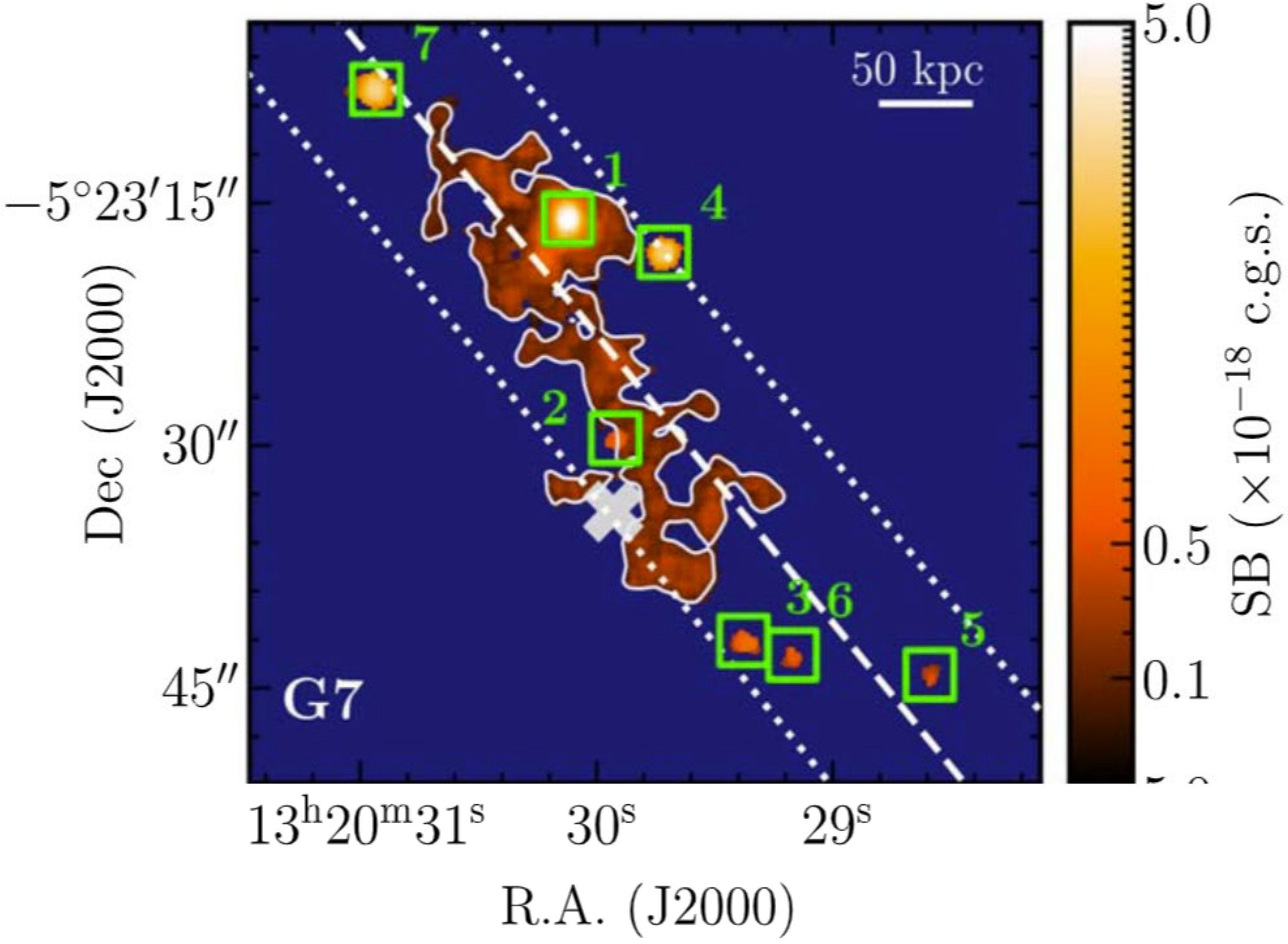
Insights from the FLAMINGO and COLIBRE cosmological hydrodynamical simulations

Joop Schaye (Leiden)

MUSEQuBES: A z = 3.6, 260 pkpc long Lyα filament

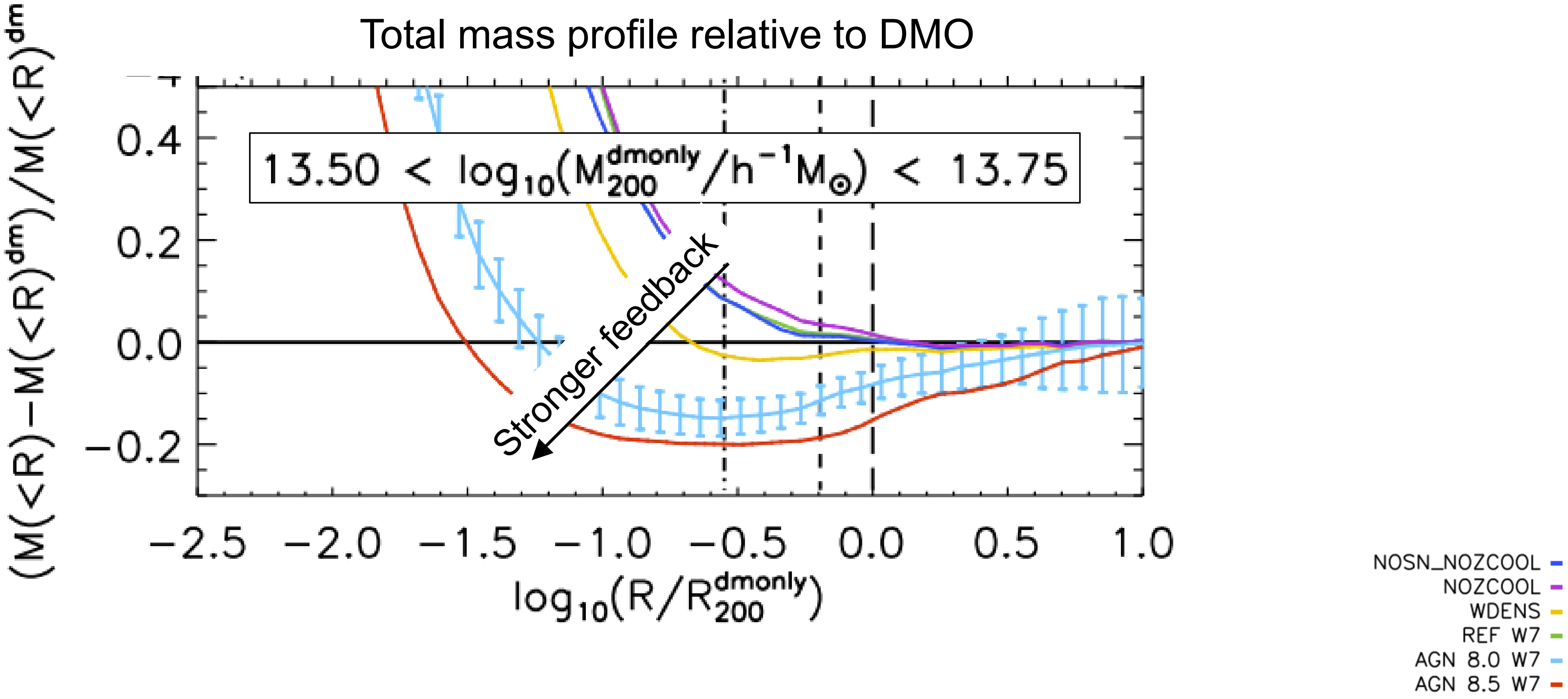


The filament contains

- 7 LAEs
- A [X/H] ~ -3.7, n_H ~ 10^{-4} cm^{-3} (Δ ~ 5) pLLS absorber

Banerjee, Muzahid, JS, Cantalupo, Johnson (2025)

Effect of baryons on halo density profiles



Baryons compress mass near the halo center, but suppress the density in the outer halo.

Velliscig, van Daalen, JS+ (2014)

MNRAS **526**, 4978–5020 (2023)

The FLAMINGO project: cosmological hydrodynamical simulations for large-scale structure and galaxy cluster surveys

Joop Schaye,[1★] Roi Kugel,[1] Matthieu Schaller,[1,2] John C. Helly,[3] Joey Braspenning,[1] Willem Elbers,[3] Ian G. McCarthy,[4] Marcel P. van Daalen,[1] Bert Vandenbroucke,[1] Carlos S. Frenk,[3] Juliana Kwan,[4] Jaime Salcido,[4] Yannick M. Bahé,[1,5] Josh Borrow,[3,6] Evgenii Chaikin,[1] Oliver Hahn,[7,8] Filip Huško,[3] Adrian Jenkins,[3] Cedric G. Lacey[3] and Folkert S. J. Nobels[1]

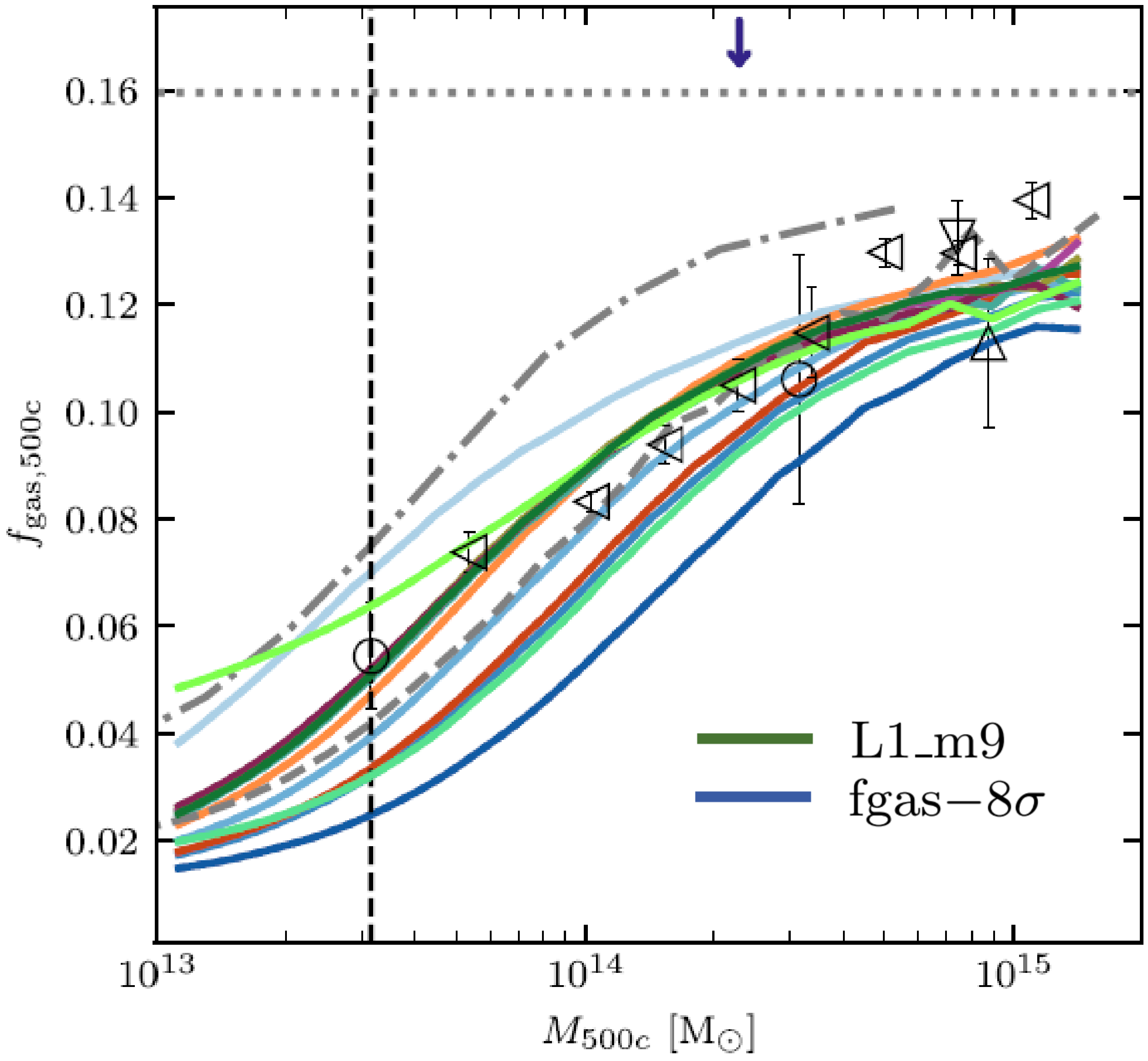
VIRGO

FLAMINGO: Basic features

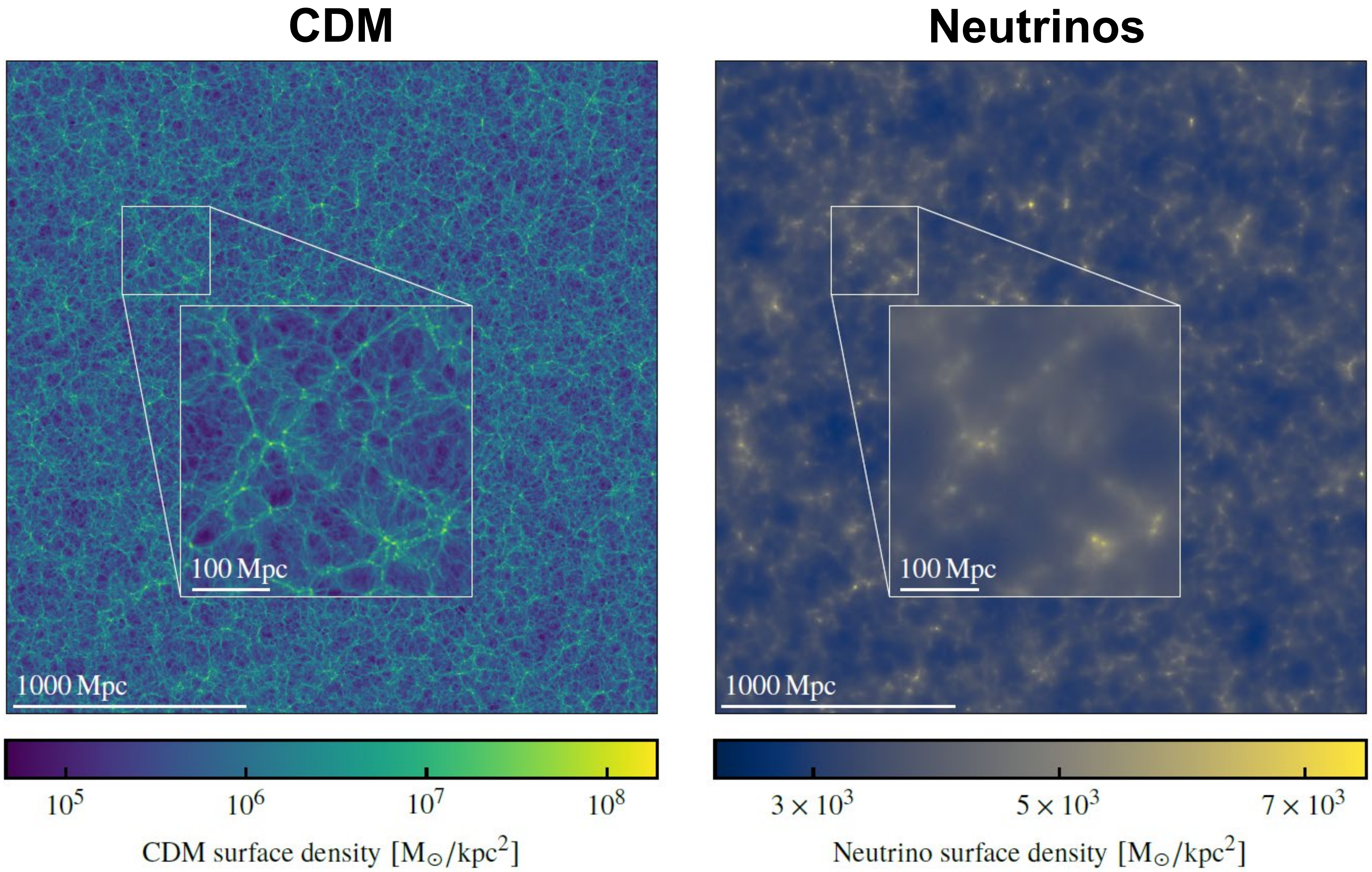
- Full physics hydro (SPH) with neutrino particles
- Subgrid stellar and AGN feedback calibrated using machine learning (emulation with Gaussian processes) to the observed:
  - Galaxy stellar mass function
  - Cluster gas fraction – halo mass relation (at R_{500}) derived from pre-eROSITA X-ray + lensing data
- Box size: ≥ 1 Gpc
- Gas particle mass: ≥ 10^8 $M_\odot$
- Up to 2.8×10^{11} particles ($2 \times 5040^3 + 2800^3$, 2.8 Gpc box)
- On-the-fly lightcone outputs
- *Variations in cosmology, neutrino mass, cluster gas fractions and stellar mass function, AGN feedback implementation*

