Impacts of Supermassive Black Hole Feedback on Galaxy Formation in IllustrisTNG Simulations

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1. Introduction

1. Introduction

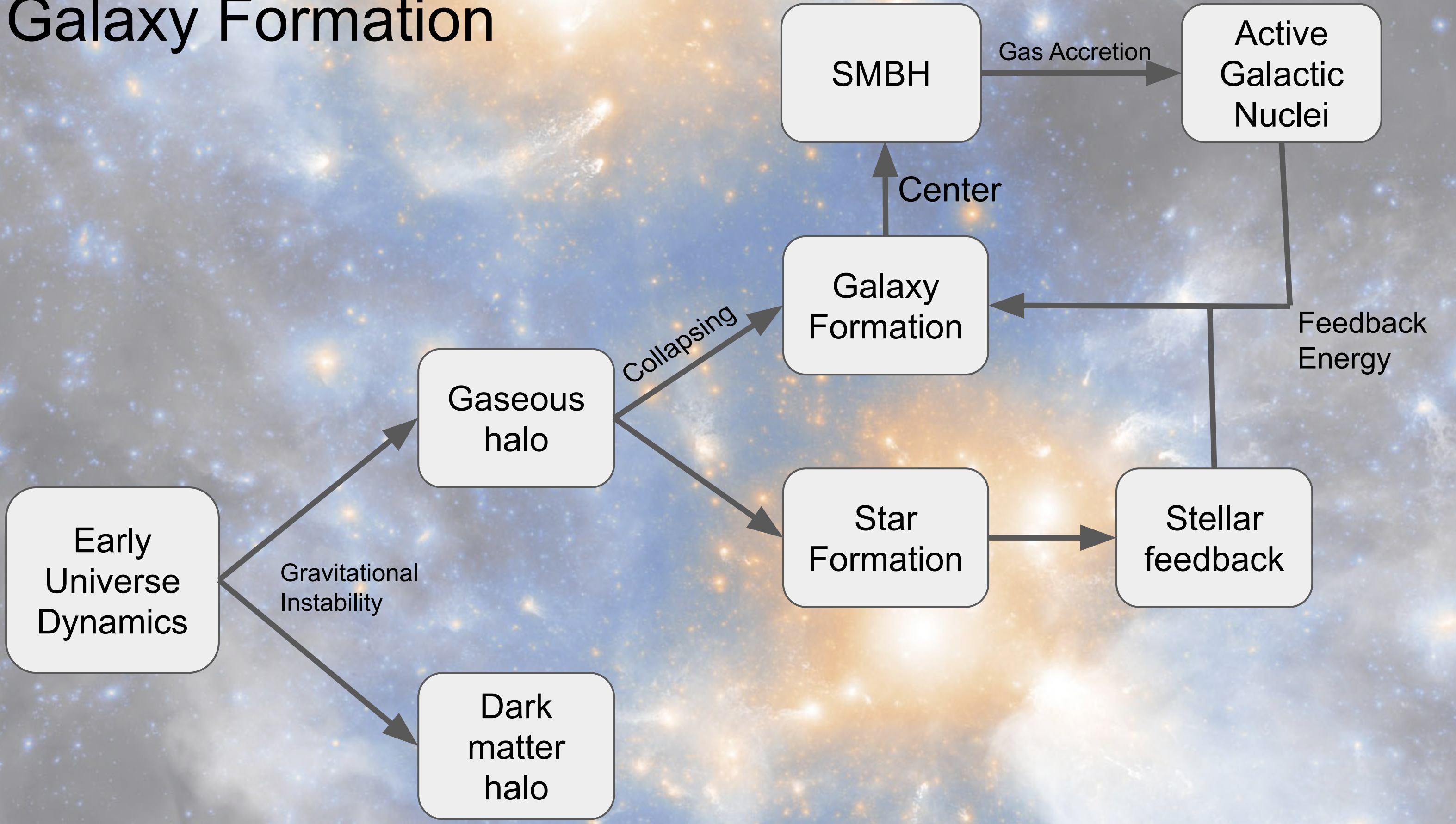
- Most galaxies in the local Universe have a Supermassive black hole (SMBH) at their center.
- SMBH feedback: a fundamental ingredient in modern cosmological simulations of galaxy formation.
- How SMBH impacts on the galaxy formation and evolution?

