Internal dark matter structure of the most massive galaxy clusters since z=1

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Based on Le Brun et al. 2018, MNRASL, arXiv:1709.07457

l'Observatoire de Paris

PSL Université Paris

2nd mm Universe @NIKA2, Rome, July 1st 2021

Universality of dark matter profiles

Navarro+96

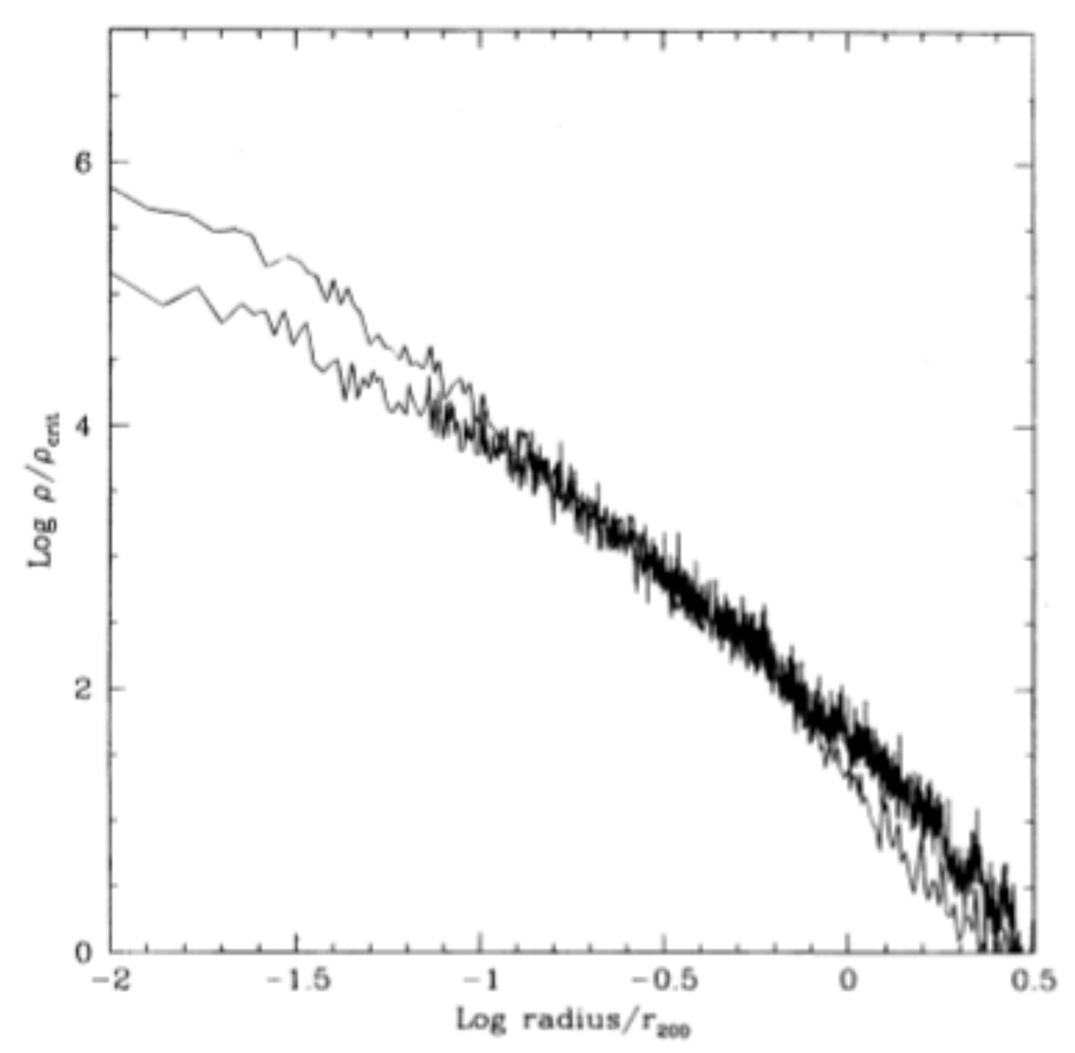
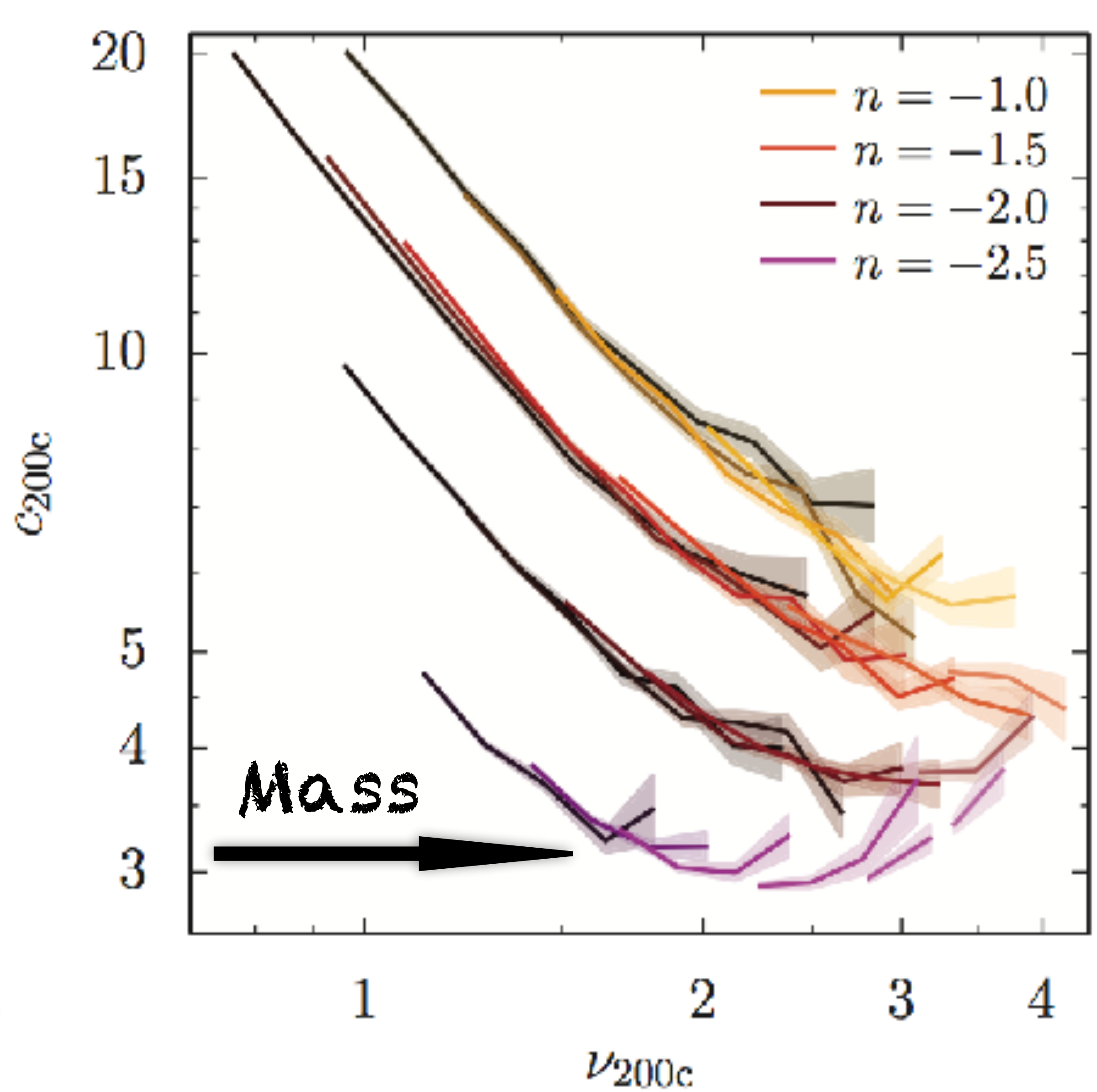


FIG. 4.—Scaled density profiles of the most and least massive halos shown in Fig. 3. The large halo is less centrally concentrated than the less massive system.



