Dark Matter Halos: with and without Baryons

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CLUES collaboration: Stefan Gottloeber (Potsdam), Gustavo Yepes, Luis Martinez-Vaquero, Alexander Knebe, Steffen Knollmann

- General remarks: with & without baryons
- PDM halos: ΛCDM phenomenology
- Theoretical Considerations:
  1. Adiabatic contraction
  2. Dynamical friction
- Analysis
  1. Dissecting the Romano-Diaz et al halo
     - I. Evolution in phase space
     - II. Radial profiles
     - III. Subhalos
  2. CLUES
     - I. Radial profiles
     - II. Subhalos
- Final statements

General remarks: DM halos with & without baryons in the ΛCDM cosmology

Notations:
- Pure DM simulations (PDM)
- Baryons + DM simulations (BDM)

- A PDM HALO is a well defined object. Almost a general consensus on radial structure, substructures, shape, angular momentum, ...
- The structure of DM halos is well known (from simulations) but is hardly understood (analytically)
- No consensus on BDM halos
- No numerical convergence
- No general consensus on the subgrid processes
- Results depends on the numerical implementations of subgrid processes

Theoretical Considerations: A. Adiabatic Contraction

THE ASTROPHYSICAL JOURNAL, **301**:27–34, 1986 February 1

CONTRACTION OF DARK MATTER GALACTIC HALOS DUE TO BARYONIC INFALL[1]

GEORGE R. BLUMENTHAL AND S. M. FABER
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
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Board of Studies in Physics, University of California, Santa Cruz
Received 1985 June 14; accepted 1985 July 9

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$$M(r)r \approx \text{const}$$

$$[M_{\rm dm}(r) + M_b(r)]r = [M_{\rm dm}(r) + M_b(r_f)]r_f$$

initial

final

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initial   final

THE ASTROPHYSICAL JOURNAL, 616:16–26, 2004 November 20

RESPONSE OF DARK MATTER HALOS TO CONDENSATION OF BARYONS: COSMOLOGICAL SIMULATIONS AND IMPROVED ADIABATIC CONTRACTION MODEL

OLEG Y. GNEDIN,[1] ANDREY V. KRAVTSOV,[2] ANATOLY A. KLYPIN,[3] AND DAISUKE NAGAI[2]
Received 2004 June 9; accepted 2004 August 3

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M (r) r ≈ const

$$[M_{\rm dm}(r) + M_b(r)]r = [M_{\rm dm}(r) +$$

initial

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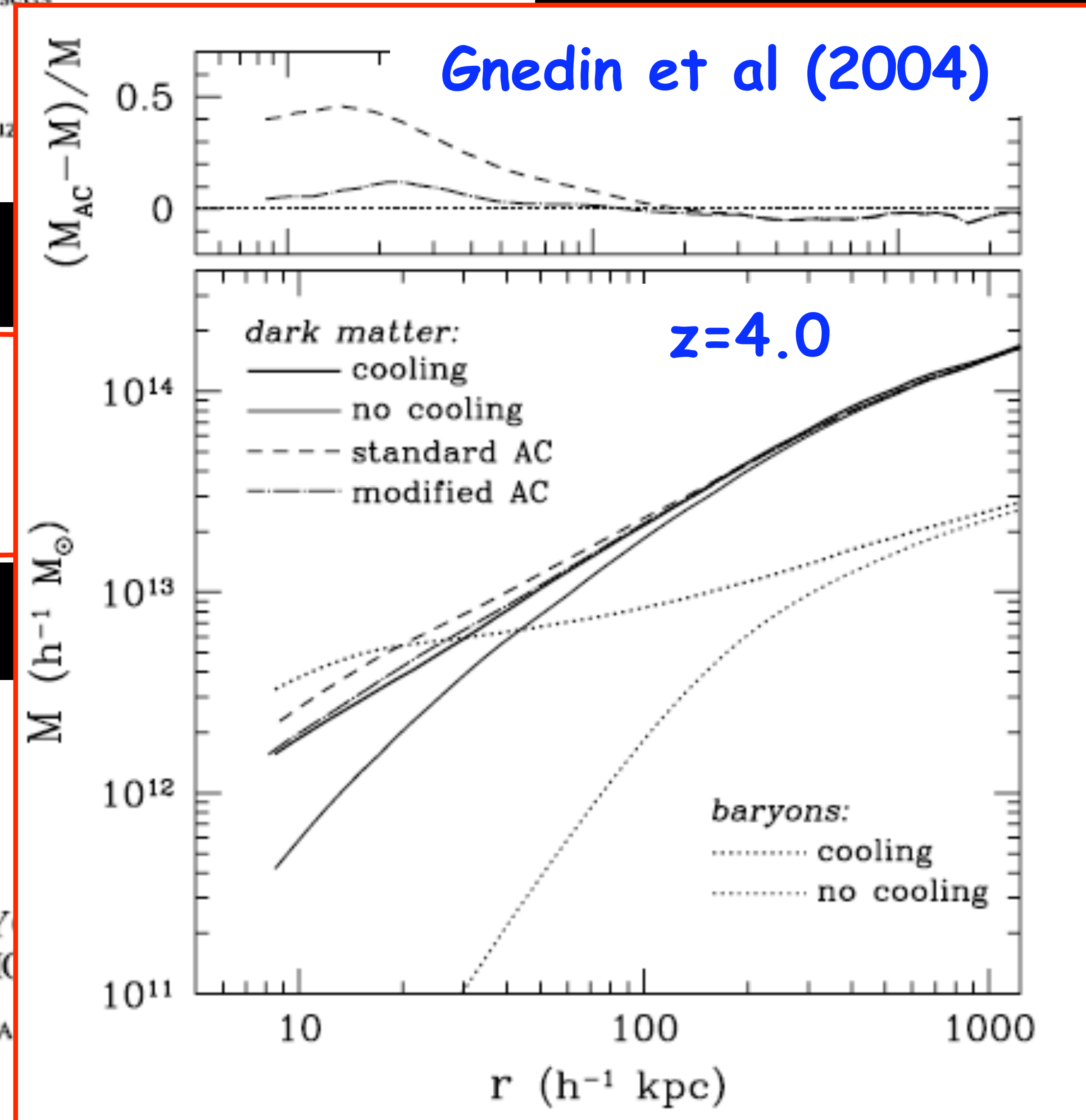

Theoretical Considerations: B. Dynamical Friction

THE ASTROPHYSICAL JOURNAL, 560:636–643, 2001 October 20

DARK HALOS: THE FLATTENING OF THE DENSITY CUSP BY DYNAMICAL FRICTION

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THE ASTROPHYSICAL JOURNAL, 607:L75–L78, 2004 June 1

FLAT-CORED DARK MATTER IN CUSPY CLUSTERS OF GALAXIES

AMR A. EL-ZANT,[1] YEHUDA HOFFMAN,[2] JOEL PRIMACK,[3] FRANCOISE COMBES,[4] AND ISAAC SHLOSMAN[5]

- Clumpy mixture of DM and baryons - clumps loose energy to the ambient DM -> heating and expansion of the DM
- A key element - clumps need to be baryon rich or otherwise there is no effect!

Theoretical Considerations: B. Dynamical Friction

THE ASTROPHYSICAL JOURNAL, 560:636–643, 2001 October 20

DARK HALOS: THE ... FRICTION

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THE ASTROPHYSICAL JOURNAL, 607:L75

FLAT ... S

AMR A. EL-ZANT,[1] YEHUDA HOFFMAN,[2] JOEL PRIMACK,[3] FRANCOISE COMBES,[4] AND ISAAC SHLOSMAN[5]

Simplified Dynamical Model

- Substructures modeled as point-like particles
- Dynamical friction is modeled by Chandrasekhar (1943) formula
- No evolution of substructures - no attempt to account for star formation, feedback, ...
- Start from NFW DM halos

- Clumpy mixture of DM and baryons - clumps loose energy to the ambient DM -> heating and expansion of the DM
- A key element - clumps need to be baryon rich or otherwise there is no effect!

Note on simulations:

- Initial conditions set by constrained realizations of Gaussian fields
- Romano-Diaz et al simulations - a first step in a project to 'design' a halo 'on demand'
- Constrained Local UniversE Simulations - use observational data to constrain the 'local universe' - Local Volume, Local Group

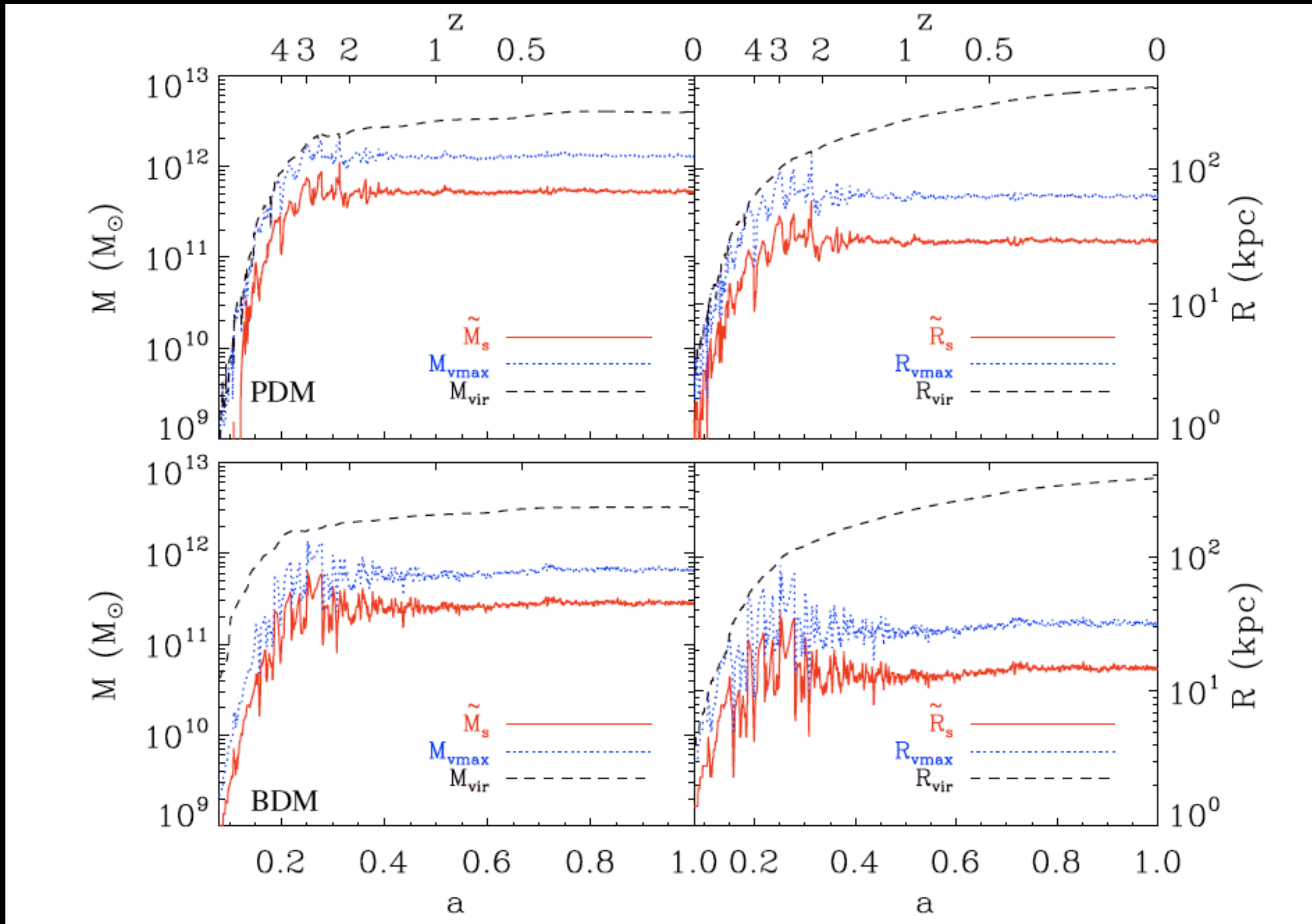
Dissecting Galaxy Formation: Comparison of the DM in PDM and BDM simulations

Romano-Diaz, Shlosman, Heller & YH (2008 - 2010)

- Code SPH (FTM - Heller & Shlosman 1994, Heller et al 2007)
- Physics: feedback - stellar winds & SN -> delayed cooling
- Physical coordinates, vacuum boundary conditions
- Computational sphere 6 Mpc/h
- N_{tot}~6.e6, m(DM particle)~2.e6M_{sun}
- Single halo sets as a constrained realization

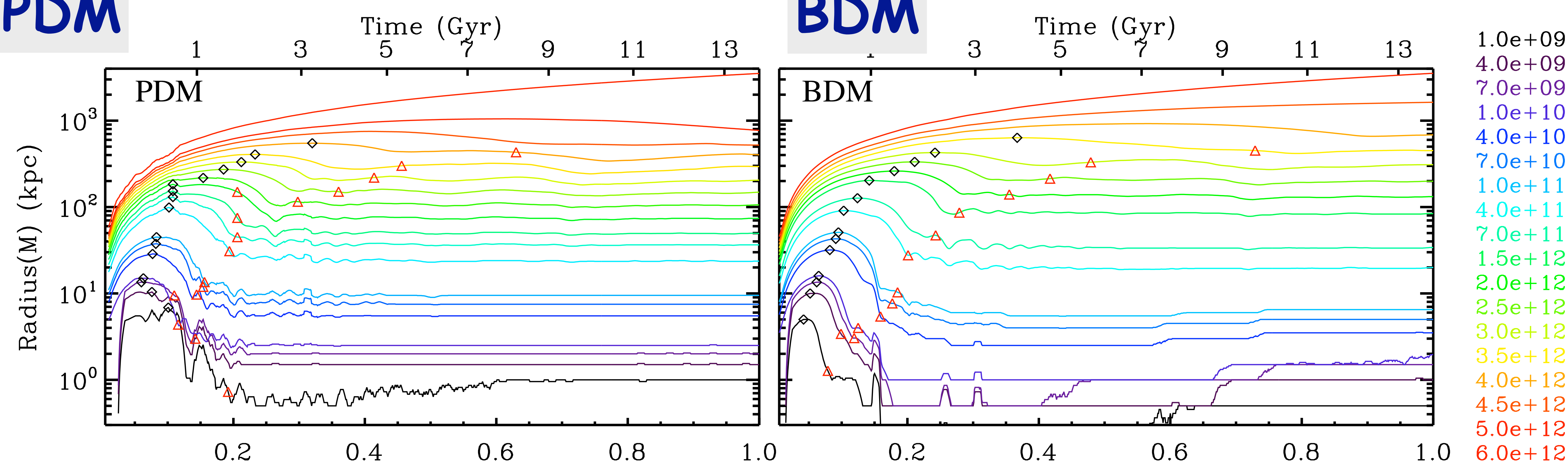
General overview of the PDM & BDM halos:

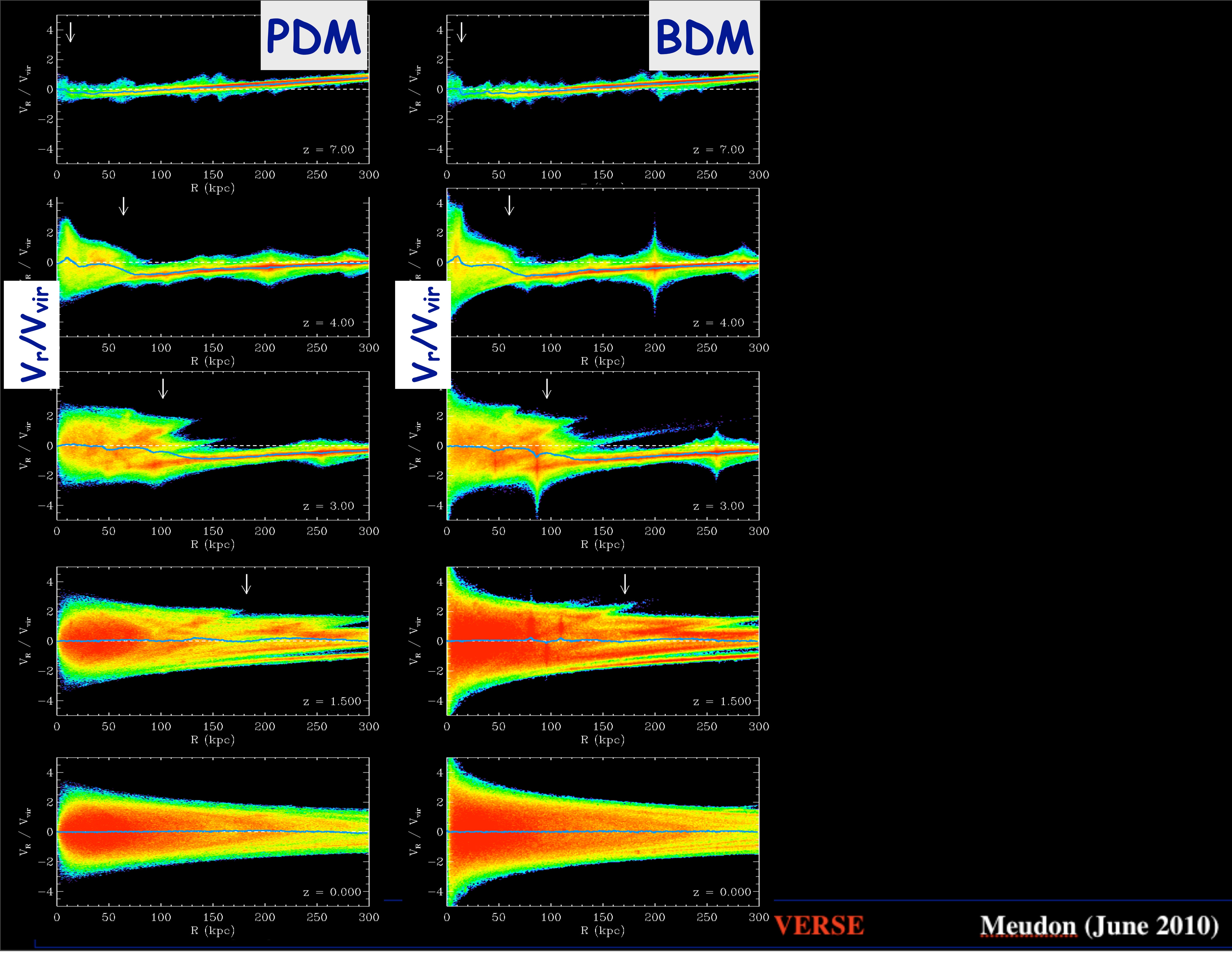
M_{vir} ~ 3.5e12 M_{sun}
R_{vir} ~ 400 kpc

