Constraining features in the Early Universe with the large-scale structure

L'Huillier, Shafieloo, Hazra, Smoot, Starobinsky MNRAS 477, 2503 (2018)

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Outline

1. Introduction
2. Models and simulations
3. Results
4. Summary

Concordance model of cosmology

Hypotheses

- Gravity described by General Relativity
- Isotropy and homogeneity
- Inflation in the early Universe, power-law primordial power spectrum

The concordance ΛCDM model

- Solution of the Einstein equations: FLRW metric
- The Universe is flat
- Universe dominated by dark energy (Λ) and cold dark matter (CDM)
- Big bang theory observationally supported:
  - Cosmological Microwave Background
  - Expansion of the Universe
  - Large-scale structures
  - ...

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Planck 2015 cosmology

Parameter	TT+lowP	TT+lowP+lensing	TT+lowP+BAO	TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02226 ± 0.00020	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1190 ± 0.0013	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04095 ± 0.00041	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.066 ± 0.016	0.080 ± 0.017	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.093 ± 0.034	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9673 ± 0.0045	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.81 ± 0.92	67.63 ± 0.57	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3104 ± 0.0076	0.3156 ± 0.0091

- Precision cosmology

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- Precision cosmology
- *But this is model-dependent*: What if the primordial power spectrum is *not* a power law?

Planck **2018** cosmology

Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10}A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

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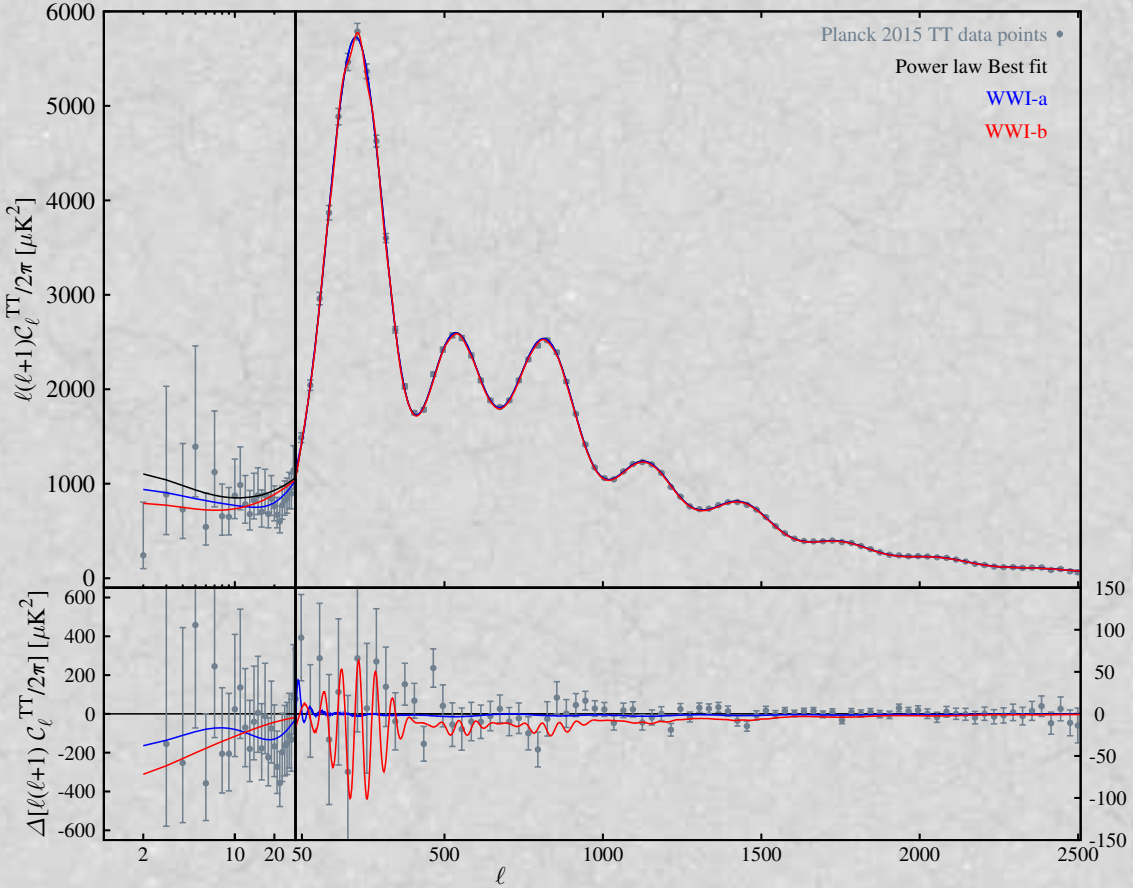
Wiggly-whipped inflation

Hazra, Shafieloo, Smoot & Starobinsky (2014ab, 2016)



- Step in the potential → wiggles in the power spectrum
- Better fit than power law
- at the expense of (a few) extra parameters

- CMB alone cannot distinguish the model
- 2D (CMB) → 3D (LSS)
- Can we use the LSS to distinguish these models?