→ We study this problem by using the Illustris TNG Simulations.

Credit: ESO/NASA/CXC/CfA/WFI/MPIfR/APEX/A.Weiss et al./R.Kraft et al.

2. Theoretical backgrounds

Galaxy Formation



Virial Theorem

Definition

$$2\langle T\rangle + \langle U\rangle = 0$$

Where T is the kinetic energy and U is the gravitational potential energy of the system.

Virial radius

Approximated as the distance where average density exceeds the critical density by a specific factor:

$$p(< r_{vir}) = \Delta_c p_{crit}(t) = \Delta_c \frac{3H(t)^2}{8\pi G}$$

Virial mass

The mass within the virial radius is:

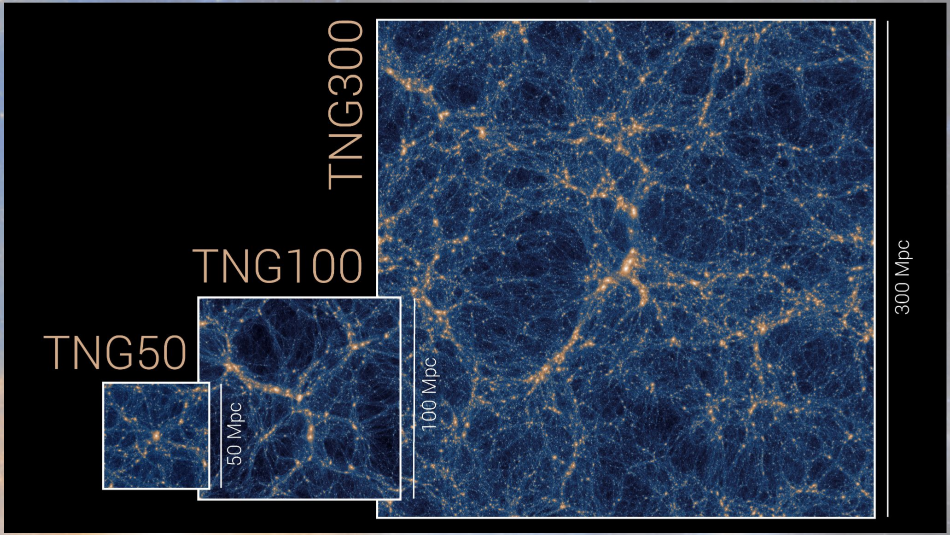
$$M_{vir} = \frac{4}{3}\pi r_{vir}^3 \Delta_c p_{crit}(t)$$

Where H is Hubble parameter, G is the gravitational constant, and factor Δ_c is called overdensity.

3. Data and Methodology

Data

- *IllustrisTNG* is a cosmological magneto-hydrodynamical simulations of galaxy formation.
- We use the simulation TNG100-1 at $z = 0.01$.
- We use R_{200c} and M_{200c} to define a halo boundary and halo mass.
- Sample selection based on central galaxy's stellar mass.



Methodology

Star Formation Rate

Baryon mass fraction

Temperature of gaseous haloes

SMBH and halo mass

Methodology: *Star Formation Rate (SFR)*

Measure SFR and sSFR in the twice half-mass radius and within physical radius of 30 kpc as the function of M_{200c}.

- Specific Star Formation Rate: $$sSFR = \frac{SFR}{M_*}$$

  where M_* is the stellar mass of the subhalo.

- Categorize the galaxies based on sSFR - M_*
  - Star-forming
  - “Green valley”
  - Quenched

Methodology: *Baryon mass fraction*

Measure the baryon including gas, star and black hole mass fraction in R_{200c} as the function of M_{200c}.

- With each i components (gas, star and blackhole), the mass fraction:

$$f_i = \frac{M_i}{M_{200c}}$$

where M_i is the mass of all particles of each component in a defined radius.