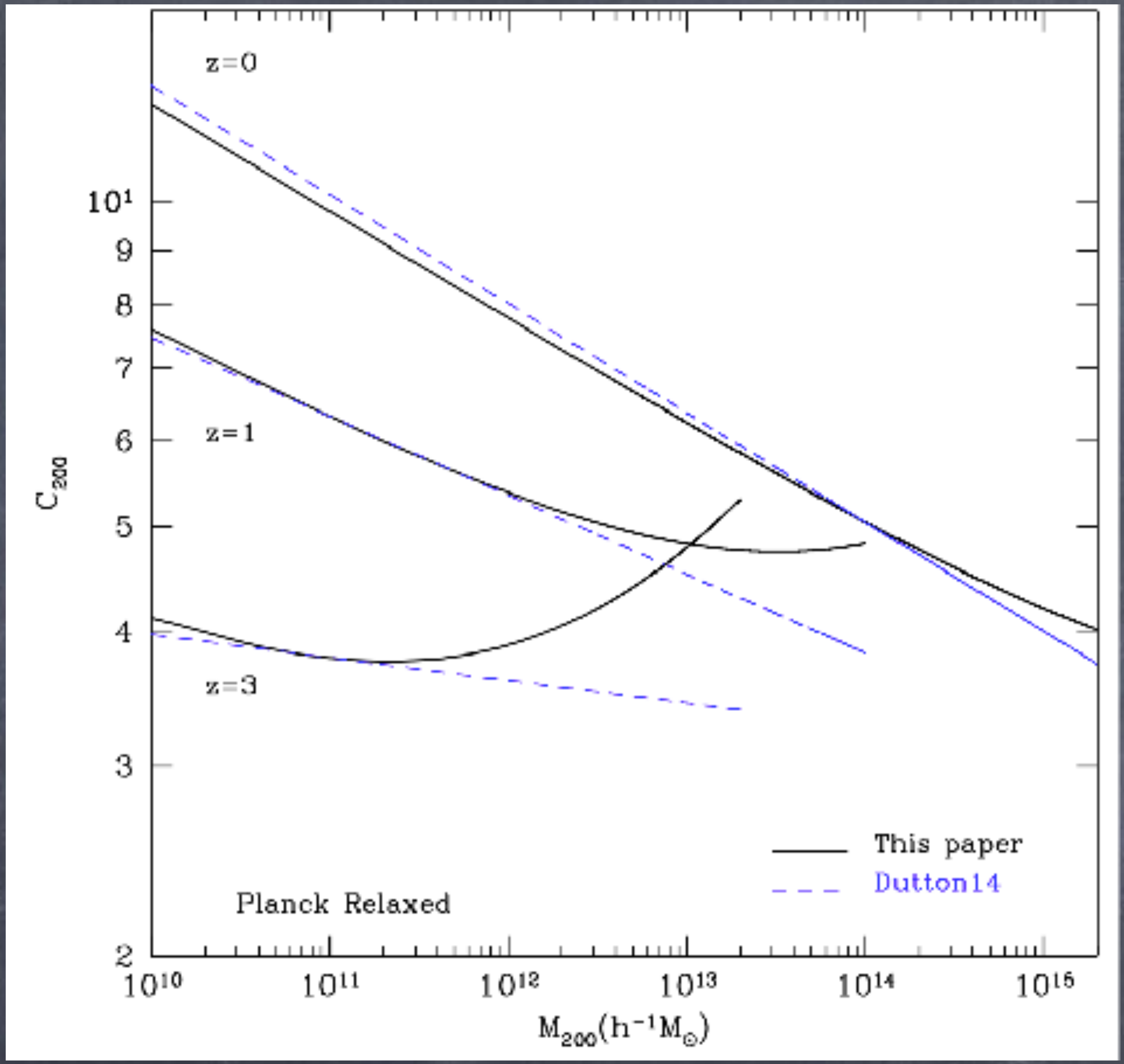
Diemer+15

See also e.g. Navarro et al. 1997, 2004, 2010, Gao et al. 2008

n: proxy for cosmology

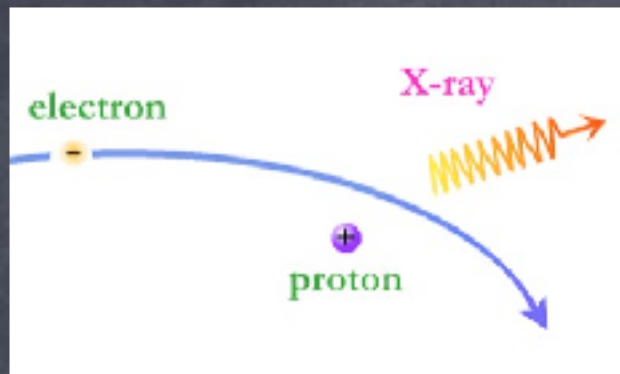
Evolution of dark matter profiles

Klypin+16

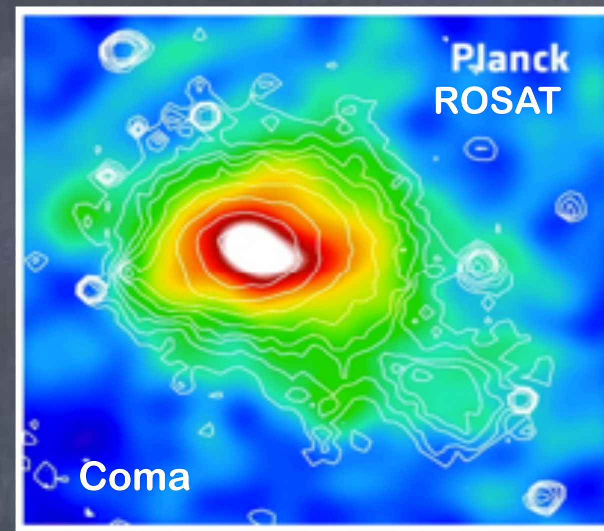


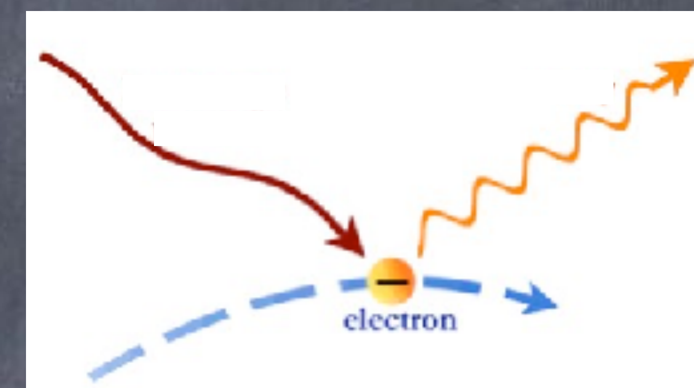
- Powerful test of ΛCDM.
- Evolution and shape of c-M are controversial especially at high-redshift and masses

X-ray and SZ observations



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





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

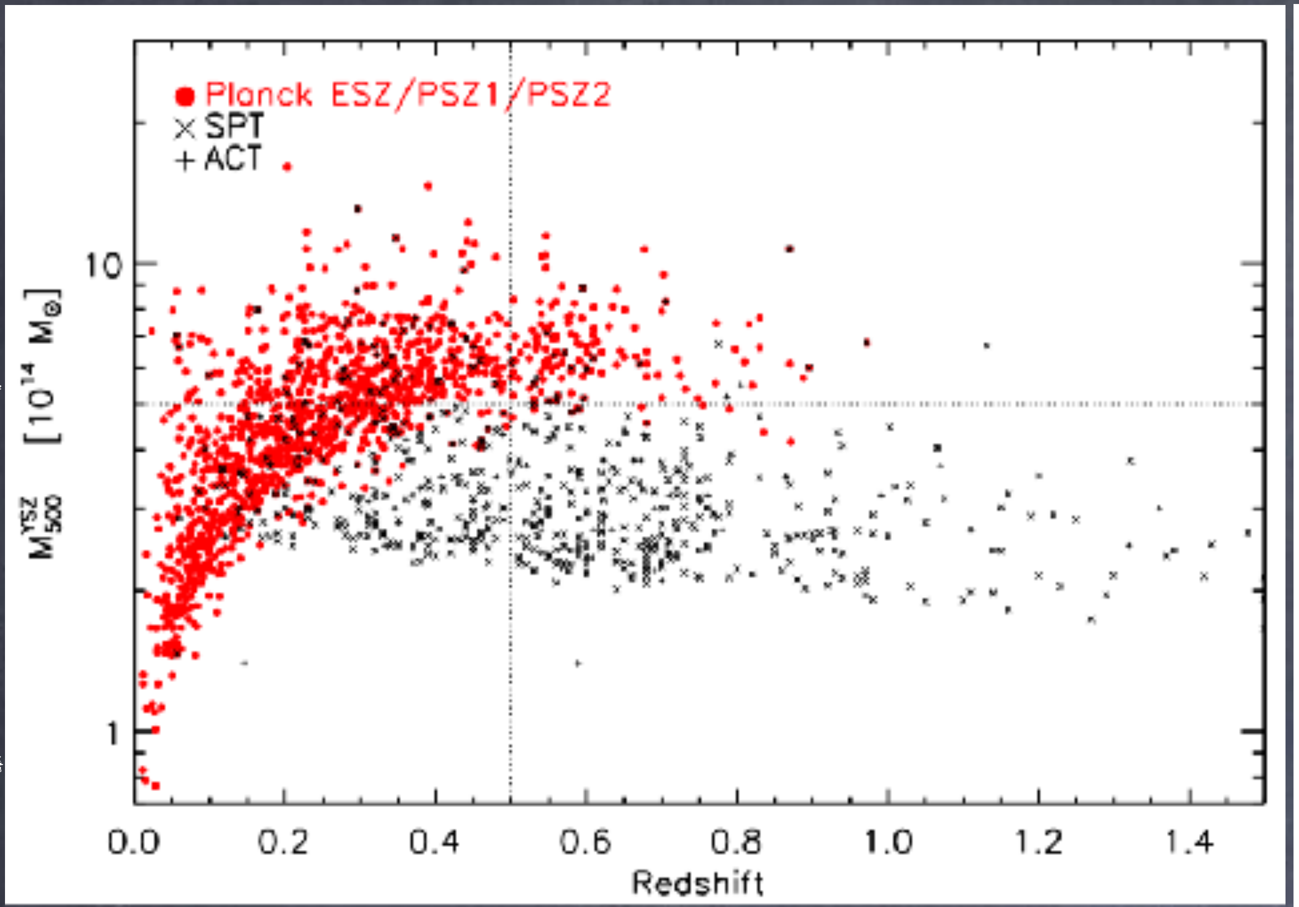
Bremsstrahlung
SB dimming with z

Inverse Compton scattering
No SB dimming with z

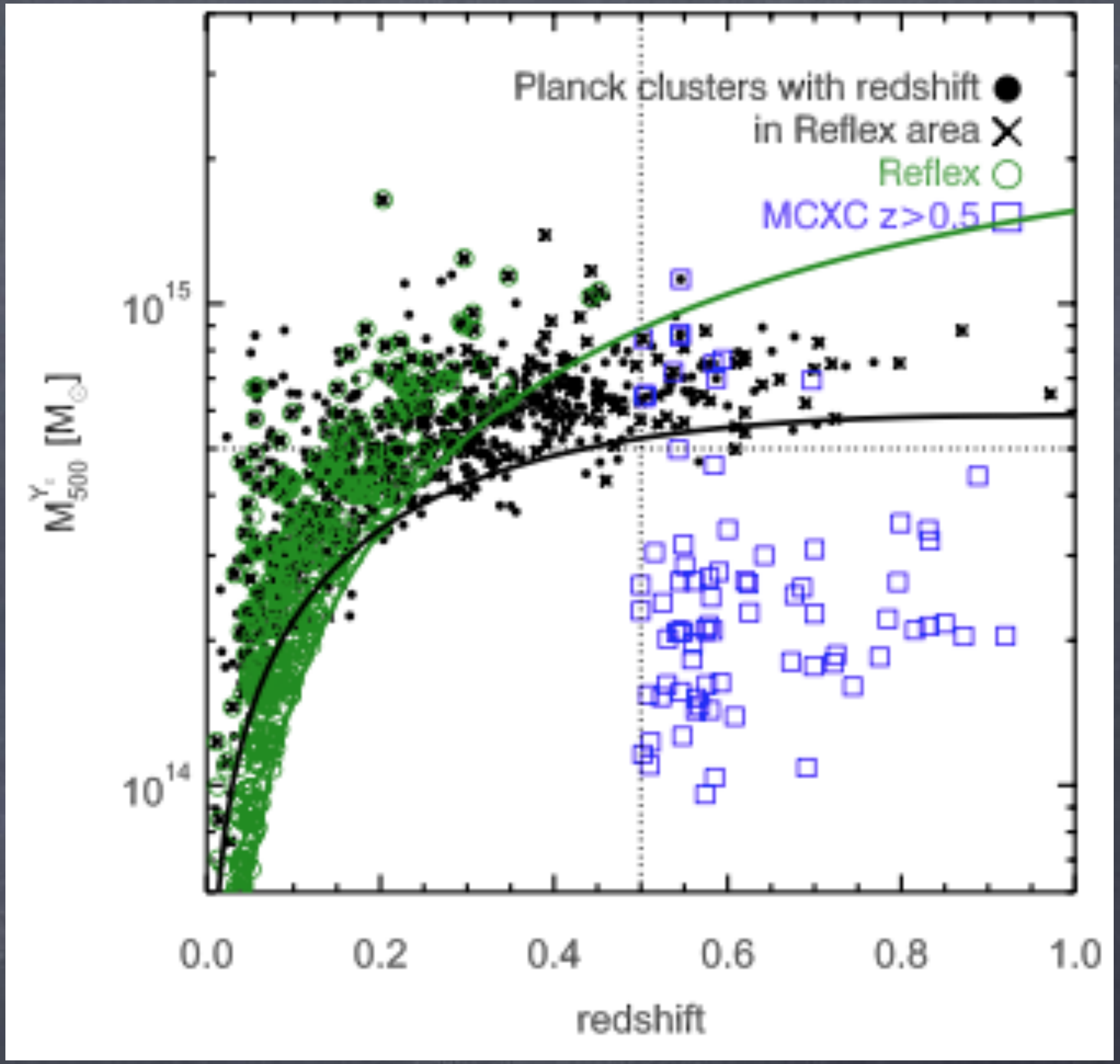
➡ Complementarity of information

Complementarity of SZ and X-ray surveys

Figure courtesy of Monique Arnaud



Data: Bleem15 (SPT), Hasselfield13 (ACT), PC VII 2011 (ESZ), PC XXIX 2013 (PSZ1), PC XXVIII 2015 (PSZ2)

