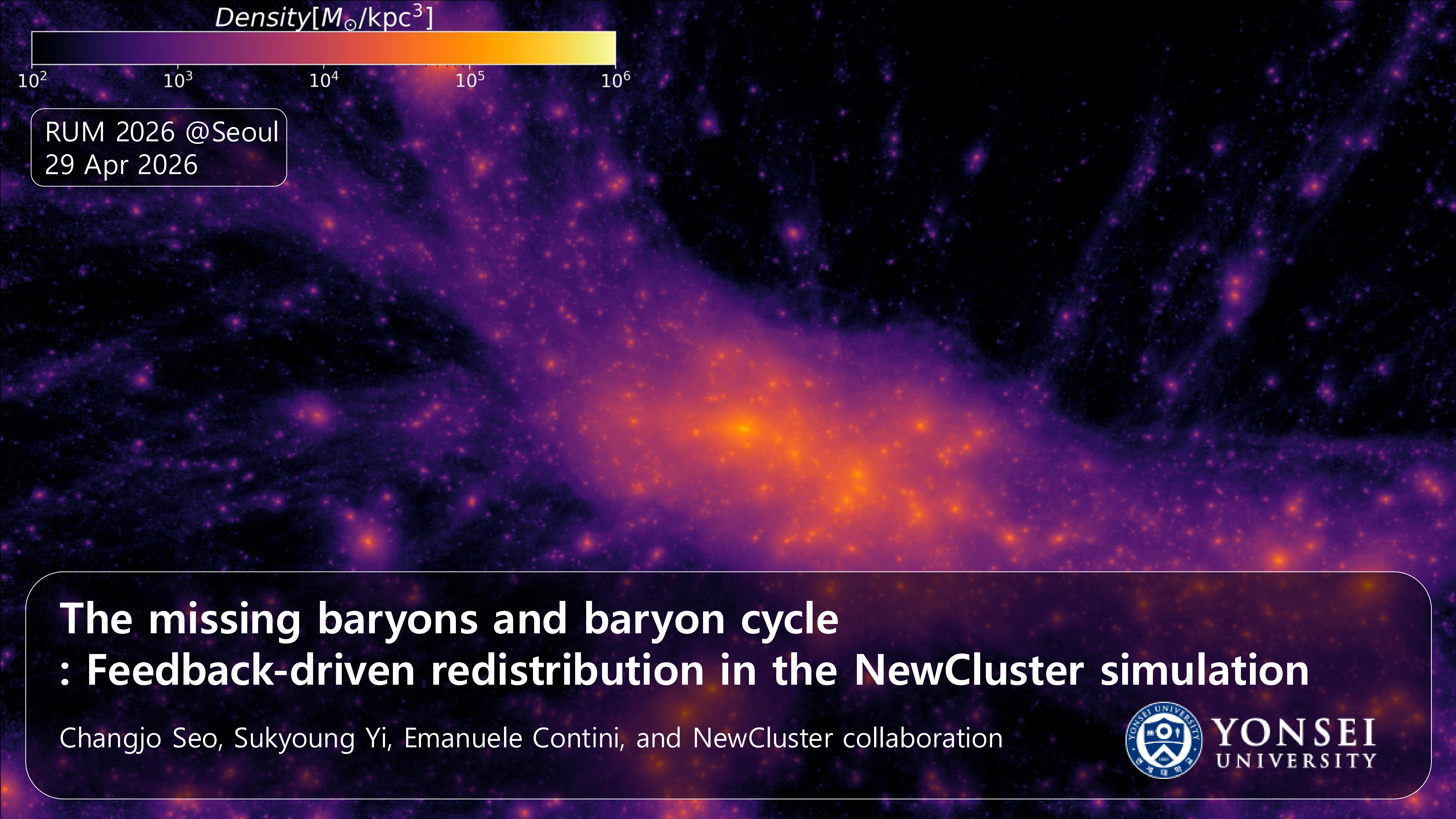


RUM 2026 @Seoul
29 Apr 2026

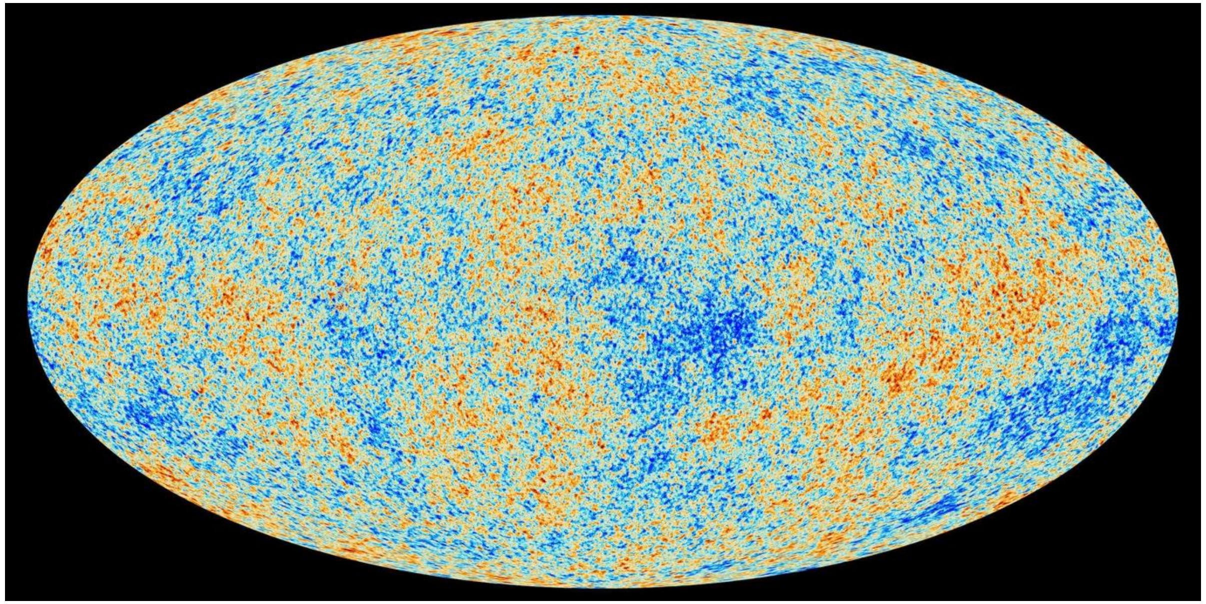
The missing baryons and baryon cycle : Feedback-driven redistribution in the NewCluster simulation

Changjo Seo, Sukyoung Yi, Emanuele Contini, and NewCluster collaboration

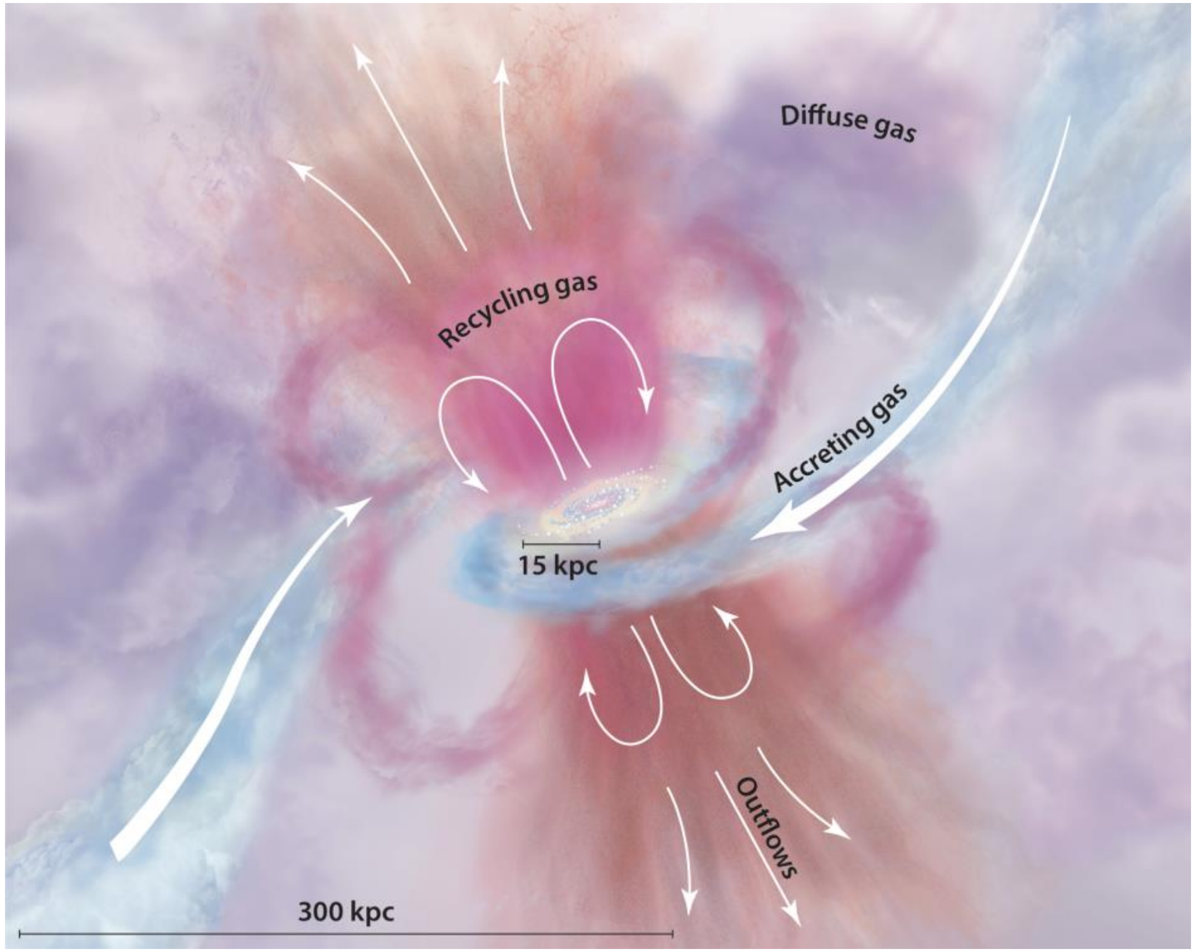
YONSEI UNIVERSITY

Introduction

ESA and the Planck Collaboration



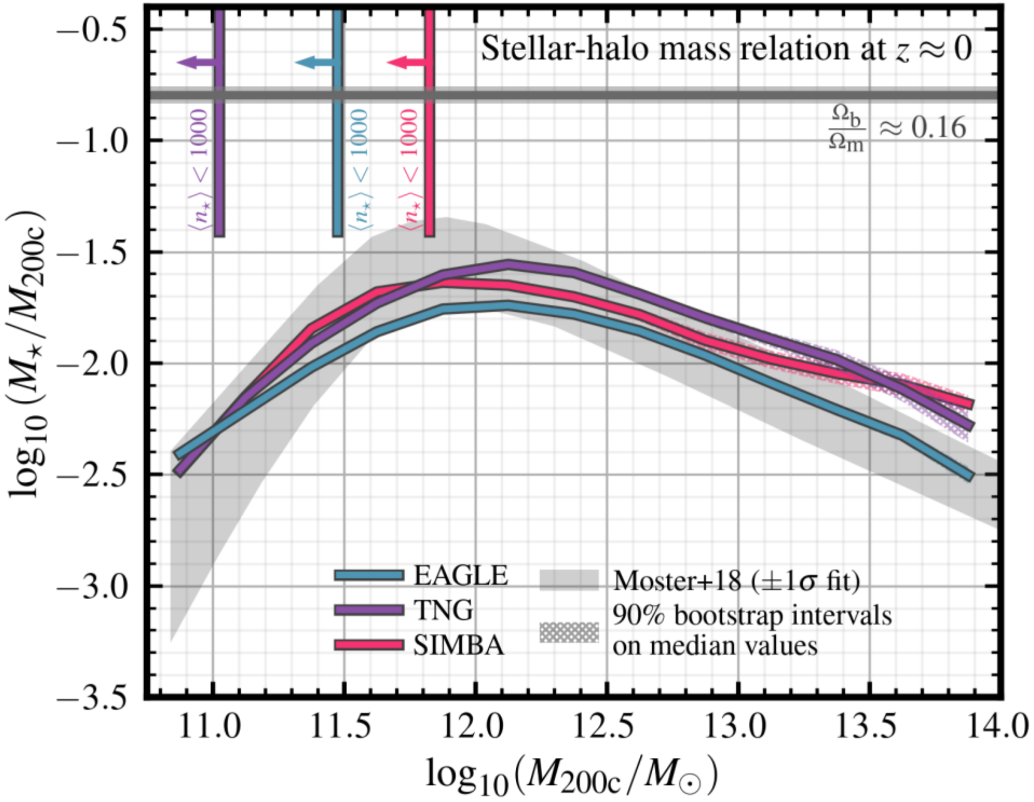
Tumlinson et al. 2017



Introduction

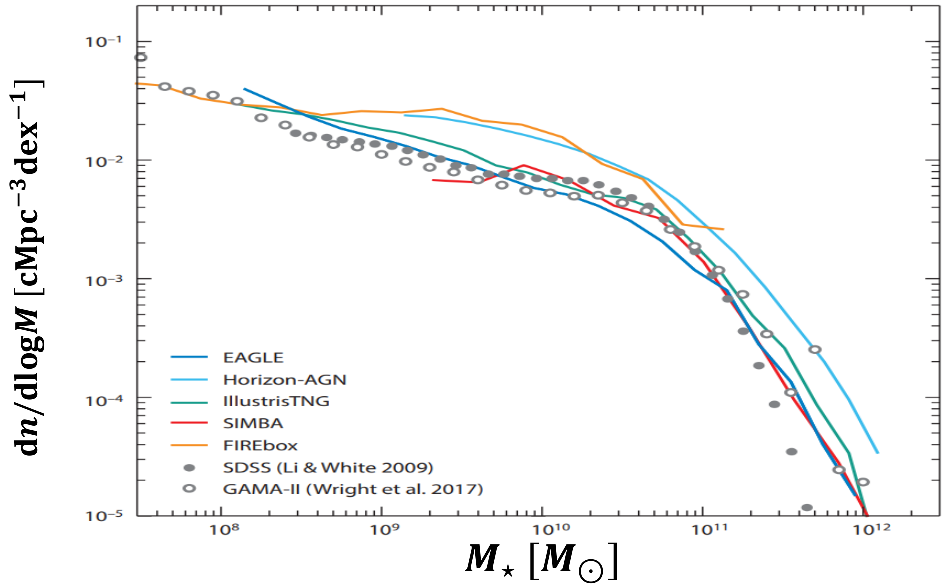
Many simulations are calibrated to match ....