JS+ (2023)

Cluster gas fractions inferred from (pre-eROSITA) X-rays + weak lensing

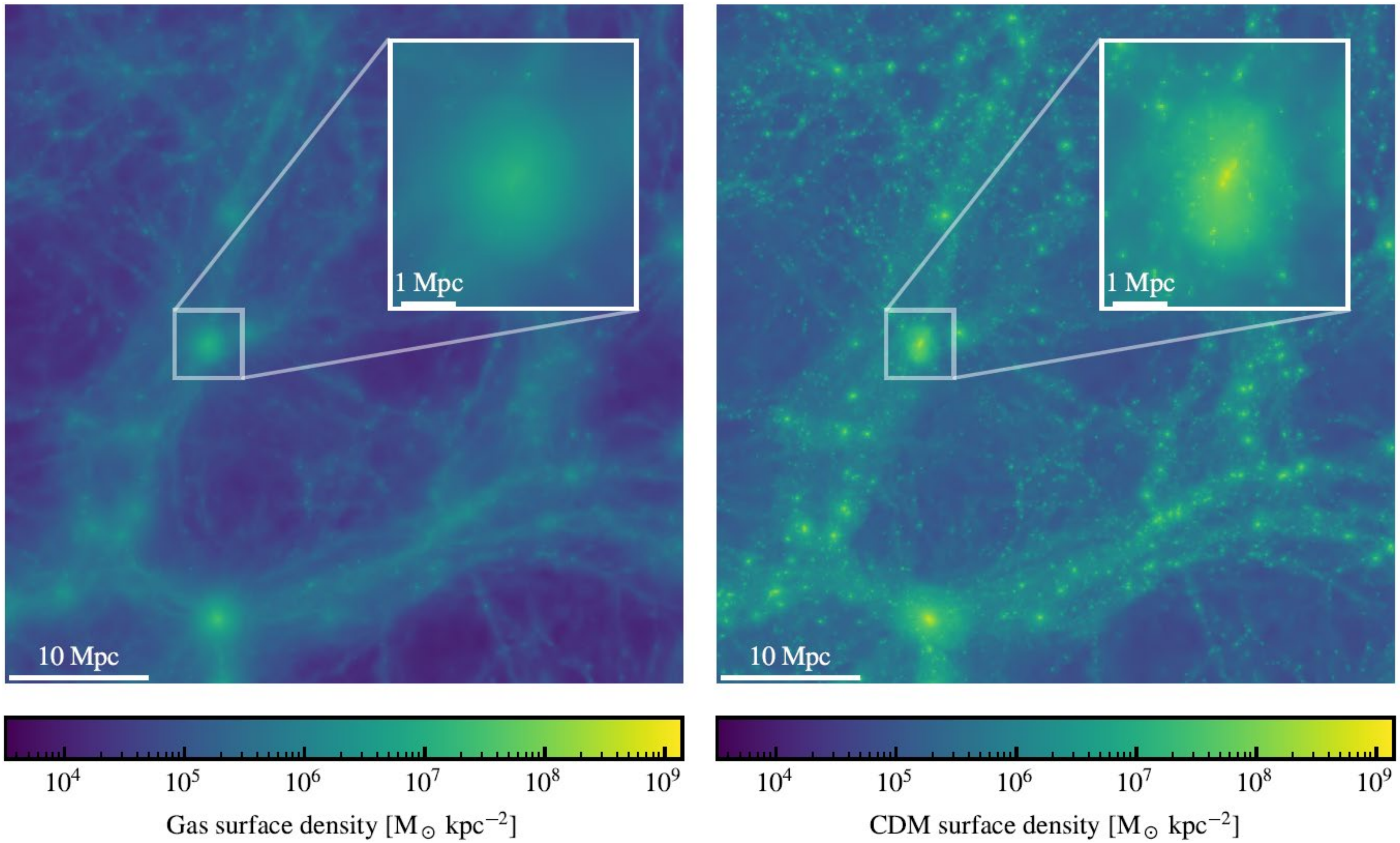


JS+ (2023)


CDM
Neutrinos
100 Mpc
1000 Mpc
100 Mpc
1000 Mpc
10^5
10^6
10^7
10^8
CDM surface density [$M_\odot/kpc^2$]
3×10^3
5×10^3
7×10^3
Neutrino surface density [$M_\odot/kpc^2$]

JS+ (2023)

Gas CDM



JS+ (2023)

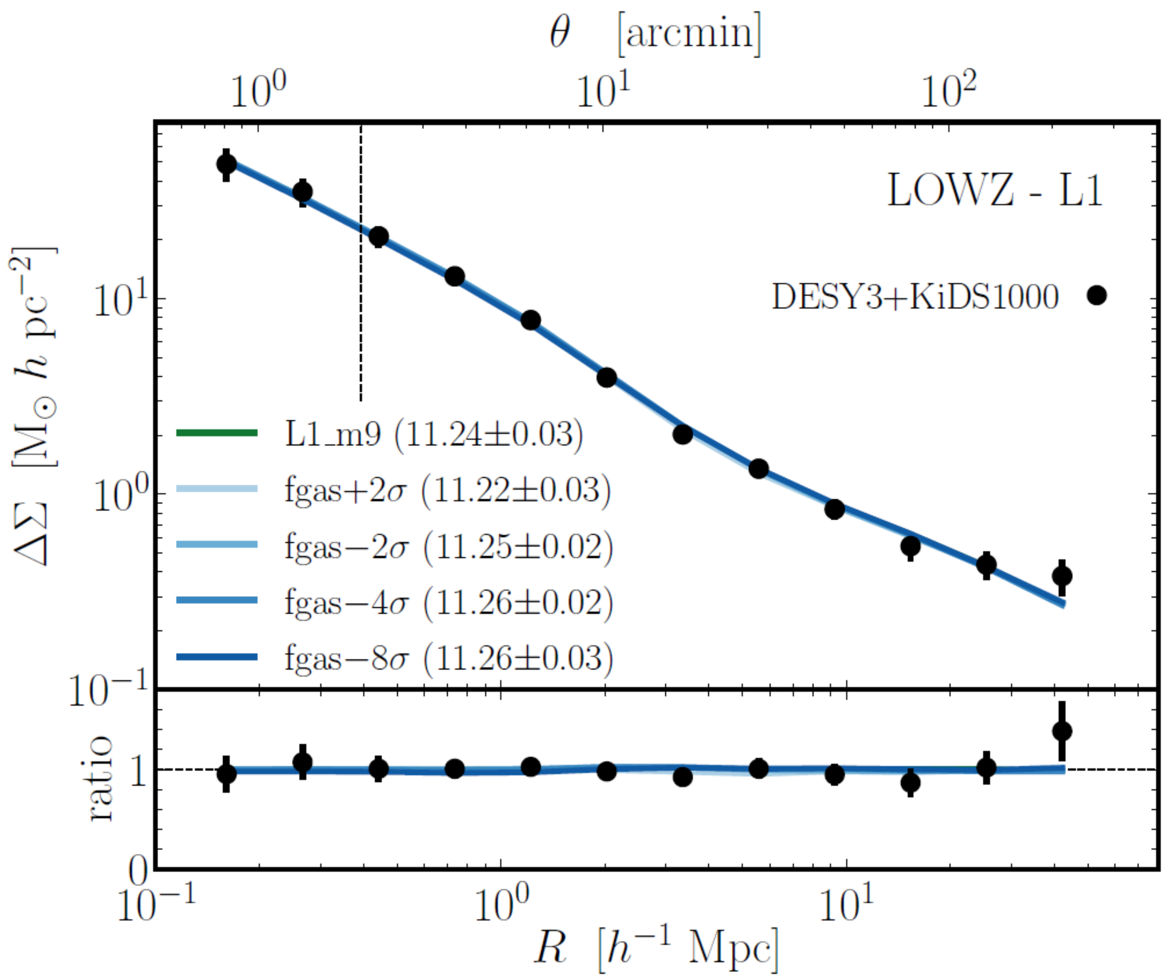
Recent developments pointing to strong feedback

- Lensing + ACT kSZ (Schneider+22, Bigwood+24, McCarthy+25, Hadzhiyska+25)
- eROSITA gas fractions (Popesso+25)
- eROSITA gas fractions + ACT kSZ (Kovač+25)
- Lensing + tSZ (Pandey+25)
- Planck tSZ power spectrum re-analysis (Efstathiou+25)

However,

- Different observables probe different halo masses, radii, and redshifts (e.g. McCarthy+23, Lucie-Smith+25)
- S_8 tension between large-scale structure and primary CMB disappearing (Wright+25, Efstathiou+25) and could probably not be solved by feedback in any case (McCarthy+18, 23)

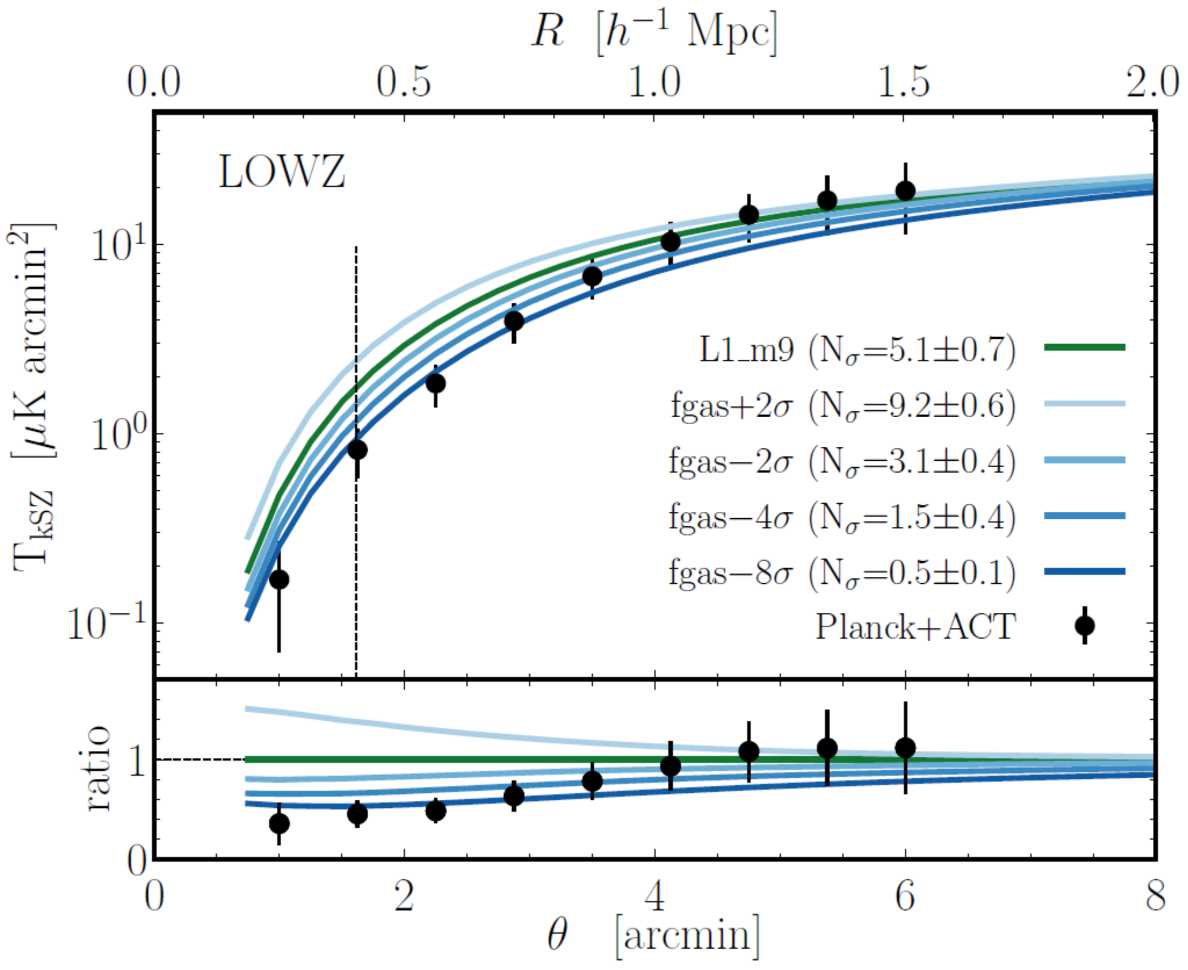
Galaxy-galaxy lensing for stacks of z~0.5 galaxies



For each model, the stellar mass is selected to match galaxy-galaxy lensing, $M^* \approx 10^{11.3}$ $M_\odot$ (as observed)

McCarthy, Amon, JS+ (2025)

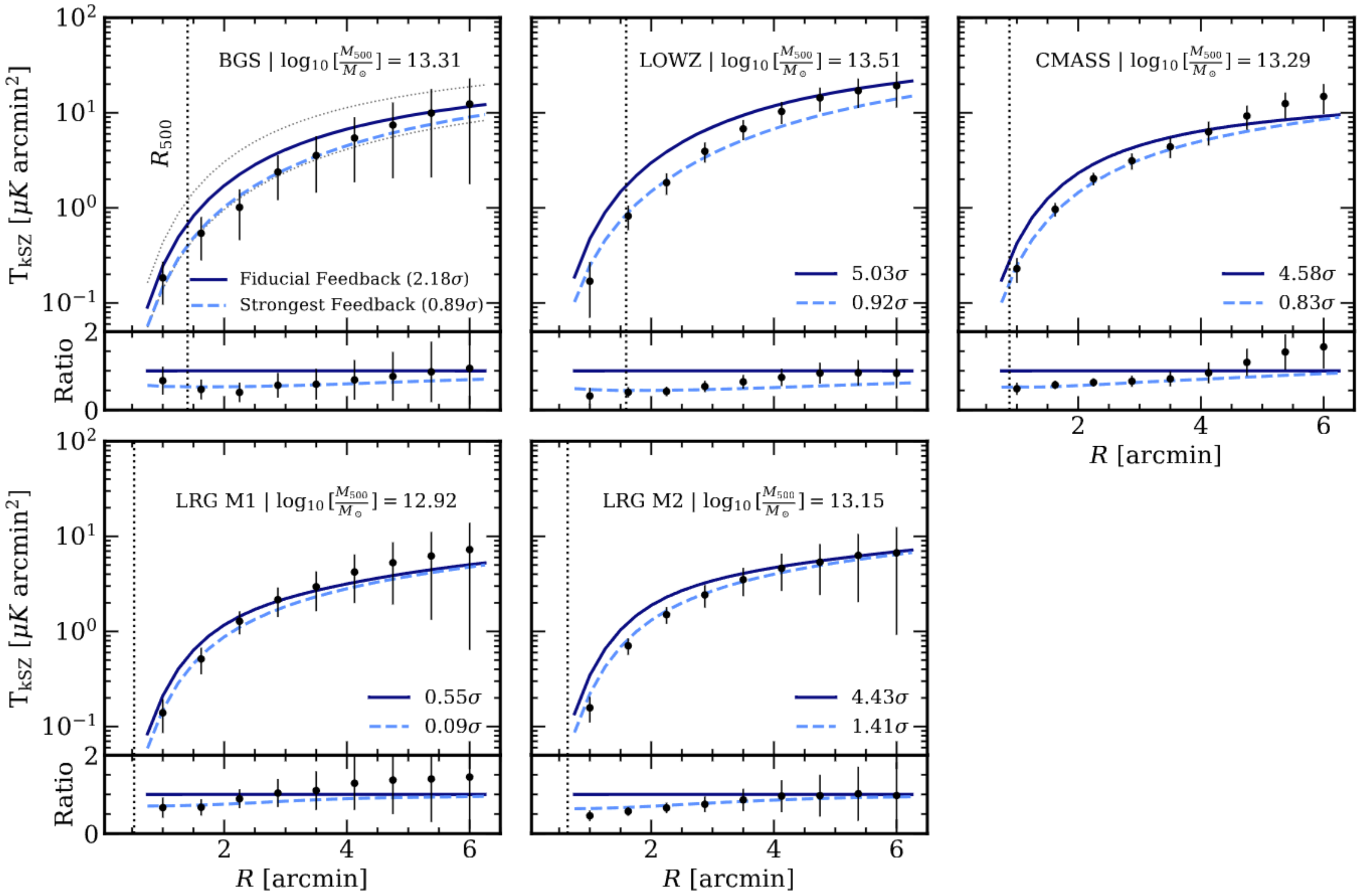
kSZ for stacks of z~0.5 galaxies with g-g lensing halo masses



kSZ prefers much lower gas fractions (fgas-8σ), than pre-eROSITA X-ray observations (L1_m9)

