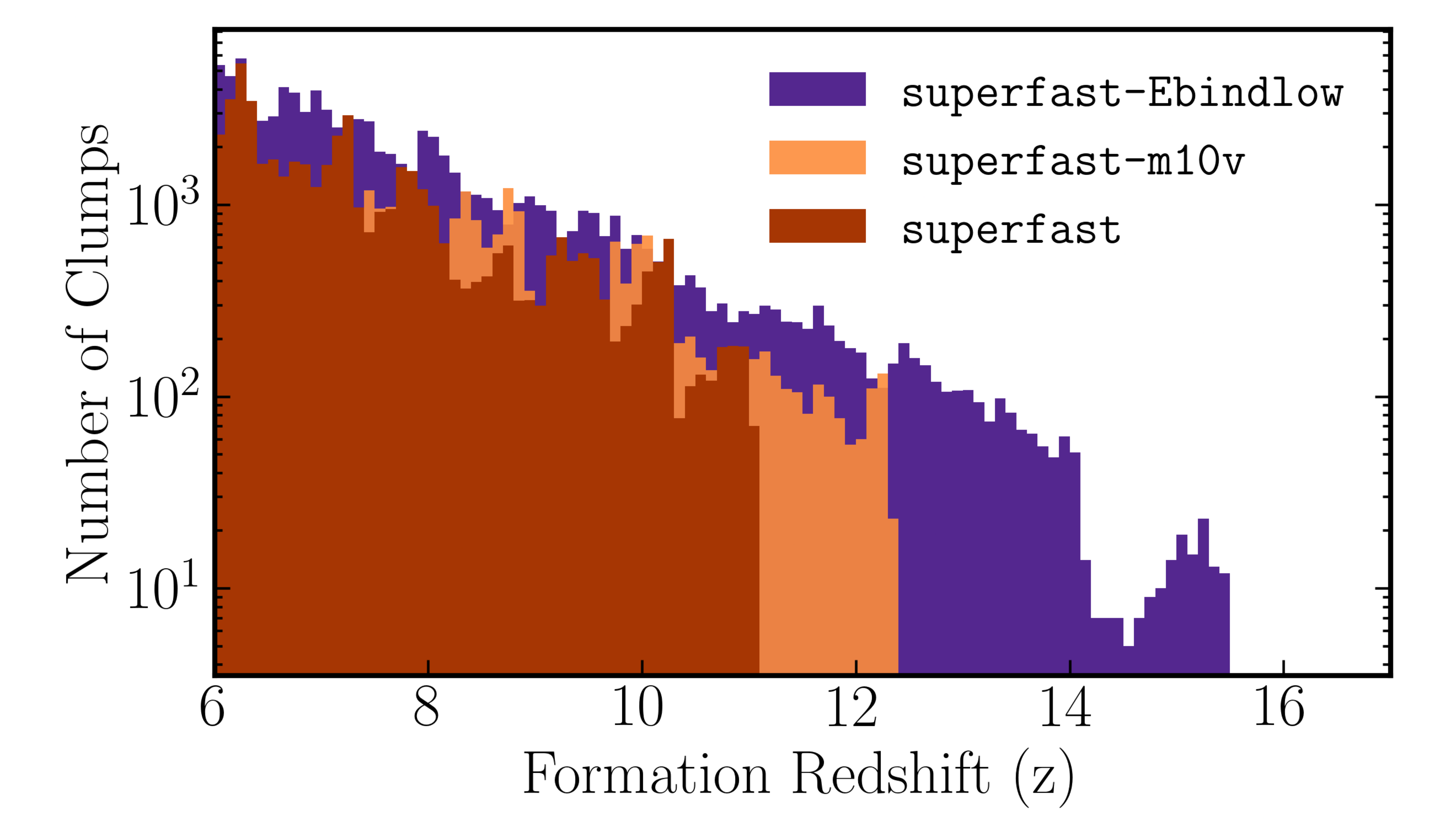


Effect of $m_{p'}$ and f' on β'_{cool} Contour

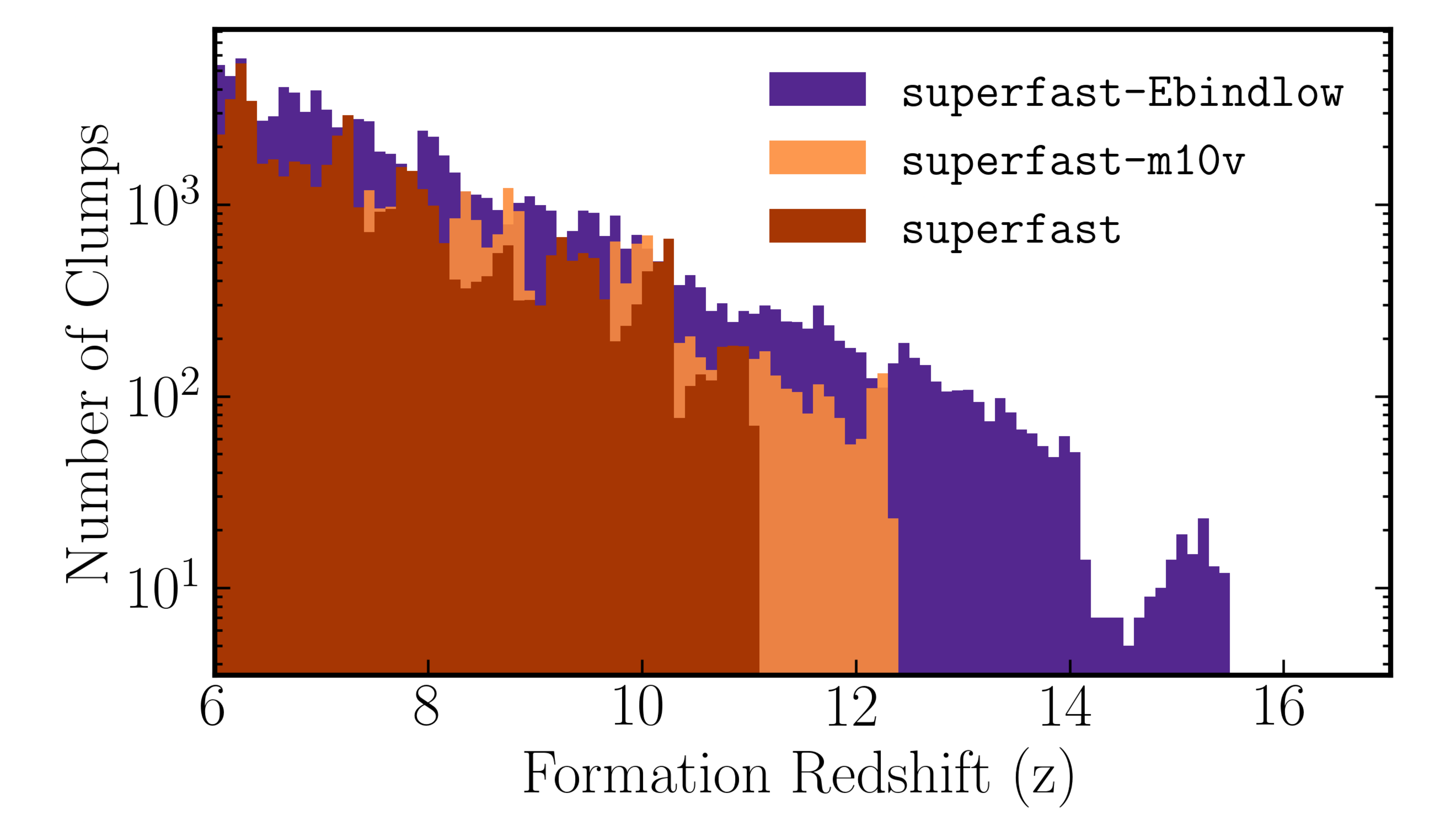


Cooling and Collapse at High Redshift

Cooling and Collapse at High Redshift



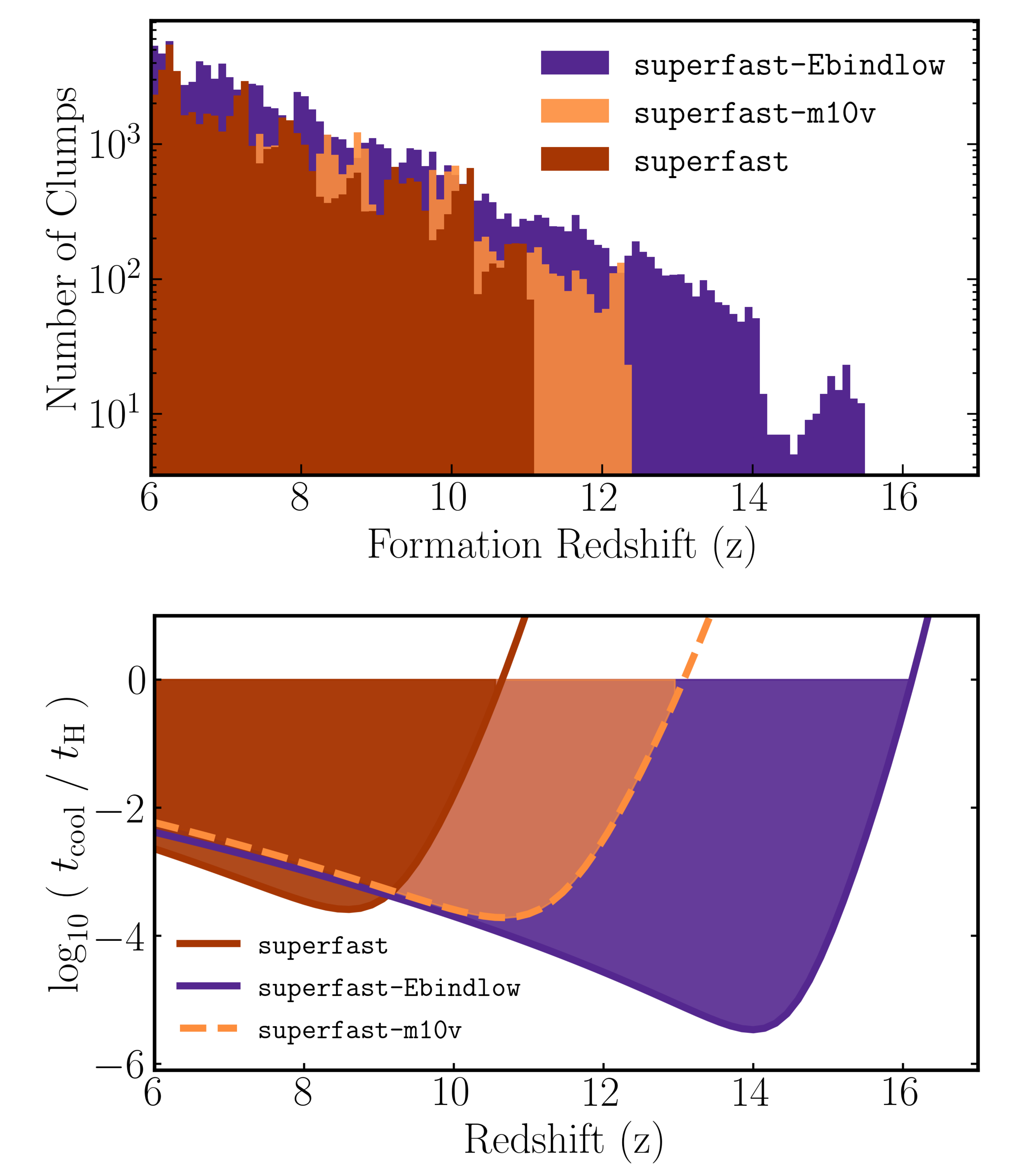
Cooling and Collapse at High Redshift



Clumps begin forming at high redshift

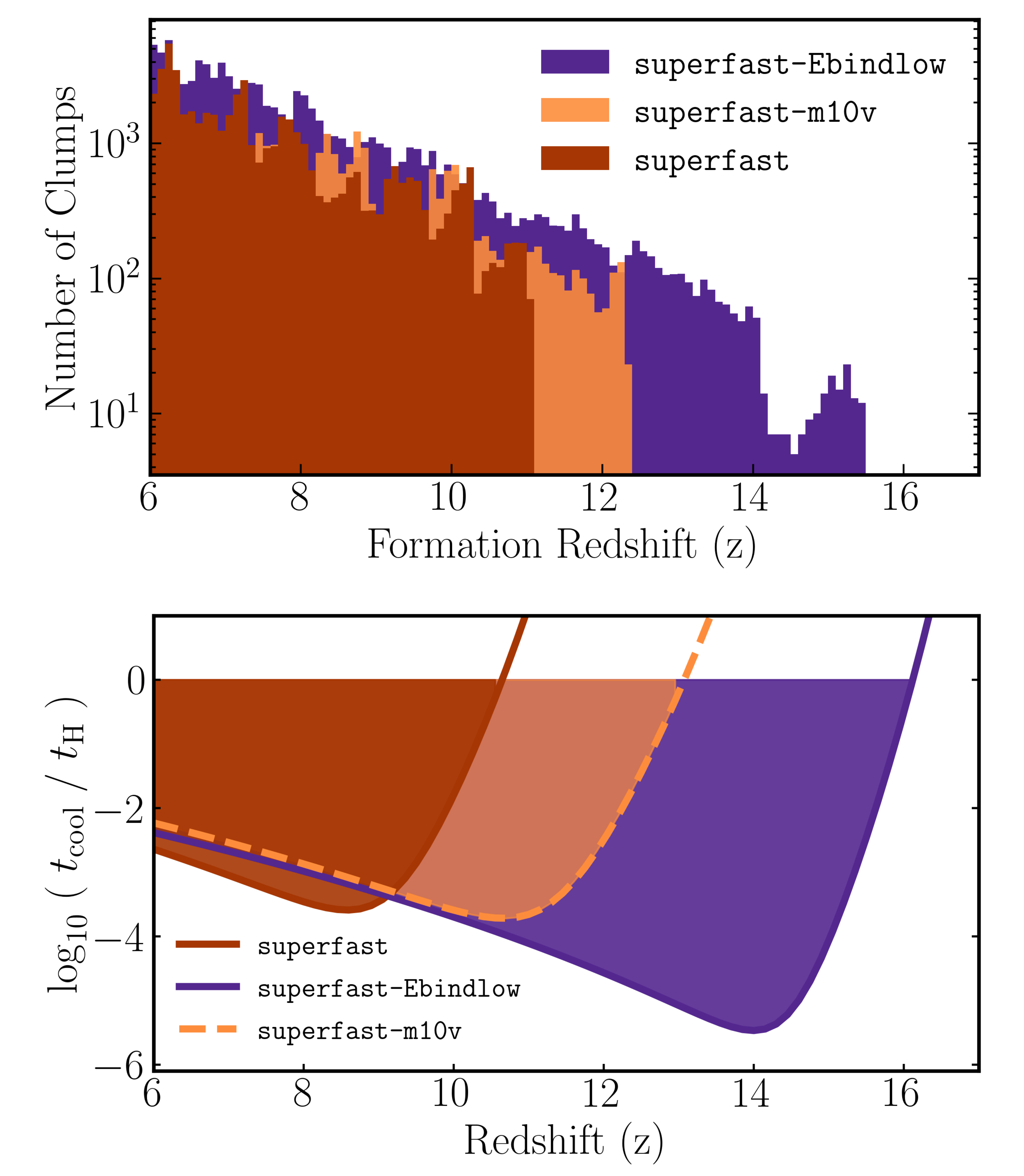
Cooling and Collapse at High Redshift

Clumps begin forming at high redshift



Cooling and Collapse at High Redshift

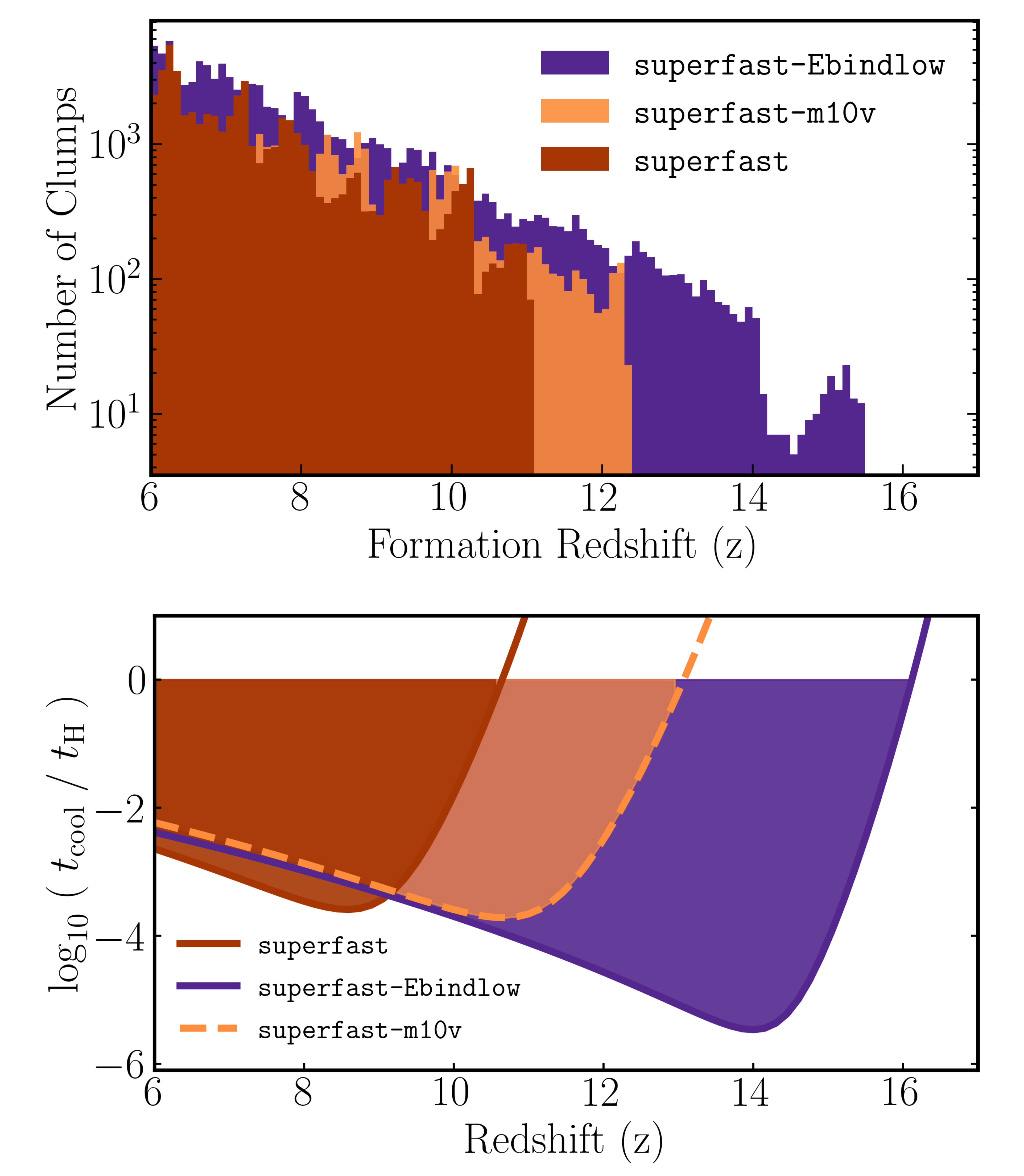
Clumps begin forming at high redshift



Cooling and Collapse at High Redshift

Clumps begin forming at high redshift

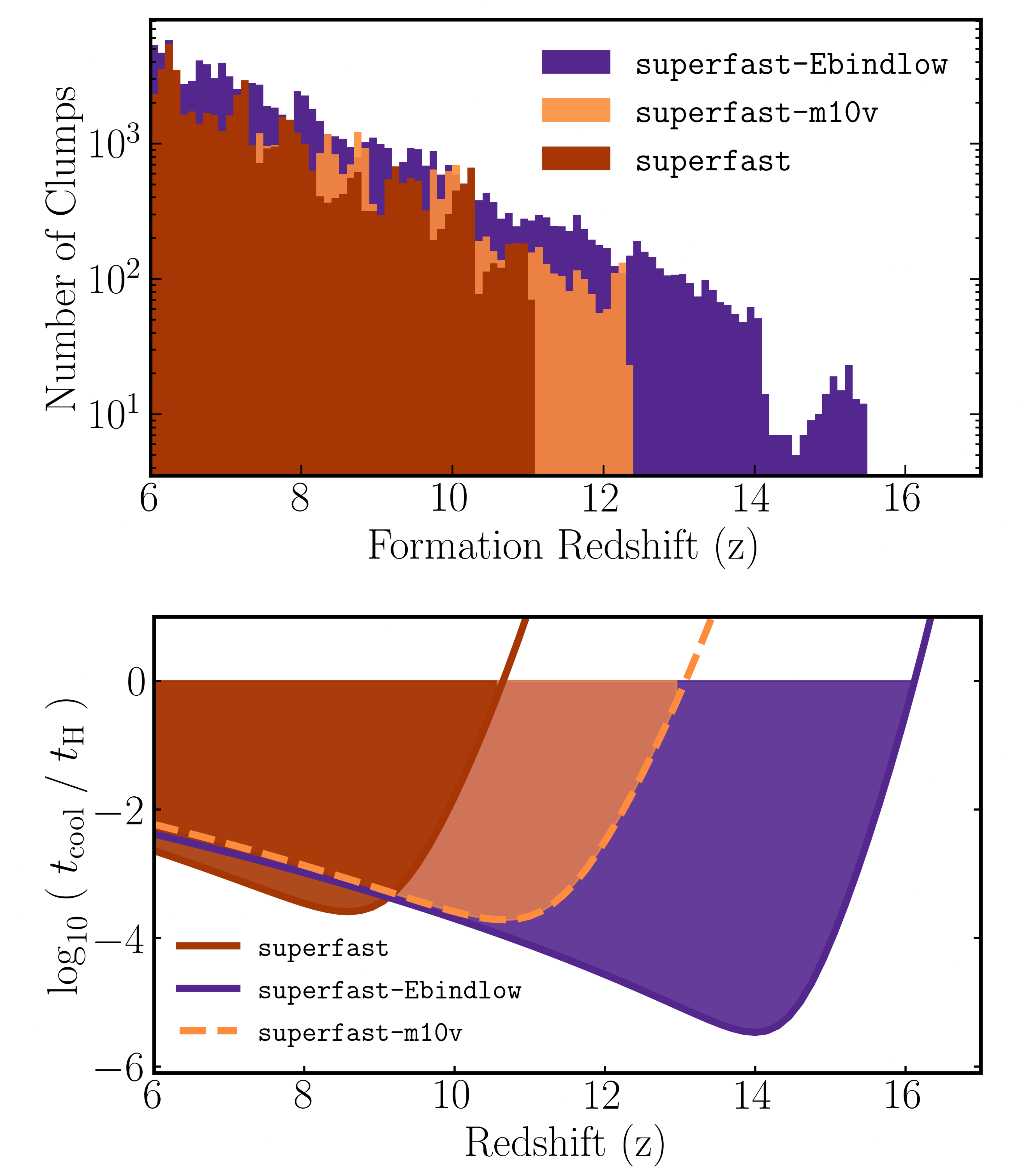
Rapid aDM cooling occurs at high redshift



