Correcting RSD at large scales:
improving the BAO peak measurement by reconstruction,
the Fast Action Minimization Method

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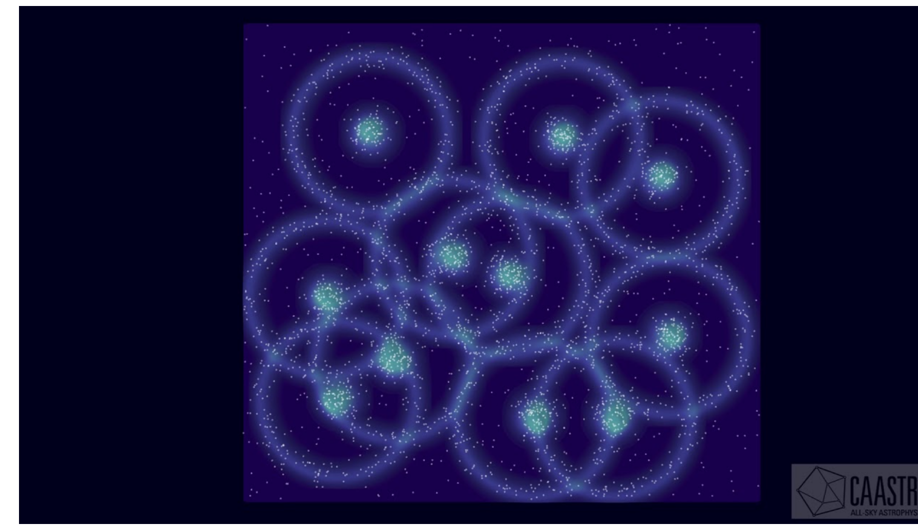
Large scales density field

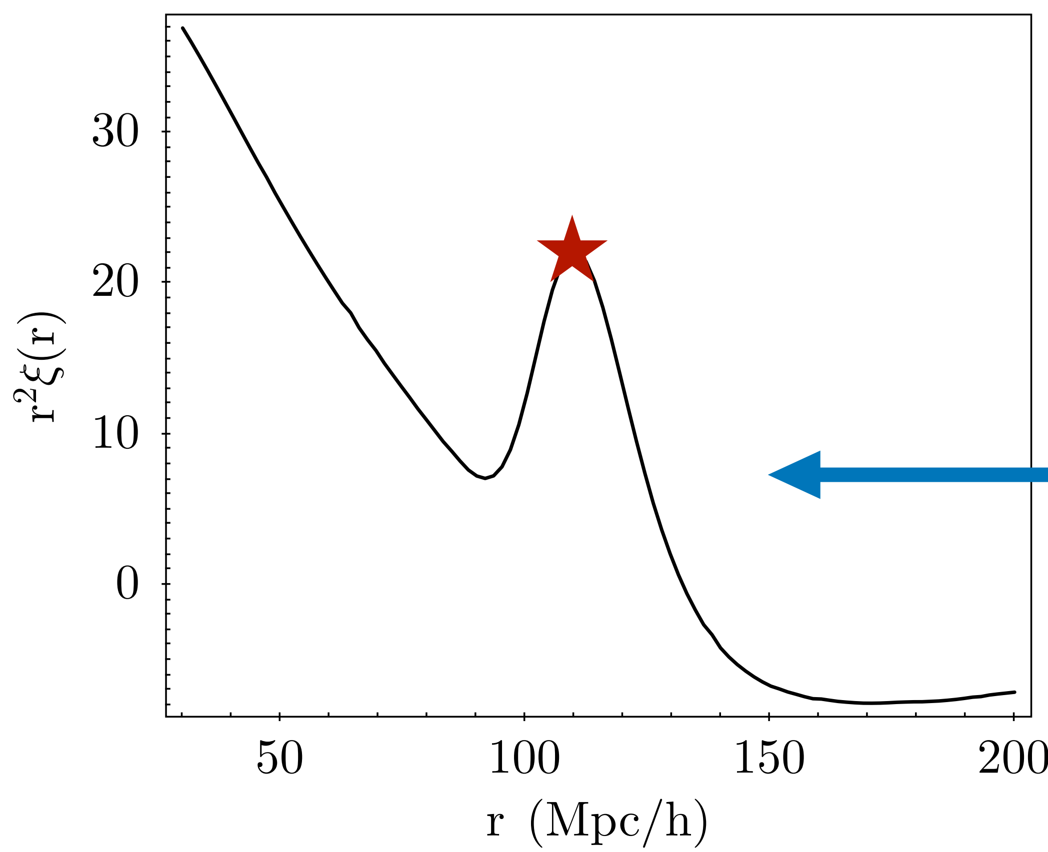
Cosmological principle: *The Universe on large scales is **homogenous** and **isotropic***

+

Baryonic acoustic oscillation:
excess of clustering at the sound horizon scale ★



Statistical description:

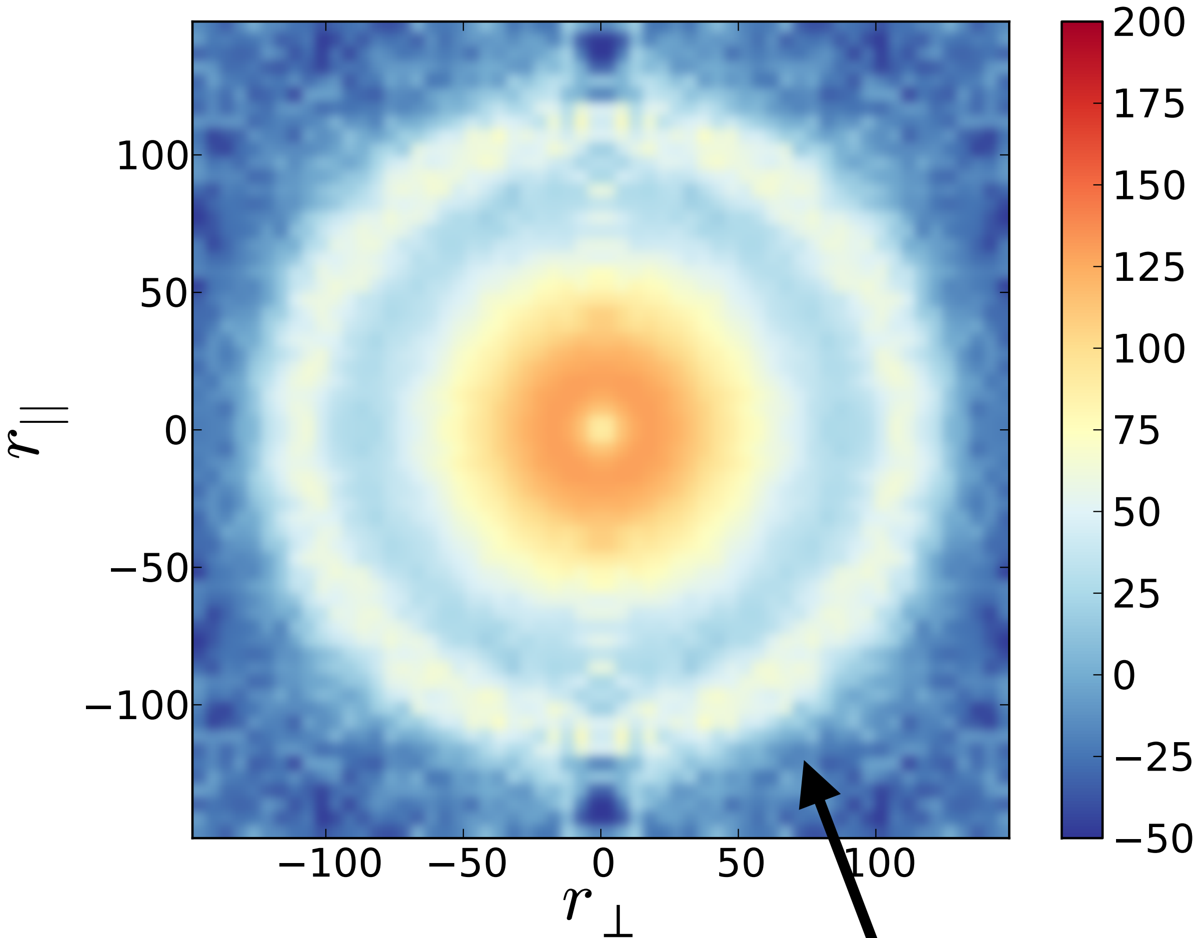


Real-space

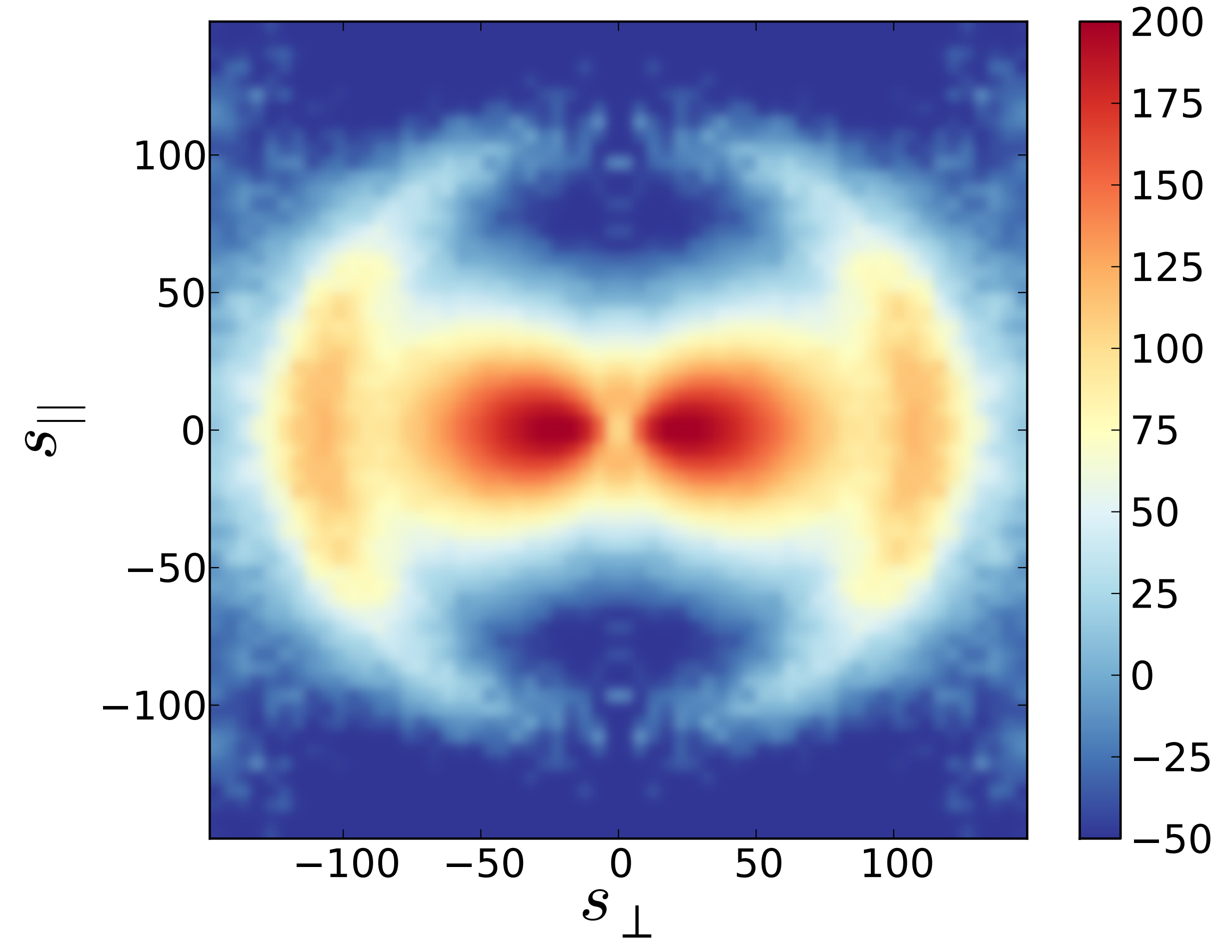
For an Isotropic and homogenous field the correlation function is a function of $|r_1 - r_2|$ and **not of their orientation**

