# Baryonic Effects on Large Scale Structure

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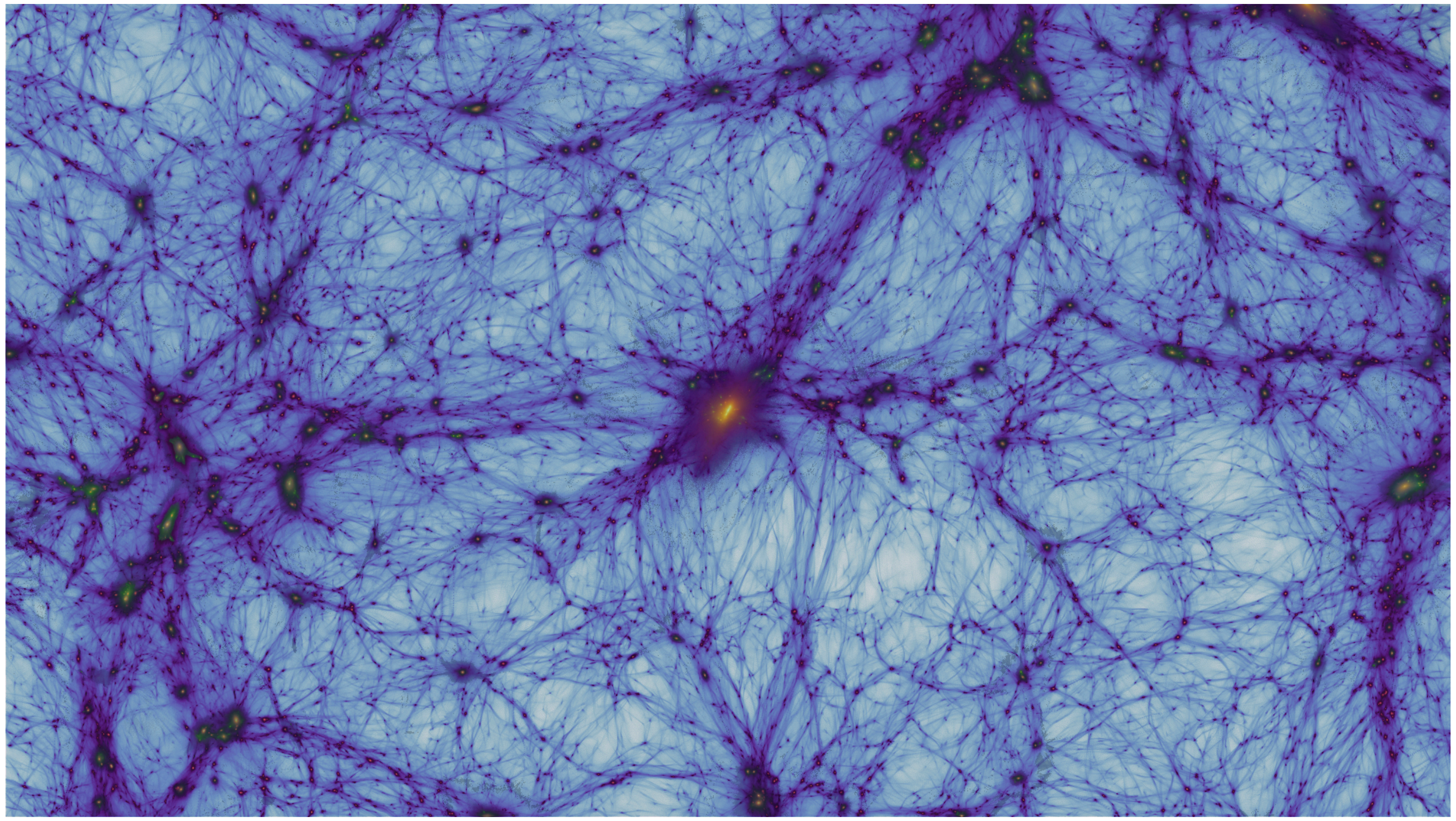
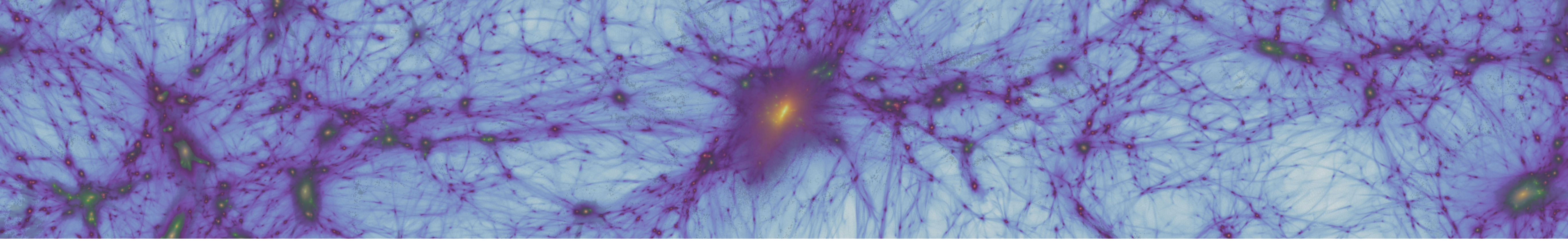


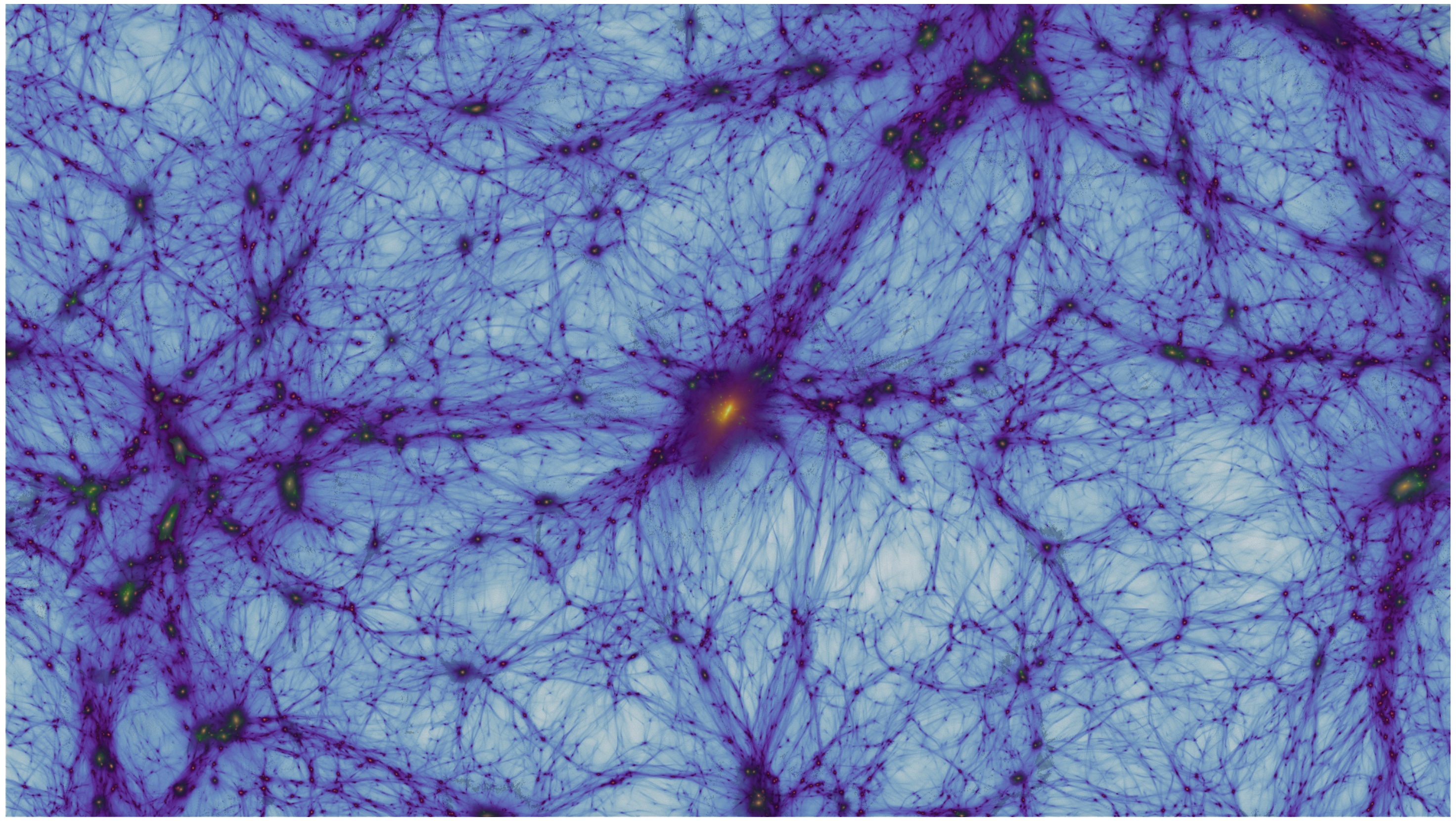
**Cosmology from Home 2022**



# Outline

- Overview of baryonic effects on Large Scale Structure
- The Baryon Correction Model
- Constraints on baryonic processes

# Overview of baryonic effects on Large Scale Structure



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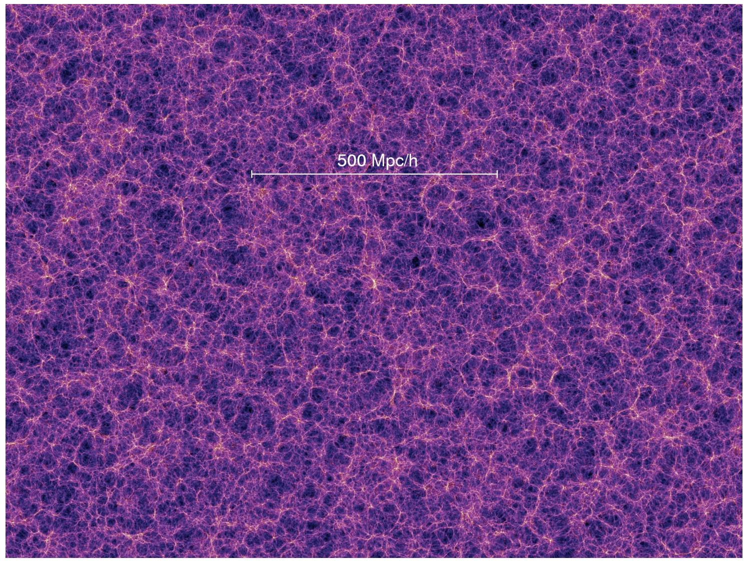
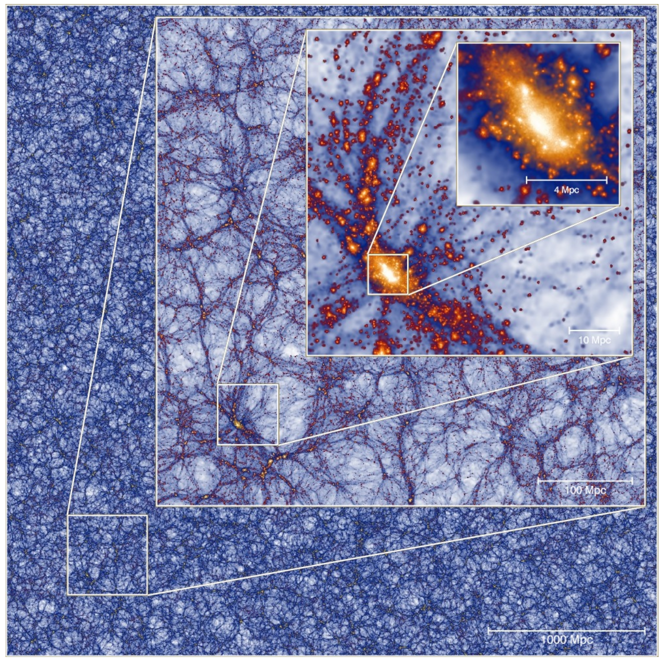
# N-body Simulations

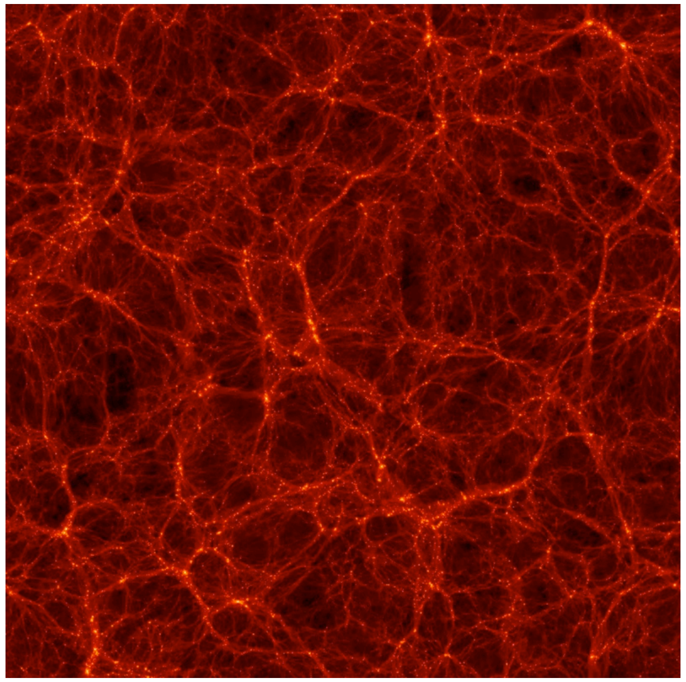
Accurately describe the formation of structure under gravity in the nonlinear regime



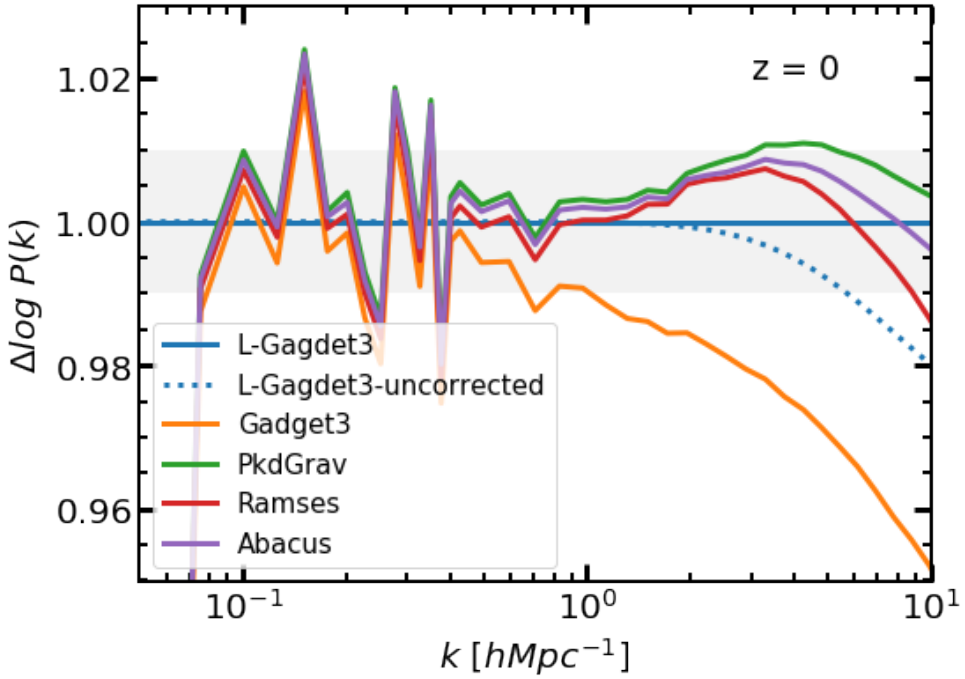
**Millennium**



**Millennium XXL**

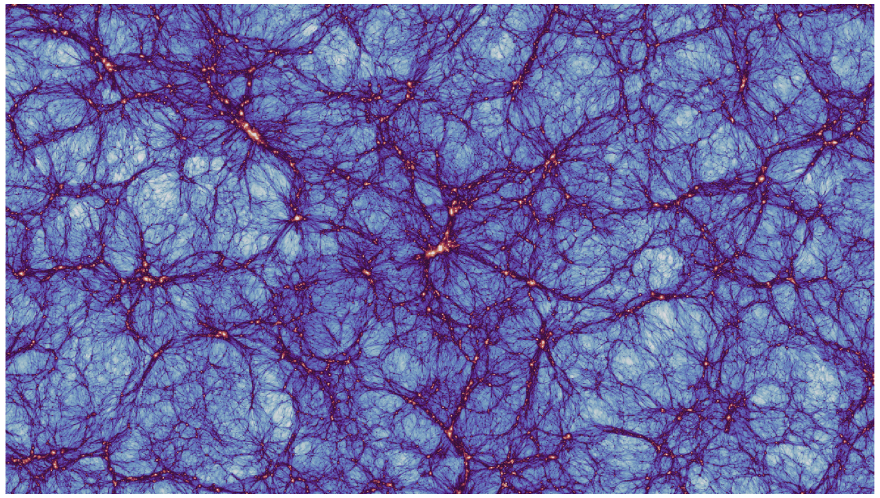


**Bolshoi**



Gravity-only sims agree at 1% level!

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



**BACCO**

**See e.g. review by Angulo & Hahn 2022**

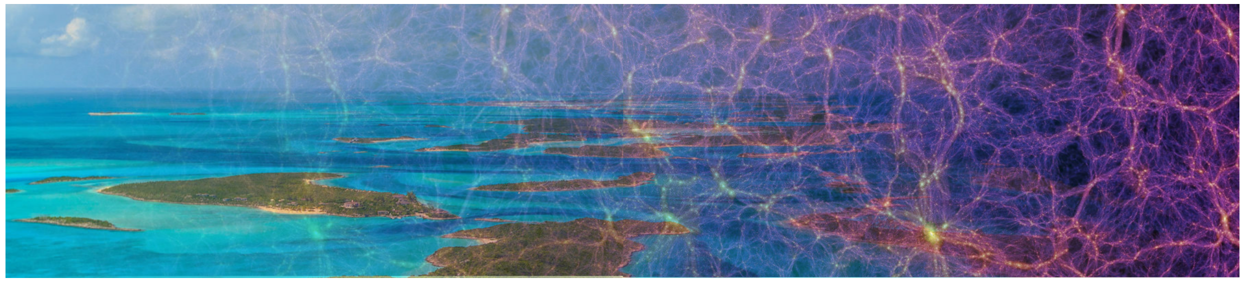
# Large Scale Structure formation

Credits: Illustris Collaboration

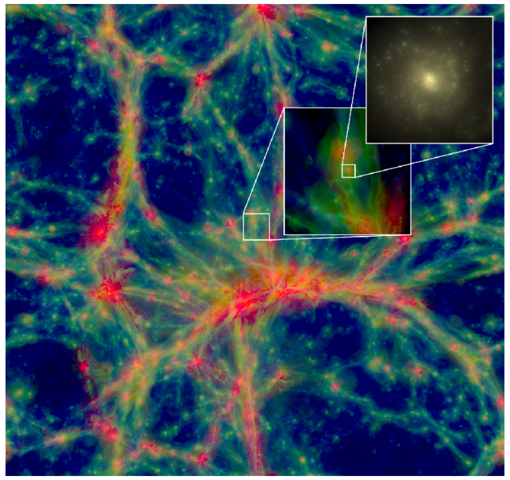
# Hydrodynamical Simulations

Solve hydrodynamical equations plus:

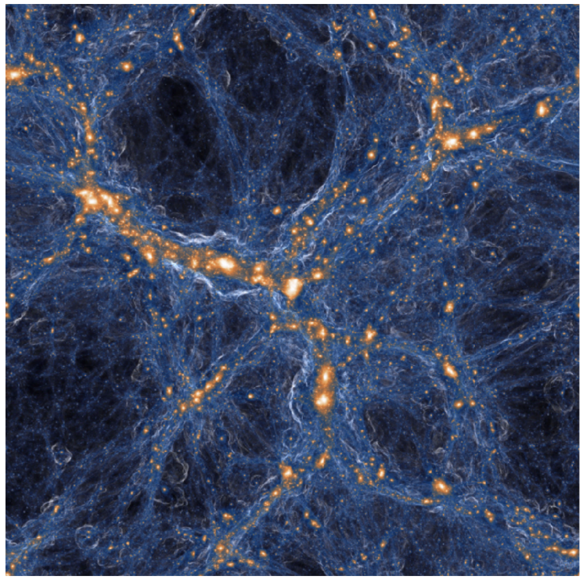
- Star formation and stellar population evolution;
- Stellar, supernovae and blackhole feedback;
- Formation, merging, and accretion of supermassive blackholes;
- Chemical enrichment;
- Gas radiation;
- Cosmic magnetic fields;



BAHAMAS

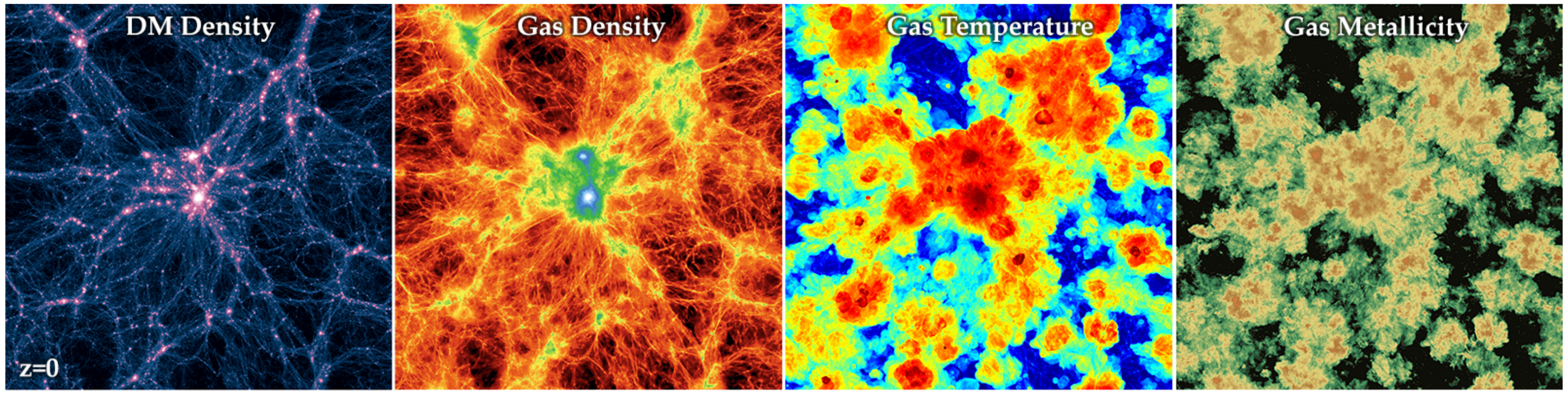


EAGLE

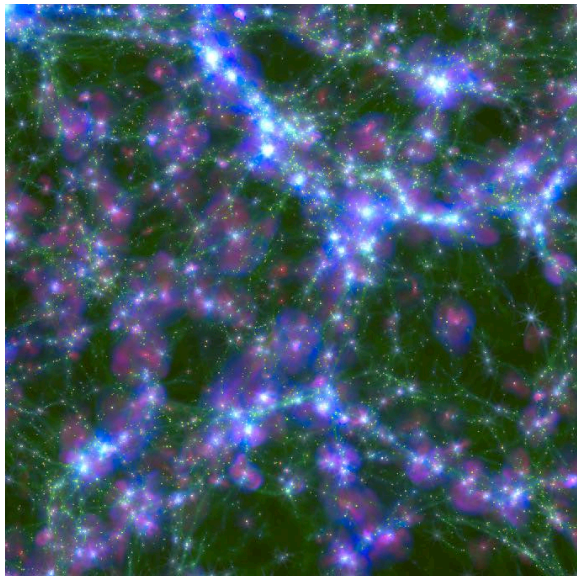


Illustris TNG

Realistic galaxy formation, colors, chemical abundance



Illustris

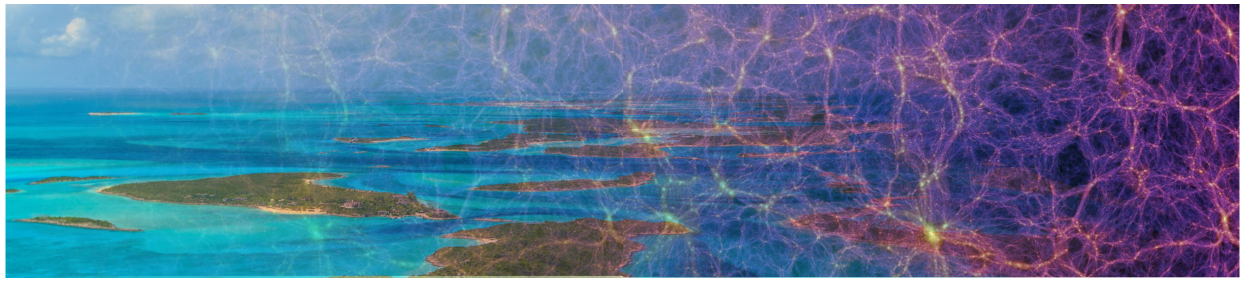


Horizon-AGN

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

# Hydrodynamical Simulations

- Computationally expensive;
- Difficult Calibration;
- Difficult Convergence;
- Sub-grid prescriptions;



