Constraining the early Universe with the large-scale structure

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CosKASI
Cosmology Group at
Korea Astronomy and Space Science Institute

Outline

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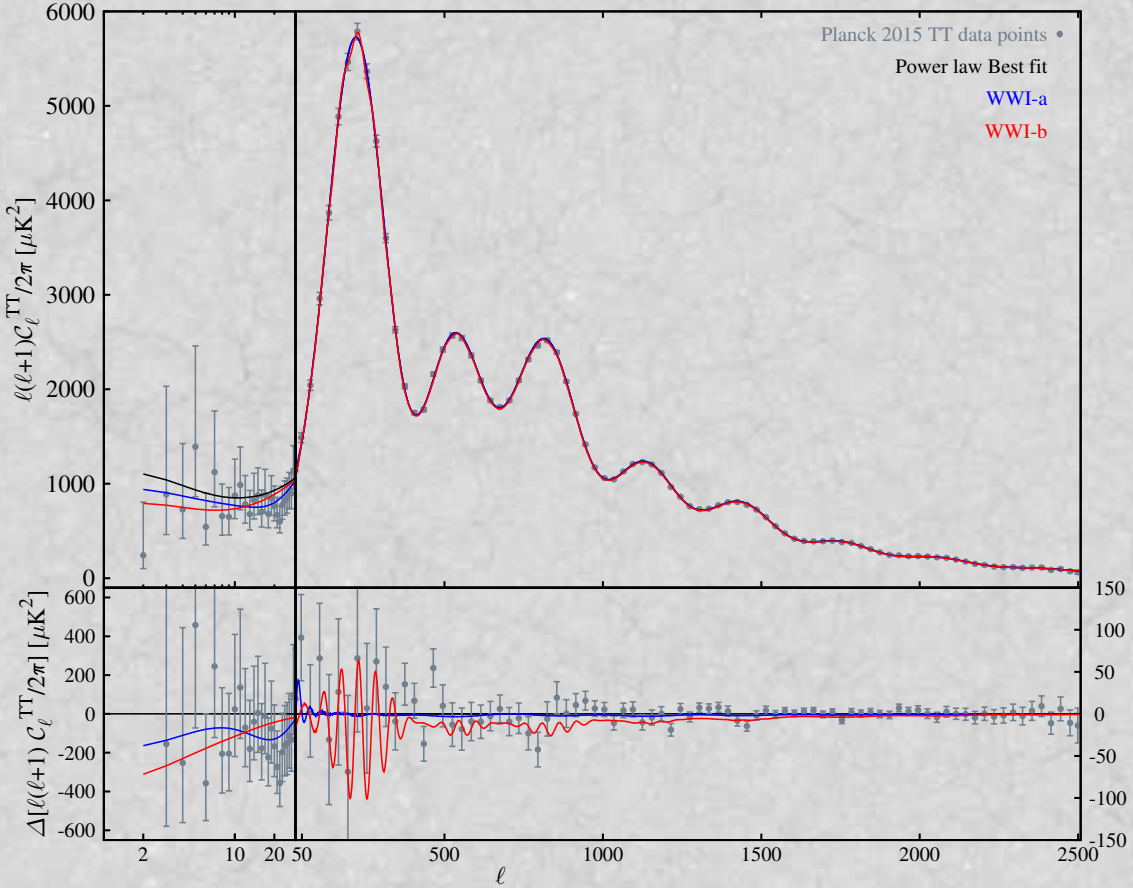
- Precision cosmology
- *But this is model-dependent*: What if the primordial power spectrum is *not* a power law?

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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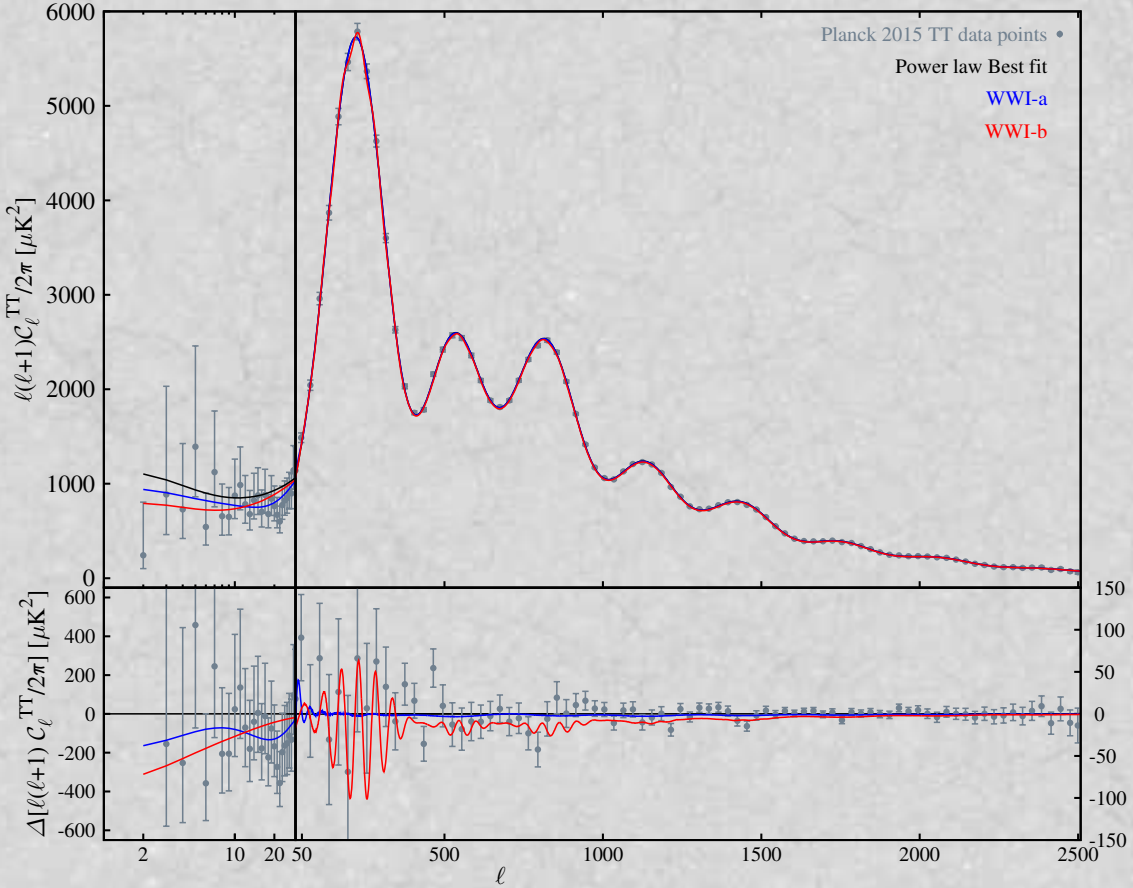

