Impact of baryons on weak lensing statistics

Diagnosing failures as a function of halo mass and radius

Max E. Lee — Cambridge CMB Group Meeting — 12/3/2026

Accounting for Baryons in Future Surveys

Baryon correction models (BCMs)

Survey Accuracy

Next-generation cosmological surveys demand percent-level systematic control to ensure precise measurements and reliable results.

Parameter Bias

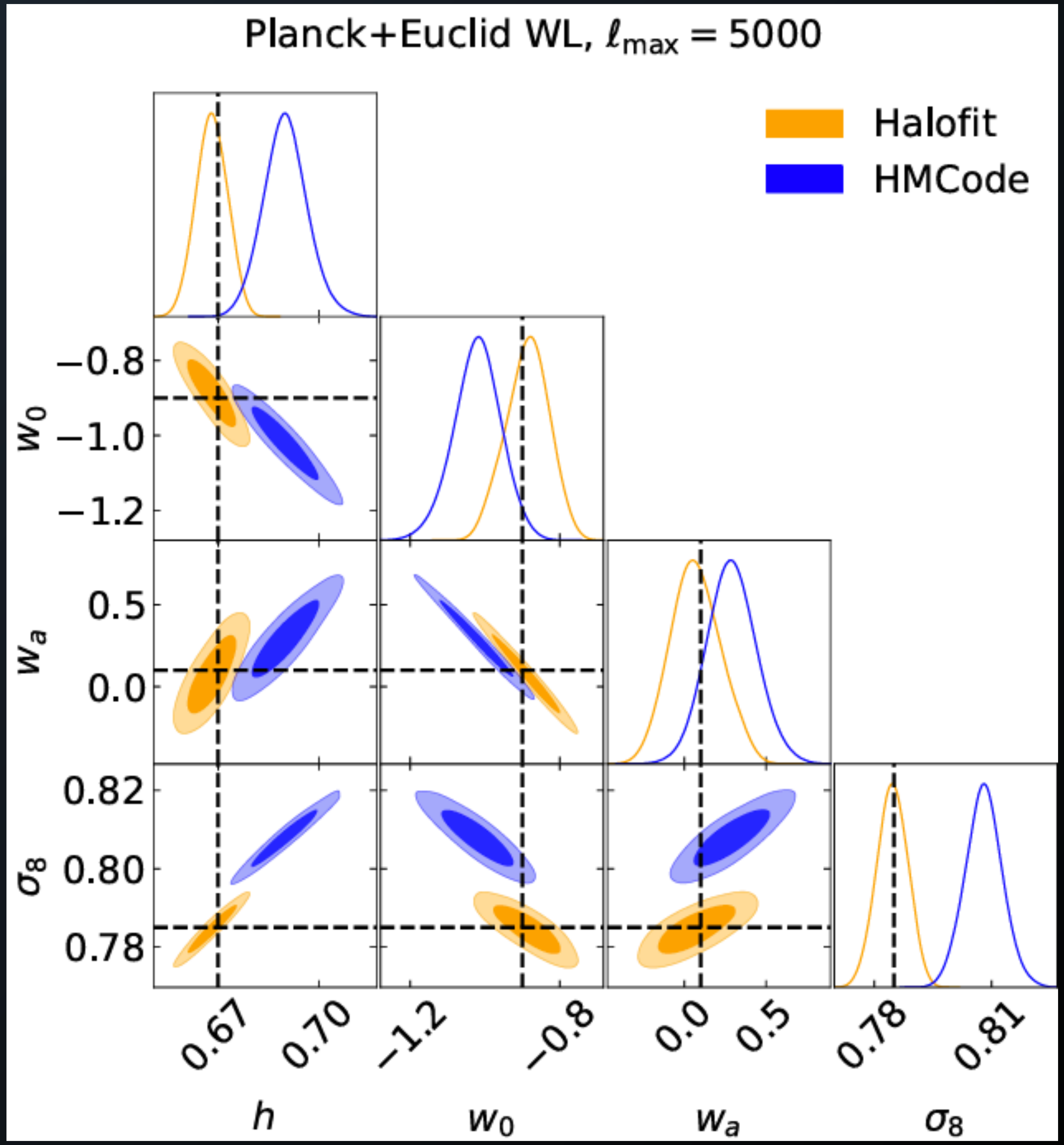
Neglecting baryonic effects introduces significant systematic bias in cosmological parameter estimation, compromising data integrity.

Computational Challenge

Hydrodynamic simulations require prohibitive computational resources, making them impractical for large-scale survey analysis pipelines.

Current Solutions

Baryon Correction Models offer a computationally efficient alternative by accurately modeling matter rearrangement within halos.

