



X-ray Signatures of the Hot Circumgalactic Medium in IllustrisTNG

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Circumgalactic Medium : How to probe?

I. What is Circumgalactic Medium (CGM) ?

- Diffuse gas surrounding a galaxy
- Reservoir of matter and energy
- Multiphase (hot & cold) ionization structure
- complex dynamics

"It fuels **star formation** & **regulates** feedback in galaxy."

II. How to probe CGM?

1. We focused on hot ($T > 10^6$ K) components of the CGM surrounding low-redshift ($z < 1$) galaxies. → tSZ, X-ray, FRB
2. Multiwavelength observation is crucial in astronomy.

We characterized X-ray signature of hot CGM through cosmological simulation.

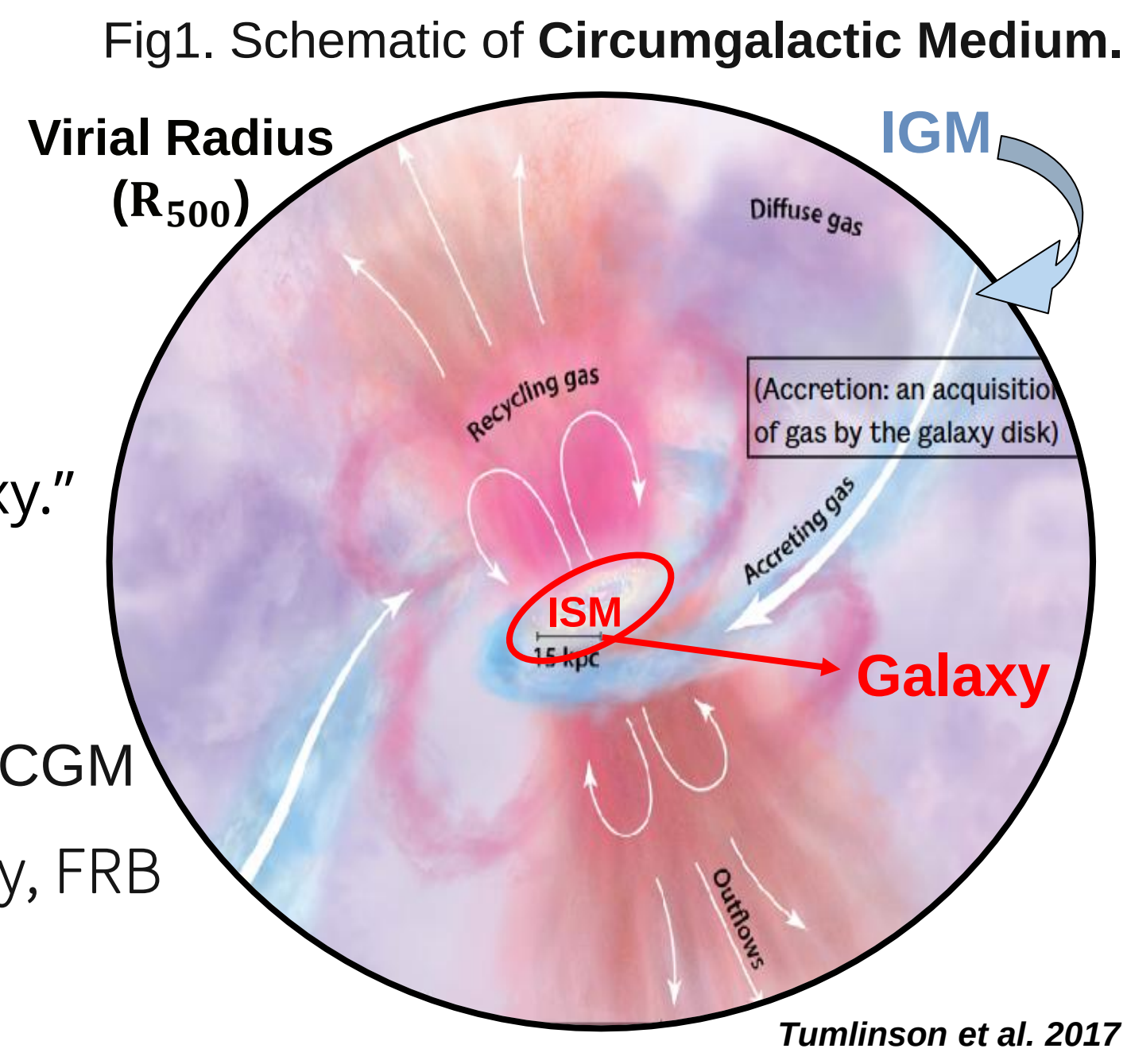
III. Brief introduction

We selected galaxies in IllustrisTNG 100-2 and classified them for population study. (Sec 2)

- Classification : **Quiescent (QU)**, **Star-forming (SF)** and **Transitional** galaxy.