- Baryon mass fraction: $f_b = f_{star} + f_{gas} + f_{blackholes}$
- Supposedly galaxies are cosmic "closed boxes", compare with baryonic fraction from Cosmic Microwave Background (Planck 2020):

$$f_{b,cosmic} = 0.157$$

Methodology: *Temperature of gaseous haloes*

Measure the average temperature in R_{200c} as the function of M_{200c}

- Temperature of each gas cell: $T = (\gamma - 1) \times \frac{u}{k_B} \times \frac{UnitEnergy}{UnitMass} \times \mu$

  where μ is the mean molecular weight, γ = 5/3 is the adiabatic index, u is the internal energy, k_B is the Boltzmann constant.

- Mass-weighted temperature: $T_{mw} = \frac{\sum(m_i * T_i)}{\sum m_i}$

  where m_i and T_i are the mass and temperature of the i^{th} gas cell.

- Compare with the virial temperature: $T_{vir} = \frac{\mu m_p}{2k_B} V_{vir}^2$

  where $V_{vir}{}^2$ = GM/R is the virial velocity.

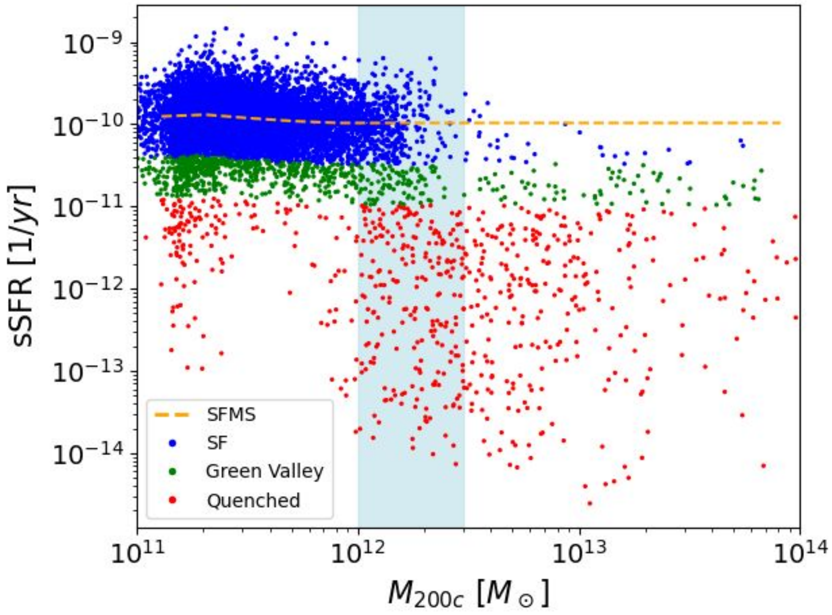
Methodology: *SMBH and halo mass*

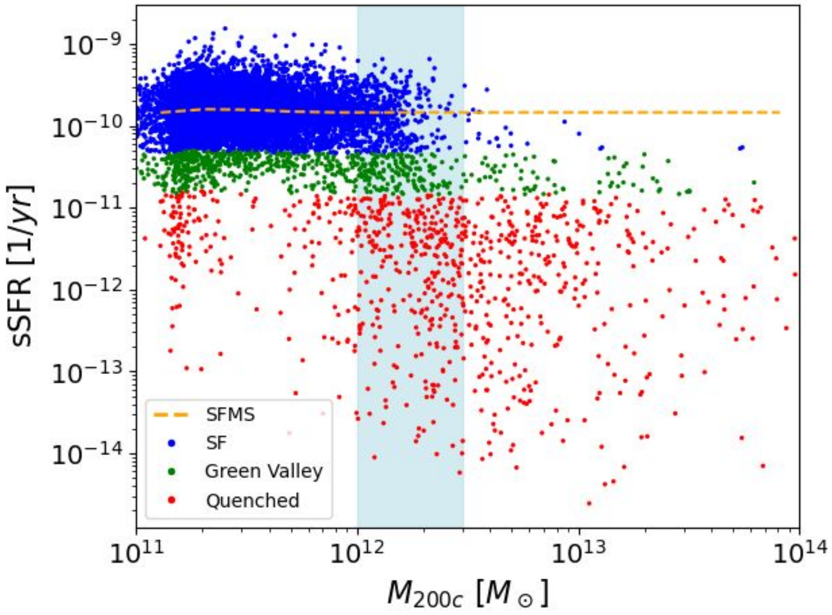
Measure black hole mass M_{BH} of the central galaxies as the function of M_{200c}

