# Theoretical predictions for the matter power spectrum: challenges of sub-percent accuracy

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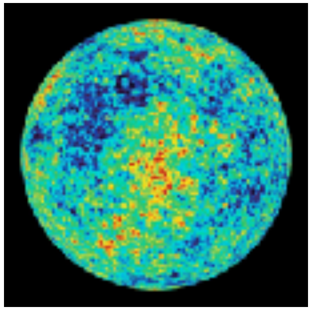
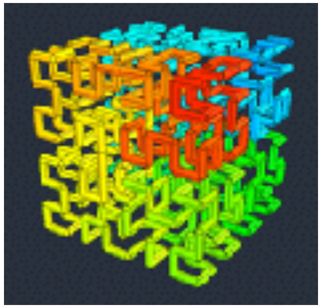
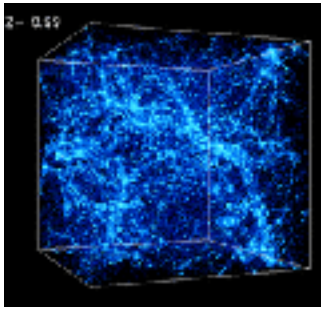
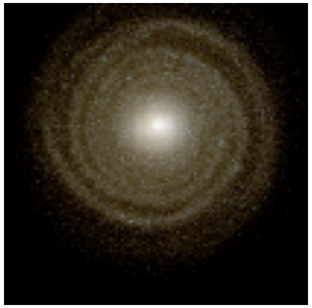





# Outline

Precision cosmology allows for discriminating exotic dark matter or modified gravity models.

Non-linear dark matter dynamics plays an important role in various cosmology probes of the dark sector.

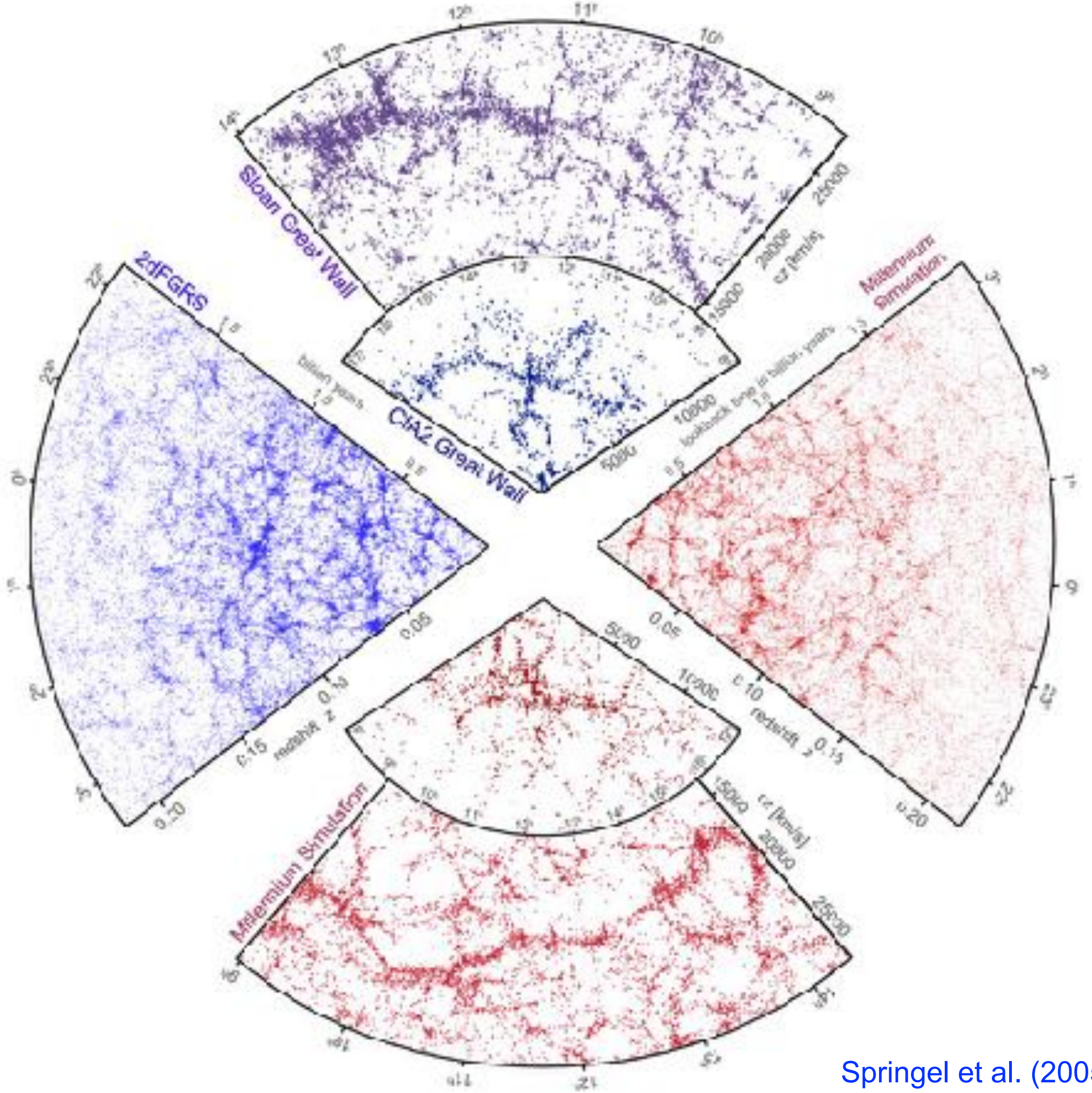
- galaxy clustering: non-linear BAO shifts
- weak lensing: non-linear boost.

Non-linear dynamics can be described using high-order perturbation theories on relatively large scales.

Small scales are affected by baryonic effects.

