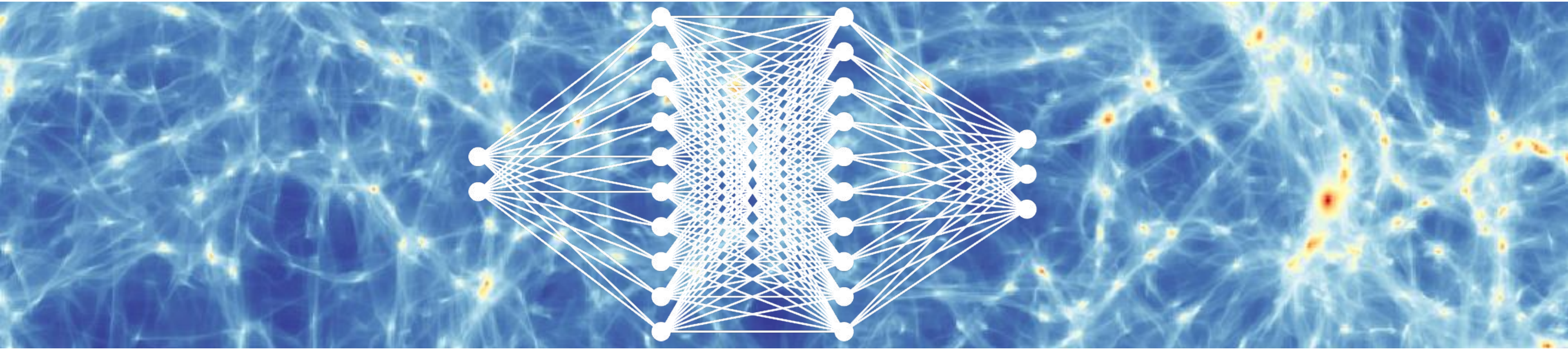
The hybrid Lagrangian bias model:

small-scale galaxy clustering and galaxy-galaxy lensing with the baccoemu emulators



Matteo Zennaro

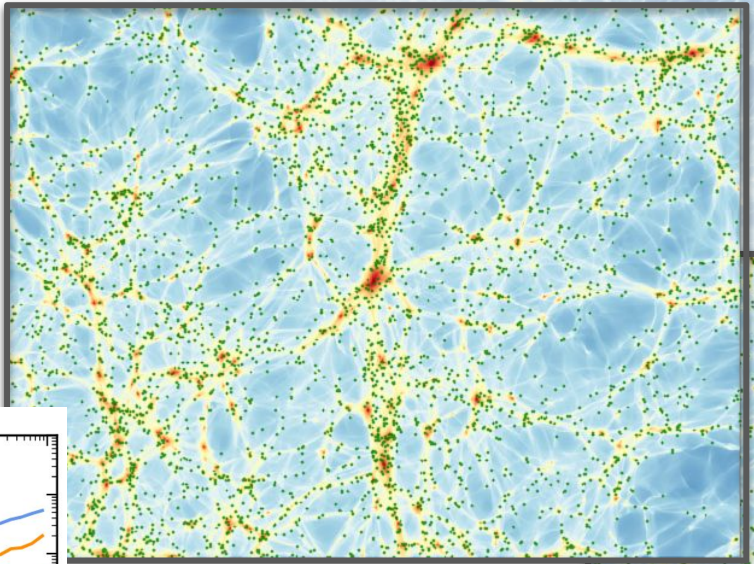
University of Oxford

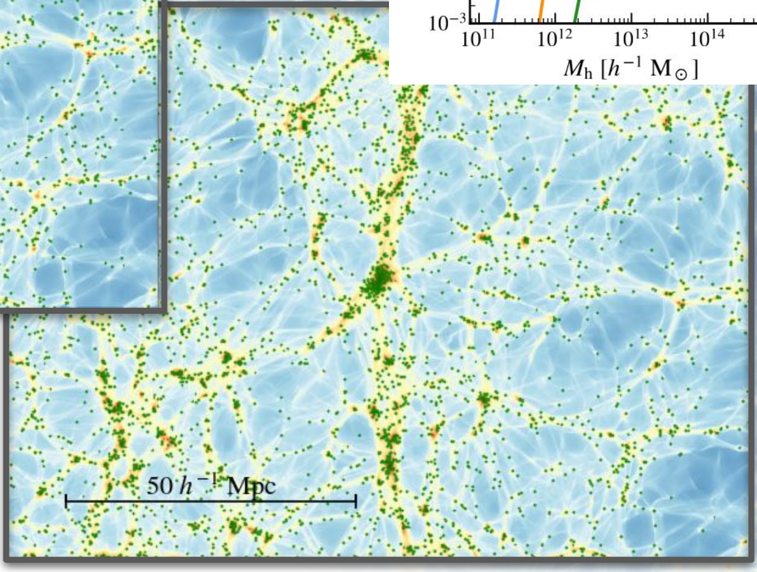
Paris, Nov 21st 2024

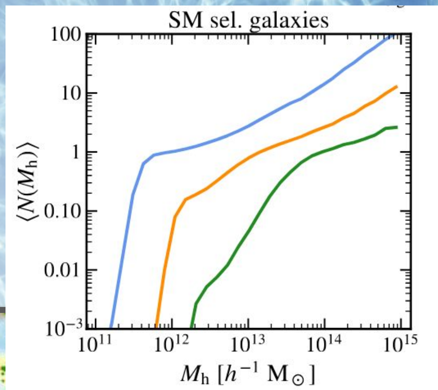
Lagrangian Bias Expansion Model

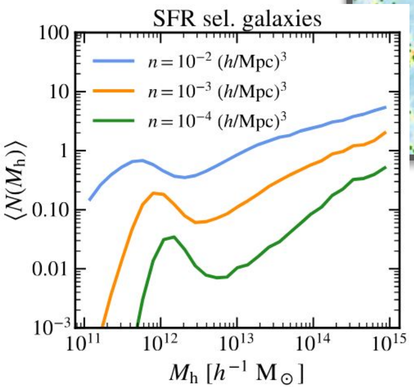
Change galaxy formation / selection:

very different galaxy samples







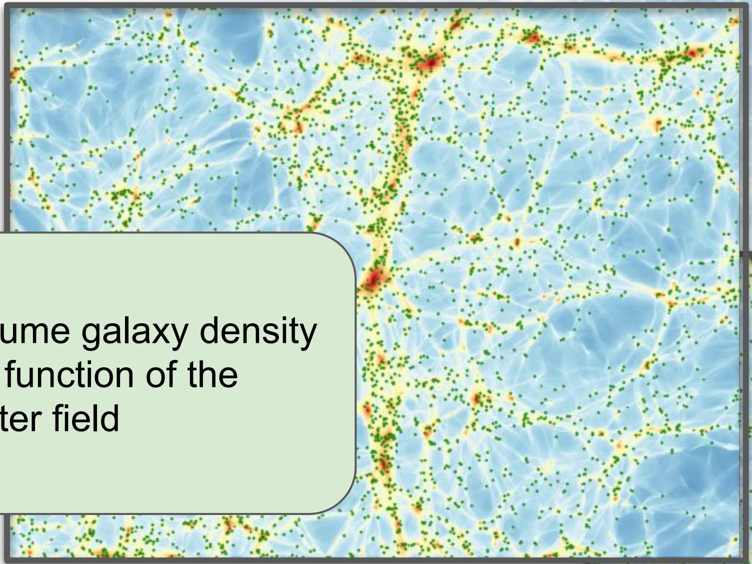


Galaxy samples generated with SHAMe (S. Contreras, R. E. Angulo and MZ, 2020b)

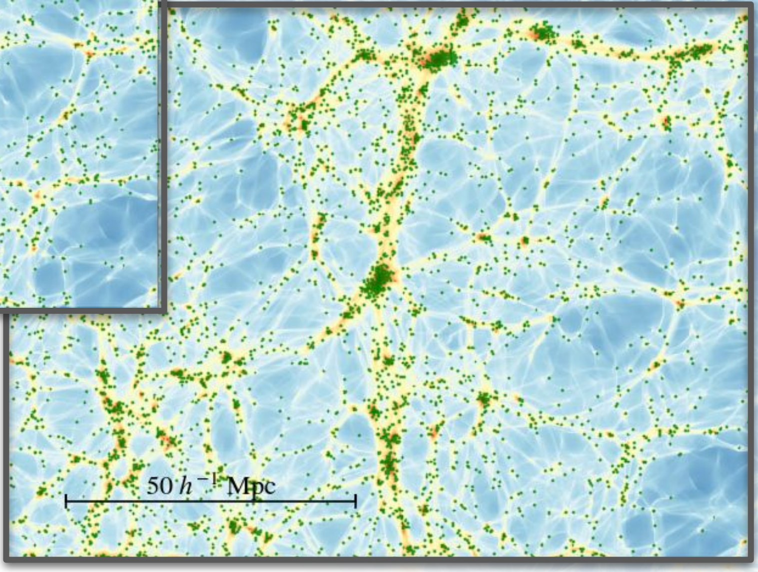
Lagrangian Bias Expansion Model

Change galaxy formation / selection:

very different galaxy samples



Assume galaxy density is a function of the matter field

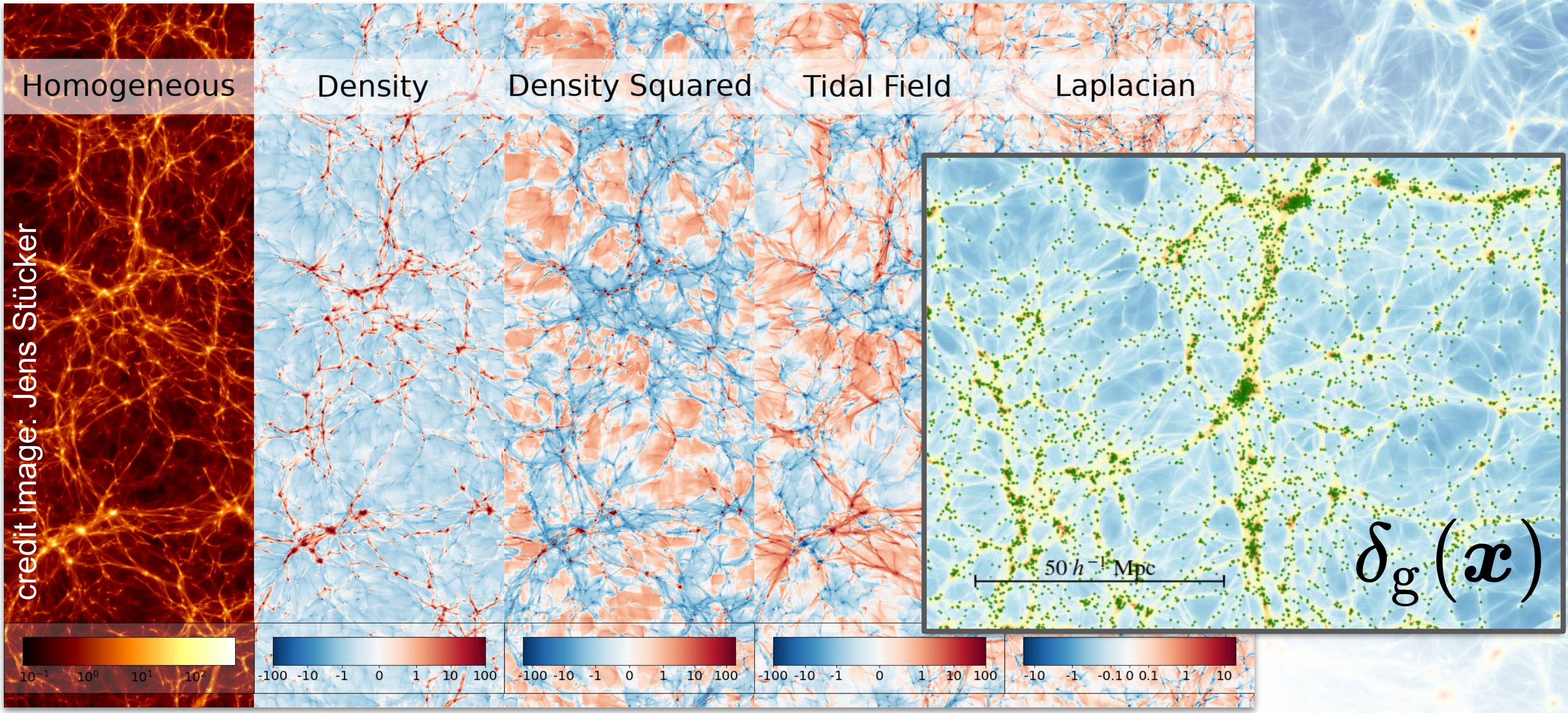


At 2nd order the ONLY terms that don't break symmetries are

$$\delta_g(\boldsymbol{q}) = F(\delta, \delta^2, s^2, \nabla^2\delta)$$

Lagrangian Bias Expansion Model

$$1 + b_1^{\mathrm{L}}\delta(\boldsymbol{q}) + b_2^{\mathrm{L}}\delta^2(\boldsymbol{q}) + b_{s^2}^{\mathrm{L}}s^2(\boldsymbol{q}) + b_{\nabla^2\delta}^{\mathrm{L}}\nabla^2\delta(\boldsymbol{q})$$



The BACCO hybrid lagrangian bias model

$$\delta_{\rm g}(\boldsymbol{x}) = \int {\rm d}^3\boldsymbol{q}[1 + b_1^{\rm L}\delta(\boldsymbol{q}) + b_2^{\rm L}\delta^2(\boldsymbol{q}) + b_{s^2}^{\rm L}s^2(\boldsymbol{q}) + b_{\nabla^2\delta}^{\rm L}\nabla^2\delta(\boldsymbol{q})]\delta_{\rm D}(\boldsymbol{x} - \boldsymbol{q} - \Psi)$$

$$P_{\rm gg}(k) = \sum_{i,j} b_i b_j P_{ij}(k) + \frac{A_{\rm sn}}{\bar{n}}$$

5 free parameters $b_1^{\rm L}, b_2^{\rm L}, b_{s^2}^{\rm L}, b_{\nabla^2\delta}^{\rm L}, A_{\rm sn}$

Modi & White (2020), MZ et al (2021); Pellejero-Ibañez et al (2022); Kokron et al (2021), Maion, Angulo, MZ (2022)

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from simulations - fully nonlinear

$$P_{\rm gg}(k) = \sum_{i,j} b_i b_j P_{ij}(k) + \frac{A_{\rm sn}}{\bar{n}}$$

5 free parameters $b_1^{\rm L}, b_2^{\rm L}, b_{s^2}^{\rm L}, b_{\nabla^2\delta}^{\rm L}, A_{\rm sn}$

Modi & White (2020), MZ et al (2021); Pellejero-Ibañez et al (2022); Kokron et al (2021), Maion, Angulo, MZ (2022)

We rely on emulators

5 sims:
Narya
Nenya
Vilya
The One
Barahir

(order 2 million core hours per paired sim)

sim details (81×10^9 part.s, 3 Gpc^3/h^3, …)

→

4000 combinations of cosmological parameters and redshifts

(order 10 core hours per paired scaling)

cosmology rescaling

→

measure 15 bacco hybrid model templates

(< 1 core hours per measurement)

lagrangian fields advected

→

train Neural Network

(1 eval in ~ 40 ms)

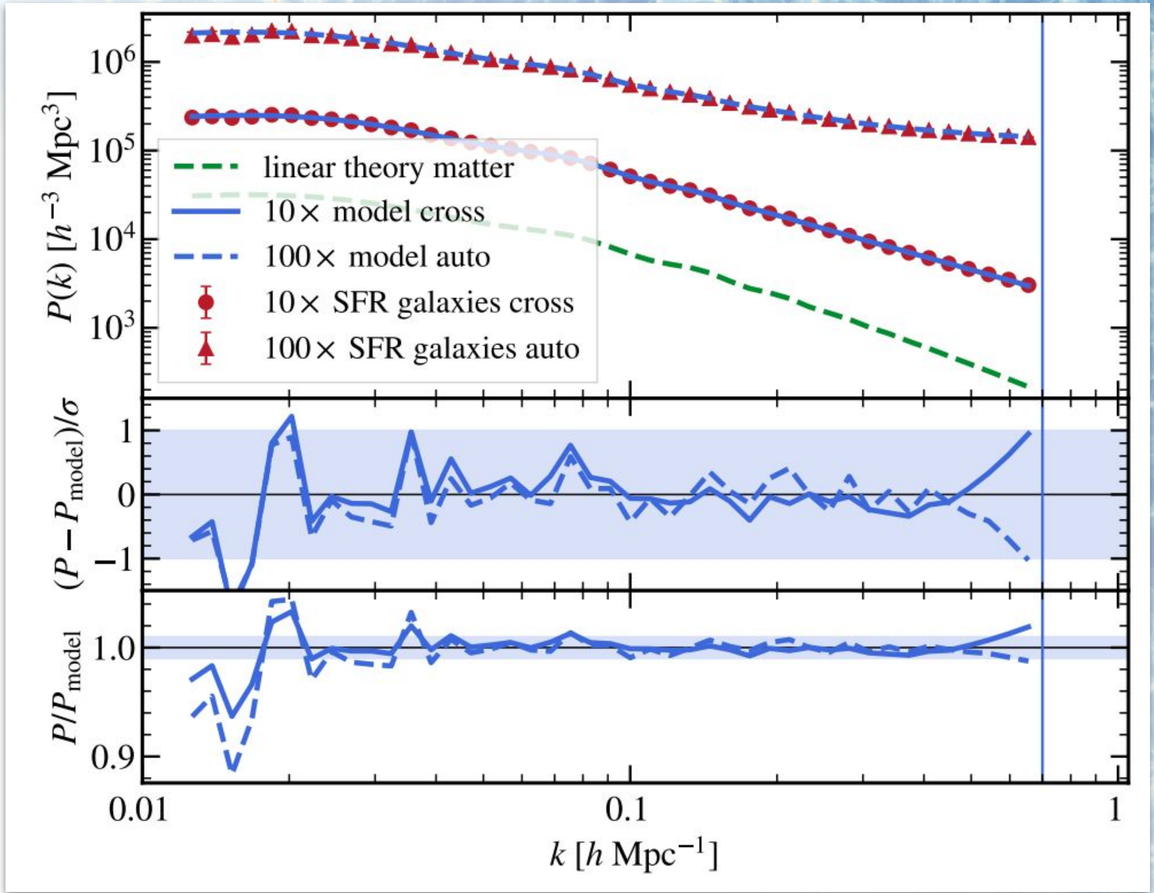
architecture, accuracy

MZ et al (2023)

Performance

8000 samples between haloes and SHAMe galaxies with different cosmologies, redshifts, number densities, SHAMe properties

Fits always accurate up to k = 0.7 h/Mpc



MZ et al (2022)

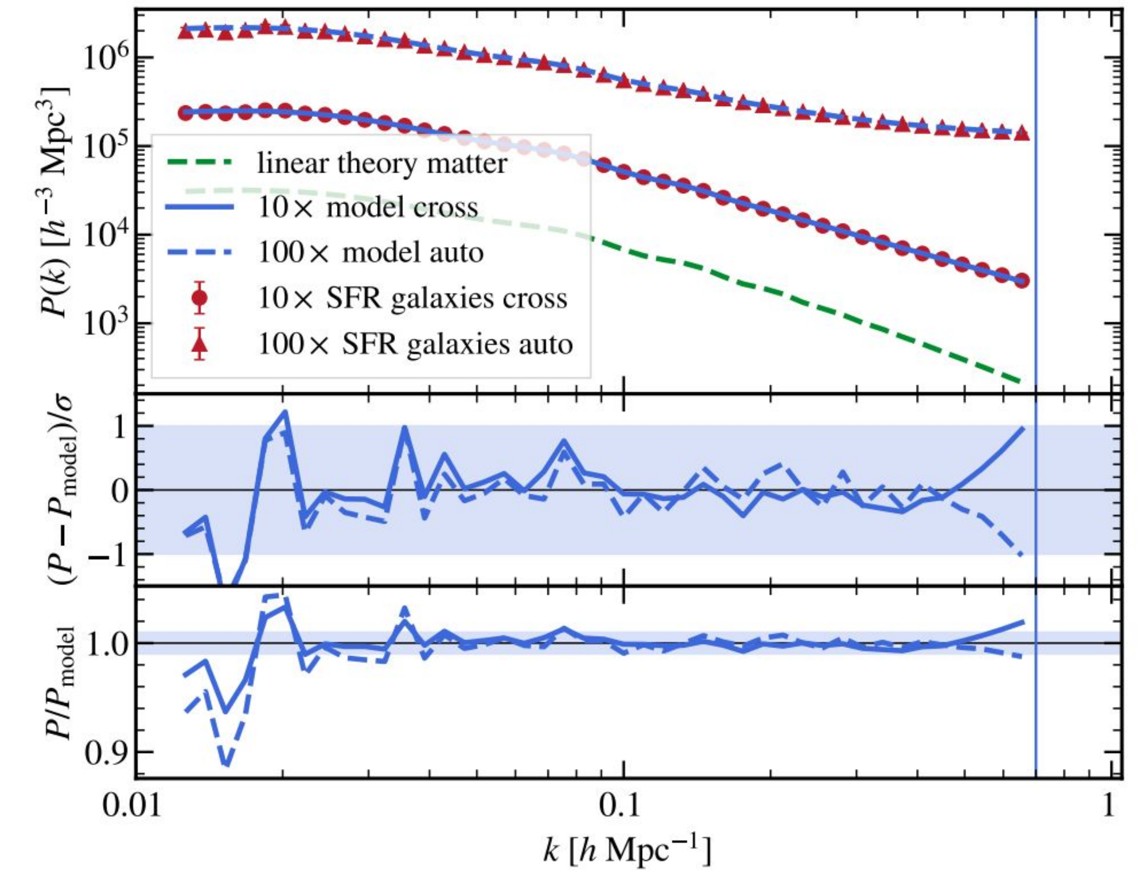
Performance

8000 samples between haloes and SHAMe galaxies with different cosmologies, redshifts, number densities, SHAMe properties

