The Cosmic Rays Corona

In Milky Way analogues

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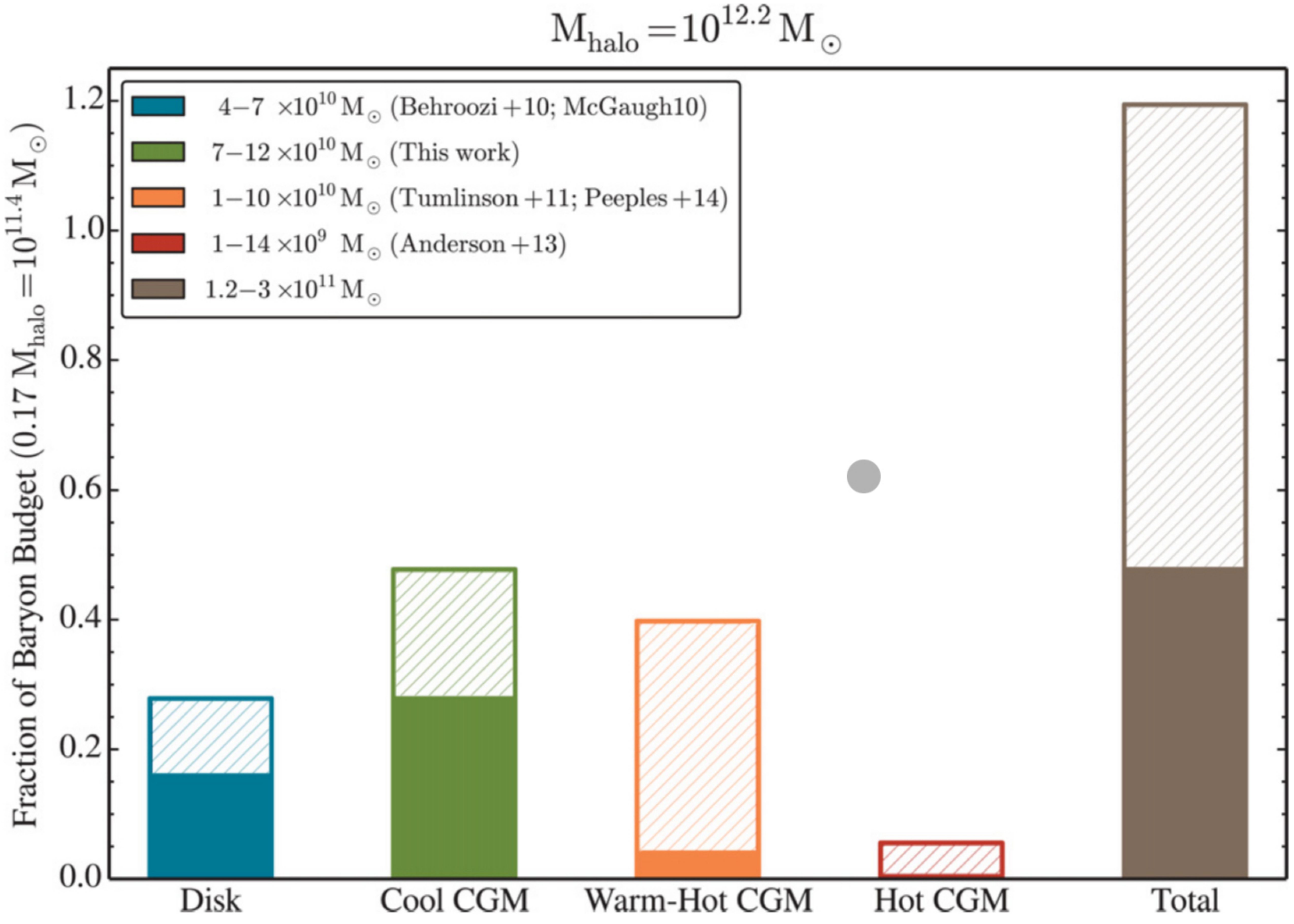
Francisco Rodríguez Montero (KICP, UChicago) - Feedback on Galaxy Formation, AIP July 2025

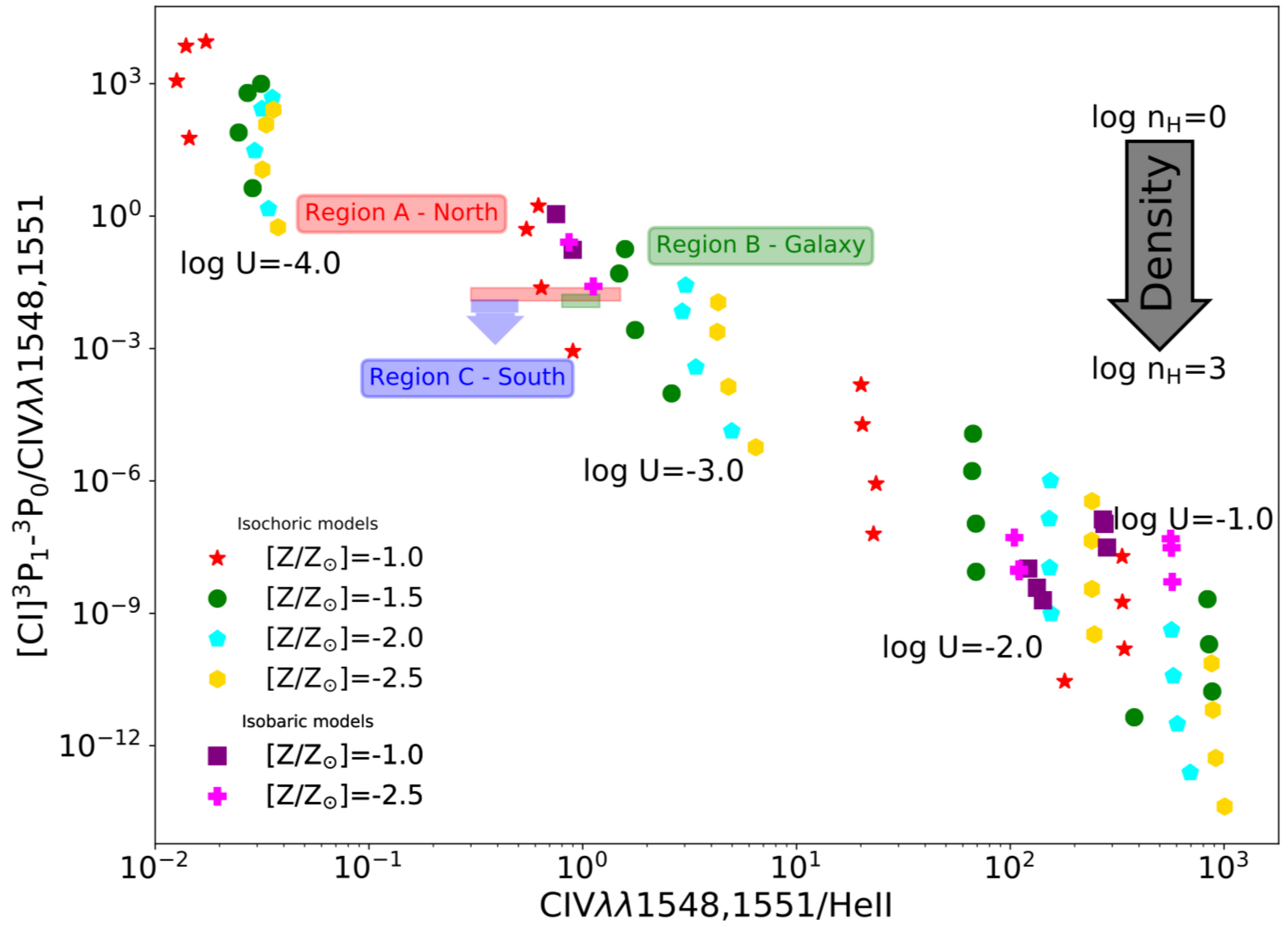
Cool gas in the CGM

There is ample observational evidence for cool (~10^4 K) gas embedded in the hot CGM

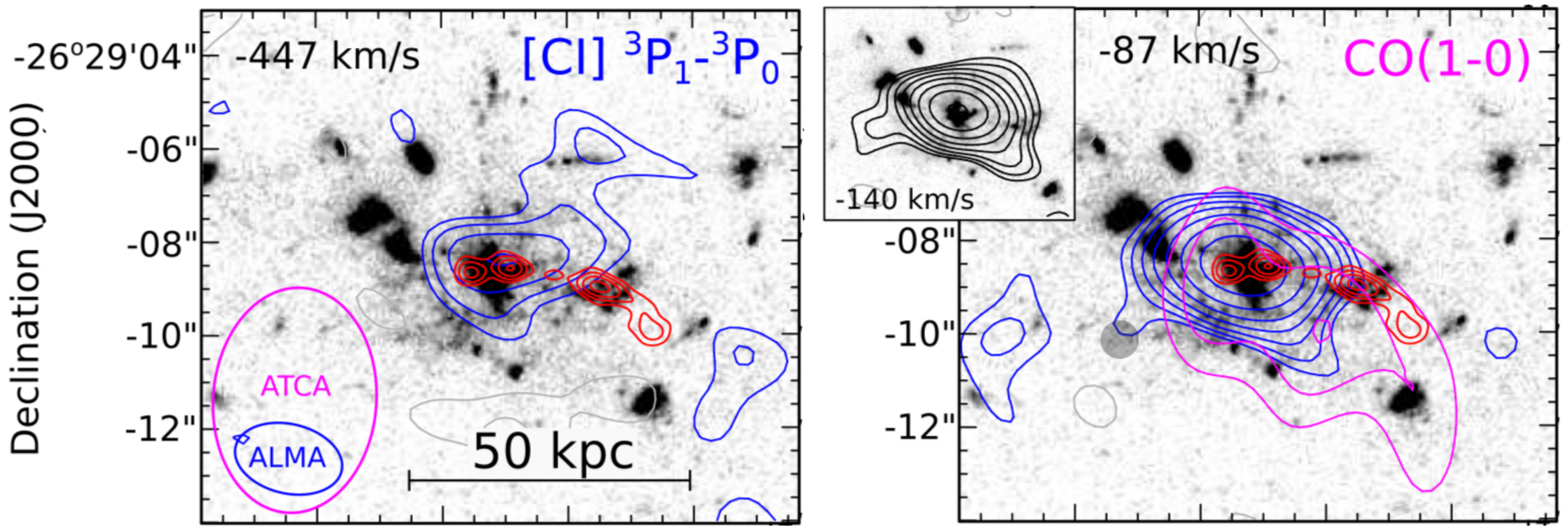


Werk et al. (2014)

Falkendal et al. (2021)



MUSE and ALMA are now mapping the contribution of cool gas at high z



Cool gas in the CGM

There are a few classes of competing ideas for the presence of **cool clouds** in outflows and the CGM:

I. **In situ formation** (Thompson+2016,Scannapieco+2017,Schneider+2018)

II.**Acceleration by the hot wind** (Klein+1994)

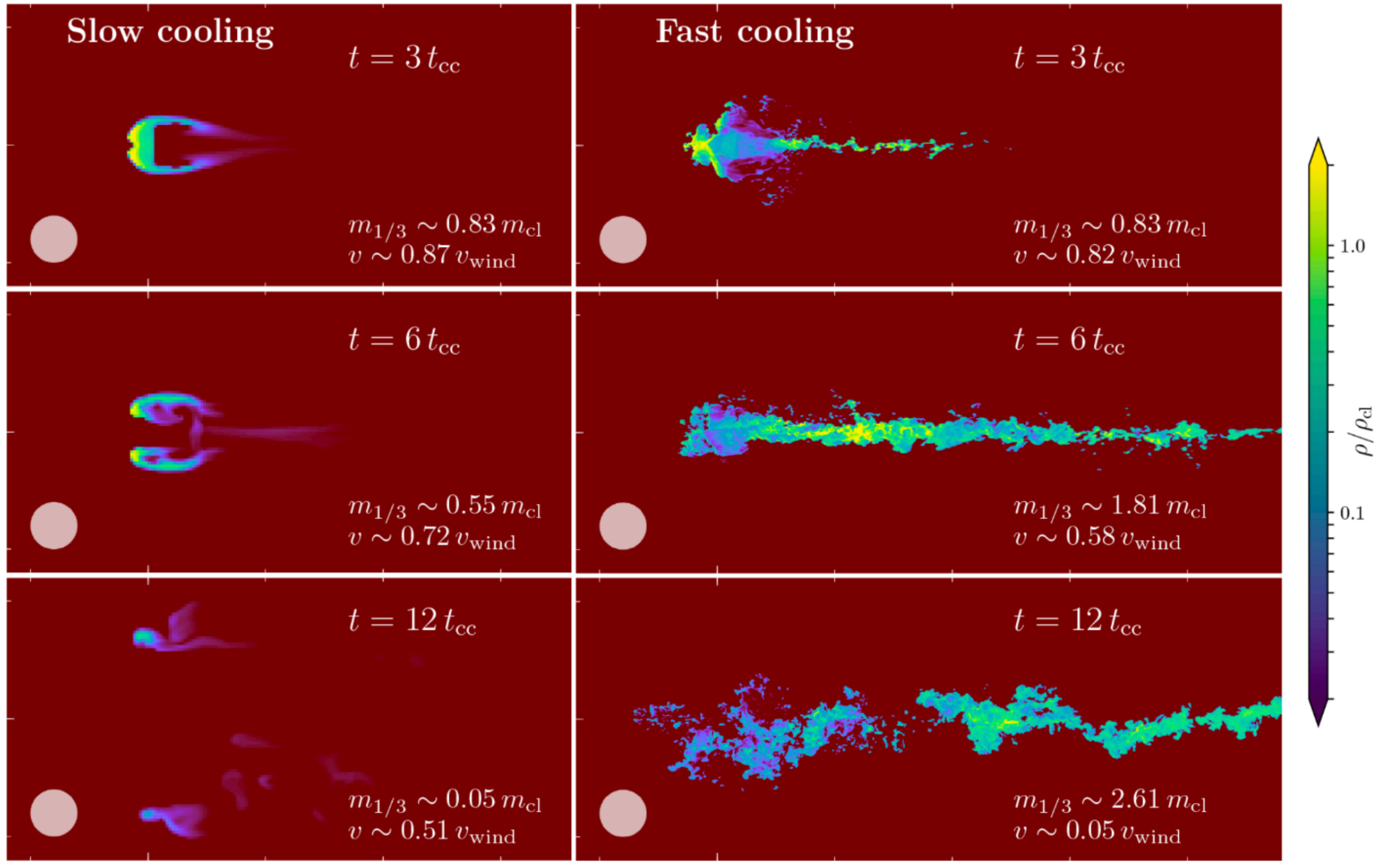
III.**Acceleration by magnetic drapping**
(Lyutikov+2006,Dursi&Pfrommer2008)

IV.**Acceleration by radiation pressure** (Murray+2011,Hopkins+2011)

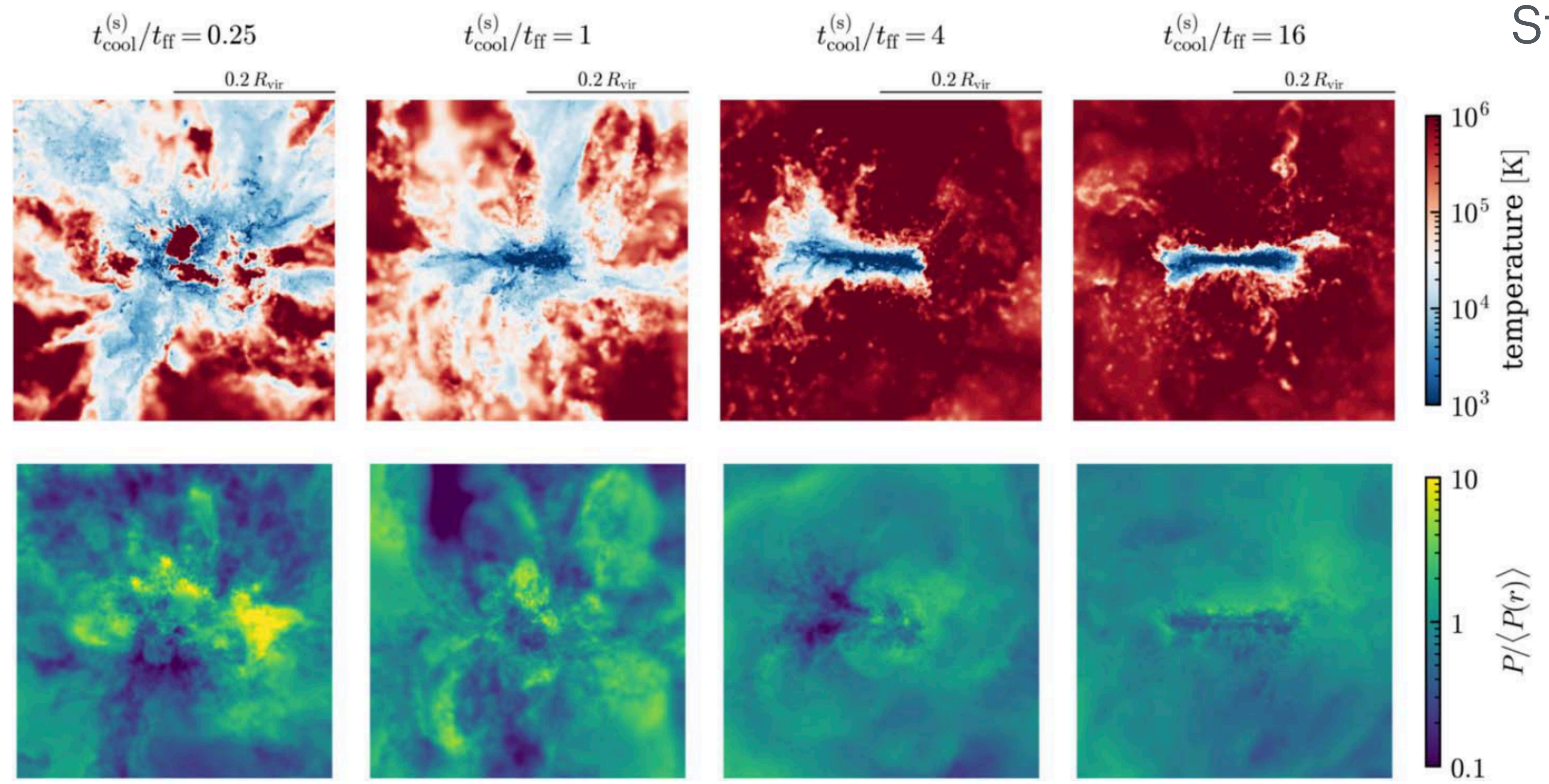
V.**CR bottlenecks** (Wiener+2017)

VI.**CR pressure gradients** (Thomas+2021,Armillotta+2022,Rodríguez Montero+2024)

