The Three Hundred[1]

The new GIZMO-Simba run

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In collaboration with Qingyang Li,
the SC: Romeel Dave, Alexander Knebe, Megan Gray, Frazer Pearce, Chris Power, Elena Rasia and Gustavo Yepes,
many members of the 300 project and **YOU**

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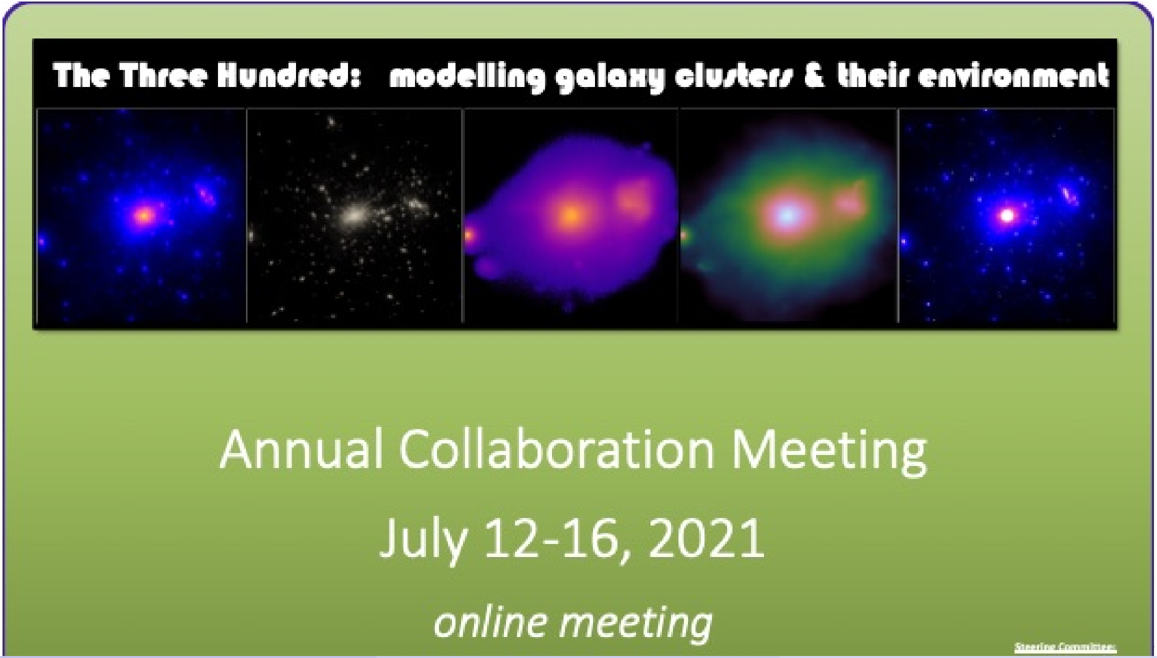
@Rome(virtual), the "mm Universe @NIKA2" Conference; 01, Jul. 2021

[1] /https://the300-project.org/
[2] https://weiguangcui.github.io

Outline


The Three Hundred: modelling galaxy clusters & their environment
Annual Collaboration Meeting
July 12-16, 2021
online meeting
Steering Committee:

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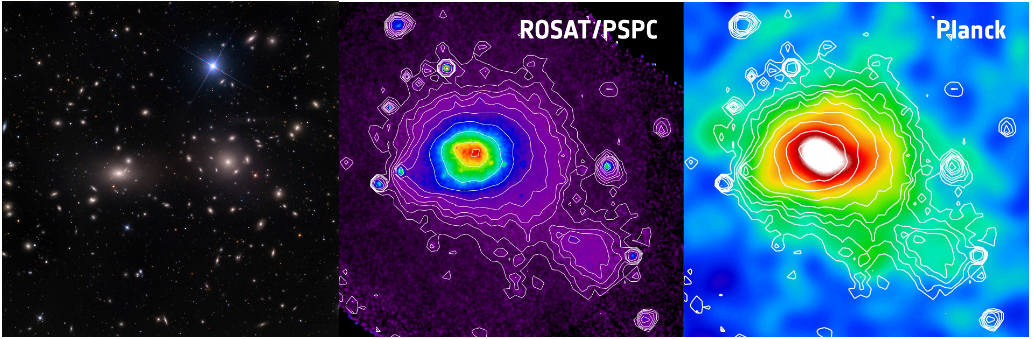
- 

Figure: The Coma cluster.

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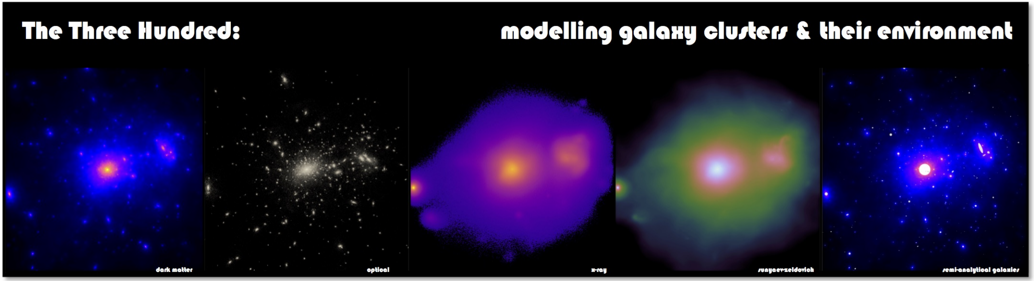
- 

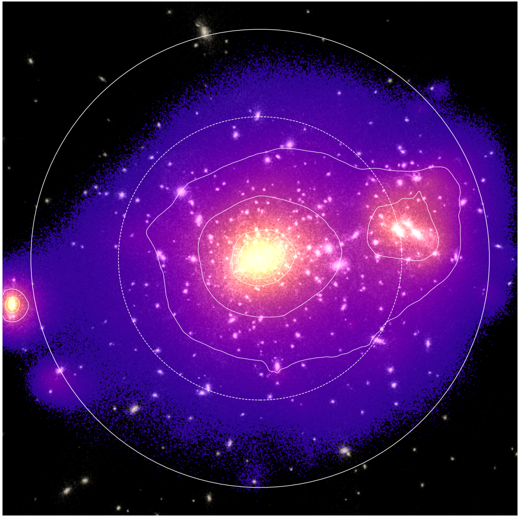
Figure: The 300 cluster.

Background: Cluster of Galaxies:

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

One simulated galaxy cluster from the 300 project

Movie credit: Gustavo Yepes.



The nIFTy galaxy cluster comparison project[3]

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

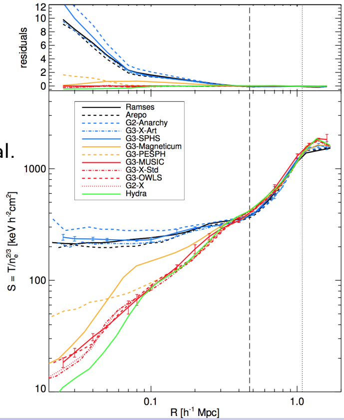
[3] Ref: Sembolini et al. 2016a,b; Elahi et al. 2016; Cui et al. 2016; Arthur et al. 2017

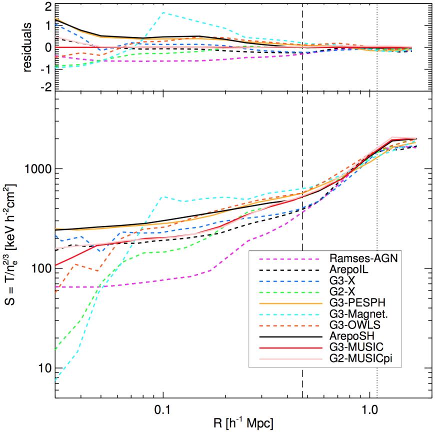
What did we find? I

- 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.

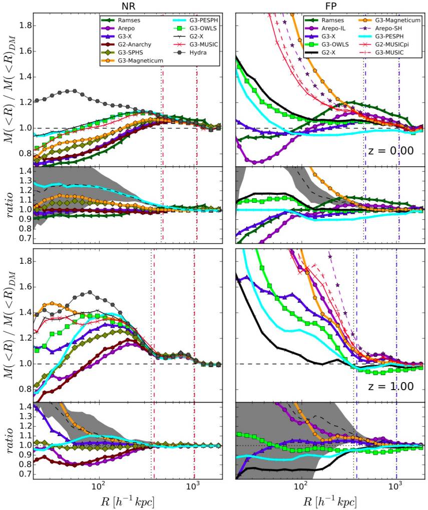




What did we find? II

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.

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A large cluster sample!

Simulated galaxy cluster projects

Table: Cluster projects. Note that only the zoomed-in cluster simulations are listed here, many cosmological hydrodynamic simulations are not included here.

Name	N	mass range	resolution (M_{DM})
MUSIC[3], 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[4], Bahe et al. 2017	24	$10^{14} < M_{200} < 2 \times 10^{15}\ h^{-1}\,\mathrm{M}_\odot$	$10^7\ h^{-1}\,\mathrm{M}_\odot$
FABLE, Henden et al. 2018	6	$\sim 10^{13} < M_{halo} <\sim 10^{15}\ h^{-1}\,\mathrm{M}_\odot$	$\sim 5.5 \times 10^7\ h^{-1}\,\mathrm{M}_\odot$

[3] No AGN

[4] Slightly different to EAGLE in AGN feedback

The advantage of the Three Hundred: Basic information

- The most massive 324 clusters are selected from the MultiDark simulation (MDPL2) [5].
- The zoomed-in ICs have a radius of 15 (40) h^{-1} Mpc for from the cluster (void) center.