SHMR

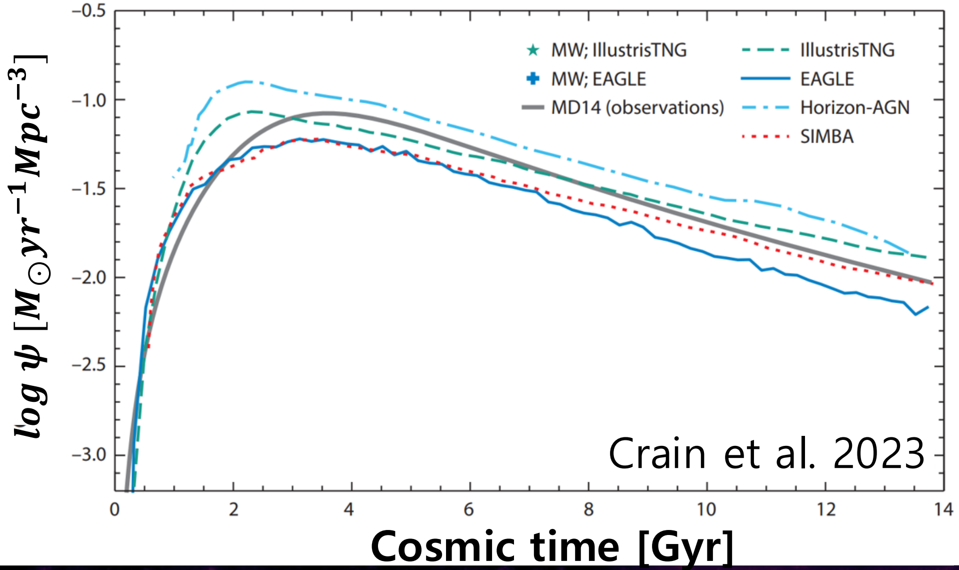


Wright et al. 2024

GSMF



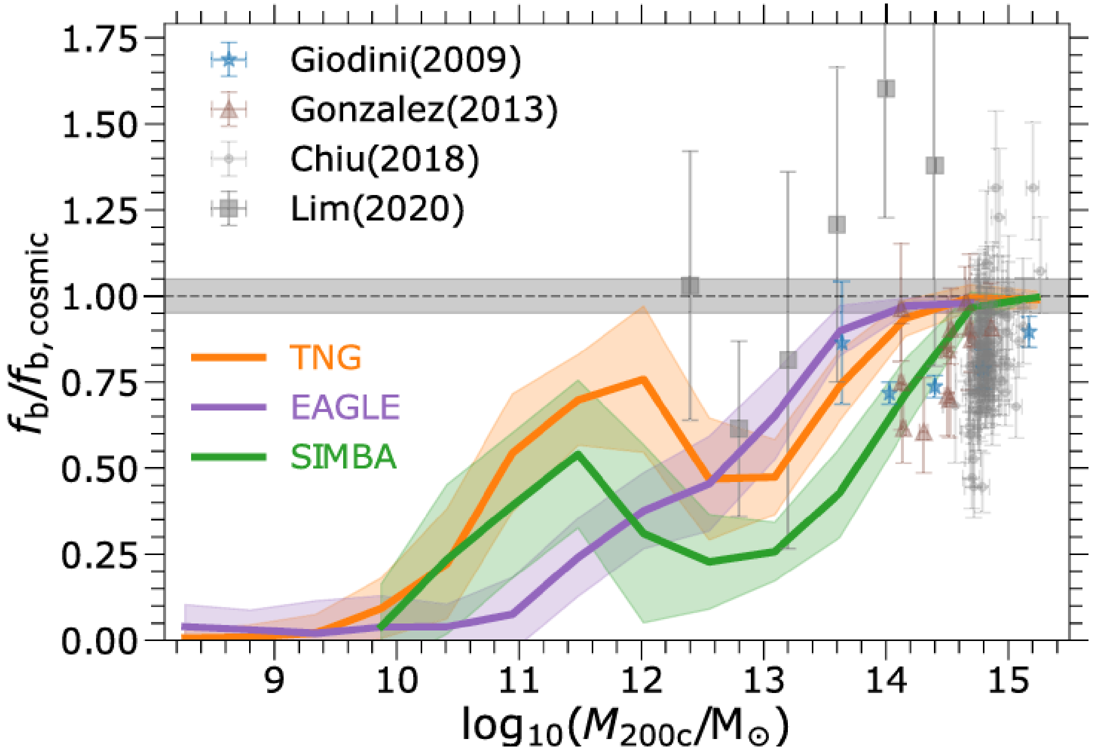
CSFR



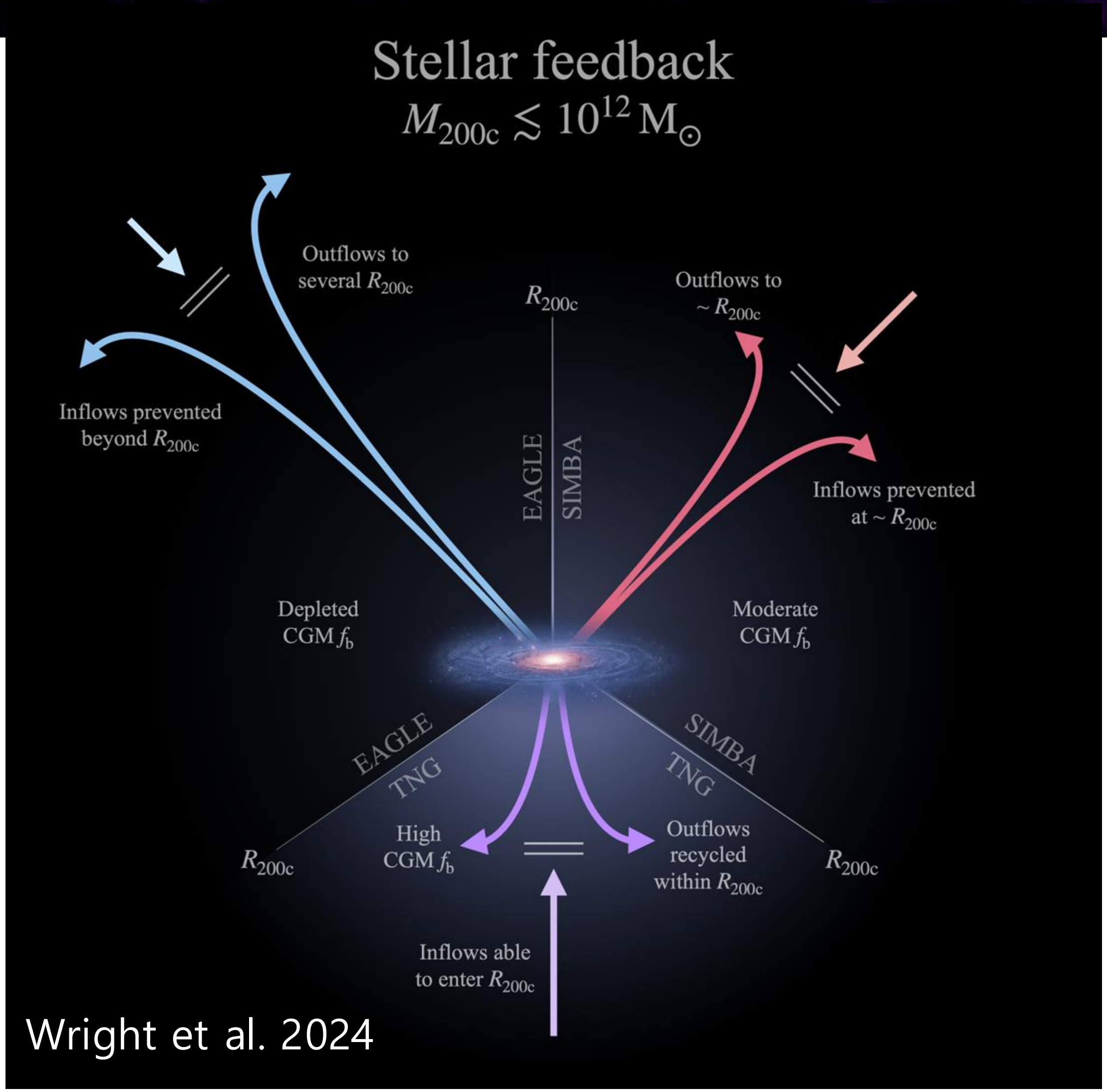
Crain et al. 2023

Introduction

The baryon fraction, which is a non-calibrated quantity, varies significantly across simulations



Ayromlou et al. 2023

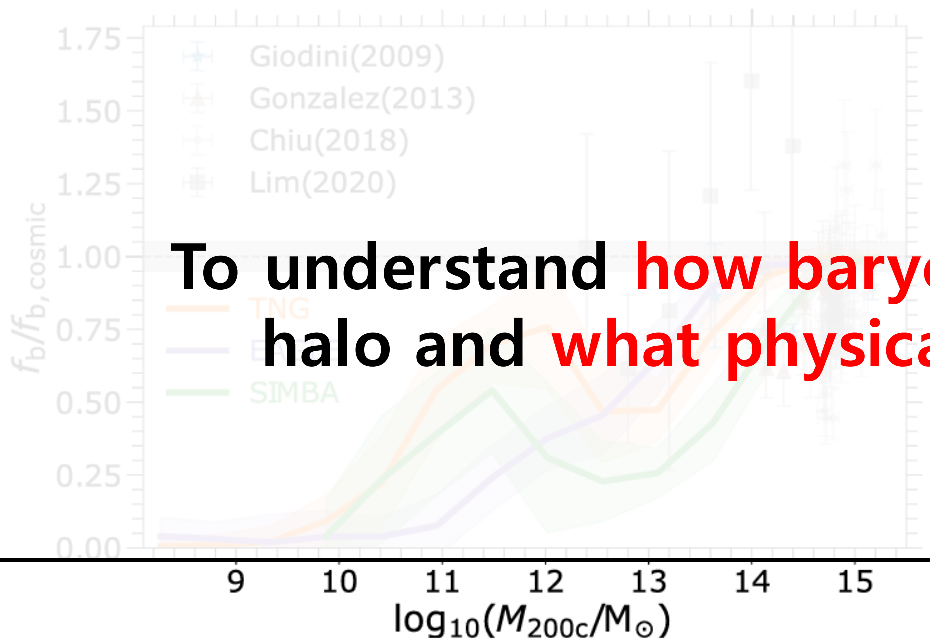


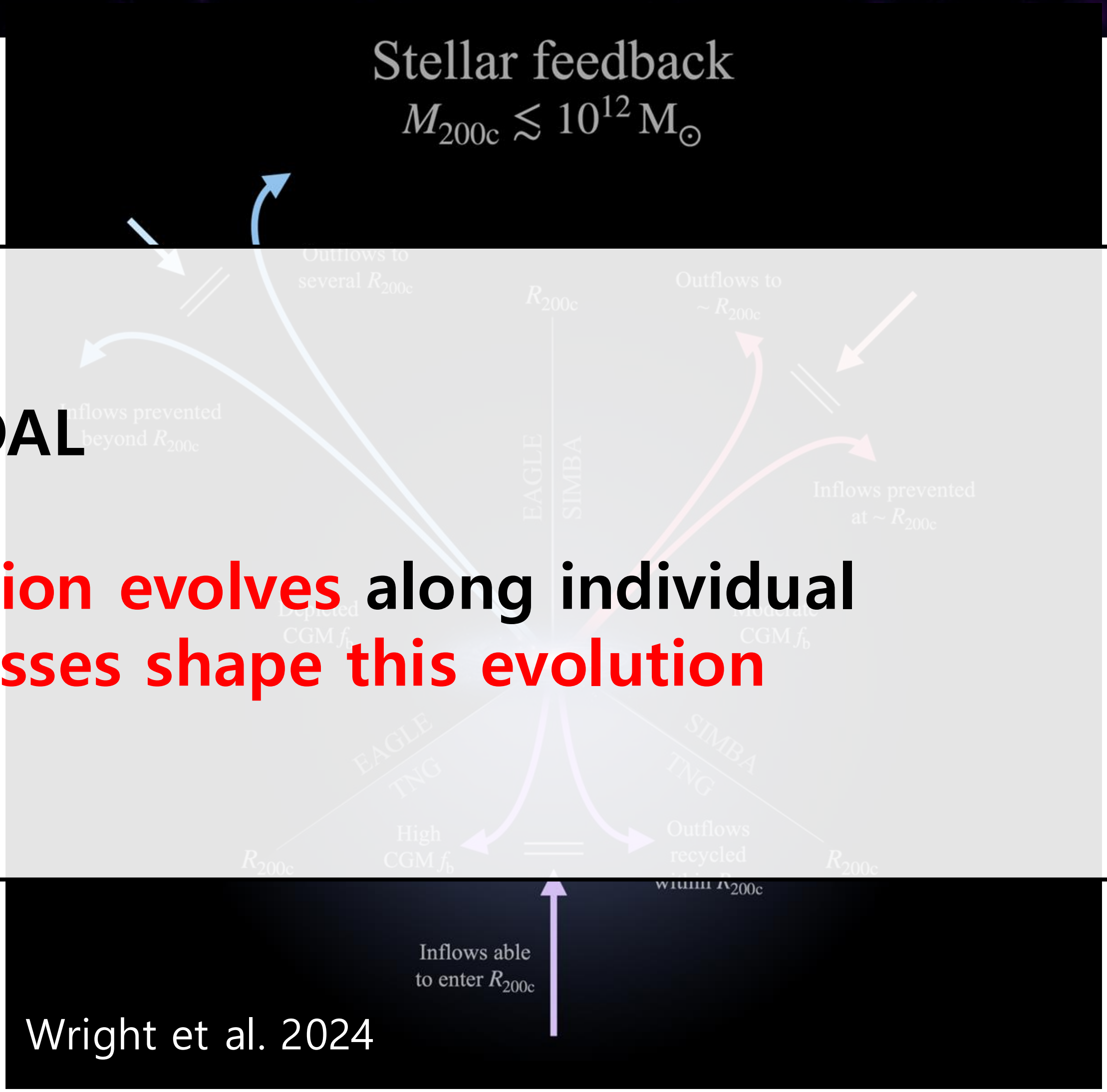
Wright et al. 2024

Since the baryon cycle is inherently time-dependent, fixed-redshift analyses are insufficient to understand halo baryon evolution

Introduction

The baryon fraction, which is a non-calibrated quantity, varies significantly across simulations





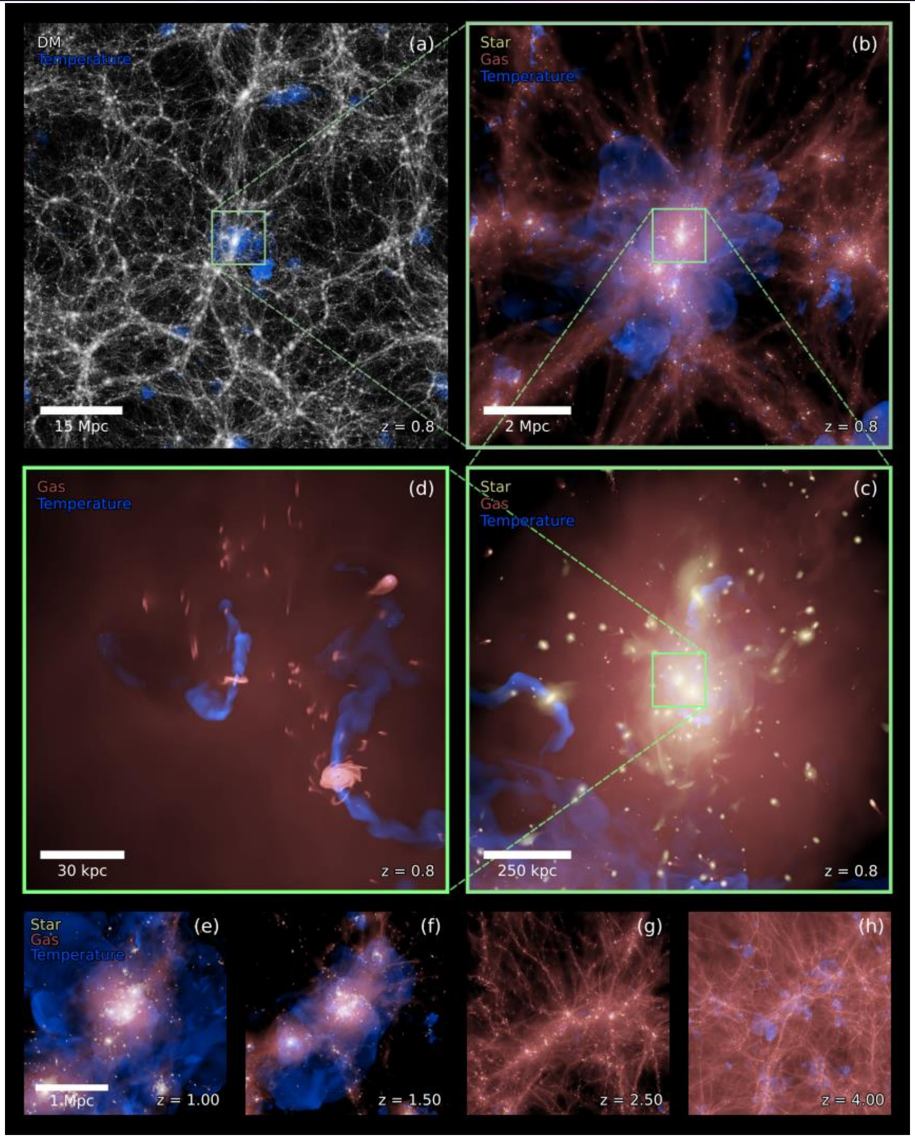
Wright et al. 2024

The GOAL

To understand how baryon fraction evolves along individual halo and what physical processes shape this evolution

Since the baryon cycle is inherently time-dependent, fixed-redshift analyses are insufficient to understand halo baryon evolution

Numerical simulation

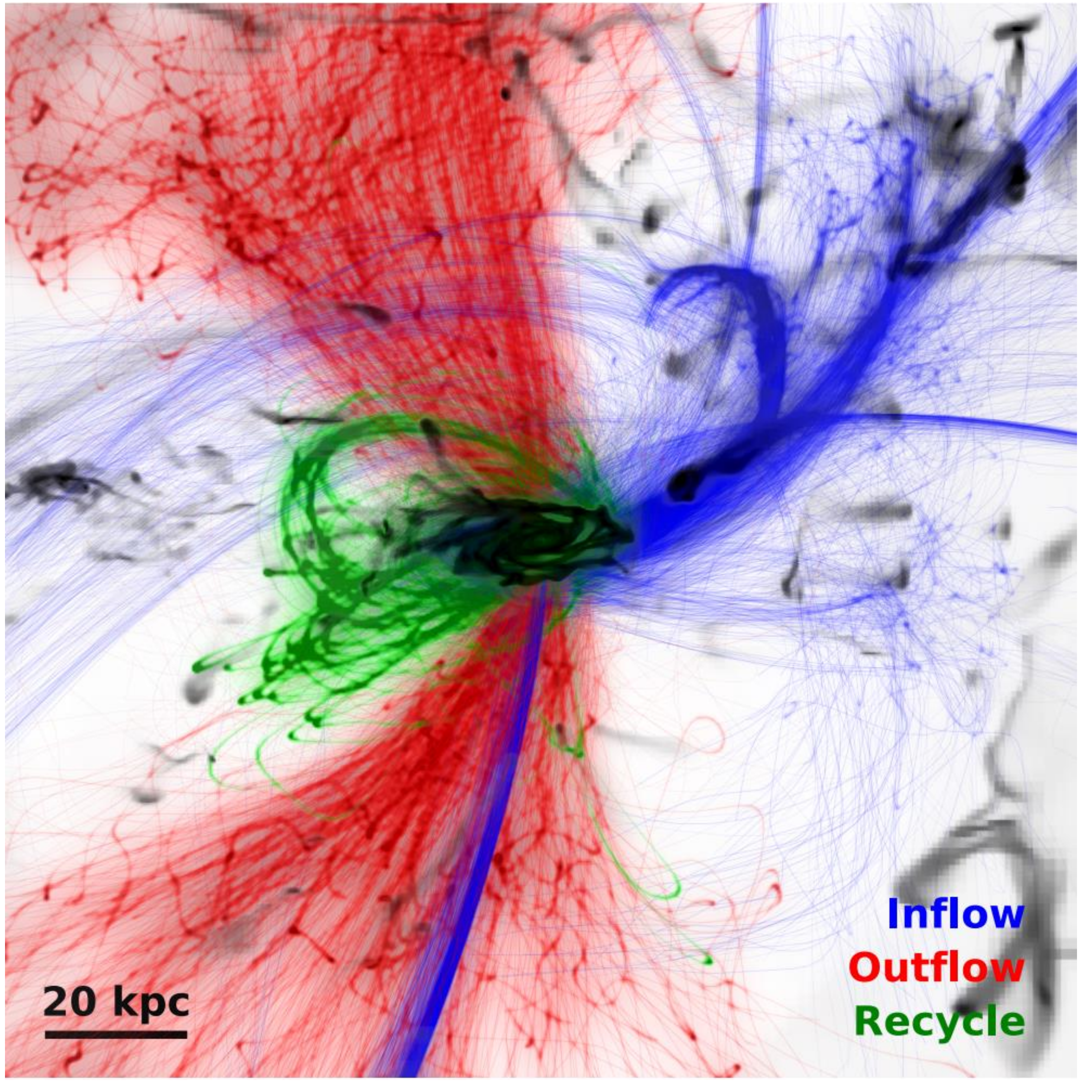


Han et al. 2026

NewCluster (Han et al. 2026)

