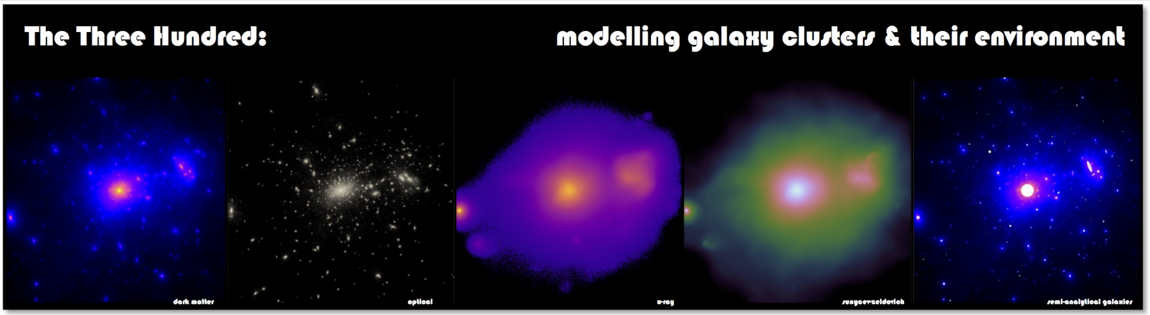


The Three Hundred: seeing the unseen

Weiguang Cui[1] In collaboration with the300 members.

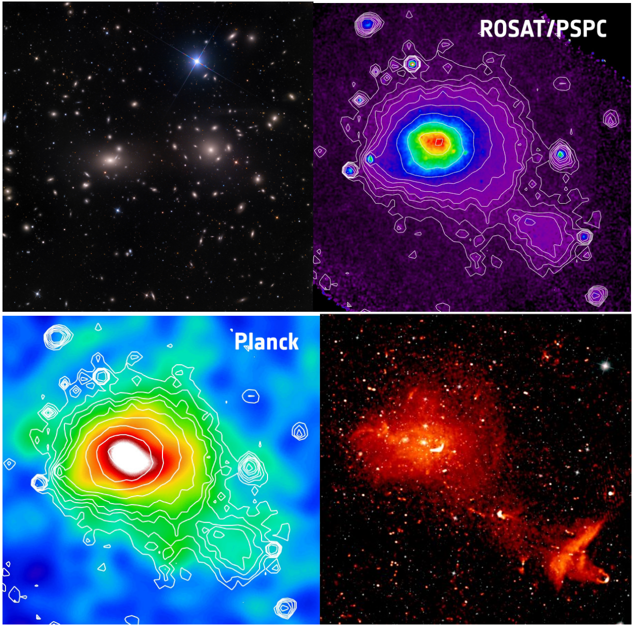
Colloquium at KIAA, Beijing University; 16, November, 2023

[1]Email: weiguang.cui@uam.es; Departamento de Fisica Teorica, UAM https://weiguangcui.github.io

Outline

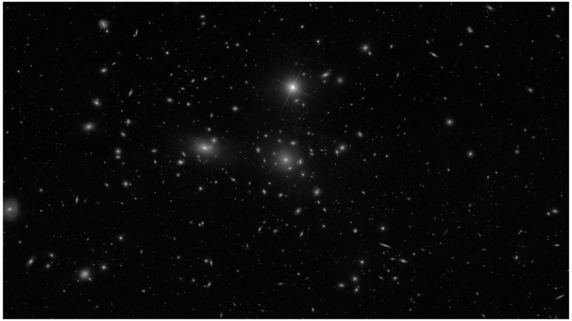
1. Introduction
   - Why galaxy cluster
   - Why (hydro-)simulation
   - Why the300
2. All about cluster dynamical state
3. The lensing crisis
4. Advanceing the machine learning applications
5. The surrounding environment of galaxy cluster – filaments
6. Conclusions

The Ultimate Cluster of Galaxies



- Cosmology
- Large-scale structure formation
- Galaxy Formation
- ICM physics
- BH
- ....

Why (hydro-)simulation – understanding by reproducing



Hydrosimulation includes sophisticated models to prescribe baryons physical processes co-evolving with dark matter.

image credit – link: https://tinyurl.com/4tdshvu5

Why The Three Hundred[4] (The300)

Table: Hydrodynamic simulated cluster. Due to the limitation of the computation power, most current cosmological hydrodynamic simulations can provide limited number of clusters. Most galaxy cluster simulations use the zoomed-in technique to only focus on the galaxy clusters only. Incomplete lists here.

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	$10^{14} < M_{200} < 2 \times 10^{15}\ h^{-1}\,\mathrm{M}_\odot$	$10^7\ h^{-1}\,\mathrm{M}_\odot$
FABLE, Henden et al. 2018	6	$\sim 10^{13} < M_{halo} <\sim 10^{15}\ h^{-1}\,\mathrm{M}_\odot$	$\sim 5.5 \times 10^7\ h^{-1}\,\mathrm{M}_\odot$
ROMULUSC, Tremmel et al. 2019	1	$\sim 10^{14}\,\mathrm{M}_\odot$	$\sim 3.4 \times 10^5\,\mathrm{M}_\odot$

Recent cosmological simulations have much larger volumes, such as BAHAMAS, TNG300, Magneticum, Millennium-TNG, FLAMINGO...

[2] No AGN

[3] Slightly different to EAGLE in AGN feedback

[4] https://the300-project.org/

Why The300: **1. Multi models**

hydrodynamic 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, Cui et al. 2022): Advanced BH/AGN models, dust model, 'calibrated' according stellar properties.

PKDGRAV3: (POTTER ET AL. 2017) IN WORKING

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.

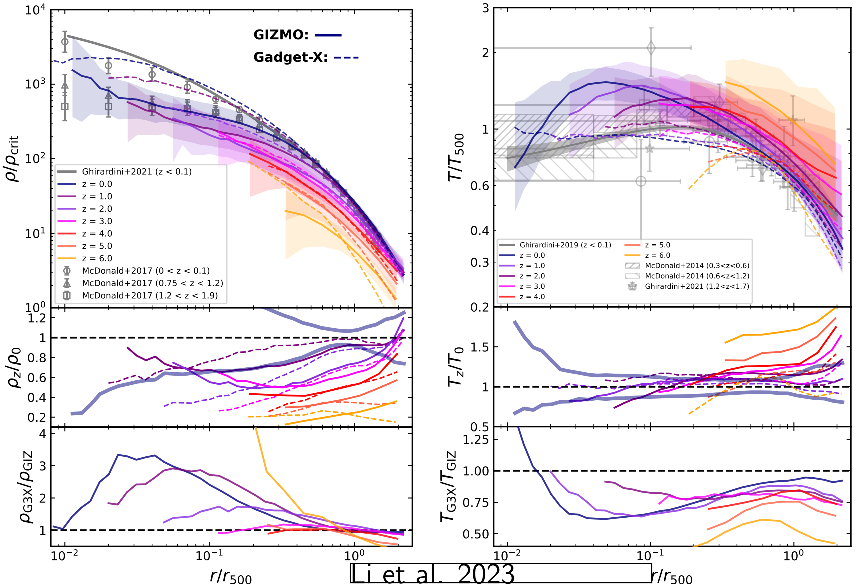
GALACTICUS (Benson 2012): no calibration. only orphan galaxy.

SAG (Cora et al. 2018): calibrated to observation. orphan galaxy + ICL.

SAGE (Croton et al. 2016): no calibration. no orphan galaxy, only ICL.

UNIVERSEMACHINE (Empirical model, Behroozi et al. 2019): in working

Notes: The catalogues are selected from the same regions as the hydrodynamic simulations.


GIZMO:
Gadget-X:
Ghirardini+2021 (z < 0.1)
z = 0.0
z = 1.0
z = 2.0
z = 3.0
z = 4.0
z = 5.0
z = 6.0
McDonald+2017 (0 < z < 0.1)
McDonald+2017 (0.75 < z < 1.2)
McDonald+2017 (1.2 < z < 1.9)
Ghirardini+2019 (z < 0.1)
McDonald+2014 (0.3<z<0.6)
McDonald+2014 (0.6<z<1.2)
Ghirardini+2021 (1.2<z<1.7)
$\rho/\rho_{\rm crit}$
ρ_z/ρ_0
$\rho_{\rm G3X}/\rho_{\rm GIZ}$
T/T_{500}
T_z/T_0
$T_{\rm G3X}/T_{\rm GIZ}$
r/r_{500}

