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Effects of supermassive black hole feedback on galactic hot atmospheres

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Supermassive black hole vs Hot Atmospheres

ISM= interstellar medium

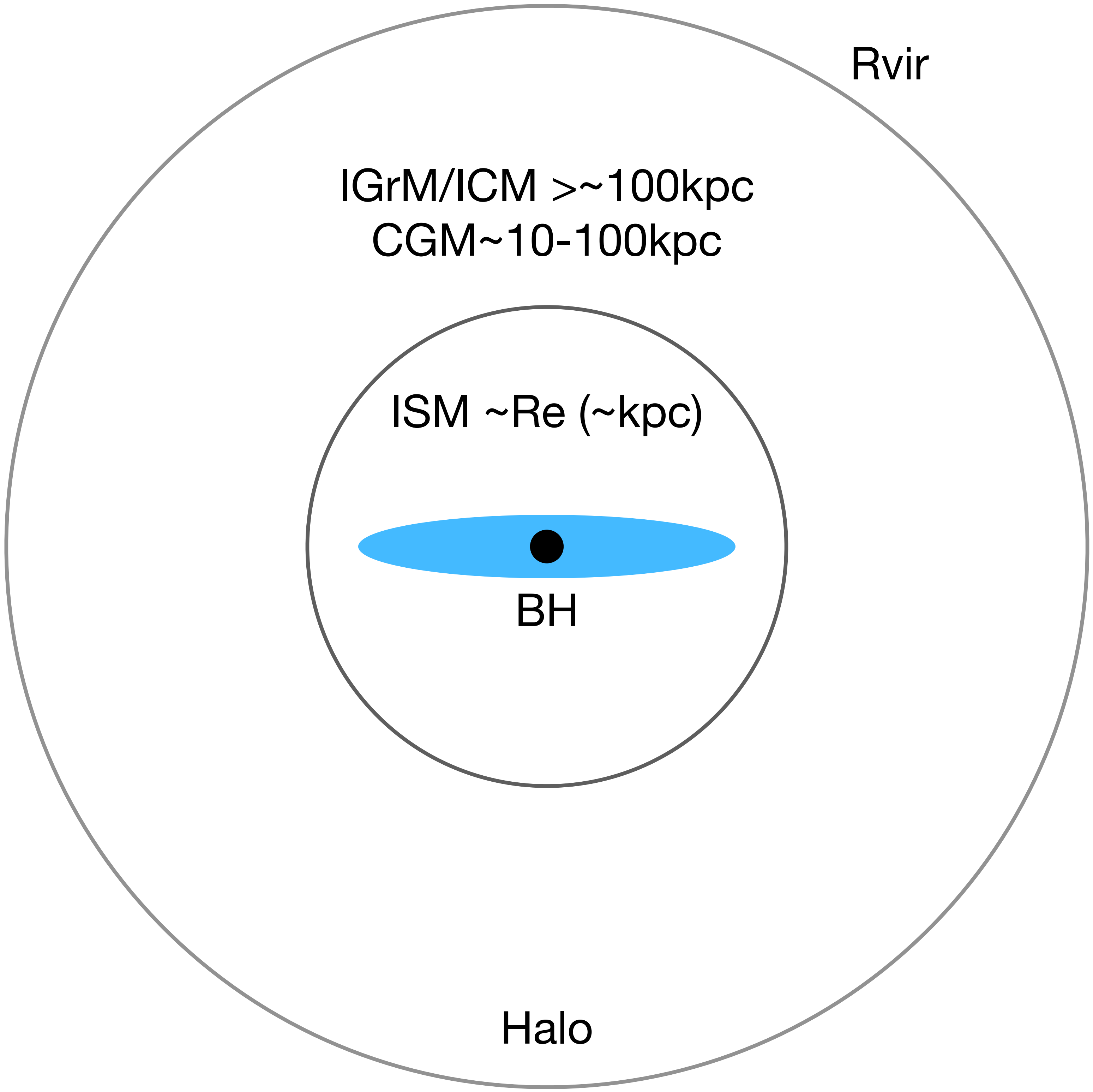
CGM= circumgalactic medidum

IGrM= intra-group medidum

ICM= intra-cluster medidum

Rvir= virial radium of the halo

Re= stellar half-light radius



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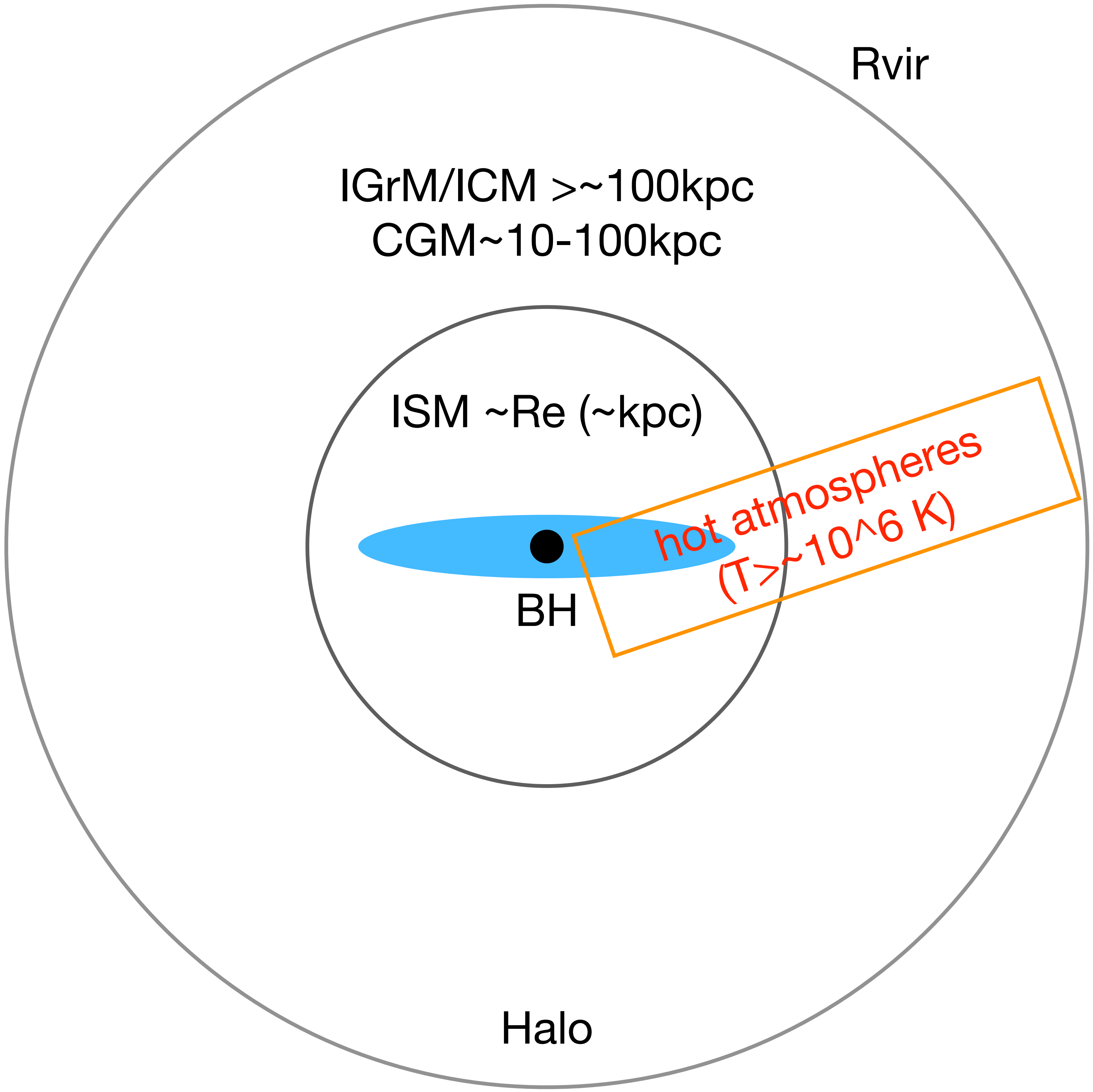


The hot atmospheres encrypt important information about SMBH feedback activity

Outline

- Main points to be addressed:

    1) X-ray signatures of SMBH feedback as quenching mechanism

    __Truong,__ Pillepich, Werner, et al. 2020

    2) Effect of SMBH feedback on the spatial distribution of the CGM

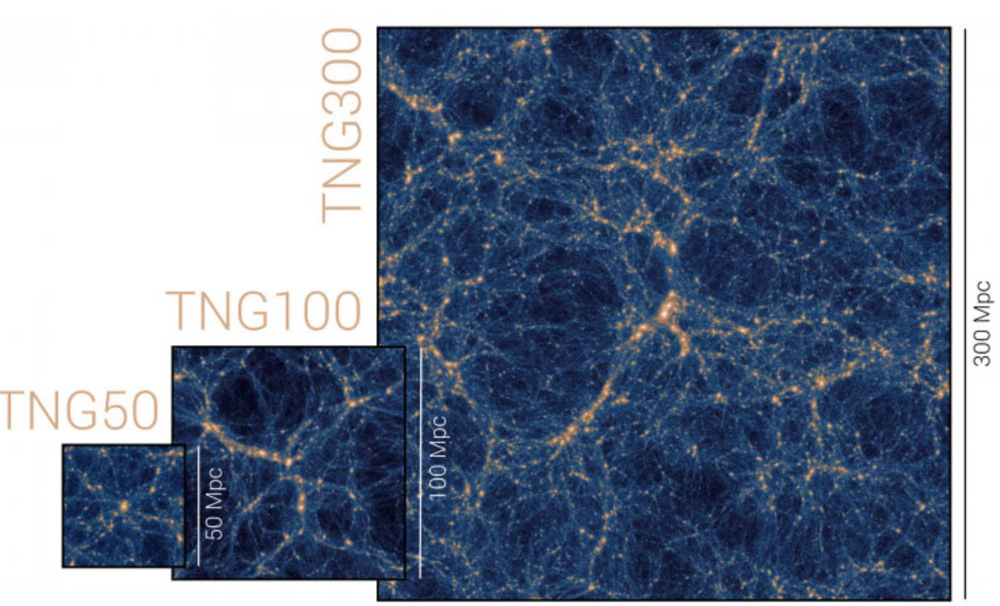
    __Truong__, Pillepich, Nelson, Werner, Hernquist, 2021b

    3) Effect of SMBH feedback on the gas fluctuations in the IGrM/ICM

    __Truong__, Pillepich et al., in prep

- Tools: + IllustrisTNG & other simulations + forward modelling

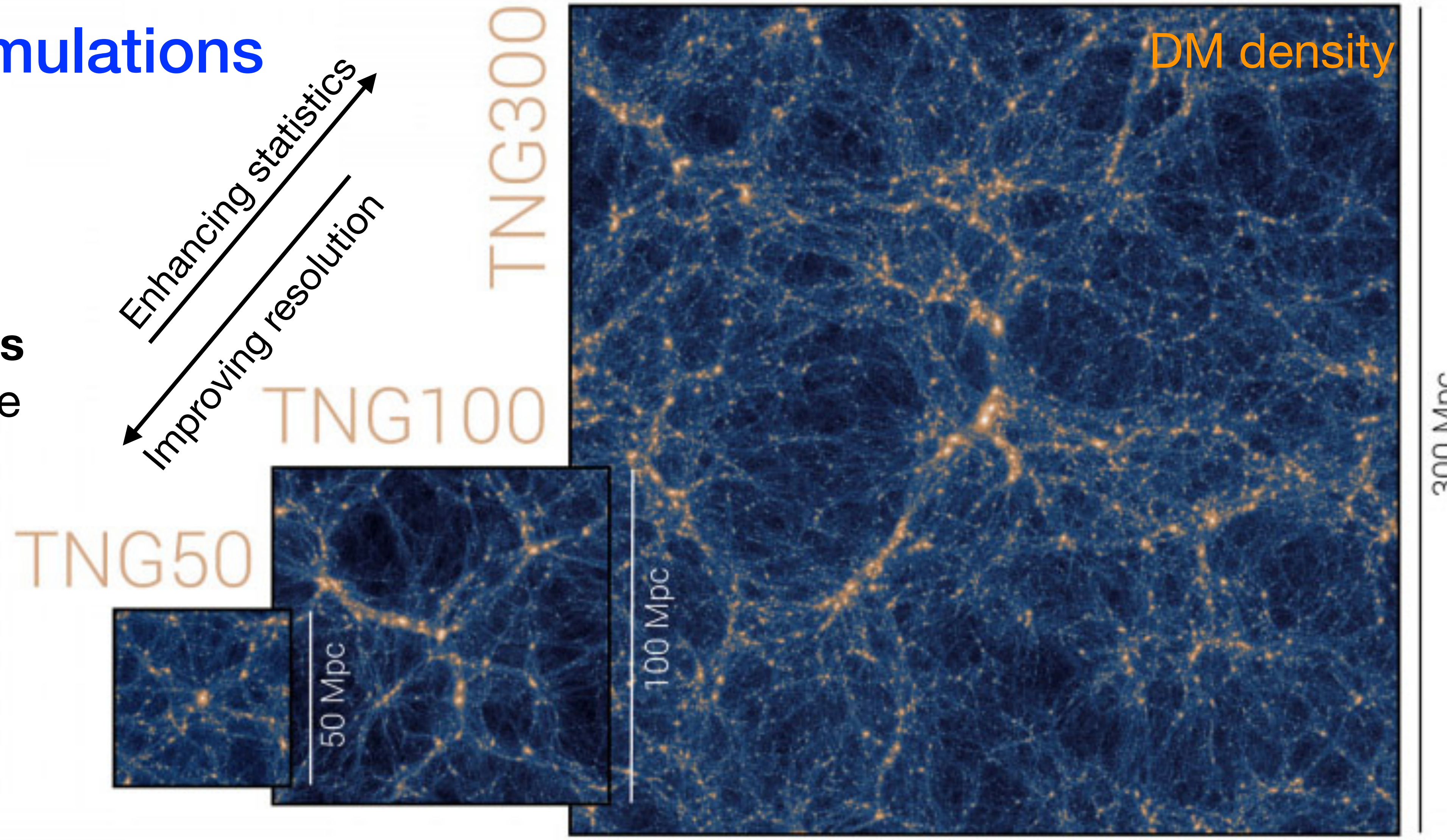
    + X-ray observations



eROSITA

The IllustrisTNG Simulations

3 flagships
Cosmological magneto-hydrodynamical simulations
of galaxy formation within the Lamda-CDM framework (Planck+2016).