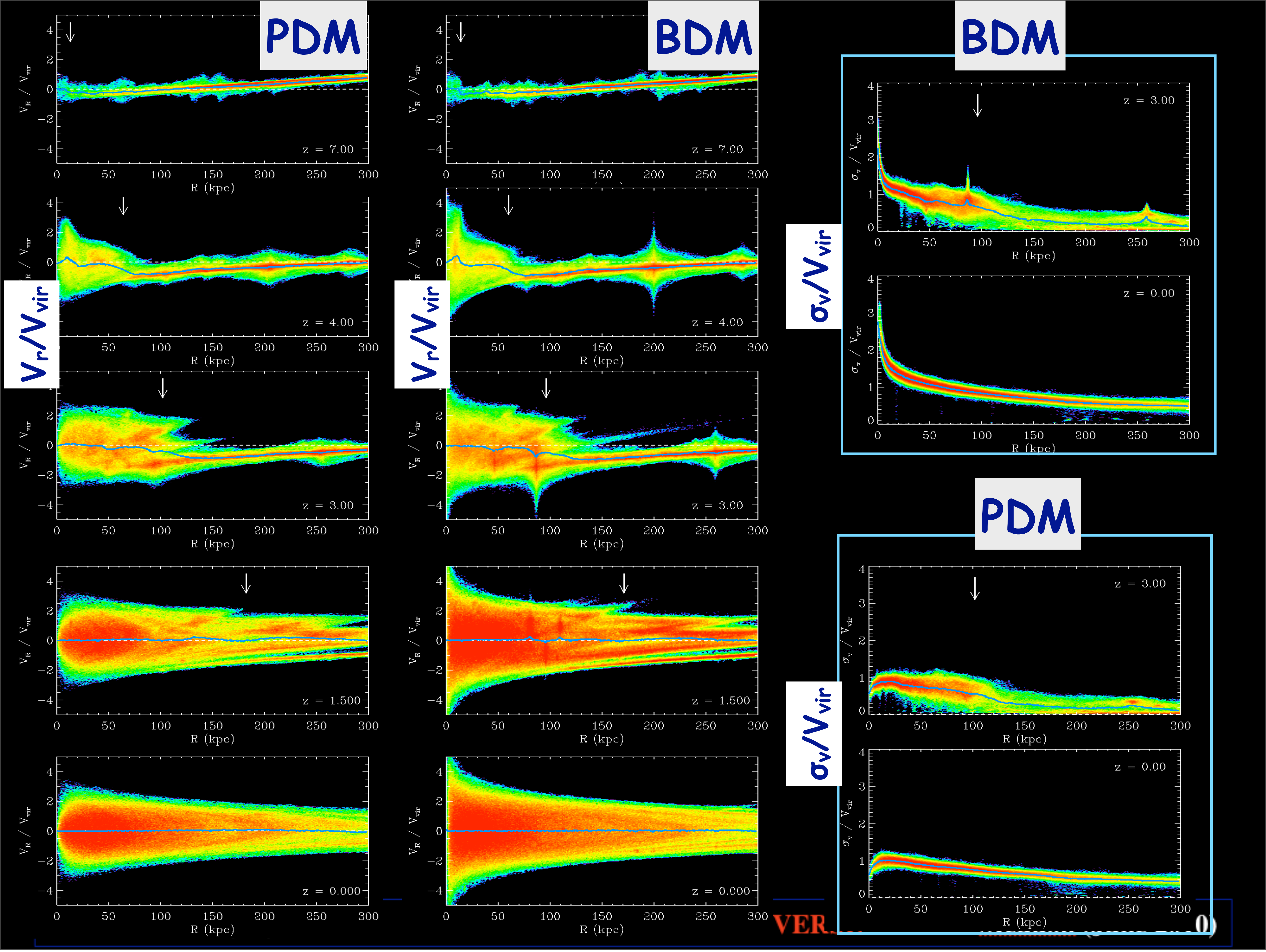


PDM

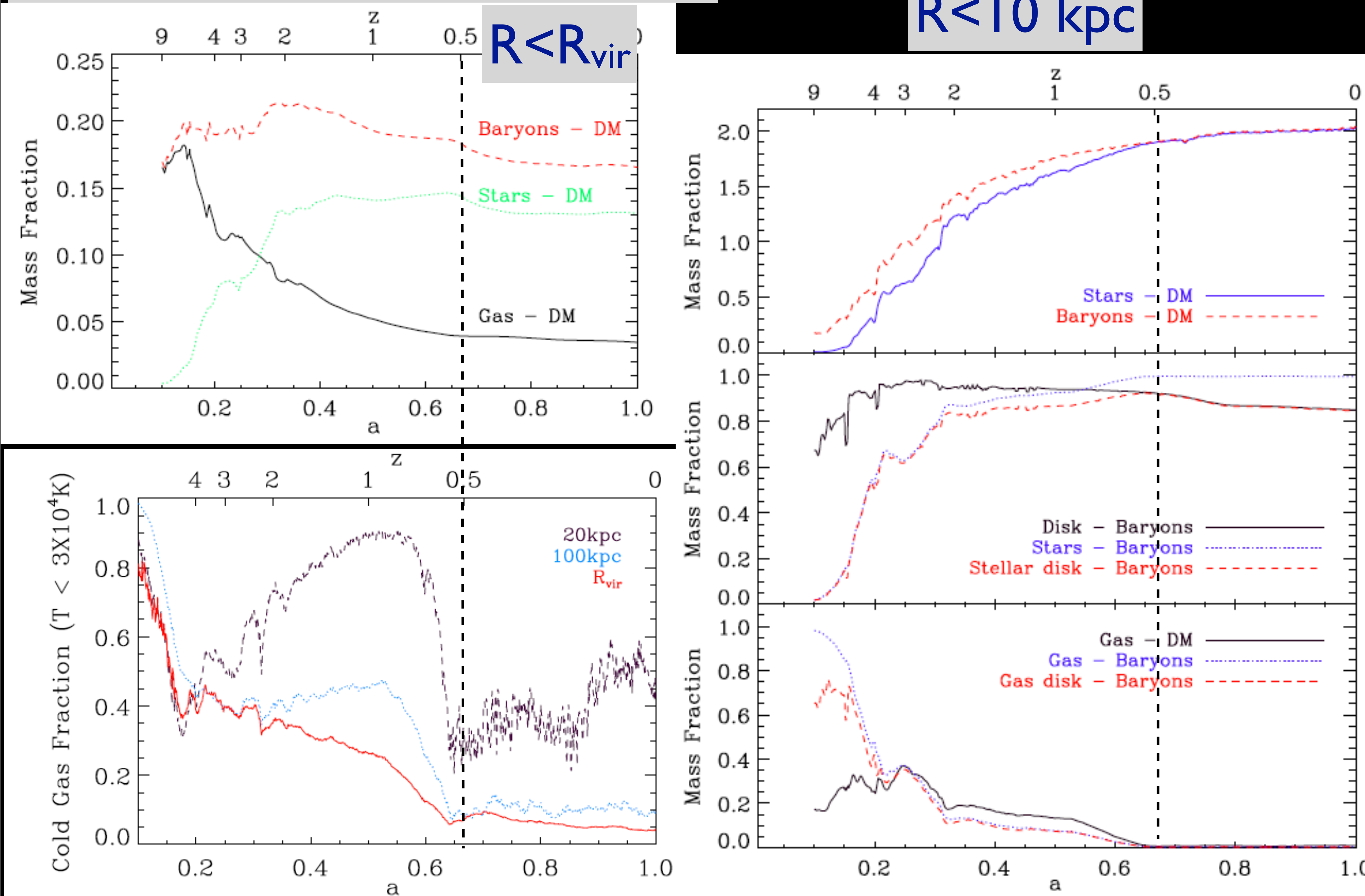
BDM

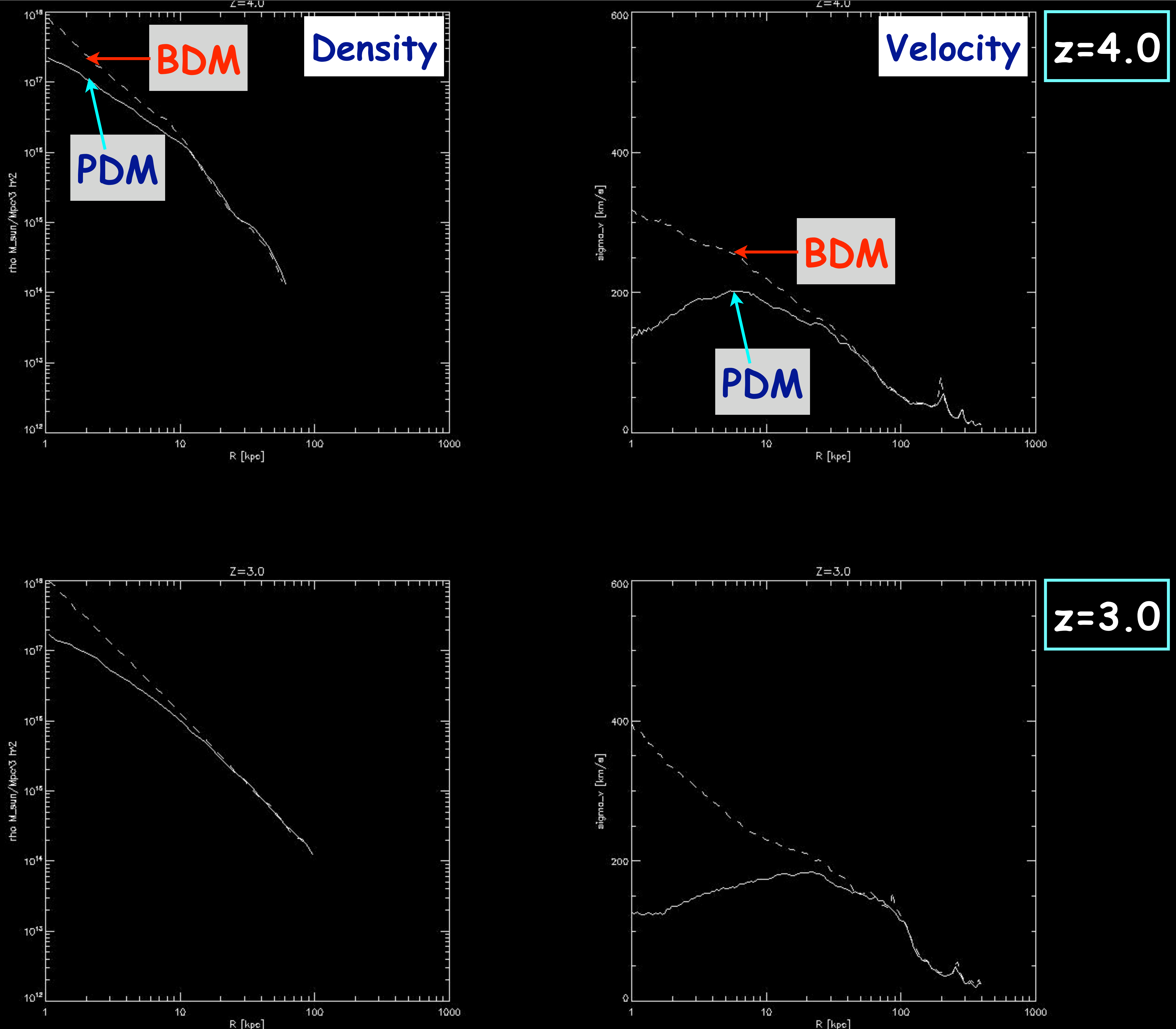


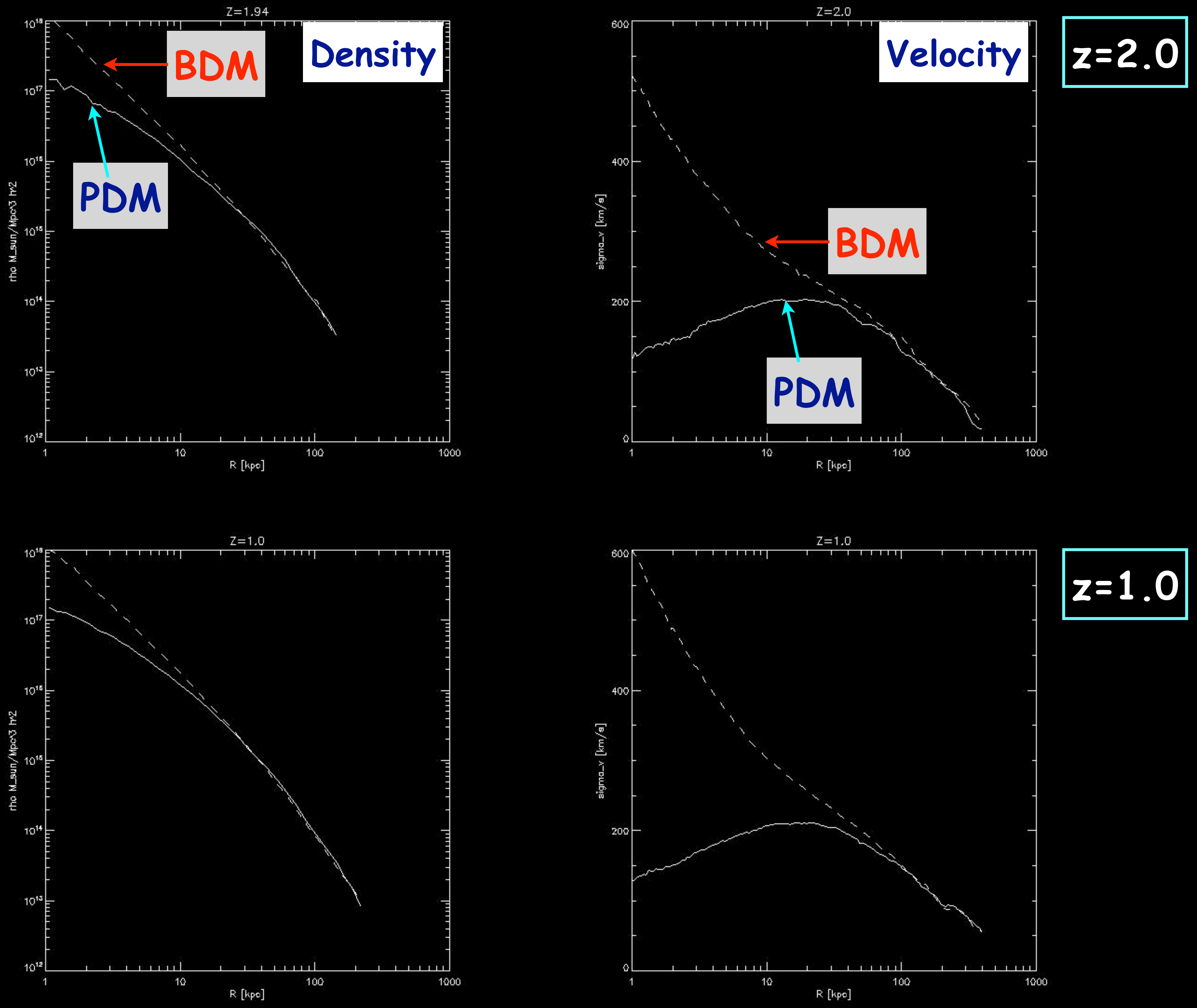

PDM
BDM
V_r/V_{vir}
V_r/V_{vir}
z = 7.00
z = 4.00
z = 3.00
z = 1.500
z = 0.000
R (kpc)
V_R / V_{vir}
VERSE
Meudon (June 2010)