- In TNG simulations, SMBH seed masses of $1.18 \times 10^6\ M_\odot$ are planted when halo masses $> 7.38 \times 10^{10}\ M_\odot$
- The distinction between two AGN feedback modes is established by the SMBH's accretion rate:
  - *Thermal mode* is active during high accretion rates
  - *Kinetic mode* is activated at low accretion rates
- Fit data to a single power law in logarithmic space
- Quantify the correlation between the two masses using the Pearson coefficient.

4. Results and Discussion

Results: *Star formation rate*

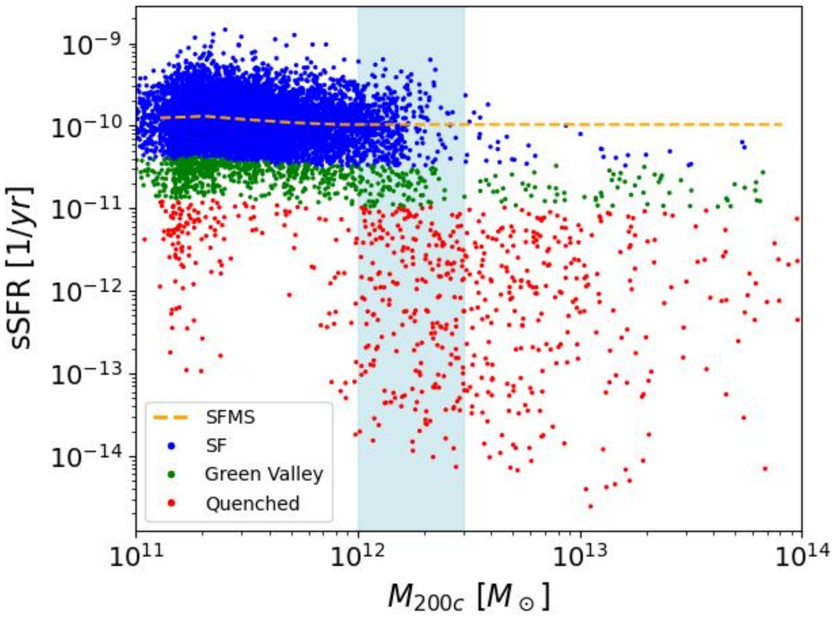




sSFR vs. M_{200c} within 2 times half-mass radius (left) and within a fixed physical radius of 30kpc (right). The orange dashed line represents the star-forming main sequence (SFMS). The blue solid circles show the star-forming galaxies (SF). The green solid circles illustrate the green valley galaxies while the red ones symbolize the quenched (quiescent) galaxies.

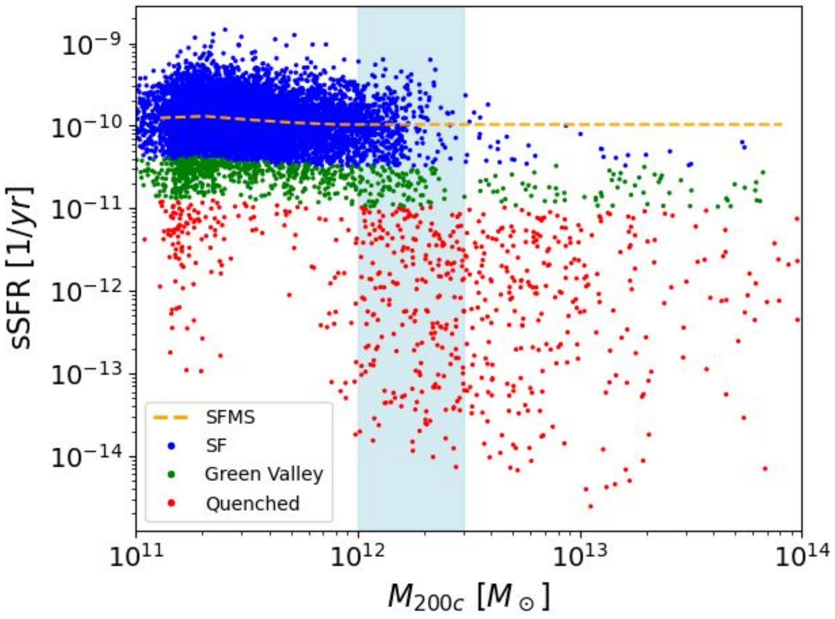
Results: *Star formation rate*

- 10^{11}-$10^{12}\,M_\odot$
  - Robust star formation activities
- SMBH feedback
  - redistributes gas
  - heats up medium
- Above $10^{12}\,M_\odot$
  - the "green valley"
  - transition to less active galaxies

