

# Simulating Atomic Dark Matter (ADM) in Milky Way Analogues

**Sandip Roy**

***Princeton University***

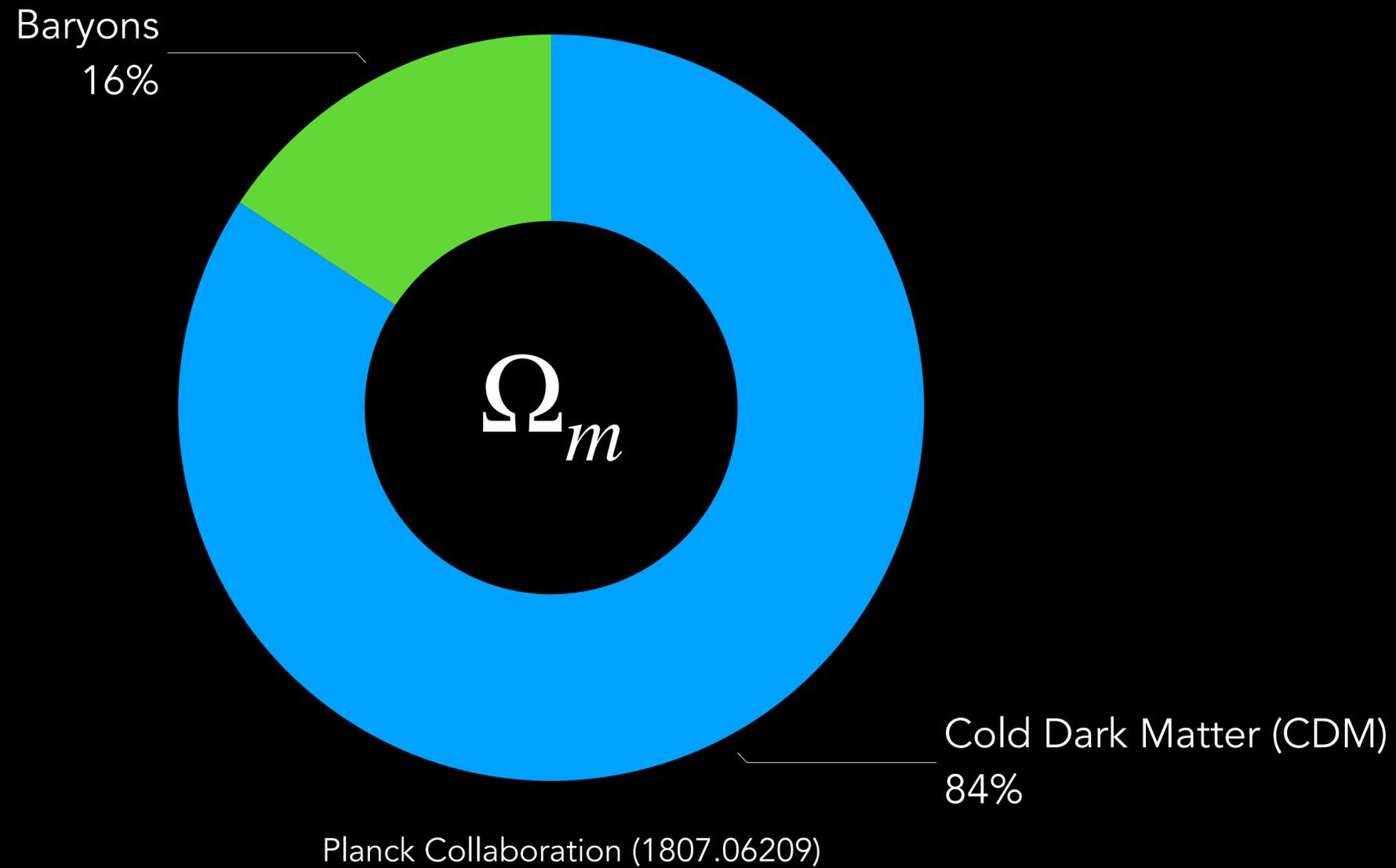
*with X. Shen, M. Lisanti, D. Curtin, N. Murray, P. F. Hopkins*

*Arxiv: 2304.09878*

*Pheno Symposium - PITT PACCC, University of Pittsburgh - May 2023*

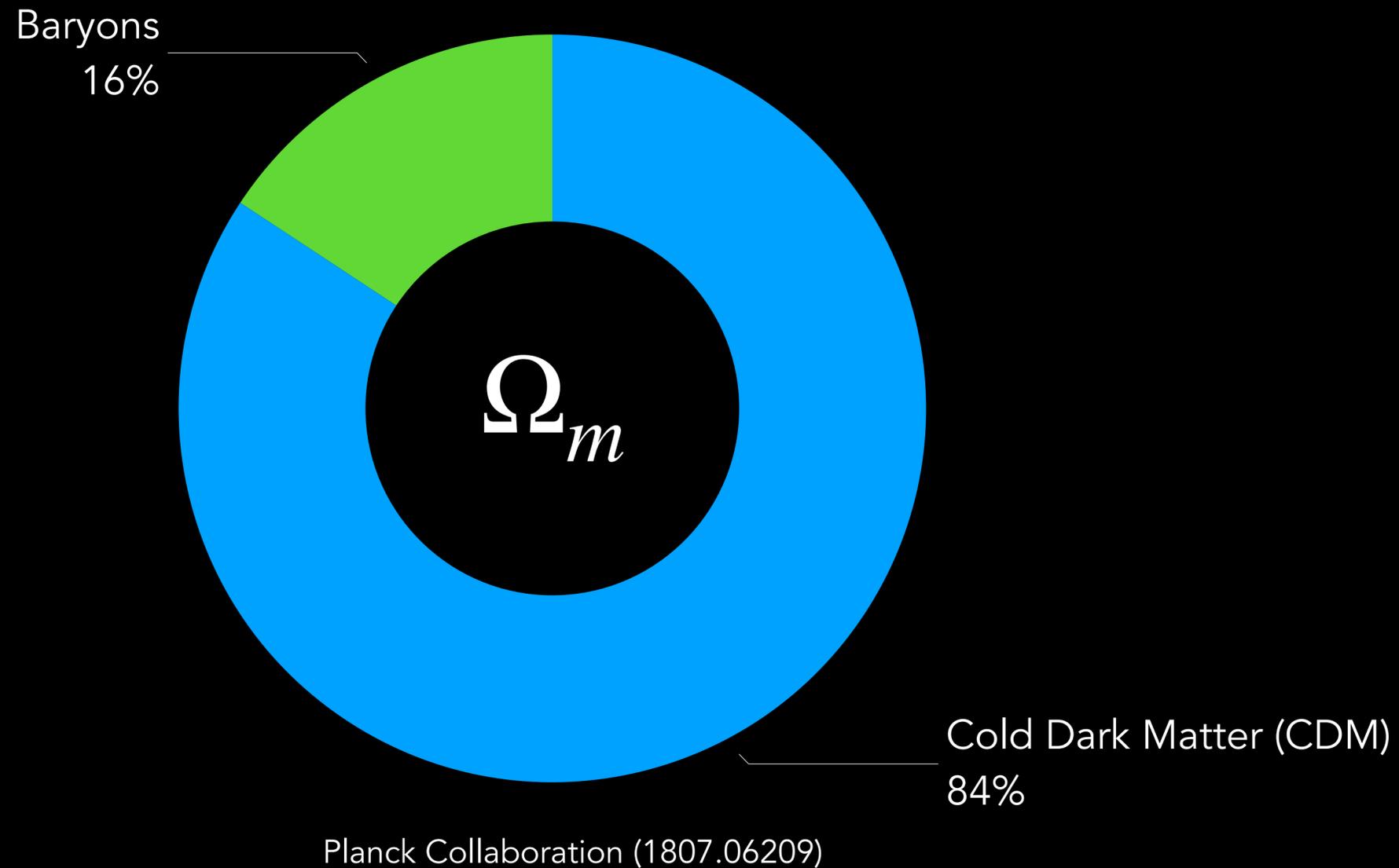
# Motivation

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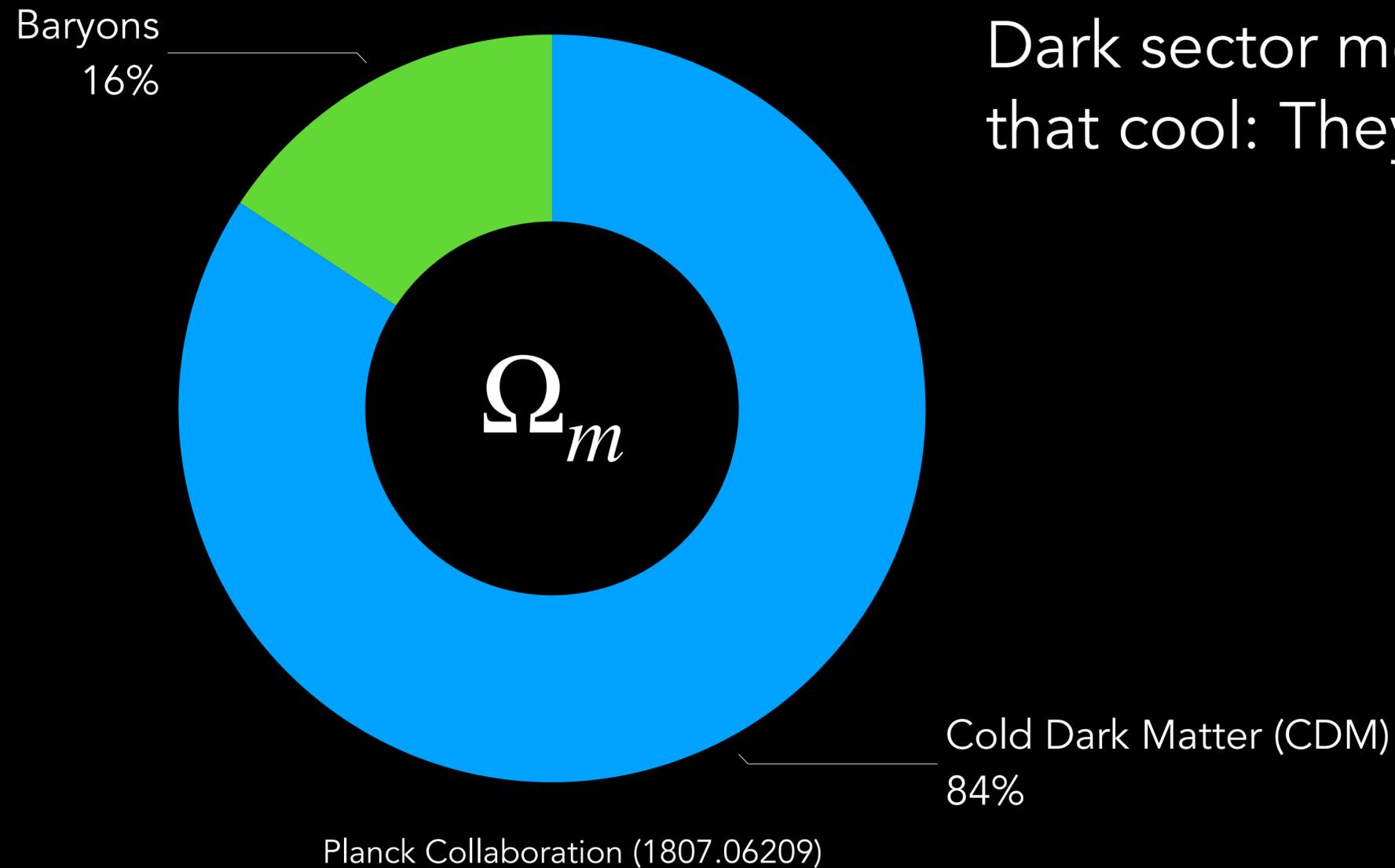
Need to test collisionless paradigm on sub-galactic scales



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Need to test collisionless paradigm on sub-galactic scales

Dark sector models predict dark subcomponents that cool: They can effect galactic morphology

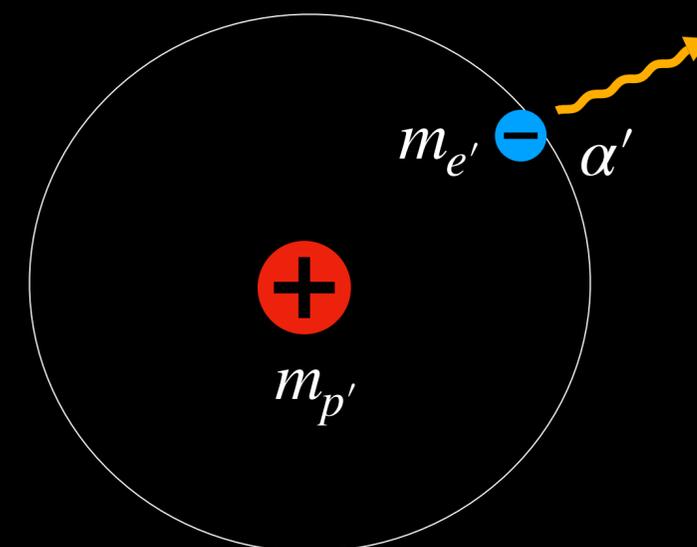
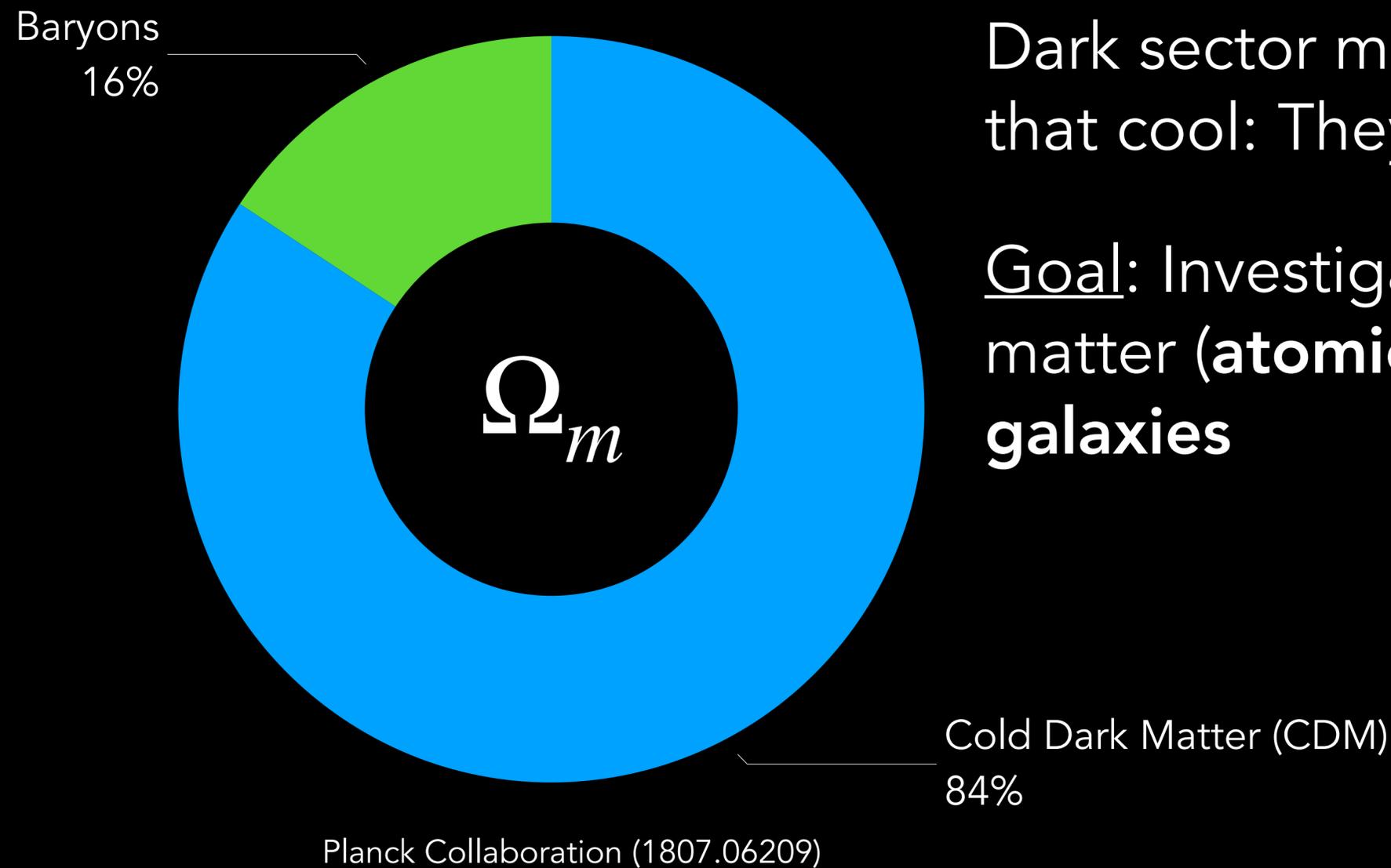


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Need to test collisionless paradigm on sub-galactic scales

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Goal: Investigate **effects** of **dissipative** dark matter (**atomic dark matter**) in **Milky Way-mass galaxies**

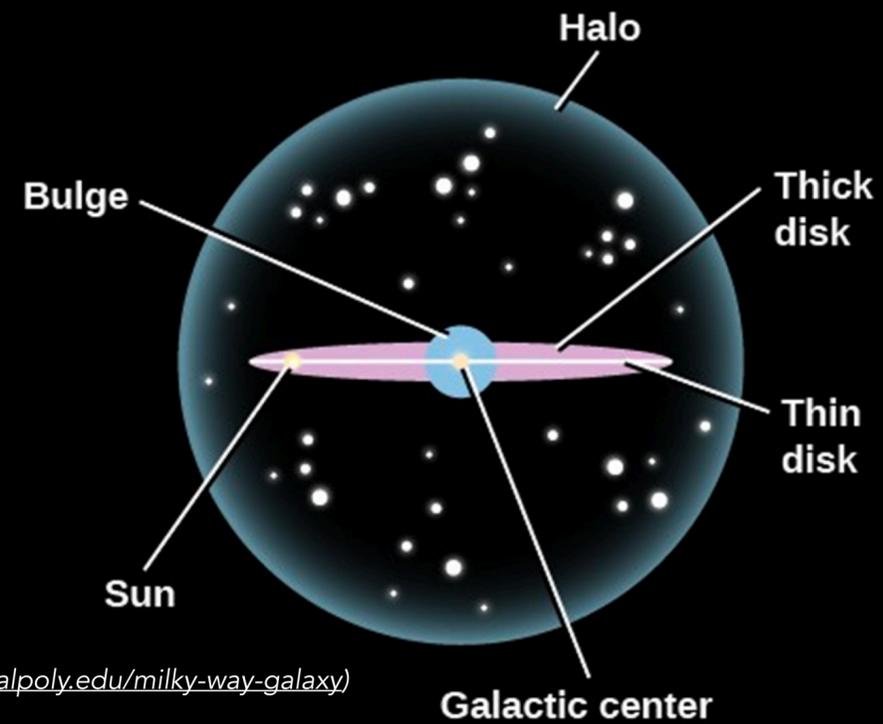


# ADM Galactic Morphology

The intuitive picture

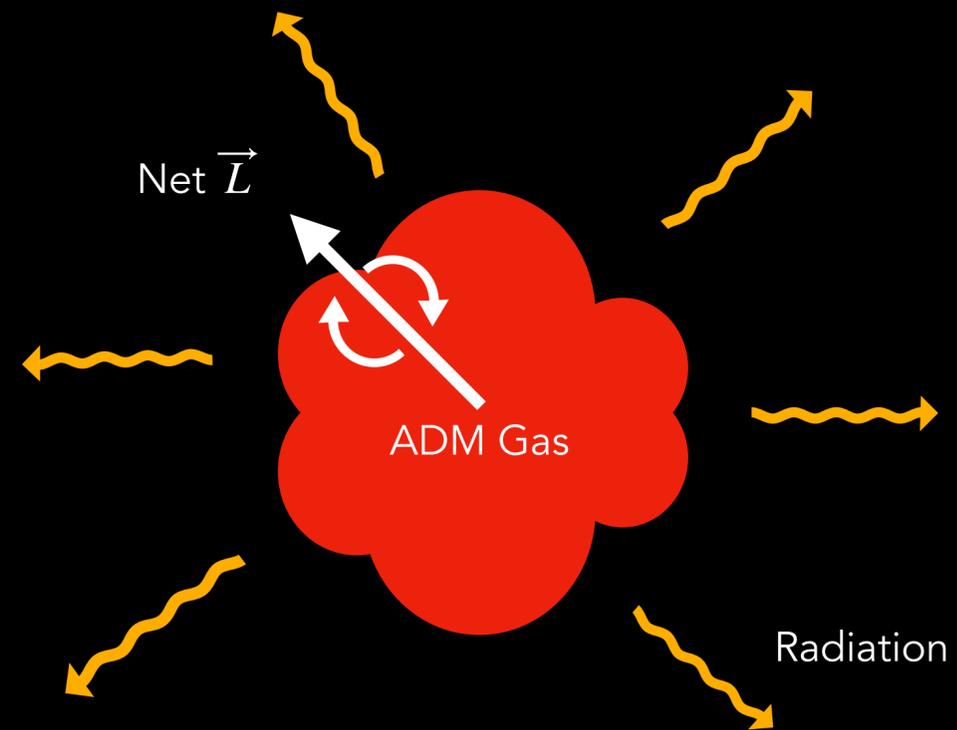
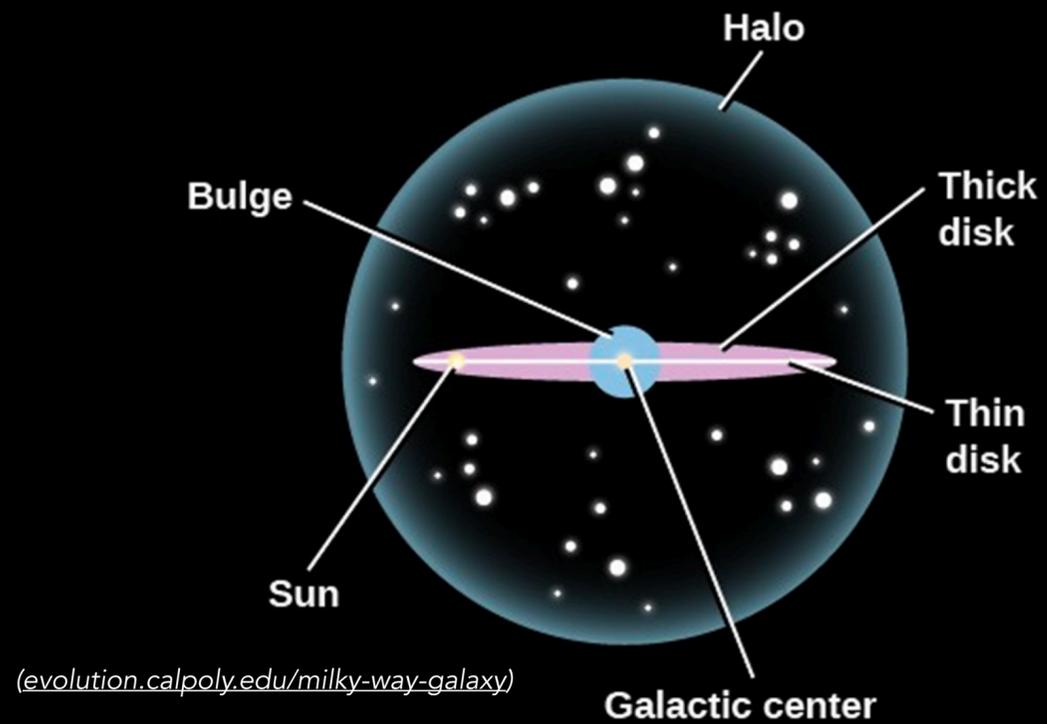
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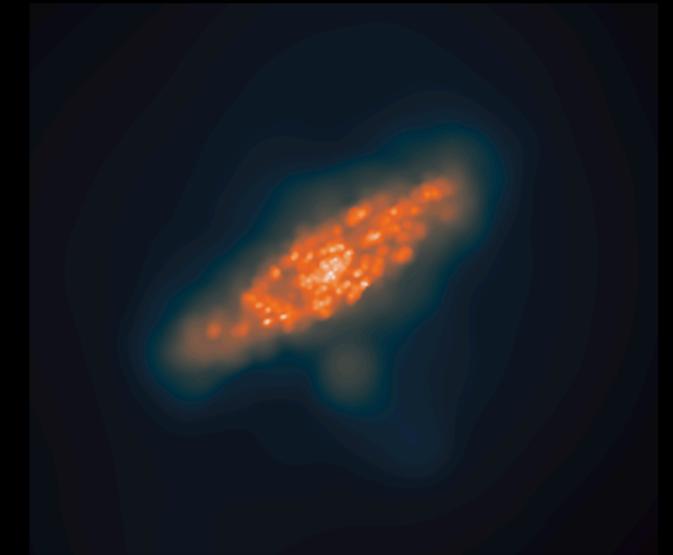
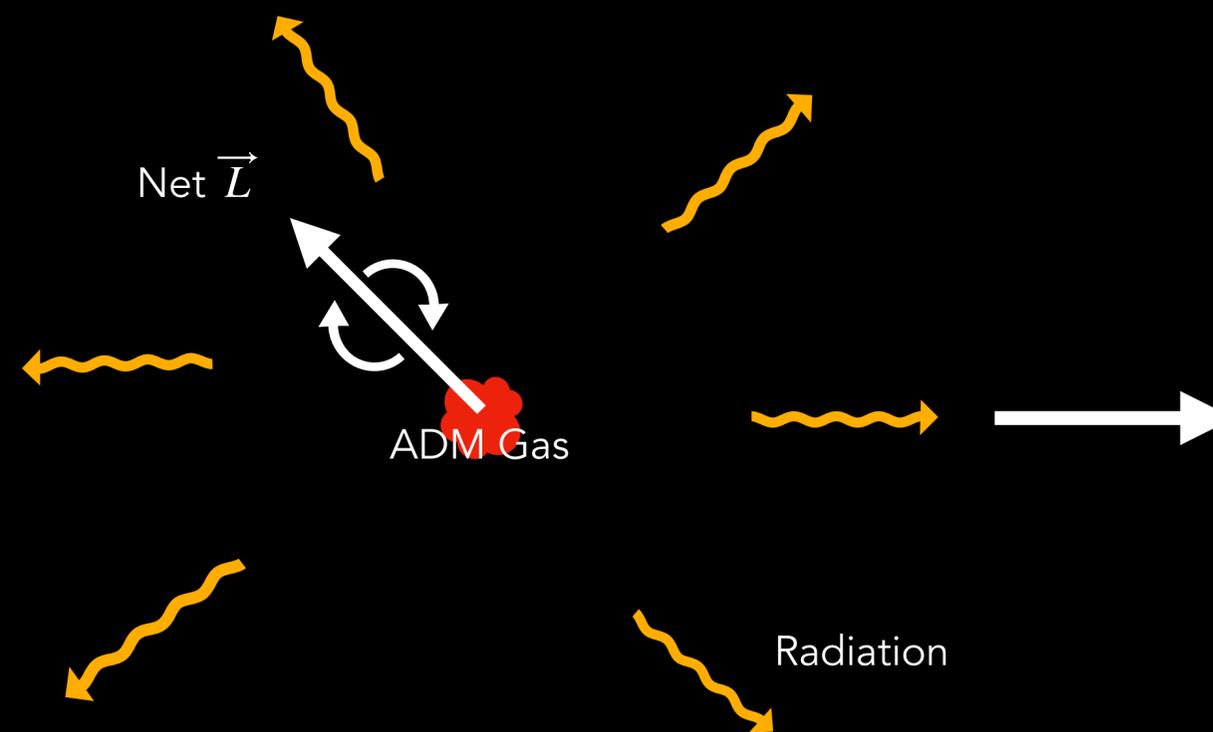
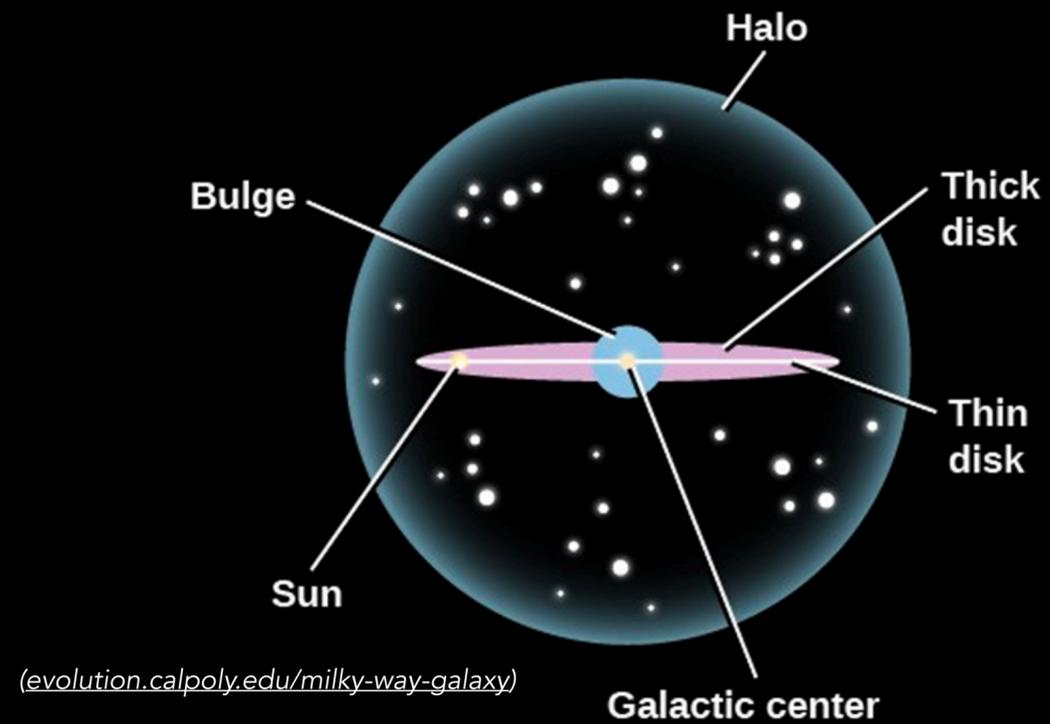
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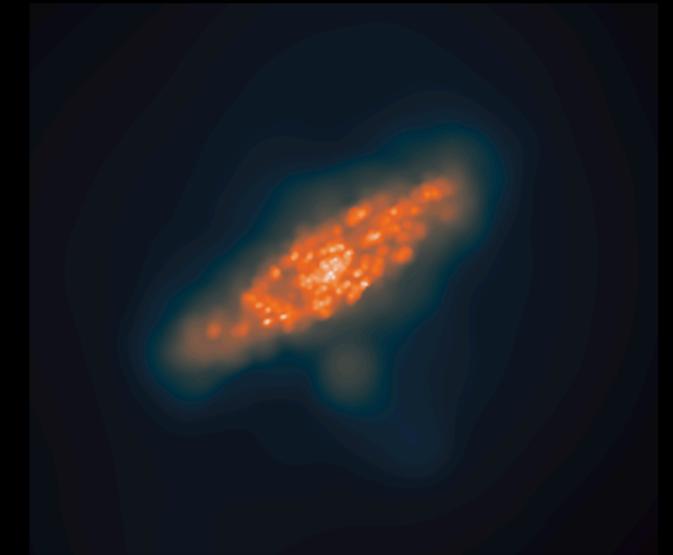
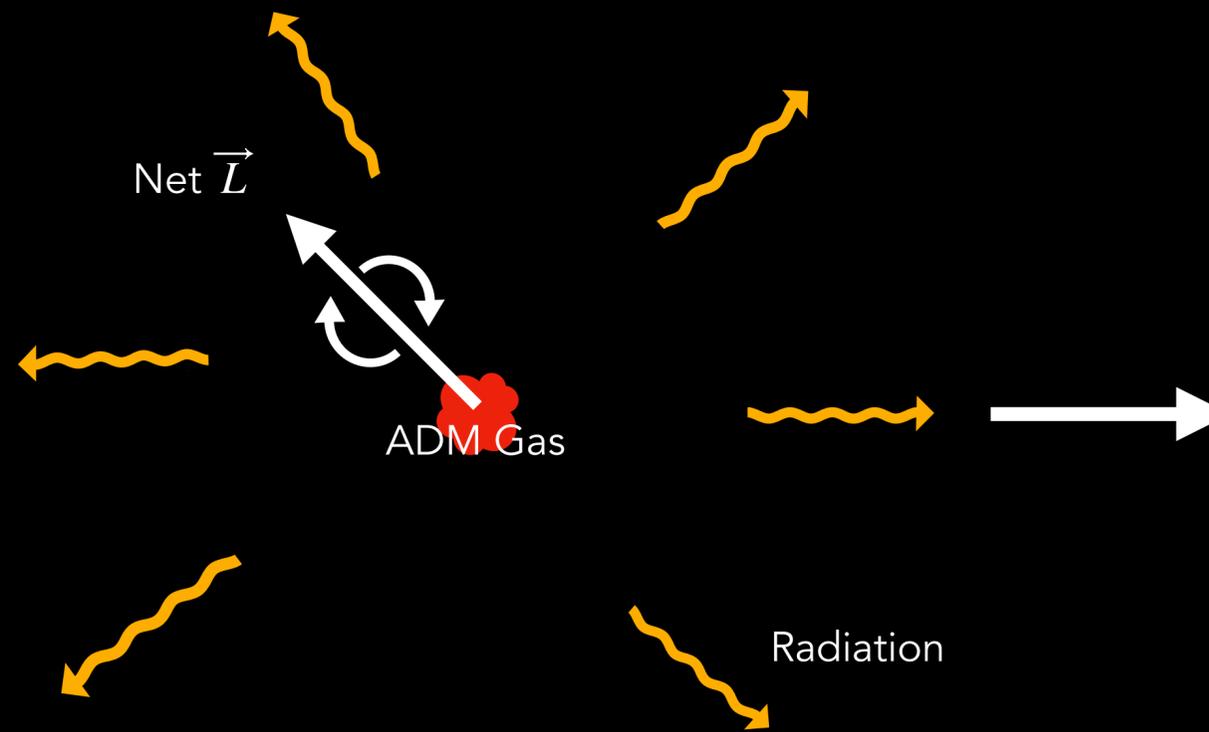
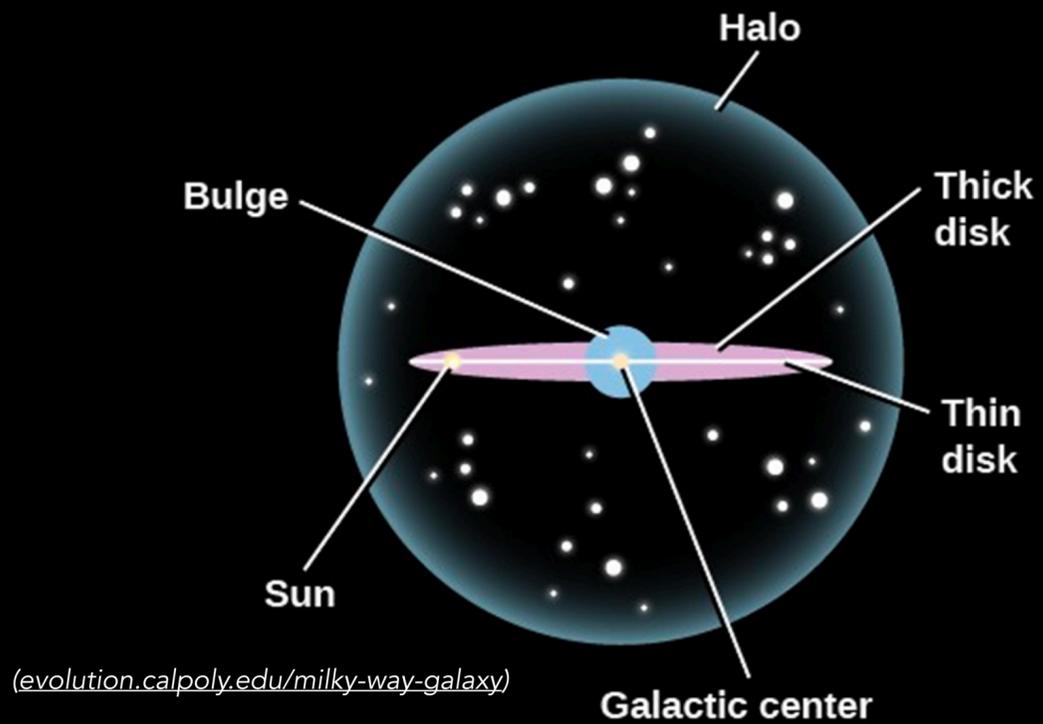
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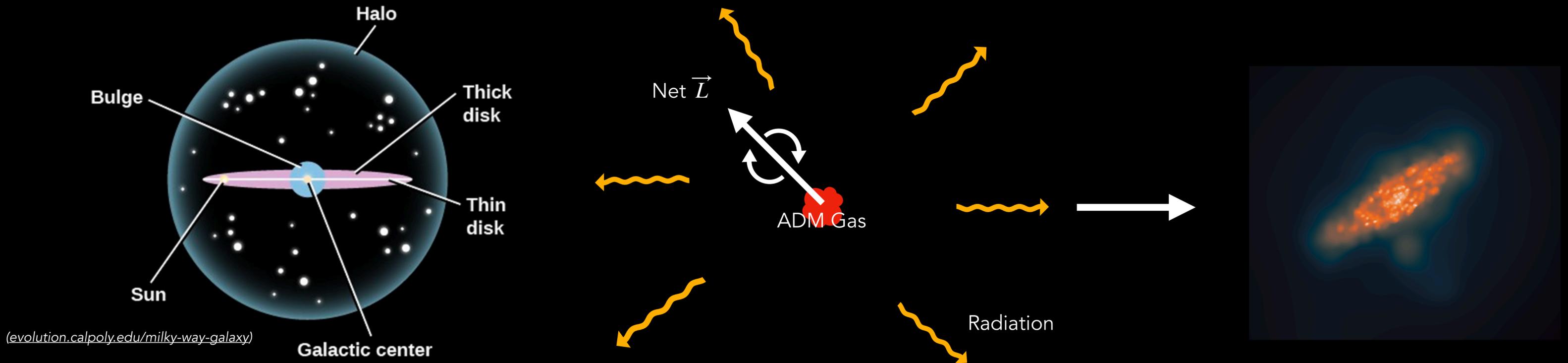
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Does a dark disk form? Fan et al. (1303.1521)

# ADM Galactic Morphology

## The intuitive picture

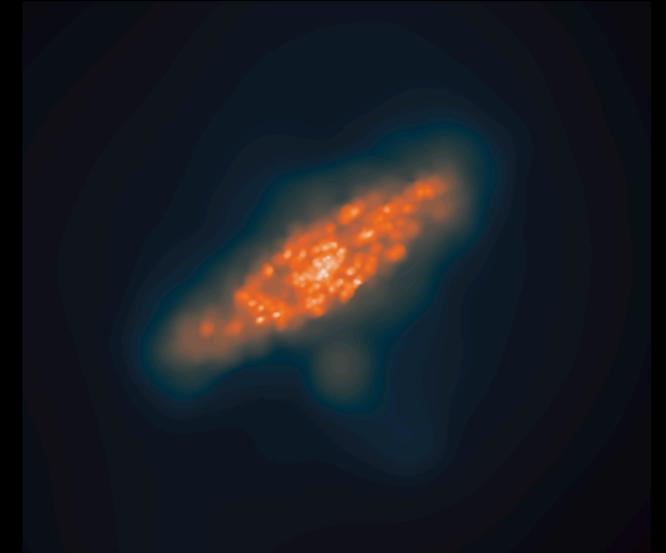
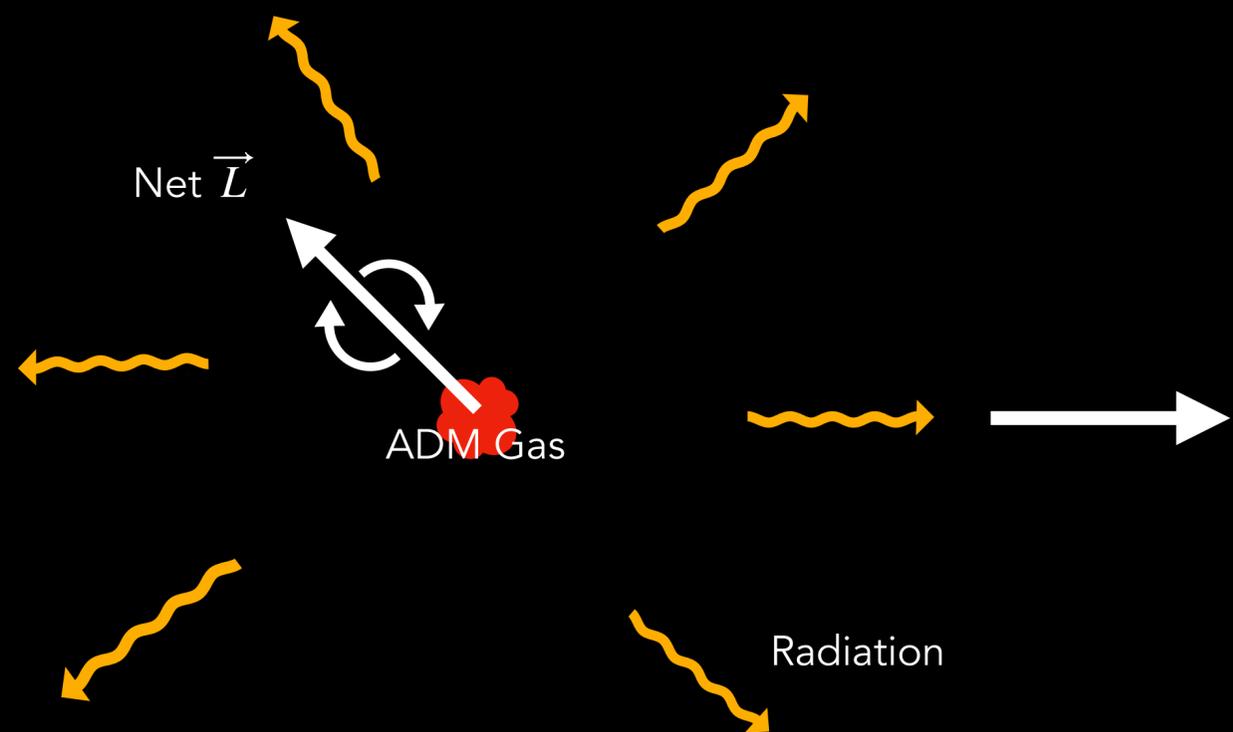
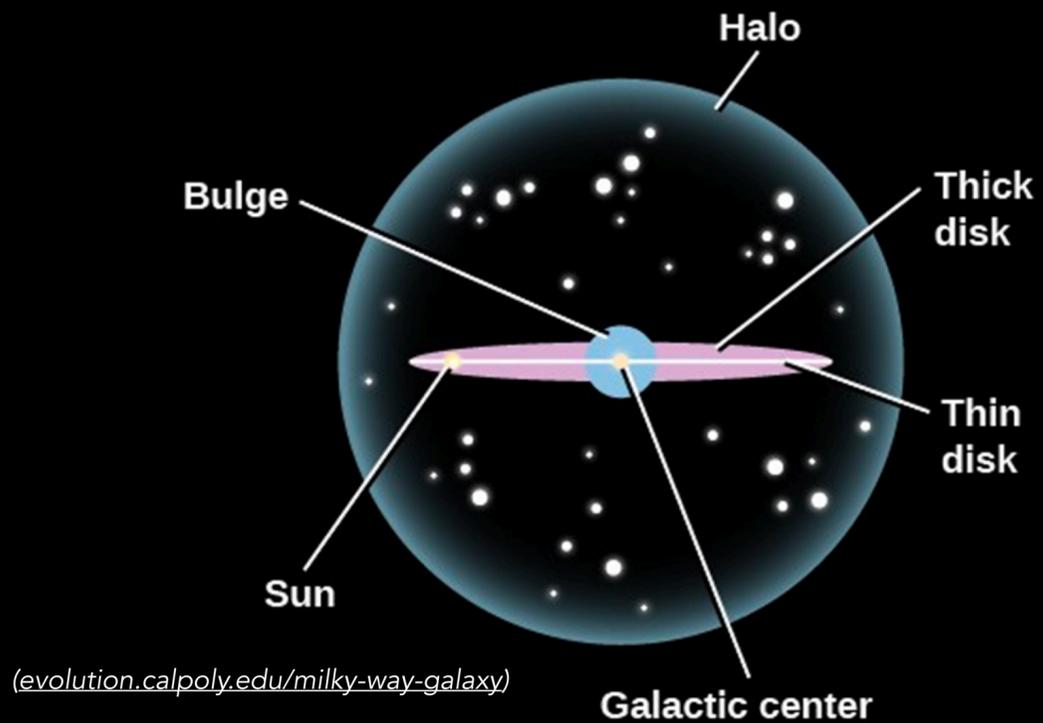