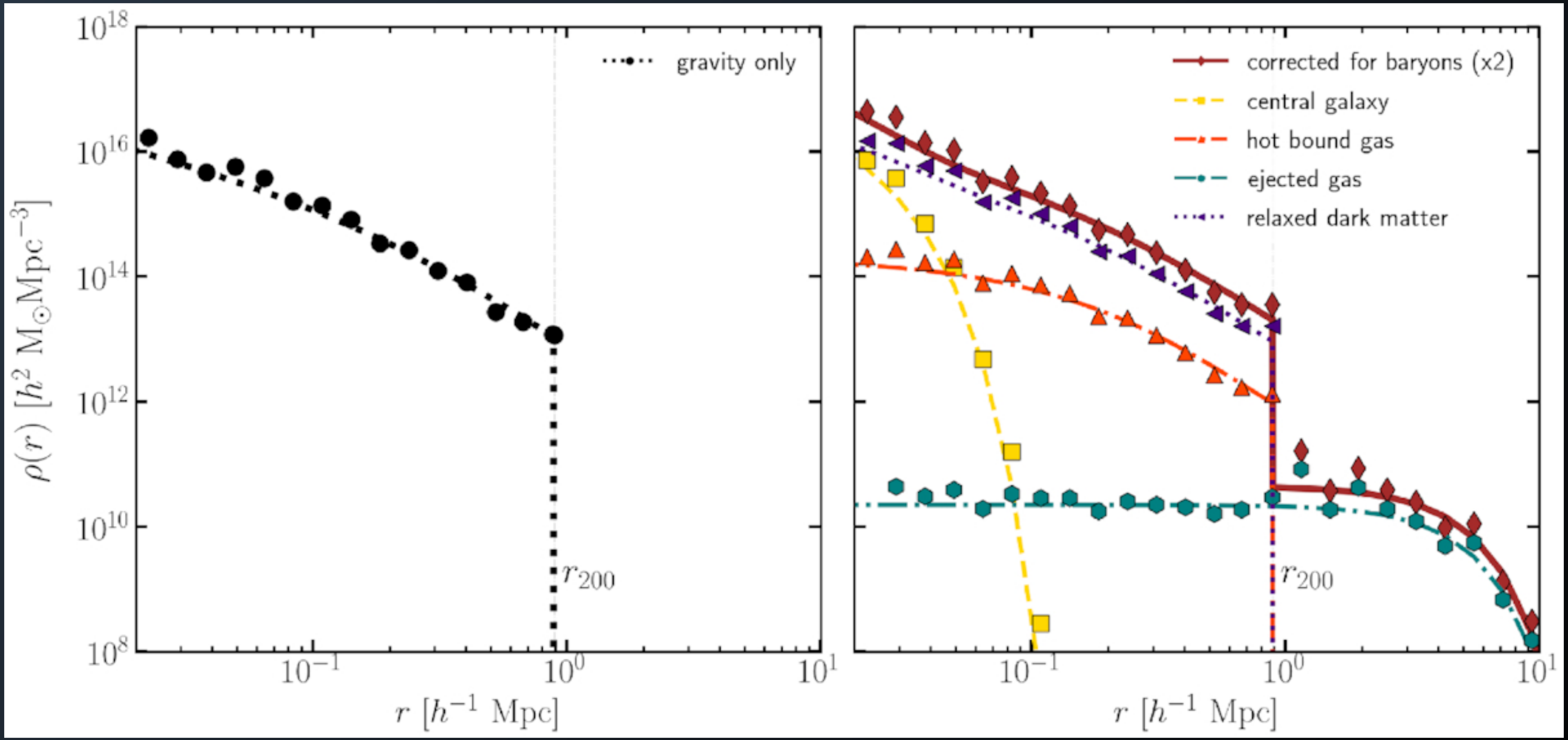


Martinelli et al. 2020

Baryonifying a Simulation

How BCMs work

$$\rho_{\mathrm{bcm}}(\mathbf{x},\theta) = \rho_{\text{relaxed dm}}(\mathbf{x},\theta) + \rho_{\text{hot bound gas}}(\mathbf{x},\theta) + \rho_{\text{ejected gas}}(\mathbf{x},\theta) + \rho_{\text{central galaxy}}(\mathbf{x},\theta)$$



Arico et al. 2019

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$$M_{\mathrm{halo}} \geq M_{\mathrm{min}}$$

$$\theta = \{\mathbf{M_c}, \mathbf{M_1}, \eta, \dots\}$$

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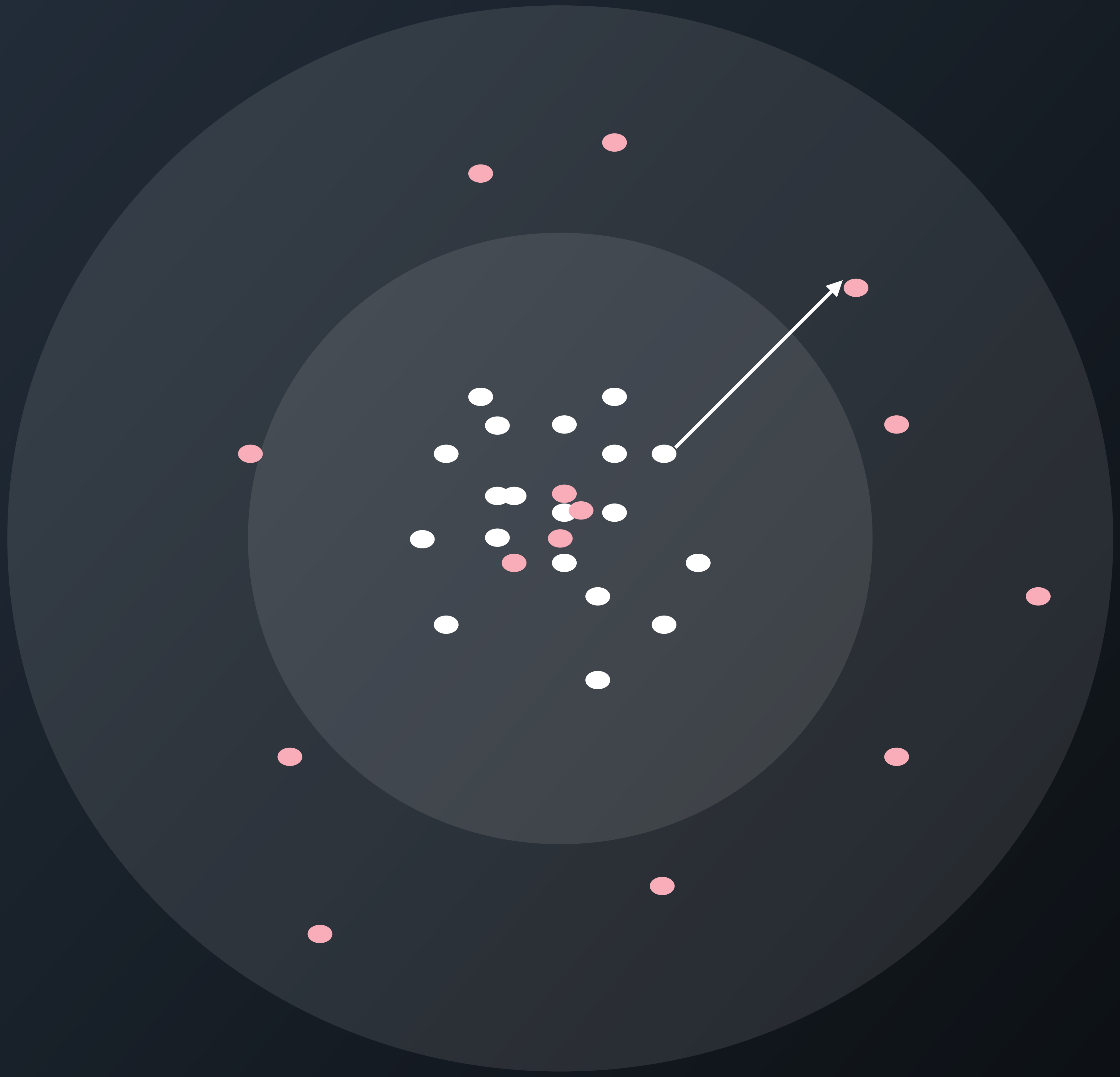


$$\Phi(r) = r\left(M_{\mathrm{BCM}}\right) - r\left(M_{DMO}\right)$$

Arico et al. 2019

BCM Victories

Statistics match, and fitting to hydro sims is possible

Power spectrum works

Match various simulations at to relatively high k values with percent level precision

