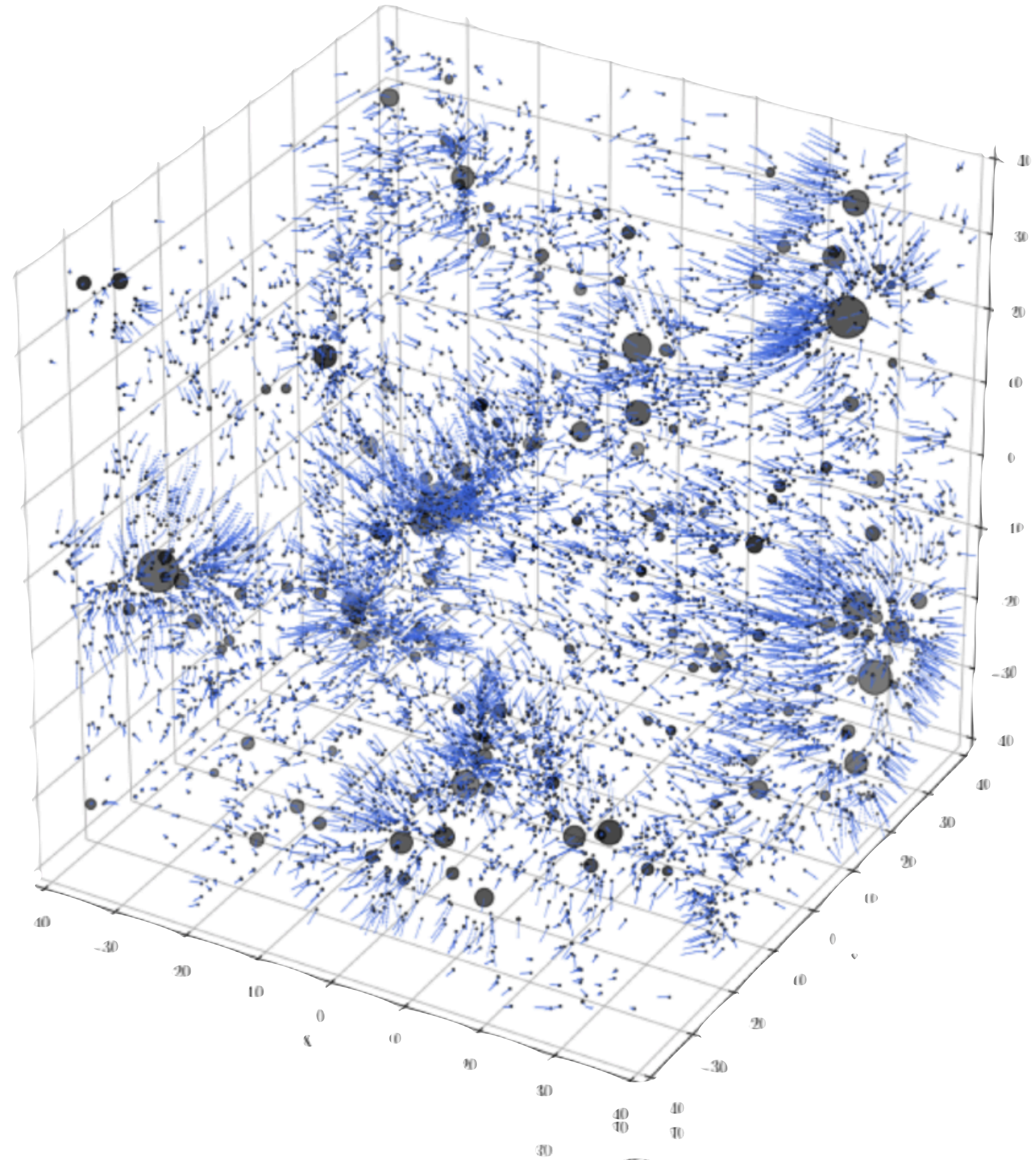


The Fast Action Minimisation method

Reconstruction of baryonic acoustic oscillations in the SDSS-DR12 Combined sample

In collaboration with:
Carlo Schimd (LAM), Sabino Matarrese (Univ. of Padova), Enzo Branchini (Univ. Roma Tre)

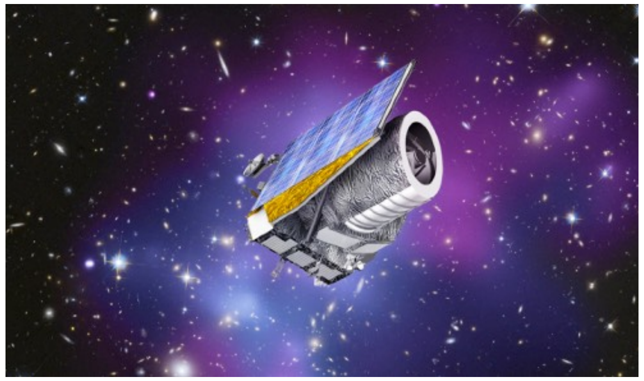
High-precision cosmology: spectroscopic surveys

Goal: measuring cosmological parameters with sub-percent precision
Strategy: Large surveyed volume, $>10^6$ tracers, precise redshifts

SDSS-DR12 (2019)

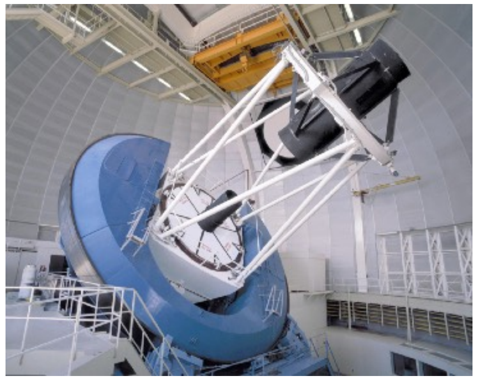
Tracers: $3\text{x}10^5$
Area: 10^4deg^2
$0.15 < z < 0.7$

Euclid (2023?)



Tracers: $3.5\text{x}10^7$
Area: $1.5\text{x}10^4\text{deg}^2$
$0.7 < z < 1.85$

DESI (2019-on going)



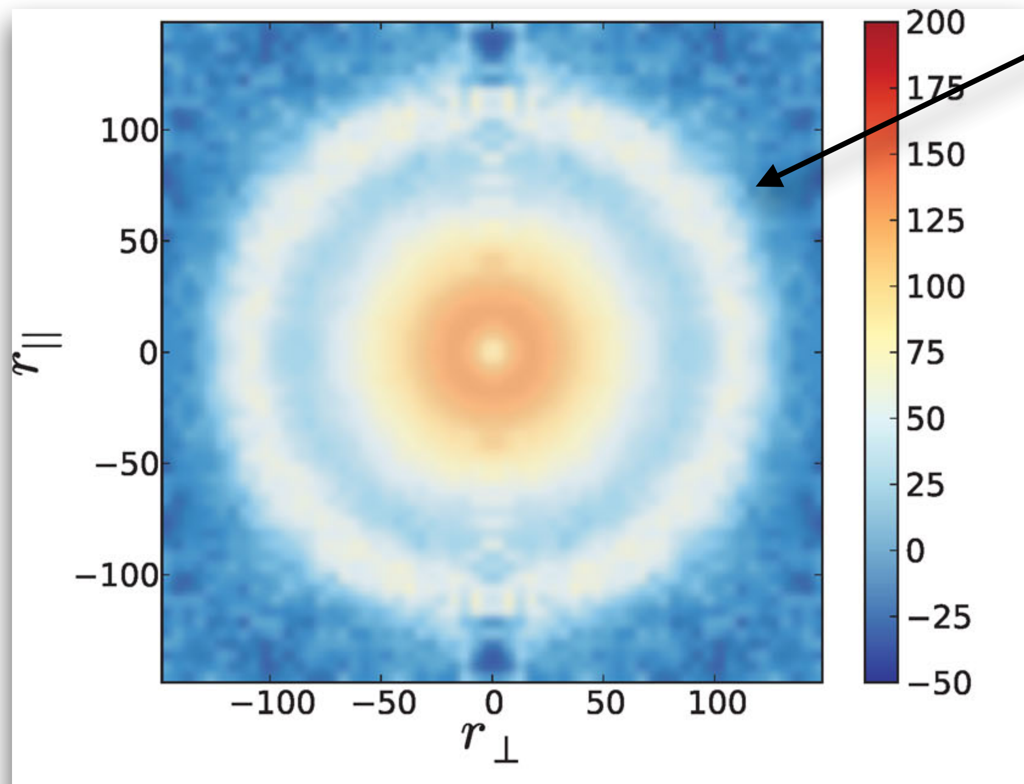
Tracers: $3\text{x}10^7$
Area: $1.\text{x}10^3\text{deg}^2$
$0. < z < 1.6$

Warning: high-precision demands an accurate modelling of the clustering signal

Galaxy clustering: Baryon acoustic oscillations

Linear theory

Anisotropic 2-pcf



(Padmanabhan et al., 2012)

BAO feature:

- **Isotropic ring**
- **Sharp contours** (peak in the monopole)
- **Intrinsic size of the wavefront:** pre-recombination expansion history, known from CMB (Planck, 2018)
- **Observed size of the wavefront** $(\Delta z, \Theta)$: post-recombination expansion history $(H(z), D_A(z))$

  $$s_\parallel^f = c/H(z)\Delta(z), \;\; s_\perp^f = (1+z)D_A\Theta$$

- **Constraining cosmology via comparison**

  $$s_\parallel^f = \alpha_\parallel s_\parallel^t \;\; , \;\; \alpha_\parallel \equiv H^t(z)/H^f(z)$$

  $$s_\perp^f = \alpha_\perp s_\parallel^t \;\; , \;\; \alpha_\perp \equiv D_A^f(z)/D_A^t(z)$$

Late-time clustering

- **Non-linear evolution:** matter overdensities departs from original position

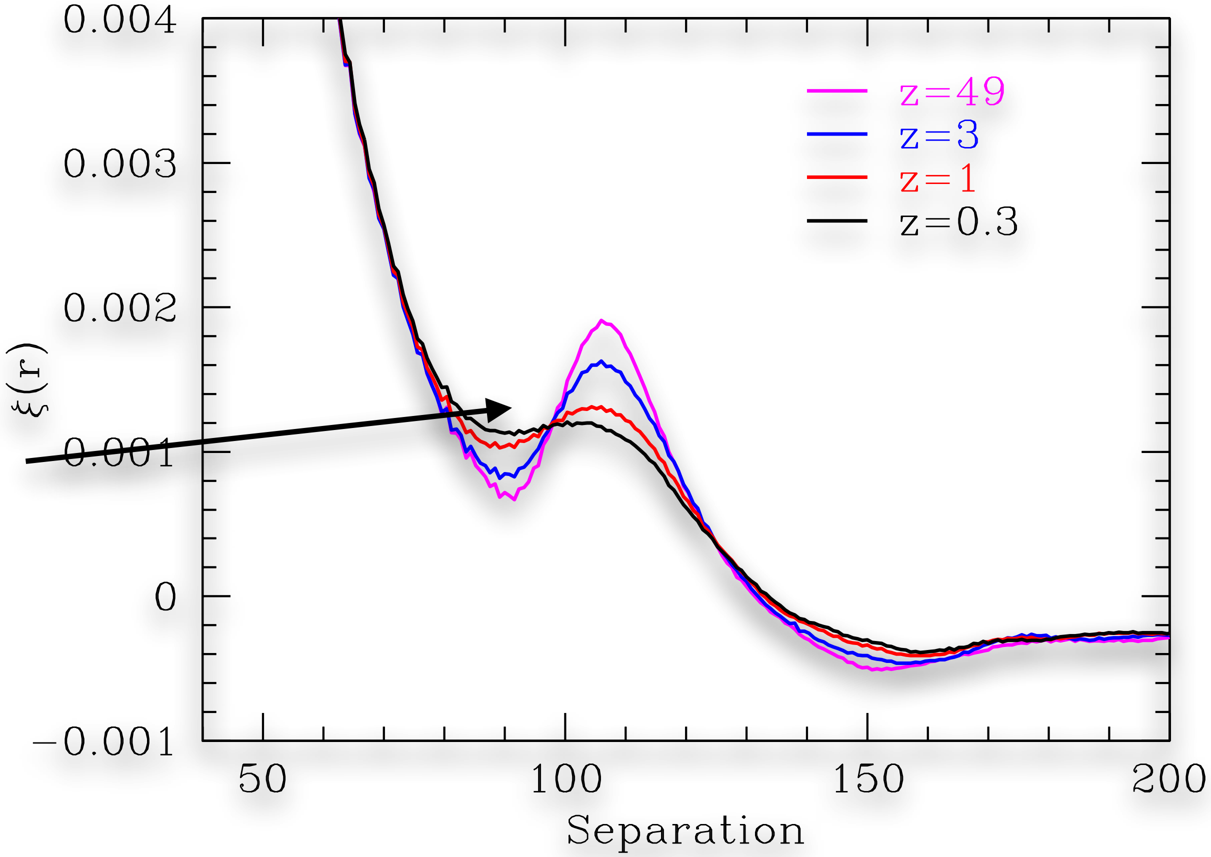
  → progressive **damping of the BAO peak**

- **Redshift-Space** (observations): Doppler shift due to neglected peculiar velocities

  → **Loss of isotropy**
  - small-scales (<10 Mpc/h) power enhanced along $s_{\|}$ (Fingers of God)
  - large-scales (>30 Mpc/h) power enhanced along $s_{\perp}$ (Kaiser Distortions)

The BAO scale measurement is degraded

Real-space 2pt correlation function

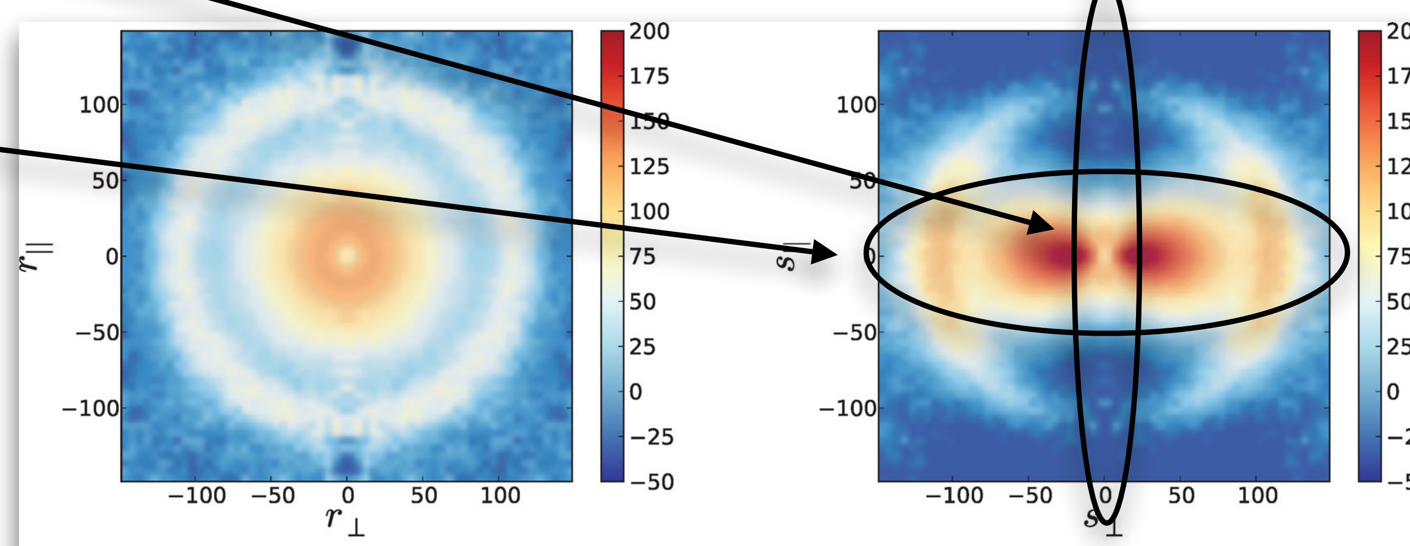


(Eisenstein, Seo & White 2007)

Anisotropic 2pt correlation function

Real-space

Redshift-space

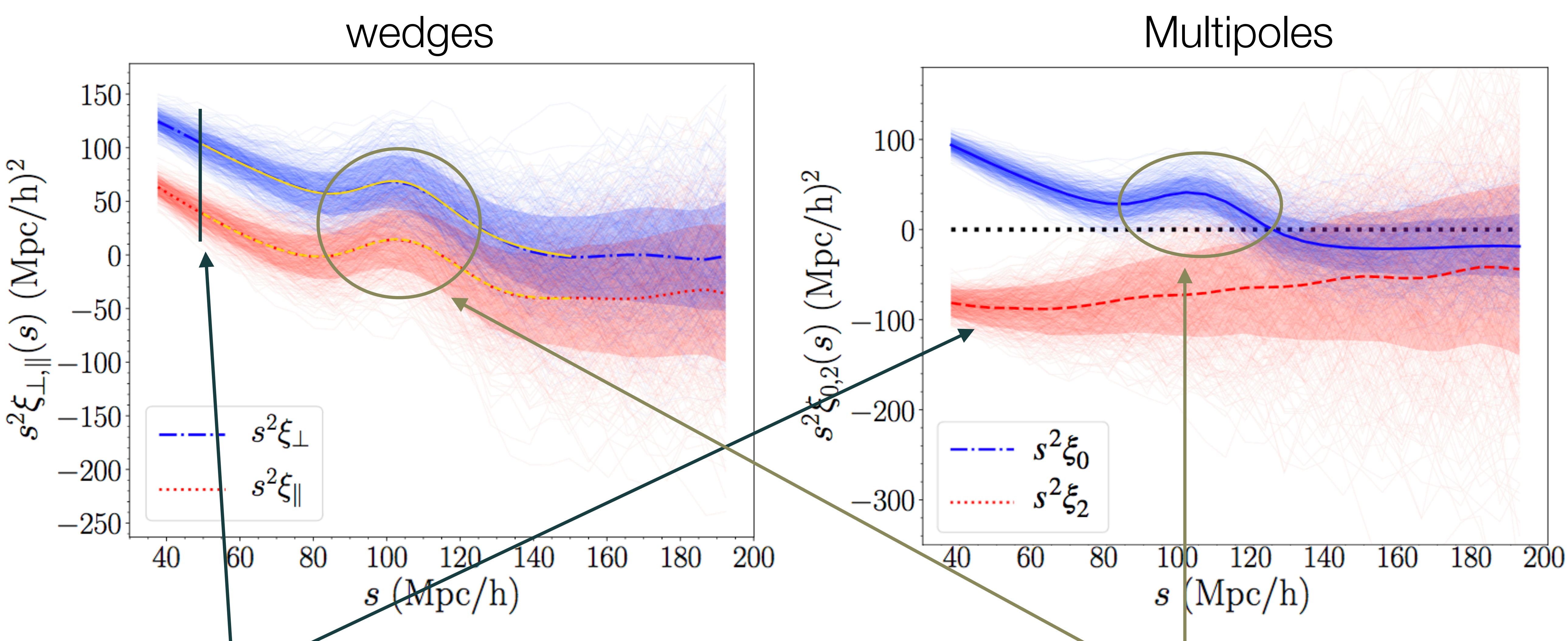


(Padmanabhan et al., 2012)