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Does it collapse into clumps? Ghalsasi et al. (1712.04779)

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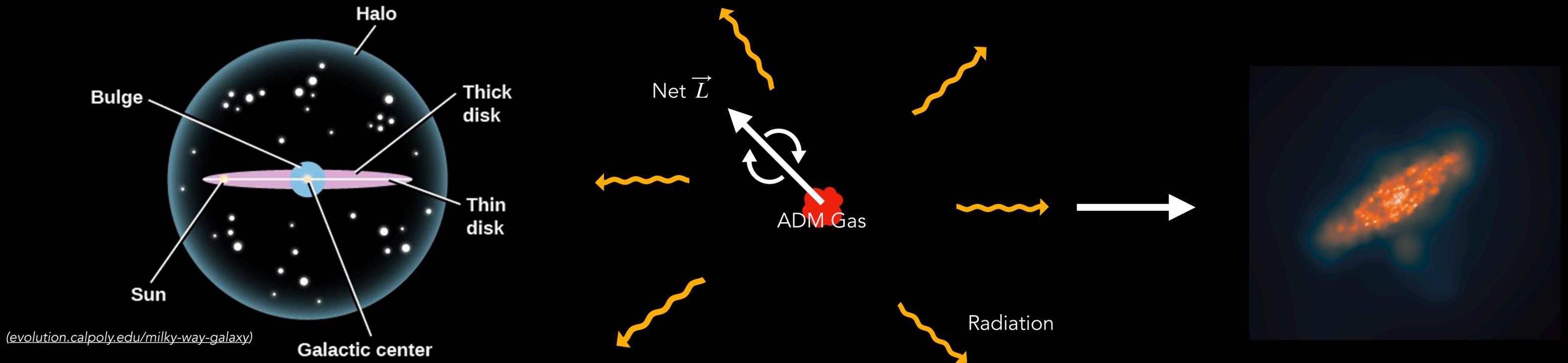
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If dark disk forms, can we observe it? Kramer et al. (1604.01407), Schutz et al. (1711.03103), Buch et al. (1808.05603), Widmark et al. (2105.14030)

# ADM Galactic Morphology

## The intuitive picture



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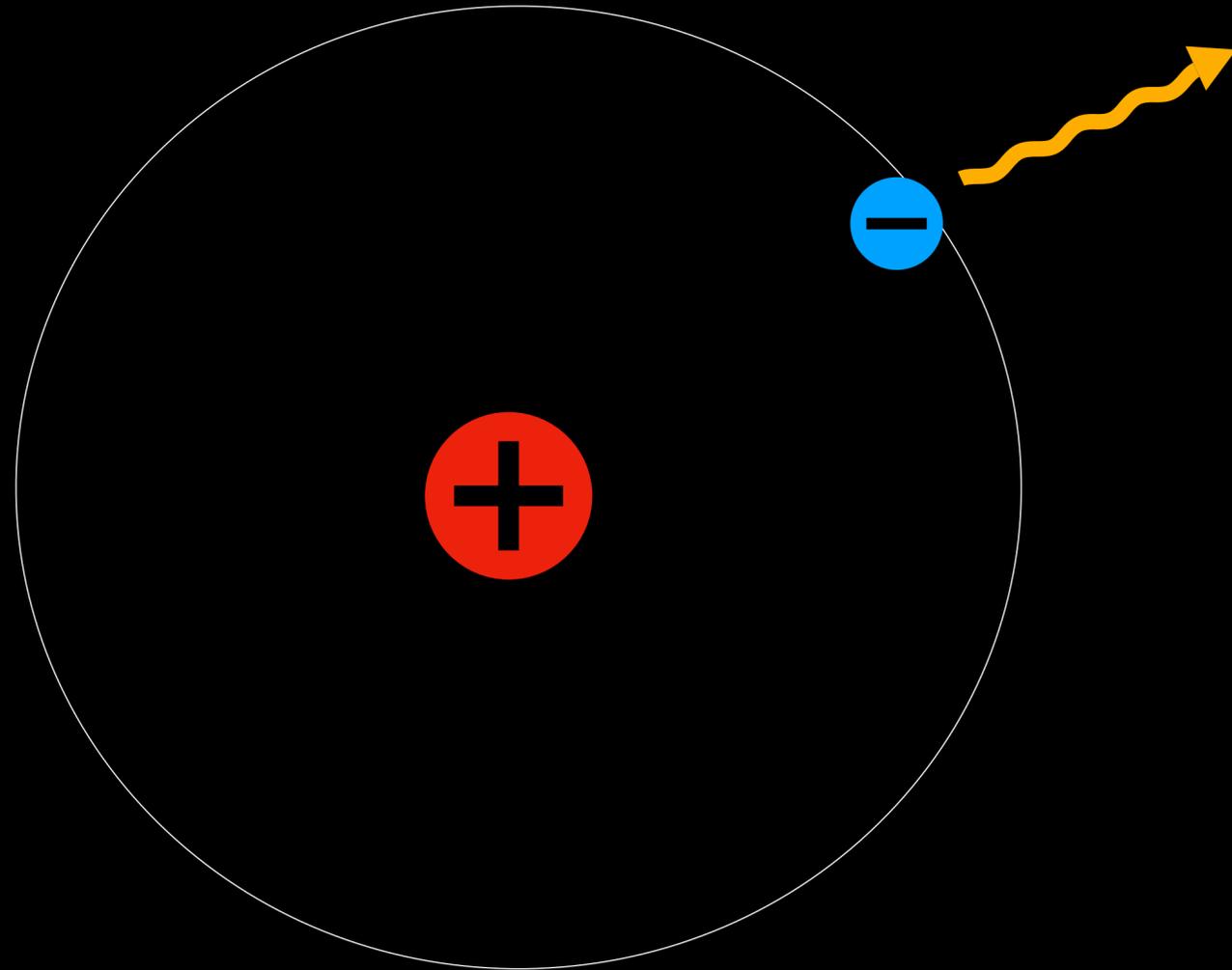
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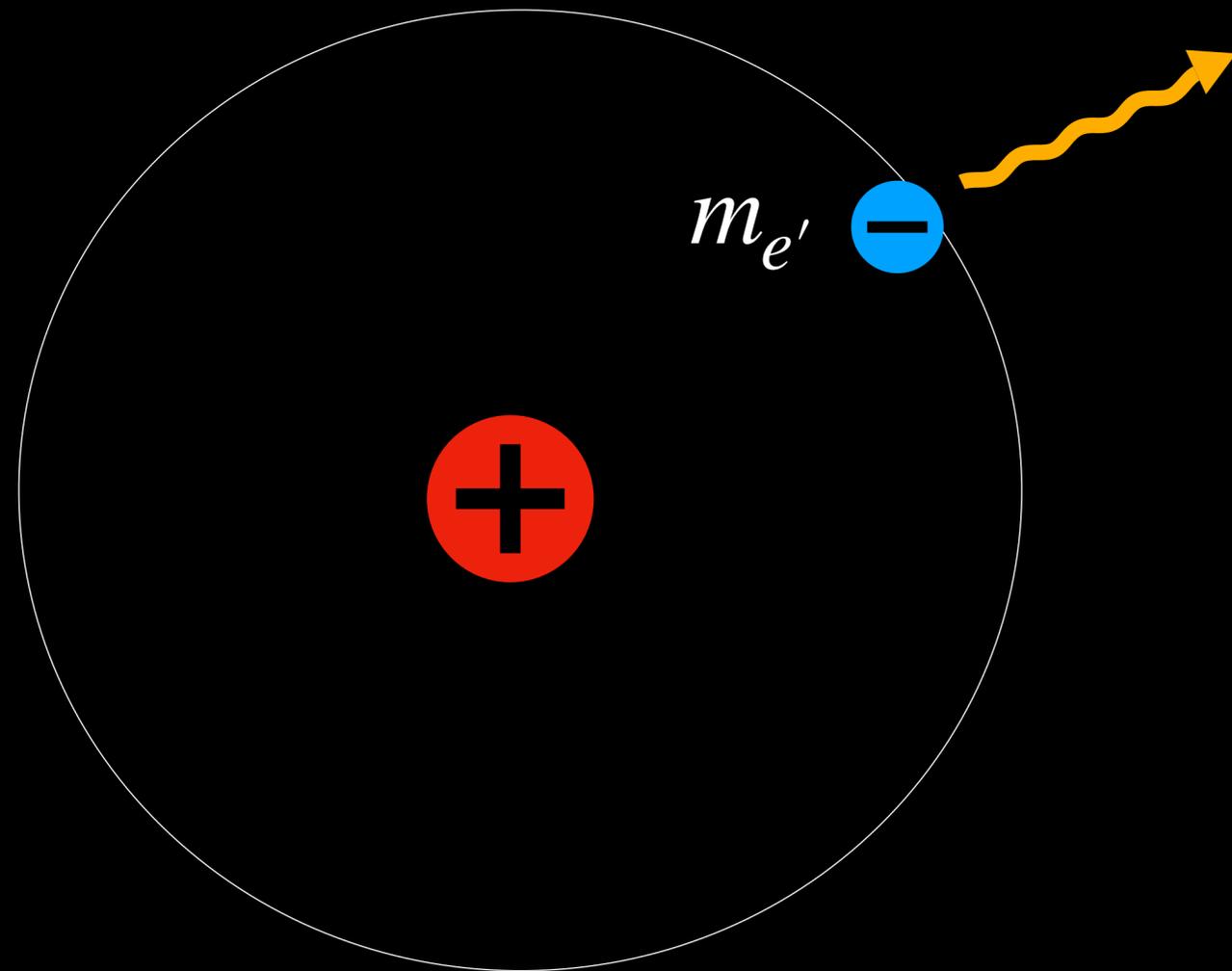
We simulated it! Results look very different!

# Atomic Dark Matter Intro & Simulation Setup

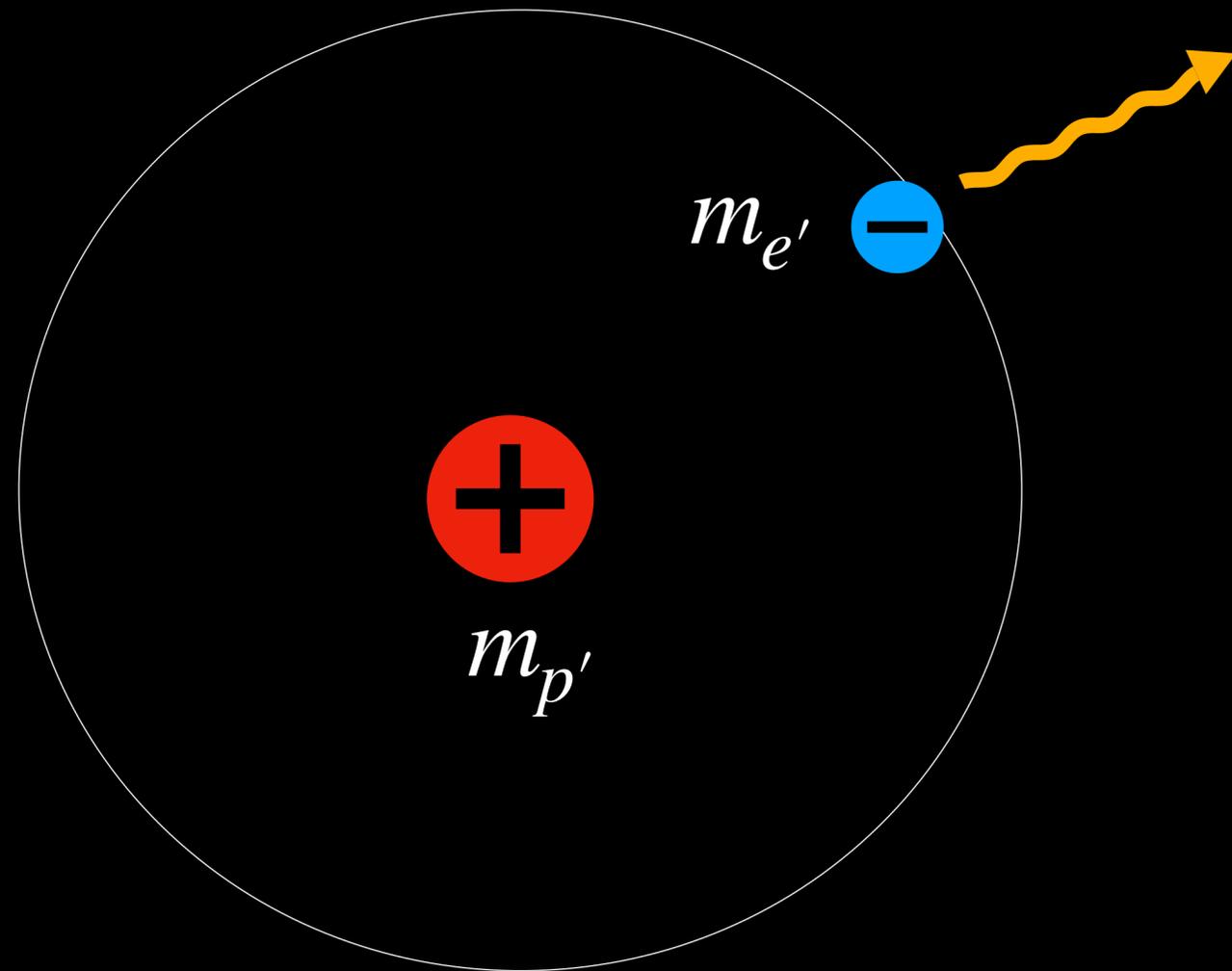
# ADM Parameters (Five Numbers...)



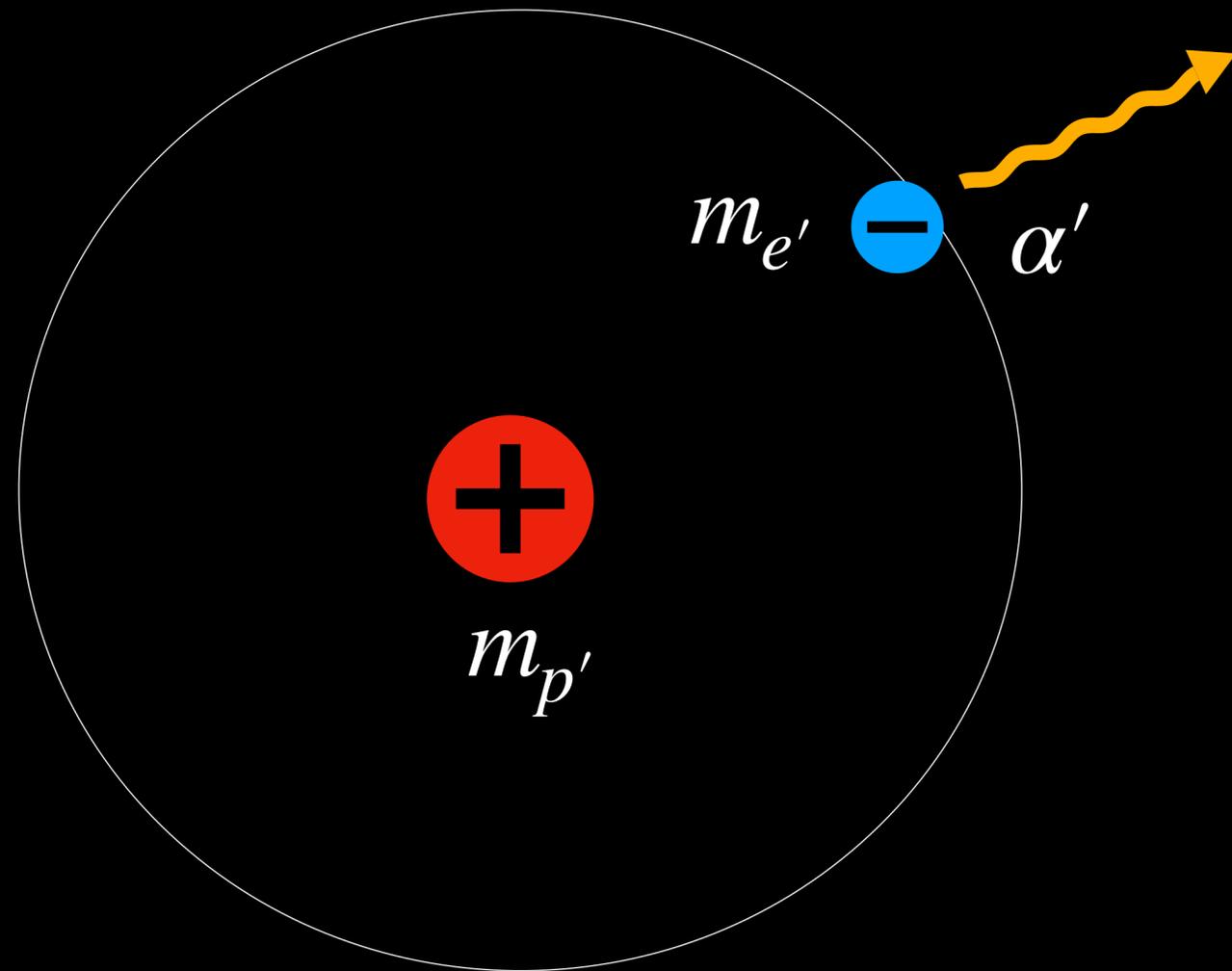
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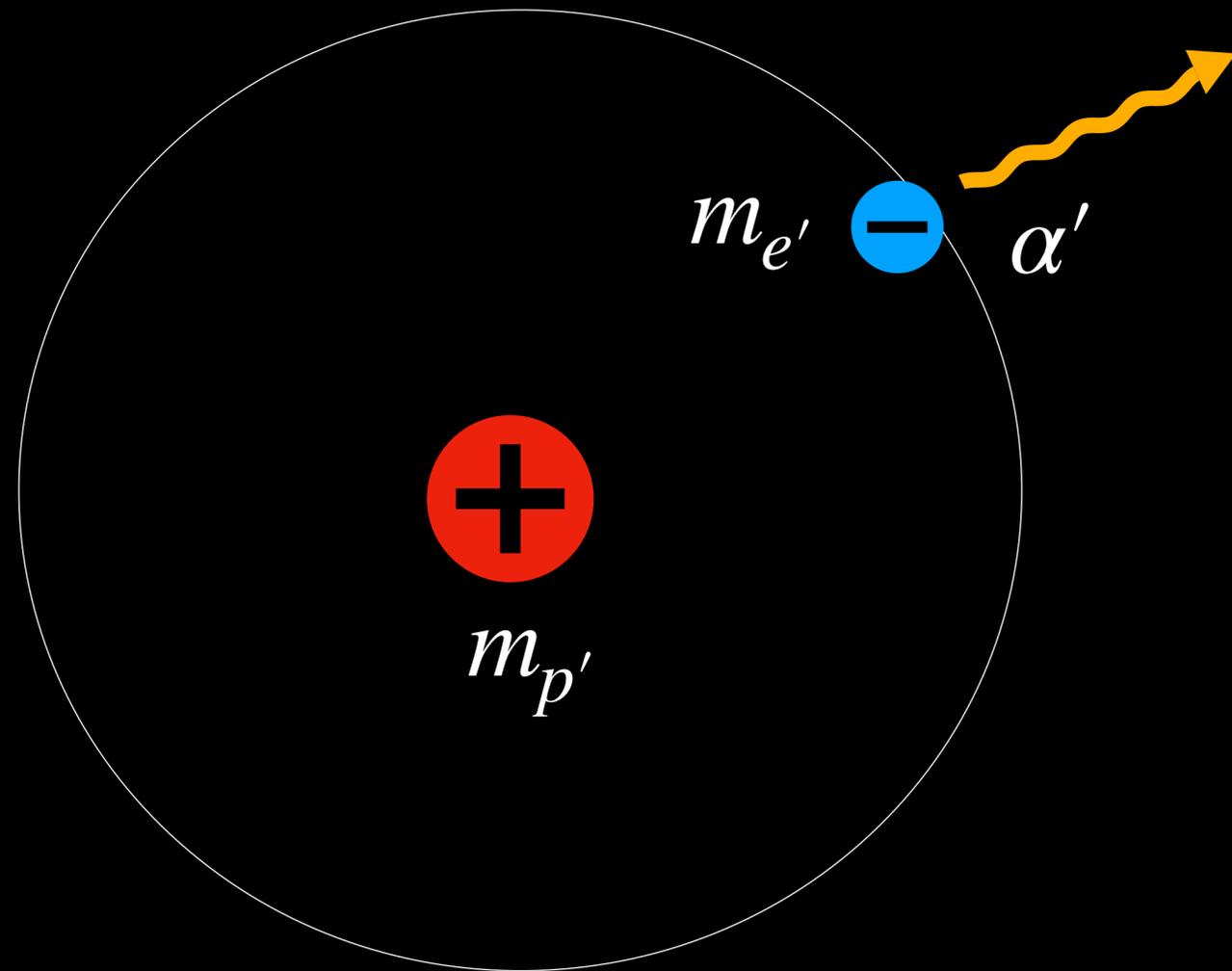
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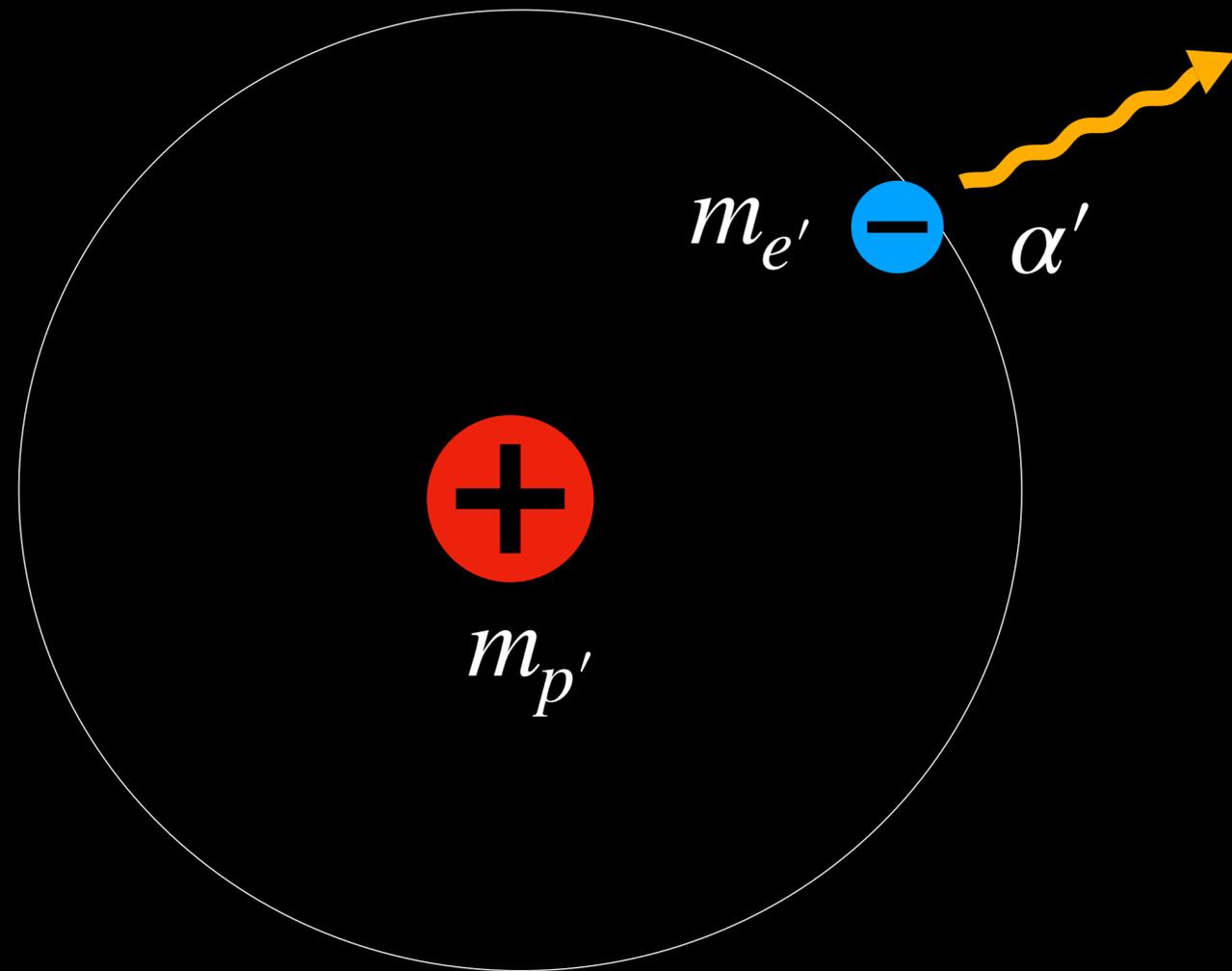


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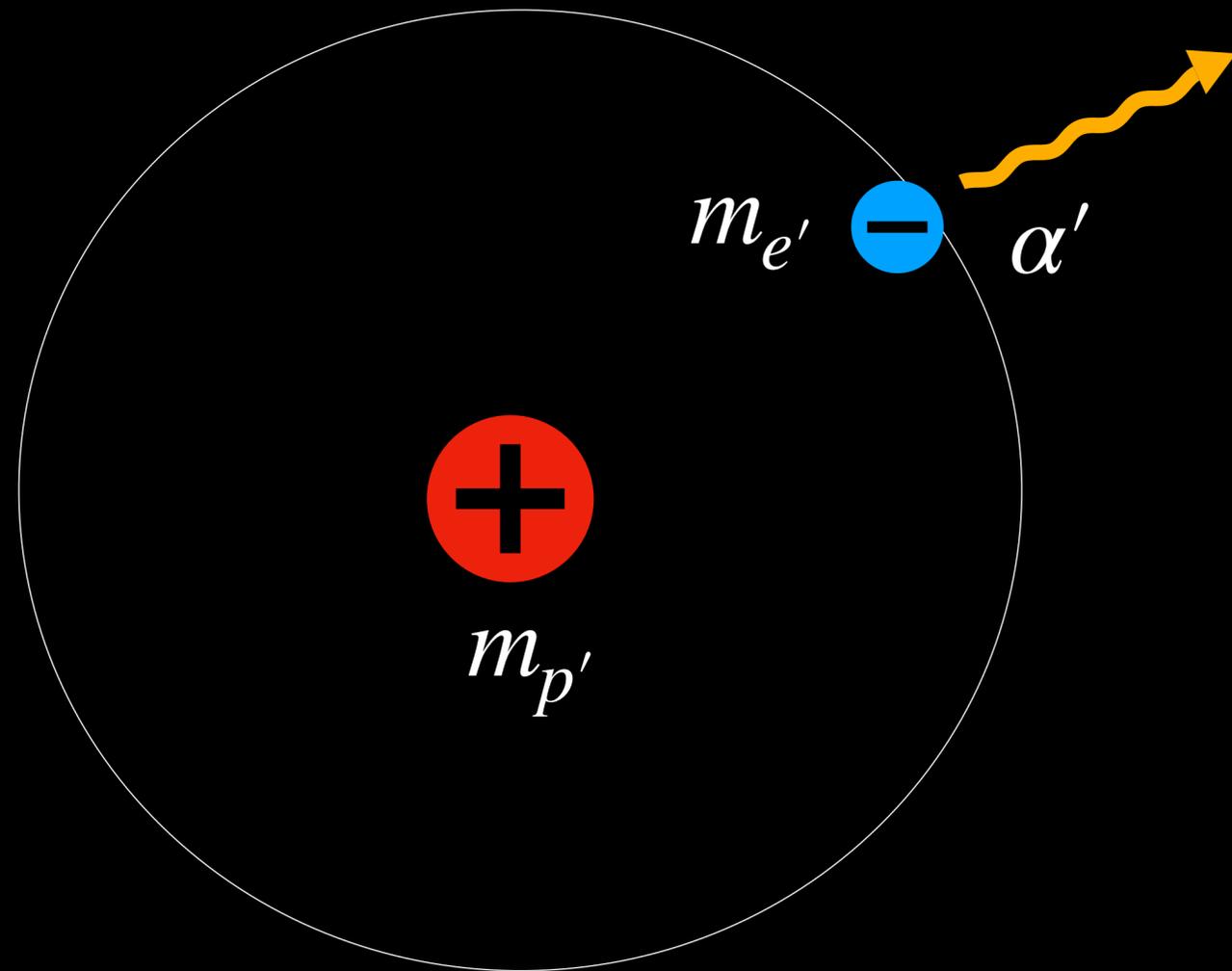
$$\xi^{\epsilon'} = \frac{T'}{T_{\text{CMB}}}$$

# ADM Parameters (Five Numbers...)



$$\xi' = \frac{T'}{T_{\text{CMB}}}$$
$$f' = \frac{\Omega_{\text{ADM}}}{\Omega_m}$$

# ADM Parameters (Five Numbers...)



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

$$f' = \frac{\Omega_{\text{ADM}}}{\Omega_m}$$

No dark nuclear physics  $\rightarrow$  No dark stars  $\rightarrow$  No dark supernovae (SN)

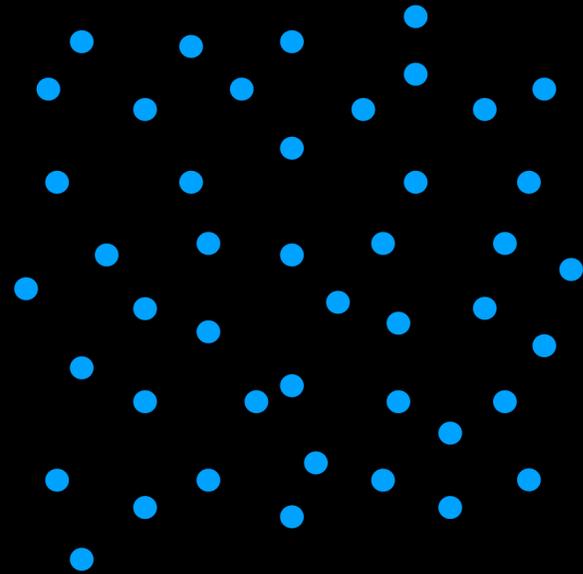
# ADM Implementation in GIZMO

## GIZMO: N-Body Hydrodynamics Code

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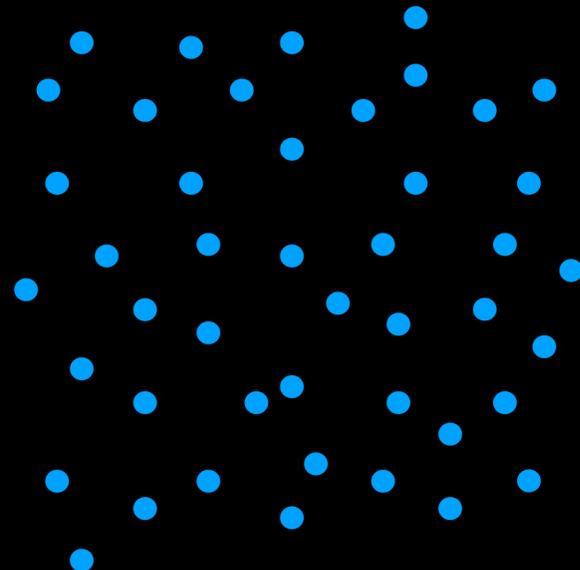
CDM



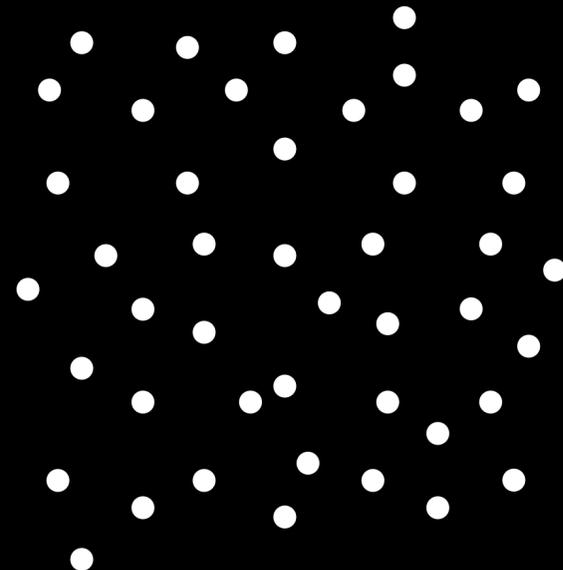
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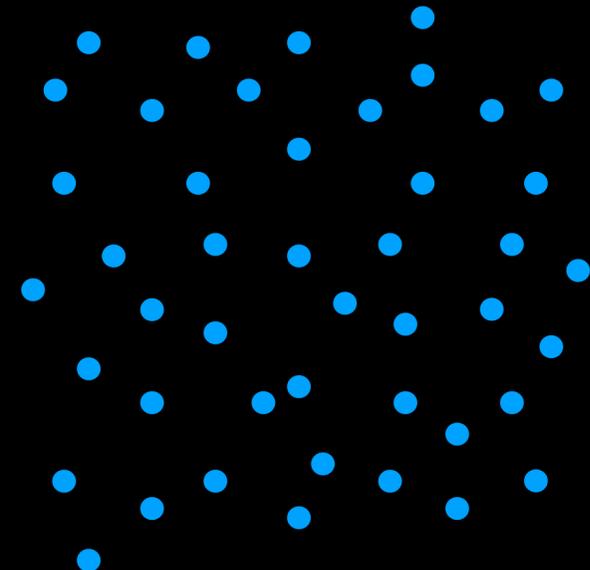
GAS



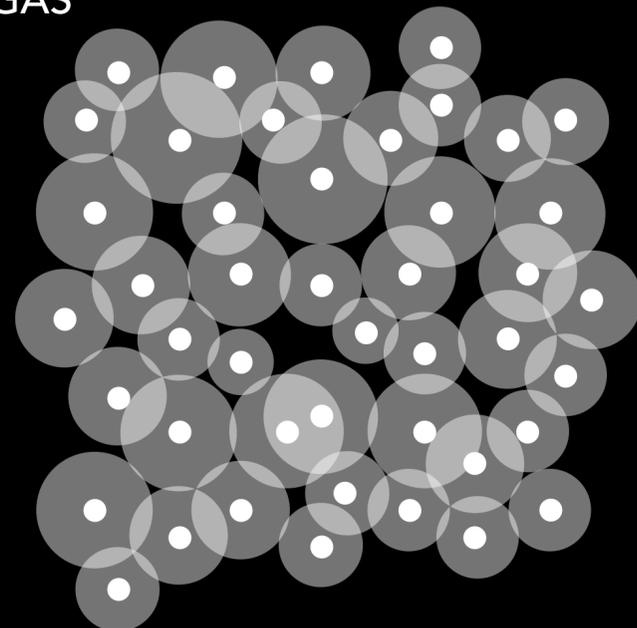
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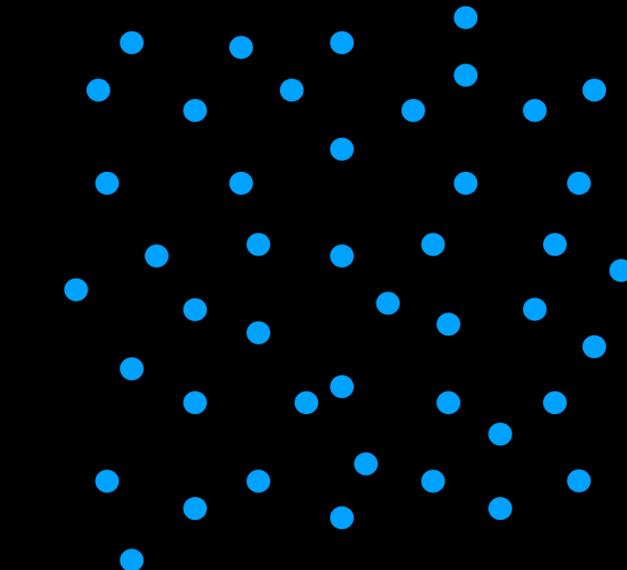
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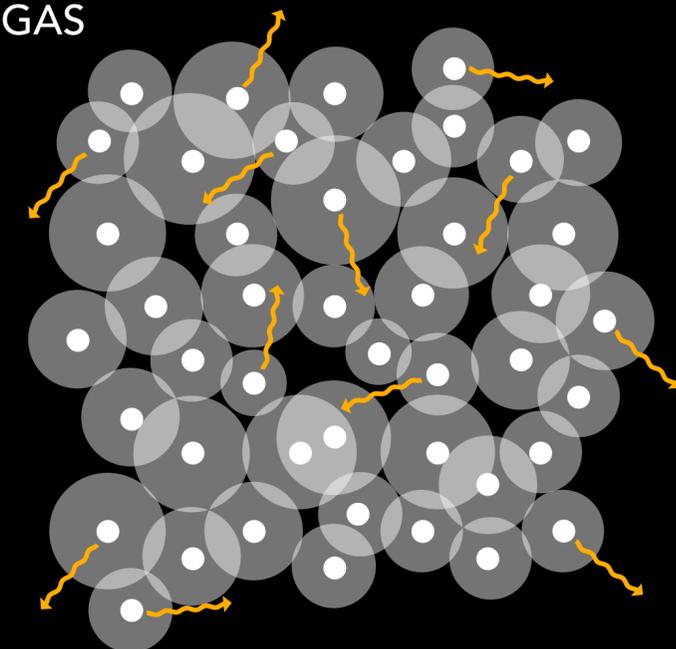
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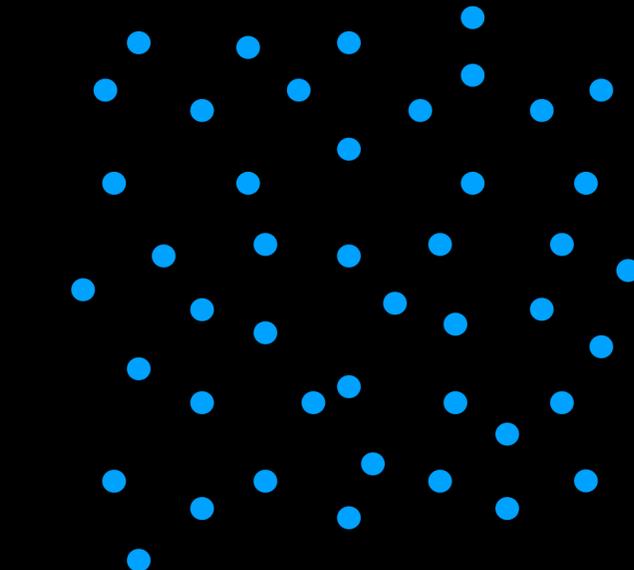
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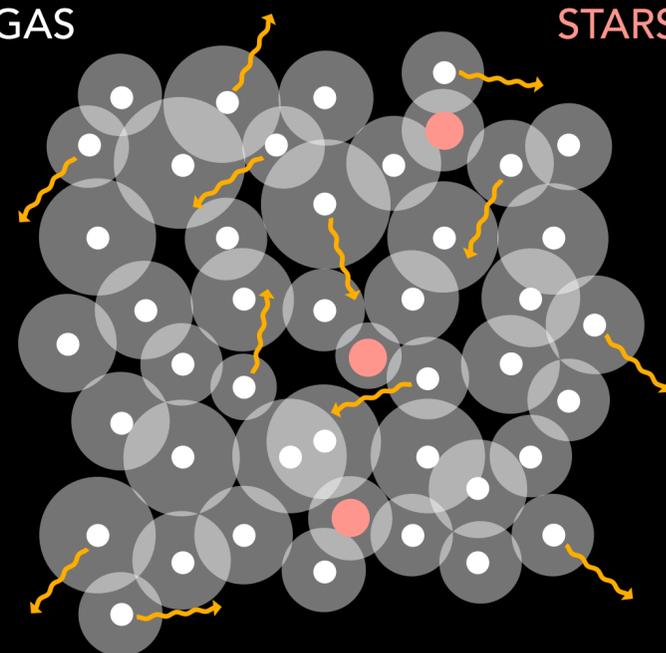
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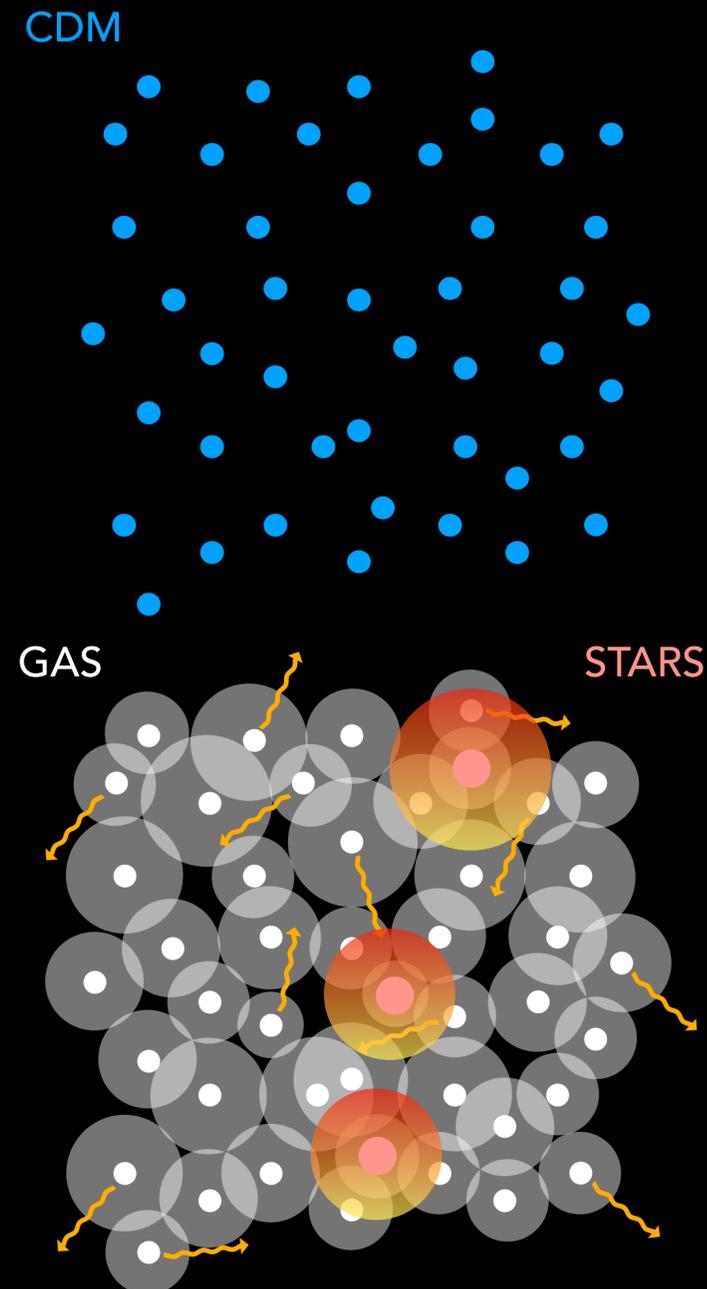
GAS

