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

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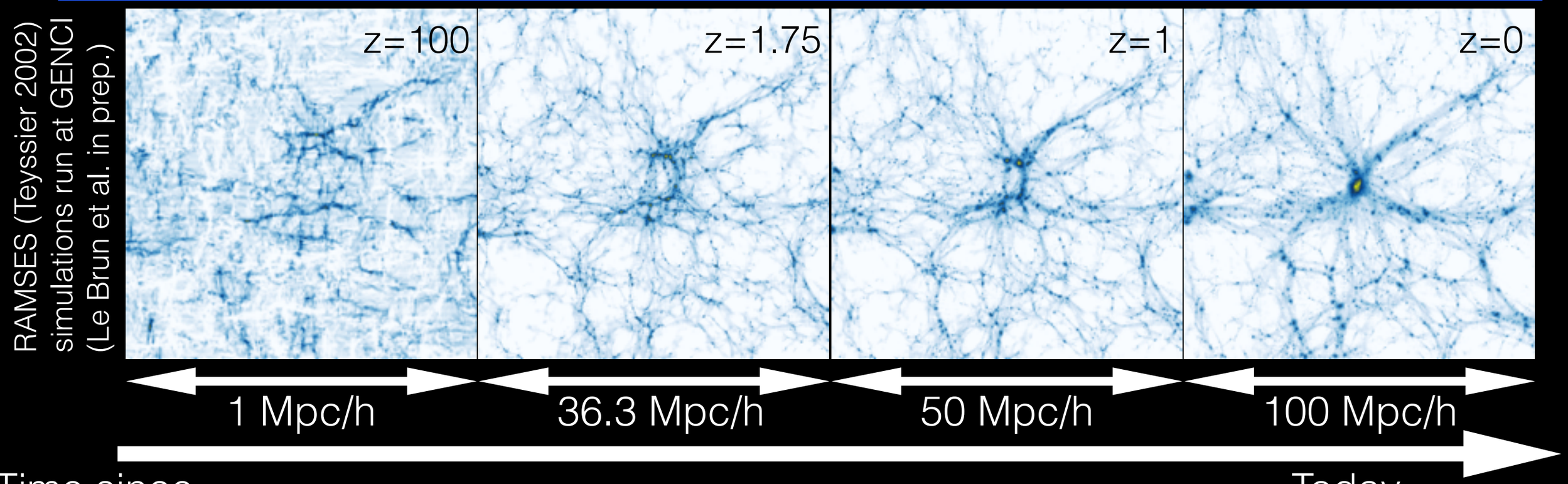
SF2A days, Lyon, June 14th-17th 2016

Galaxy clusters and structure formation



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

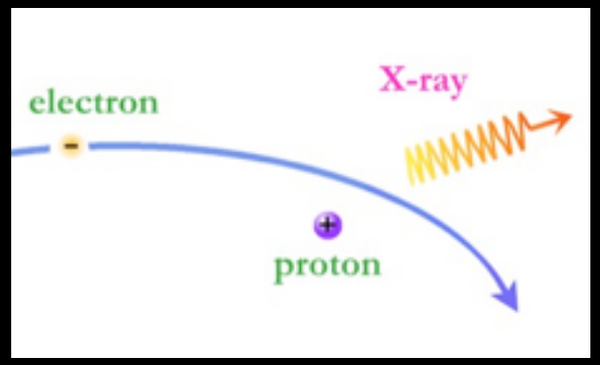
➡ test of the physics of hierarchical Dark Matter driven structure formation (Dark Matter and baryons)

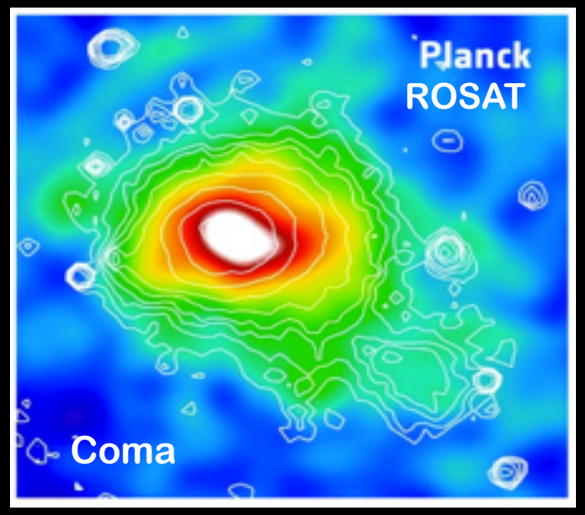
➡ cosmological parameters via N(M,z) or f_{gas}

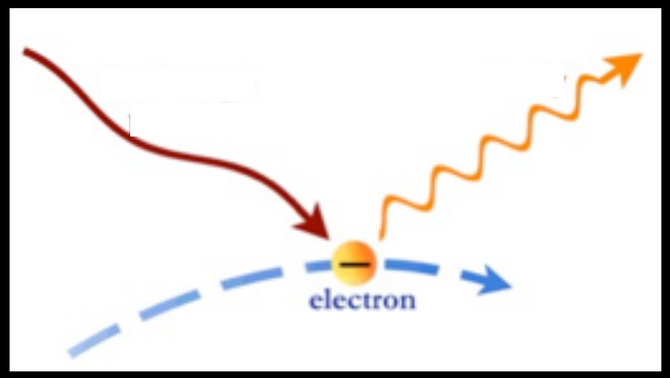
Evolution of dark matter profiles

- 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~1 recently enabled by large surveys using the Sunyaev-Zel'dovich (SZ) effect.
- Requires a systematic comparison between observations and cosmological simulations.

X-ray and SZ observations







Bremsstrahlung
SB dimming with z

$$L_X \propto \int_V n_e^2 \Lambda(T)\, dV$$

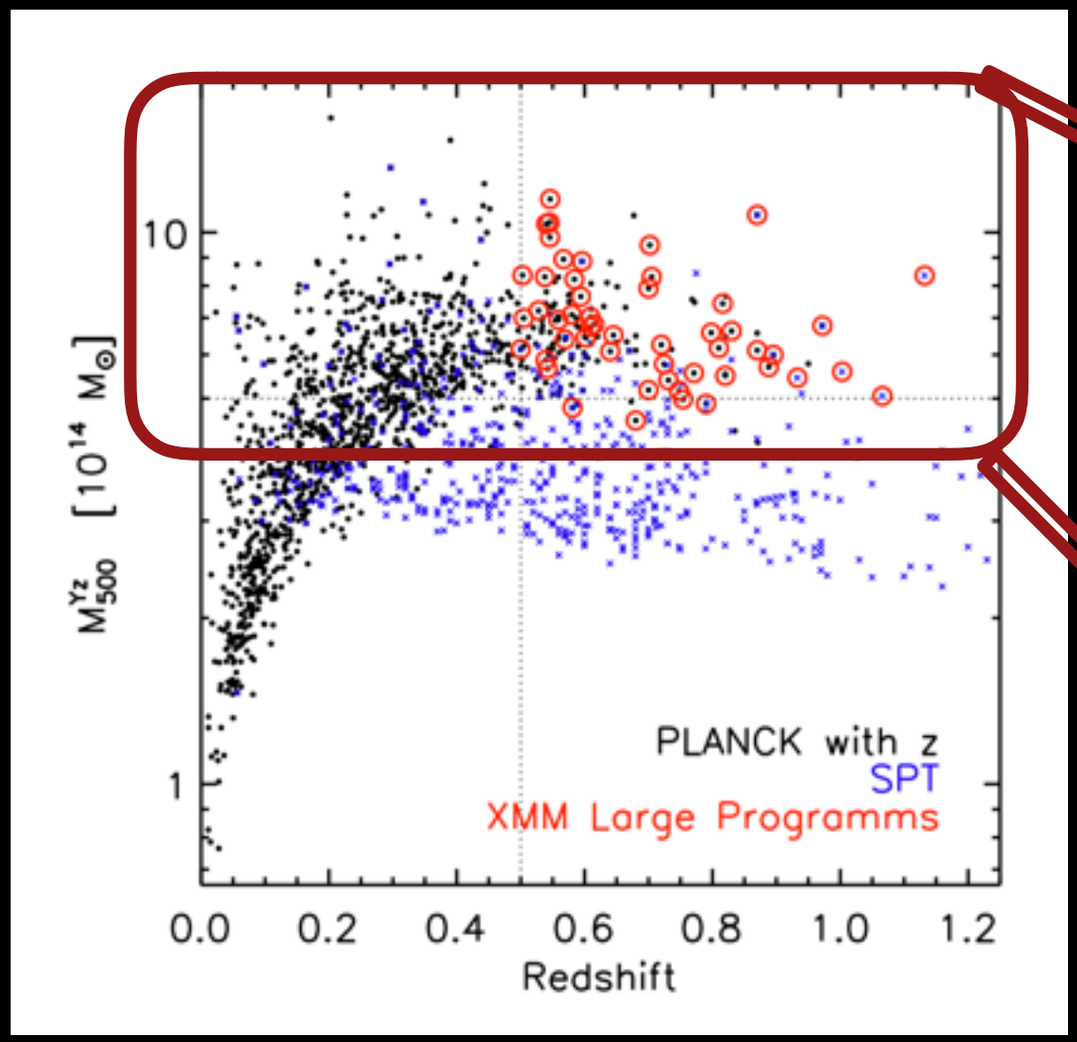
Inverse Compton scattering
No SB dimming with z

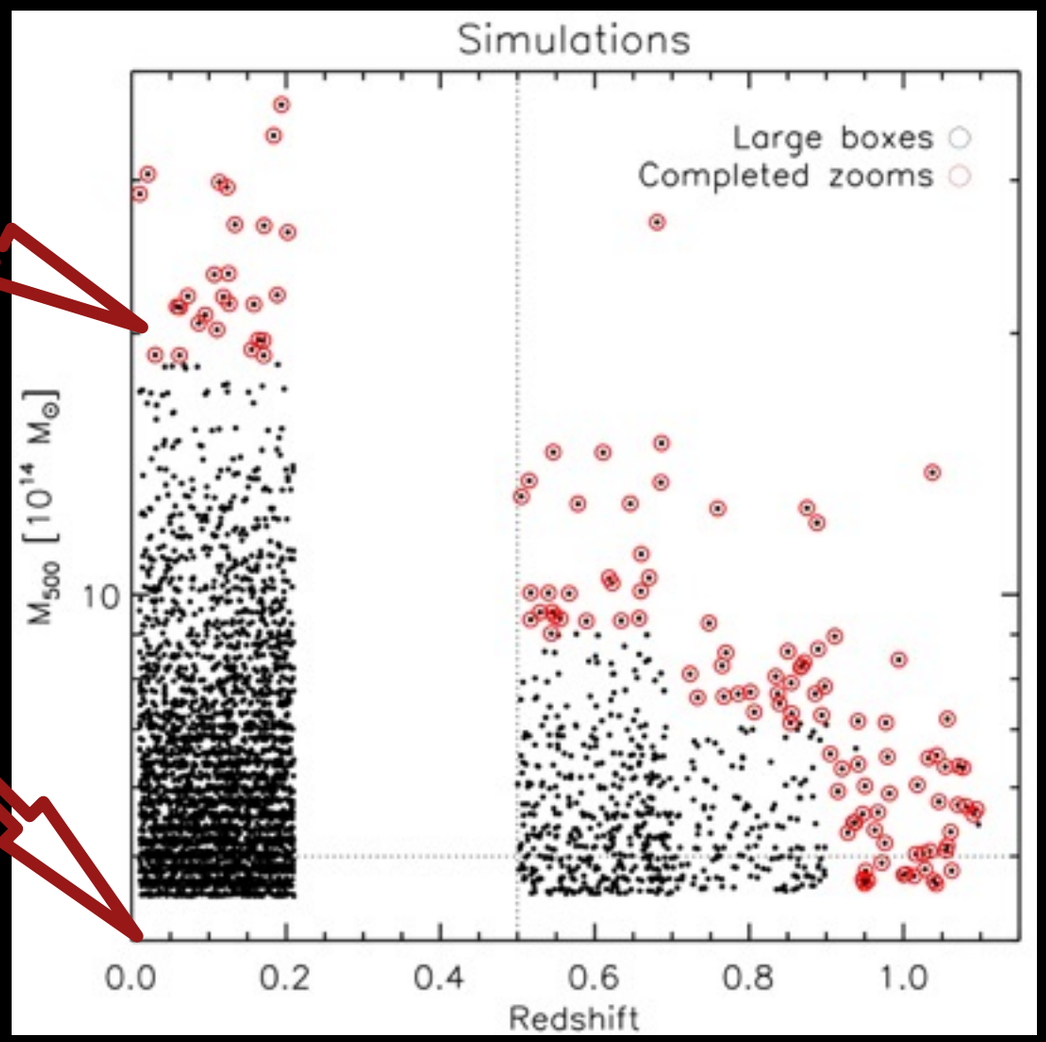
$$Y_{SZ} \propto \int_V (P = n_e T)\, dV$$