We modeled X-ray emission to calculate X-ray luminosity (L_X) by using Astrophysical Plasma Emission Code (APEC) via PyAtomDB. This is used for the following:

- 1) **Scaling relation** with mass & star formation rate (SFR) to find correlation.
- 2) **Radial profile** to find gas property dominantly influencing.
- 3) **Evolution history** to answer how CGM changes as its galaxy evolves.
- 4) **Causal inferences** through machine learning to find main physical driver.



Tumlinson et al. 2017

Galaxy selection & classification

I. How to get galaxy in the IllustrisTNG 100-2

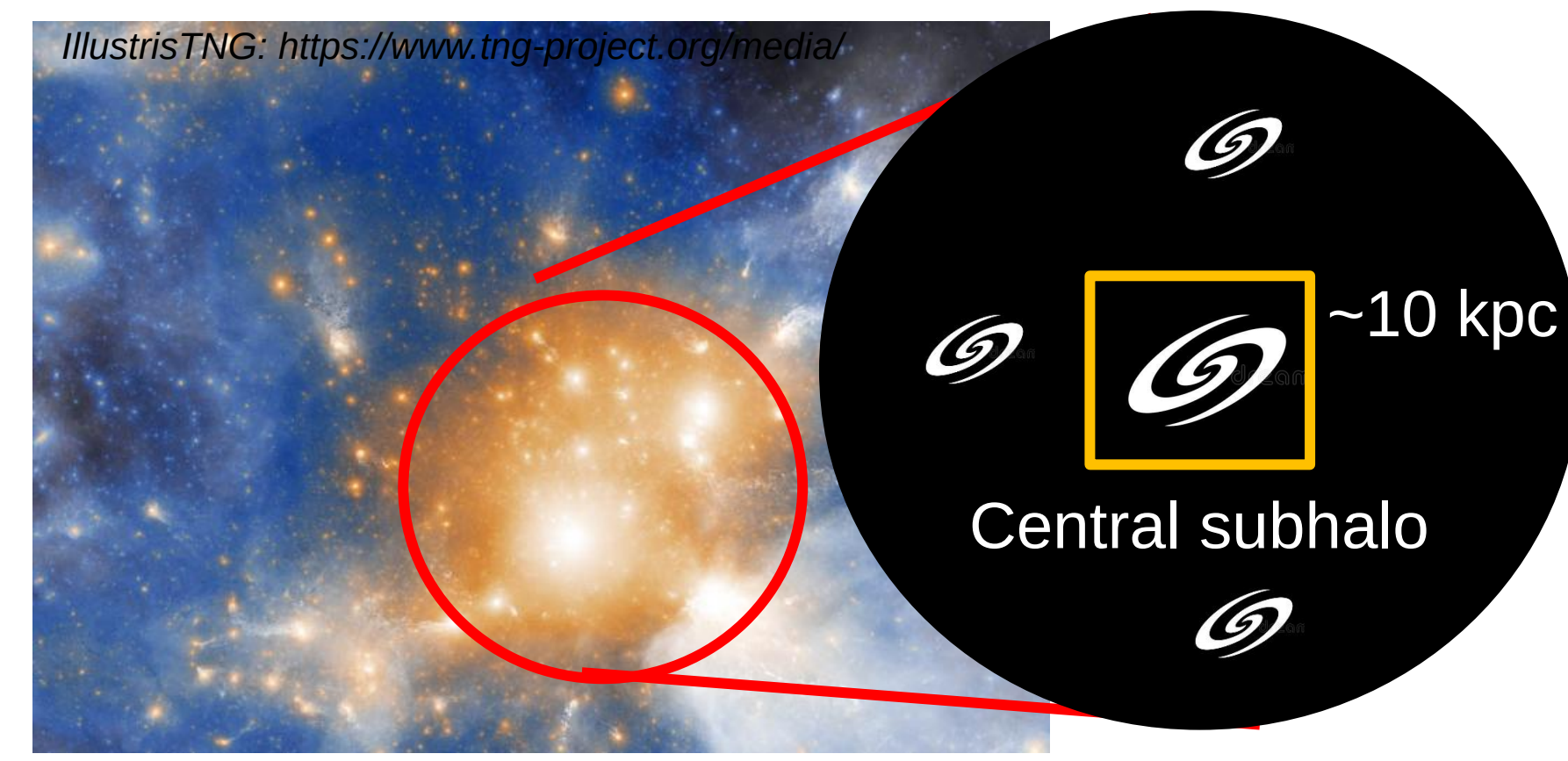
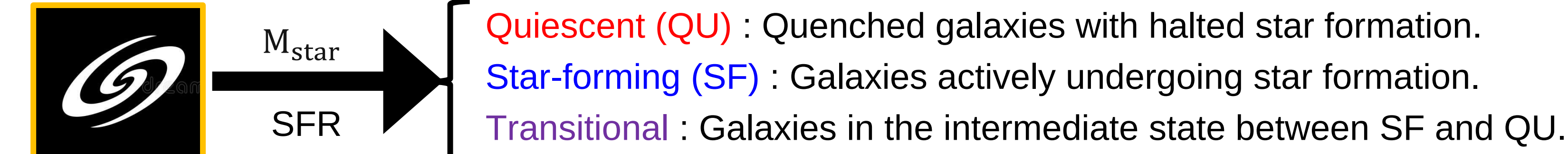