McCarthy, Amon, JS+ (2025)

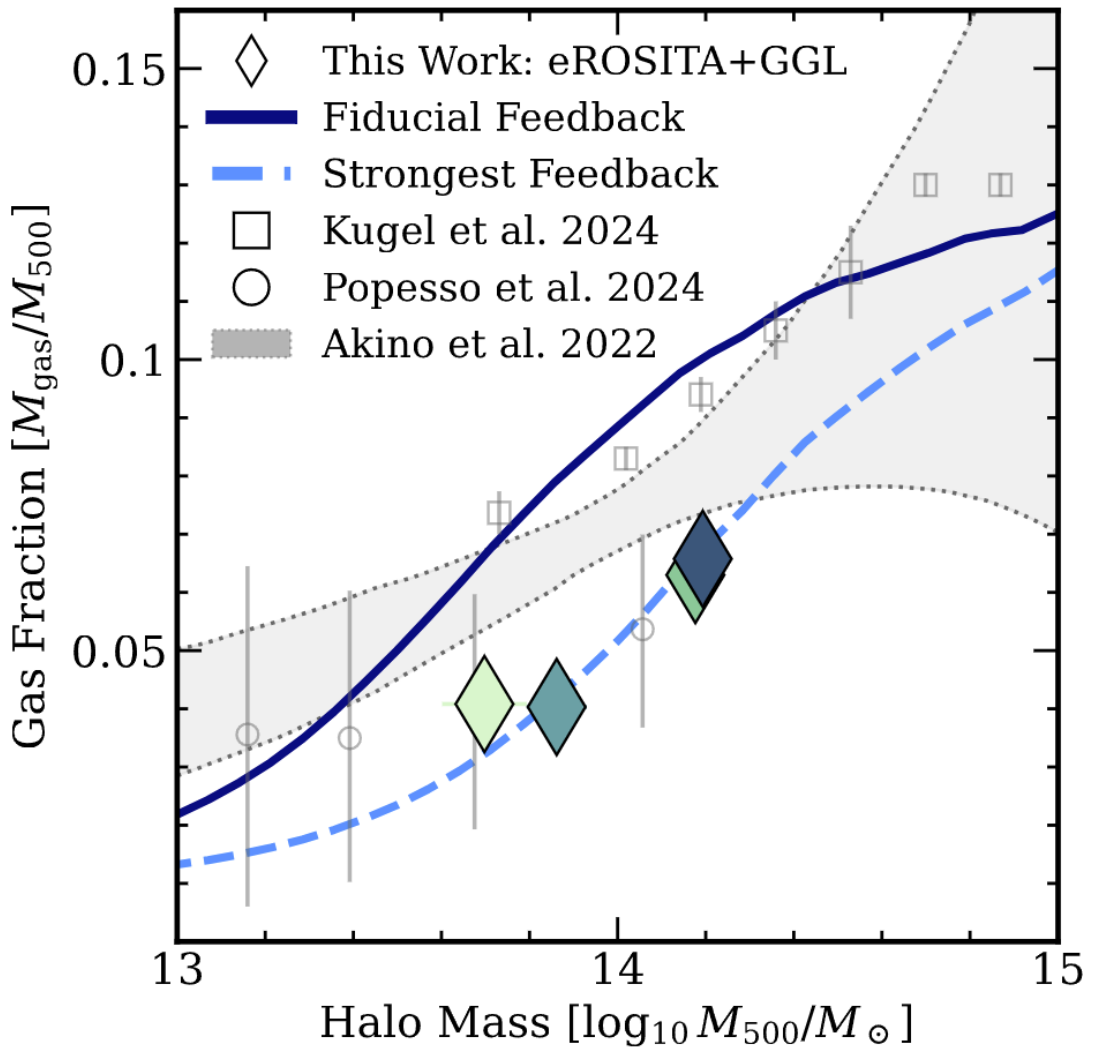
ACT kSZ for stacks of z < 1 galaxies with g-g halo masses



kSZ prefers much lower gas fractions (fgas-8σ), i.e. stronger feedback, than pre-eROSITA X-ray observations (L1_m9)

Siegel+ (in prep)

Constraints on the gas fraction halo mass relation



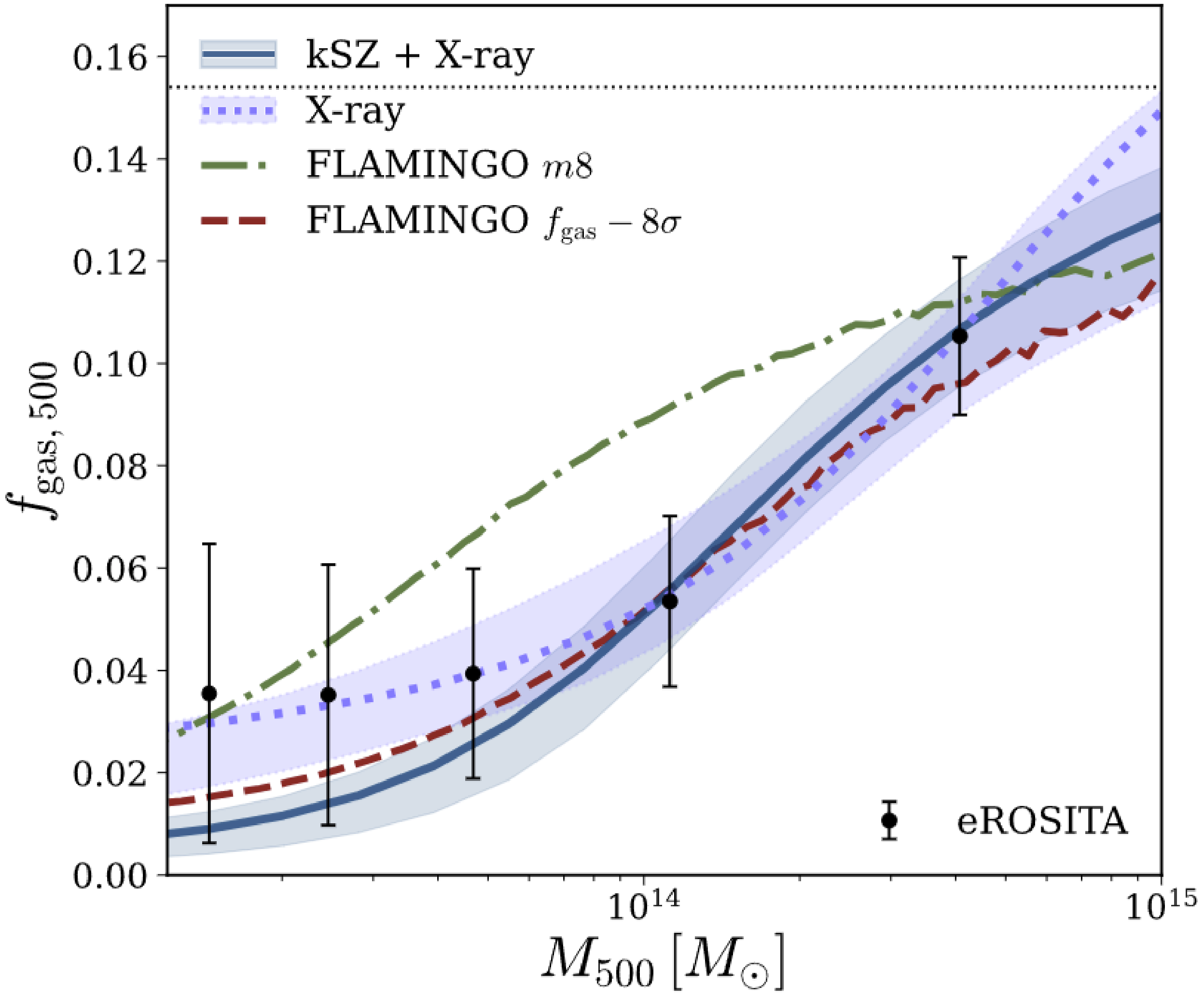
Halo masses of eROSITA sample validated using DES Y3 lensing

Siegel+ (in prep)

Fitting eROSITA gas fractions & ACT kSZ with baryonification

eROSITA (Popesso+ 2025):

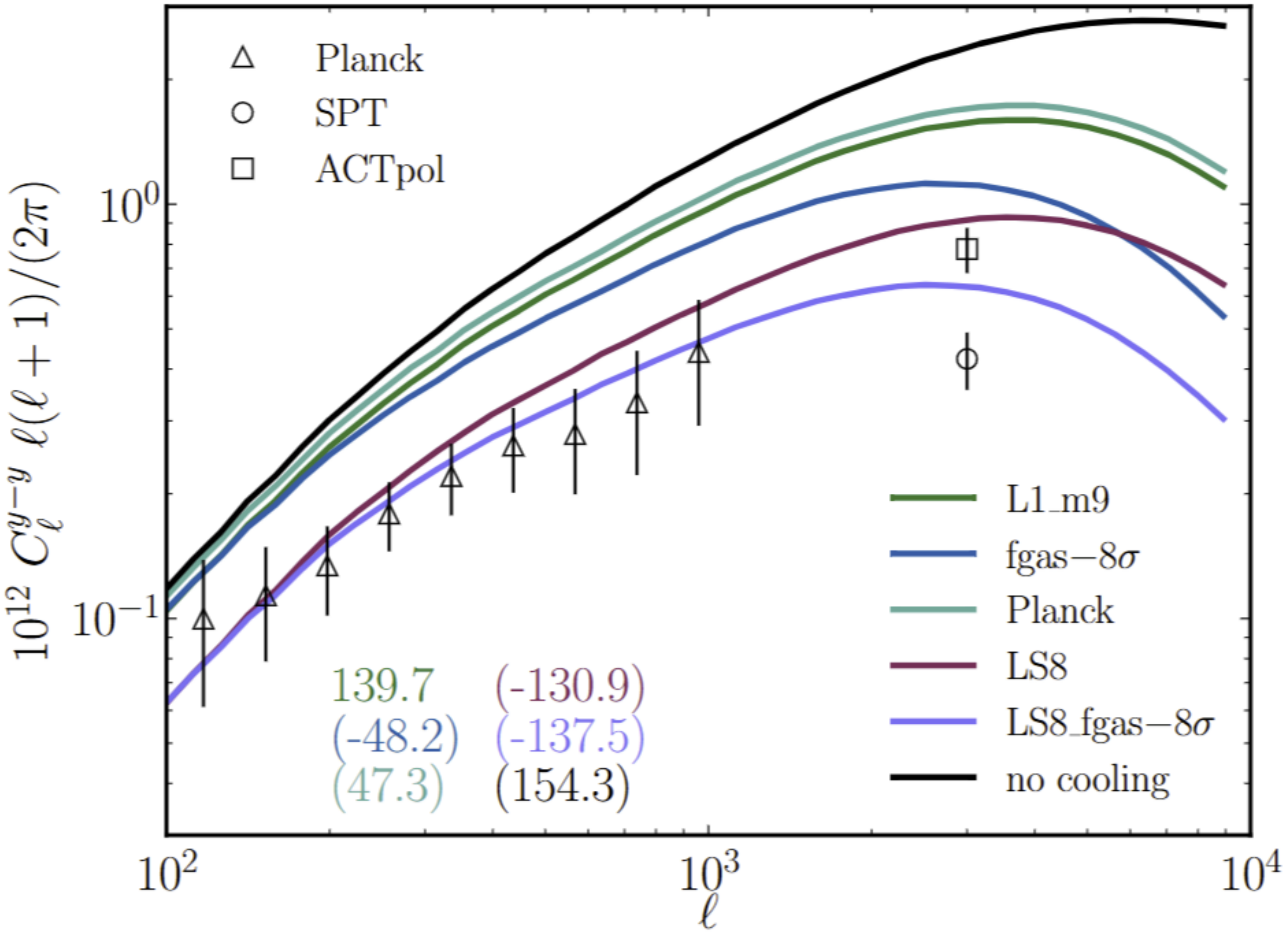
- X-ray stacks of optically-selected GAMA clusters
- Halo mass from total optical luminosity
- X-ray temperature from halo mass scaling relation
- Gas mass from X-ray temperature and surface brightness profile



kSZ and kSZ+eROSITA X-ray prefer much lower gas fractions (fgas-8σ), than pre-eROSITA X-ray observations (L1_m8)

Kovač+ (2025)

Thermal SZ power spectrum

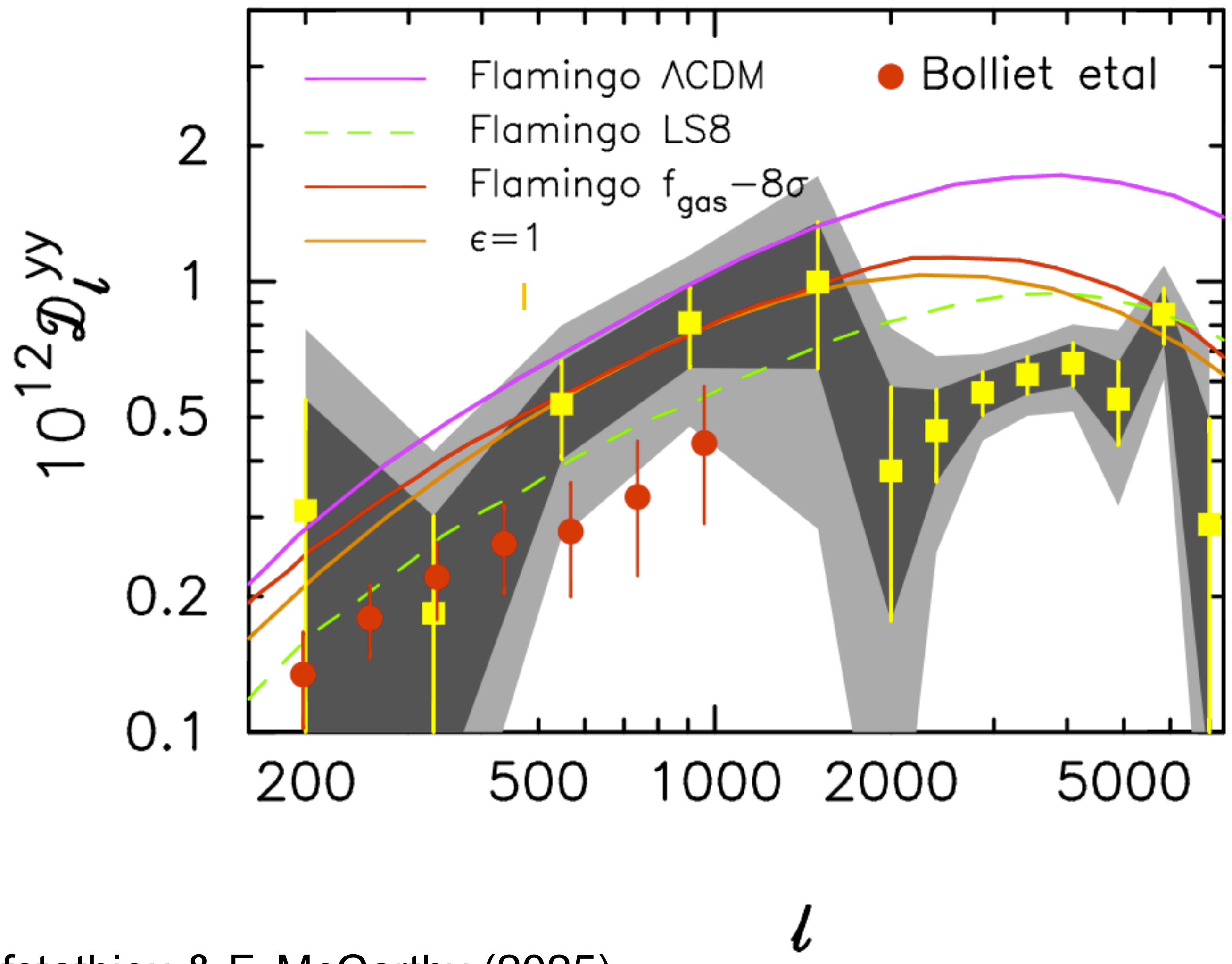


The tSZ power spectrum prefers low S_8 and is insensitive to baryonic physics on large scales
Small scales appear to require a low S_8 plus very strong feedback