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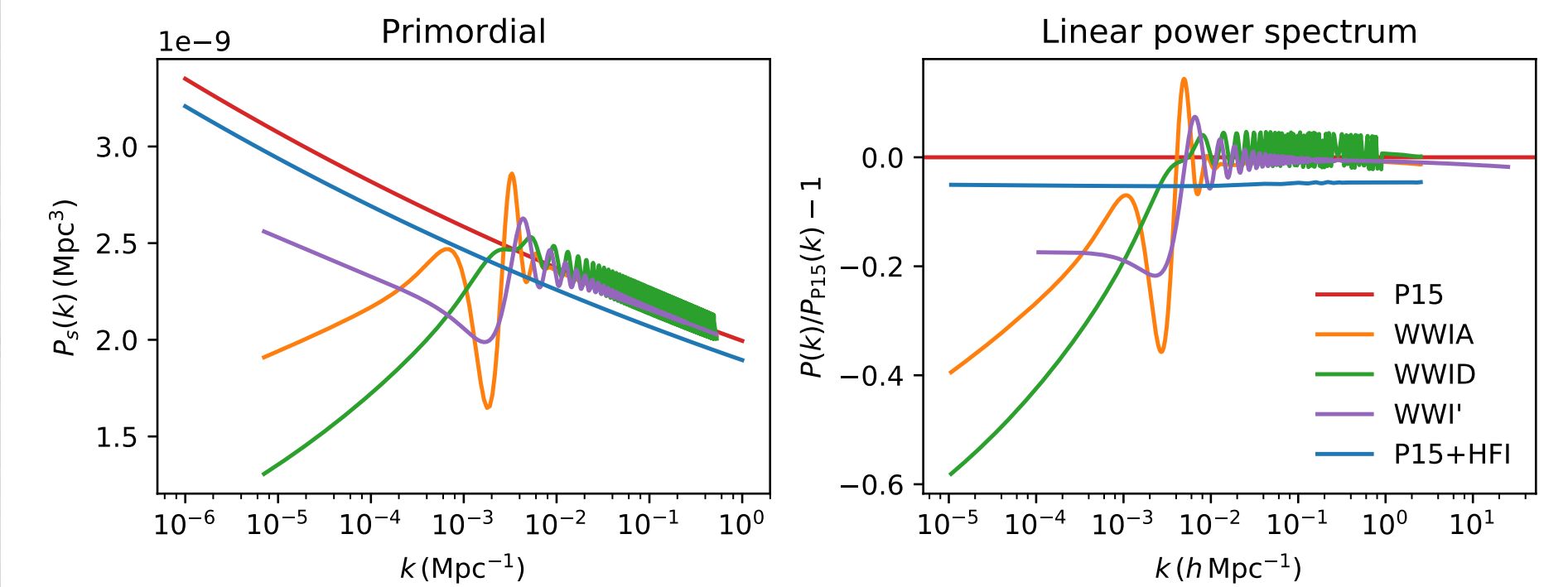
Primordial power spectrum



- 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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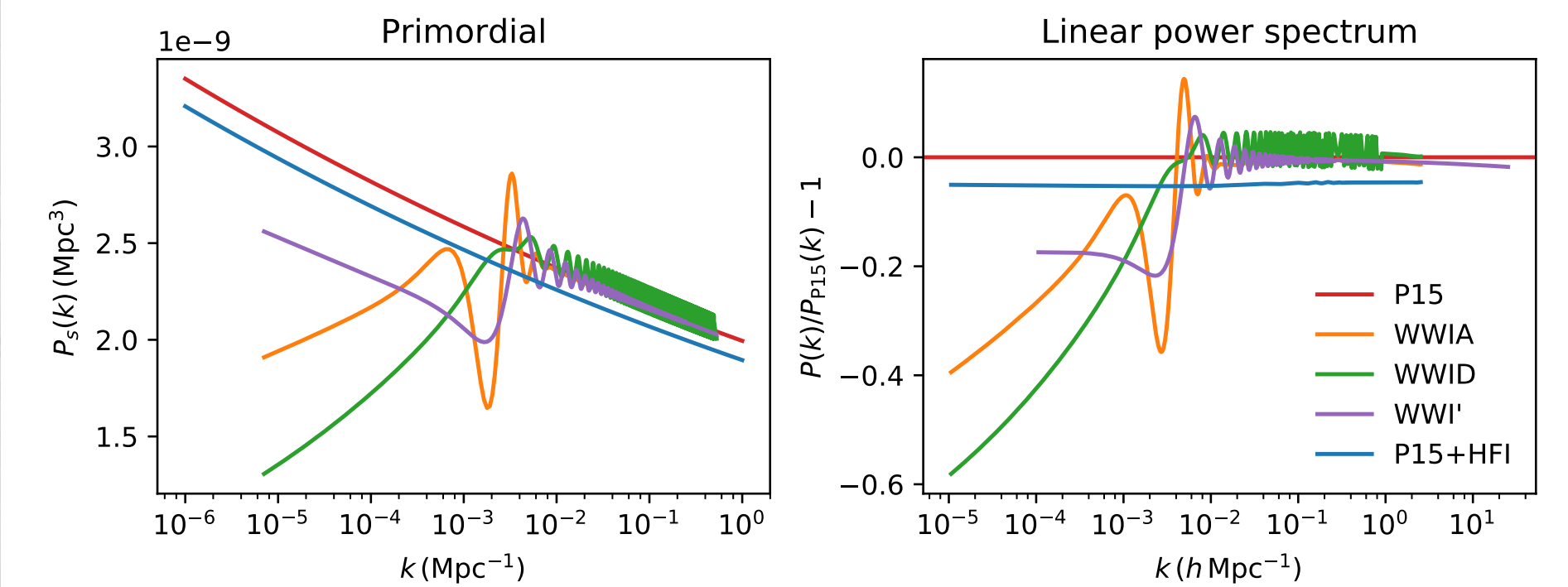
Primordial power spectrum



