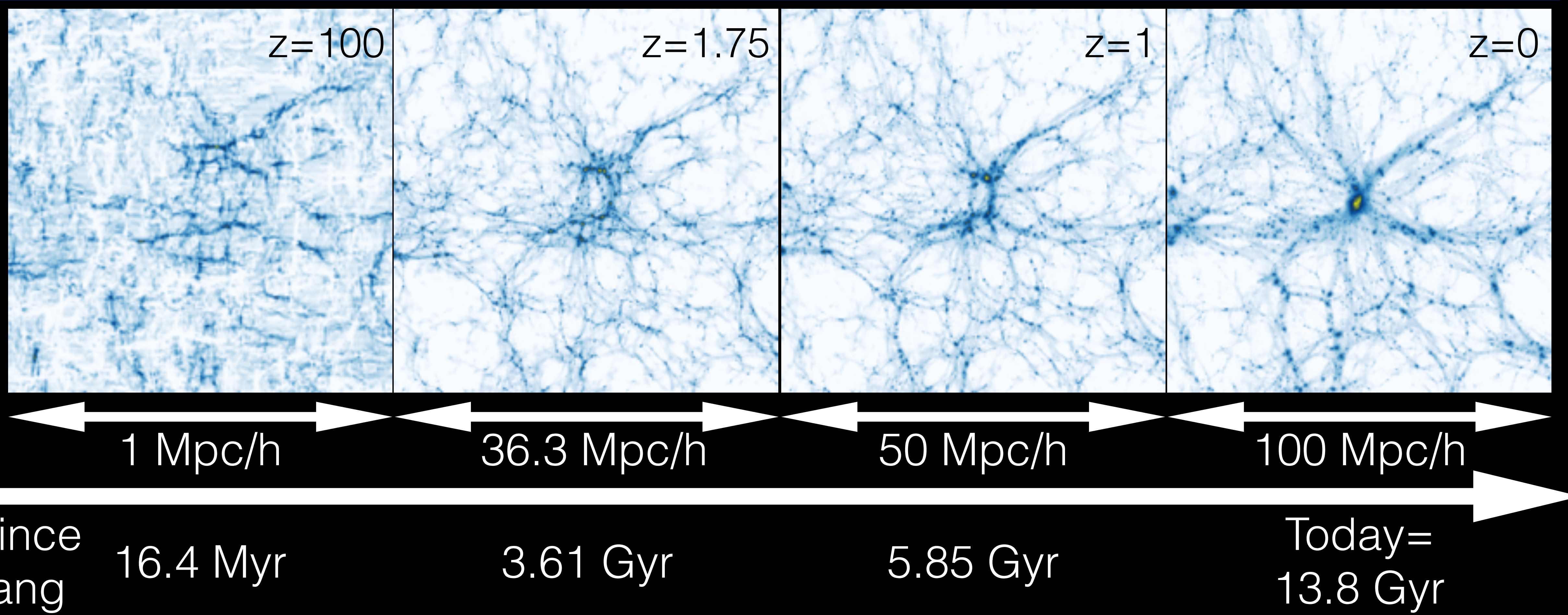
Evolution of the dark matter profiles of the most massive galaxy clusters since redshift 1

Amandine M. C. Le Brun
CEA Saclay DRF/IRFU Service d'Astrophysique

Collaborators: Romain Teyssier (Zürich), Monique Arnaud (CEA Saclay), Gabriel Pratt (CEA Saclay)

Galaxy clusters and structure formation



RAMSES (Teyssier 2002) simulations (Le Brun et al. in prep.)

- Galaxy clusters: 85% Dark Matter, 12 % hot gas, 3% galaxies
- Form and evolve through merger/accretion along filaments

➡ test of the physics of hierarchical Dark Matter driven structure formation (Dark Matter and baryons)

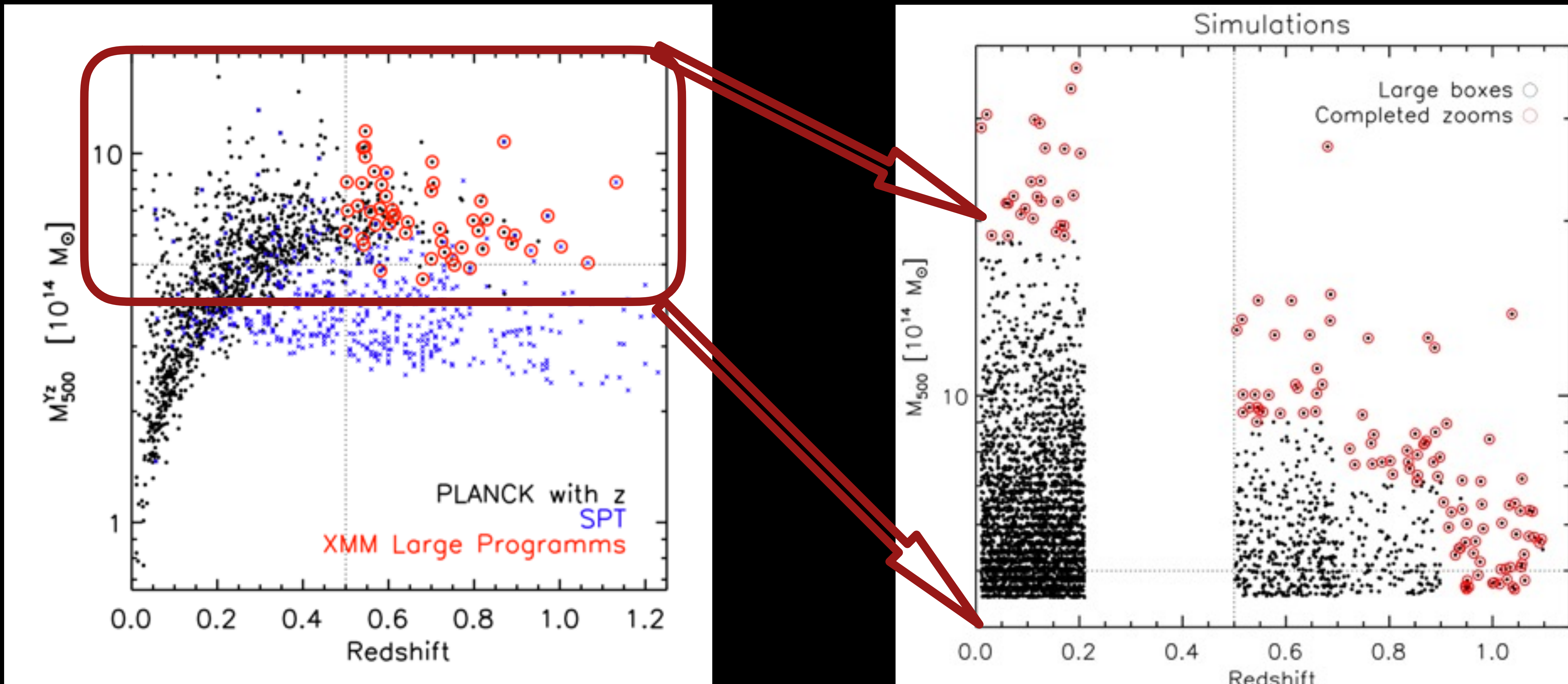
➡ cosmological parameters via N(M,z) or f_{gas}

Evolution of dark matter profiles

- Powerful test of ΛCDM.
- So far mainly been tested in the local Universe and using mostly non-representative samples.
- Detection of large and representative samples of the most massive clusters up to redshift $z \sim 1$ recently enabled by large surveys using the Sunyaev-Zel'dovich (SZ) effect.
- Requires a systematic comparison between observations and cosmological simulations.

