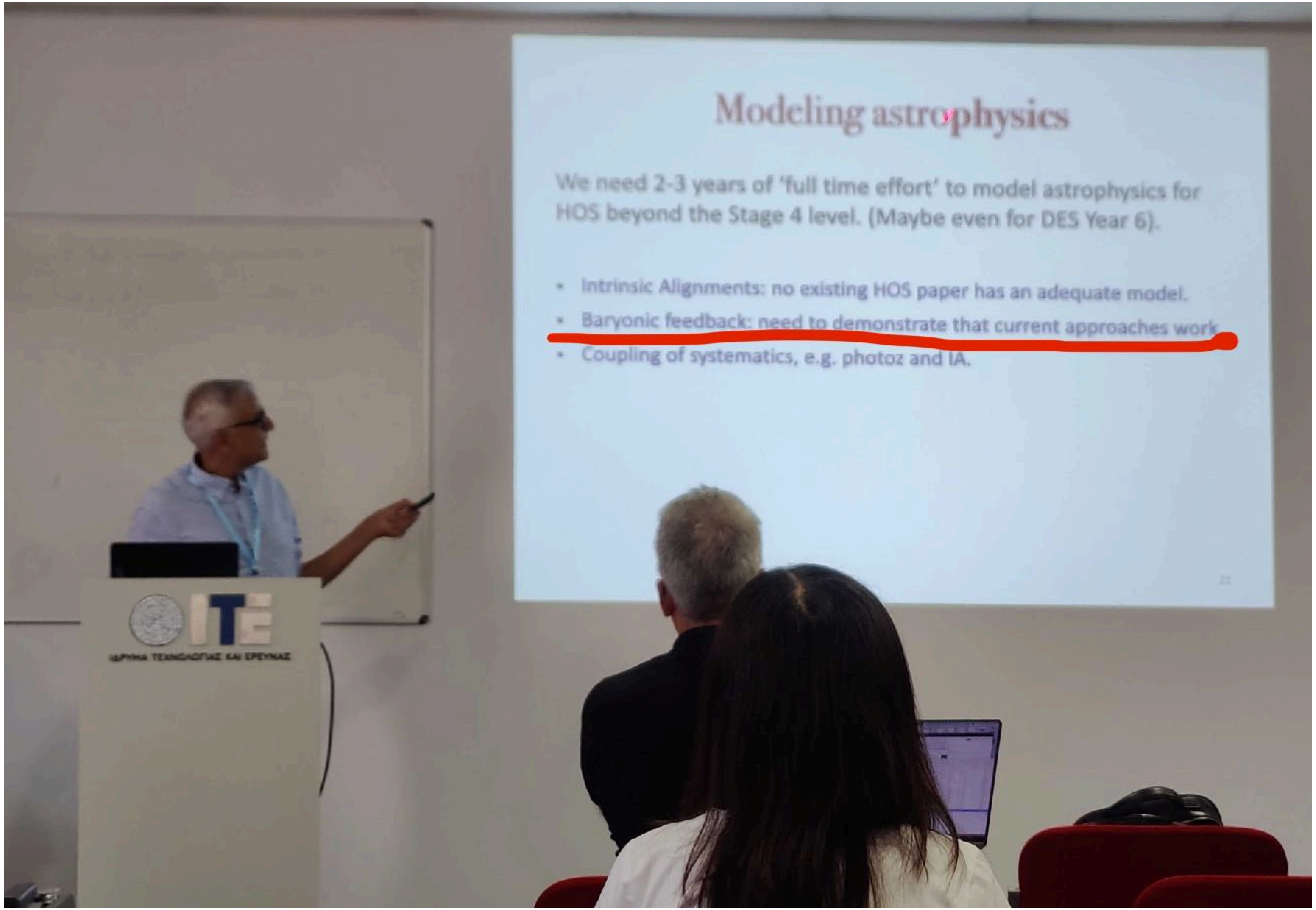
Higher-order baryonic modelling for the Euclid mission

Giovanni Aricò

INFN Bologna

The Non-Gaussian Universe, Heraklion, 17/06/2026

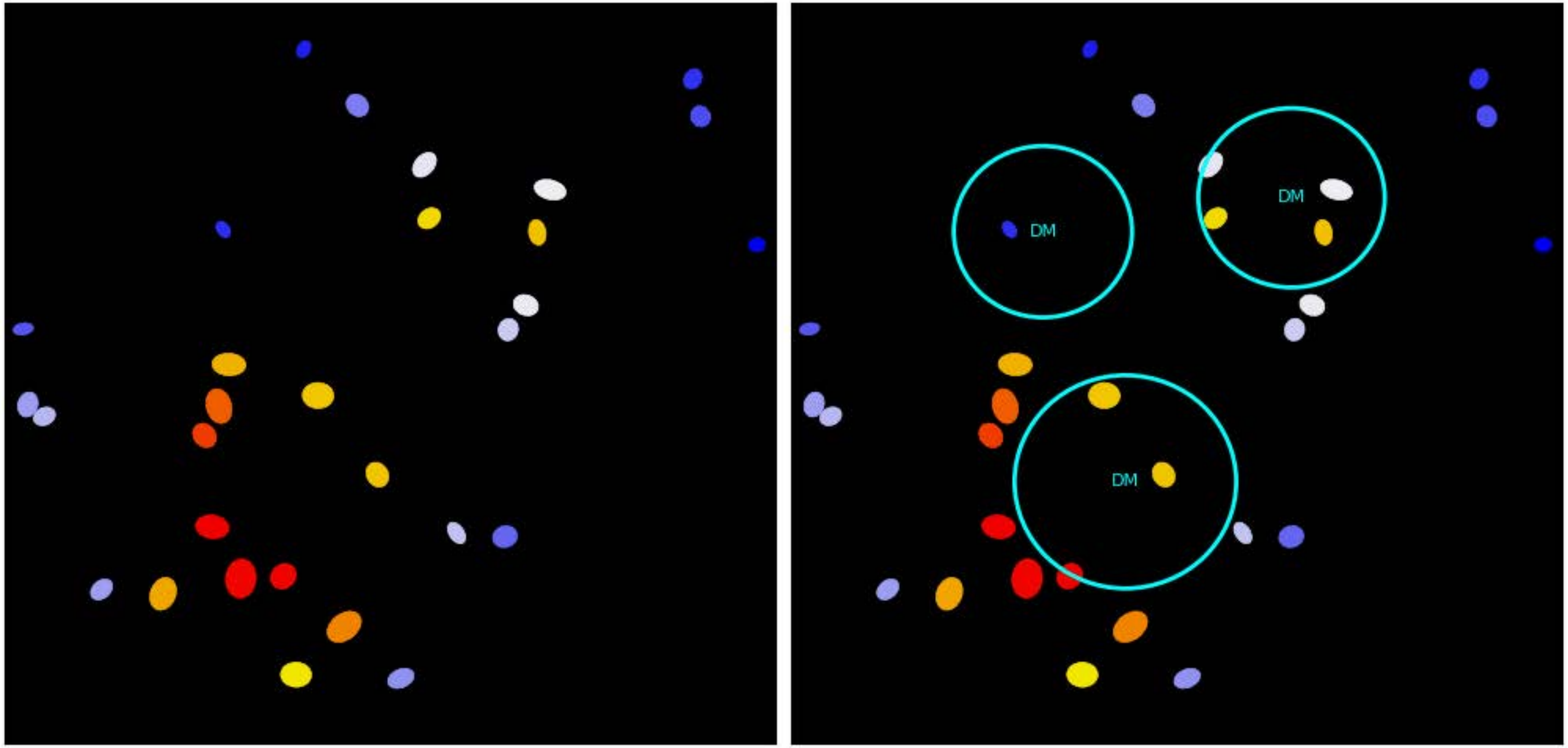
Baryonic feedback: need to demonstrate that current approaches work



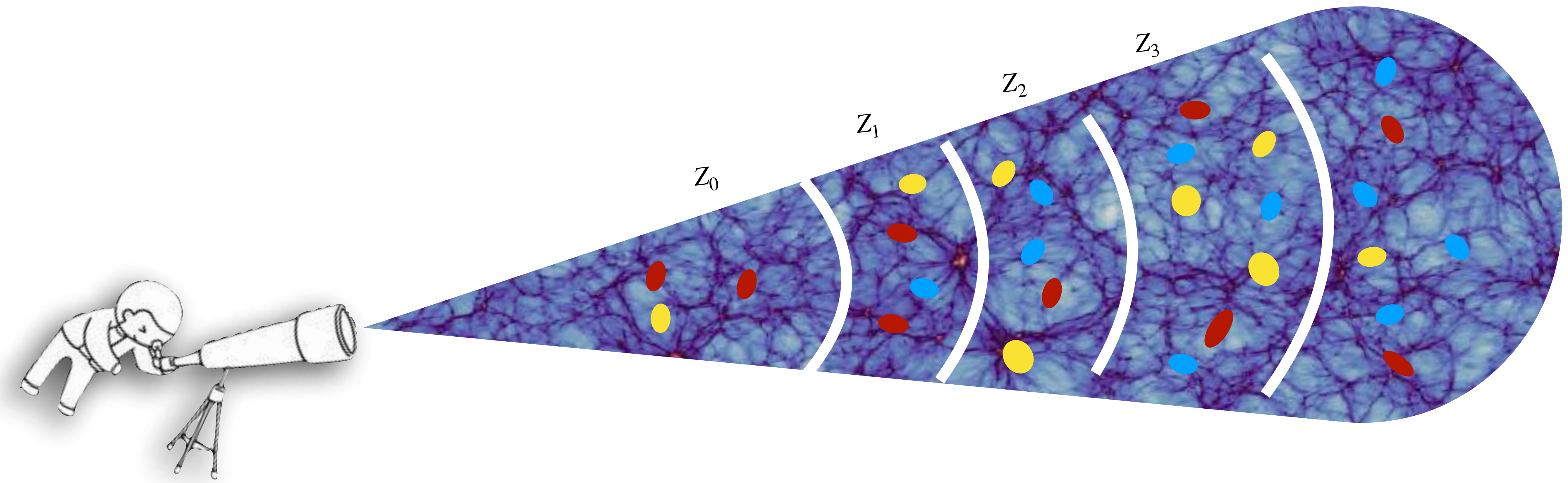
Snapshot of Bhuvnesh's talk this morning

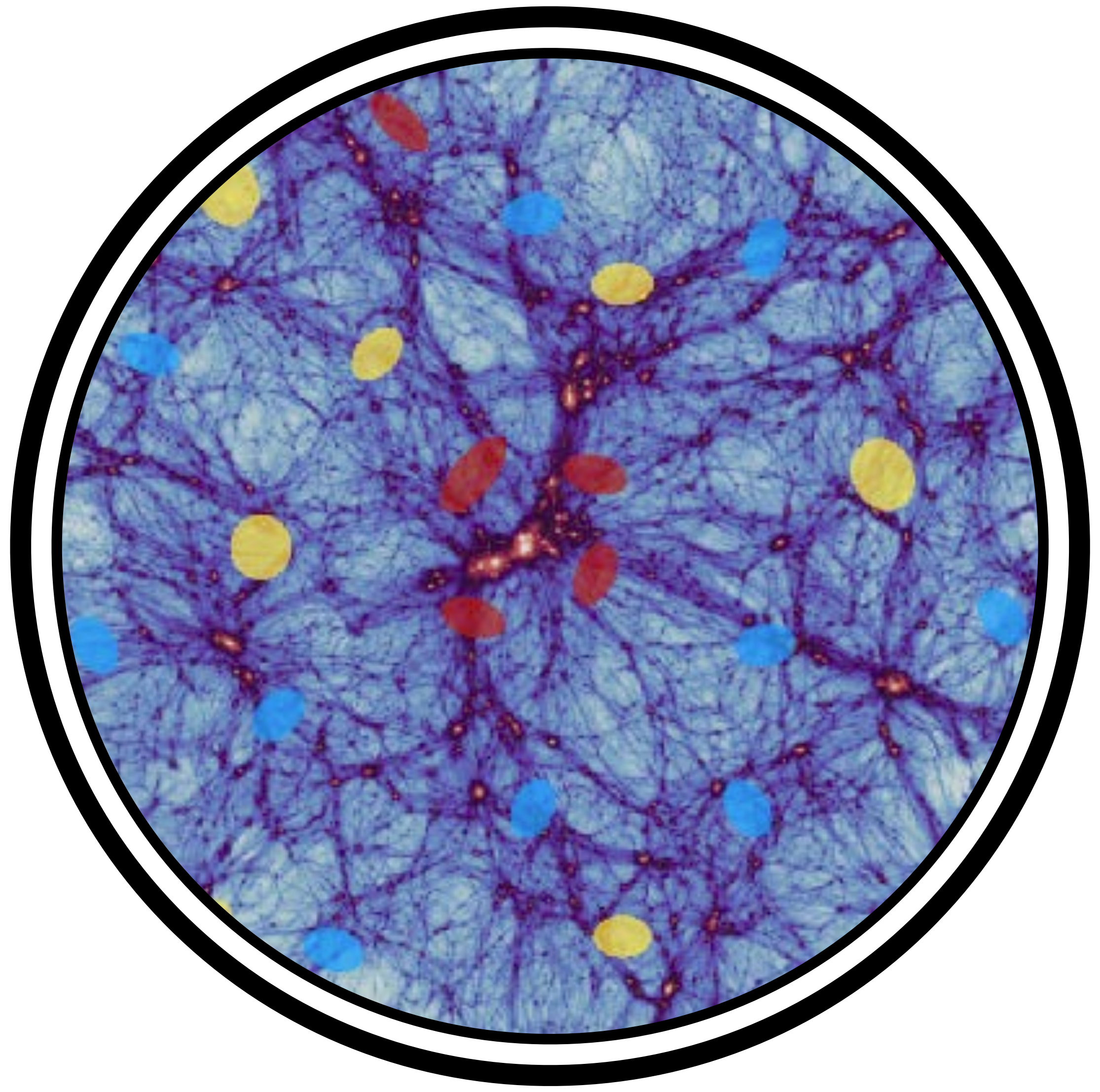
Surveying the Universe

Weak lensing: cosmic shear



Weak lensing: cosmic shear tomography





Aperture mass moments

Second

$$\langle M_{\rm ap}^2\rangle(\theta_{\rm ap}) = \int_{\mathbb{R}_+} \frac{{\rm d}\ell\, \ell}{2\pi} P_{\kappa\kappa}(\ell)\, \hat{u}^2(\theta_{\rm ap}\ell)$$

Third

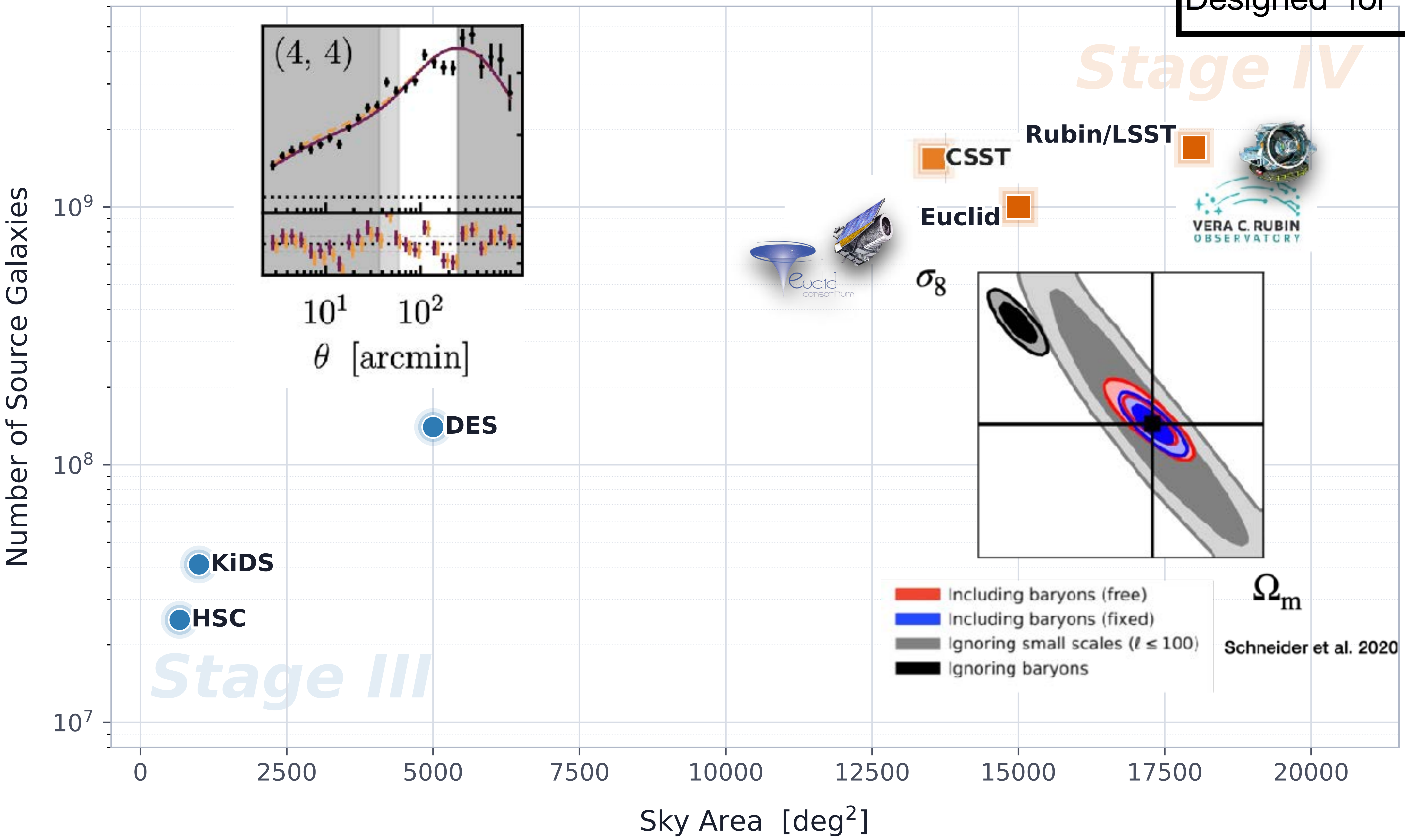
$$\langle M_{\rm ap}^3\rangle(\theta_{\rm ap,1}, \theta_{\rm ap,2}, \theta_{\rm ap,3}) = \int_{\mathbb{R}_+^2} \frac{{\rm d}^2\ell_1}{(2\pi)^2} \int_{\mathbb{R}_+^2} \frac{{\rm d}^2\ell_2}{(2\pi)^2} \times B_{\kappa\kappa\kappa}(\ell_1, \ell_2, \ell_3)\, \hat{u}(\theta_{\rm ap,1}\ell_1)\, \hat{u}(\theta_{\rm ap,2}\ell_2)\, \hat{u}(\theta_{\rm ap,3}\ell_3)$$

Compensated filter $\hat{u}(\alpha) = \frac{\alpha^2}{2} \exp\left(-\frac{\alpha^2}{2}\right)$

Weak lensing surveys

Stage IV wider and deeper

Designed for 1% Dark Energy EoS



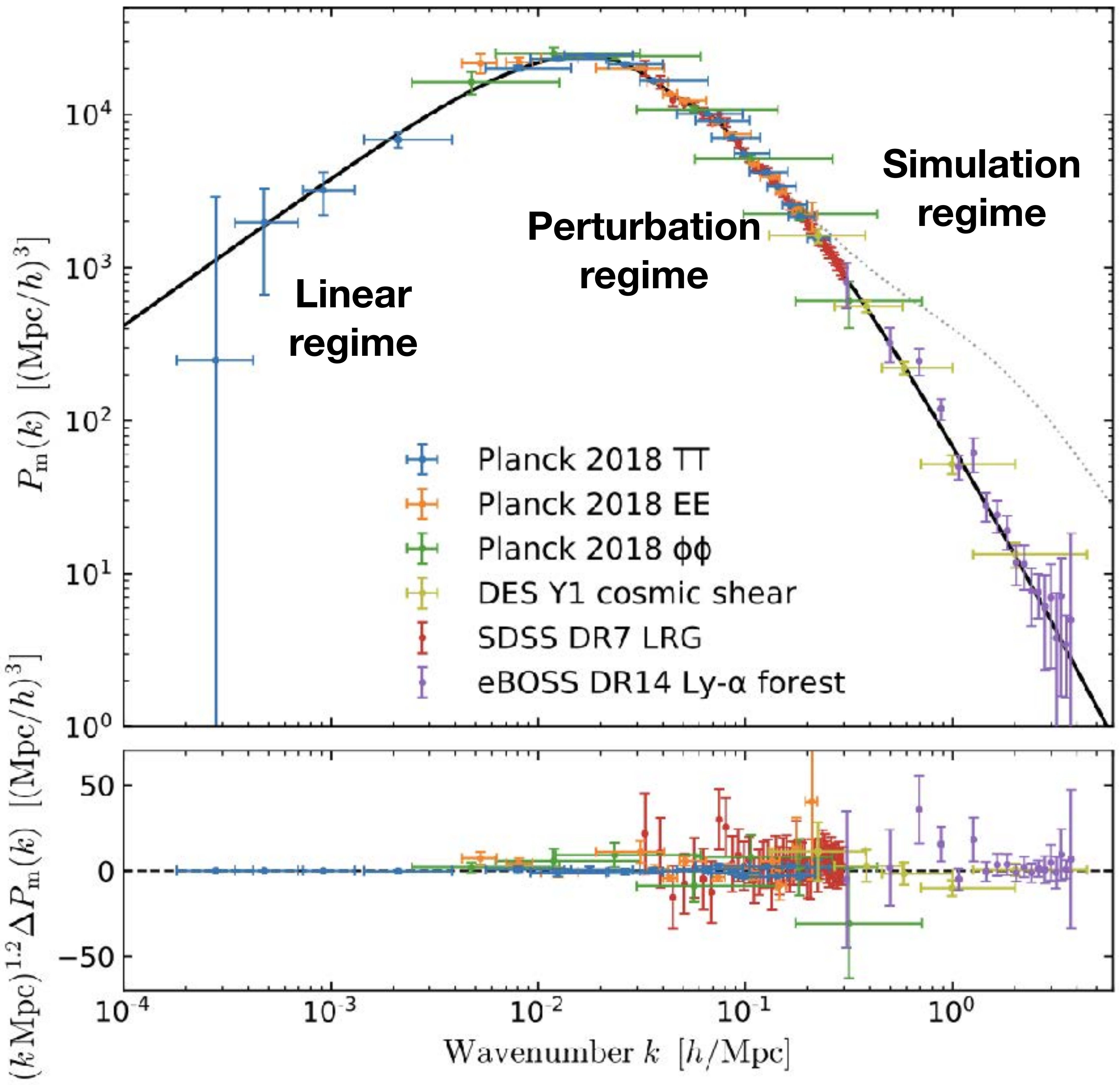
Expected peak sensitivities around $1h\mathrm{Mpc}^{-1} \leq k \leq 7h\mathrm{Mpc}^{-1}$

1% accuracy in $P(k)$ required (Taylor et al., 2018)

Need to deal with baryonic physics

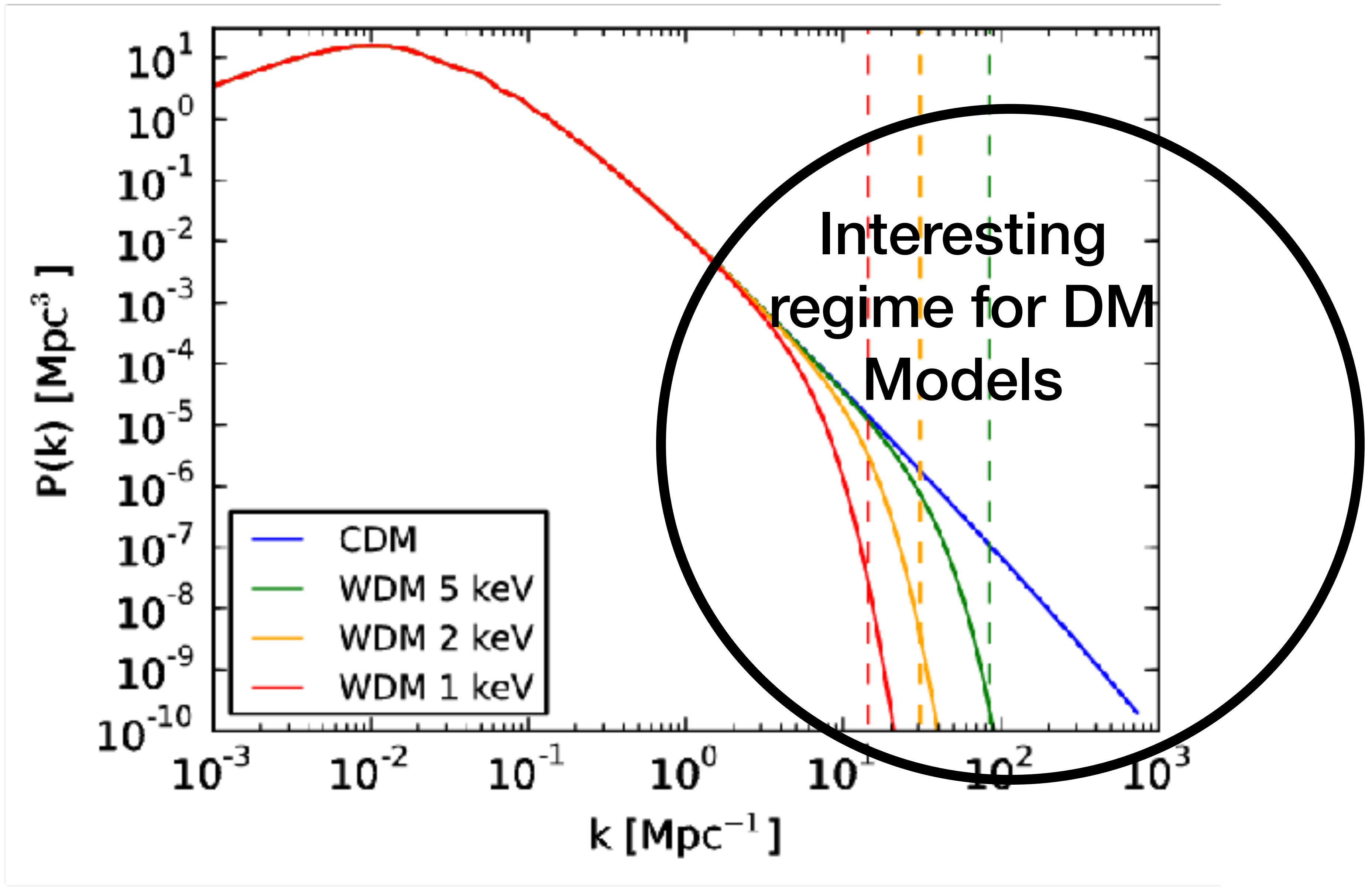
With high-accuracy even at higher-order/field level!