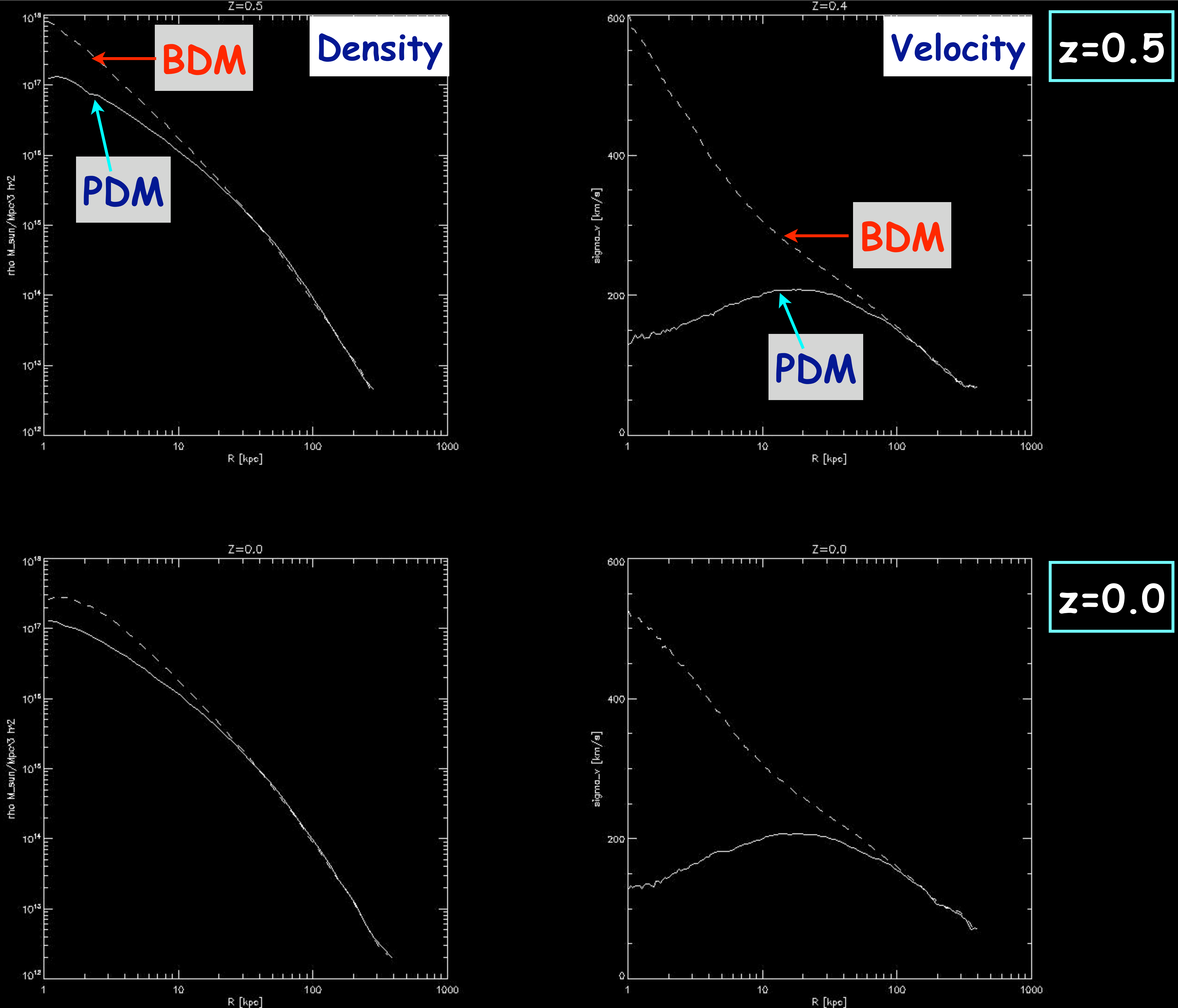

PDM
BDM
BDM
PDM
Vr/Vvir
Vr/Vvir
σv/Vvir
σv/Vvir
V_R / V_vir
σ_v / V_vir
R (kpc)
z = 7.00
z = 4.00
z = 3.00
z = 1.500
z = 0.000
z = 3.00
z = 0.00

The state of the baryons:



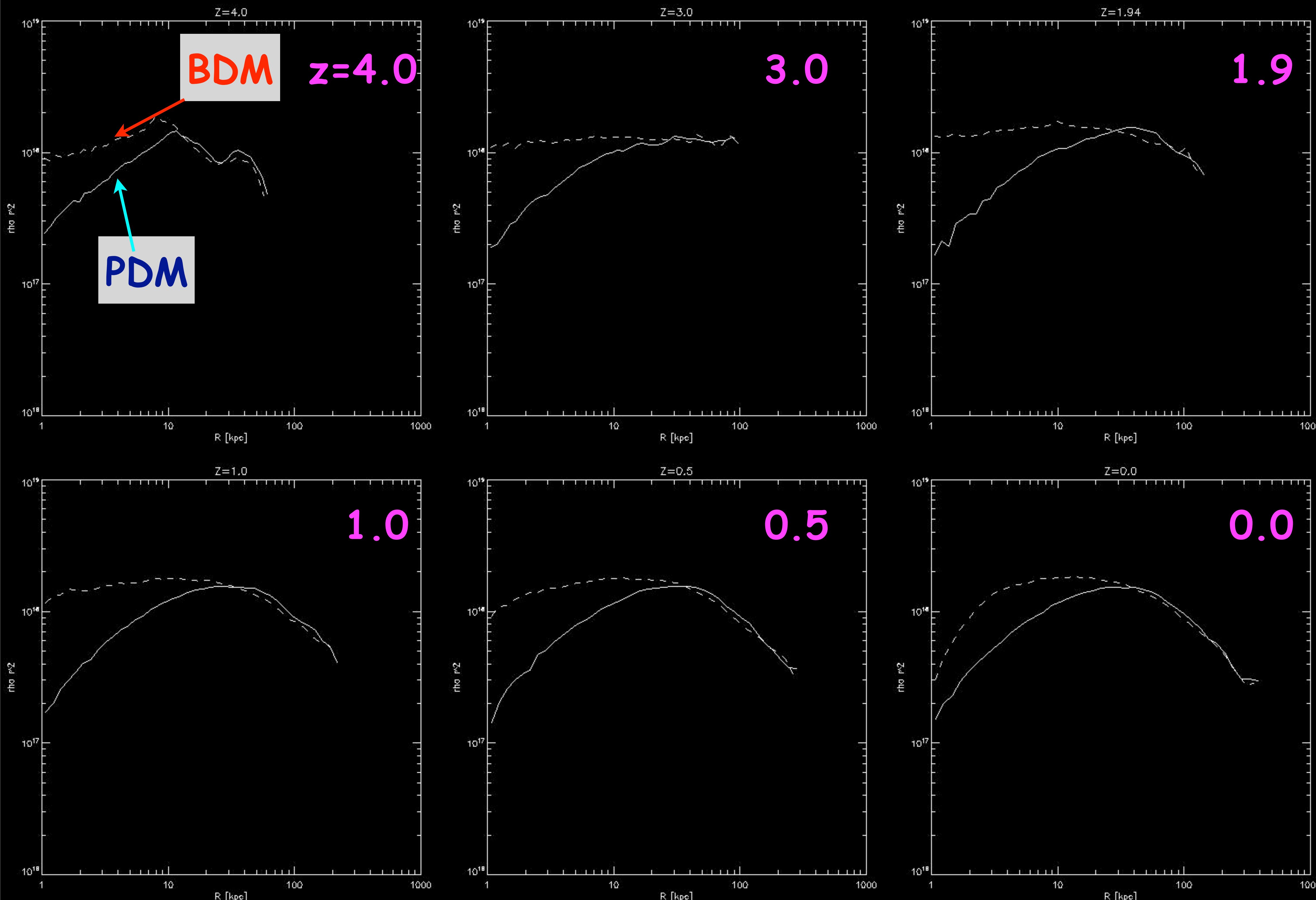

Density
BDM
PDM
Velocity
z=4.0
BDM
PDM
z=3.0
Z=3.0
Z=3.0
R [kpc]
R [kpc]
R [kpc]
R [kpc]


Z=1.94
Density
BDM
PDM
rho M_sun/Mpc^3 h^2
R [kpc]
Z=2.0
Velocity
BDM
PDM
sigma_v [km/s]
R [kpc]
z=2.0
Z=1.0
rho M_sun/Mpc^3 h^2
R [kpc]
Z=1.0
sigma_v [km/s]
R [kpc]
z=1.0

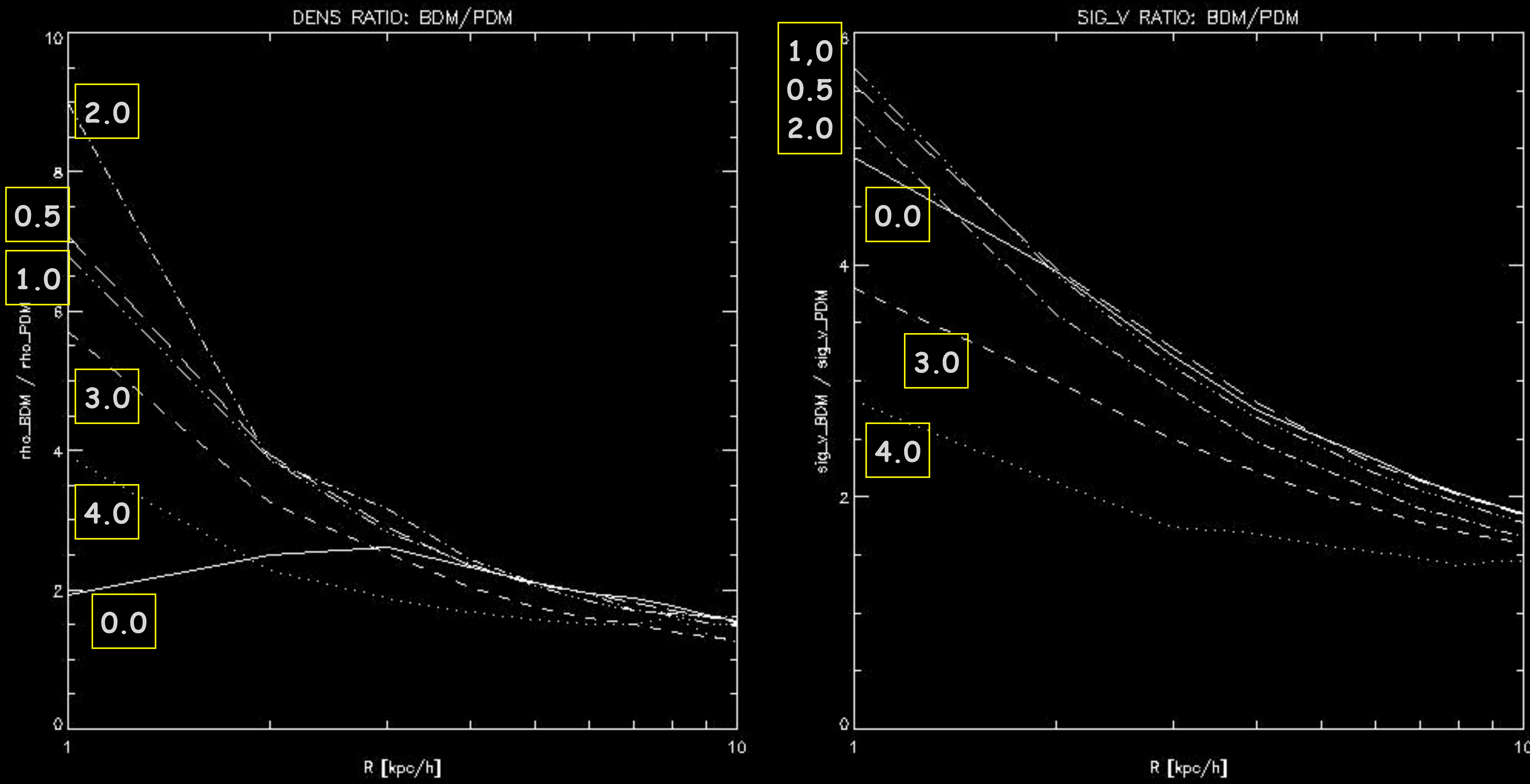


Z=0.5
Density
BDM
PDM
rho M_sun/Mpc^3 h^2
R [kpc]
Z=0.4
Velocity
BDM
PDM
sigma_v [km/s]
R [kpc]
z=0.5
Z=0.0
rho M_sun/Mpc^3 h^2
R [kpc]
Z=0.0
sigma_v [km/s]
R [kpc]
z=0.0

ρr^2



Z


DENS RATIO: BDM/PDM
rho_BDM / rho_PDM
R [kpc/h]
2.0
0.5
1.0
3.0
4.0
0.0
SIG_V RATIO: BDM/PDM
sig_v_BDM / sig_v_PDM
1,0
0.5
2.0
0.0
3.0
4.0

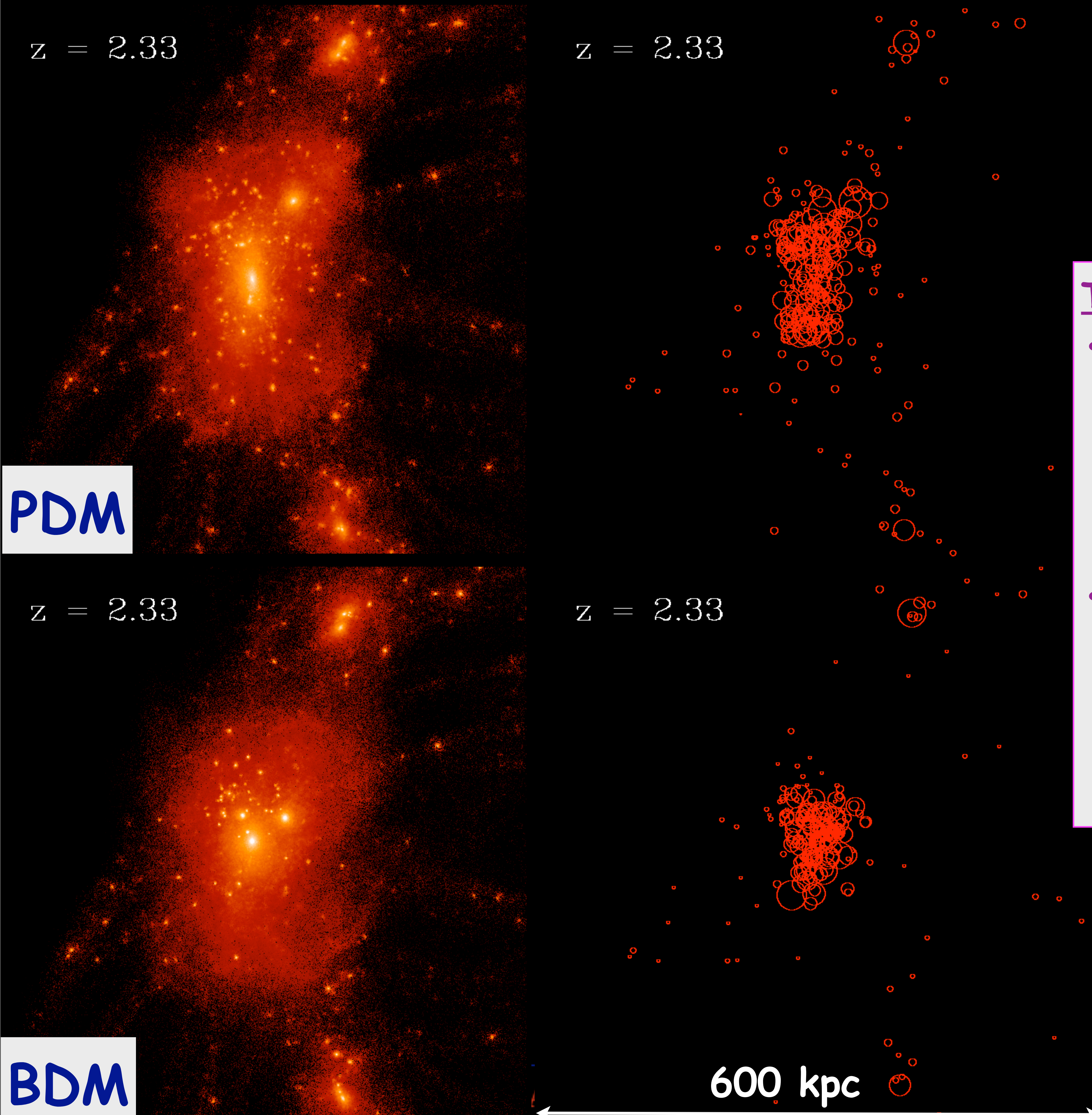
1st Interim Report

- Adiabatic contraction works:
    1. At z~4 the DM density profile is almost isothermal
    2. At all times BDM density profile exceeds the PDM (at small r's).