Pillepich+2018a,b, Pillepich+2019, Weinberger+2017, Springel+2018, Nelson+2018, Nelson+2019a,b Naiman+2018, Marinacci+2018

Galaxy formation model:

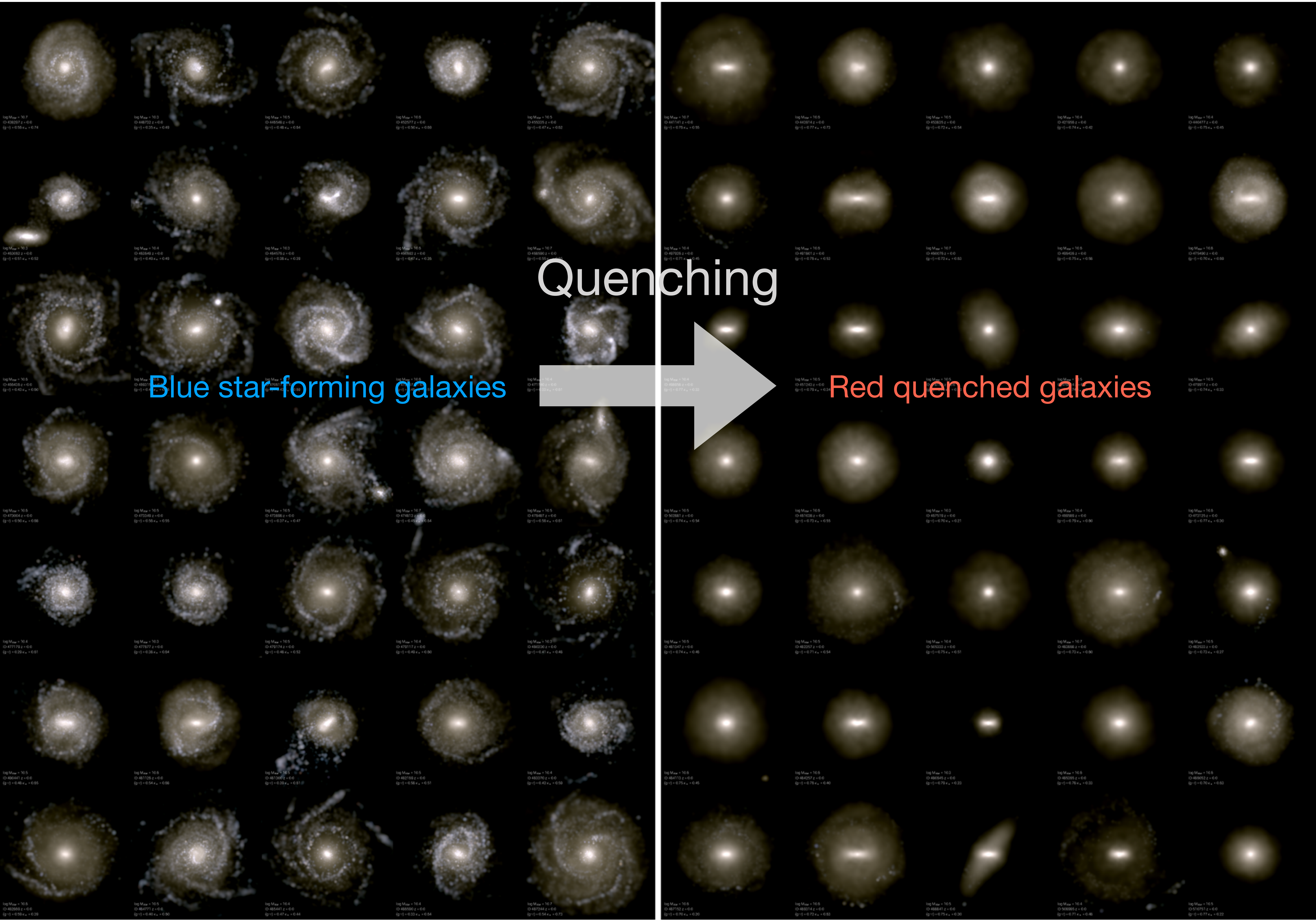
- Gas radiative cooling/heating
- Star formation and stellar evolution, chemical enrichment
- SNe and SMBH feedback

		TNG50	TNG100	TNG300
Volume	[Mpc^3]	51.7^3	110.7^3	302.6^3
L_{box}	[Mpc/h]	35	75	205
N_{GAS}	-	2160^3	1820^3	2500^3
N_{DM}	-	2160^3	1820^3	2500^3
N_{TR}	-	2160^3	2×1820^3	2500^3
m_{baryon}	[$\mathrm{M}_\odot$]	8.5×10^4	1.4×10^6	1.1×10^7
m_{DM}	[$\mathrm{M}_\odot$]	4.5×10^5	7.5×10^6	5.9×10^7
$\epsilon_{\mathrm{gas,min}}$	[pc]	74	185	370
$\epsilon_{\mathrm{DM},\star}$	[pc]	288	740	1480

#1: X-ray signatures of SMBH feedback as quenching mechanism

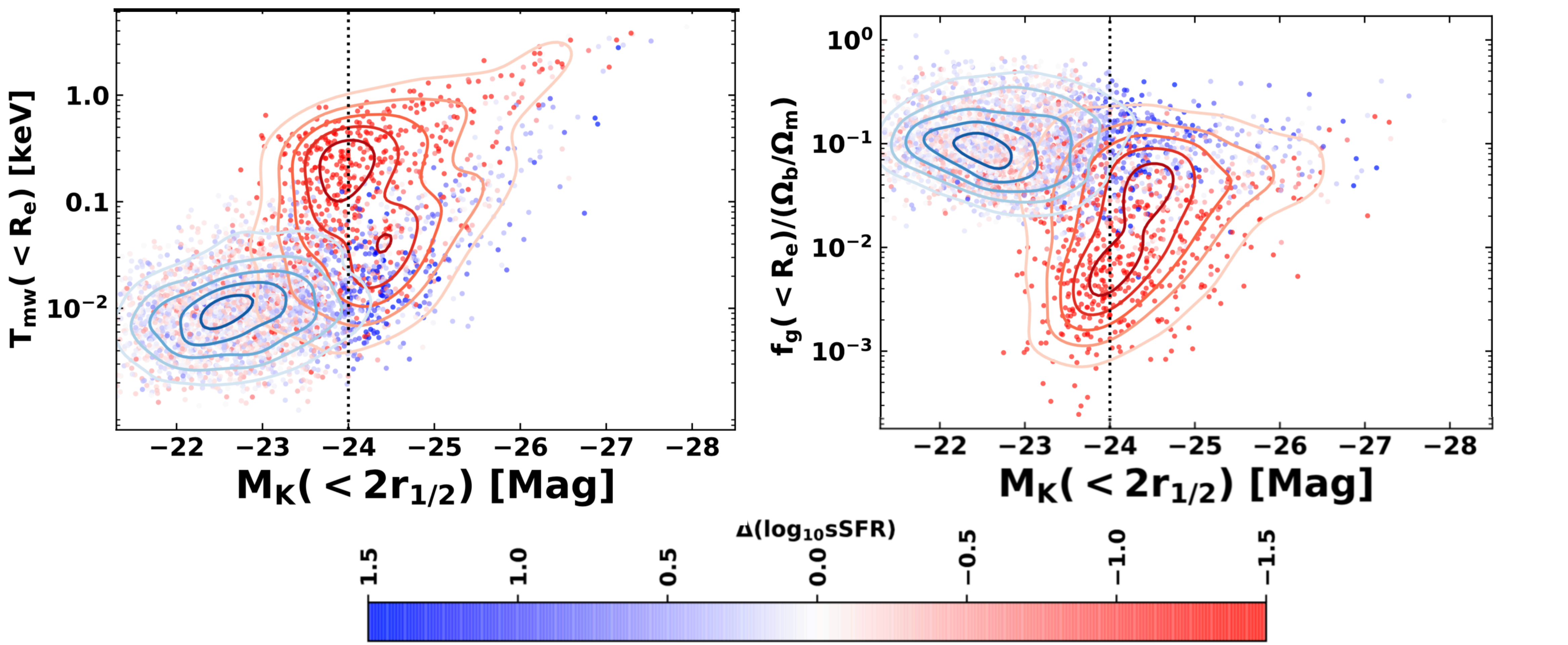
Galaxy colour bimodality: TNG100

Nelson et al. 2018



SMBH kinetic feedback: ejective and preventative effects

Truong, Pillepich, Werner et al. 2020
See also Zinger et al. 2020, Davies et al. 2019



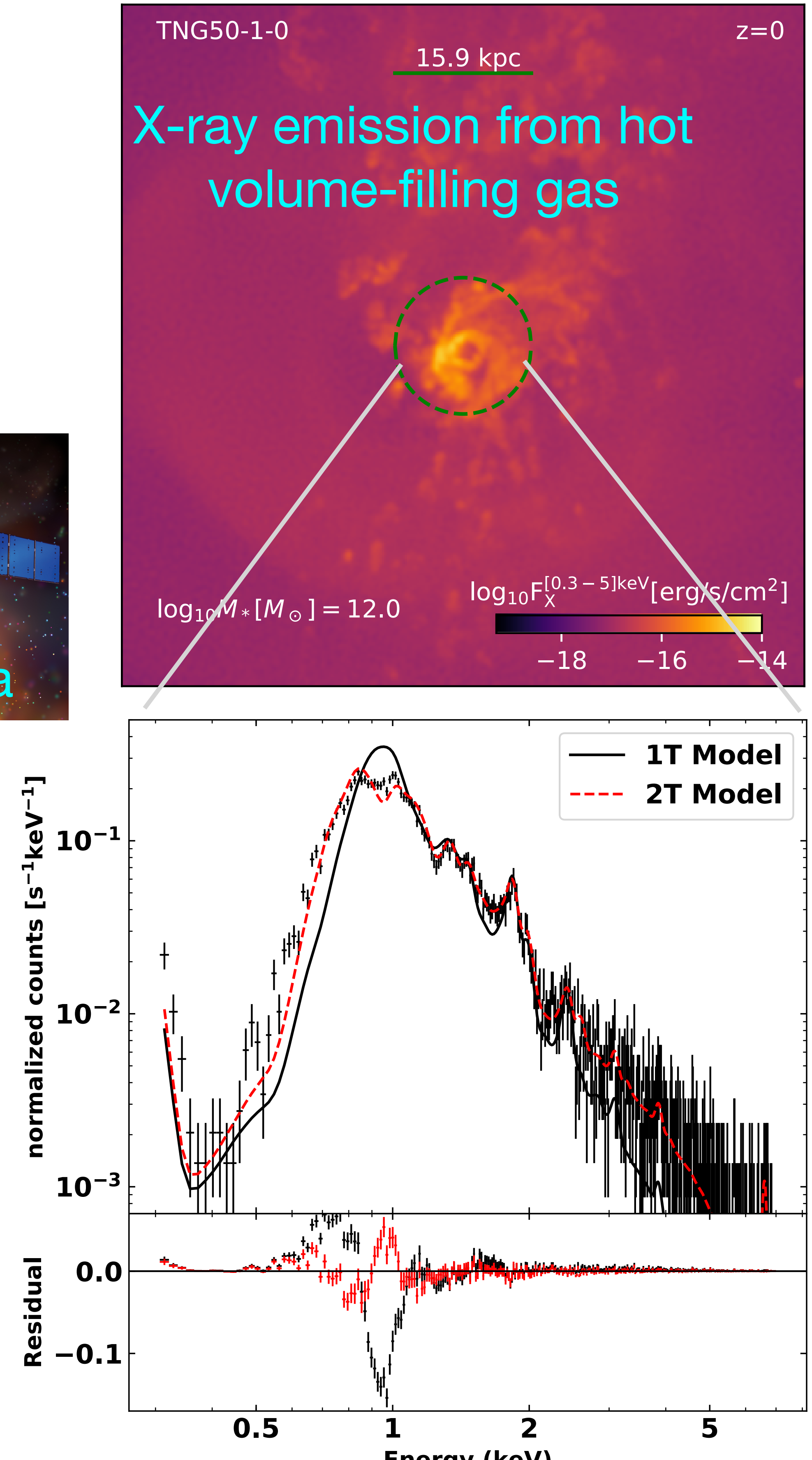
TNG100 SF-ing galaxies **TNG100 Quiescent galaxies**

The quenching in TNG is achieved mainly via gas expulsion driven by SMBH feedback + sustained via gas heating

—> Is this supported by observations?

Forward modelling of simulation data: mock X-ray analysis

- Mock X-ray spectrum is produced for each galaxy assuming:
  - Emission model: APEC (XSPEC).
  - Exposure: 100 ks.
  - Galactic absorption nH=10^20 cm^-2.
  - Response: Chandra ACIS-S.



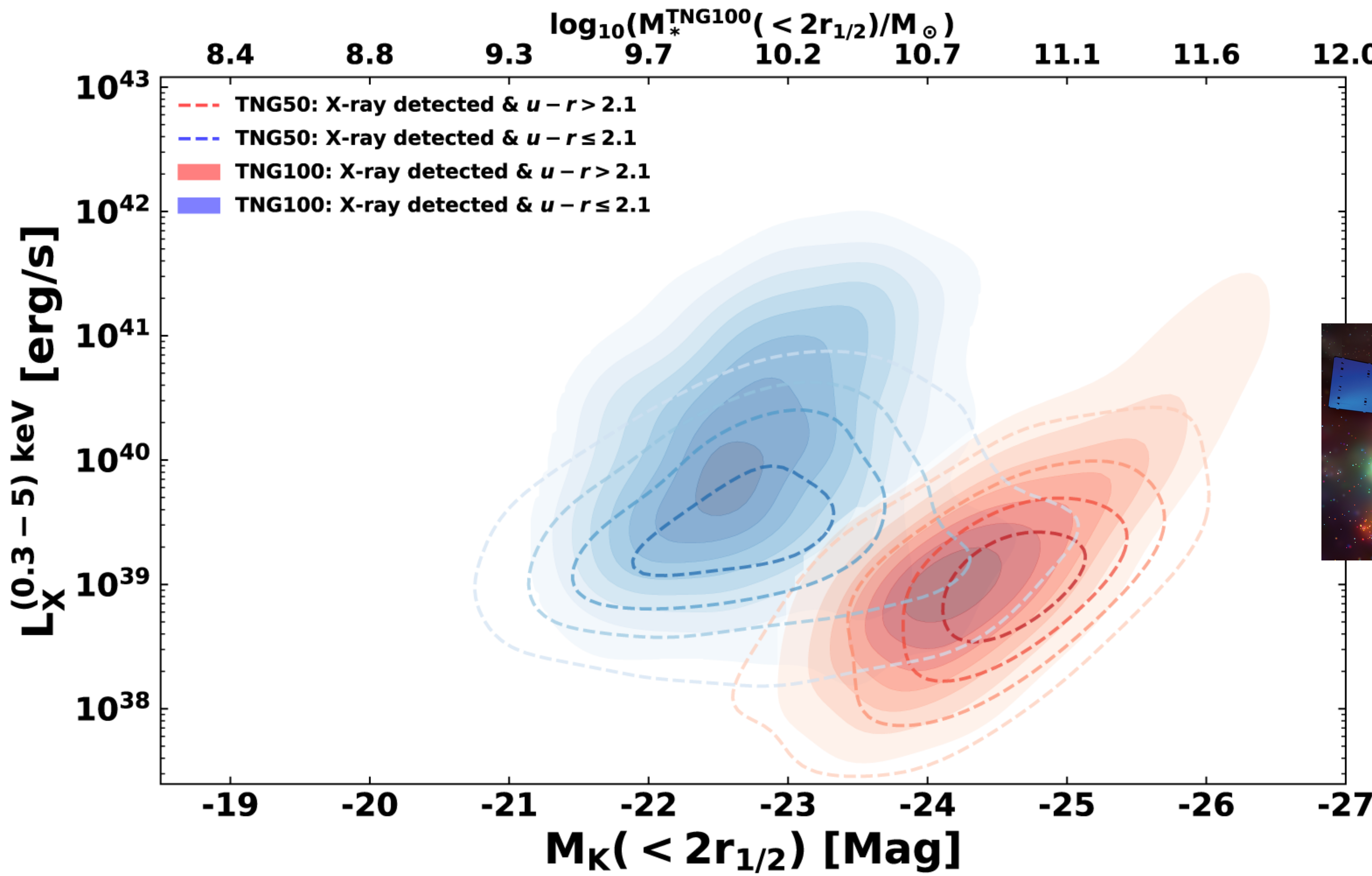
Truong, Pillepich, Werner et al. 2020

TNG prediction: Lx dichotomy between star-forming vs quenched galaxies

At small galactocentric distances: <Re

Remember $L_X \propto T^{1/2} f_{gas}^2$

Truong, Pillepich, Werner et al. 2020



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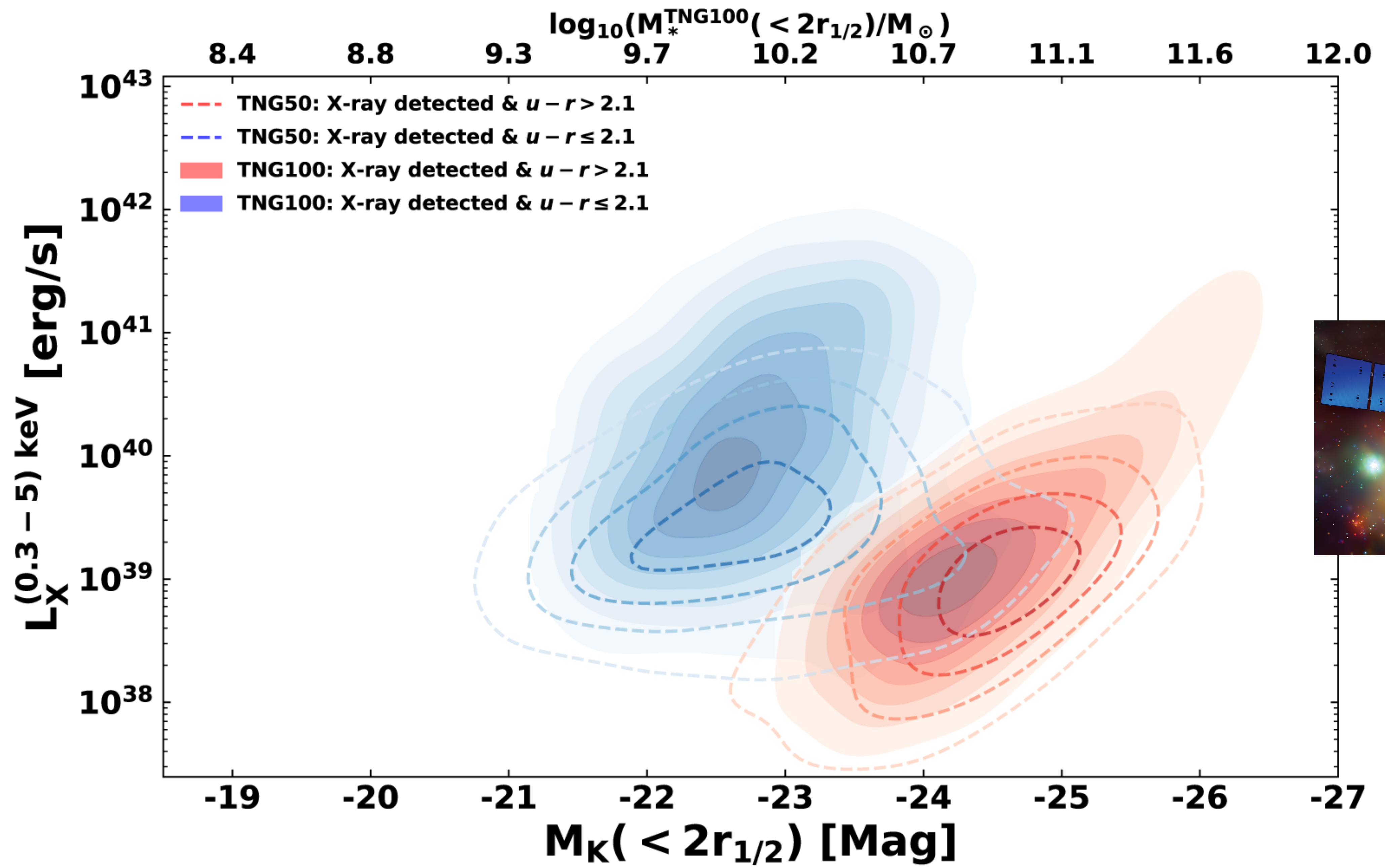