Li et al. 2023

Why The300: **1. Multi models: the advantage of** SIMBA

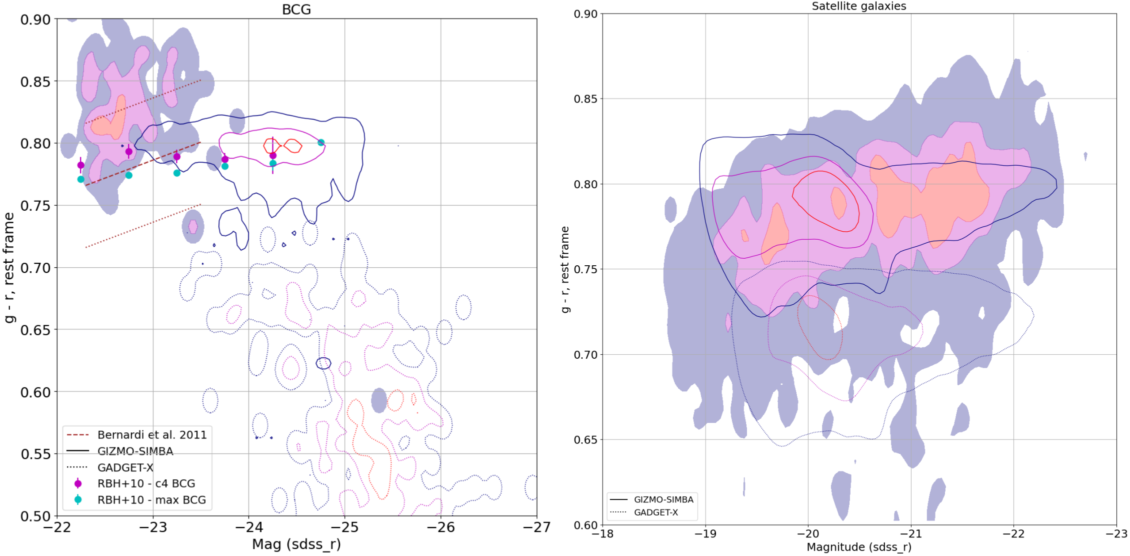


Figure: Cui et al. 2022

Why The300: **1. Multi models: the advantage of** SIMBA

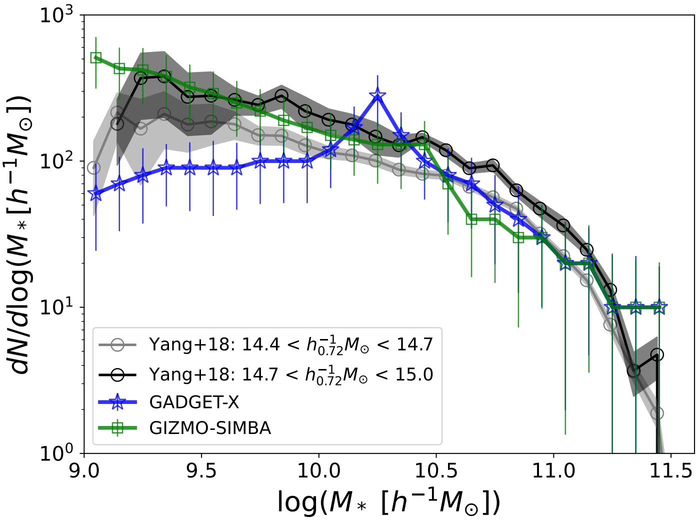


Figure: Cui et al. 2022

Why The300: 2. mass-complete samples, large regions and **high-resolution runs**

The most massive 324 clusters are selected from the MultiDark simulation (MDPL2) [5].

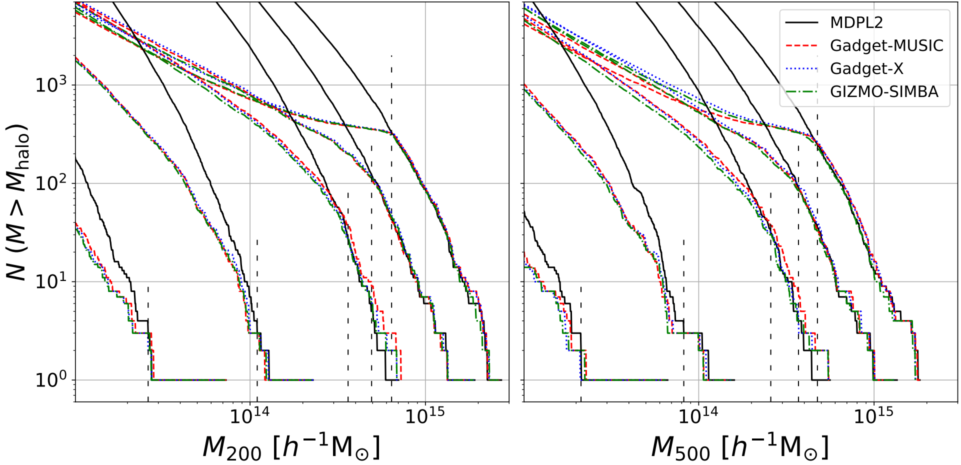
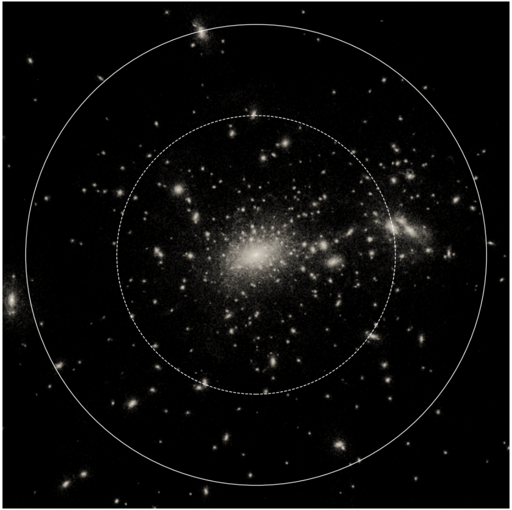
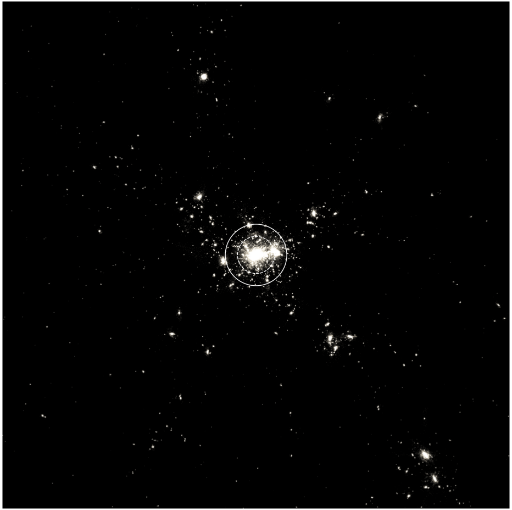


Figure: Cumulative halo mass functions. Cui et al. 2022

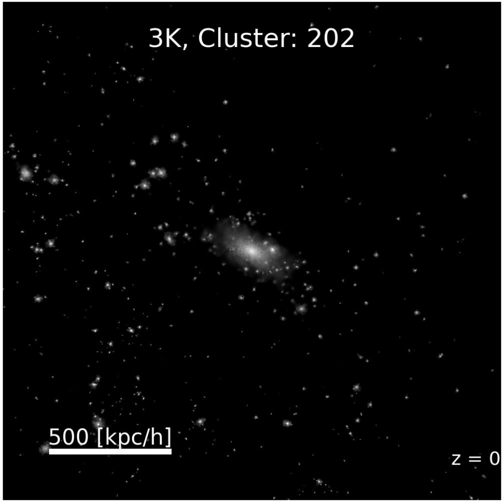
Why The300: 2. mass-complete samples, large regions and **high-resolution runs**

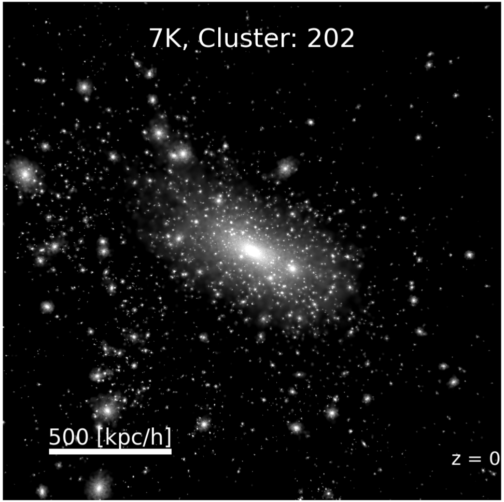
The zoomed-in ICs have a radius of 15 h^{-1} Mpc from the cluster center. The connection between the central cluster with its surrounding environments (filaments) can be studied.





Why The300: 2. mass-complete samples, large regions and **high-resolution runs**





Currently on working. Stay tuned!

Why The300: **3. multi-wavelength mock observations**

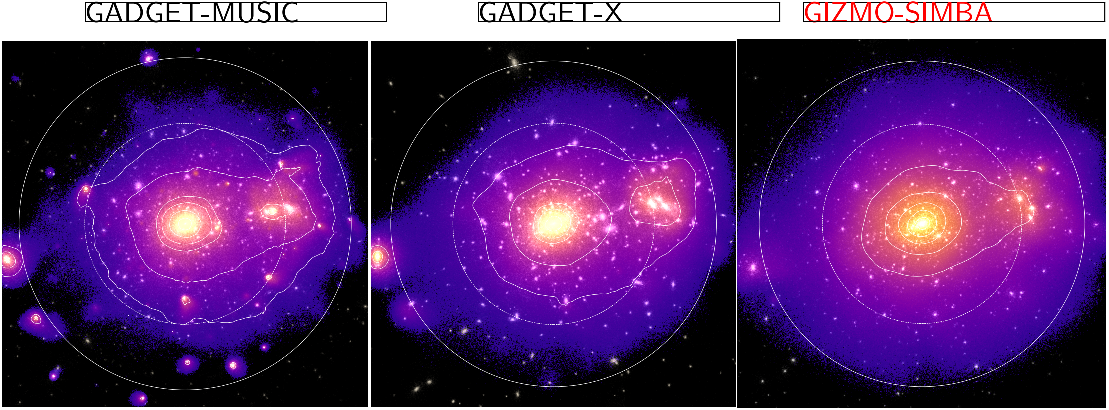


Figure: Mock multi-wavelength observations. From left to right, GADGET-MUSIC, GADGET-X, and GIZMO-SIMBA. Galaxies are shown by combining sdss u, g, r band images; X-ray photons is presented in colour map and SZ-y signal is highlight in contours. We also have **lensing maps** thanks to Massimo Meneghetti and Carlo Giocoli.

1 Introduction

2 All about cluster dynamical state
- The similarity of density profiles with cluster dynamical state
- What is dynamical state and how to quantify it?

