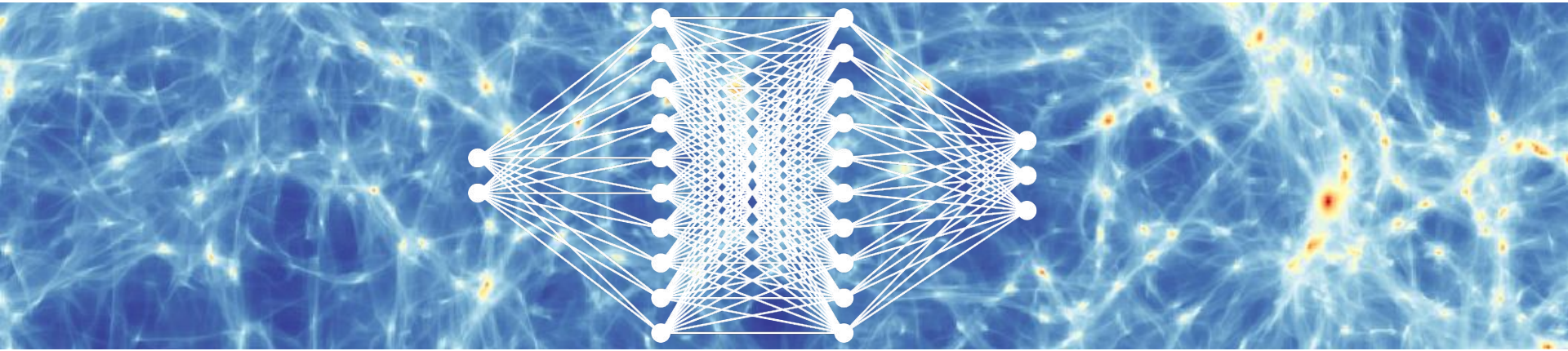
The BACCO emulators project:

Accelerating cosmological analysis with emulators



Matteo Zennaro

University of Oxford

LSS workshop - Prague 28-29 June 23

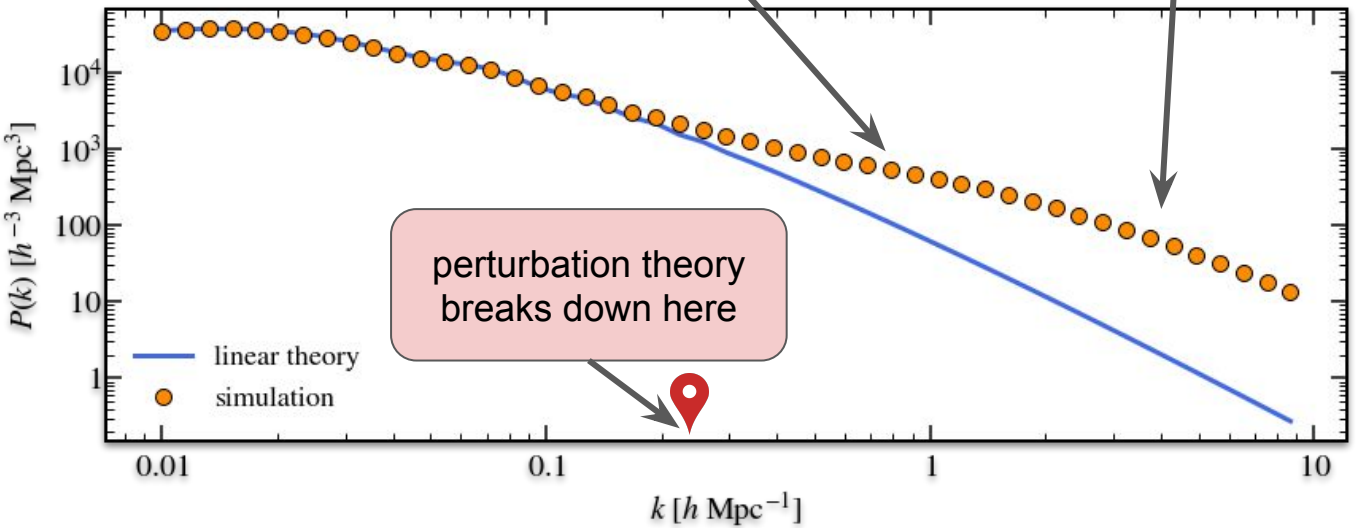
Nonlinear scales: …?

and more!

still lots of cosmological information: nonlinear response to Ω_{matter}, neutrino mass, theory of gravity…

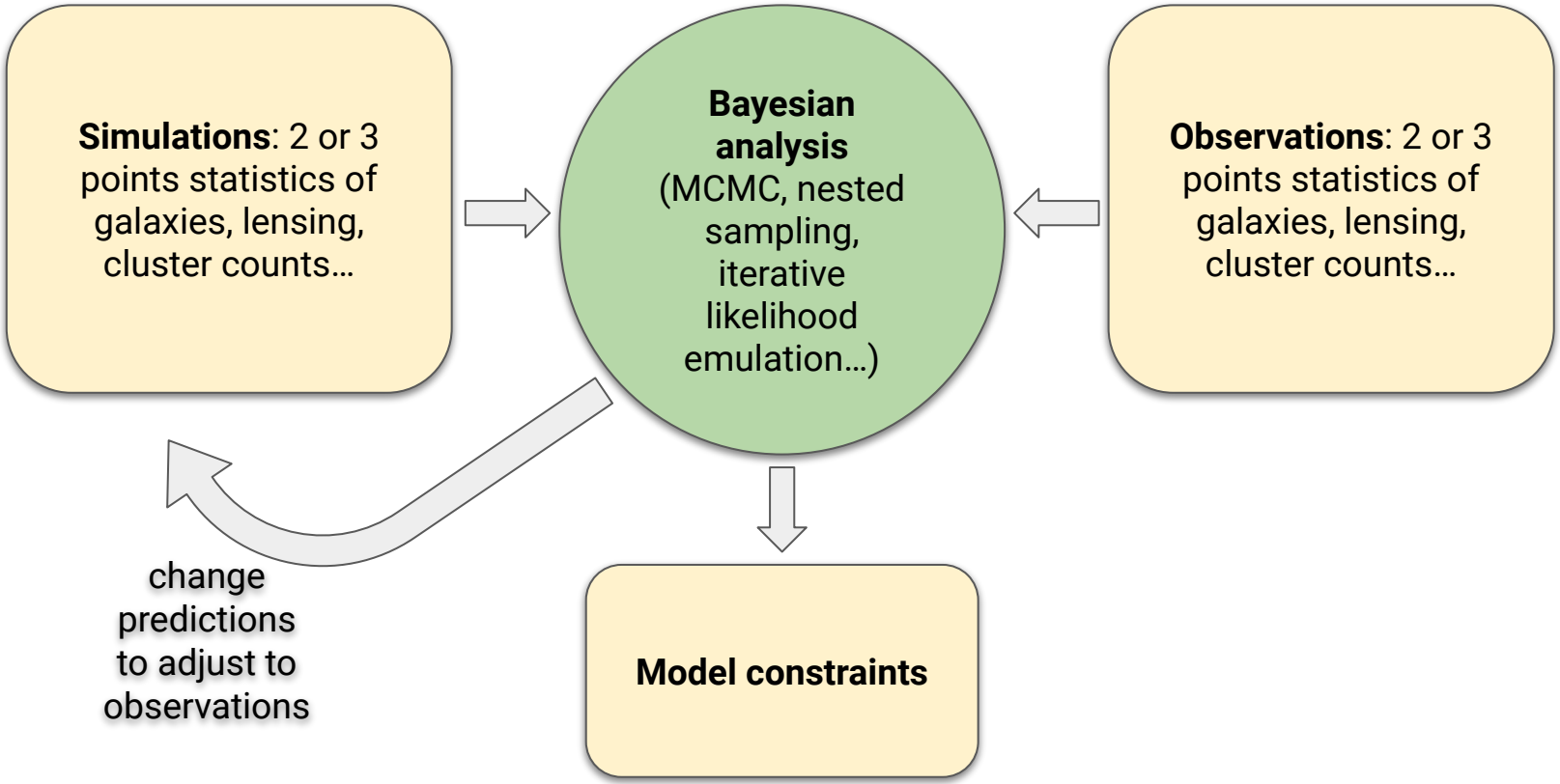
highly nonlinear inner profile of haloes, interplay with baryons

matter power spectrum full shape: fundamental for galaxy clustering, lensing, kSZ, neutrino effects…