Most sensitive to k ~ 0.5 – 3 h/Mpc, z ~ 0.2-0.7

McCarthy, Amon, JS+ (2025)

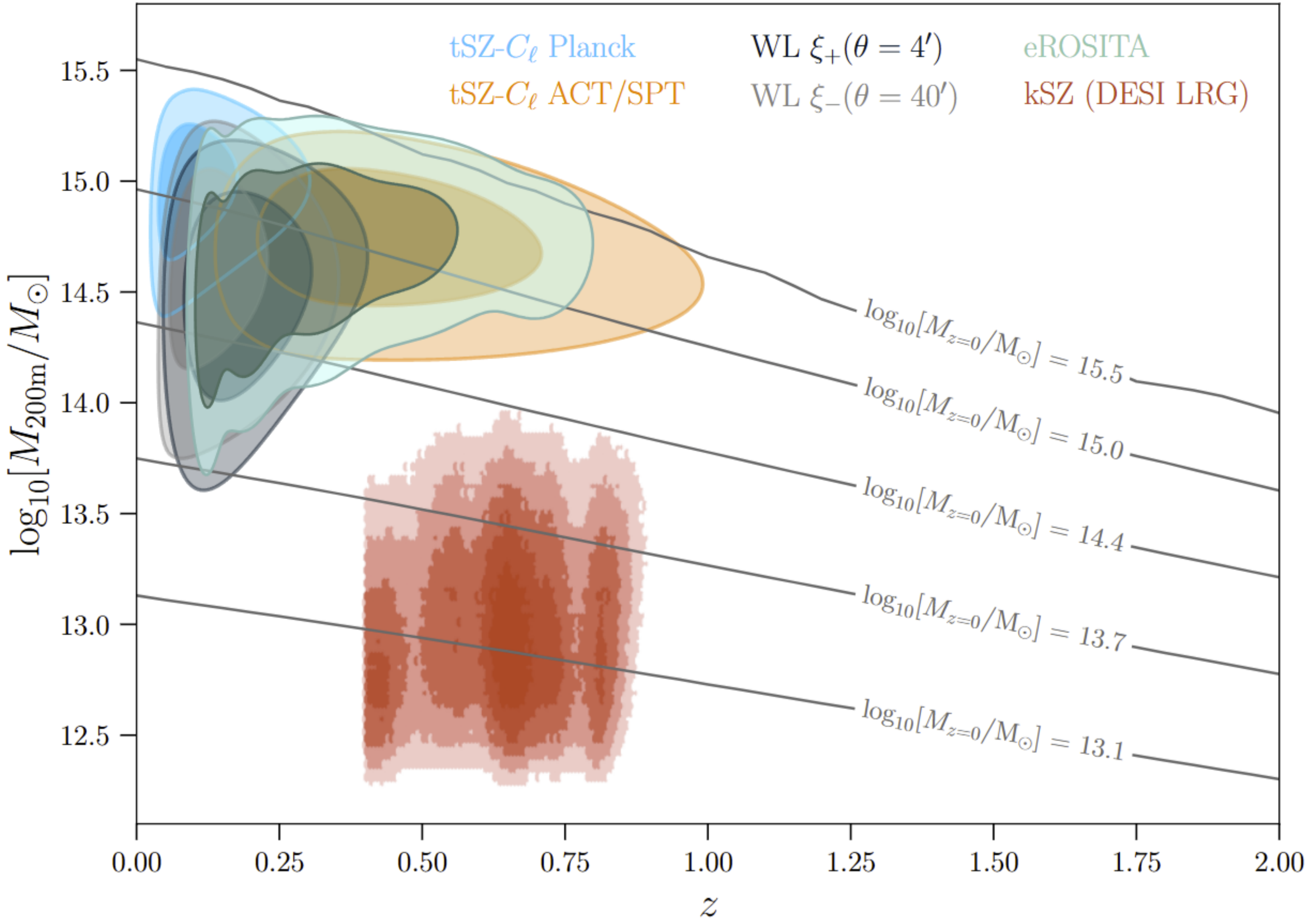
tSZ power spectrum: Strong feedback and/or systematics?



- Yellow data points: Efstathiou & F. McCarthy (2025)
- tSZ measured by fitting parametric model for CIB to the power spectrum at different frequencies instead of measuring tSZ from Compton y-maps
- Improves agreement for Planck S_8 on large scales

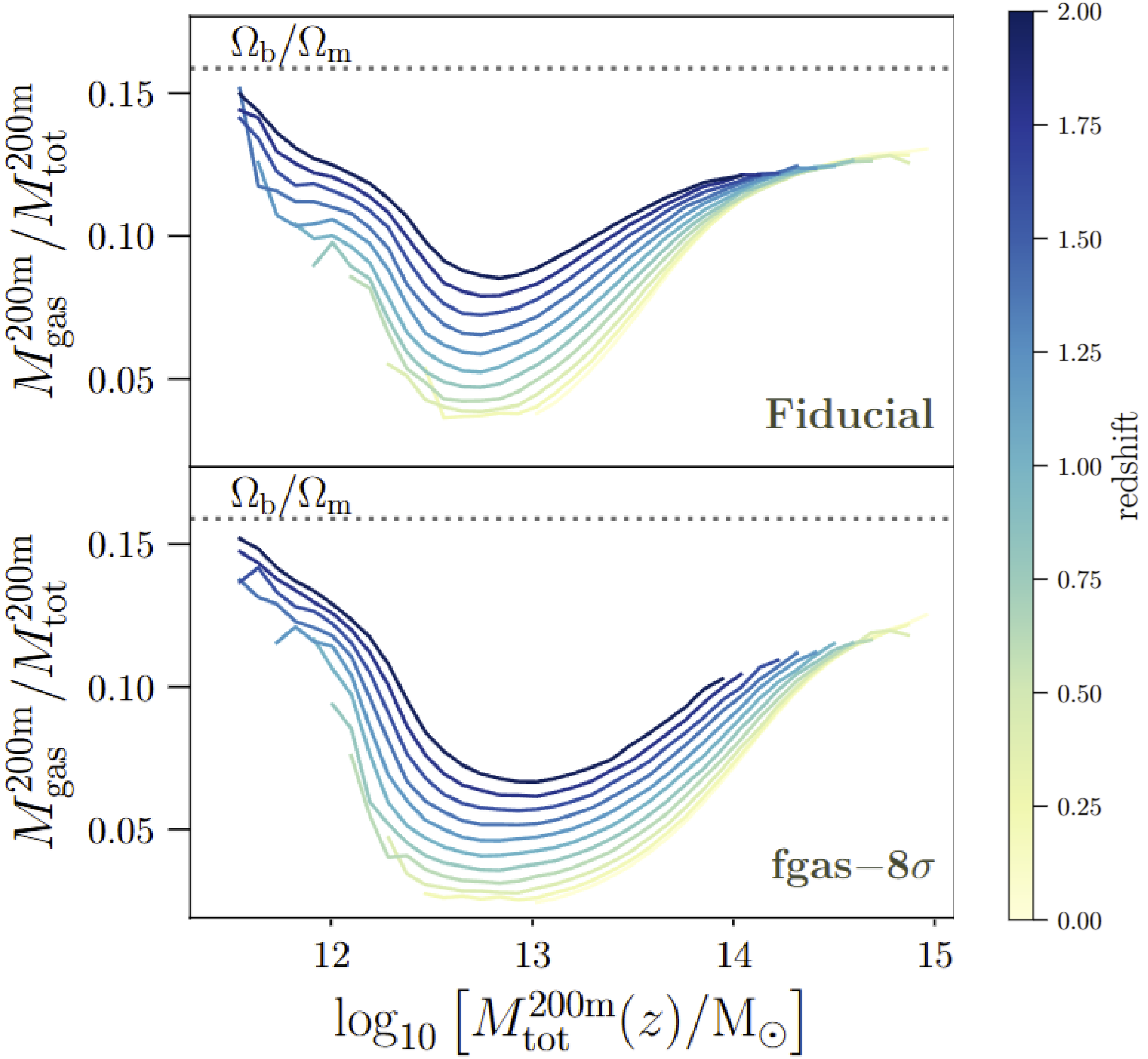
Efstathiou & F. McCarthy (2025)
See also McCarthy, Amon, JS+ (2025)

kSZ probes different objects than currently used for cosmology



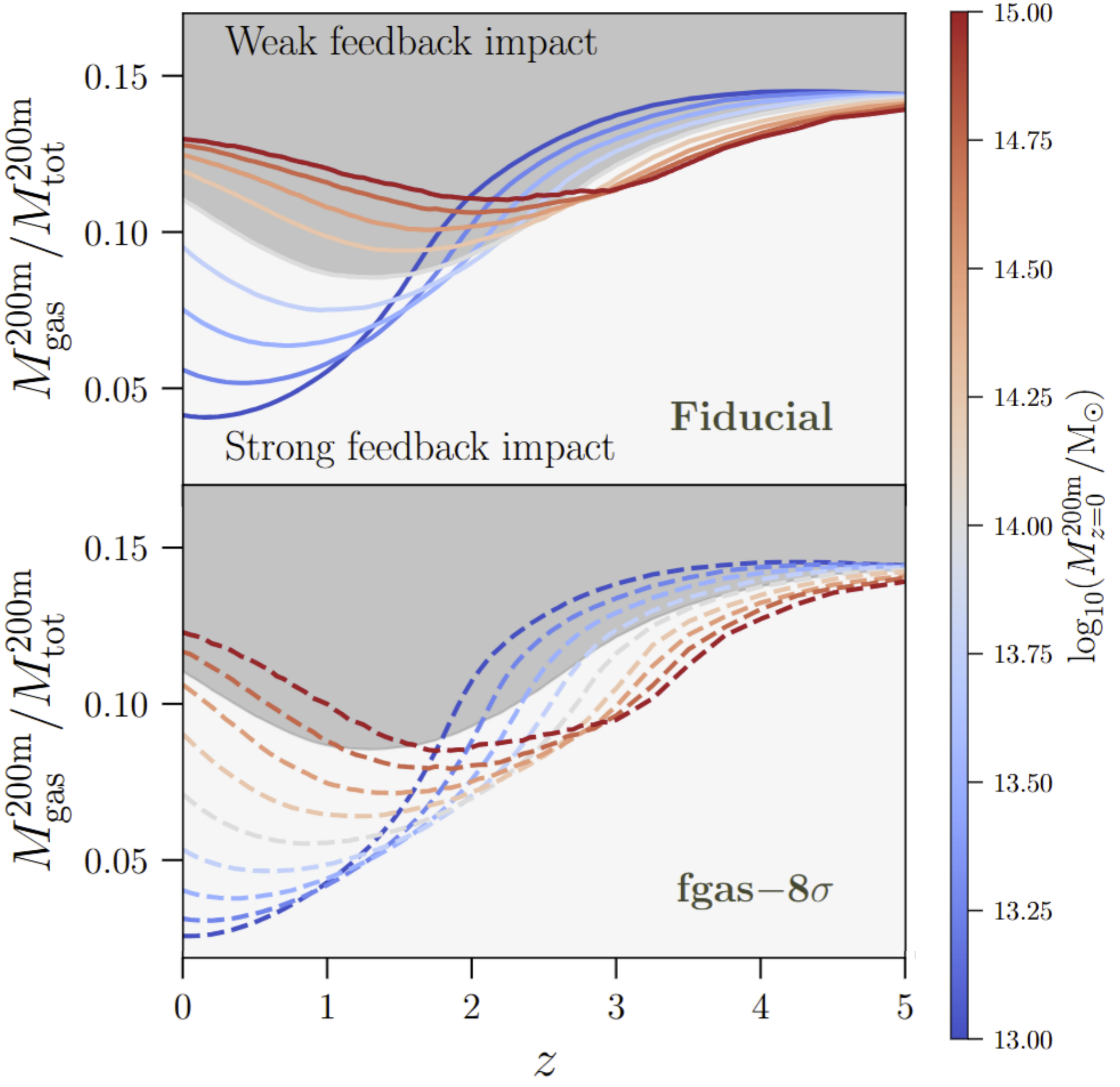
Lucie-Smith+ (2025)

Evolution of the gas fraction – halo mass relation



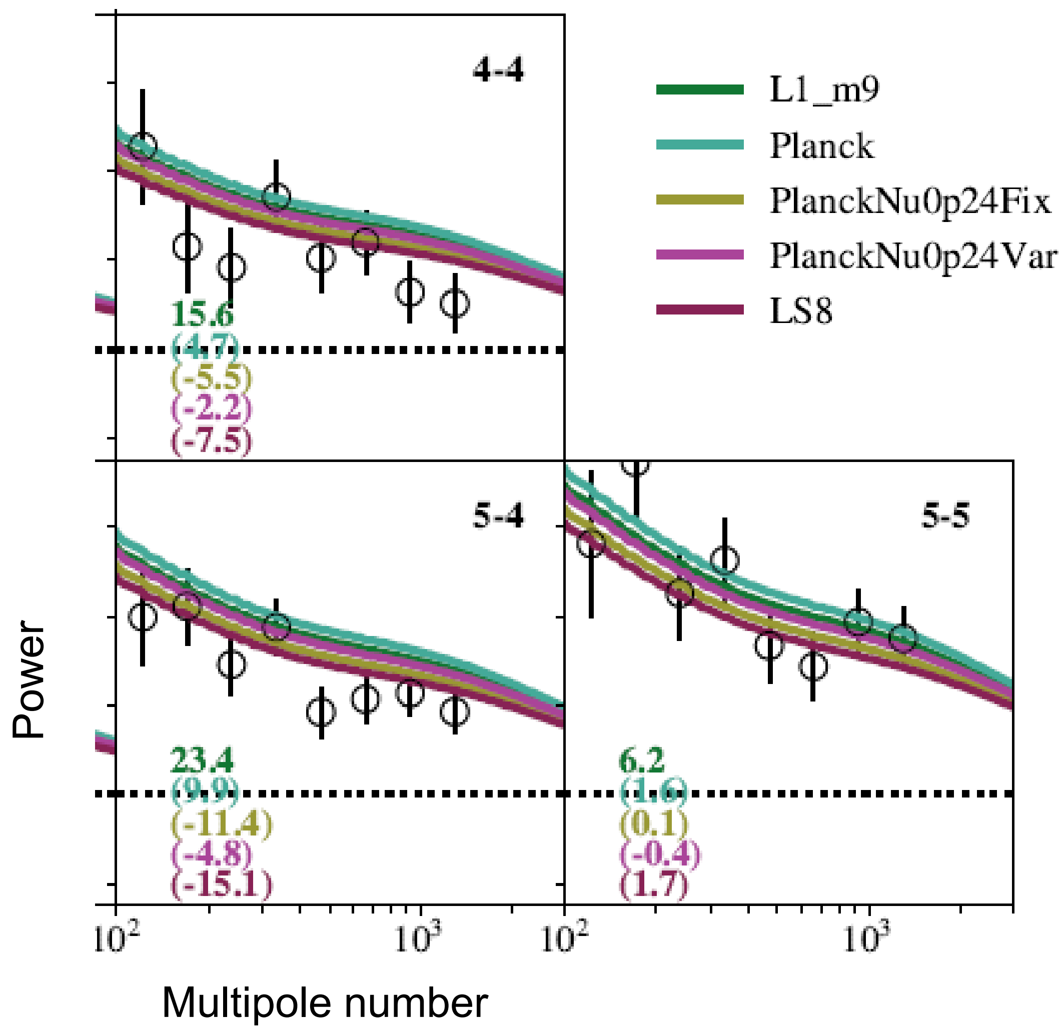
Lucie-Smith+ (2025)