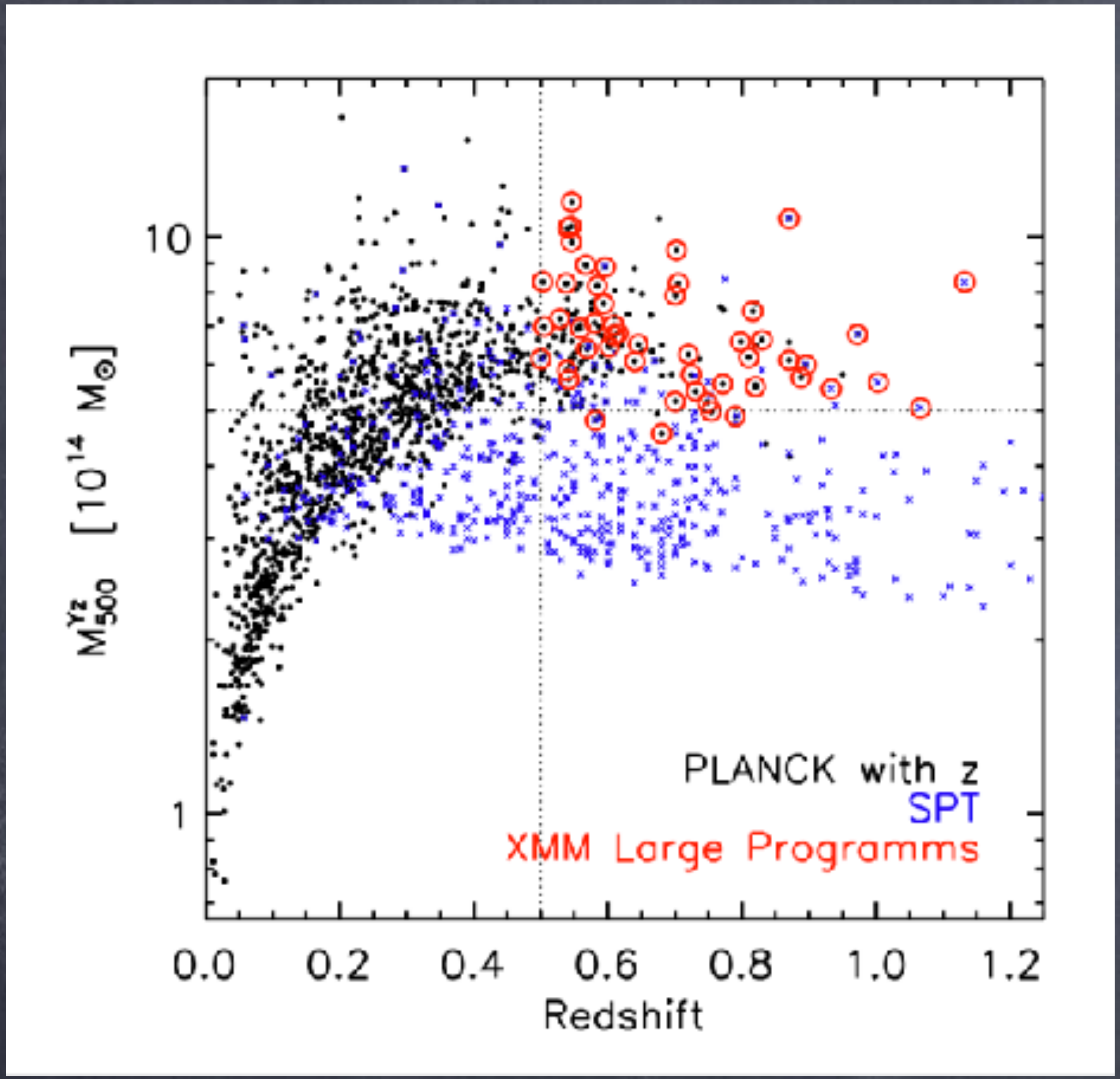


PC XXIX 2013 (PSZ1)

SZ selection supposed to be closer to a mass selection

The M2C project (PI M. Arnaud)

Figure courtesy of Monique Arnaud



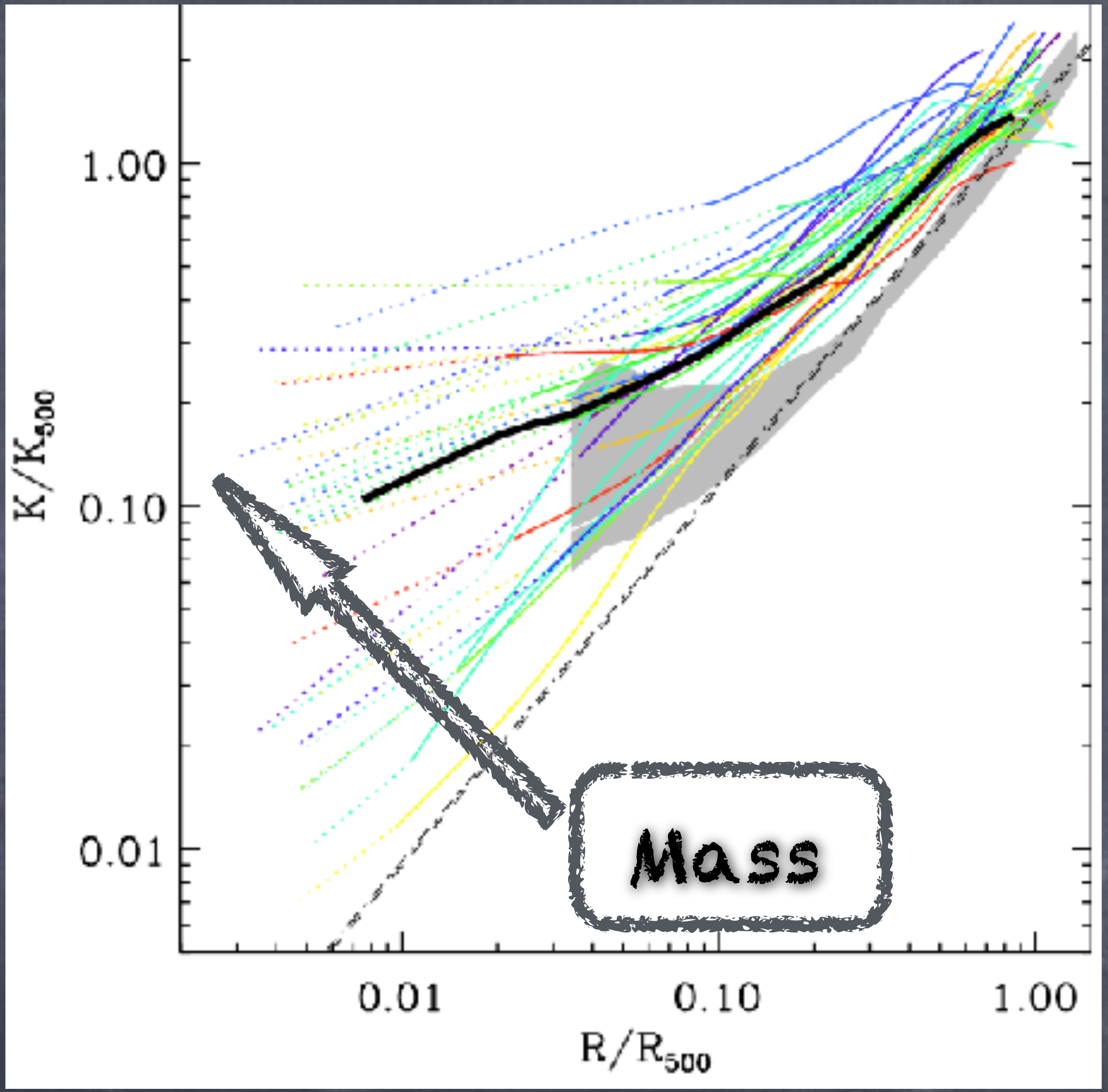
New representative SZ-selected sample of the most massive clusters up to high z

- NIR for confirmation and stellar content
- Chandra/XMM follow-up
- Mass profiles from hydrostatic equilibrium
- Systematic comparison with simulations