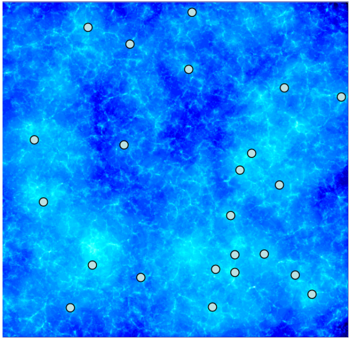

Table: Cosmological Parameters

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 $[10^8\ h^{-1}\ \mathrm{M}_\odot]$

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

Halos and subhalos in hydrodynamic simulations are identified with AHF [6].

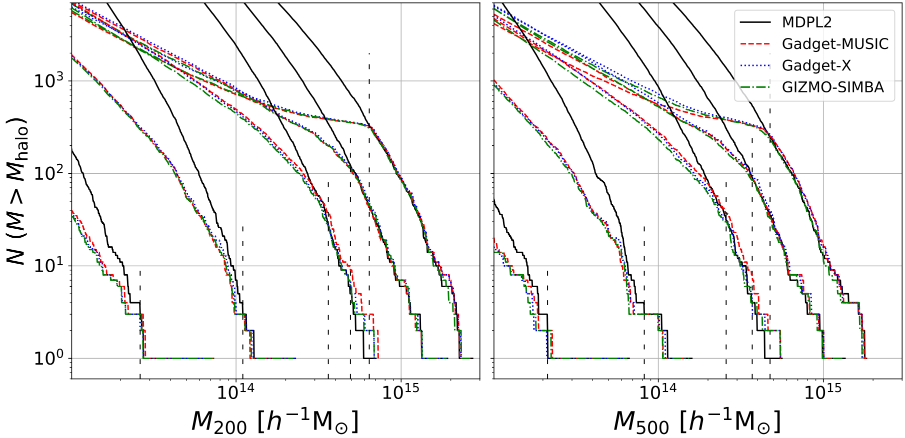

Figure: Cumulative halo mass functions.

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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/GIZMO	M_{500c} $[10^{14}\ h^{-1}\ \mathrm{M}_{\odot}]$	N_{500c} MUSIC/X/GIZMO
0.0	6.41	324 / 327 / 306	4.75	254 / 261 / 228
0.5	4.93	109 / 116 / 113	3.71	88 / 96 / 84
1.0	3.62	38 / 27 / 27	2.58	37 / 31 / 30
2.3	1.10	3 / 3 / 3	0.82	3 / 3 / 3
4.0	0.27	3 / 2 / 3	0.21	2 / 1 / 2

[6] Knollmann & Knebe 2009

The advantage of the Three Hundred

hydrodynamical simulations with baryonic models:

GADGET-MUSIC (Sembolini et al. 2013): classic SPH method. Radiative cooling, star formation with both thermal and kinetic Supernove (SN) feedback.
GADGET-X (Murante et al. 2010): 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-SIMBA: (Dave, et al 2019): New baryon model. Advanced BH/AGN model, 'calibrated'.

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.

The advantage of Three Hundred

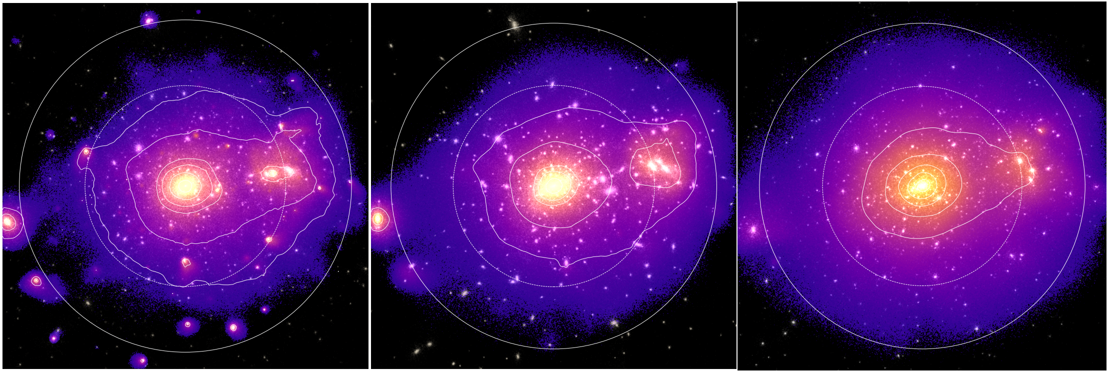


Figure: Mock multi-wavelength observations. From left to right, GADGET-MUSIC, GADGET-X, and GIZMO-SIMBA. Galaxies are shown by combining sdss u, g, r band images; X-ray is presented in colour map and SZ-y signal is highlight in contours.

The advantage of the Three Hundred: theoretical models

- A mass-complete sample for $M_{200} \gtrsim 6.4 \times 10^{14}\ h^{-1}\,\mathrm{M}_{\odot}$ for cosmology.
- Very large re-simulation regions, 15 (40) $h^{-1}\,\mathrm{Mpc}$ in radius for clusters (voids), for environmental studies, such as filaments around galaxy clusters.
- Multiple hydro-simulation codes with additional SAM catalogues for galaxy formation.
- Different halo/subhalo catalogues, merger trees and multi-wavelength mock observation images: optical, X-ray, SZ and lensing maps.

The 300 Project

- General cluster properties Cui et al. 2018
- The GIZMO-Simba run Cui et al. in prep. Preliminary results!
- the cluster radial properties Mostoghiu et al. 2019, Li et al. 2020, Mostoghiu et al. 2021, Li et al. 2021 in prep.
- The cluster dynamical state Capalbo et al. 2021, De Luca et al. 2021, Zhang et al. and Contreras-Santos et al. in prep.
- Filamentary structures around clusters Kuchner et al. 2019, Rost et al. 2021, Kuchner et al. 2021
- The cluster mass Ansarifard et al. 2020, Li et al. 2021, Gianfagna et al. 2021 in prep.
- Back-splash galaxies Hagger et al. 2020, Knebe et al. 2020
- Many other works that not listed here can be found https://ui.adsabs.harvard.edu/user/libraries/j5Ck2ByeTHSsSvUjO8dpGw.

The introduction paper

General Properties: Baryon effects on halo mass

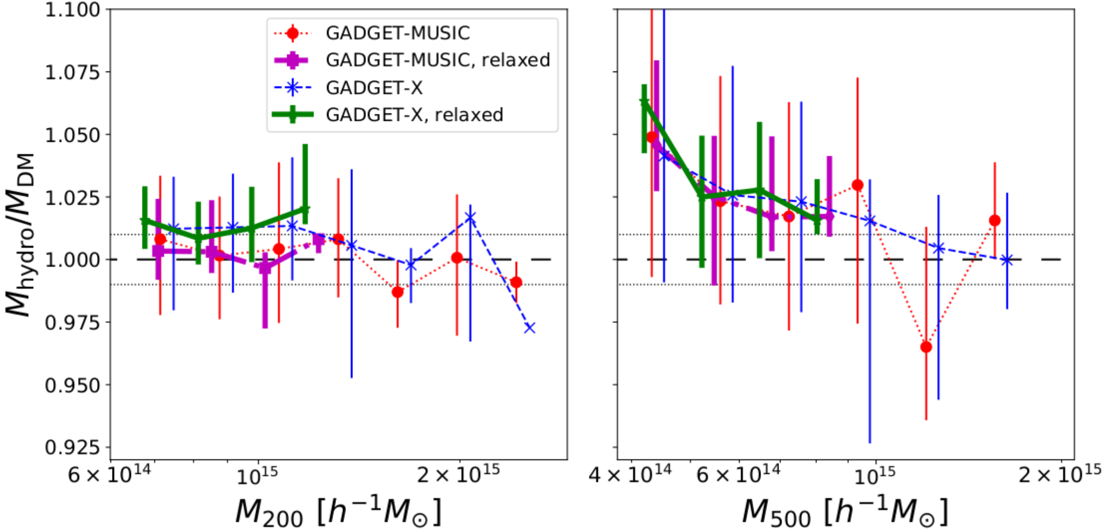
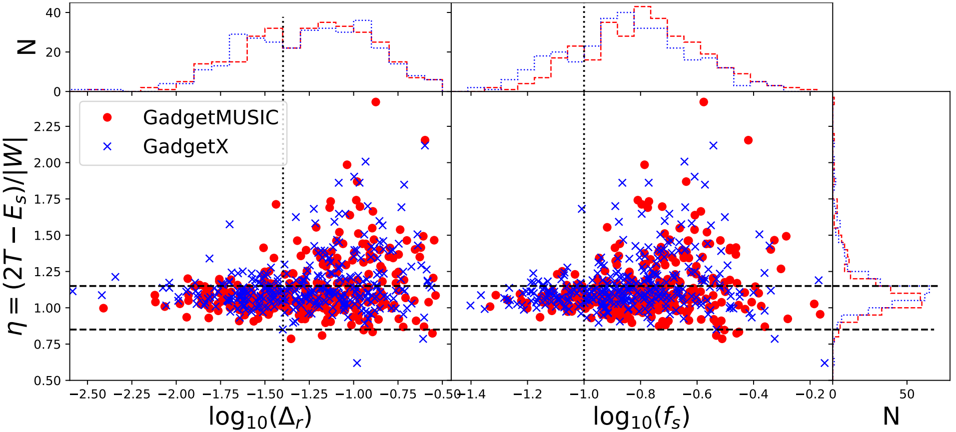


Figure: halo mass difference respected to the DM run.