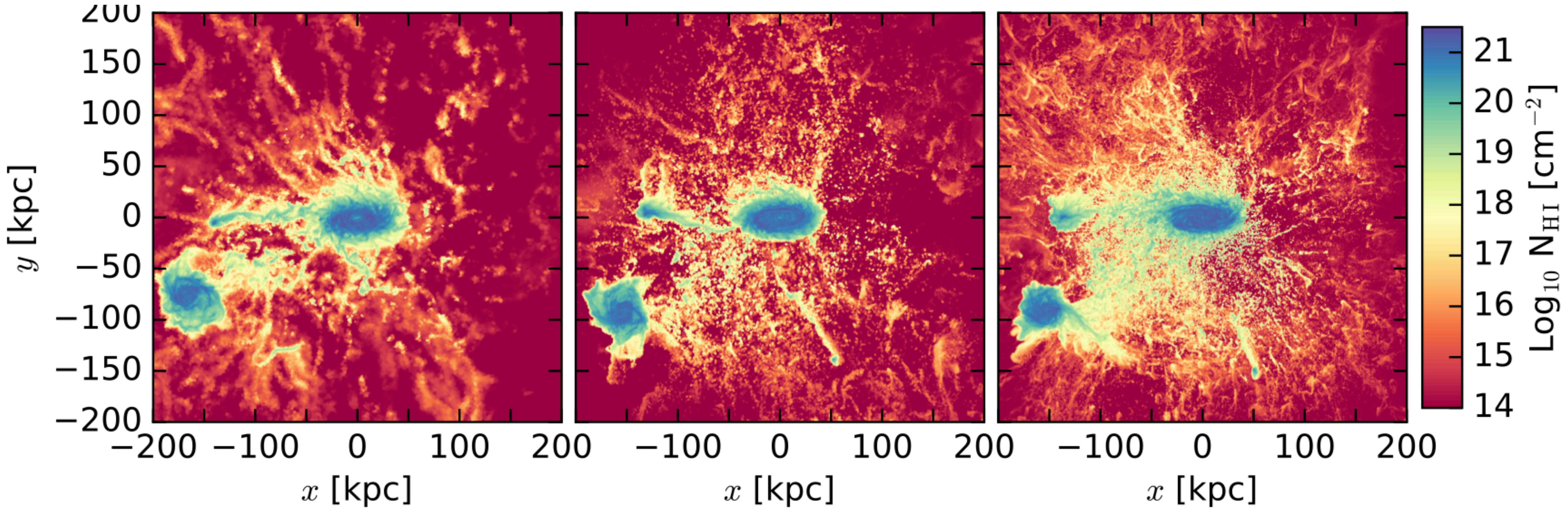
Gronke&Oh+2018



Stern+2021



van de Voort+2018

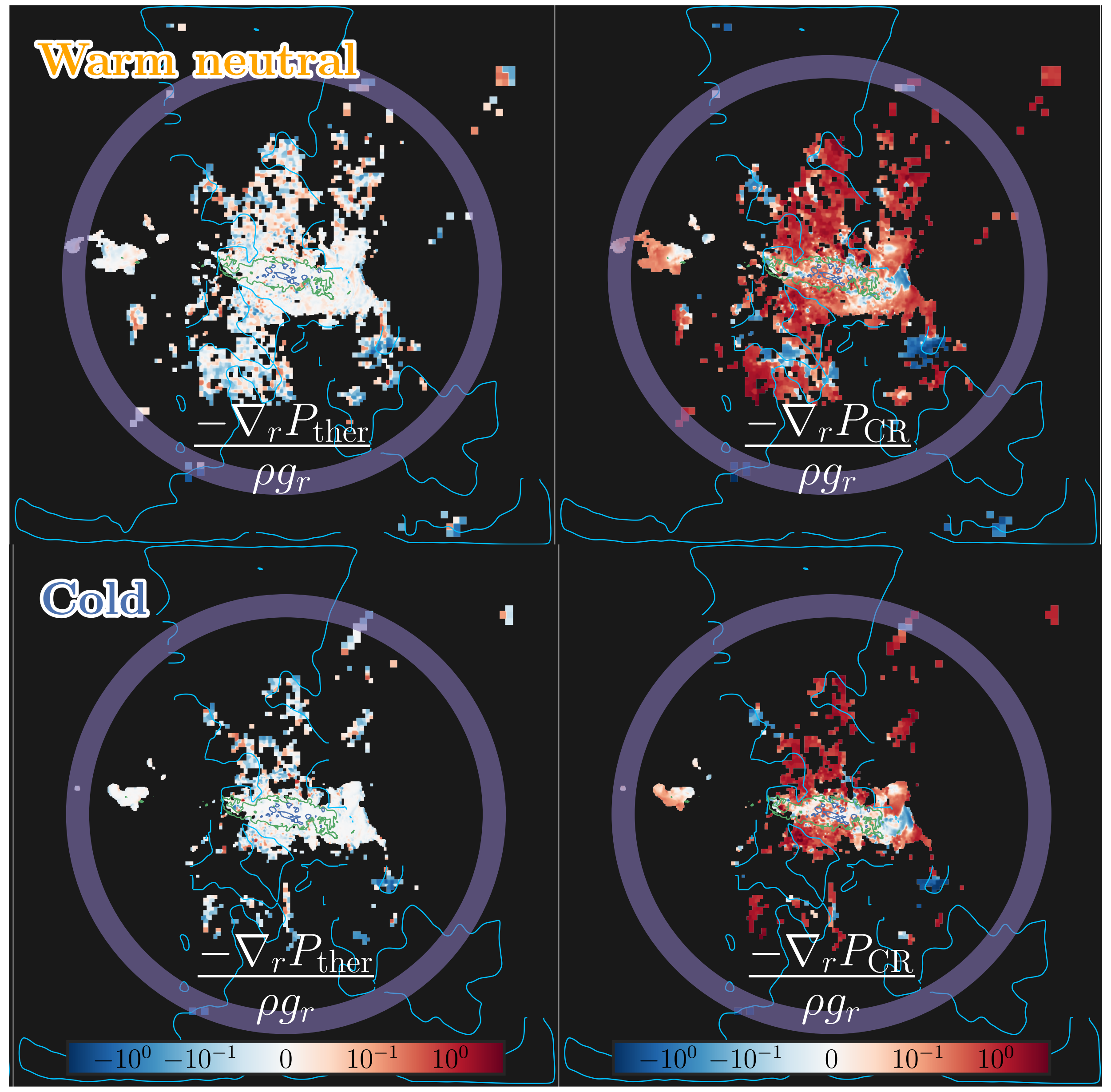


CRs in the CGM

CRs can influence the presence of cool gas in the CGM

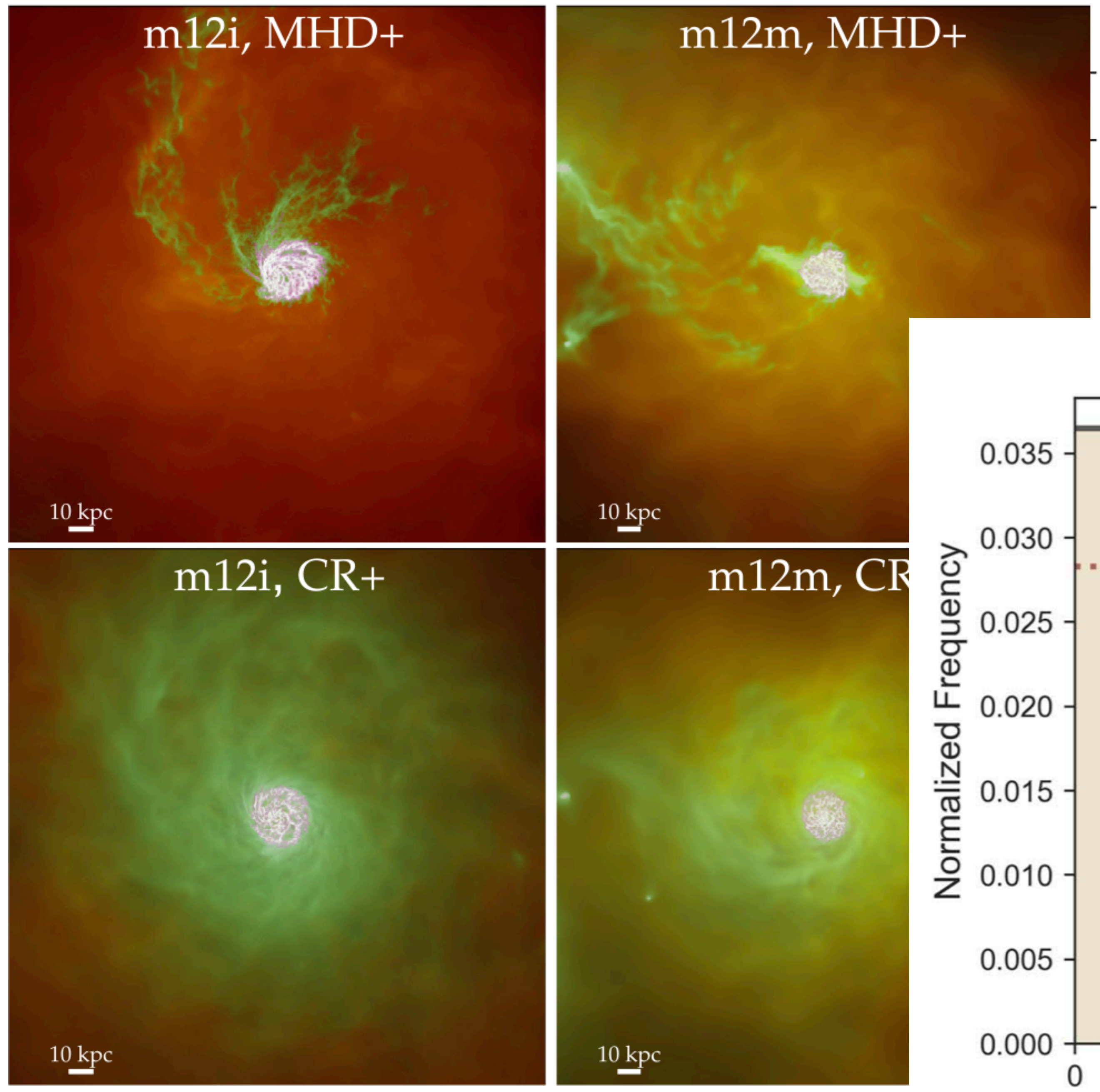
By carrying it in outflows

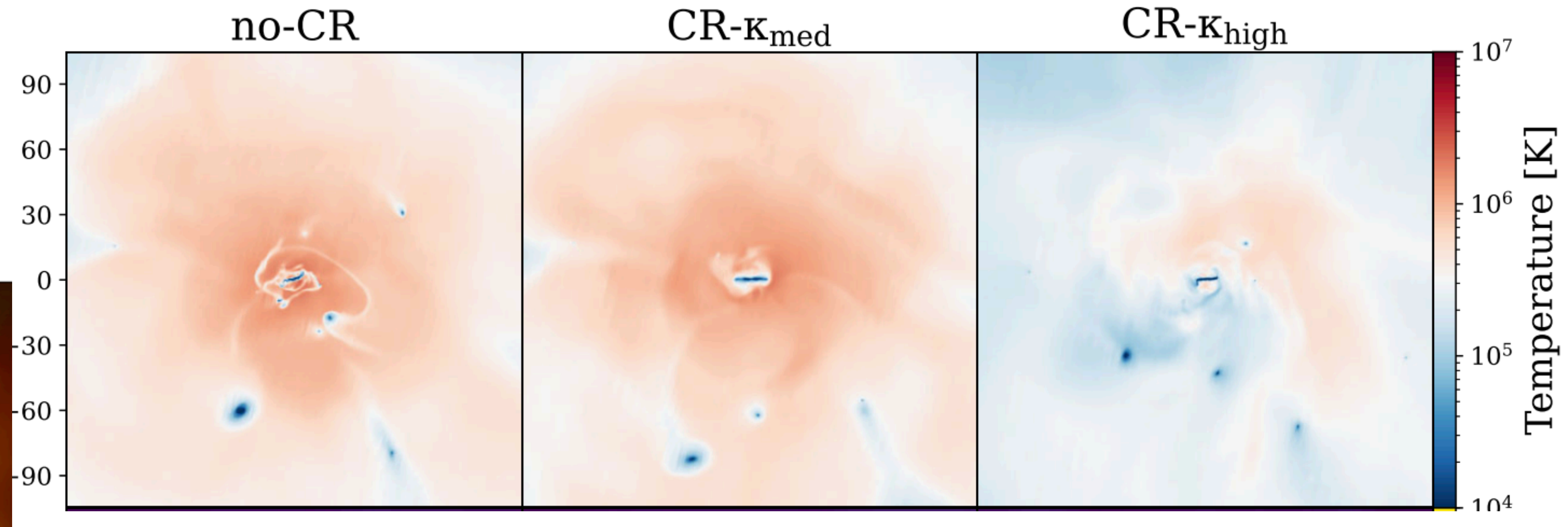
By influencing the CGM thermal instability