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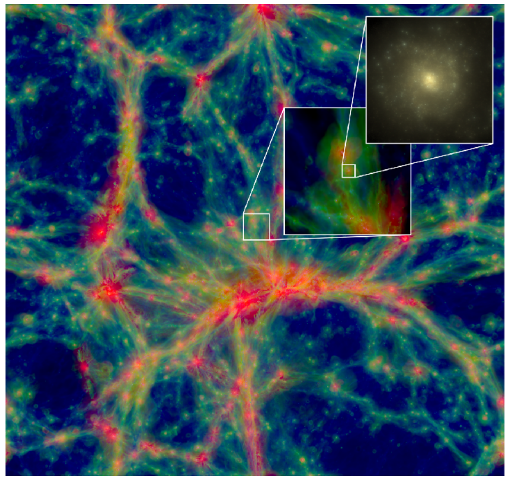

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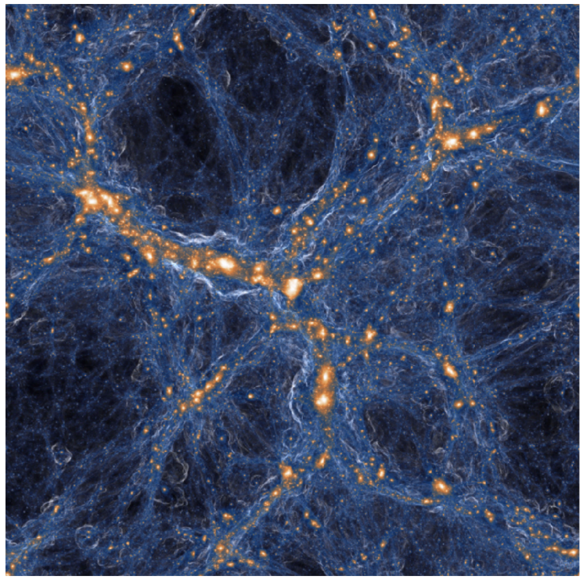
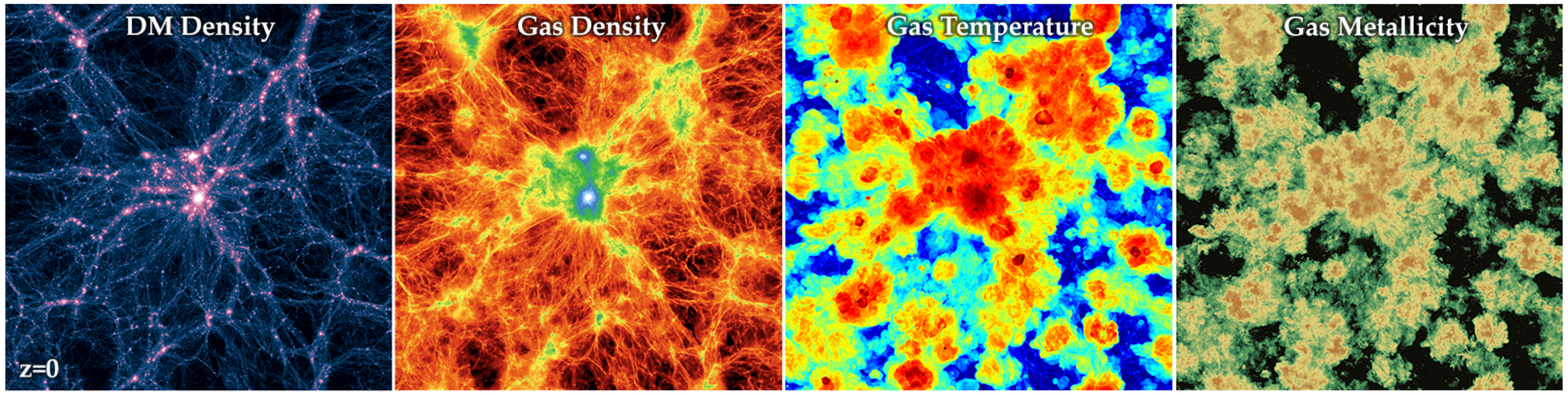


Illustris TNG



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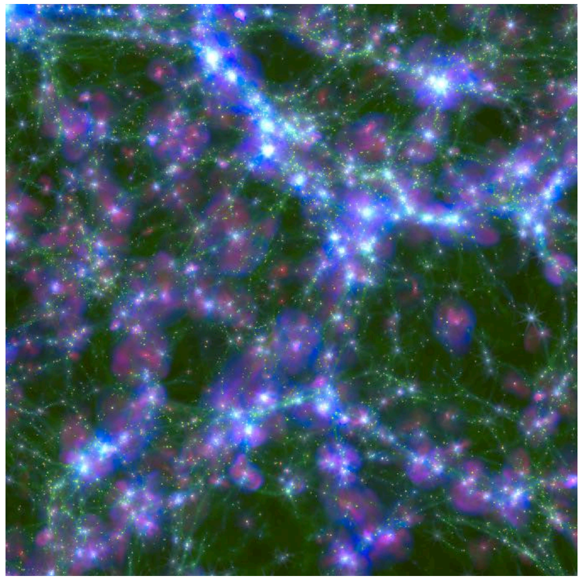

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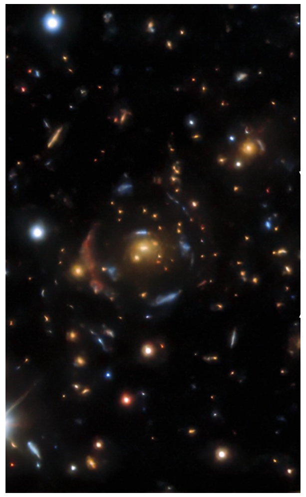
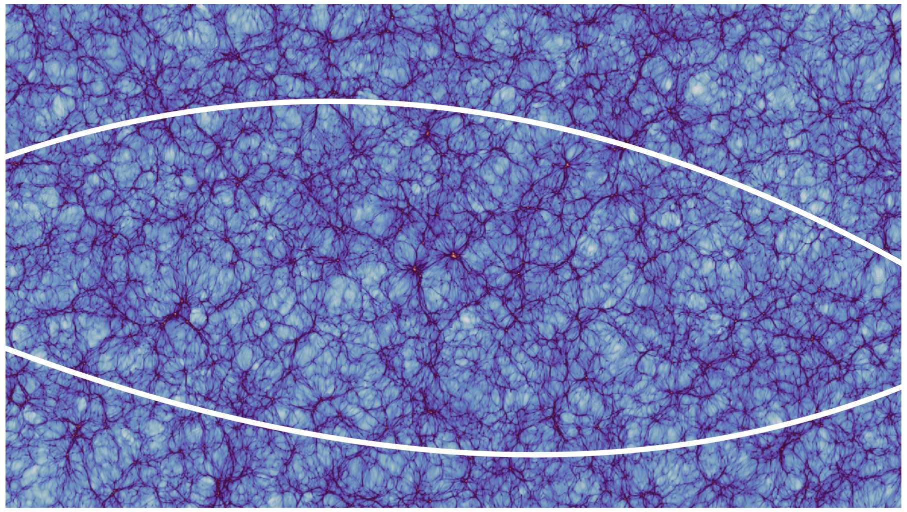
# Baryonic impact on LSS statistics

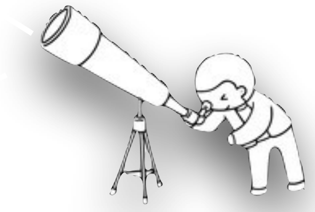
## Weak Gravitational Lensing: Cosmic Shear



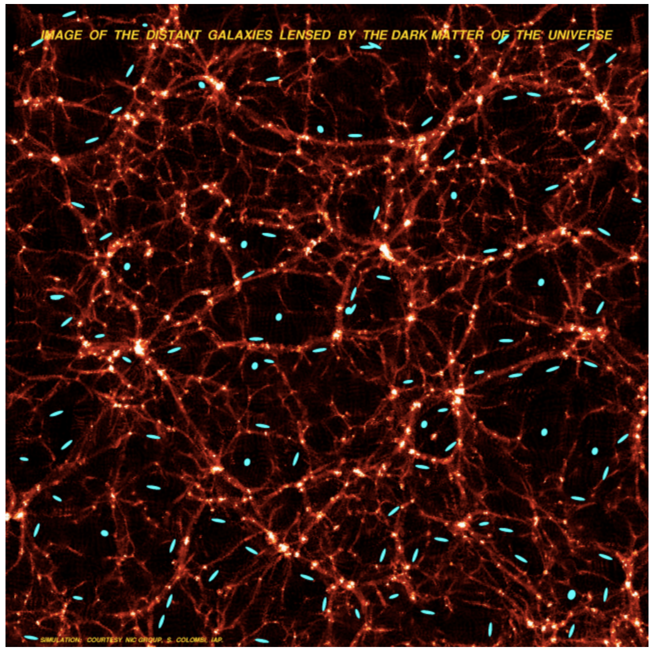
**Far galaxies**



**Large Scale Structure: DM + baryons**



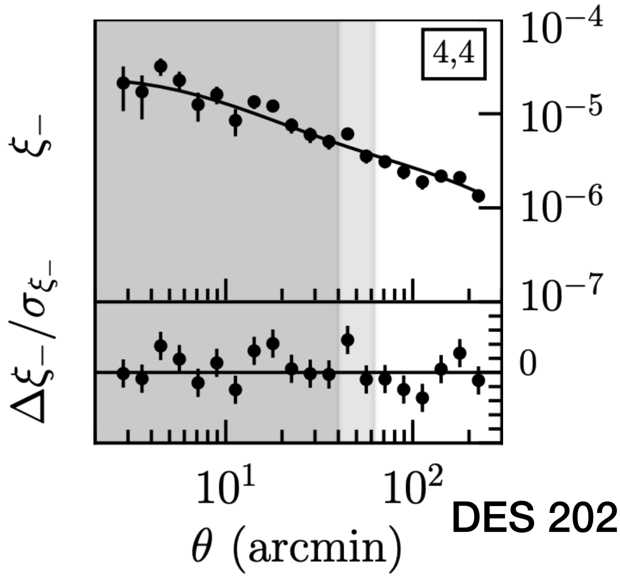
**Observer**



Courtesy of NYC group, S.Colombi

Correlation of galaxy shapes due to LSS gravity

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



**DES 2022**

# Baryonic impact on LSS statistics

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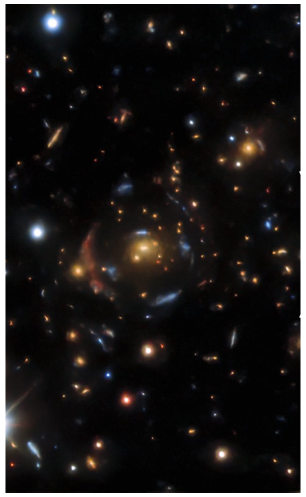

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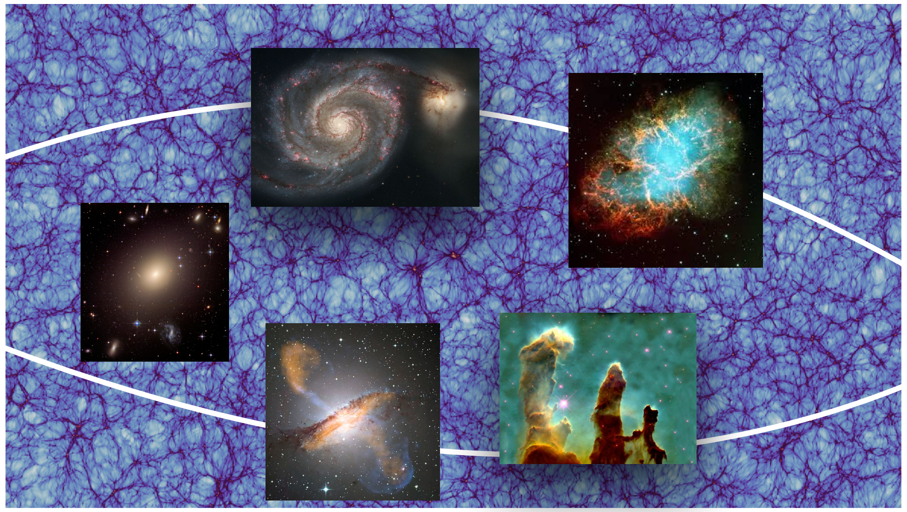

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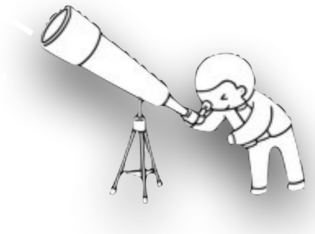
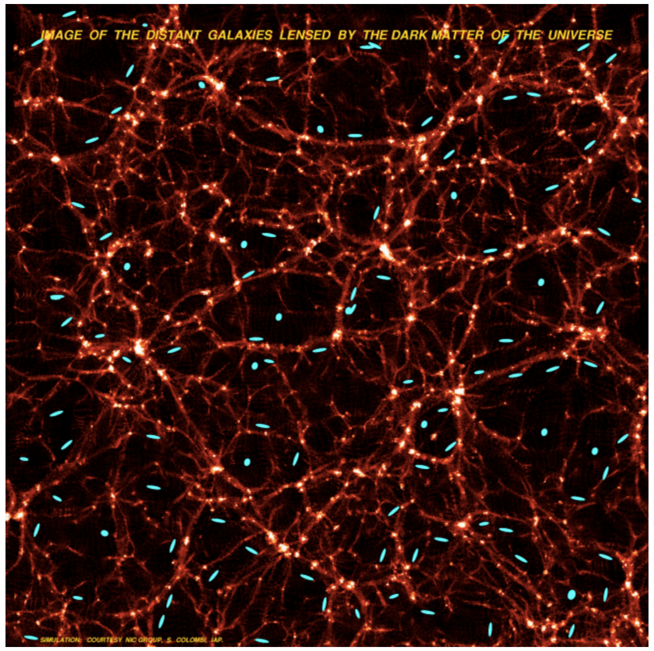


Observer



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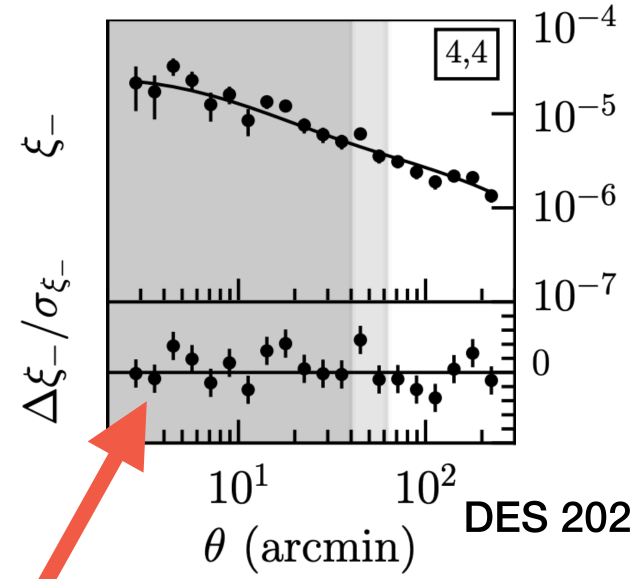
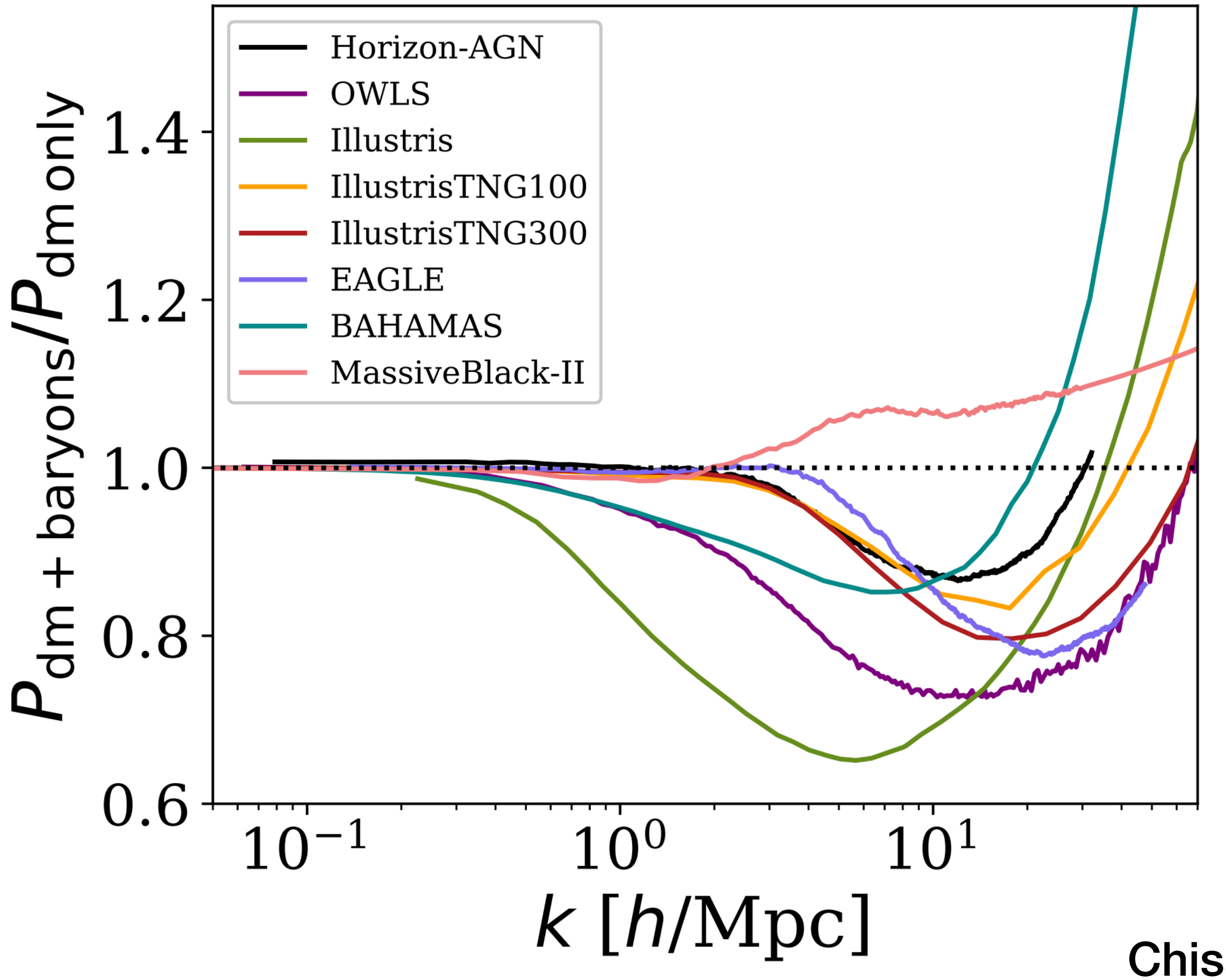


