Turning dispersion into signal: density-split measurements of pairwise velocities

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July 2025

arXiv: 2505.00608

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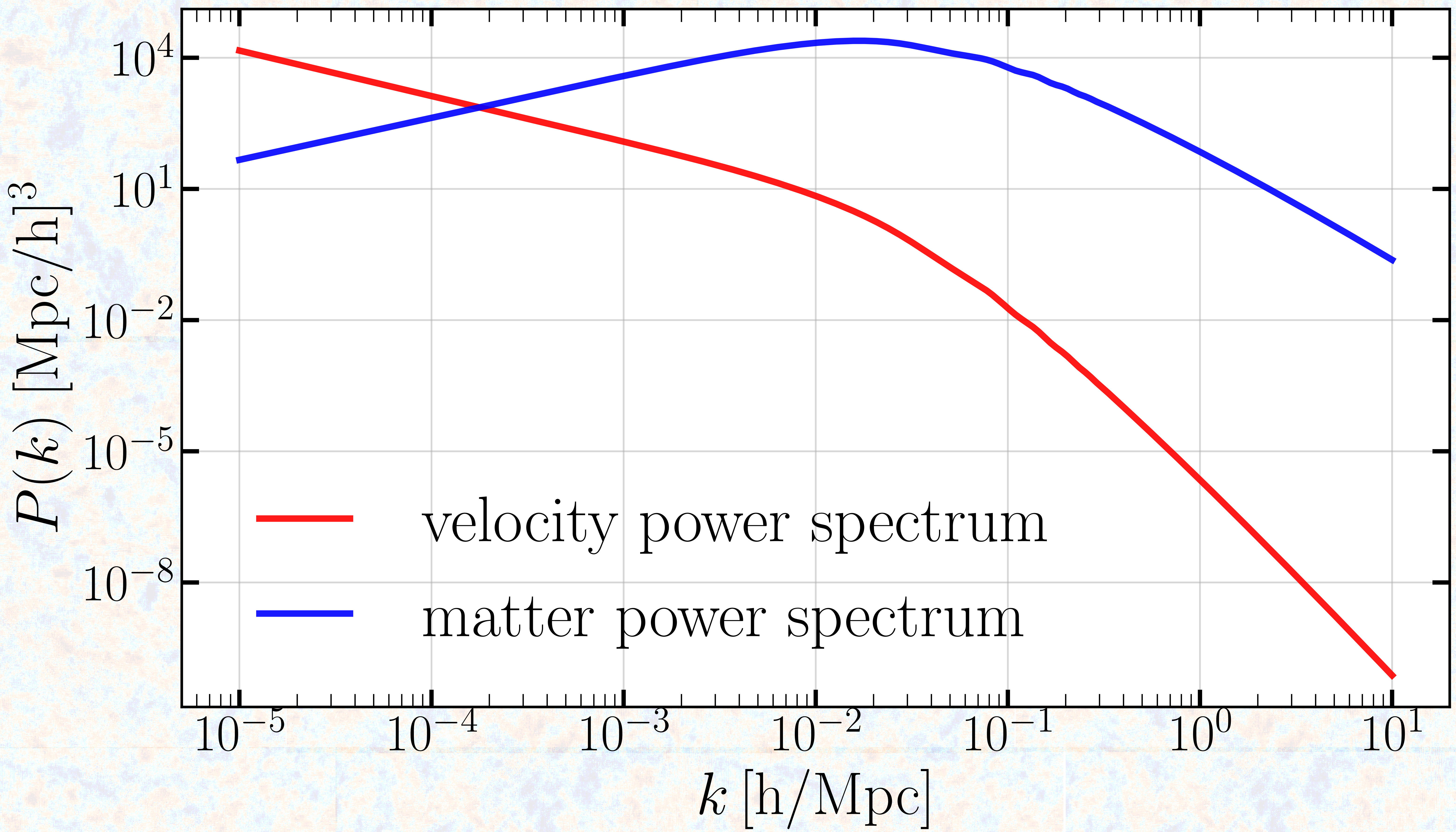
The peculiar velocity field

Homogeneous distribution

Sourced by inhomogeneities

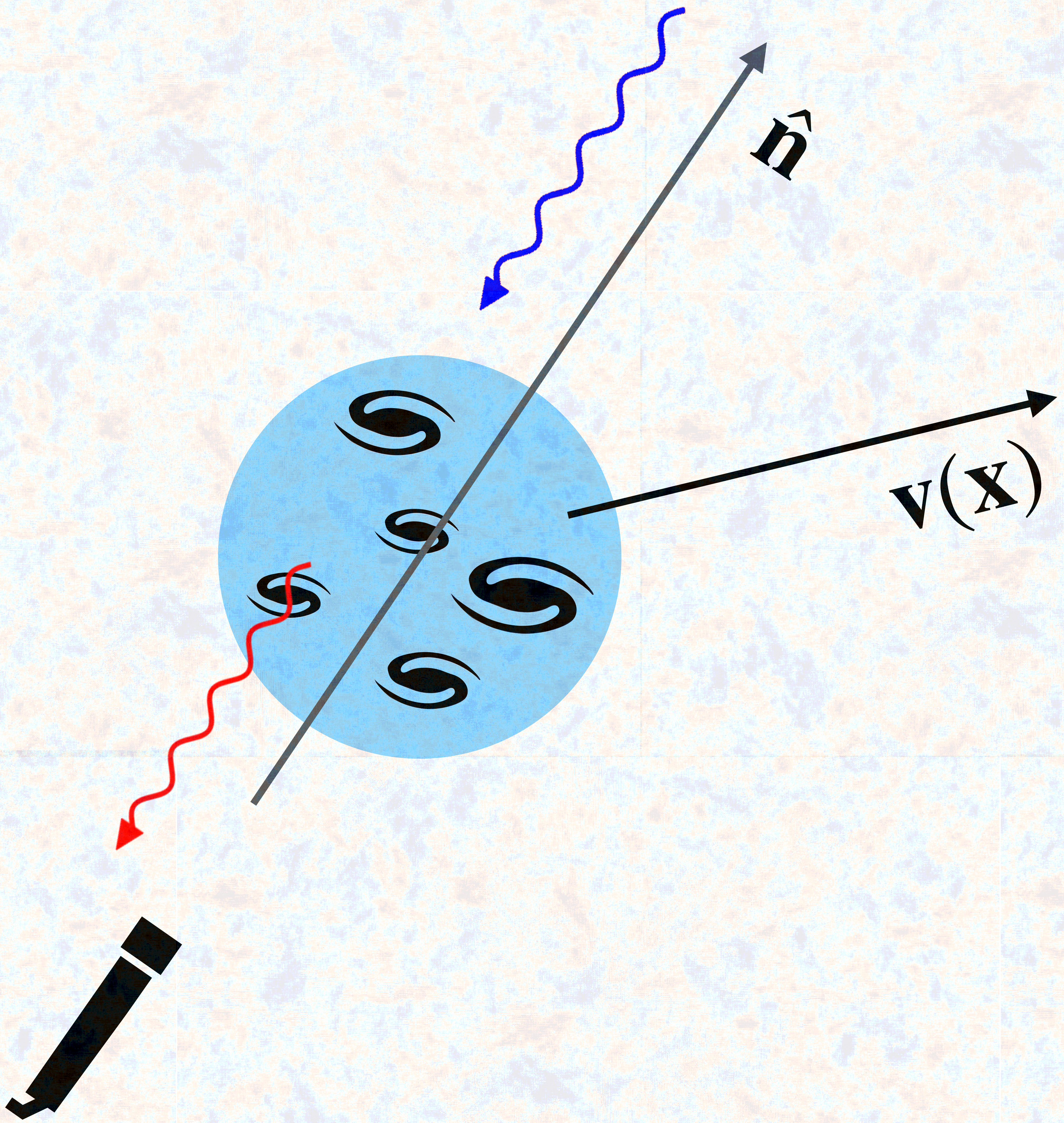
$$v = H_0\, d + v_{pec}$$



In Fourier space:

$$\mathbf{v_{pec}}(\mathbf{k}) = i\mathrm{afH}\,\frac{\delta_{\mathbf{k}}}{k^2}\,\mathbf{k}$$

The kinetic SZ effect



$$\frac{\Delta T}{T_{\rm CMB}}(\hat{\mathbf{n}}) = \tau_{\rm eff} \left(\mathbf{v}(\mathbf{x}) \cdot \hat{\mathbf{n}}\right) \equiv \mathscr{T}(\hat{\mathbf{n}})$$