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The simulations

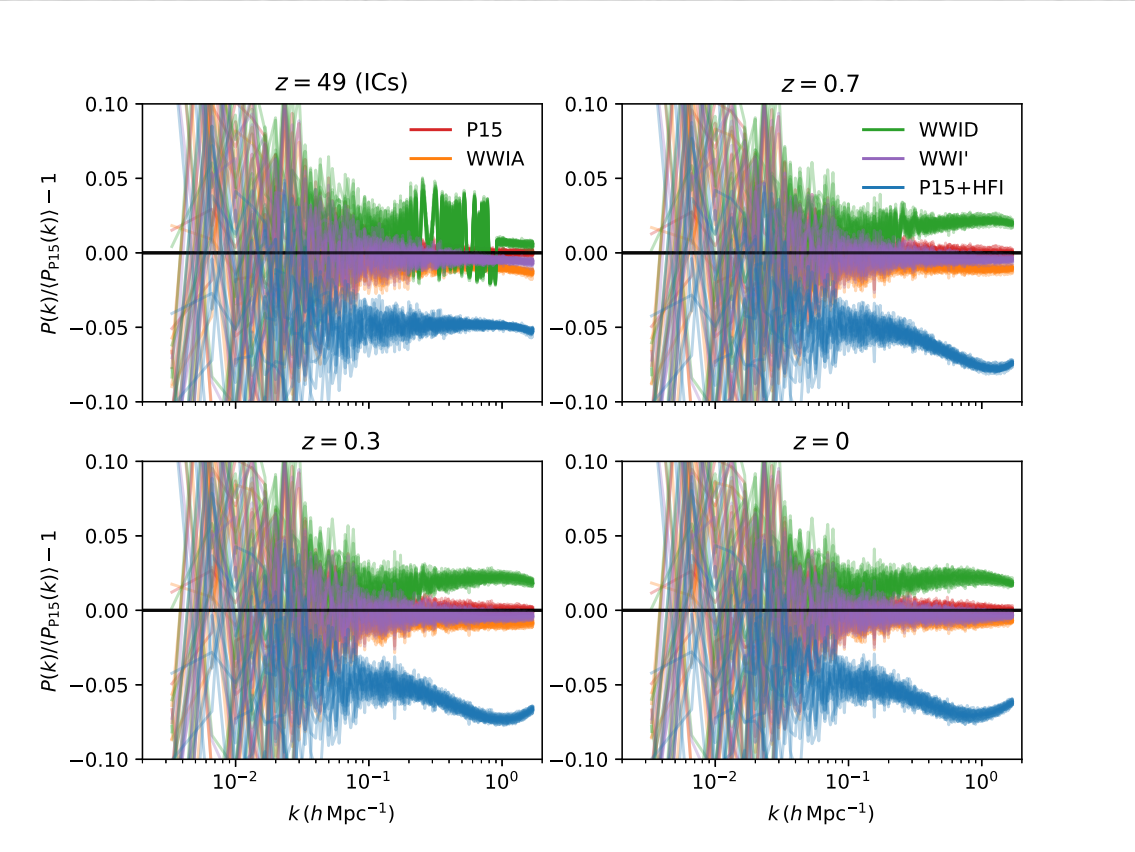
- N-body simulations with GADGET-2 Springel 2005
- 5 models $\times$ 15 random realizations
- Volume: $L = 1.89\,h^{-1}\mathrm{Gpc}$, $N = 1024^3$ (DESI survey)

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

Outline

Matter power spectrum

L'Huillier et al. (2017, in prep.)



Relative difference $P(k)/\langle P_{\mathrm{P15}}(k)\rangle - 1$

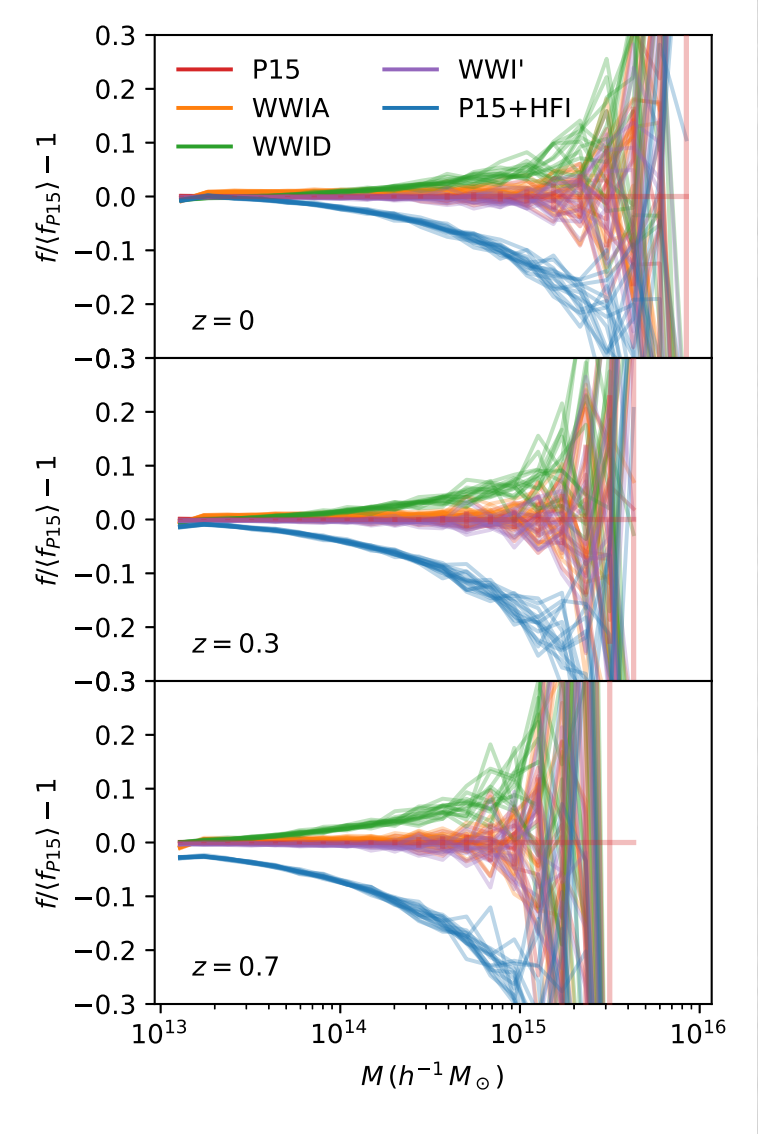
$$\delta(\mathbf{x}) = (\rho(\mathbf{x}) - \bar{\rho})/\bar{\rho},$$