Redshift space distortions

Real-space



Redshift-space

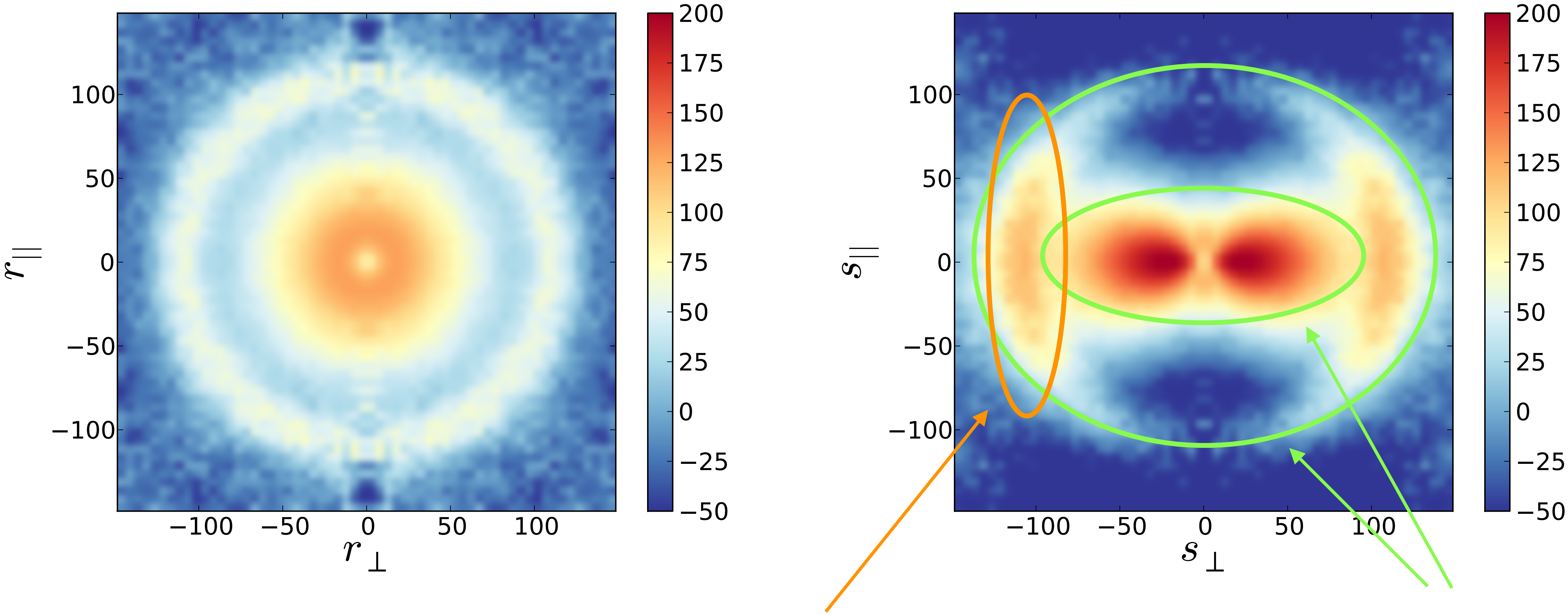


(Padmanabhan et al. 2012)

Isotropic !

Redshift space distortions

Real-space | **Redshift-space**



(Padmanabhan et al. 2012)

Reconstruction of the velocity and density fields to remove RSD

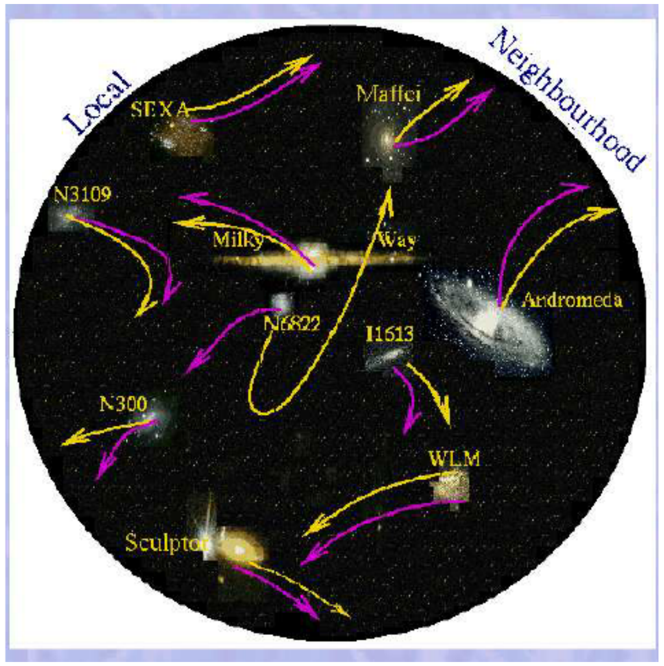
The reconstruction technique

The Least Action Principle (Peebles 1989)

Idea: Reconstruction of particles trajectories backward in time by *minimisation of the action*

- *"mixed boundary condition problem"*:

  observed positions/redshifts & initial velocities
- Point-like particles, with equal mass,
- interacting only by gravity in a FLRW Universe + Newtonian approximation



Key: fully non-linear method

Action (Peebles 1989)

$$S = \int_0^{t_0} dt \sum_{i=0}^{N} \left\{ \frac{1}{2} m_i a^2 \dot{\mathbf{x}}_i^2 - m_i \left[-\frac{G}{a} \frac{1}{2} \sum_{j=0, j\neq i}^{N} \frac{m_j}{|\mathbf{x}_i - \mathbf{x}_j|} - \frac{2}{3} G \pi \rho_m a^2 \mathbf{x}_i^2 \right] \right\}$$

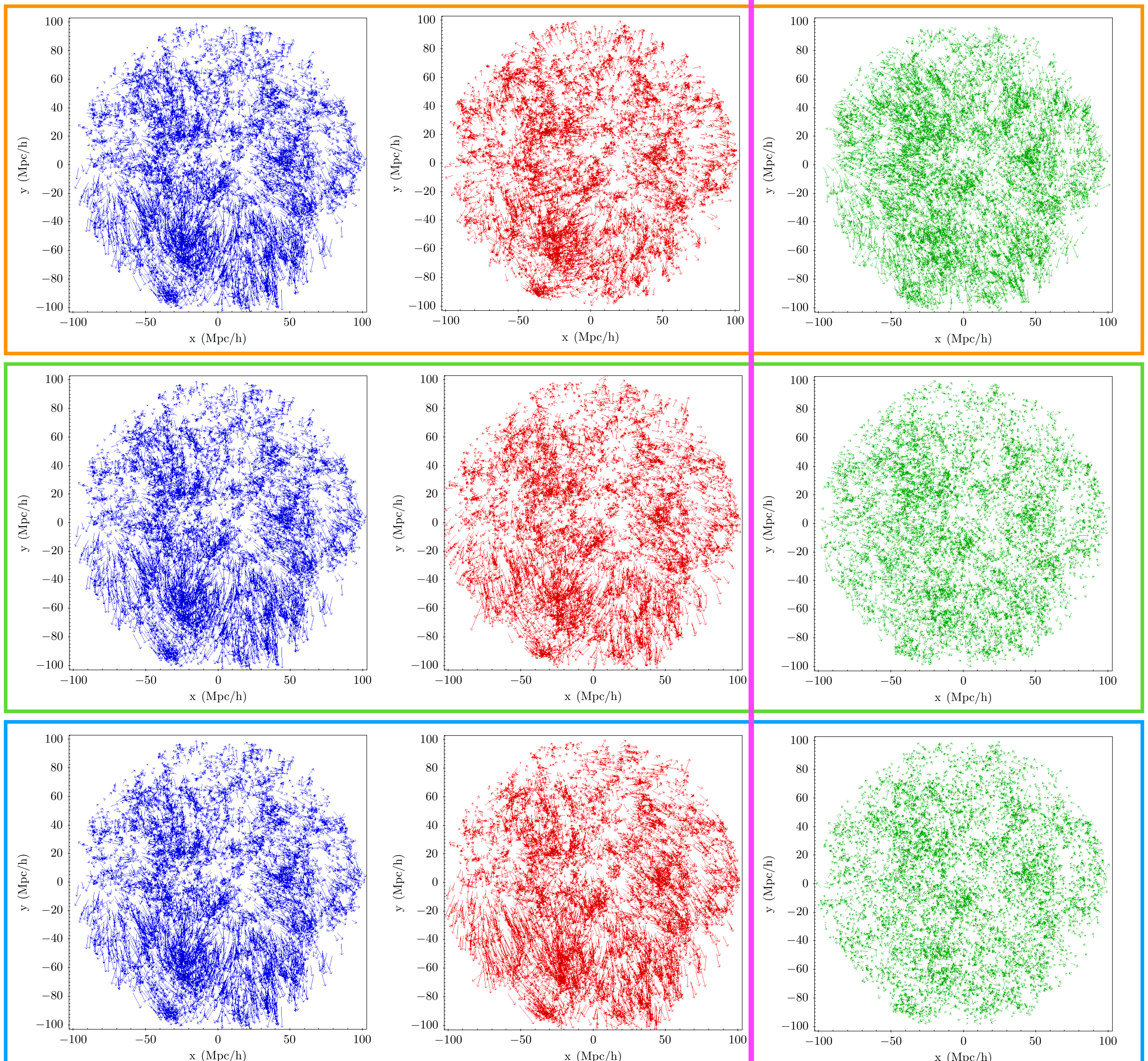
Orbits parametrisation: $$\mathbf{x}_i(D) = \mathbf{x}_{i,\mathrm{obs}} + \sum_{n=0}^{M} \mathbf{C}_{i,n} q_n(D).$$