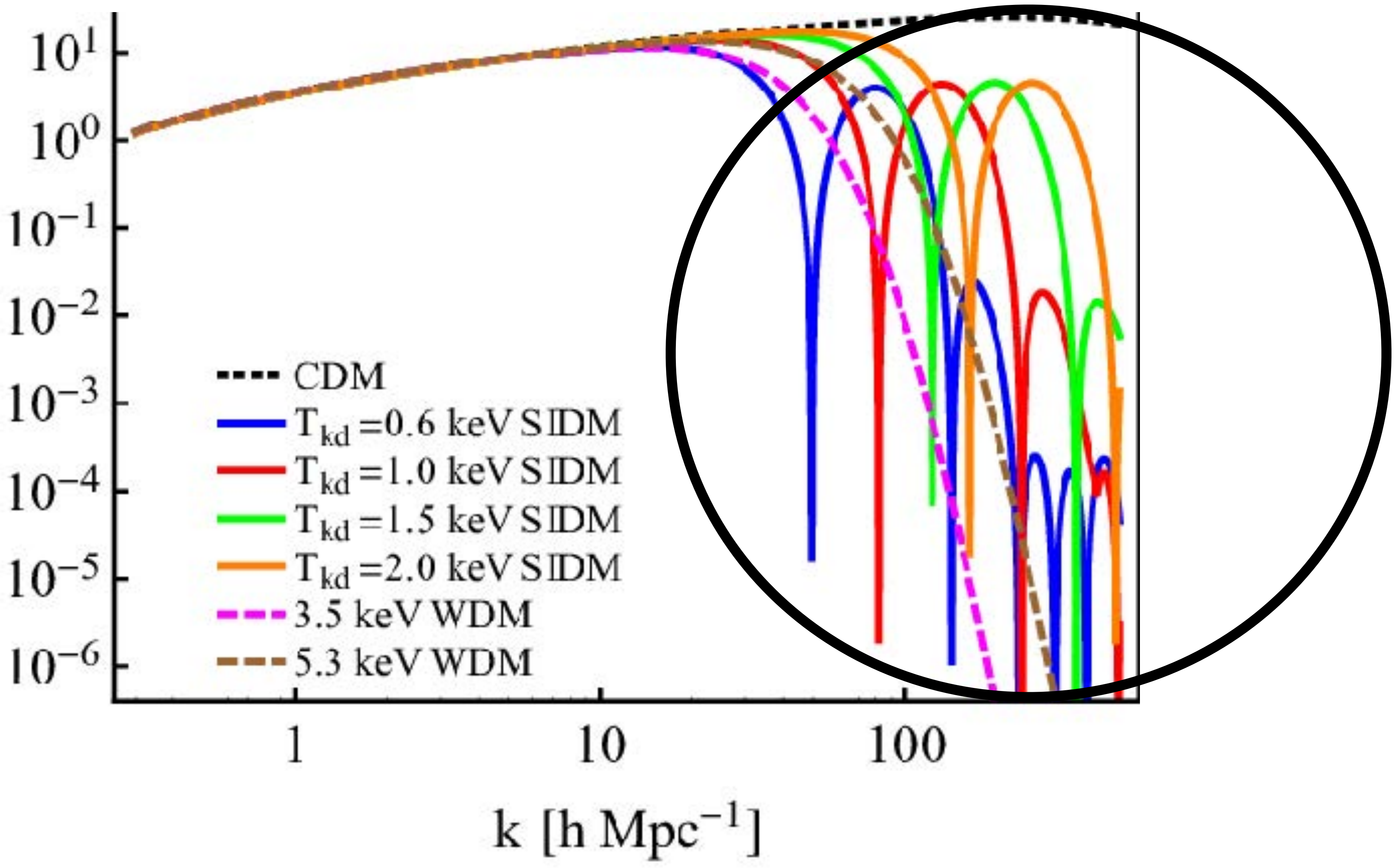
Matter power spectrum



Chabanier+2019

How to discriminate between cold, warm, wave, self-interacting DM, etc. ?

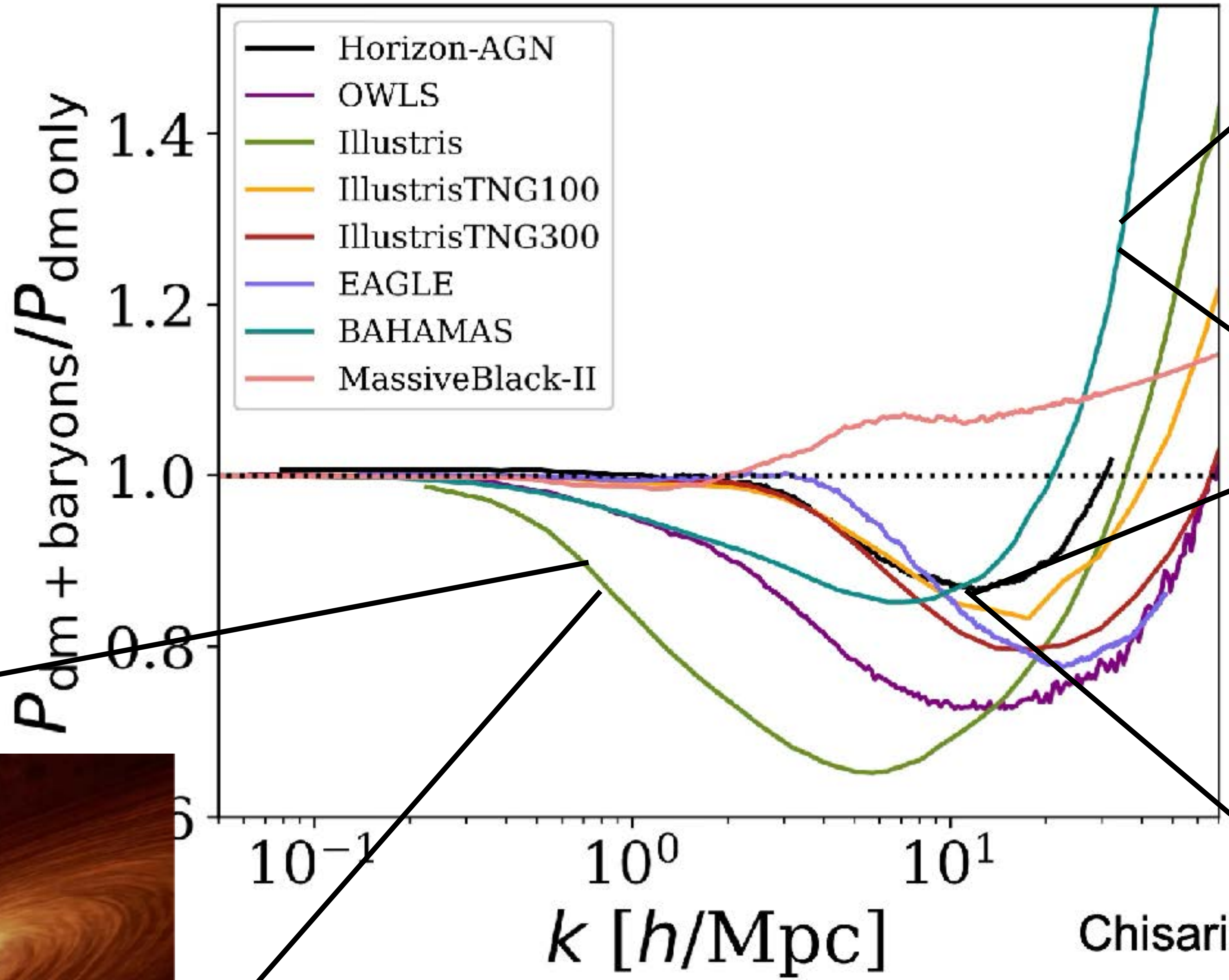


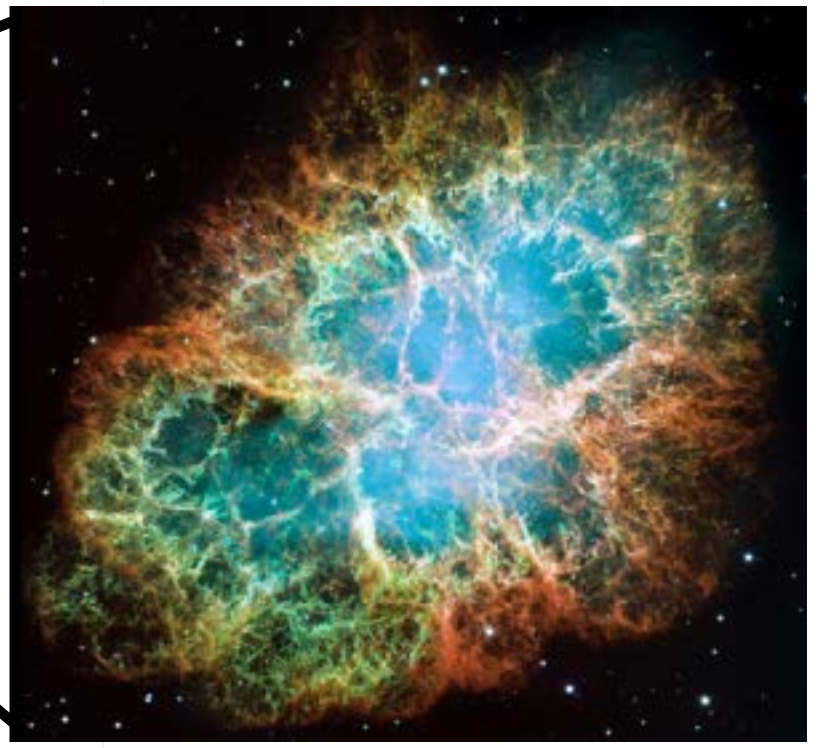


Baryonic effects on the matter power spectrum

Hydrodynamic simulations predict very different P(k)!