The M2C project

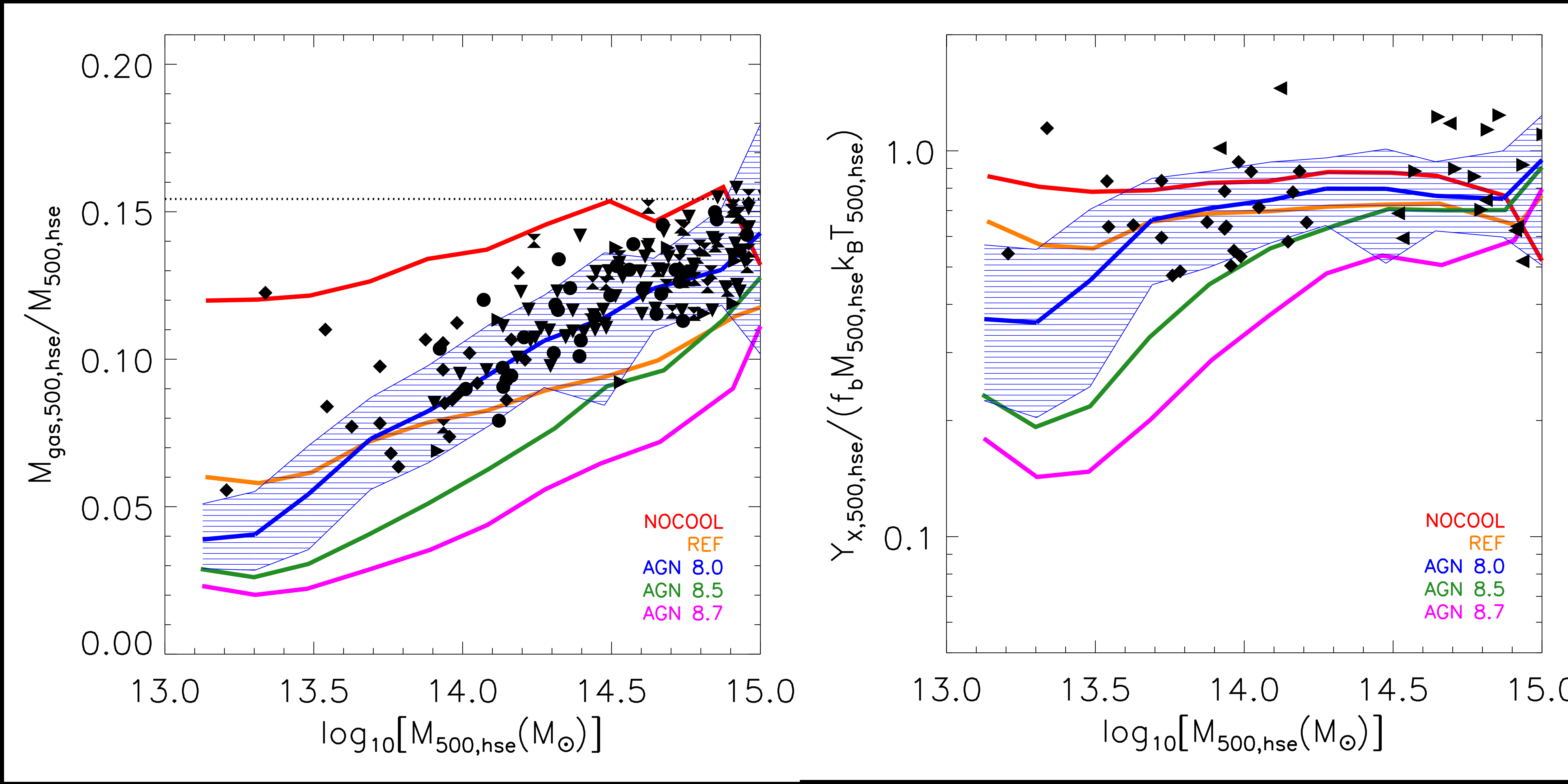
Figure courtesy of Monique Arnaud



- ~30 SZ selected clusters with $M_{500}>5\times10^{14}$ $M_\odot$ in 3 $\Delta z=0.2$ redshift bins at $z>0.5$
- Confirmation and stellar content using NIR
- Follow-up with XMM and Chandra
- Mass profiles obtained using hydrostatic equilibrium assumption

Le Brun et al. 2014

Impact of baryonic physics?



Data: REXCESS, Vikhlinin06, Lin12, Maughan08 and Sun09

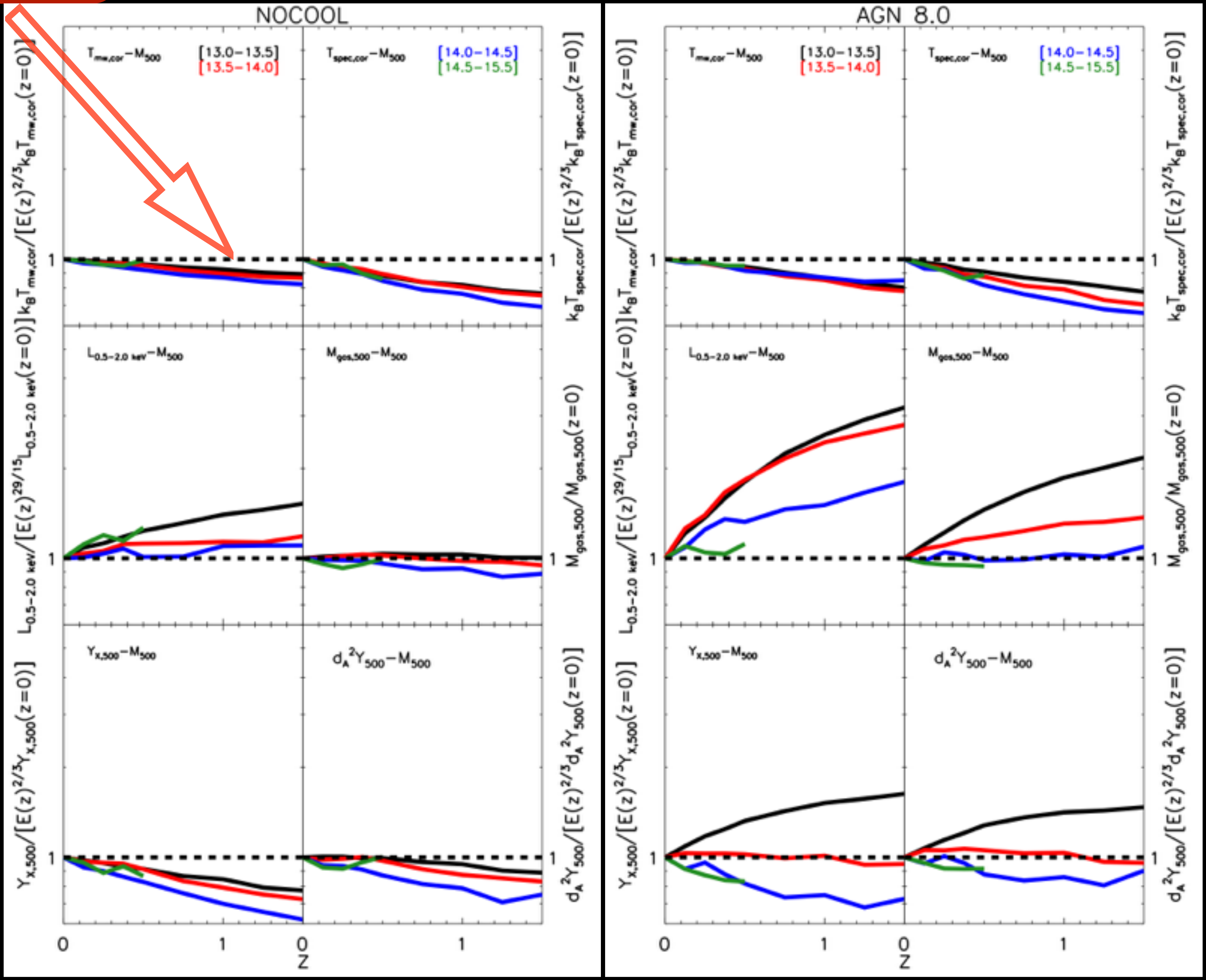
Data: Vikhlinin06, Planck Intermediate Results IV, Sun09

See also e.g. Allen et al. 2004, Kravtsov et al. 2006

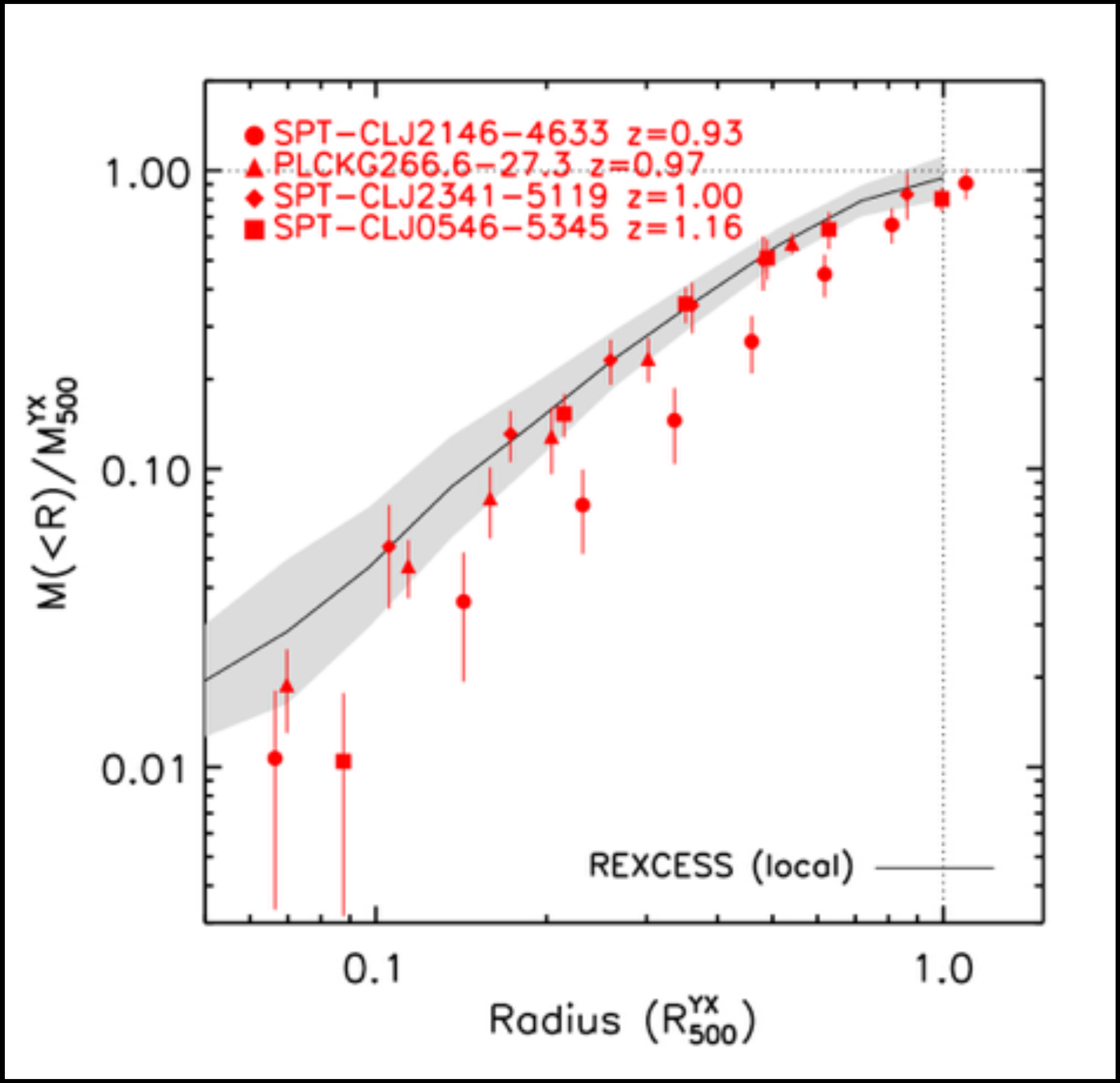
Impact of baryonic physics?