Continuation as part of CHEX-MATE

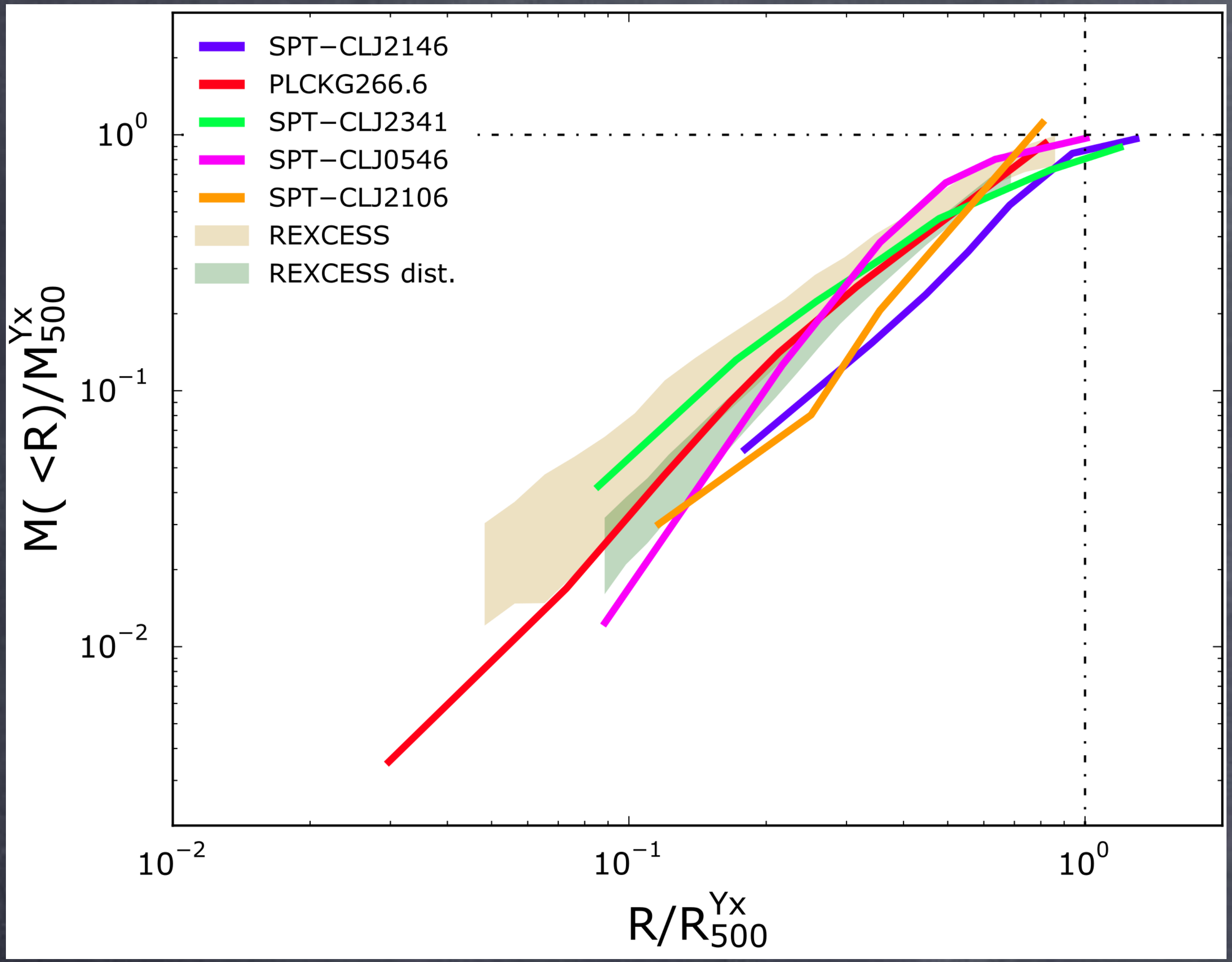
Why high-mass systems?

Pratt+10



- Faster convergence to the 'self-similar' expectation
- Much less impact of the non-gravitational physics

Pilot study of mass profiles at z~1

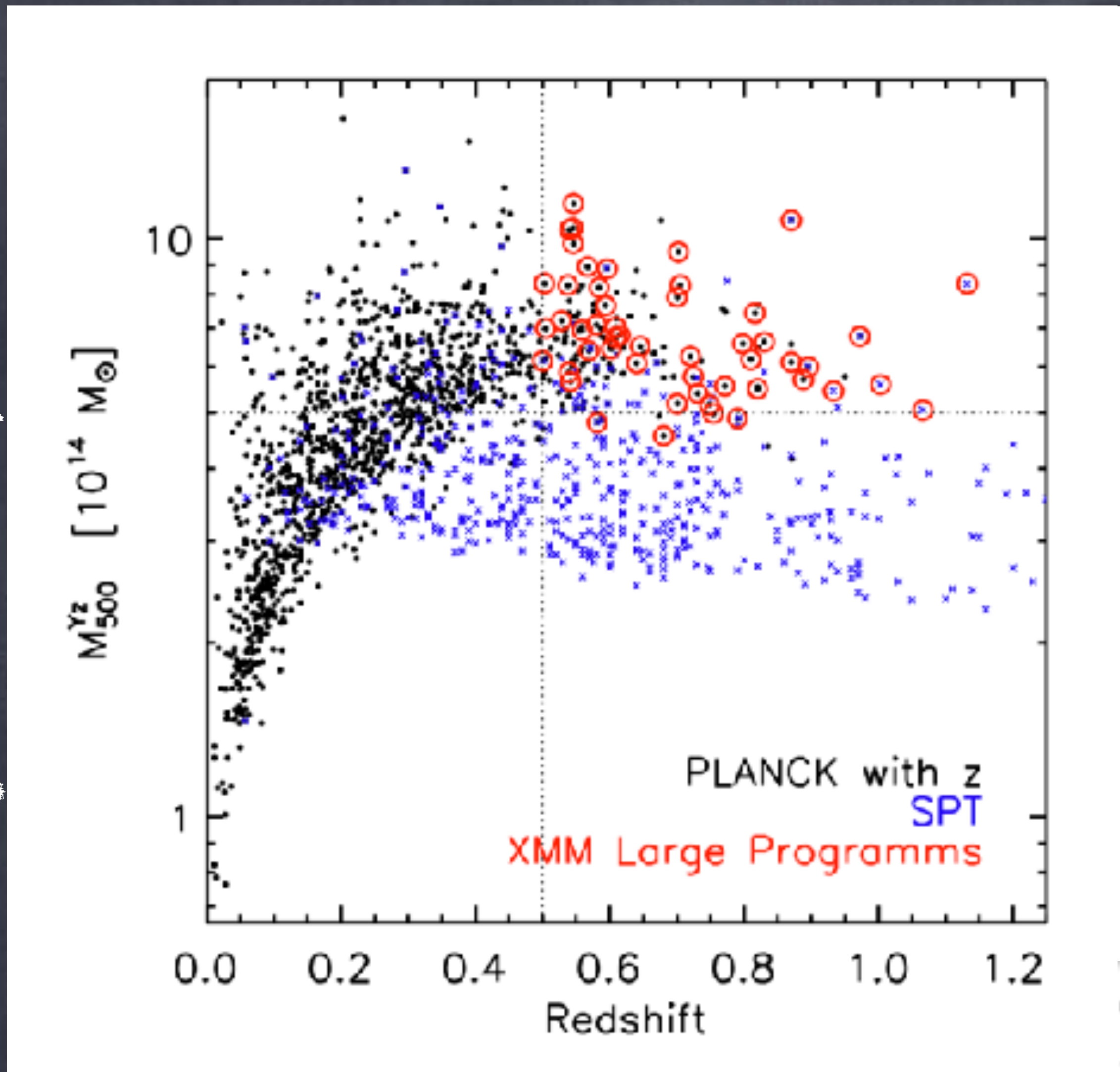


Bartalucci, Arnaud, Pratt and Le Brun 2018 (arXiv: 1803.07556)

- Less concentrated than average local cluster?
- Higher dispersion?
- Consistent with theory?

⇒ Need larger sample and new cosmological simulations

Why new simulations?



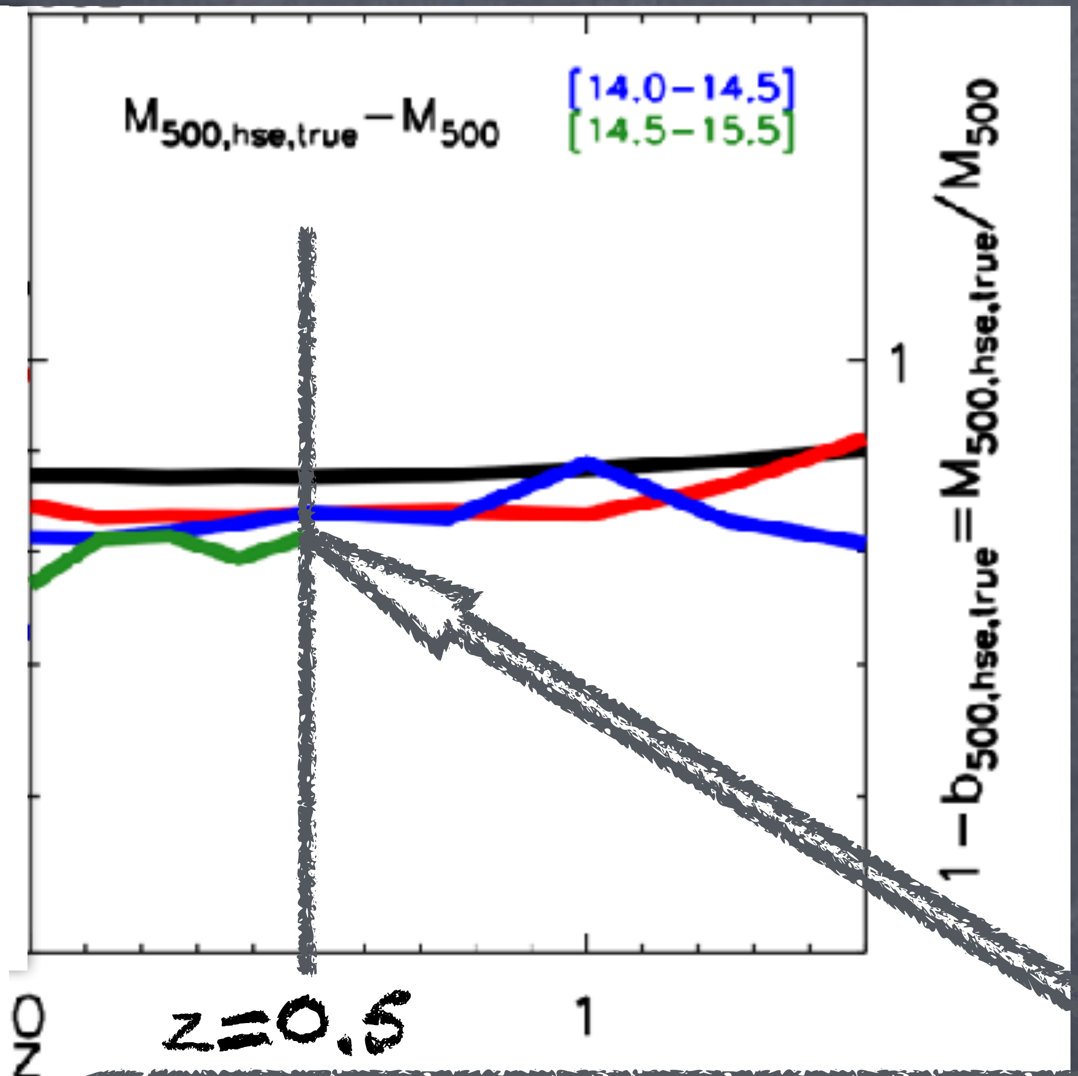


Figure courtesy of Monique Arnaud

Le Brun+17

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

No massive clusters at z>0.5 in existing simulations

- Cannot directly measure masses and mass profiles
- Need e.g. to assume hydrostatic equilibrium (HSE)
- Need simulations to e.g. constrain HSE bias

Why new simulations?

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.

Why new simulations?