Galaxy formation





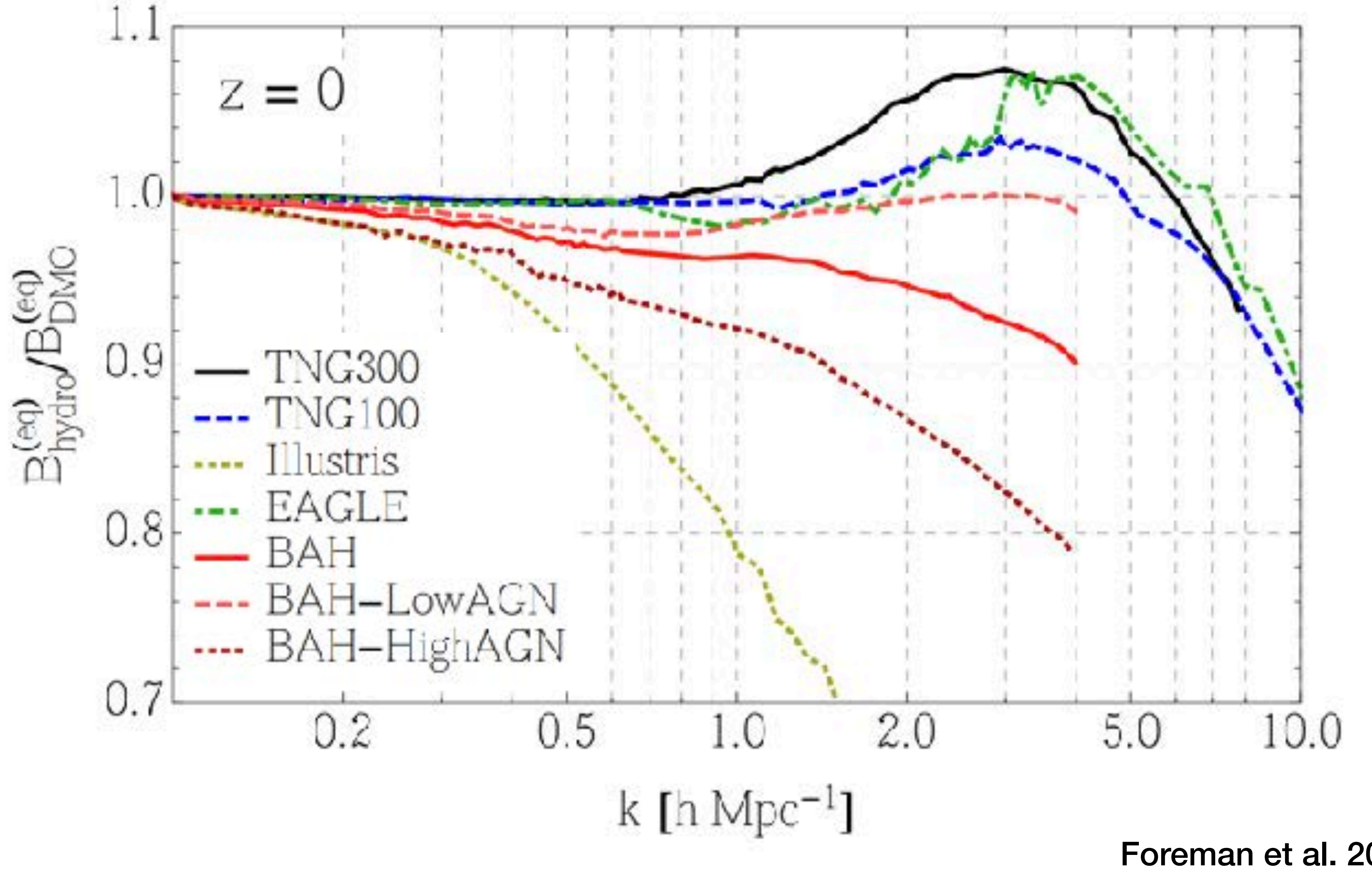
SN feedback

Chisari et al. 2019

AGN feedback

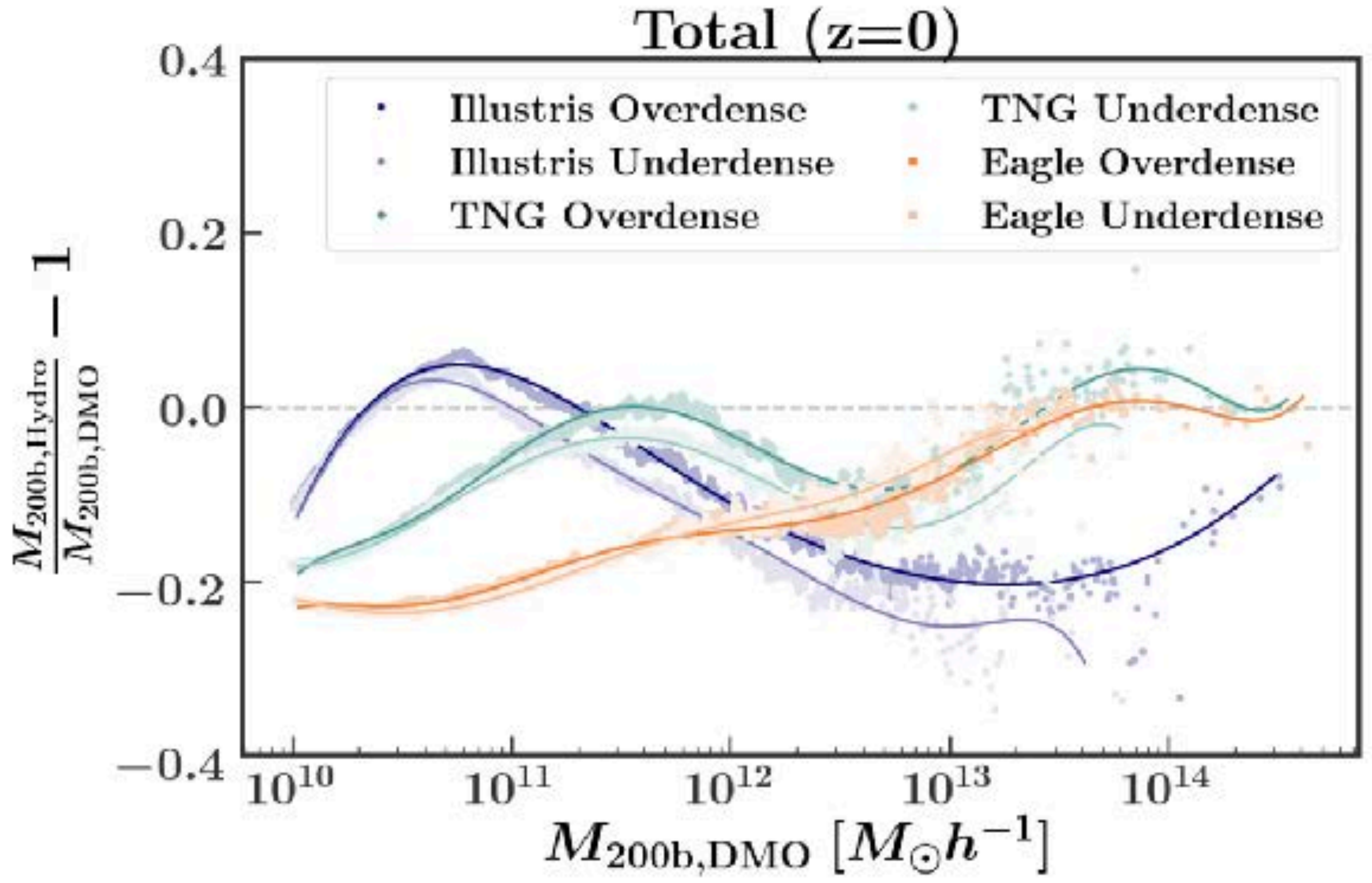
Baryonic impact on LSS statistics

Matter bispectrum



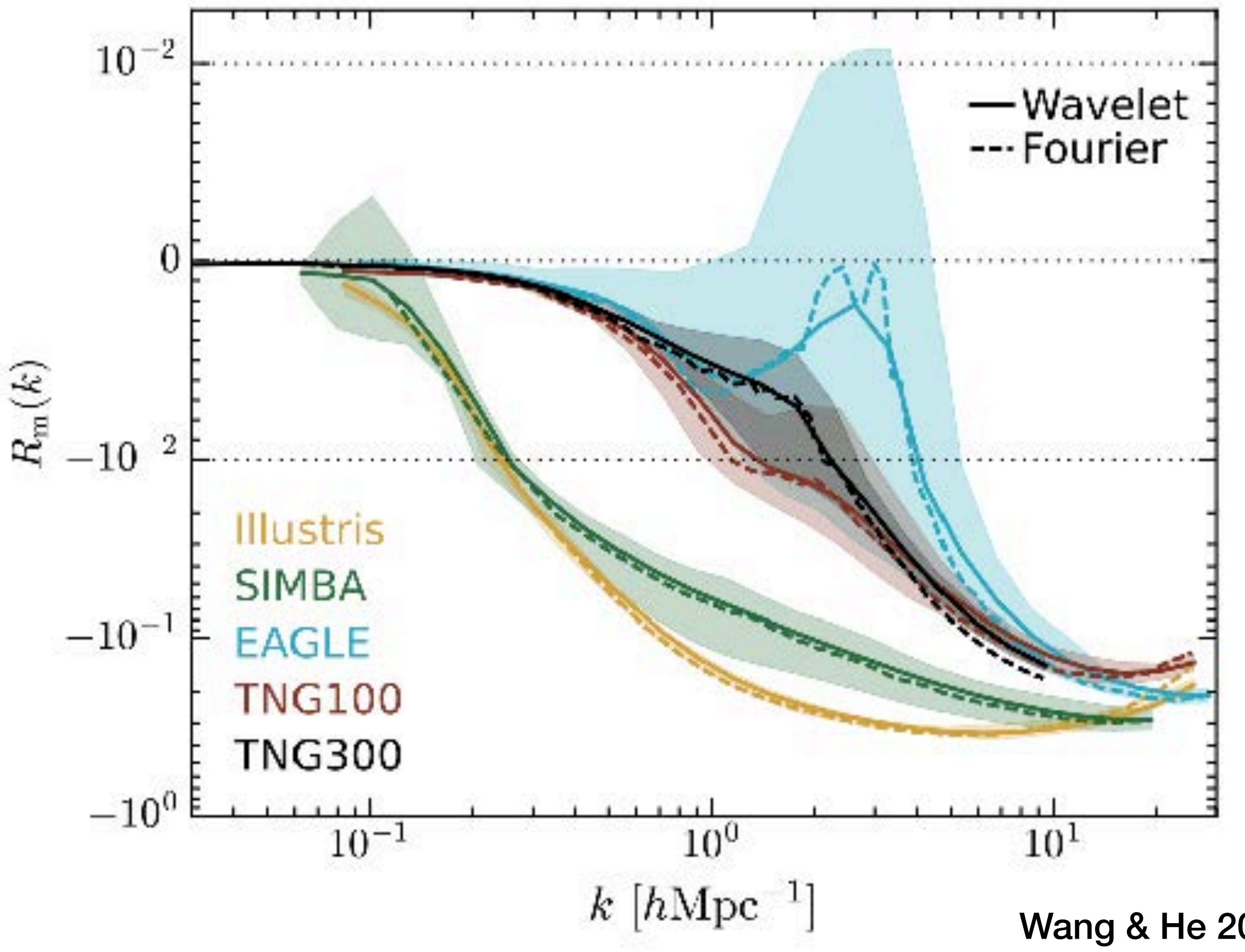
Foreman et al. 2020

Halo mass function



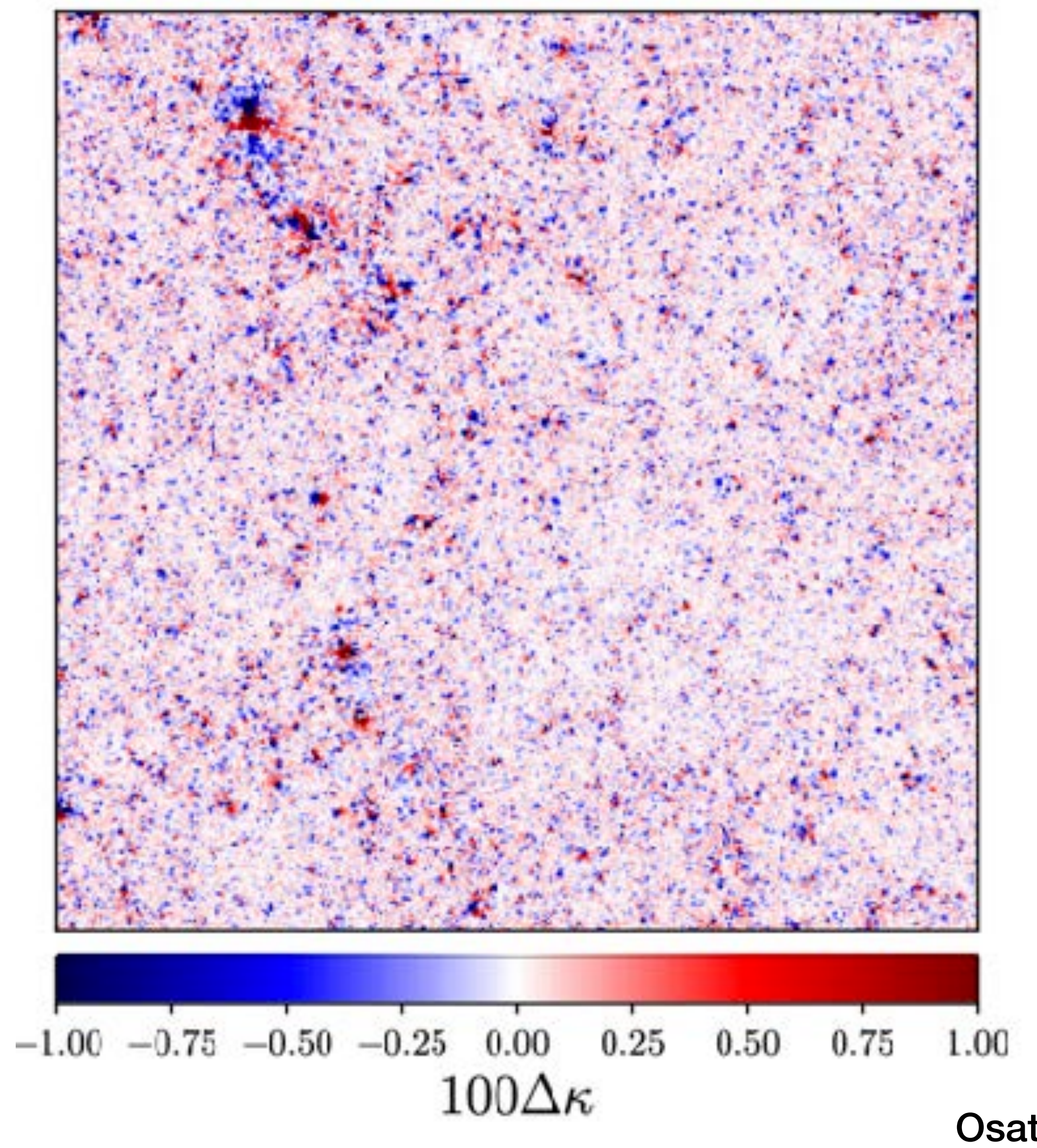
Beltz-Mohrmann & Berlind 2021

Wavelets



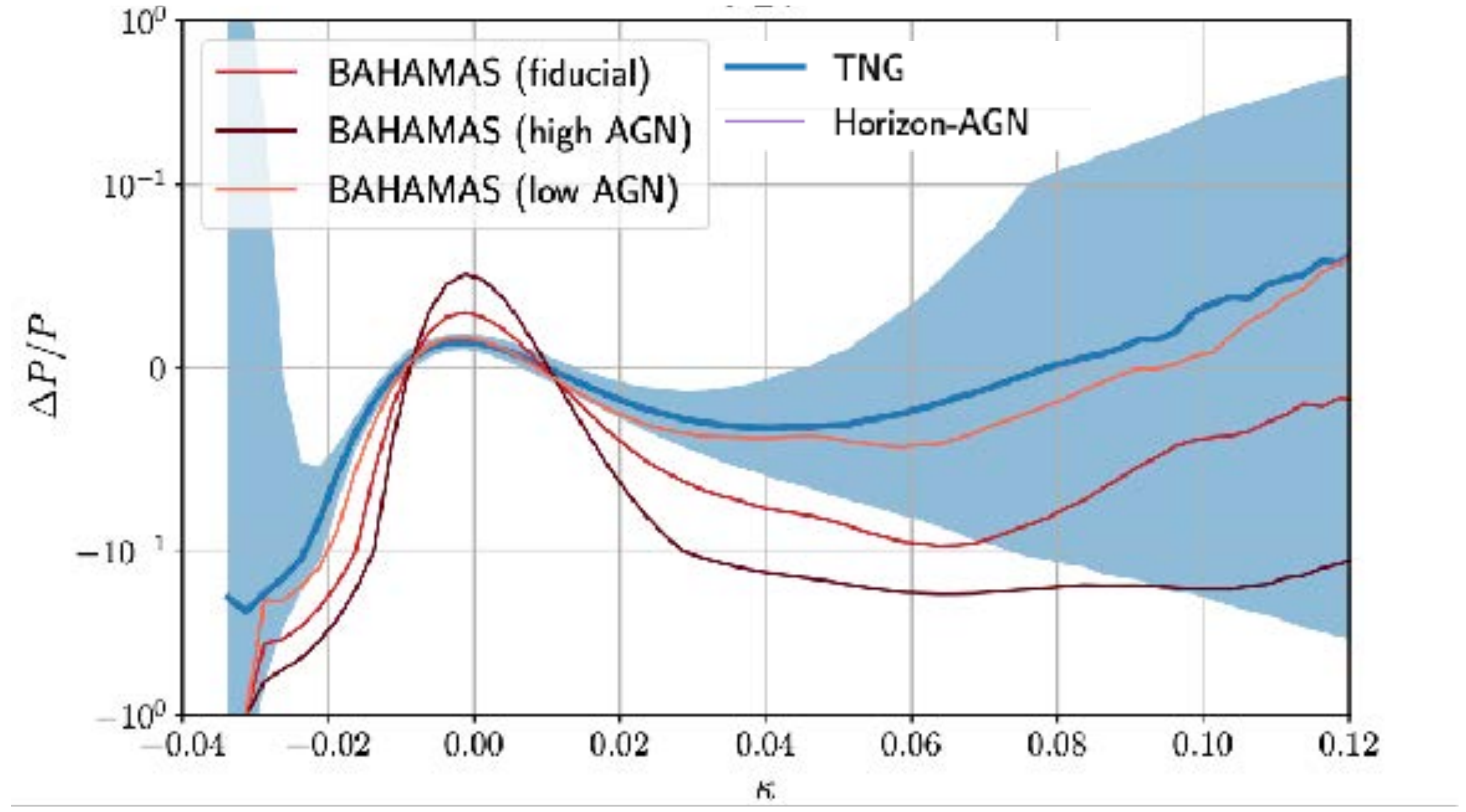
Wang & He 2024

Field level



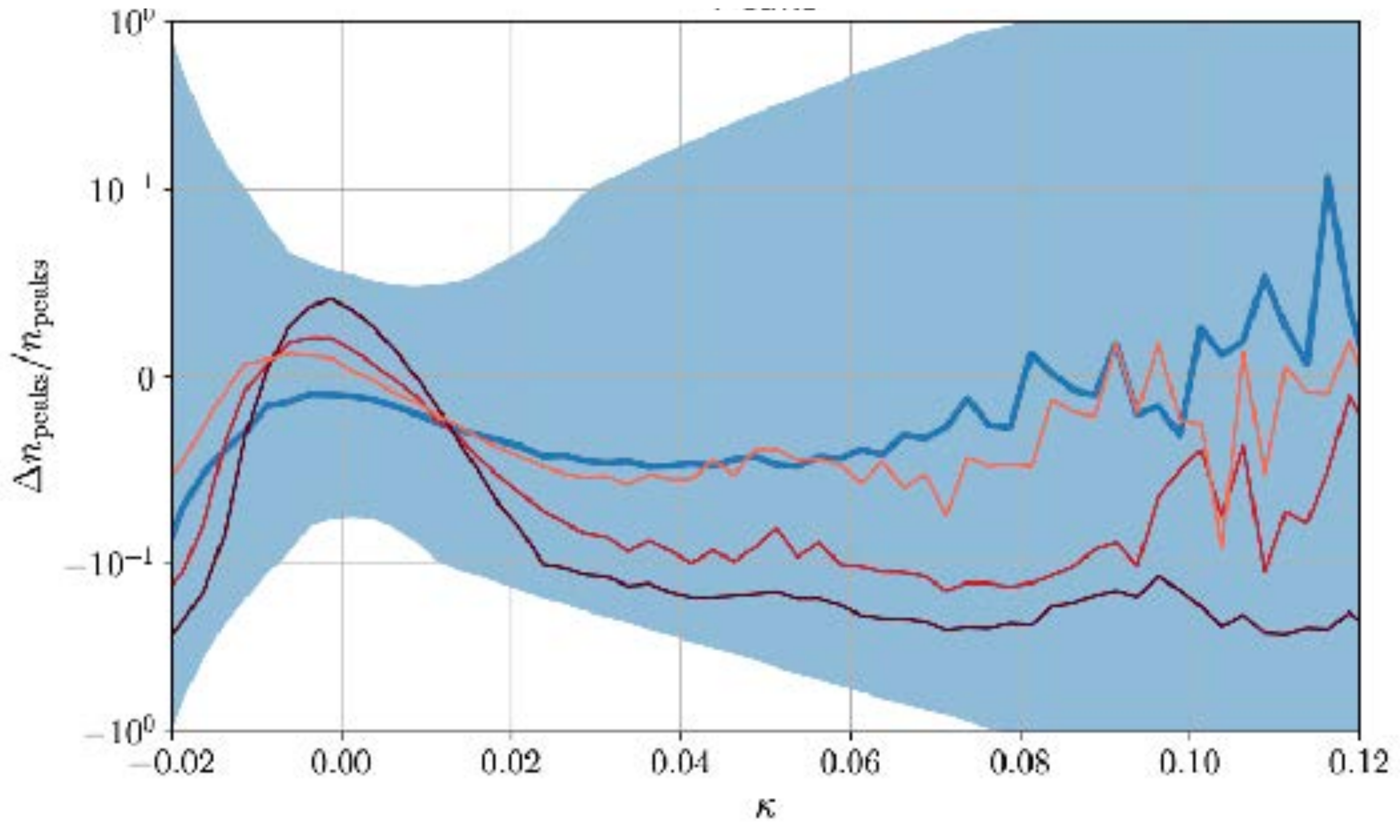
Osato et al. 2021

Convergence PDF



Osato et al. 2021

Convergence Peaks

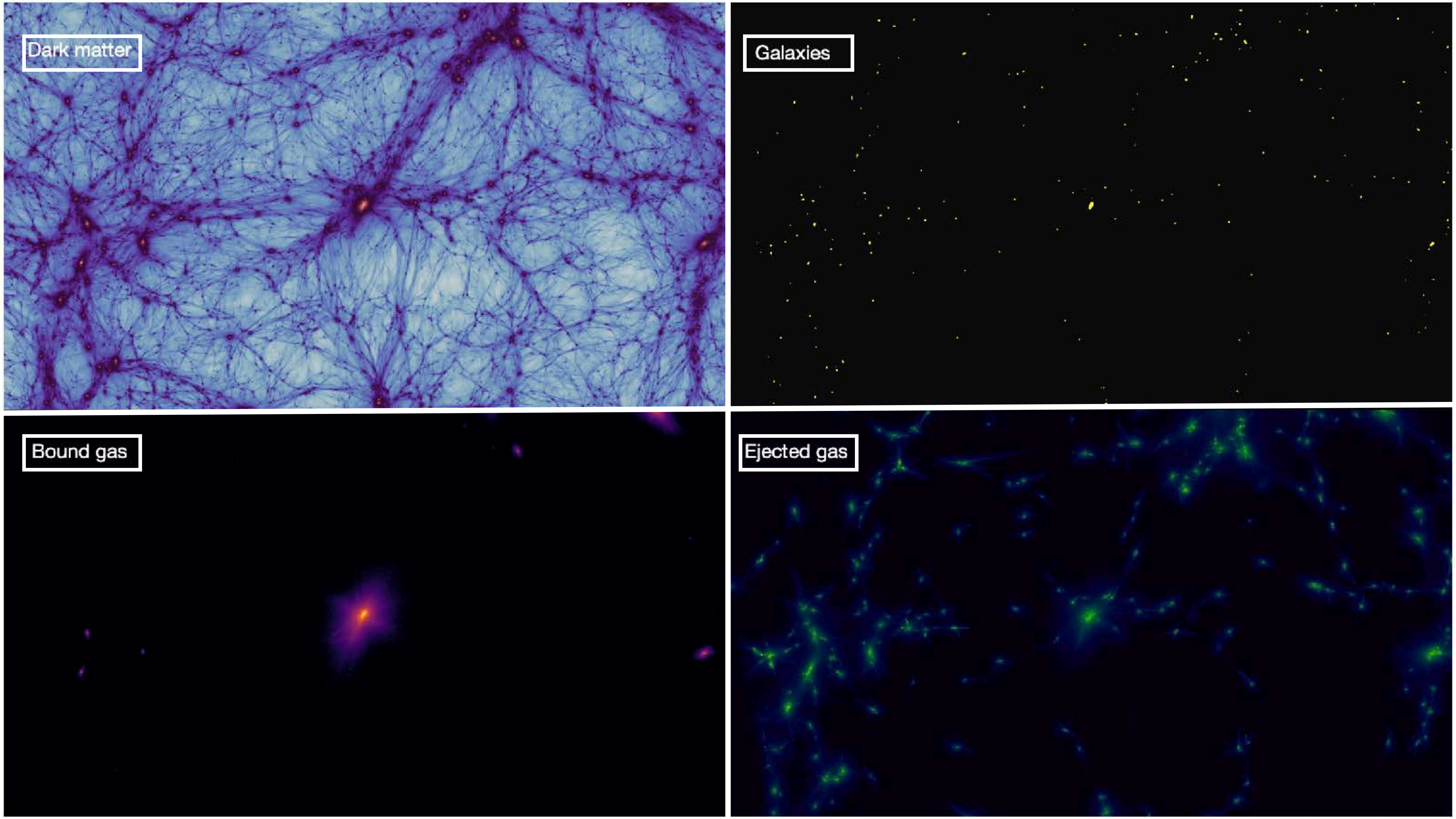


Osato et al. 2021

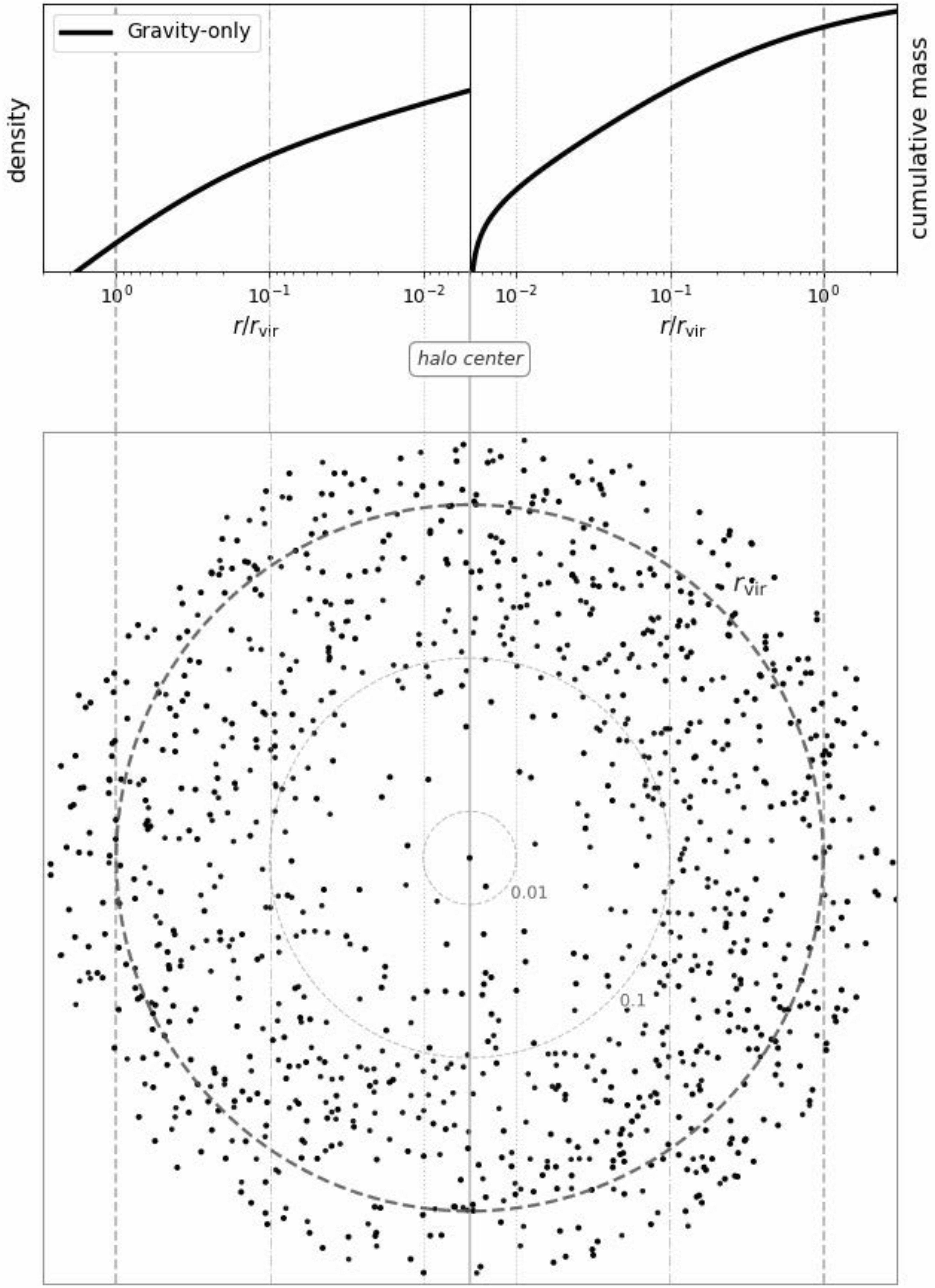
How to model baryons at the field level?

Baryonification

Aricò & Angulo 2024



Baryonification



Baryon correction model

Mass fractions: imposing mass conservation $f_{DM} + f_{gas} + f_{stars} = 1$

Dark Matter

Comic baryon fraction

$$f_{DM} = 1 - \Omega_b/\Omega_m$$

Stars

Abundance Matching

$$f_{stars} = \epsilon \left(\frac{M_1}{M_{200}} \right) 10^{g(\log_{10}(M_{200}/M_1)) - g(0)}$$

Gas

Bound in halos

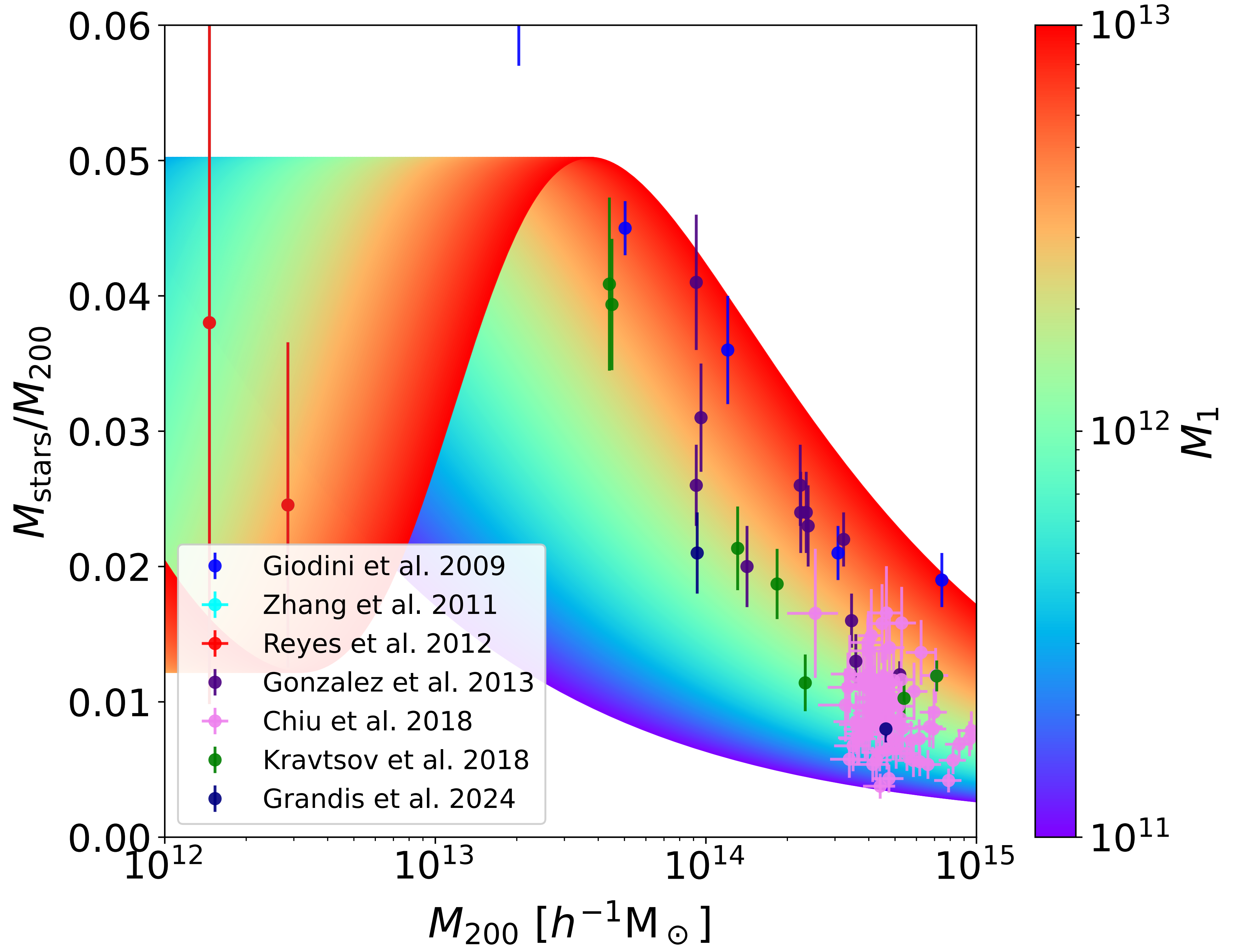
$$f_{gas} = \frac{\Omega_b/\Omega_m - f_{stars}}{1 + (M_c/M_{200})^{\beta}}$$

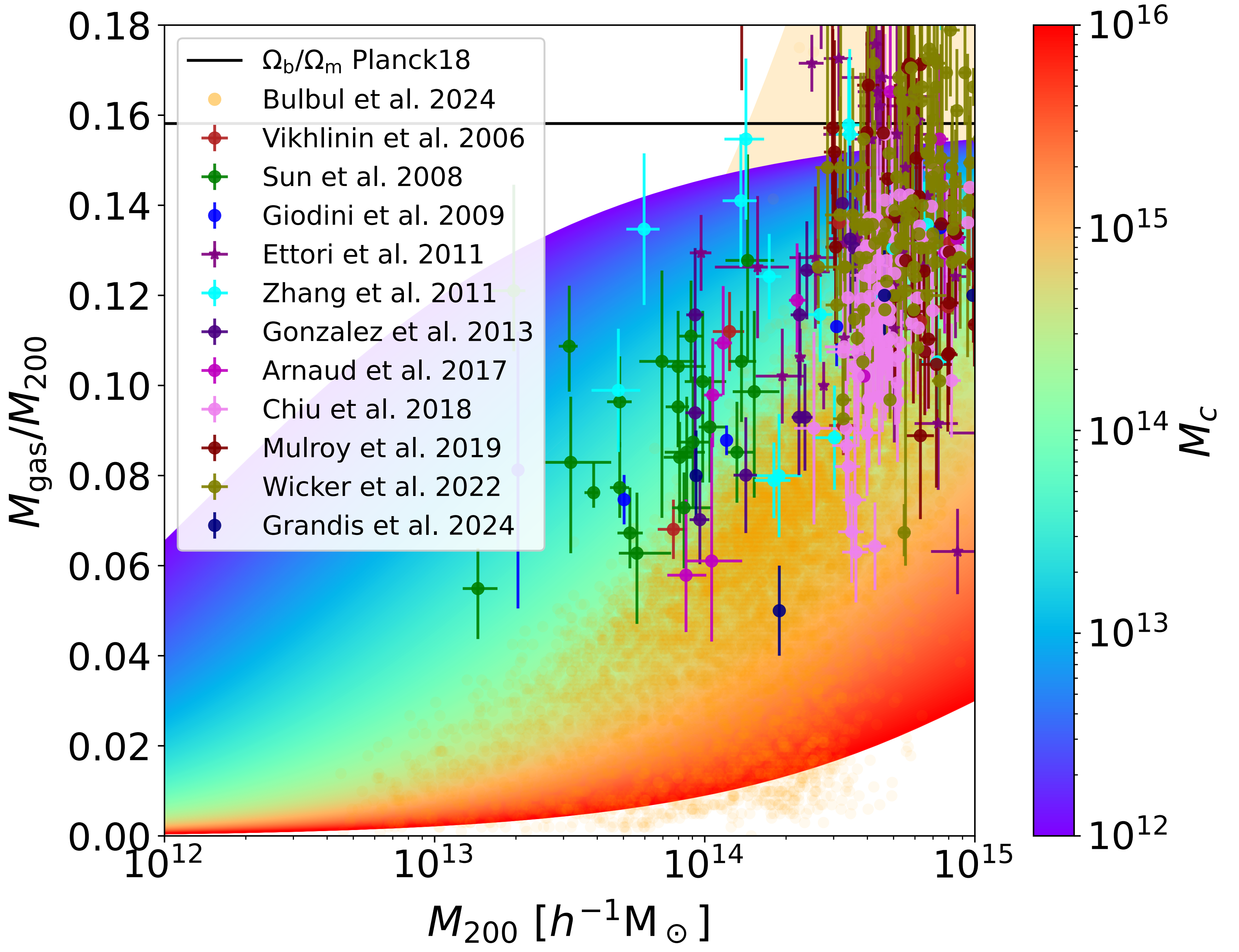
Ejected

$$f_{gas,ej} = 1 - (f_{DM} + f_{gas,bo} + f_{stars})$$

Aricò et al. 2020

M_c, β, M_1 free parameters

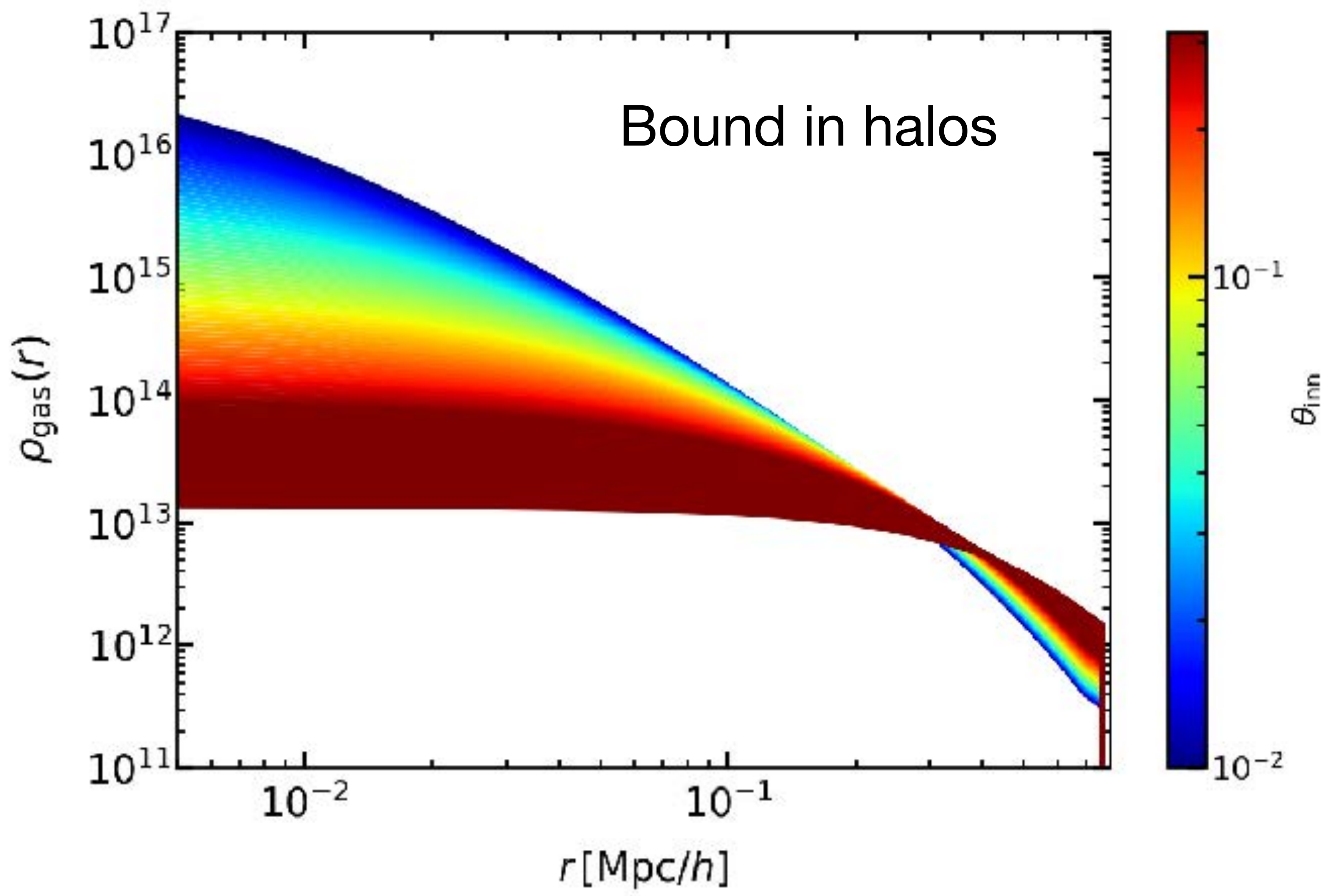


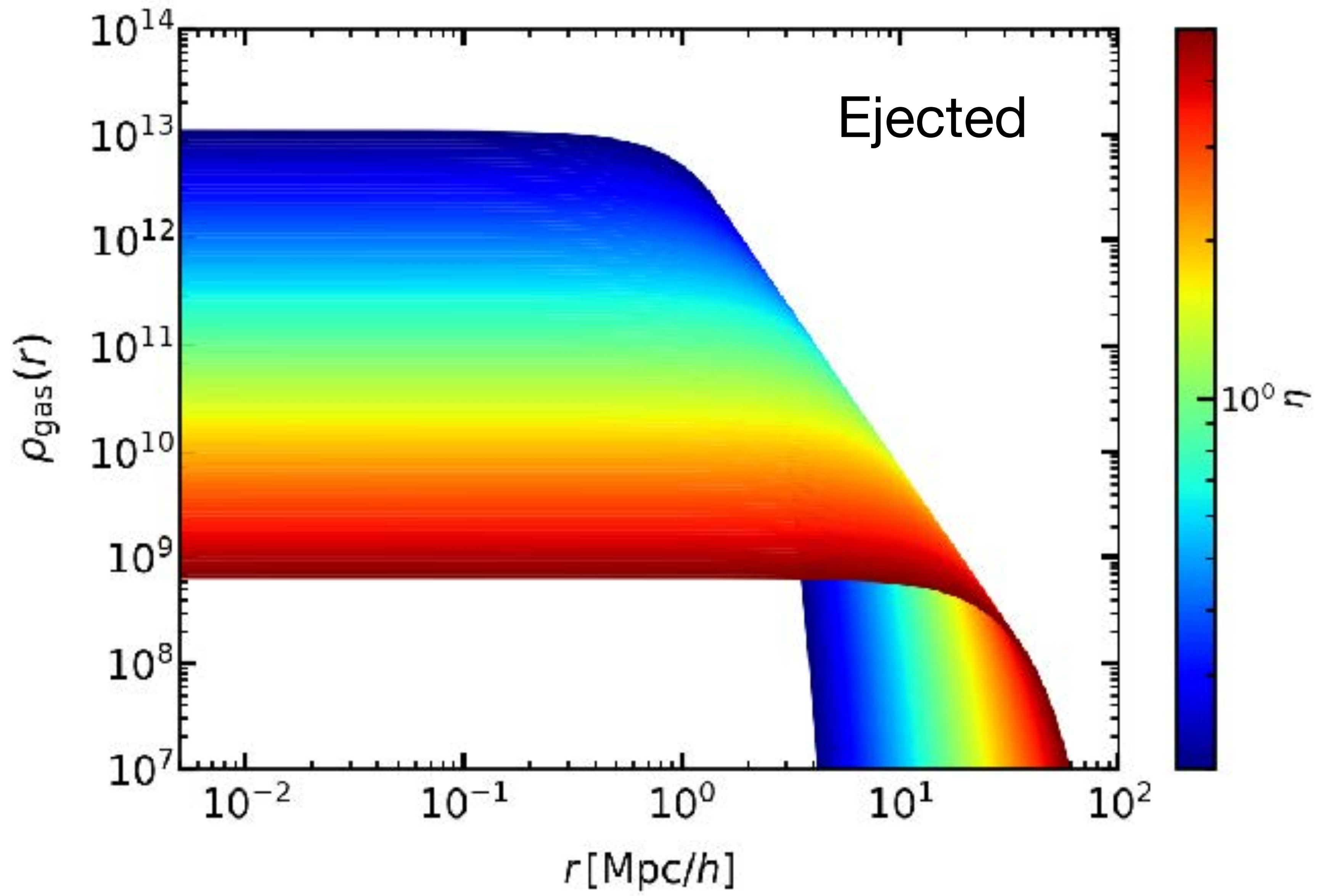


Baryon correction model

Density profiles (imposing continuity)

Dark Matter	NFW + quasi adiabatic relaxation (baryonic back-reaction)
Stars	Power Law + cut-off
Gas	Bound in halos $\rho_{\mathrm{gas,bo}} \propto \frac{1}{(1 + r/r_{\mathrm{inn}})^{\beta_{\mathrm{inn}}}(1 + (r/r_{\mathrm{out}})^2)^2}$ Ejected from halos $\rho_{\mathrm{EG}} = \frac{M_{200}}{(2\pi r_{\mathrm{ej}}^2)^{3/2}} \exp\left(-\frac{1}{2}\left(\frac{r}{r_{\mathrm{ej}}}\right)^2\right)$ $r_{\mathrm{ej}} \propto \eta\, r_{\mathrm{escape}}$

