Entropy profiles of MUSIC clusters

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Universidad Autónoma de Madrid

CLUES Workshop 2012

Objective

- Extend the work done in Faltenbacher et al. 2007 (MARENOSTRUM **adiabatic** simulation)

Entropy of gas and dark matter in galaxy clusters

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[2] *UCO/Lick Observatory, University of California at Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA*
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- Entropy profiles in MUSIC clusters with **radiative physics**
- **Redshift evolution**

Outline

Outline

I. Introduction

- ***Entropy profiles*** of the ICM gas and the DM in ***galaxy clusters***

$$K_g = \frac{3k_B}{\mu m_p} T_g \rho_g^{-2/3} = \sigma_g^2 \rho_g^{-2/3} \qquad K_{DM} = \sigma_{DM}^2 \rho_{DM}^{-2/3}$$

μ = 0.588

3D velocity dispersion

$$S = \ln\left(K^{3/2}\right) + constant$$

$\boxed{\text{Convention: } S \rightarrow K}$

- Velocity dispersion of the gas

$\boxed{\text{kinetic energy = proper velocity + thermal dispersion}}$

$$\sigma_{Turbulent}^2 = \sigma_x^2 + \sigma_y^2 + \sigma_z^2 \qquad \sigma_{Thermal}^2 = \frac{3k_B T_g}{\mu m_p}$$

$$\sigma_{Extended}^2 = \sigma_{Thermal}^2 + \sigma_{Turbulent}^2$$

- ***Phase-space density***: $Q_{DM} = \rho_{DM}\sigma_{DM}^{-3} \rightarrow \boxed{Q_{DM} = K_{DM}^{-2/3}}$

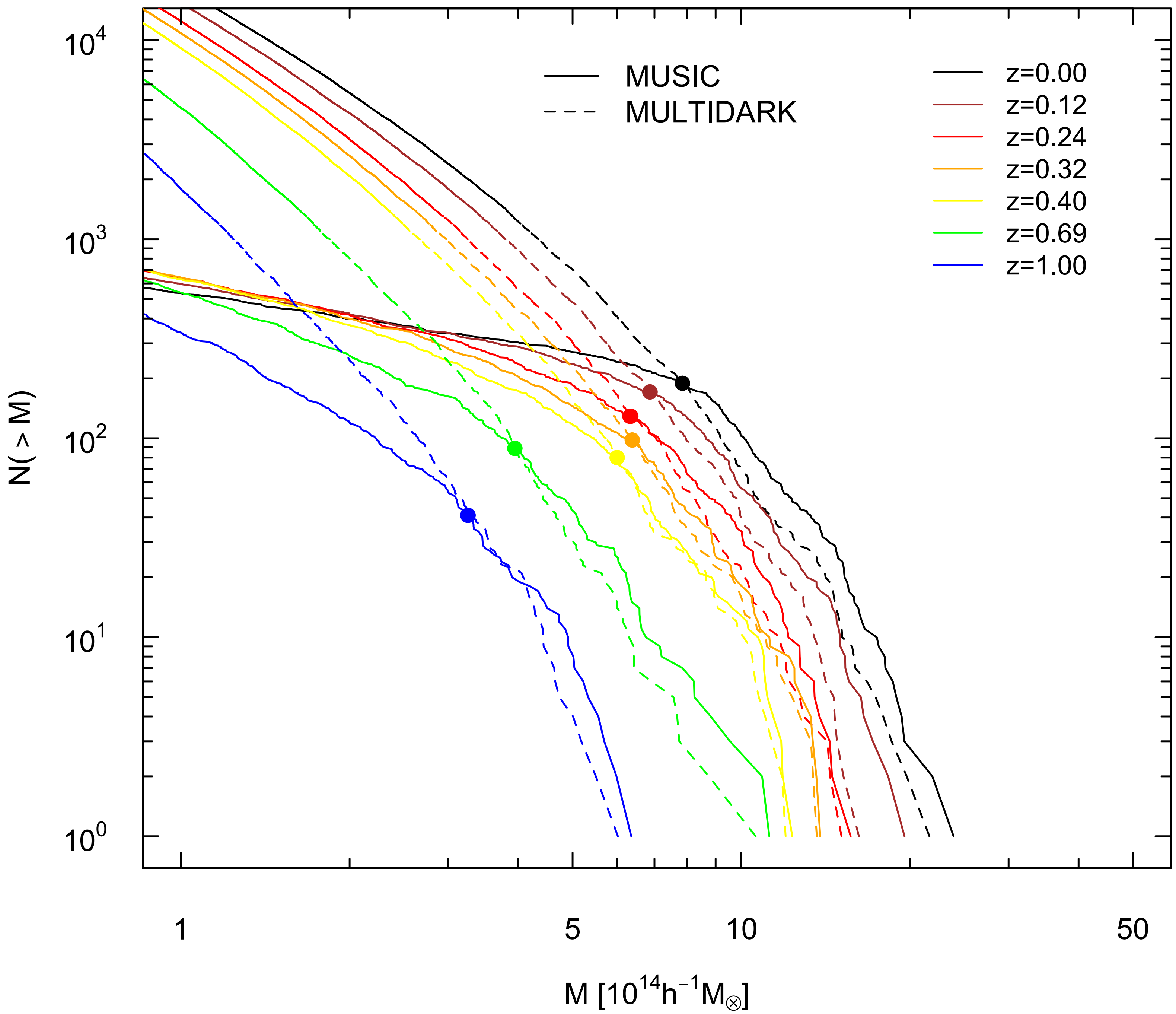
Outline

2. MUSIC clusters

- ***Multidark*** simulation: ART dark matter only simulation (Anatoly Klypin @ NAS Ames)
  - WMAP7 ($\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$, $\Omega_m = 0.0469$, $\sigma_8 = 0.82$, $h = 0.7$)
  - 8.6 billion particles
  - 1 $(\mathrm{Gpc}/h)^3$ volume

- ***MUSIC*** (***Mu***ltidark re***si***mulated ***c***lusters)
  - 8 times more resolution in 6 Mpc region
  - over 800 clusters with $M > 10^{14}\ h^{-1}M_\odot$ up to $z = 1$
  - SPH gas particles: → Adiabatic; → Radiative (cooling, UV photoionization, star formation, galactic winds)
  - $m_{dm} = 9.01 \times 10^8\ h^{-1}M_\odot$; $m_{gas} = 1.09 \times 10^8\ h^{-1}M_\odot$

2. MUSIC clusters



z	$M(10^{14}\ h^{-1}M_\odot)$	$N\ (\geq M)$
0,00	7,85	188
0,11	6,87	171
0,25	6,34	128
0,33	6,39	99
0,43	6,00	81
0,67	3,94	89
1,00	3,25	41

2.1. Relaxed and unrelaxed clusters

- ***Substructure mass fraction (fsub):*** mass fraction in substructures within R_{vir} (most masive substructure not included)

$$\boxed{fsub < 0.1}$$

- ***Centre of mass displacement (s):*** normalized offset between the centre of mass of the halo and the potential centre

$$\boxed{s\ (1 / Rvir) < 0.07}$$

- ***Virial ratio:***

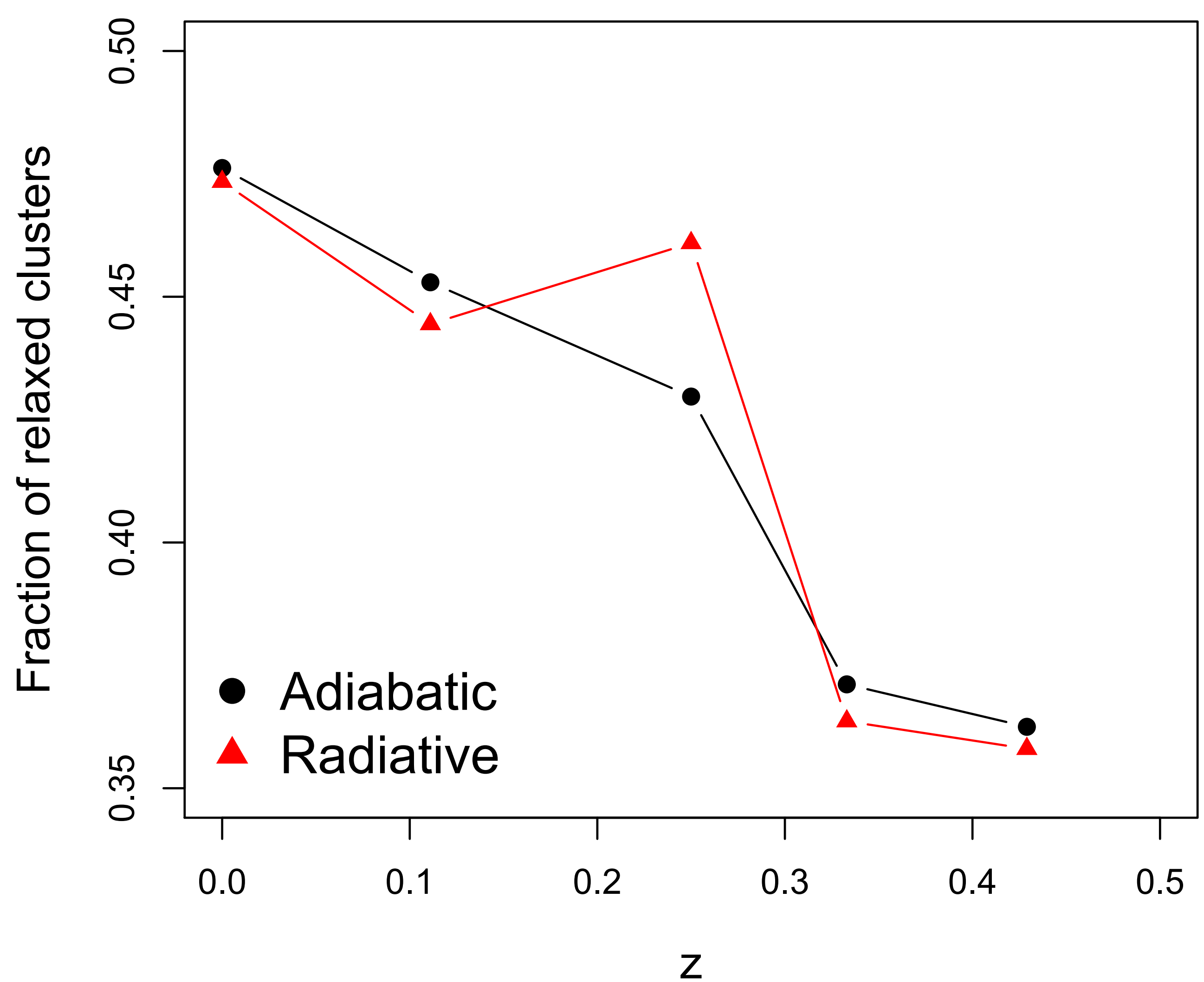
$$\boxed{2T/|U| < 1.35}$$

(Neto et al. 2007)

2.1. Relaxed and unrelaxed clusters

ADIABATIC		
z	N (≥M)	$N_{relaxed}$ (≥M)
0,00	189	90
0,11	170	77
0,25	128	55
0,33	97	36
0,43	80	29

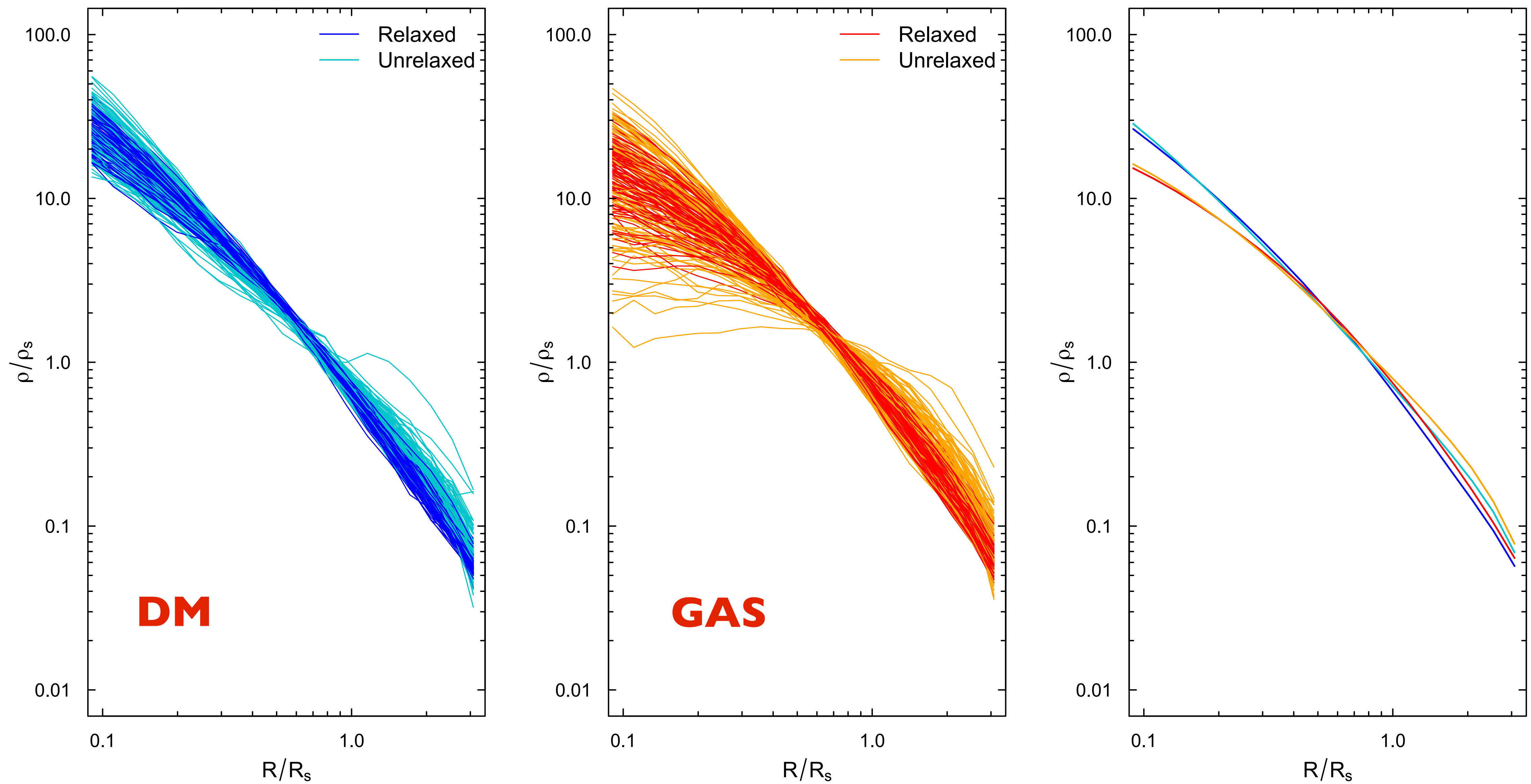
RADIATIVE		
z	N (≥M)	$N_{relaxed}$ (≥M)
0,00	188	89
0,11	171	76
0,25	128	59
0,33	99	36
0,43	81	29