Lx dichotomy is manifestation of SMBH-driven quenching mechanism

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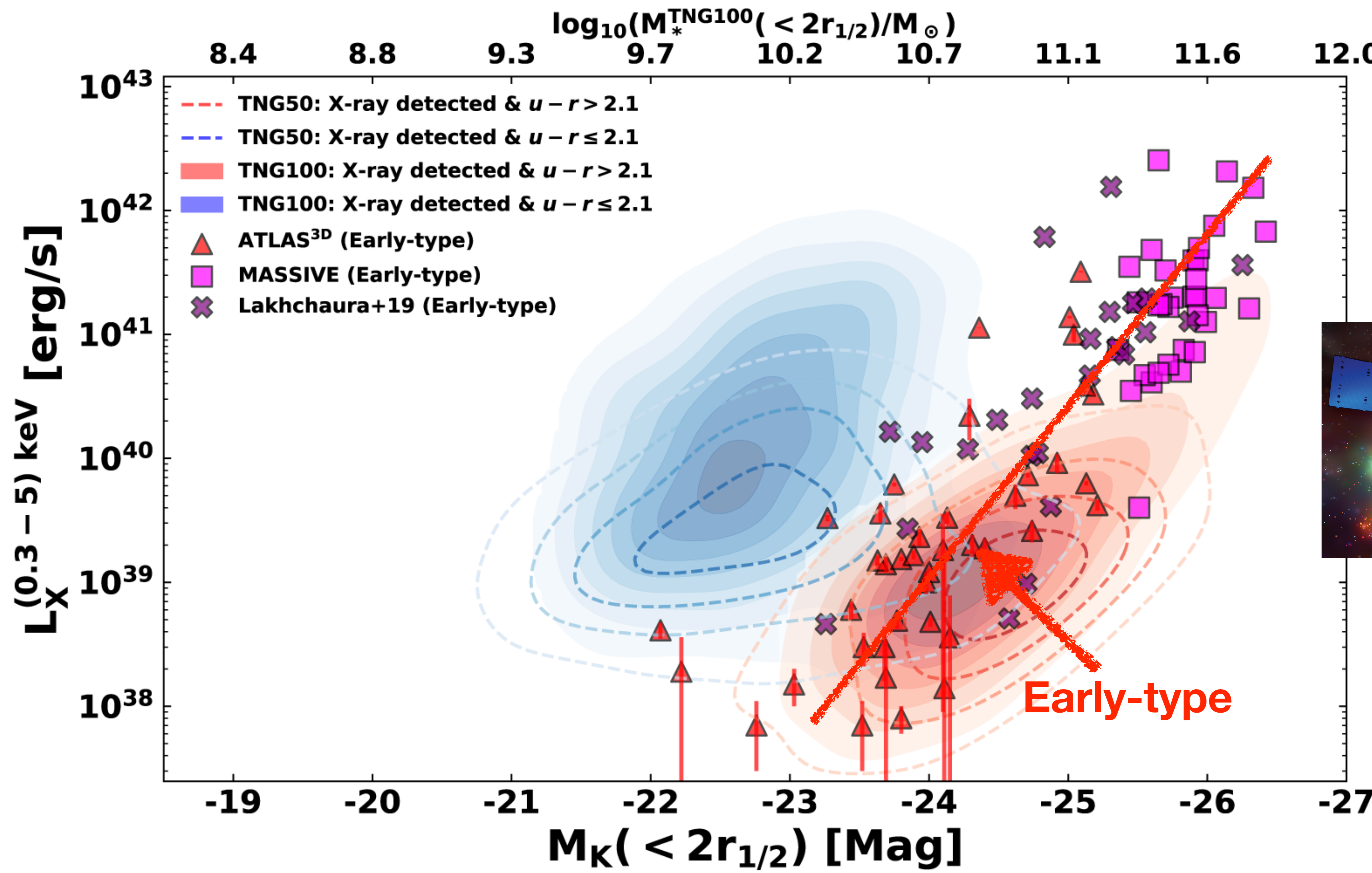

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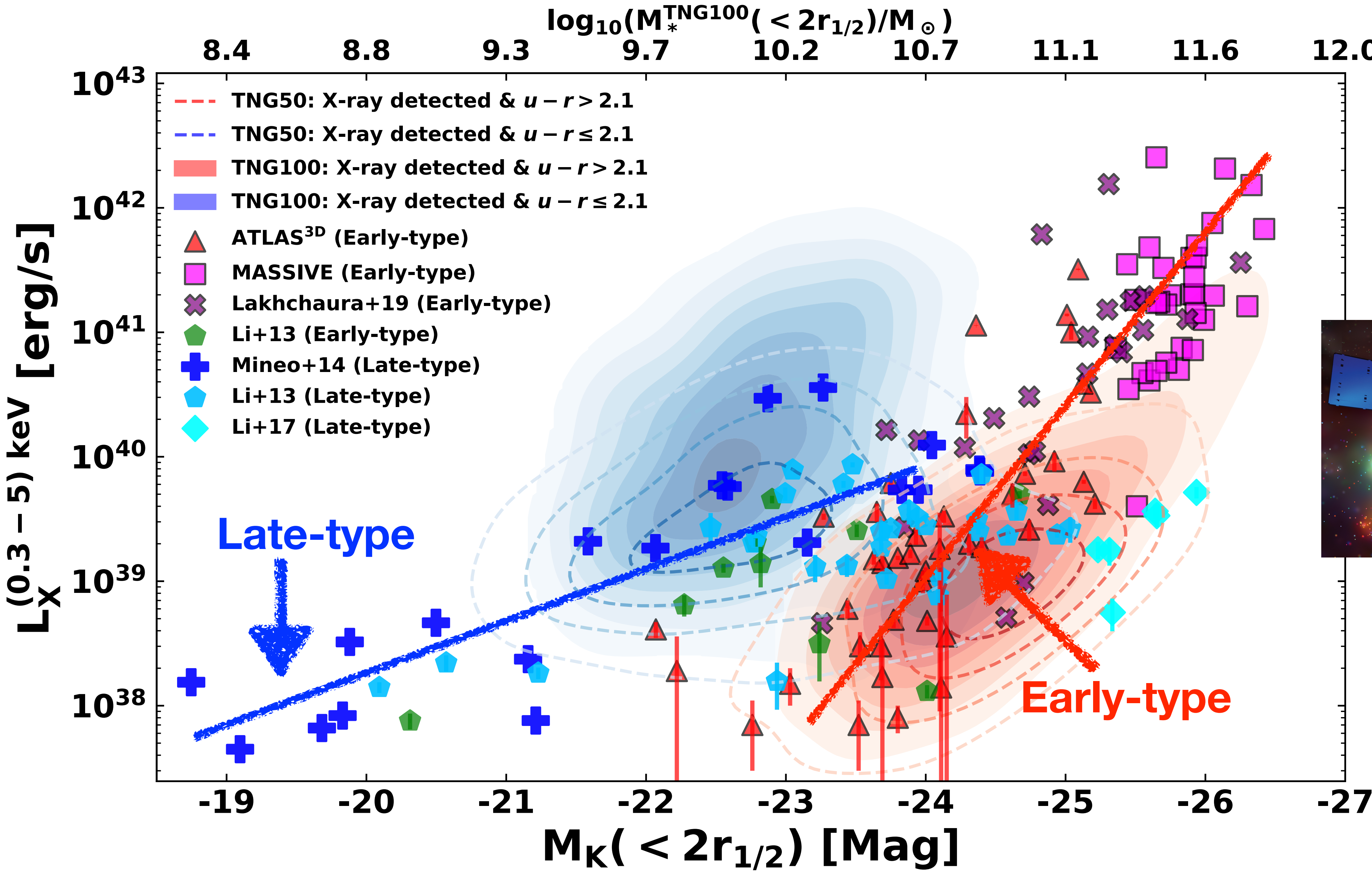


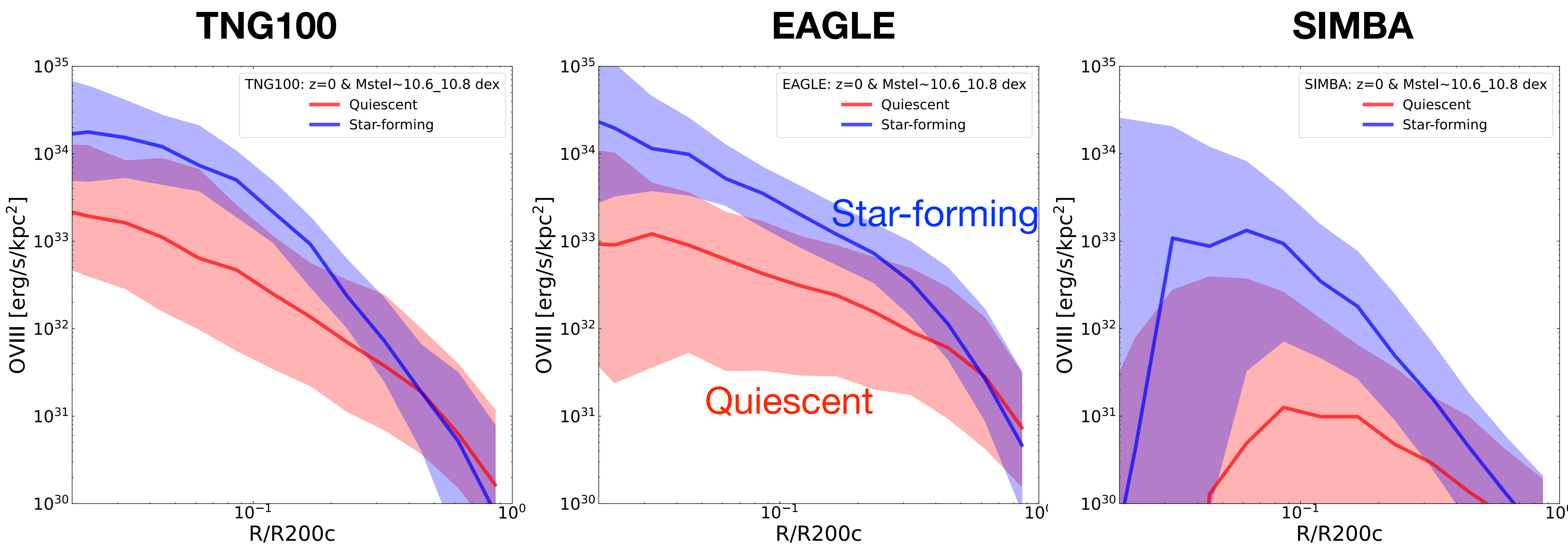
Lx dichotomy is manifestation of SMBH-driven quenching mechanism

Quantitatively supported by Chandra observations

Lx dichotomy at large distances:
Prediction for soft-Xray line emission

Truong, Pillepich et al., in prep1

OVIII surface brightness radial profile



Future X-ray missions with micro-calorimeter onboard and large FoV
will be able to detect CGM emission of individual galaxies at large radii

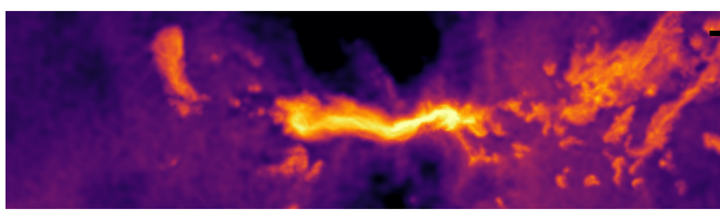
see also Oppenheimer+20, Comparat+22, Chadayammuri+22 for stacking analysis

See talk by Maxim Markevitch on Wednesday!

#2: SMBH Feedback Effects on the CGM Spatial Distribution

Outflows shaping the CGM: at the individual galaxy level

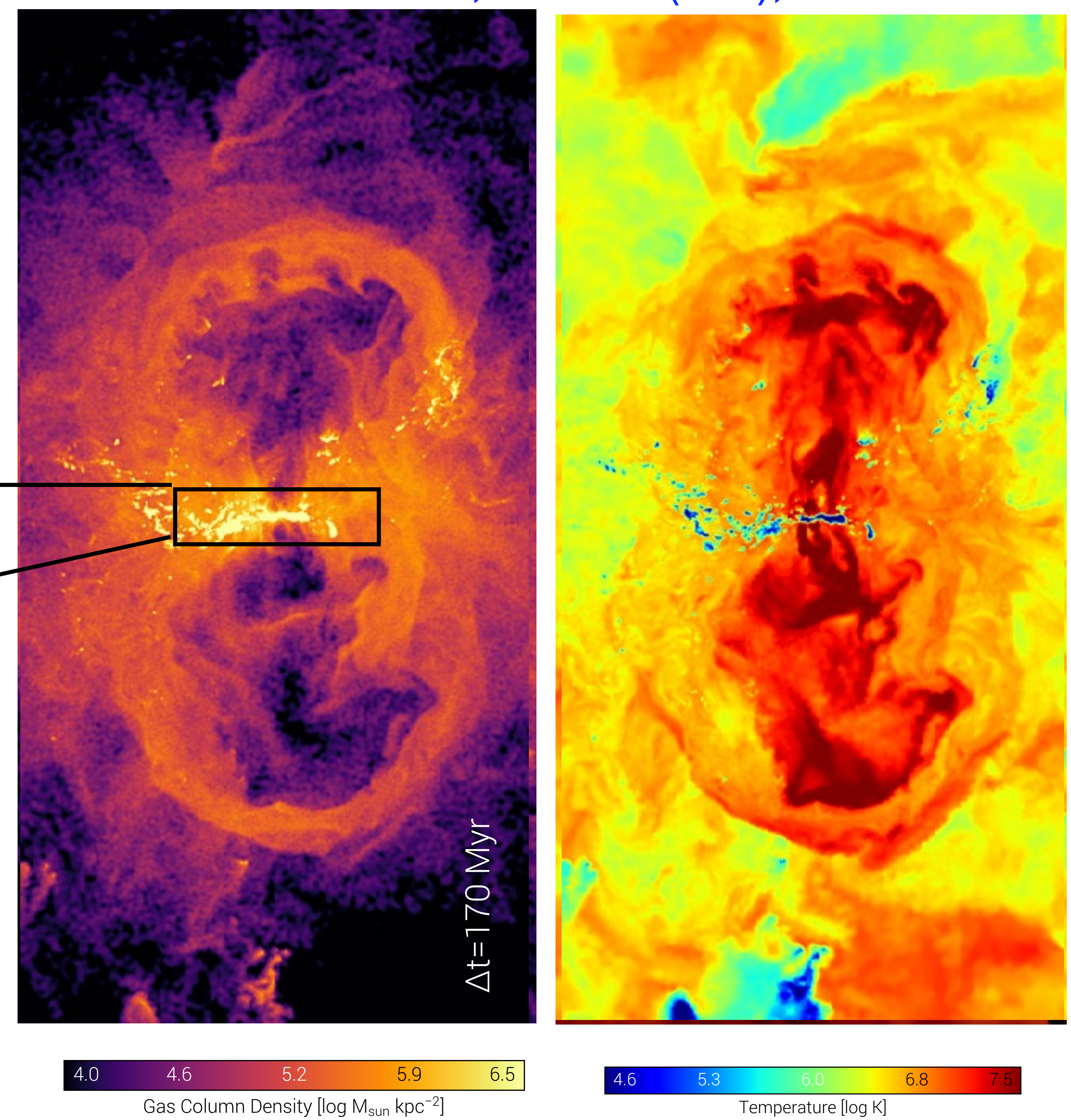
- SMBH-driven galactic outflows exhibit natural collimation despite isotropic launching.



