Title: Review Talk: Simulations at the intersection of galaxy formation and cosmology

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Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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Abstract:

Observational surveys of the distribution of matter in the universe are becoming ever more precise and continue to be extended to smaller scales. This necessitates accounting for the fact that baryons do not precisely trace the dark matter. The redistribution of baryons by galactic winds, which is the major bottleneck in our understanding of galaxy evolution, therefore requires a convergence between models of large-scale structure and cosmology. I will discuss some of the insights gained from cosmological, hydrodynamical simulations, and challenges that need to be overcome to make further progress. I will present recent results from the FLAMINGO suite of large-volume cosmological, hydrodynamical simulations, which provide insight into the importance of baryonic effects for cosmology using large-scale structure and galaxy clusters. Finally, I will present the COLIBRE simulations of galaxy formation, a new suite of cosmological hydrodynamical simulations that removes important shortcomings of previous simulations.

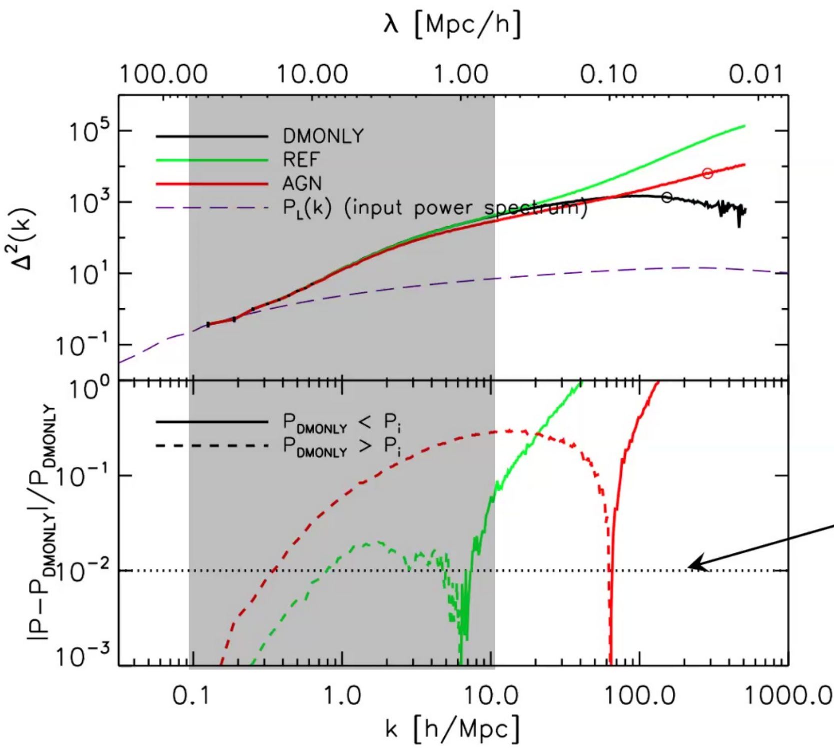
Simulations at the intersection of galaxy formation and cosmology

Joop Schaye (Leiden)

Why do we need (many) hydrodynamical simulations at the interface between large-scale structure and galaxy formation?

- Galactic outflows can redistribute baryons on scales up to 10 Mpc
- Baryons make up 16% of the matter
- Observational cosmology using large-scale structure is
  - Using ever more observables
  - Becoming ever more precise
  - Probing ever smaller scales
- Feedback processes in galaxy formation
  - Are uncertain → simulations should vary them
  - Need to be taken into account by observational cosmology
  - Can be constrained using observational cosmology

Baryons and the matter power spectrum



The feedback required to solve the overcooling problem suppresses power on large scales

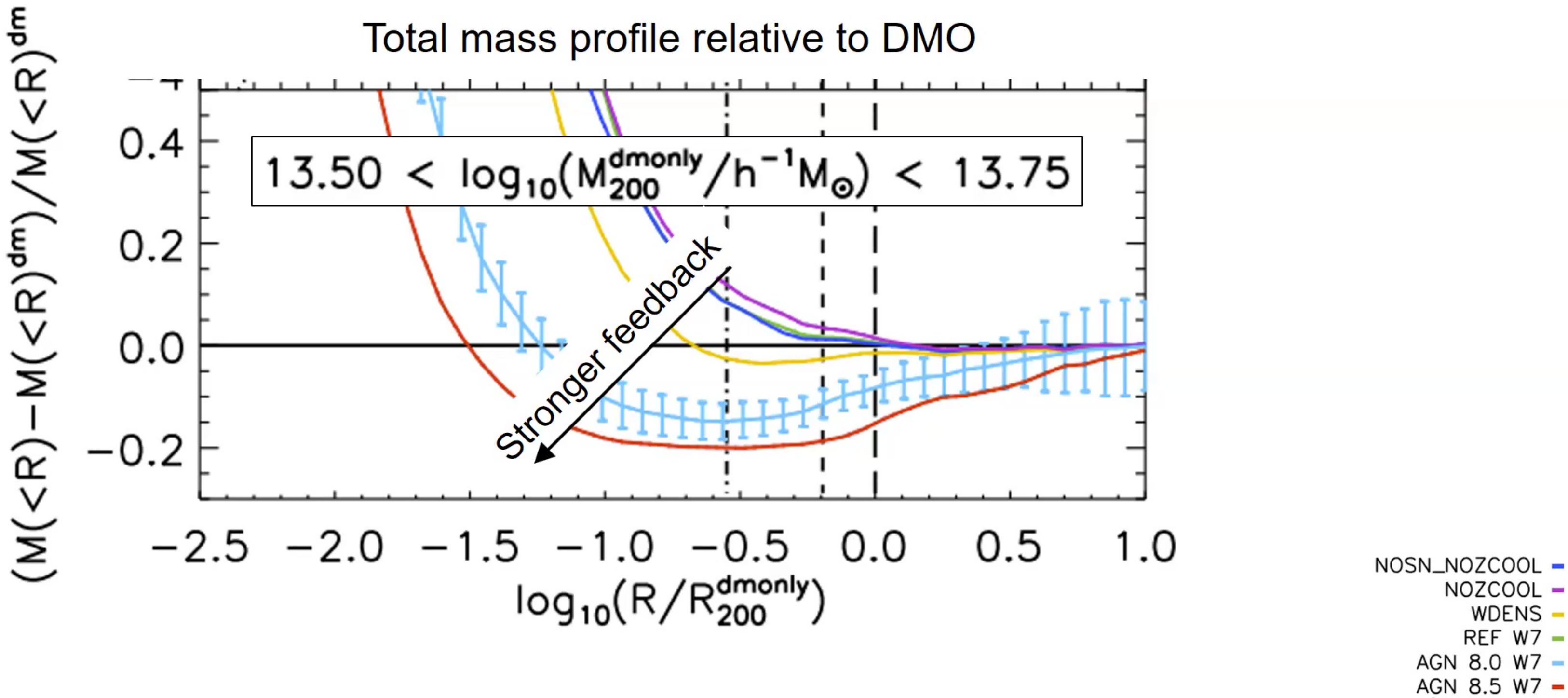
1% difference wrt dark matter only

Range of interest for cosmic shear

Van Daalen, JS+ (2011)

Catastrophic consequences for Euclid cosmic shear (Semboloni, Hoekstra, JS+ 2011)