Le Brun et al. 2016a submitted

Self-similar expectation for the evolution



Pilot study of mass profiles at z~1



Arnaud, Bartalucci et al. in prep.

- Suggest less concentrated than average local cluster
- Higher dispersion? consistent with theory?
- Need larger sample and new numerical simulations

Evolution of the dark matter profiles of the most massive galaxy clusters since redshift 1

Simulations

Le Brun et al. in preparation

No existing hydrodynamical cosmological simulations combines a large enough volume and a high enough resolution to simulate the most massive galaxy clusters as:

- they are rare and appear in large volumes (need to simulate volumes of Gpc^3)

- high resolution (~kpc) is required to resolve their internal structure.

Simulations

Le Brun et al.
in preparation

Klypin16

Simulation	Box	Particles	m_p	ϵ	Ω_M	Ω_B	Ω_Λ	σ_8	n_s	H_0	Code
BigMD27	2.5	3840^3	2.1×10^{10}	10.0	0.270	0.047	0.730	0.820	0.95	70.0	GADGET-2
BigMD29	2.5	3840^3	2.2×10^{10}	10.0	0.289	0.047	0.711	0.820	0.95	70.0	GADGET-2
BigMD31	2.5	3840^3	2.4×10^{10}	10.0	0.309	0.047	0.691	0.820	0.95	70.0	GADGET-2
BigMDPL	2.5	3840^3	2.4×10^{10}	10.0	0.307	0.048	0.693	0.829	0.96	67.8	GADGET-2
BigMDPLnw	2.5	3840^3	2.4×10^{10}	10.0	0.307	0.048	0.693	0.829	0.96	67.8	GADGET-2
HMDPL	4.0	4096^3	7.9×10^{10}	25.0	0.307	0.048	0.693	0.829	0.96	67.8	GADGET-2
HMDPLnw	4.0	4096^3	7.9×10^{10}	25.0	0.307	0.048	0.693	0.829	0.96	67.8	GADGET-2
MDPL	1.0	3840^3	1.5×10^{9}	5	0.307	0.048	0.693	0.829	0.96	67.8	GADGET-2
MultiDark	1.0	2048^3	8.7×10^{9}	7.0	0.270	0.047	0.730	0.820	0.95	70.0	ART
SMDPL	0.4	3840^3	9.6×10^{7}	1.5	0.307	0.048	0.693	0.829	0.96	67.8	GADGET-2
BolshoiP	0.25	2048^3	1.5×10^{8}	1.0	0.307	0.048	0.693	0.823	0.96	67.8	ART
Bolshoi	0.25	2048^3	1.3×10^{8}	1.0	0.270	0.047	0.730	0.820	0.95	70.0	ART

Ludlow14

Simulation	N_p	L_{box} (Mpc h^{-1})	ϵ (kpc h^{-1})	m_p ($M_\odot h^{-1}$)
MS-XXL	6720^3	3000	10	6.17×10^9
MS-I	2160^3	500	5	8.61×10^8
MS-II	2160^3	100	1	6.89×10^6
Aq-A-2	5.3×10^8	–	0.050	1.00×10^4
Aq-A-1	4.3×10^9	–	0.015	1.25×10^3

Box	L (h^{-1} Mpc)	N^3	m_p ($h^{-1} M_\odot$)	ϵ (h^{-1} kpc)	$\epsilon/(L/N)$
L1000	1000	1024^3	7.0×10^{10}	33.0	1/30
L0500	500	1024^3	8.7×10^{9}	14.0	1/35
L0250	250	1024^3	1.1×10^{9}	5.8	1/42
L0125	125	1024^3	1.4×10^{8}	2.4	1/51
L0063	62.5	1024^3	1.7×10^{7}	1.0	1/60