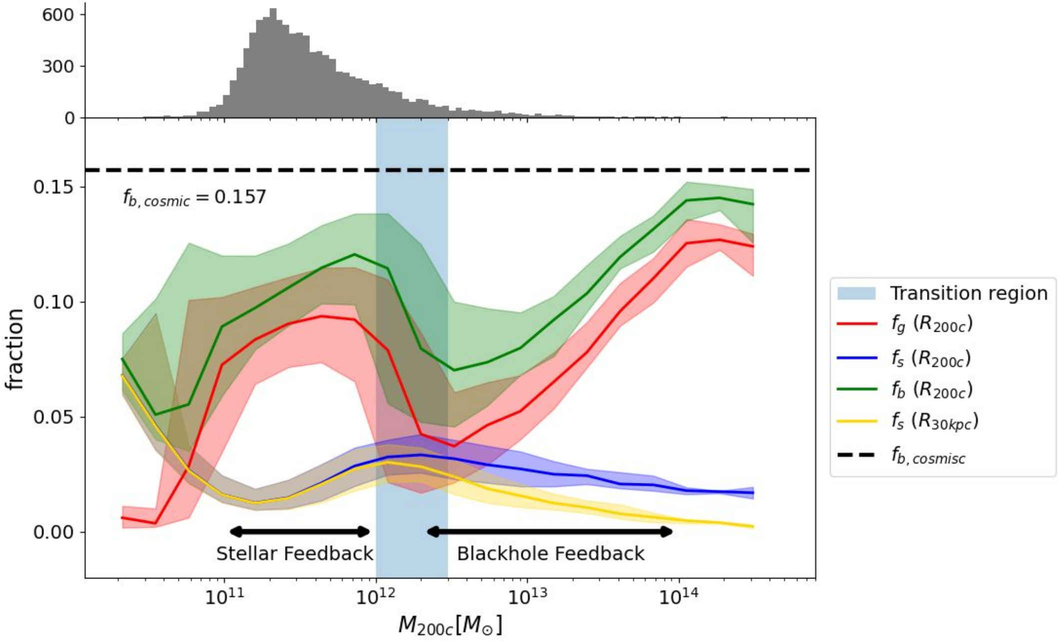


Results: *Star formation rate*

- 10^{11}-10^{12} $M_\odot$
  - Robust star formation activities
- SMBH feedback
  - redistributes gas
  - heats up medium
- Above 10^{12} $M_\odot$
  - the "green valley"
  - transition to less active galaxies
- M_{200c}~10^{12} $M_\odot$
  - quenched galaxies prevail
  - efficient gas regulation