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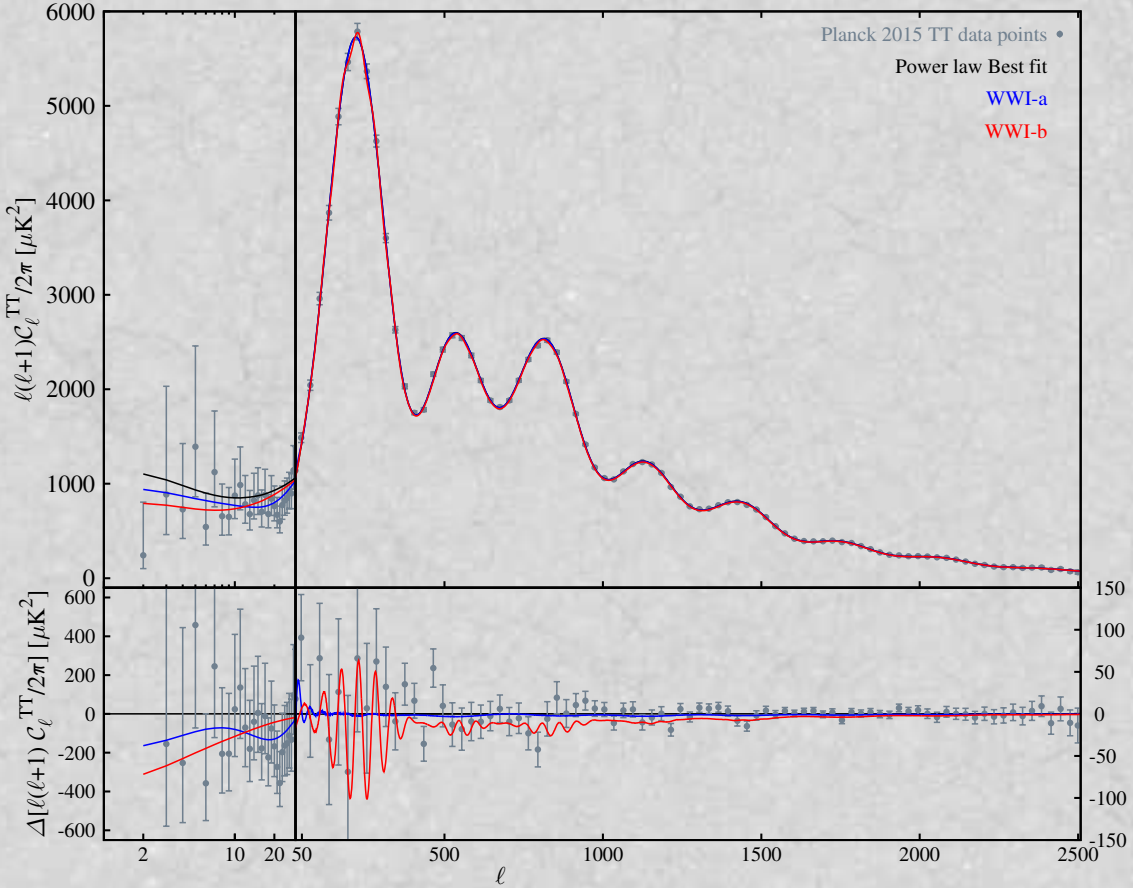

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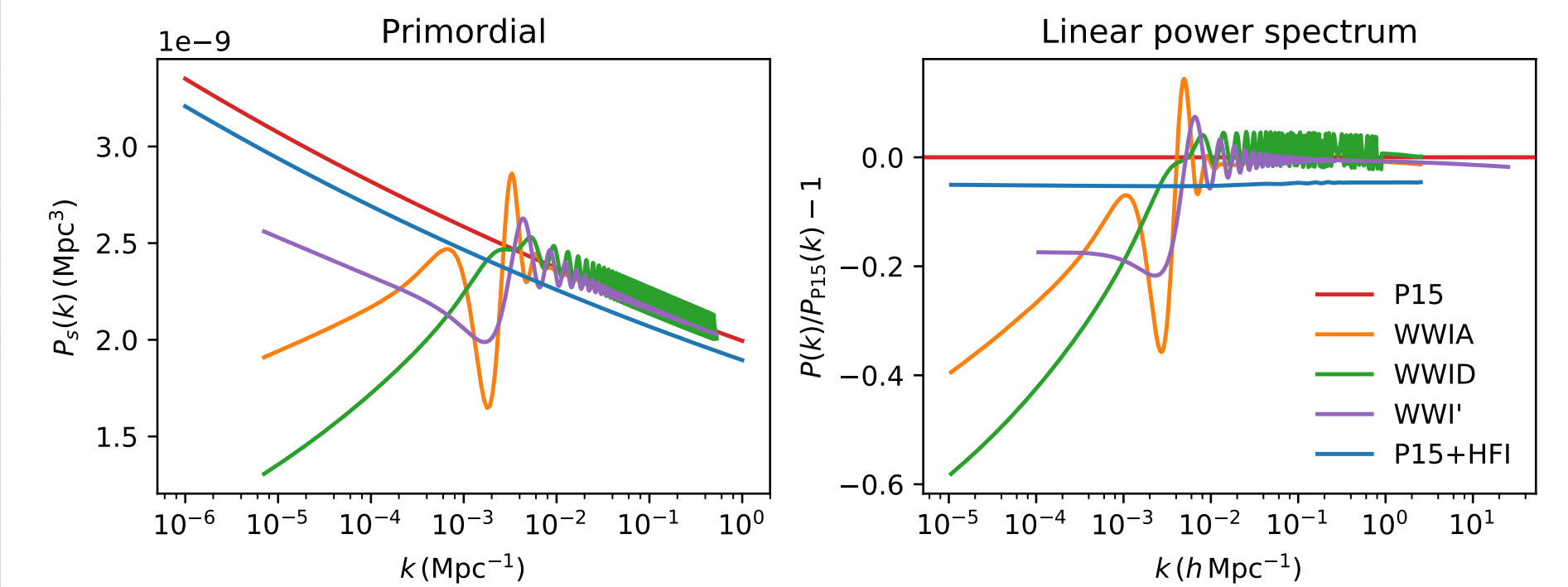
Primordial power spectrum