DES 2022

baryonic effects in *P(k)*

# Baryonic impact on LSS statistics

Matter power spectrum

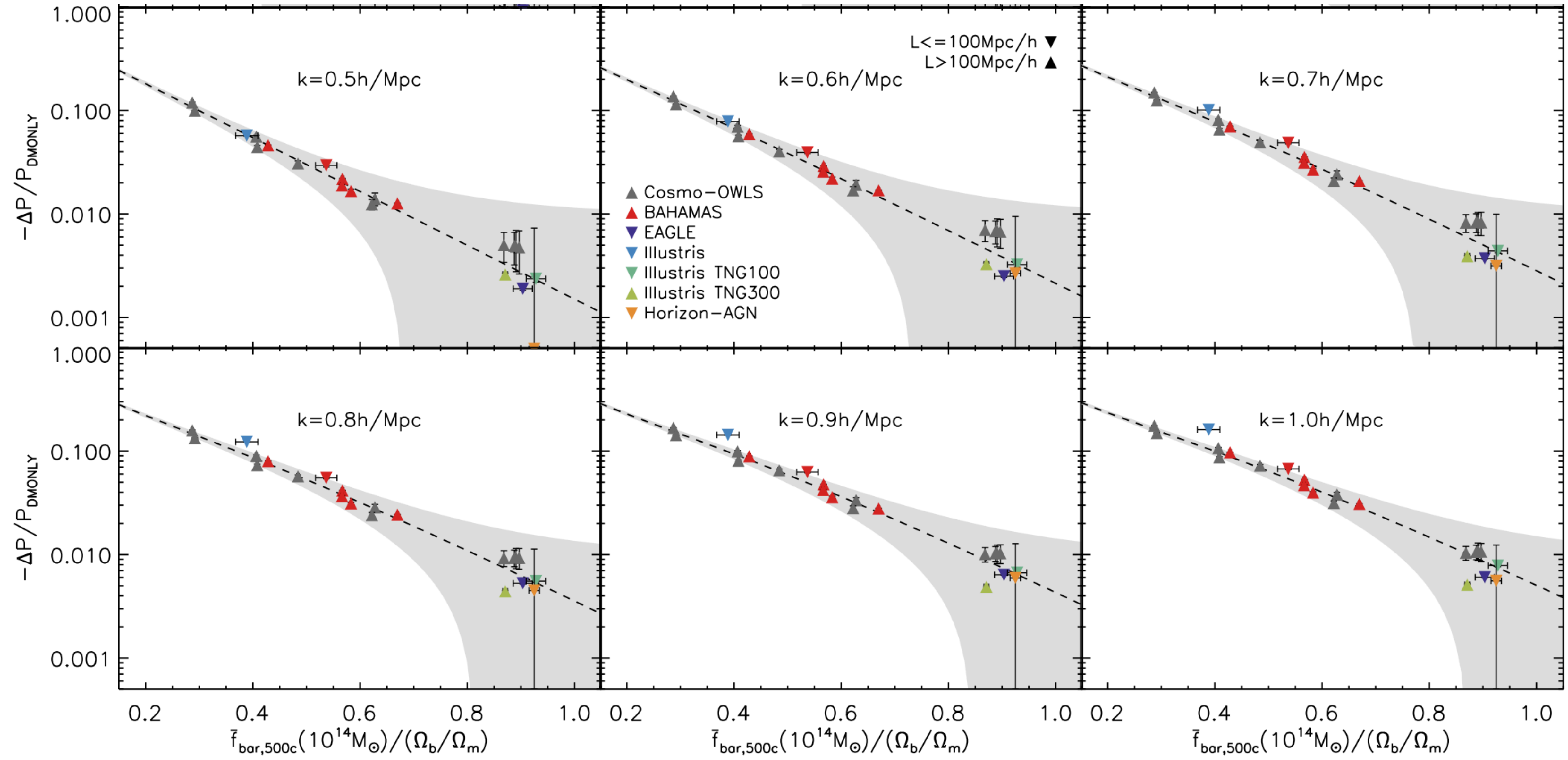


Chisari et al. 2019

Predictions differ by 40%! Different calibration and sub-grid prescriptions

# Baryonic impact on LSS statistics

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



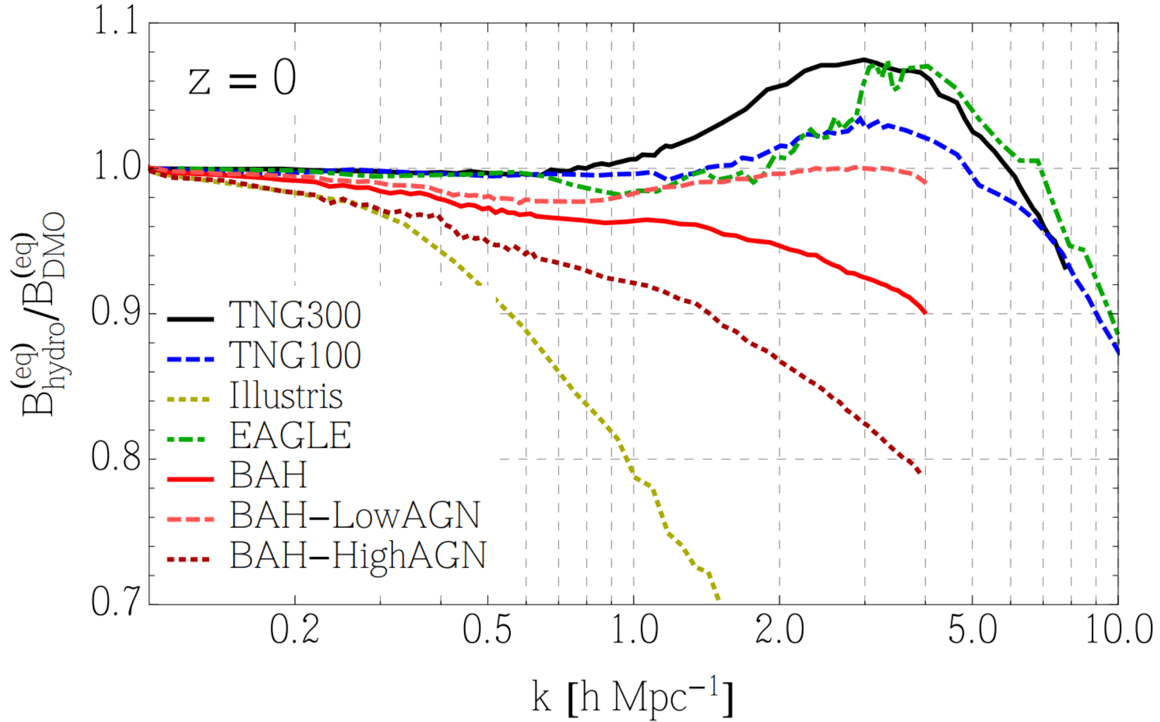
**Van Daalen et al. 2020**

Library with more than 100 power spectra

freely available at https://powerlib.strw.leidenuniv.nl/

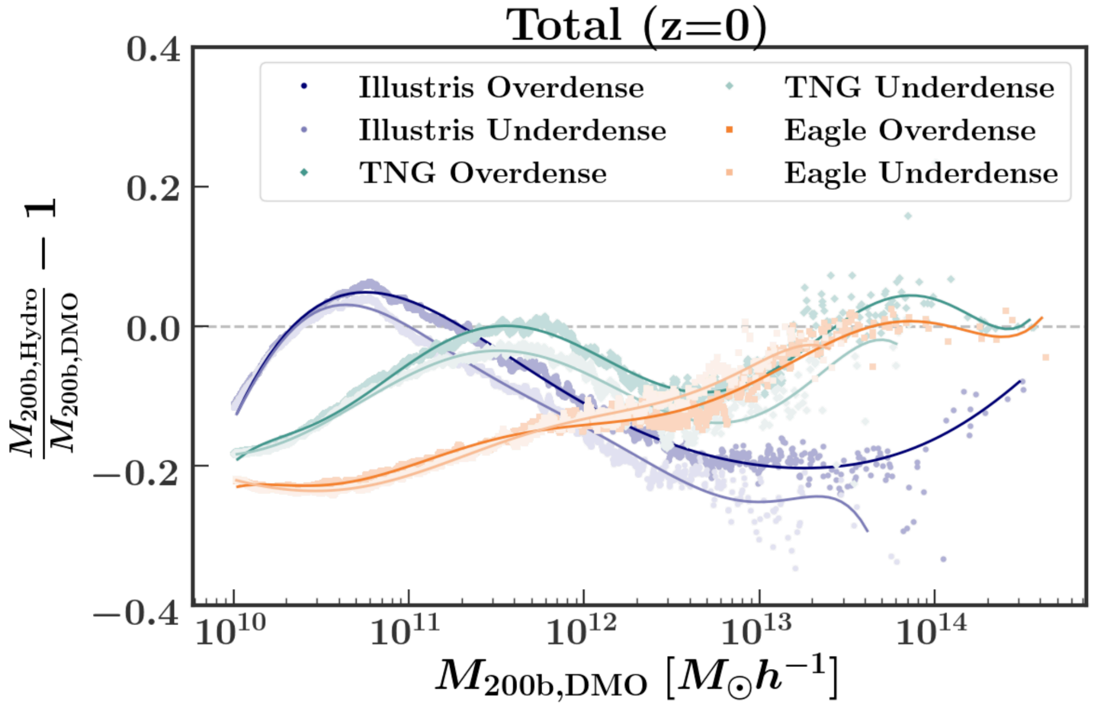
# Baryonic impact on LSS statistics

## Matter bispectrum



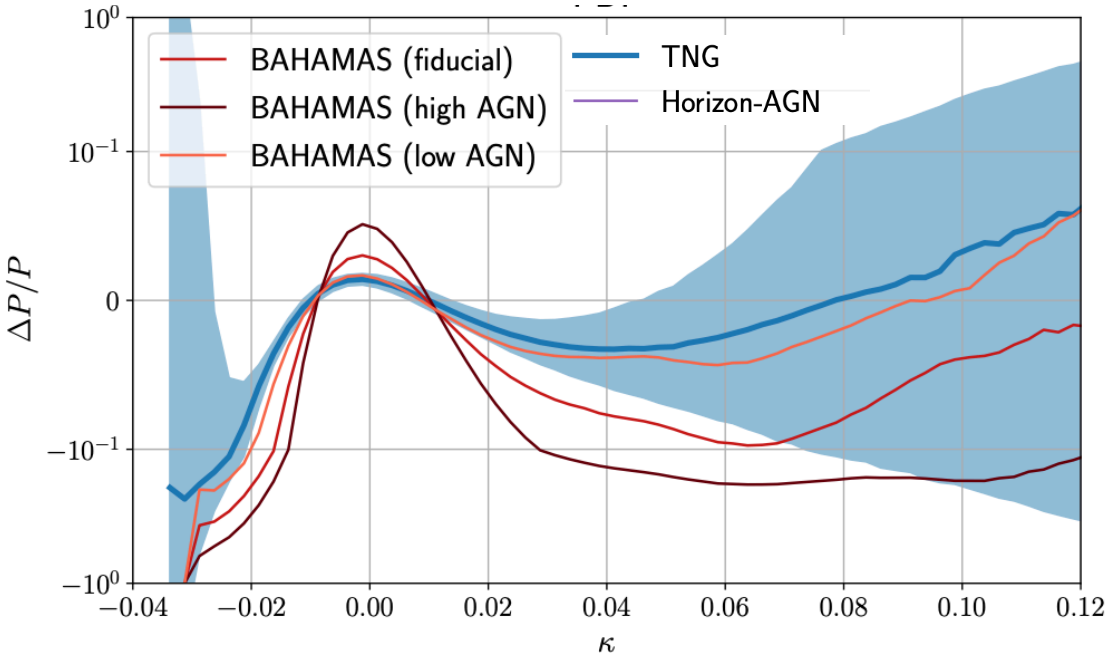
Foreman et al. 2020

## Halo mass function



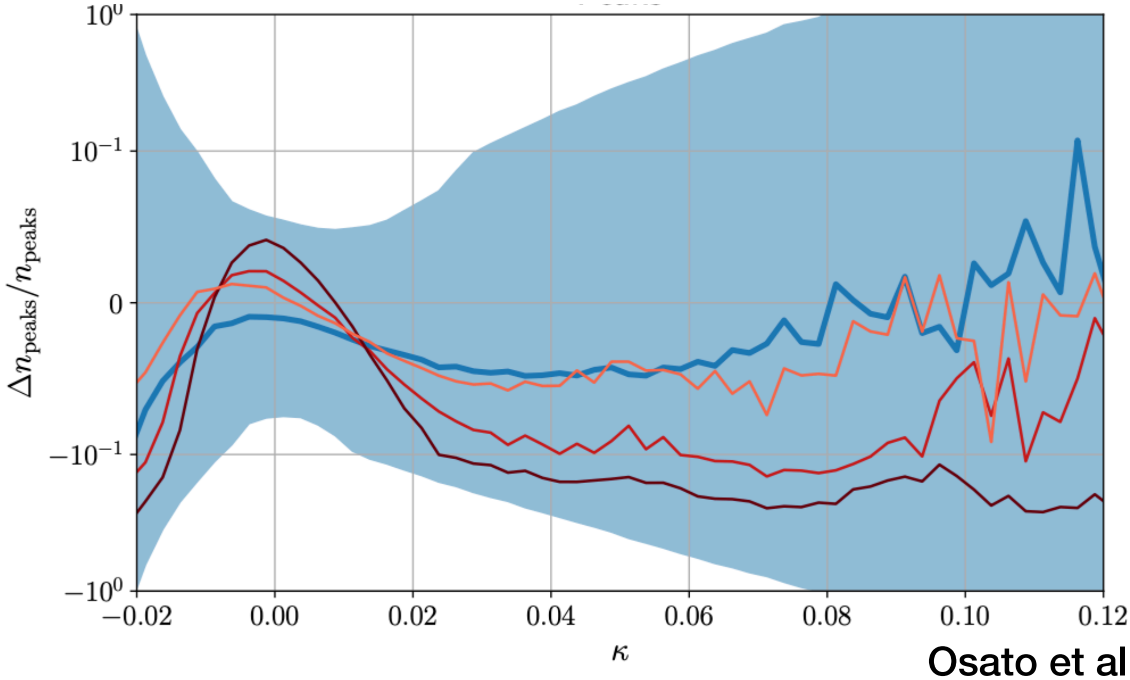
Beltz-Mohrmann & Berlind 2021

## Convergence PDF



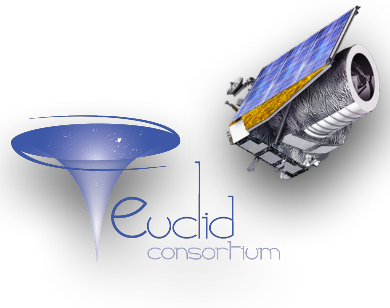
Osato et al. 2021

## Convergence Peaks



Osato et al. 2021

# Forecasts for stage IV surveys (Euclid, LSST)



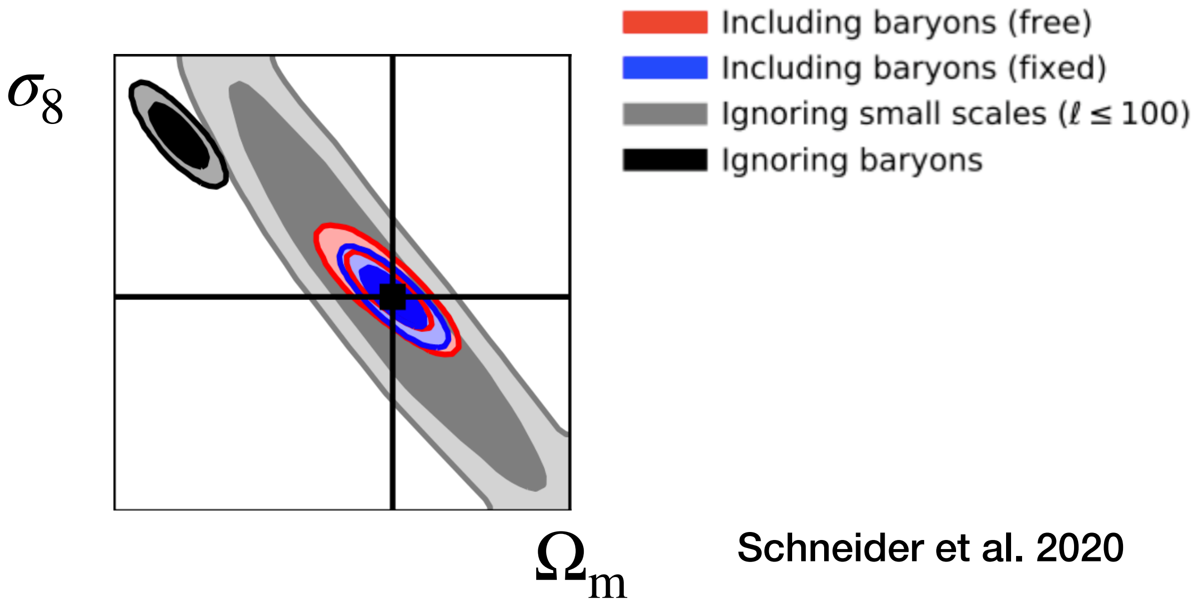
Wider and deeper surveys

Designed to achieve 1% accuracy in the Dark Energy EoS

Expected peak sensitivities at scales

$1h\mathrm{Mpc}^{-1} \leq k \leq 7h\mathrm{Mpc}^{-1}$ ,

need 1% accuracy in $P(k)$ (e.g.Taylor et al., 2018)

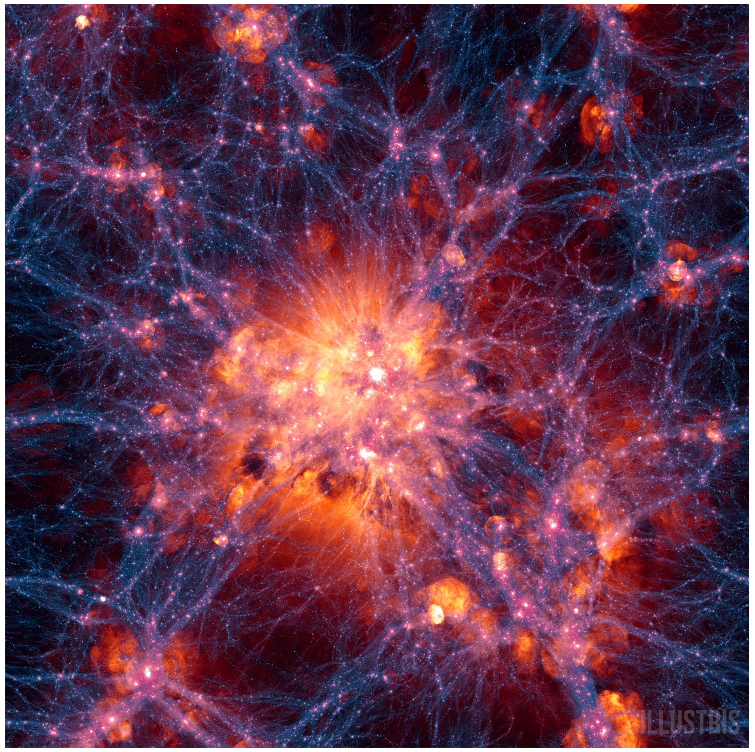


Schneider et al. 2020

1. Baryonic effects cannot be ignored —> **sever bias in cosmology!**
2. Different hydrodynamical simulations give different predictions!

Effect of different sub-grid implementations, calibration, resolution, physical prescriptions: baryonic processes in LSS are still largely unknown!

# How to (properly) model baryonic effects in LSS analyses?*



Illustris

*special focus on matter power spectrum, but generalisation possible!

# Baryonic modelling

See review of Chisari et al. 2019

**PCA**

**Halo Model**

**Machine Learning**

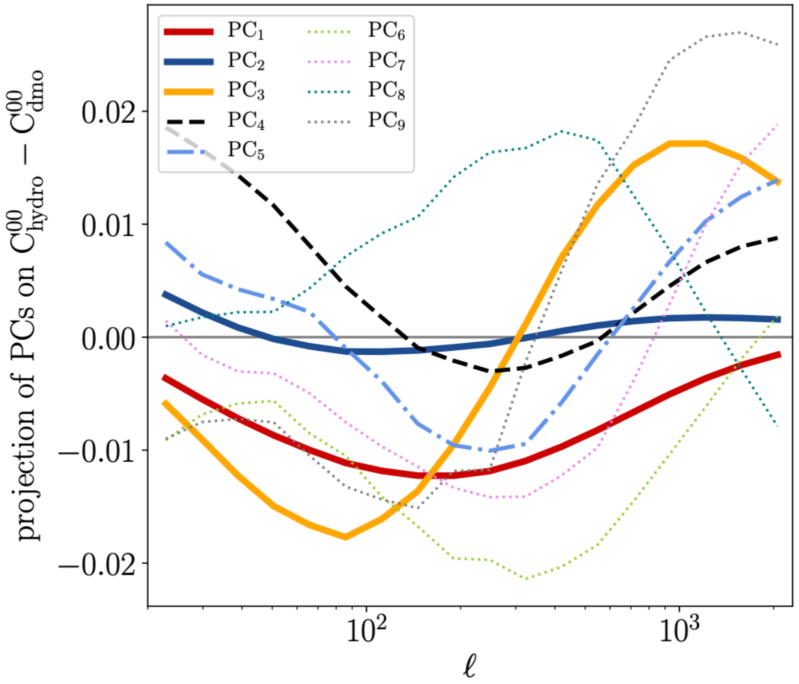
**Hybrid Methods**

# Baryonic modelling

See review of Chisari et al. 2019

PCA

See e.g.:
Eifler et al. 2014;
Huang et al. 2019;



Huang et al. 2019

## Halo Model

## Machine Learning

## Hybrid Methods

# Baryonic modelling

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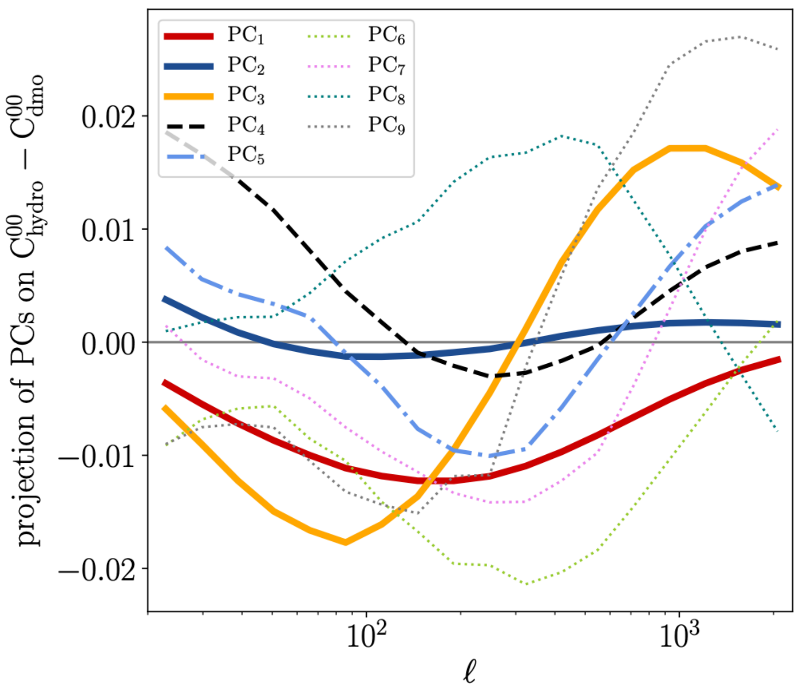
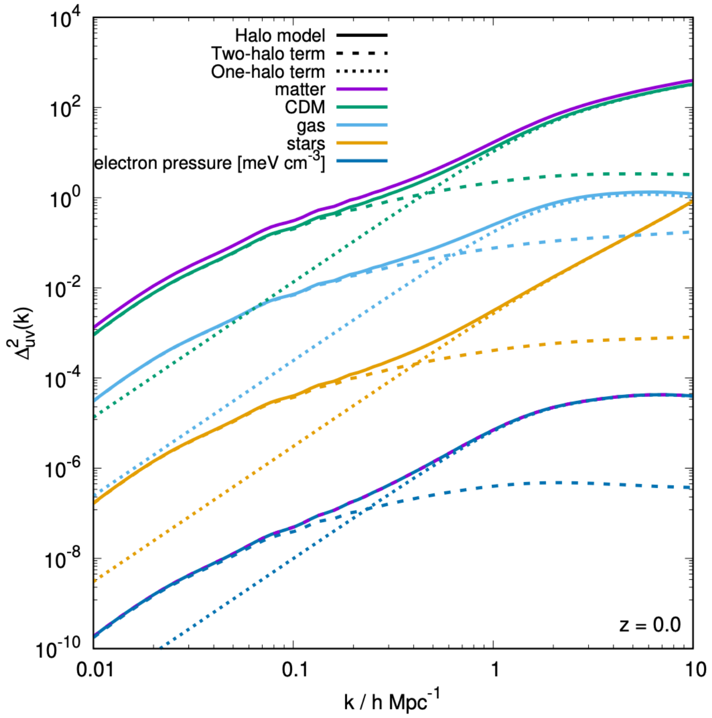


Huang et al. 2019

Halo model

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



Mead et al. 2021

## Machine Learning

## Hybrid Methods

# Baryonic modelling

See review of Chisari et al. 2019

## PCA

See e.g.:
Eifler et al. 2014;
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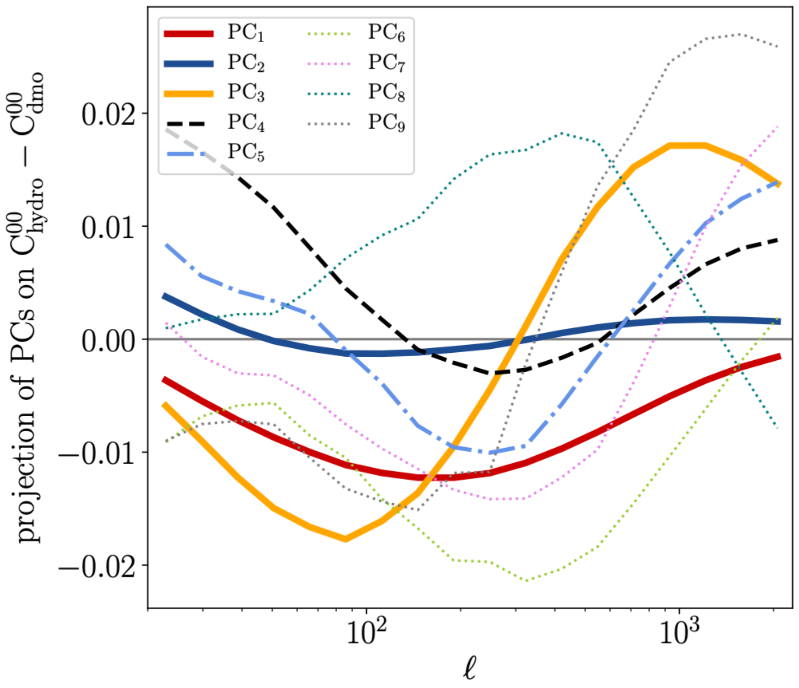