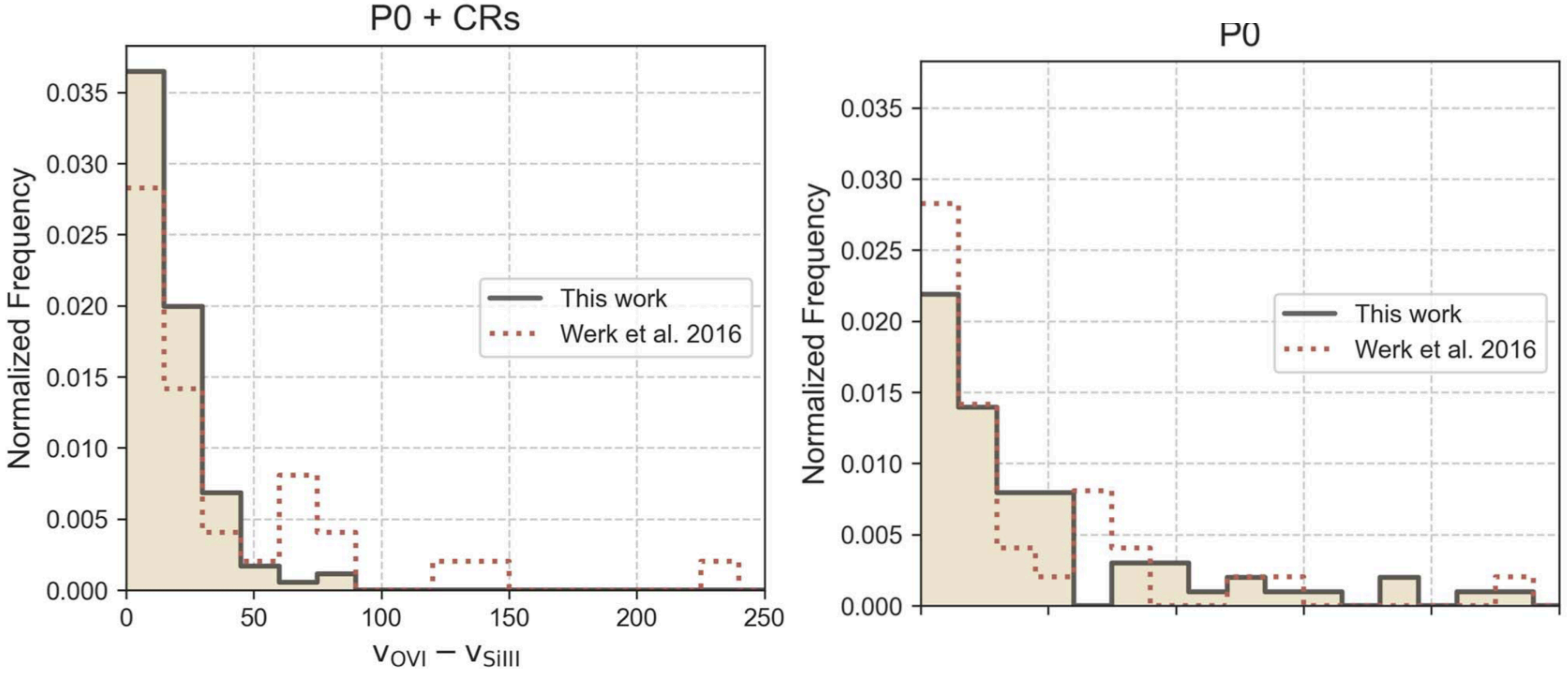
Rodríguez Montero+2024

Ji+2020





DeFelippis+2024



Butsky+2022

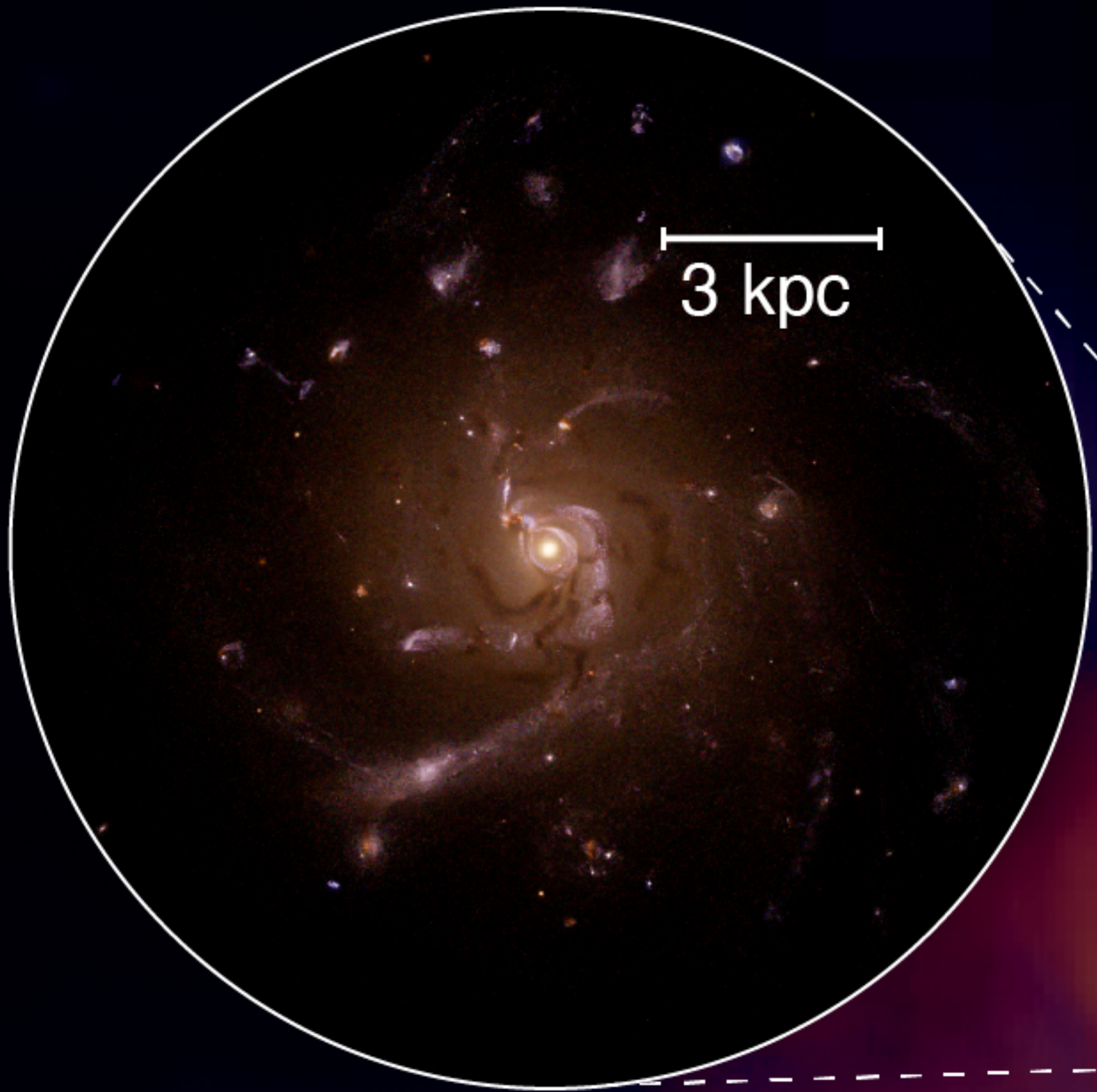
The NUT suite of simulations

High resolution cosmological context for CR feedback

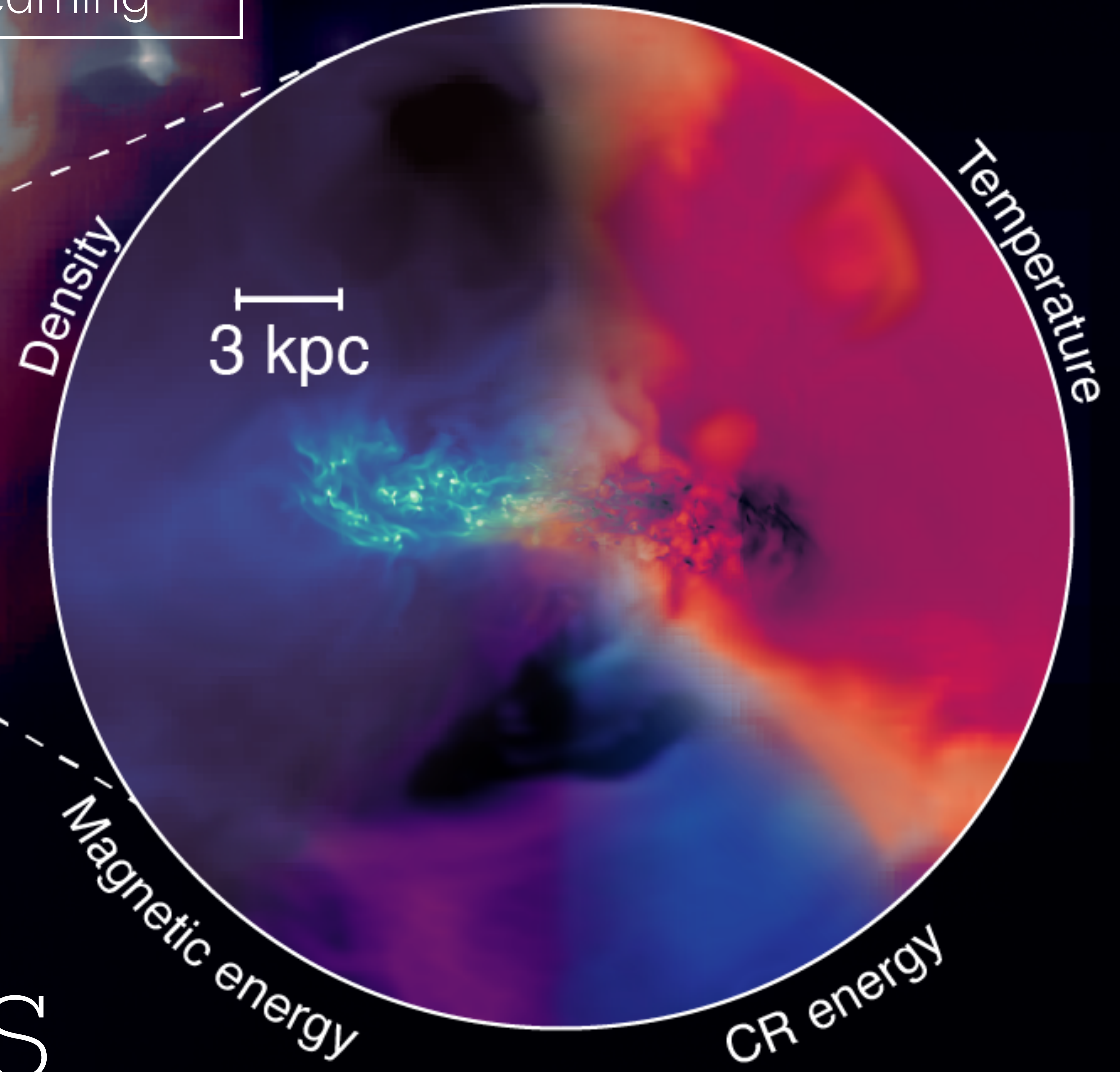
- Cooling down to 15 K
- Local star formation efficiency
- Mechanical feedback model
- Supernova metal enrichment
- UV Background turned on at $z = 9$
- Initial magnetic field of 3×10^{-12} G
- $\kappa_{\rm diff} = 3 \times 10^{28} {\rm cm/s}^2$ + streaming

$z = 1.5$

50 kpc

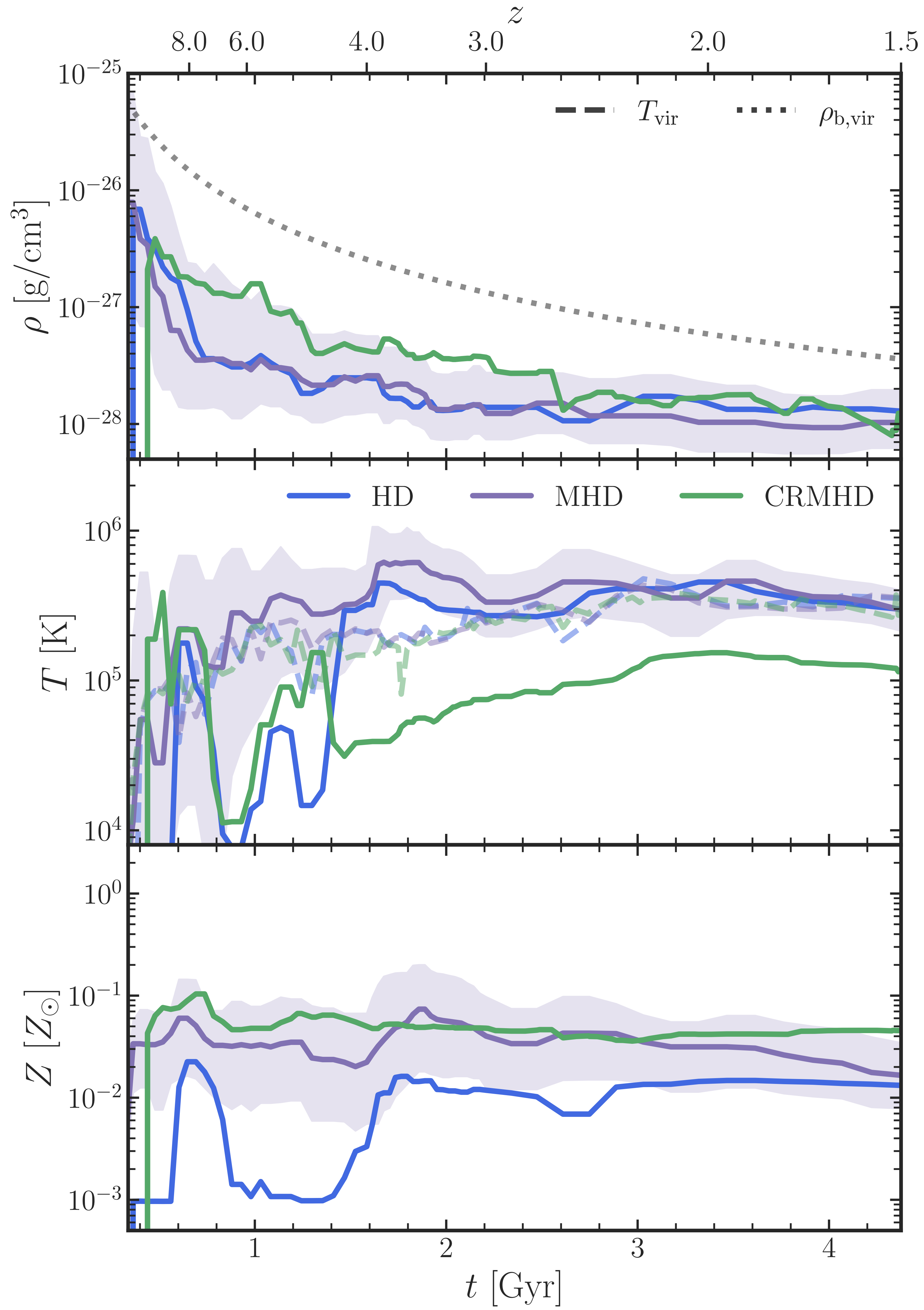


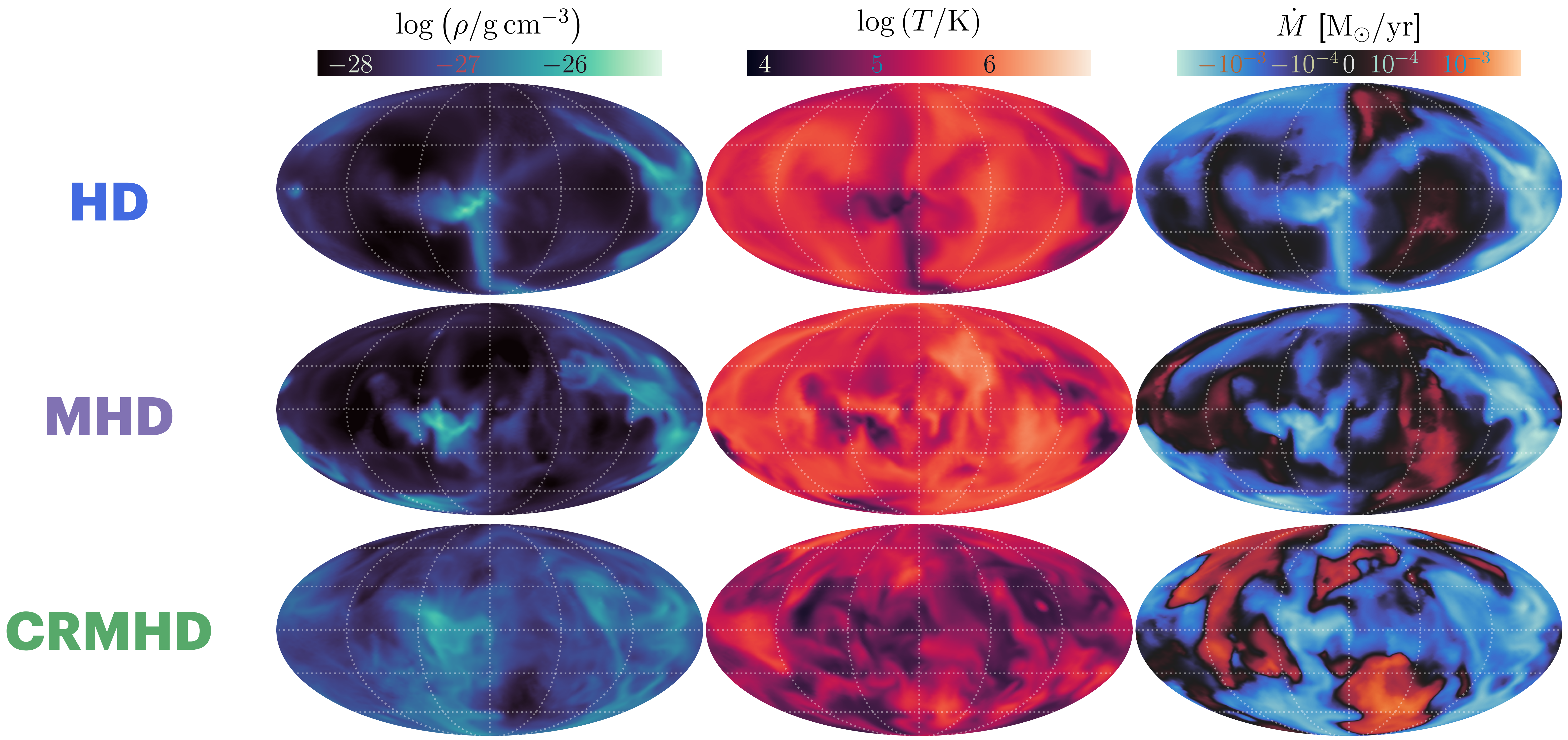
[F200W,F150W,F090W]$_{\rm JWST}$



See Rodríguez Montero et al. (2024a)

