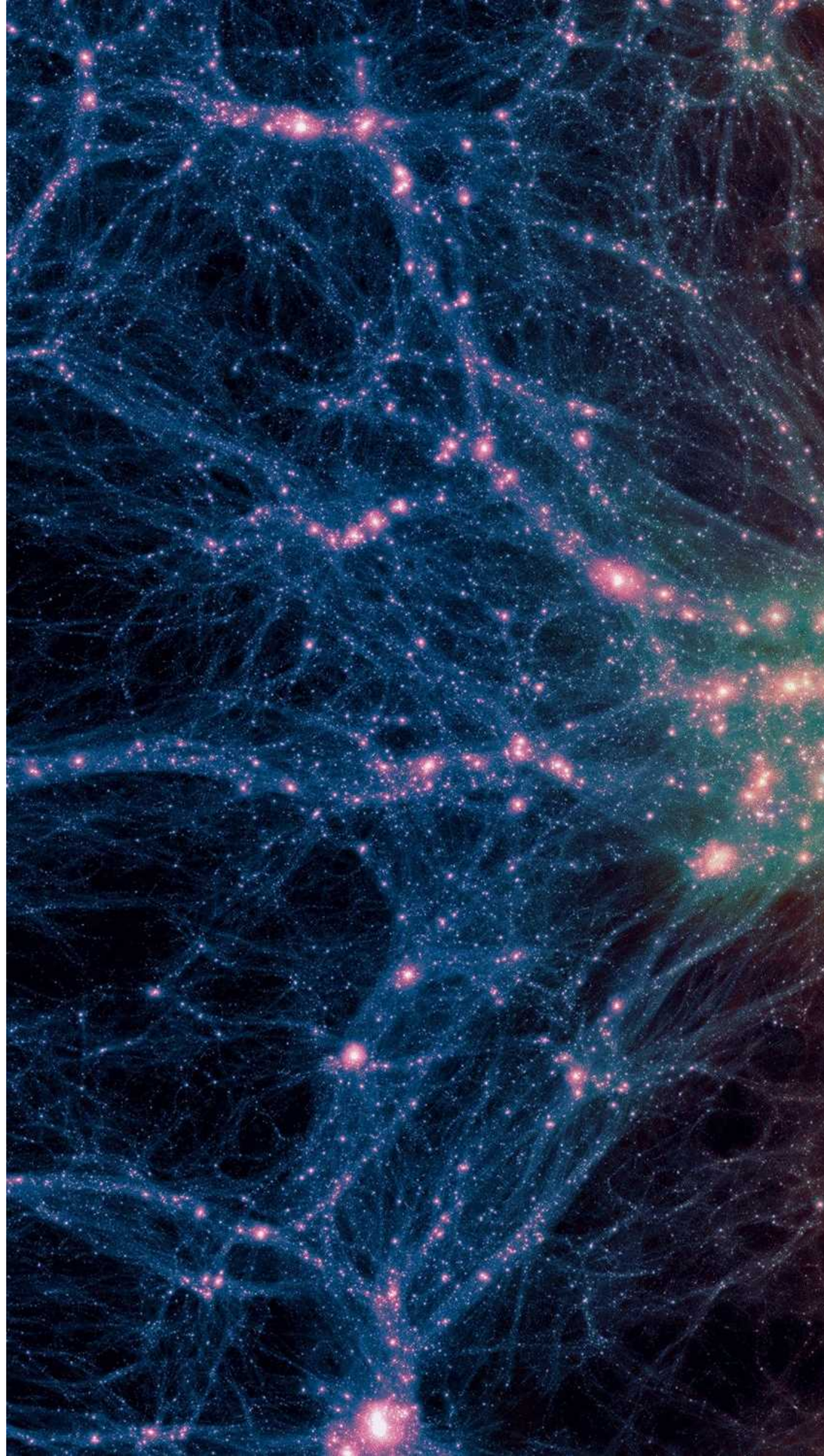
COSMOLOGICAL SIMULATIONS FOR PRECISION COSMOLOGY WITH GALAXY SURVEYS

ICE INSTITUT DE CIÈNCIES DE L'ESPAI

CSIC Consejo Superior de Investigaciones Científicas

IEEC

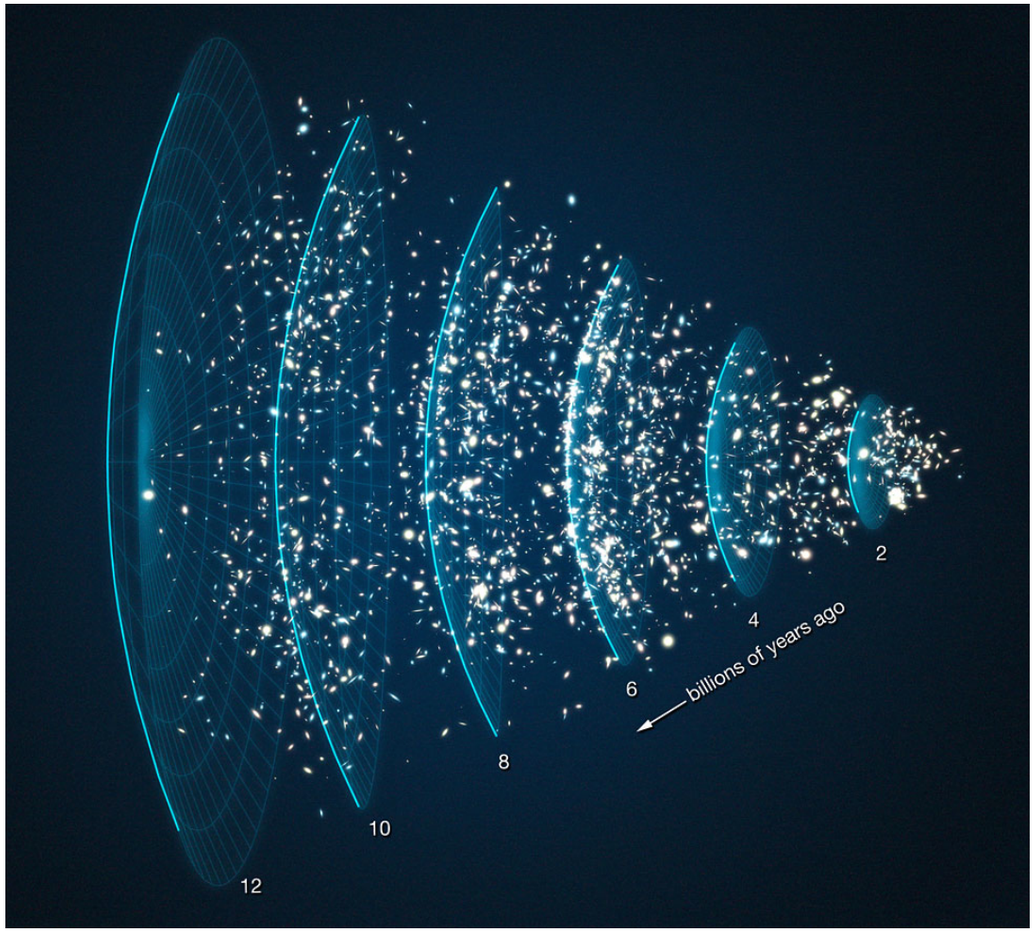
Linda Blot



PRECISION COSMOLOGY

- Beginning: COBE CMB map (1994)
- Features:
  - Standard model with few parameters
  - Data-driven
- History:
  - CMB -> Hot Big Bang
  - SN Ia -> ΛCDM
  - LSS -> ?

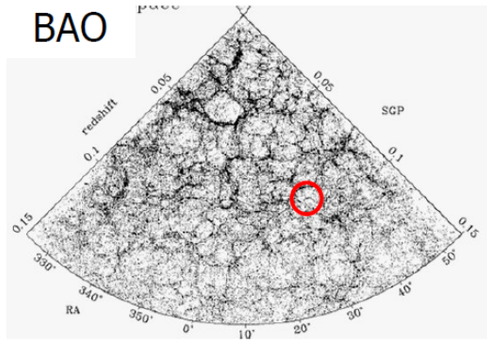
LARGE SCALE STRUCTURE SURVEYS

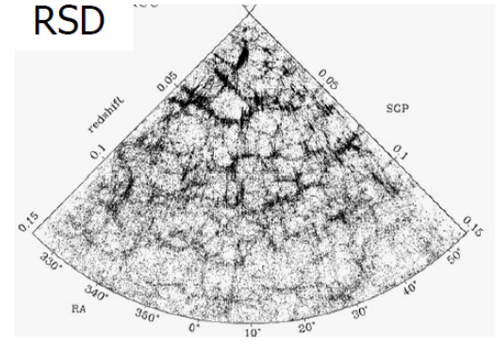