Minimisation: $$\mathbf{C}_{i,n} \; : \; \frac{\partial S}{\partial \mathbf{C}_{i,n}} = 0$$

Recovering the bulk flow

Input | V_{Nbody} | V_{eFAM} | $V_{Nbody}-V_{eFAM}$ | **Output**

r_{int} +100 Mpc/h



Inclusion of External density field r_{ext}

Velocity Residuals

r_{int} +200 Mpc/h

Recovering the bulk flow

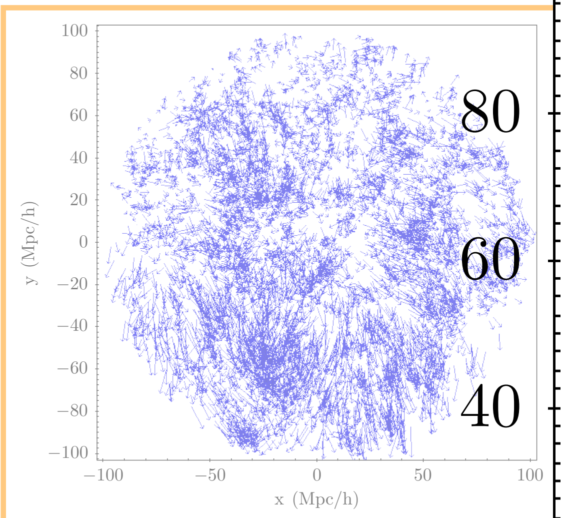
Input

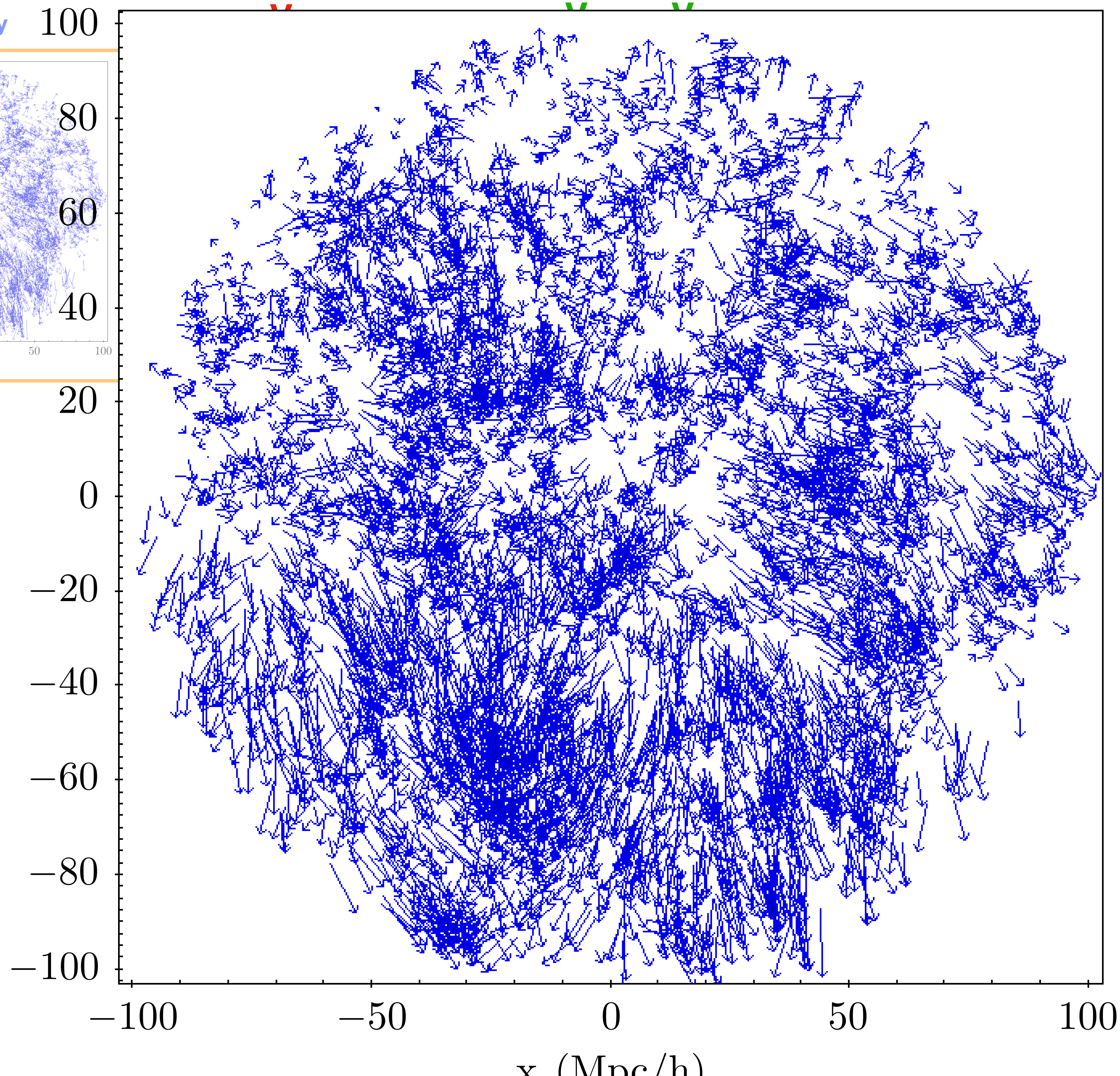
r_{int} + 100 Mpc/h

Inclusion of External density field r_{ext}

r_{int} + 200 Mpc/h

v_{Nbody}





Recovering the bulk flow

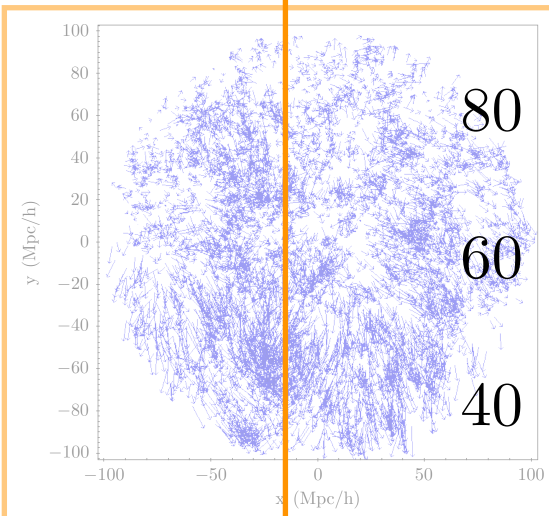
Input

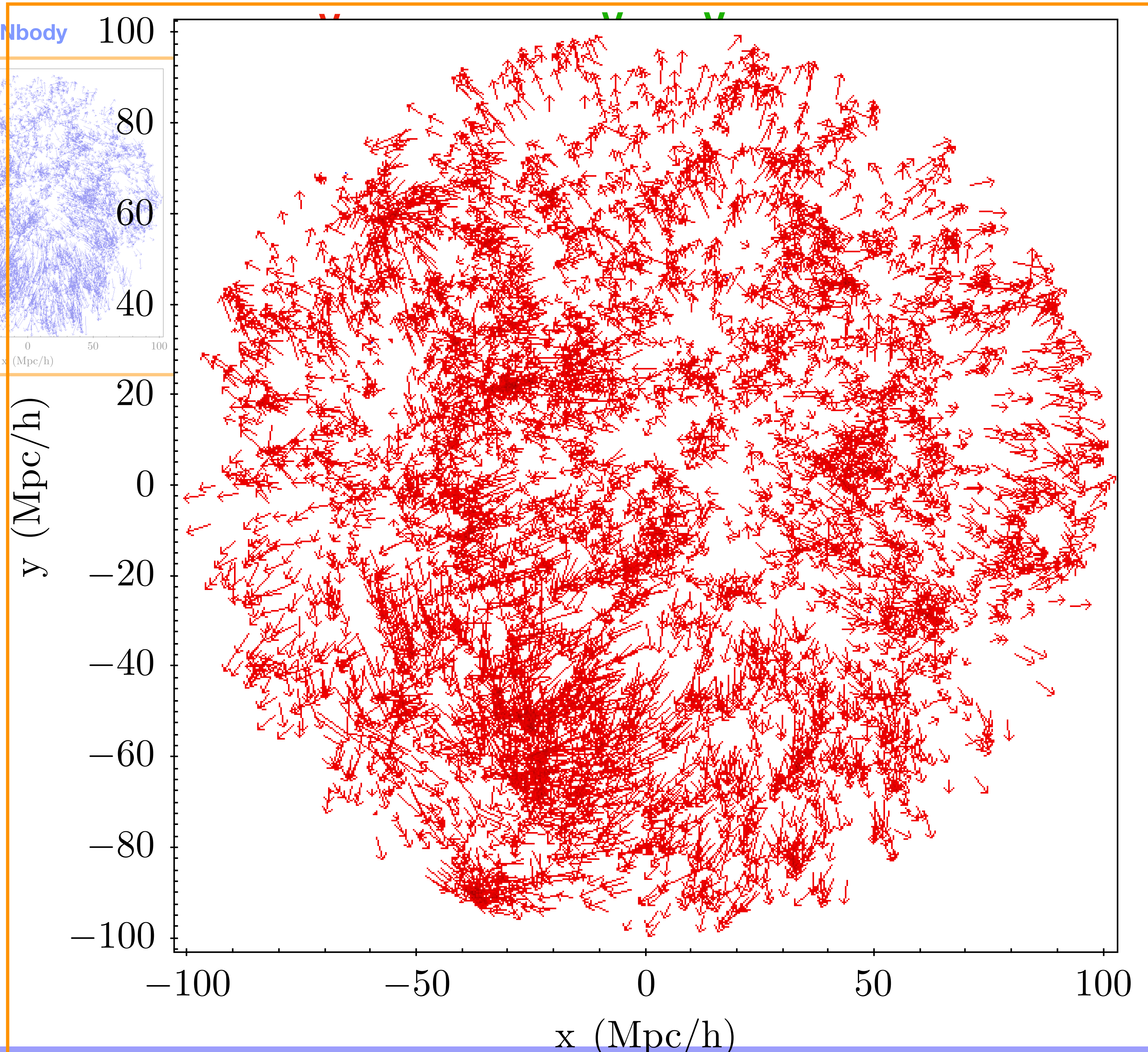
r_{int} + **100** Mpc/h

Inclusion of
External density field
r_{ext}

r_{int} +200 Mpc/h

V_{Nbody}



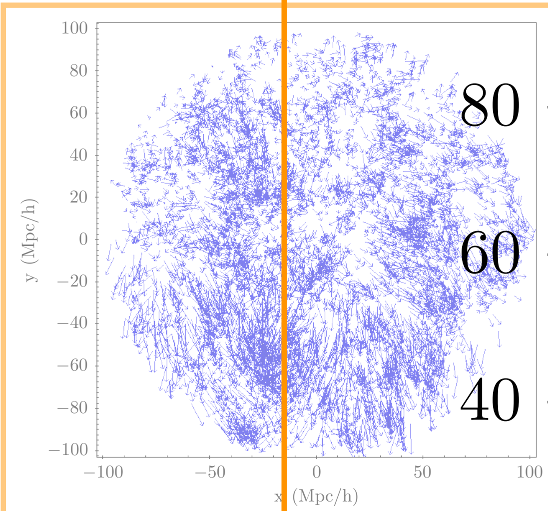


