Baryons in Large Scale Structure: A simulation point of view

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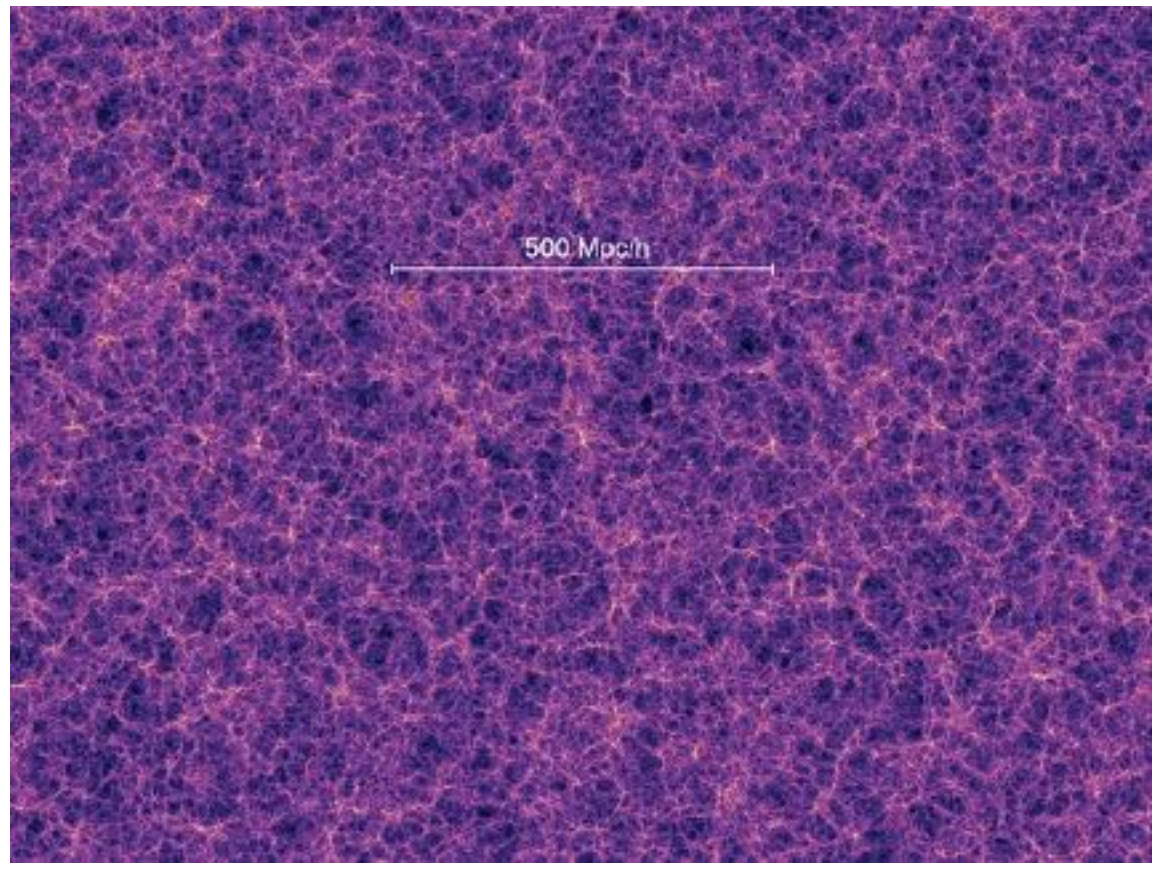
Outline

- Simulating baryonic processes in LSS
- Modelling baryonic processes in LSS
- Constraining baryonic processes in LSS

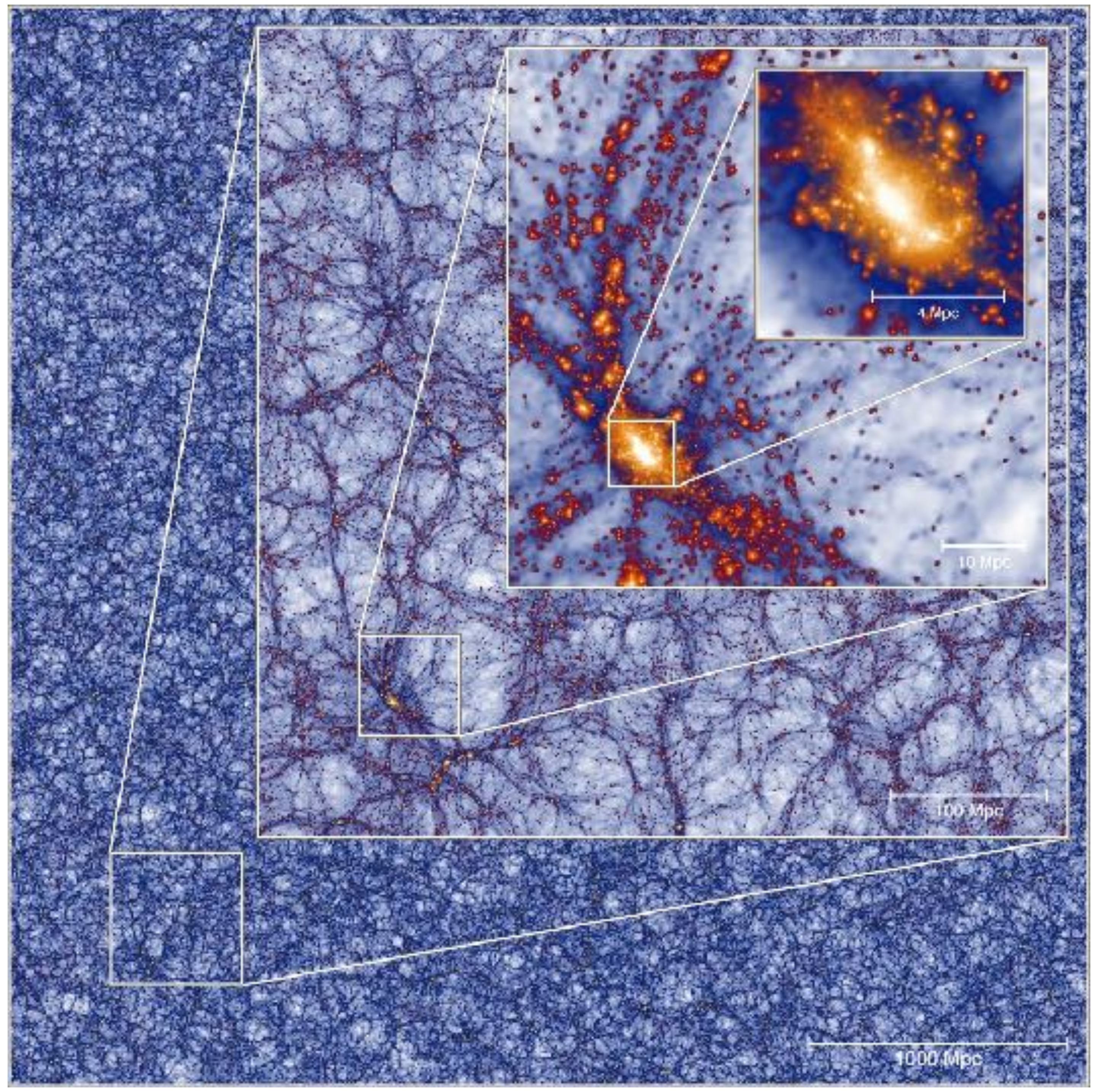
N-body simulations

Accurately describe the formation of structure under gravity, deeply in the nonlinear regime

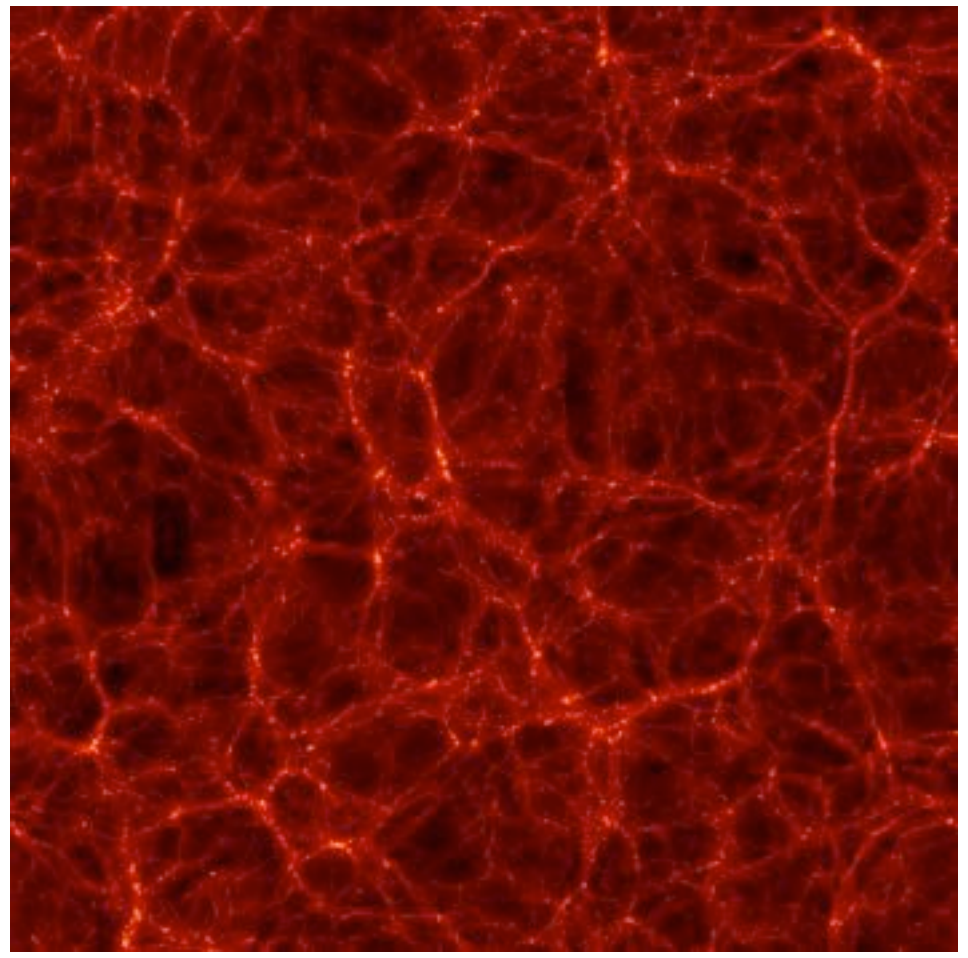
Gigaparsecs boxes, trillion particles achievable



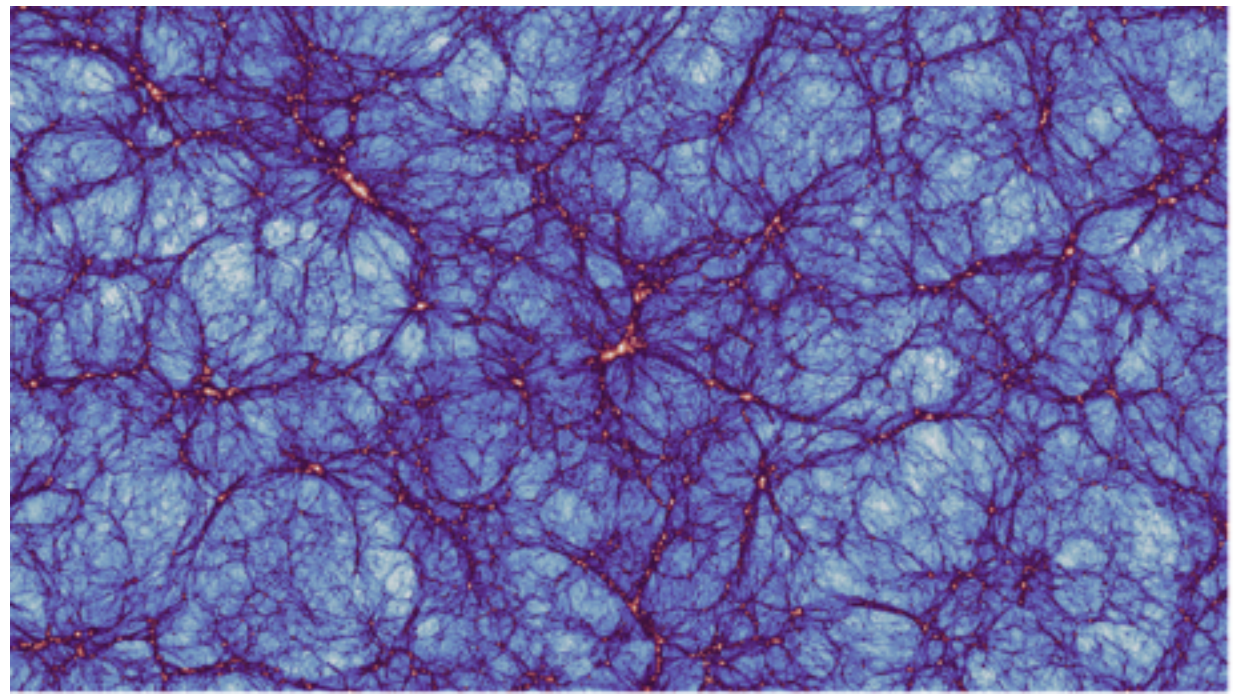
Millennium



Millennium XXL

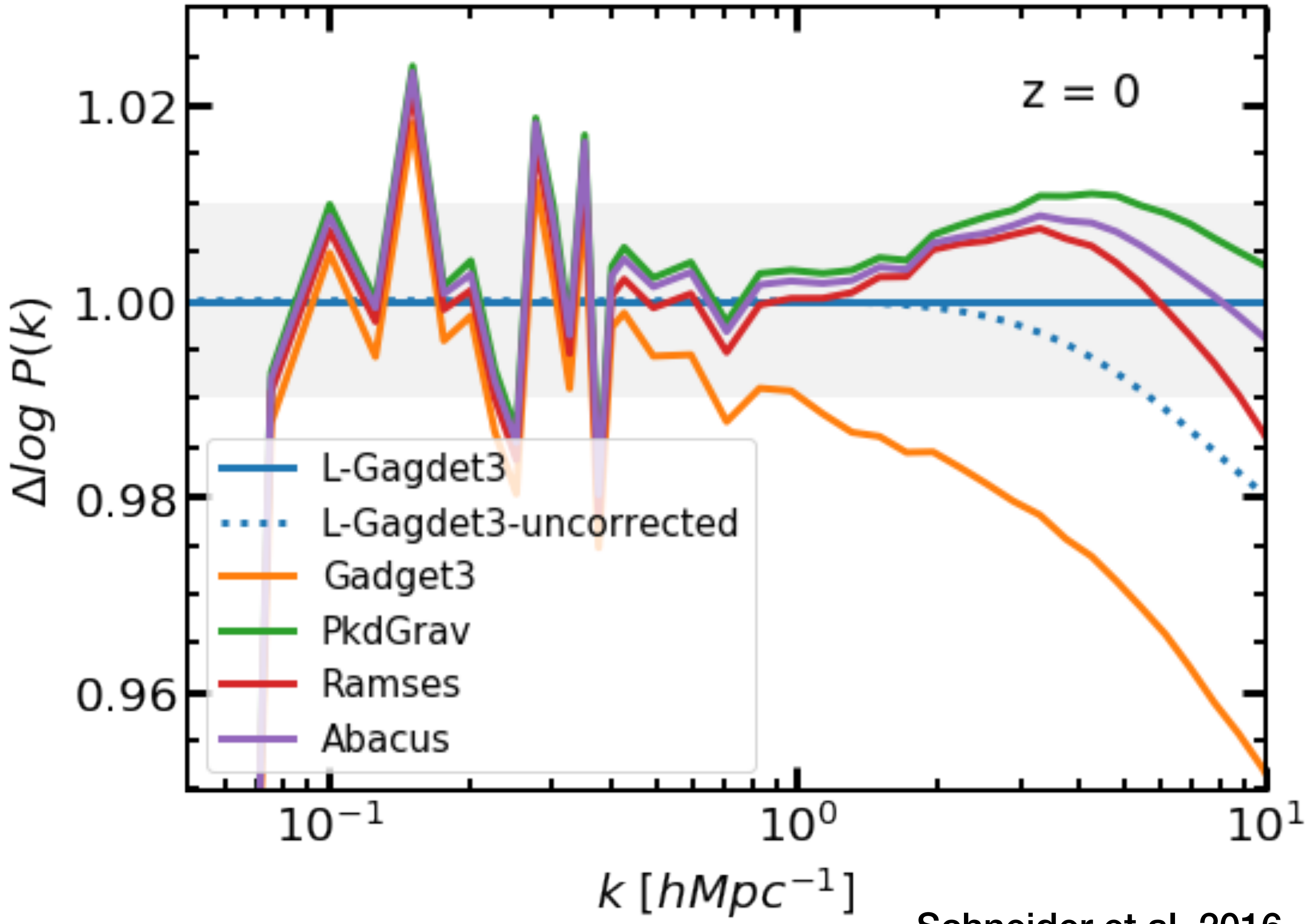


Bolshoi



BACCO

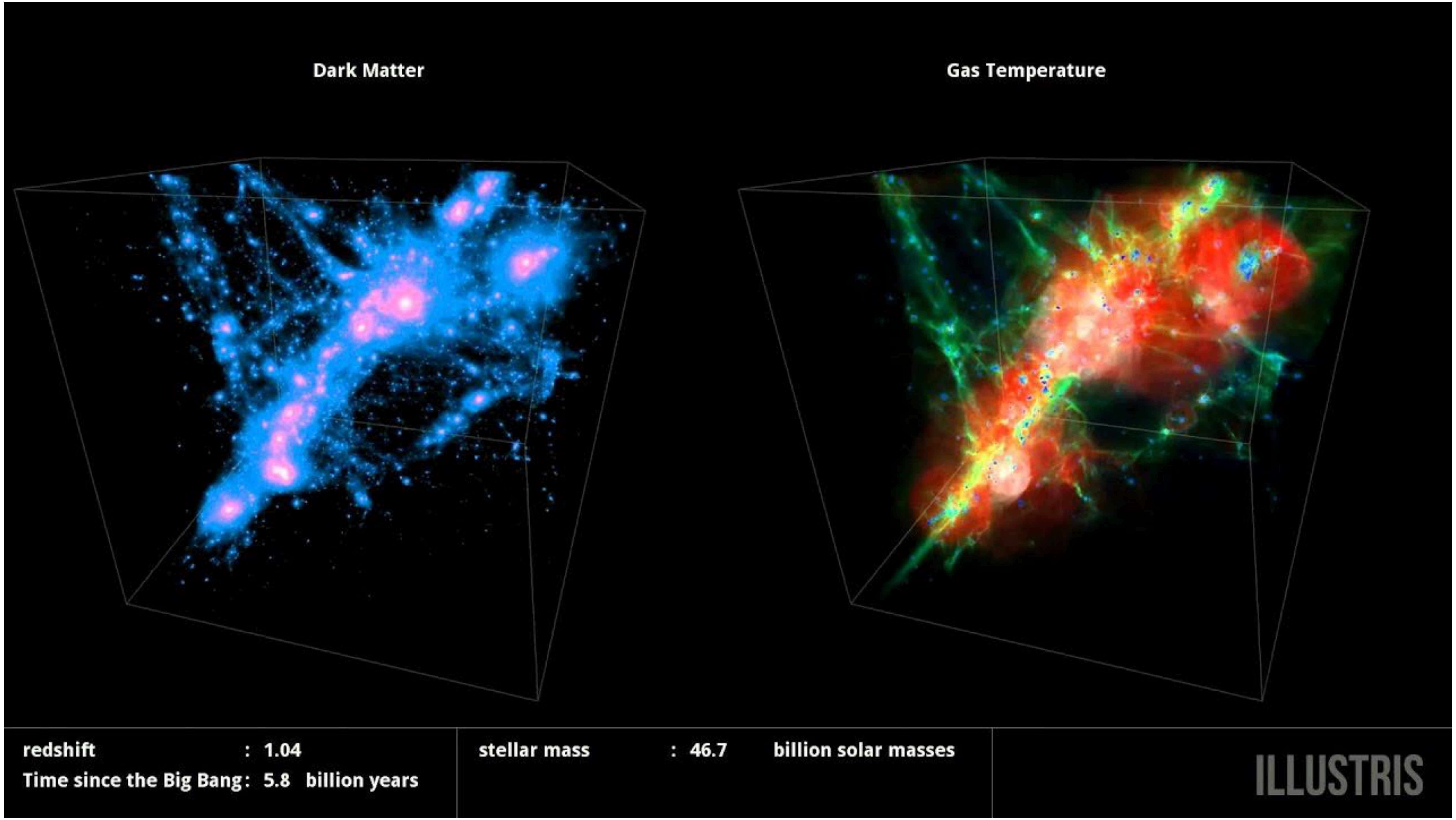
Relatively well understood, converged at 1% level



Schneider et al. 2016
Garrison et al. 2019
Angulo et al. 2021

See e.g. review by Angulo & Hahn 2022

Structure formation and (g)astrophysics



Credits: Illustris Collaboration

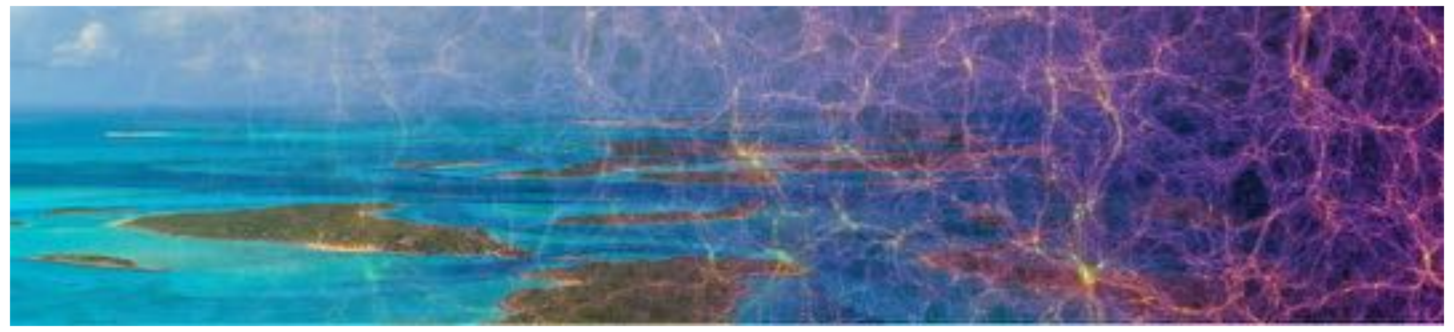
Cosmological hydrodynamic simulations

Solve hydrodynamical equations plus:

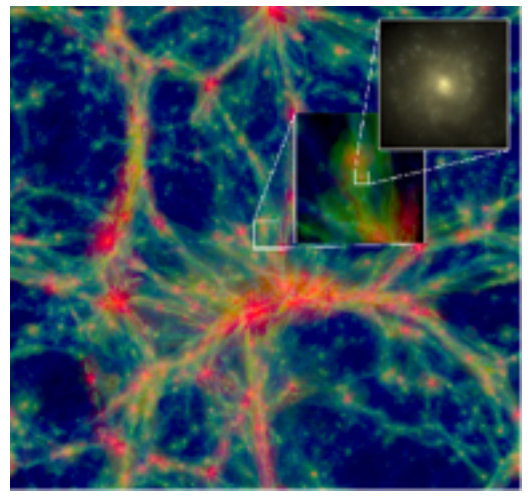
- Star formation and stellar population evolution;
- Stellar, supernovae and blackhole feedback;
- Formation, merging, and accretion of supermassive blackholes;
- Chemical enrichment;
- Gas radiation;
- Cosmic magnetic fields;

But:

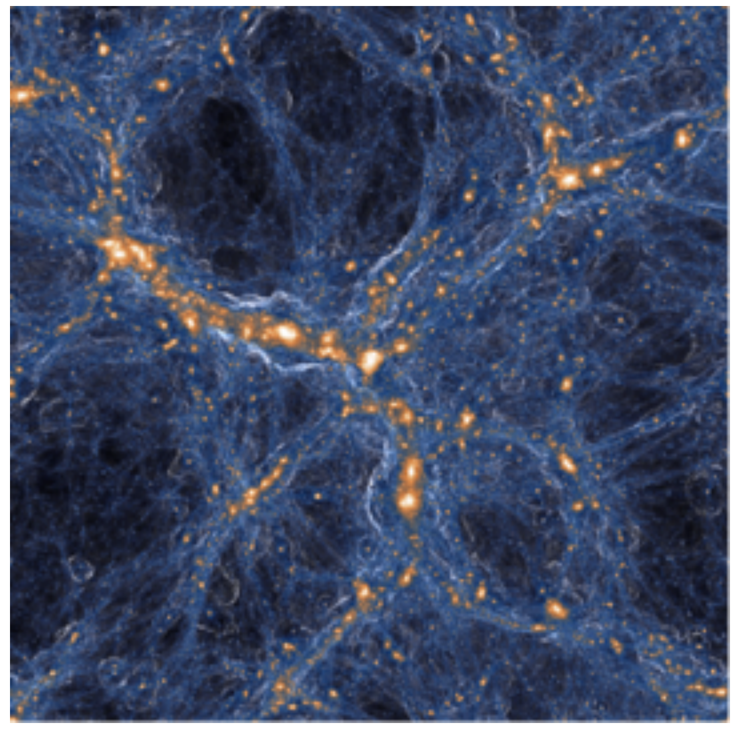
- Computationally expensive;
- Difficult Calibration;
- Difficult Convergence;
- Uncertain sub-grid prescriptions;