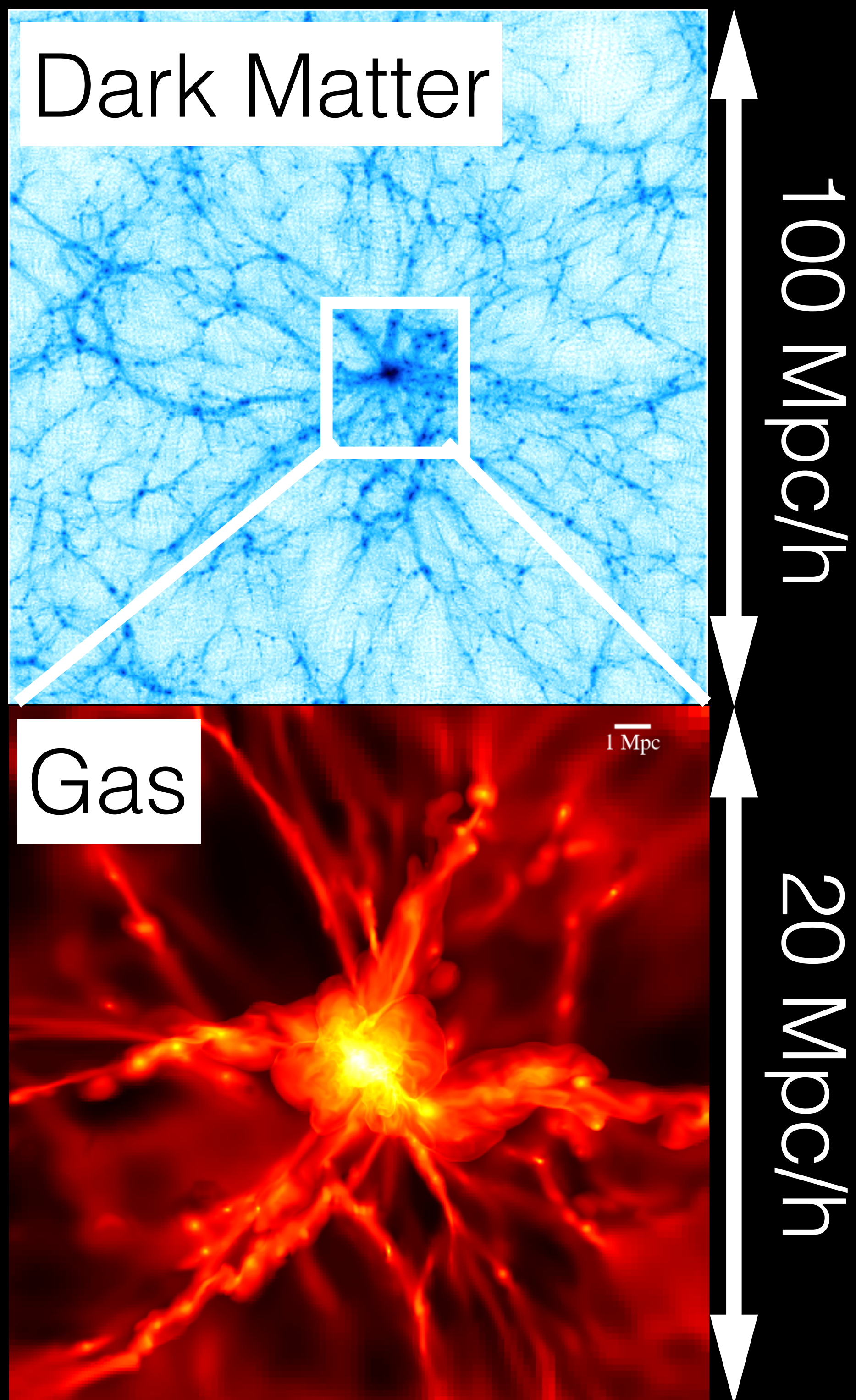
Diemer14

Dutton14

Name	Box size, L (h^{-1} Mpc)	N	Part. mass, m_p ($h^{-1} M_\odot$)	Force soft., ϵ (h^{-1} kpc)
P-20.1	20	300^3	2.611×10^7	1.67
P-20.2	20	300^3	2.611×10^7	1.67
P-20.3	20	300^3	2.611×10^7	1.67
P-20.4	20	300^3	2.611×10^7	1.67
P-30.1	30	300^3	8.811×10^7	2.50
P-30.2	30	300^3	8.811×10^7	2.50
P-60	60	600^3	8.811×10^7	2.50
P-45.1	45	300^3	2.974×10^8	3.75
P-45.2	45	300^3	2.974×10^8	3.75
P-90	90	450^3	7.049×10^8	5.00
P-80	80	350^3	1.052×10^9	5.71
P-130	130	450^3	2.124×10^9	7.22
P-180	180	450^3	5.639×10^9	10.0
P-270	270	450^3	1.903×10^{10}	15.0
P-400	400	450^3	6.188×10^{10}	22.2
P-600	600	600^3	8.811×10^{10}	25.0
P-1000	1000	600^3	4.079×10^{11}	41.7

- Large enough size
- Too low mass and **spatial** resolution and sometimes size

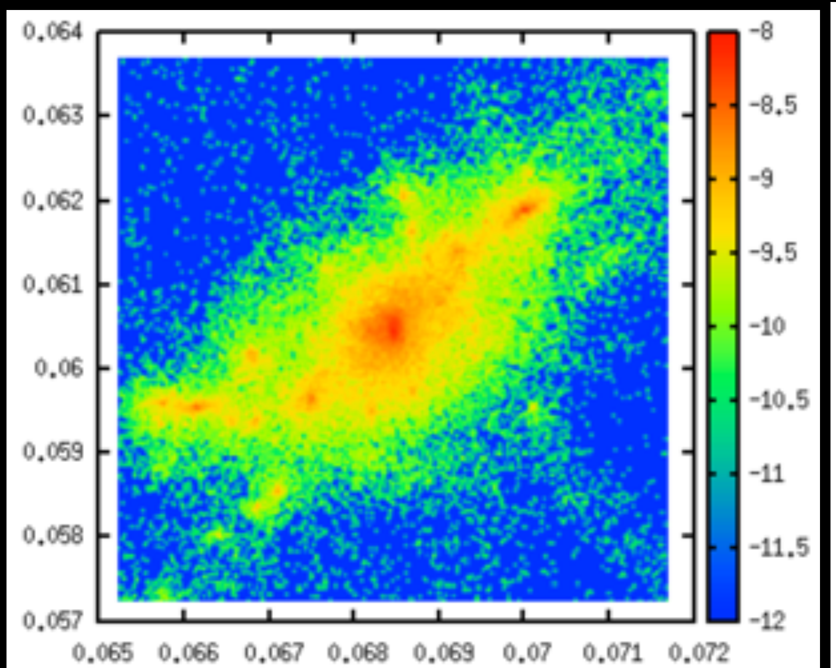
Simulations

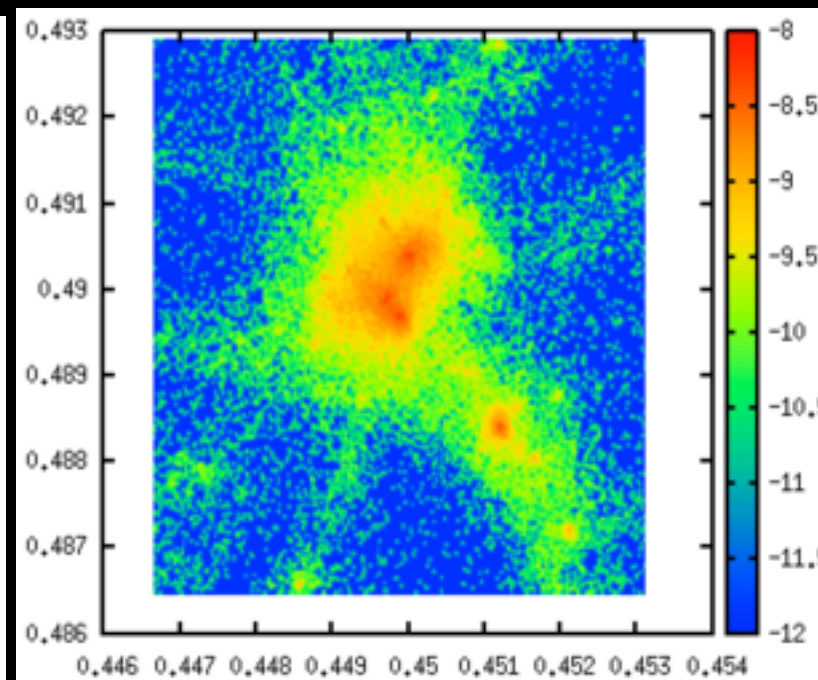


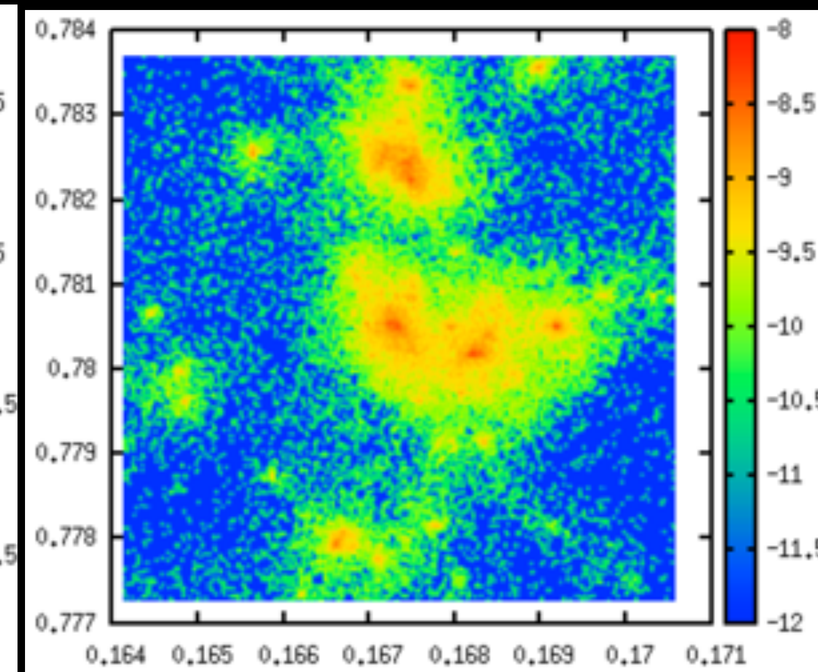
- In practice: (i) **doing three large (1 Gpc/h on a side with 2048^3 DM particles)** DM only simulations and (ii) **zooming at high resolution** (a few kpc) o**n 50-100 galaxy clusters in each of the redshift bins** which will progressively include the relevant galaxy formation physics.

- All the simulations are done with the AMR code RAMSES (Teyssier 2002) on the OCCIGEN supercomputer at CINES in Montpellier using a **large French computing time-allocation** (>13 million CPU hours already allocated over 2015-2016; PI Le Brun).

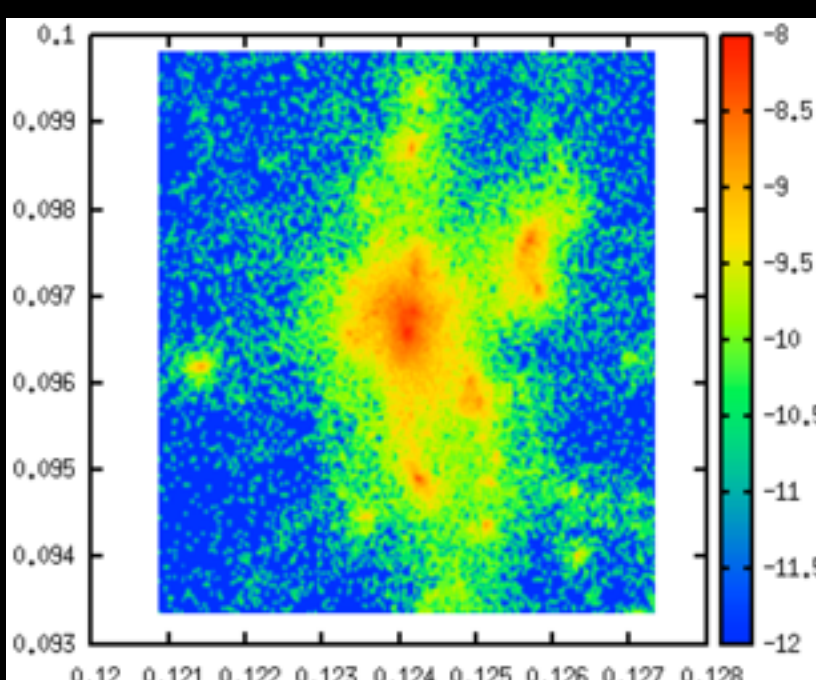
Most galaxy clusters at z=1 are disturbed