Klypin+16

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

Ludlow+14

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

Diemer+14

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

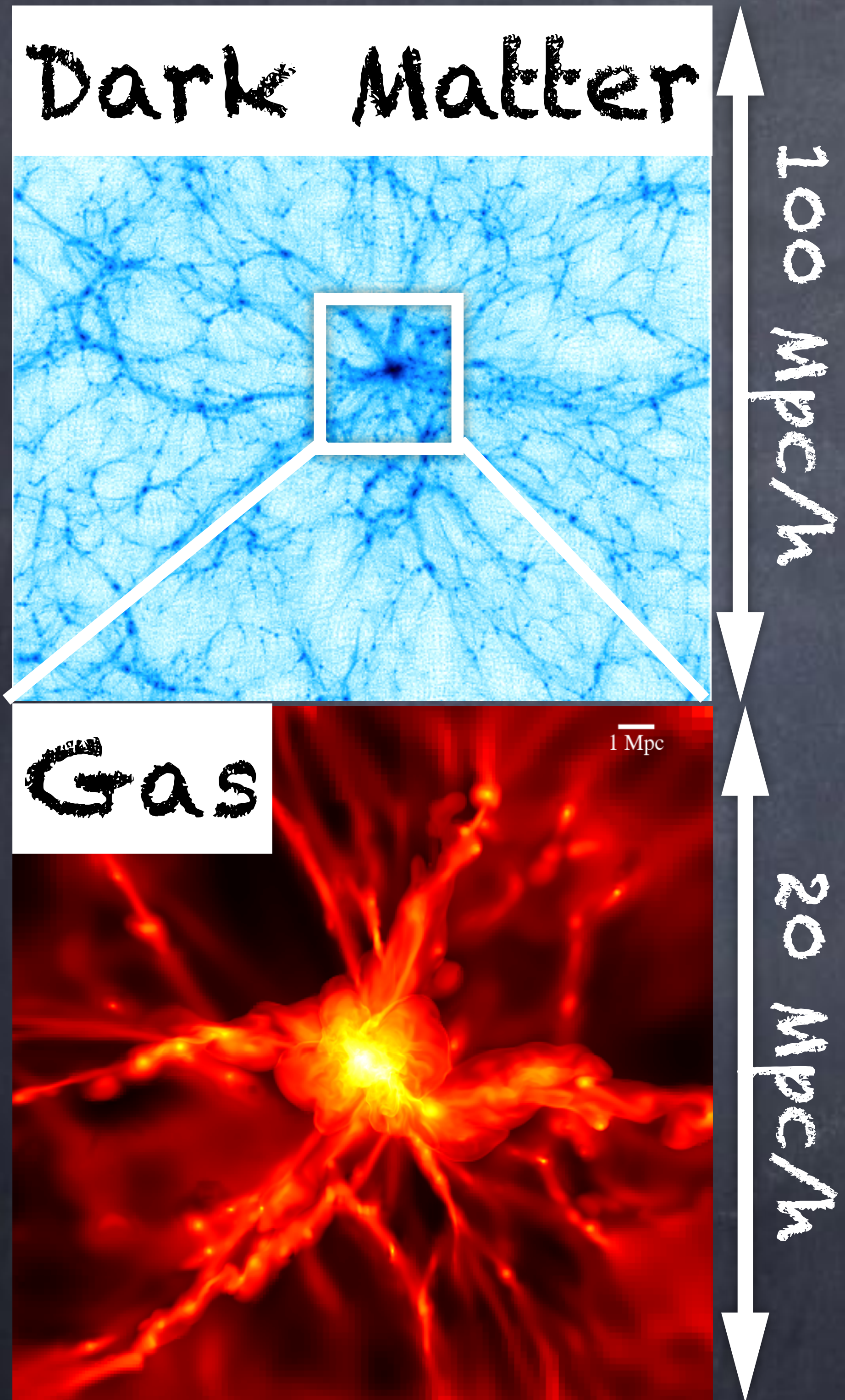
Dutton+14

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

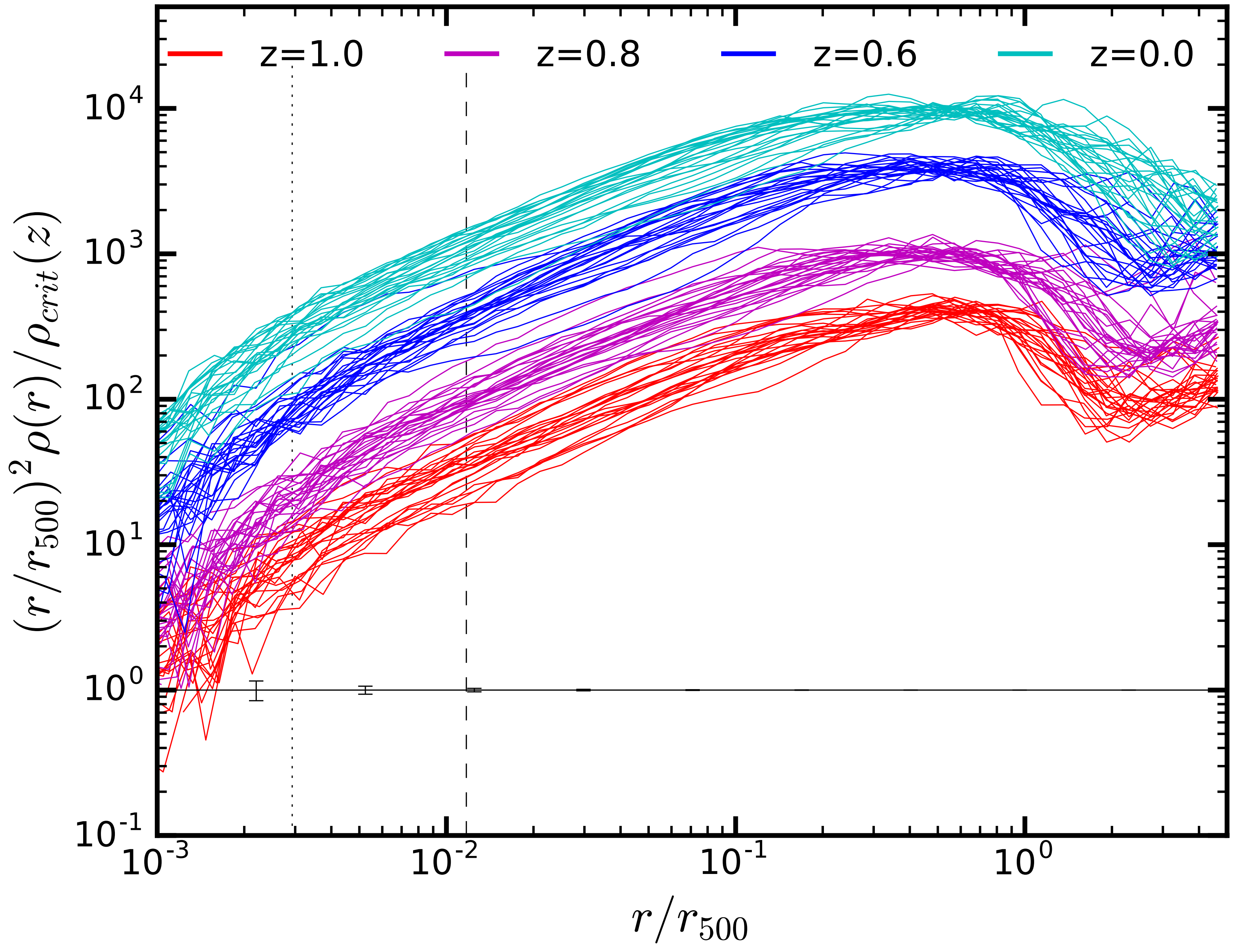
Le Brun et al. 2018 and in prep.



- AMR code RAMSES (Teyssier 2002)
- >15×10^6 CPU hours (PI Le Brun)
- 3 DMO simulations 1 $(\mathrm{Gpc}/h)^3$
- >470 few kpc-resolution zooms for selected systems with $M_{500} > 4.49 \times 10^{14}\ M_\odot$:
  - 50 at z=1
  - 170 at z=0.8
  - 181 at z=0.6
  - 75 at z=0
- Both DMO and NR runs and tests with more elaborate physics