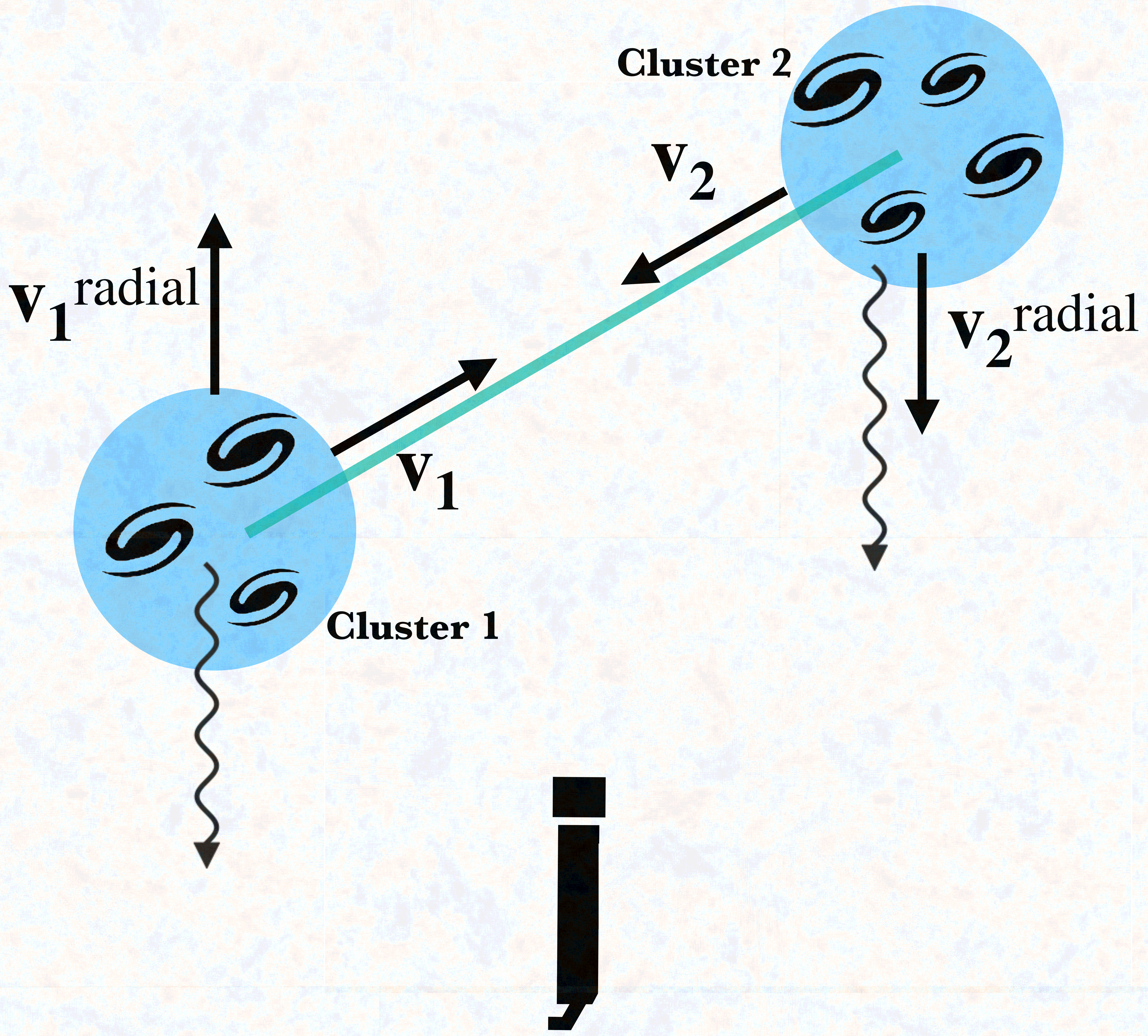
$\tau_{\rm eff} \sim 10^{-4}$

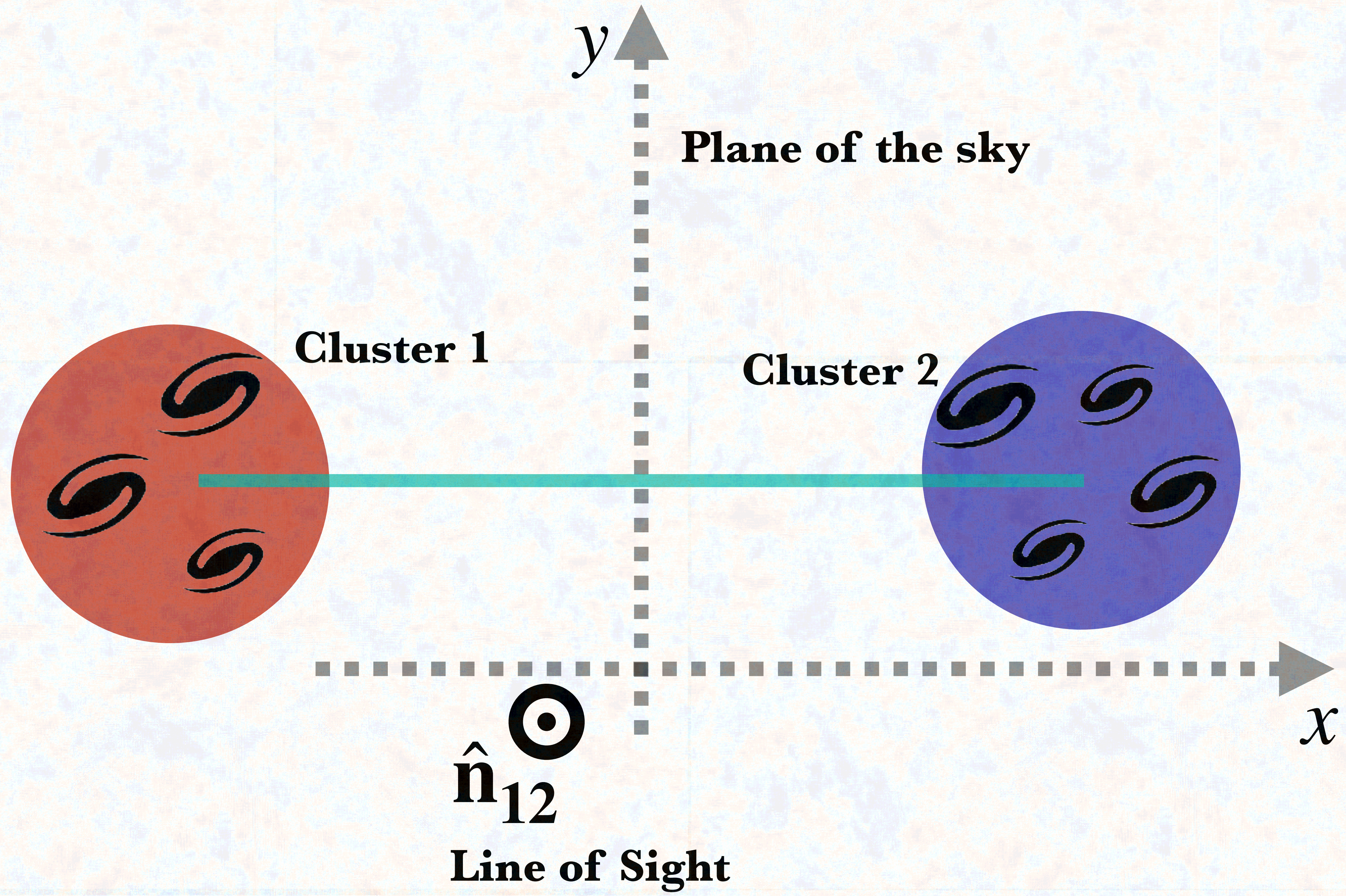
$v_r \sim 10^{-3}$

$$\frac{\Delta T}{T_{\rm CMB}} \sim 0.1\ \mu K$$

1. The pairwise kSZ effect

Two galaxy clusters falling towards each other will induce a kSZ effect of opposite signs





Pairwise kSZ estimator

$$\hat{T}_{\text{pairwise}} = \sum_i w_i \left(\mathscr{T}_{i1} - \mathscr{T}_{i2}\right)$$

All the cosmological information present

$$\hat{T}_{\text{pairwise}} = \sum_i \tau^i_{eff}\, w_i \left(\mathbf{v}_{i1} - \mathbf{v}_{i2}\right) \cdot \hat{n}_i$$

Pairwise velocity statistics

Theory

$$\bar{v}^p(r) = \left\langle \left(\mathbf{v_1}(\mathbf{r_1}) - \mathbf{v_2}(\mathbf{r_2})\right) \cdot \left(\frac{\mathbf{r_1} - \mathbf{r_2}}{|\mathbf{r_1} - \mathbf{r_2}|}\right) \right\rangle$$

$$\bar{v}^p(r) = \frac{\left\langle \left(\mathbf{v_1} - \mathbf{v_2}\right) \cdot \hat{\mathbf{r}}\,(1+\delta_1)(1+\delta_2) \right\rangle}{\left\langle (1+\delta_1)(1+\delta_2) \right\rangle}$$

$$\bar{v}^p(r) = -\frac{2}{3}\frac{[\mathrm{afH}](z)\,\bar{\xi}(r)}{1+\xi(r)}$$

Pairwise velocity statistics

Theory

$$\bar{v}^p(r) = \left\langle \left(\mathbf{v_1}(\mathbf{r_1}) - \mathbf{v_2}(\mathbf{r_2})\right) \cdot \left(\frac{\mathbf{r_1} - \mathbf{r_2}}{|\mathbf{r_1} - \mathbf{r_2}|}\right) \right\rangle$$