Pre-reconstruction 2pt correlation function (SDSS-DR12 mocks)

(Sarpa et al 2021, arXiv:2010.10456)

400 mocks, **known cosmology**, reproducing north galactic cap



Redshift-space distortions

- difference in wedges amplitudes
- non-vanishing quadrupole

Non-linearities

- broad BAO peak

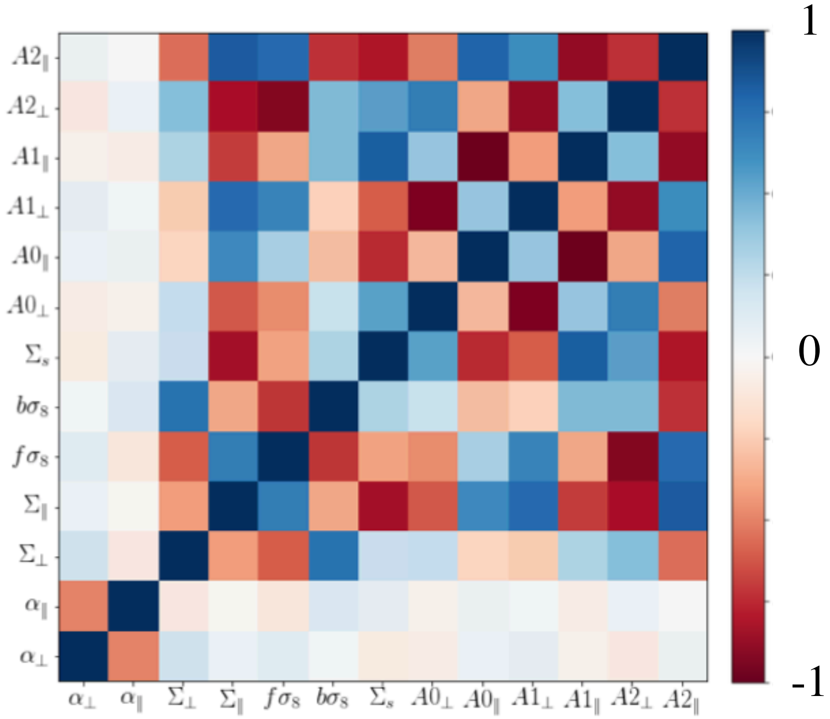
Fitting single mocks pre-reconstruction

Fitting range: [50 ,150] Mpc/h)~linear (Sarpa et al 2021, arXiv:2010.10456)

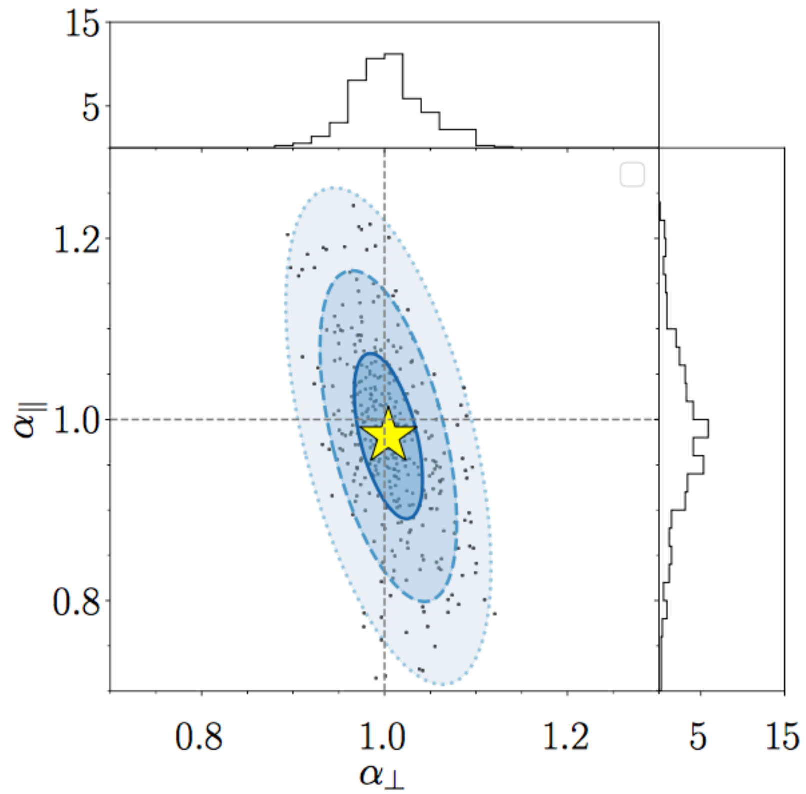
Non-linear Model: (13 parameters)

- Non-linear evolution: exponential dumping
- RSD: Kaiser (linear) + Lorenzian streaming (non-linear)
- Broad band

Results: Parameters correlation matrix



2D distribution of dilation parameters



- Degenerate fitting parameters

Need for a solution!

- Bias estimation of acoustic scale
  $|\langle\alpha_{\perp,\parallel}\rangle - 1| > 0$
- Large uncertainty on $\alpha_\parallel$

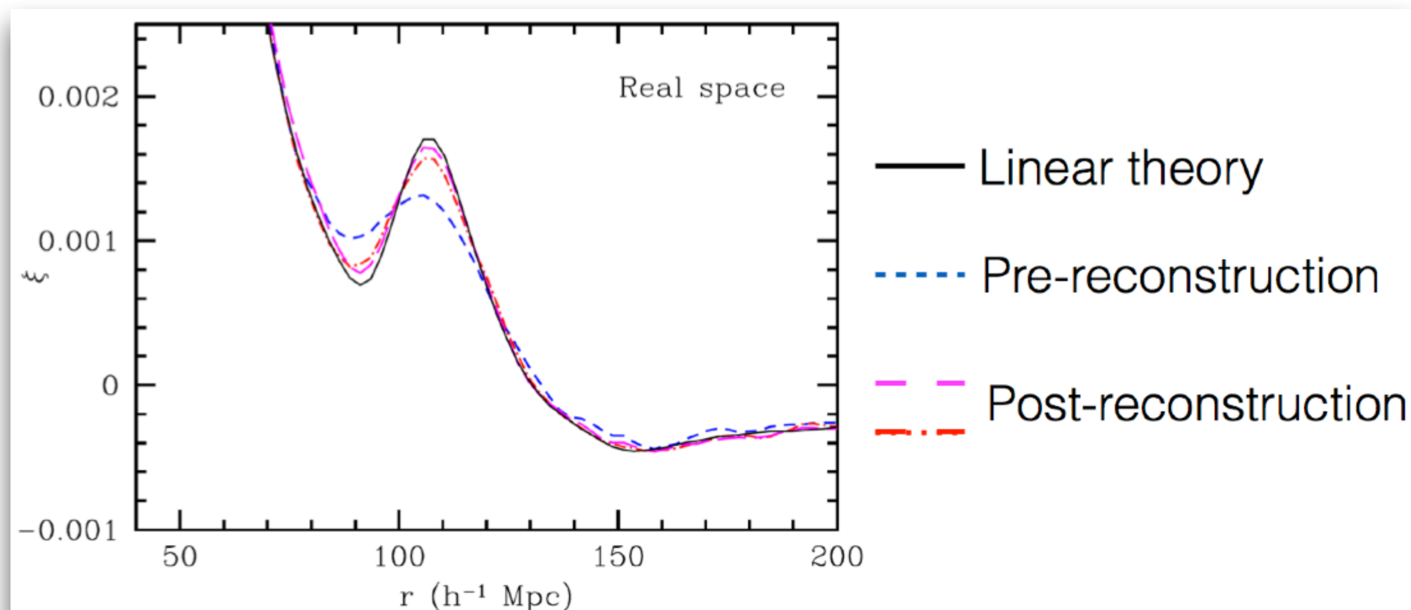
Reconstruction

(Eisenstein et al., 2007)

Idea: Improve BAO measurement by displacing the observed mass distribution backwards-in-time

Reversing non-linear dumping

2pt correlation function

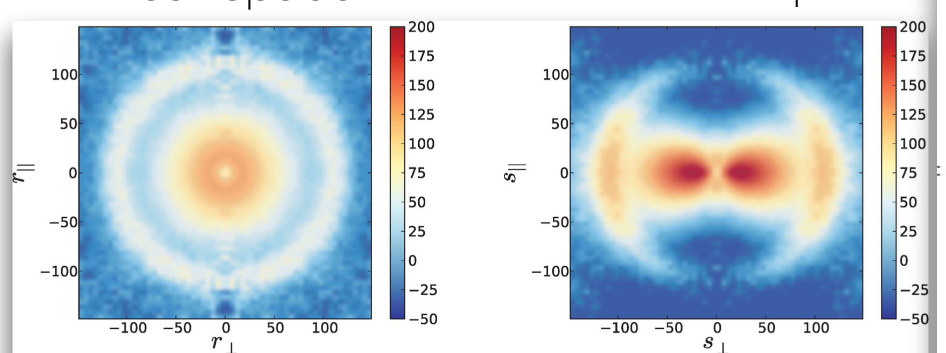


(Eisenstein et al., 2007b)

