

## Focus Week

*The astrophysics of large-scale structures  
in the era of eROSITA, Euclid, SPT-3G:  
the emergence of the cosmic web*

**Galaxy Evolution  
Meets  
Large Scale Structure**

**M. Reza Ayromlou**

Argelander Fellow  
(University of Bonn)



Argelander-  
Institut  
für  
Astronomie

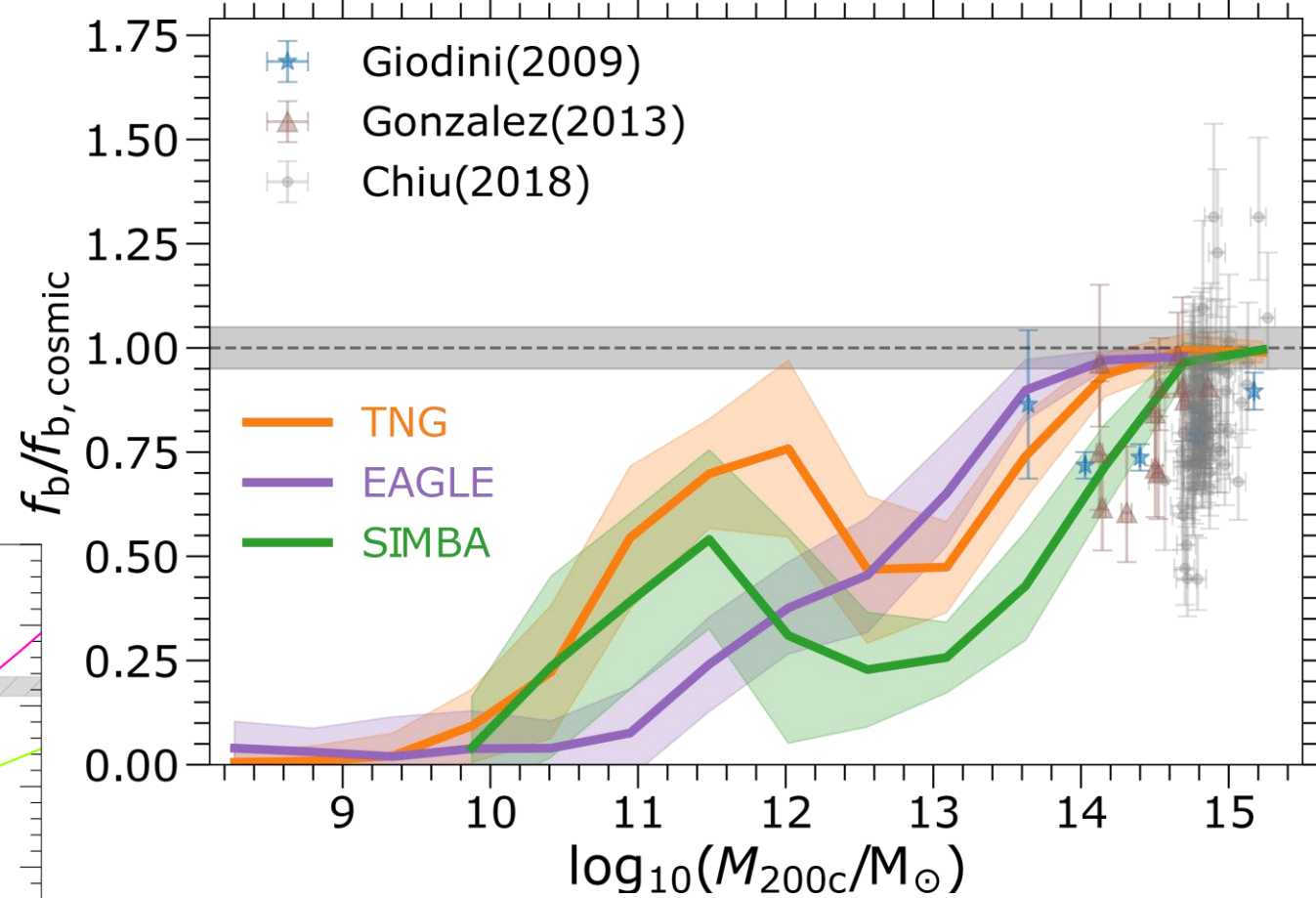
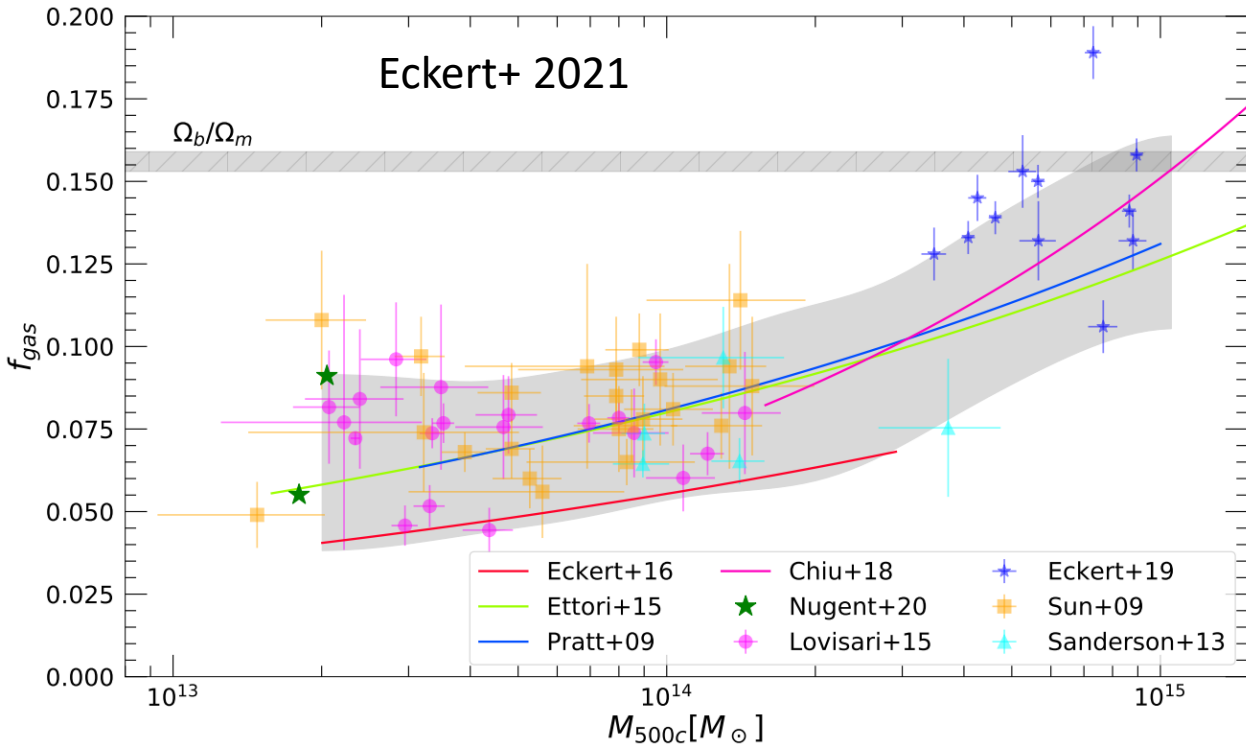
UNIVERSITÄT **BONN**



**Part I**  
**The Closure Radius**

Baryon redistribution out to  
large-scales

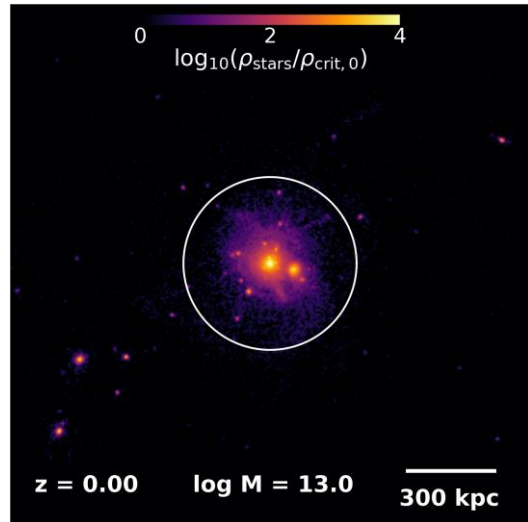
# Halo Baryon Fraction in Models and Observations



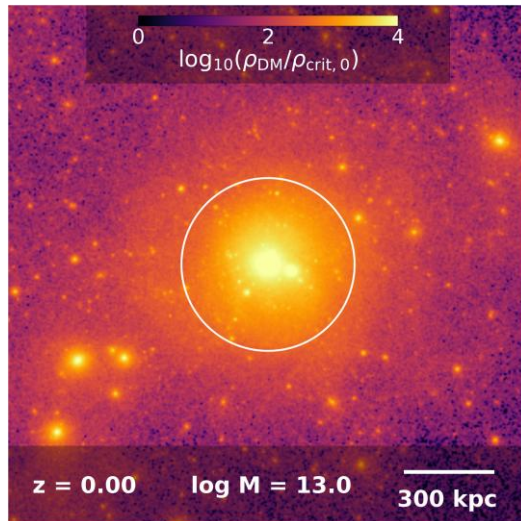
*See also talks by Dominique, Paola,  
and Matteo*

See also Sun+ 09, Pratt+ 09, Sanderson+13, Lovisari+ 15, Etti+15,  
Eckert+16, Chiu+18, Nugent+ 20, Eckert+21, Popesso+ 24, Reiprich+ 25

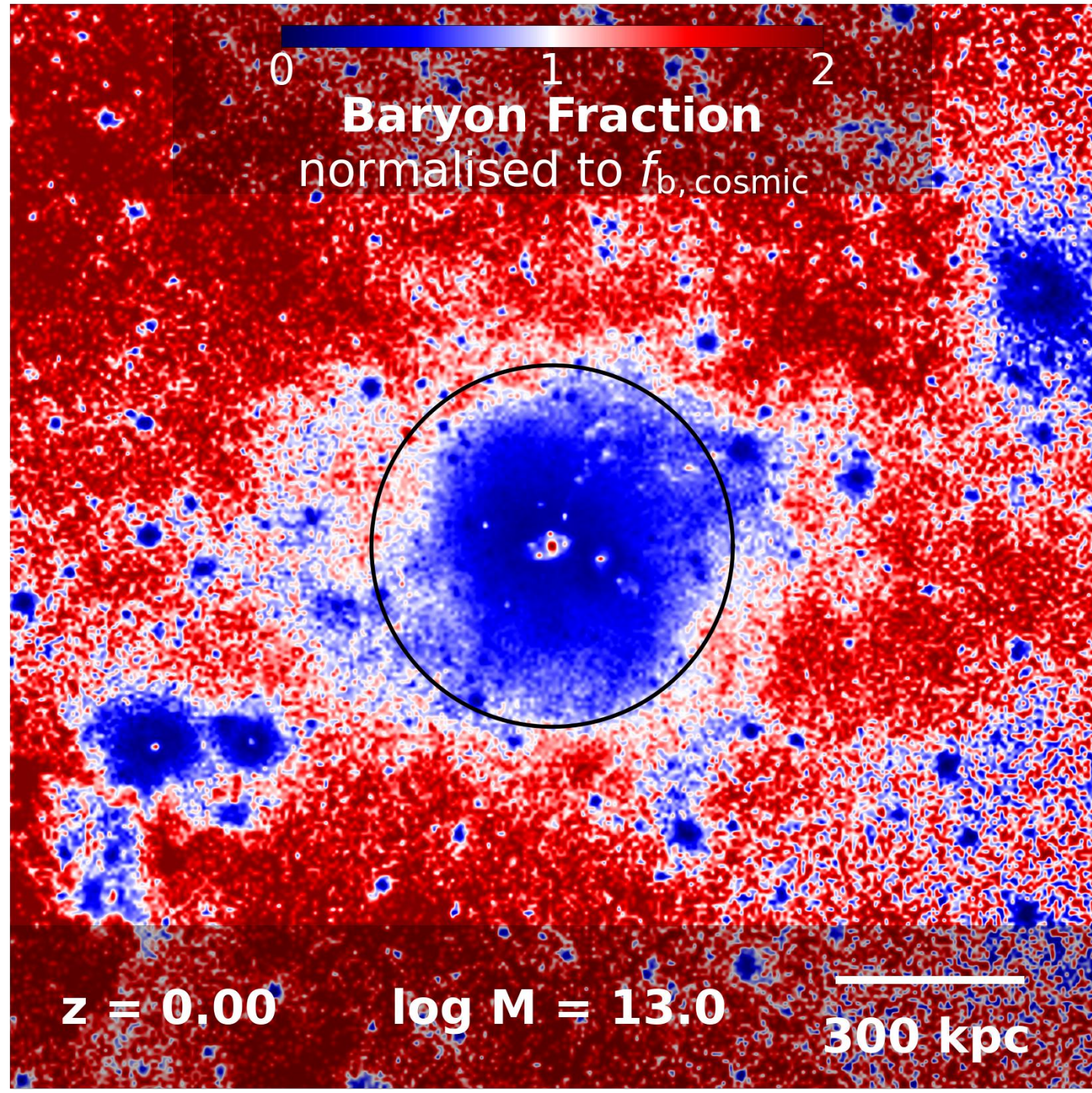
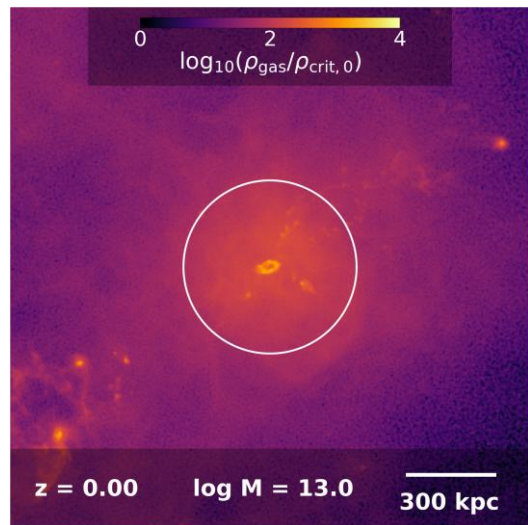
## Stellar Density



## Dark Matter Density



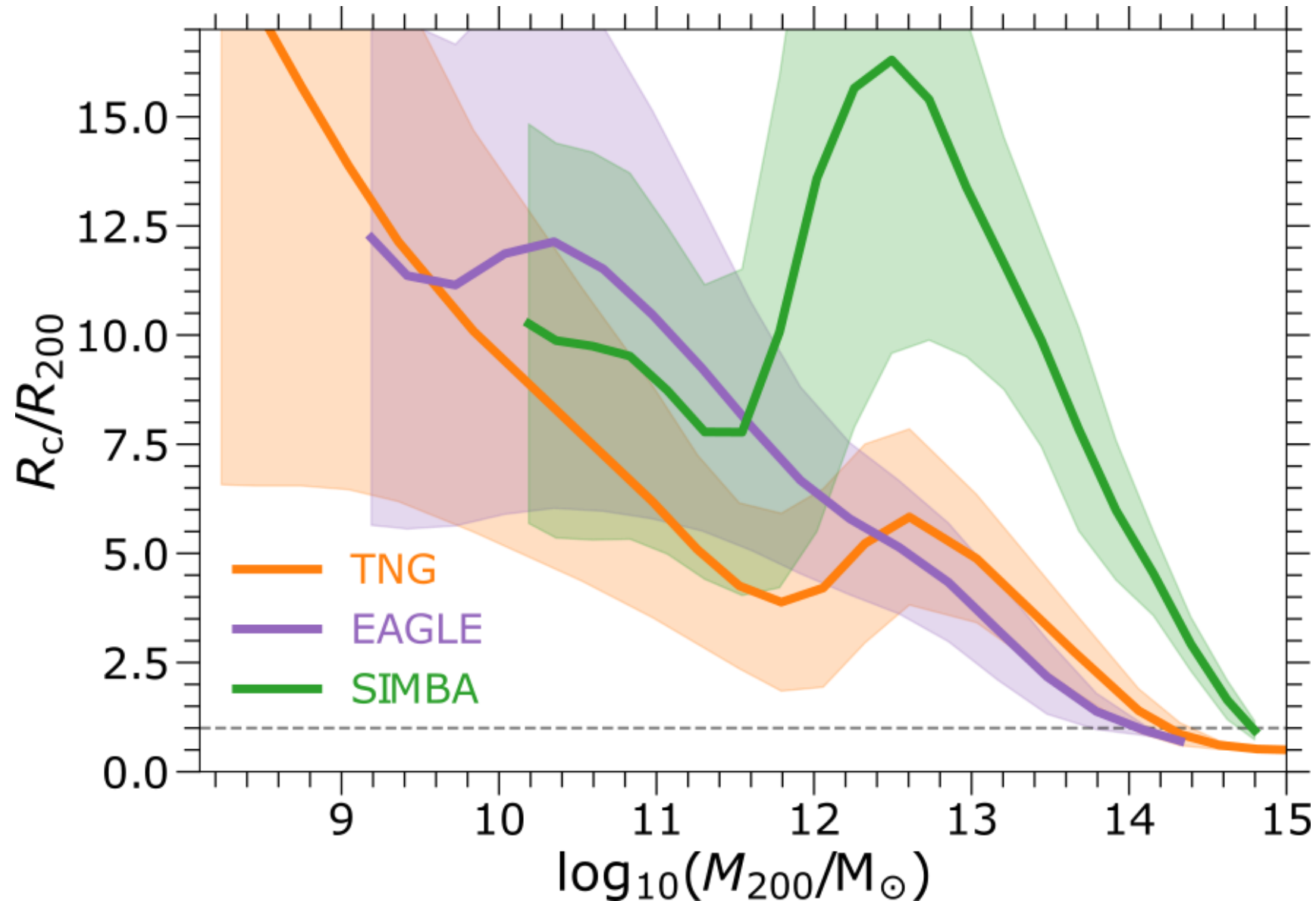
## Gas Density



# The Closure Radius

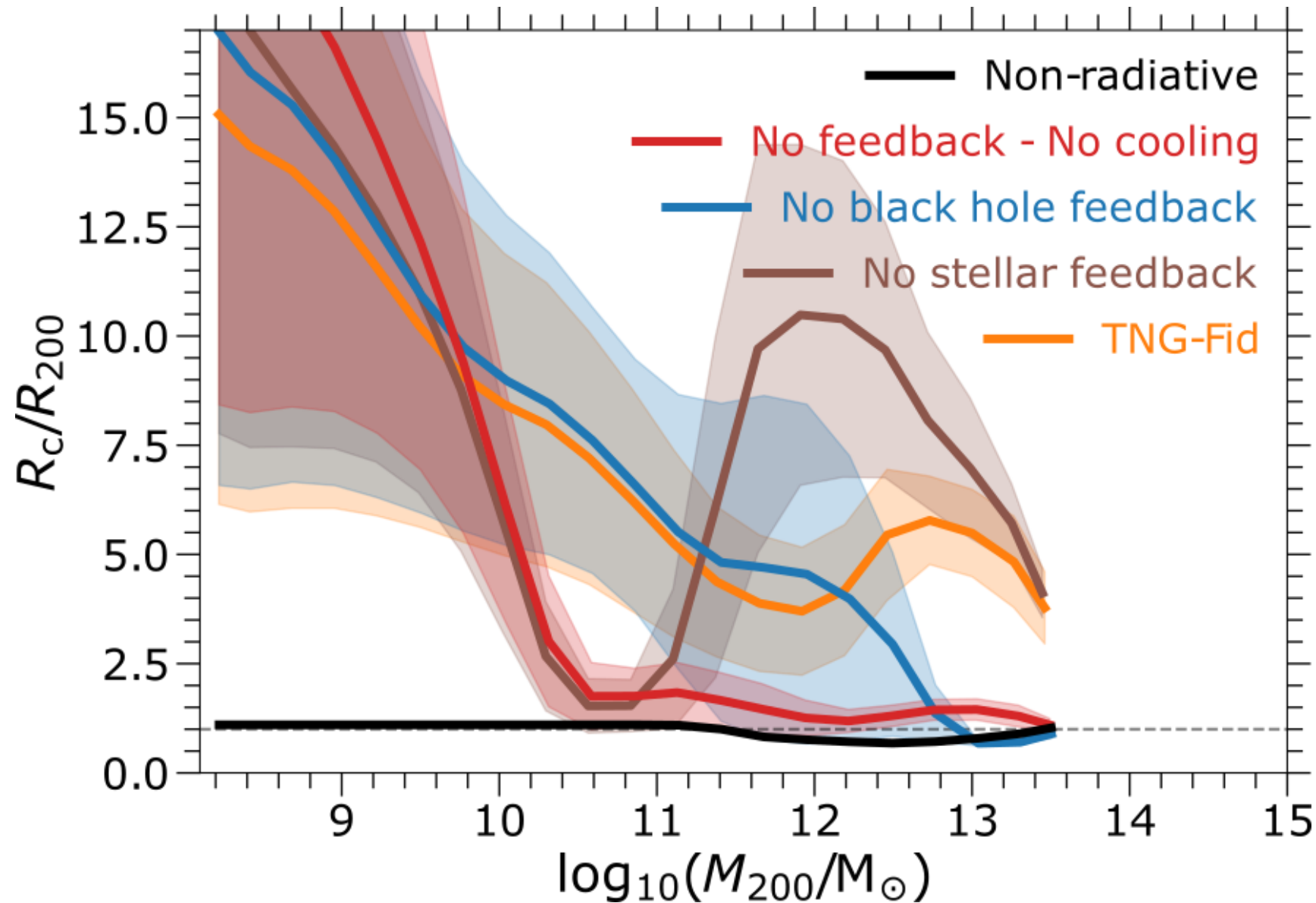
The radius within which  
all baryons associated  
with DM are found.