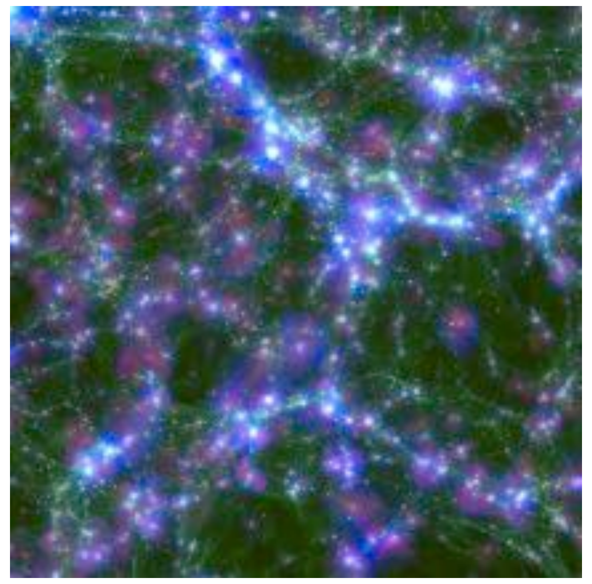
BAHAMAS



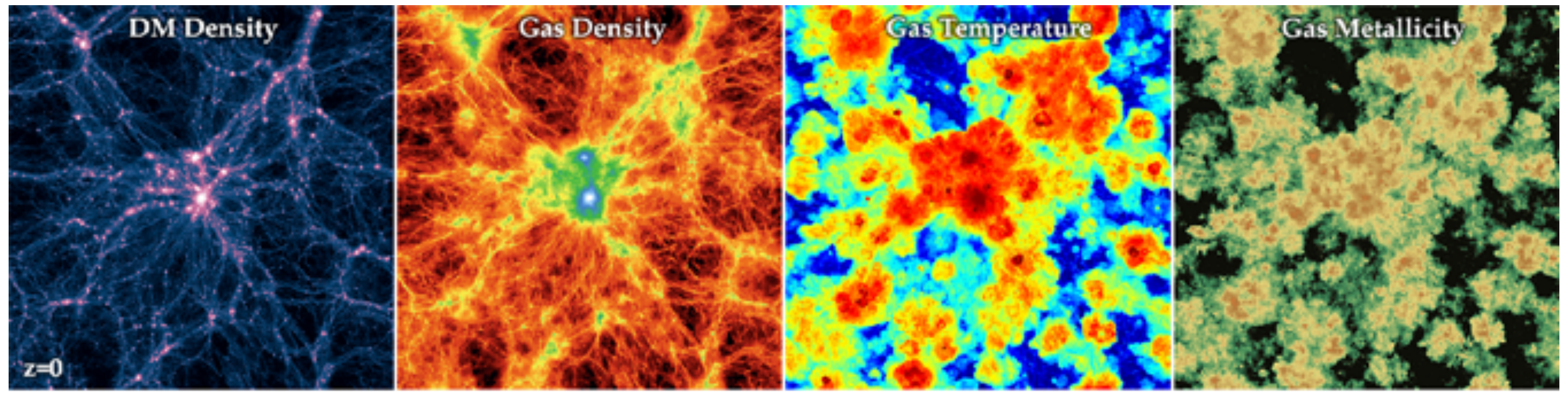
EAGLE



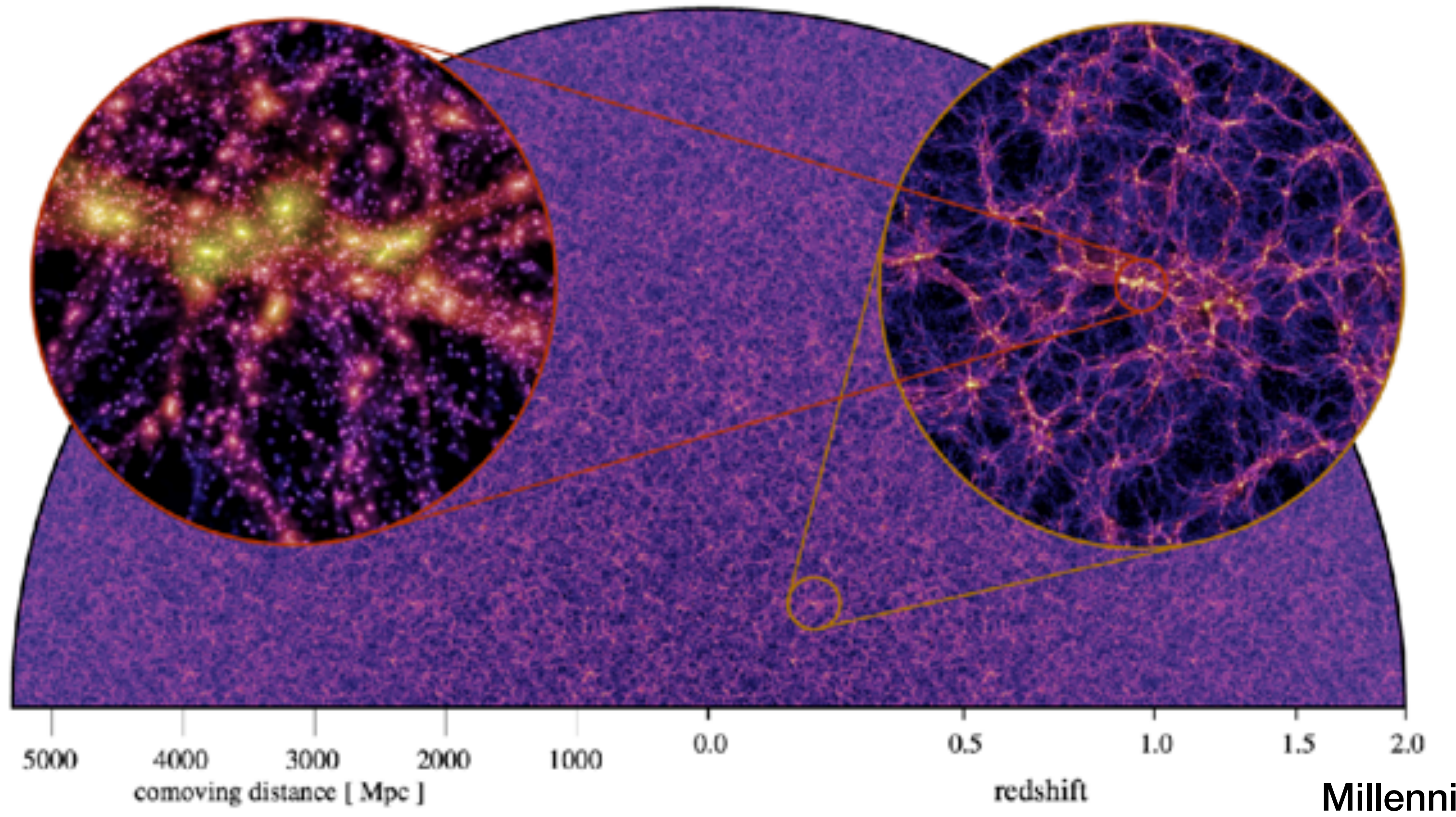
Illustris TNG



Horizon-AGN



Illustris

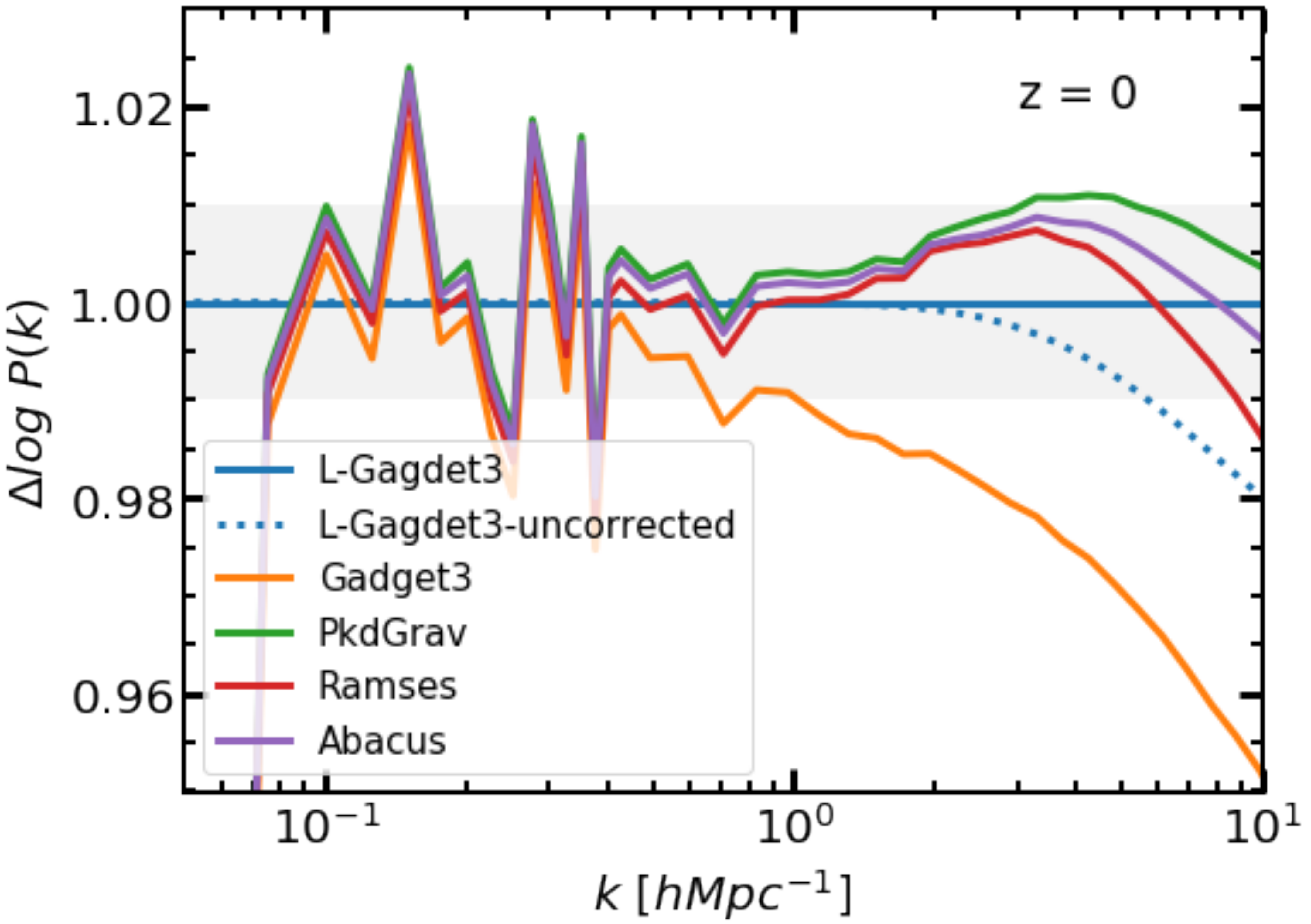


Millennium-TNG

See e.g. review by Vogelsberger et al. 2019

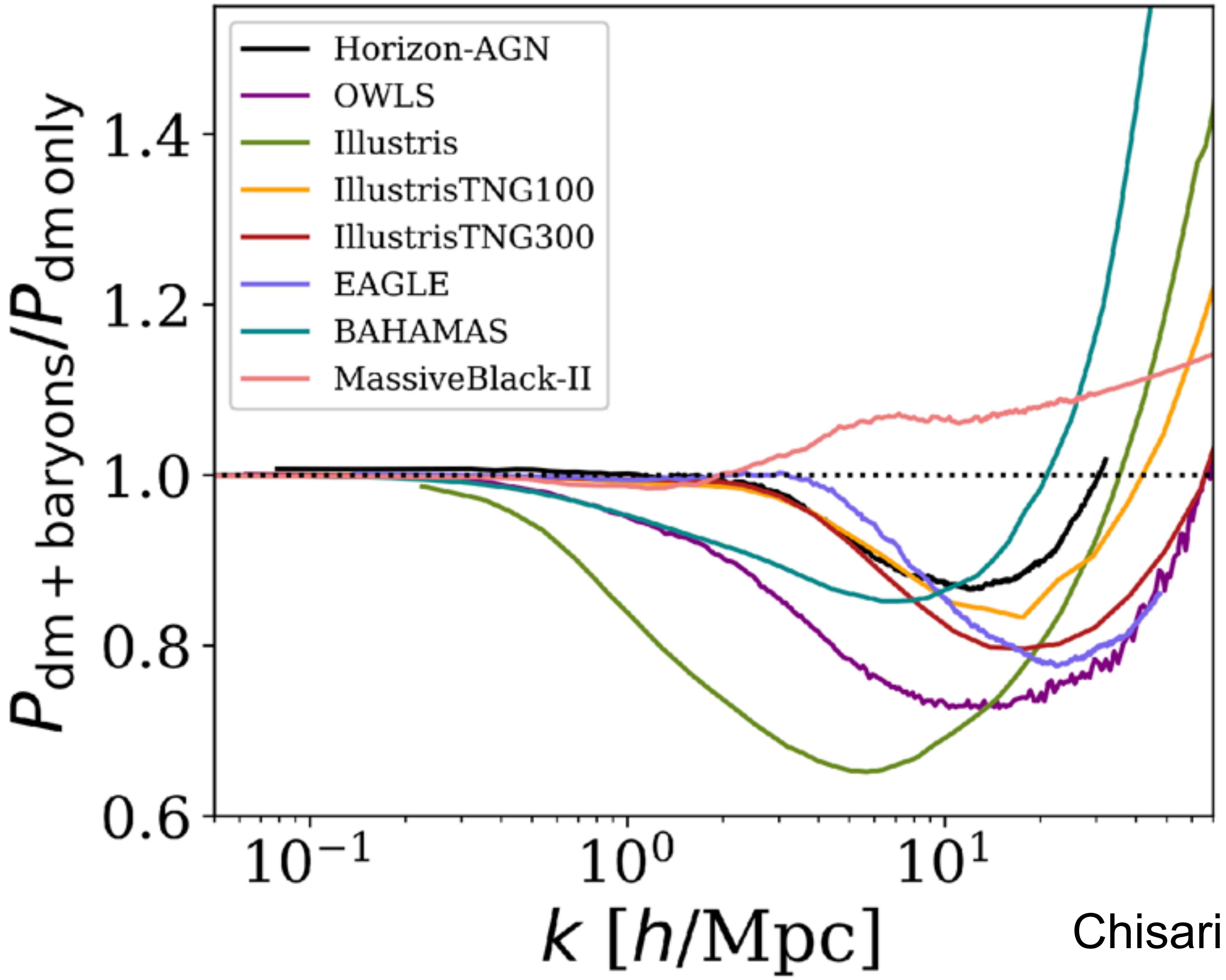
Baryonic effects on the matter power spectrum

Gravity-only N-body codes in good agreement!



Schneider et al. 2016,
Garrison et al. 2019,
Angulo et al. 2021

Hydrodynamic simulations predict very different P(k)!