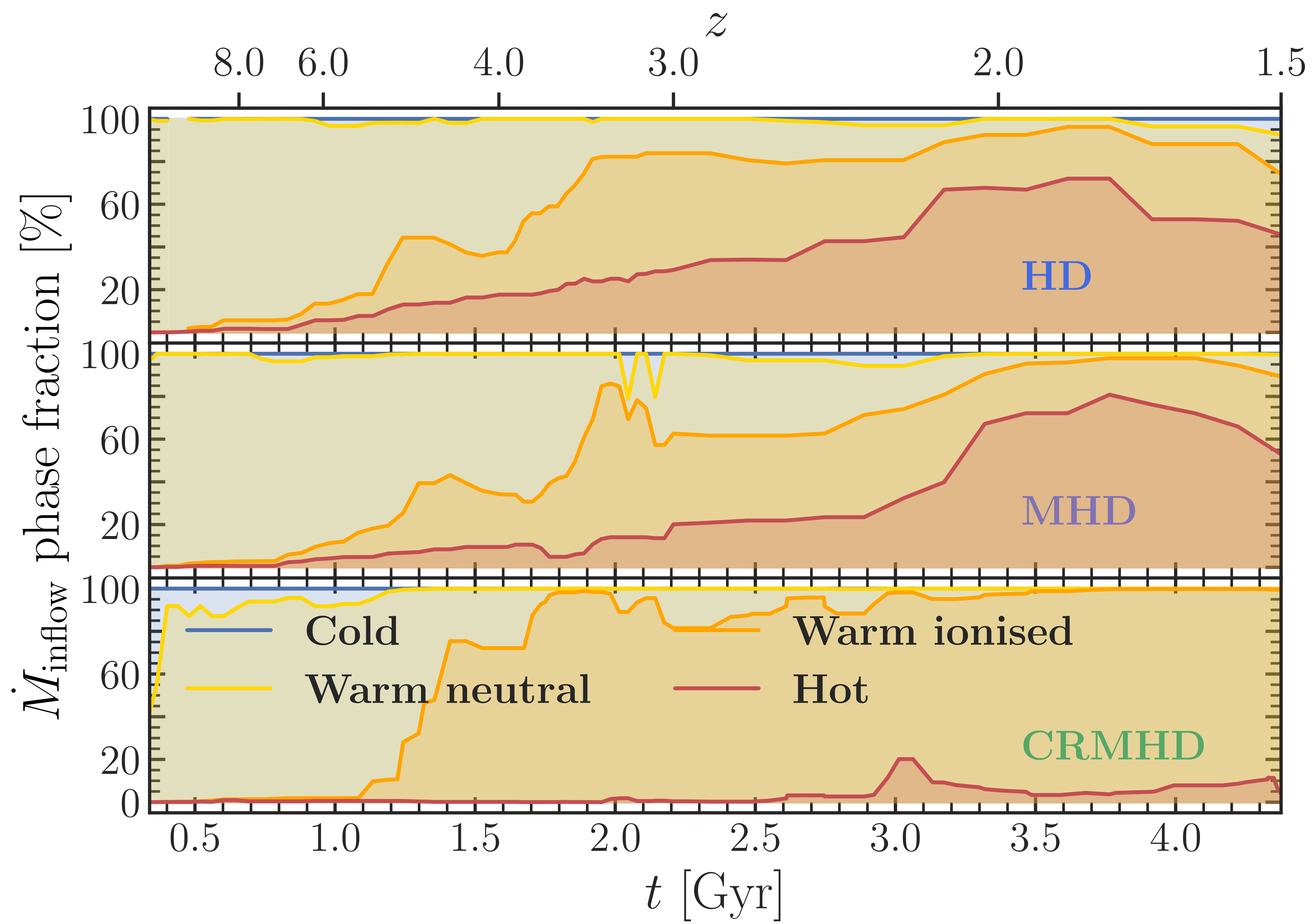
The CGM of NUT across cosmic time

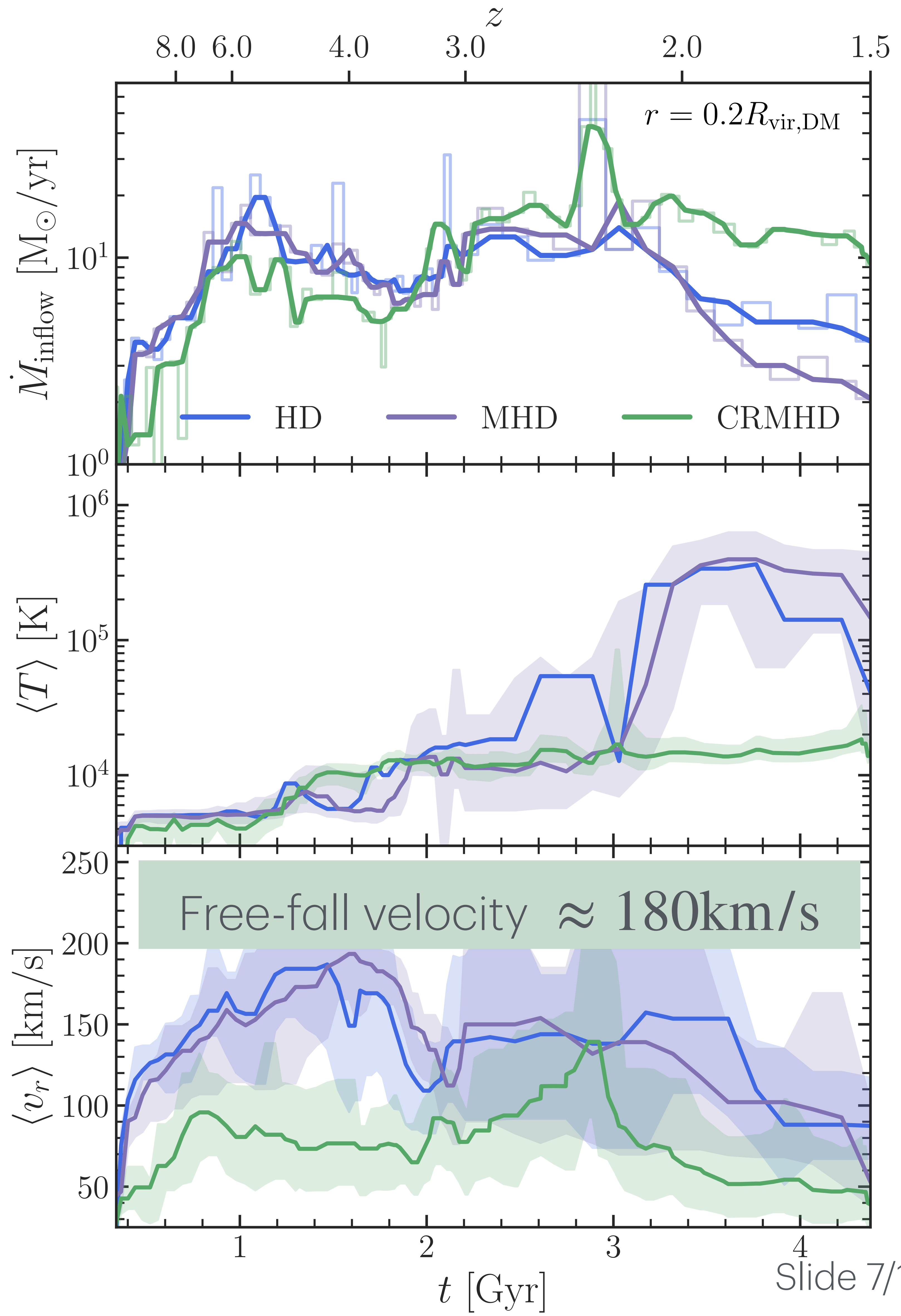




With CRs: Diffuse, cool and dense CGM; filaments highly disturbed

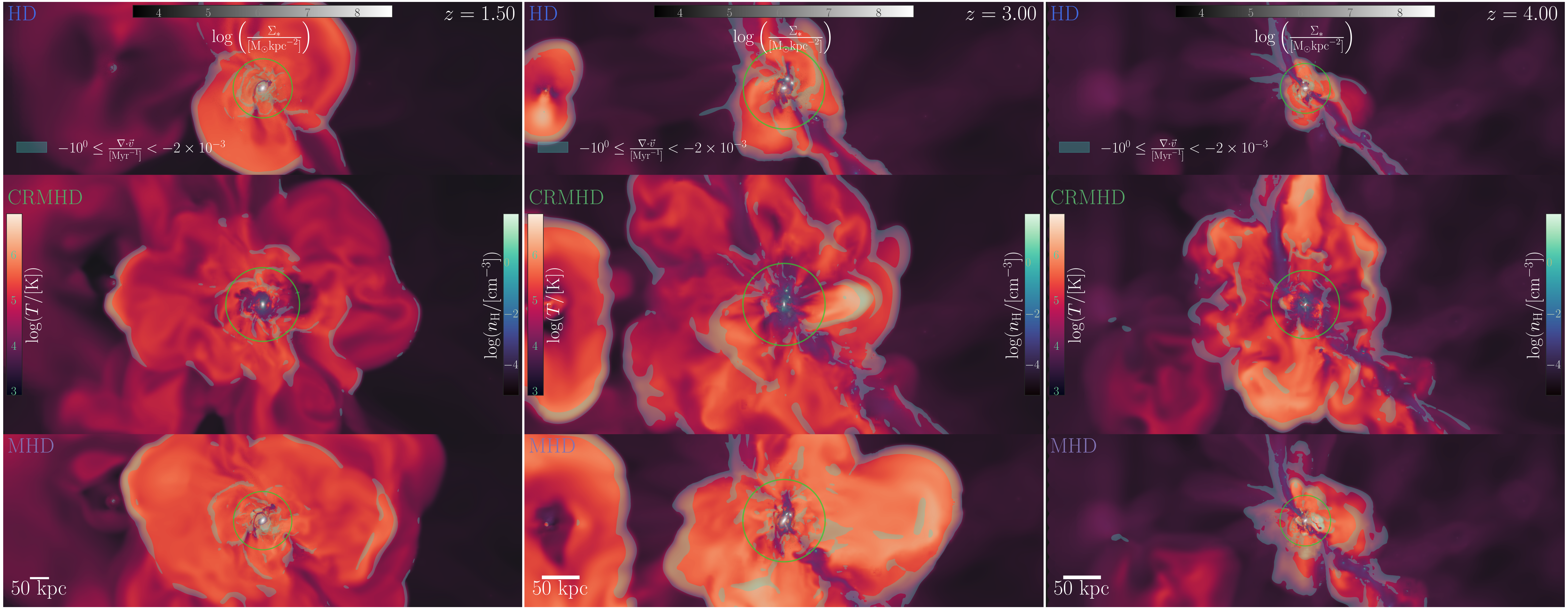
Gas inflow from super-halo scales

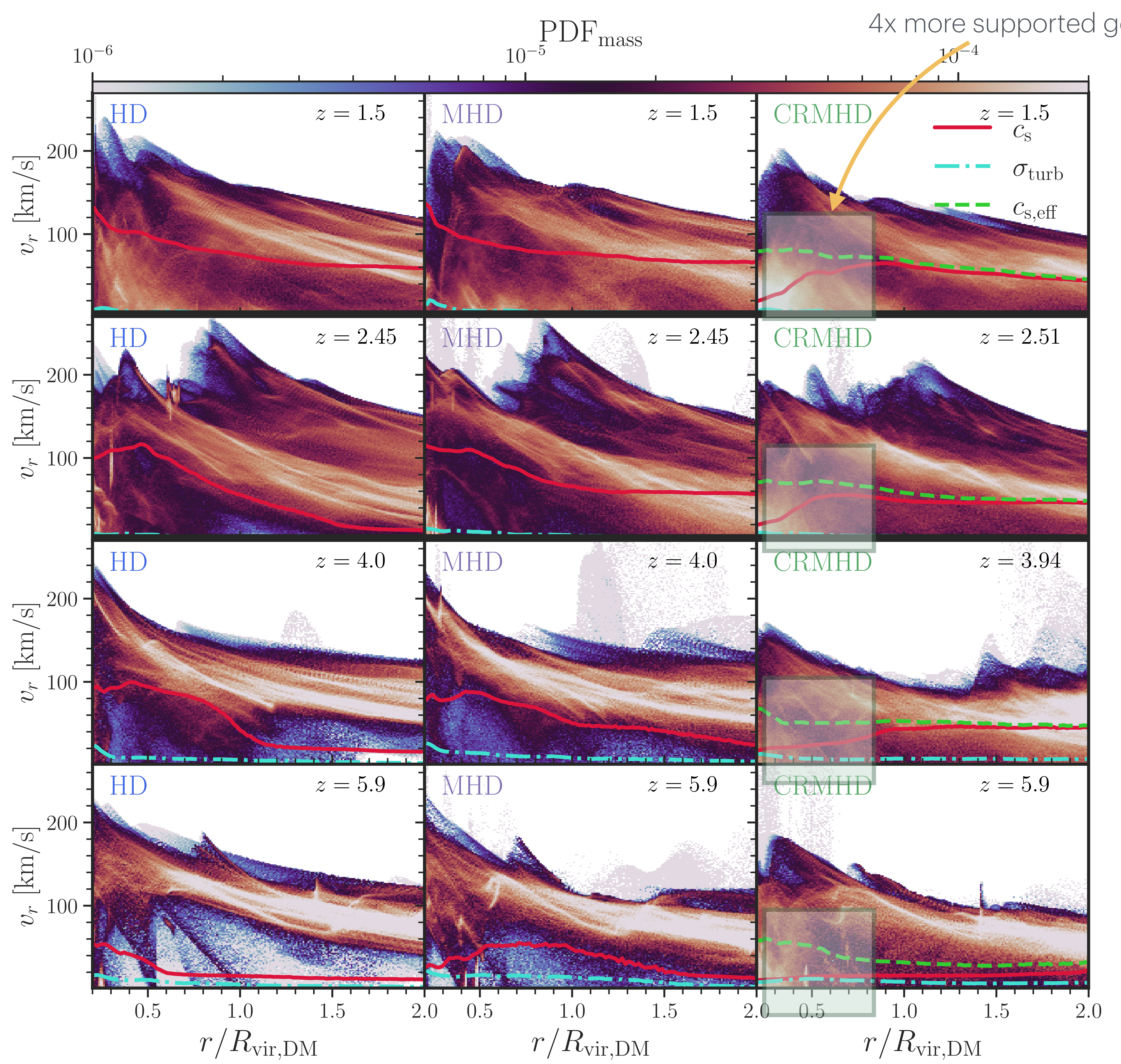




Gas inflow from super-halo scales

Later in cosmic time





Gas inflow from super-halo scales

$$c_{s,eff} = \sqrt{\frac{\gamma_{gas}P_{th} + \gamma_{CR}P_{CR}}{\rho}}$$

Thermal pressure support

$\nabla_r P_{ther} \geq \rho \nabla_r \phi$

Rotational support