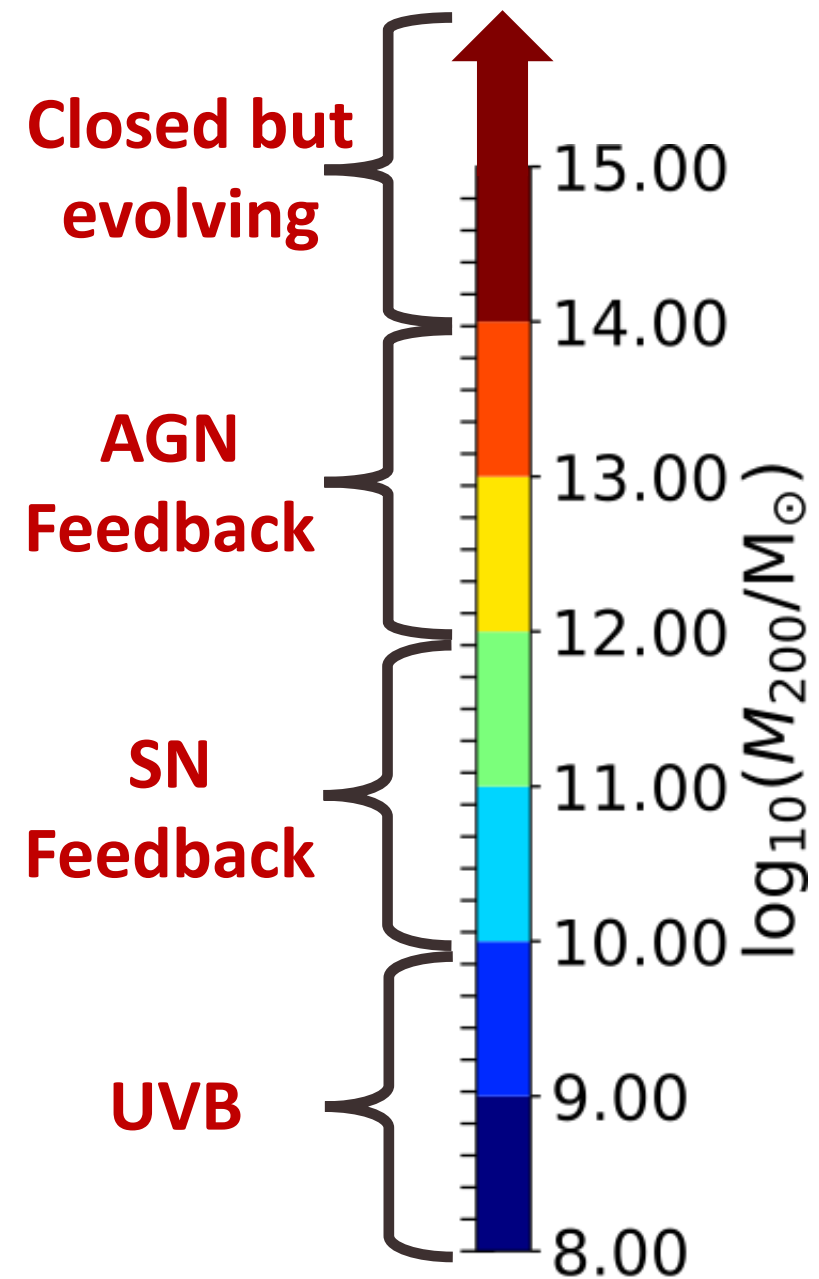
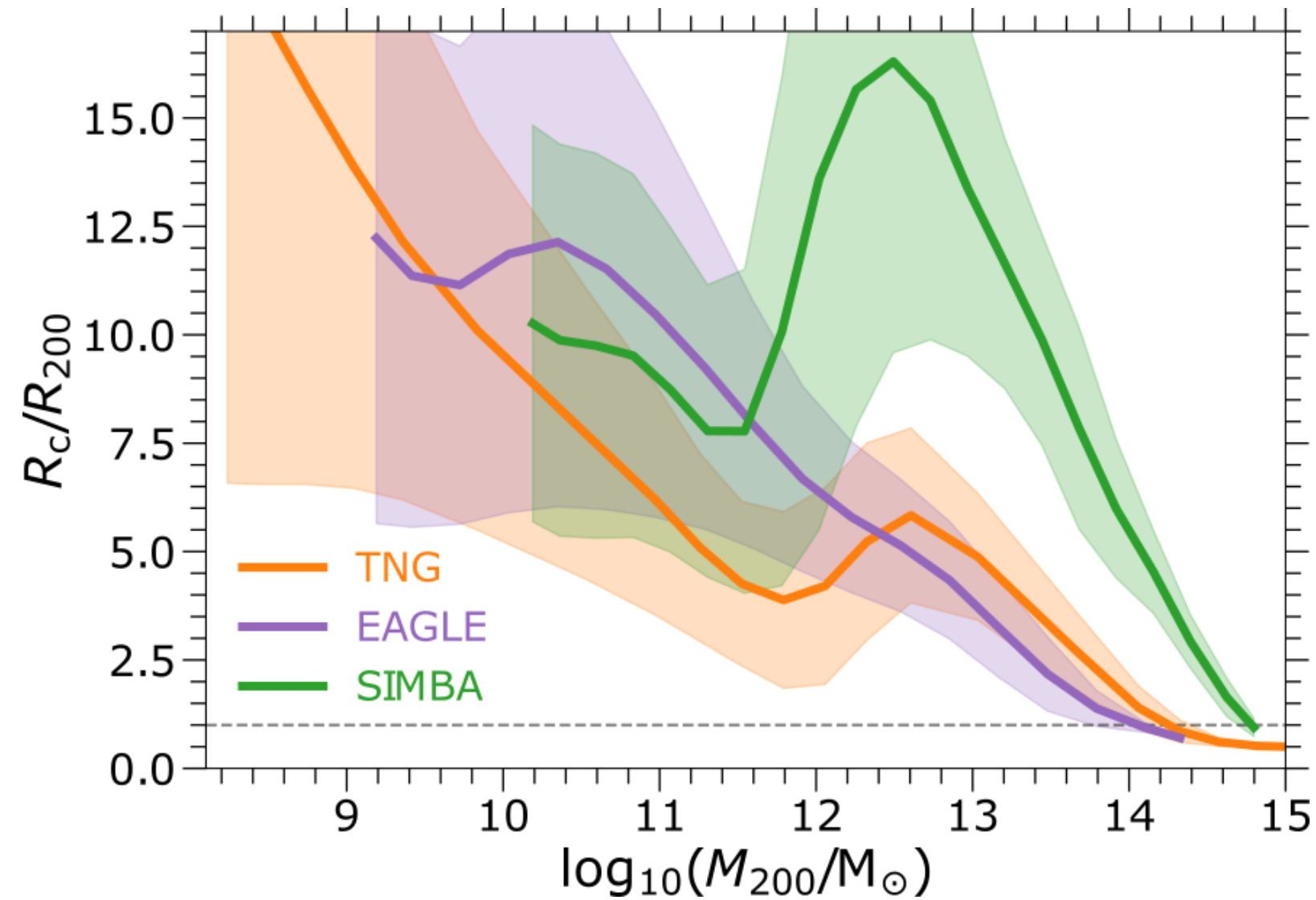
$$f_b(< \mathbf{R_c}) = \Omega_b / \Omega_m$$



# Processes that impact the Closure Radius

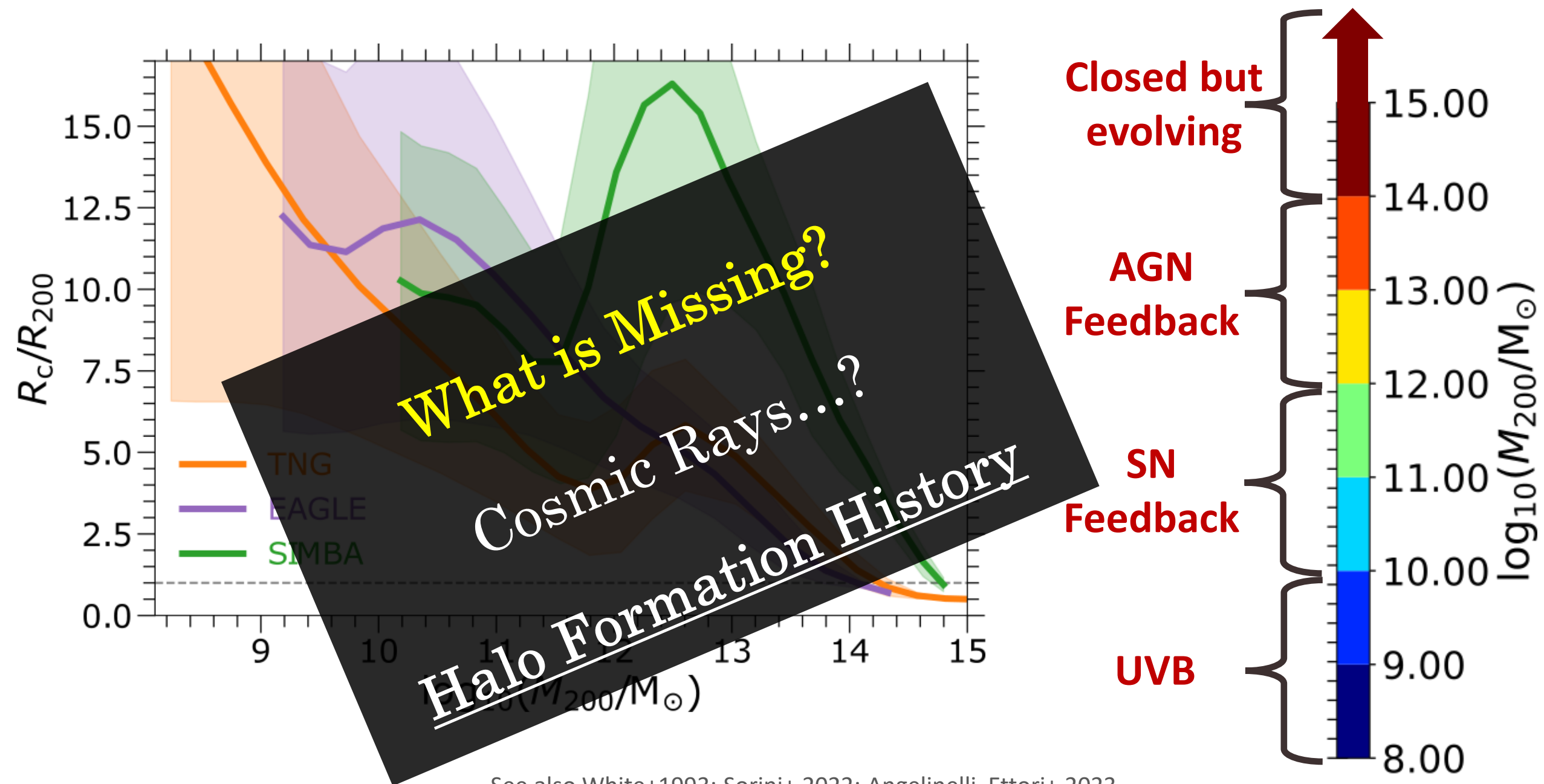
Comparing several variants of TNG, which selectively exclude certain physical processes.





See also White+1993; Sorini+ 2022; Angelinelli, Ettori+ 2023, Zhang+ 2024, ...

Ayroumlou+ 2023b



See also White+1993; Sorini+ 2022; Angelinelli, Ettori+ 2023, Zhang+ 2024, ...

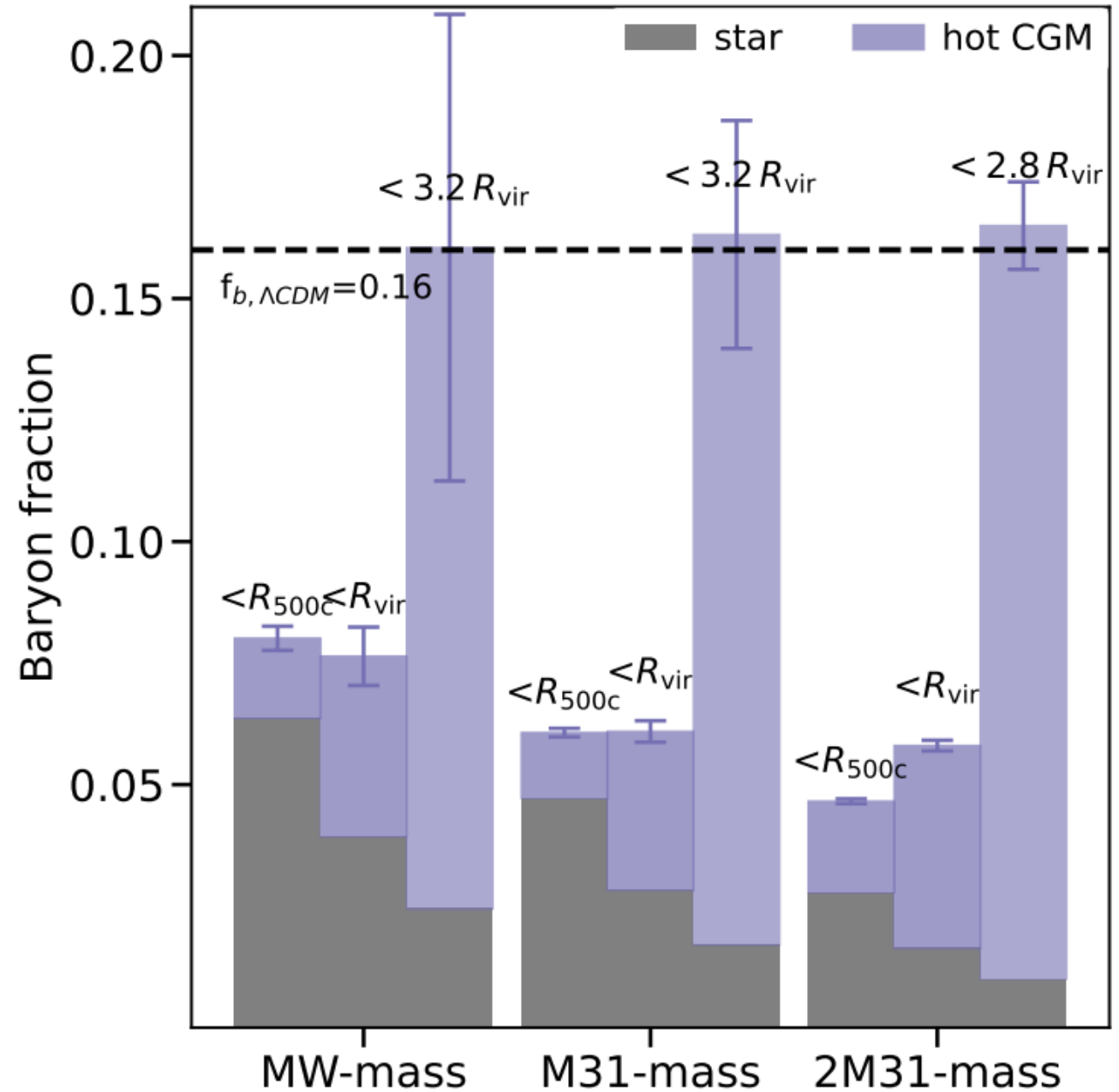
Ayroumlou+ 2023b

# Still Part I

Closure Radius in Observations

# Closure Radius in Observations

- Closure Radius measured employing eROSITA data, extrapolating the gas profiles to several  $R_{500}$ .
- DM density estimation using an NFW profile, extending to several  $R_{500}$ .
- *Main caveats: Gas profile extrapolation and neglecting the two-halo term.*

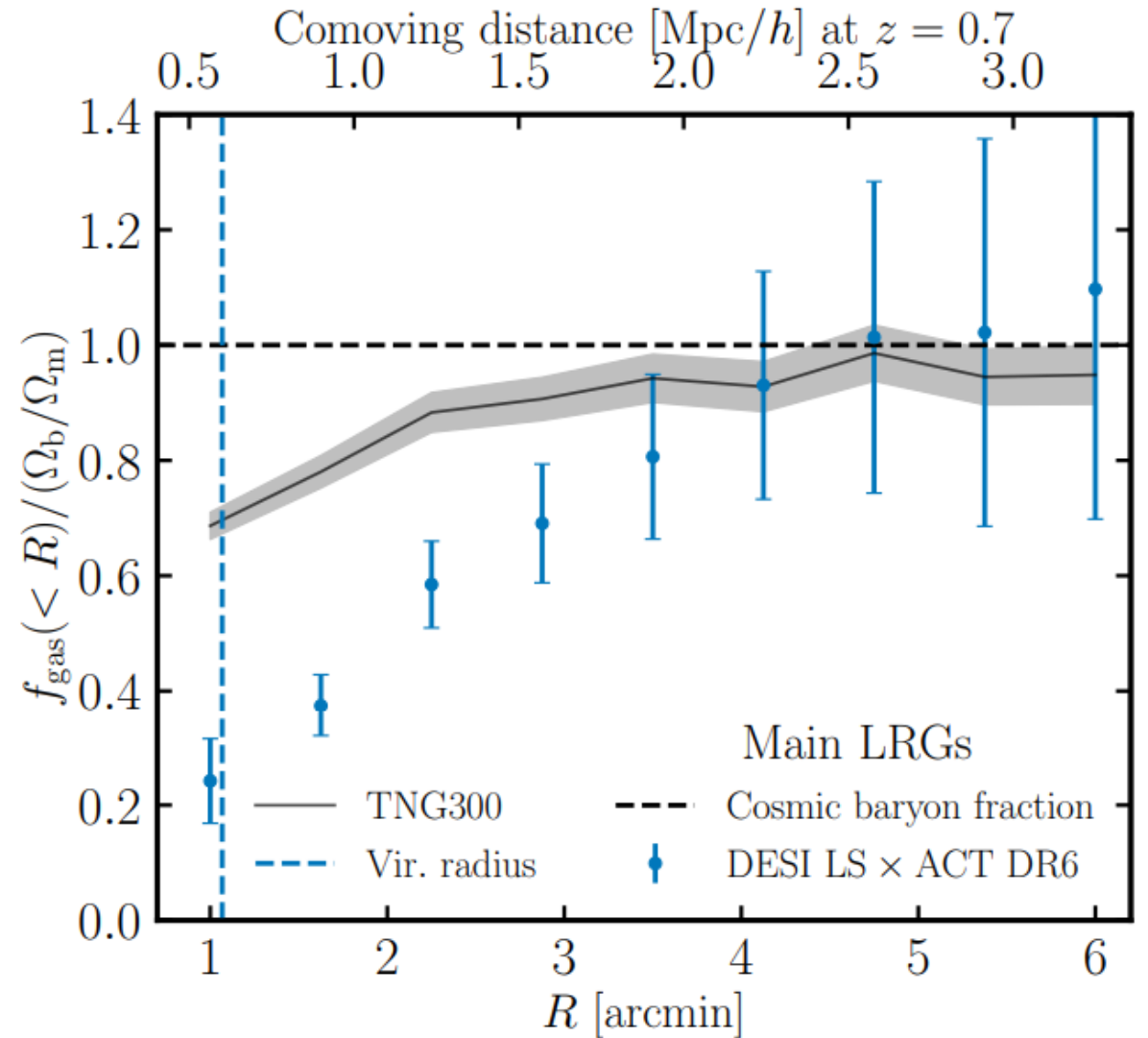


# Closure Radius in Observations

- Gas profile estimation using SZ data
- Mass profile via WL (M200~13.2)

## Main caveats

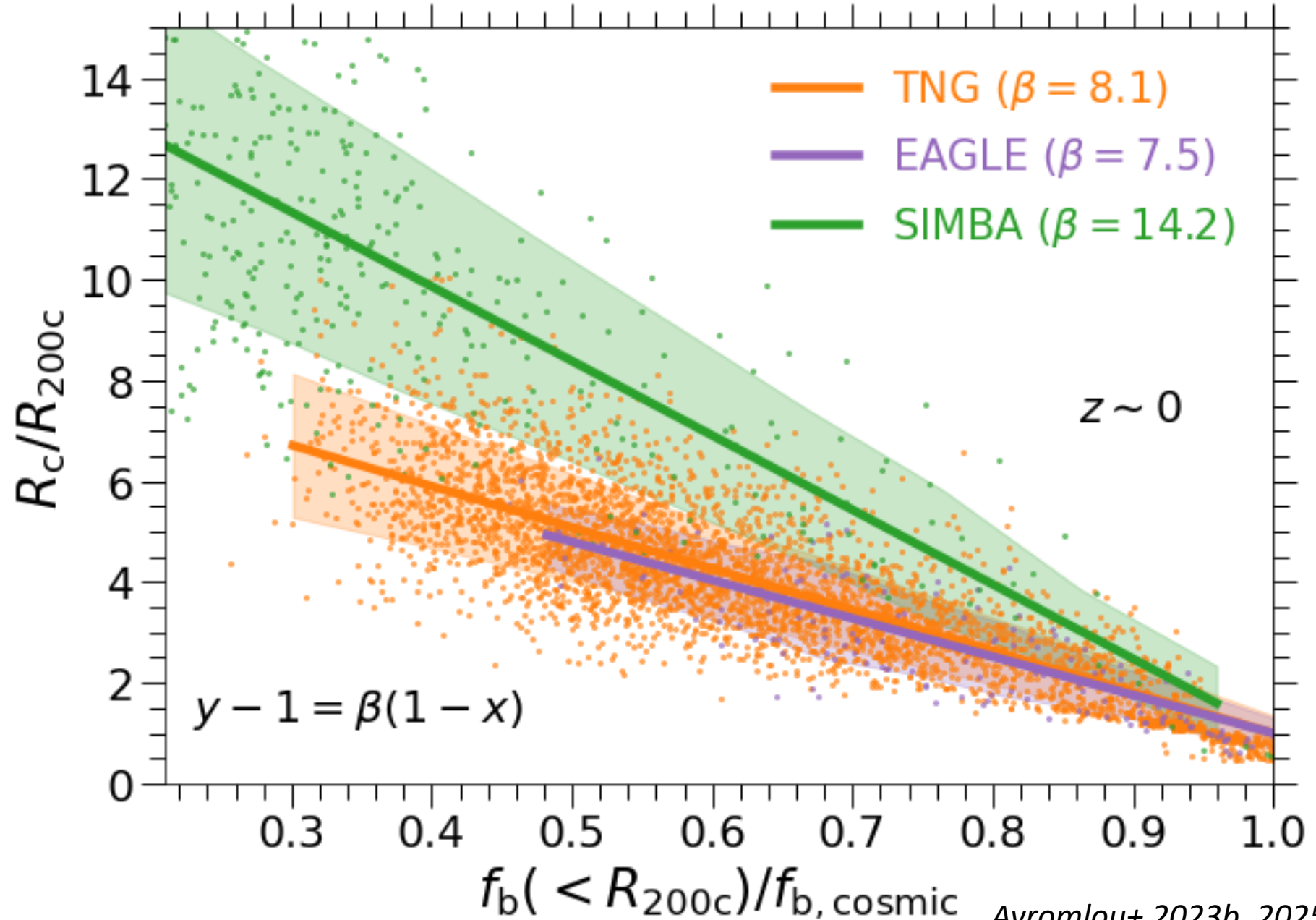
- *Using HOD for populating halos with galaxies (introduces significant uncertainties)*
- *Lack of having stars (not really baryon fraction but gas fraction)*
- *+ SZ and WL uncertainties and stacking*



Hadzhiyska+ 2025

# Predicting the Closure Radius: A Universal Relation

The scaling relation is Universal in the sense that it is valid across all simulations.



# Predicting the closure radius: A Universal Relation

Closure radius  
(normalized)

Halo baryon fraction  
(normalized)

$$\frac{R_c}{R_{200c,500c}} - 1 = \beta(z) \left[ 1 - \frac{f_b(< R_{200c,500c})}{f_{b,\text{cosmic}}} \right]$$

$$\beta(z) = \alpha (1+z)^\gamma$$

Free parameters

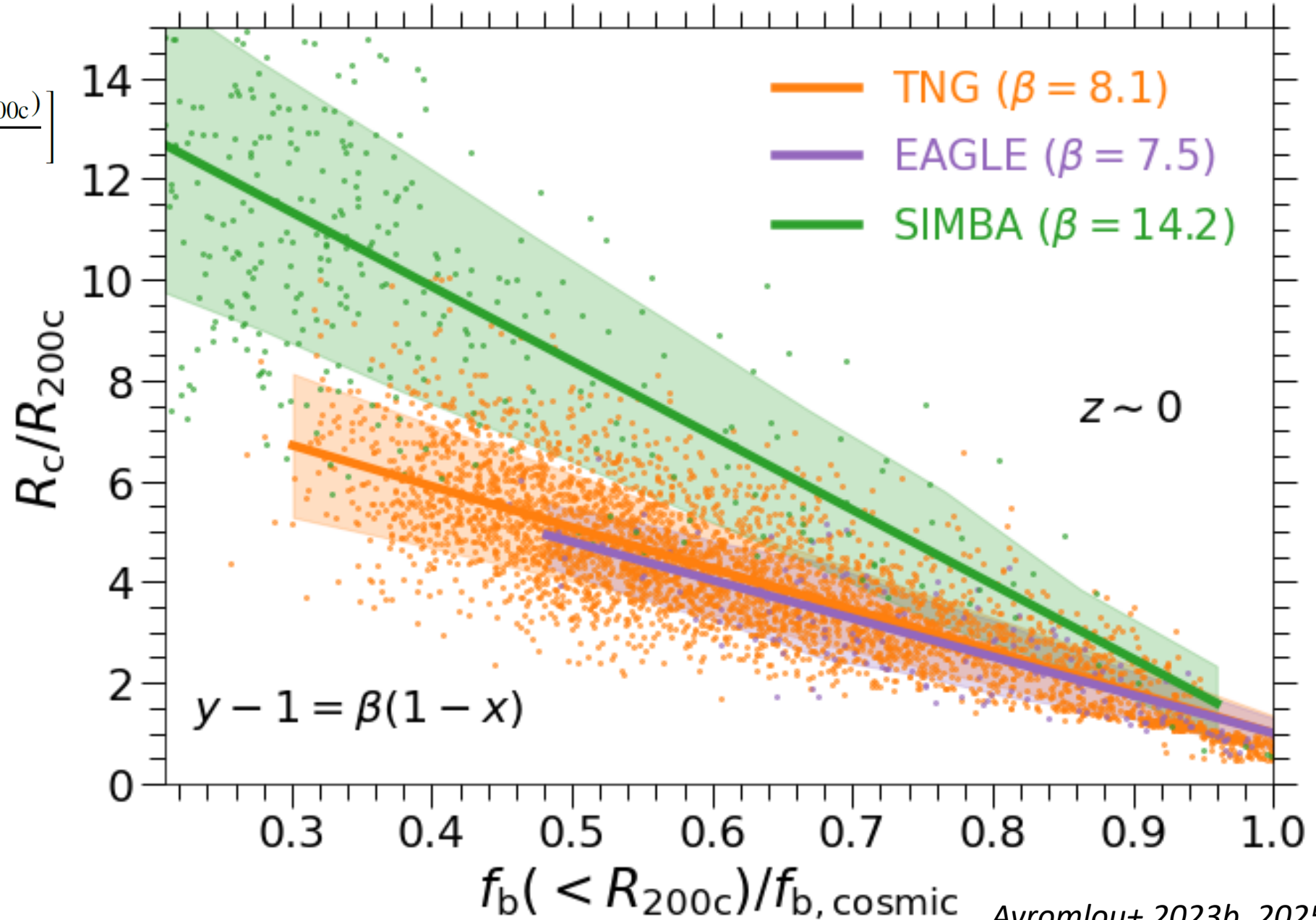
*Ayromlou+ 2023b, 2025 (to be submitted)*