Effect of baryons on haloes



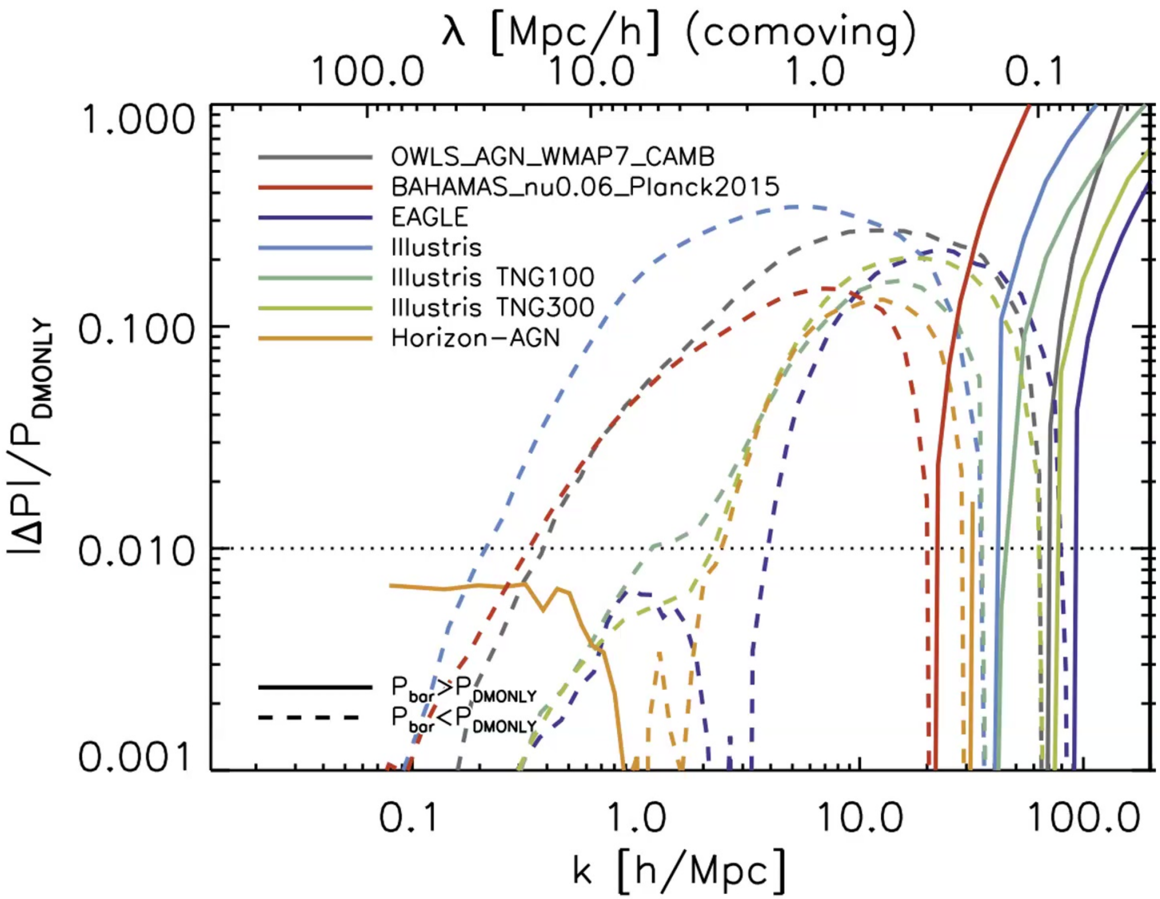
Baryons compress mass near the halo center, but suppress the density in the outer halo.

Velliscig, van Daalen, JS+ (2014)

But why should we believe cosmological hydro simulations?

- You should not!
- However, you may want to take notice if
  - The effect is understood
  - The simulations reproduce the most relevant observations
  - The effect is confirmed using different implementation of subgrid models
  - The effect is confirmed using observationally constrained analytic/semi-empirical models

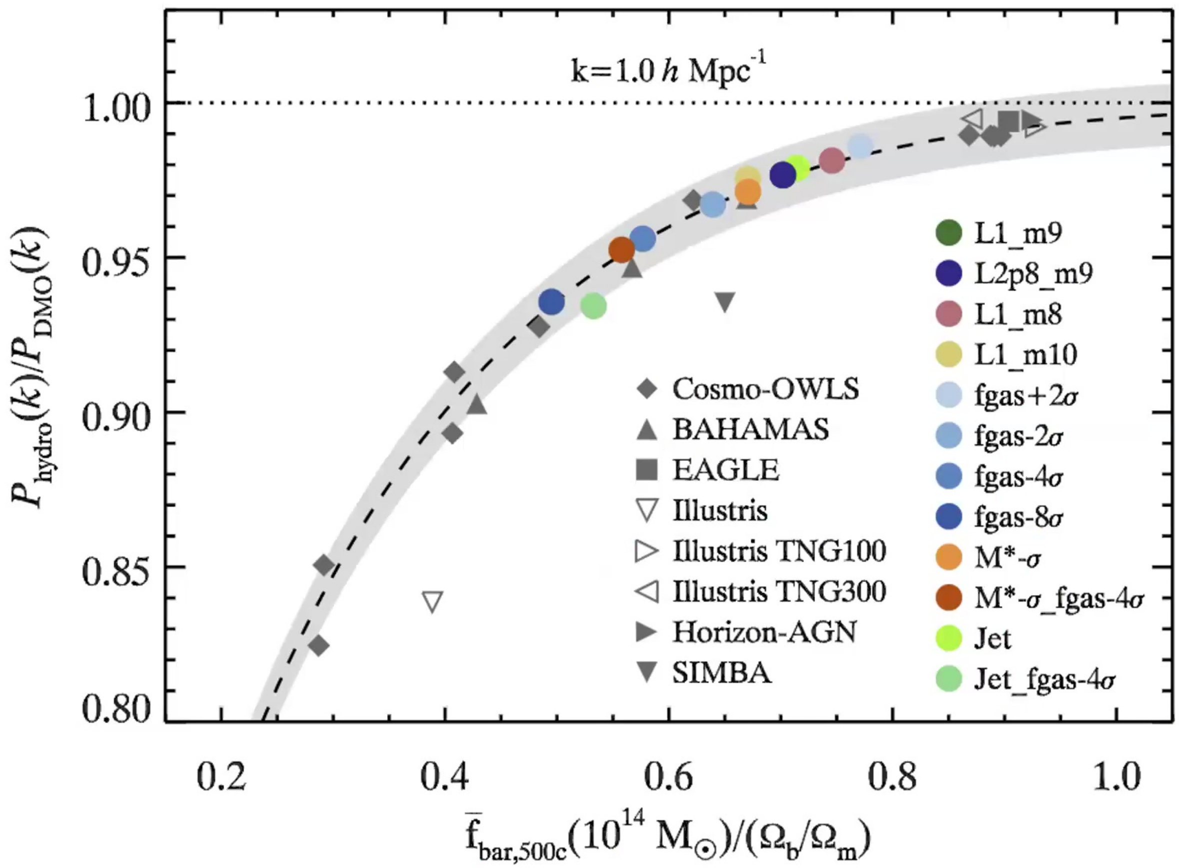
Baryonic suppression predicted by different hydro simulations



Results are all over the place!

Van Daalen, McCarthy, JS (2020)

Baryonic suppression versus cluster baryon fraction

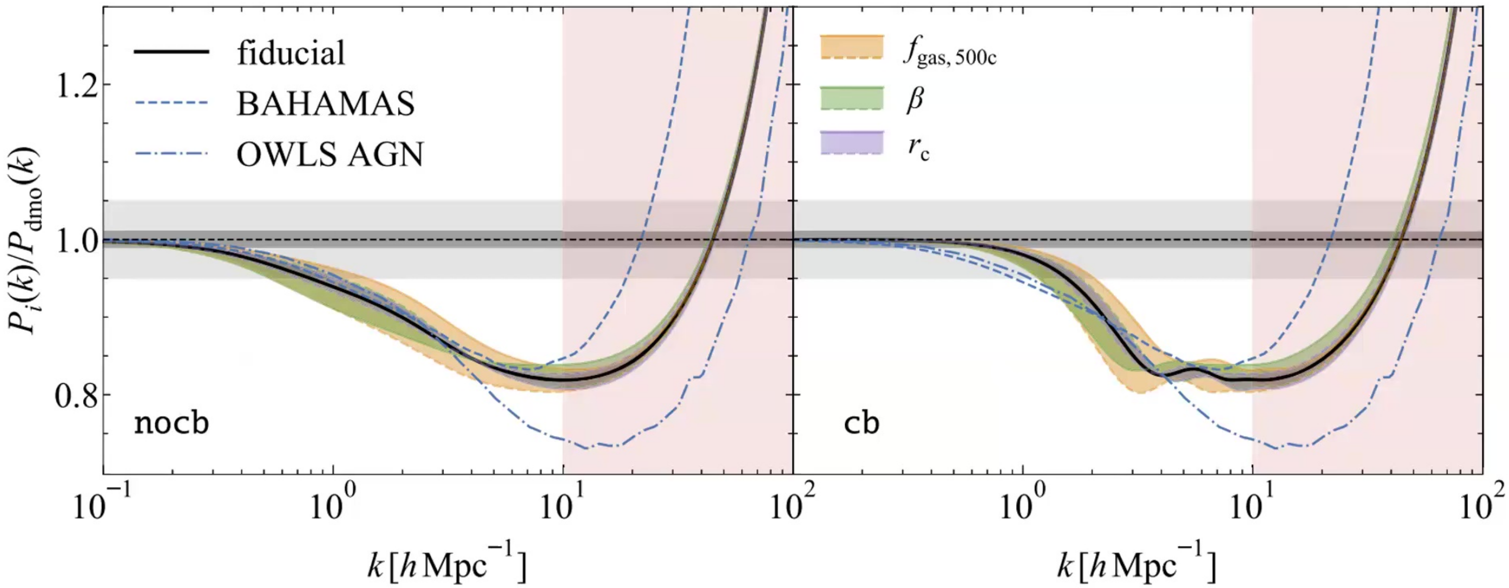


All simulations follow a universal relation between cluster baryon fraction and power spectrum suppression