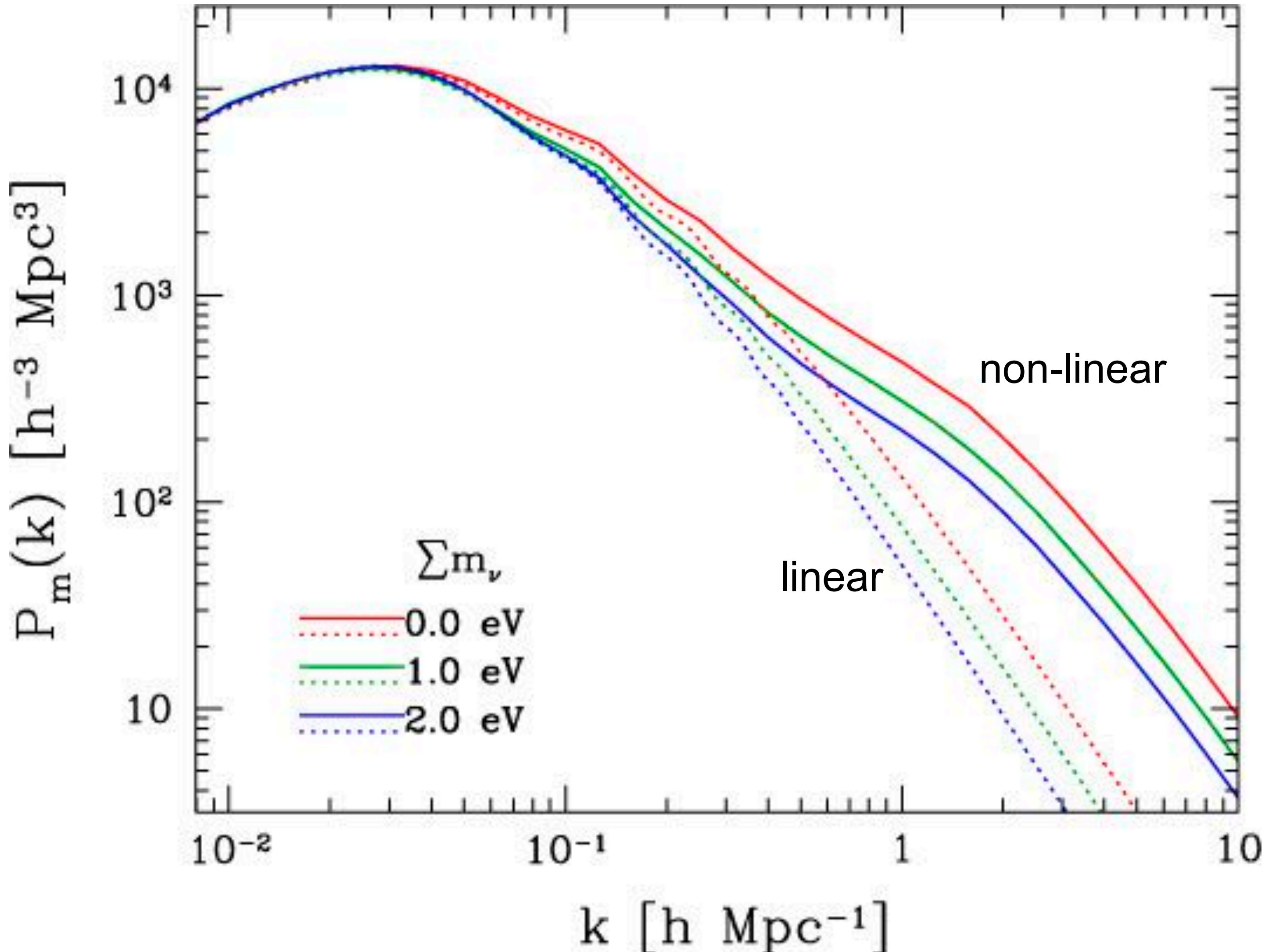
N-body models are the only viable alternative at intermediate scales.

# Large scale structures: towards precision cosmology?




Springel et al. (2005)

# Matter power spectrum: a tool to discriminate models




Hannestad et al. (2006)

# Computing non-linear dark matter dynamics

N body codes solve the Vlasov-Poisson equations using a Lagrangian sampling of phase space. So far, most competitive approach, but for how long ?

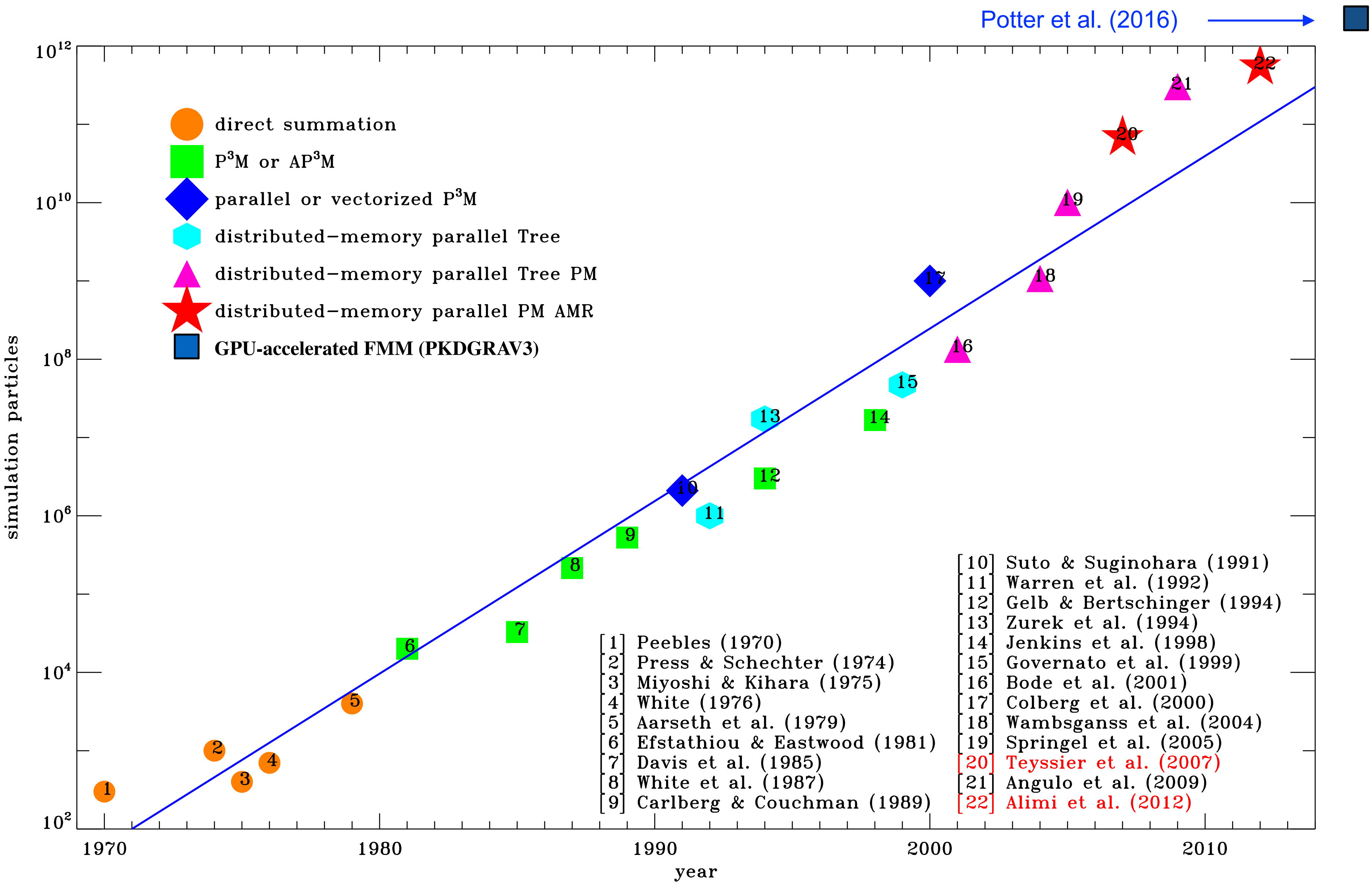
Main numerical limitations are:

1. Finite box size
2. Finite number of particles
3. Finite force resolution

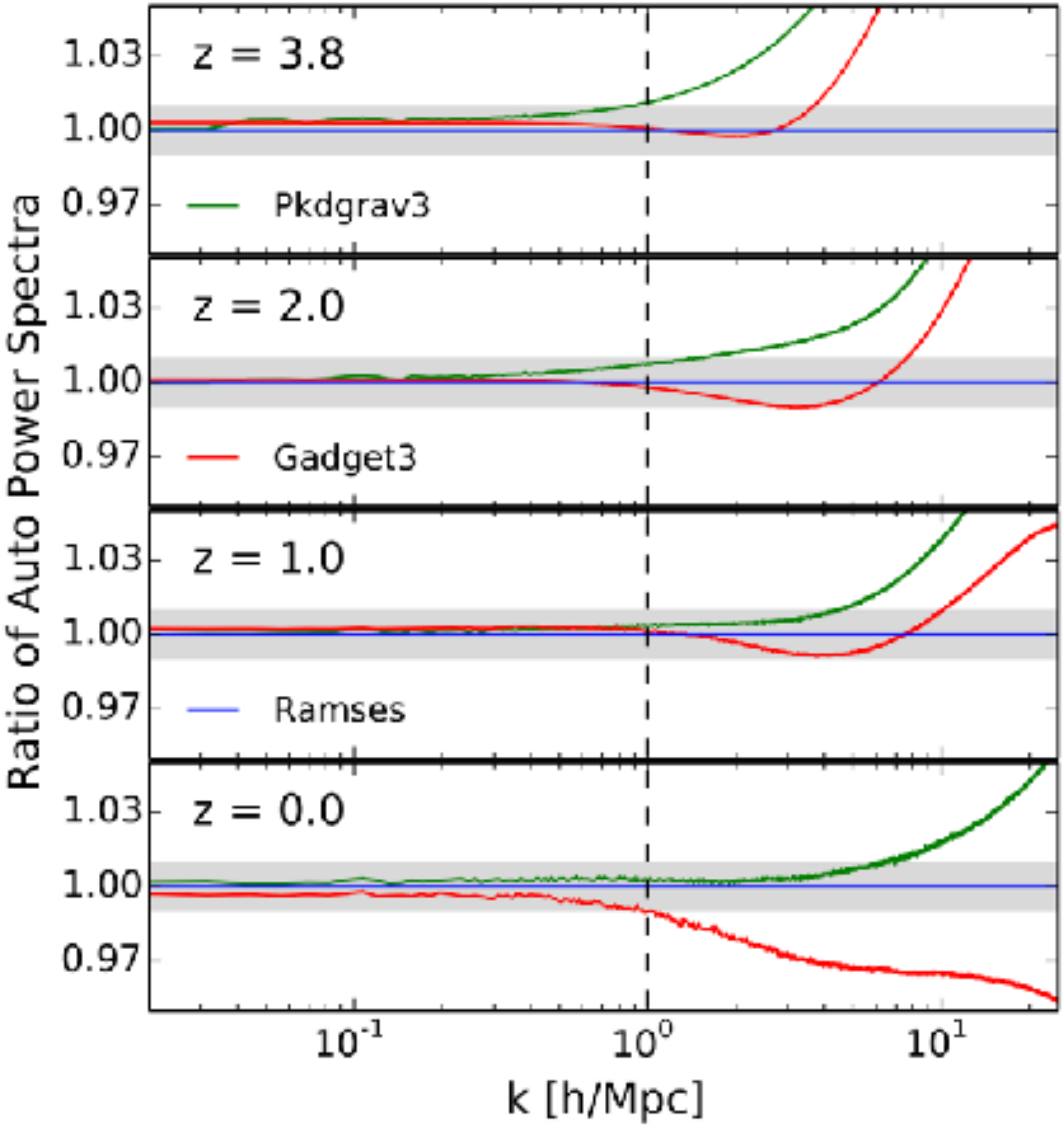
Popular techniques are, in chronological order:

1. Direct N body, scaling as $N^2$
2. PM: Fast Fourier Transform solvers, N log N, low resolution
3. P3M (PP + PM): order N log N if large box, $N^2$ if small box, low resolution
4. Tree codes, O(N log N), high resolution, see also Tree-PM
5. Adaptive Mesh Refinement (AMR) and Multigrid solver, O(N), high resolution
6. Fast Multipole Method (FMM), O(N), high resolution

# Performance of N body codes

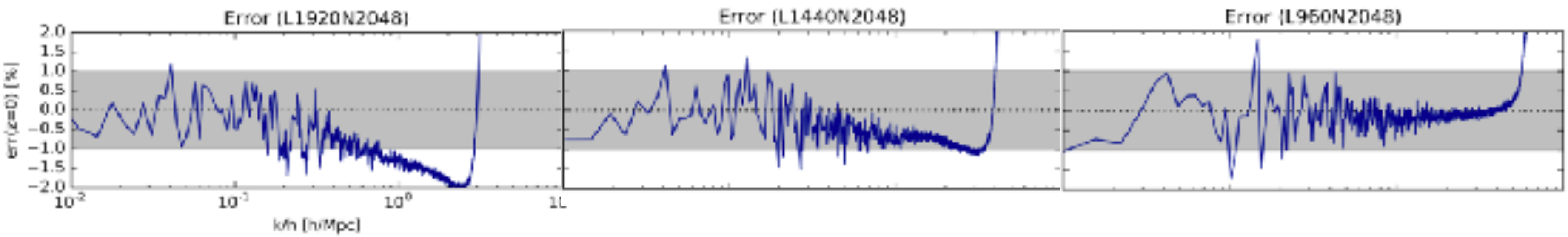


# Systematic errors in N body codes ?



# Designing the optimal N body simulation

Effect of box size (cosmic variance and non-linear finite volume effects)



