

X-ray Signatures of the Hot Circumgalactic Medium in IllustrisTNG

Minjae Kim¹ & Junhan Kim¹

¹Department of Physics, Korea Advanced Institute of Science and Technology (KAIST)

heromj27@kaist.ac.kr

What is Circumgalactic Medium (CGM)?

Definition: Diffuse gas surrounding a galaxy

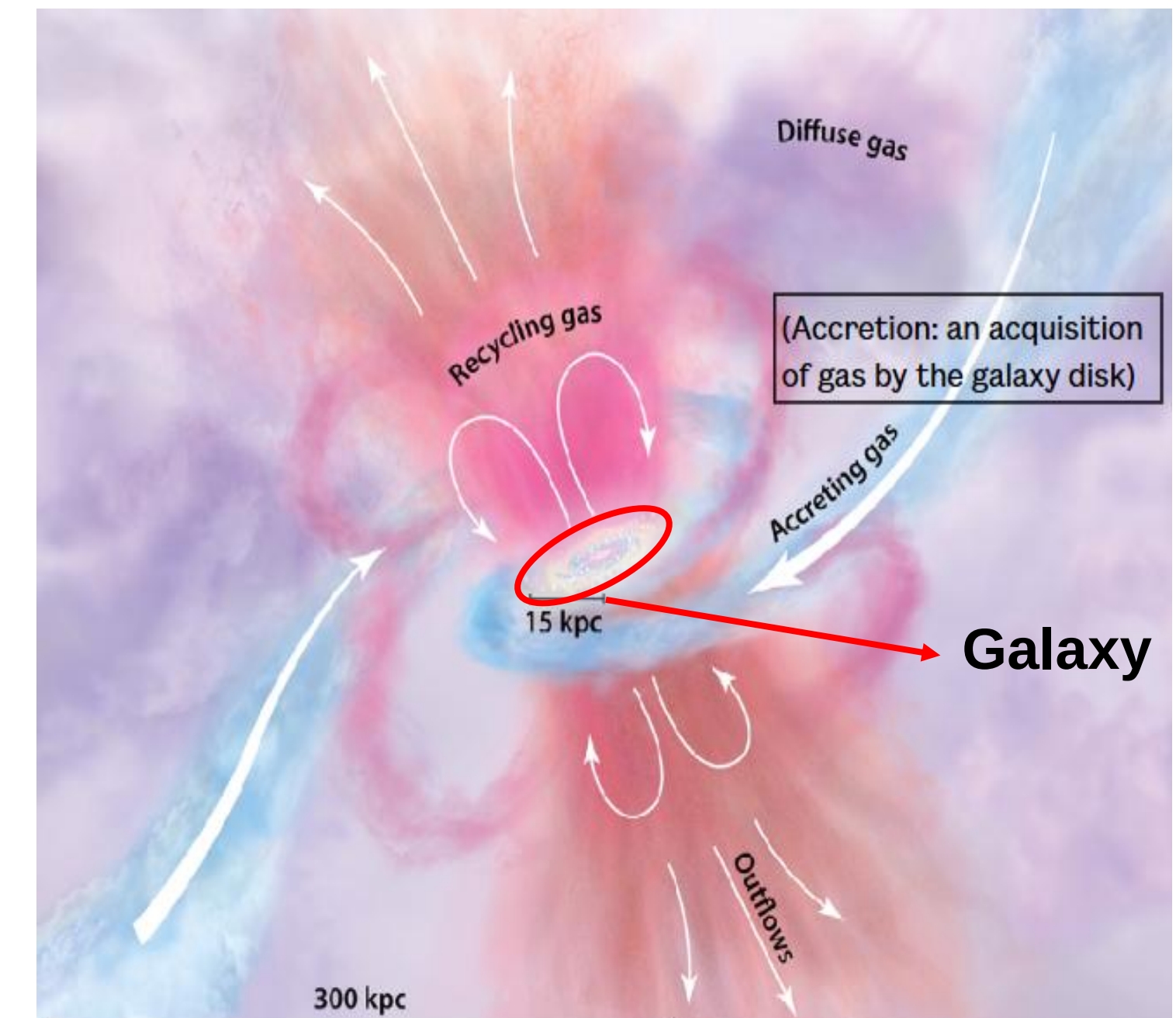
- Reservoir of matter and energy
- Multiphase ionization structure & complex dynamics
= Consists of both hot & cold gas components

Q. Why do we study the CGM?

- It fuels **star formation** and **regulates** feedback processes in galaxies

“ Understanding the baryonic physics that governs galaxy evolution ”

Schematic of Circumgalactic Medium



Tumlinson et al. 2017

Feedback processes : self-regulating mechanism where energy and momentum from stars and black holes are injected back into the surrounding gas.

How to probe the CGM?

Focusing on the hot ($T > 10^6$ K) components of the CGM surrounding galaxies.

Local ($z < 1$)

+

Gas around galaxy

Target Regime : Low-redshift galaxies

Optimal observation tool : tSZ, FRBs and X-rays

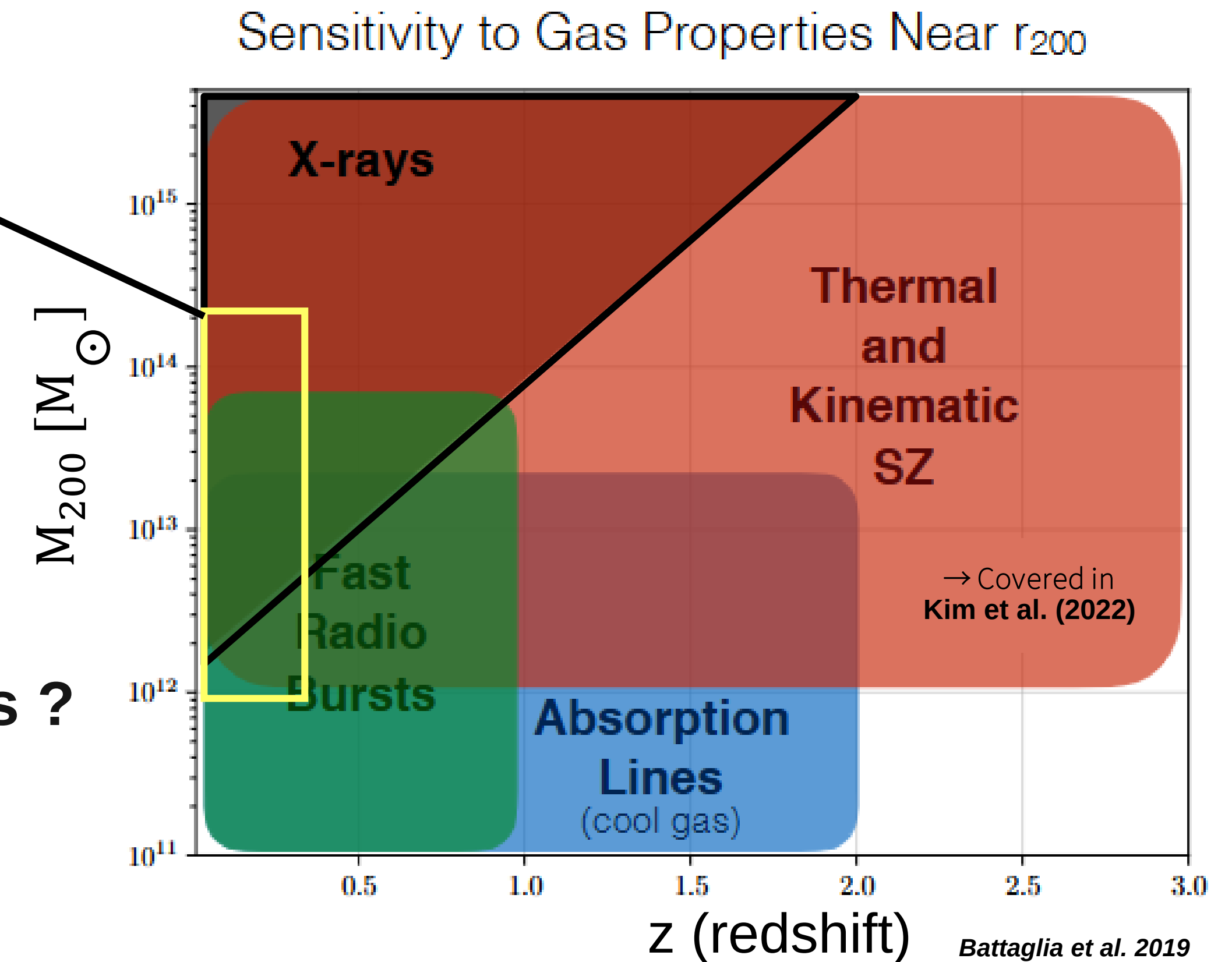
Kim et al. 2022 studied CGM by using tSZ effect.

- Multiwavelength study is crucial in astronomy.
- How about transitioning from tSZ to **X-ray signatures** ?

FYI



Research goal : Characterizing X-ray signatures of the hot CGM



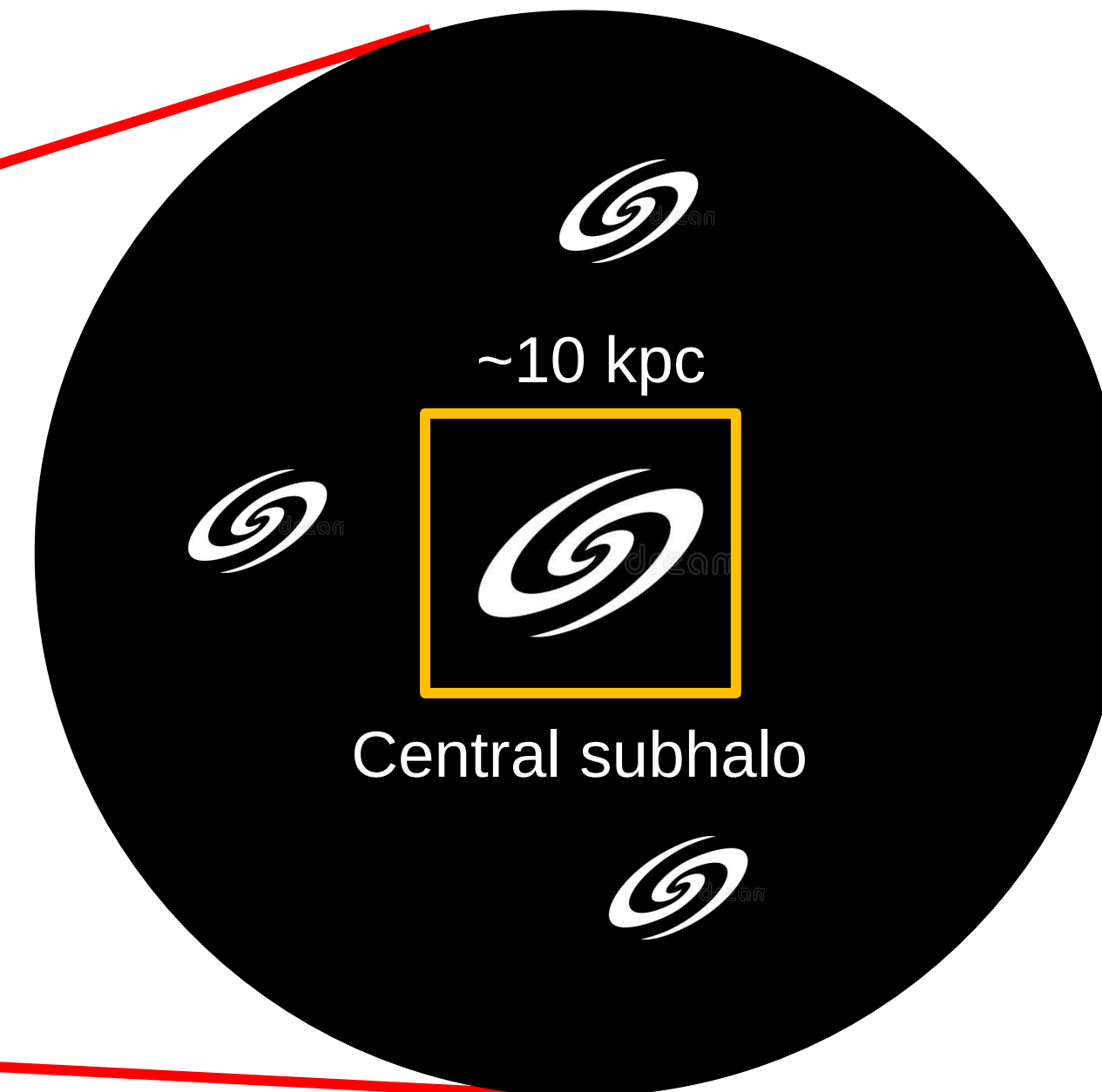
Galaxy Sample Selection & Classification

Numerical Tool: IllustrisTNG 100-2 cosmological magnetohydrodynamic simulations.