3 The lensing crisis

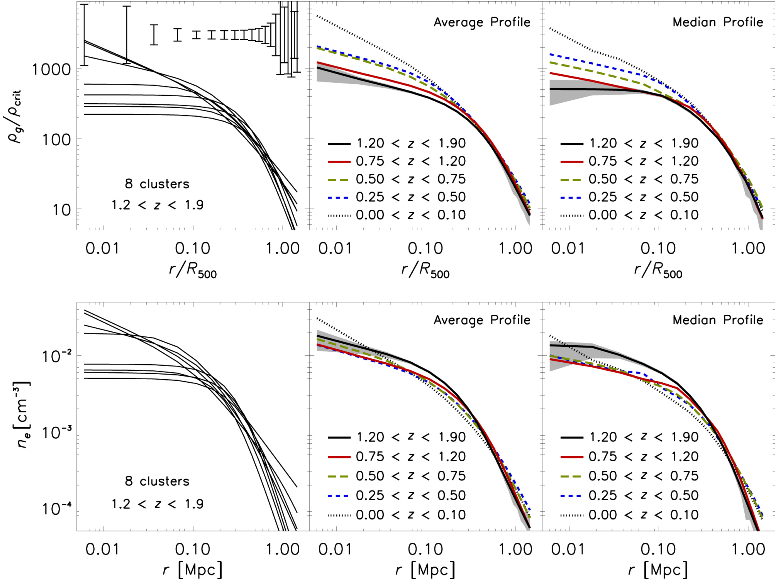
4 Advanceing the machine learning applications

5 The surrounding environment of galaxy cluster – filaments

6 Conclusions

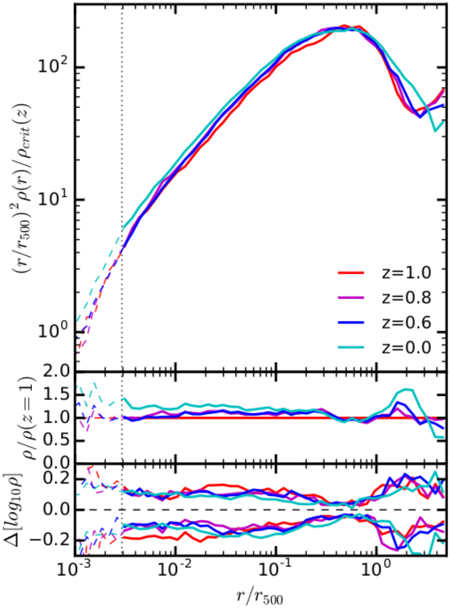
The motivation

The self-similarity evolution in galaxy clusters is well-known, e.g. McDonald et al. 2017:



The motivation

The rescaled total density profiles. Le Brun et al. 2018



The effect of cluster dynamical state on the self-similar density profile

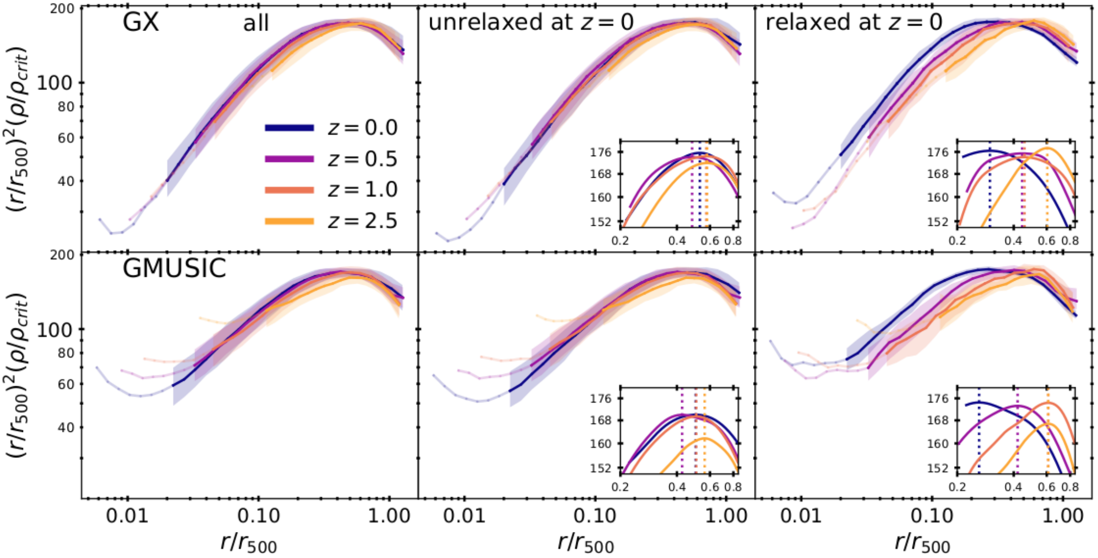


Figure: Mostoghiu et al. 2018

The effect of cluster dynamical state on the self-similar density profile

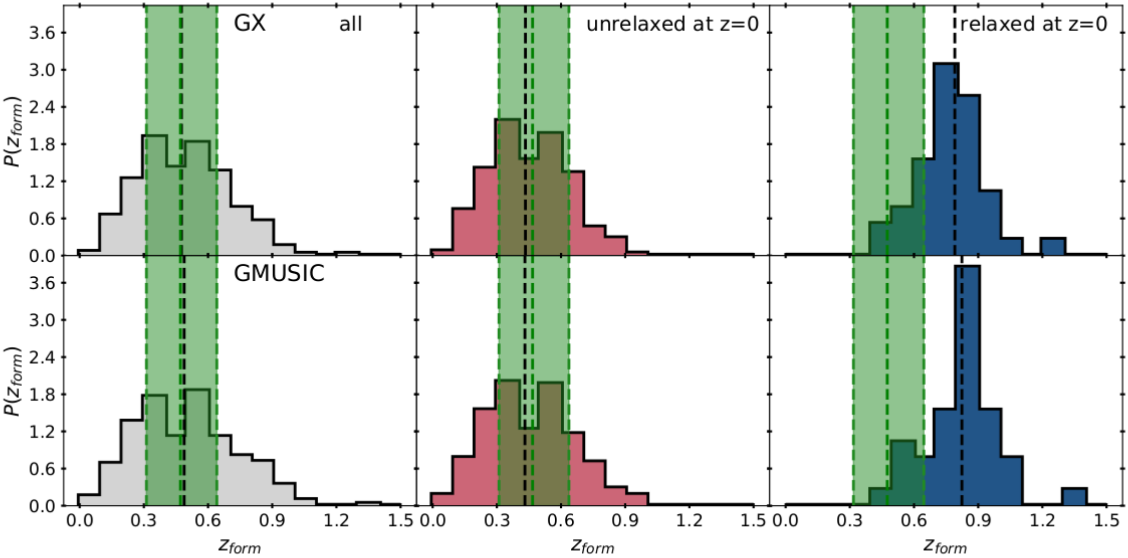


Figure: Formation time of relaxed and un-relaxed galaxies. Mostoghiu et al. 2018

The effect of cluster dynamical state on the self-similar density profile

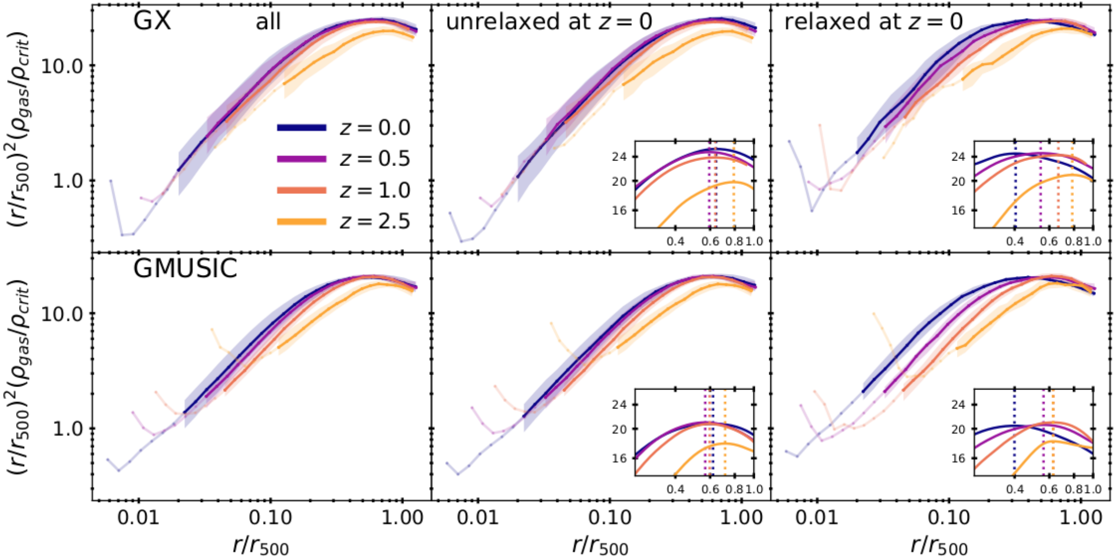
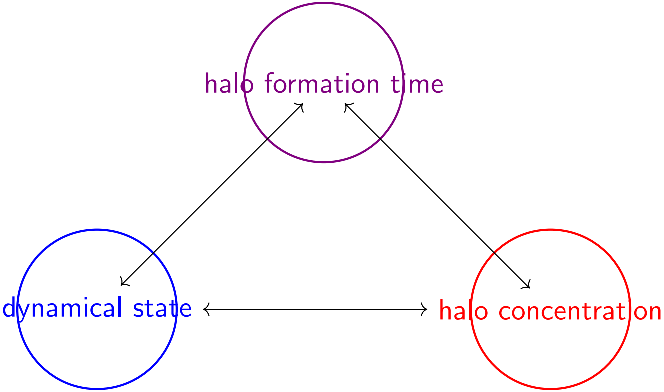


Figure: Gas density profiles. Mostoghiu et al. 2018

The connection the problem and impact



Since the three are connected to each other, relaxed clusters tend to form earlier and have a higher concentration.

Quantifying the dynamical state is more tricky compared to the two, but it is probably the only one that can be directly measured in observation.

Their impacts on galaxy cluster property, or galaxy properties should be examined with care.