perturbation theory breaks down here

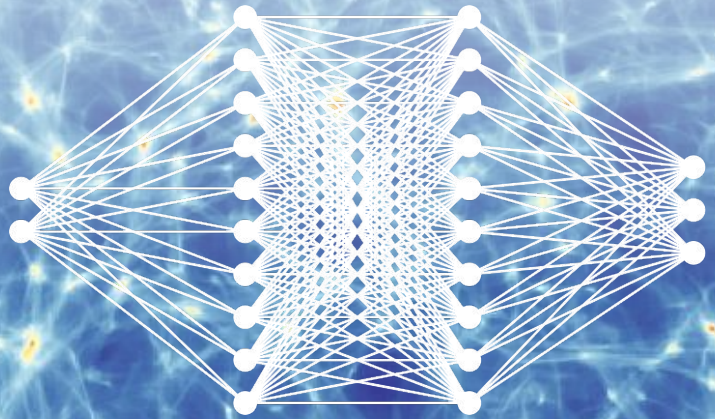
Nonlinear scales: simulations as models



Artificial neural networks as emulators

Measure cosmological observables in **many simulations**

Train a **NN** to predict observables in function of cosmo parameters



Obtain (fully nonlinear) observables in **milliseconds**

Plug into **Bayesian analysis**

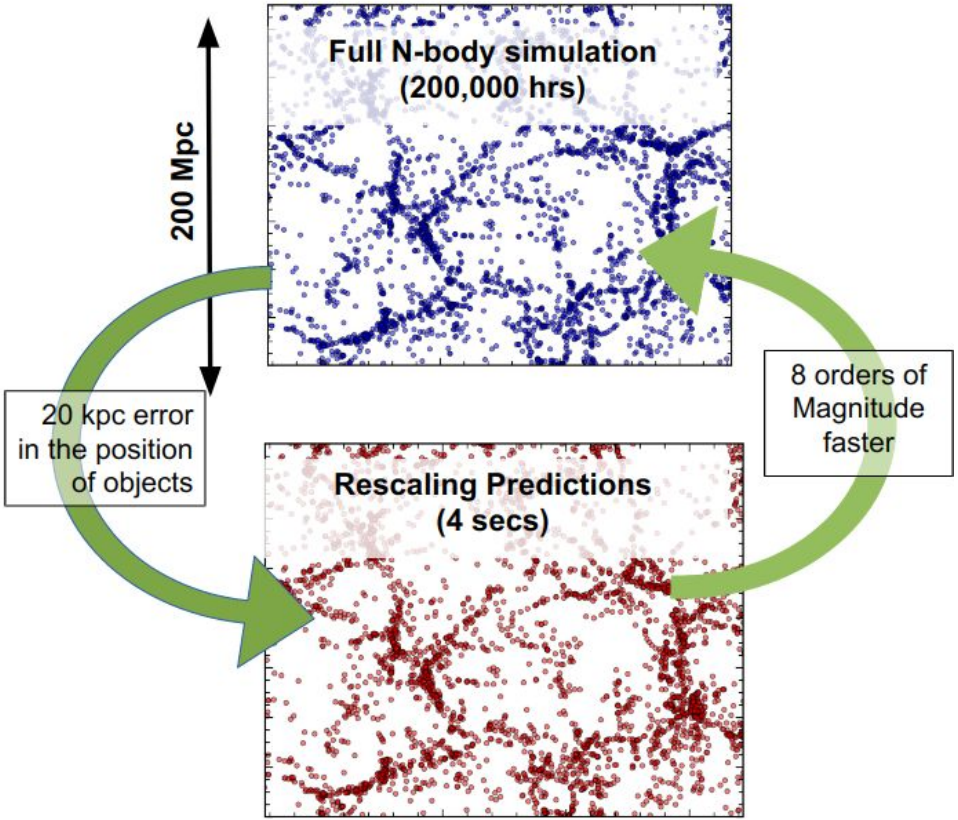
The workhorse: cosmology rescaling

Apply time and space transformations to **change the cosmology** of a N-body simulation

Validated for:

- real/redshift-space
- correlation function/power spectra
- 3-point correlation functions
- (sub)halo mass function
- abundance of voids
- different redshifts/cosmologies

Obtain **thousands** of simulations, running only **a handful**



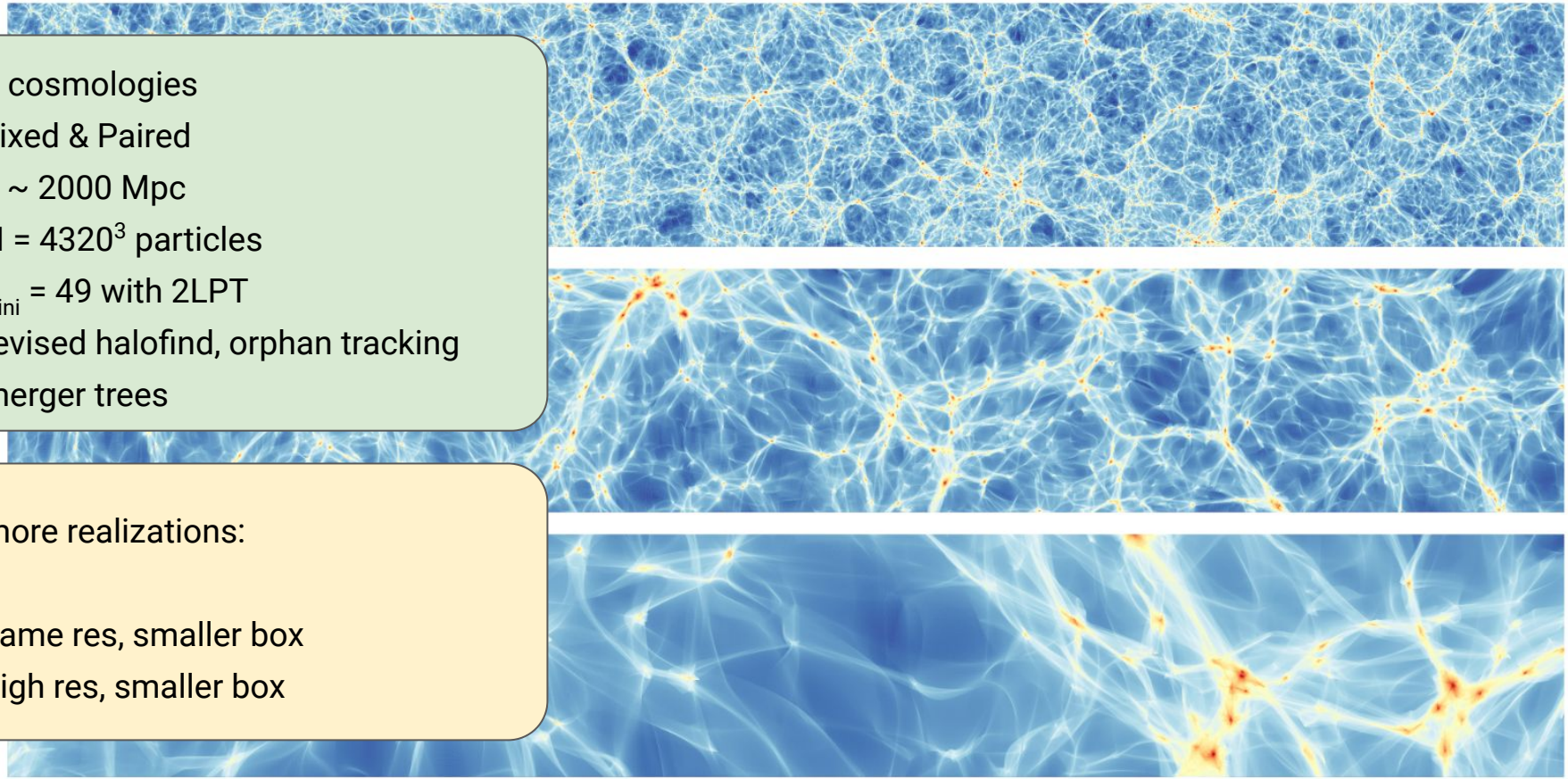
Angulo & White (2010), MZ et al (2019), Contreras, MZ, et al (2020), Angulo, MZ, et al (2020), Ondaro-Mallea, MZ, et al (2021), López-Cano, MZ, et al (2022)

The bacco simulation suite

5 cosmologies
Fixed & Paired
L ~ 2000 Mpc
N = 4320^3 particles
z_{ini} = 49 with 2LPT
revised halofind, orphan tracking
merger trees

more realizations:

same res, smaller box
high res, smaller box



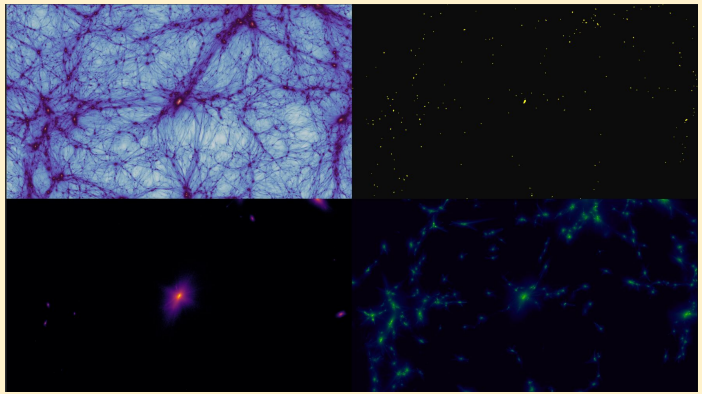
Baryons and galaxies

Baryonification or BCM:

Displace particles inside haloes to reproduce baryonic effects

7 free parameters, physically motivated

Flexible enough to reproduce **many different hydro sims**



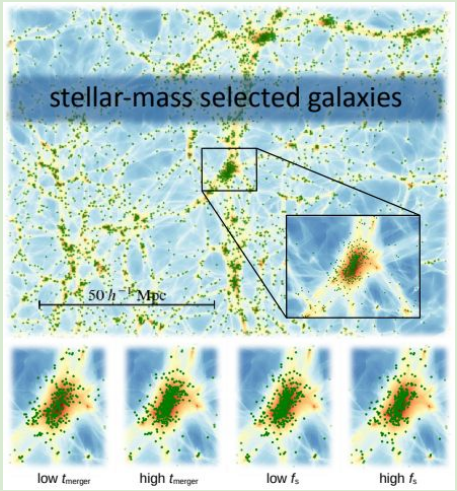
Aricò et al (2020, 2021, 2022), Schneider et al (2017, 2019)