➡**Complementarity of information**

The M2C project

Figure courtesy of Monique Arnaud

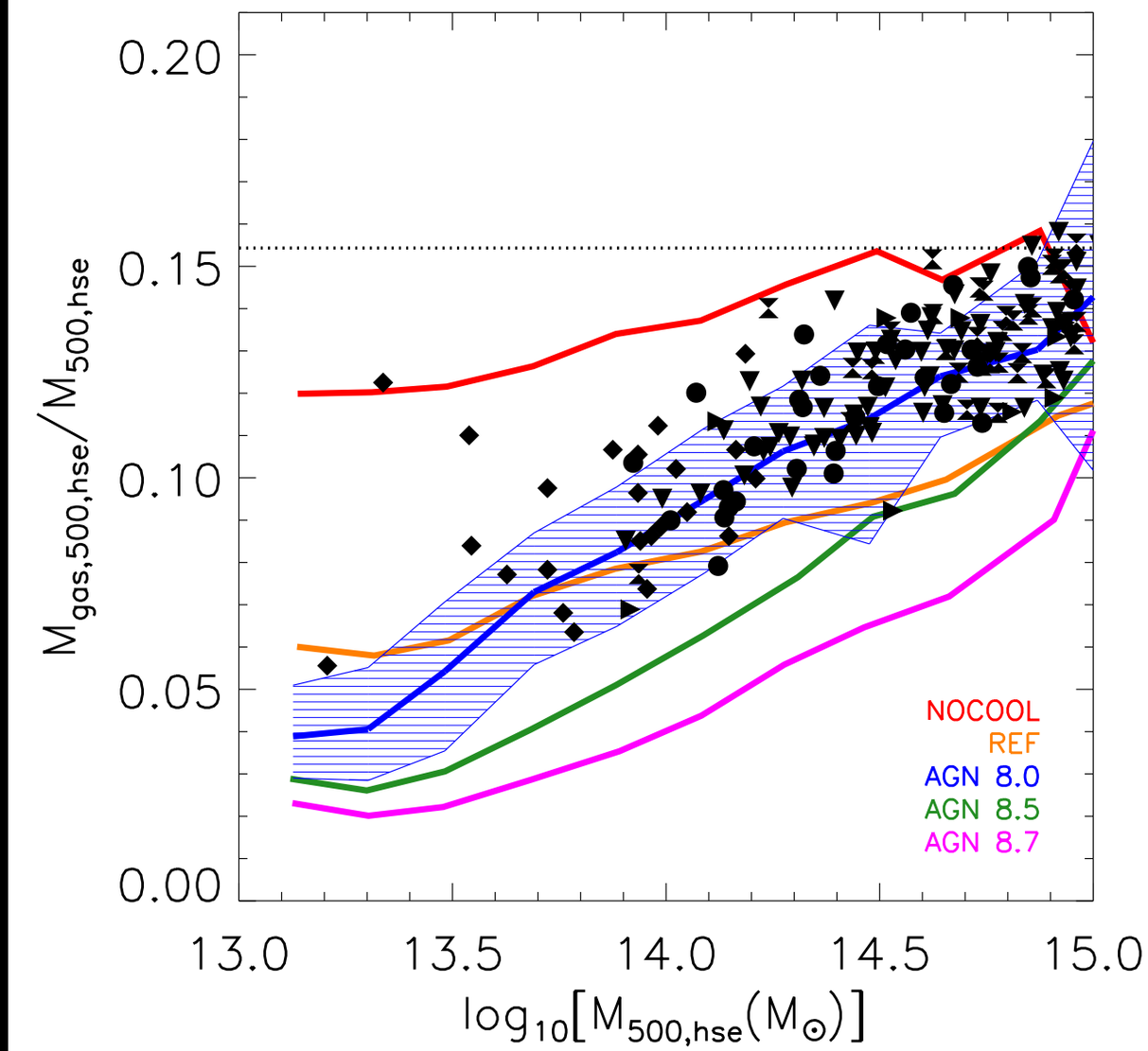




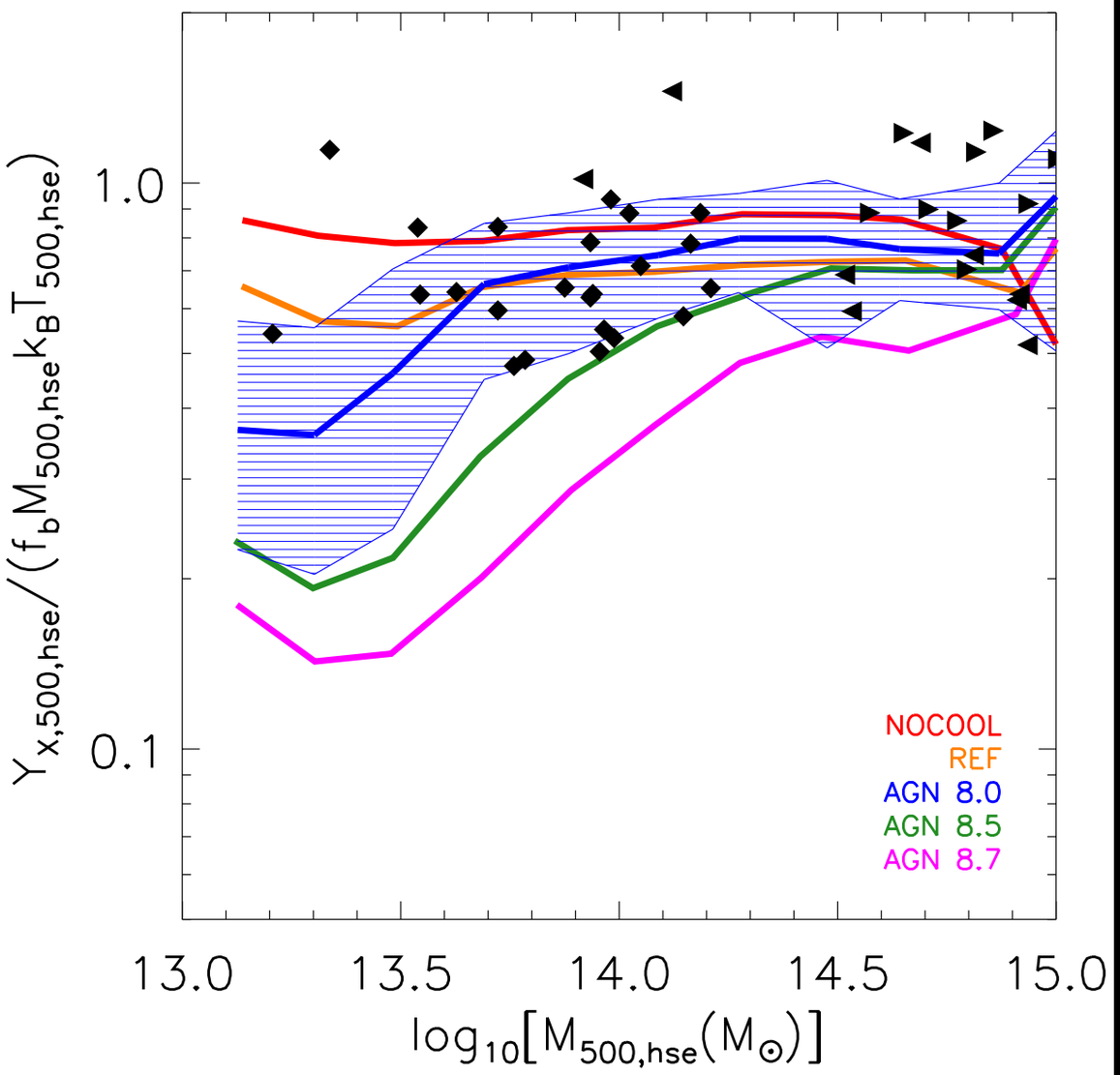
- ~30 SZ selected clusters with $M_{500}>5x10^{14}$ $M_\odot$ in 3 $\Delta z=0.2$ redshift bins at $z>0.5$
- Confirmation and stellar content using NIR
- Follow-up with XMM and Chandra
- Mass profiles obtained using hydrostatic equilibrium assumption

Le Brun et al. 2014

Impact of baryonic physics?