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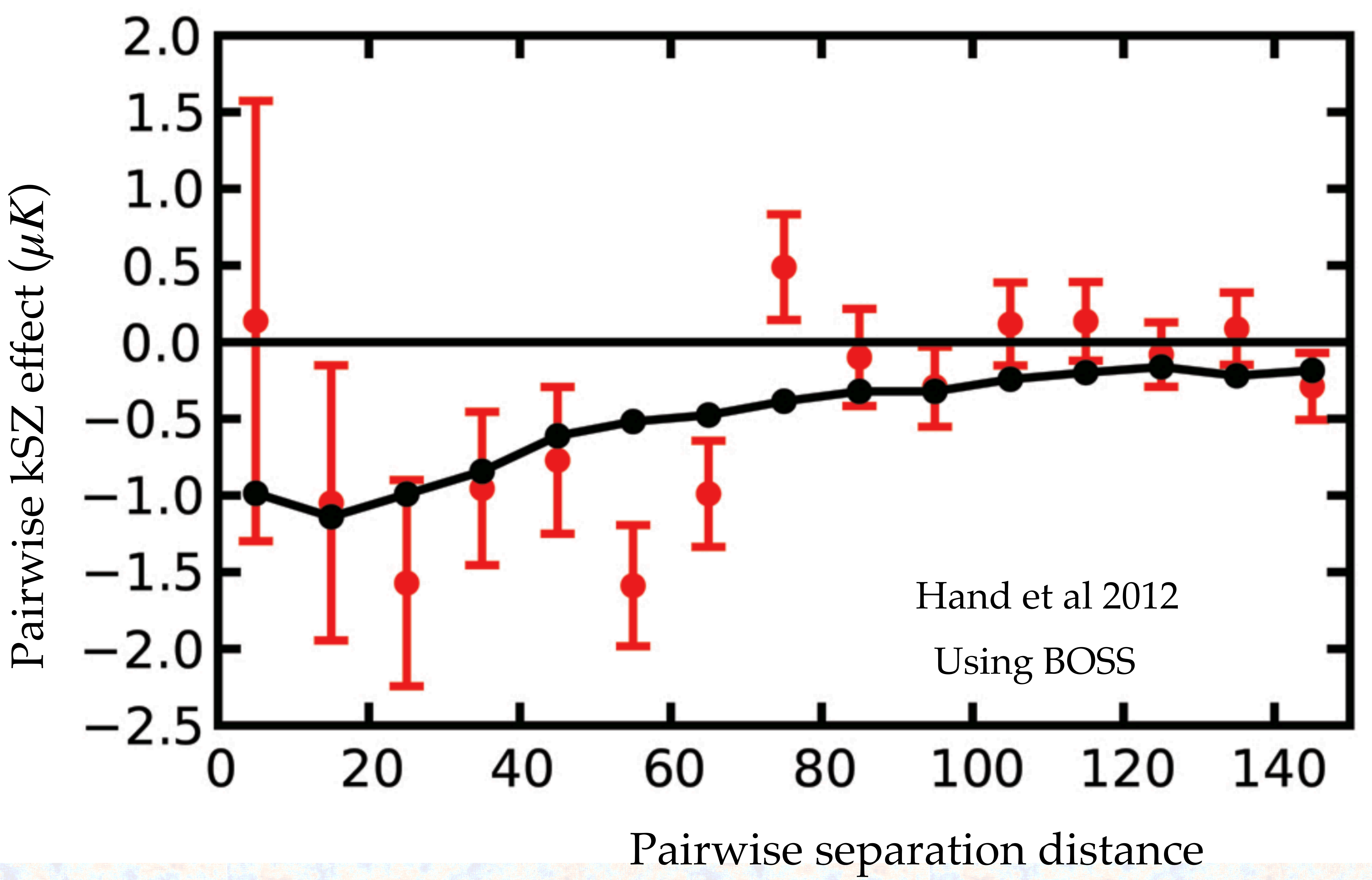
$$\bar{v}^p(r) = -\frac{2}{3}\frac{[\mathrm{afH}](z)\,\bar{\xi}(r)}{1+\,\xi(r)}$$

Observation

$$\bar{v}^p(r) = \sum_i \left[\left(\mathbf{v_1}(\mathbf{r_1}) - \mathbf{v_2}(\mathbf{r_2})\right) \cdot \left(\frac{\mathbf{r_1} - \mathbf{r_2}}{|\mathbf{r_1} - \mathbf{r_2}|}\right) \right]_i$$