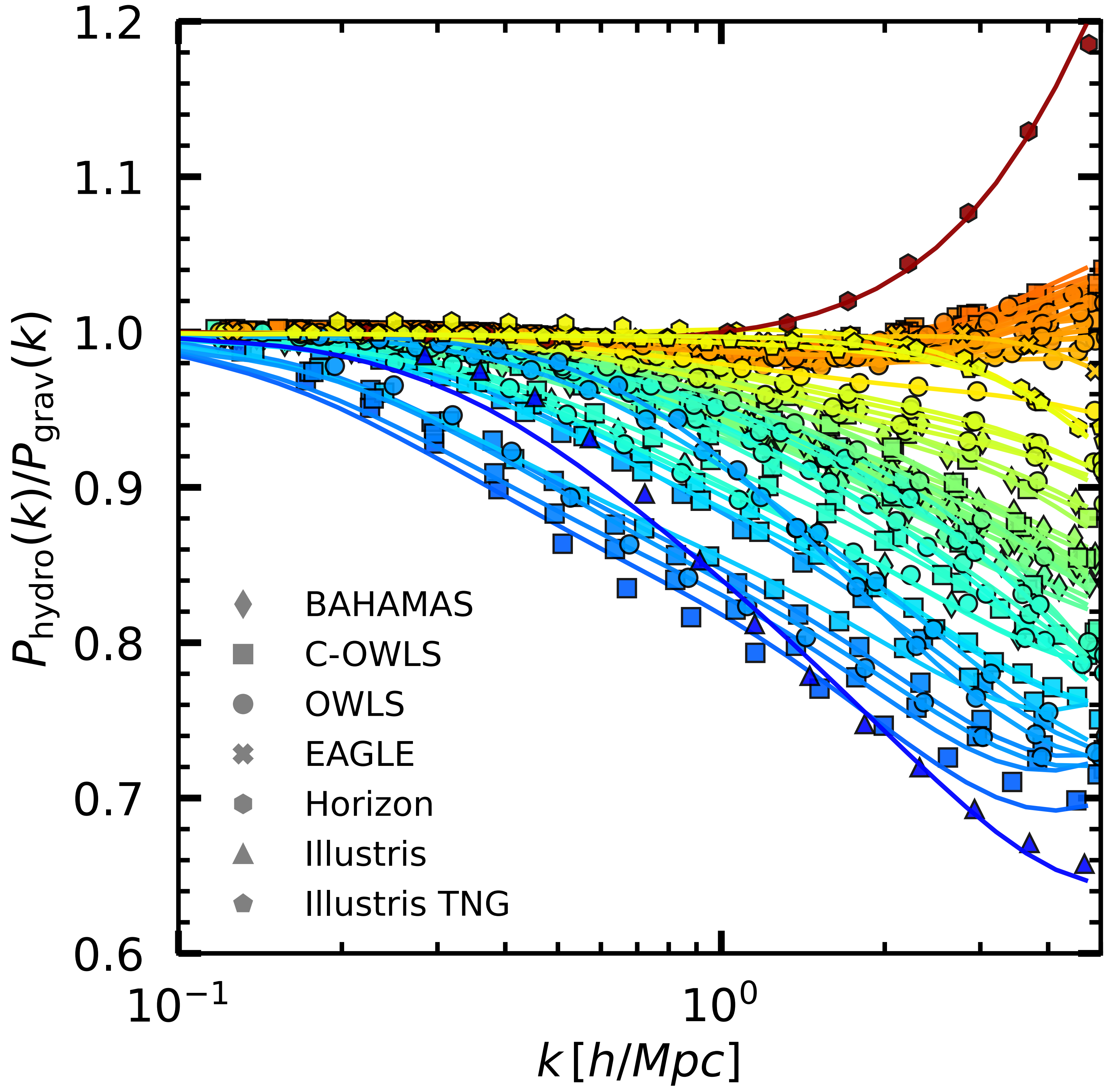


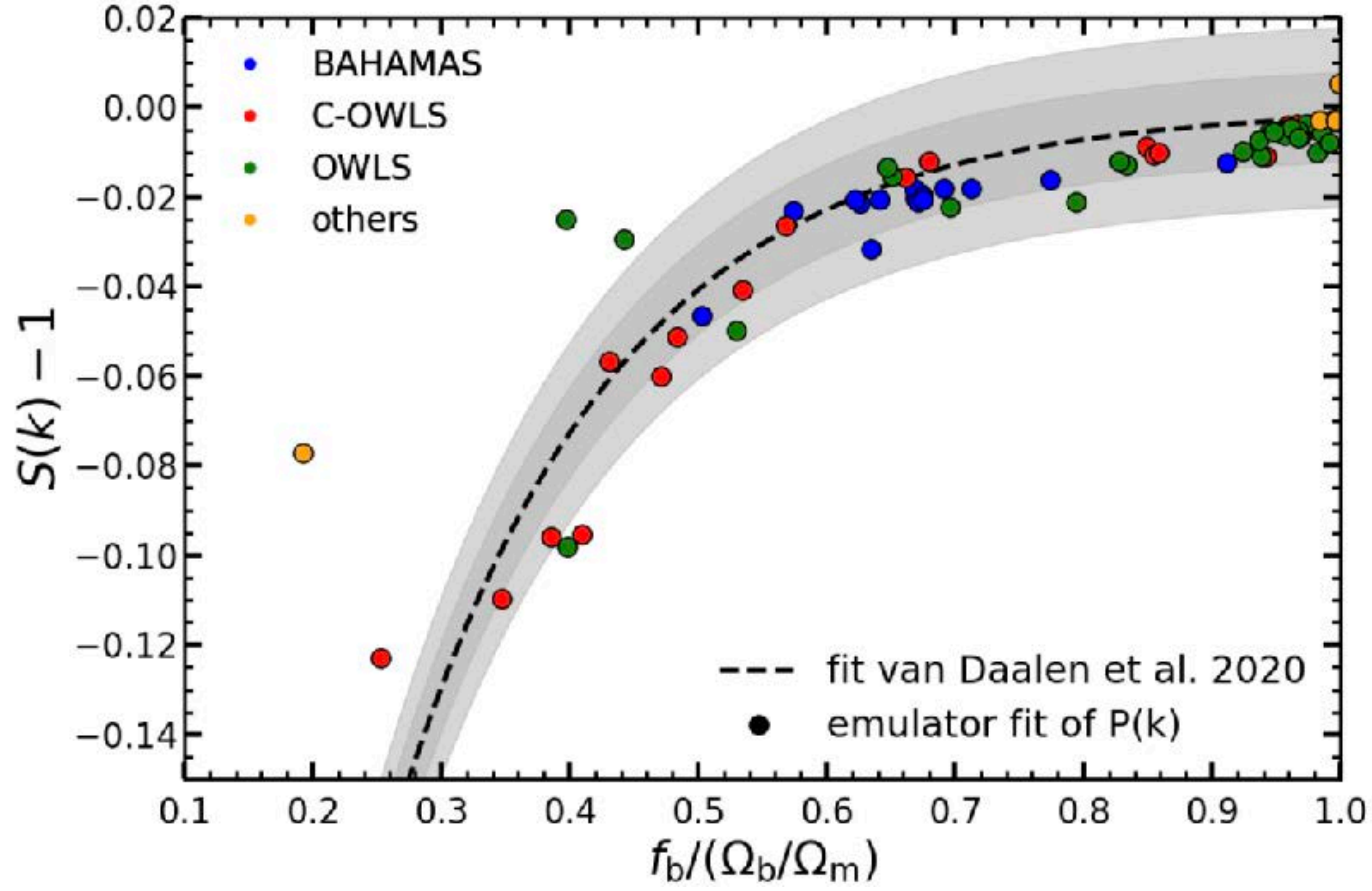


Aricò et al. 2021

$r_{\mathrm{inn}}, r_{\mathrm{out}}, \eta, \beta_{\mathrm{inn}}$ free parameters

Validation with hydrodynamical simulations





Adapted from Aricò+2021b

Fit of 74 different hydrodynamical simulations;
1% accurate P(k)

Predictions of the baryon fractions in halos
in agreement with hydro sims

Baryonification extended to Sunyaev-Zel'dovich

Pressure profiles

polytropic EoS

$$P_{\rm BG}(r) = P_0 \cdot \rho_{\rm BG}(r)^{\Gamma}$$

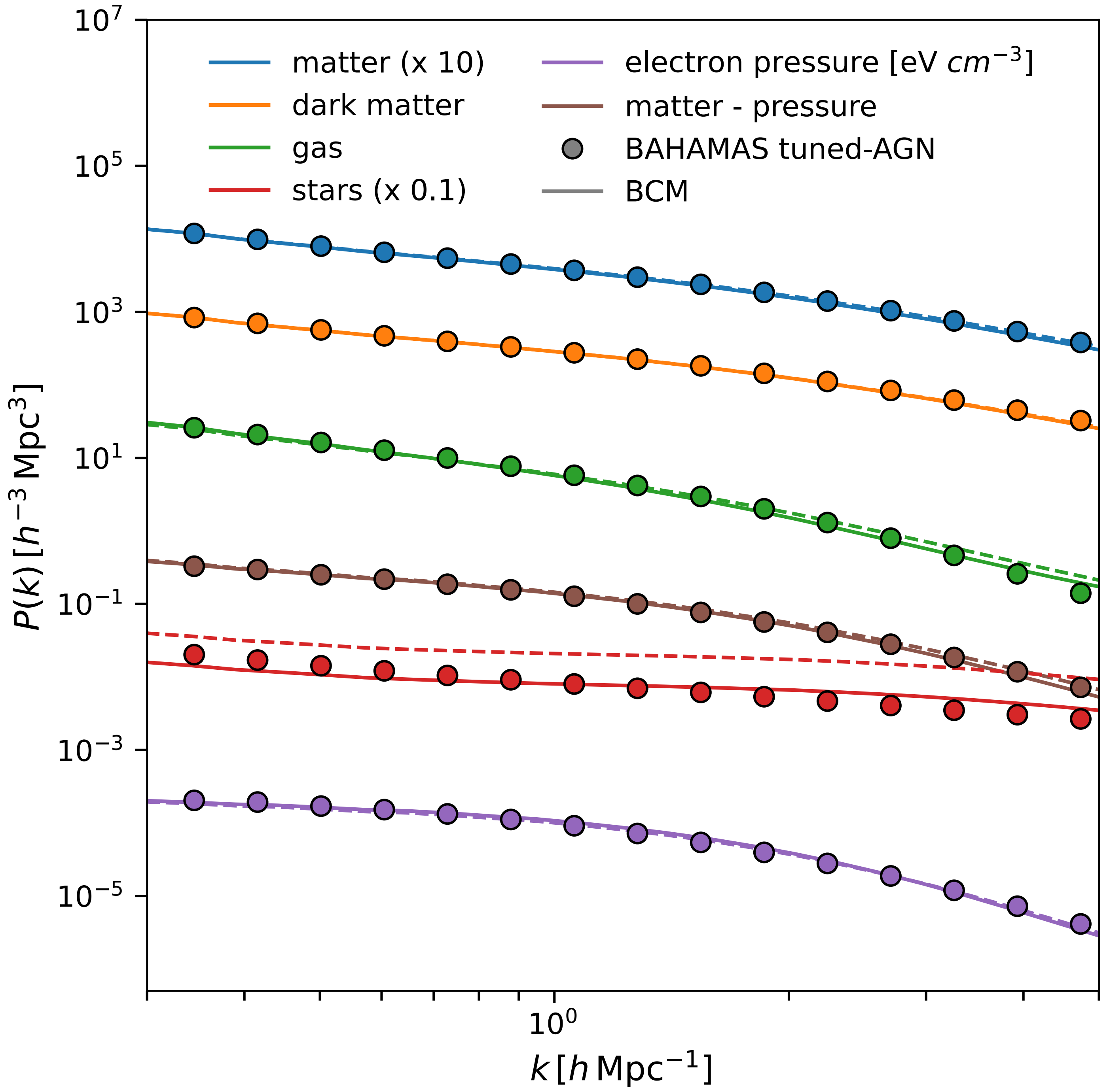
Compton weight

given to each particle

$$\Upsilon_i = \frac{\sigma_{\rm T} k_{\rm B} T_i \, m_i}{\mu_{\rm e} m_{\rm p} m_{\rm e} c^2}$$

Just 2 extra free parameters

3D power spectra

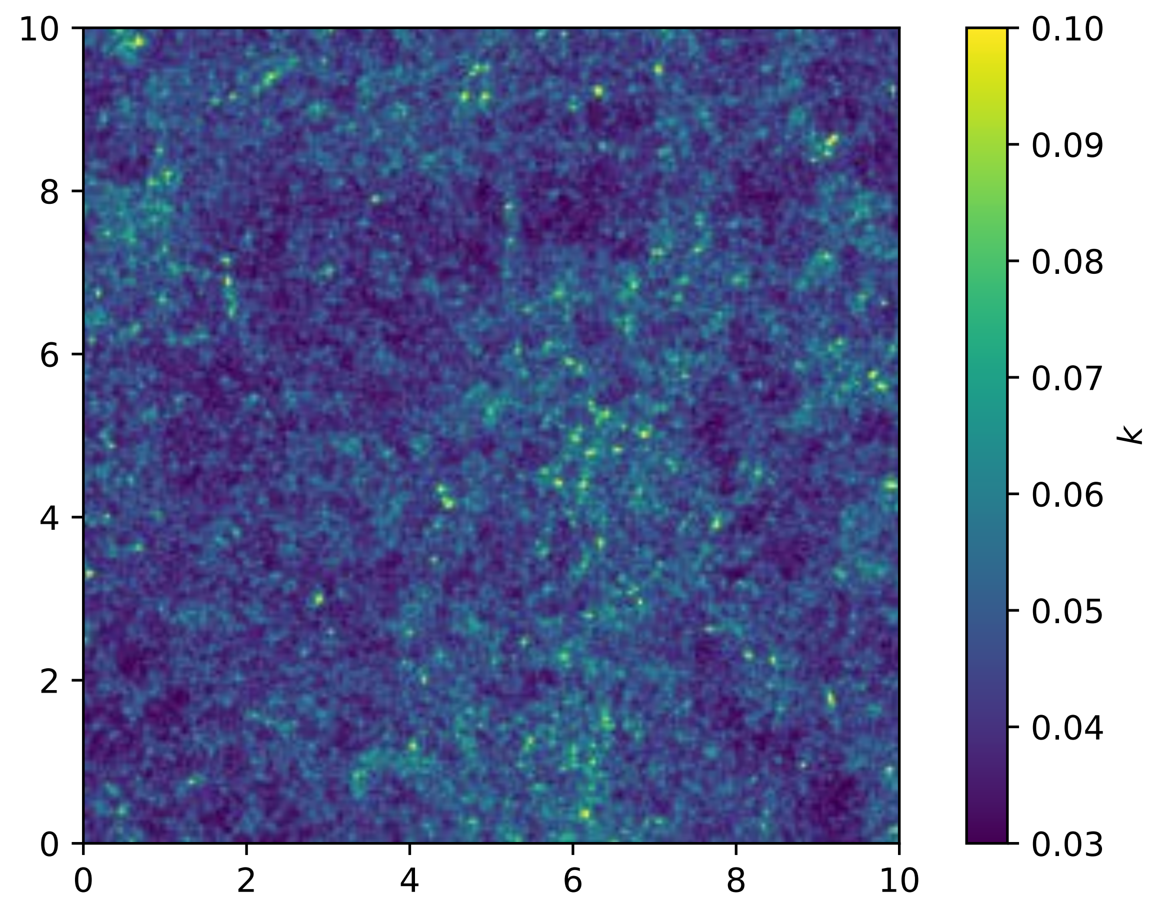


Matter, gas, dark matter

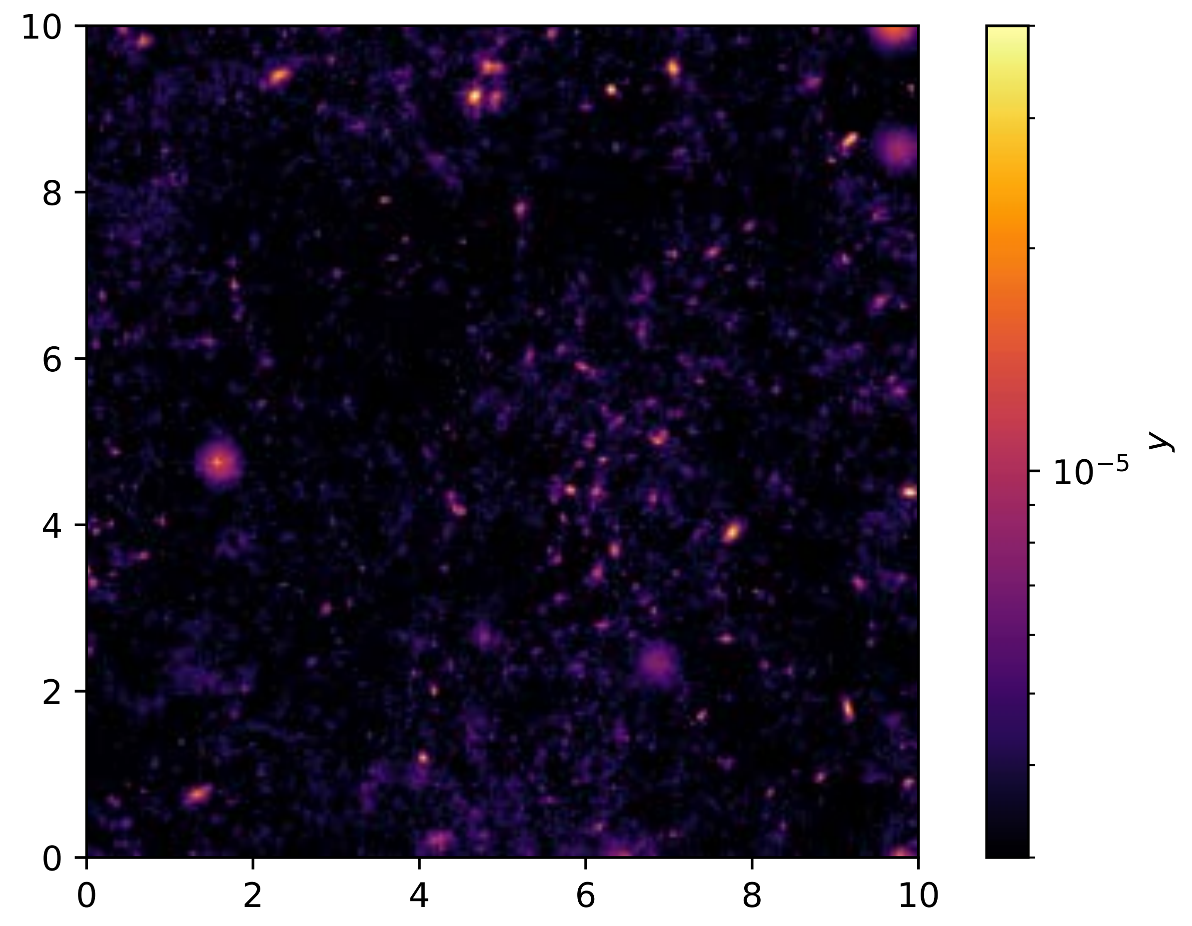
accurately reproduced

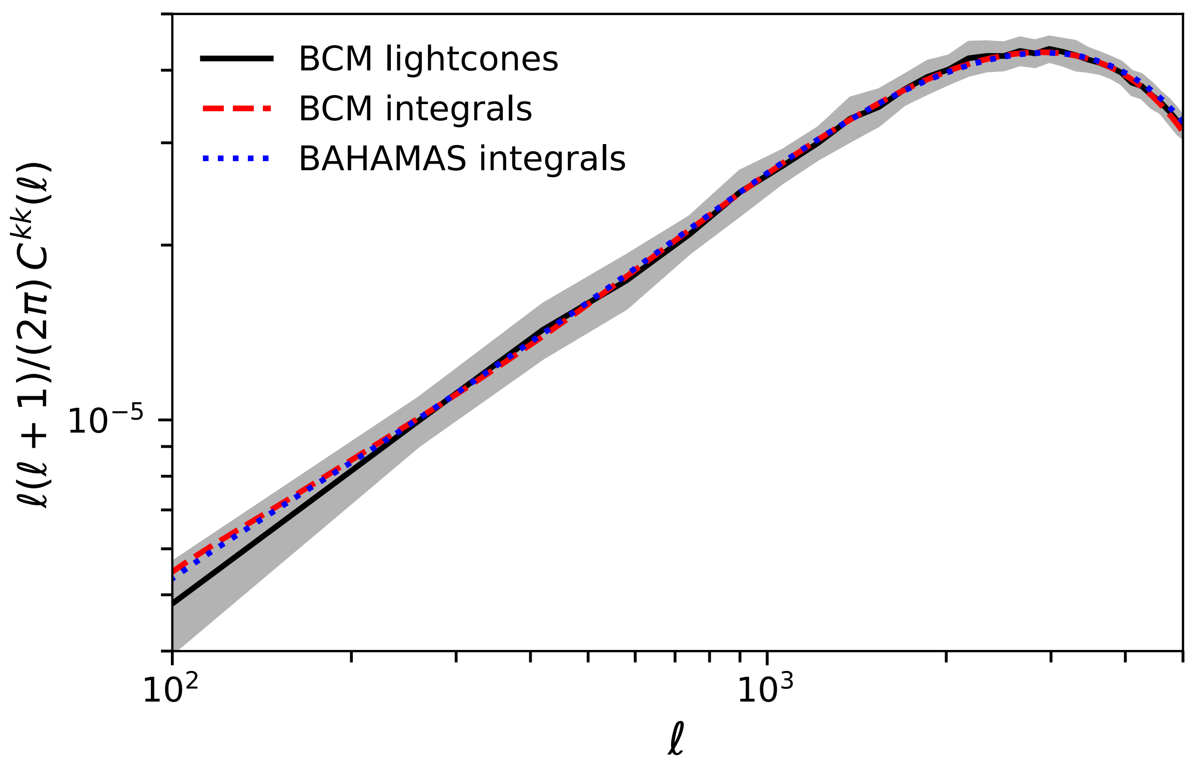
in BAHAMAS

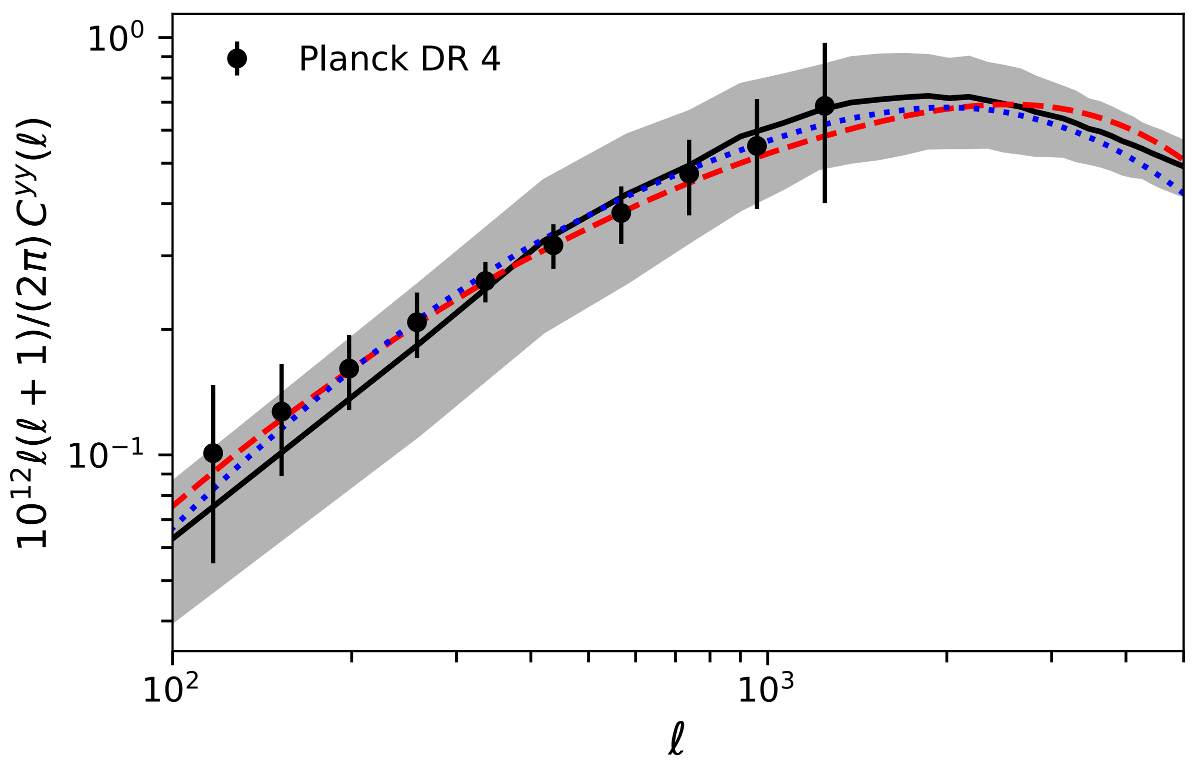
Convergence



Thermal SZ



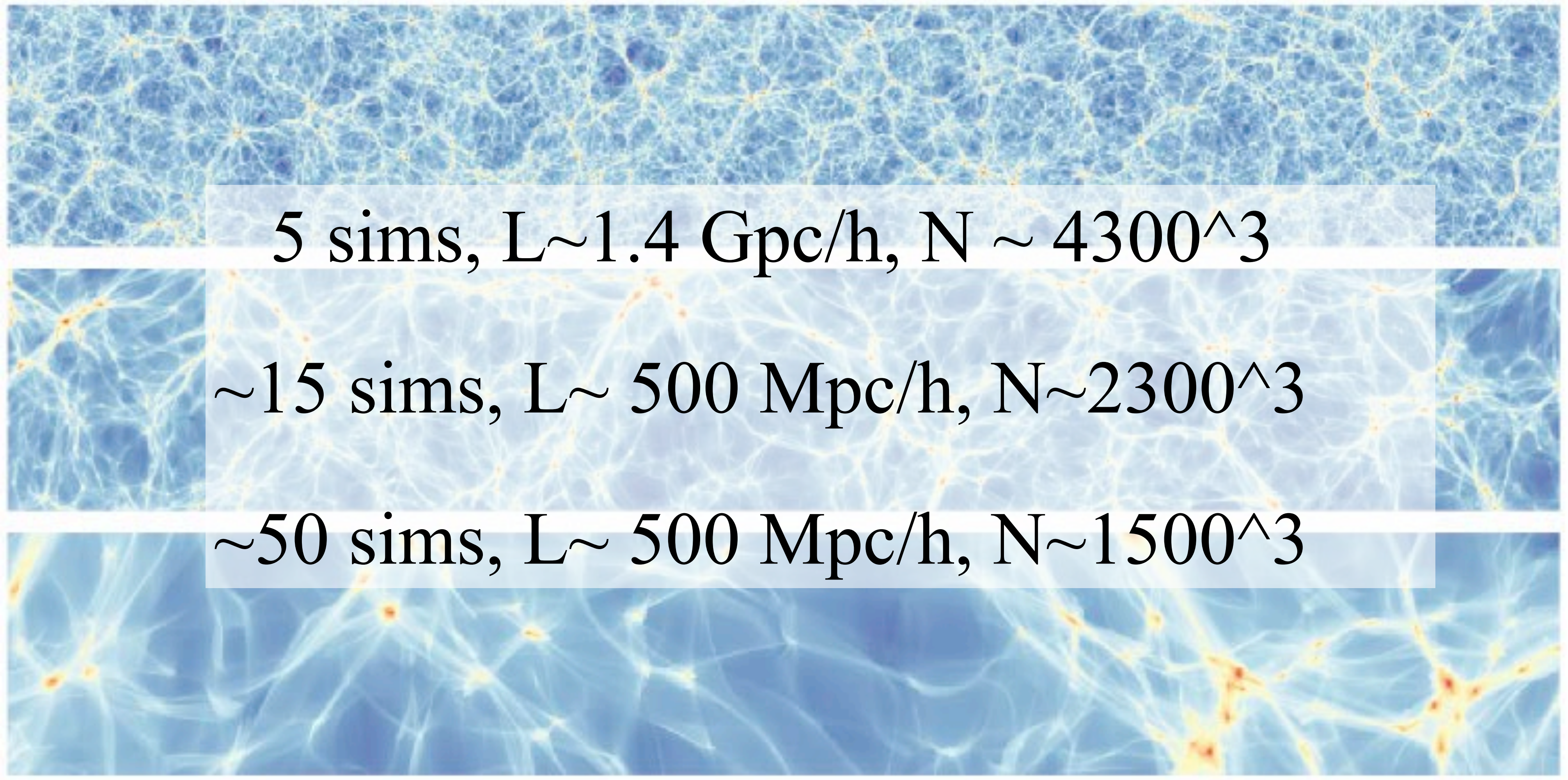




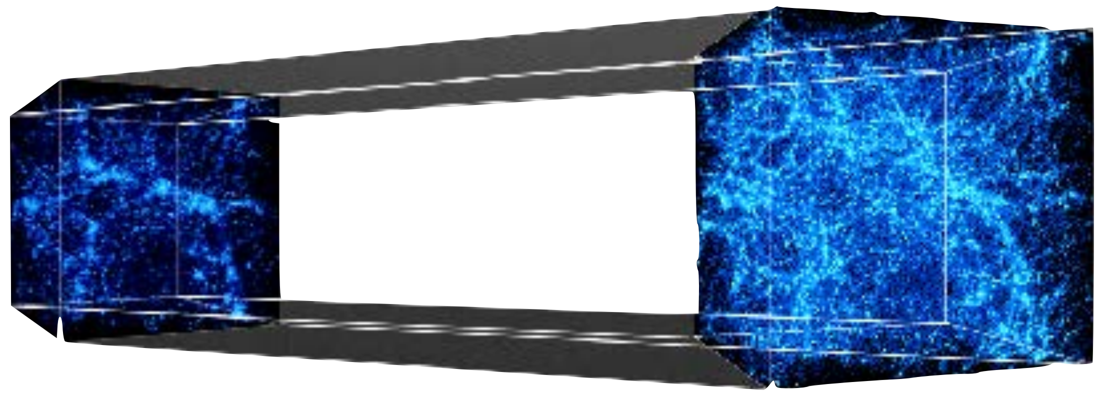
Aricò & Angulo 2024

Accurate convergence, tSZ, and cross

Bacco Simulation Project



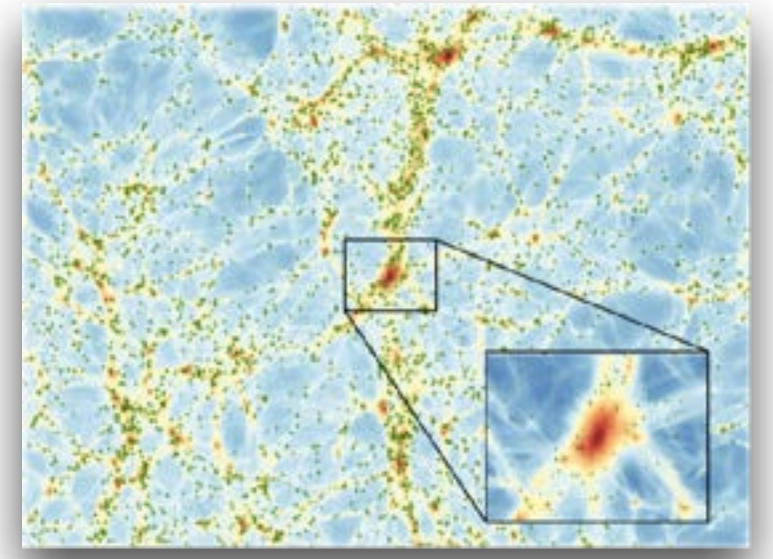
Cosmology



with
Cosmology scaling

Angulo+2022;
Zennaro+2019; Contreras+2021;