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



General Properties: the dynamical state

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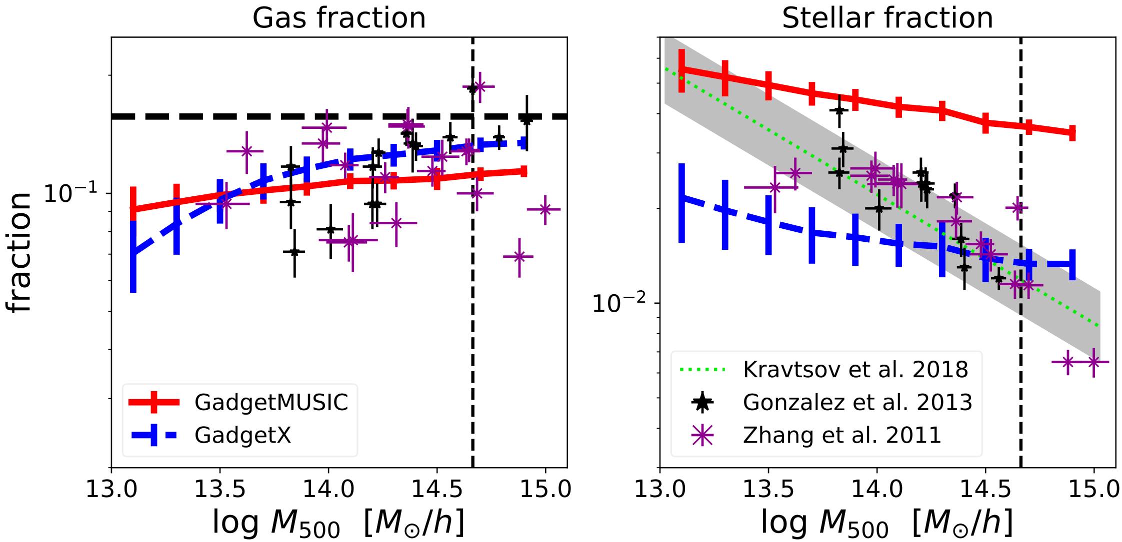
Table: The fractions of relaxed clusters with different combinations of criteria.

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
> 6.42	0.15 / 0.17	0.16 / 0.21	0.17 / 0.23

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



General Properties: the halo - central galaxy mass relation

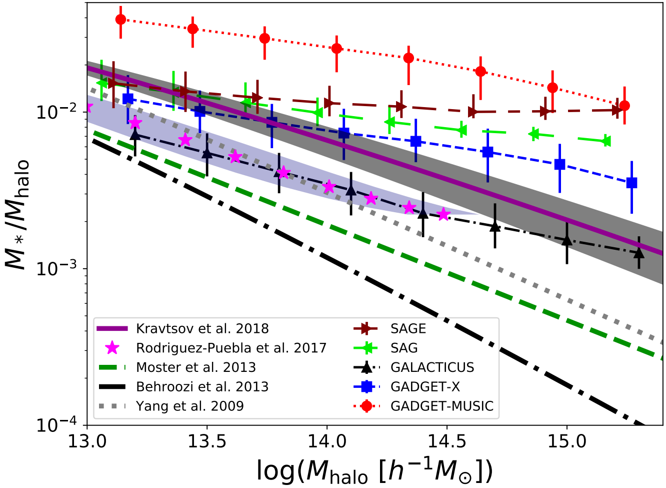


Figure: The halo mass - central galaxy mass relation.

Optical relations

The complete sample is used here.

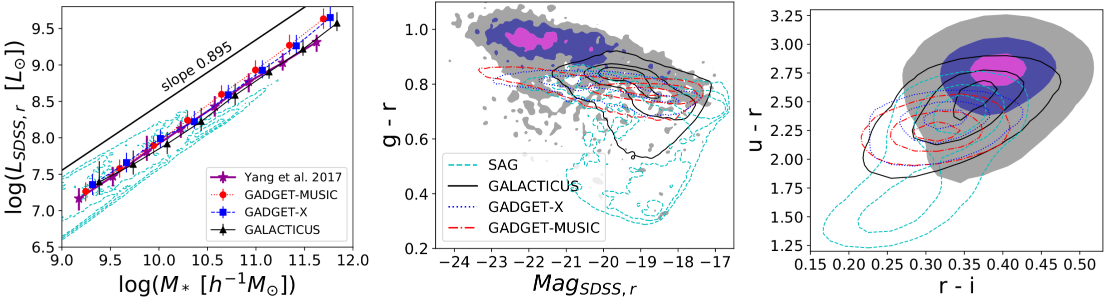


Figure: The optical relations.

Optical relations: the satellite stellar mass function

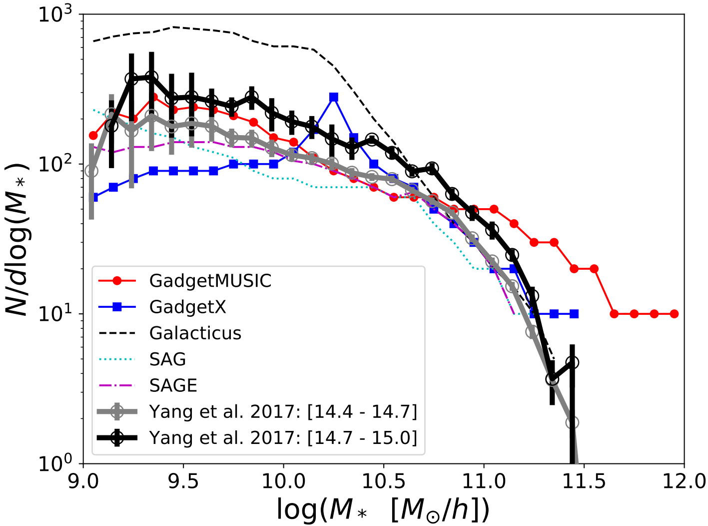


Figure: The satellite stellar mass function.

Gas scaling relations

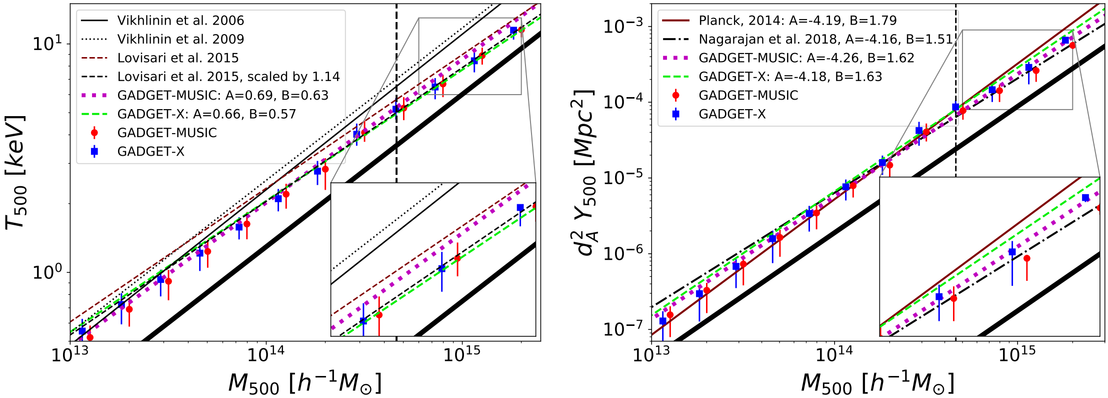


Figure: The gas scaling relations. Fitting function – $Y_{500} = 10^A(\frac{M_{500}}{6\times10^{14}M_{\odot}})^B$

Conclusion

- The baryons have a negligible impact on the halo mass for both M_{200} and M_{500} at the most massive end, but slight increase the halo mass (several percent) at towards smaller cluster mass.
- $\sim 20\%$ 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 (the problem of ICL), galaxy color in clusters seems a little blue.

jump to the last slide

jump to the list

The new GIZMO-Simba run

The GIZMO-Simba run of the 300 clusters: basic information

- This GIZMO-Simba version of the 300 cluster is based on the success of the Simba simulation (Dave et al. 2019).
- The simulation code is based on GIZMO (Hopkins 2015, 2017), MUFASA model (Dave et al. 2016) with a new advanced BH model (Angles-Alcazar et al. 2017) and a dust model (Li et al. 2019). See next slide for details.
- Other input physics: GRACKLE-3 for gas radiative cooling and photoionization heating, Haardt & Madau (2012) ionizing background with self-shielding, an H_2-based star formation rate, 11 elements are tracked with chemical enrichment from Type II supernovae (SNe), Type Ia SNe, and Asymptotic Giant Branch (AGB) stars, stellar feedback with mass loading factor follows Angles-Alcazar et al. (2017b).
- This GIZMO-Simba clusters are "re-calibrated" mainly with stellar properties: 1) baryonic contents within R_{500}; 2) satellite stellar mass function; 3) BCG-halo mass relation.

The Simba simulation (Dave et al. 2019): the advanced BH model

Two types of BH accretion:

- the torque-limited accretion model for cold gas ($T<10^5$ K, Angles-Alcazar et al. 2015, 2017)
- Bondi-Hoyle-Lyttleton accretion model for hot gas ($T>10^5$ K)

Three BH feedback models:

- 'Radiative feedback' in high Eddington ratios $f_{Edd} \gtrsim 0.02$ with a wind speed of 1000 km/s.
- Jet feedback (kinetic) in low $f_{Edd} \lesssim 0.02$ ejects the hot gas in collimated jets with a wind speed 15000 km/s (about 2 times higher than the original SIMBA setup).
- X-ray feedback for galaxies in jet-mode with gas fraction $f_{gas} < 0.2$.

The Simba simulation (Dave et al. 2019): the dust model

- Dust is passively advocated following the gas particles.
- It has the same physical properties with a fixed radius a $=0.1\ \mu m$.
- Dust is produced by condensation of metals from eject of SNe and AGB stars.
- Once dust grains are produced, they can grow by accreting gas phase metals.
- Dust will be destroyed instantaneously in the process of hot winds (for example AGN X-ray heating or jets) and star formation, with all dust mass and metals being returned to the gaseous phase.