JS+ (2023)
Van Daalen, McCarthy, JS (2020)

Halo model constrained by observations

Baryonically closed haloes



- Intermediate-scale suppression predicted by halo model agrees with simulations that reproduce cluster gas fractions
- Large-scale suppression unconstrained by cluster observations

Debackere, JS, Hoekstra (2020)
See also Schneider+ (2019)

Simulations at the interface between large-scale structure and galaxy formation:
Ingredients

- Essential
  - Large box size (>> 100 Mpc; though cluster zooms also useful)
  - Hydrodynamics
  - Radiative cooling, star formation, metal enrichment, SN & AGN feedback
  - Subgrid feedback calibrated to reproduce the *most relevant* observables
  - Model variations
- Important
  - Neutrinos
- Nice but only if it does not limit the ability to do the essentials
  - High resolution
  - More physics

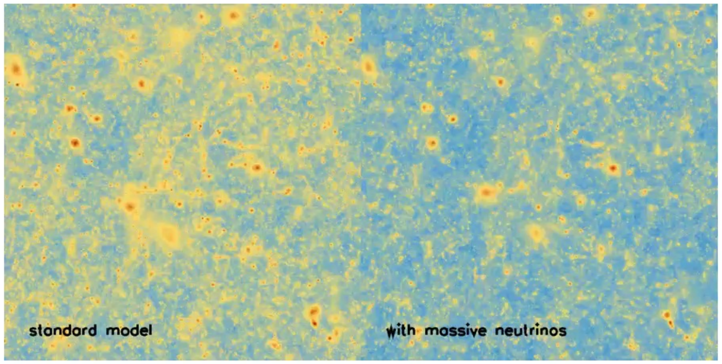
FLAMINGO: Basic features

- 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*

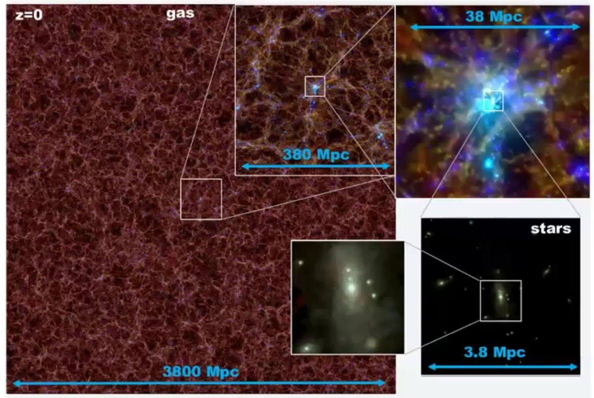
JS+ (2023)