Galaxy disk

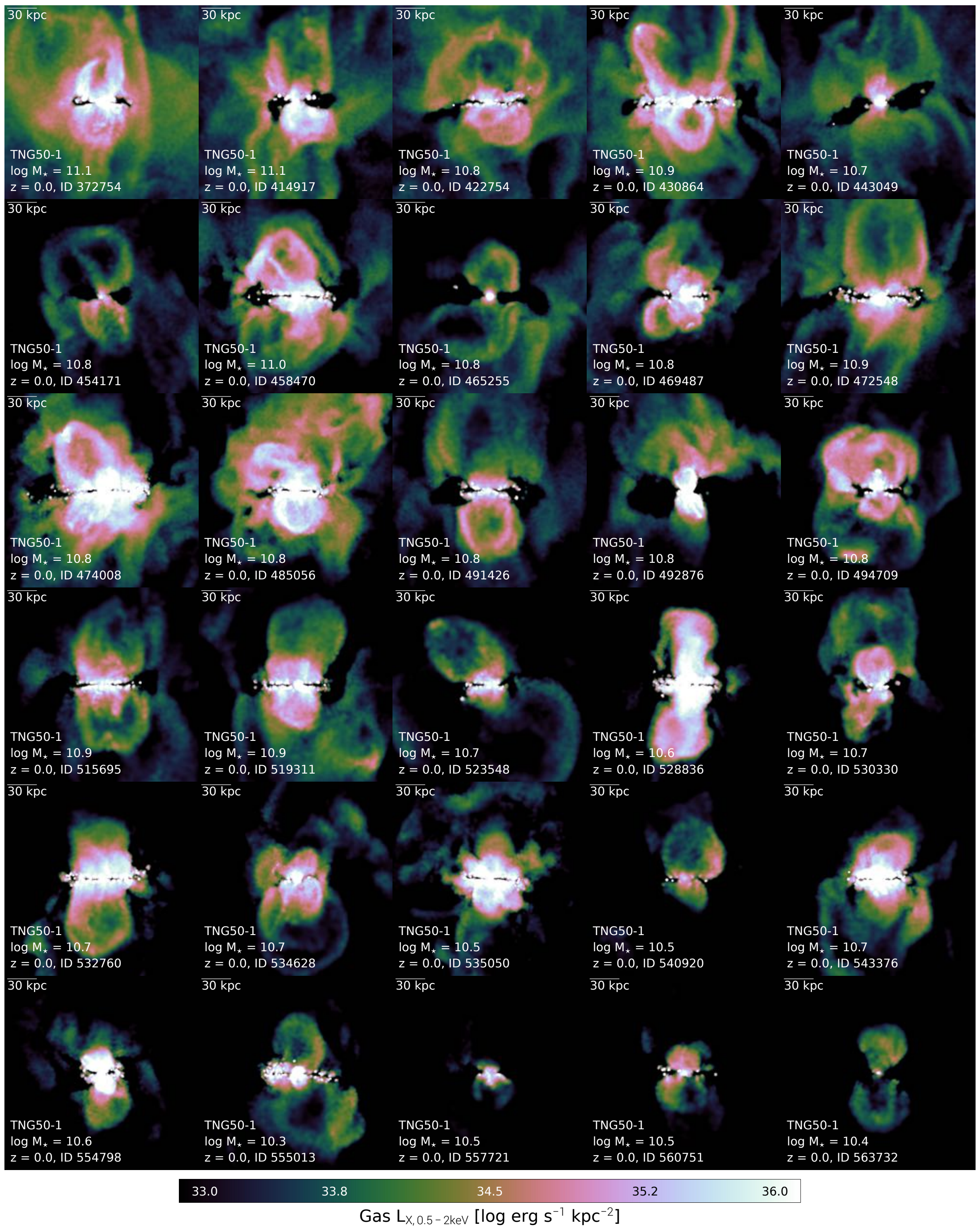
- The outflows modulate the distribution of the gas thermodynamic properties above and below the disk

SMBH feedback in action, TNG50 (z=1), *Nelson+2019*



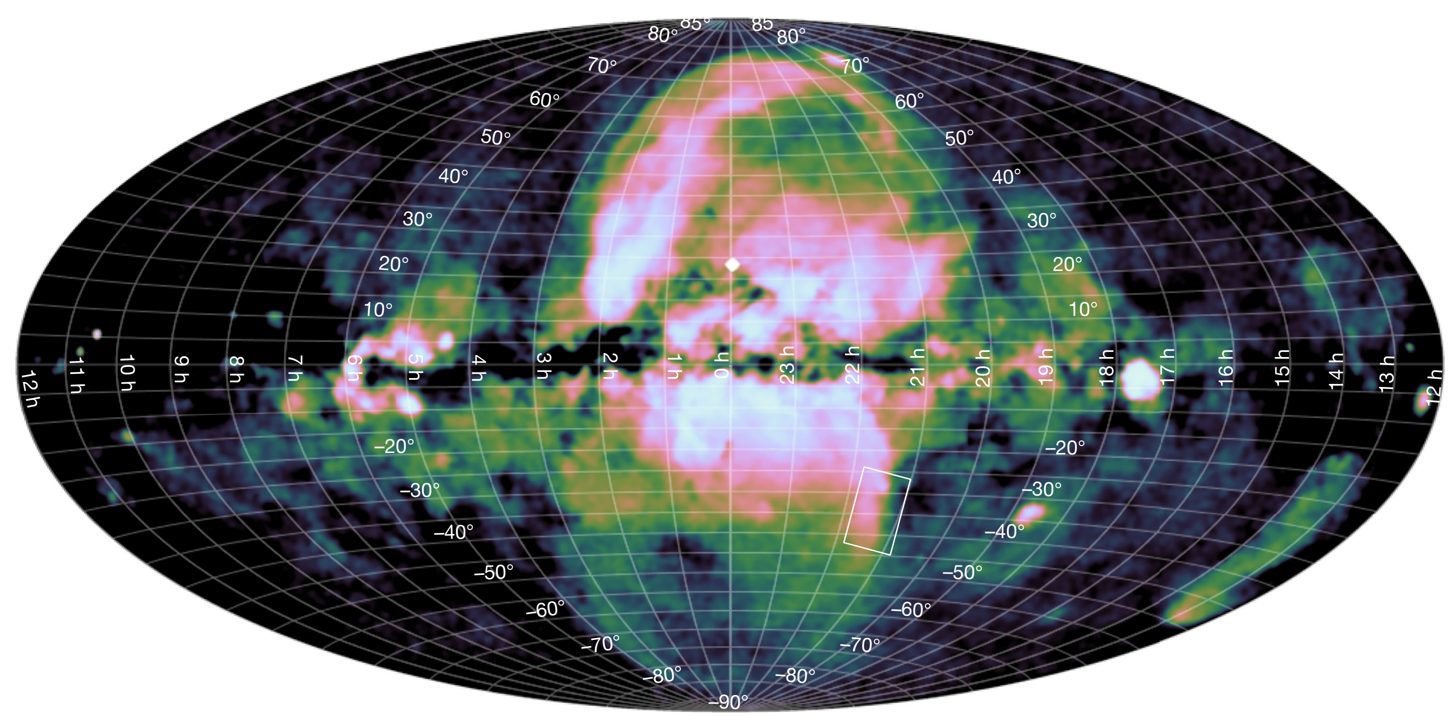
X-ray bubbles in MW-like Galaxies

TNG50 bubbles



A. Pillepich, D. Nelson, N. Truong, et al. 2021

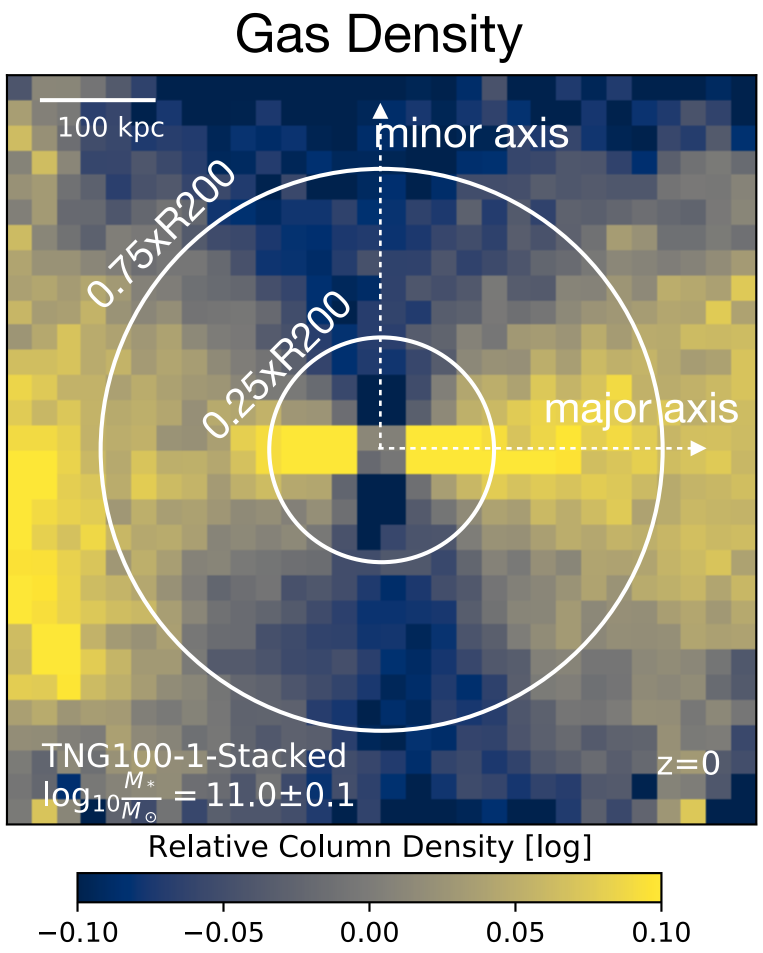
eROSITA bubbles



Predehl et al. 2020

Outflows shaping the CGM: at the population level

Edge-on stacked maps of galaxies with M_*~$10^{11.0}$ M_{sun}:



N.Truong, A. Pillepich, D. Nelson, N. Werner, L. Hernquist, 2021b

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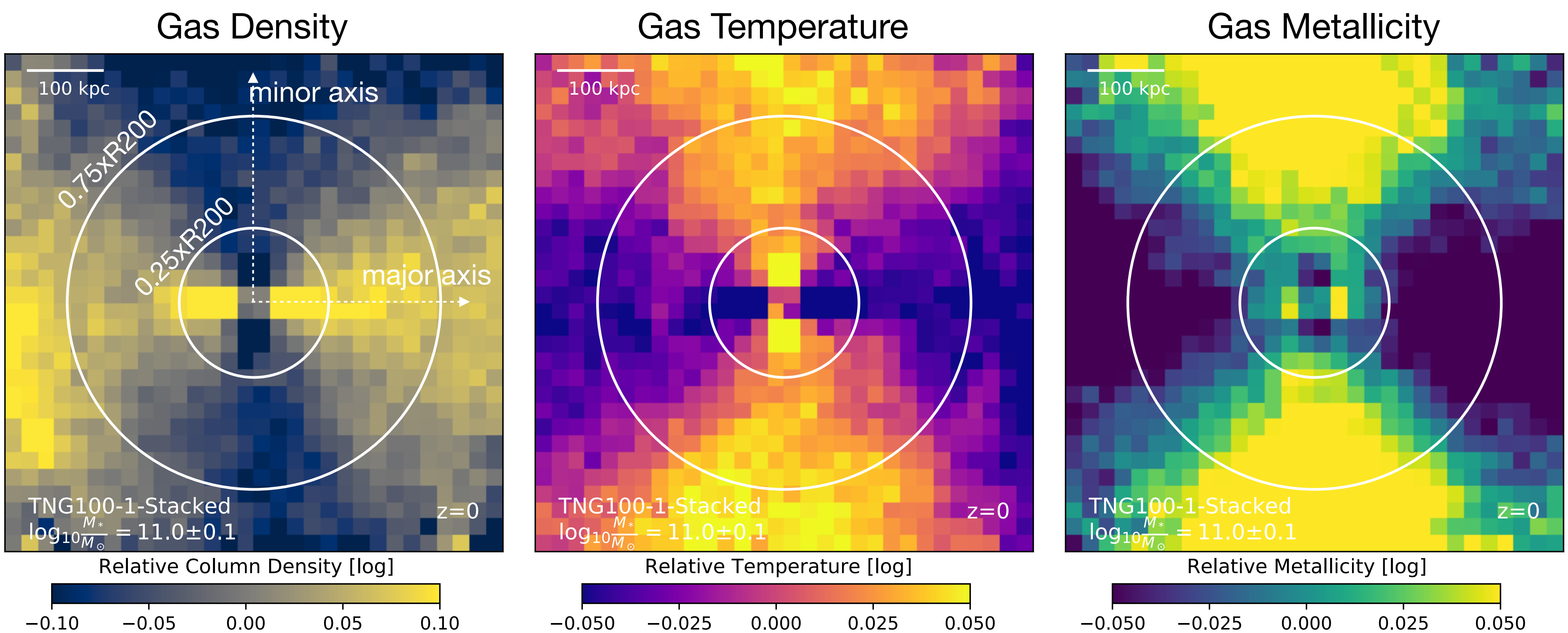
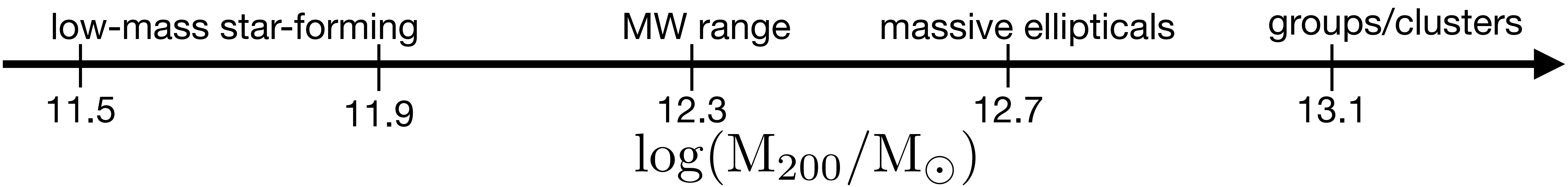


N.Truong, A. Pillepich, D. Nelson, N. Werner, L. Hernquist, 2021b

SMBH-driven outflows cause the CGM to be anisotropic in its thermodynamics and chemical content.