IllustrisTNG: <https://www.tng-project.org/media/>



Visualizing dark matter halos (orange)
within massive galaxy groups.



Central subhalo

Dark Matter Halo

Identify central subhalo as
primary targets

Mass Range: $10^{11} < M_{500}/M_{\odot} < 10^{13.5}$

IllustrisTNG 100-2 : sophisticated cosmological simulation used to model the complex physics of gas and dark matter that shapes the galaxies

Galaxy Sample Selection & Classification

Classification: Categorizing galaxies into three distinct populations based on star formation activity.

Target Galaxy



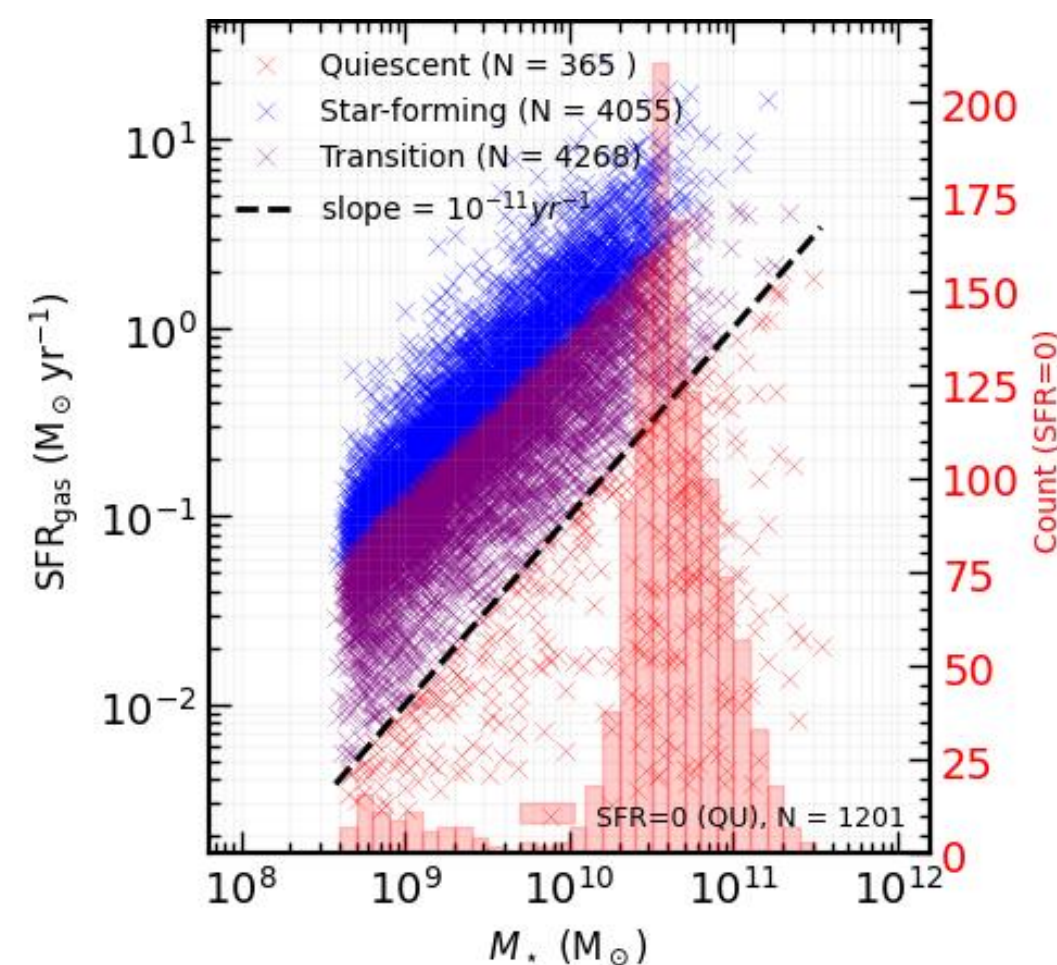
M_{star} & Star Formation Rate (SFR)

Quiescent (QU) : Quenched galaxies with halted star formation.

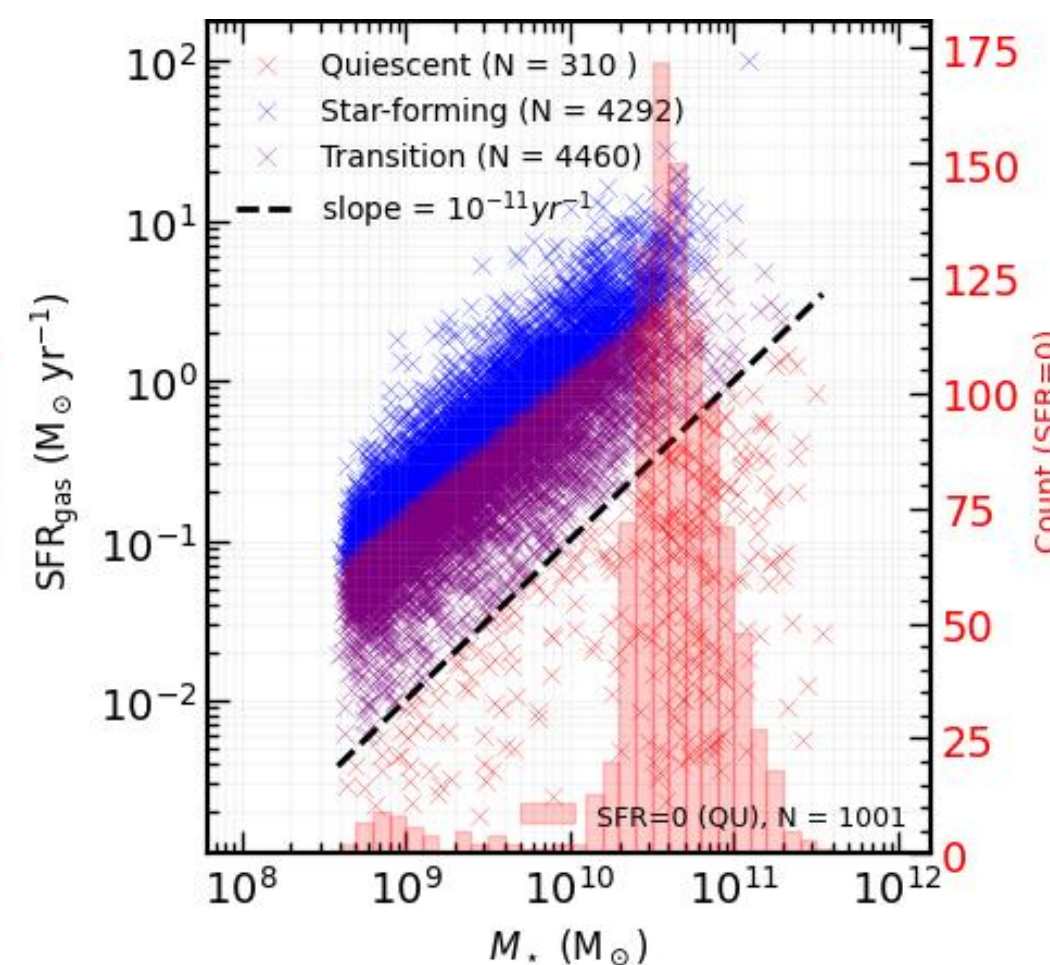
Star-forming (SF) : Galaxies actively undergoing star formation.

Transitional : Galaxies in the intermediate state between SF and QU.

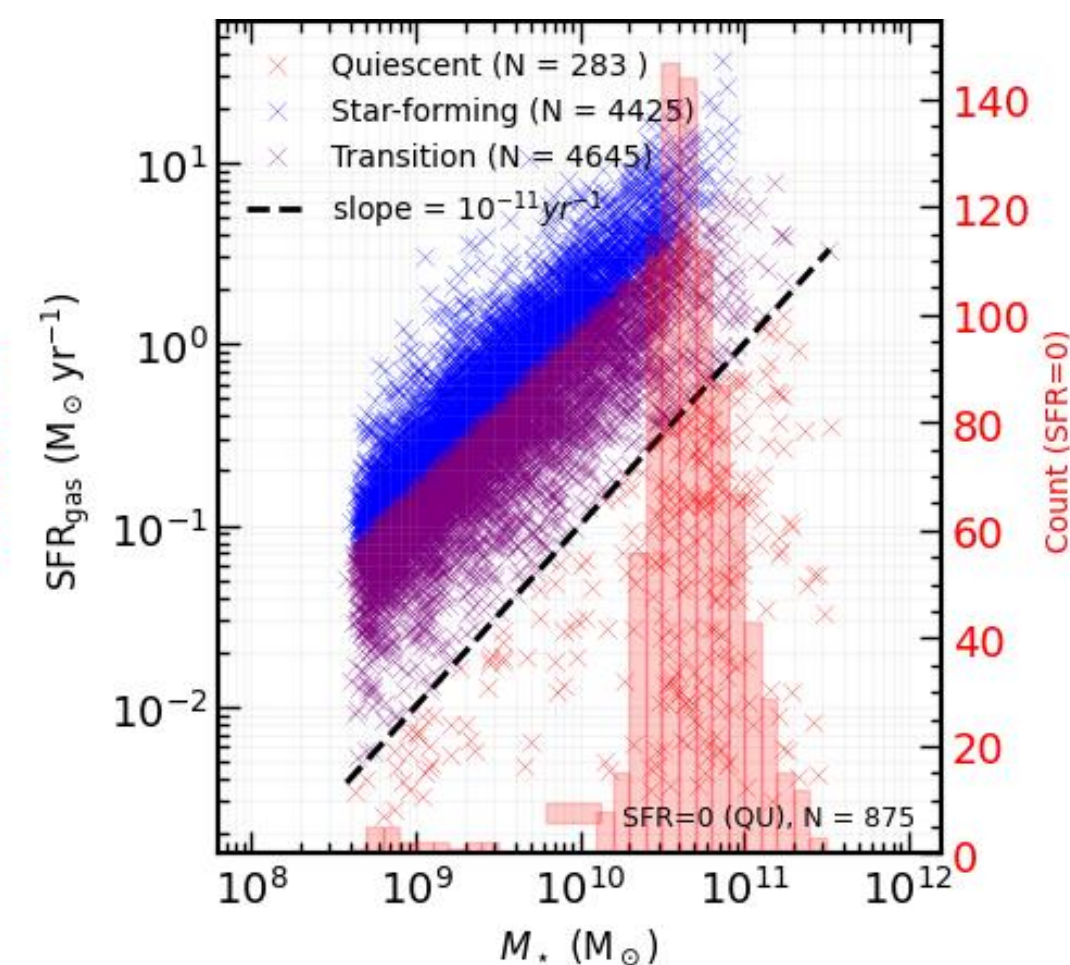
SFR = How much solar masses of stars are formed per year?