Large-scale hydrodynamical simulations

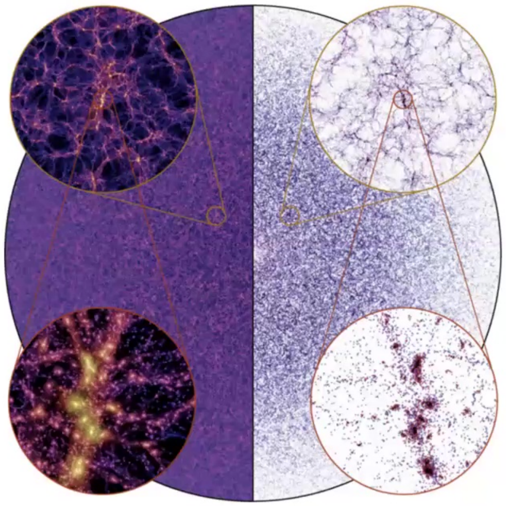
BAHAMAS

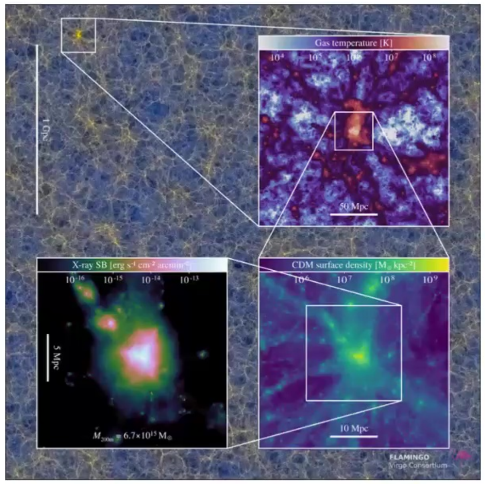


Magneticum



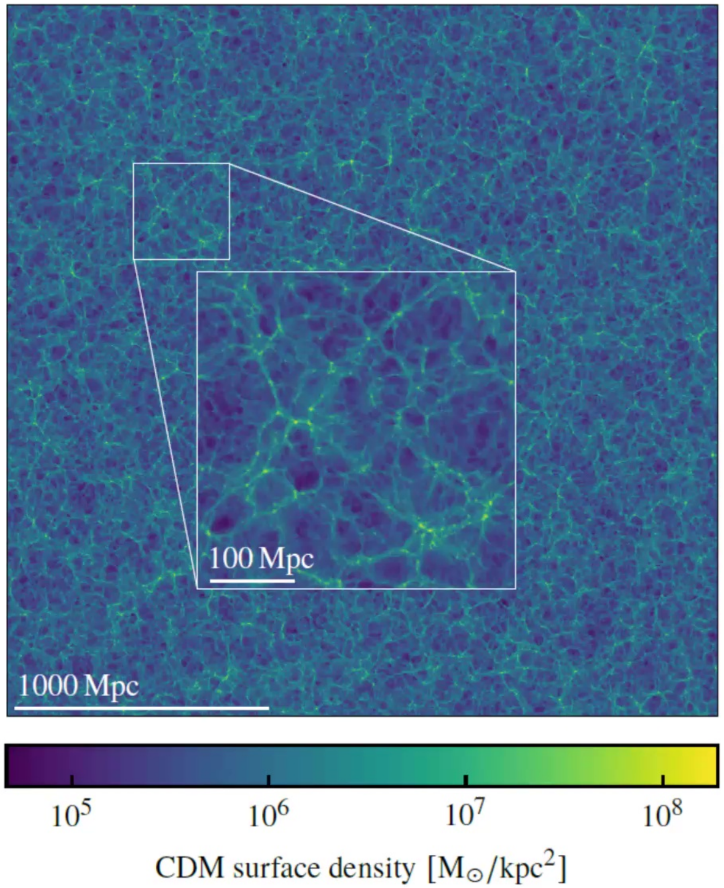
MillenniumTNG



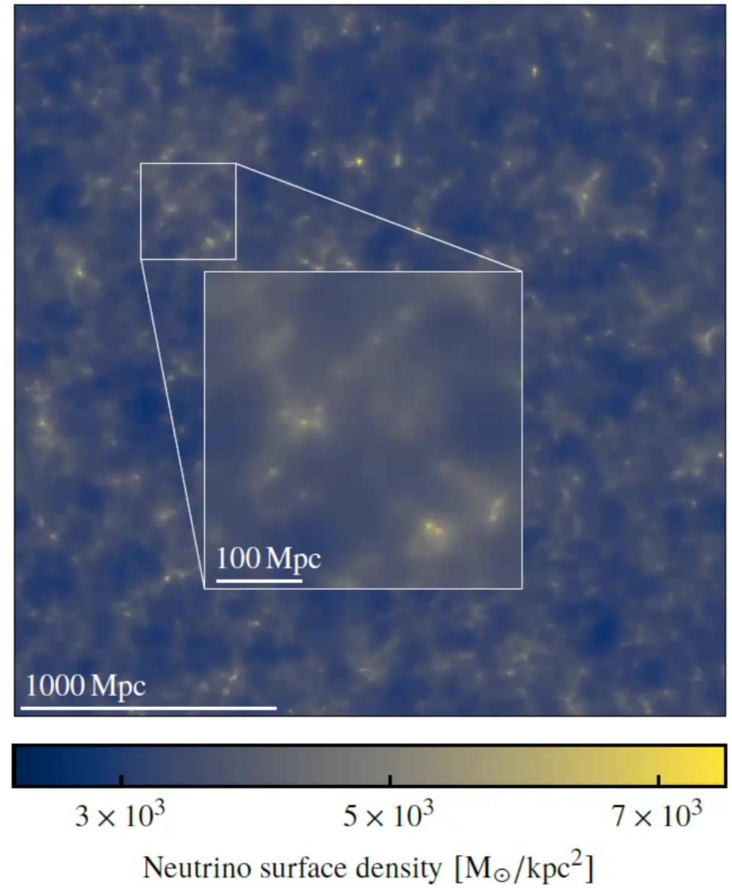


FLAMINGO

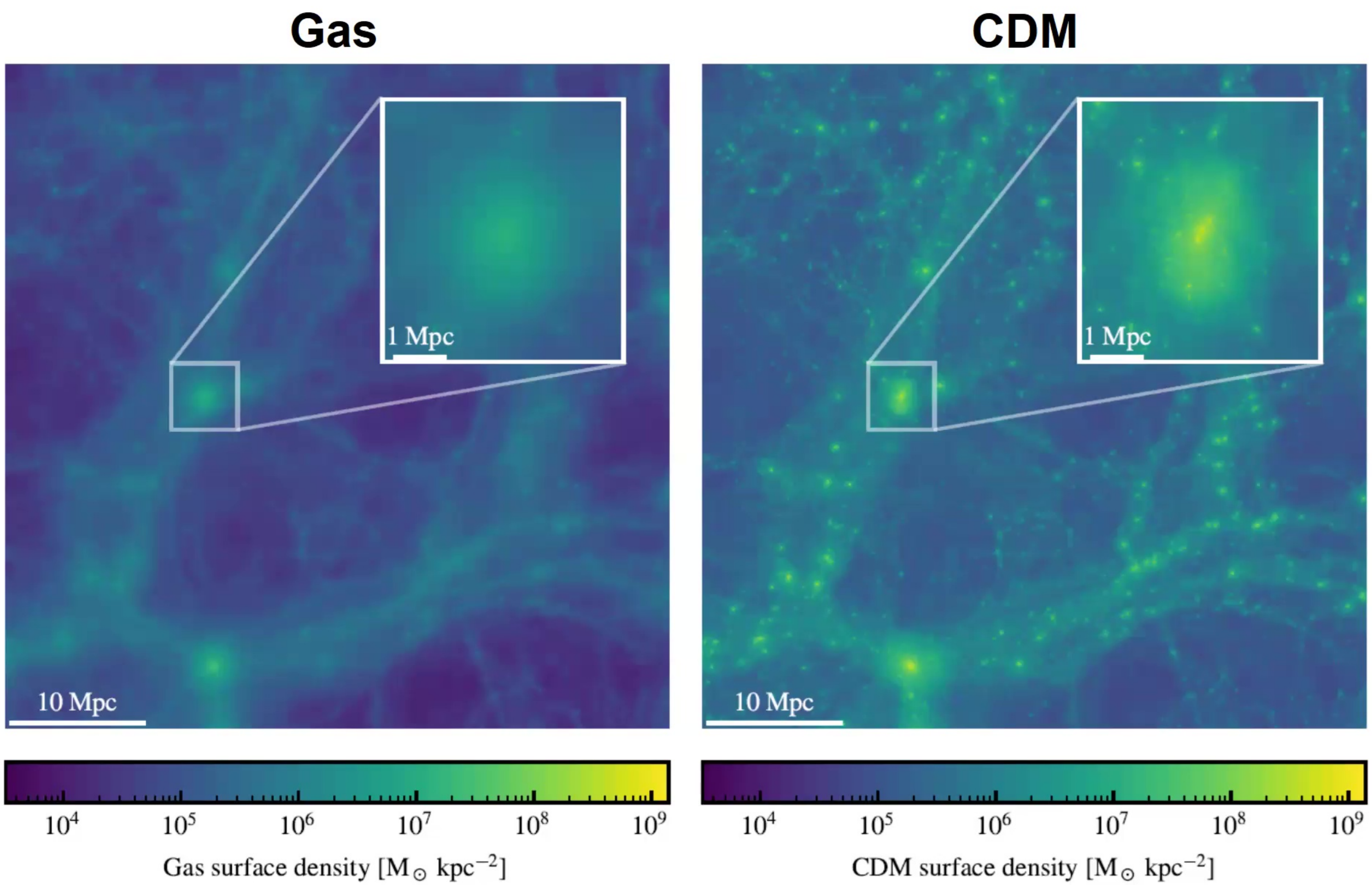
CDM



Neutrinos



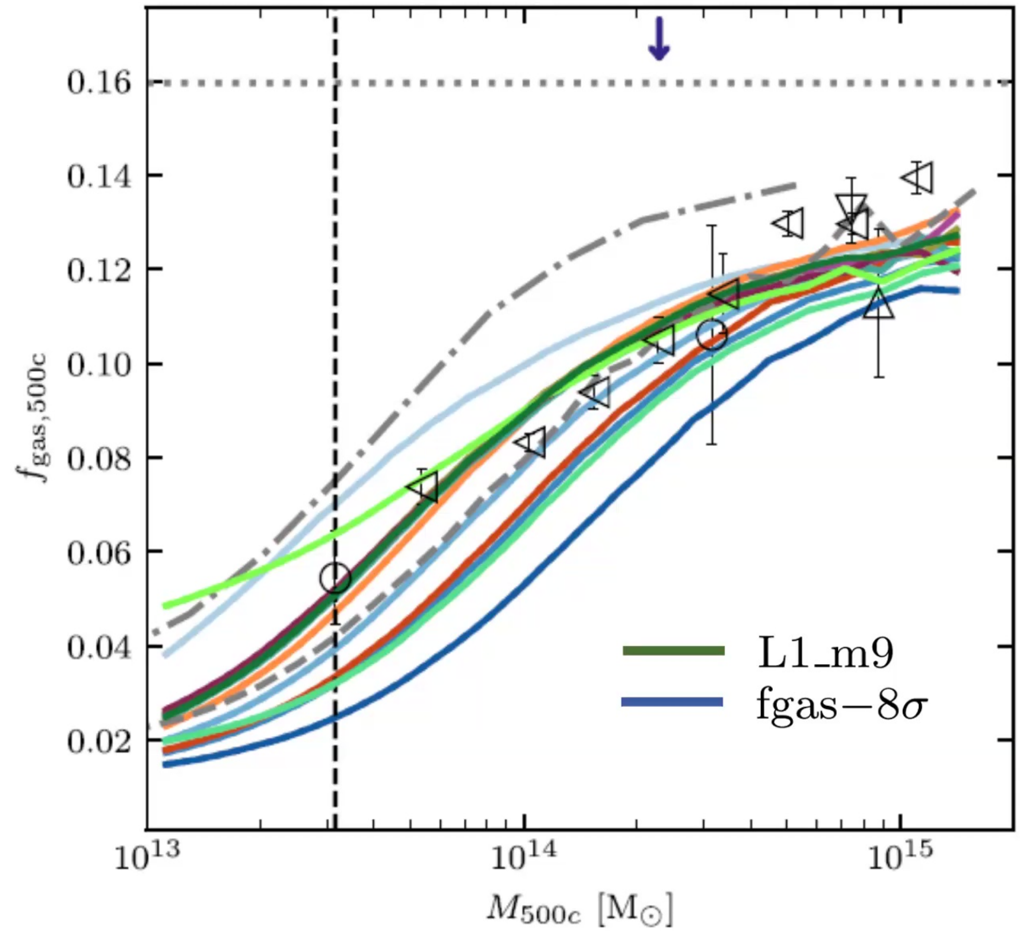
JS+ (2023)



Gas
CDM
1 Mpc
1 Mpc
10 Mpc
10 Mpc
10^4 10^5 10^6 10^7 10^8 10^9
10^4 10^5 10^6 10^7 10^8 10^9
Gas surface density [M⊙ kpc^-2]
CDM surface density [M⊙ kpc^-2]

JS+ (2023)

Cluster gas fractions inferred from X-rays + weak lensing



JS+ (2023)

S8 tension

Systematics?
New physics?
Baryonic feedback?

