The Three Hundred

A large galaxy cluster catalogue for cosmological and astrophysical applications.

Weiguang Cui,* [1]

In collaboration with Alexander Knebe, Gustavo Yepes, Frazer Pearce, Chris Power, Romeel Dave, Robert Mostoghiu, Yang Wang, etc.

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Universidad Autónoma de Madrid, 28049 Madrid, Spain

University of Valencia, 5 July, 2018

Results are from Cui et al. 2018 (submitted), Mostoghiu et al. in final prep. and Wang et al. 2018 in final prep.

[1] https://weiguangcui.github.io

Figure: Join Us!

Background: Cluster of Galaxies:

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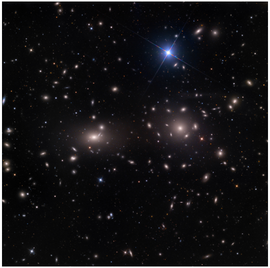
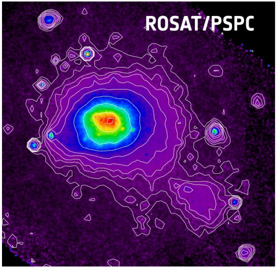

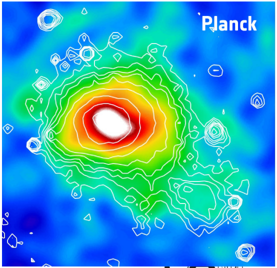

Figure: The Coma cluster.

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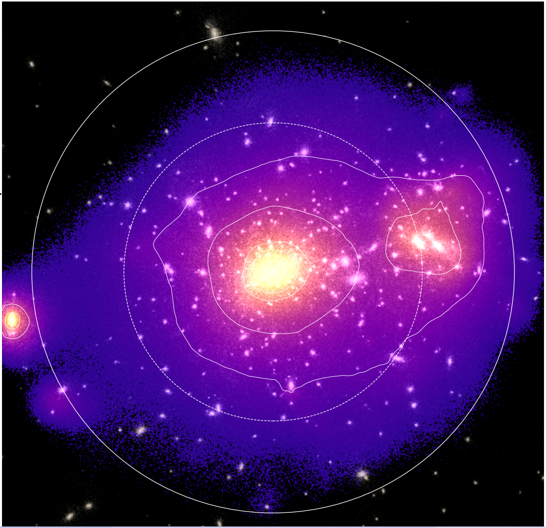
Background: Cluster of Galaxies:

To understand these observational results, especially how they are formed, we need simulations.

Simulated Cluster 17 from the 300 project

credit: Gustavo Yepes.



The nIFTy galaxy cluster comparison project[2]

11 different (in both algorithms and baryon models) simulation codes are used to simulate the same galaxy cluster.

Type	Code name, Reference	Baryonic models			
		DM gravity solver	NR gas treatment	FP noAGN	AGN
Grid-based	Ramses, Teyssier (2002)	AMR	Godunov scheme with Riemann solver	N	Y
Moving-mesh	Arepo, Springel (2010)	TreePM	Godunov scheme on moving mesh	Y[a]	Y[b]
Modern SPH	G2-Anarchy, Dalla Vecchia et al. in prep.	TreePM	SPH kernel: Wendland C2	N	N
	G3-Sphs, Read & Hayfield (2012)	TreePM	Wendland C4	N	N
	G3-Magneticum, Hirschmann et al. (2014)	TreePM	Wendland C6	N	Y
	G3-x, Beck et al. (2016)	TreePM	Wendland C4	N	Y
	G3-PeSPH, Huang et al. in prep.	TreePM	HOCTS B-spline	Y	N
Classic SPH	G3-Music, Sembolini et al. (2013)	TreePM	Cubic spline	Y[c]	N
	G3-Owls, Schaye et al. (2010)	TreePM	Cubic spline	N	Y
	G2-x, Pike et al. (2014)	TreePM	Cubic spline	N	Y
	Hydra, Couchman et al. (1995)	AP^3M	Cubic spline	N	N

[2]Ref: Sembolini et al. 2016a,b; Elahi et al. 2016; Cui et al. 2016; Arthur et al. 2017

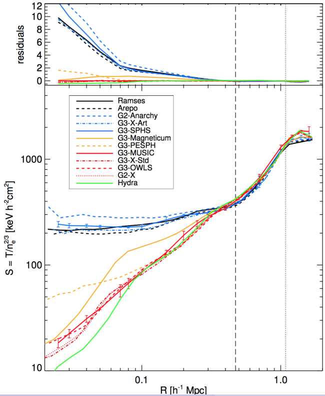
The motivation of the Three Hundred: A successor of the nIFTy project