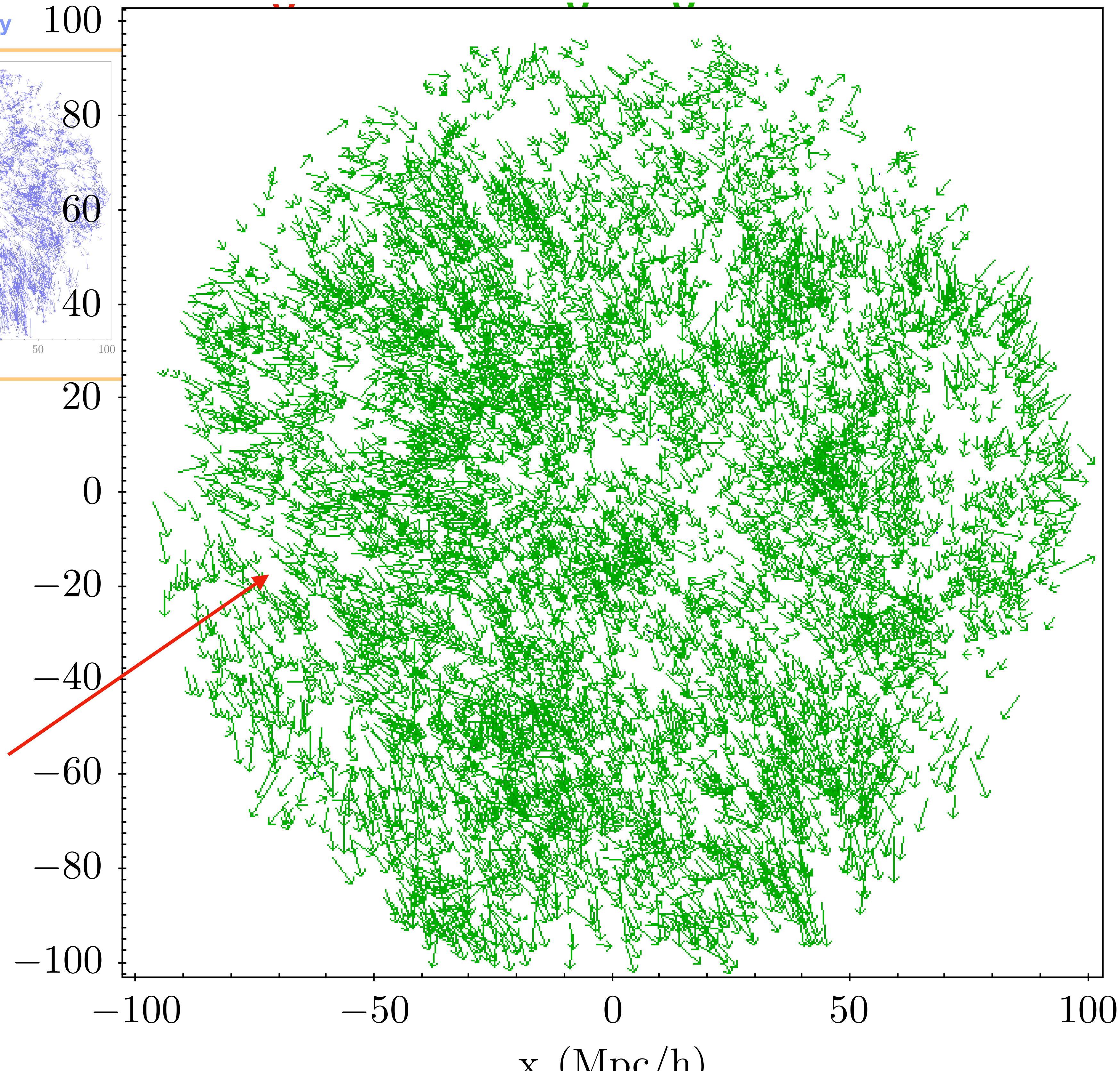
Recovering the bulk flow

Input

r_{int} + **100** Mpc/h

V_{Nbody}





Inclusion of External density field r_{ext}

Residuals == bulk flow

r_{int} +200 Mpc/h

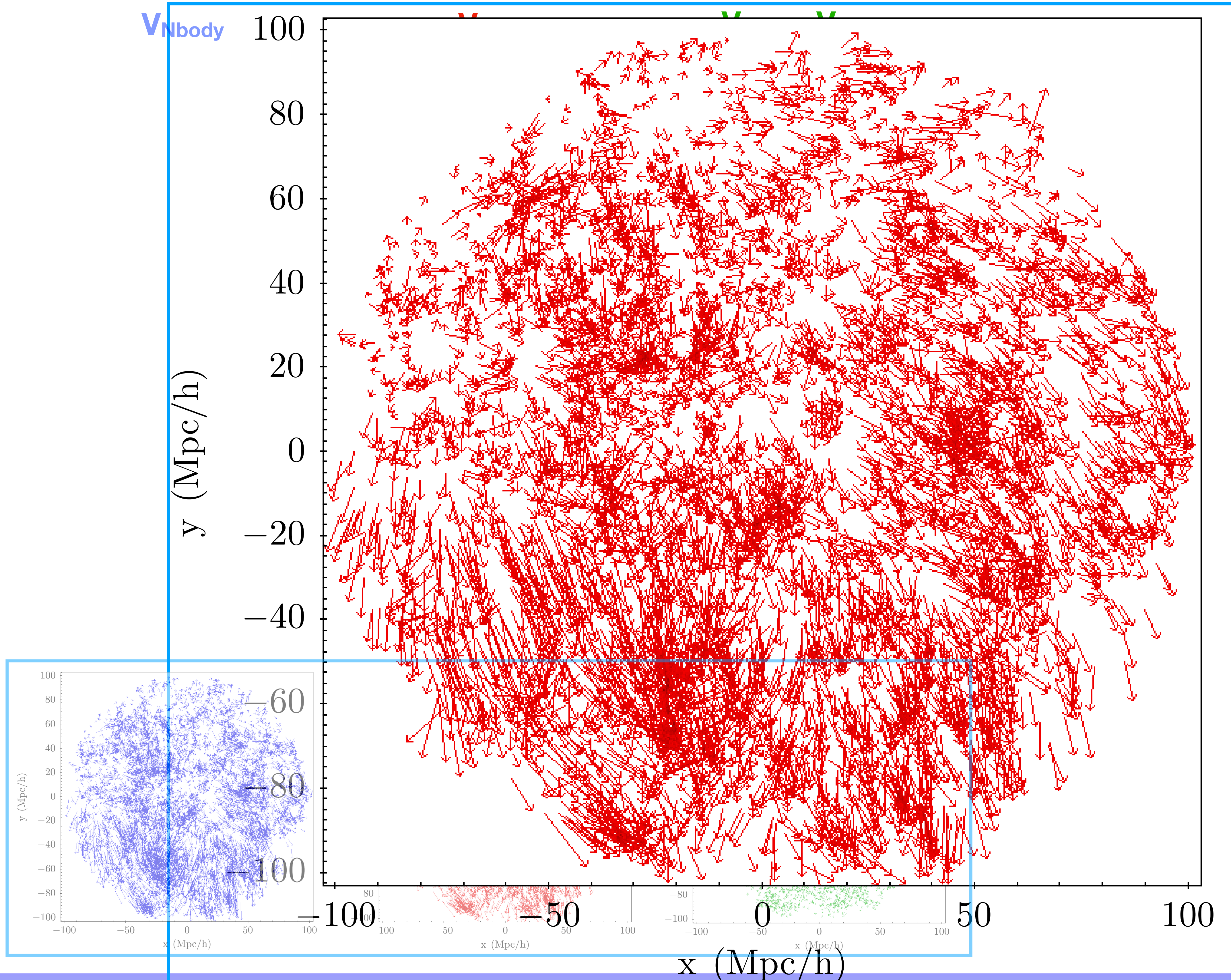
Recovering the bulk flow

Input

r_{int} +100 Mpc/h

Inclusion of External density field r_{ext}

r_{int} +200 Mpc/h



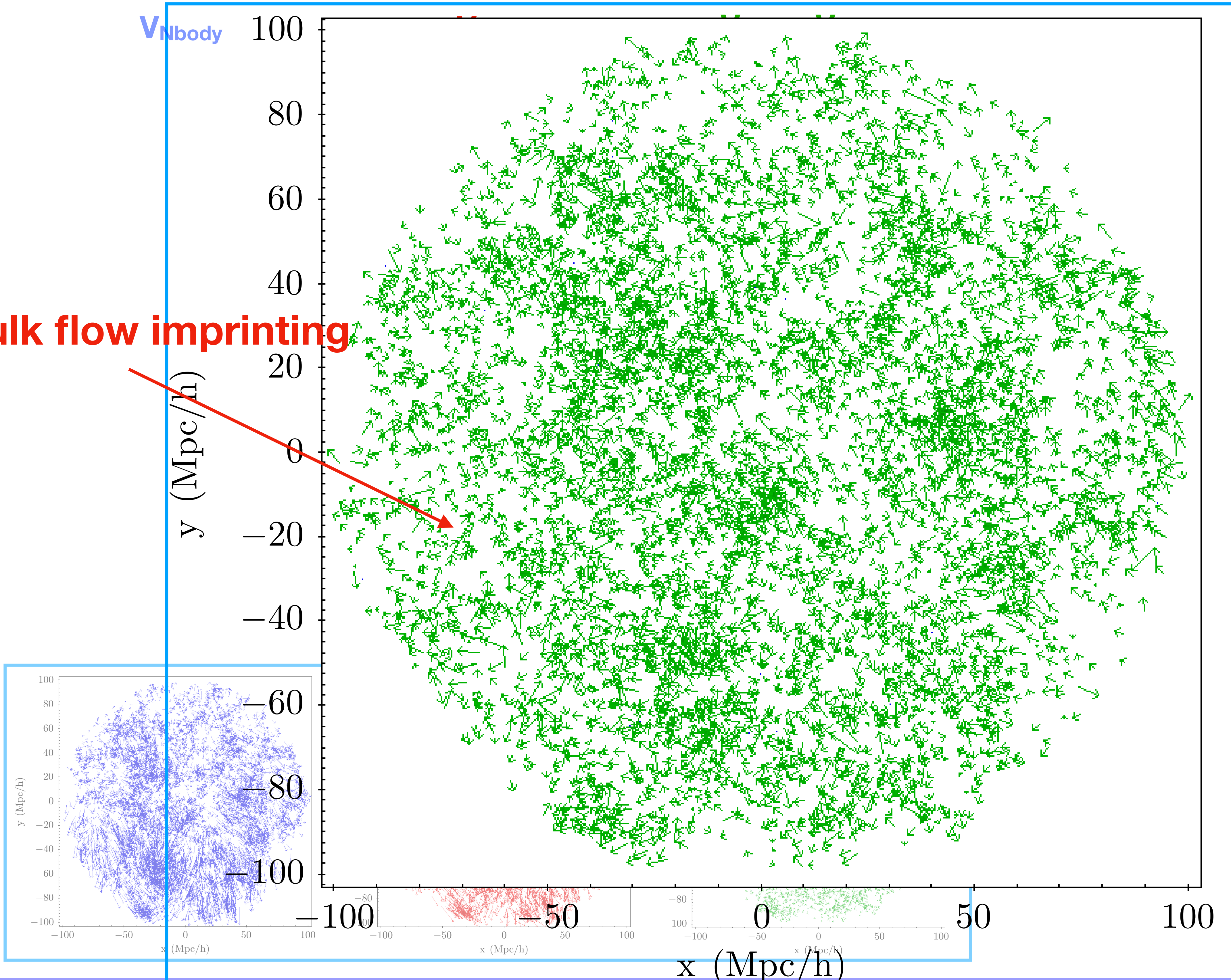
Recovering the bulk flow

Input

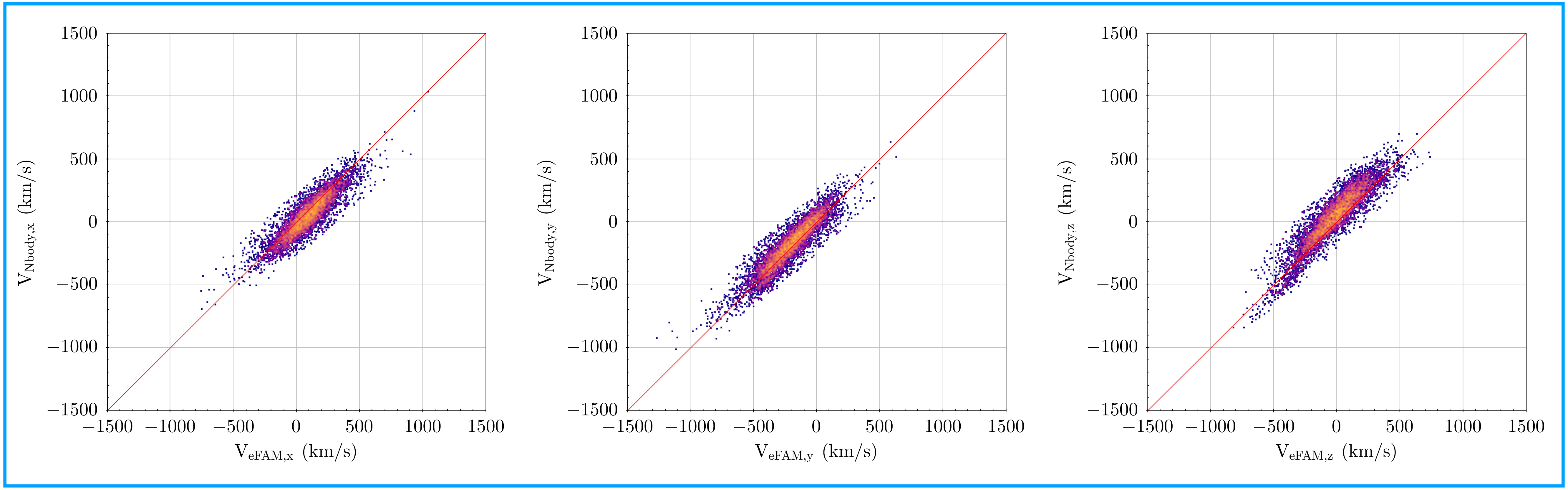
r_{int} +100 Mpc/h

Inclusion of
External density field
r_{ext}

r_{int} +200 Mpc/h



V_{eFAM} vs. V_{Nbody}



	Slope	Bulk flow (km/s)	RMS of residuals (km/s)
Vx	**0.845** +/- 0.006	-21 +/- 1	78
Vy	**0.920** +/- 0.005	8 +/- 2	81
Vz	**0.981** +/- 0.006	63 +/- 1	91

eFAM accurately recovers the velocity field!