Physical Parameters

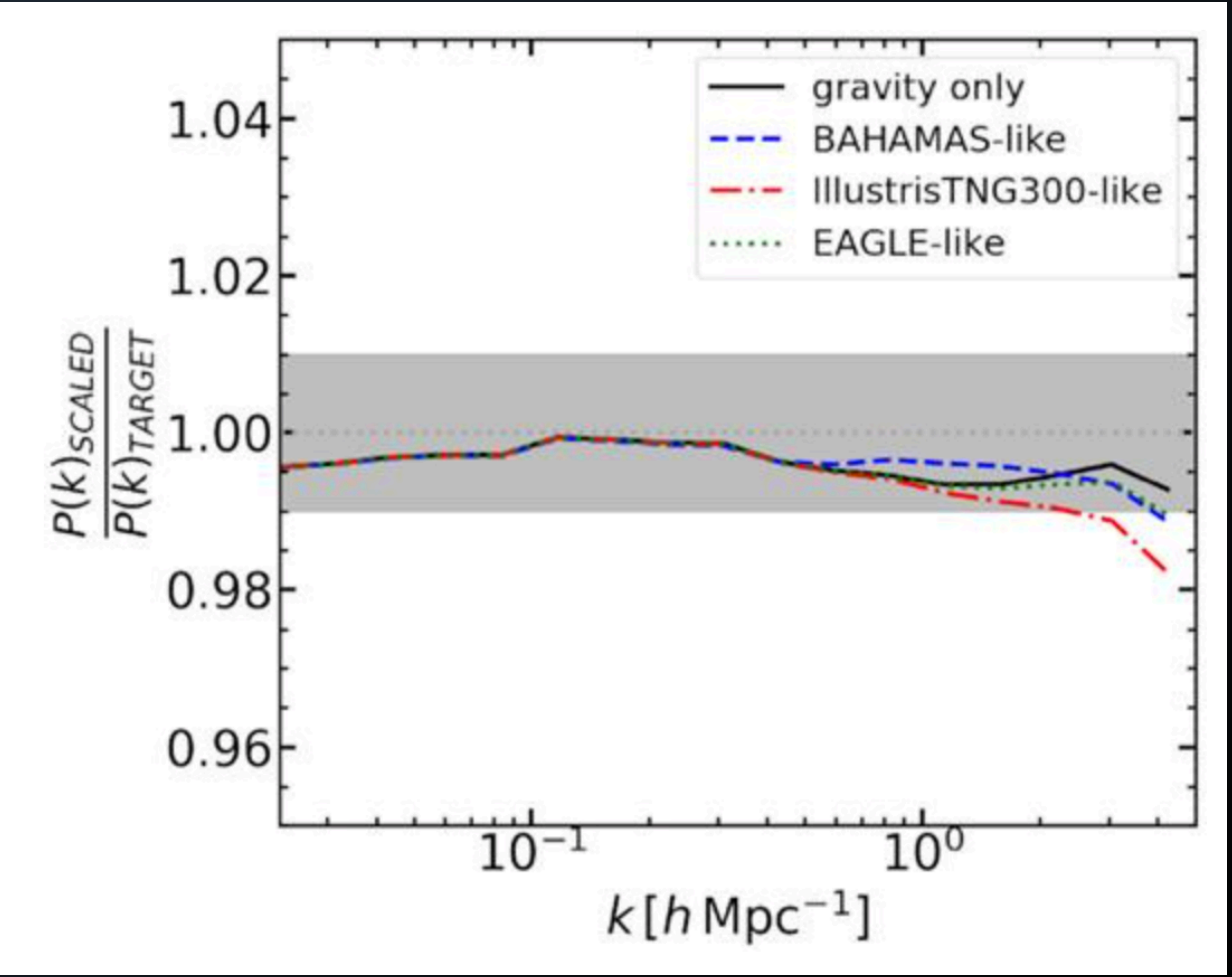
The BCM parameters typically are physically meaningful like, gas ejection radius, or, halo mass at which half of the gas is retained

Observably fit

In various formulations, the BCM parameters can be fit to to observable data from Xray/SZ/FRB

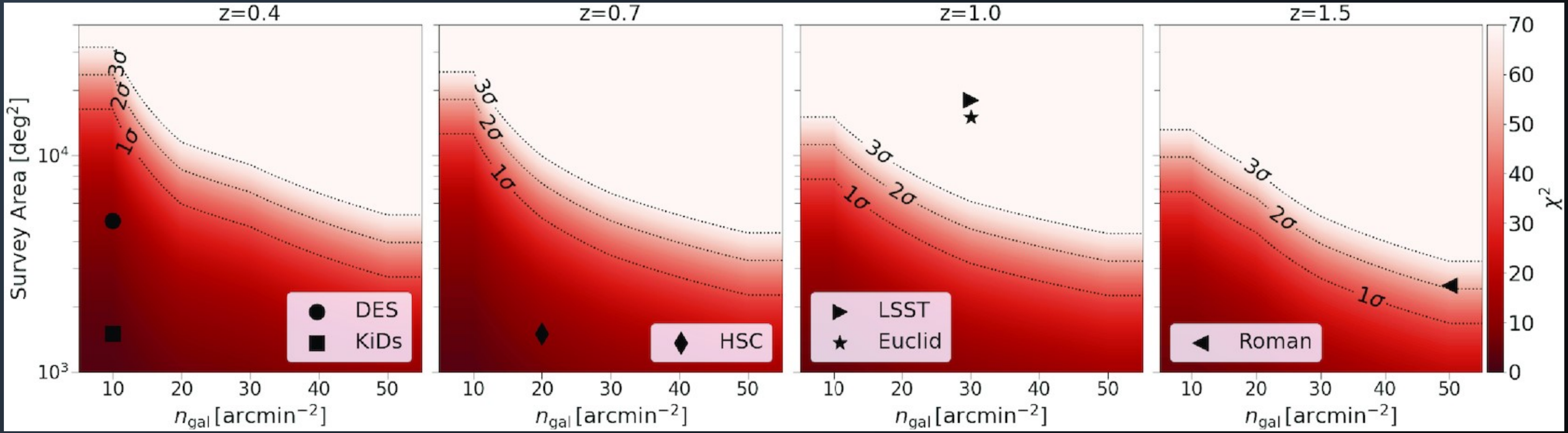
Already being used!

DES and HSC already employing BCMs, LSST plans to. They have become prevalent!



Arico et al. 2019

BCM Worries



Peak count failures

We have shown in previous work that BCMs matched fit to P(k) FAIL at the level of peak counts for stage four surveys.

Selection and application

When performing BCMs we have to make a choice of the minimum mass, we approximate with spherical shifts to particles

M.E. Lee et al 2023

BCMs are calibrated to statistics and applied to halos at the field level.

We tune density profiles until P(k) matches.

But
Does the correct field level distribution actually produce the target statistic

Hydro replacement method

Our diagnostic tool

Replacement approach

We systematically replace DMO particles with hydro particles within mass bins and radial shells. This is NOT a BCM, it is a diagnostic tool

DMO density

Hydro density

$$\rho_R(\mathbf{x}, \mathbf{z}) = \rho_{\mathbf{D}}(\mathbf{x}, \mathbf{z}) + \sum_{\mathbf{i} \in \mathbf{A}(\mathbf{M}, \mathbf{z})} \theta_{\mathbf{i}}(\mathbf{x}) \left[\rho^{\mathbf{i}}_{\mathbf{H}}(\mathbf{x}, \alpha) - \rho^{\mathbf{i}}_{\mathbf{D}}(\mathbf{x}, \alpha) \right]$$