Data: REXCESS, Vikhlinin06, Lin12, Maughan08 and Sun09



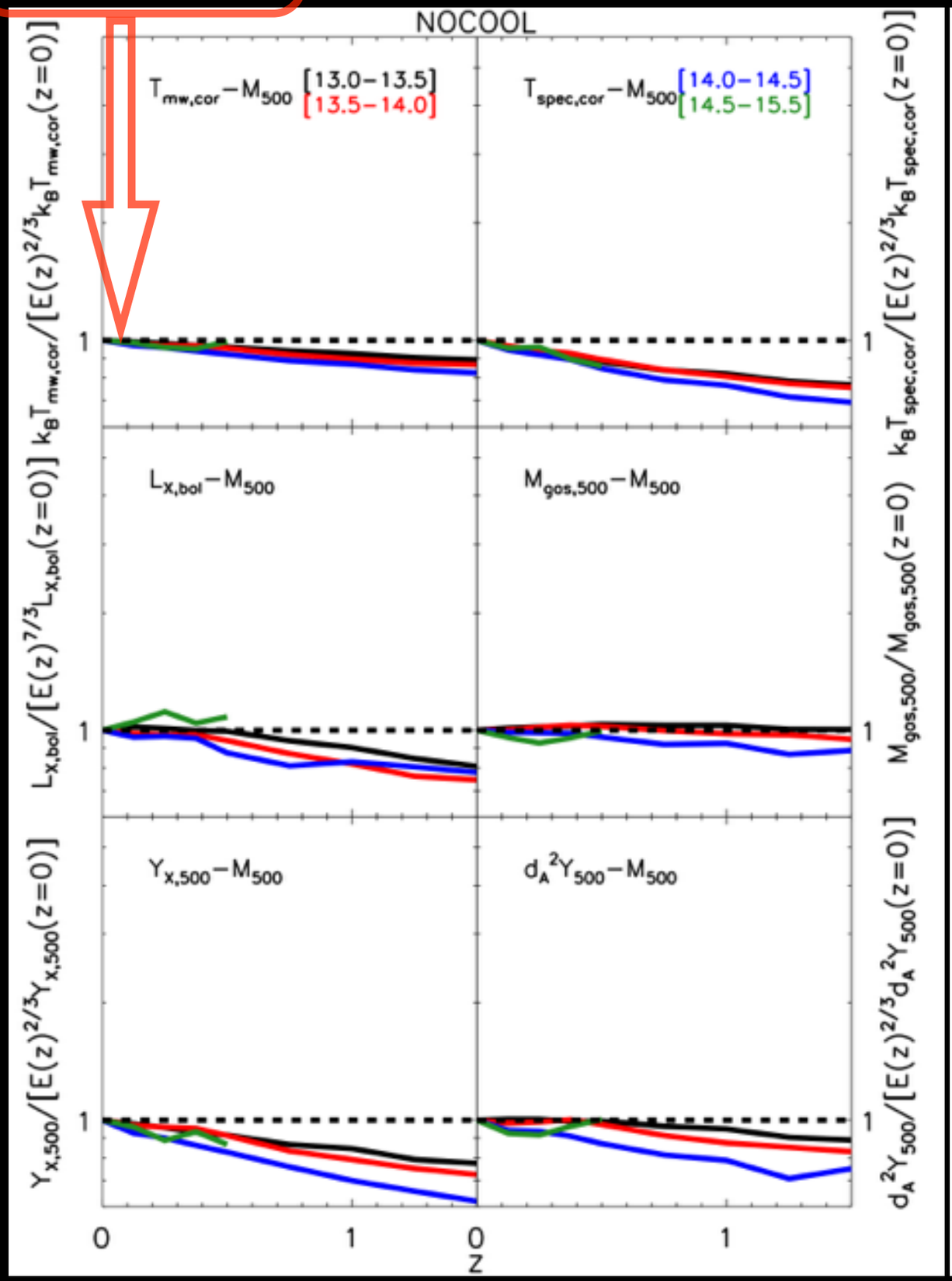
Data: Vikhlinin06, Planck Intermediate Results IV, Sun09

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

Self-similar expectation for the evolution

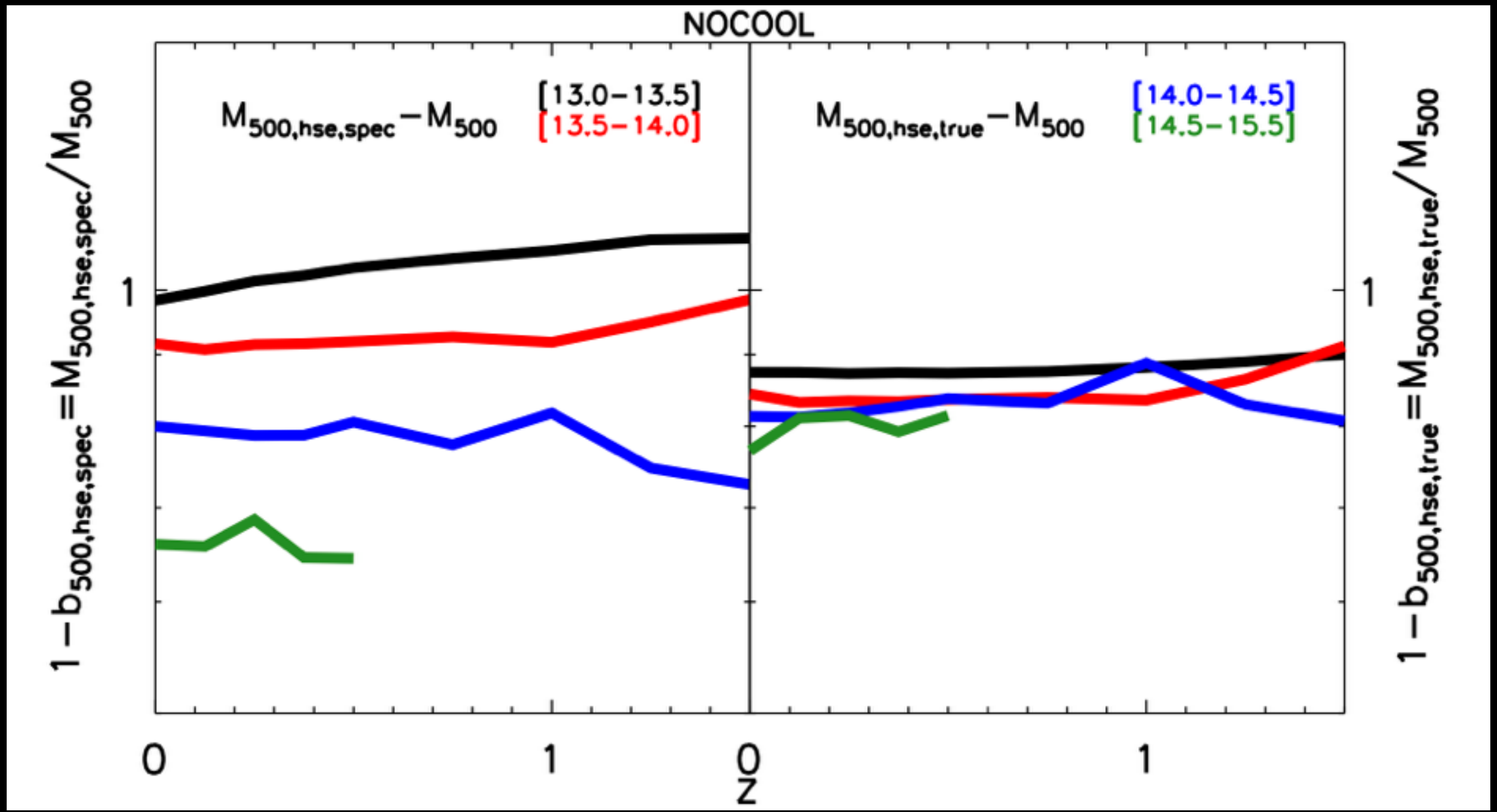
Impact of baryonic physics?

Le Brun et al. 2016a submitted



Evolution of HSE bias

Le Brun et al. 2016a submitted



$$M(r) = -\frac{r\,kT(r)}{G\mu m_{\rm p}}\left[\frac{d\,\ln n}{d\,\ln r} + \frac{d\,\ln T}{d\,\ln r}\right]$$

Evolution of HSE bias

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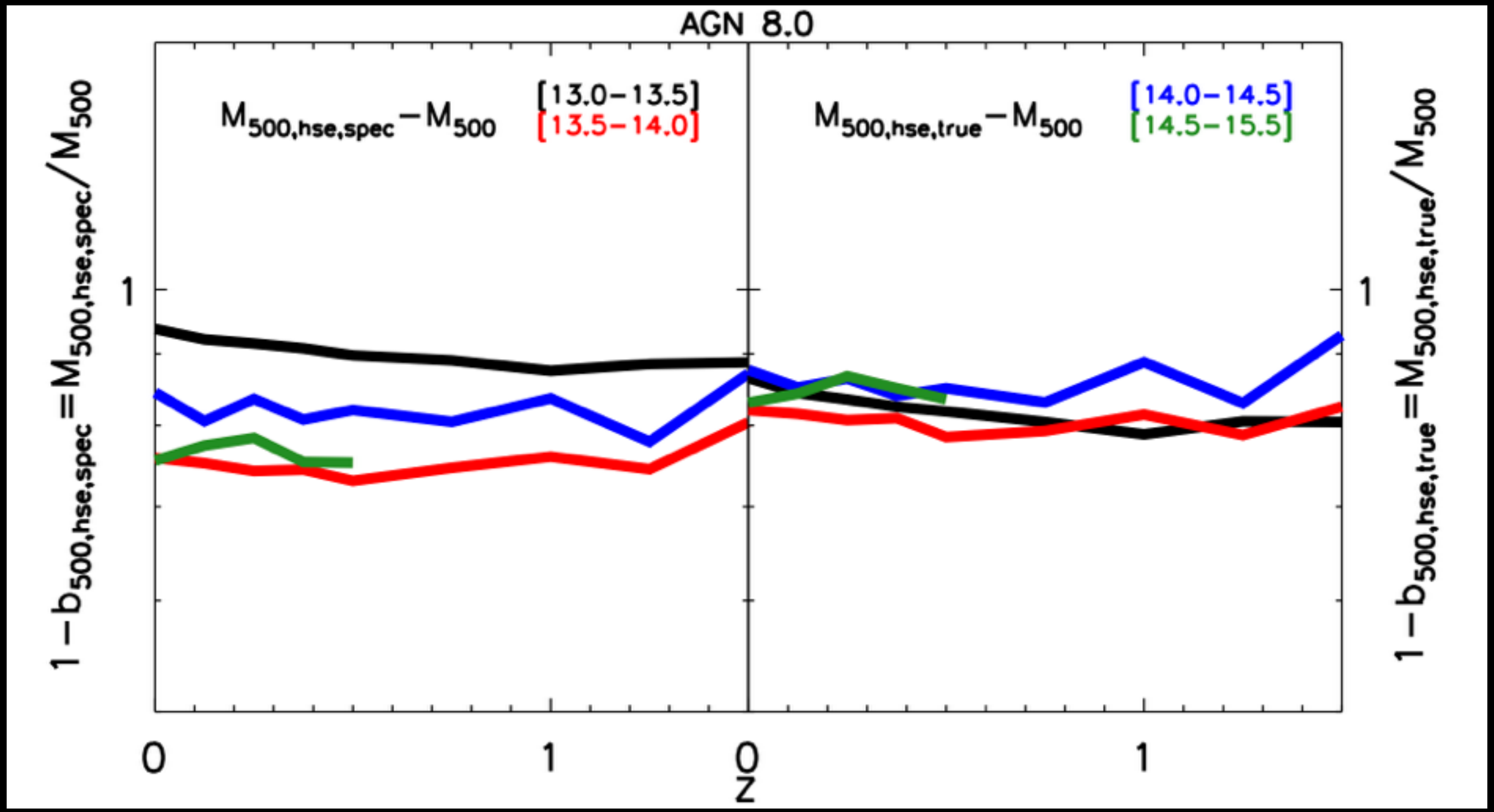
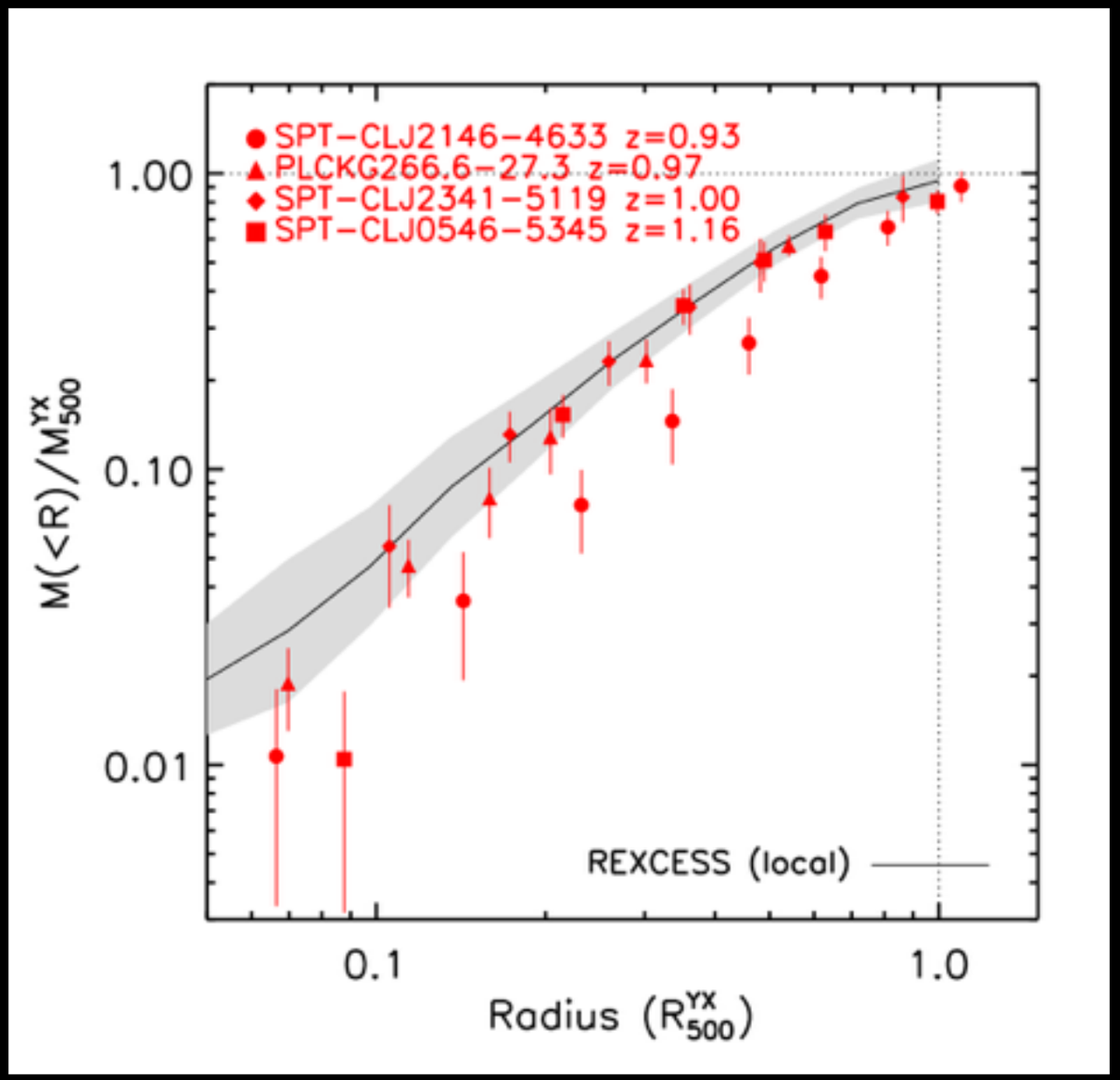