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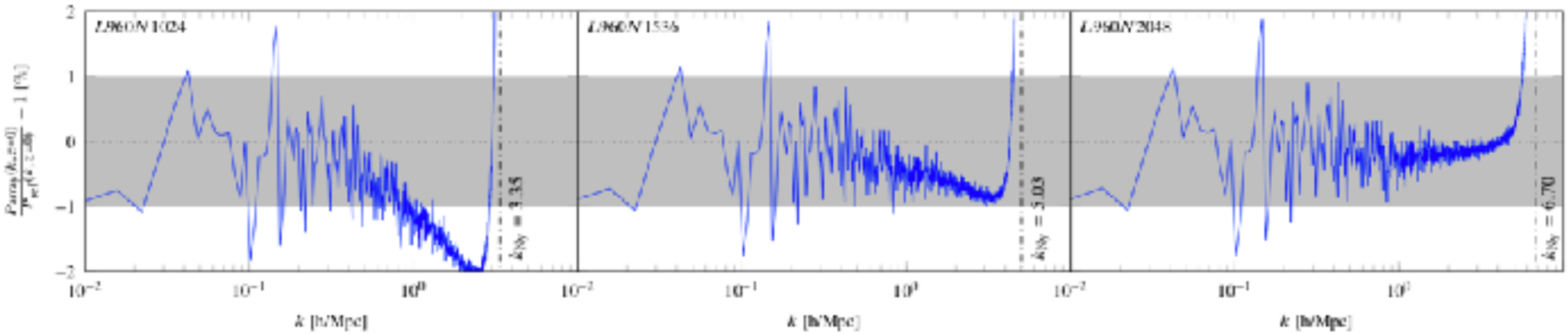
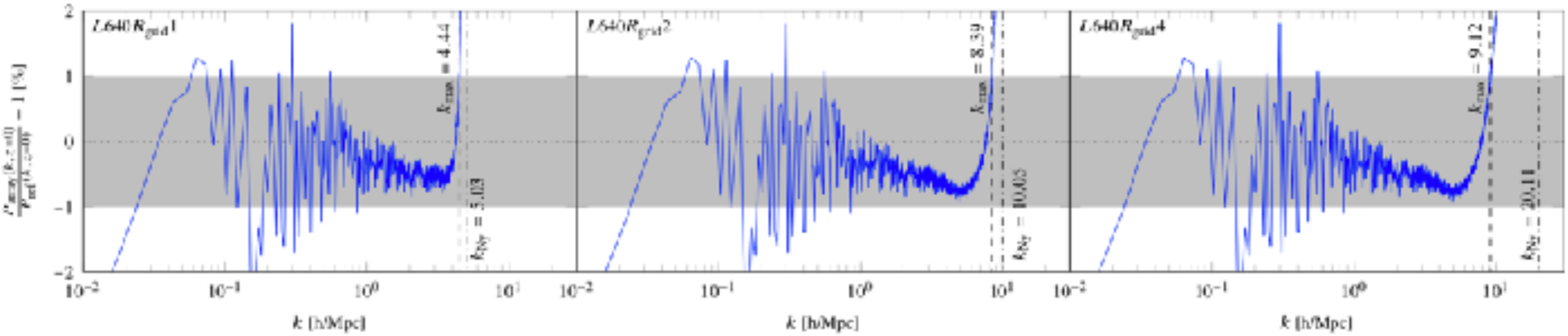
# Designing the optimal N body simulation

Effect of particle number



# Designing the optimal N body simulation

Effect of Fourier analysis grid



# Designing the optimal N body simulation

1. Box size larger than 2000 Mpc/h
2. N larger than 4096^3 particles
3. For each parameter set, use 2 simulations with pairing and fixing (Angulo and Pontzen 2016) to suppress variance on large scale
4. Measure the power spectrum using Rgrid=2 (N larger than 8192^3)

# Emulating the power spectrum

In order to fit galaxy survey data using non-linear corrections, one needs to explore the 8-dimensional parameter space to perform the likelihood analysis.

Each individual simulation is very expensive.

Goal: replace N body simulations by a surrogate model with the same sub-percent accuracy.

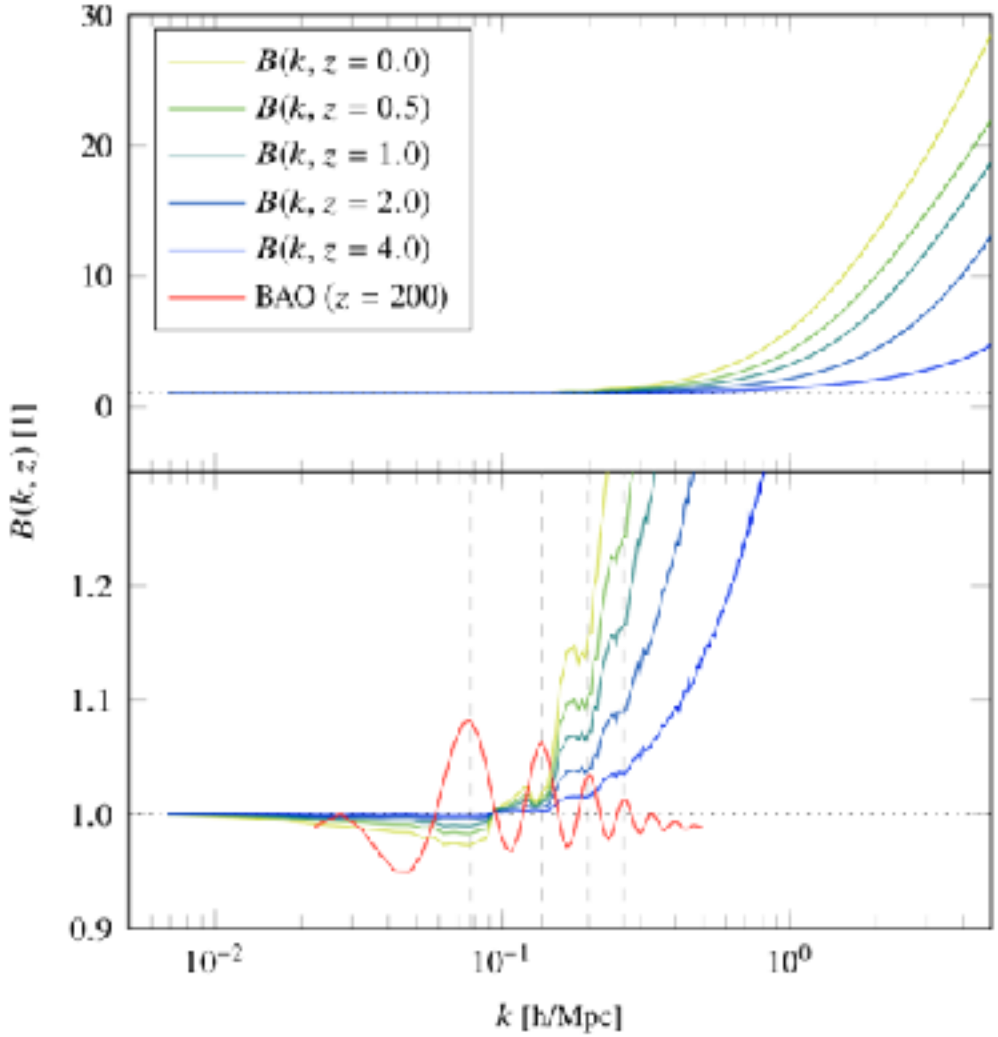
Uncertainty quantification techniques used routinely in engineering.