With no need of any smoothing

BAO reconstruction

Probing Non-linear dynamics

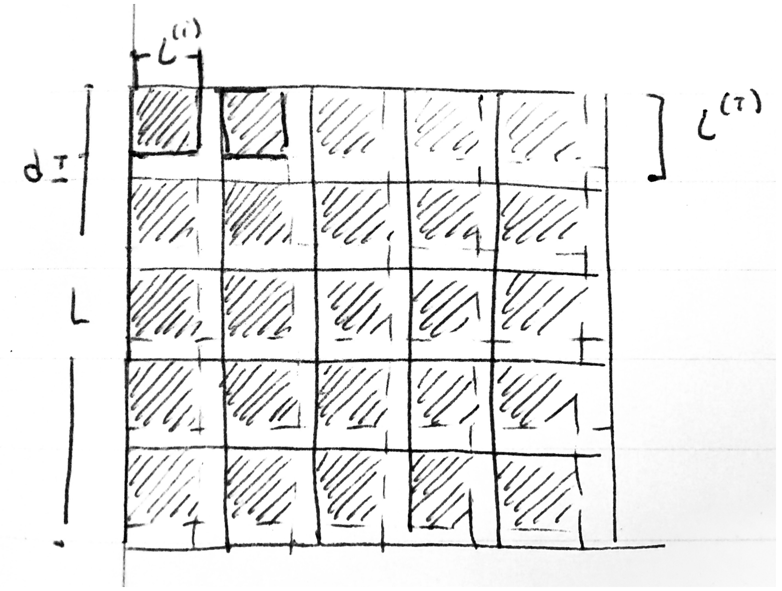
Simulation: DEUS-FUR

$z = 0$	$M_{halo} > 10^{12} M_{sun}$ ~ 100 DM part	$L_{box} = 21$ Gpc h^{-1}	Cosmology: LCDM, WMAP7

Mocks: sub-cubes*

Cutting the Parent simulation into **512** Sub-cubes of **Lsub = 2 Gpc h^{-1} (N_{halos} ~ 23k)**
Separated by a 0.5 Gpc h^{-1} (Norberg et al. 2008)

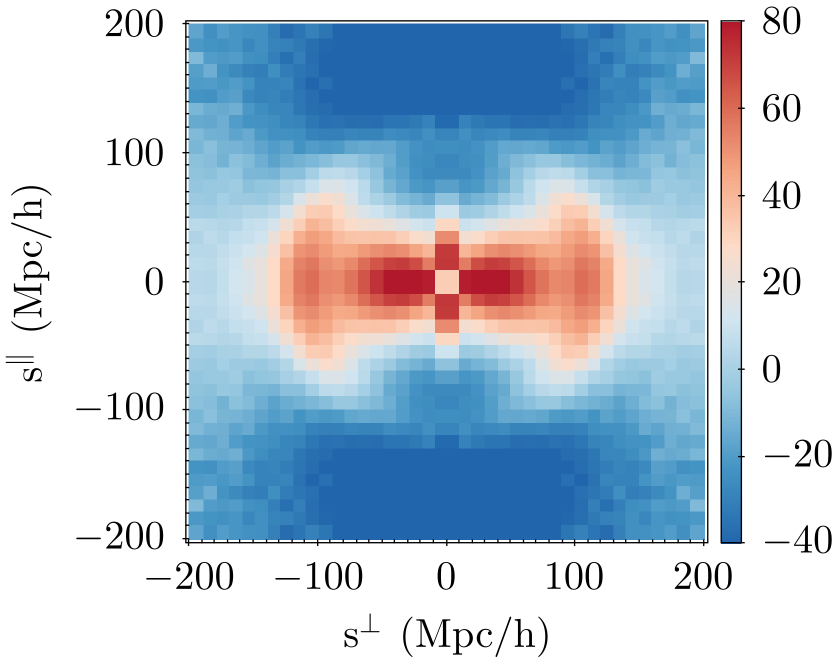
* *Non-linear* numerical action method instead of Lagrangian *perturbative* à la Padmanabhan



*** Pure N-body sim. ≠ COLA Mocks generated using 2LPT**

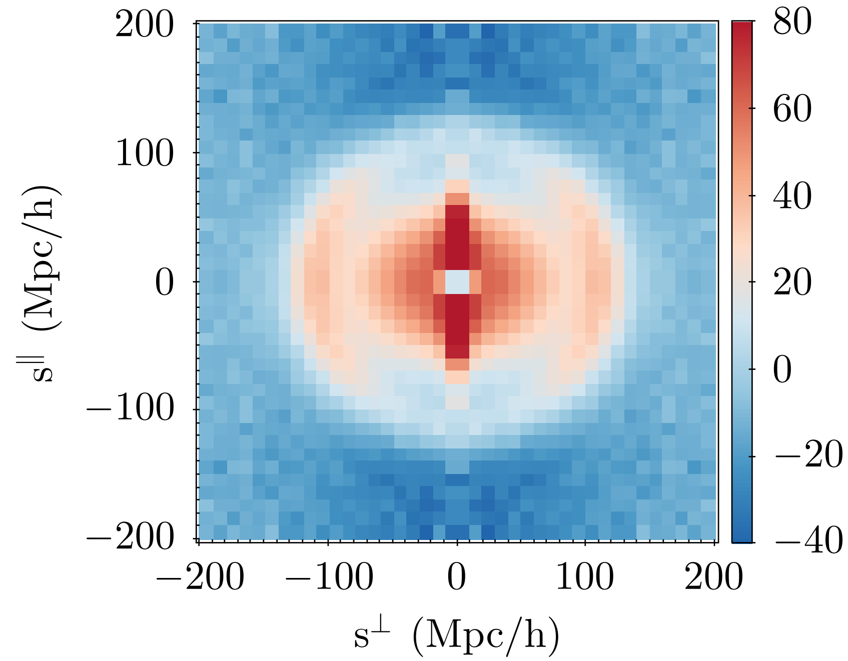
Recovering the monopole

Pre-rec



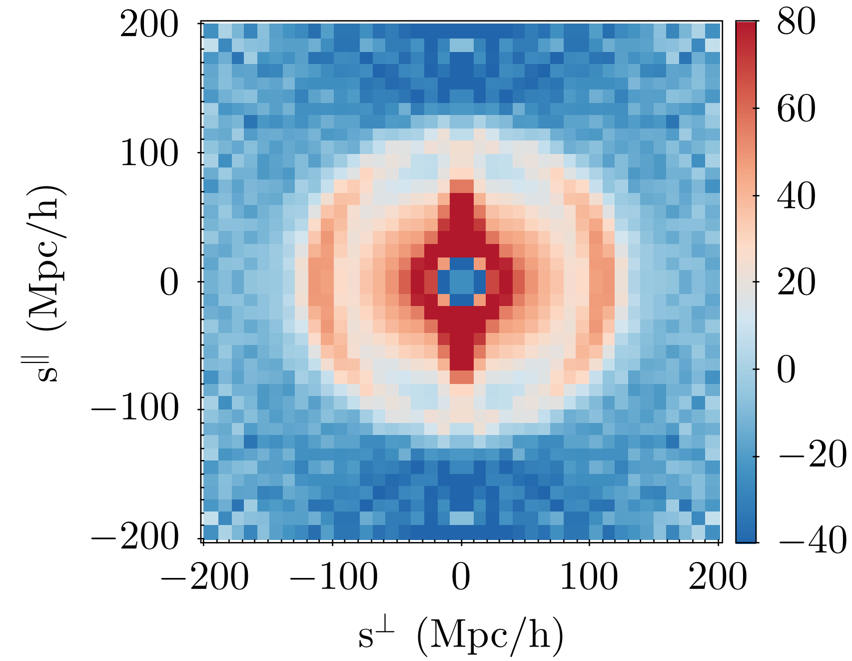
- Broadening: Non-linear RSD
- Squashing: linear RSD
- No clear BAO ring