SubHalo Abundance Matching extended:

Improved **subhalo tracing**

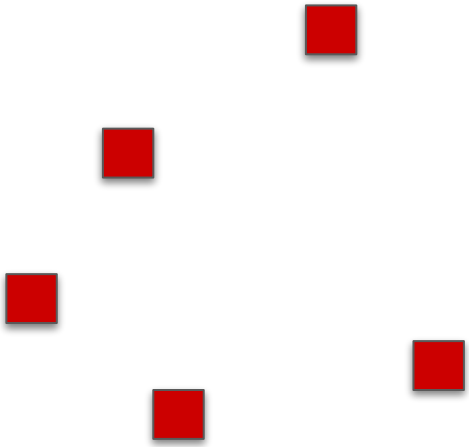
Realistic galaxy samples matching **stellar mass function** or **star formation rate**

Galaxy distribution, velocities, velocity bias, assembly bias **naturally predicted** within the simulation



Contreras et al (2020, 2021, 2022)

Nonlinear matter P(k) emulator

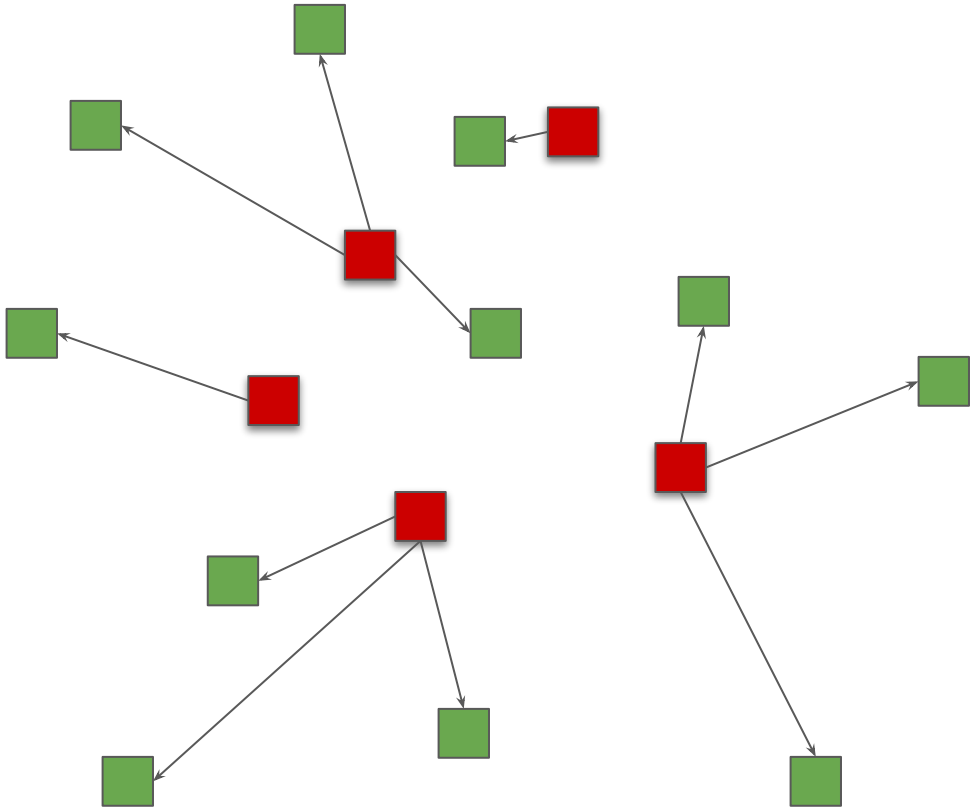


5 sims:
Narya
Nenya
Vilya
The One
Barahir

(order 15 million core hours)

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

Nonlinear matter P(k) emulator

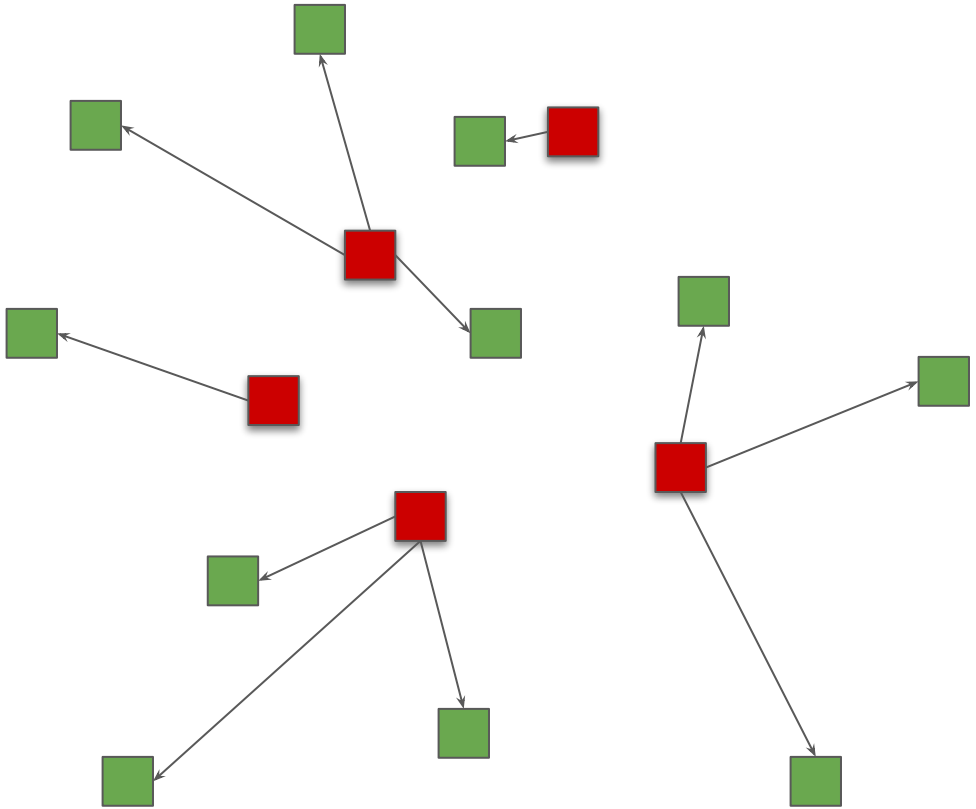


8000 combinations of cosmological parameters and redshifts

(order 1 core hour per paired scaling)