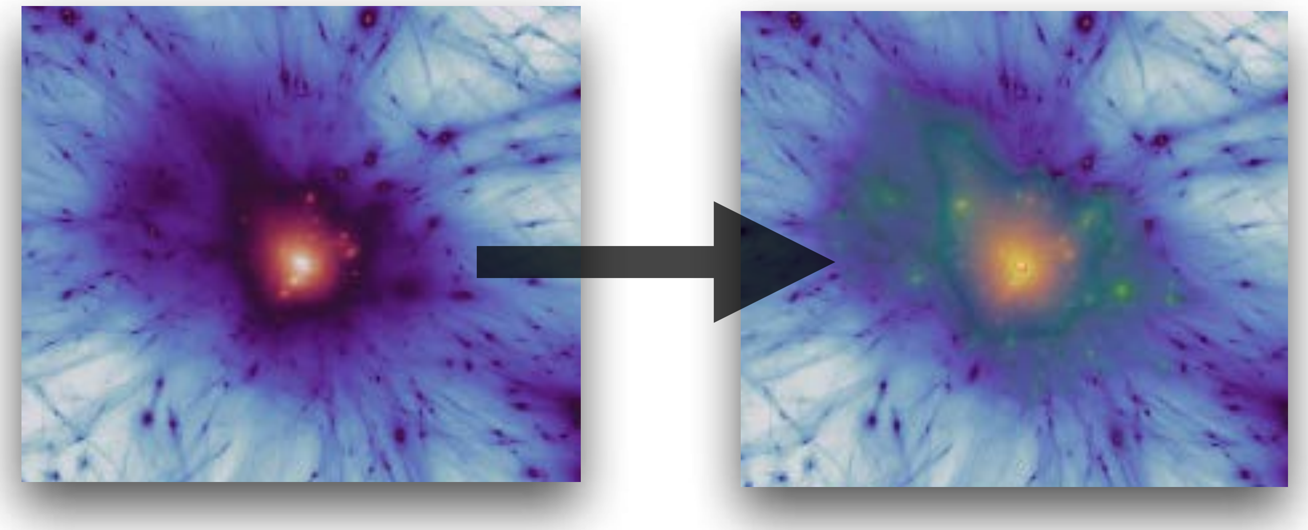
Galaxies



with hybrid Lagrangian
bias expansion/SHAM

Zennaro+2023;
Pellejero-Ibañez+2023
Contreras 2023

Baryons



with
Baryonification

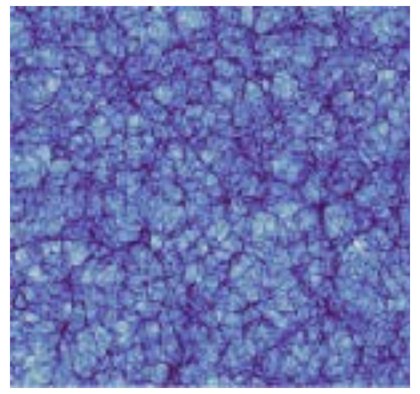
Aricò+2020;2021;

Raul Angulo, GA, Matteo Zennaro, Sergio Contreras, Marcos Pellejero-Ibañez, Lurdes Ondaro,
Jens Stücker, Daniel Lopez, Francisco Maion, Tamara Richardson, Sara Ortega, and others

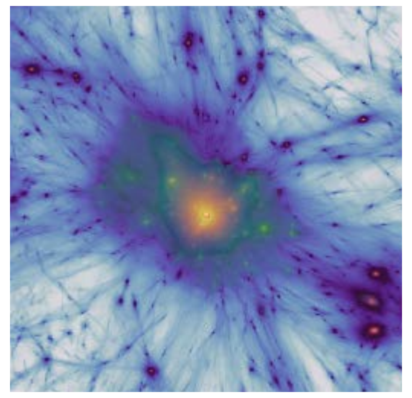
BACCOemu

Boltzmann solver: CLASS

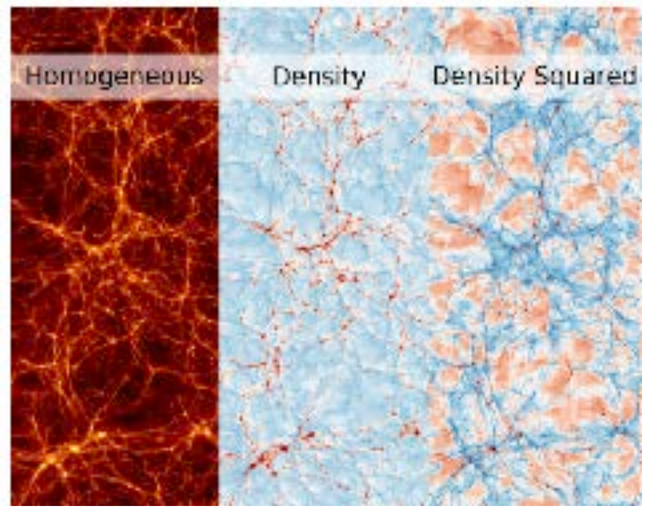
N-body simulations
+cosmology rescaling



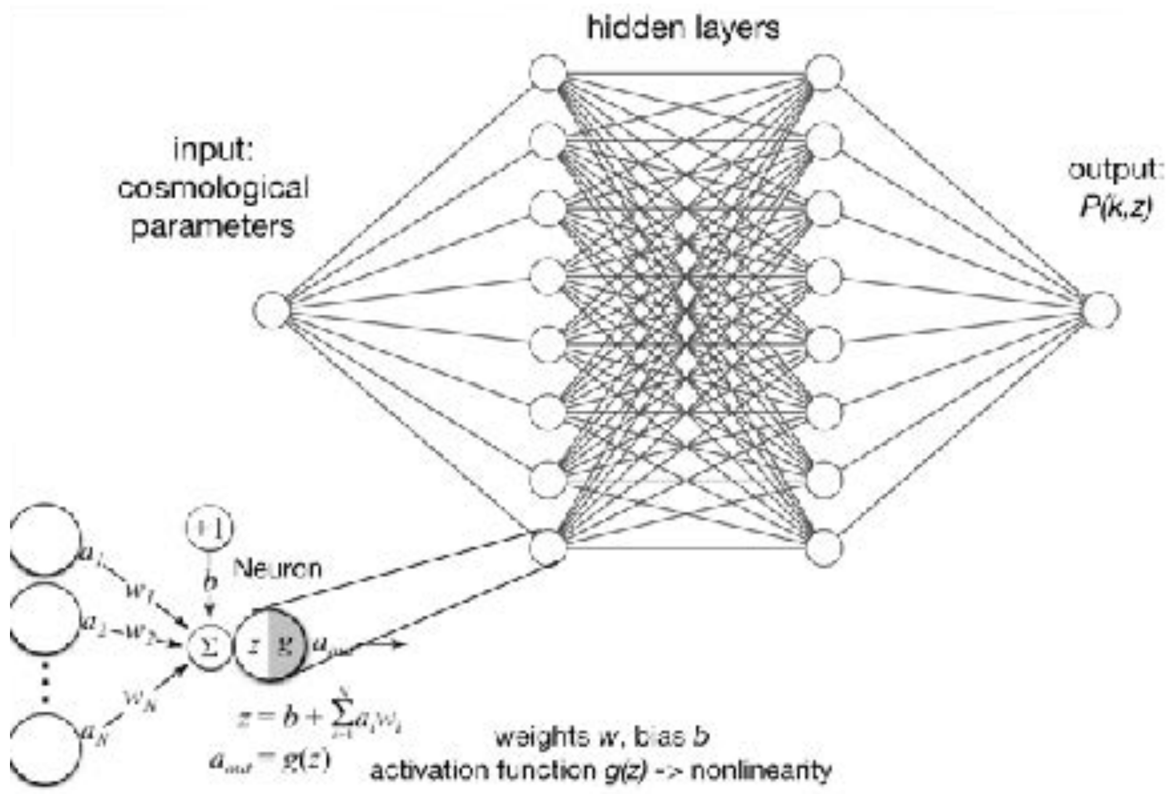
+baryonification



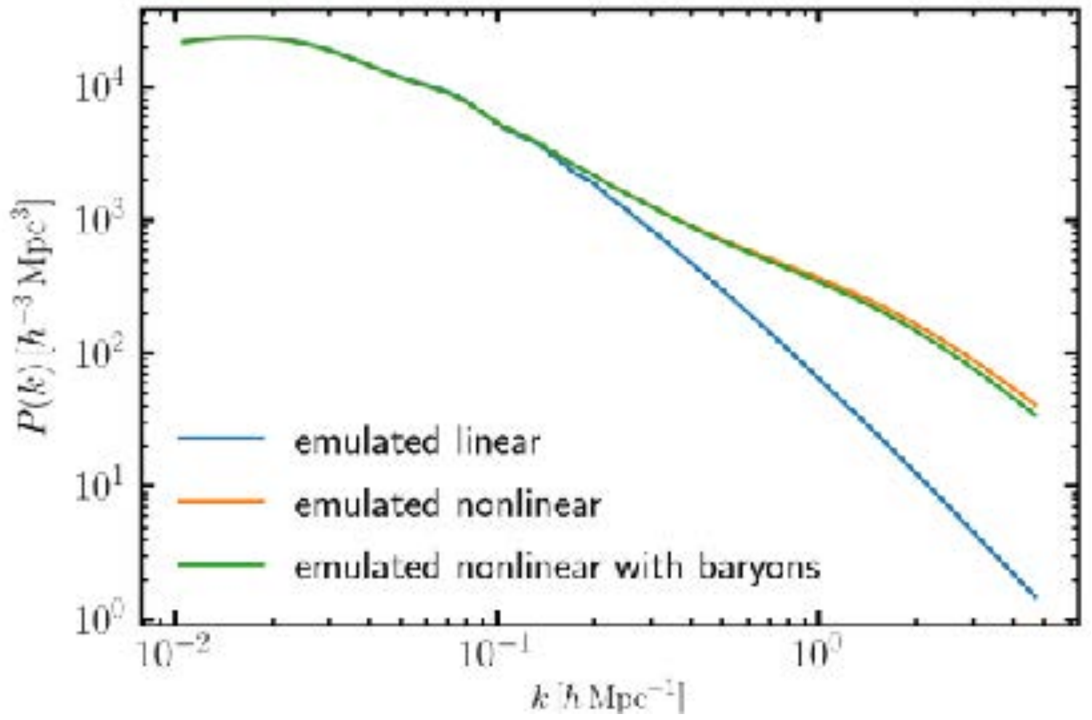
+hybrid Lagrangian



Neural networks



Emulation:
Matter power spectrum:
- Linear
- Non-linear boost
- Baryon suppression
- Biased tracers (galaxies)

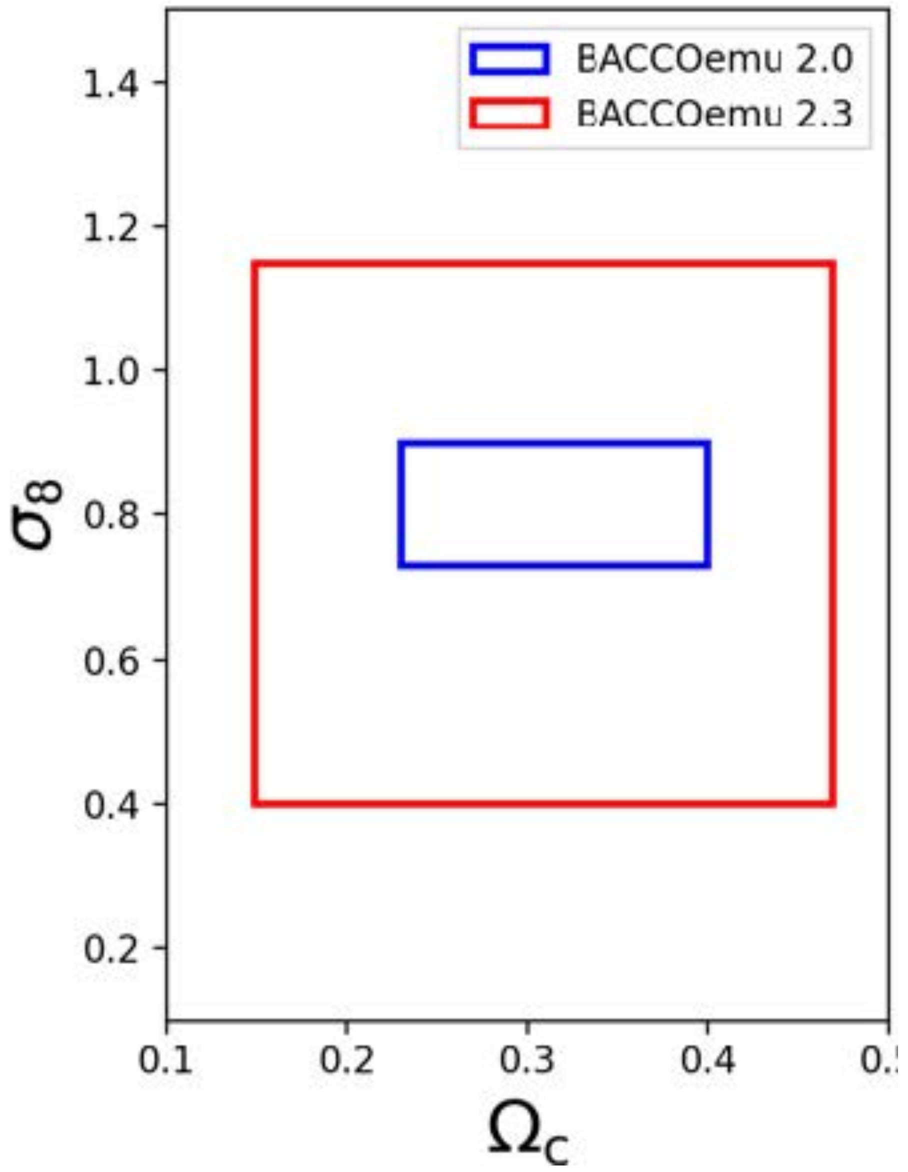


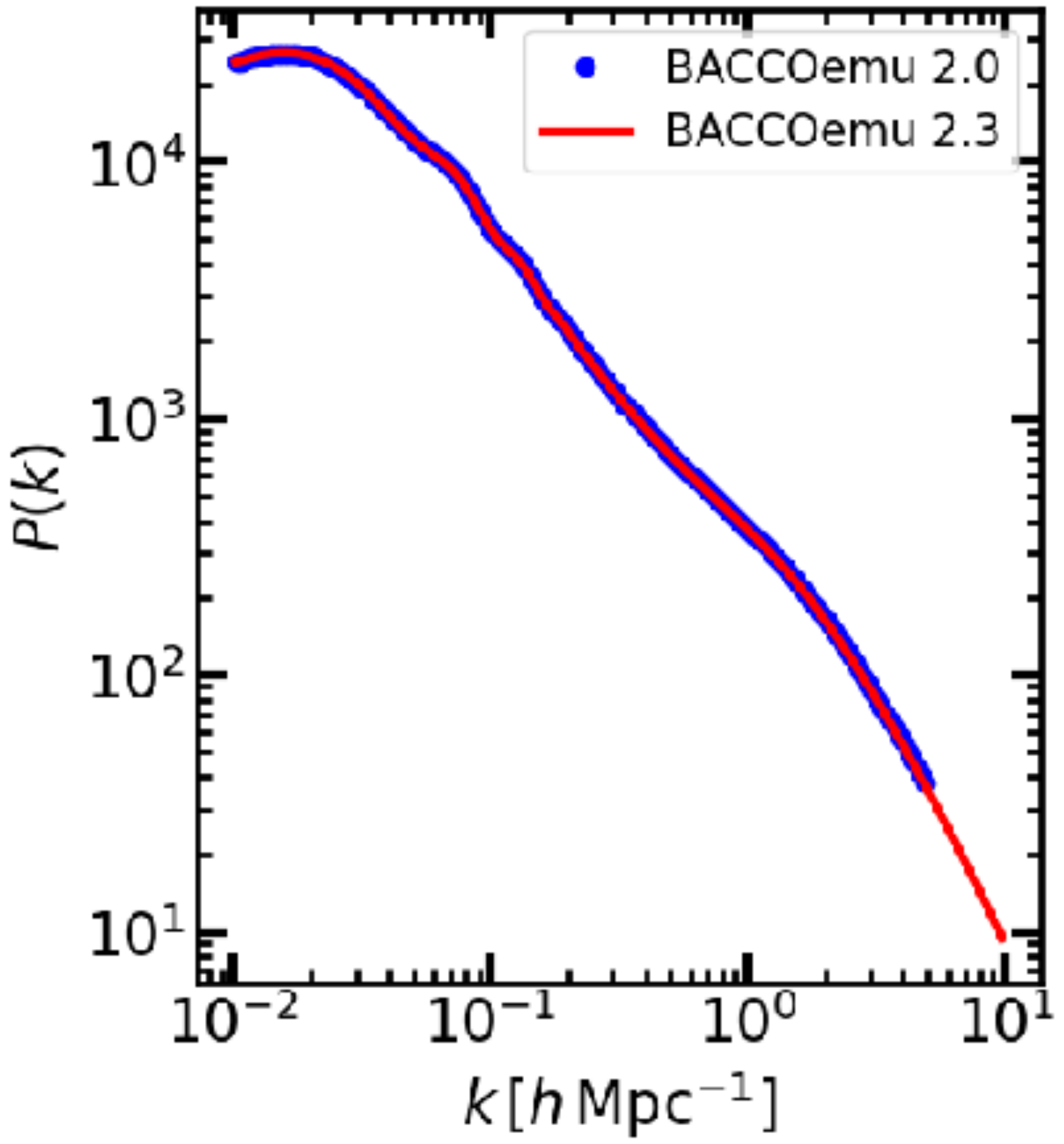
Accuracy of a few%, in a few ms!

https://bacco.dipc.org/emulator.html
https://baccoemu.readthedocs.io/en/latest/

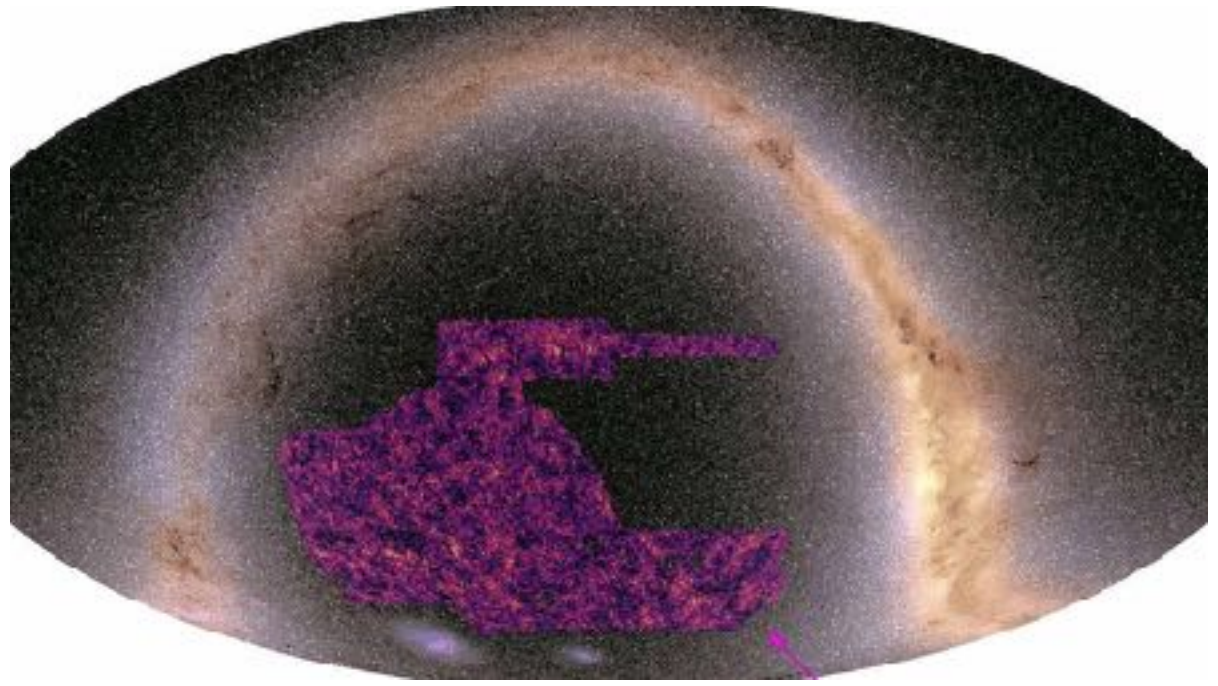
New release: 2.3.0

- New nonlinear matter power spectrum;
- Baryonic effects on matter bisepctrum;
- **Higher resolution**, **larger** cosmological **parameter space, higher z** (inference-ready);
- All implementation in **JAX**, easy to install and very fast (millisecond evaluation, vectorisation available)
- Adopted by Euclid and LSST pipelines

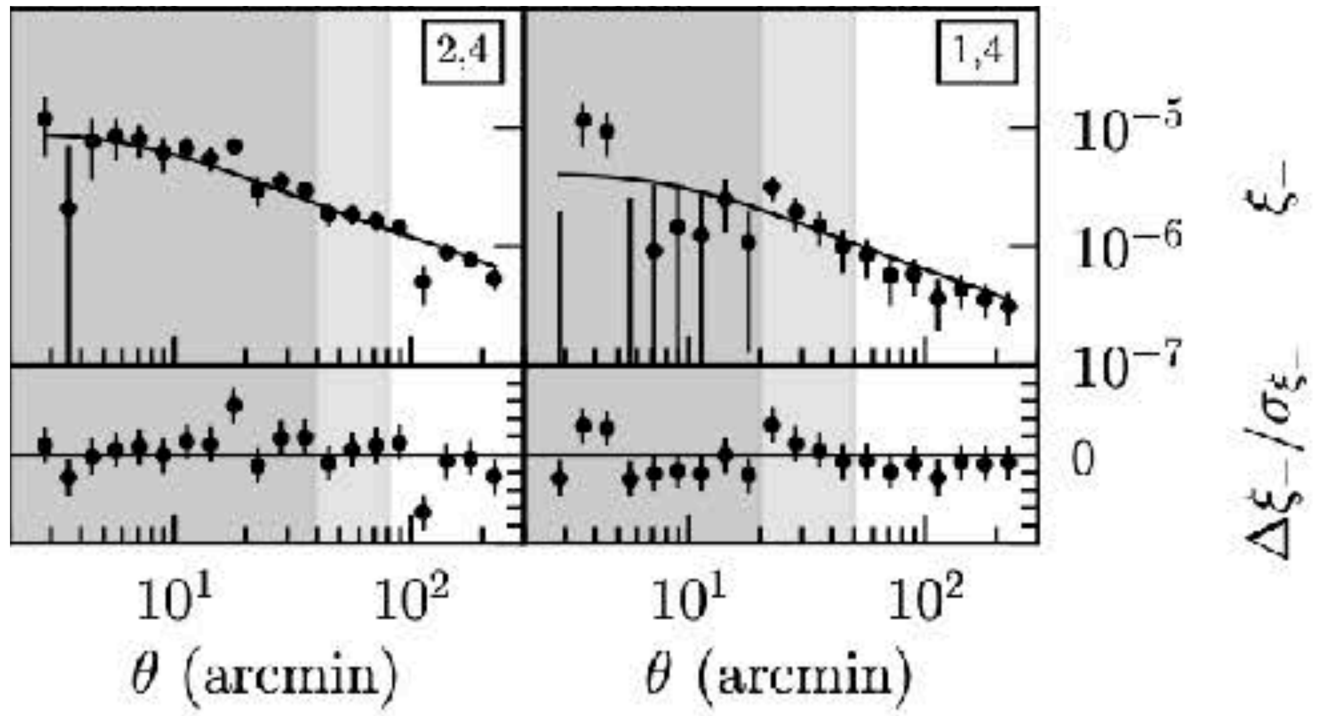




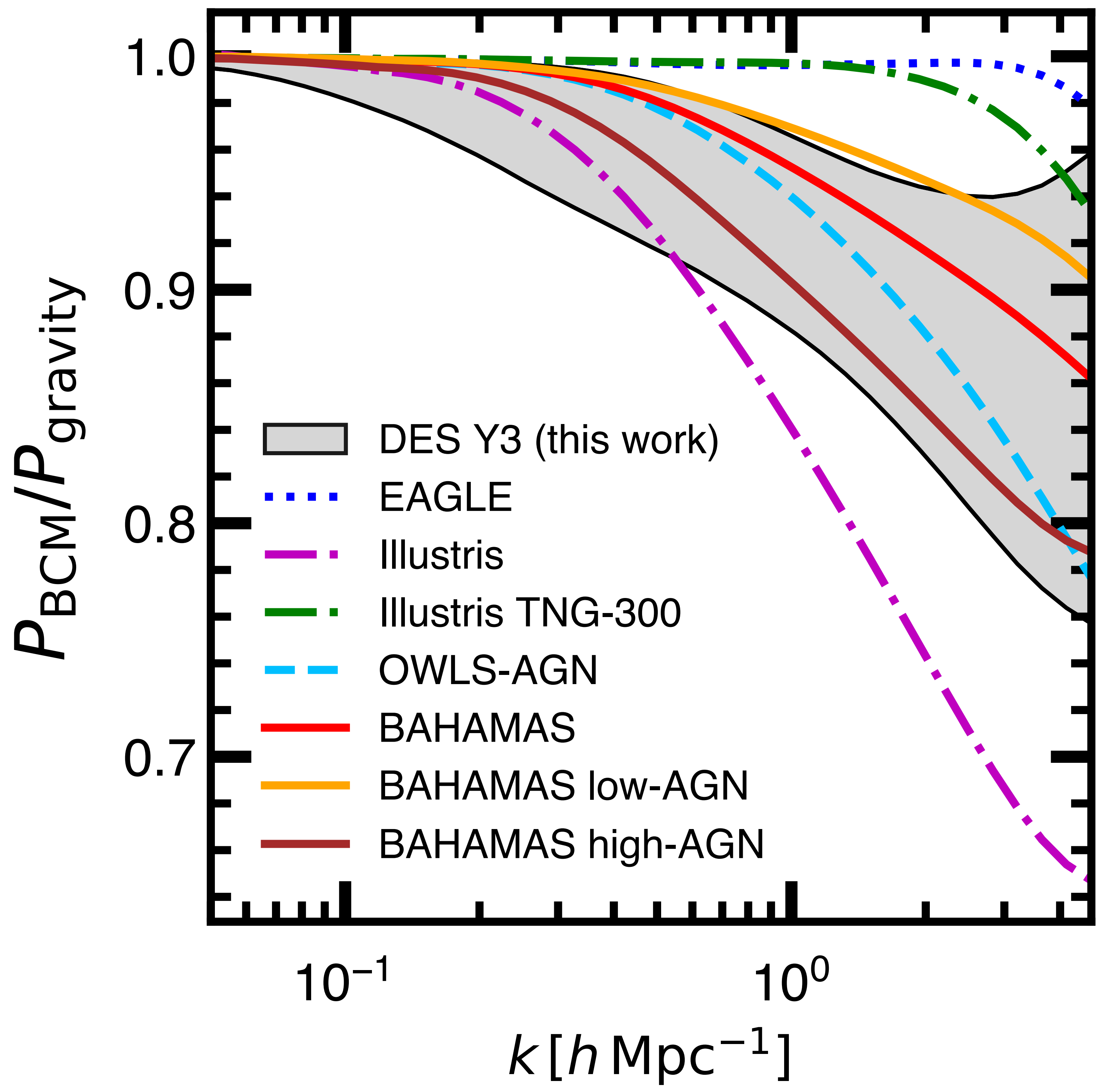
Constraints on cosmology and baryons
DES y3 cosmic shear without scale cuts