The theoretical understanding and approach

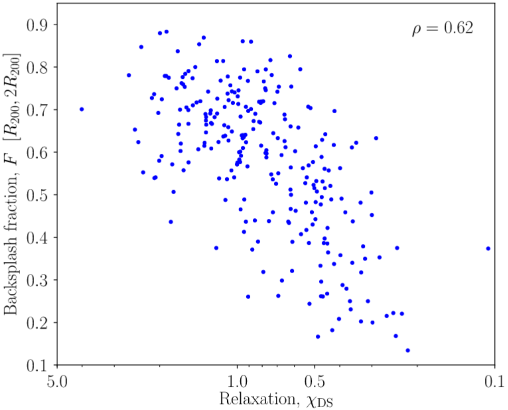
Terminology: The dynamical state is used to describe, but not quantify, how the system deviates from equilibrium. One can qualitatively separate the cluster into relaxed and unrelaxed/disturb state. However, it turns out that it is not an easy task to quantify the cluster dynamical state because halo is not an isolated system.
Theoretically, these quantities are used to make classifications of cluster dynamical state (see e.g. Neto et al 2007, Pool et al 2013, Cui et al. 2017):

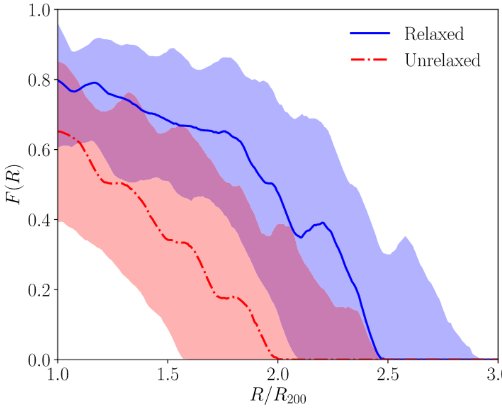
- η virial ratio is based on the virial theorem: $\eta = \frac{2T - E_s}{|W|}$. Here, total kinetic energy is T, its energy from surface pressure is Es, and W is its total potential energy.
- Δ_r , Centre-of-mass offset is the distance between CoM and density peak/minimum potential position, normalized by halo radius R200 or R500.
- f_s , Subhalo mass fraction can be total or the most massive subhalo mass fraction.

The simplified X and backsplash galaxies

In Haggar et al. 2020, they proposed one combined parameter X to simplify the cluster dynamical state quantification:

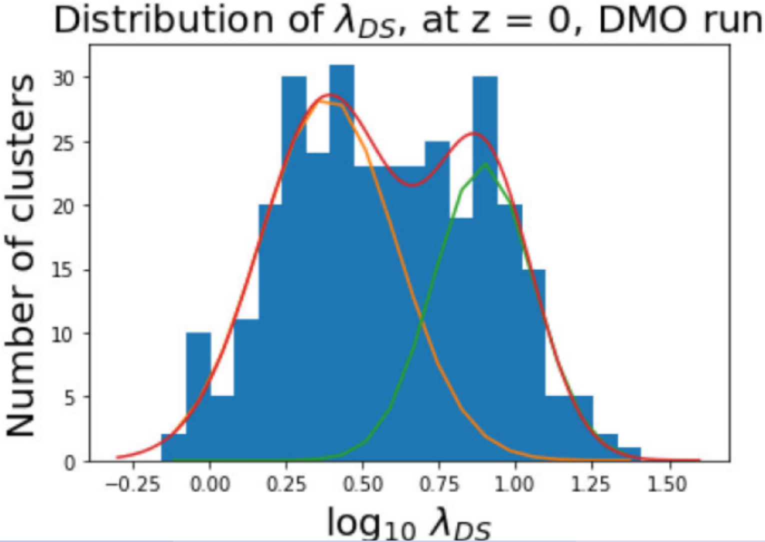
$$\mathrm{X}_{DS} = \sqrt{\frac{3}{(\frac{\Delta_r}{0.04})^2 + (\frac{f_s}{0.1})^2 + (\frac{|1-\eta|}{0.15})^2}} \quad (1)$$





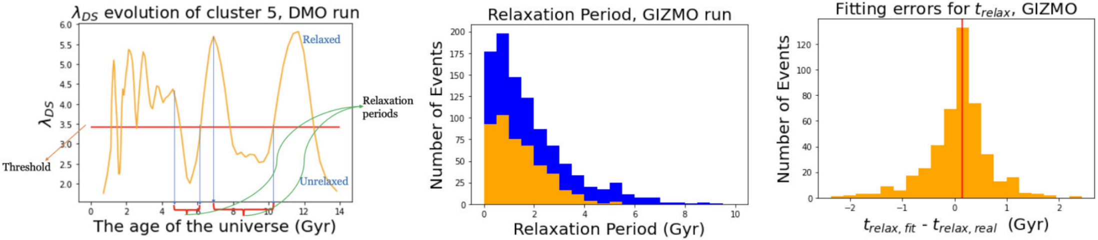
The threshold-free method and relaxation time

In Zhang et al. 2022, we introduce another single parameter λ_{DS} to quantify the cluster dynamical state, which reproduces its double peak distribution.



The threshold-free method and relaxation time

We use this definition to further investigate how much time the cluster requires to restore its relaxation state from a merger event.

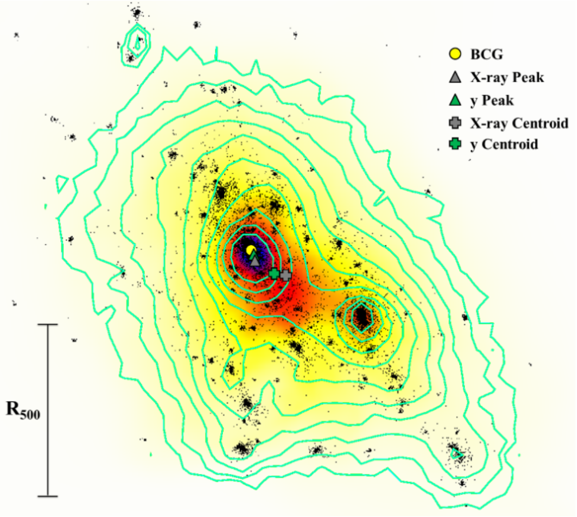


Quantify the cluster dynamical state from images

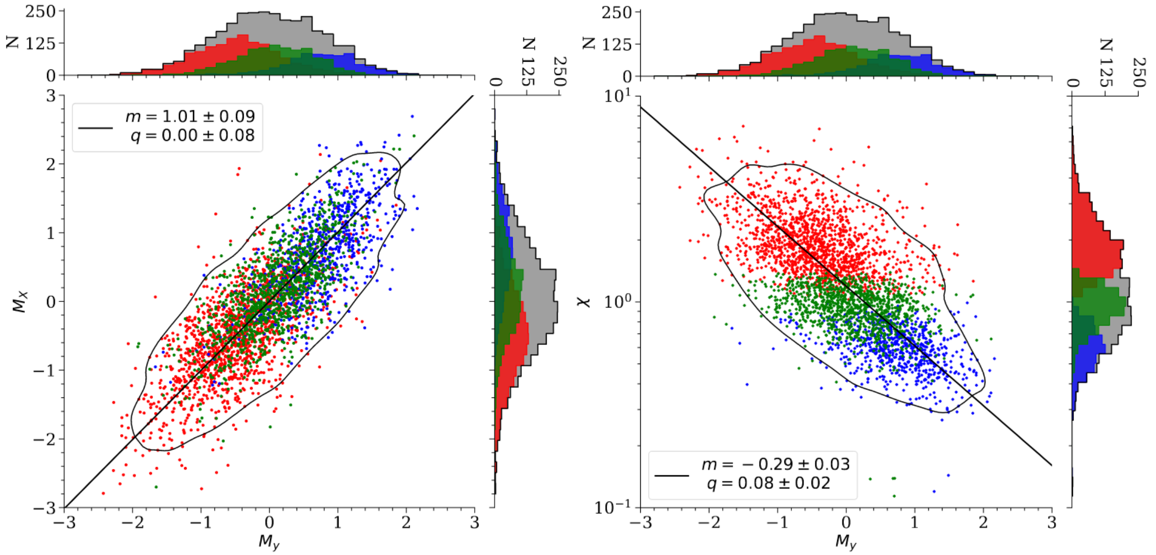
- A Asymmetry
- c Light Concentration Ratio
- w Centroid Shift
- P Power Ratio
- G Gaussian Fit
- S Strip
- M A combination of these parameters

See De Luca et al. 2021 for details

See Capalbo et al. 2021 for a new method with the Zernike polynomial decomposition method



Quantify the cluster dynamical state from images



1 Introduction

2 All about cluster dynamical state

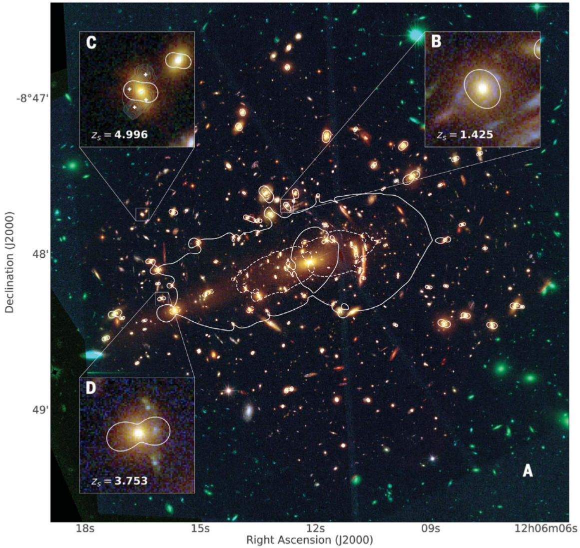
3 The lensing crisis
- Background
- GGSL
- $M_{\rm sub} - V_{max}$