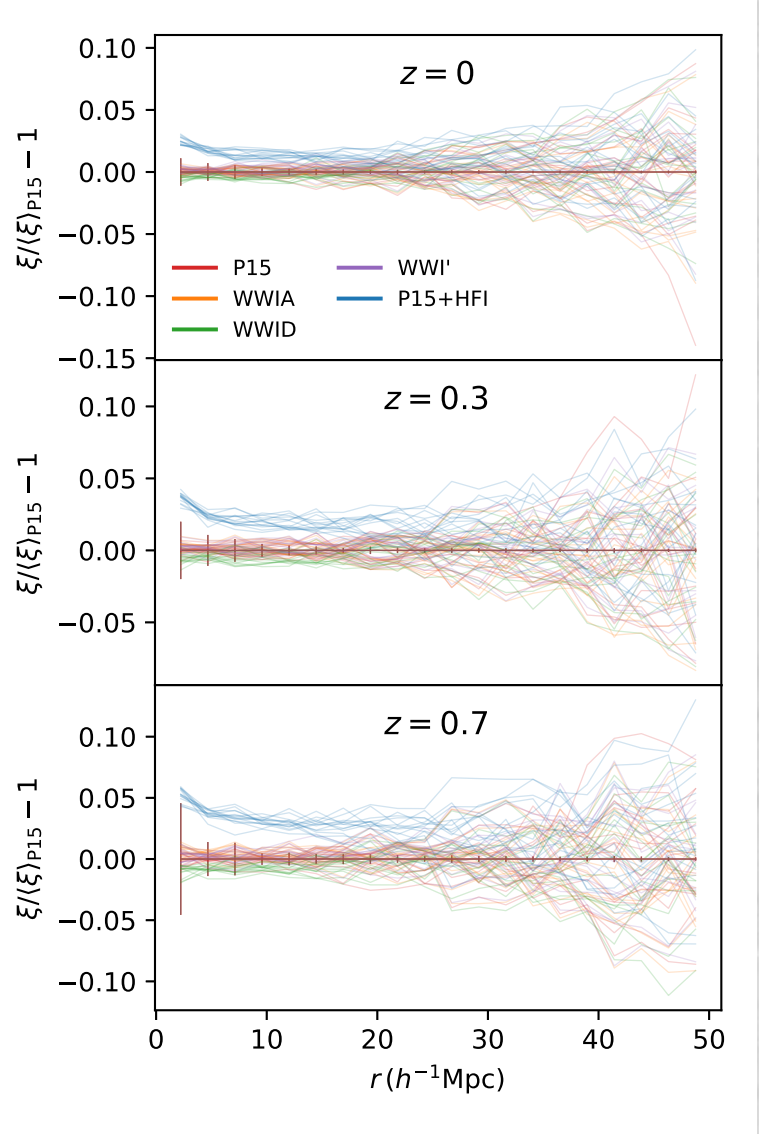
$$P(k) = \frac{1}{V}\left\langle |\delta(\mathbf{k})|^2 \right\rangle_{|\mathbf{k}|=k}.$$

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

Haloes: mass and correlation functions

L'Huillier et al. (2017, in prep.)