Anisotropic signals in the CGM: mass dependency



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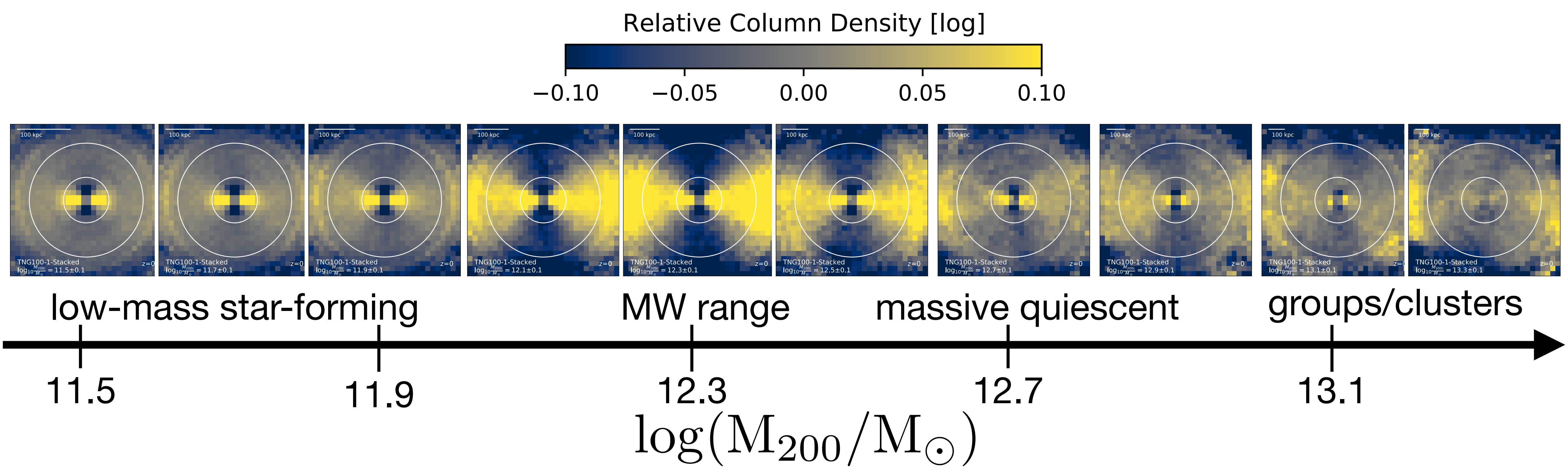

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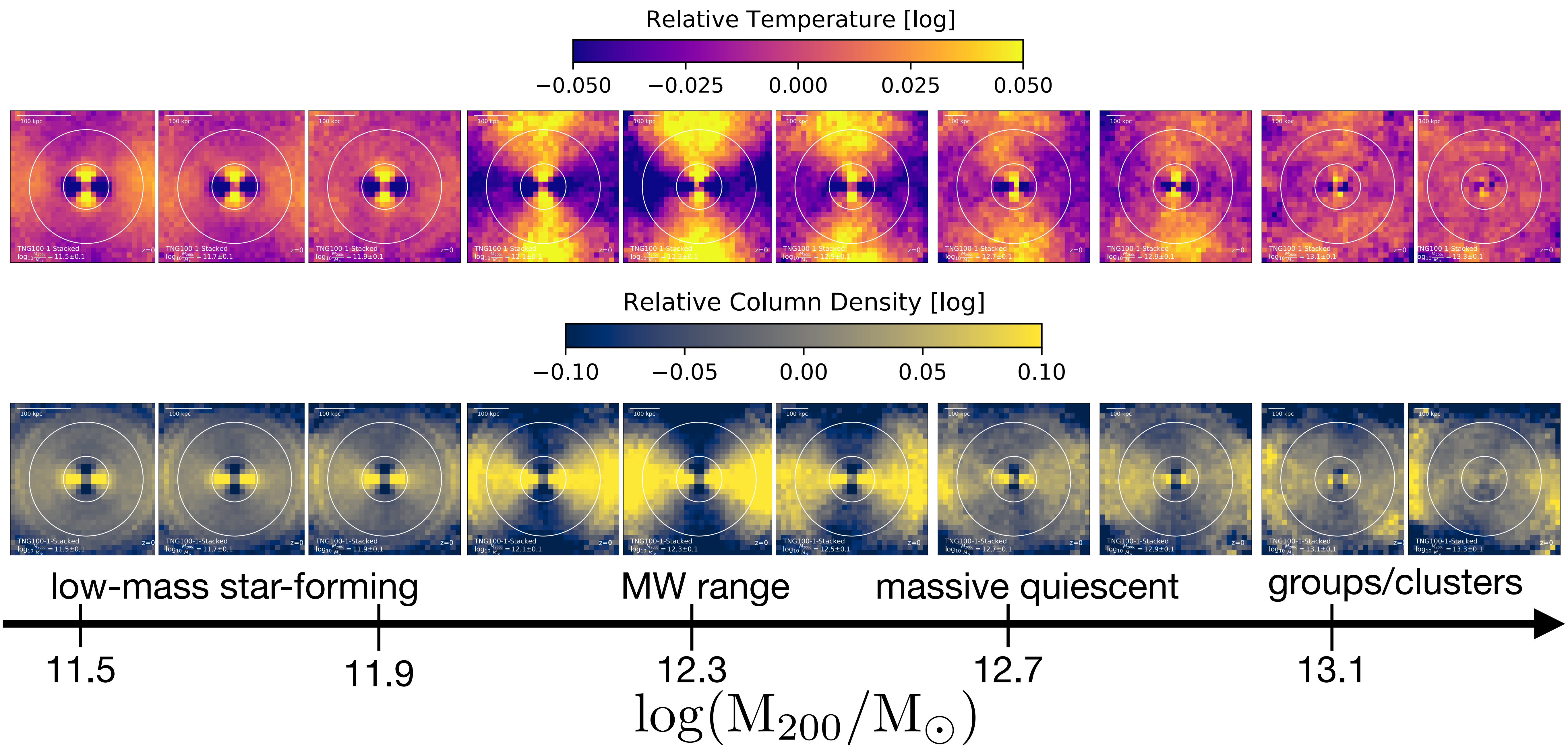

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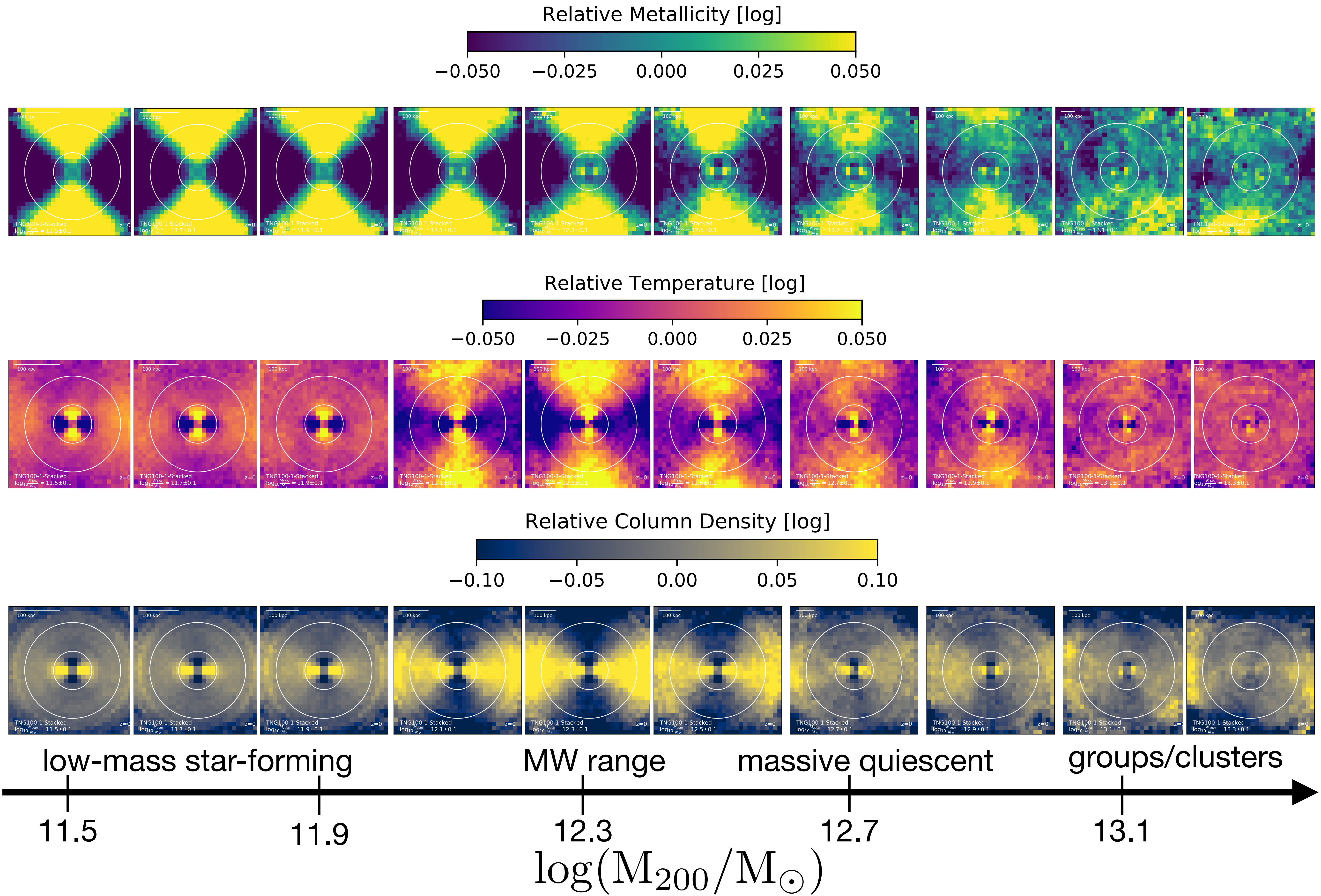

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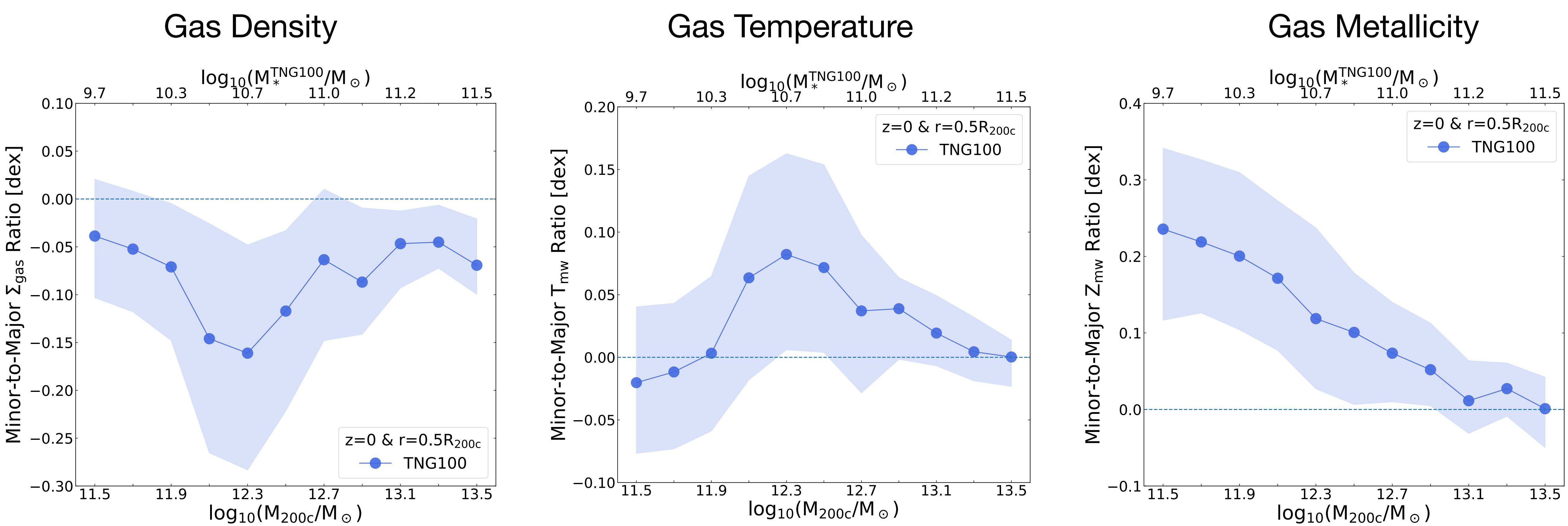
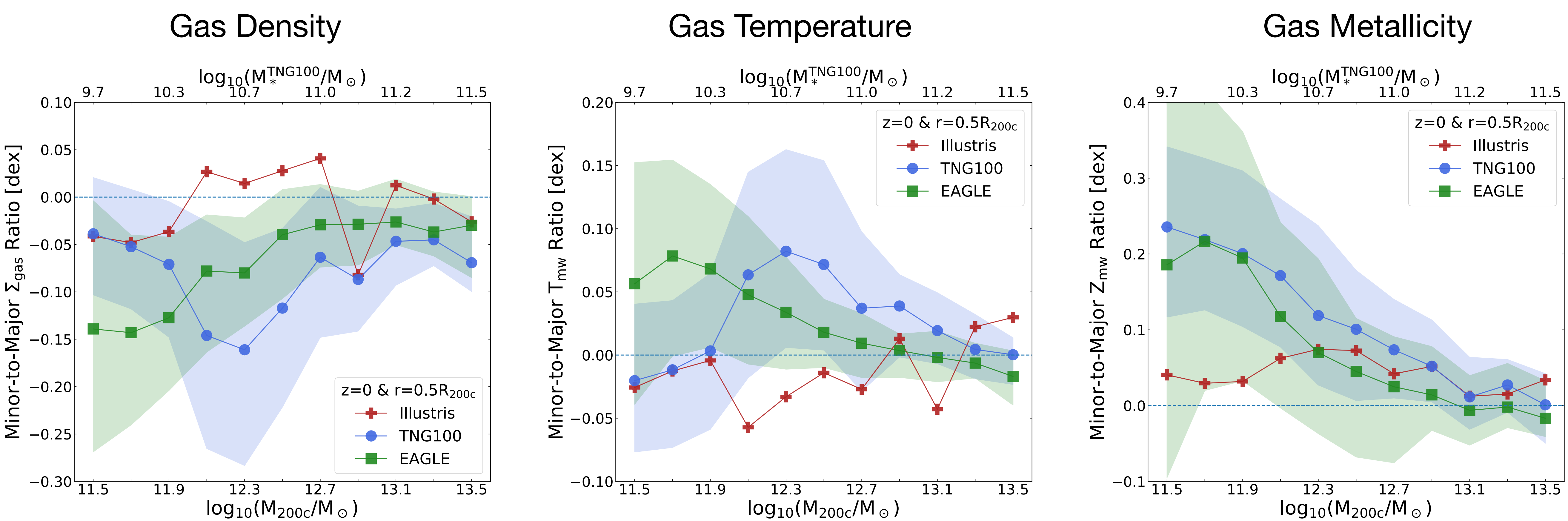


N.Truong, A. Pillepich, D. Nelson, N. Werner, L. Hernquist, 2021b

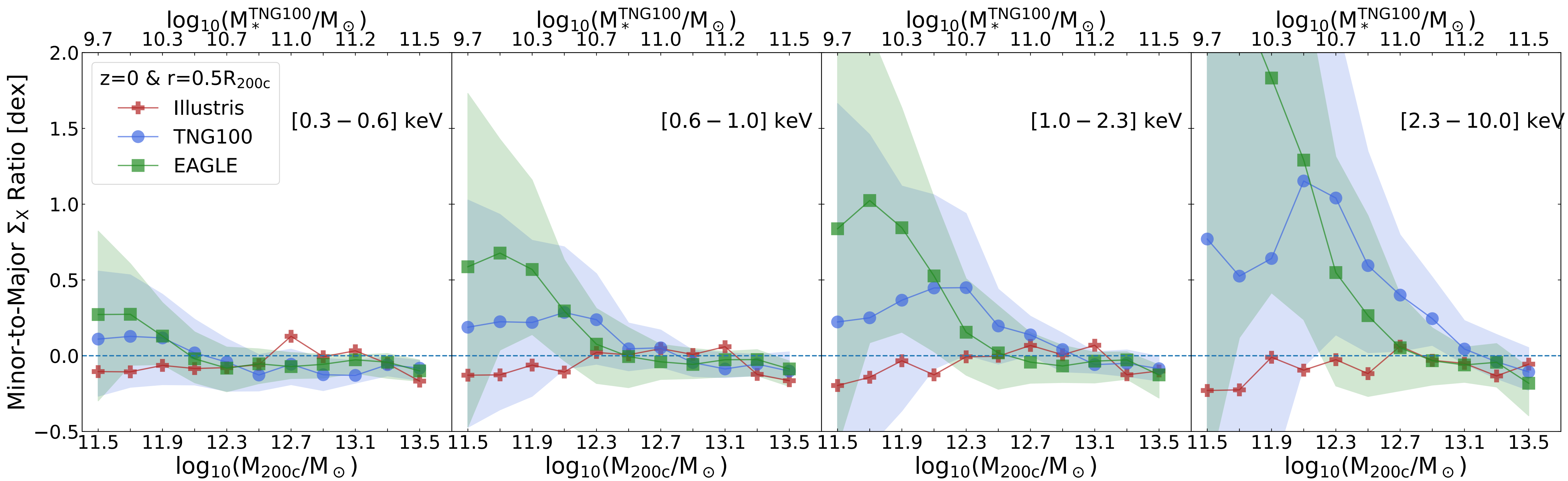
Anisotropic signals in the CGM: comparison between simulations