The *"calibrated"* baryon fractions

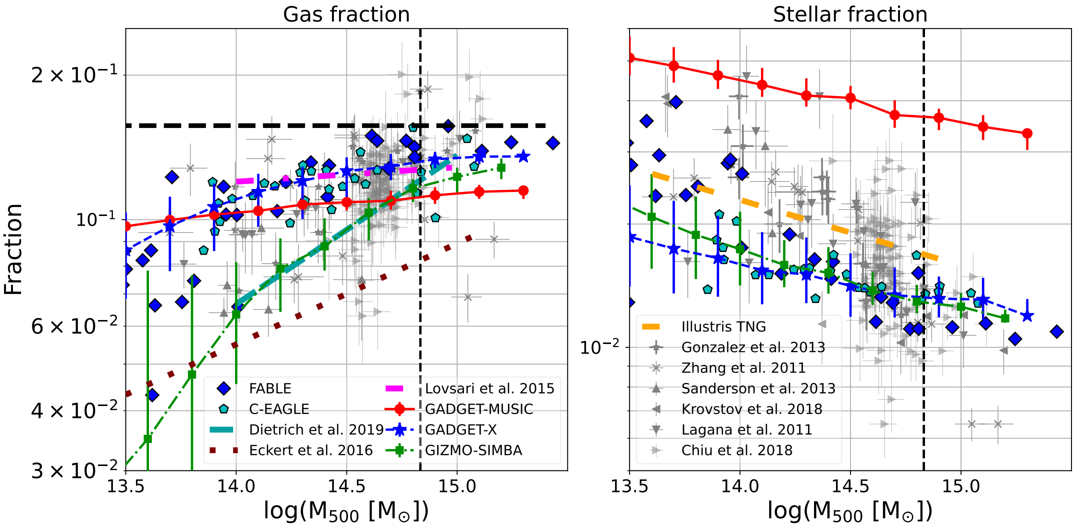


Figure: @z = 0. The stellar fraction at the massive end are still slightly higher than observations.

The evolution of the baryon fractions

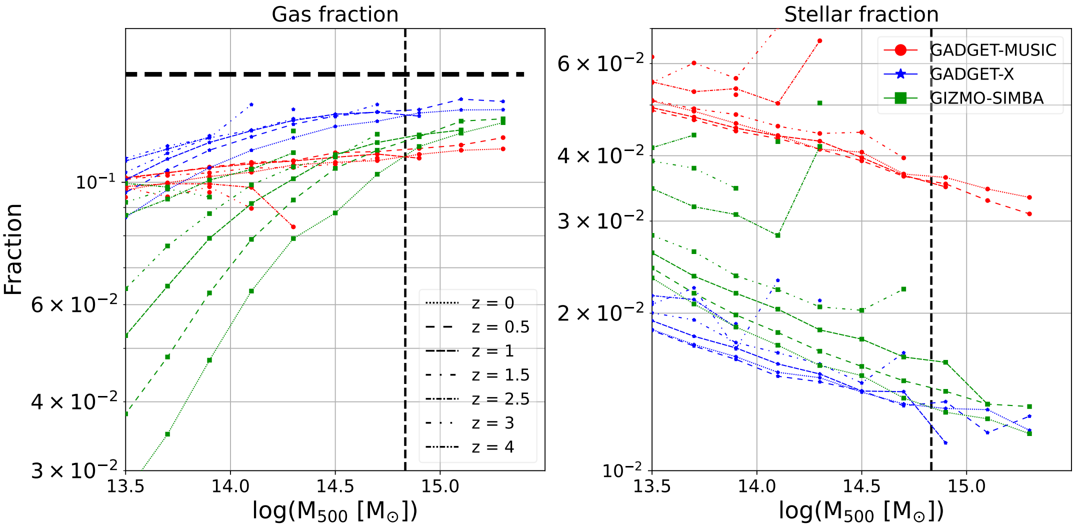


Figure: The gas and stellar fractions evolution at different halo mass range.

The evolution of the baryon fractions

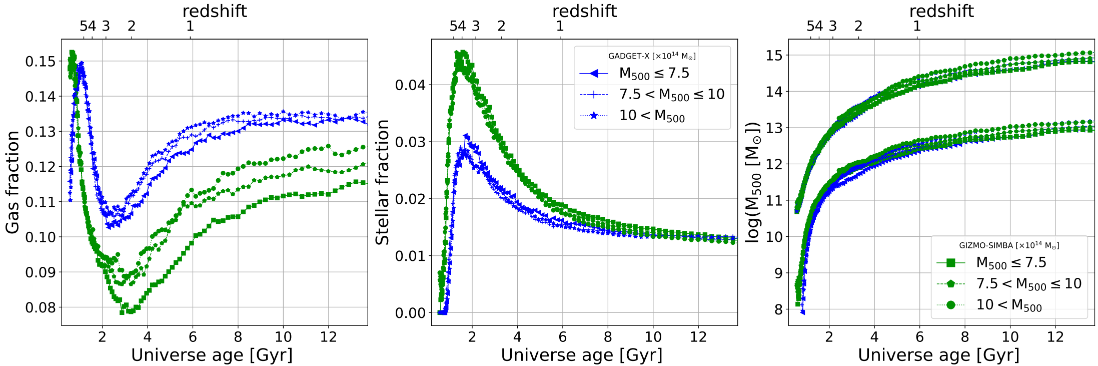
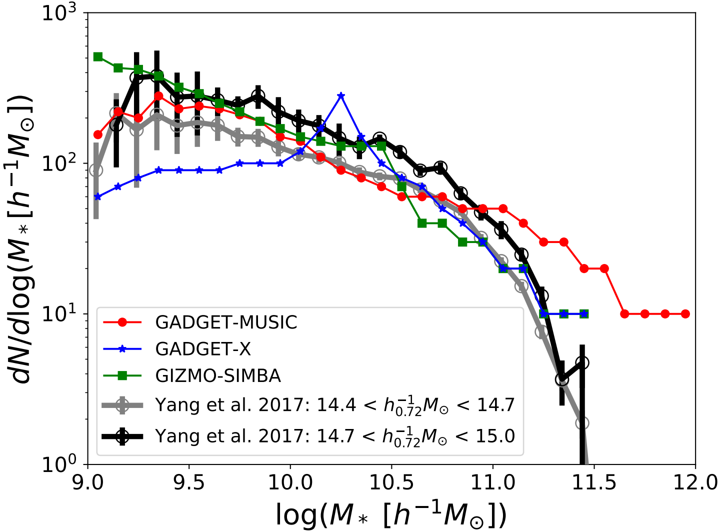


Figure: The gas and stellar fractions and masses evolution by tracking the central clusters separated into 3 mass bins.

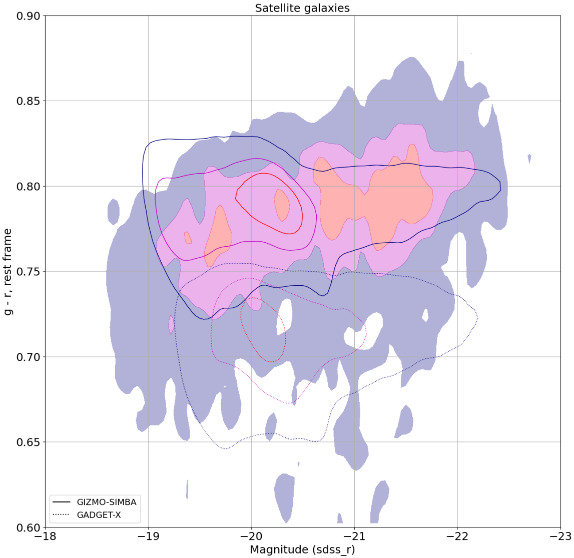
The *"calibrated"* satellite stellar mass function



The satellite stellar mass function – stellar mass function but only for satellite galaxies within clusters.

The agreement for GIZMO-SIMBA is shown for both high and low stellar mass galaxies.

The color-magnitude diagram for satellite galaxies in the central clusters



The satellite galaxy colour-magnitude diagram at rest frame.
SDSS satellite galaxy distribution is shown in the colour map. The same percentiles (16th-50th-84th) are used for GIZMO-SIMBA and GADGET-X contours. The same stellar mass cut $M_* > 10^{10} M_\odot$ is applied.