- Dynamical friction works:
    1. At z<1 the BDM density profile flattens
    2. The excess of DM (in the BDM vs PDM) at the center decreases in time

- But the total effect depends on the details: mostly on the feedback - controls the amount of baryons in the substructures

SUBSTRUCTURES



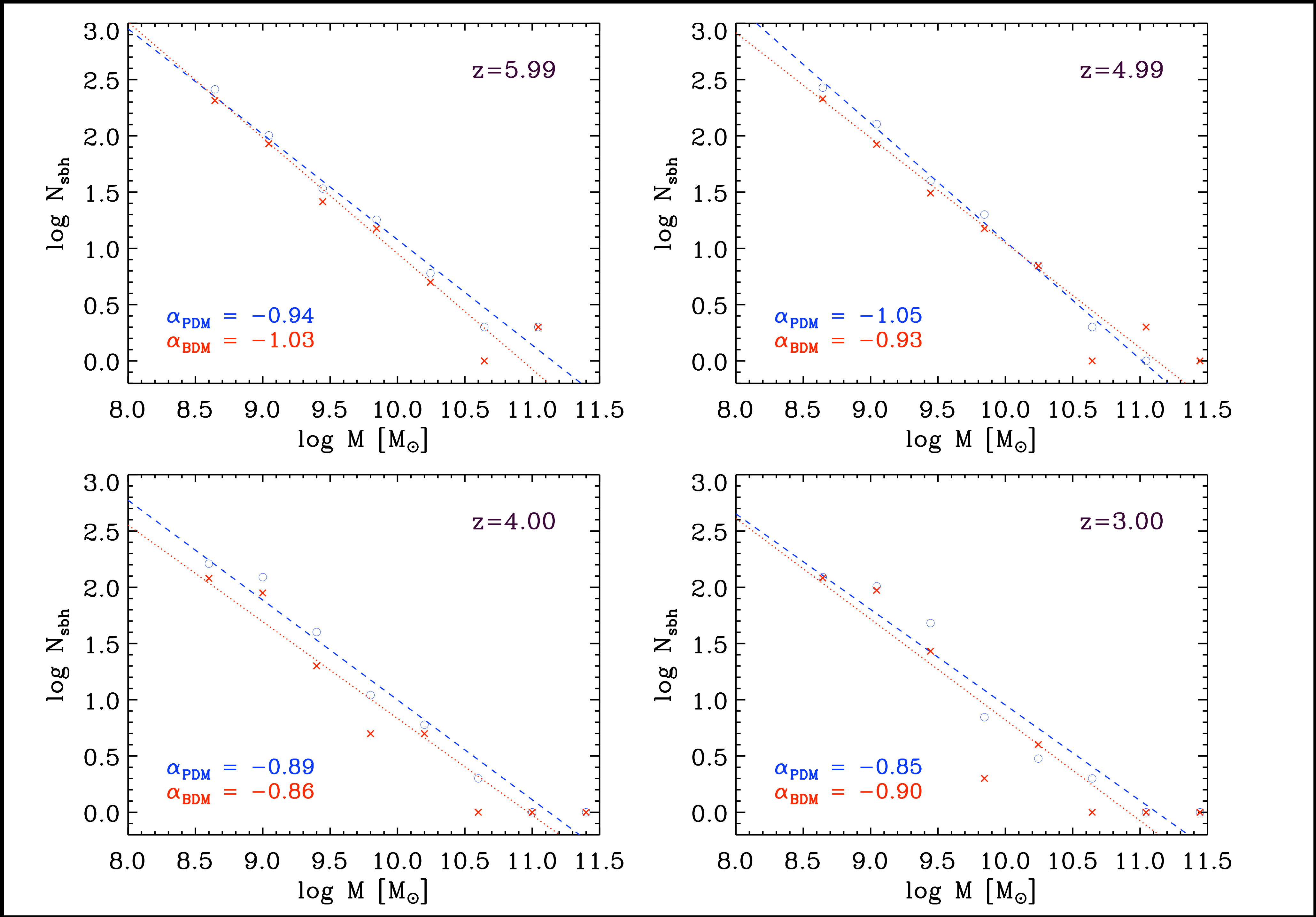
<u>Two competing effects:</u>

- The dissipative gas makes the DM substructures more resilient to tidal disruption.
- The host halo has a deeper potential well - hence stronger tidal field.

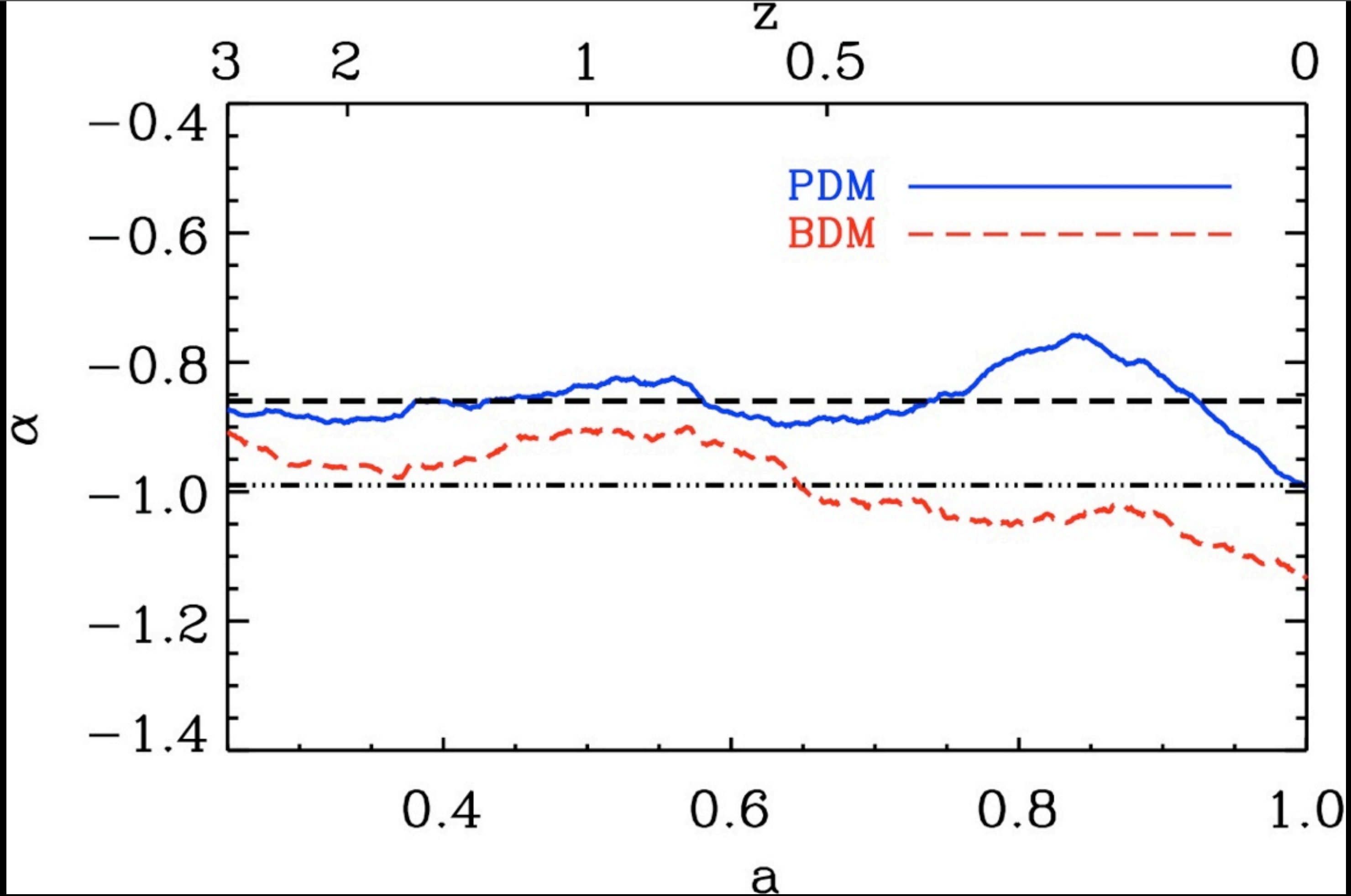
And the winner is ...?

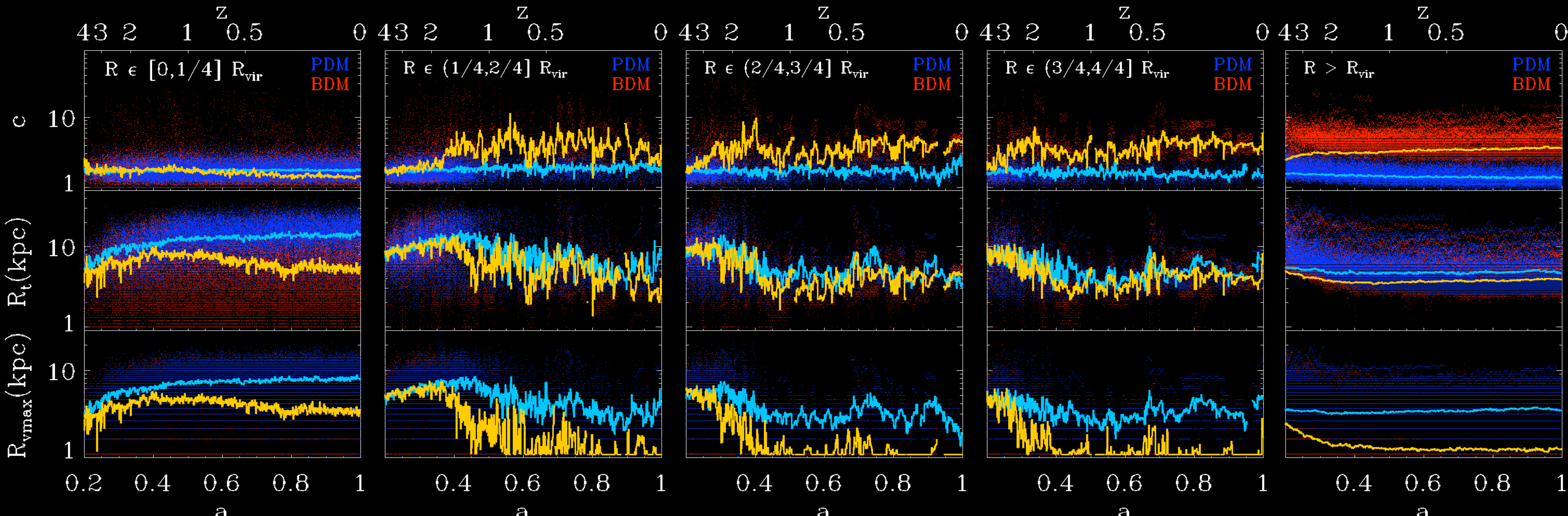
Meudon (June 2010)

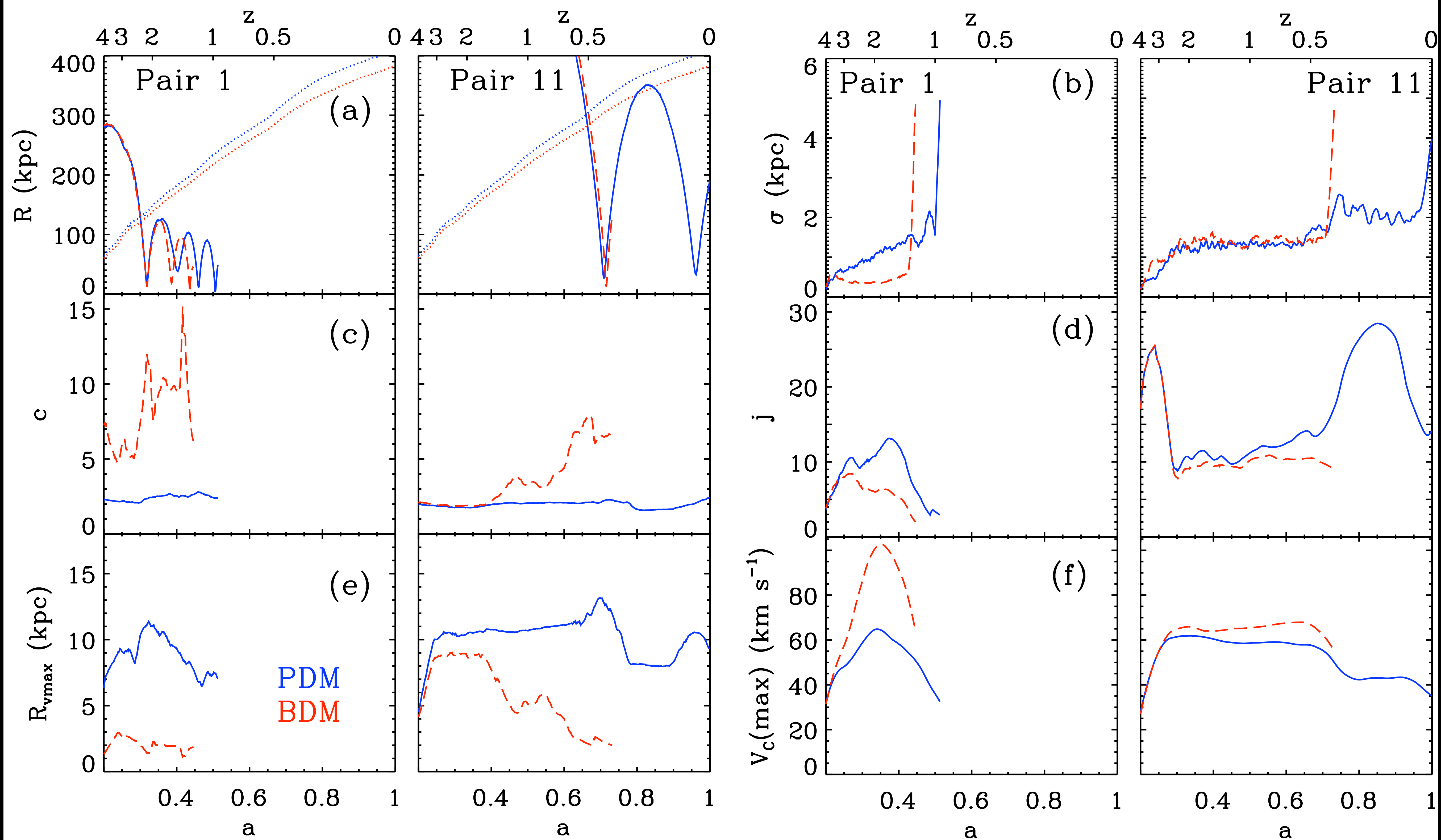
Substructure (DM) mass function:



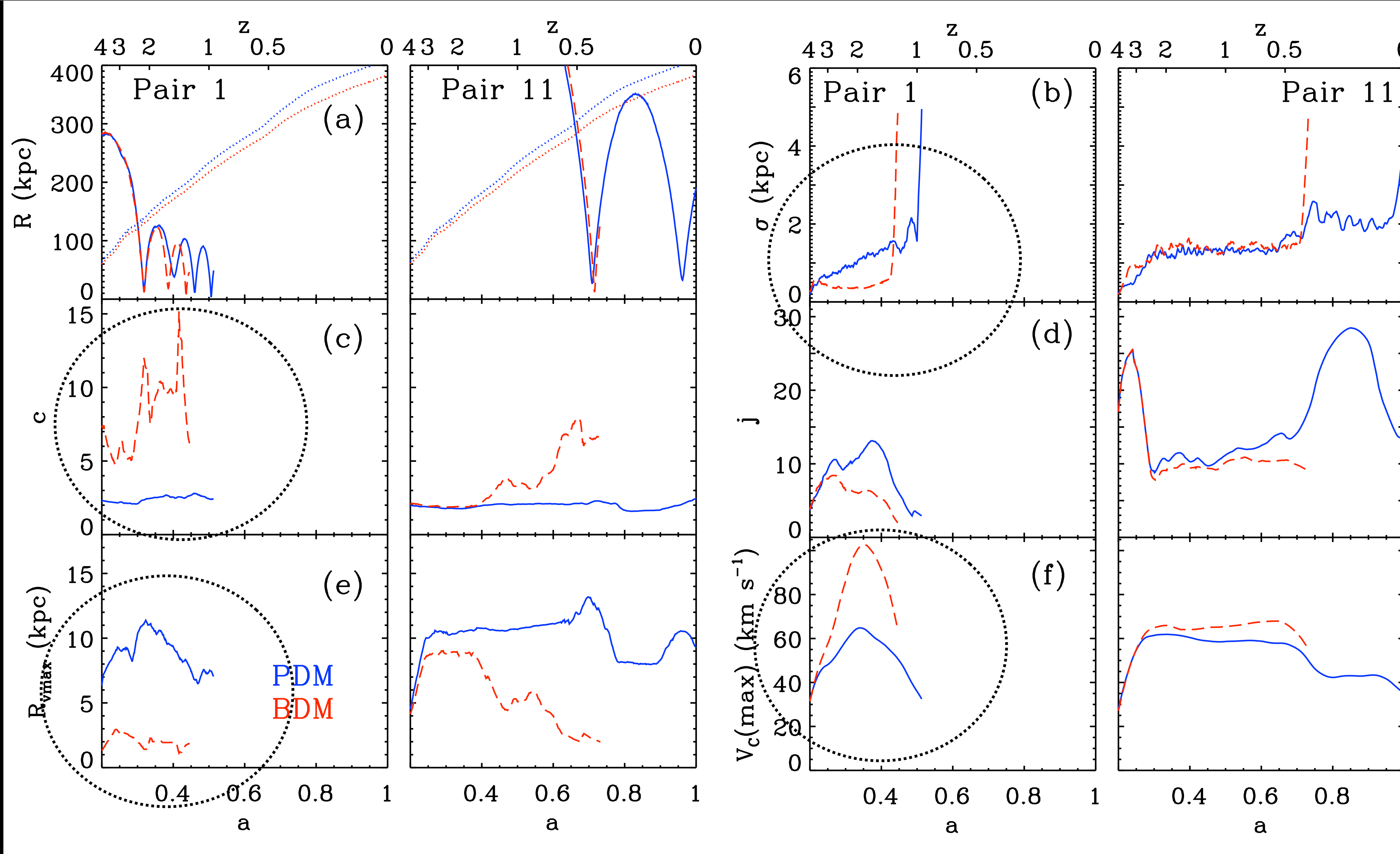
Time evolution of substructures parameters:



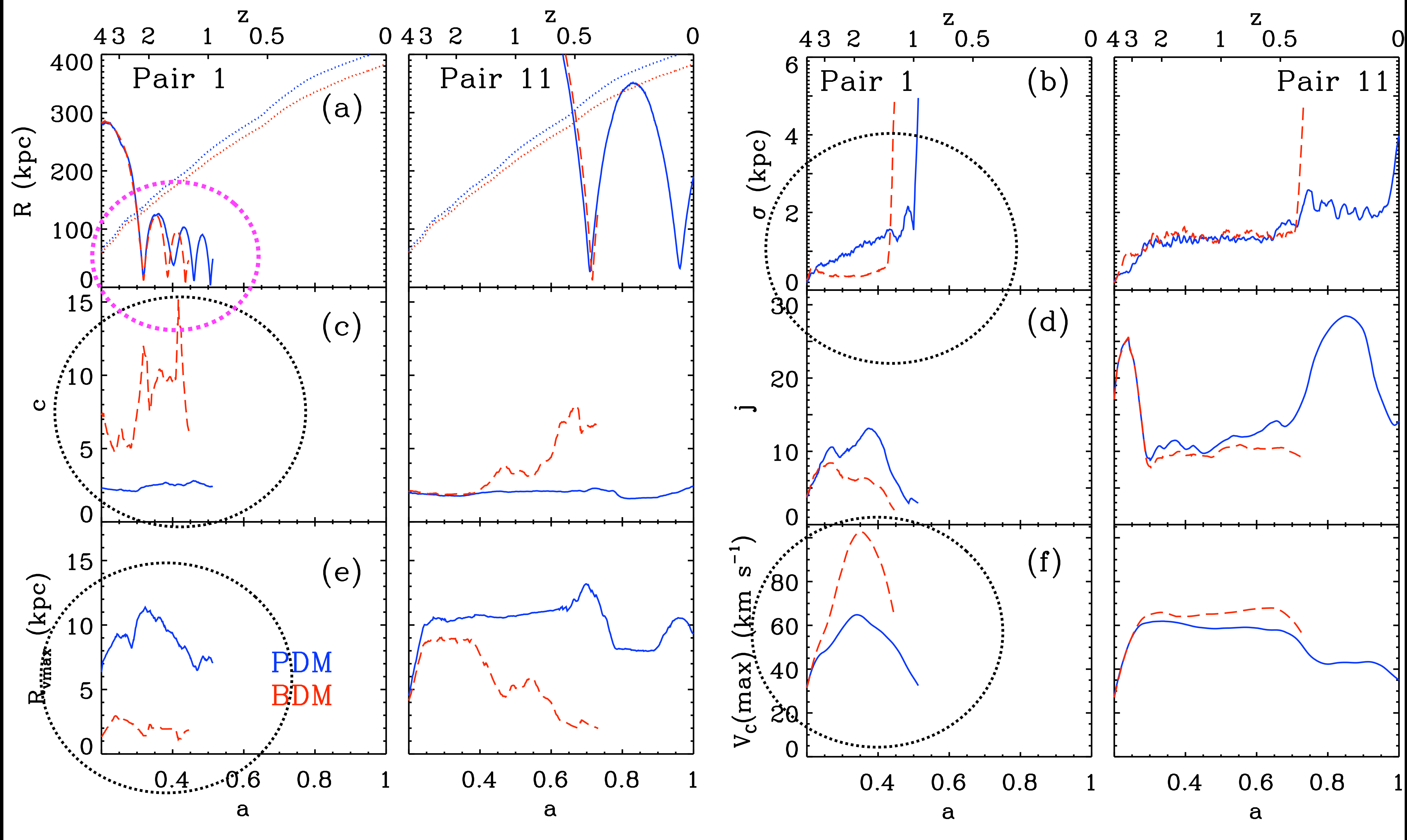




Pair 1
Pair 11
(a)
(b)
(c)
(d)
(e)
(f)
R (kpc)
σ (kpc)
c
j
R_{vmax} (kpc)
V_c(max) (km s^{-1})
PDM
BDM
z
a

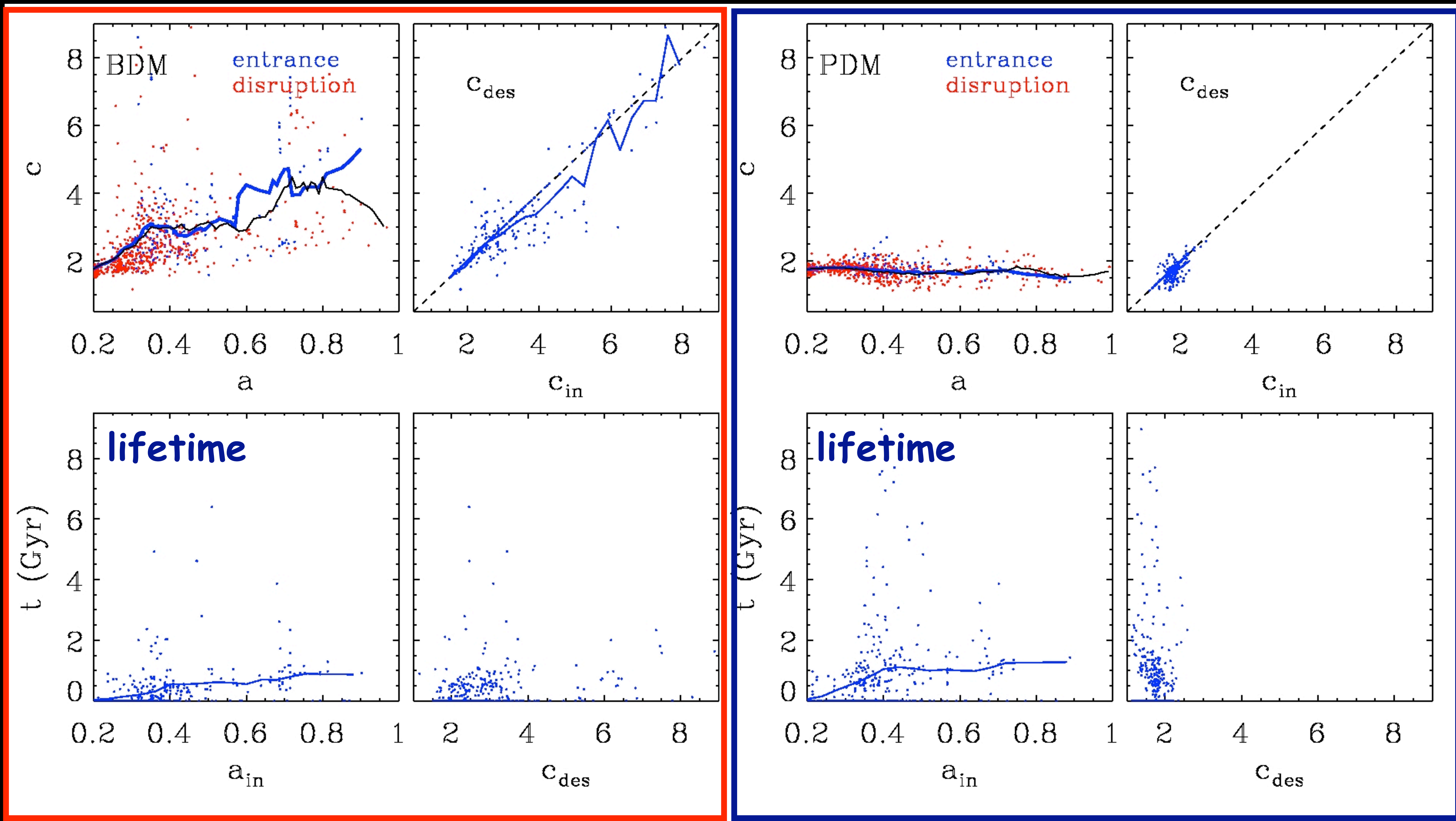


BDM subhalos are more tightly bound



BDM subhalos are more tightly bound

BDM subhalos loose orbital energy faster



BDM
entrance
disruption
c
a
c_{des}
c_{in}
lifetime
t (Gyr)
a_{in}
c_{des}
PDM
entrance
disruption
c
a
c_{des}
c_{in}
lifetime
t (Gyr)
a_{in}
c_{des}

2nd Interim Report: Substructures

- Subhalos mass function: $n_{BDM}(M) \propto n_{PDM}(M) \propto M^{-\alpha}$ ($\alpha \sim 0.9$)

- BDM subhalos are more tightly bound, but so is the host halo: Compared with the PDM the BDM subhalos
  1. 'die younger'
  2. loose more of their mass
  3. loose more of their orbital energy
  4. population is depleted faster

- But the total effect depends on the details: mostly on the feedback - controls the amount of baryons in the substructures

AIP

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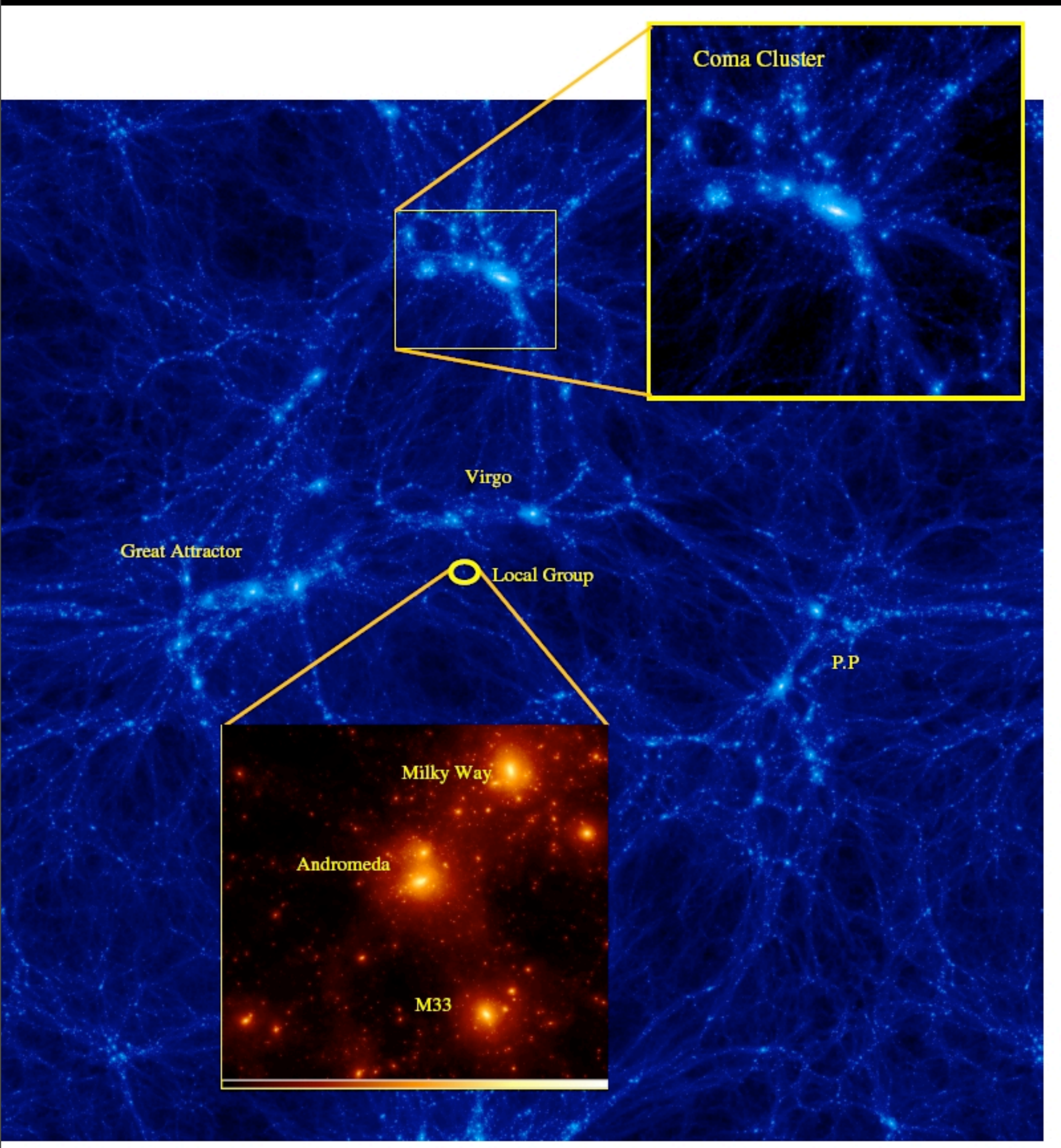