First implementation for cosmology by Heitmann et al. (2010): CosmicEmu.

This work: used the platform UQLab developed at ETH Zurich by Sudret and collaborators to design new, more accurate emulators for the Euclid mission.

# New approach: emulate the non-linear boost

$$B(k, z) = \frac{P_{\mathrm{non-lin}}(k, z)}{P_{\mathrm{lin}}(k, z)}$$



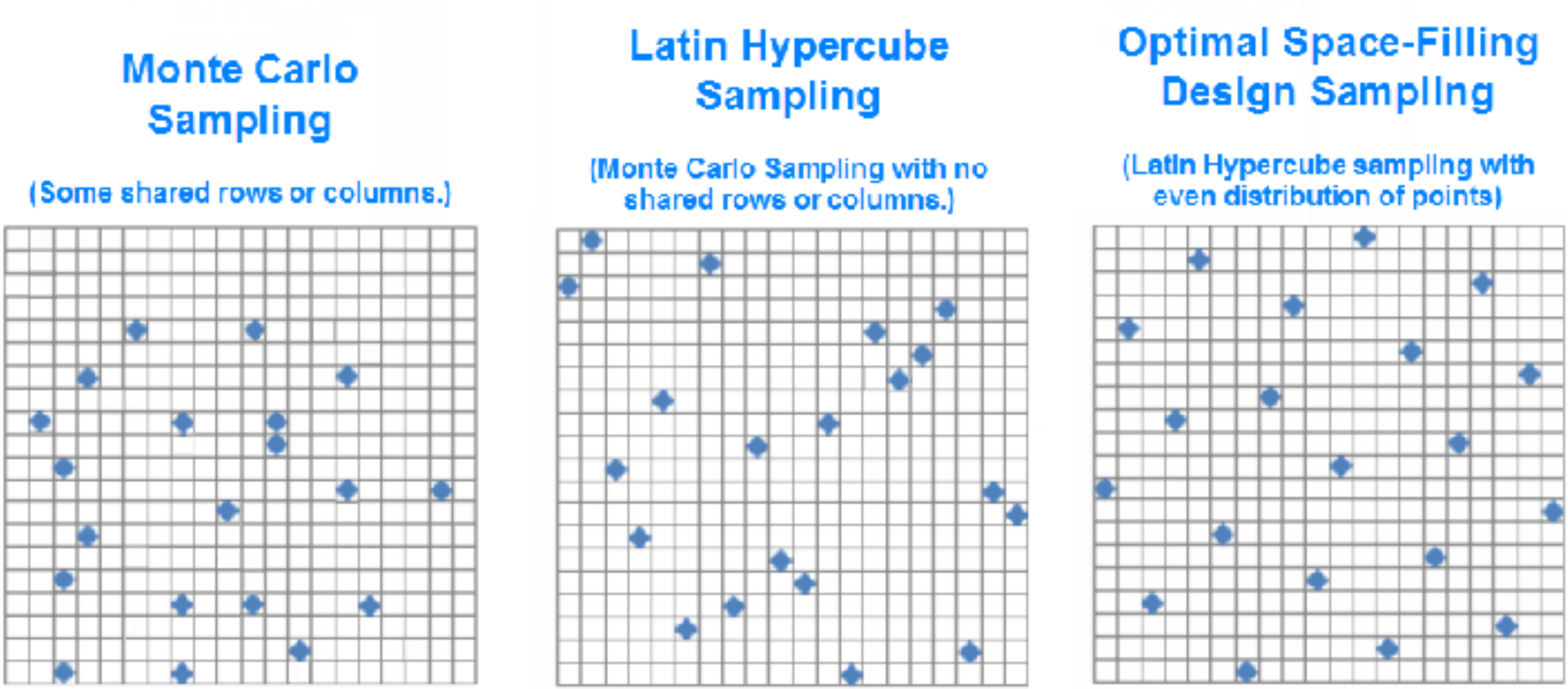
# Optimising the experimental design

How many simulations do we need to perform ?

How do we sample the parameter space ?

How do we interpolate the power spectrum in between the sampling points ?

# Optimal LHS sampling



# Interpolation strategy

First, define the parameter space

$$\omega_b \in [0.0215, 0.0235]$$
$$\omega_m \in [0.1306, 0.1546]$$
$$n_s \in [0.9283, 1.0027]$$
$$h \in [0.6155, 0.7307]$$
$$w_0 \in [-1.30, -0.70]$$
$$\sigma_8 \in [0.7591, 0.8707]$$

Second, define $n_{ED}$, the number of points in the experimental design.

Third, perform a Principal Component Analysis

$$\mathbf{D} = \sum_{i=1}^{n_{ED}} \lambda_i(\omega_b, \omega_m, n_s, h, w_0, \sigma_8) \mathrm{PC}_i(k, z)$$

Fourth, interpolate the eigenvalues with Legendre polynomials of order p.