Gas fraction evolutionary tracks

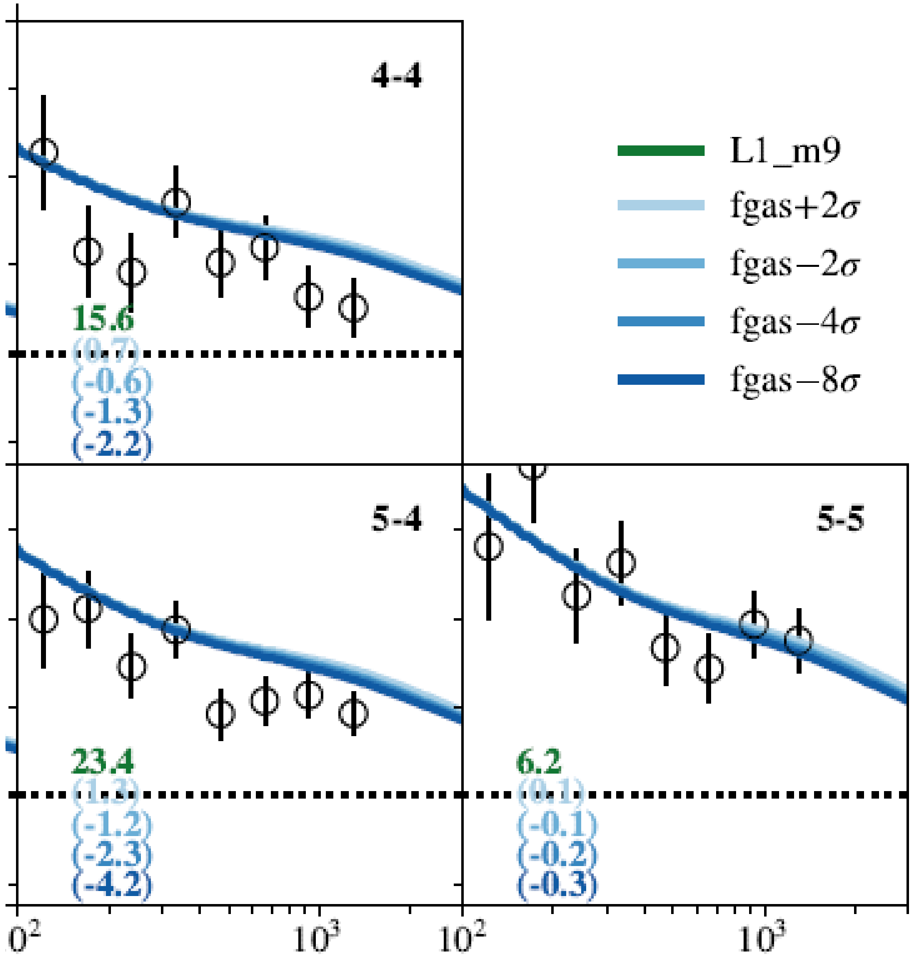


Lucie-Smith+ (2025)

Cosmic shear from KiDS-1000



S_8
0.815
0.833
0.789
0.807
0.766



Cosmic shear prefers a low S8 cosmology and is currently insensitive to baryonic physics

Most sensitive to k ~ 0.2 – 2 h/Mpc, z ~ 0.1-0.4

McCarthy, Salcido, JS+ (2023)

Conclusions Part I

- FLAMINGO simulations for cosmology and cluster physics
  - Very large volumes → very large numbers of (proto-)clusters
  - Neutrino particles
  - Lightcone output
  - Many cosmology and galaxy formation variations
  - Two different implementations of AGN feedback for a fixed calibration
- Baryonic feedback may be much stronger than suggested by most pre-eROSITA analyses based on X-ray clusters
- Cosmic shear, SZ, and cluster count cosmology are systematics limited
- It is critical to validate observational constraints using models with varying strength and implementations of feedback
- Many systematics can be eliminated by directly emulating observables as a function of both cosmology and baryon physics
- *Feel free to contact me if you would like to use the simulations*

Key limitations of EAGLE and similar simulations

- ISM is kept warm (≥ 10^4 K) and is therefore too smooth

  → *COLIBRE includes non-equilibrium cooling, self-shielding, molecules, and coupled dust formation and evolution*

- Spurious heating of stellar particles by dark matter particles

  →*COLIBRE uses similar mass resolution for dark matter and baryons*

- AGN feedback is critical but highly uncertain

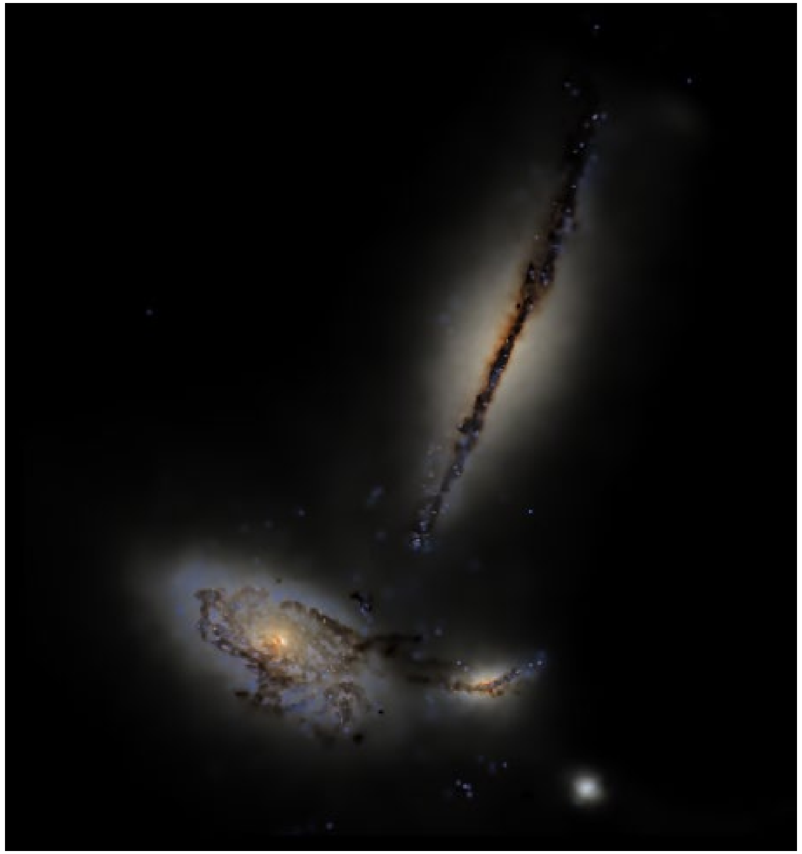
  → COLIBRE includes two calibrated models for AGN feedback

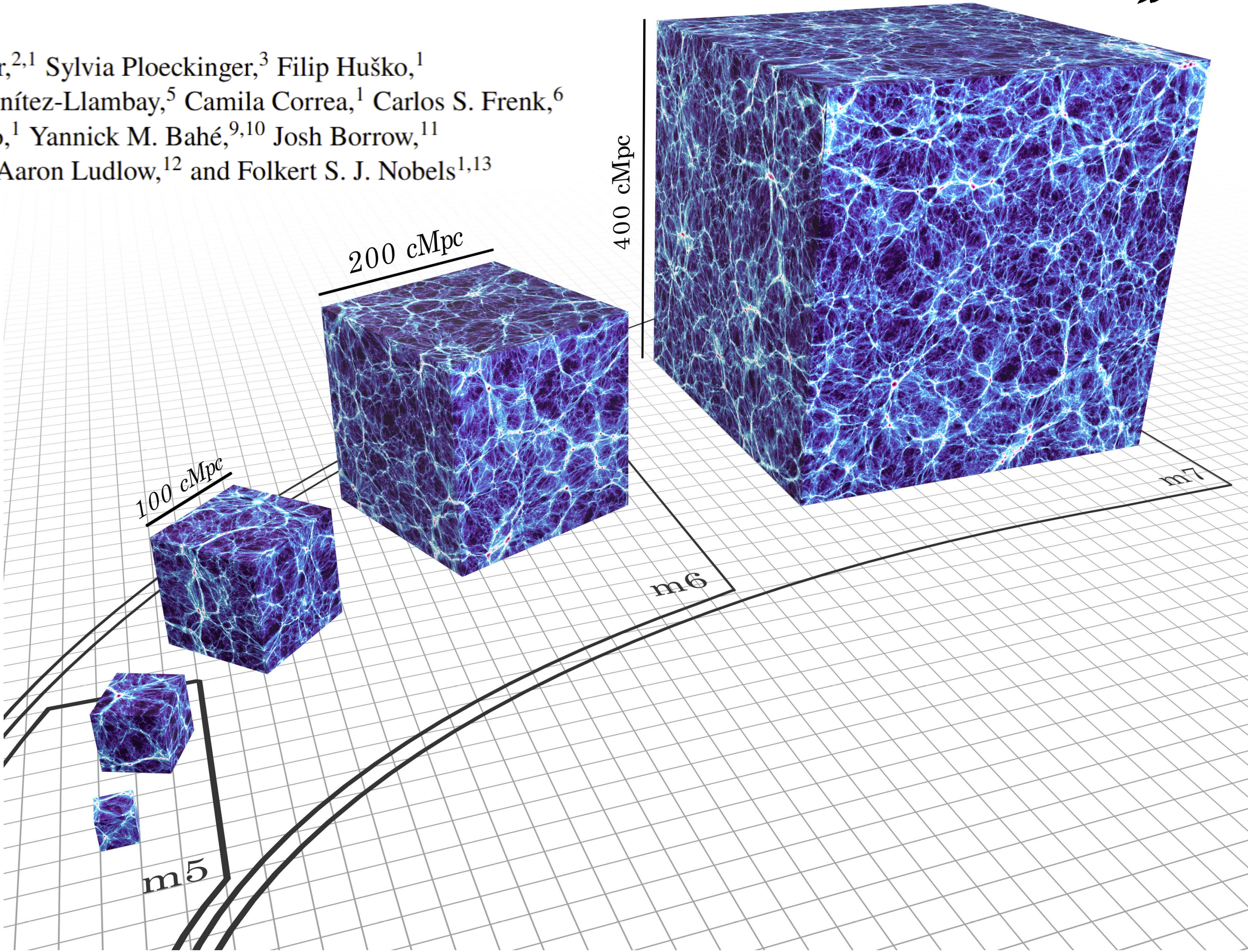
- Box size (L = 25-100 Mpc) is too small for studies of large-scale structure, clusters, high-z galaxies

  → *COLIBRE use an order of magnitude larger volumes at the same resolution*

The COLIBRE project: cosmological hydrodynamical simulations of galaxy formation and evolution

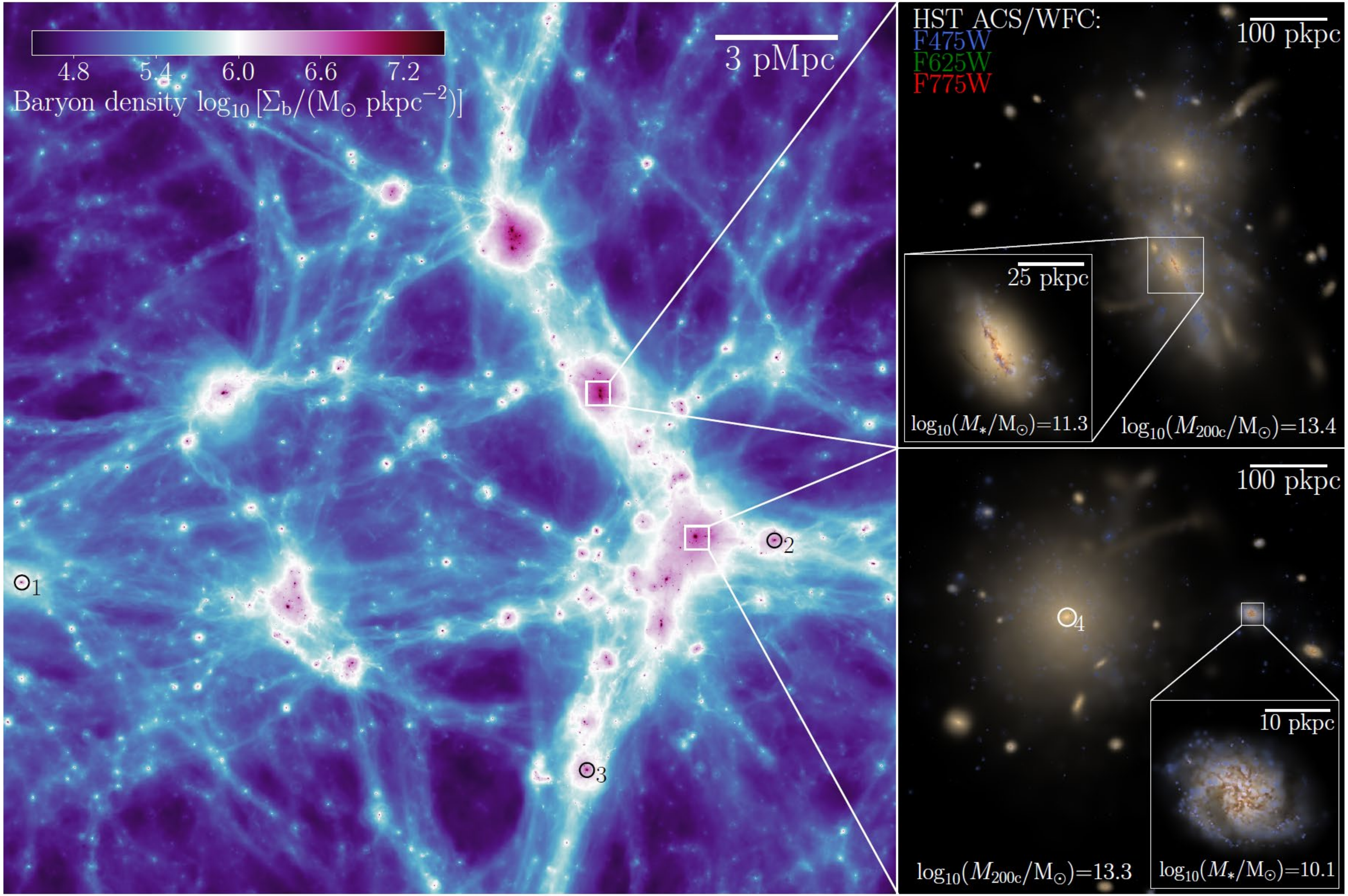
Joop Schaye,[1★] Evgenii Chaikin,[1] Matthieu Schaller,[2,1] Sylvia Ploeckinger,[3] Filip Huško,[1]
Rob McGibbon,[1] James W. Trayford,[4] Alejandro Benítez-Llambay,[5] Camila Correa,[1] Carlos S. Frenk,[6]
Alexander J. Richings,[7,8] Victor J. Forouhar Moreno,[1] Yannick M. Bahé,[9,10] Josh Borrow,[11]
John C. Helly,[6] Adrian Jenkins,[6] Cedric G. Lacey,[6] Aaron Ludlow,[12] and Folkert S. J. Nobels[1,13]





COLd Ism and Better Resolution (COLIBRE)

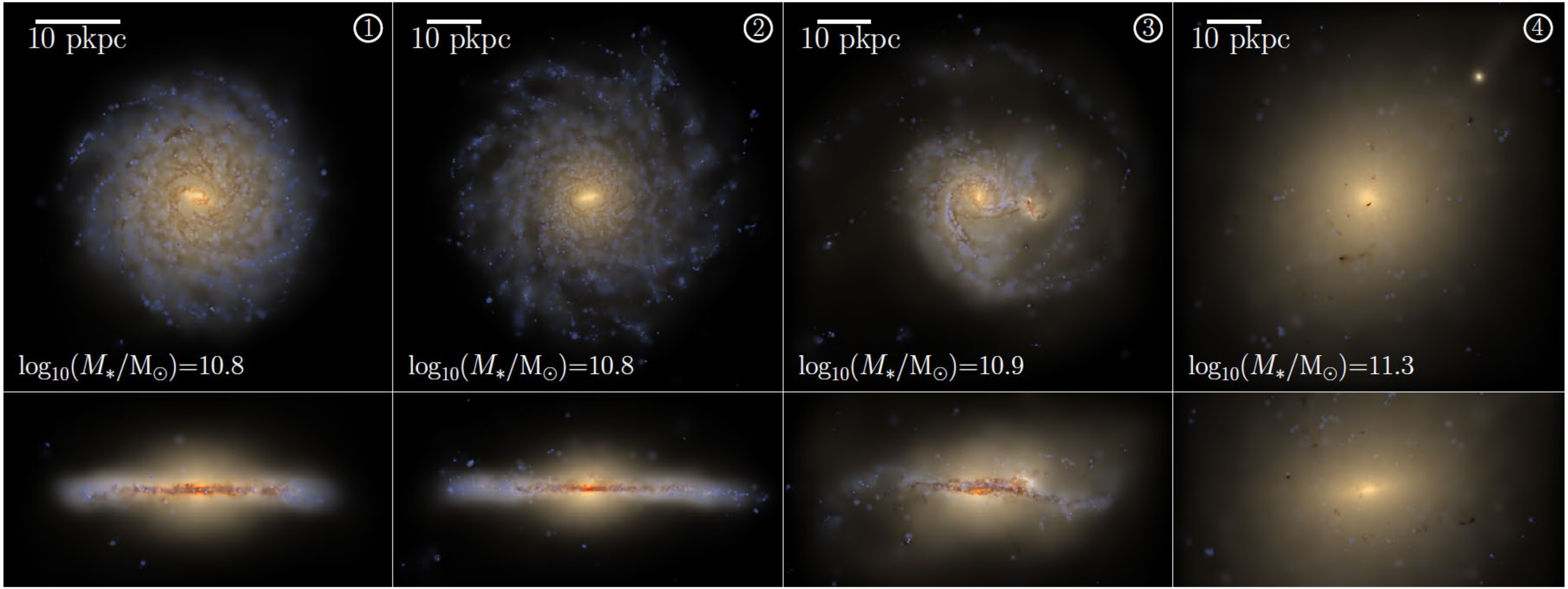
- Includes
  - Cold ($T << 10^4$ K) interstellar gas
  - Cooling (non-equil. H, He, e^-; self-shielding, UVB and interstellar radiation)
  - Dust (3 grain species, 2 grain sizes; coupled to cooling)
  - ‘Chemistry’ (updated yields, diffusion, new SNIa, s- and r-process elements)
  - Stellar feedback (HII regions, winds, turbulence, improved stochastic SN feedback)
  - BH and AGN physics (also runs with BH spin and jet feedback)
  - Star formation (Schmidt law with instability criterion)
- Suppresses spurious energy transfer from DM to baryons by using 4x more DM than baryonic particles
- Very large simulations, up to 3008^3 baryonic and 4768^3 DM particles (20 times more particles than EAGLE)
- Wedding cake strategy:
  - Box sizes ranging from 400 Mpc to 25 Mpc
  - Particle masses ranging from $\sim 10^7$ to 10^5 $M_\odot$