Redshift = 0



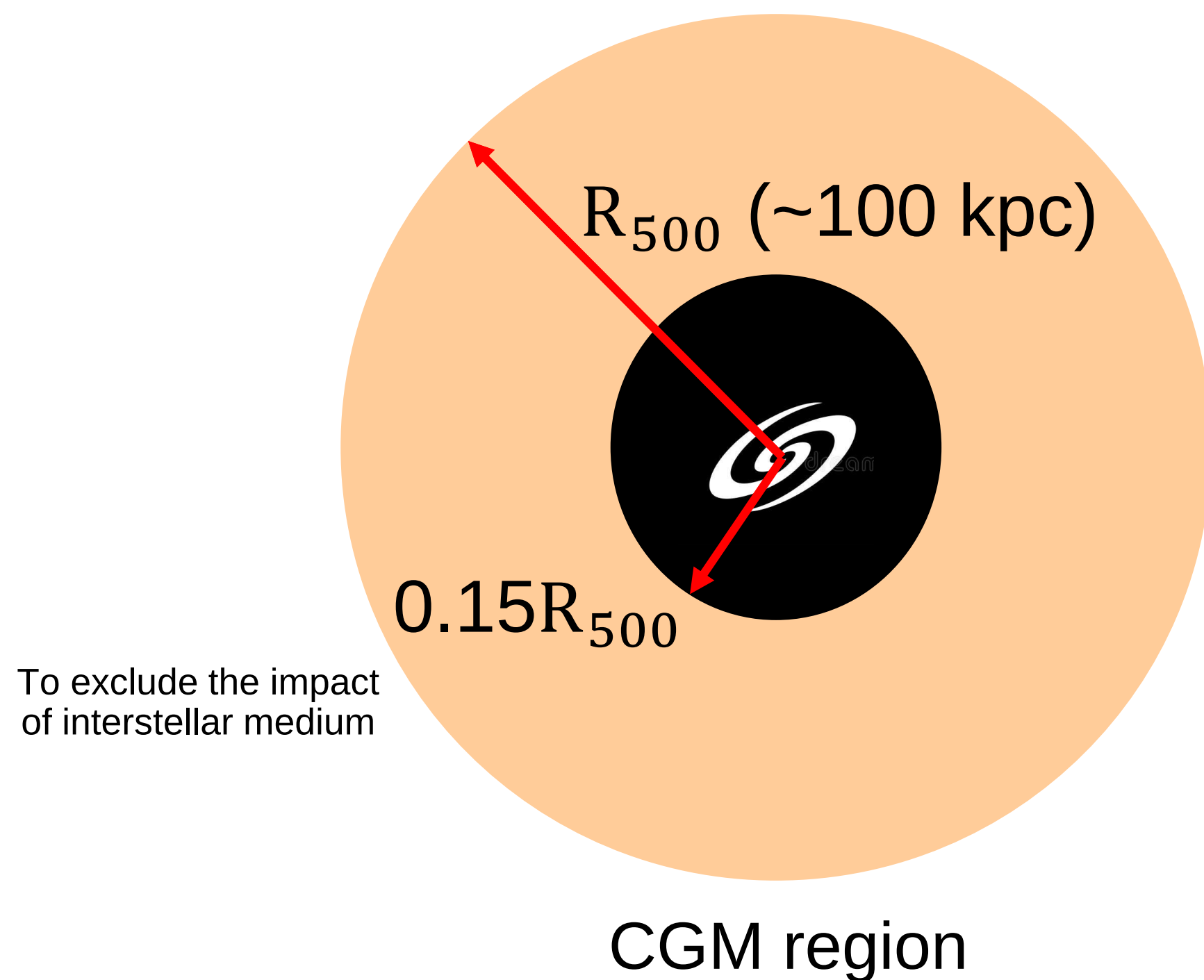
Redshift = 0.1



Redshift = 0.2

CGM Gas X-ray Emission Modeling

Spatial Definition of the CGM: Including gas cells within $0.15 < r/R_{500} < 1.0$ from the center.



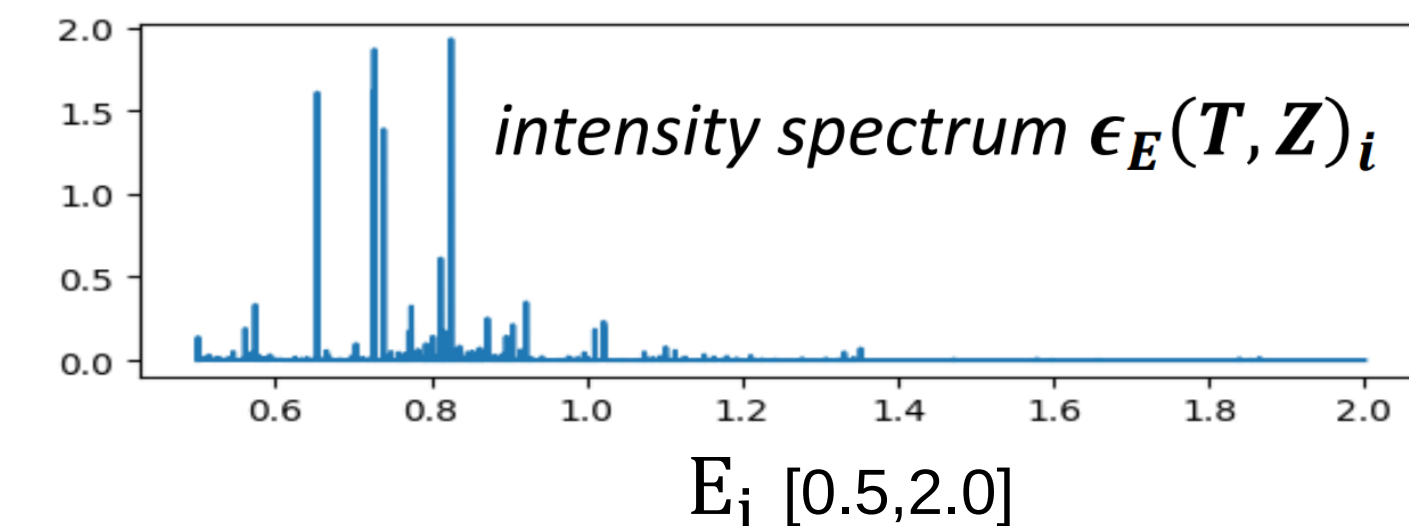
Modeling soft X-ray luminosity (0.5 – 2.0 keV) of single gas cell is :

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

n_e : electron number density

n_H : Hydrogen number density

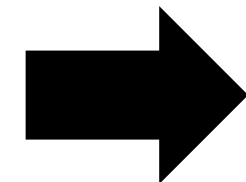
$\epsilon_E(T, Z)_i$: interpolated emissivity at energy bin E_i



→ Luminosity calculations were performed using the Astrophysical Plasma Emission Code (APEC) via PyAtomDB.

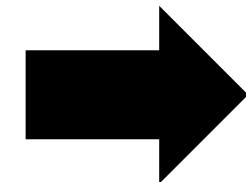
Result we get & physical implication

Scaling relation between L_x and mass, star formation rate



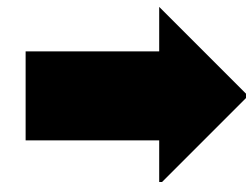
What physical parameter has correlation?

Radial profile of L_x



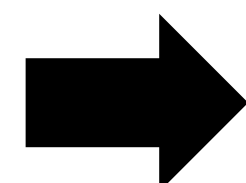
What gas parameter has high impact to L_x ?

Evolutionary history of L_x



How L_x of CGM changes as its galaxy evolves?

Causal inferences of L_x through Machine learning



What physical drivers has genuinely high causal influence to L_x ?

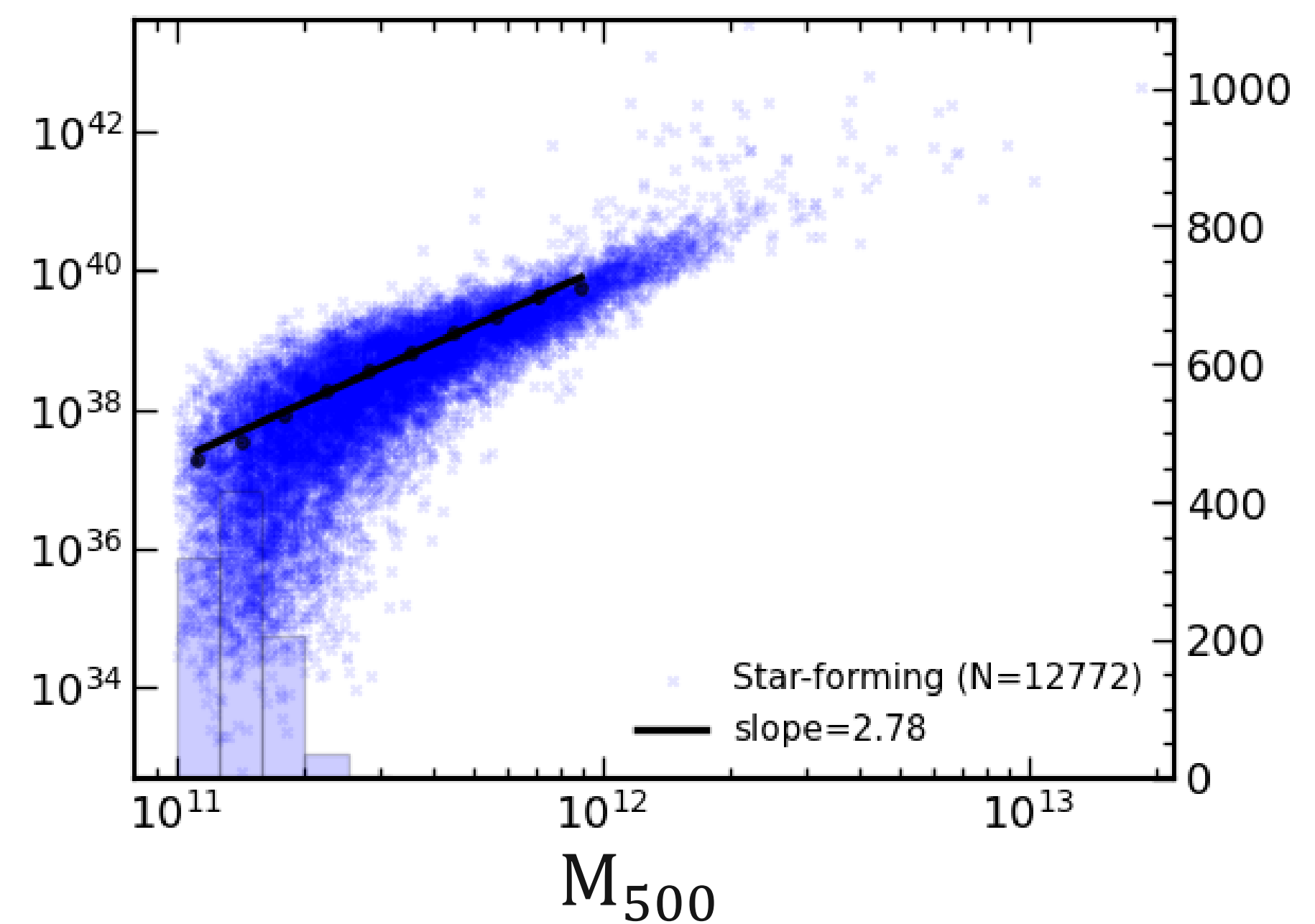
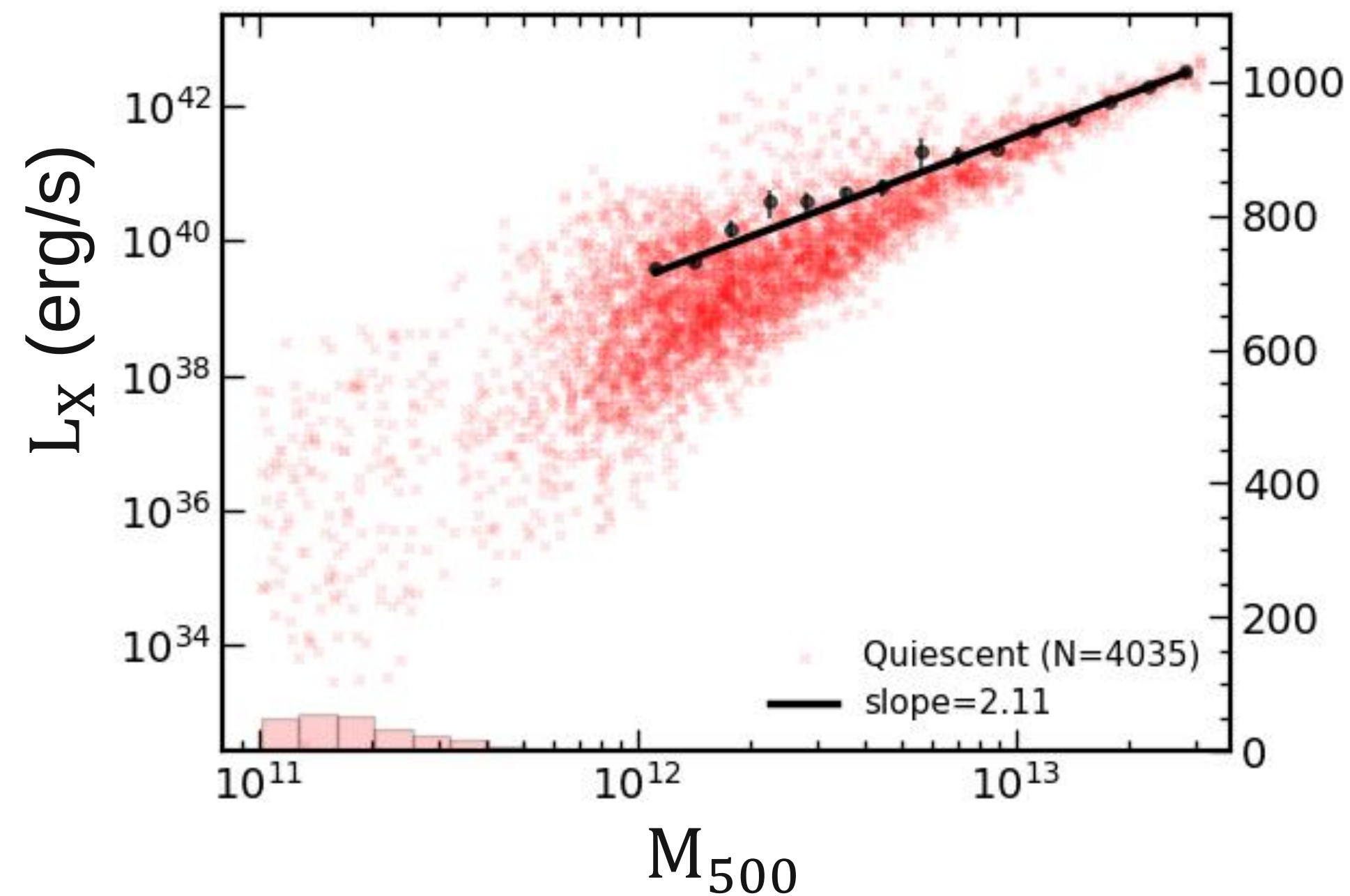
Our analysis so far