ESO/L. Calçada/ESO-GOODS team

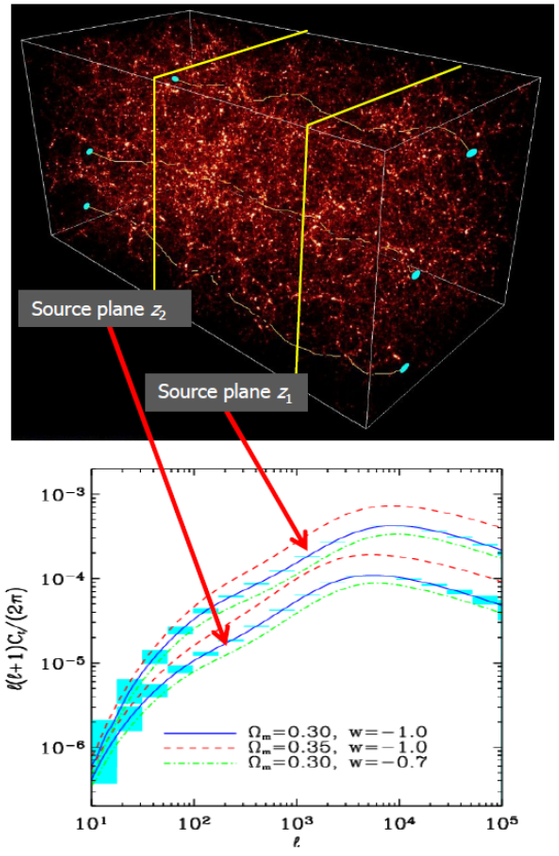
BAO, RSD and WL over 15,000 deg^2

50 million galaxies with redshifts





1.5 billion sources with shapes, 10 slices



EUCLID collaboration

Competitive with standard probes to constrain cosmological parameters values

LARGE SCALE STRUCTURE SURVEYS: WHY WE NEED SIMULATIONS

- Non-linear regime of structure collapse: no analytical solution
- Bayesian data analysis:

$$P(\boldsymbol{\theta}|\mathbf{D}, M) = \frac{P(\mathbf{D}|\boldsymbol{\theta}, M)\, P(\boldsymbol{\theta}|M)}{P(\mathbf{D}|M)}$$