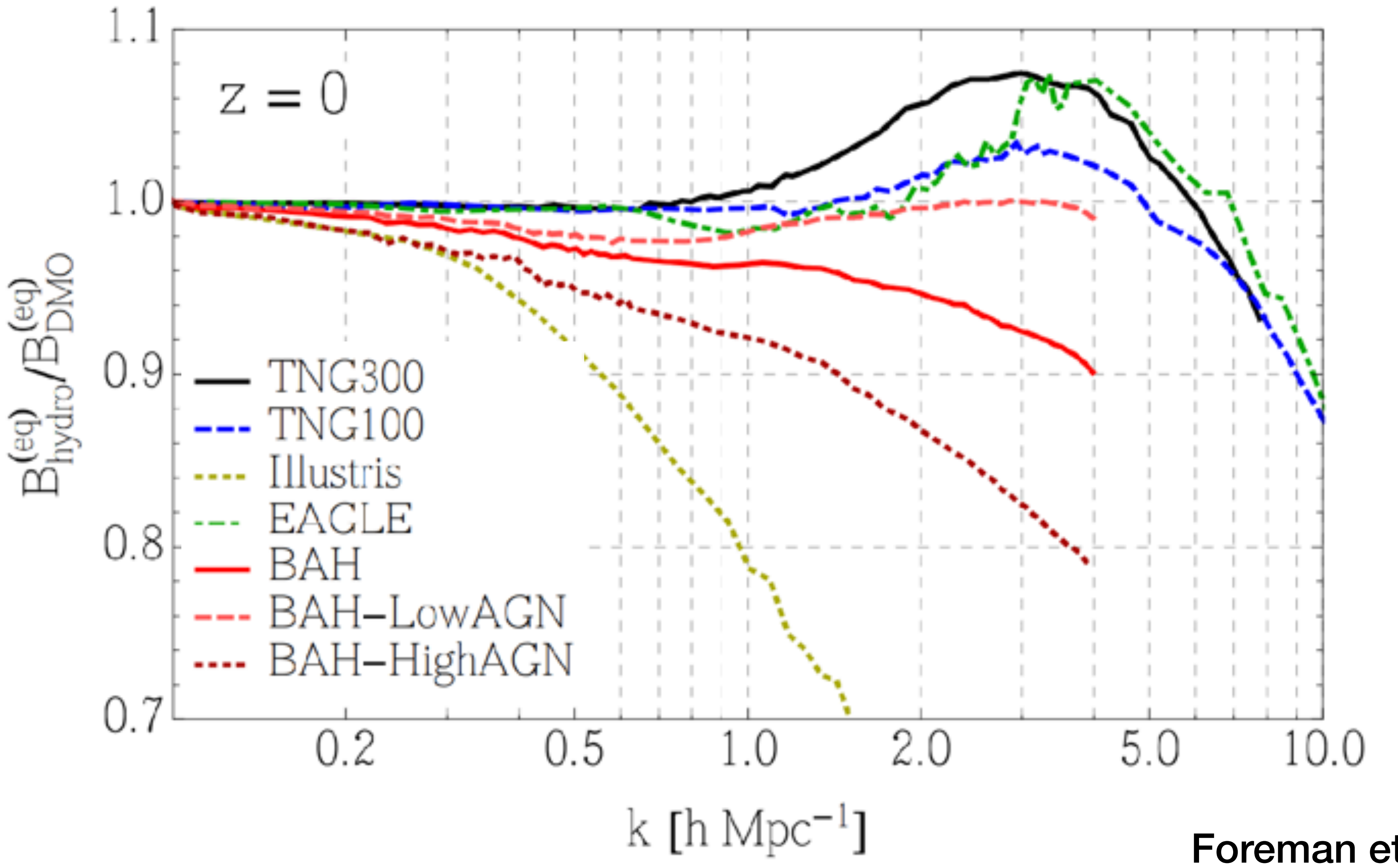


Chisari et al. 2019

Different calibration and sub-grid prescriptions

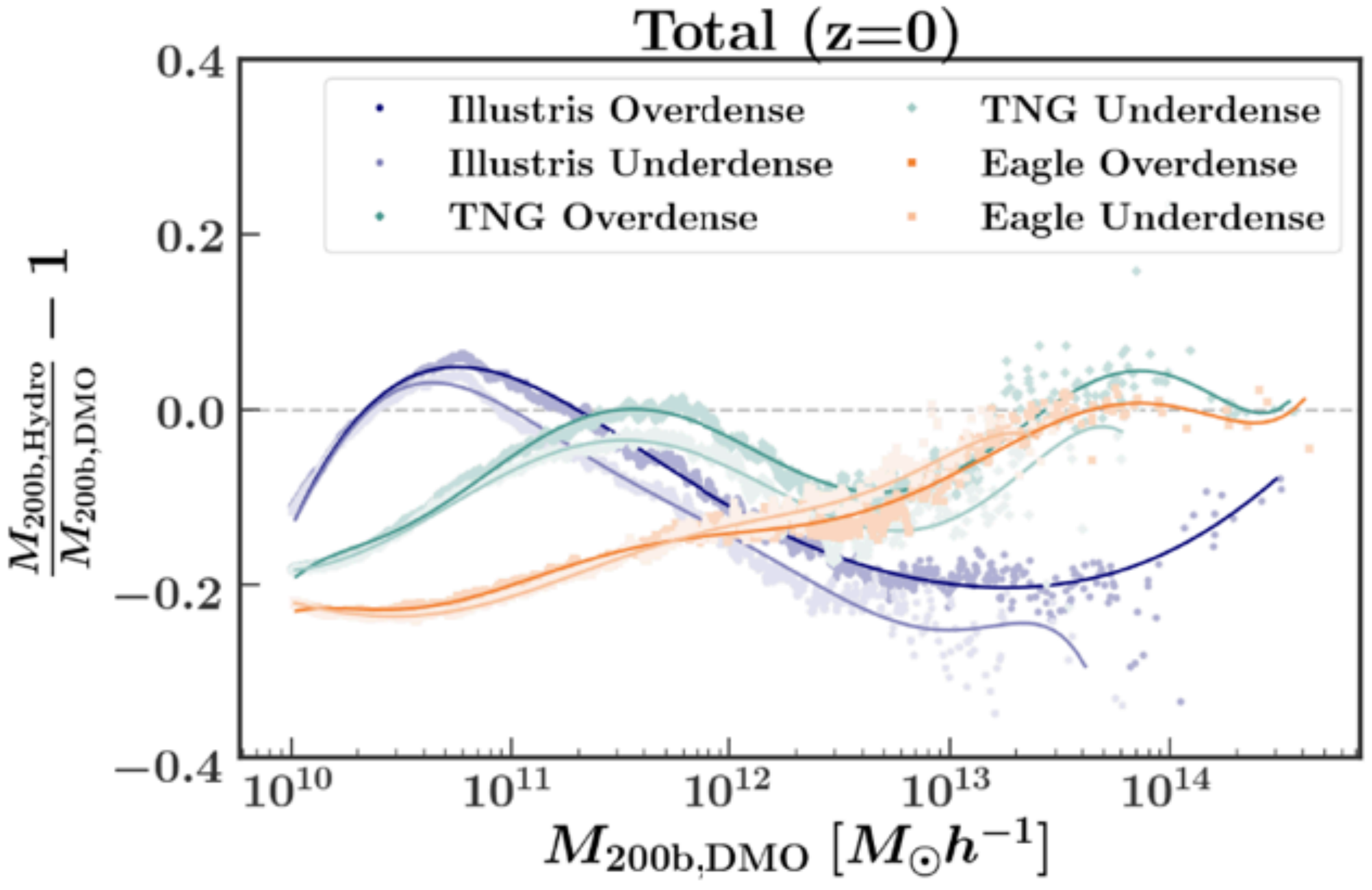
Baryonic effects on the LSS

Matter bispectrum



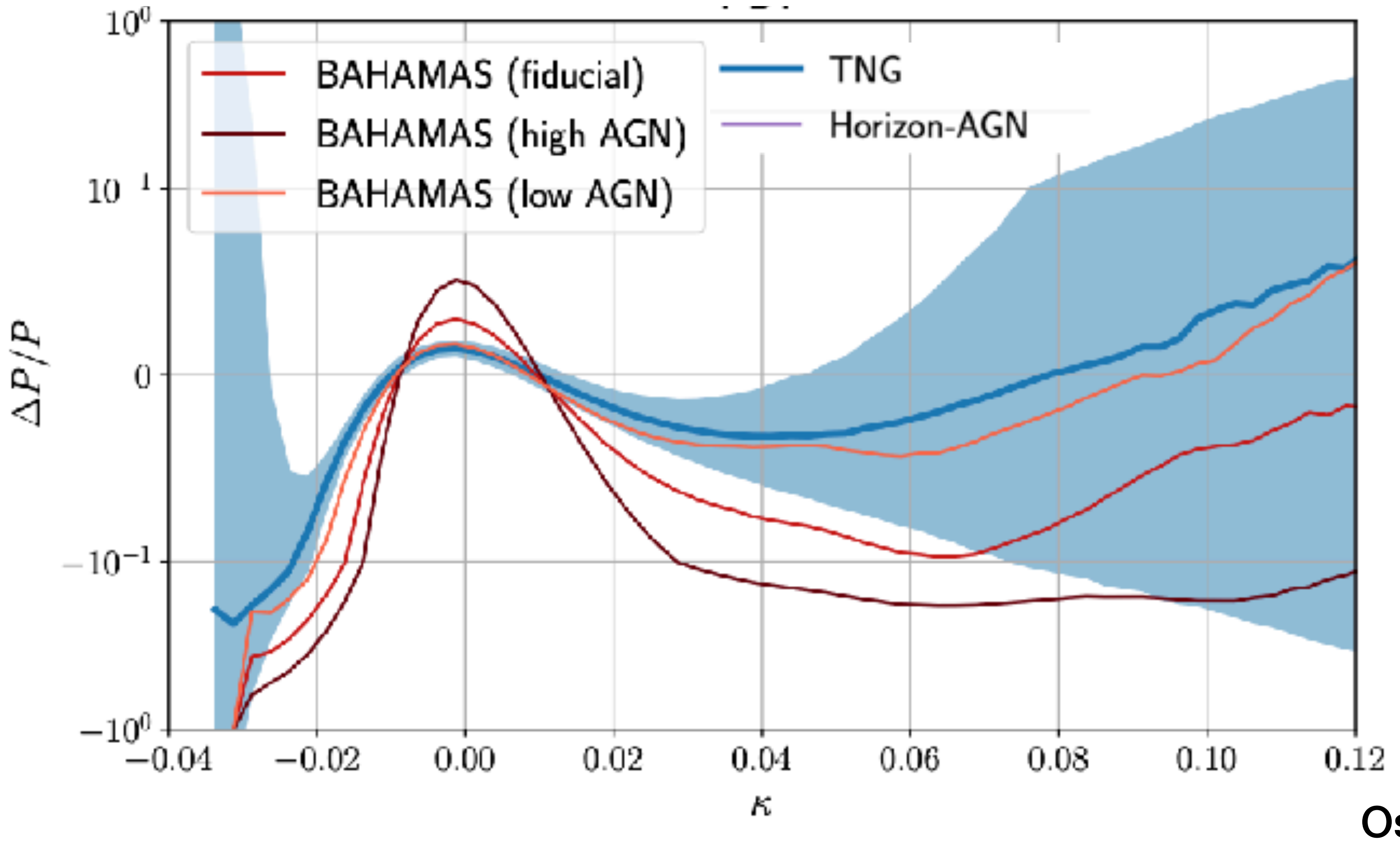
Foreman et al. 2020

Halo mass function



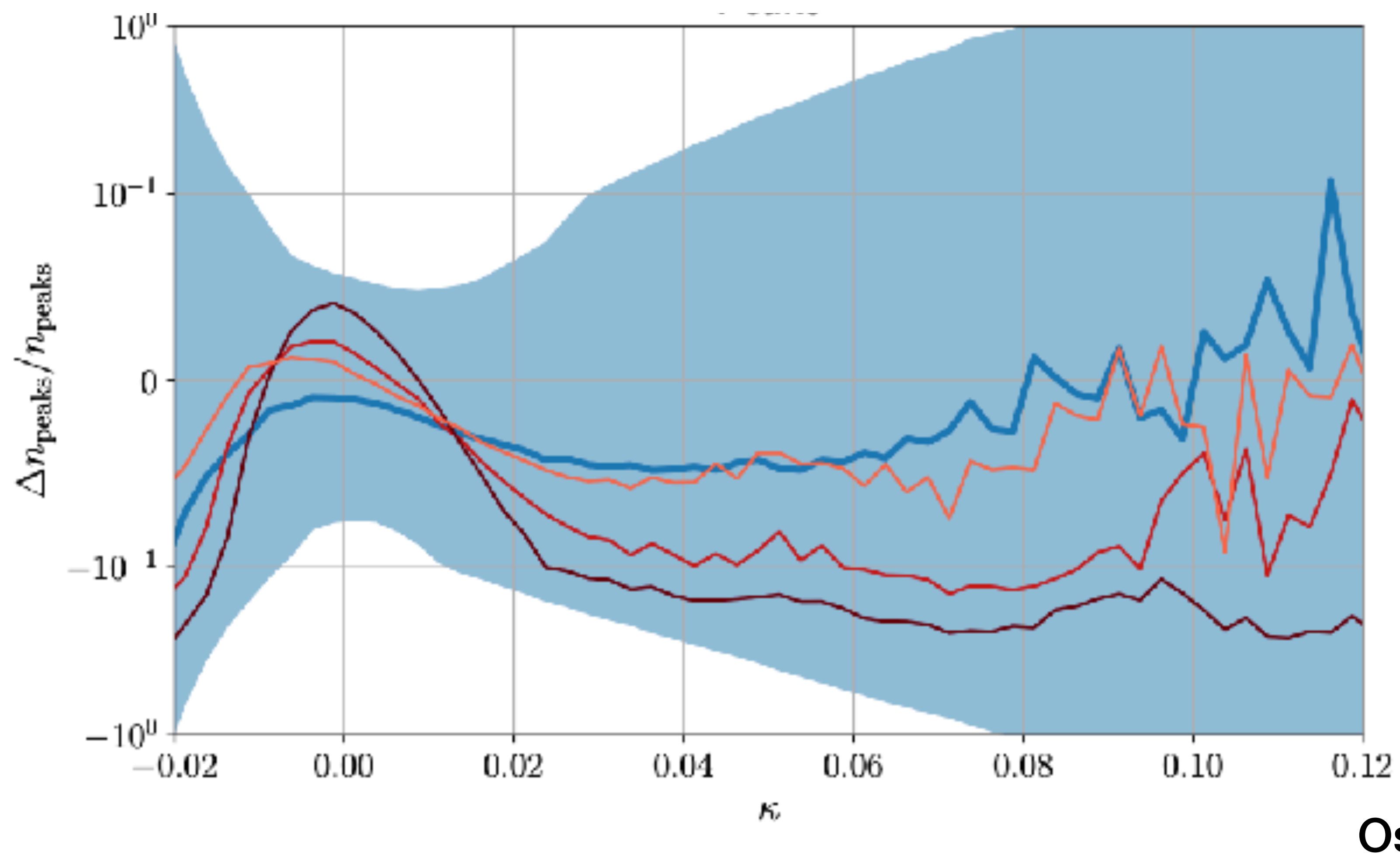
Beltz-Mohrmann & Berlind 2021

Convergence PDF



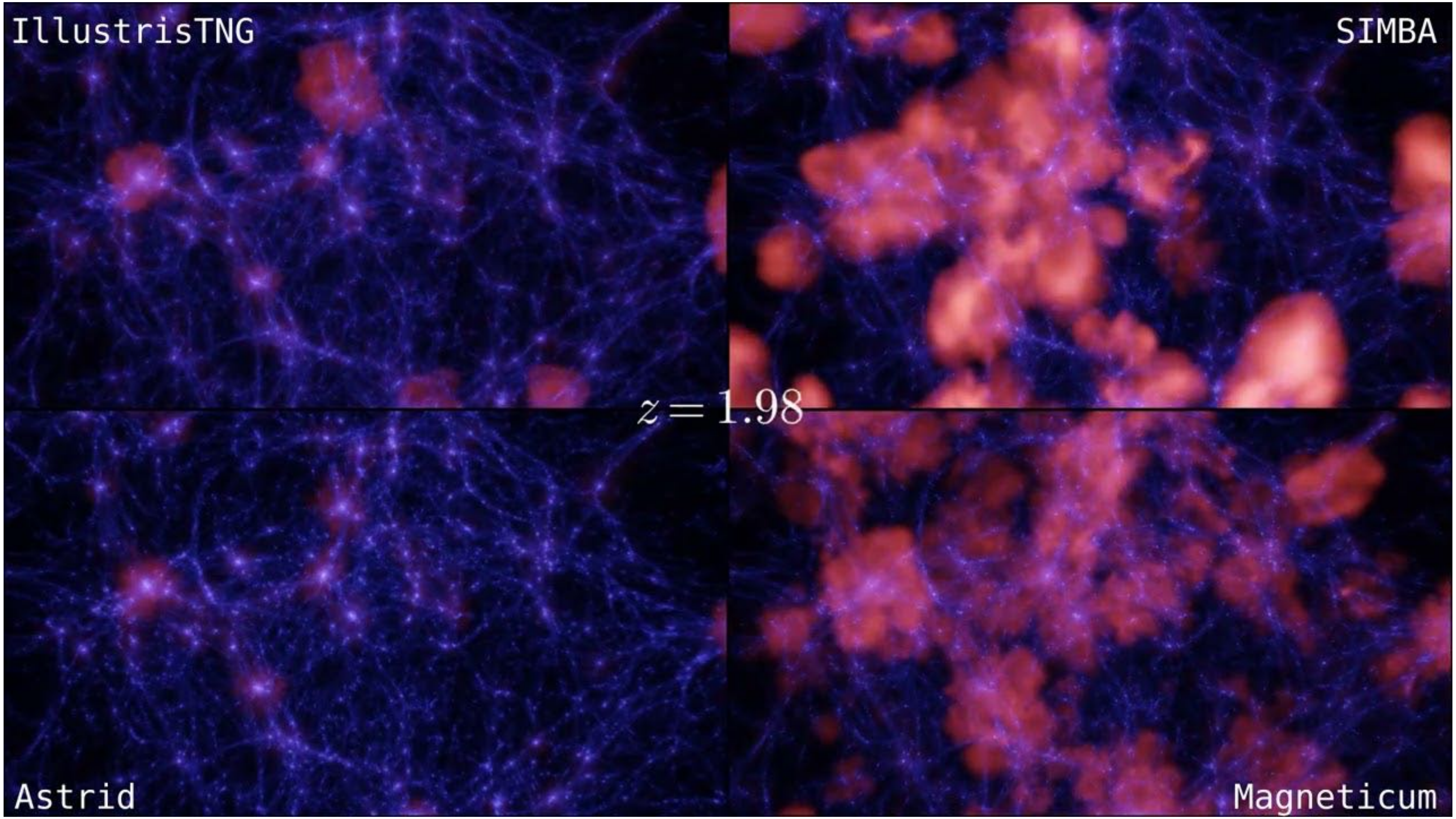
Osato et al. 2021

Convergence Peaks



Osato et al. 2021

Impact of sub-grid models in hydrodynamical simulations

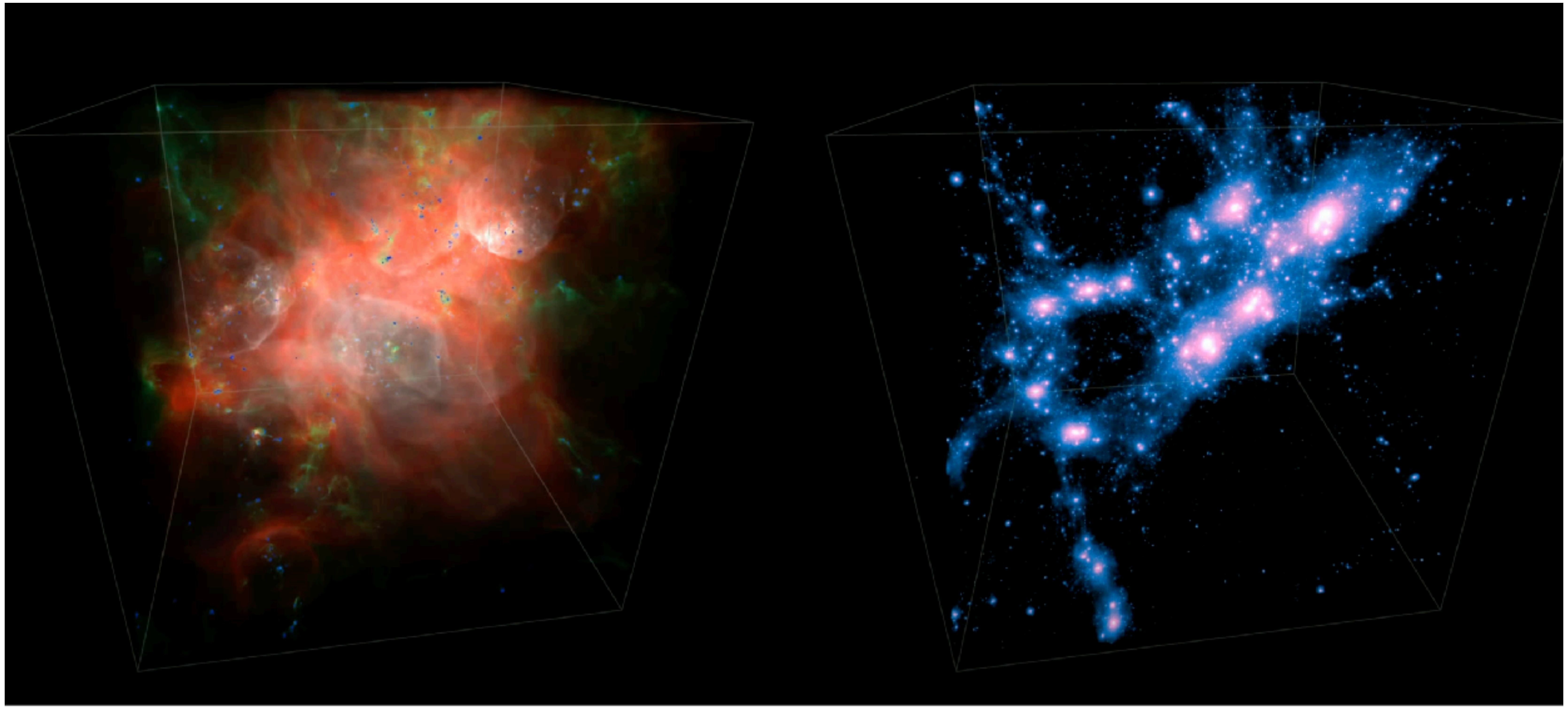


Credits: CAMELS, Villaescusa-Navarro

Baryonic effects on LSS

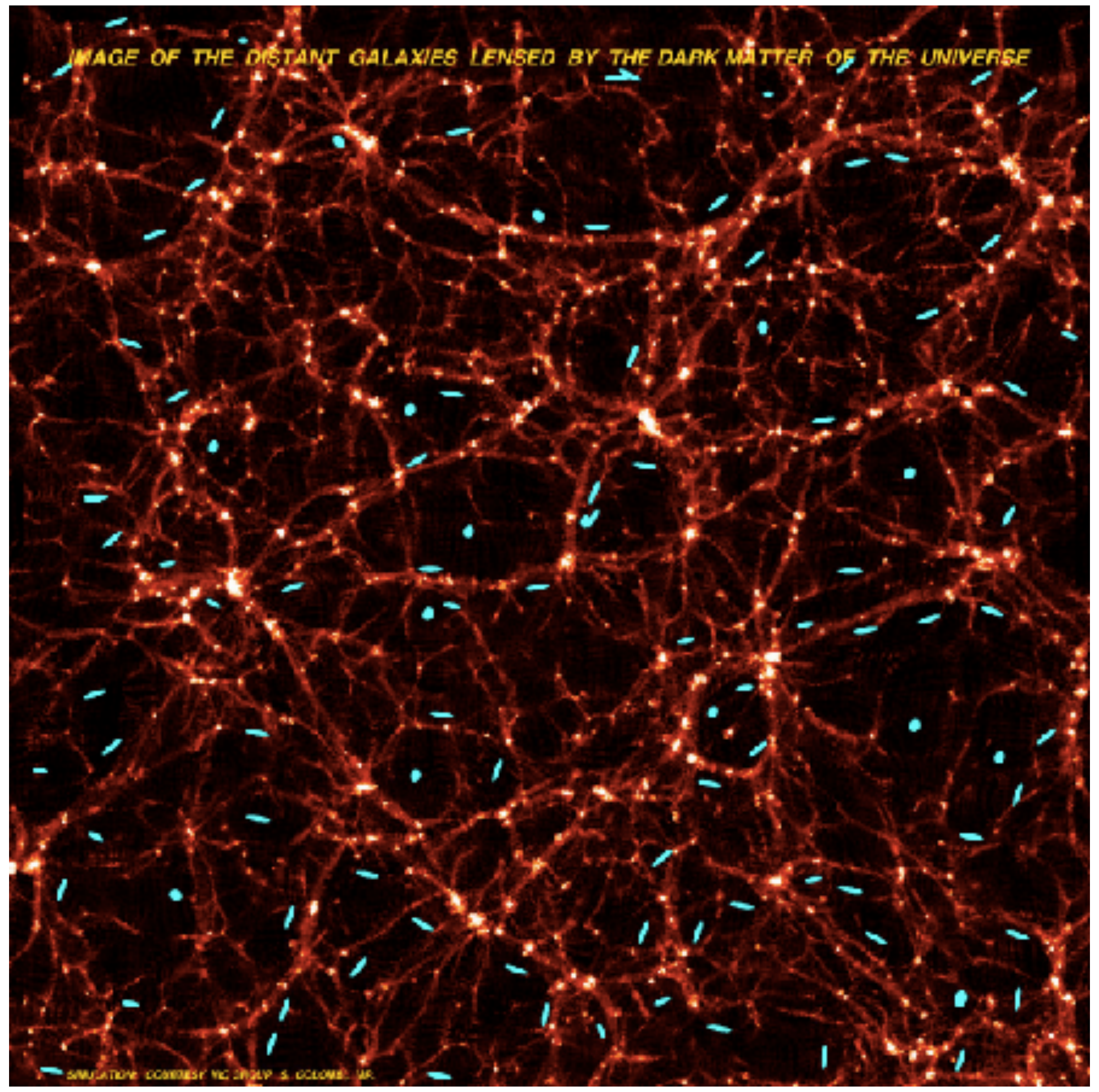
Gas temperature

Dark matter density



Credits: CAMELS, Villaescusa-Navarro

Baryonic effects on the LSS: cosmic shear



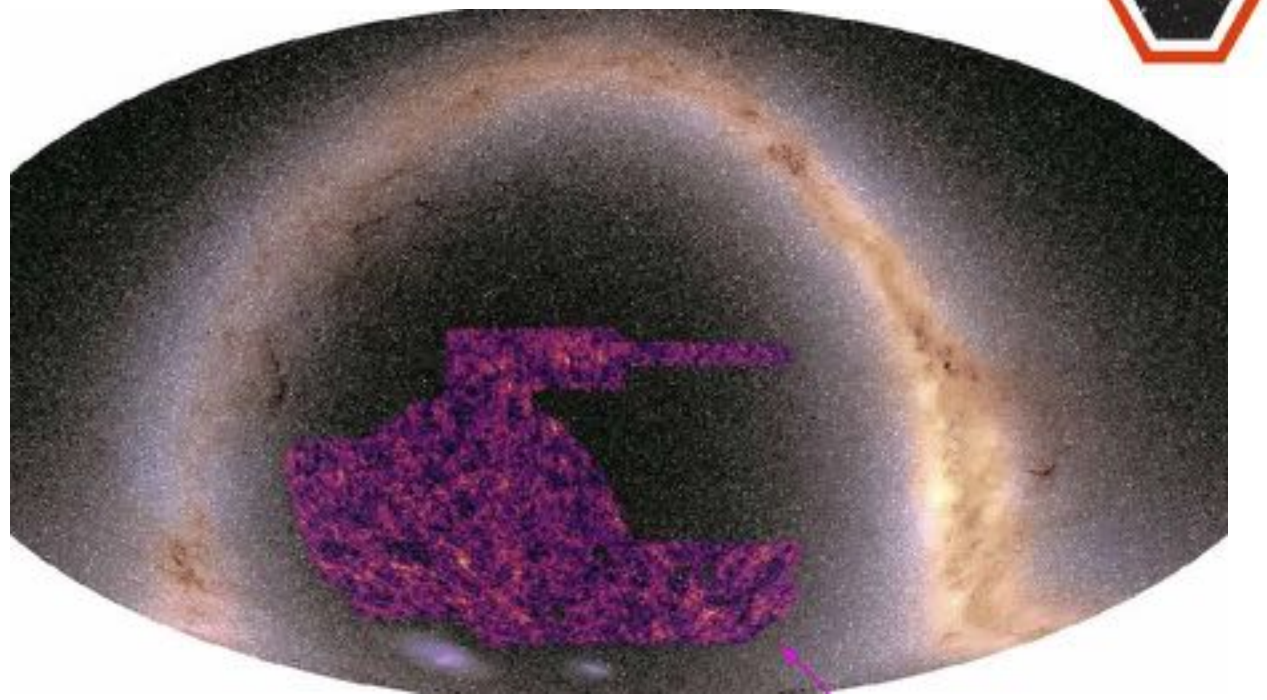
Courtesy of NYC group, S.Colombi

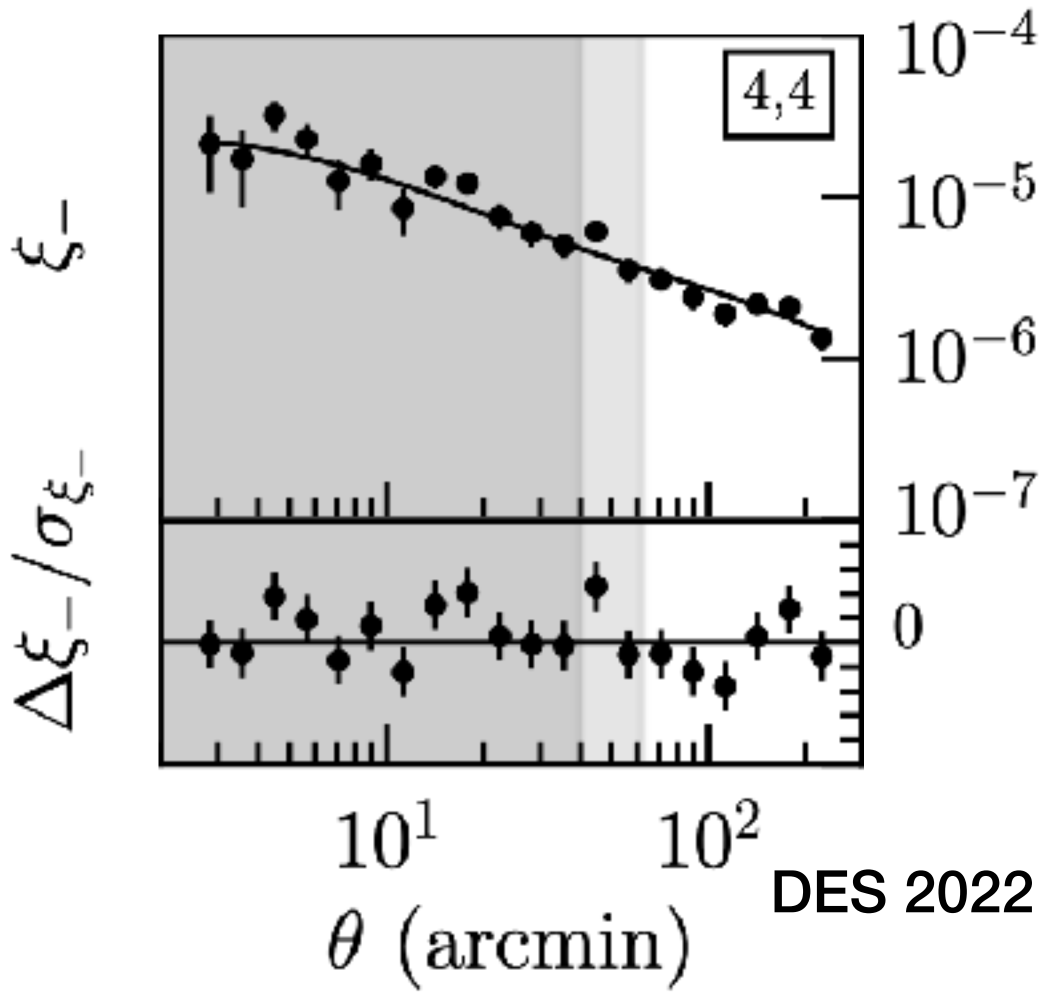
Correlation of galaxy shapes due to LSS gravity

$$C_{\gamma_i,\gamma_j}(\ell) = \int_0^{\chi_H} \frac{g_i(\chi)g_j(\chi)}{\chi^2} P\left(\frac{\ell}{\chi}, z(\chi)\right) d\chi$$

Sensitivity to growth of structure $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$

Stage III, e.g. Dark Energy Survey

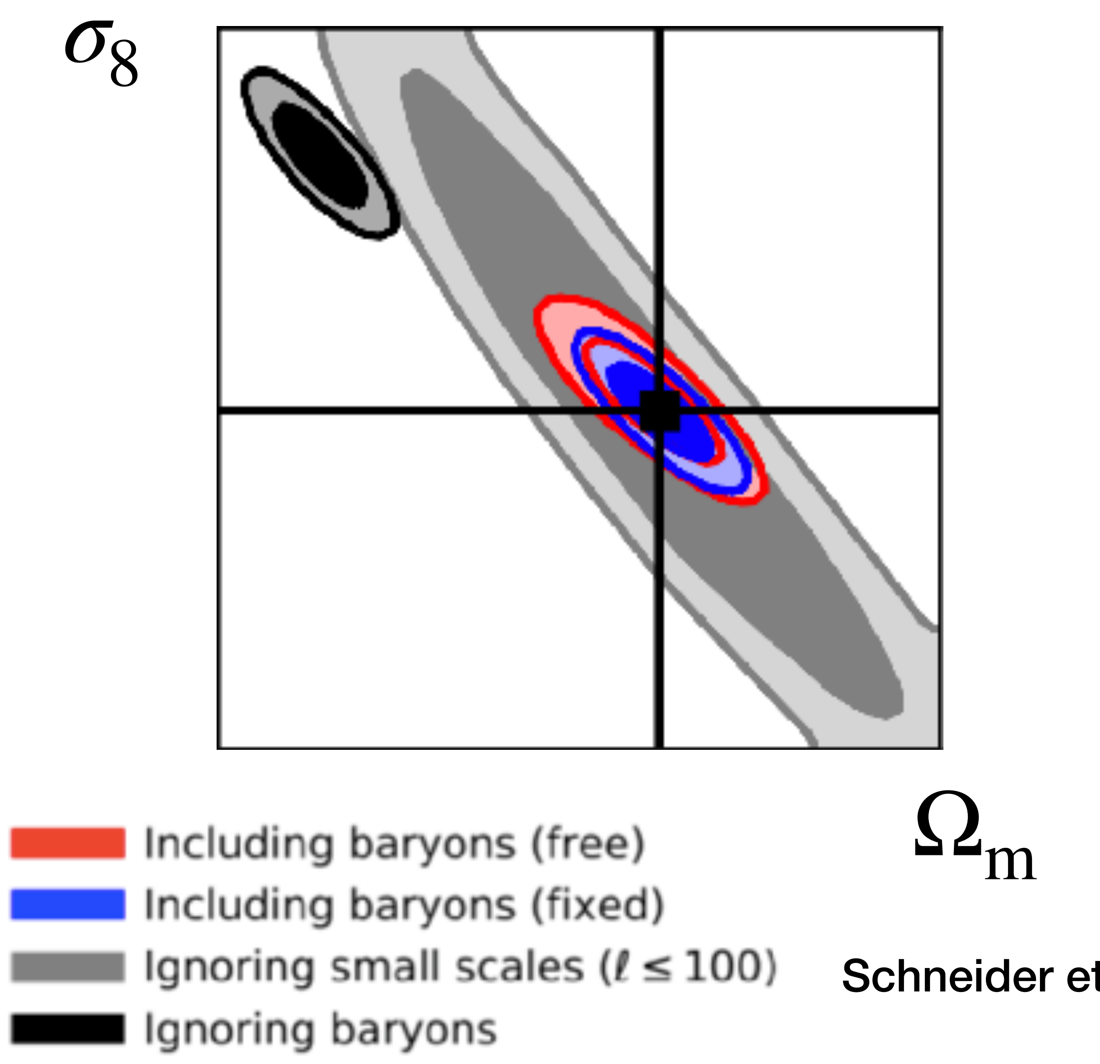




DES 2022

~50% of data not used

Stage IV, e.g. Euclid



Schneider et al. 2020

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- Simulating baryonic processes in LSS
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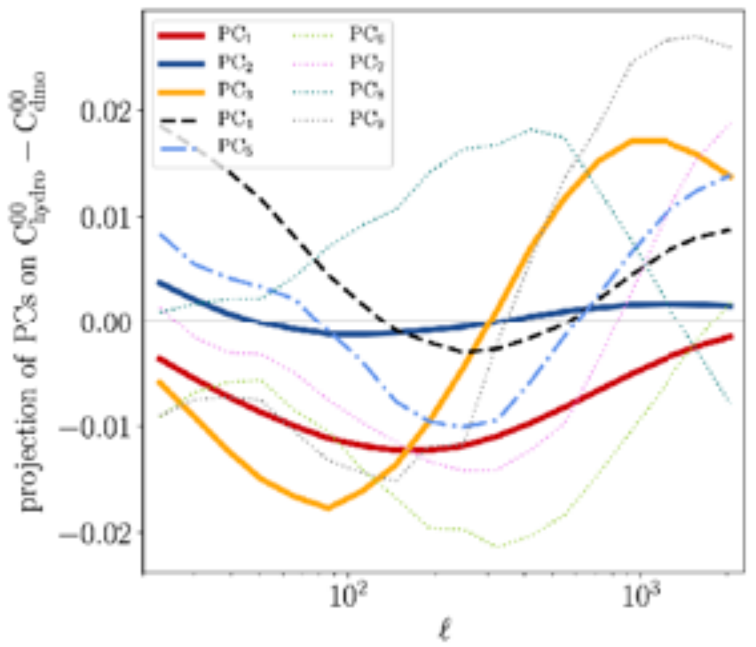
Baryonic modelling

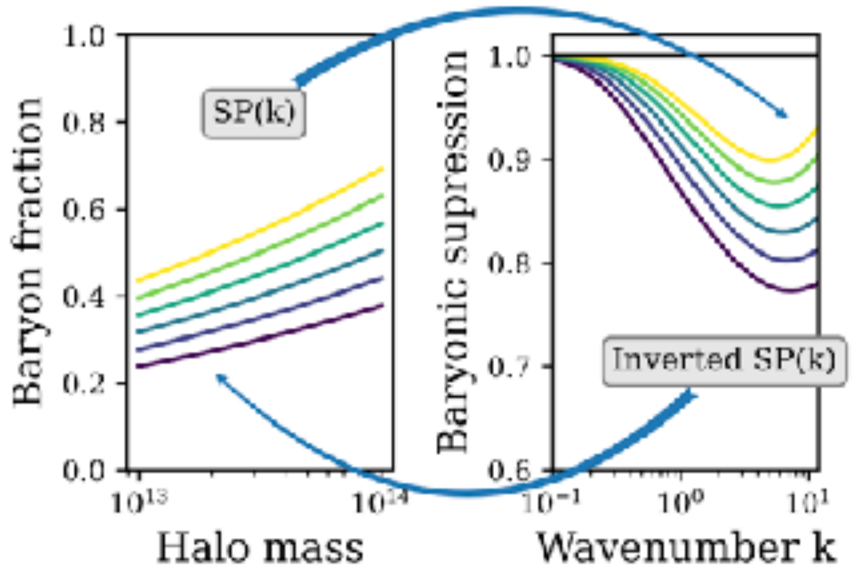
Direct hydrodynamical simulations

PCA, see e.g.:
Eifler et al. 2014;
Huang et al. 2019;



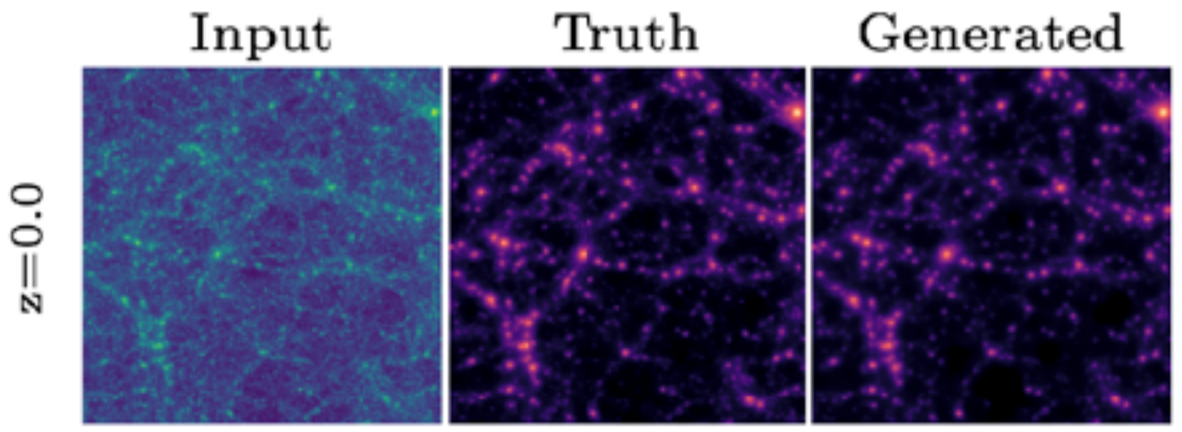
Huang et al. 2019

Analytical models,
Salcido et al. 2023;
Van Loon & van Daalen 2023;



CAMELS, Villaescusa et al. 2021

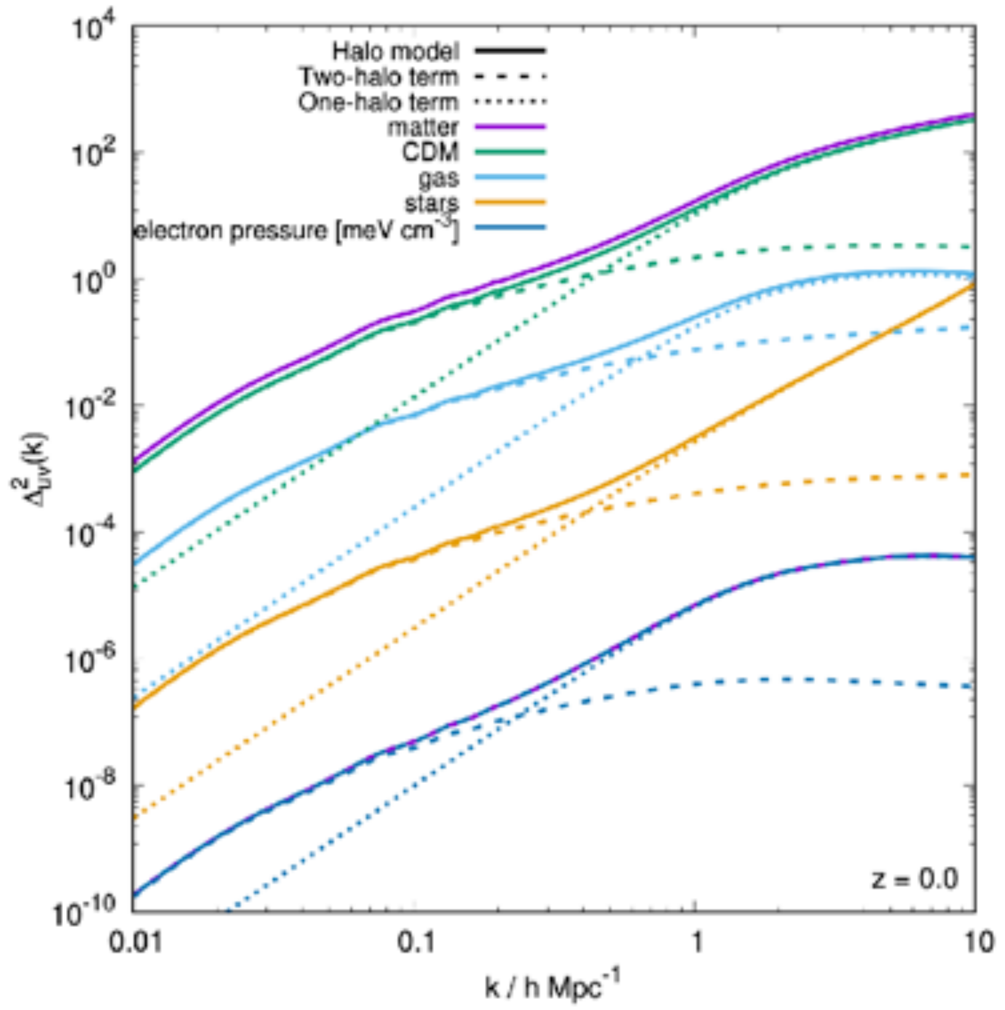
Machine learning, see e.g.
Tröster et al. 2019;
Dai & Seljak 2020;
Villaescusa et al. 2021;
Schaller et al. 2024;



Tröster et al. 2019

See review of Chisari et al. 2019

Halo model

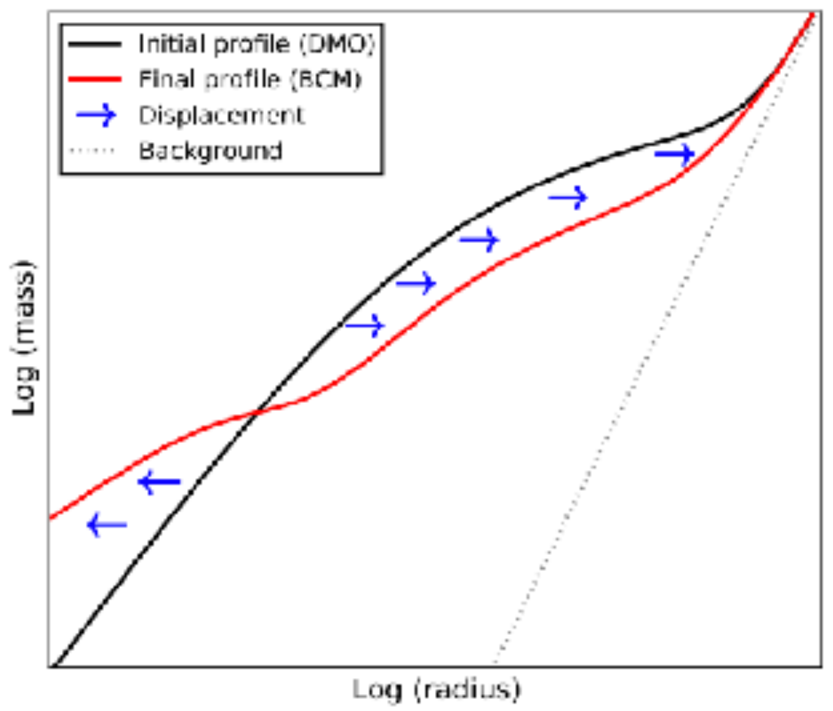


Mead et al. 2021

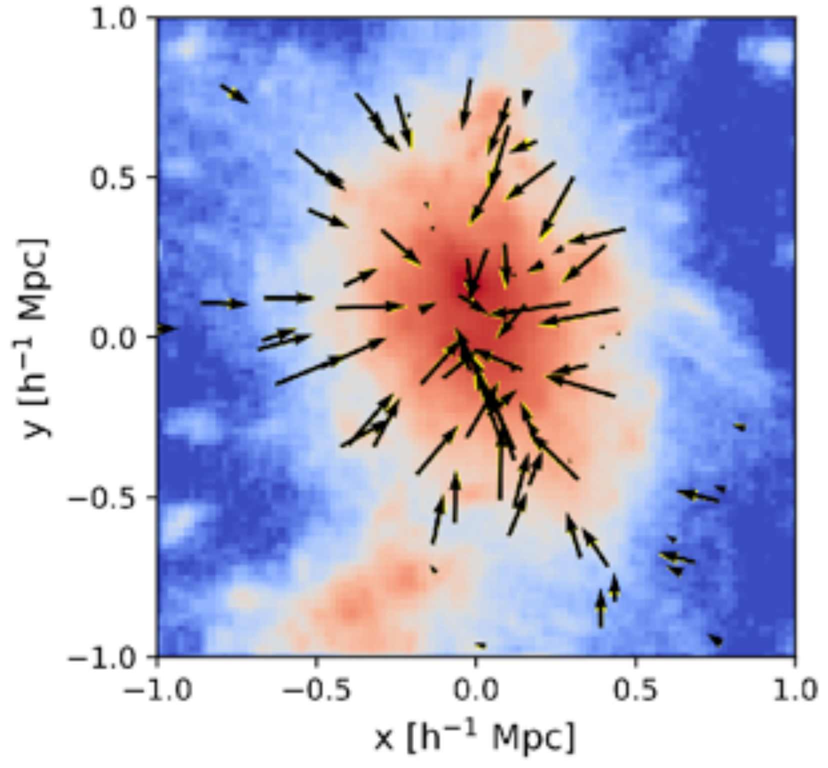
See e.g.:
Semboloni et al. 2011,2013;
Fedeli 2014;
Mohammed et al. 2014;
Mead et al. 2015;
Debackere et al. 2020;
Mead et al. 2021;
Acuto et al. 2021;

Hybrid

(Baryonification, gradient descendent methods,
Baryon Pasting Algorithm)