Cooling and Collapse at High Redshift

Clumps begin forming at high redshift

Rapid aDM cooling occurs at high redshift

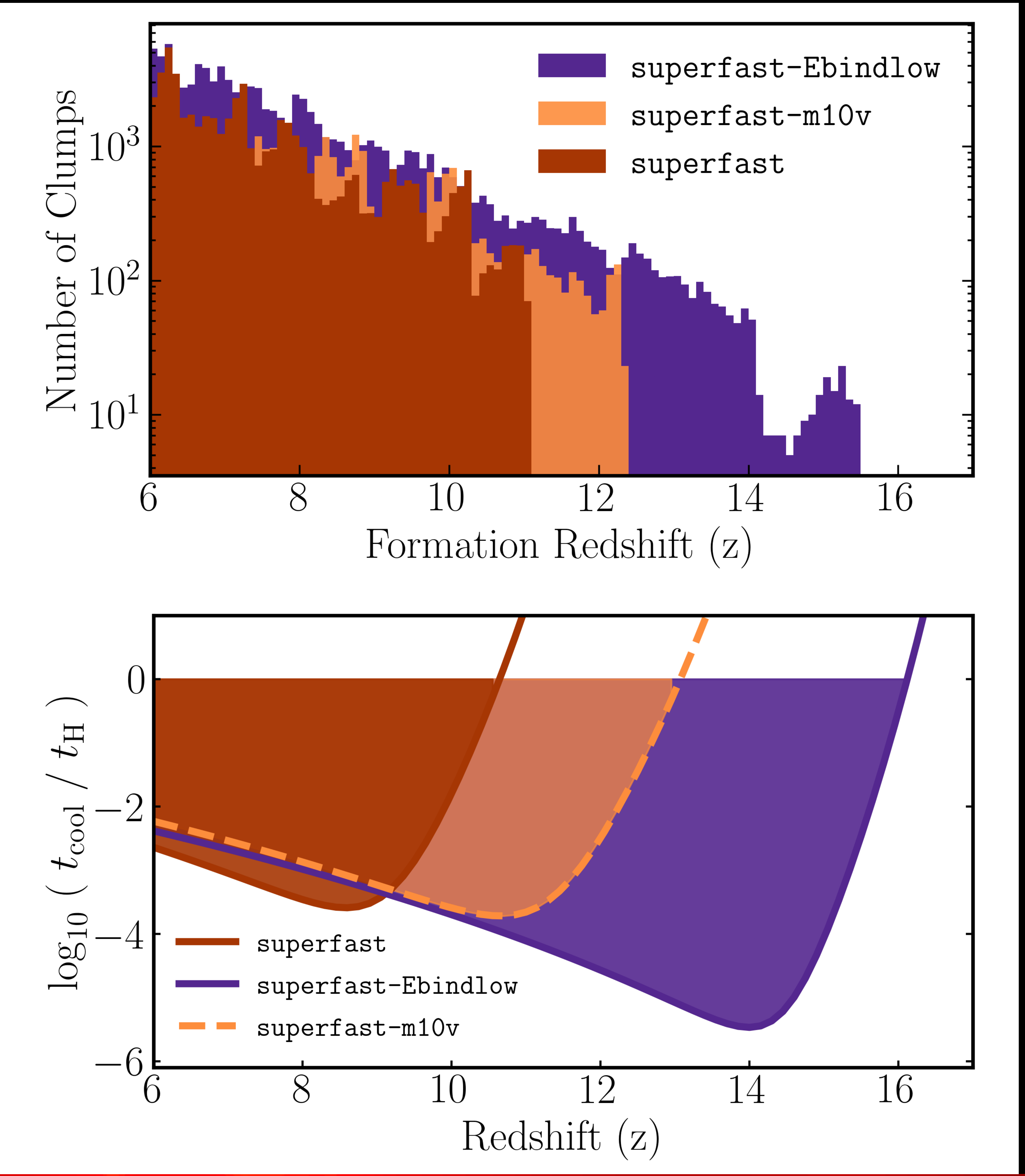


Cooling and Collapse at High Redshift

Clumps begin forming at high redshift

Rapid aDM cooling occurs at high redshift

Equilibration of aDM in aggressively-dissipative regime



Fitting Functions and Scaling Laws

Fitting Functions and Scaling Laws

$$\rho'_{\rm adm}(r) = \rho'_0 \left(\frac{r}{r'_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r'_s}\right)^2\right]^{-(\beta-\gamma)/2}$$

Fitting Functions and Scaling Laws

$$\rho'_{\rm adm}(r) = \rho'_0 \left(\frac{r}{r'_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r'_s}\right)^2\right]^{-(\beta-\gamma)/2}$$

$$\rho'_0 \propto f'$$

Fitting Functions and Scaling Laws

$$\rho'_{\rm adm}(r) = \rho'_0 \left(\frac{r}{r'_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r'_s}\right)^2\right]^{-(\beta-\gamma)/2}$$

$$\rho'_0 \propto f'$$

$$\rho_{\rm cdm}(r) = \rho_0 \exp\left(-\frac{2}{\alpha_E}\left[\left(\frac{r+r_c}{r_s}\right)^{\alpha_E} - 1\right]\right)$$

Fitting Functions and Scaling Laws

$$\rho'_{\rm adm}(r) = \rho'_0 \left(\frac{r}{r'_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r'_s}\right)^2\right]^{-(\beta-\gamma)/2}$$

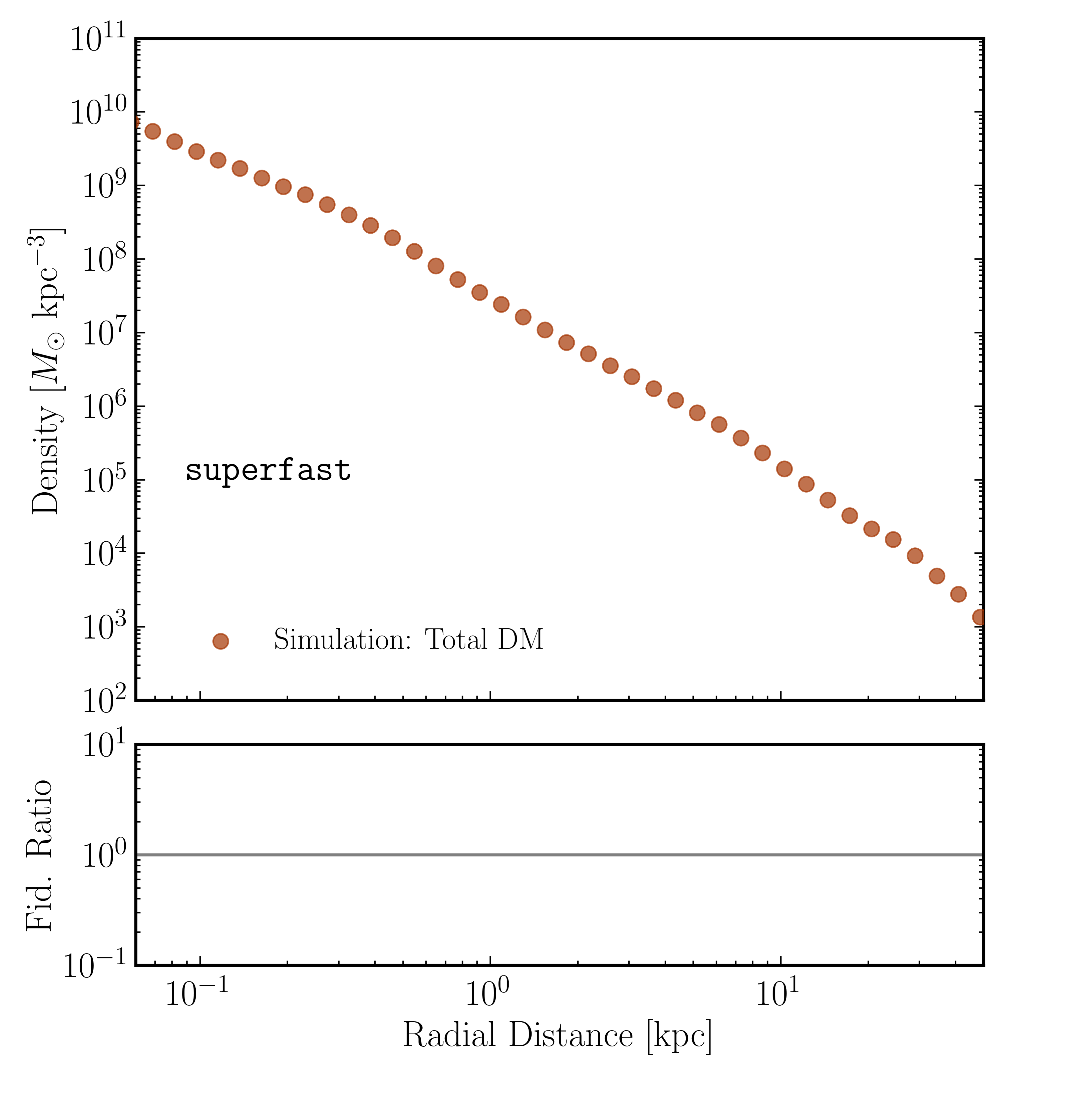
$$\rho'_0 \propto f'$$

$$\rho_{\rm cdm}(r) = \rho_0 \exp\left(-\frac{2}{\alpha_E}\left[\left(\frac{r+r_c}{r_s}\right)^{\alpha_E} - 1\right]\right)$$