Replace density

Mass, z selection

Indicator function

A Worked Example

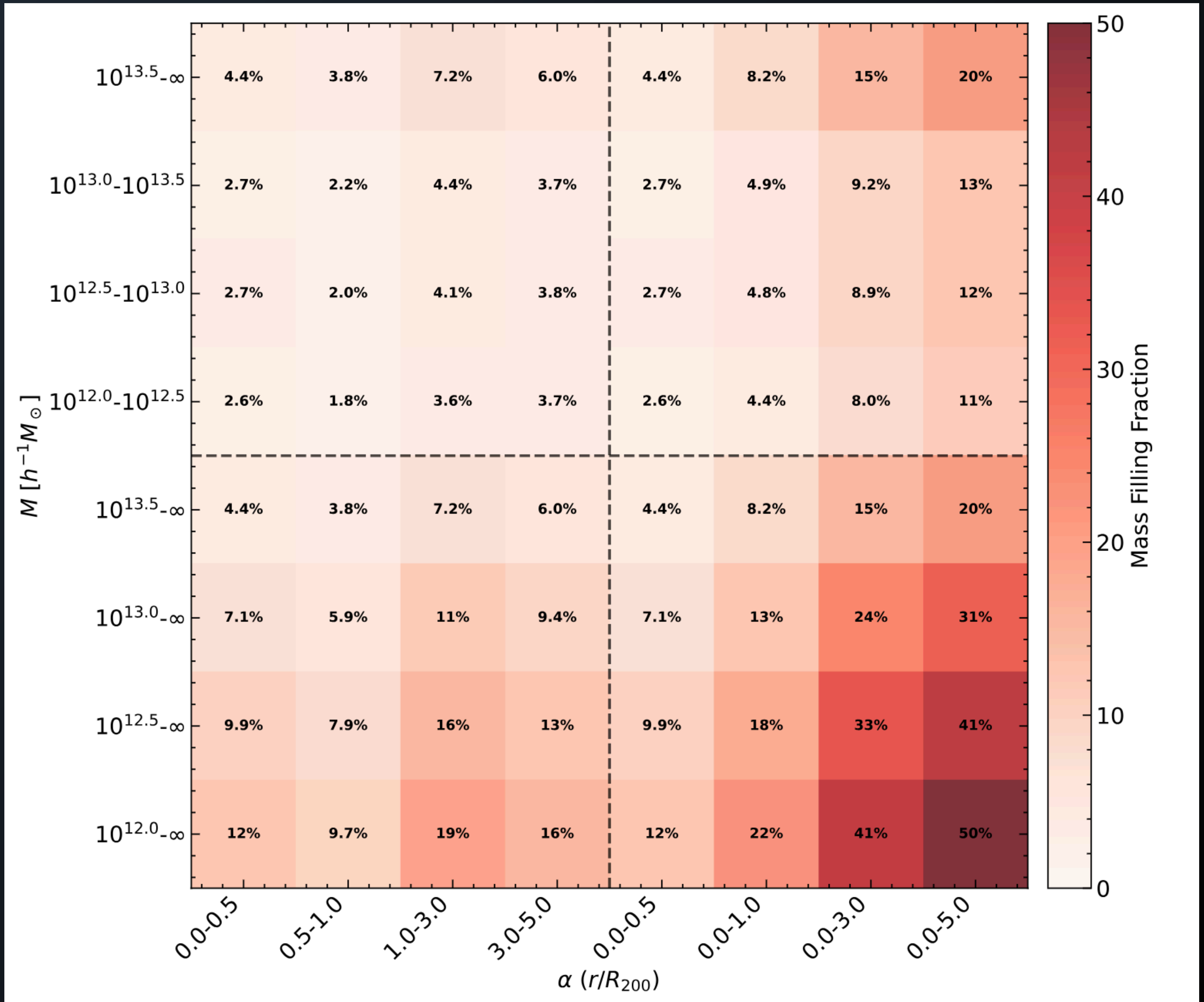
Power spectrum suppression with IllustrisTNG

Methodology

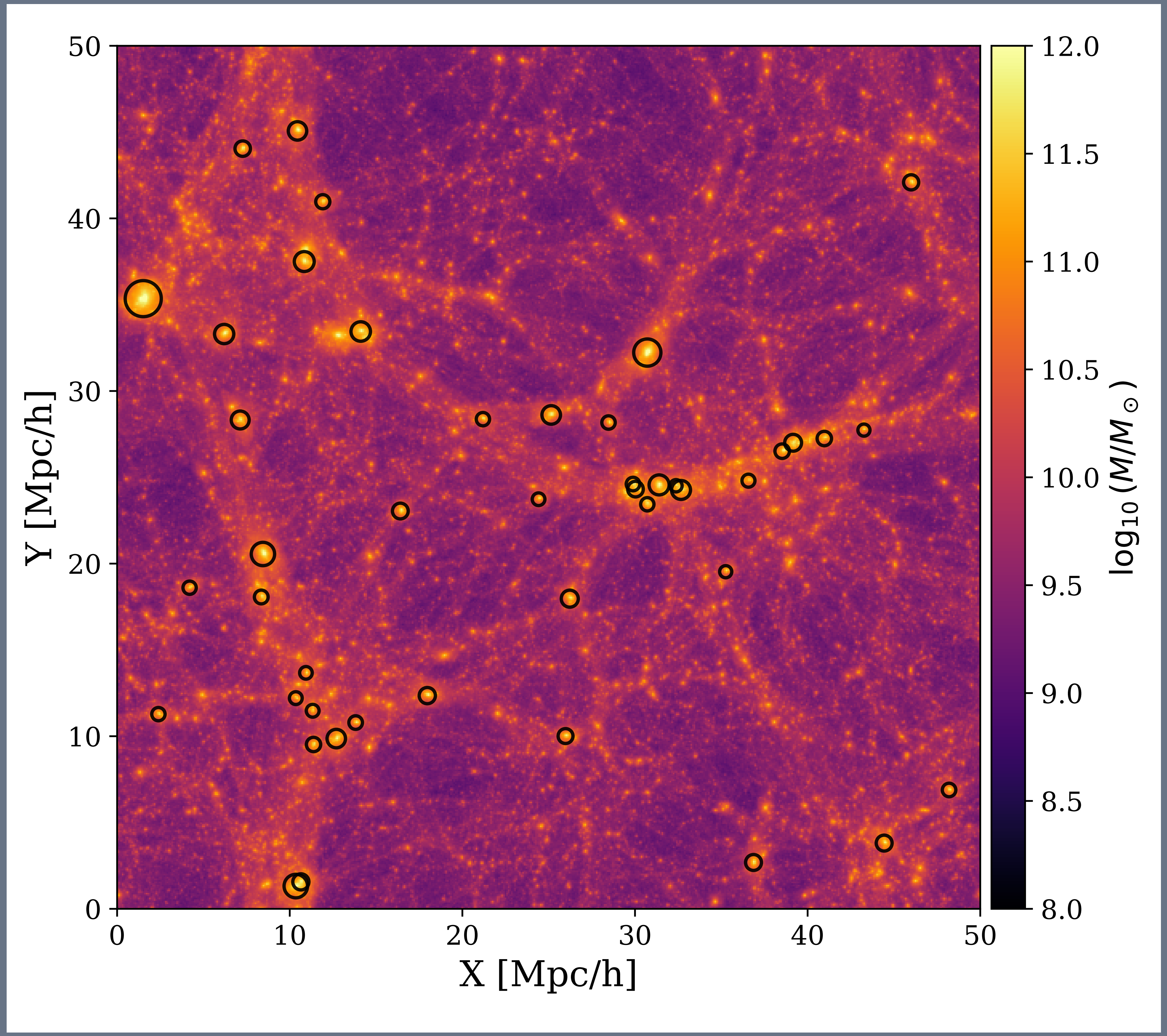
We measure the power spectrum suppression