- Reference model: Planck 2015 TTTEEE (P15)
- Wiggly-whipped inflation (Hazra et al. 2014ab, 2016): WWIA, WWID, WWI'
- Planck 2015 TTTEEE+HFI (P15+HFI)
- The WWI models give better fit to the CMB data than power law: indistinguishable
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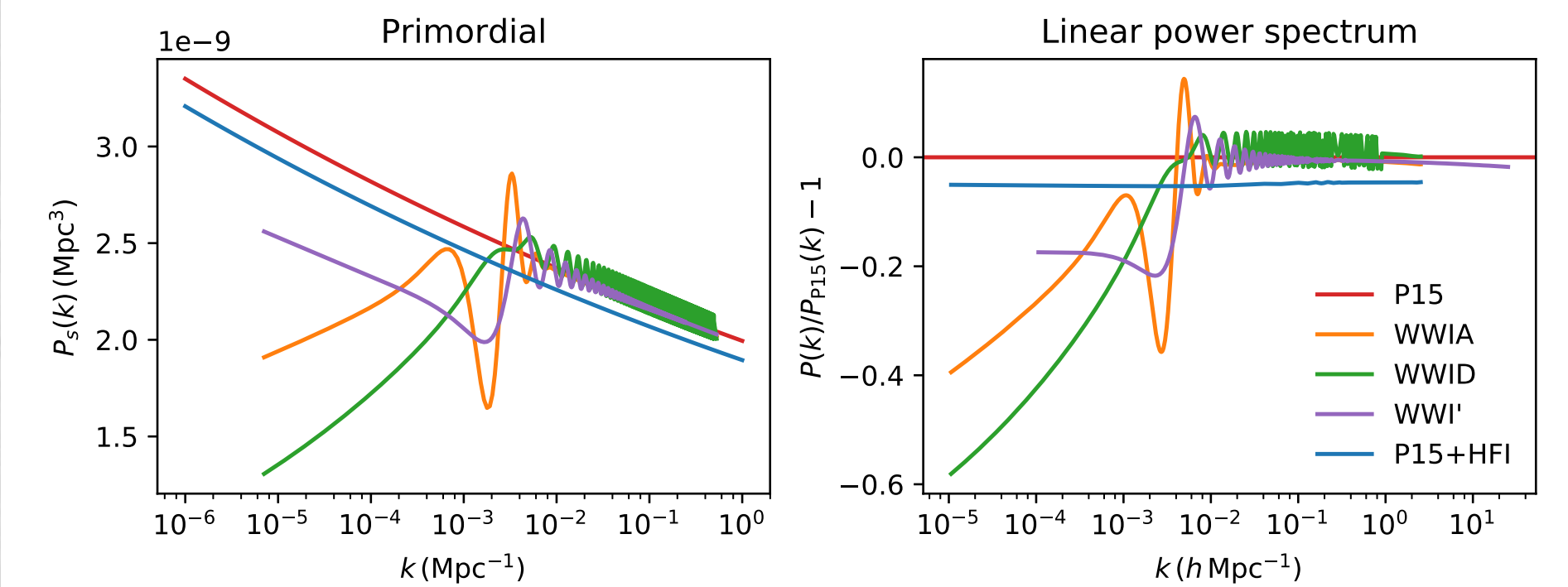
Primordial power spectrum



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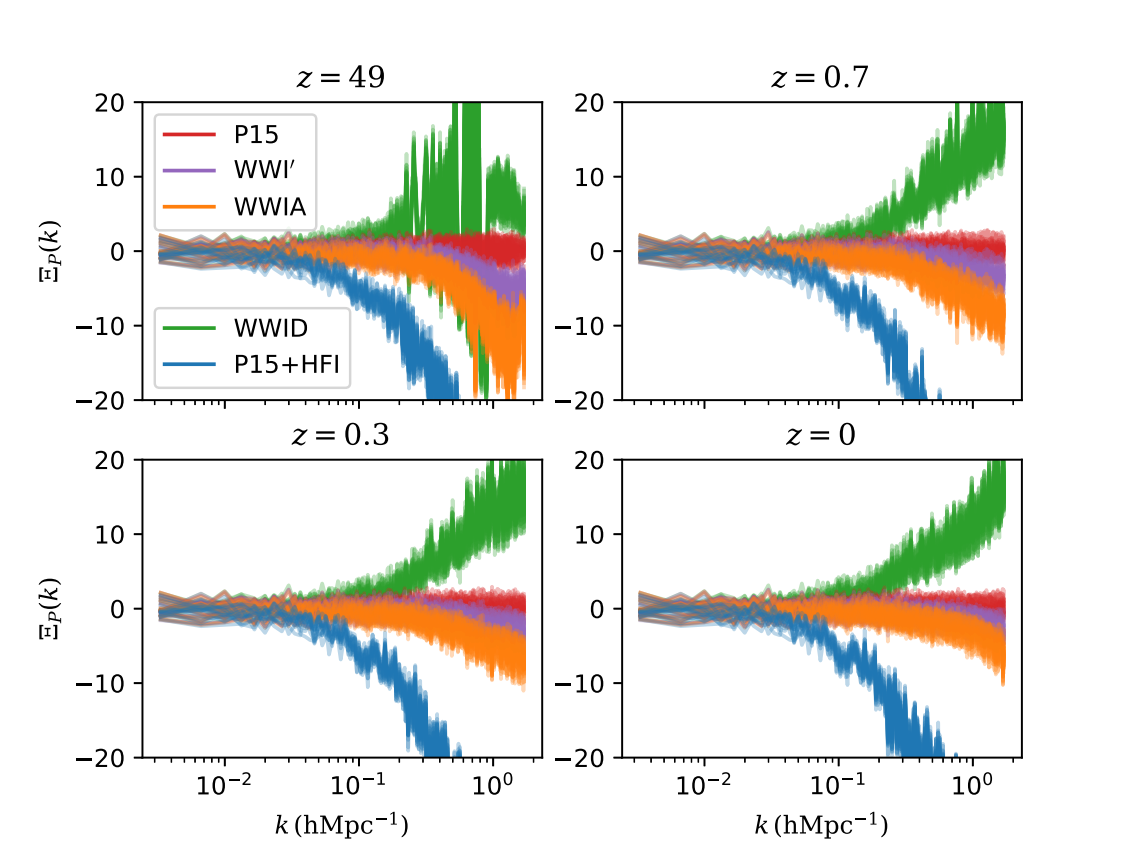
The simulations