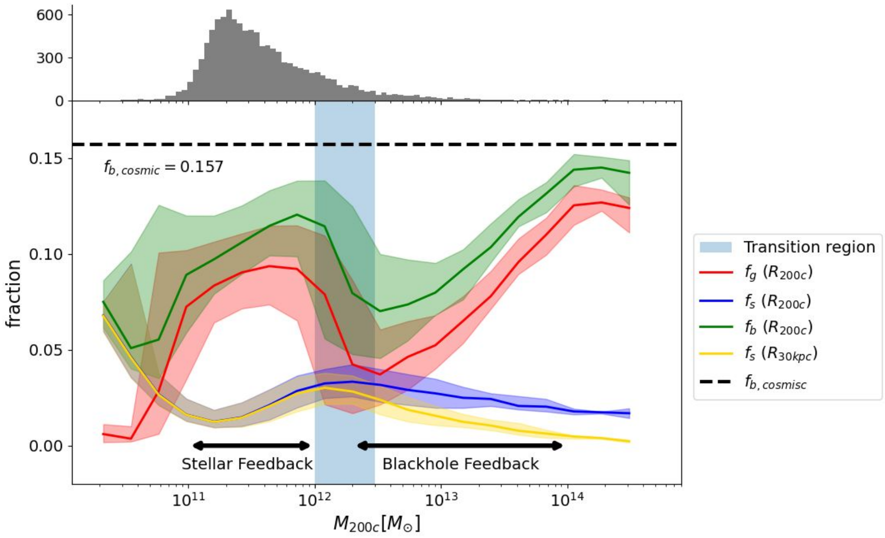
Results: *Baryon mass fraction*



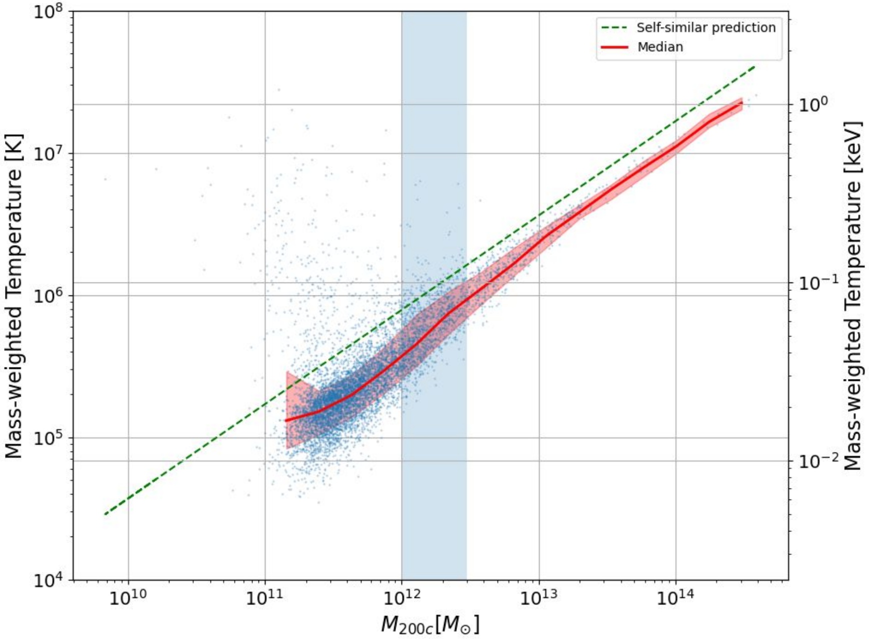
The relation between the halo mass and halo gas, stars and baryon fraction within R_{200c} and stars fraction within 30 kpc. Colored lines represent the median of mass fraction of each components. Shaded areas represent the 16th to 84th percentile. Dashed line shows the observational cosmic baryonic fraction. Top panel: The histogram of M_{200c}. The majority of the selected sample mass falls within 10^{11} to 10^{14} $M_\odot$

Results: *Baryon mass fraction*

- 10^{11}-10^{12} $M_\odot$
  - stellar feedback
  - eject the interstellar gas
  - high SFR
- 10^{12}-10^{14} $M_\odot$
  - AGN feedback
  - push inner gas out
  - low SFR
  - kinetic feedback phase of SMBH
- $> 10^{14}$ $M_\odot$
  - gravitational potential wells
  - $f_b \sim f_{b,\ cosmic}$