# Predicting the closure radius: A Universal Relation

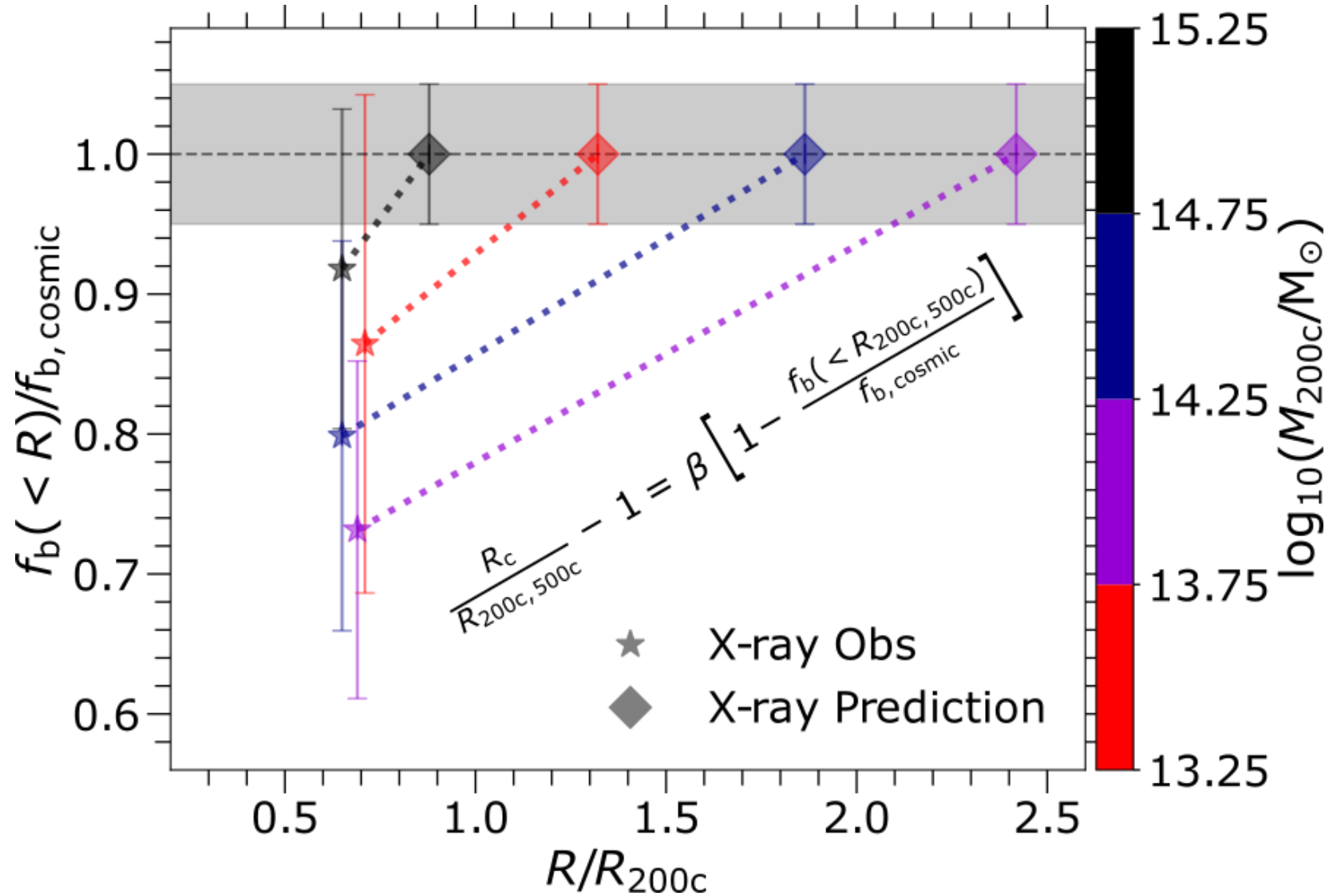
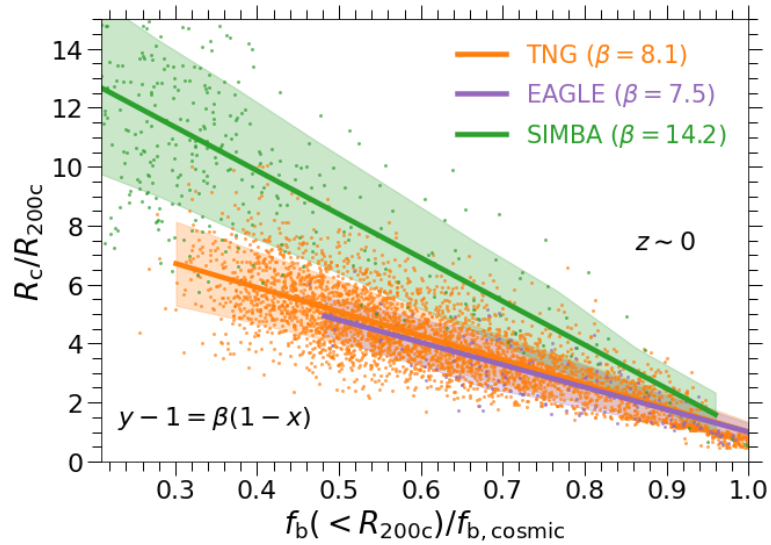
$$\frac{R_c}{R_{200c,500c}} - 1 = \beta(z) \left[ 1 - \frac{f_b(< R_{200c,500c})}{f_{b,\text{cosmic}}} \right]$$

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The  
**Universal Equation**  
is valid across  
all simulations.



# Applying the Universal Relation to Observations

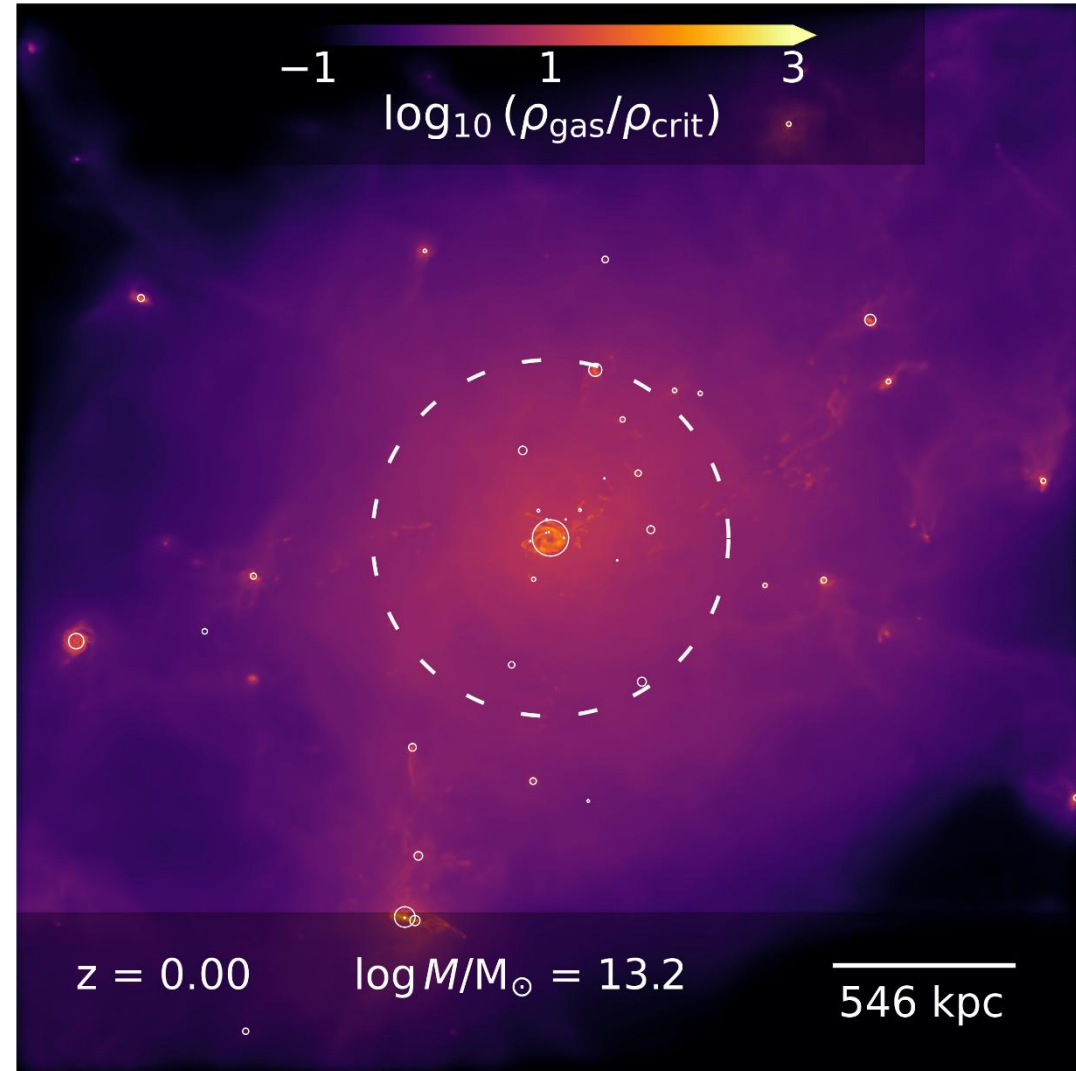
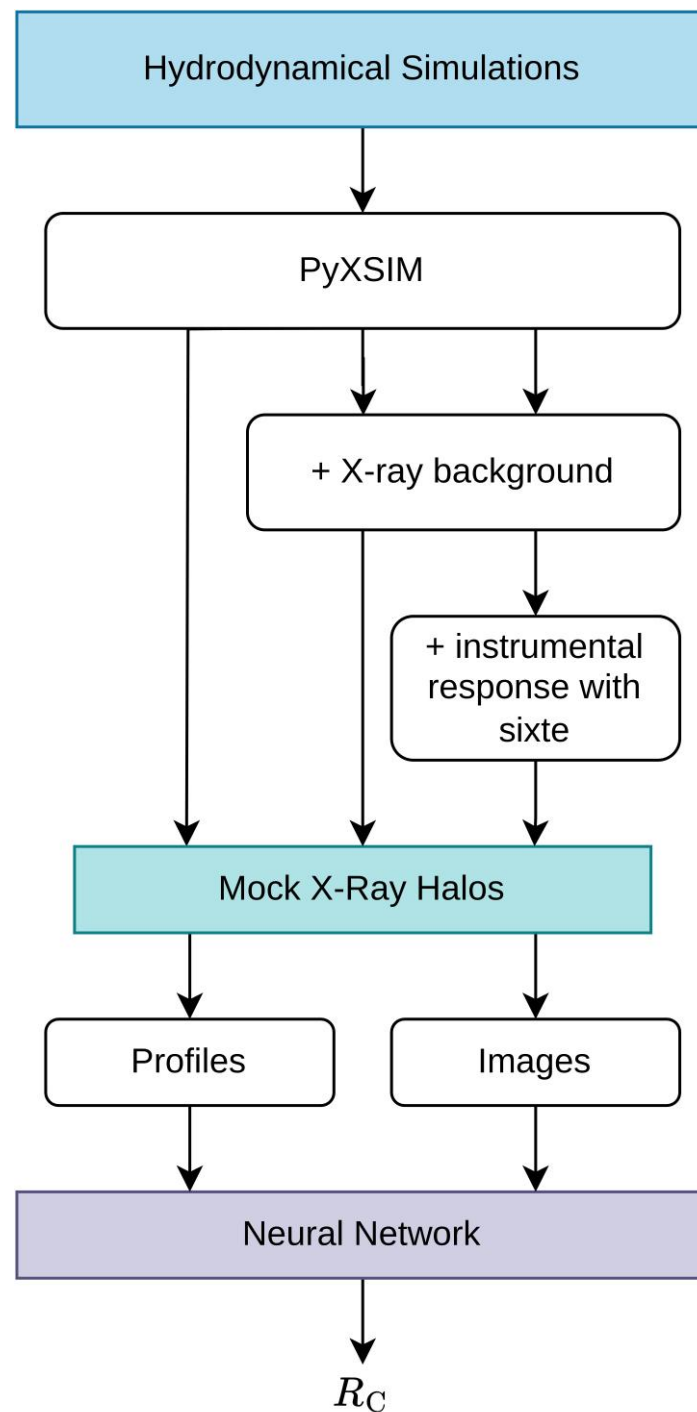


# Closure Radius Estimation using Machine Learning

**By David Leonhard**

(with Thomas Reiprich, Florian Pacaud, Jakob Dietl)

A pipeline to train a ML framework using hydrodynamical simulations to predict the Closure Radius of the Observed Halos



*Leonhard+, in prep.*

## Part II

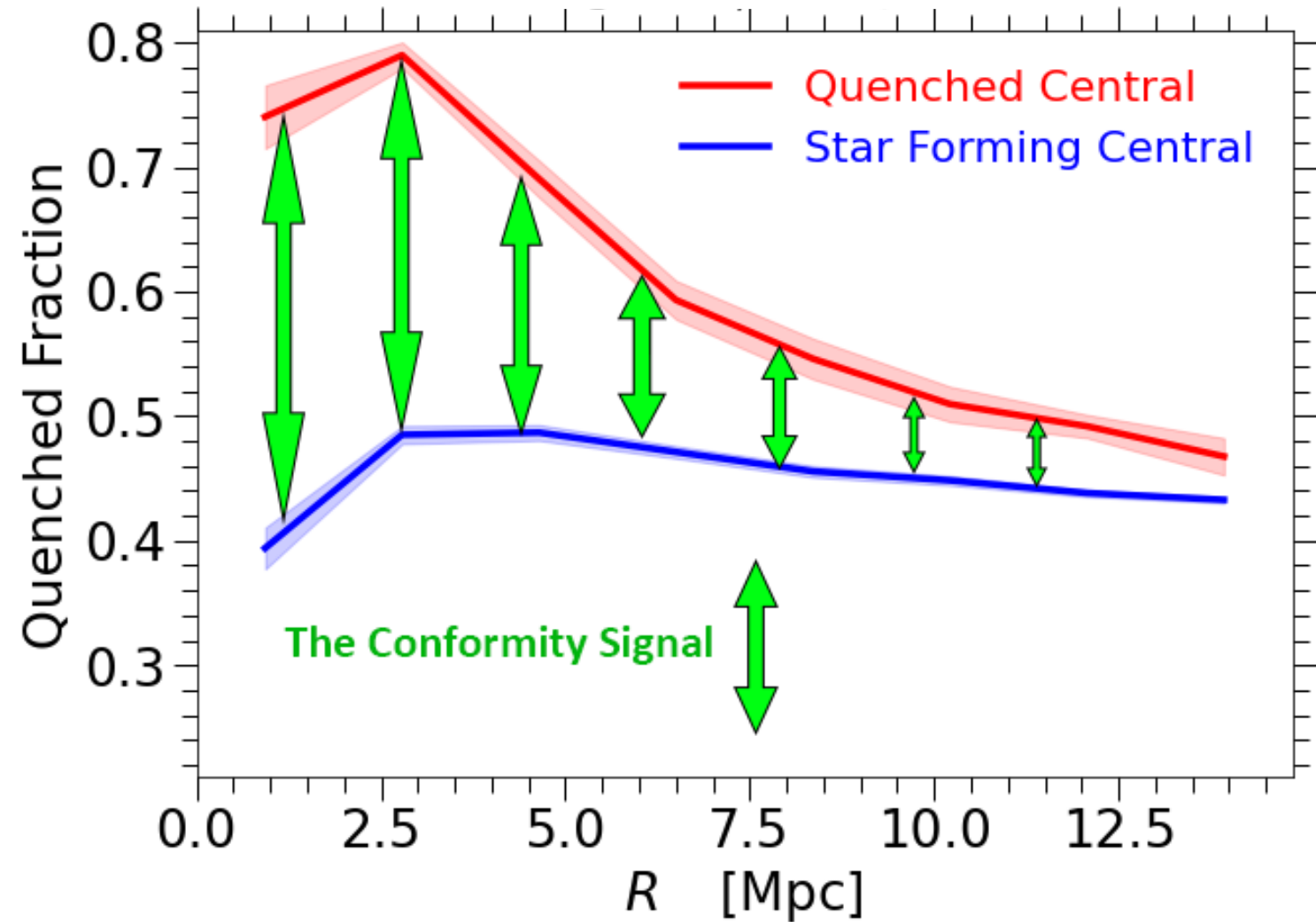
# Galaxy Physics Beyond the Halo Boundary

# The Conformity Signal

$$\Delta f_q = f_q \text{ [quenched primary]}$$

$$- f_q \text{ [star forming primary]}$$

- Introduced first by Weinmann+ 2006 (small scales) and Kauffmann+ 2013 (large scales)
- The existence and origin of conformity is a matter of debate (see e.g. Sin+ 2017, Tinker+ 2018, Sun+ 2018, Lacerna+ 2018)



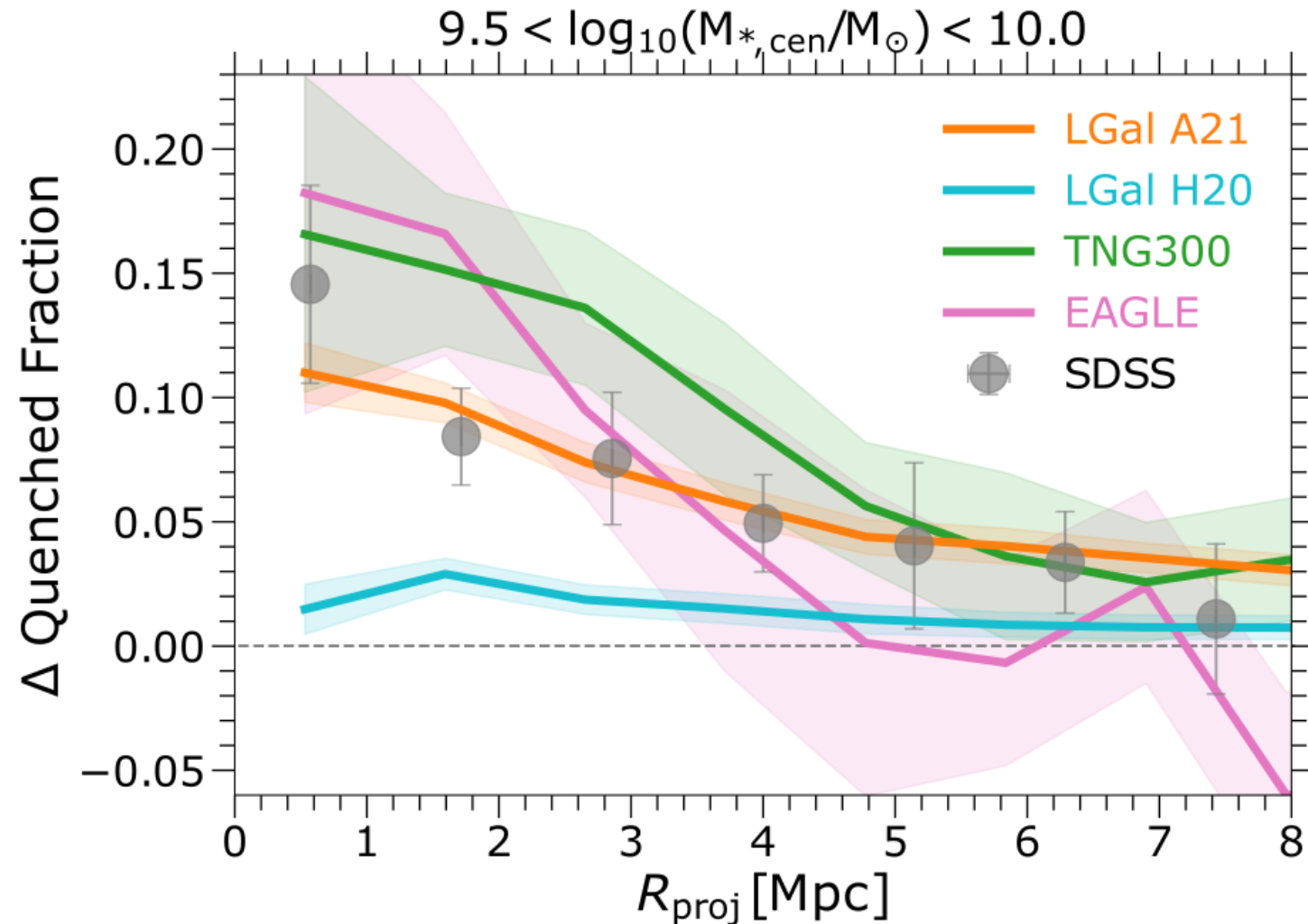
# The Conformity Signal: SDSS vs. Simulations

**→ The signal is present out to at least 5 Mpc in**

- SDSS
- LGal - A21
- TNG
- EAGLE

**→ The signal is missing in**

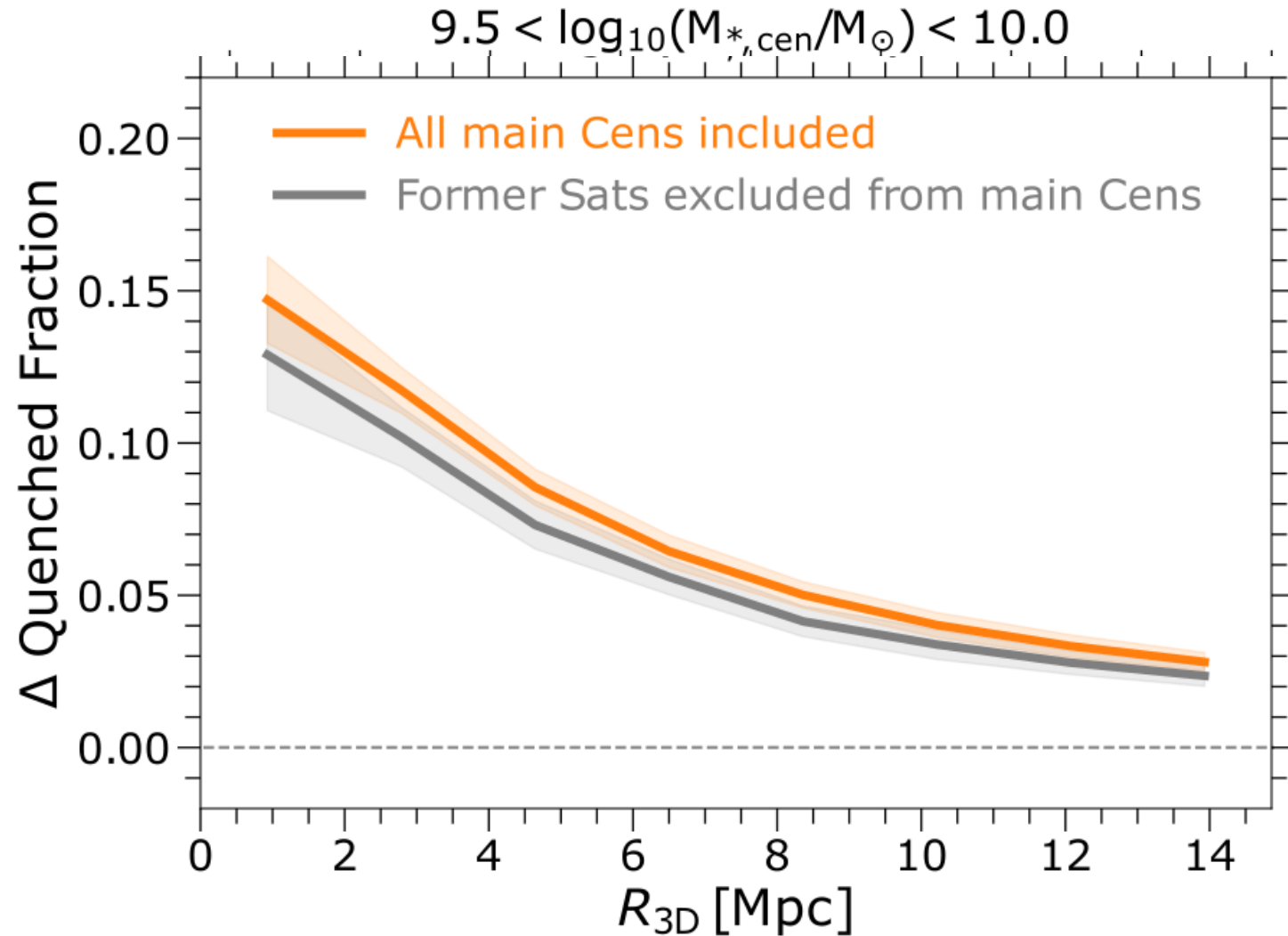
- LGal - H20 (no stripping beyond R200)