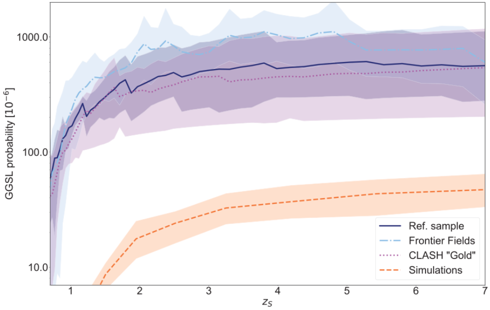
4 Advanceing the machine learning applications

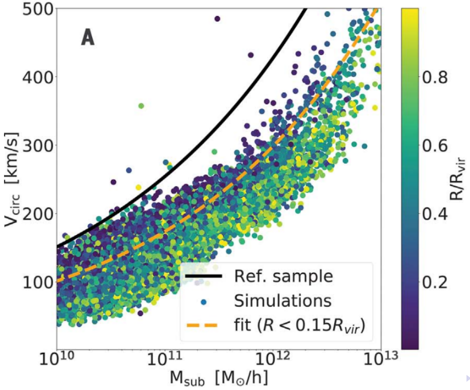
5 The surrounding environment of galaxy cluster – filaments

6 Conclusions

The starting point

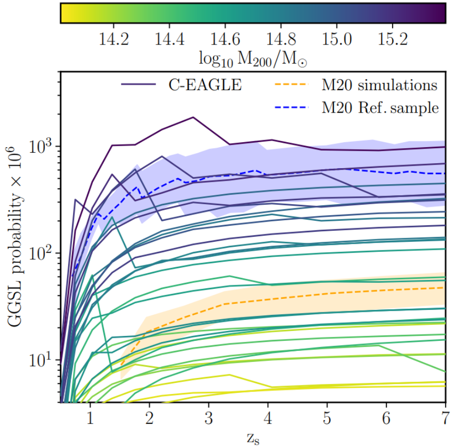




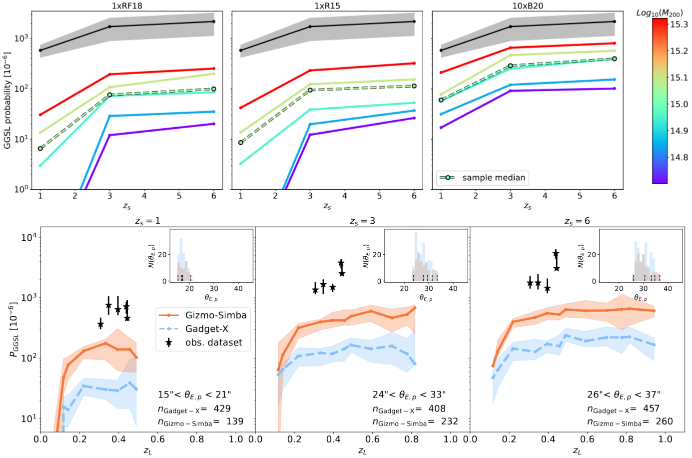


Meneghetti et al. 2020

Galaxy-Galaxy Strong Lensing

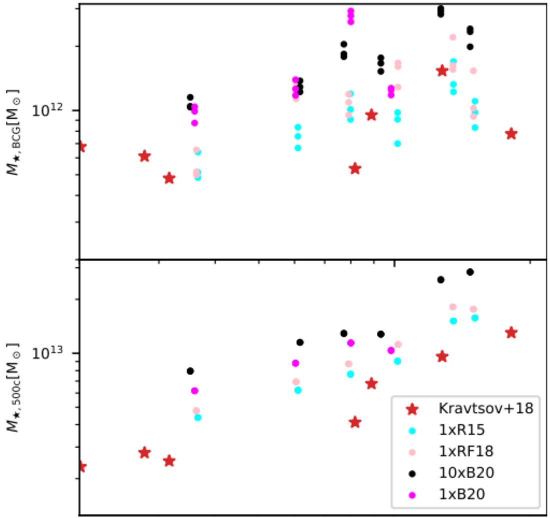


Robertson 2021 (C-EAGLE)



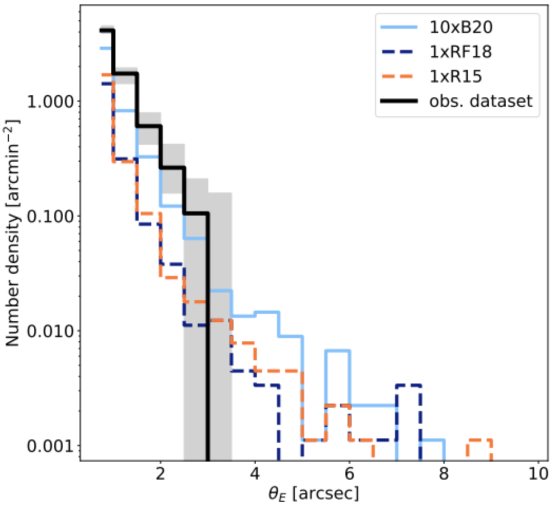
Meneghetti et al. 2022, 23

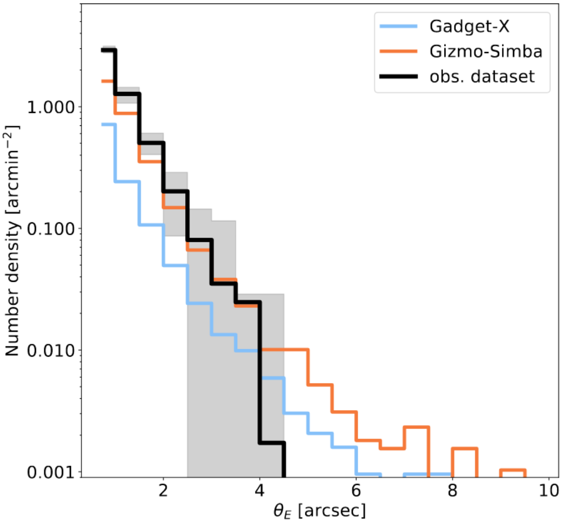
Galaxy-Galaxy Strong Lensing: New problems!



Ragagnin et al. 2022

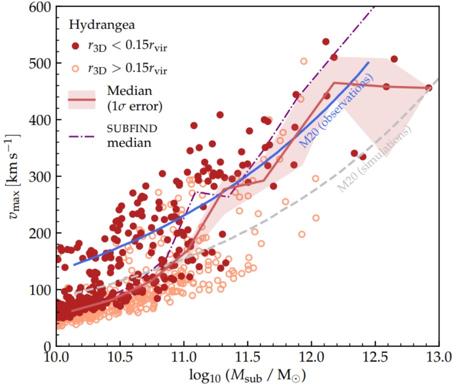
Galaxy-Galaxy Strong Lensing: New problems!



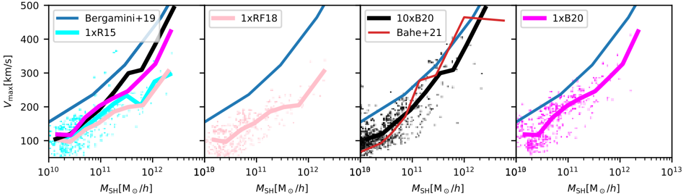


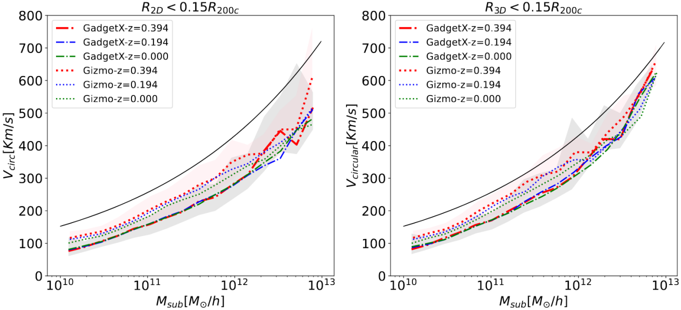
Meneghetti et al. 2022, 23

The $M_{\rm sub} - V_{max}$ relation



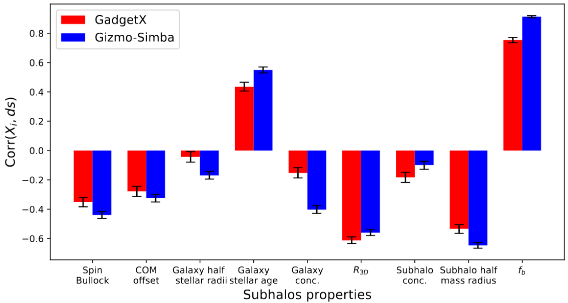
Bahe 2021 (C-EAGLE)

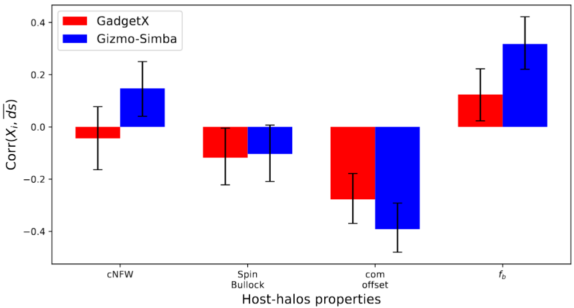




Ragagnin et al. 2022 (top); Srivastava et al. 2023 (bottom)

Possible solutions





Sri

et al. 2023; Maybe early star formation?