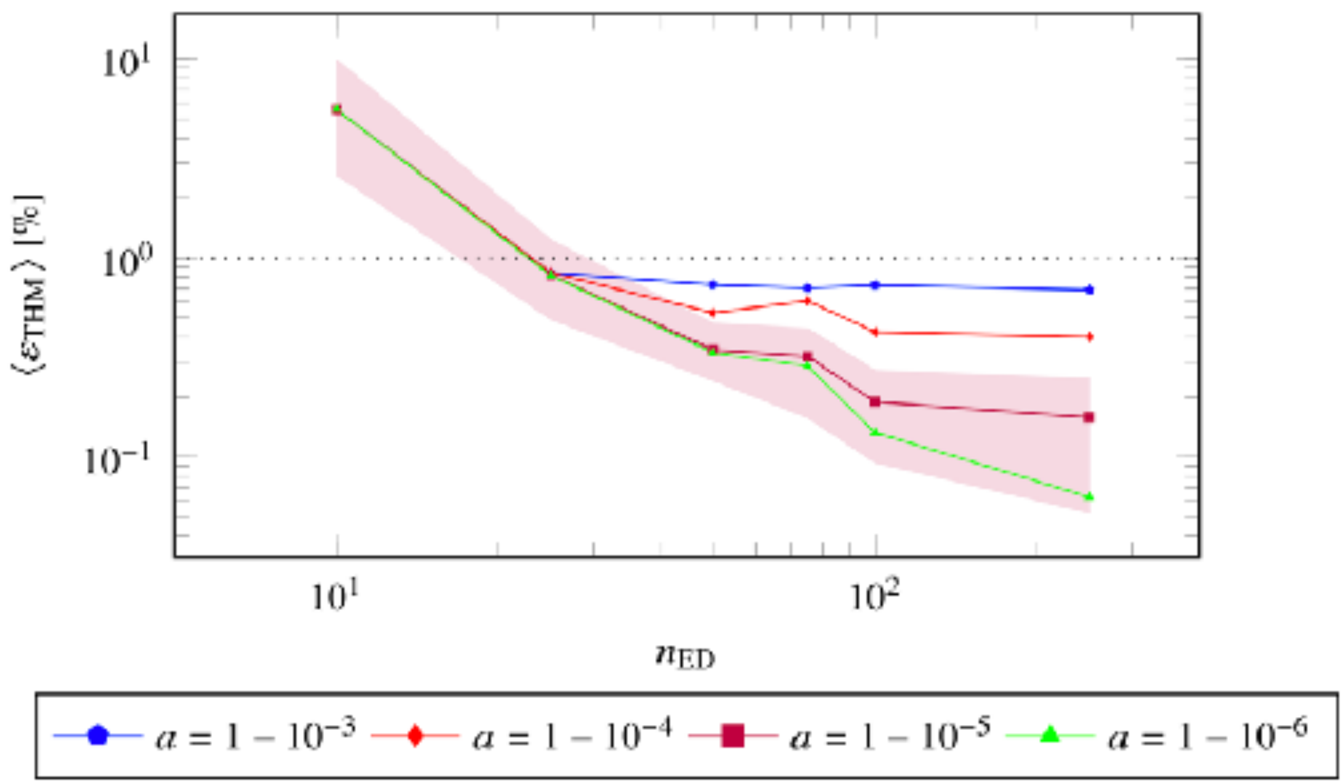
$$\lambda_i(\omega_b, \omega_m, n_s, h, w_0, \sigma_8) \approx \sum_{\alpha \in \mathcal{A}} \eta_\alpha \Psi_\alpha(\mathbf{x})$$

Polynomial coefficients are computed by regression.

Key parameters:
- Number of points in the experimental design $n_{ED}$
- Number of PCs $N_{PC}$ or accuracy parameter a
- Polynomials order p

# Defining the emulation parameters

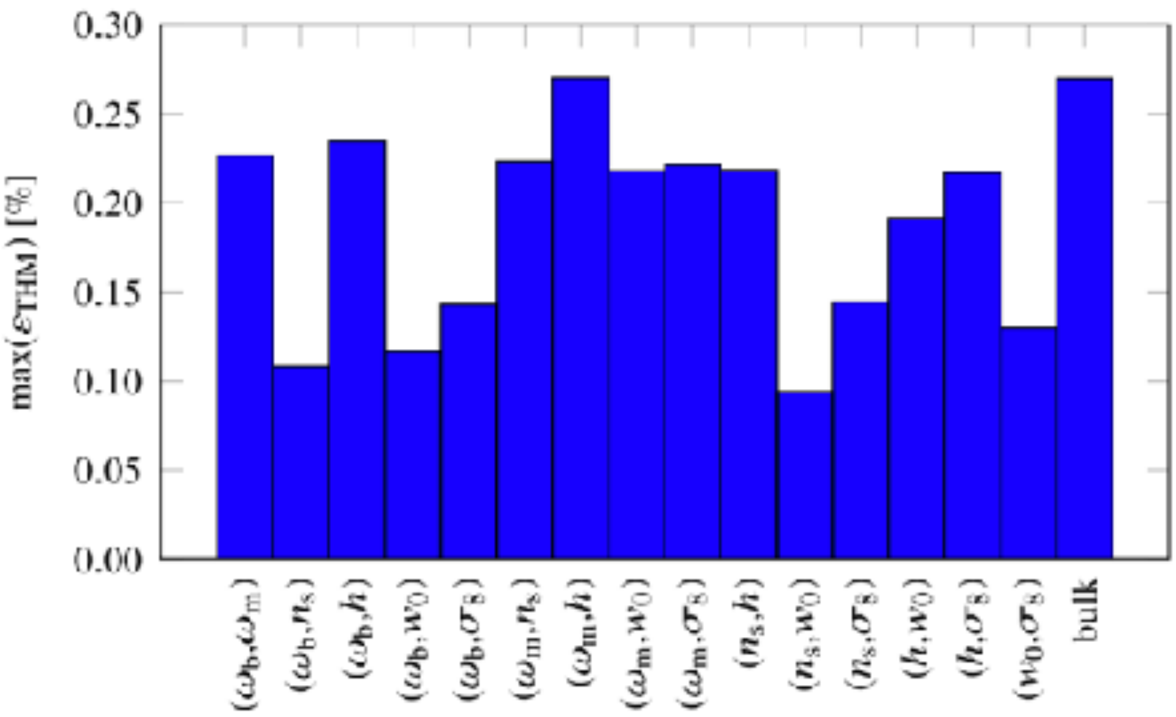
We use Takahashi's Halofit to mock N body simulations.
We estimate the Emulation-Only-Error (EOE).
Required number of simulations depends on the PCA truncation parameter.