Huang et al. 2019

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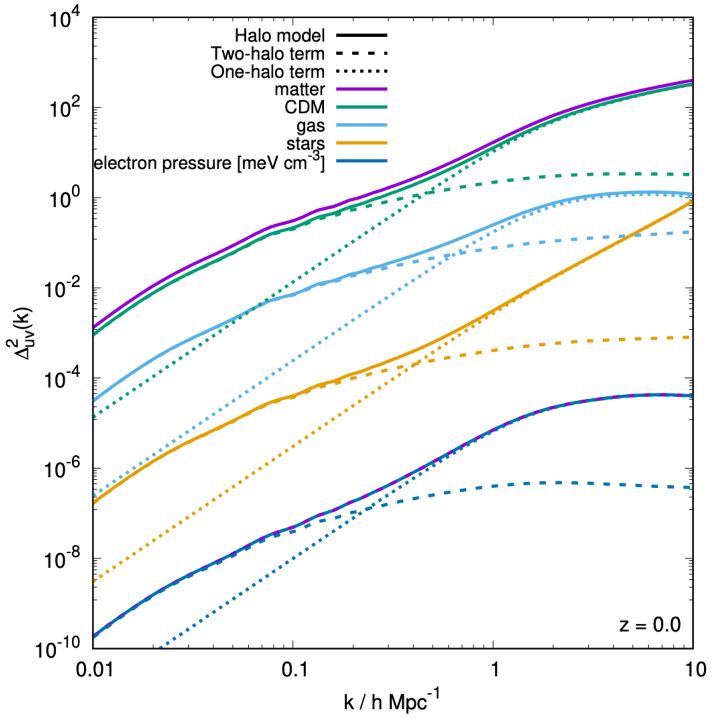
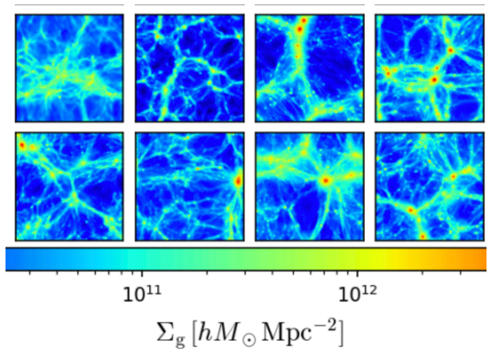


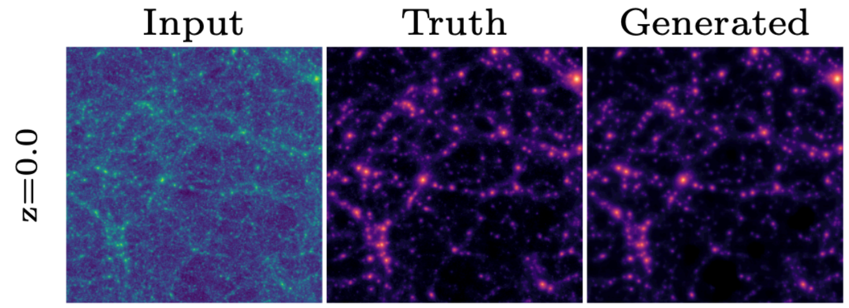
Mead et al. 2021

## Machine learning

See e.g.:
Tröster et al. 2019;
Dai & Seljak 2020;
Villaescusa et al. 2021;



CAMELS, Villaescusa et al. 2021



Tröster et al. 2019

# Hybrid Methods

# Baryonic modelling

See review of Chisari et al. 2019

## PCA

**See e.g.:**
**Eifler et al. 2014;**
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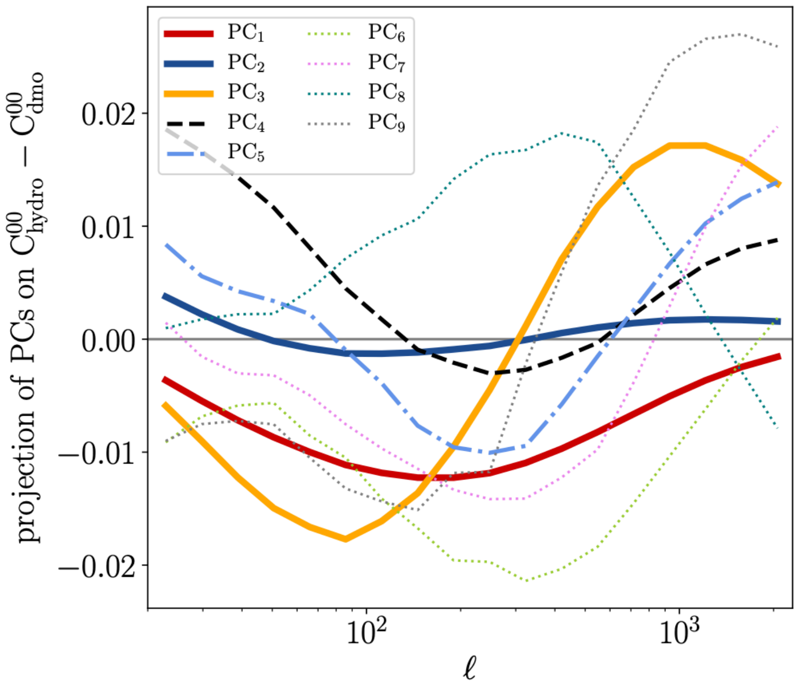

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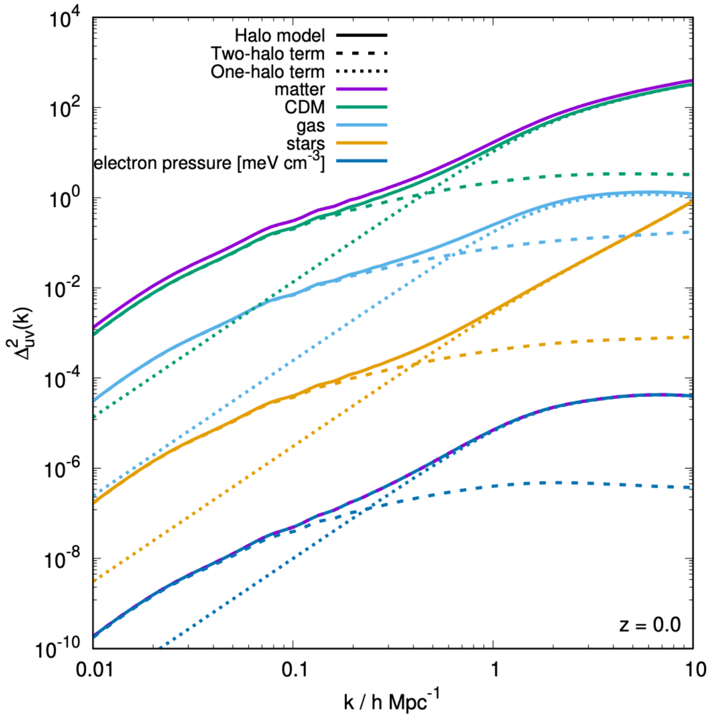

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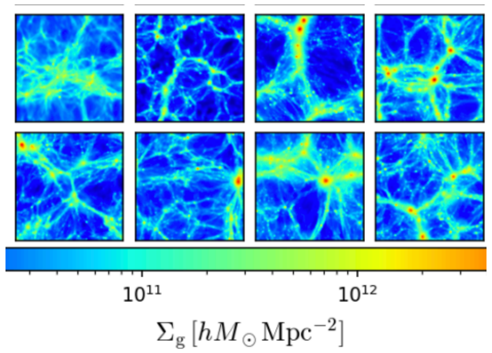

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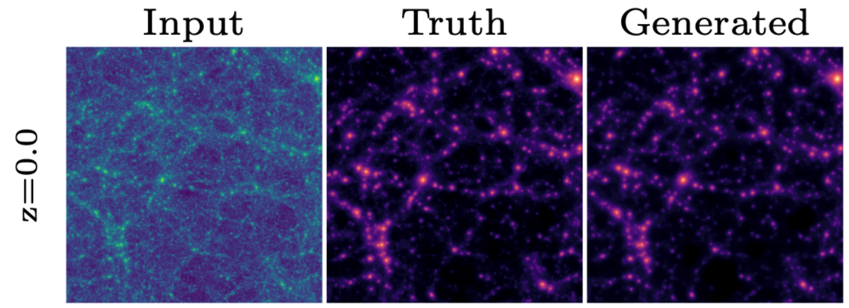
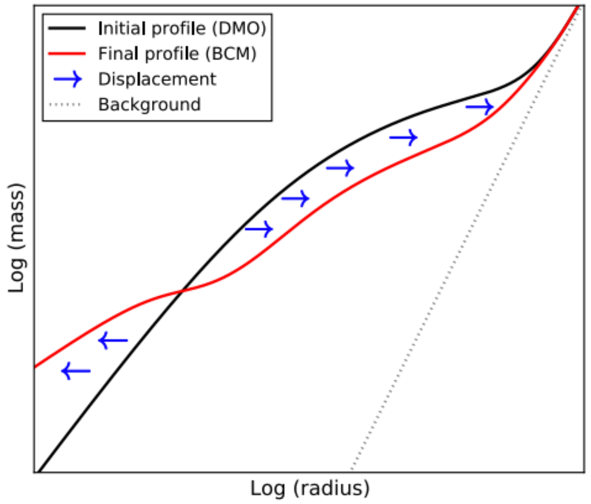


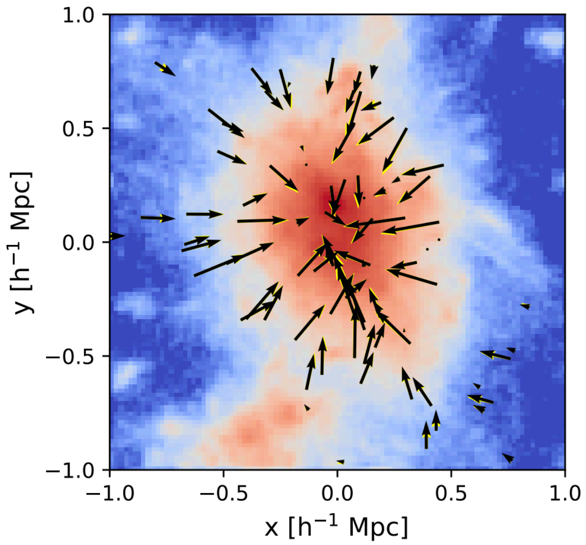
Tröster et al. 2019

## Hybrid

**(Baryonification, gradient descendent methods, Baryon Pasting Algorithm)**



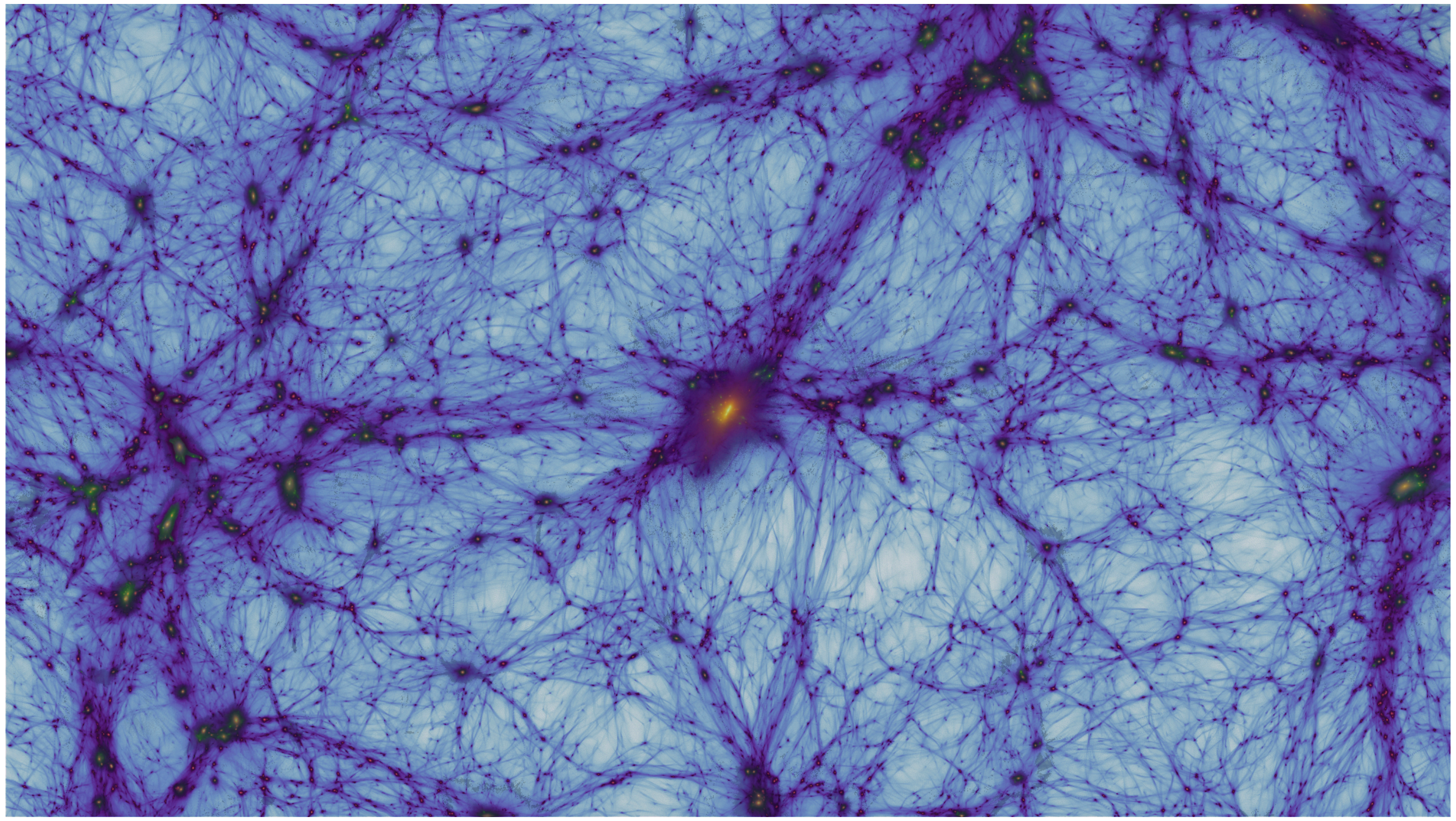
Schneider & Teyssier 2015



Dai et al. 2019

See also: Aricò et al. 2019; Dai & Seljak 2020; Osato & Nagai 2022

# The Baryon Correction Model

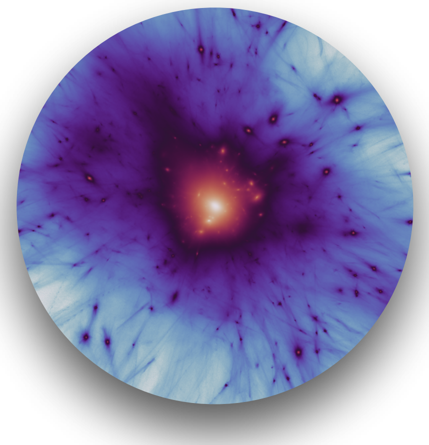


Giovanni Aricò

Institute for Computational Science, University of Zurich

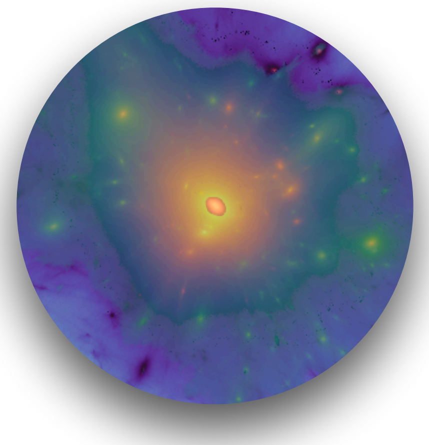
**Cosmology from Home 2022**

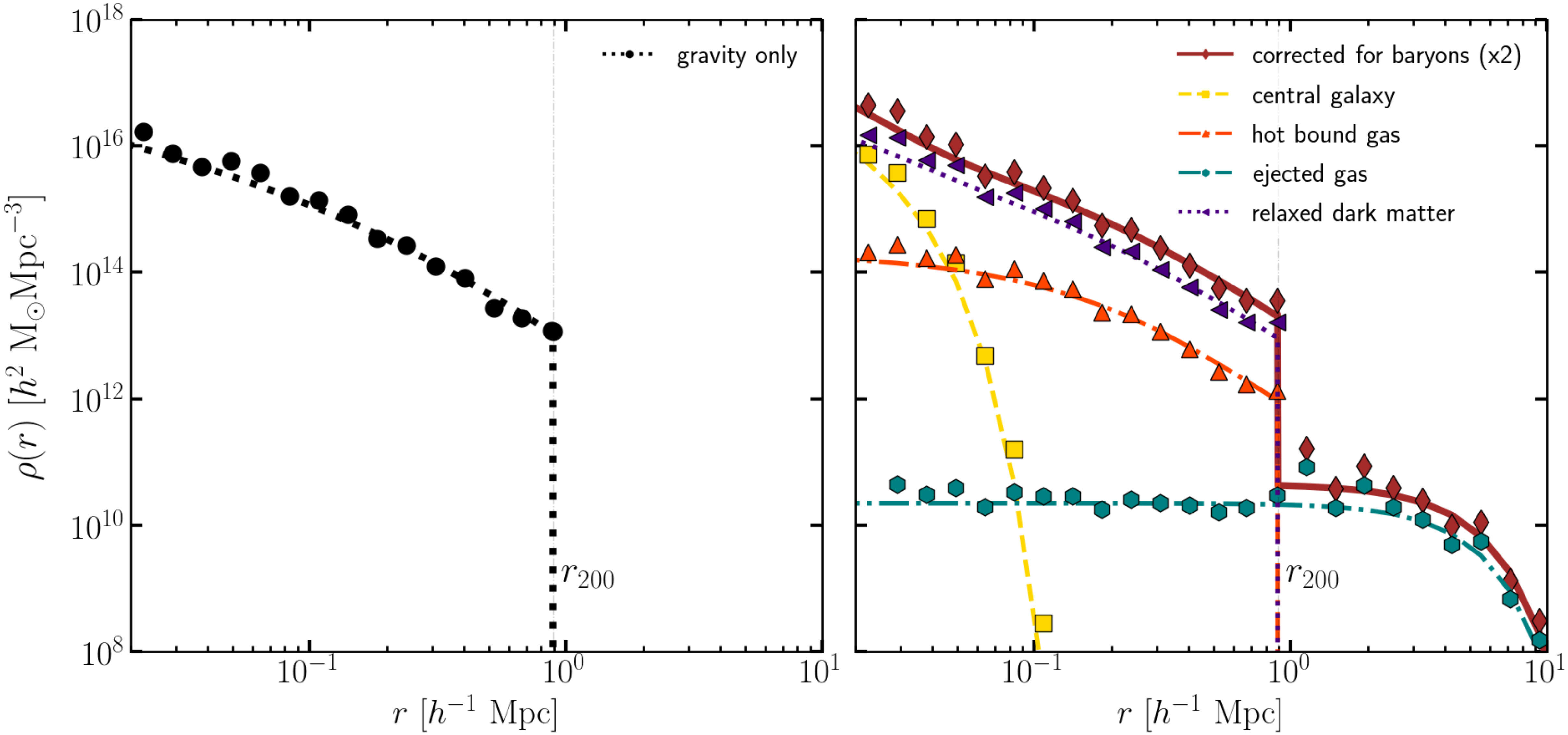
# Baryon Correction Model
# a.k.a. baryonification



before
baryonification

after
baryonification





Schneider & Teyssier 2015; Aricò et al. 2019

# BCM: the Model

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

**Dark Matter**

Comic baryon fraction

$$f_{\rm DM} = 1 - \Omega_{\rm b}/\Omega_{\rm m}$$

**Stars**

Abundance Matching

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

**Gas**

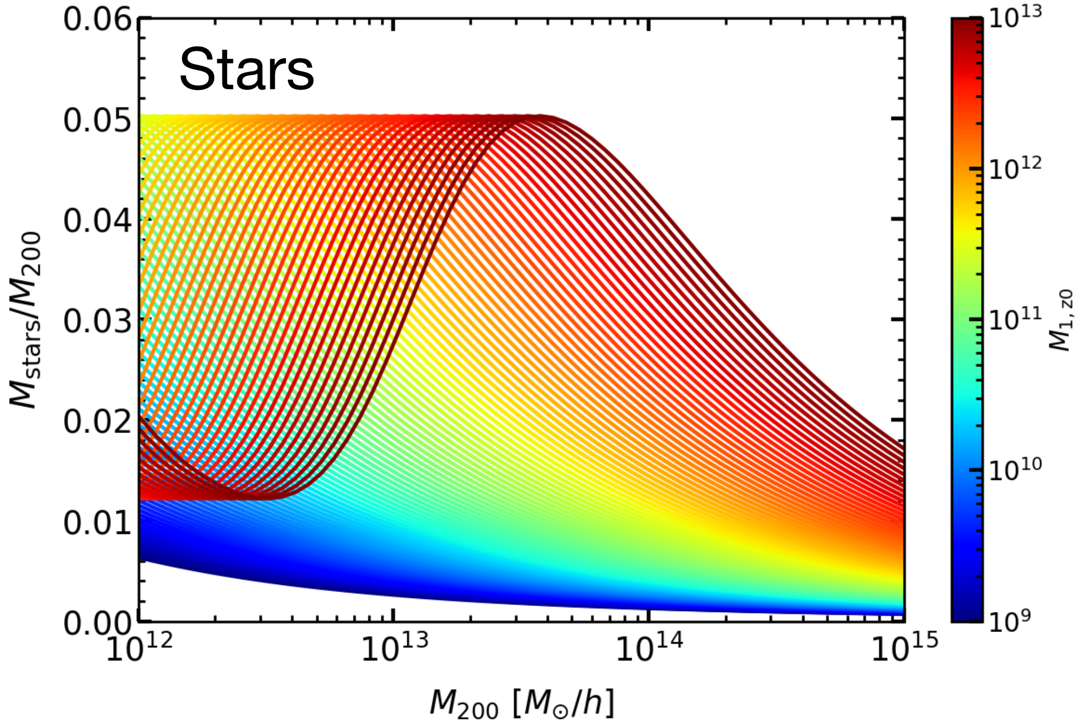
Bound in halos

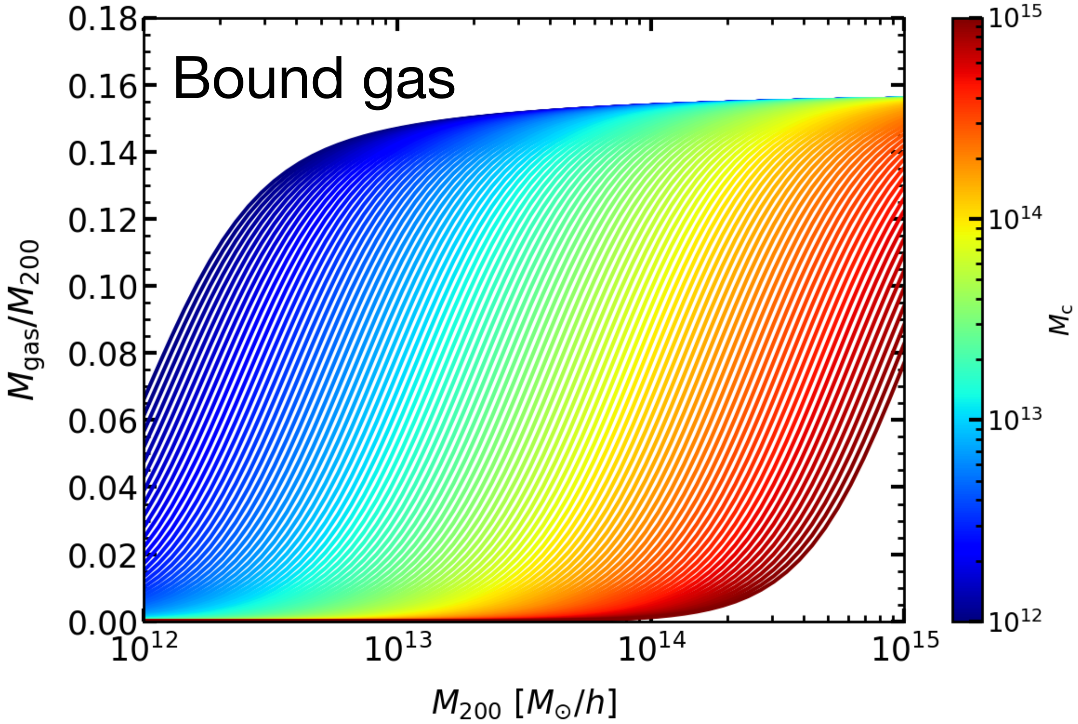
$$f_{gas} = \frac{\Omega_{\rm b}/\Omega_{\rm m} - f_{\rm stars}}{1 + (M_{\rm c}/M_{200})^{\beta}}$$