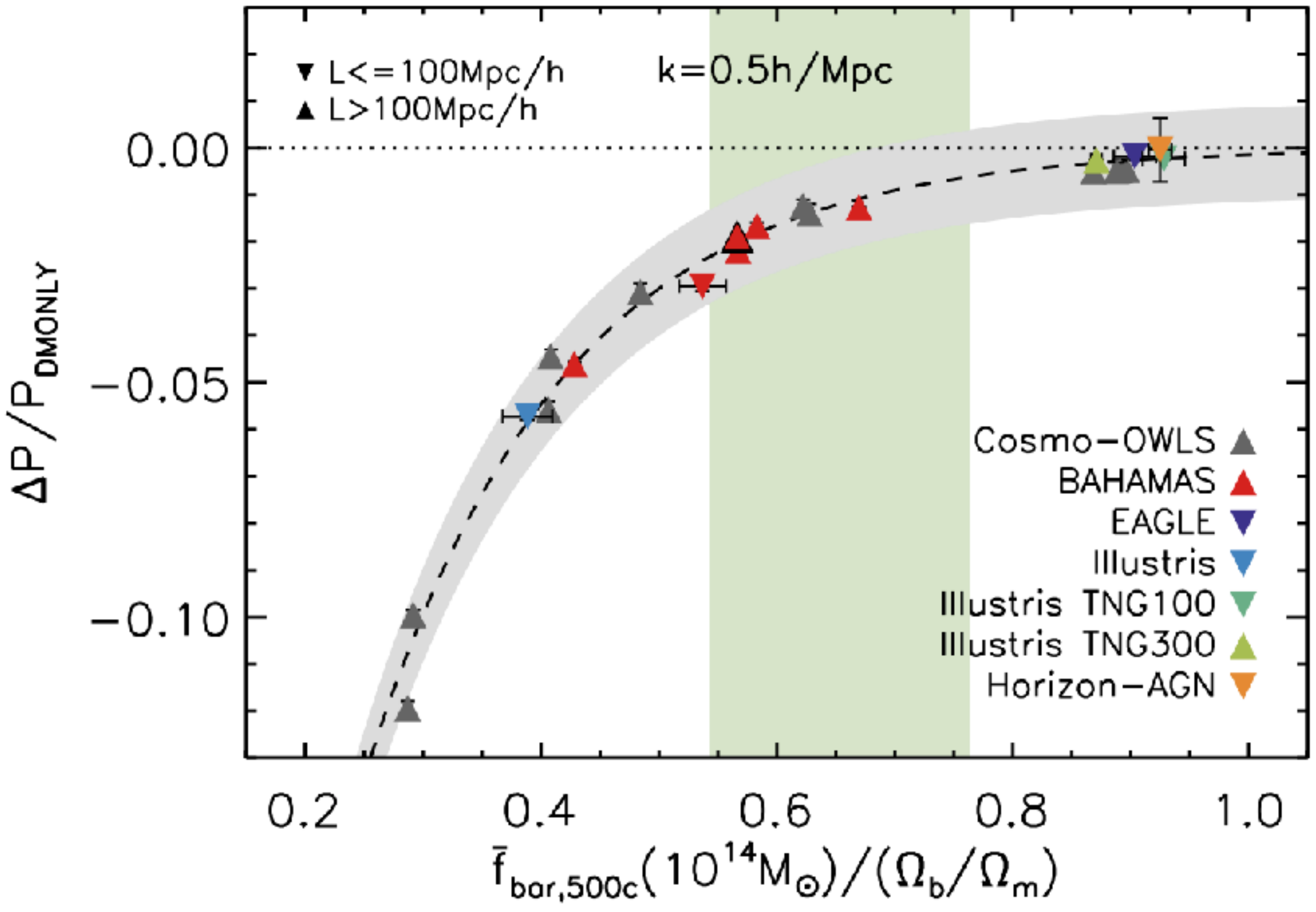
Schneider & Teyssier 2015



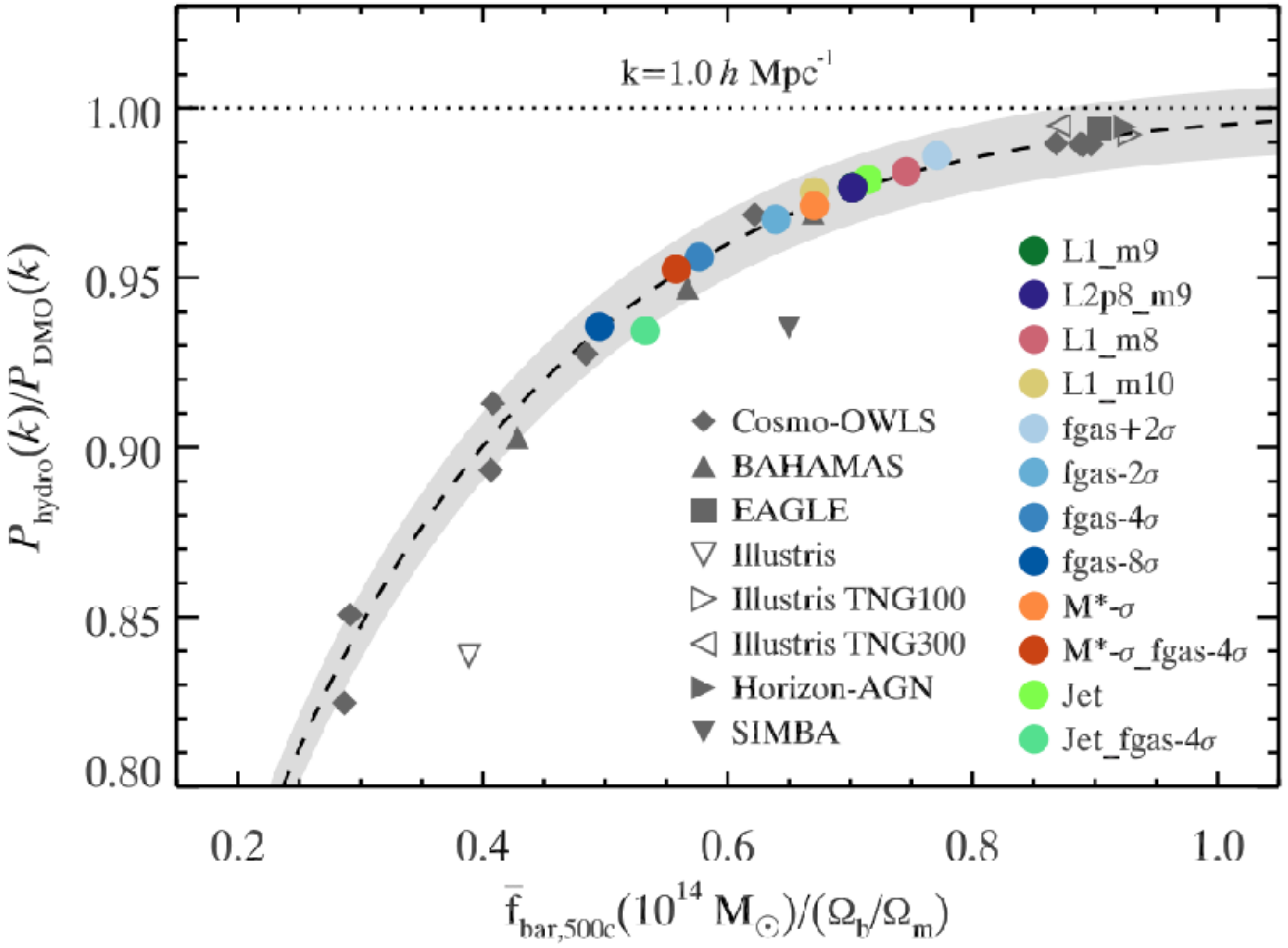
Dai et al. 2019

See e.g. Aricò et al. 2019; Dai & Seljak 2020; Osato & Nagai 2022

Physical insights from hydrodynamical simulations



Van Daalen et al. 2020



Schaye et al. 2024

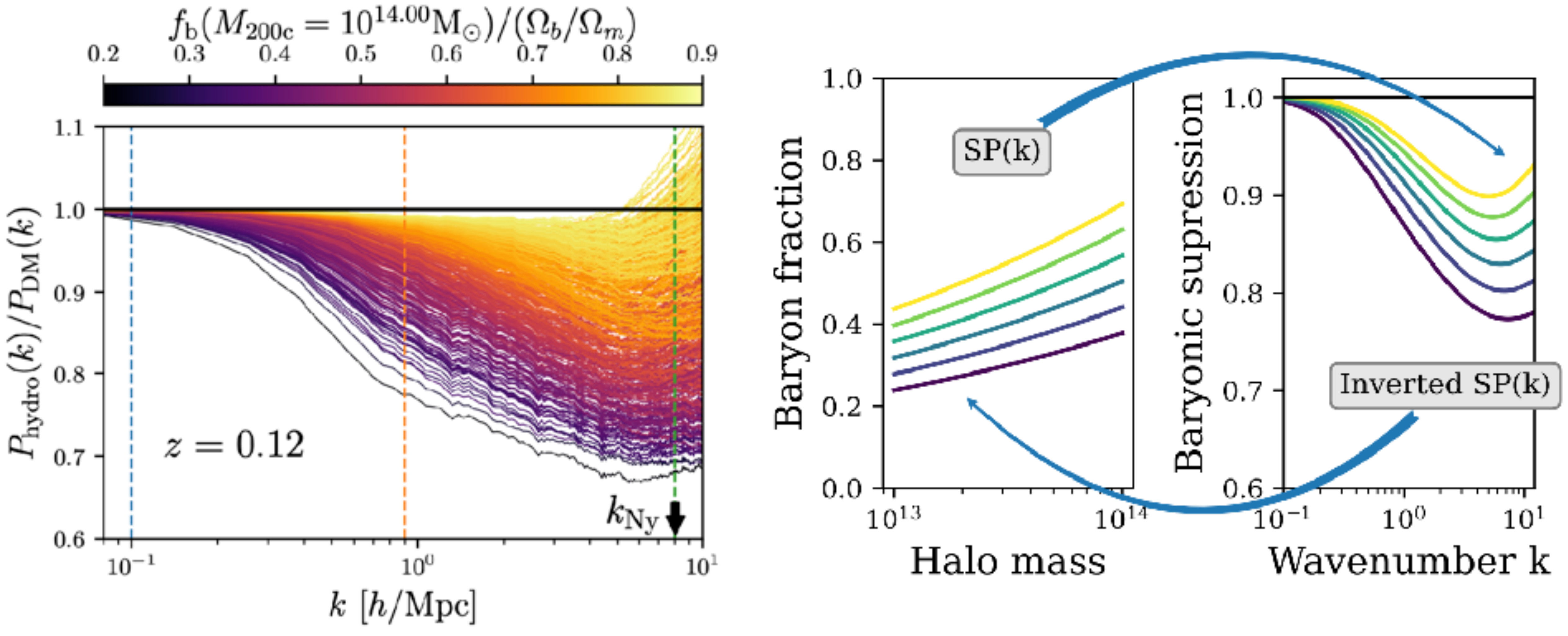
Tight correlation (1%) between baryon suppression in *P(k)* and baryon fraction in halos!

Does the correlation holds for different sub-grid prescriptions and smaller scales?

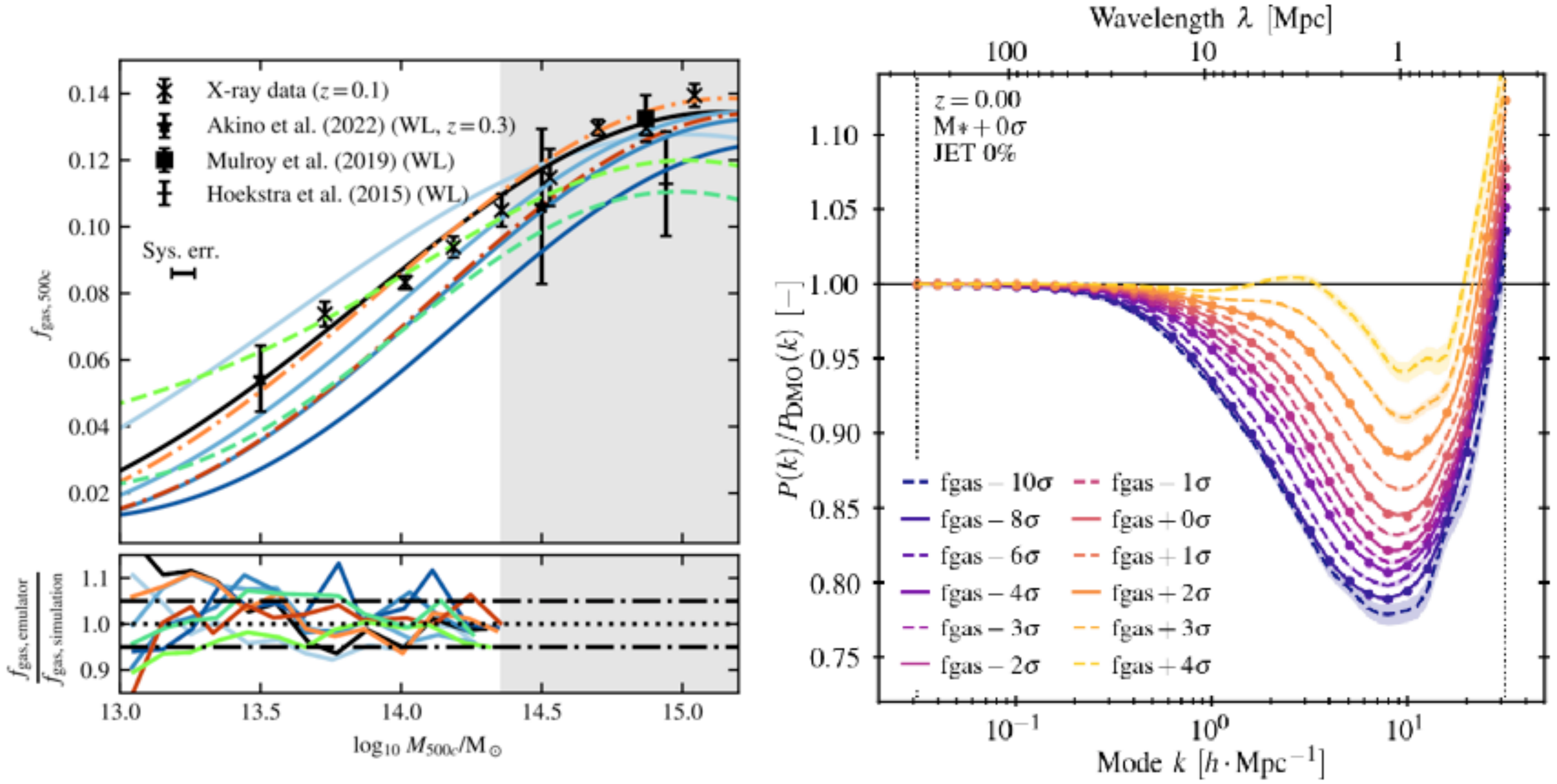
Models based on hydrodynamical simulations

Antilles suite, 400 simulations (100 Mpc/h)

FLAMINGO suite, ~ 20 simulations (> 700 Mpc/h)



Salcido et al. 2023



Analytical models fitted to multiple hydro sims,

e.g. Salcido+2023; Van Loon & van Daalen 2023;

Calibrating hydro sims to observations of halo mass functions,

building emulators over the suite;

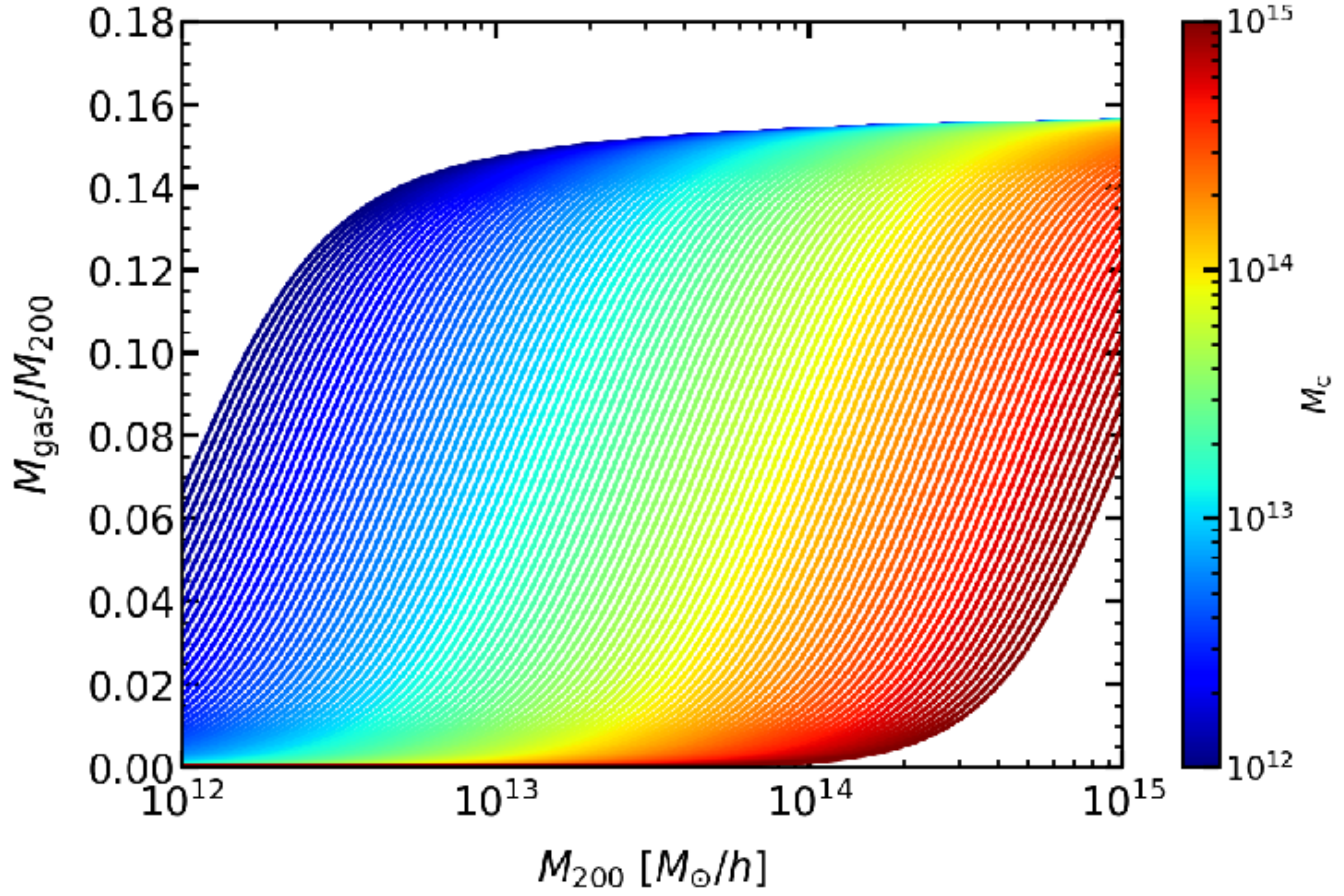
e.g. Schaye+2024; Kugel+2024;

The baryon correction model

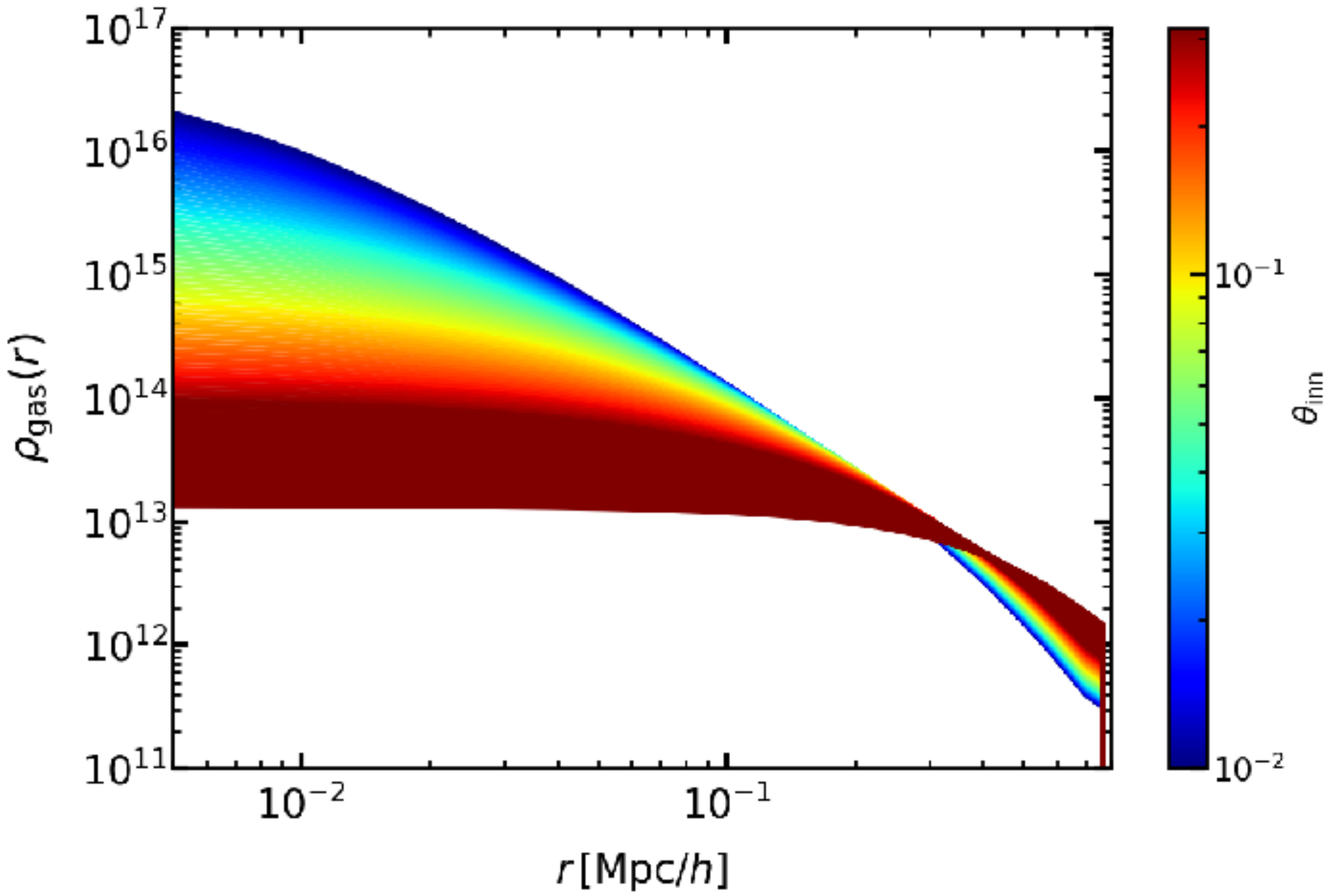
First step

Inspired by the halo model:
Analytical functions for dark matter, gas, and stars density in haloes

Gas mass fraction



Gas density profiles



$$f_{gas} = \frac{\Omega_b/\Omega_m - f_{stars}}{1 + (M_c/M_{200})^{\beta}}$$

~7 free parameters, directly observables!

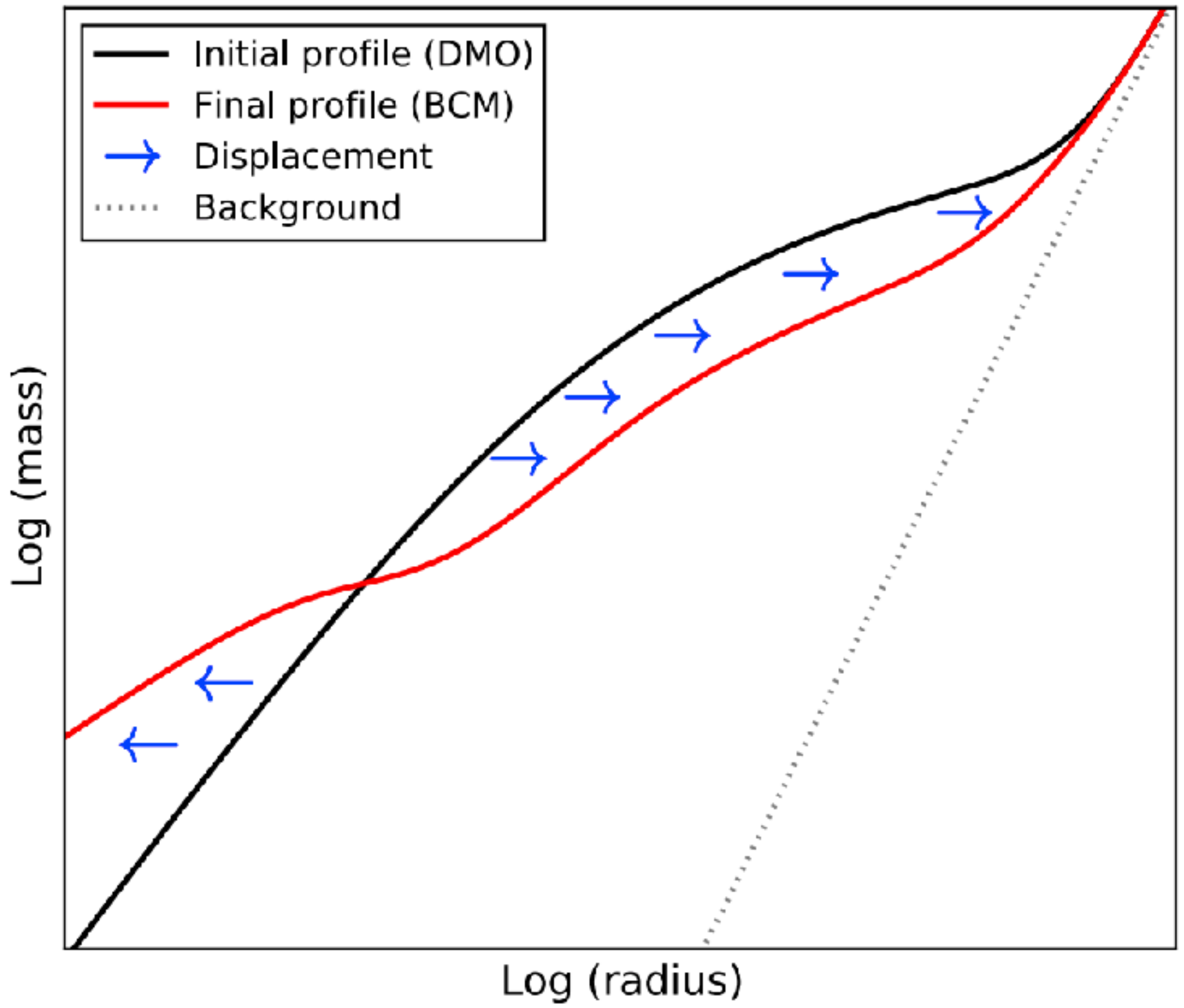
$$\rho_{gas,bo} \propto \frac{1}{(1 + r/r_{inn})^{\beta_{inn}}(1 + (r/r_{out})^2)^2}$$

Schneider & Teyssier 2015; Aricò et al. 2020

The baryon correction model

Second step

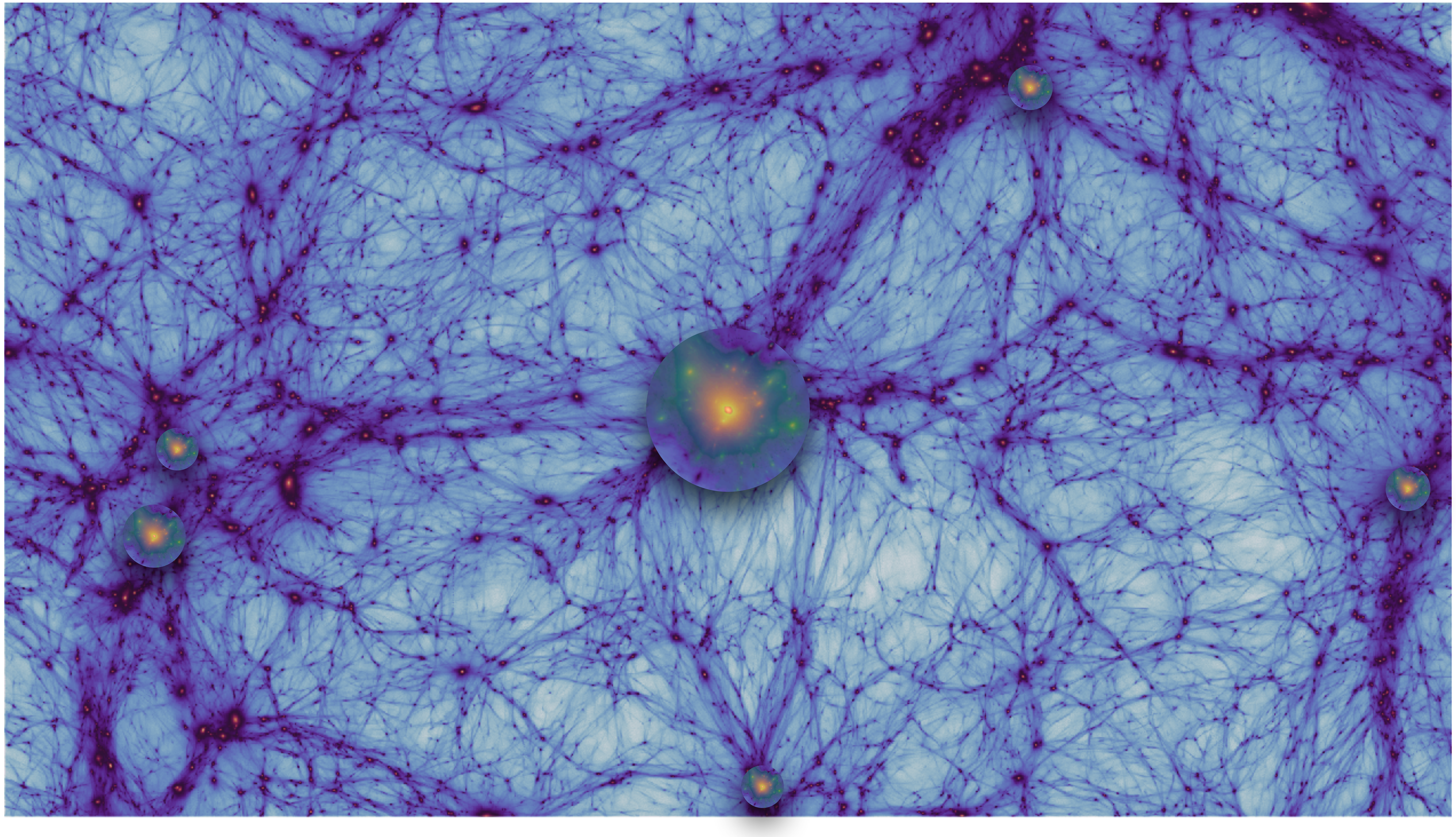
Working out a displacement field gravity-only —> baryon-corrected