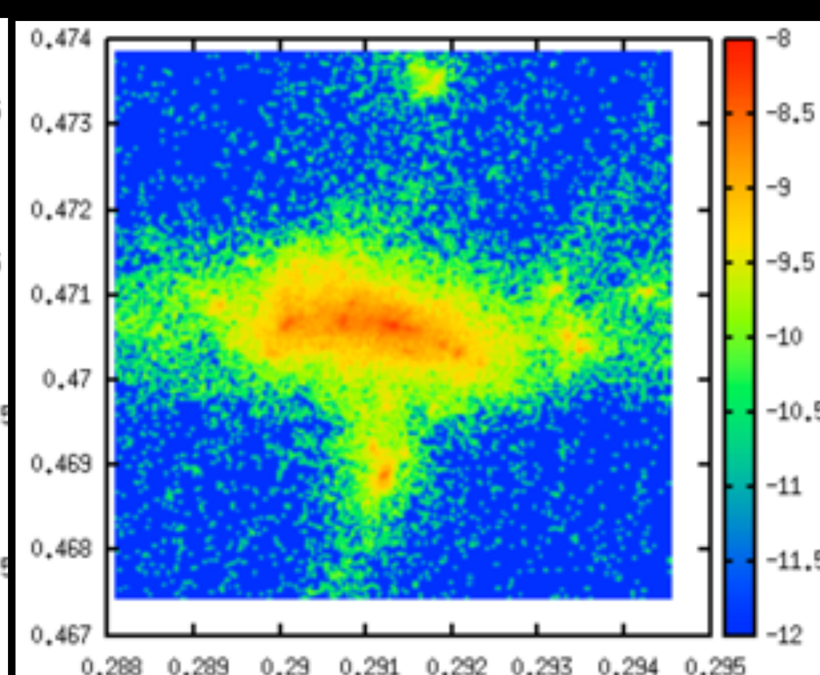


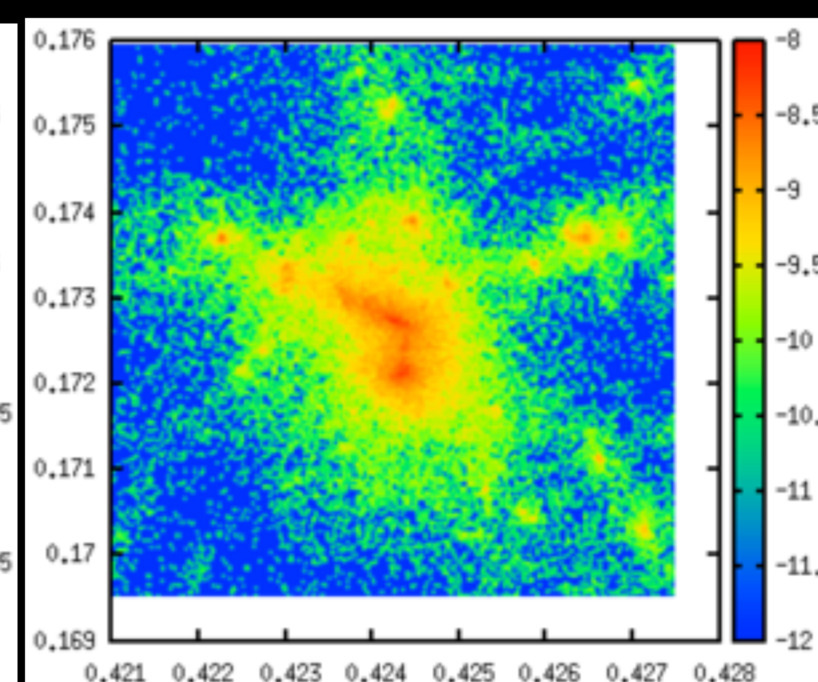




The Turtle cluster The Horse cluster The Rubber Duck cluster

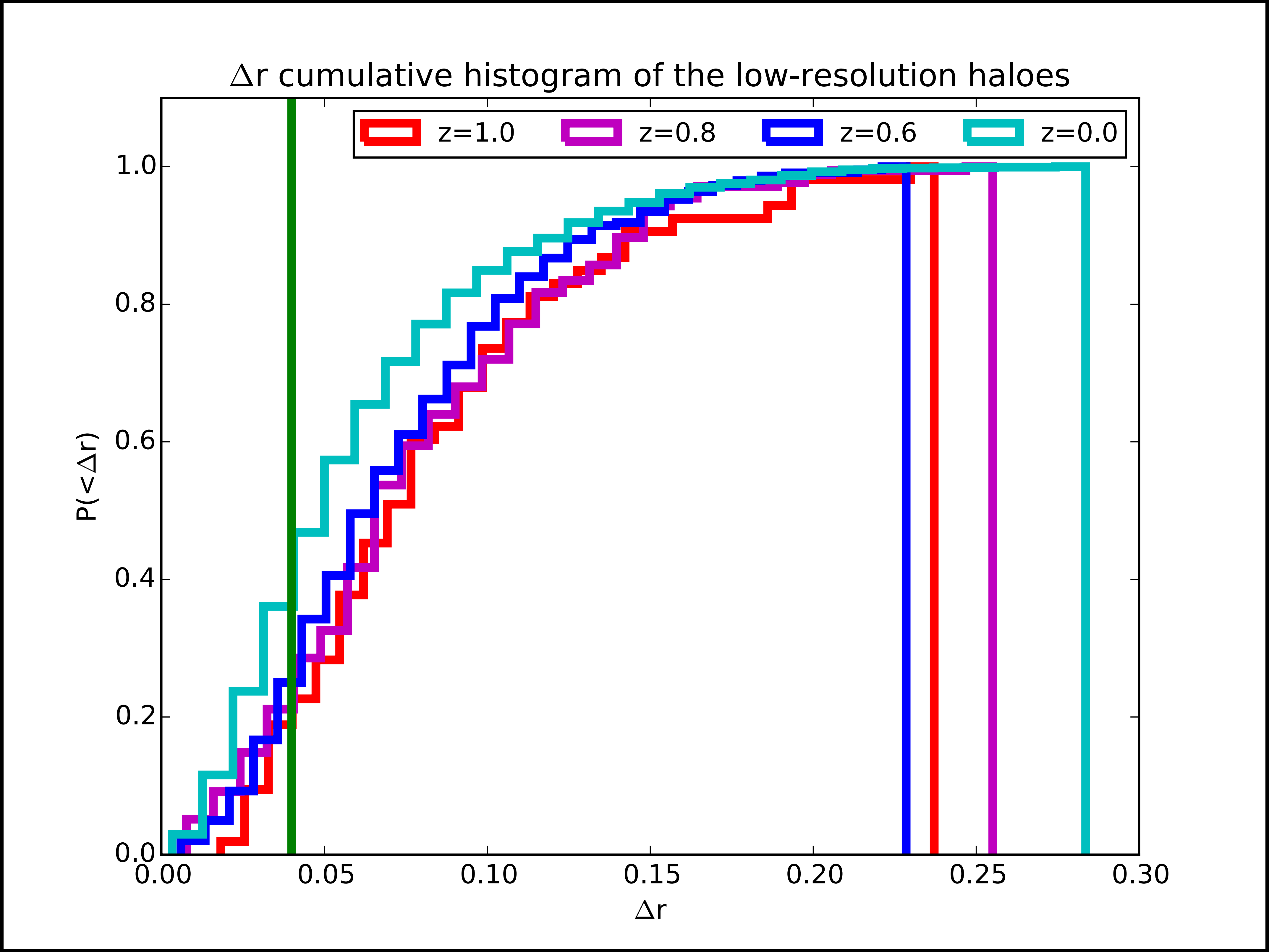






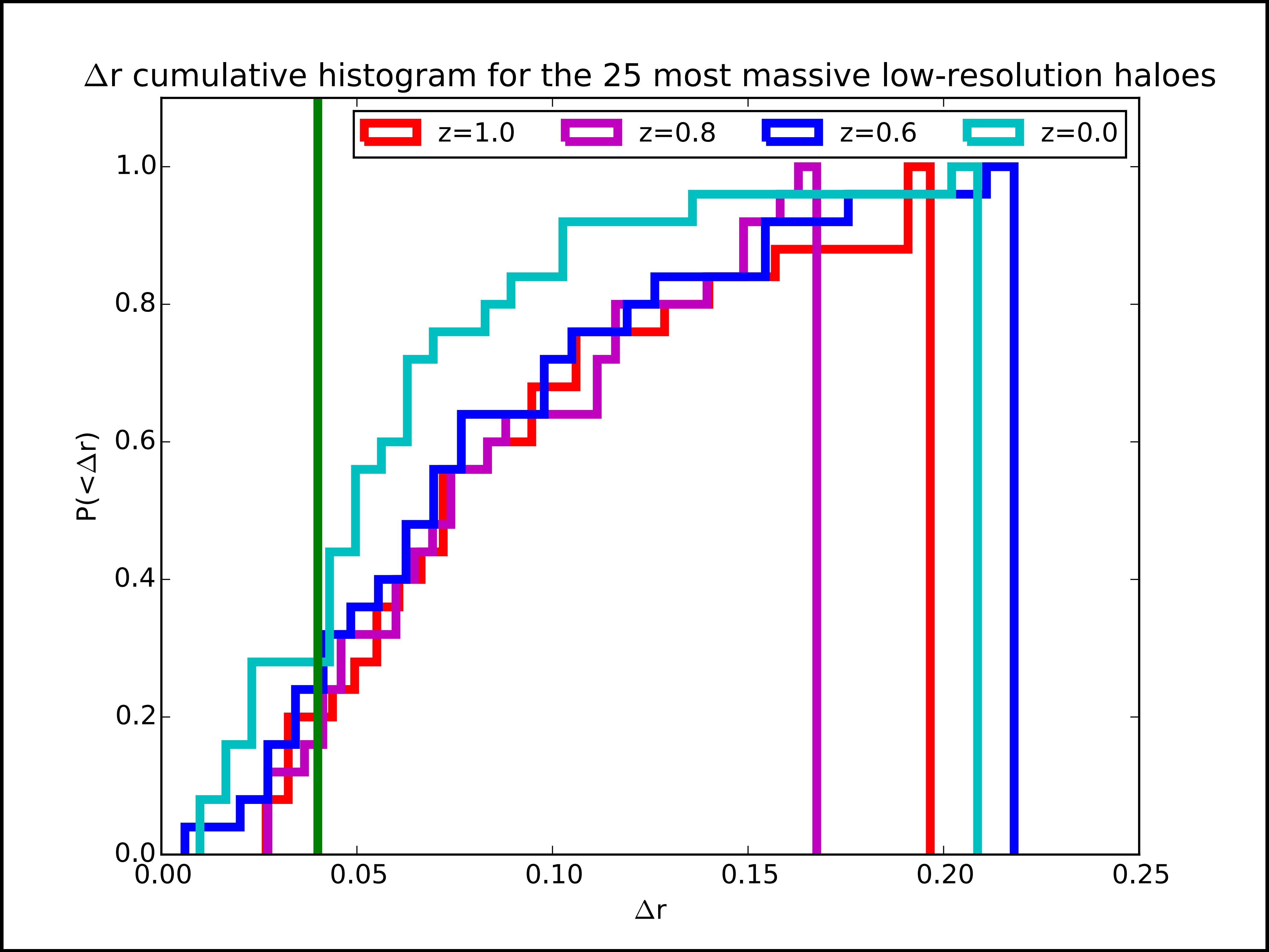
Evolution of relaxation state

Le Brun et al. in preparation



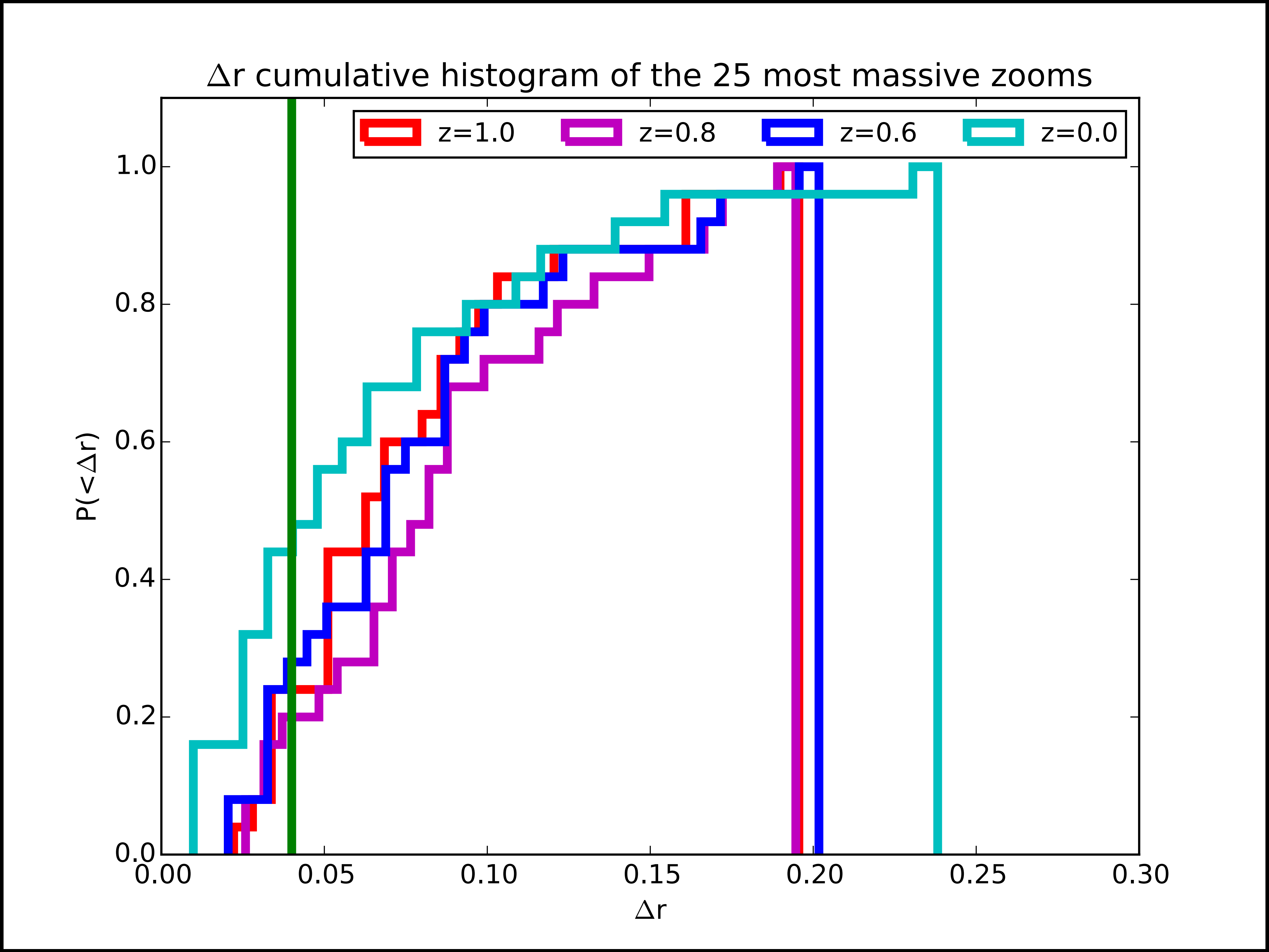
Evolution of relaxation state