Fits always accurate up to k = 0.7 h/Mpc

Marcos Pellejero-Ibáñez

model in **redshift space (emulator** available)



MZ et al (2022)

Galaxy bias priors

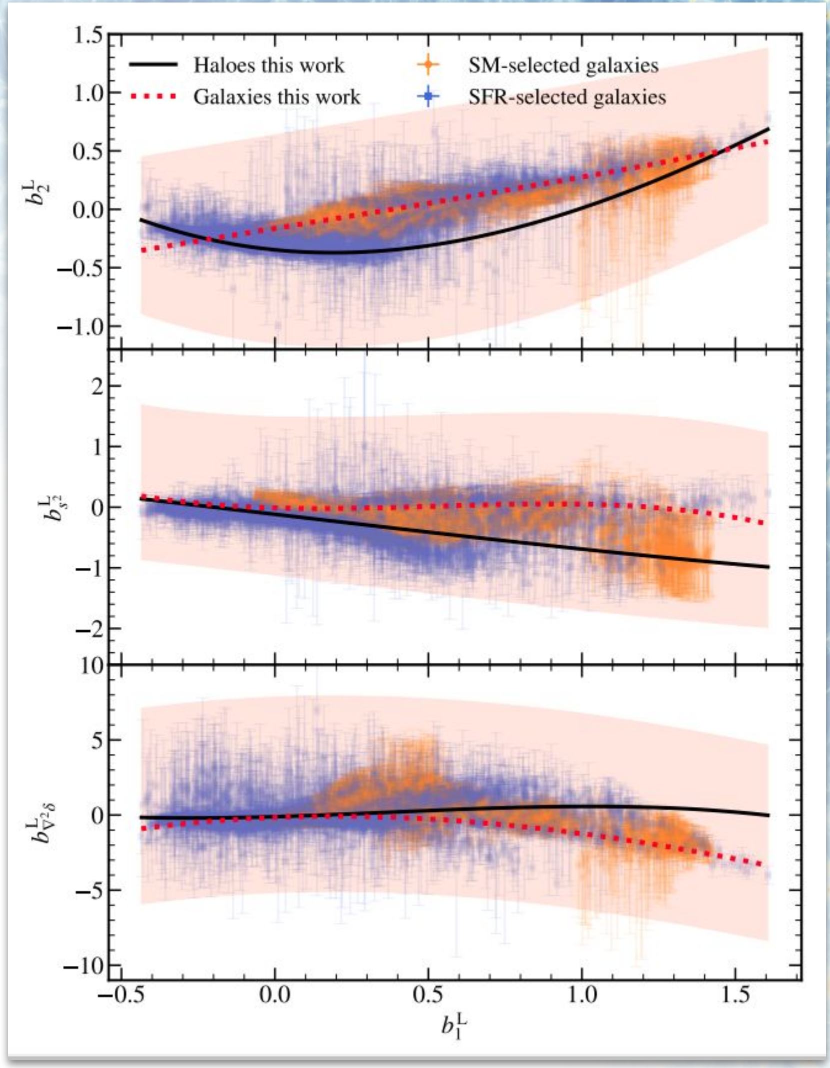
8000 samples between haloes and SHAMe galaxies with different cosmologies, redshifts, number densities, SHAMe properties

Fits always accurate up to k = 0.7 h/Mpc

Coevolution relations for these bias parameters:

$$b_2(b_1) \qquad b_{s^2}(b_1)$$

$$b_{\nabla^2\delta}(b_1)$$



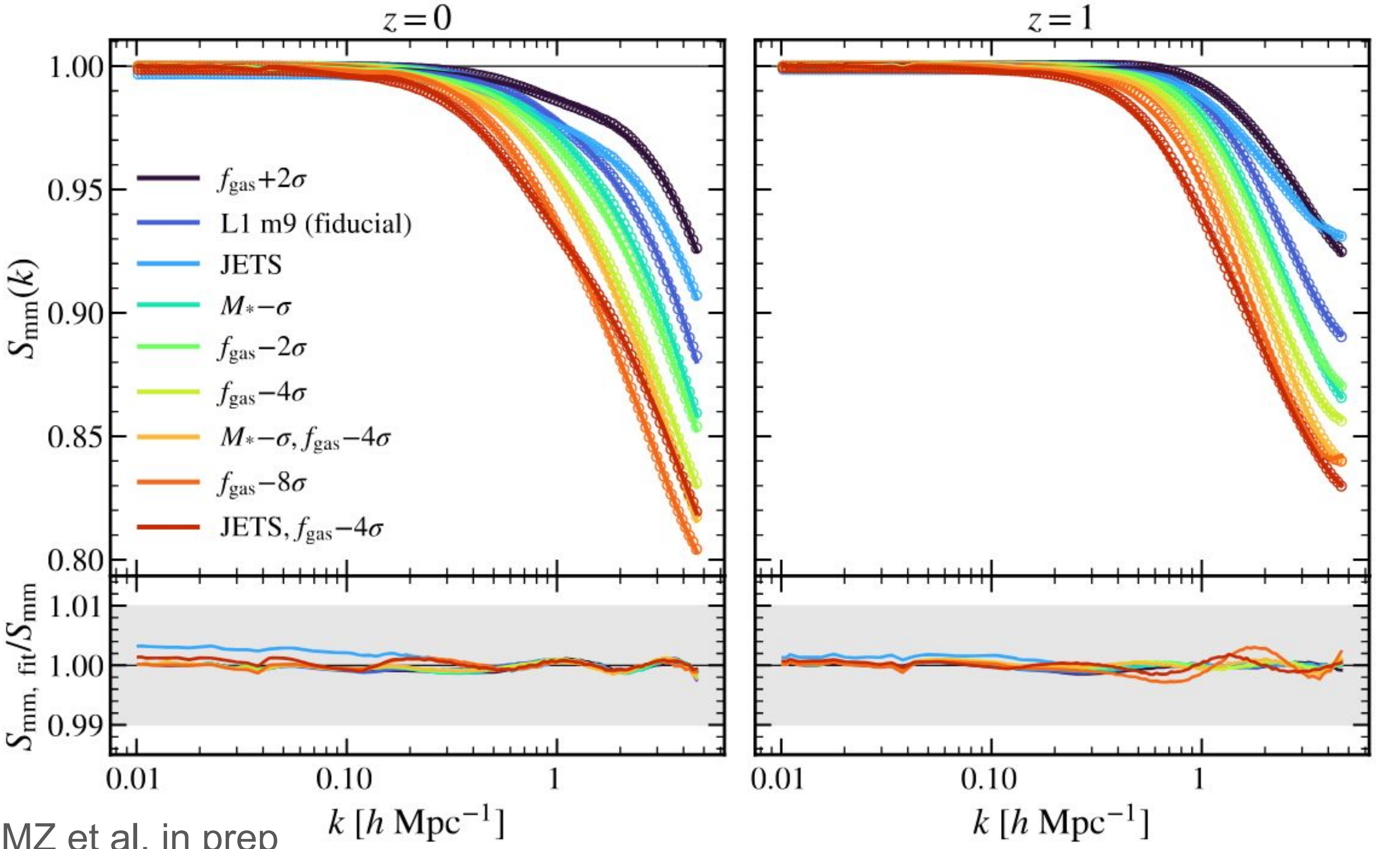
MZ et al (2022), conf. from data Pellejero-Ibáñez et al (2024)

The effect of baryons - matter: $S_{mm} = P_{mm,hydro} / P_{mm,dmo}$

9 baryon models from **FLAMINGO** simulations

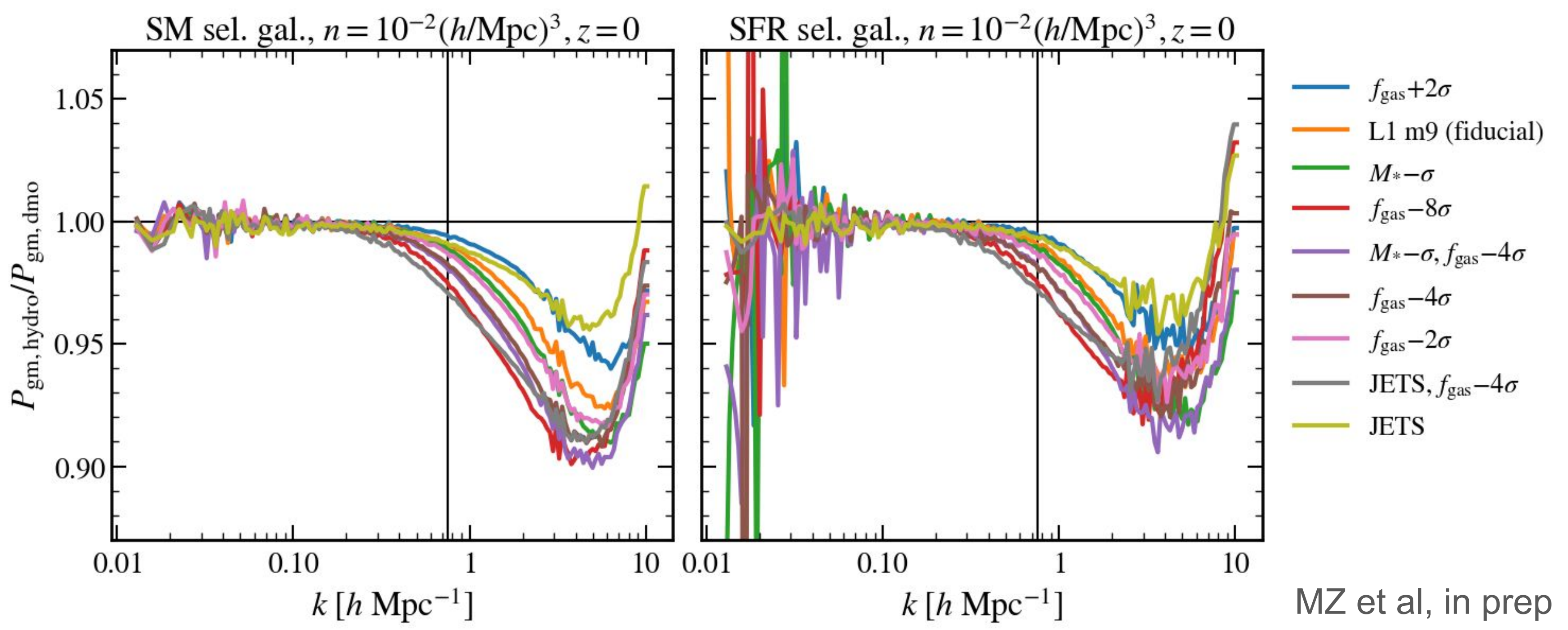
Fits with **baccoemu** (matter + BCM)
Angulo et al (2020)
Aricò et al (2021)

Giovanni's baryonification (yesterday)