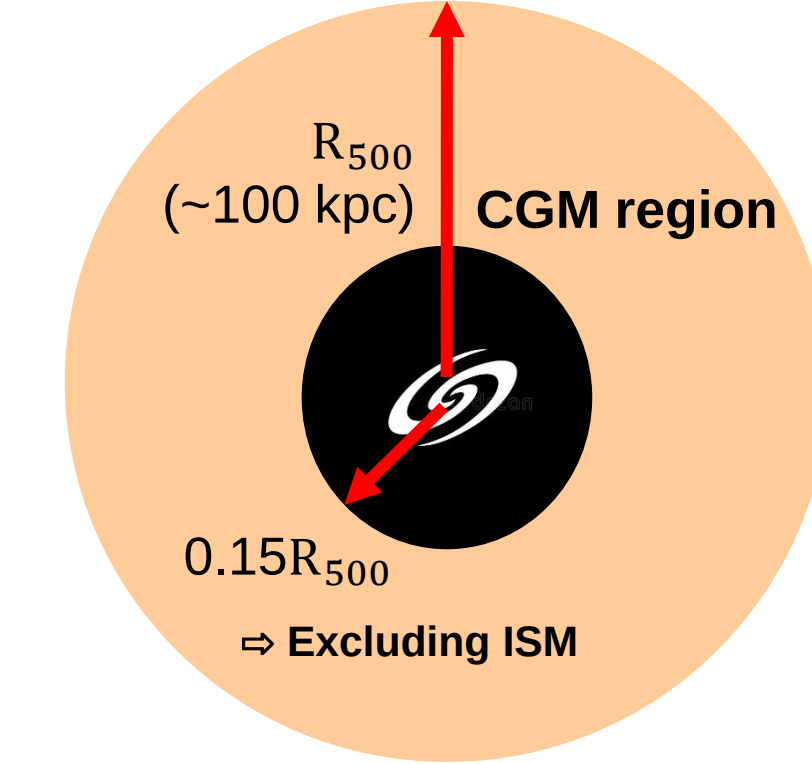
Fig 2. Visualizing dark matter halos (orange) within massive galaxy groups(left) and dark matter halo (Right)

II. Galaxy Classification & X-ray emission modeling



Target Galaxy ($z = 0, 0.1$ & 0.2) $N = 29665$

Soft X-ray luminosity (0.5 – 2.0 keV) of a gas cell through equation.



$$L_X = \sum_i n_e n_H \epsilon_E(T, Z)_i E_i V$$

$n_e(n_H)$: Electron (hydrogen) number density

$\epsilon_E(T, Z)_i$: Interpolated emissivity at energy bin E_i

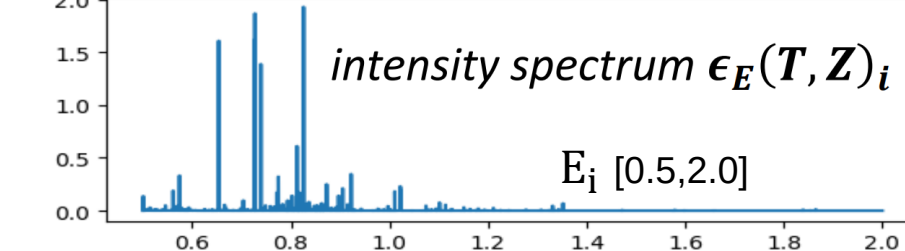


Fig 3. Schematic of CGM in our study.

We included gas cells within $0.15 < r/R_{500} < 1.0$ from the center.