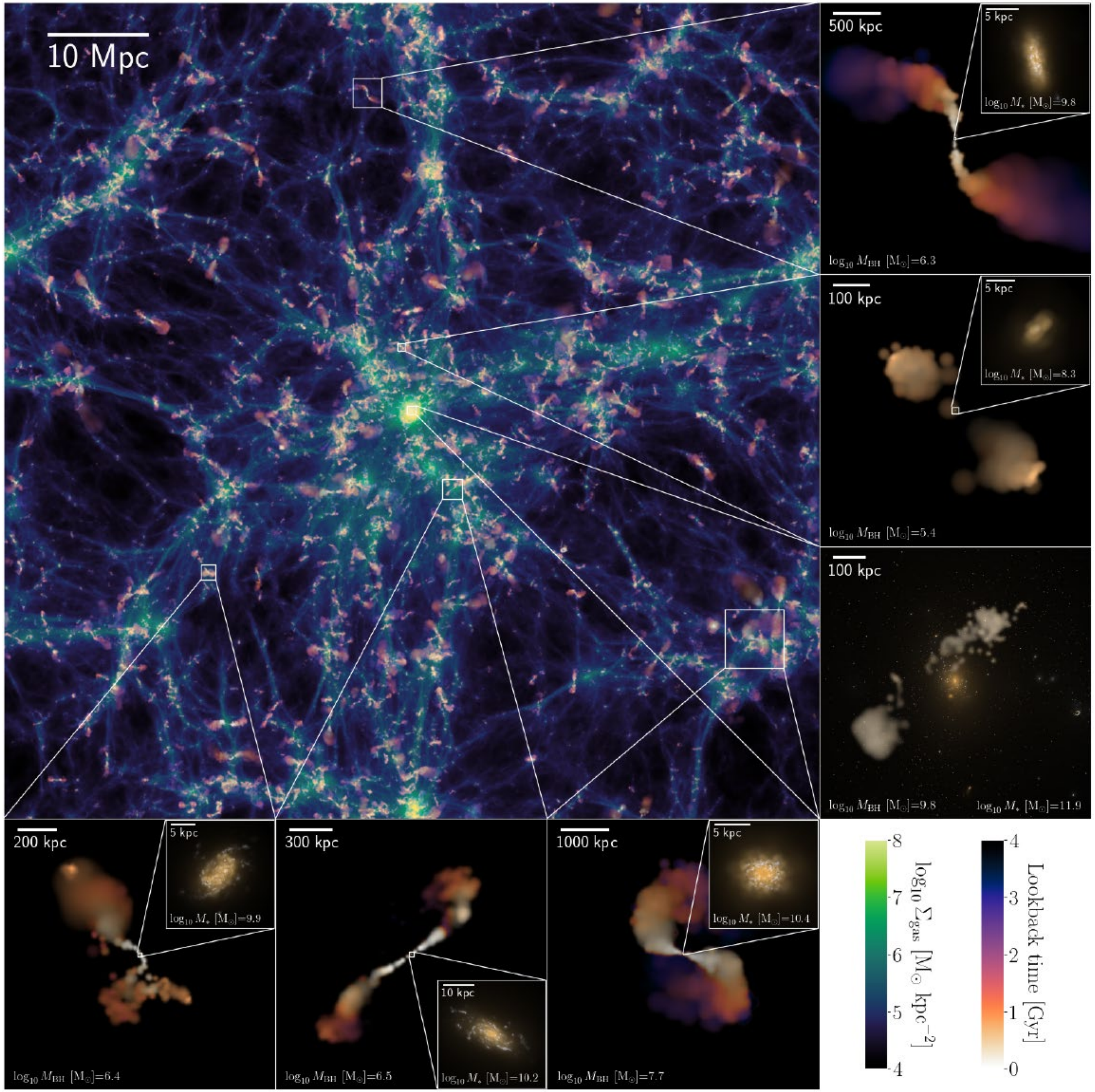
4.8
5.4
6.0
6.6
7.2
Baryon density $\log_{10}[\Sigma_b/(M_\odot\ pkpc^{-2})]$
3 pMpc
1
2
3
HST ACS/WFC:
F475W
F625W
F775W
100 pkpc
25 pkpc
$\log_{10}(M_*/M_\odot)$=11.3
$\log_{10}(M_{200c}/M_\odot)$=13.4
100 pkpc
4
10 pkpc
$\log_{10}(M_{200c}/M_\odot)$=13.3
$\log_{10}(M_*/M_\odot)$=10.1

JS+ (2025)

Galaxies in the L025m5 simulation at z = 0



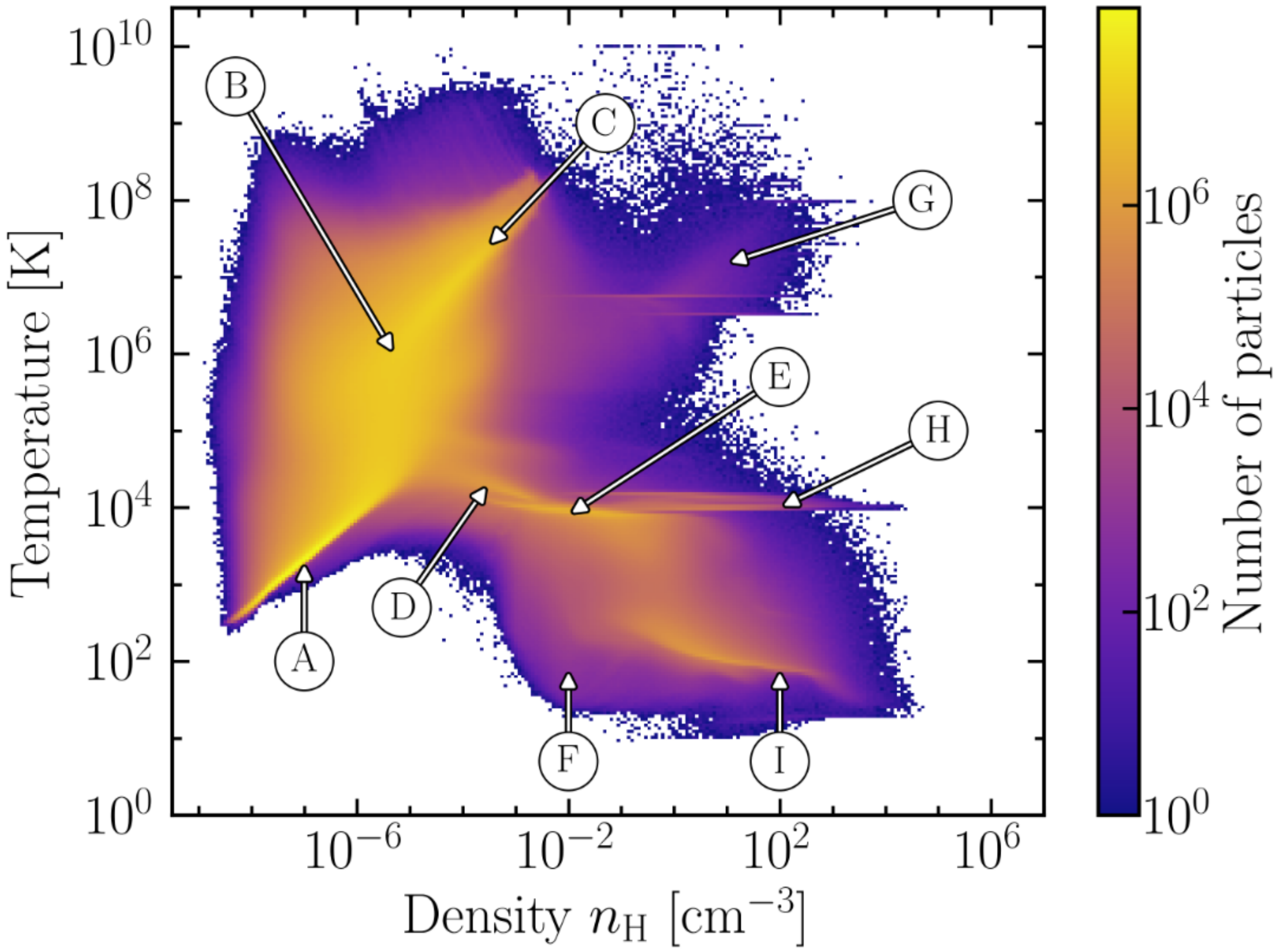
JS+ (2025)



COLIBRE L100m6h, z = 0

Husko+ (2025b)

Distribution of mass in temperature-density space

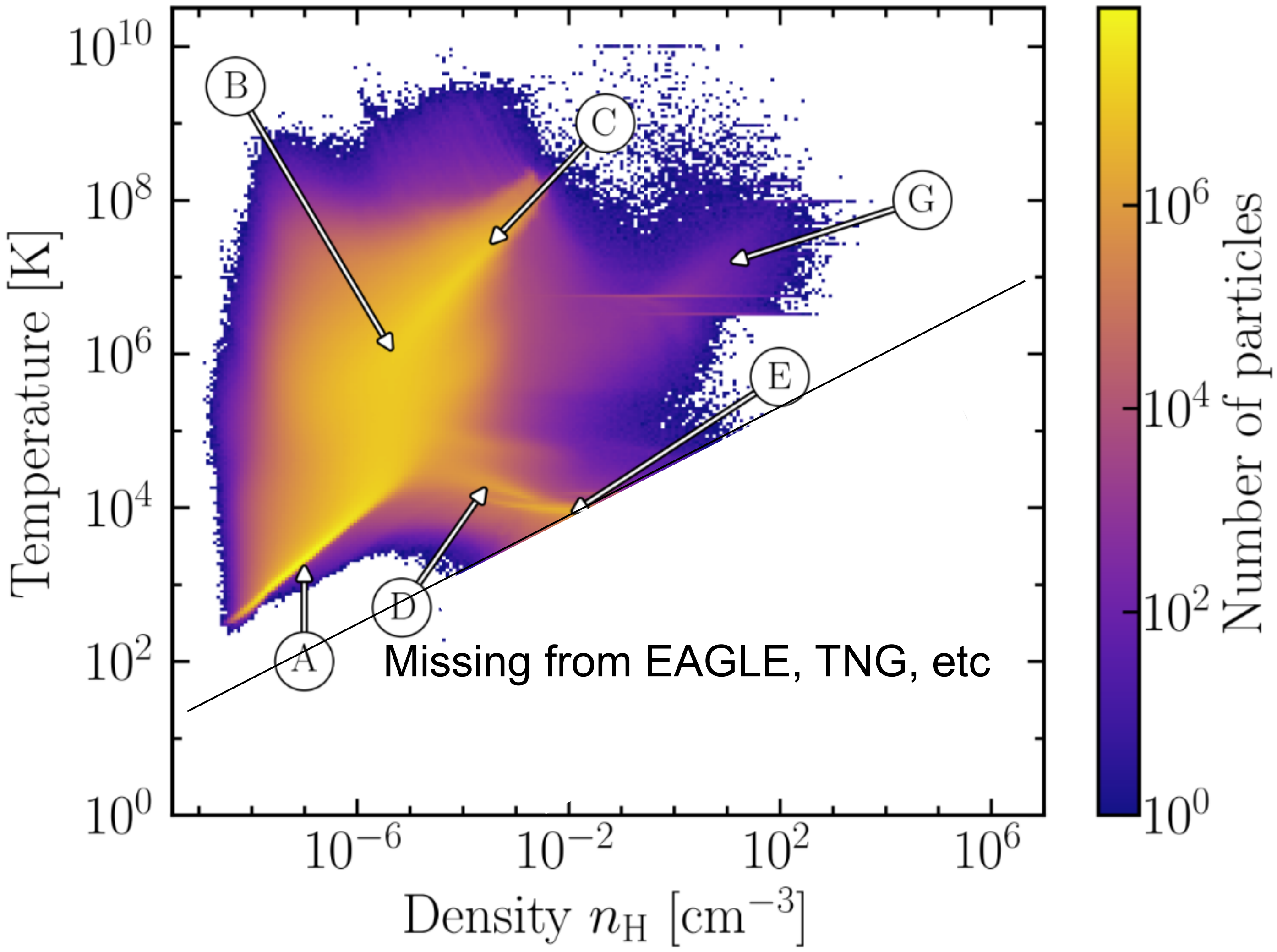


A: Diffuse IGM
B: WHIM
C: ICM
D: Cool outer CGM
E: Cool inner CGM
F: Out of equil.
G: Winds
H: HII regions
I: GMCs

z = 0
COLIBRE L200m6

JS+ (2025)

Distribution of mass in temperature-density space



A: Diffuse IGM
B: WHIM
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D: Cool outer CGM
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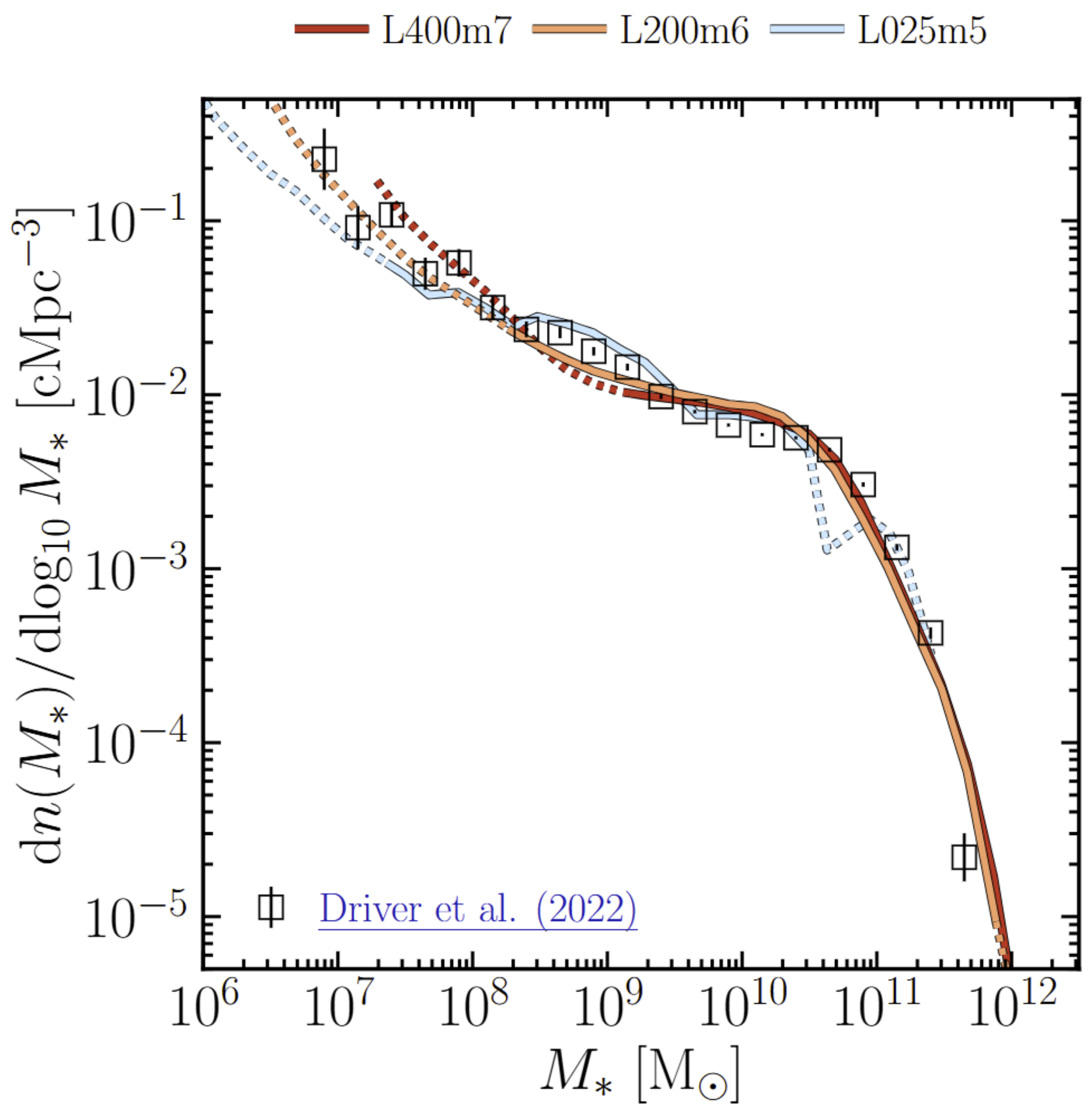
F: Out of equil.
G: Winds
H: HII regions
I: GMCs