STARS



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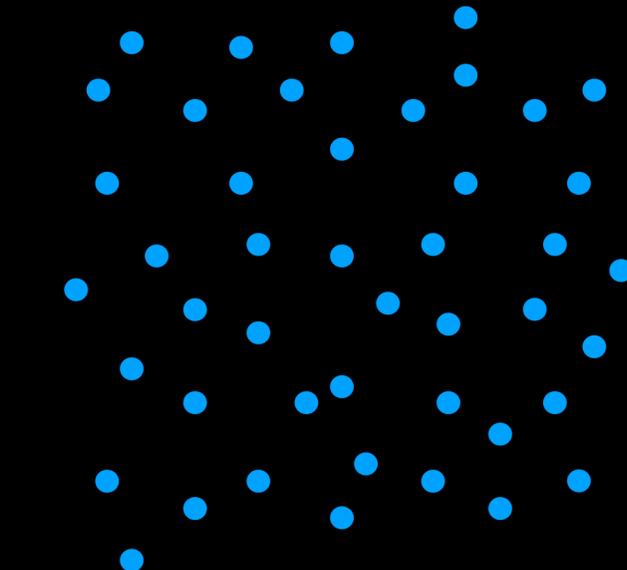
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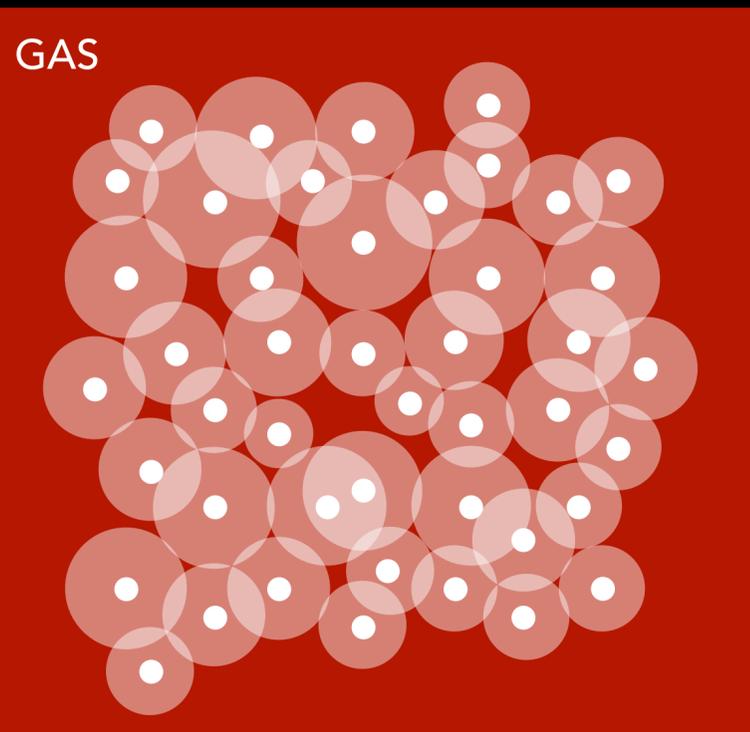
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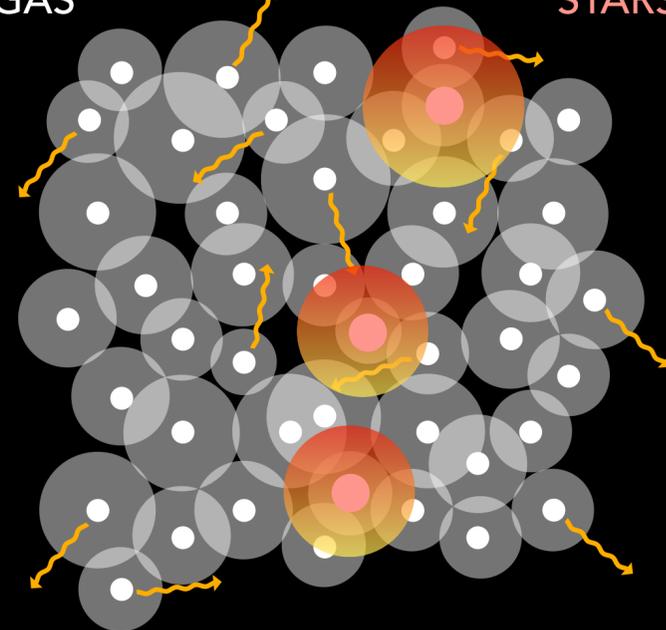


ADM



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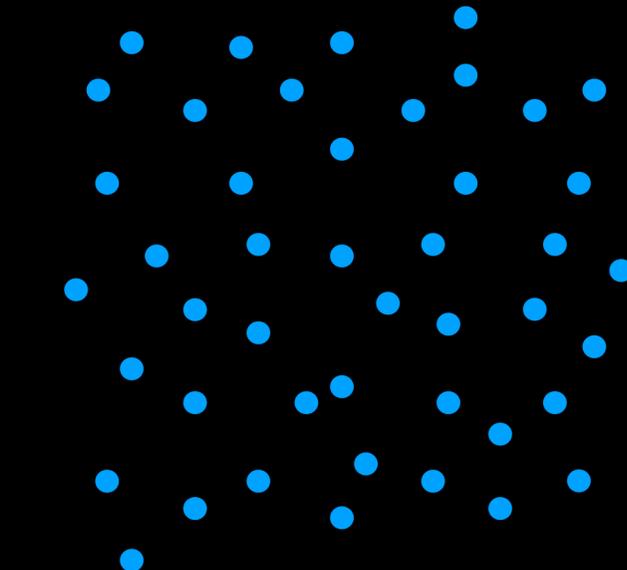
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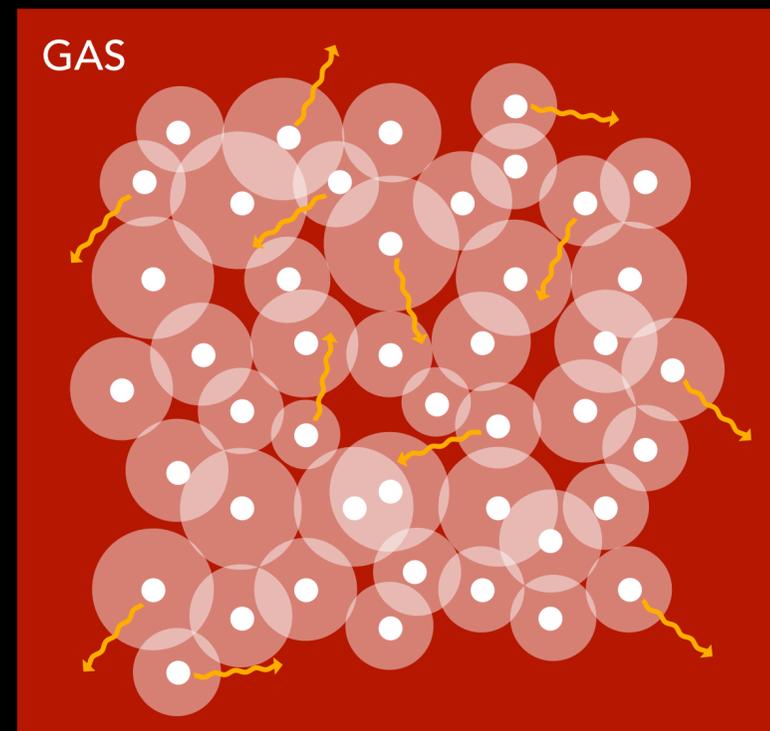
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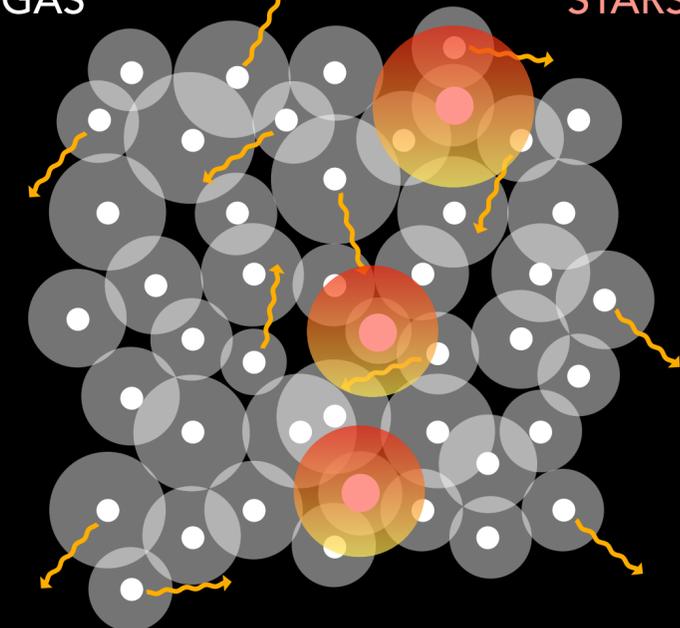


ADM



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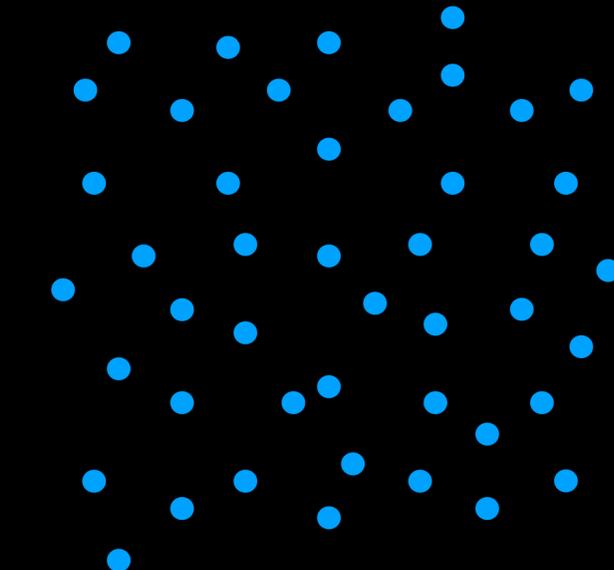
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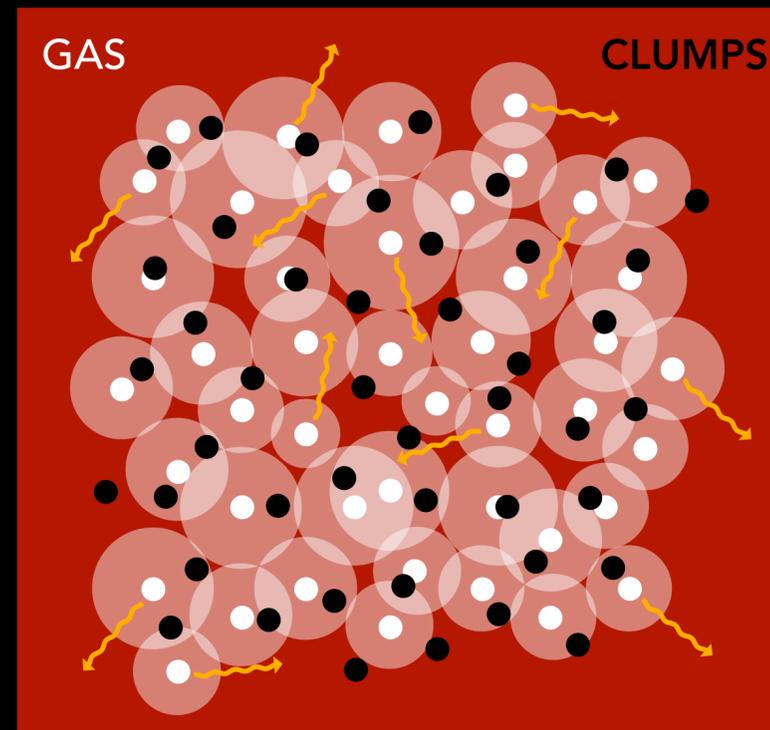
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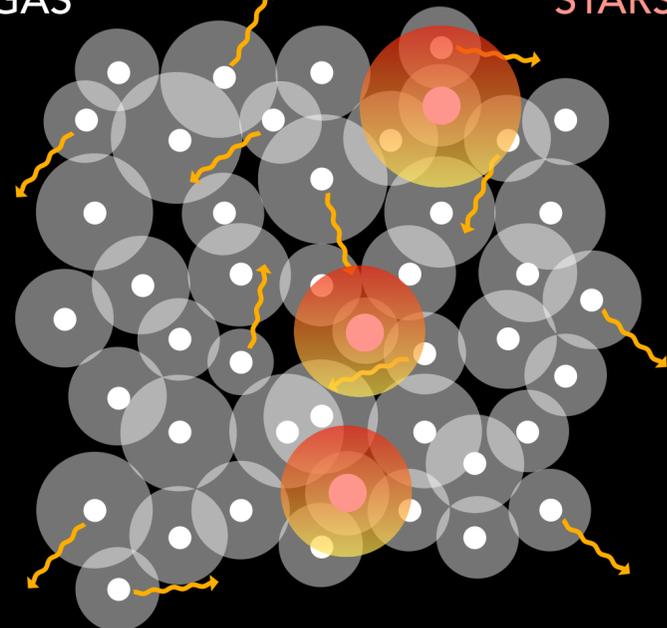


ADM



GAS

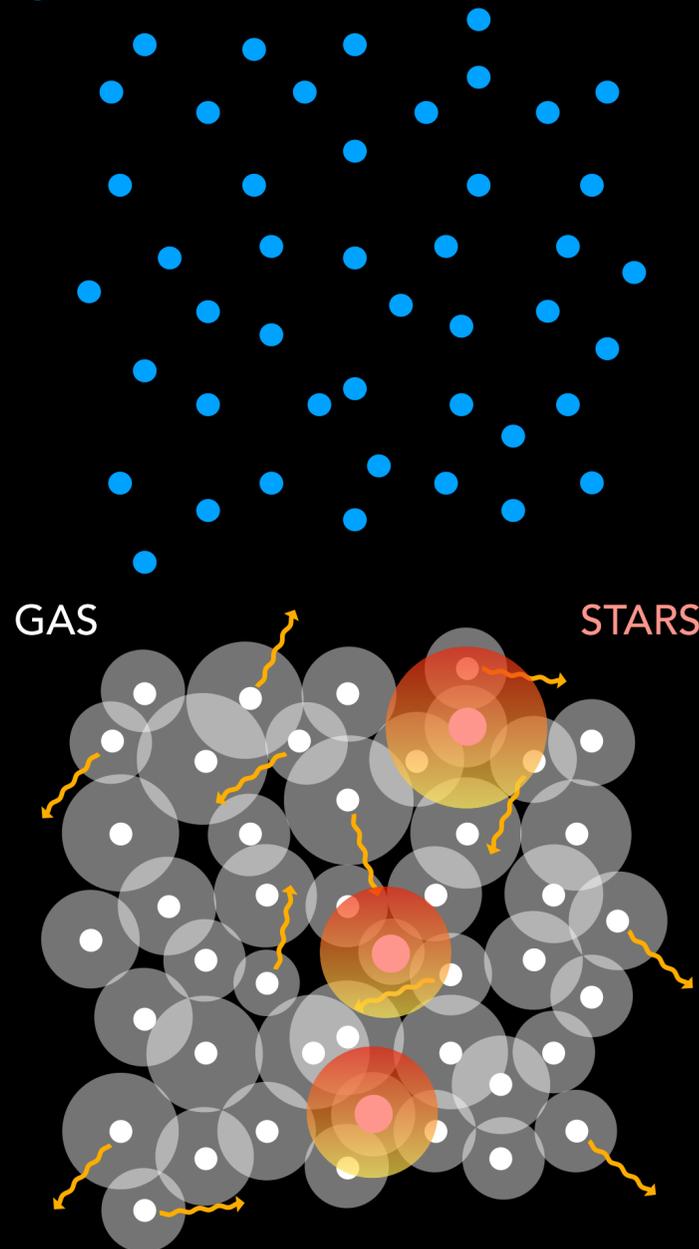
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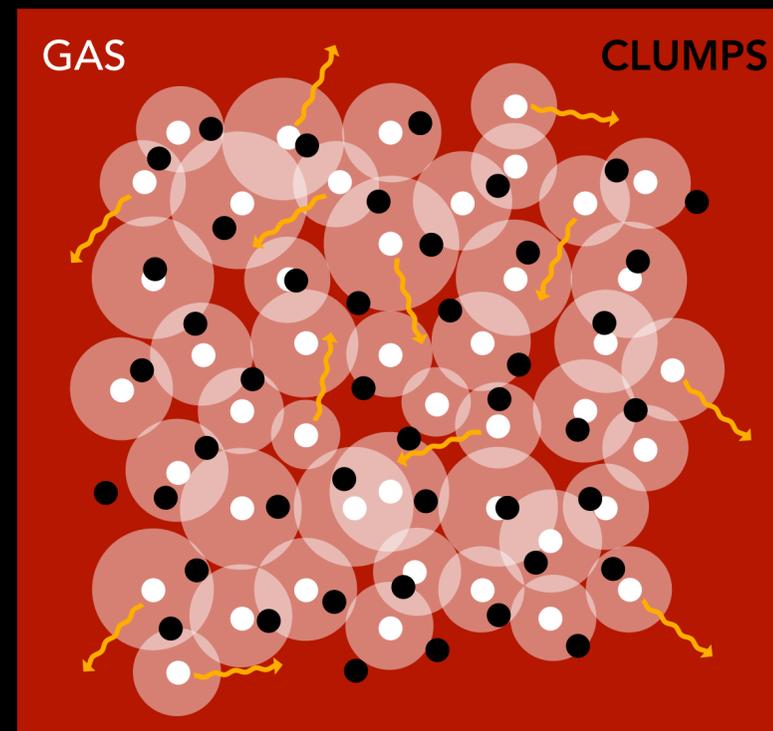
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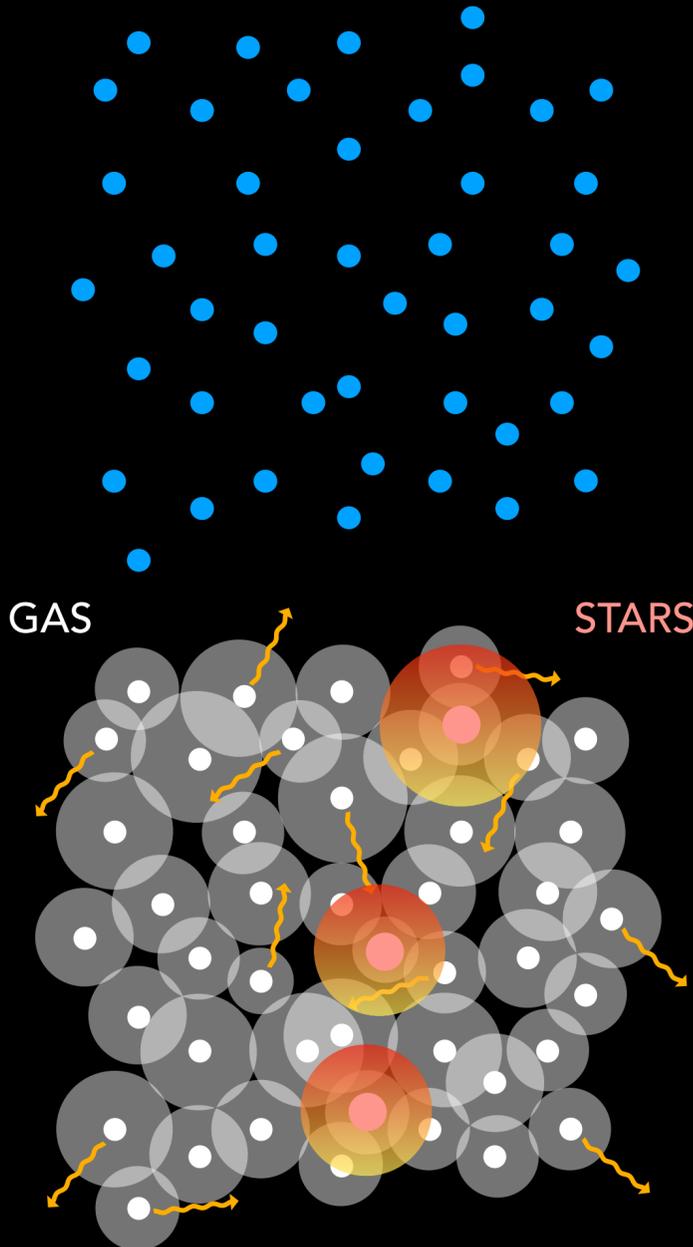
Physics

Particles

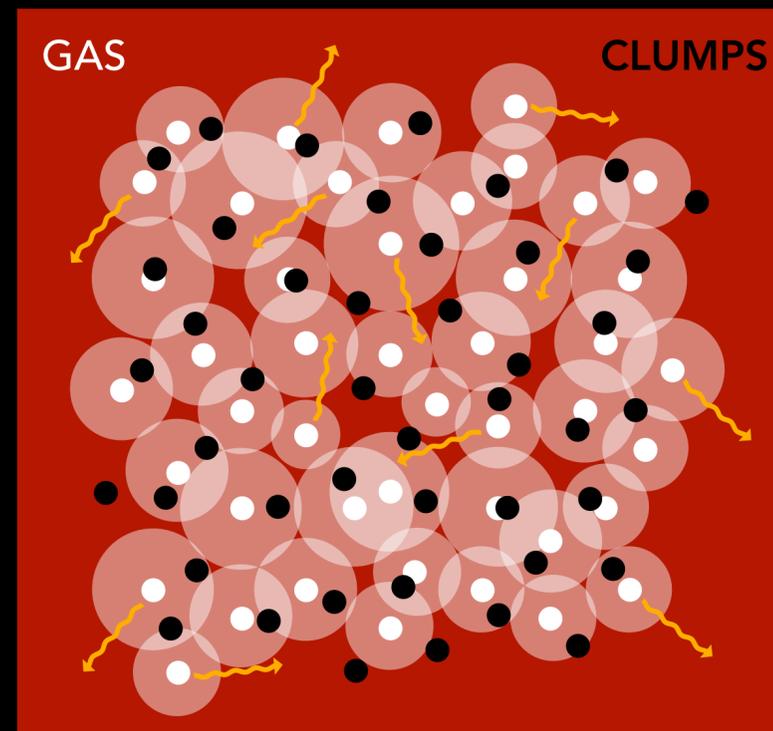
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ADM



Physics

Gravity

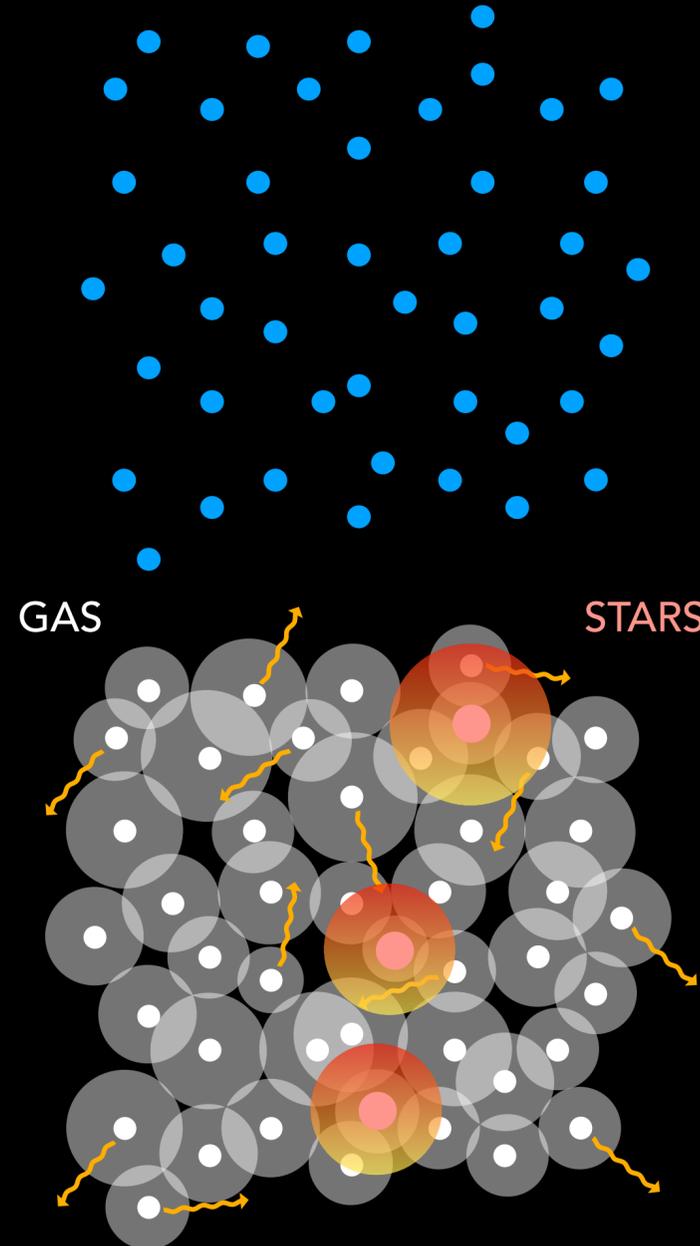
Particles

All

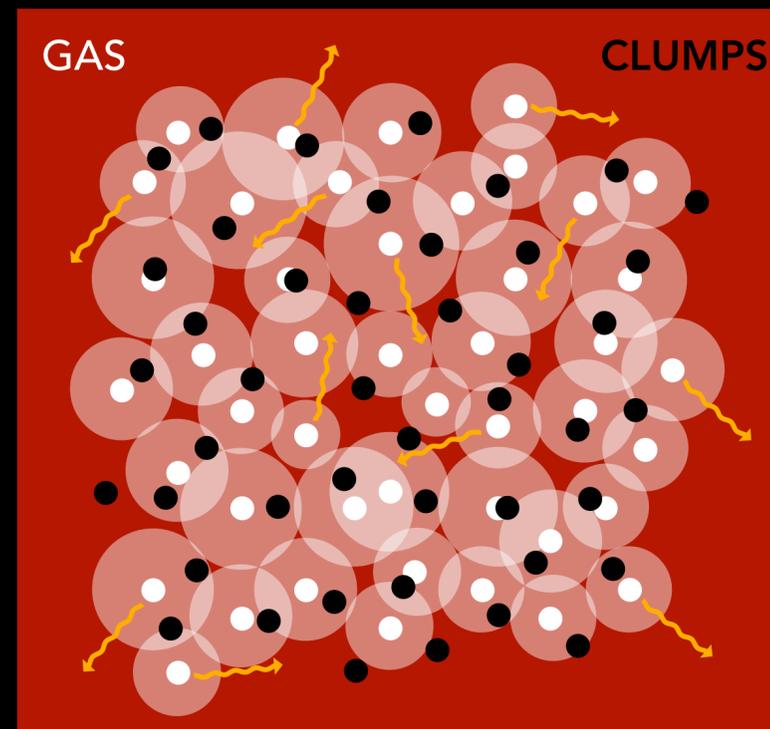
# ADM Implementation in GIZMO

## GIZMO: N-Body Hydrodynamics Code

CDM



ADM

Physics

Gravity

Cooling &amp; collapse

Particles

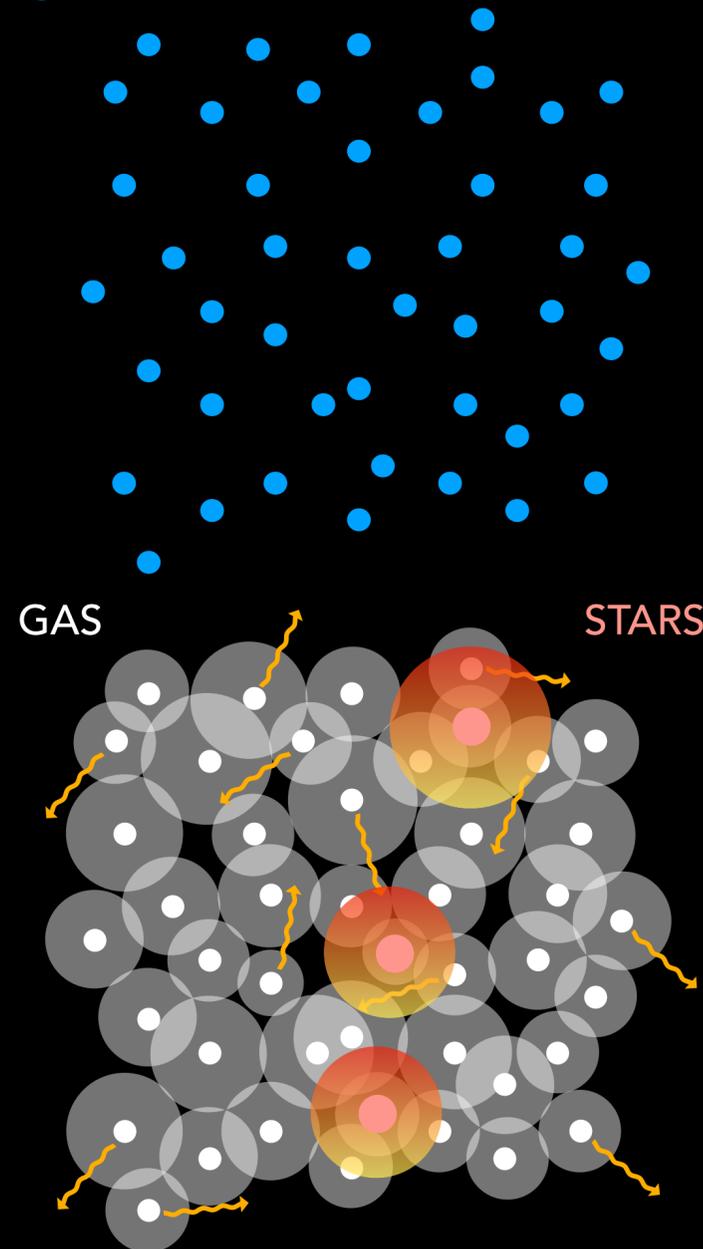
All

Baryonic &amp; ADM gas

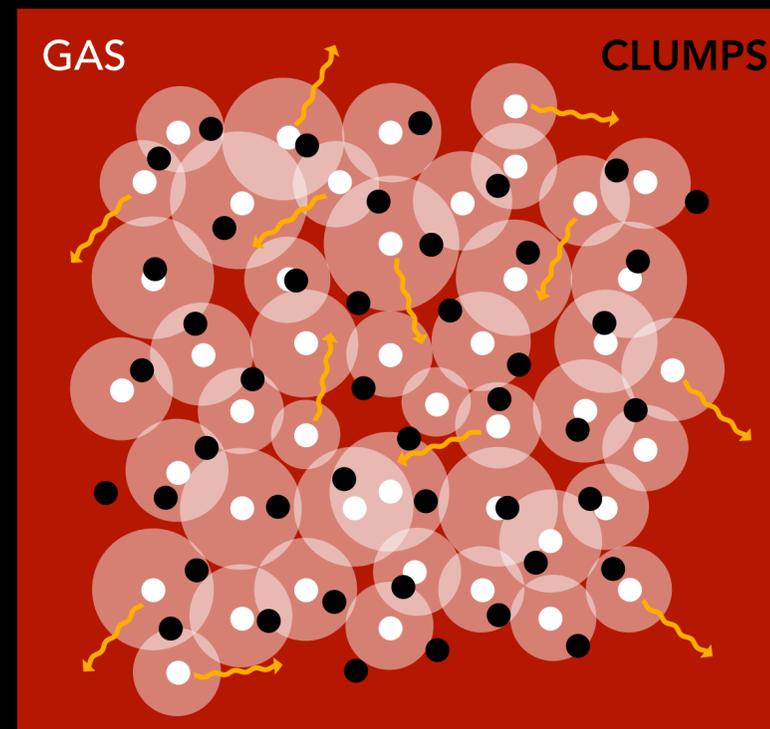
# ADM Implementation in GIZMO

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CDM



ADM



Physics

Gravity

Cooling &amp; collapse

Supernovae  
feedback

Particles

All

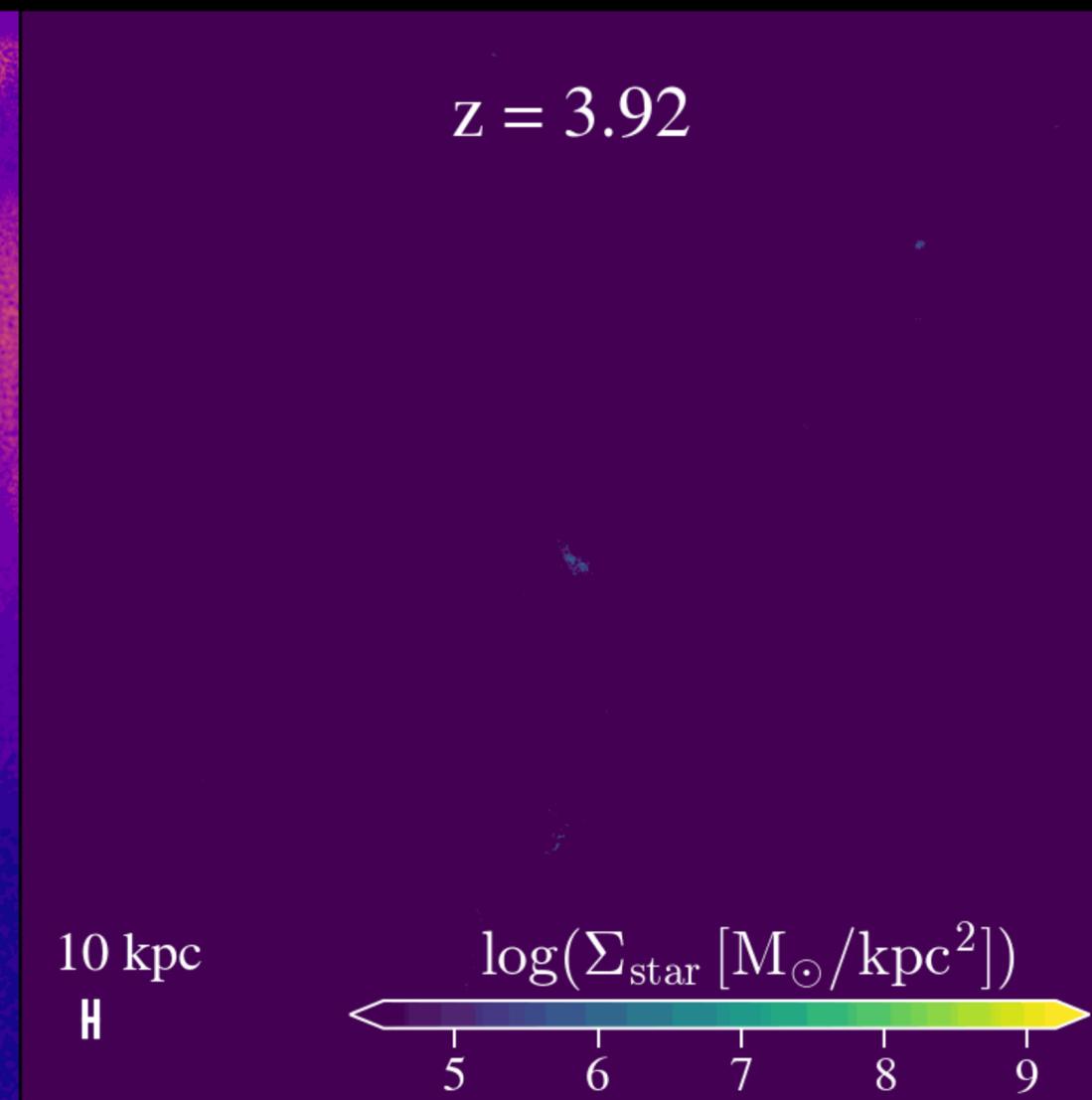
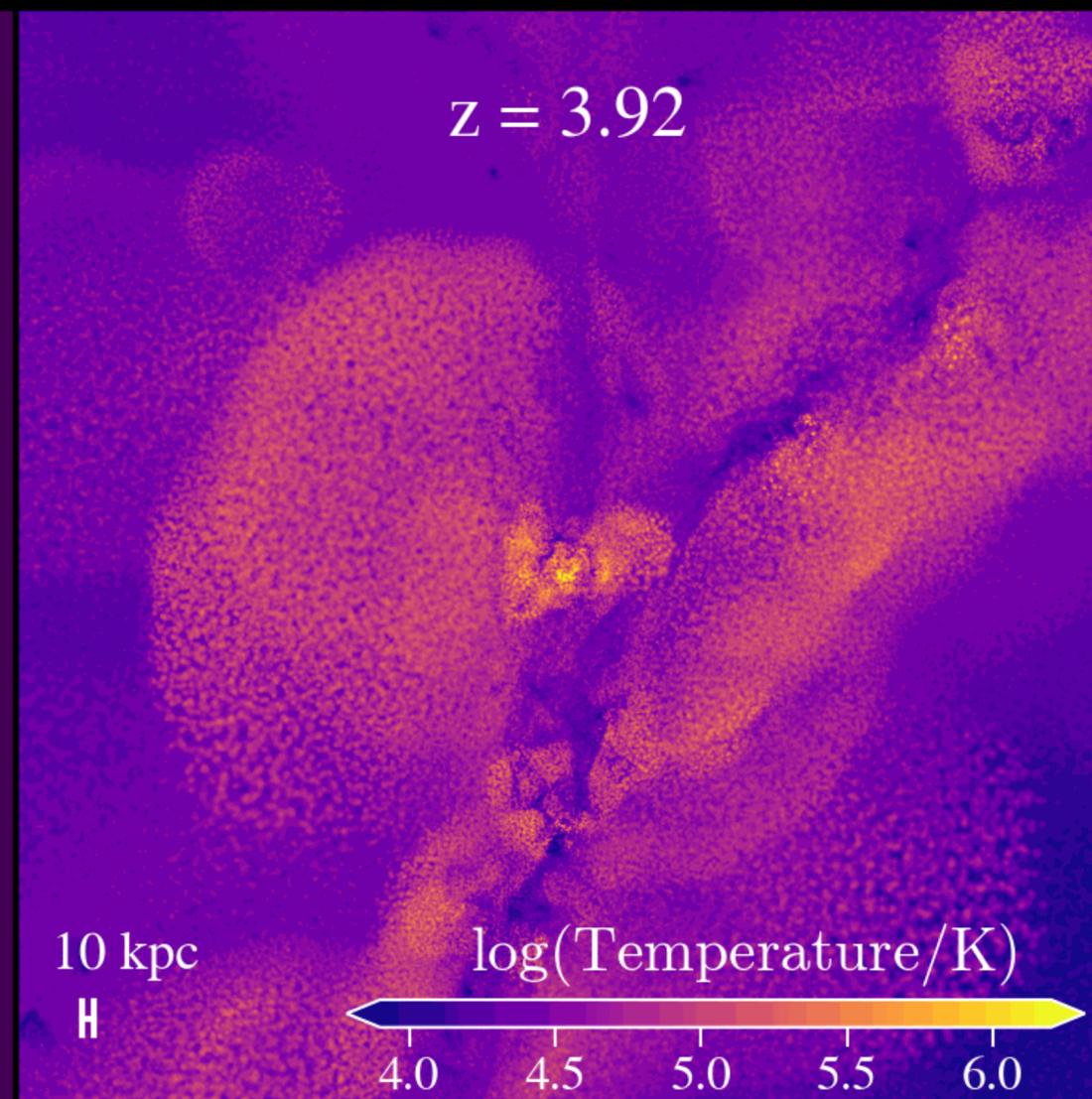
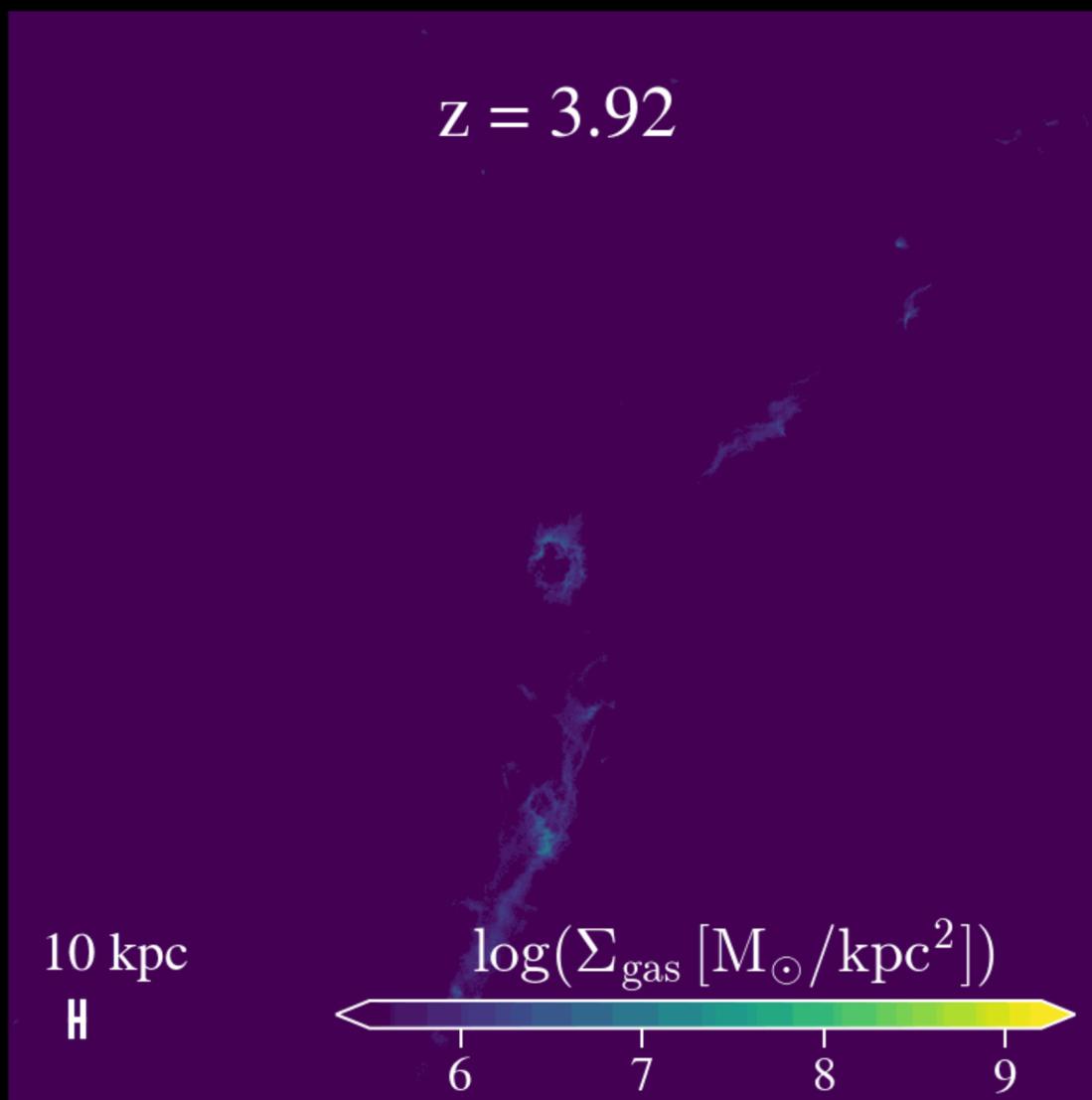
Baryonic &amp; ADM gas