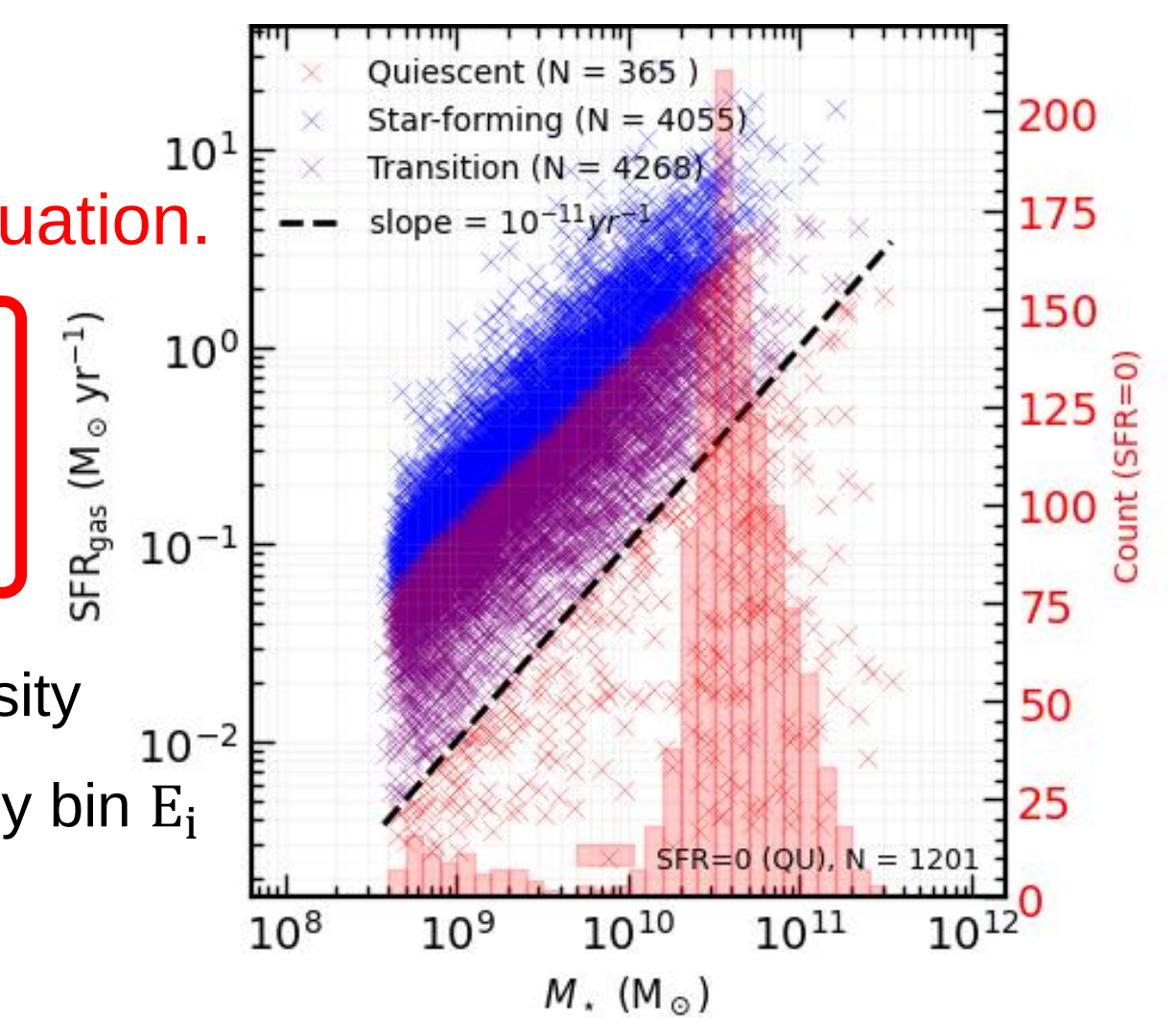


Fig 4. Galaxy classification at $z = 0$ by using SFR & stellar mass of CGM.