Our question want to answer

Scaling Relations with Mass

Scaling Relations: Comparing our results with previous observational and theoretical studies. ($Y \propto M^\alpha$)

- Theoretical Expectation: Following the self-similarity model, L_X is expected to scale with M_{500} (~Viral mass).
- **Population Analysis**: Does the scaling relation vary across different galaxy types (QU, Transition, SF)?

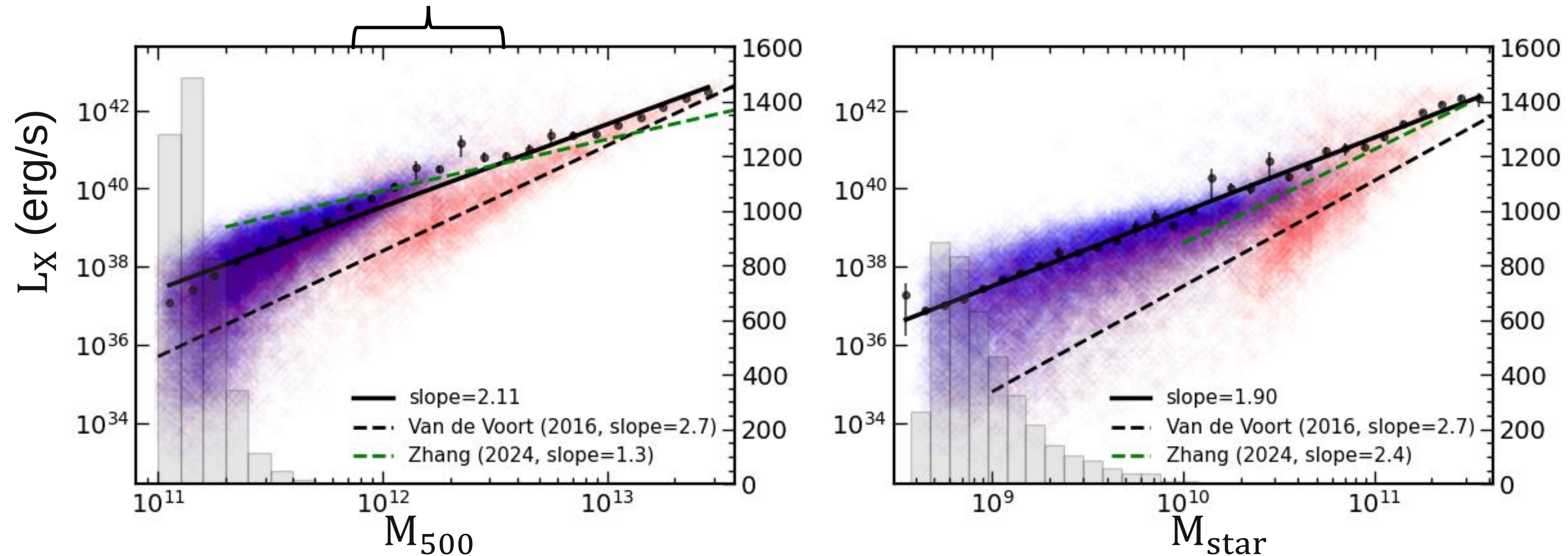


Scaling relation between L_X and mass : QU ($\alpha = 2.11$) & SF ($\alpha = 2.78$)

Scaling Relations with Mass

Key findings : Our $L_X - M$ relations show better agreement with **observational data** compared to previous simulation-based studies.

Milky-way mass galaxies ($10^{11.75} < M_{500}/M_{\odot} < 10^{12.25}$) : Comparable **QU** vs **SF** minimizing mass dependency



Scaling relation between L_X and mass : Total ($\alpha = 2.11$ & 1.90)

Scaling Relations with SFR

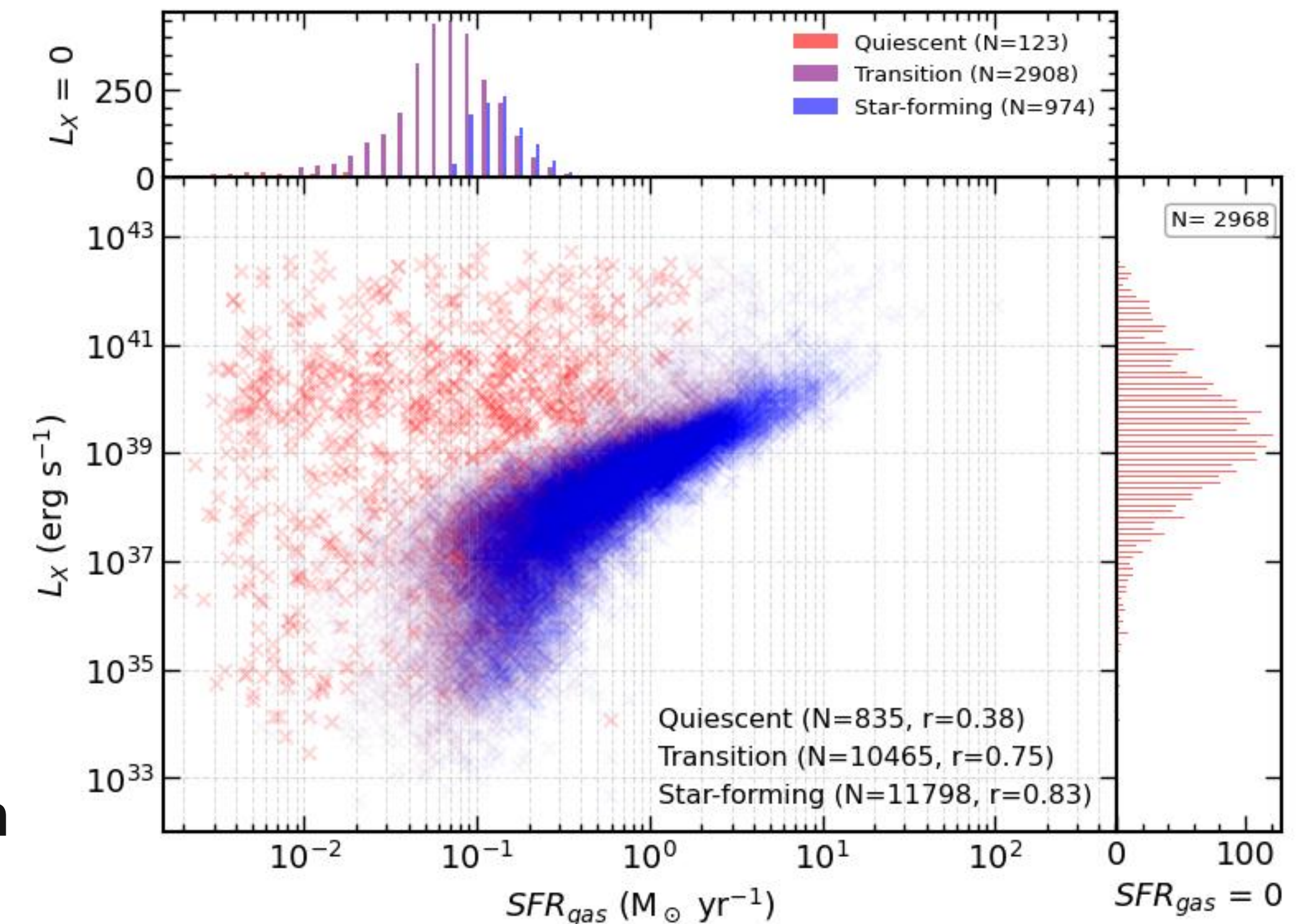
The impact of star formation : Investigating the L_X dependence on the **Star Formation Rate (SFR)**

Correlation Analysis

- **SF** : High correlation ($r = 0.83$)
- **QU** : Significantly weaker ($r = 0.38$)

Specifically, for group with high sSFR ($=\text{SFR}/M_{\text{star}}$) like **SF**, L_X has high correlation with SFR.