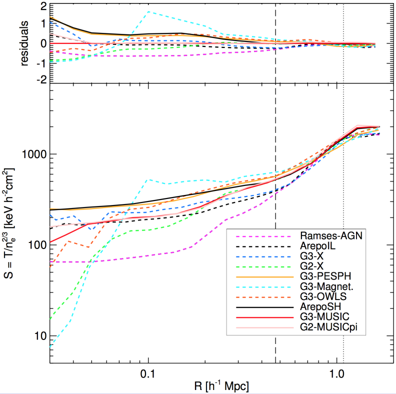
What did we find? I

- The modern SPH codes produce correct entropy profiles as AMR, moving mesh.
- The baryon models have larger effects than the fluid simulating techniques by mixing the entropy profiles.

Entropy profile.

Ref: Sembolini et al. 2016a,b.

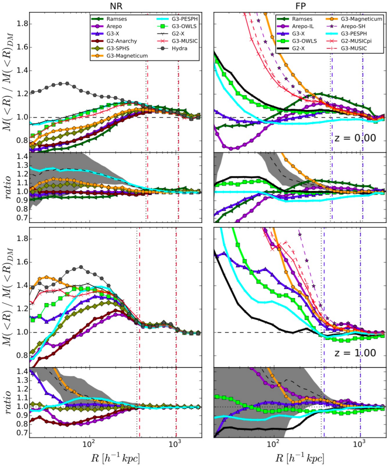




What did we find? II

E.g. Baryon effects on density profile.

Ref: Cui et al. 2016



What's next?

Aim: to understand the formation and evolution of galaxy clusters.

- Comparisons between models to understand the theoretical predictions.
- Comparisons between models and observations to constrain the models.

A large cluster sample!

Other works

Table: Cluster projects

Name	N	mass range	resolution (M_{DM})
MUSIC[2], Sembolini et al. 2013	500	$10^{14} < M_v < 2 \times 10^{15}\ h^{-1}\ \mathrm{M}_\odot$	$1.03 \times 10^9\ h^{-1}\ \mathrm{M}_\odot$
Dianoga, Planelles et al 2013	29	$M_{500} > 2 \times 10^{14}\ h^{-1}\ \mathrm{M}_\odot$	$8.5 \times 10^8\ h^{-1}\ \mathrm{M}_\odot$
Rhapsody-G, Hahn et al. 2017	10	$M_v \sim 10^{15}\ h^{-1}\ \mathrm{M}_\odot$	$8.3 \times 10^8\ h^{-1}\ \mathrm{M}_\odot$
MACSIS, Barnes et al. 2017a	390	$M_{FoF} > 10^{15}\ h^{-1}\ \mathrm{M}_\odot$	$4.4 \times 10^9\ h^{-1}\ \mathrm{M}_\odot$
C-EAGLE, Barnes et al. 2017b	30	$10^{14} < M_{200} < 2.5 \times 10^{15}\ h^{-1}\ \mathrm{M}_\odot$	$10^7\ h^{-1}\ \mathrm{M}_\odot$
Hydrangea[3], Bahe et al. 2017	24	$10^{14} < M_{200} < 2 \times 10^{15}\ h^{-1}\ \mathrm{M}_\odot$	$10^7\ h^{-1}\ \mathrm{M}_\odot$

[2] No AGN

[3] Slightly different to EAGLE in AGN feedback

The advantage of the Three Hundred: Basic information

- The most massive ($M_{vir} > 8 \times 10^{14}\ h^{-1}\,\mathrm{M}_{\odot}$) 324 clusters are selected from the MultiDark simulation(MDPL2)[4].
- The zoomed-in ICs are generated by cutting a spherical region with a radius of 15 h^{-1} Mpc from the cluster center.