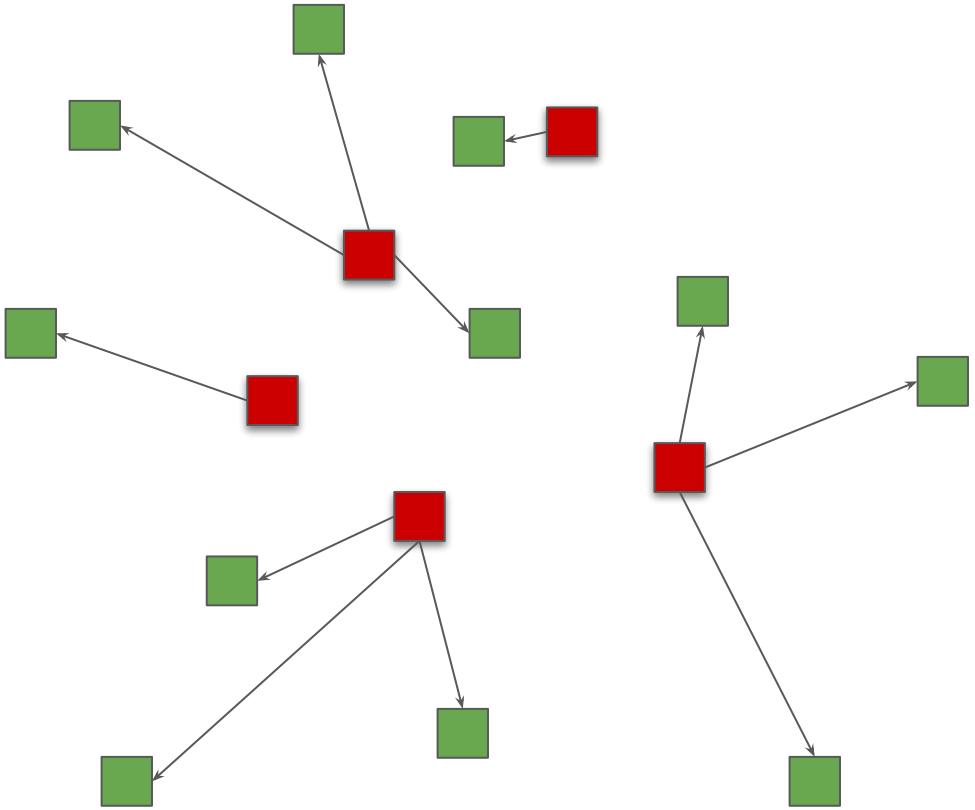
cosmology rescaling

Nonlinear matter P(k) emulator



50,000 combinations of cosmological parameters, redshifts and BCM parameters

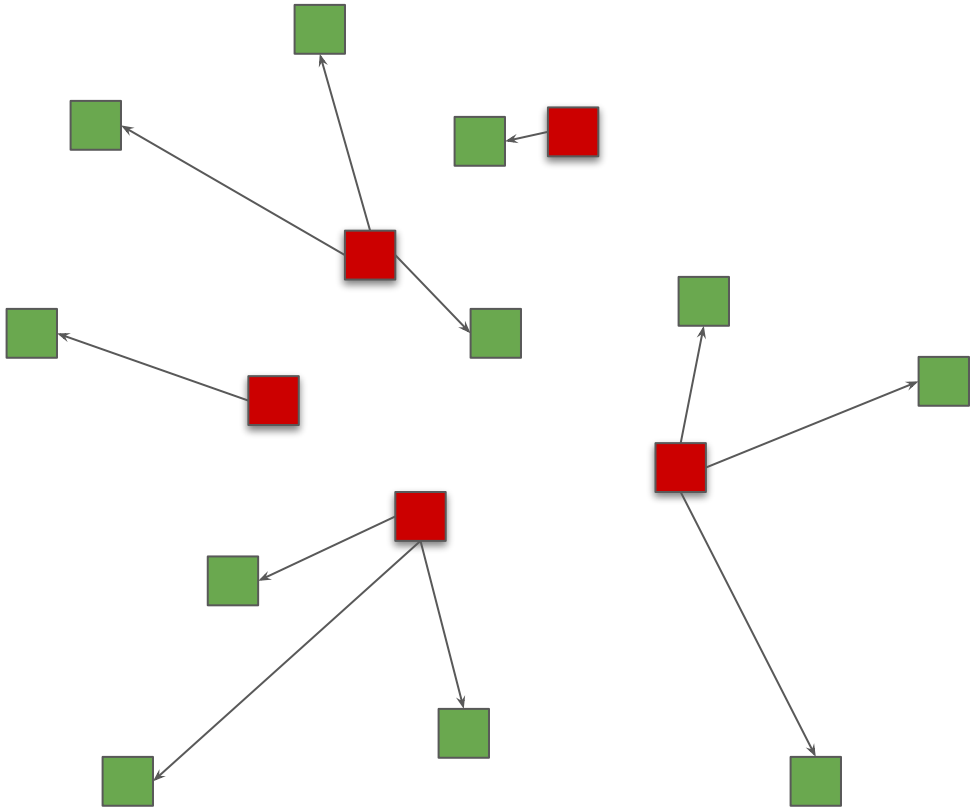
Nonlinear matter P(k) emulator



Measure matter power spectra, bias templates, baryonic boost etc…

(< 1 cpu hours per measurement)

Nonlinear matter P(k) emulator



$\Omega_{\rm cold} \in [0.23, 0.4]$

$\Omega_{\rm b} \in [0.04, 0.06]$

$\sigma_{8,\rm cold} \in [0.65, 0.9]$

$n_{\rm s} \in [0.92, 1.01]$

$h \in [0.6, 0.8]$

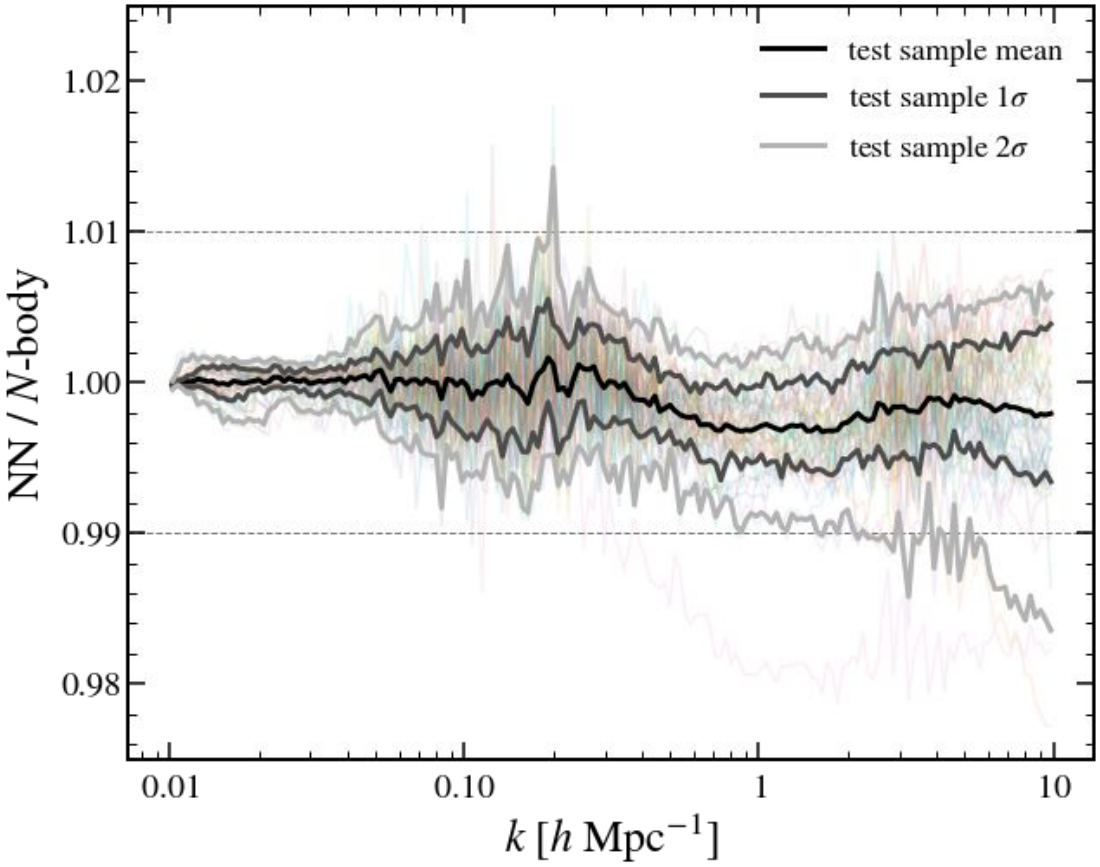
$M_\nu \in [0, 0.4]$

$w_0 \in [-1.15, -0.85]$

$w_a \in [-.3, 0.3]$

$a \in [0.3, 1.1]$

baccoemu: nonlinear matter P(k)



MZ et al (in prep)

baccoemu: nonlinear matter P(k), from v1 to v2

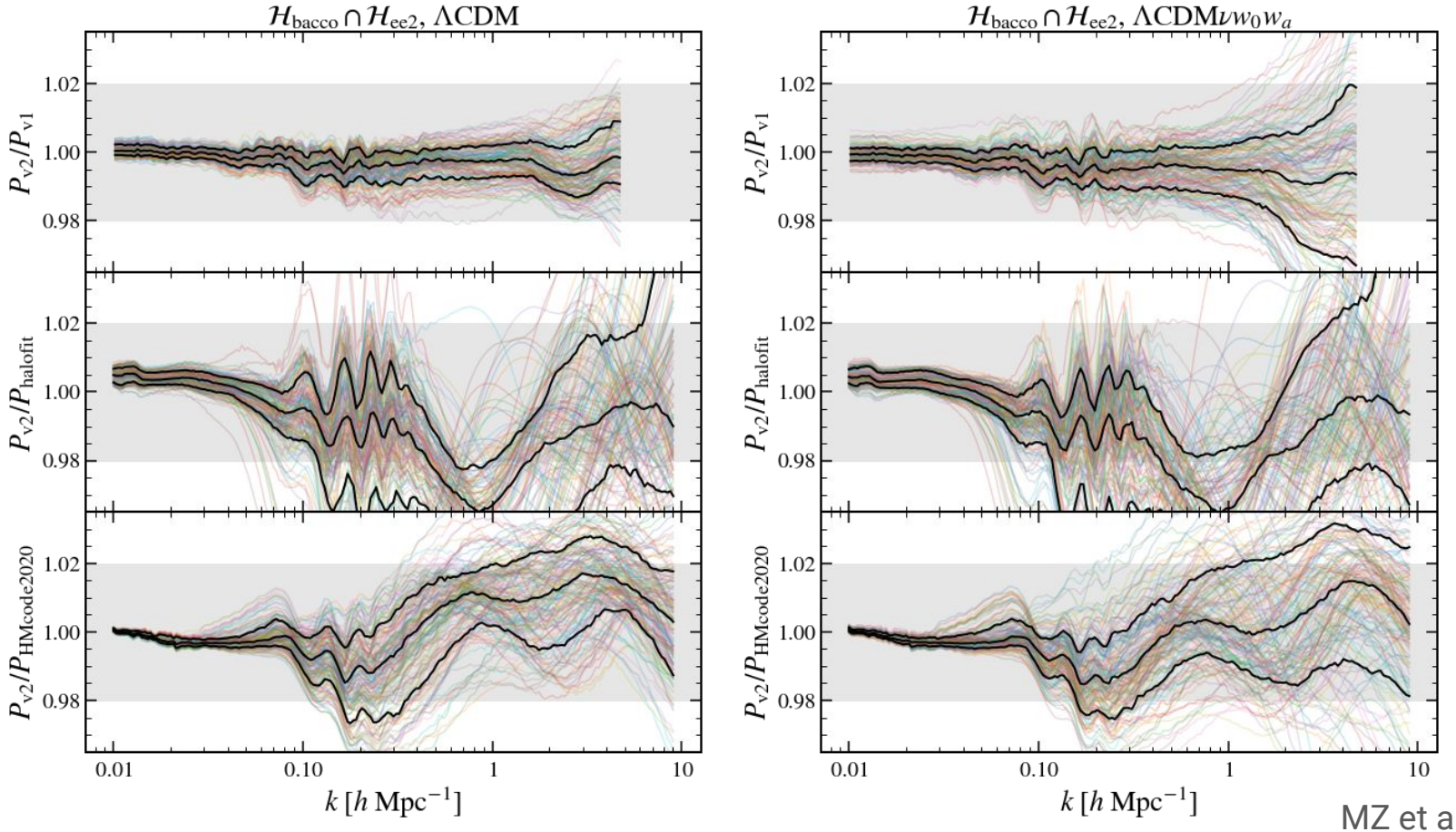
- Higher k range: k_max: 5 -> 10 h/Mpc
  - Suite of 3x times higher res simulations
- Higher z range: z_max: 1.5 -> 2.7
  - Better treatment of shotnoise
- Larger parameter space
- Noise reduction via Zeldovich control variates
- Curvature via SU
- Includes automatic differentiation