Detection of pairwise kSZ effect



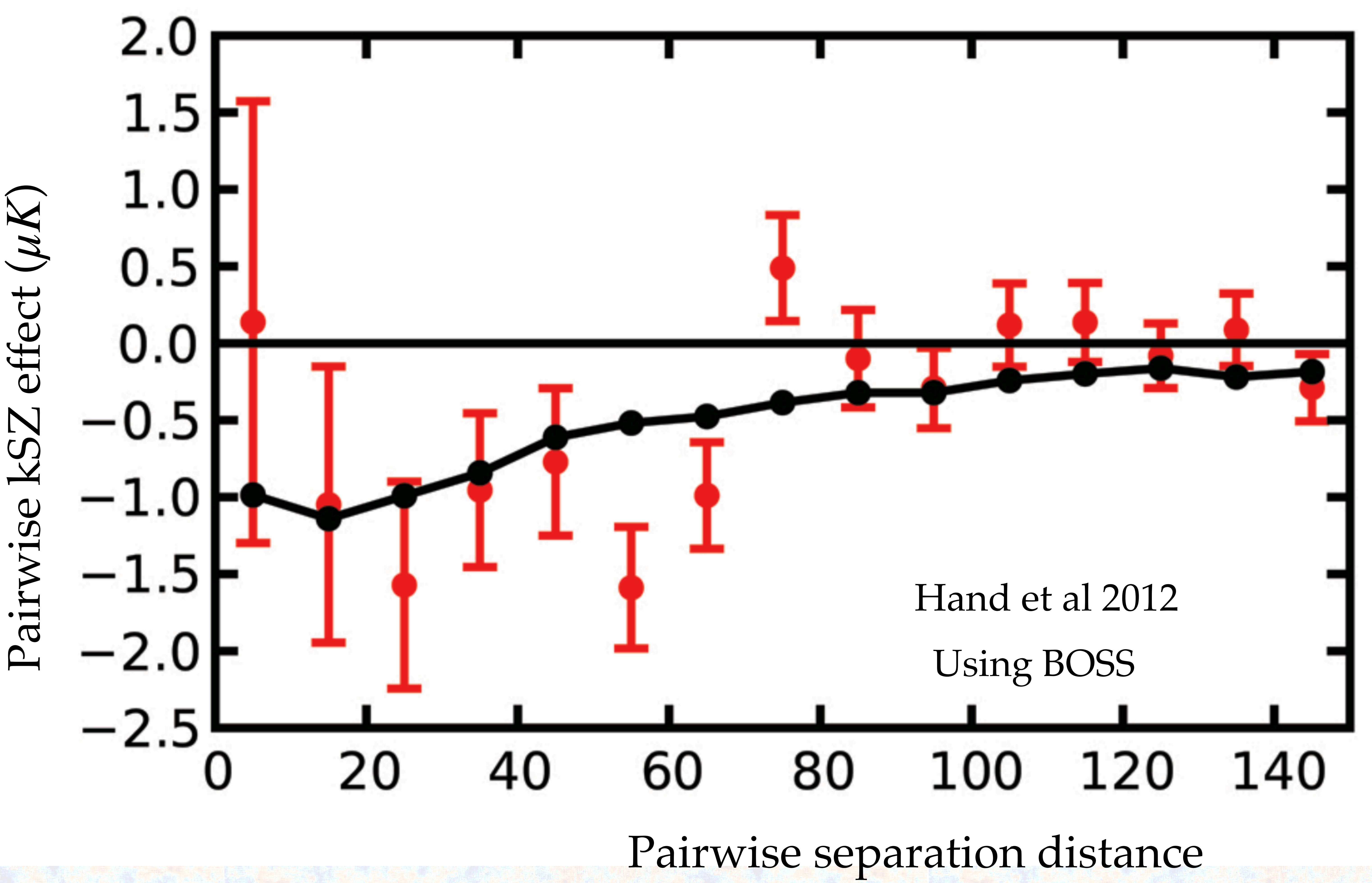
Mueller et al 2014

Soergel et al 2016

Schiappucci et al 2022

Gong et al 2024, 2025

Detection of pairwise kSZ effect



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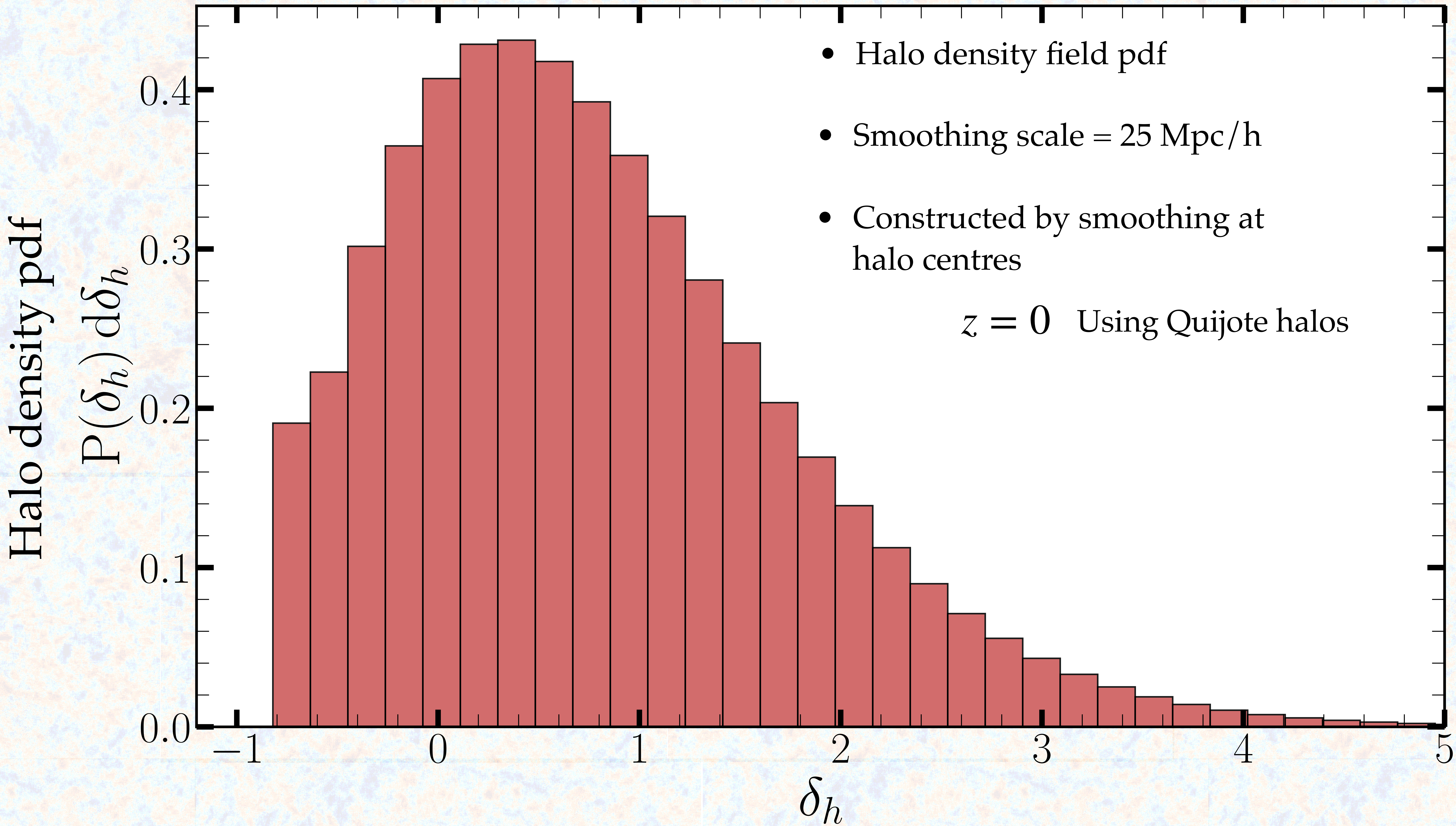
Gong et al 2024, 2025

Can we do something better ?