N.Truong, A. Pillepich, D. Nelson, N. Werner, L. Hernquist, 2021b
see also A. Nica, B. Oppenheimer et al. 2022

The signals amplitude and their mass dependency are sensitive to the underlying feedback model

Anisotropic signals in the CGM: X-ray emission

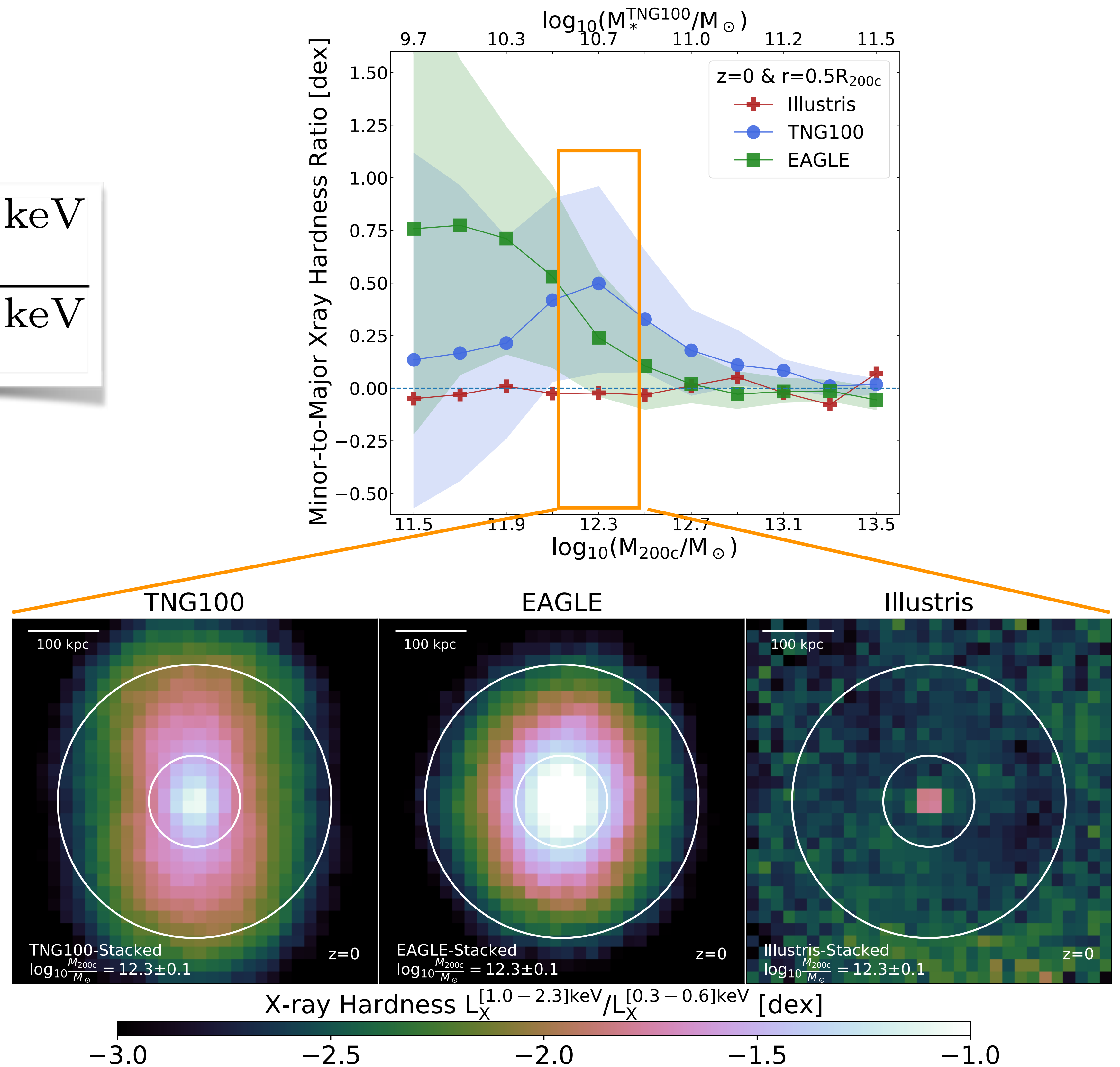


N.Truong, A. Pillepich, D. Nelson, N. Werner, L. Hernquist, 2021b

The signal in X-ray emission is complex and energy-dependent.

Anisotropic signals in the CGM: X-ray hardness

$$\mathrm{Hardness} = \frac{L_X^{[1.0-2.3]\mathrm{keV}}}{L_X^{[0.3-0.6]\mathrm{keV}}}$$



The X-ray hardness of the CGM is a promising observable in distinguishing different feedback models.

N.Truong, A. Pillepich, D. Nelson, N. Werner, L. Hernquist, 2021b

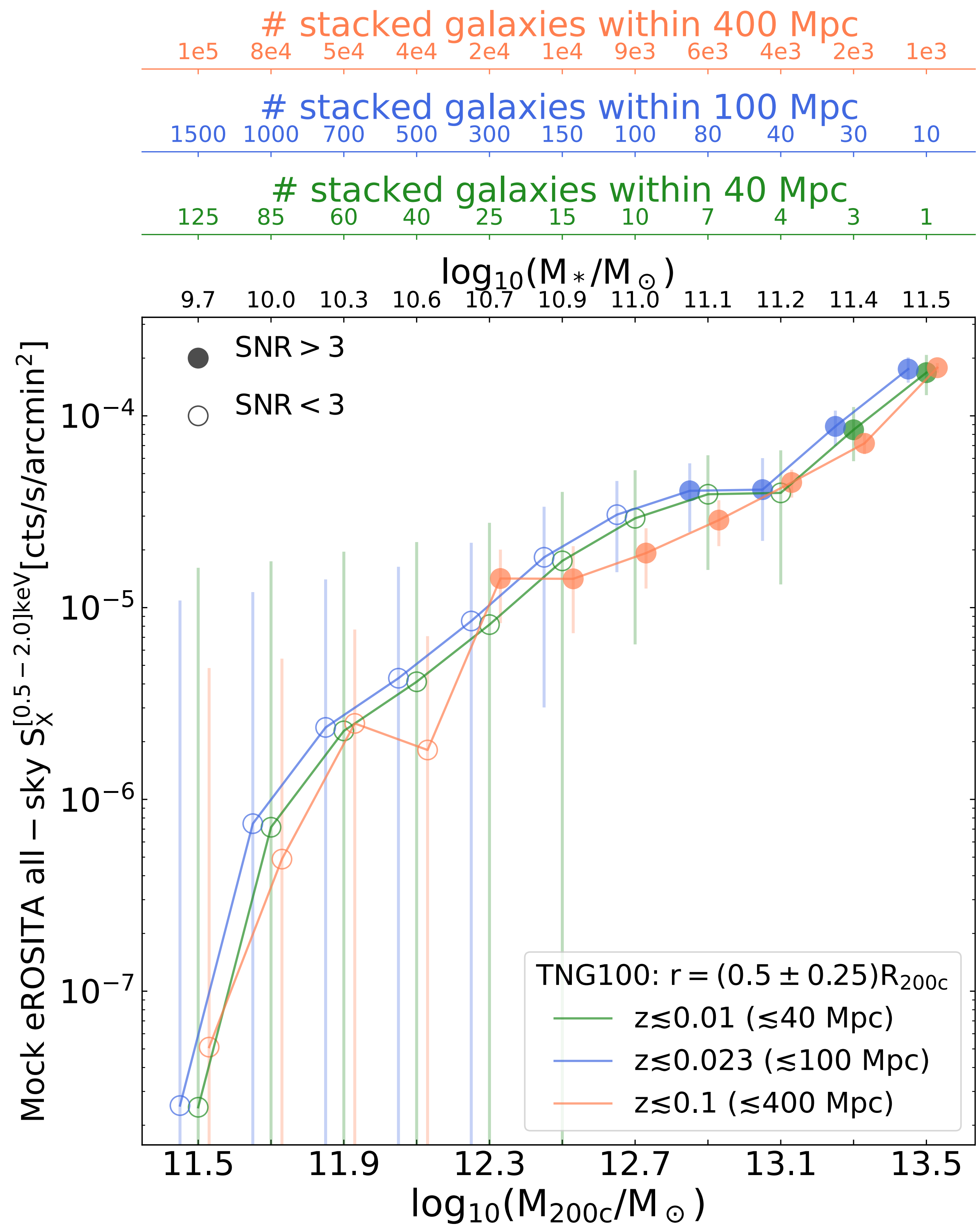
Potential detection with future X-ray observations

Future eROSITA all-sky surveys have the potential to detect signals down to the mass range of M200~10$^{12.3}$ M$_{sol}$ via stacking.

Detection of X-ray extended emission in the CGM via stacking events from the eFEDS survey:

J. Comparat, N. Truong, A. Merloni, A. Pillepich, G. Ponti, et al. 2022

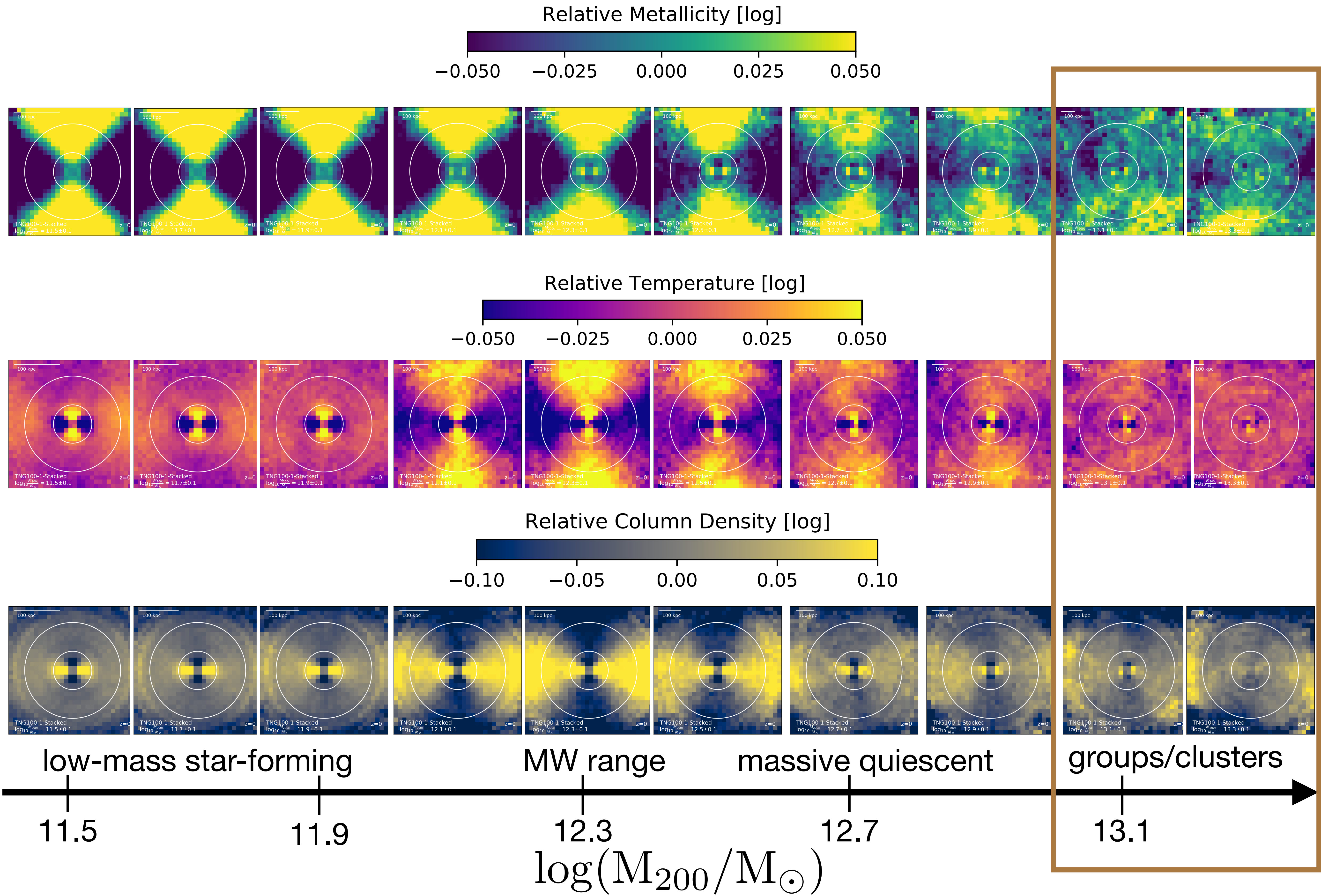
U. Chadayammuri, A. Bogdan, B. Oppenheimer, et al. 2022



N.Truong, A. Pillepich, D. Nelson, N. Werner, L. Hernquist, 2021b

#3:Effect of SMBH feedback on gas fluctuations in the IGrM/ICM

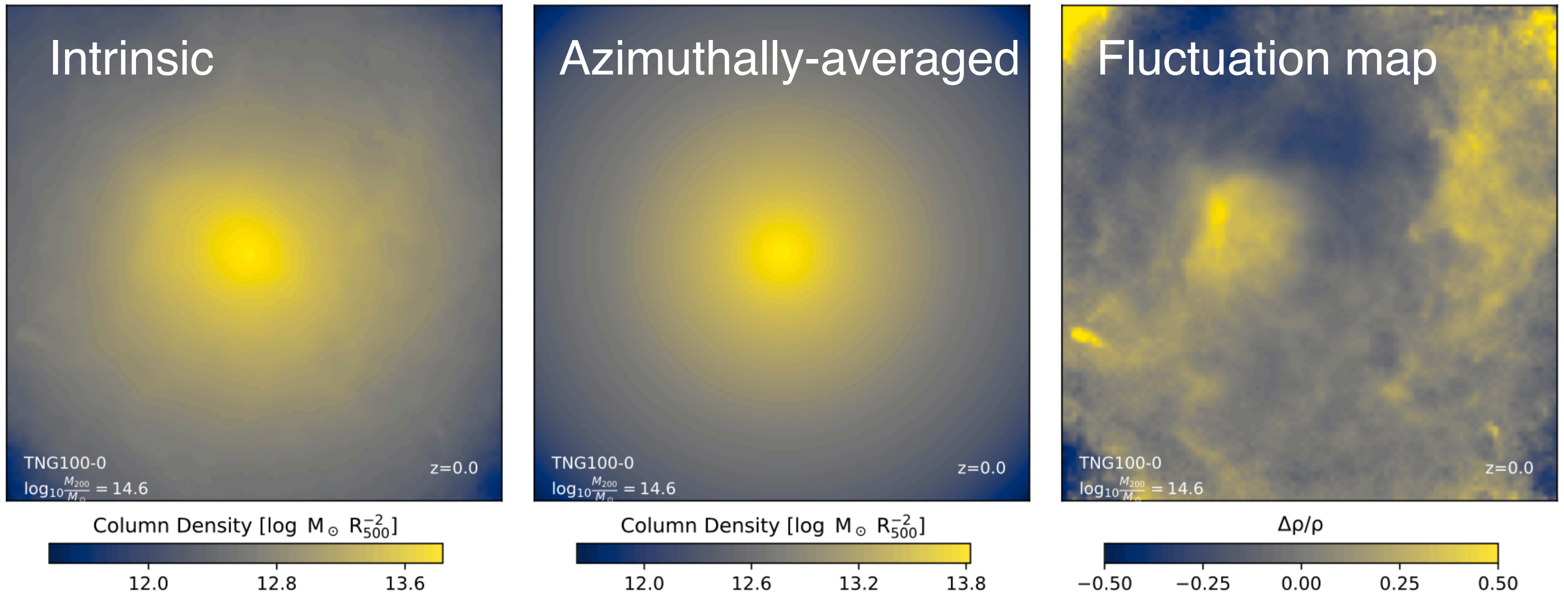
Anisotropic signals in the CGM: mass dependency