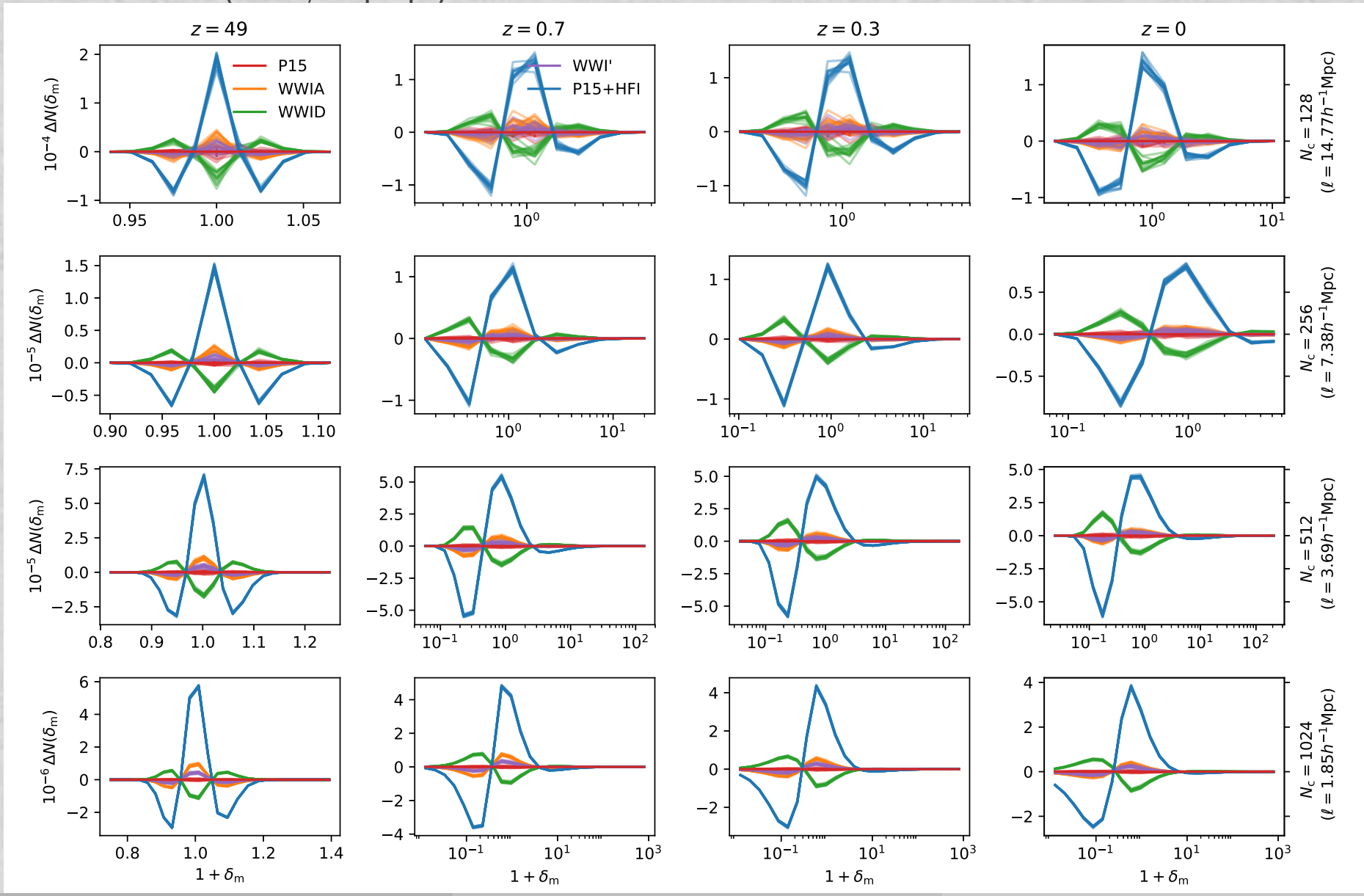




No extra information

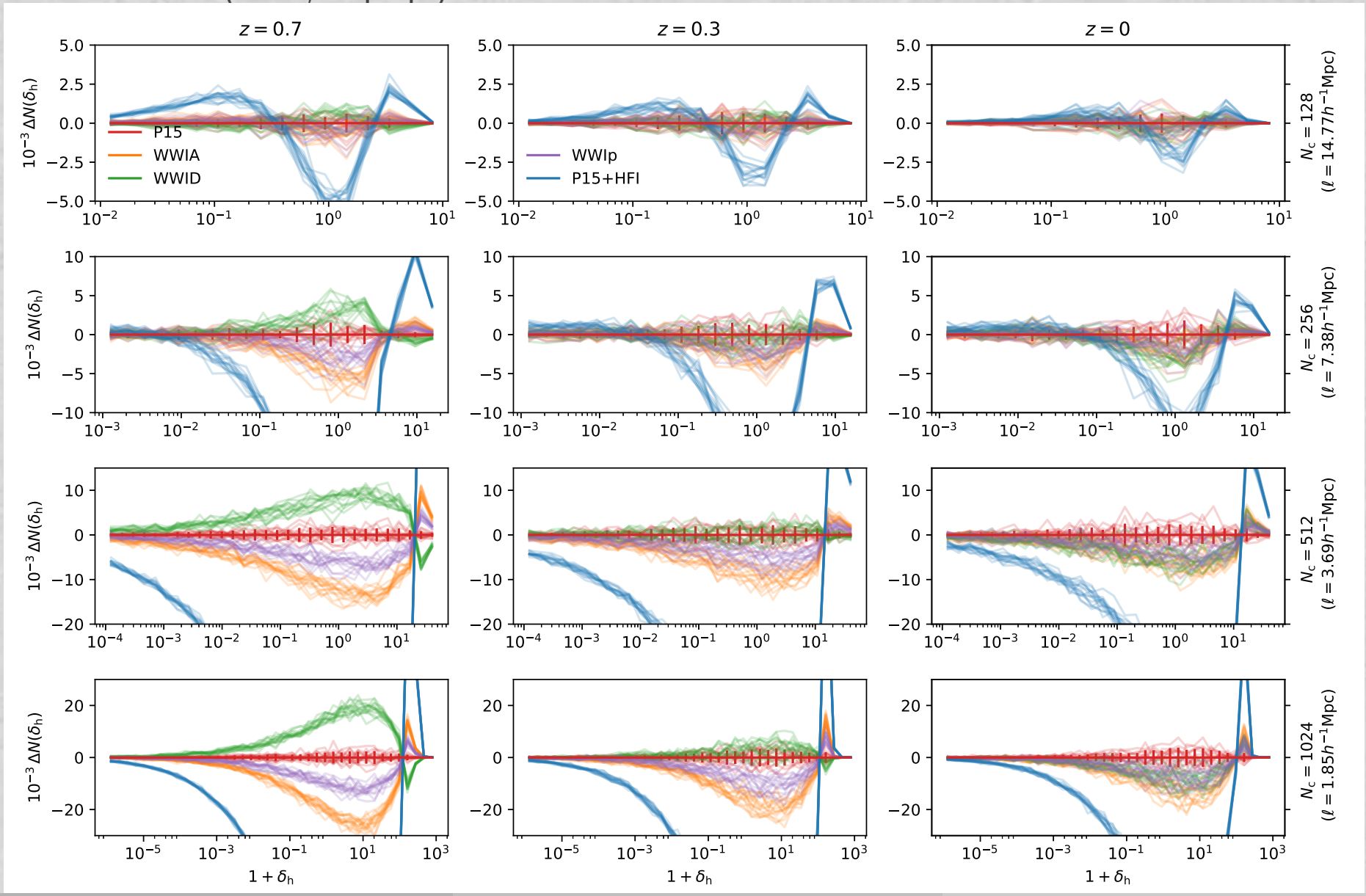
Matter density

L'Huillier et al. (2017, in prep.)



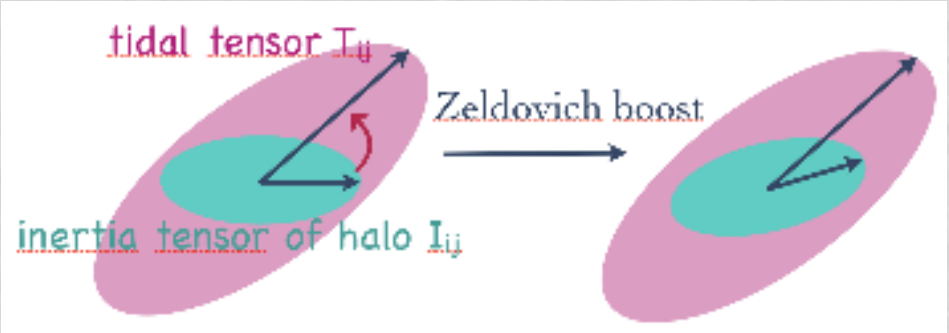
Halo mass density

L'Huillier et al. (2017, in prep.)



Outline

How do galaxies get their orientations?



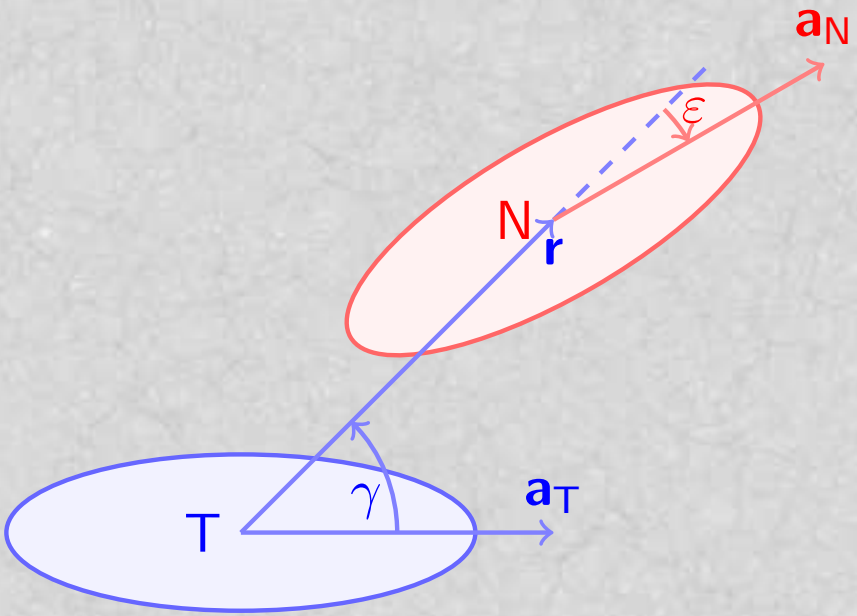
Codis et al. (2015)