[4] https://www.cosmosim.org

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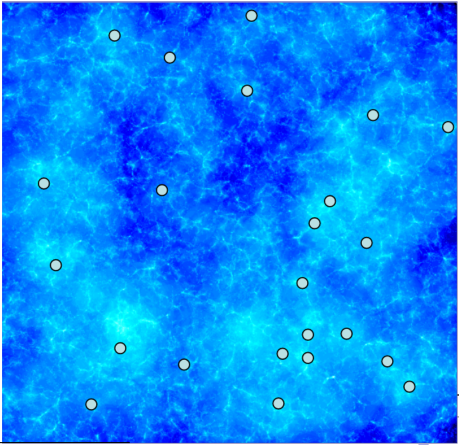

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Table: Parameters of the Three Hundred simulations

Parameter	Value	Description
Ω_M	0.307	Total Matter density parameter
Ω_B	0.048	Baryon density parameter
Ω_Λ	0.693	Cosmological Constant density parameter
h	0.678	Hubble constant in units of 100 km/s/Mpc
σ_8	0.823	Normalization of Power spectrum
n_s	0.96	Power index
z_{init}	120	Initial redshift of the simulations
ϵ_{phys}	6.5	Plummer equivalent softening in h^{-1} kpc
Particle mass	2.36 (12.7)	gas (dark matter) particle mass in $[10^8\ h^{-1}\,\mathrm{M}_{\odot}]$

[4] https://www.cosmosim.org

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The advantage of the Three Hundred: theoretical models

hydrodynamical simulations with baryonic models:

GADGET-MUSIC: classic SPH method. Radiative cooling, star formation with both thermal and kinetic Supernove (SN) feedback.
GADGET-X: modern SPH with the Wendland C4 kernel. Gas cooling with metal contributions, star formation with chemical enrichment, SN feedback with AGB phase, and AGN feedback.
GIZMO: running.
GADGET-PESPH: running.

SAMs from MultiDark-Galaxies:

Three different models GALACTICUS, SAG and SAGE (see Knebe et al. 2018 for details) are applied on the cosmological MultiDark simulation.
GALACTICUS: (Benson 2012) no calibration. only orphan galaxy.
SAG: (Cora et al. 2018) calibrated to observation. orphan galaxy + ICL.
SAGE: (Croton et al. 2016) no calibration. no orphan galaxy, only ICL.
Notes: We select these catalogues from the same regions as the hydrodynamical simulations.

Summary:

- A mass-complete sample for $M_{200} > 6.4^{14}\ h^{-1}\,\mathrm{M}_\odot$ for cosmology.
- Very large re-simulation region 15 h^{-1} Mpc for large-scale environments[5].
- Multiple hydro-simulation codes with additional SAM catalogues for galaxy formation.
- Different halo/subhalo catalogues, merger trees and multi-wavelength mock observation images.

[5] re-simulated void regions are also available

Halos and subhalos in hydrodynamical simulations are identified with AHF (Ref: Knollmann & Knebe 2009).

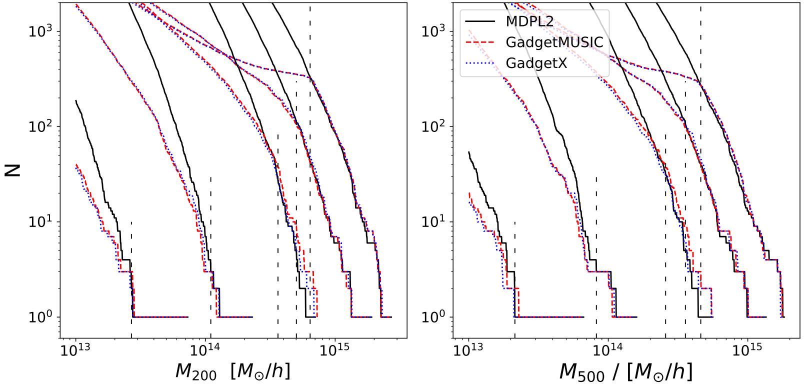

Figure: Cumulative halo mass functions.

The Three Hundred: the catalogues

Halos and subhalos in hydrodynamical simulations are identified with AHF (Ref: Knollmann & Knebe 2009).

Table: The mass-complete sample of the Three Hundred cluster catalogues at different redshifts.

redshift	M_{200c} $[10^{14}\ h^{-1}\ \mathrm{M}_\odot]$	N_{200c} MUSIC/X	M_{500c} $[10^{14}\ h^{-1}\ \mathrm{M}_\odot]$	N_{500c} MUSIC/X
0.0	6.4	324 / 324	4.6	270 / 270
0.5	5.02	104 / 110	3.57	94 / 103
1.0	3.62	38 / 27	2.57	37 / 31
2.3	1.10	3 / 3	0.82	3 / 3
4.0	0.27	3 / 2	0.21	2 / 1