Baryonic stars (&amp; gas)

# "Vanilla" Baryonic Physics

## Baryon Gas

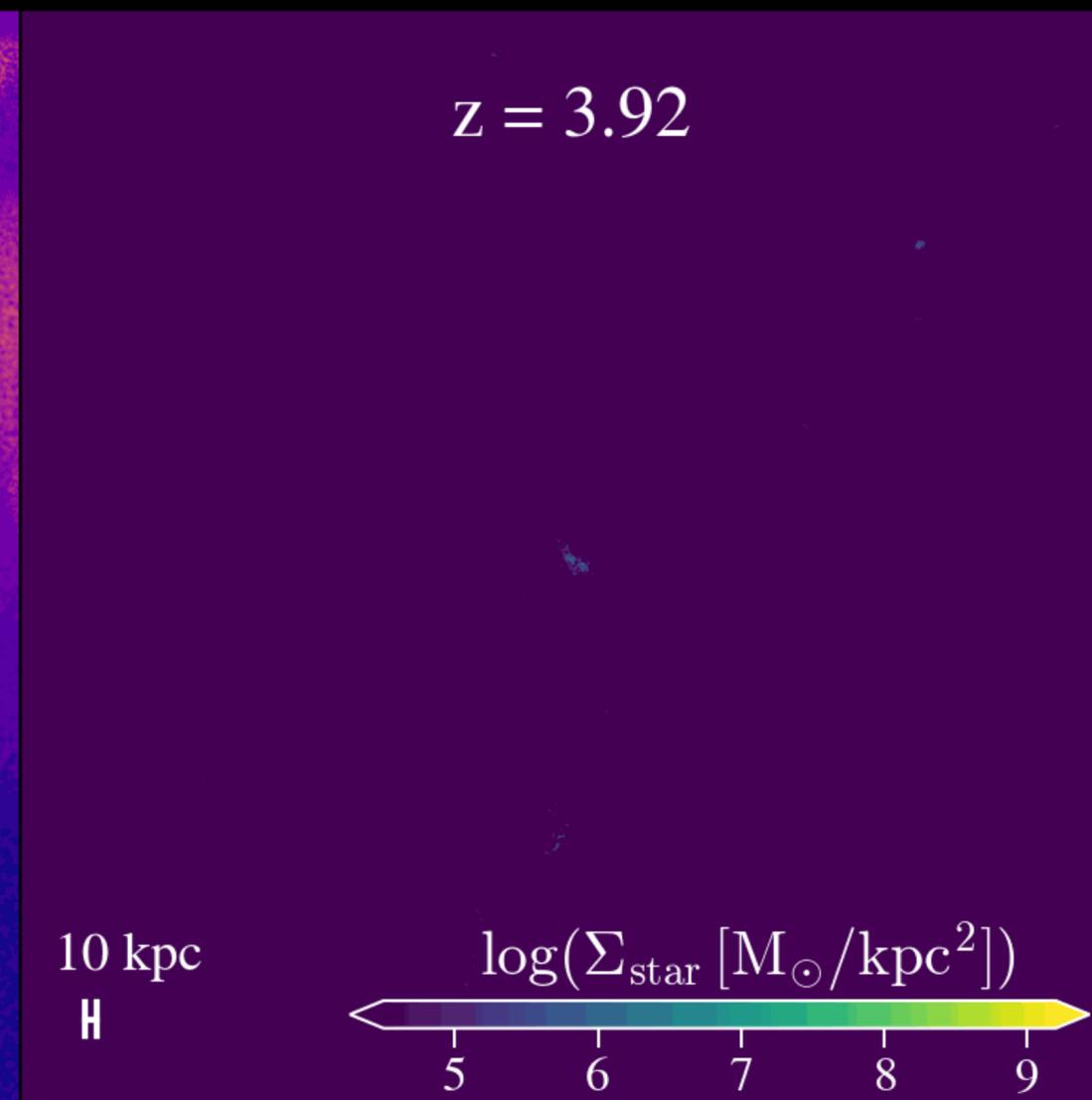
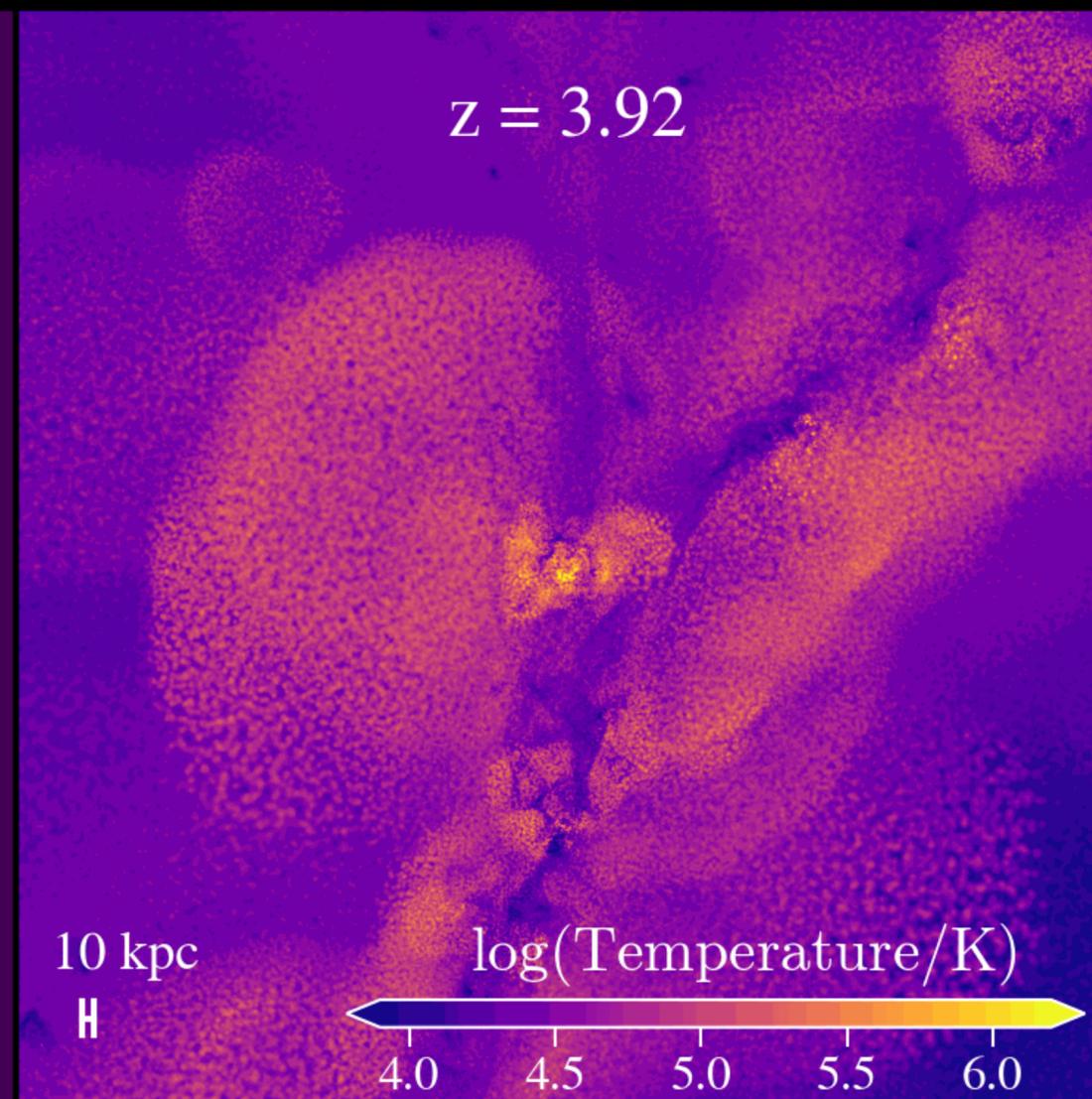
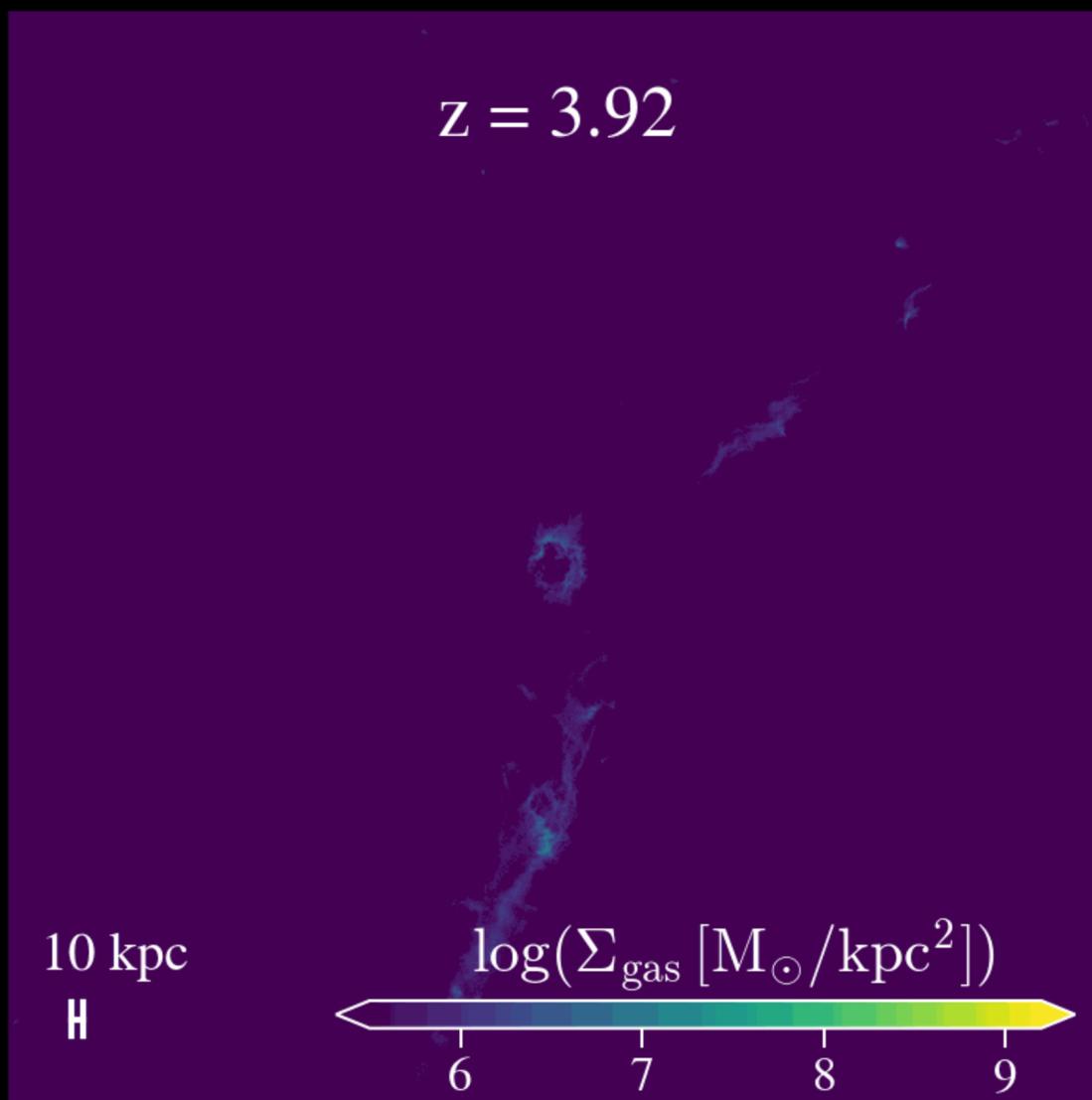
## Baryon Stars



# "Vanilla" Baryonic Physics

## Baryon Gas

## Baryon Stars



# Simulation Parameters

# Simulation Parameters

CDM

CDM-NF  
(No FB, no UV background)

ADM-1

ADM-2

# Simulation Parameters

CDM

CDM-NF

(No FB, no UV background)

ADM-1

ADM-2

$f'$

0

0

5%

5%

# Simulation Parameters

	CDM	CDM-NF (No FB, no UV background)	ADM-1	ADM-2
$f'$	0	0	5%	5%
$m_{e'}/m_e$			$\approx 0.5$	$\approx 0.5$

# Simulation Parameters

	CDM	CDM-NF (No FB, no UV background)	ADM-1	ADM-2
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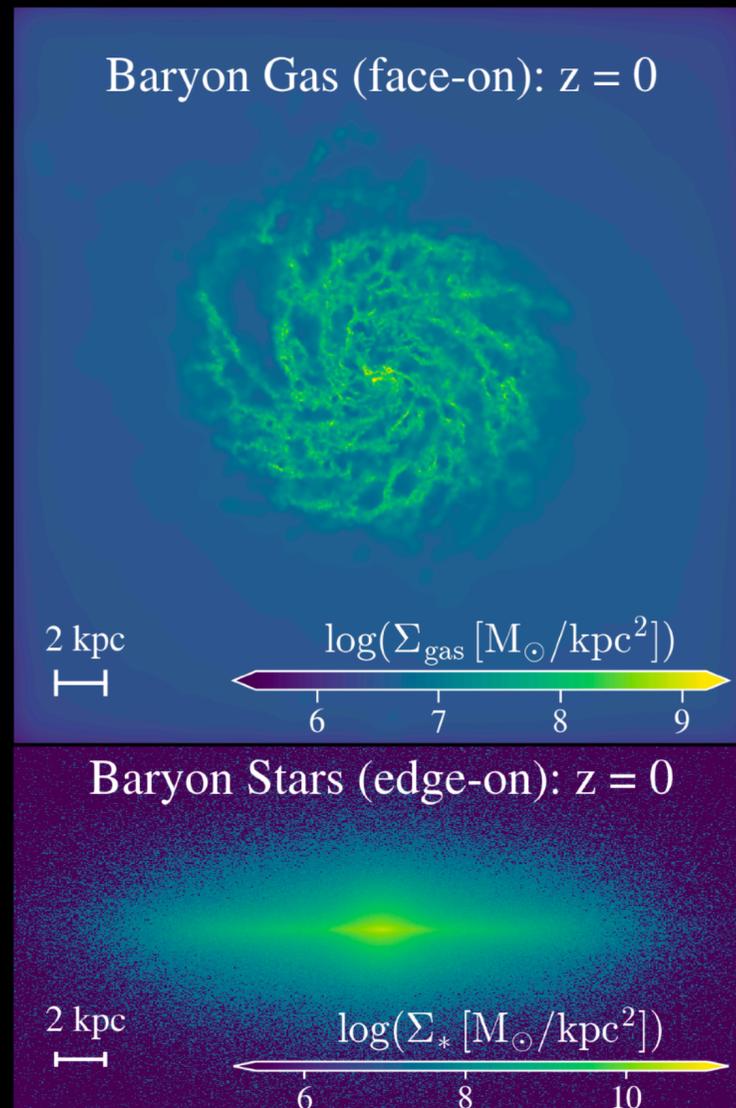
ADM gas in ADM-2 cools faster than in ADM-1

# Final Results

# Gas and Stellar/Clump Morphology

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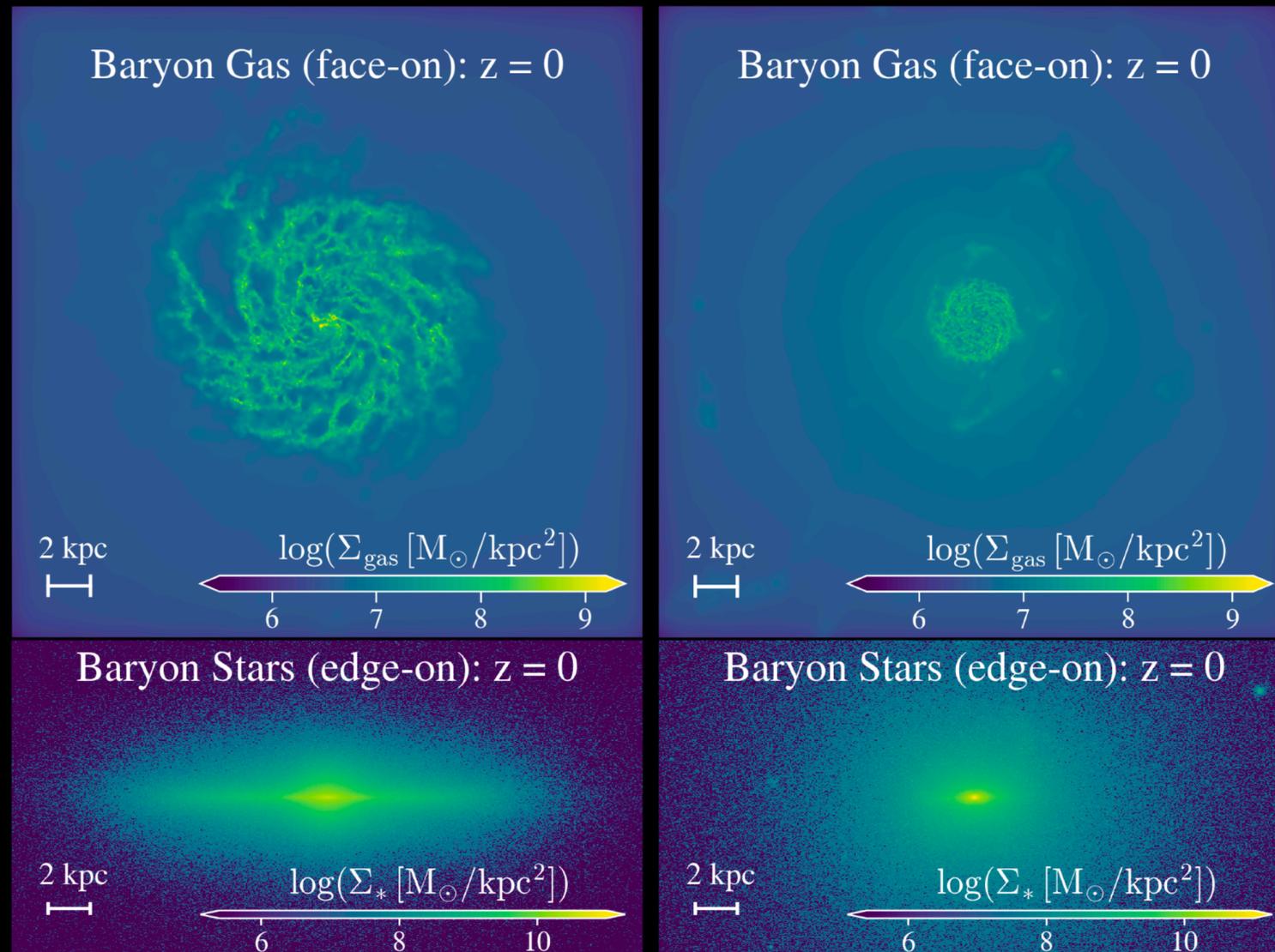
CDM



# Gas and Stellar/Clump Morphology

CDM

CDM-NF

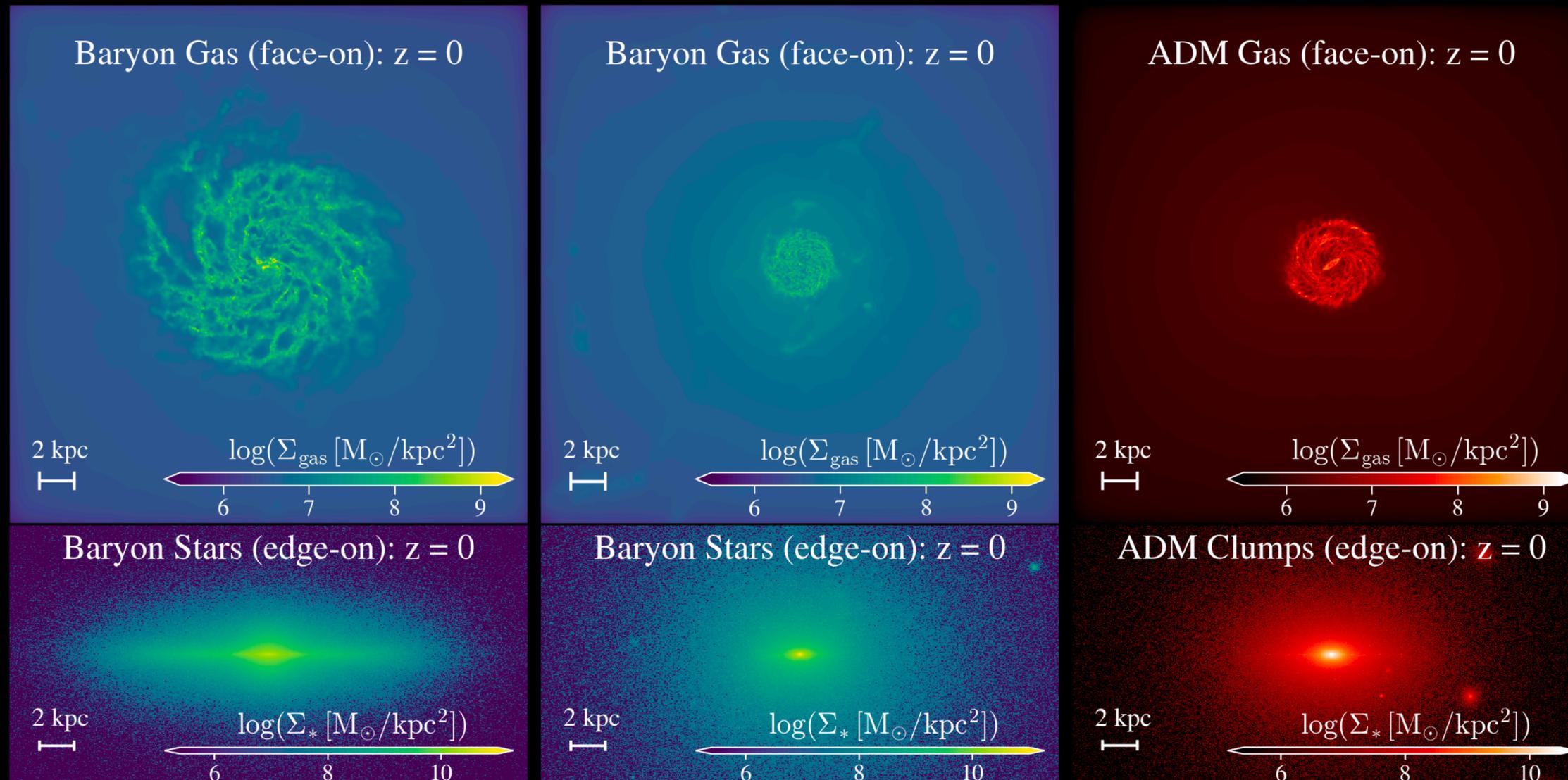


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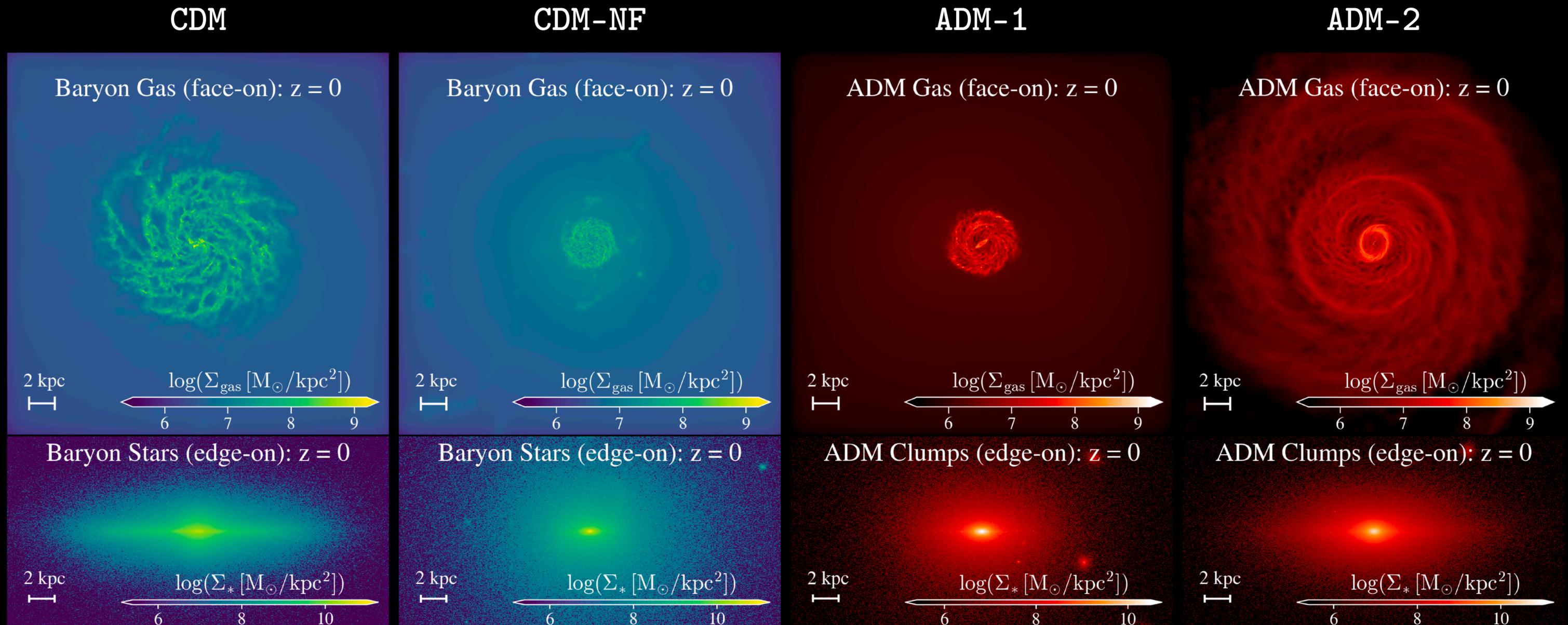
CDM

CDM-NF

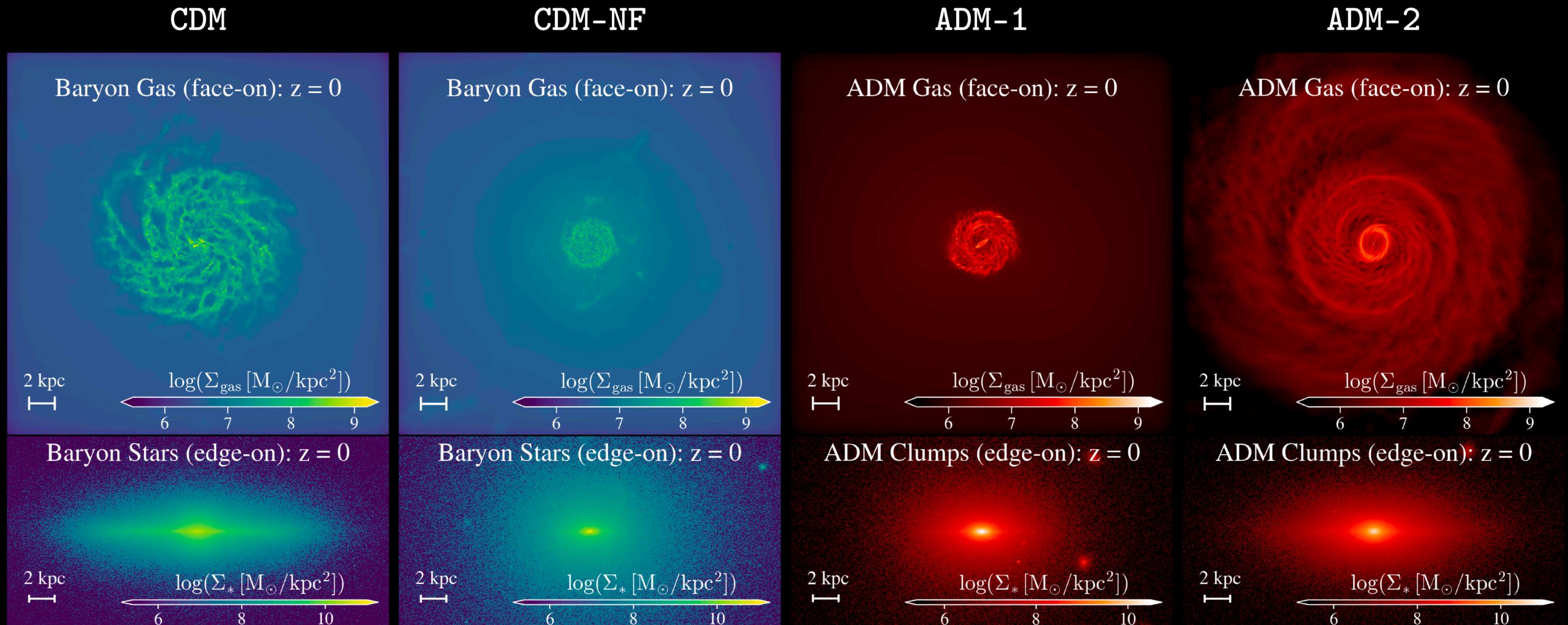
ADM-1



# Gas and Stellar/Clump Morphology



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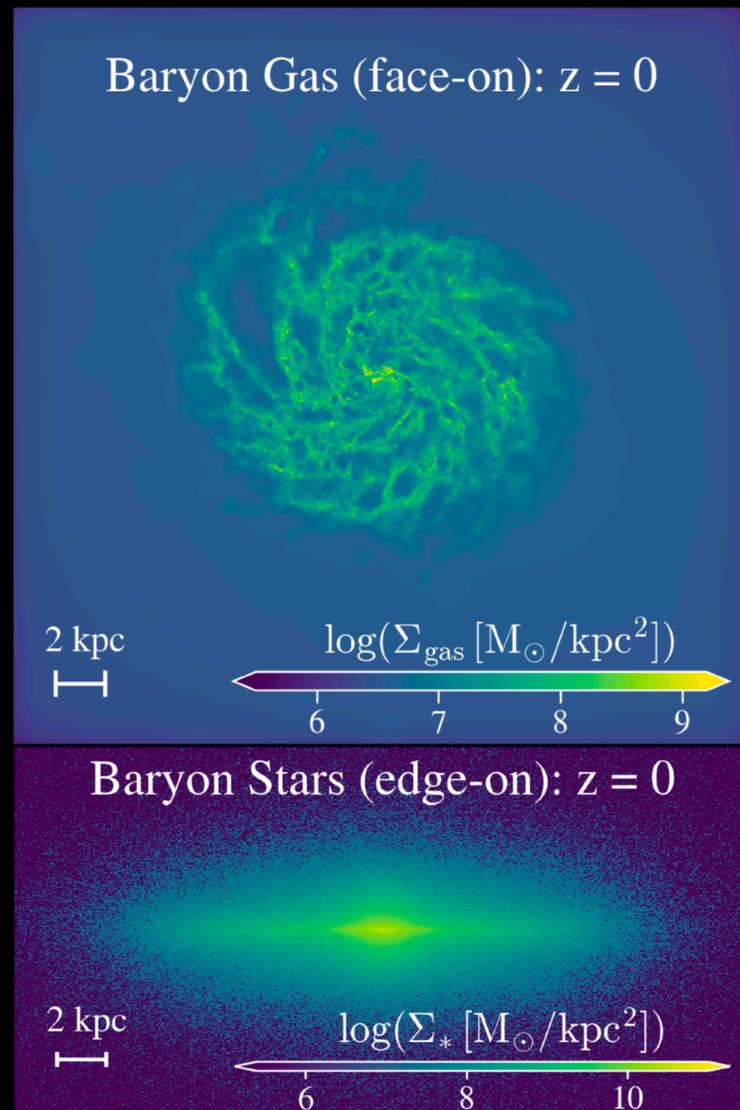


Lacking feedback: Early gas collapse, forms prominent thick disk and bulge

# ADM Backreaction on Baryons

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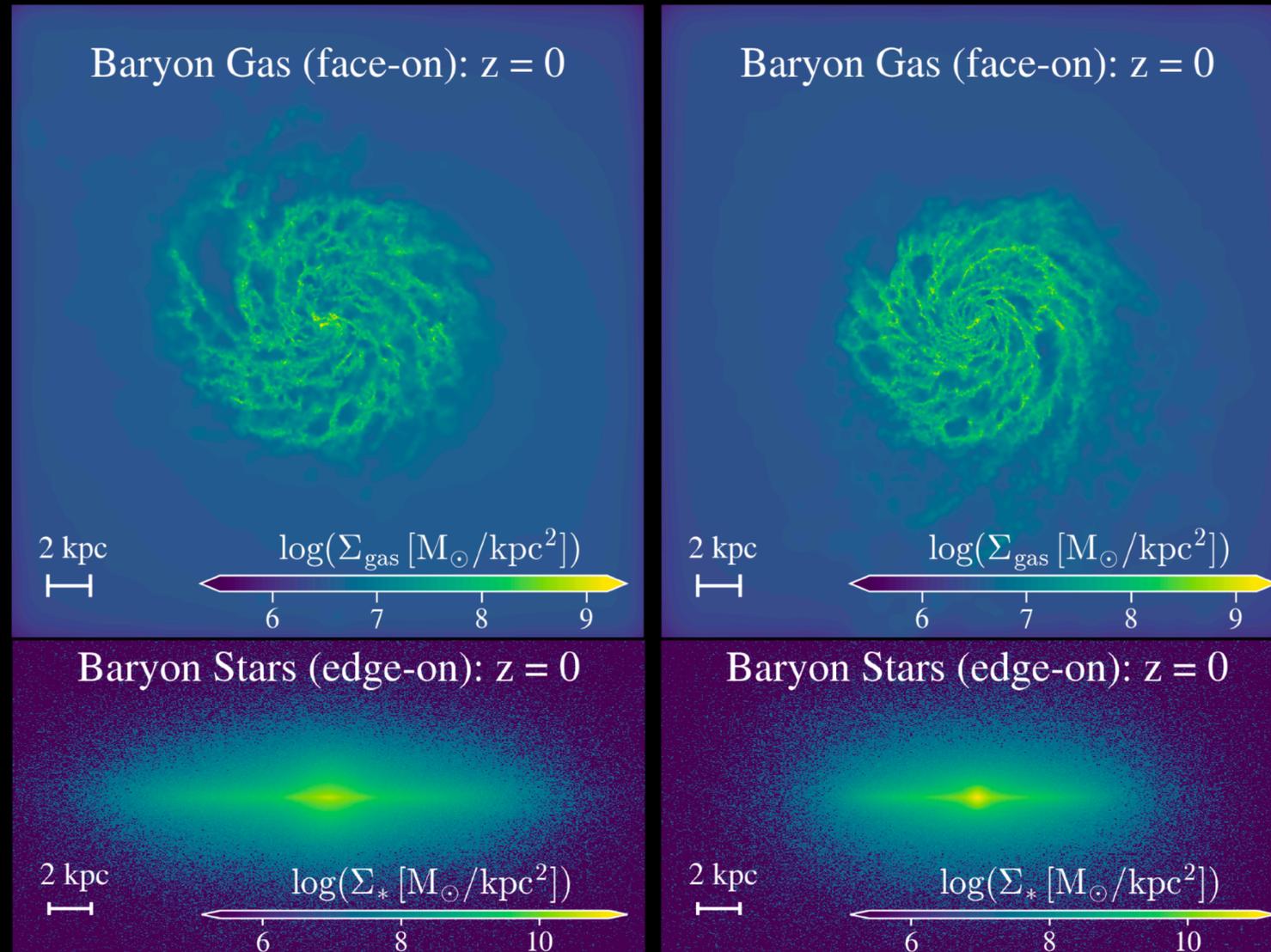
CDM