z = 0
COLIBRE L200m6

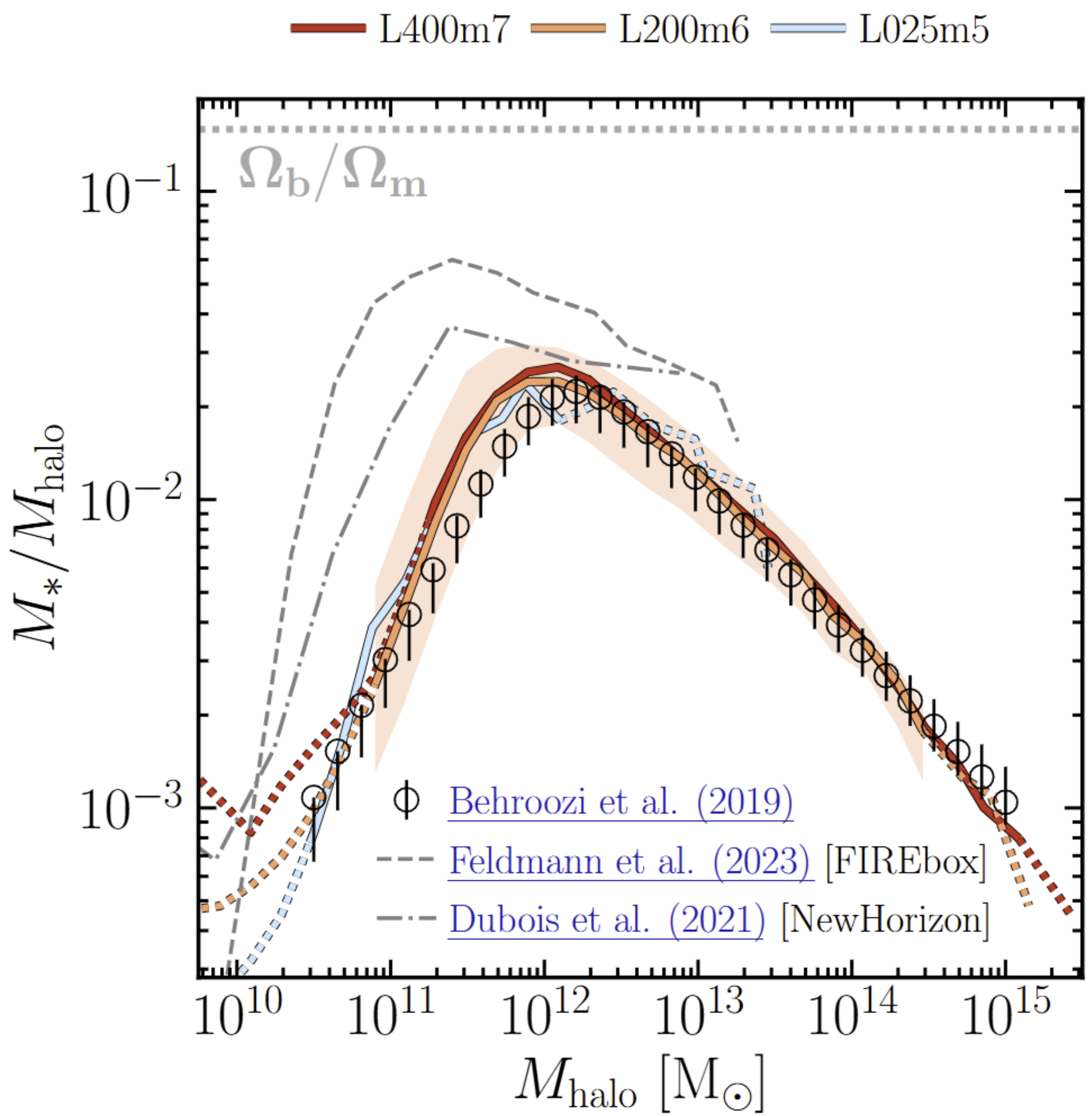
JS+ (2025)

Galaxy stellar mass function at z = 0



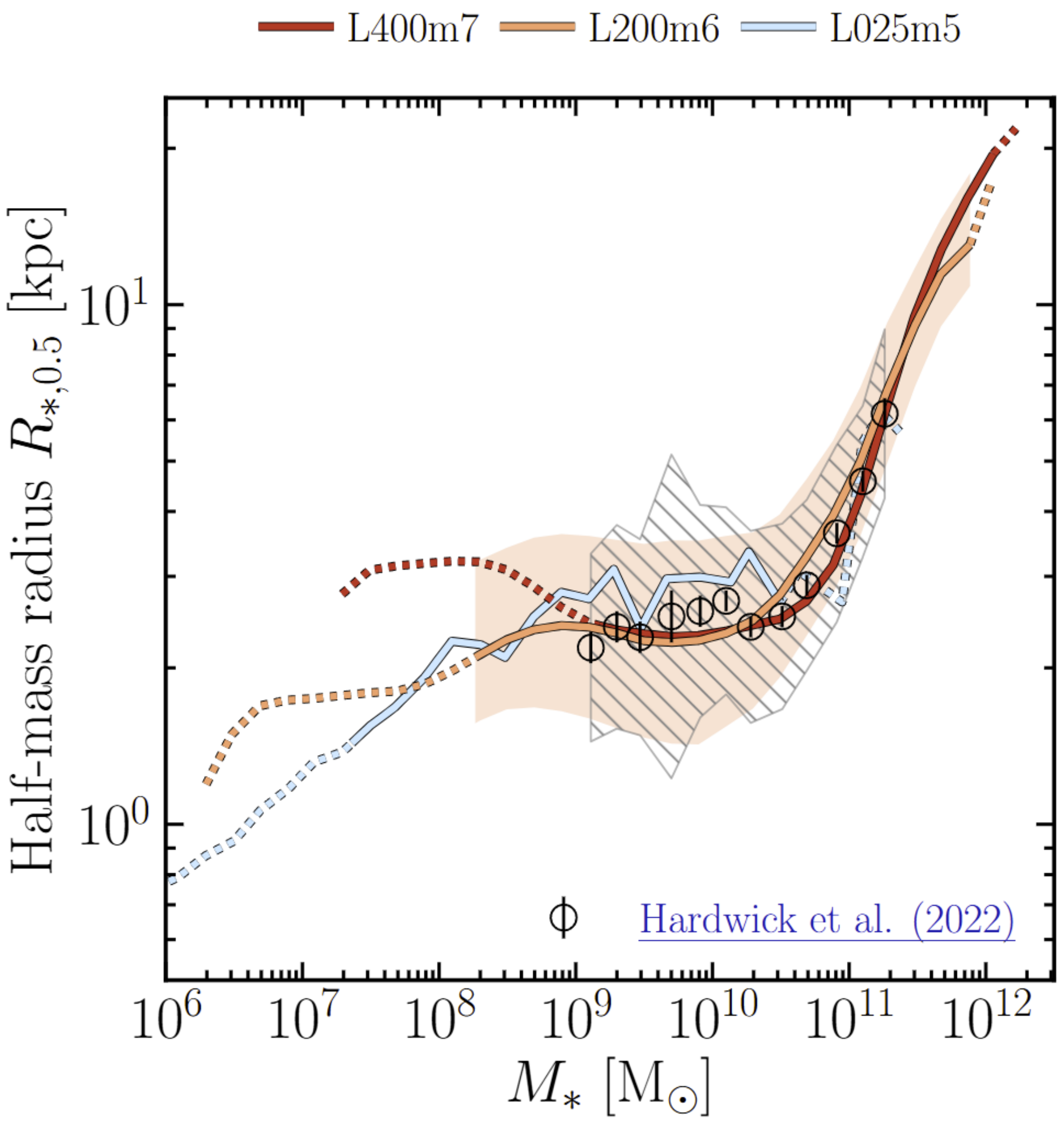
JS+ (2025)

Stellar mass – halo mass ratio at z = 0



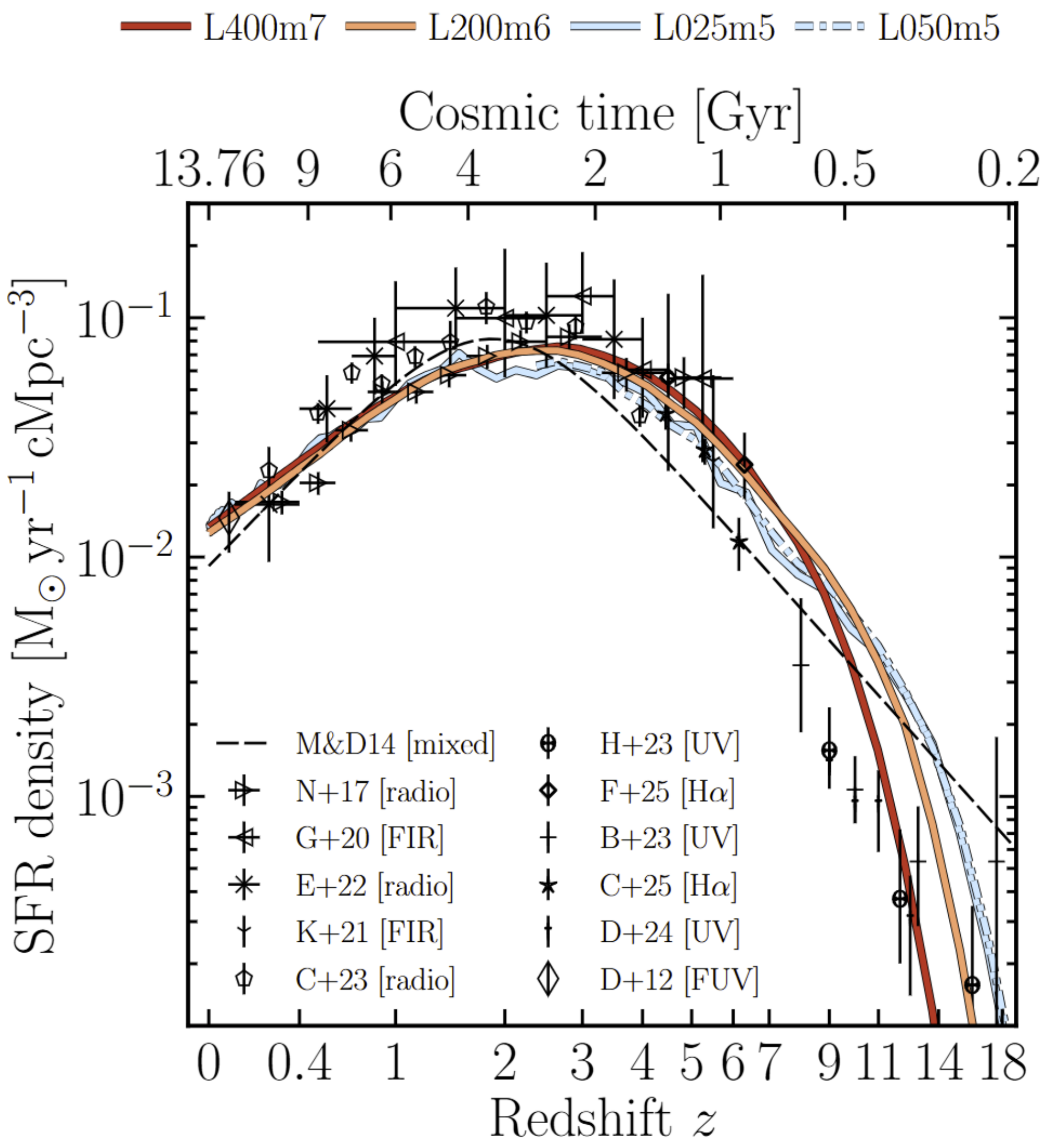
JS+ (2025)

Galaxy size – mass relation at z = 0



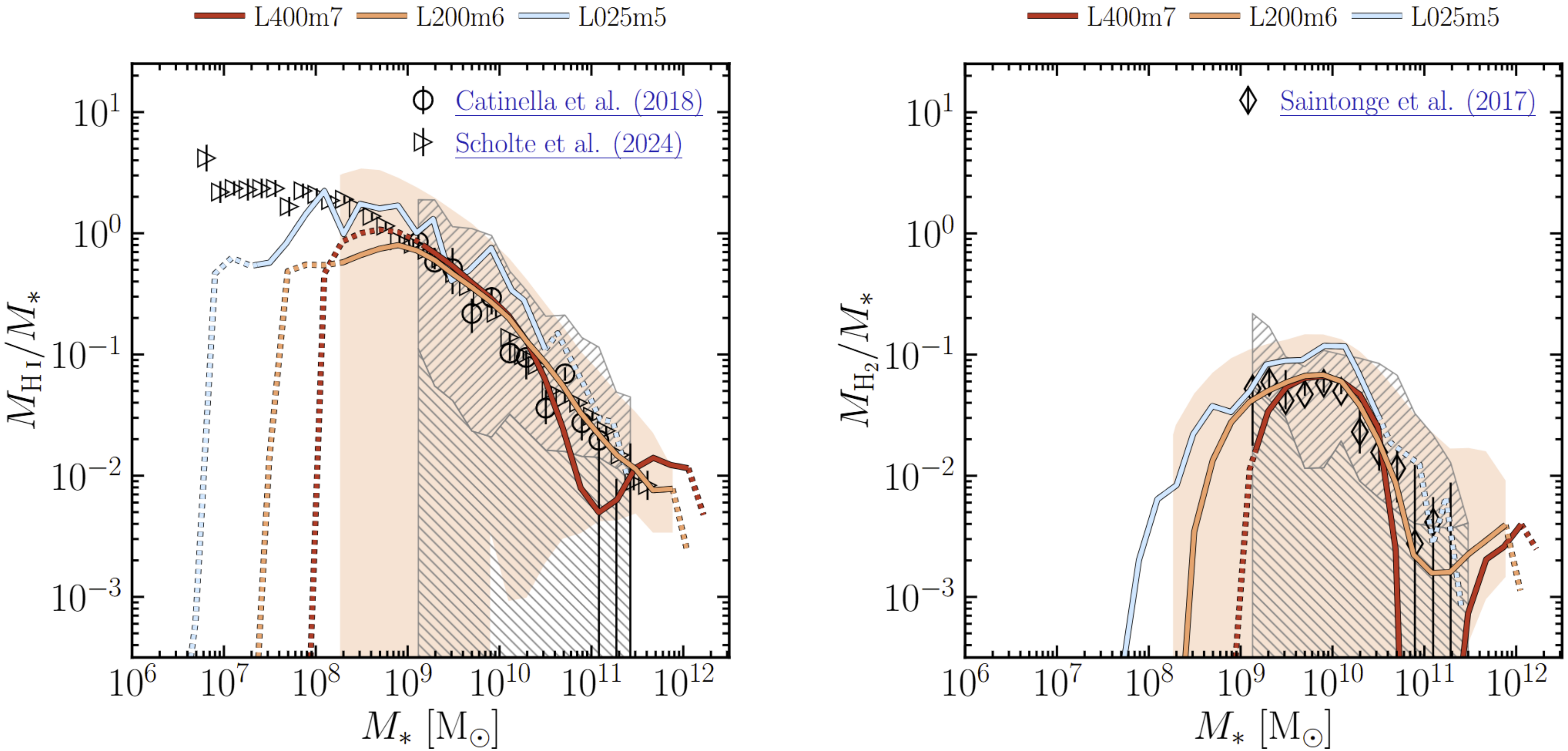
JS+ (2025)