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The results

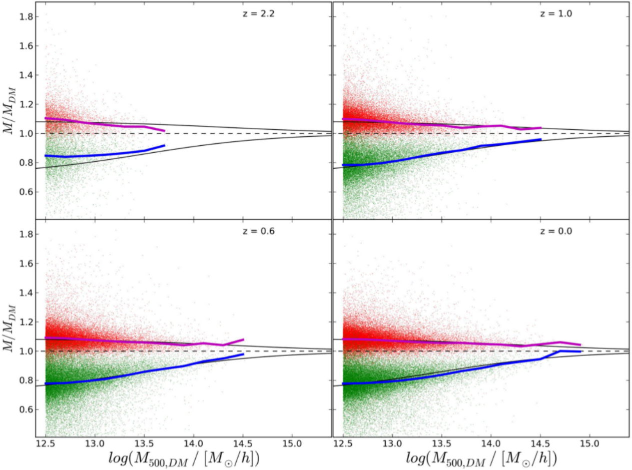

Figure: halo mass (M_{500}) difference respected to the DM run. Ref: Cui et al. 2014

General Properties: Baryon effects on halo mass

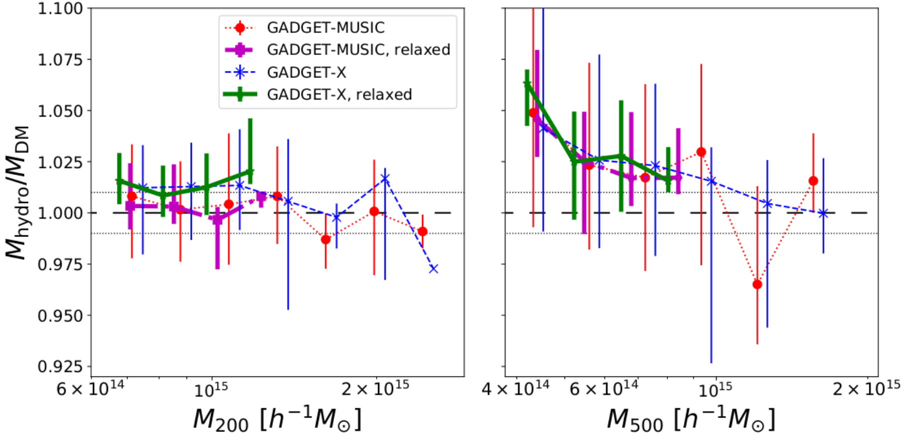

Figure: halo mass difference respected to the DM run.

General Properties: the dynamical state

Classifying the cluster's dynamical state into relaxed and un-relaxed: the virial ratio $\eta = (2T - E_s)/|W|$ with $0.85 < \eta < 1.15$, center-of-mass offset $\Delta_r = |R_{cm} - R_c|/R_{200c}$ <0.04 and subhalo mass fraction $f_s = \sum M_{sub}/M_{200c}$ <0.1. Cui et al. 2017

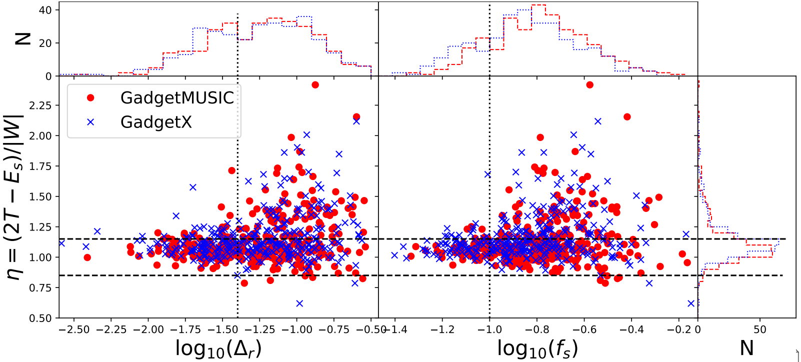

Figure: The relations between the three parameters.

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Table: The fractions of relaxed clusters with different combinations of criteria.

M_{200c} $10^{14}\ h^{-1}\ \mathrm{M}_\odot$	η, Δ_r & f_s MUSIC/X	Δ_r & f_s MUSIC/X	f_s MUSIC/X
0.10 – 0.50	0.44 / 0.36	0.56 / 0.48	0.70 / 0.65
0.50 – 1.00	0.36 / 0.34	0.45 / 0.46	0.56 / 0.57
1.00 – 6.41	0.27 / 0.29	0.30 / 0.35	0.43 / 0.48
6.41 – 10	0.18 / 0.21	0.20 / 0.24	0.21 / 0.26
> 10	0.06 / 0.08	0.07 / 0.13	0.07 / 0.14

Table: The Cool Core cluster fraction (two methods: Rosetti et al. 2011 and central entropy) in the complete sample: $f_{CC} = \frac{N_{CC}}{N_{total}}$, the CC fraction in dynamically relaxed clusters $f_{CC/dr} = \frac{N_{CC,relaxed}}{N_{relaxed}}$ and the relaxation fraction in CC $f_{dr/CC} = \frac{N_{CC,relaxed}}{N_{CC}}$.