Schneider & Teyssier 2015; Aricò et al. 2020

The baryon correction model

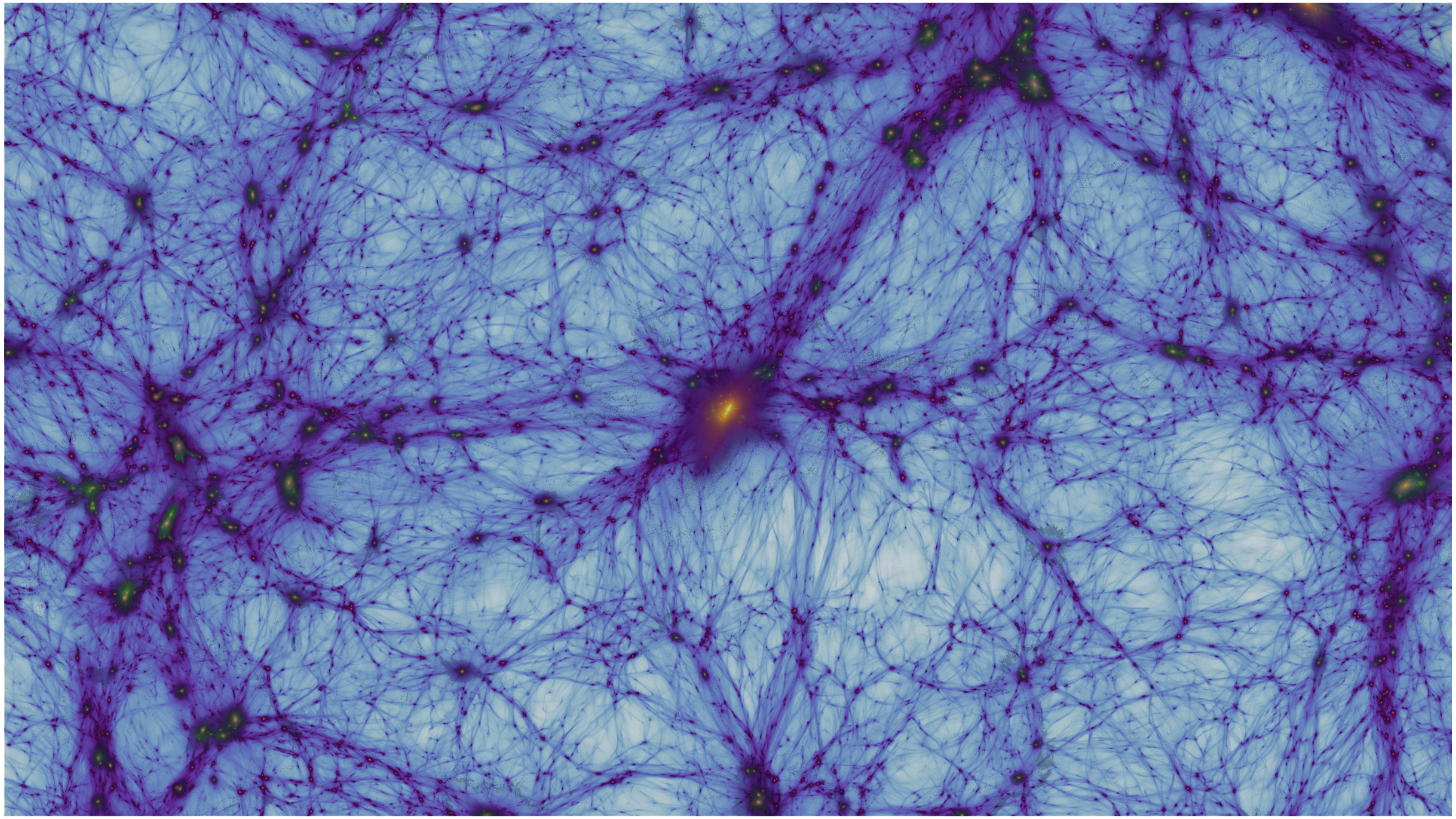
Third step



Schneider & Teyssier 2015; Aricò et al. 2020

The baryon correction model

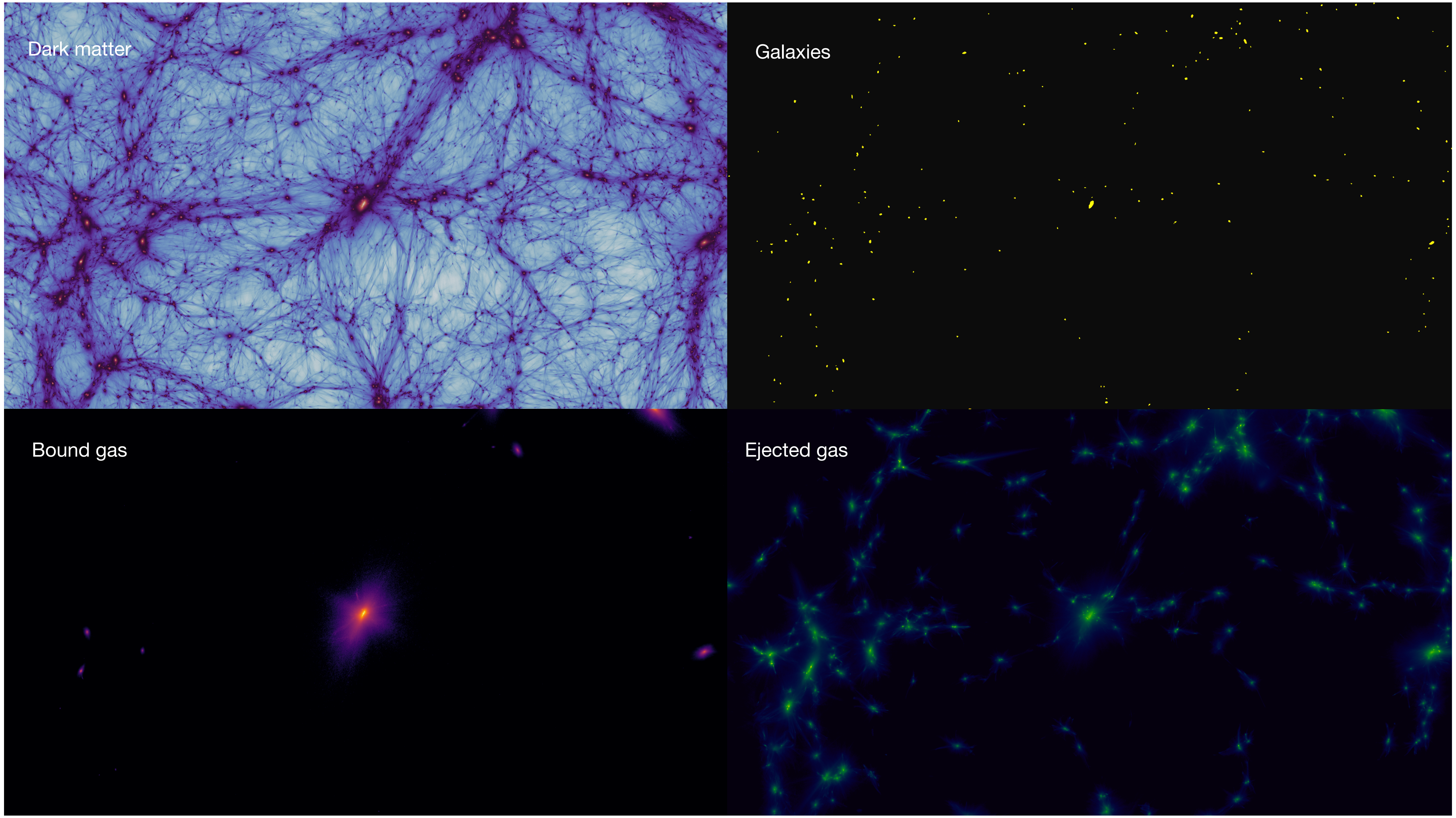
Third step



Schneider & Teyssier 2015; Aricò et al. 2020

The baryon correction model

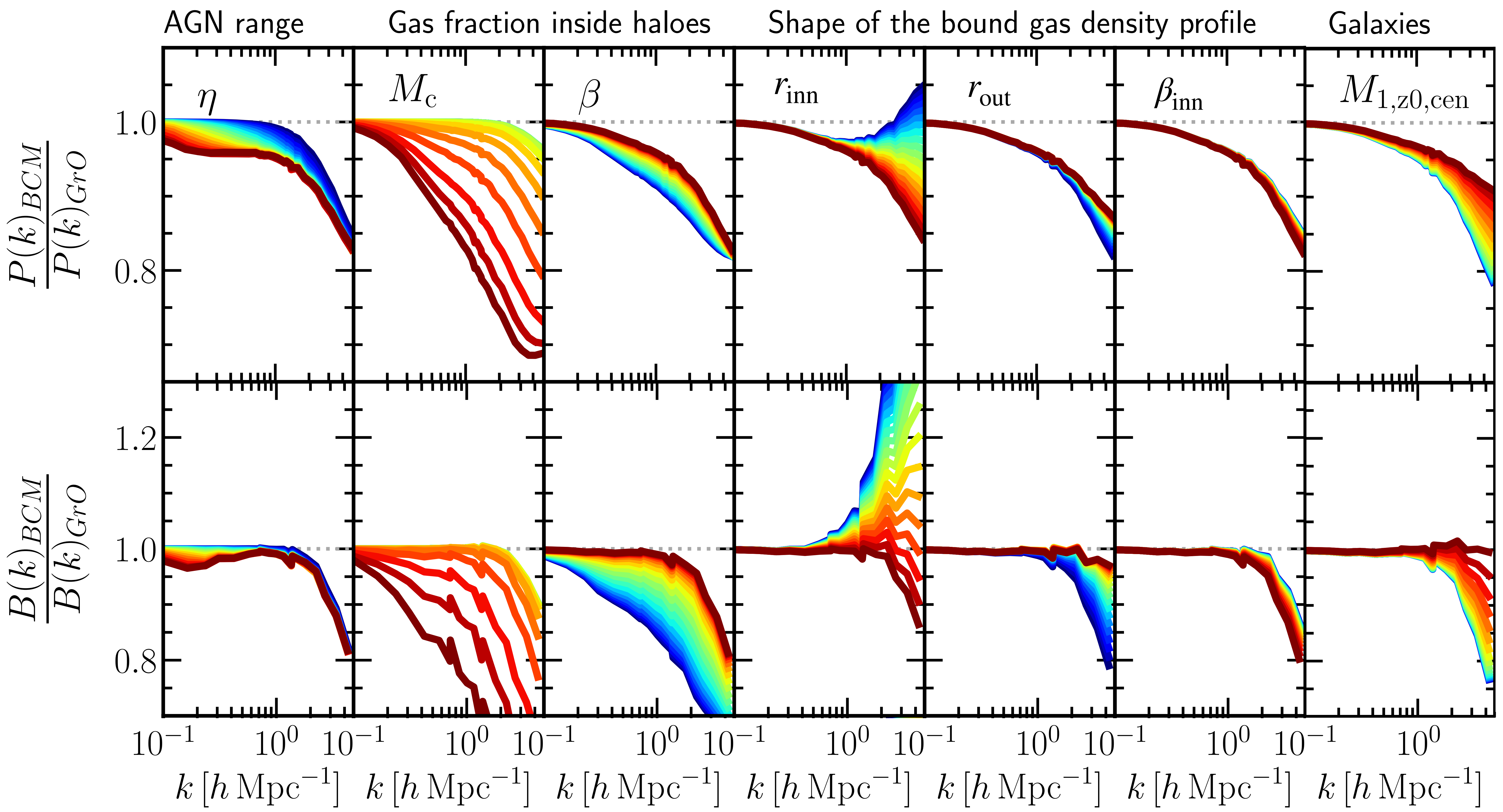
Third step



Schneider & Teyssier 2015;
Multiple cosmic fields —> Aricò et al. 2020;
Thermodynamical properties —> Aricò & Angulo 2024;

BCM: clustering predictions

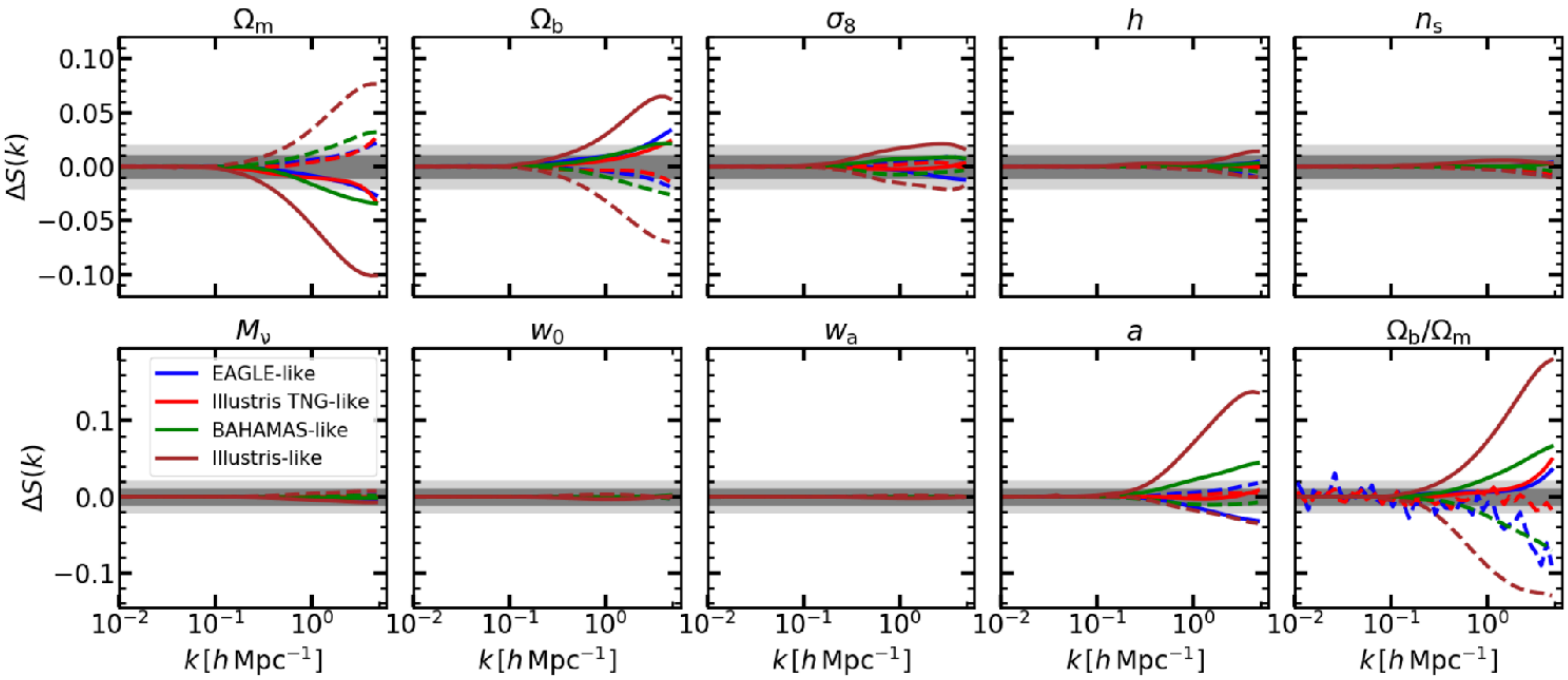
Dependency on astrophysics



Aricò et al. 2021a

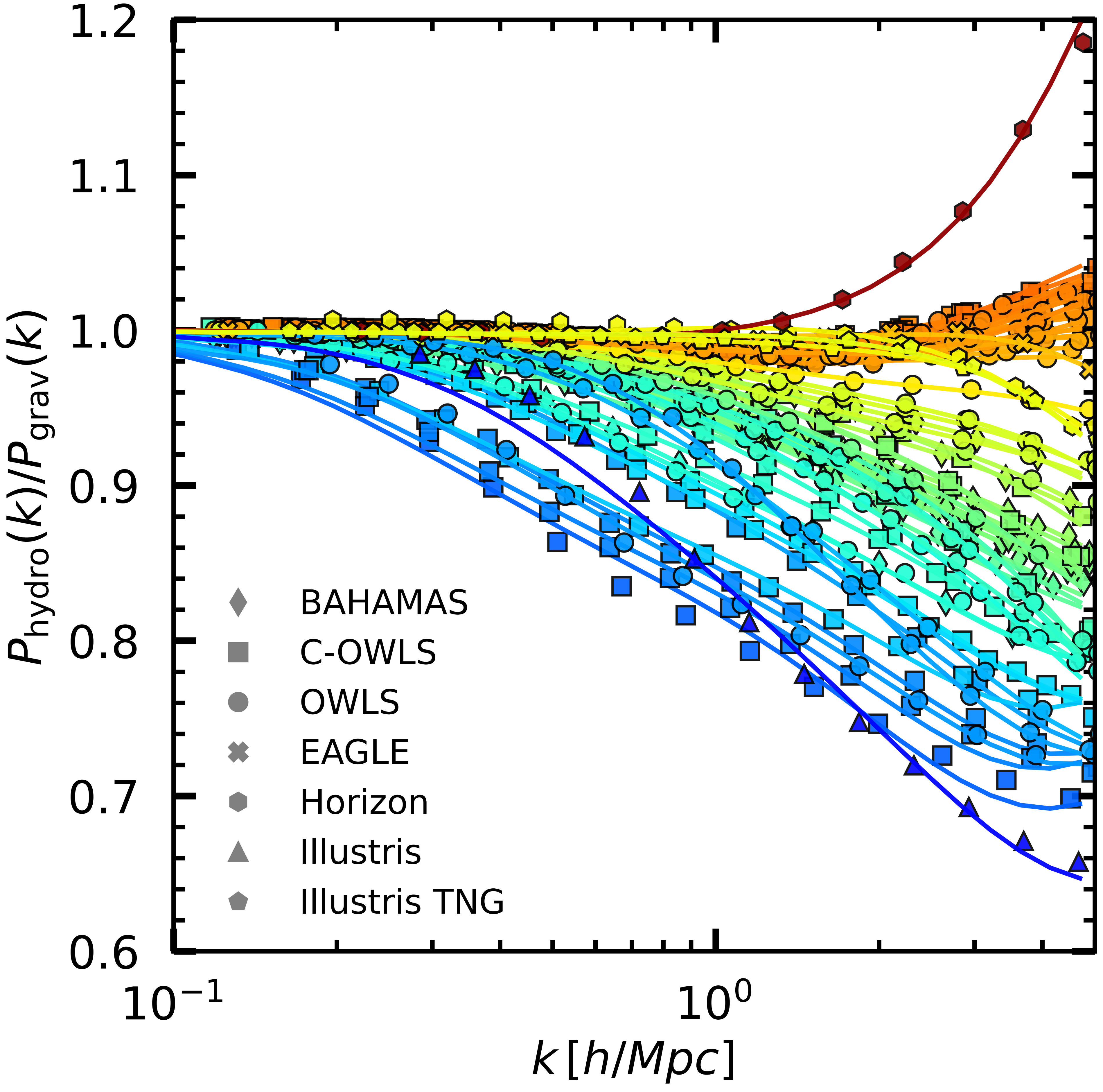
BCM: clustering predictions

Dependency on cosmology

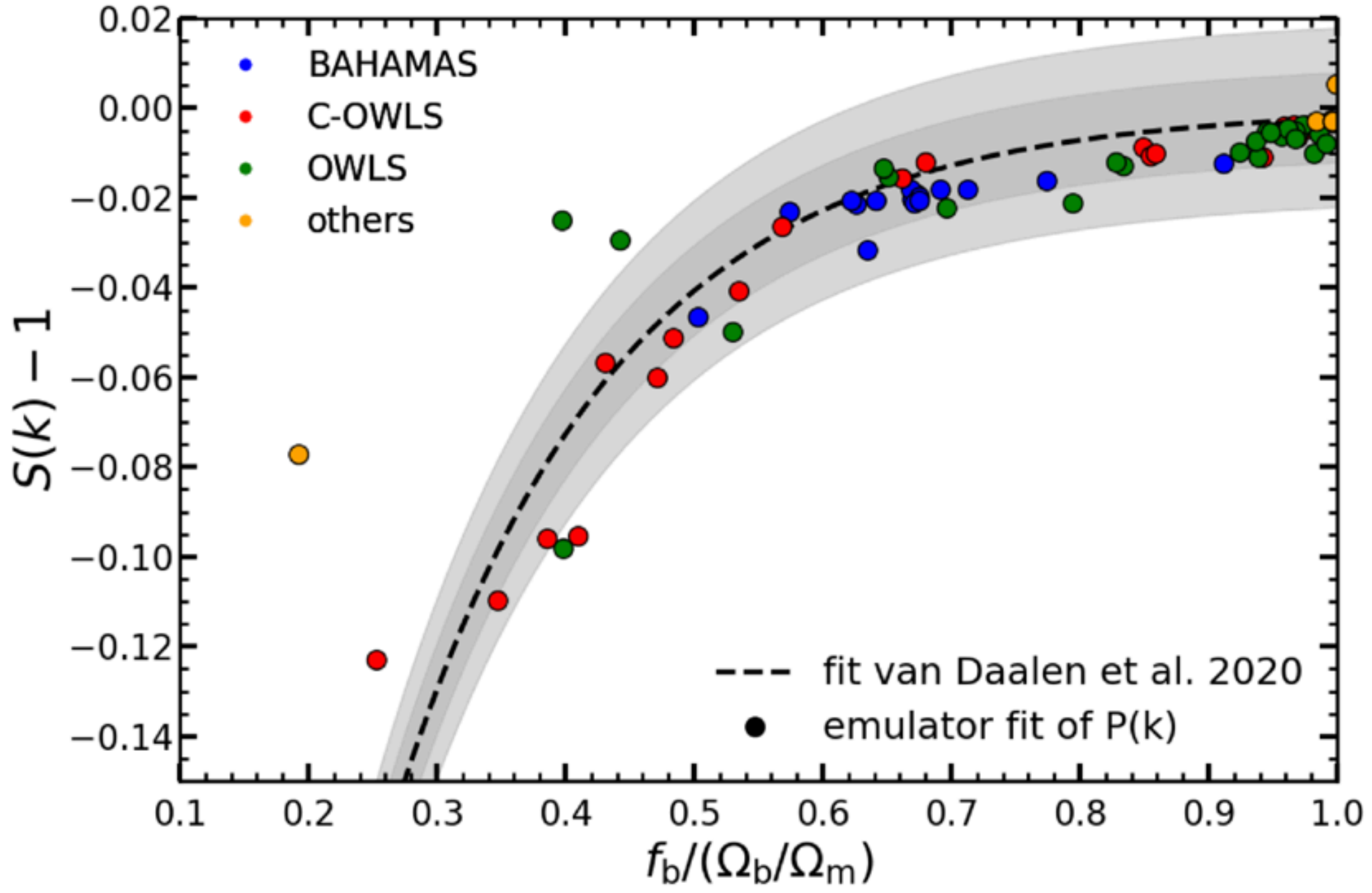


Aricò et al. 2021b

BCM: test with hydrodynamical simulations



Fitting at 1% the P(k) of 74 hydro sim

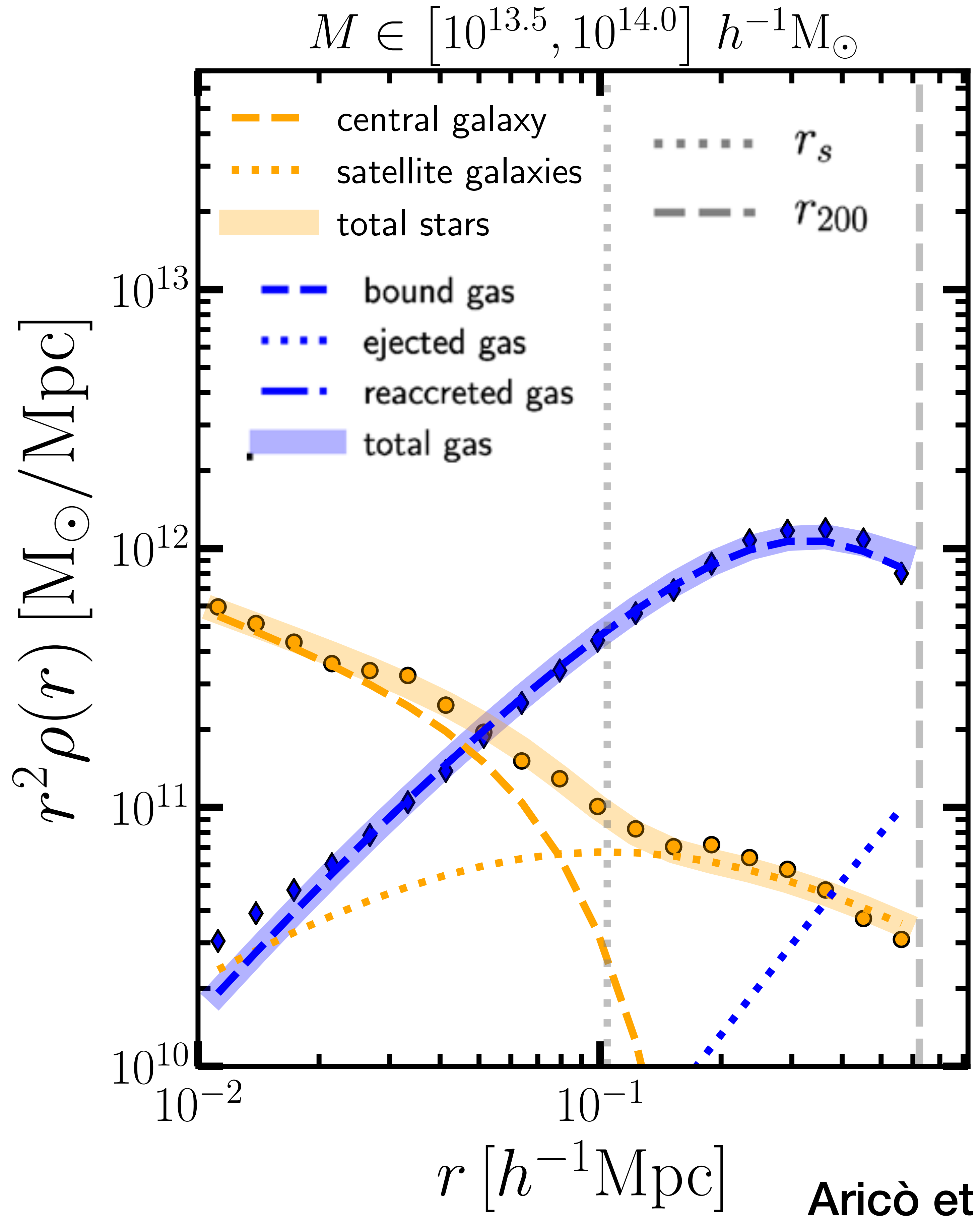


Adapted from Aricò et al, 2021b

Well recovered baryon fractions in haloes

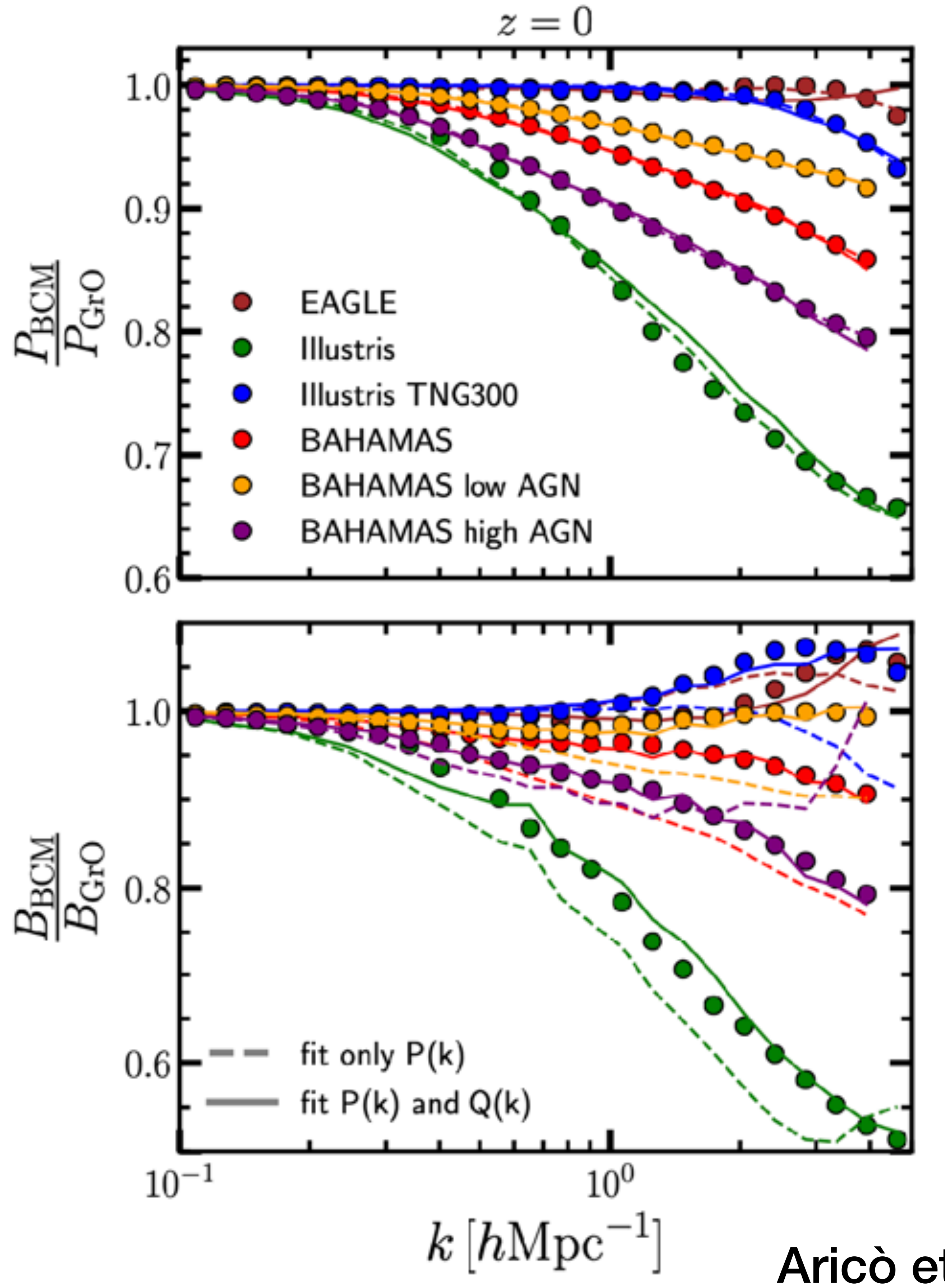
BCM: test with hydrodynamical simulations