# The Conformity Signal: The Role of Backsplash Galaxies

 The 3D signal is present out to at least 10 Mpc in

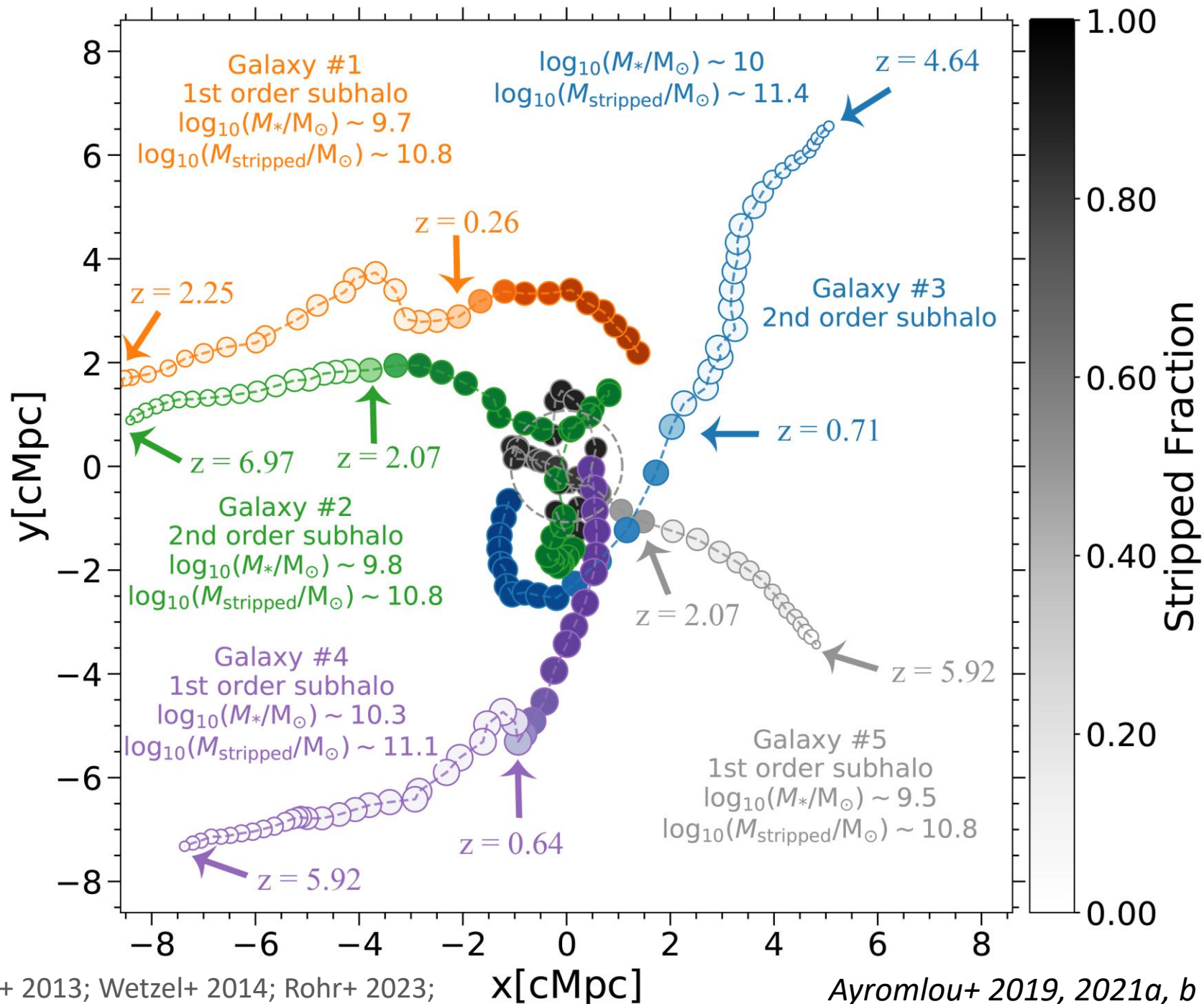
- *Former Satellites: Currently central galaxies that have been a member of a halo other than their current halo in the past*
- **Excluding former satellite galaxies does not change the signal significantly**



# Gas Stripping through Time

We measure the actual amount of the stripped gas on the fly in the **L-Galaxies** semi-analytical model.

**A significant fraction of galaxies lose their entire CGM gas in the outskirts massive halos.**

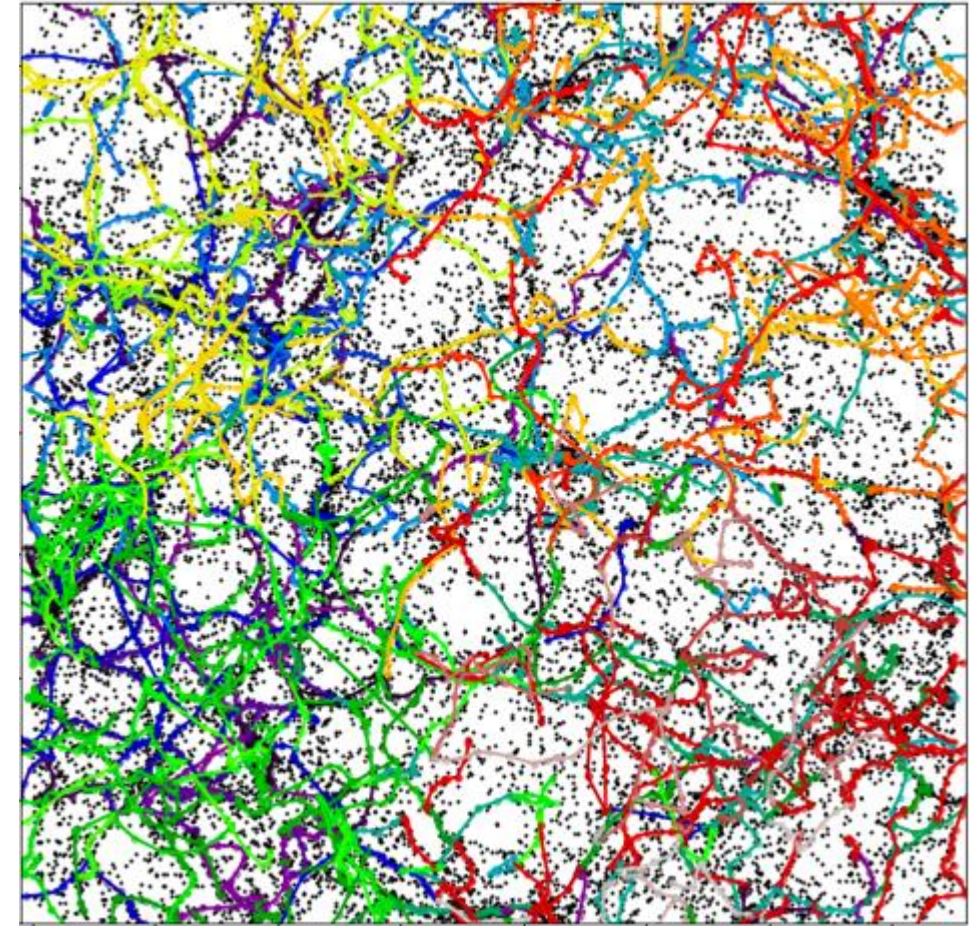
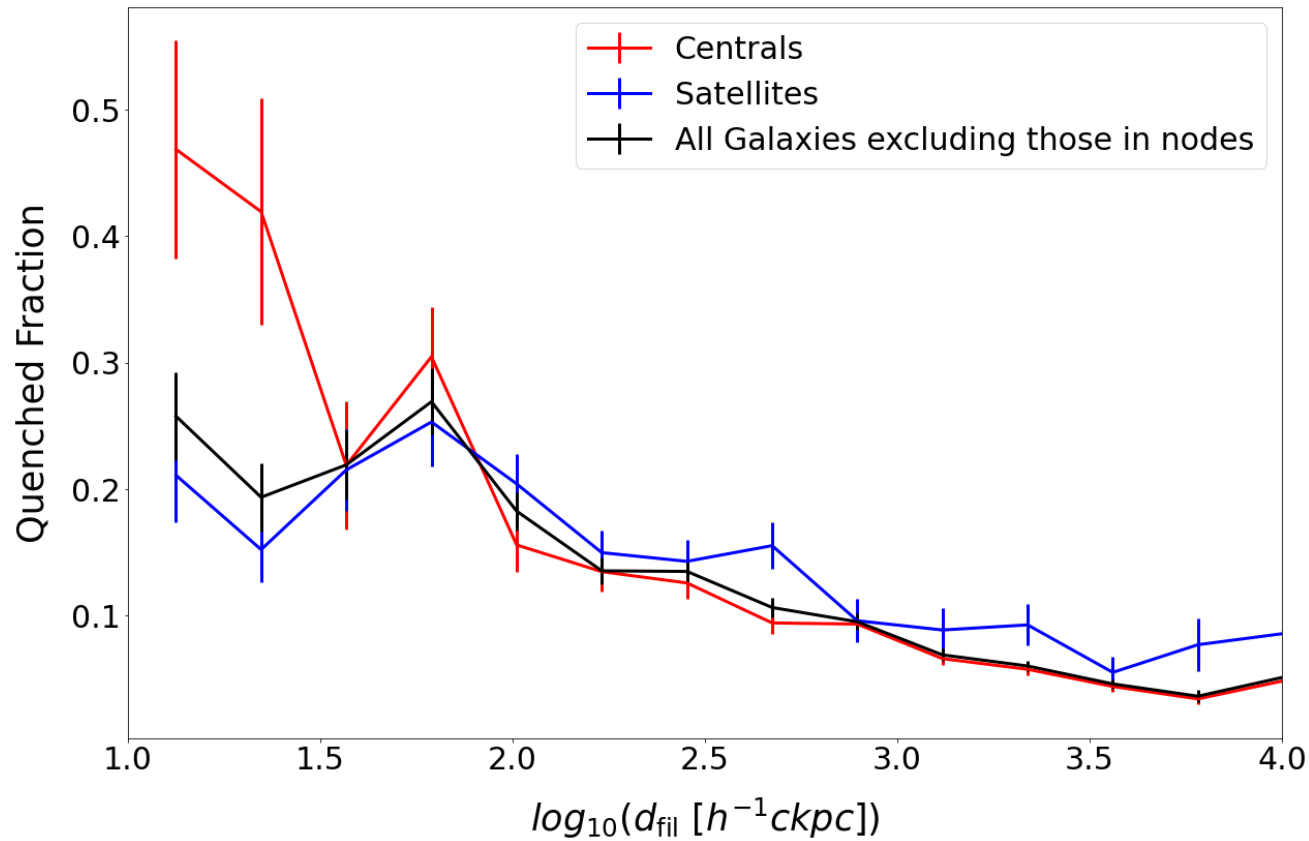


# Galaxy Quenching in and around Filaments



Emmanouela Gerakaki

[See also talks by Daniela and Nicola](#)



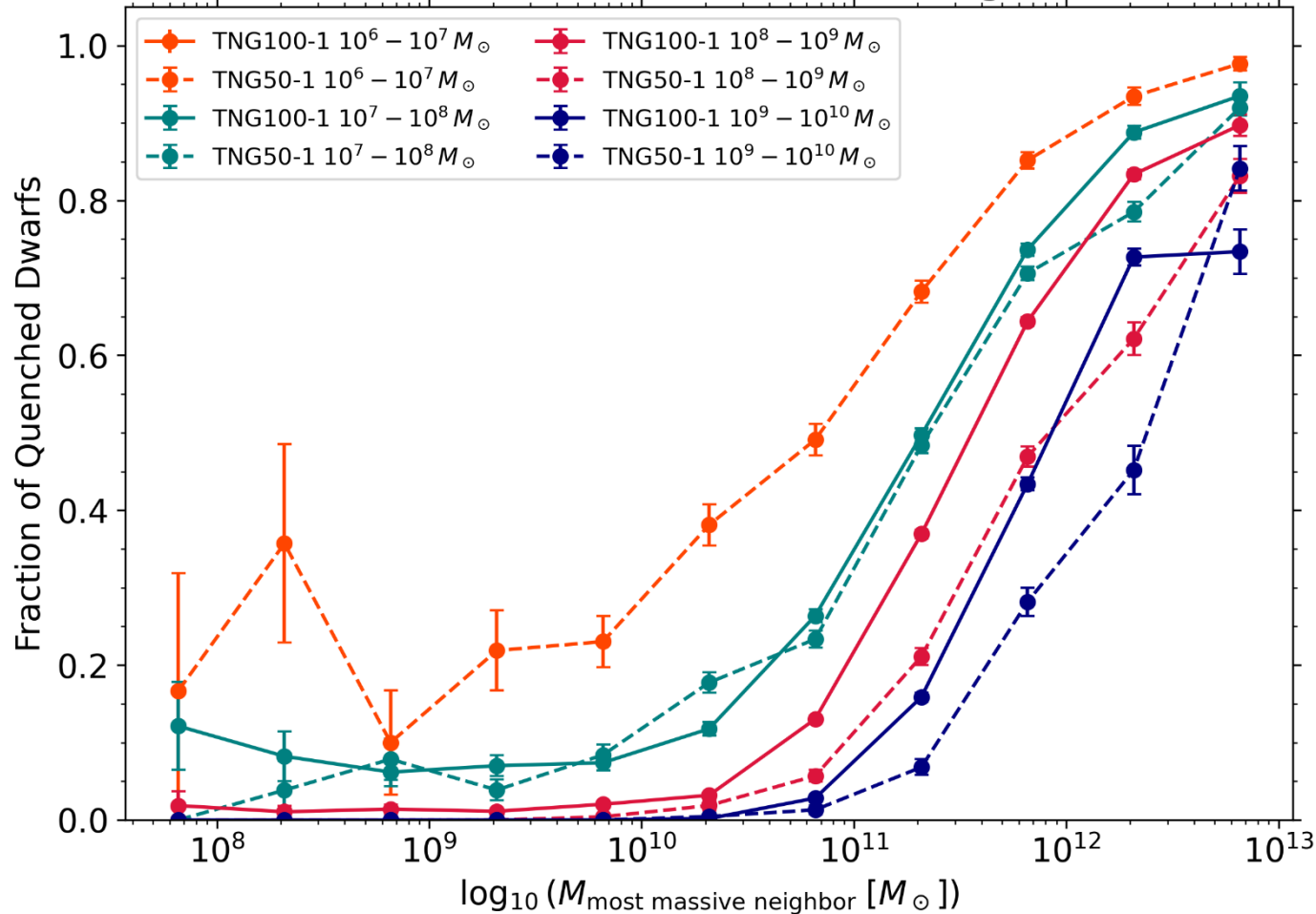
*Gerakaki+, in prep.*

# Galaxy Quenching Near Massive Systems



Sahar Sarmadian

Quenched Fraction vs. Most Massive Neighbor Mass



In simulations (and observations), strong correlations are found between quenching and the mass of the most massive neighbor, regardless of halo membership.

See also Peng+ 2010, Bahe+ 2013, Wetzell+ 2014, Rohr+ 2023

*Sarmadian+, in prep.*

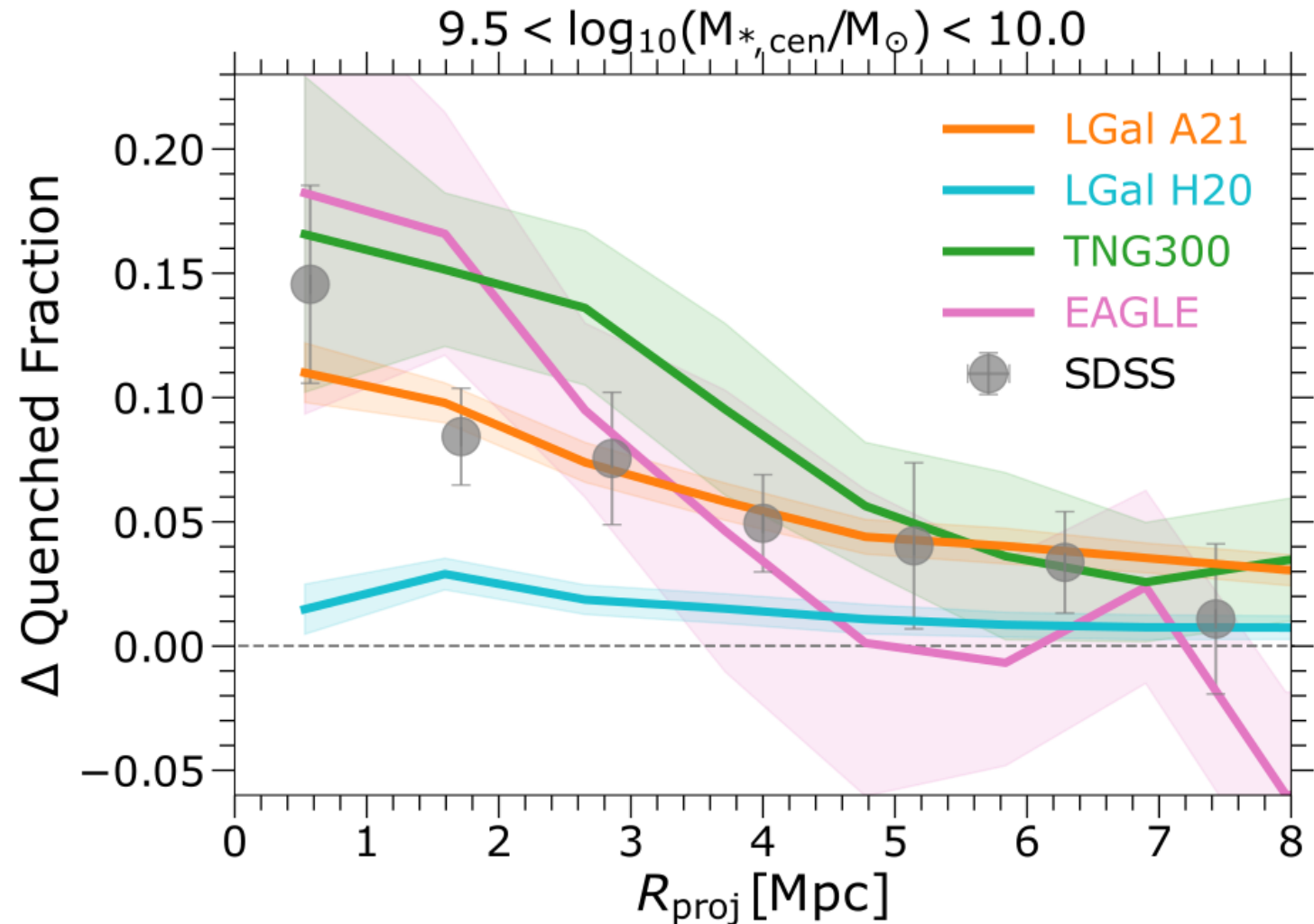
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## Part III

# The High-Redshift Universe and its Challenges

# AGN Feedback and Quenching

## Low-z Picture:

- Stellar feedback regulates star formation at  $M < \text{Milky Way}$
- Milky Way-like galaxies are the least influenced by feedback
- AGN feedback regulates and quenches star formation at  $M > \text{Milky Way}$ .

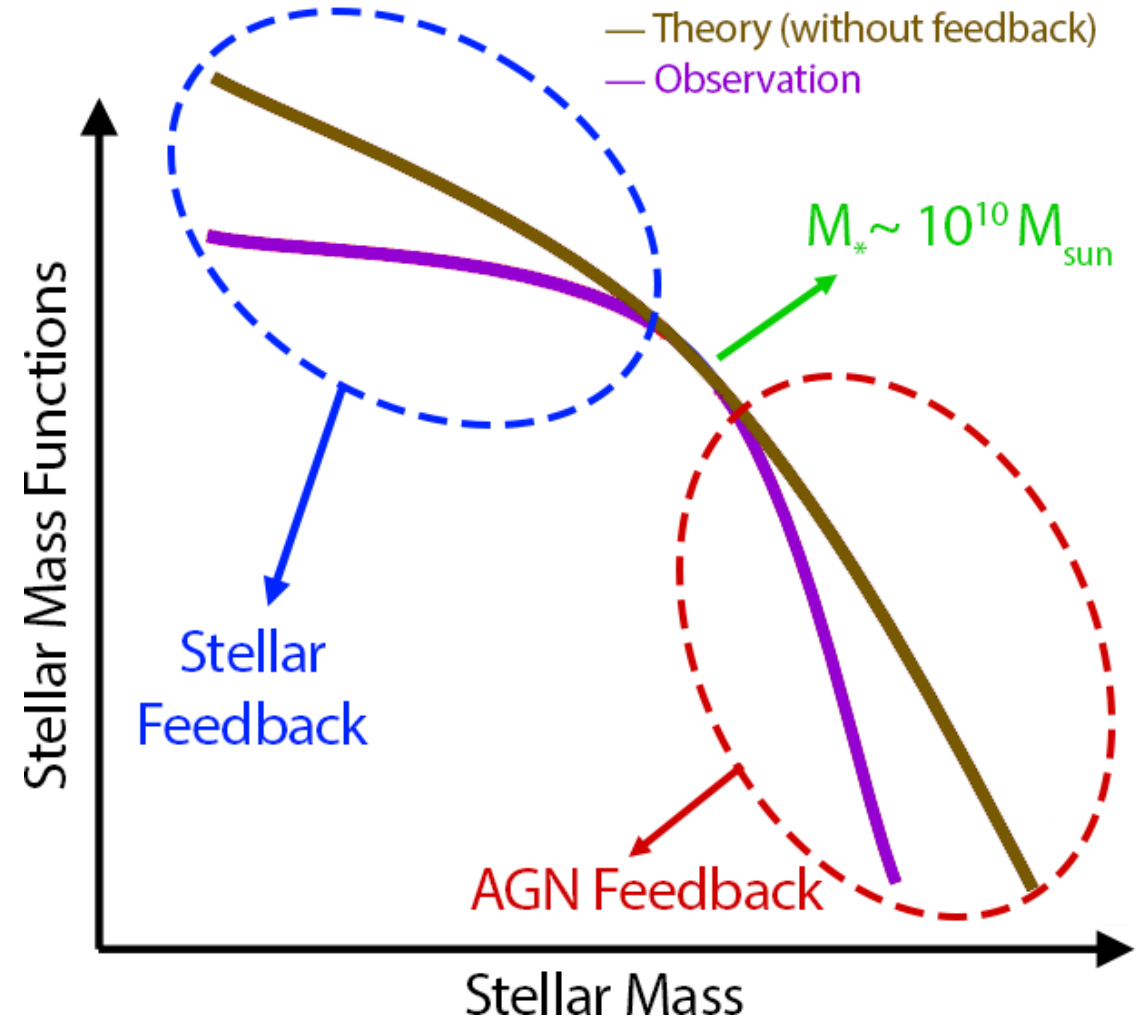
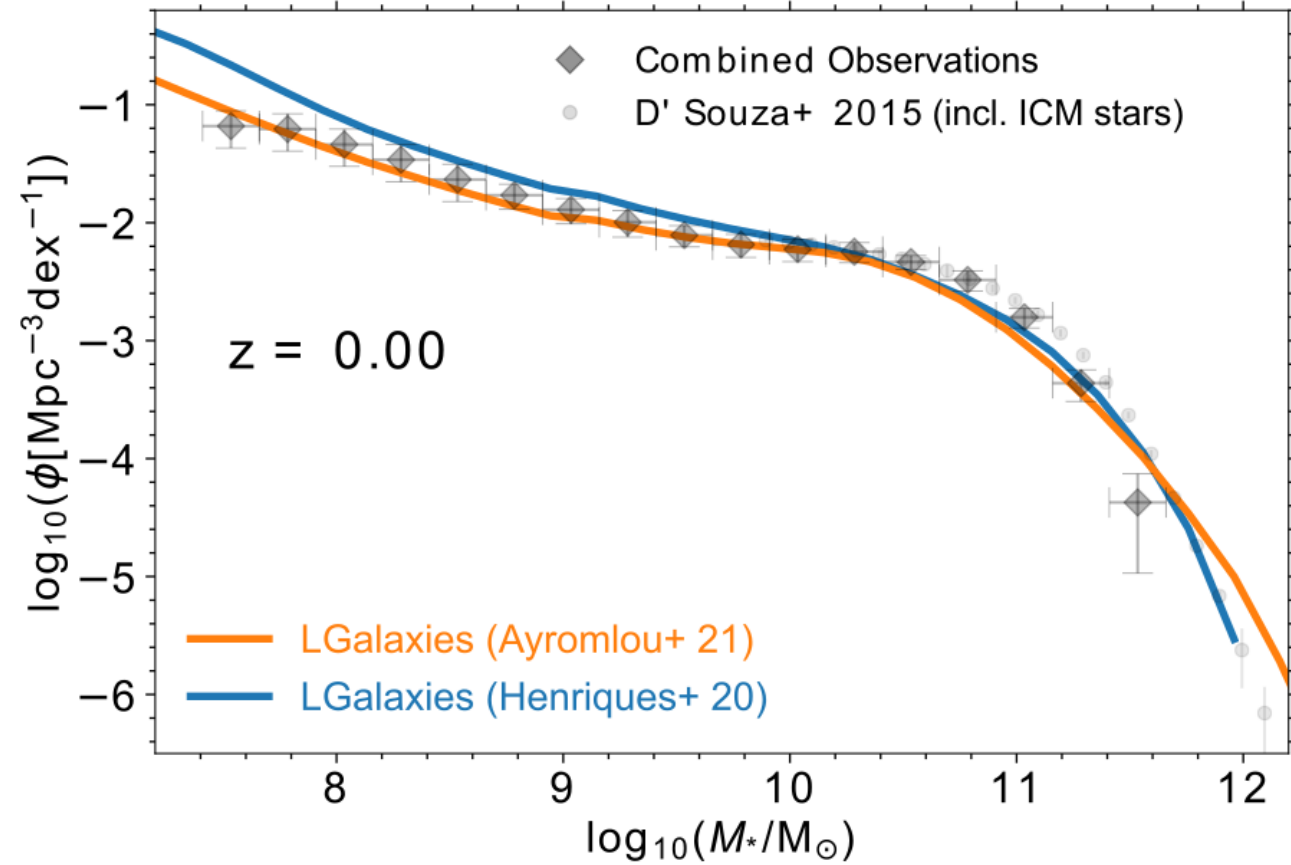
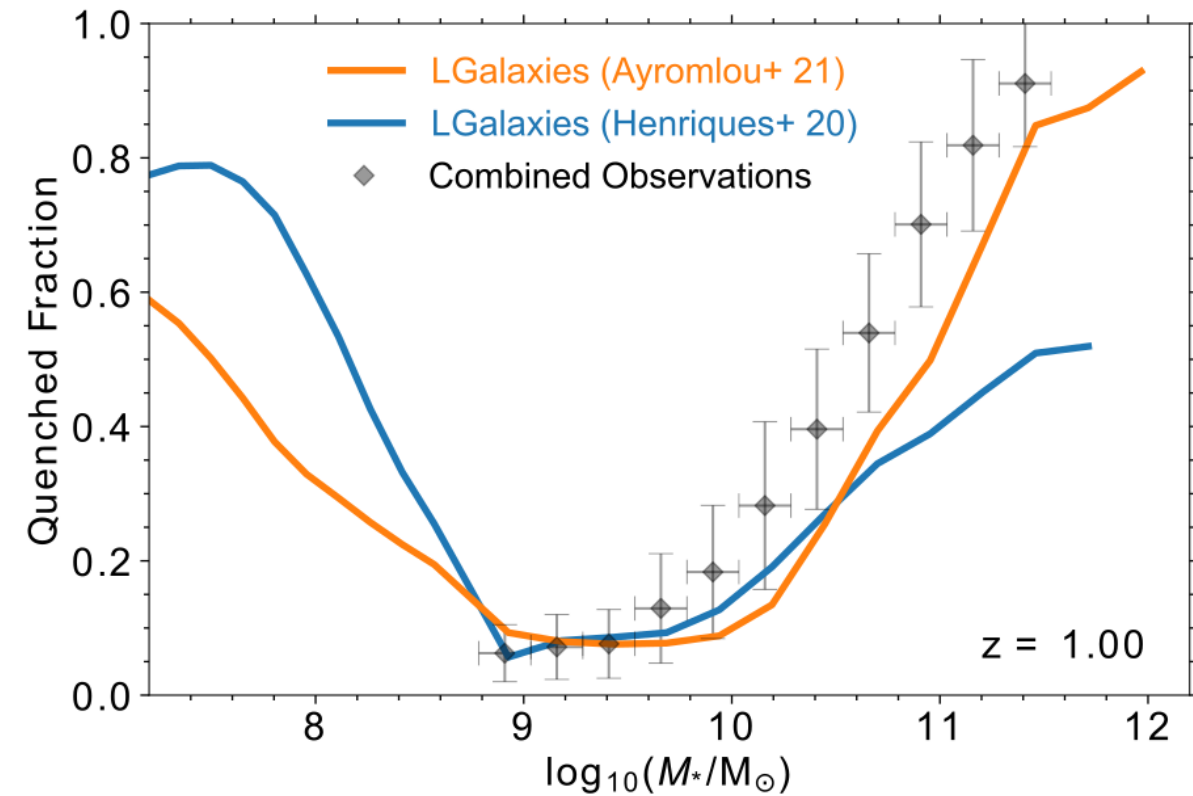