Simulation	f_{CC}	$f_{CC/dr}$	$f_{dr/CC}$
MUSIC	0.09	0.04	0.07
X	0.26	0.33	0.21

General Properties: the baryon fractions

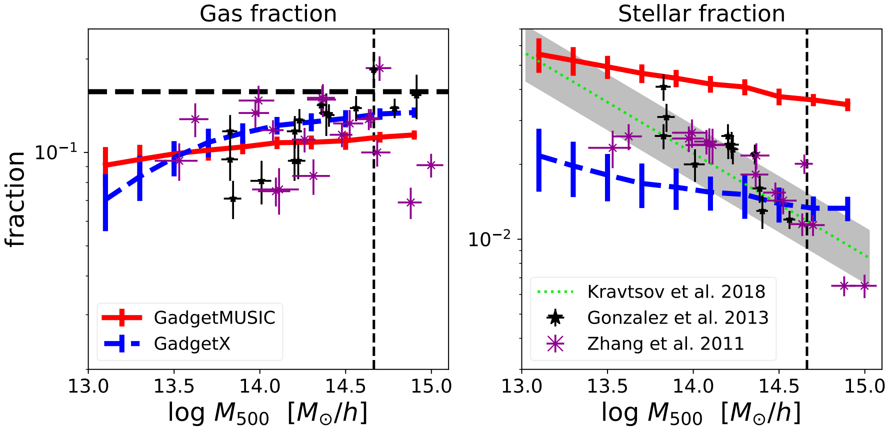


Figure: The baryon fractions.

General Properties: the baryon fractions

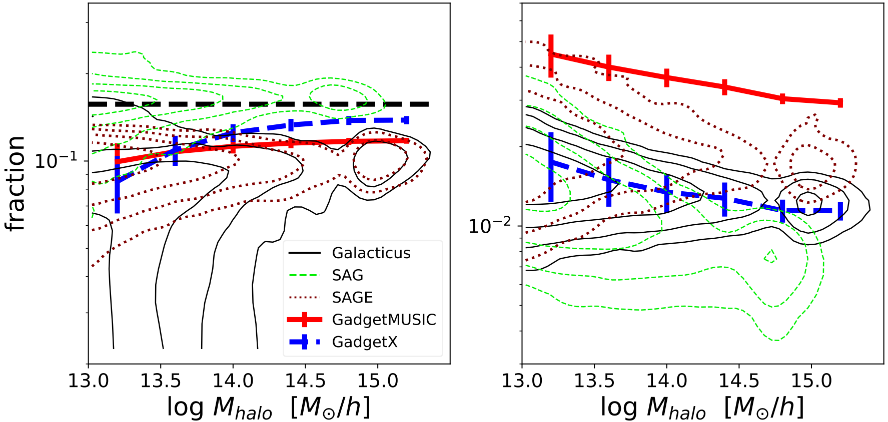
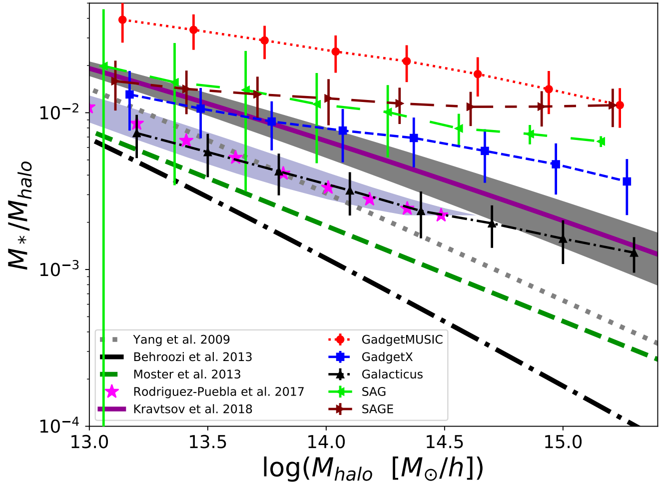


Figure: The baryon fractions.