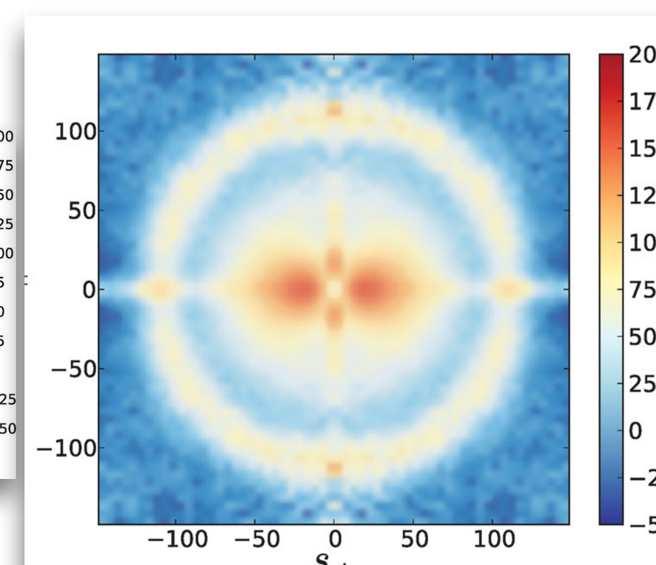
Removing RSD

Real-space

Redshift-space



Reconstructed



(Padmanabhan et al., 2012)

The extended Fast Action Minimisation method (eFAM)

Based on Least action Principle (Peebles,1989 & Nusser & Branchini 2000)

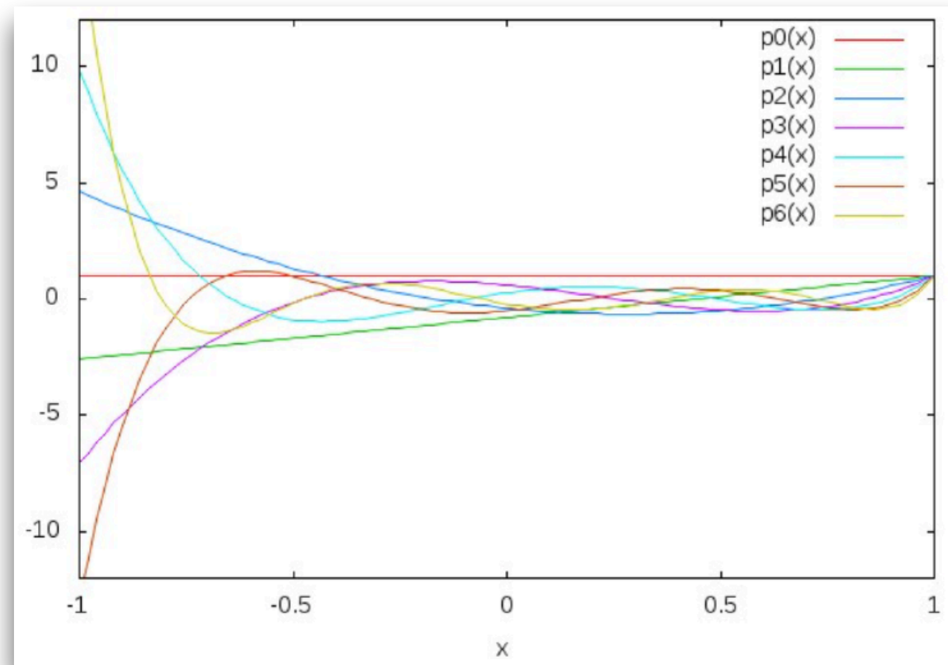
Idea: reconstruct the past-trajectories of the mass tracers by minimising the action of the system **(fully non-linear)**

- Mixed boundary conditions: $\mathbf{x}_{i,0}$
  - observed positions/redshifts
  - vanishing initial peculiar velocities

- Action:

$$S = \int_{t_i}^{t_0} dt \sum_{i=1}^{N} m_i \left\{ \frac{1}{2} a^2 \dot{\mathbf{x}}_i^2 - \left[\frac{-G}{2a} \sum_{j=1, j\neq i}^{N} \frac{m_j}{|\mathbf{x}_i - \mathbf{x}_j|} - \frac{2}{3} G\pi\rho_b a^2 \mathbf{x}_i^2 \right] \right\}$$

Polynomials



- Minimisation:
  - polynomial expansion of trajectories $\mathbf{x}_i(t) = \mathbf{x}_{i,0} + \sum_n \mathbf{C}_{i,n} q_n(t)$
  - determine the set of coefficient $\{\mathbf{C}_{i,n} q_n(t)\}$

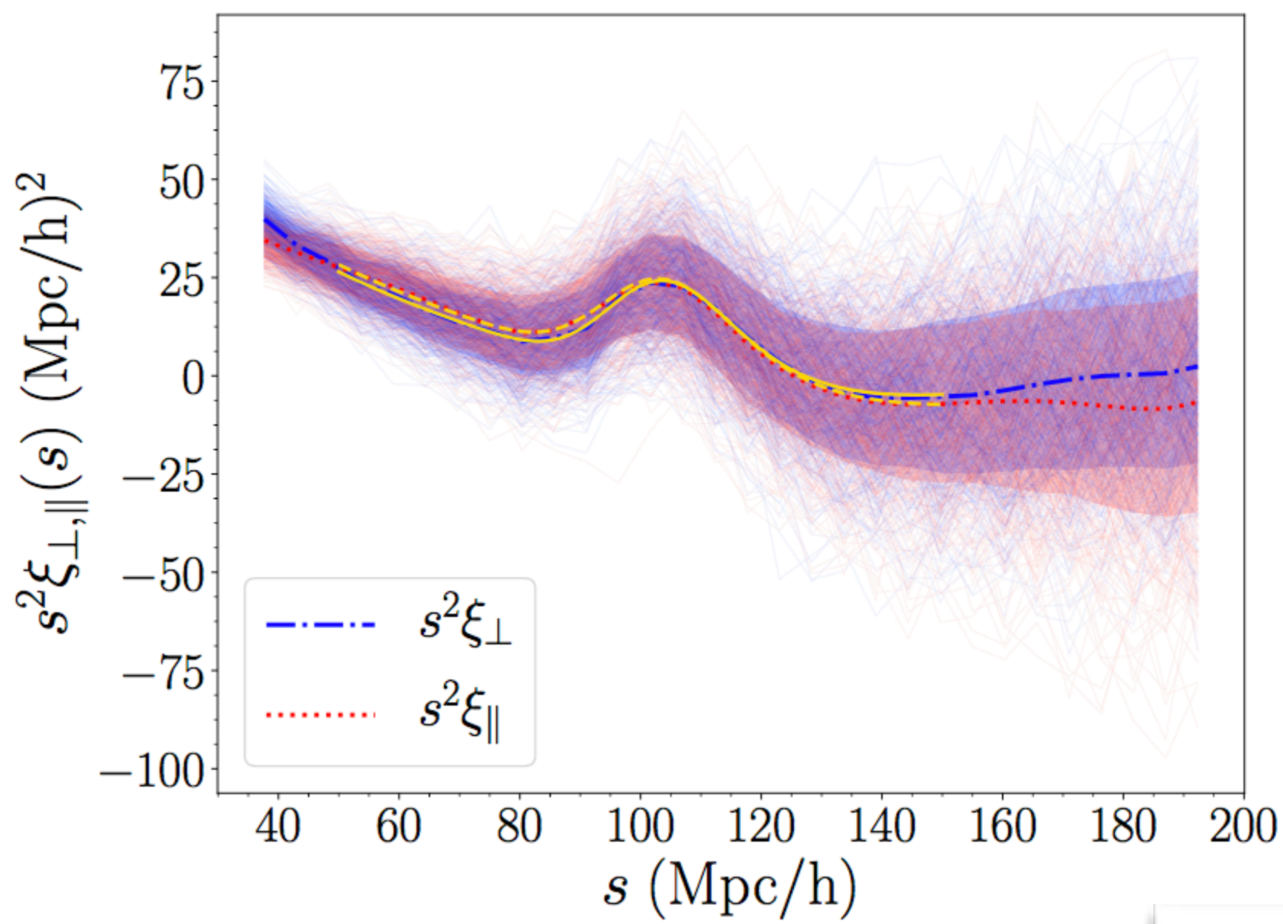
  that stationaries the action

Reconstructed real-space 2pt correlation function, *high redshift* (mocks)