Figure from Ayromlou+ 2025 in prep.  
(inspired by Silk & Mamon 2012)

# Low-z Calibration of Models

- Models are typically calibrated against **low-z data** such as **SMF (right)** and **Quenched fraction (left)**



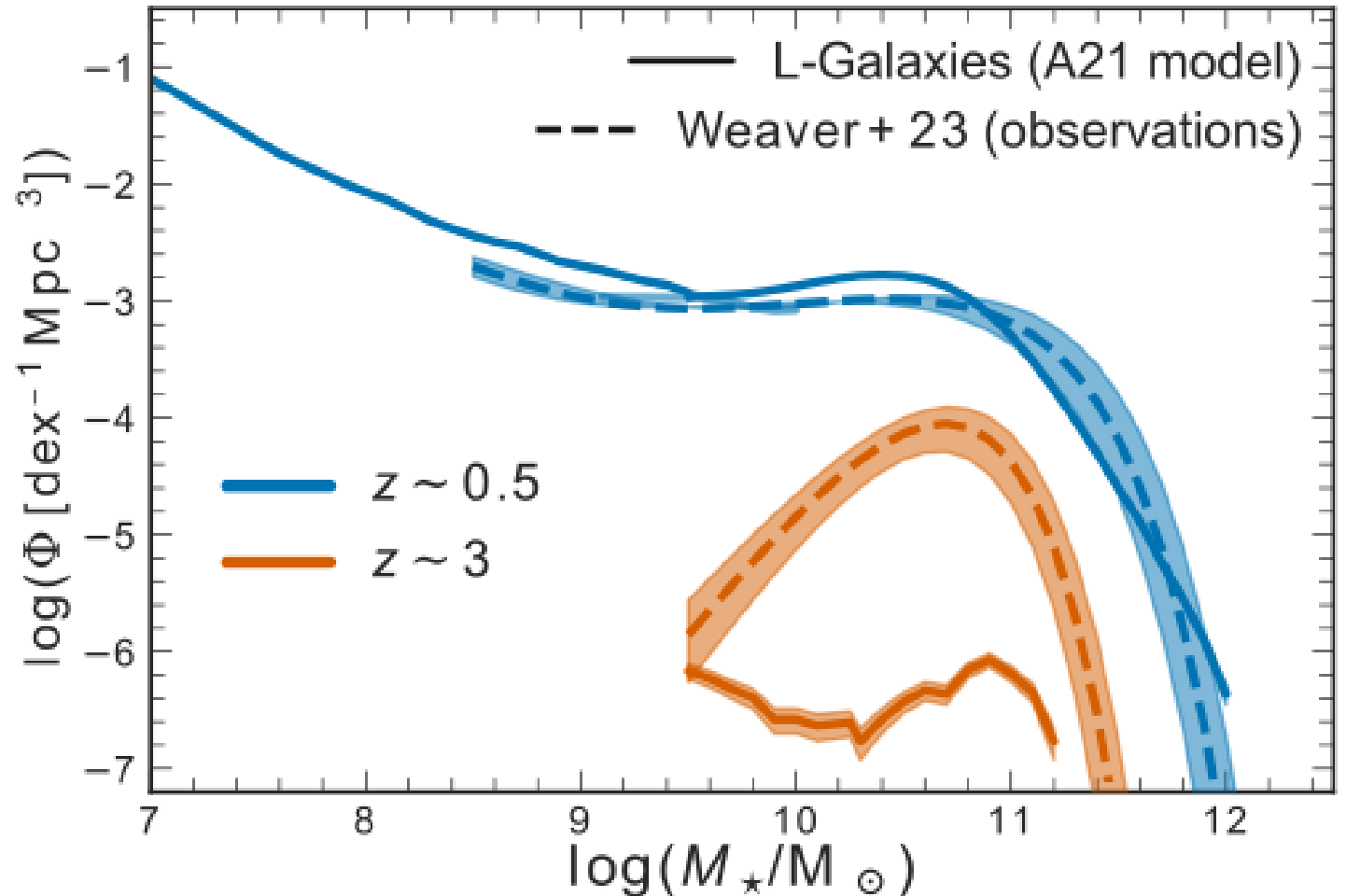
# Stellar Mass Function of Quenched Galaxies



Akash  
Vani

- The total galaxy stellar mass function of agrees with data out to  $z=6$
- **L-Galaxies underpredicts the stellar mass function of quenched galaxies at  $z>2$**

See also Valentino+ 2023, Hartley+ 2023, Remus+2024, De Lucia+ 2024, Lagos+ 2024, Weller+2024, and ...



# Environmental Quenching at High-z

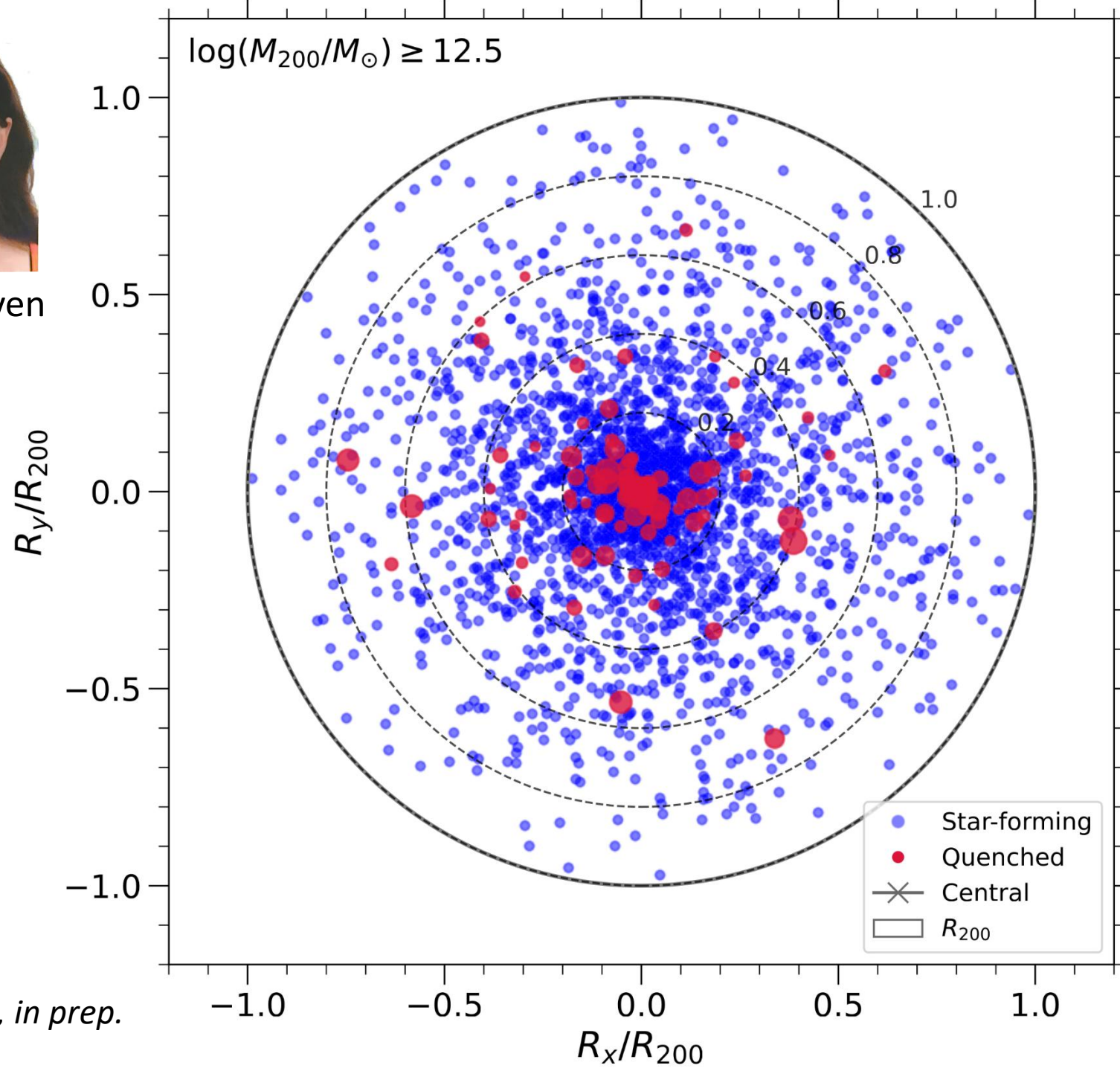


Aleyna Döven

- Environmental Quenching can happen even at high-redshifts ( $z > 3$ ).
- Nearly 10% of satellites in near the halo center are quenched at  $z=4$ , according to L-Galaxies.

[See also talks by Stefano and Sebastiano](#)

*Döven+, in prep.*



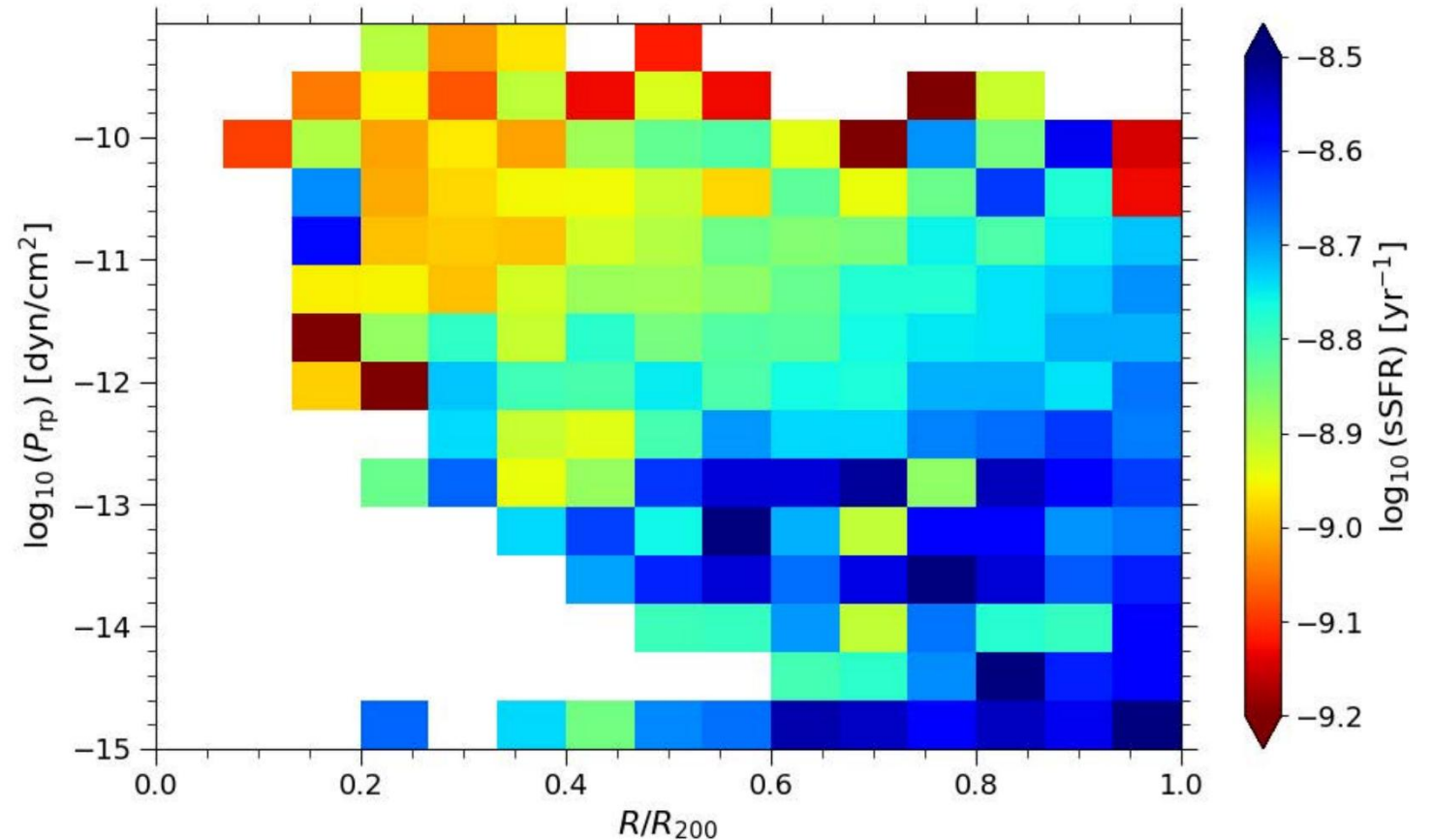
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Aleyna Döven

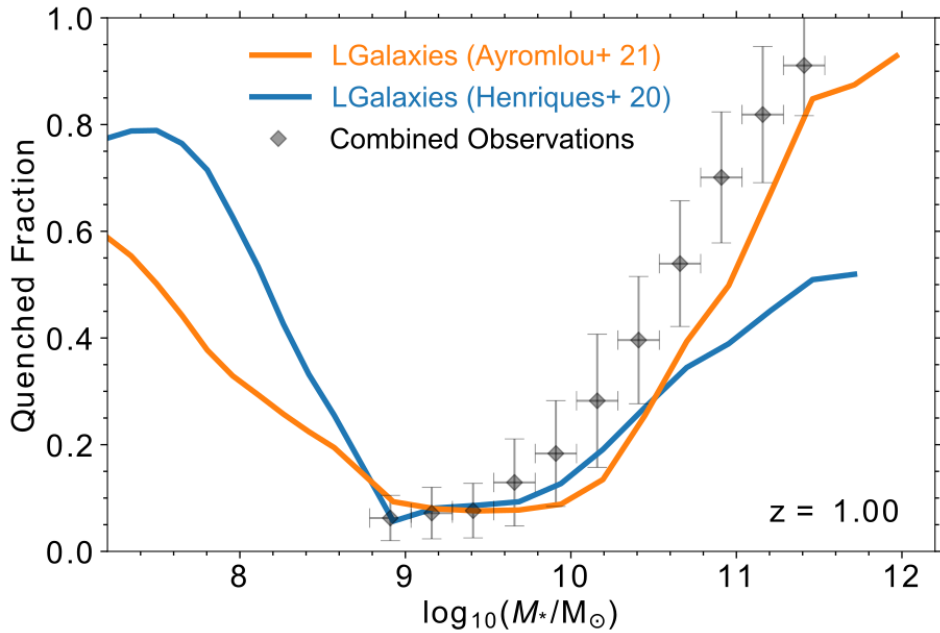
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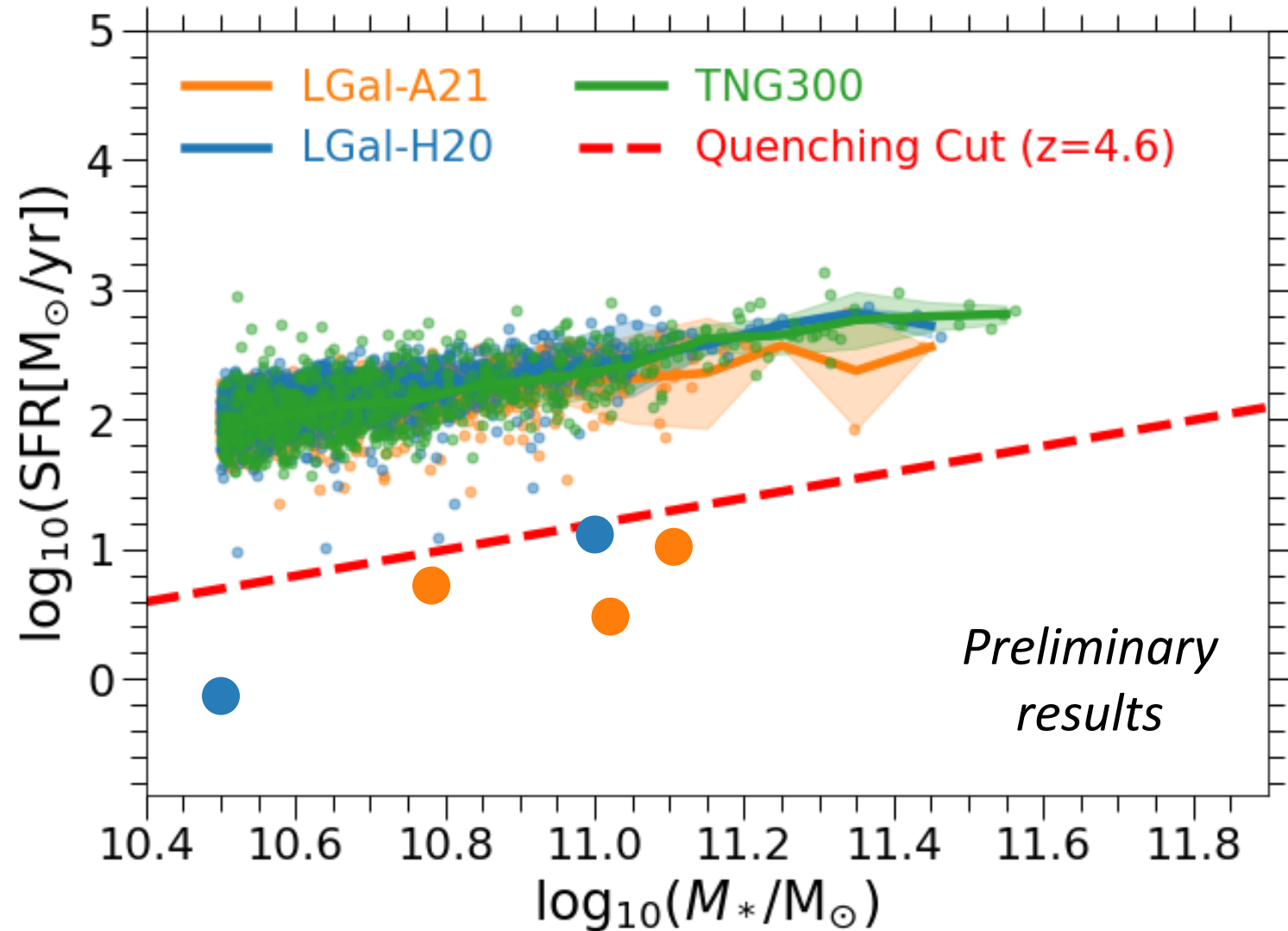