MZ et al, in prep

The effect of baryons - gm cross spectrum



MZ et al, in prep

$$S_{gm} = P_{gm,hydro} / P_{gm,dmo}$$

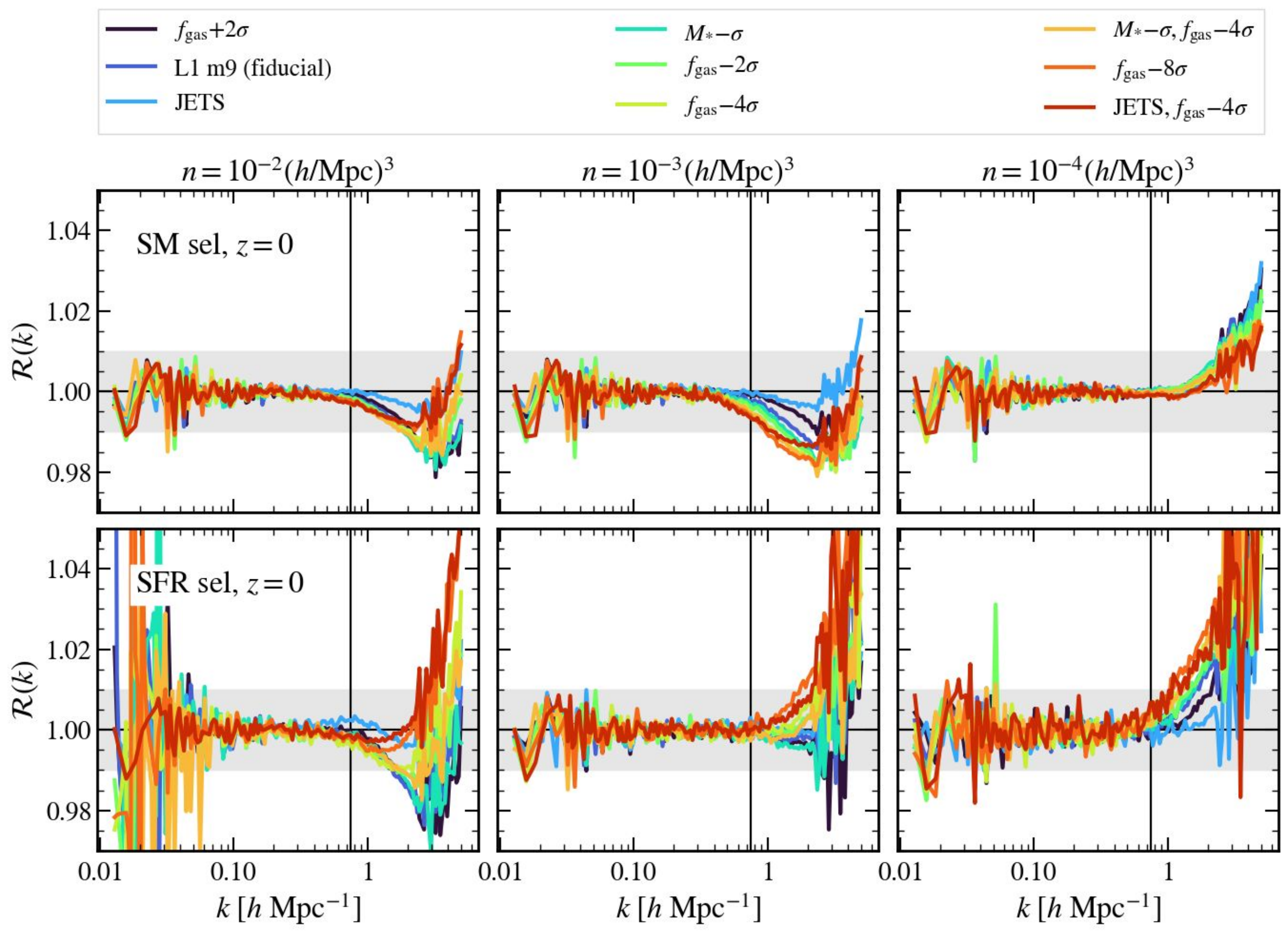
$$S_{gm} \overset{?}{\sim} \sqrt{S_{mm}}$$

The effect of baryons - gm cross spectrum

$R = S_{gm} / \sqrt{S_{mm}}$

Hybrid model valid up to k ~ 1 h/Mpc

1% accuracy on these scales



MZ et al, in prep

The effect of baryons

Ignore baryons in Pgm:

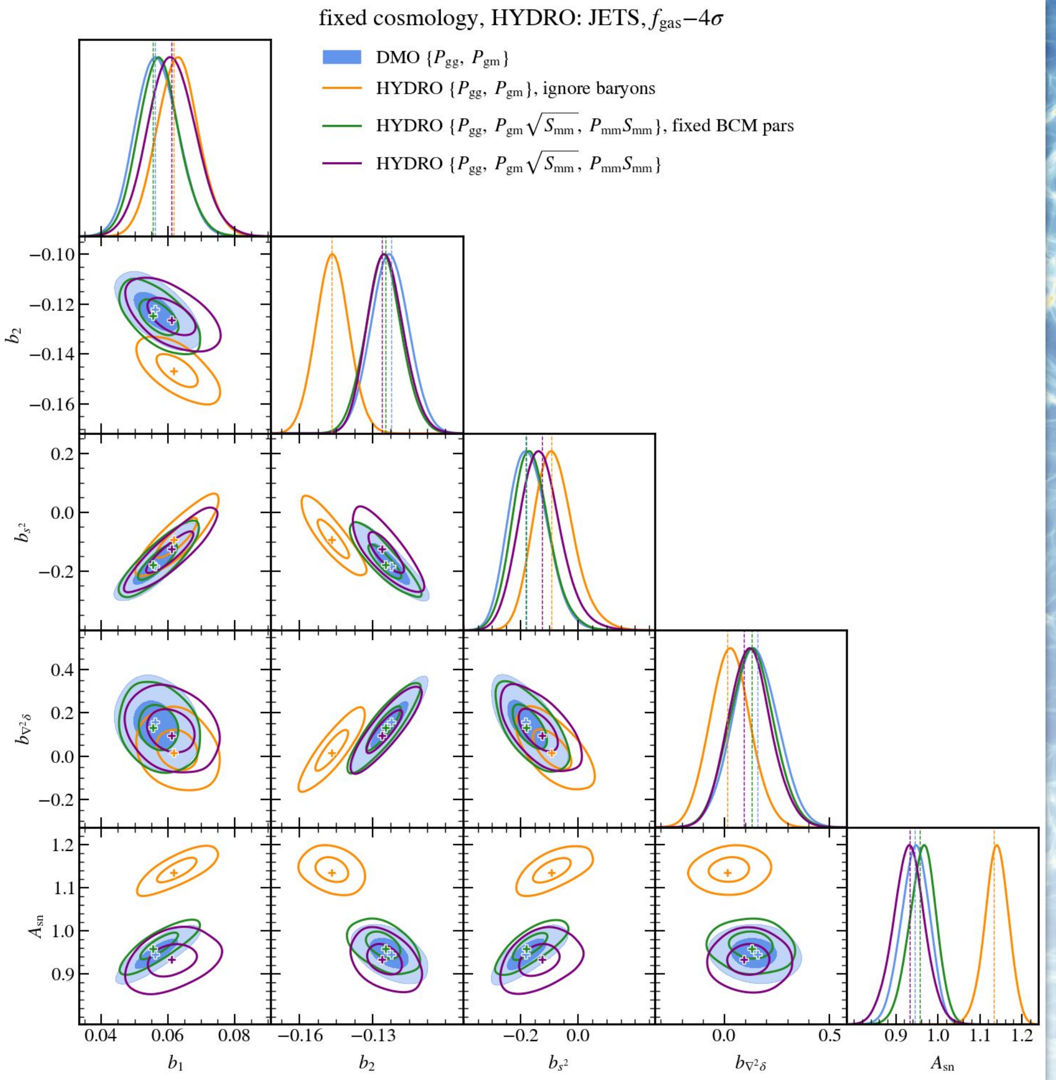
- still good fits
- bias parameters different from fiducial ones

Include baryons (fixed to best fits):

- recover fiducial bias params

Include baryons (free):

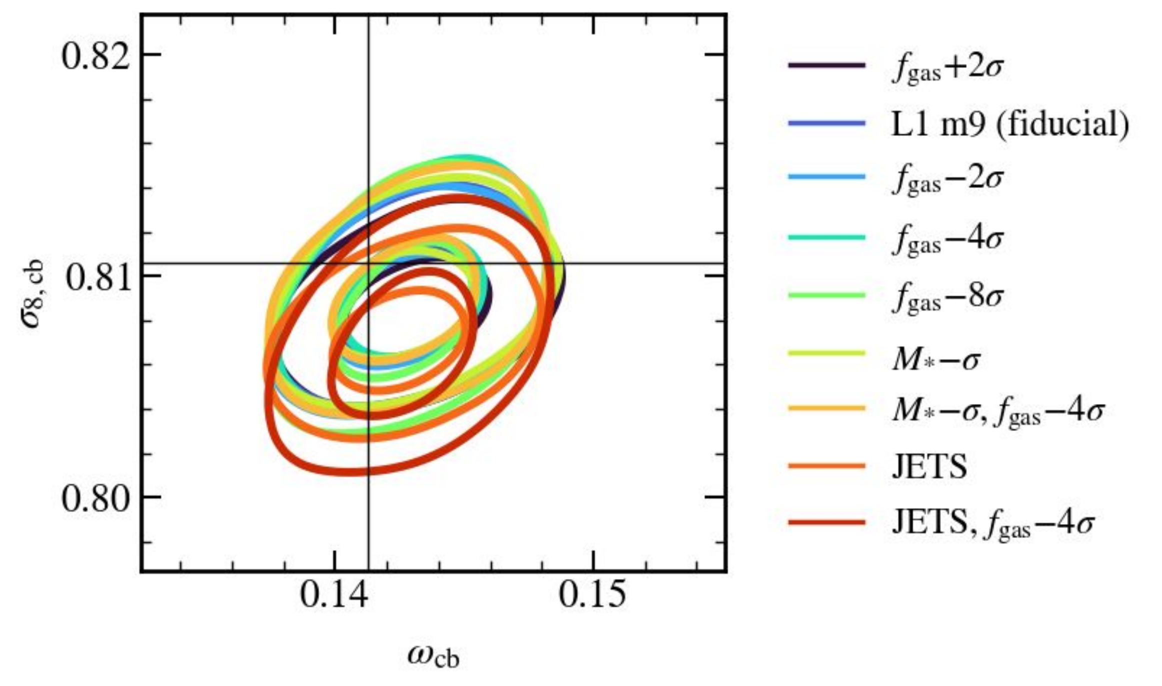
- recover fiducial bias params
- larger contours (more free params)



MZ et al, in prep

The effect of baryons - free cosmology

For all baryon models, including baryons in the P_{gm} model, **unbiased** cosmological parameters