Pilot study of mass profiles at z~1



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}

Diemer14

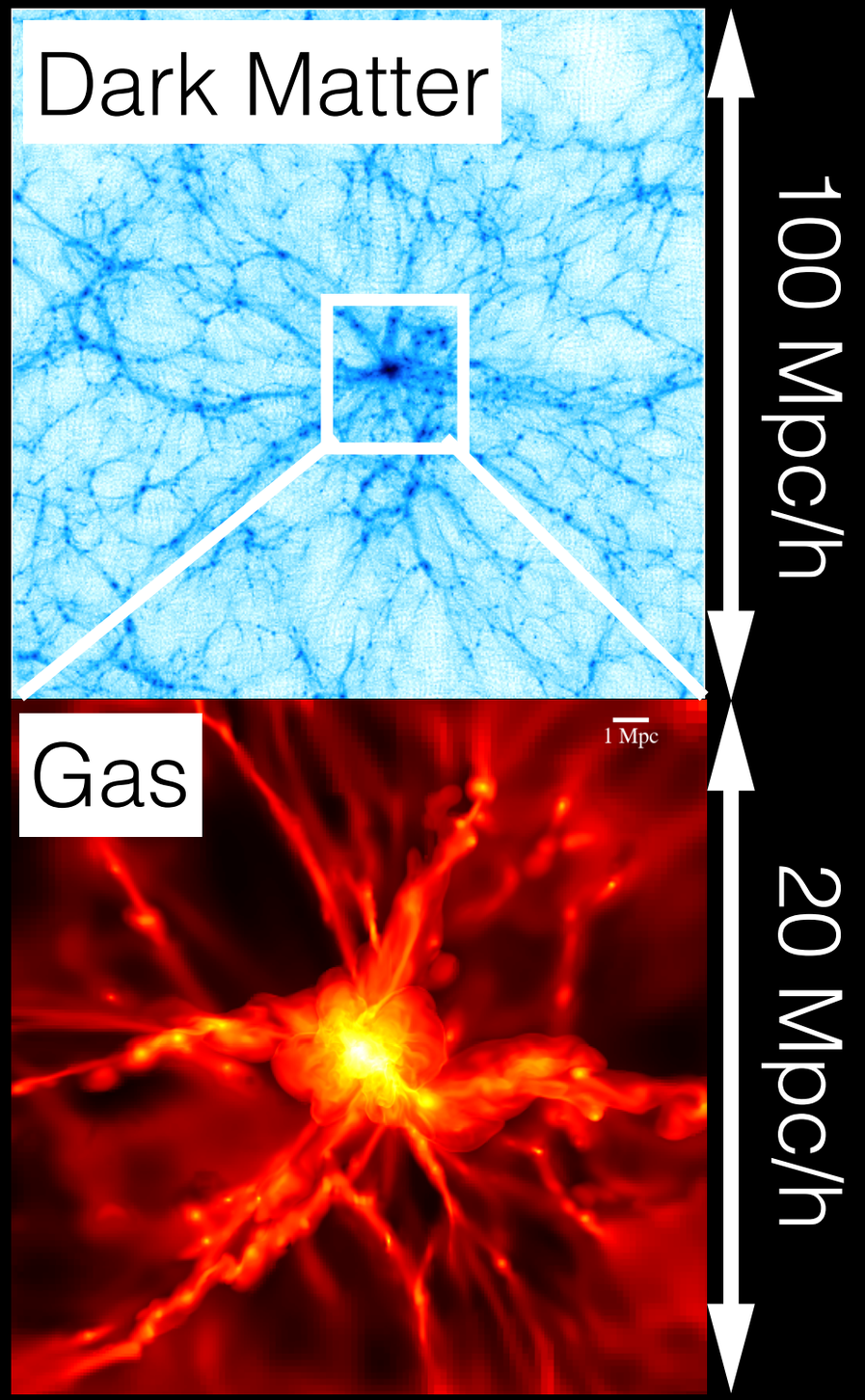
Box	L (h^{-1} Mpc)	N^3	m_p (h^{-1} $M_\odot$)	ϵ (h^{-1} kpc)	$\epsilon/(L/N)$
L1000	1000	1024^3	7.0×10^{10}	33.0	1/30
L0500	500	1024^3	8.7×10^{9}	14.0	1/35
L0250	250	1024^3	1.1×10^{9}	5.8	1/42
L0125	125	1024^3	1.4×10^{8}	2.4	1/51
L0063	62.5	1024^3	1.7×10^{7}	1.0	1/60

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

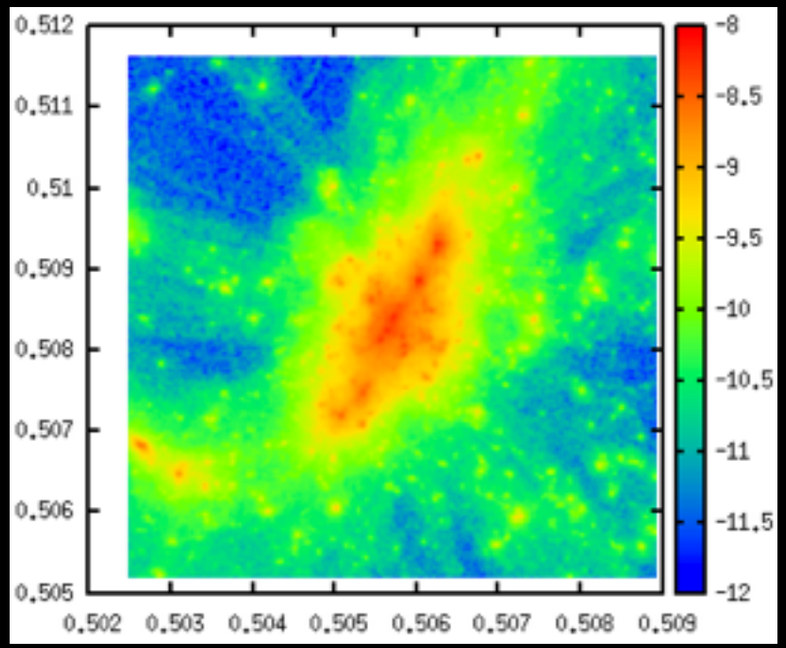
Simulations

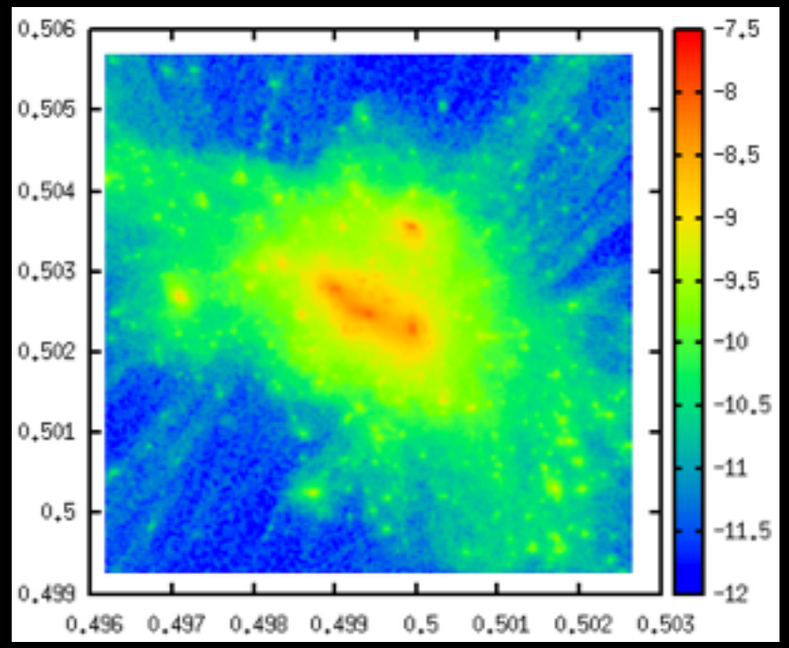


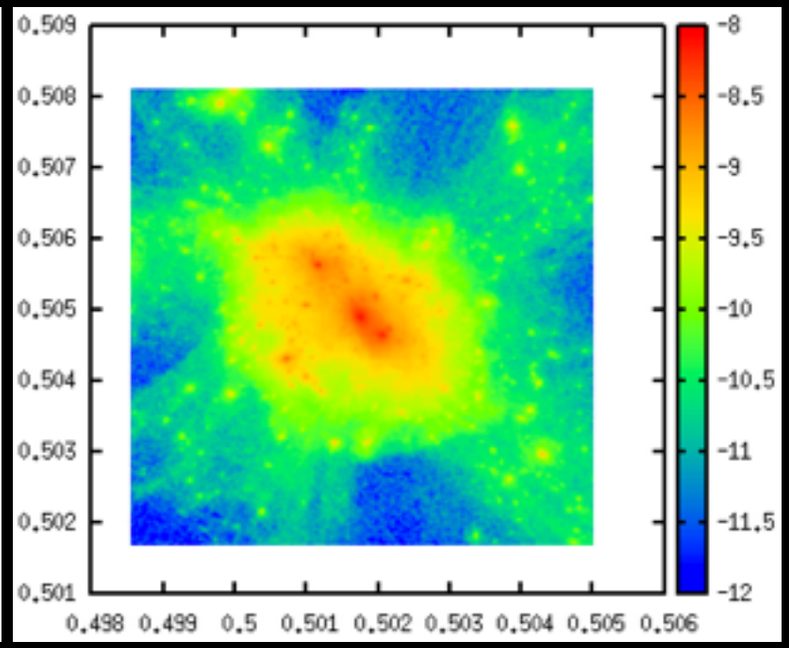
- In practice: (i) **doing three large (1 Gpc/h on a side with 2048³ DM particles)** DM only simulations and (ii) **zooming at high resolution** (a few kpc) o**n 50-100 galaxy clusters in each of the redshift bins** which will progressively include the relevant galaxy formation physics.