*Döven+, in prep.*

# Galaxy Quenching at $z \sim 4.6$

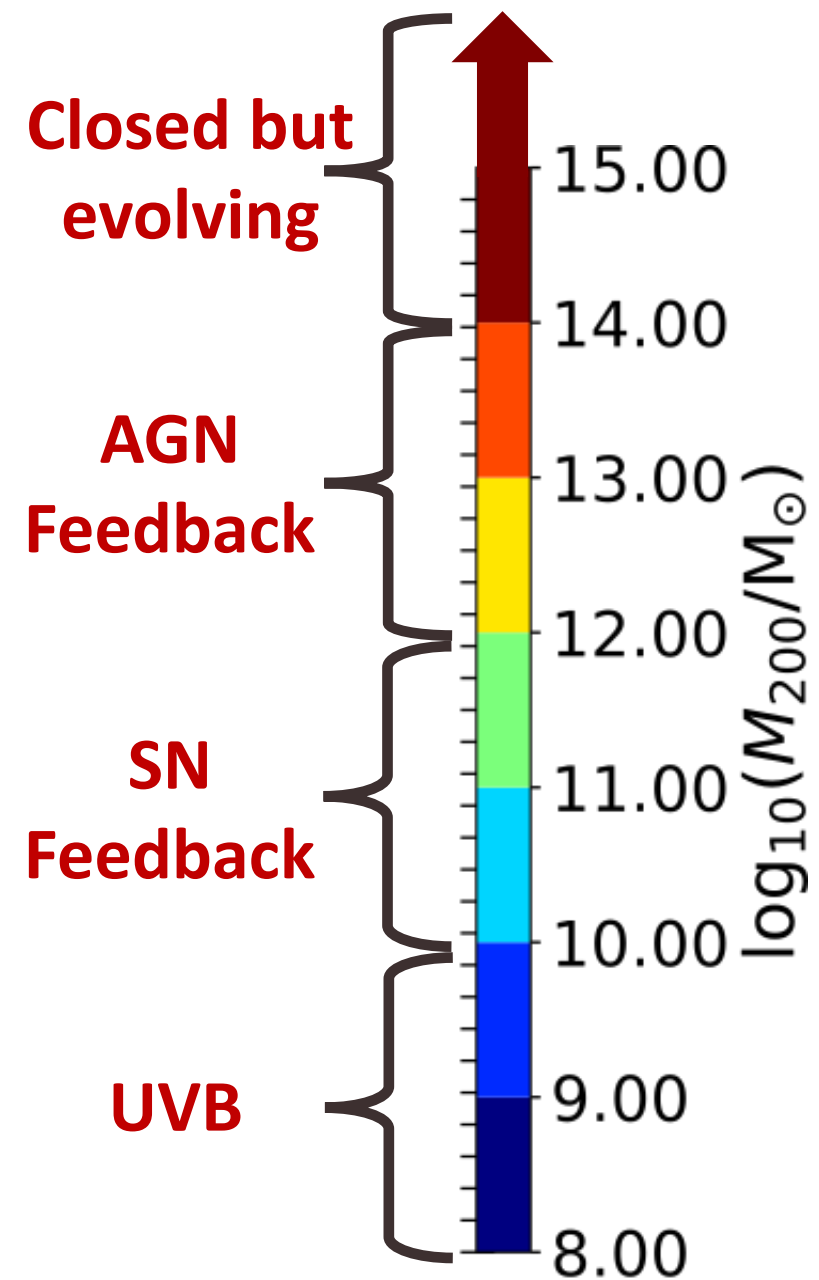
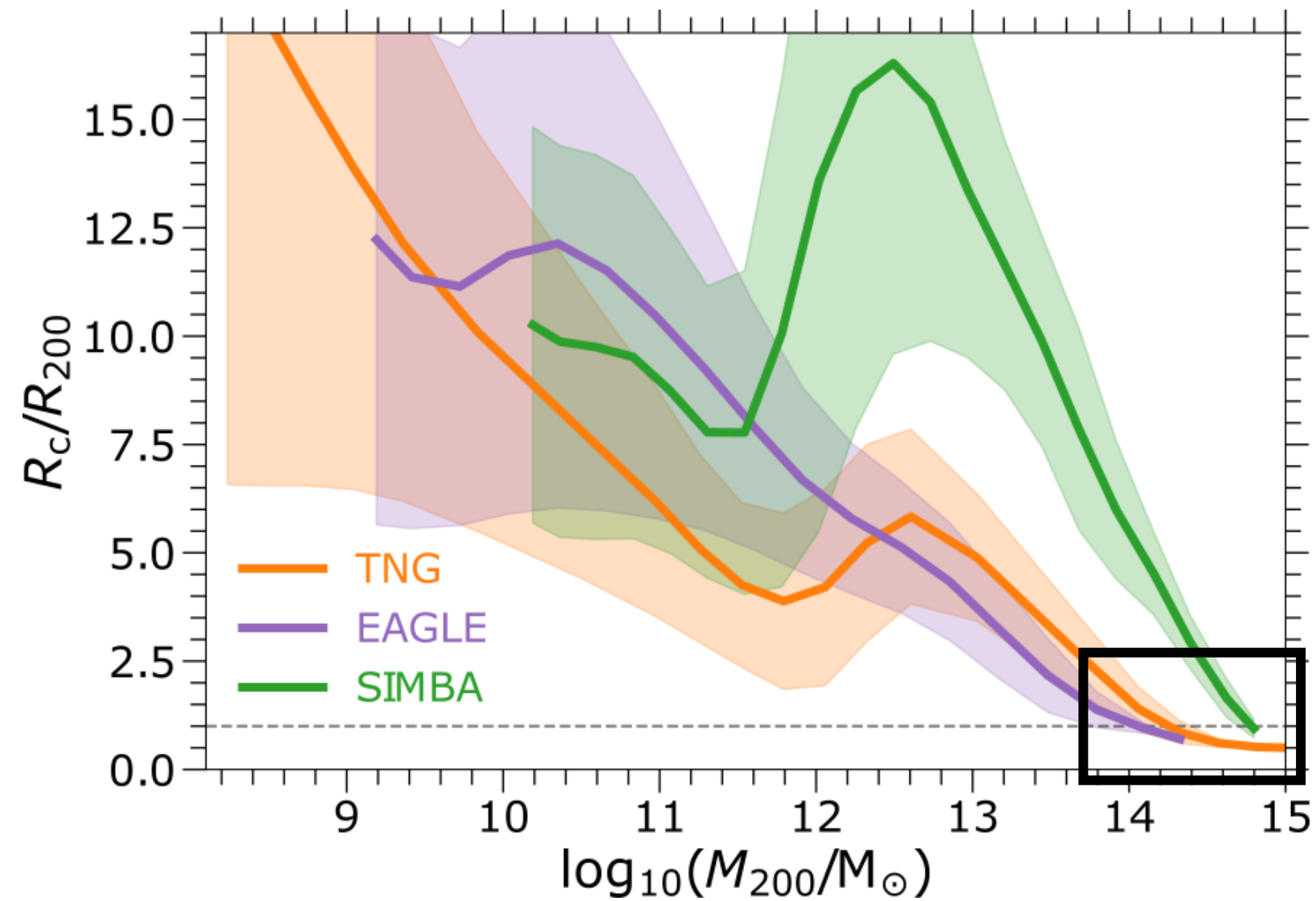


Simulations may have a few quenched galaxies at  $z > 3$ , but not enough to reproduce the high- $z$  observations.



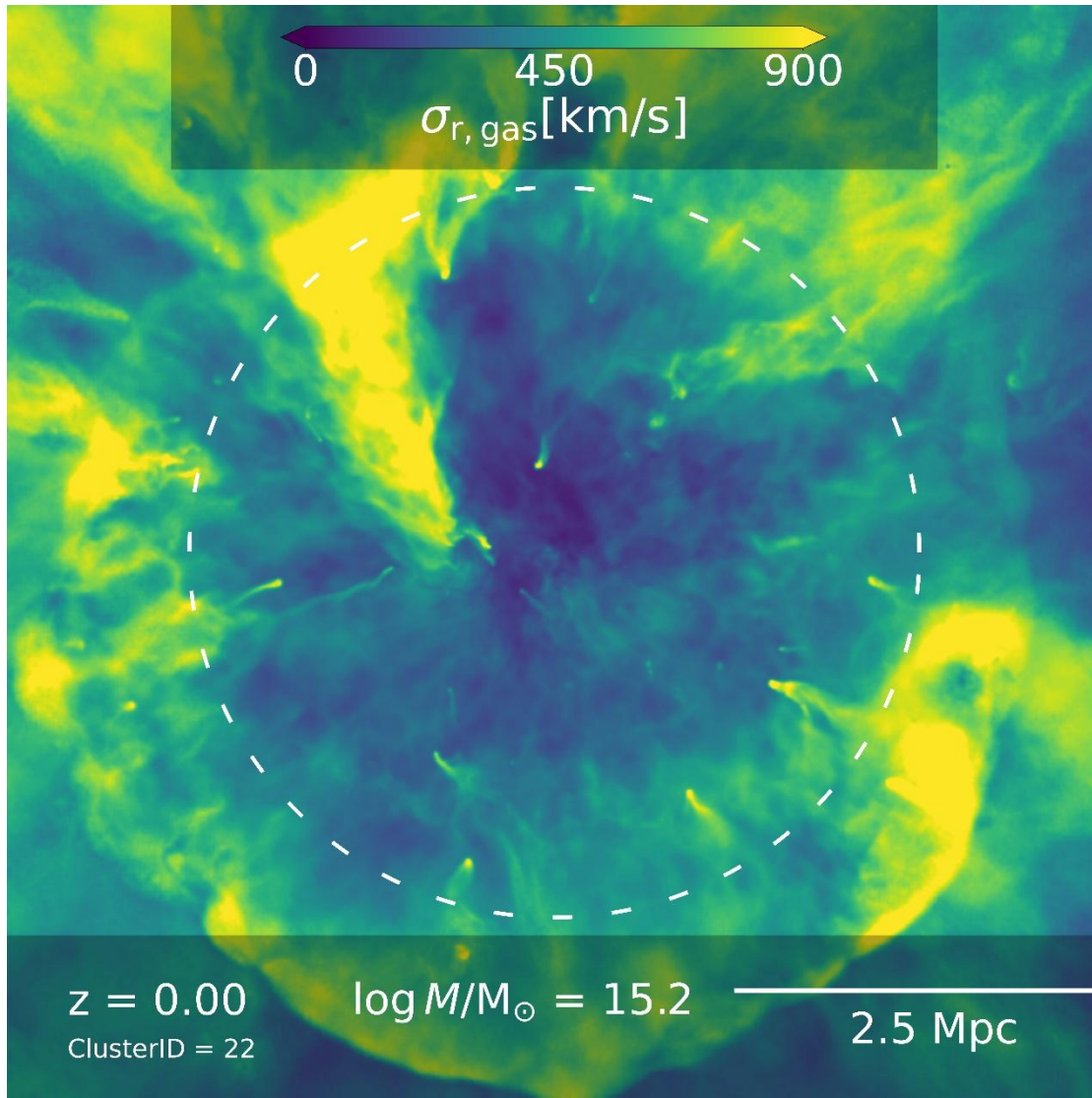
## Part IV

# The Physics of Galaxy Clusters

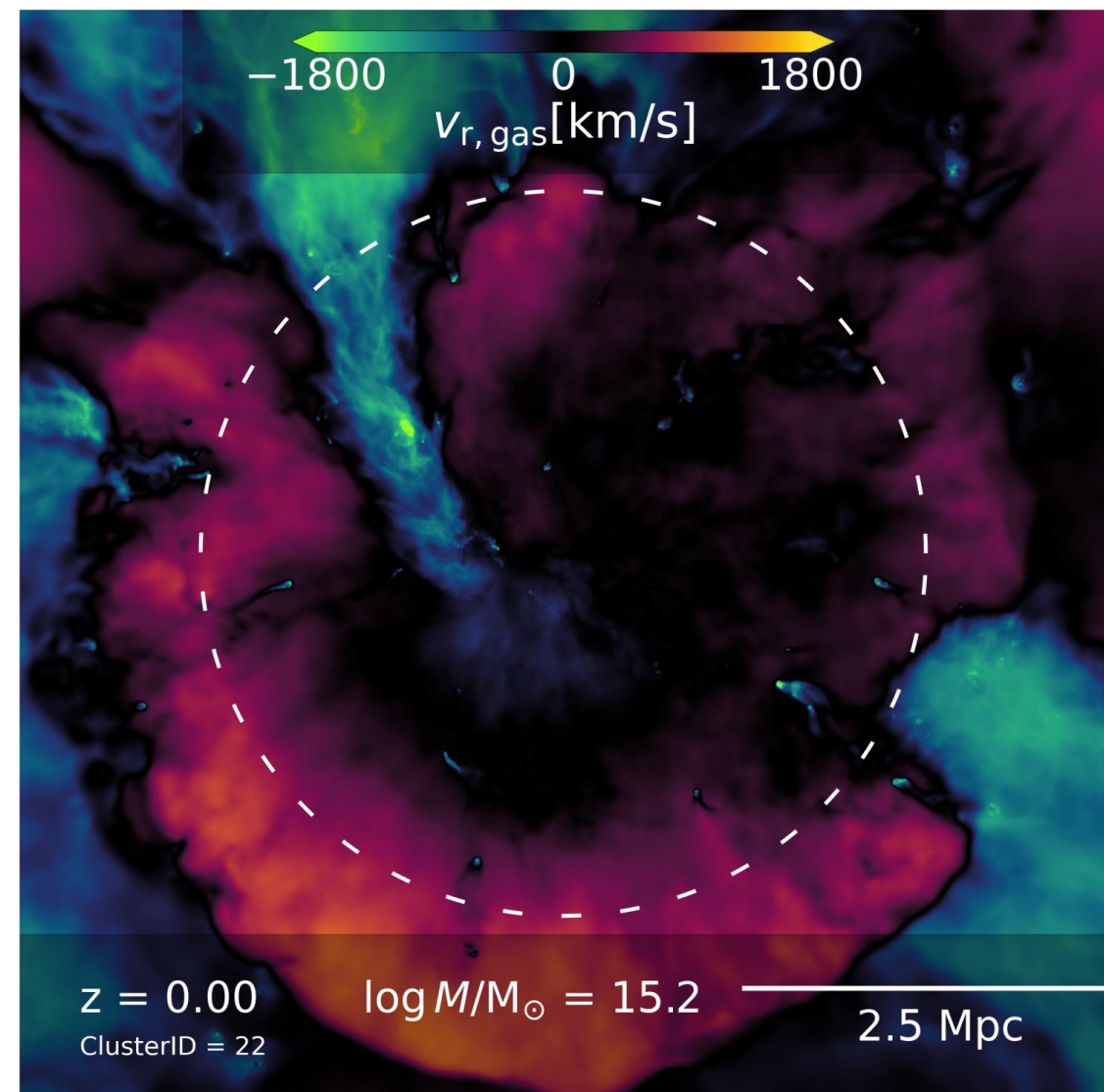


# Clusters are Closed but Dynamically Evolving Systems

## Gas Velocity Dispersion

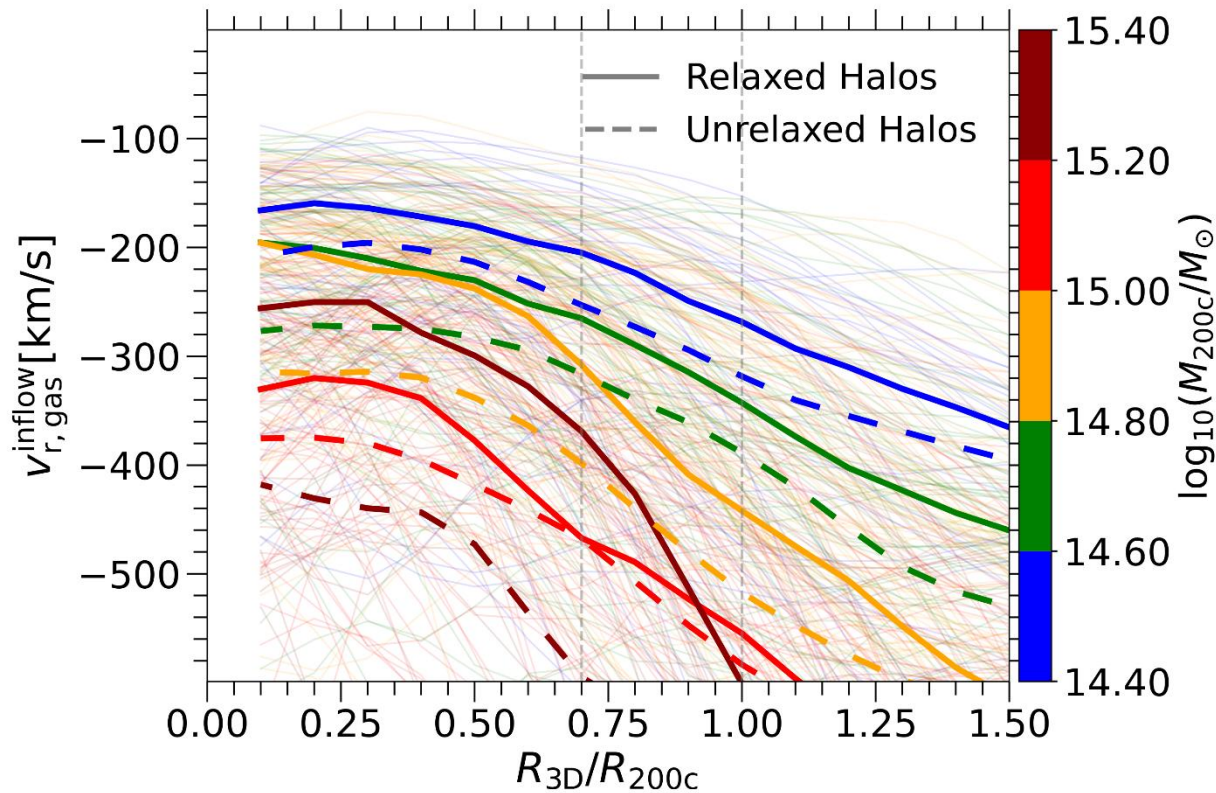


## Gas Radial Velocity

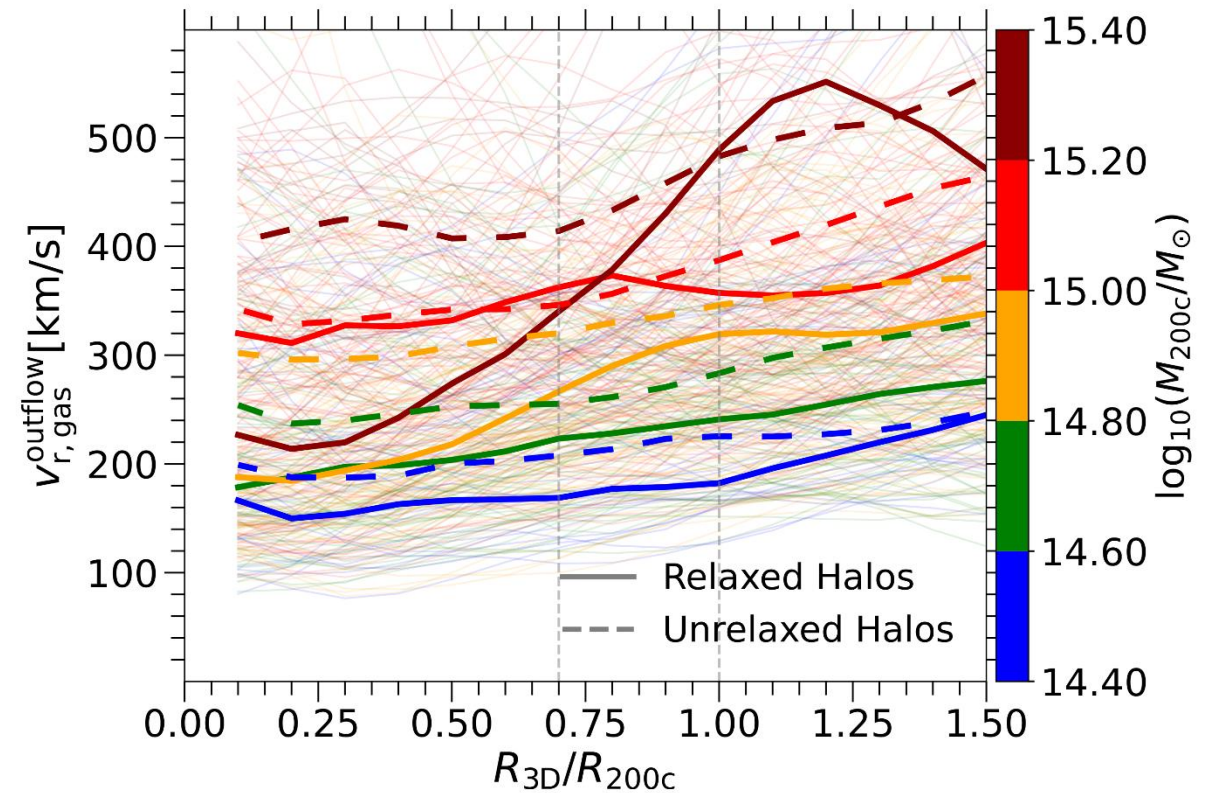


# Gas Kinematics in Clusters: The impact of SMBHs

## Gas Inflow Velocity

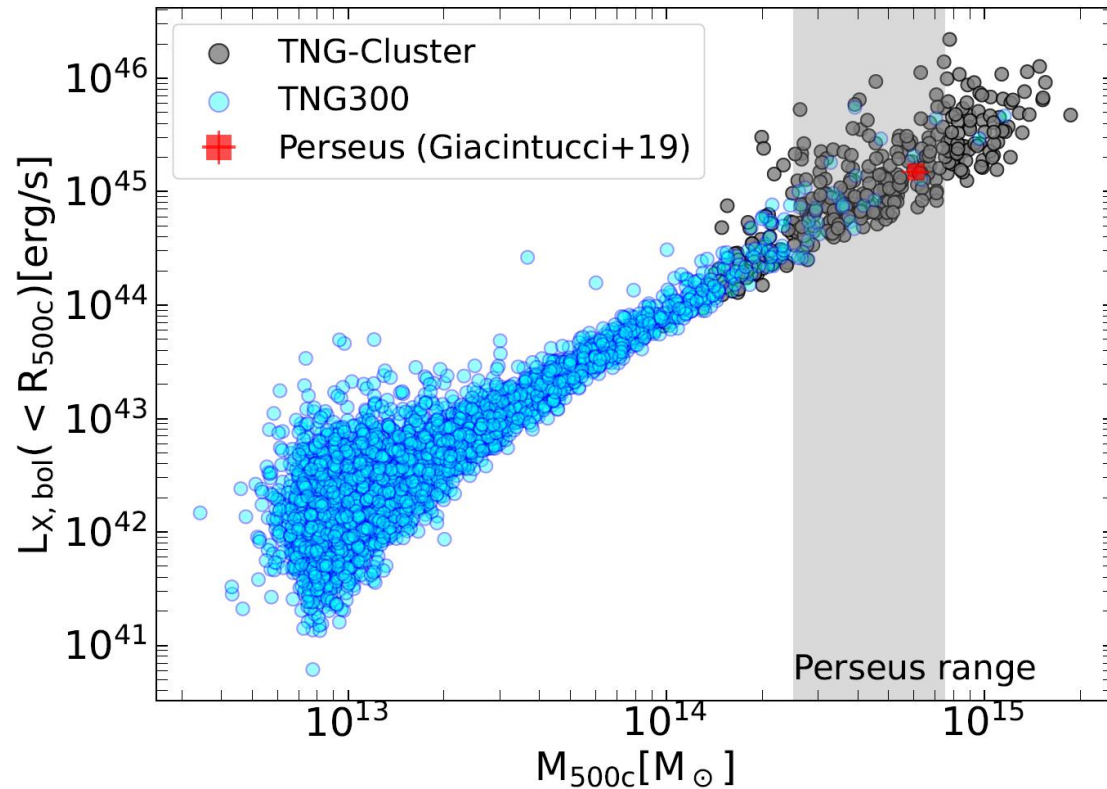


## Gas Outflow Velocity

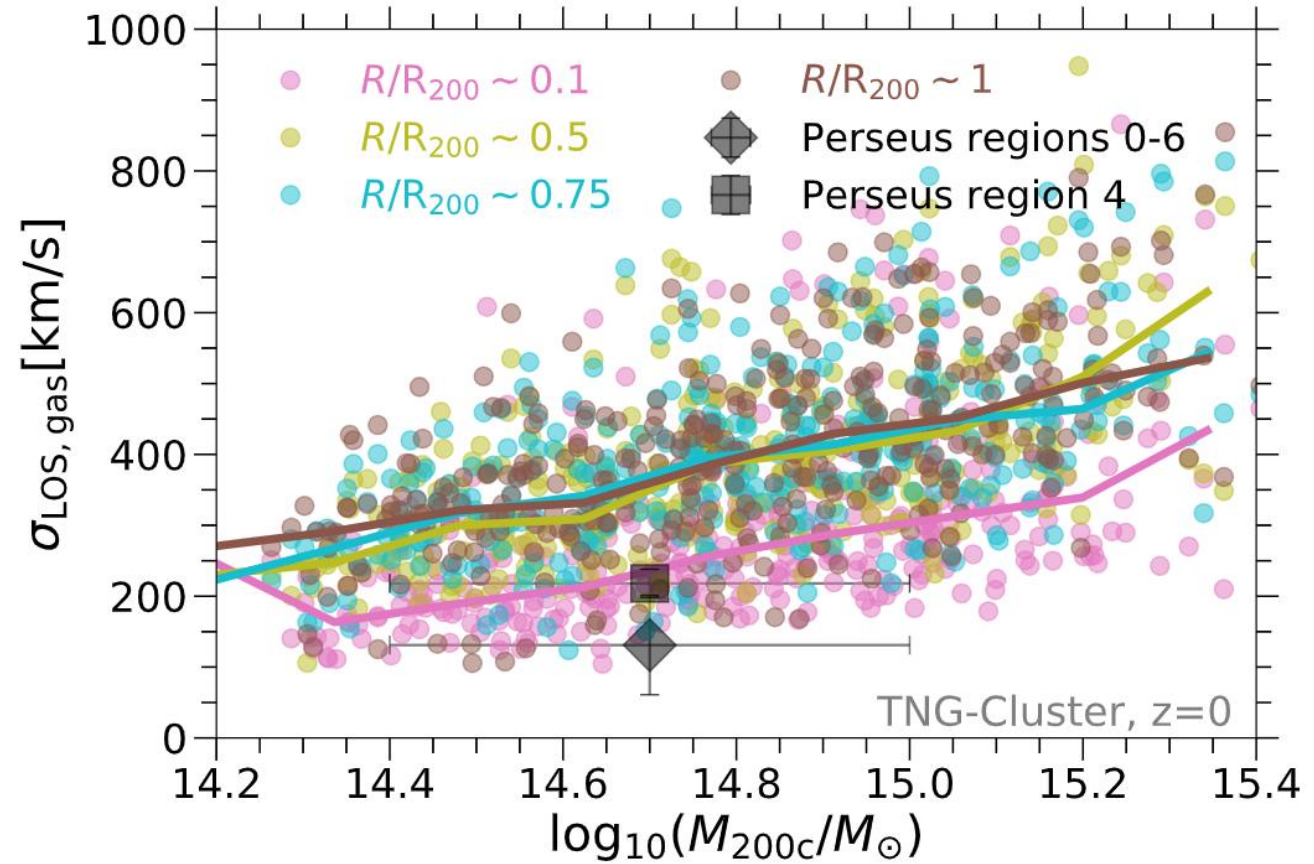


# Line-of-sight velocity dispersion

The TNG-Cluster haloes are in good agreement with Hitomi observations of the core of the Perseus cluster.