$\boldsymbol{\theta}$ parameters

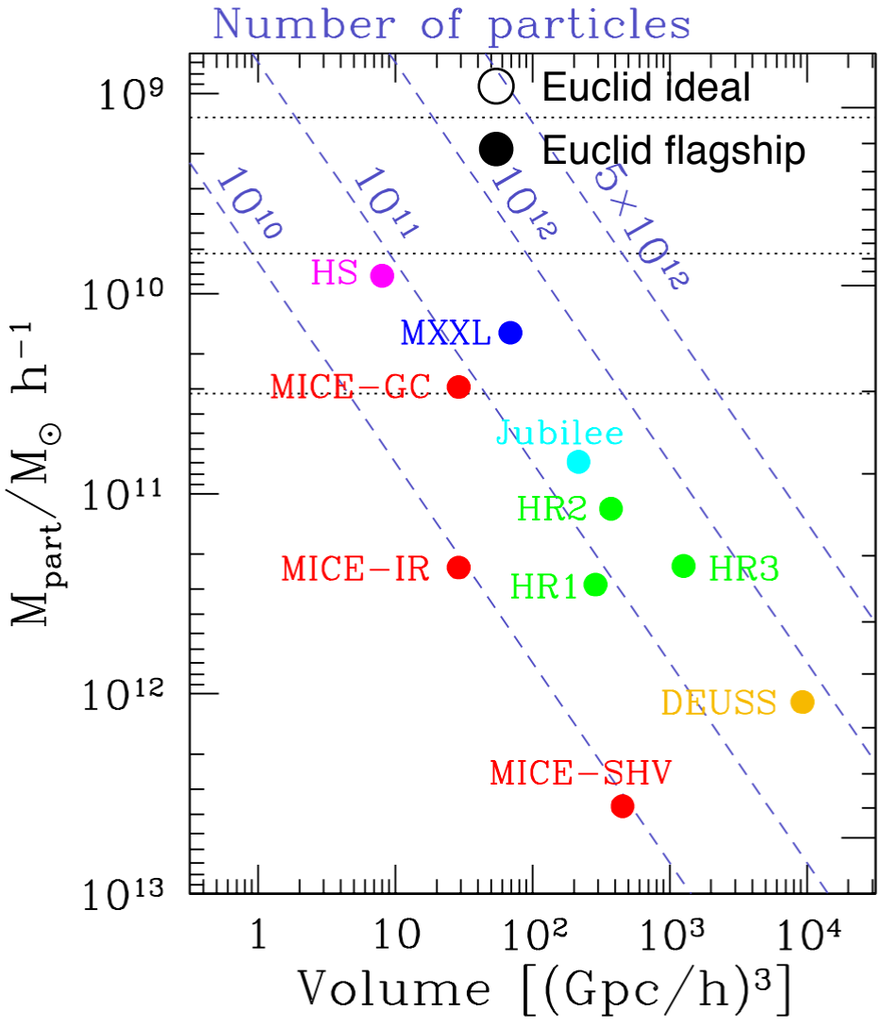
$\mathbf{D}$ data

M model

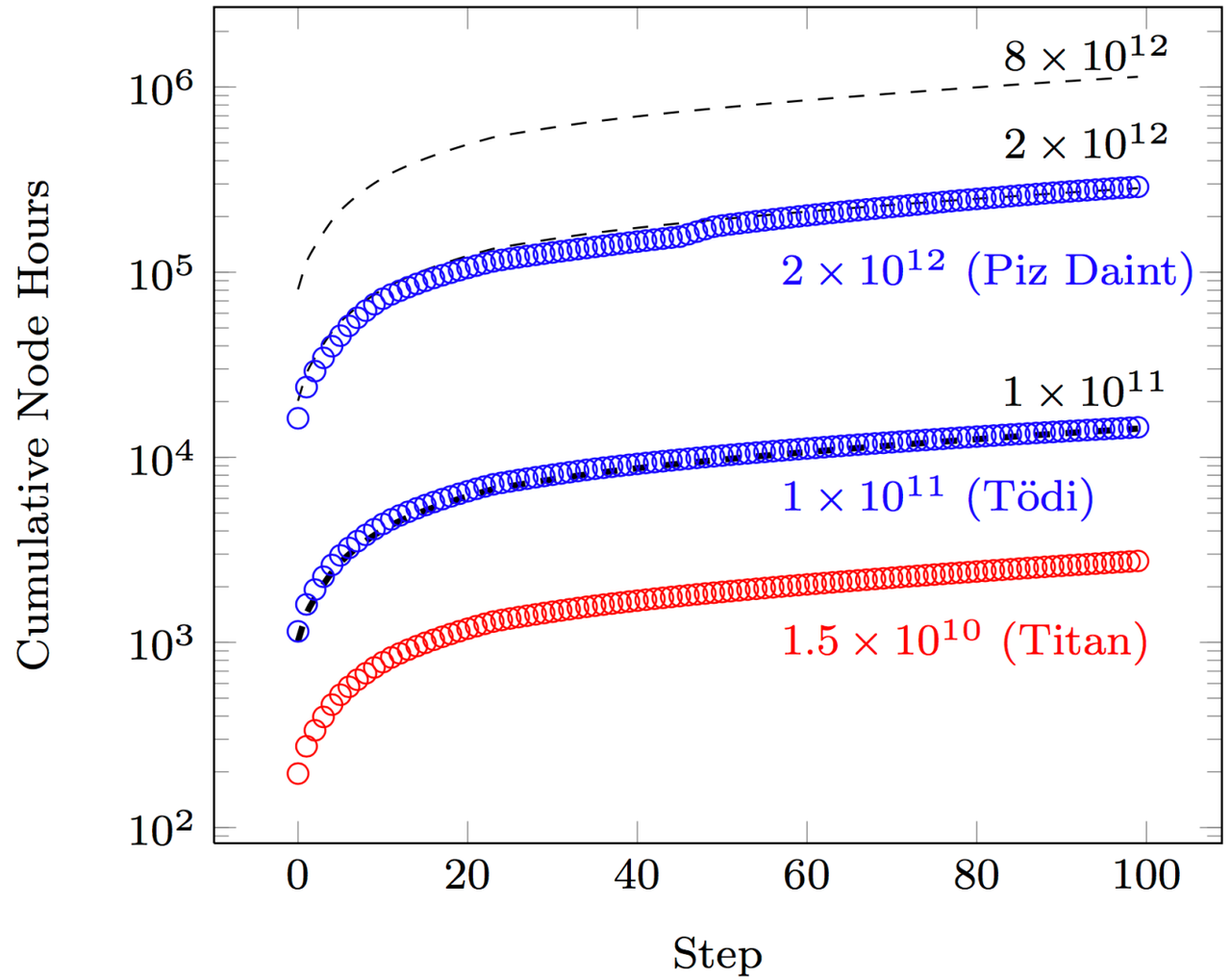
$$P(\mathbf{D}|\theta, M) \propto \exp\left(-\frac{1}{2}\sum_{ij}(D_i - D_M)cov_{ij}^{-1}(D_j - D_M)\right)$$