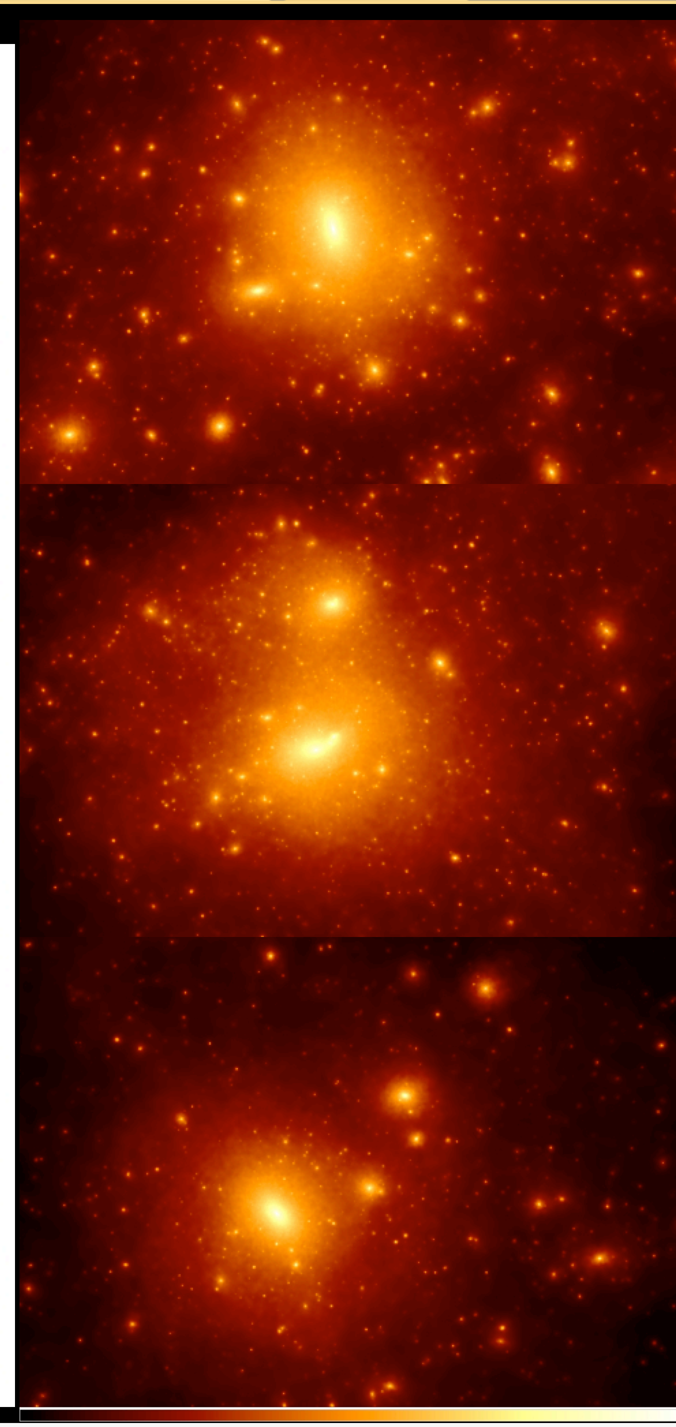

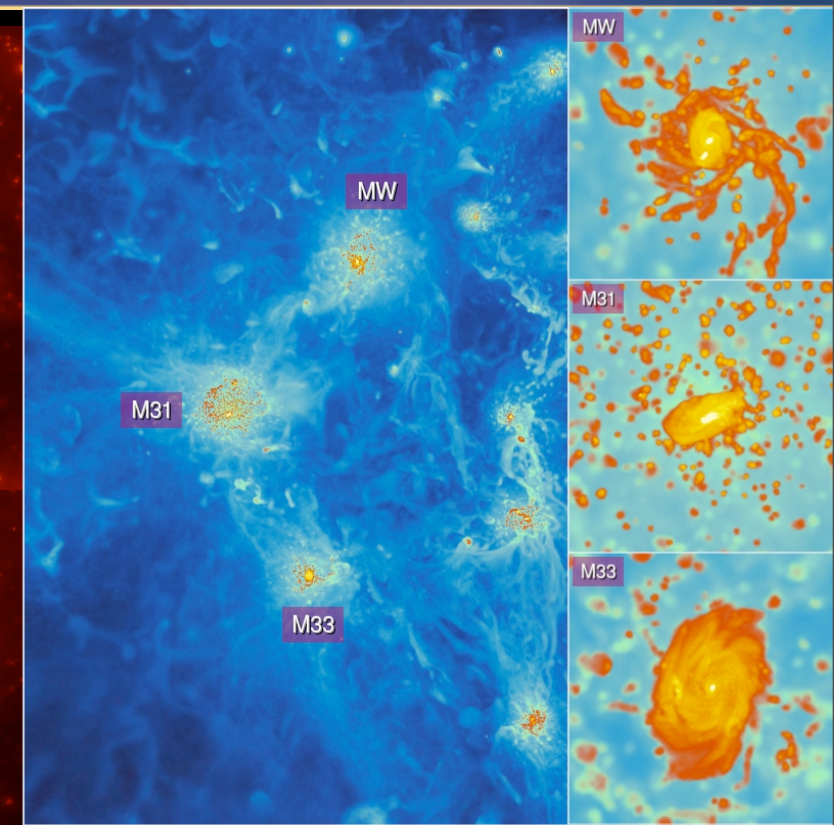

Stefan Gottloeber
Anatoly Klypin
Gustavo Yepes
YH

The CLUES' WMAP3 LG

Cosmology: WMAP3 (σ_8=0.75, Ω_m=0.24, h=0.73)

- LG: MW, M31, M33
- D(MW-M31)=0.9 Mpc/h
- D(LG-Virgo)=9.7 Mpc/h

	M_{vir}, M_{sellar} [1.e11Msun/h]	R_{vir} [kpc/h]	V_{max} [km/s]
M31	5.7	174	128
(BDM)	0.14		182
MW	4.6	162	131
(BDM)	0.12		155
M33	2.2	127	112
(BDM)	0.06		118

Simulations

- Code: GADGET-2
- Halo finder: AHF
- Box: 64 Mpc/h
- zoom: R=2 Mpc/h
  effective 4096^3
- PDM: DM=2.5e5 Msun/h
- BDM: DM=2.1e5 Msun/h
  gas=4.4e4 Msun/h
  stars=2.2e4 Msun/h

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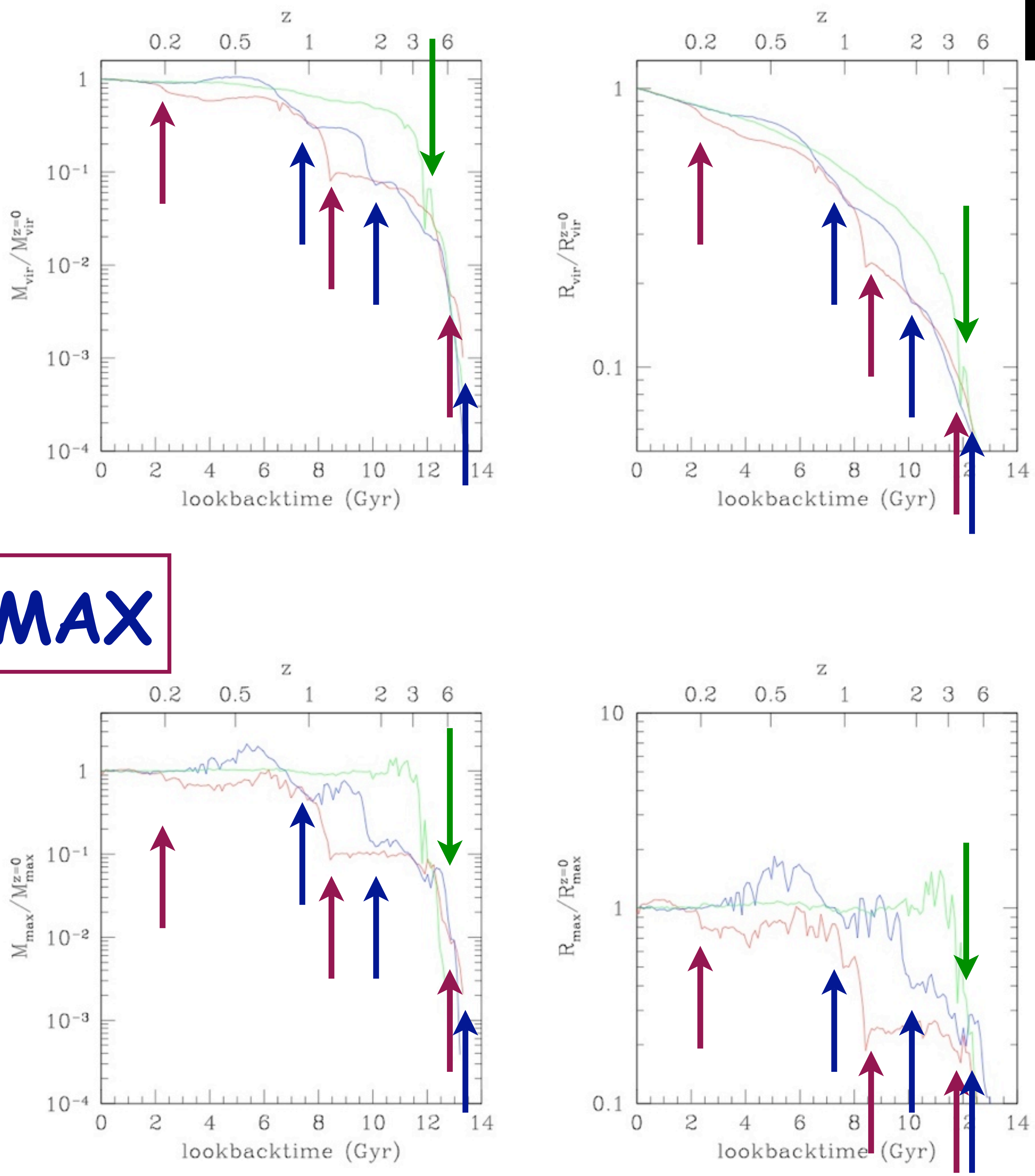
  stars=2.2e4 Msun/h

Work in progress ...

Mass Accretion History

VIR

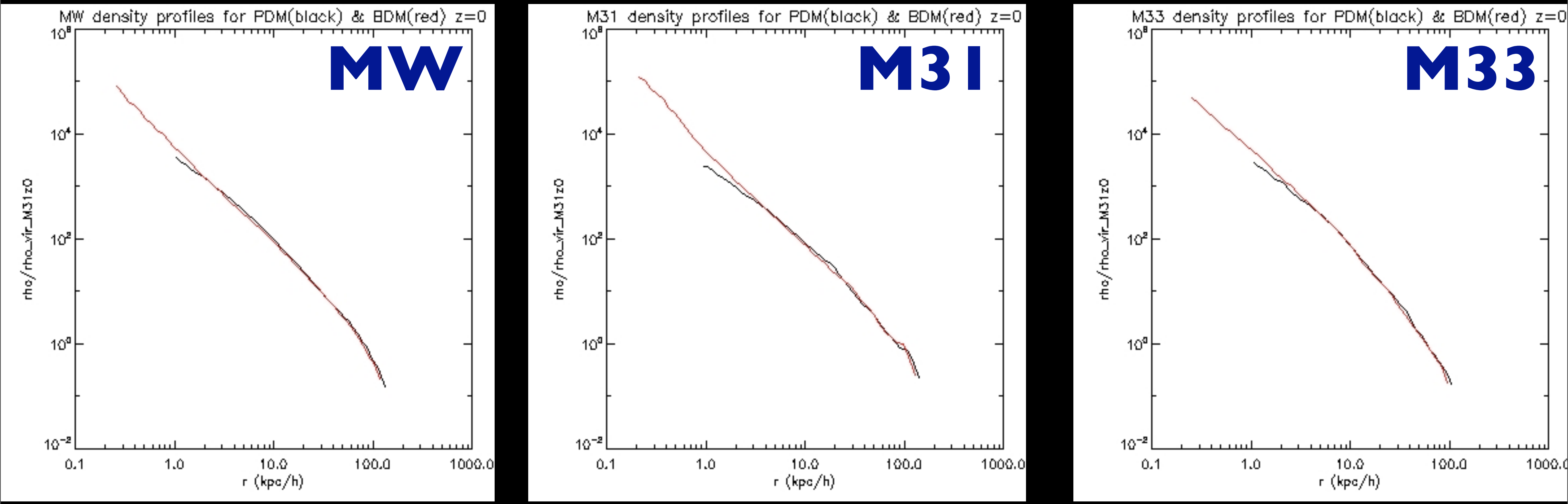
MAX



M31
MW
M33

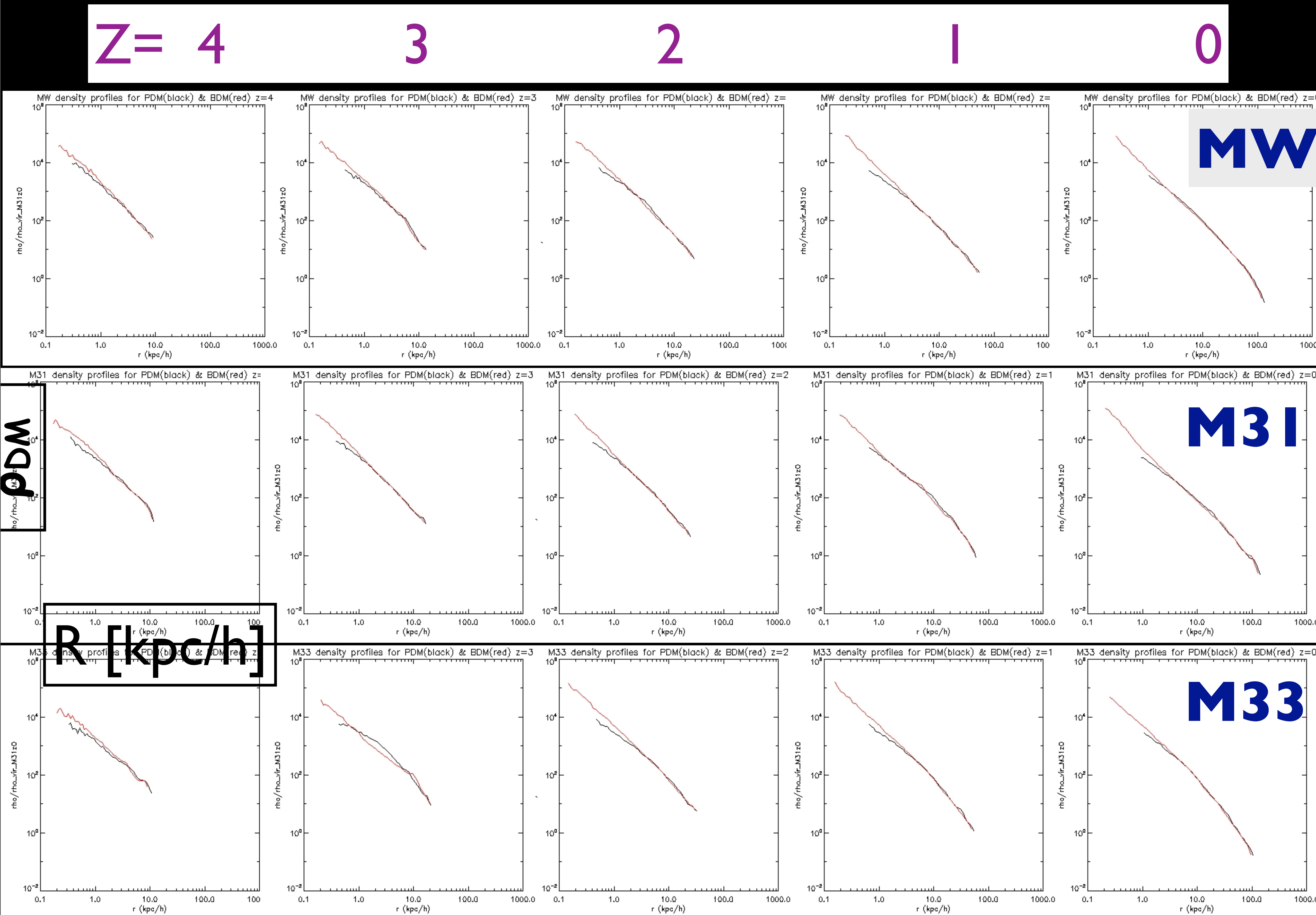
Arrows indicate epochs of major mergers

DM density profiles (z=0):



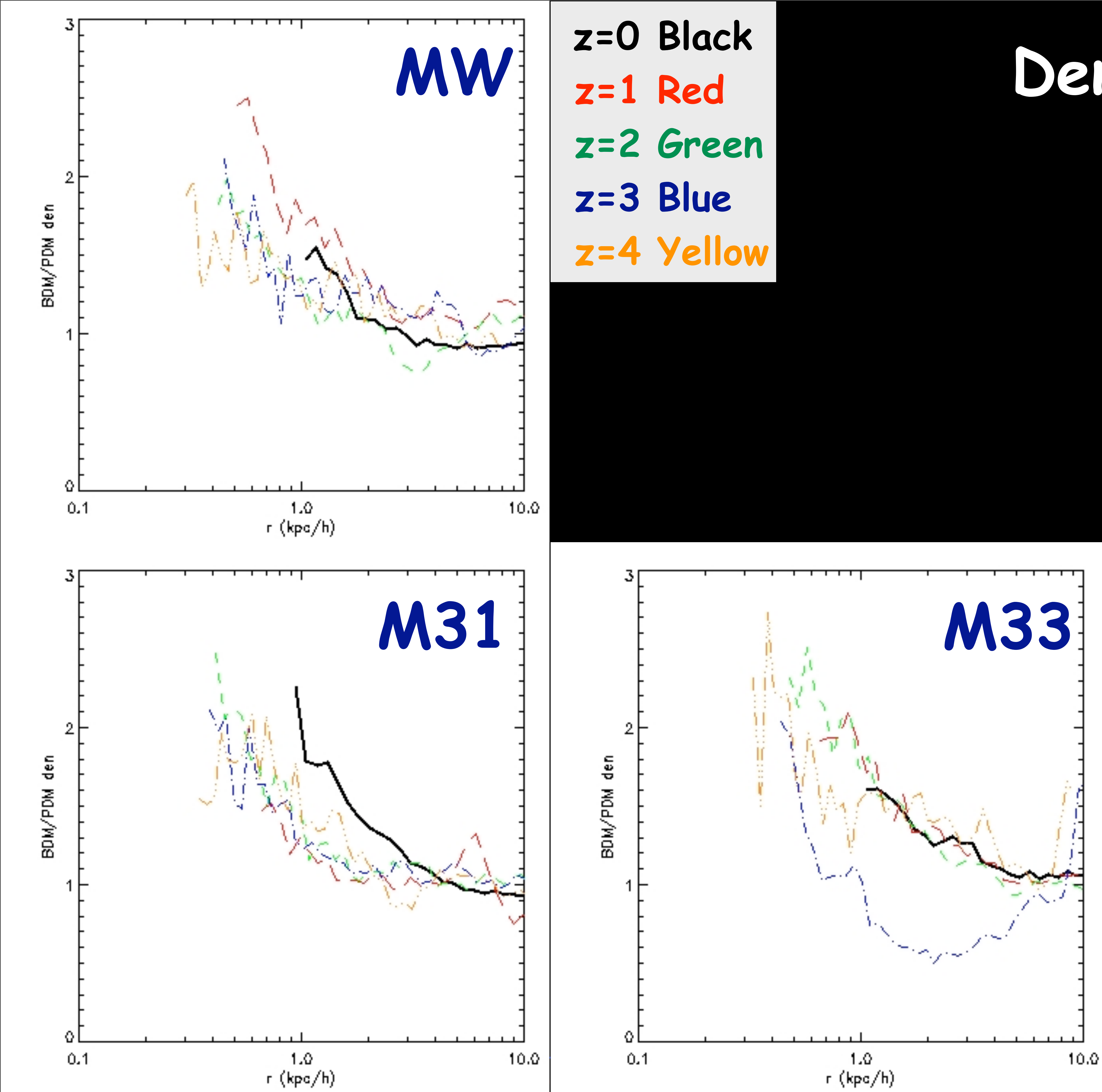
Apparent disagreement with Romano-Diaz et al - no flattening of ρ(r)