Truong+ 2024



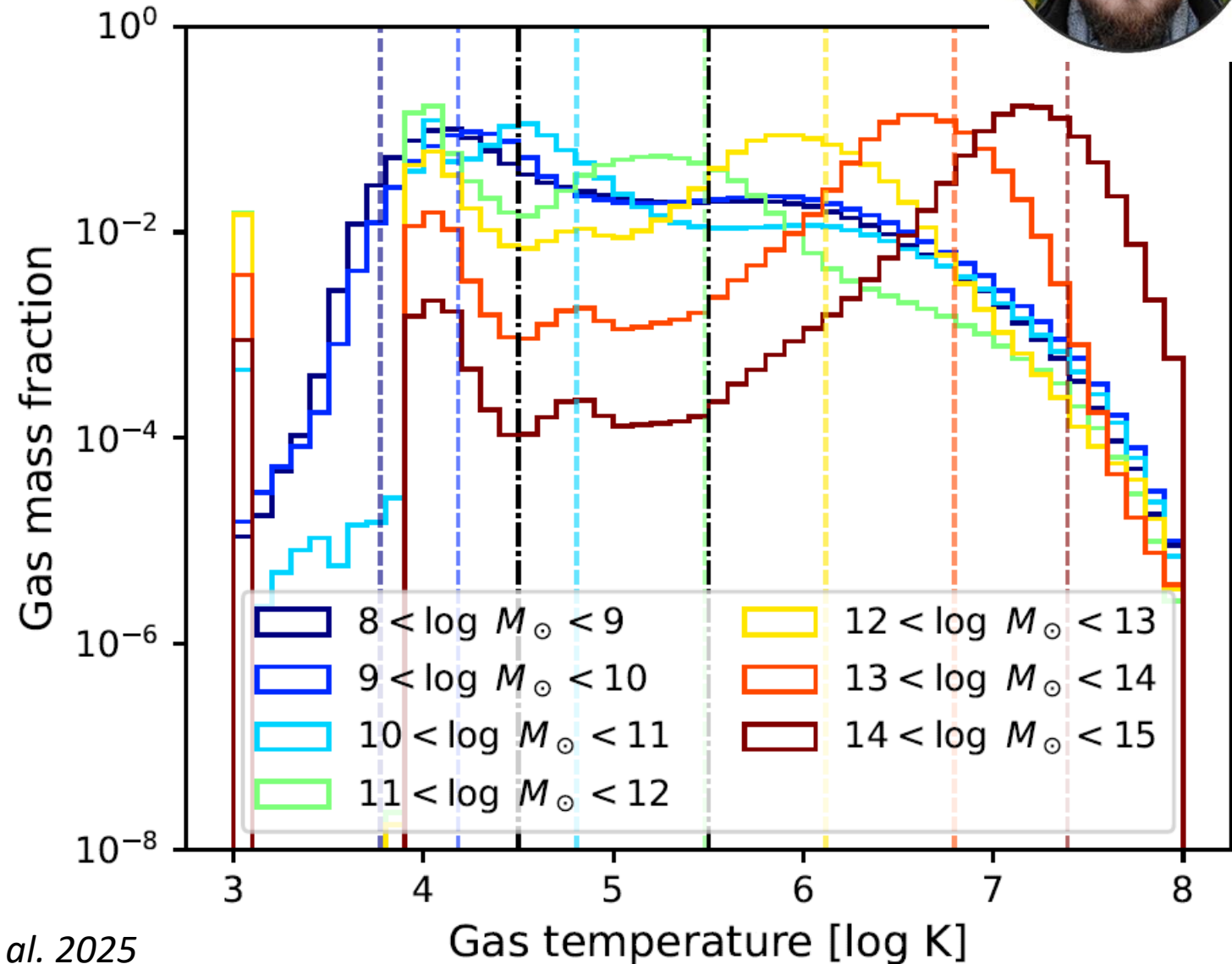
Velocity dispersion in TNG-Cluster cores (**pink dots**) compared to Hitomi measurements (**black symbols**).

Ayromlou+ 2024

# The Halo Gas is Multiphase!

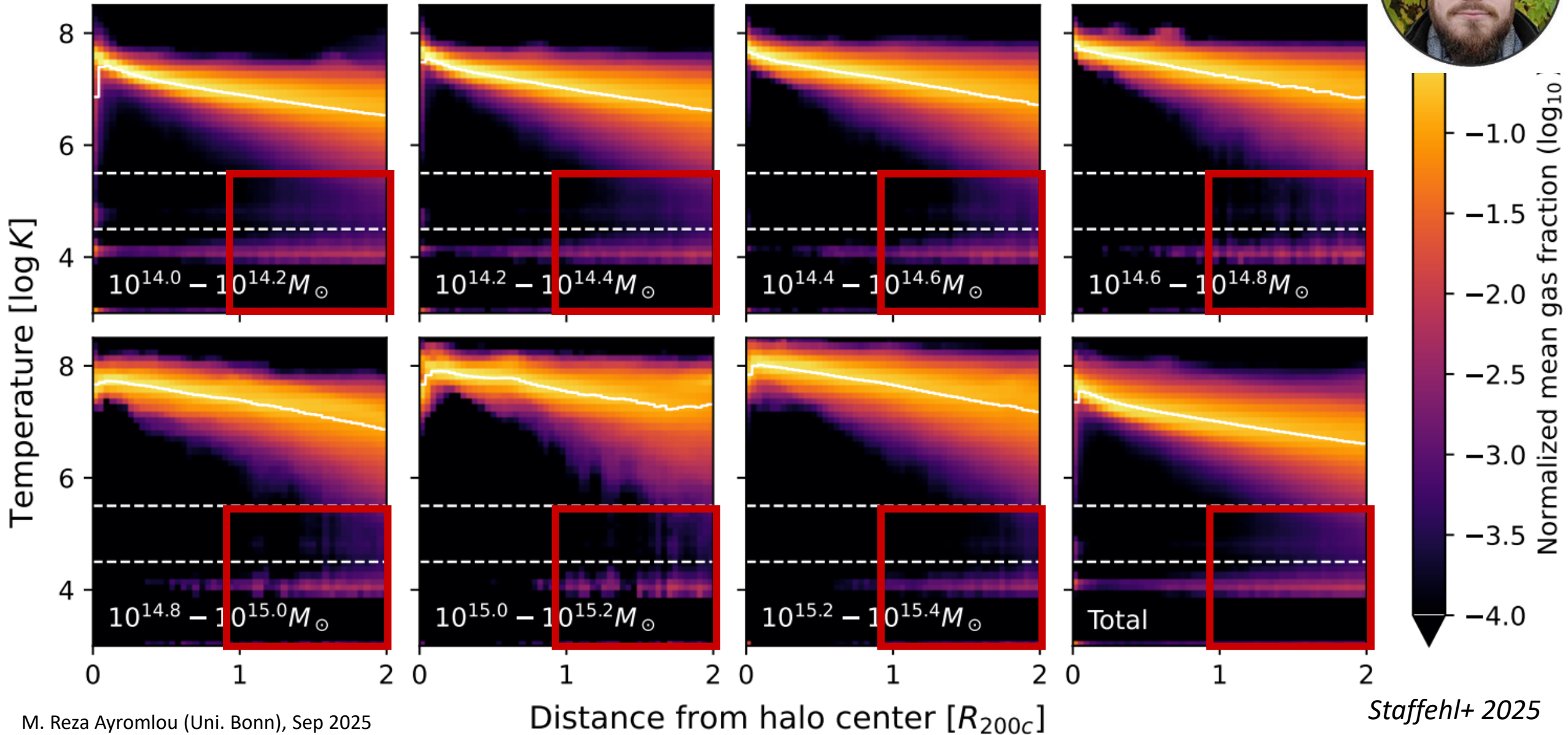


- Average temperature increases with the halo mass
- However, the halo remains multiphase, even for the most massive galaxy clusters
- What is the origin of the cold gas in massive clusters?



# The Halo Gas is Multiphase!

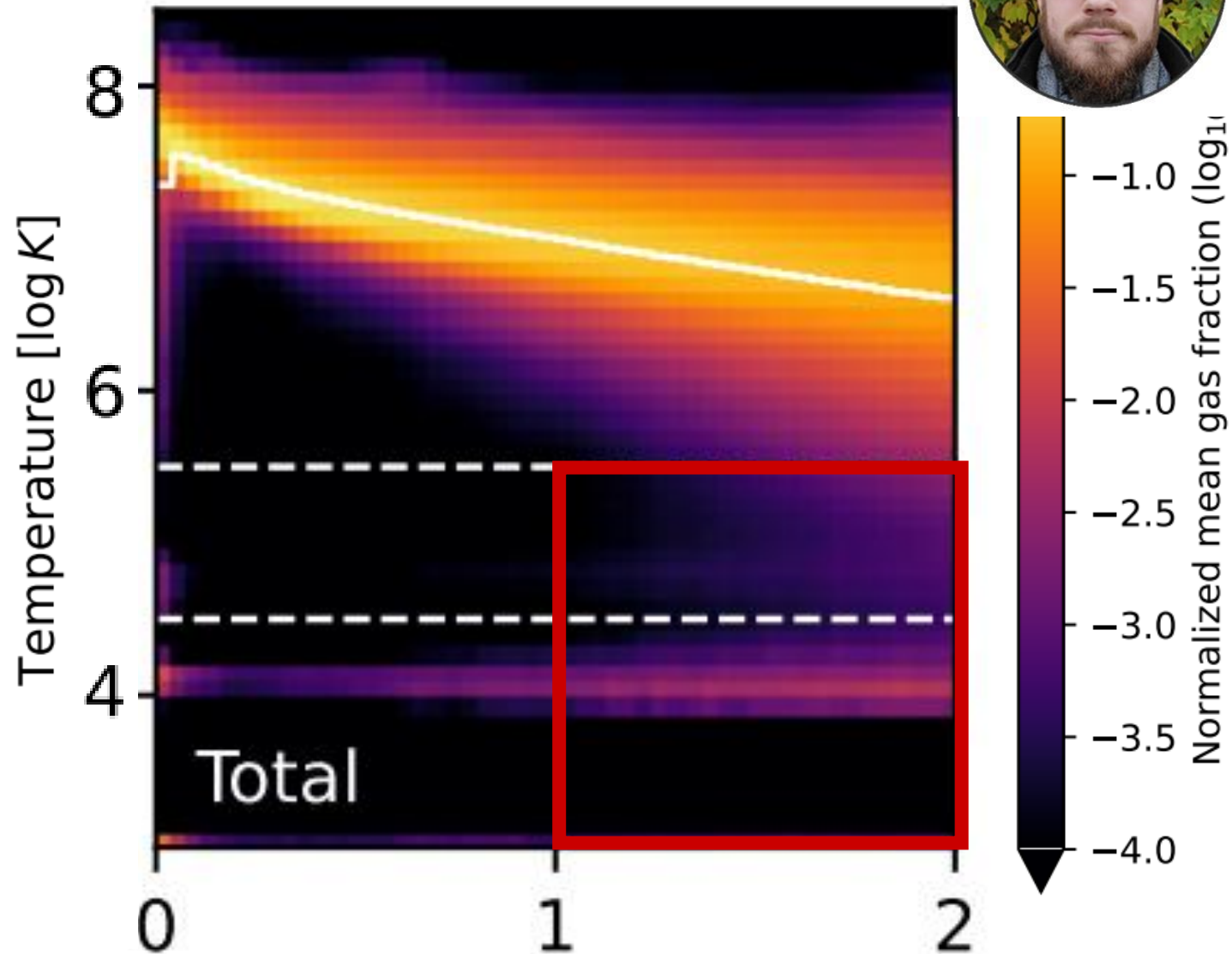
Milan  
Staffehl



# The Halo Gas is Multiphase!

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- What is the origin of the cold gas in massive clusters?

Milan Staffehl



Staffehl+ 2025

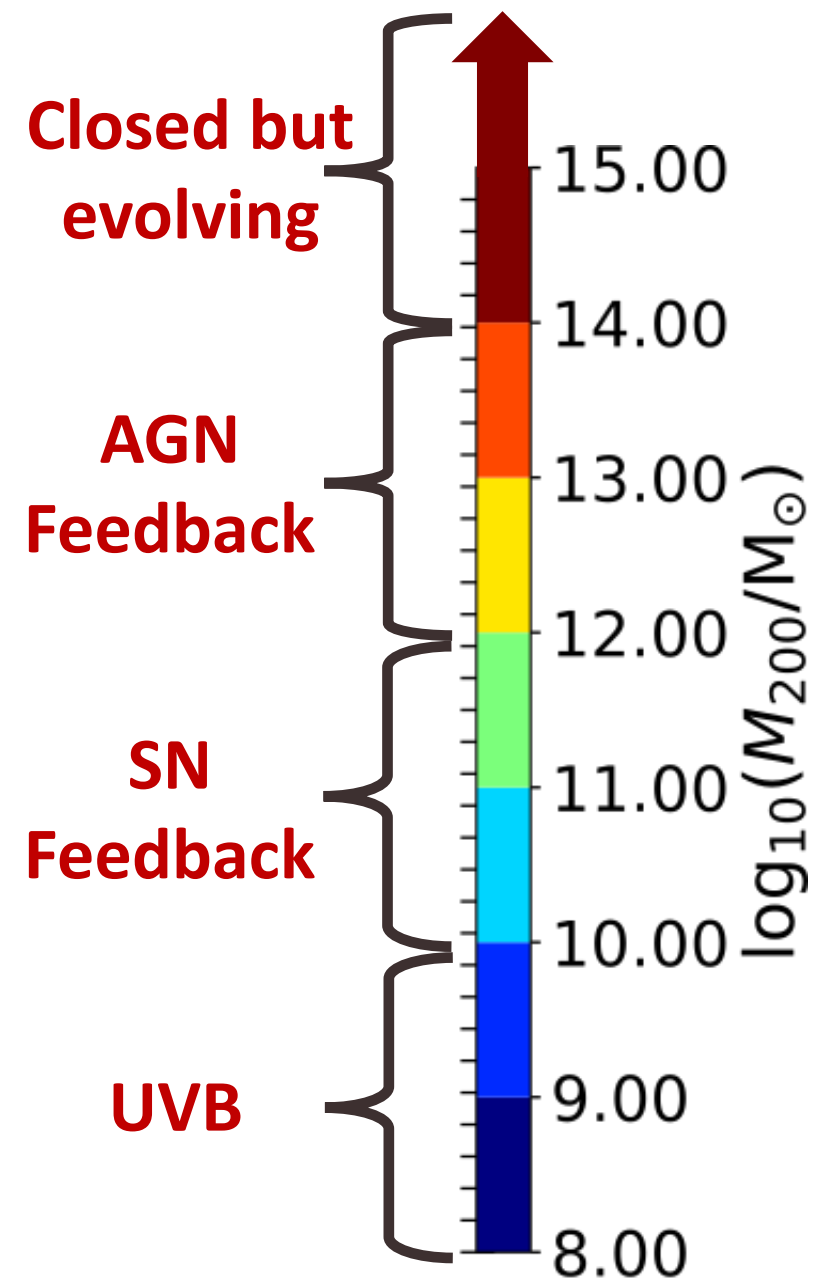
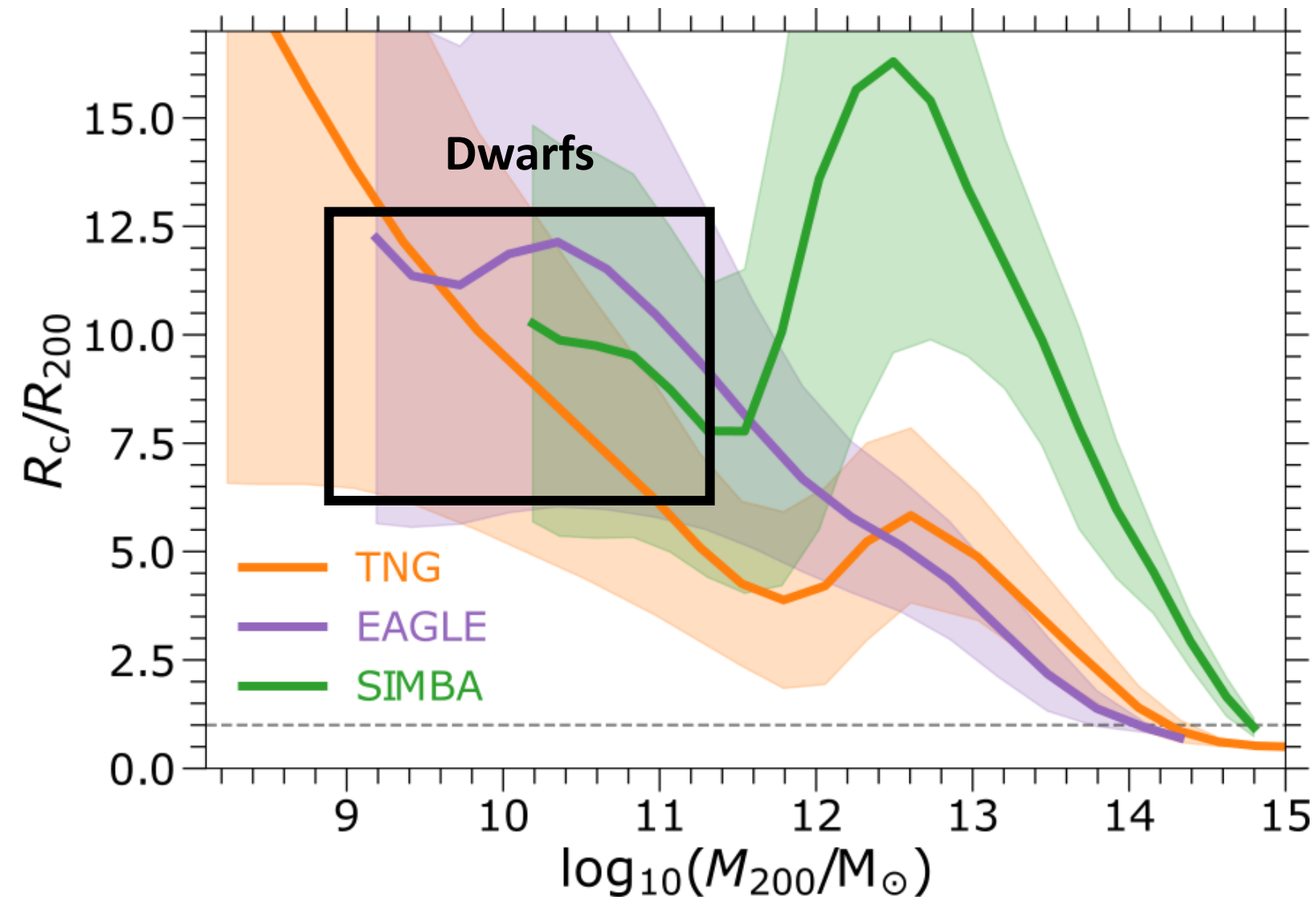
## Part V

# Back To the Future: Modeling AGN Feedback in Simulations

# Physically Based, Spin-Dependent AGN Feedback

- Kinetic and Thermal modes based on **Weinberger+ 2017**
  - Spin evolution based on **Bustamante & Springel 2019**
- 

- Thermal and kinetic modes coexist (there is no switch)
- Energy budget for each mode as well as radiative efficiency depend  $\dot{M}_{BH}$ ,  $M_{BH}$ , and SMBH Spin.