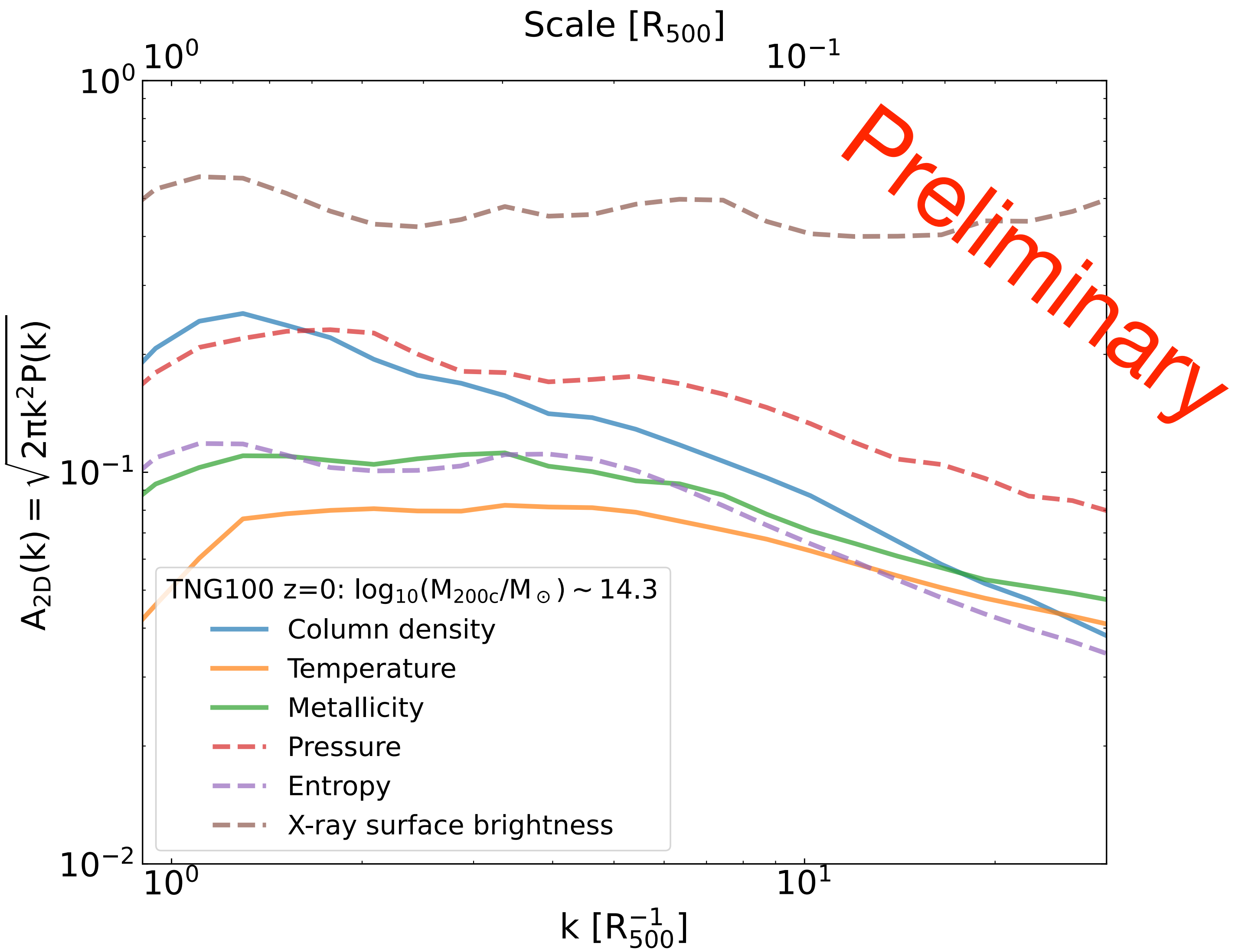
Gas fluctuations in the IGrM/ICM

Truong, Pillepich et al., in prep2

2D projected maps of a $10^{14.6}$ M⊙ halo from TNG100 (>3e5 K gas; 2R500c x 2R500c)



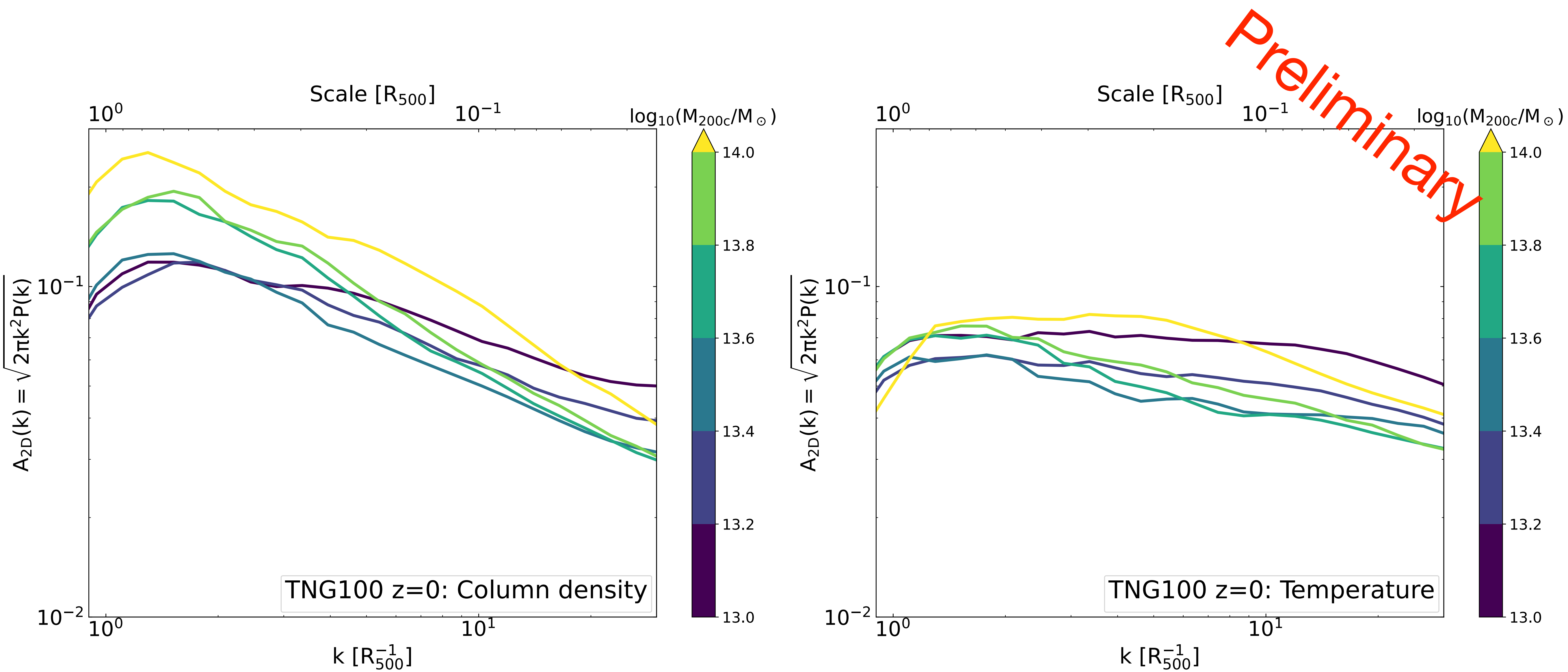
2D characteristic amplitude of the gas fluctuations



As proposed by Churazov+12, Gaspari+13, Zhuravleva+13,+14

Halo mass dependence of the fluctuations

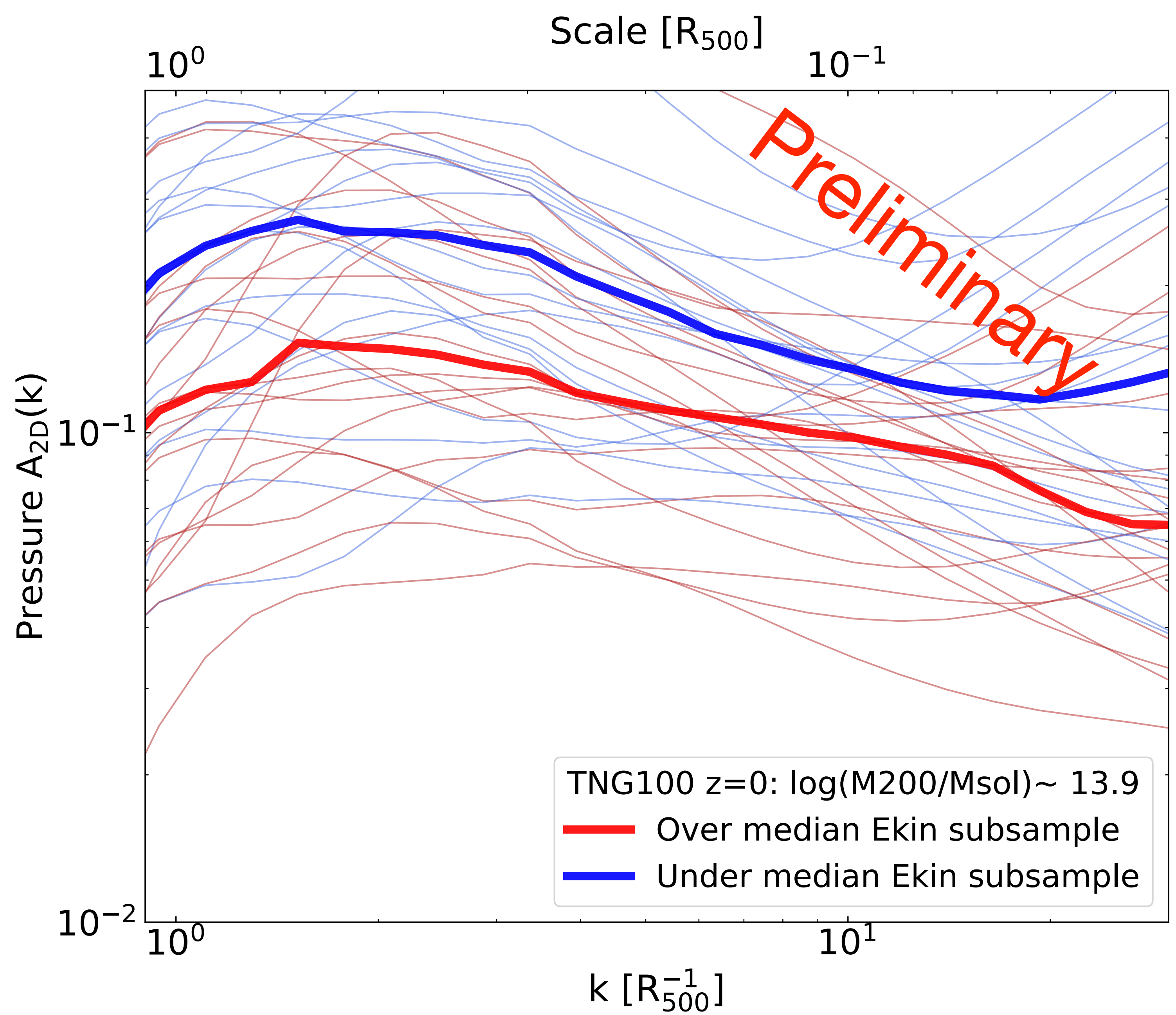
Truong, Pillepich et al., in prep2



Effects of SMBH kinetic feedback

Truong, Pillepich et al., in prep2

Halos are subdivided into 2 subsamples based on their accumulated SMBH kinetic feedback energy (Ekin).



Anti-correlation between the fluctuation amplitude and the amount of injected feedback energy

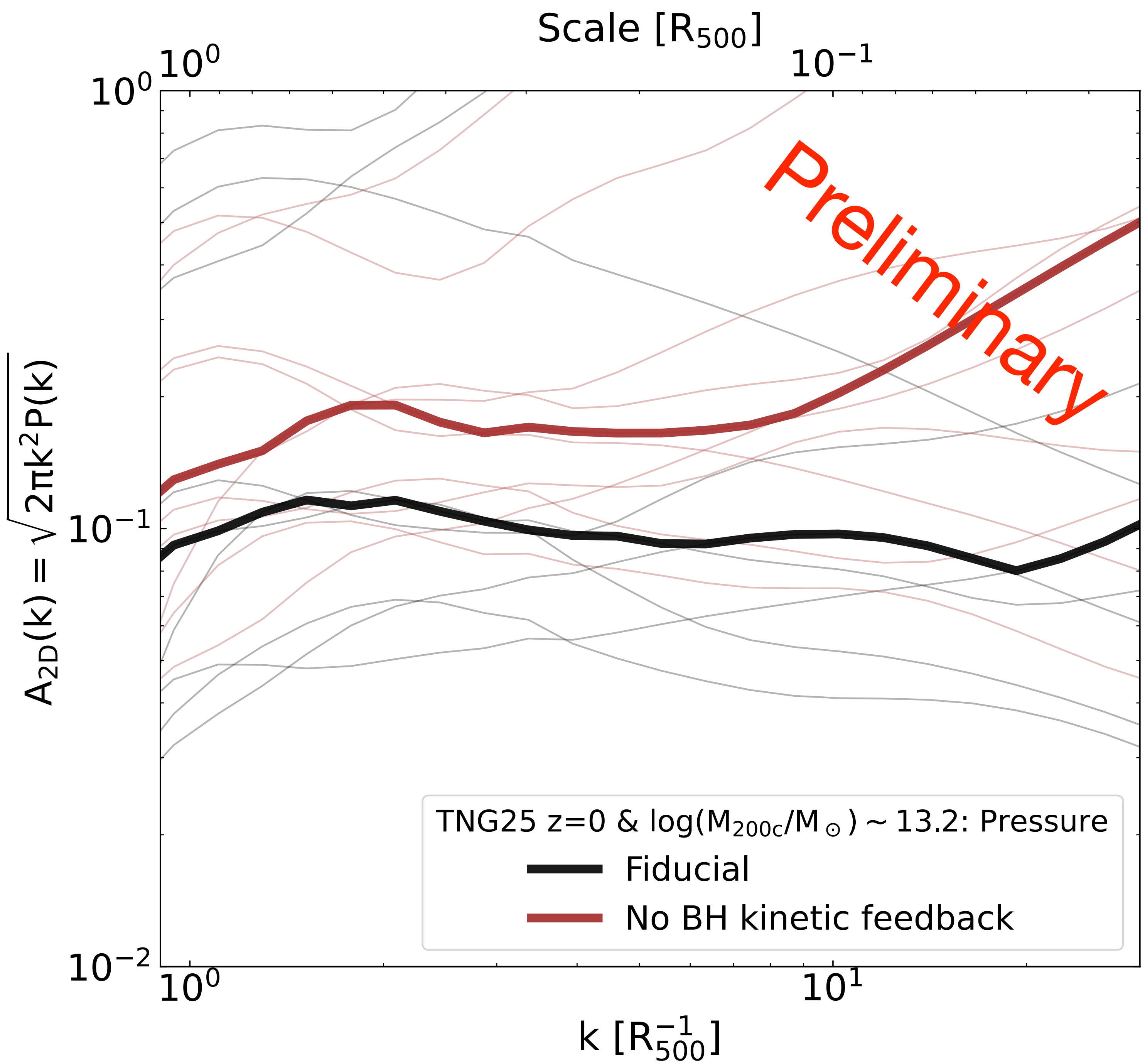
Effects of SMBH kinetic feedback

Truong, Pillepich et al., in prep2

Comparison between 2 model variations in TNG simulations of ~37 Mpc/side box, similar resolution to TNG100