MZ et al, in prep

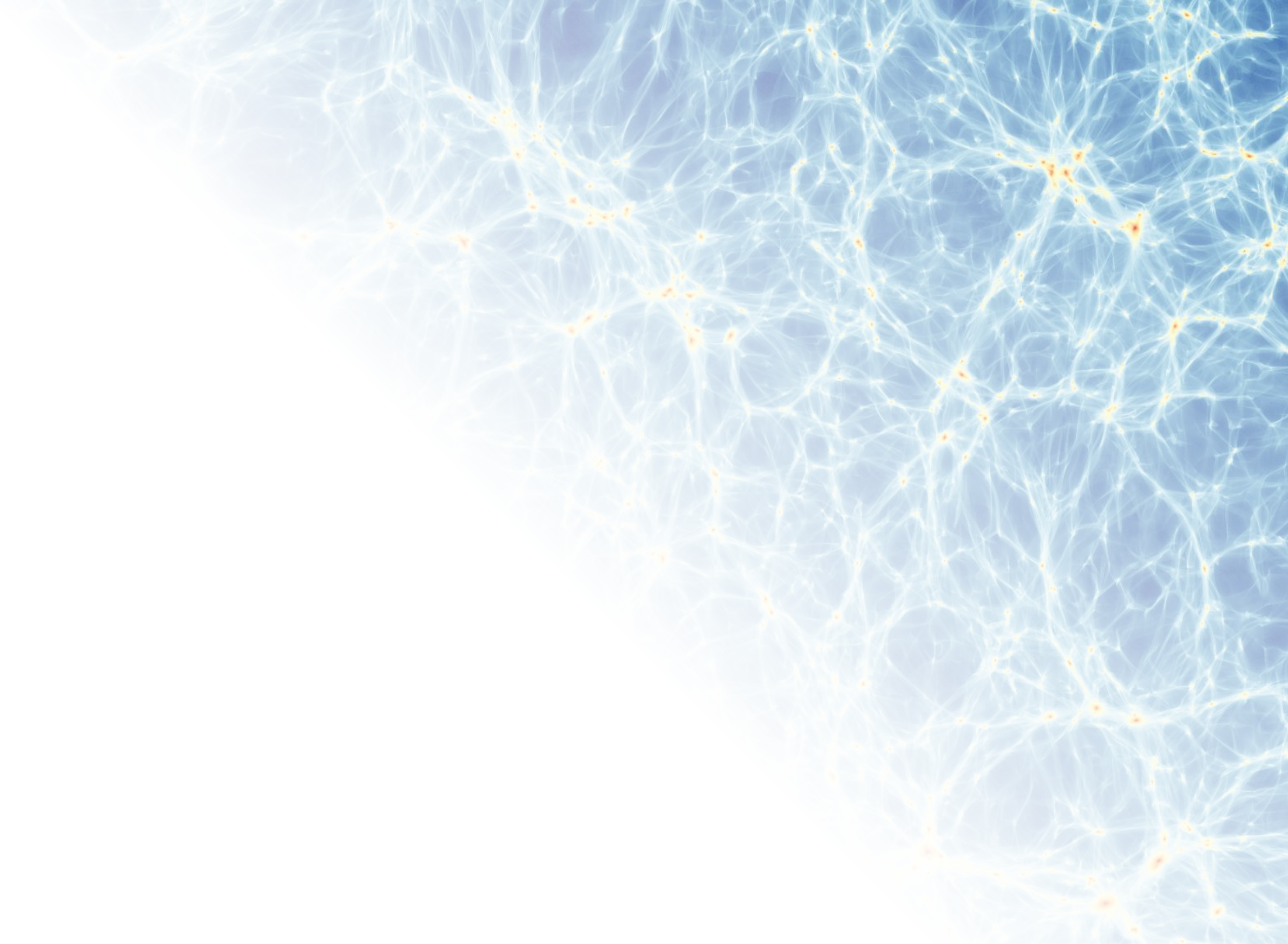
Conclusions

Hybrid Lagrangian bias model:

- percent-level accuracy for galaxy clustering up to k=0.7 h/Mpc
- fast emulator to predict P_{gg} and P_{gm} for LCDM + neutrinos + $w_0 w_a$
- priors on galaxy bias parameters
- very promising for 3x2points analysis

Effect of baryons on P_{gm}:

- can be captured by galaxy bias, but inconsistently
- matter power spectrum suppression is a good approximation (1% accurate) on interesting scales ($k < 1$ h/Mpc)
- unbiased cosmological parameters



baccoemu: a full suite of emulators

Nonlinear **matter** power spectrum

Baryon Correction Model (BCM)

Nonlinear templates for hybrid Lagrangian bias expansion in real space

Nonlinear templates for hybrid Lagrangian **bias** expansion in **redshift space**

Galaxy clustering from SHAMe models

Linear matter power spectrum (tot matter)

Linear matter power spectrum (cdm+b)

Linear matter power spectrum with **smeared BAO** (cdm+b) in real and redshift space

Linear matter power spectrum **dewiggled** (cdm+b)

2LPT templates for hybrid Lagrangian **bias** expansion is real and redshift space

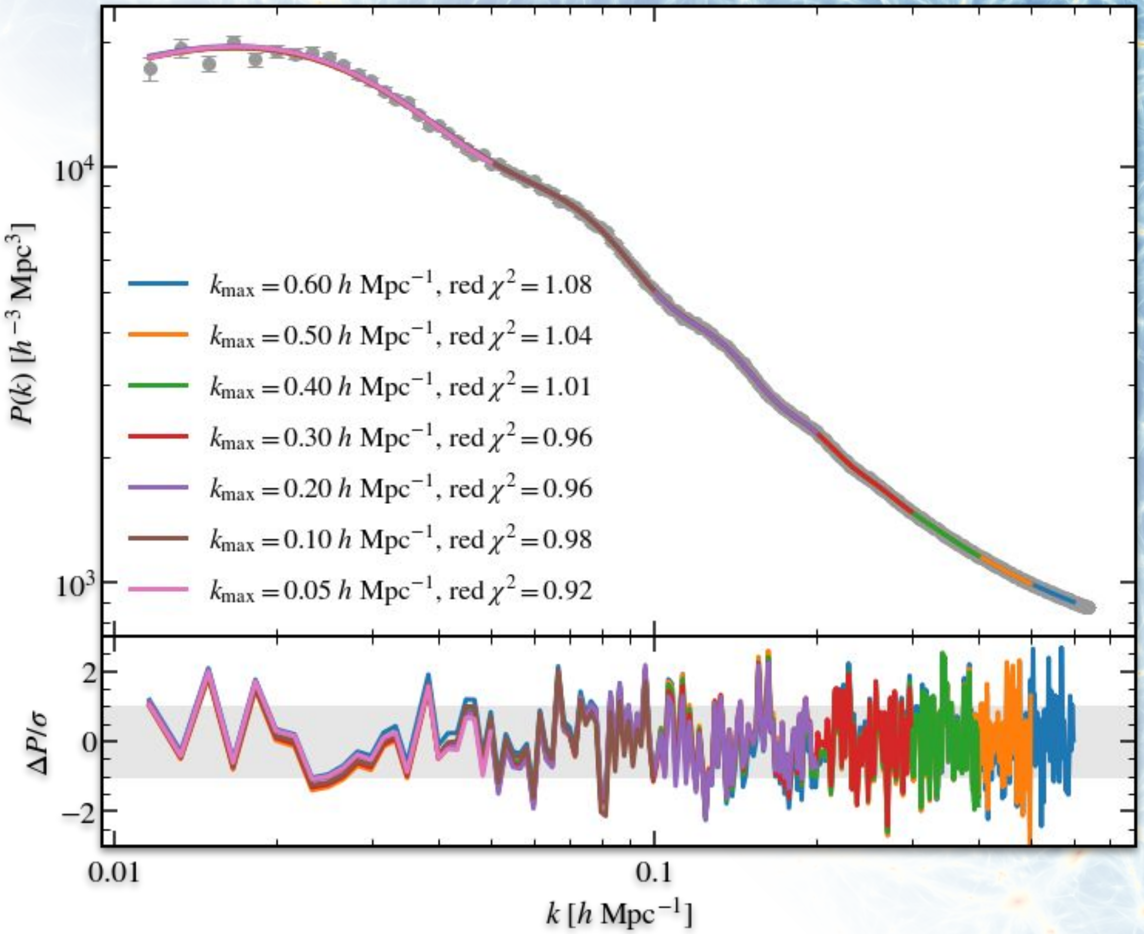
As -> $\sigma_{8,cold}$, $\sigma_{8,tot}$, $\sigma_{12,cold}$, $\sigma_{12,tot}$