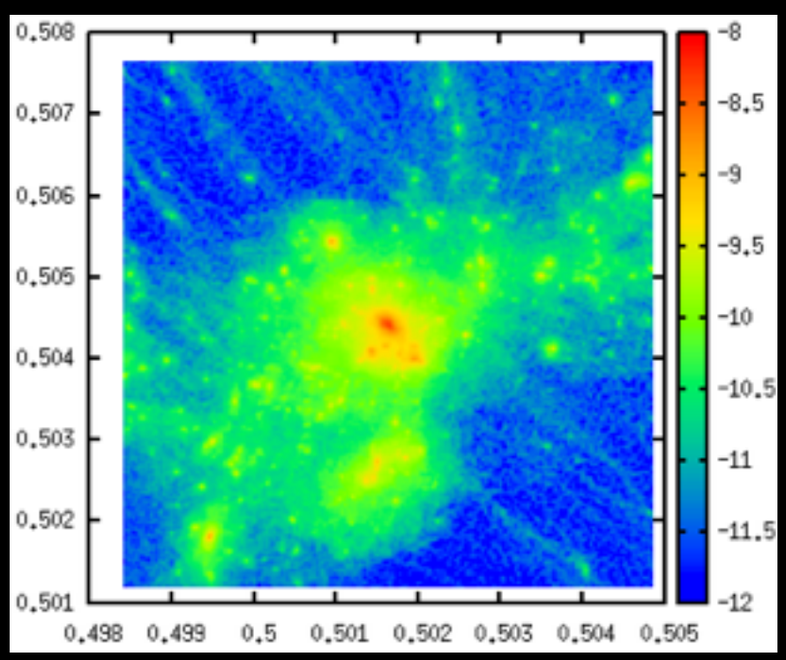
- All the simulations are done with the AMR code RAMSES (Teyssier 2002) on the OCCIGEN supercomputer at CINES in Montpellier using a **large GENCI computing time-allocation** (>11 million CPU hours already allocated over 2015-2016; PI Le Brun).

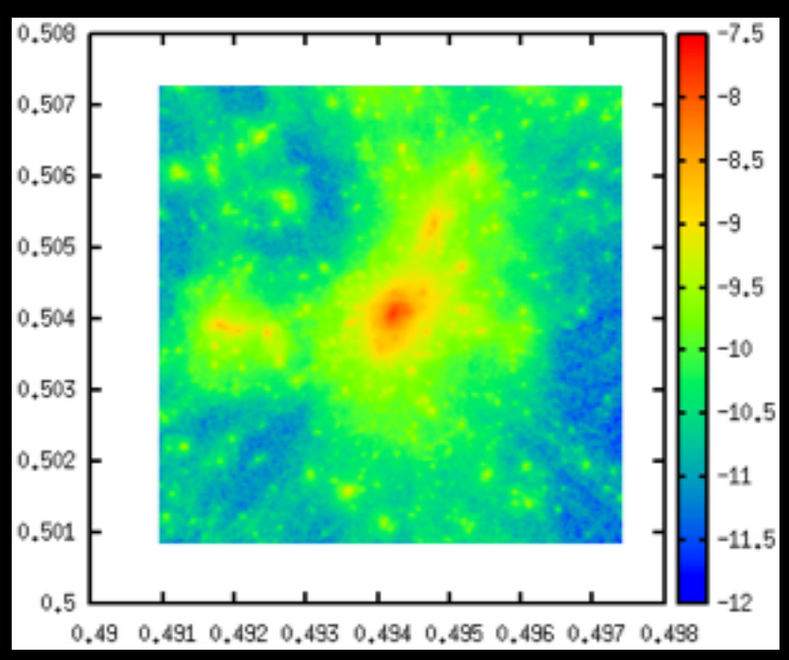
Most galaxy clusters at z=1 are disturbed