Ejected

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

$M_{\rm c}, \beta, M_1$ free parameters





Aricò et al. 2020

# BCM: the Model

## Density profiles (imposing continuity)

**Dark Matter**

NFW + quasi adiabatic relaxation
(baryonic back-reaction)

**Stars**

Power Law + cut-off

**Gas**

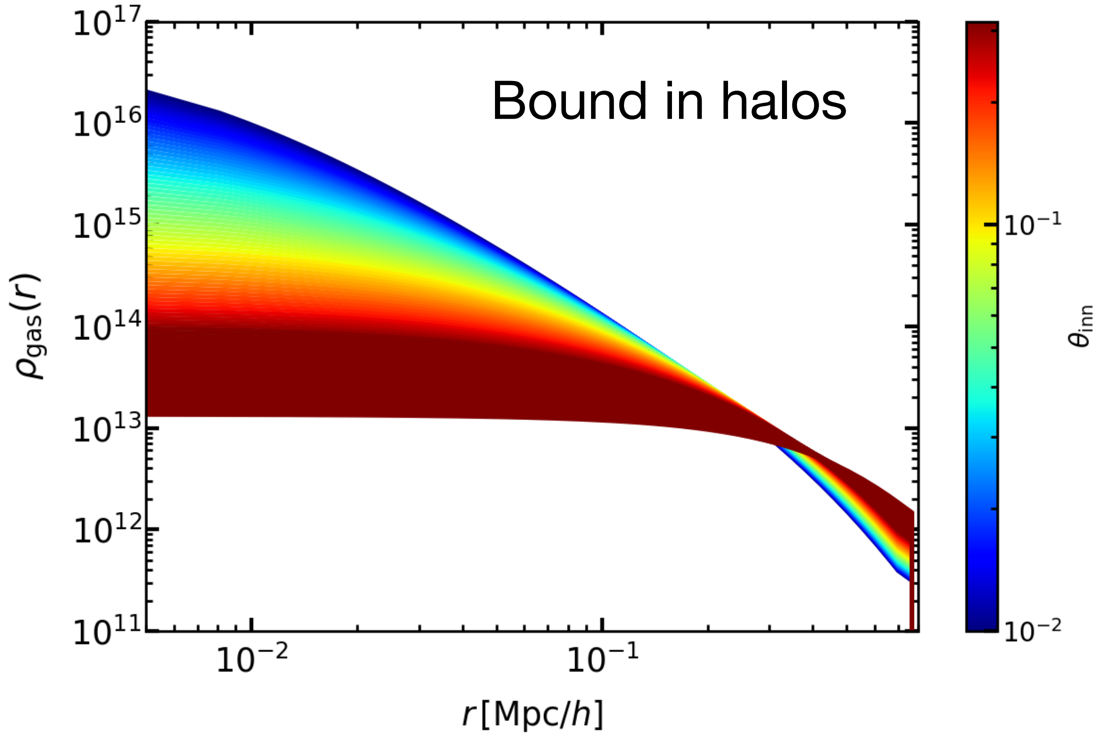
Bound in halos

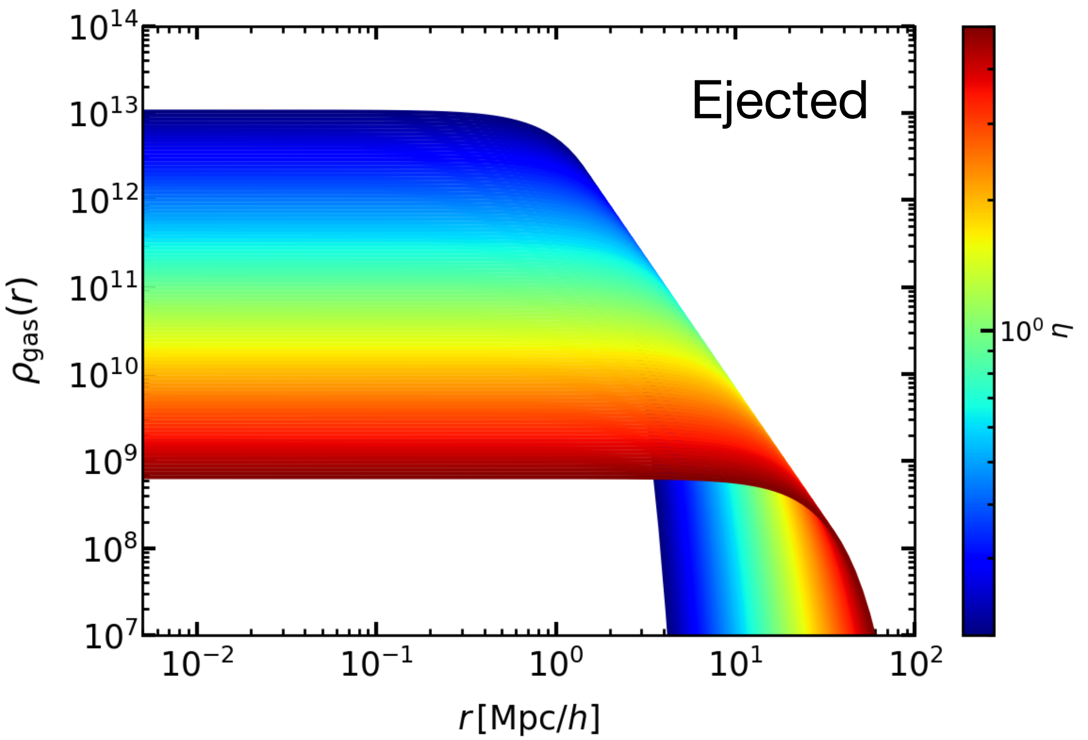
$$\rho_{\rm gas,bo} \propto \frac{1}{(1 + r/\boxed{r_{\rm inn}})^{\boxed{\beta_{\rm inn}}} \, (1 + (r/\boxed{r_{\rm out}})^2)^2}$$

Ejected from halos

$$\rho_{\rm EG} = \frac{M_{200}}{(2\pi r_{\rm ej}^2)^{3/2}} \exp\left(-\frac{1}{2}\left(\frac{r}{r_{\rm ej}}\right)^2\right)$$

$$r_{\rm ej} \propto \boxed{\eta}\, r_{\rm escape}$$





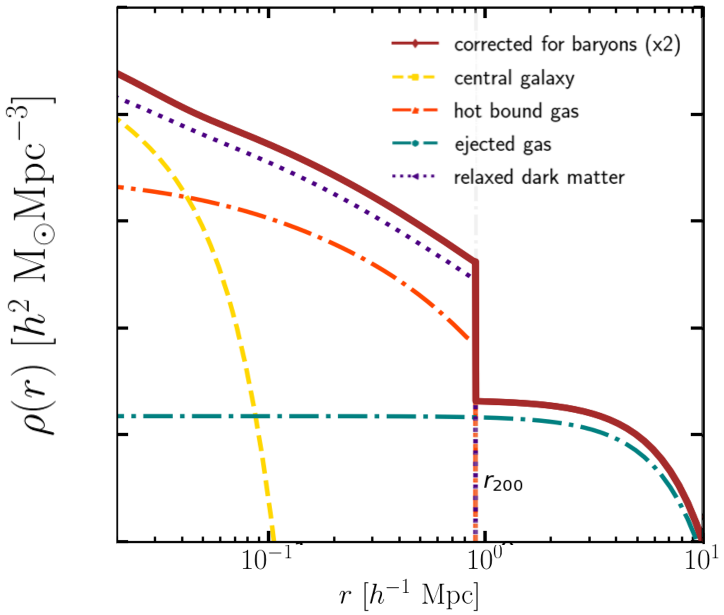
$r_{\rm inn}, r_{\rm out}, \eta, \beta_{\rm inn}$ **free parameters**