https://bacco.dipc.org/emulator.html

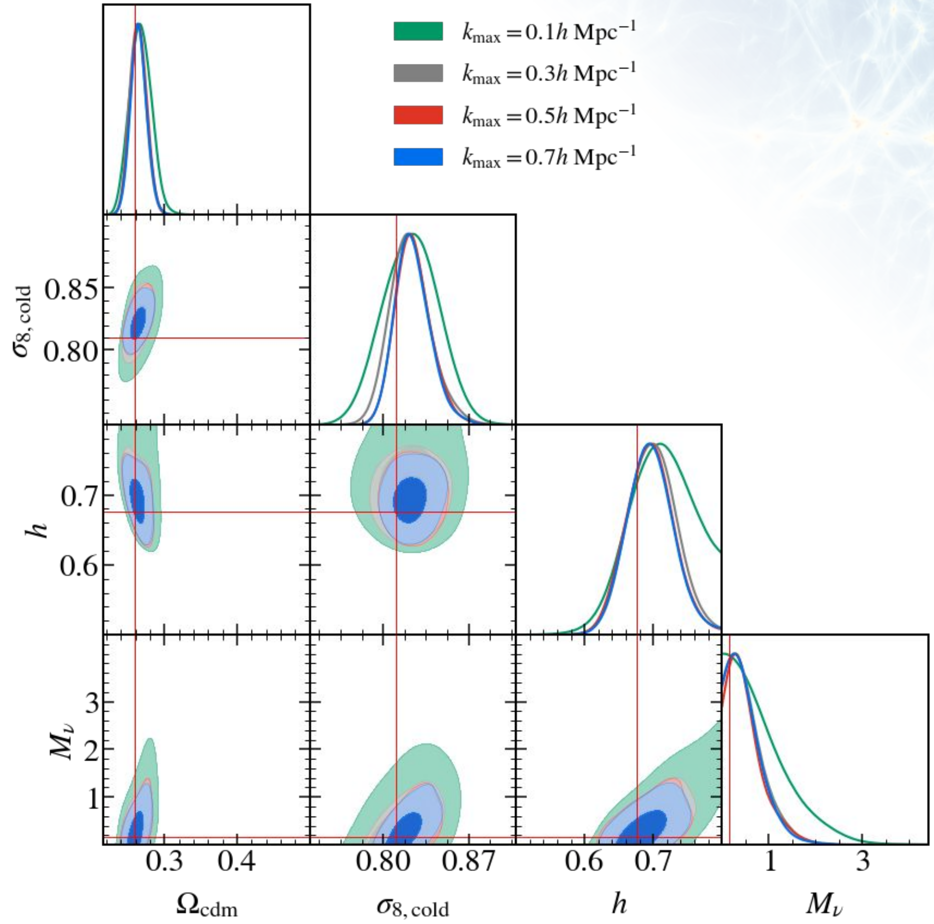
The BACCO hybrid lagrangian bias model

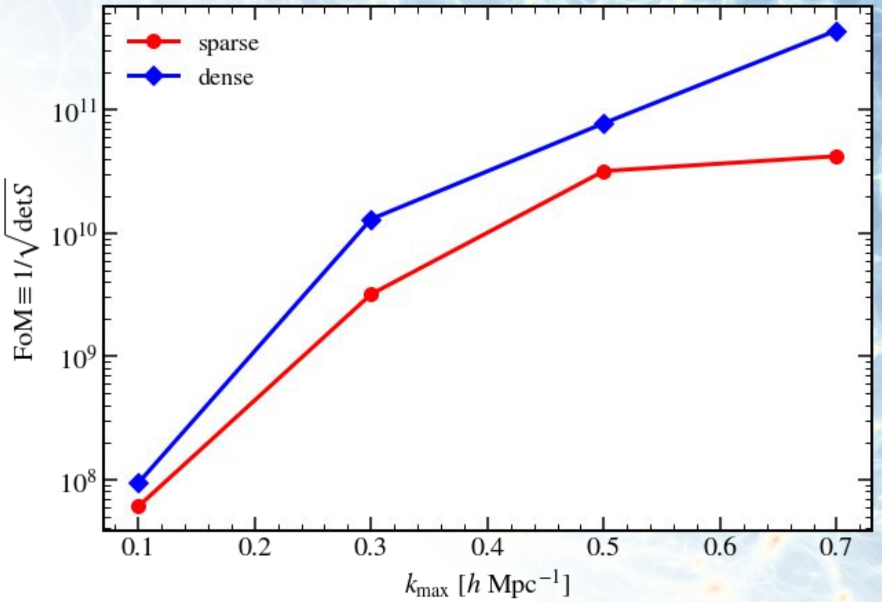
Euclid-like galaxies at z~1

Gaussian errors corresponding to volume of Euclid z~1 redshift bin

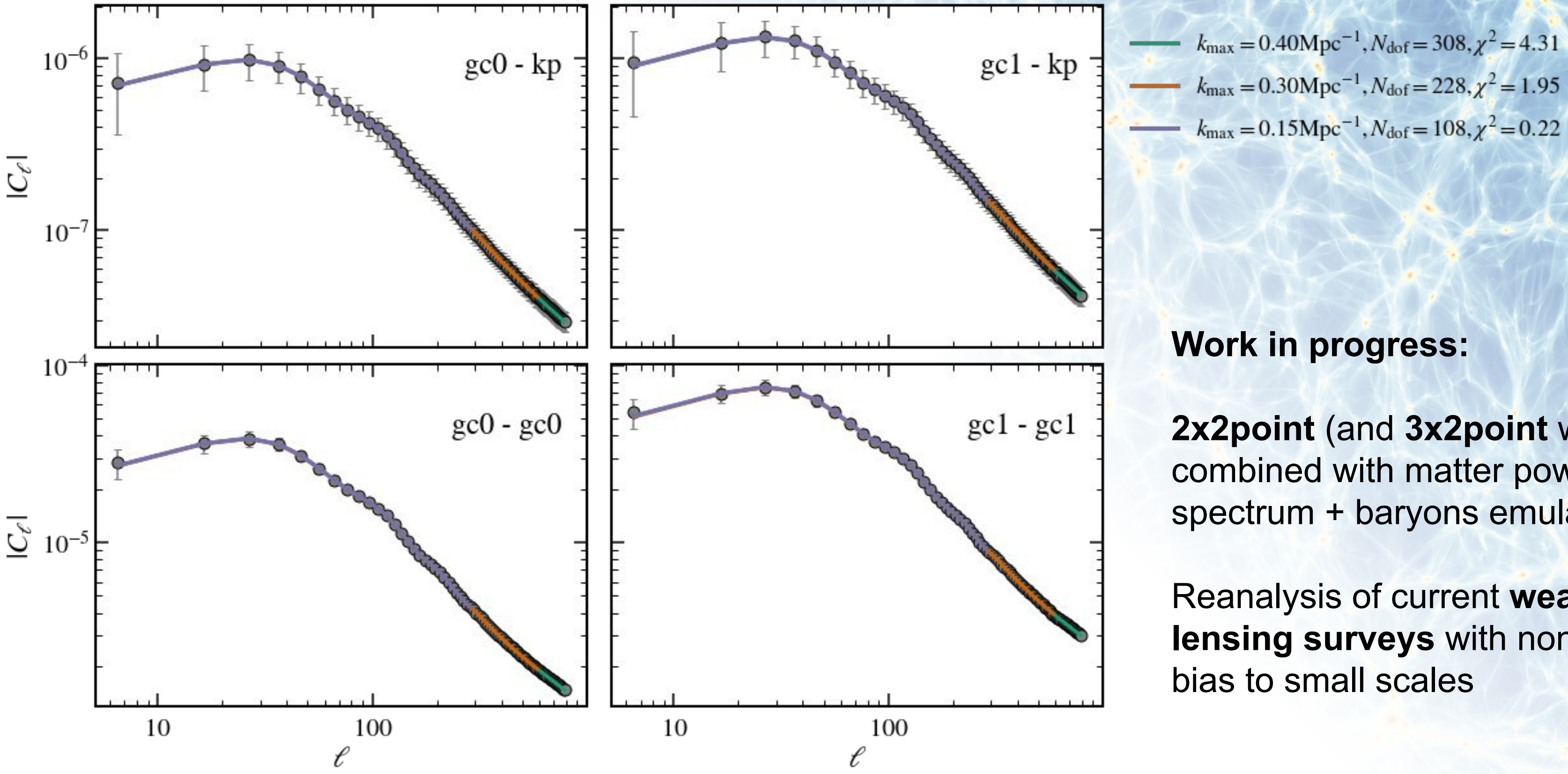


The BACCO hybrid lagrangian bias model





The BACCO hybrid lagrangian bias model

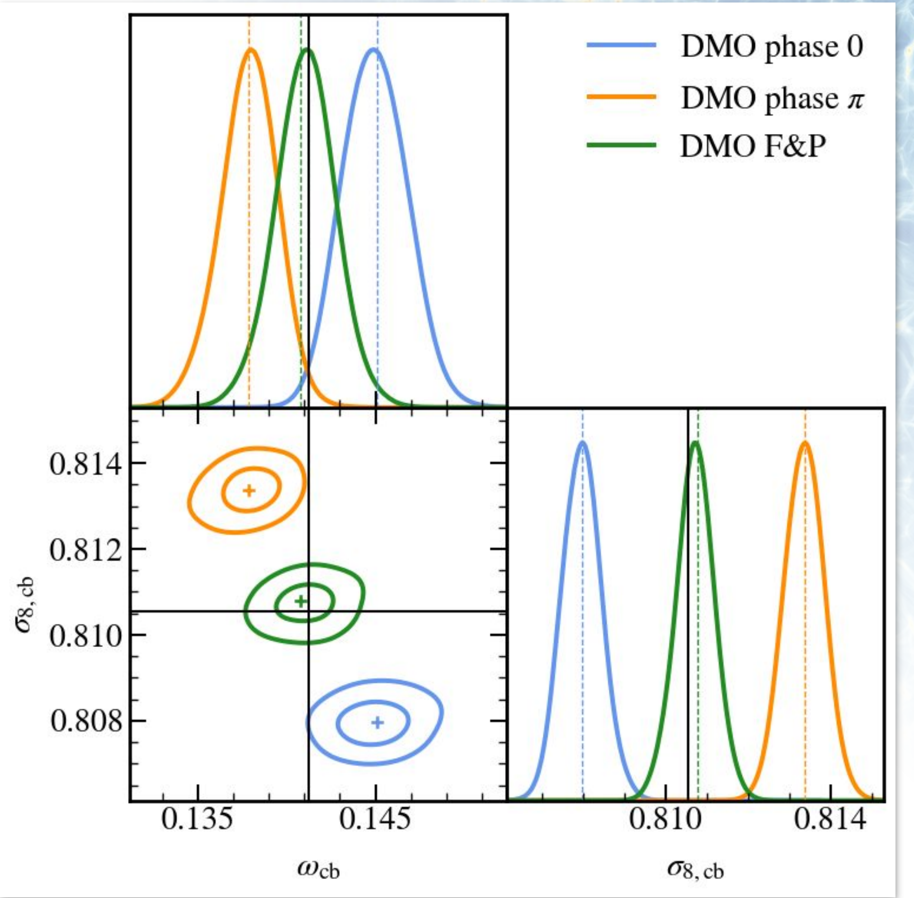


Work in progress:

2x2point (and **3x2point** when combined with matter power spectrum + baryons emulator)

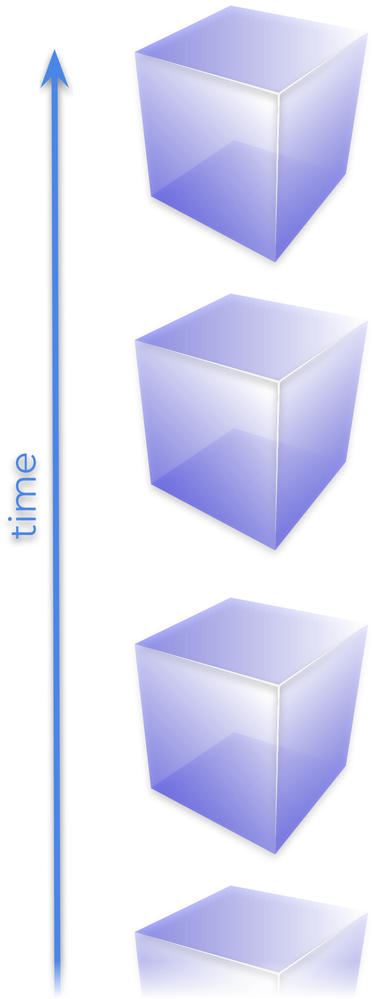
Reanalysis of current **weak lensing surveys** with nonlinear bias to small scales