- Zoom-in simulation targeting a galaxy cluster
- High-resolution
  - $\Delta m_* \sim 2 \times 10^4\ M_\odot$
  - $\Delta m_{\rm DM} \sim 1.3 \times 10^6\ M_\odot$
  - $\Delta x_{\rm best} \sim 70\ \rm pc$
  - $\Delta t_{\rm output} \sim 15\ \rm Myr$
- Radiative cooling & heating
- Star formation & stellar feedback
  - SNII (Kimm & Cen 2014), SNIa, and stellar wind
- Quasar (thermal) & radio (kinetic) mode AGN feedback (Dubois et al. 2012)
- Tracer particle (Cadiou et al. 2019)
  - $\Delta m_{\rm tracer} = 5.17 \times 10^5\ M_\odot$ (tracer has unique mass)

Tracer particle

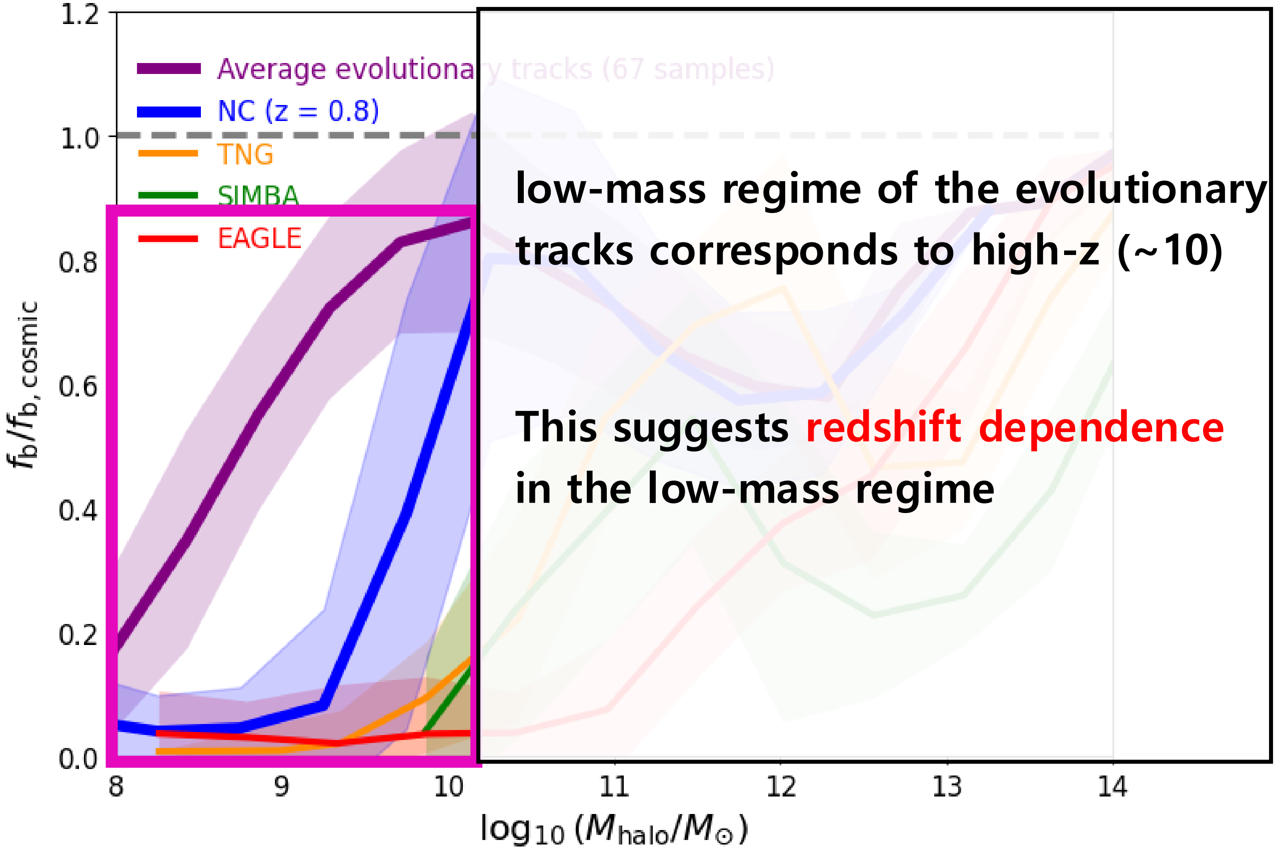


Han et al. 2026

- Background
  - In AMR simulation, due to its grid-based nature, tracking the Lagrangian history of the gas is difficult
  - It is hard to estimate exact inflow/outflow mass and understand each gas motion
- Implement (Cadiou et al. 2019)
  - tracer has been extended to track the full Lagrangian history of baryon in any phase

f_b distribution vs Evolutionary tracks

$f_b = M_{baryon}/M_{halo}$ within R_{vir}

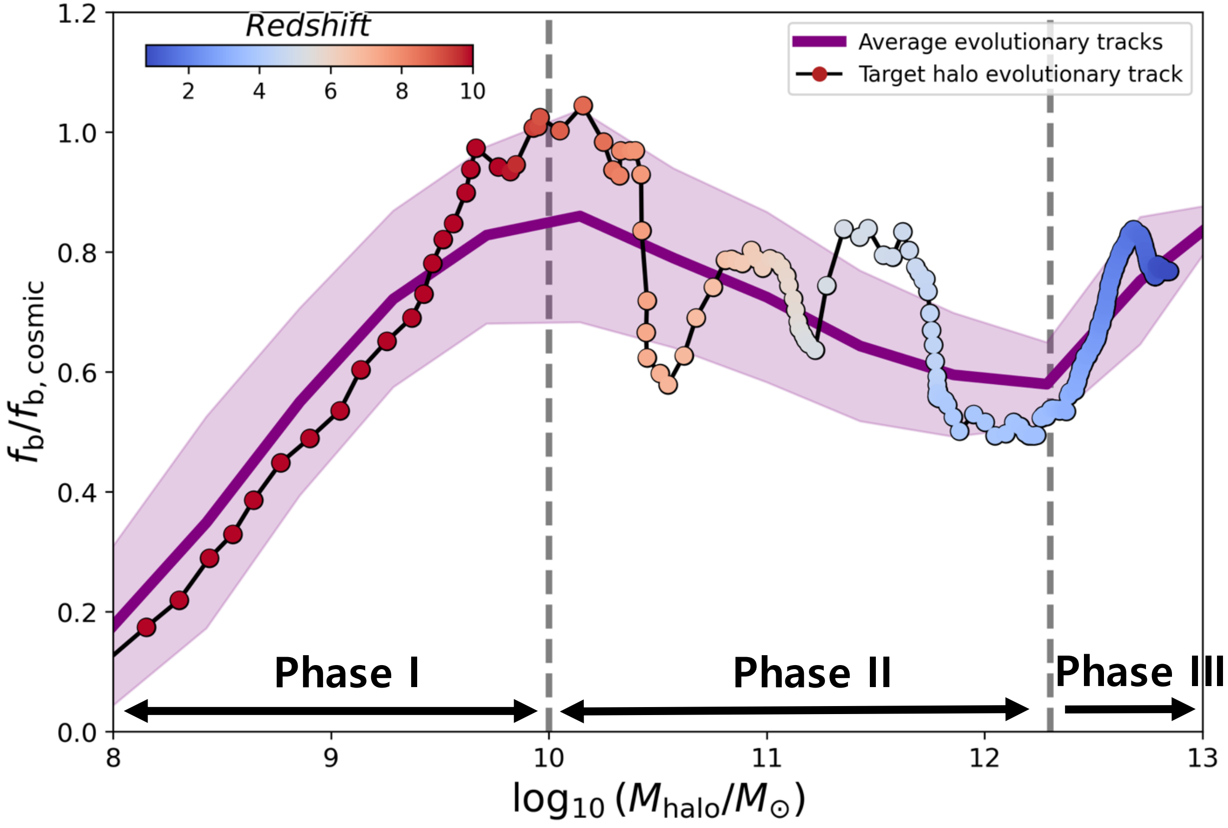


low-mass regime of the evolutionary tracks corresponds to high-z (~10)

This suggests redshift dependence in the low-mass regime

- f_b distribution varies significantly across simulations
  - highly sensitive to implemented subgrid physics
- How about evolutionary tracks of individual halos?
- We select 67 halos ($> 10^{11} M_\odot$ $at\ z = 0.8$) and follow their evolution

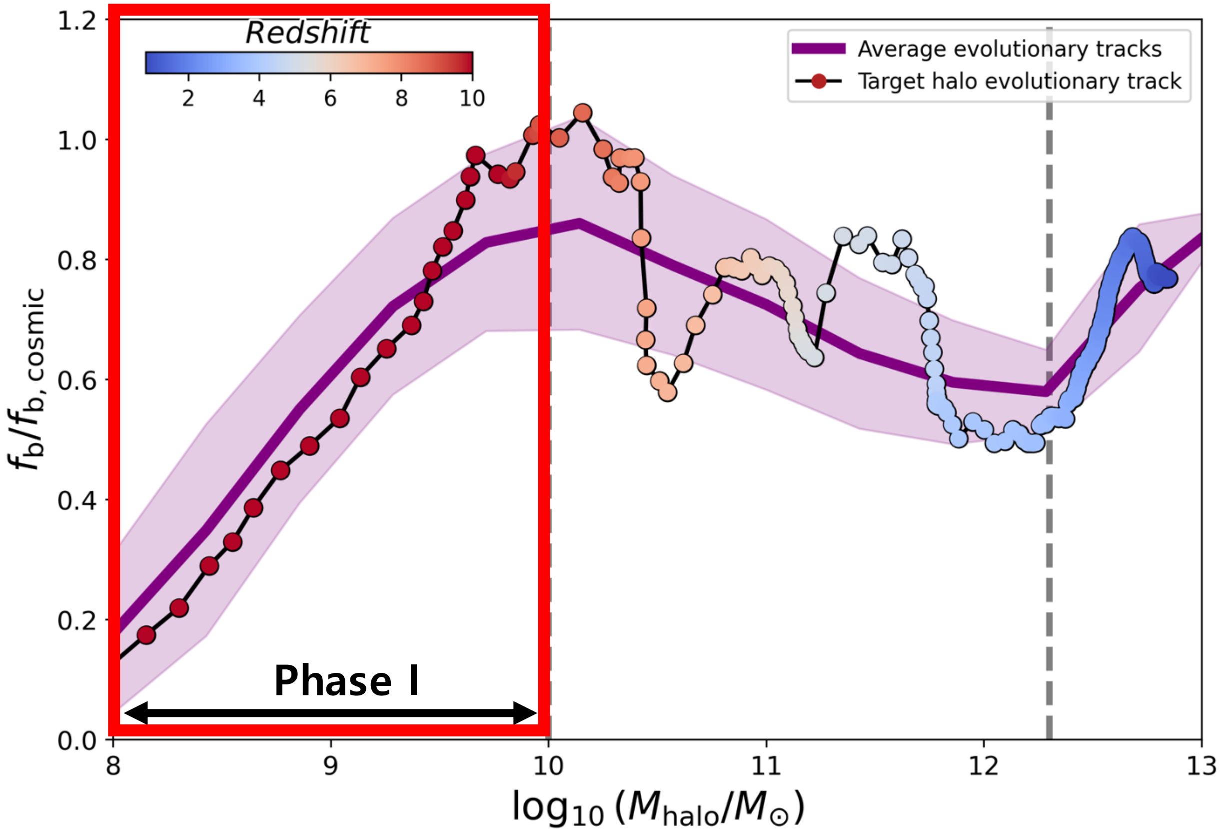
Evolutionary tracks – How they are shaped

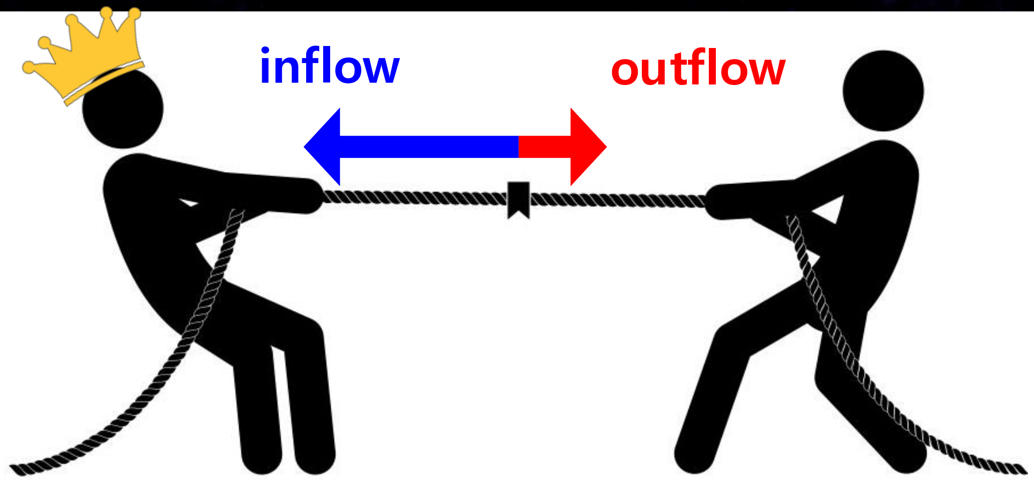


- **There are 3 distinct phases in evolutionary tracks**
  - **Phase I ($M_{halo} \lesssim 10^{10} M_{\odot}$) : Increasing phase**
  - **Phase II ($M_{halo} = 10^{10}$~$10^{12} M_{\odot}$) : Decreasing phase**
  - **Phase III ($M_{halo} \gtrsim 10^{12} M_{\odot}$) : Increasing phase**

- **To investigate the physical origin in each phase, we select a representative halo whose evolutionary track closely follows the average trend**

Evolutionary tracks – Phase I





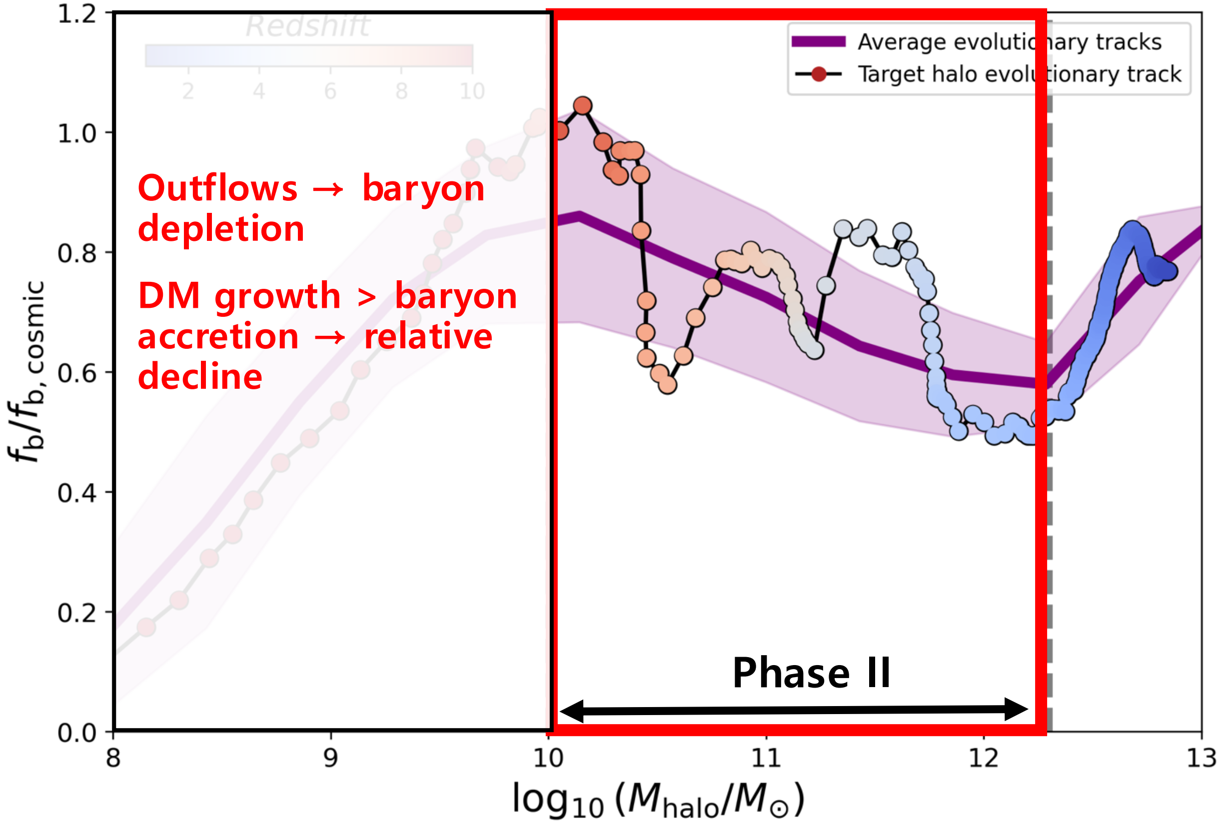
Phase I ($M_{halo} \lesssim 10^{10} M_\odot$) : Increasing phase, corresponding to high-z

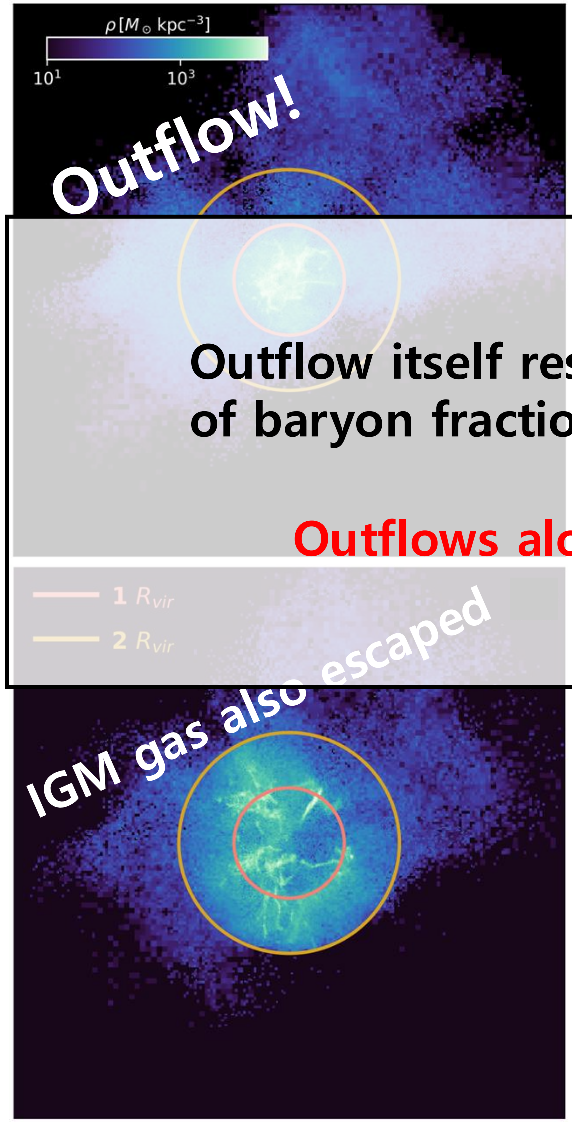
- Dark matter collapses first → forms gravitational potential
- Baryons fall into pre-existing potential well

Why?