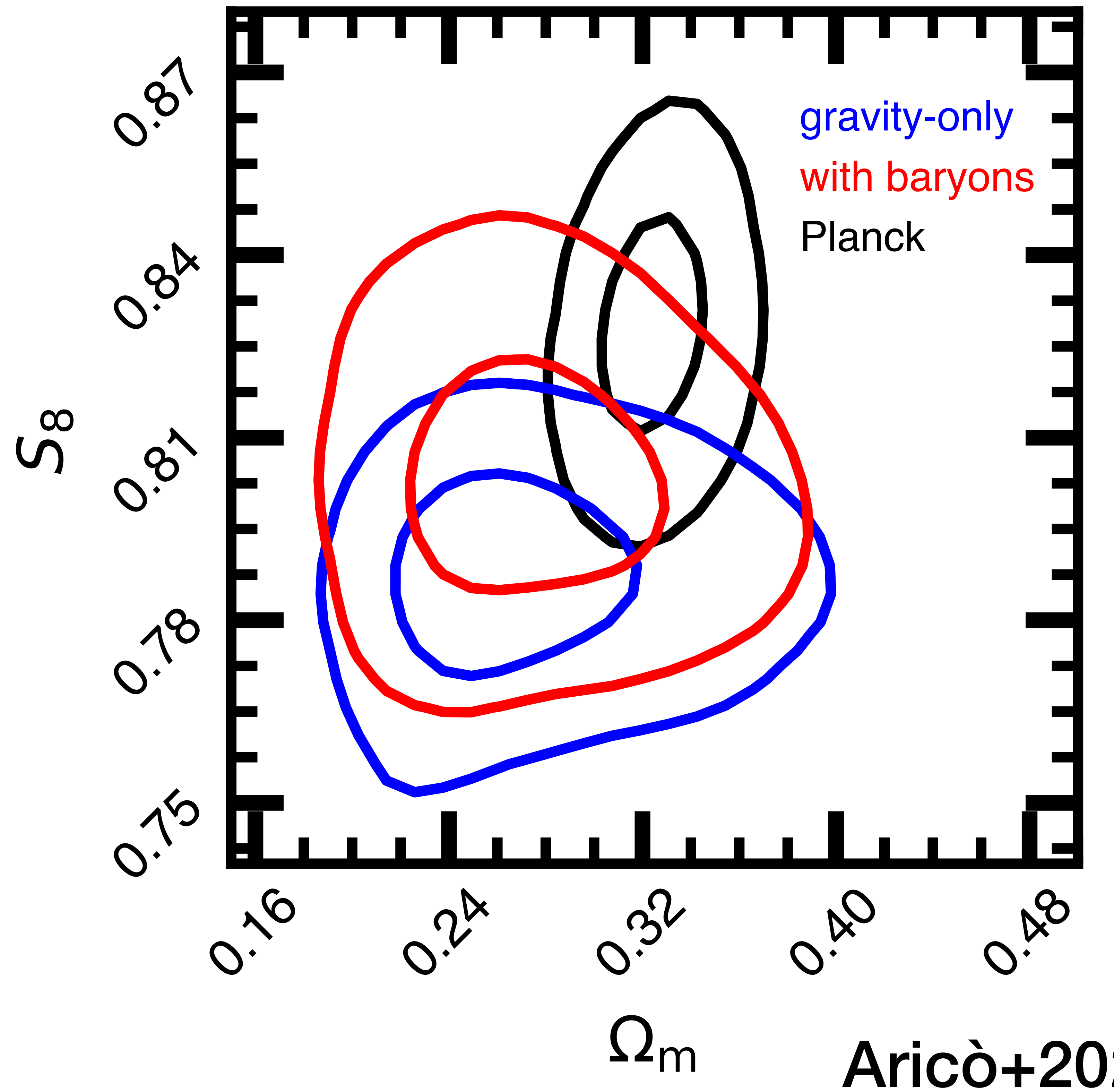
GOLD catalogue (year 3):
- Area 4143 deg^2
- 100 million galaxies
- Mean redshift $z = 0.63$



DES Y3 scale cuts: 173/400 data points removed (~45%)



Mild AGN feedback favoured



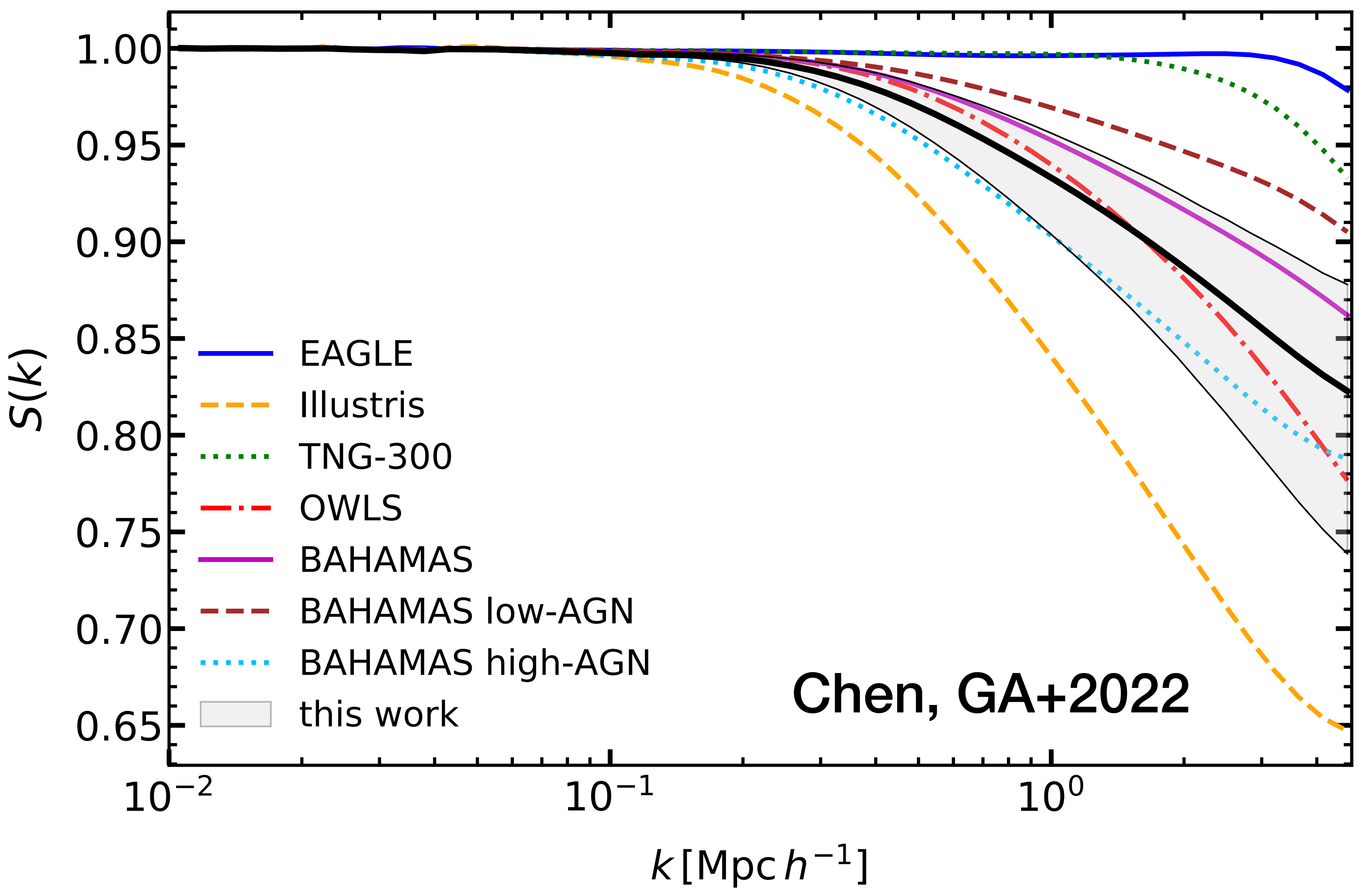
Aricò+2023

Agreement at <1 σ with Planck

See Garcia-Garcia et al. 2024
DES+KiDS+HSC with baccoemu

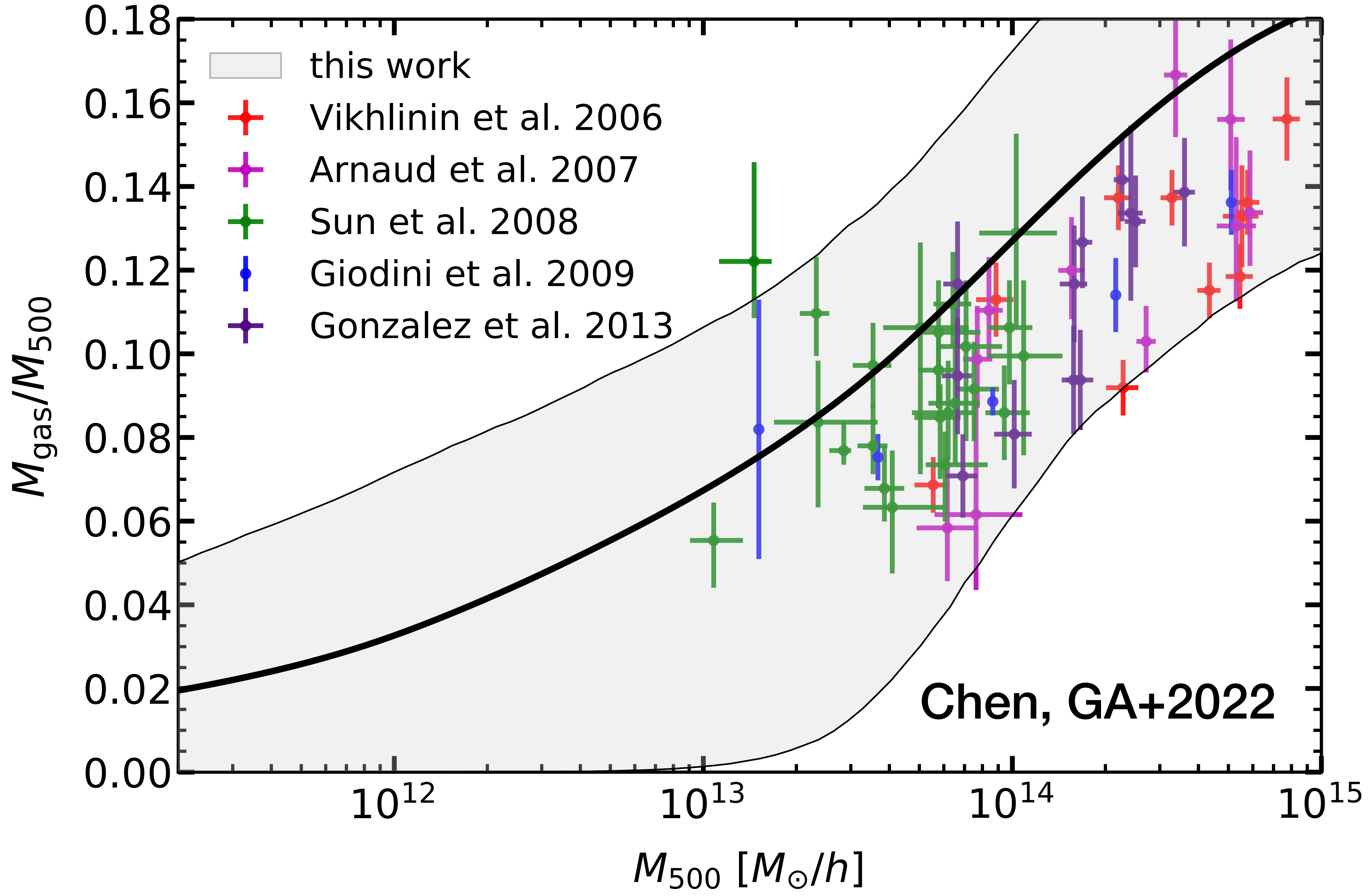
Consistency checks and multi-probe analyses

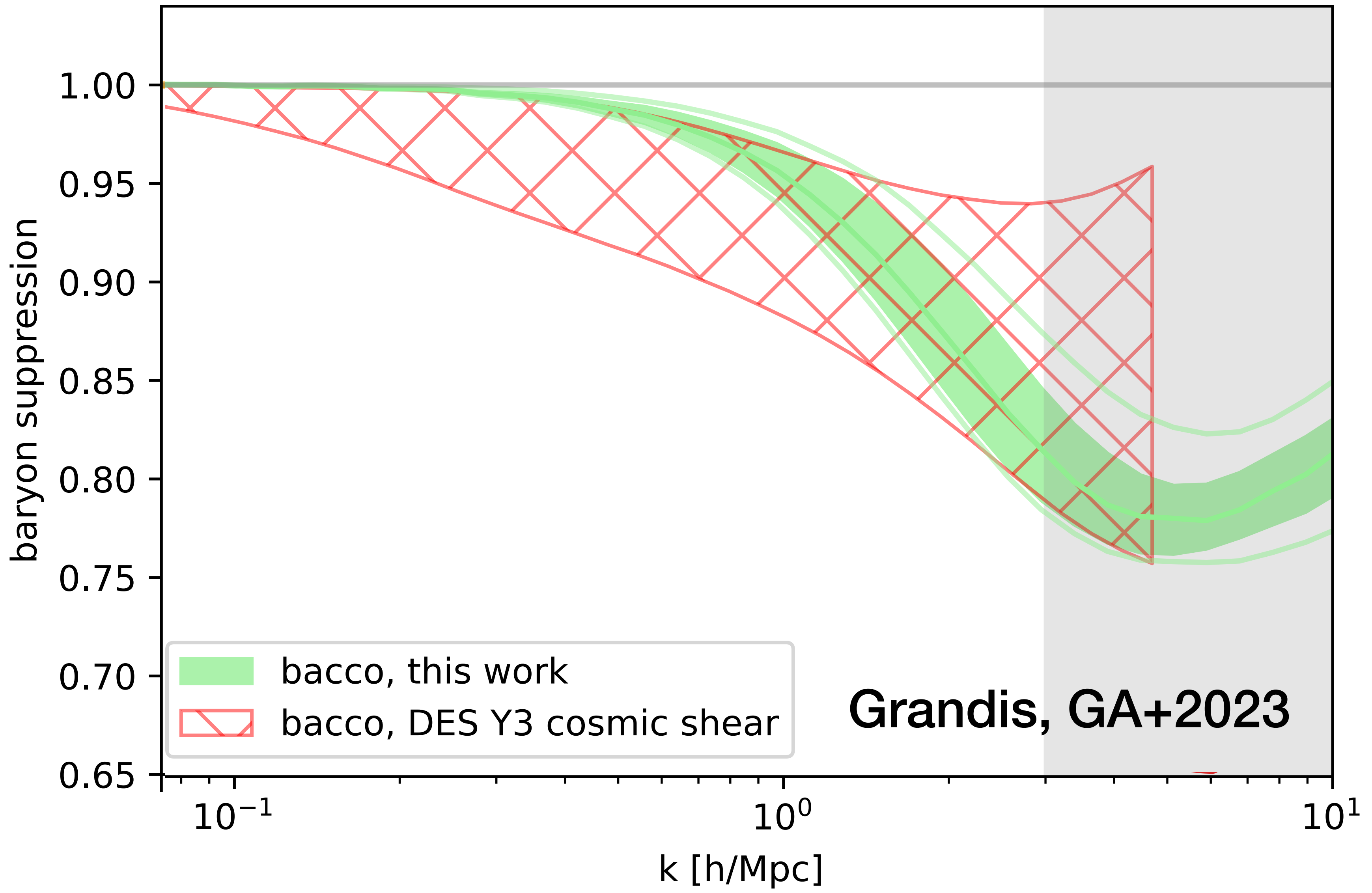
P(k)
(Cosmic shear)



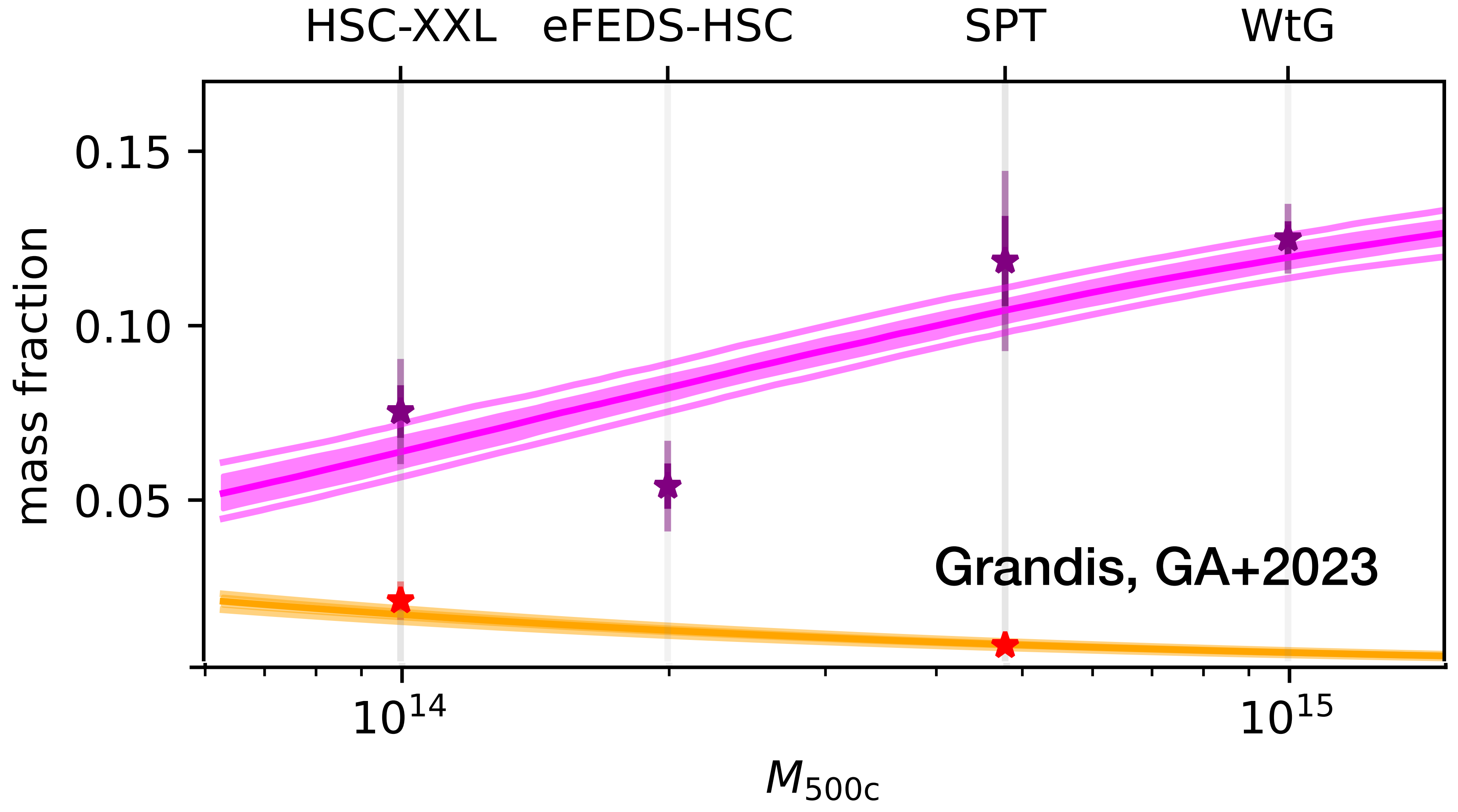
From P(k)
to baryon fractions

Gas and stellar fractions

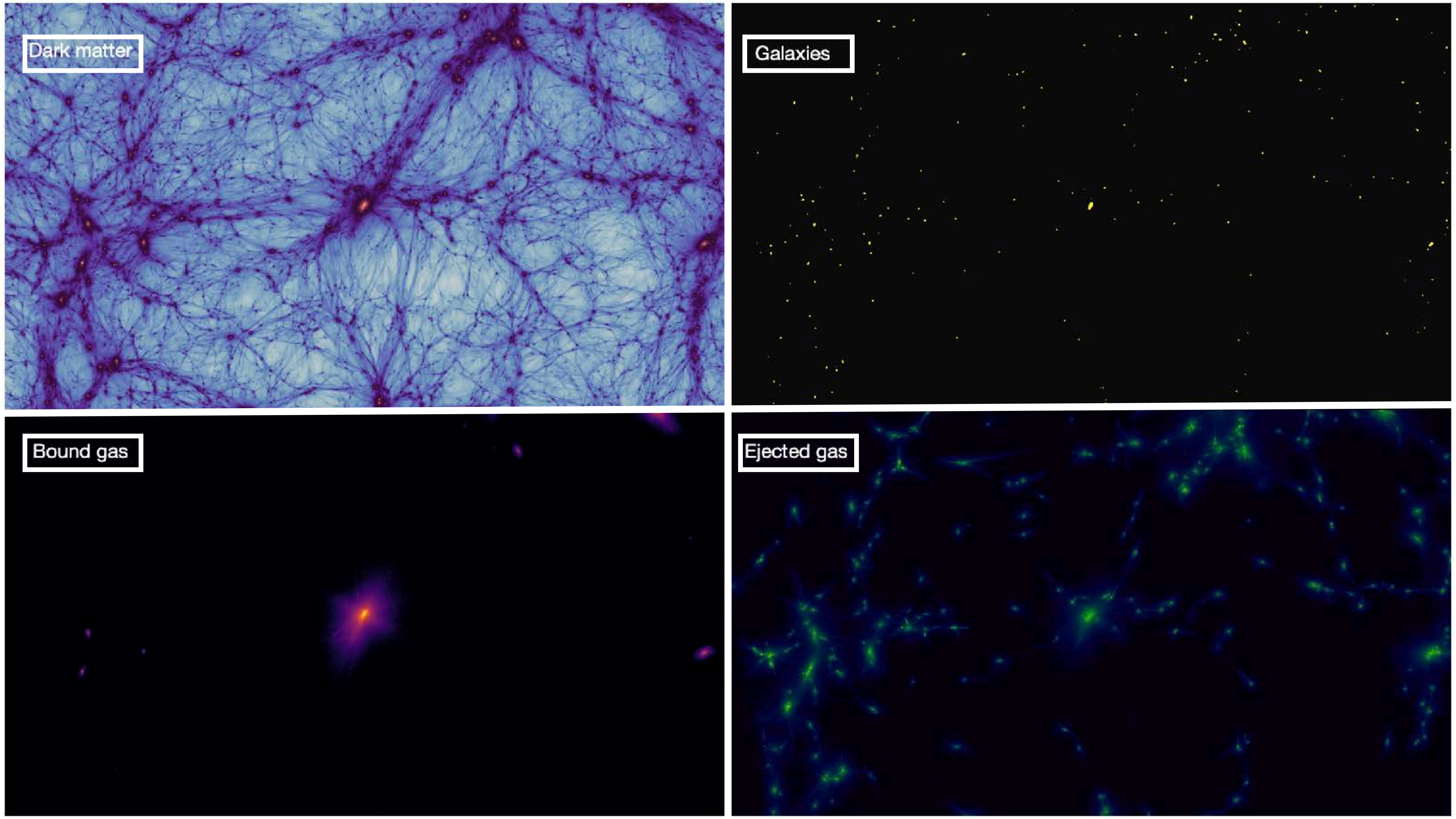




From baryon fractions
To P(k)



Baryonification for stage IV higher-order statistics



i) is it needed?
ii) If so, is it accurate enough to give unbiased results?
iii) How much is the information gain from higher-order analysis with small scales?

Euclid: An emulator for baryonic effects on the matter bispectrum★

P. A. Burger[1,2], G. Aricò★★[3,4], L. Linke[5], R. E. Angulo[6,7], J. C. Broxterman[8,9], J. Schaye[9], M. Schaller[9,8], M. Zennaro[10], A. Halder[11,12,13,14], L. Porth[15], S. Heydenreich[16,15], M. J. Hudson[1,2,17], A. Amara[18], S. Andreon[19],

Do we need to model baryons for Euclid DR1?

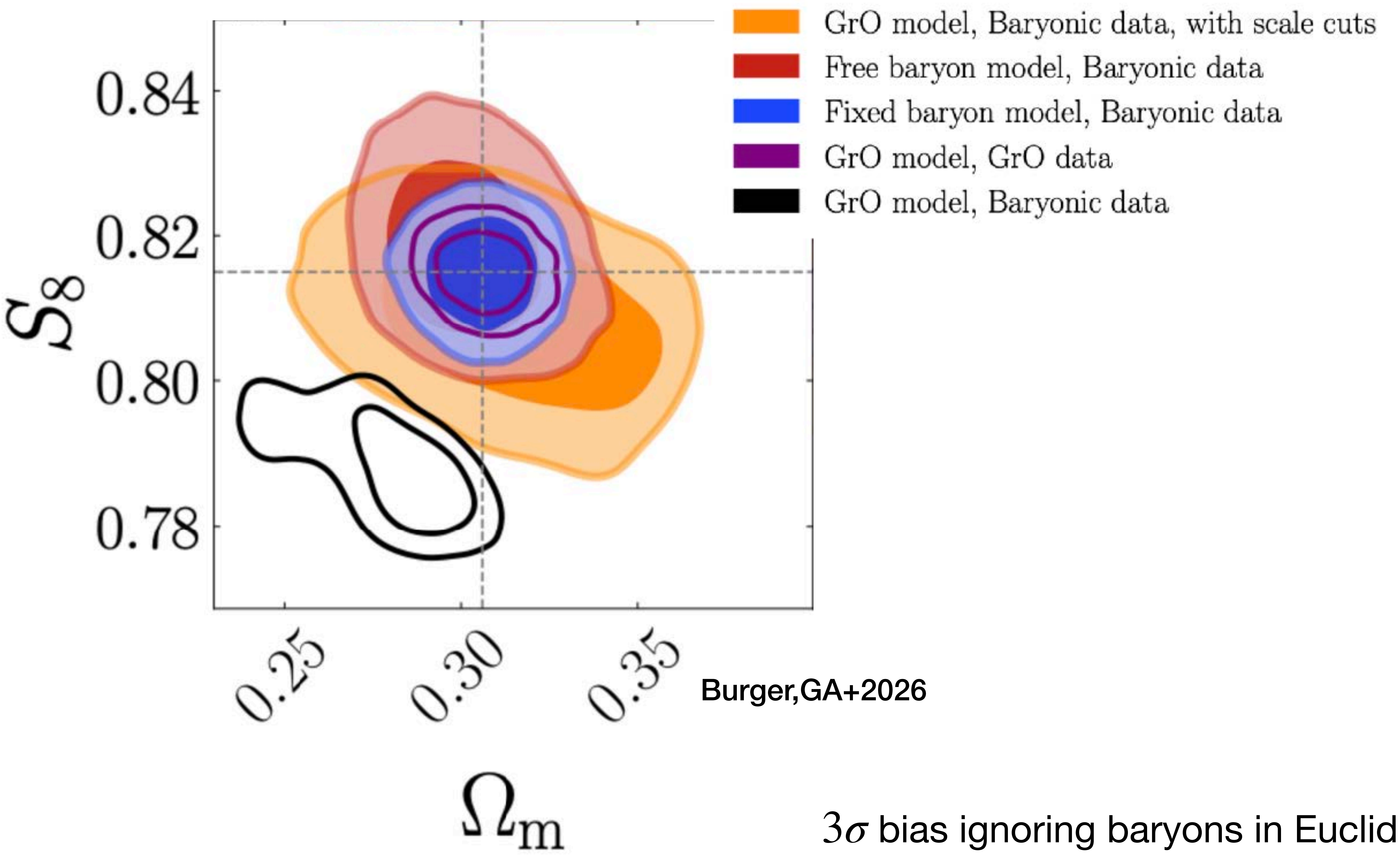
KP-JC4
CS-SWG-WP2
HOWLS

Do we need to model baryons for Euclid DR1?