Stellar-Halo mass relation



Optical relations

The complete sample is used here.

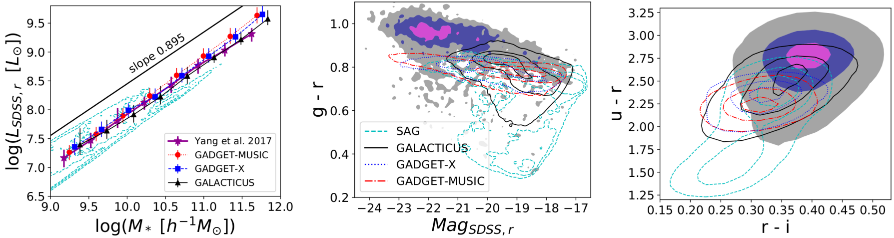


Figure: The optical relations.

Optical relations: the satellite stellar mass function

The complete sample is used here.

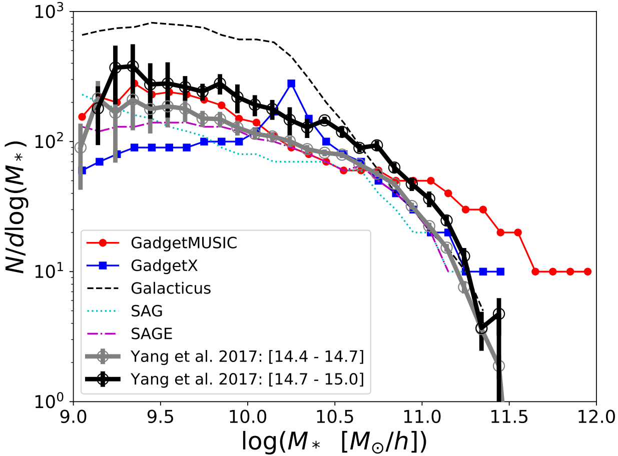


Figure: The satellite stellar mass function.

Gas scaling relations

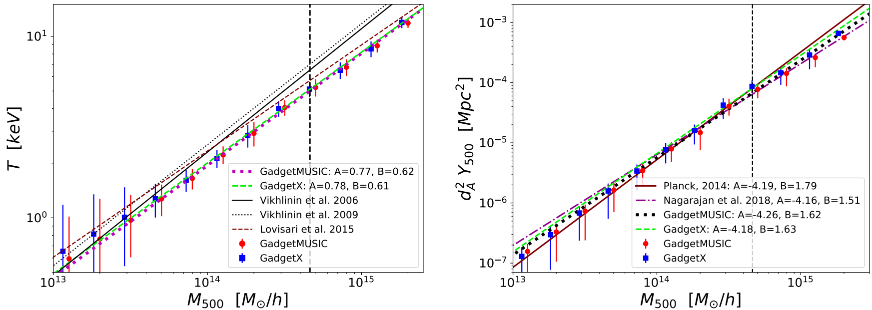


Figure: The gas relations.

The cluster density profiles: Mostoghiu et al. in prep.

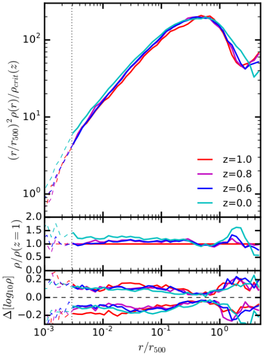


Figure: Density profiles. Le Brun et al. 2018

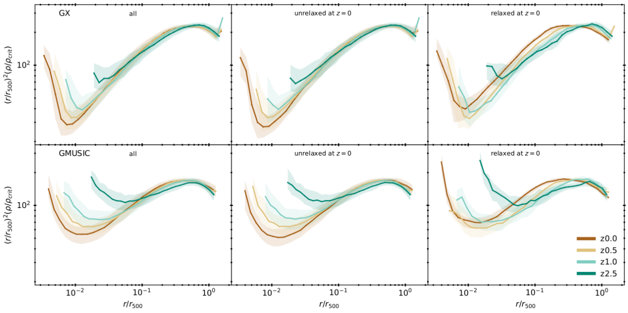


Figure: Density profiles from the mass-complete sample. credit: Robert Mostoghiu

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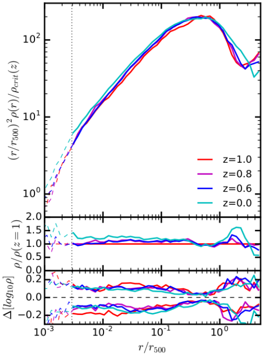
The cluster density profiles: Mostoghiu et al. in prep.