- High redshift → weak (or absent) feedback
- Gas is mostly cold → efficient accretion

Evolutionary tracks – Phase II





Tracer particles that have ever been within $1R_{\mathrm{vir}}$

18% tracer particles escape $1R_{\mathrm{vir}}$

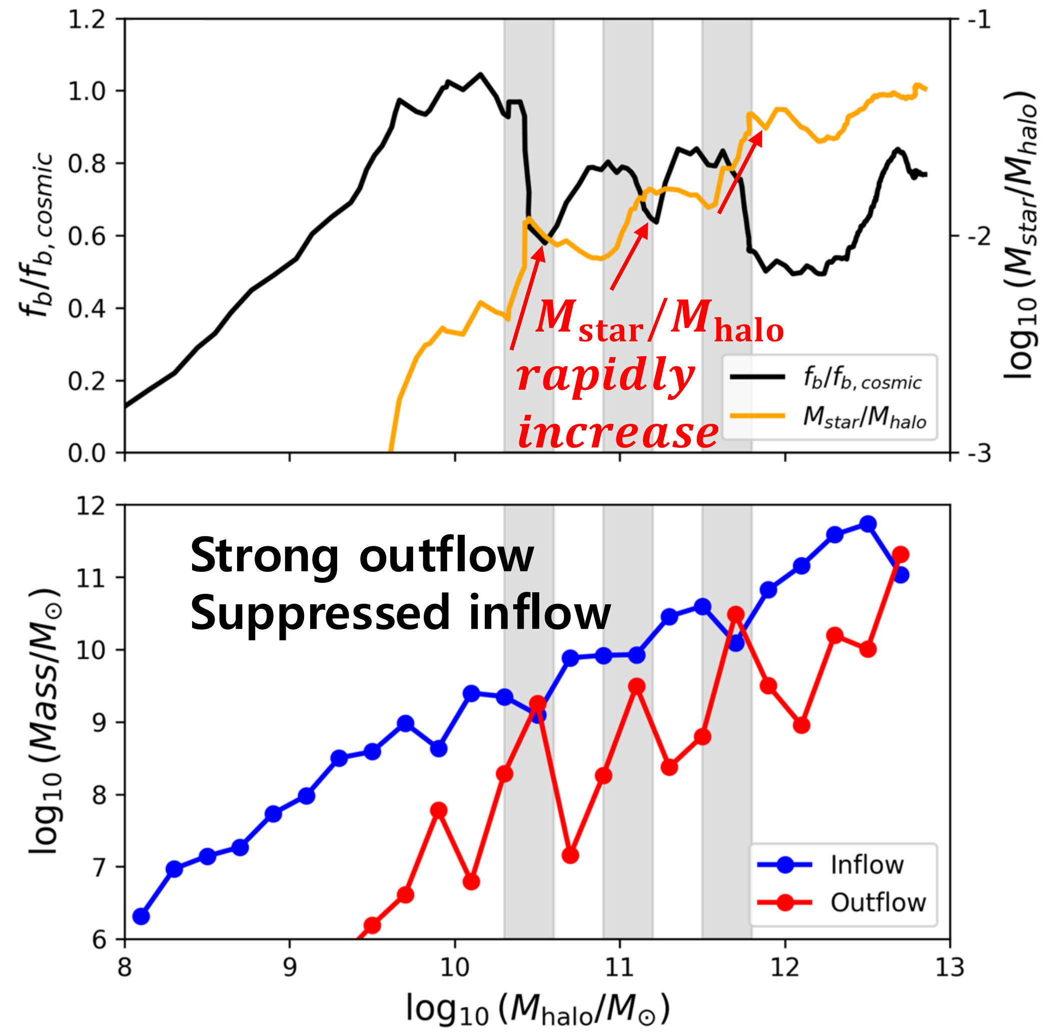
Outflow itself results in ~18% decrease of baryon fraction at $M_{halo} = 10^{12}M_\odot$

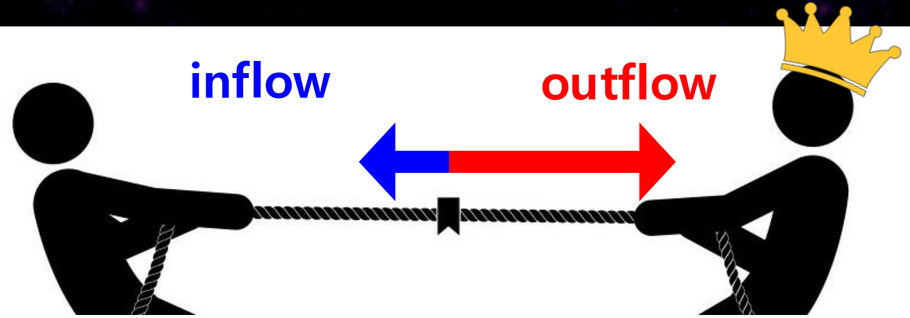
Outflows alone are insufficient!

Tracer particles that have ever been within $1\sim2R_{\mathrm{vir}}$

12.6% tracer particles escape $2R_{\mathrm{vir}}$

Evolutionary tracks – Phase II

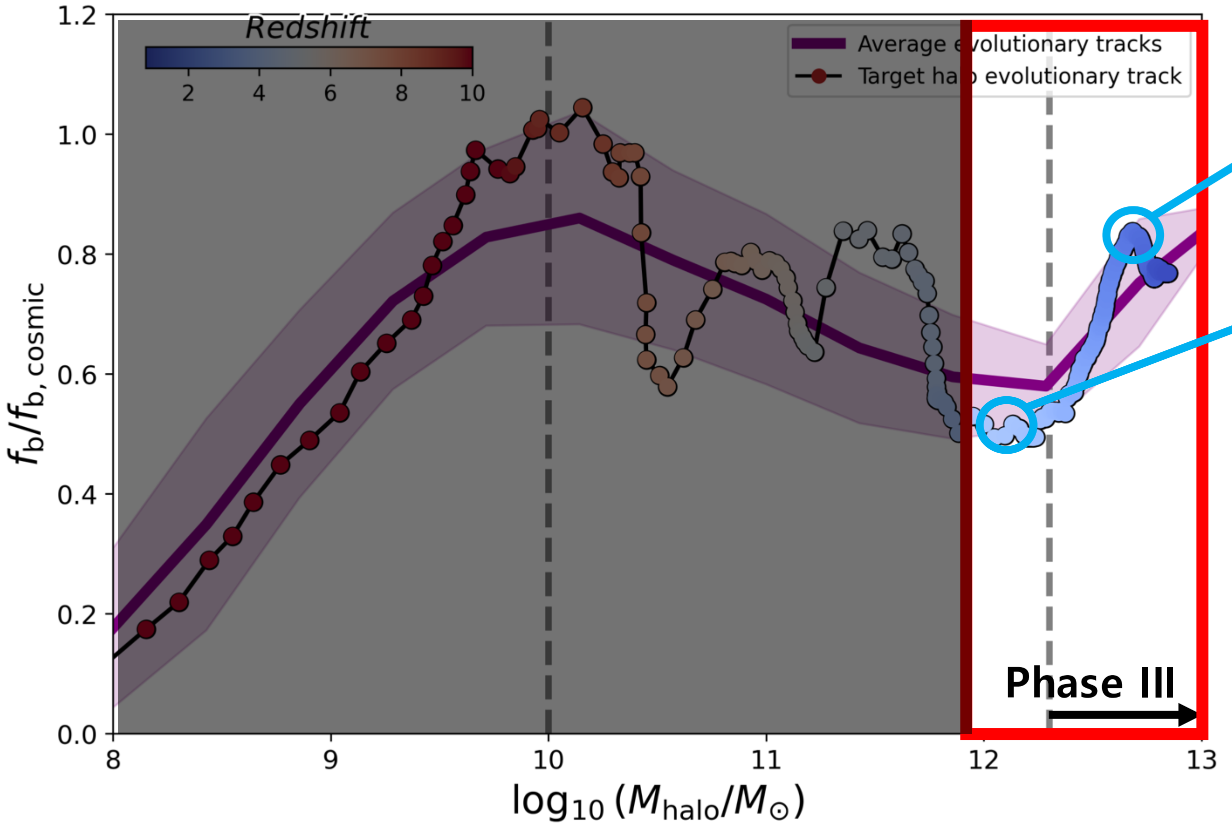




- 3 distinct intervals – baryon fraction decrease rapidly
  - Coincide with Enhanced star formation (M_{star}/M_{halo} ↑)
  - When outflow is strong, inflow is suppressed
    – 'preventative feedback'

- Key Message:
  SN feedback not only removes gas from halos but also suppresses (and even expels) inflowing gas

Evolutionary tracks – Phase III

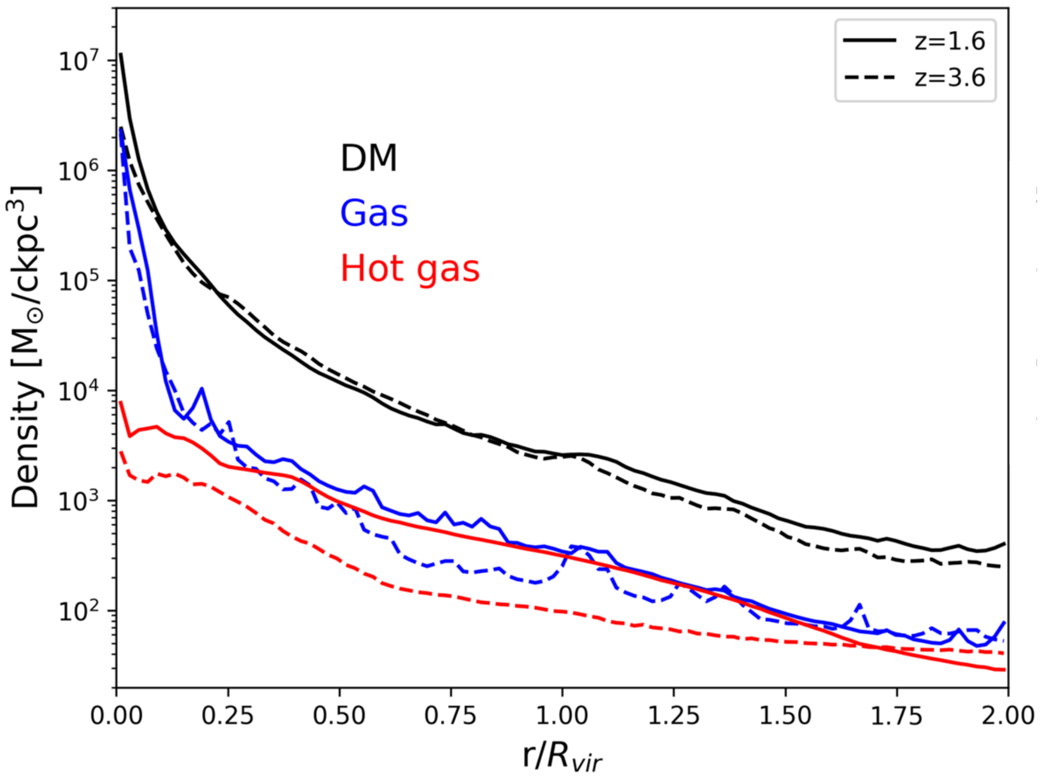


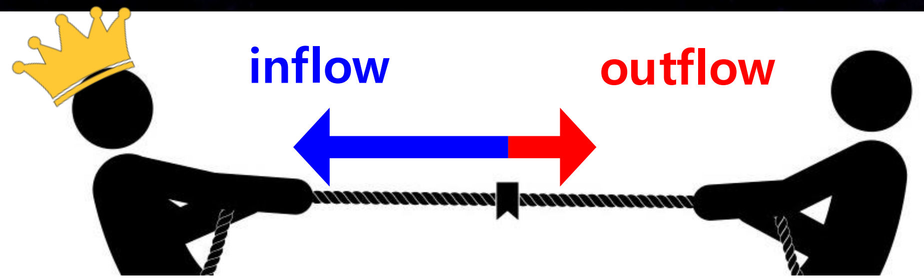
$M_{\mathrm{halo}} \sim 5 \times 10^{12} M_\odot$ at $z = 1.6$: recovered point

$M_{\mathrm{halo}} \sim 10^{12} M_\odot$ at $z = 3.6$: minimum point

Let's see what is difference between 2 points

Evolutionary tracks – Phase III

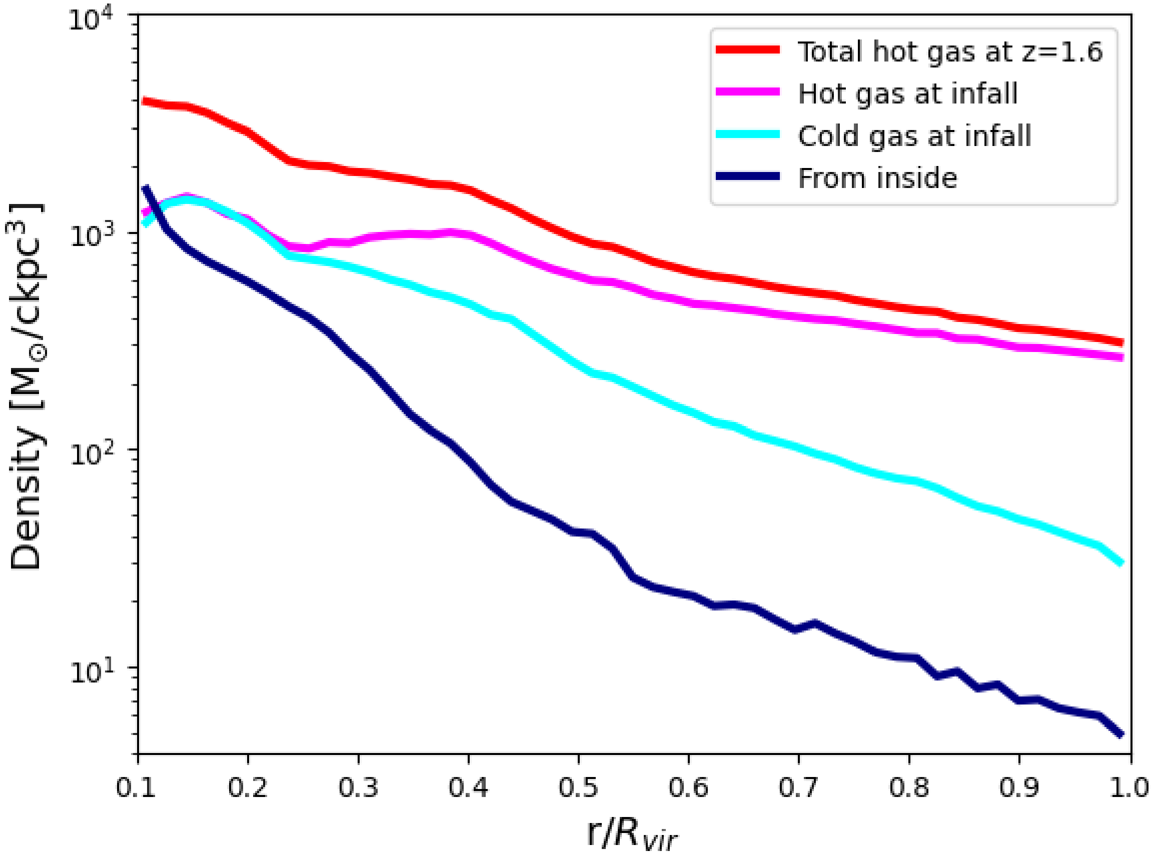




- **DM density profiles show little difference**
- **Gas is enriched in 0.25$\lesssim r/R_{\rm vir} \lesssim$1**
- **Hot gas component shows significantly increase**