$$S(k) = \frac{P_{\mathrm{hydro}}(k)}{P_{\mathrm{DMO}}(k)}$$

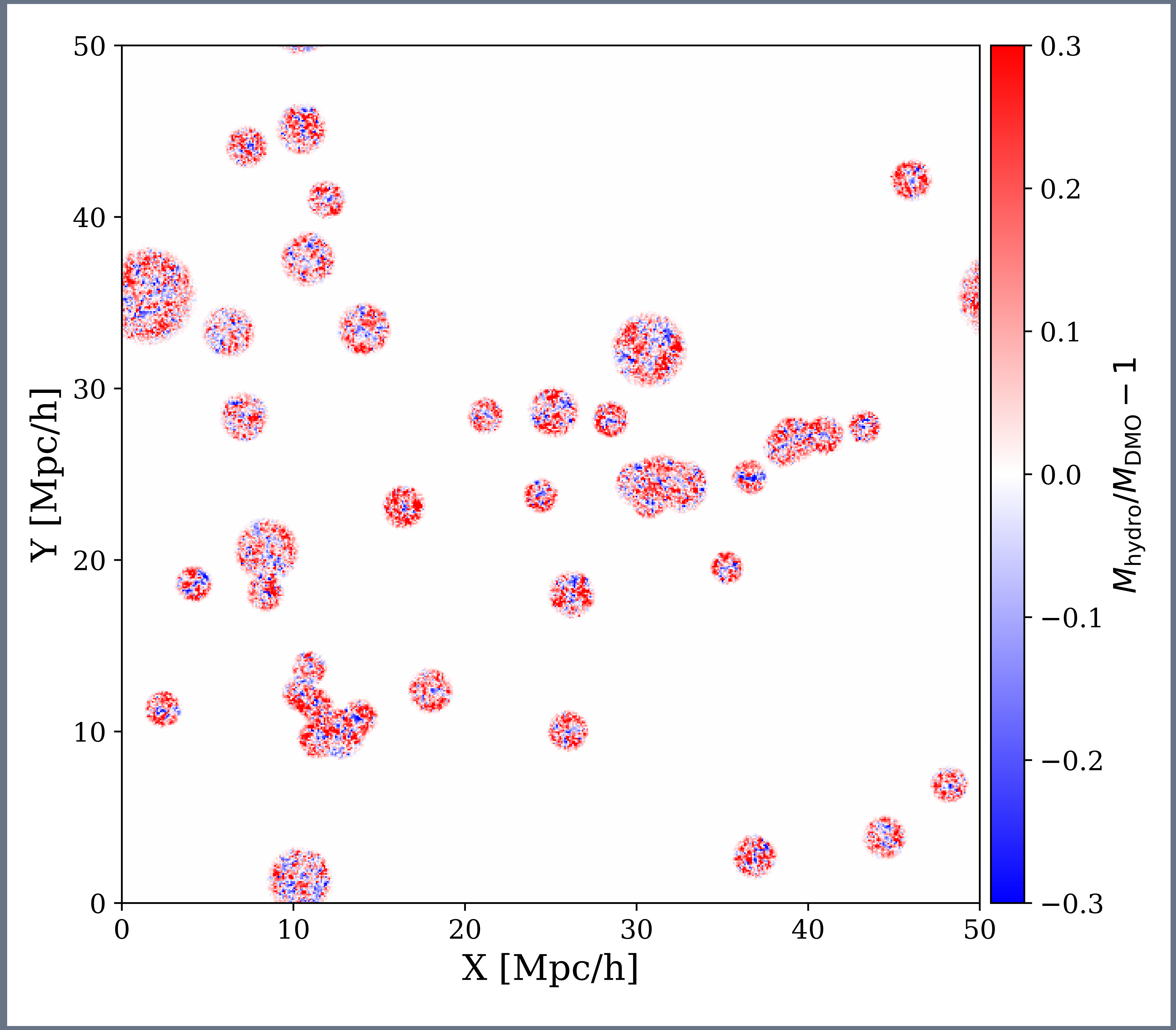
From TNG, TNG dark and a range of 64 replacement models with different mass bins and radial shells



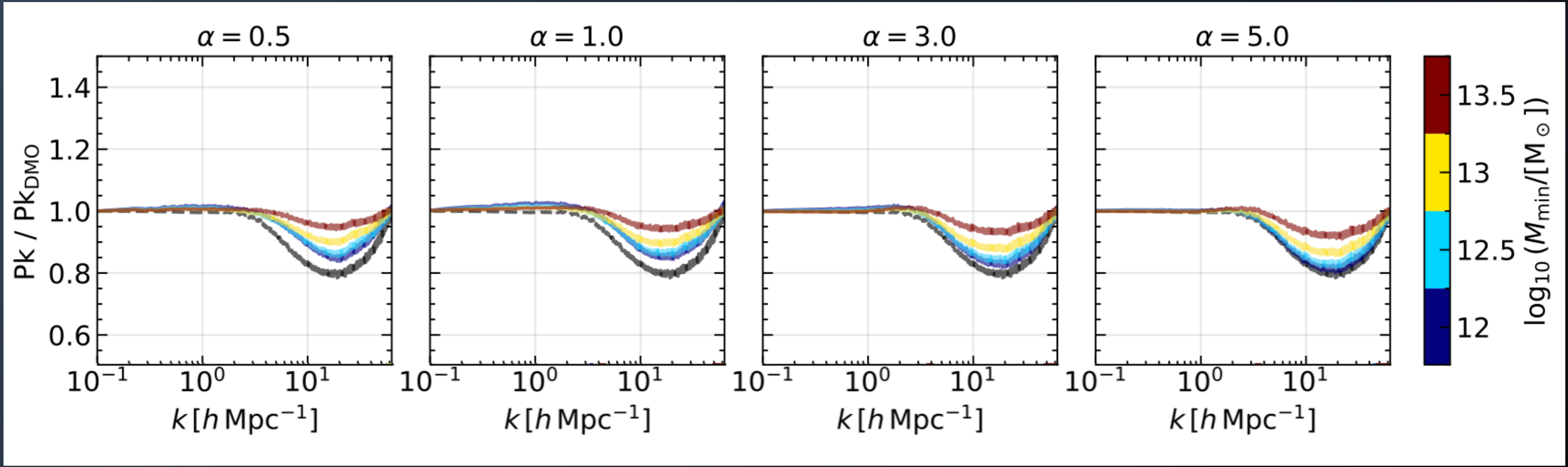
Dark Matter density Field — ρ_D



Replaced field residual — ρ_R/ρ_D



$$\rho_R(\mathbf{x},\mathbf{z}) = \rho_\mathbf{D}(\mathbf{x},\mathbf{z}) + \sum_{\mathbf{i}\in\mathbf{A}(\mathbf{M},\mathbf{z})} \theta_\mathbf{i}(\mathbf{x})\left[\rho^\mathbf{i}_\mathbf{H}(\mathbf{x},\alpha) - \rho^\mathbf{i}_\mathbf{D}(\mathbf{x},\alpha)\right]$$



Power spectrum should not work for BCMs!

This implies that a perfect BCM, which can capture the field of all halos of $M \geq 10^{13}\,h^{-1}M_\odot$ out to each of their $5R_{200}$ should be $> 20\,\%$ off from the true power spectrum suppression!

We can treat this as a "response"

In the next few slides, we will show this result as a "response" fraction or the fractional change in a statistic when replacing particles in some (M, α) bin