Outline

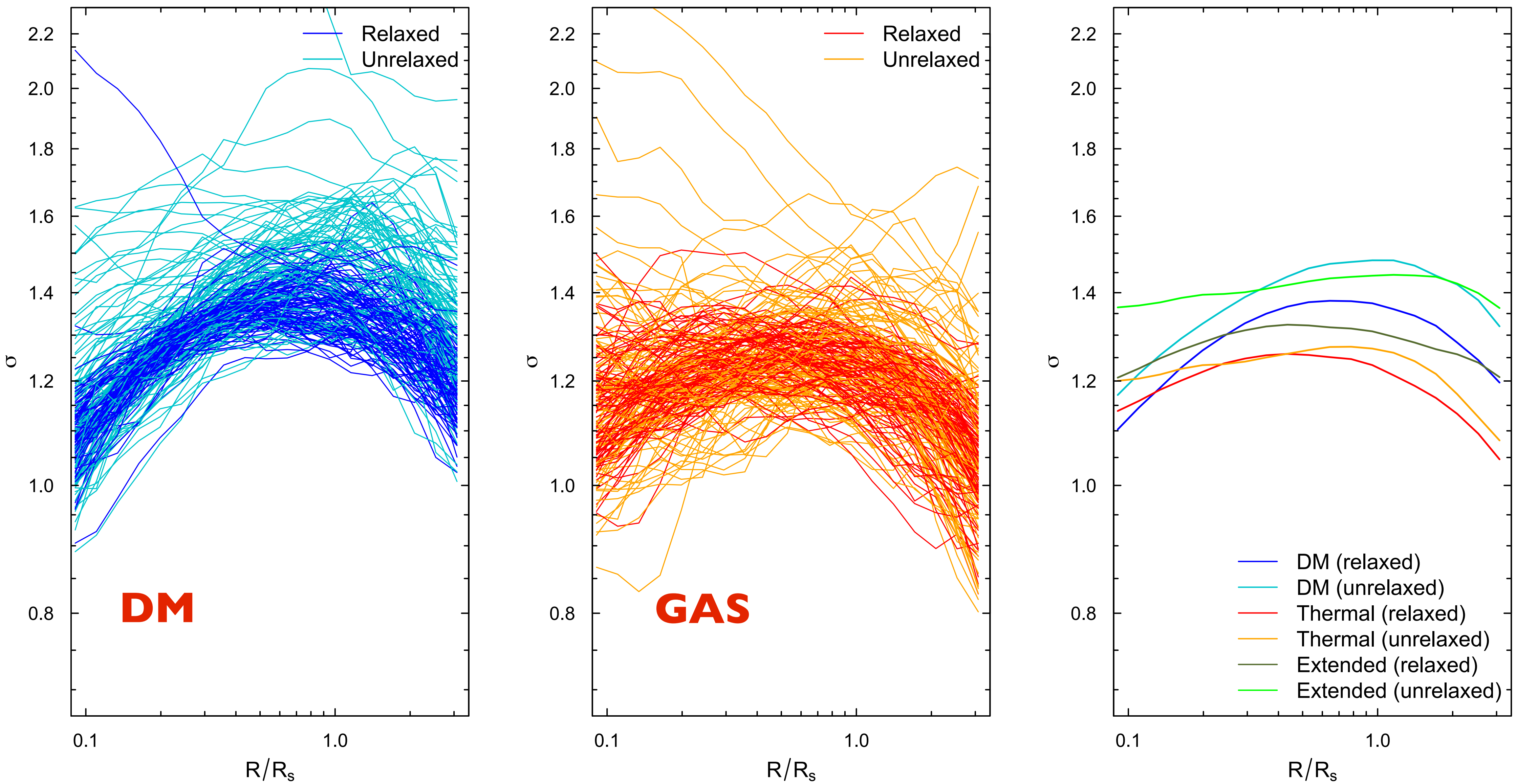
3.1. Adiabatic clusters

Density profiles



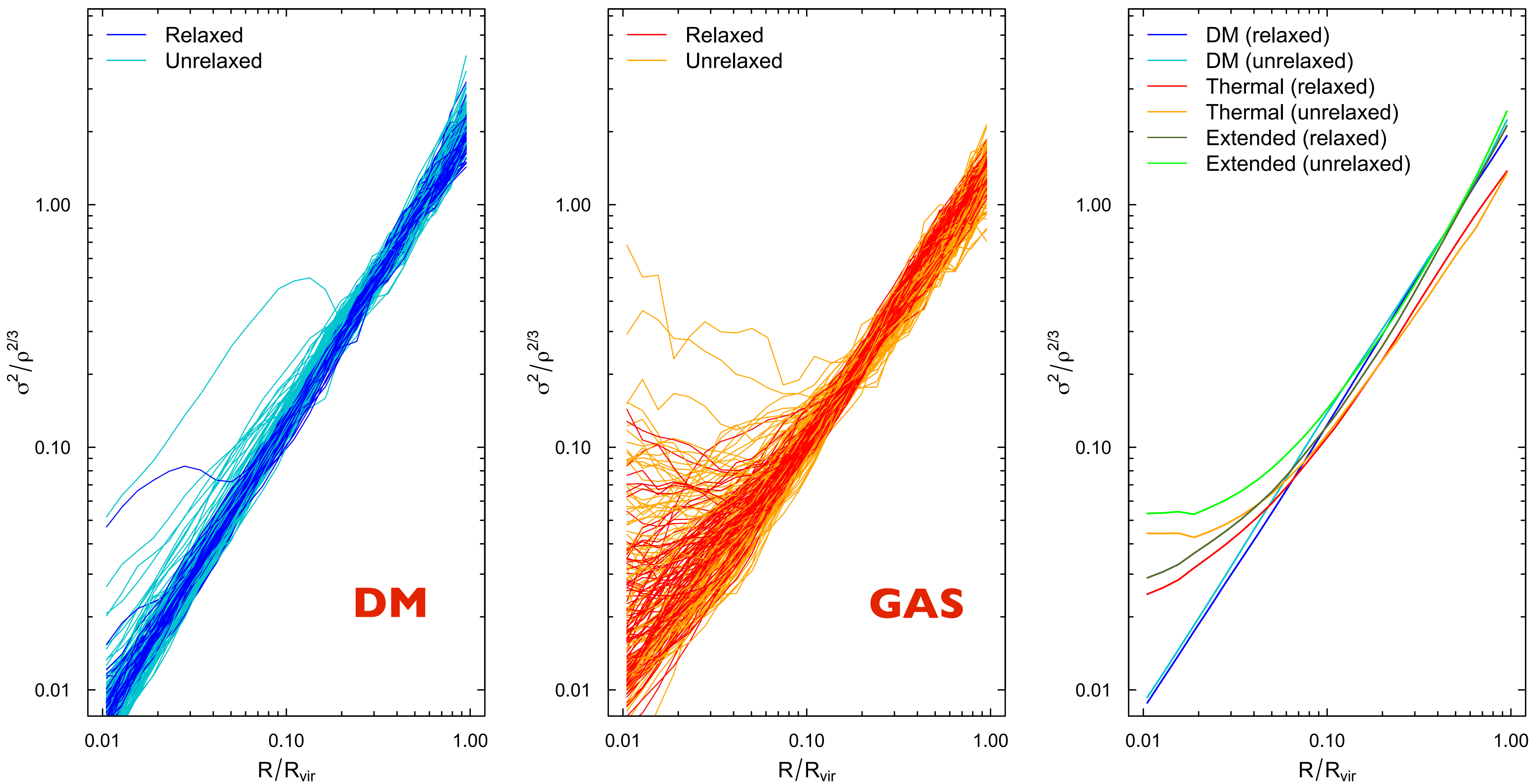
3.1. Adiabatic clusters

Velocity dispersion profiles



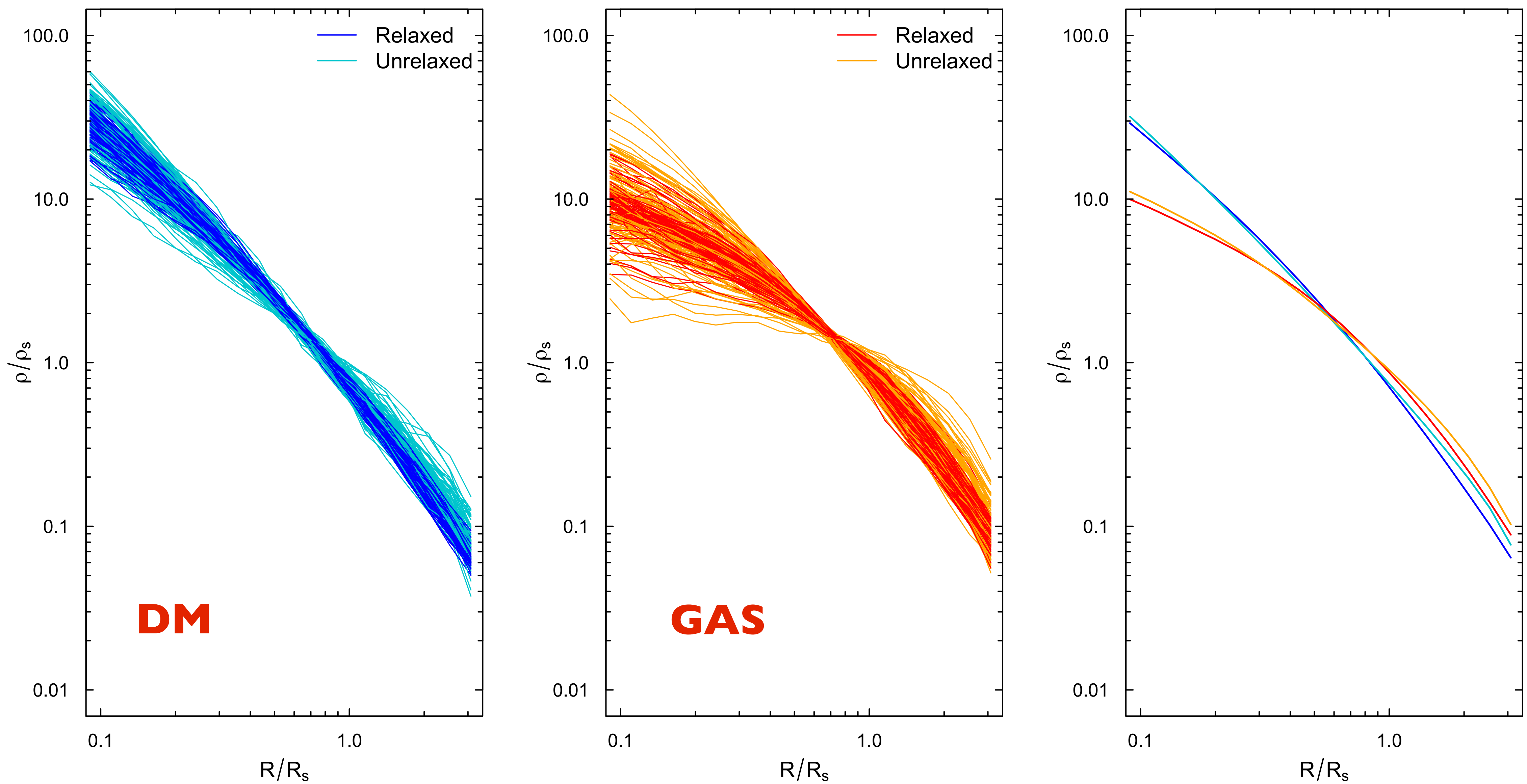
3.1. Adiabatic clusters

Entropy profiles



3.2. Radiative clusters

Density profiles



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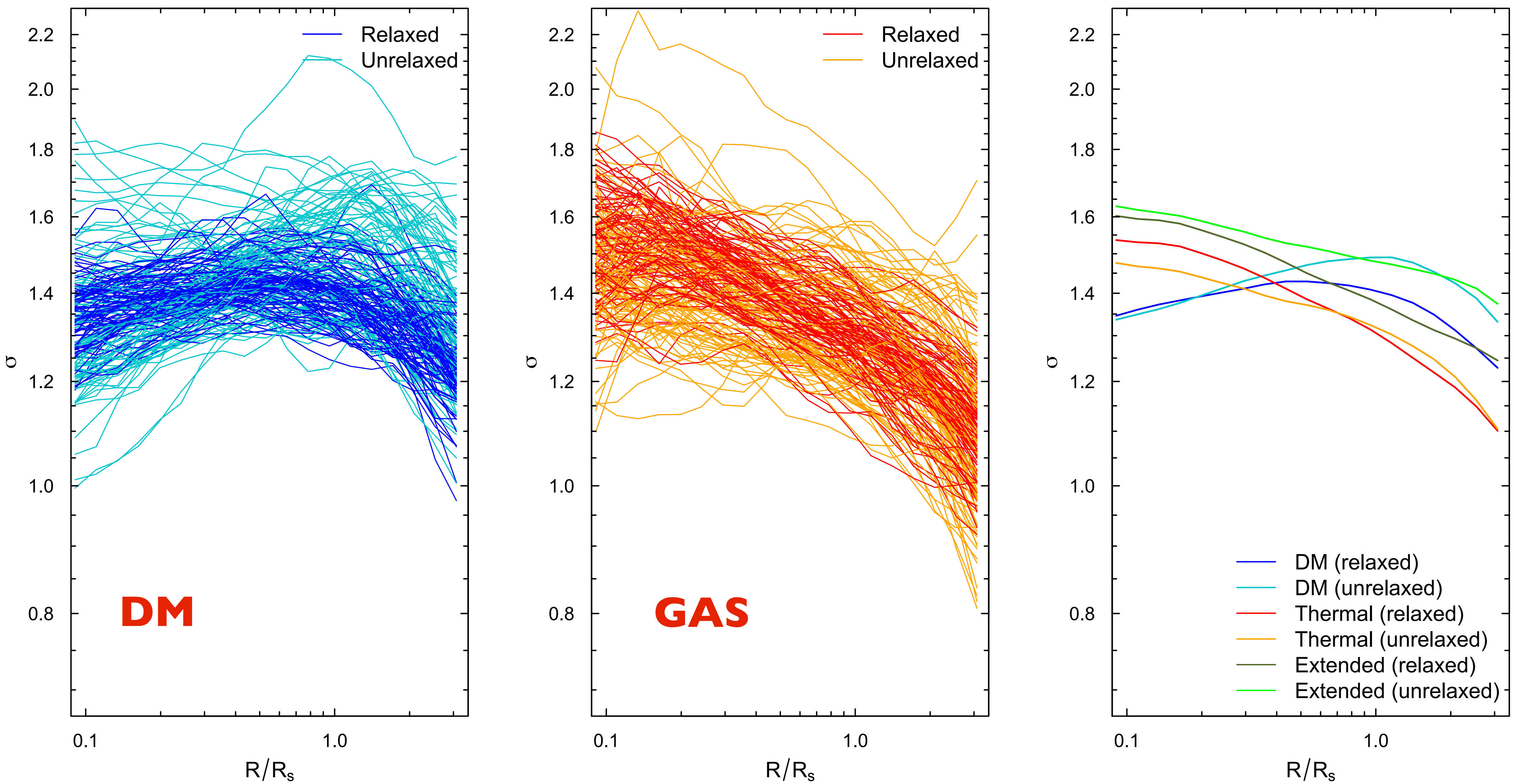

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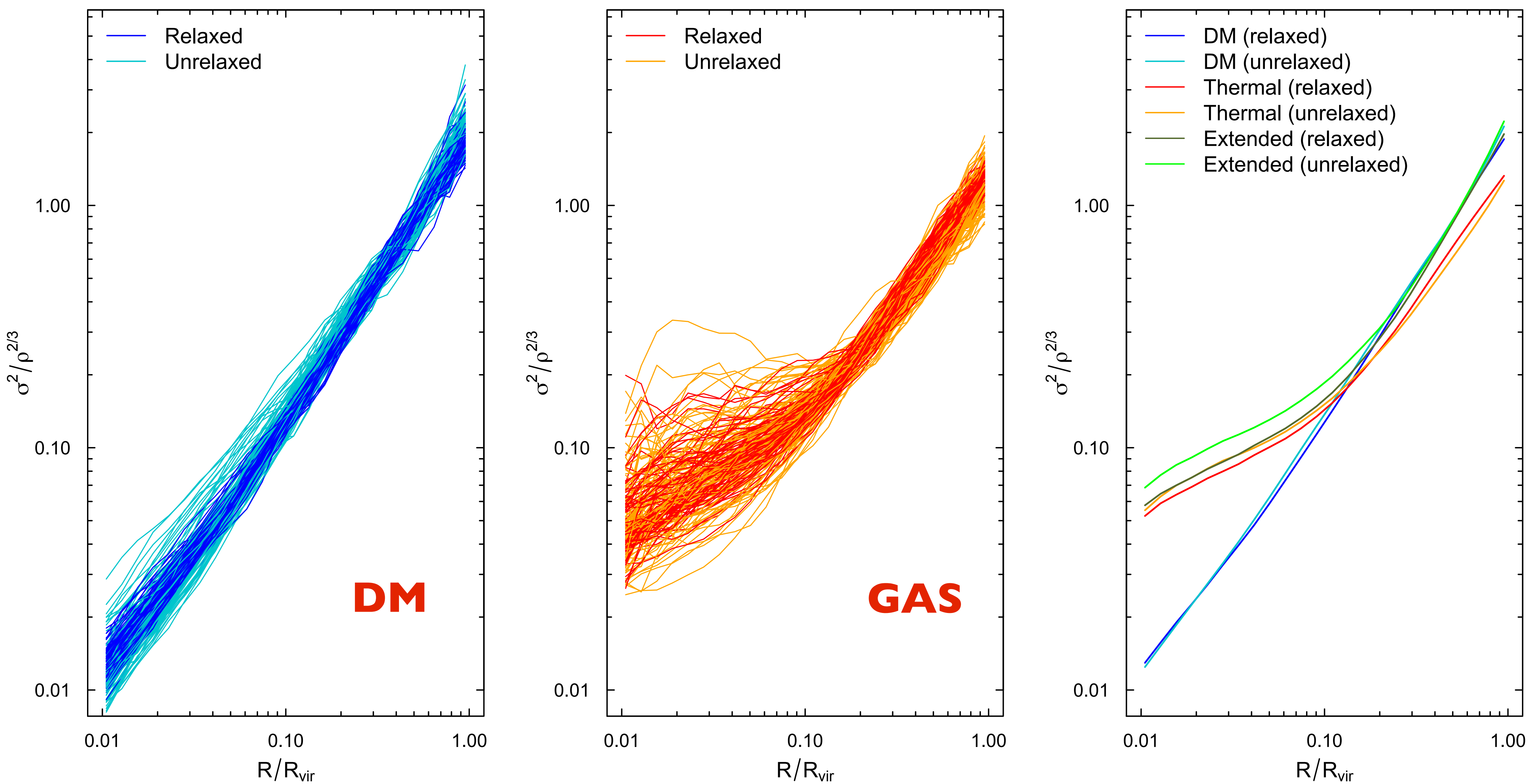
3.2. Radiative clusters