More accurate: 3% at k=5 to 2% at k=10 h/Mpc

- 2 new simulations (5 cosmologies in total) to the bacco suite
- Improved rescaling, especially for w0-wa and Mnu
- Better mass-concentration-redshift relations (López-Cano+22)
- Non-universal mass function (Ondaro-Mallea+21)

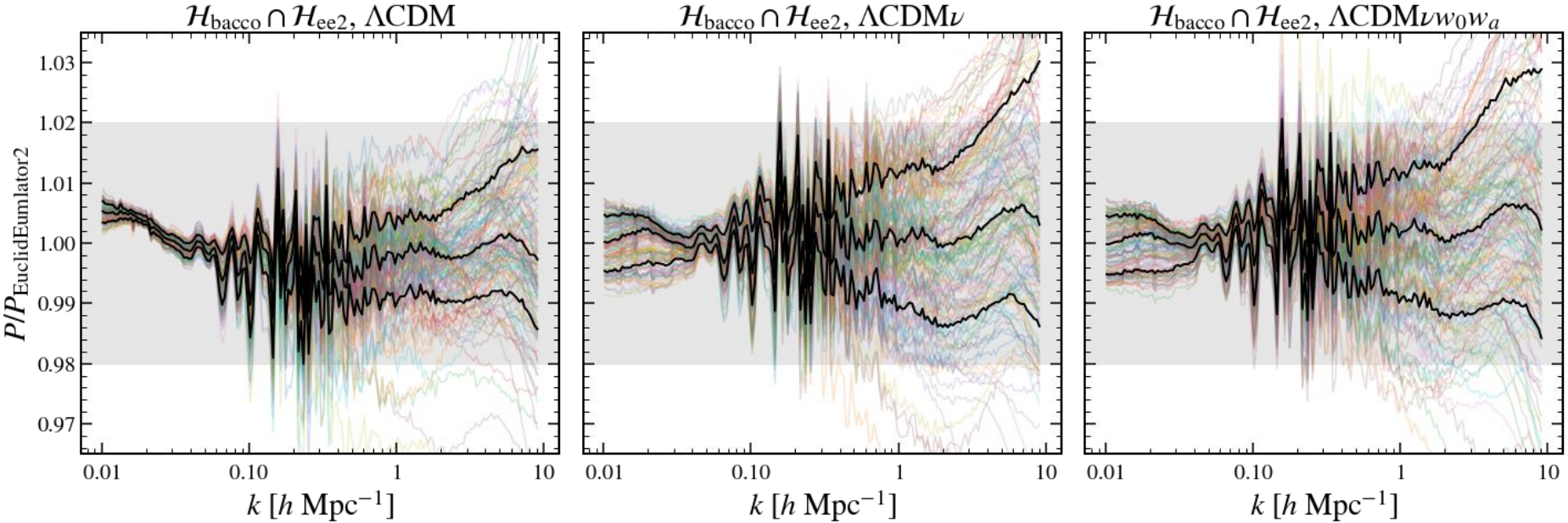
MZ et al (in prep)

baccoemu: nonlinear matter P(k)



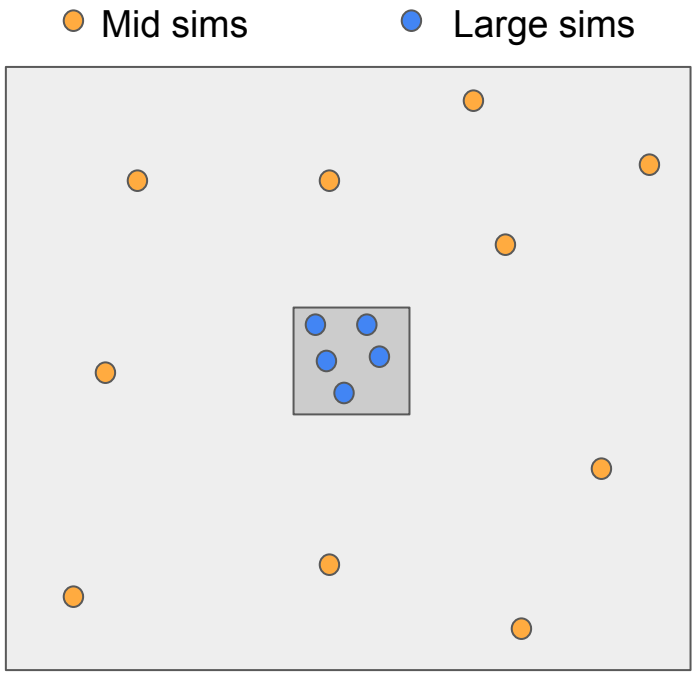
MZ et al (in prep)

baccoemu: nonlinear matter P(k)



MZ et al (in prep)

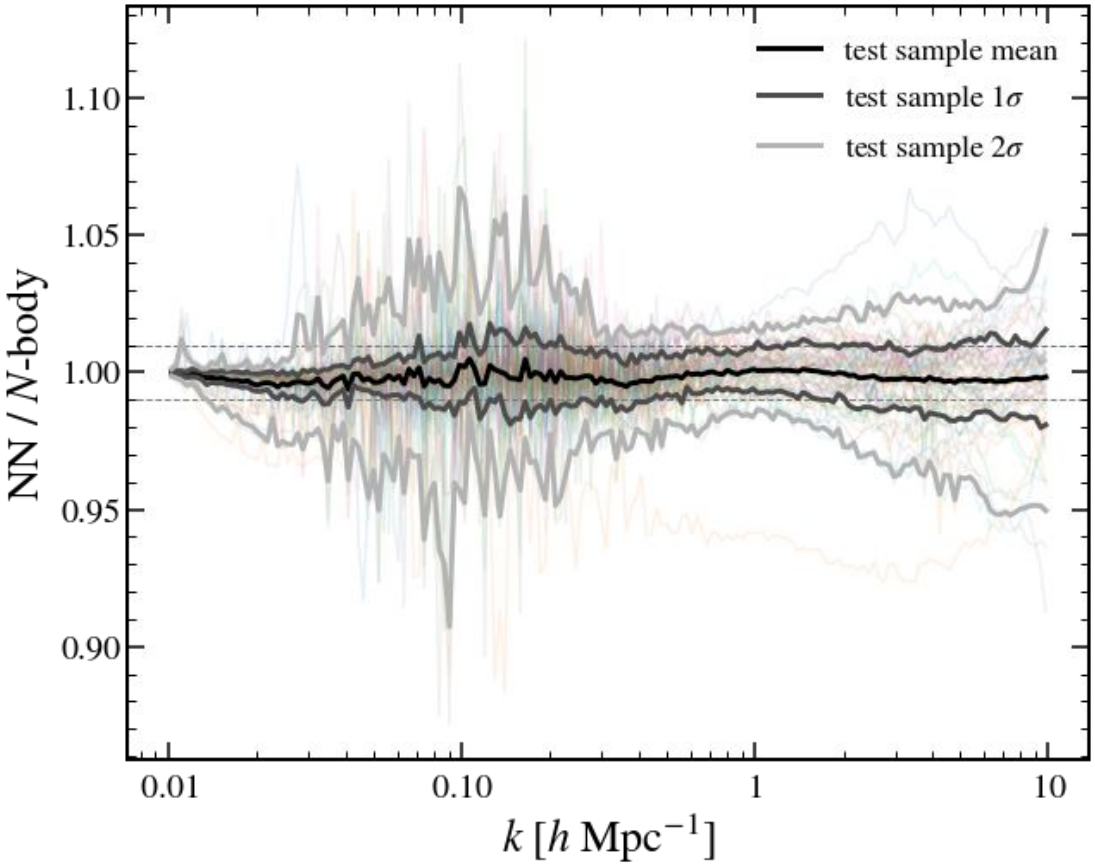
baccoemu: extended parameter space



$$\Omega_{\rm cold} \in [0.15, 0.47]$$
$$\sigma_{8,\rm cold} \in [0.4, 1.15]$$
$$\Omega_{\rm b} \in [0.03, 0.07]$$
$$n_{\rm s} \in [0.83, 1.1]$$
$$h \in [0.5, 0.9]$$
$$M_\nu \in [0.0, 0.4]$$
$$w_0 \in [-1.4, -0.6]$$
$$w_a \in [-0.5, 0.5]$$
$$a \in [0.275, 1.1]$$