The "*calibrated*" BCG-halo mass relation

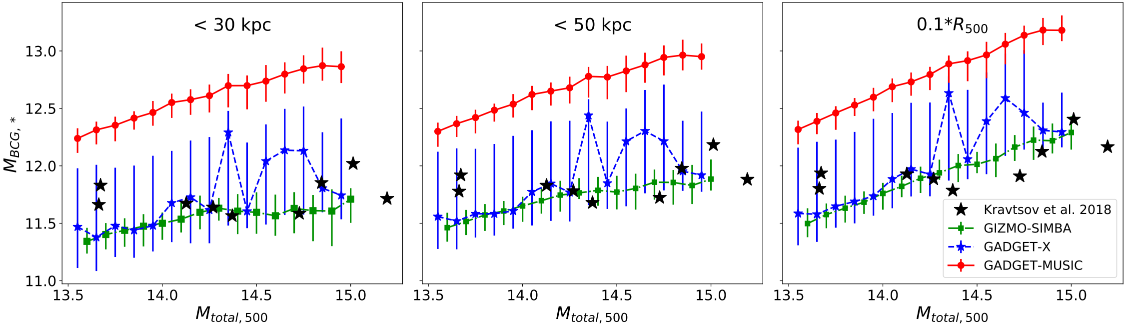
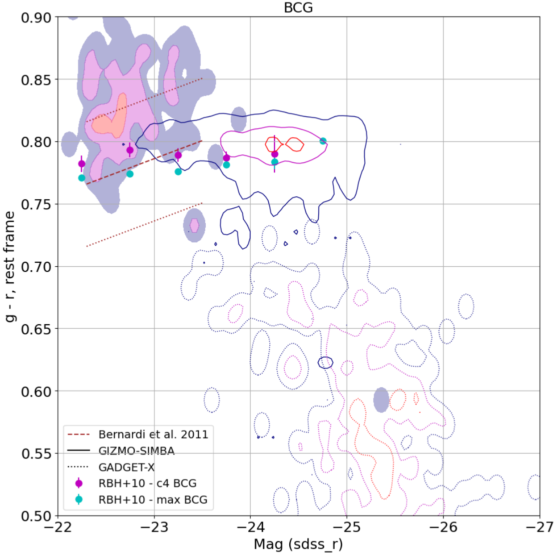


Figure: The halo mass M_{500} VS. BCG stellar mass calculated within 30, 50 and $0.1R_{500}$ (3D from simulation) from left to right panels.

The BCG colour-magnitude diagram



The BCG colour-magnitude diagram at rest frame. Everything is the same as the colour-magnitude diagram for satellite galaxies, but shown the BCG instead here. Note that the Bernardi et al. 2011 results show the massive red sequence galaxies.

The BH-galaxy-halo relations

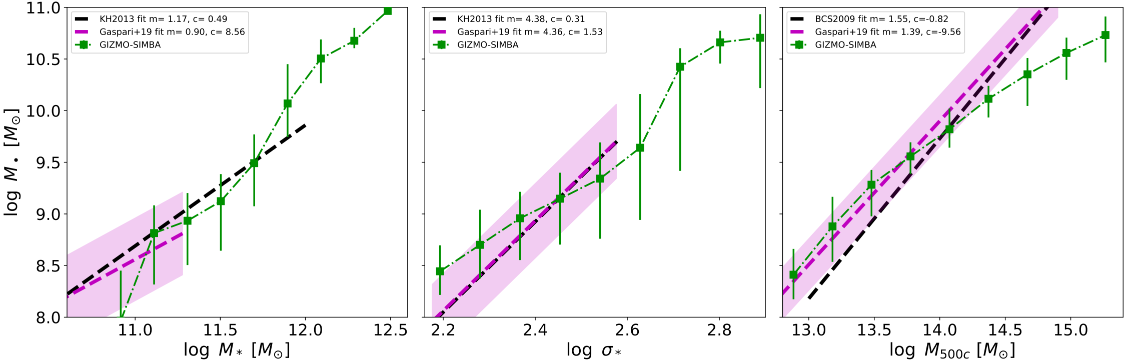
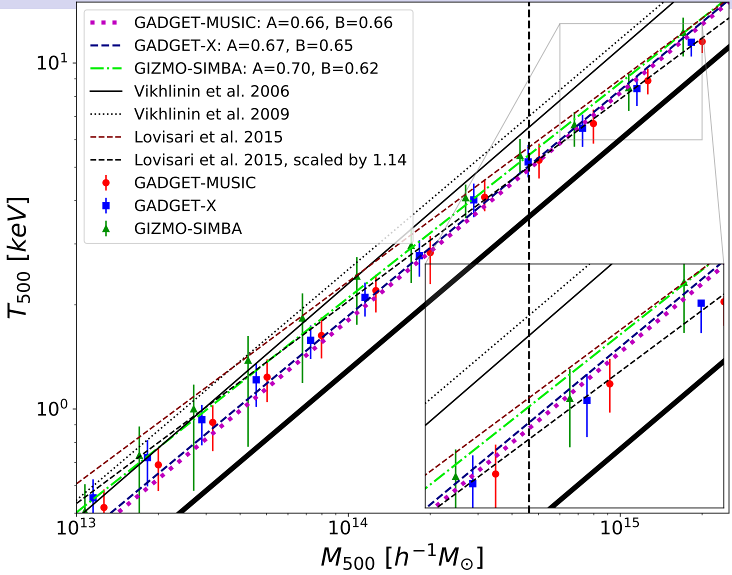
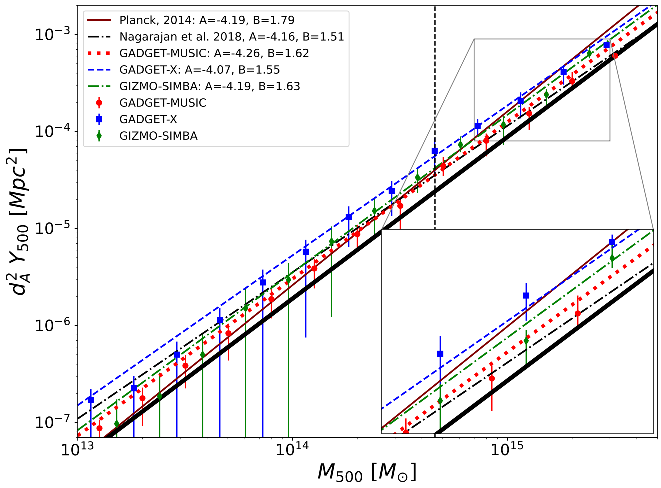


Figure: The $M_\bullet$ - M_* (left), $M_\bullet$ - σ_* (middle) and $M_\bullet$ - M_{halo} (right) relations. GIZMO-SIMBA is in good agreement with observational results at lower masses. It predicts a slight deviation from the interpolations: A higher ($\sim$ 2 times) BH mass in $M_* \gtrsim 10^{12} M_\odot$; A flatter trend in $M_\bullet$ - σ_* (middle) and $M_\bullet$ - M_{halo} (right) relations.

The Gas properties



The mass-weighted temperature - halo mass relation.
GIZMO-SIMBA seems to have slightly higher temperature compared to GADGET-X, especially at lower halo mass range.



The Y_{500} - M_{500} relation. Note, mass-weighted fitting based on their completeness fraction is adopted for all three simulation models.

Conclusion

The new GIZMO-SIMBA run which is completely different baryon model (also hydrodynamics), by designed, have a different constrains (mostly focusing on galaxy/stellar properties) to highlight the agreement/disagreement between these models.

- I hope that I have convinced you that GIZMO-SIMBA provide a more realistic galaxy/stellar properties.
- There is clear much more differences between GIZMO-SIMBA and GADGET-X at high redshift.
- The gas scaling relations are generally in line with each other and with observations at z=0.
- GIZMO-SIMBA also predicts that the BH scaling relations can be different at the most massive objects.

jump to the last slide jump to the list

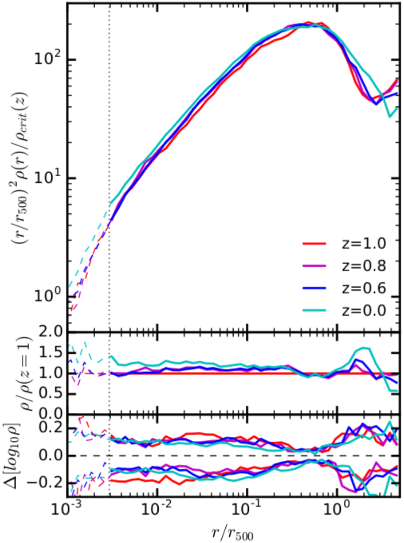
1. **The self-similarity of galaxy cluster density profiles**
2. **The galaxy cluster physical profiles**
3. **The evolution of the galaxy cluster profiles**

The self-similarity of galaxy cluster density profiles

Mostoghiu et al. 2019, MNRAS, 483, 3390

The self-similarity of galaxy cluster density profiles

The motivation:



Density profiles. Le Brun et al. 2018

The self-similarity of galaxy cluster density profiles

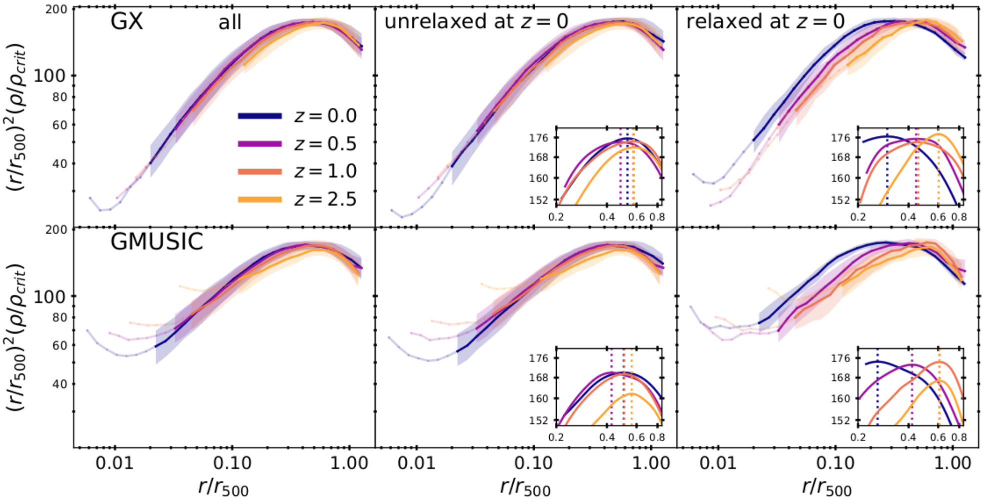
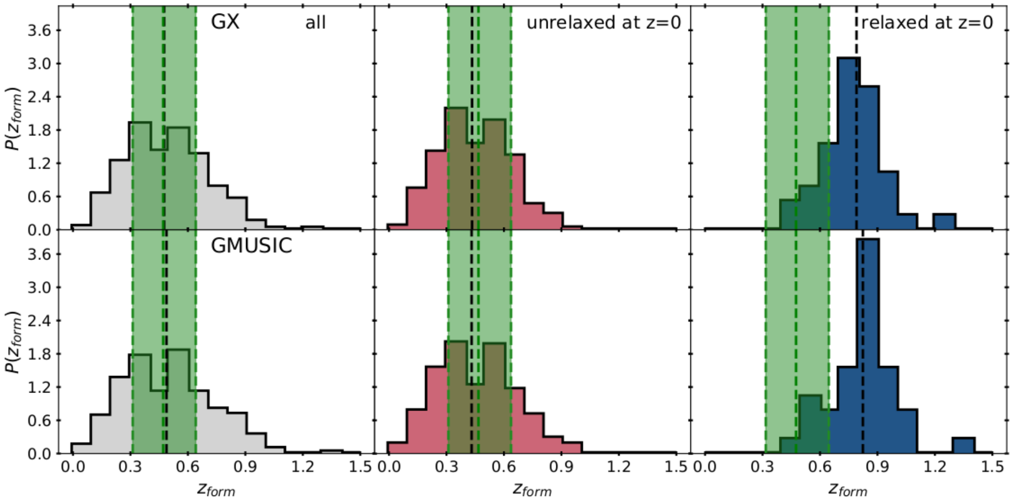
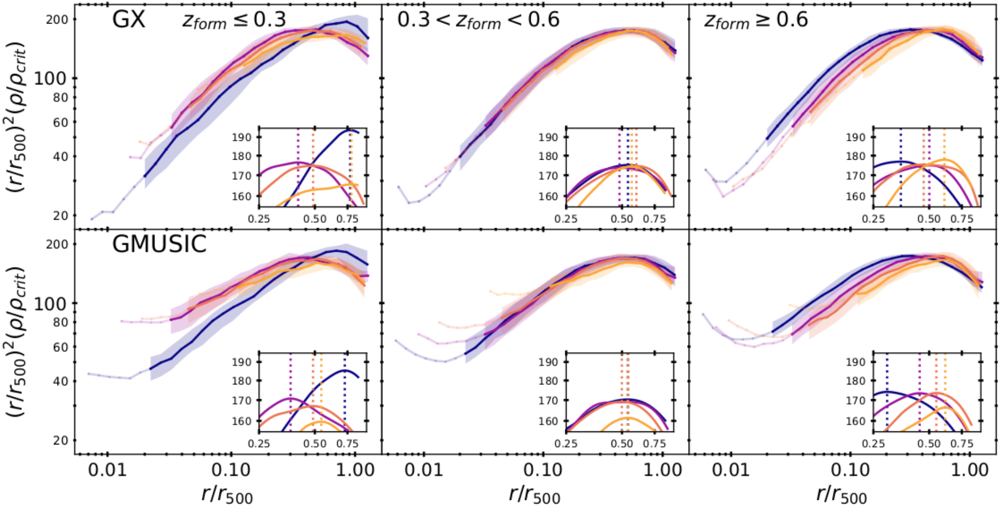


Figure: Galaxy cluster density profiles are separated into relaxed and un-relaxed sample. Mostoghiu et

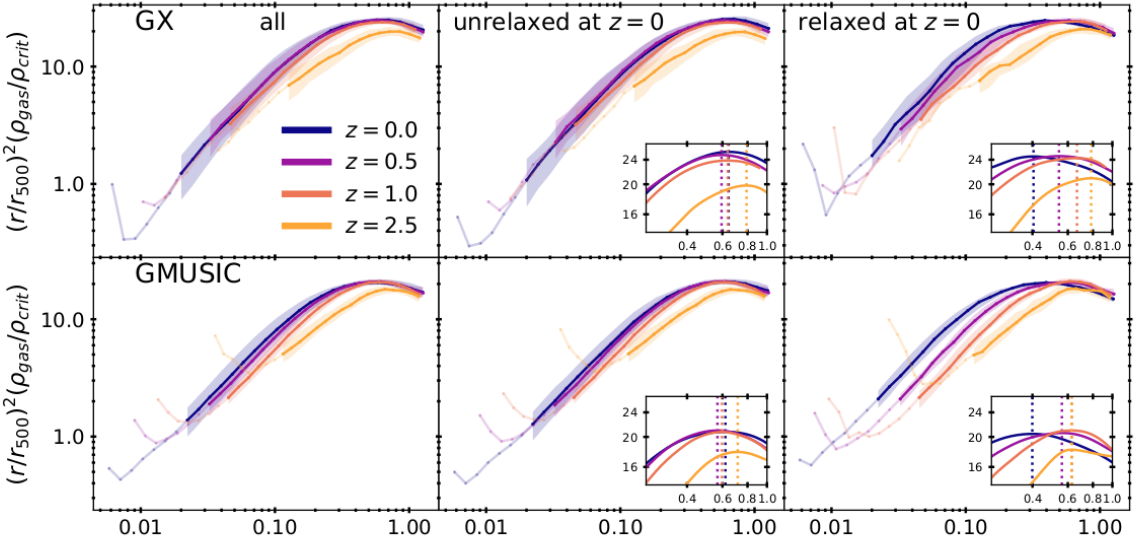
The self-similarity of galaxy cluster density profiles



The self-similarity of galaxy cluster density profiles



The self-similarity of galaxy cluster density profiles



Conclusion

- Agree with LeBrun et al 2018, the density profile shows self-similarity up to $z = 2.5$.
- However, separating the relax clusters from the un-relax ones, we found the density peaks from the relax clusters show redshift evolution.
- This redshift evolution of the density peak, is due to their earlier formation time.
- The gas density profiles agree with the total density profiles beside the redshift $z=2.5$, which could due to mergers and/or star formation.

jump to the last slide jump to the list jump to the subsection

The galaxy cluster physical profiles

Li et al. 2020, MNRAS, 495, 2930

some slides need update!!

The galaxy cluster physical profiles

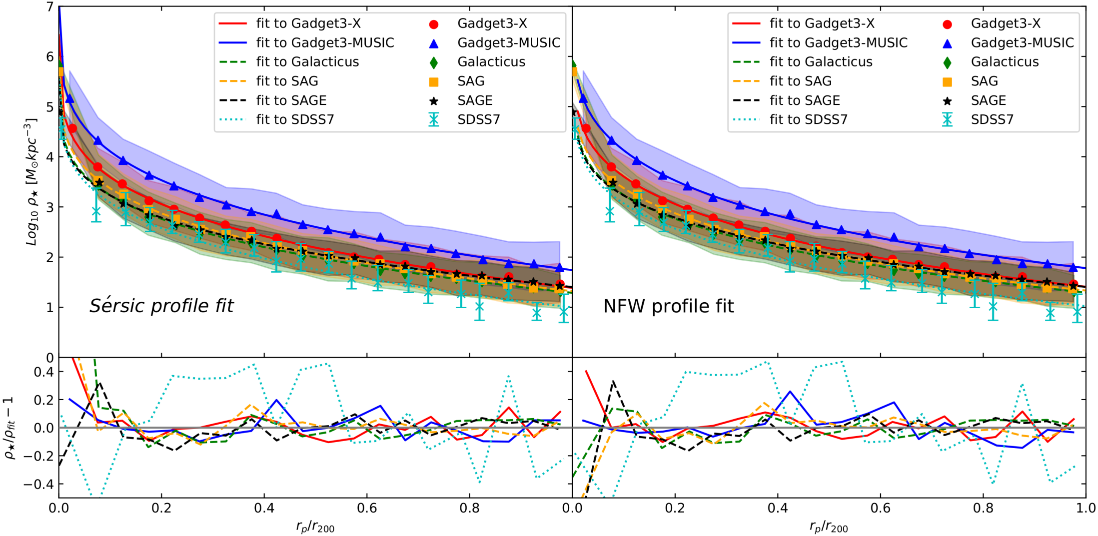


Figure: The stellar density profile.

The galaxy cluster physical profiles

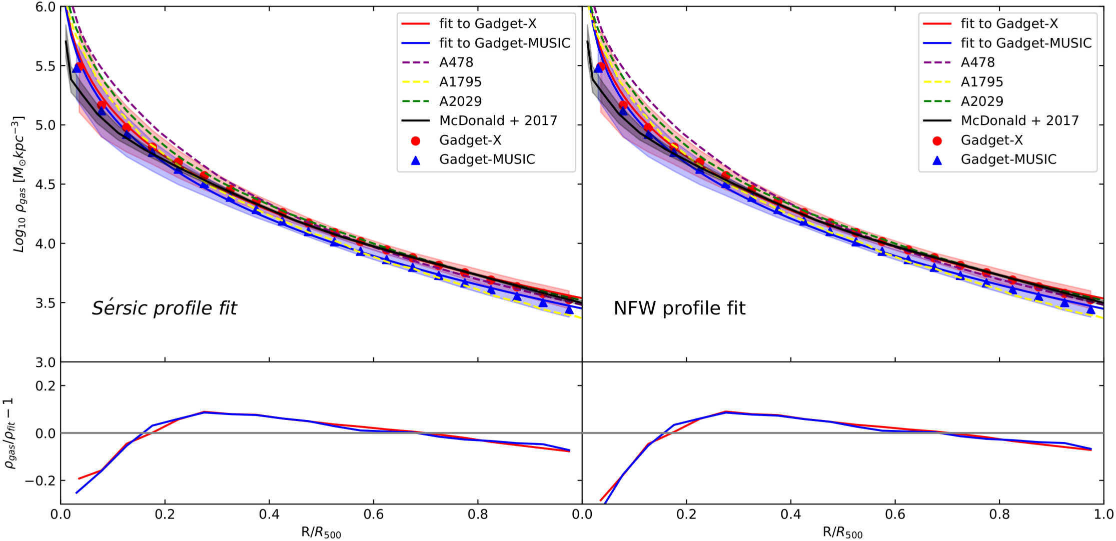


Figure: The stellar density profile.