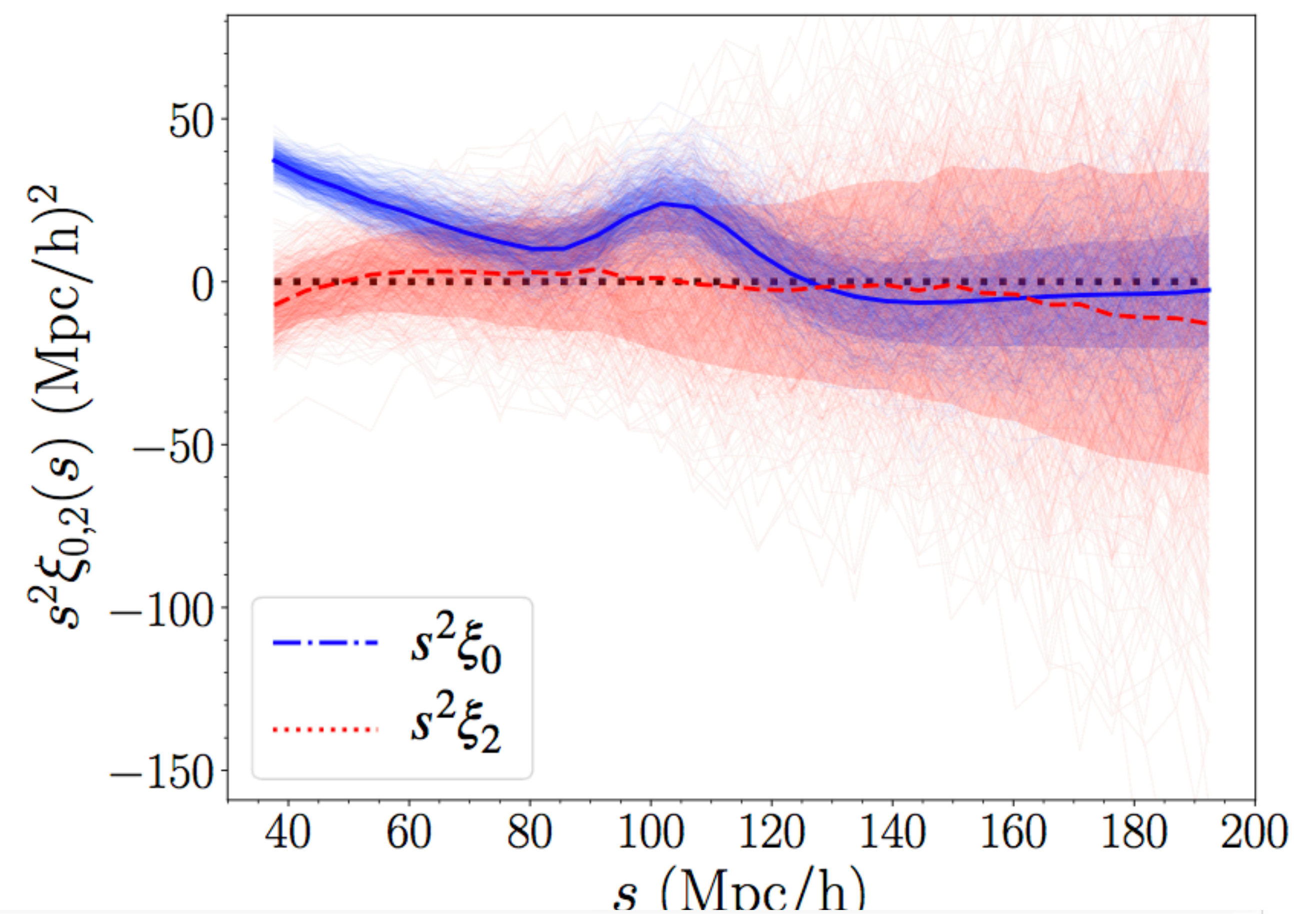
(Sarpa et al 2021, arXiv:2010.10456)

400 mocks, known cosmology, reproducing north galactic cap

wedges

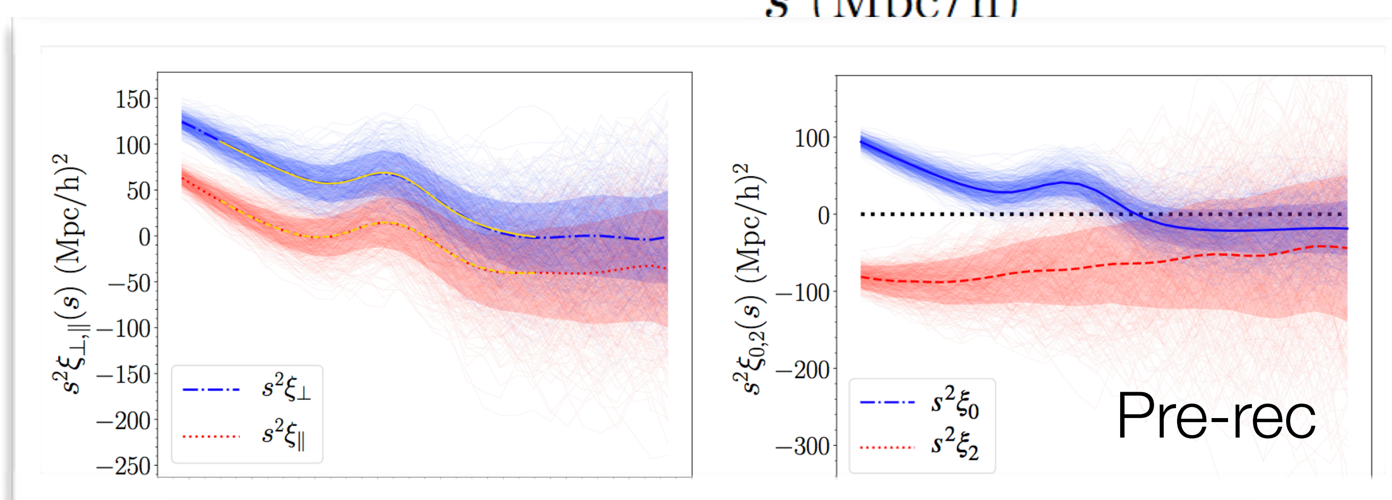


Multipoles



- Sharper peak
- Wedges ~ superimposed
- ~ vanishing quadrupole

Noise at high scale due to border effects

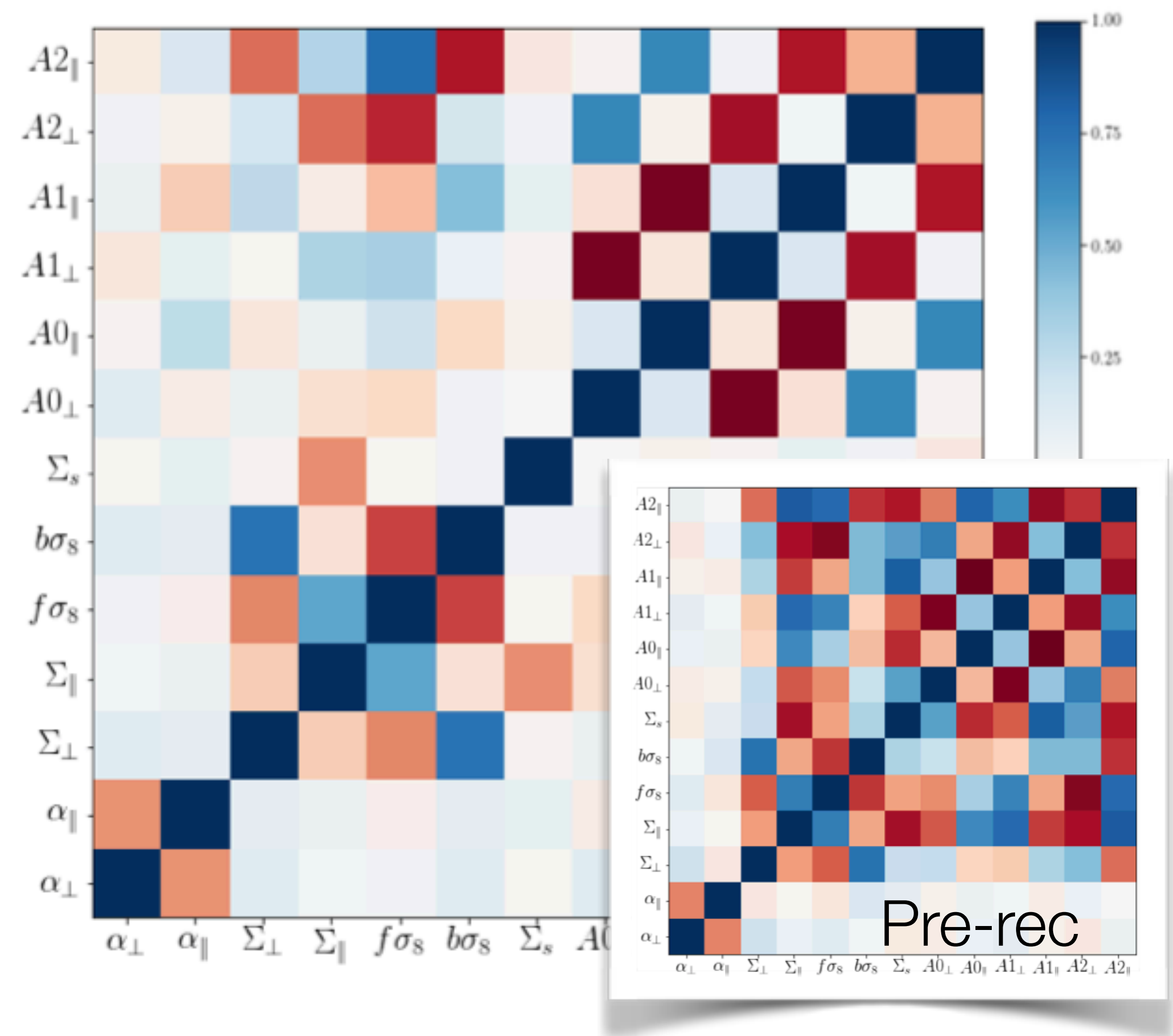


Fitting the mean wedges averaged over the mocks, *Post-reconstruction at high redshift*