Power spectrum suppression for various $M_{\rm min}$ and $\alpha_{\rm max}$

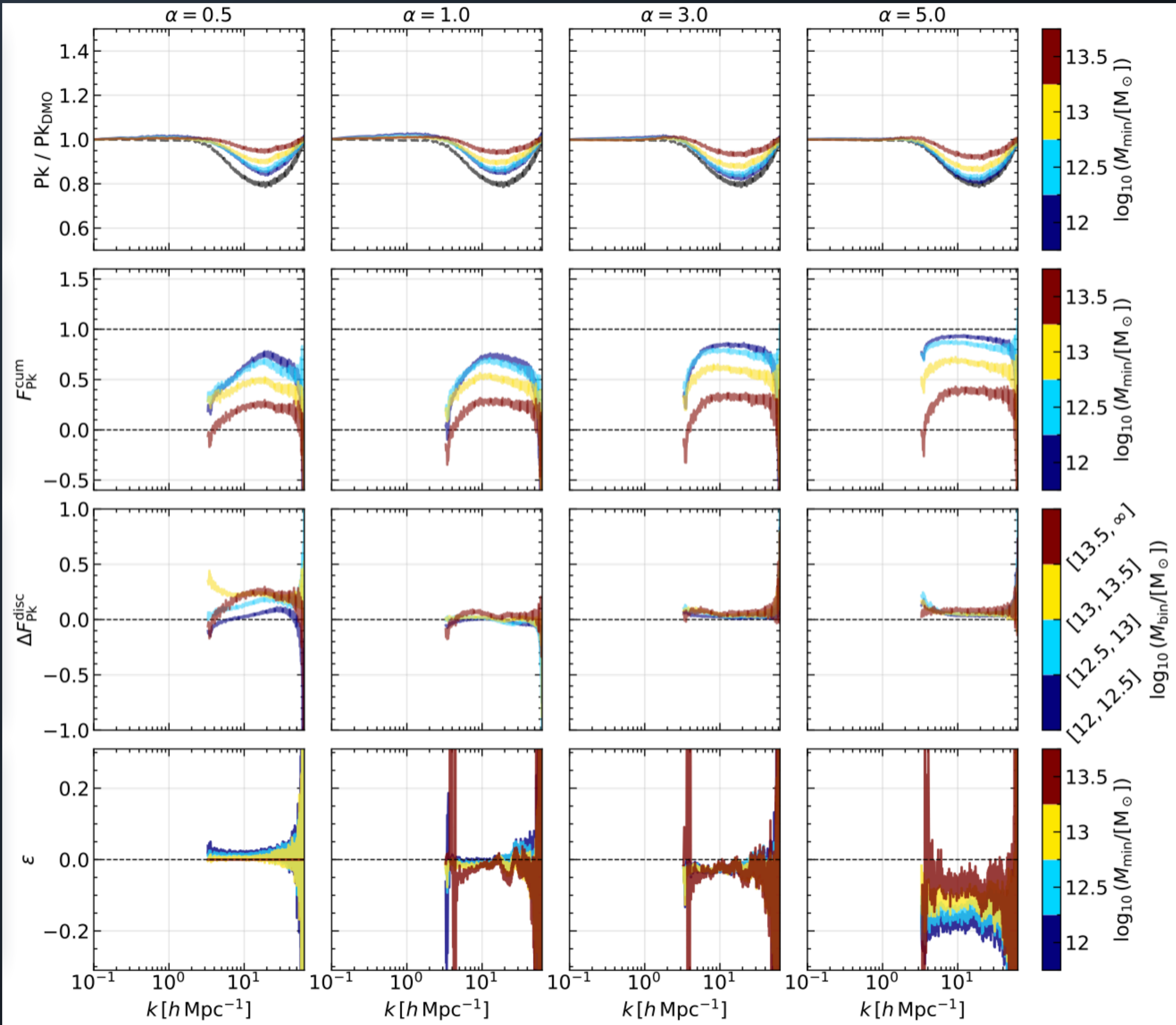
Cumulative response of P(k) to baryons with

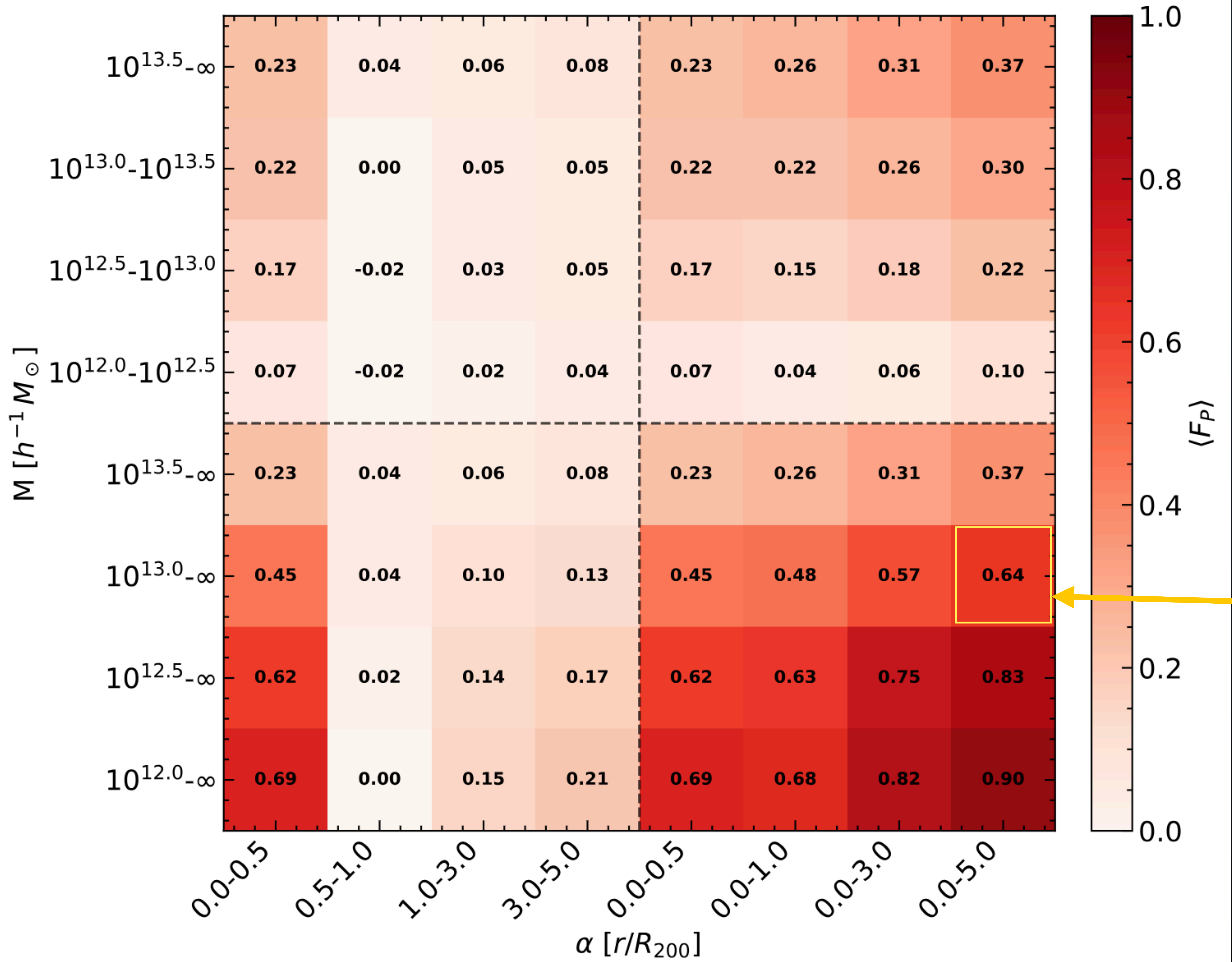
$$F_S(M_{\rm min}, \alpha_{\rm max}) = \frac{S_R(M_{\rm min}, \alpha_{\rm max}) - S_D}{S_H - S_D}$$

Response of P(k) in mass and radial bins

$$\Delta F_S^{\rm bin}(M_a, M_{a+1}; \alpha_i, \alpha_{i+1}) = \frac{S_R(M_a, M_{a+1}; \alpha_i, \alpha_{i+1}) - S_D}{S_H - S_D}$$

Linearity of P(k) with respect to mass bins and radial shells: Does summing bins in row 3 equal cumulative results in row 2





We can boil down that last slide by averaging over k to get just a single value representing a replace models ability to reproduce the true hydro statistic.