Aricò et al. 2021

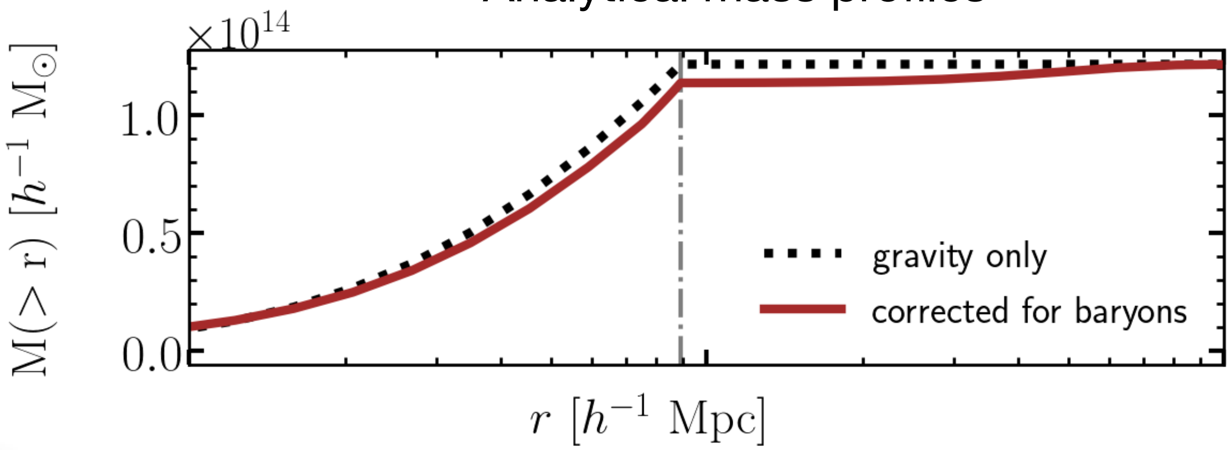
# Baryon Correction Model

Integrate

Halo analytical density profiles



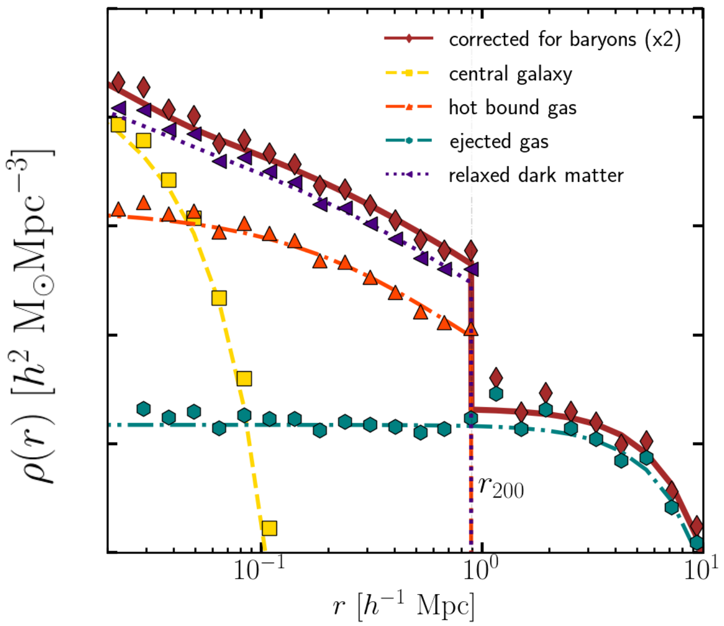
Analytical mass profiles

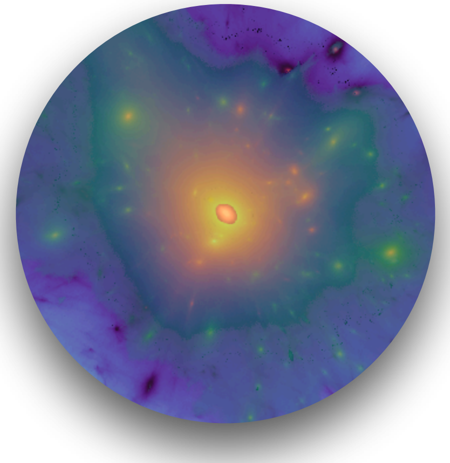


Invert

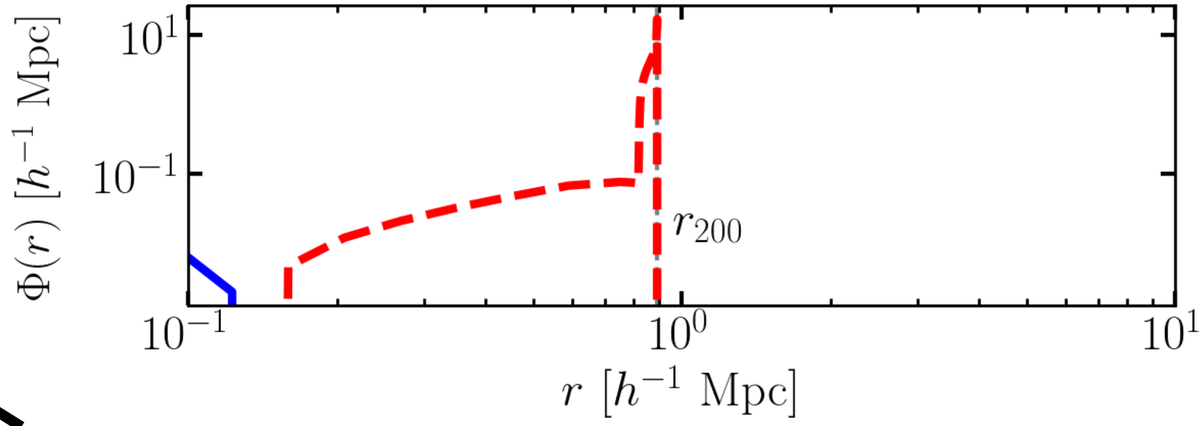
Another halo

Halo measured density profiles





Radial displacement of particles

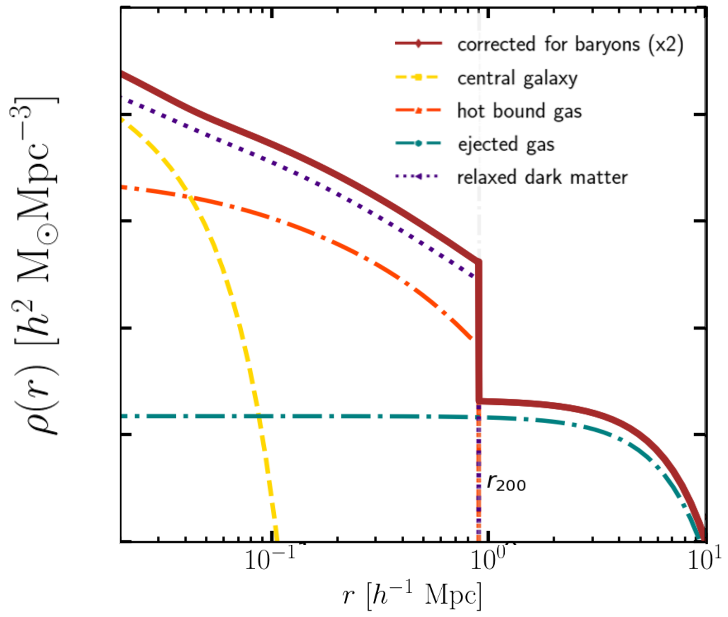


Apply

**Aricò et al. 2019**

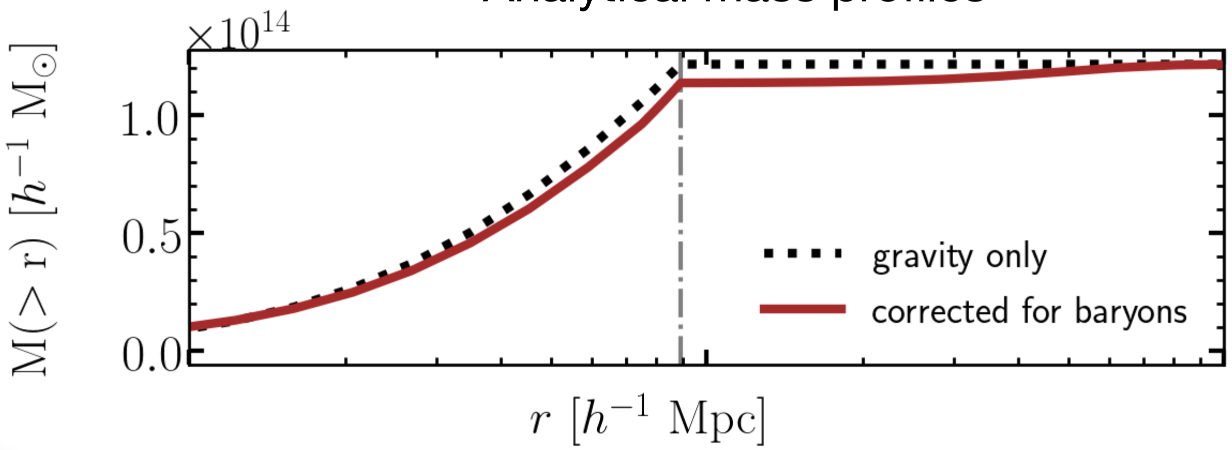
# Baryon Correction Model

Halo analytical density profiles



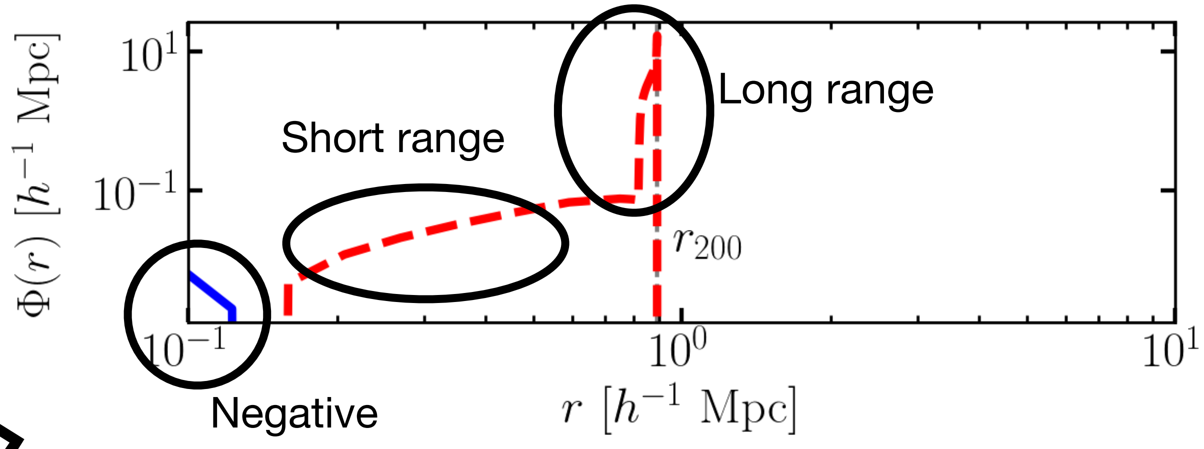
Integrate

Analytical mass profiles



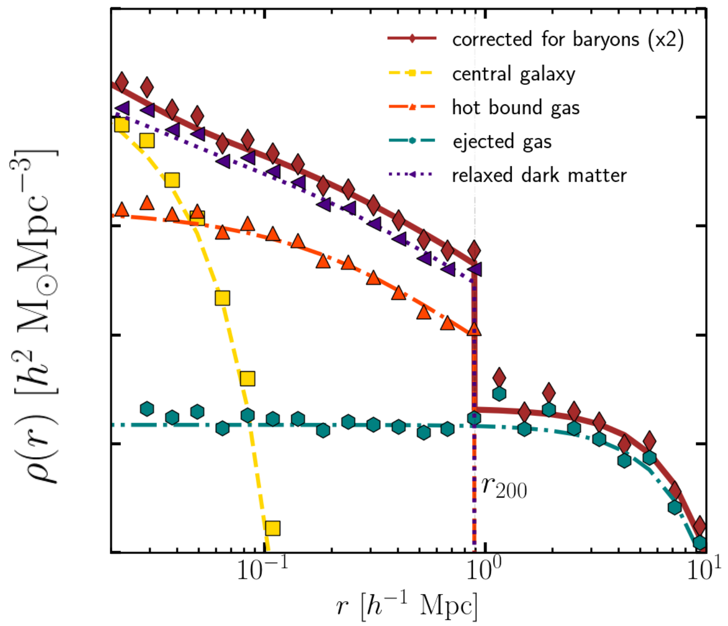
Invert

Radial displacement of particles

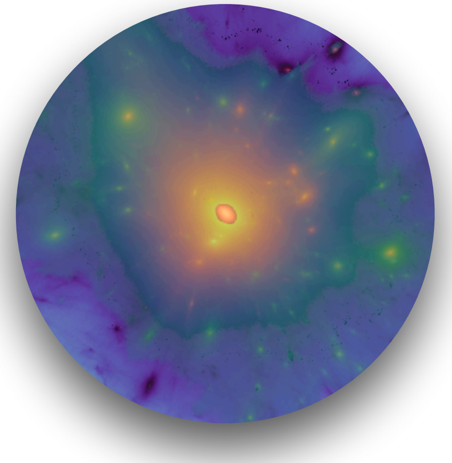


Apply

Halo measured density profiles

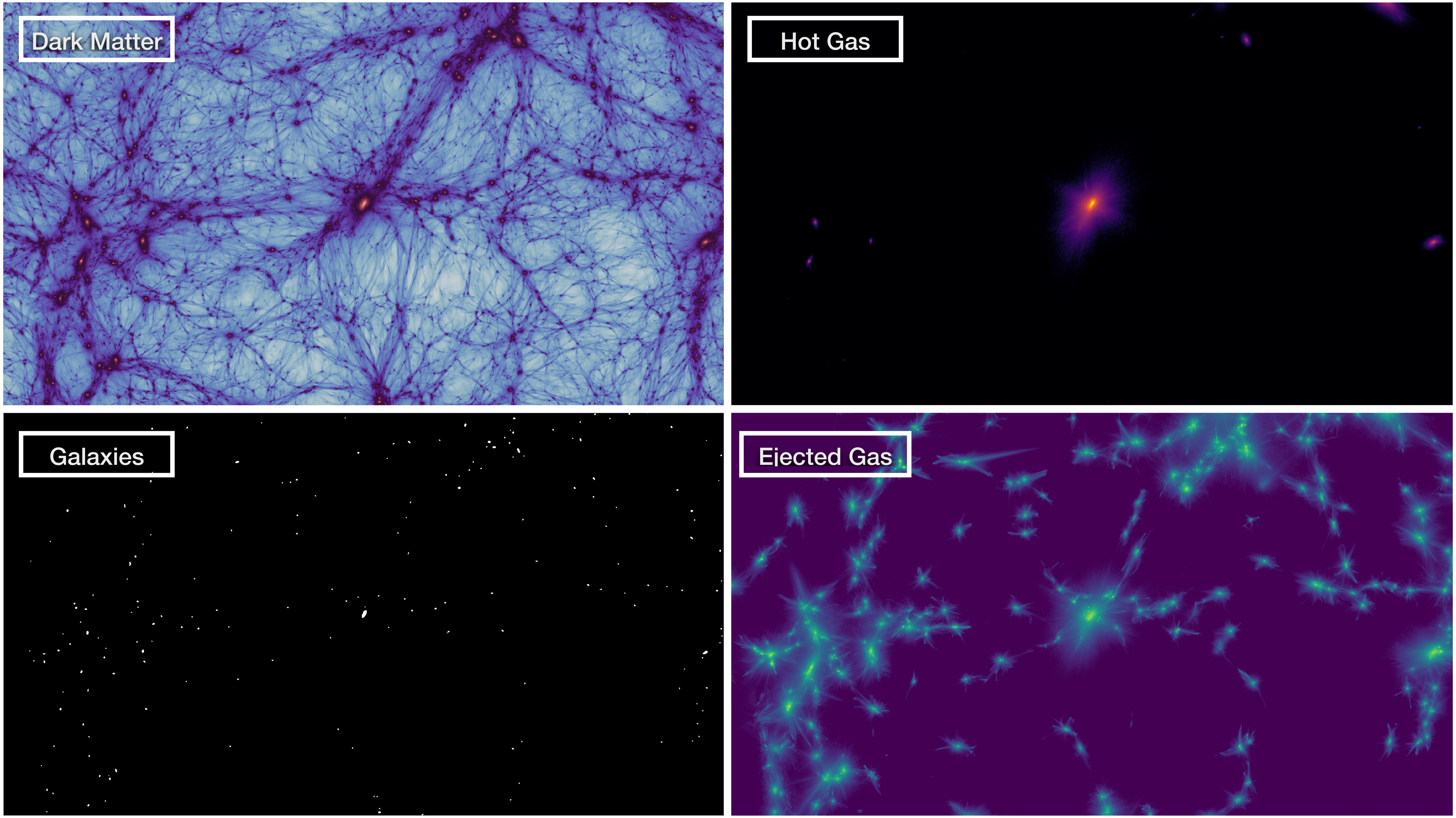


Another halo

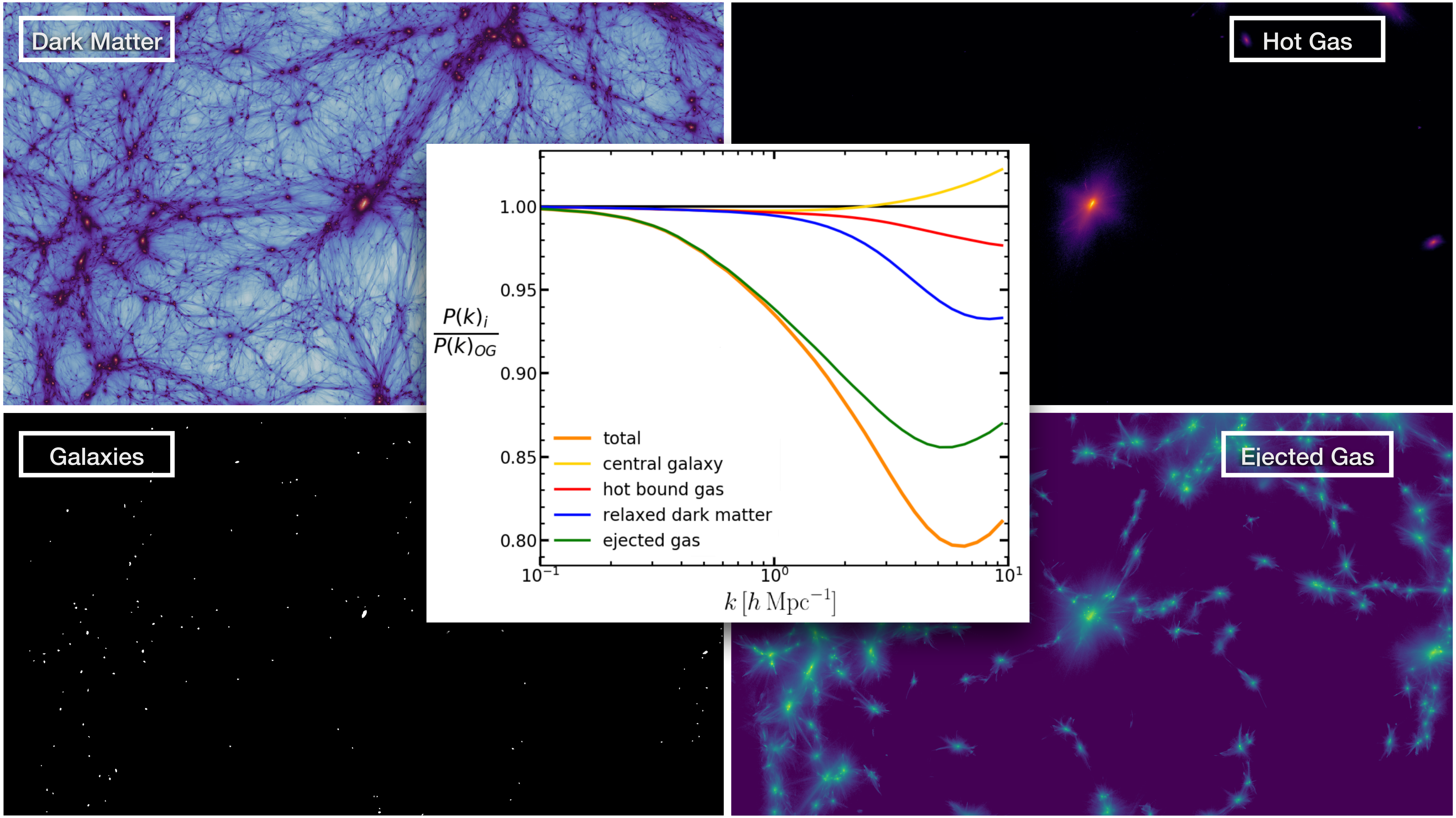


**Aricò et al. 2019**

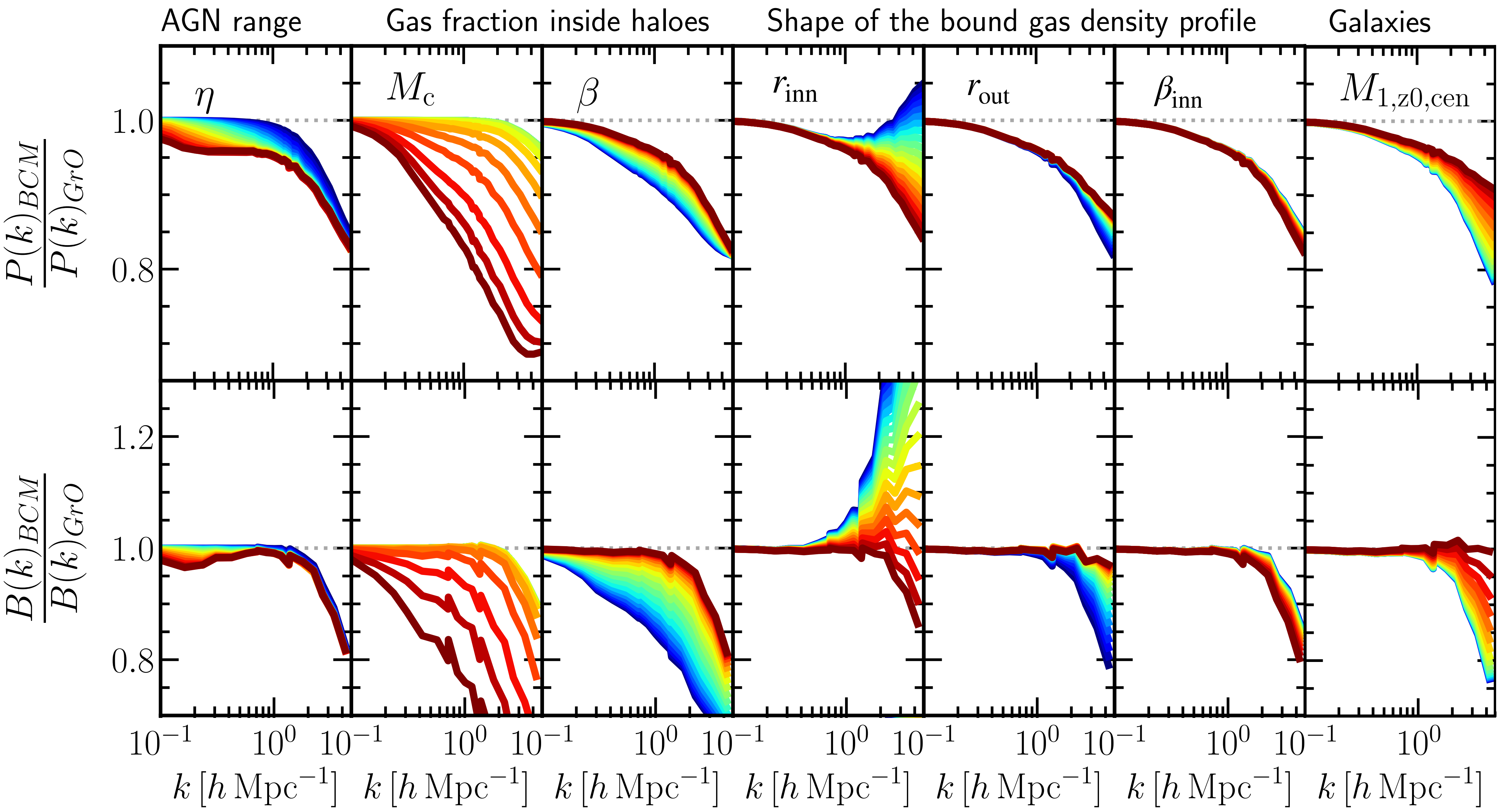
# Baryon Correction Model
# a.k.a. baryonification



# Baryon Correction Model
# a.k.a. baryonification



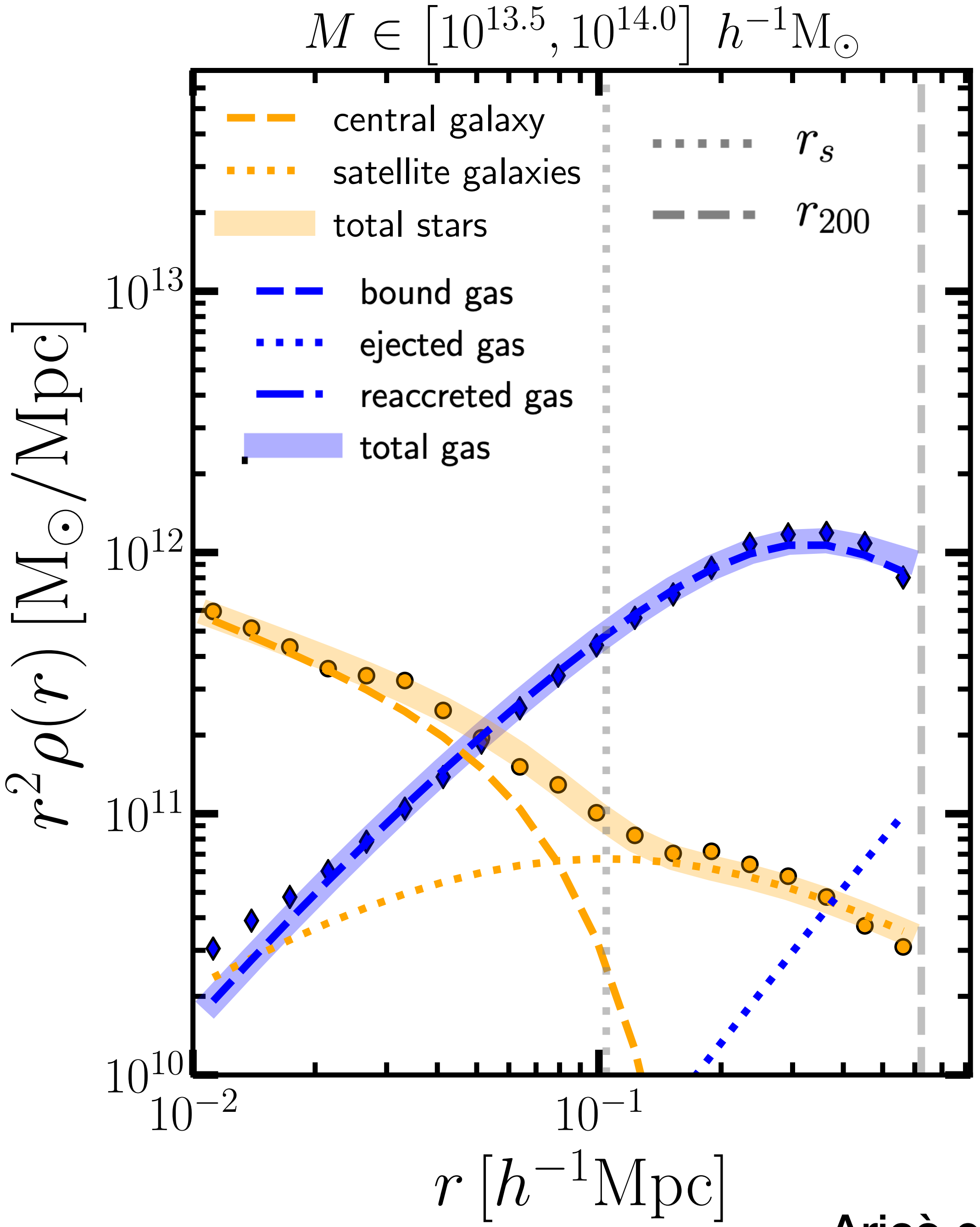
# BCM: impact of the parameters on clustering



Aricò et al. 2021b

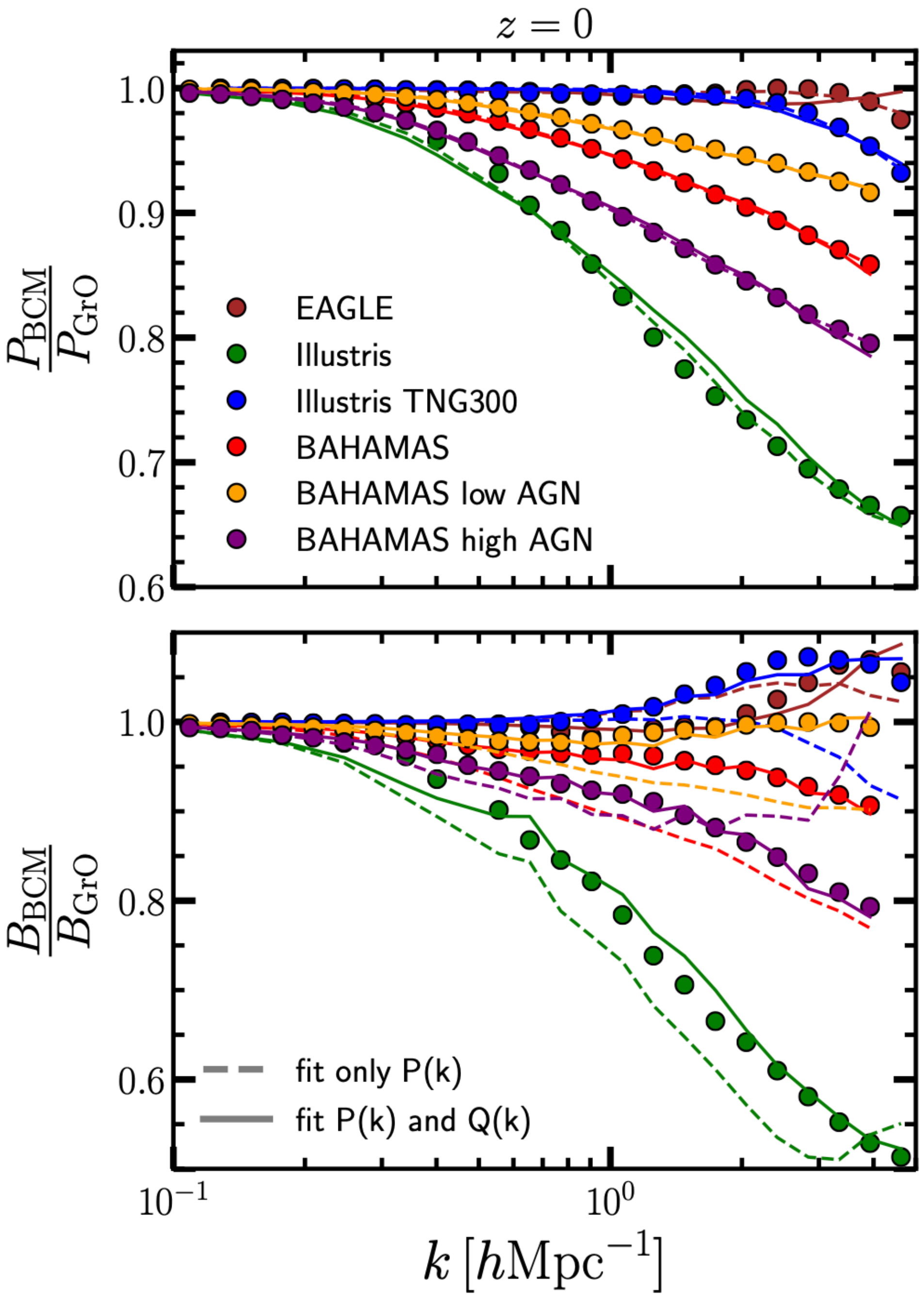
# BCM: tests with hydrodynamical simulations

## Fitting Illustris-TNG density profiles



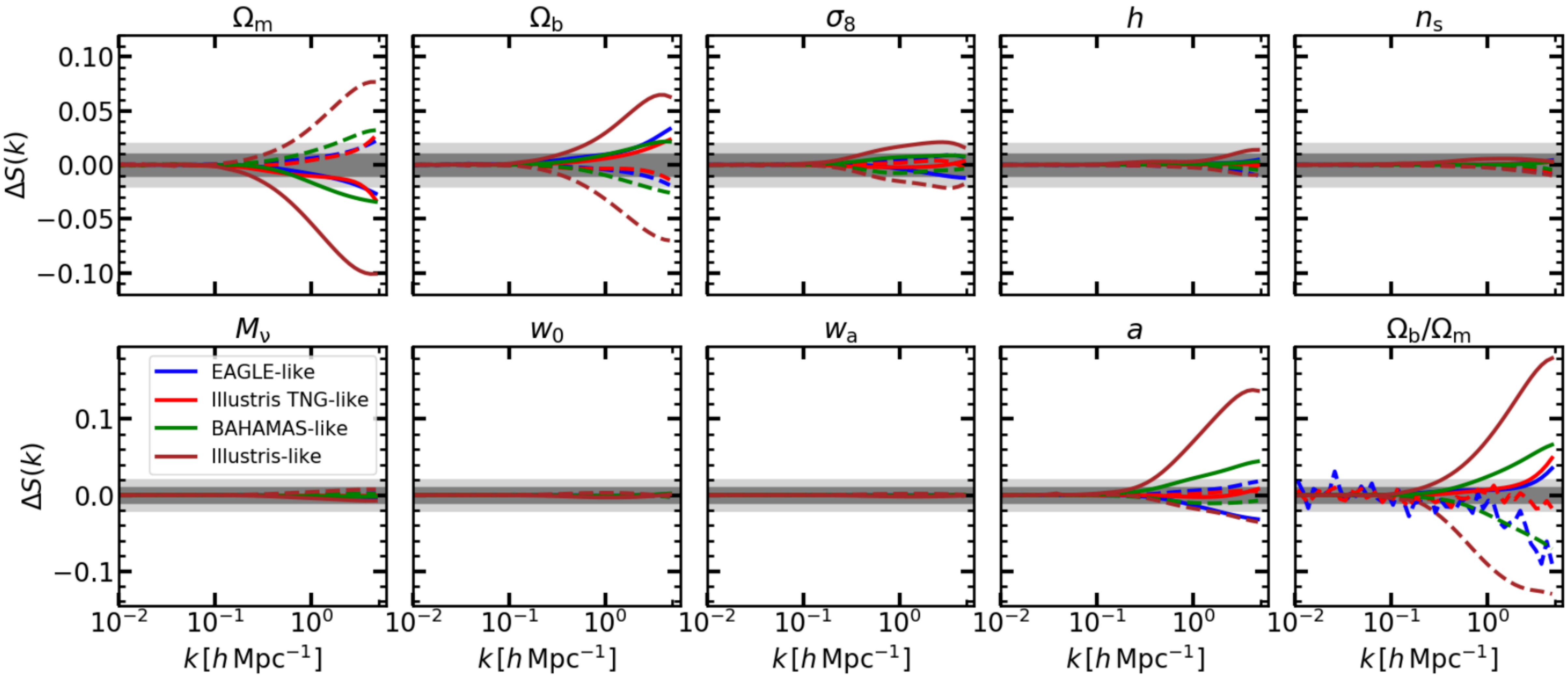
Aricò et al. 2021b

## Fitting power spectrum and bispectrum



Aricò et al. 2021b

# Correlation between cosmology and astrophysics



Aricò et al. 2021c

Main dependence of baryonic effects through $\Omega_\mathrm{b}/\Omega_\mathrm{m}$

Minor dependences (1-2%) on $\sigma_8, h, n_\mathrm{s}$

# BACCOemu

## Parameters

### 7 Baryonic parameters

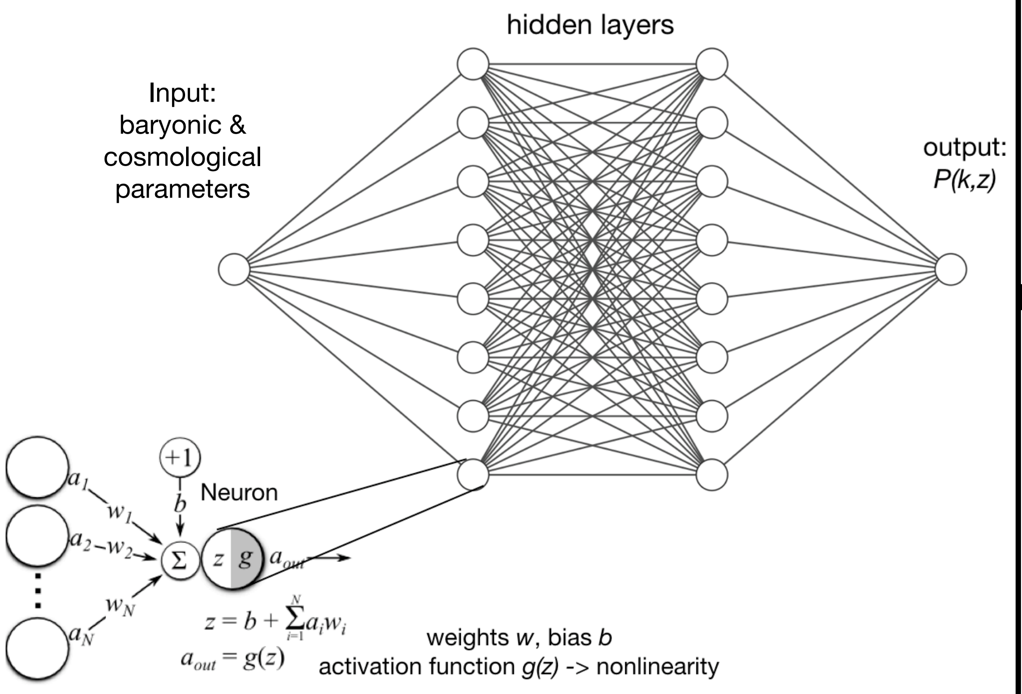
$\log M_{\rm c}/(h^{-1}{\rm M}_\odot) \in [9.0, 15.0]$
$\log \eta \in [-0.7, 0.7]$
$\log \beta \in [-1, 0.7]$
$\log M_{1,{\rm z0,cen}}/(h^{-1}{\rm M}_\odot) \in [9, 13]$
$\log M_{\rm inn}/(h^{-1}{\rm M}_\odot) \in [9, 13.5]$
$\log \theta_{\rm inn} \in [-2, -0.5]$
$\log \theta_{\rm out} \in [-0.5, 0]$