1 Introduction

2 All about cluster dynamical state

3 The lensing crisis

4 Advanceing the machine learning applications
- Background
- 0D mass prediction
- 1D mass profile
- 2D mass maps

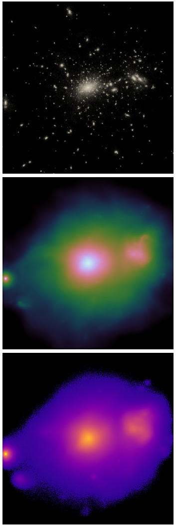
5 The surrounding environment of galaxy cluster – filaments

6 Conclusions

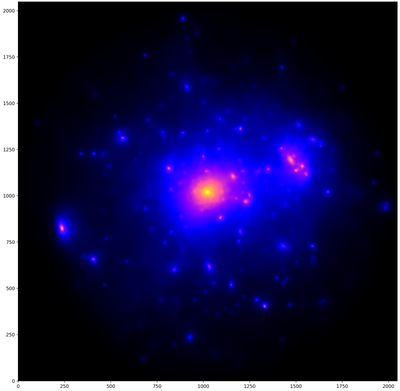

帮我画一个鱼香肉丝
AI 作图

Background

Our main aim of using AI is to directly derive the cluster property – mass from images.

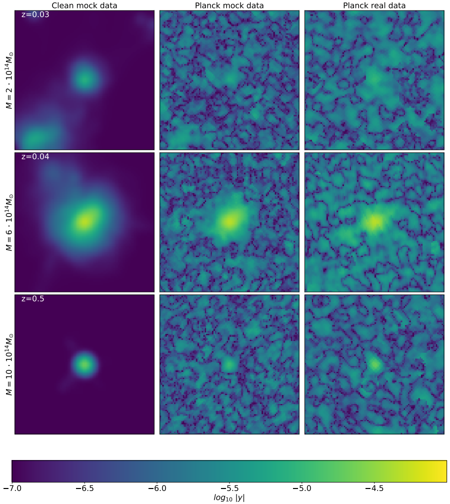


Machine Learning

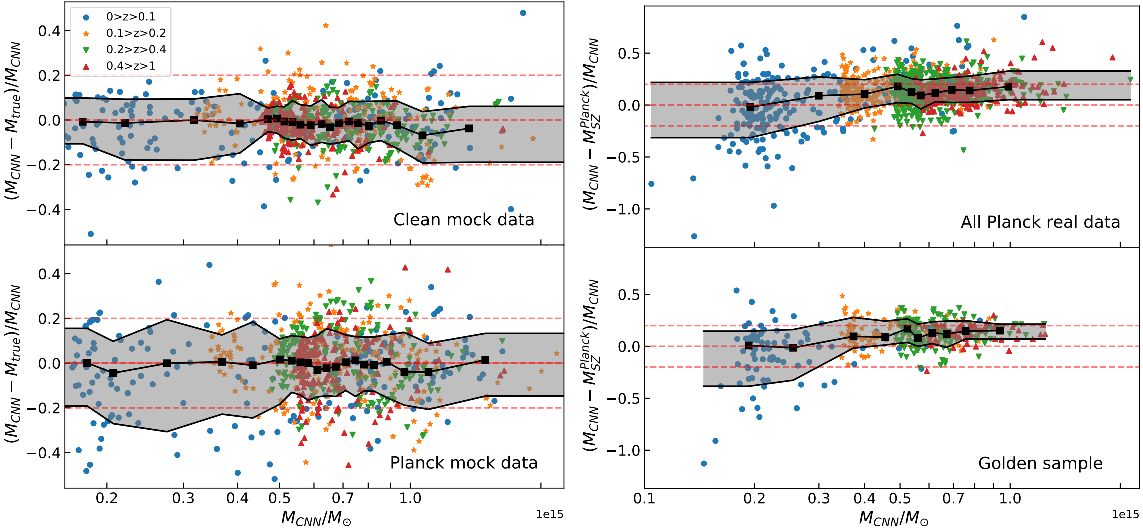


Cluster mass prediction for Planck

This is not new to use CNN to make predictions of cluster mass using simulation results, see for example, Ntampaka et al. 2019, Yan et al. 2020 for the proof of concept. In de Andres et al. 2022, we applied the trained ML model to real Planck SZ maps to get the cluster masses.

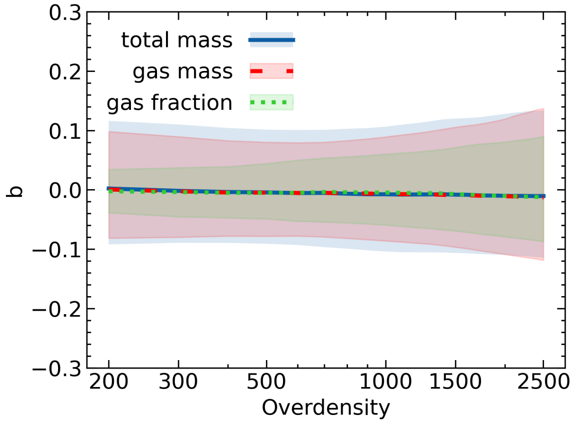


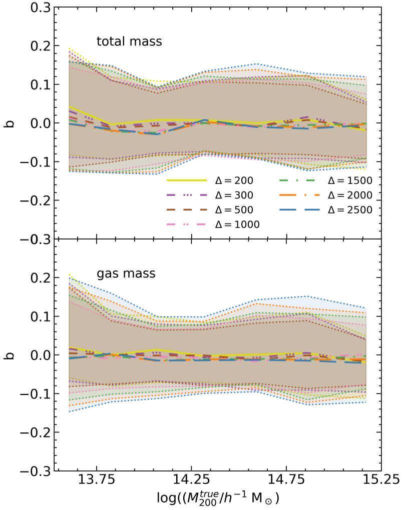
Cluster mass prediction for Planck



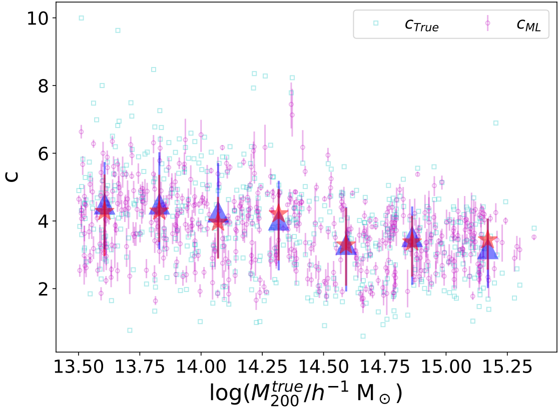
de Andres et al. 2022; Prediction and model are available at
https://github.com/The300th/DeepPlanck

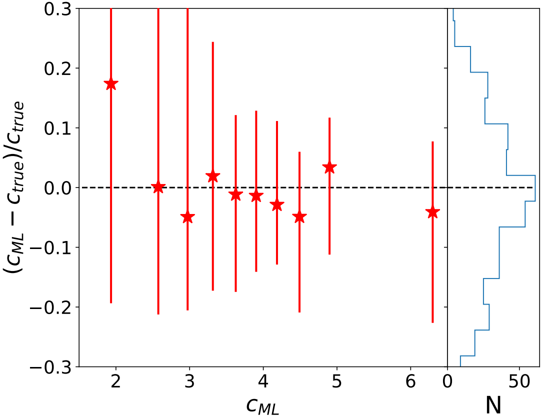
Applying an advanced ML model – Autoencoder, we are able to derive the important vectors for regressing cluster masses at different radii. Ferragamo et al. 2023





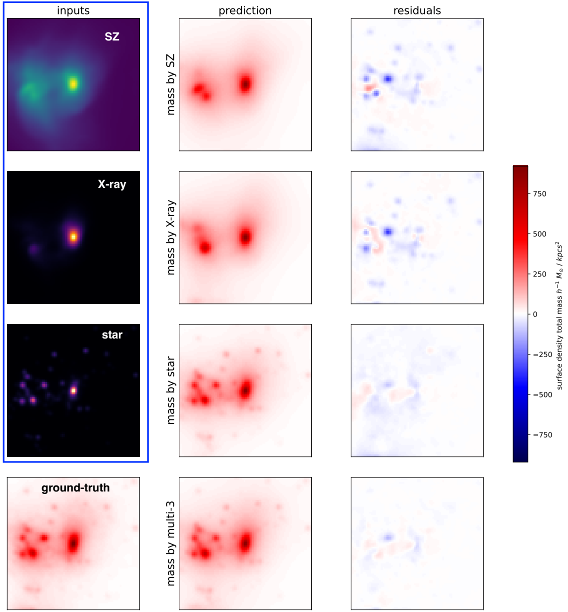
Application of the mass profile



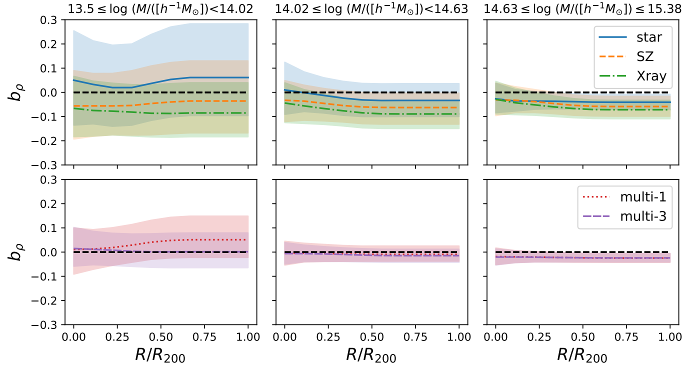


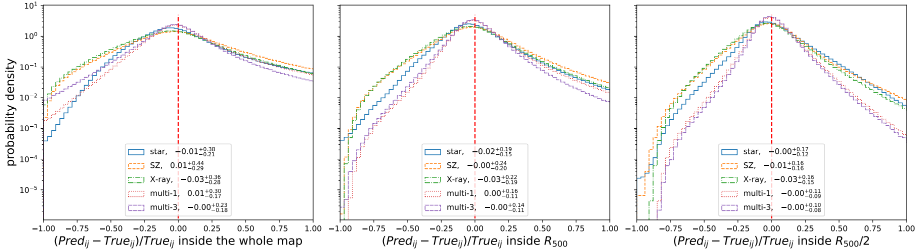
Predicting mass maps

In de Andres et al. 2023, a different ML model – Unet, is adopted to generate total mass maps from these observation images.