The galaxy cluster physical profiles

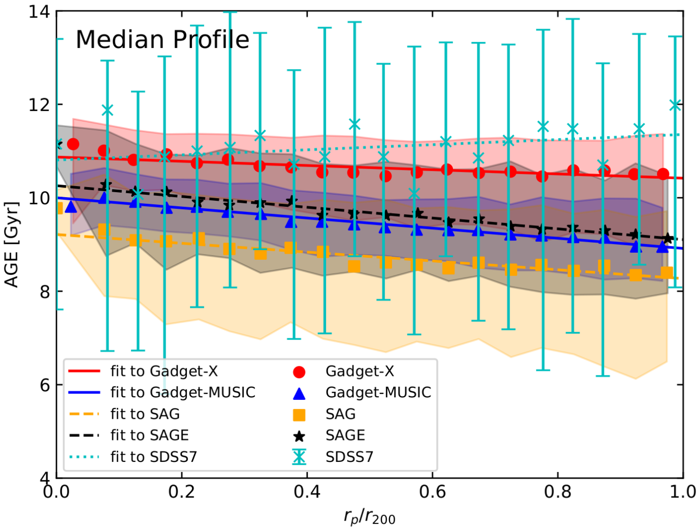


Figure: The stellar age profile.

The galaxy cluster physical profiles

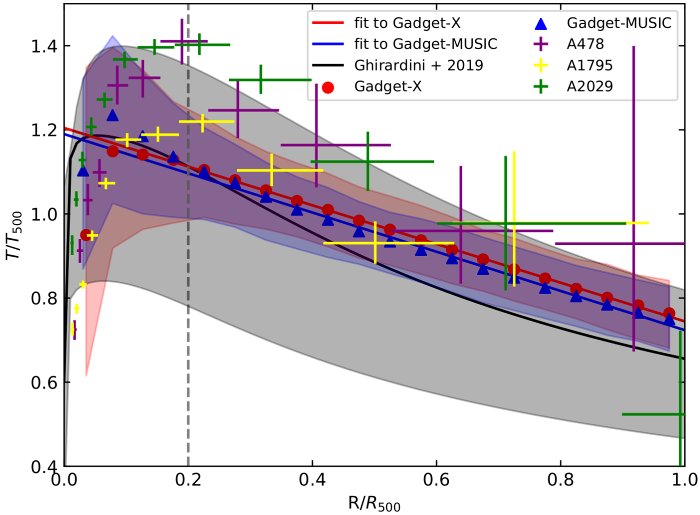


Figure: The gas temperature profile.

Conclusion

Stay tuning...

The evolution of the galaxy cluster profiles with GIZMO-SIMBA!

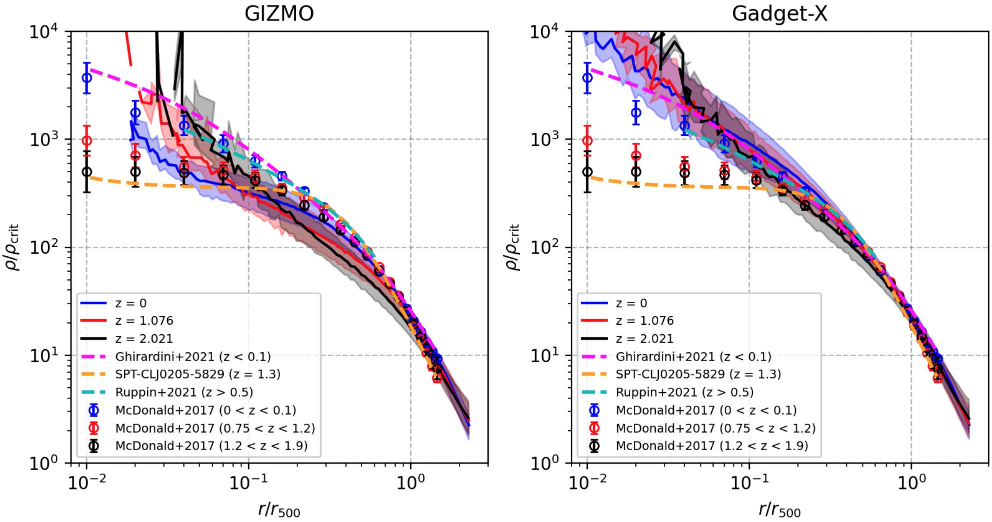
Li et al. 2021, in prep. Preliminary results!!!

The evolution of the galaxy cluster profiles

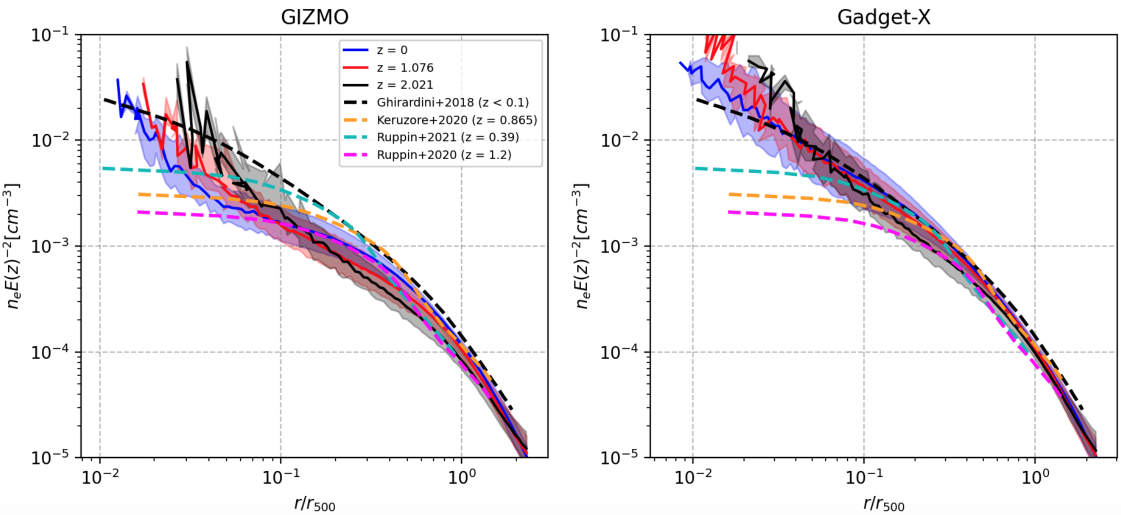
The motivation:

- The physical profiles will give structure information for comparisons.
- It connects with many important quantities of the clusters, such as concentration.
- Its evolution will reveal galaxy cluster formation in detail.

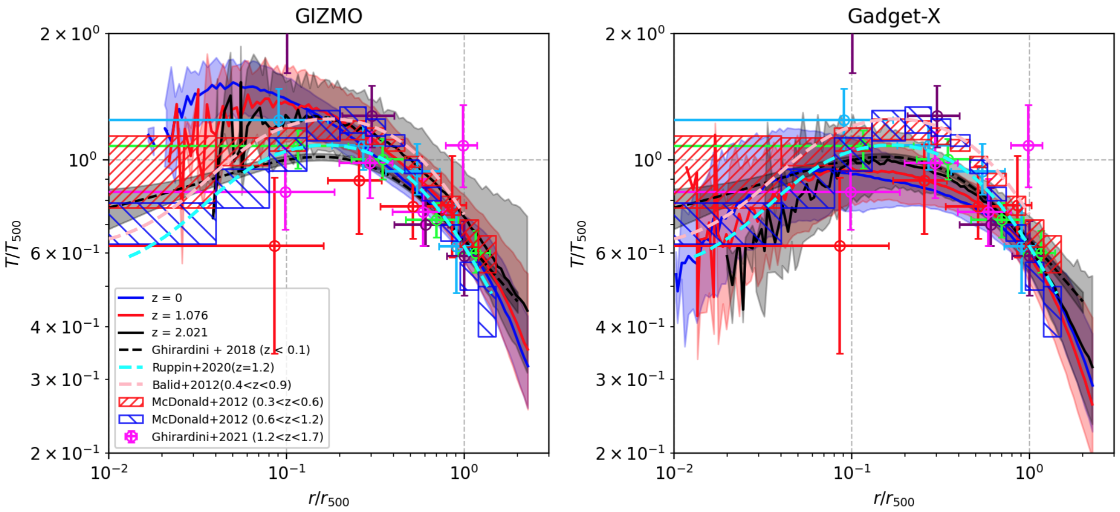
The evolution of the galaxy cluster profiles