- N-body simulations with GADGET-2 Springel 2005
- 5 models $\times$ 15 random realizations
- Volume: $L = 1.89\,h^{-1}\mathrm{Gpc}$, $N = 1024^3$ (DESI survey)

Model	Ω_m	H_0 (km s^{-1} Mpc^{-1})	σ_8	n_s
P15	0.317	67.05	0.836	0.9625
WWIA	0.320	66.86	0.834	-
WWID	0.318	67.01	0.842	-
WWI'	0.317	67.04	0.834	-
P15+HFI	0.319	66.93	0.816	0.9619

Matter power spectrum

L'Huillier et al. (2018)



Normalized difference:

$$\Xi(k) = \frac{(P(k) - \langle P_{\mathrm{P15}}(k)\rangle)}{\sigma_P(k)}$$

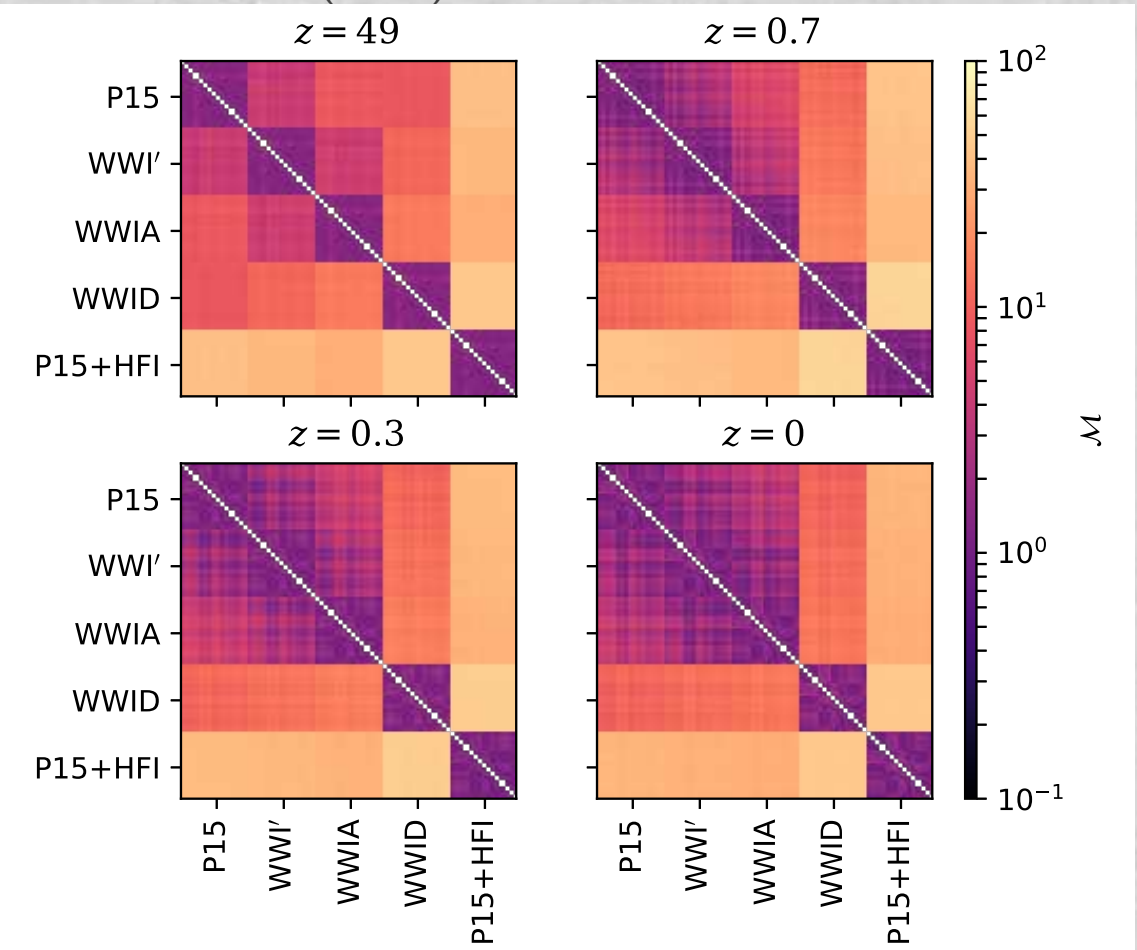
$$\delta(\mathbf{x}) = (\rho(\mathbf{x}) - \bar{\rho})/\bar{\rho},$$

$$P(k) = \frac{1}{V}\left\langle |\delta(\mathbf{k})|^2 \right\rangle_{|\mathbf{k}|=k}.$$