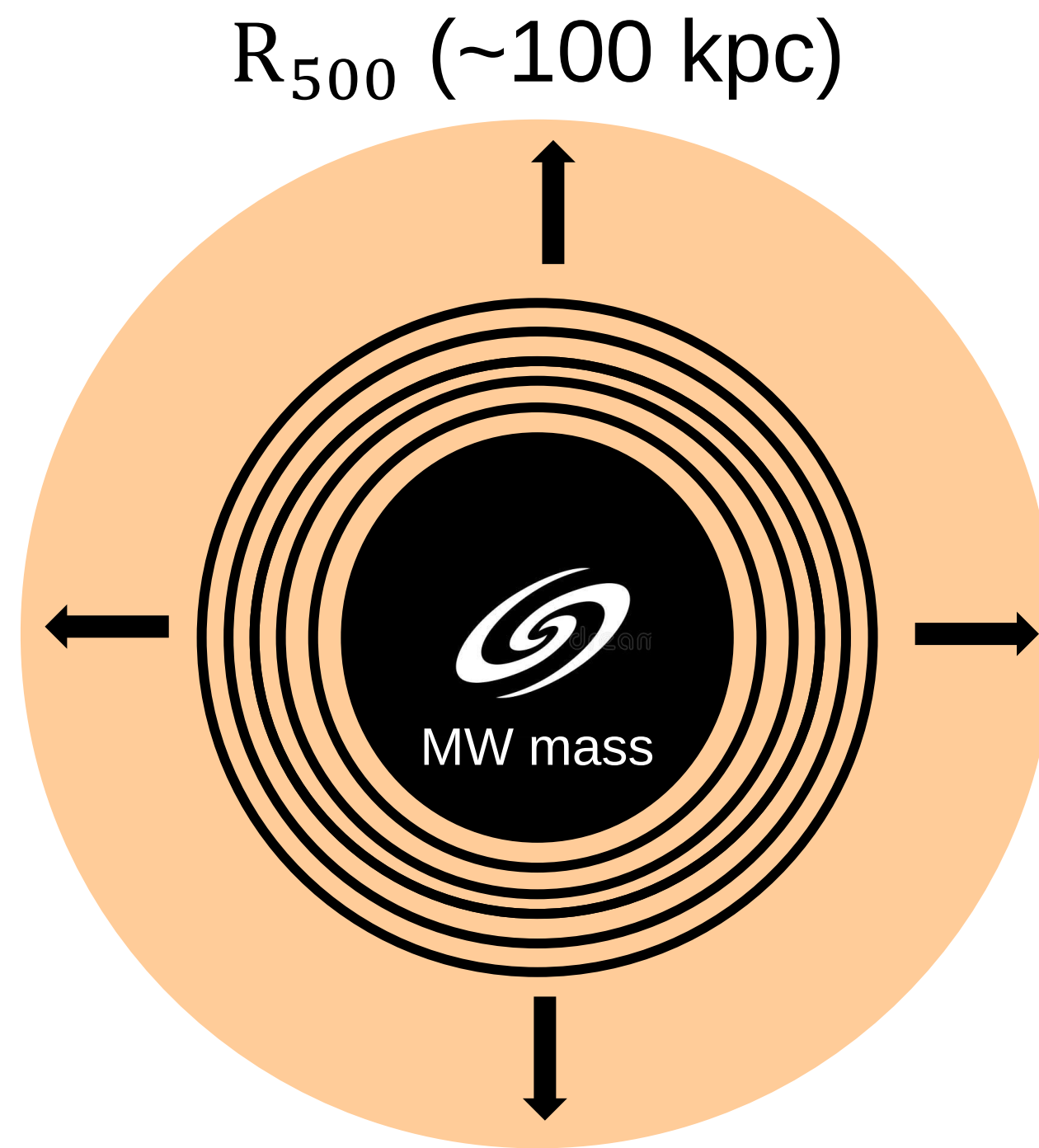
Physical Implication



Beyond the primary mass dependency, **SFR-related processes** (stellar feedback) appear to play a significant role in governing the L_X budget especially of **SF** galaxies.

Radial Profile of Milky-way mass galaxy

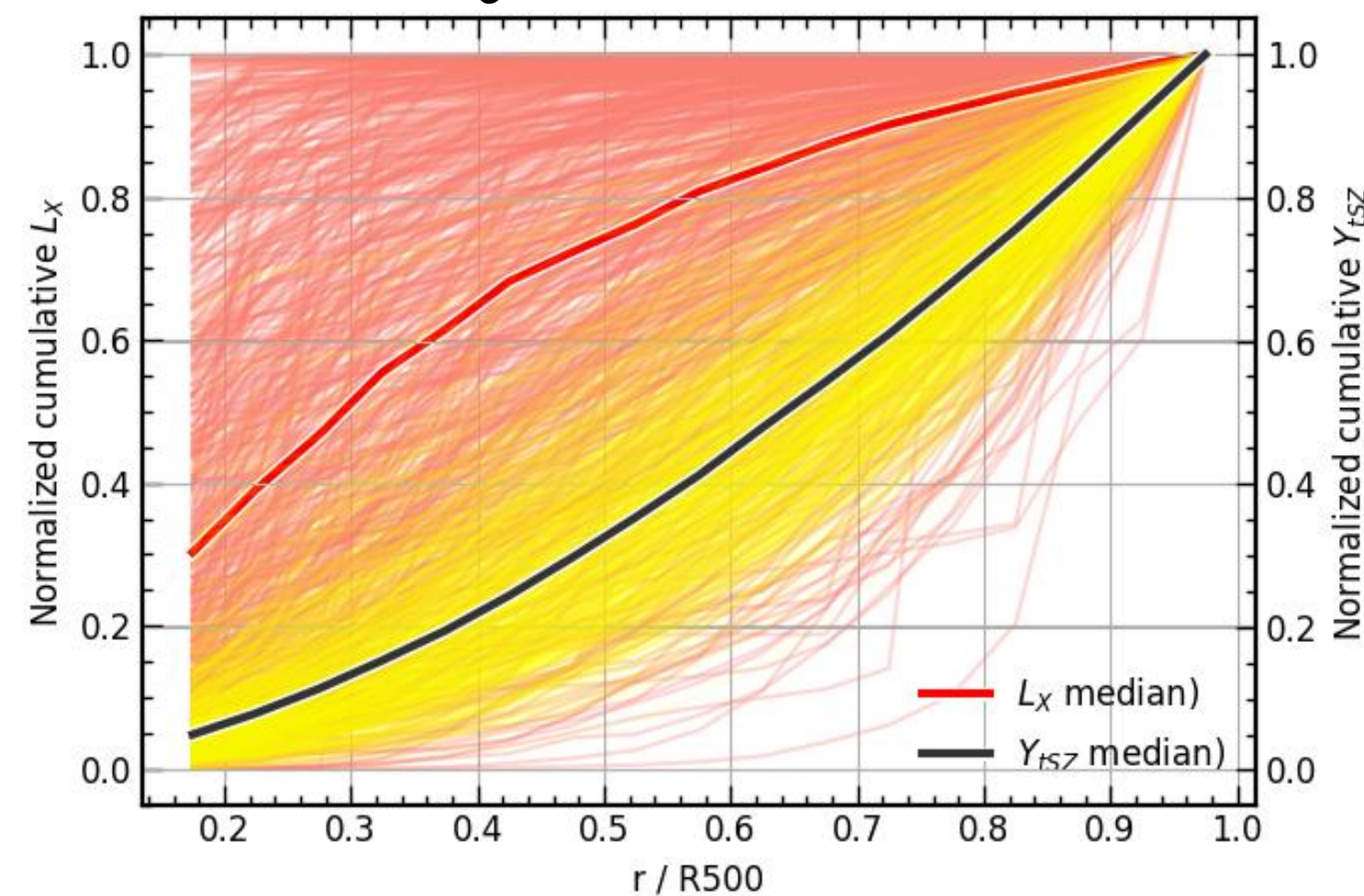
Radial analysis : Cumulative L_X profiles calculated up to R_{500} with a $0.05 R_{500}$ bin size.