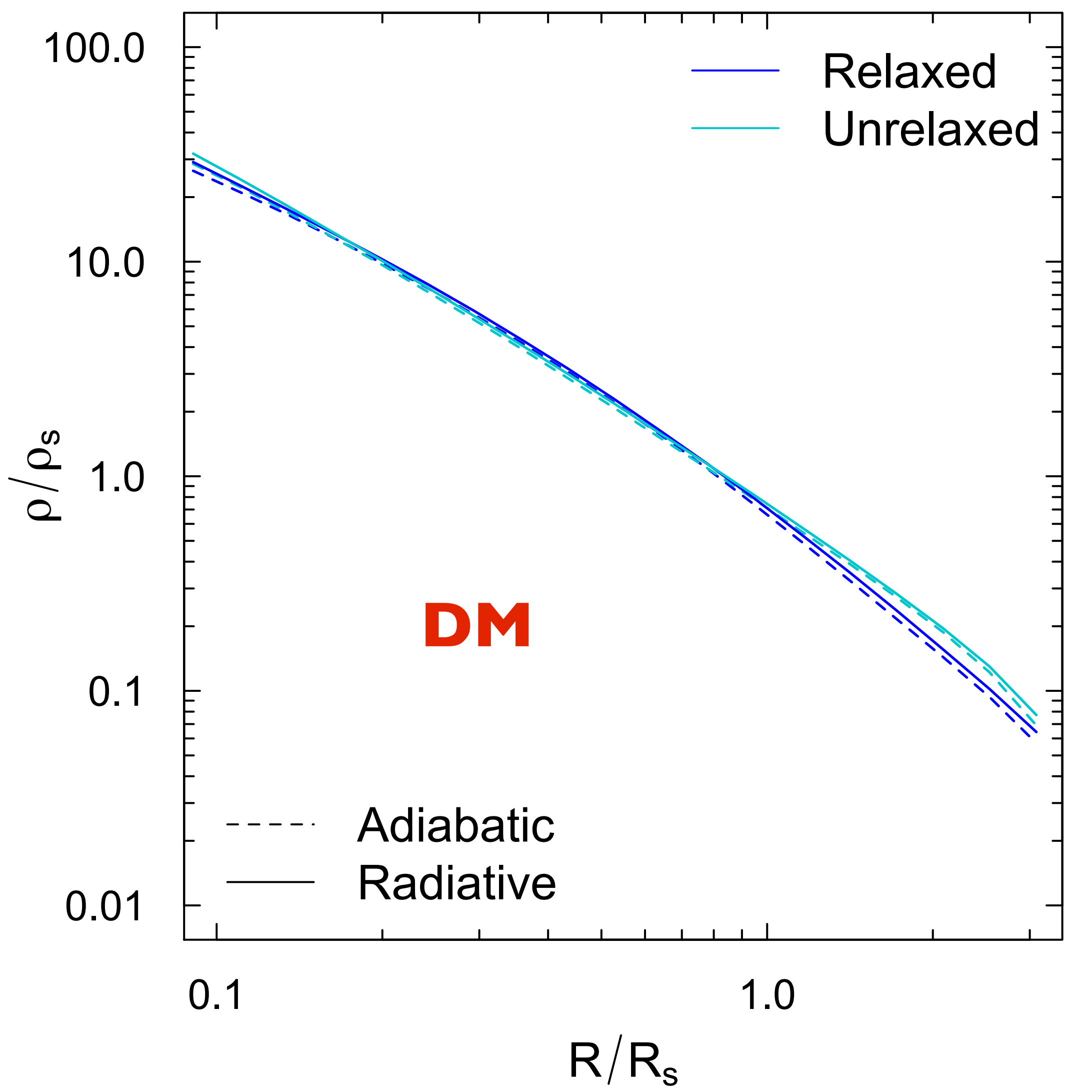
Entropy profiles

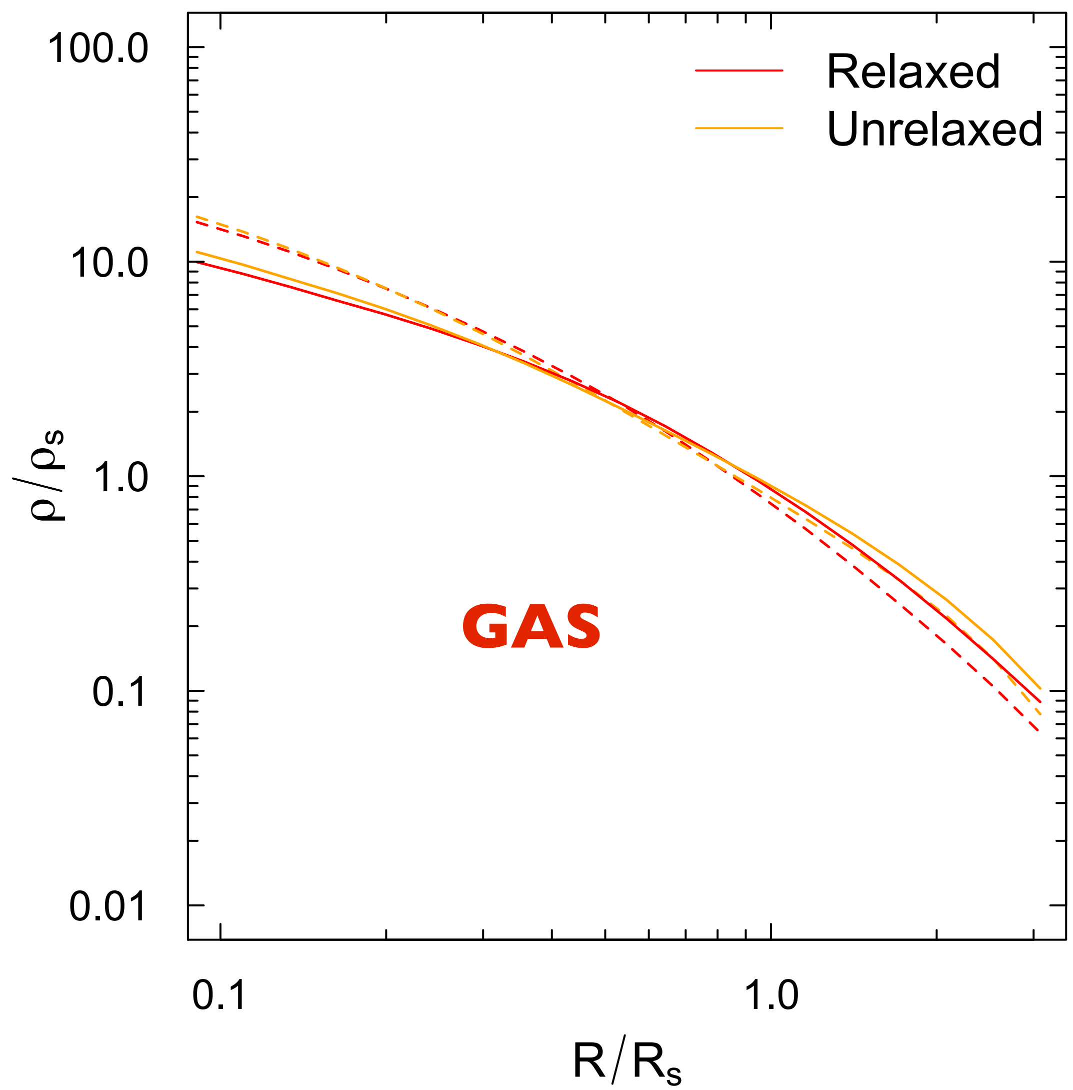


Outline

3.3. Effects of radiative physics

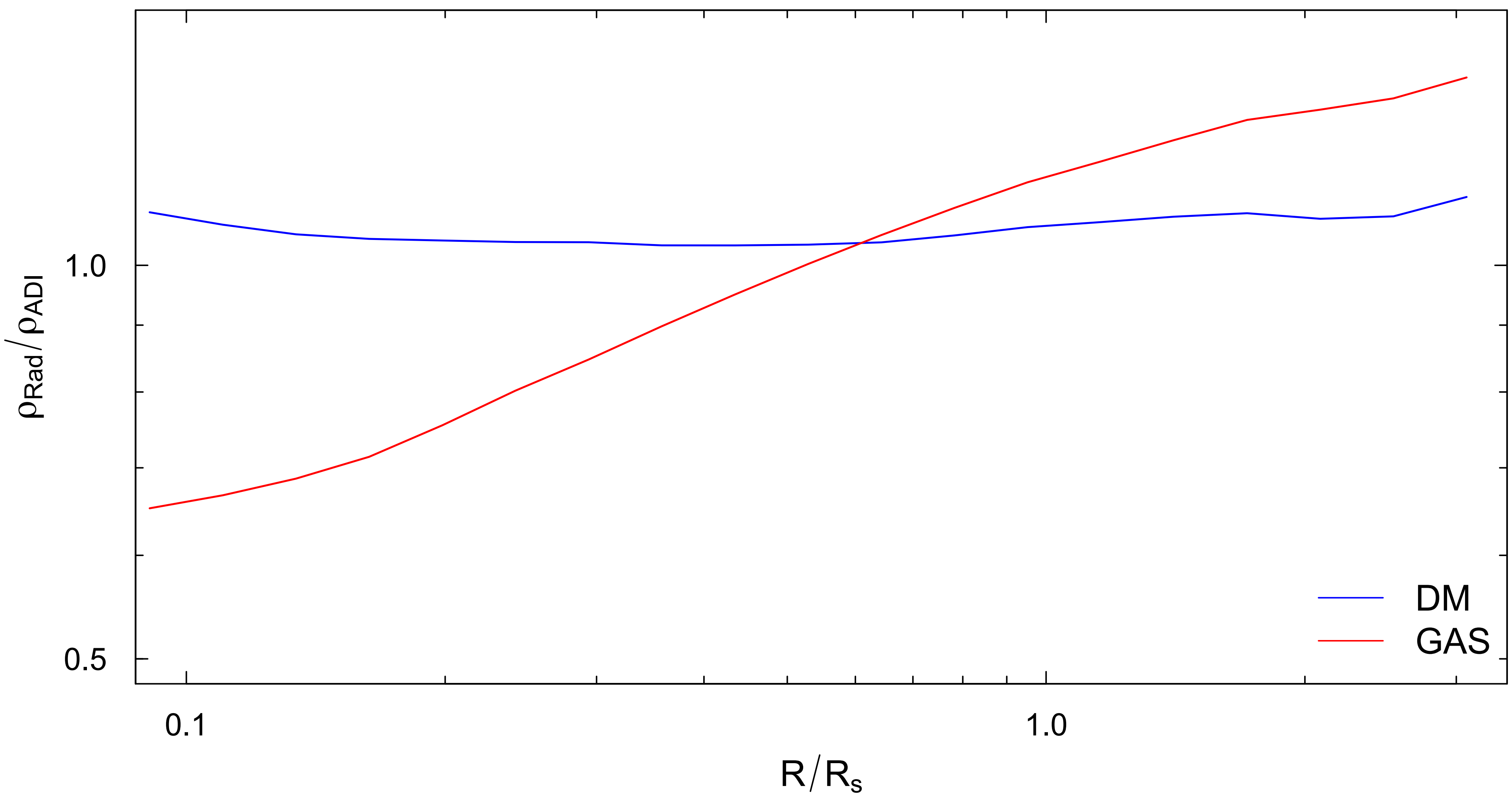
Density profiles





3.3. Effects of radiative physics

Density profiles



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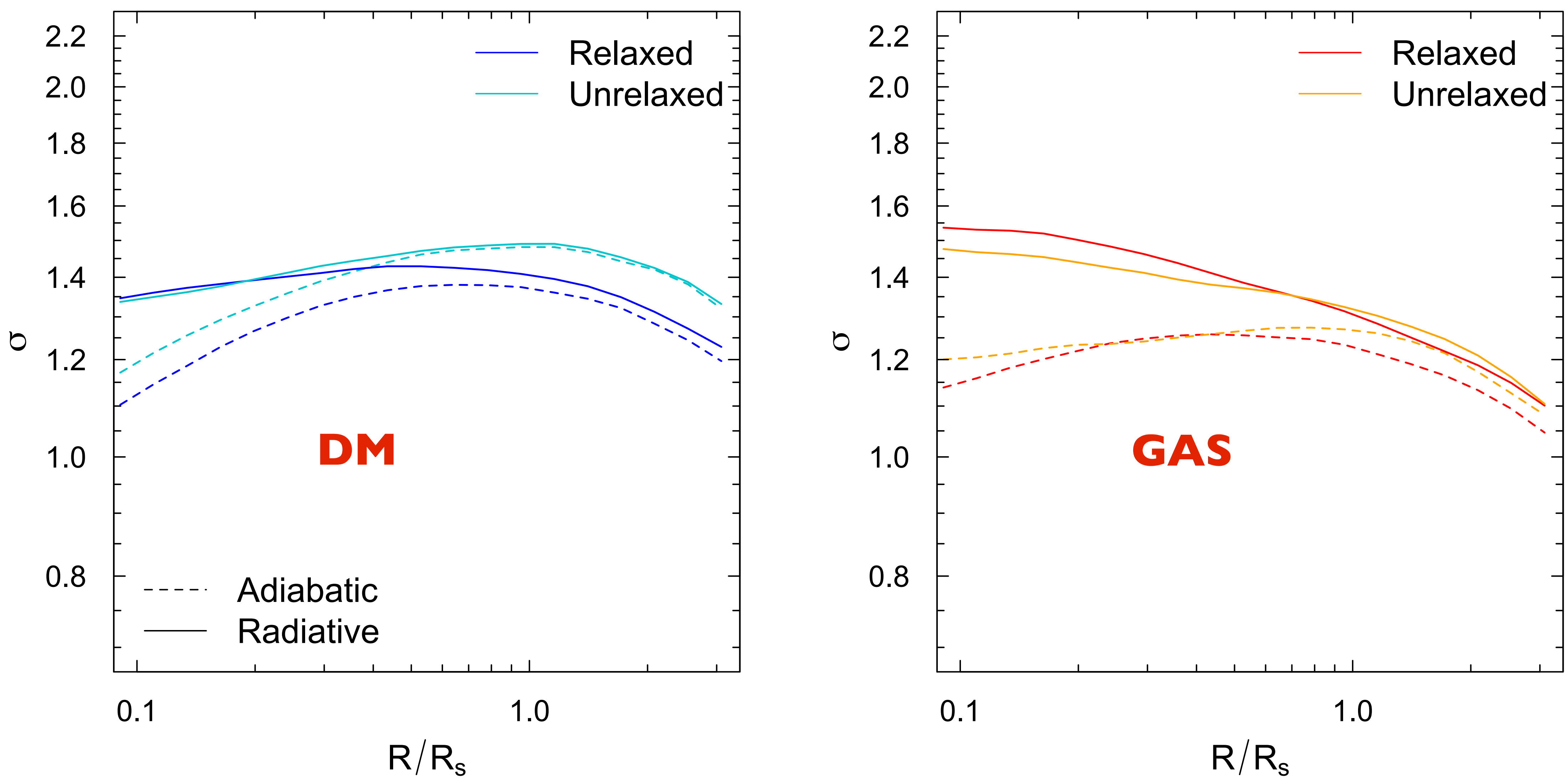
Velocity dispersion profiles



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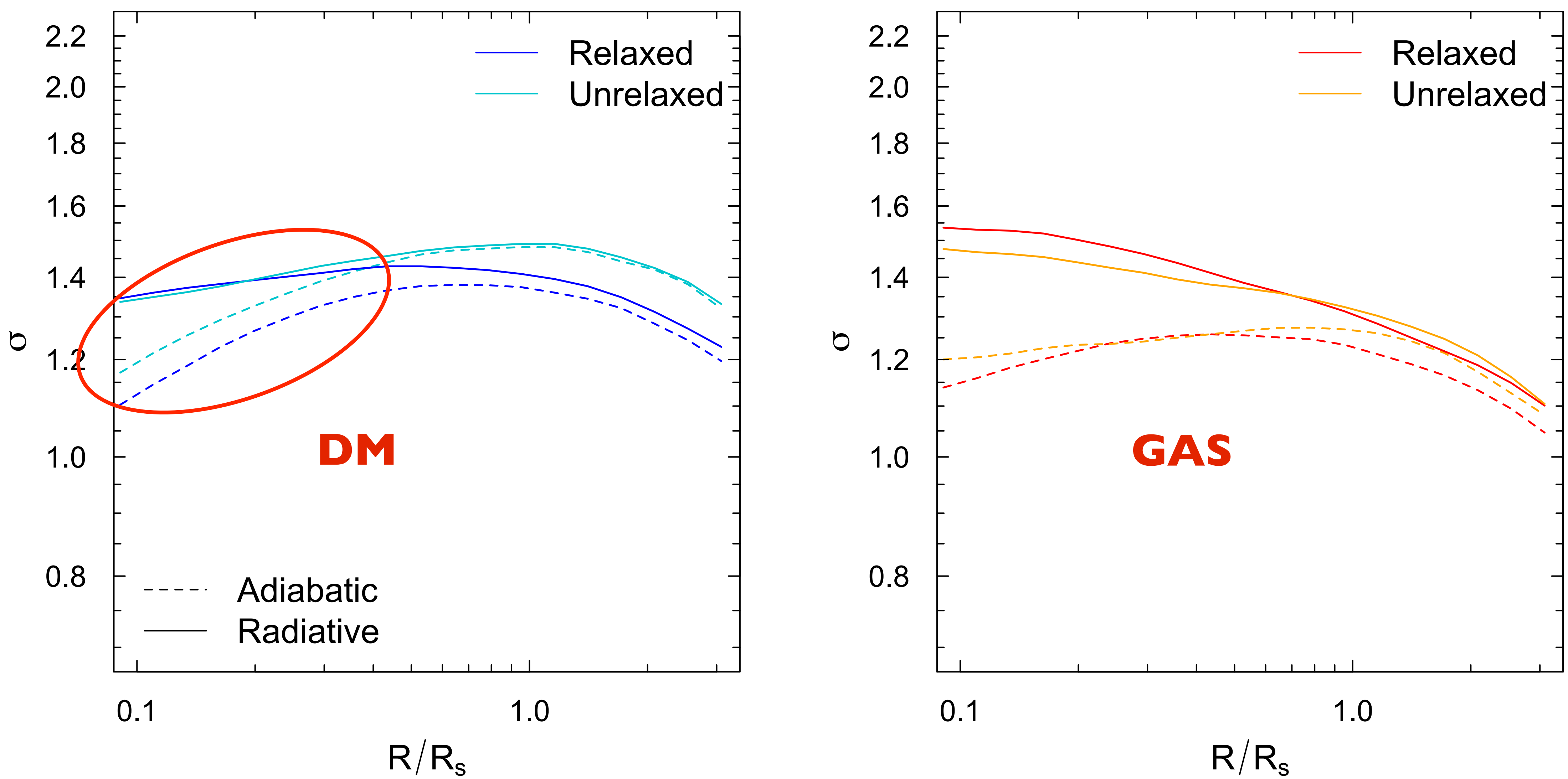

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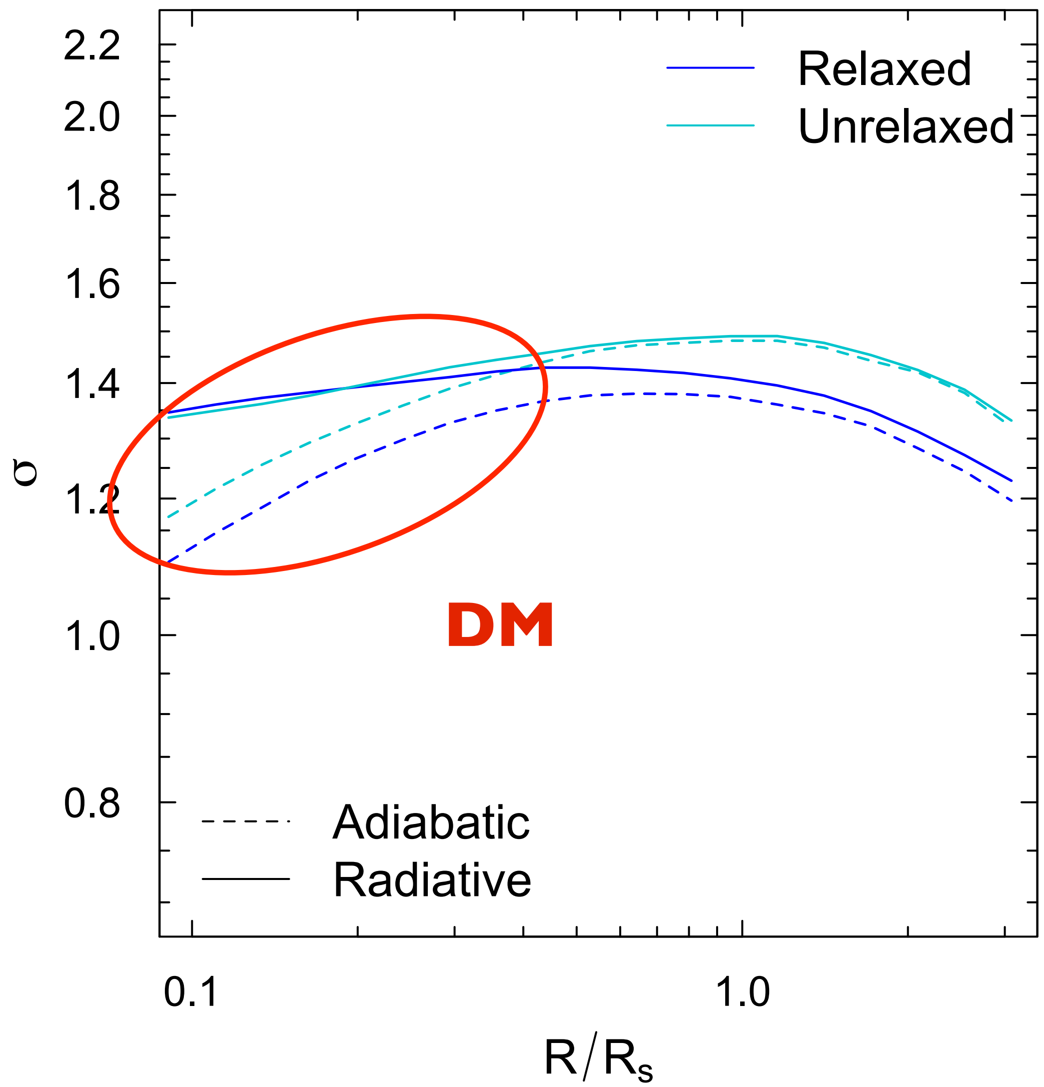