# ADM Backreaction on Baryons

CDM

ADM-1

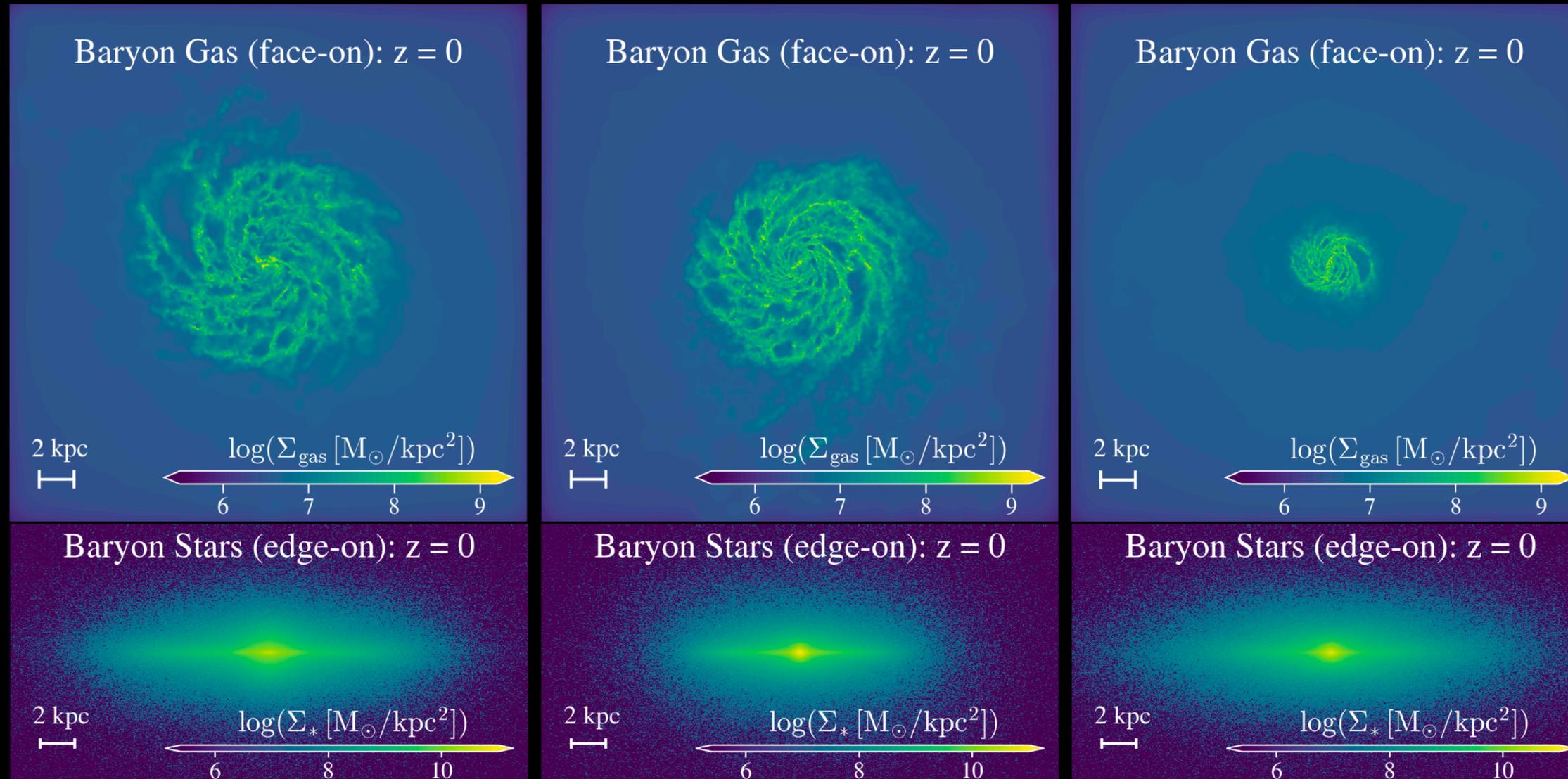


# ADM Backreaction on Baryons

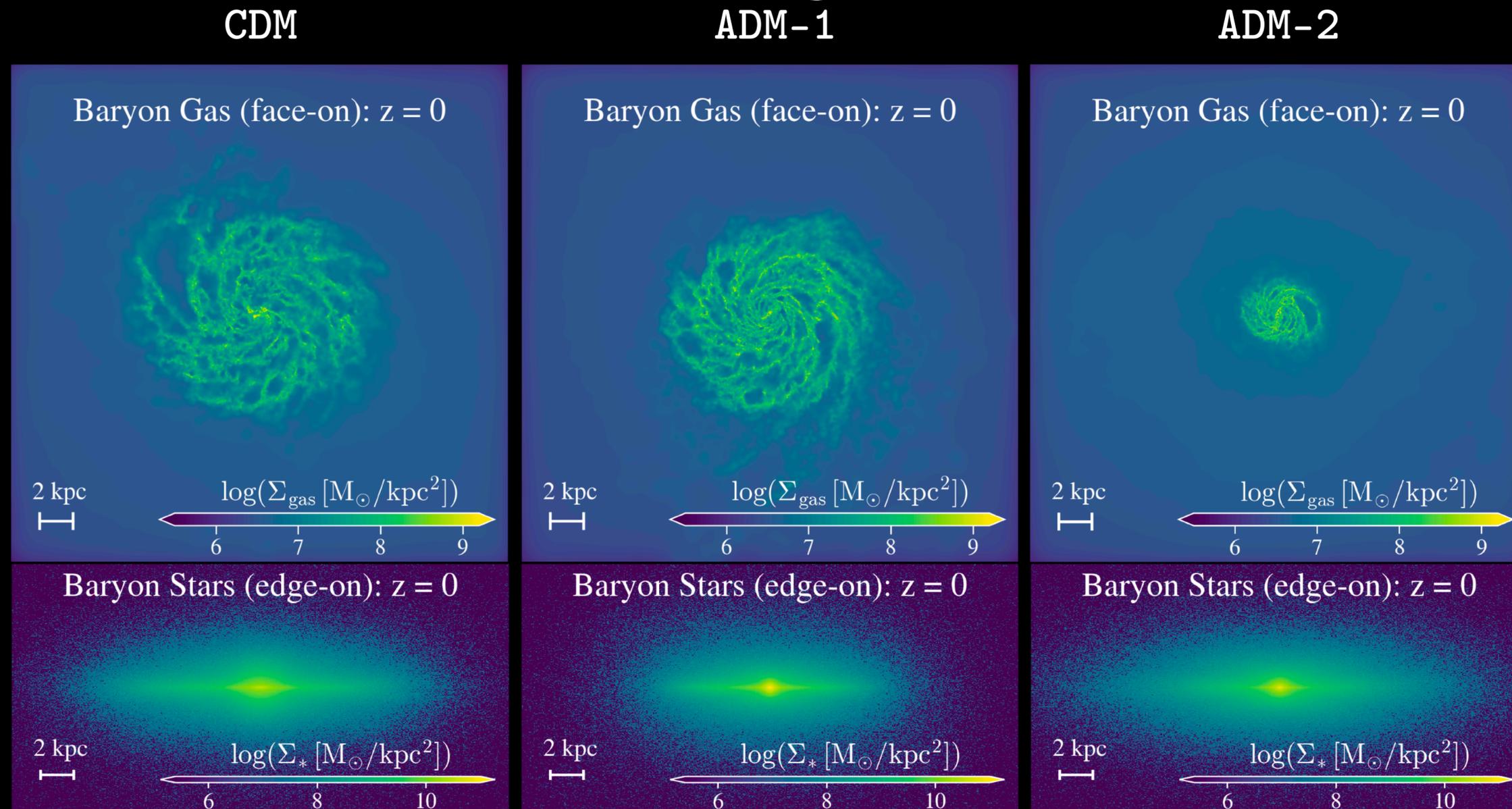
CDM

ADM-1

ADM-2

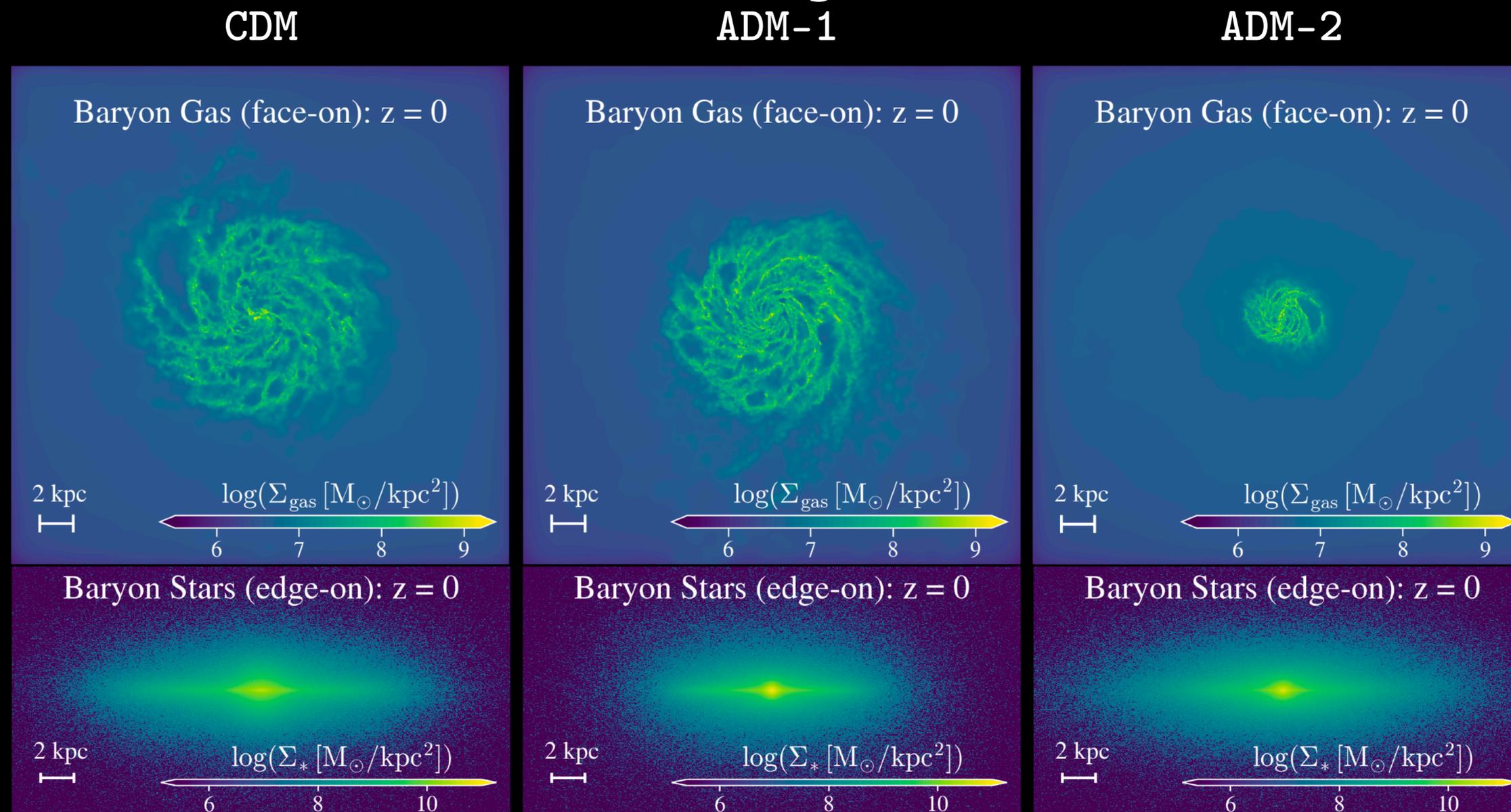


# ADM Backreaction on Baryons



ADM concentrates centrally, enhances central density of baryons & CDM

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ADM in ADM-2 destroys the baryonic gas! (probably ruled out)

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What about the outer substructure of the galaxy? **See Caleb's talk next!**

# Supplementary Slides

# What We Did

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Modified cosmological hydrodynamics code to simulate it! Can simulate CDM, ADM & baryons together.

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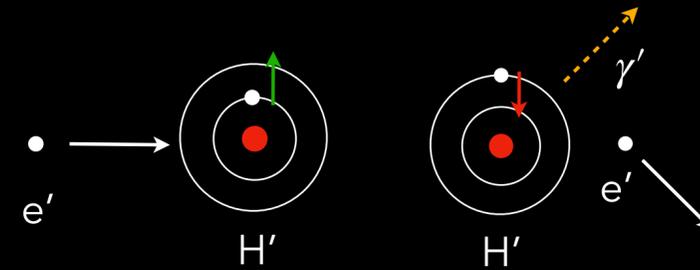
Ran simulations of Milky Way-mass galaxies with ADM.

**Found that even ~5% ADM can have significant effects on galactic scales!**

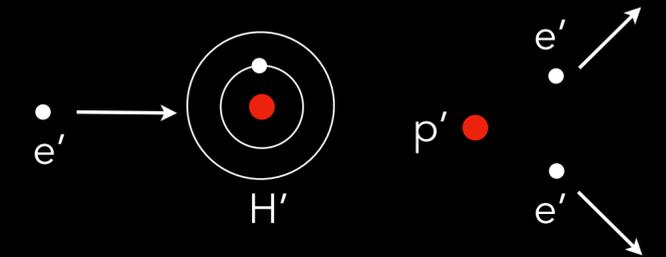
# ADM Cooling Processes

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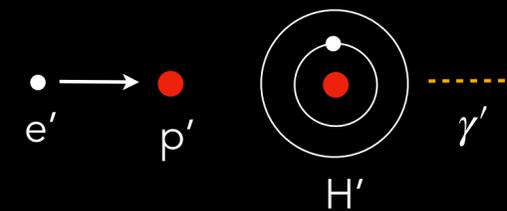
## Collisional Excitation



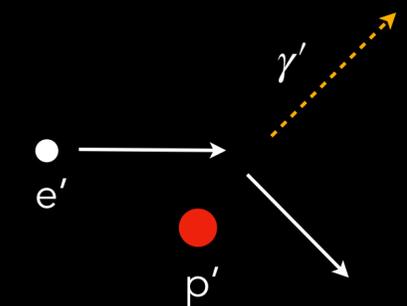
## Collisional Ionisation



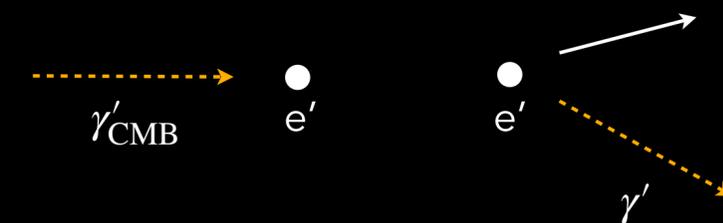
## Recombination



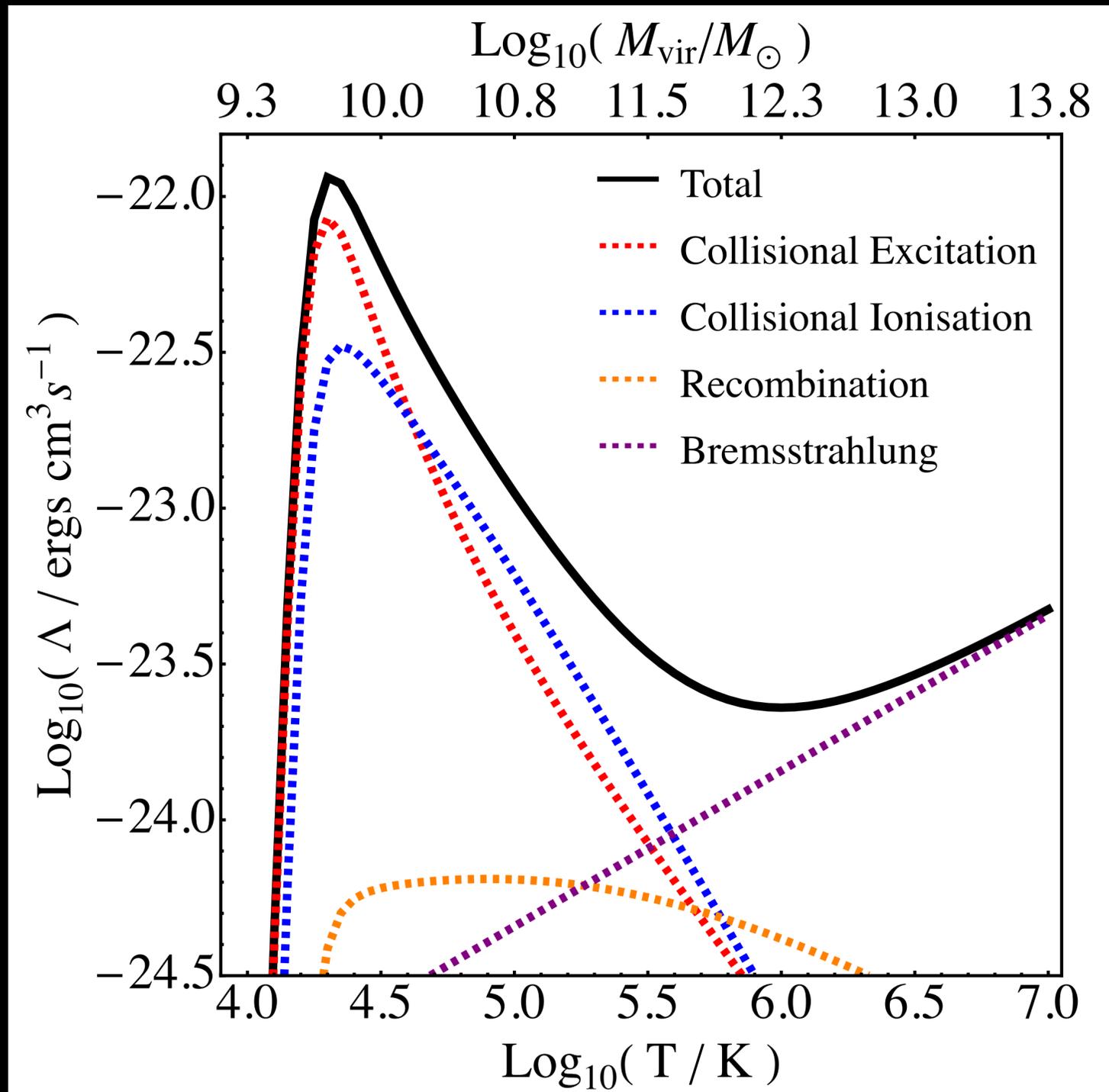
## Bremsstrahlung



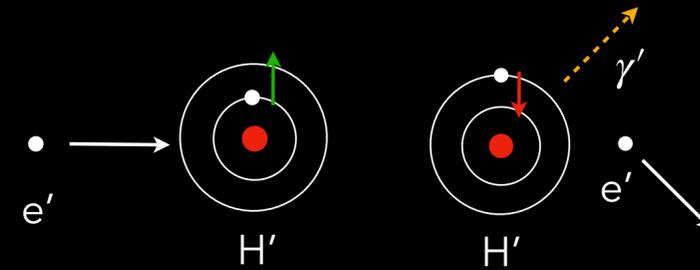
## CMB Compton



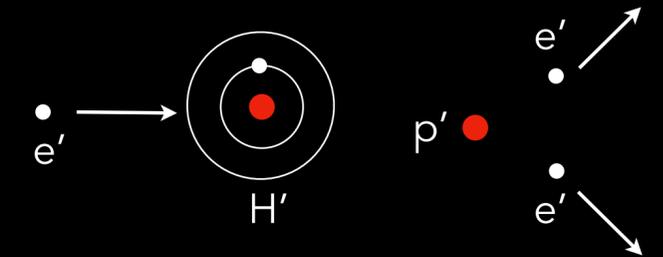
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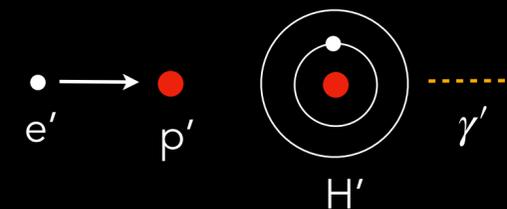
## Collisional Excitation



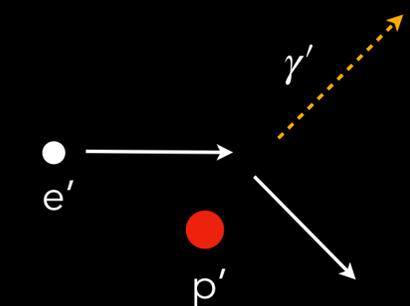
## Collisional Ionisation



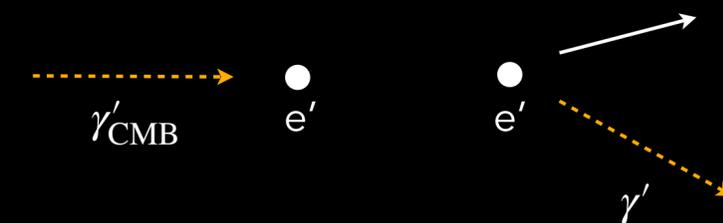
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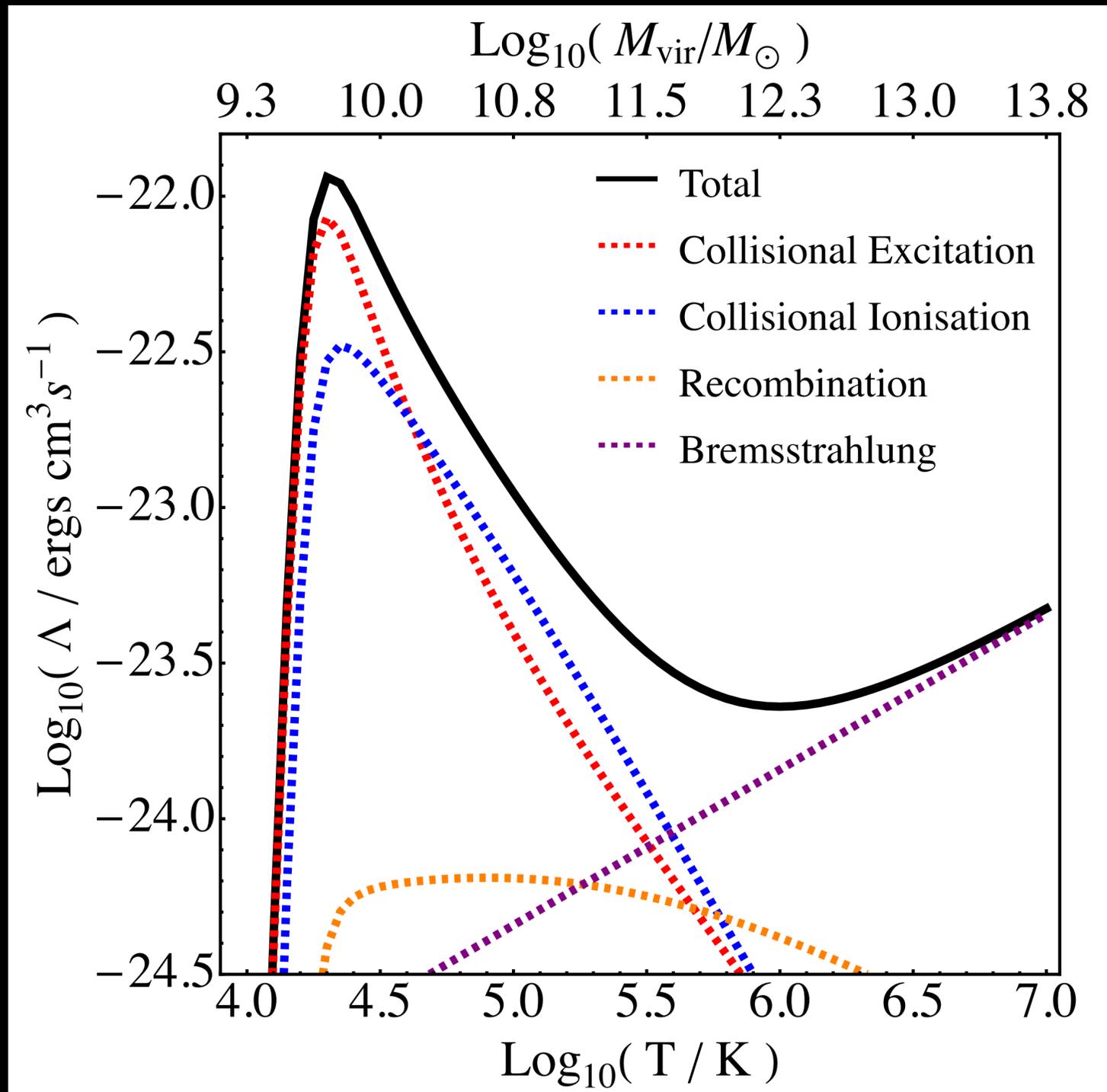
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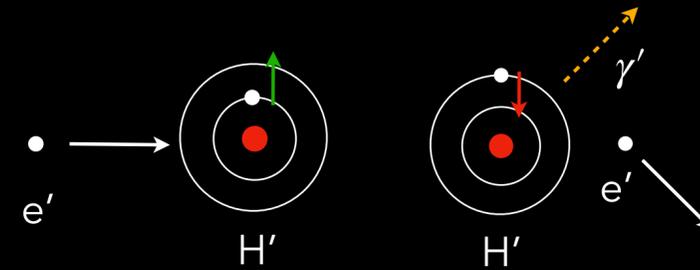
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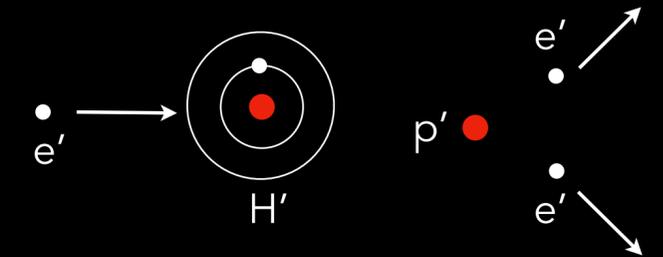
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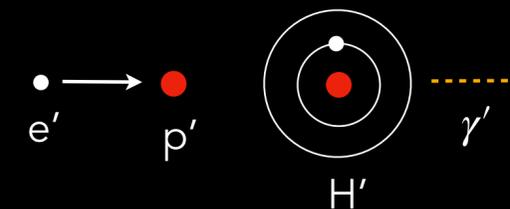
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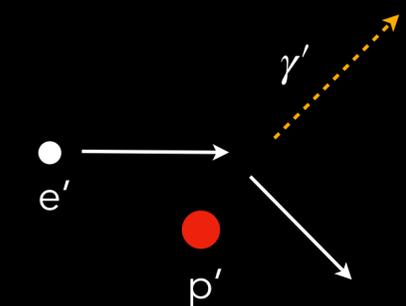
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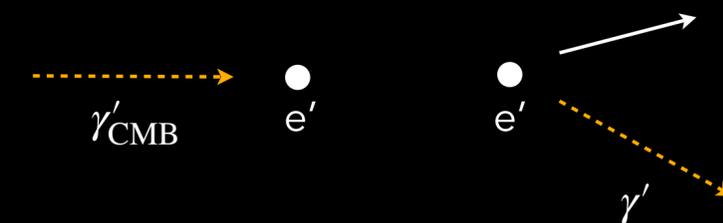
## Recombination



## Bremsstrahlung



## CMB Compton



$$T_{\text{cut-off}} \propto B' \propto m_{e'} (\alpha')^2$$

# Initial Conditions/Cosmology

## Modified Einstein-Boltzmann Solver (CLASS)

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Dark recombination

+

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

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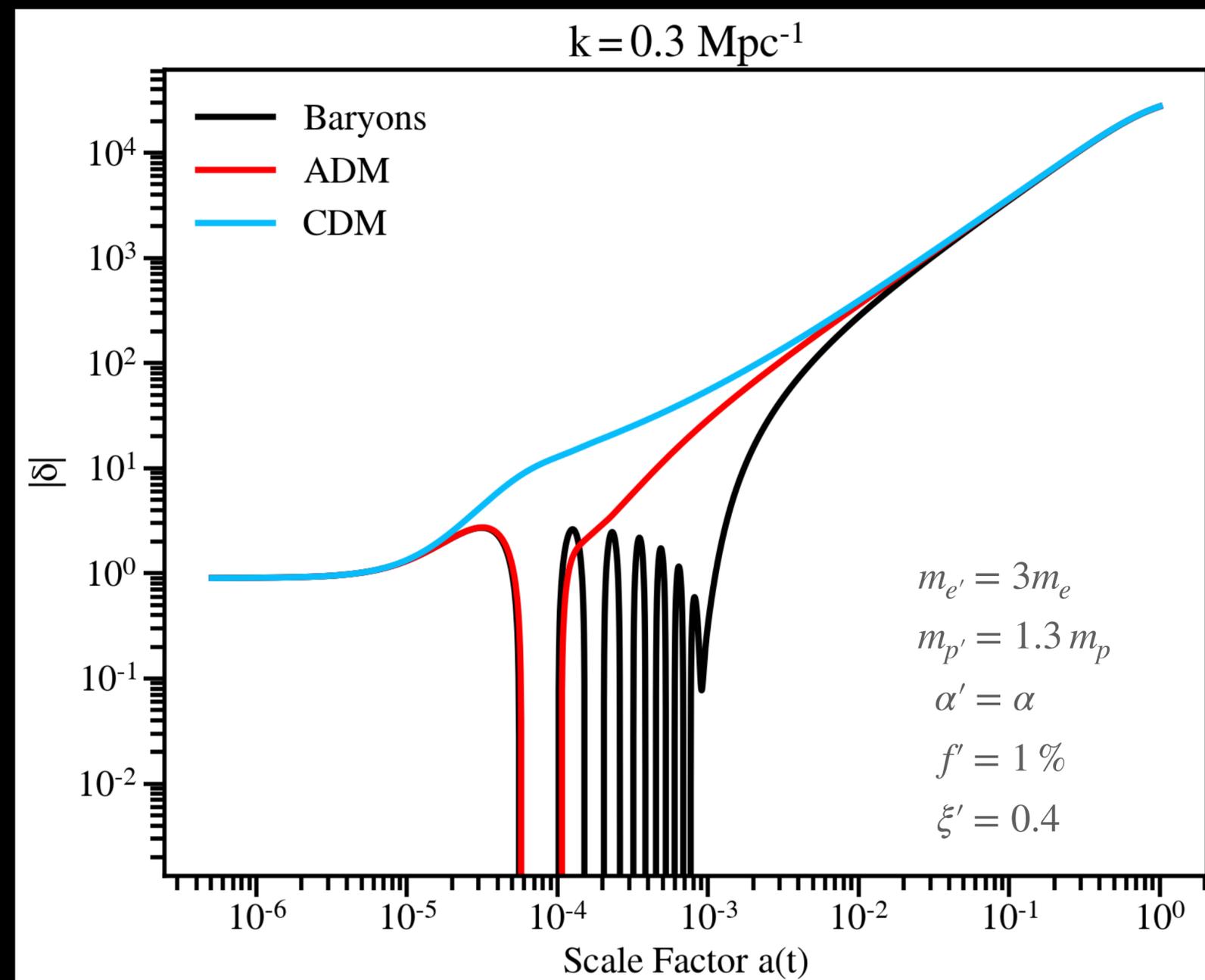
$$\delta G_{\mu\nu} = 8\pi G \left( \delta T^{\mu\nu} + \delta T_{\text{ADM}}^{\mu\nu} \right)$$



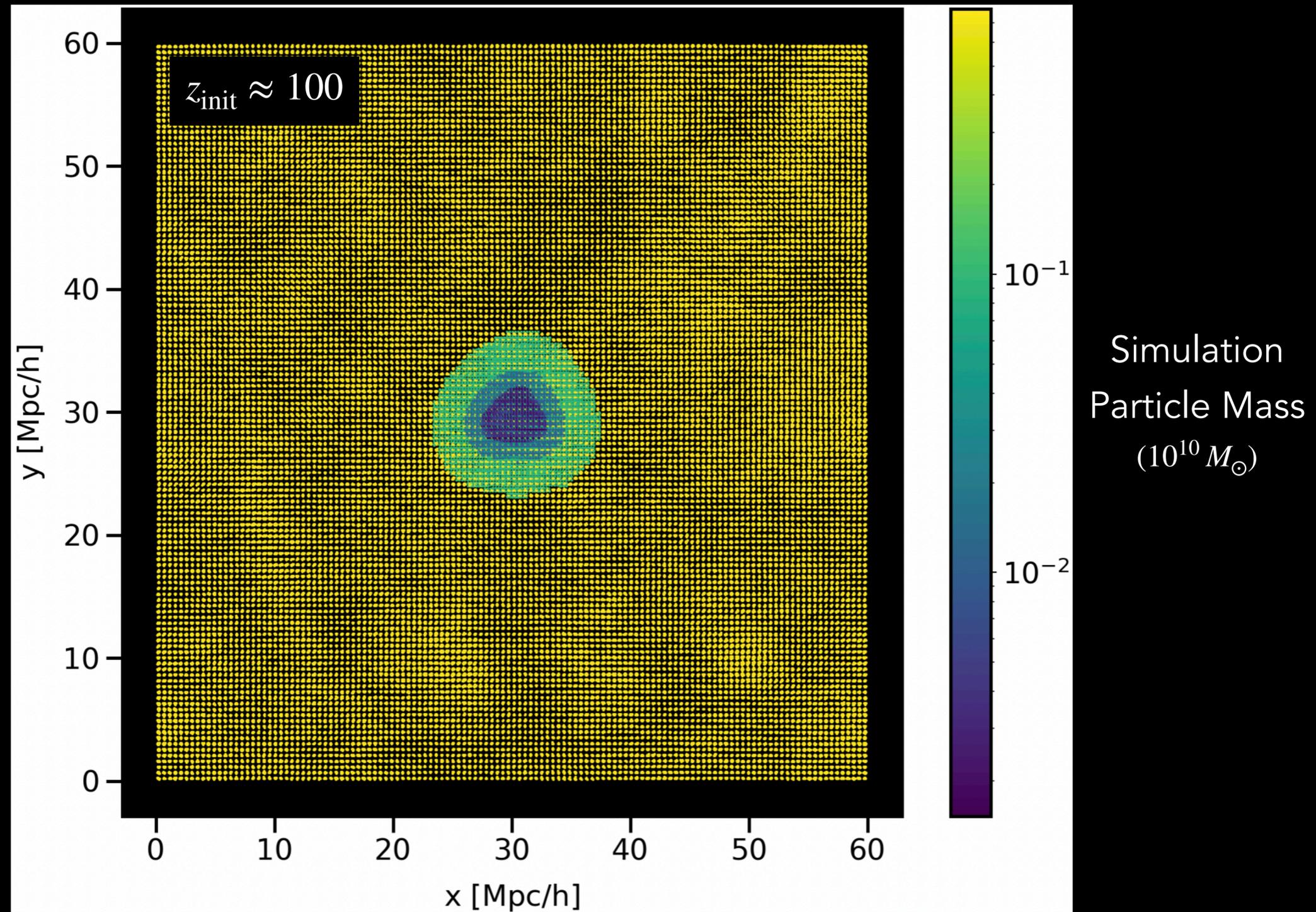
Input

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

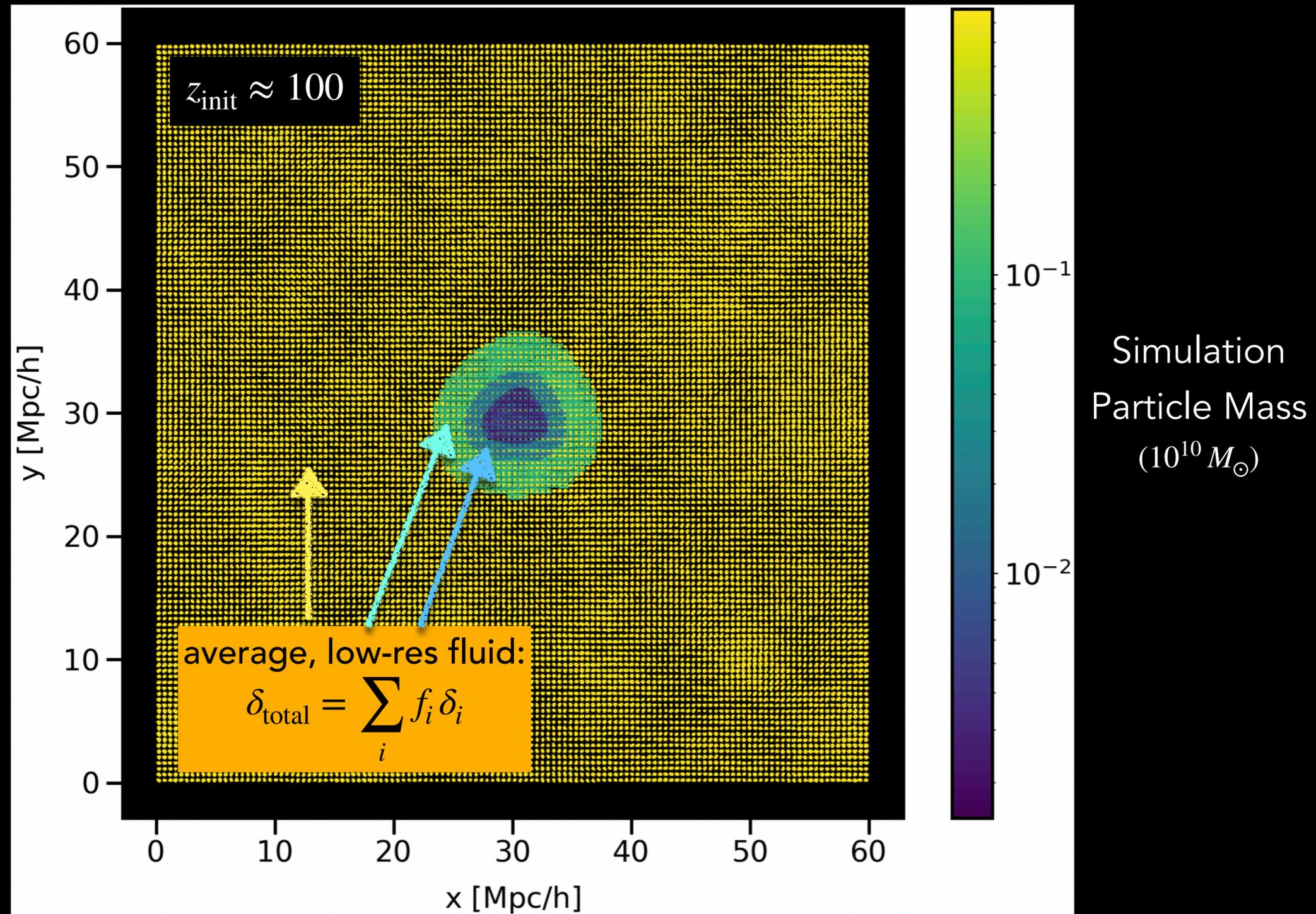
Based on Barron et al. (2212.02487) , Bansal et al. (2110.04317) & Cyr-Racine et al. (1209.5752)



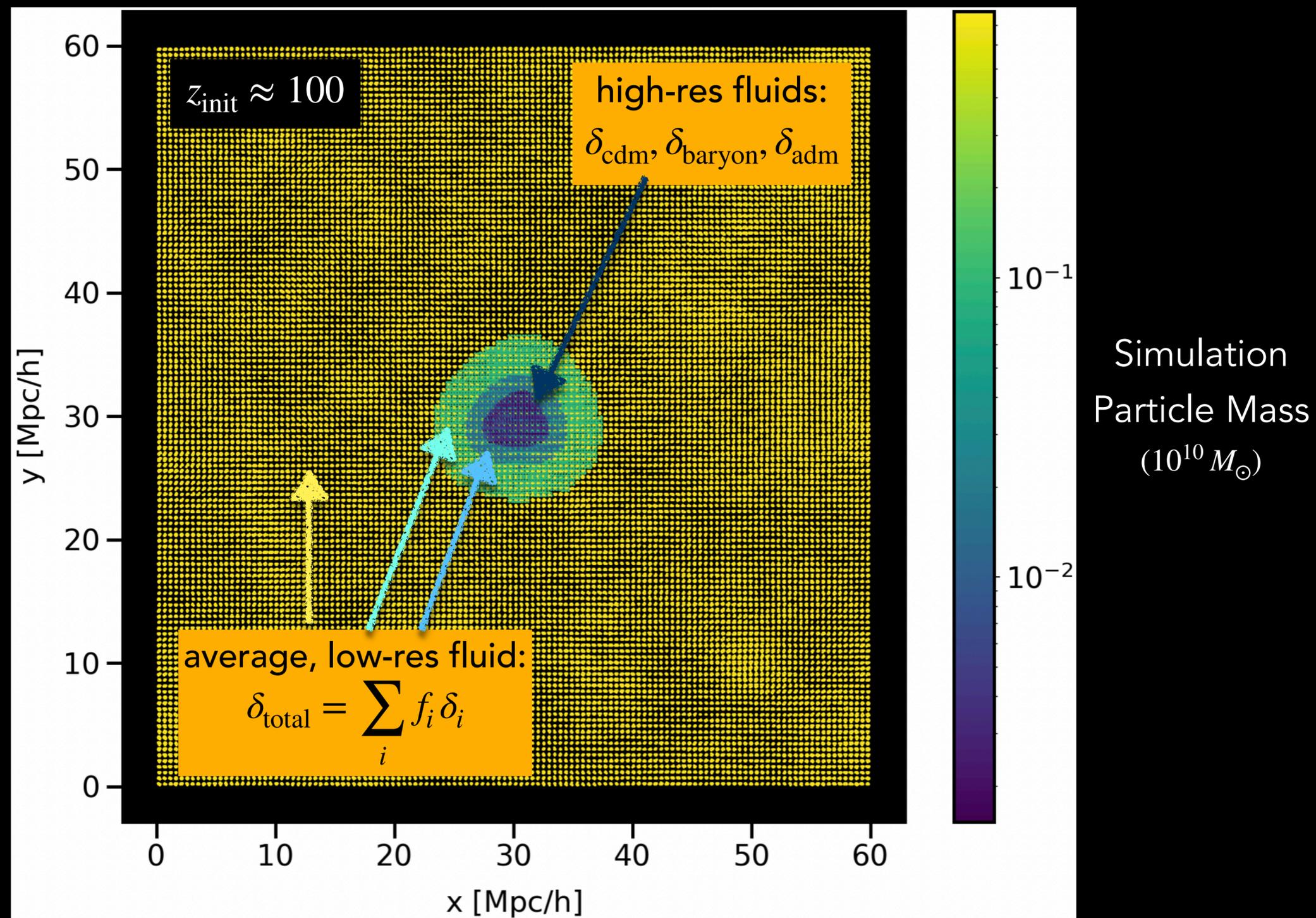
# Zoom-In Simulations



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# Simulation Parameters

CDM

CDM-NF  
(No FB, no UV background)

ADM-1

ADM-2

# Simulation Parameters

	CDM	CDM-NF (No FB, no UV background)	ADM-1	ADM-2
$m_b/M_\odot$	$5.6 \cdot 10^4$	$5.6 \cdot 10^4$	$5.6 \cdot 10^4$	$5.6 \cdot 10^4$

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$m_{e'}/m_e$			0.55	0.55
$m_{p'}/m_p$			1.3	1.3

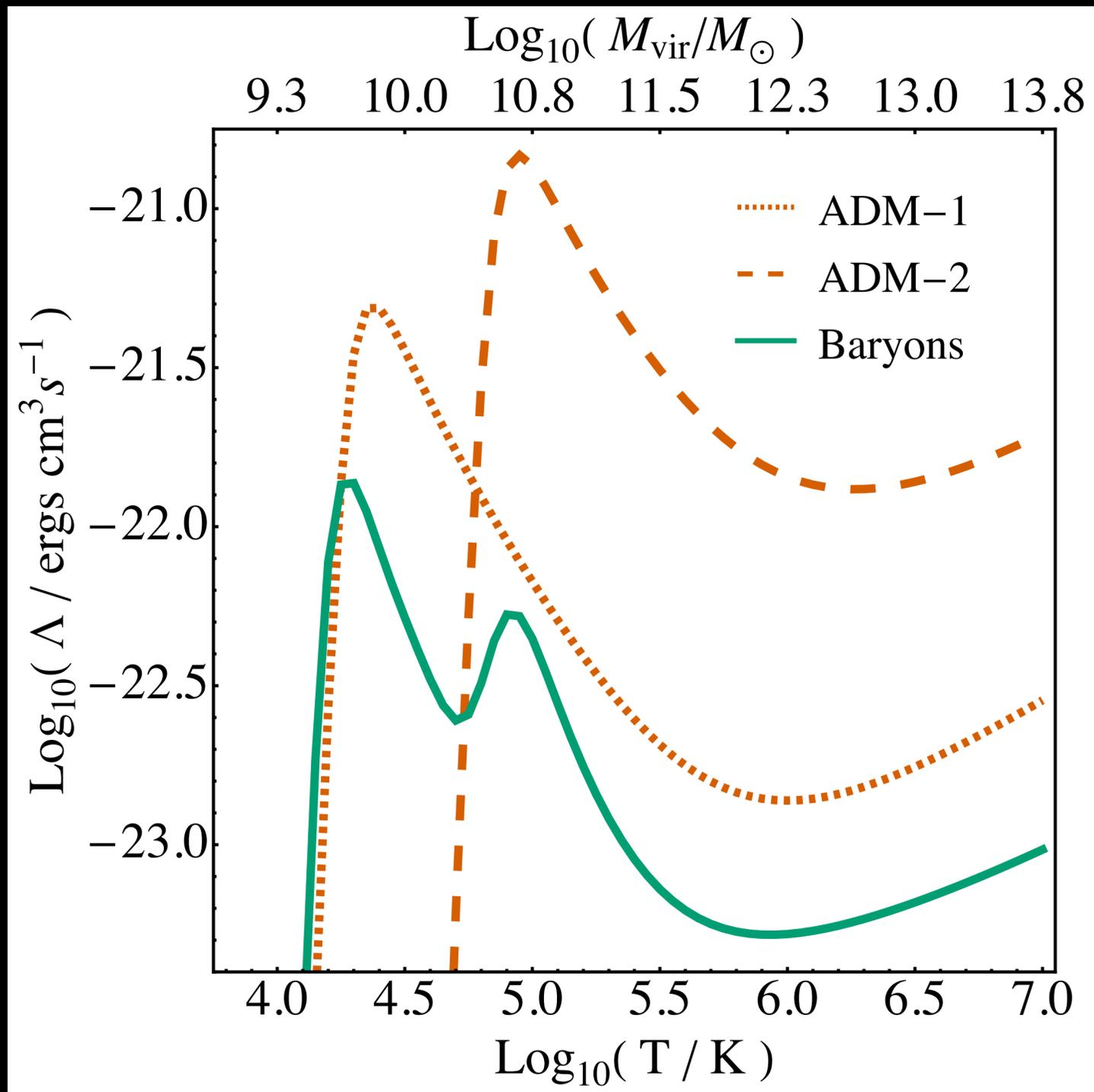
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$\alpha'/\alpha$			$1/\sqrt{0.55}$	2.5