CMB

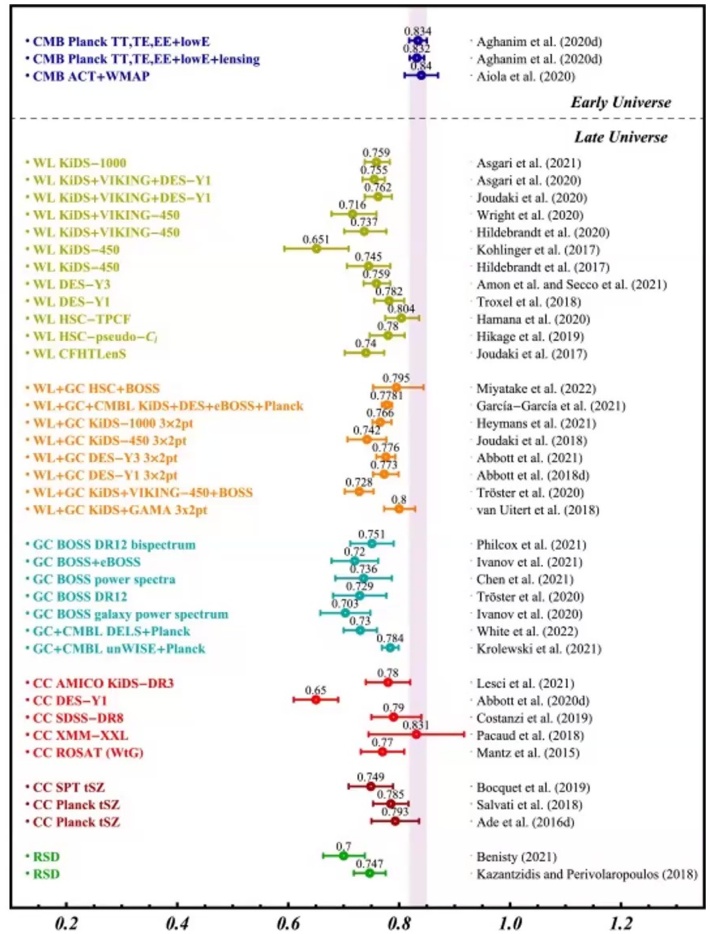
Weak lensing

Weak lensing + galaxy clustering

Galaxy clustering

Cluster counts

Redshift space distortions



$$S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$$

Also, tSZ power spectrum, …

Abdalla+ (2022)

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)

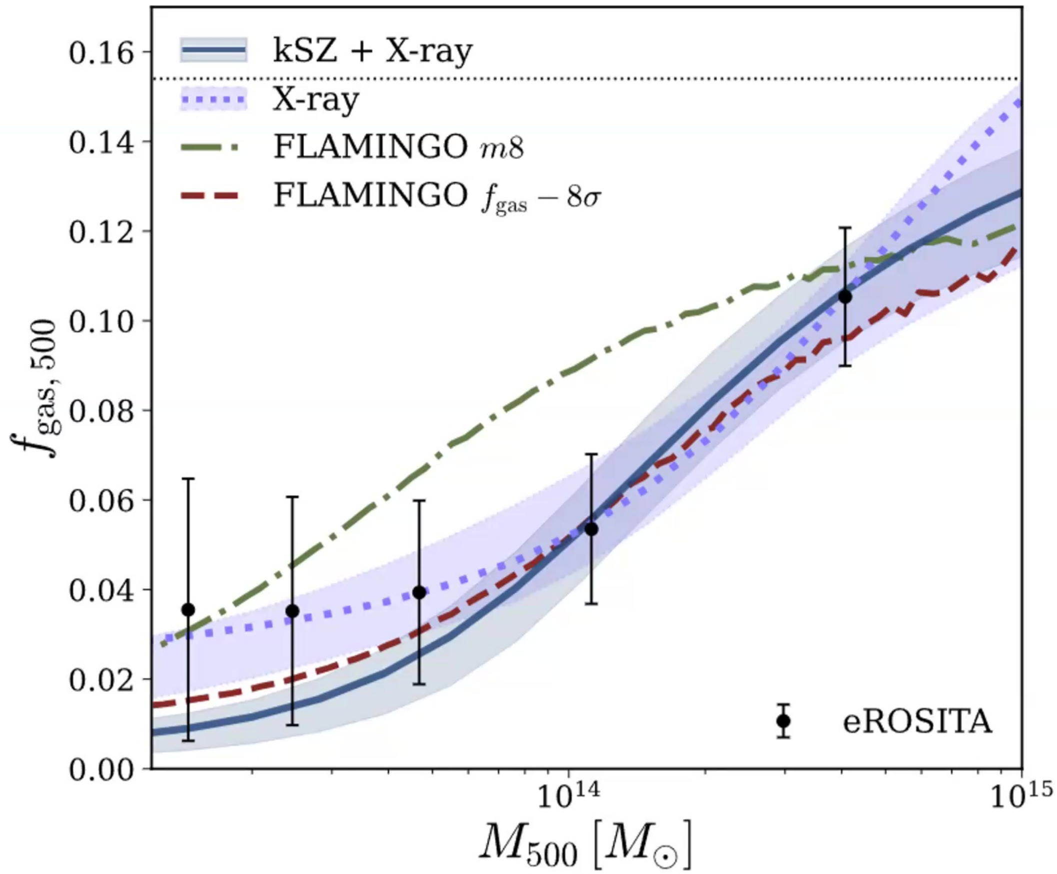
However,

- 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)

Fitting eROSITA gas fractions & ACT kSZ with baryonification

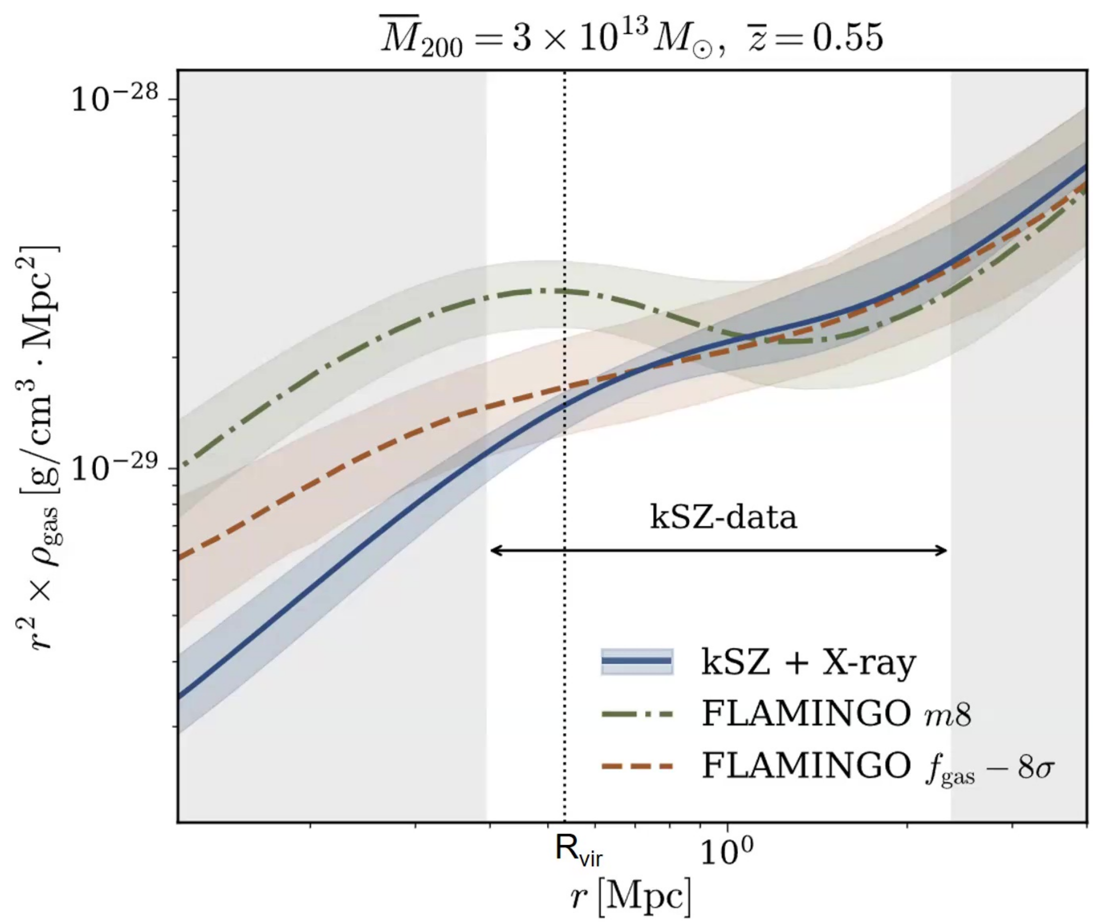
eROSITA (Popesso+ 2025):