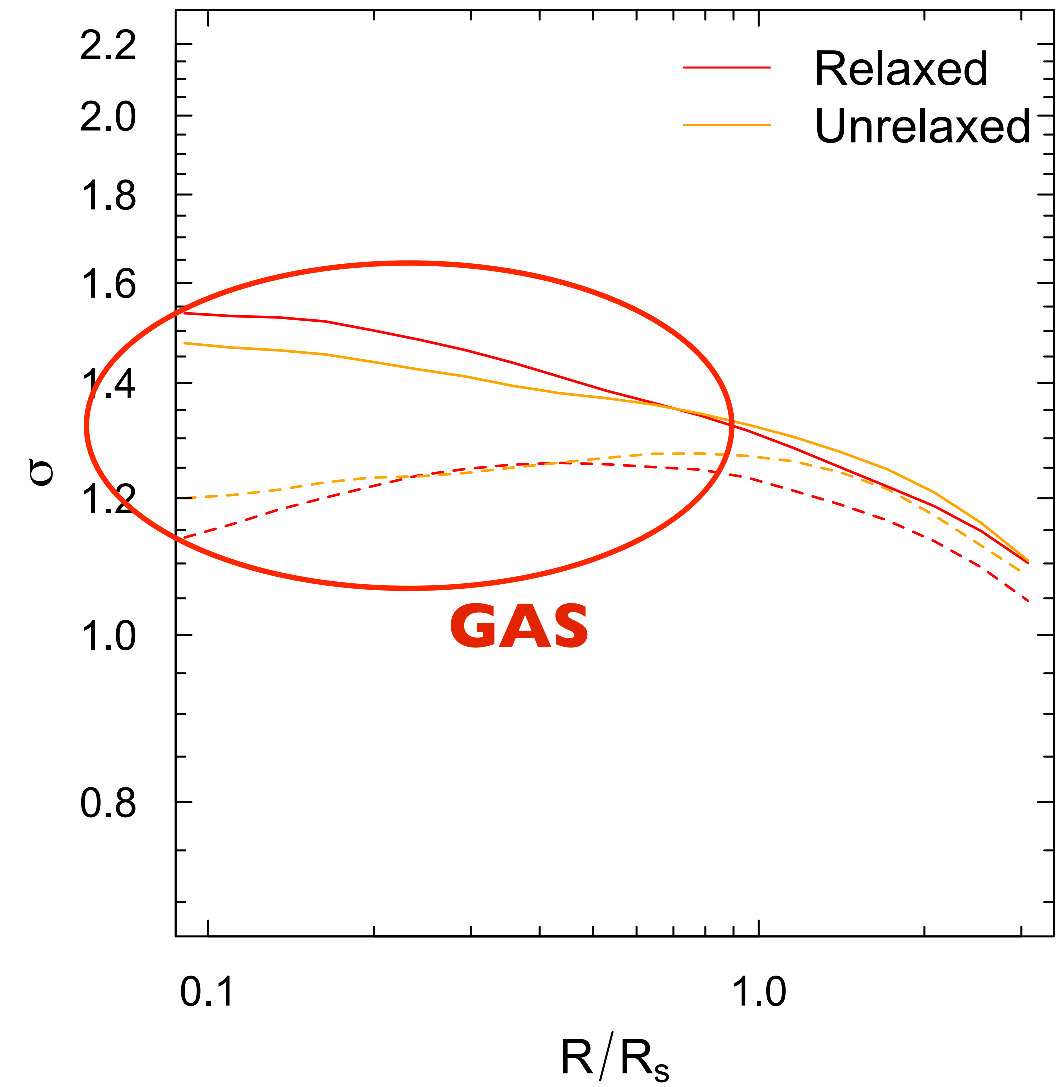

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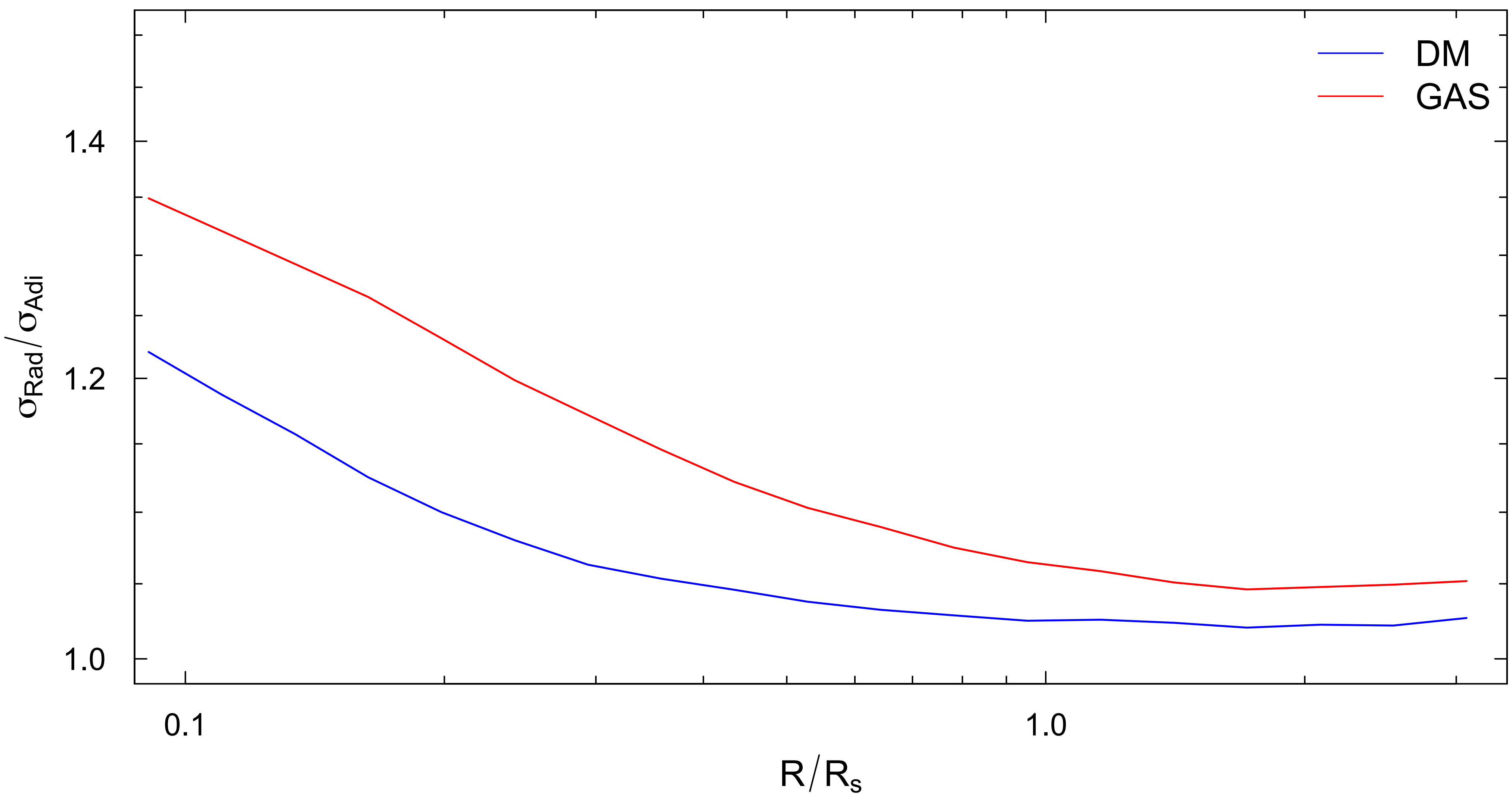
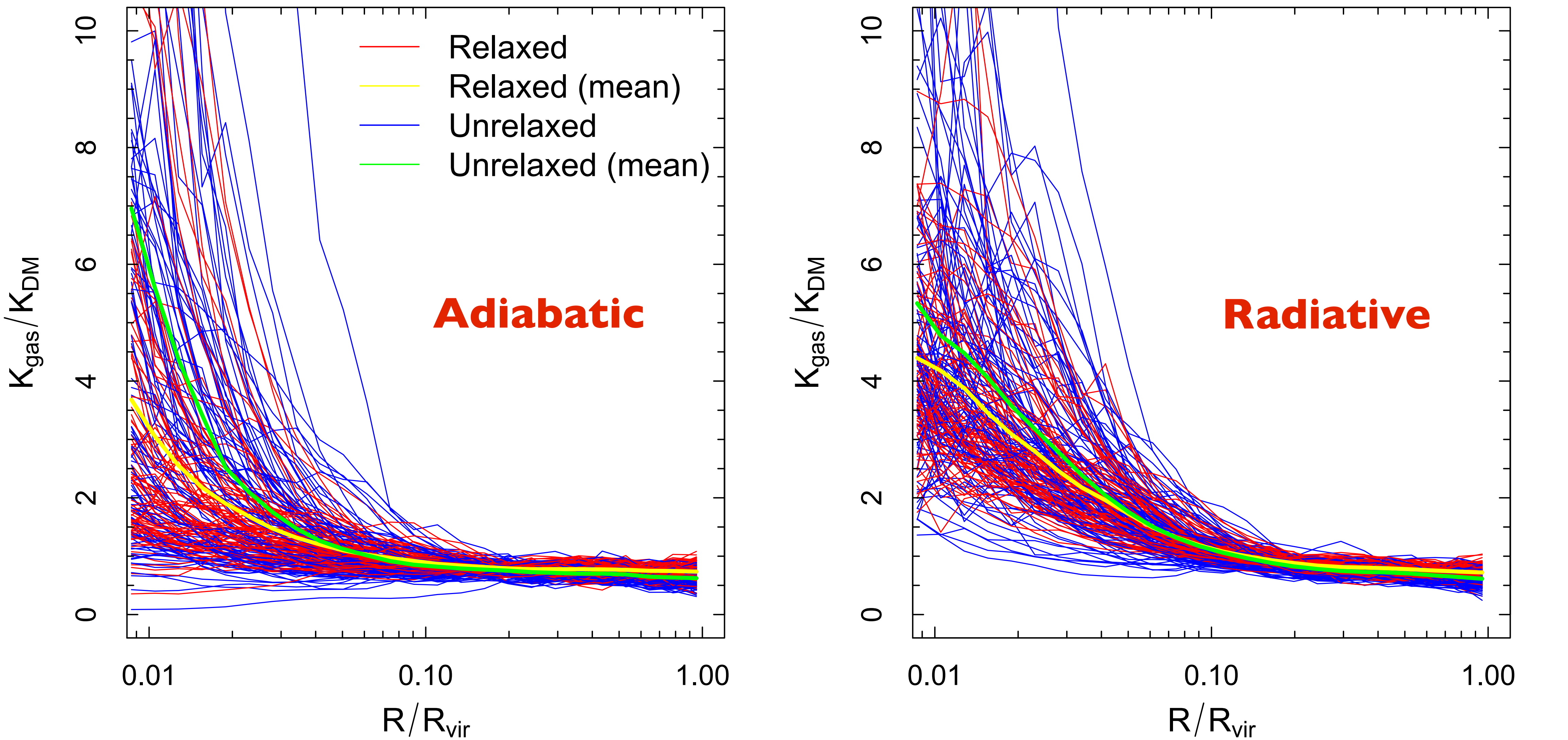


3.3. Effects of radiative physics

Gas-to-DM entropy ratio



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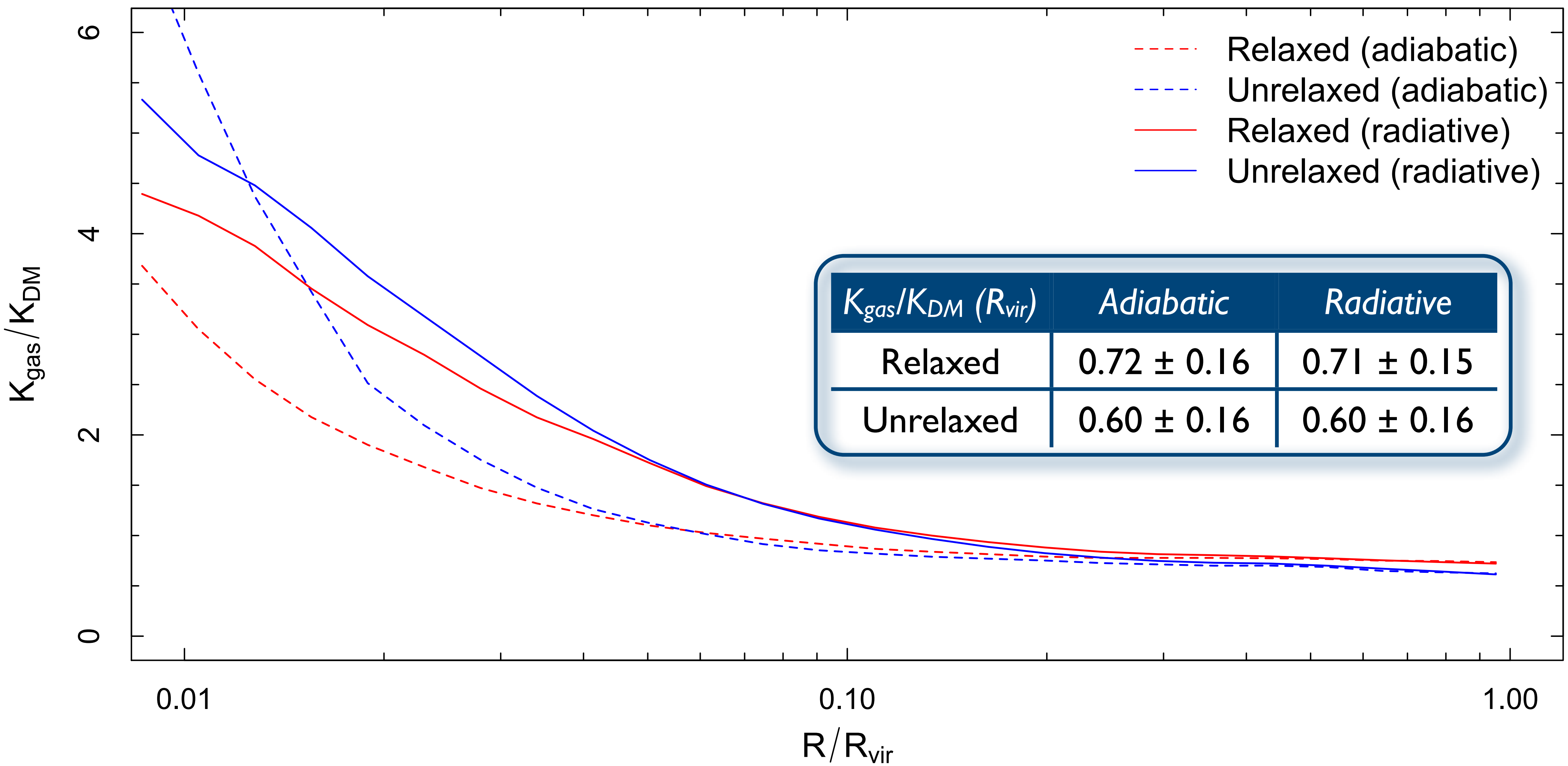
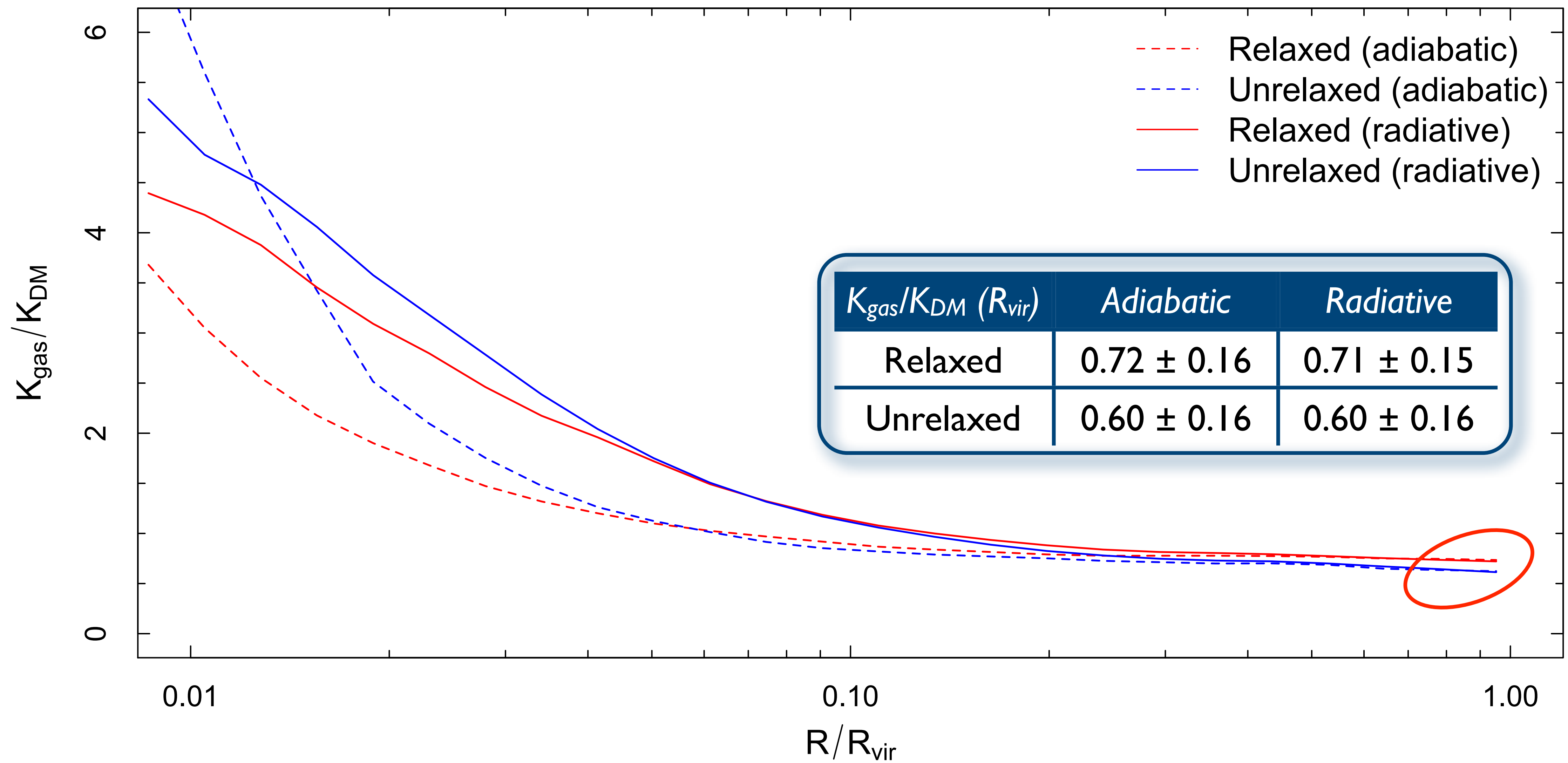


K_{gas}/K_{DM} (R_{vir})	Adiabatic	Radiative
Relaxed	0.72 ± 0.16	0.71 ± 0.15
Unrelaxed	0.60 ± 0.16	0.60 ± 0.16

3.3. Effects of radiative physics

Gas-to-DM entropy ratio



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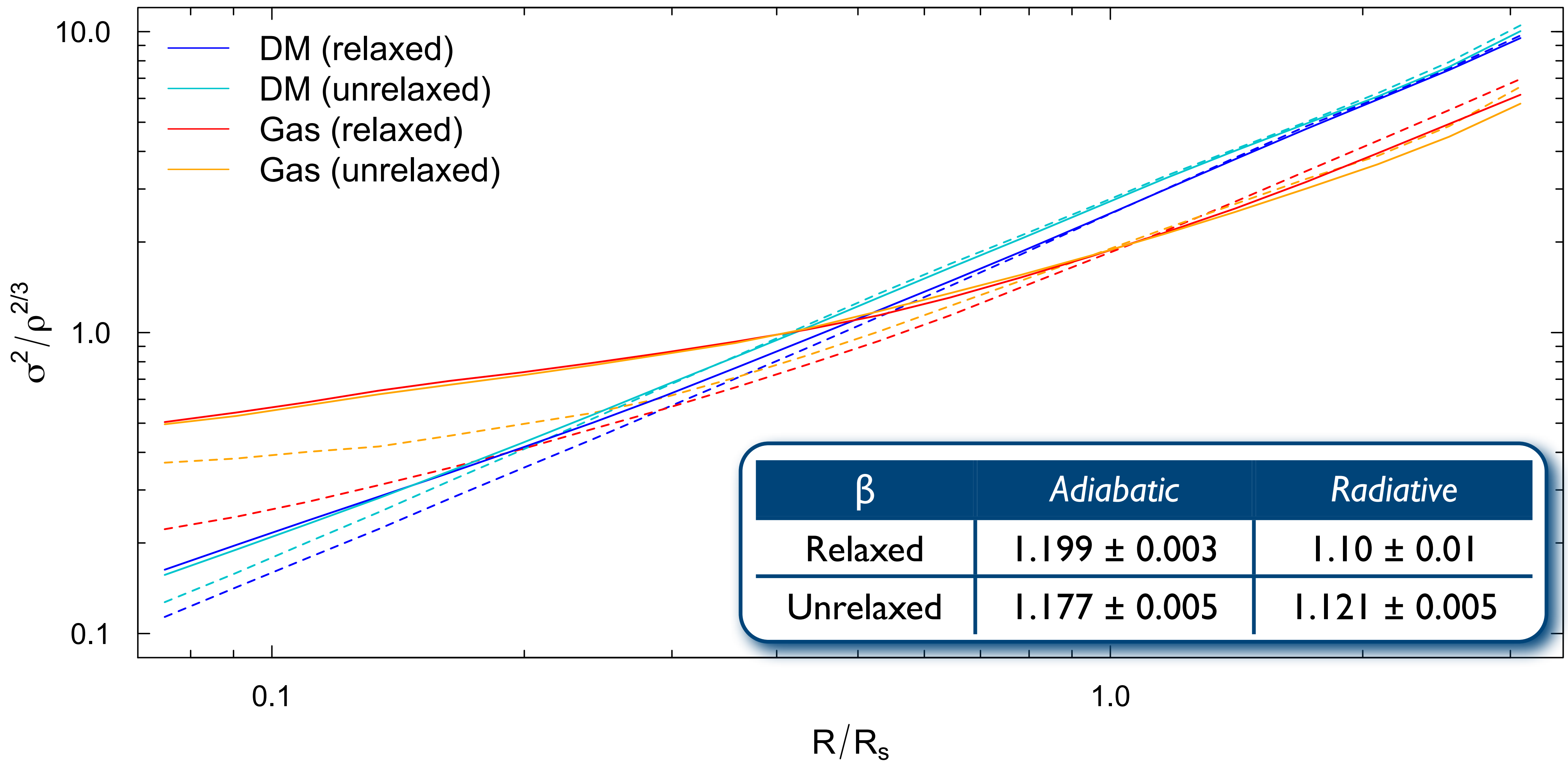
3.3. Effects of radiative physics