- Galaxy mock catalogues to understand observational systematics

COSMOLOGICAL SIMULATIONS: COMPUTATIONAL COST



Fosalba et al. 2015



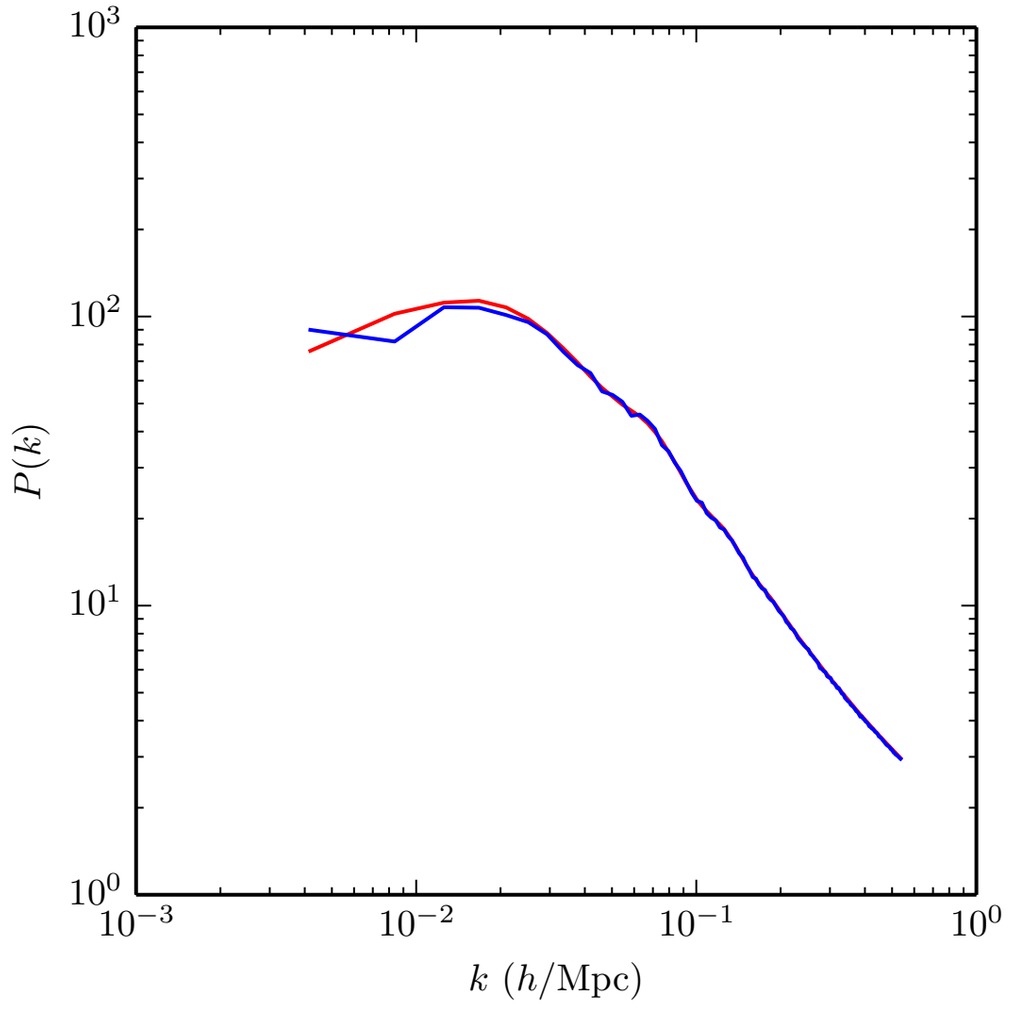
Potter, Stadel, Teyssier 2016

- 40 Billion halos, 5.5 Tb of data only for halos in the LC!

Big data

PAIRED AND FIXED SIMULATIONS FOR EMULATORS

- The pairing and fixing is a technique to reduce sample variance in simulations using only 2 simulations



- Currently being used to build an emulator

COSMOLOGICAL SIMULATIONS – INITIAL CONDITIONS

Gaussian field

$$\delta(\vec{x}) = \frac{1}{(2\pi)^3} \int d^3k \sqrt{P(k)} \lambda_{\vec{k}} e^{i\vec{k}\cdot\vec{x}}$$

$$\Pr(|\lambda(\vec{k})|, \theta) = \frac{|\lambda(\vec{k})|}{\pi} \exp(-|\lambda(\vec{k})|^2)$$

Independence condition

$$\langle \lambda_{\vec{k}_1} \lambda^*_{\vec{k}_2} \rangle = (2\pi)^3 \delta^3_D(\vec{k}_2 - \vec{k}_1)$$

Reality condition

$$\lambda^*_{\vec{k}} = \lambda_{-\vec{k}}$$

COSMOLOGICAL SIMULATIONS – FIXED INITIAL CONDITIONS

Fixed amplitude

$$\delta(\vec{k}) = \sqrt{P(\vec{k})}\exp(i\theta)$$

$$\Pr(|\lambda(\vec{k})|, \theta) = \frac{1}{2\pi}\delta_D(|\lambda(\vec{k})| - 1)$$