Fitting range: [50 ,150] Mpc/h

sample	$\alpha_\perp$	$\alpha_\parallel$	$\Sigma_\perp\,(h^{-1}\mathrm{Mpc})$	$\Sigma_\parallel\,(h^{-1}\mathrm{Mpc})$	f	$\Sigma_s\,(h^{-1}\mathrm{Mpc})$
Obs	0.997 ± 0.003	1.011 ± 0.007	7.37 ± 0.45	10.20 ± 1.82	0.51 ± 0.13	4.43 ± 1.83
RecZ	0.997 ± 0.003	1.011 ± 0.006	7.79 ± 0.36	9.12 ± 0.68	0.07 ± 0.06	1.09 ± 1.18
RecL	$\mathbf{0.997 \pm 0.002}$	$\mathbf{1.010 \pm 0.004}$	$\mathbf{5.21 \pm 0.39}$	$\mathbf{6.93 \pm 0.53}$	$\mathbf{0.06 \pm 0.05}$	$\mathbf{1.02 \pm 0.88}$

Correlation matrix of fitting parameters



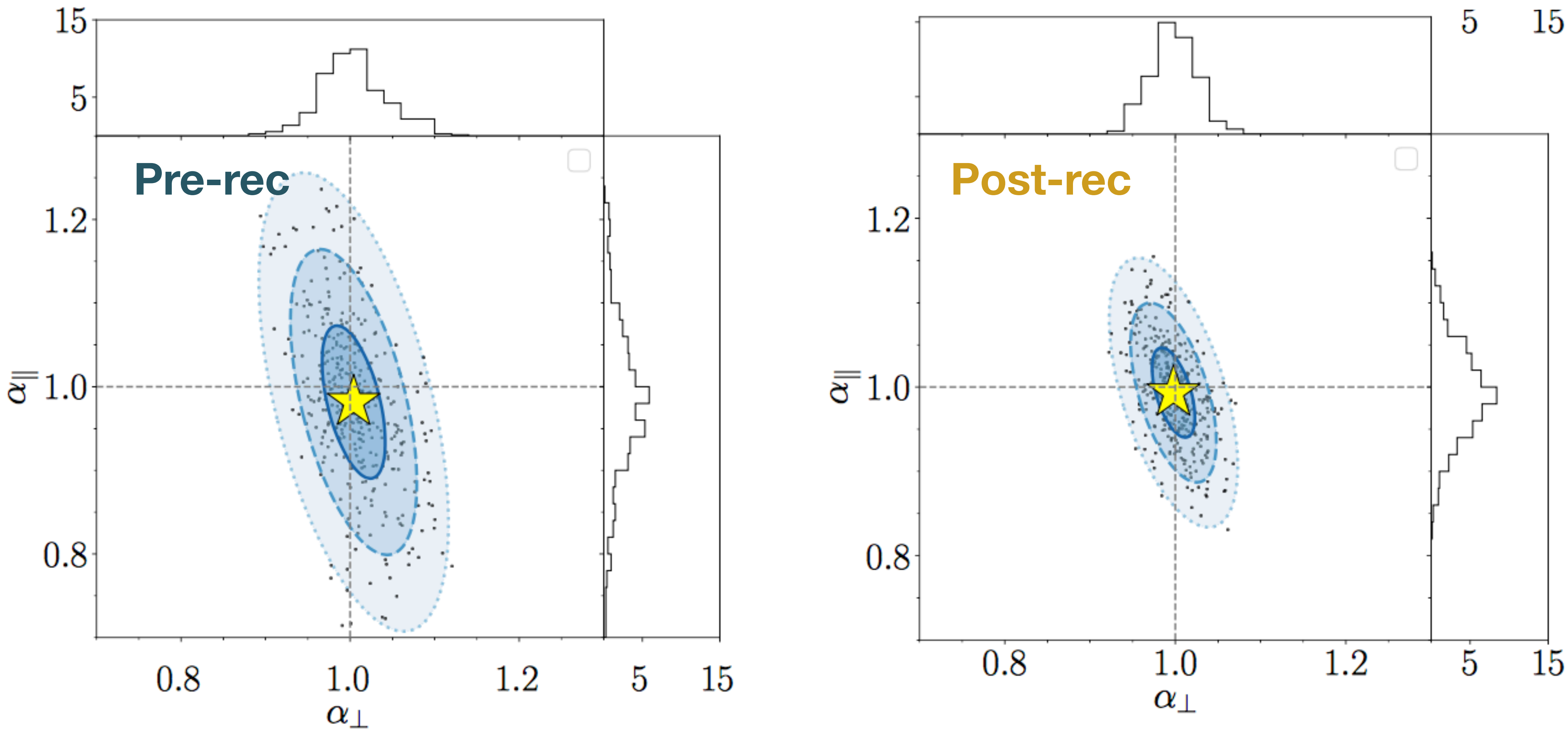
- Better constraints on $\alpha_{\parallel,\perp}$
- Lower $\Sigma_{\parallel,\perp}$
- *NO* Degeneracy
- RSD parameters compatibles with zero

We can use the real-space template from 13 to 11 parameters

Fitting single mocks: Pre vs Post-reconstruction

Fitting range: [50 ,150] Mpc/h

(Sarpa et al 2021, arXiv:2010.10456)



- Reduced bias in $\langle\alpha_{\perp,\parallel}\rangle$ estimates (golden star)
- Reduced uncertainty for $\langle\alpha_{\perp,\parallel}\rangle$

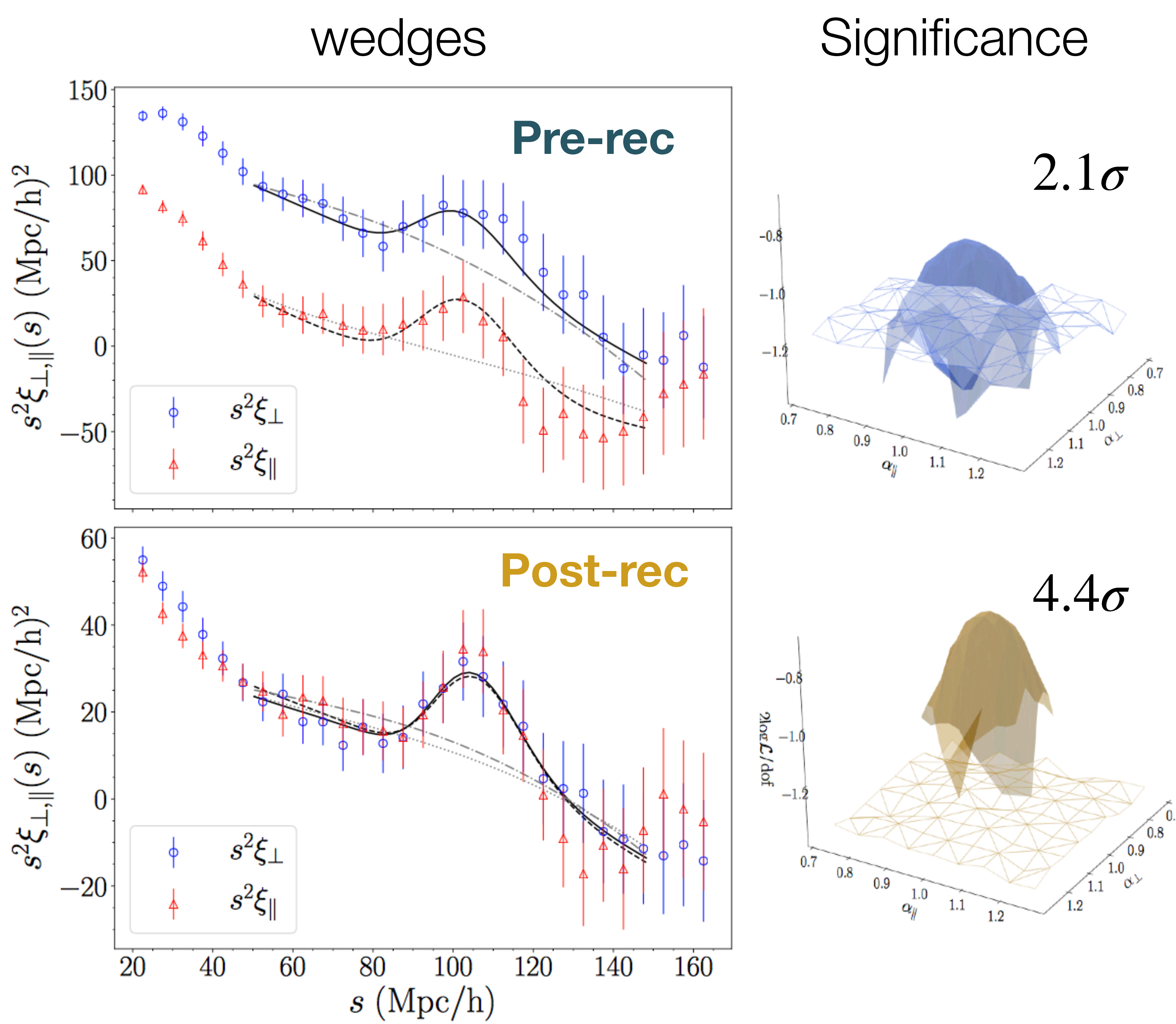
Fitting SDSS-DR12 data: Pre vs Post reconstruction