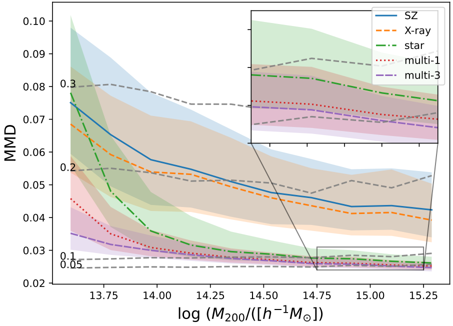


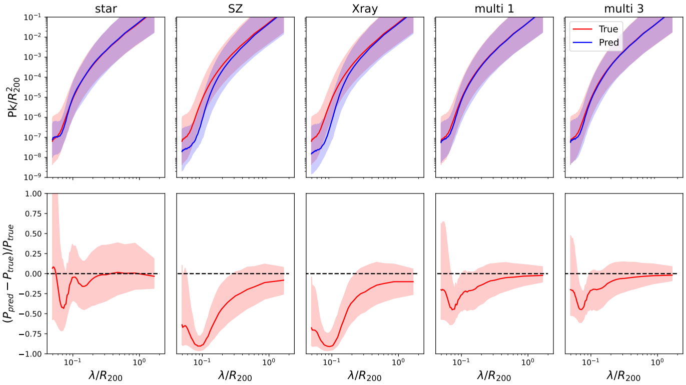
Validating the results





Validating the results





1 Introduction

2 All about cluster dynamical state

3 The lensing crisis

4 Advanceing the machine learning applications

5 The surrounding environment of galaxy cluster – filaments

6 Conclusions

Frame Title

Conclusion

The aim of this talk is to draw your attention to the300 project, join us to solve your scientific problems.
We are not only pushing to high and ultra-high resolutions, but also expanding the models and catalogues.

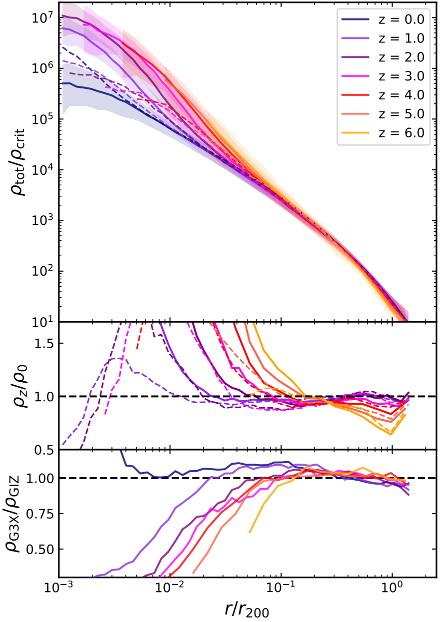
- Quantifying cluster dynamical state is not an easy task. We have methods to do that, but no one is perfect.
- The crisis is still there with new problems. We have some idea, so it may be fixed. Keep tuning.
- ML is a powerful method. Looking forward to new applications/models/ideas.

Supplement materials

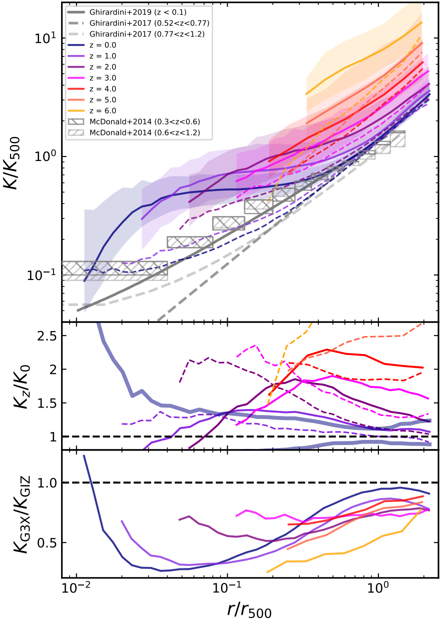
The GIZMO-Simba run of the 300 clusters: basic information

- 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).

Total density

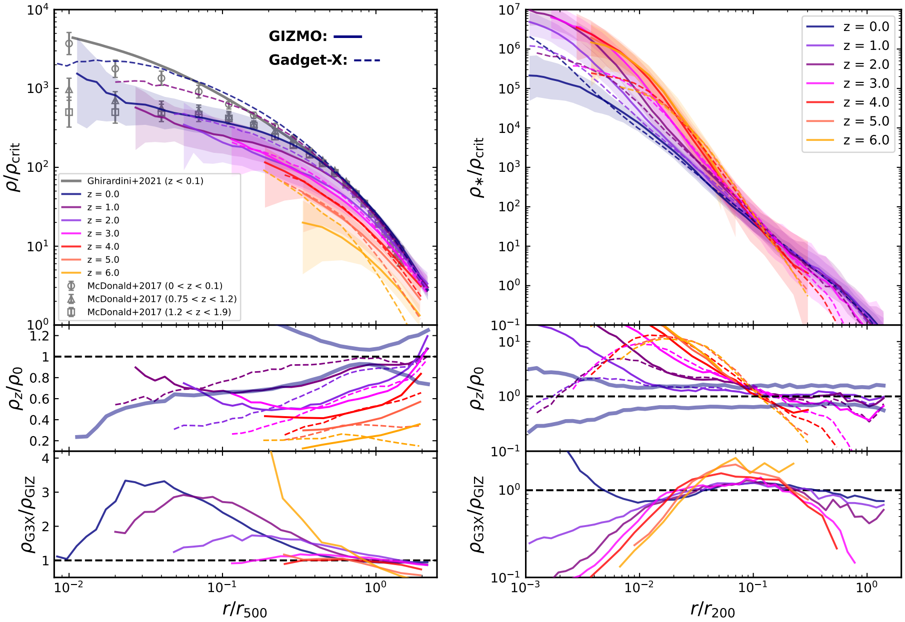


Entropy



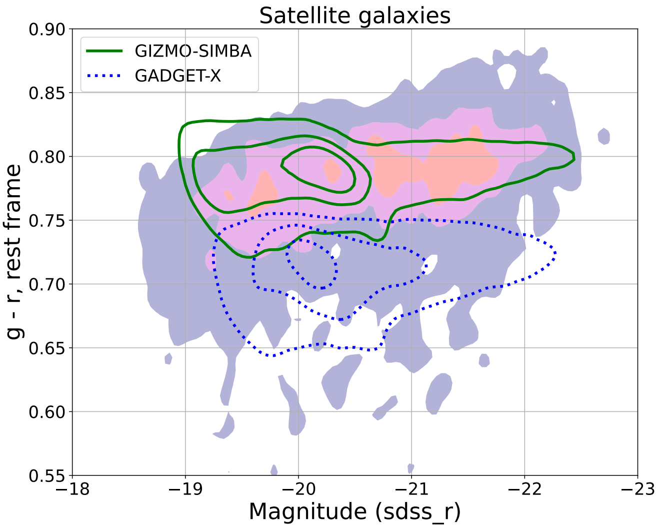
Ghirardini+2019 (z < 0.1)
Ghirardini+2017 (0.52<z<0.77)
Ghirardini+2017 (0.77<z<1.2)
z = 0.0
z = 1.0
z = 2.0
z = 3.0
z = 4.0
z = 5.0
z = 6.0
McDonald+2014 (0.3<z<0.6)
McDonald+2014 (0.6<z<1.2)
K/K500
Kz/K0
KG3X/KGIZ
r/r500

The evolution of the baryon profiles

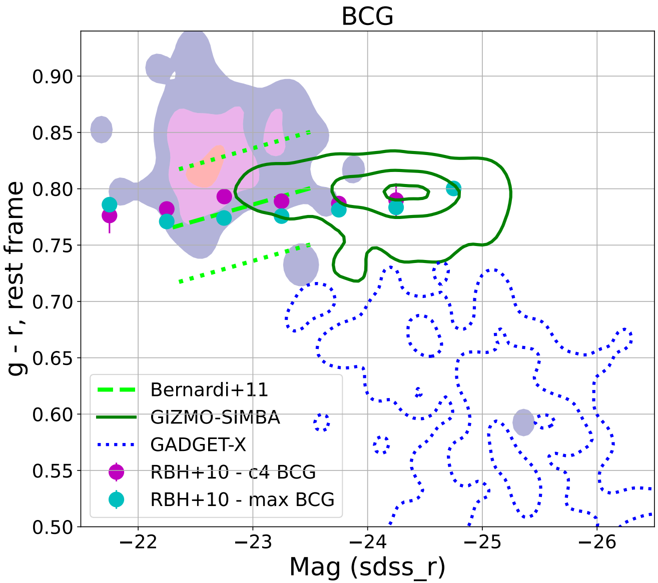


Left figure: Gas density profile evolution. Right figure: stellar density profile evolution. Li et al. in prep.