- **the recovery of the baryon fraction**
  -closely linked to the onset of efficient gas accretion, especially hot gas accretion in massive halos

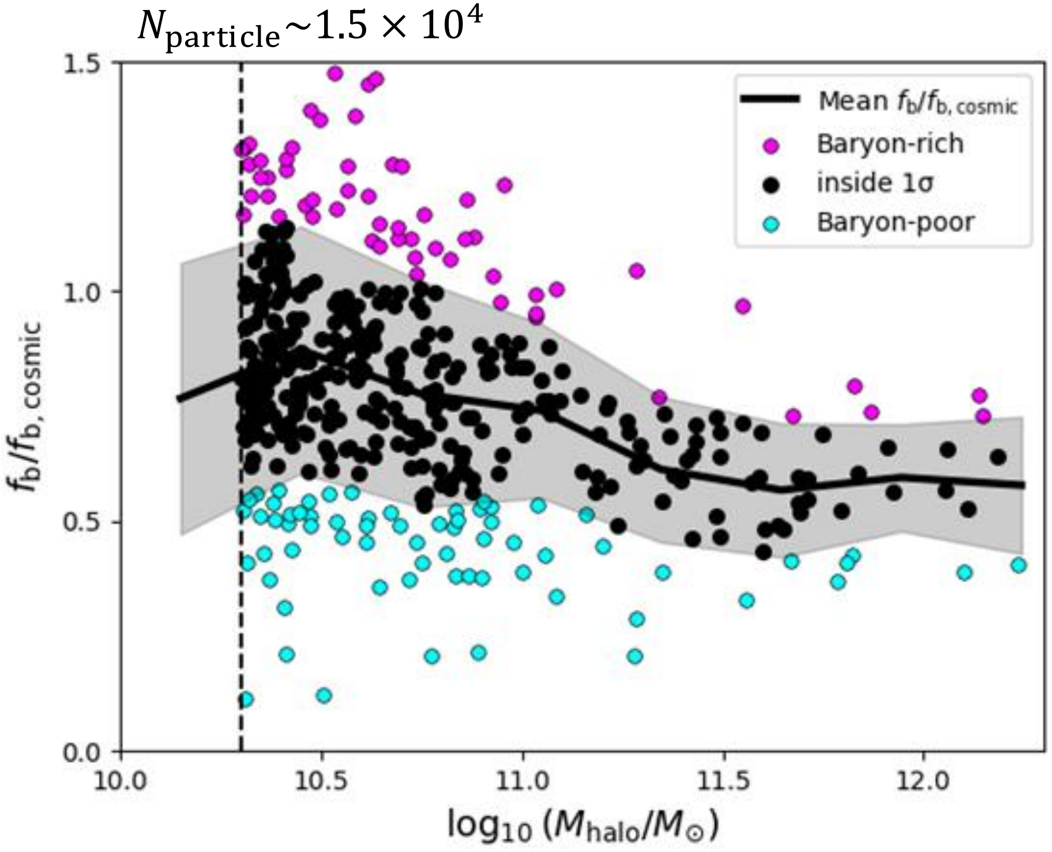
Evolutionary tracks – Phase III

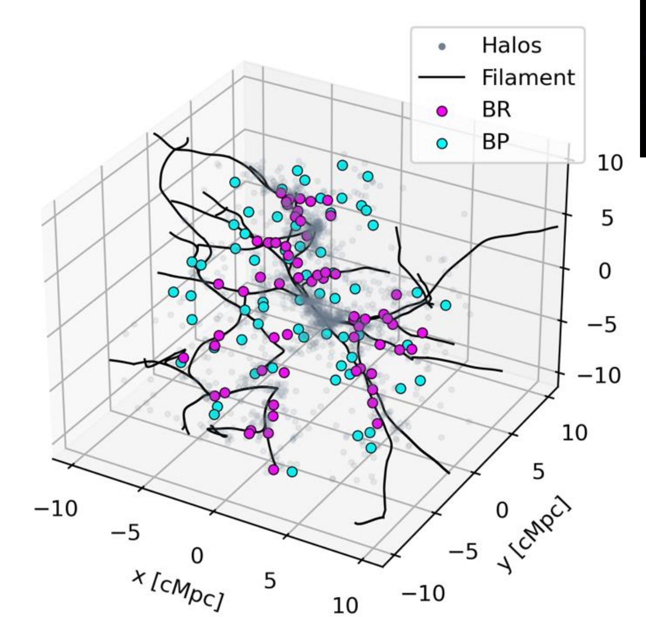


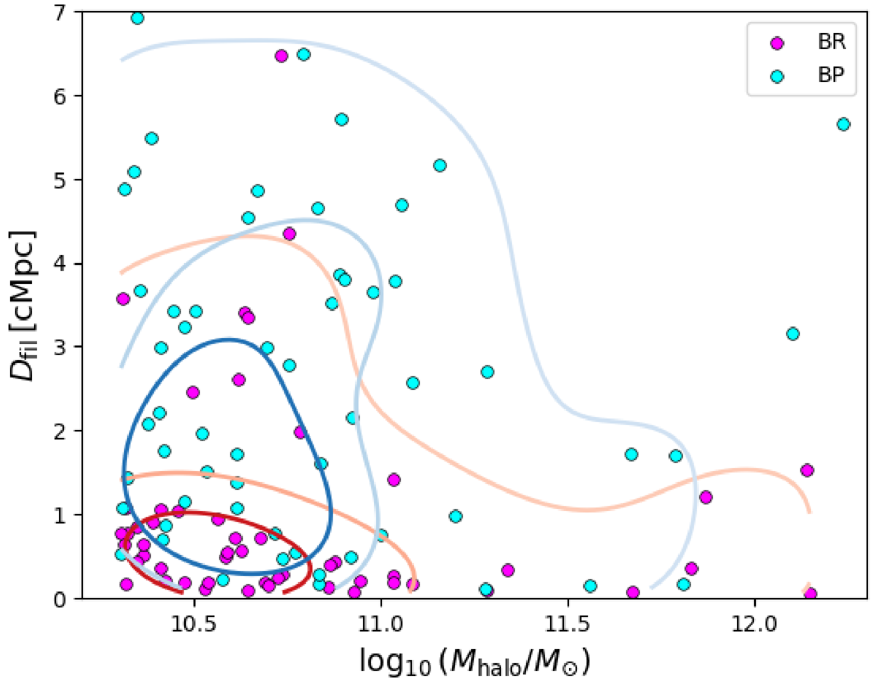
- **Divide into 3 categories**
  1. **Hot gas at infall** ($\mathrm{T} \geq 10^6\mathrm{K}$)
  2. **Cold gas at infall** ($\mathrm{T} < 10^6\mathrm{K}$)
  3. **From inside** ($<0.1R_{\mathrm{vir}}$)
- **Potential well related (hot-mode acc) : 1**
- **Feedback related : 2, 3**
- **the enhanced hot gas mainly originates from hot-mode accretion, rather than from in-situ heating by feedback processes**

Scatter on f_b at fixed M_{halo}?

DisPerSE

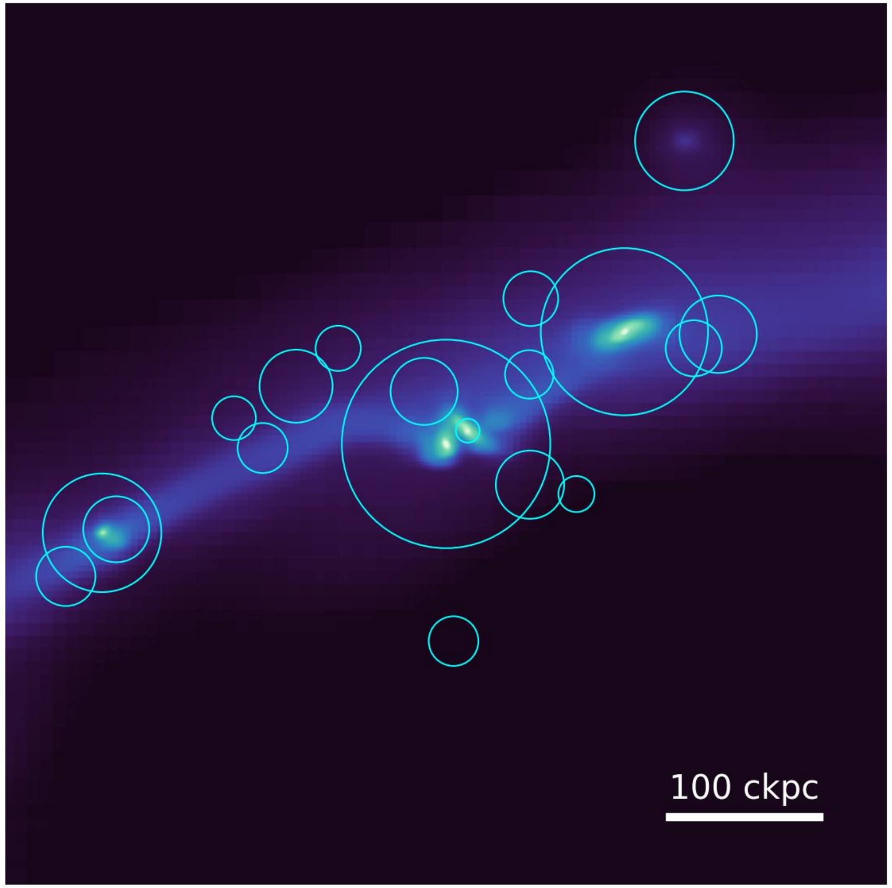






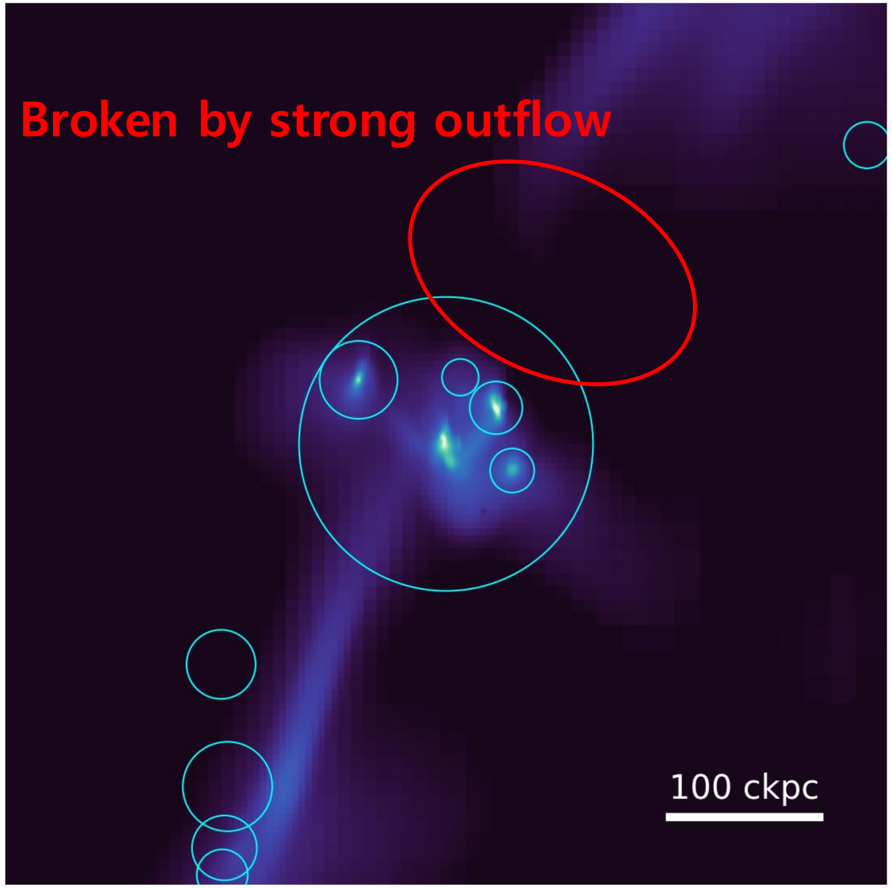
Future work – accretion history

Baryon-rich halo



Continuous gas accretion along filaments

Baryon-poor halo



Less collimated gas accretion is disrupted by outflows

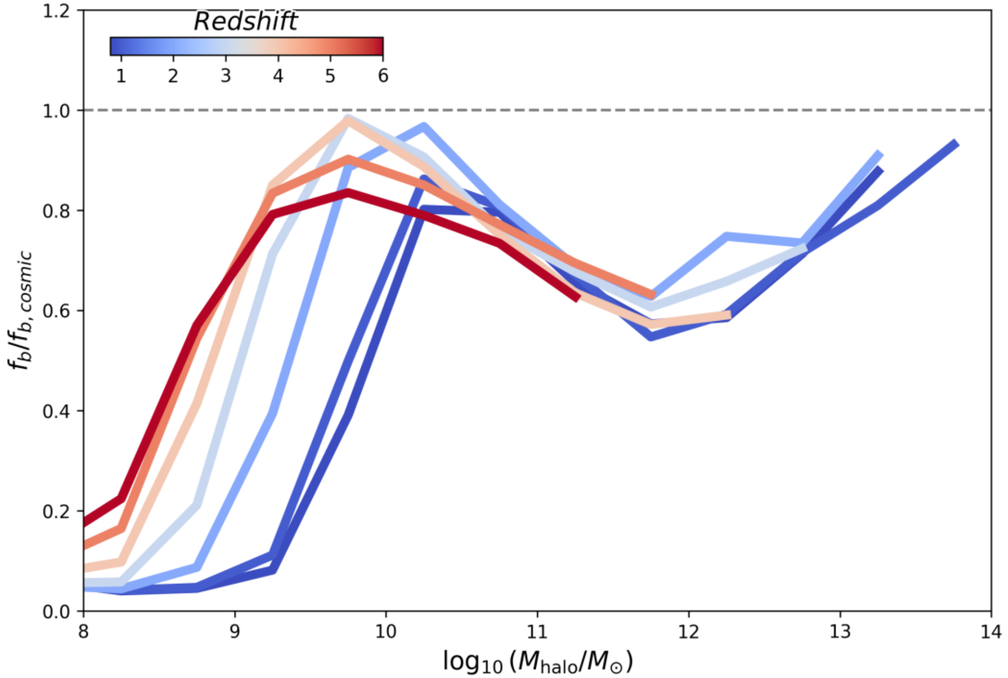
Summary

1. Baryon fraction distribution $\neq$ evolutionary track - redshift dependence
   - f_b is highly sensitive to implemented subgrid physics

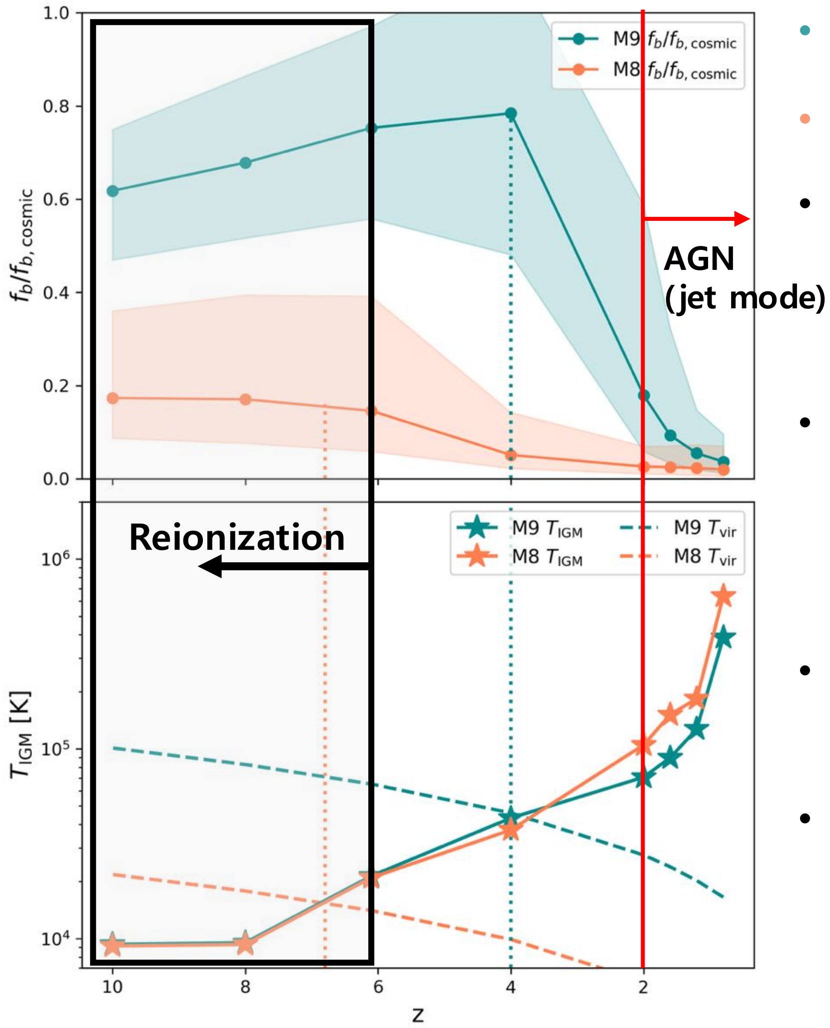
2. We identify 3 distinct phases in evolutionary tracks
   - First phase - Efficient cold accretion builds up baryons in halos
   - Second phase - SN feedback suppresses f_b via gas outflows and prevented inflow
   - Third phase - Deep potentials enable gas re-accretion, restoring f_b via hot-mode accretion

Future work
: Scatter in f_b at fixed mass seems to be correlated with filaments, please stay tuned!