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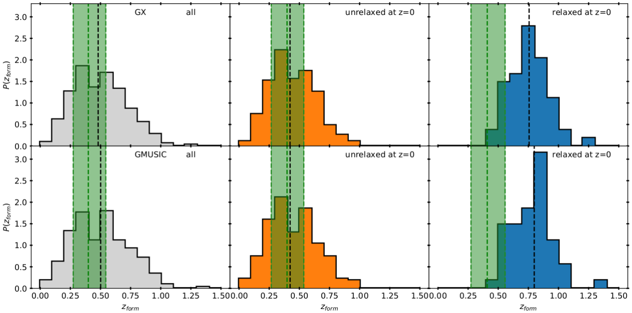
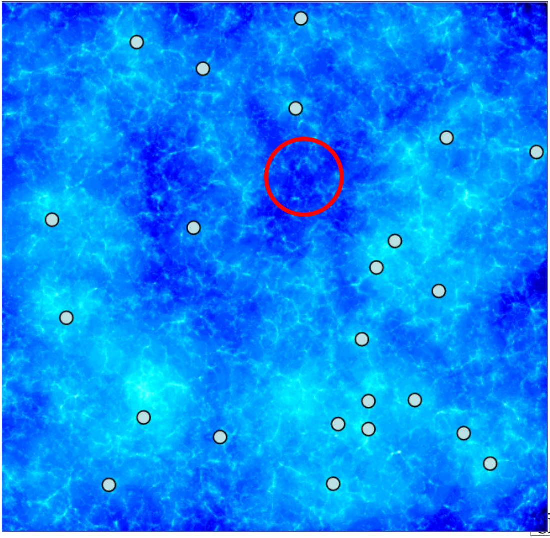


Figure: Formation time. credit: Robert Mostoghiu

The environmental effects: Wang et al. in prep.



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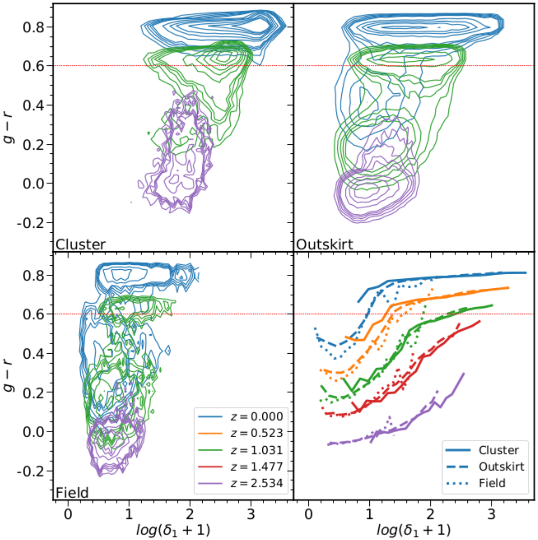

Figure: color–environment relation. credit: Yang Wang

The environmental effects: Wang et al. in prep.

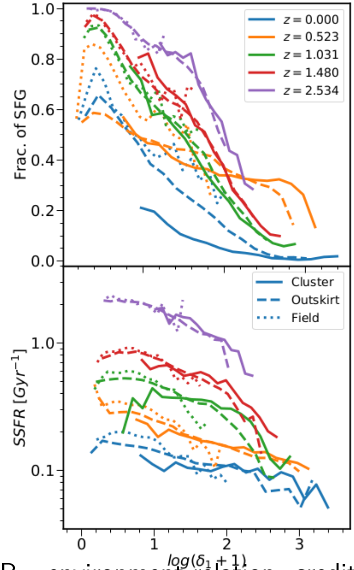

Figure: sSFR – environment relation. credit: Yang Wang

Conclusion

- The baryons have a negligible impact on the halo mass for both M_{200} and M_{500}.
- $\sim$ 20% of the complete sample is relaxed clusters, 26% (9%) of the sample is CC for GadgetX (MUSIC).
- Compare with observations (Agreement): The baryon fractions for cluster mass range, optical relations and gas scaling relations are generally in agreement with the observations.
- Compare with observations (Disagreement): stellar-halo mass relation (A problem of ICL), galaxy color in clusters seems a little blue.
- Relaxed clusters show a weak redshift evolution of the density profile, which is due to their earlier formation time.
- There is a weak environmental effects.