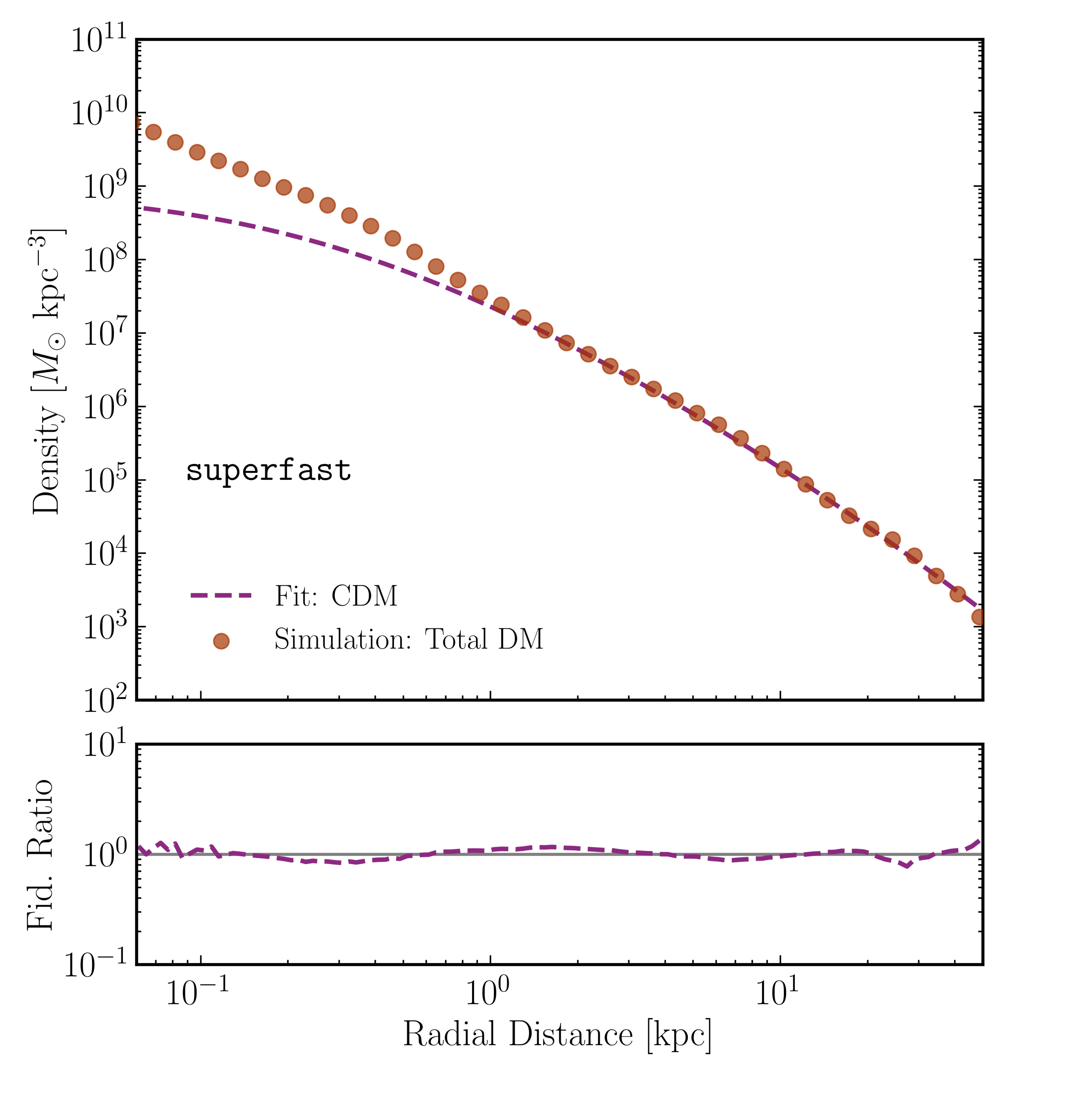
$$\rho_0 \propto (1 - f')$$

Fitting Functions and Scaling Laws

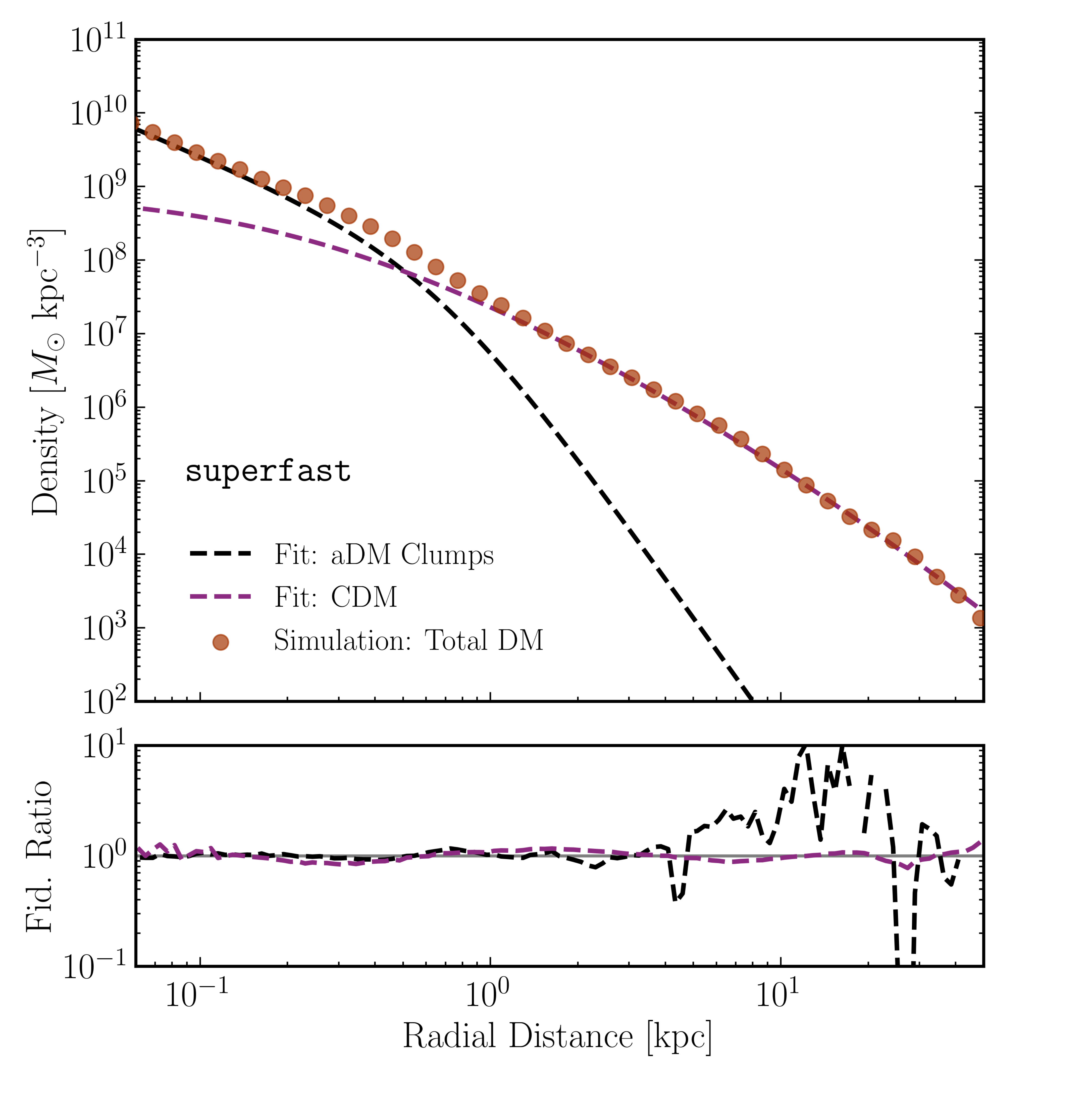
Fitting Functions and Scaling Laws



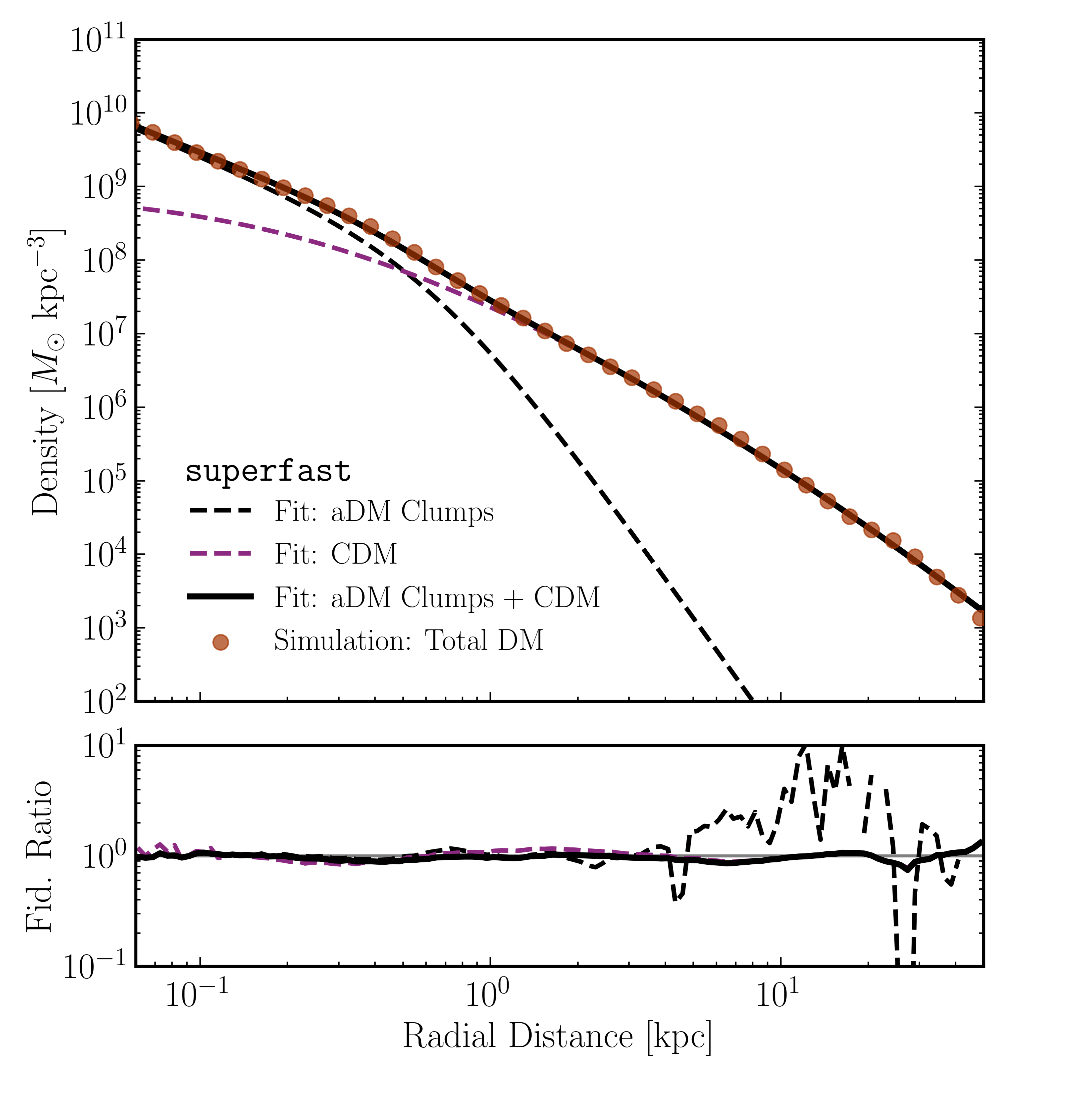
Fitting Functions and Scaling Laws



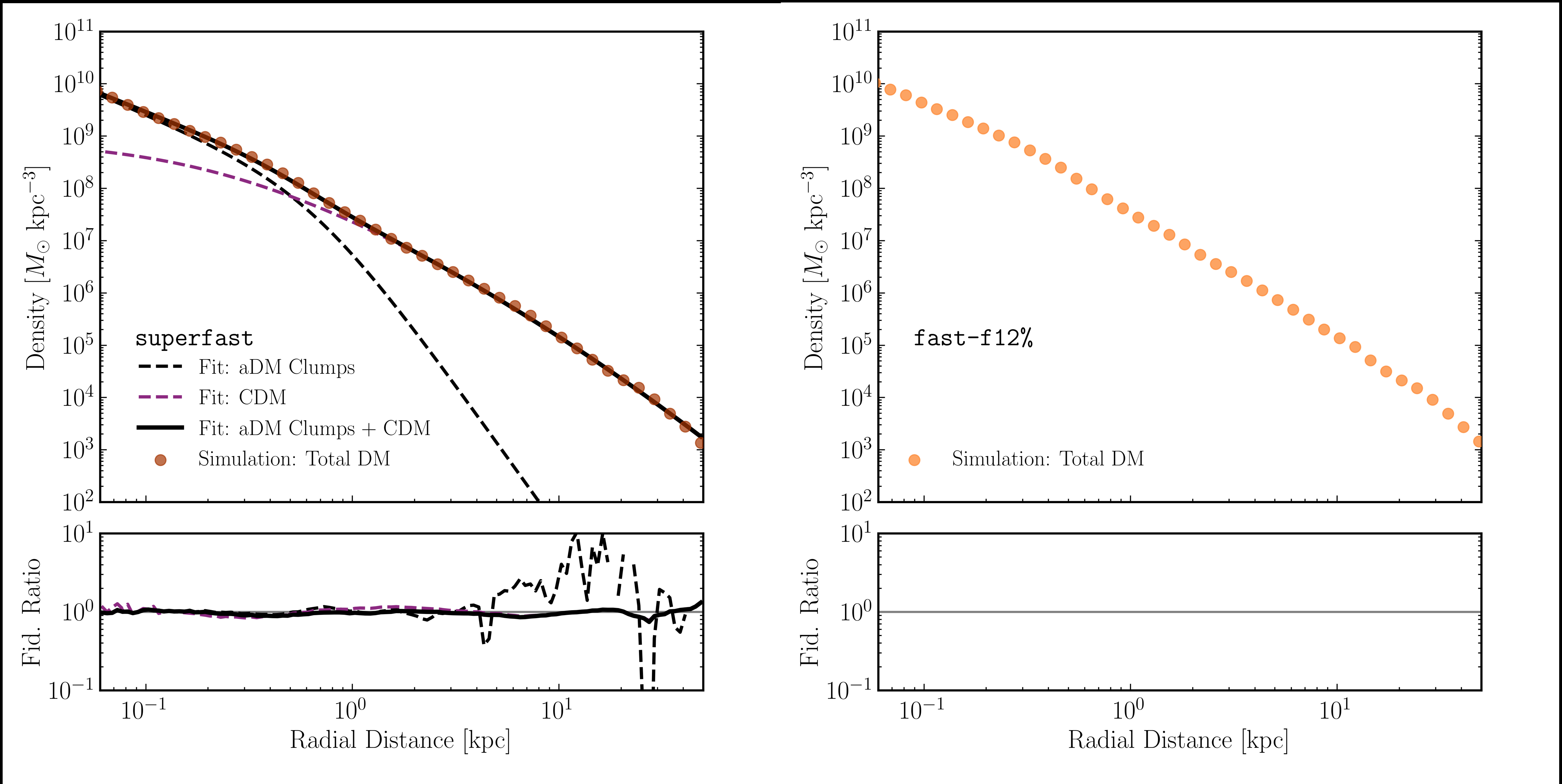
Fitting Functions and Scaling Laws



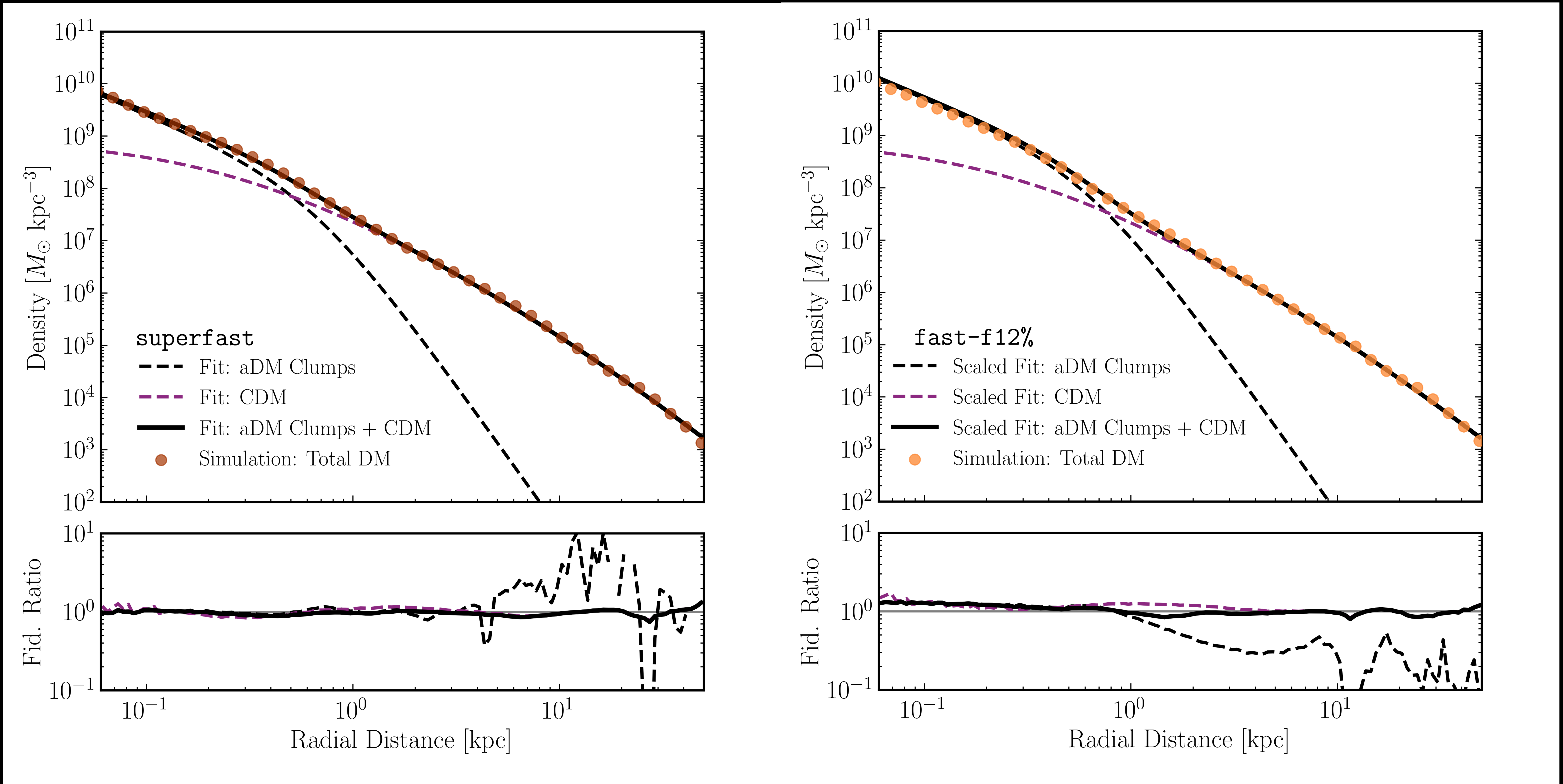
Fitting Functions and Scaling Laws



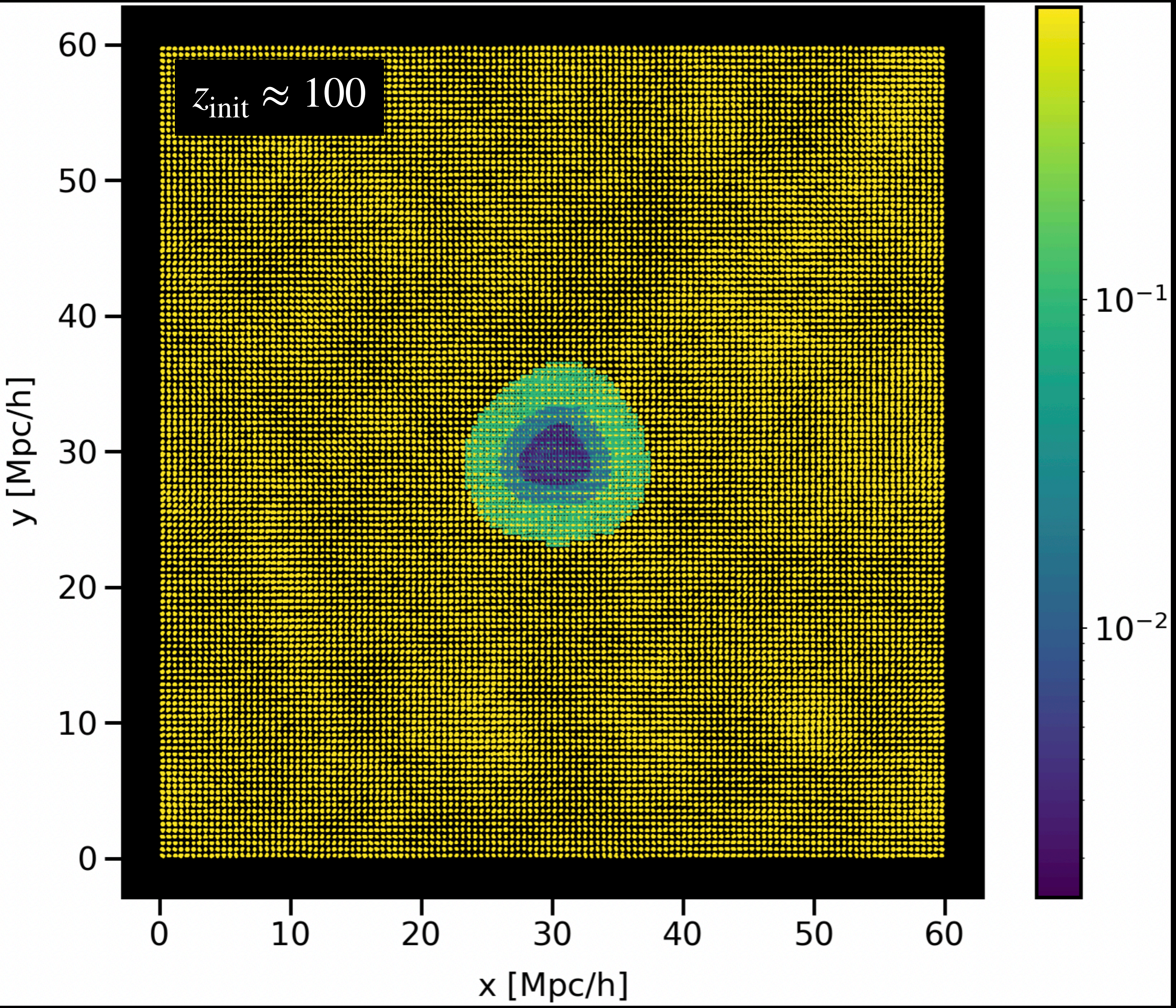
Fitting Functions and Scaling Laws



Fitting Functions and Scaling Laws

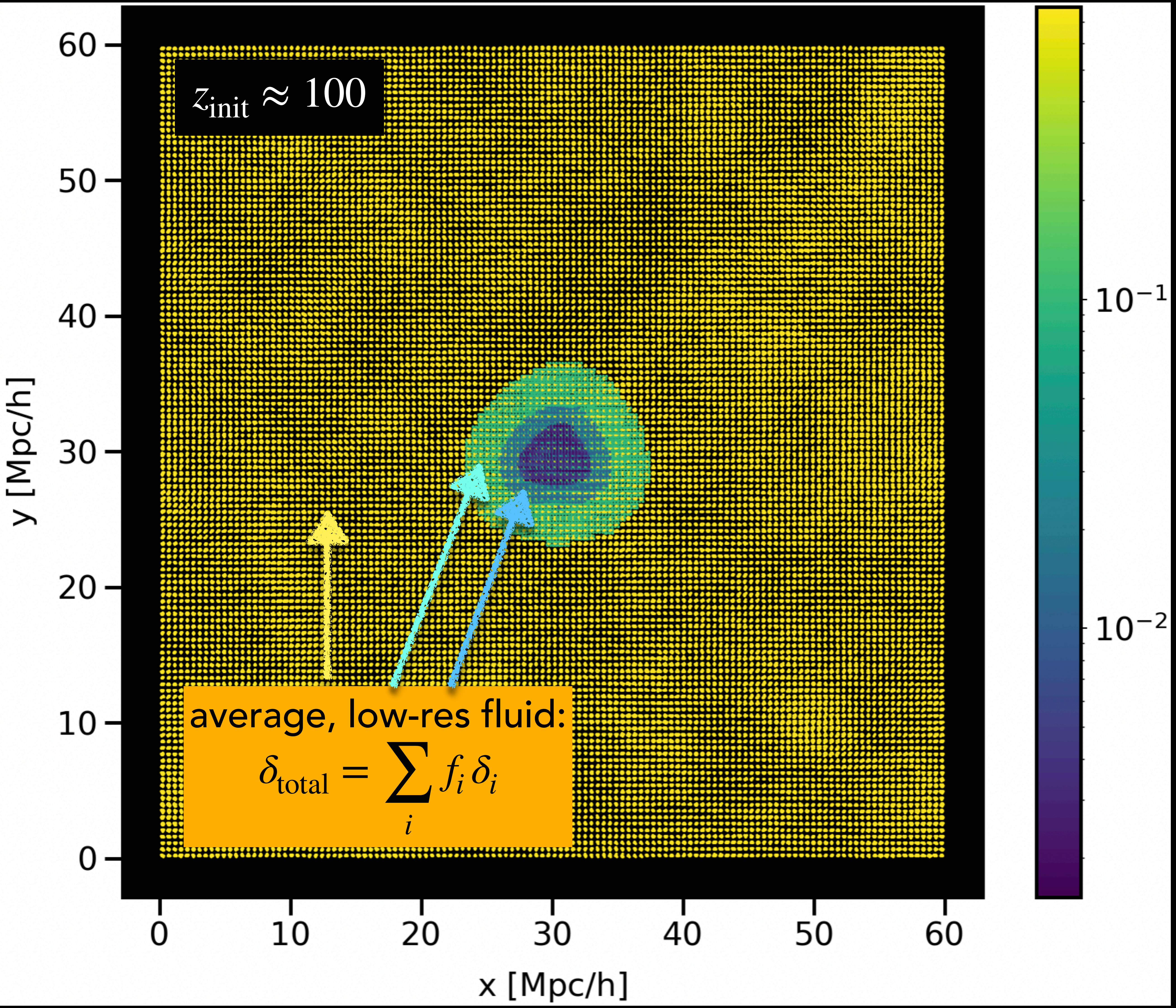


Zoom-In Simulations



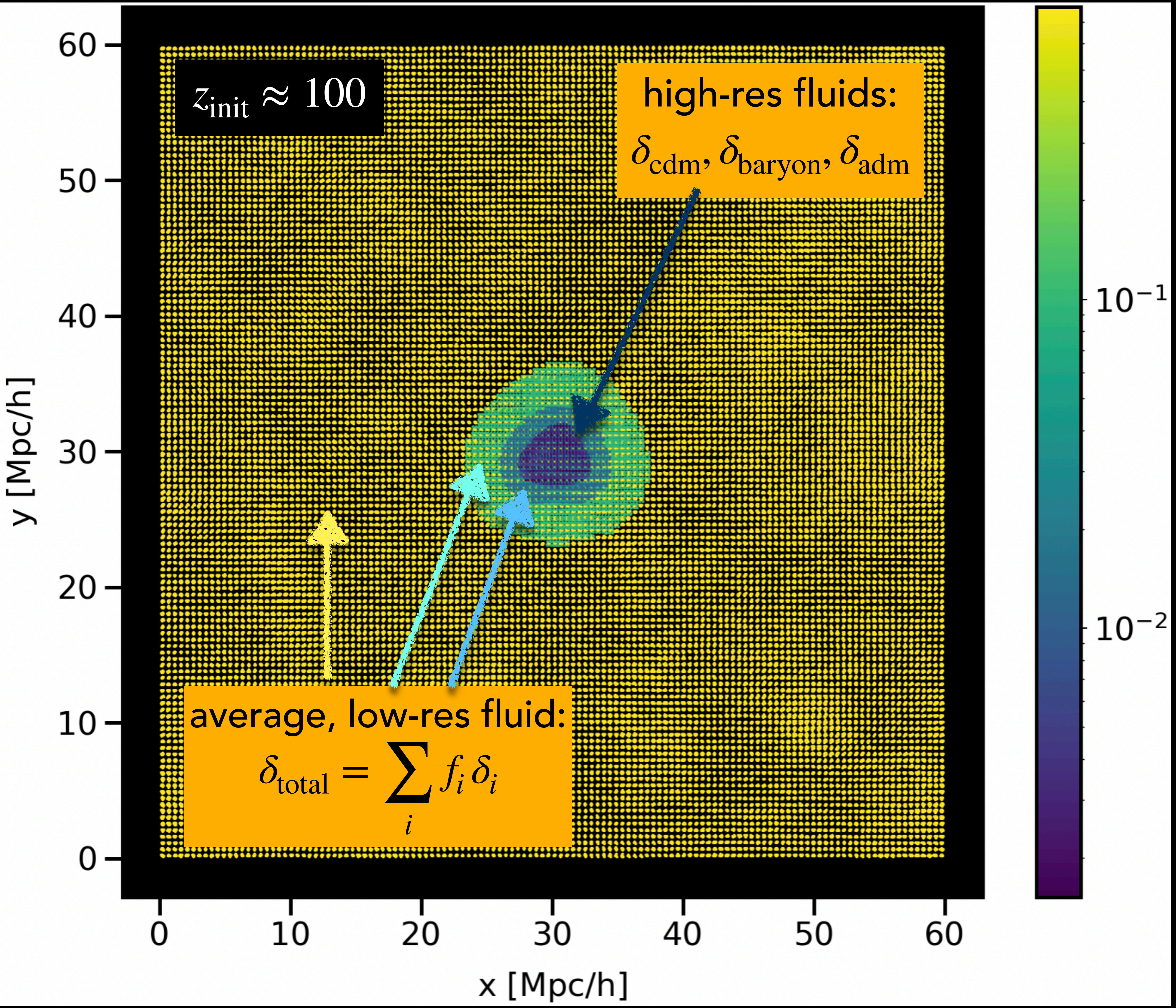
Simulation Particle Mass ($10^{10}\,M_\odot$)