Illustris-TNG density profiles



Aricò et al. 2021a

power spectra & bispectra



Aricò et al. 2021a

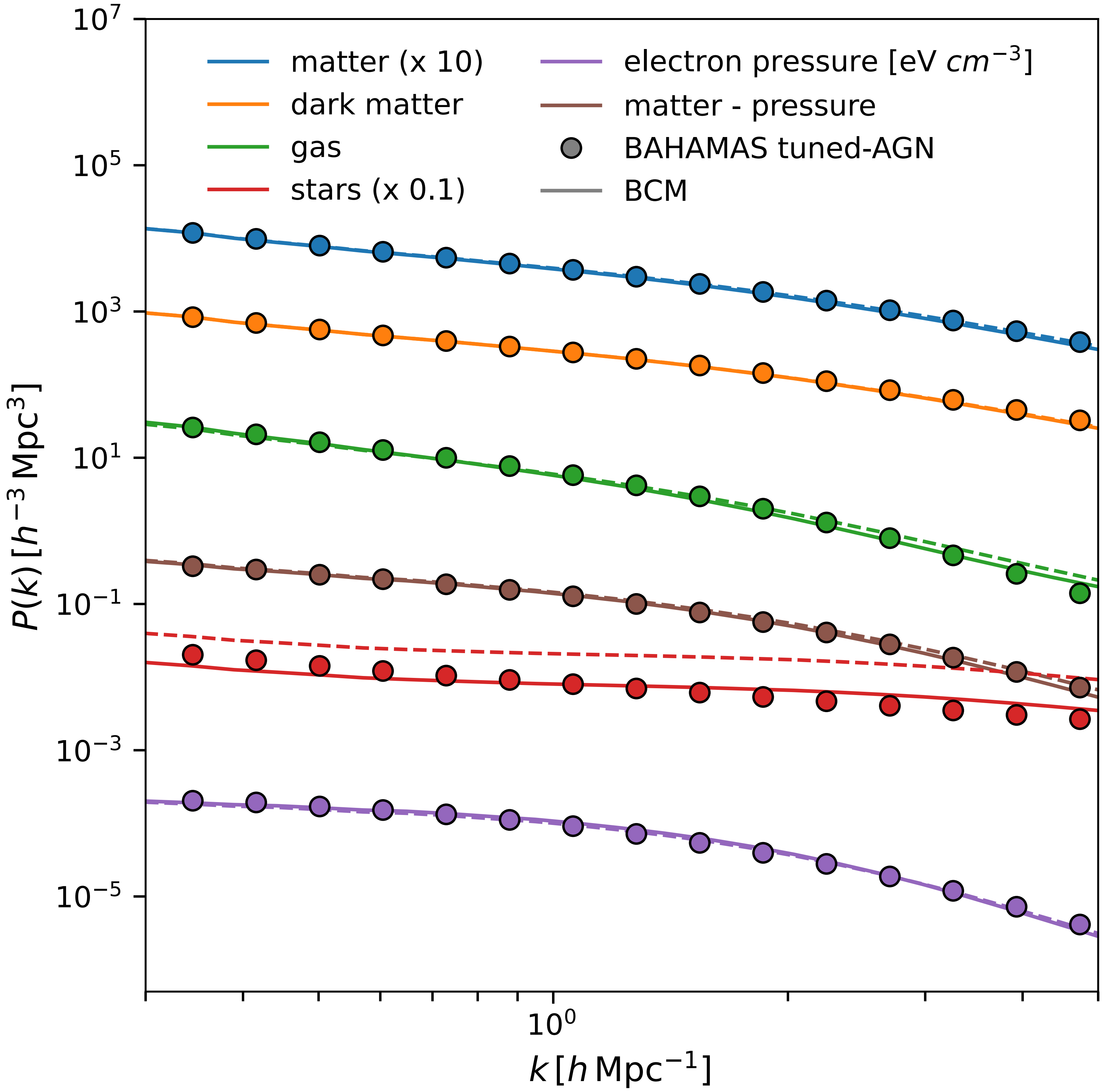
galaxy-galaxy lensing

See the talk of **Matteo Zennaro** tomorrow

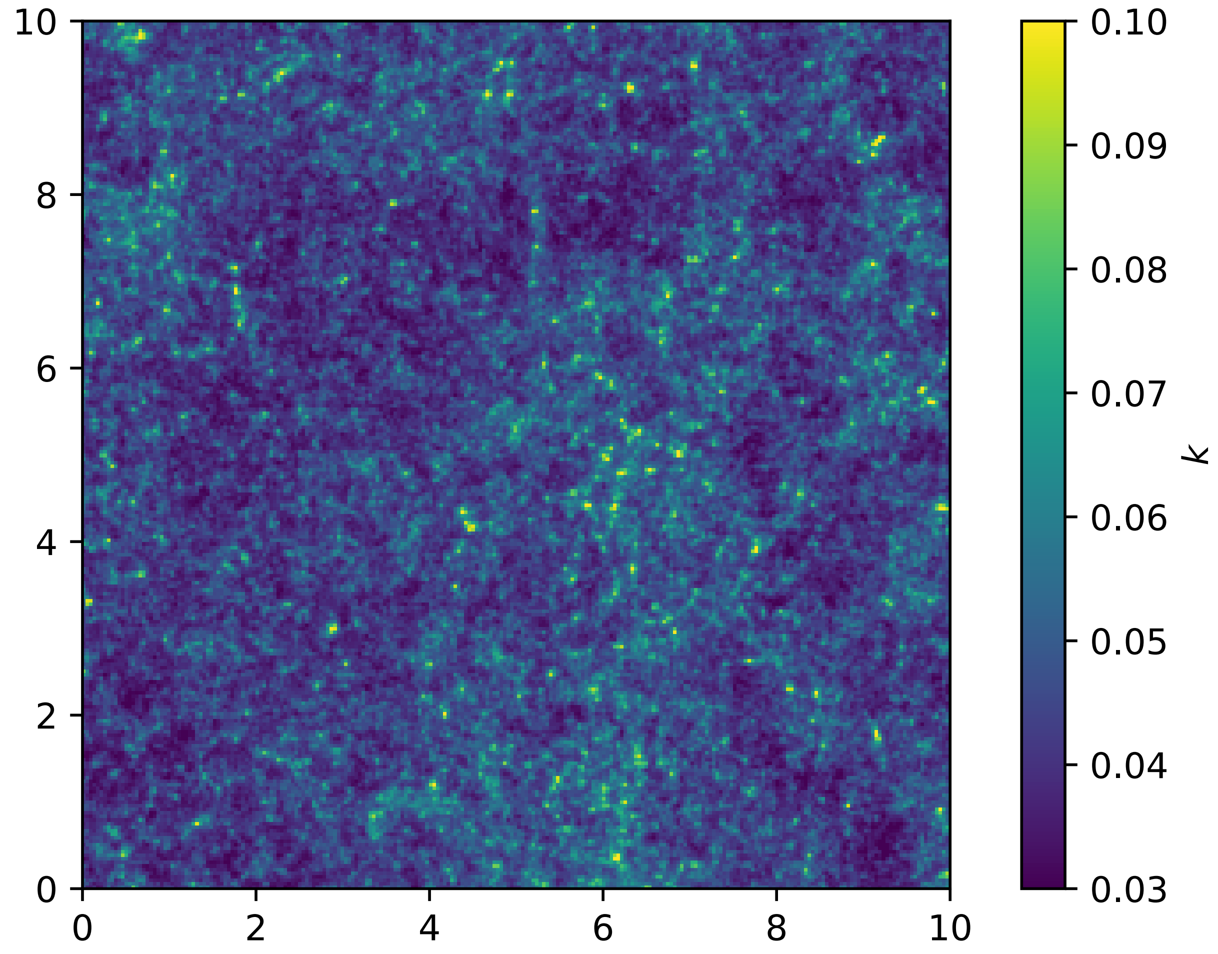
kinetic Sunyaev-Zel'dovich

see the talk of **Lurdes Ondaro** tomorrow

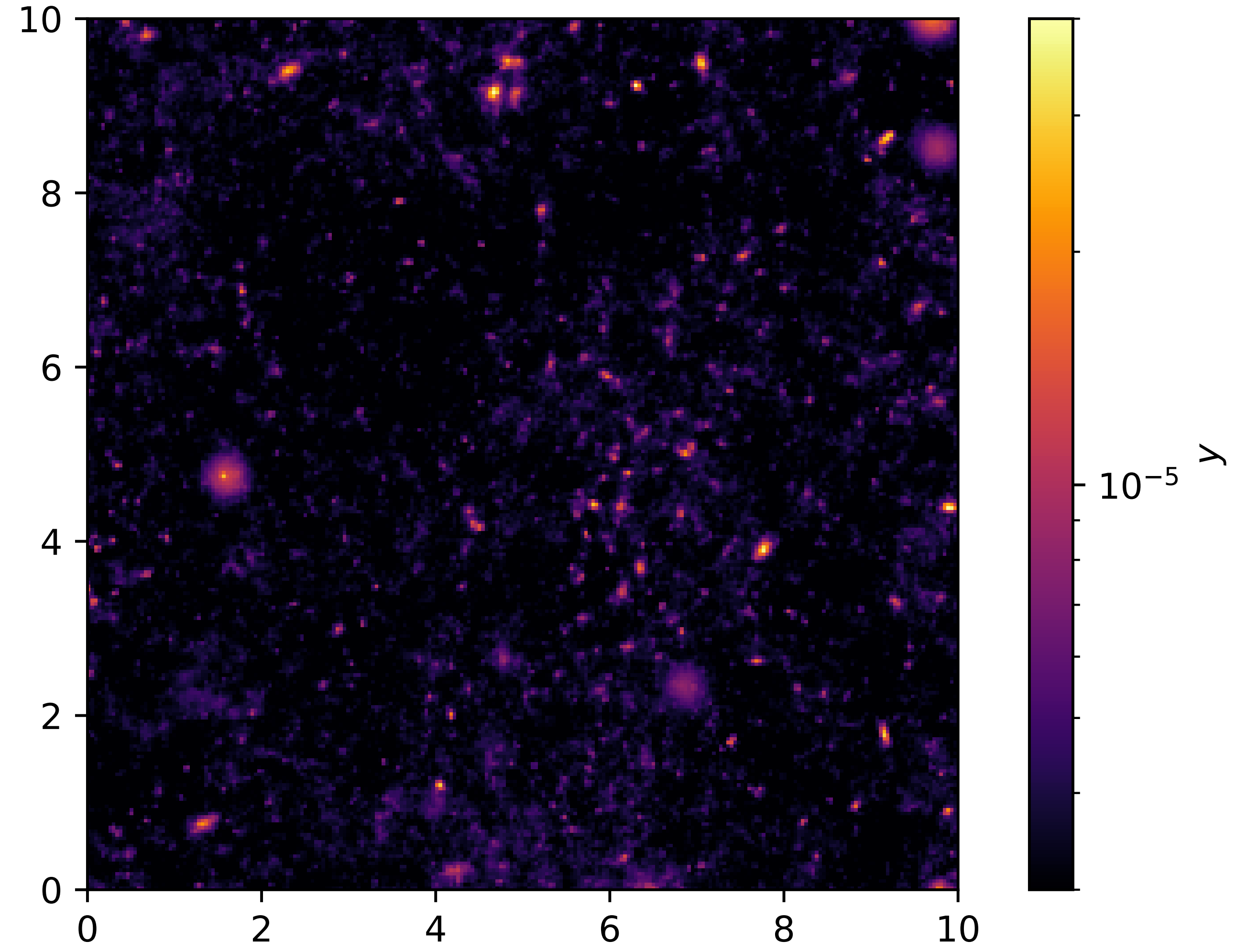
Extending the BCM to thermal Sunyaev-Zel'dovich effect

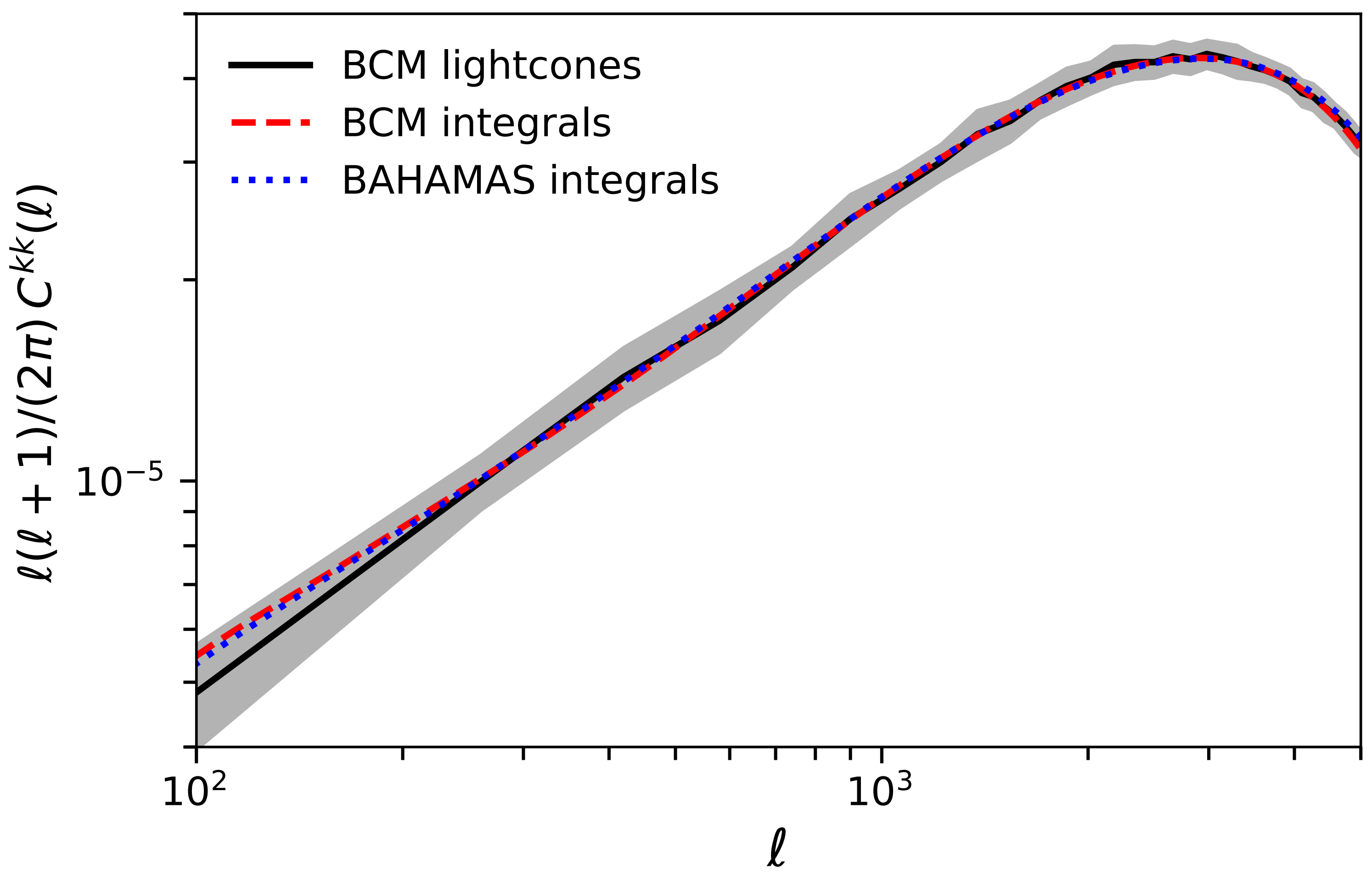


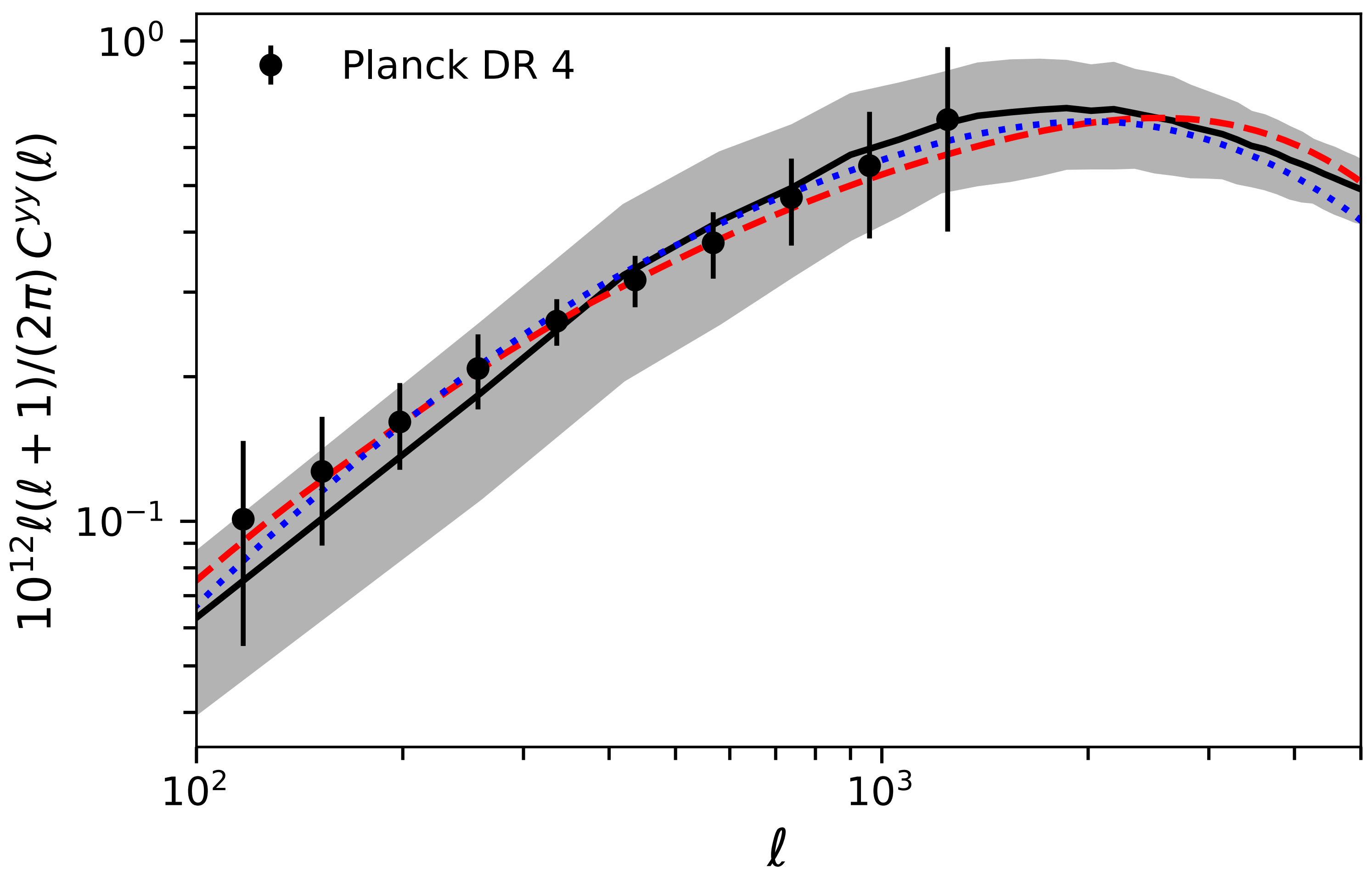
BCM convergence



BCM thermal SZ







Baryonic density end electron pressure

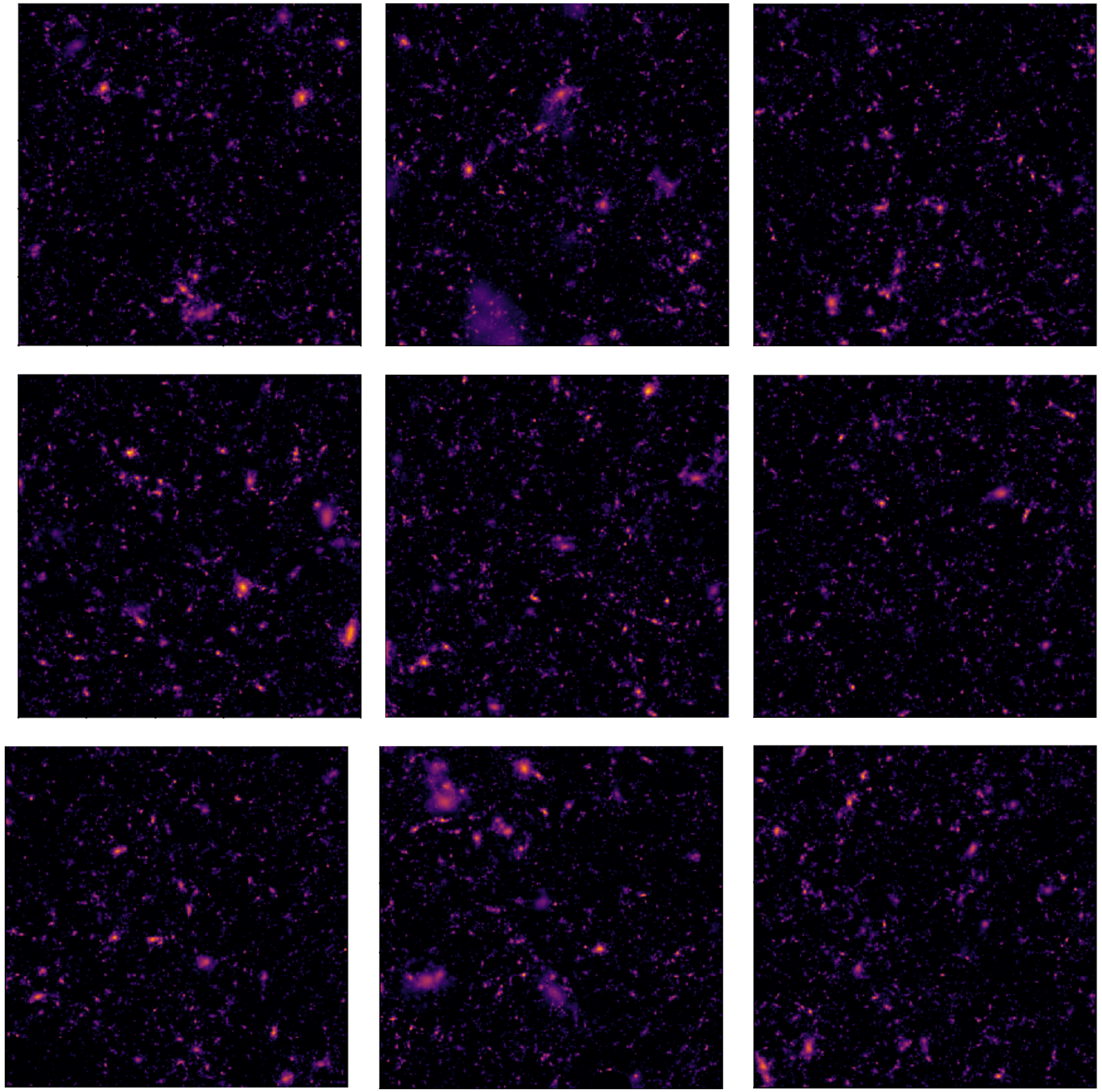
of BAHAMAS accurately reproduced

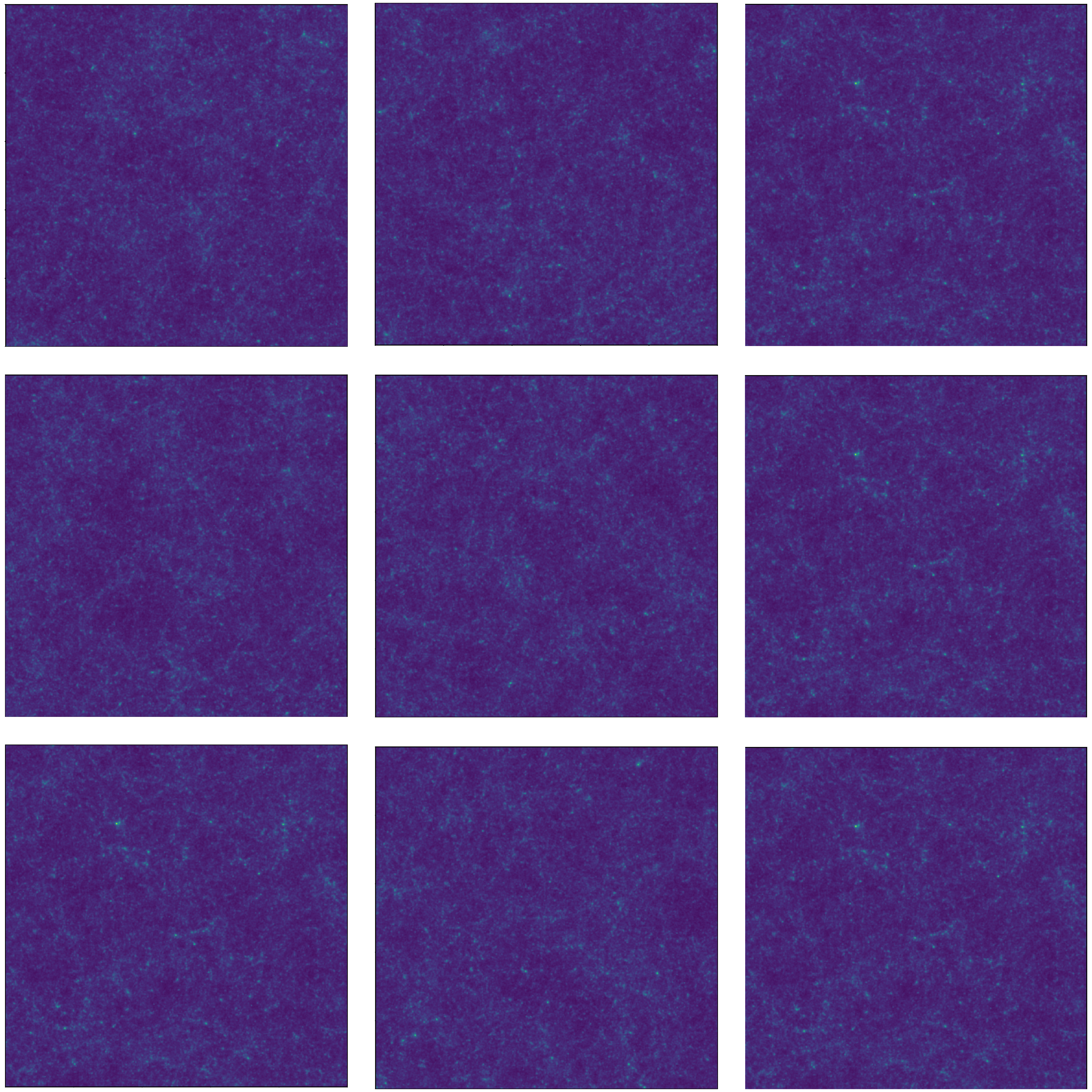
~ 1% accuracy in convergence
~10% accuracy in tSZ

Aricò & Angulo 2024

Fast production of SZ and convergence maps

varying cosmology and astrophysics





BACCOemu

Parameters

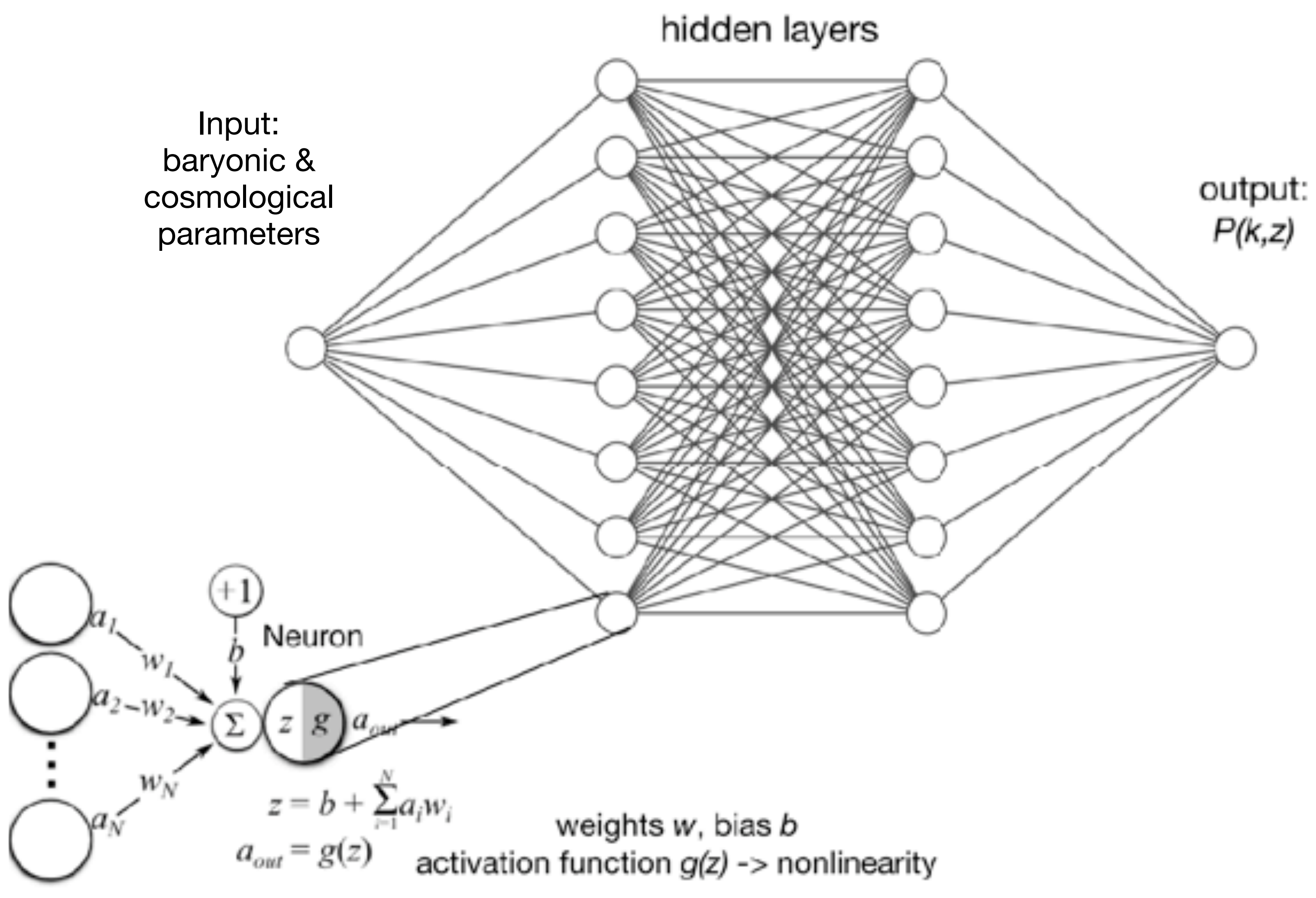
7 Baryonic parameters

$$\log M_c/(h^{-1}\mathrm{M}_\odot) \in [9.0, 15.0]$$
$$\log \eta \in [-0.7, 0.7]$$
$$\log \beta \in [-1, 0.7]$$
$$\log M_{1,z0,\mathrm{cen}}/(h^{-1}\mathrm{M}_\odot) \in [9, 13]$$
$$\log M_{\mathrm{inn}}/(h^{-1}\mathrm{M}_\odot) \in [9, 13.5]$$
$$\log \theta_{\mathrm{inn}} \in [-2, -0.5]$$
$$\log \theta_{\mathrm{out}} \in [-0.5, 0]$$