Density profiles

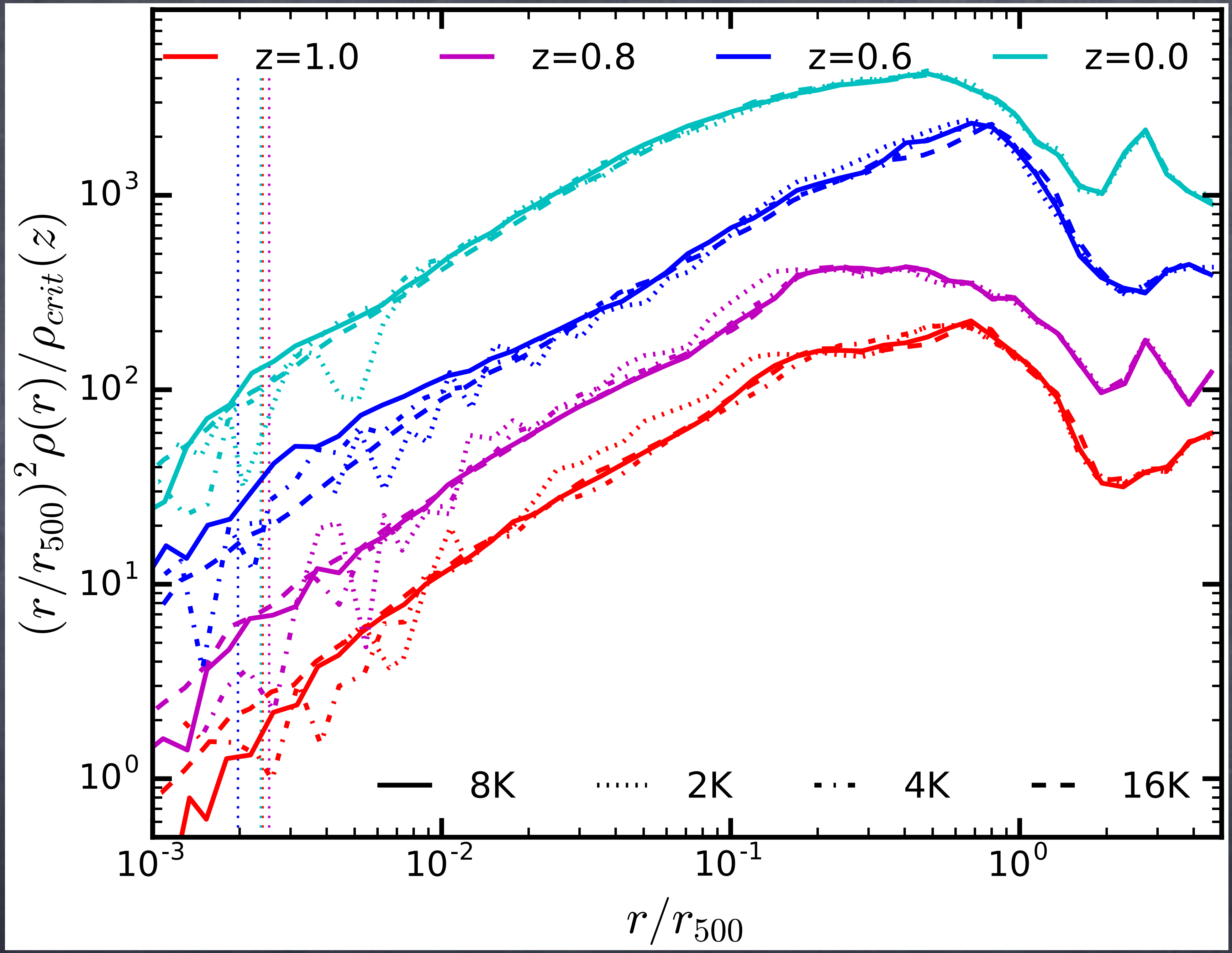
Le Brun et al. 2018



- Zoom ⇒ gain of a factor > 5 in spatial resolution
- Fluctuations are real

Resolution study

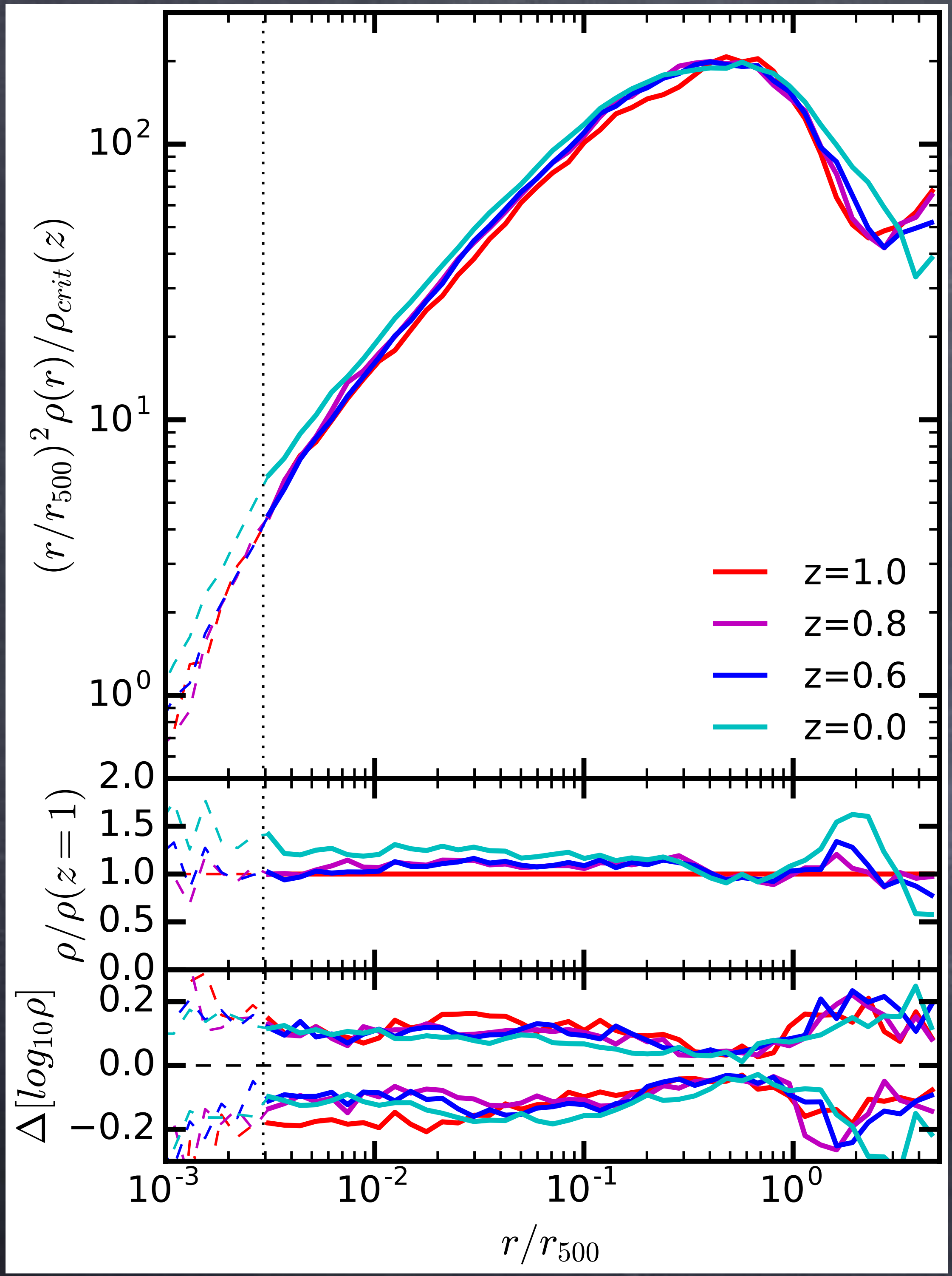
Le Brun et al. 2018



- 8K and 16K converged over the whole resolved range
- Effective resolution of 8192^3 is minimum required

Density profiles

Le Brun et al. 2018



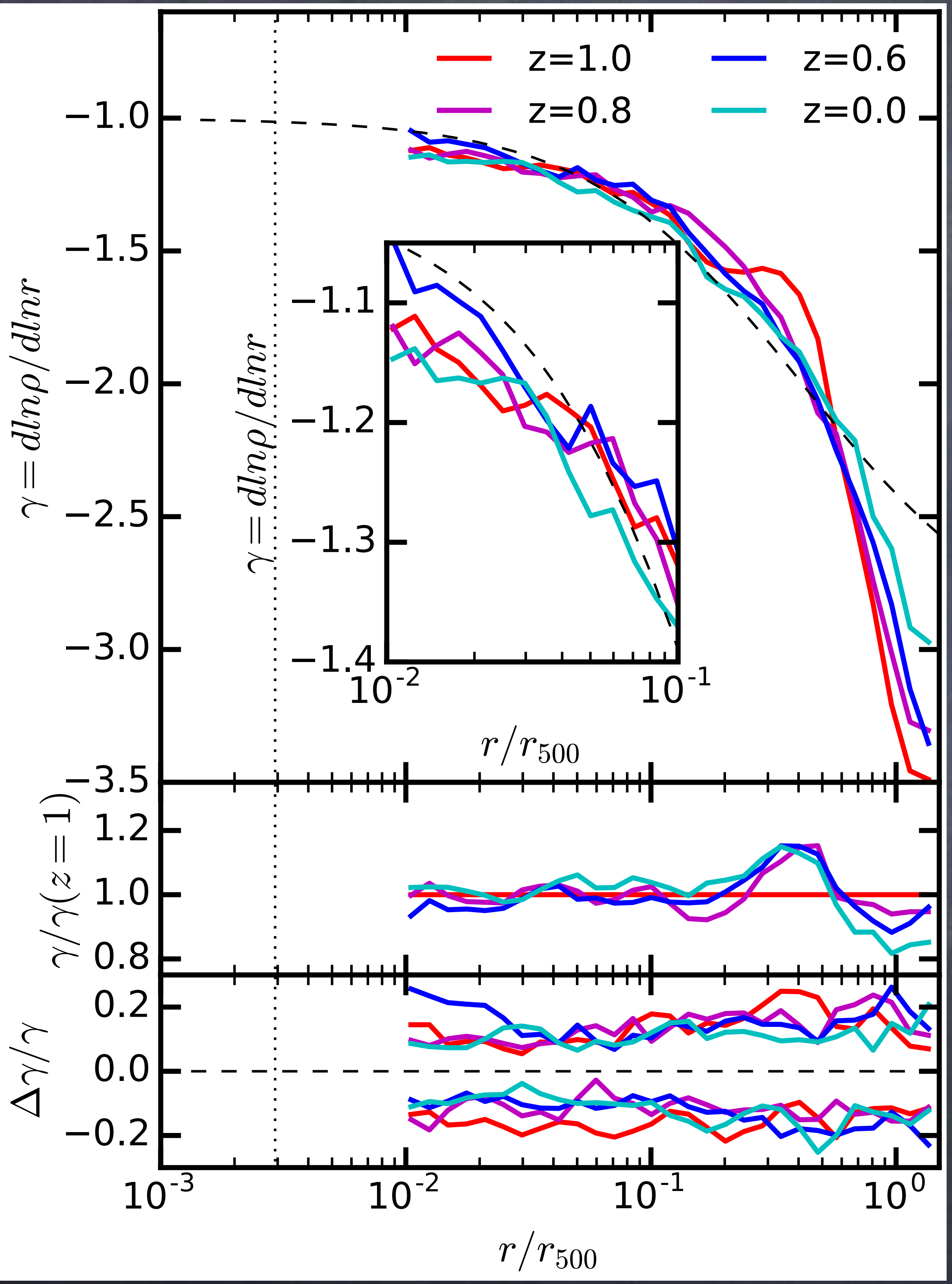
- z ≥ 0.6: nearly no evolution
- z ≤ 0.6: slightly more evolution in core and outskirts

⇒ Consistent with 'stable clustering'