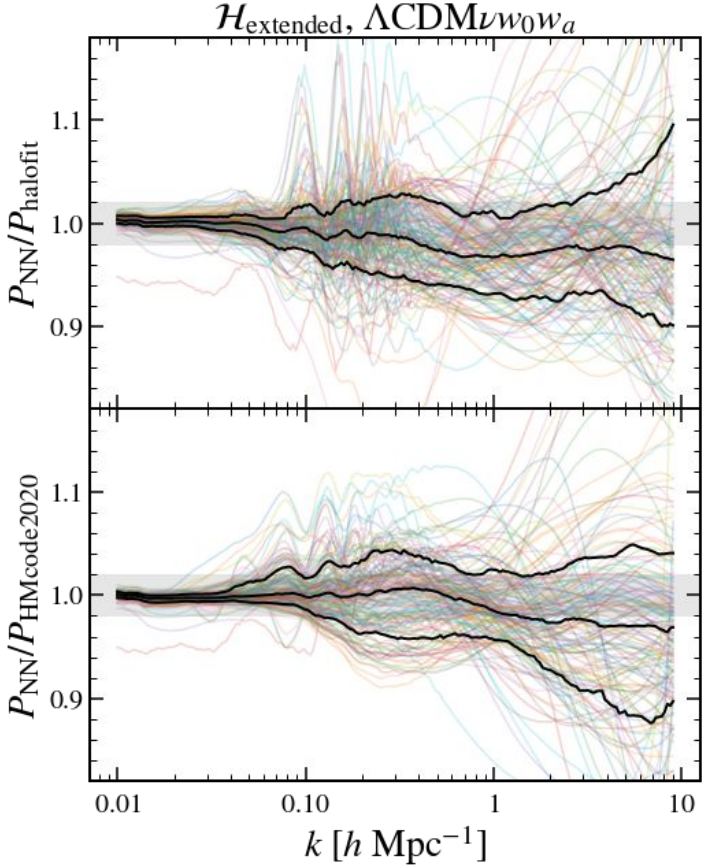
MZ et al (in prep)

baccoemu: extended parameter space



MZ et al (in prep)

baccoemu: extended parameter space



MZ et al (in prep)

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

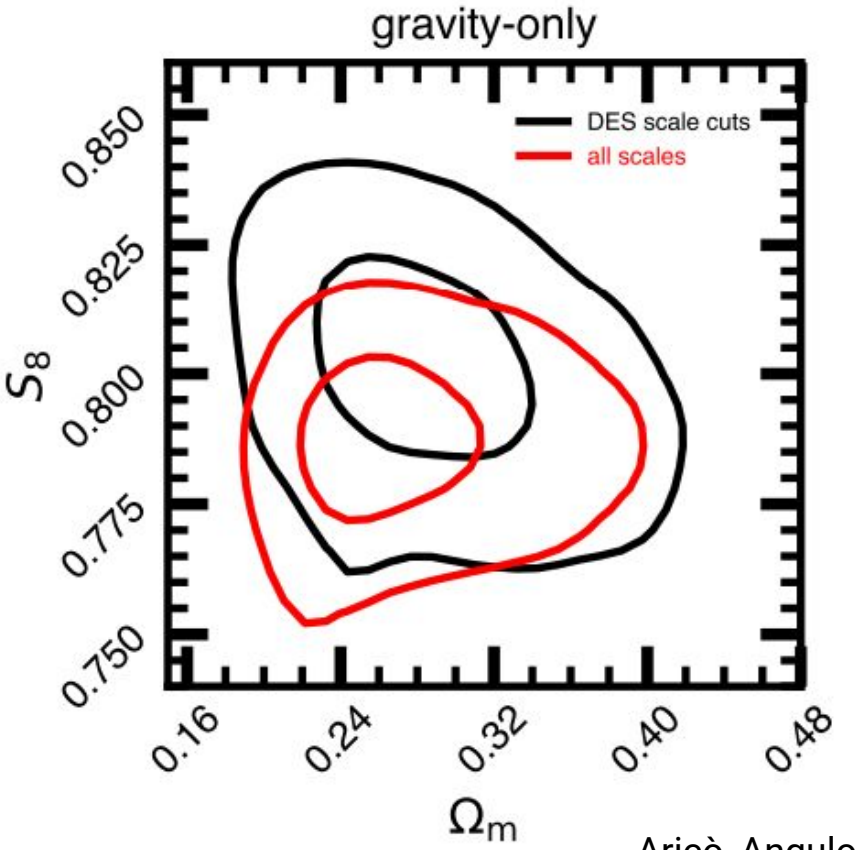
Application to DES Y3 data

- official DES Y3 data products:
  - 4 redshift bins
  - public n(z)
  - ξ± 2.5-250 arcmin
  - 400 data points (227 with DES scale cuts)
  - public covariance

- No scale cuts
- baccoemu for NL P(k) with baryon effects
- Intrinsic alignments with NLA

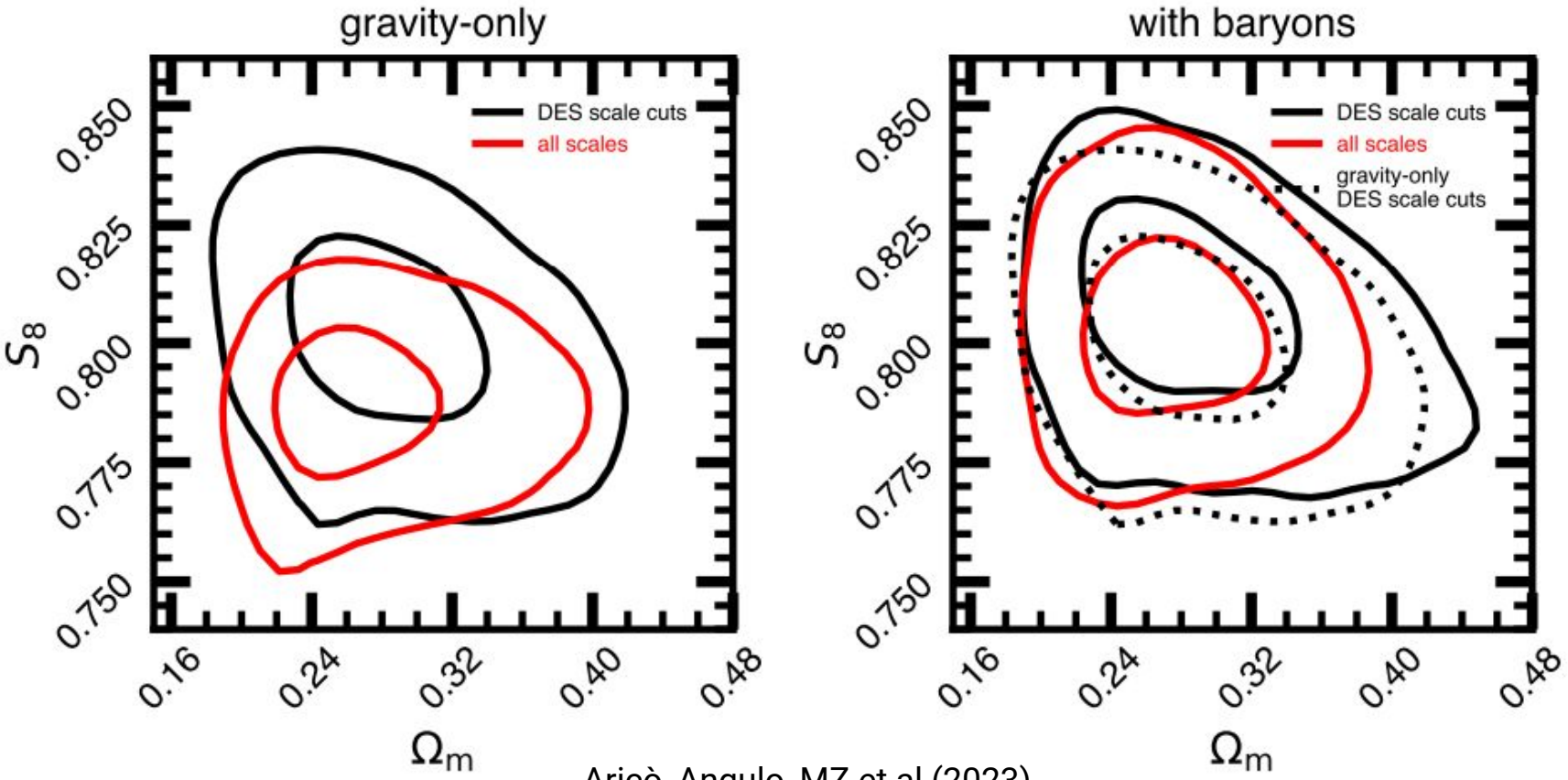
Aricò, Angulo, MZ et al (2023)

Application to DES Y3 data



Aricò, Angulo, MZ et al (2023)