One random realization



Simulation rescaling

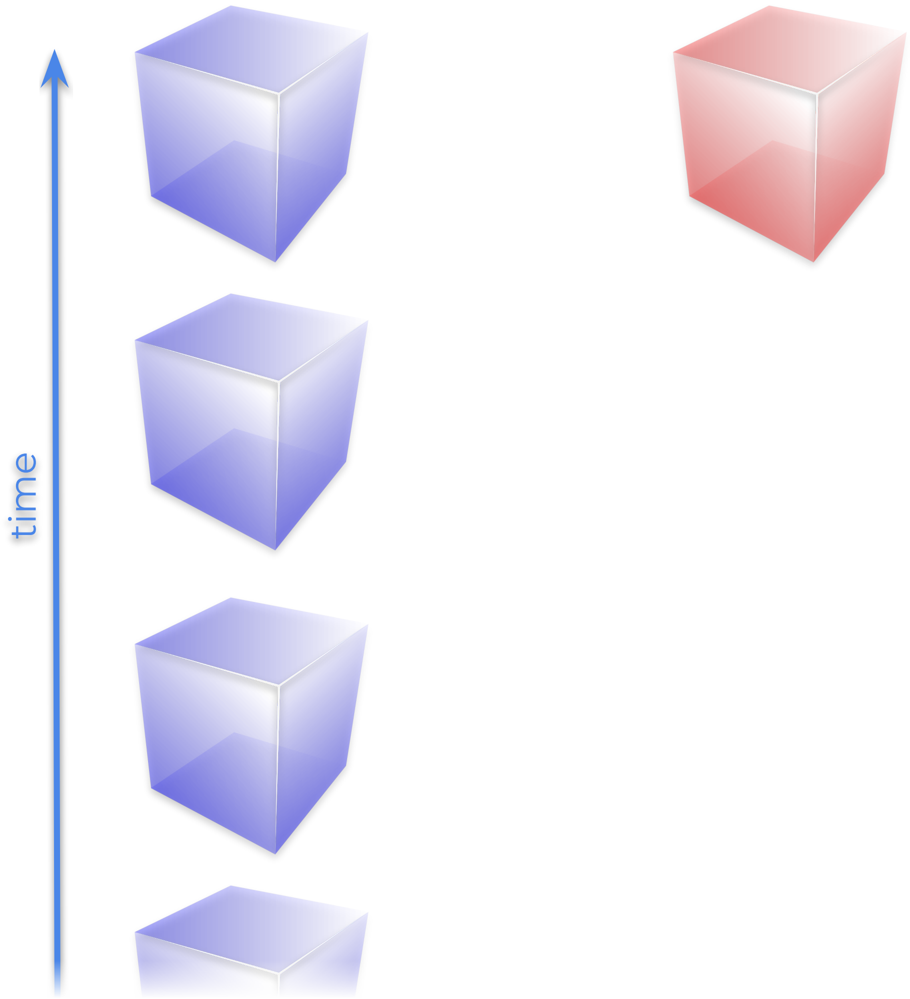
- **original simulation** with outputs at different redshifts



Angulo & White (2010)

Simulation rescaling

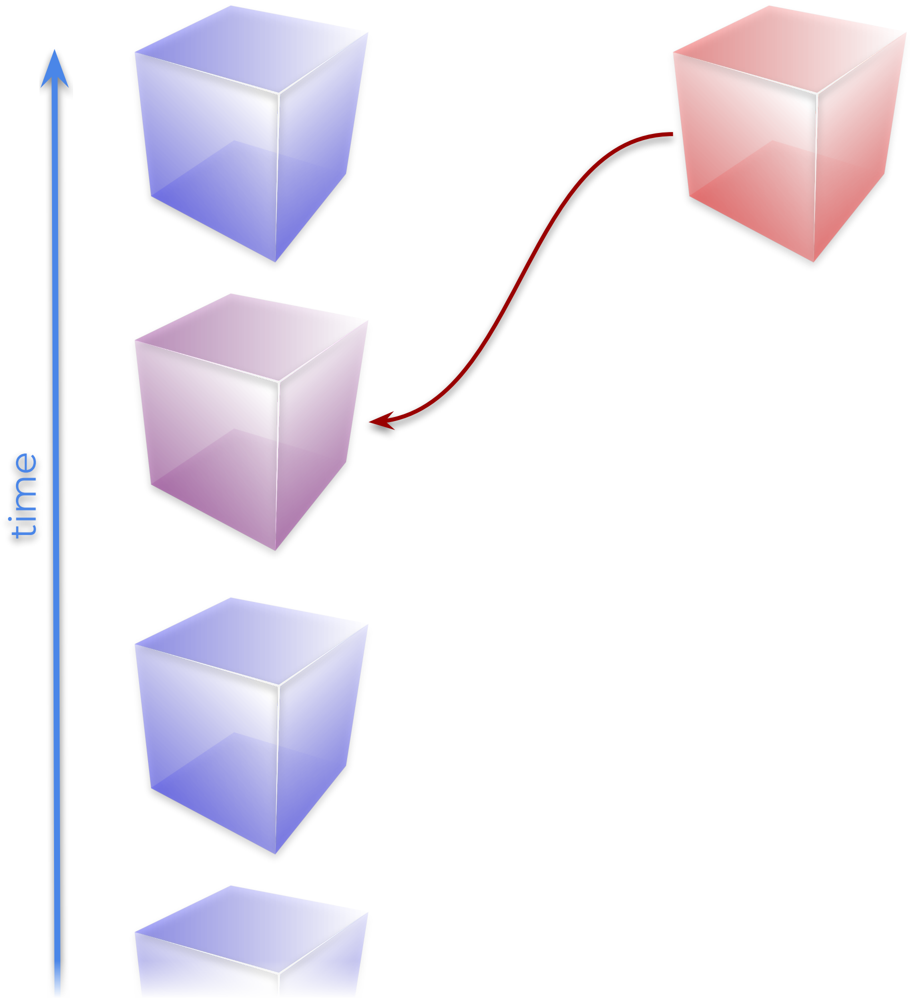
- **original simulation** with outputs at different redshifts
- **target cosmology** at a given redshift



Angulo & White (2010)

Simulation rescaling

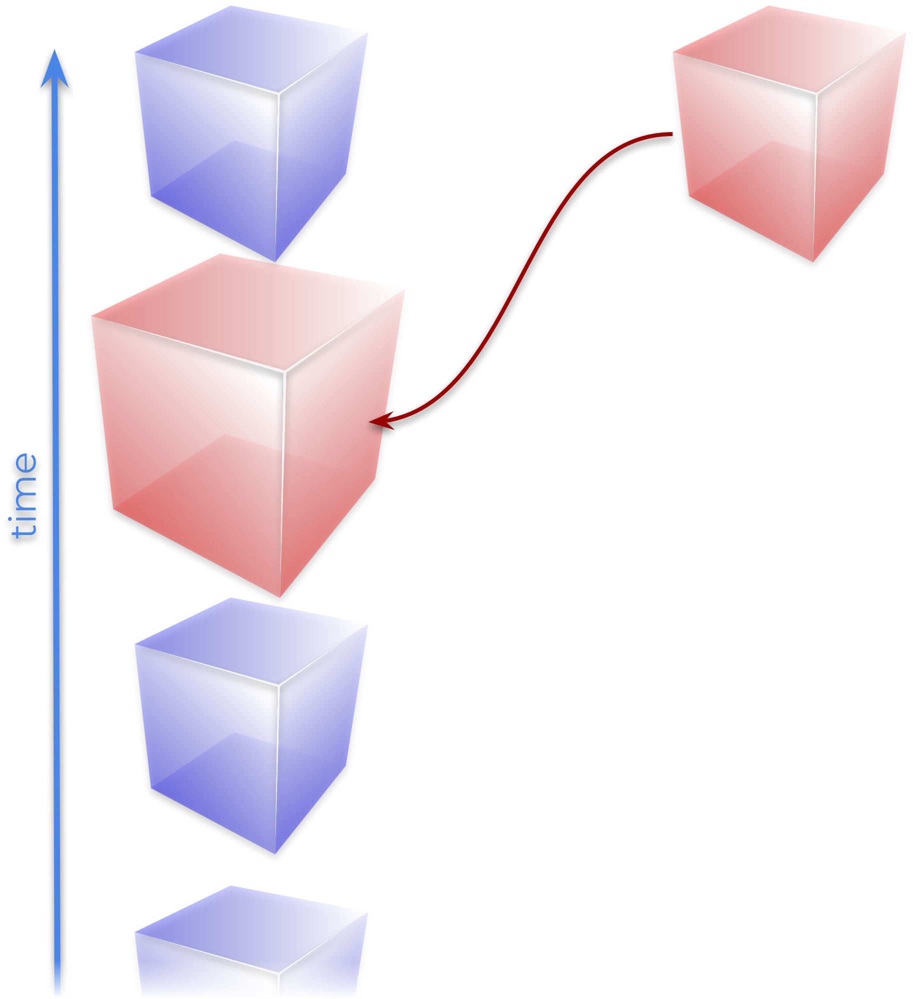
- original simulation with outputs at different redshifts
- target cosmology at a given redshift
- match the linear variance of the two cosmologies and get
    - a **time transformation** (this selects an output of the original simulation)



Angulo & White (2010)

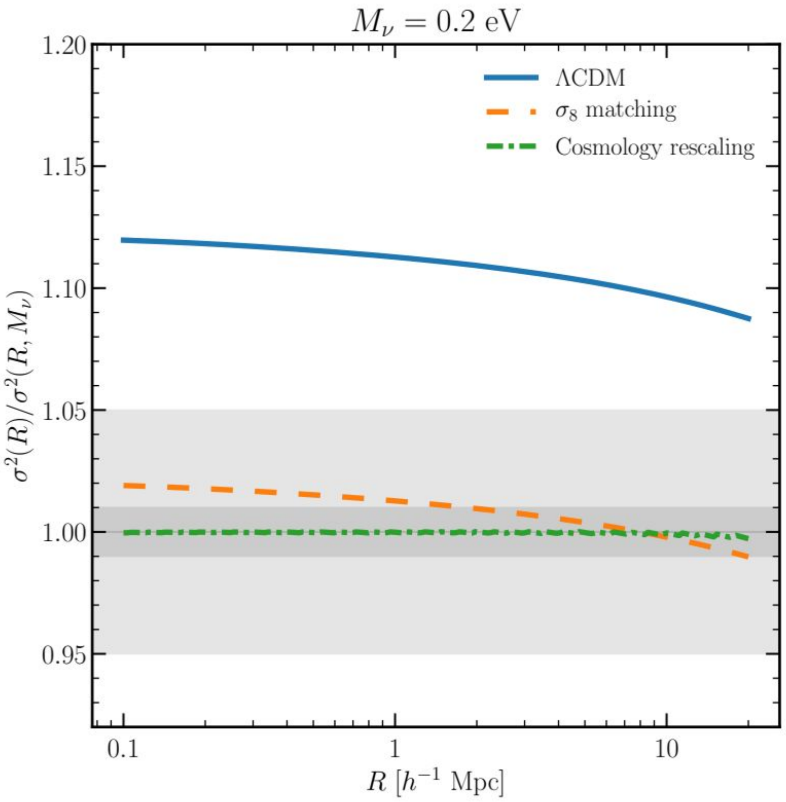
Simulation rescaling

- original simulation with outputs at different redshifts
- target cosmology at a given redshift
- match the linear variance of the two cosmologies and get
  - a **time transformation** (this selects an output of the original simulation)
  - a **space transformation** (this shrinks or expands the box)
- then apply **other corrections** to make the rescaling more accurate (bulk flow velocities, virialised object velocities, match large scales…)



Angulo & White (2010)