Density field consists of both clusters and voids



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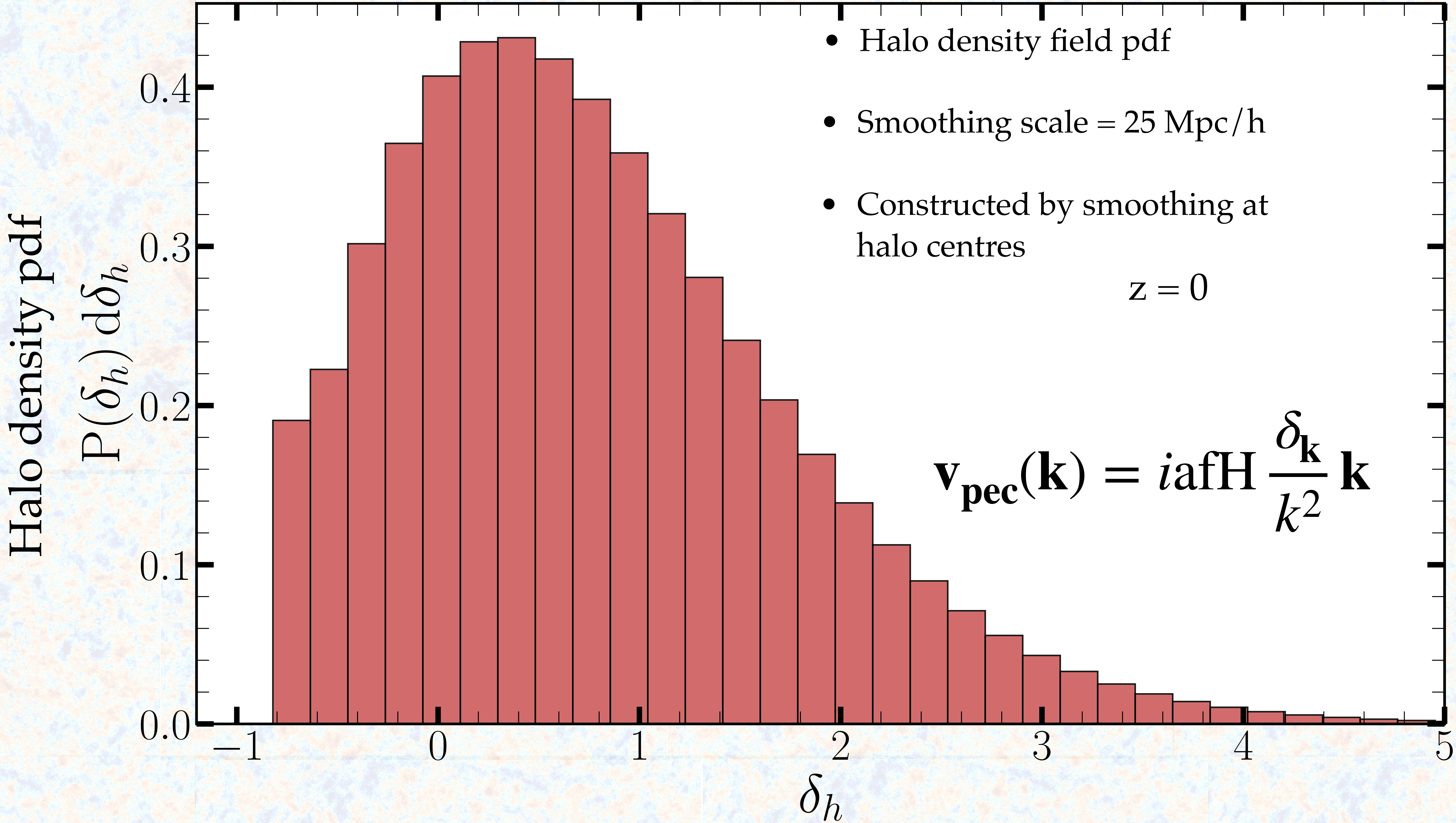
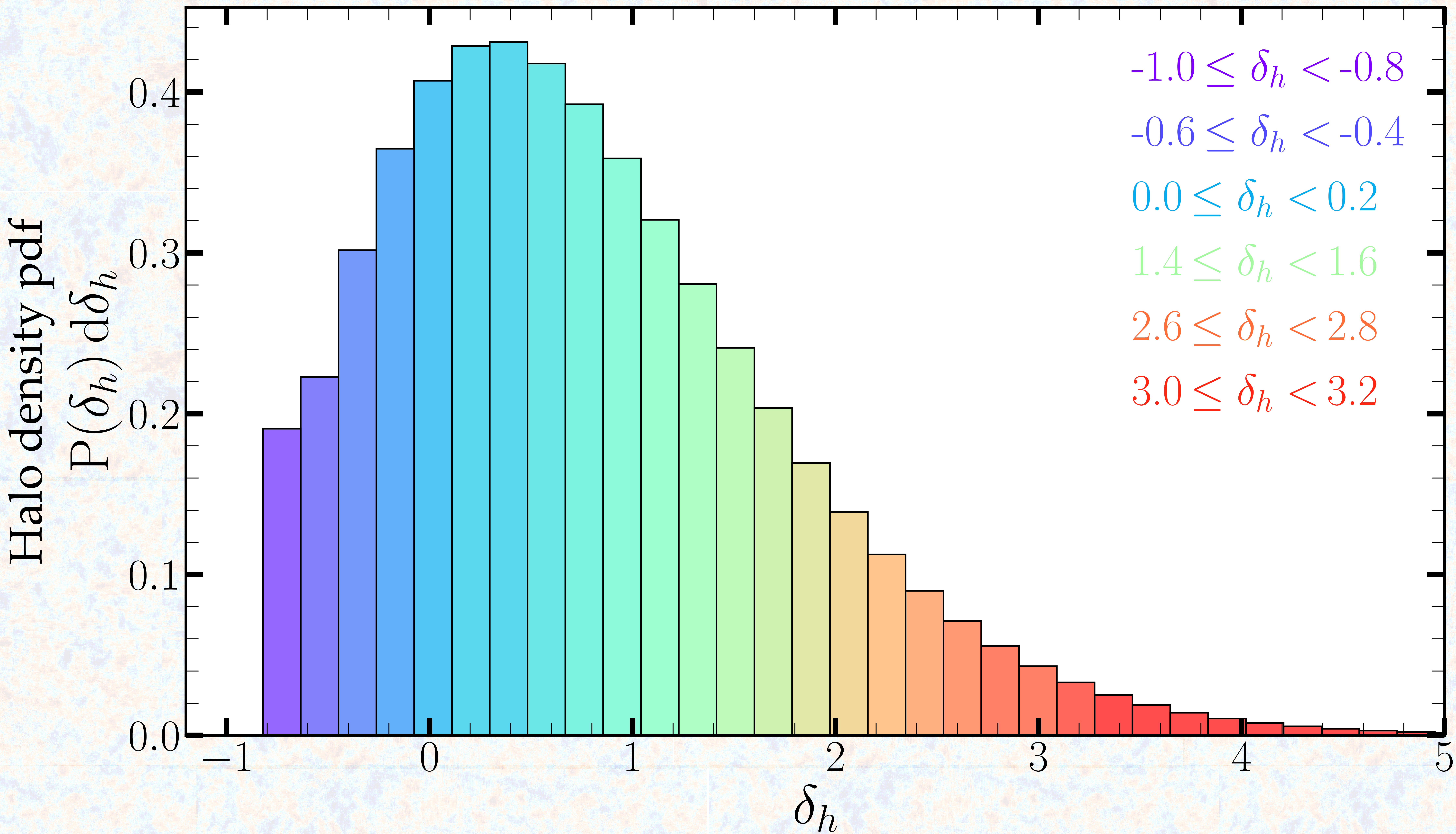
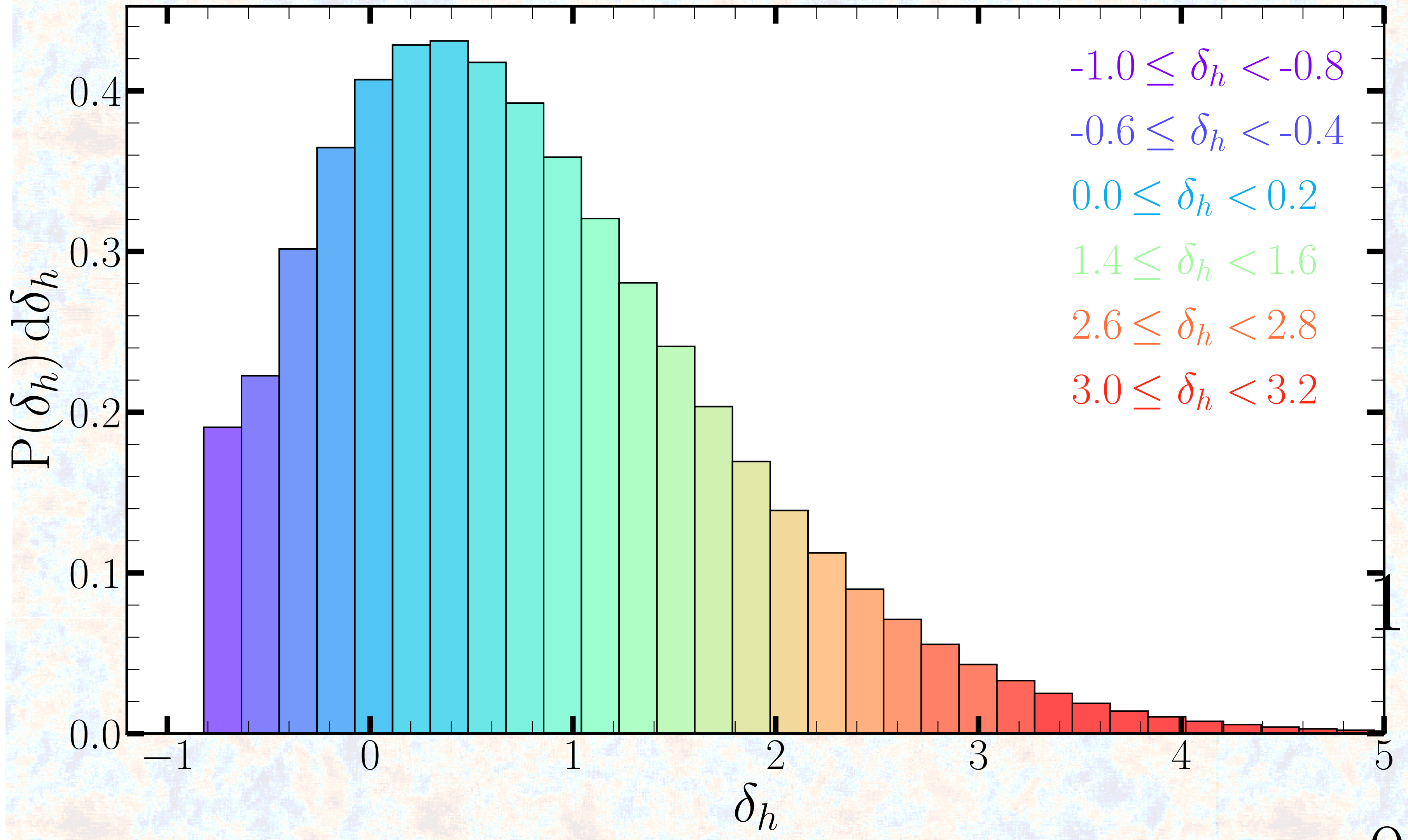


$$\mathbf{v_{pec}}(\mathbf{k}) = i\mathrm{afH}\,\frac{\delta_{\mathbf{k}}}{k^2}\,\mathbf{k}$$