Scaling relation ($Y \propto X^\alpha$) & Radial Profile

I. Scaling relation with mass (M_{500}) & SFR

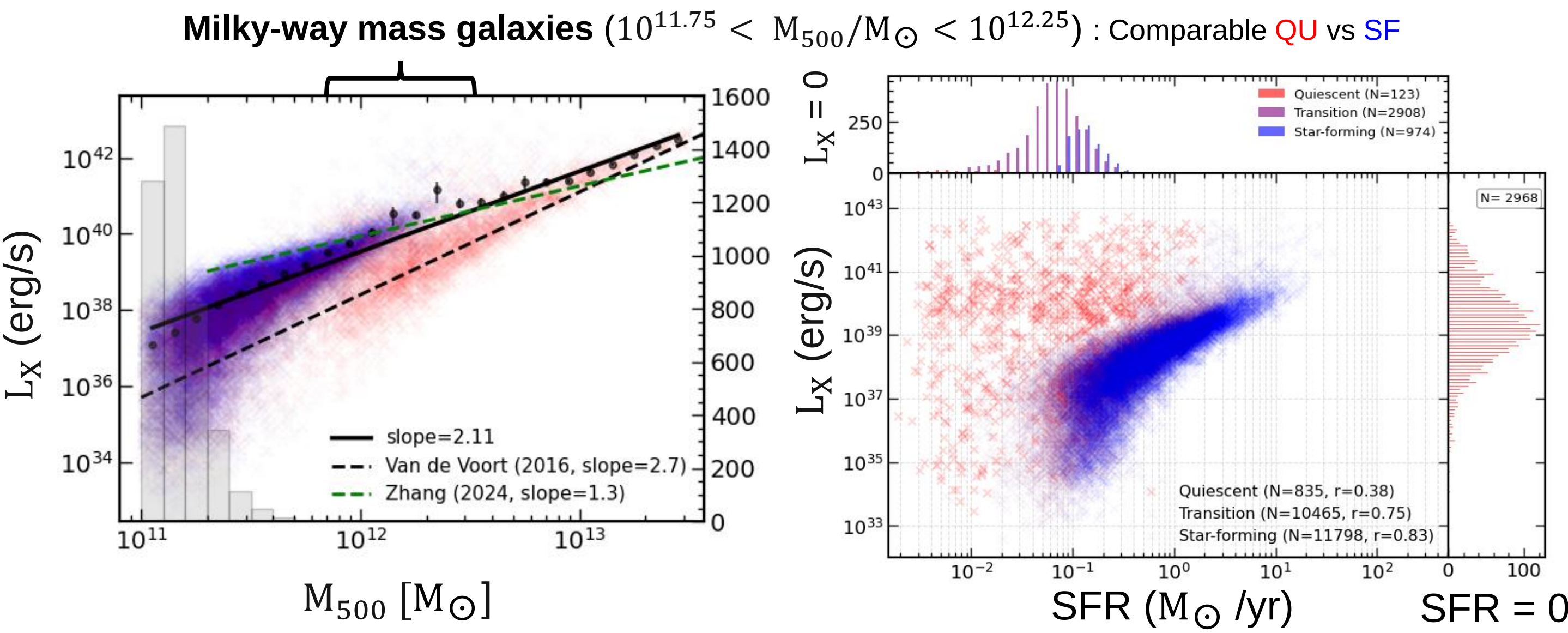


Fig 5. Scaling relation between L_X and M_{500} . α of total galaxies is 2.11 (left) . Scaling relation between L_X and SFR. While **SF** shows high correlation ($r = 0.83$), **QU** has significantly weaker ($r = 0.38$) (right)

1. Our $L_X - M$ relations show better agreement with **observational data** compared to previous simulation-based studies.
2. Scaling in **QU** ($\alpha = 2.11$) & **SF** ($\alpha = 2.78$) show distinct differences which supports their group characteristic.
3. For group with high sSFR ($=SFR/M_{star}$) like **SF**, L_X has high correlation with SFR.
4. Process related to SFR (e.g. stellar feedback) plays a significant role in governing the L_X budget beyond the primary mass dependency.