Independence condition

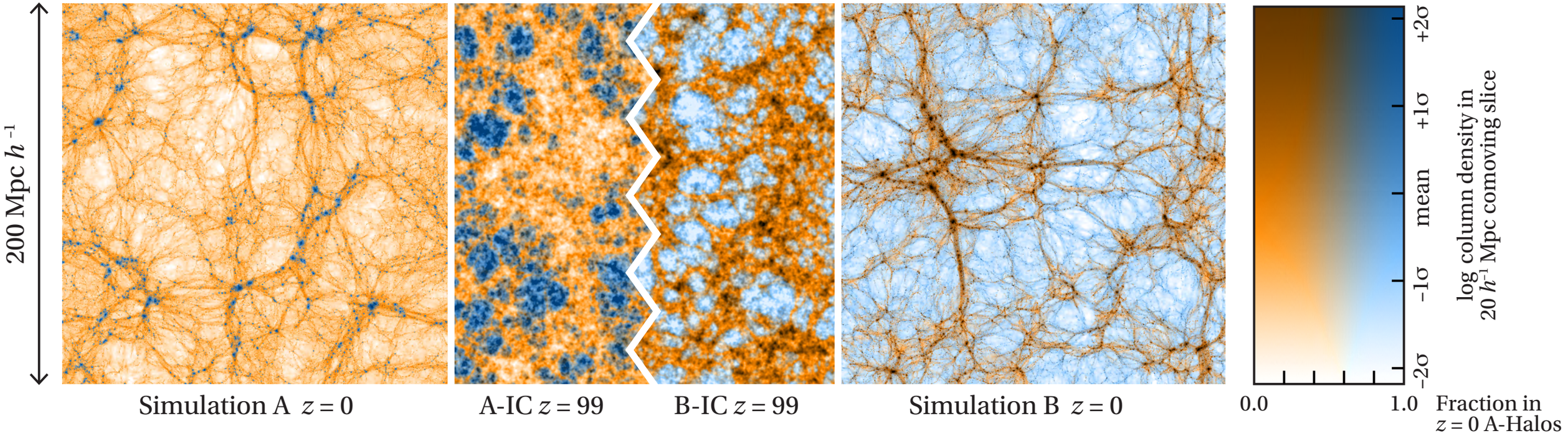
$$\langle \lambda_{\vec{k}_1} \lambda^*_{\vec{k}_2} \rangle = (2\pi)^3 \delta^3_D(\vec{k}_2 - \vec{k}_1)$$

Reality condition

$$\lambda^*_{\vec{k}} = \lambda_{-\vec{k}}$$

PAIRED INITIAL CONDITIONS

$$\delta(\vec{k}) = \sqrt{P(\vec{k})}\exp(i\theta) \qquad \theta \to \theta + \pi$$



Pontzen et al. 2016

PAIRED INITIAL CONDITIONS

Pairing partially cancels sample variance

$$\tilde{P}(k) \simeq \frac{1}{N_k} \sum_{i \in S_k} \left(\delta^*_{i,L} \delta_{i,L} + G_{ijk} \left(\delta^*_{j,L} \delta^*_{k,L} \delta_{i,L} \right) + \text{c.c.} + \cdots \right)$$

since $\quad \langle \tilde{P}(k) \rangle = P_L(k) + \cdots$

$$\tilde{P}(k)_{\text{corr},1} = \tilde{P}_{AA}(k) + P_L(k) - \tilde{P}_{LL}(k)$$

$\tilde{P}(k)_{\text{corr},1} - \langle \tilde{P}(k) \rangle$ is third order in δ

PAIRED INITIAL CONDITIONS

Pairing partially cancels sample variance

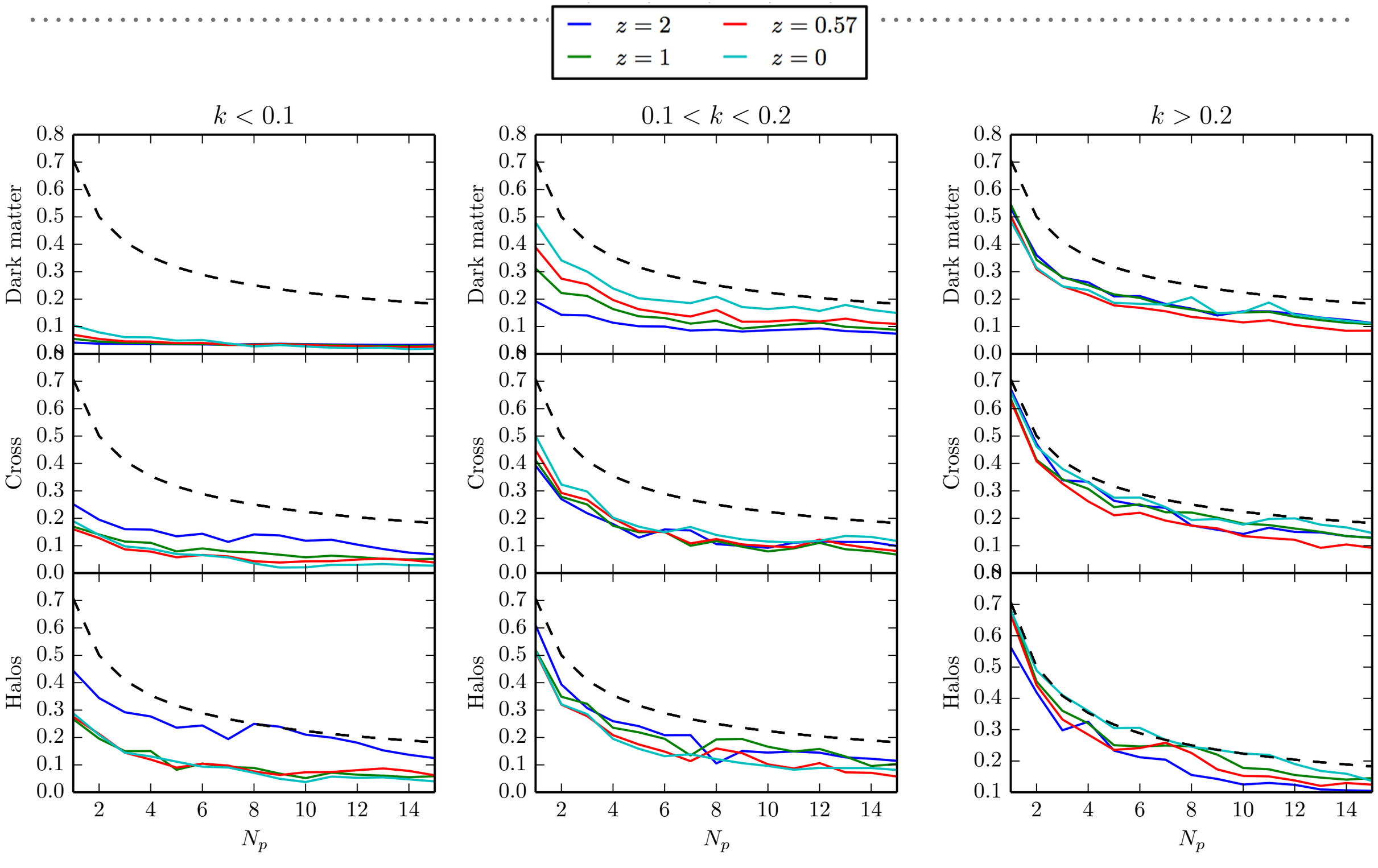
$$\tilde{P}(k) \simeq \frac{1}{N_k} \sum_{i \in S_k} \left(\delta^*_{i,L} \delta_{i,L} + G_{ijk} \left(\delta^*_{j,L} \delta^*_{k,L} \delta_{i,L} \right) + \text{c.c.} + \cdots \right)$$