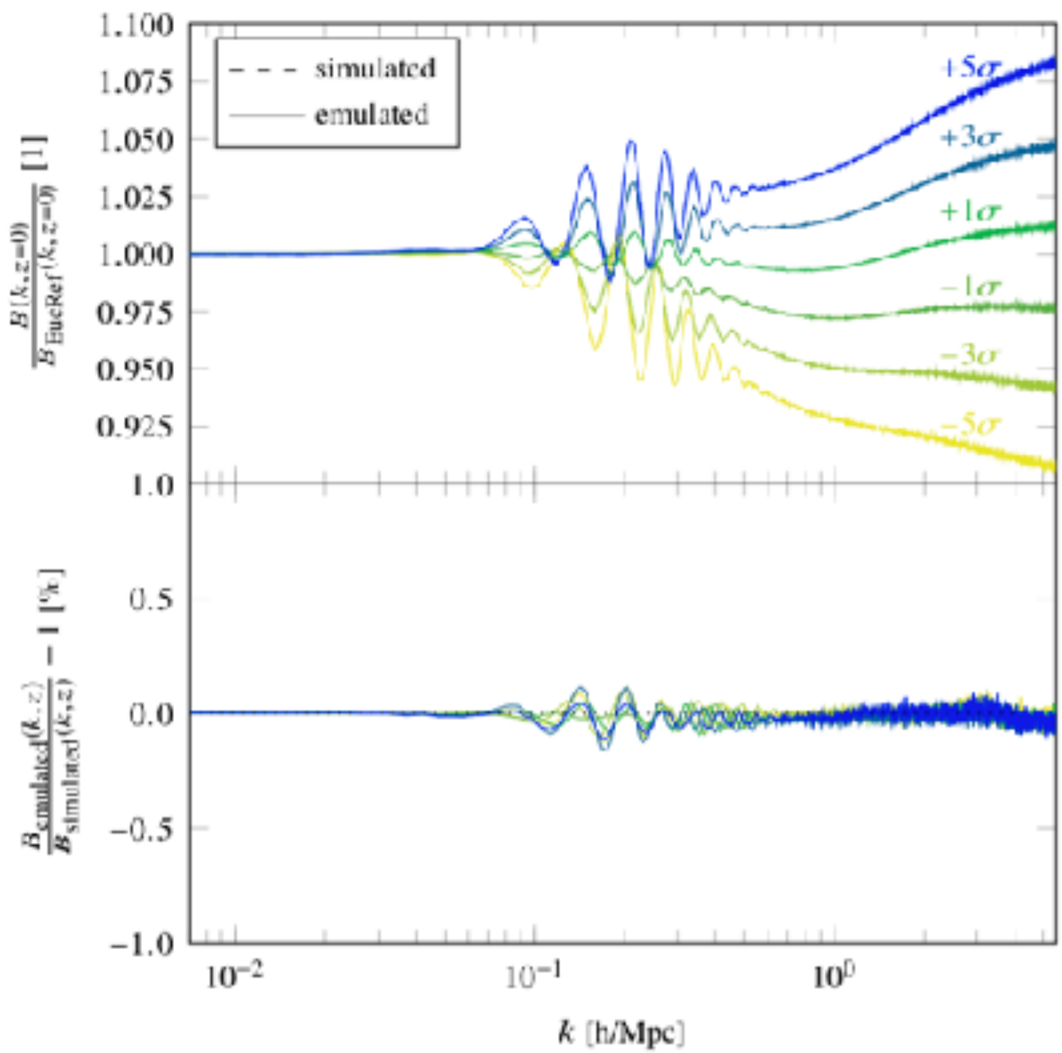
# Characterising the final strategy

We set the polynomial order to p=2, the size of the experimental design to 100 points and the number of PC to 11 (a=1-10$^{-5}$).

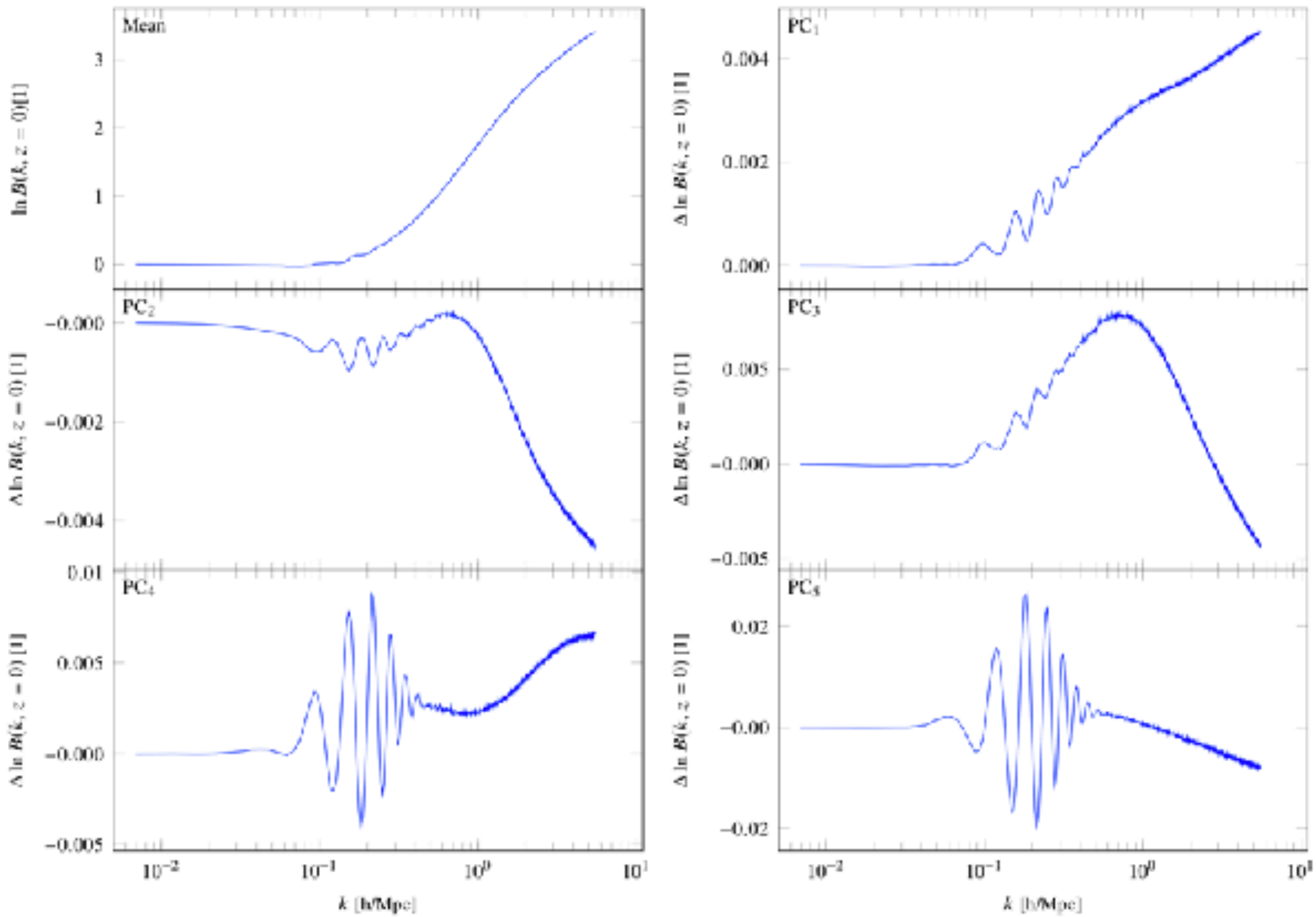
We test the corresponding emulator using Halofit in 2D cuts through the parameter space.