Post-rec, z=0



- **Reduced broadening**
- **~ No squashing**
- Dumped BAO feature

Post-rec, z=33.6



- **~ No broadening**
- **No Squashing**
- **Clear BAO ring**

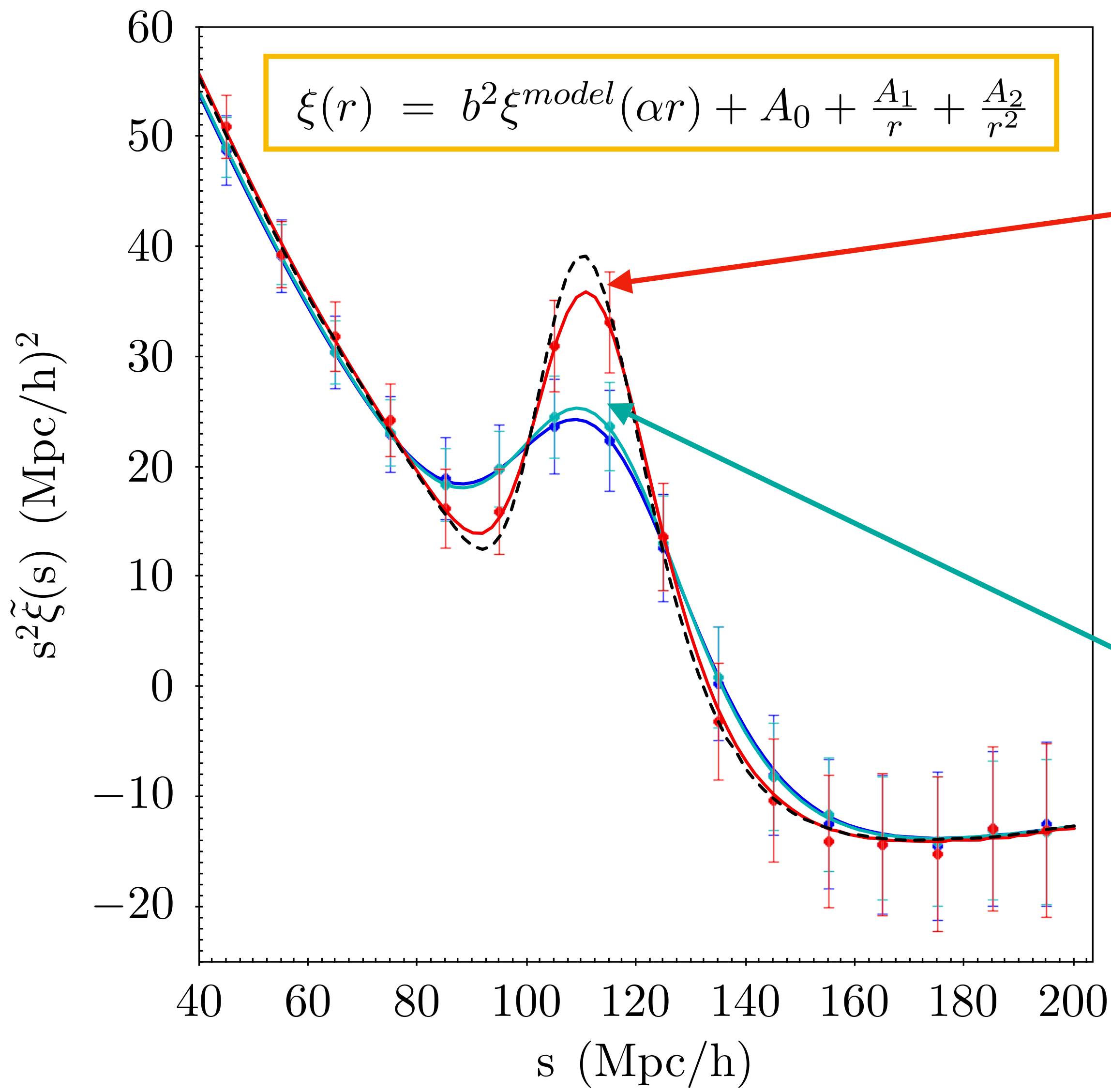
(Sarpa et al. 2018, in prep.)

Recovering the monopole

Angle averaged

	Pre Rec	Post Rec z=0	Post Rec z=33.6
α	1.007	1.005	0.997
σ_α	0.002	0.002	0.001
Σ_{nl}	(11.8 ± 0.3) Mpch^{-1}	(11.0 ± 0.3) Mpch^{-1}	**(4.0 ± 0.5) Mpch^{-1}**

- Pre reconstruction
- Post-reconstruction z=0
- Post-reconstruction z=33.6
- Linear theory



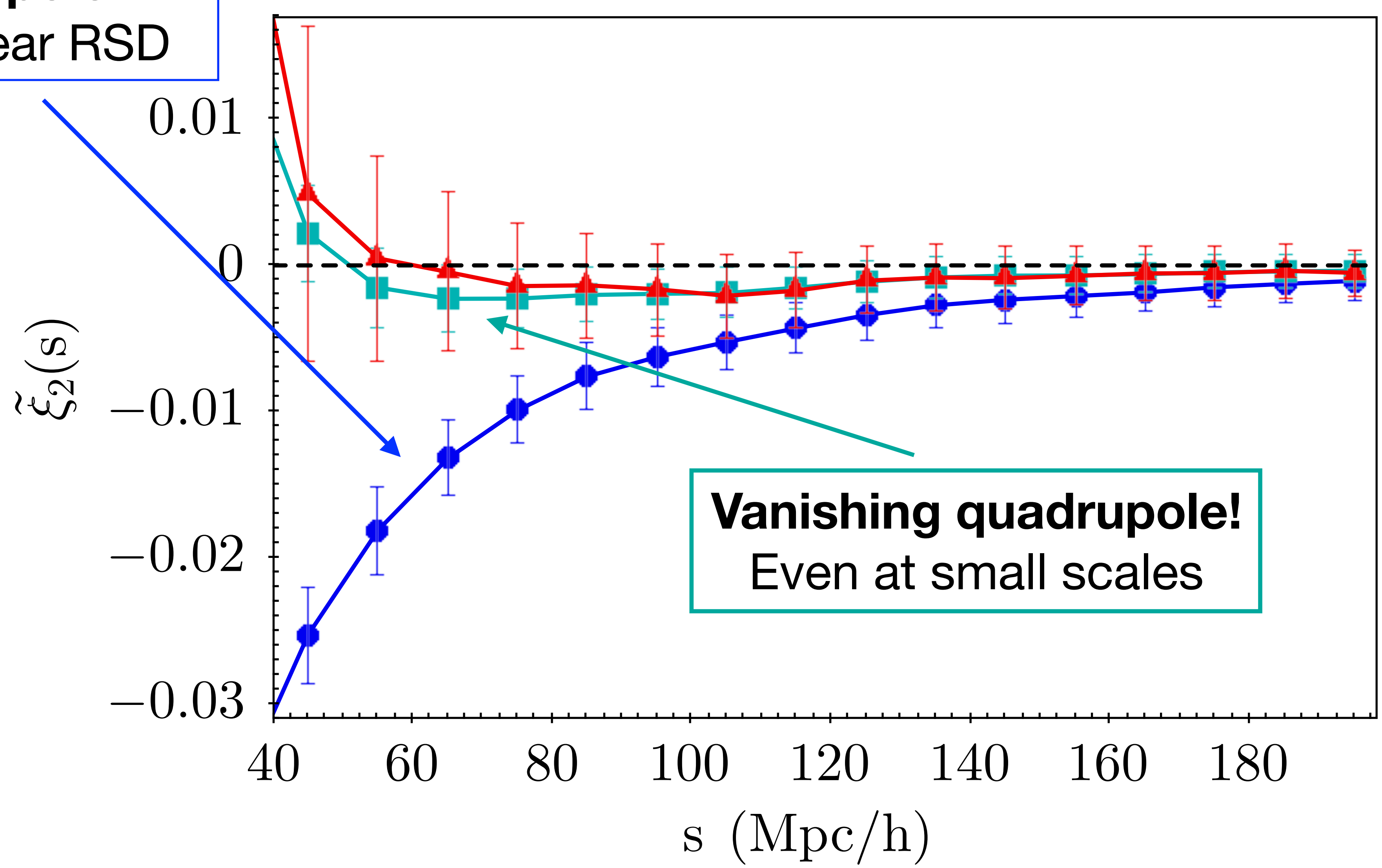
At z=33.6 non-linear evolution is almost completely reversed !

At z=0 the peak is slightly sharpened

(Sarpa et al. 2018, in prep.)