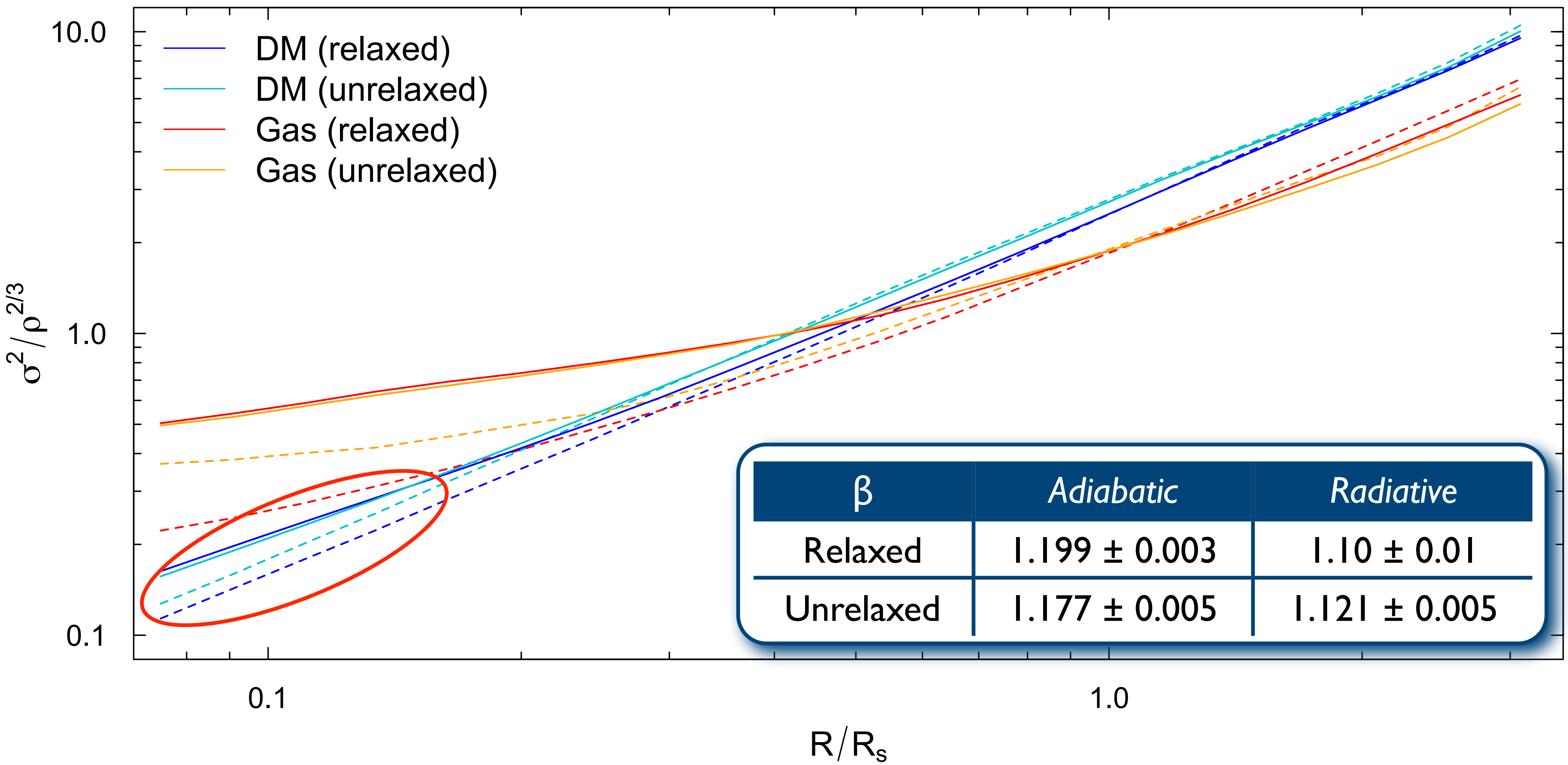
Power-law



β	*Adiabatic*	*Radiative*
Relaxed	1.199 ± 0.003	1.10 ± 0.01
Unrelaxed	1.177 ± 0.005	1.121 ± 0.005

3.3. Effects of radiative physics

Power-law



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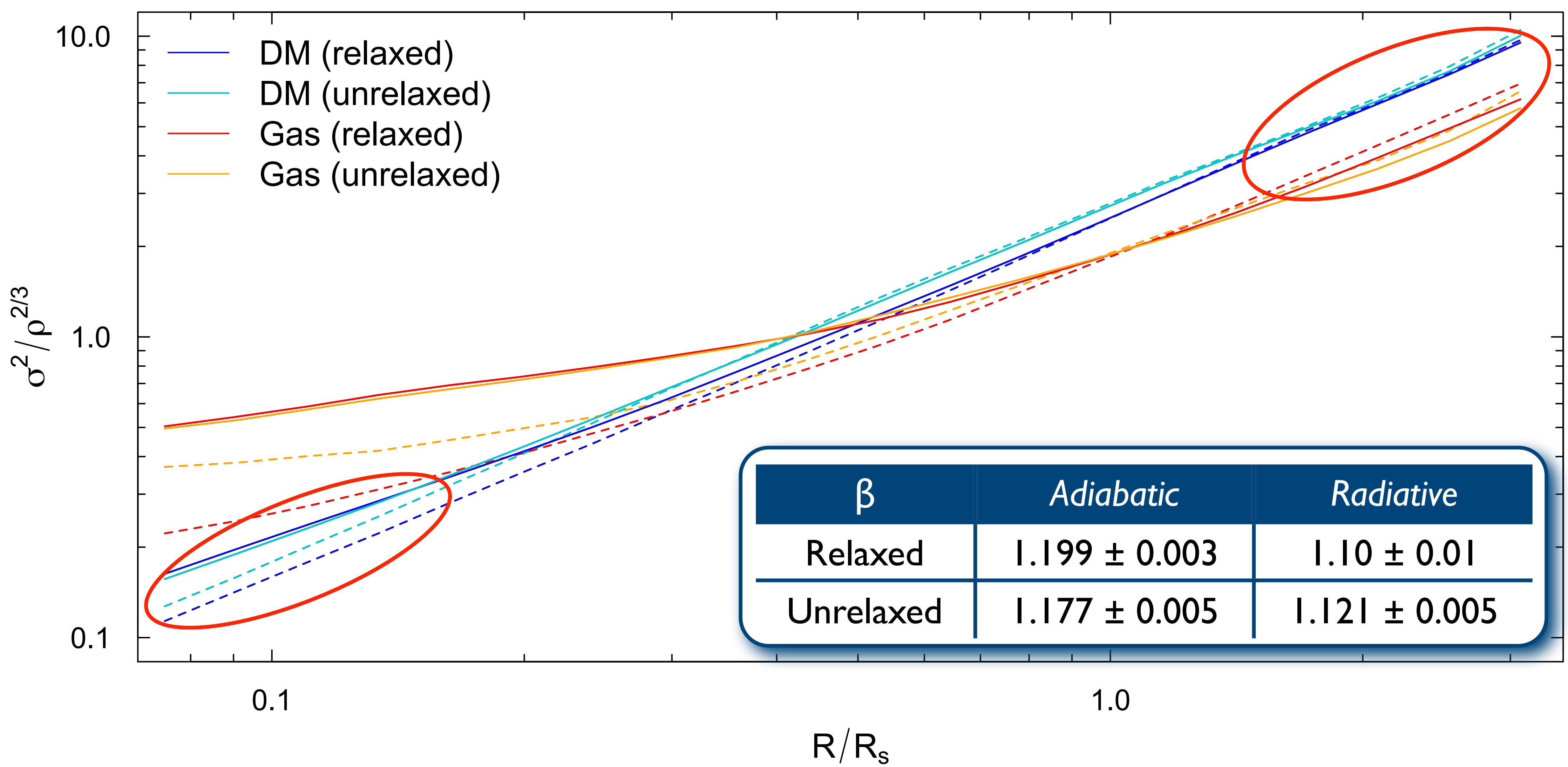

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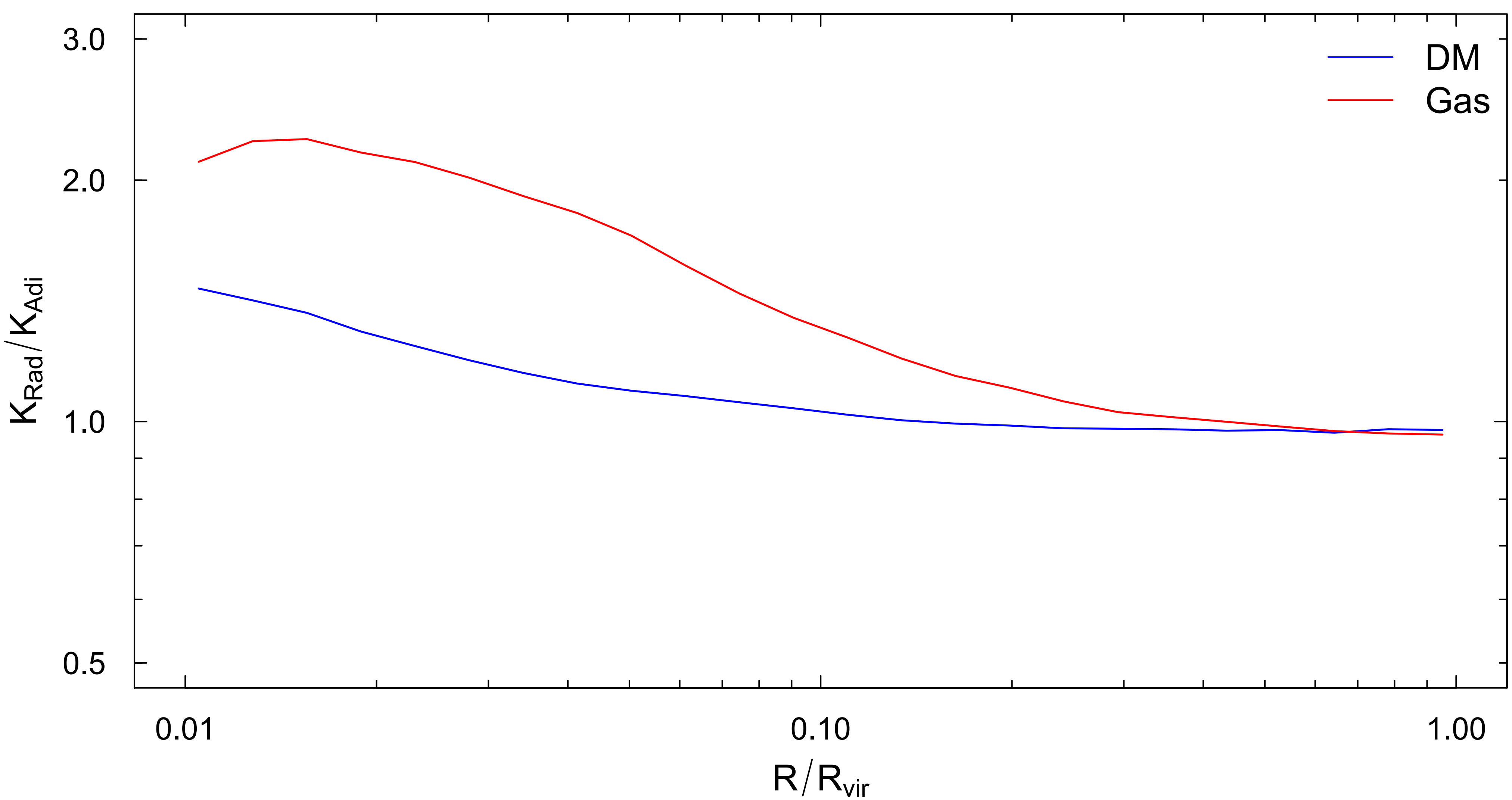
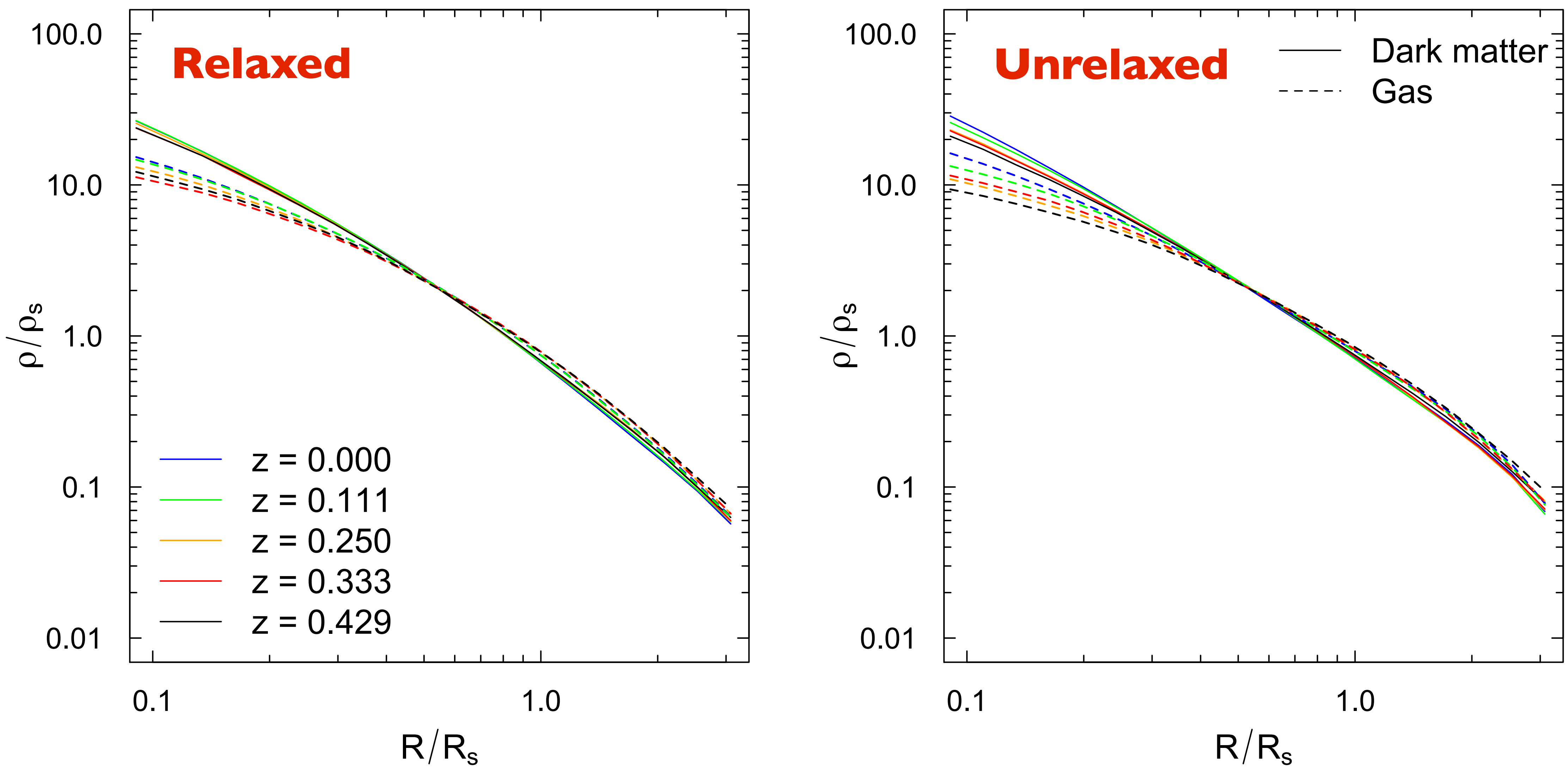


Outline

1. Introduction
2. MUSIC clusters
    2.1. Relaxed and unrelaxed clusters
3. Entropy profiles of gas and dark matter
    3.1. Adiabatic clusters
    3.2. Radiative clusters
    3.3. Effects of radiative physics
    3.4. Redshift evolution
    3.5. Gas entropy cores
4. Conclusions