Le Brun et al.
in preparation



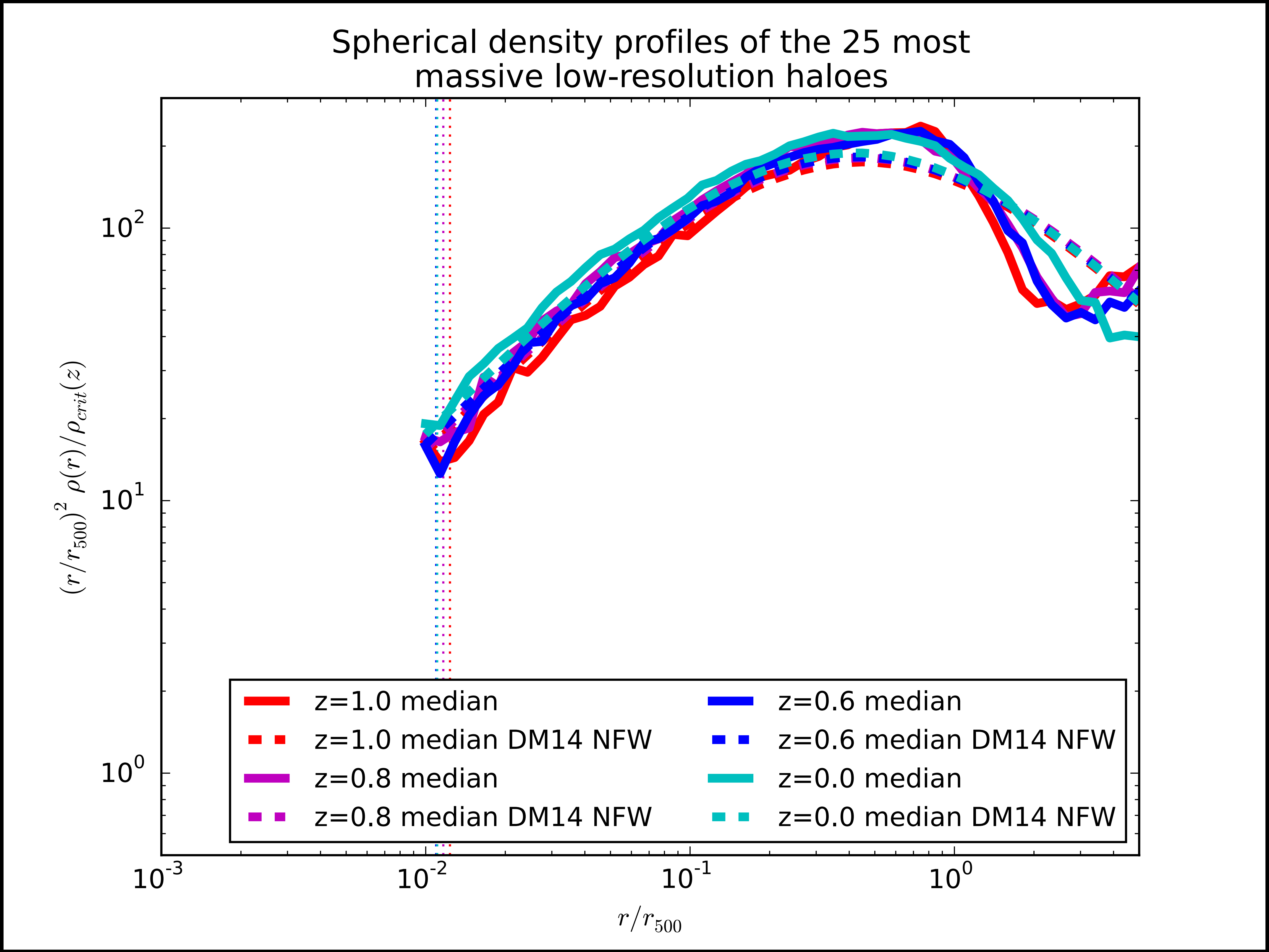
Evolution of relaxation state

Le Brun et al. in preparation



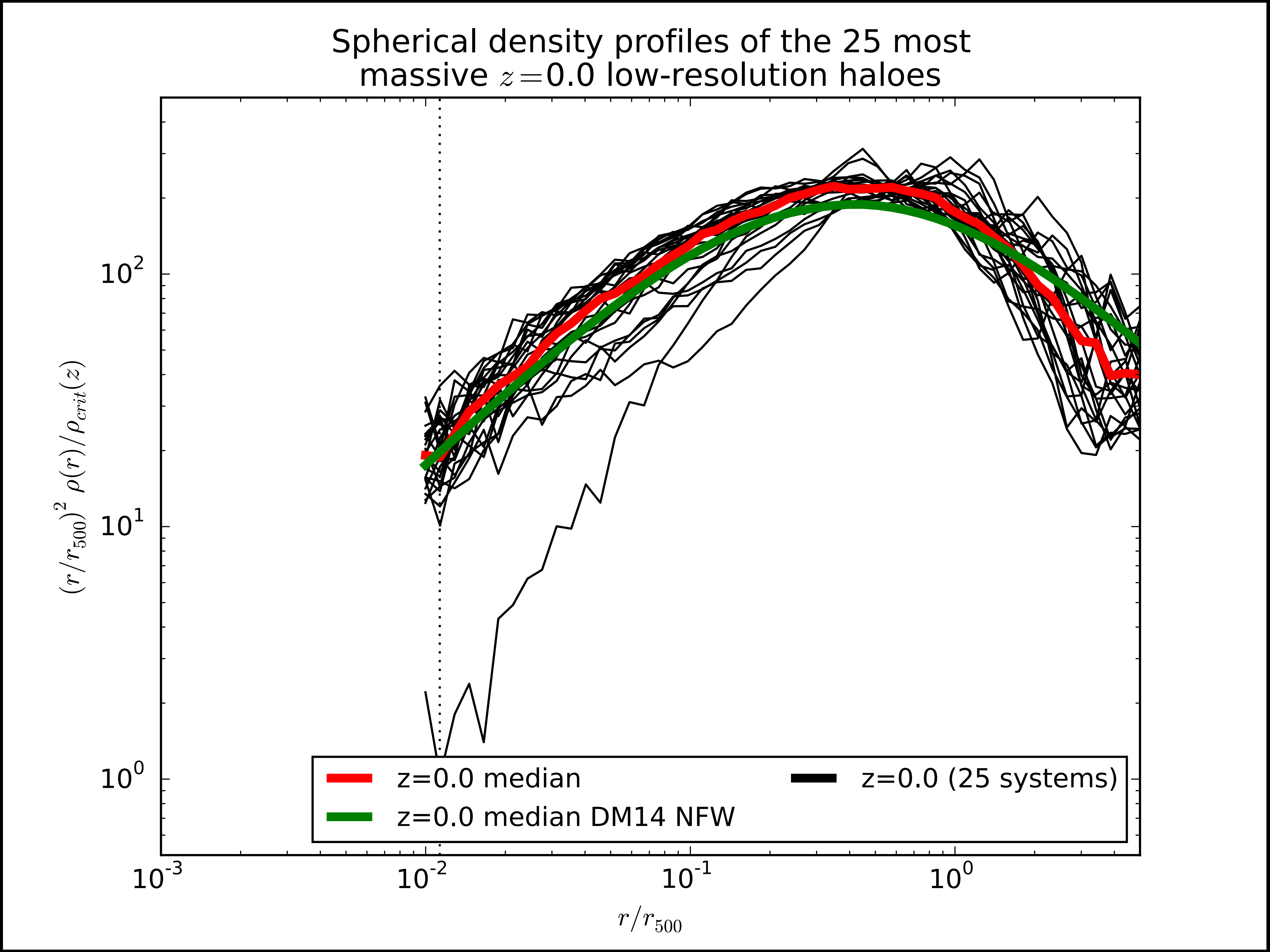
Evolution of density profiles

Le Brun et al. in preparation



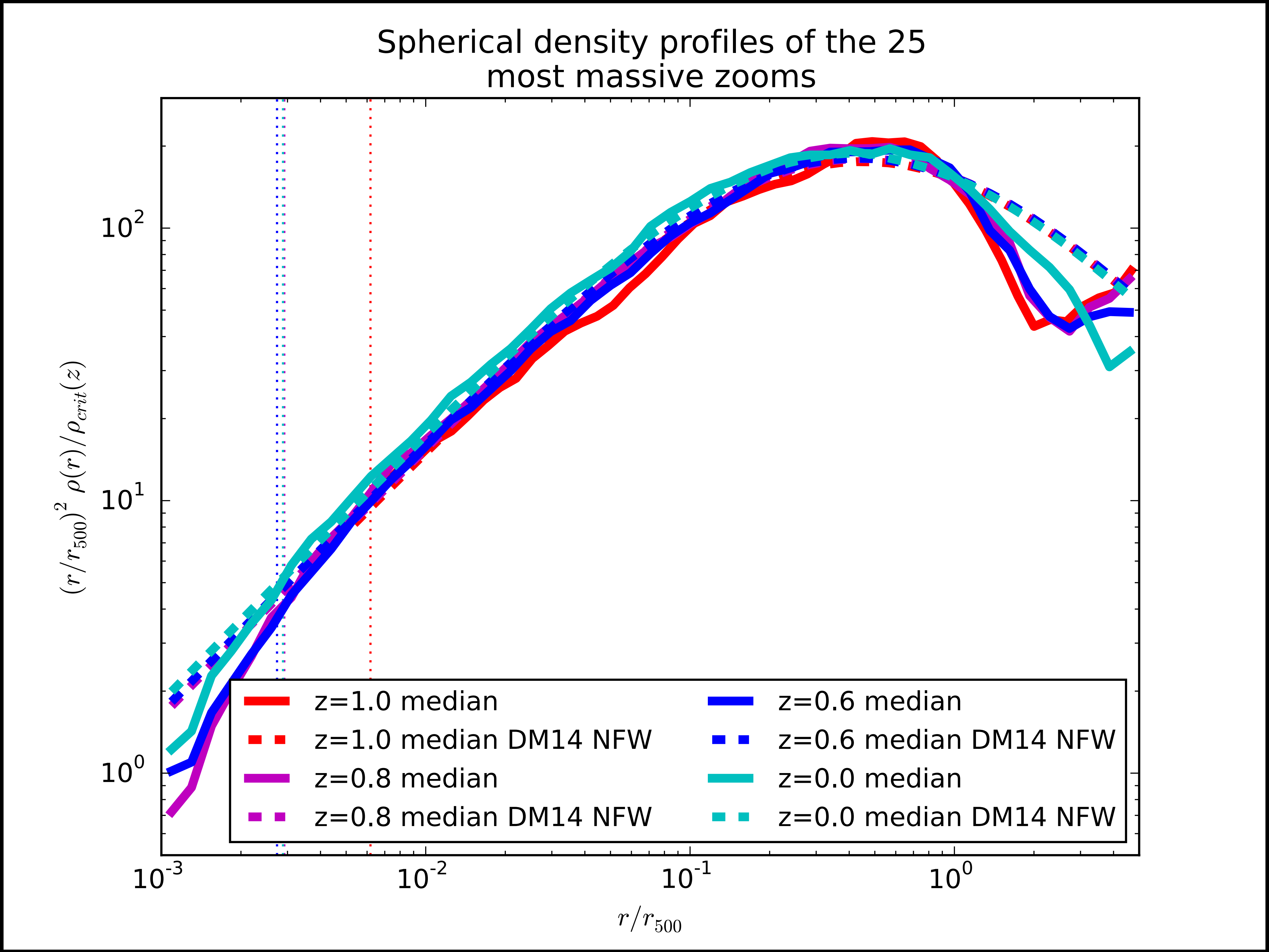
Density profiles

Le Brun et al. in preparation



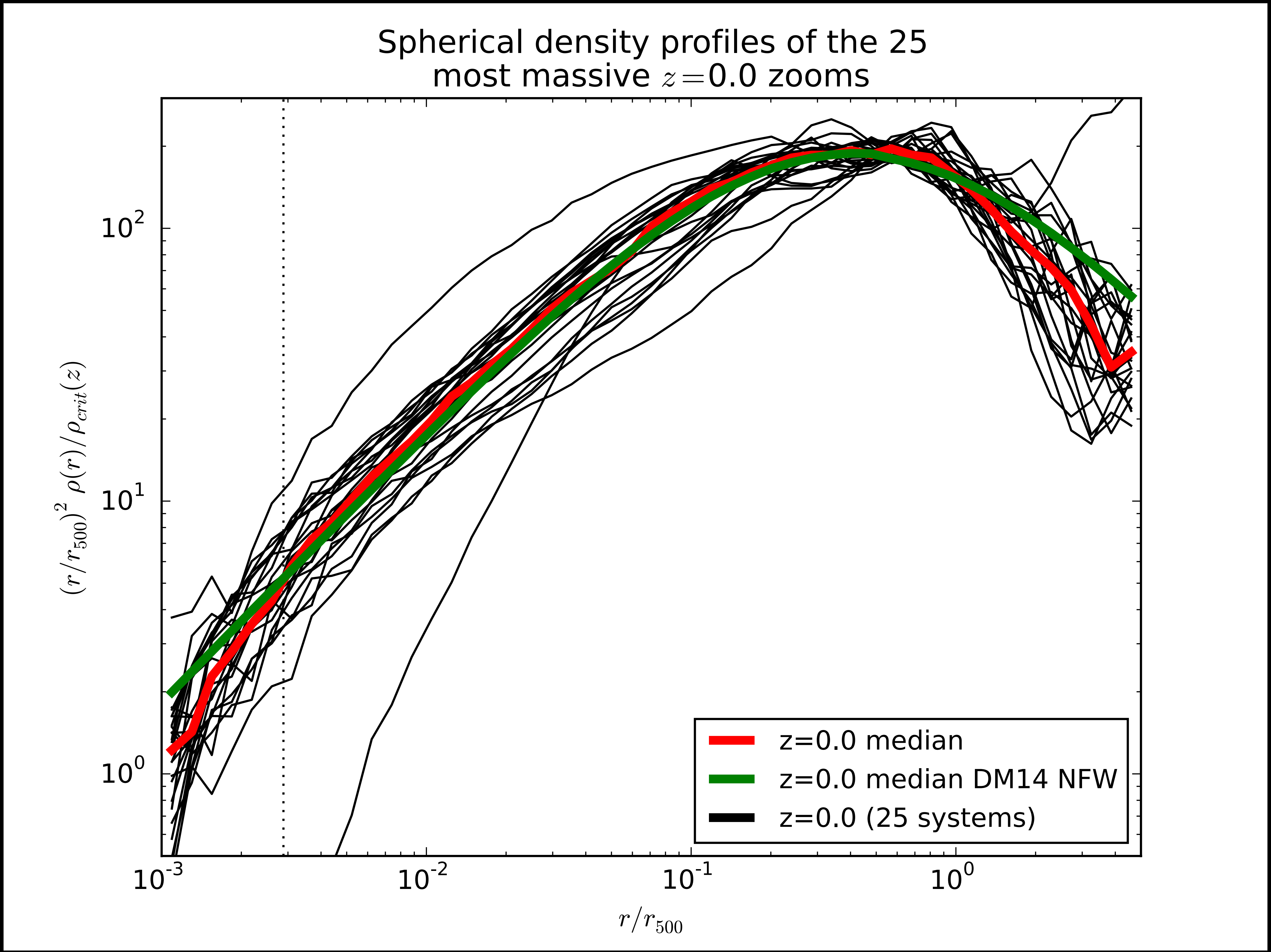