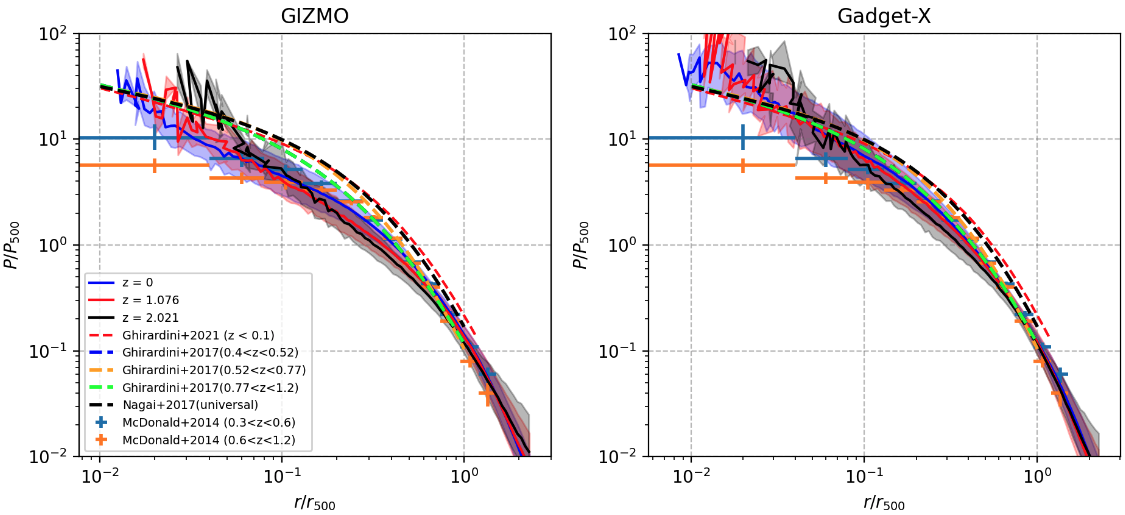
The evolution of the galaxy cluster profiles



The evolution of the galaxy cluster profiles



The evolution of the galaxy cluster profiles



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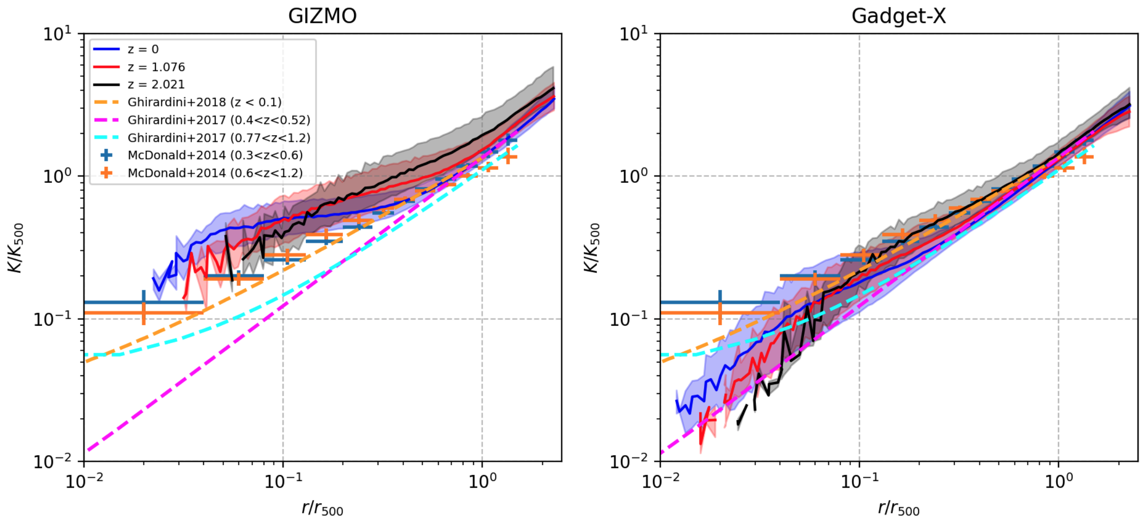

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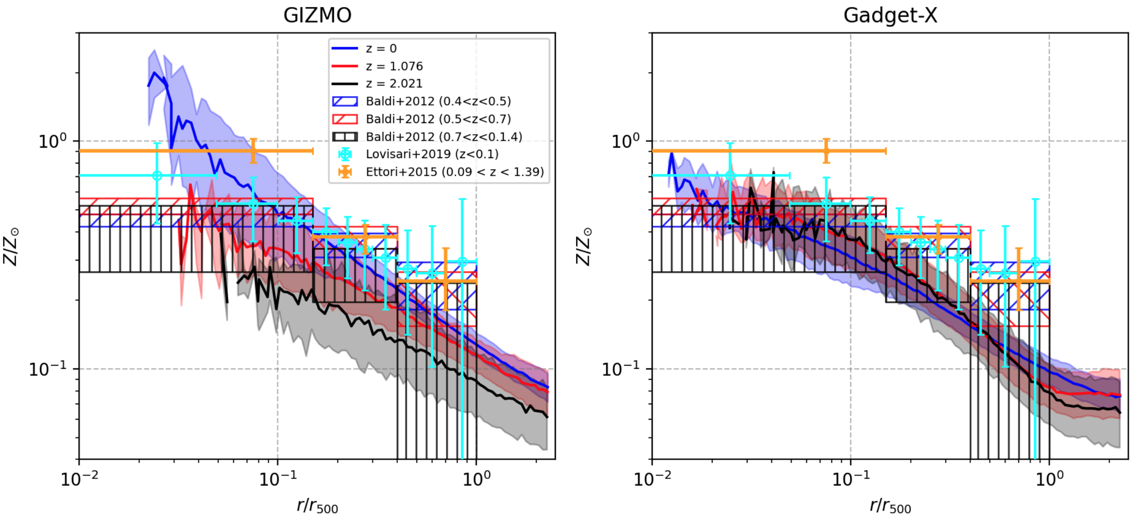
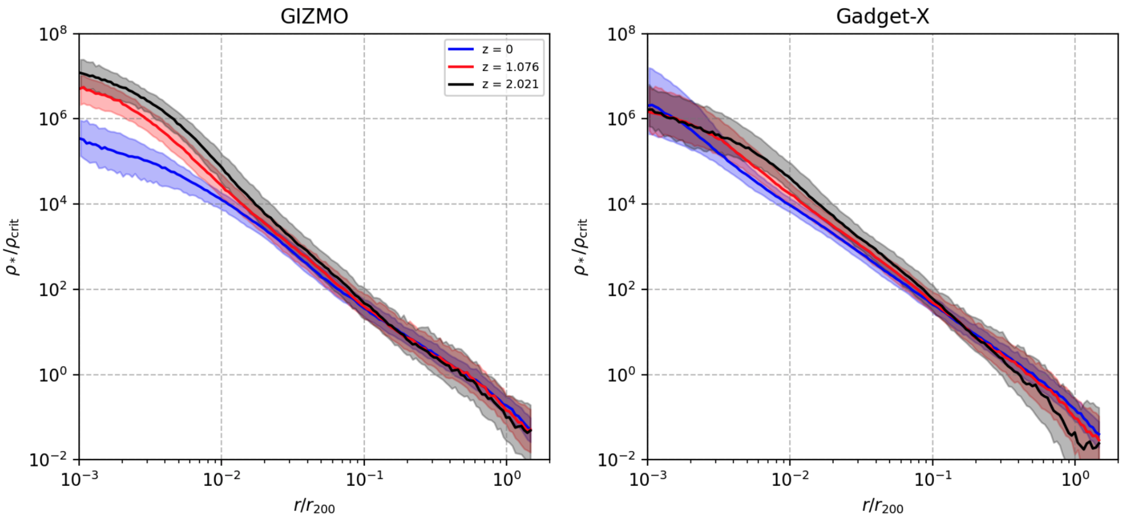


The evolution of the galaxy cluster profiles



Conclusion

- Agreed to previous finding, GIZMO-SIMBA tends to have larger redshift evolution compared to GADGET-X, especially for metallicity and gas density profiles.
- The evolution is basically in the same direction, but radial dependent: larger in the inner region than outer region.
- Additional checks and even high redshift results are needed. To be continued.

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correcting for the hydrostatic-equilibrium mass bias in X-ray and SZ surveys

Backsplash galaxies in simulations of clusters

The 300 organization and policy

- **An open organization** >100 members from over 30 institutes in 13 different countries.
- **a fair-play policy** Every member will need to read and agree to the 300 policy document. All data is accessible for the members. Contributions of each authors to the paper will be clearly showing in the paper (same as nature paper).
- **Well-defined project with education opportunities**[7] See next page for the projects. We hold a workshop each year for the collaborators to meet and discuss any questions or problems, and to work on the projects.

[7] especially for students who want to know numerical simulation

The 300 organization and policy

The routine to join the 300 project[7]:

1. A very brief proposal to state what you are going to do with these simulated clusters. Meantime, you will get our policy document to read.
2. In case of no conflicts and you agree to the 300 policy. You will be added to the member list.
3. We open the pbwork page (for projects) and the data server accesses (for simulation data/catalogue) for you.
4. In case of conflict of interests to on-going works, we will especially reply with detailed information. For project ideas (proposed, but no one is working on that), we will coordinate with the project leader for transferring or collaborating on this project.

[7] For students who are interested to learn or do some simulation-related work without knowing what to do, please get in touch! We have a lot of projects without a leader!

Planned/proposed simulations

- High-resolution (HD) runs, 8X more high-resolution particles with $M_{DM} \sim 10^7\ h^{-1}\,\mathrm{M}_\odot$. 30 (10%) selected clusters with ultra-high resolution.
- Protocluster runs focusing on the protocluster regions with extra-high resolution at high redshift.
- Alternative cosmology/DM model runs.

Project lists

Thank you

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Università degli Studi di Trieste
Center for Astrophysics — Harvard & Smithsonian
Penn — University of Pennsylvania
TLS
ASIAA
Alma Mater Studiorum Università di Bologna
UC — Universidad de Cantabria
Carnegie Institution for Science
CONICET — UNC Universidad Nacional de Córdoba — IATE
esa — European Space Agency
IAFE — CONICET — UBA
IALP — CONICET — UNLP
University of Iceland
Lancaster University
Université de Lyon
McMaster University
LMU — Ludwig-Maximilians-Universität München
AIP — Leibniz-Institut für Astrophysik Potsdam
Princeton University
Pontificia Universidad Católica de Chile
Sapienza Università di Roma
Russian Academy of Sciences
Stanford University
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