$v_t^2/r \geq \nabla_r \phi$

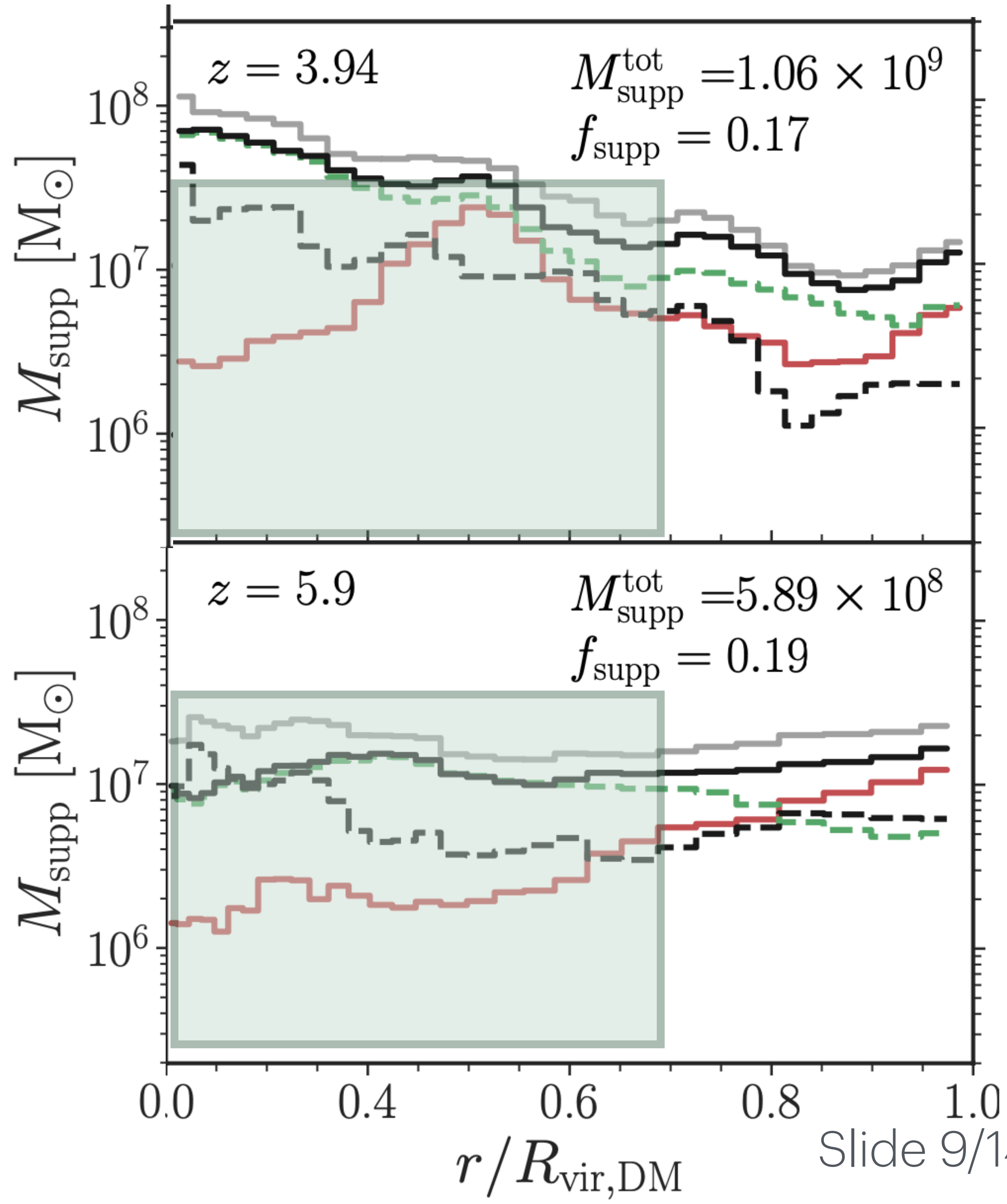
CR pressure support

$\nabla_r P_{CR} \geq \rho \nabla_r \phi$

$\nabla_r P_{tot} \geq \rho \nabla_r \phi$

Spin-realignment region

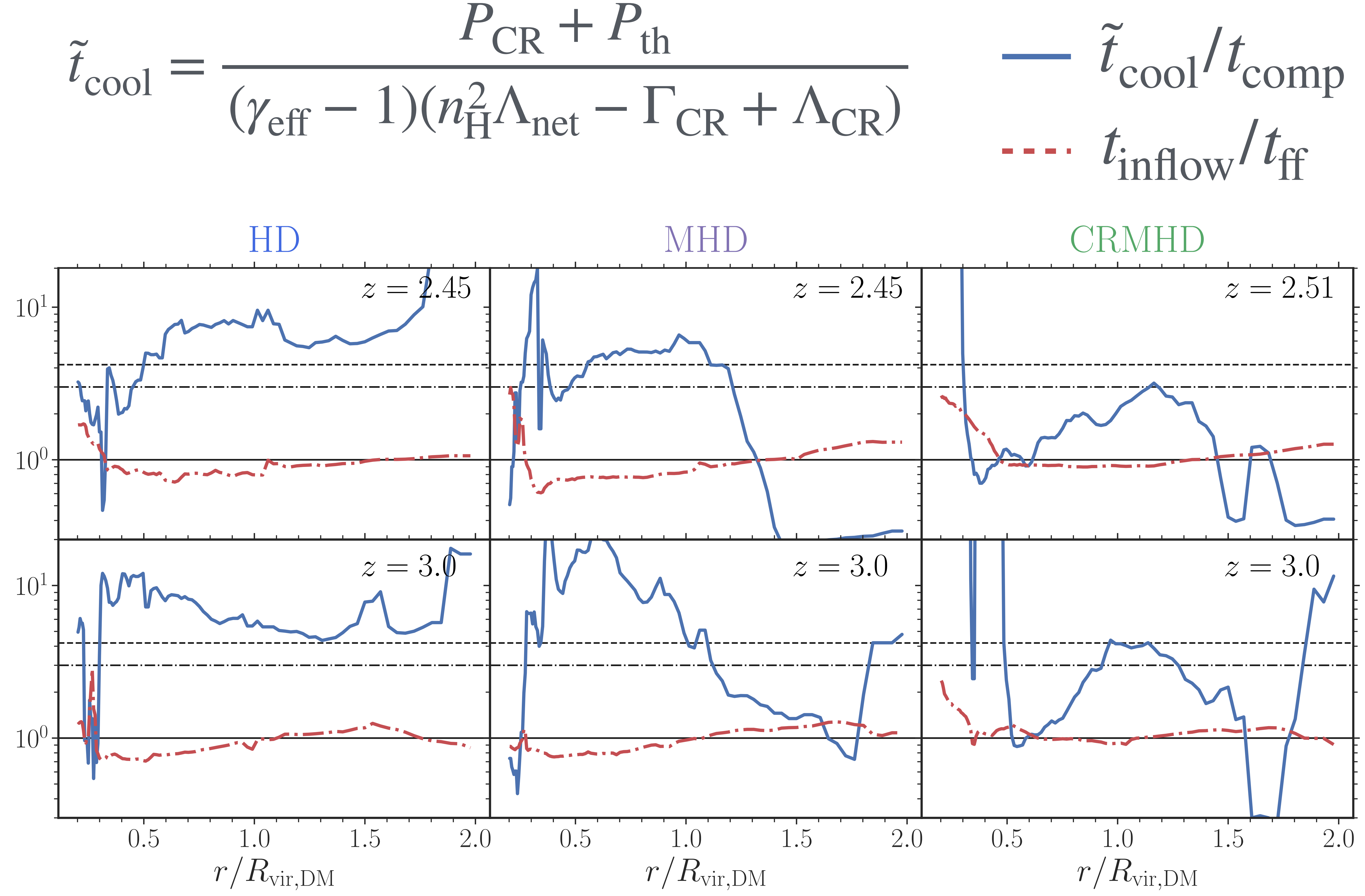
Danovich+2015, Cadiou+2022

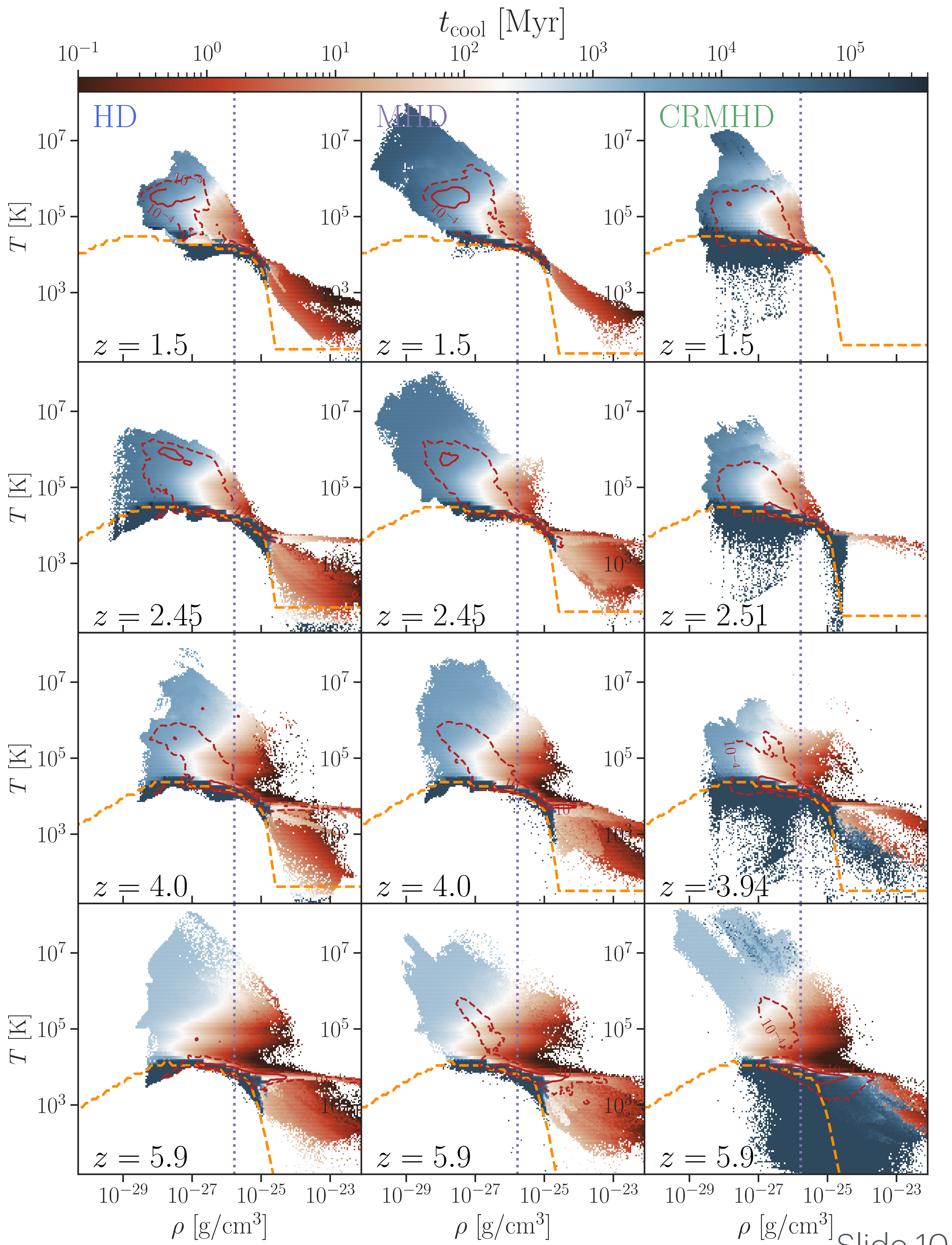


Cooling in the presence of CRs

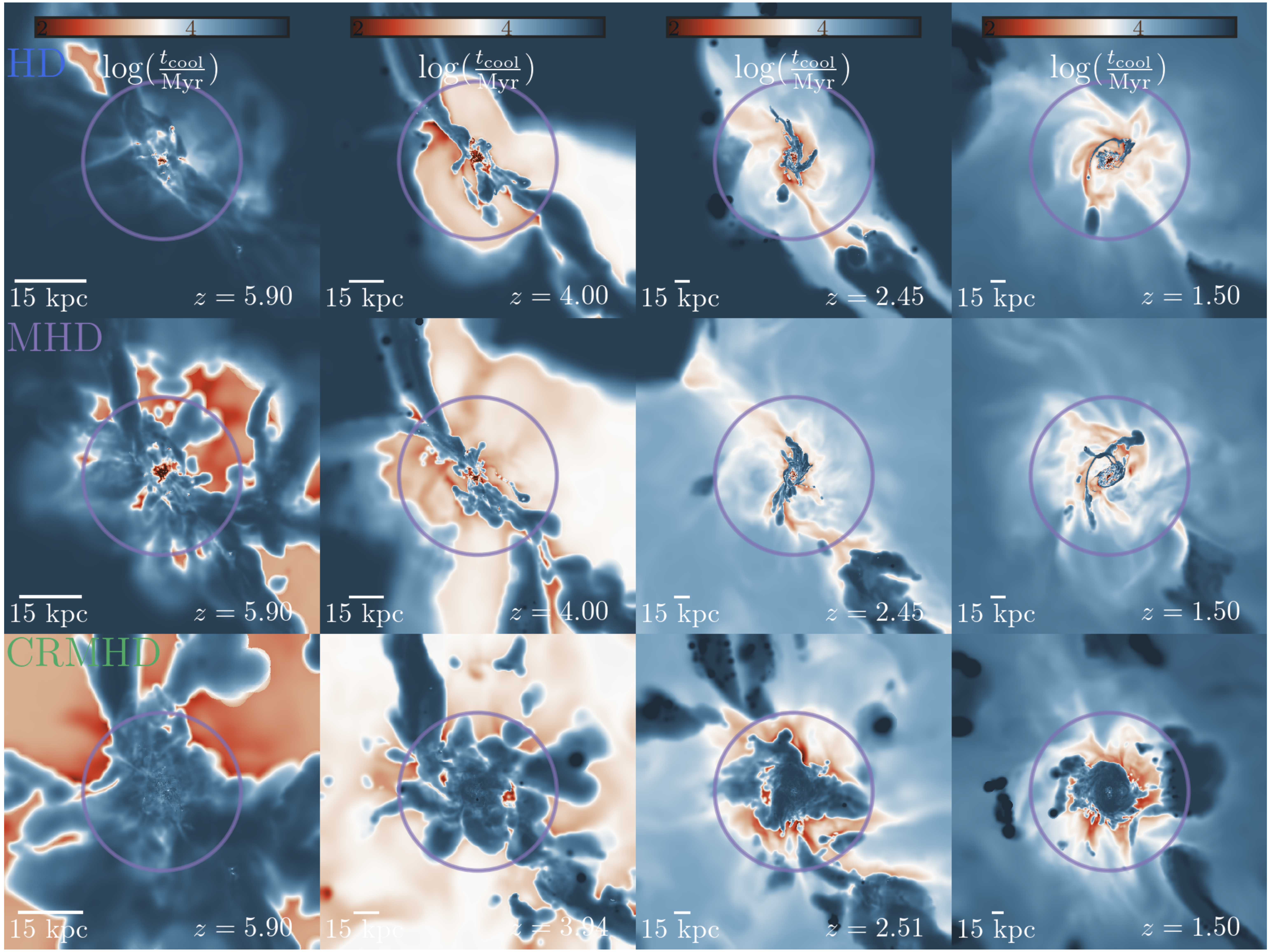
Cooling timescale for the CR+gas mixture

$$\tilde{t}_{\rm cool} = \frac{P_{\rm CR} + P_{\rm th}}{(\gamma_{\rm eff} - 1)(n_{\rm H}^2 \Lambda_{\rm net} - \Gamma_{\rm CR} + \Lambda_{\rm CR})}$$