- Power spectrum calculated by ComputePk (L'Huillier 2014)
- Features vanish in the non-linear regime.
- WWID and P15+HFI can be distinguished, but not WWIA, WWID and P15

Separability Matrix

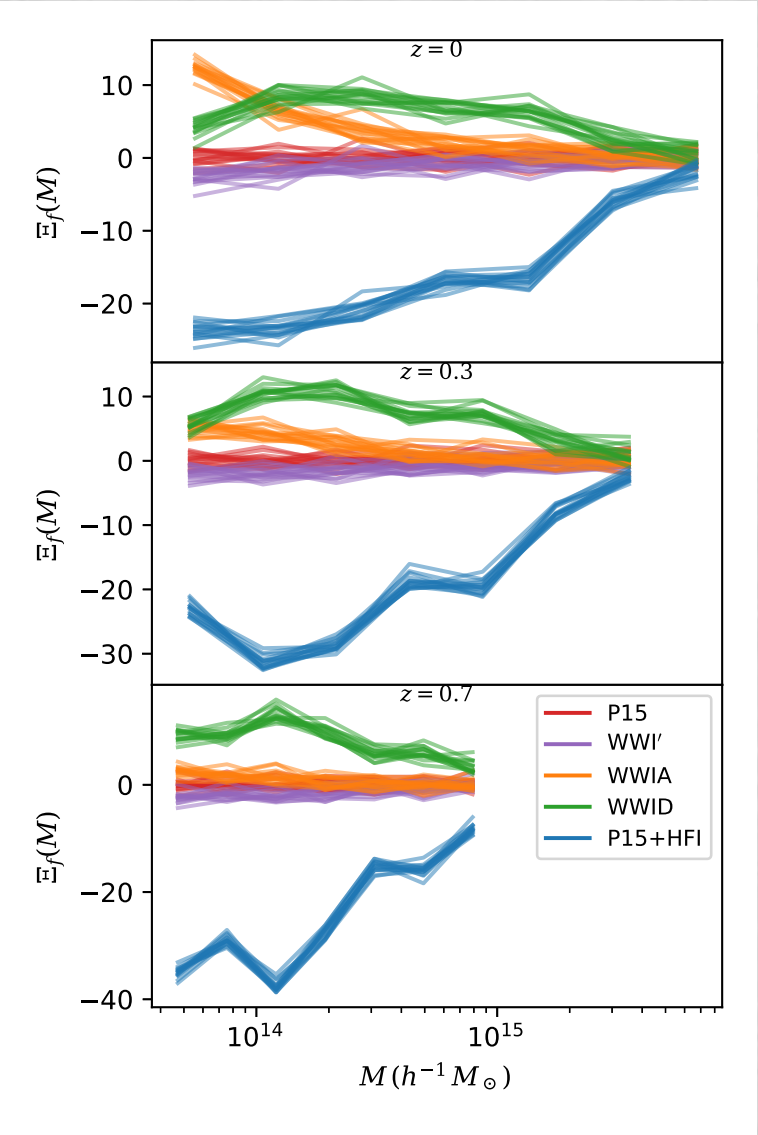
L'Huillier et al. (2018)