Tidal Torque Theory (White 1984)

- Initial angular momentum: misalignment between inertia tensor of the proto-galaxy and the tidal field
- Subsequent evolution: non-linear (mergers). Does it still stand? Not so much (Porciani et al. 2002)

- Studying galaxy orientation is important for understanding their formation
- Intrinsic alignment is a systematic for lensing surveys (EUCLID)
- 2 types of alignments:
  - Large-scale (with the LSS)
  - Small-scale: central-satellite, satellite-satellite

Shape alignment

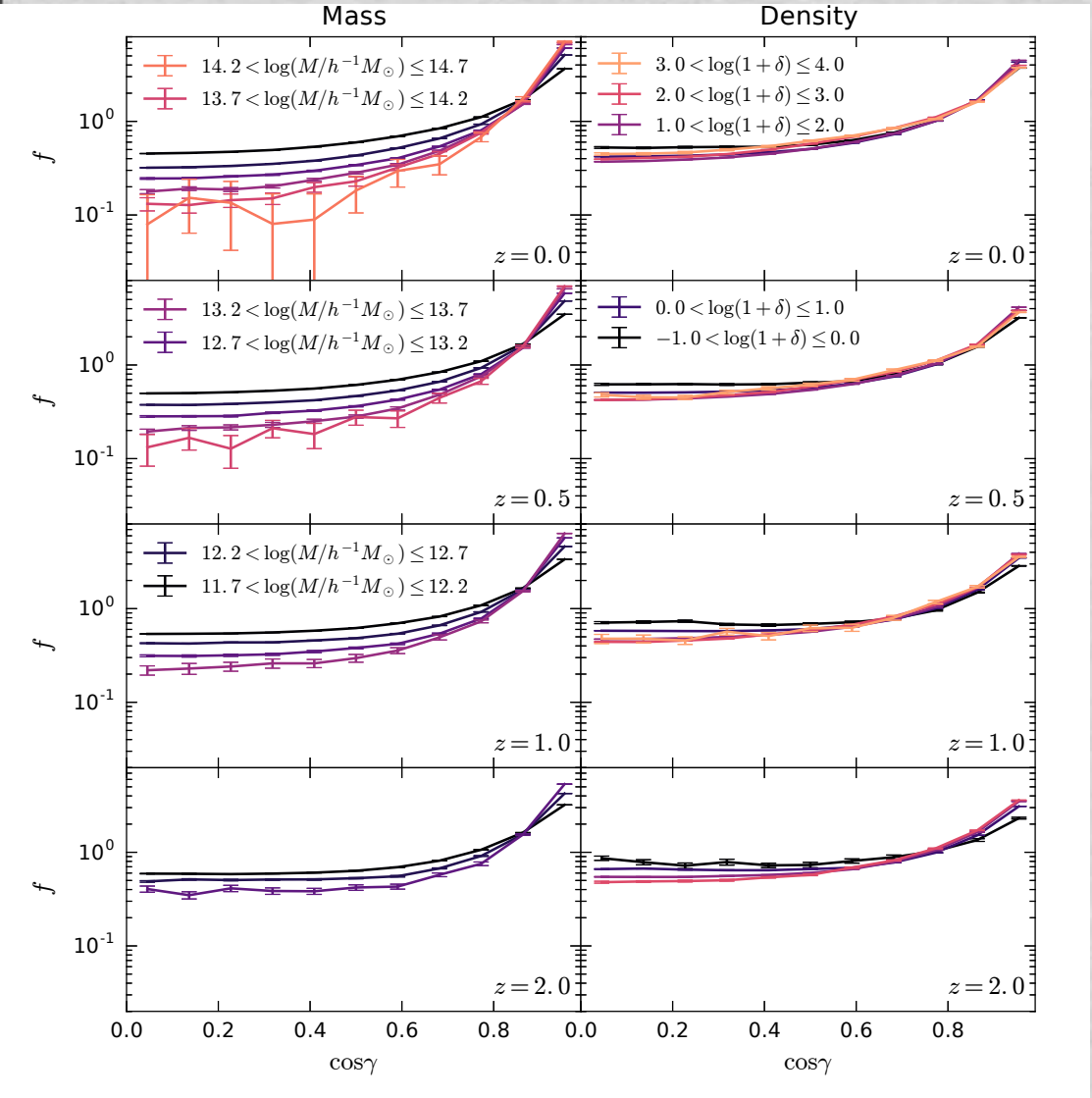


$\gamma = (\mathbf{a}_\mathrm{T}, \mathbf{r})$: angle between major axis (target) and direction neighbour

$\varepsilon = (\mathbf{a}_\mathrm{N}, \mathbf{r})$: angle major between the major axis of the neighbour and the direction of the target

Alignment major axis – neighbour

L'Huillier et al. (2017a) MNRAS 466, 4875



- $\gamma = (\mathbf{a}_\mathrm{T}, \mathbf{r})$
- Position of the neighbour aligned with the major axis of the target
- Alignment increases with mass
- Little dependence on the large-scale density