Redshift dependence

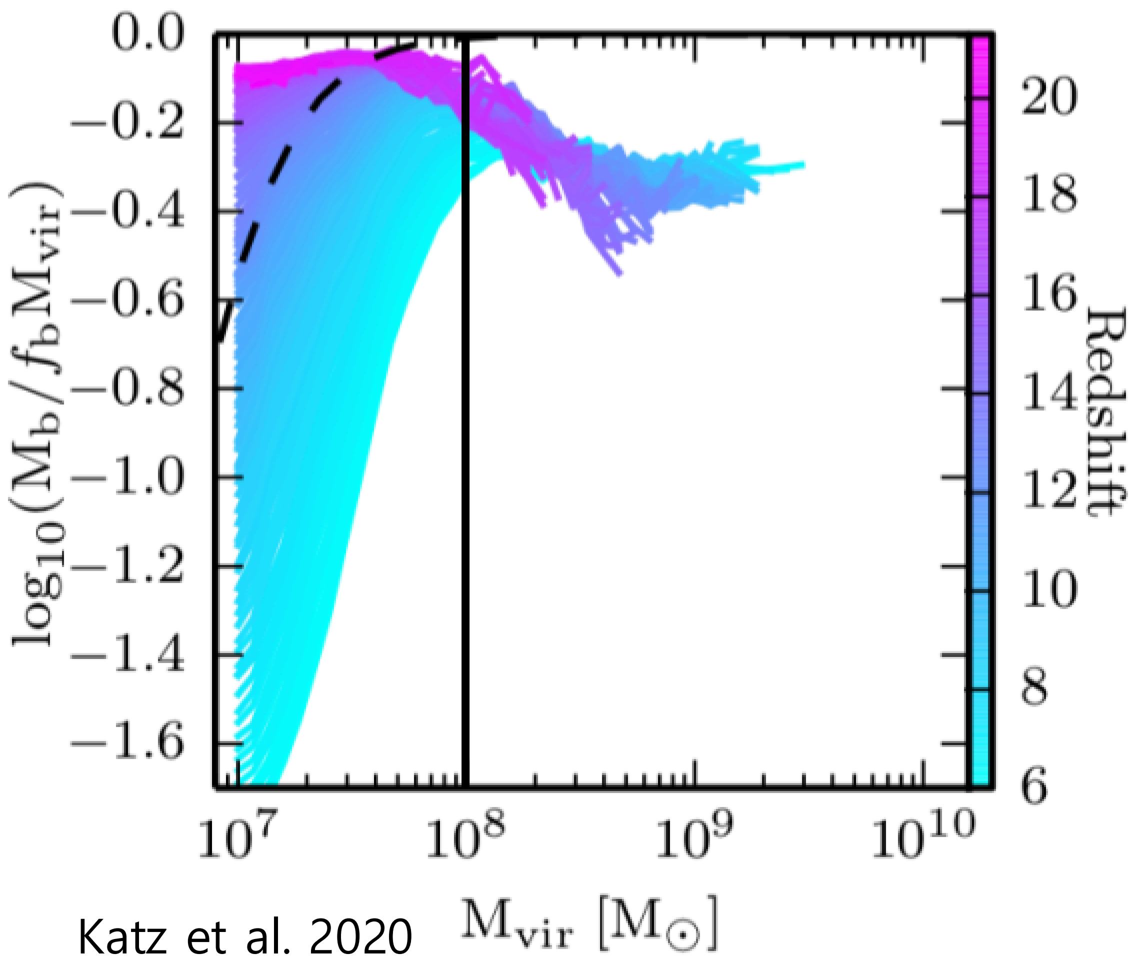


Baryon fraction suppression starts from low-mass halos to higher masses over time



- M8 : $1 \sim 3 \times 10^8 M_\odot$
- M9 : $1 \sim 2 \times 10^9 M_\odot$
- f_b suppression condition
  - $\mathrm{T_{IGM}} > \mathrm{T_{vir}}$
- Reionization
  - Heats gas up to $\sim 10^4$K, but insufficient to suppress M8 and M9
- SN feedback
  - Dominant at $z \sim 6 - 2$
- AGN feedback
  - Important after $z \sim 2$, extends suppression to higher-mass halos

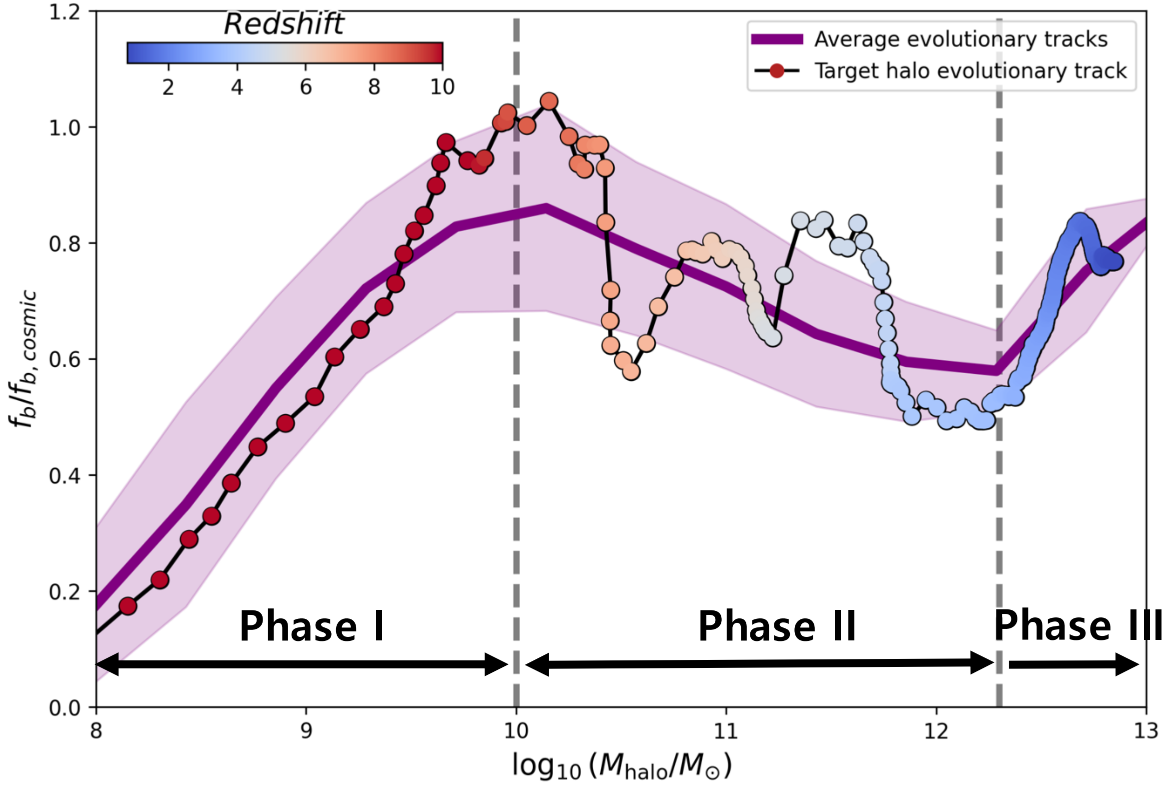
Reionization effect?



Katz et al. 2020

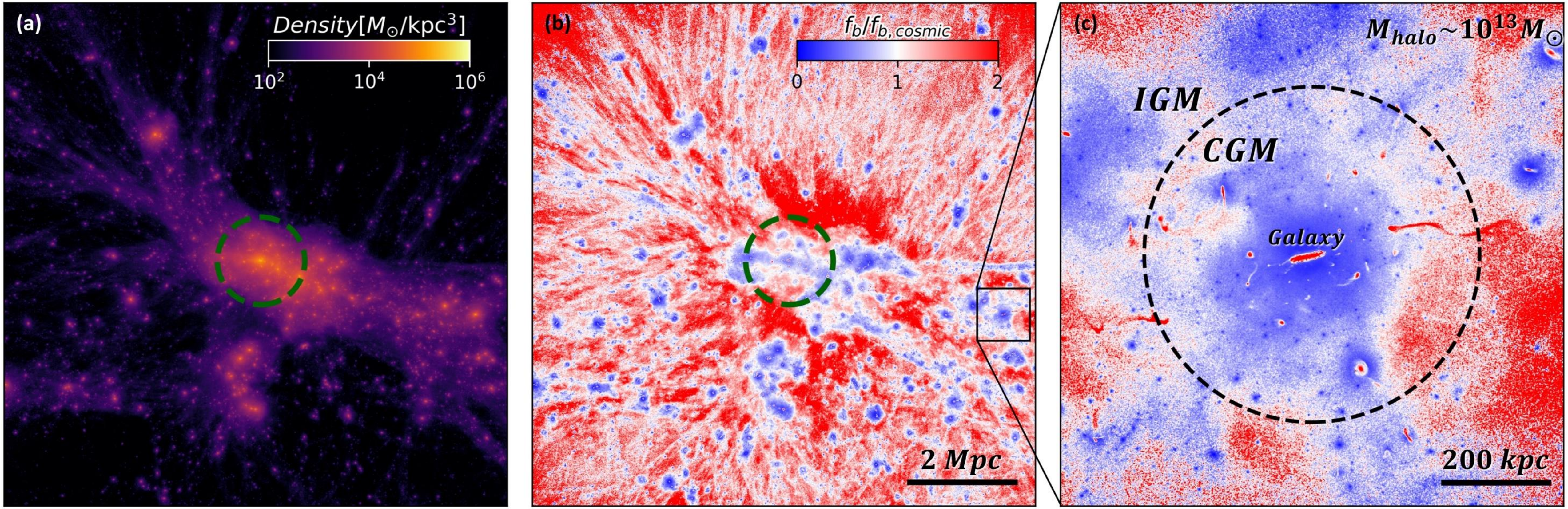
Reionization effect is significant below $10^8 M_\odot$

Snapshot output resolution?

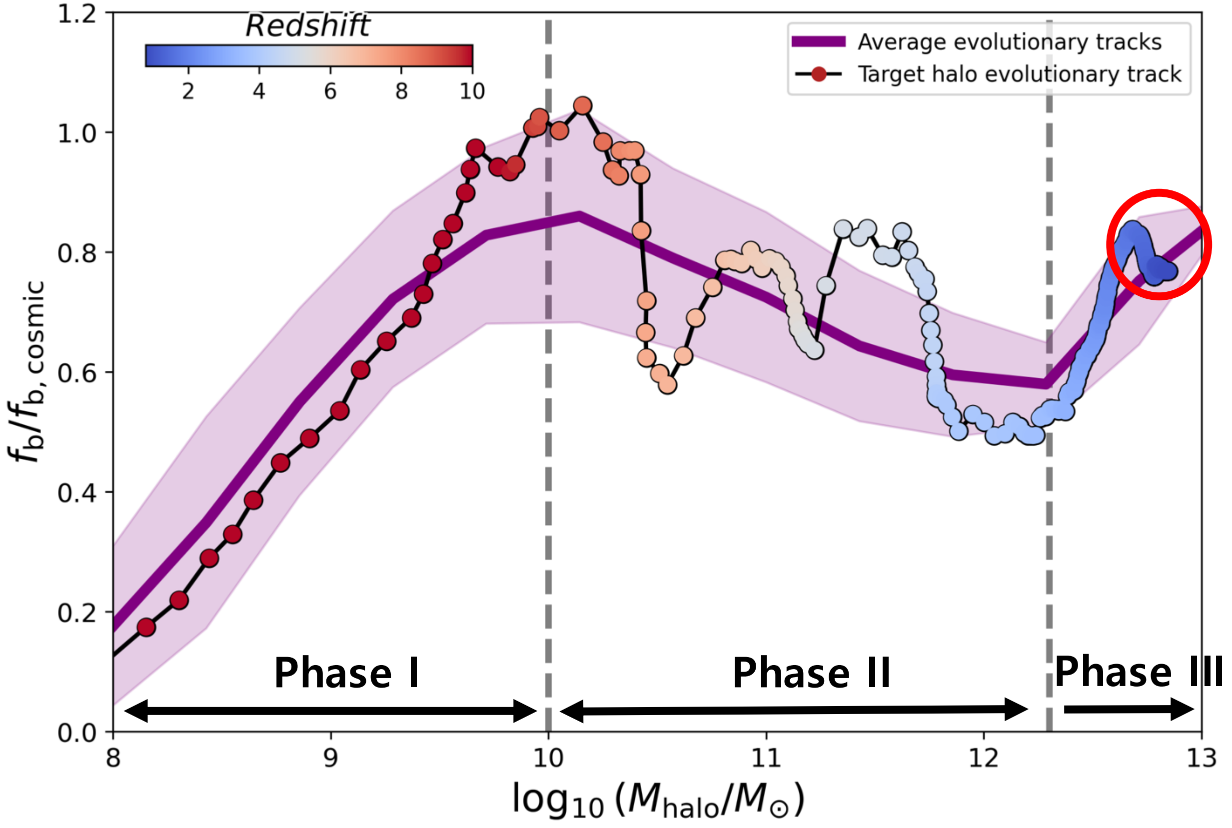


- **With high temporal resolution (~15Myr), it is possible to resolve episodic events**

Baryon fraction distribution in halo



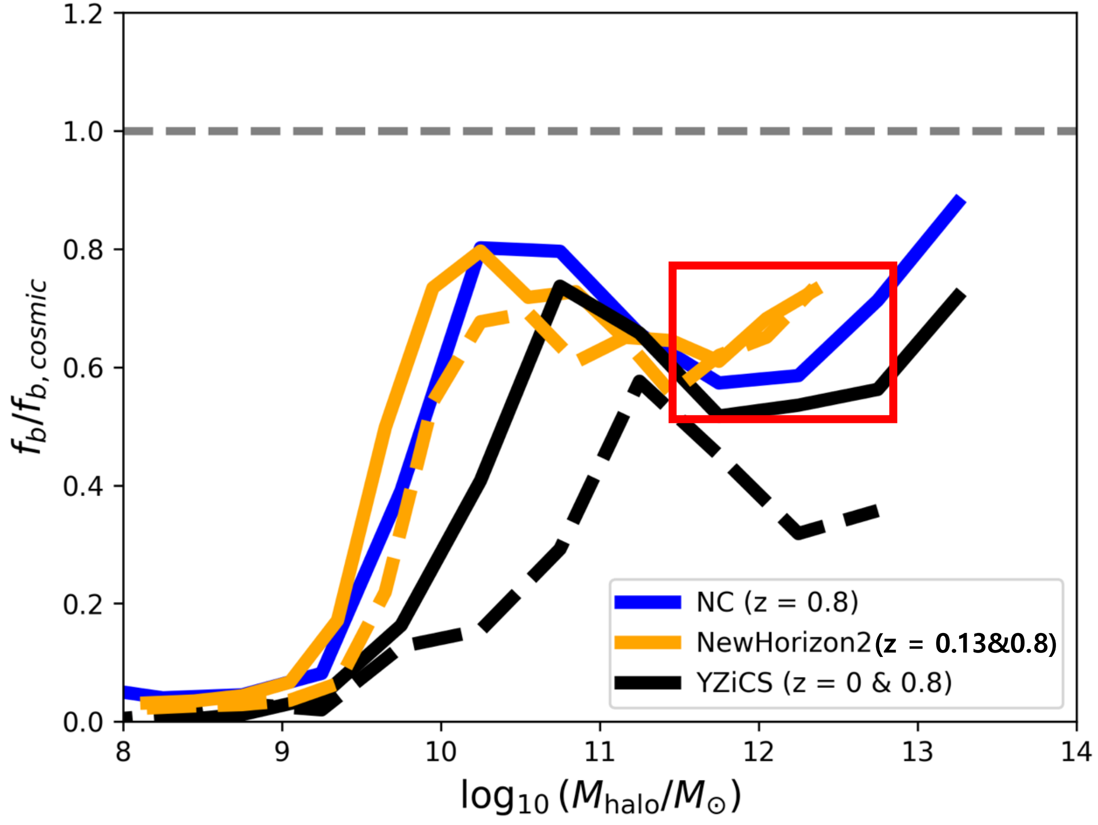
AGN



- **AGN jet mode induce transient decrease**
    - **Since mode change depends on Eddington ratio, activated masses are different in each halo**