Zoom-In Simulations



Simulation Particle Mass ($10^{10}\, M_\odot$)

Zoom-In Simulations



Simulation Particle Mass ($10^{10}\, M_\odot$)

Initial Conditions/Cosmology

Modified Einstein-Boltzmann Solver (CLASS)

Initial Conditions/Cosmology

Modified Einstein-Boltzmann Solver (CLASS)

Dark recombination

+

$$\delta G_{\mu\nu} = 8\pi G \left(\delta T^{\mu\nu} + \delta T^{\mu\nu}_{\text{ADM}} \right)$$

Initial Conditions/Cosmology

Modified Einstein-Boltzmann Solver (CLASS)

Dark recombination

+

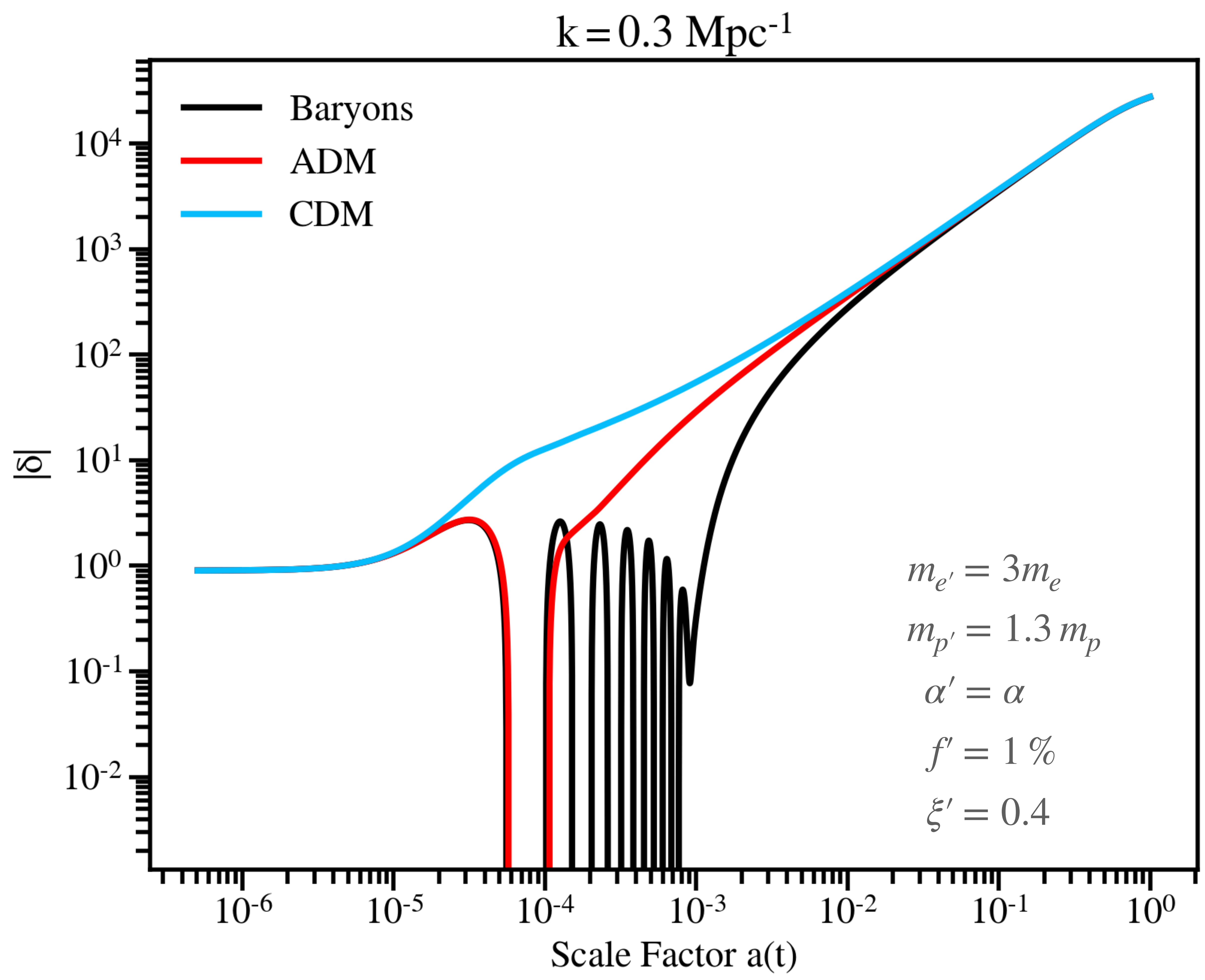
$$\delta G_{\mu\nu} = 8\pi G \left(\delta T^{\mu\nu} + \delta T^{\mu\nu}_{\rm ADM} \right)$$

↓

Input

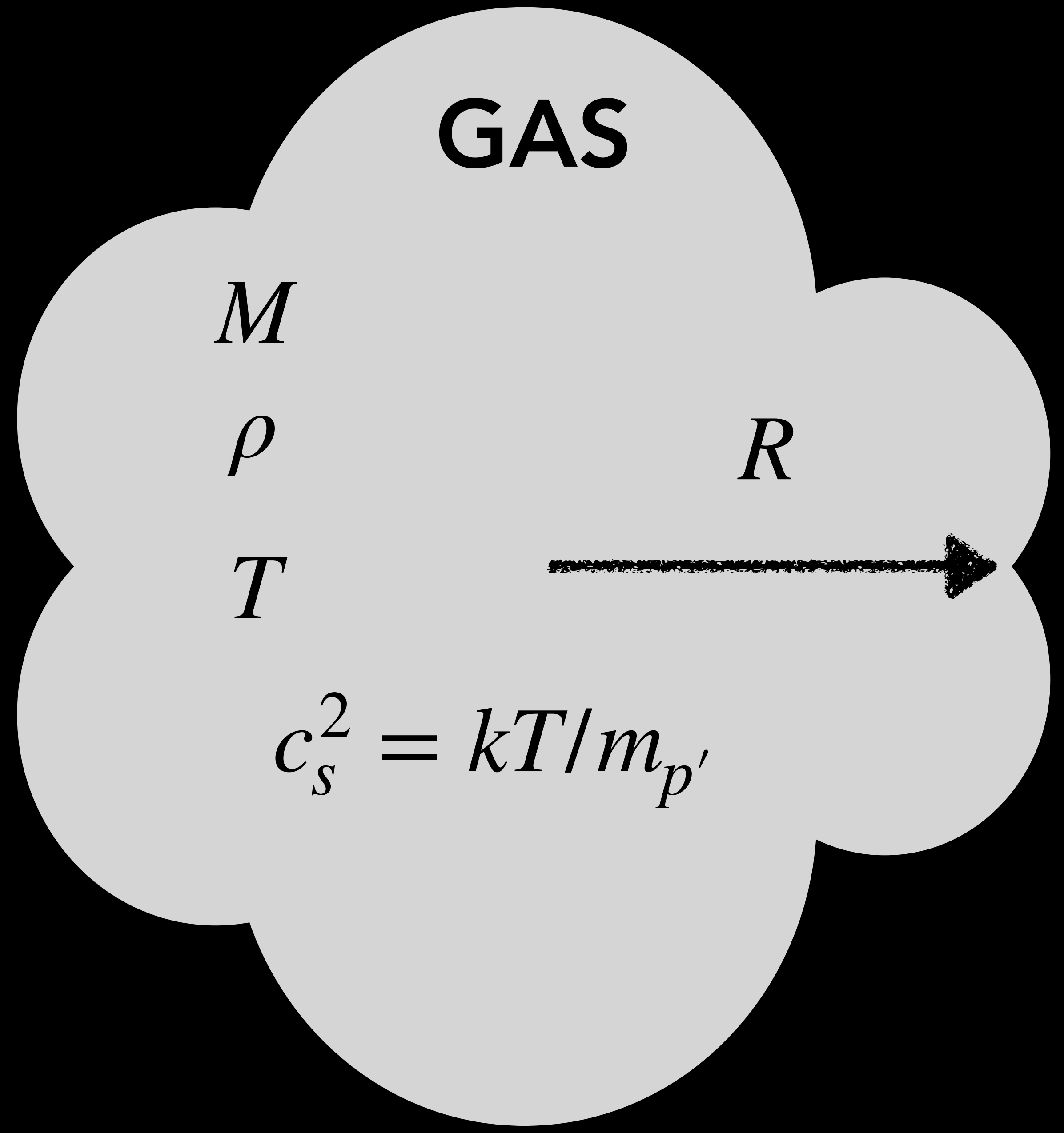
$$\delta_{\rm ADM}(k, z_i)$$

Based on **Barron et al. (2212.02487)** , Bansal et al. (2110.04317) & Cyr-Racine et al. (1209.5752)

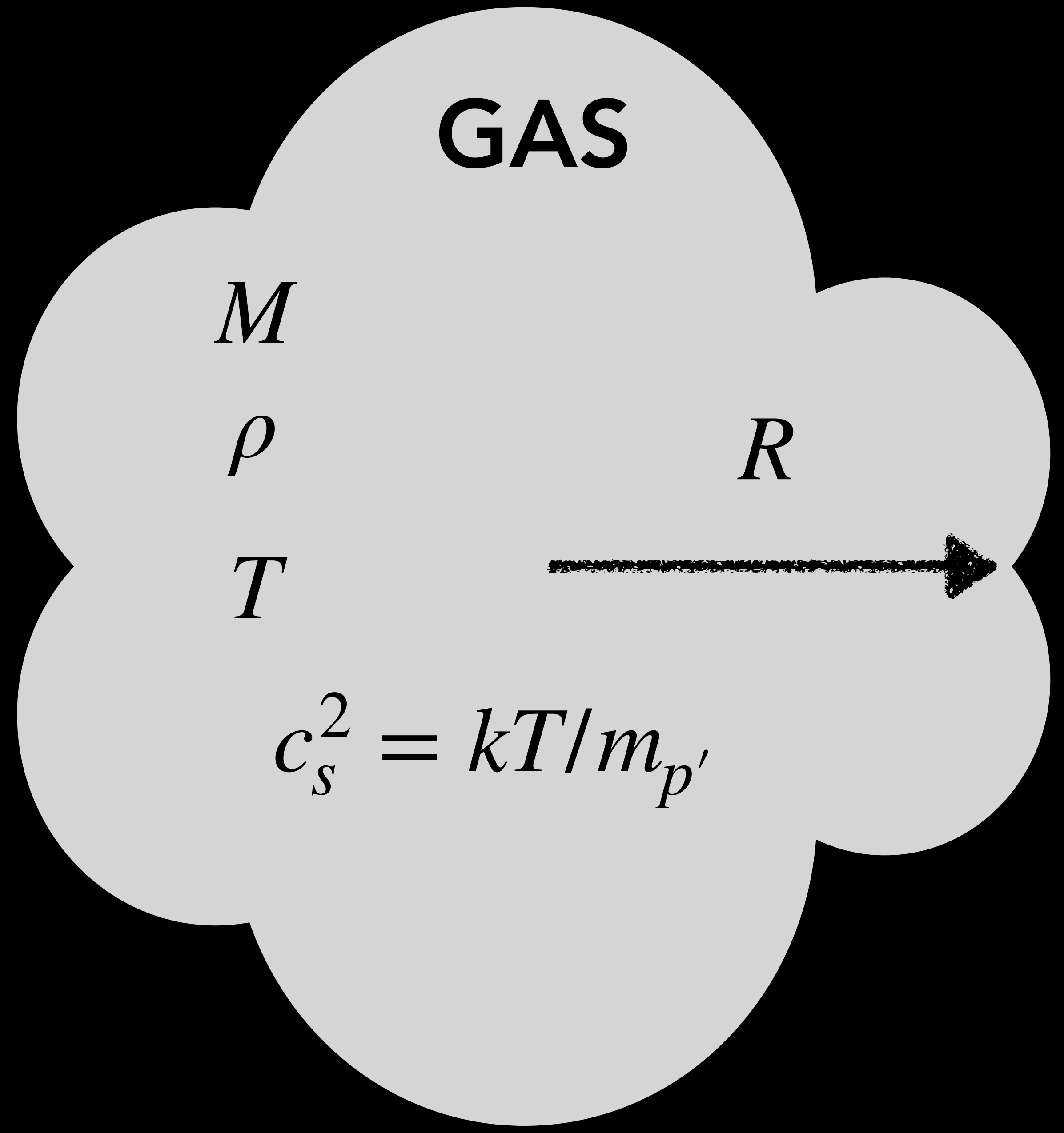


How Dense Can the Gas Become?

How Dense Can the Gas Become?



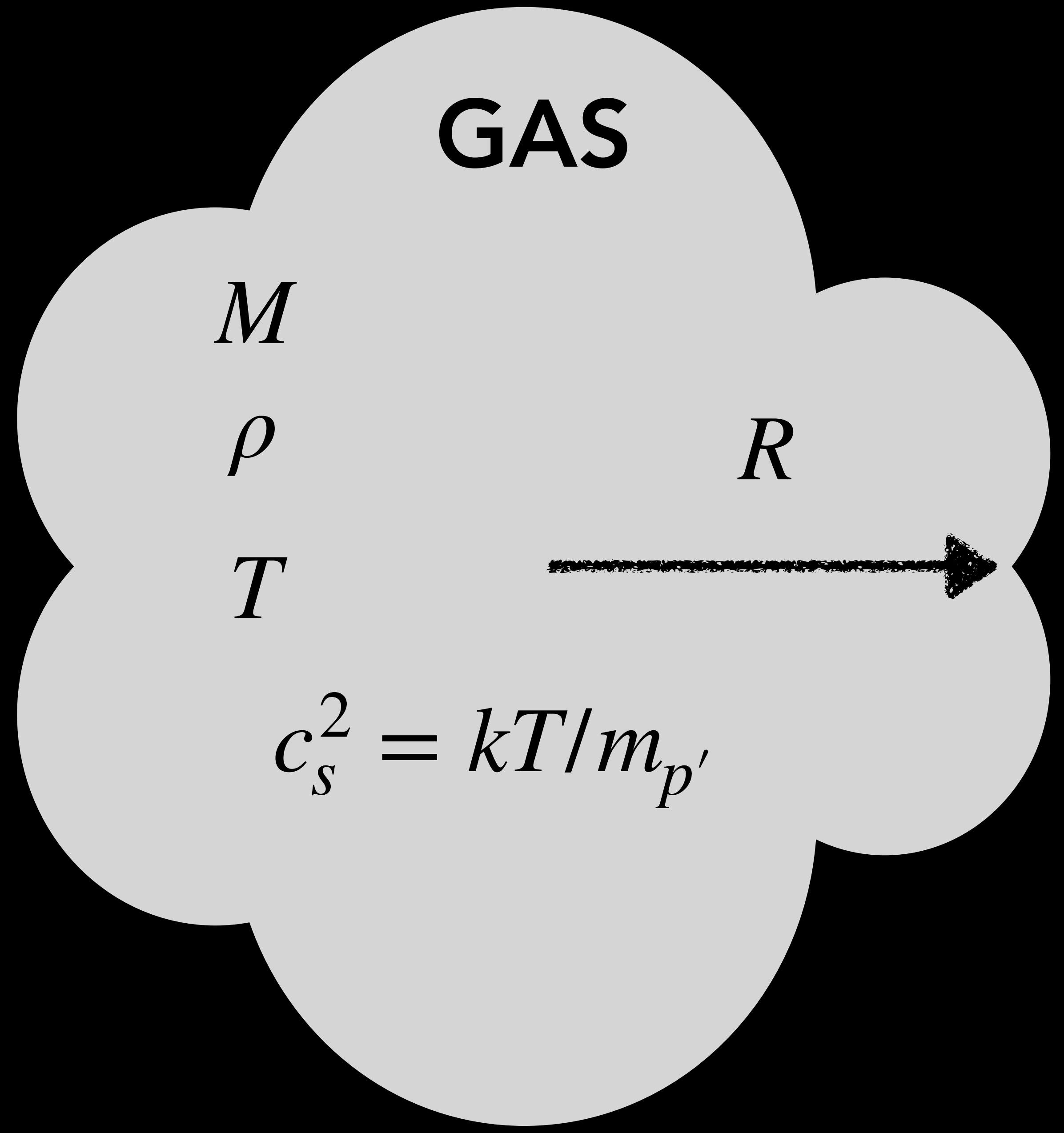
How Dense Can the Gas Become?



Instability Criterion:

$$\frac{t_{ff}}{t_s} \sim \frac{1/\sqrt{G\rho}}{R/c_s} \sim \frac{1}{R} \cdot \left(\frac{kT}{m_{p'} G \rho} \right)^{1/2} < 1$$

How Dense Can the Gas Become?

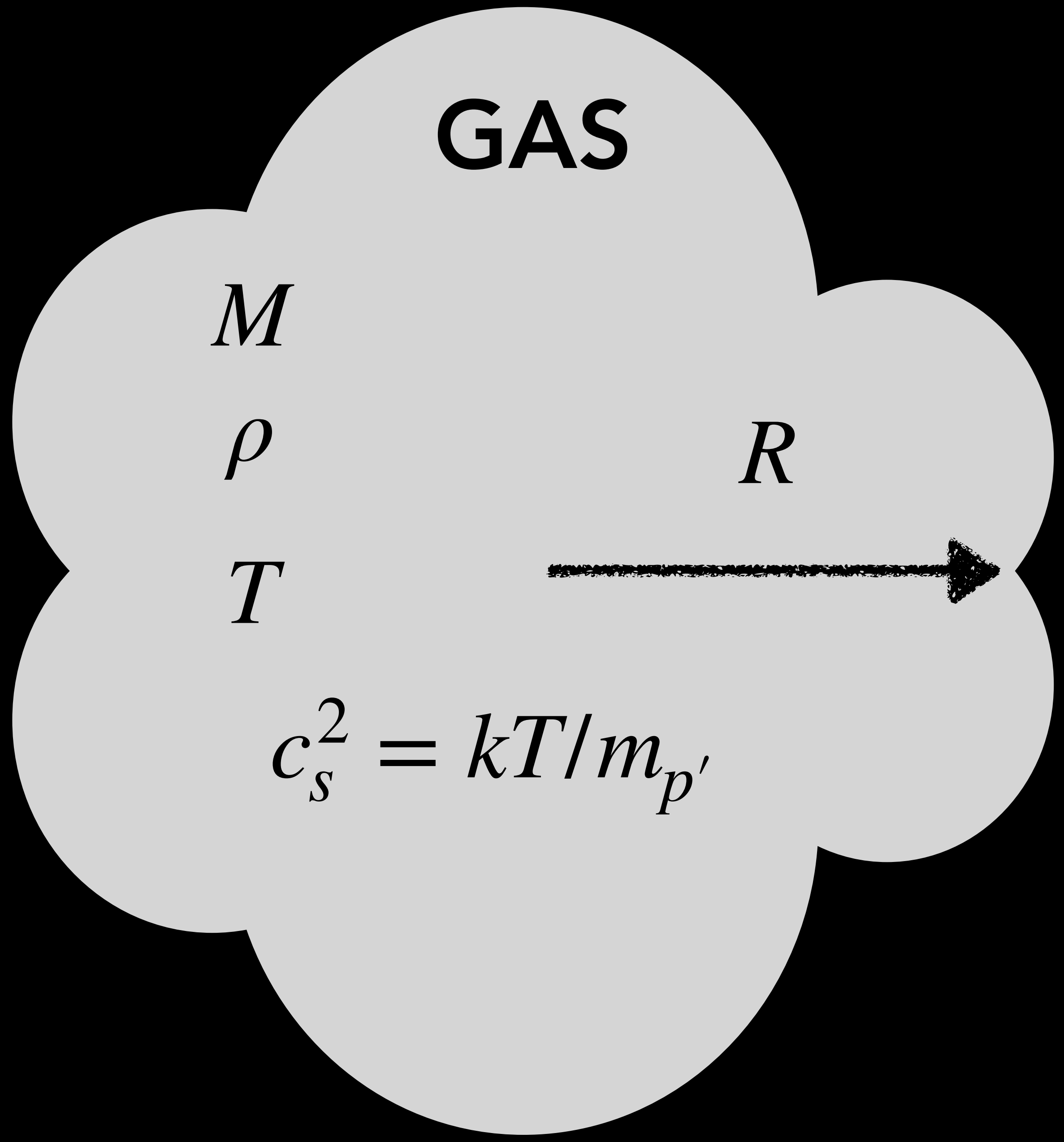


Instability Criterion:

$$\frac{t_{ff}}{t_s} \sim \frac{1/\sqrt{G\rho}}{R/c_s} \sim \frac{1}{R} \cdot \left(\frac{kT}{m_{p'}\, G\, \rho} \right)^{1/2} < 1$$

$$\rho > \frac{1}{R^2} \cdot \left(\frac{kT}{m_{p'}\, G} \right)$$

How Dense Can the Gas Become?