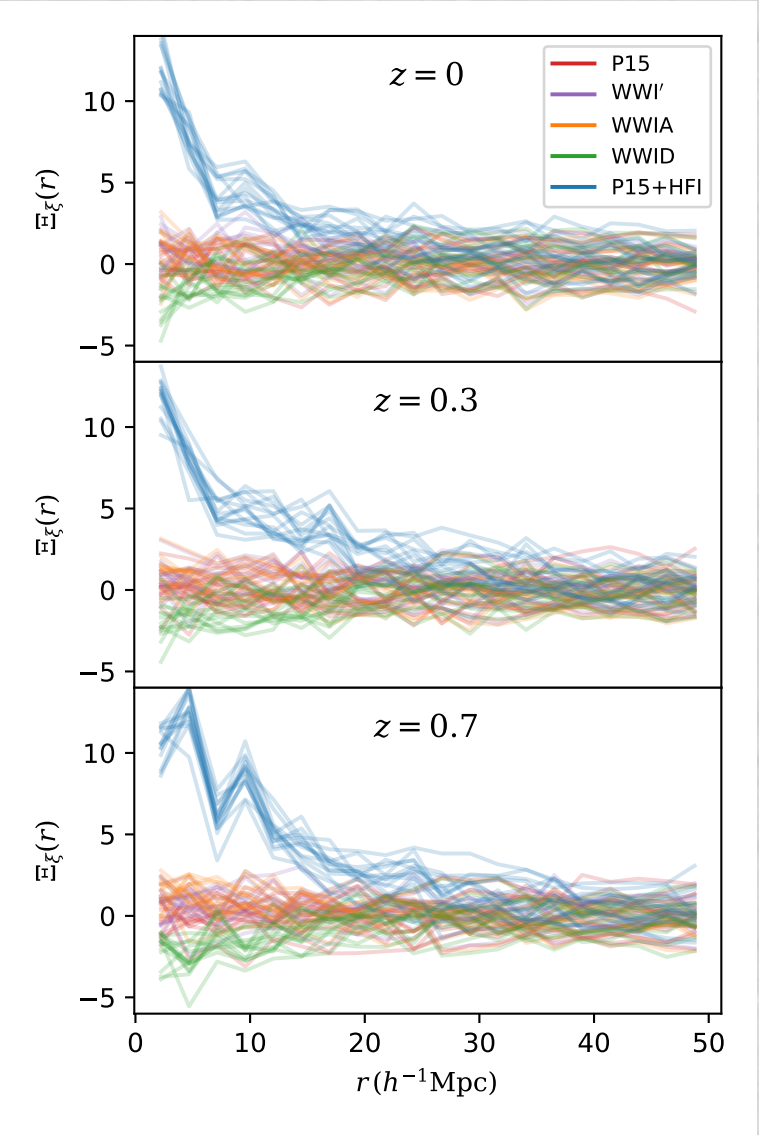


- Separability Matrix M: r.m.s. of the normalized difference between two simulations: 75×75 matrix
- At $z = 49$: all all models well distinguished
- By $z = 0$: WWID and P15+HFI well distinguished, but P15, WWI′, WWIA are not

$$M_{P,i,j}(k) = \sqrt{\frac{1}{N_k} \sum_k \left(\frac{P_i(k) - P_j(k)}{\sigma_P(k)} \right)^2}$$