Recovering isotropy: the quadrupole

Non vanishing quadrupole
due to linear RSD



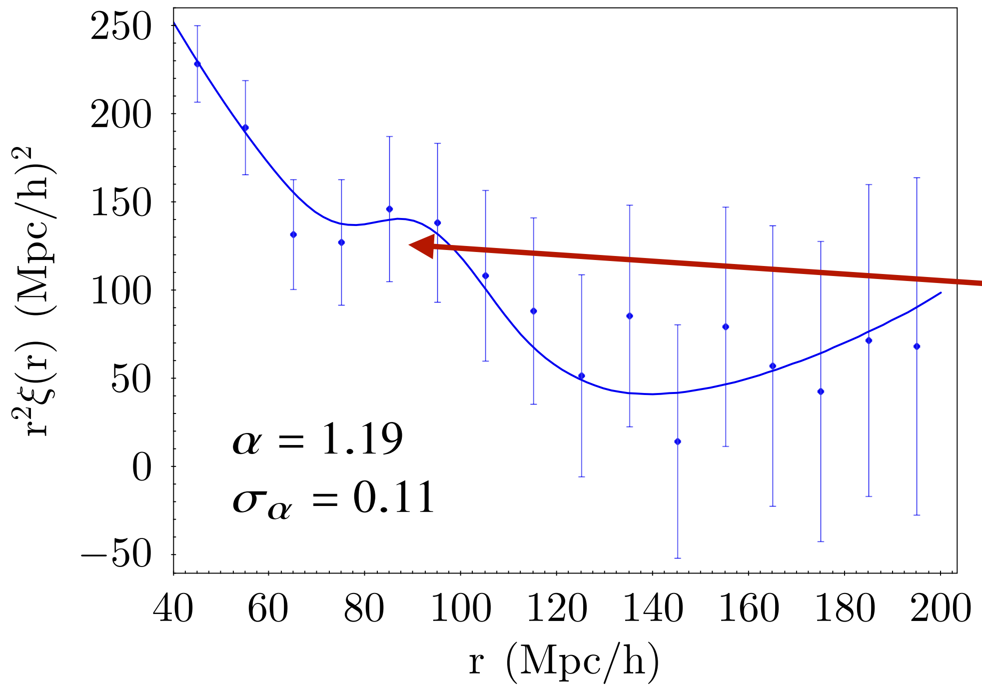
Vanishing quadrupole!
Even at small scales

(Sarpa et al. 2018, in prep.)

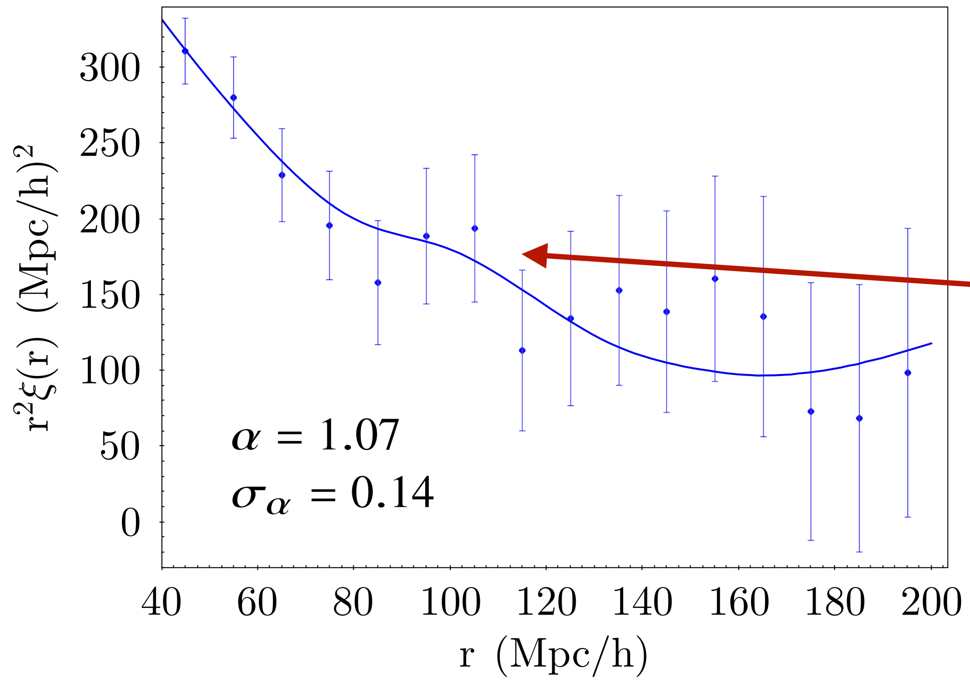
Pre reconstruction — Post-reconstruction z=0 — Post-reconstruction z=33.6 — Expected value