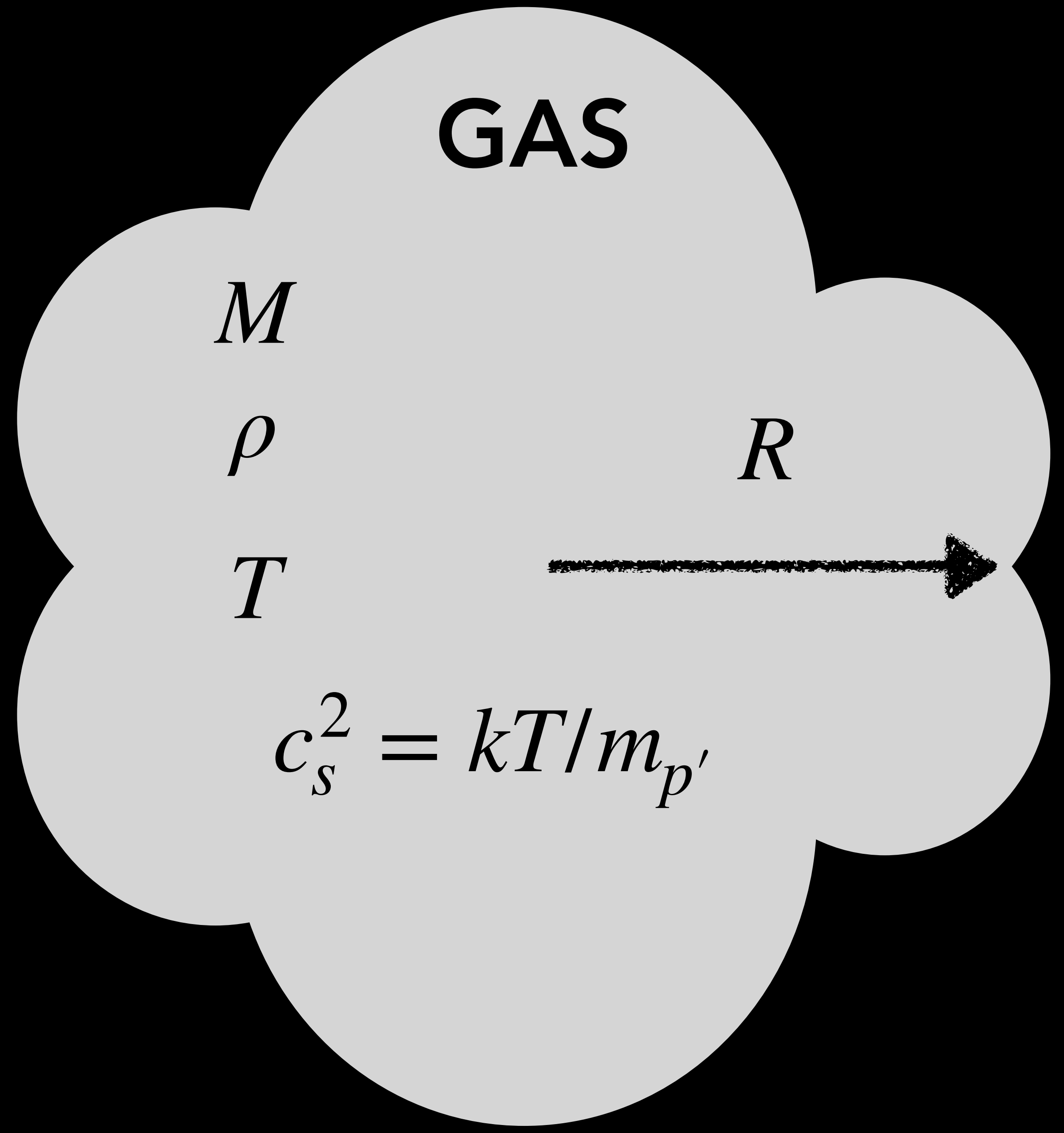


Instability Criterion:

$$\frac{t_{ff}}{t_s} \sim \frac{1/\sqrt{G\rho}}{R/c_s} \sim \frac{1}{R} \cdot \left(\frac{kT}{m_{p'} G \rho} \right)^{1/2} < 1$$

$$\rho > \frac{1}{R^2} \cdot \left(\frac{kT}{m_{p'} G} \right) \longrightarrow \text{ADM gas} \rightarrow \text{Clump}$$

How Dense Can the Gas Become?



<u>Instability Criterion:</u>

$$\frac{t_{ff}}{t_s} \sim \frac{1/\sqrt{G\rho}}{R/c_s} \sim \frac{1}{R} \cdot \left(\frac{kT}{m_{p'} G \rho} \right)^{1/2} < 1$$

$$\rho > \frac{1}{R^2} \cdot \left(\frac{kT}{m_{p'} G} \right) \longrightarrow$$ **ADM gas→Clump**

Caveat: Baryons have more criteria (fixed ρ_{star}, molecular, etc.)

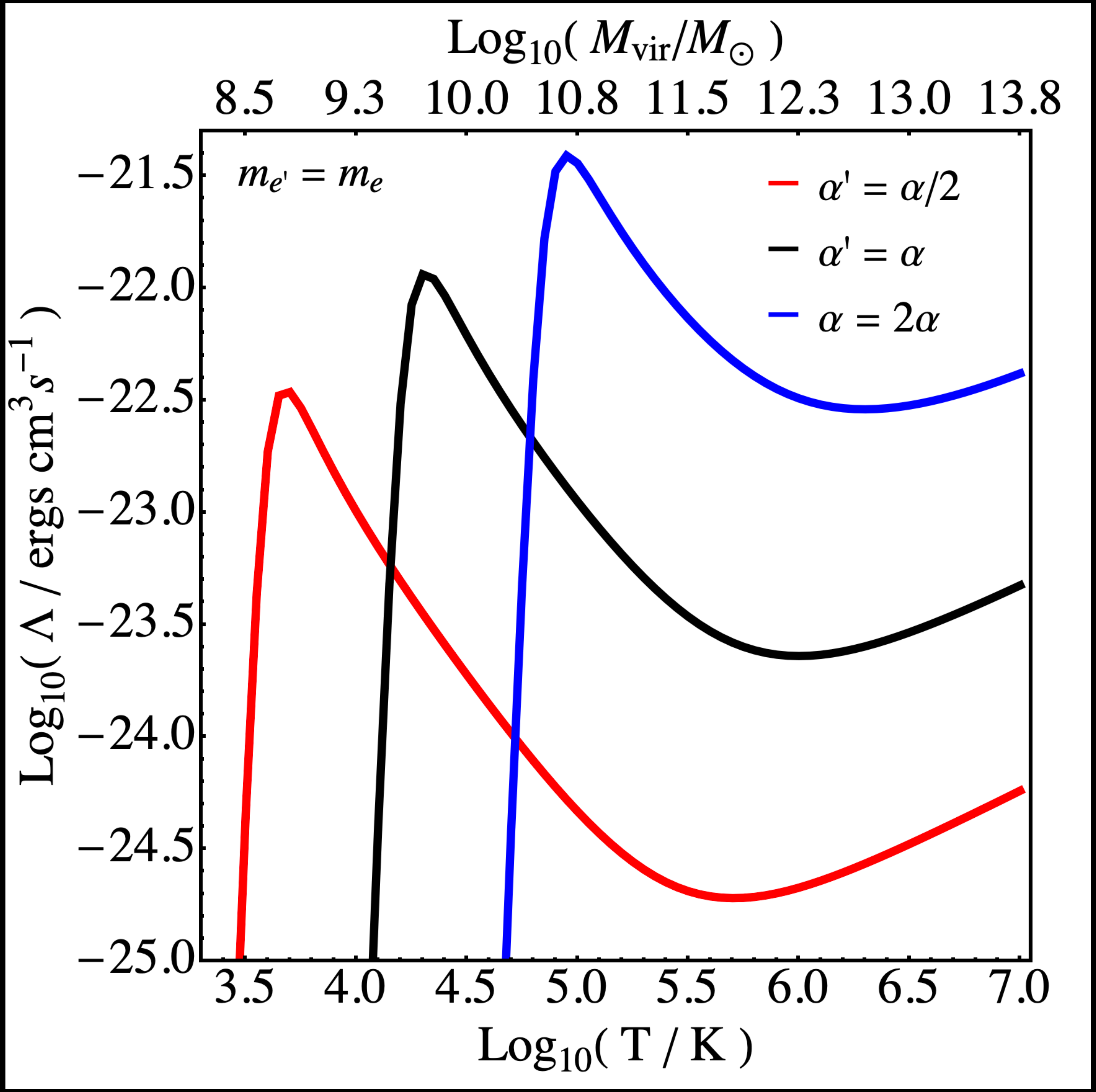
Ionisation-Recombination Equilibrium

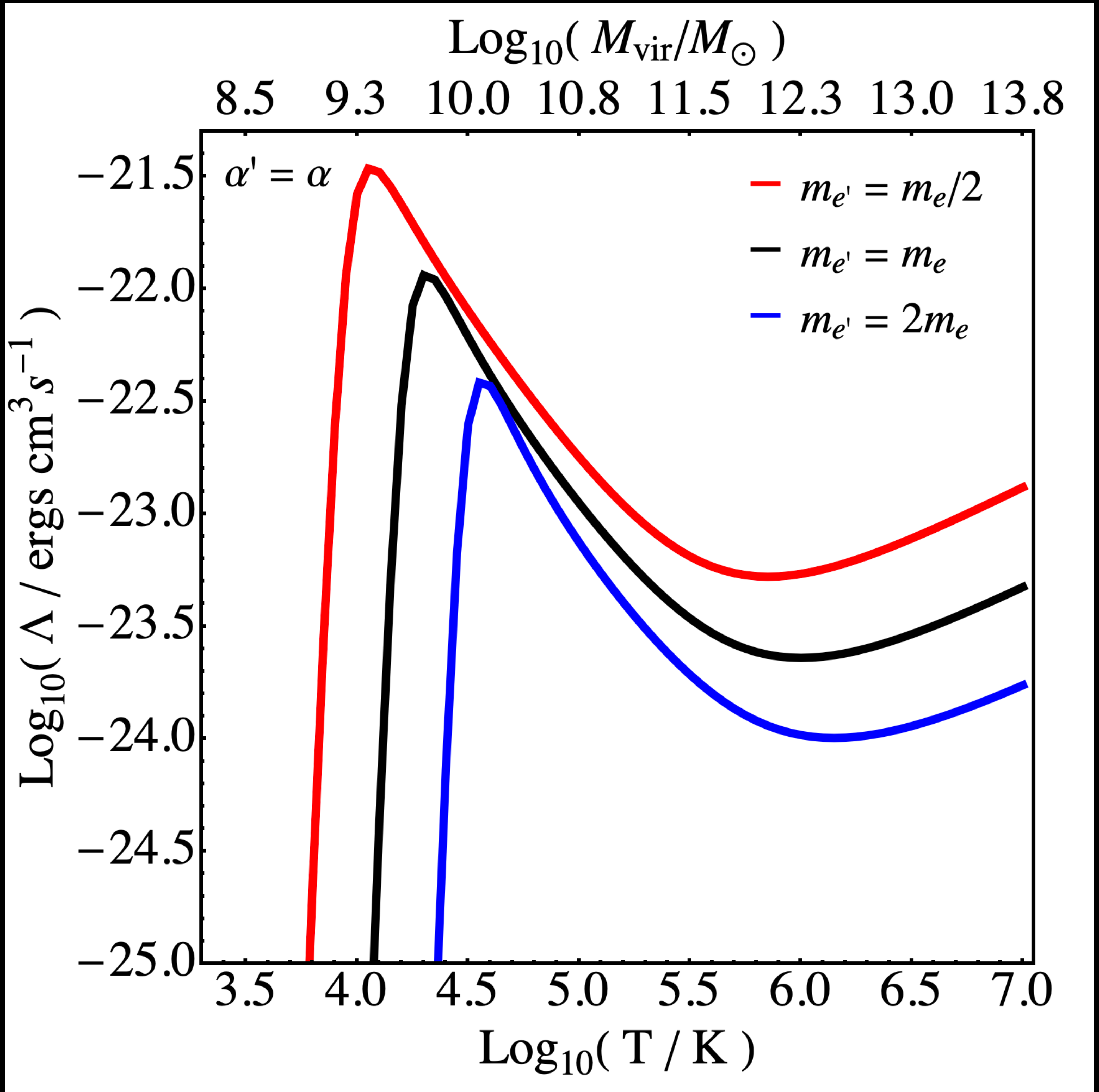
Given a neutral gas cell with temp T, what is the ionisation fraction?

If $t_{\text{ionise, recombine}} \ll t_{\text{dynamical}}$ and define $x_i = n_i / n_{\text{H}'}$ where $n_{\text{H}'} = n_{\text{p}'} + n_{\text{H}_0'}$ and $n_{\text{e}'} = n_{\text{p}'}$ then can assume $\langle \sigma_{\text{ionise}} v \rangle \, x_{\text{e}'} x_{\text{H}_0'} \approx \langle \sigma_{\text{recombine}} v \rangle \, x_{\text{e}'} x_{\text{p}'}$

$$x_{\text{e}'} = \frac{\langle \sigma_{\text{ionise}} v \rangle}{\langle \sigma_{\text{ionise}} v \rangle + \langle \sigma_{\text{recombine}} v \rangle} \qquad x_{\text{H}_0'} = \frac{\langle \sigma_{\text{recombine}} v \rangle}{\langle \sigma_{\text{ionise}} v \rangle + \langle \sigma_{\text{recombine}} v \rangle}$$

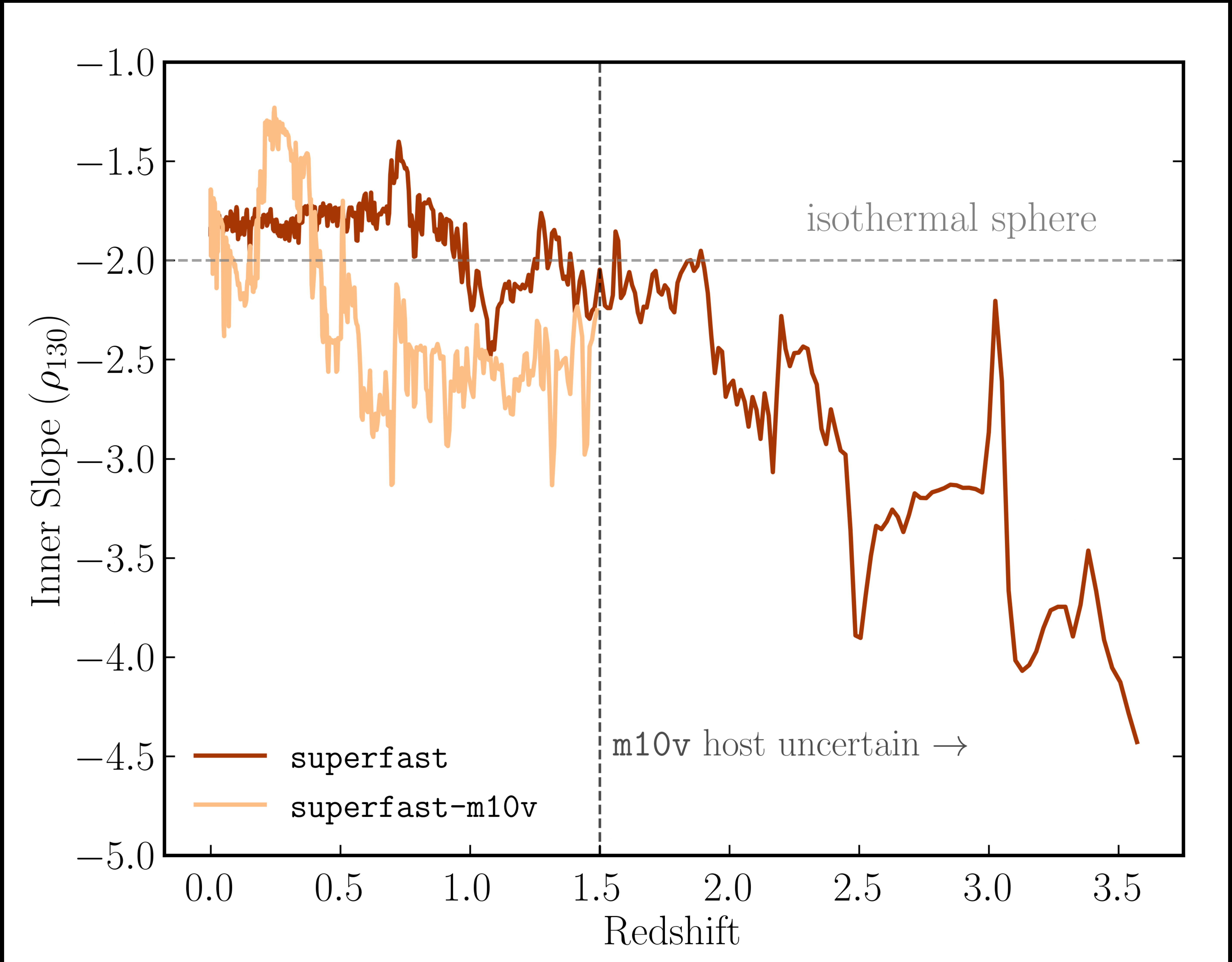
Cooling Rate with Varying ADM Parameters