- Fiducial model
- No SMBH kinetic feedback model

Each sims produces ~10 halos with $M_{200}>10^{13}$ M_{sol}



Gas density clumping factor

$$C_\rho = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

as proposed by Mathiesen, Evrard, Mohr, 1999

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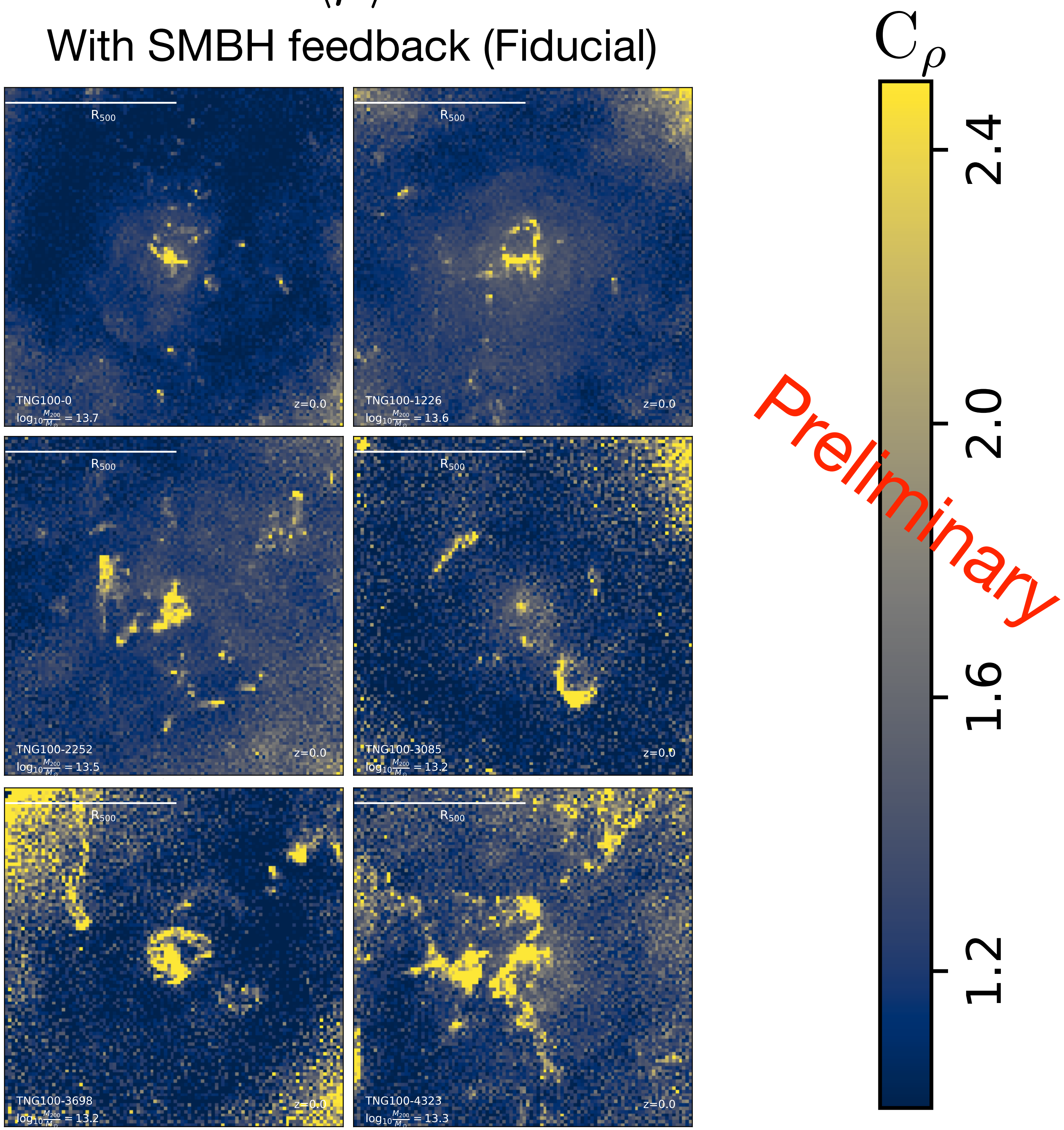
Truong, Pillepich et al., in prep2

With SMBH feedback (Fiducial)



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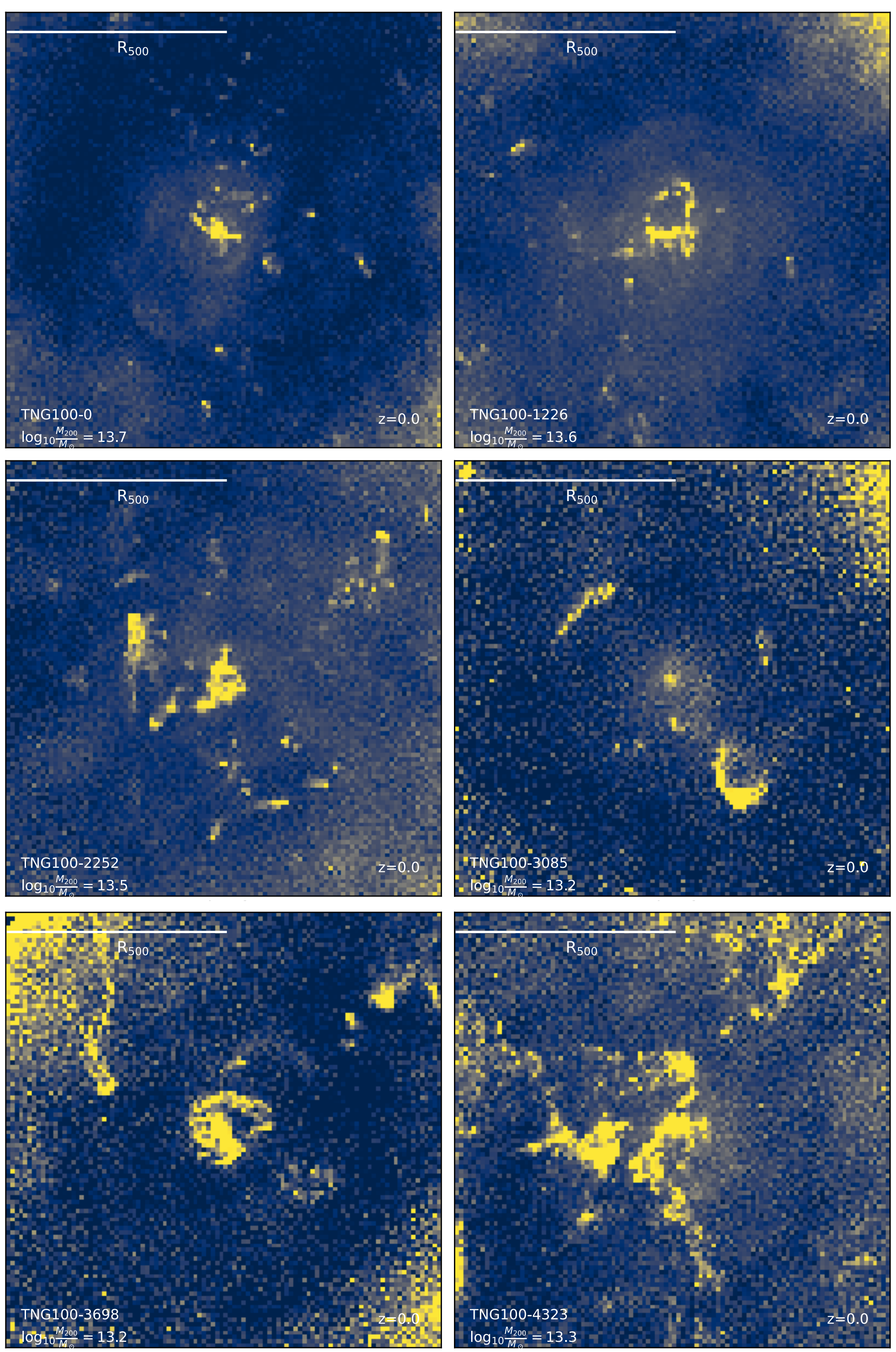
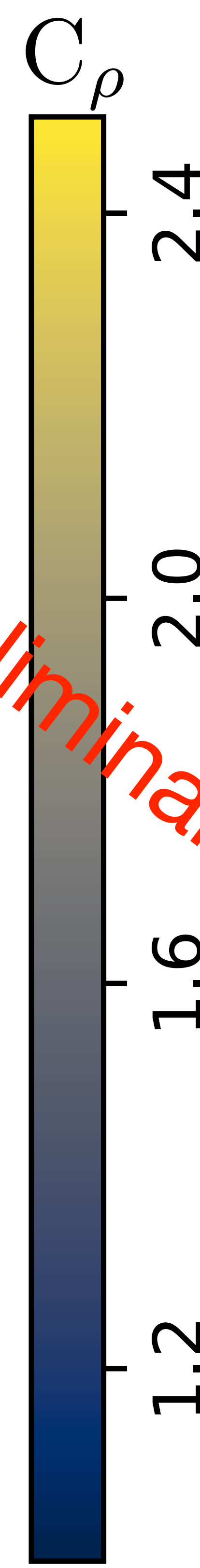
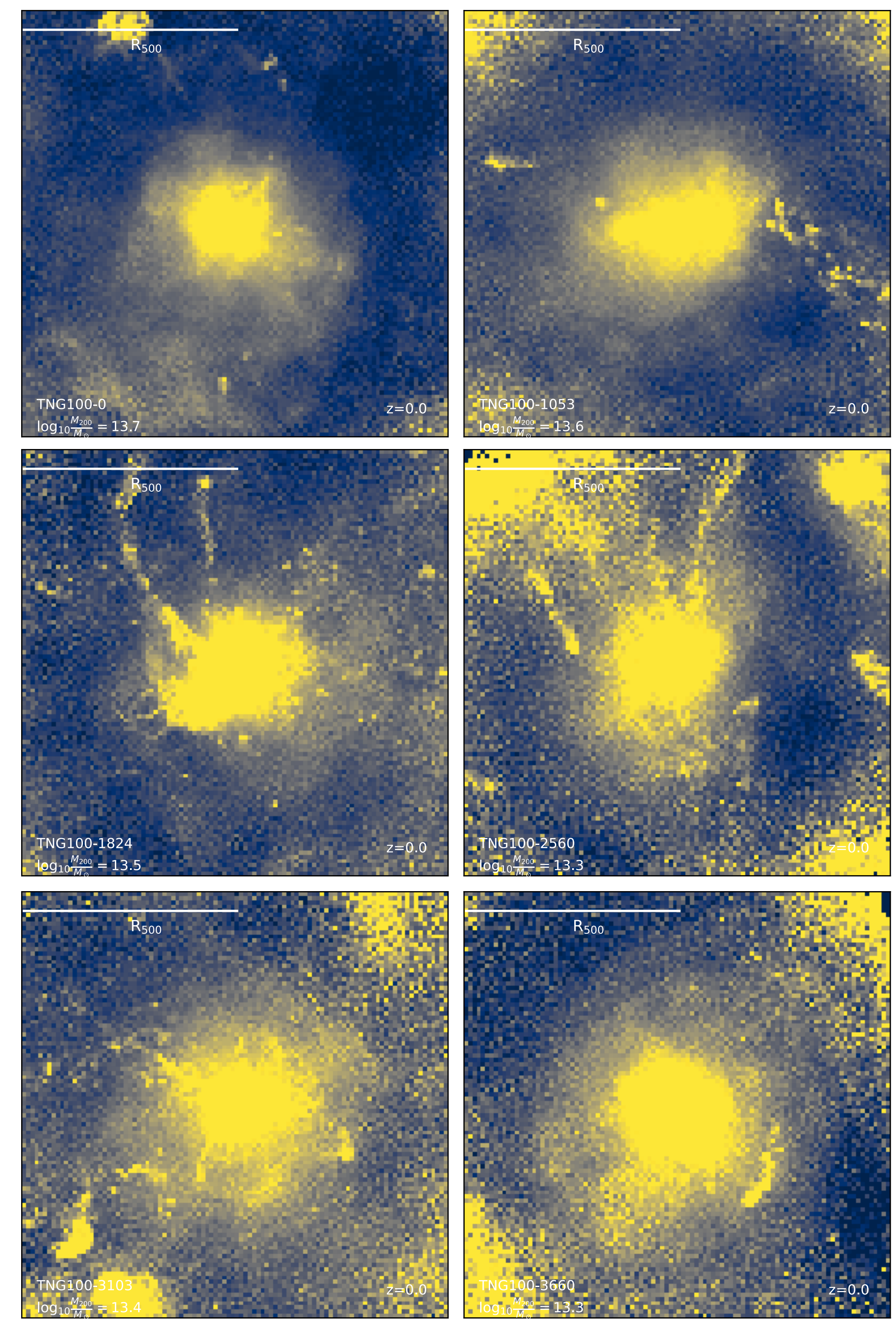




Without SMBH feedback



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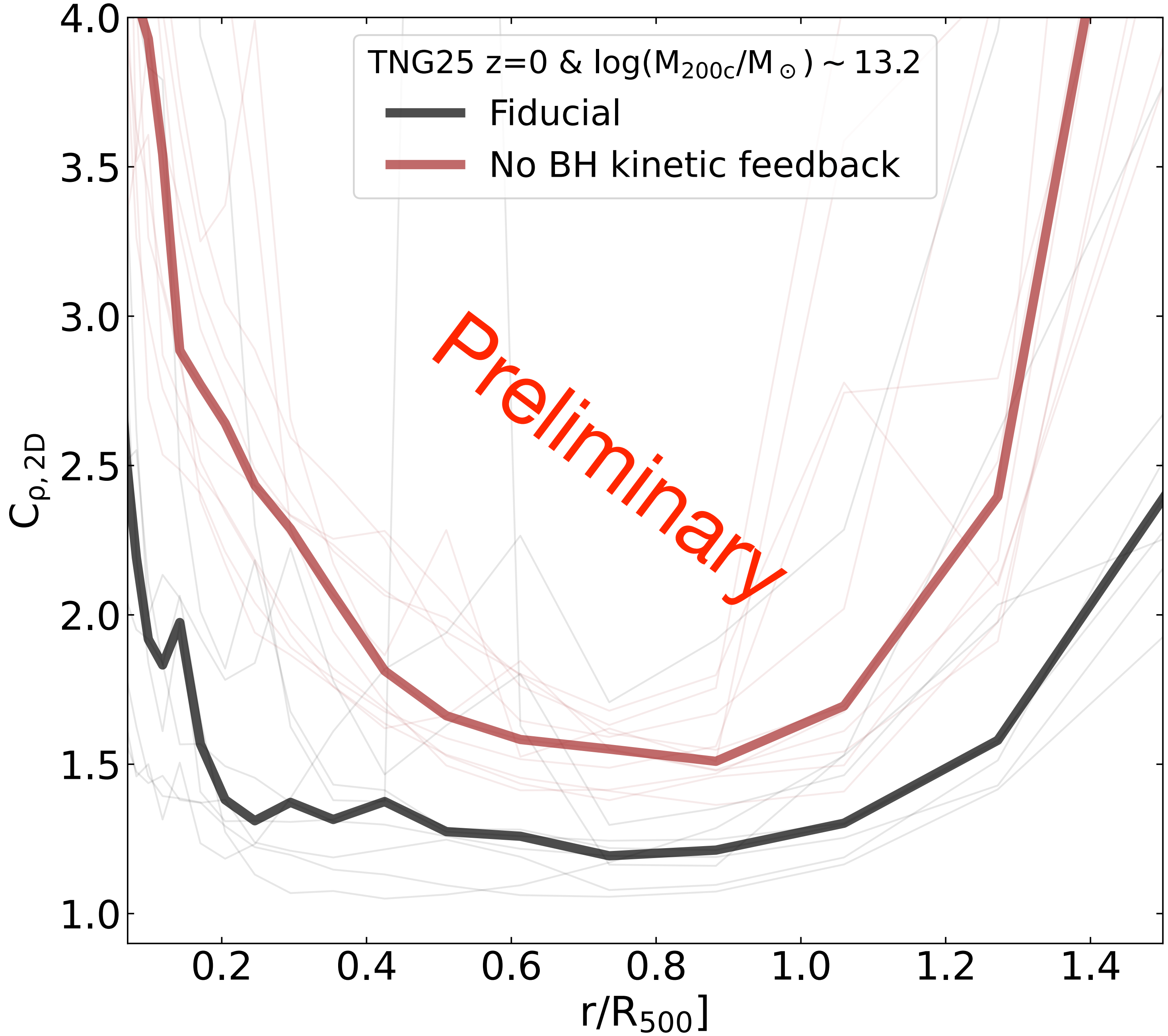

In TNG SMBH feedback helps to smooth out the density and thermal distribution

see also Planelles+14, Rasia+14, Vazza+13, Nagai & Lau 11

Summary & Conclusion

How does SMBH feedback affect the hot gaseous atmospheres (at the population level)?

Predictions from IllustrisTNG simulations:

1. Quenching mechanism:

   SMBH ejective effect manifests in Lx dichotomy between Sf-ing vs quenched galaxies.

2. Anisotropy in the CGM:

   SMBH-driven outflows cause the CGM anisotropic in its thermodynamics and chemical content.

3. Inhomogeneity in the IGrM/ICM:

   SMBH feedback helps reduce gas fluctuations (preliminary!).