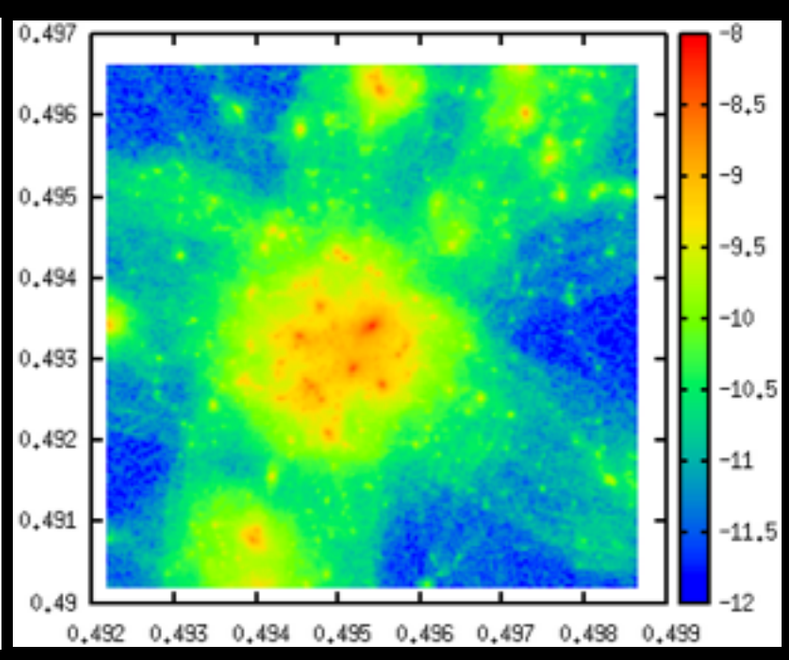






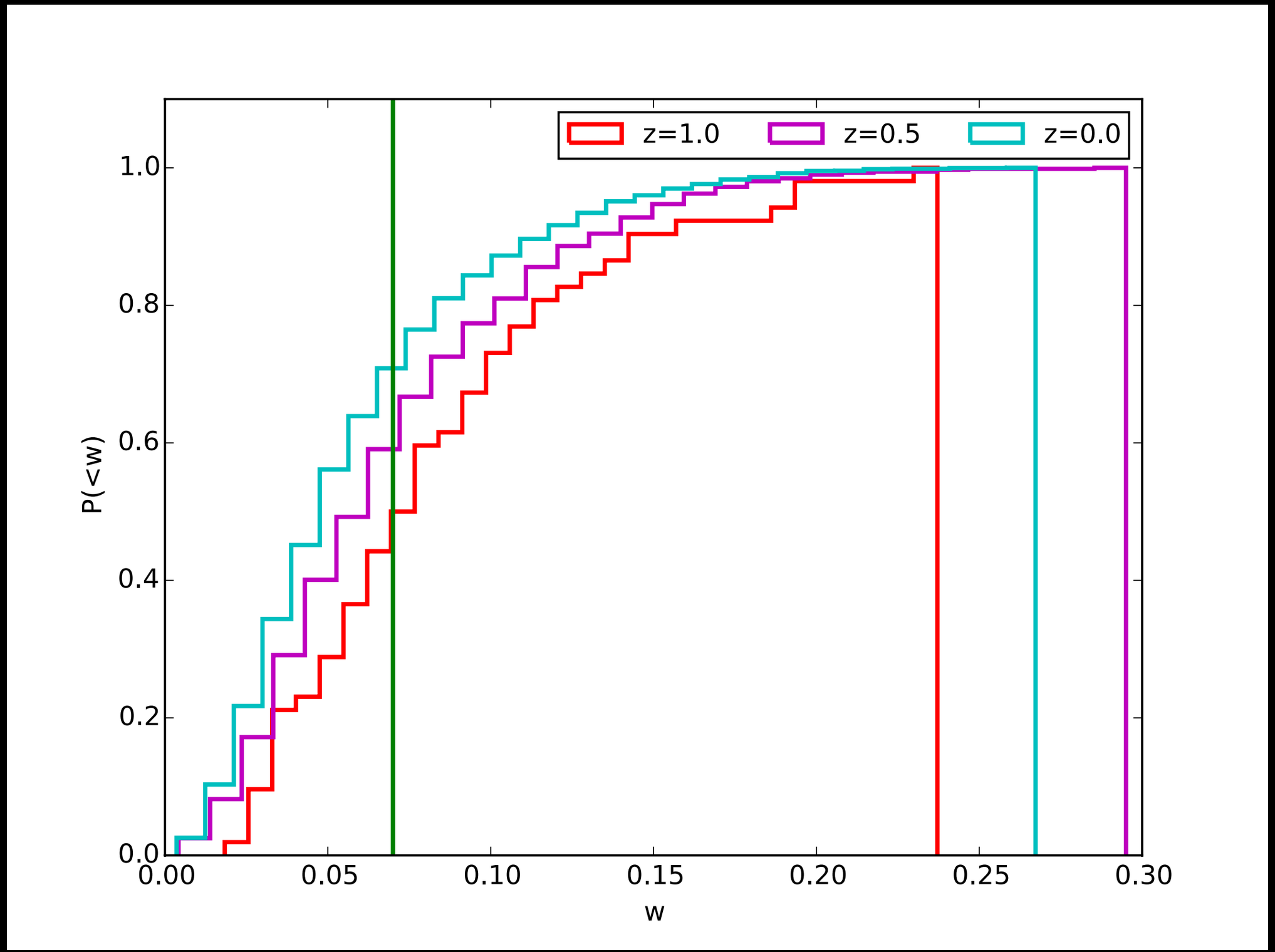






Evolution of relaxation state

Le Brun et al. in preparation



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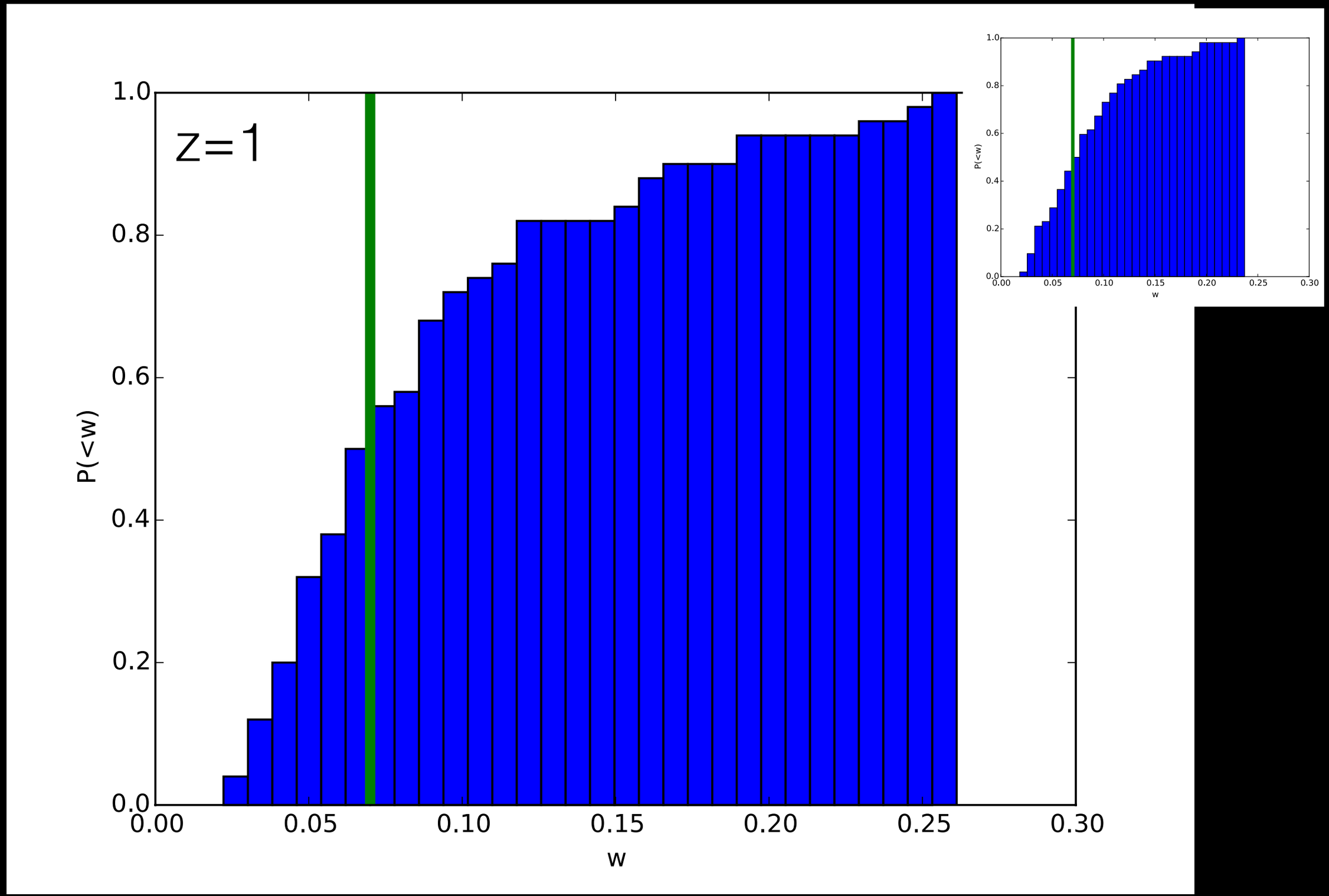
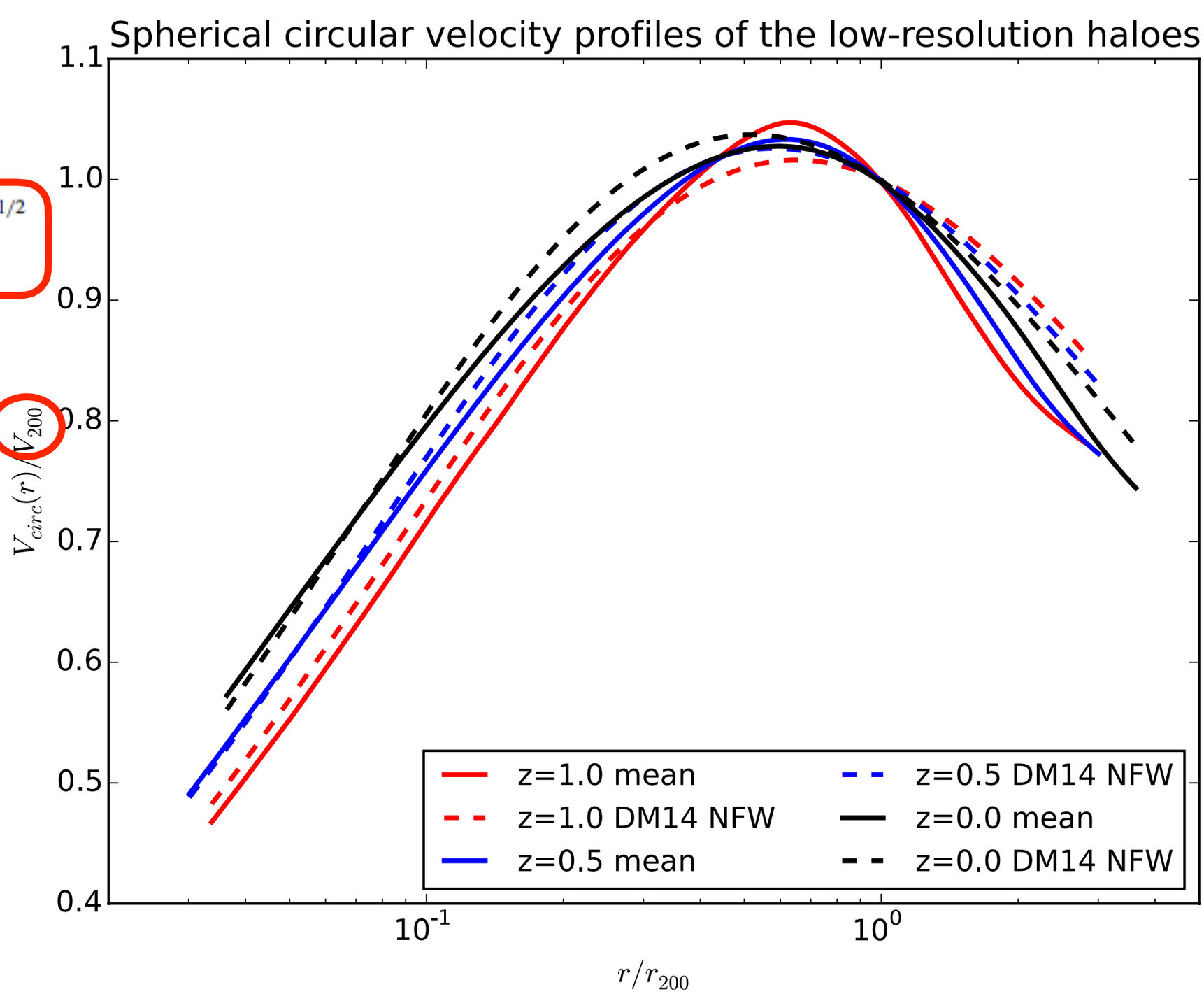