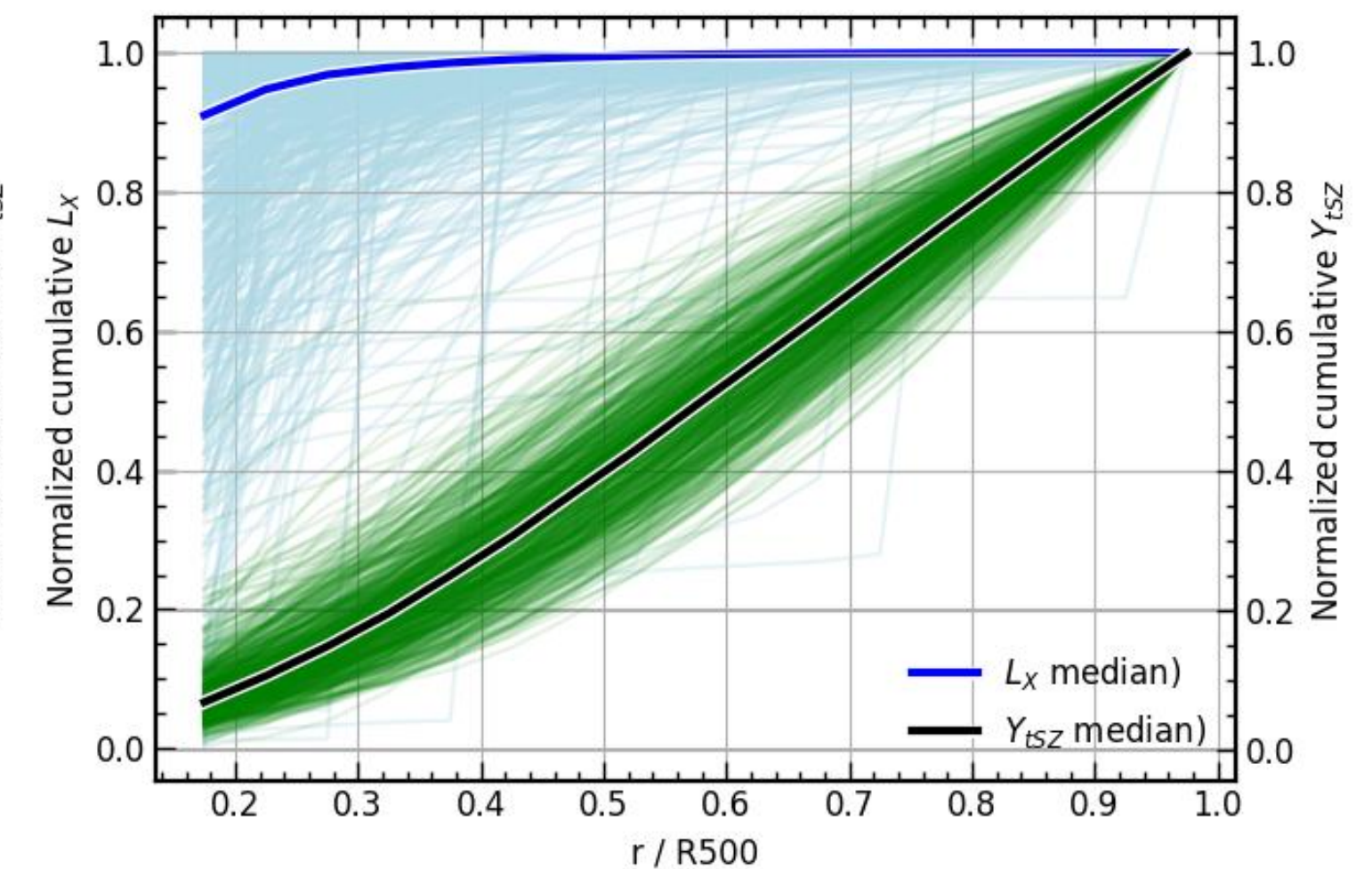
Milky-way mass galaxies

$$(10^{11.75} < M_{500}/M_{\odot} < 10^{12.25})$$

$$N_{QU,Z=0} = 653$$



$$N_{SF,Z=0} = 607$$

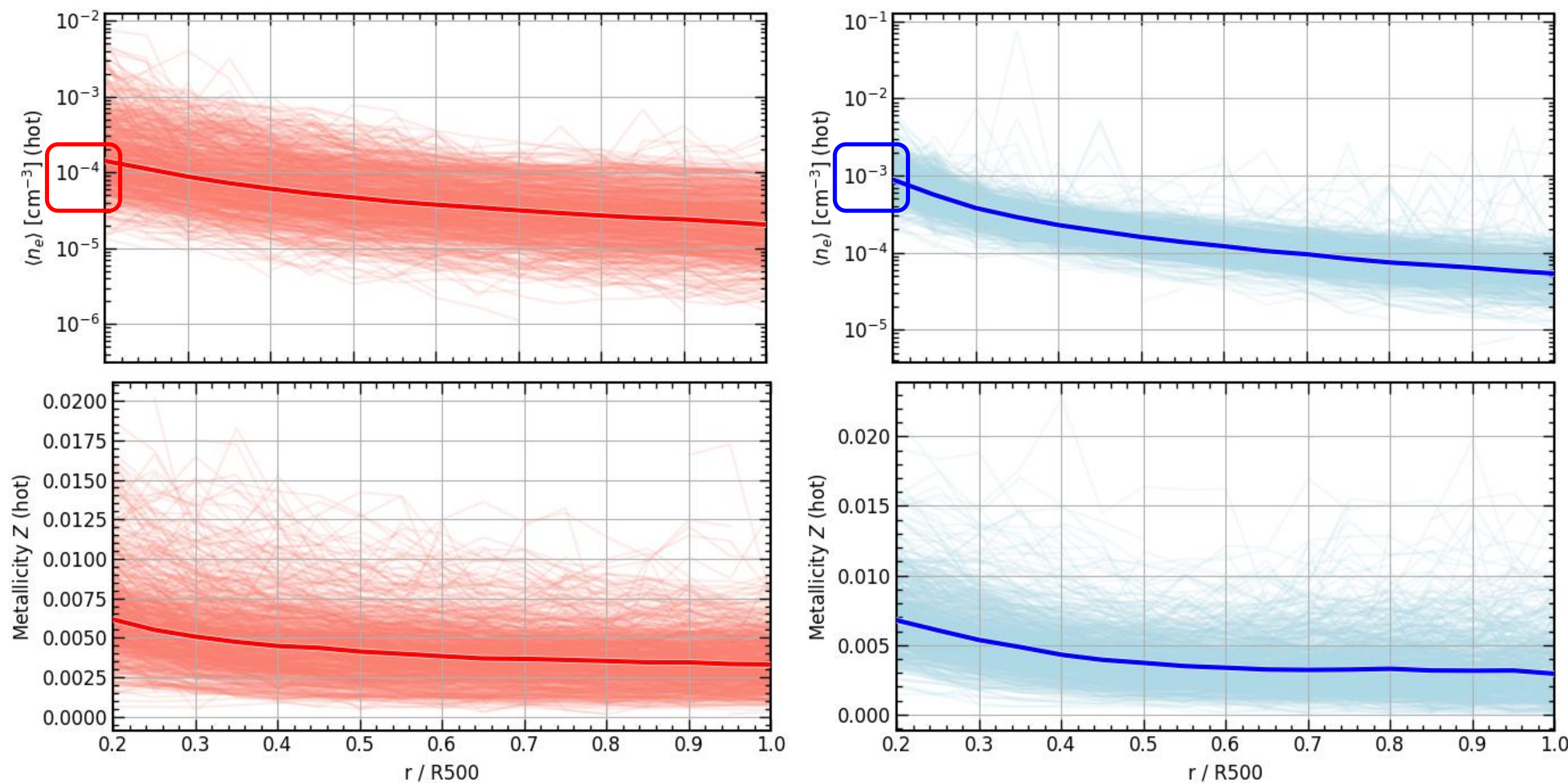


By comparing **cumulative L_X** with the *Compton-y parameter* :
(Related to thermal SZ effect, from Kim et al. 2022)

- **SF** galaxies exhibit **more centrally concentrated** X-ray emission compared to **QU** galaxies.
- Why L_X of **SF** sample is higher & centrally concentrated?

Radial Profile of Milky-way mass galaxy

Driving factor : The distinct radial profiles between **QU** & **SF** primarily originate from differences in their gas density profiles.



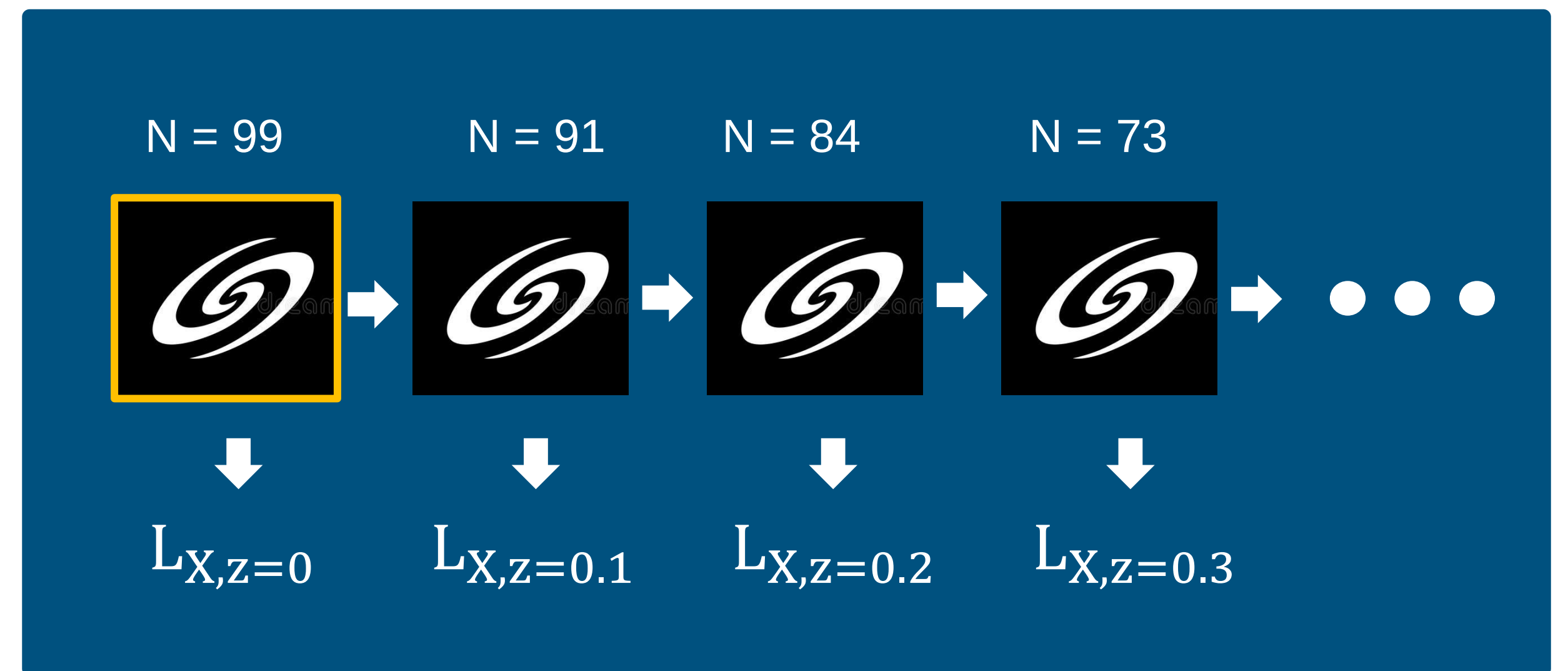
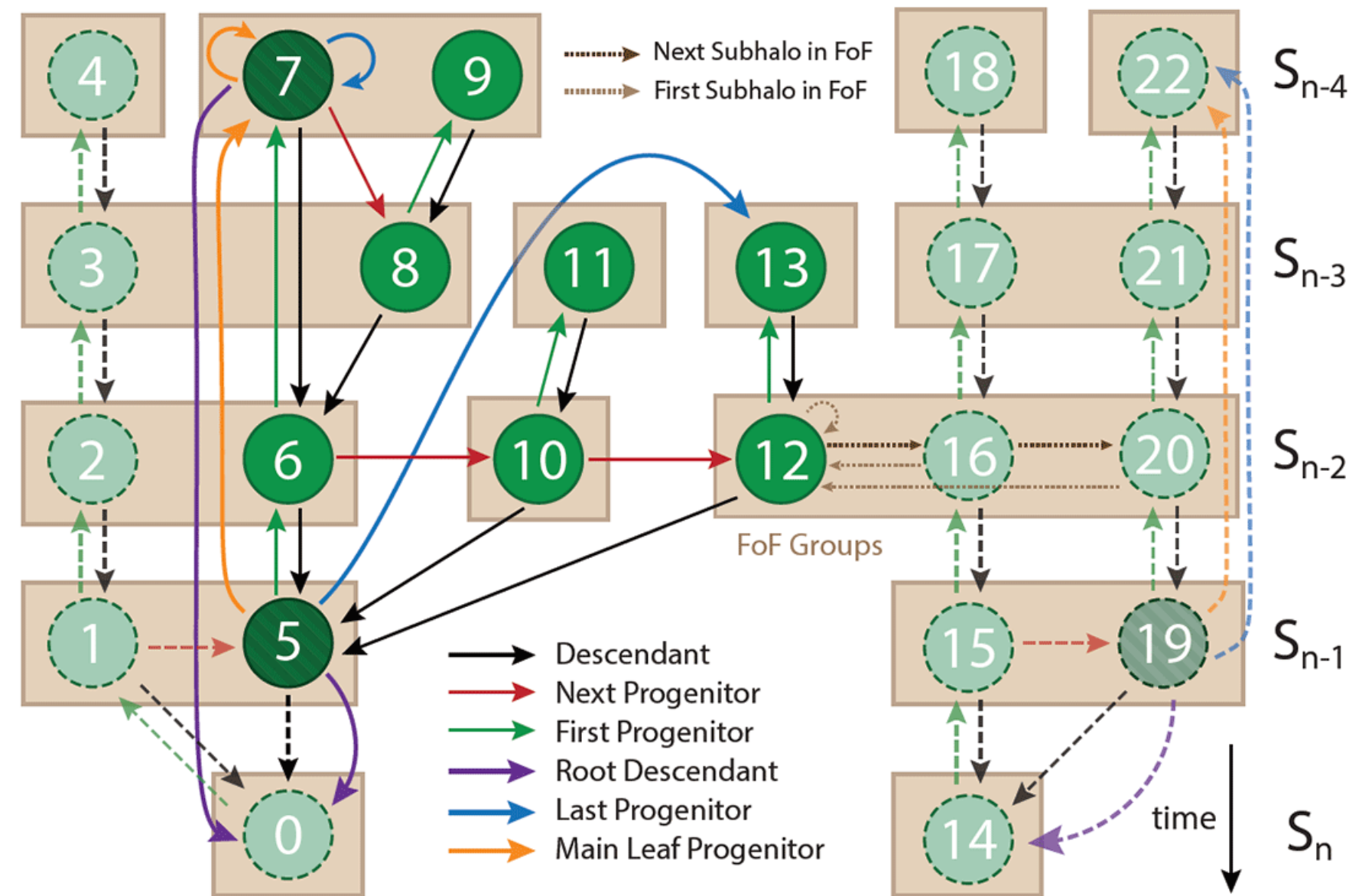
Gas density ~ 10 times higher in **SF**.

Trend of metallicity remain similar.

Overall scale of L_X is dominated by gas density for each cell.

Evolution history of Milky-way mass galaxy

Temporal evolution : How does L_X of the CGM evolves alongside its host galaxy?