Beyond RSD …

Overcoming cosmic variance issues with eFAM



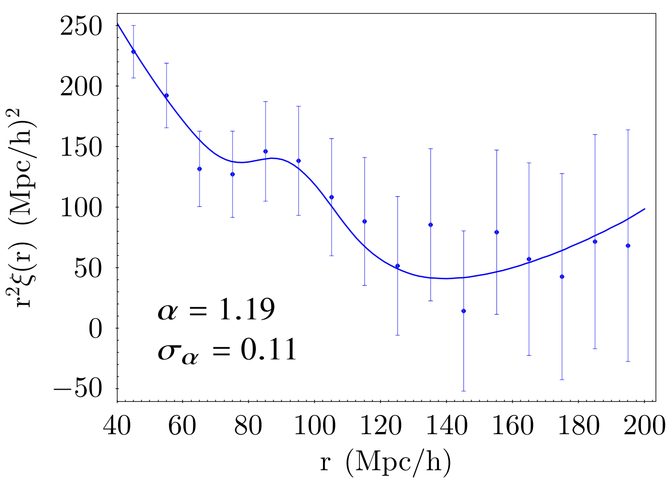
Shifted BAO peak

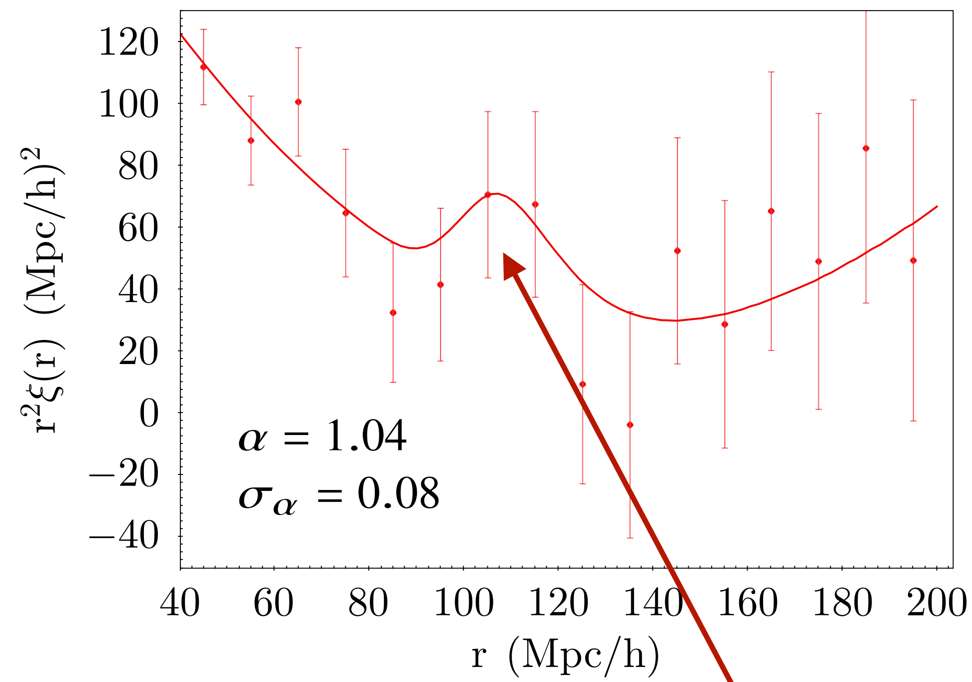


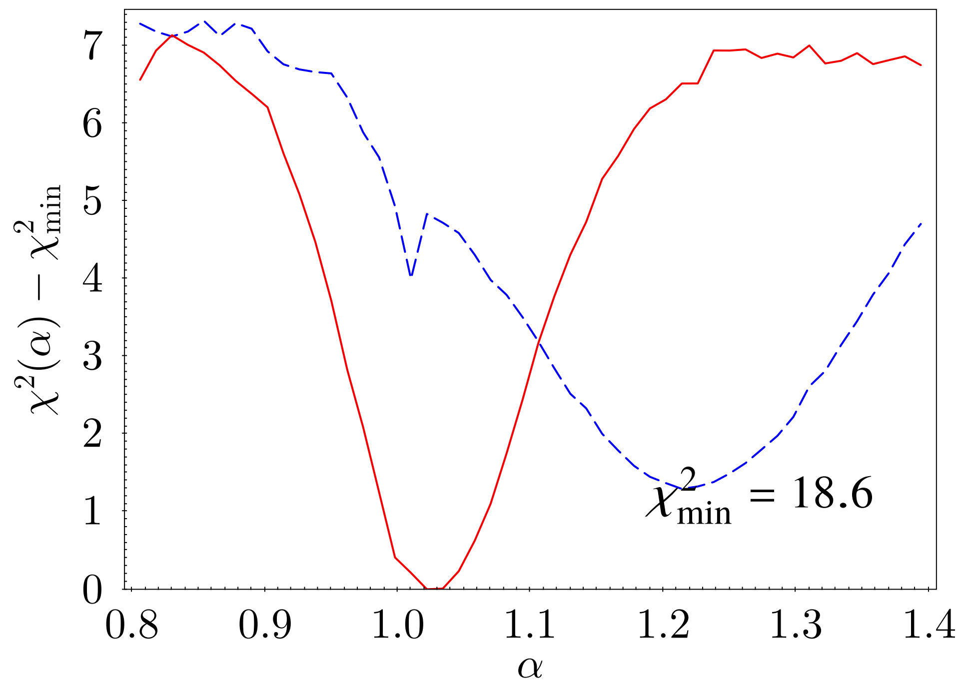
No clear BAO feature

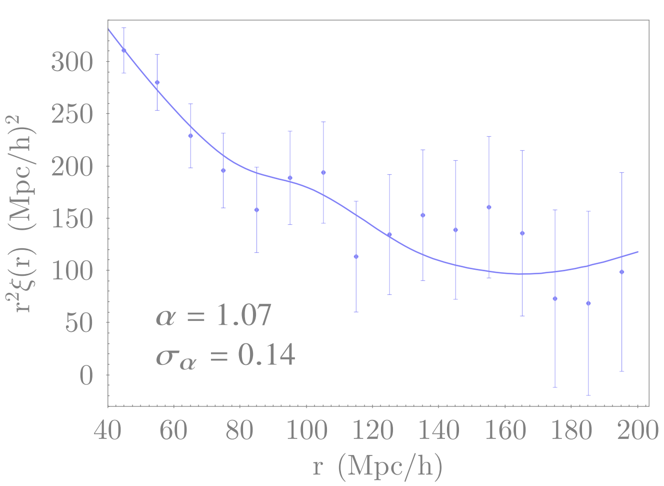
Beyond RSD …

Overcoming cosmic variance issues with eFAM







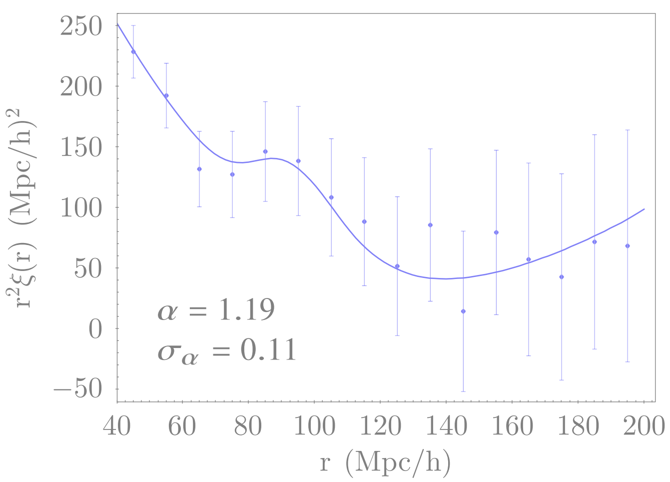


Peak shifted towards the correct value

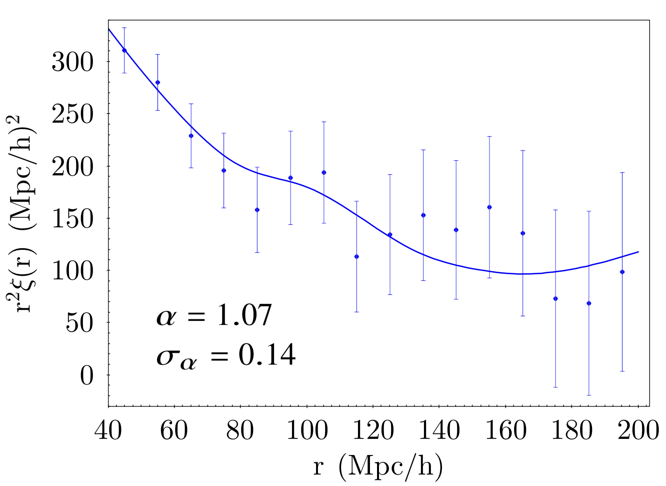
(Sarpa et al. 2018, in prep.)

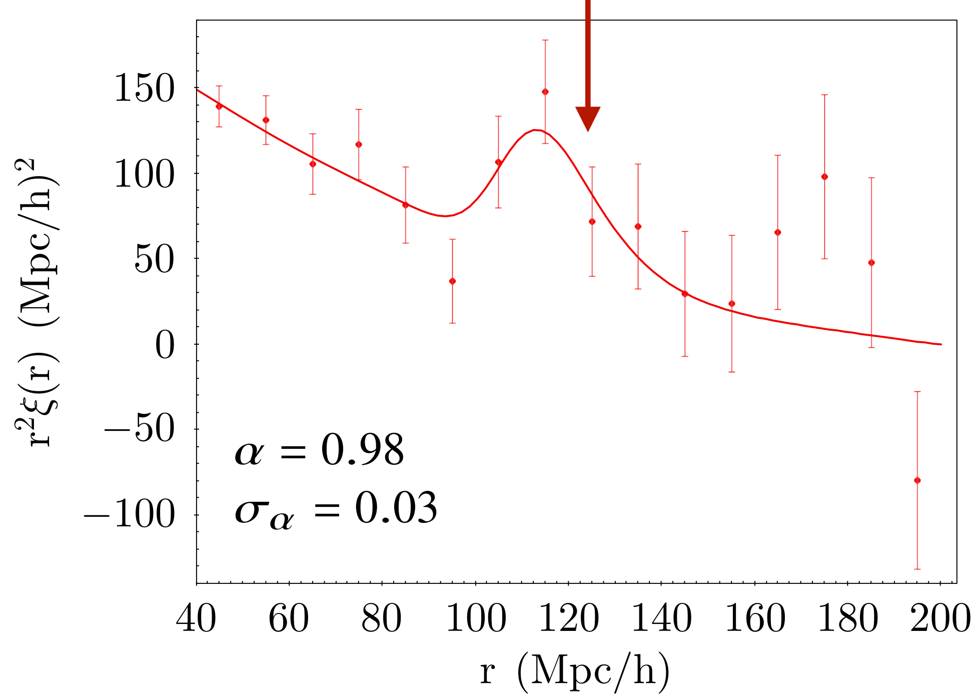
Beyond RSD …

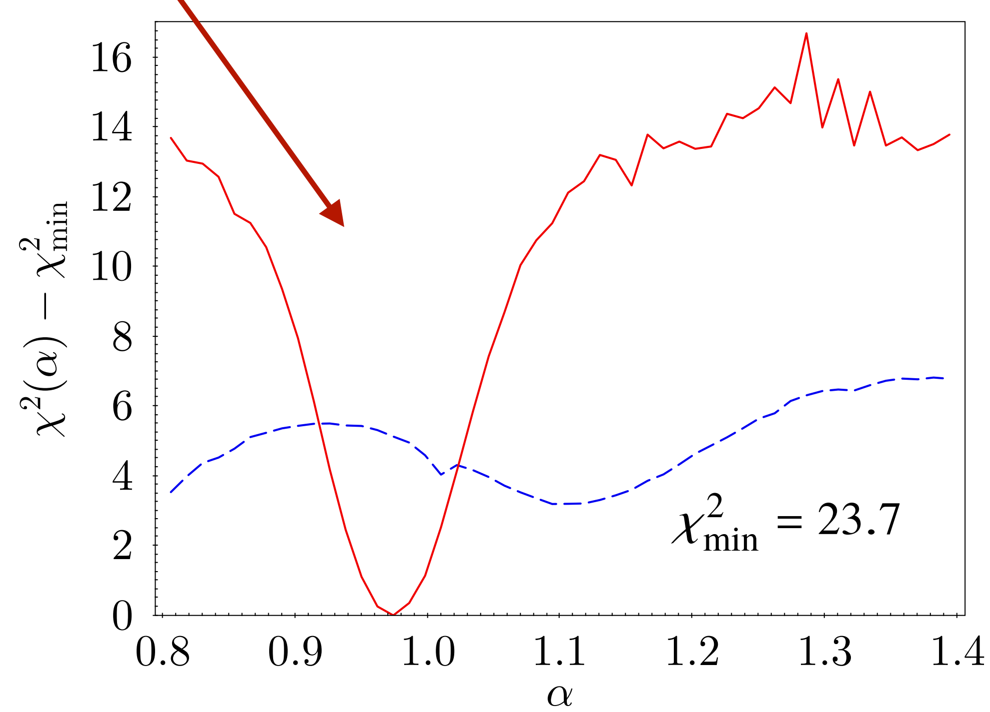
Overcoming cosmic variance issues with eFAM



Recovered BAO feature







(Sarpa et al. 2018, in prep.)

Summary

- eFAM efficiently recovers the velocity field
- eFAM efficiently restores the isotropy correcting for linear RSD already at the observed redshift
- eFAM efficiently sharpened the BAO features almost recovering the linear correlation function at high redshift
- eFAM improved the signal-to-noise ratio also for anomalous mocks

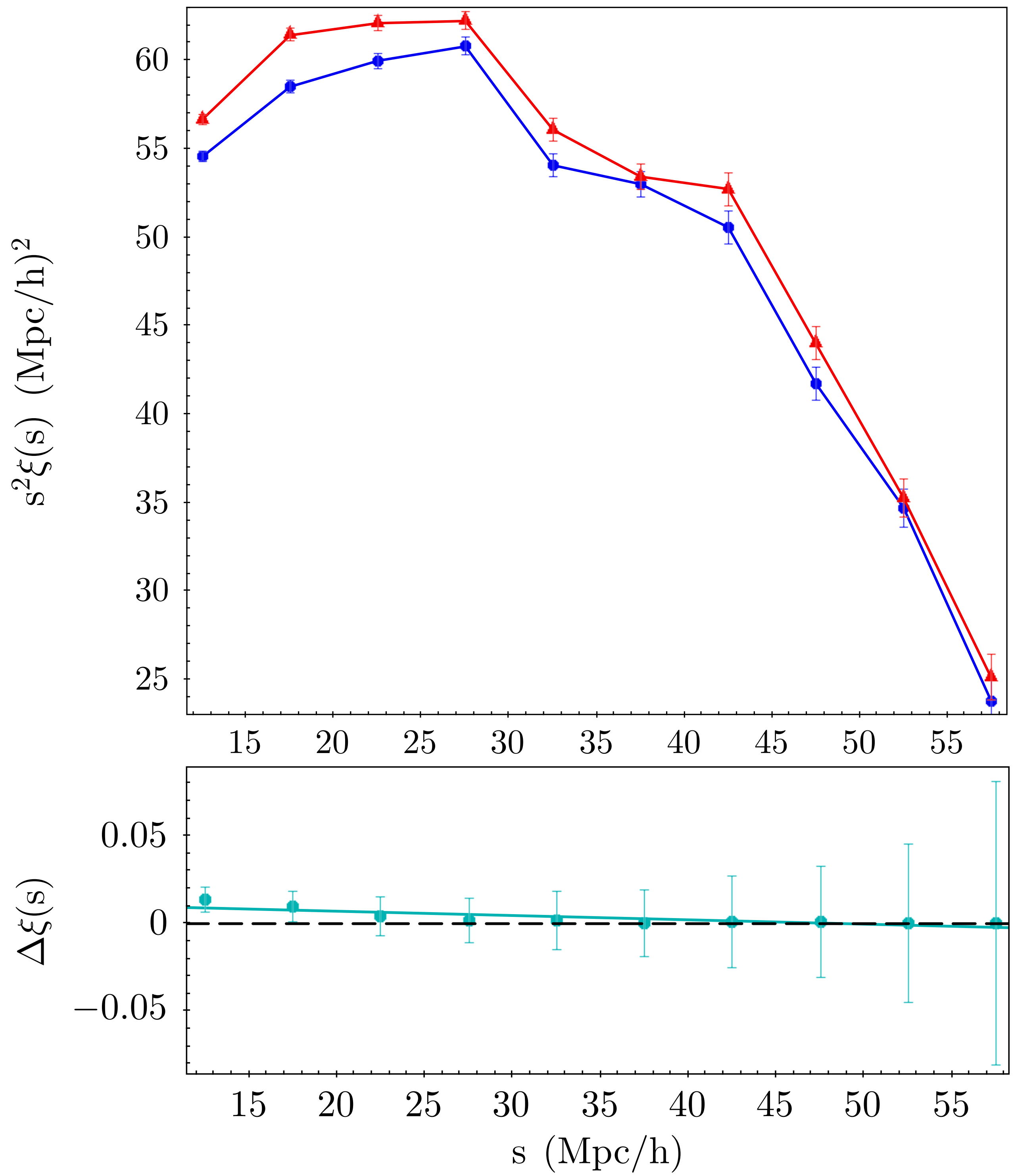
Future prospectives

- Apply eFAM to CosmicFlow-3 data comparing the reconstructed velocity field with the measured one
- Apply eFAM to mocks w/ pNG to improve its measurement disentangling it from RSD effects

Thanks for your attention

Backup slides

Coherent velocities



Comparison with ZA-based reconstruction