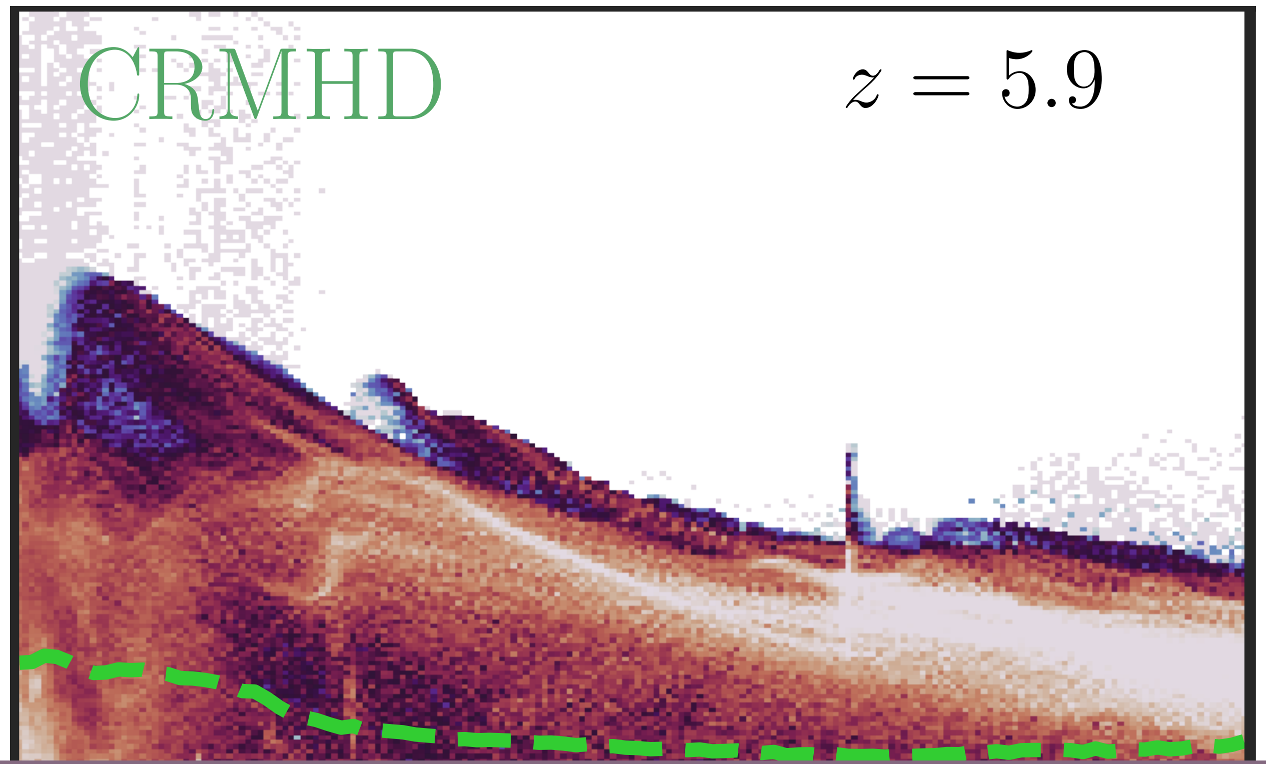




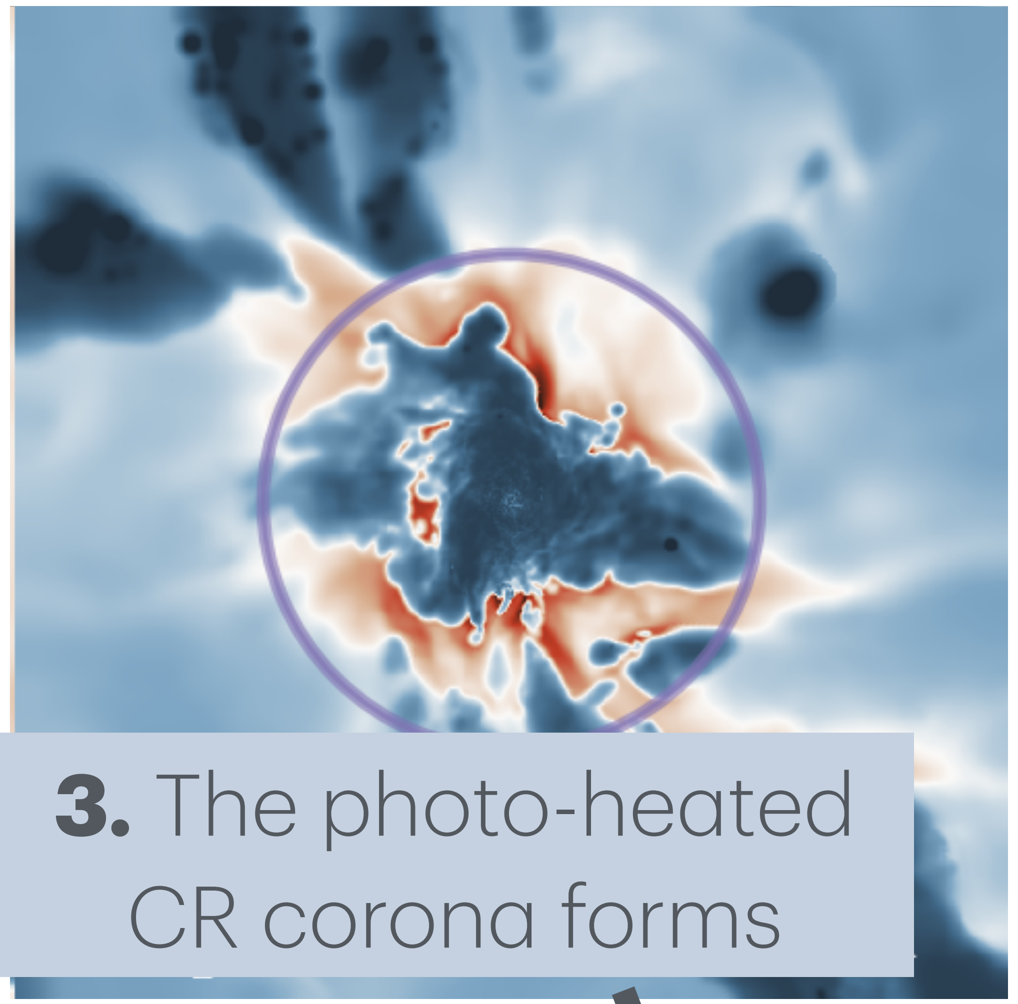
The "meta-stable" CR corona



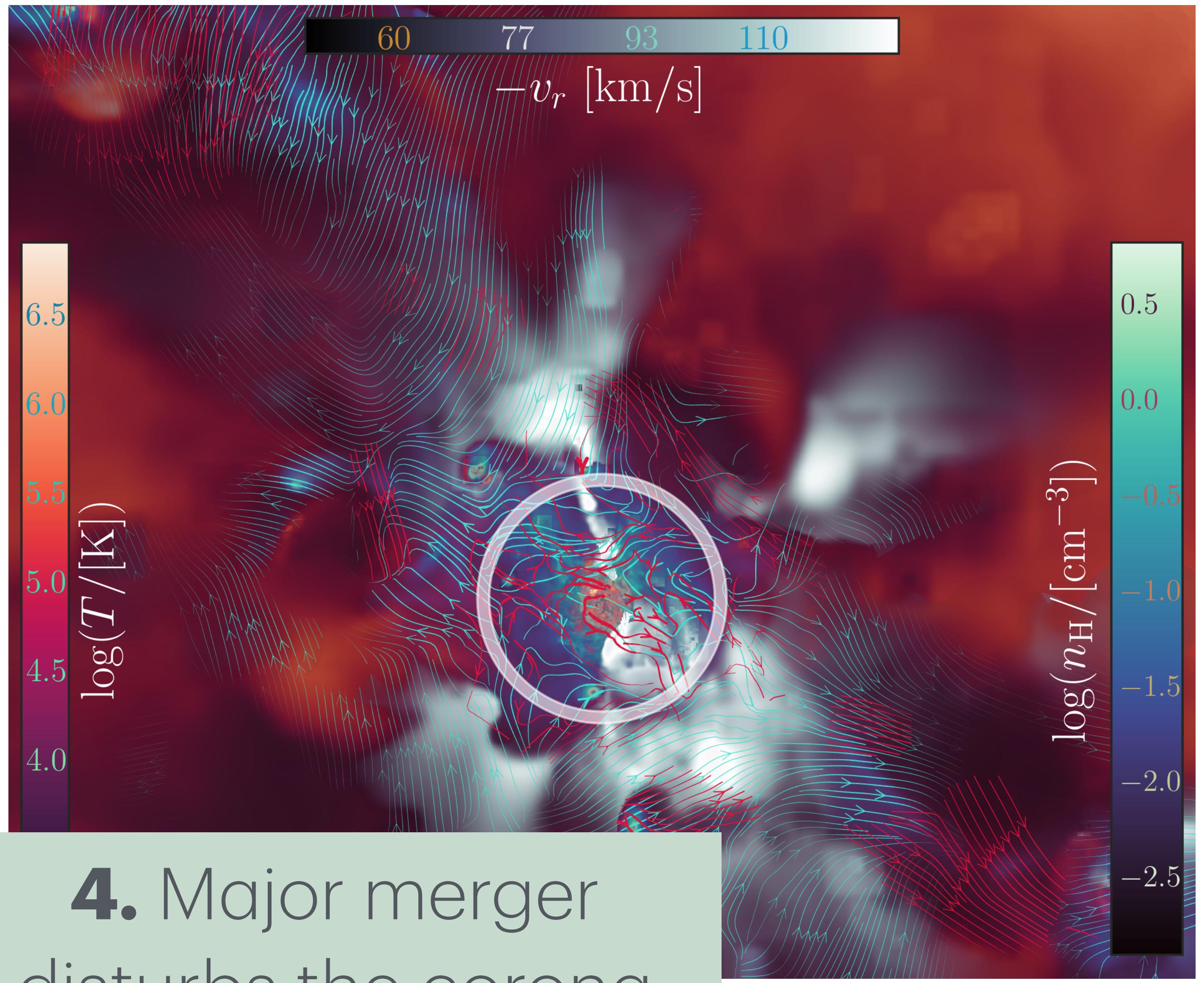
The "meta-stable" CR corona



2. CR pressure slows down inflows, preventing accretion shocks

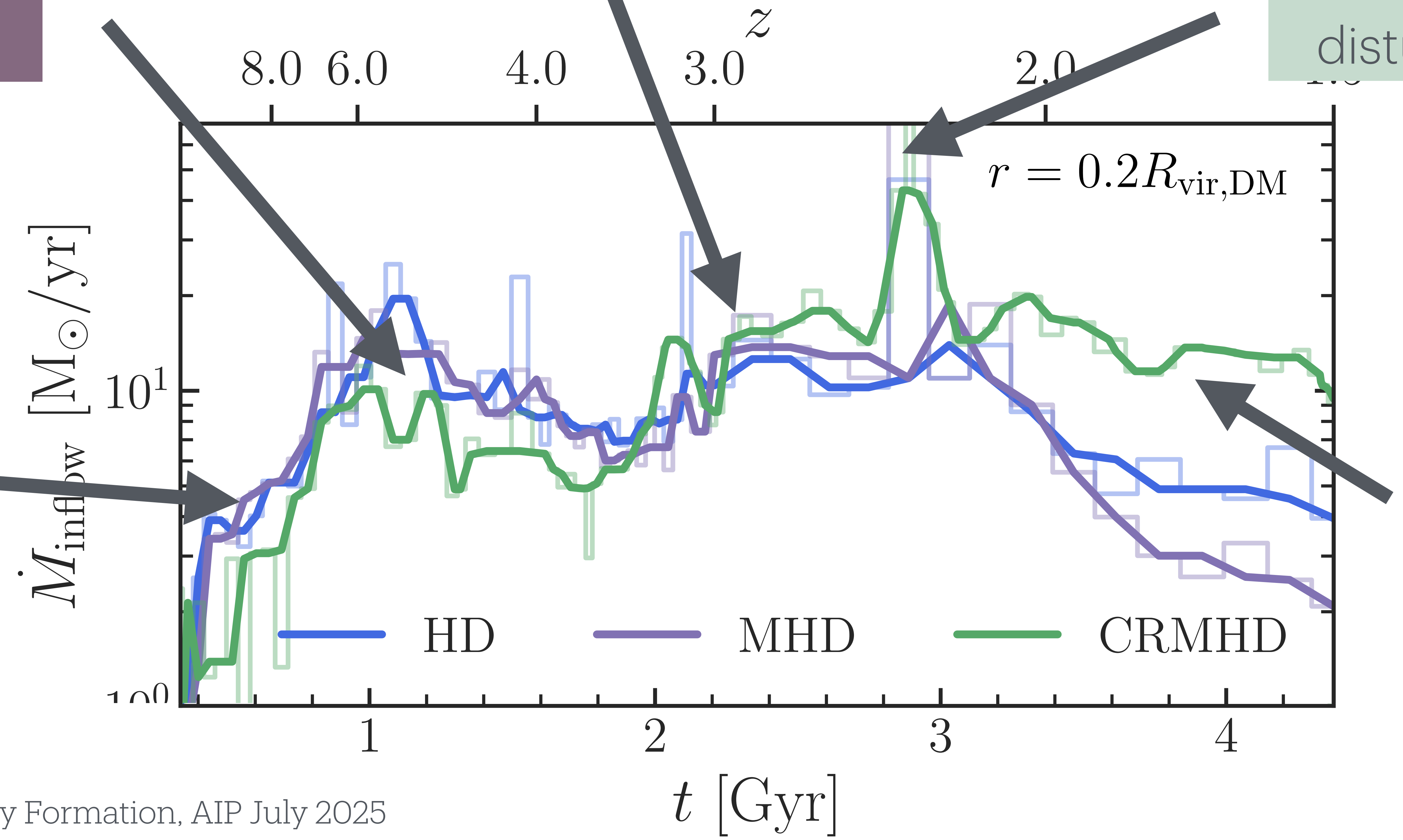


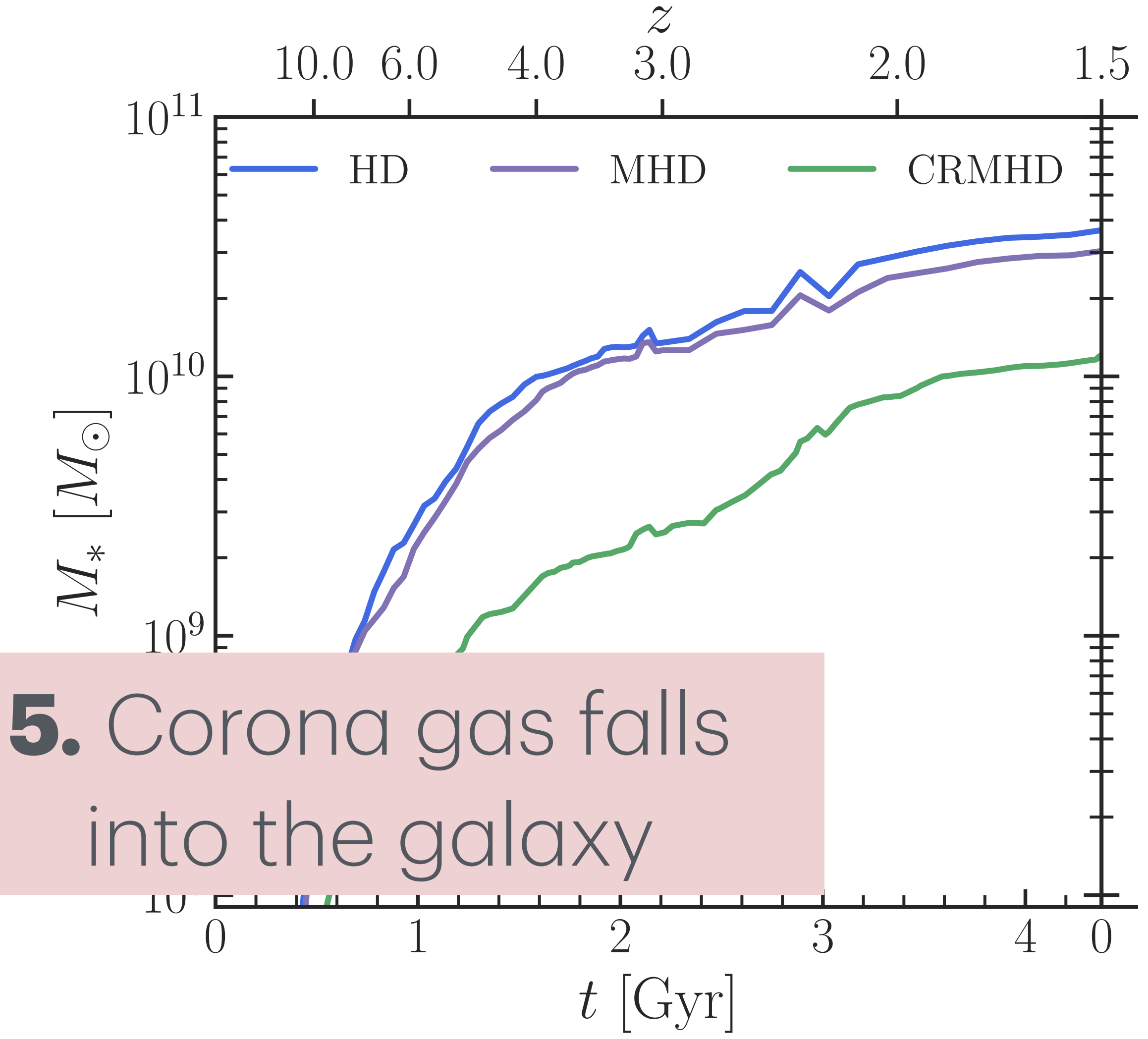
3. The photo-heated CR corona forms



4. Major merger disturbs the corona

1. Strong feedback disturbs inflows





5. Corona gas falls into the galaxy

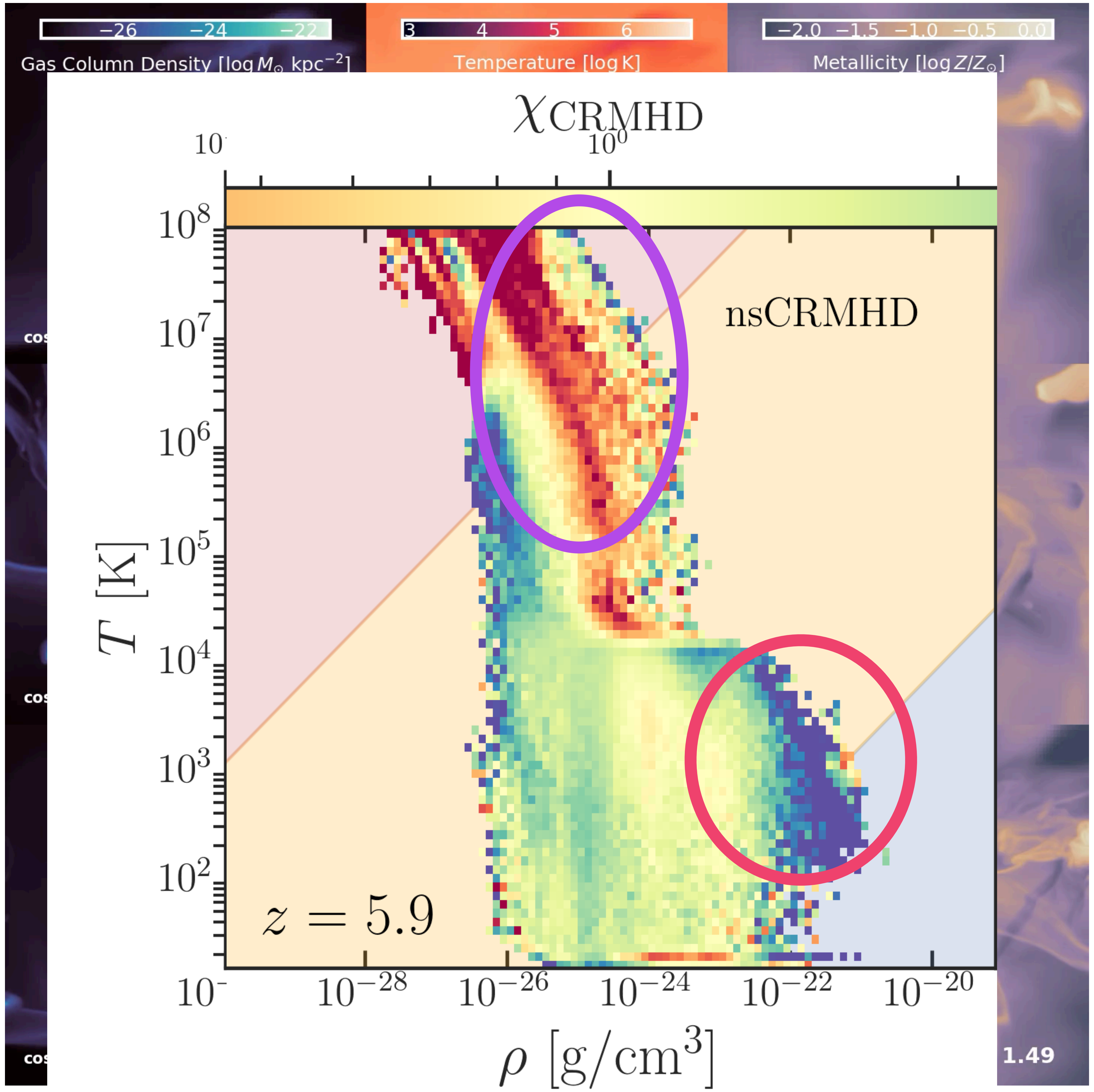
Future Work

I. Improved CGM resolution

II. Streaming heating has a non-negligible influence in the disk-halo interface

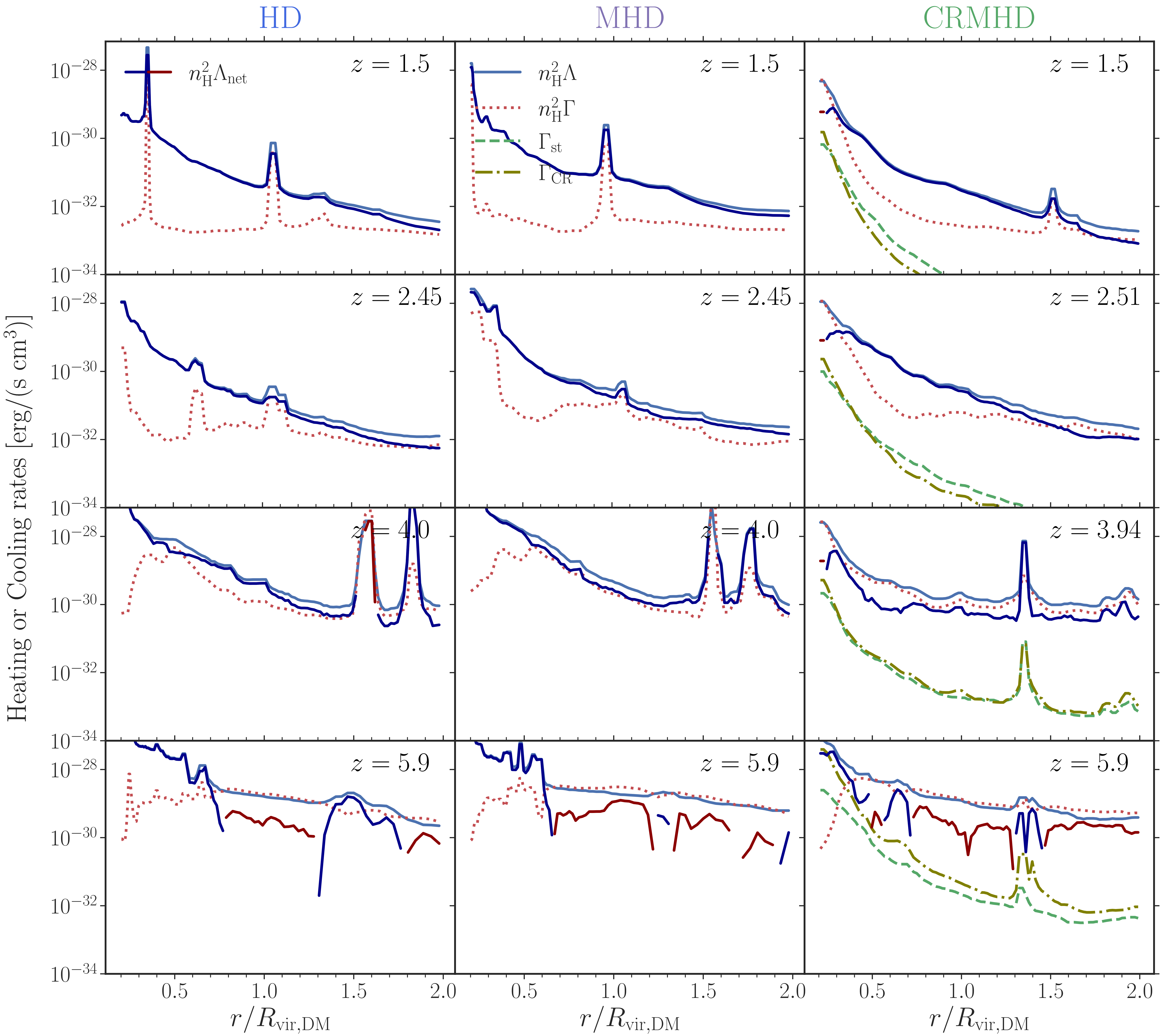
III. Does the meta-stable halo survives with local sources of UV?

IV. Variable CR diffusion speed?

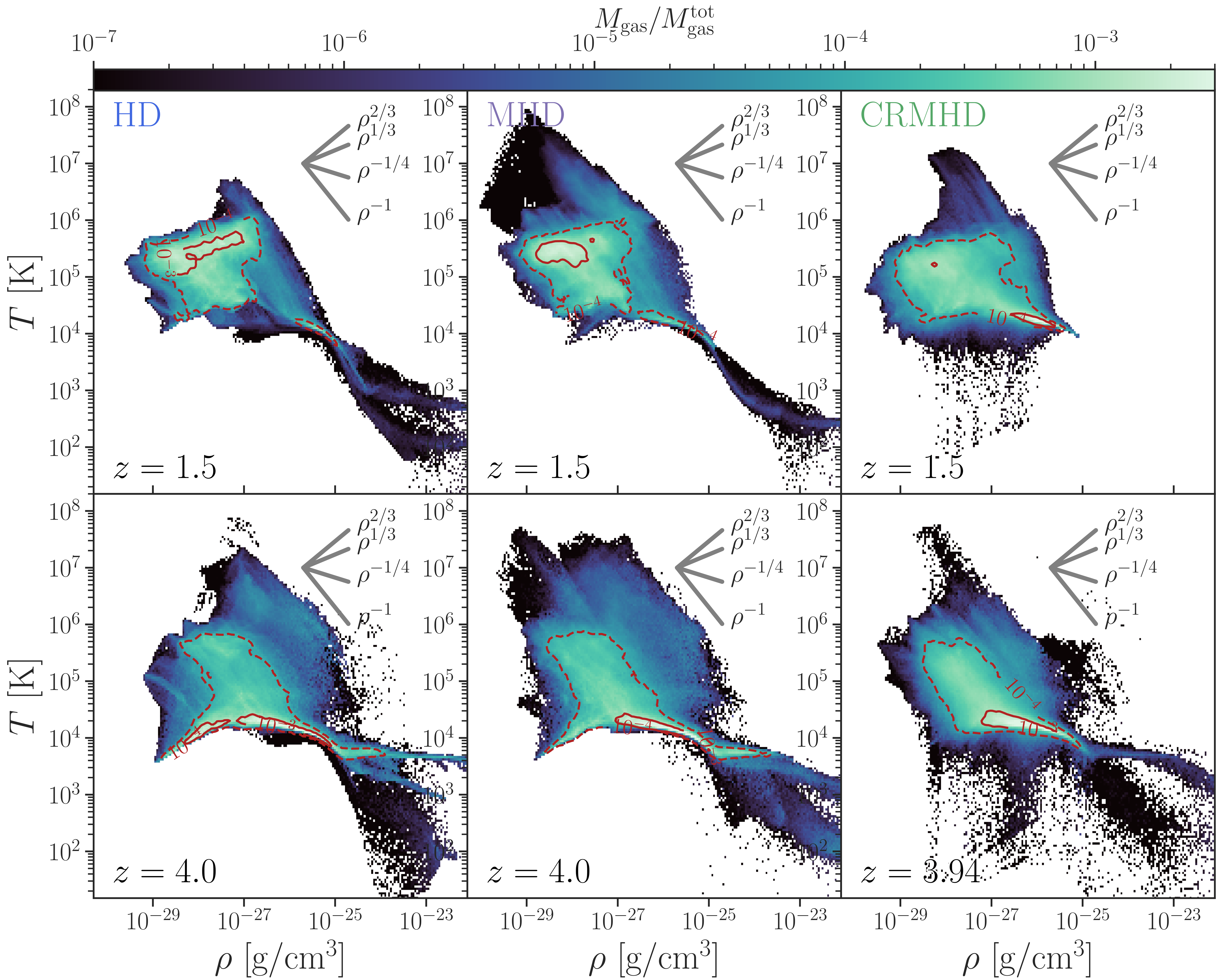


Thank you!