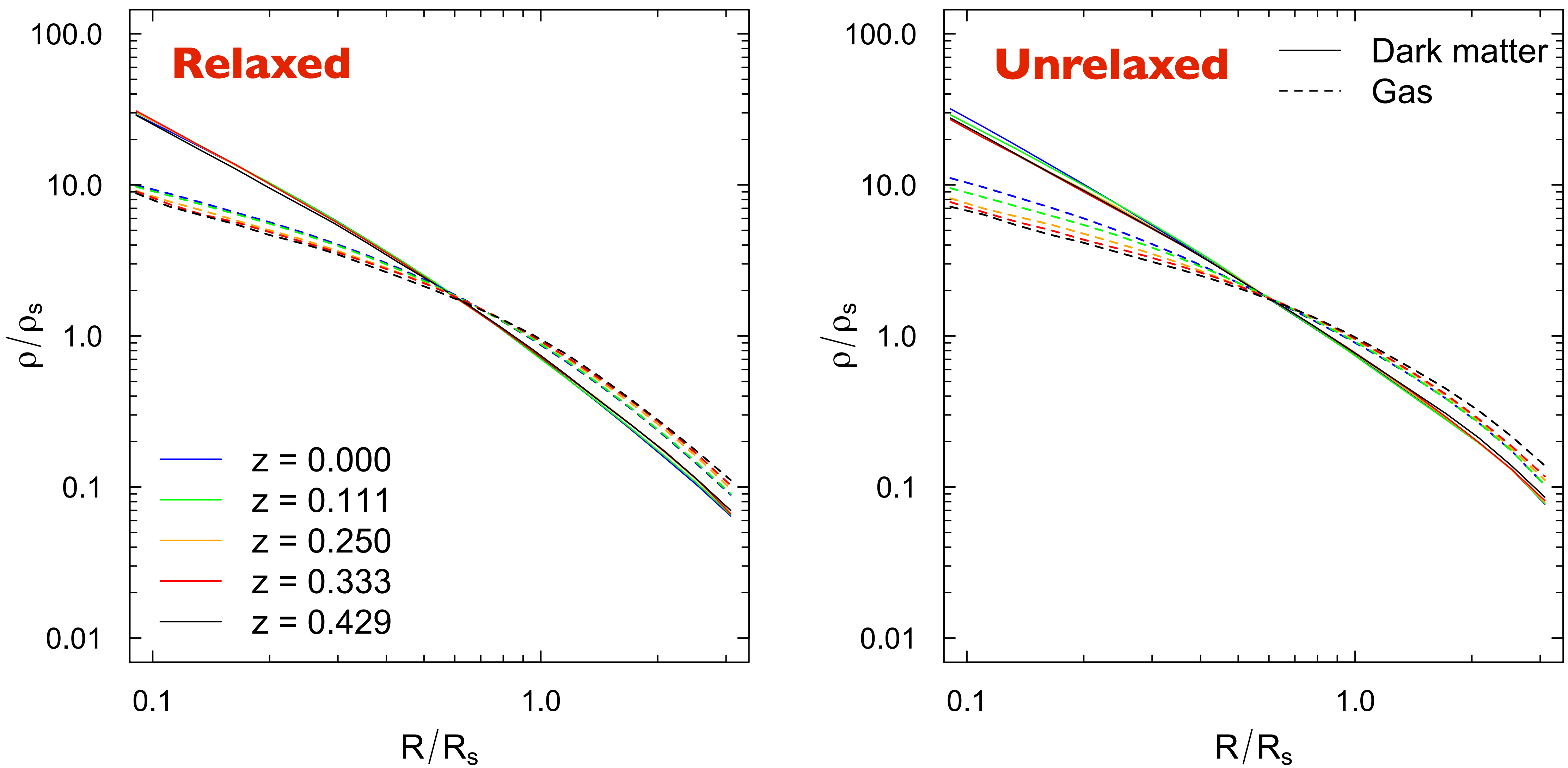
3.4. Redshift evolution

Adiabatic density profiles



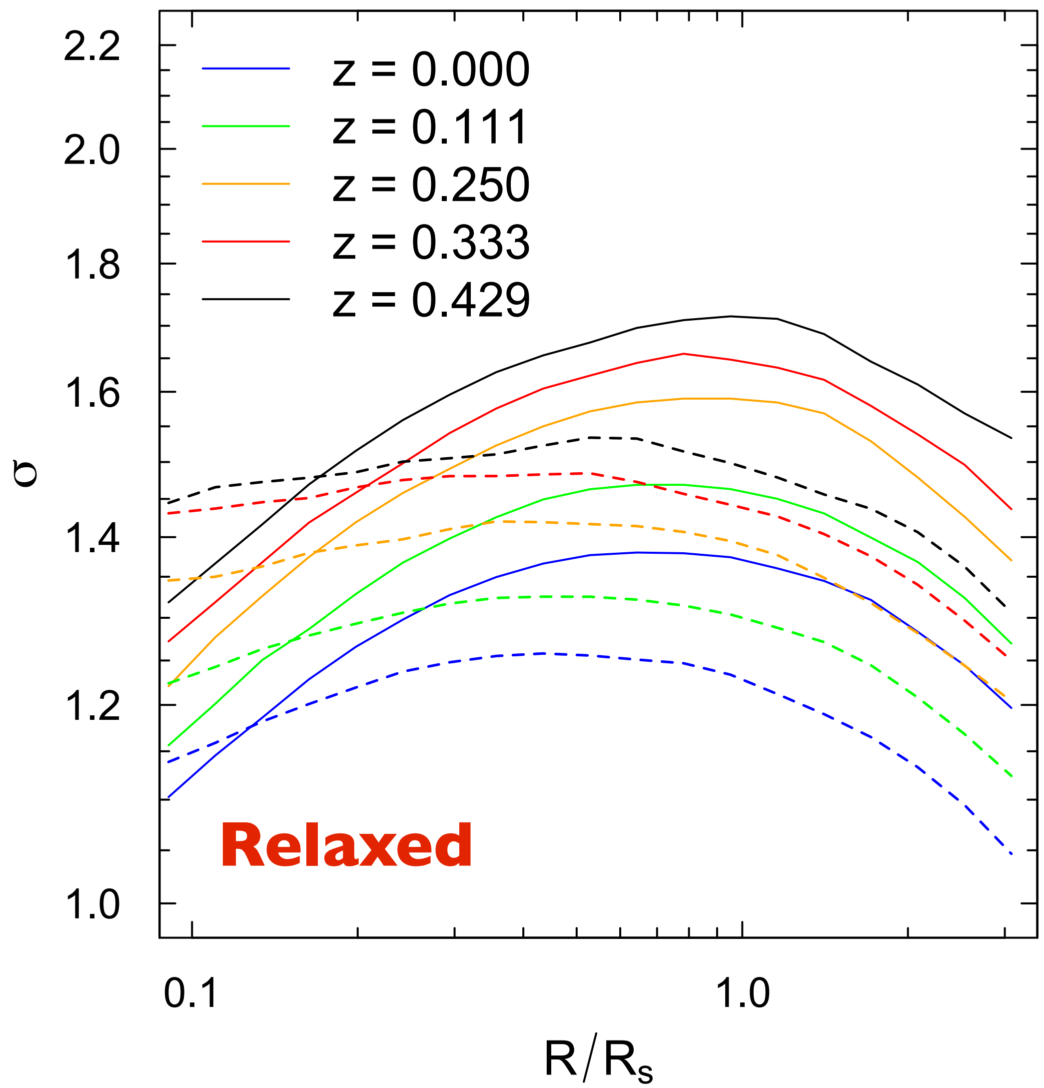
3.4. Redshift evolution

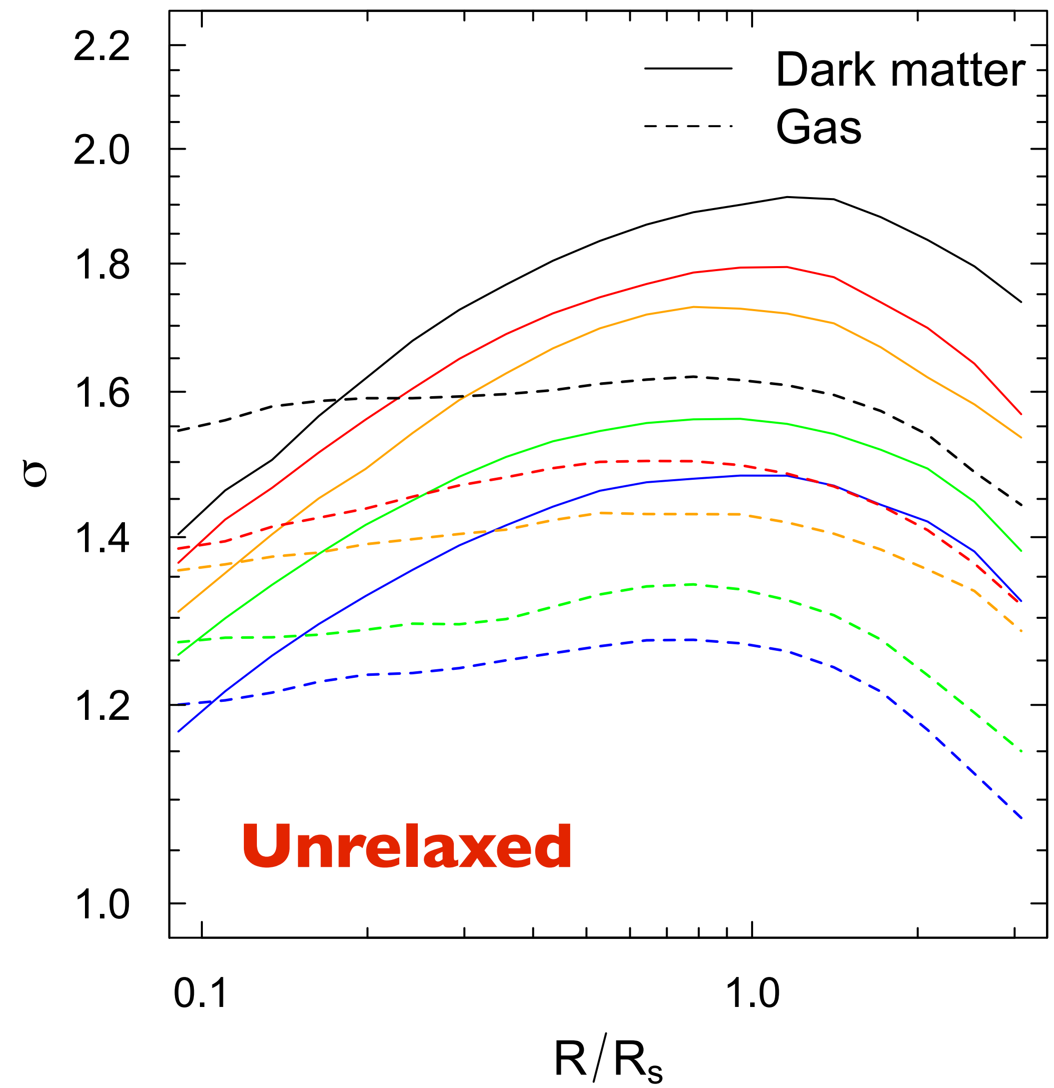
Radiative density profiles



3.4. Redshift evolution

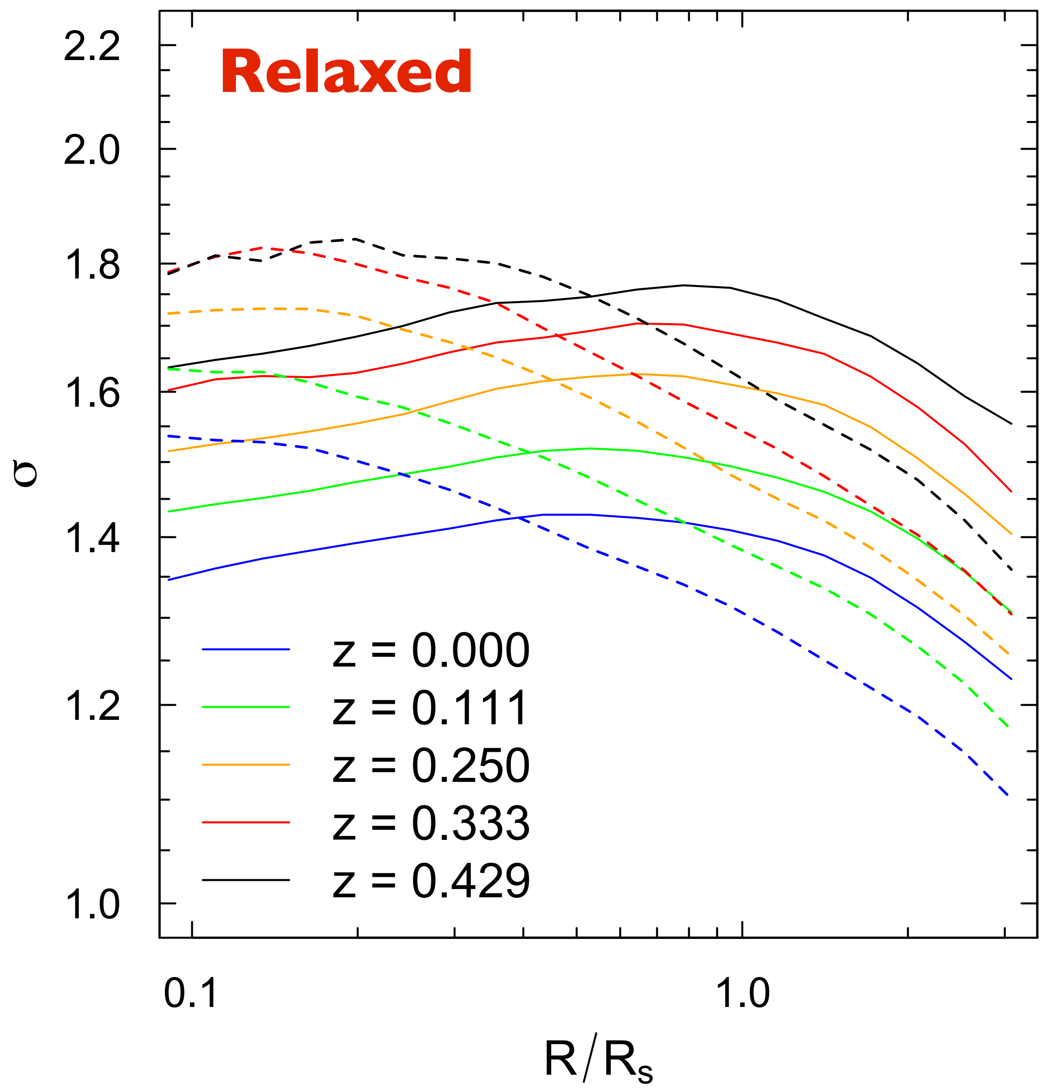
Adiabatic velocity dispersion profiles

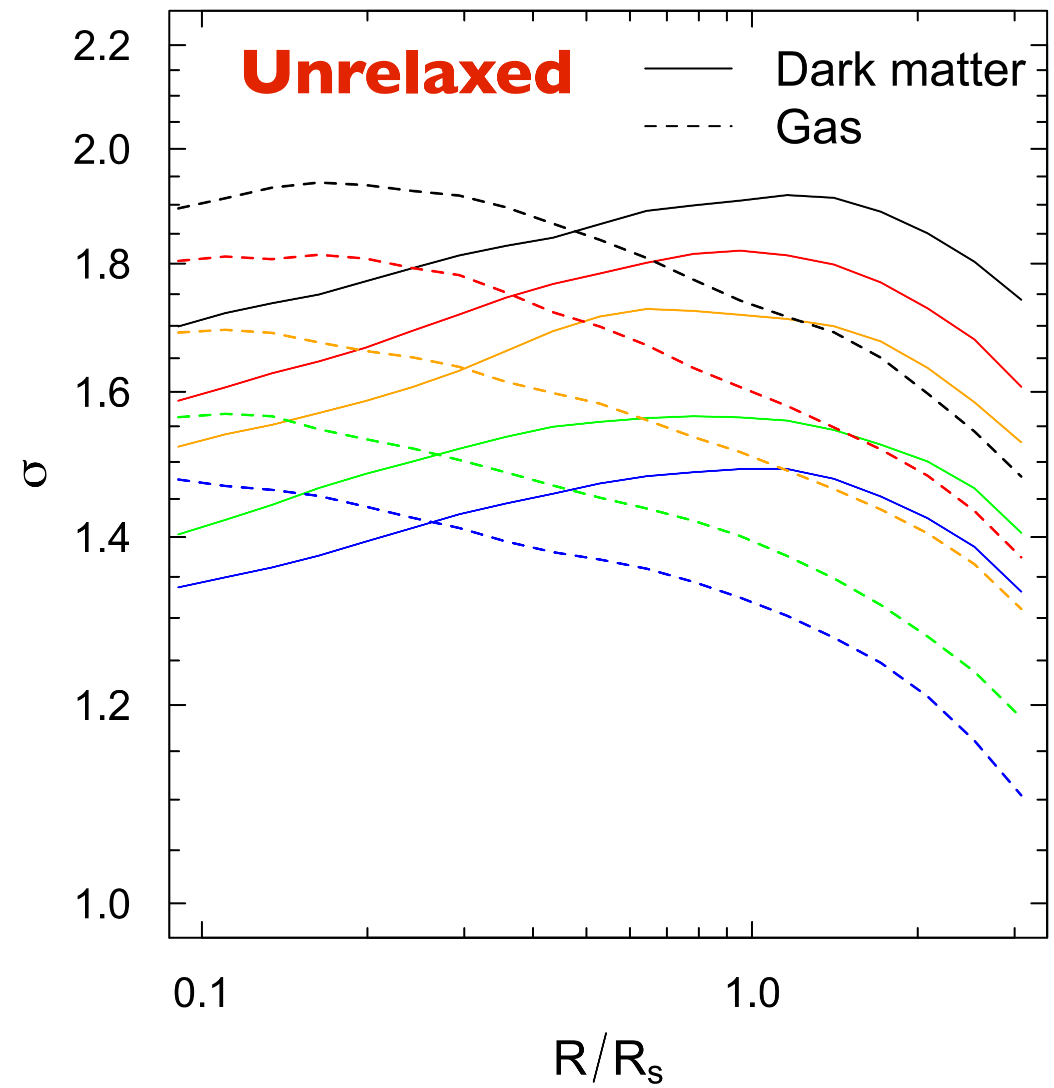




3.4. Redshift evolution

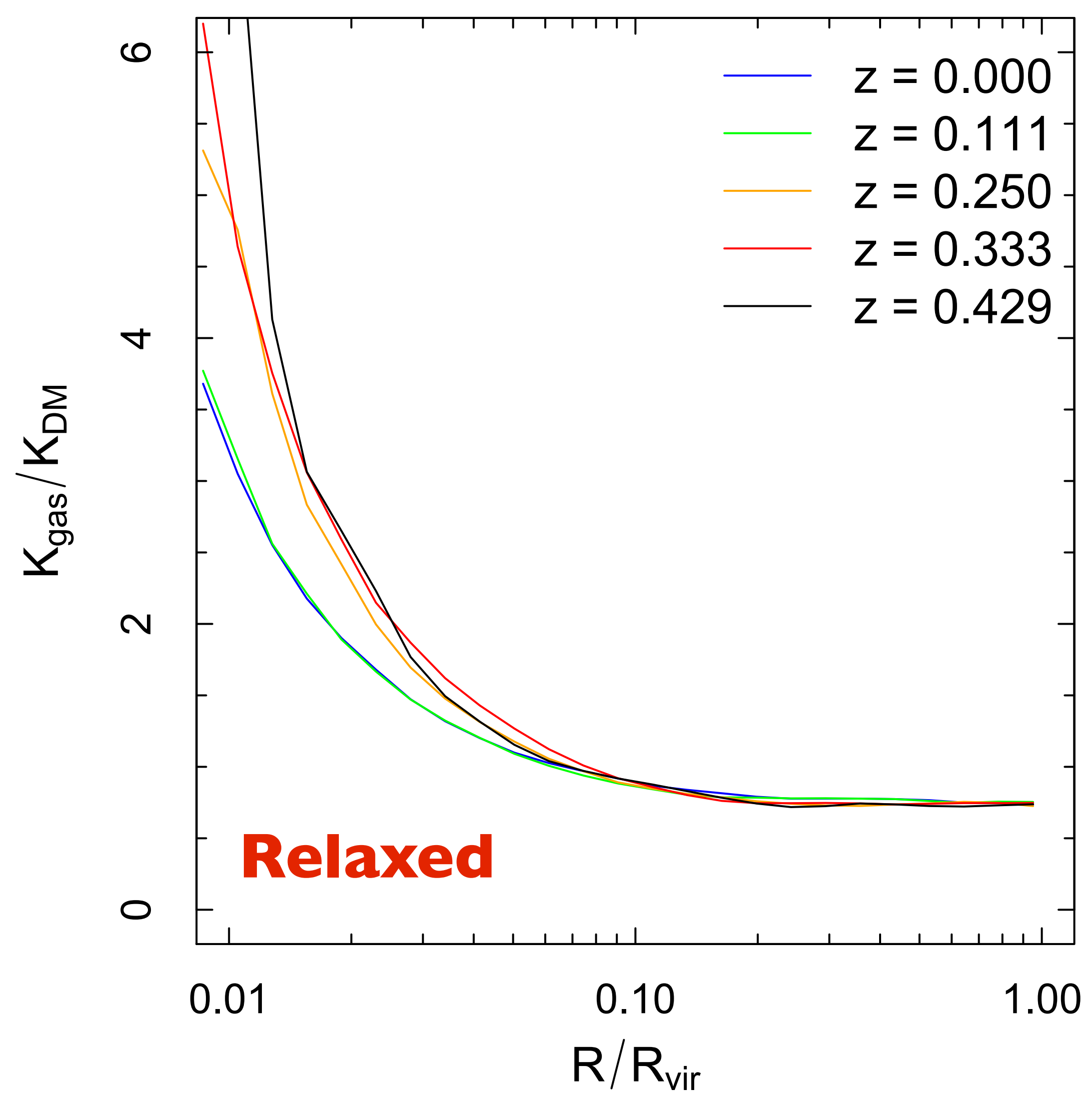
Radiative velocity dispersion profiles

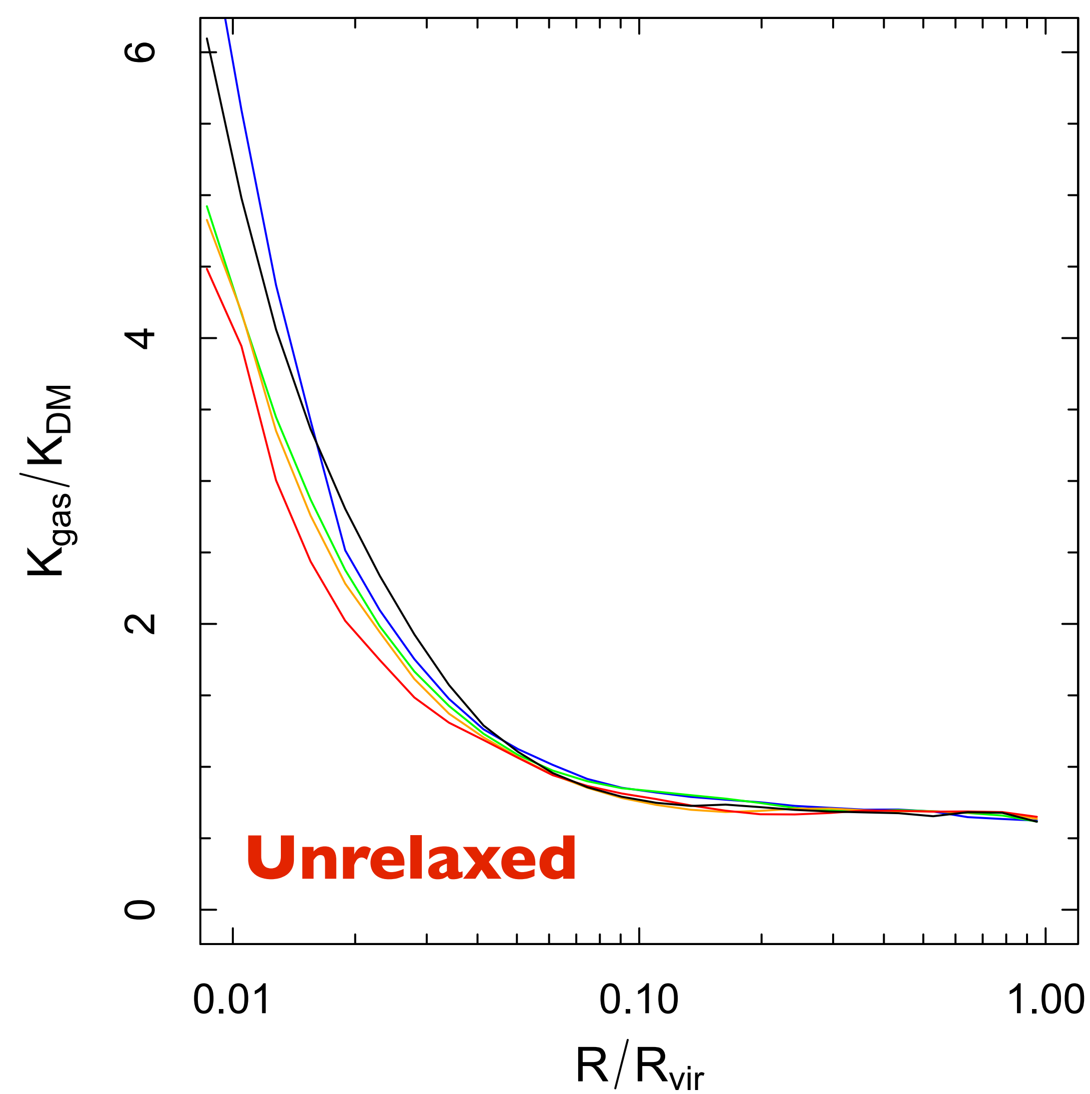