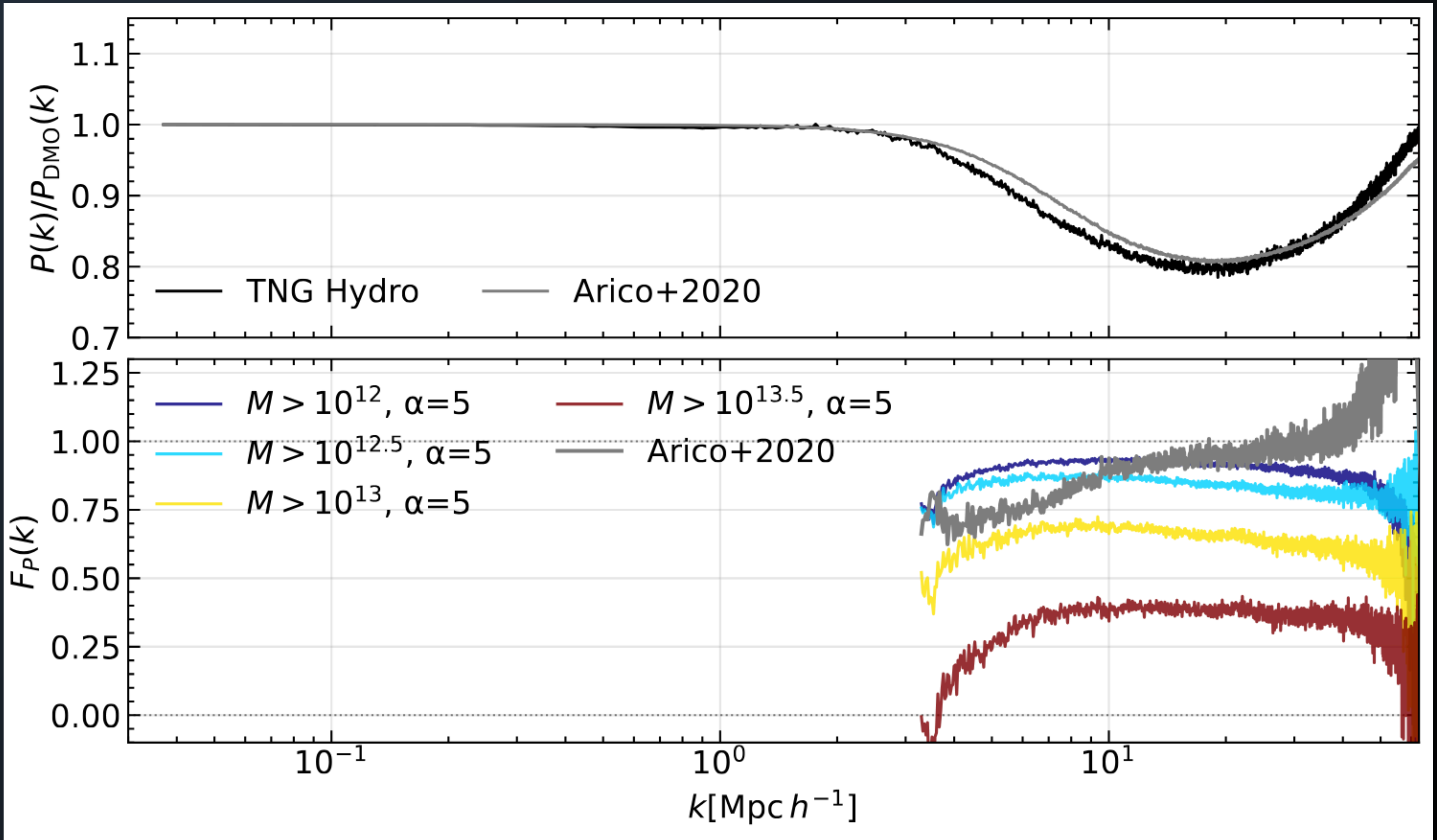
This represents the mean error that should exist for BCMs!
But they find percent level accuracy

The Resulting BCMs

Do two wrongs make a right?

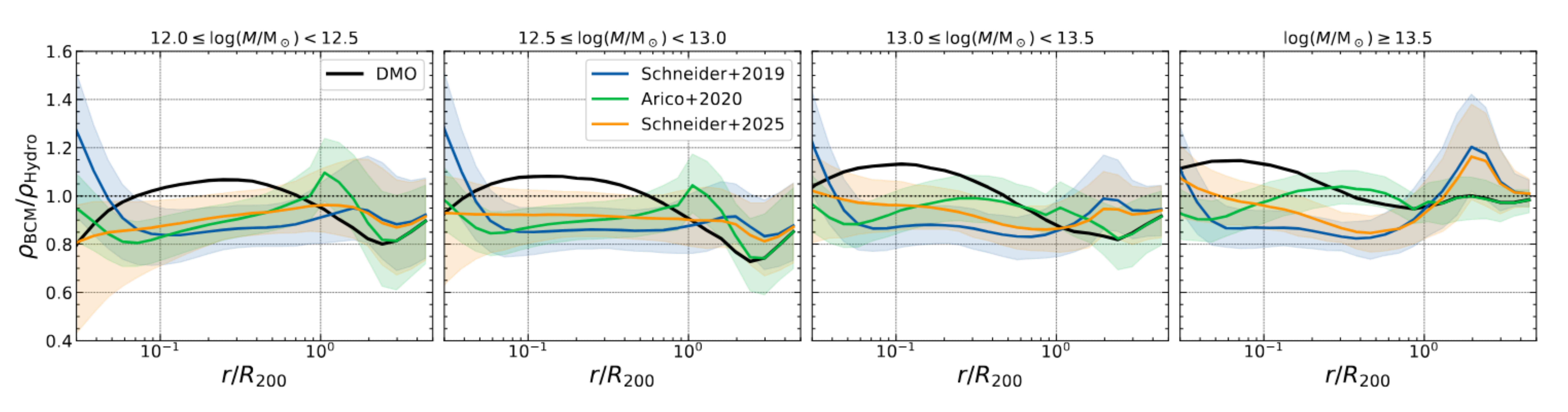
BCMs cant be this good!

The Arico model though matches at percent level for most k values despite only being applied to high mass halos! So how is this possible?



Resulting density profiles

Do two wrongs make a right?



#1 - Mass limited

They are ignoring baryonic effects in regions outside of a lower mass threshold and beyond some correction radius

Two cancelling mistakes are made

#2 - Overcorrected

The models apply corrections that over suppress in the interior, and over expell near the center and towards the exterior

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Will this remain true for other statistics such as those from weak lensing?

WL Summary Statistics

Do two wrongs always make a right?!