Fitting range: [50 ,150] Mpc/h

(Sarpa et al 2021, arXiv:2010.10456)

Post-reconstruction:

- No RSD
- Sharper peak
- Gained significance



(D_A,H) Pre vs Post reconstruction

Fitting range: [50 ,150] Mpc/h

(Sarpa et al 2021, arXiv:2010.10456)

- σ_H/H from 3.5% to 2.5%
- σ_{D_A}/D_A from 5% to 3.6%
- Better agreement w/
  - fiducial cosmology
  - Ross17

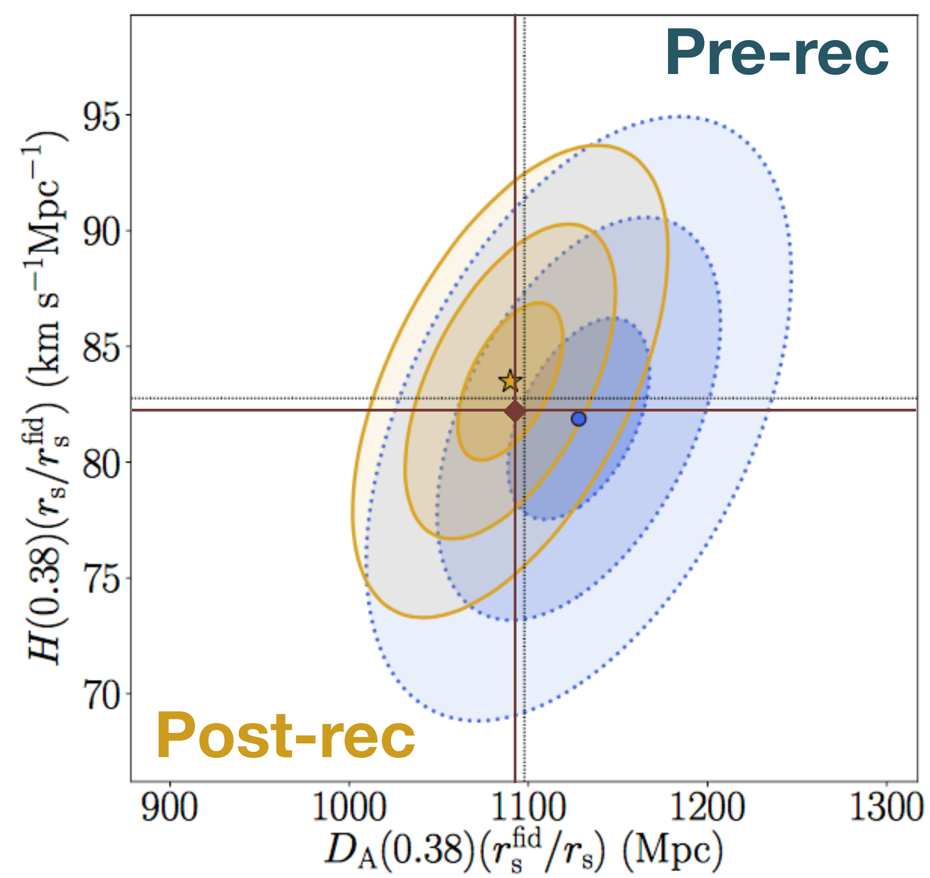


Table 4. Fit results from the SDSS-DR12 Combined Sample.

sample	$D_A(0.38)(r_s^{fid}/r_s)$ (Mpc)	$H(0.38)(r_s/r_s^{fid})$ (km s^{-1} Mpc^{-1})
Obs	1129 ± 40	82 ± 4
RecL	1090 ± 29	83 ± 3

Summary and conclusions

- Reconstruction techniques are useful tools to extract additional informations from observations, being vital to improve BAO measurements.

- eFAM can help. Applied on SDSS-DR12 eFAM yields:
  - 2x significance of BAO detection
  - 2x precision on cosmological parameters
  - robust estimation of the cosmological parameters with respect to the fitting range

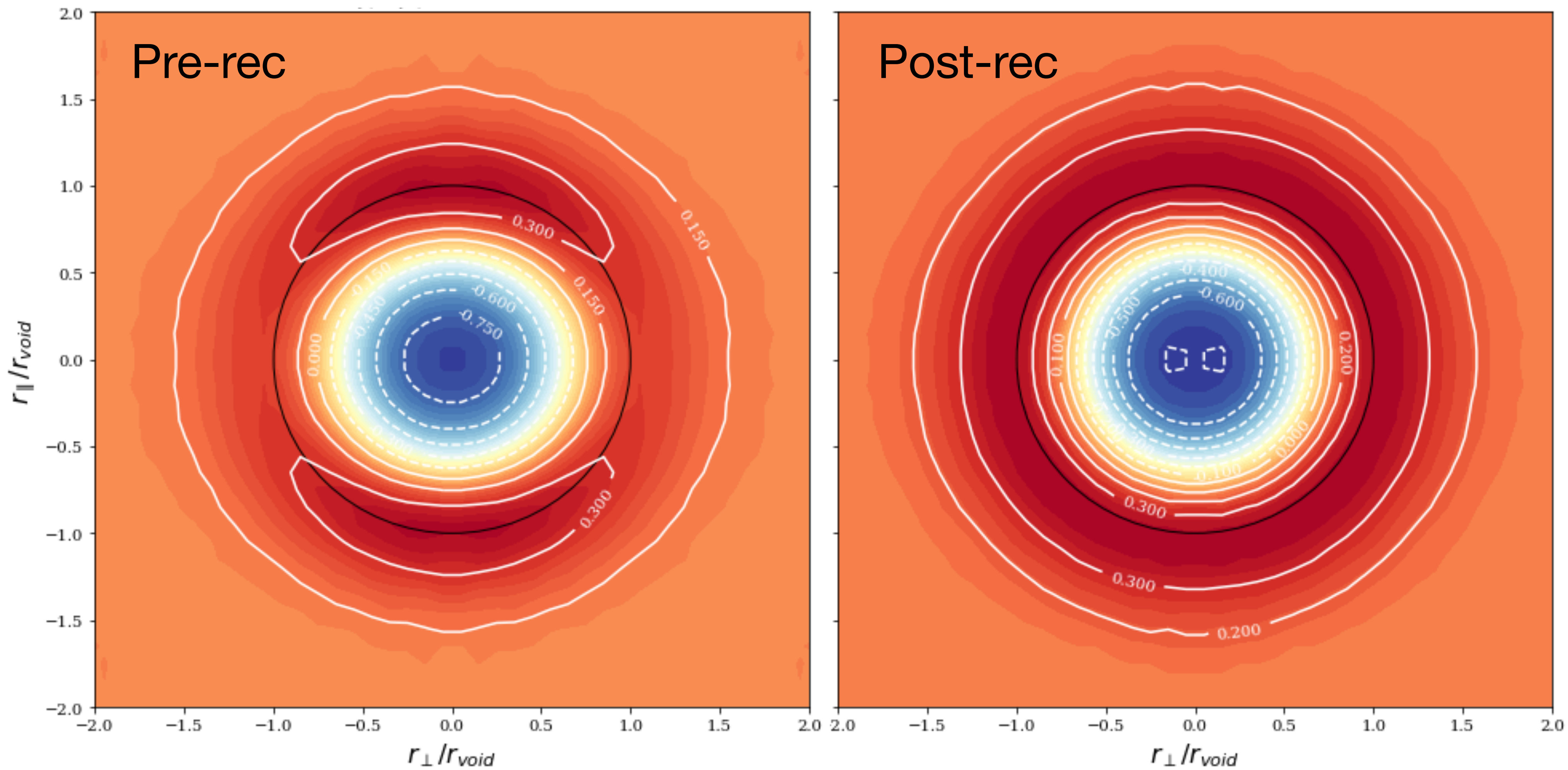
- Towards a unique reconstruction: same reconstruction for many purposes …

Voids reconstruction on SDSS-DR12

(Sarpa, Degni, Aubert, Pisani, Hawken, Branchini in prep.)