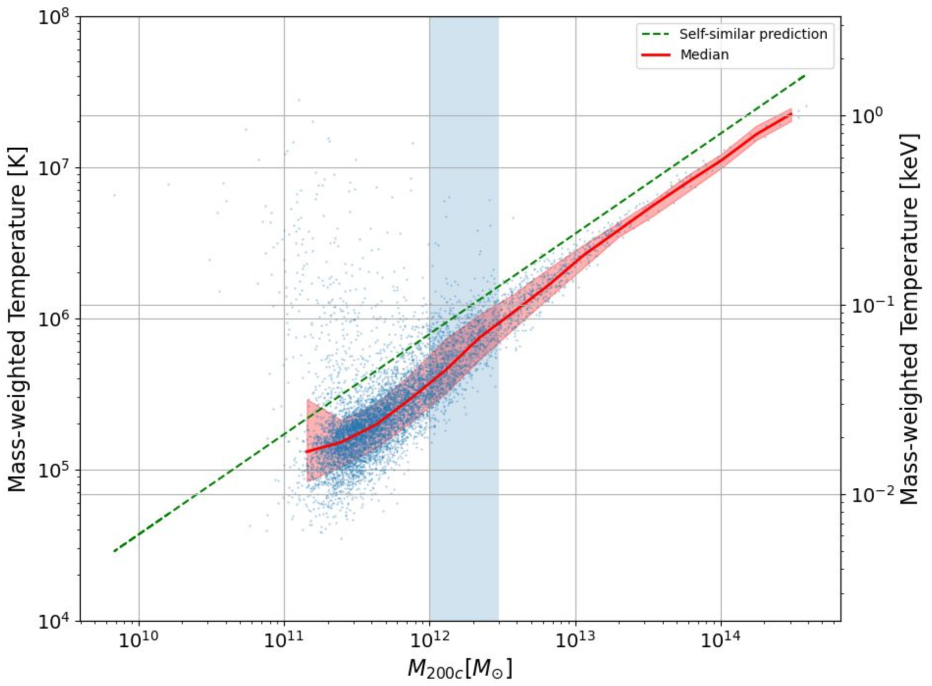
Results: *Temperature of the gaseous haloes*



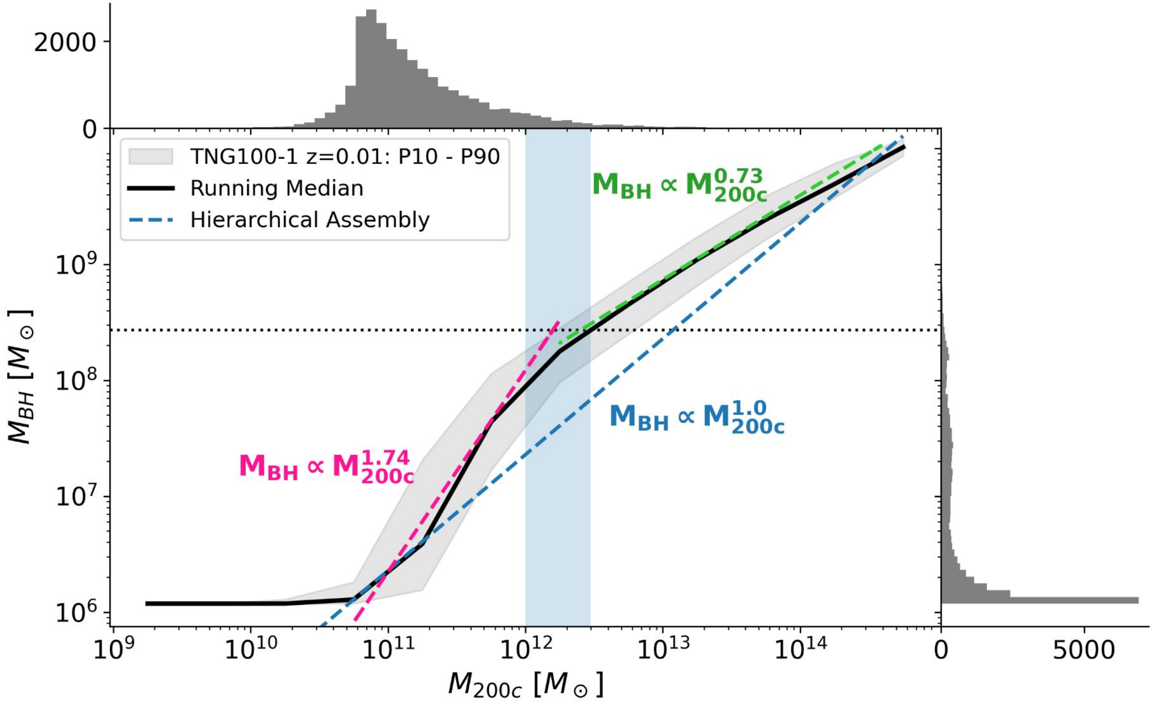
Comparison between T_{vir} vs M_{200c} and T_{mw} vs M_{200c}. The data points represent the mass-weighted temperature of each galaxies. The red line represents the median value of the galaxies' temperature as a function of M_{200c}. The green dashed line is the relation between virial temperature of galaxies and their virial mass.