II. Radial profile of Milky-way(MW) mass galaxies.

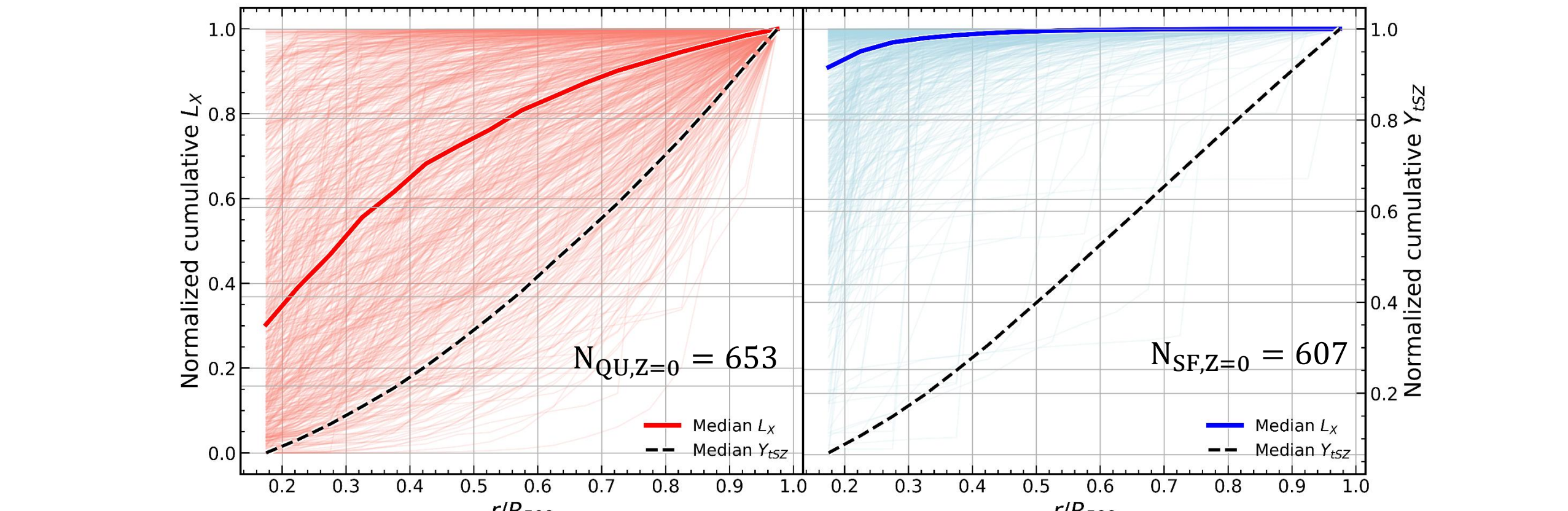


Fig 6. Comparison of cumulative L_X from **QU** & **SF** galaxies (right) shows centrally concentrated X-ray emission compared to **QU** galaxies (left).

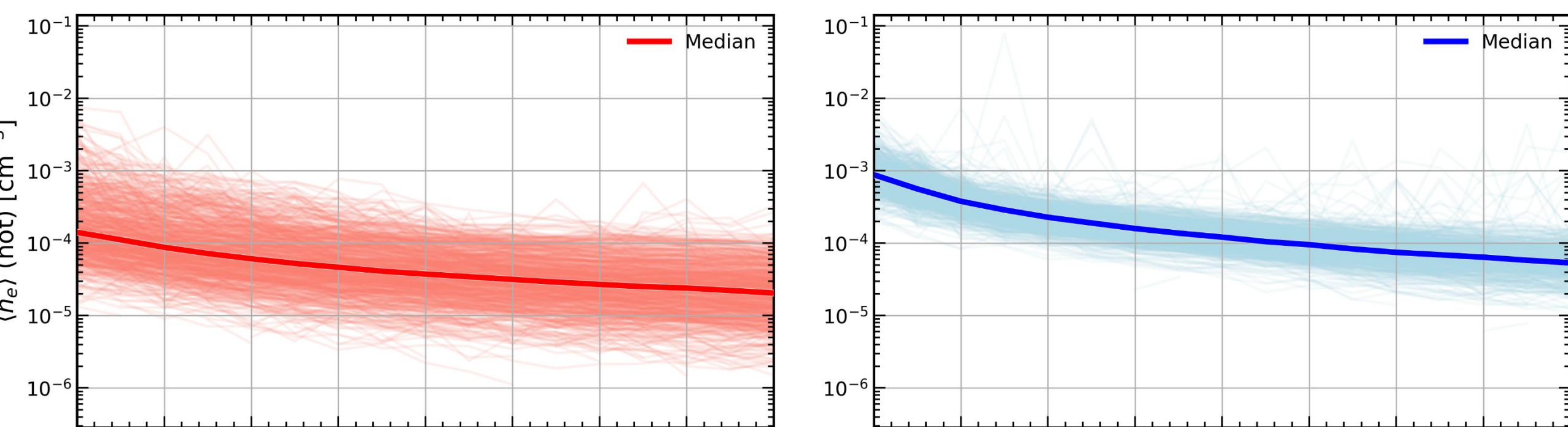


Fig 7. Radial profile of gas number density of **QU** (left) and **SF** (Right).

1. We analyzed radial X-ray emission profile of MW mass galaxy to exclude dominant mass dependency.
2. We found that X-ray emission in SF is highly concentrated to its center.
3. This difference of galaxy sample originate from its radial gas density distribution.

References

[1] Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197 [2] Battaglia, N., et al. 2019, arXiv:1903.04647 [3] Chadayammuri, U., Bogdan, A., et al. 2022, MNRAS, 511, 1234 [4] Kim, J., et al. 2022, ApJ, 926, 179 [5] Lovisari, L., et al. 2021, A&A, 649, A89 [6] Tumlinson, J., et al. 2017, ARA&A, 55, 389 [7] van de Voort, F., et al. 2016, MNRAS, 466, 3810 [8] Zhang, Y., et al. 2024b, A&A, 690, A267