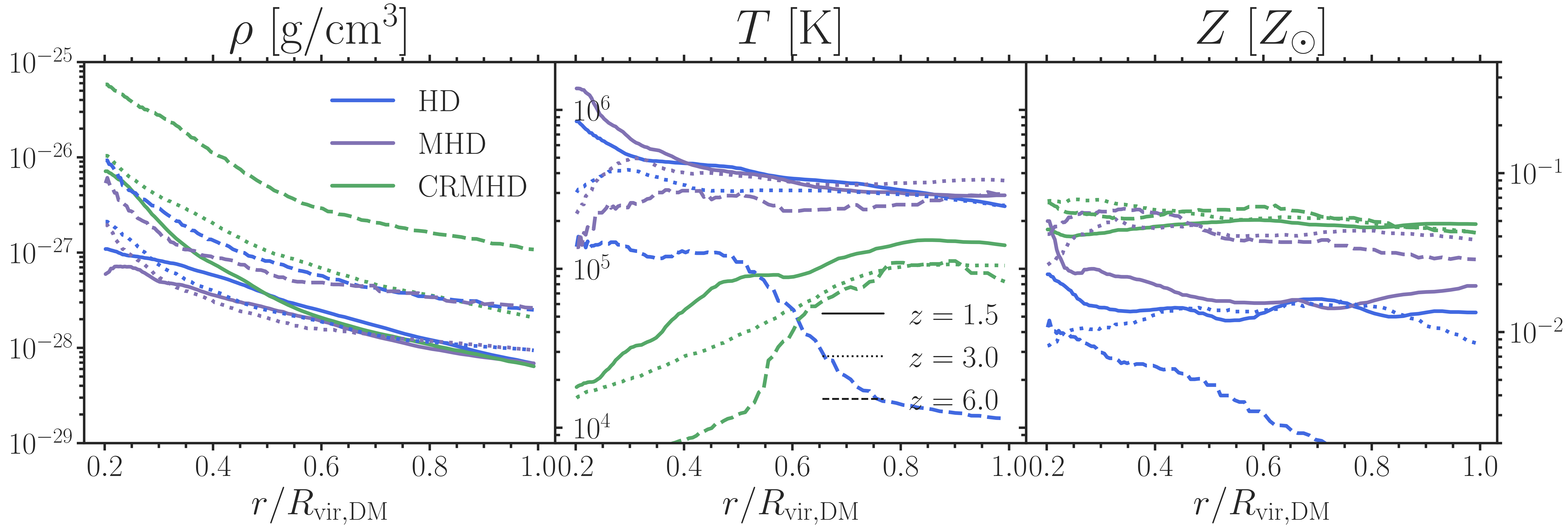
Backup slides



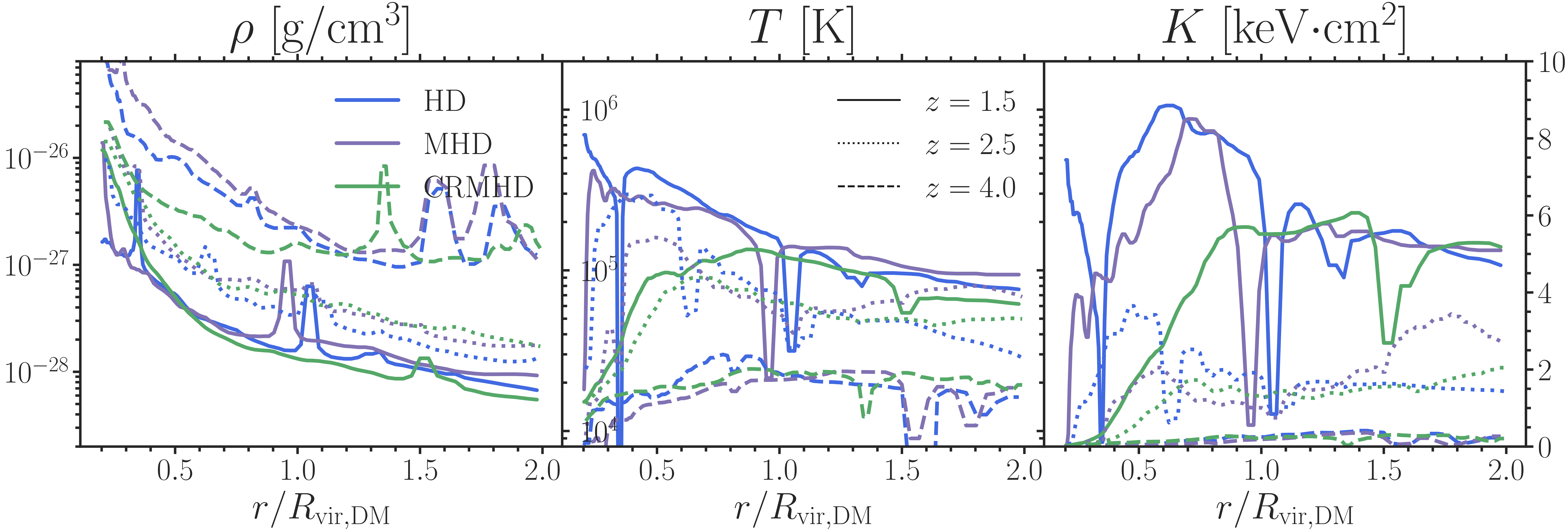
HD
MHD
CRMHD
$n_H^2\Lambda_{net}$
$n_H^2\Lambda$
$n_H^2\Gamma$
Γ_{st}
Γ_{CR}
$z = 1.5$
$z = 2.45$
$z = 2.51$
$z = 4.0$
$z = 3.94$
$z = 5.9$
Heating or Cooling rates [erg/(s cm^3)]
10^{-28}
10^{-30}
10^{-32}
10^{-34}
$r/R_{vir,DM}$
0.5
1.0
1.5
2.0



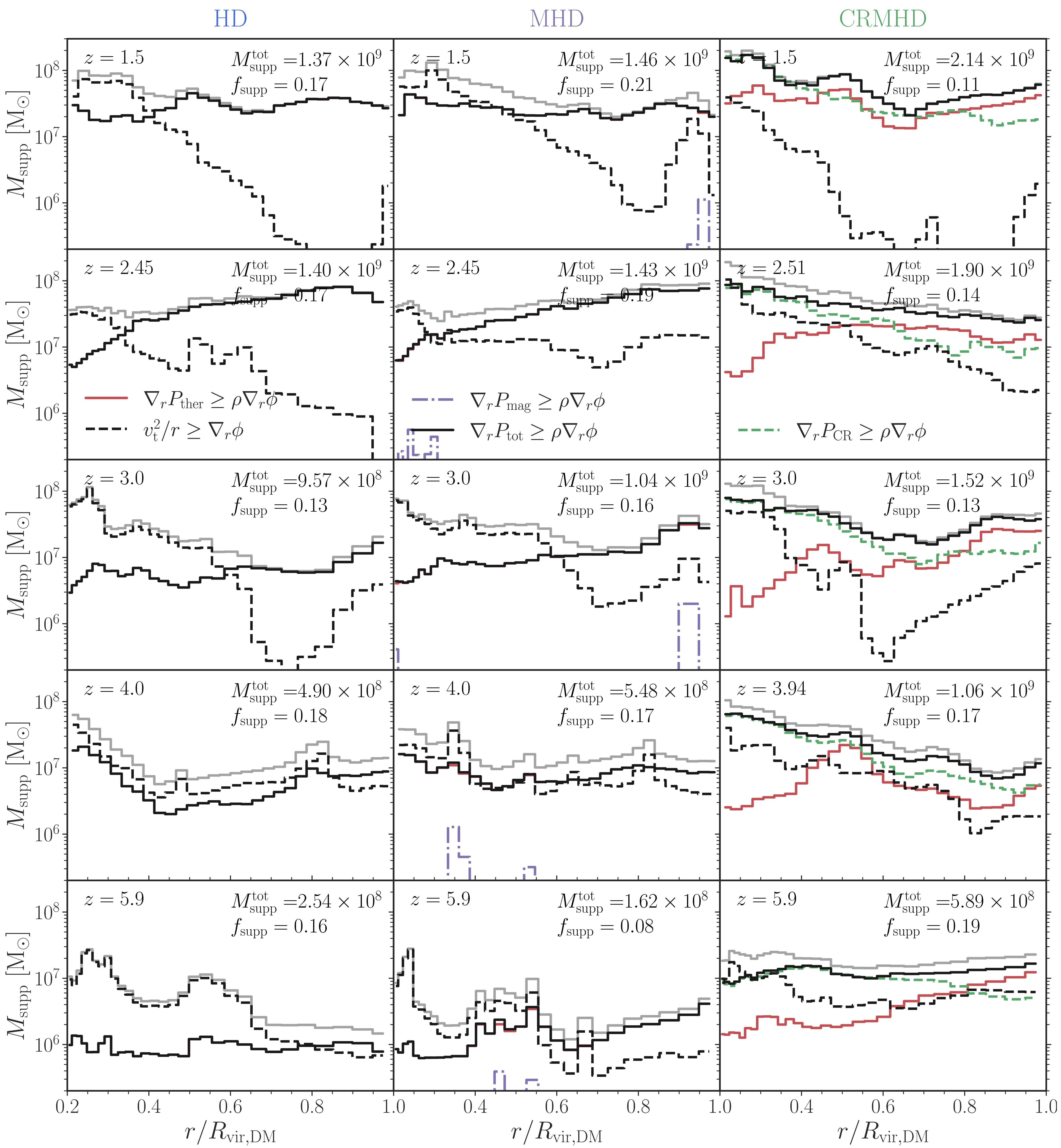
M_{gas}/M_{gas}^{tot}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
HD
MHD
CRMHD
$\rho^{2/3}$
$\rho^{1/3}$
$\rho^{-1/4}$
ρ^{-1}
$z = 1.5$
$z = 4.0$
$z = 3.94$
T [K]
ρ [g/cm^3]
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{-29}
10^{-27}
10^{-25}
10^{-23}

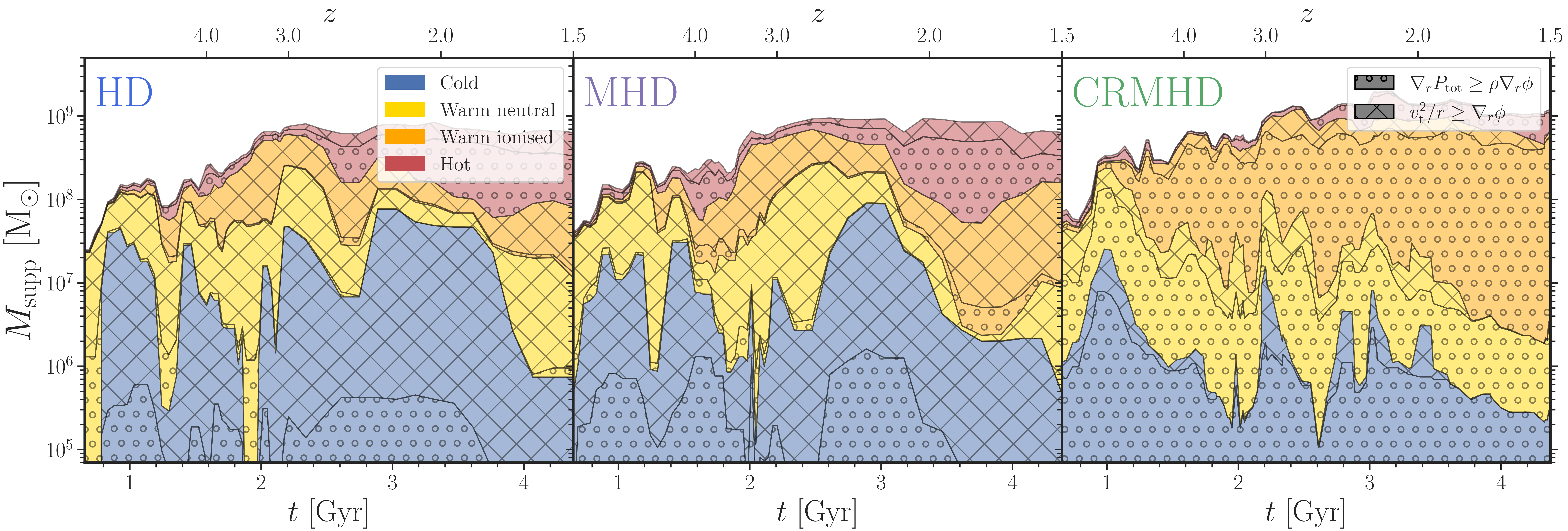


ρ [g/cm^3]
T [K]
Z [Z$_\odot$]
HD
MHD
CRMHD
$z = 1.5$
$z = 3.0$
$z = 6.0$
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{6}
10^{5}
10^{4}
10^{-1}
10^{-2}
0.2
0.4
0.6
0.8
1.0
$r/R_{\rm vir,DM}$

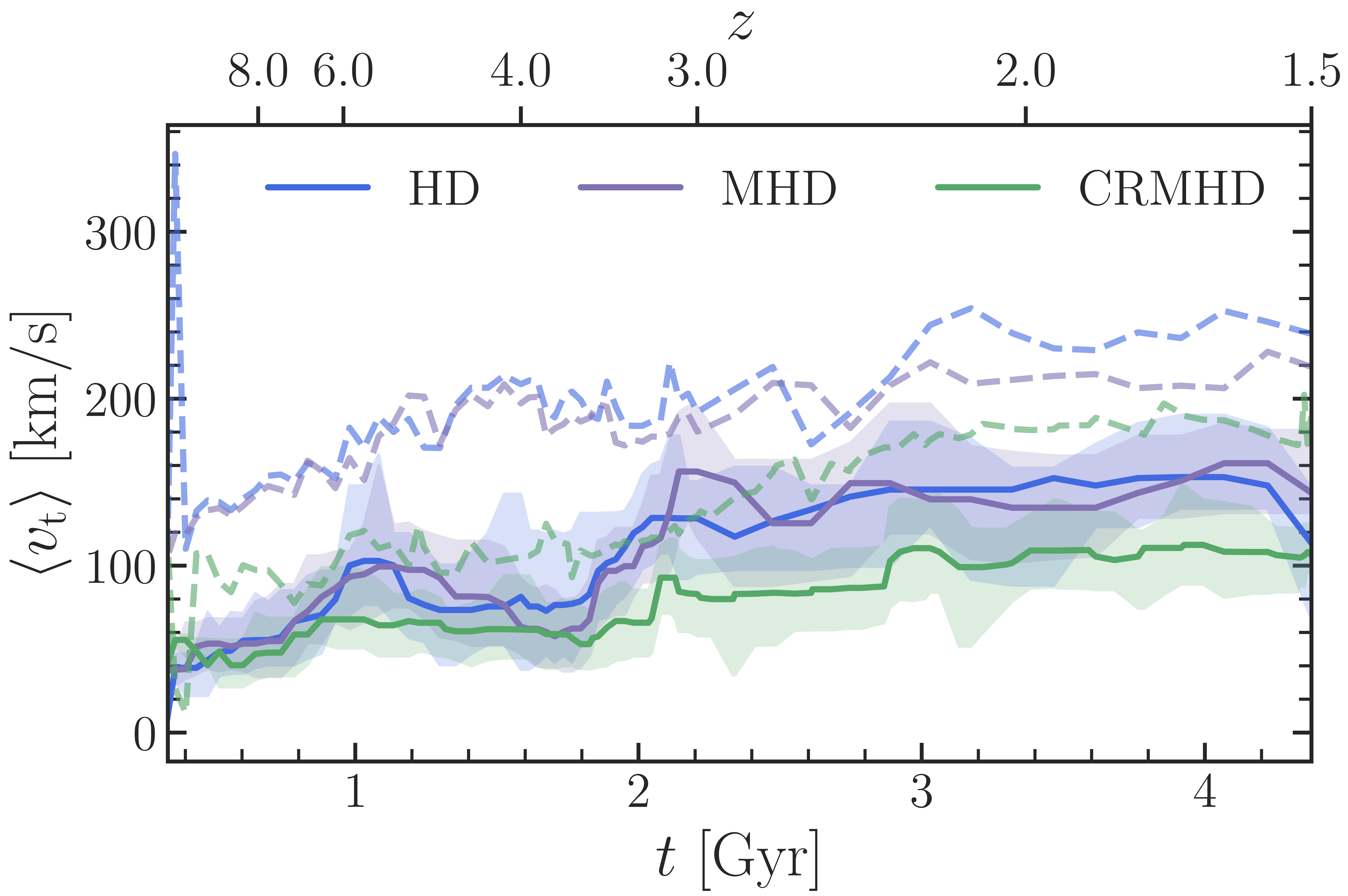


ρ [g/cm^3]
T [K]
K [keV·cm^2]
HD
MHD
CRMHD
$z = 1.5$
$z = 2.5$
$z = 4.0$
10^{-26}
10^{-27}
10^{-28}
10^6
10^5
10^4
10
8
6
4
2
0
0.5
1.0
1.5
2.0
$r/R_{\rm vir,DM}$

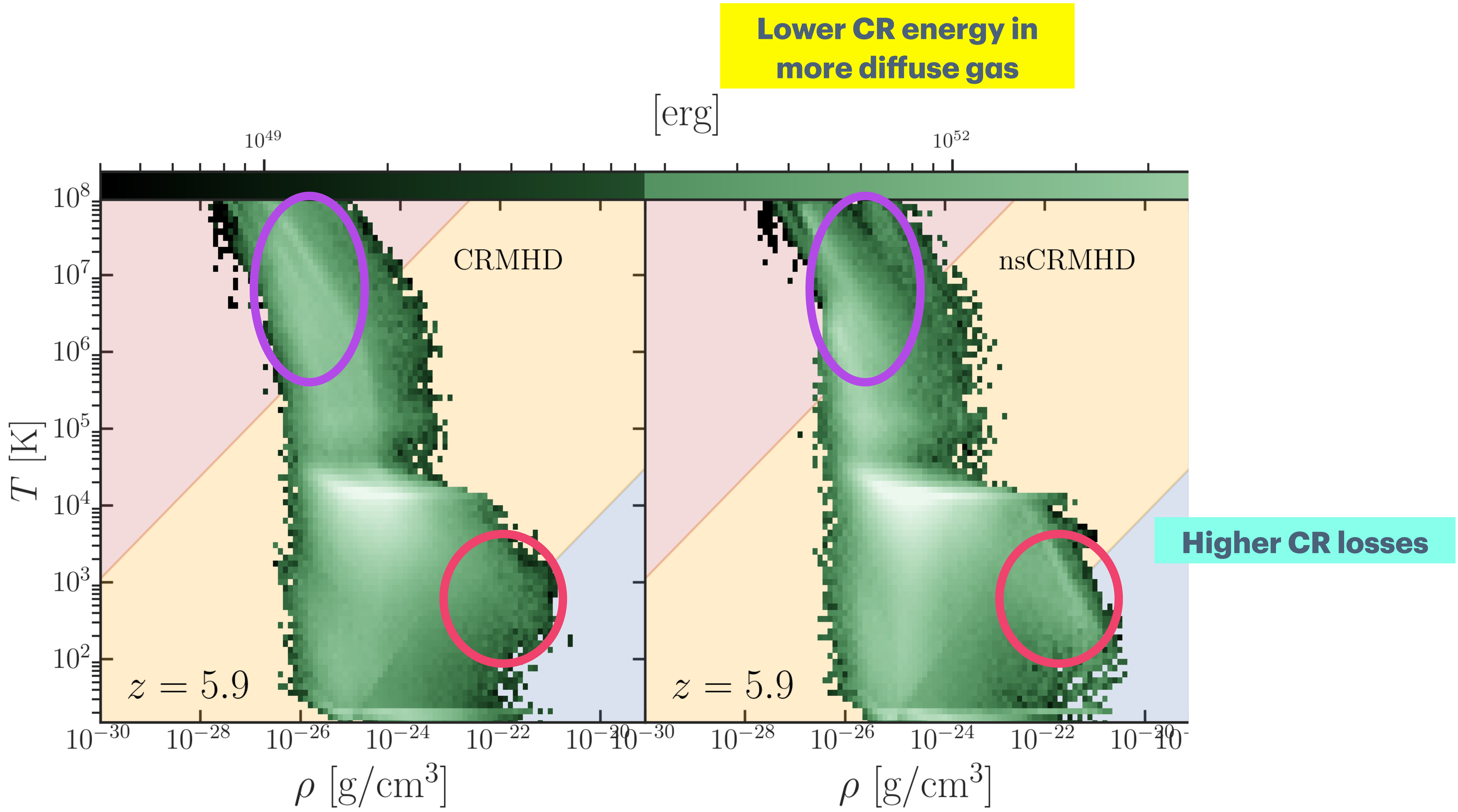

HD
MHD
CRMHD
z = 1.5
$M_{\rm supp}^{\rm tot}$ =1.37 × 10^9
$f_{\rm supp}$ = 0.17
z = 1.5
$M_{\rm supp}^{\rm tot}$ =1.46 × 10^9
$f_{\rm supp}$ = 0.21
z = 1.5
$M_{\rm supp}^{\rm tot}$ =2.14 × 10^9
$f_{\rm supp}$ = 0.11
z = 2.45
$M_{\rm supp}^{\rm tot}$ =1.40 × 10^9
$f_{\rm supp}$ = 0.17
z = 2.45
$M_{\rm supp}^{\rm tot}$ =1.43 × 10^9
$f_{\rm supp}$ = 0.19
z = 2.51
$M_{\rm supp}^{\rm tot}$ =1.90 × 10^9
$f_{\rm supp}$ = 0.14
$\nabla_r P_{\rm ther} \geq \rho \nabla_r \phi$
$v_{\rm t}^2/r \geq \nabla_r \phi$
$\nabla_r P_{\rm mag} \geq \rho \nabla_r \phi$
$\nabla_r P_{\rm tot} \geq \rho \nabla_r \phi$
$\nabla_r P_{\rm CR} \geq \rho \nabla_r \phi$
z = 3.0
$M_{\rm supp}^{\rm tot}$ =9.57 × 10^8
$f_{\rm supp}$ = 0.13
z = 3.0
$M_{\rm supp}^{\rm tot}$ =1.04 × 10^9
$f_{\rm supp}$ = 0.16
z = 3.0
$M_{\rm supp}^{\rm tot}$ =1.52 × 10^9
$f_{\rm supp}$ = 0.13
z = 4.0
$M_{\rm supp}^{\rm tot}$ =4.90 × 10^8
$f_{\rm supp}$ = 0.18
z = 4.0
$M_{\rm supp}^{\rm tot}$ =5.48 × 10^8
$f_{\rm supp}$ = 0.17
z = 3.94
$M_{\rm supp}^{\rm tot}$ =1.06 × 10^9
$f_{\rm supp}$ = 0.17
z = 5.9
$M_{\rm supp}^{\rm tot}$ =2.54 × 10^8
$f_{\rm supp}$ = 0.16
z = 5.9
$M_{\rm supp}^{\rm tot}$ =1.62 × 10^8
$f_{\rm supp}$ = 0.08
z = 5.9
$M_{\rm supp}^{\rm tot}$ =5.89 × 10^8
$f_{\rm supp}$ = 0.19
$M_{\rm supp}$ [M$_\odot$]
$r/R_{\rm vir,DM}$