- 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



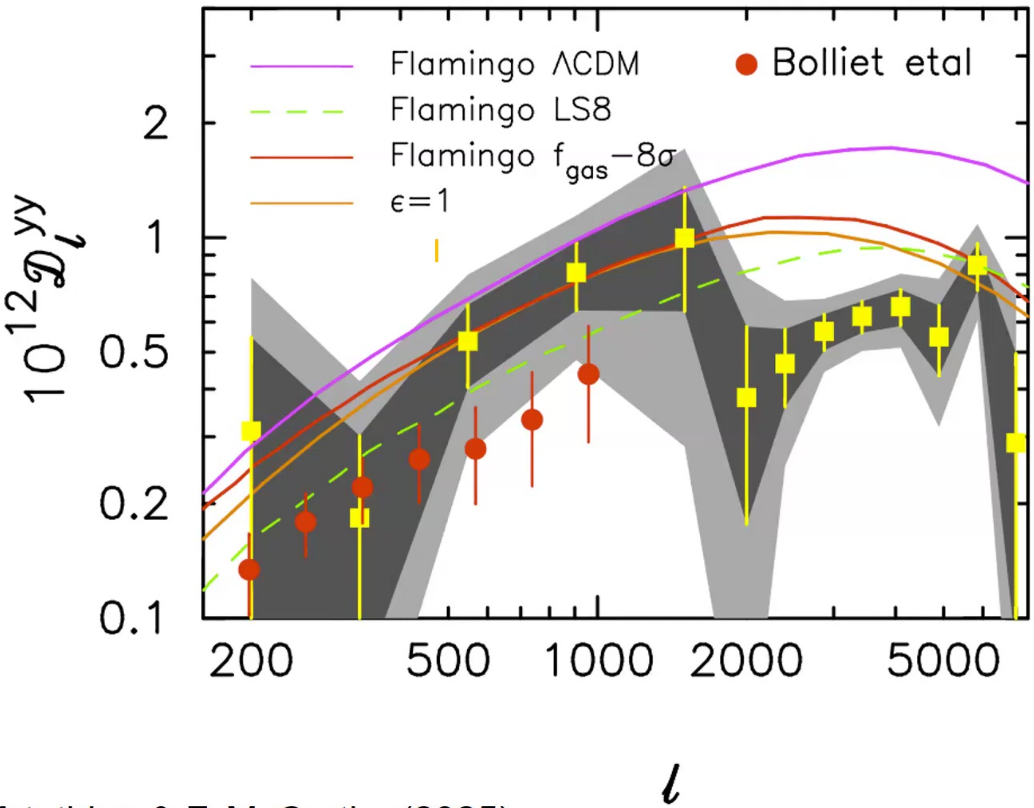
Kovač+ (2025)

Fitting eROSITA gas fractions & ACT kSZ with baryonification



Kovač+ (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)

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 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 ($\geq 10^4$ 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

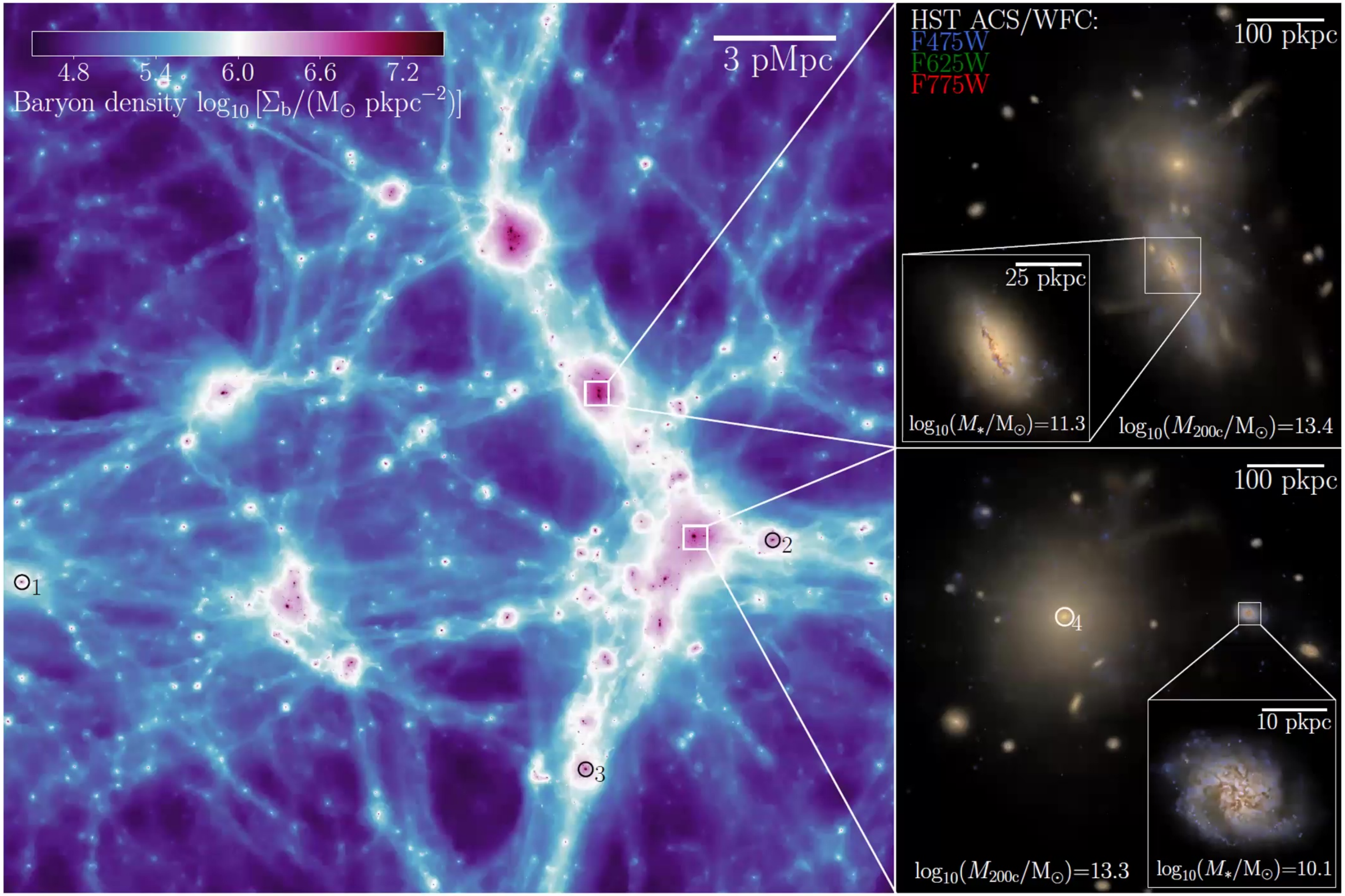
- AGN feedback is critical but highly uncertain

  → 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

COLd Ism and Better Resolution (COLIBRE)

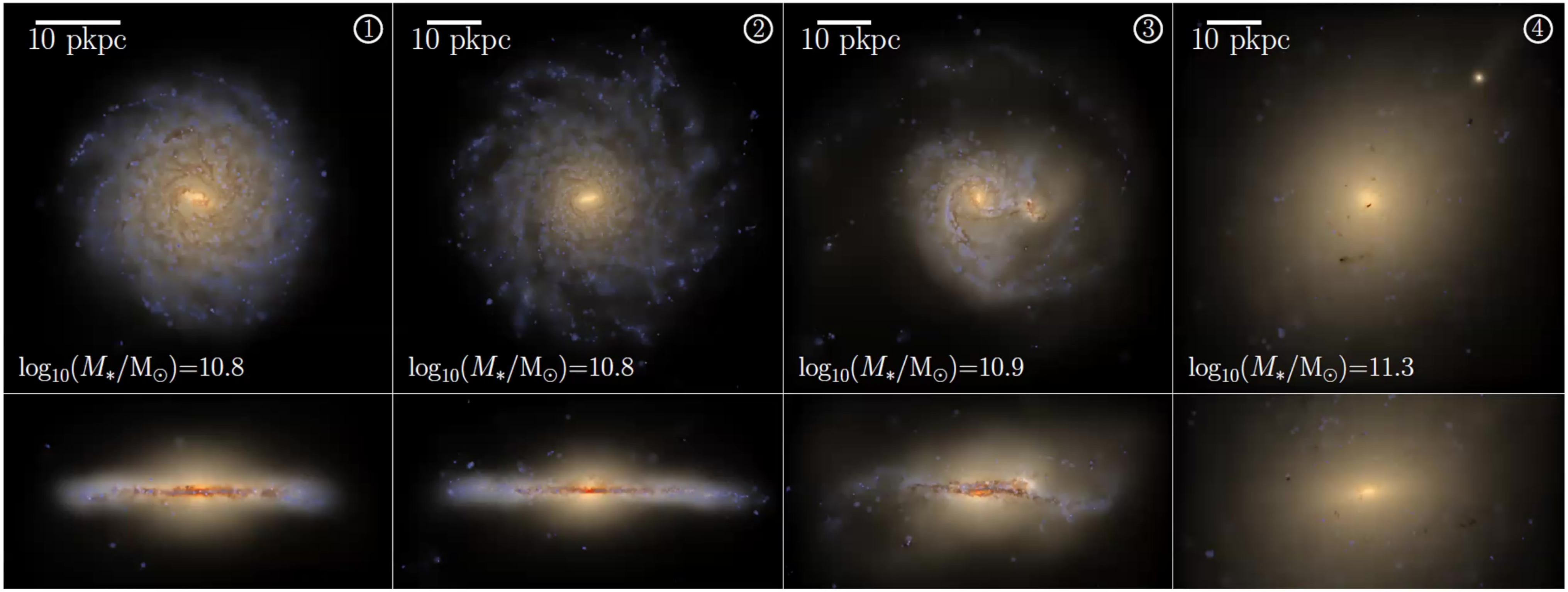
- Includes
  - Cold (T << 10^4 K) interstellar gas
  - New cooling (non-equil. H, He, e^-; self-shielding, UVB and interstellar radiation)
  - Dust (3 grain species, 2 grain sizes; coupled to cooling)
  - New ‘chemistry’ (new yields, diffusion, new SNIa, s- and r-process elements)
  - New stellar feedback (HII regions, winds, turbulence, improved stochastic SN feedback)
  - Improved BH and AGN physics (also runs with BH spin and jet feedback)
  - New 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, 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 ~10^7 to 10^5 $M_\odot$