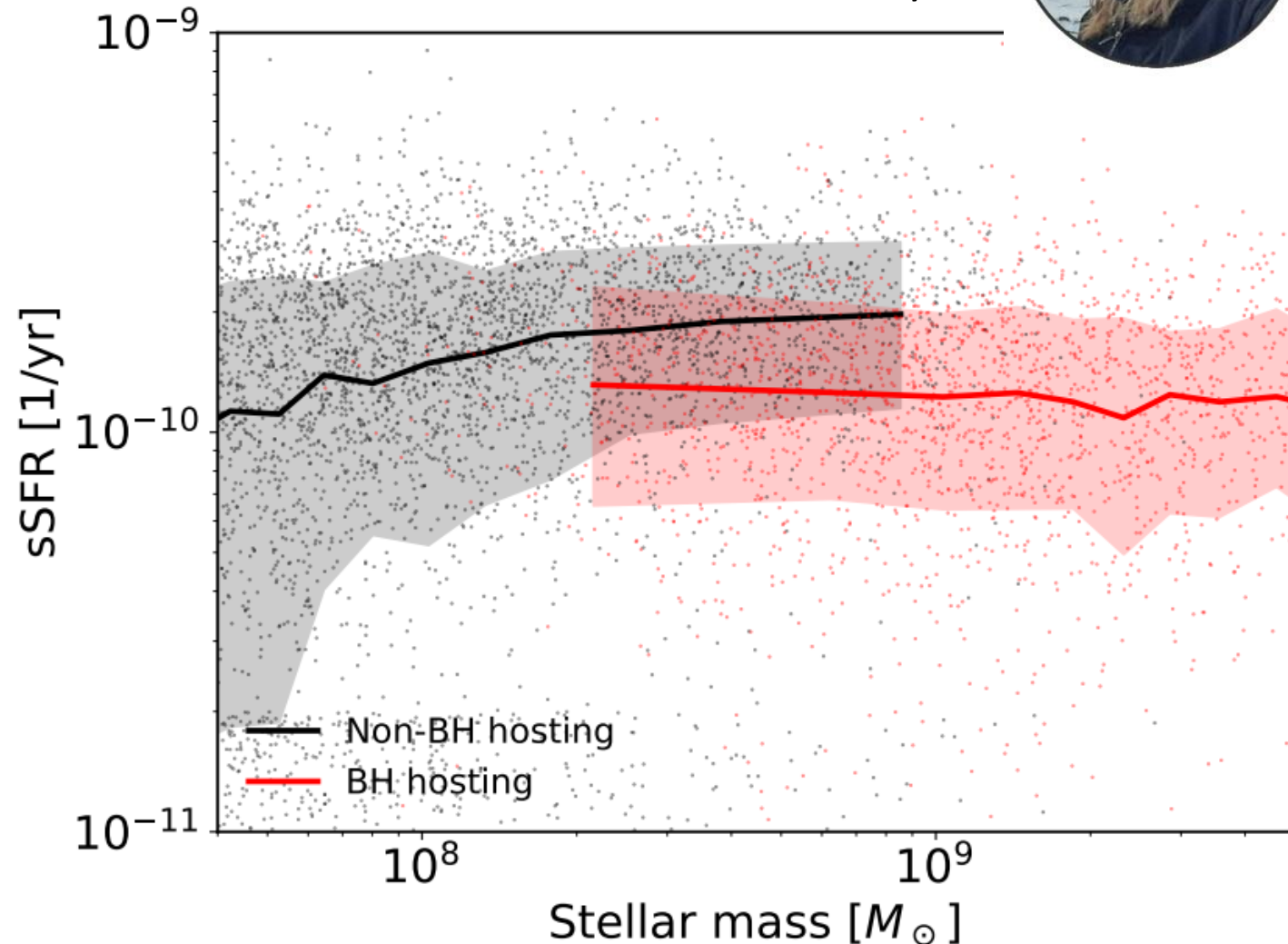


# AGN Feedback in Dwarf Galaxies?

Finlay  
Taylor

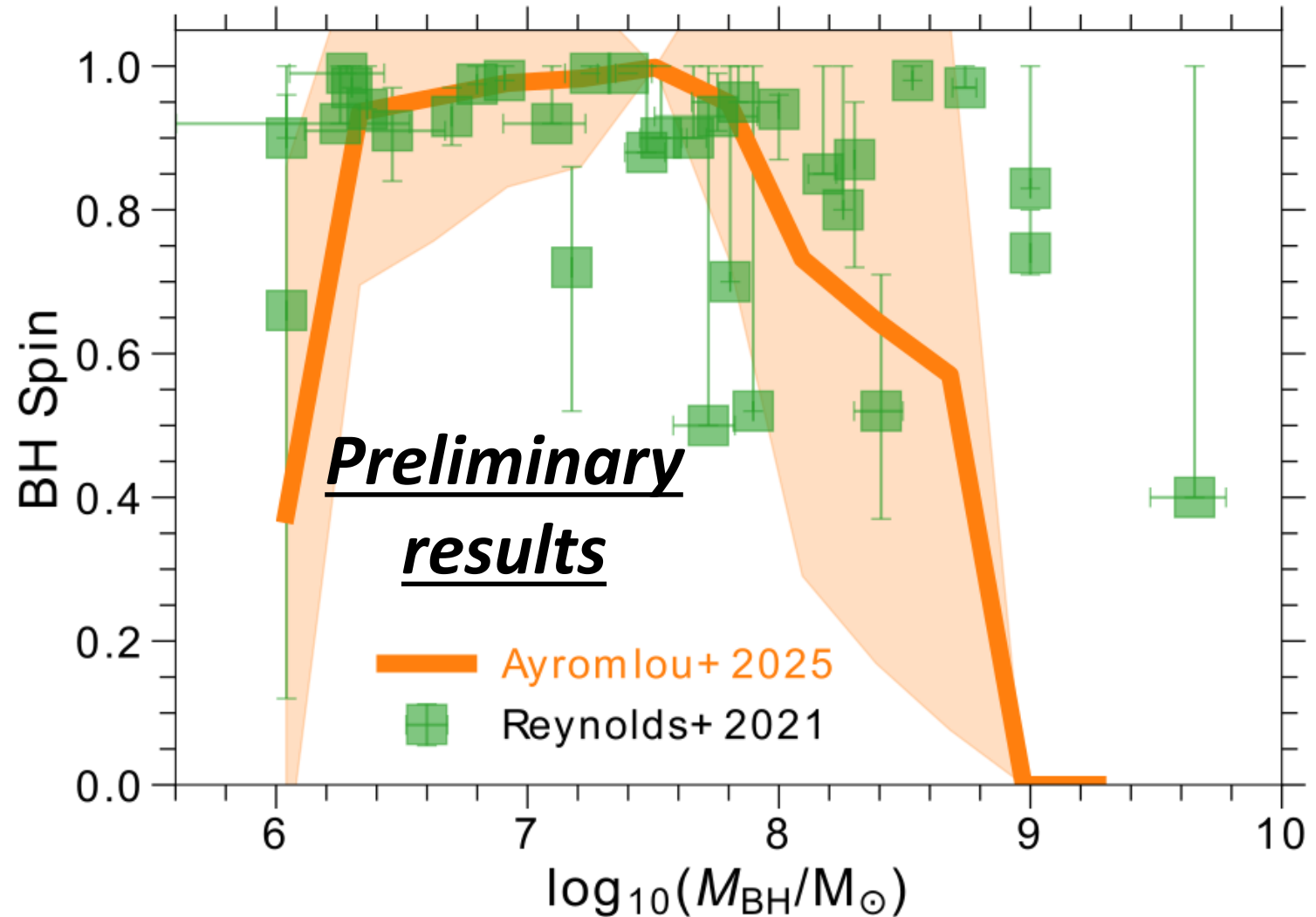


- AGN feedback typically impacts the SFR of systems more massive than the Milky Way
- However, some observations and simulations show evidence of AGN feedback in low-mass galaxies (dwarfs) too.
- What is the origin of the AGN feedback in Dwarfs?



# Physically Based, Spin-Dependent AGN Feedback

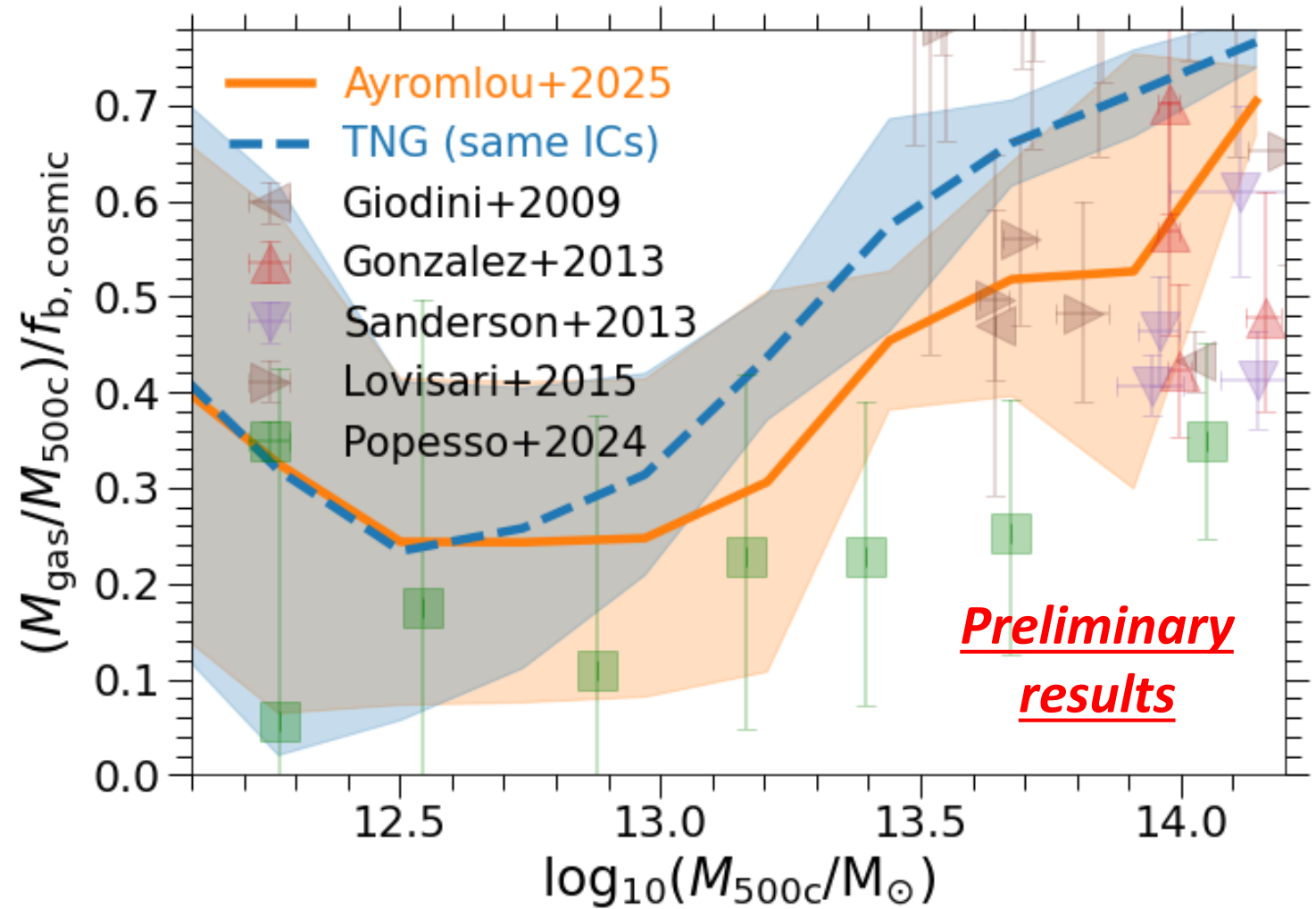
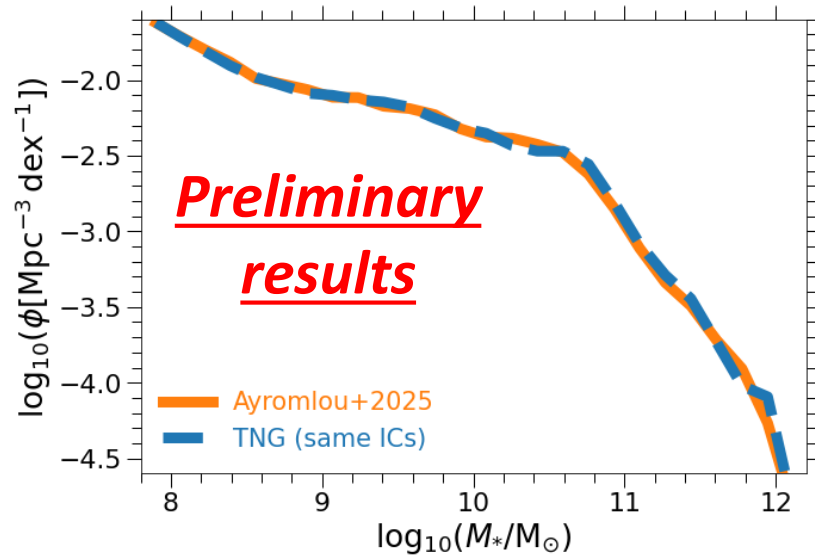
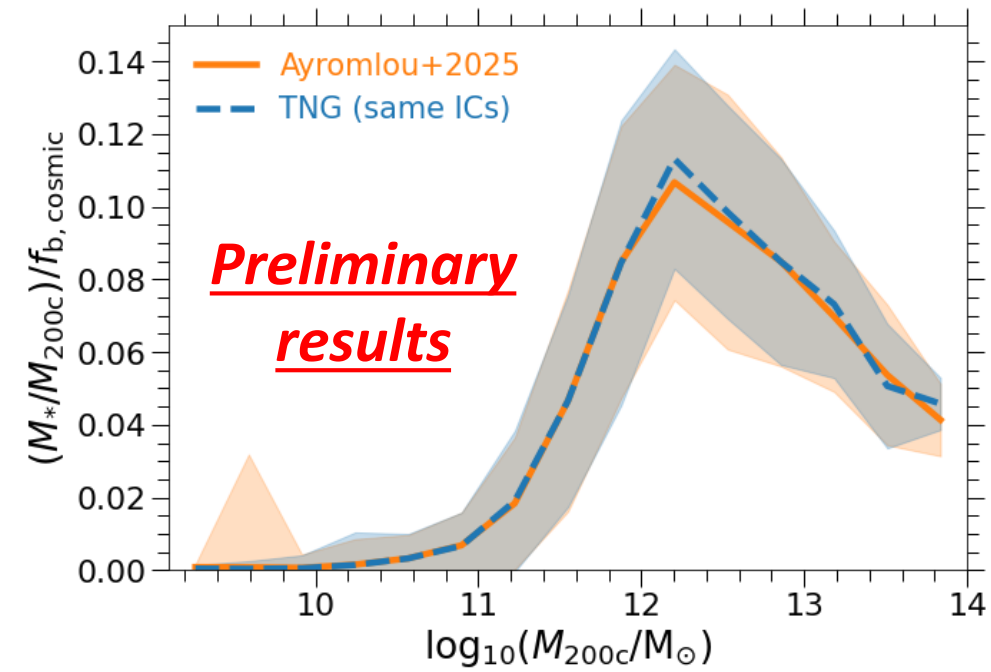
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  - Energy budget for each mode as well as radiative efficiency depend  $\dot{M}_{BH}$ ,  $M_{BH}$ , and SMBH Spin.



See also Fanidakis+ 2011 and Griffin+ 2019 (GALFORM),  
Dubois+ 2021 (NewHorizon), Huško+ 2025 (Swift), and ...

*Ayromlou+ 2025 in prep.*

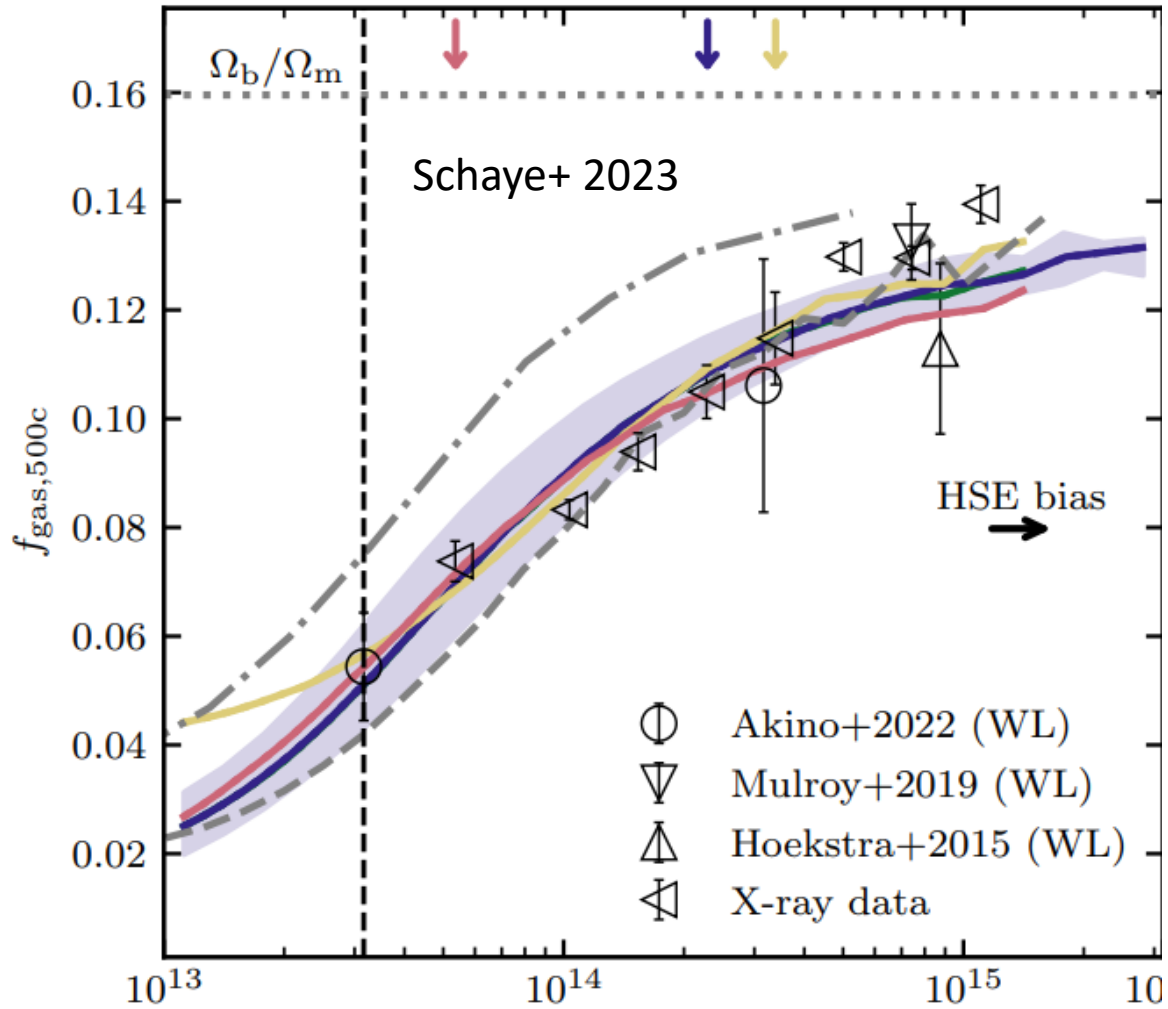
# Halo Gas Fraction



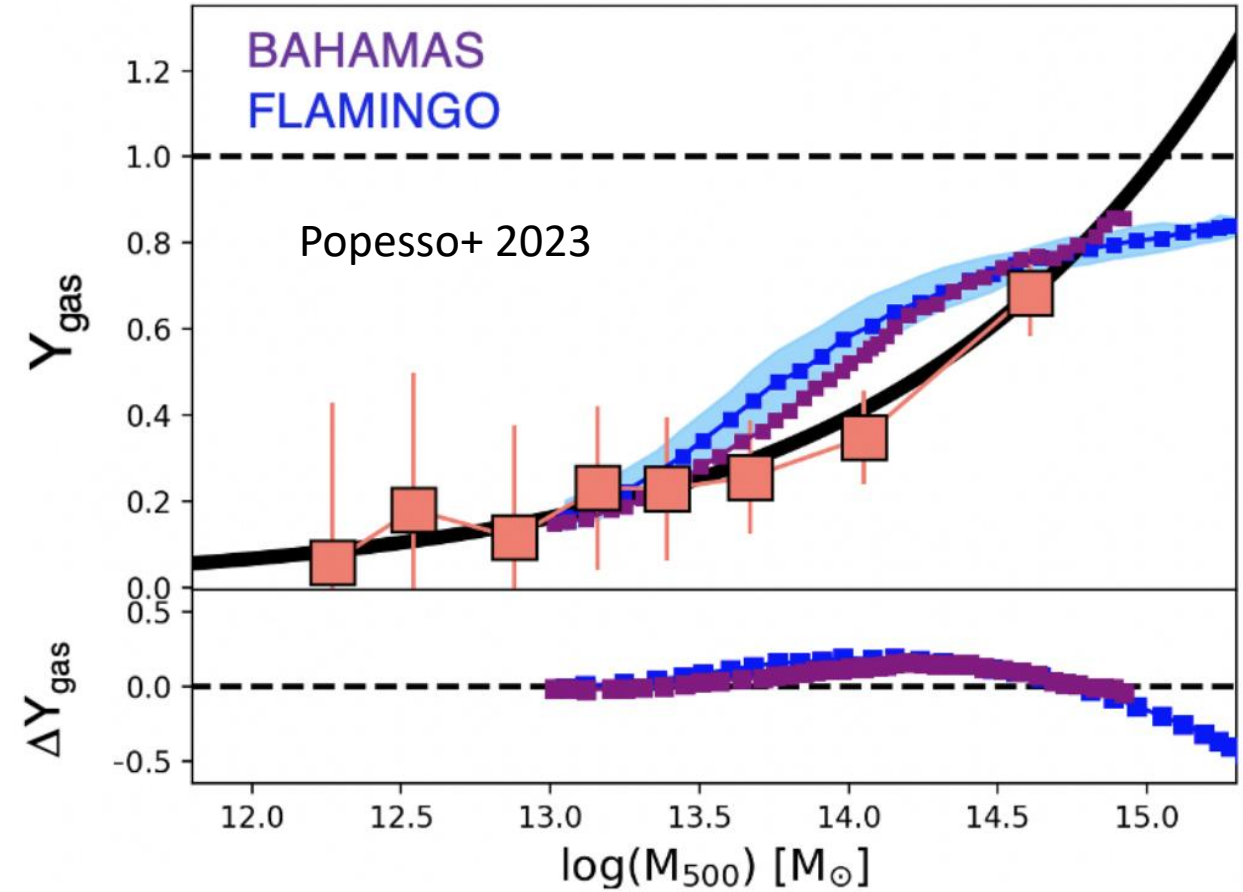
See also Fanidakis+ 2011 and Griffin+ 2019 (GALFORM),  
Dubois+ 2021 (NewHorizon), Huško+ 2025 (Swift), and ...

*Ayromlou+ 2025 in prep.*

# Model Calibration: The Case of Flamingo



*See also talks by Joop, Paola, and Dominique*

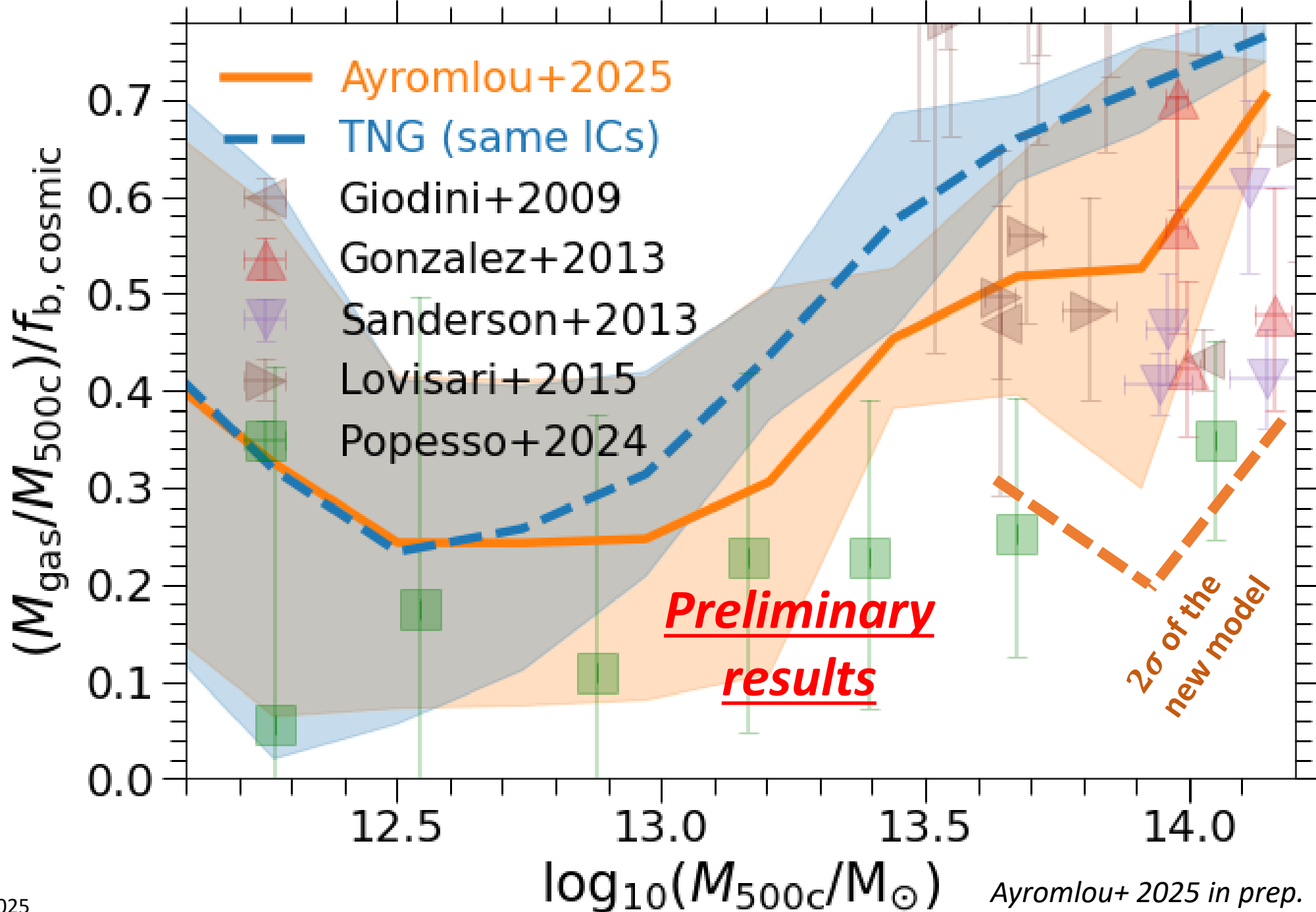


See also Sun+ 09, Pratt+ 09, Sanderson+13, Lovisari+ 15, Ettori+15, Eckert+16, Chiu+18, Nugent+ 20, Eckert+21, Popesso+ 24, Reiprich+ 25

# Halo Gas Fraction Measurements

## Uncertainties:

- Halo mass
- Gas mass
- Hot gas mass
- S/N
- Stacking
- Completeness
- Selection effects
- Extrapolation
- Mocks
- etc.



# Summary

- **The Closure Radius** is the halocentric distance within which all baryons associated with dark matter are found.
- **The Universal Equation** predicts the closure radius in observations.
- **The majority of satellites** lose their **entire CGM gas** before infall
- **Galactic Conformity:** Galaxy properties are correlated out to large scales.
- **Galaxy Clusters** are closed, but dynamically evolving systems.
- **High-z Galaxy Quenching:** Simulations struggle to reproduce the JWST-observed massive quenched galaxies at high-redshifts ( $z > 3$ )
- **AGN Feedback Modelling:** A novel spin dependent model for AGN feedback