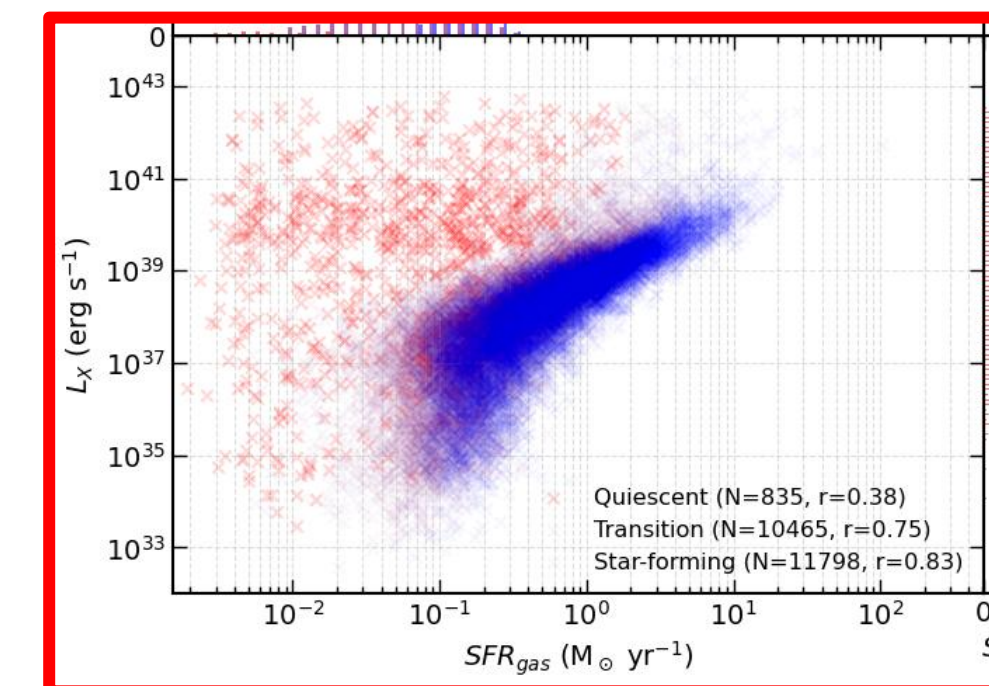
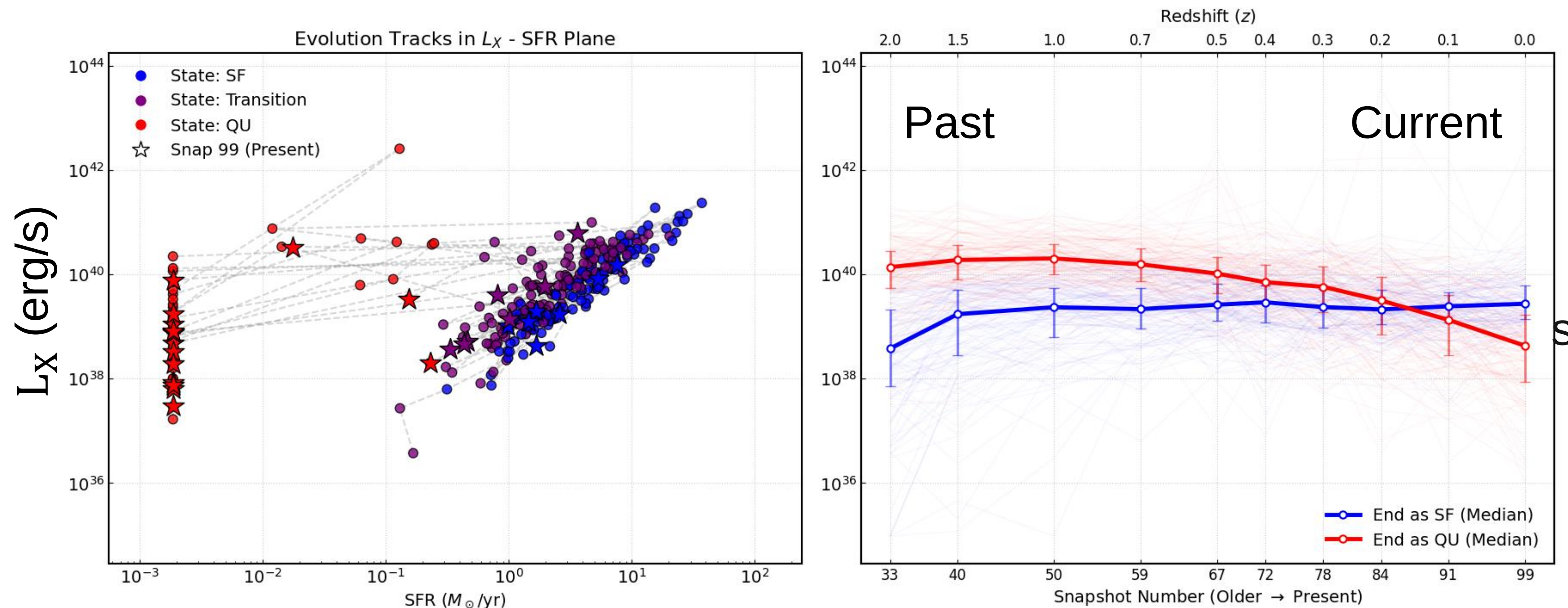


Find progenitor(previous) galaxy in simulation

Methodology: Progenitor tracking using merger trees to monitor the evolution of X-ray emission.

Evolution history of Milky-way mass galaxy

Time evolution of L_X shows distinct difference between group



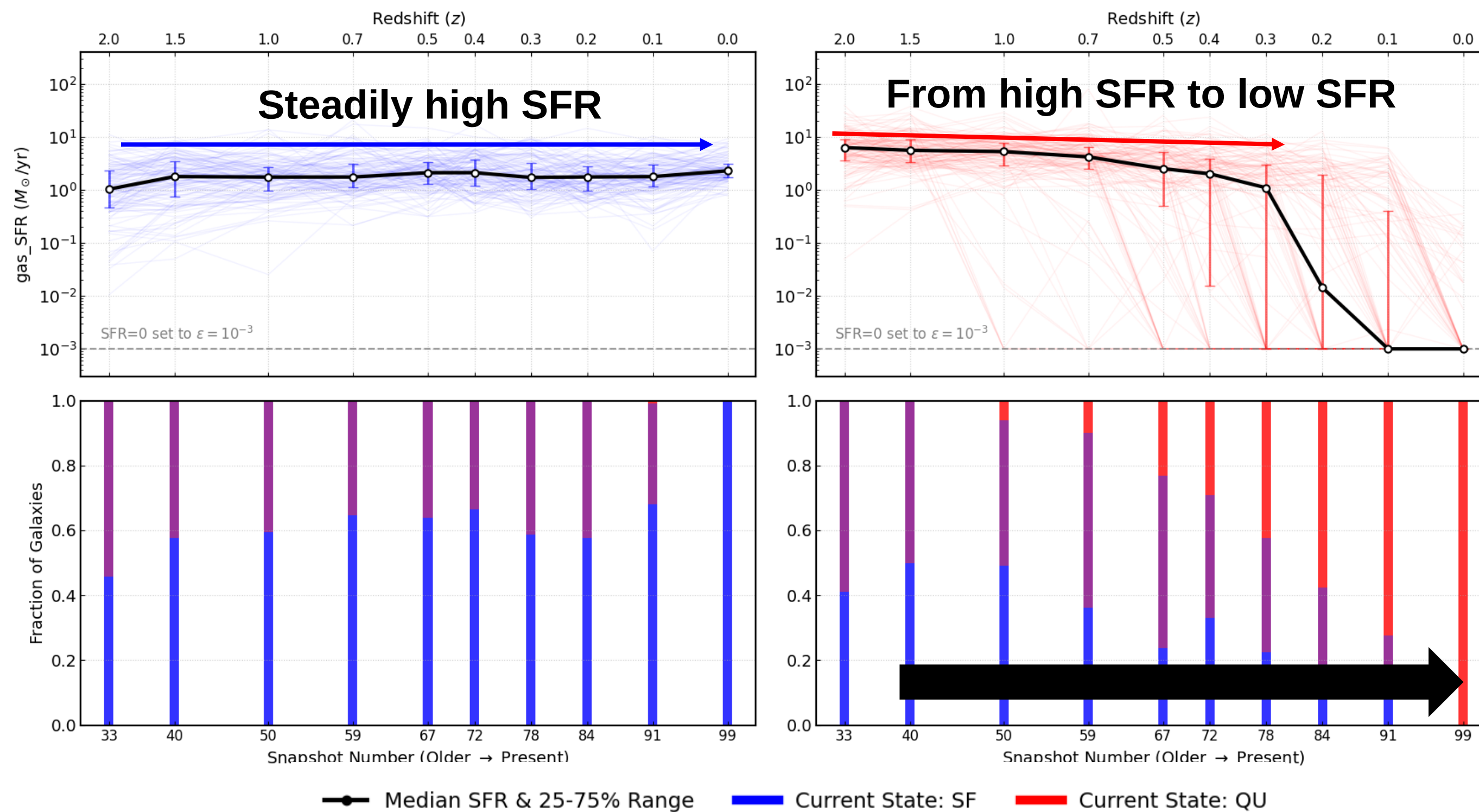
$L_X - SFR$ for $z = 0$

- Reconfirm of $L_X - SFR$ correlation for SF & Transitional galaxies.
- Present-day **QU** galaxies which has low $L_{X,z=0}$, exhibit significantly high L_X in their past star-forming stages.

Evolution history of Milky-way mass galaxy

How do we interpret this result?

- Relatively dense gas primarily contribute to L_X increase. (From radial profile analysis)
- At past, progenitor galaxy of **QU** was actively forming stars.

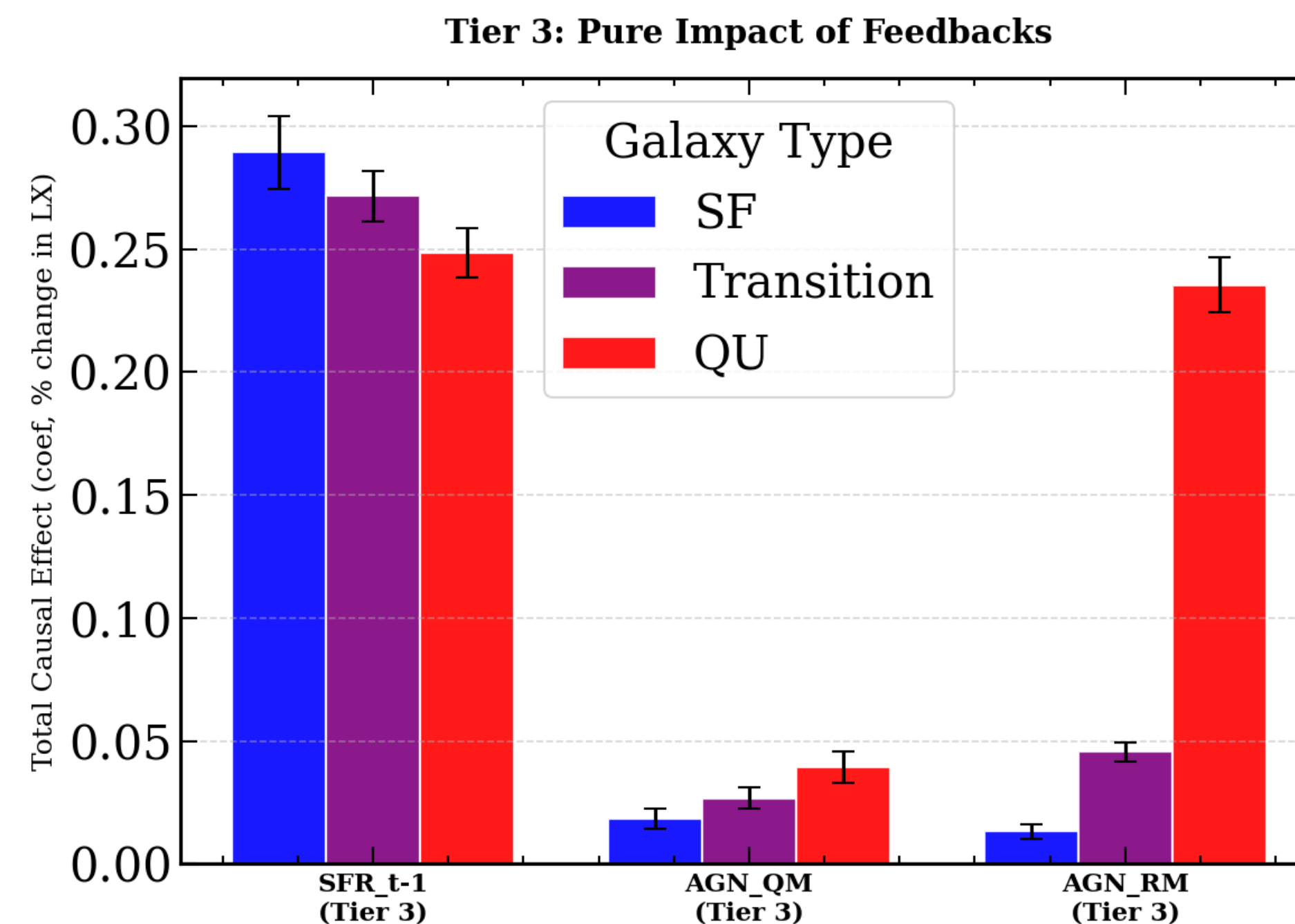
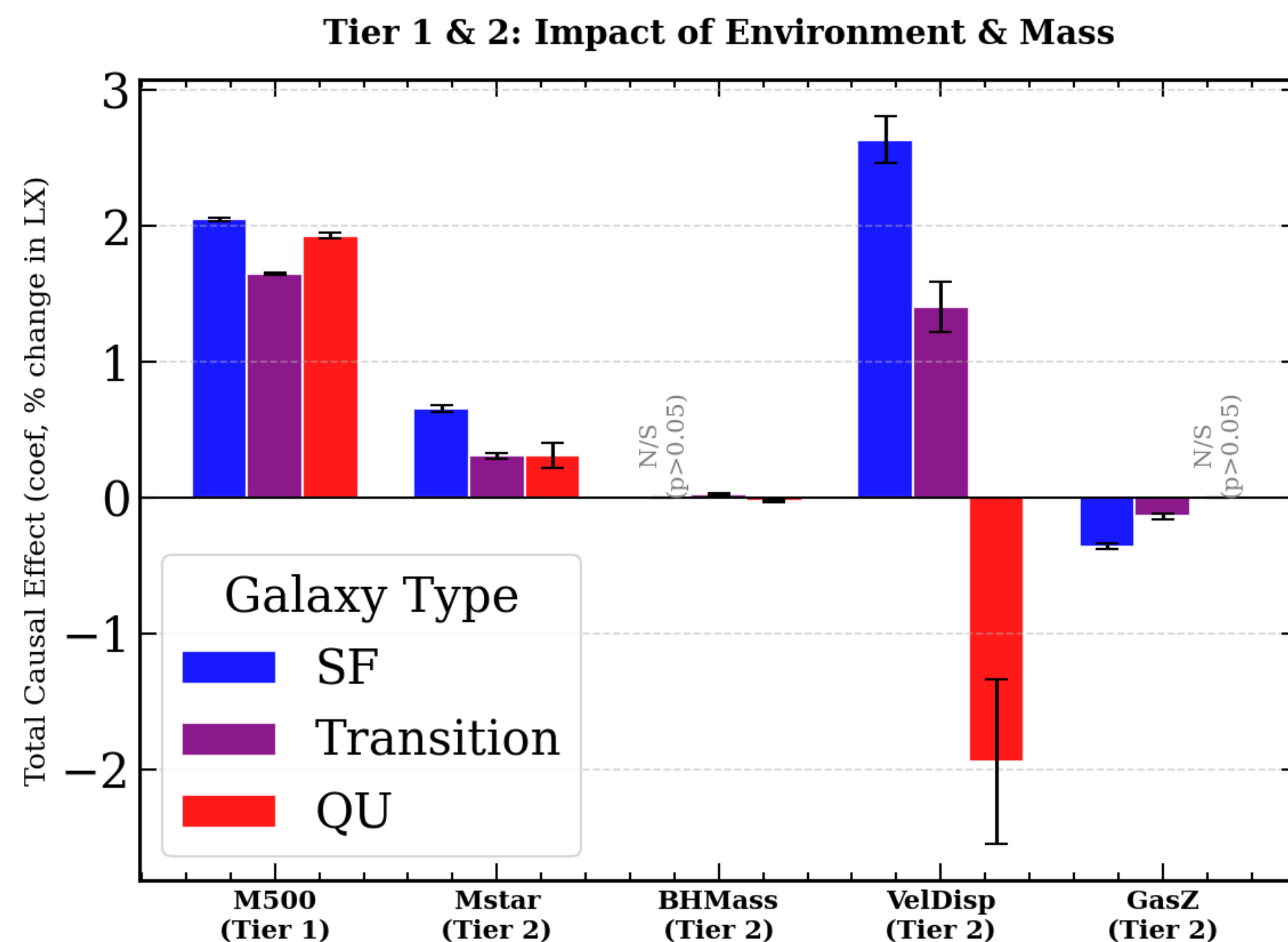