3.4. Redshift evolution

Adiabatic gas-to-DM entropy ratio





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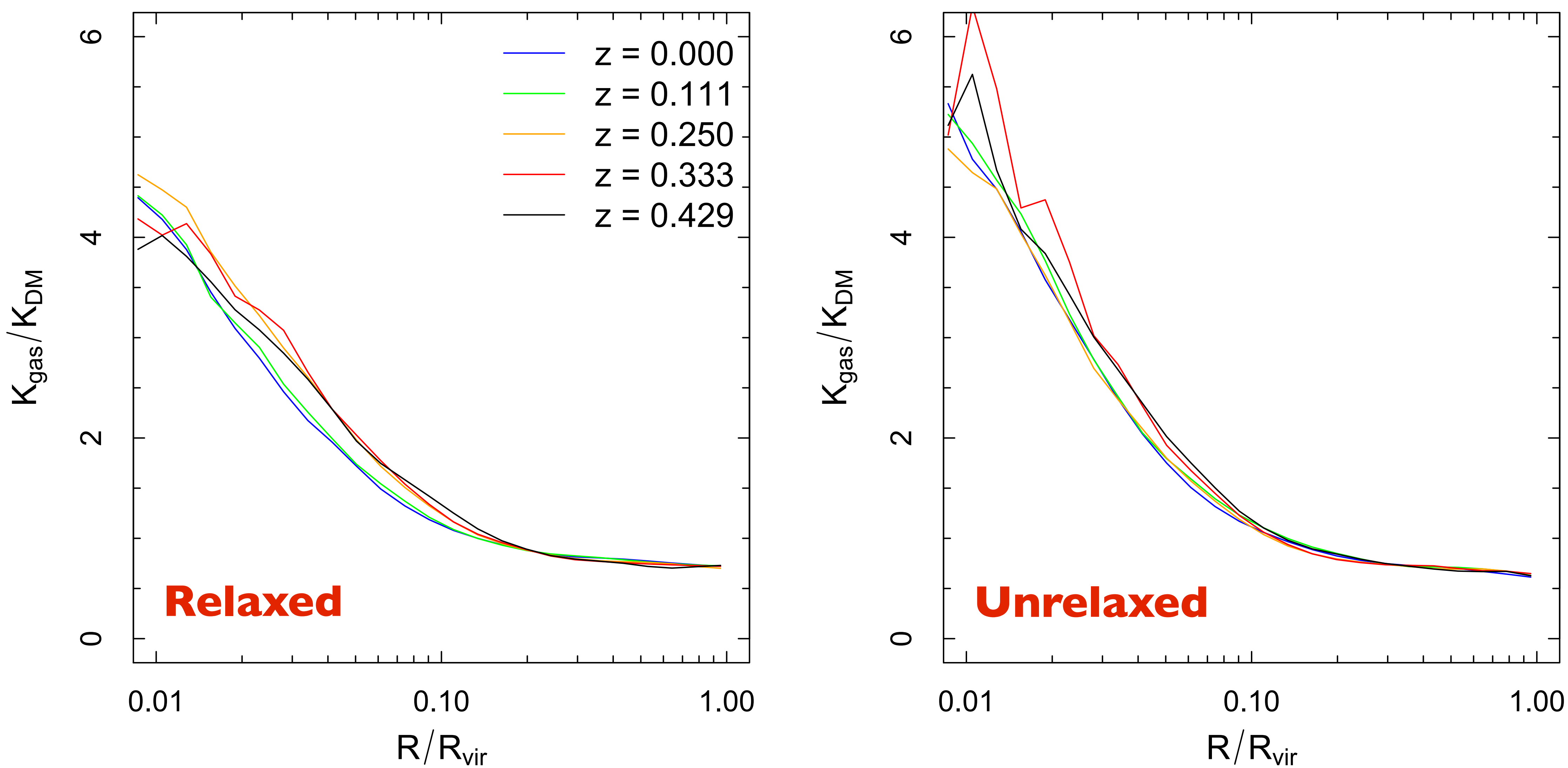
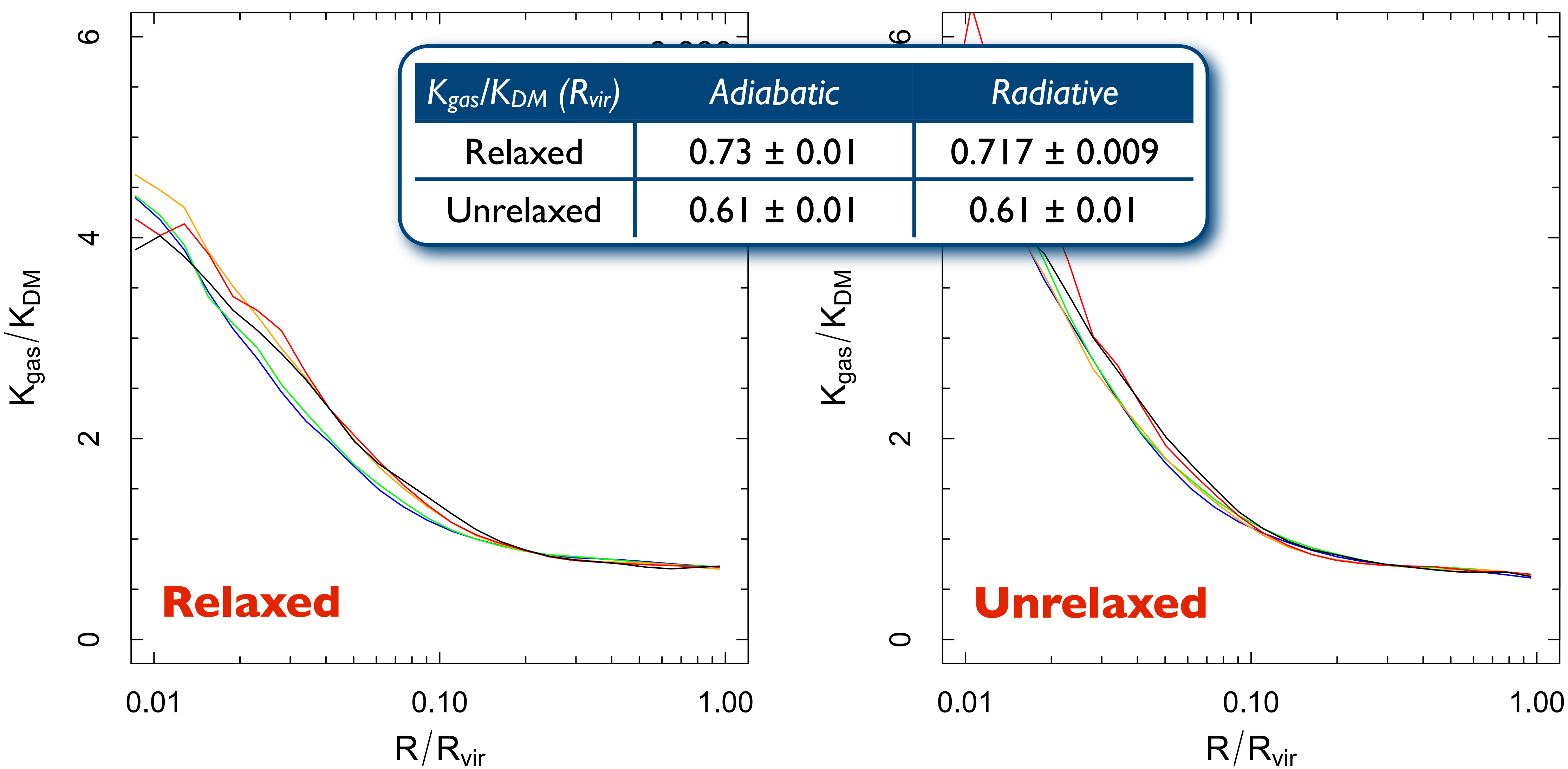
Radiative gas-to-DM entropy ratio



3.4. Redshift evolution

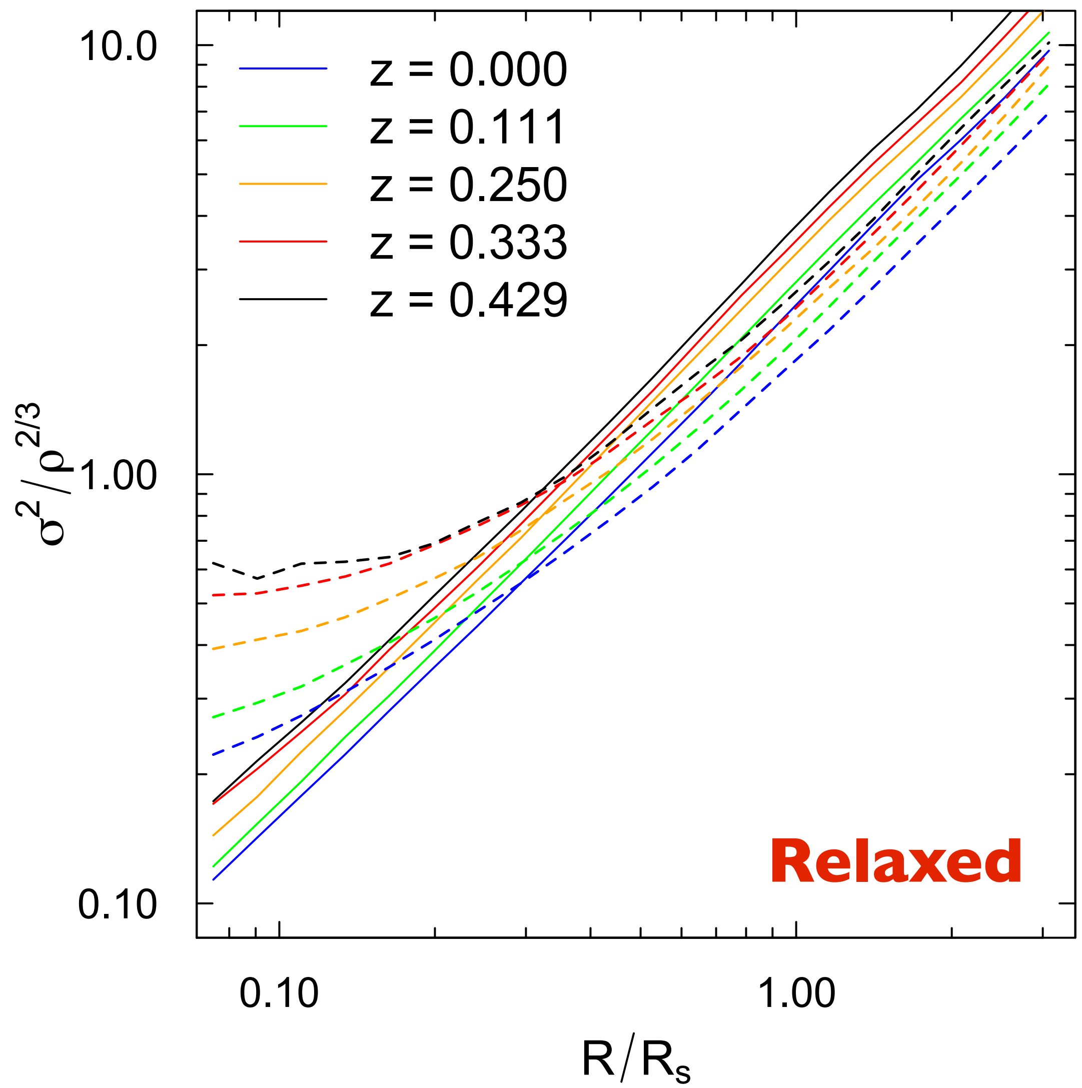
Radiative gas-to-DM entropy ratio

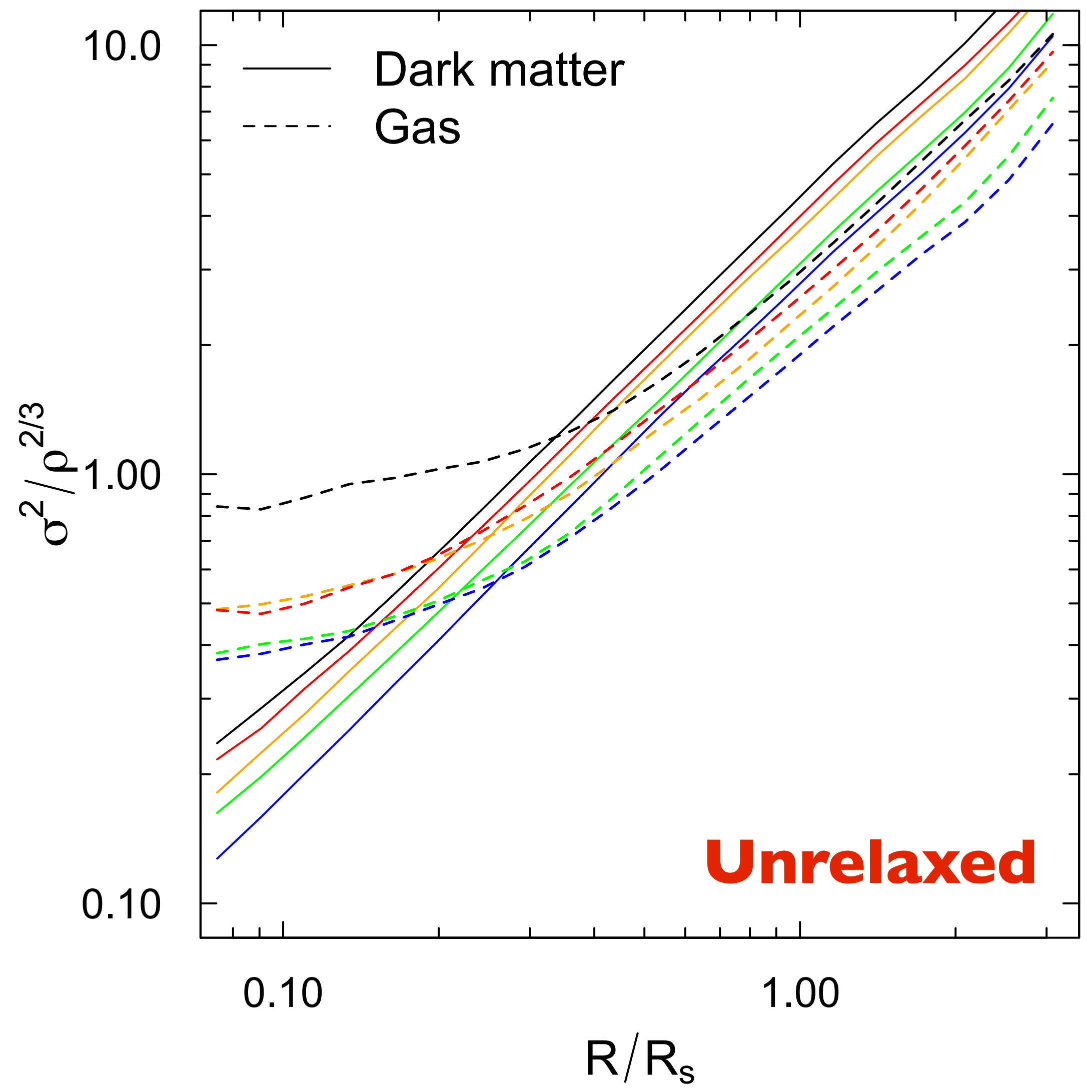
K_{gas}/K_{DM} (R_{vir})	*Adiabatic*	*Radiative*
Relaxed	0.73 ± 0.01	0.717 ± 0.009
Unrelaxed	0.61 ± 0.01	0.61 ± 0.01