Joint 2nd and 3rd moments

Fiducial scales $\theta > 2'$

Scale cuts remove
data points with $> 0.4\sigma$
difference gravity-baryons
resulting in $\theta > 32'$



Burger,GA+2026

3σ bias ignoring baryons in Euclid DR1!

Scale cuts degrade Ω_m by **80%,** S_8 by **10%**

Simultaneous modelling of matter power spectrum and bispectrum in the presence of baryons

Giovanni Aricò[1*], Raul E. Angulo[1,2], Carlos Hernández-Monteagudo [3,4,5] Sergio Contreras[1], & Matteo Zennaro[1].

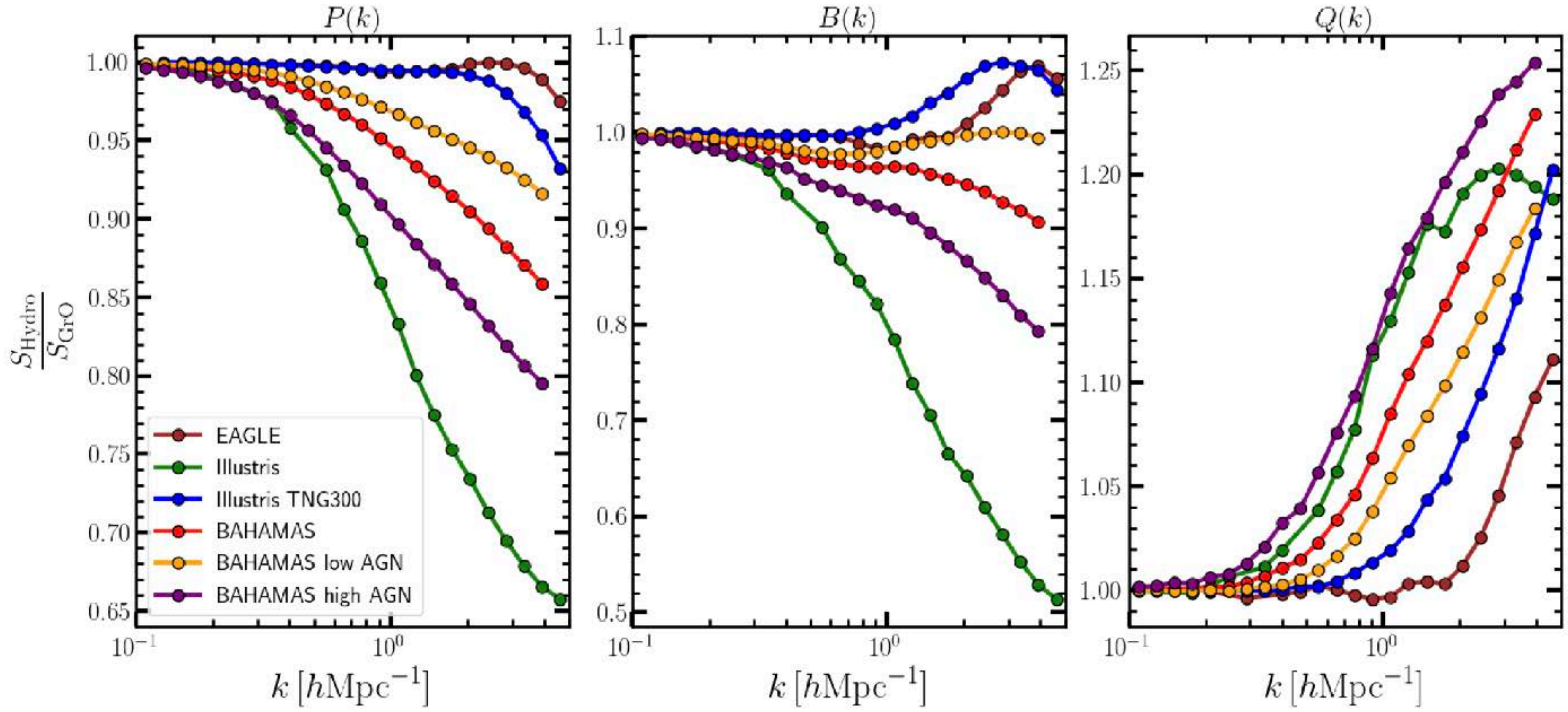
Is baryonification accurate for higher order statistics?

(bispectrum)

Aricò+2021a

Simultaneous modelling of matter power spectrum and bispectrum in the presence of baryons

Giovanni Aricò[1★], Raul E. Angulo[1,2], Carlos Hernández-Monteagudo [3,4,5] Sergio Contreras[1], & Matteo Zennaro[1].

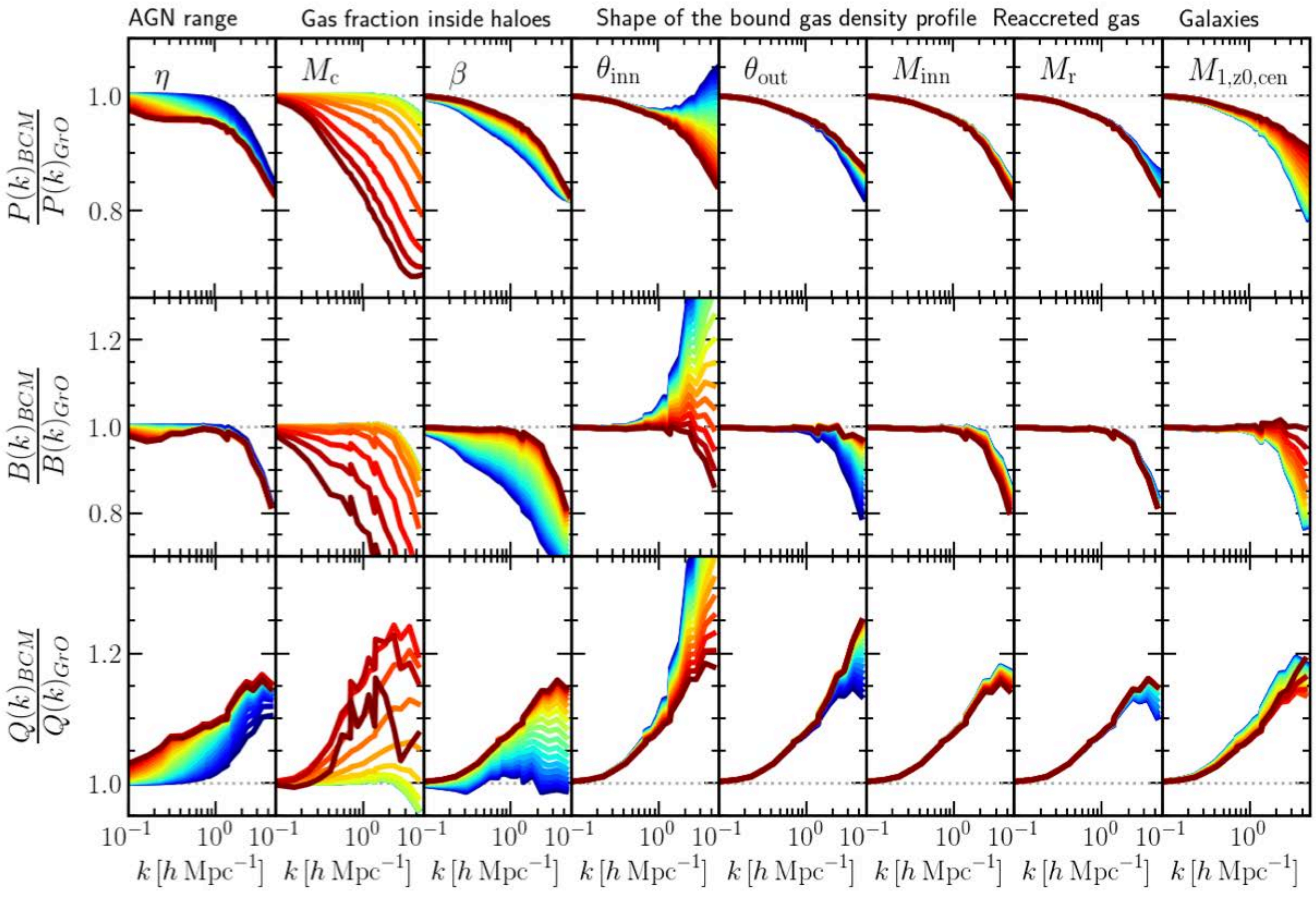


Equilateral triangles, reduced bispectrum

$$Q(\mathbf{k}) = \frac{B(\mathbf{k})}{3P(k)^2}$$

Aricò+2021a

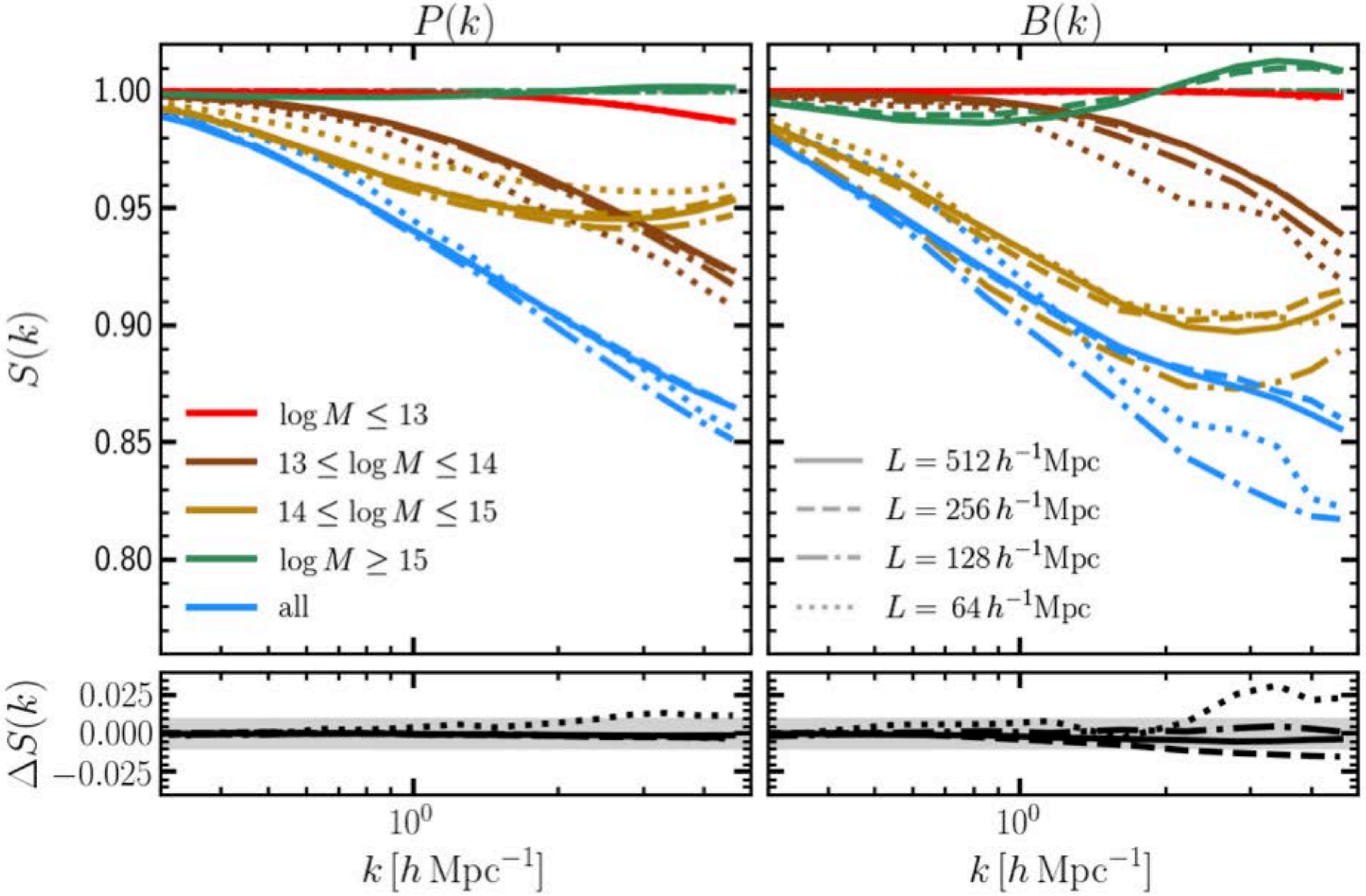
Impact of baryonic parameters



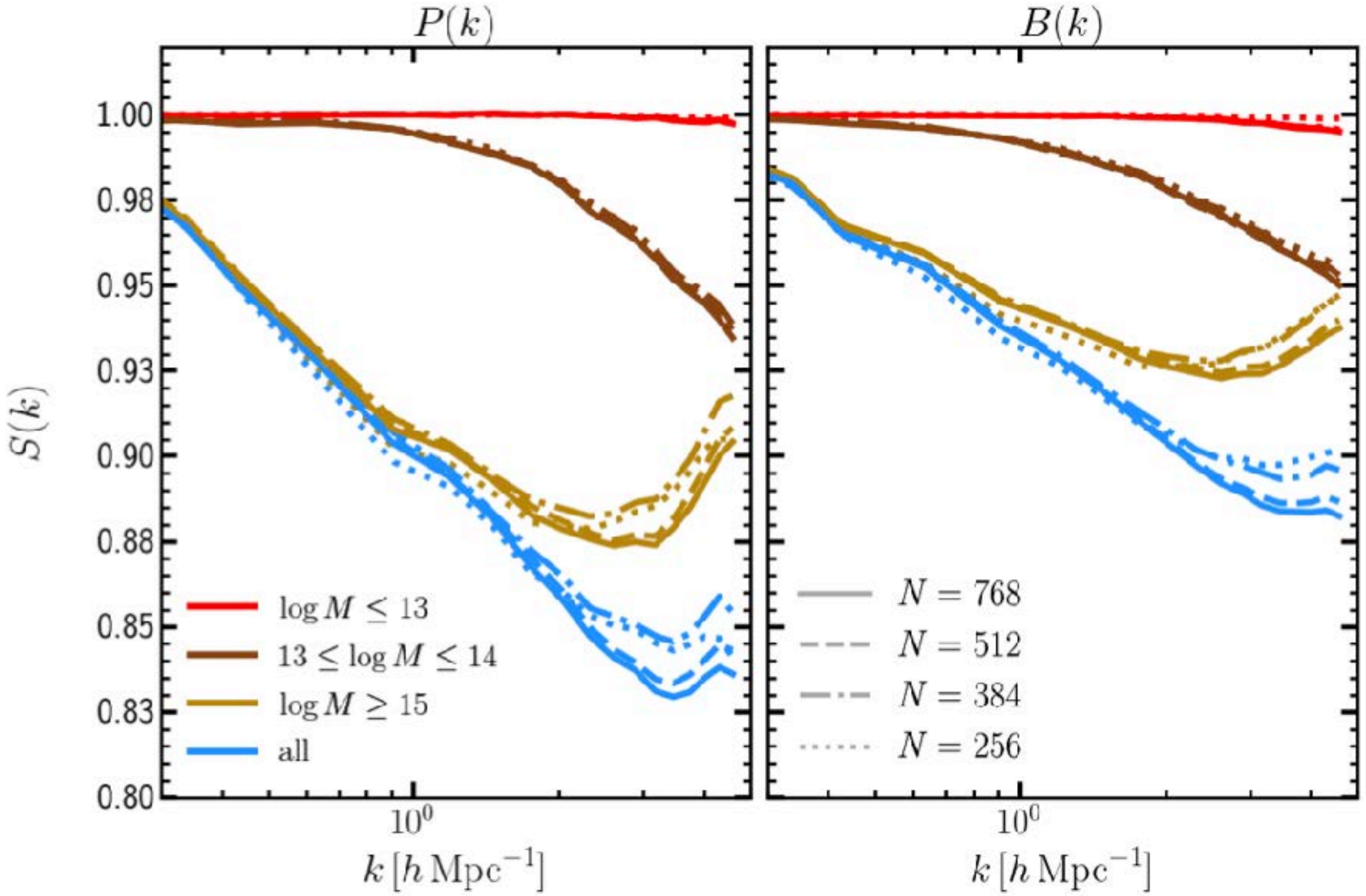
Aricò+2021a

Convergence analysis

Box size

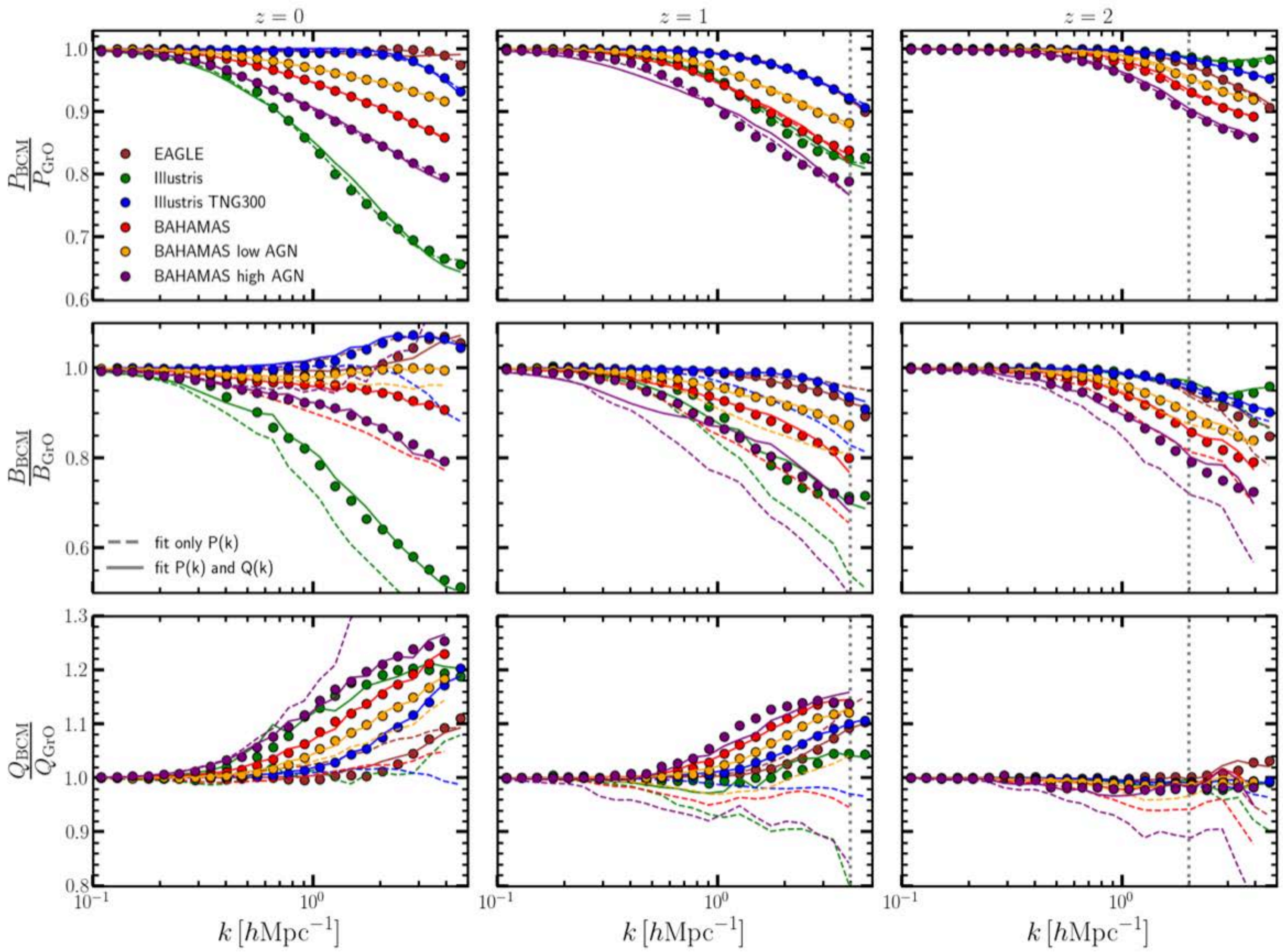


Resolution



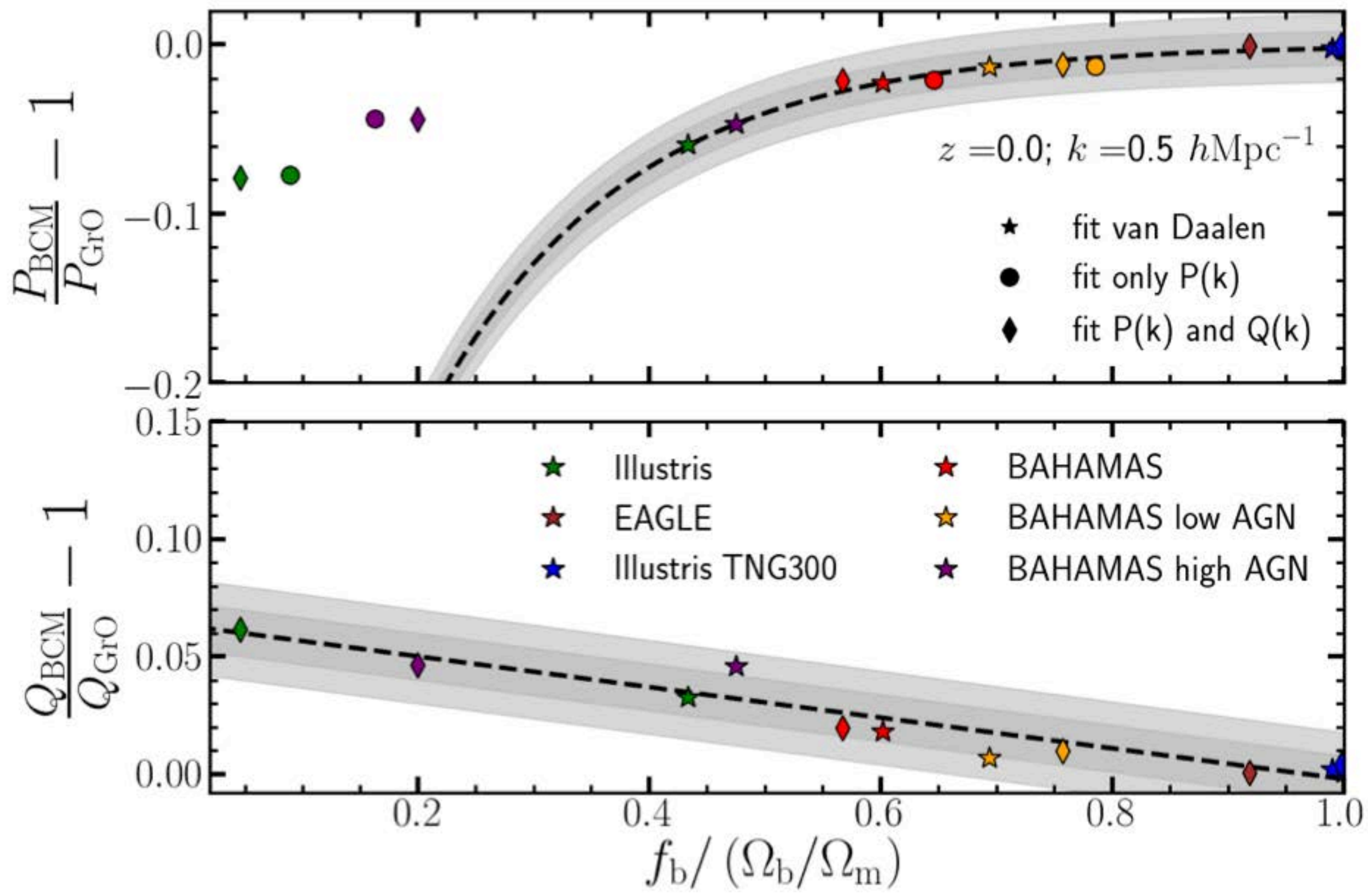
Aricò+2021a

Accuracy of 2- and 3-point clustering fits



Aricò+2021a

Correlations of 2- and 3-point clustering with baryon fraction in halos



Aricò+2021a

Euclid: An emulator for baryonic effects on the matter bispectrum★

P. A. Burger[1,2], G. Aricò★★[3,4], L. Linke[5], R. E. Angulo[6,7], J. C. Broxterman[8,9], J. Schaye[9], M. Schaller[9,8], M. Zennaro[10], A. Halder[11,12,13,14], L. Porth[15], S. Heydenreich[16,15], M. J. Hudson[1,2,17], A. Amara[18], S. Andreon[19],

Several challenges:

- Accurate nonlinearities;
- Accurate baryonic modelling;
- Large parameter space;
- Small measurement time;
- Wide scale range probed;

~1200 simulations of 2288^3 particles in a 512 Mpc/h box ($m \approx 10^9 h^{-1} M_\odot$);

Cosmological scaling + baryonification

New bispectrum code on GPUs github.com/llinke1/BiG

Folding of particles to access scales of $k \approx 20 h^{-1}\mathrm{Mpc}$

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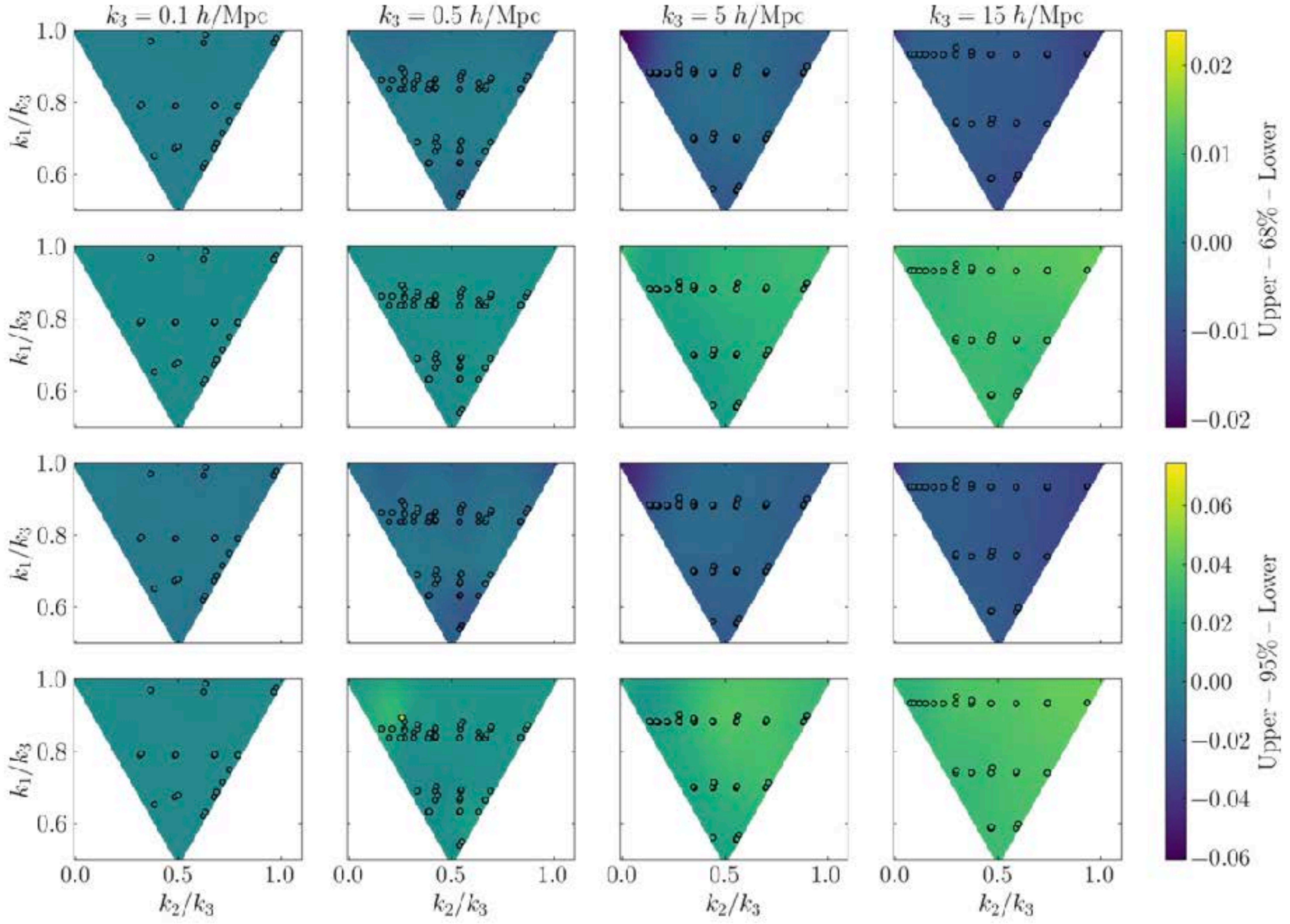
Cosmological scaling + baryonification