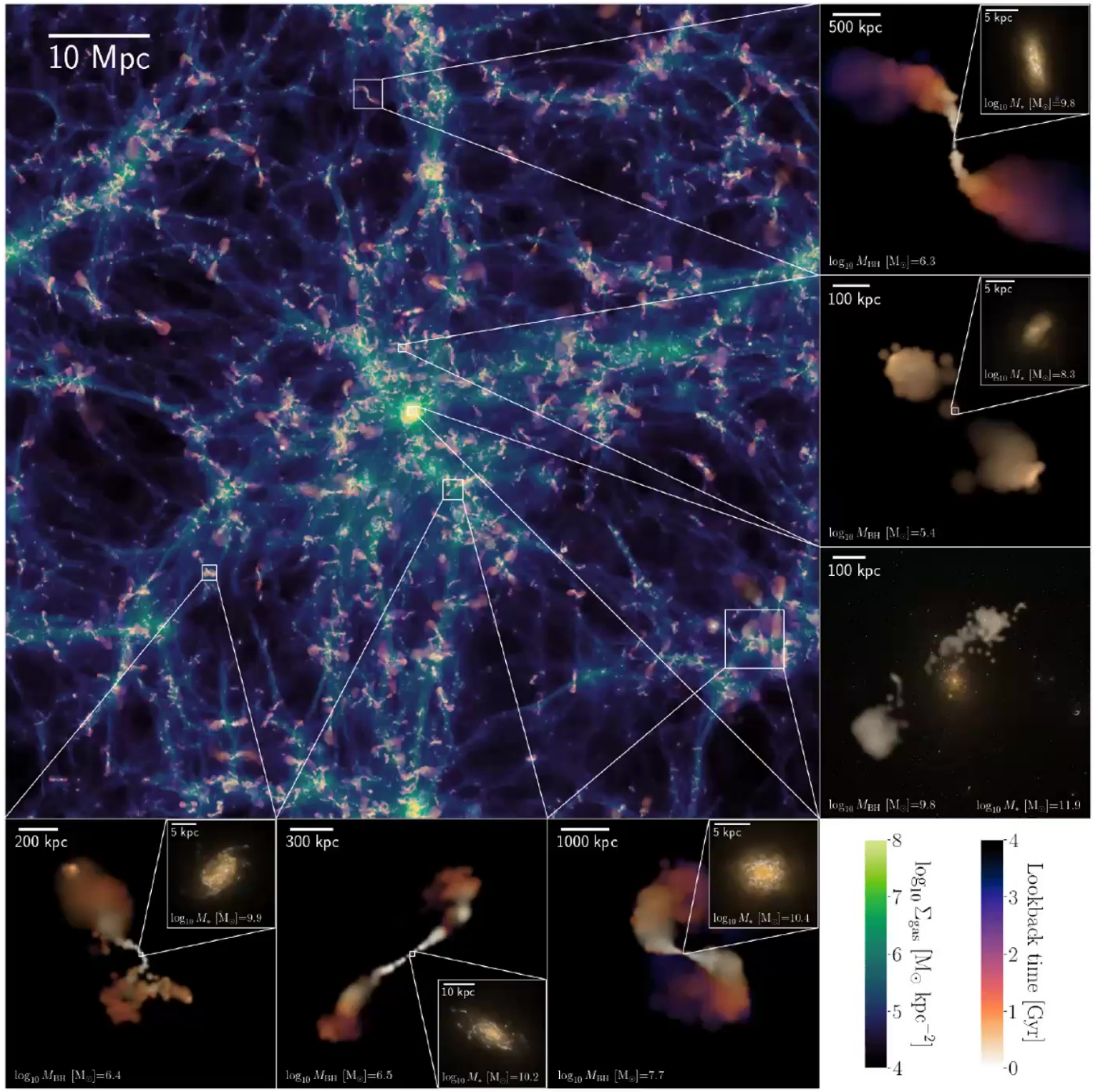
4.8
5.4
6.0
6.6
7.2
Baryon density $\log_{10}[\Sigma_b/(M_\odot\ \mathrm{pkpc}^{-2})]$
3 pMpc
1
2
3
HST ACS/WFC:
F475W
F625W
F775W
100 pkpc
25 pkpc
$\log_{10}(M_*/M_\odot)$=11.3
$\log_{10}(M_{200c}/M_\odot)$=13.4
100 pkpc
4
10 pkpc
$\log_{10}(M_{200c}/M_\odot)$=13.3
$\log_{10}(M_*/M_\odot)$=10.1

JS+ (in prep)

Galaxies in the L025m5 simulation at z = 0

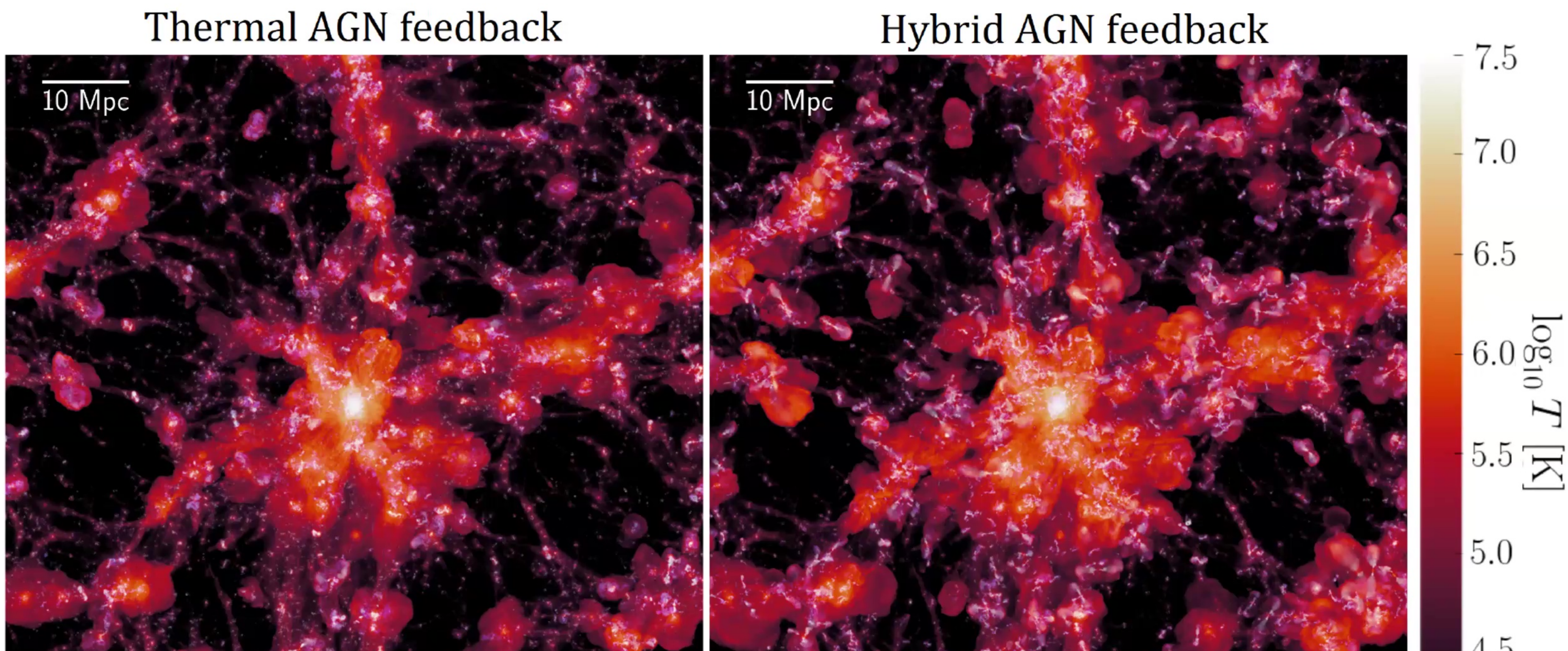


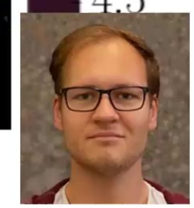
JS+ (in prep)