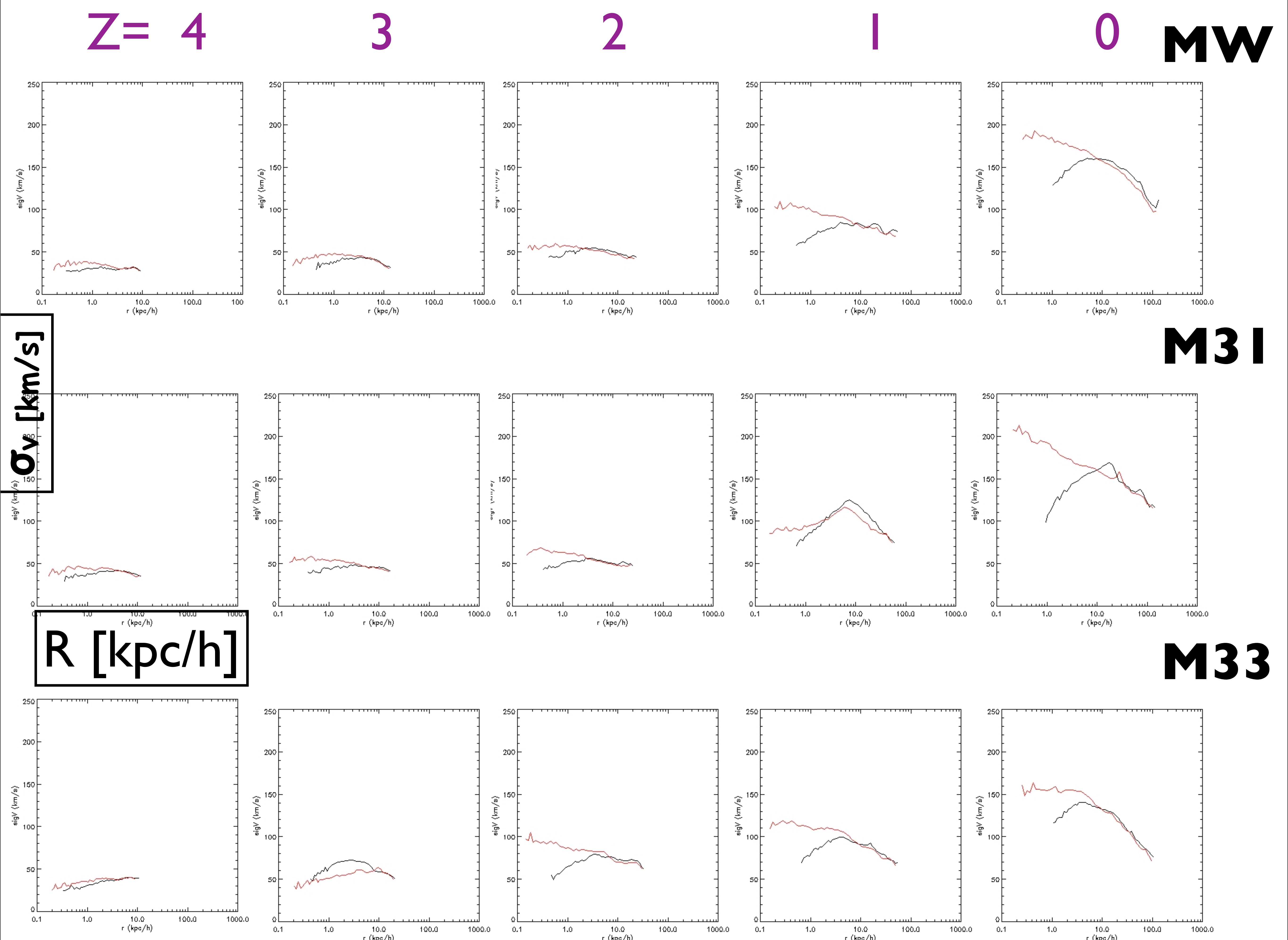
- Different codes (numerics, resolution, ...)
- Different physics (feedback, ...)
- Different halos:
  - ✦mass
  - ✦merging history



Yehuda Hoffman (HU) DARK MATTER IN THE UNIVERSE Meudon (June 2010)

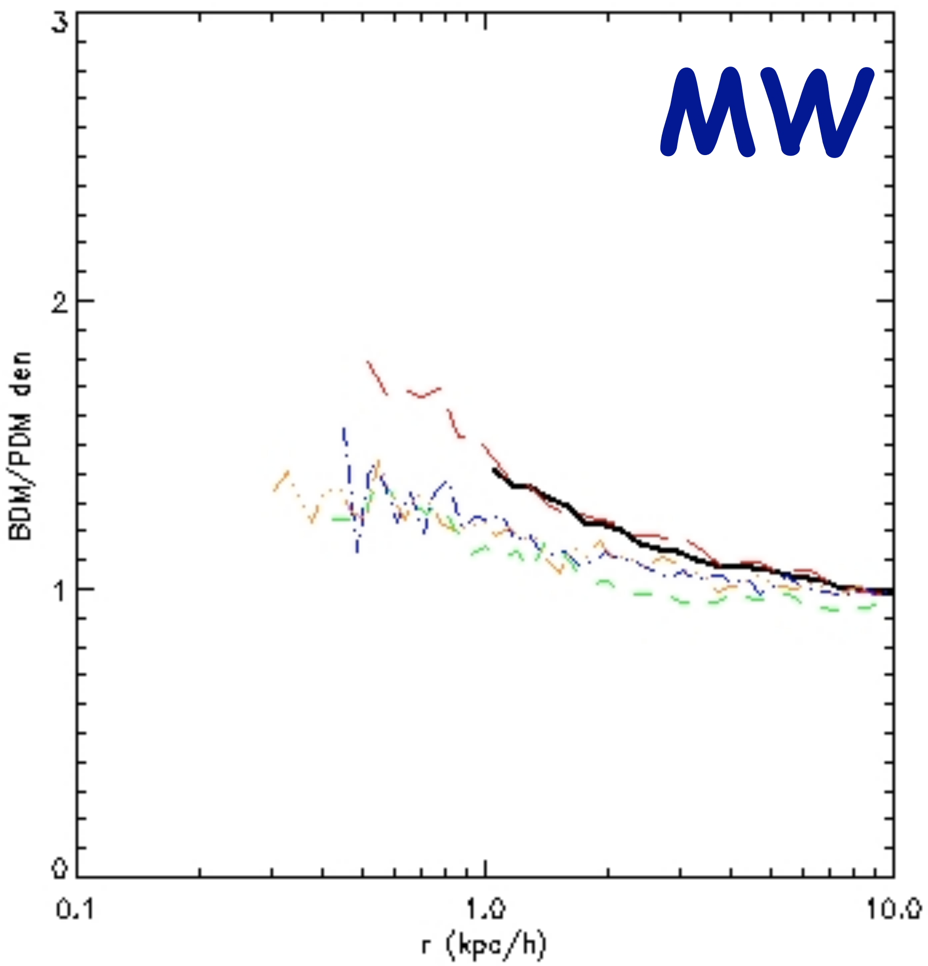
Density Ratio

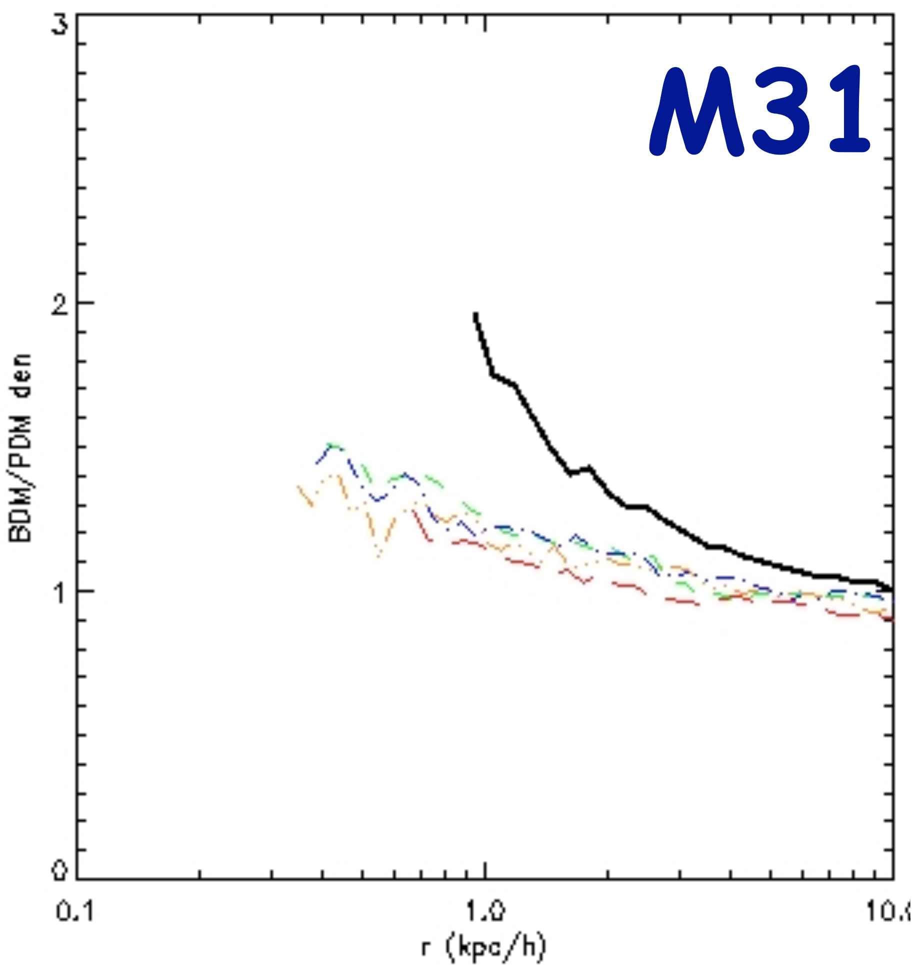


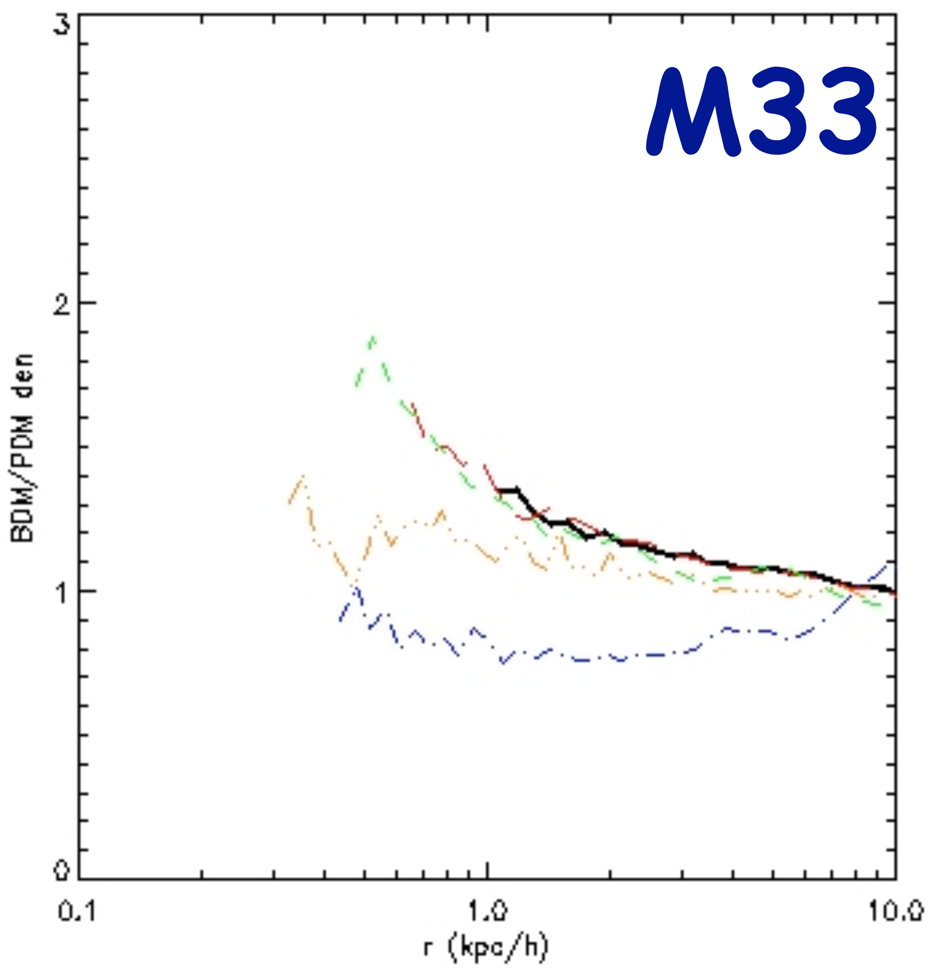

Z= 4
3
2
1
0
MW
M31
M33
σv [km/s]
R [kpc/h]
sigV (km/s)
r (kpc/h)