Evolution of circular velocity profiles

$$V_{200} = \left(\frac{GM_{200}}{R_{200}}\right)^{1/2}$$



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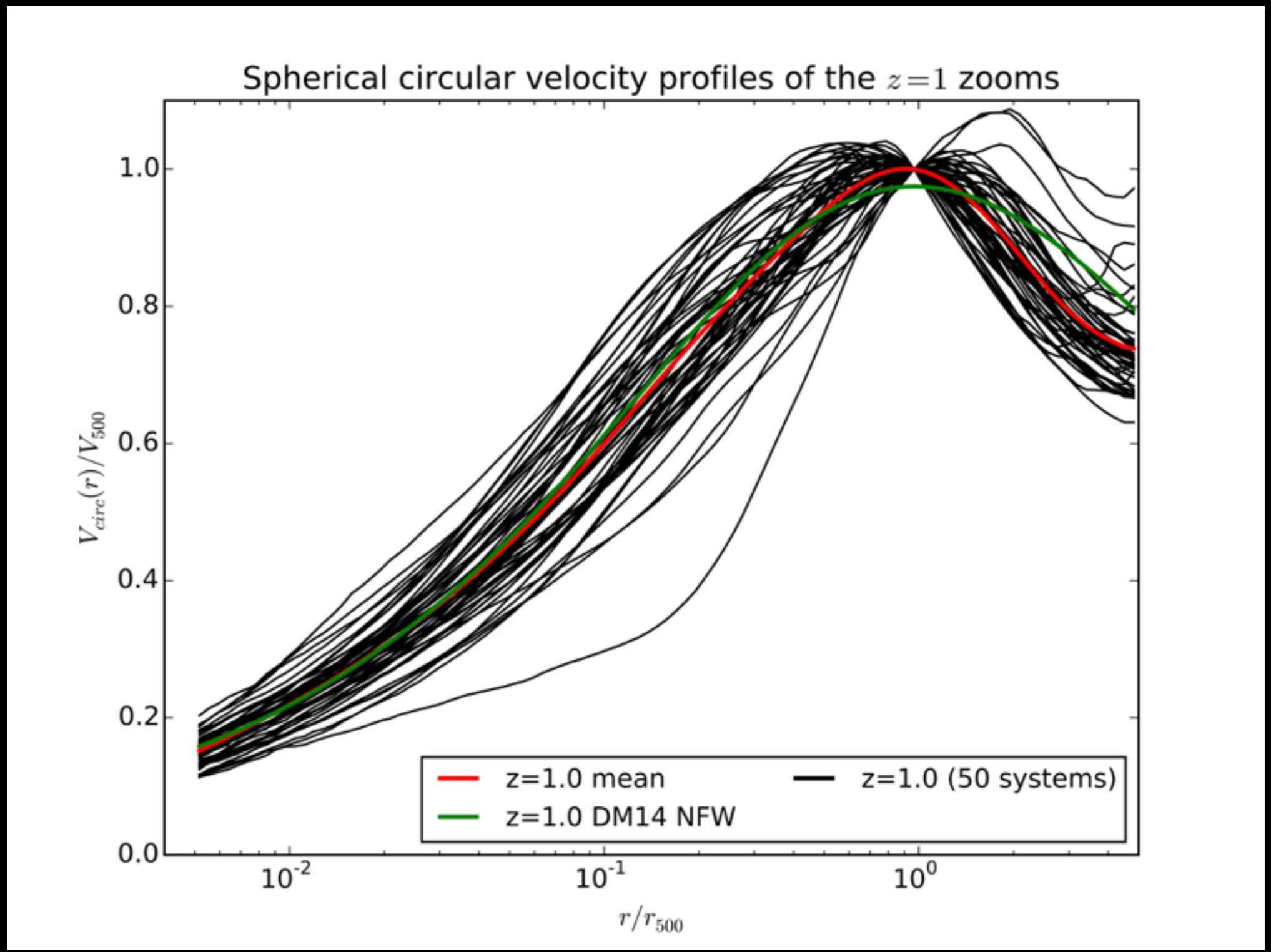
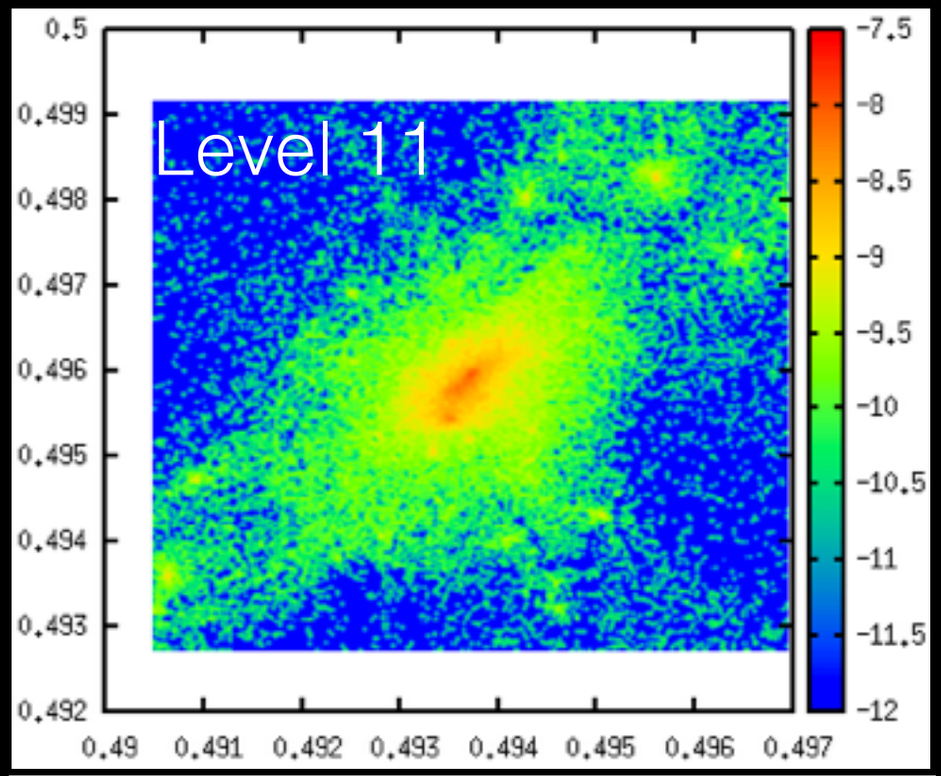
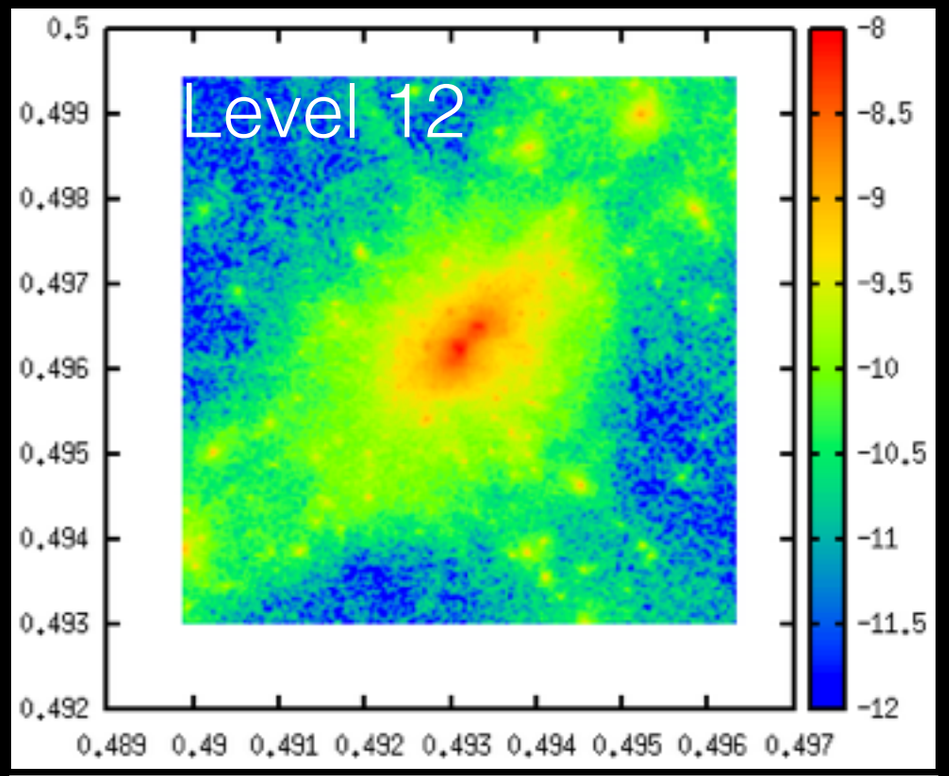
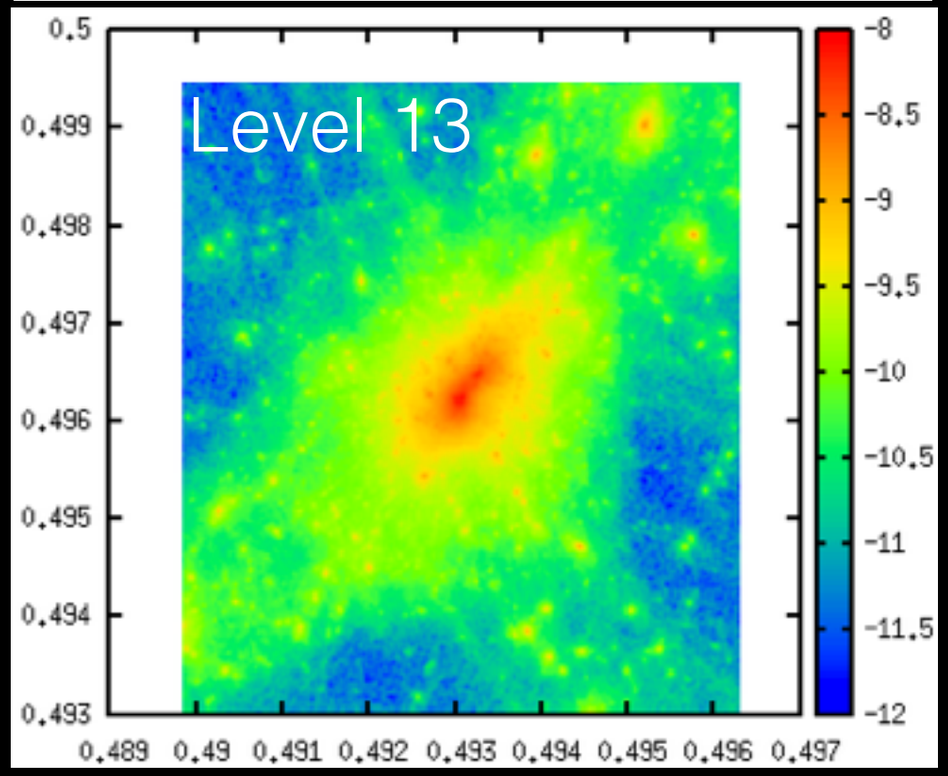
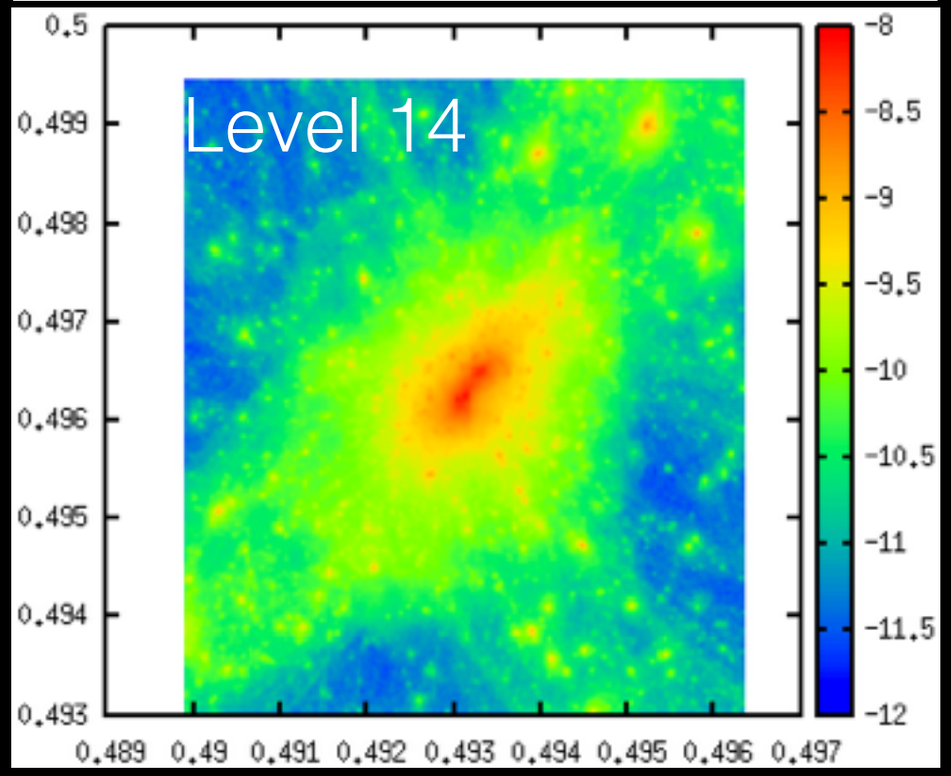