- Remarkably small scatter with mild increase with z

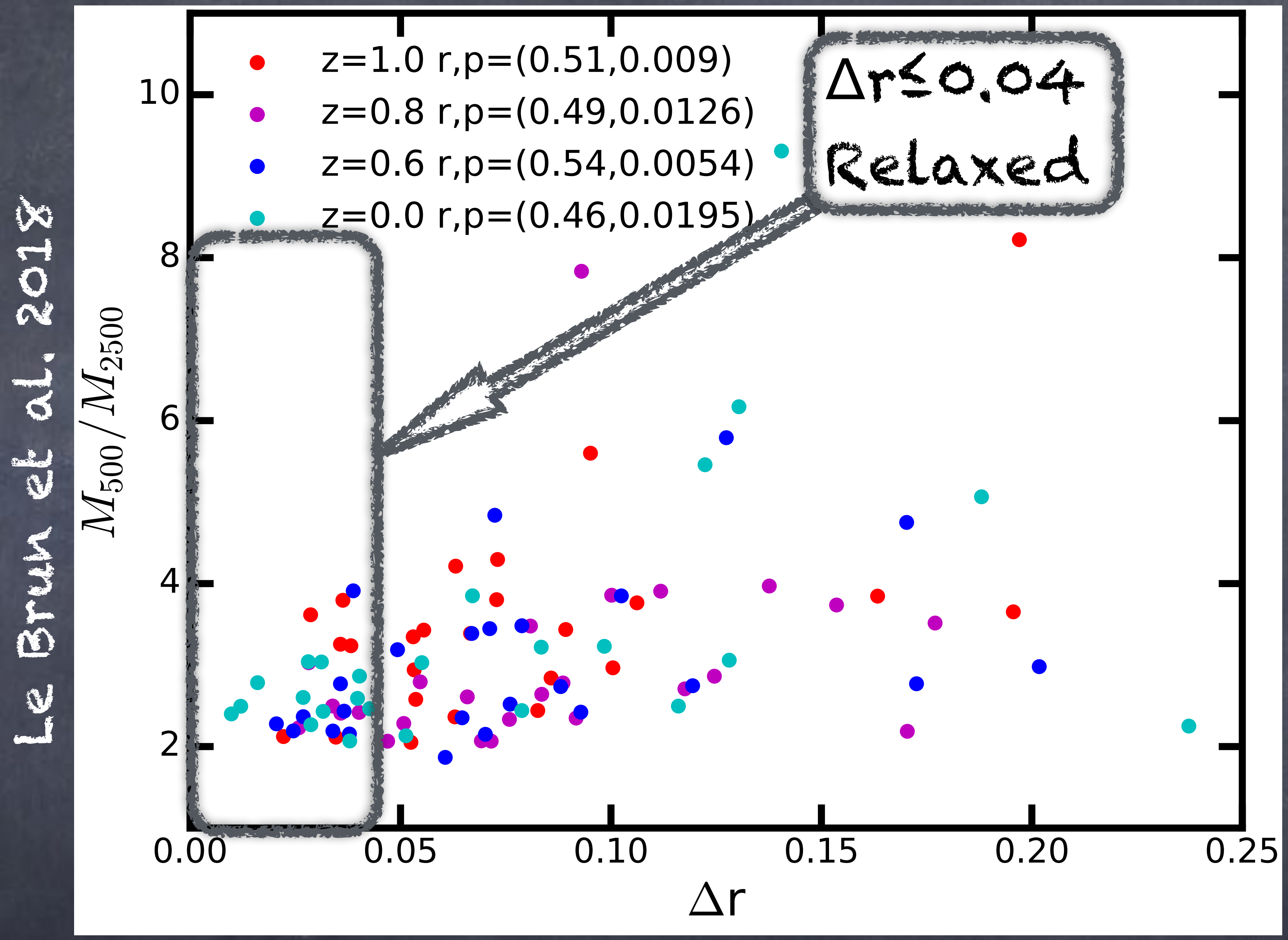
Logarithmic slope

Le Brun et al. 2018



- Small amounts of evolution and scatter at all z
- Evolution more important in inner and outer regions
- Nearly no evolution of scatter which is similar in amplitude to that of density profiles
- No signs of inner slope converging to asymptotic value

Correlation with relaxation state



- Most relaxed clusters centrally concentrated
- Unrelaxed ones span larger variety of profile shapes

Discussion I

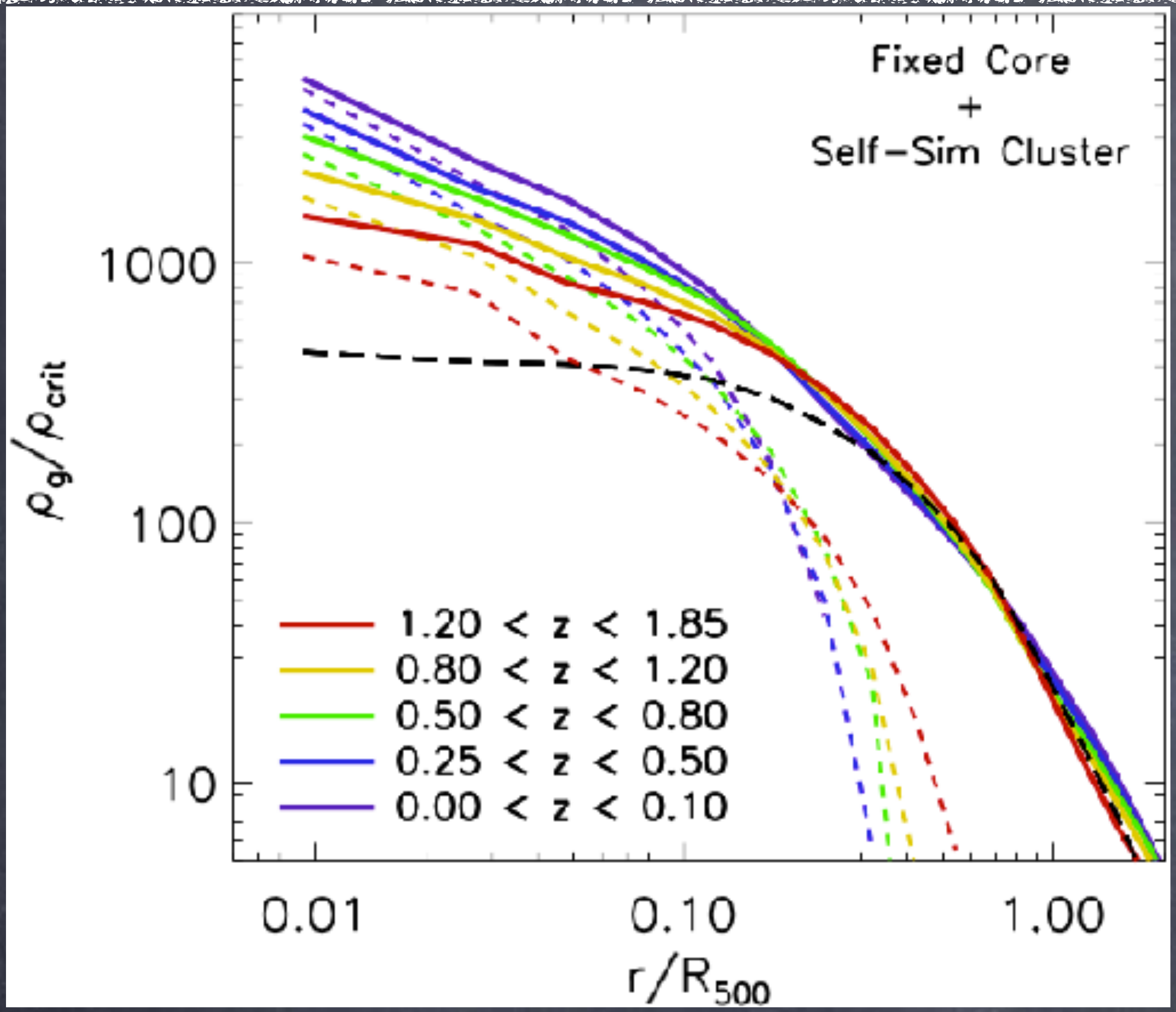
Le Brun et al. 2018

- High-mass systems at z = 1 had > 1 major merger during the preceding 4 Gyr. Relaxation time close to about 16 Gyr
- Naively expect profile has not yet converged to the near-universal form
- Surprising result that suggests the 'universal' profile already in place at z > 1 and robust to merging activity
- Similar to what was obtained for primordial haloes by Angulo et al. 2016 and Ogiya et al. 2016, but at scales that are 21 orders of magnitude larger

Discussion II

Le Brun et al. 2018

McDonald+17



- McDonald et al. 2017 found remarkably self-similar evolution in stacked hot gas profile beyond cooling core in massive clusters up to z ~ 1.9
- Natural consequence of self-similar evolution of underlying dark matter distribution as these systems are dark-matter dominated and gas evolution is dominated by simple gravitational physics

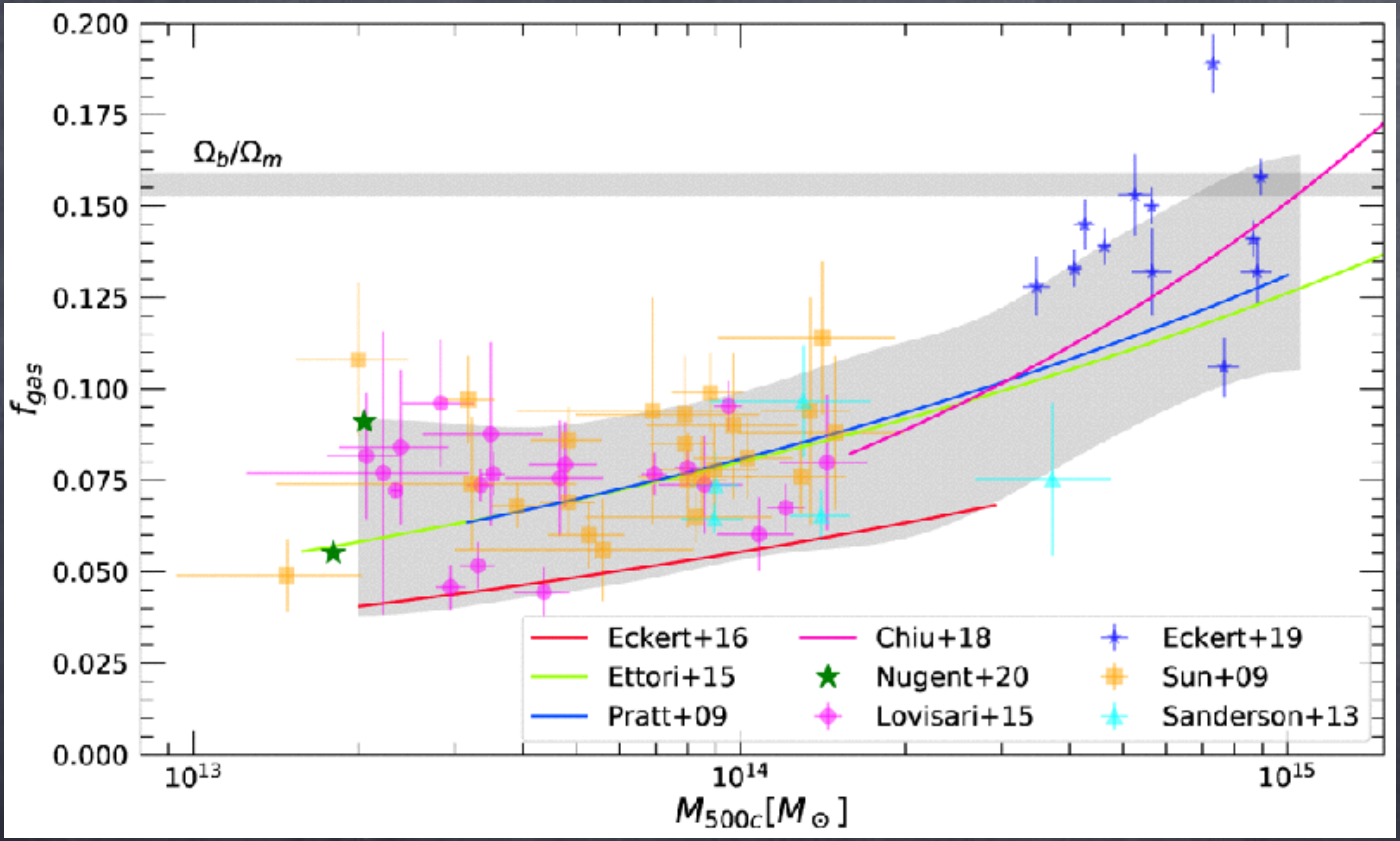
Conclusions

- Study the 25 most massive clusters at z=0, 0.6, 0.8 and 1. $M_{500} > 5.5 \times 10^{14}\ M_\odot$ at z=1.
- Scaled DM profiles strikingly similar within r_{500}:
  - Low dispersion of 0.15 dex at each z in spite of the variety of dynamical states.
  - Little evolution (never more than ~50%)
- Little evolution of the logarithmic slope and its scatter.
- Have running power law shape typical of NFW-type profiles but show no signs of converging to an asymptotic slope in central regions

Suggest that this type of profile is already in place at z>1 in the highest-mass haloes and remains exceptionally robust to merging activity.