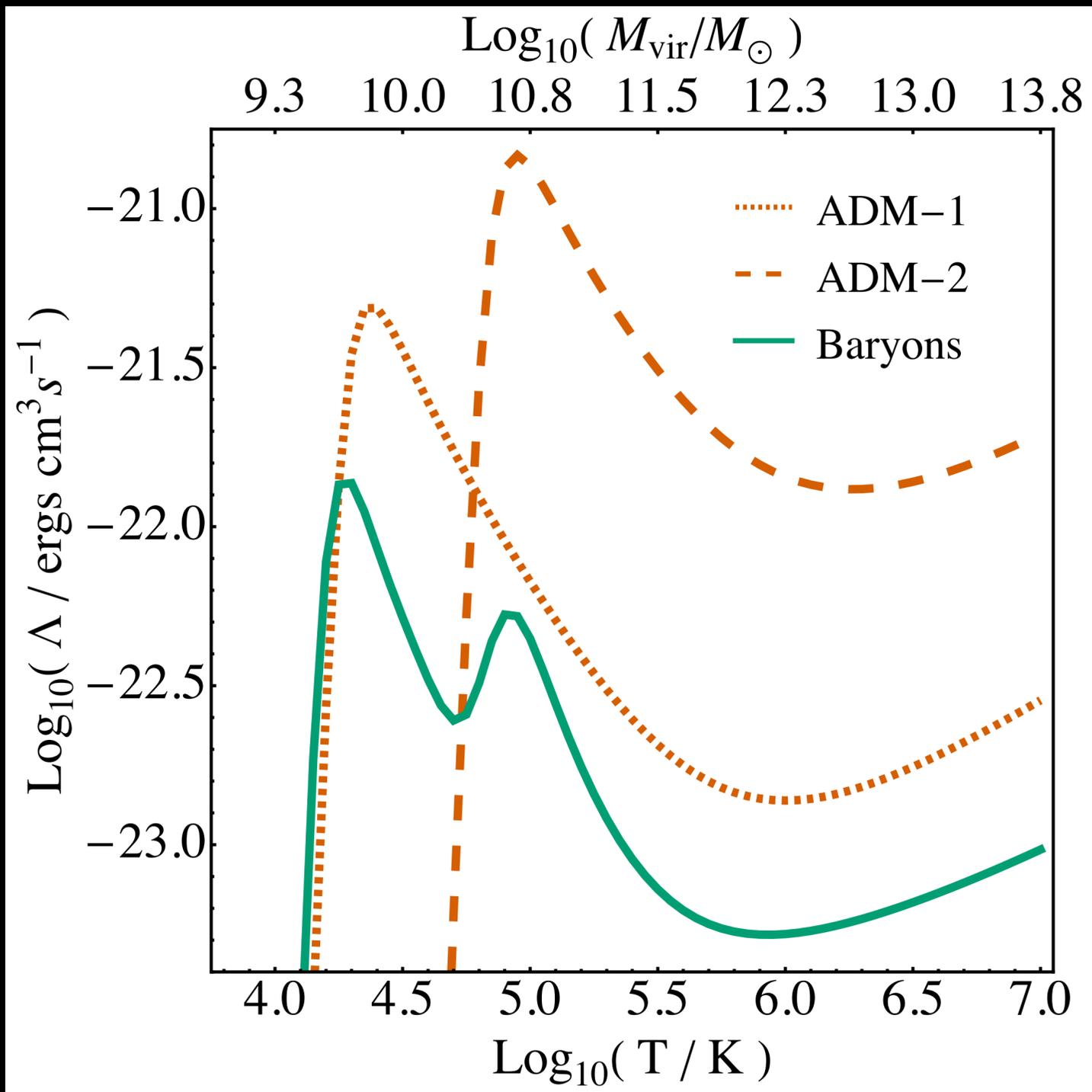
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$B'/B$			1	3.4
$(\propto m_{e'}(\alpha')^2)$				

# Cooling Physics and Intuition



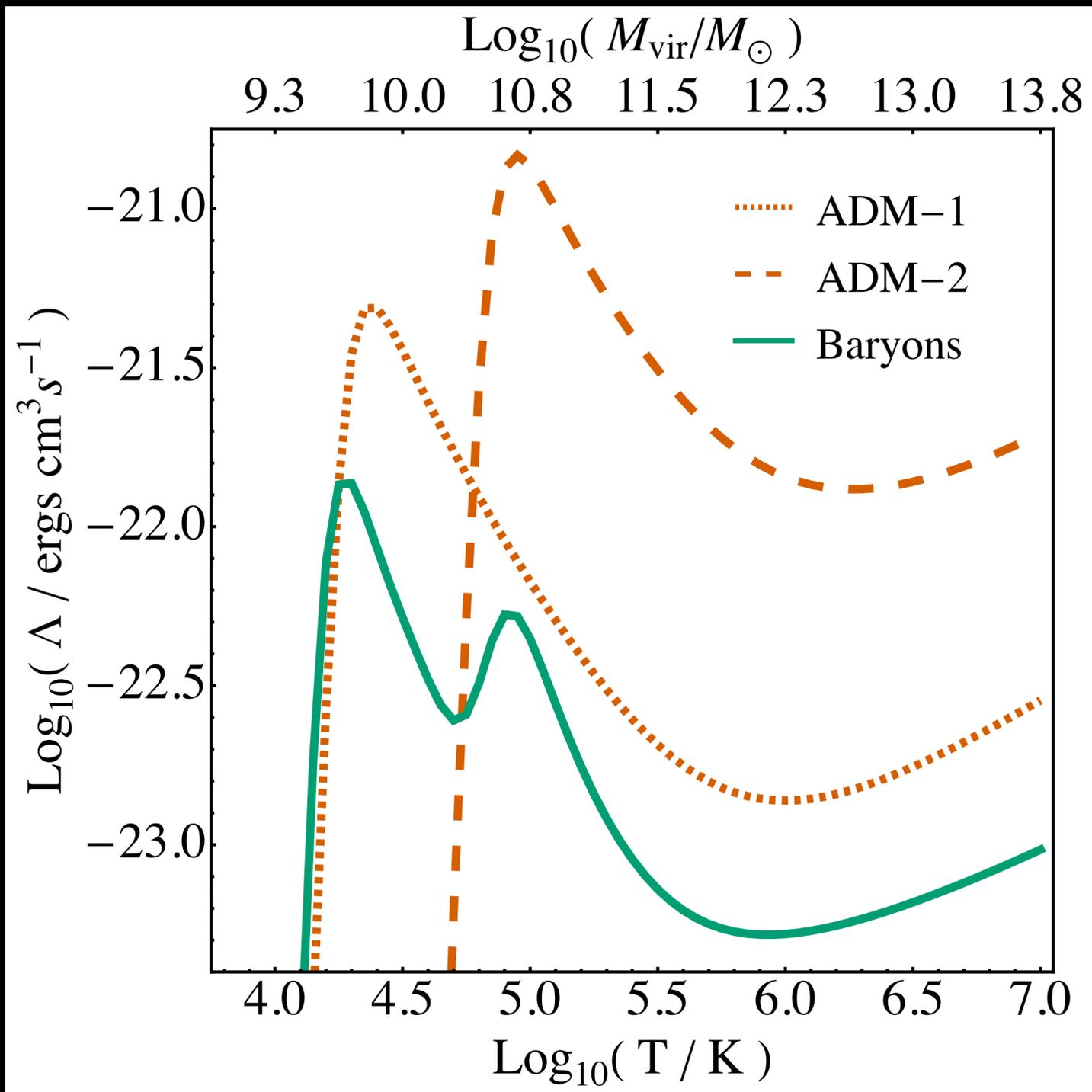
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ADM 2 gas disk accretes faster

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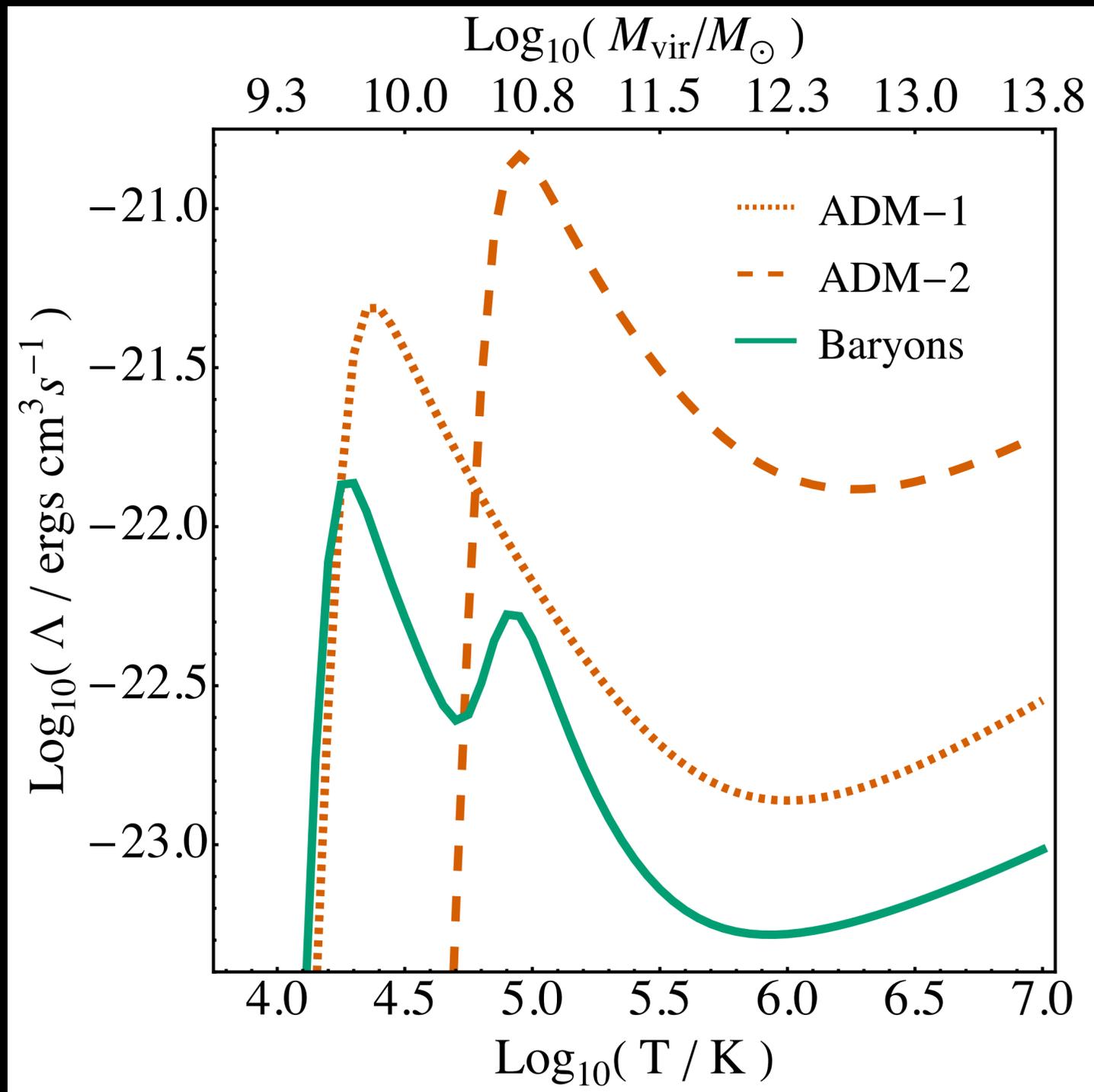
ADM 2 gas disk accretes faster

$$P_{\text{min}} \propto T_{\text{cut-off}}$$

$$\rho_{\text{collapse, ADM2}} > \rho_{\text{collapse, ADM1}}$$

ADM 2 harder to fragment

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Lacking feedback will likely increase gas collapse and fragmentation

# Ionisation-Recombination Equilibrium

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

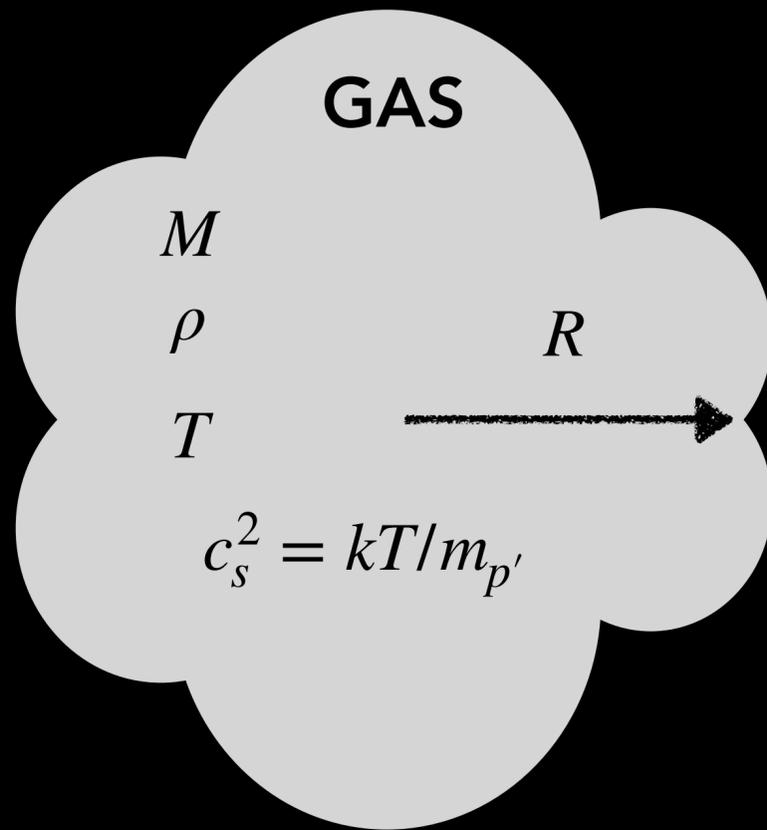
If  $t_{\text{ionise, recombine}} \ll t_{\text{dynamical}}$  and define  $x_i = n_i/n_{\text{H}'}$  where  $n_{\text{H}'} = n_{\text{p}'} + n_{\text{H}'_0}$  and  $n_{\text{e}'} = n_{\text{p}'}$ , then can assume  $\langle \sigma_{\text{ionise}} \nu \rangle x_{\text{e}'} x_{\text{H}'_0} \approx \langle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

$$x_{\text{e}'} = \frac{\langle \sigma_{\text{ionise}} \nu \rangle}{\langle \sigma_{\text{ionise}} \nu \rangle + \langle \sigma_{\text{recombine}} \nu \rangle}$$

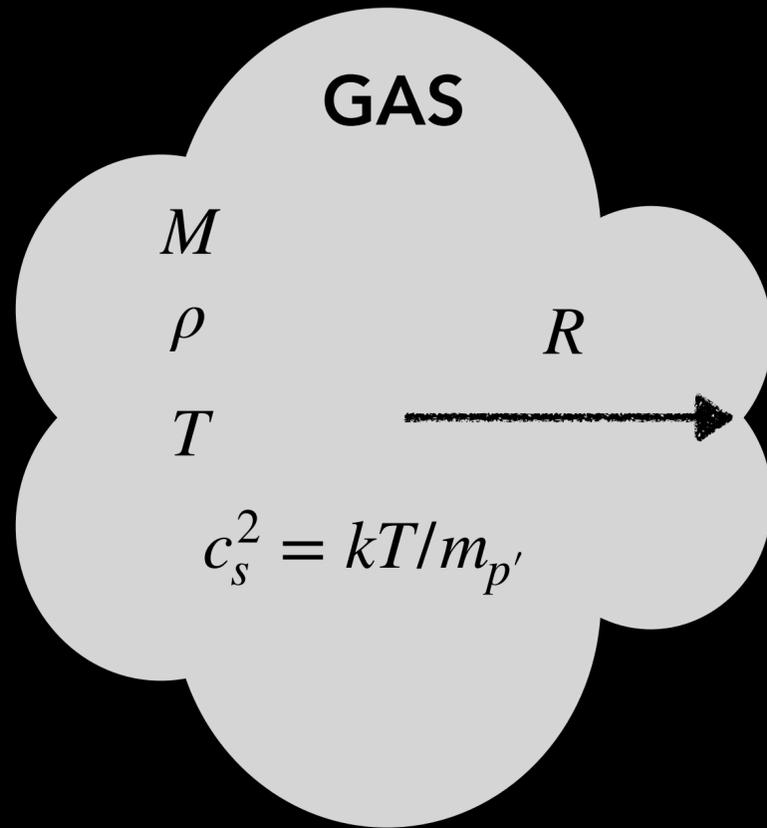
$$x_{\text{H}'_0} = \frac{\langle \sigma_{\text{recombine}} \nu \rangle}{\langle \sigma_{\text{ionise}} \nu \rangle + \langle \sigma_{\text{recombine}} \nu \rangle}$$

# How Dense Can the Gas Become?

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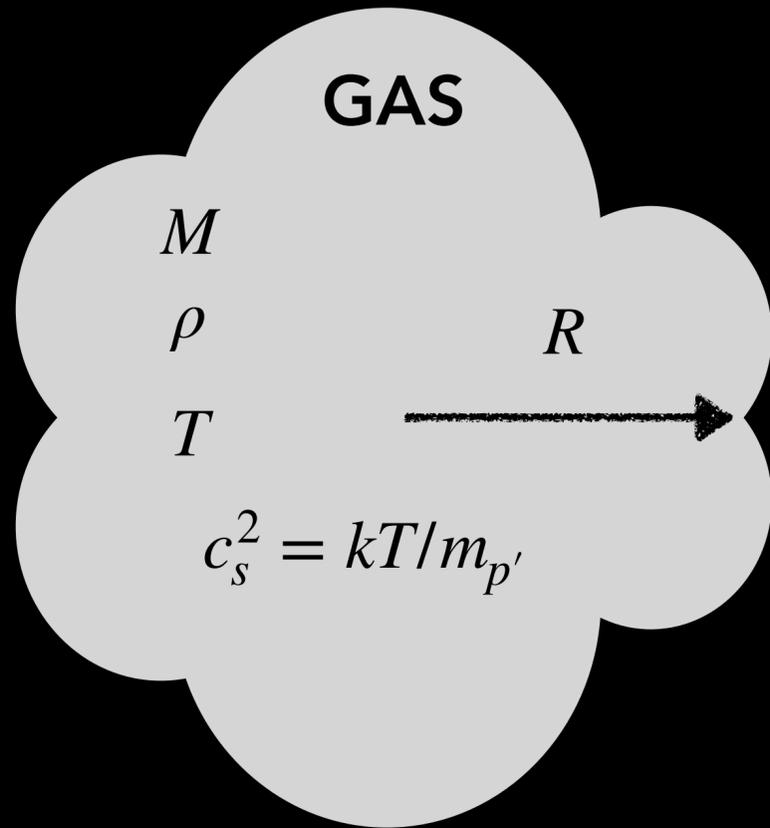
# How Dense Can the Gas Become?



Instability Criterion:

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

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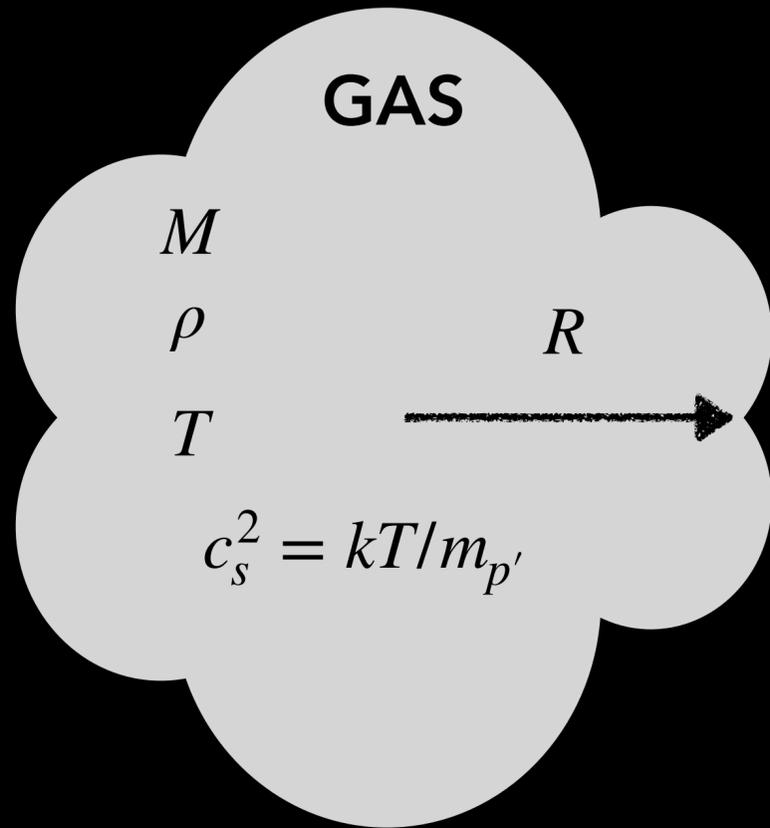


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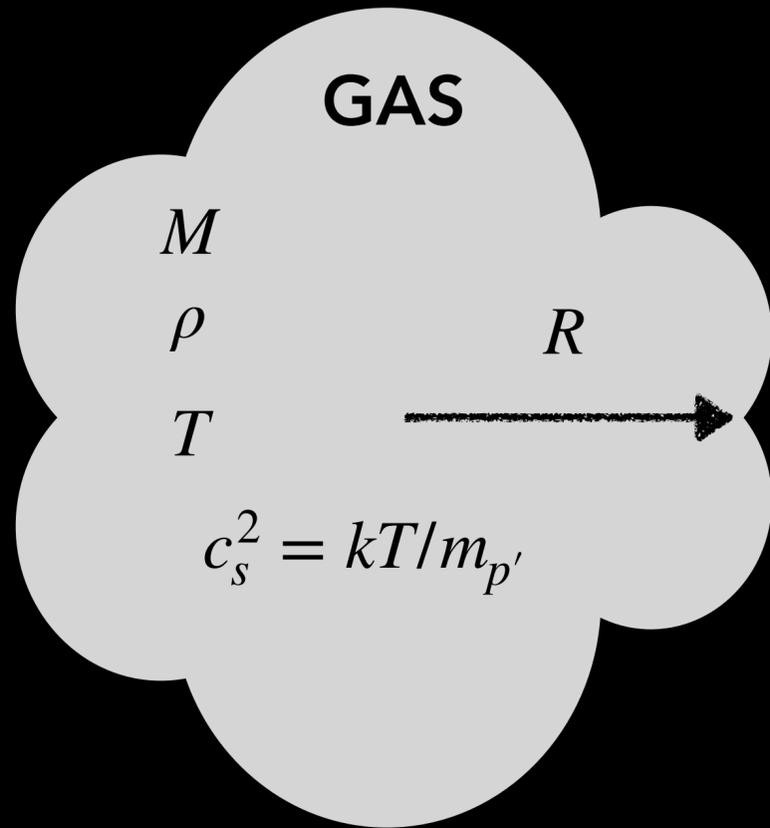
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**Baryon gas → Star**  
**ADM gas → Clump**

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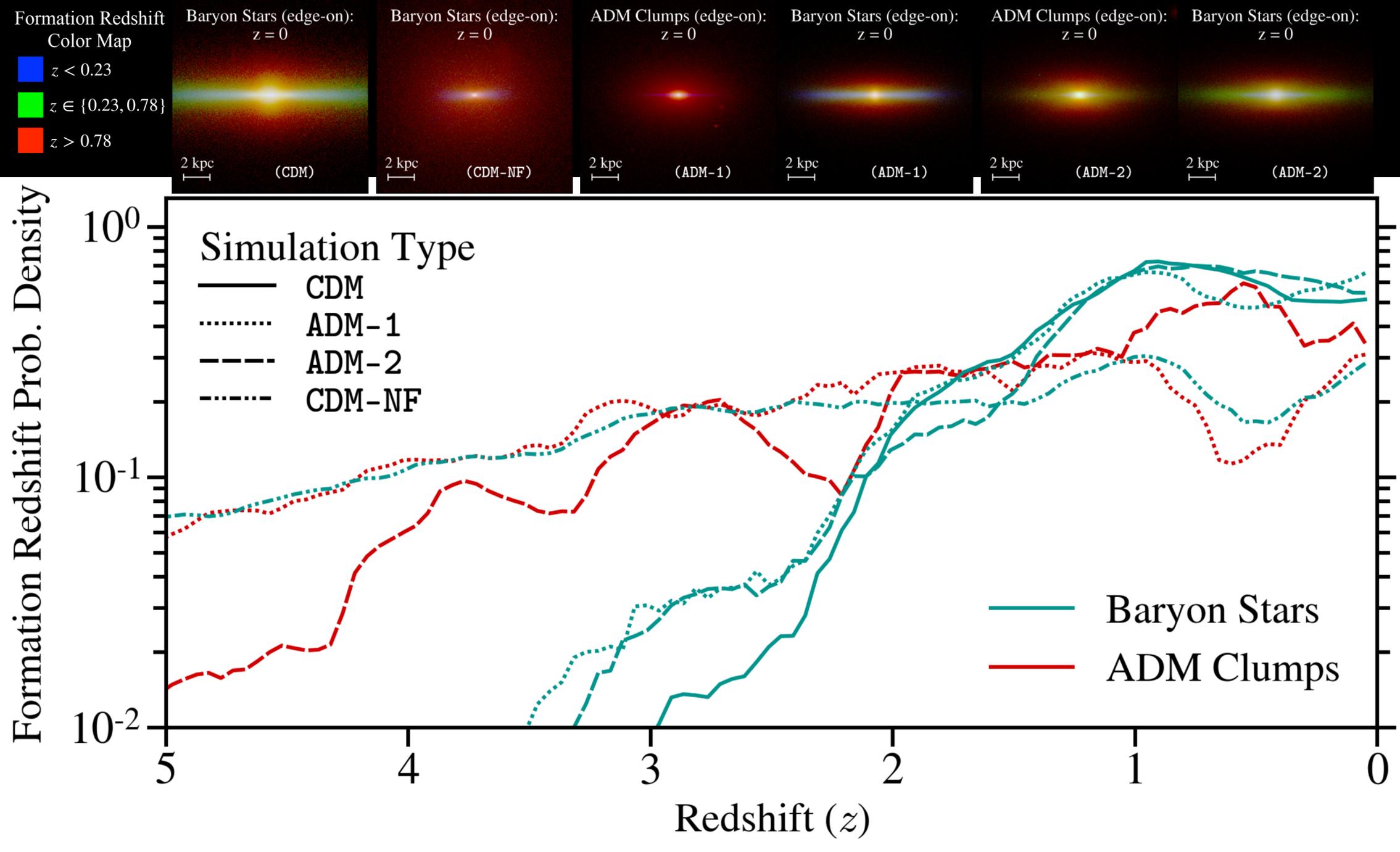
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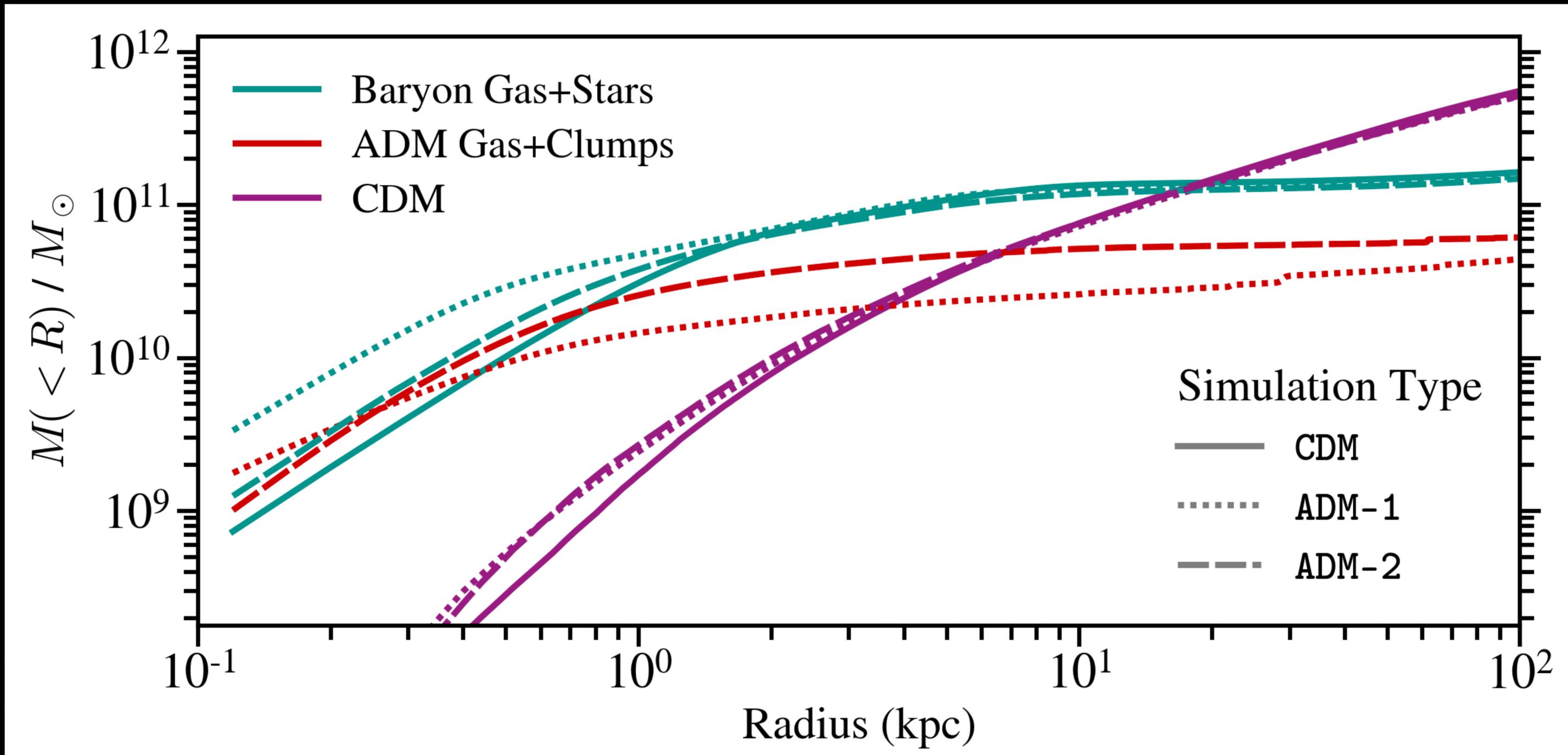
$$\rho > \frac{1}{R^2} \cdot \left( \frac{kT}{m_{p'} G} \right) \longrightarrow \begin{array}{l} \text{Baryon gas} \rightarrow \text{Star} \\ \text{ADM gas} \rightarrow \text{Clump} \end{array}$$

Caveat: Baryons have more criteria (fixed  $\rho_{\text{star}}$ , molecular, etc.)

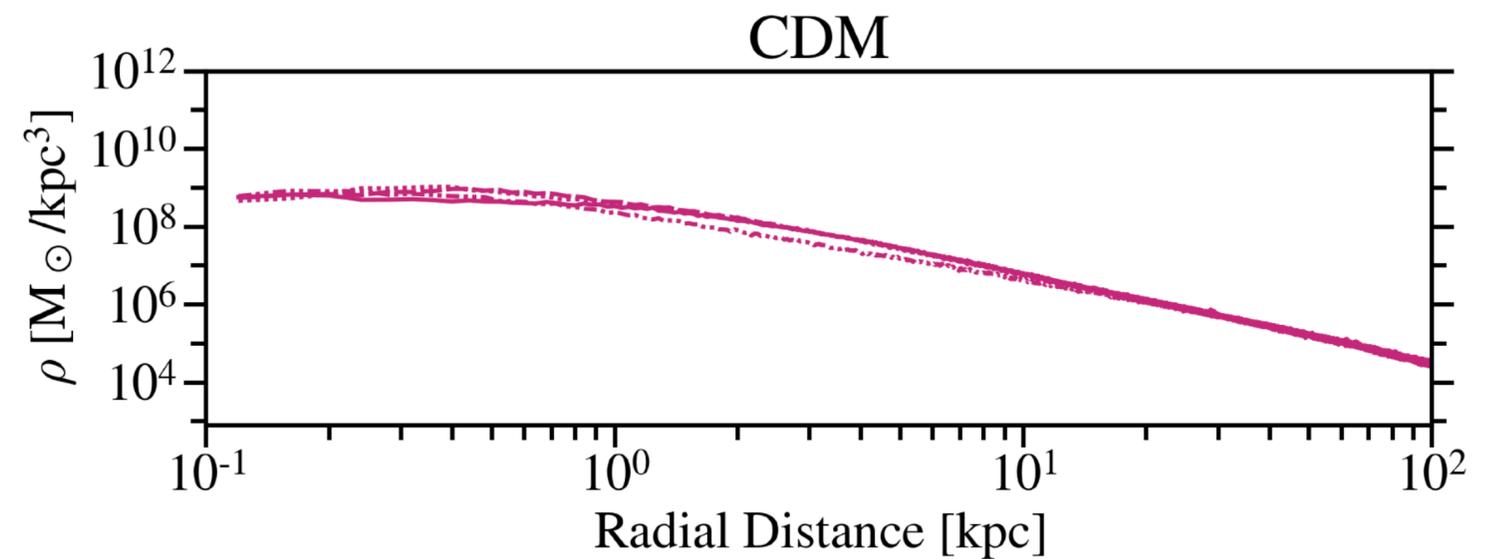
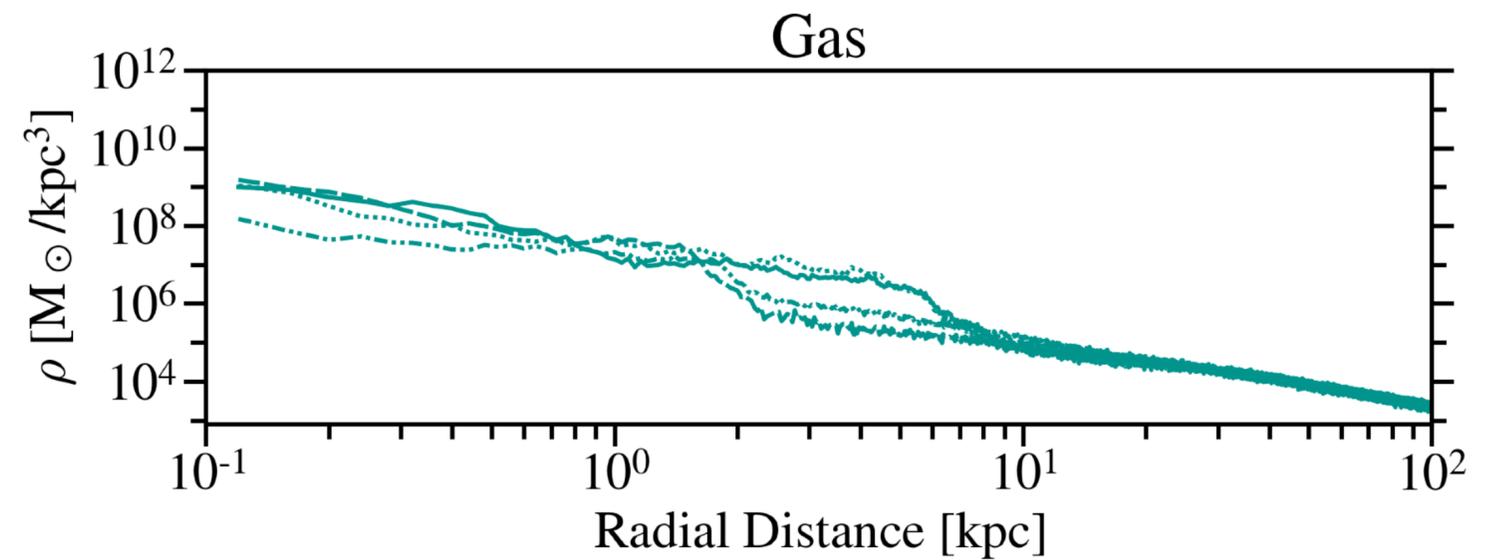
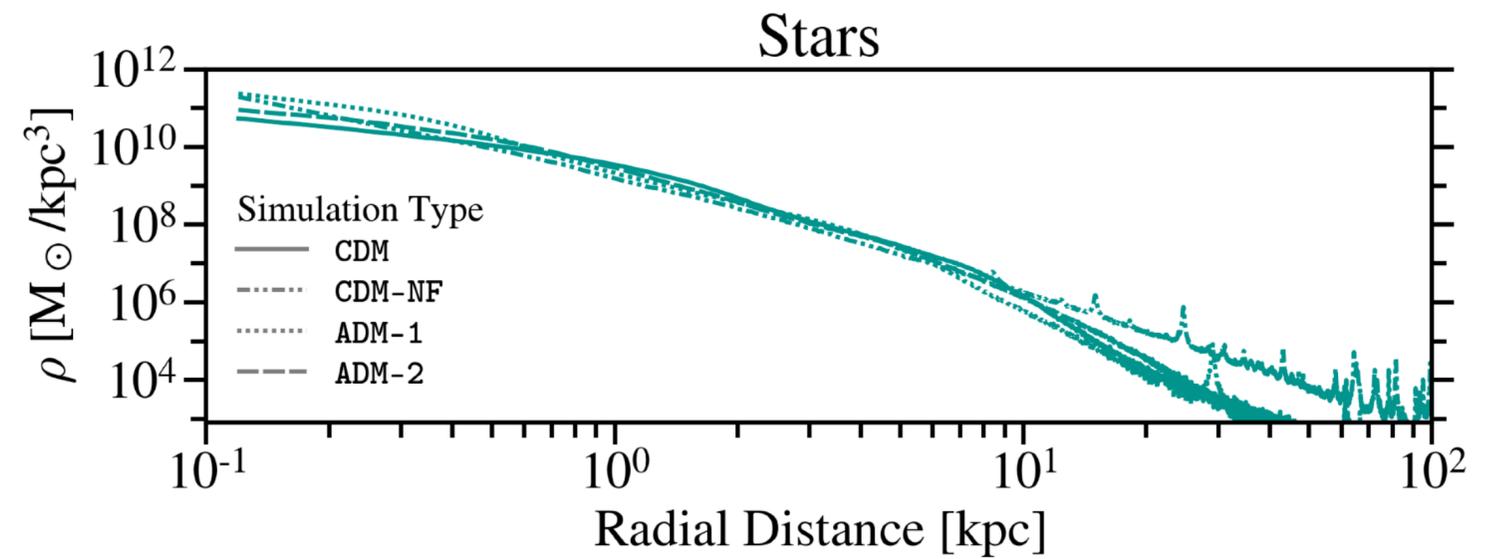
# Baryonic Star and ADM Clump Formation



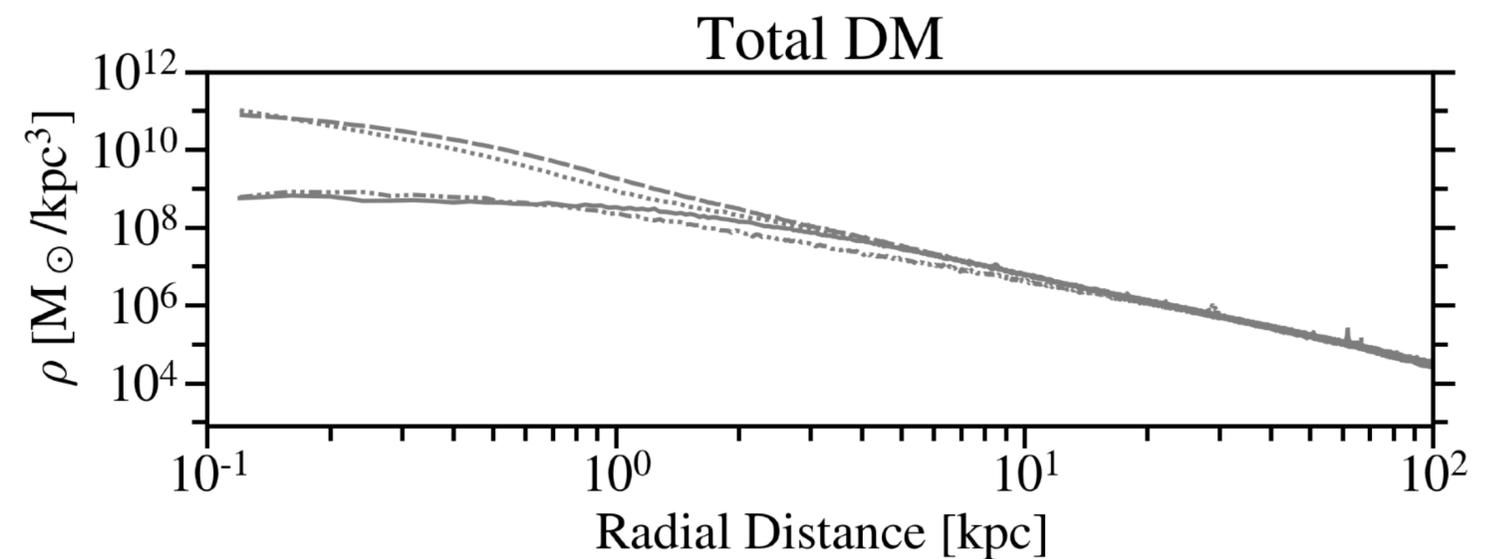
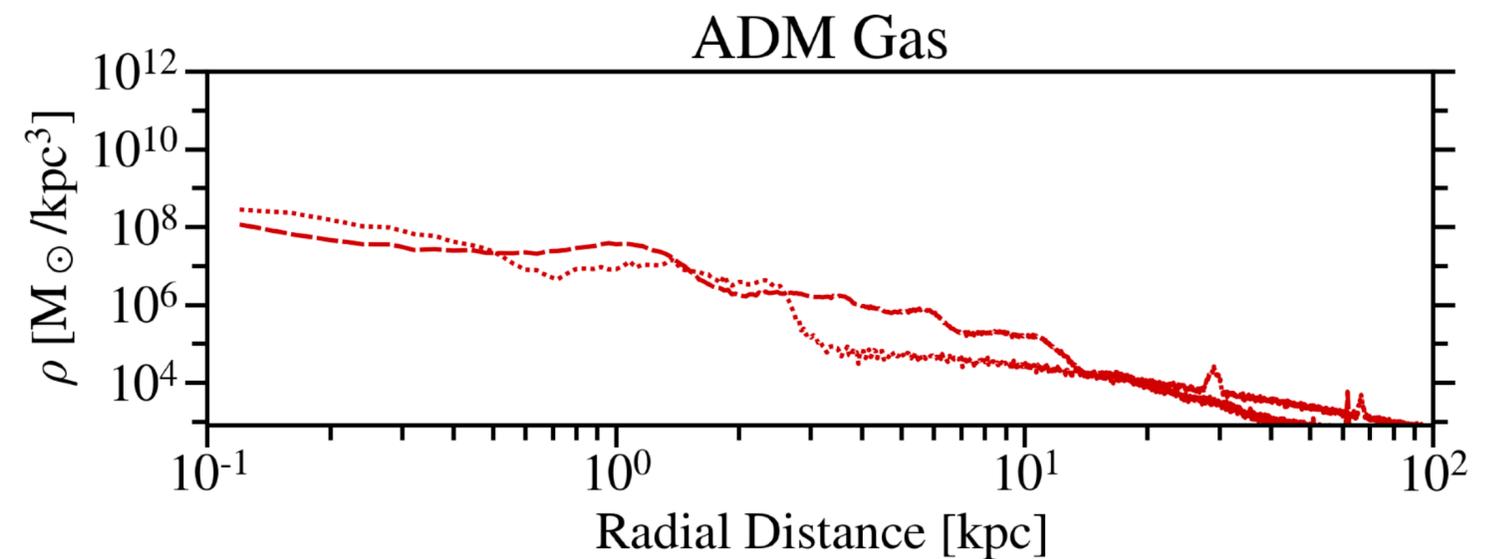
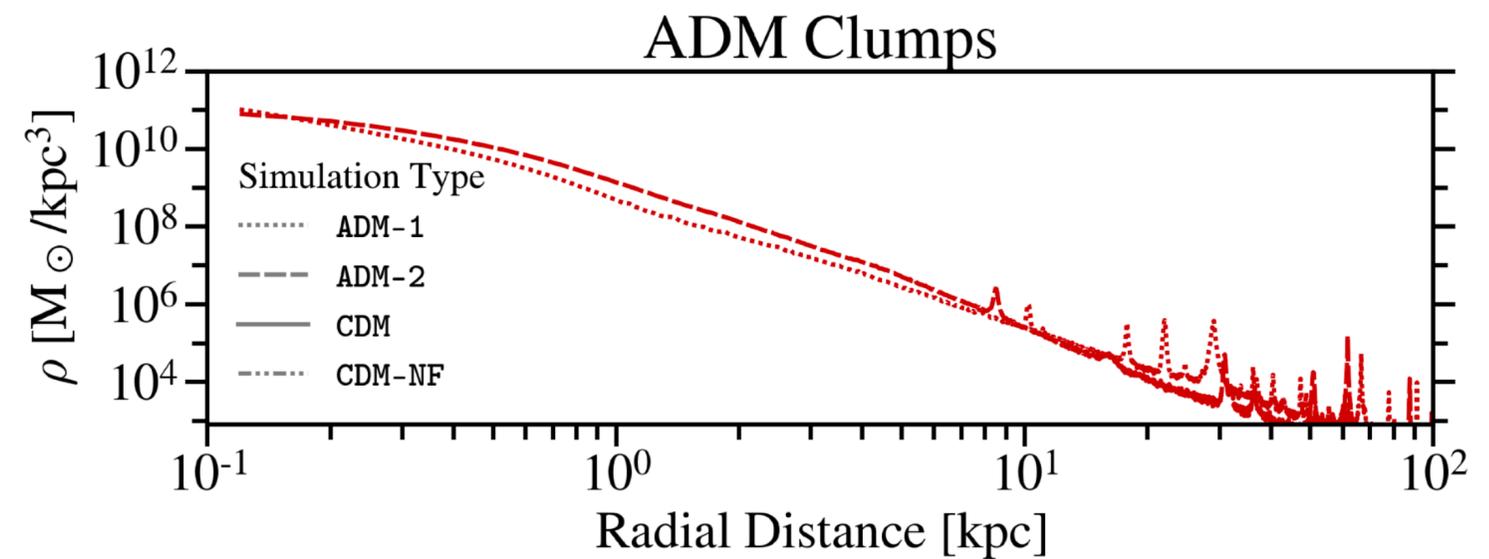
# Enclosed Mass Profiles