Haloes: mass and correlation functions

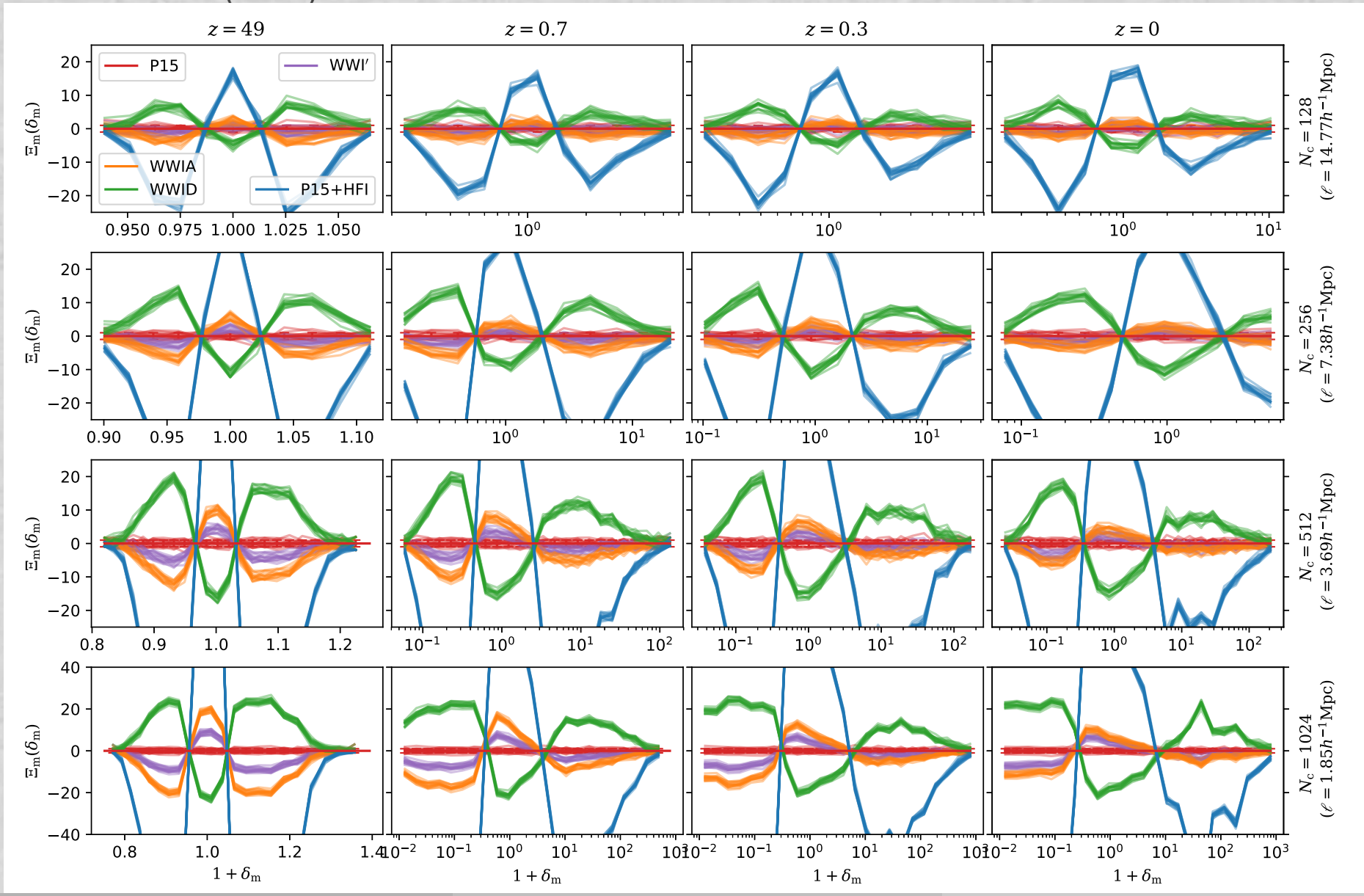




No extra information

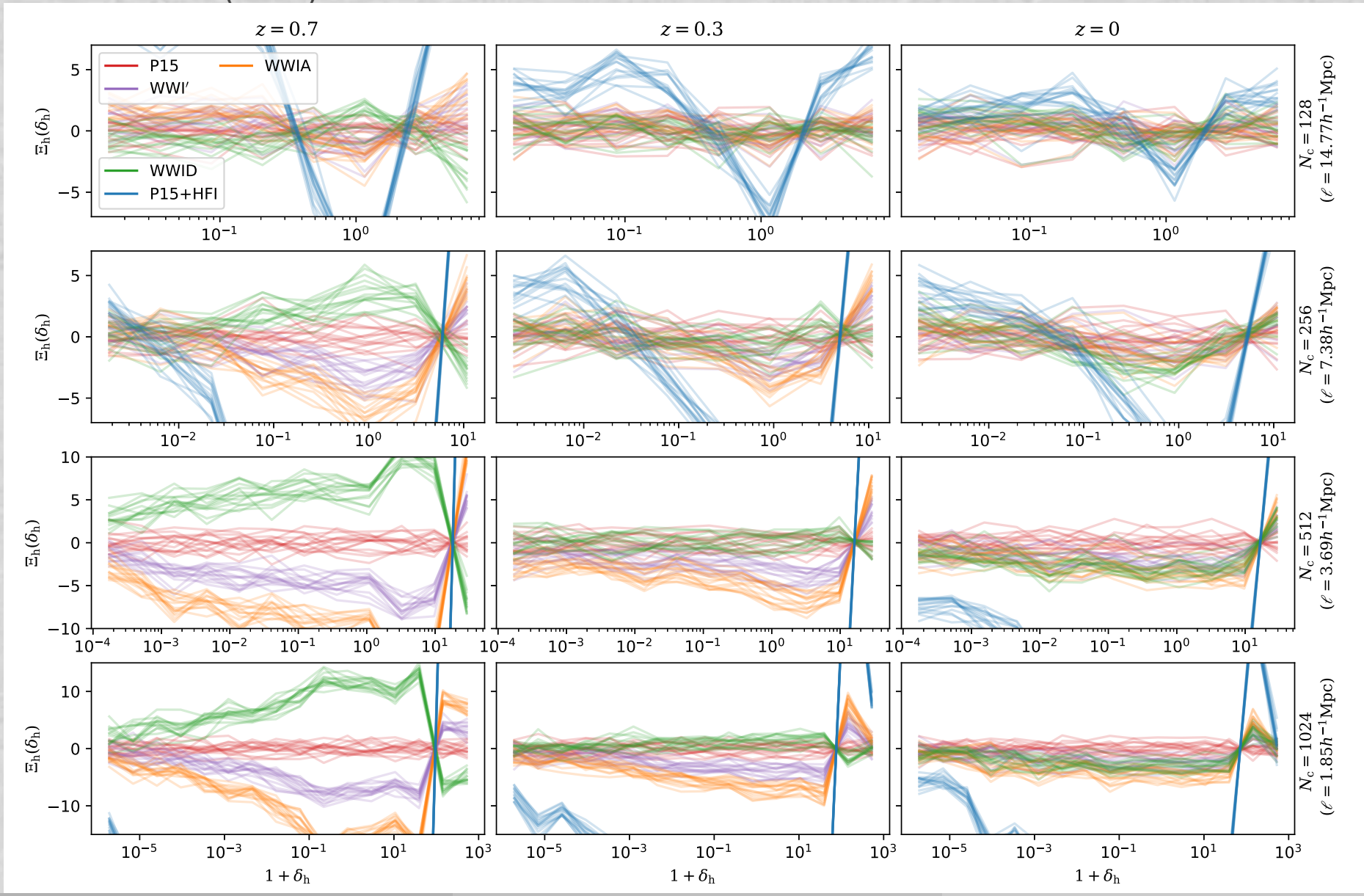
Matter density

L'Huillier et al. (2018)