- **In average evolutionary tracks, trend tend to average out**

AGN

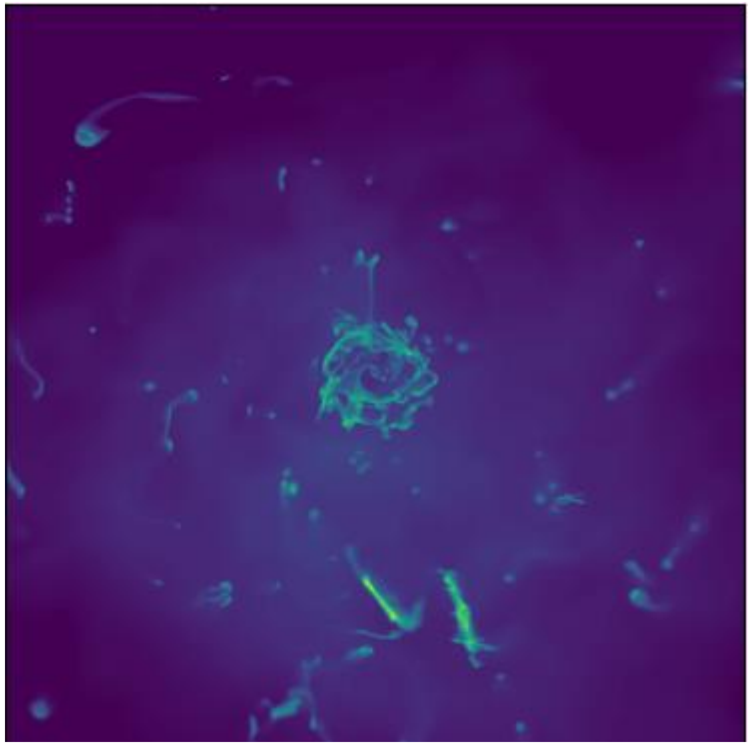


- **NH2 – BH centering problem**
  - **Almost no AGN simulation**

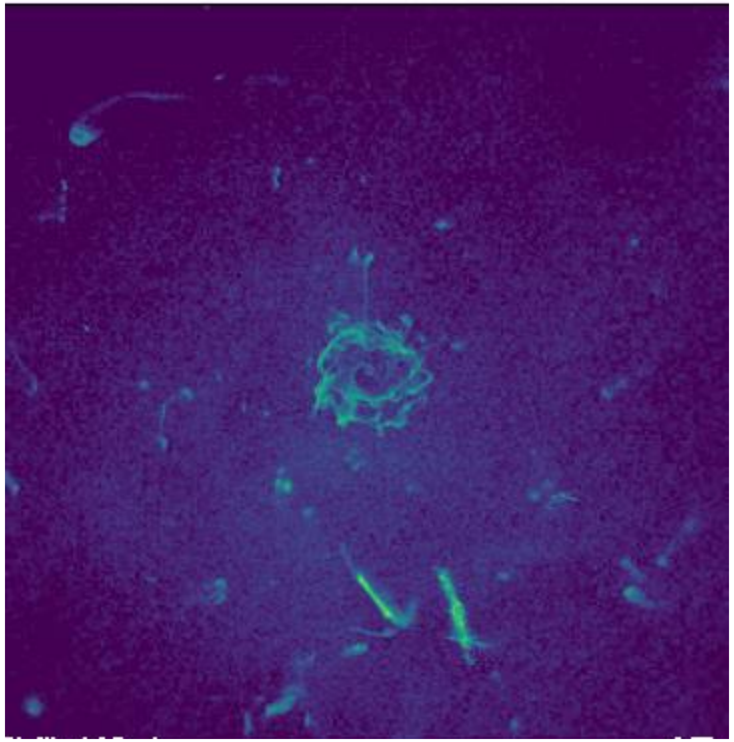
- **Without AGN feedback, increase become steeper**

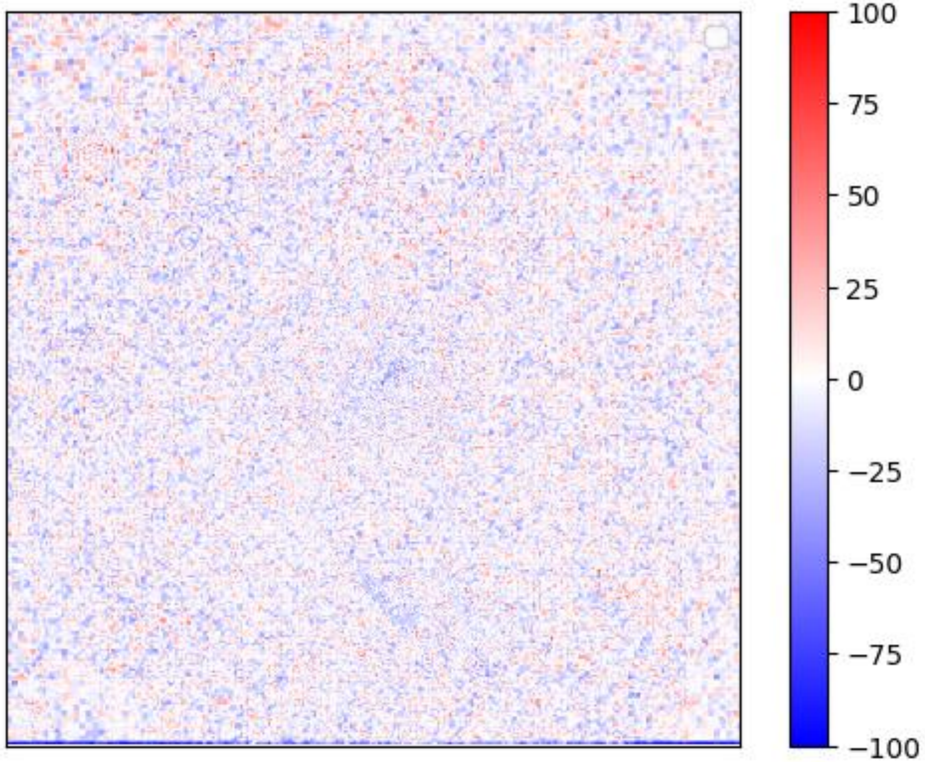
Tracer particle validation

Cell (gas)