Velocity dispersion Ratio

z=0 Black
z=1 Red
z=2 Green
z=3 Blue
z=4 Yellow

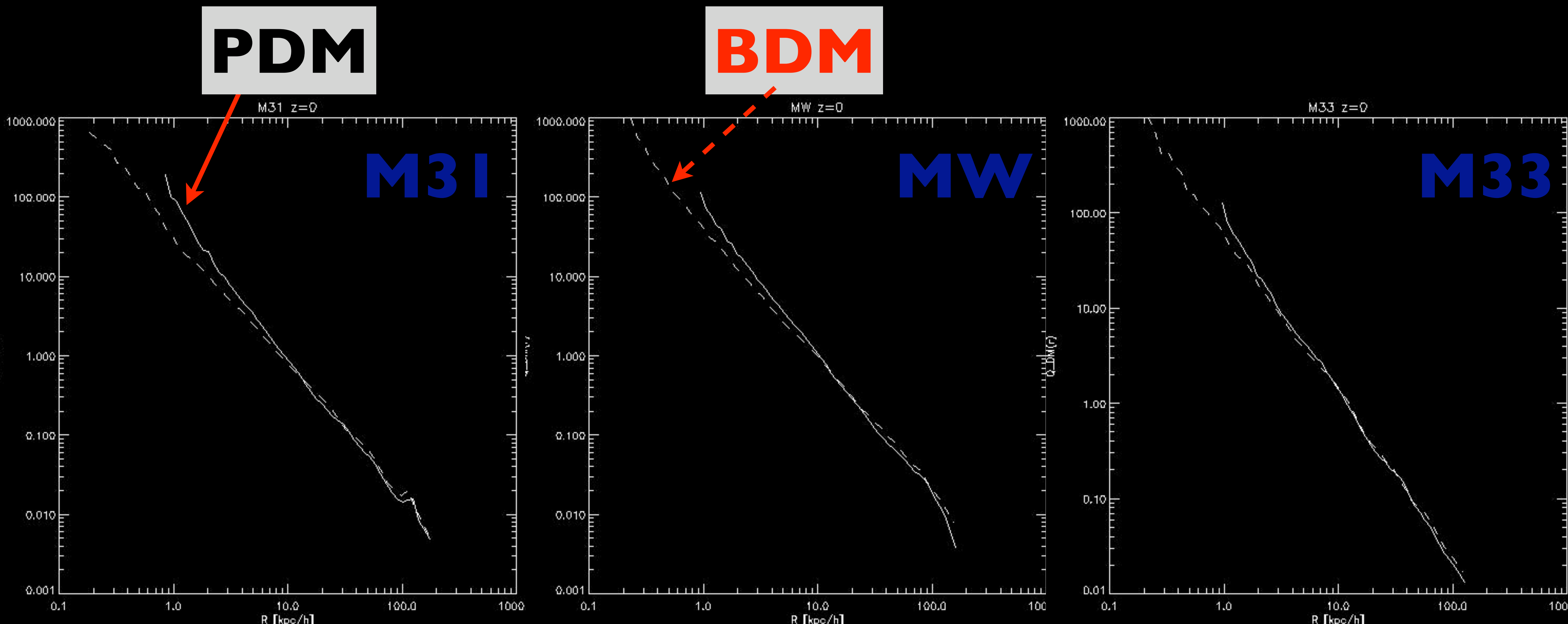






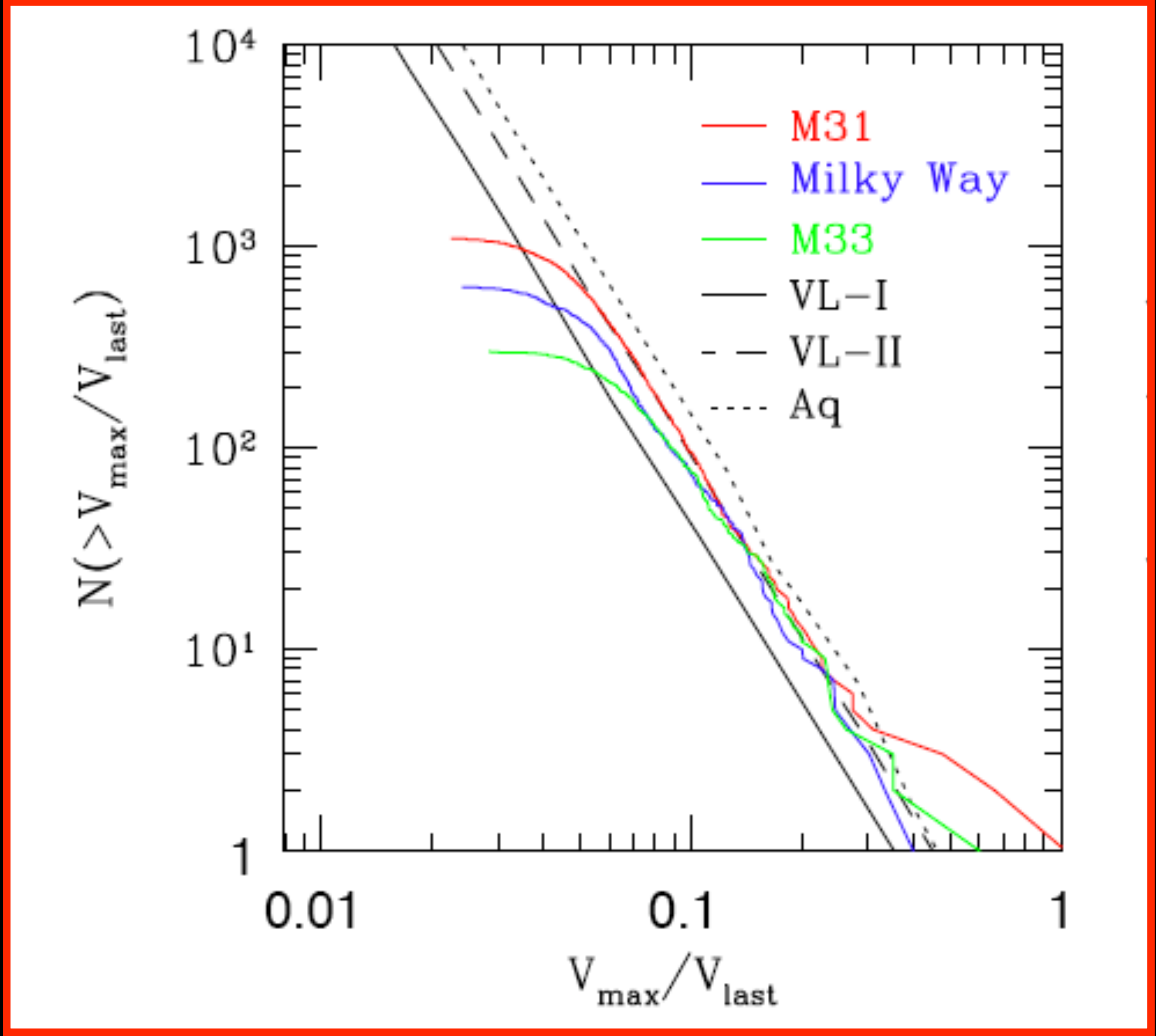
Meudon (June 2010)

$$Q(r) = \frac{\rho}{\sigma_v^3}$$



Self-Similar Nature of (PDM) Subhalos Abundance

Self-Similar Nature of (PDM) Subhalos Abundance

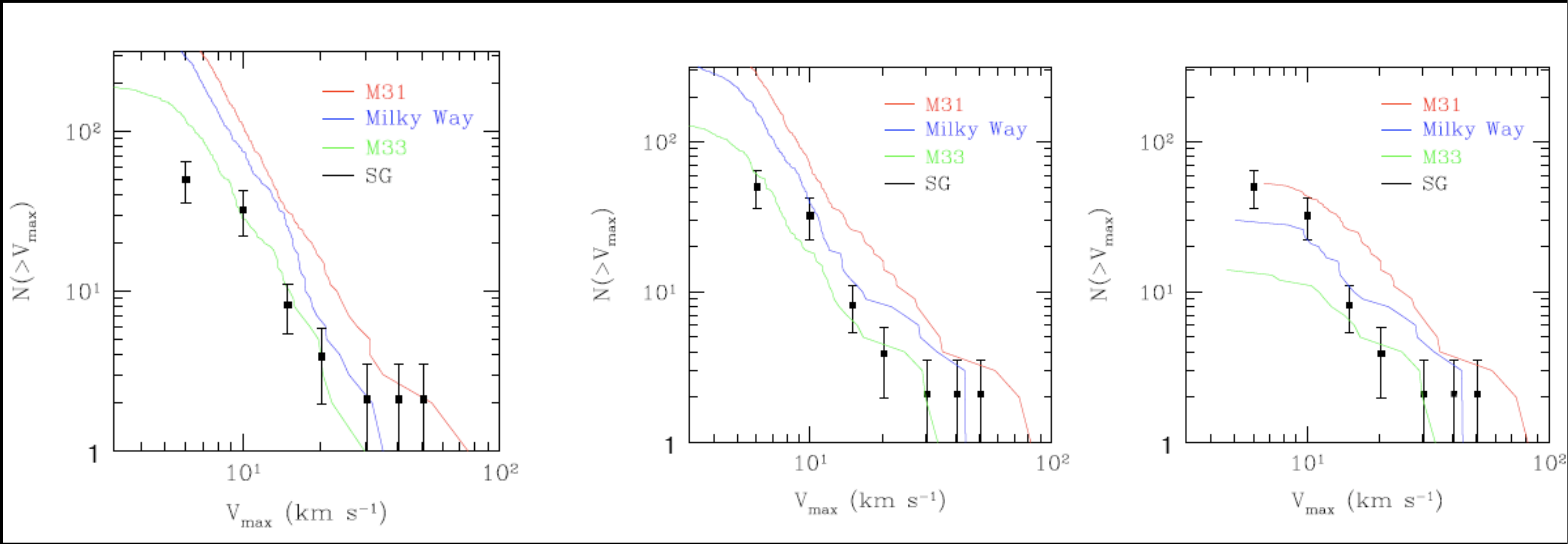


Substructures: PDM vs BDM

PDM - subhalos

BDM - subhalos

BDM - satellites

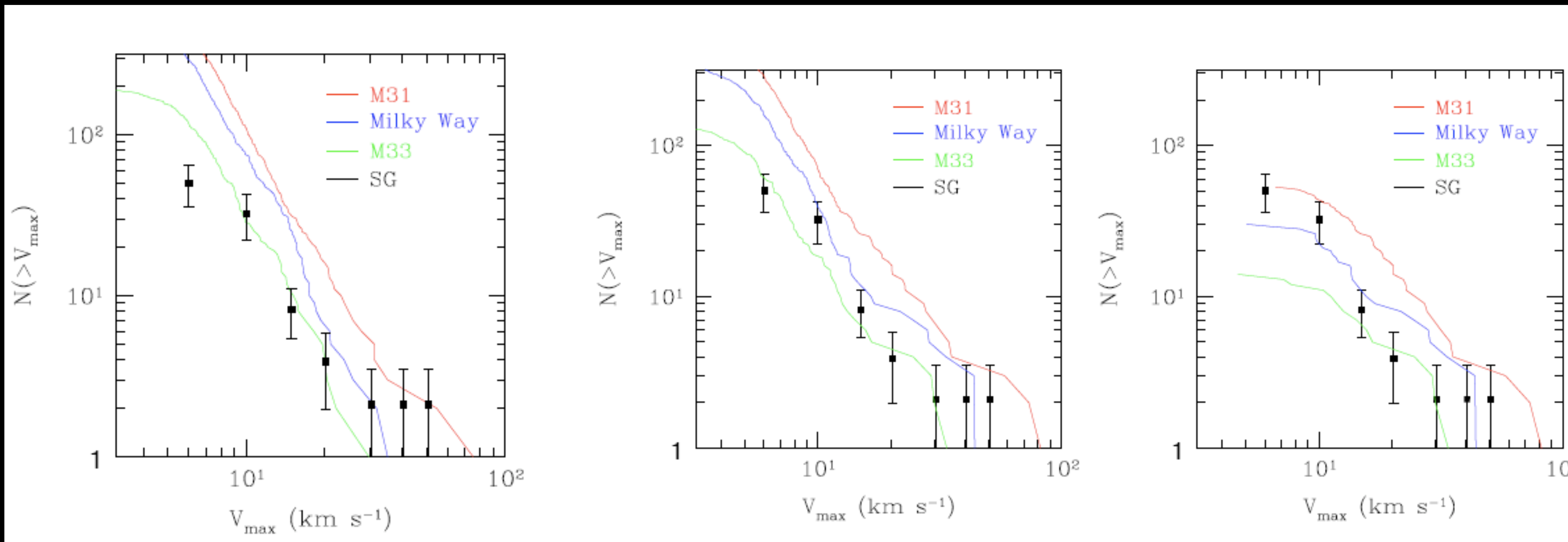


Substructures: PDM vs BDM

PDM - subhalos

BDM - subhalos

BDM - satellites



PDM & BDM V_{max} functions are similar

$$\left(\frac{d\mathbf{V}_M}{dt}\right)_{\rm DF} = -\frac{4\pi G^2 \ln\Lambda \rho M}{V_M^3} \times \left(\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}} \exp\left[-X^2\right]\right) \mathbf{V}_M$$

$$X \equiv \mathbf{V}_M/\sqrt{2}\sigma$$

$$\Lambda = bV_M^2/G(M+m)$$

$$\theta \equiv M_{tot}/M$$

In virial equilibrium:

$$\tau_{\rm DF}/\tau_{\rm dyn} \approx 0.75\theta/\ln\theta$$

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τ_{DF}/τ_{dyn} is expected to be (roughly) scale independent!

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3rd Interim Report: Adiabatic Contraction, Dynamical Friction and (BDM) central density profile

Romano-Diaz et al (2008, 2009, 2010) Johansson, Naab & Ostriker (2009)

→ In massive (> few 10^{12} M_{sun}) halos, dynamical friction by substructures efficiently reduces the central DM density and flattens the inner density cusp.

CLUES WMAP3 LG simulations Pedrosa, Tissera & Scannapieco (2009, 2010) & Tissera et al (2010)

→ In less massive ($\lesssim 10^{12}$ M_{sun}) halos, dynamical friction by substructures is less effective - reduces the central DM density but does not flatten the inner density cusp.

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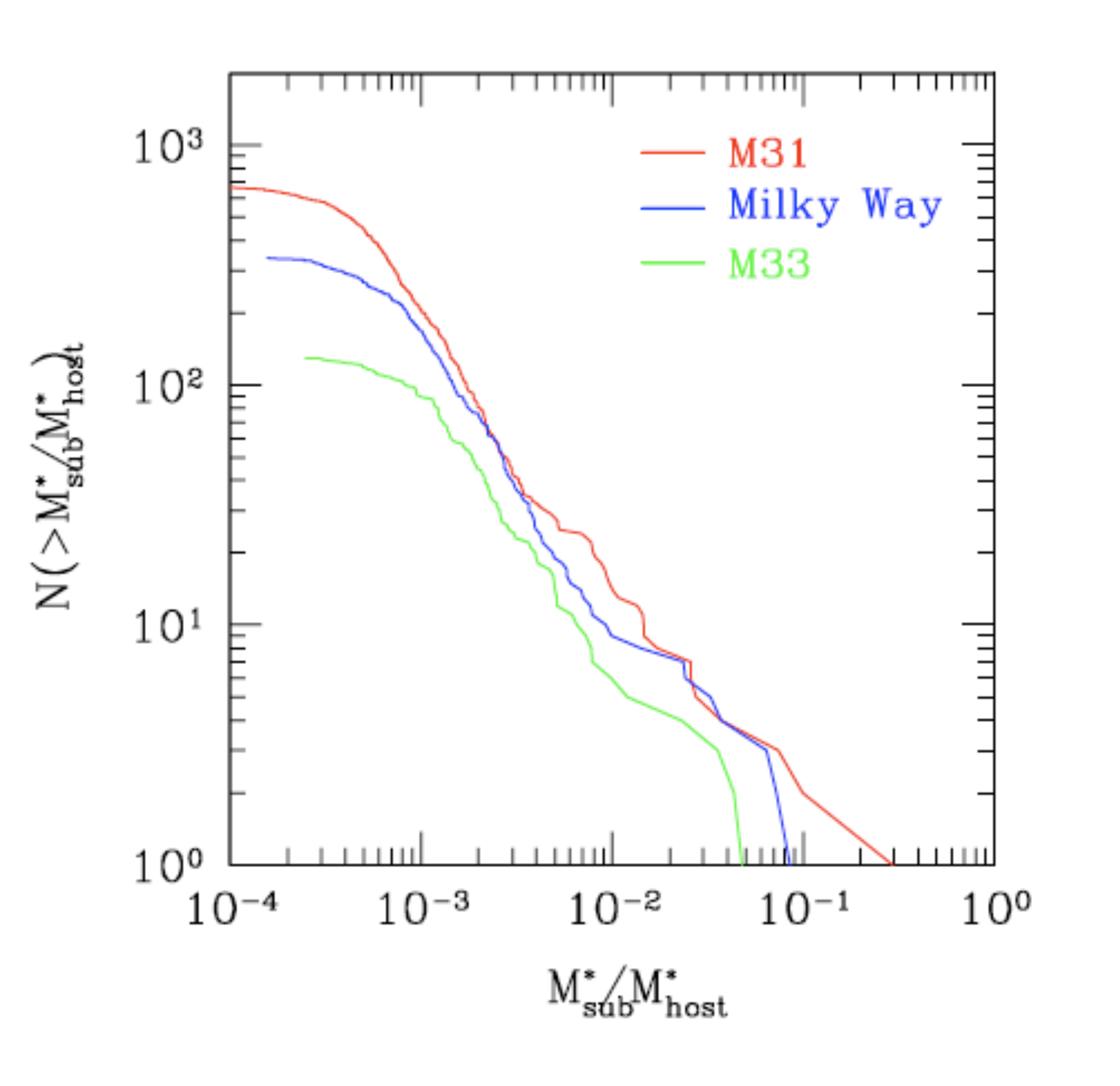
WHY?

Substructures: baryonic (stellar) mass function



The self-similarity does not hold for the baryonic component

But ...

- $M_{substructure}$ scales with M_{host} - the more massive is the host halo the more massive are the substructures.
- A conjecture: More massive substructures are more baryon rich.

- It follows that in more massive hosts the dynamical friction brings in more stellar rich substructures to the center, whose orbital energy is pumped into the DM distribution.

SUMMARY

- Adiabatic contraction works - in all simulations the central BDM DM density profile exceeds the PDM profile
- Dynamical friction on substructures:
  - ✦ Dynamical friction is the mechanism that transfers energy to the DM
  - ✦ Key point - substructures need to be baryon rich, so as to replace DM by baryons
  - ✦ The magnitude of the effect depends on the details of baryonic physics: star formation, feedback, ...
  - ✦ The effect depends on the halo (mass, merging history?)
- Both effects play a role in the interaction of baryons with DM

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THANK YOU