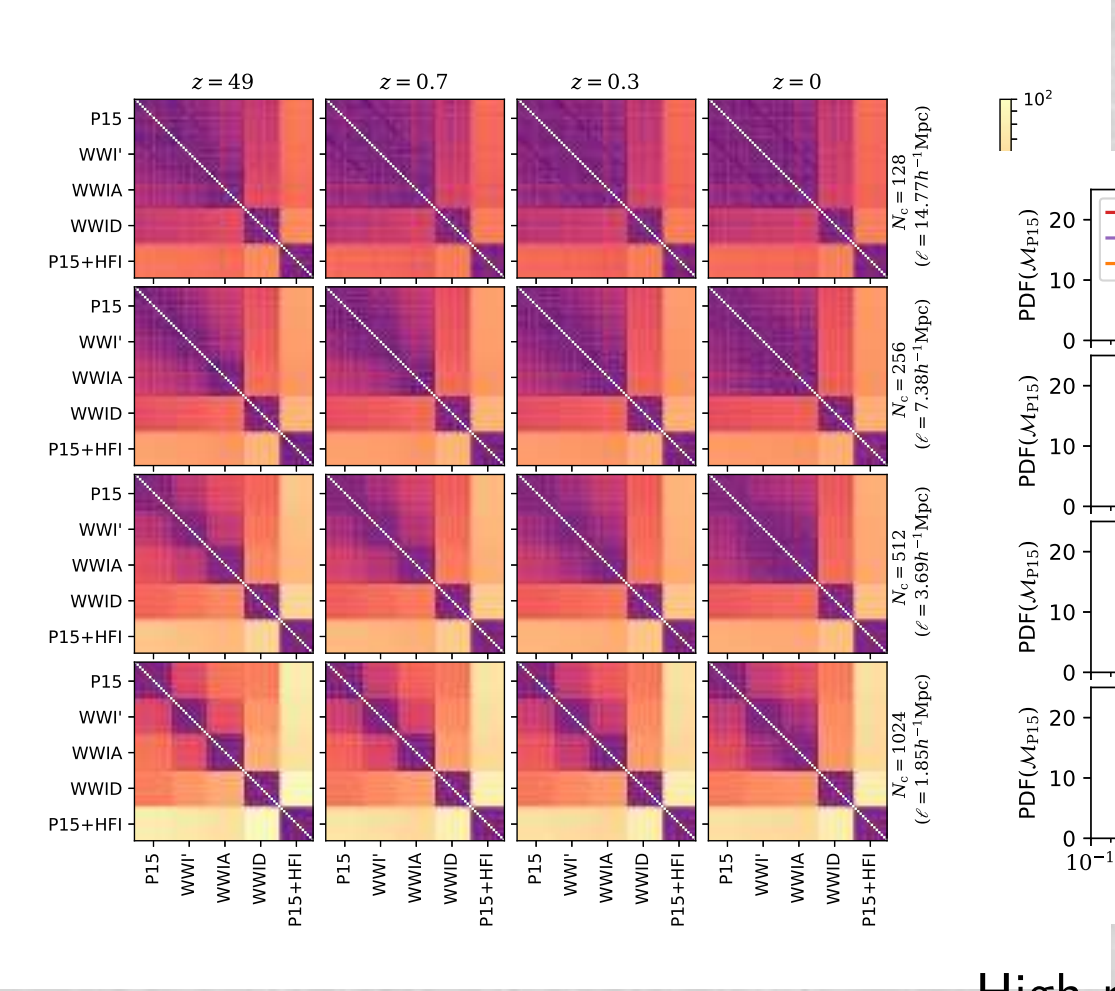


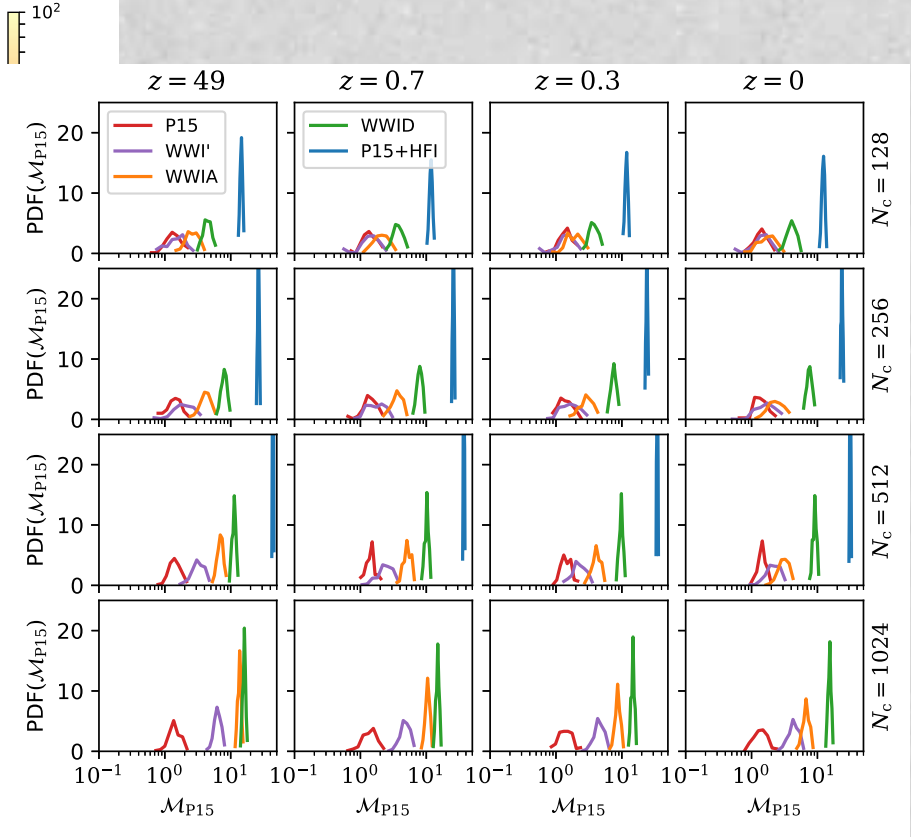
Halo mass density

L'Huillier et al. (2018)



Separability by count-in-cells





Separability matrix: can distinguish between models for high resolution and $z \geq 0.3$

High-resolution: Red distribution doesn't overlap with the others

Summary

- Degeneracy in the CMB: non-power law models can exist
- Can the LSS break the degeneracy?
- Power spectrum: reduces the dimension $\rightarrow$ loss of information
  - Power spectrum normalization: still degeneracy (WWIA, WWI')
  - Halo mass and correlation functions: not helpful
  - Count-in-cell: the difference in the density PDF (large number of pixels)
  - Still holds for biased tracers at $z \simeq 0.7$
  - Euclid, LSST will probe these scales
  - Baryons?

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감사합니다!

ありがとうございました!