8 Cosmological parameters

$$\sigma_8 \in [0.73, 0.9]$$
$$\Omega_{\mathrm{m}} \in [0.23, 0.4]$$
$$\Omega_{\mathrm{b}} \in [0.04, 0.06]$$
$$n_{\mathrm{s}} \in [0.92, 1.01]$$
$$h \in [0.6, 0.8]$$
$$M_\nu\,[\mathrm{eV}] \in [0.0, 0.4]$$
$$w_0 \in [-1.15, -0.85]$$
$$w_{\mathrm{a}} \in [-0.3, 0.3]$$

Neural Network

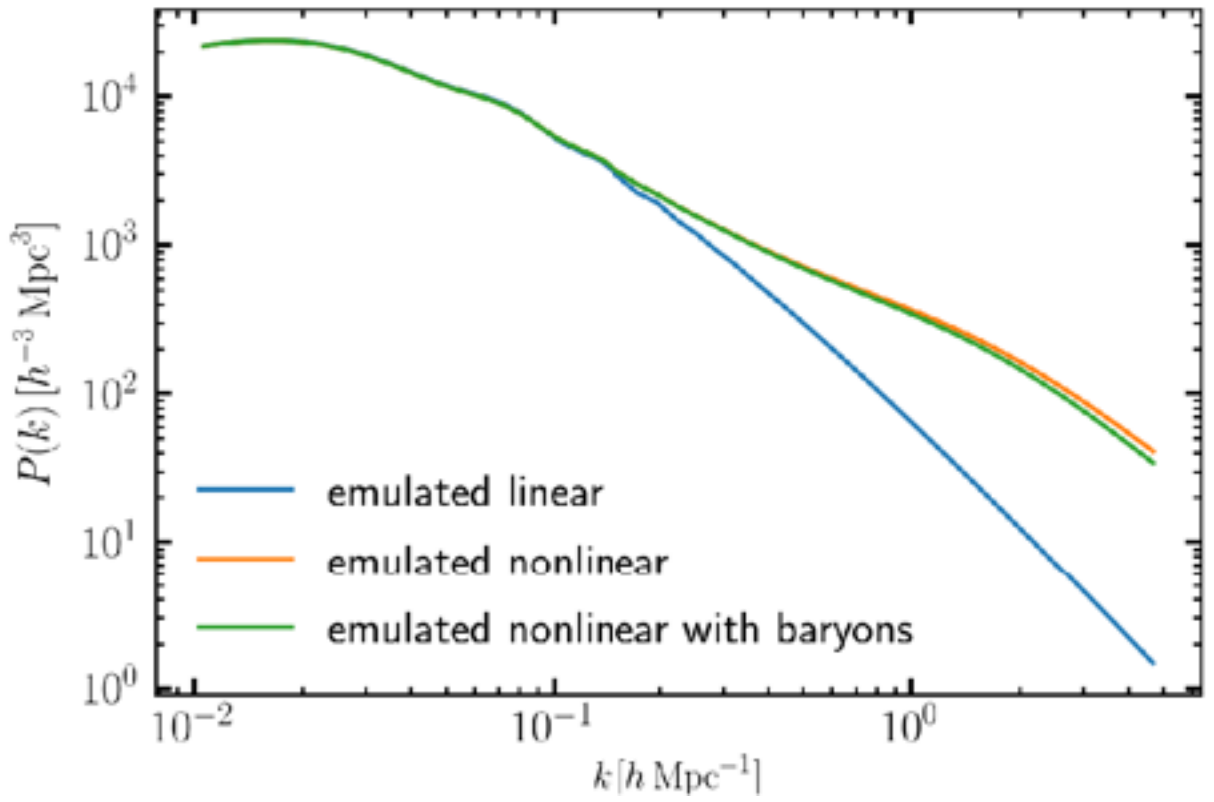


$$\lambda = \left\langle \frac{|P_{\mathrm{NN}}| - P_{\mathrm{TRAIN}}}{P_{\mathrm{TRAIN}}} \right\rangle$$

Matter power spectrum

3 components:

- Linear (CLASS, Lesgourges+ 2011)
- Non-linear boost (cosmo-scaling, Angulo+2020)
- Baryonic suppression (BCM, Aricò+2021)



Angulo et al 2020; Aricò et al. 2021c; Aricò et al. 2022; Zennaro 2023;

Percent accuracy on emulation ⇨ emulation errors subdominant!

Evaluation in milliseconds ⇨ analyses from months to few minutes!

Publicly available ⇨ https://www.dipc.org/bacco

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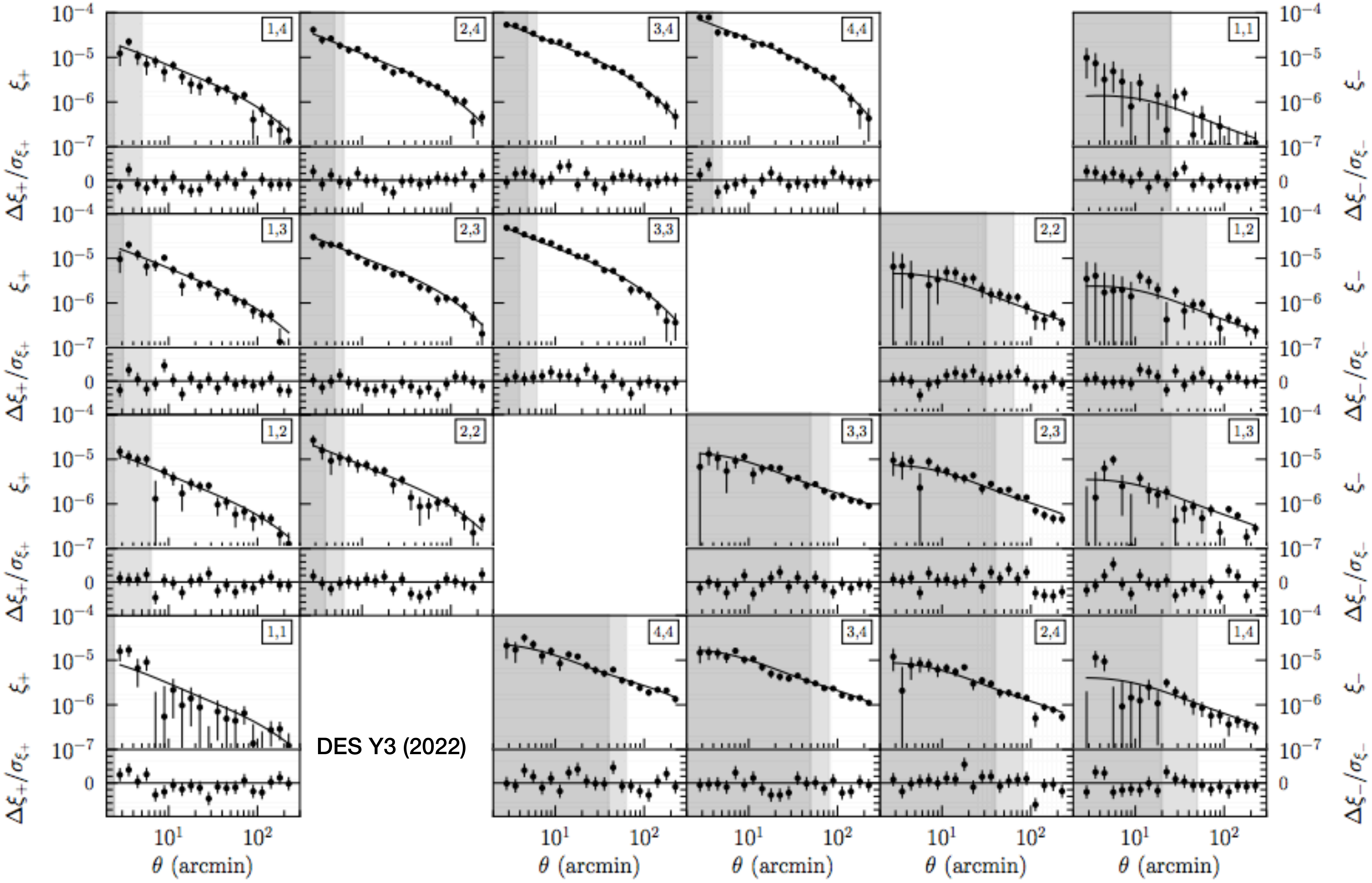
- Simulating baryonic processes in LSS
- Modelling baryonic processes in LSS
- Constraining baryonic processes in LSS

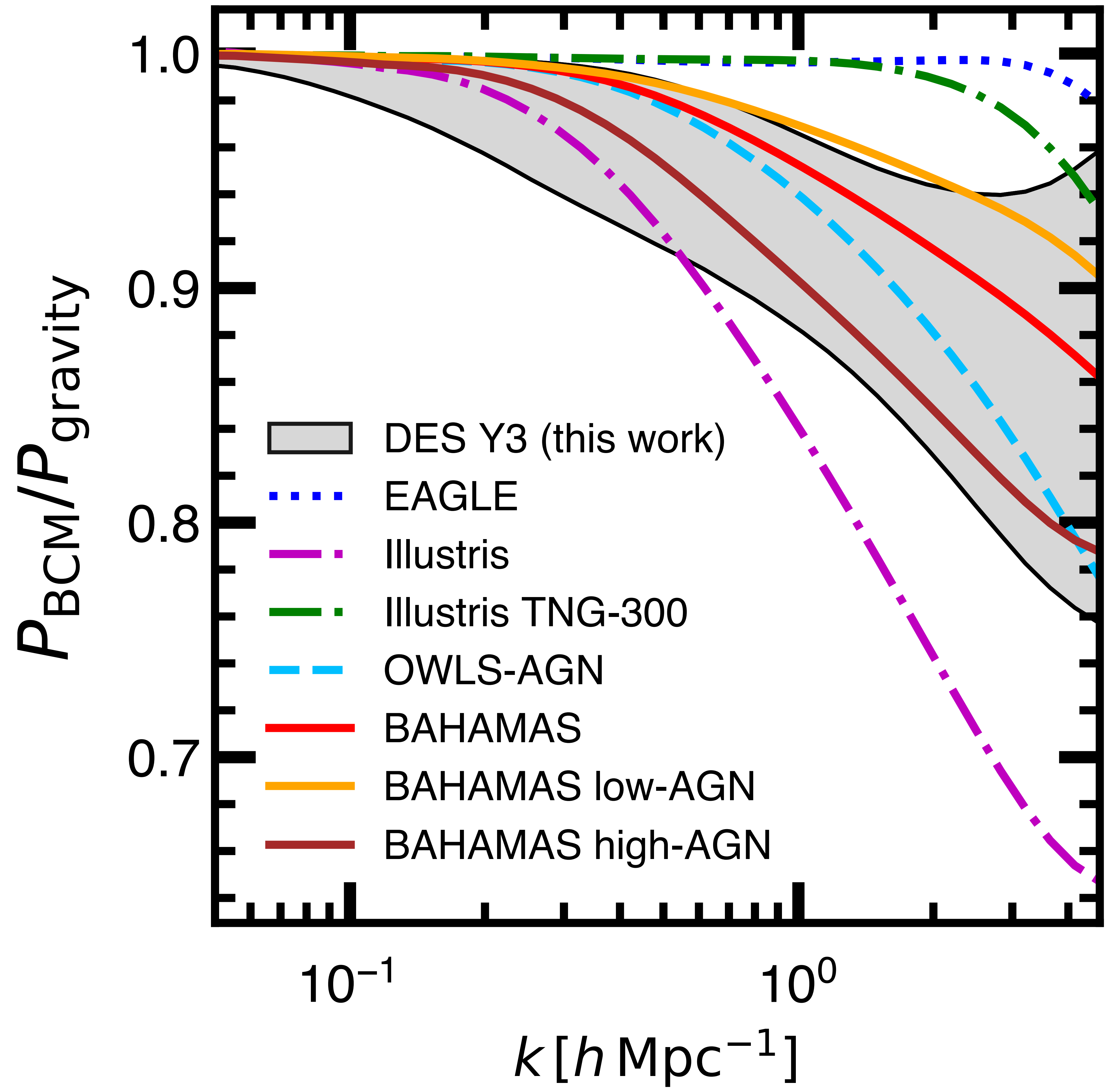
Constraints from cosmic shear

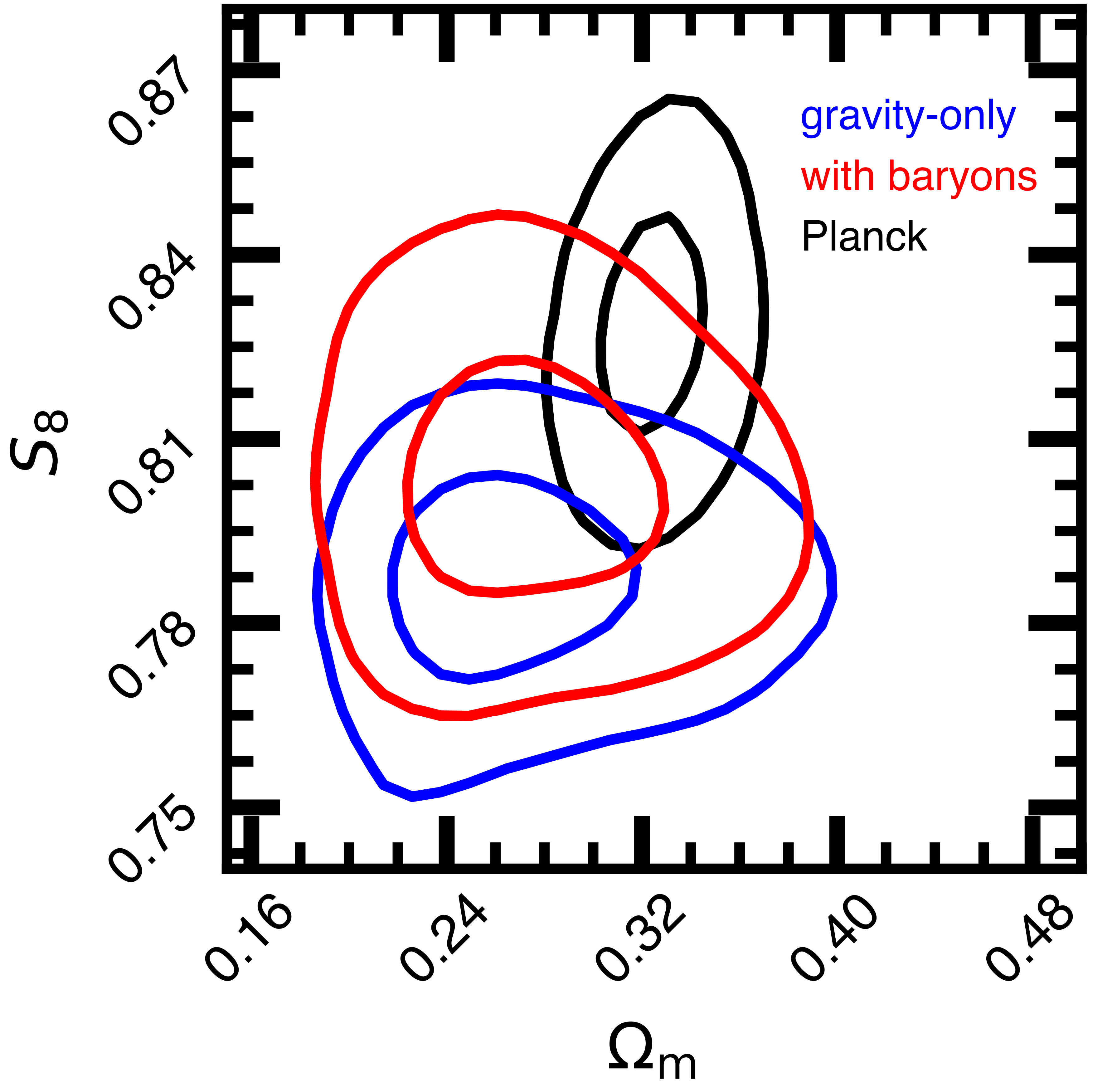


Aricò+2023

Giovanni Aricò, Paris-Saclay Astroparticle workshop 2024

Constraints from cosmic shear



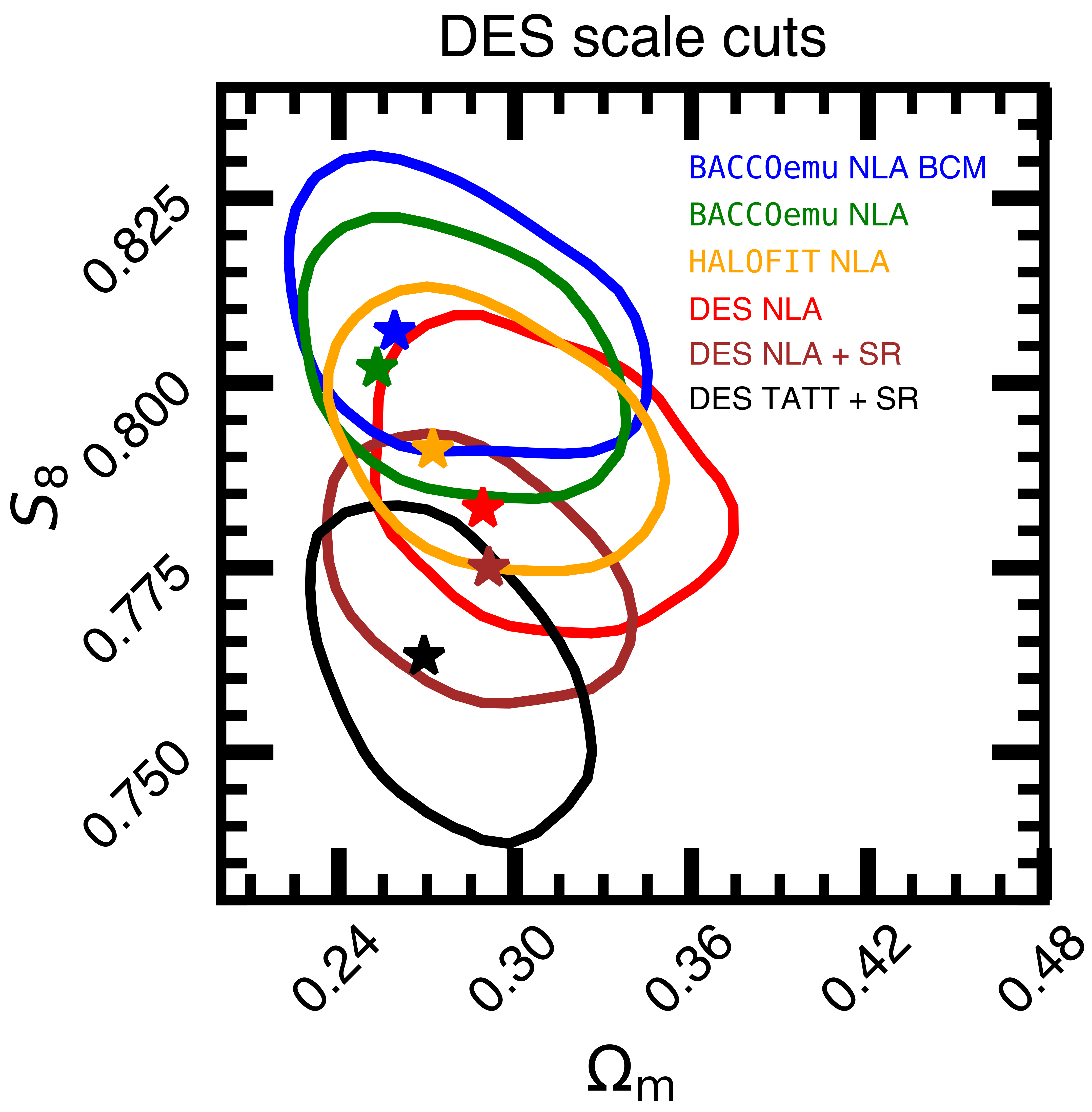


Aricò+2023

Characteristic halo mass for which half of the gas is depleted due to AGN:

$$\log\, M_c = 14.38^{+0.60}_{-0.56}\, \log(h^{-1}\mathrm{M}_\odot)$$

Differences with DES Collaboration's results



Disagreement in S_8

Our fiducial - DES fiducial 1.4σ

Baryons $\approx 0.2\sigma$

Non-linearities $\approx 0.4 - 0.5\sigma$

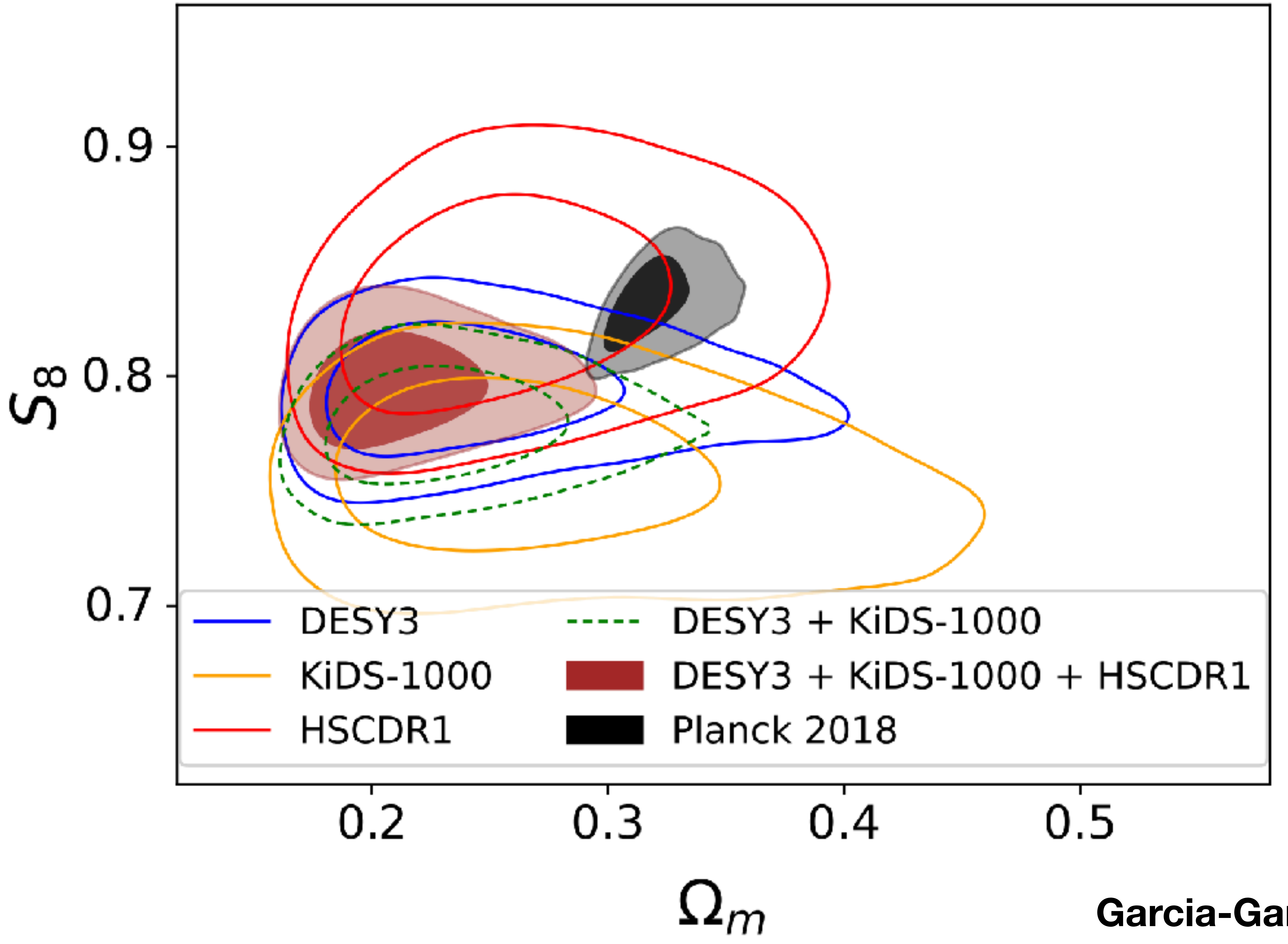
Pipeline/priors $\approx 0.2\sigma$

Shear ratios $\approx 0.1 - 0.3\sigma$

TATT-NLA $\approx 0.4 - 0.7\sigma$

KiDS+DES 2023 reanalysis
in agreement with our finding!

Combining stage III weak lensing surveys



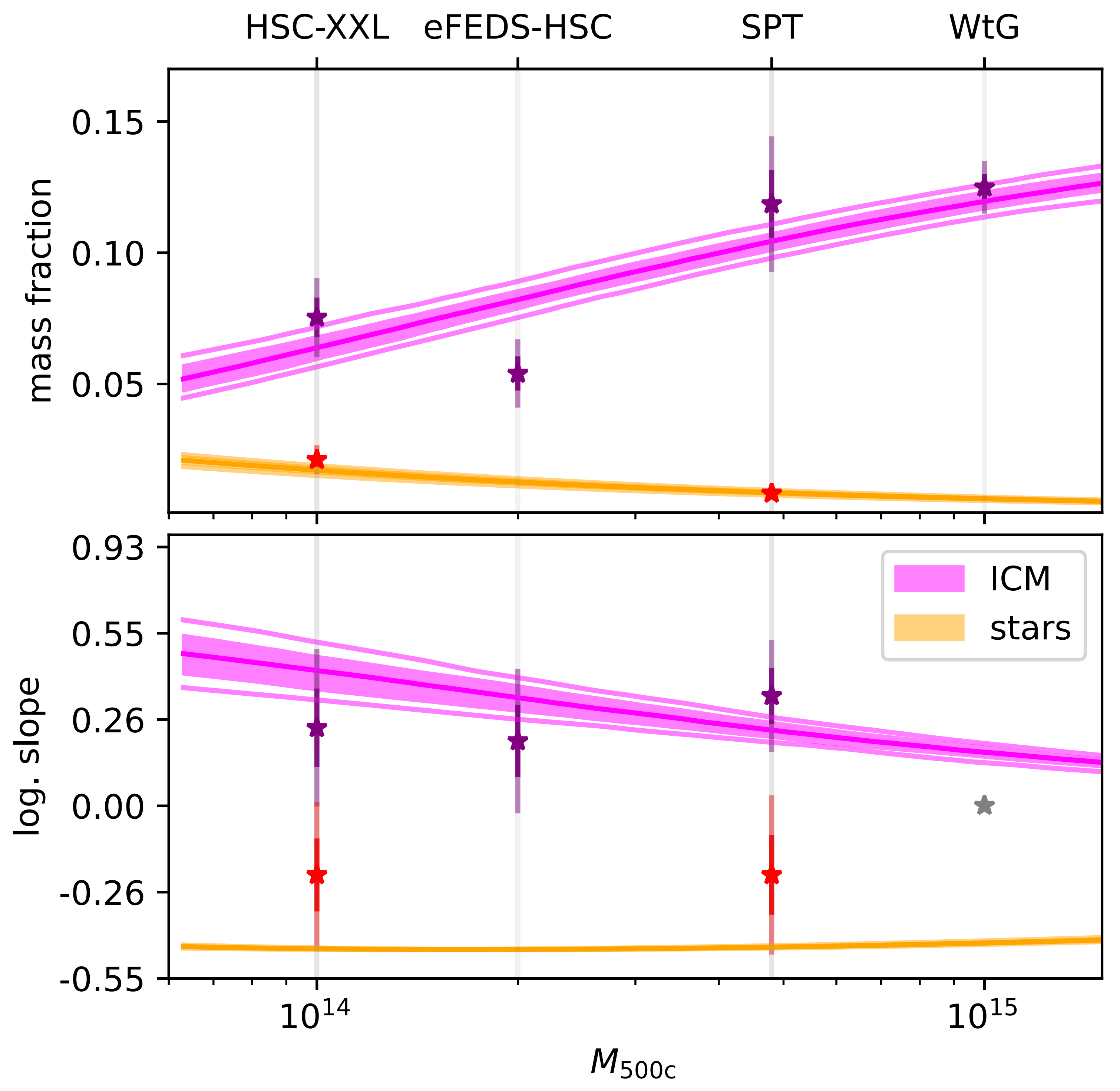
Garcia-Garcia,..,GA+2024

Survey combination, Ω_m tension instead of S_8 tension?