Evolution of density profiles

Le Brun et al. in preparation



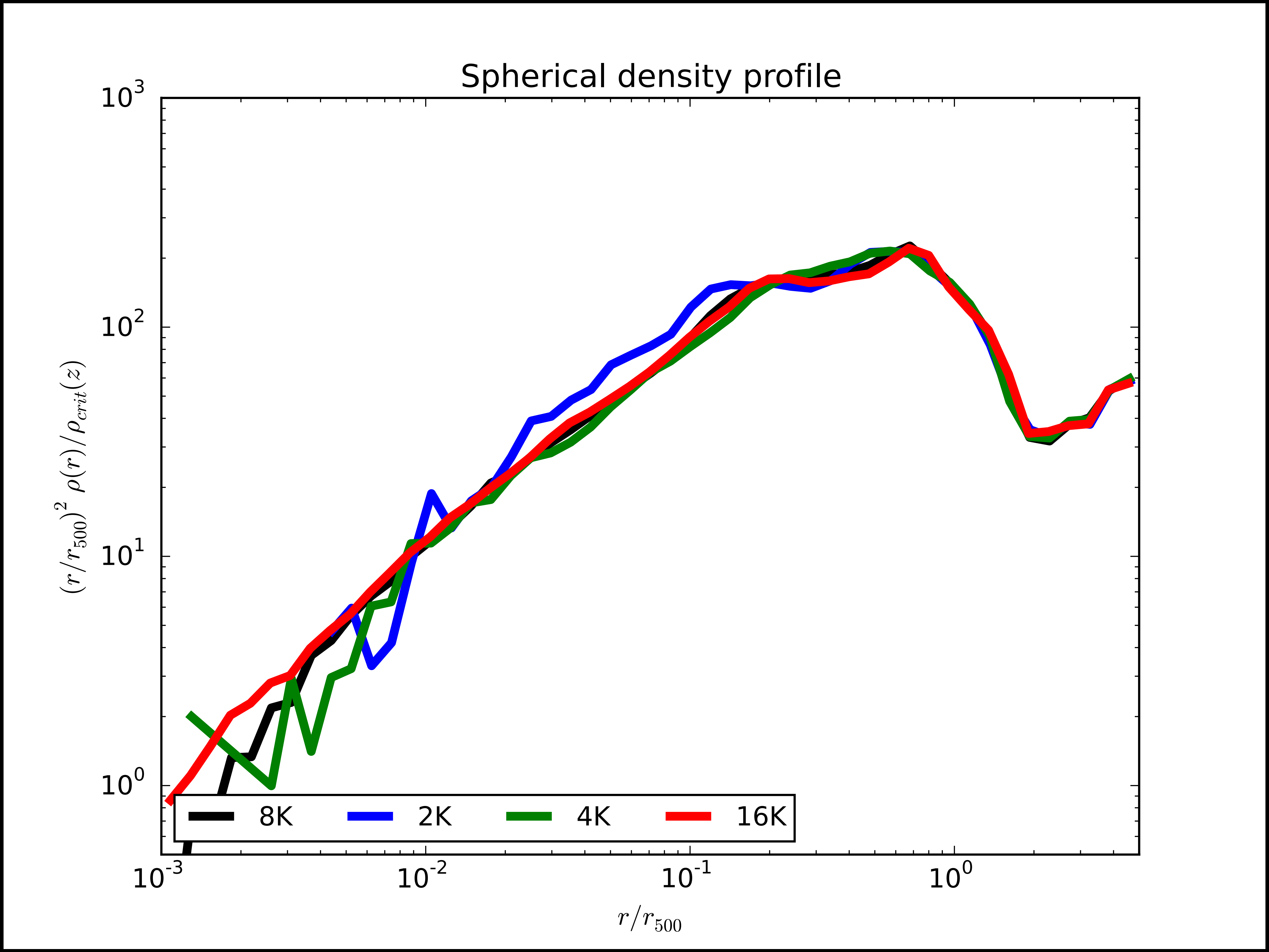
Density profiles

**Le Brun et al.
in preparation**



Impact of resolution

Le Brun et al. in preparation



Conclusions

- The most massive galaxy clusters could be powerful cosmological probes as:

1. They should be less affected by non-gravitational physics
2. They are supposed to be the most sensitive to the paradigm of structure formation

- **BUT** they are still forming and therefore far from being relaxed
- Inner structure of the 25 most massive clusters shows no signs of converging to an asymptotic slope. Gets much shallower than the asymptotic NFW slope.
- Seems to get shallower as redshift decreases (at least since z=1).