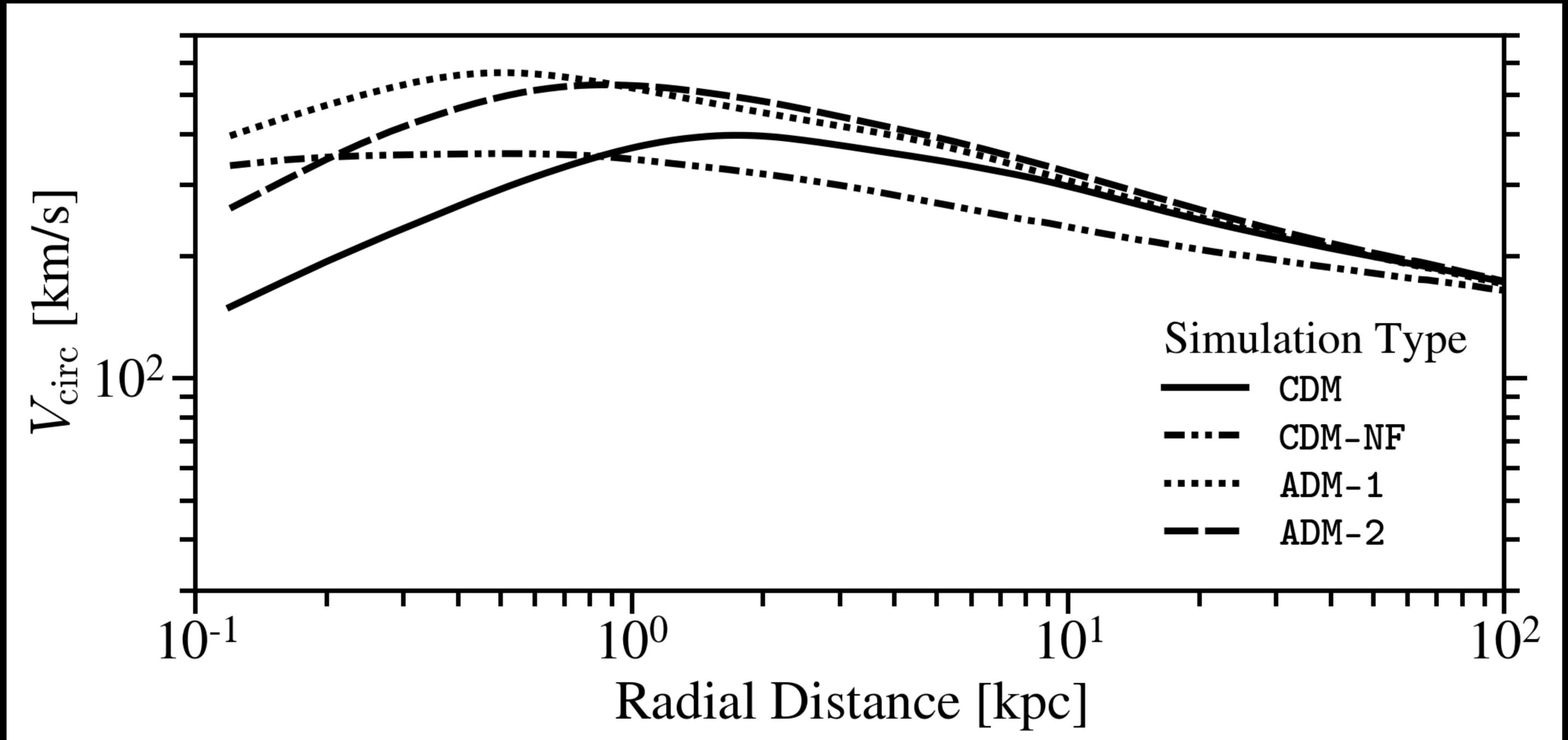
# Baryon and CDM Density Profiles



# Dark Matter Density Profiles

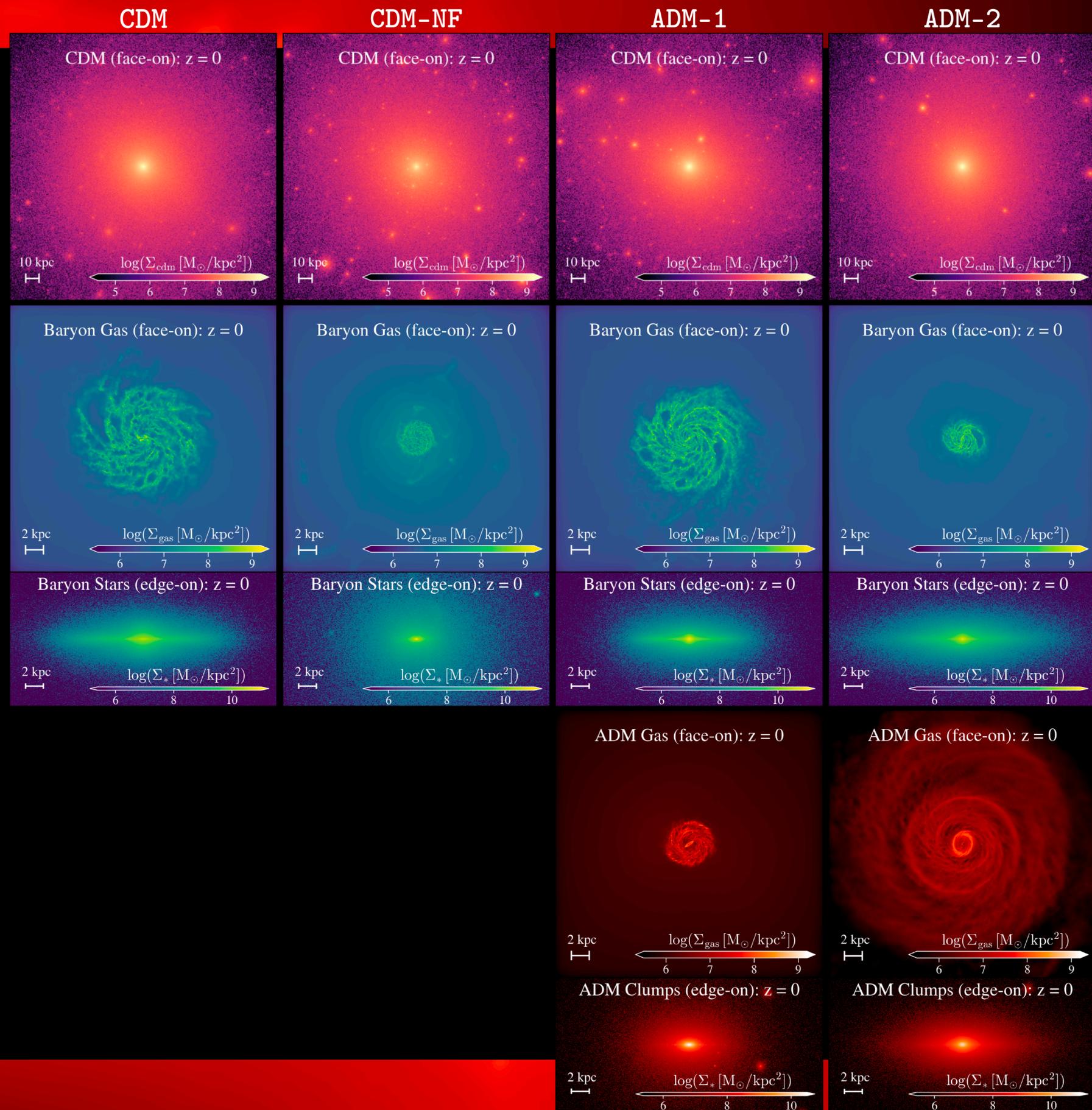


# Circular Velocity Profiles



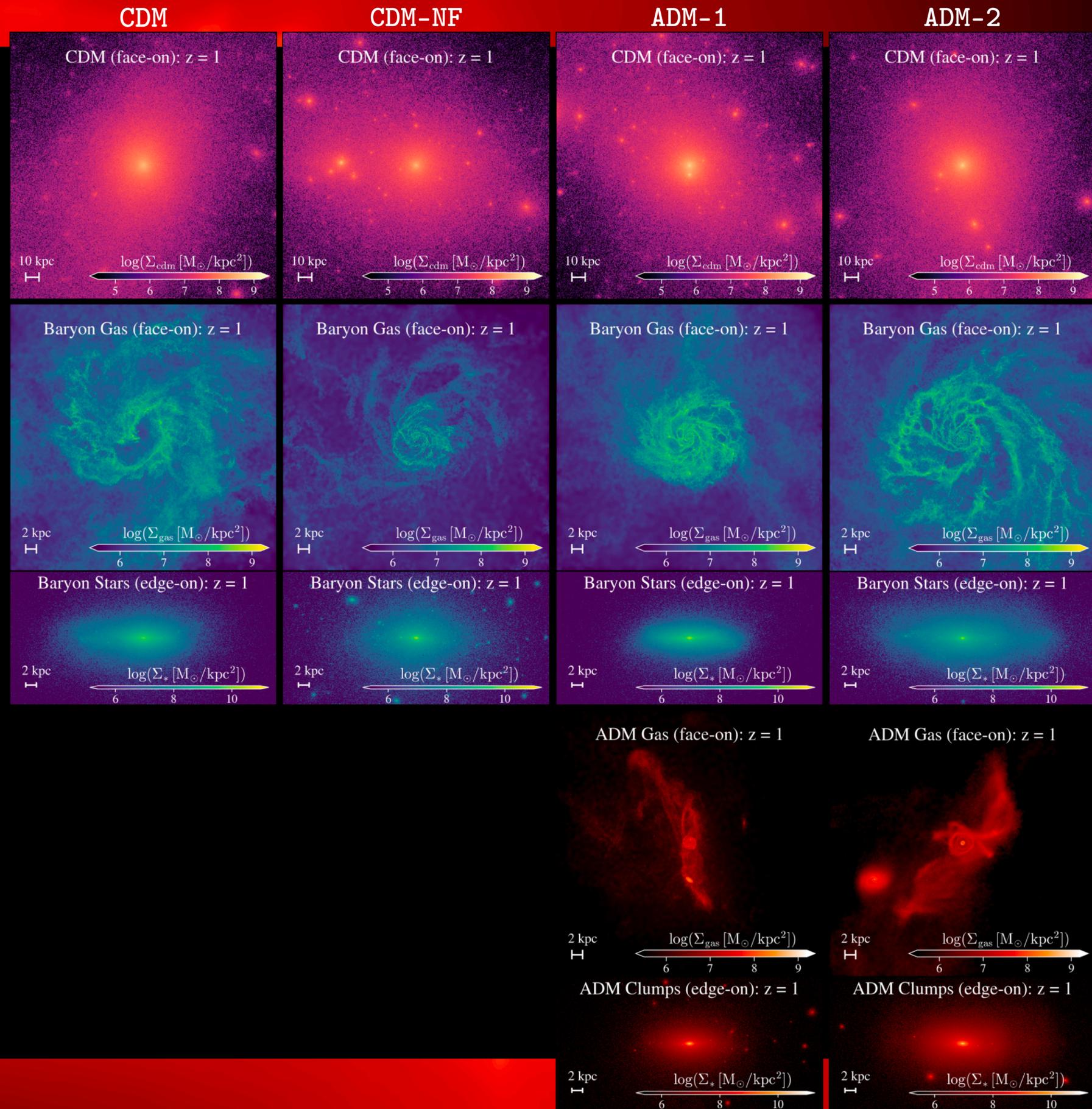
# Morphology

$z = 0$

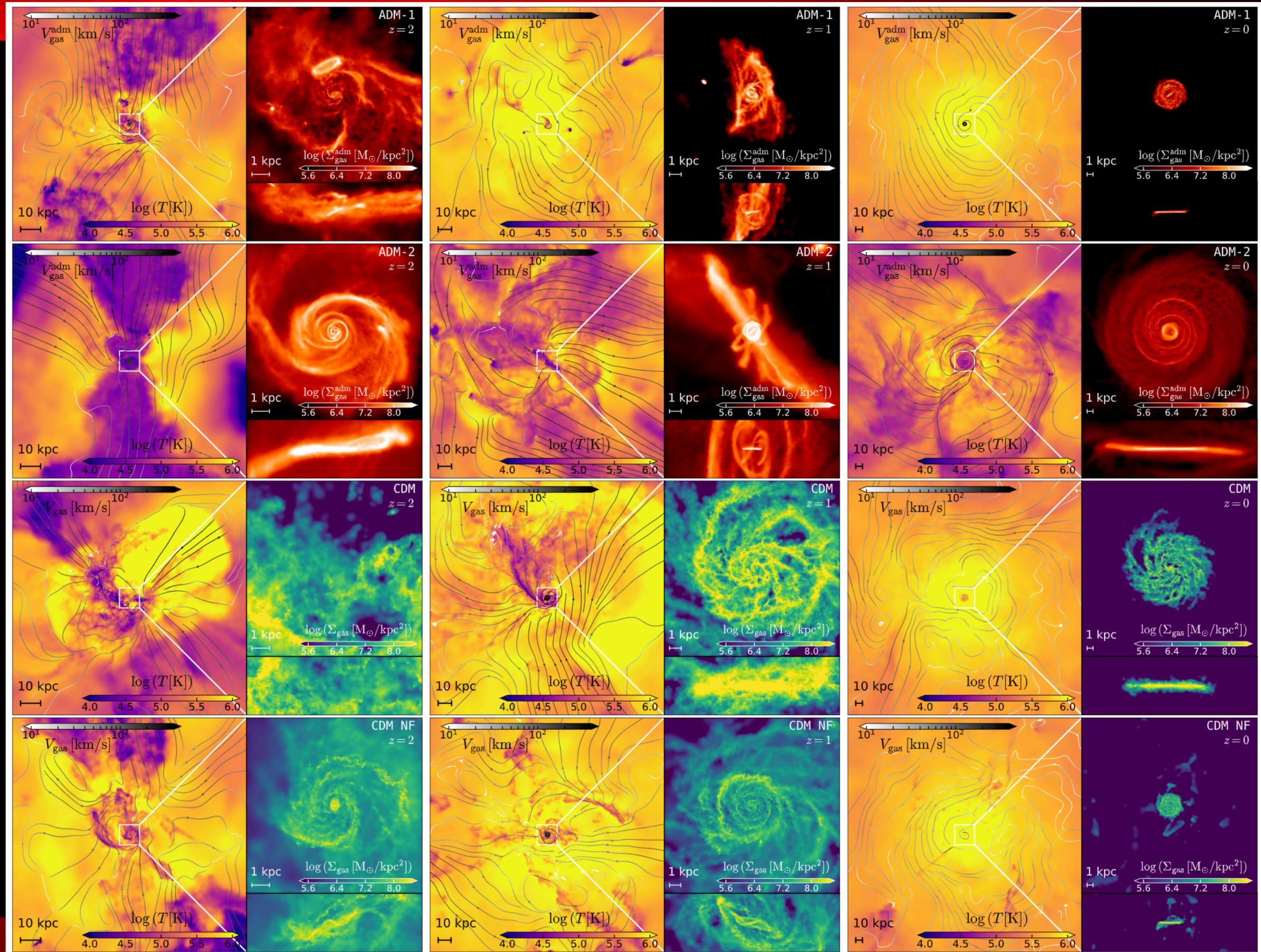


# Morphology

$z \sim 1$



# Gas Evolution



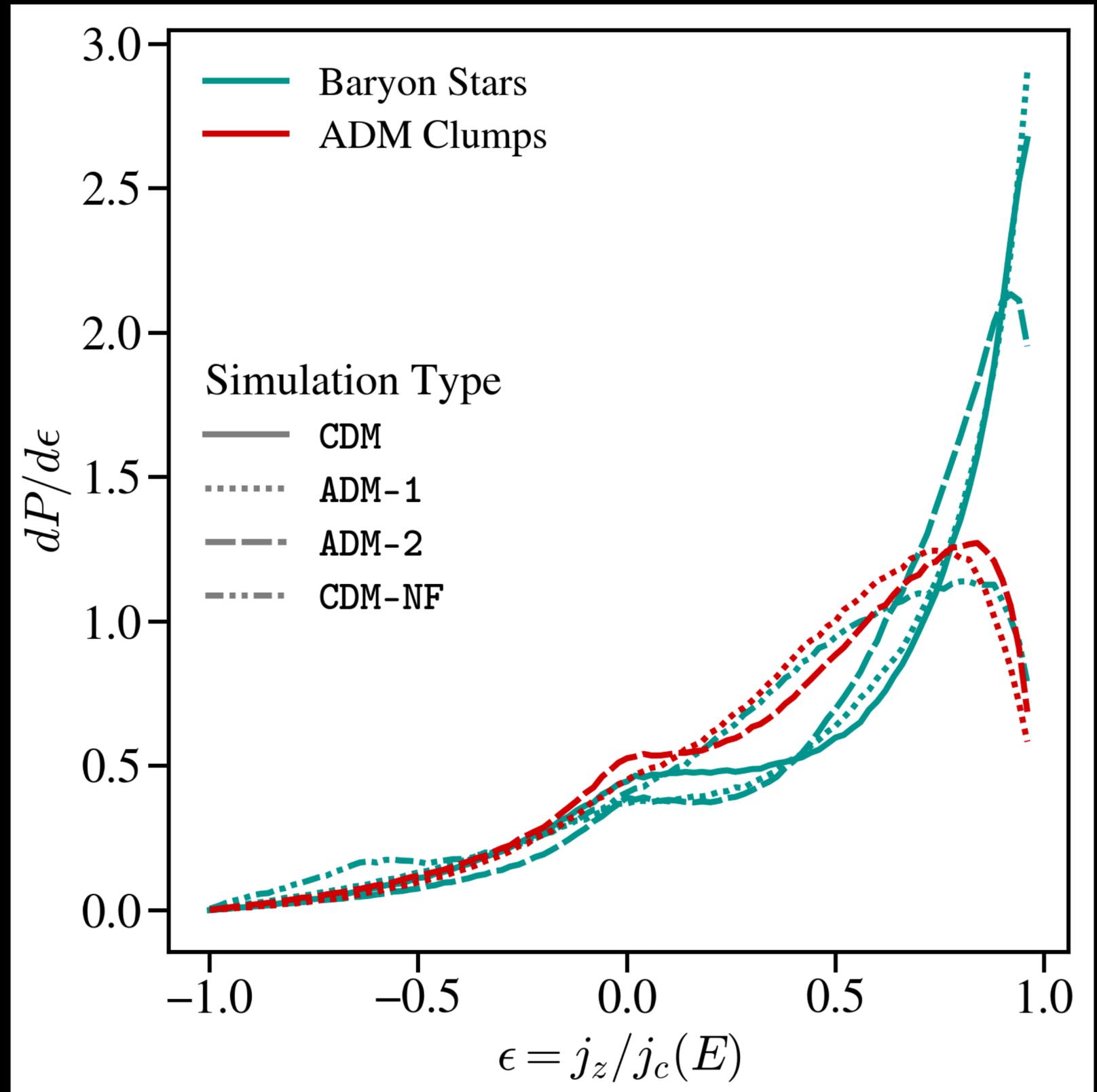
# Morphology Metrics

	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
$f_{\text{thin}}$	0.94	0.38	0.67	0.20	0.97	0.39	0.86	0.19	0.81	0.37	0.99	0.21
$f_{\text{thick}}$	0.05	0.39	0.32	0.53	0.03	0.40	0.14	0.57	0.18	0.45	0.01	0.52
$f_{\text{spheroid}}$	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

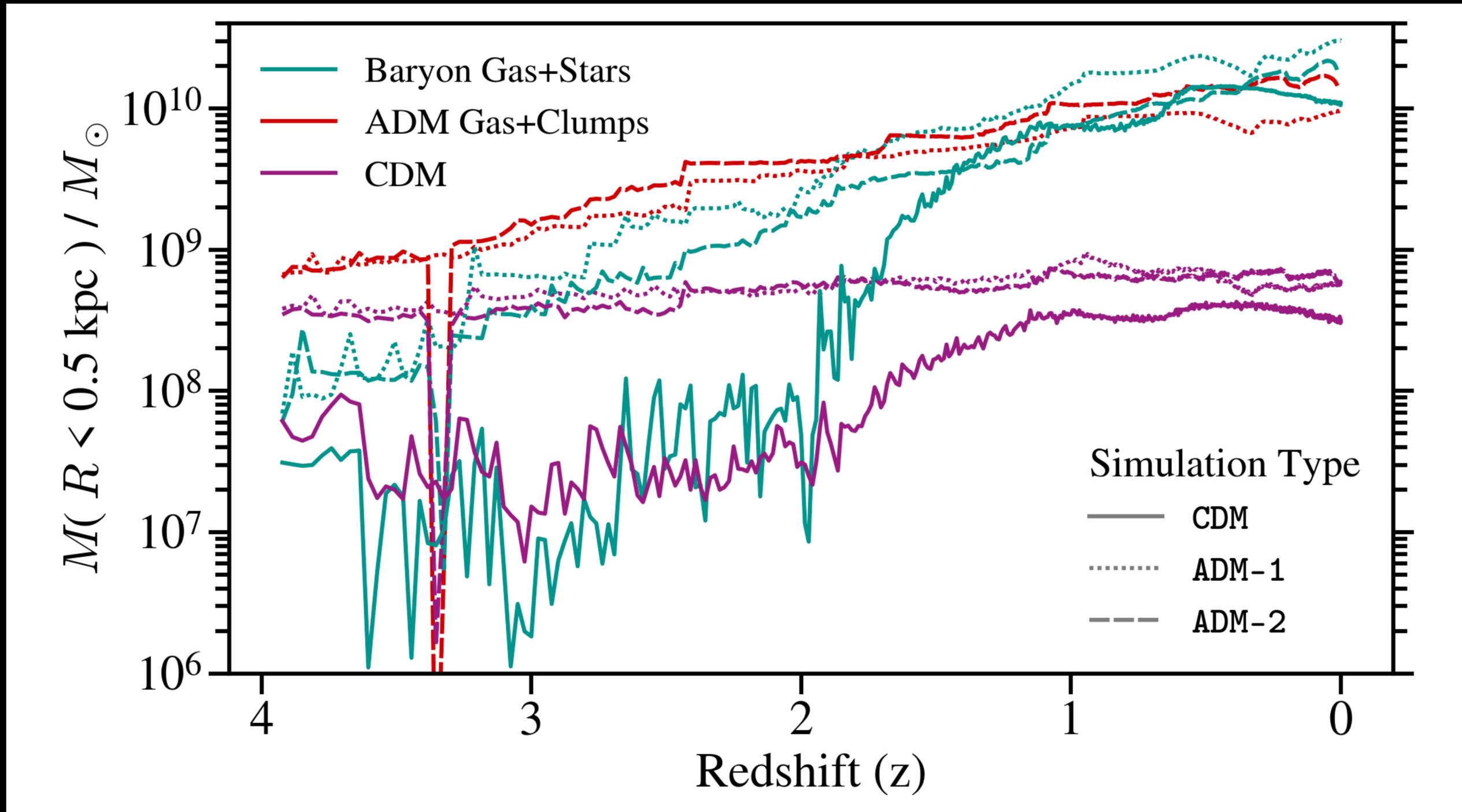
**Table E1.** A table of morphology metrics for the baryonic stars and ADM clumps in CDM, CDM-NF, ADM-1, and ADM-2.  $r_{1/2}$ ,  $z_{1/2}$ ,  $z_{9/10}$ ,  $f_{\text{thin}}$ ,  $f_{\text{thick}}$ , and  $f_{\text{spheroid}}$  are all defined in the main text.  $\tilde{f}$  is the flatness parameter, with  $\tilde{f} \rightarrow 1$  approaching a thin-disk distribution and  $\tilde{f} \rightarrow 0$  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.

# Orbital Circularities

Method based on Abadi et al. (0212282)



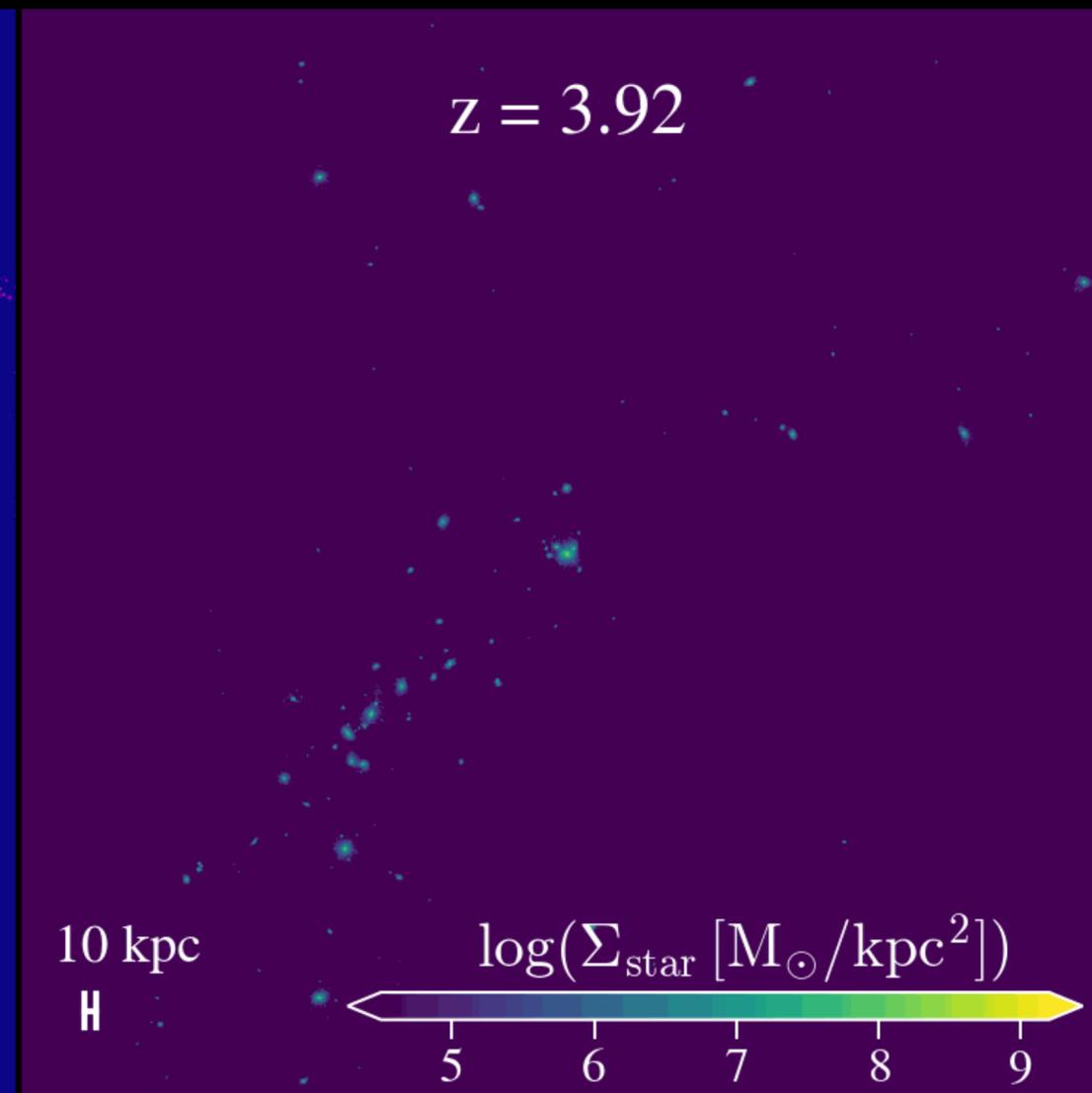
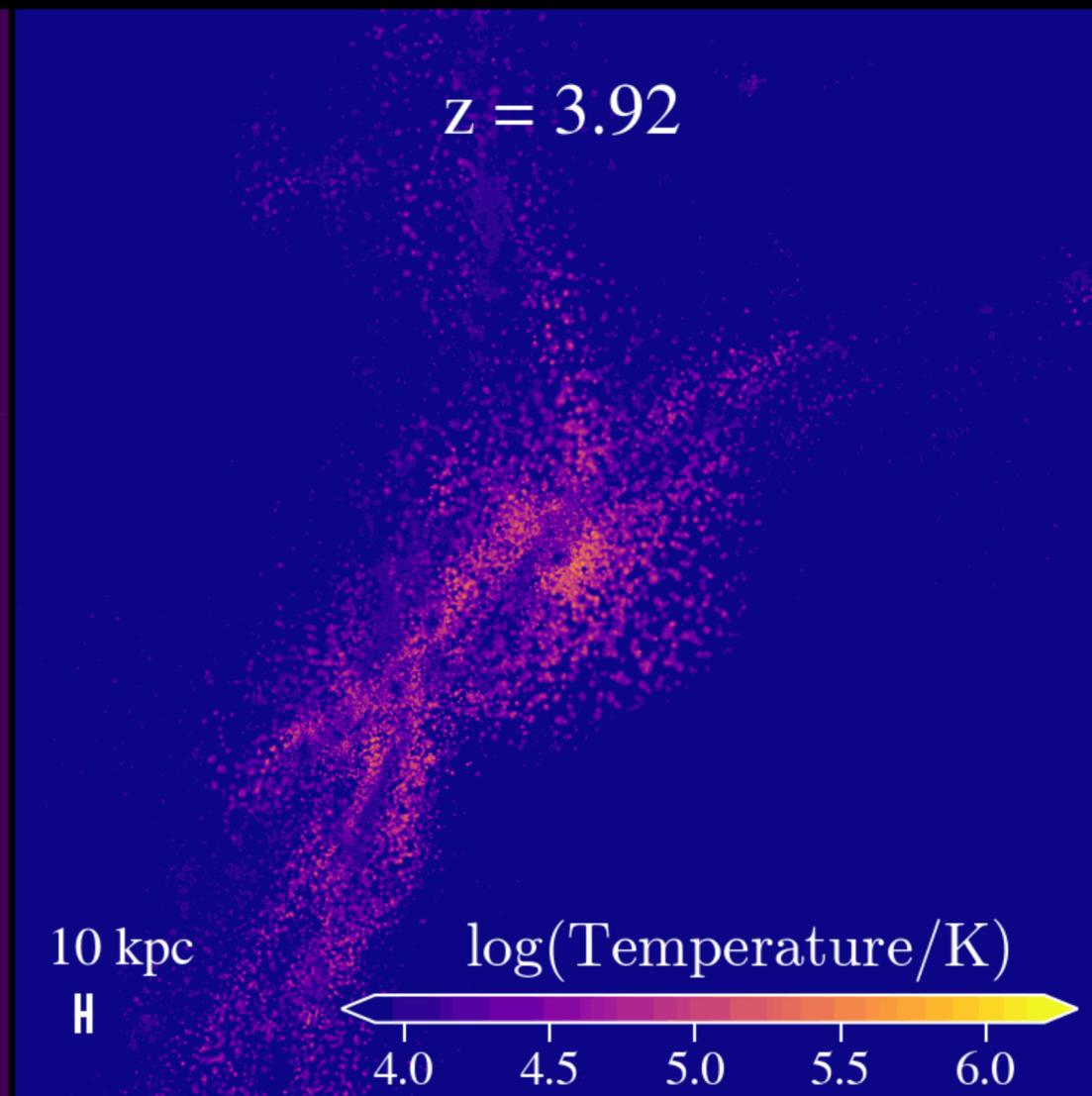
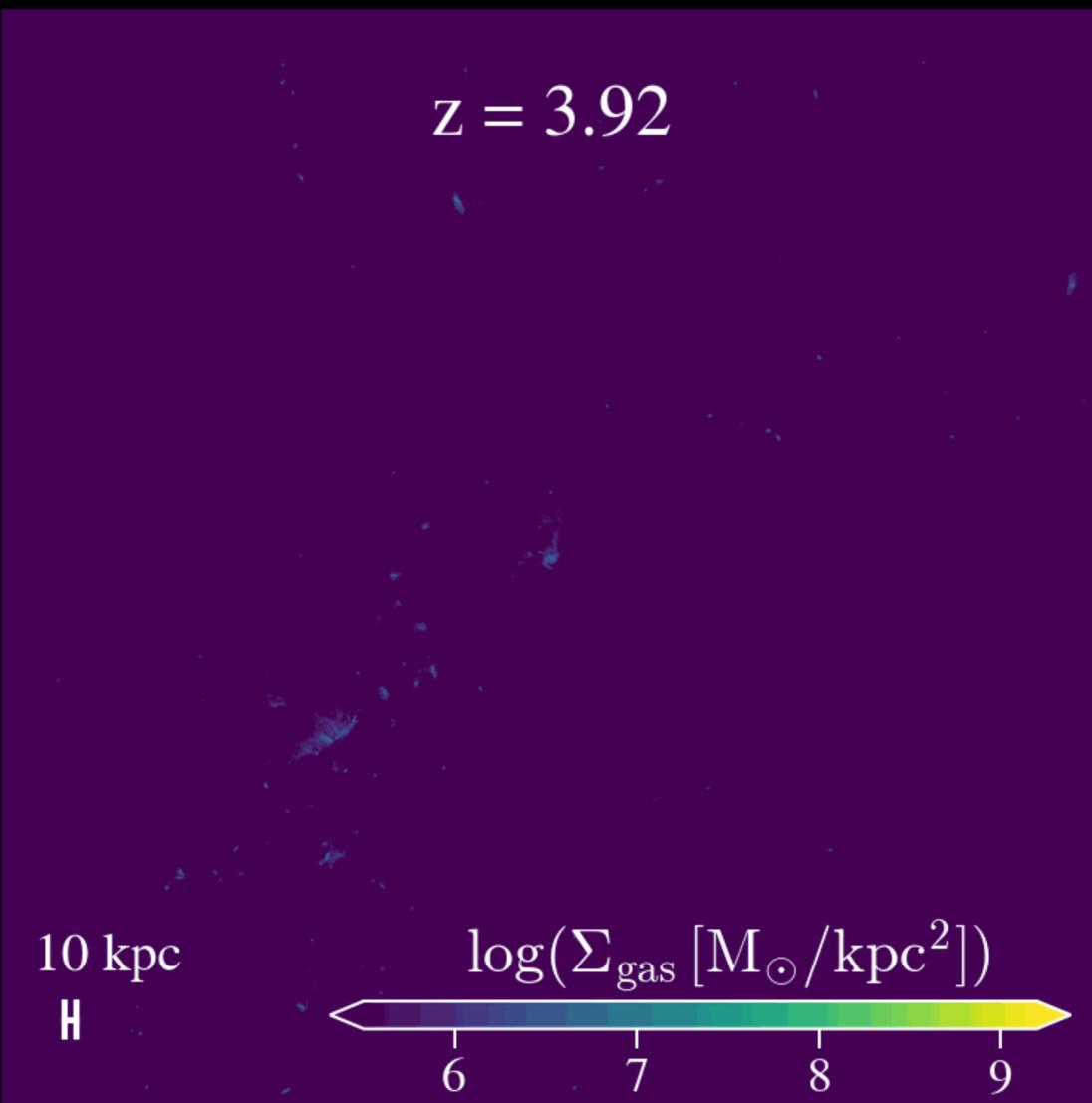
# Central Density Evolution