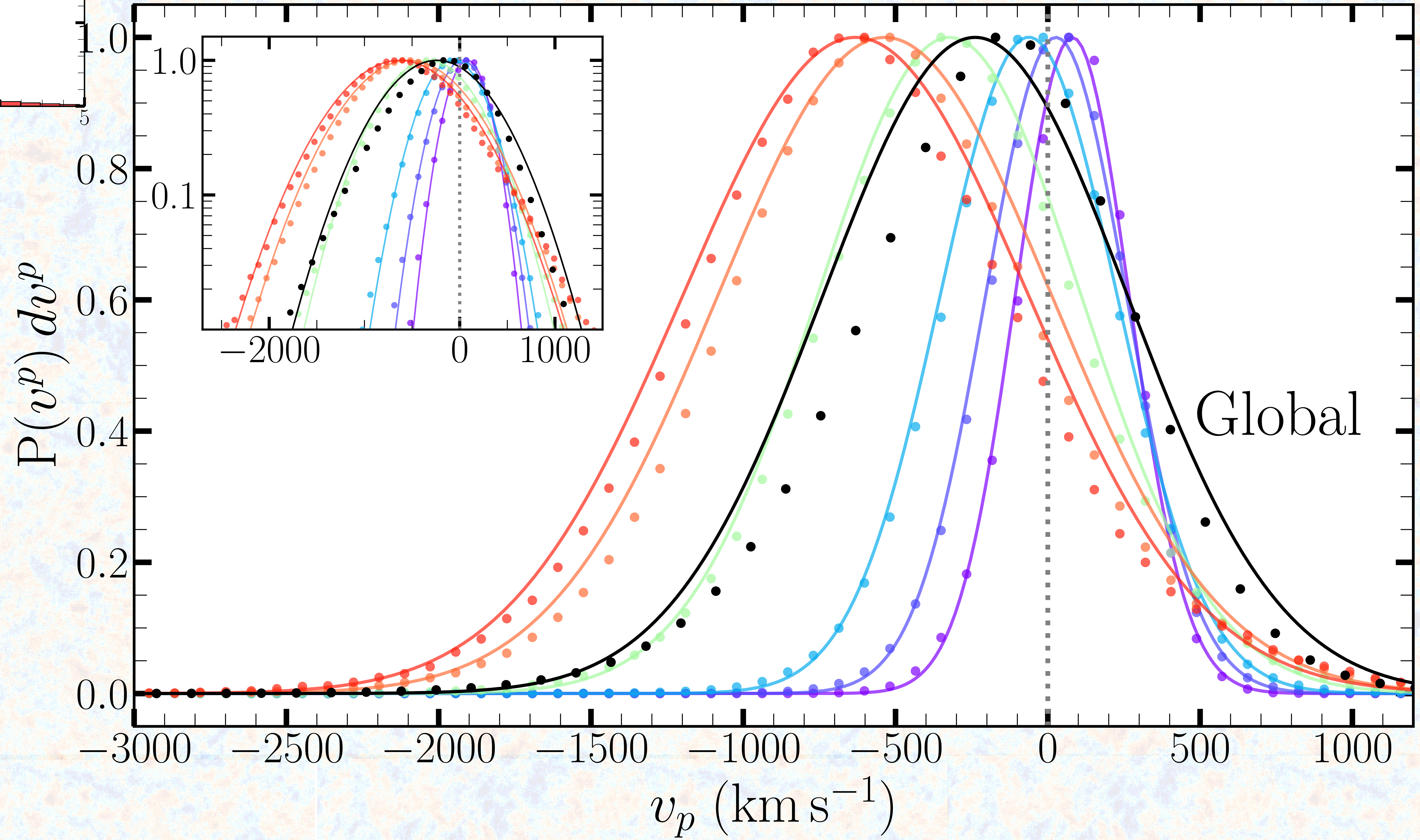
Splitting into different density bins



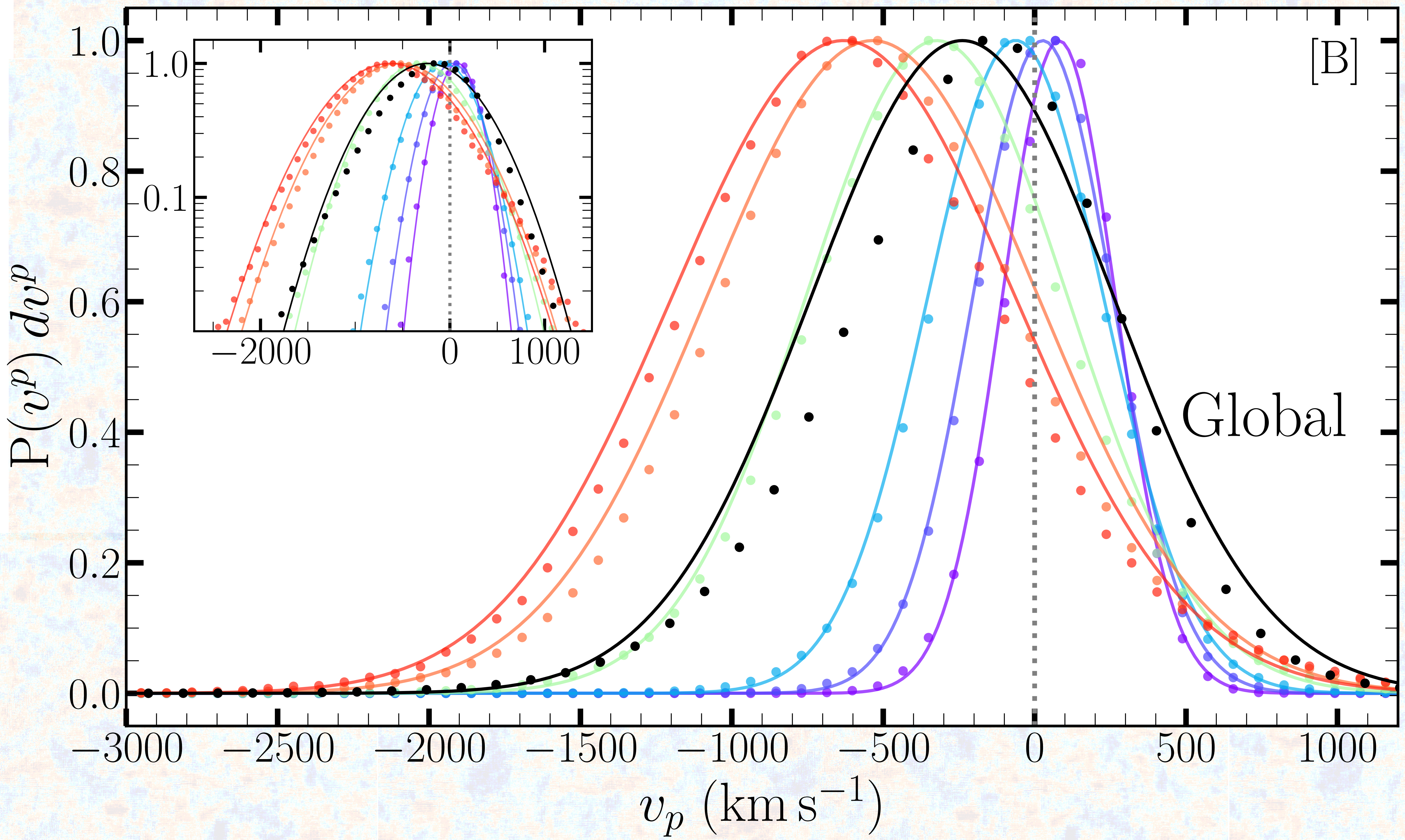


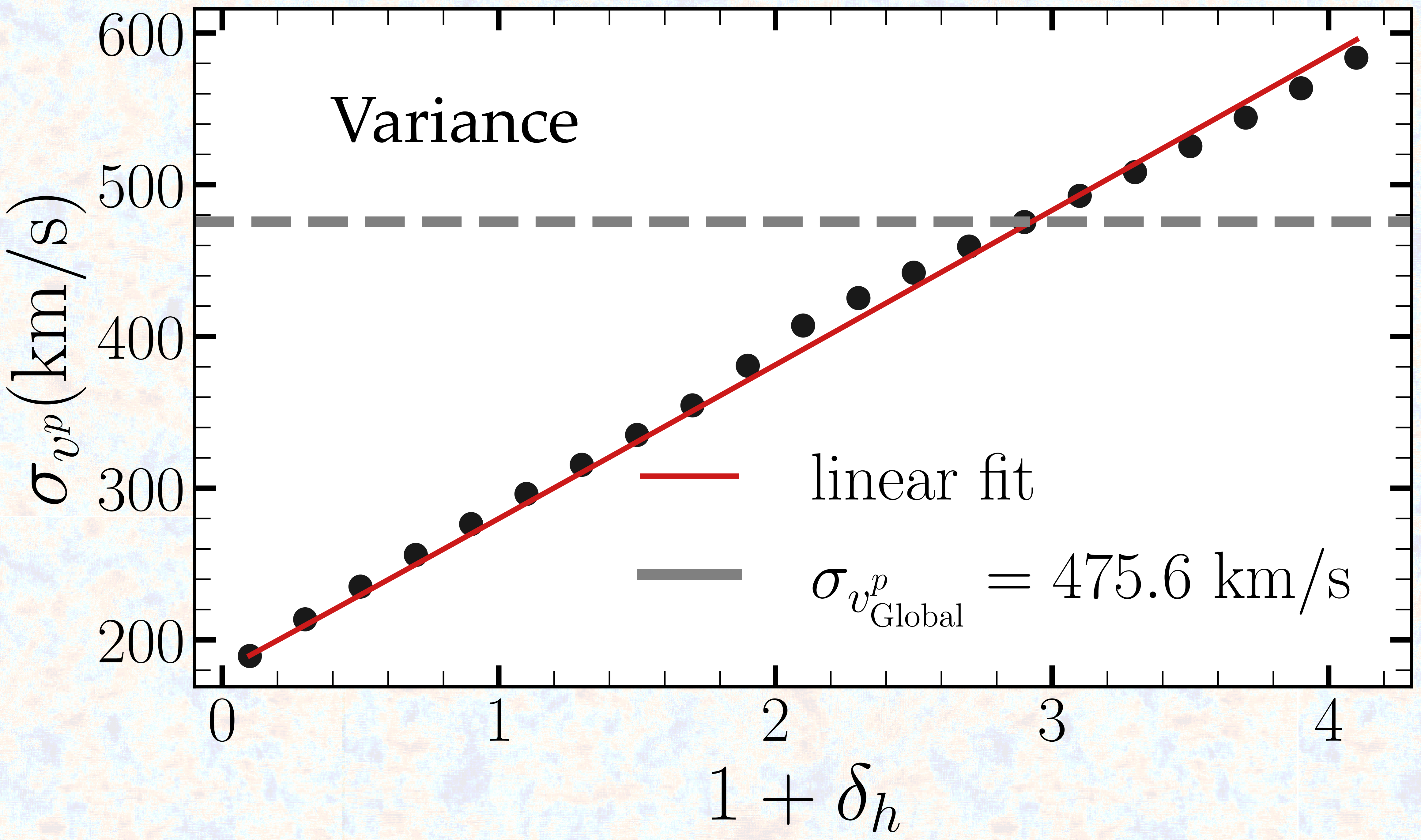
Pairwise velocity pdf for different density bins