since $\quad \langle \tilde{P}(k) \rangle = P_L(k) + \cdots$

$$\tilde{P}(k)_{\text{corr},2} = \frac{1}{2} \left(\tilde{P}_{AA}(k) + \tilde{P}_{BB}(k) \right) + P_L(k) - \tilde{P}_{LL}(k)$$

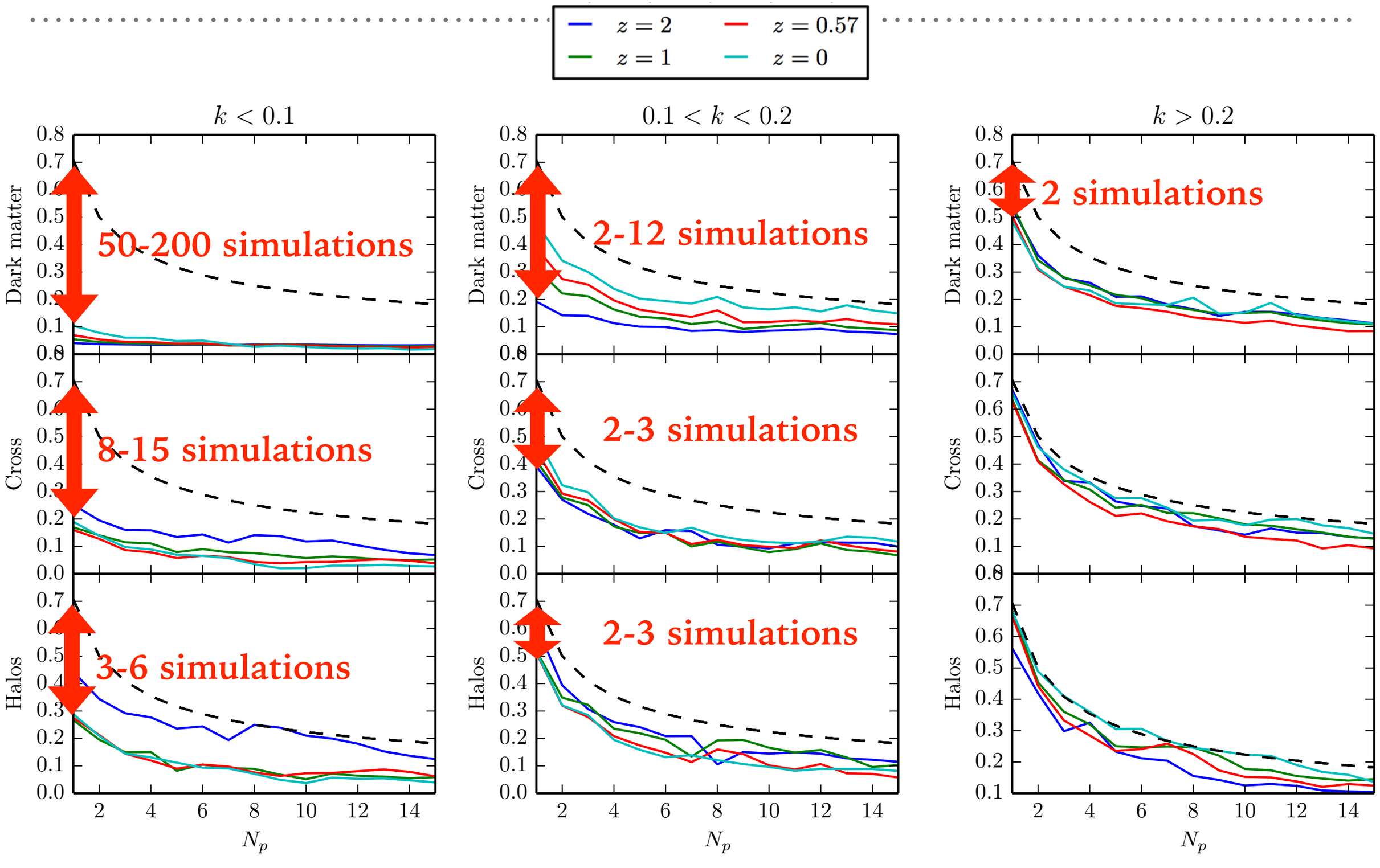
$\tilde{P}(k)_{\text{corr},2} - \langle \tilde{P}(k) \rangle$ $\quad$ is fourth order in δ

PAIRED AND FIXED SIMULATIONS – ERROR



Blot, Crocce, Sanchez, dalla Vecchia, in prep.

PAIRED AND FIXED SIMULATIONS – ERROR



Blot, Crocce, Sanchez, dalla Vecchia, in prep.