The color-magnitude diagram for satellite galaxies



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 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

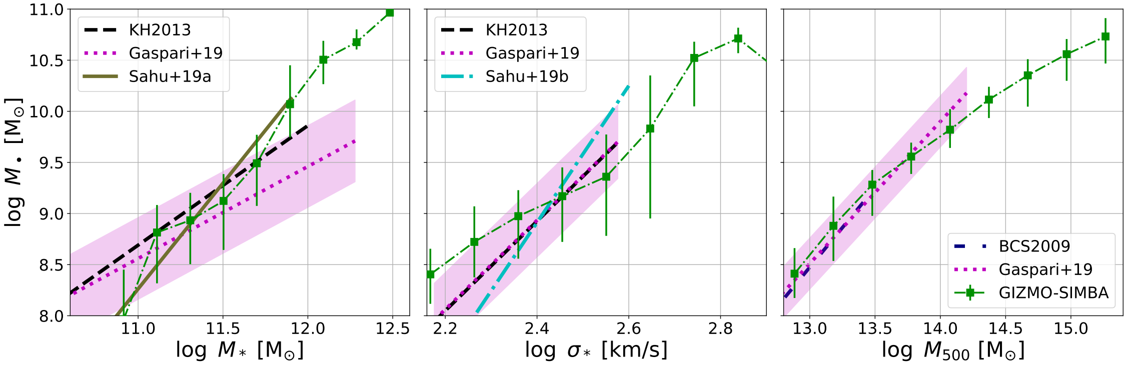
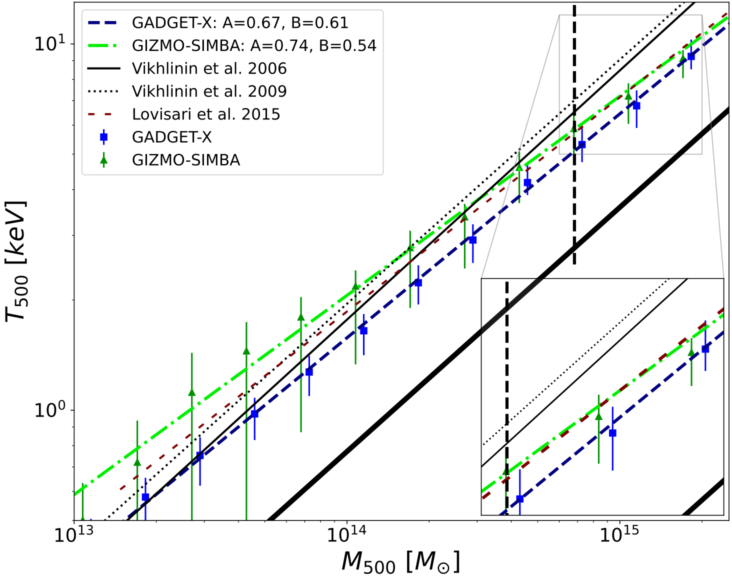
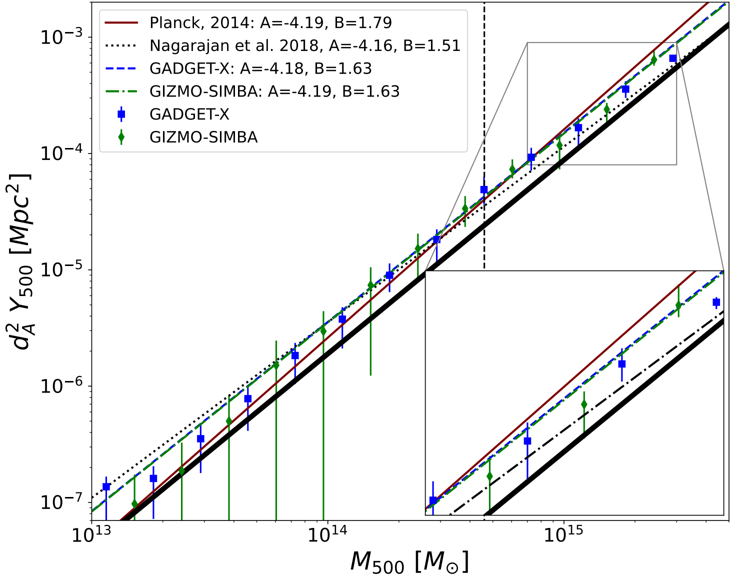


Figure: The $M_\bullet$ - M_* (left), $M_\bullet$ - σ_* (middle) and $M_\bullet$ - M_{halo} (right) relations. GIZMO-SIMBA is in good agreement with observational results at lower masses. It predicts a slight deviation from the interpolations: A higher ($\sim$ 2 times) BH mass in $M_* \gtrsim 10^{12}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



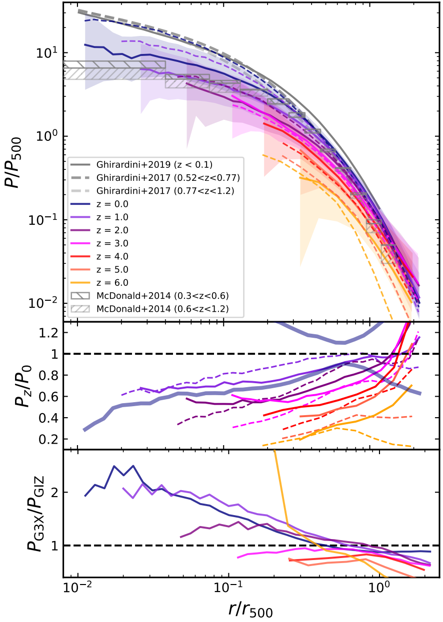
The mass-weighted temperature - halo mass relation.
GIZMO-SIMBA seems to have slightly higher temperature compared to GADGET-X, especially at lower halo mass range.

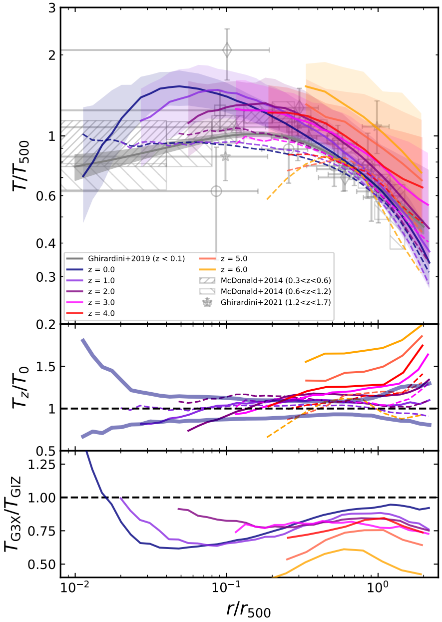
The Gas properties



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

The evolution of gas physical profiles



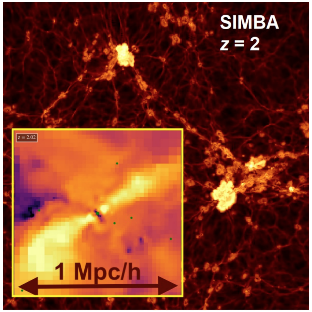


Left figure: Gas pressure profile evolution. Right figure: gas temperature profile evolution. Li et al. in prep.

Why SIMBA: *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.

Christiansen et al. 2020

Why SIMBA: *the dust model*

- Dust is passively advocated following the gas particles.
- It has the same physical properties with a fixed radius a =0.1 μm.
- 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.

See Li et al. 2019 for details.

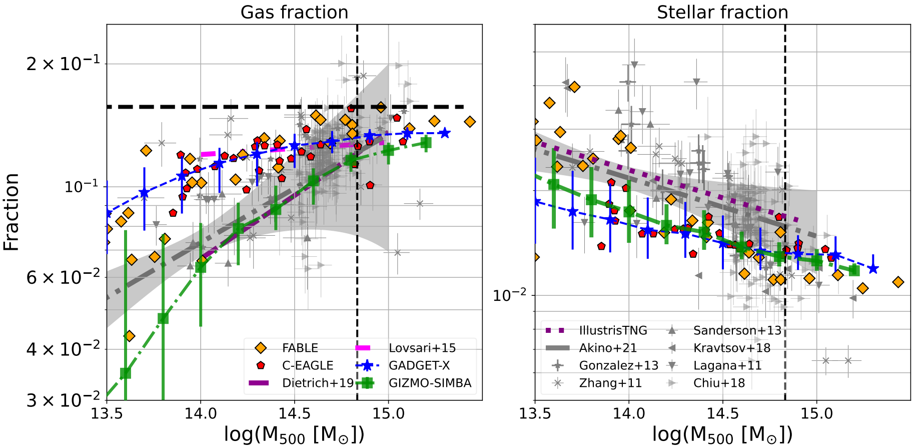
Why SIMBA: *the "calibrated" stellar properties*

The "calibrated" is quoted as we are not calibrating total 324 clusters. We only calibrated one random selected cluster and apply the calibrated parameters to all the other clusters. Calibration is not an easy thing, especially to calibrate three relations together.

- The total stellar fractions
- satellite stellar mass function
- BCG-halo mass relation

Why SIMBA: *the "calibrated" stellar properties*

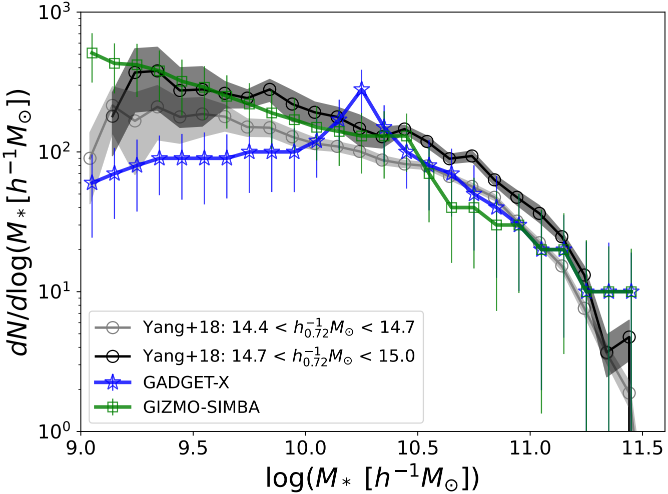
- The total stellar fractions



- satellite stellar mass function
- BCG-halo mass relation

Why SIMBA: *the "calibrated" stellar properties*

- The total stellar fractions
- satellite stellar mass function



- BCG-halo mass relation

Why SIMBA: *the "calibrated" stellar properties*

- The total stellar fractions
- satellite stellar mass function
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