WL pipeline

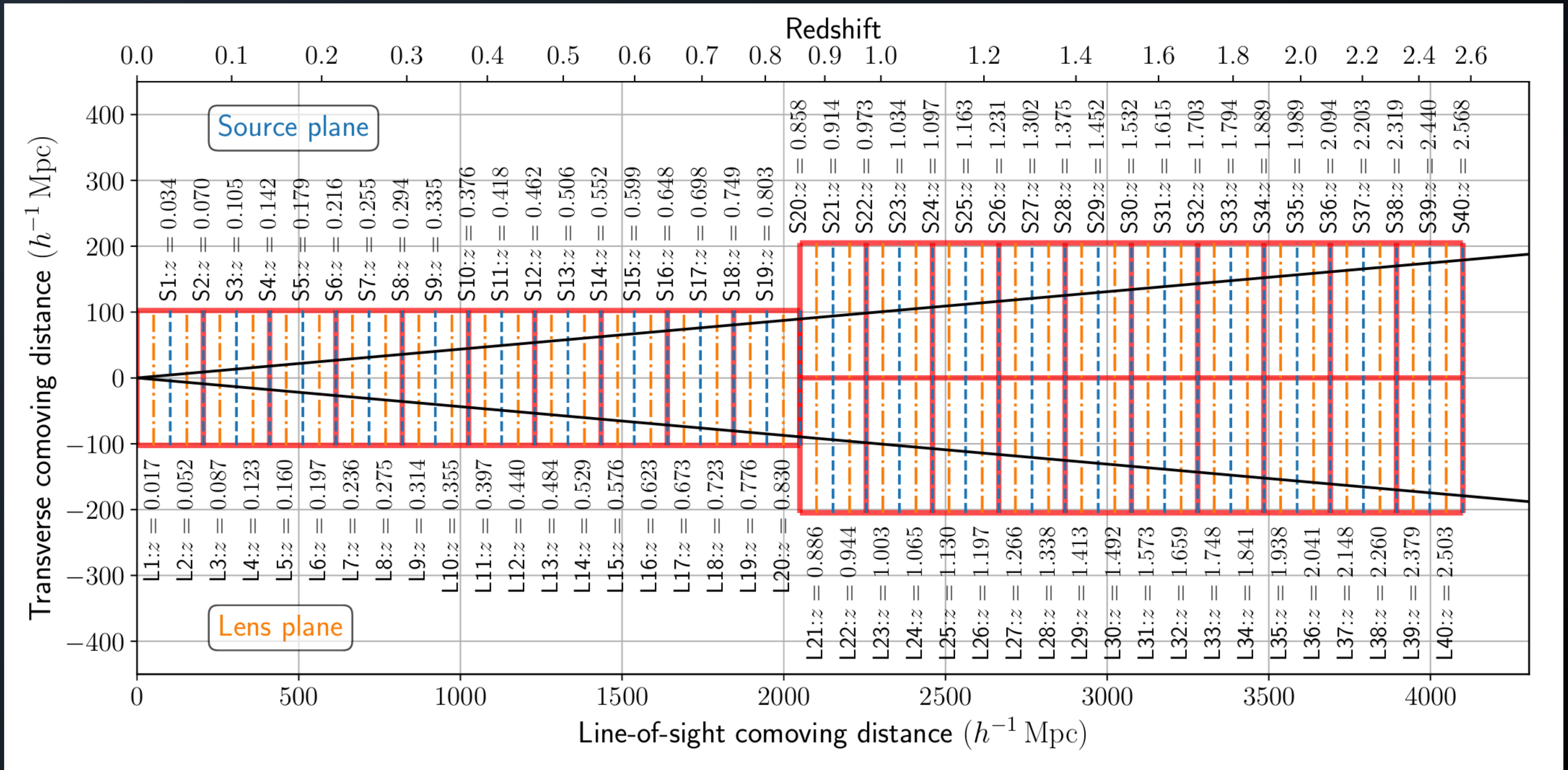
We generate 2,000 pseudo-independant ray traced maps at 40 redshifts to z=2.5 for each of the 64 replace model: 5Million maps!

WL stats

We compute C_ℓ, Peaks, Minima, Minkowski functionals for each map

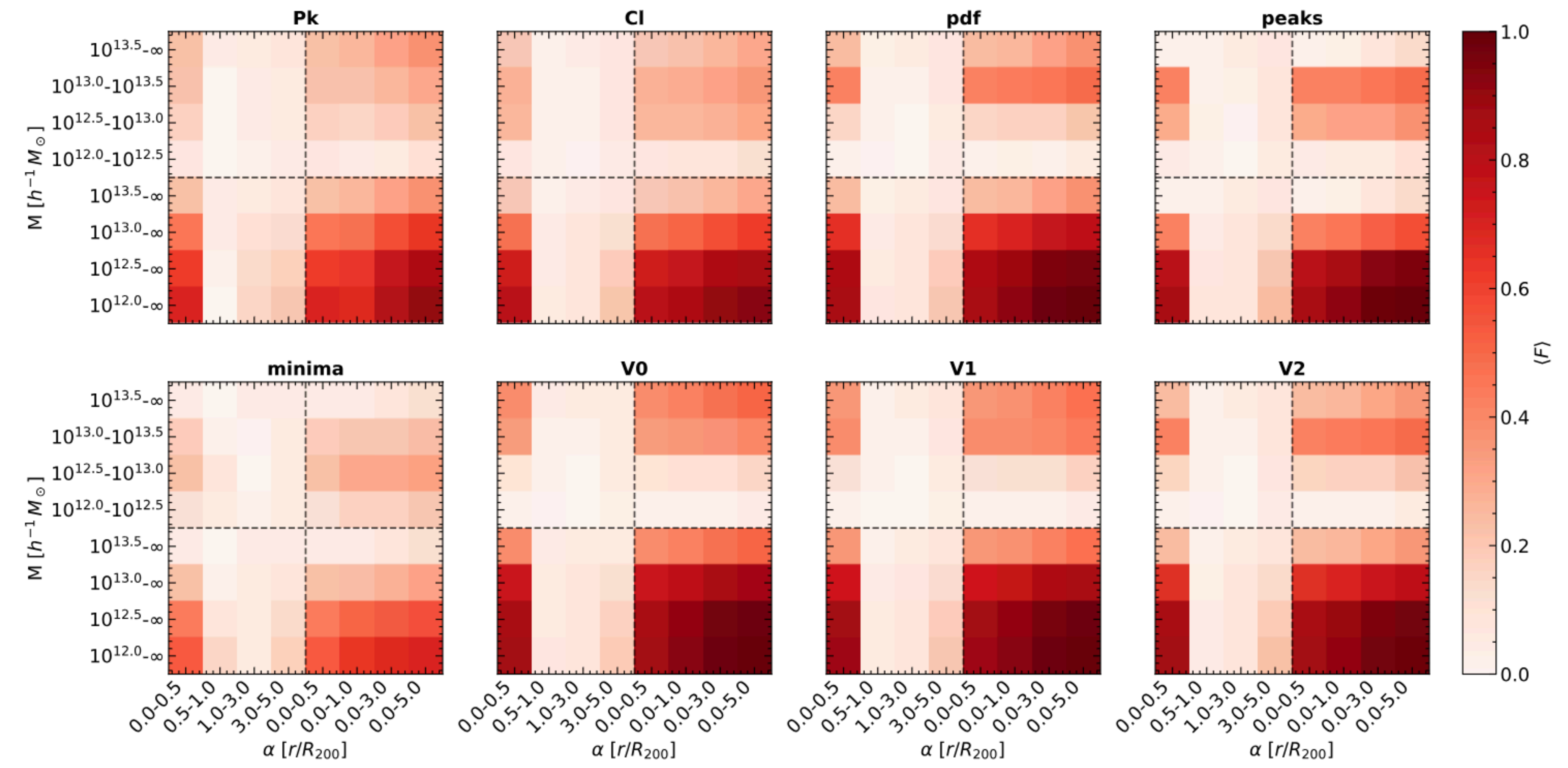
WL Response

We then follow the same response framework to find the sensitivity of stats to baryons



Responses for other summary statistics

Baryon fingerprints on weak lensing statistics



Moving forwards

What does this mean for baryon accounting moving forward?

1. **Different Fingerprints → Failures for different statistics** (e.g. peak counts fail when BCM is fit to power spectrum
2. **Joint fits may help if orthogonal**, i.e. Joint fits for BCMs dont automatically break degeneracies, and will not if they have overlapping fingerprints
3. **BCMs succeed by being wrong in precisely the right way**. They match P(k) because two mistakes cancel. This is why they're not portable across statistics, and why field-level reconstruction fails even when P(k) matches