Progenitors of **QU**

- High SFR & classified as **SF** or Transitional
- Following evolutionary path from **SF** to **QU**

From **SF** to **QU**

Identifying the primary drivers using Machine Learning



$\theta_{Total} \sim 2.0$ for M_{500} is consistent with our scaling relation.

SFR still plays an unneglectable role.

FYI

If you are interested, please get into the QR code for more information.



Summary : Key Take-aways

- **CGM** is a critical component for understanding galaxy evolution. We utilized **X-ray** to get insight of its complex nature.
- Distinct **scaling relations** between L_X and other physical drivers (mass, star formation rate) supports the significance of baryonic process & **different characteristics** of **QU**, **SF** and **transitional** galaxy.
- **Radial profile** analysis of Milky Way-mass galaxies reveals that **gas density is the primary driver** of CGM X-ray emission.
- Current CGM L_X is significantly influenced by a galaxy's past **evolutionary history**. High L_X in the progenitors of present-day quiescent (**QU**) galaxies highlights the **lasting impact of feedback**.

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

References : Core selected

- [1] Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
- [2] Battaglia, N., et al. 2019, *arXiv:1903.04647*
- [3] Chadayammuri, U., Bogdán, Á., 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

Any Questions?

Various Medium : ISM, CGM and IGM

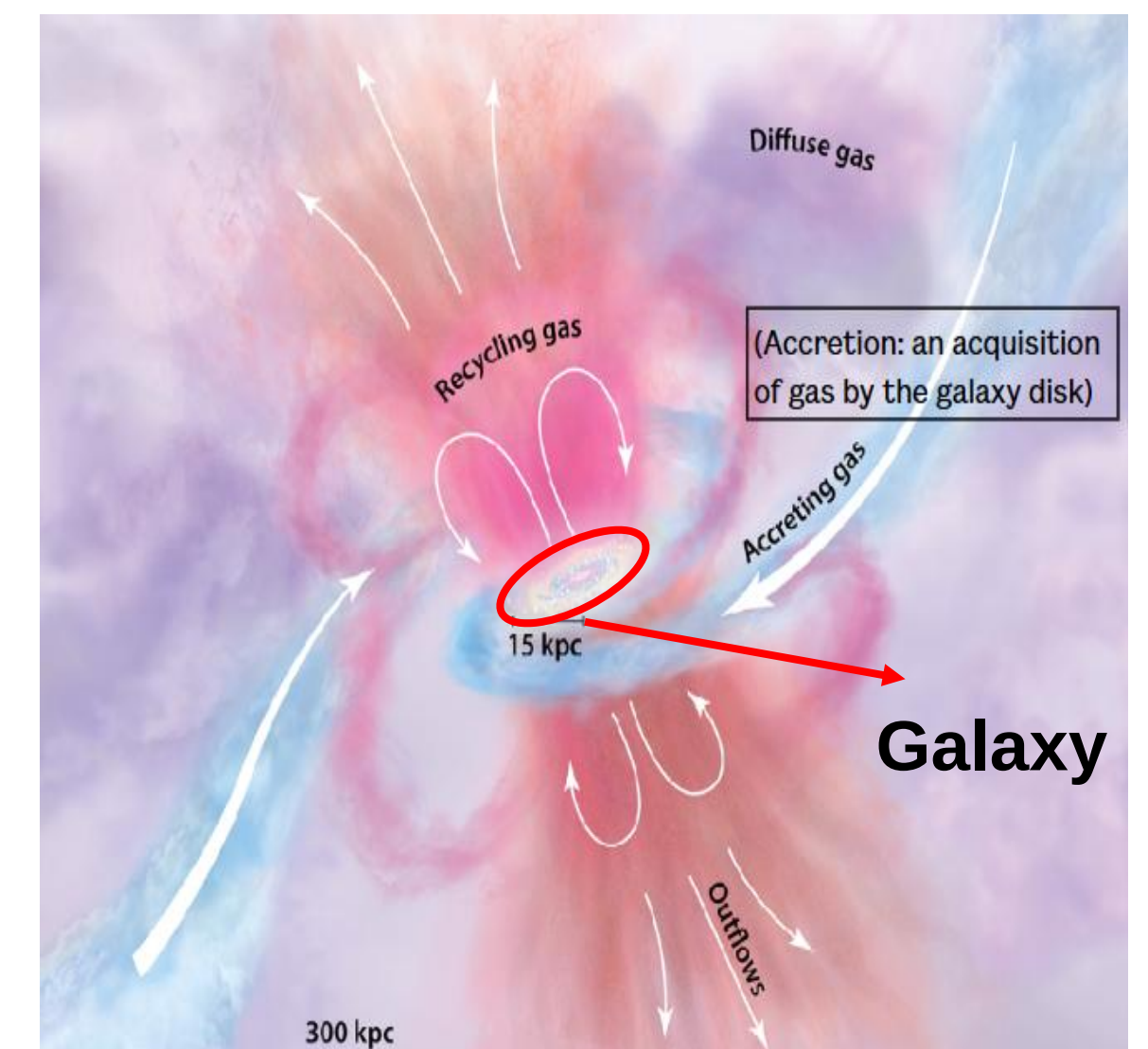
Generally, these are defined through spatial distribution.

Interstellar Medium (ISM) : Medium within galactic disk. Gas ingredients of star formation

Circumgalactic Medium (CGM) : Medium surrounding galaxy up to virial radius.

Intergalactic Medium (IGM) : Outside the virial radius, gas within cosmic web.

→ Baryonic cycle : accretion, outflow and recycling

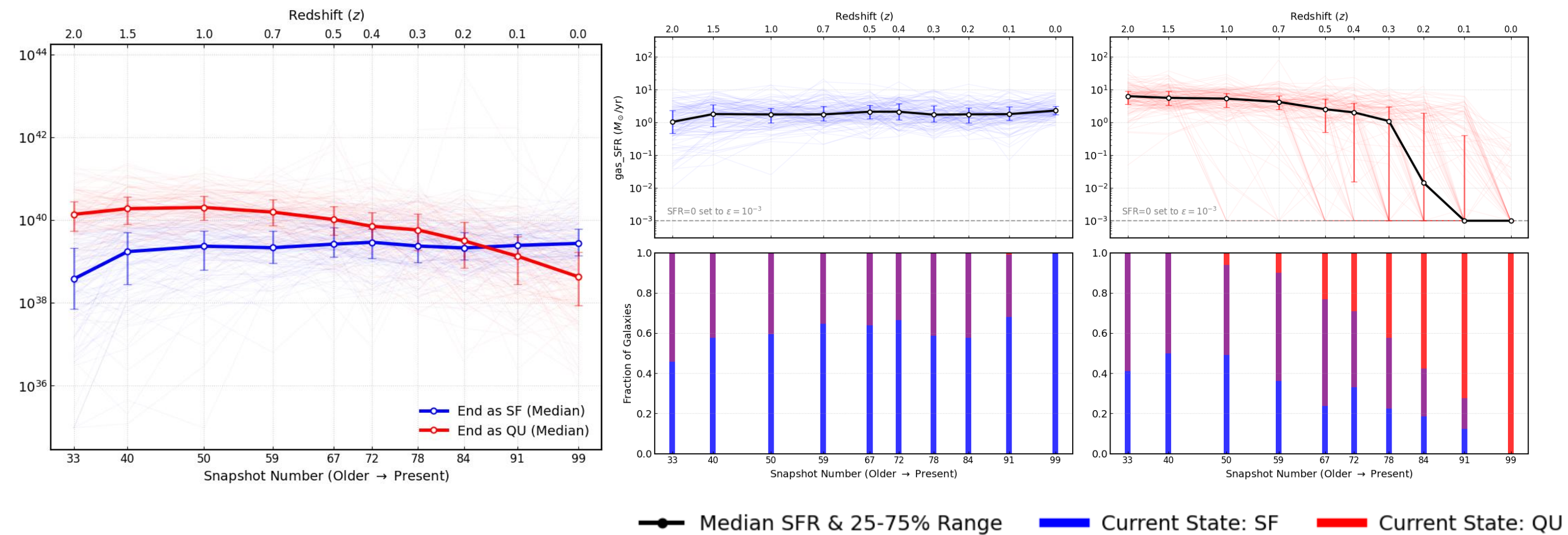


Tumlinson et al. 2017

Evolution history of Milky-way mass galaxy

Then, what makes its current difference?

Both starting with active star forming but currently separated into QU vs SF?



One simple scenario for isolated galaxy

Current QU

Active star formation (with high L_X) $\rightarrow$ strong feedback, quenched (with decreasing SFR & L_X)

Current SF

Moderate star formation (with smaller L_X) $\rightarrow$ weaker feedback, still star forming (steady SFR & L_X)