Based on Le Brun et al. 2018, MNRASL, arXiv:1709.07457

AGN feedback in groups review



Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, in press (arXiv:2106.13259)

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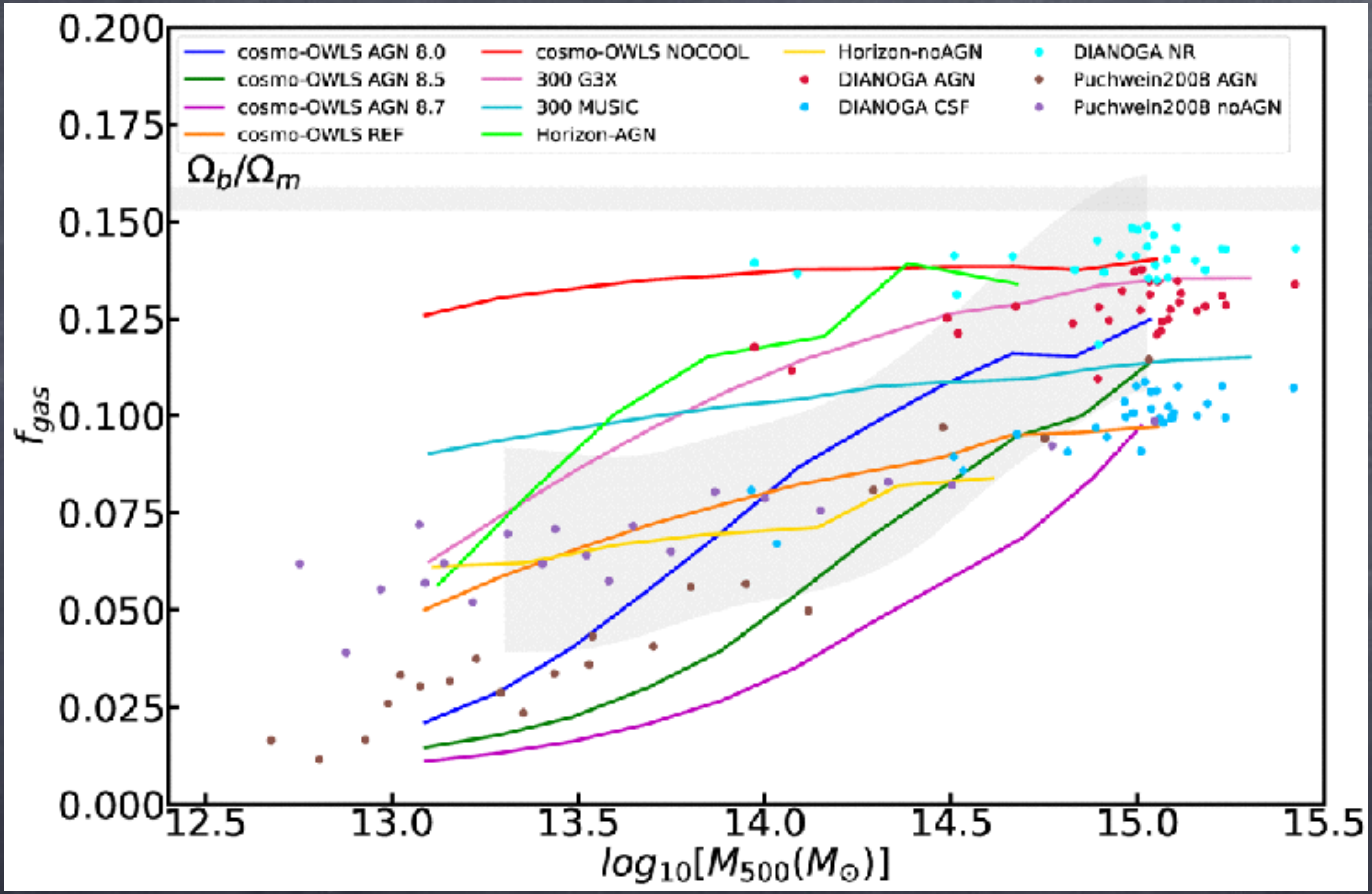

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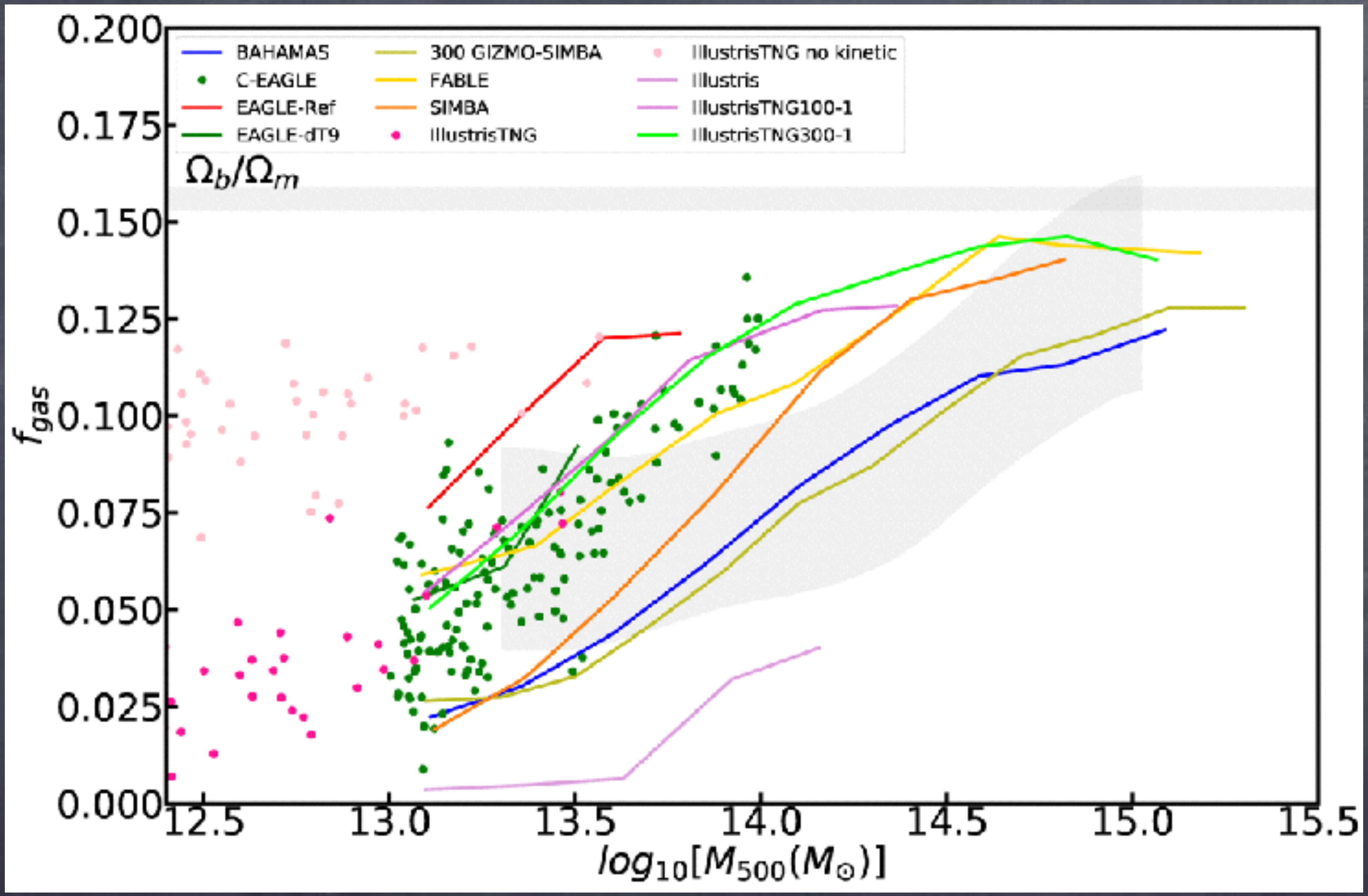


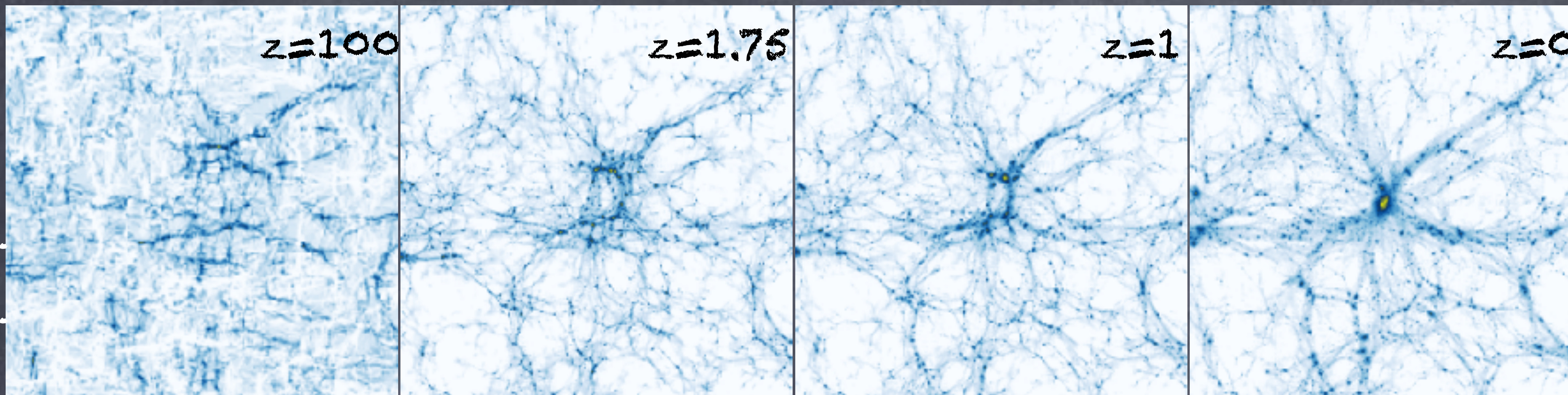
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, in press (arXiv:2106.13259)

Thank you!

Backup slides

Galaxy clusters and structure formation

Le Brun et al. in prep.



Time since Big Bang

	1 Mpc/h	36.3 Mpc/h	50 Mpc/h	100 Mpc/h
Time since Big Bang	16.4 Myr	3.61 Gyr	5.85 Gyr	Today= 13.8 Gyr

- 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}