Idea: Improve AP test modelling RSD

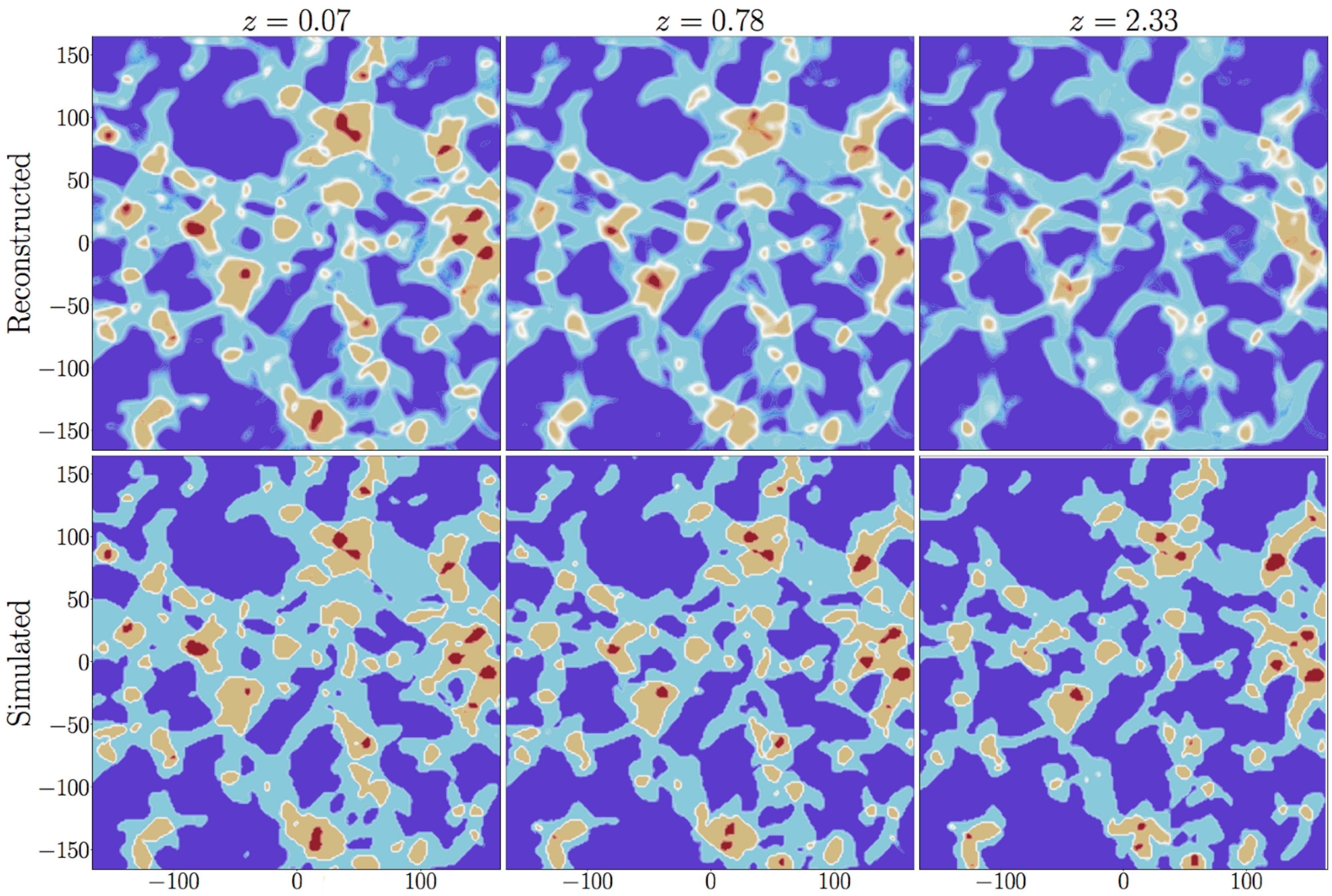
2pt galaxy-voids cross-correlation function



(plot by Giulia Degni)

Exploring the evolution of the cosmic web

(Sarpa, Kraljic, Longobardi, Schimd, Veropalumbo, 2021)



Thank you for the attention …

Fitting single mocks: Pre vs Post-reconstruction

Varying the fitting range

fitting range	sample	$\langle\alpha_\perp\rangle - 1$	$S_{\langle\alpha_\perp\rangle}$	$\langle\sigma_{\alpha_\perp}\rangle$	$S_{\langle\sigma_{\alpha_\perp}\rangle}$	$\langle\alpha_\parallel\rangle - 1$	$S_{\langle\alpha_\parallel\rangle}$	$\langle\sigma_{\alpha_\parallel}\rangle$	$S_{\langle\sigma_{\alpha_\parallel}\rangle}$
$[50, 150]\,h^{-1}$Mpc	Obs	0.002	0.036	0.031	+0.017 -0.004	-0.017	0.081	0.053	+0.067 -0.005
	RecL	-0.002	0.024	0.024	+0.013 -0.002	-0.010	0.056	0.049	+0.032 -0.006
$[40, 150]\,h^{-1}$Mpc	Obs	0.002	0.035	0.032	+0.024 -0.004	-0.026	0.088	0.054	+0.061 -0.004
	RecL	-0.002	0.025	0.027	+0.007 -0.004	-0.011	0.051	0.043	+0.030 -0.004
$[25, 150]\,h^{-1}$Mpc	Obs	0.004	0.036	0.033	+0.017 -0.004	-0.032	0.091	0.059	+0.065 -0.007
	RecL	0.000	0.023	0.026	+0.013 -0.003	-0.010	0.053	0.048	+0.030 -0.004

- Pre-reconstruction (obs):
  - increasing bias in $\langle\alpha_\parallel\rangle$ with decreasing s_{min}
  - increasing $S_{\langle\alpha_\parallel\rangle}$ with decreasing s_{min}
- Post-reconstruction (RecL)
  - *stable measurements at all scales*

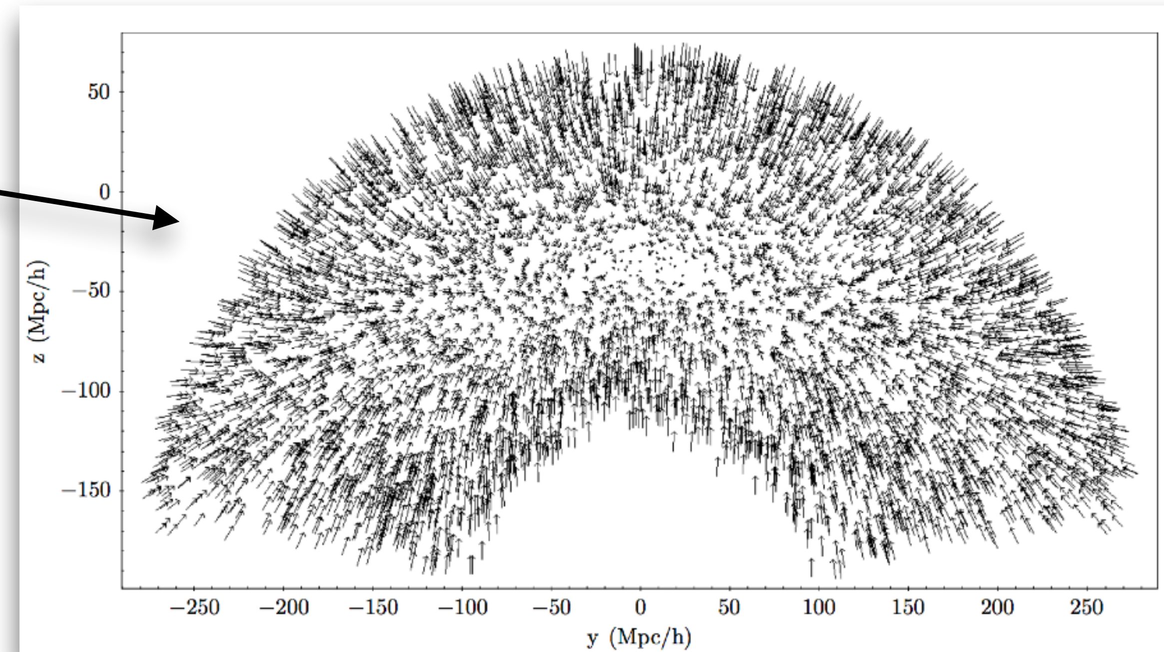
We can extend the fitting range

(Sarpa et al 2020, arXiv:2010.10456)

Survey geometry and masked regions

(Sarpa et al., 2021)

- Assumption: observed galaxies as an isolated system
  - non-spherical symmetry
    → artificial *large-scale* bulk-flow
  - masked regions
    → spurious small-scale motion



- Solution: Newton's shell theorem
  - split internal and external contributions:
  - Compute $\phi_{\rm ext}$ from random distribution filling the survey
    assuming $\phi^{\rm R}_{\rm tot}(\mathbf{x}) = 0$ and $\phi^{\rm R}_{\rm ext}(\mathbf{x}) = \phi^{\rm g}_{\rm ext}(\mathbf{x})$

    → $\phi^{\rm g}_{\rm tot}(\mathbf{x}) = \phi^{\rm g}_{\rm int}(\mathbf{x}) - \phi^{\rm R}_{\rm int}(\mathbf{x})$

Note: equivalent to embed the survey in an larger random distribution but computational more efficient

Galaxy bias

(Sarpa et al., 2021)

- Standard FAM (Branchini et al., 2002)
  - no biasing scheme: total mass is split among visible objects

- Fiducial biasing scheme: peak-background split
  - linear bias relation: $\delta = \delta_{\mathrm{g}}/b$
  - assumption: bi-modal dark matter distribution, clustered + smooth uniform background

$$\rho_{\mathrm{tot}}(\mathbf{x}) = \rho'_{\mathrm{g}}(\mathbf{x}) + \bar{\rho}_{\mathrm{DM}} \sum_{\mathrm{g}} \left[1 - \delta^{\mathrm{D}}(\mathbf{x} - \mathbf{x}_{\mathrm{g}})\right]$$

  - new masses

$$\rho'_{\mathrm{g}}(\mathbf{x}) = \left(\frac{\delta_{\mathrm{g}}(\mathbf{x})}{b} + 1\right) \frac{\Omega_{\mathrm{m},0} 3H^2}{8\pi G}$$

  - smooth background contribution modelled as an extra tidal fields

Biasing scheme