3.4. Redshift evolution

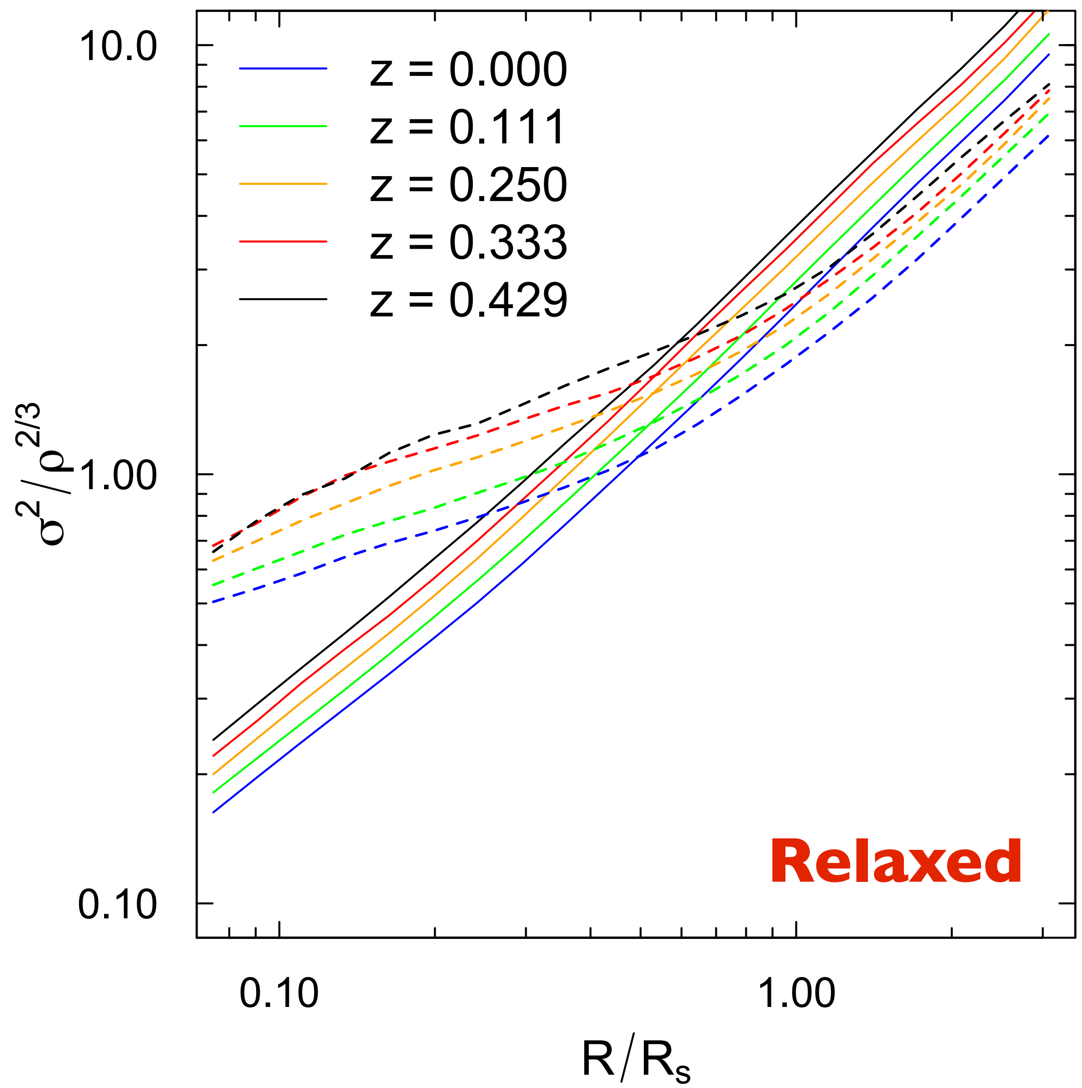
Adiabatic power-law

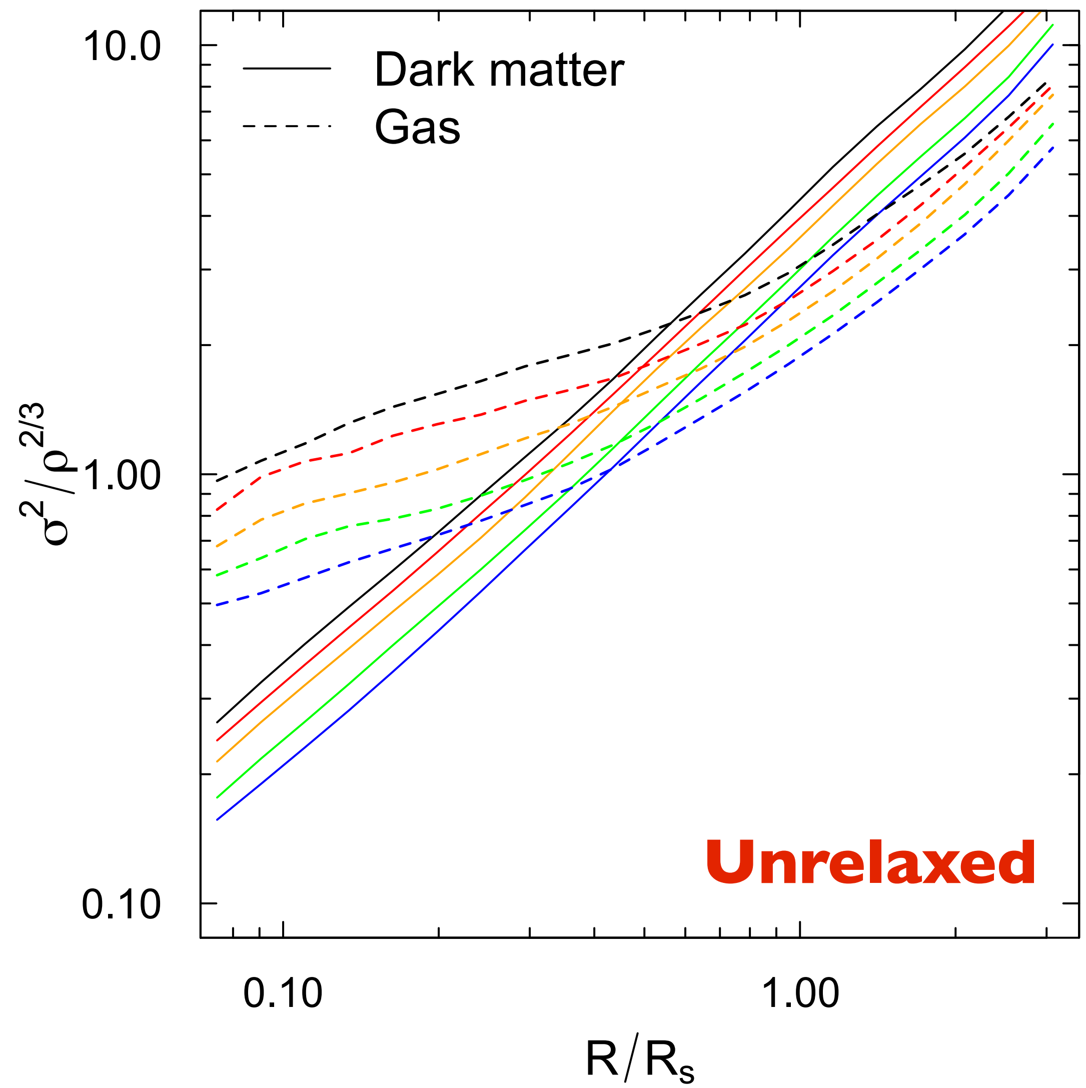




3.4. Redshift evolution

Radiative power-law

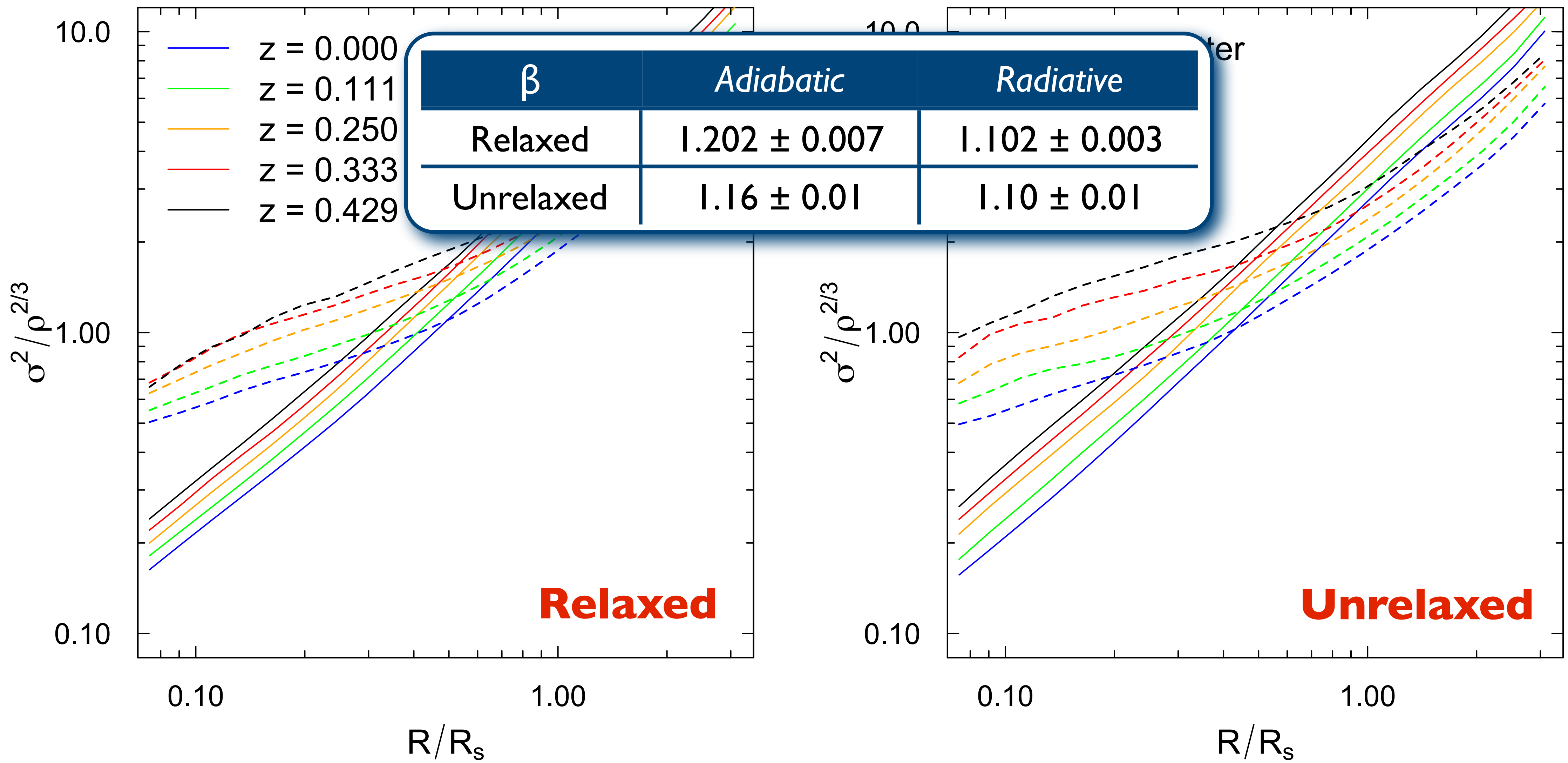




3.4. Redshift evolution

Radiative power-law

β	*Adiabatic*	*Radiative*
Relaxed	1.202 ± 0.007	1.102 ± 0.003
Unrelaxed	1.16 ± 0.01	1.10 ± 0.01



Outline

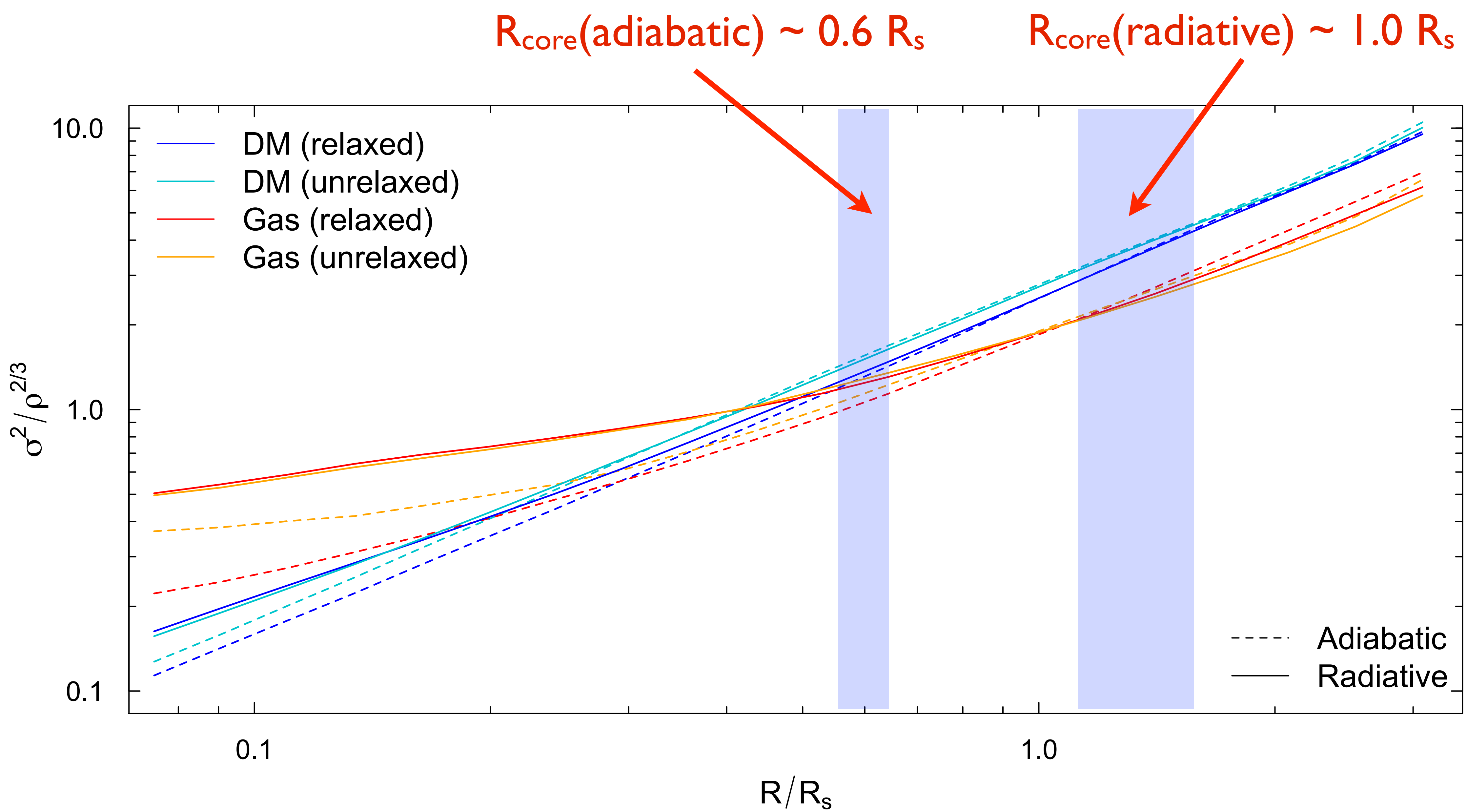
3.5. Gas entropy cores

- ***Entropy core*** in adiabatic simulations is a ***real physical effect*** (Voit et al. 2005, Ascasibar et al. 2003)
- ***Resolution*** of the SPH simulations: ***sufficient with MUSIC*** (Lin et al. 2006)
- ISM in ***hydrostatic equilibrium***:

  gas entropy excess within $R_{core} \Rightarrow$ $\boxed{\begin{array}{c}\text{gas hotter}\\ \text{and/or}\\ \text{gas density flatter}\end{array}}$ than the DM

- ***Core radius*** coincides with the radius at which the ***DM temperature*** reaches its ***maximal*** value

3.5. Gas entropy cores



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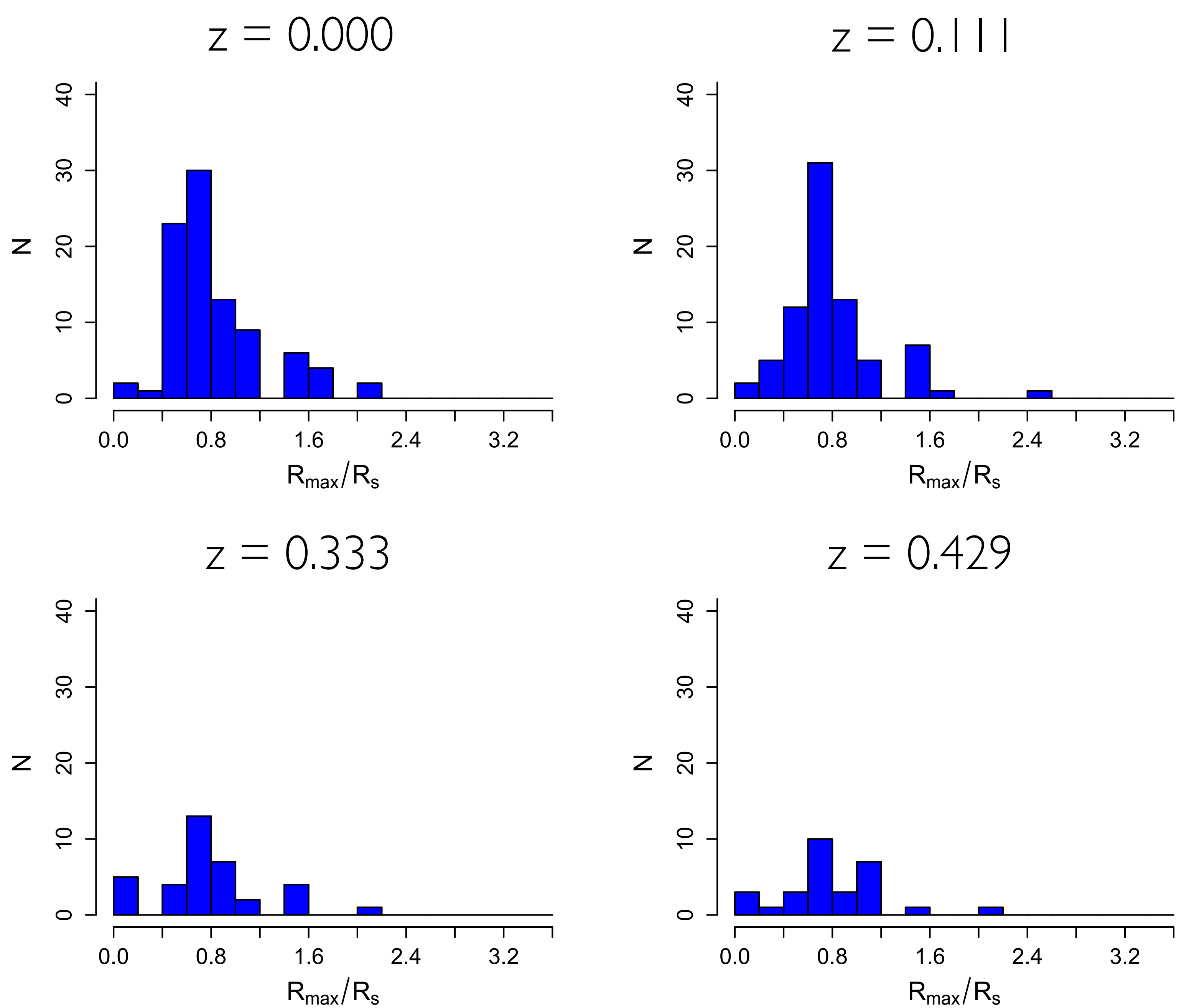
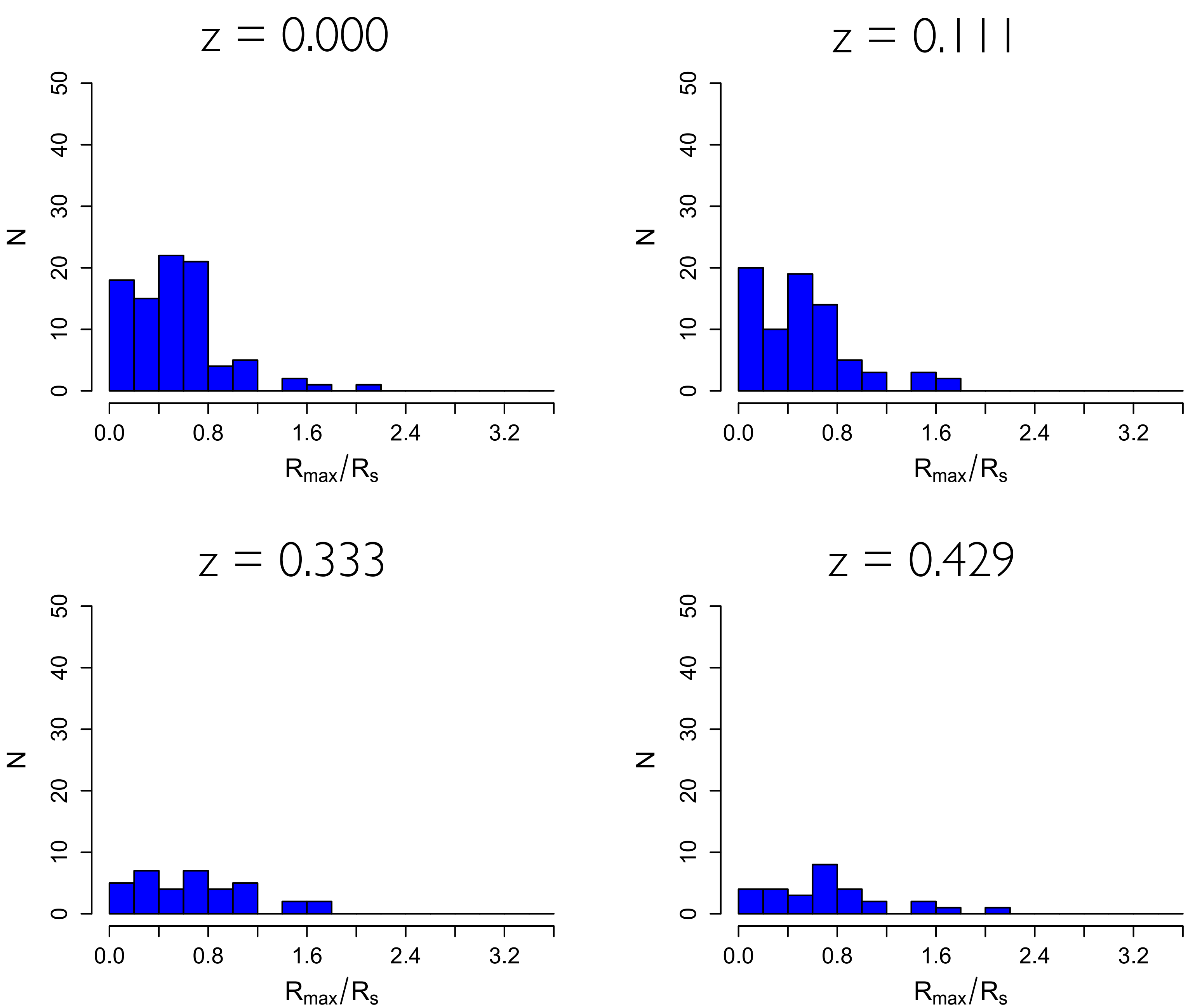


Adiabatic

$R_{max} / R_s = 0.8 \pm 0.4$

$R_{max} / R_s \sim 0.8 \pm 0.4$
(Faltenbacher et al. 2007)

3.5. Gas entropy cores



Radiative

NO core

Outline

4. Conclusions

- Gas and DM entropies follow one to another very closely
- **Constant ratio** of the thermal gas entropy to that of the DM at large radii

K_{gas}/K_{DM} (R_{vir})	*Adiabatic*	*Radiative*
Relaxed	0.72 ± 0.16	0.71 ± 0.15

- **Radiative**: gas hotter (25%), no DM temperature inversion (15%) towards the center.

- DM entropy profile follows a **power law**: $K_{DM} \propto r^{\beta}$

Faltenbacher et al. 2007	*Adiabatic*	*Radiative*
$K_{DM} \propto r^{1.21}$	$K_{DM} \propto r^{1.20}$	$K_{DM} \propto r^{1.10}$
$Q_{DM} \propto r^{-1.82}$	$Q_{DM} \propto r^{-1.80}$	$Q_{DM} \propto r^{-1.65}$

- **No** significant **redshift evolution** (entropy ratio or power law)
- Gas **entropy core**: ~ 0.6 R_s (adiabatic) and ~ R_s (radiative)
- **Max DM temperature**: R_{max} / R_s = 0.8 ± 0.4 (adiabatic)
- **No entropy cores** in **radiative clusters**

4. Conclusions

- Gas and DM entropies follow one to another very closely
- **Constant ratio** of the thermal gas entropy to that of the DM at large radii

Faltenbacher et al. 2007

K_{gas}/K_{DM} = 0.71 ± 0.18

K_{gas}/K_{DM} (R_{vir})	Adiabatic	Radiative
Relaxed	0.72 ± 0.16	0.71 ± 0.15

- **Radiative**: gas hotter (25%), no DM temperature inversion (15%) towards the center.

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$Q_{DM} \propto r^{-1.82}$	$Q_{DM} \propto r^{-1.80}$	$Q_{DM} \propto r^{-1.65}$

Adiabatic simulations (Faltenbacher et al. 2007)
$\beta \approx 1.21$

10 relaxed clusters observed XMM-Newton (Pratt et al. 2006)
$\beta \approx 1.1$

31 REXCESS clusters (Pratt et al. 2010)
$\beta \approx 1.1$

- **No** significant **redshift evolution** (entropy ratio or power law)
- Gas **entropy core**: ~ 0.6 R_s (adiabatic) and ~ R_s (radiative)
- **Max DM temperature**: R_{max} / R_s = 0.8 ± 0.4 (adiabatic)
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Thank you!