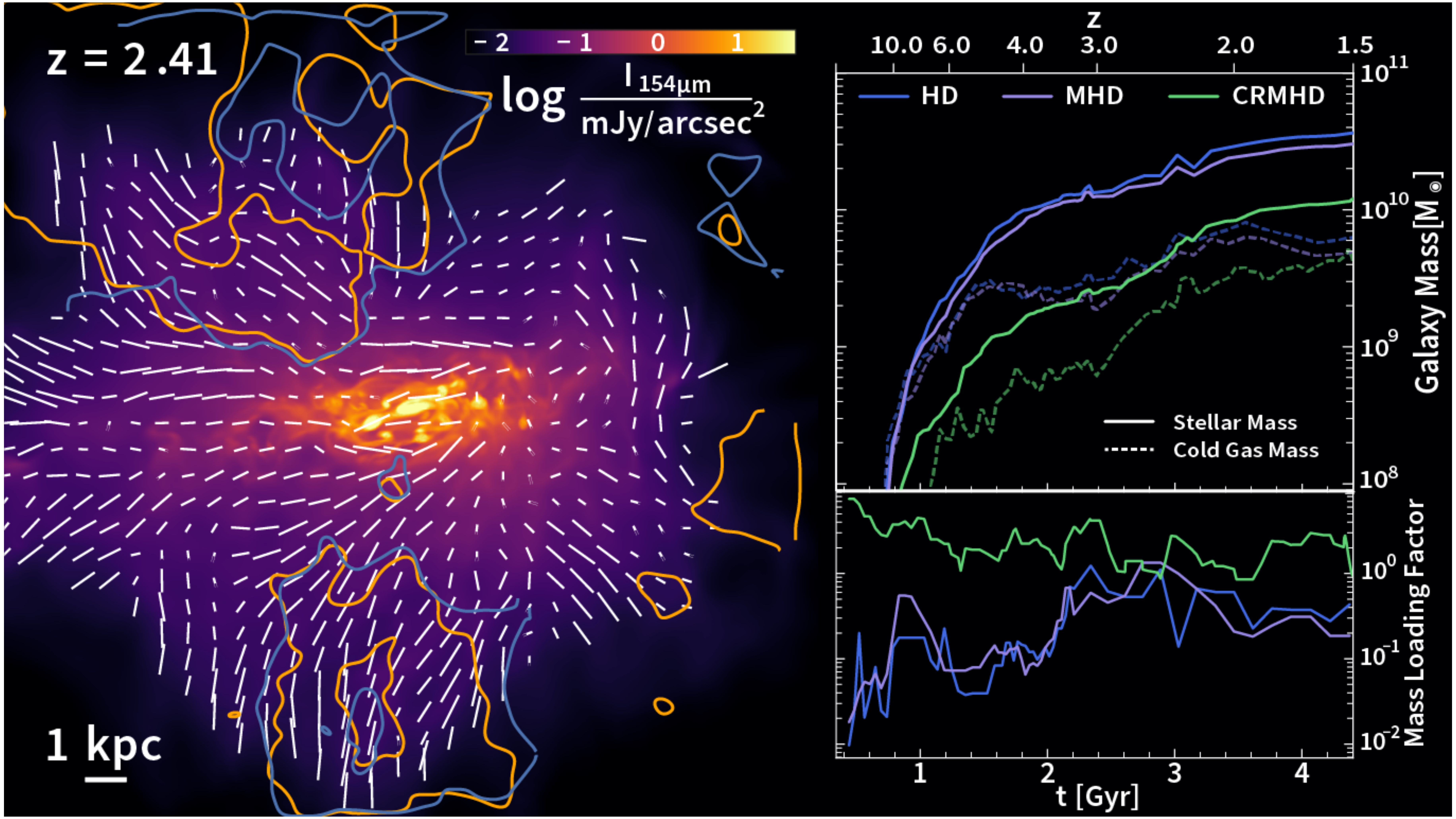
HD
MHD
CRMHD
Cold
Warm neutral
Warm ionised
Hot
$\nabla_r P_{\rm tot} \geq \rho \nabla_r \phi$
$v_{\rm t}^2/r \geq \nabla_r \phi$
$M_{\rm supp}$ [$\rm M_\odot$]
t [Gyr]
z



z
8.0
6.0
4.0
3.0
2.0
1.5
HD
MHD
CRMHD
300
200
100
0
⟨v_t⟩ [km/s]
1
2
3
4
t [Gyr]



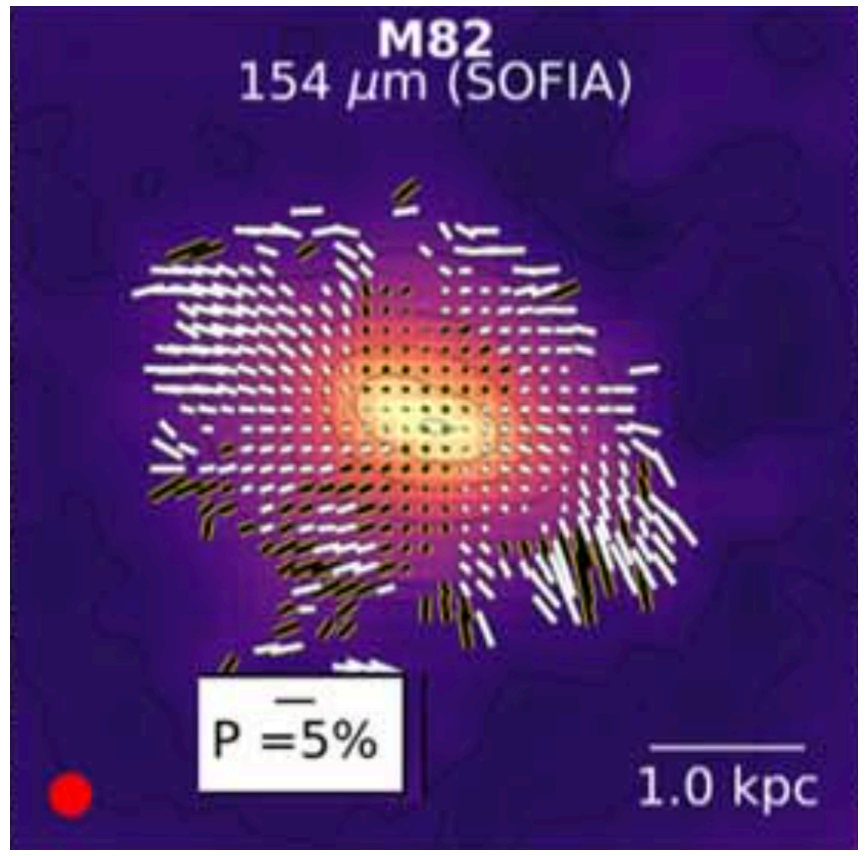
Lower CR energy in more diffuse gas
[erg]
10^{49}
10^{52}
CRMHD
nsCRMHD
Higher CR losses
T [K]
$z = 5.9$
$z = 5.9$
ρ [g/cm^3]
ρ [g/cm^3]



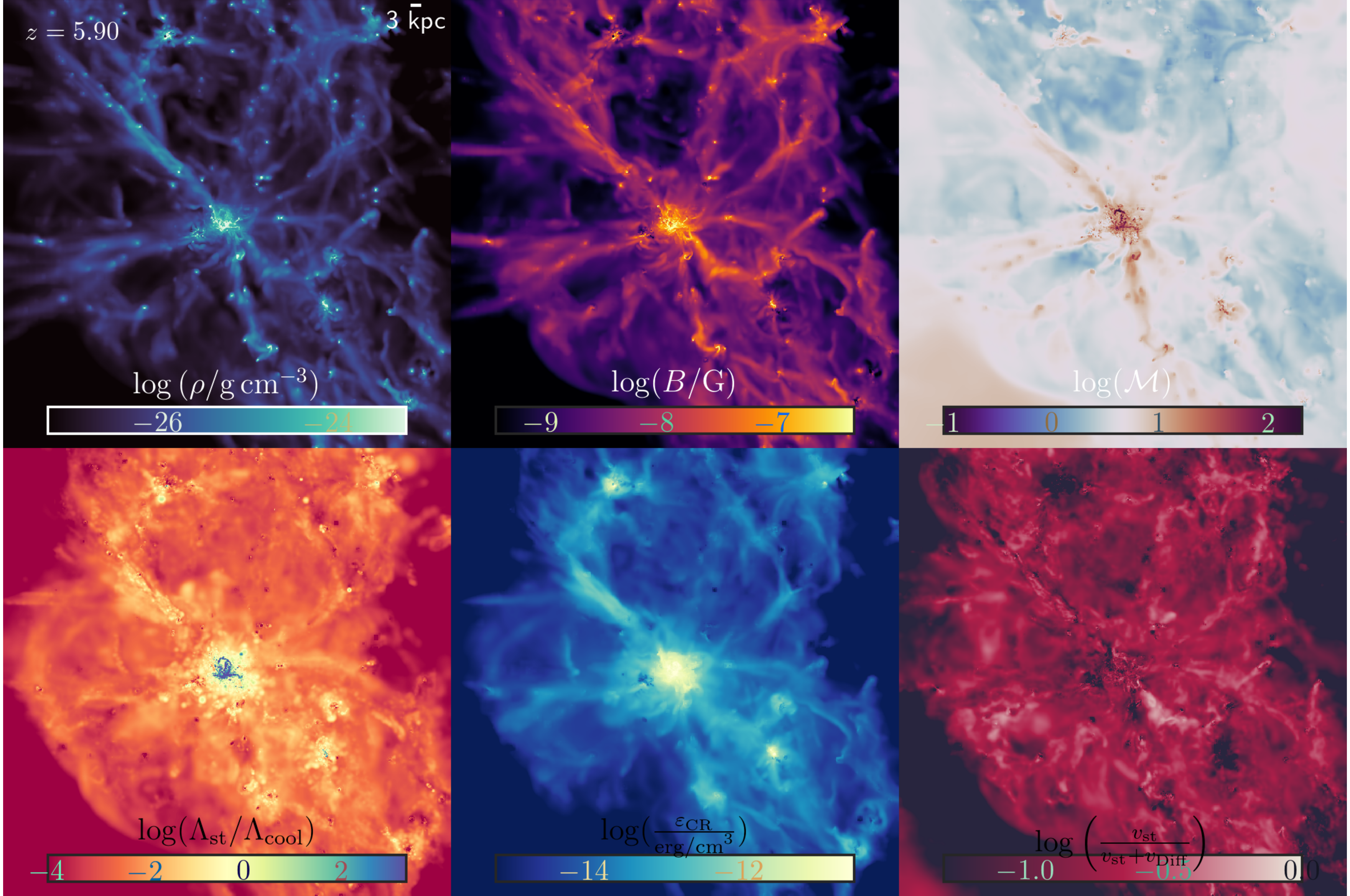
Adding CRs decreases the stellar mass by ~1 dex at high redshift and a factor 4 at lower redshift

Large depletion of cold gas compared to HD and MHD (lower star formation efficiency)

High mass loading outflows in the presence of CRs, which are cooler and observed in **FIR polarised emission**

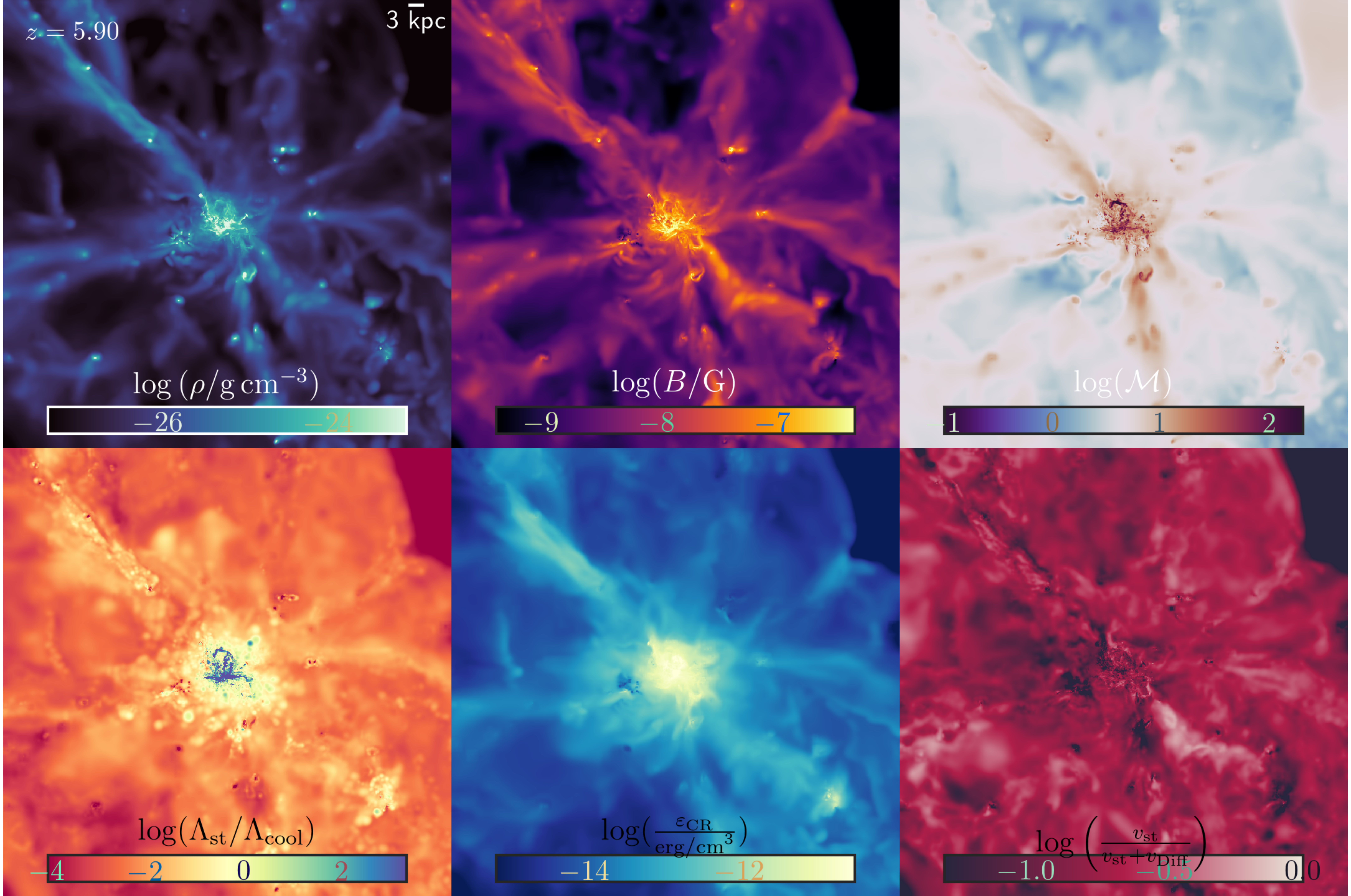


Lopez-Rodriguez2023



$z = 5.90$
3 kpc
$\log(\rho/\mathrm{g\,cm^{-3}})$
−26
−24
$\log(B/\mathrm{G})$
−9
−8
−7
$\log(\mathcal{M})$
−1
0
1
2
$\log(\Lambda_{\rm st}/\Lambda_{\rm cool})$
−4
−2
0
2
$\log(\frac{\varepsilon_{\rm CR}}{\rm erg/cm^3})$
−14
−12
$\log\left(\frac{v_{\rm st}}{v_{\rm st}+v_{\rm Diff}}\right)$
−1.0
−0.5
0.0

$z = 5.90$
3 kpc
$\log(\rho/\mathrm{g\,cm^{-3}})$
−26 −24 −22
$\log(T/\mathrm{K})$
3 4 5 6
$\log(B/\mathrm{G})$
−8 −6
v_r [km/s]
-10^2 -10^1 10^1 10^2
$\log(\frac{v_{\rm Diff}}{\rm kms^{-1}})$
0 1 2
$\log(\frac{v_{\rm A}}{\rm kms^{-1}})$
−2 −1 0 1
$\log(\frac{\nabla P_{\rm CR}}{\rm erg/cm})$
−34 −32
$\log\left(\frac{v_{\rm st}}{v_{\rm st}+v_{\rm Diff}}\right)$
−1.5 −1.0 −0.5 0.0



$z = 5.90$
3 kpc
$\log(\rho/\mathrm{g\,cm^{-3}})$
-26 -24
$\log(B/\mathrm{G})$
-9 -8 -7
$\log(\mathcal{M})$
-1 0 1 2
$\log(\Lambda_{\mathrm{st}}/\Lambda_{\mathrm{cool}})$
-4 -2 0 2
$\log\left(\frac{\varepsilon_{\mathrm{CR}}}{\mathrm{erg/cm^3}}\right)$
-14 -12
$\log\left(\frac{v_{\mathrm{st}}}{v_{\mathrm{st}}+v_{\mathrm{Diff}}}\right)$
-1.0 -0.5 0.0

Momentum deposition

$p_0 = 14181 M_\odot \mathrm{km\ s^{-1}}$
(Naab&Ostriker2014)