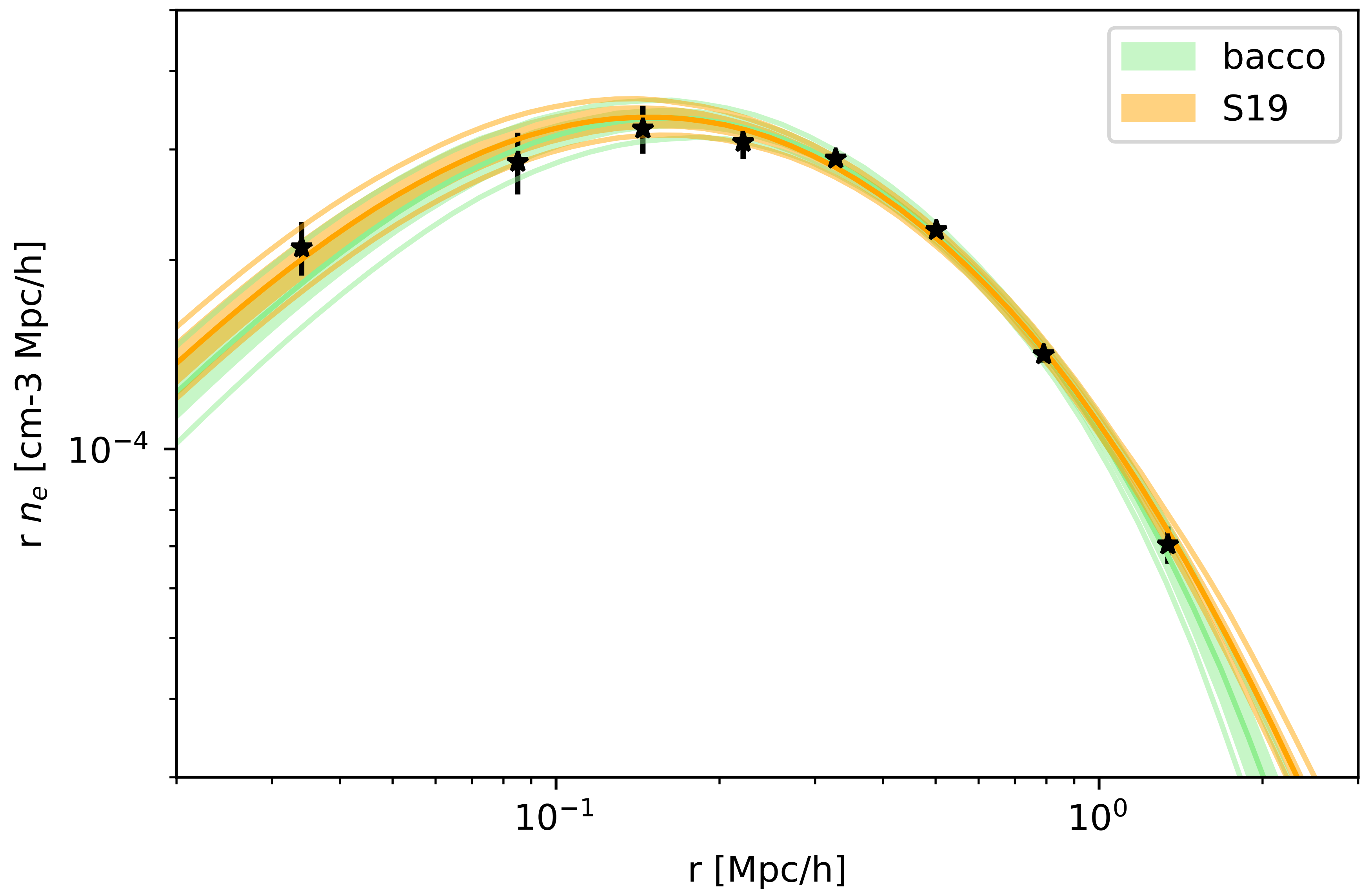
$$\log M_\mathrm{c} \approx 10^{14} \log(h^{-1}\mathrm{M}_\odot)$$

Constraints from galaxy clusters

Using the BCM to fit ~800 galaxy clusters' gas & stellar fractions

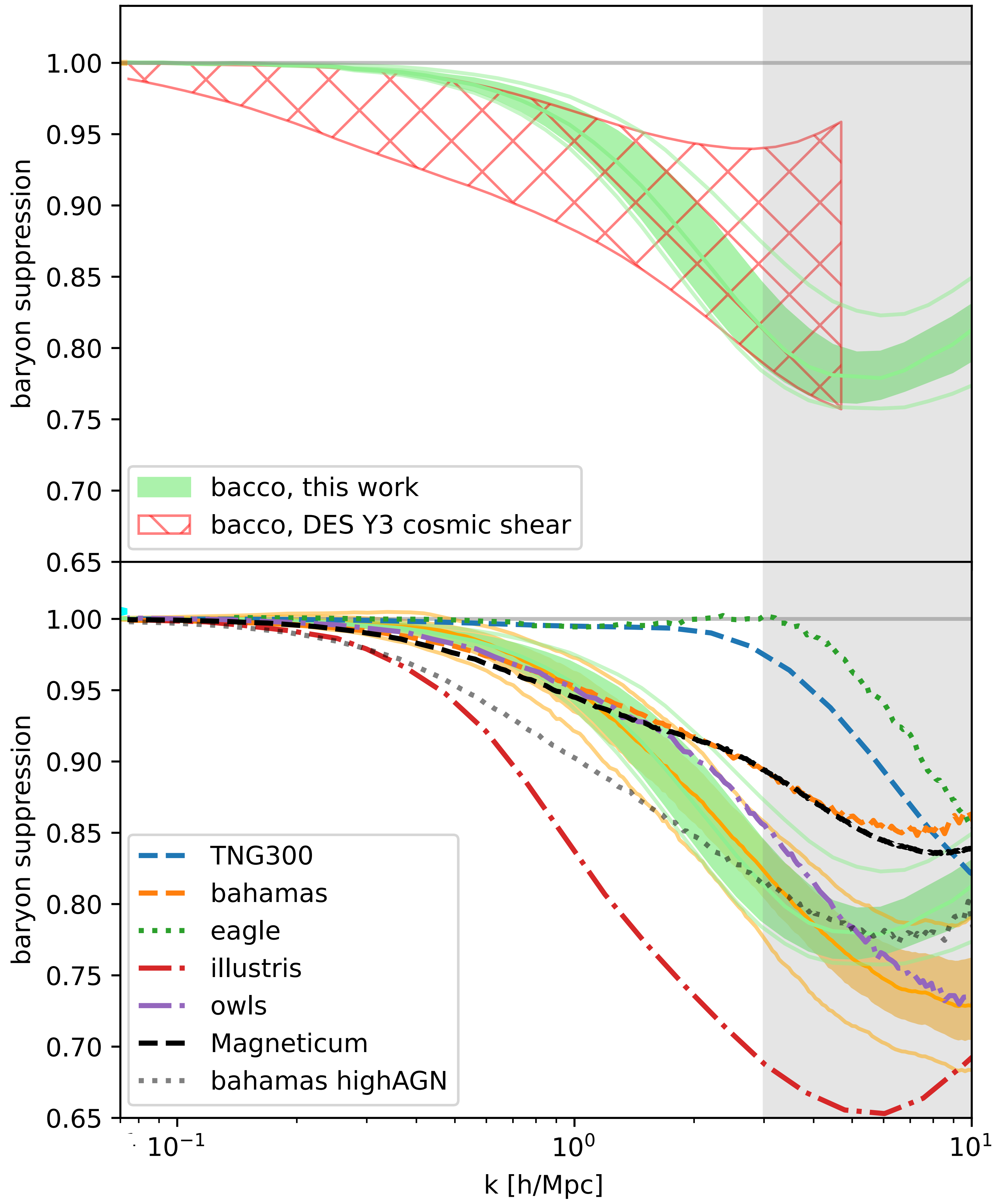


X-ray gas density profiles (X-COP, Eckert et al. 2017)



$$\log M_c = 13.82 \pm 0.36 \log(h^{-1}\mathrm{M}_\odot)$$

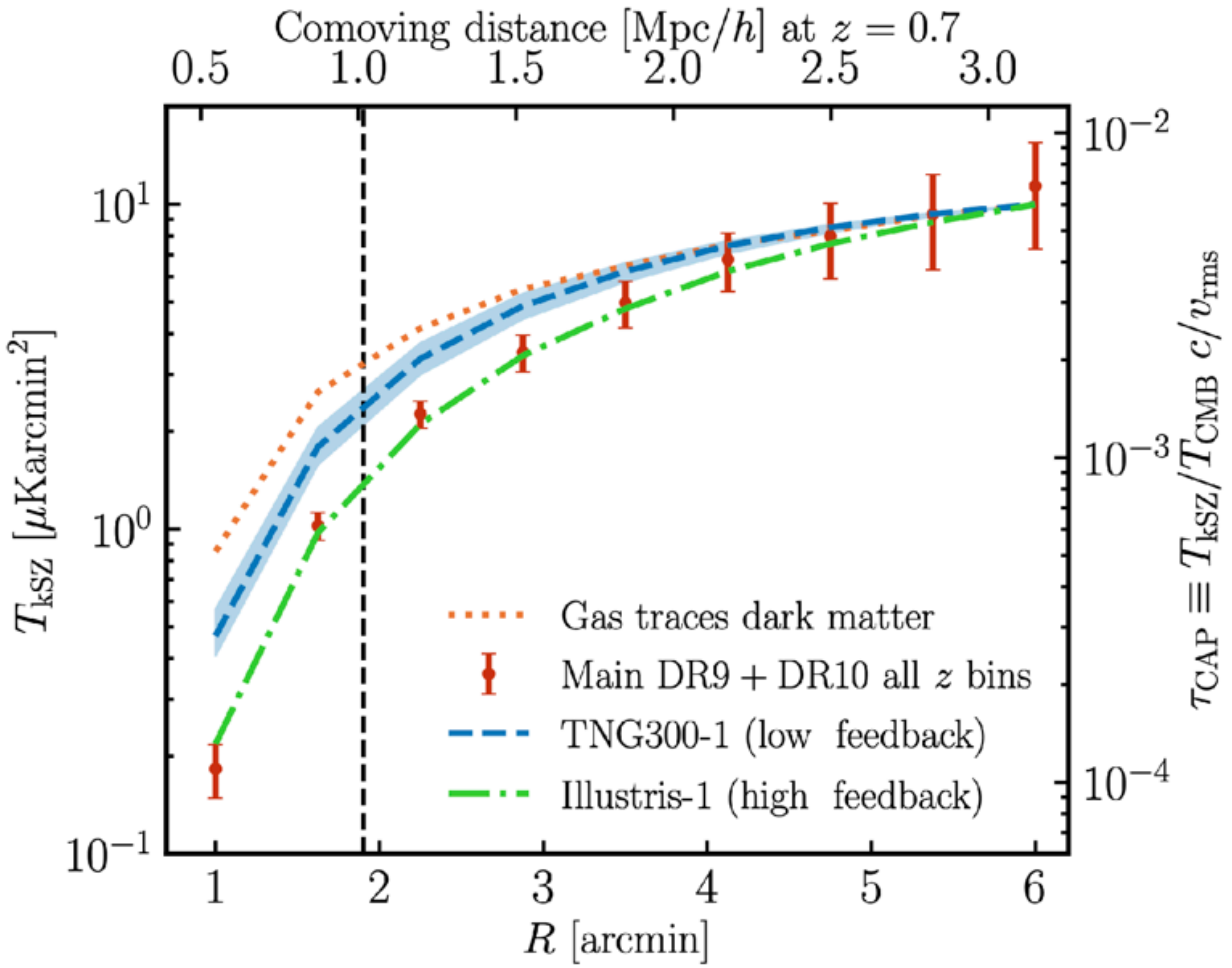
Tight constraints the baryonic effects on the matter power spectrum



Grandis, Aricò,+2023

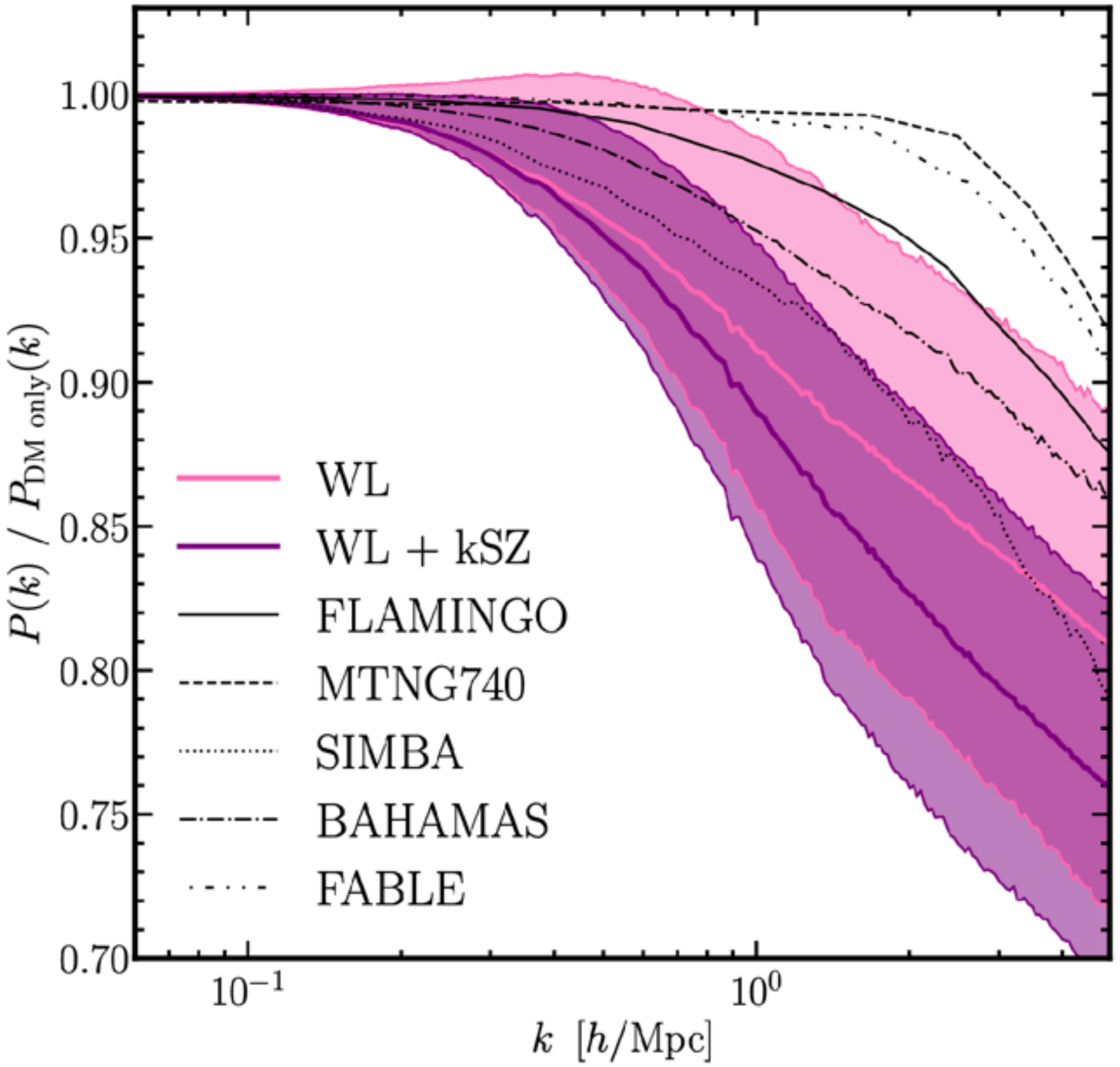
Constraints with kinetic Sunyaev Zel'dovich

ACT kSZ



Hadzhiyska+2024

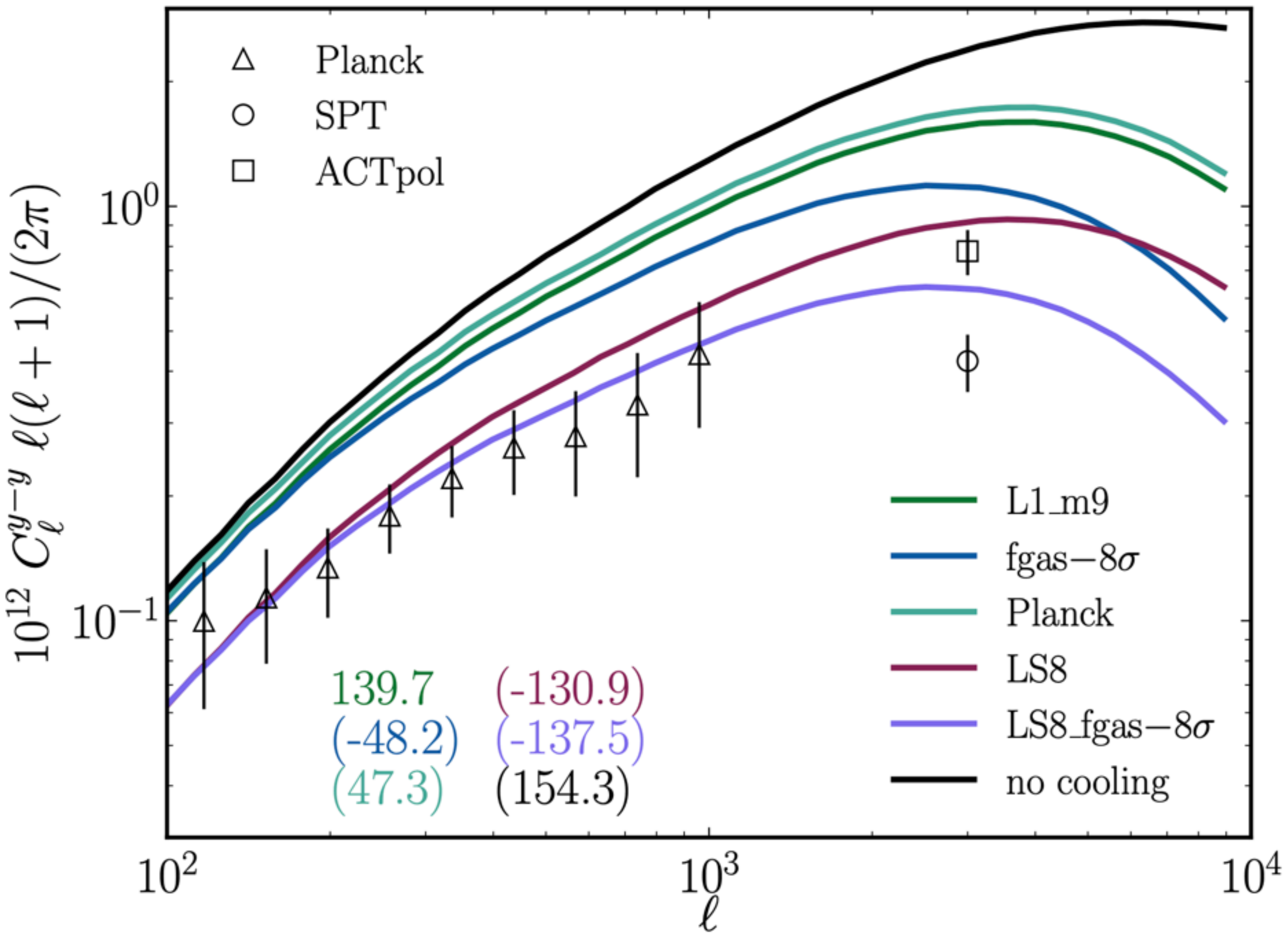
DES shear + ACT kSZ



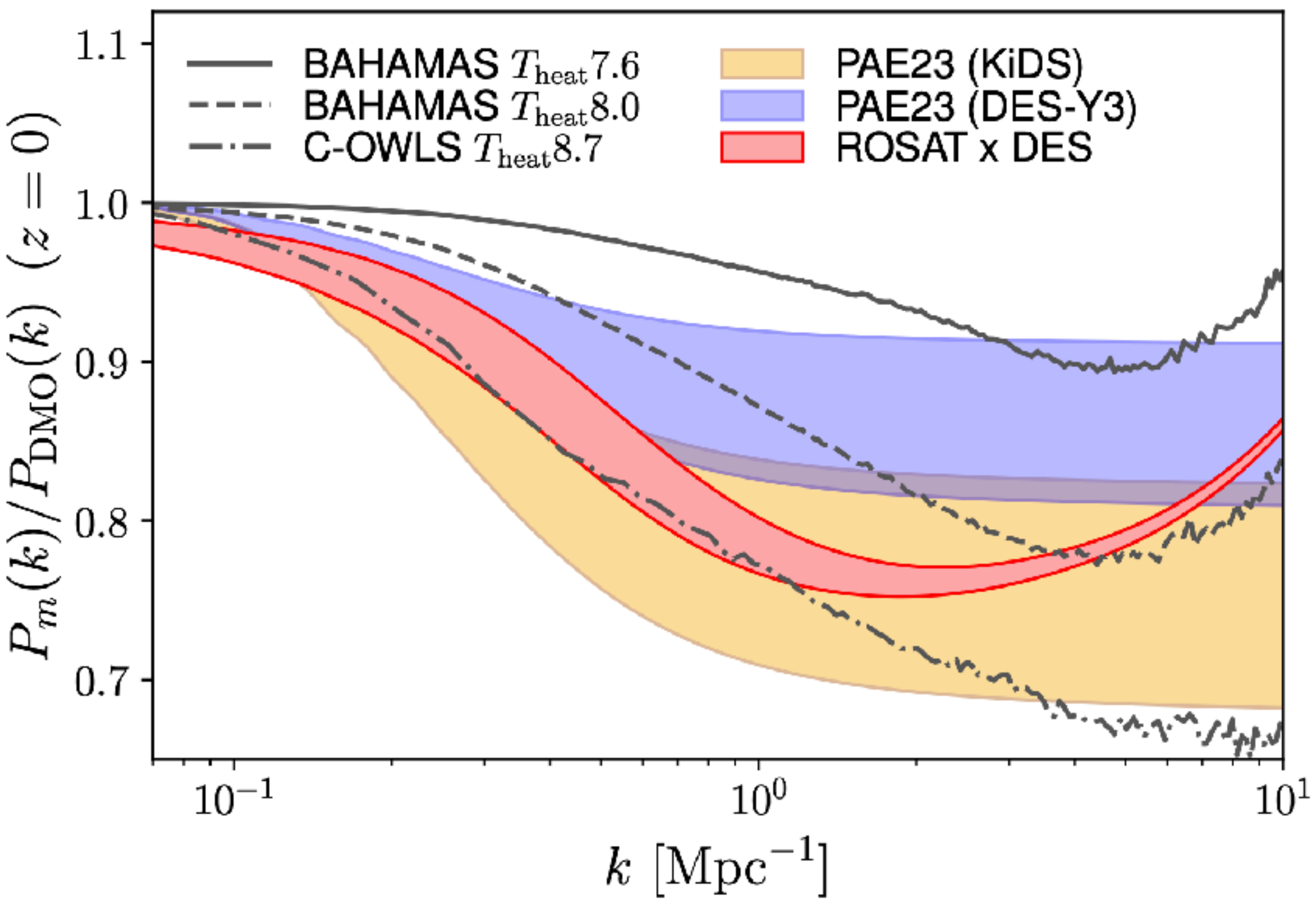
Bigwood+2024

Schneider+2022

Constraints from thermal Sunyaev Zel'dovich and X-ray

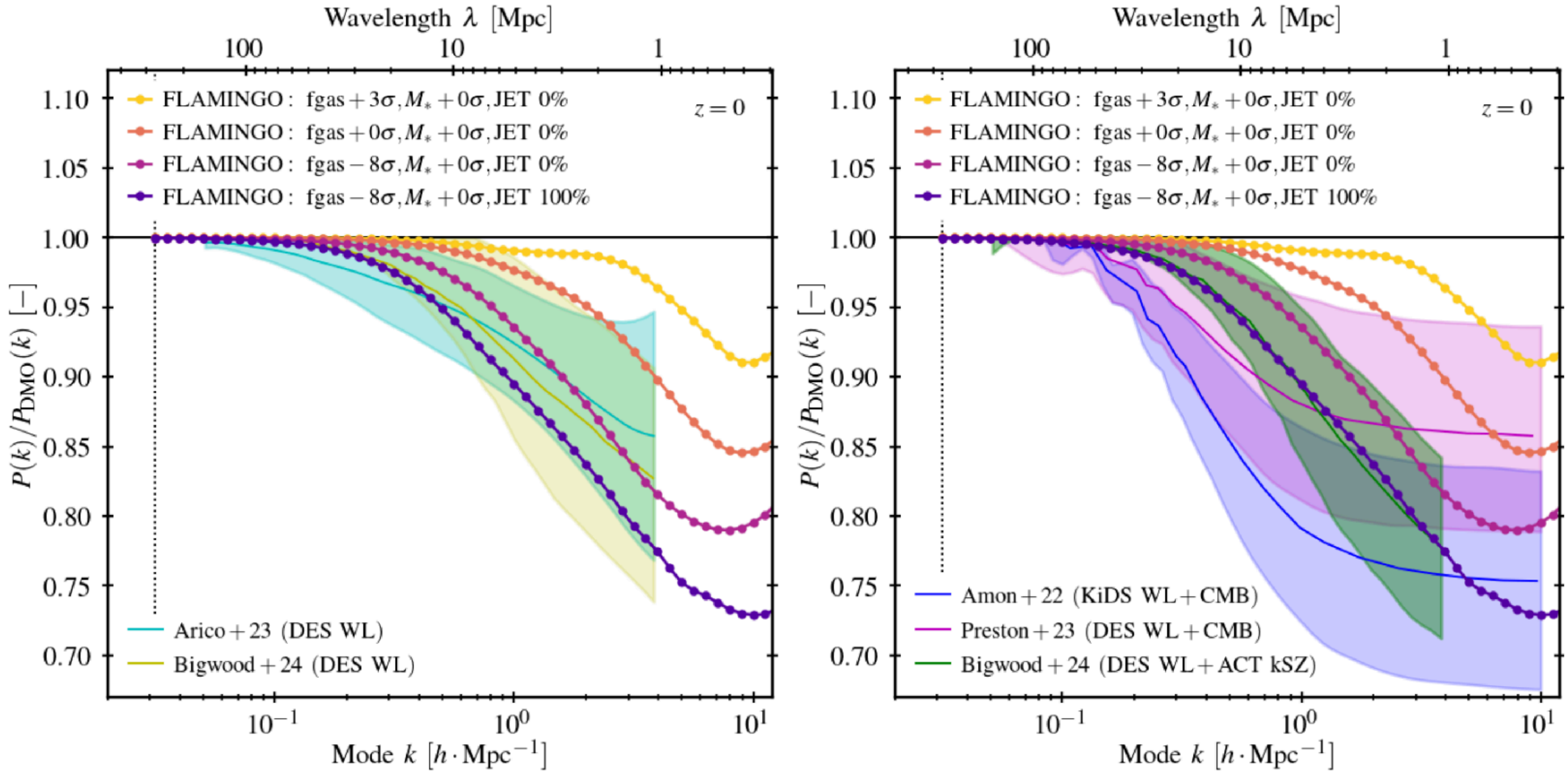


McCarthy+2024
Tröster+2022



Ferreira+2024

What is going on?



Schaller+2024

Systematics in X-ray or kSZ modelling/observations? Selection effects?
Dependency on mass-scale-redshift not accounted for?

In summary

- To optimally exploit current and next cosmological LSS surveys, we need non-linear models of gravity and baryonic processes;

- Hydrodynamical simulations should not be trusted at face value, needed calibration to relevant observables (e.g. gas and stellar fractions in halos);

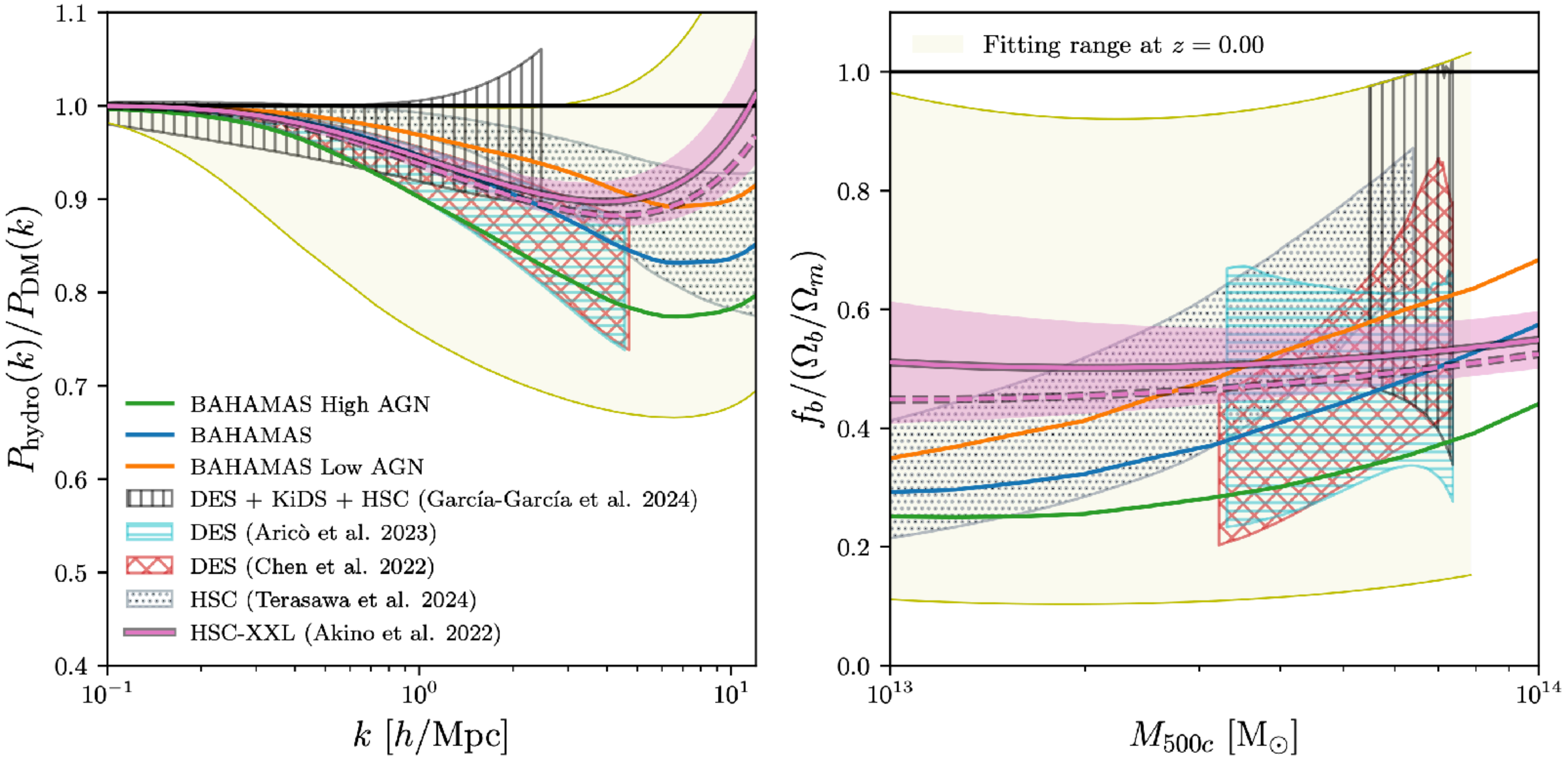
- Methods like the BCM can reproduce hydro sims results and marginalise over both astrophysics and cosmology;

- kSZ and tSZ suggest stronger feedback than baryon fractions X-ray/galaxy clusters, weak lensing is not (yet) constraining enough to discriminate between the two;

- Stage IV surveys like Euclid will significantly improve the current constraints.

Other slides

What is going on?



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