COLIBRE L100m6h, z = 0

Husko+ (in prep)



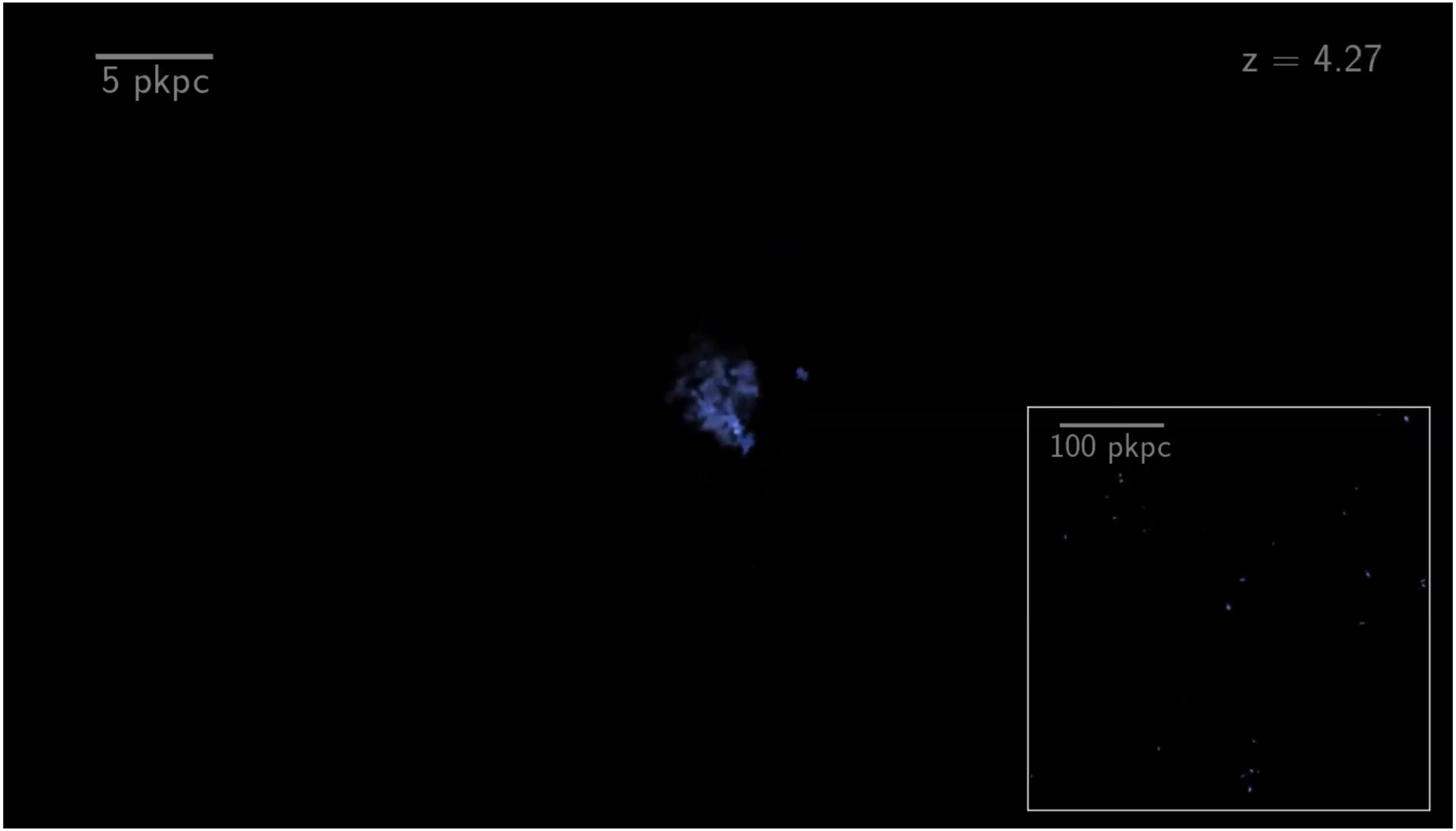


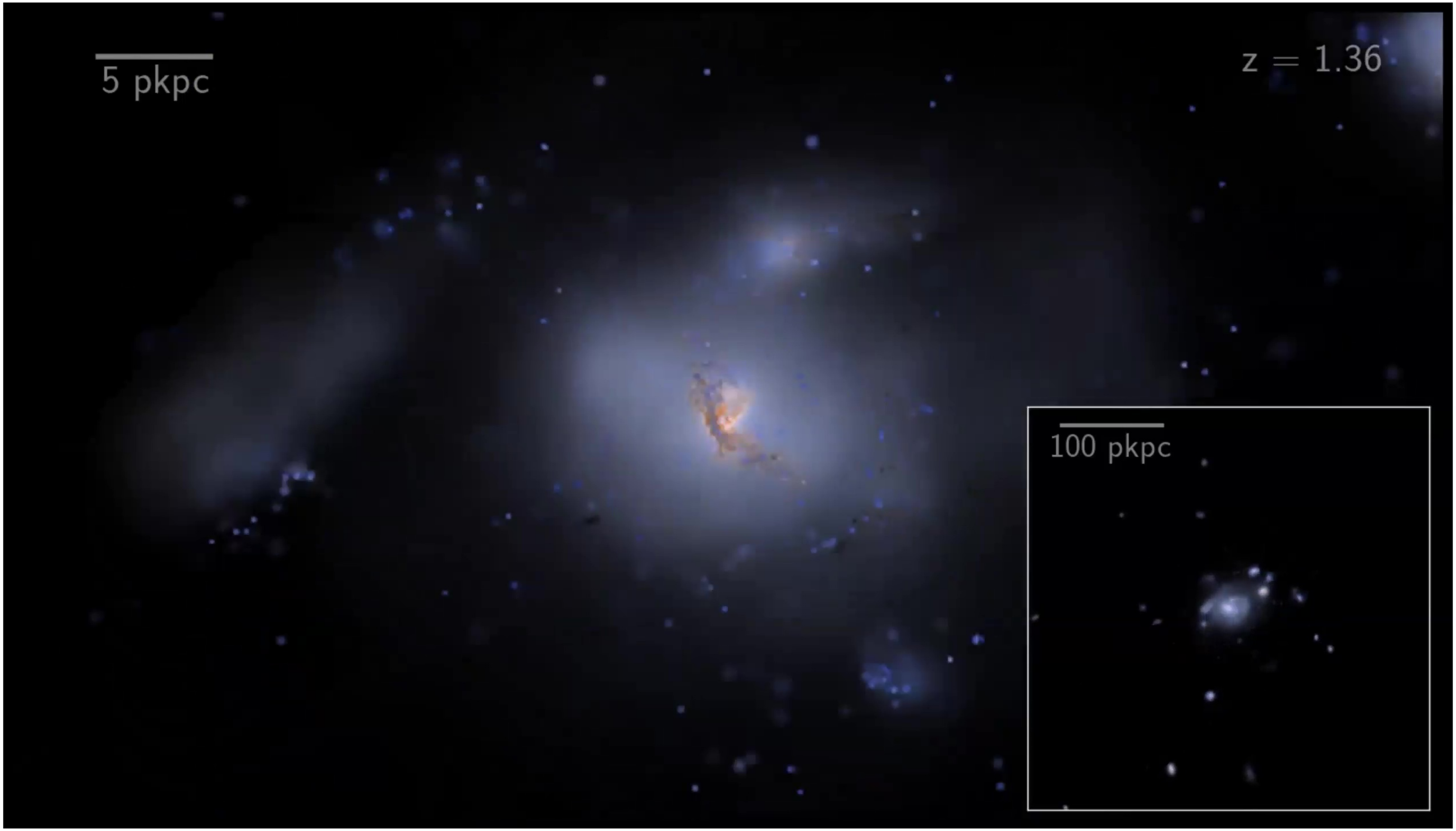
COLIBRE L100m6 & L100m6h, z = 0

Husko+ (in prep)

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*


5 pkpc
z = 4.27
100 pkpc


5 pkpc
z = 1.36
100 pkpc