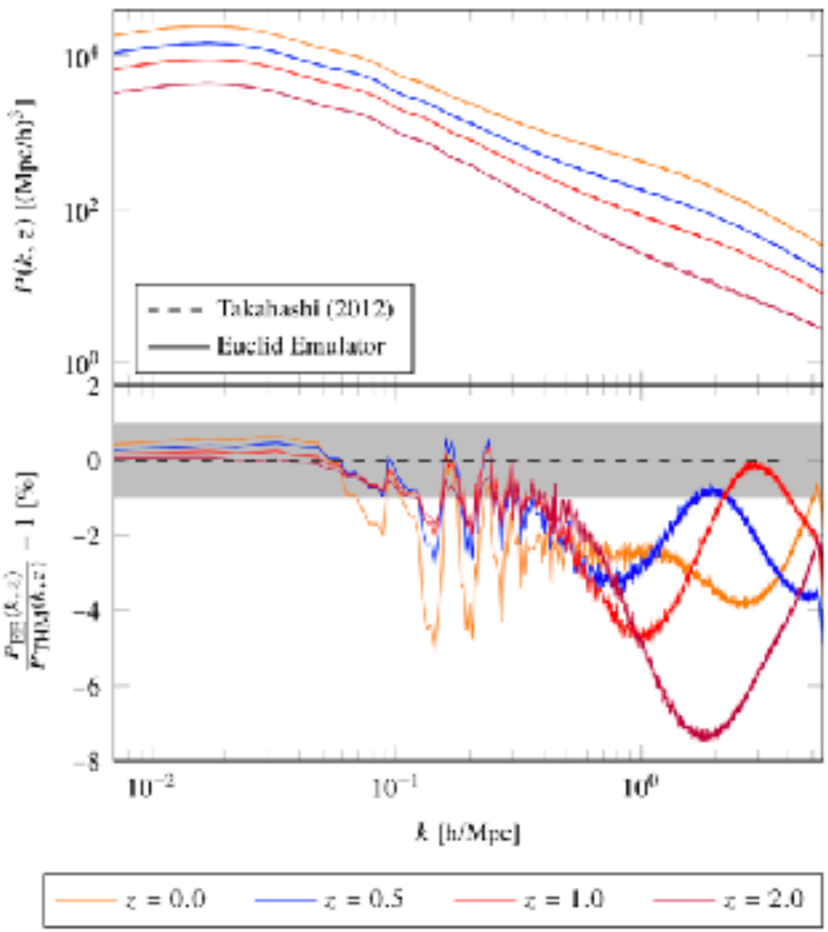
# Testing the final Euclid Emulator

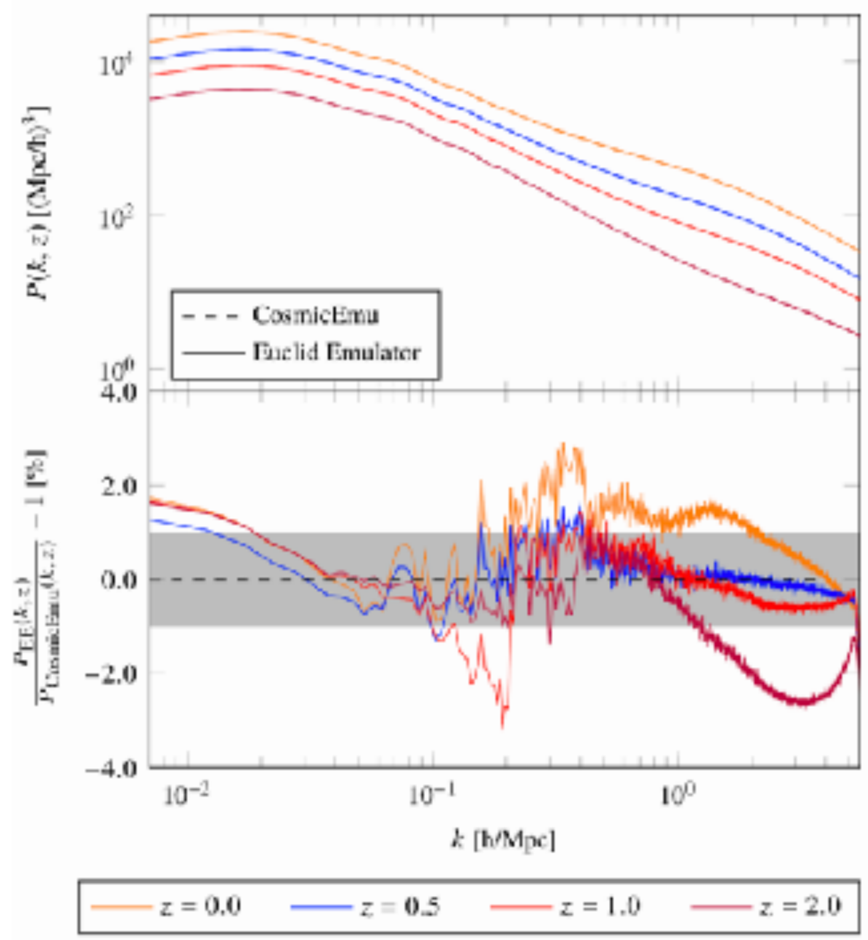


# PCs of the final emulator



# Comparison with previous work



# Conclusions

Given a reasonably sized parameter space, we can design an emulator for the non-linear boost of the matter power spectrum with « emulation-only-errors » as low as 0.2% (EuclidEmulator, Knabenhans et al. submitted).

Systematic errors due to N body simulation below 3% at k<5 h/Mpc

For weak lensing, baryonic effects kick in at k=1 h/Mpc (pessimistic scenario). They can be encoded as a baryonic boost with additional parameters, and marginalised over.

For galaxy clustering, halo occupation effects will likely dominate. HOD parameters could be added as new parameters and marginalised over (Aemulus, DeRose et al. 2018).

Future work:

- include massive neutrinos (Mira-Tiran, Lawrence et al. 2017)
- higher resolution simulations
- emulate other observables (mass function, RSD, surveys…)