APPROXIMATE METHODS FOR COVARIANCE ESTIMATION

$$\mathrm{cov}(k_1, k_2) = \frac{2}{N_{k_1}} P^2(k_1)\delta_{k_1,k_2} + \frac{1}{V}\int_{\Delta_{k_1}}\int_{\Delta_{k_2}} \frac{d^3\mathbf{k_1'}}{V_{k_1}}\frac{d^3\mathbf{k_2'}}{V_{k_2}} T(\mathbf{k_1'}, -\mathbf{k_1'}, \mathbf{k_2'}, -\mathbf{k_2'})$$

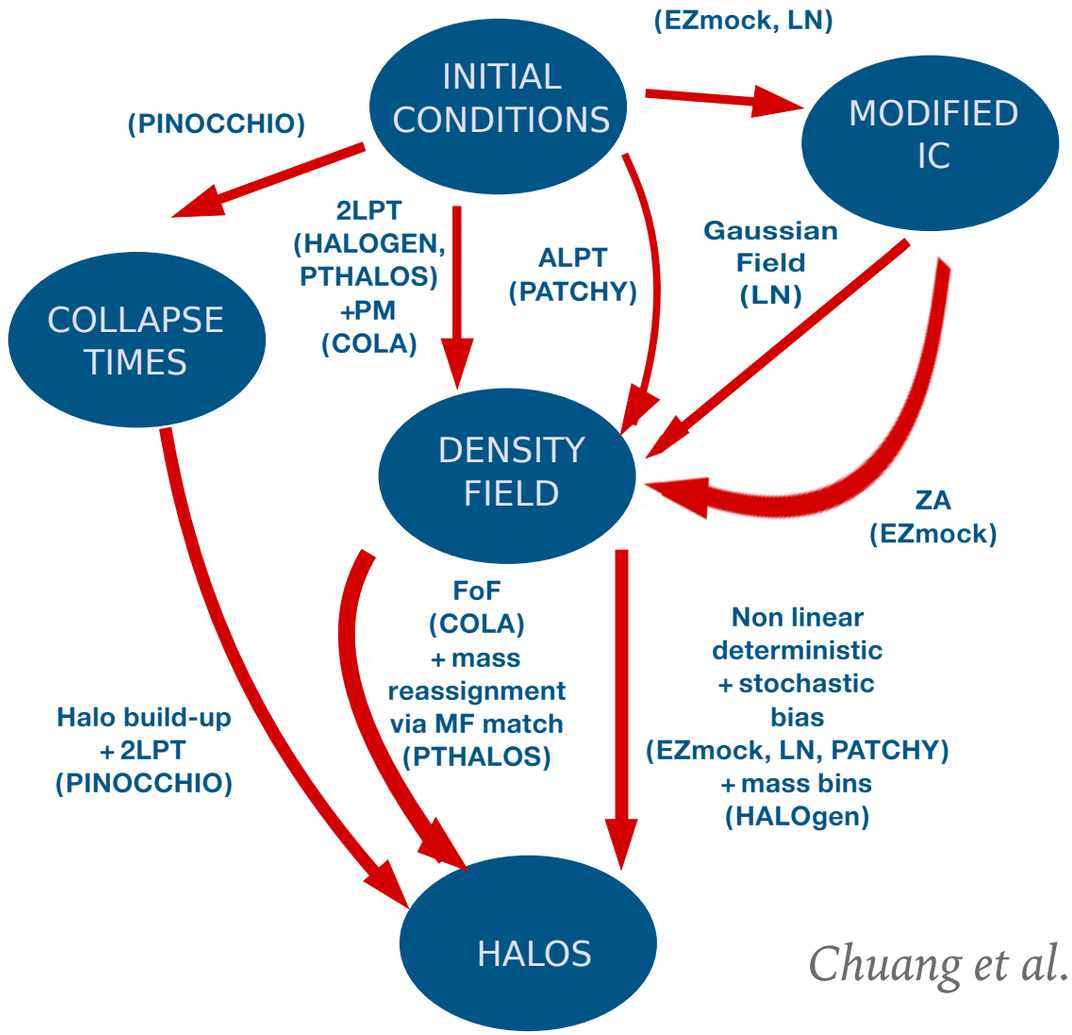
- Sample covariance estimator

$$\widehat{\mathrm{cov}}(k_1, k_2) = \frac{1}{N_s - 1}\sum_{i=1}^{N_s}[\hat{P}_i(k_1) - \bar{P}(k_1)][\hat{P}_i(k_2) - \bar{P}(k_2)]$$

- Additional error on parameters coming from covariance error
- Need a few 1000s simulations to reduce this error to acceptable levels for future surveys
- Not possible with full N-body simulations (too costly)

APPROXIMATE METHODS FOR COVARIANCE ESTIMATION

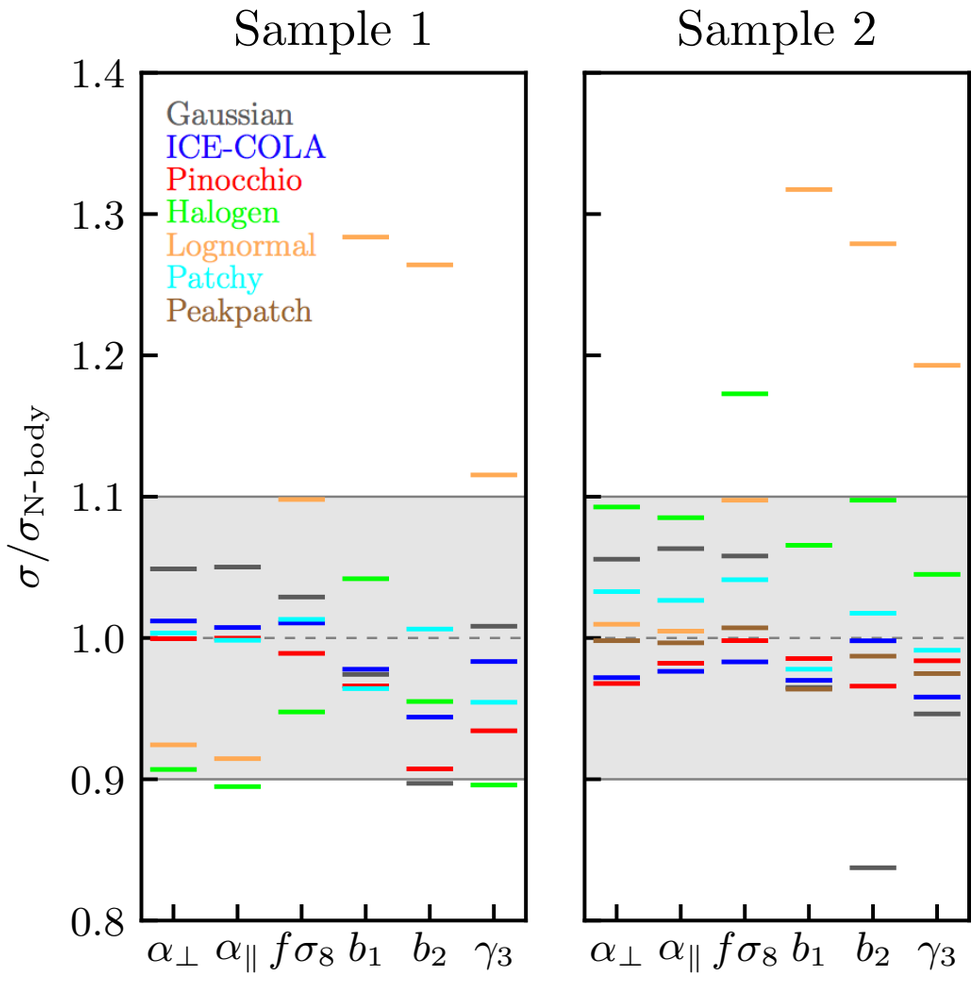
- PM-based methods: COLA, FastPM, QPM…
- LPT-based methods: Pinocchio, PeakPatch, Patchy, …