Evolution history & causal Inference through ML

III. Evolution history of MW mass galaxy

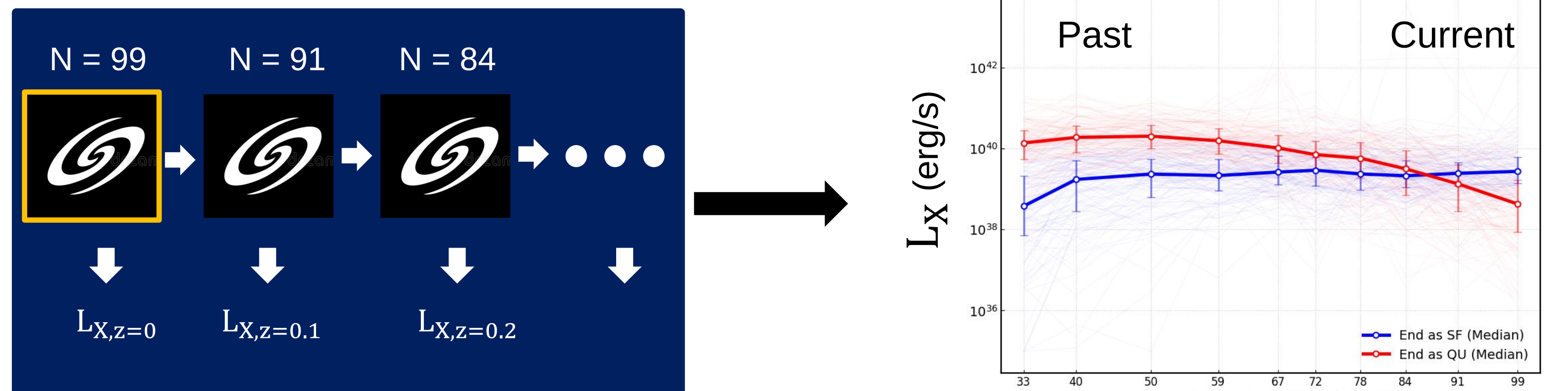
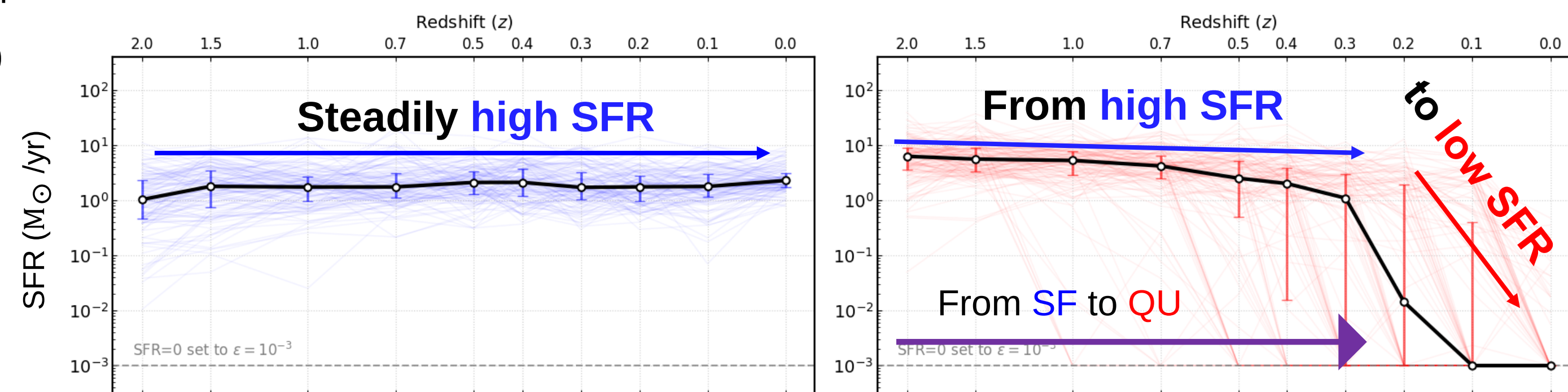
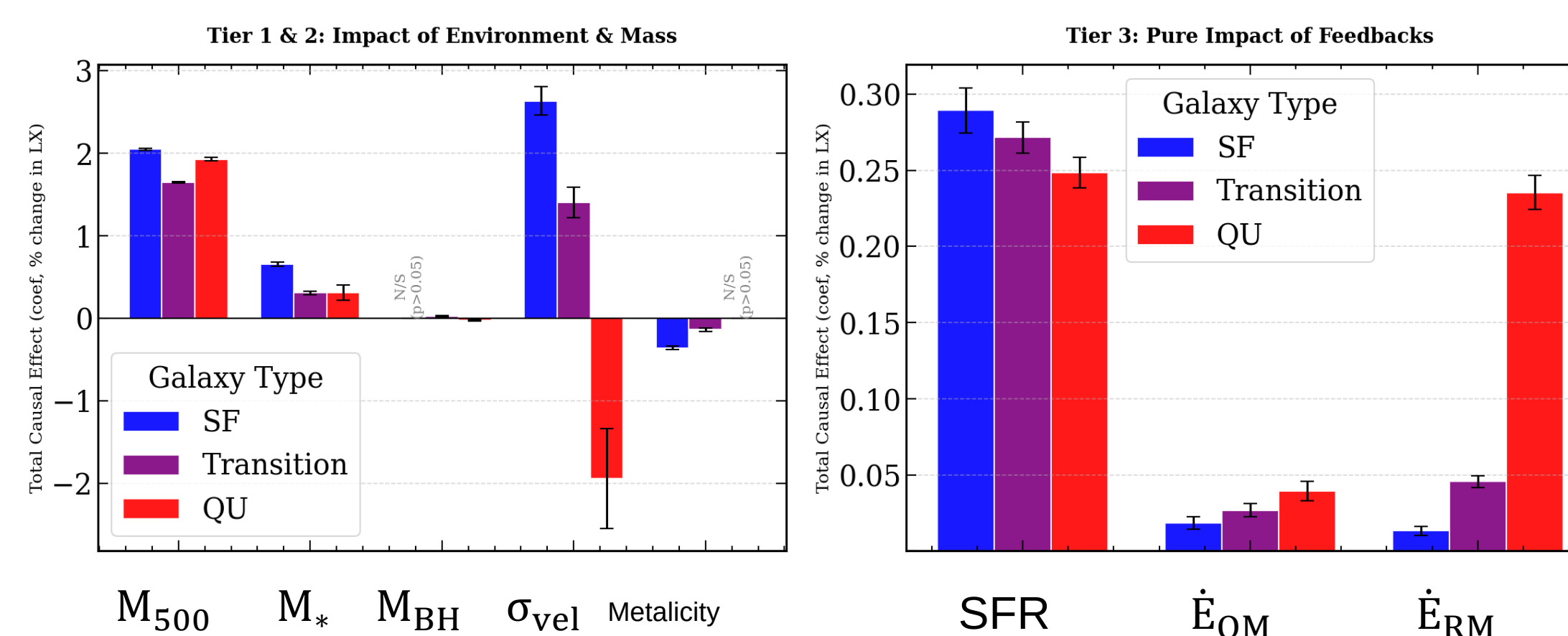
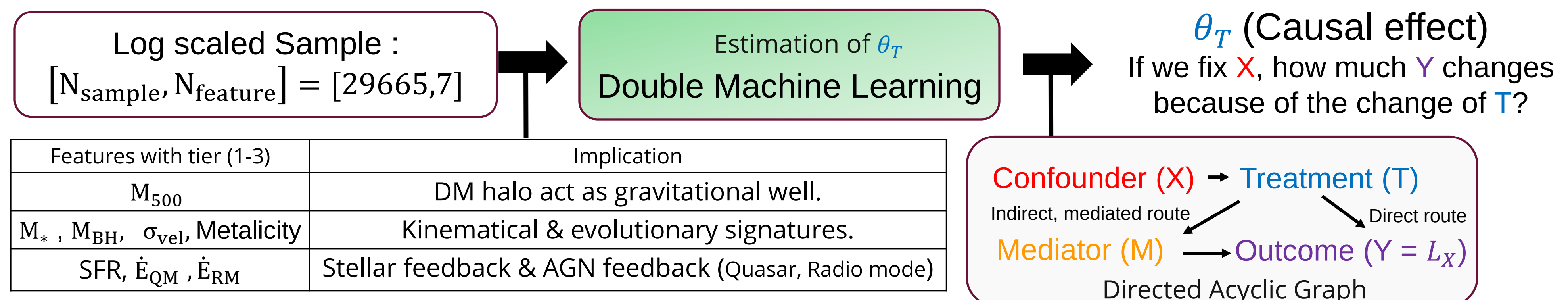


Fig 8. Finding progenitor(previous) galaxy in simulation through merger tree (left) and time evolution of L_X showing distinct difference between **QU** & **SF** (right).



IV. Causal inferences with Double Machine Learning



1. For halo mass, $\theta_{T=M_{500}} \sim 2.0$ which is consistent with our initial result (See fig 5)
2. Although $\theta_{T=\sigma_{vel}}$ is huge, it should be understood carefully since the scale of σ_{vel} is small.
3. SFR or stellar feedback is shown to play an substantial role for all galaxy population.

Summary & Conclusion

1. **CGM** is a critical for understanding galaxy evolution. We used **X-ray** to get insight of its complex nature.
2. Distinct **scaling relations** supports the significance of baryonic process & **different characteristics** of **QU**, **SF**.
3. **Radial profile** analysis reveals that **gas density is the primary driver** of X-ray emission.
4. In **evolutionary history**, high L_X in the progenitors of present-day **QU** highlights the **lasting impact of feedback**.
5. Through **Causal Inference**, mass plays an crucial role while **SFR still has substantial contribution** to L_X .

The hot CGM is not just a passive gas reservoir, but a dynamic record of a galaxy's feedback and evolutionary history.