Results: *Temperature of the gaseous haloes*

- Thermal Properties and Total Mass:
  - **Strong increasing relation**
- Temperature of haloes > prediction: SMBH feedback (Davies et al. 2019).
  - **Potential cooling effect**
- Outliers and Feedback Impact:
  - Small galaxies
  - Halo mass↗: Feedback from stars and SMBHs ↘



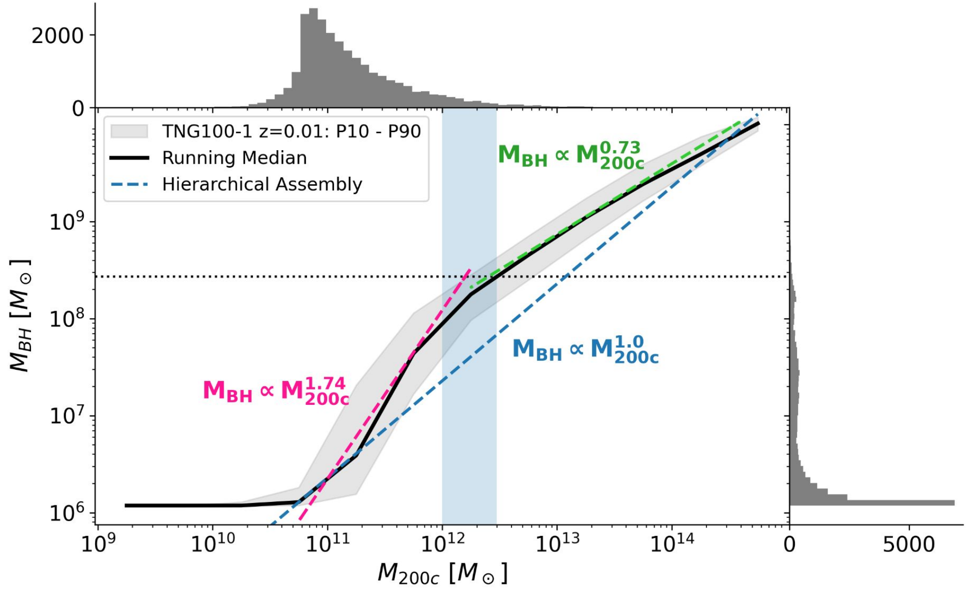
Results: *The relationship between SMBH and halo mass*



Growth of SMBHs mass in the TNG100-1 simulation. The pink and green dashed lines are best fit lines showing the data's slopes in the second and third phases, while the blue dashed line shows the SMBH - halo mass scaling relation by the hierarchical assembly through galaxy merging.

Results: *The relationship between SMBH and halo mass*

- First phase:
  - Seed mass planted
  - **Minimal growth** due to stellar feedback
- Second phase:
  - Counteraction from gravitational forces
  - Radiative cooling
  - → **Rapid expansion**
- Third phase:
  - Thermal → Kinetic feedback → efficient expulsion of gas
  - → **Growth decline**
  - Hierarchical assembly.



5. Summary and Conclusions

Summary and Conclusions:

The project focuses on investigating the influence of SMBH feedback on the baryonic components of galaxies at the present epoch (z~0) using simulated data from the IllustrisTNG simulations.

- The study of the correlation between sSFR and M200c in the crowded region of 10^{11}-10^{12} $M_\odot$ revealed a dynamic stage of star formation up to 10^{12} $M_\odot$, beyond which star formation declines, leading to quenched galaxies dominating.
- A relationship between baryon mass fraction and halo mass is identified, with stellar and AGN feedback playing significant roles in different mass ranges.
- The connection between temperature and halo mass shows convergence towards theoretical predictions, suggesting a cooling effect on the halo.
- The evolution of SMBHs in simulations reveals three phases, highlighting the influence of feedback mechanisms on SMBH growth.

THANK YOU FOR LISTENING