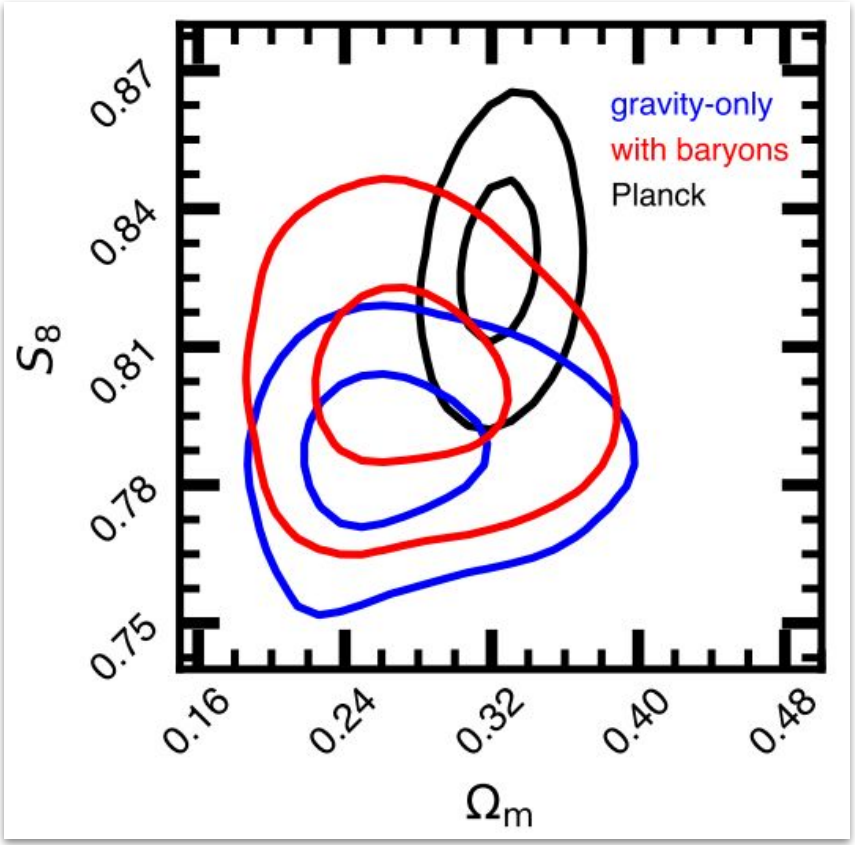
Application to DES Y3 data



Aricò, Angulo, MZ et al (2023)

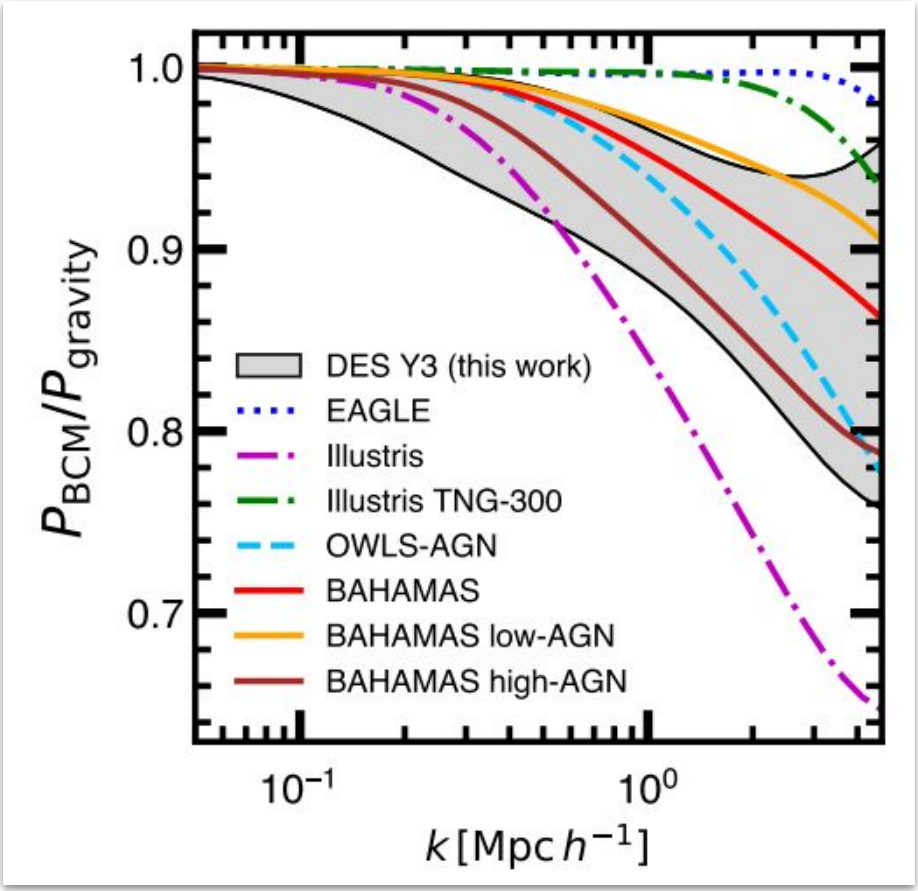
Application to DES Y3 data

- 15% tighter constraints when including all scales and baryons
- with baryons contours remain stable for different scale cuts
- S8 tension at ~0.9σ (depends a lot also on IA model and excluding shear ratios)



Application to DES Y3 data

- parameters of the baryonic model have physical interpretability
- fits can be compared to hydro sims
- most constrained is $\log_{10}[M_c/(M_\odot/h)] \sim 14.38$



Conclusions

Full set of emulators of **linear** and **nonlinear** quantities

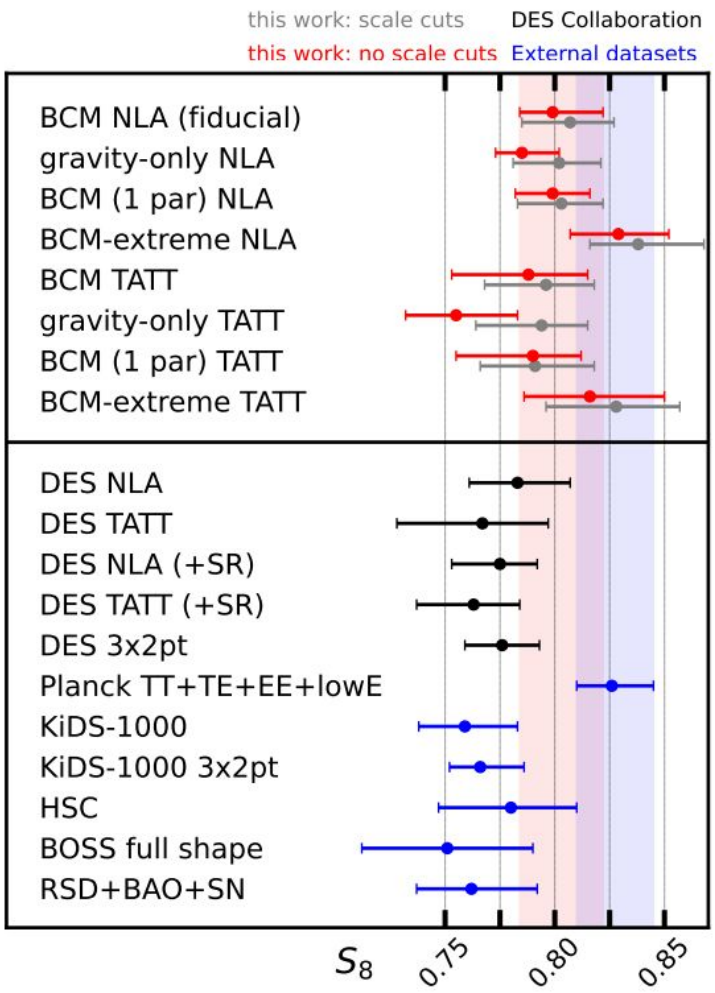
In particular **matter power spectrum** with **baryons** and **galaxy power spectrum** in real and redshift space