DM haloes in modified gravity

L'Huillier et al. (2017b) MNRAS 468, 3174

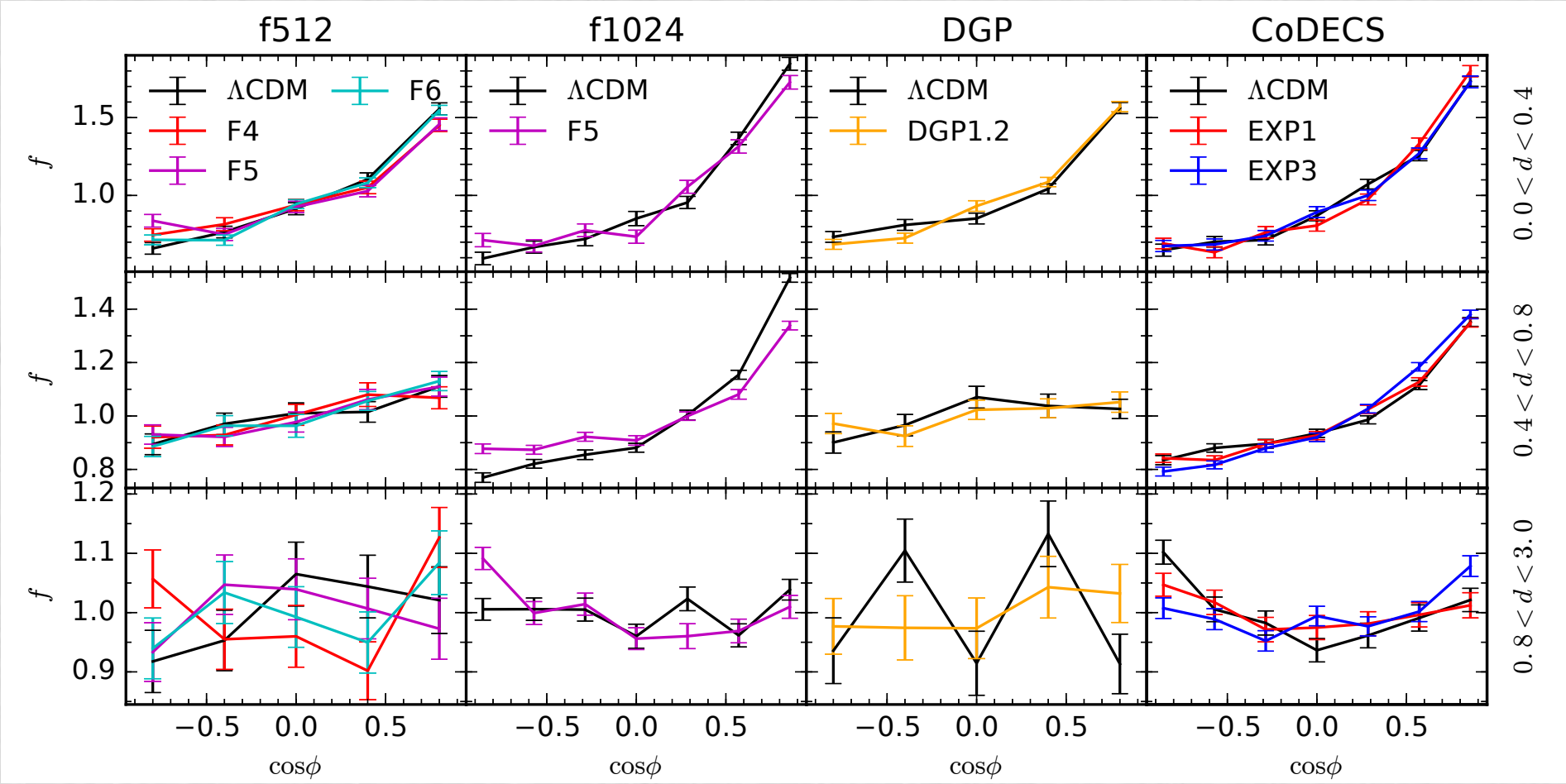
Studing DM Haloes in MG

- GR or modified gravity (MG)?
- How do haloes form in MG?
- Can the alignment tell us somehting about MG?

Simulations

- $f(R)$ (10^{-4}, 10^{-5}, 10^{-6}): $256\,h^{-1}\mathrm{Mpc}, 512^3$, and $1\,h^{-1}\mathrm{Gpc}, 1024^3$
- DGP ($r = 1.2$): $250\,h^{-1}\mathrm{Mpc}, 512^3$
- Dynamical DE Baldi et al 2012: $1\,h^{-1}\mathrm{Gpc}, 1024^3$