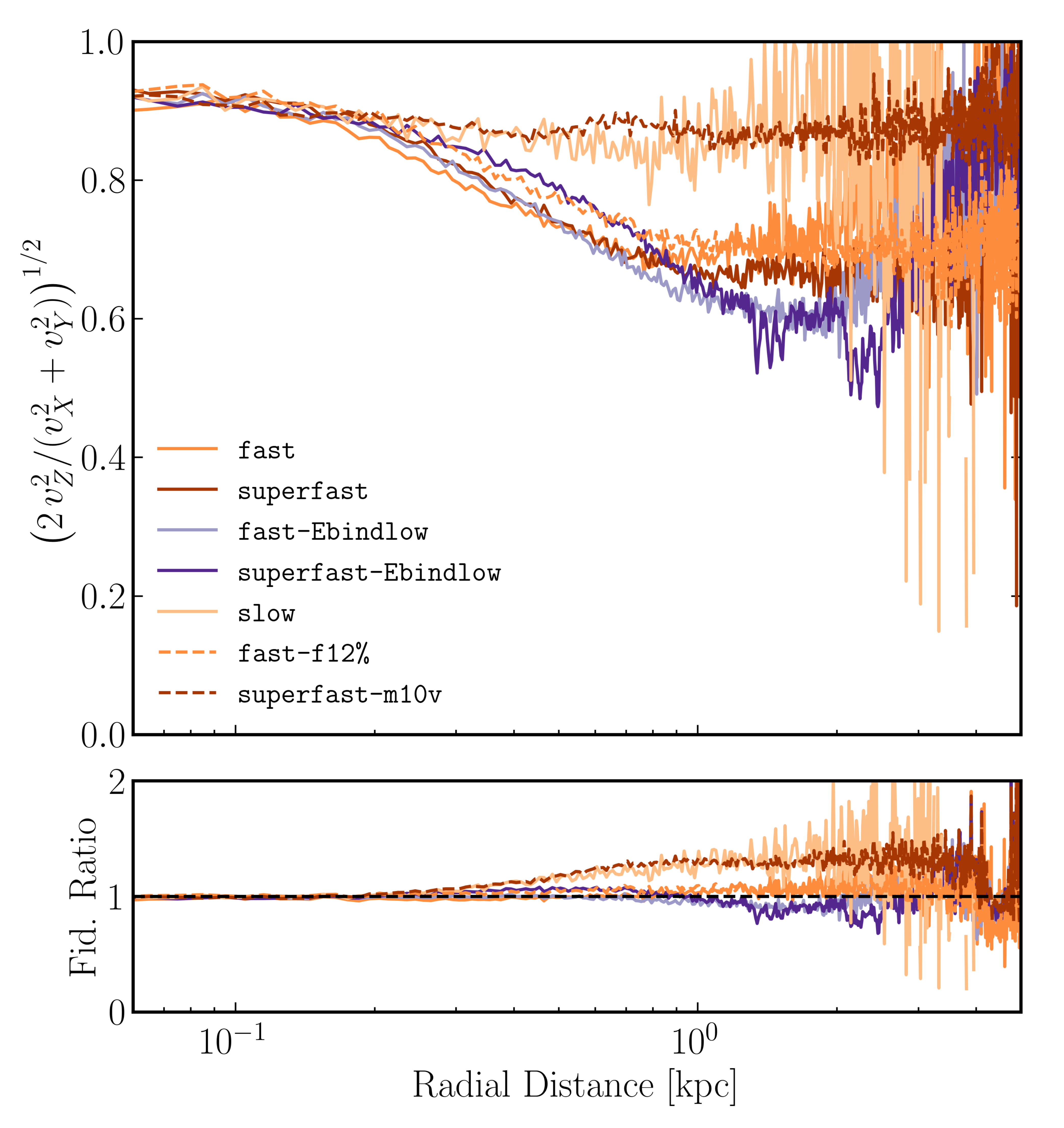


Fiducial Simulation

Inner Slope Evolution

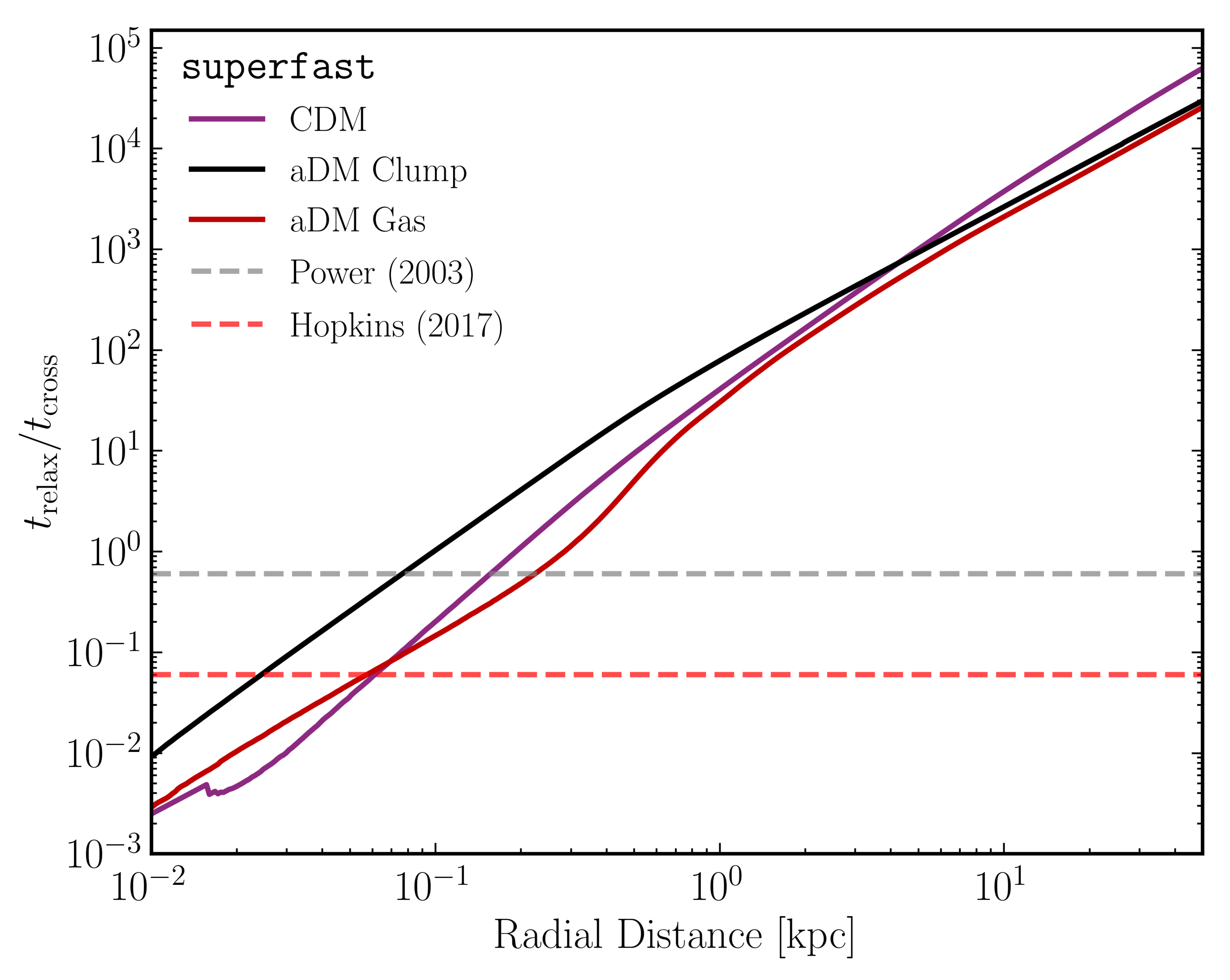


aDM Clump Velocity Anisotropy

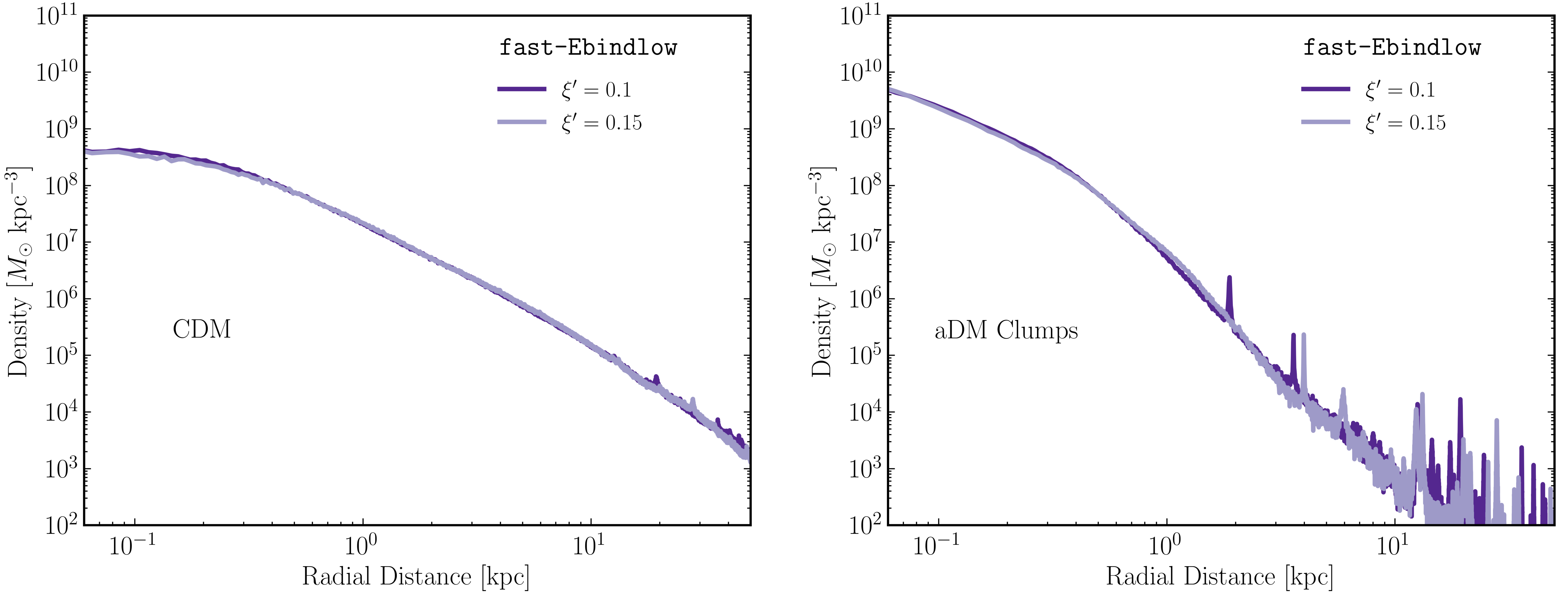


Clump Formation History

Is the Sim Even Resolved?

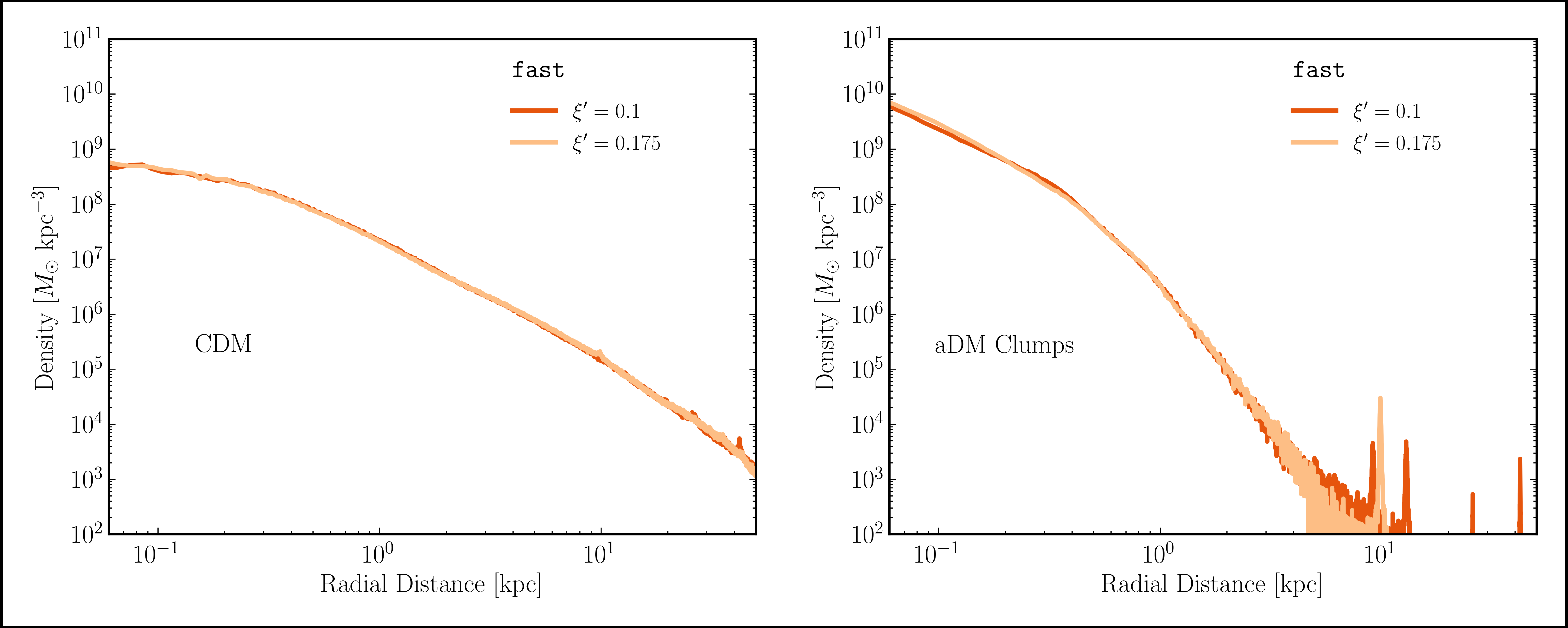


Effect of ξ'



fast-Ebindlow
$\xi' = 0.1$
$\xi' = 0.15$
CDM
Density $[M_\odot\ \mathrm{kpc}^{-3}]$
Radial Distance [kpc]
fast-Ebindlow
$\xi' = 0.1$
$\xi' = 0.15$
aDM Clumps
Density $[M_\odot\ \mathrm{kpc}^{-3}]$
Radial Distance [kpc]

Effect of ξ'



fast
$\xi' = 0.1$
$\xi' = 0.175$
CDM
Density $[M_\odot\ \mathrm{kpc}^{-3}]$
Radial Distance [kpc]
fast
$\xi' = 0.1$
$\xi' = 0.175$
aDM Clumps
Density $[M_\odot\ \mathrm{kpc}^{-3}]$
Radial Distance [kpc]

Morphology Metrics

Simulation	aDM Particle Type	$\tilde{\epsilon}$	$Z_{9/10}$	$R_{9/10}$	$Z_{1/2}$	$R_{1/2}$	z'_0	z'_{90}	$f'_{\rm gas}(0.5\,{\rm kpc})$	$f'_{\rm gas}(5\,{\rm kpc})$
superfast	clumps	0.63	0.27	1.1	0.078	0.31	11.1	1.3	0.02	0.5
	gas	0.91	0.14	4.1	0.038	1.2	-	-		
fast	clumps	0.63	0.25	0.86	0.065	0.23	10.7	0.6	0.09	0.6
	gas	0.84	0.22	3.1	0.030	0.65	-	-		
slow	clumps	0.49	0.26	0.65	0.081	0.20	9.5	2.7	0.02	0.9
	gas	no gas disk					-	-		
fast-f12%	clumps	0.61	0.37	1.6	0.098	0.36	10.9	0.8	0.03	0.4
	gas	0.92	0.17	4.0	0.059	1.5	-	-		
superfast-m10v	clumps	0.38	0.61	1.5	0.11	0.24	7.2	0.3	0.04	0.2
	gas	0.82	0.25	5.6	0.053	0.86	-	-		
fast-Ebindlow	clumps	0.65	0.31	1.4	0.084	0.35	15.2	0.7	0.01	0.2
	gas	0.88	0.11	3.2	0.035	1.4	-	-		
superfast-Ebindlow	clumps	0.61	0.32	1.8	0.088	0.31	15.5	0.9	0.001	0.2
	gas	0.92	0.17	6.6	0.070	2.91	-	-		

Table D1. Morphology metrics for the aDM clumps and aDM gas in the central halos of all the simulations in this suite. The metrics $\tilde{\epsilon}$, $Z_{9/10}$, $R_{9/10}$, $Z_{1/2}$, $R_{1/2}$, and $f'_{\rm gas}$ are all defined in the main text (see Sec. 4). The metrics z'_0 and z'_{90} focus on the aDM clumps in the region $r \leq 50\,{\rm kpc}$ of the halo at $z = 0$. They respectively correspond to the redshift at which the first of the aDM clumps form and the redshift by which 90% of these aDM clumps form.

"Vanilla" Baryonic Physics

Baryon Gas

Baryon Stars

"Vanilla" Baryonic Physics

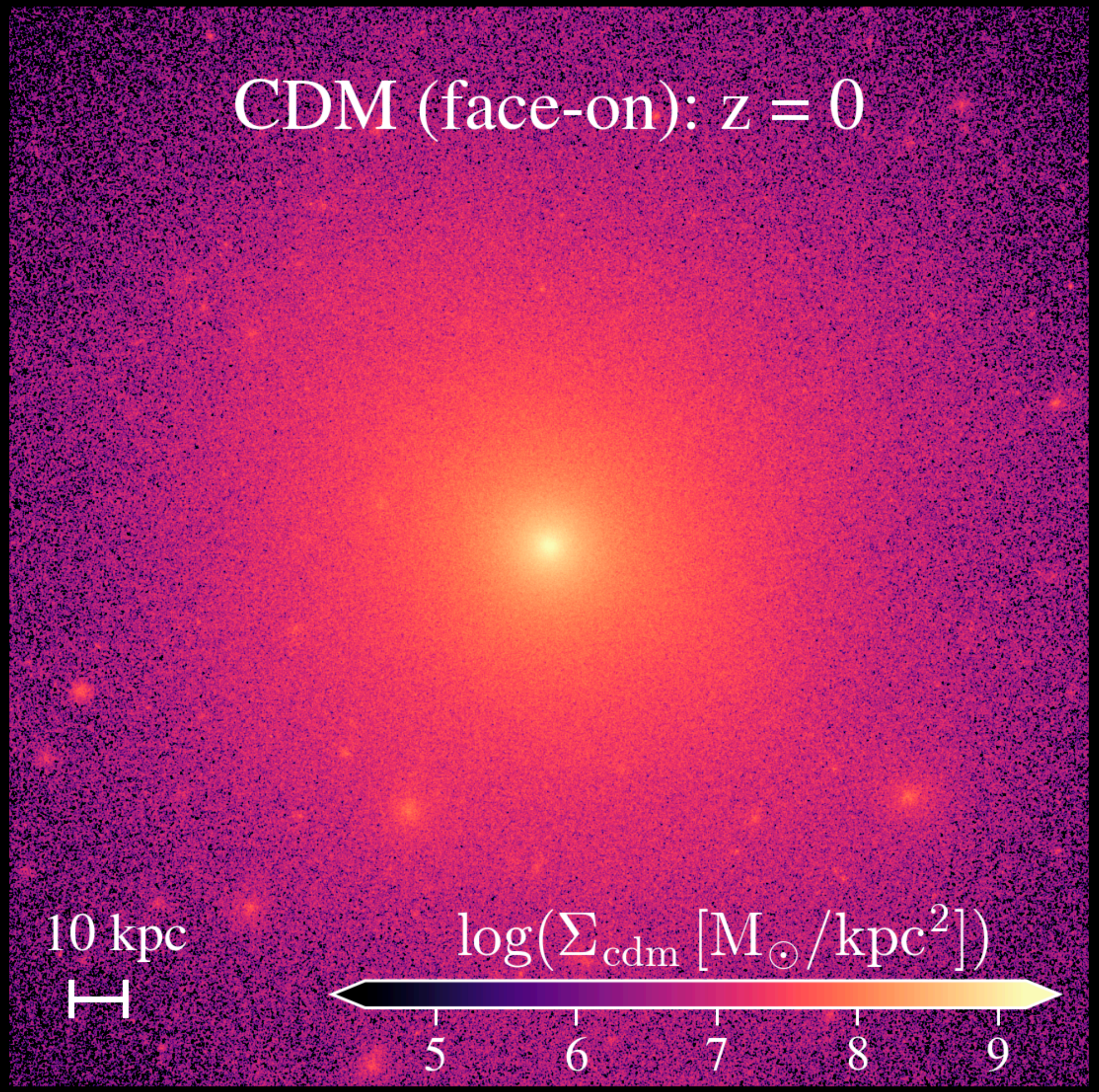
Baryon Gas

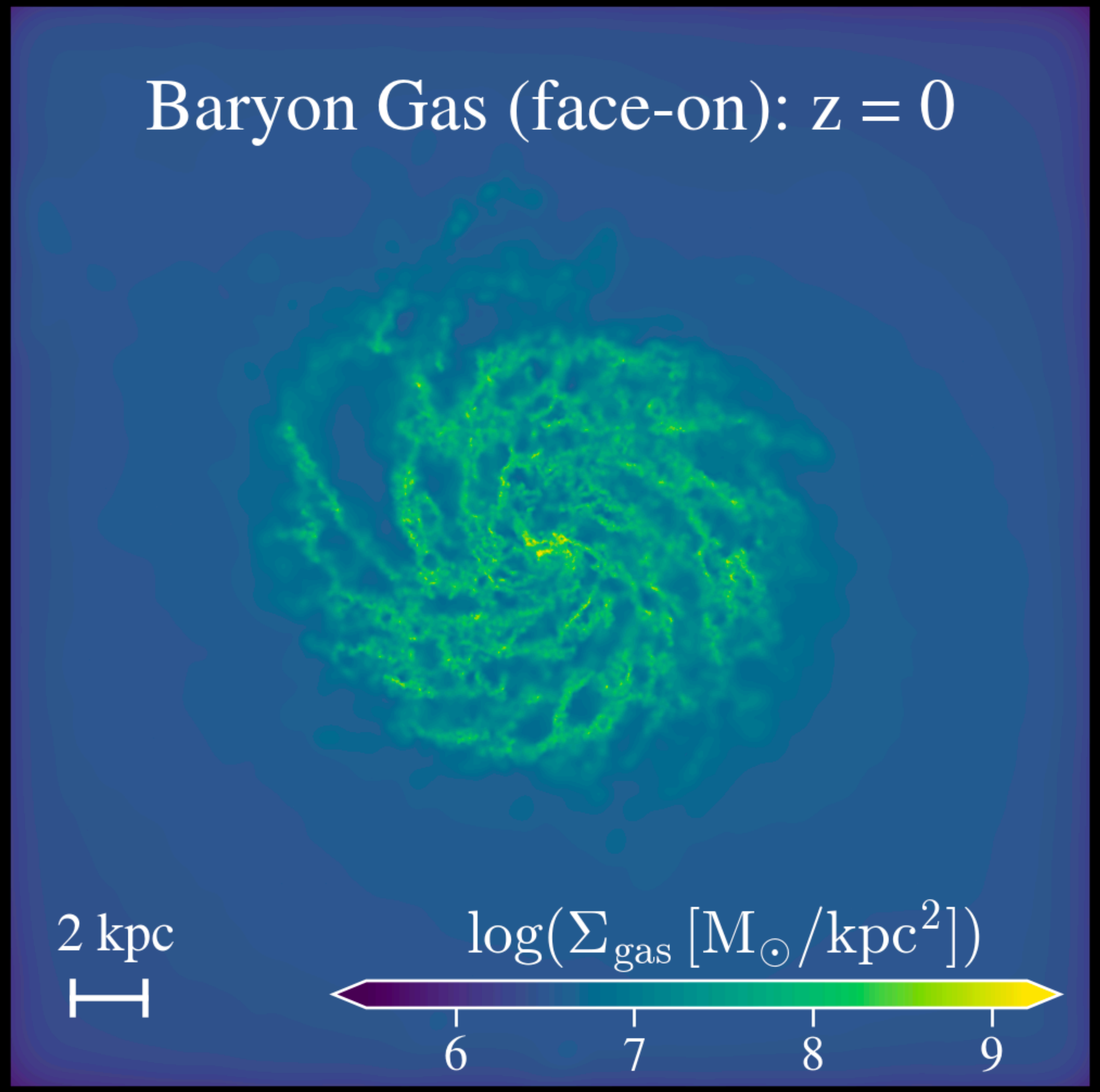
Baryon Stars

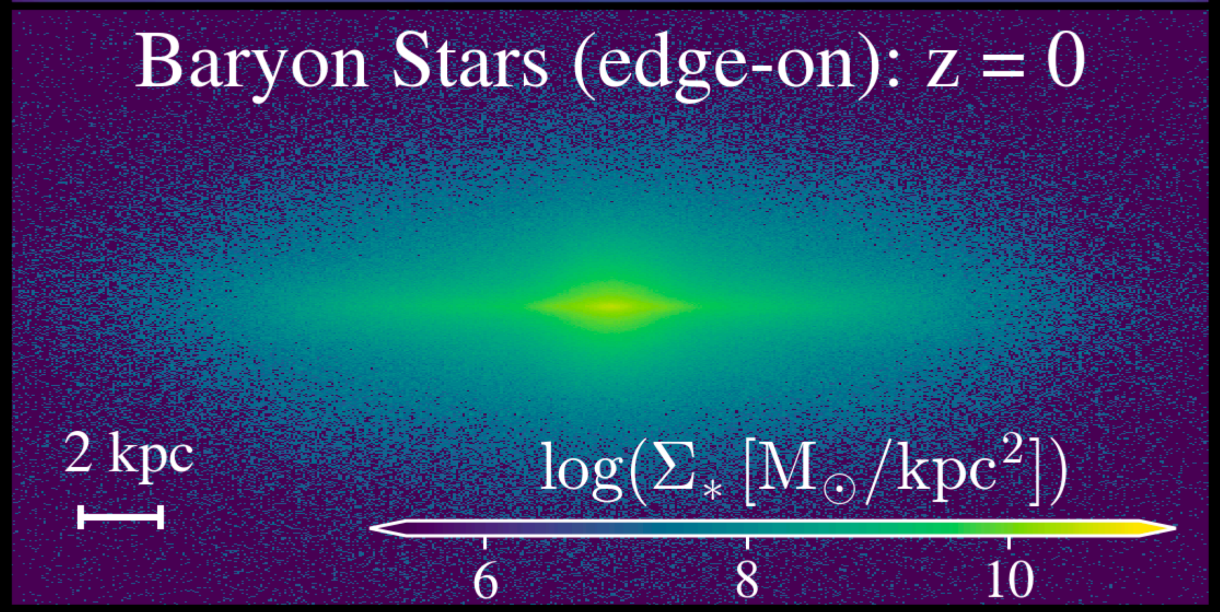
Effects of aDM in Milky Way-Mass Galaxies