### 8 Cosmological parameters

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

⇨

## Neural Network



weights *w*, bias *b*
activation function *g(z)* -> nonlinearity

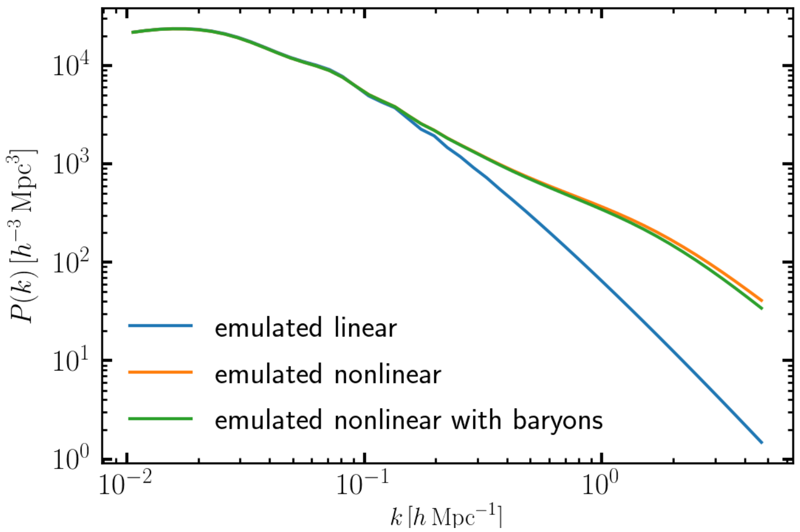
$$\lambda = \left\langle \frac{|P_{\rm NN}| - P_{\rm TRAIN}}{P_{\rm TRAIN}} \right\rangle$$

⇨

## 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

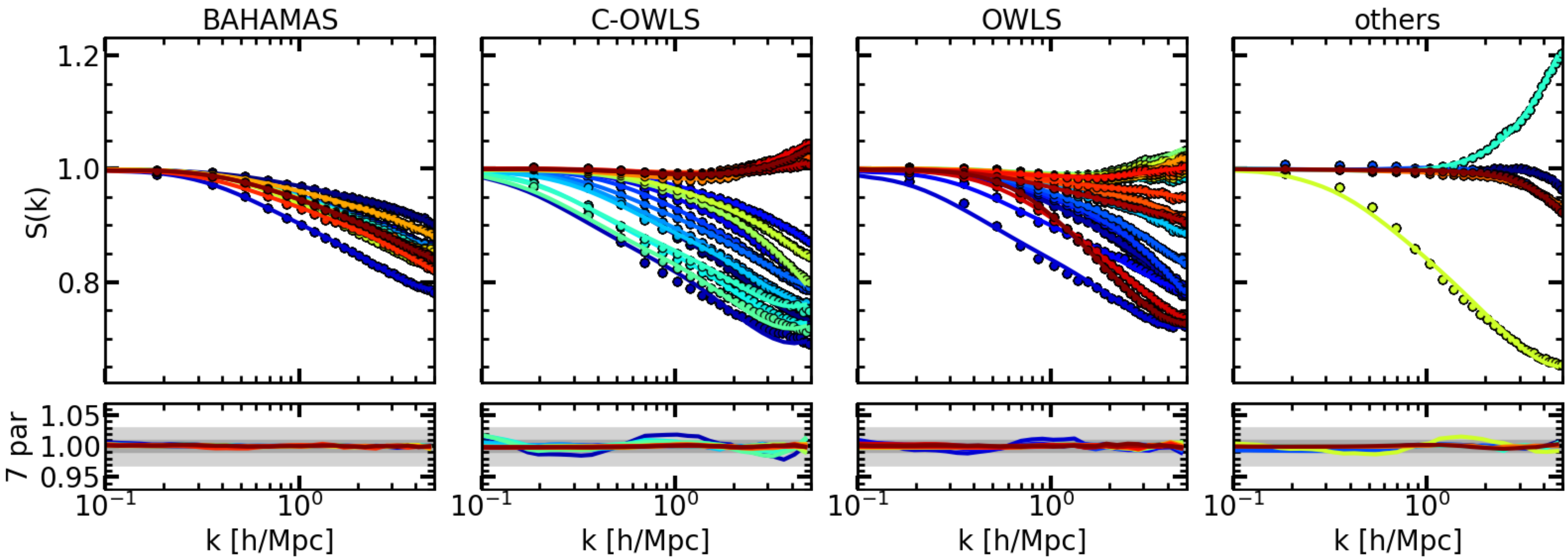
Percent accuracy on emulation ⇨ emulation errors subdominant!

Evaluation in milliseconds ⇨ analyses from months to few minutes!

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

# BACCOemu

Fitting van Daalen et al. 2020  power spectra library (74 hydro sims) with BACCOemu

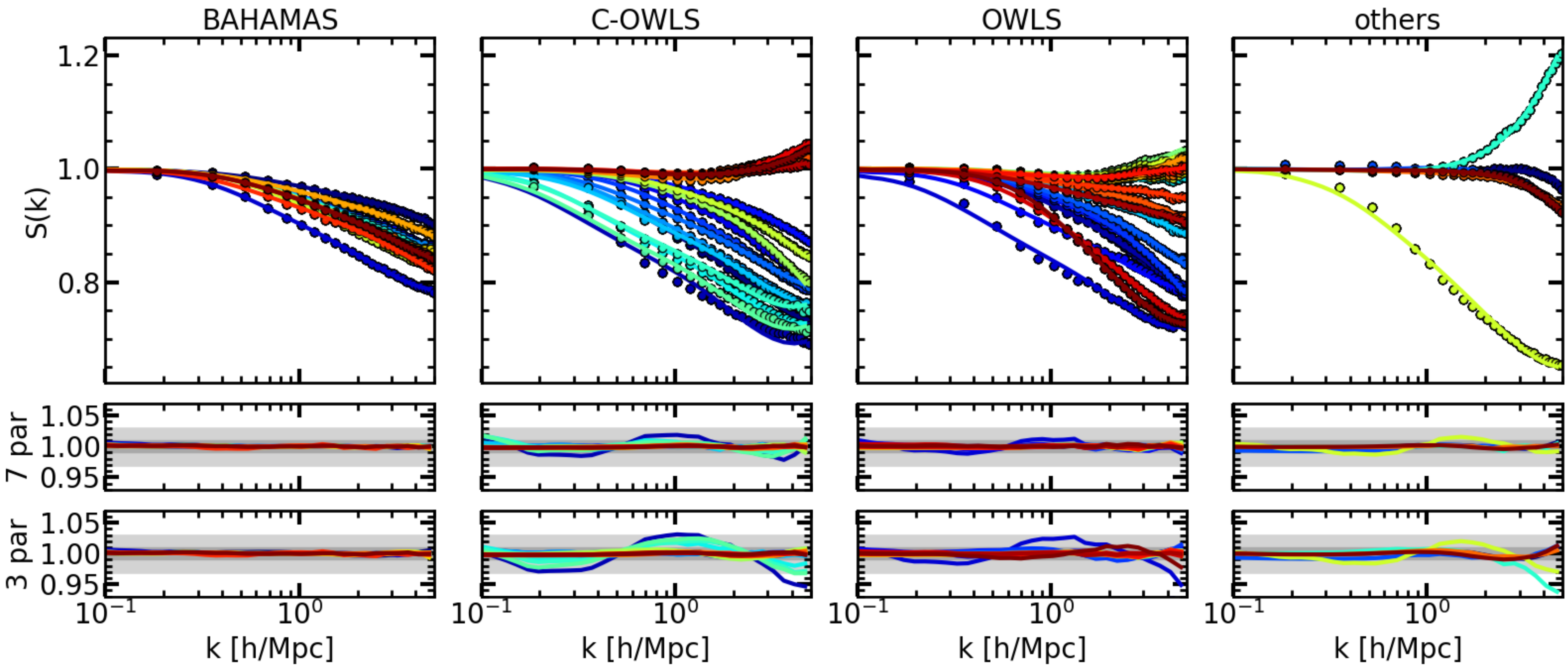


Aricò et al. 2021c

1% fit to all the power spectra!

# BACCOemu

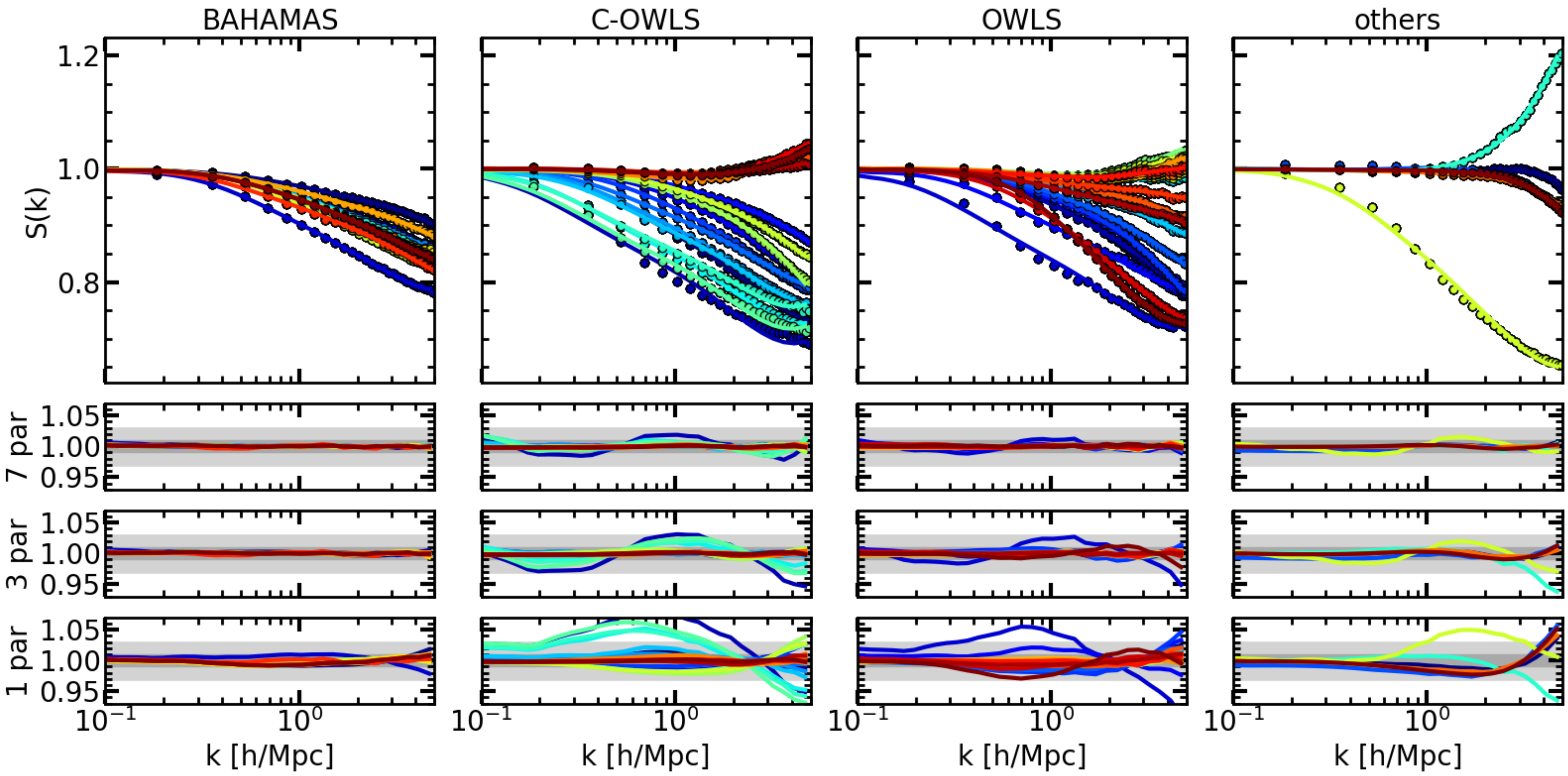
Fitting van Daalen et al. 2020  power spectra library (74 hydro sims) with BACCOemu



Aricò et al. 2021c

# BACCOemu

Fitting van Daalen et al. 2020 power spectra library (74 hydro sims) with BACCOemu



**Aricò et al. 2021c**

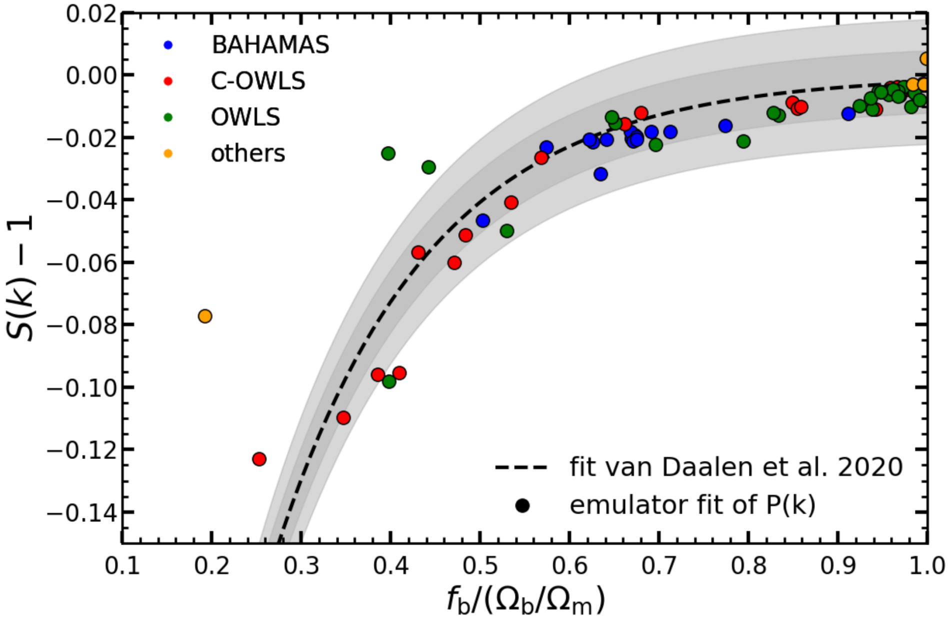
1% fit to all the power spectra, few% with just 1 parameter!

# BACCOemu

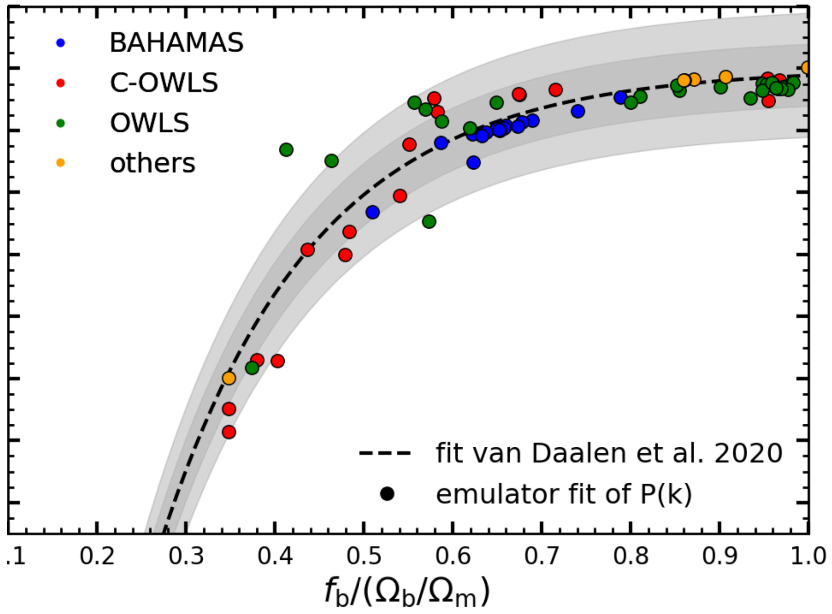
Fit van Daalen et al. 2020  power spectra library (74 hydro sims)

Predict the baryonic fraction in haloes $(10^{14}\, M_{\odot}/h\,)$

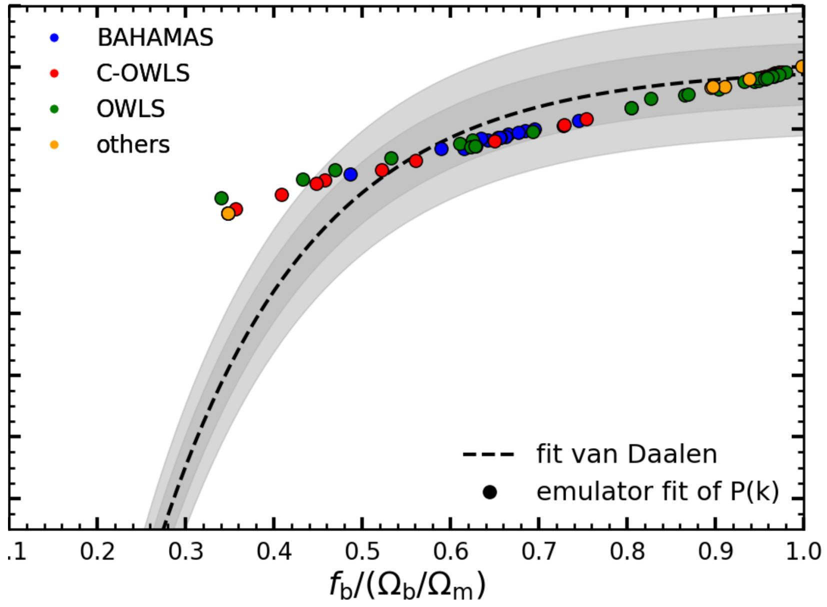
3 free parameters



2 free parameters



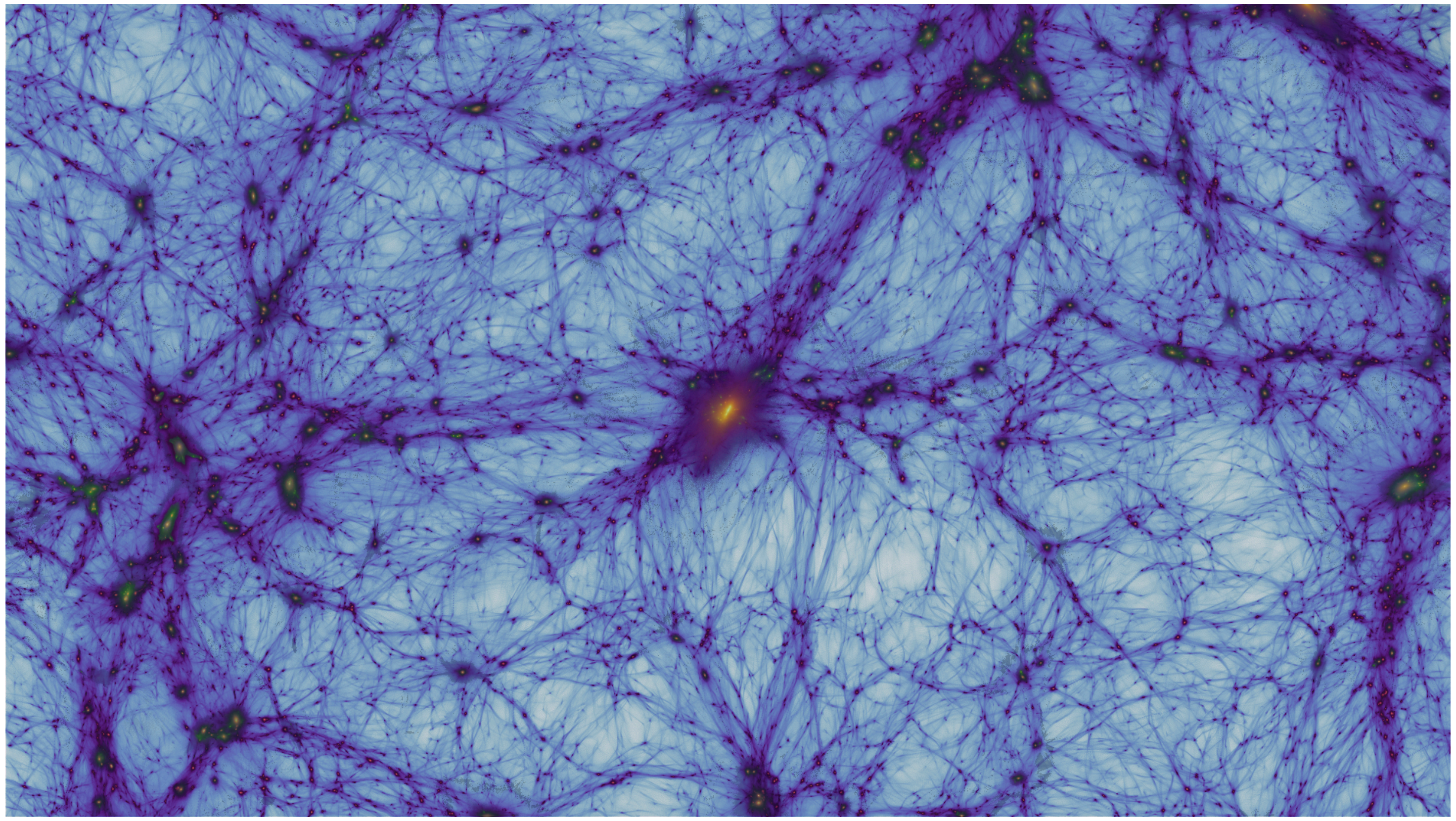
1 free parameter



van Daalen fitting function well recovered with 2 baryonic parameters,

1 parameter does not have enough freedom for very strong feedback!

# Constraints on baryonic processes

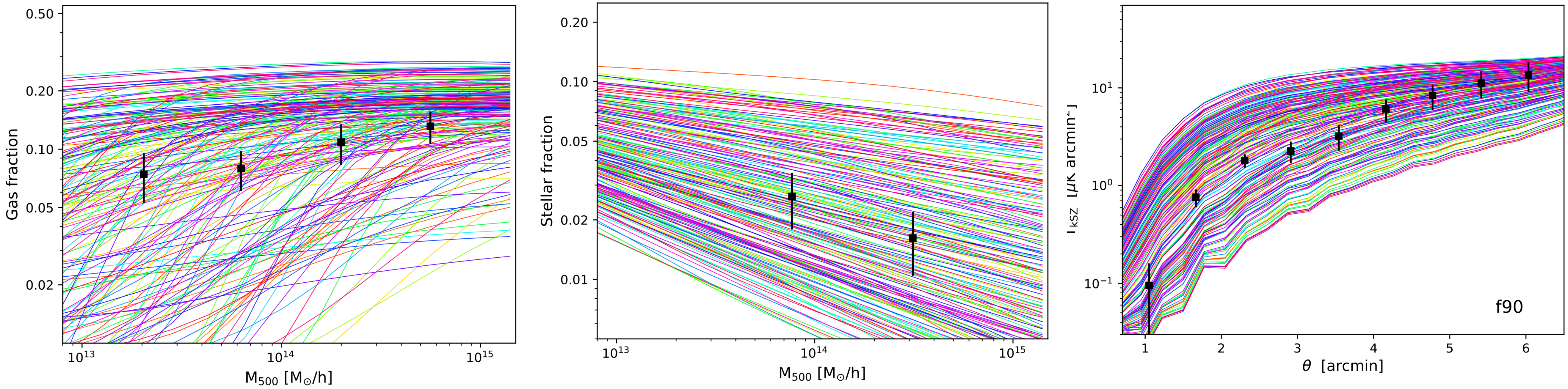


Giovanni Aricò

Institute for Computational Science, University of Zurich

**Cosmology from Home 2022**

# BCM: constraining parameters with observations



gas fraction

stellar fraction

kSZ profile

Schneider et al. 2022

Observations can constrain
tightly the BCM parameters!