Alignment of interacting pairs

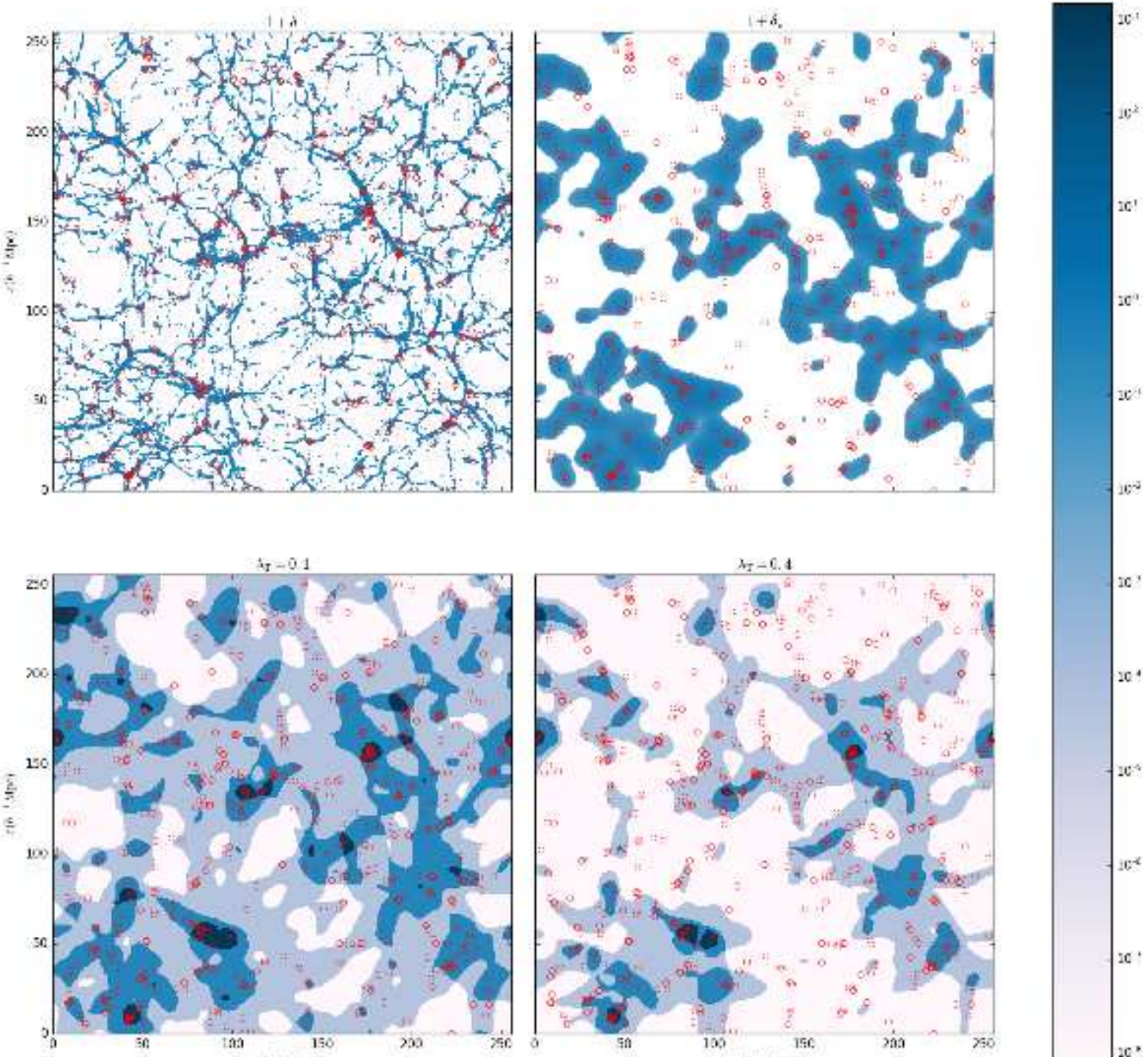


- ϕ: angle between the spins of interacting pairs
- $f(R)$: weaker alignment in low-density
- DGP: too little statistics?
- Dynamical DE: slightly stronger alignment in low-density

Alignment with the large-scale structures (LSS)

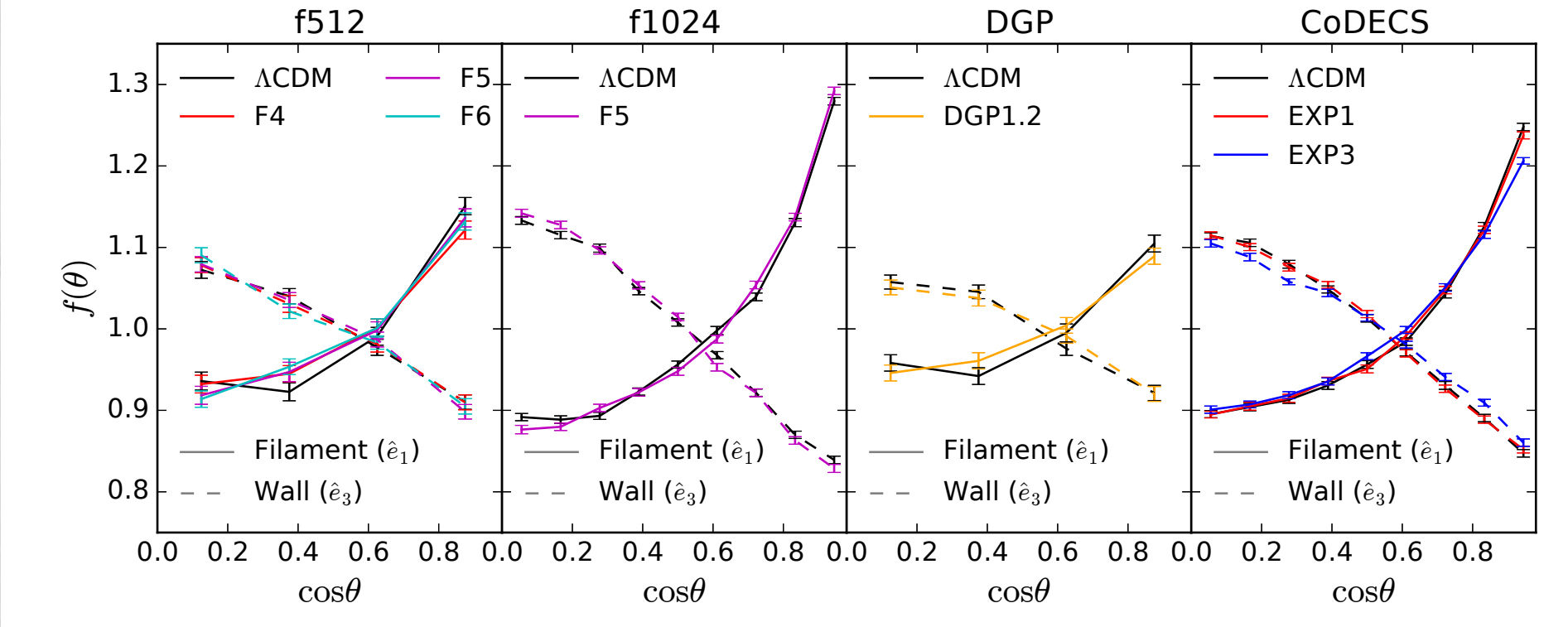
How to characterize the LSS?

- Overdensity $\delta(\mathbf{x}) = \rho(\mathbf{x}, t)/\bar{\rho}(t) - 1$ ($\mathbf{x}$: comoving coordinates)
- calculate the tidal field $T_{ij} = \partial_i \partial_j \phi$, where $\nabla^2 \phi = \delta$,
- Eigenvectors $\hat{e}_i$ of $\mathbf{T}$: direction of contractions ($\lambda_i > 0$) or expansion ($\lambda_i < 0$)
- Sort eigenvalues $\lambda_1 \leq \lambda_2 \leq \lambda_3$
- Voids, filaments, walls, knots have 0,1,2, or 3 eigenvalues $> \lambda_{\text{thresh}}$. we chose $\lambda_{\text{thresh}} = 0.4$ (visually ok)
- $\hat{e}_3$ normal to walls; $\hat{e}_1$ direction of the filaments


$1+\delta$
$1+\delta_c$
$\lambda_T = 0.1$
$\lambda_T = 0.4$
0
50
100
150
200
250

Alignment with the LSS

L'Huillier et al. (2017b) MNRAS 468, 3174



- Alignment of the major axis of haloes witht the directions of the walls (dash-dotted) and filaments (dashed)
- f512 and DGP: box too small, no difference
- EXP001 and ΛCDM agree, EXP003: weaker alignment

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Summary

- Degeneracy in the CMB: non-power law models can exist
- Can the LSS break the degeneracy?
  - 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 $z \simeq 0.7$
  - DESI, Euclid, LSST will probe these scales
- Halo alignment: stronger for massive haloes, independent of the density
- MG: little effect on the alignment
  - Assuming GR to model intrinsic alignment seems fine
- Baryons?

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감사합니다!

ありがとうございました!