S. Roy, et al. (2304.09878); C. Gemmell, S. Roy, et al. (2311.02148)

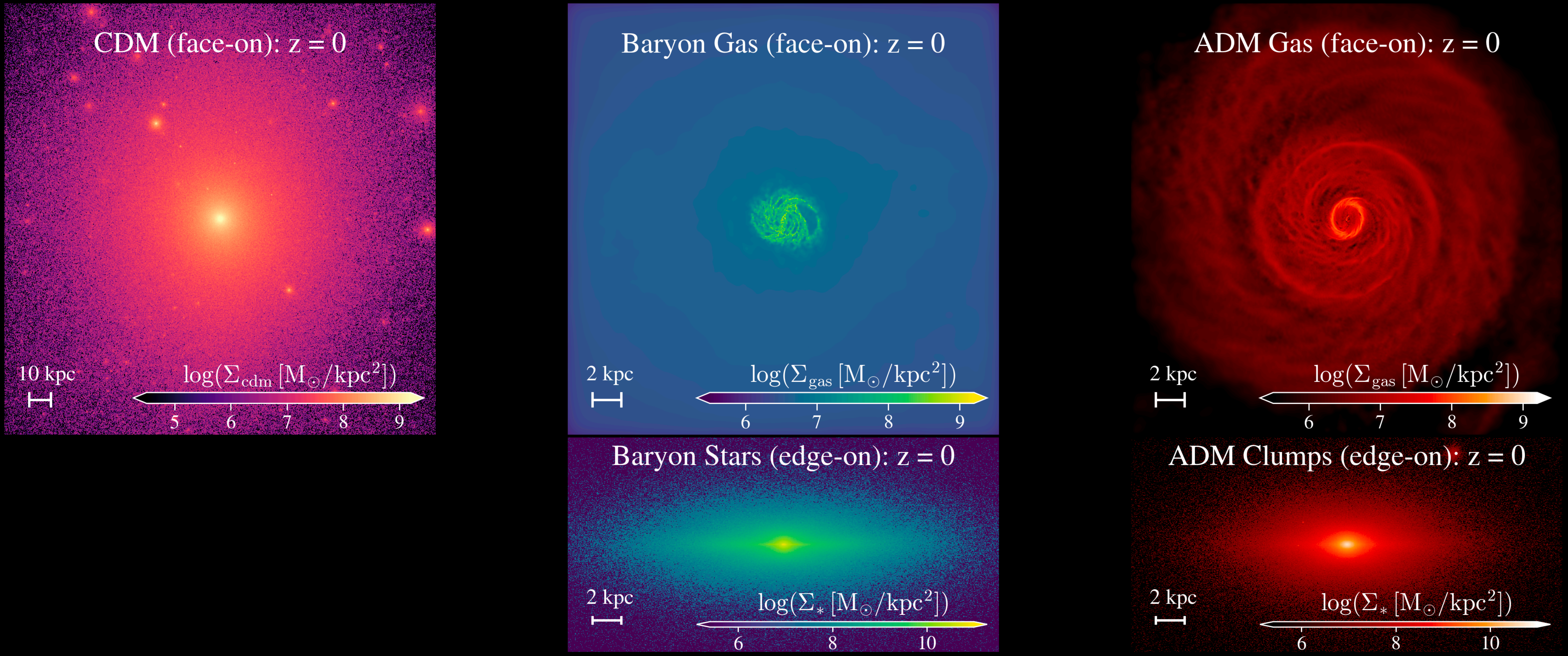
Effects of aDM in Milky Way-Mass Galaxies



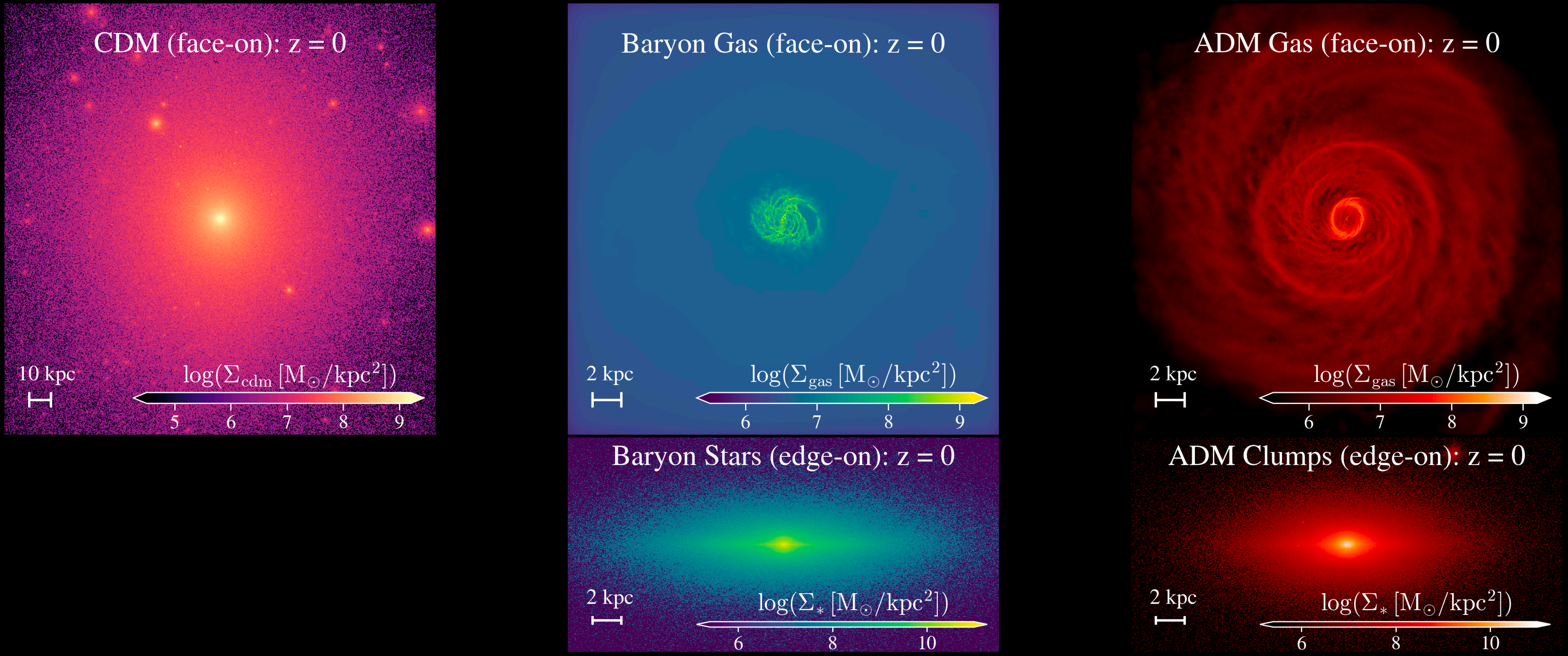




Effects of aDM in Milky Way-Mass Galaxies



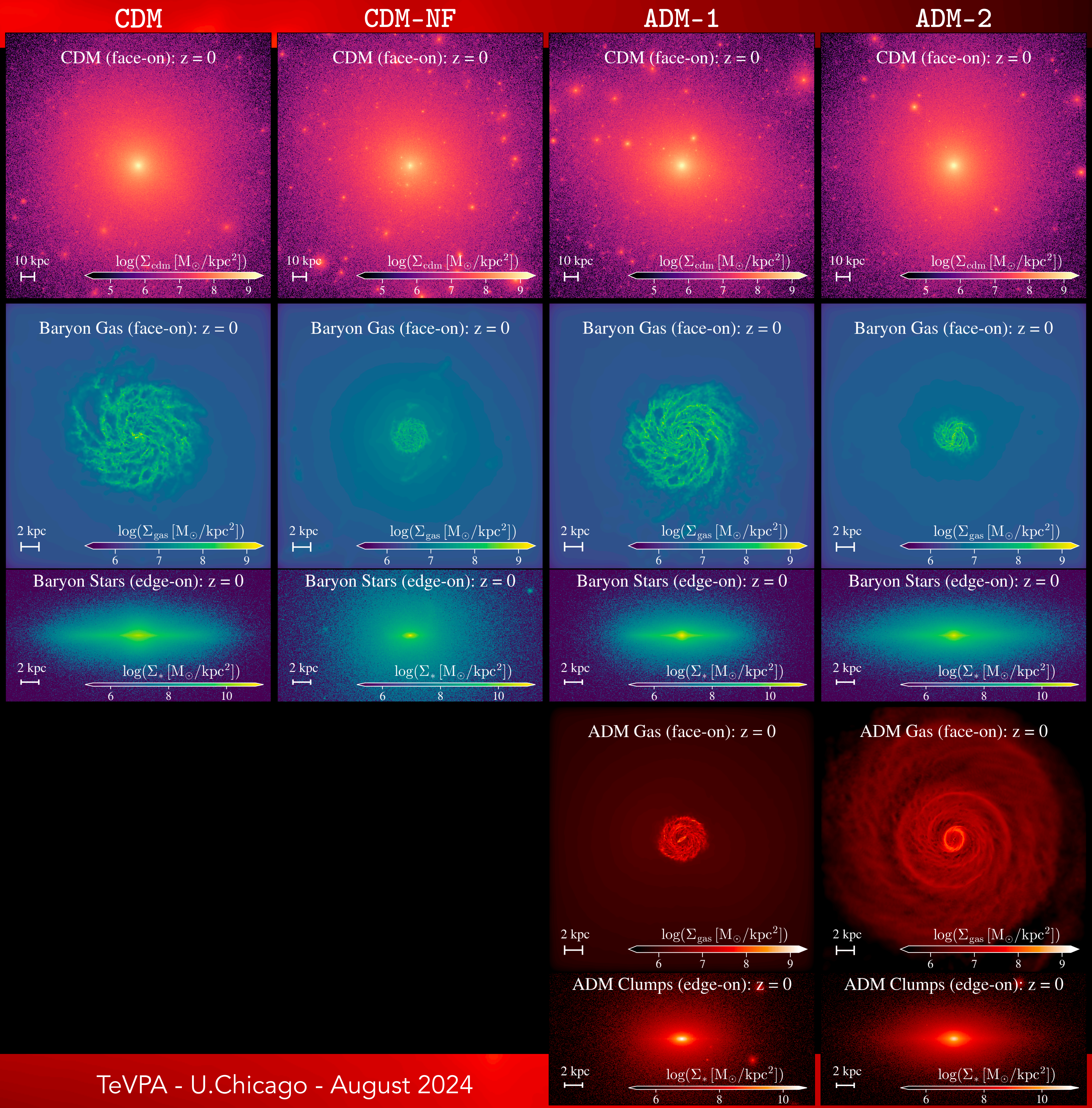
Effects of aDM in Milky Way-Mass Galaxies



We broke the Milky Way :)

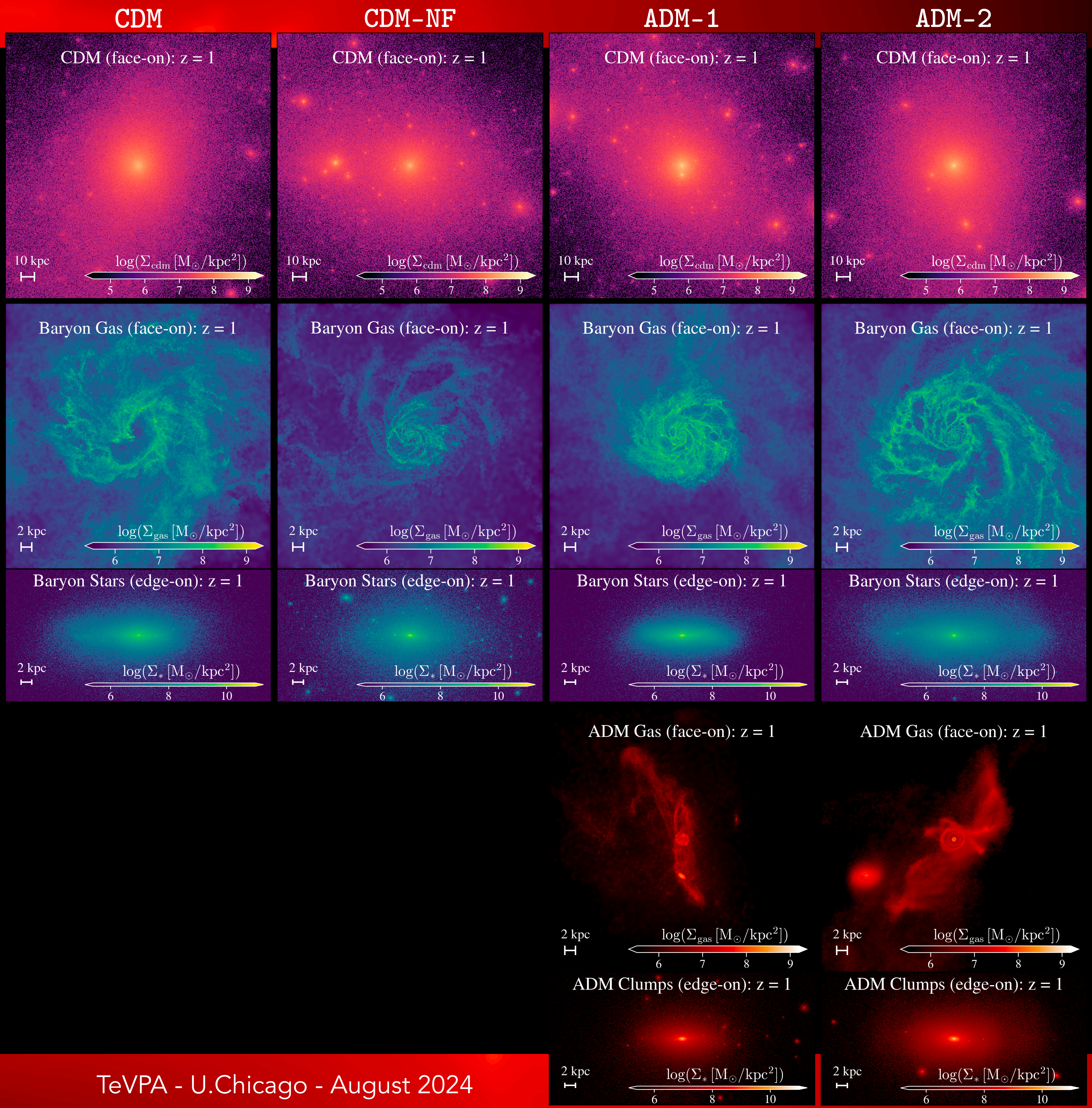
MW Morphology

$z = 0$

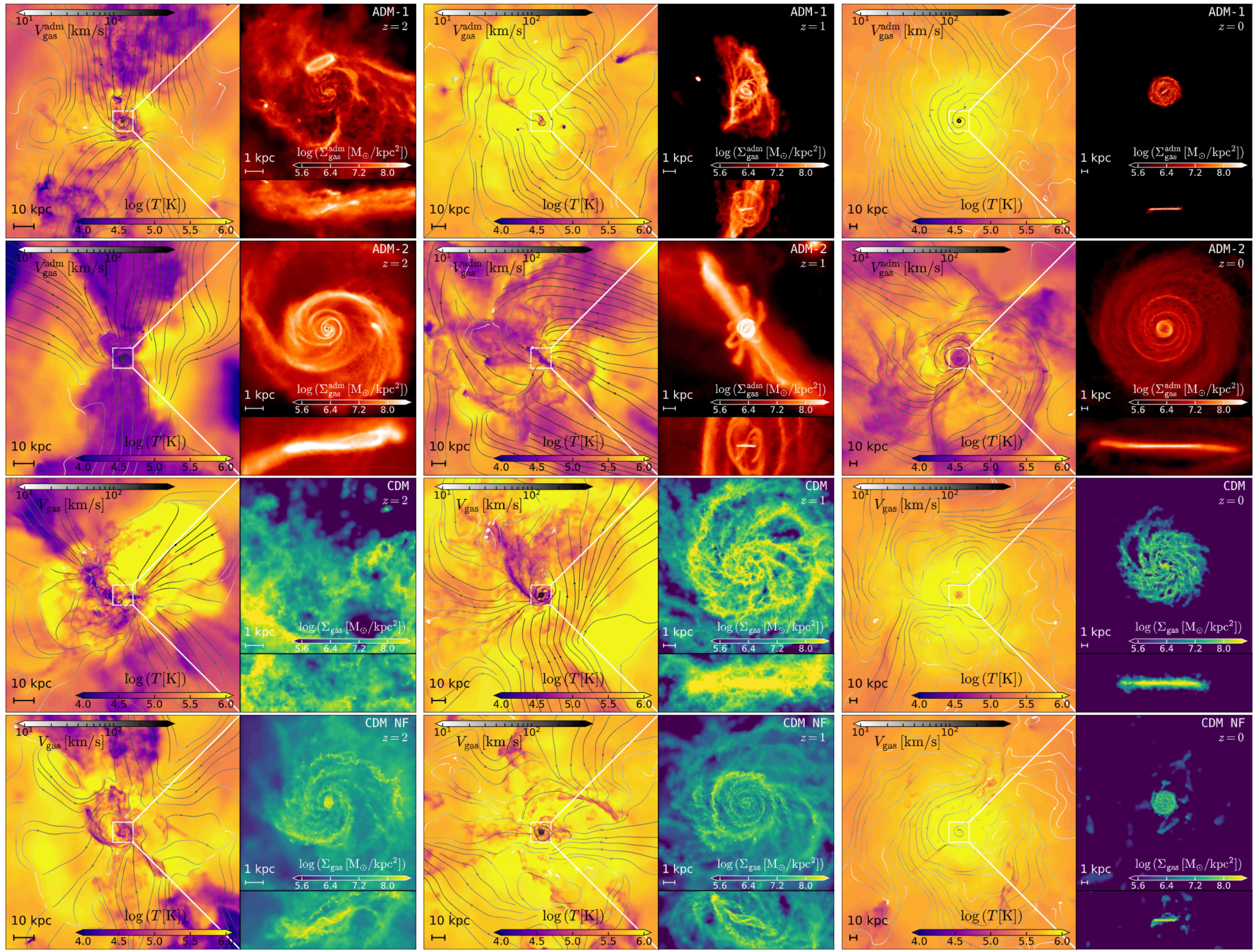


MW Morphology

$z \sim 1$



MW Gas Evolution



Sandip Roy (2408.15317)