# Central Baryon Evolution (CDM-NF)

## Baryon Gas

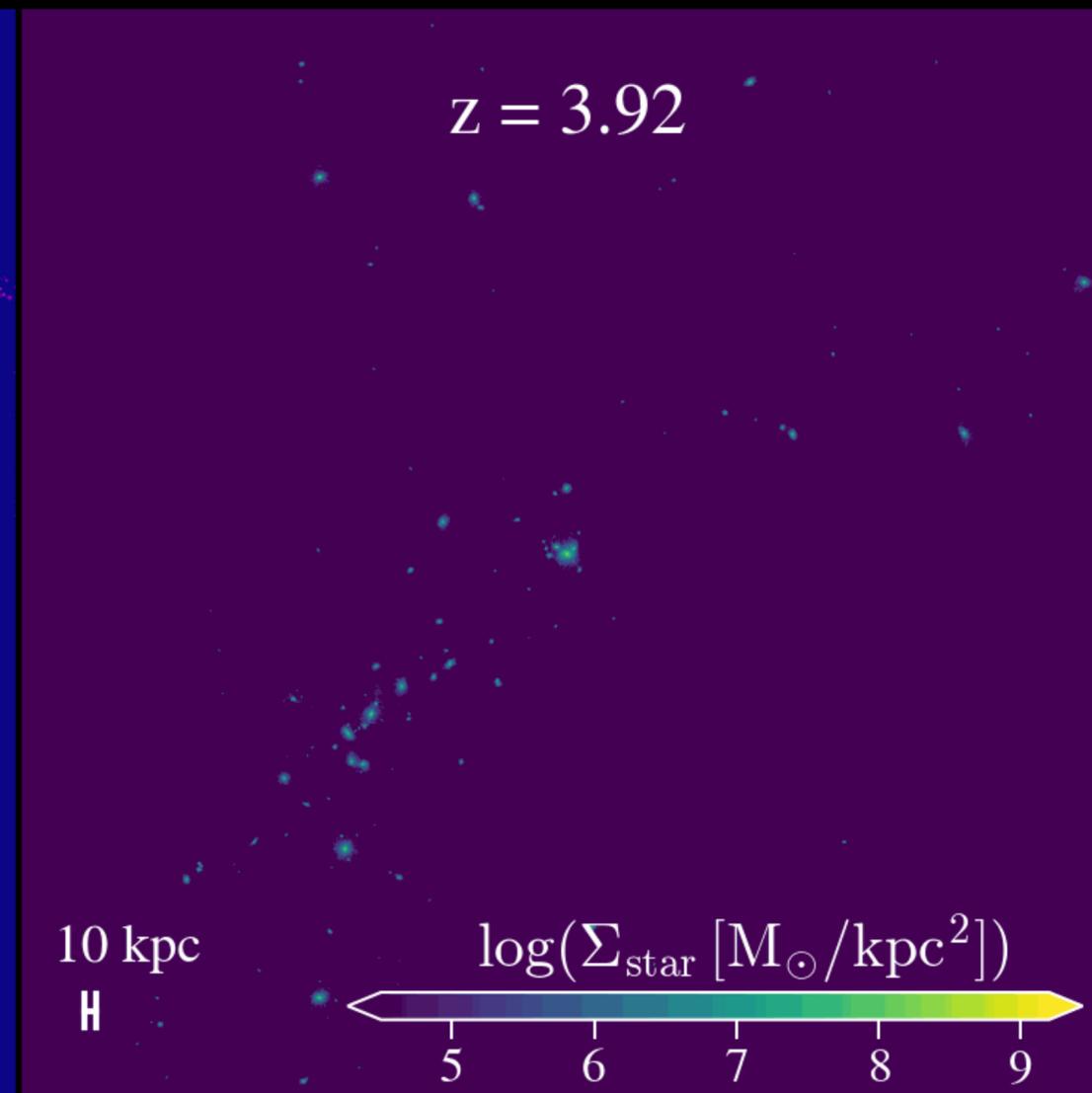
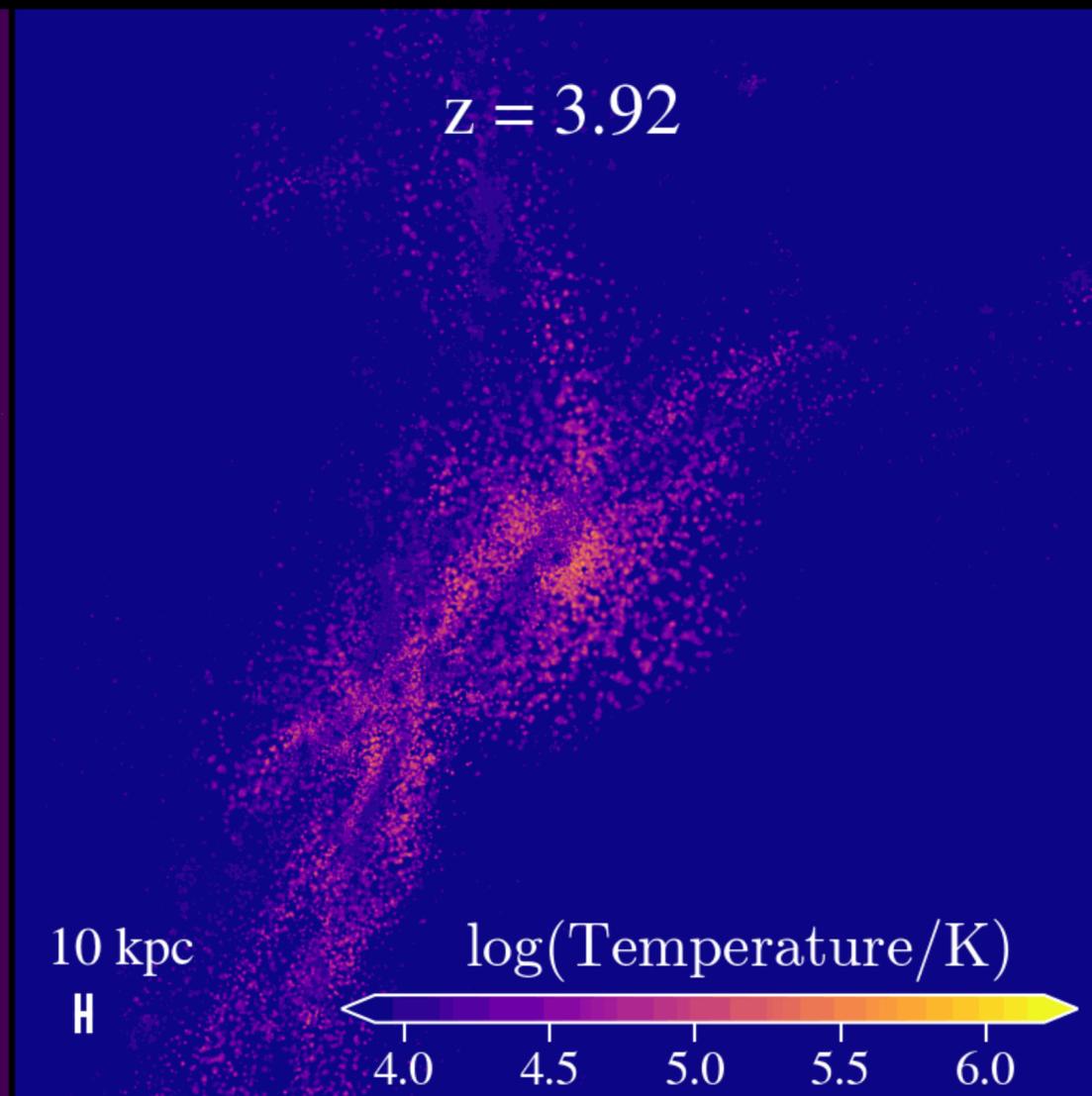
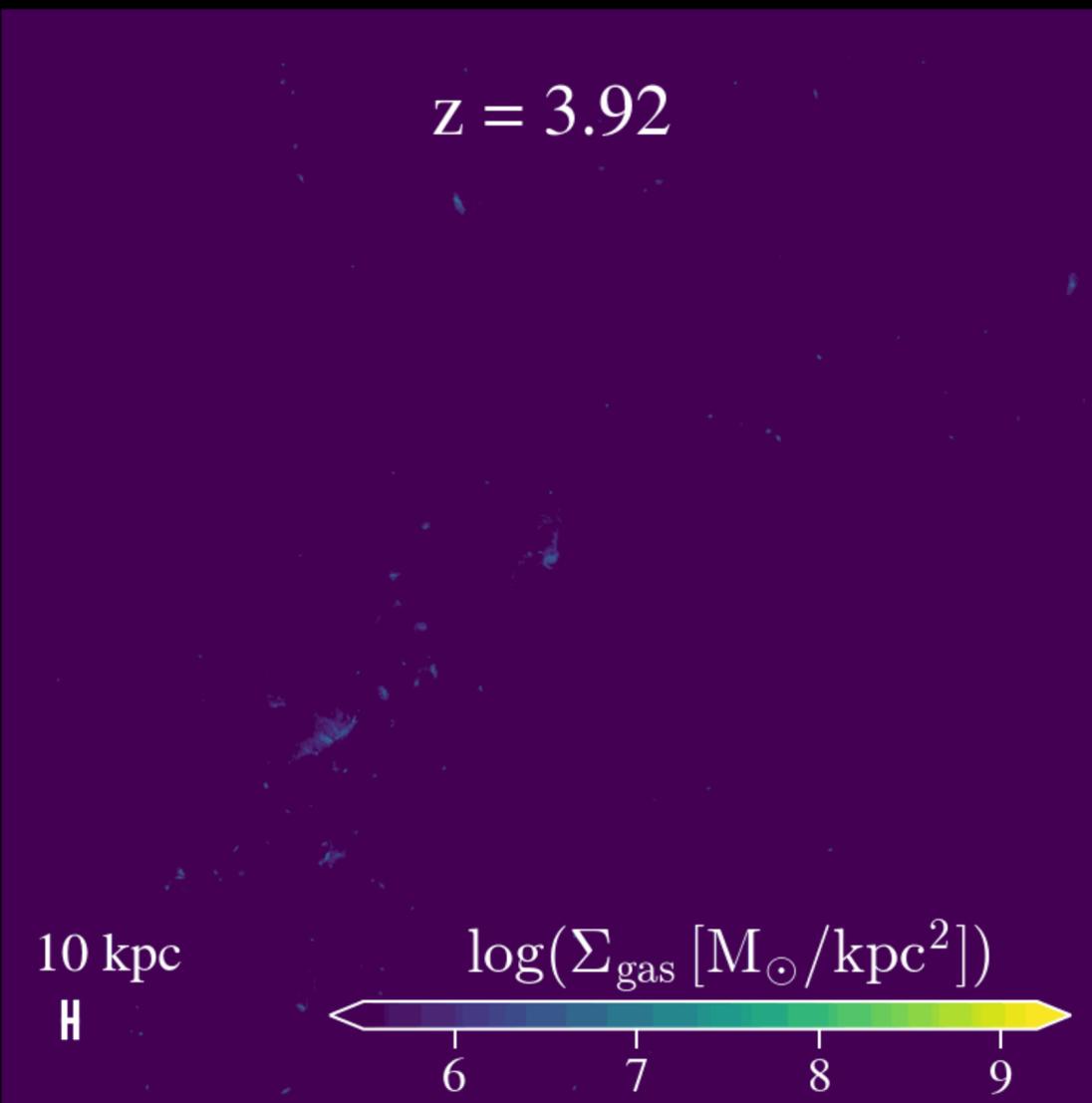
## Baryon Stars



# Central Baryon Evolution (CDM-NF)

## Baryon Gas

## Baryon Stars



# Central ADM Evolution (ADM-1)

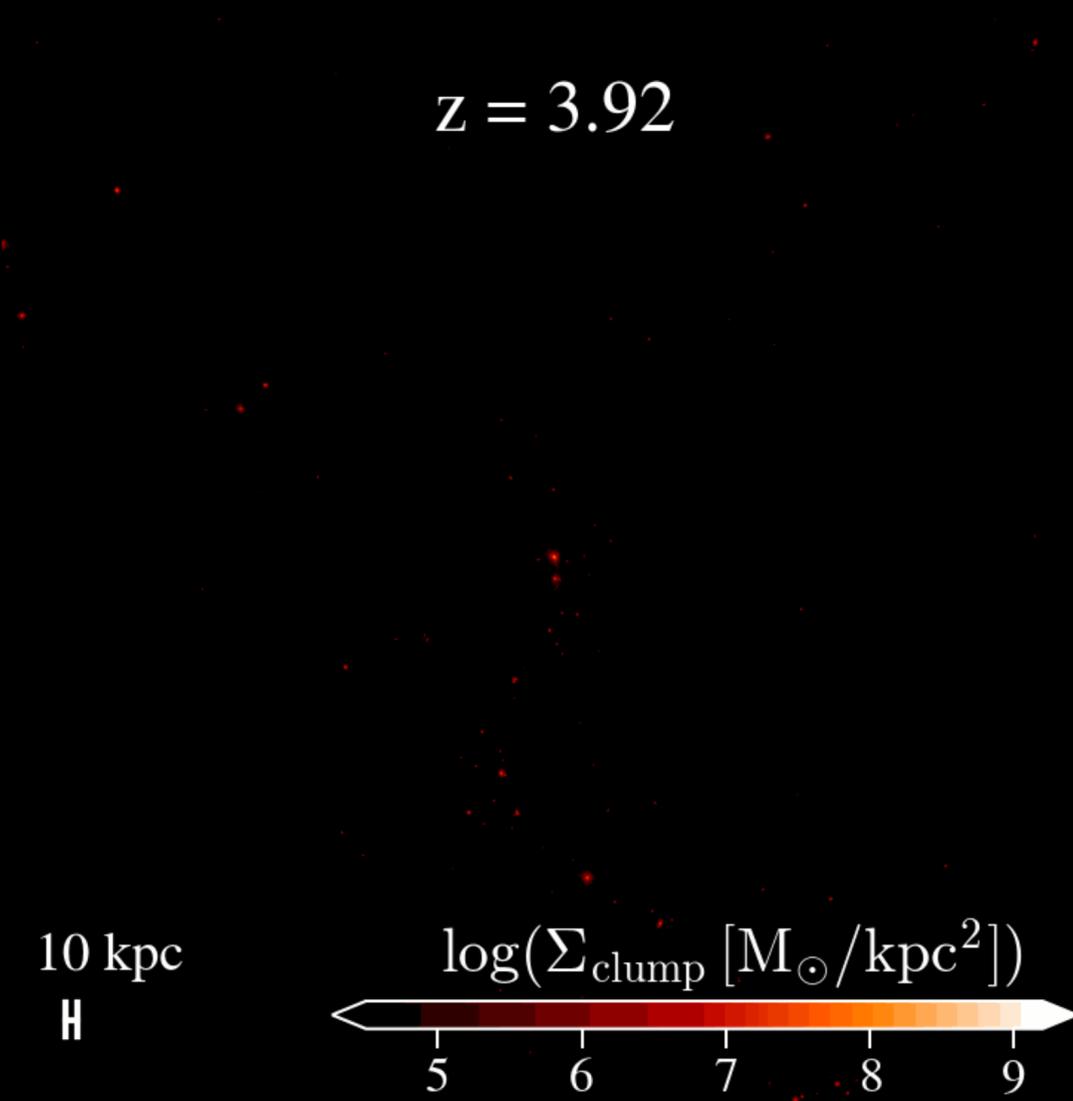
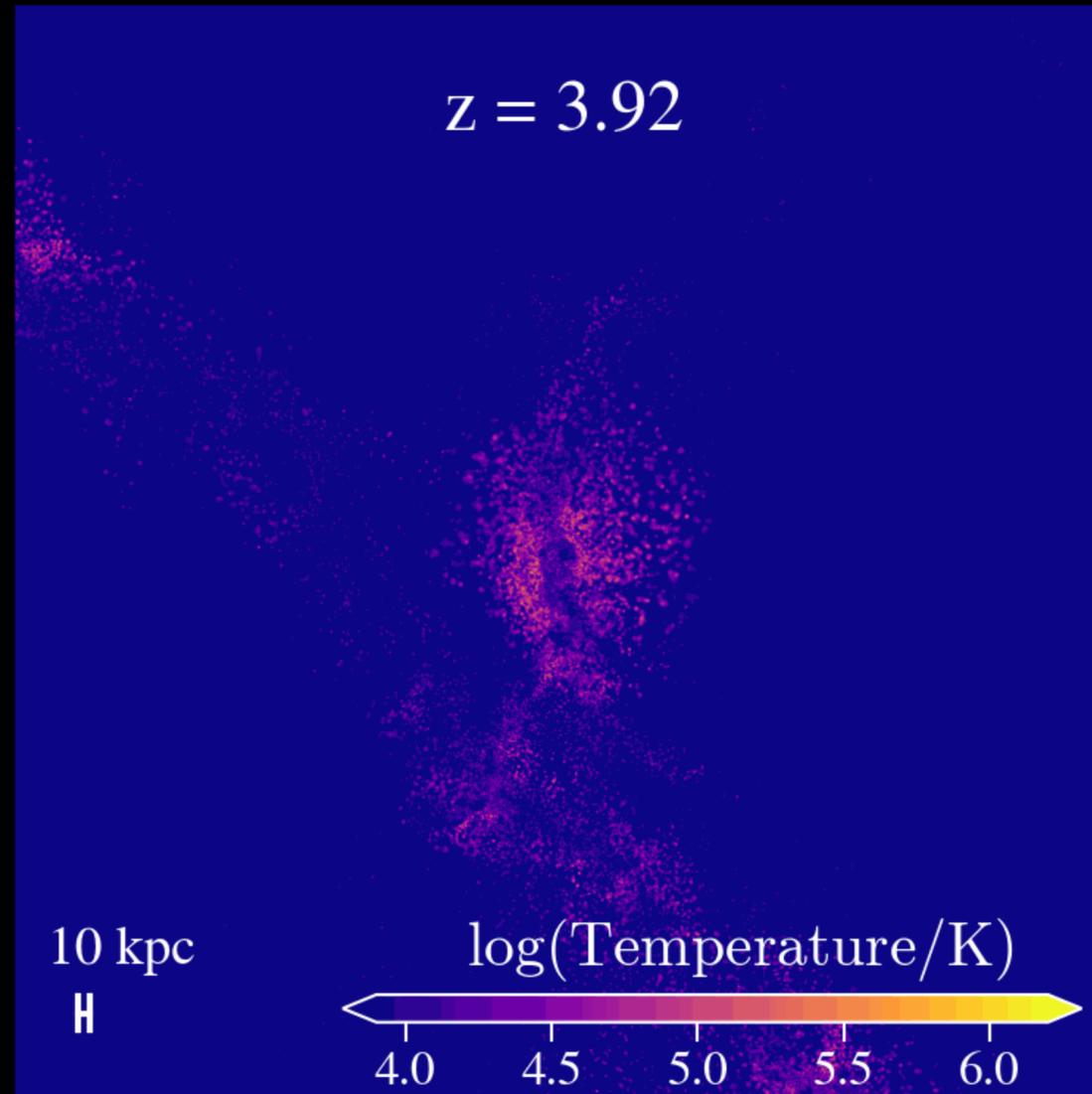
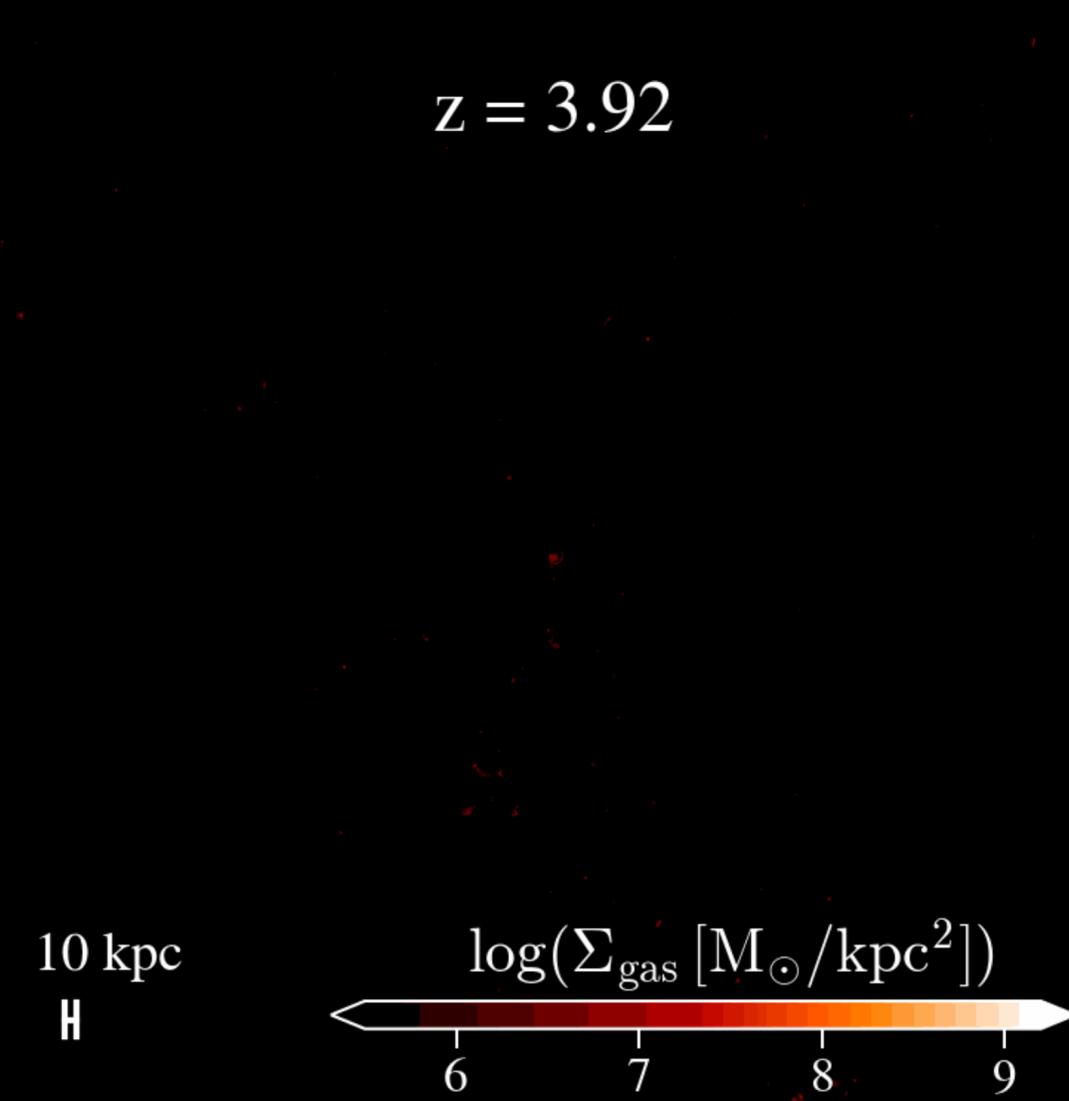
## ADM Gas

## ADM Clumps

$z = 3.92$

$z = 3.92$

$z = 3.92$



# Central ADM Evolution (ADM-1)

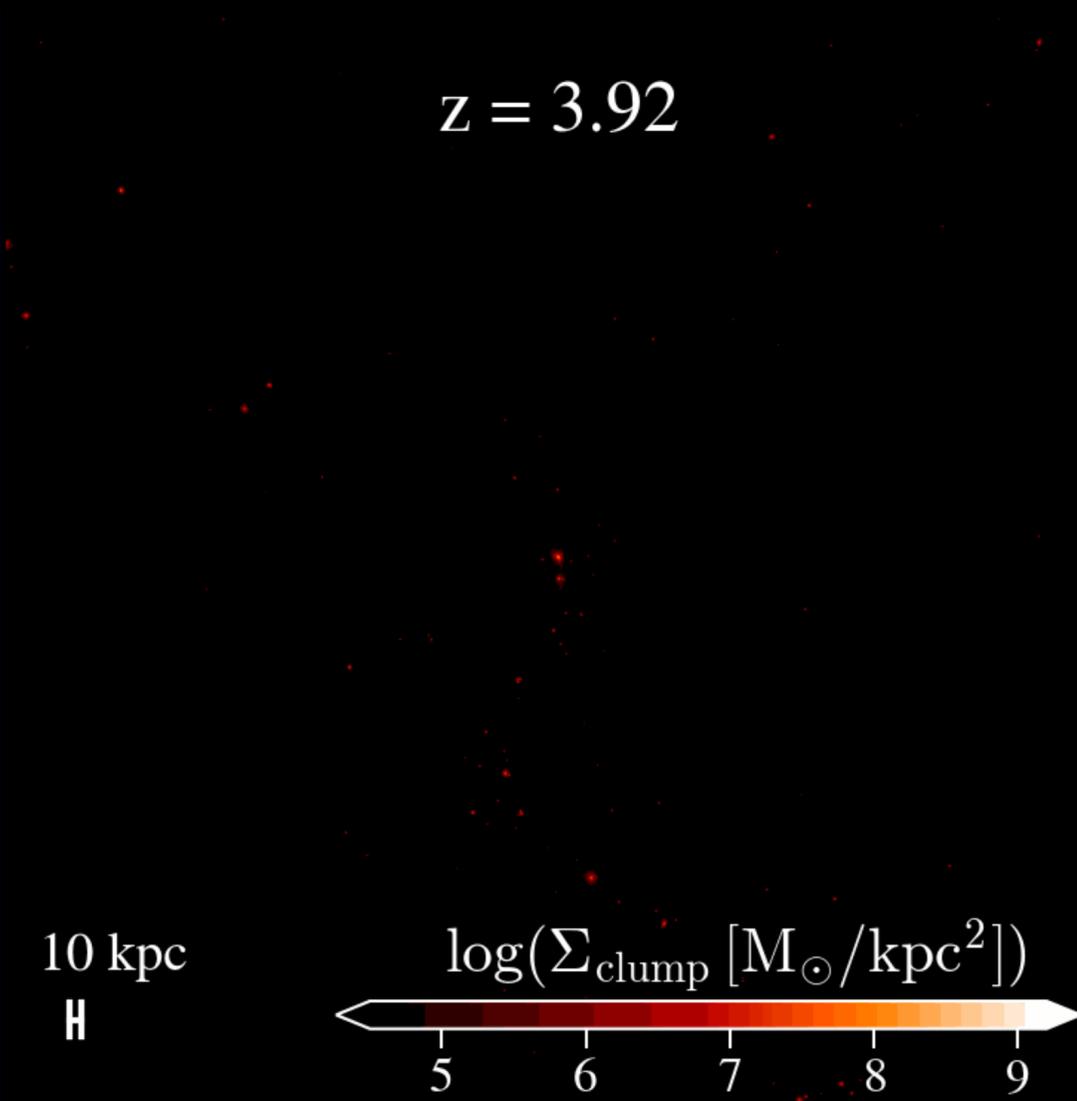
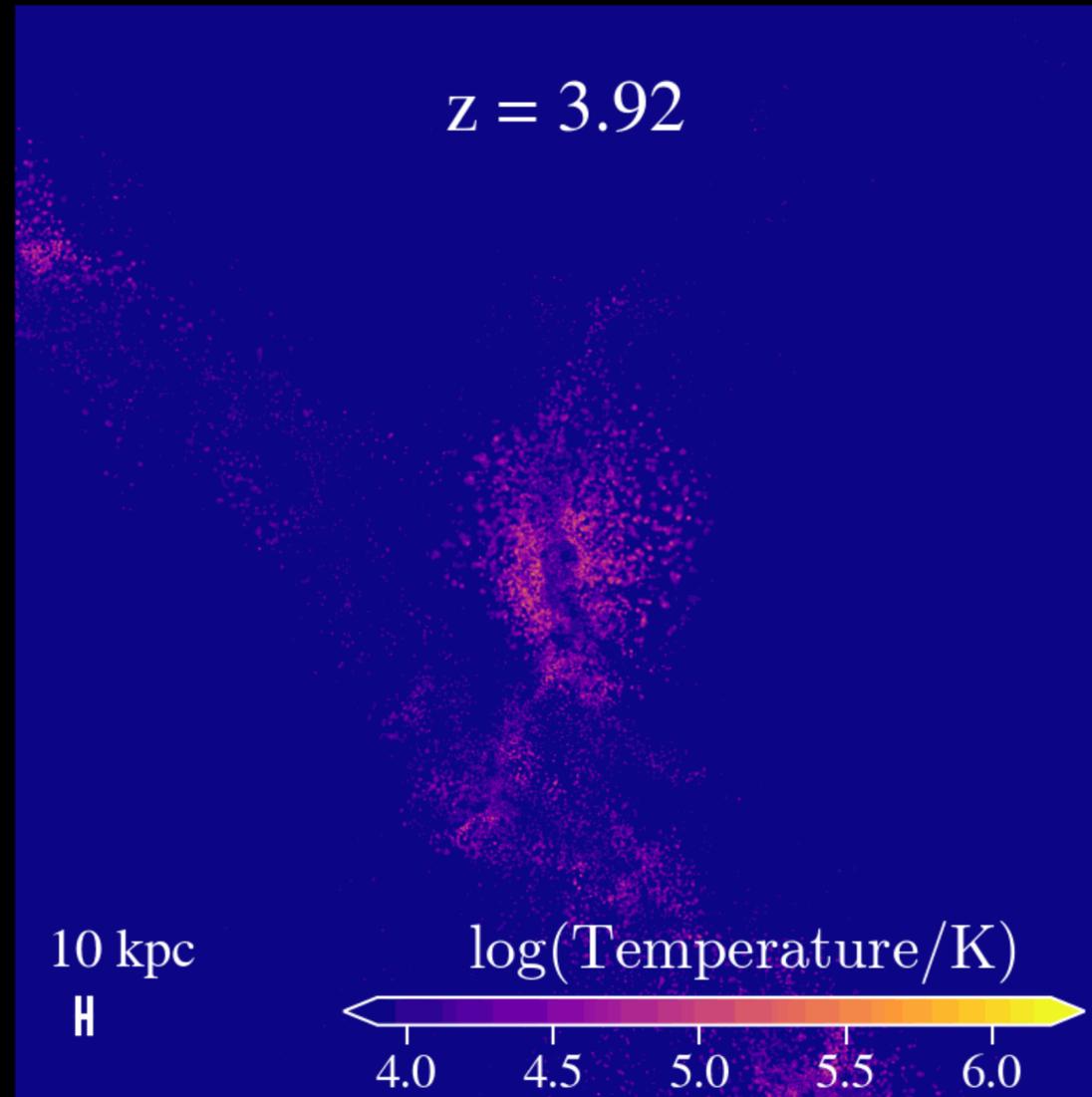
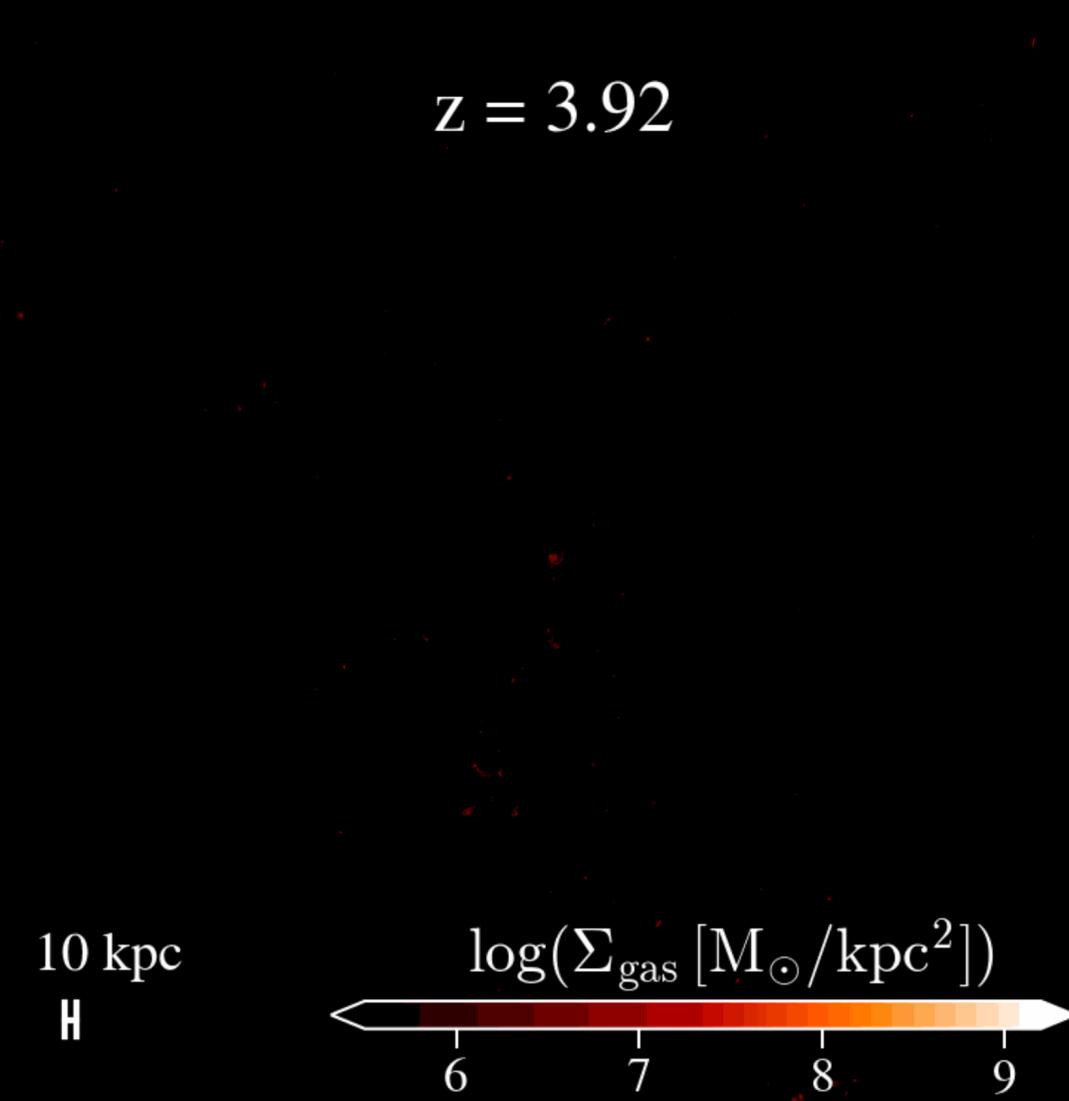
## ADM Gas

## ADM Clumps

$z = 3.92$

$z = 3.92$

$z = 3.92$

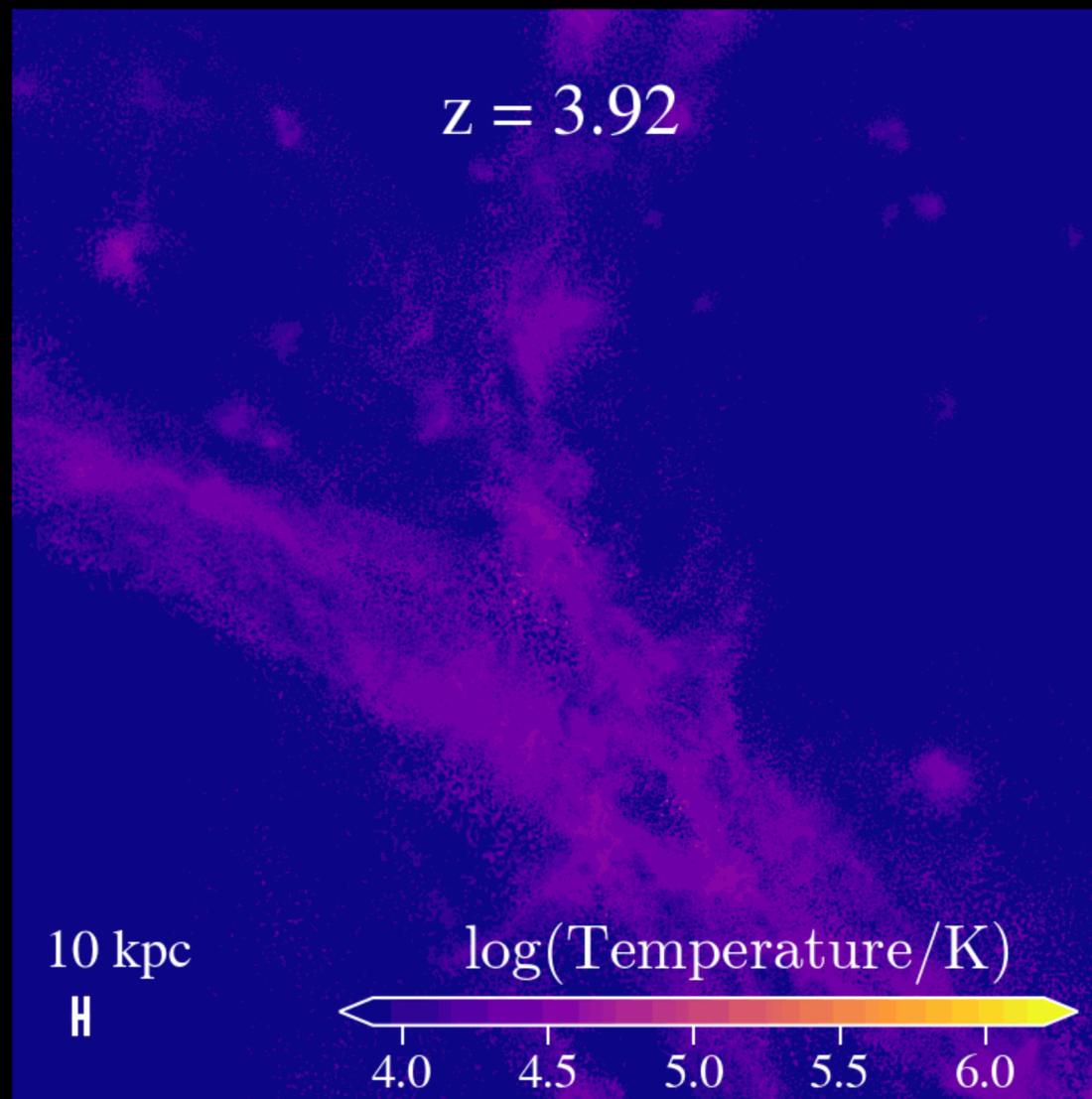


# Central ADM Evolution (ADM-2)

## ADM Gas

$z = 3.92$

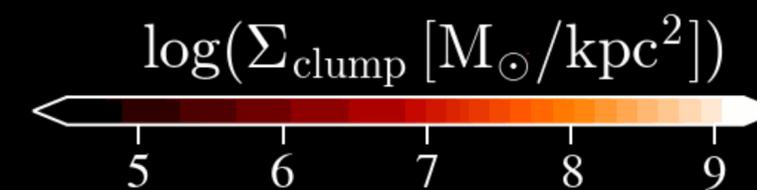
10 kpc  
H



## ADM Clumps

$z = 3.92$

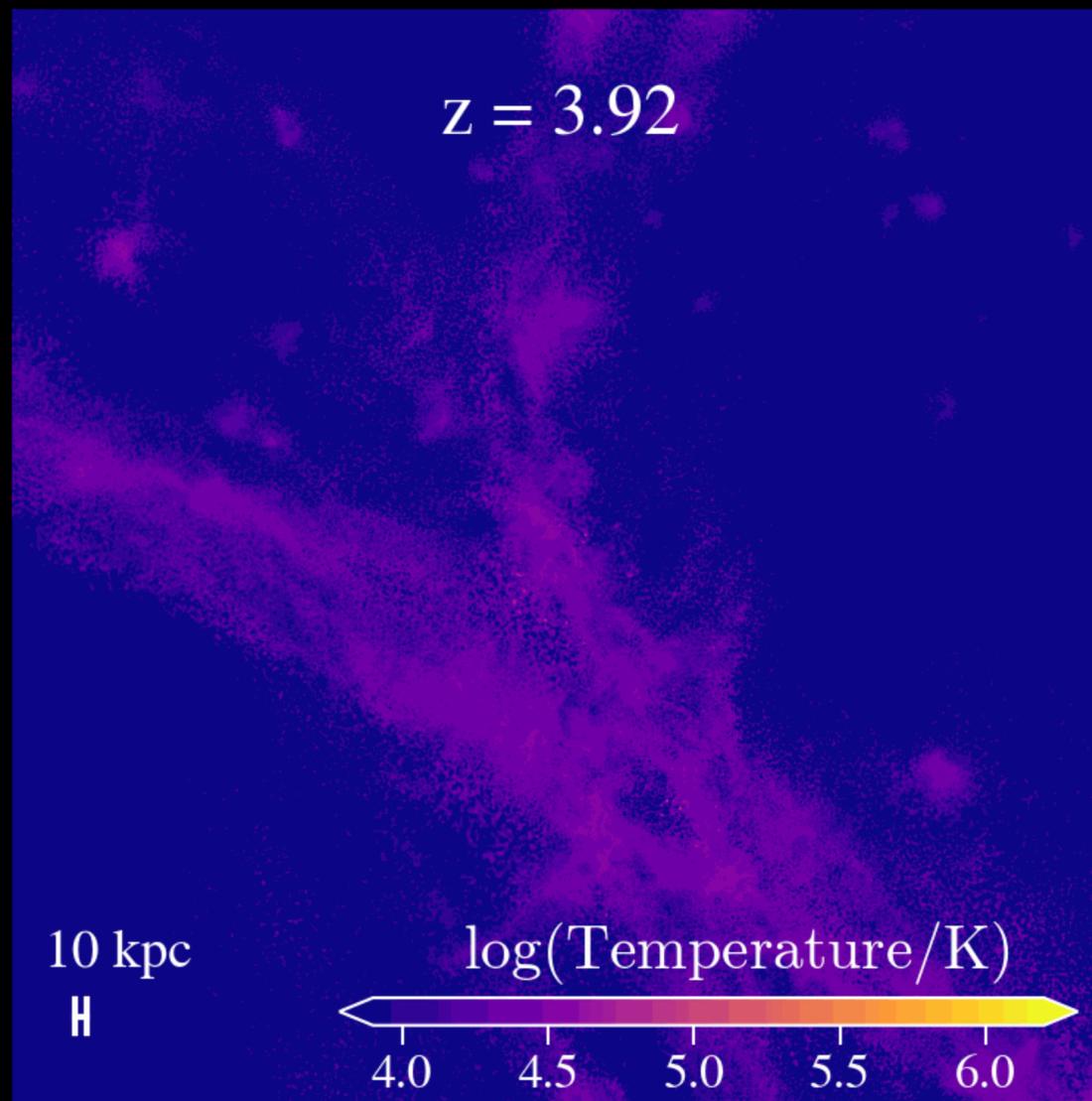
10 kpc  
H



# Central ADM Evolution (ADM-2)

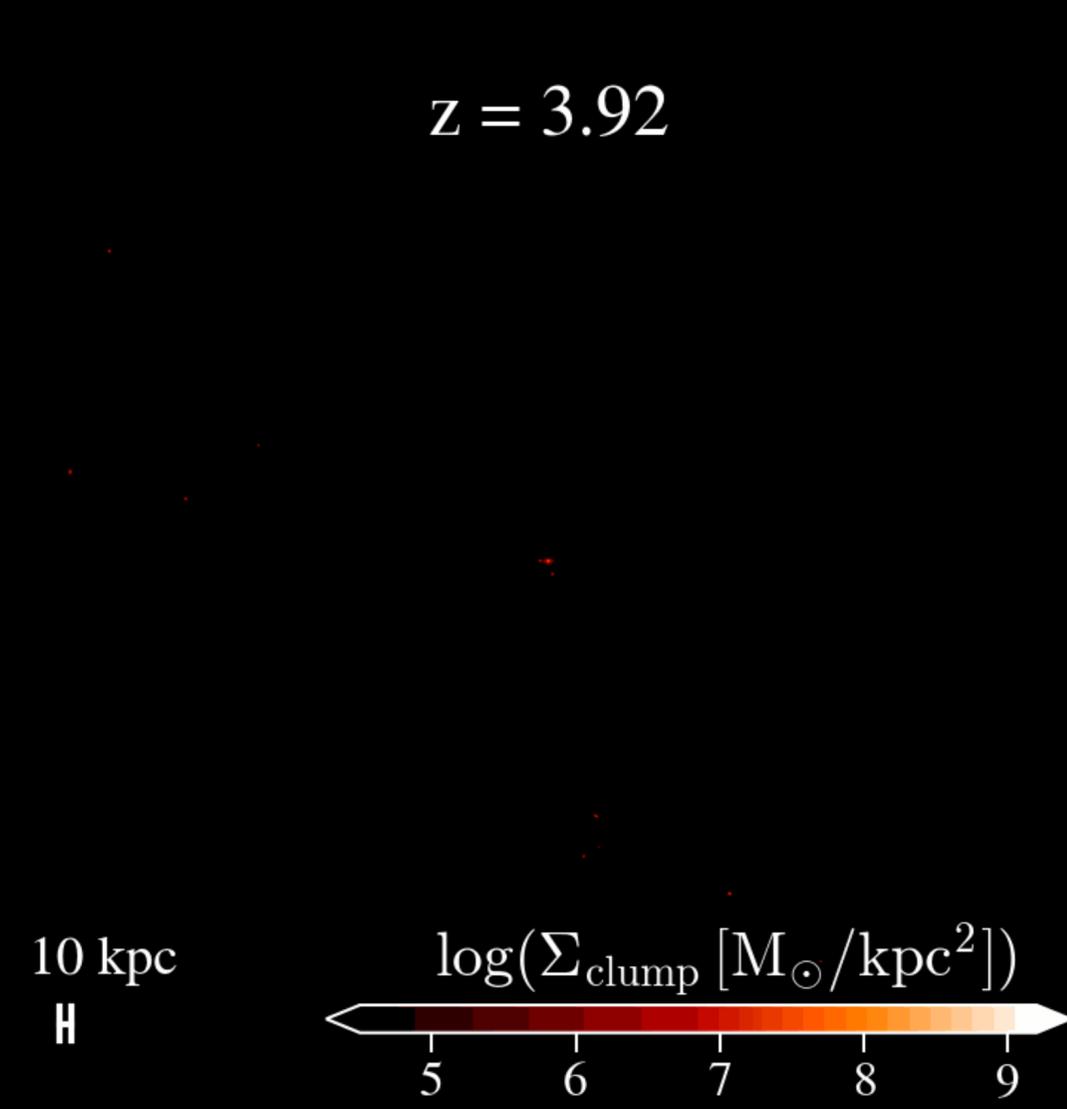
## ADM Gas

$z = 3.92$



## ADM Clumps

$z = 3.92$



# Cooling Rate with Varying ADM Parameters