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Future works

Glenfiddling Projects (2018):

Feel free to add/remove your name to projects and edit the titles to be more accurate.

	Project	Lead	Participants	Comments	Infrastructure	Status
1	Evolution of cluster density profiles	Robert	Alexander, Weiguang	to be submitted during week 11-15 June		Advanced draft
2	Influence of environment	Yang	Frazer, Alexander	to be submitted before end of June		Draft
3	Mock observations (optical)	Robert	Meghan, Lyndsay, Weiguang, Alexander, Romeel	plan to use ProFound (https://arxiv.org/pdf/1502.00937.pdf) and get Aaron Robotham onboard... *Note (CP): Can you let me know exactly what you want done and I can help with this? -> AK: check project page for very brief description ;-)* To be finalized during Robert's visit to ICRAR spring 2019 Romeel might supply improved optical maps until then		
4	HI and large scale structure	Katarina	Sofia Romeel	Using Disperse.		
5	Metallicity/age/temperature/SFR profiles	Weiguang	Qingyang	To understand the baryonic processes/different baryonic models through these profiles		
6	Gas environments & tracking haloes	Jake		Combine gas environments / disperse / hessian. Statistical analysis of halo environment. How many haloes are arriving in filaments? Link to Lilian & Pascals evolution tables.		
7	Backsplash	Jake, Alexander	Lyndsey	How does backsplash contamination depend on cluster properties? Are different clusters more contaminated? Apart from kinematics, are backsplash halo properties different to infalling population? Can machine learning algorithms tell them apart? Paper to be finalized during Jake's visit to UAM Oct/Nov 2018...		to be finished Oct/Nov 2018
8	Radiative transfer in gizmo	Margherita	Romeel	Long ways off. Needs RT code inserting into Gizmo and new runs.		
9	Evolution of halo properties wrt orbits.	Lilian, Pascal	Chris, Adam, Sofia, Jake	Emphasis on gas fractions and stripping. Tracking with VELOCIraptor trees. (Lillian:continuing to work on gas fractions, Pascal updating trees/catalogs) Lillian: focus on hot/cold gas fractions during infall and perhaps SFR (worry about resolution) Pascal: where does this stripped gas go, does it stall as whim or deposit cold/metal rich gas, looking at synchrotron/x-ray emitting. *comment from AK: compare against SAM results, too...*		
10	(Radial) alignment of substructures	Alexander	Kai, Charlotte, Rodrigo	Kai will pick this up again in autumn 2018		
11	X-ray scaling relations and profiles in Gizmo	Dylan	Weiguang Romeel	Scaling relation plots ready to go for Gizmo; just need the actual runs (see infrastructure).		
12	Environmental quenching timescale. Role of mass.	Tomas	Sofia	Hydro vs SAM To be pushed forward during Tomas' visit to Nottingham June/July 2018		
13	Dynamical state vs wavelength	Lyndsay	Meghan, Weiguang, Ian, Gustavo, Marco, Silvia, D. de Luca (Sapienza)	(this is the same project as the Crystal Clear one below...)		
14	Lensing	Jesus Vega	Gustavo	Possible applications: lensing efficiency in clusters, comparison with HFF, Magnification of z>5 galaxies...		
15	Machine Learning applications	Gustavo	Federico Sembolini	Use of ML methods to learn from SZ and Xray maps from 300th and apply them to clusters size halos in Large scale DM only sims..		ongoing
16	UCD formation and evolution	Julian	Frazer, Alfonso Aragon-Salamanca	Track stripped and early forming DM halos and compare galaxies within them to properties of observed UCDs. Contrast formation scenarios.		ongoing
17	Supporting WEAVE survey preparation	Meghan	Jake, Frazer, Ulrike Kuchner, Alfonso Aragon-Salamanca	Create a "truth table" for galaxy environments and create observational galaxy quantities tuned to the JPLUS photometric survey, in order to plan/test/refine the targetting strategy for the WEAVE cluster infall spectroscopic survey		ongoing
18	Phase space	Jake	Lilian, Pascal, Meghan	Phase space plane over 300 clusters. Gas fractions (Stripping regions). Binning cluster properties. Projection effects. Few interesting clusters. Looking for preprocessing.		

Figure: Tasks from GlenFindding workshop.

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Future works

Figure: Be one of us!

Contact me cuiweiguang@gmail.com, Alexander alexander.knebe@uam.es or Gustavo gustavo.yepes@uam.es

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