~1200 simulations of 2288^3 particles in a 512 Mpc/h box ($m \approx 10^9 h^{-1} M_\odot$);

Parameter	Prior Range
$\log_{10}(M_c/h^{-1}M_\odot)$	[10, 16]
$\log_{10}(M_1/h^{-1}M_\odot)$	[9, 13]
$\log_{10}(\beta)$	[−1.0, 0.7]
$\log_{10}(\eta)$	[−0.7, 0.2]
$\log_{10}(\theta_{inn})$	[−2.0, 0.0]
Ω_m	[0.23, 0.40]
Ω_b	[0.04, 0.06]
σ_8	[0.73, 0.90]
a	[0.24, 1.01]



Accuracy of ~2%

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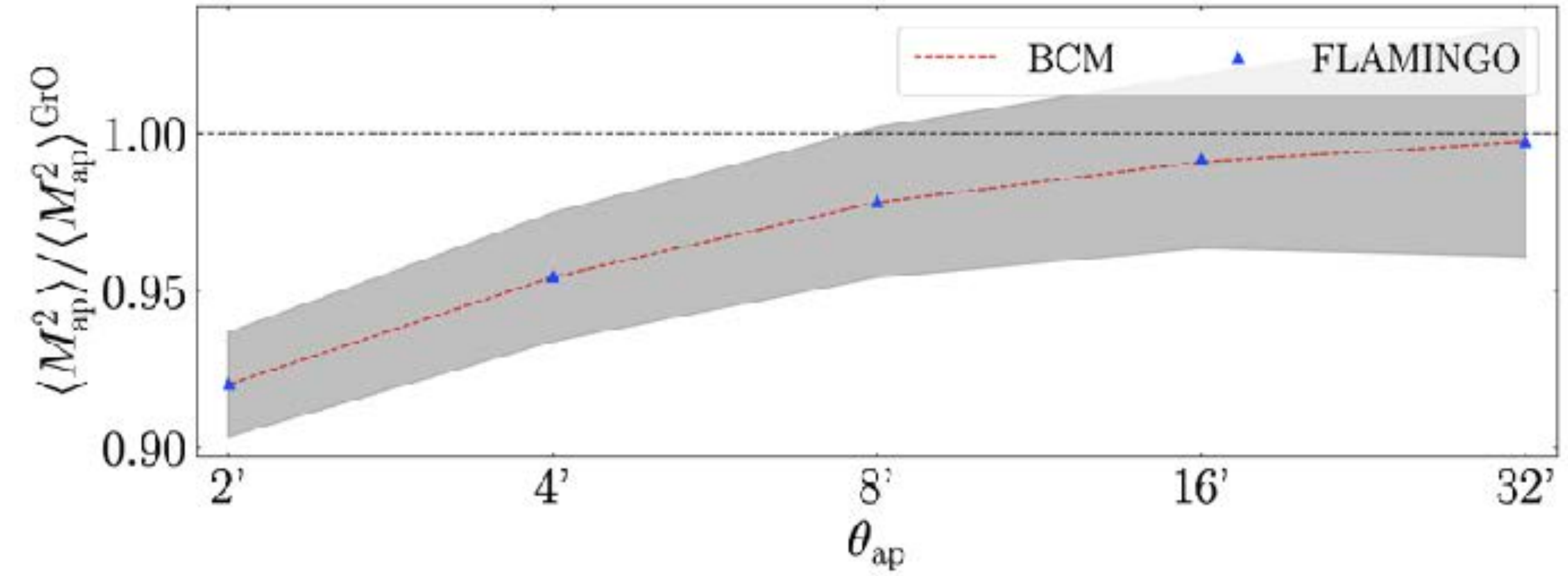
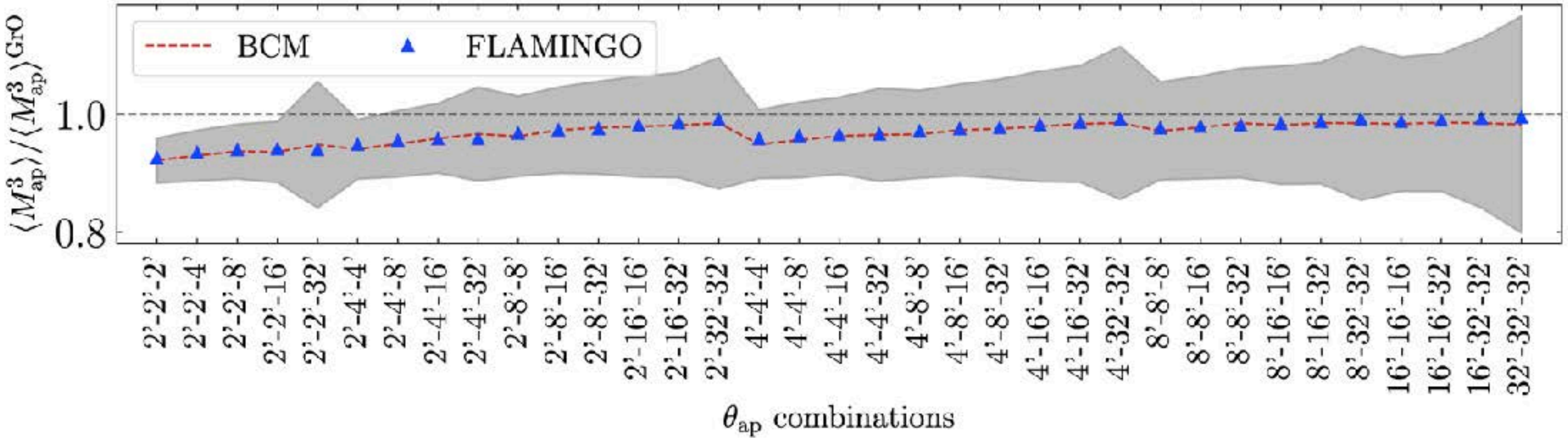
Validation with FLAMINGO simulations





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How much do we gain including higher-order statistics?

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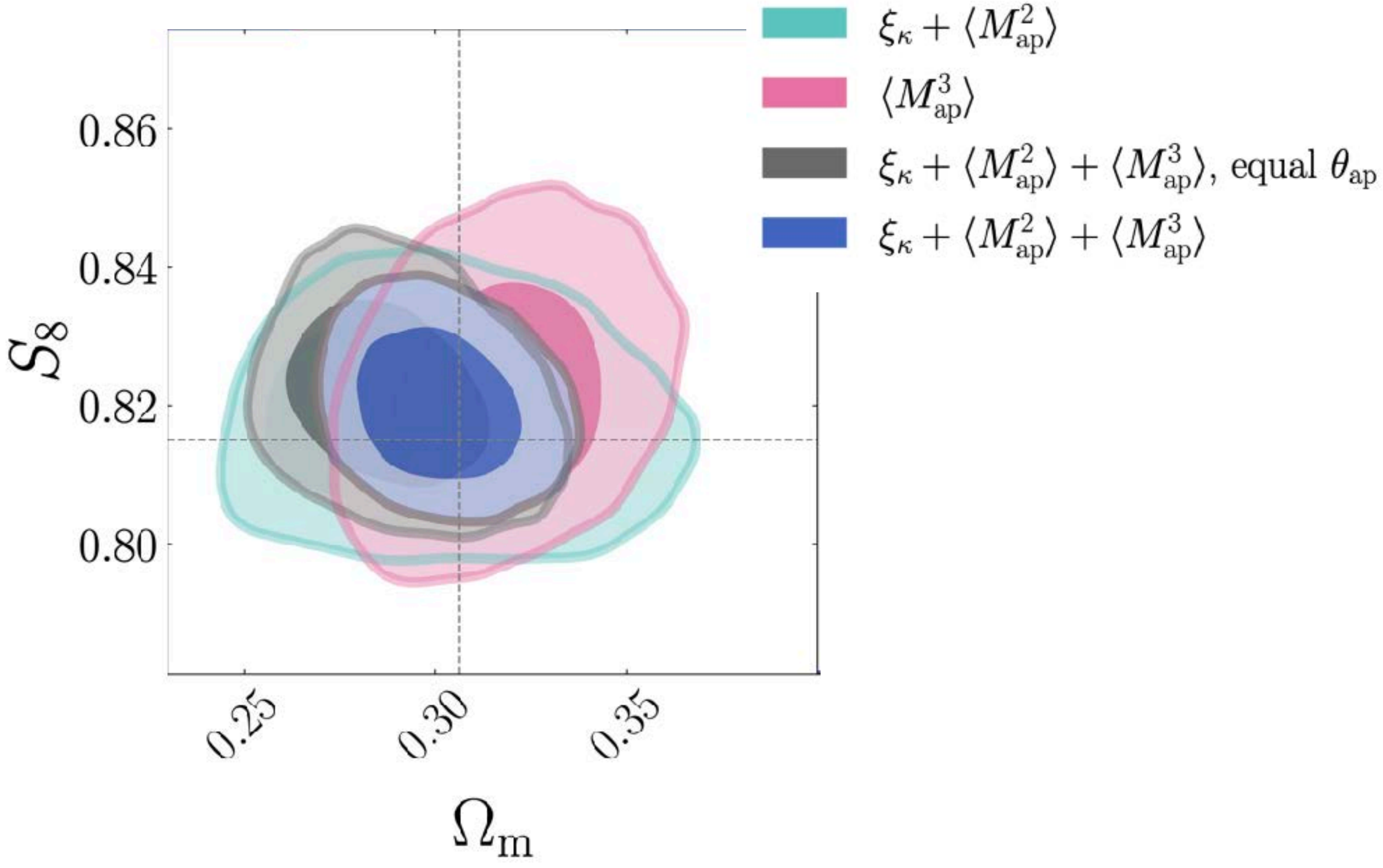

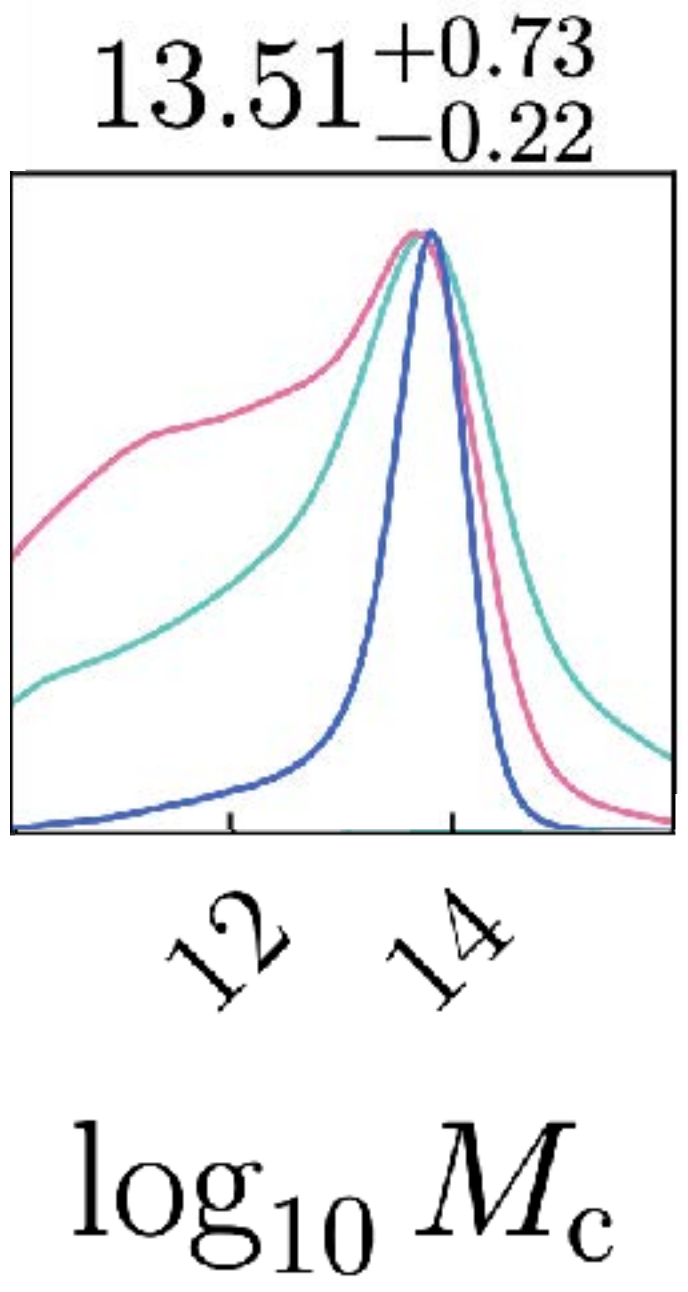

3pt increases $\Omega_{\rm m}$ by **50%** and S_8 by **20%**

Baryonic physics significantly more constrained!

Burger,GA+2026

***Euclid*: An emulator for baryonic effects on the matter bispectrum**[★]

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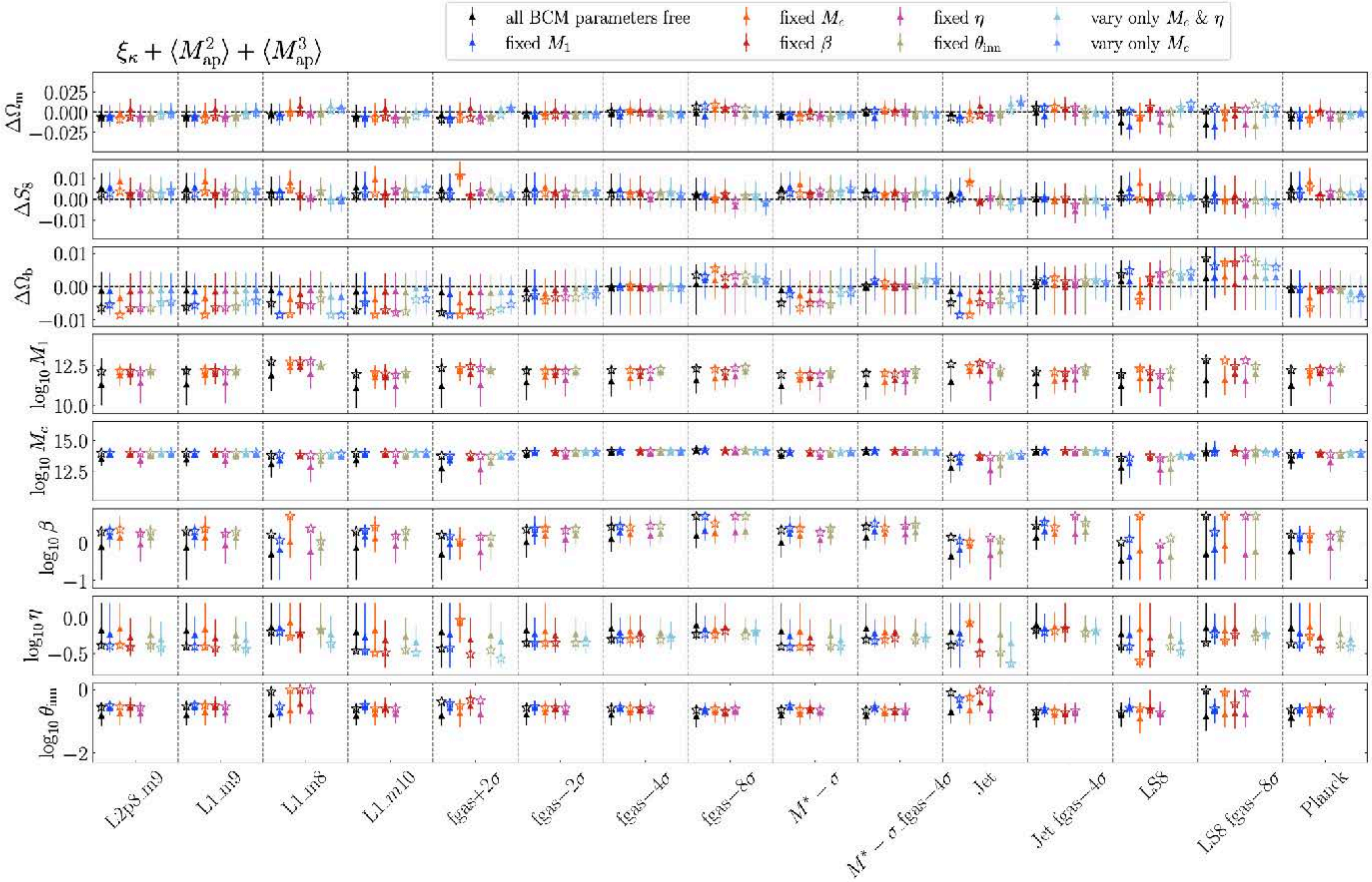
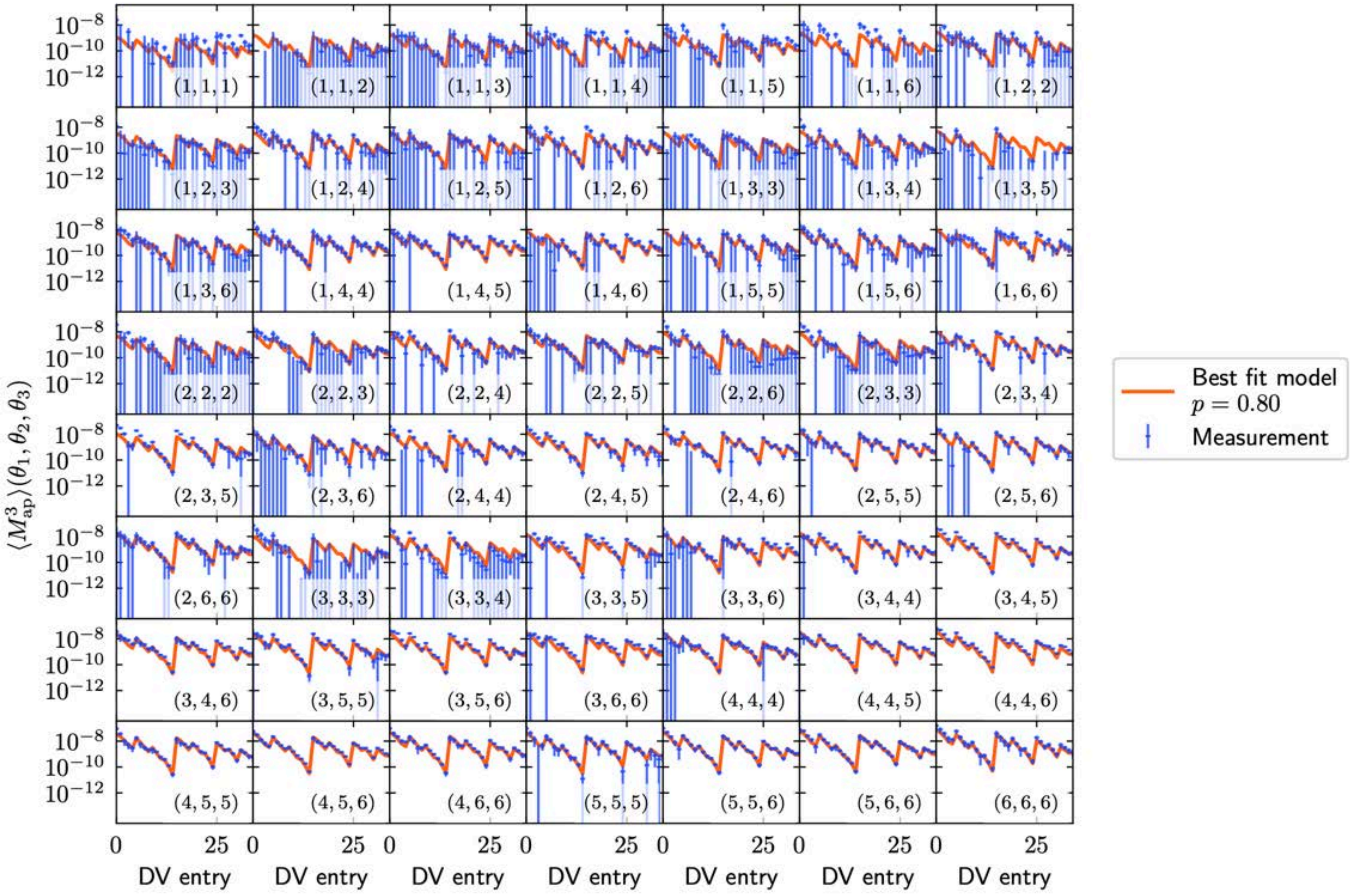
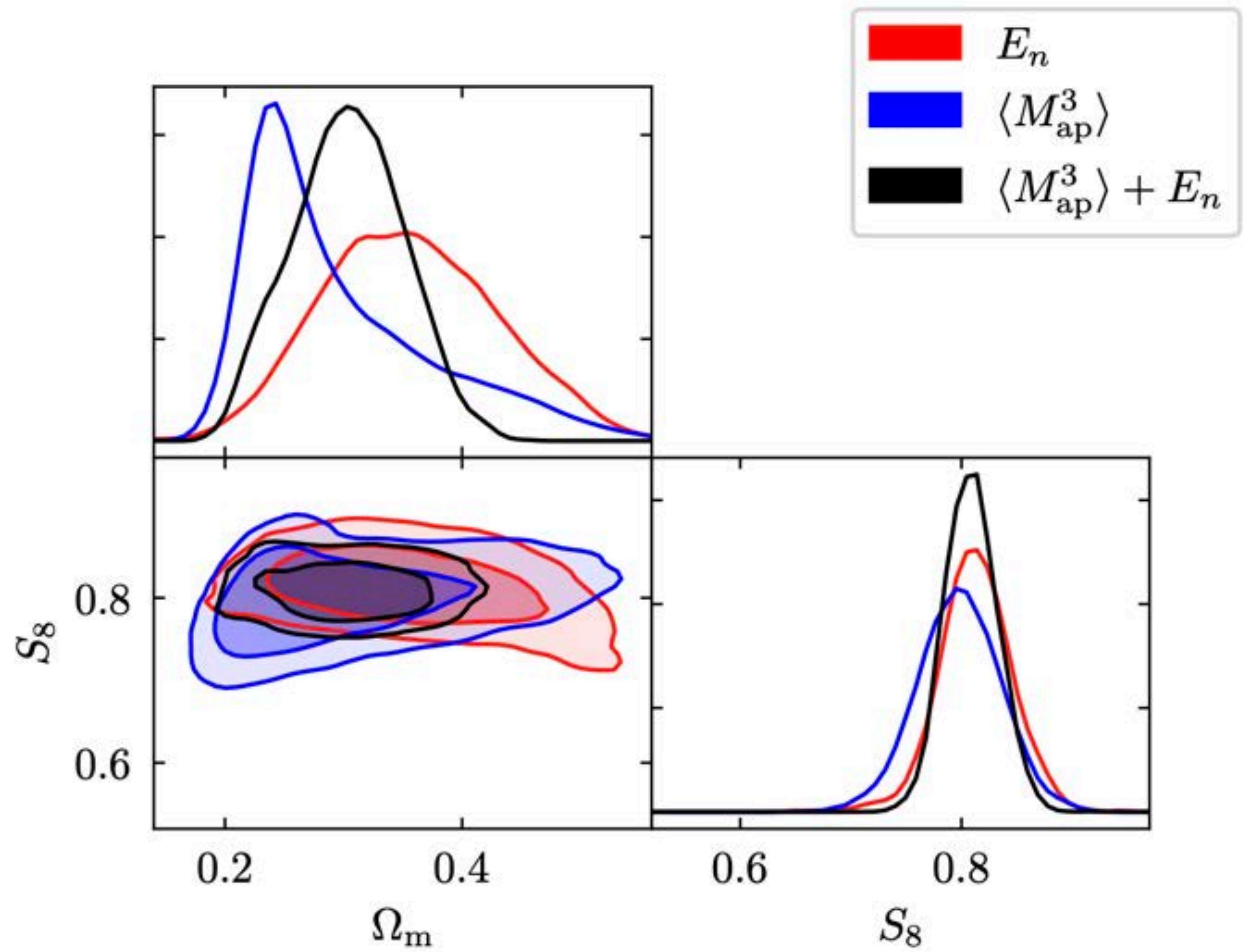
The inference is robust?



Bispectrum emulator results robust to all FLAMINGO's feedback, cosmological variations, setups

BACCOemu applied to KiDS-Legacy data





Linke et al. 2026

Summary

- Baryonification works at field level, can be in principle used with your favourite higher-order statistics;

- Its few physical parameters can be inferred directly with observations, no hydro sims needed;

- Hydro sims needed to validate the methods, making sure that prescriptions holds for a given statistics and scales;

- 2pt and 3pt statistics works well for scales probed by stage III and IV surveys, significant gains adding small scales and higher-order;

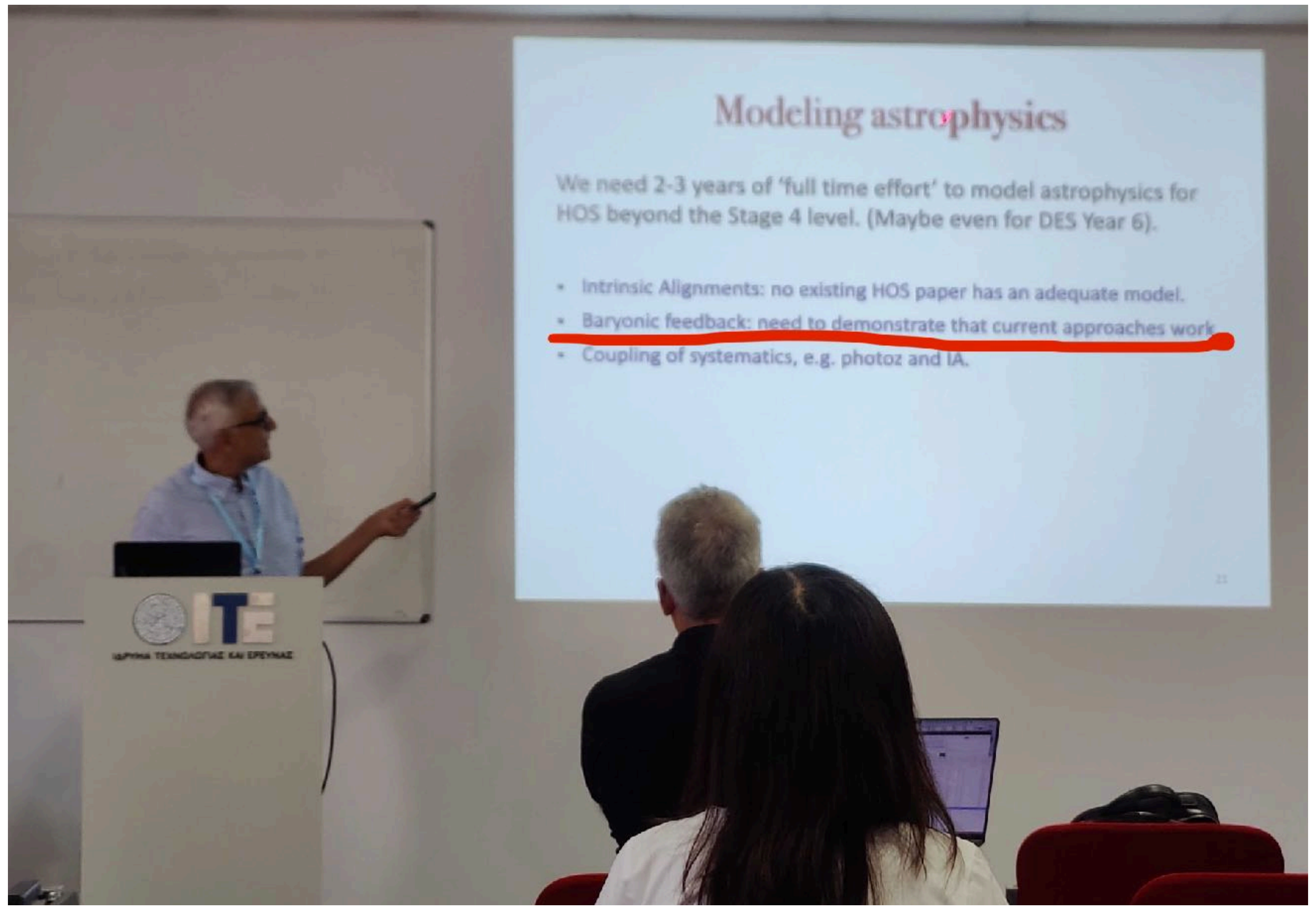
- We also learn something about baryonic physics along the way;

- Easy to extend the model, implement new physics and add more probes!

Backup Slides

Survey

Baryonic feedback: need to demonstrate that current approaches work



Are you convinced?

☐ Yes

☐ No, I'd like to see…