Impact of resolution



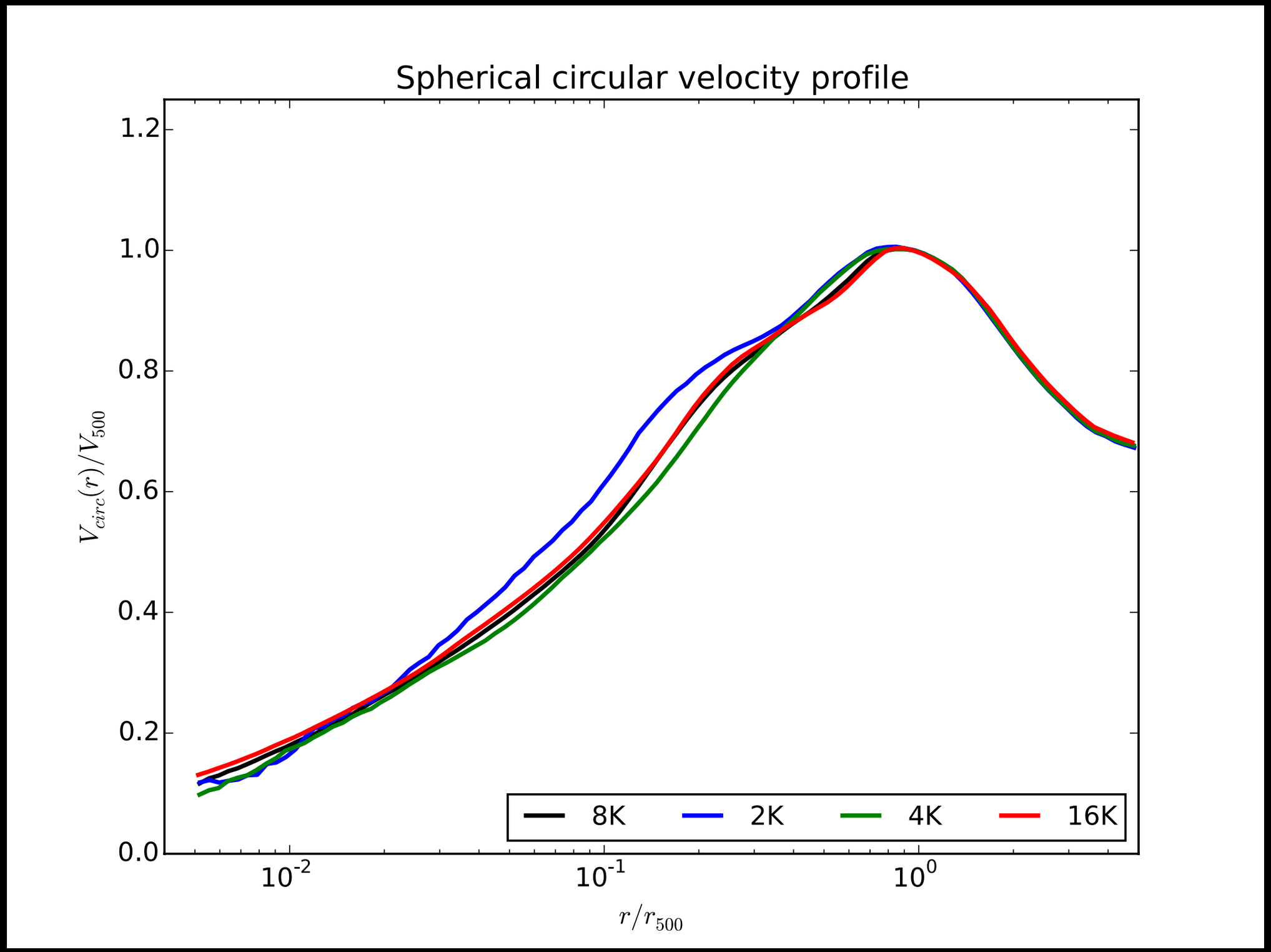






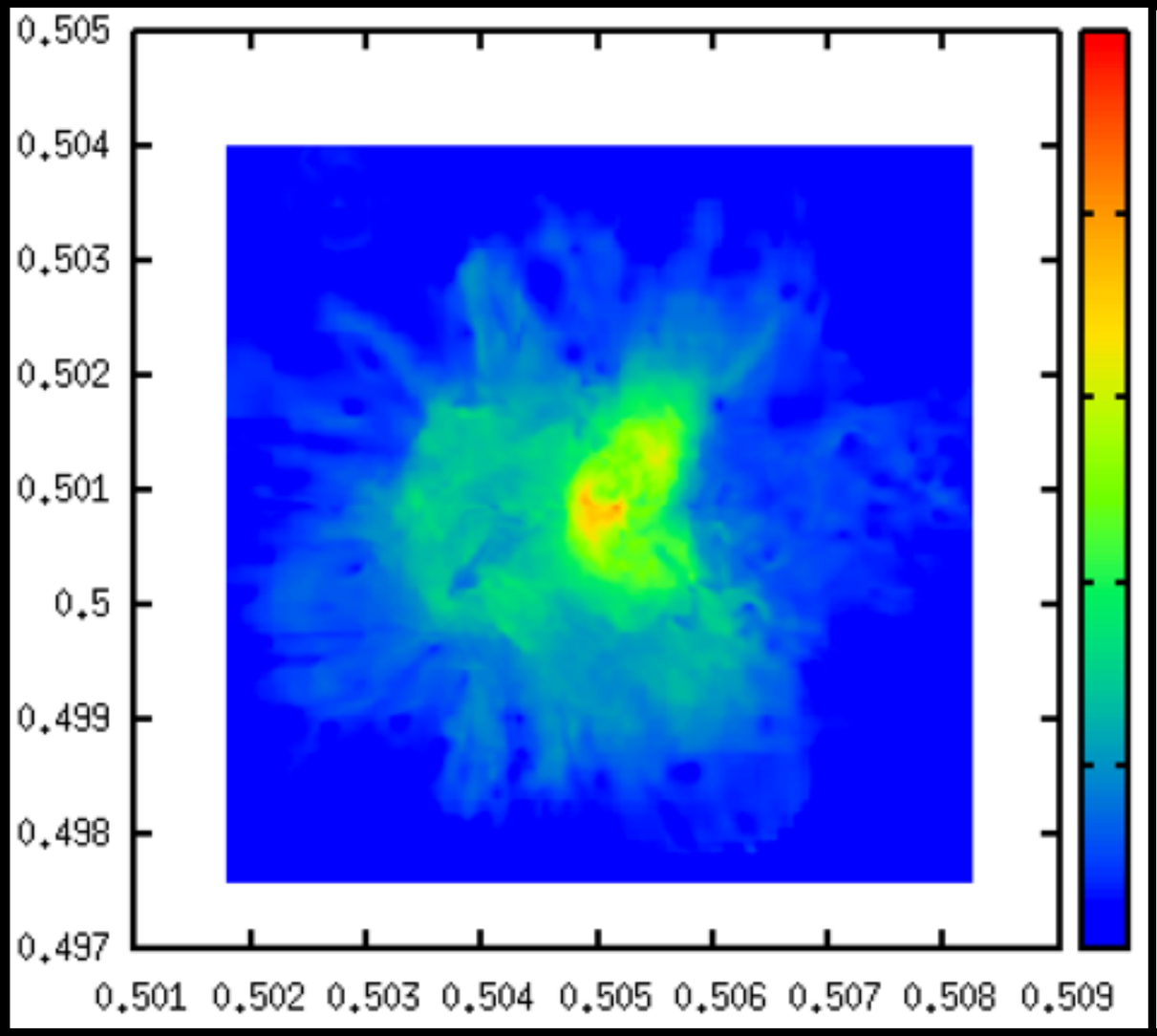
Impact of resolution

**Le Brun et al.
in preparation**

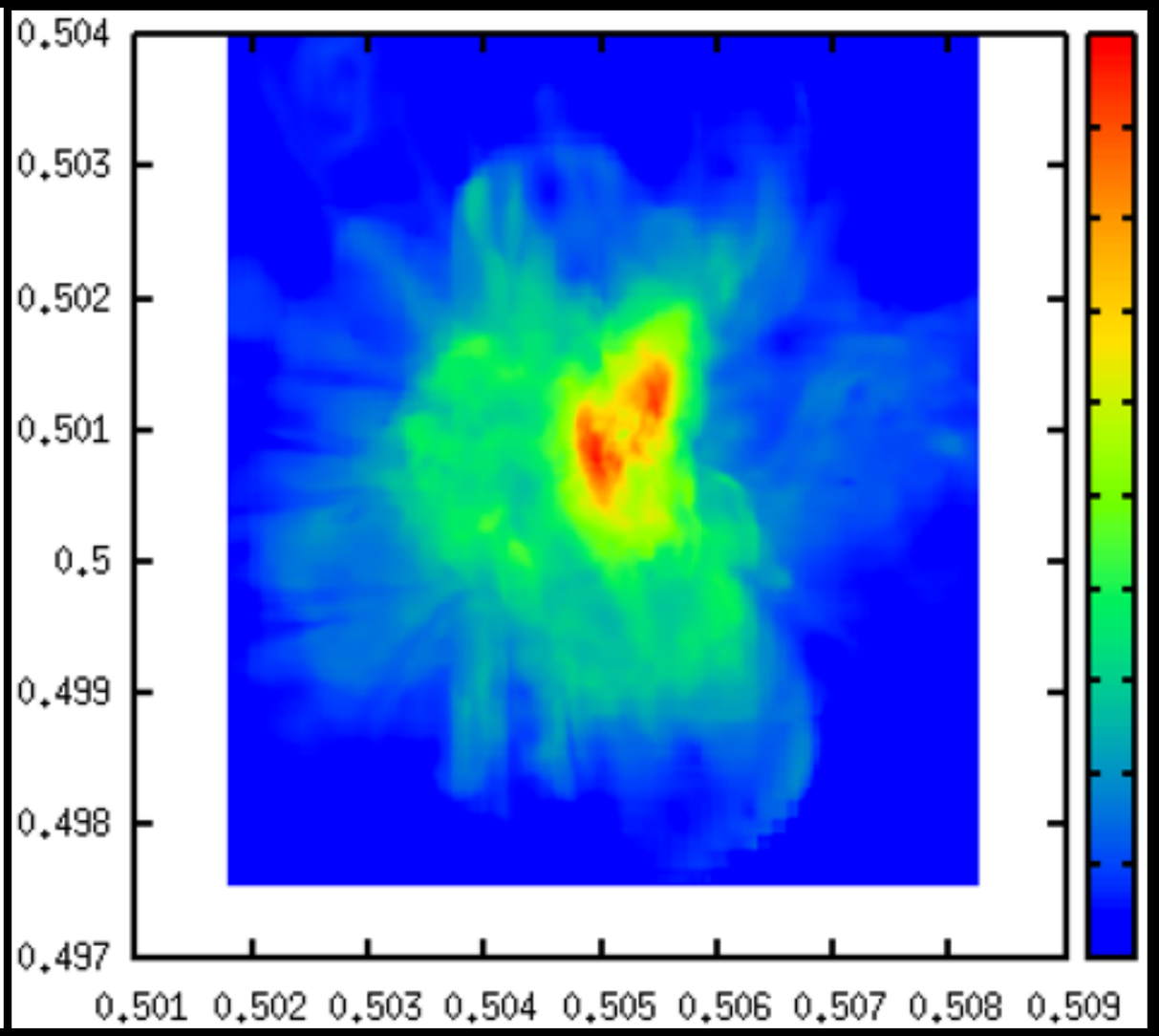


Impact of the slope limiter on NR runs

Pressure maps



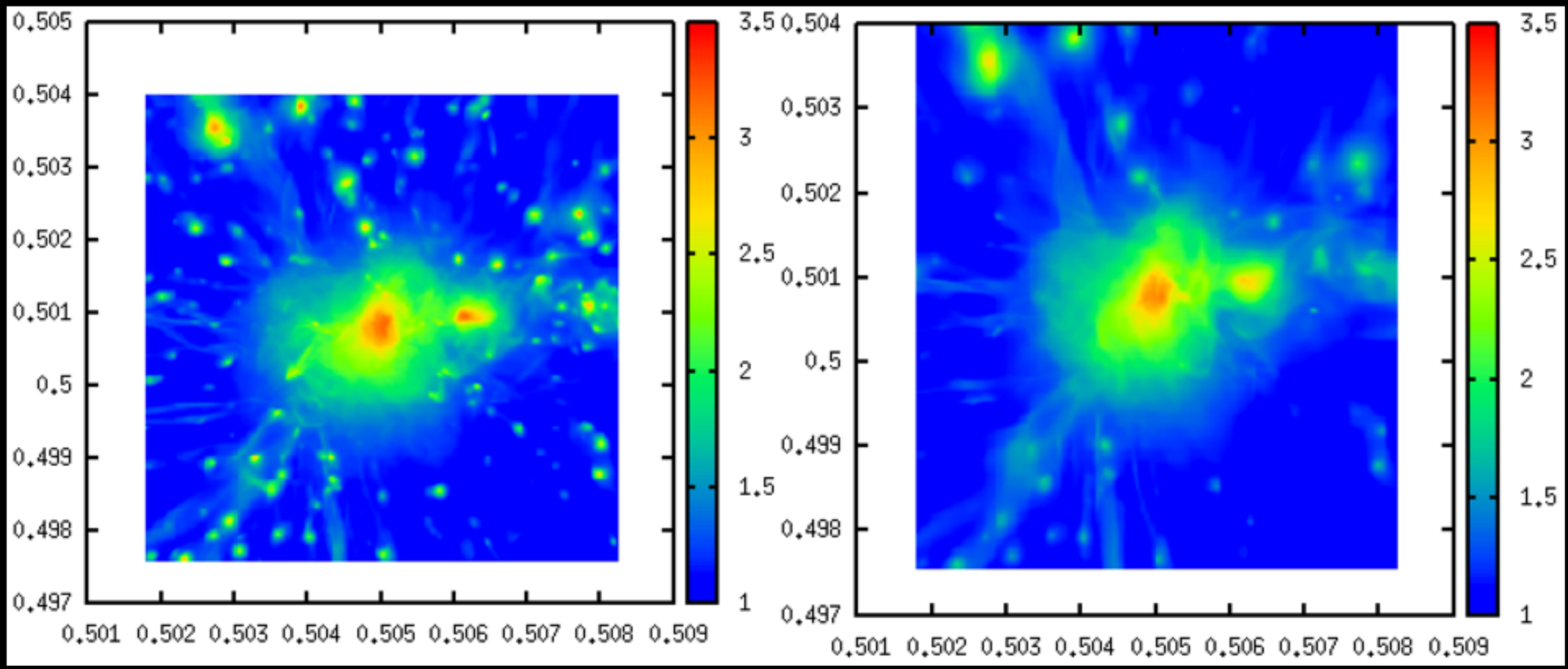
slope_type=2 i.e. a less conservative choice



slope_type=1 i.e. standard in cosmological simulations

Impact of the slope limiter on NR runs

Density maps



slope_type=2 i.e. a less conservative choice

slope_type=1 i.e. standard in cosmological simulations

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**:

1. They are still forming and therefore more of them are far from being relaxed

2. Nevertheless, there is some regularity in shape

3. Evolution of e.g. the HSE bias needs to be constrained further