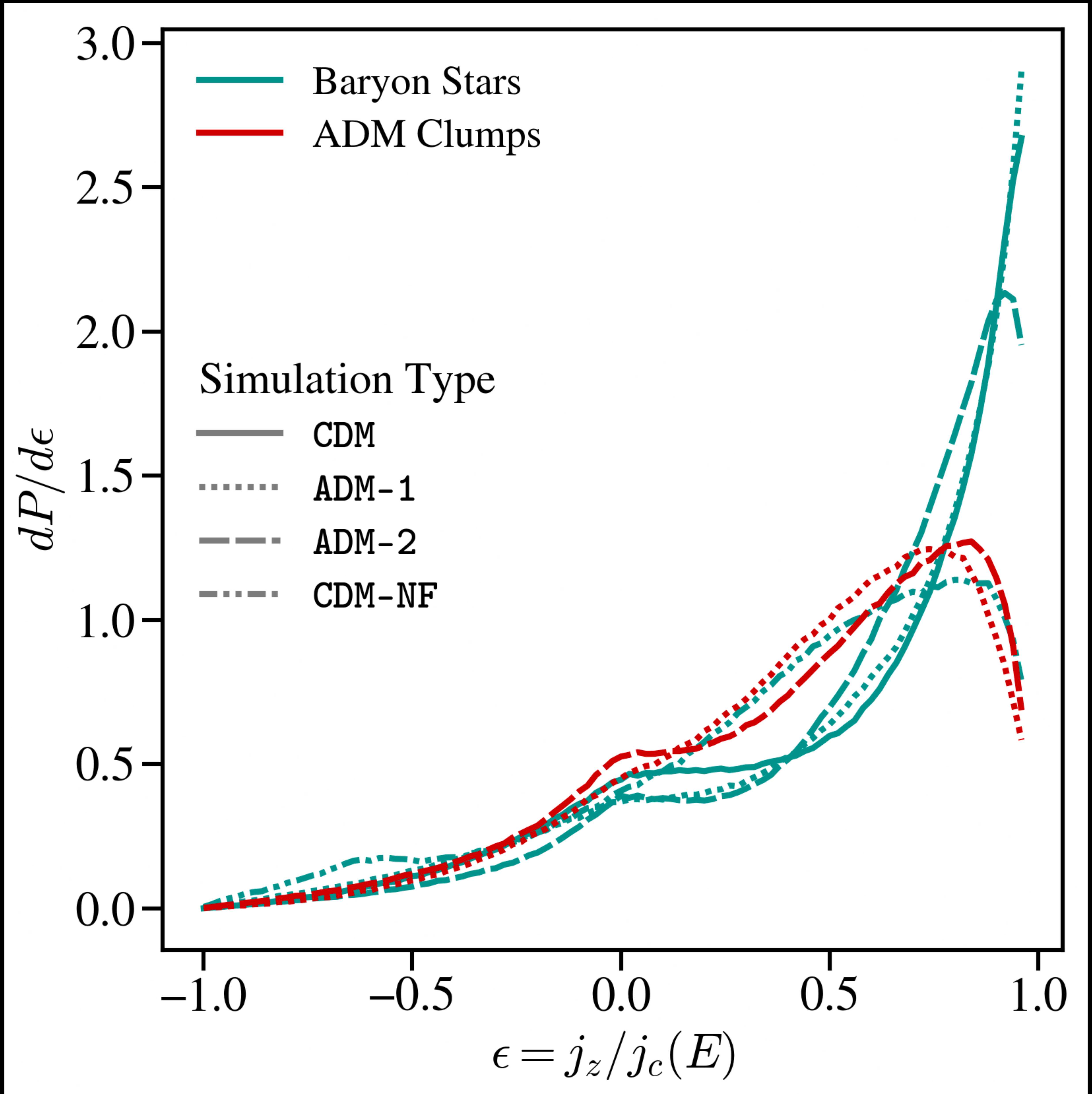
MW Morphology Metrics

	CDM		CDM-NF		ADM-1				ADM-2			
	Baryons		Baryons		Baryons		ADM		Baryons		ADM	
	Gas	Stars	Gas	Stars	Gas	Stars	Gas	Clumps	Gas	Stars	Gas	Clumps
$r_{1/2}$[kpc]	3.83	1.83	1.42	1.58	3.35	1.34	1.64	0.63	1.19	1.59	2.91	0.78
$z_{1/2}$[kpc]	0.039	0.28	0.035	0.22	0.022	0.17	0.014	0.14	0.022	0.21	0.015	0.18
$z_{9/10}$[kpc]	0.12	0.99	0.119	1.64	0.087	0.63	0.045	0.75	0.086	0.75	0.035	0.71
$f_{\rm thin}$	0.94	0.38	0.67	0.20	0.97	0.39	0.86	0.19	0.81	0.37	0.99	0.21
$f_{\rm thick}$	0.05	0.39	0.32	0.53	0.03	0.40	0.14	0.57	0.18	0.45	0.01	0.52
$f_{\rm spheroid}$	0.01	0.23	0.01	0.27	0.00	0.21	0.00	0.24	0.01	0.18	0.00	0.27
$\tilde{f}$	0.95	0.71	0.95	0.51	0.96	0.71	0.98	0.53	0.96	0.68	0.97	0.50

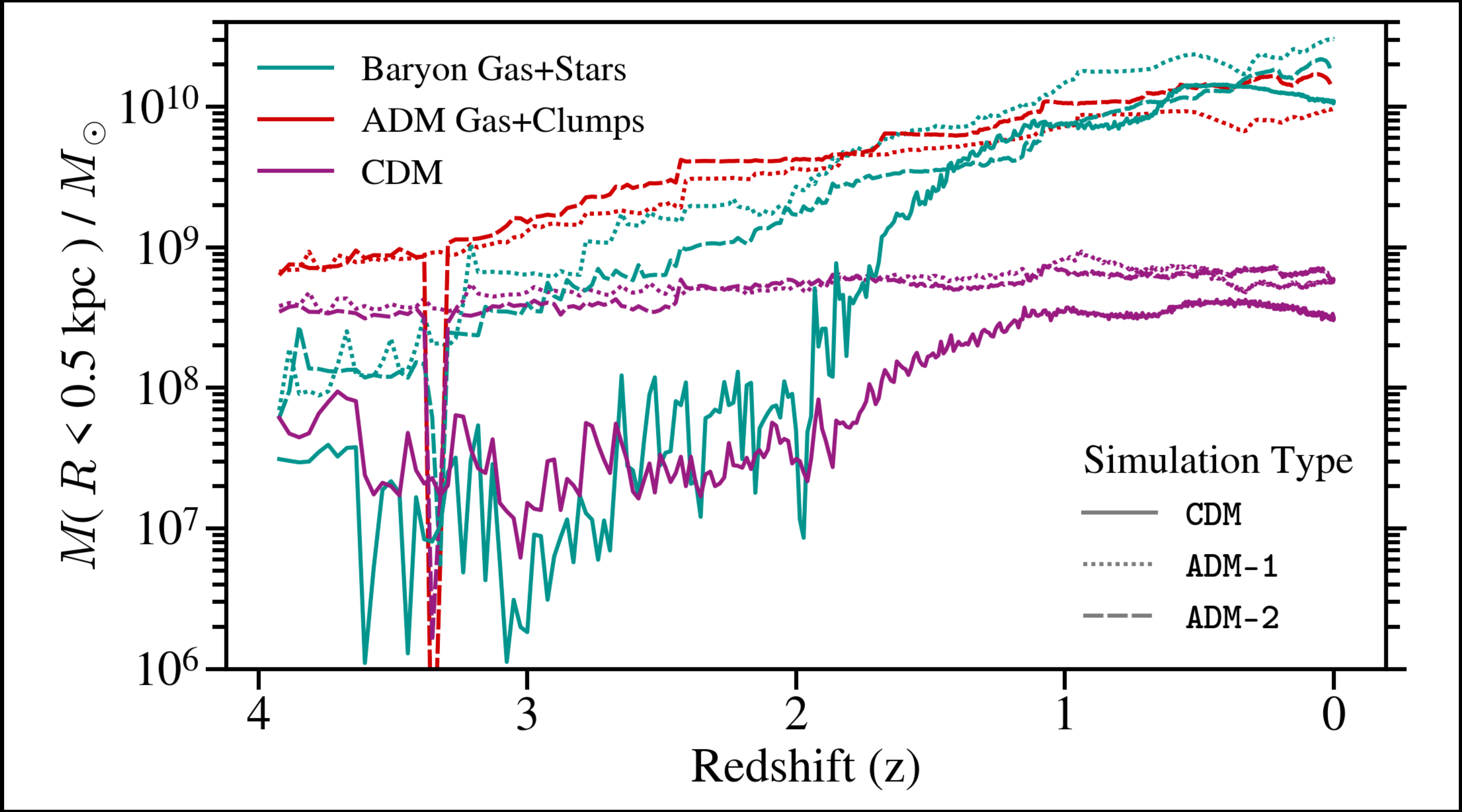
Table E1. A table of morphology metrics for the baryonic stars and ADM clumps in CDM, CDM-NF, ADM-1, and ADM-2. $r_{1/2}$, $z_{1/2}$, $z_{9/10}$, $f_{\rm thin}$, $f_{\rm thick}$, and $f_{\rm spheroid}$ are all defined in the main text. $\tilde{f}$ is the flatness parameter, with $\tilde{f} \to 1$ approaching a thin-disk distribution and $\tilde{f} \to 0$ approaching a spherical distribution. To obtain $\tilde{f}$, we compute the moment of inertia tensor of the stars or ADM clumps in the central 10 kpc of the galaxy and compare the values to that of a uniform ellipsoid, obtaining its effective triaxial dimensions. We then repeat the process with particles within the derived ellipsoid boundaries until the boundary values converge to within 10%. Flatness is then defined as $\tilde{f} = 1 - c/a$, where a (c) is the final semi-major (semi-minor) value of the iterative calculation.

MW Orbital Circularities

Method based on Abadi et al. (0212282)

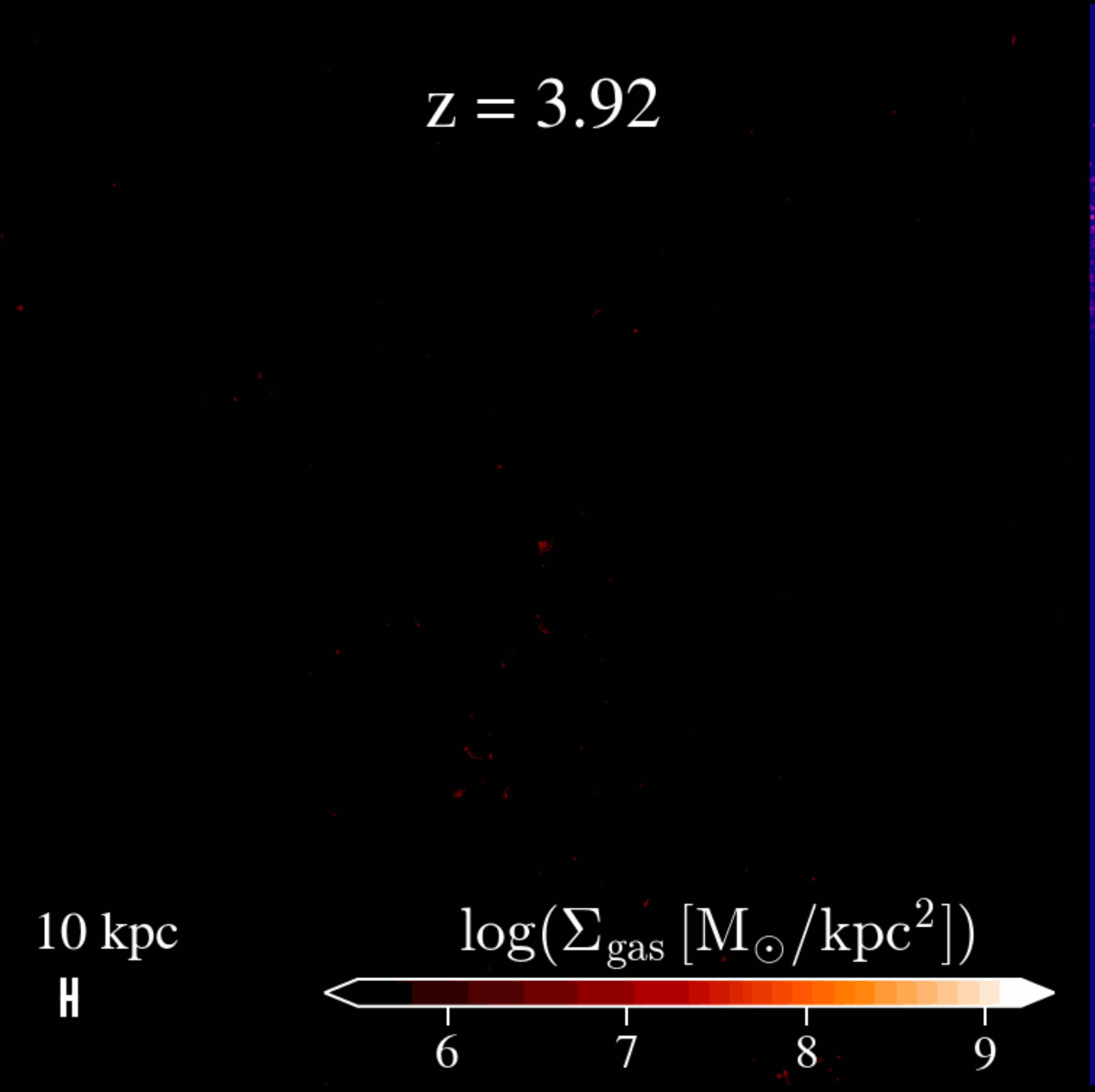


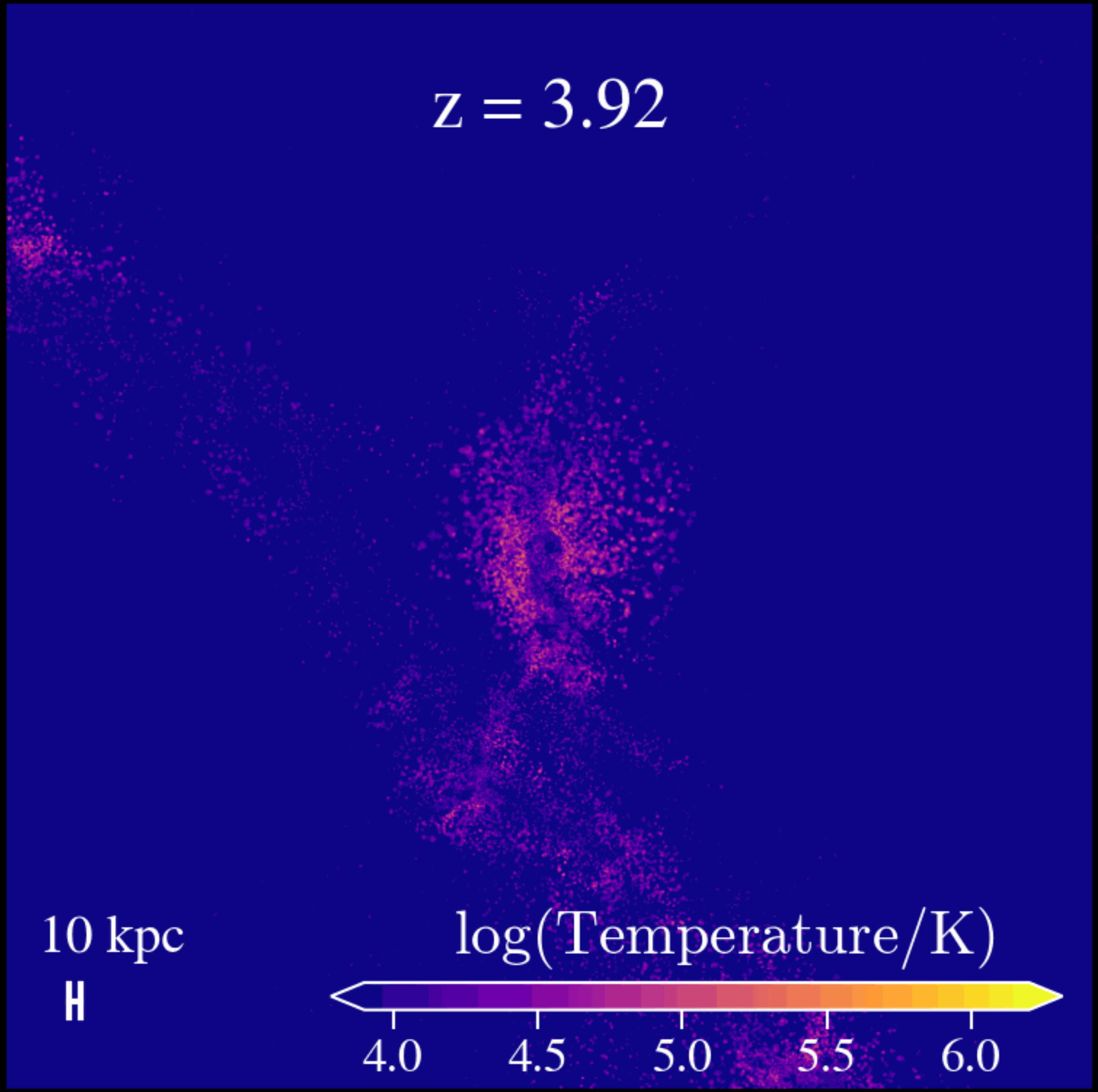
MW Central Density Evolution



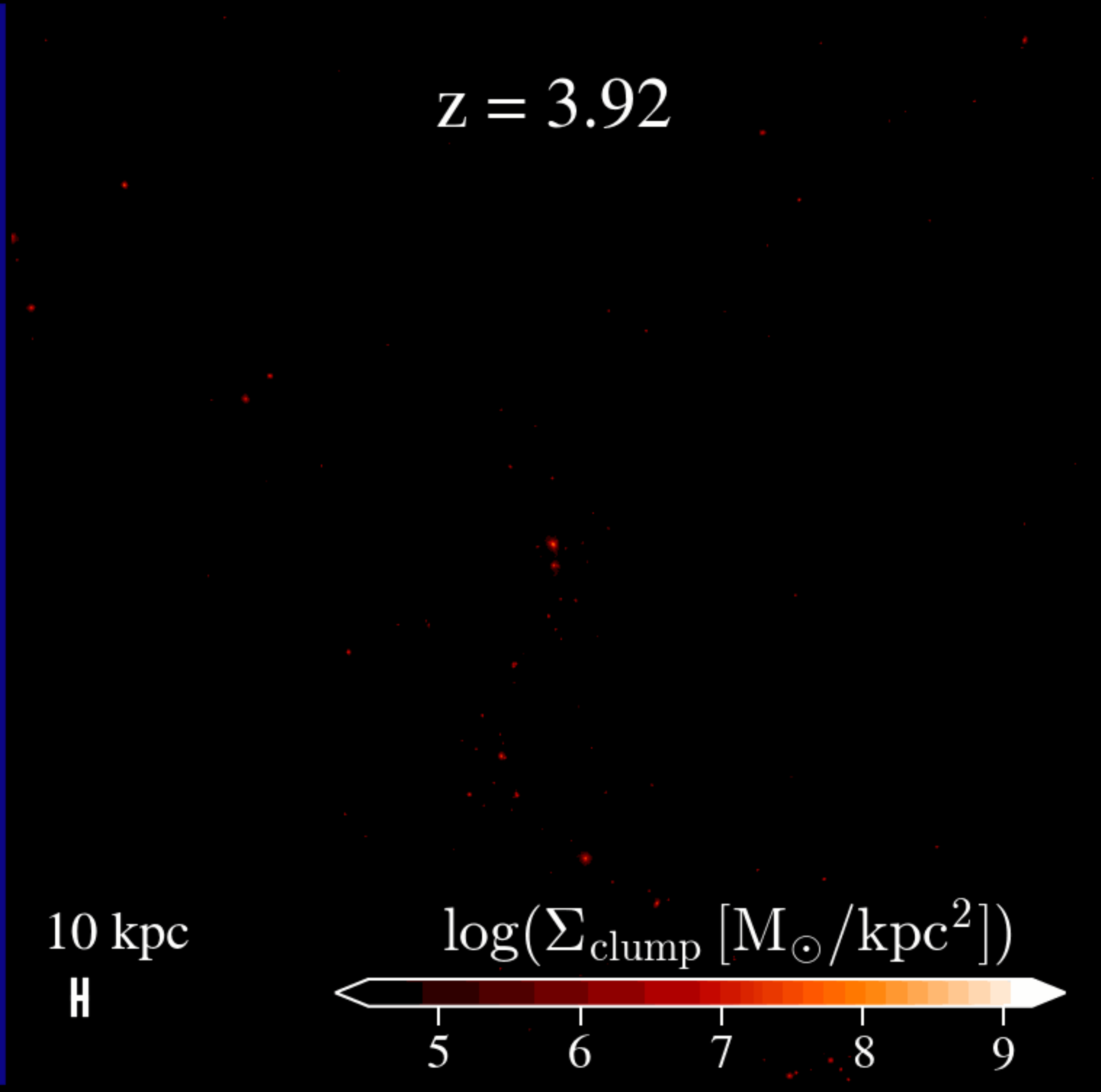
MW Central ADM Evolution (ADM-1)

ADM Gas





ADM Clumps



MW Central ADM Evolution (ADM-1)

ADM Gas

ADM Clumps

MW Central ADM Evolution (ADM-2)

ADM Gas

ADM Clumps

MW Central ADM Evolution (ADM-2)

ADM Gas

ADM Clumps