Cosmic star formation history



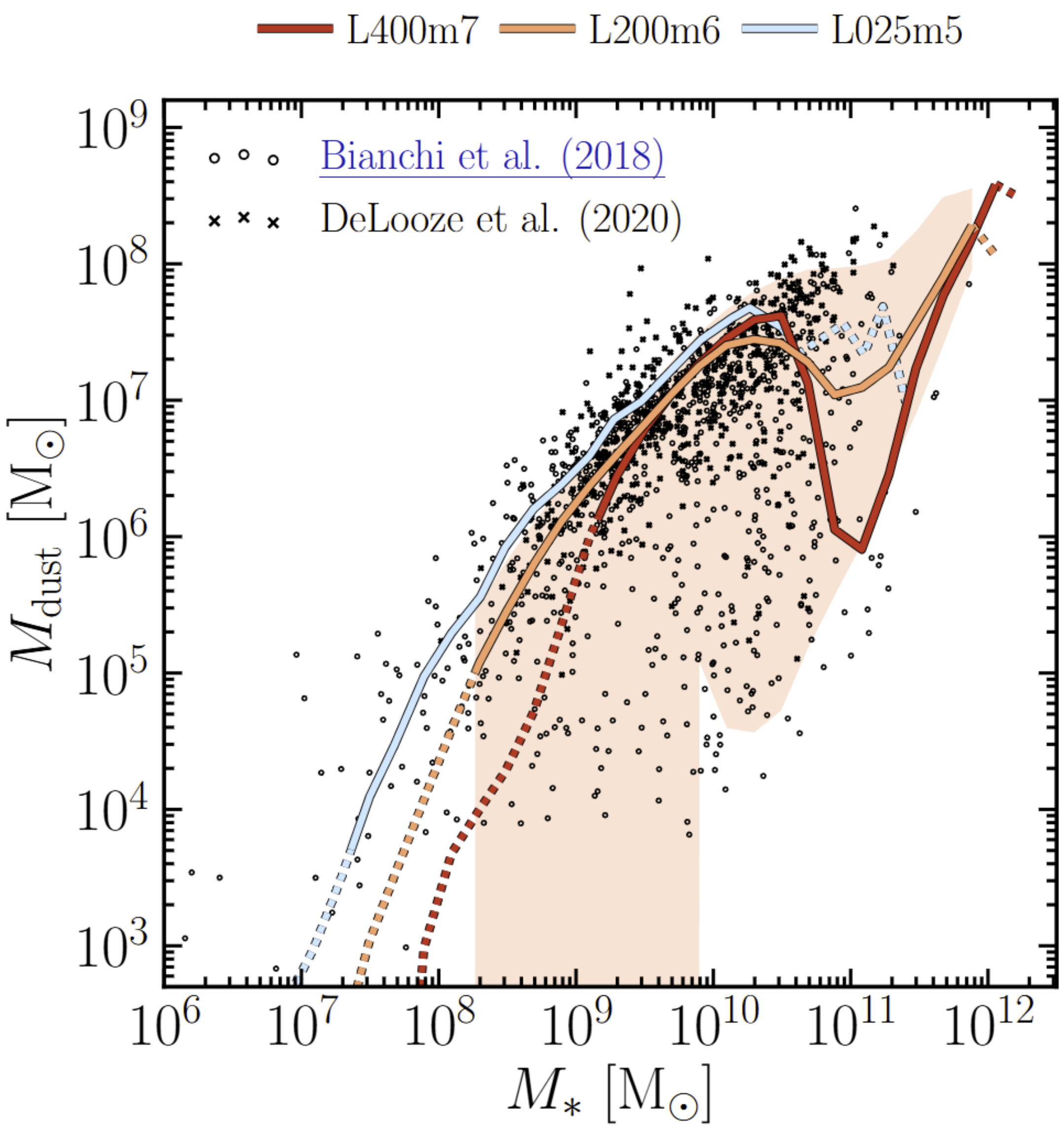
JS+ (2025)

HI and molecular masses at z = 0



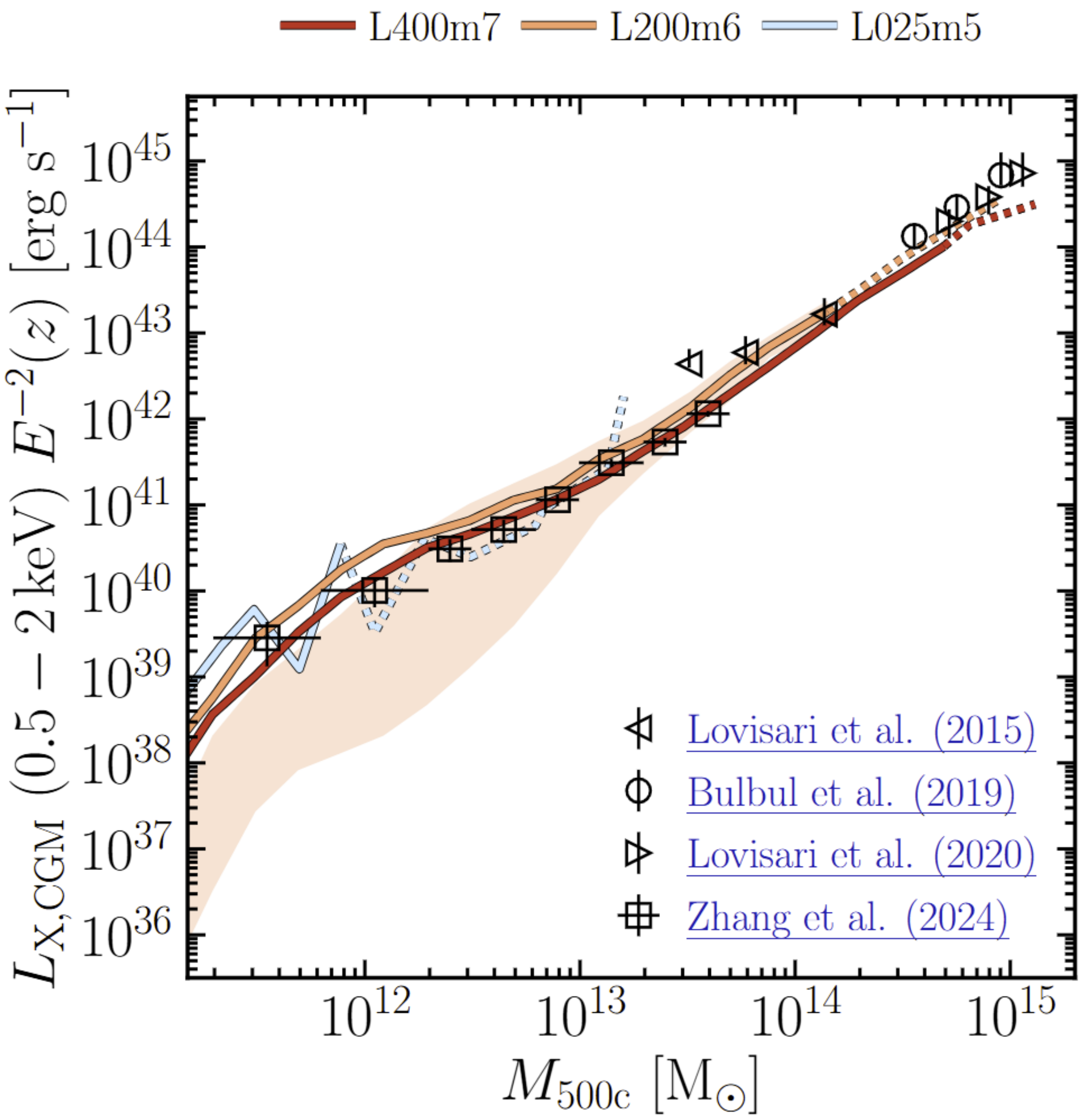
JS+ (2025)

Dust mass – stellar mass relation at z = 0



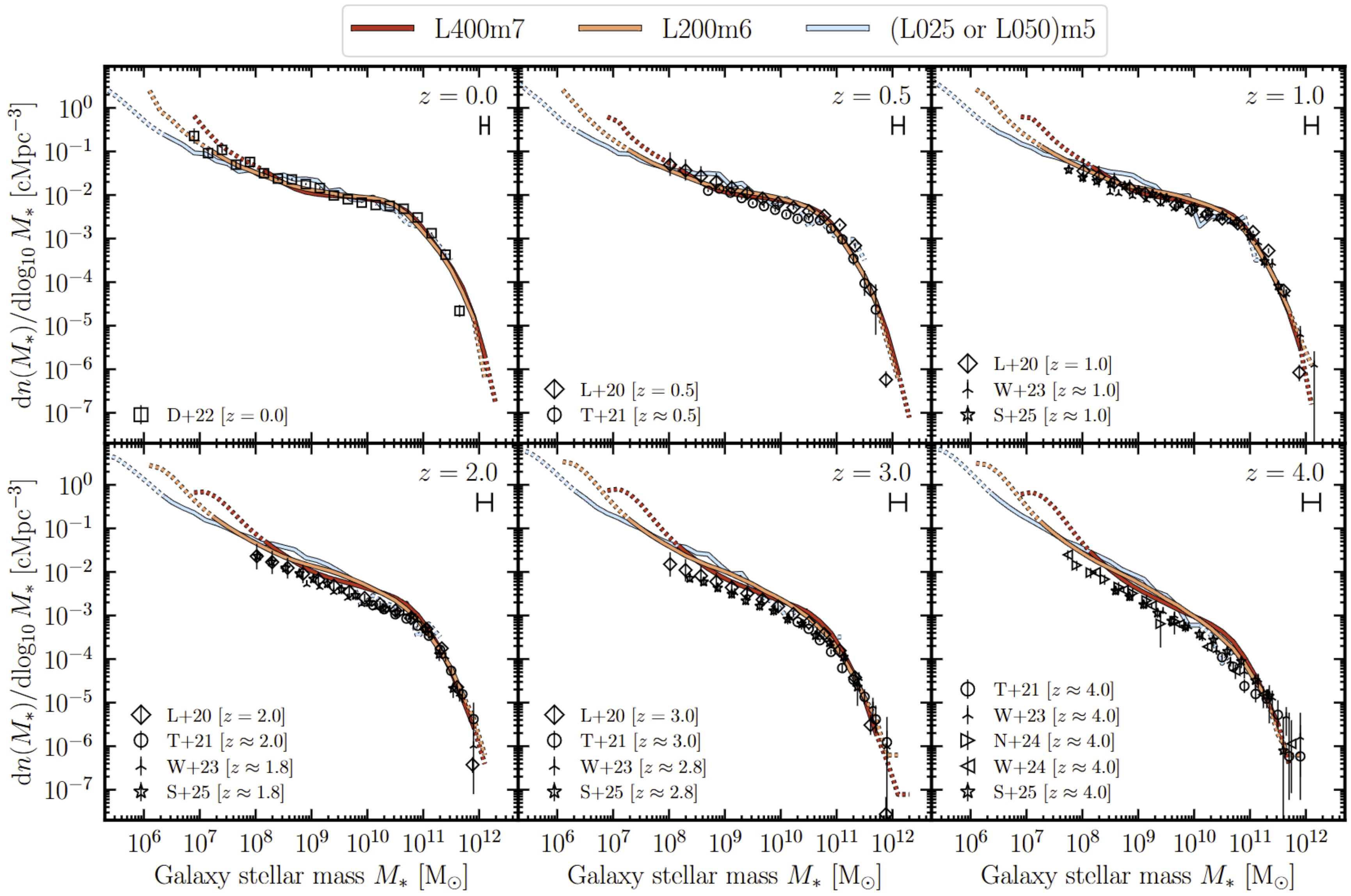
JS+ (2025)

CGM X-ray luminosity



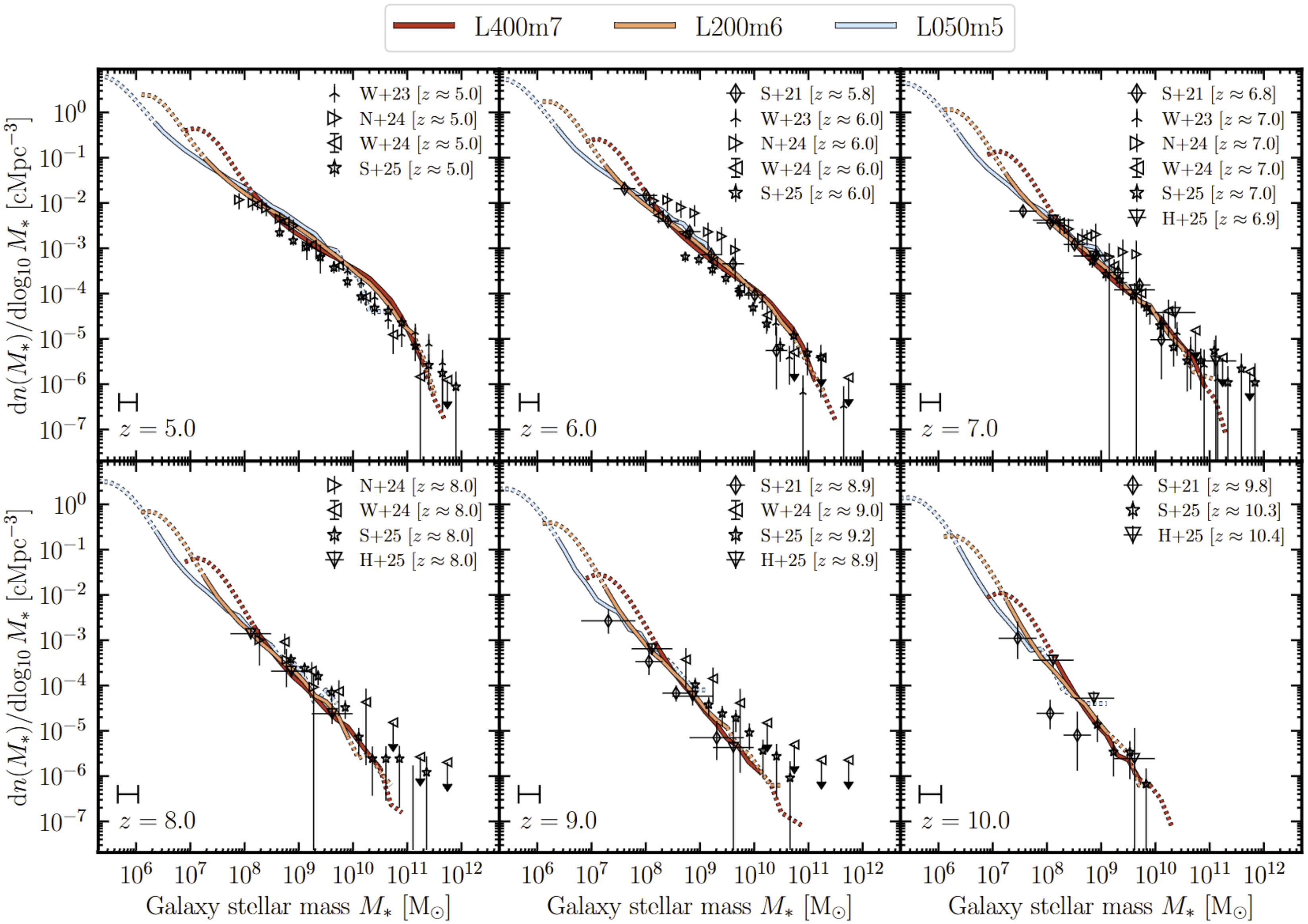
JS+ (2025)

Evolution of the mass function from z = 0 - 4



Chaikin, JS+ (2025)

Evolution of the mass function from z = 5 - 11



Chaikin, JS+ (2025)

Conclusions Part II

- COLIBRE simulations for galaxy formation and cosmology
  - Multiphase ISM including live dust grain model coupled to non-equil. cooling
  - Similar dark matter and baryonic particle masses to suppress spurious heating of stars
  - Order of magnitude more resolution elements than previous generation
  - Wide range of volumes and resolutions
  - Two different implementations of AGN feedback for a fixed calibration
- First results show very good convergence and excellent agreement with a wide range of observations
- Together, FLAMINGO and COLIBRE span 6 orders of magnitude in resolution
- *Feel free to contact me if you would like to use the simulations*