Matching the linear variance



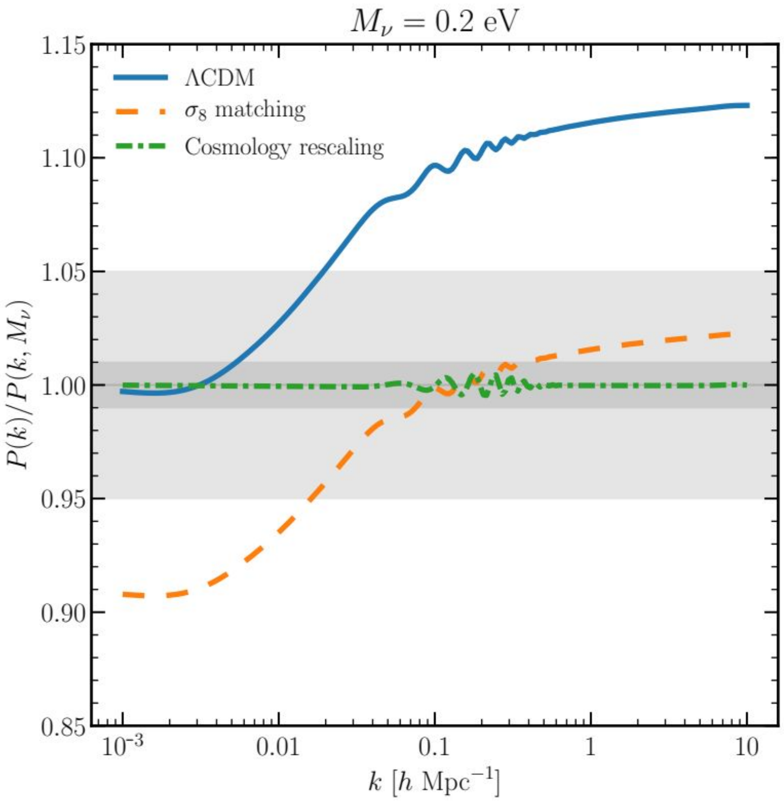
- Minimize (any cost function will do)

$$\delta^2_{\rm rms}(s, z_*) \equiv \frac{1}{\ln(R_2/R_1)} \int_{R_1}^{R_2} \frac{{\rm d}R}{R} \left[1 - \frac{\sigma(s^{-1}R, z_*)}{\sigma'(R, z_{\rm t})}\right]^2$$

- which σ(R, z)? **cdm+baryons**

$$\sigma^2(R, z) = \int_0^\infty \frac{k^2 {\rm d}k}{2\pi^2} W^2(kR) D^2_{\rm cold}(k, z) P_0(k)$$

Matching the predicted cold matter P(k)



- Only σ_8 matching leaves spurious structure in the P(k) shape
- **Large-scale correction** essential

Large-scale correction

- Matching σ(R, z) reproduces well the clustering on **mildly-nonlinear** to **nonlinear** scales

- Spurious contribution of long wavelength modes: **subtract** and **add** back with a displacement field

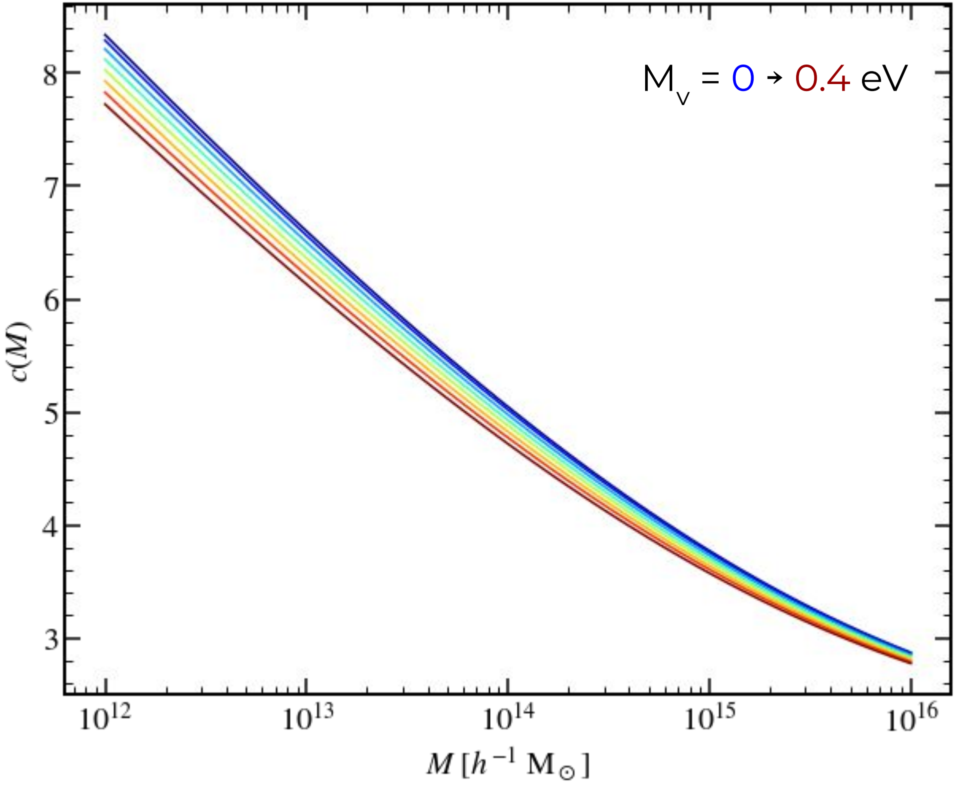
$$\boldsymbol{x}' = \boldsymbol{x} - \boldsymbol{\Psi}_{\rm original} + \boldsymbol{\Psi}_{\rm target}$$

$$\boldsymbol{\Psi} = {\rm iFT}\left[-i\frac{\boldsymbol{k}}{k^2}\delta(\boldsymbol{k})\right]$$

- Same for velocities, using the large-scale limit of the scale dependent growth rate f(k)

$$\boldsymbol{v}' = \boldsymbol{v} - (aHf\boldsymbol{\Psi})_{\rm original} + (aHf\boldsymbol{\Psi})_{\rm target}$$

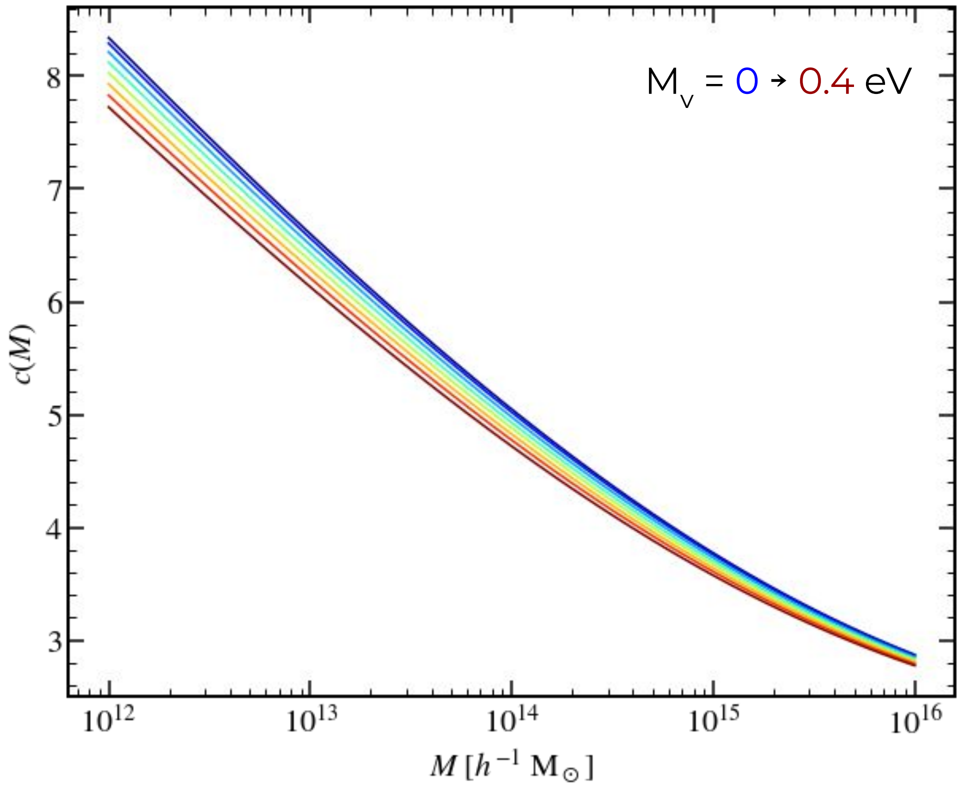
Concentration correction



- Ludlow et al (2016) using Ω_{cold} instead of Ω_m
- At a fixed time and halo mass, higher neutrino mass means less concentrated halo

Concentration correction

... yeah but, is Ludlow+16 a good description of the c-M relation with neutrinos?
Lopez-Cano et al (2023)



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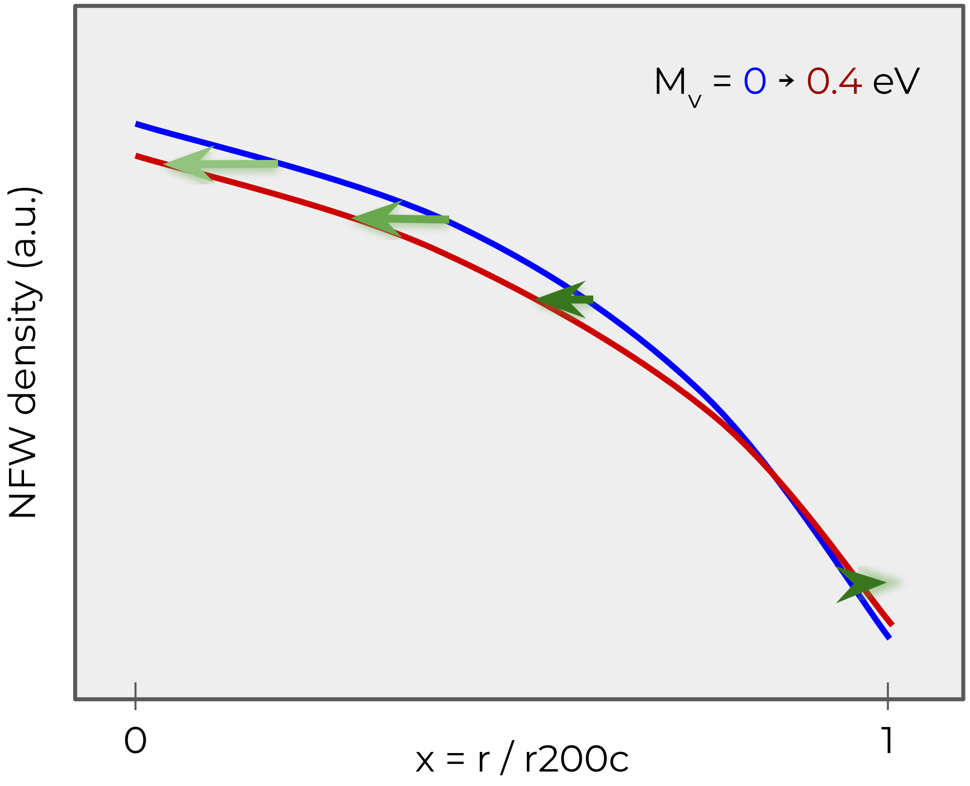
Concentration correction



- Compute **halo-by-halo** displacement field
- Displacement computed from difference of **theoretical NFW** profiles
- Applied to **actual in-halo particles**
  - No profile is ‘forced’
  - Keep triaxiality of halo

Velocities of virialised particles in haloes

Correct particles inside haloes to guarantee they are virilised even with the new halo mass and radius

$$\boldsymbol{v}'_{\mathrm{in-halo}} = \sqrt{\frac{a\Omega'_{\mathrm{cold}}}{a'\Omega_{\mathrm{cold}}}}\frac{h'}{h}\boldsymbol{s}\boldsymbol{v}_{\mathrm{in-halo}}$$

primed = target cosmology
non-primed = original cosmology