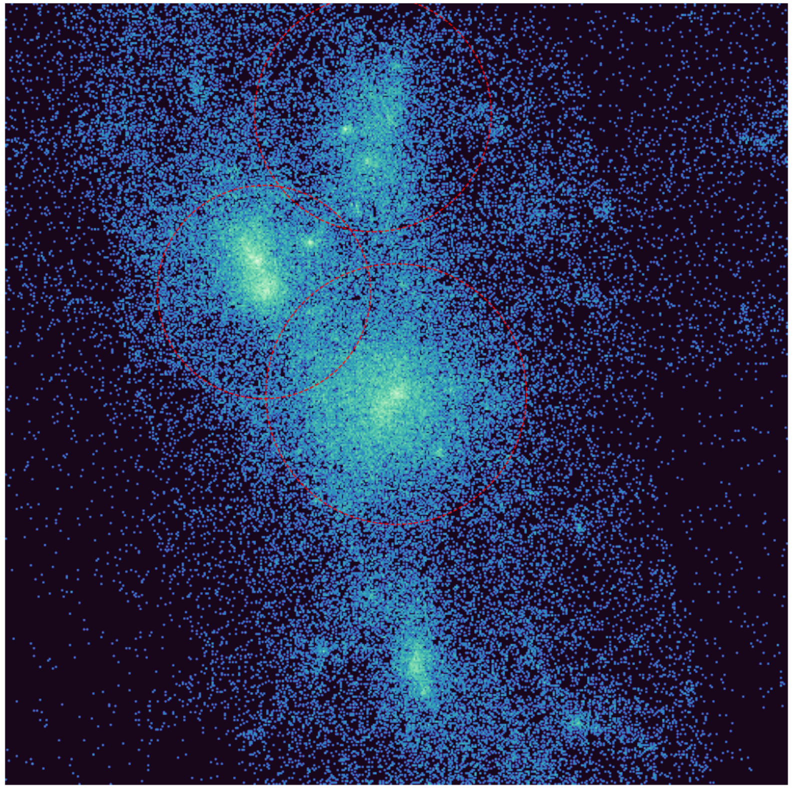


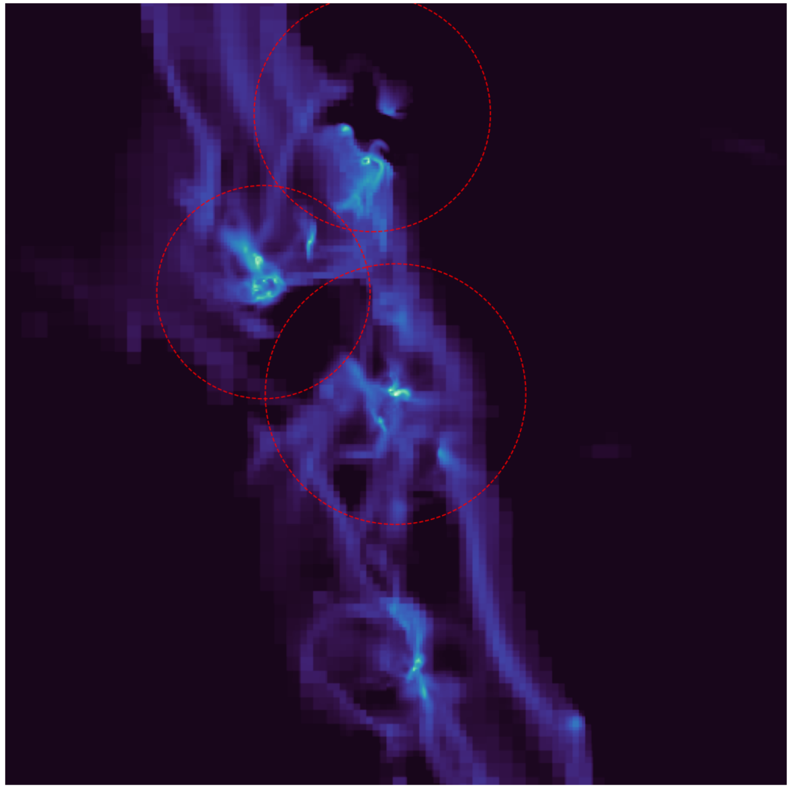
Gas tracer

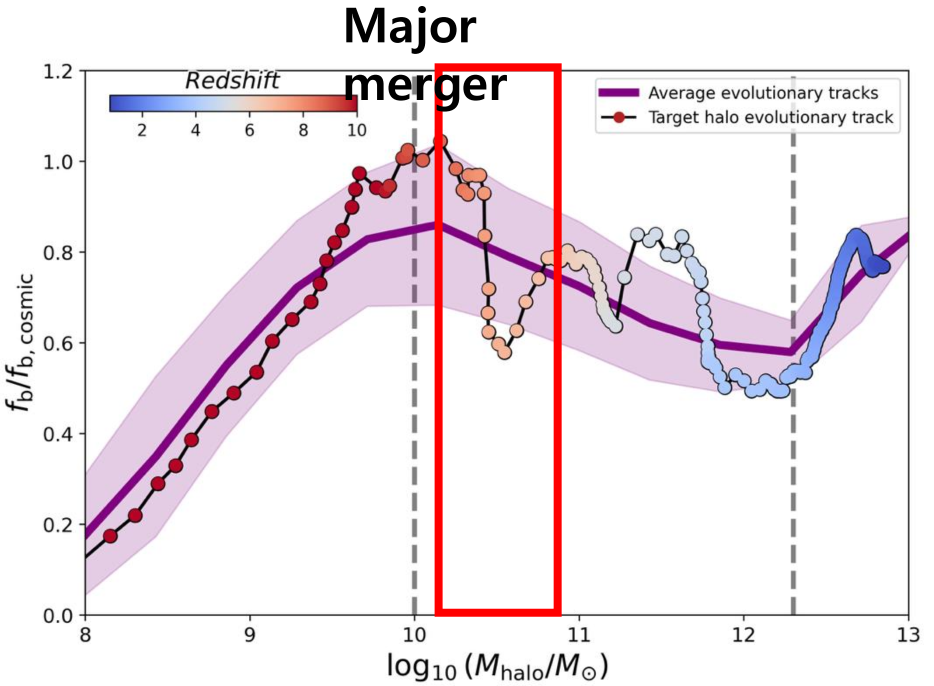




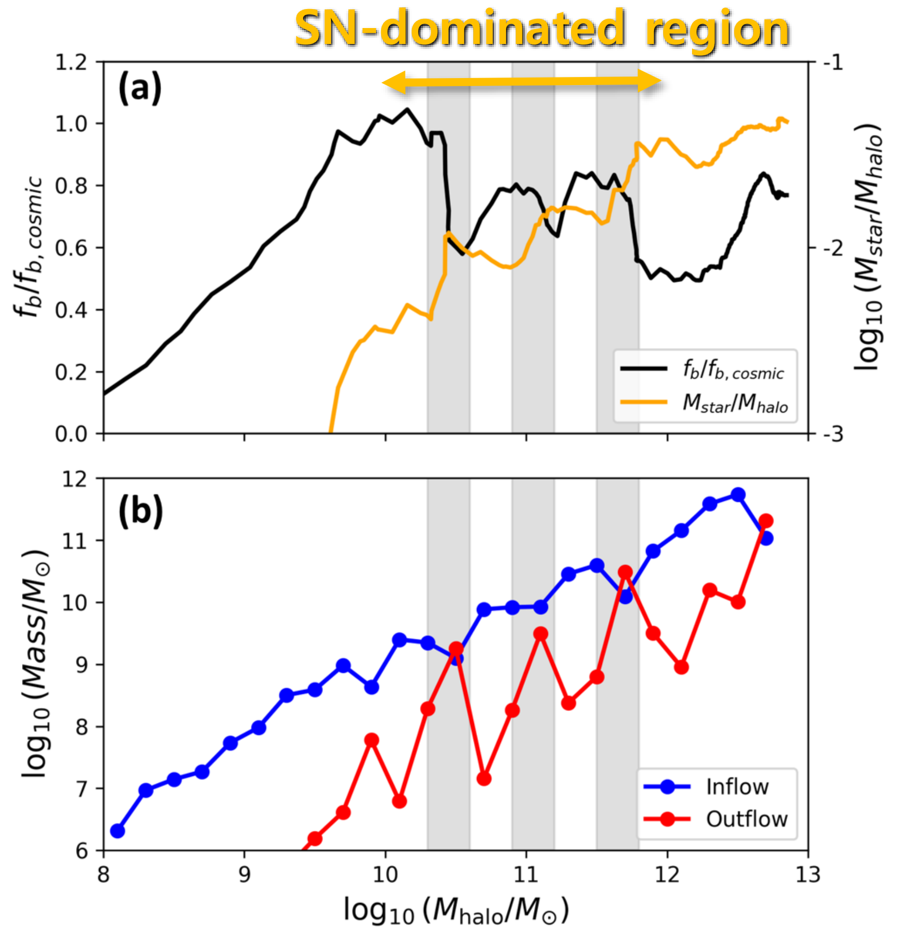
Merger effect

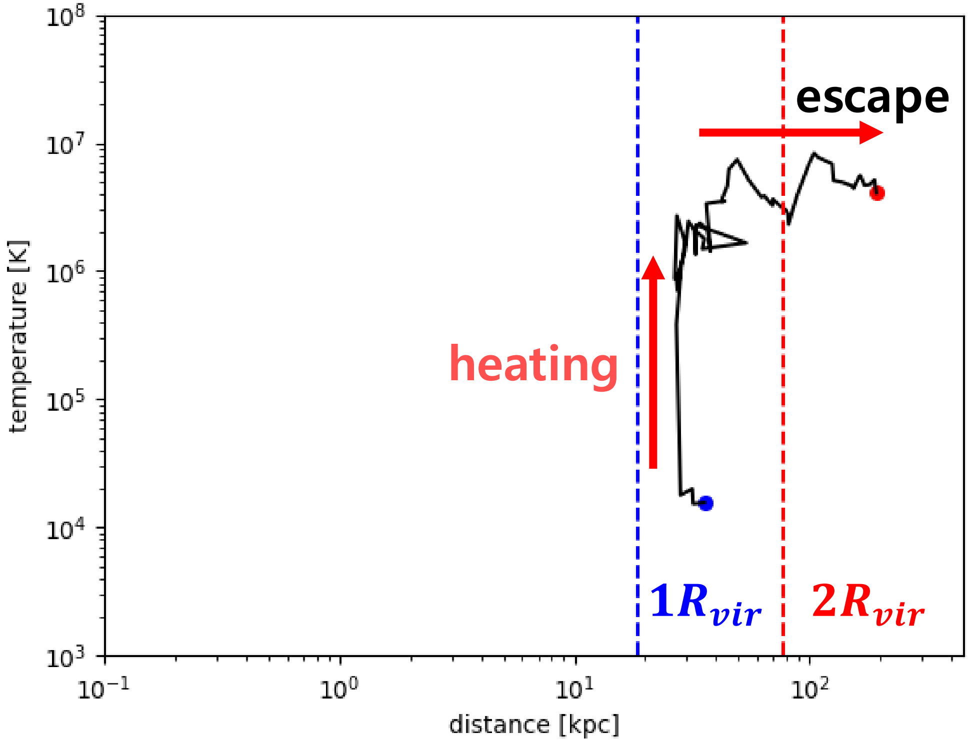






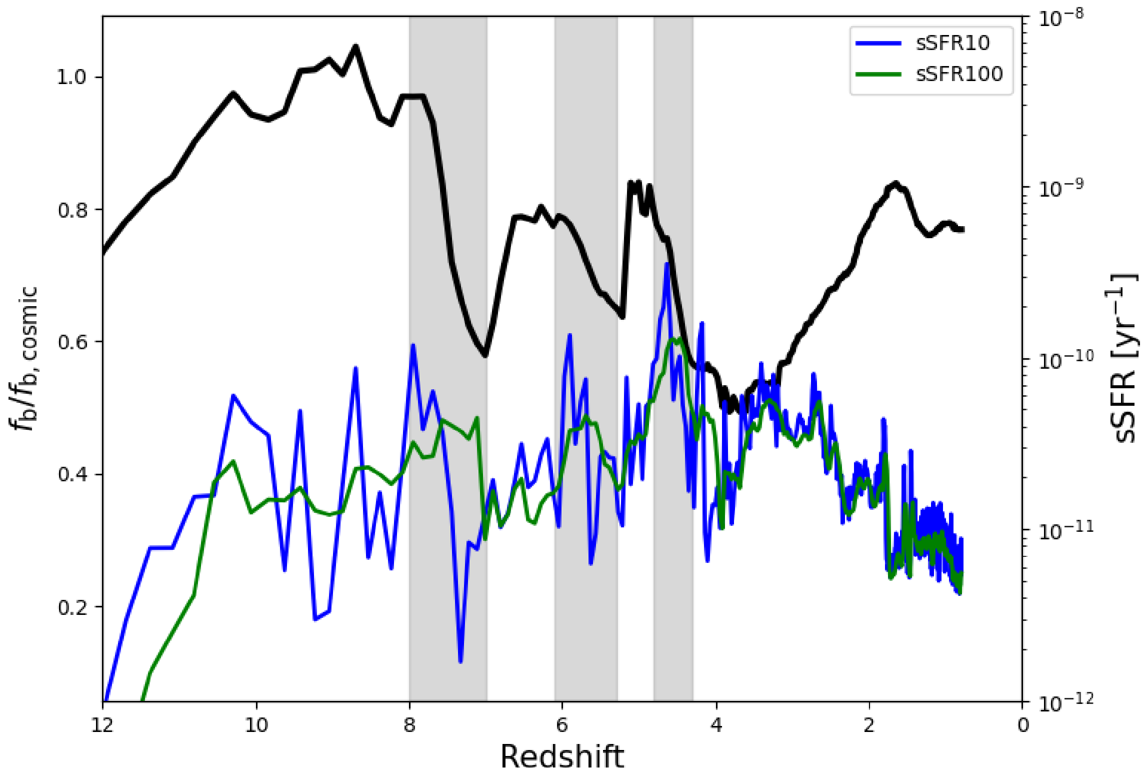
Preventative feedback

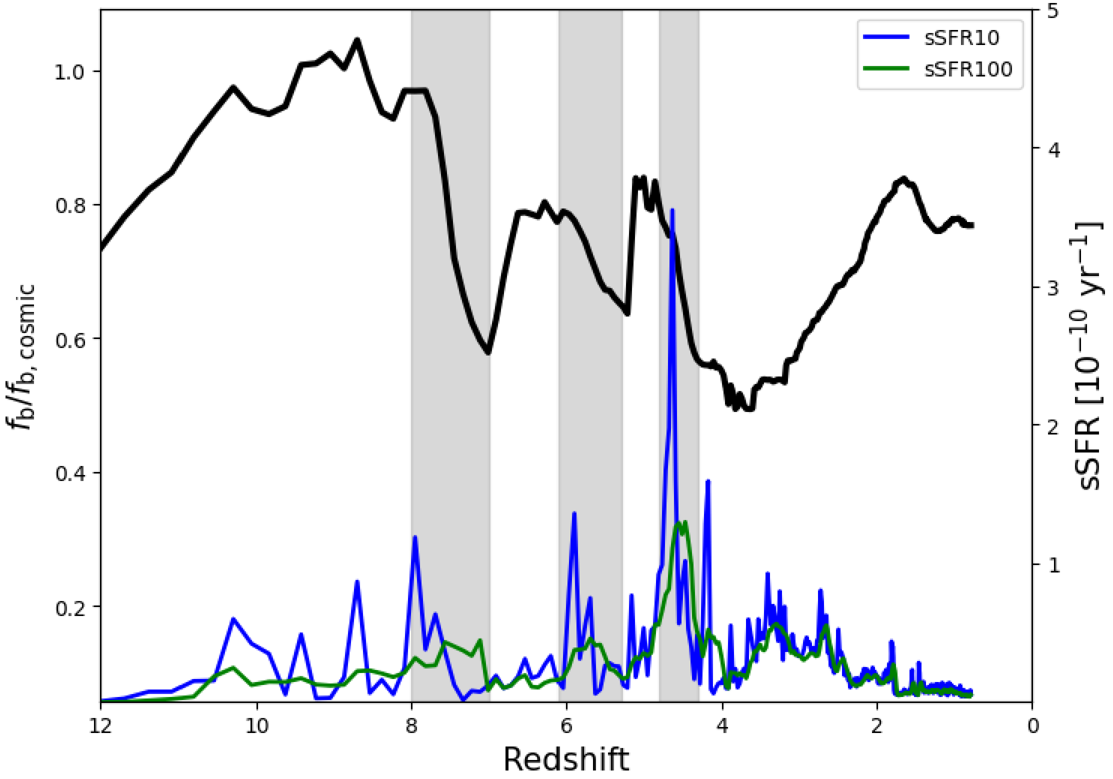




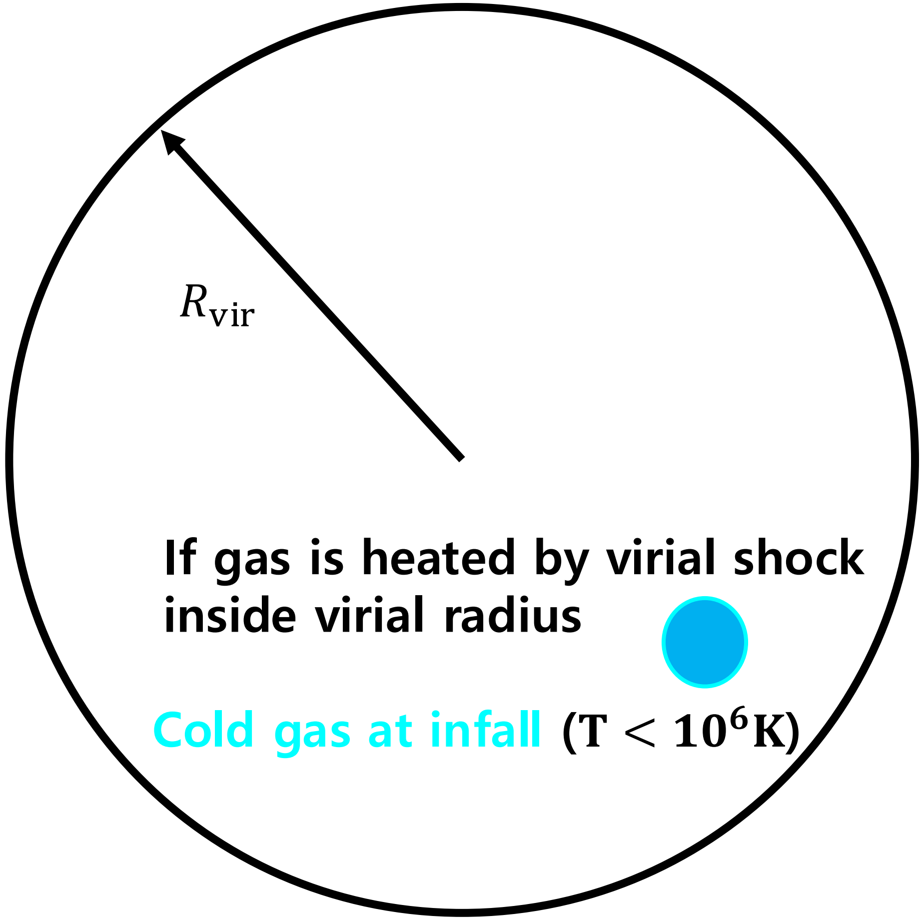
- **When outflow mass is huge -> inflow mass is also suppressed.**
- **IGM($1R_{vir}$~ $2R_{vir}$) gas is heated -> inflow gas is suppressed and even escape!**

SFR in the second phase





Virial shock in the third phase

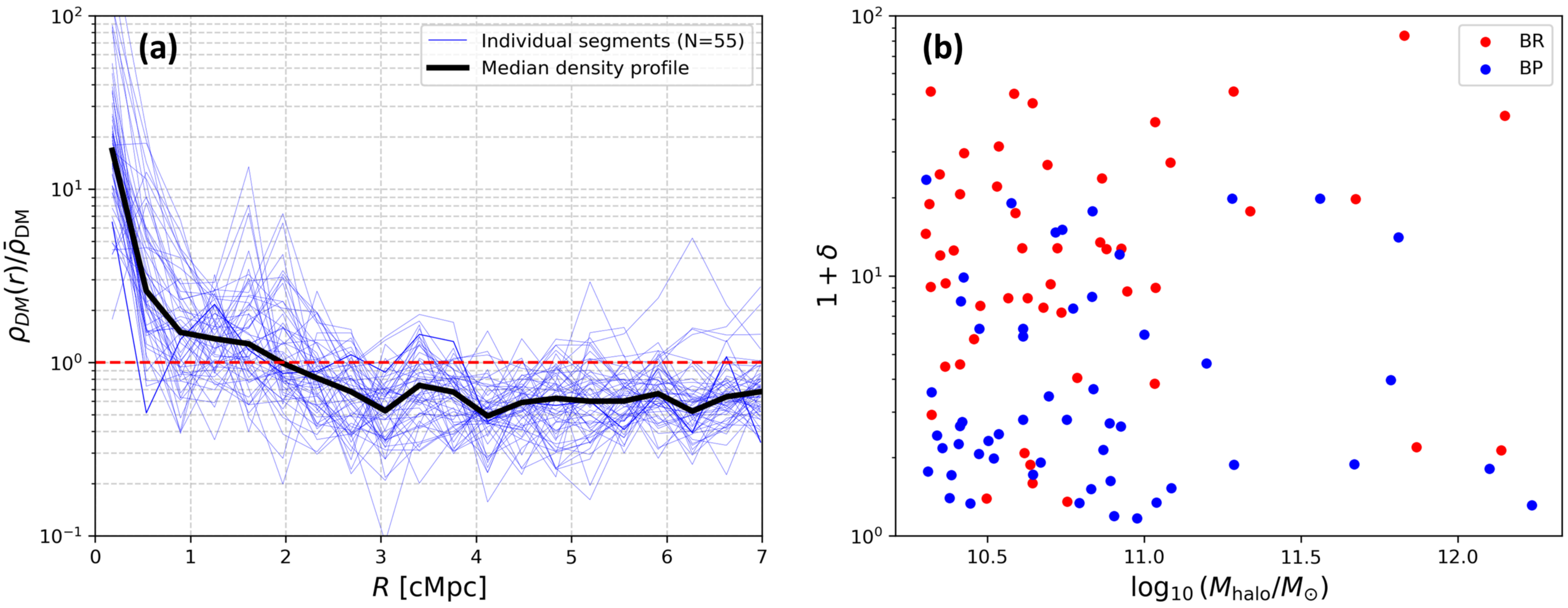


If gas is heated by virial shock outside virial radius

Hot gas at infall $(\mathrm{T} \geq 10^6\mathrm{K})$

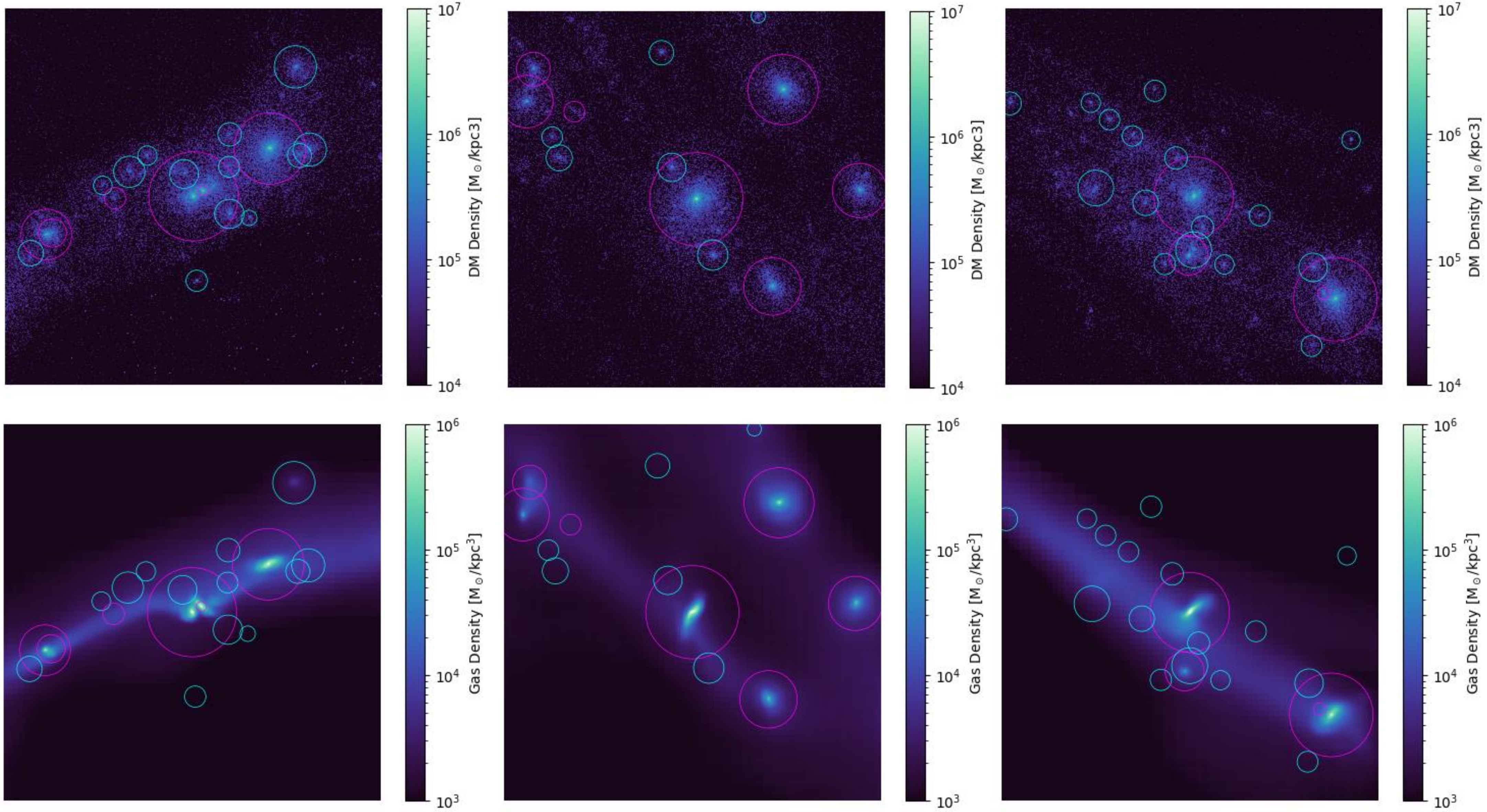
Whatever the origin of the hot gas, its presence within the halo reflects the deepening of the potential well.

D_{fill}

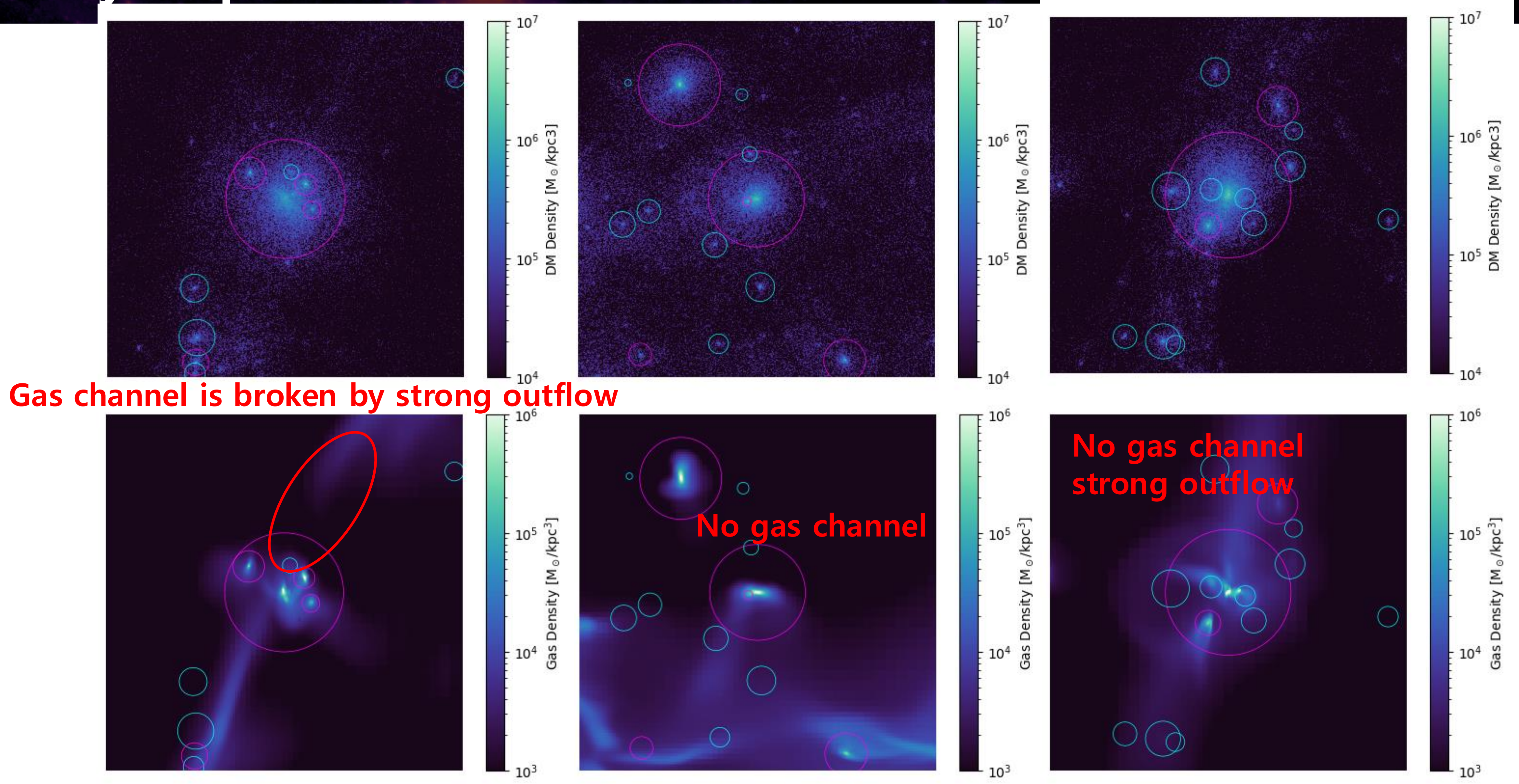


Baryon-rich halos

Many small DM halos, clear gas channel



Baryon-poor halos



Accretion difference