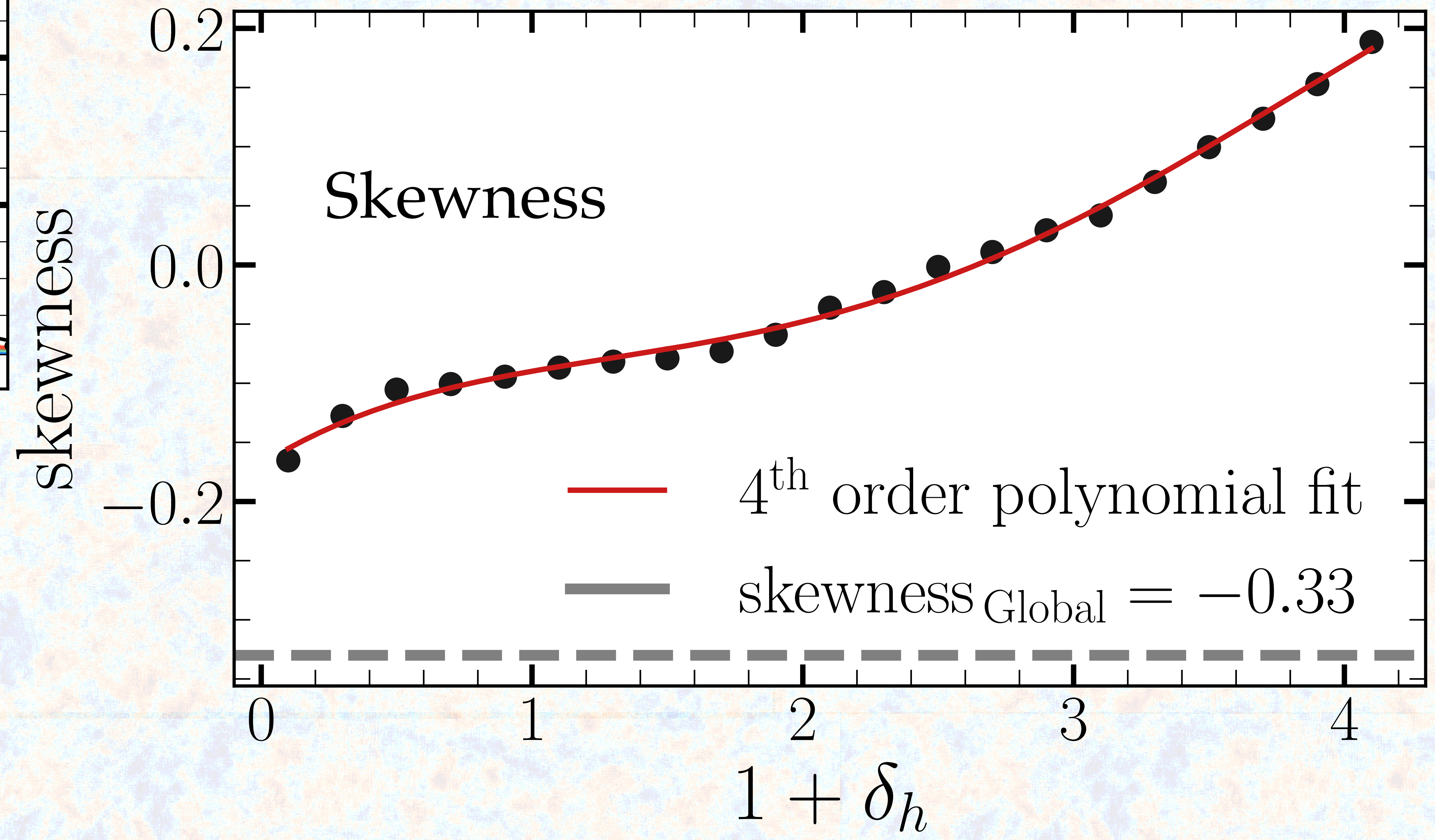
Pairwise velocity pdf



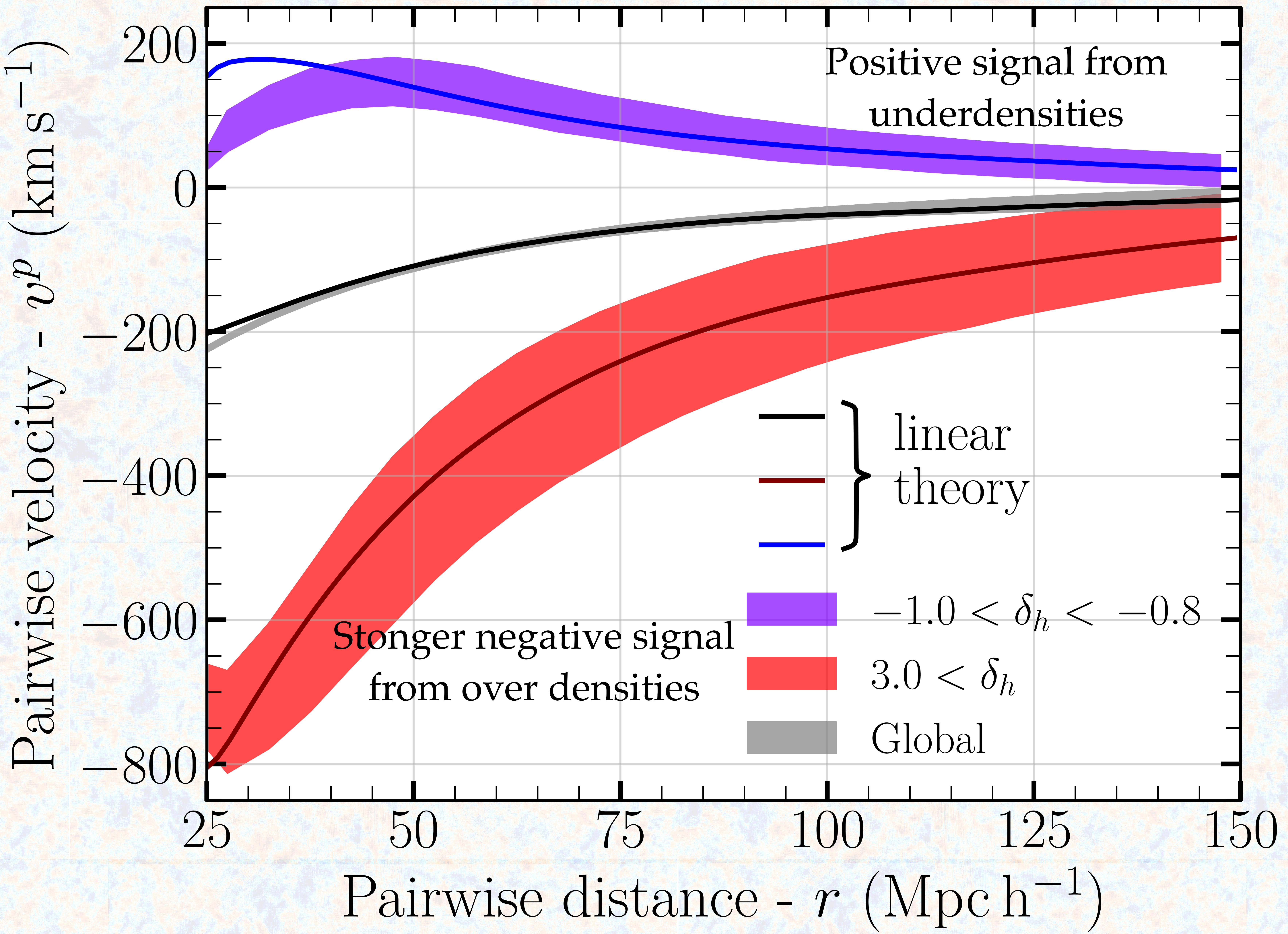
Splitting results in more Gaussian distribution