Example of use when applied to **DES Y3 data**

Including **baryons** results are **robust against scale cuts**

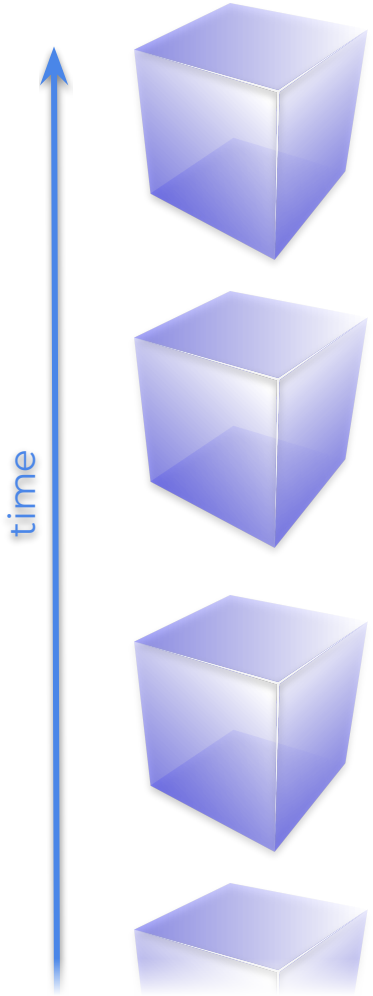
More information from **small scales**

Application to DES Y3 data



Simulation rescaling

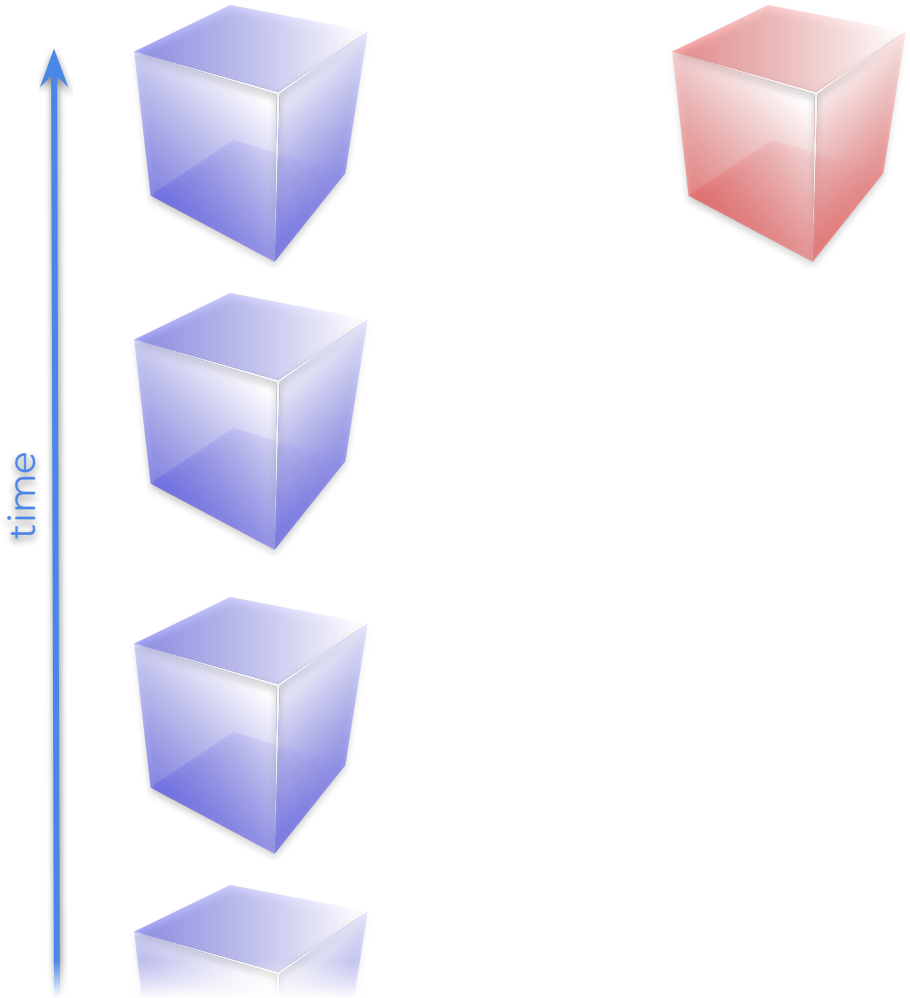
- **original simulation** with outputs at different redshifts



Angulo & White (2010)

Simulation rescaling

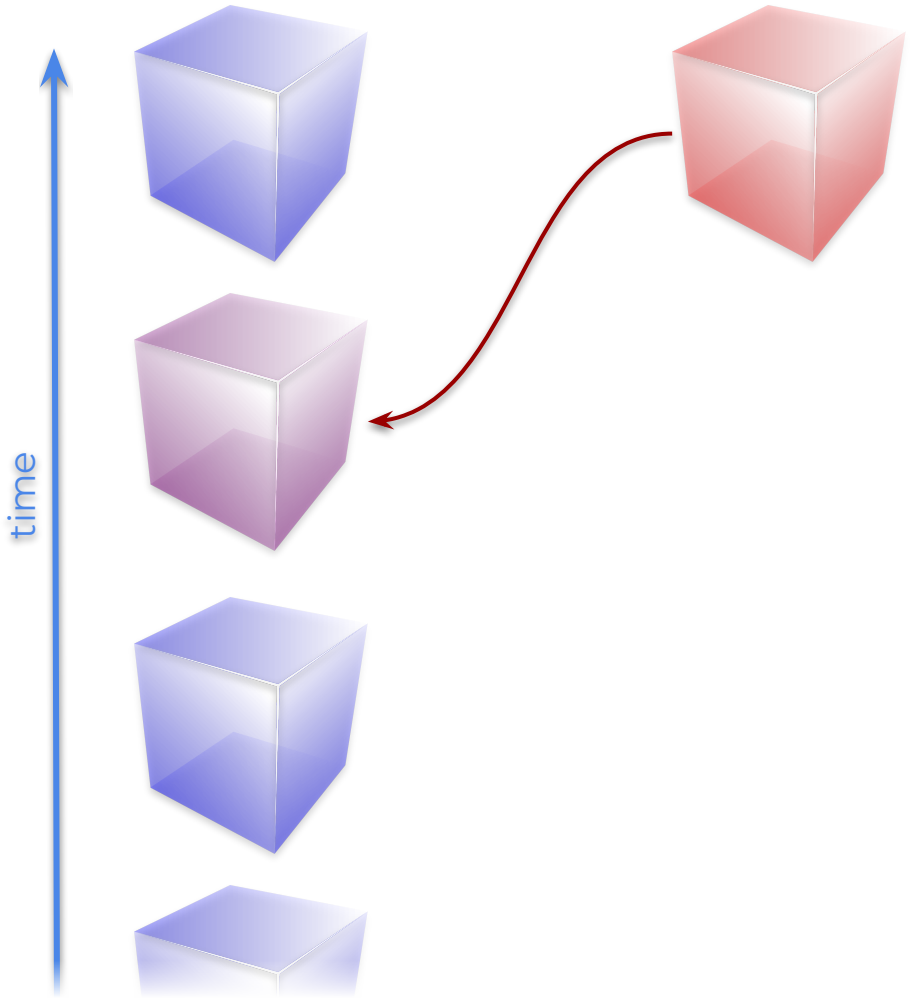
- **original simulation** with outputs at different redshifts
- **target cosmology** at a given redshift



Angulo & White (2010)

Simulation rescaling

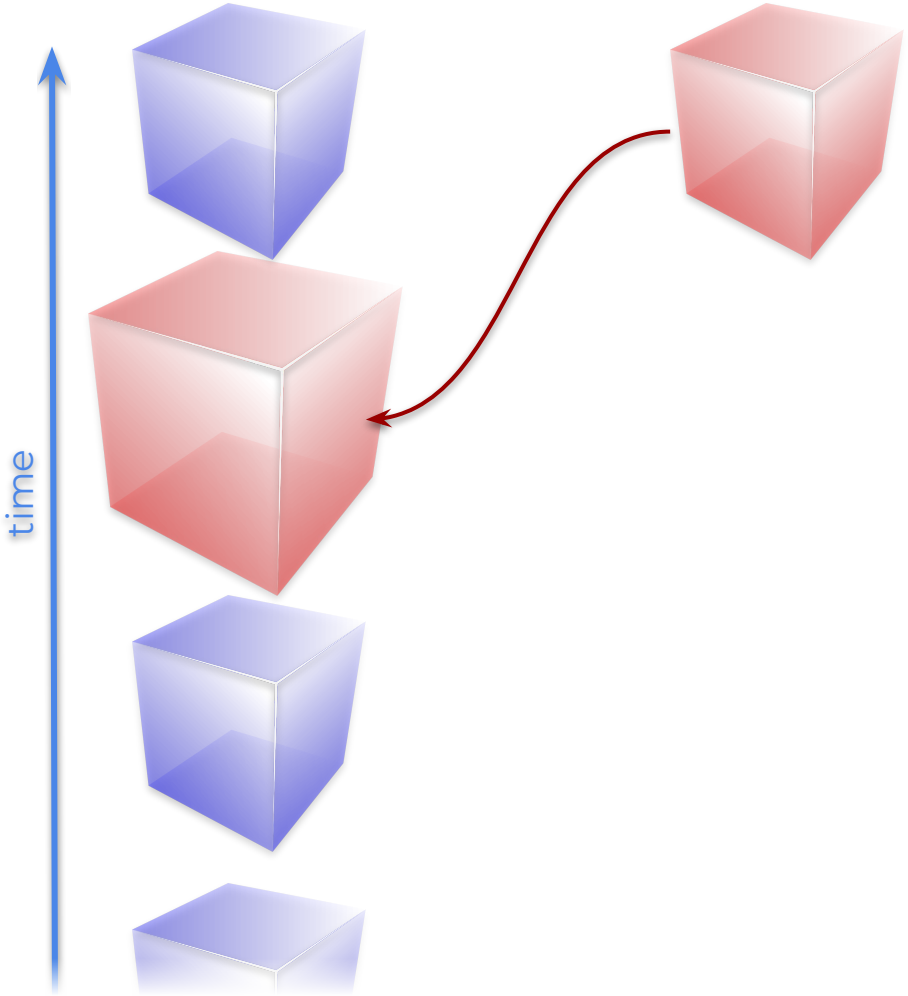
- **original simulation** with outputs at different redshifts
- **target cosmology** at a given redshift
- match the linear variance of the two cosmologies and get
  - a **time transformation** (this selects an output of the original simulation)



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)