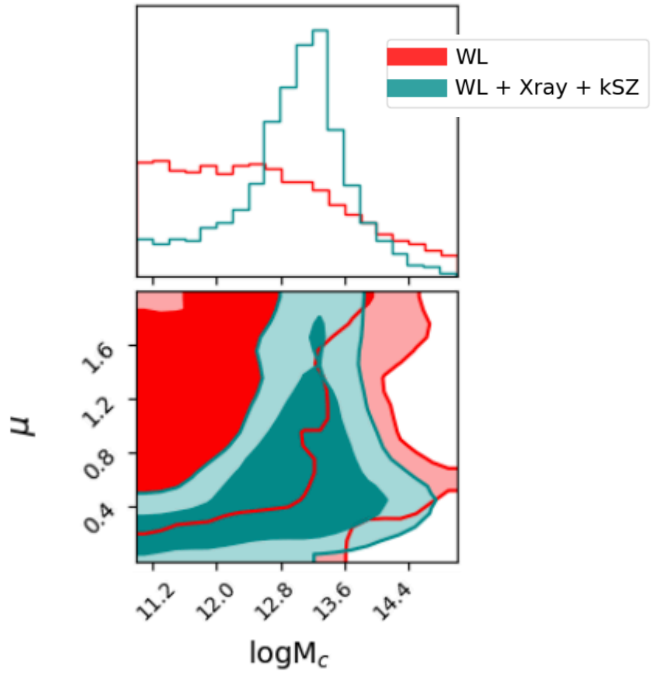
Gravity given by N-body simulations,
Baryonic perturbations in a data-driven way

# BCM: results

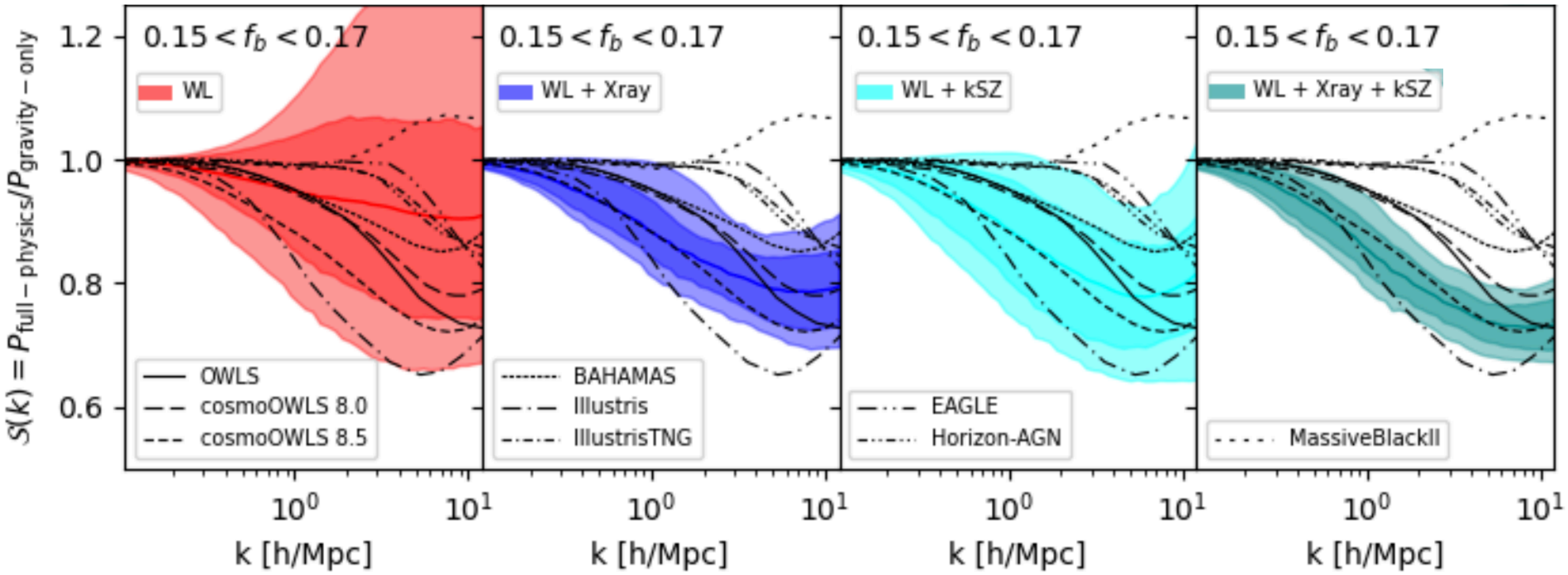
Schneider et al. 2022

Constraining baryons with Cosmic Shear (KIDS 1000), X-ray data and kSZ (ACT & Planck)

Constraining 7 BCM parameters



Predicting the suppression in the matter power spectrum



Most of the constraints

from X-ray data

Predicted relatively strong feedback!

BCemu: Emulator of BCM (Schneider+2020)

with Gaussian Process (Giri & Schneider 2021)

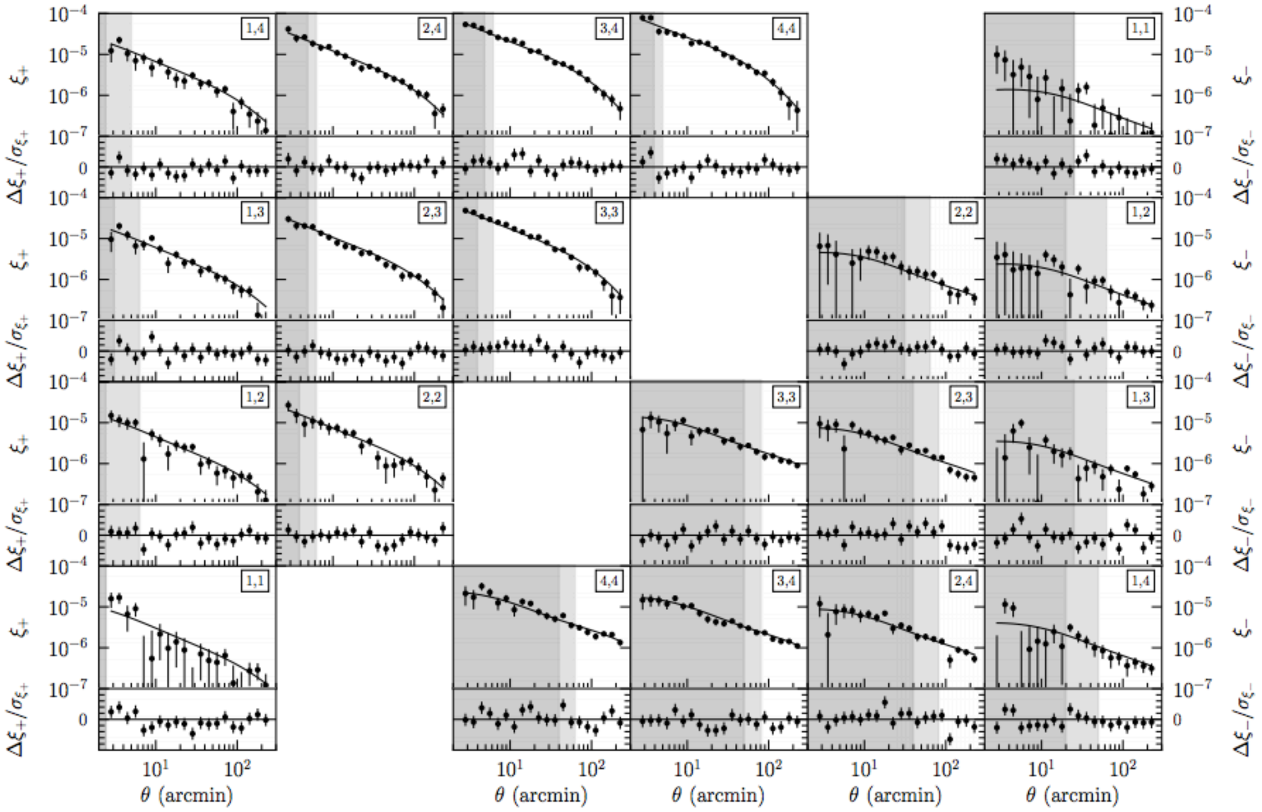
https://github.com/sambit-giri/ BCemu

# BCM: results

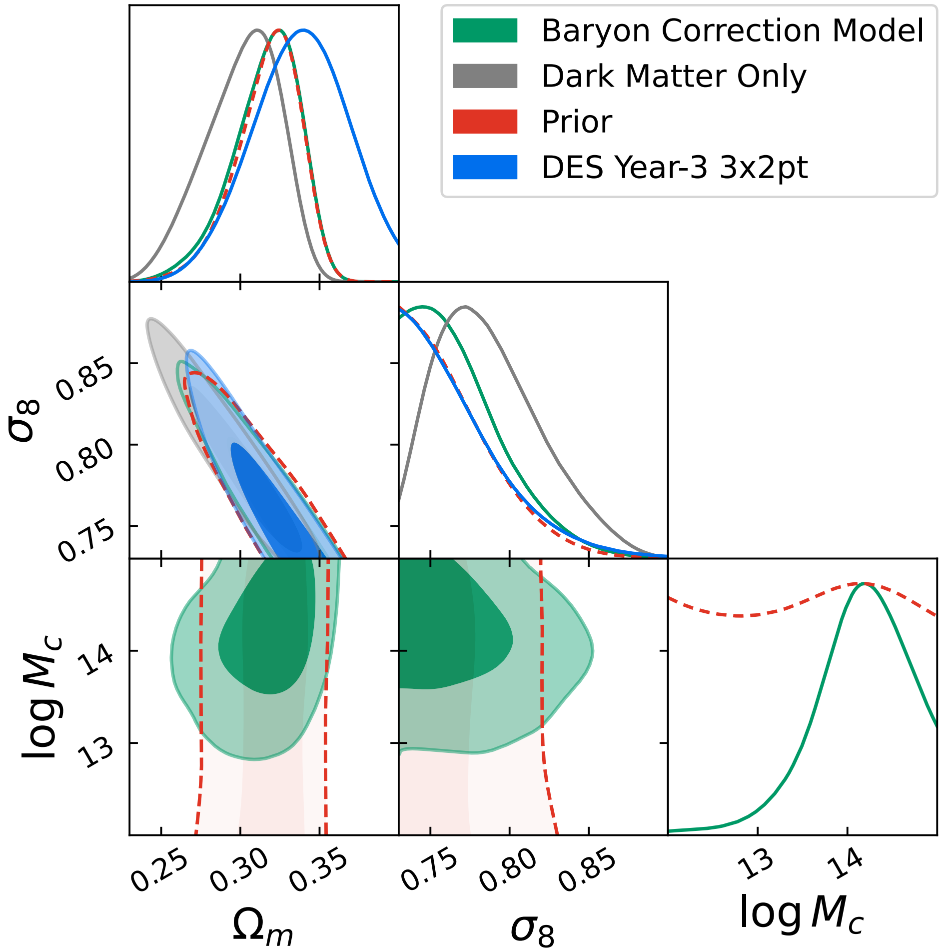
Chen, Aricò, Huterer, Angulo, +DES, 2022

Constraining baryonic effects with cosmic shear only

DES Y3 small-scales data



DES Y3 (2022)



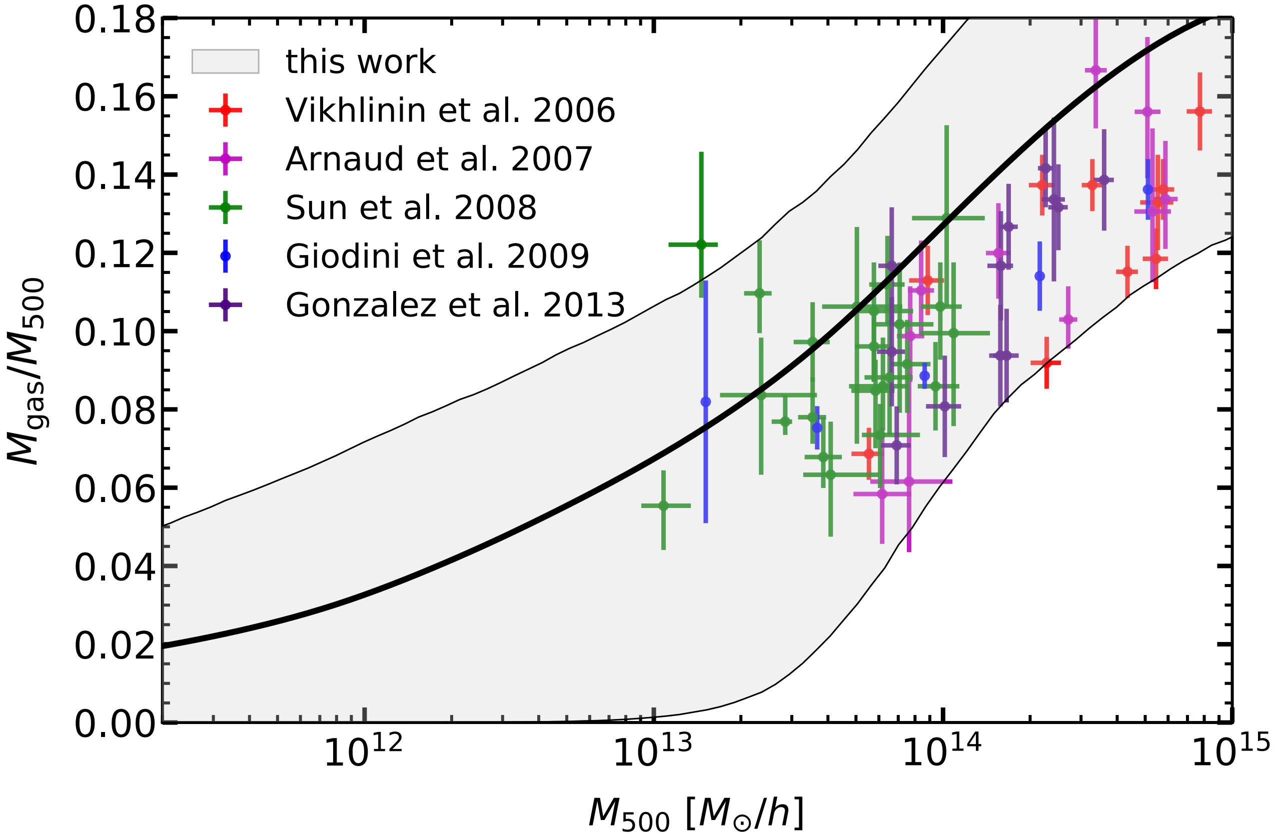
Only small scales to constrain baryons

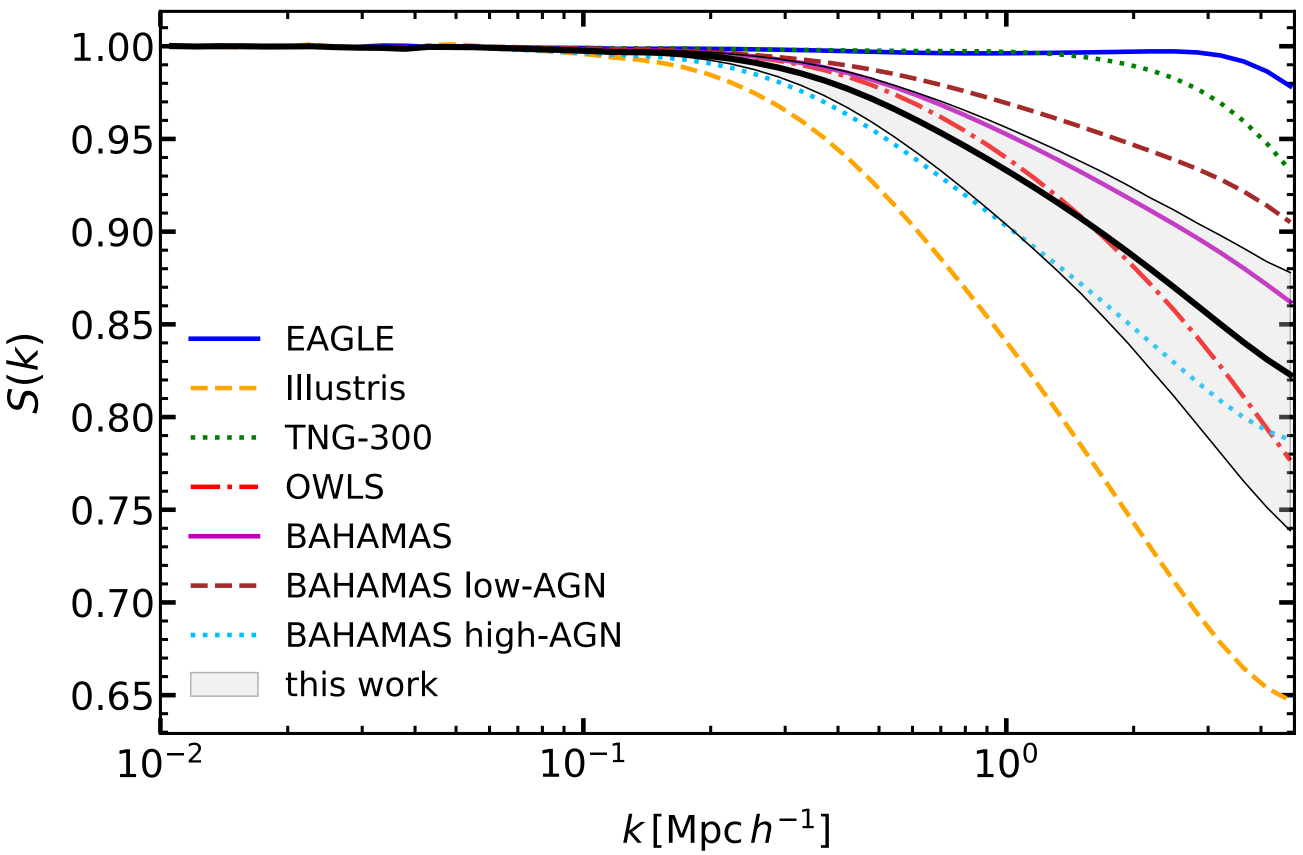
Only large scales to constrain cosmology

Constrained $\log M_{\rm c} = 14.12^{+0.62}_{-0.37}$ at ~ $2\sigma$

# BCM: results

Chen, Aricò, Huterer, Angulo, +DES, 2022





Agreement with gas fractions

From X-ray data

Mild feedback,

agreement with OWLS and BAHAMAS

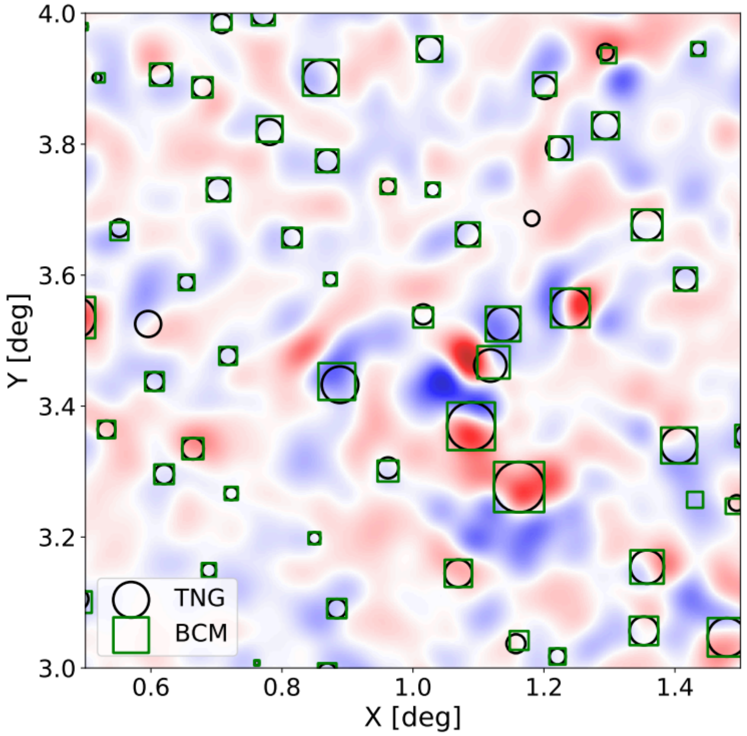
# Maximise cosmological and astrophysical information

Some ideas for the live discussion

## Higher-order statistics

- Convergence peaks, minima, PDF;
  (e.g. Coulton et al.2020, Osato&Nagai 2020, Lu&Haiman 2021, Lee et al. 2022)
- Bispectrum, integrated bispectrum;
  (e.g. Semboloni et al. 2013, Foreman et al. 2020, Barreira et al. 2020, Aricò et al. 2021, Gatti et al. 2021, Halder&Barreira 2022)
- Minkowski Functionals/Wavelets;
  (e.g. Parroni et al. 2020, Ajani et al. 2021, Grewal et al. 2022)
- Field level; (e.g. Porqueres et al. 2022, Fluri et al. 2022)

**Convergence peaks**



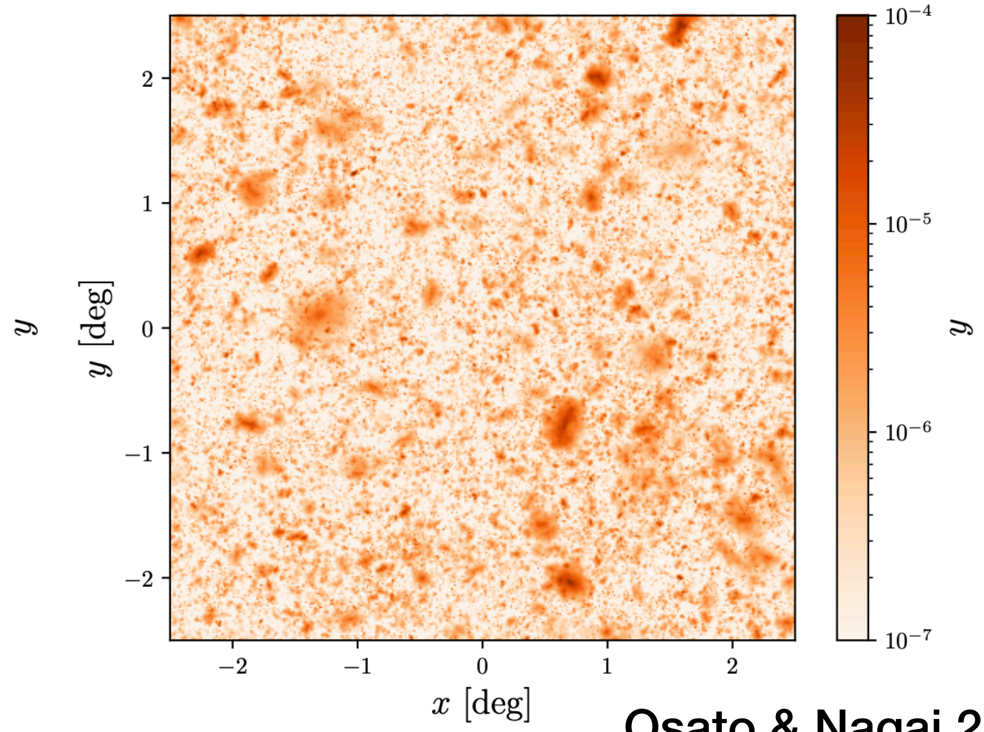
**Lee et al. 2022**

## Cross-correlations

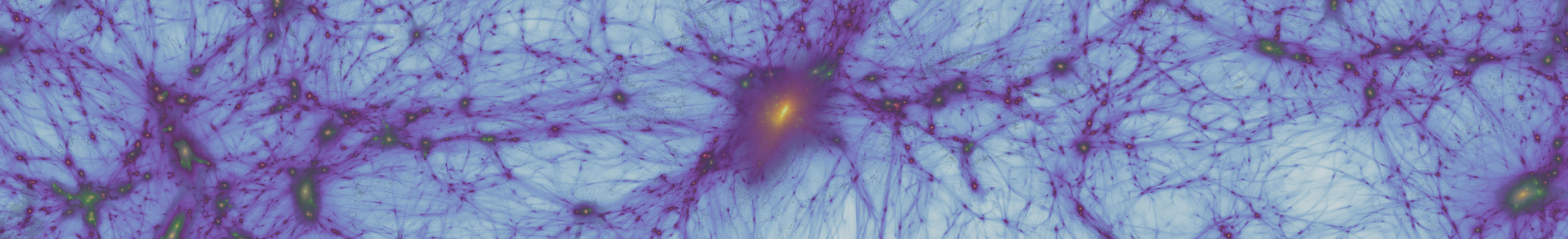
tSZ - Weak Lensing

Van Waerbeke et al. (2014); Hojjati et al. (2017);
Osato et al. (2020); Tröster et al. (2021);
Gatti et al. (2021); Pandey et al. (2021);

**tSZ (Baryon Pasting Algorithm)**



**Osato & Nagai 2022**



# Summary

- Baryon physics should not be treated as a simple nuisance for cosmology analyses;

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

- We need physically-motivated, accurate, and flexible models to join multi-wavelength observations and cross-correlate consistently different datasets:
  baryonification is a very good candidate;