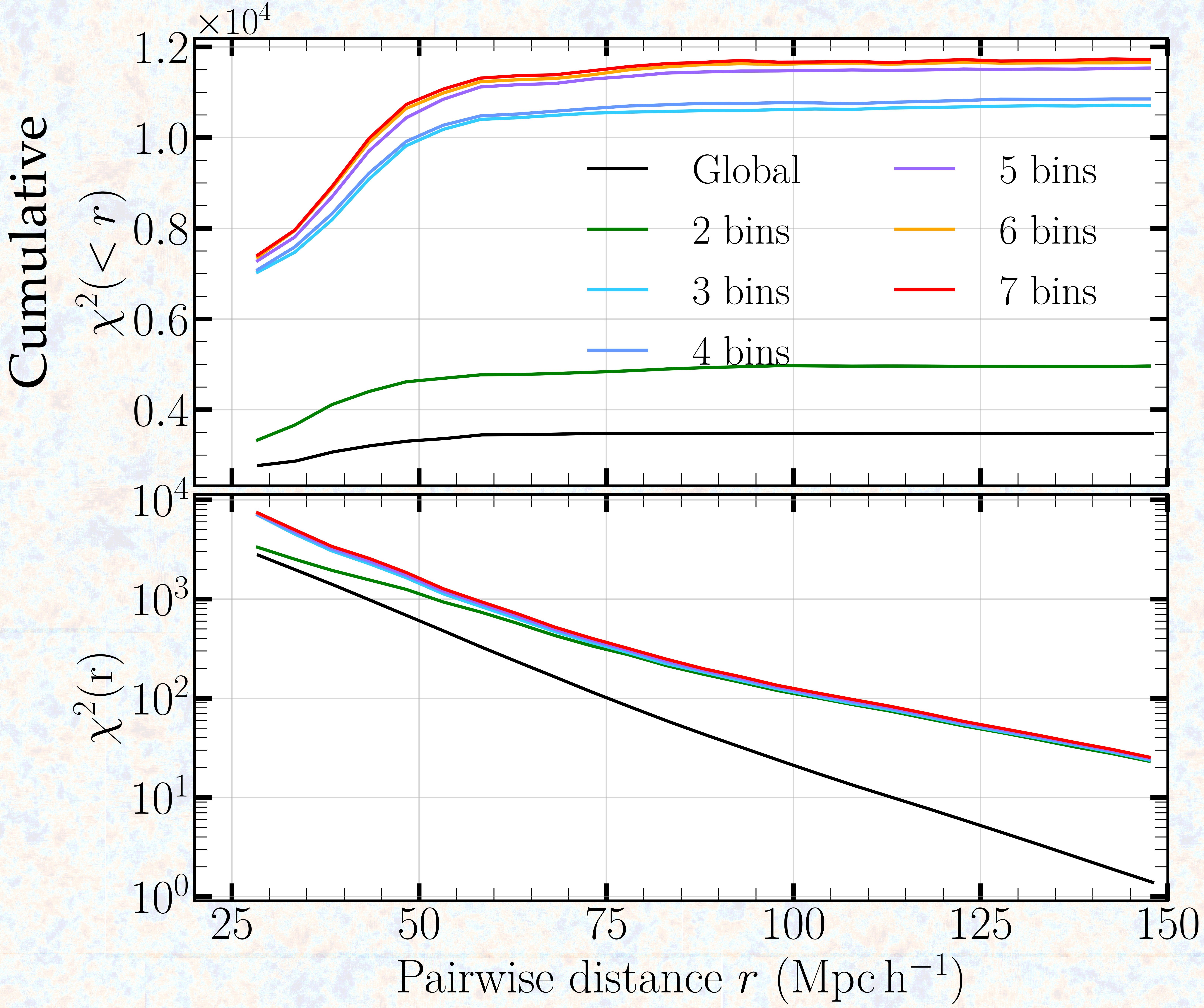






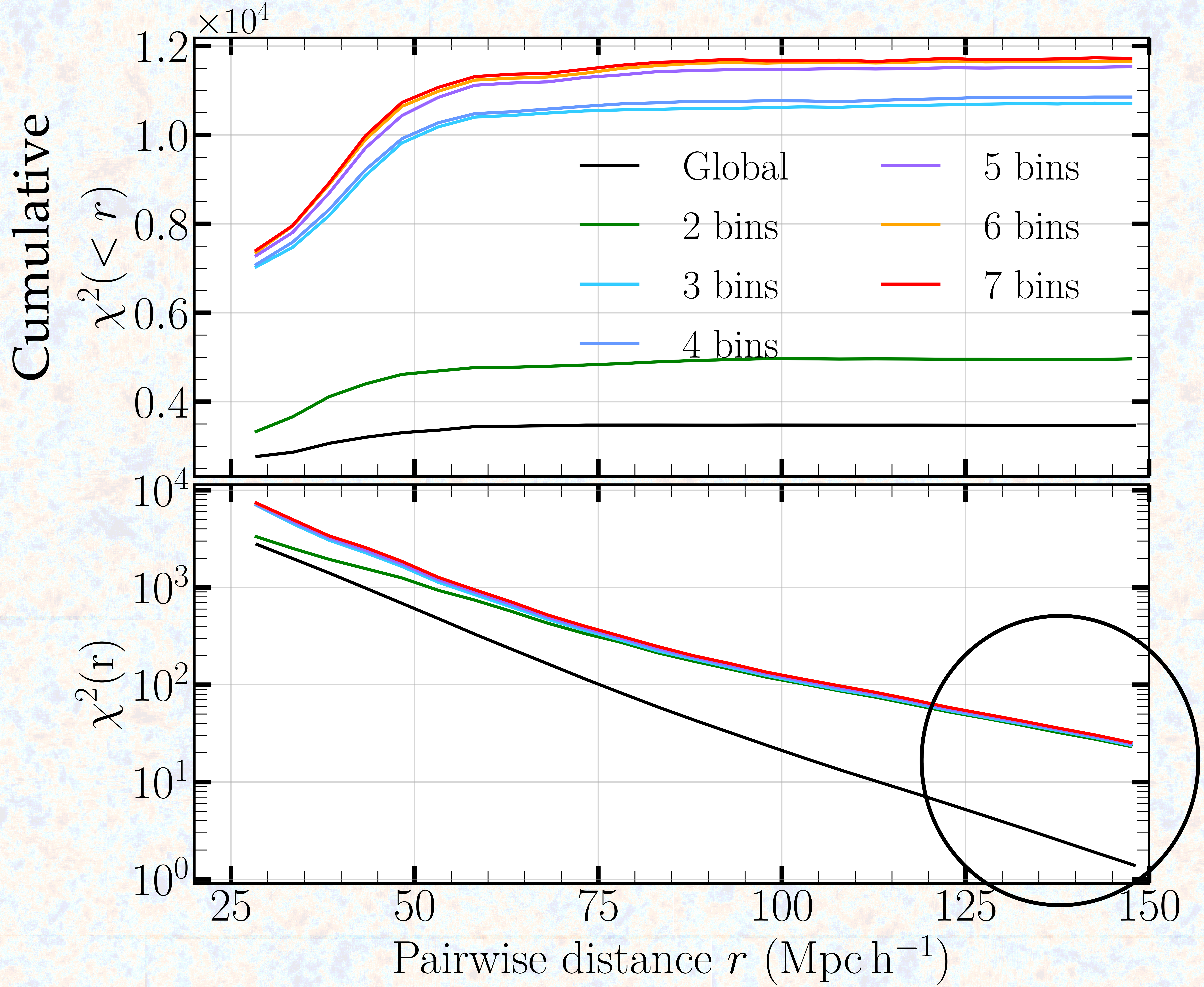
Pairwise velocity for overdense and underdense regions





$$\chi^2 = \bar{v}^p \, C^{-1} \, (\bar{v}^p)^T$$

Better S/N ratio!!!



$$\chi^2 = \bar{v}^p \, C^{-1} \, (\bar{v}^p)^T$$

At large scales the improvement is stronger arXiv: 2505.00608

Conclusions

- Averaging the global distribution yields a single coherent streaming velocity corresponding to the global clustering, or 2PCF – at the cost of canceling the positive and negative streaming velocities between the low and high dense regions, yielding a large dispersion.

- By splitting, we recover the multiple components of outflows and infalls. We are effectively turning the noise – the global velocity dispersion, into signal – the local means of positive or negative velocities.

- The gain of information with the DS-technique on large scales suggests that non-Gaussianity is not a necessary condition for the DS-method to be effective, as the PVD on such large scales is much closer to Gaussian.

- The significant increase of the signal-to-noise for the pairwise velocities measured using the density split technique suggests great potential for improving the measurement of pairwise kSZ.

Thank You