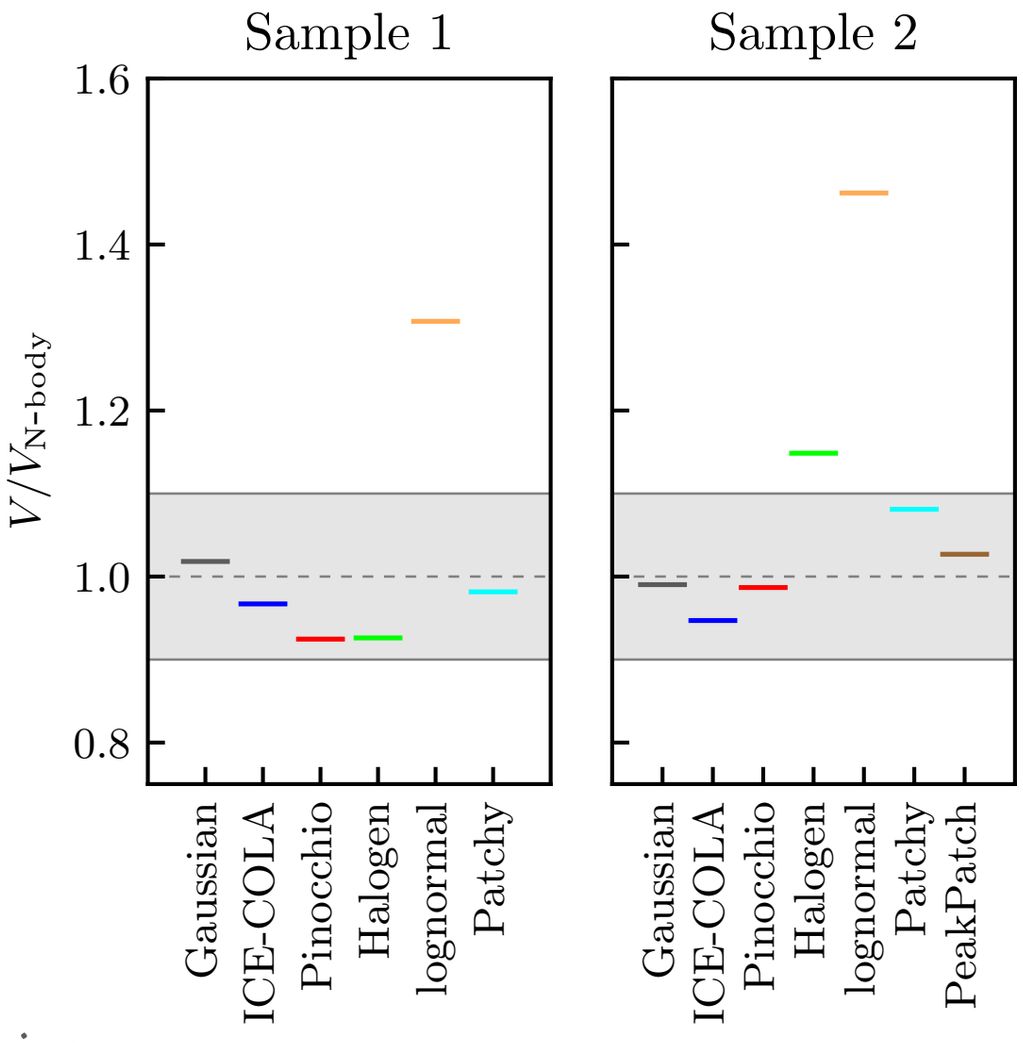


Chuang et al. 2015

APPROXIMATE METHODS FOR COVARIANCE ESTIMATION

Method	$\bar{n}_{halos}$ $(h^3\mathrm{Mpc}^{-3})$	M_{min} $(h^{-1}\,\mathrm{M}_\odot)$
	Sample 1	
N-body	2.130×10^{-4}	1.121×10^{13}
ICE-COLA	2.123×10^{-4}	1.086×10^{13}
PINOCCHIO	2.148×10^{-4}	1.044×10^{13}
HALOGEN	2.138×10^{-4}	1.121×10^{13}
Lognormal	2.131×10^{-4}	1.121×10^{13}
PATCHY	2.129×10^{-4}	1.121×10^{13}
	Sample 2	
N-body	5.441×10^{-5}	2.670×10^{13}
ICE-COLA	5.455×10^{-5}	2.767×10^{13}
PINOCCHIO	5.478×10^{-5}	2.631×10^{13}
HALOGEN	5.393×10^{-5}	2.670×10^{13}
Lognormal	5.441×10^{-5}	2.670×10^{13}
PATCHY	5.440×10^{-5}	2.670×10^{13}
PEAKPATCH	5.439×10^{-5}	2.355×10^{13}





Blot et al. in prep.

SUMMARY

- Simulations are fundamental for the cosmological analysis of galaxy survey data
- Main issue: computational cost
- Possible solutions
  - technique to reduce sample variance in the signal
  - approximate methods for covariance estimation