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Unlocking Non-linear Pairwise Velocities in the LSST Era

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Peculiar velocities provide a complementary probe of large-scale structure by directly tracing the gravitational dynamics of structure formation. Yet observational analyses of pairwise velocities and the pairwise kinetic Sunyaev-Zel'dovich signal remain largely restricted to linear and quasi-linear scales, leaving substantial cosmological information at smaller separations untapped.

We present a simulation-calibrated likelihood for the mean pairwise velocity, v12(r,a), based on the exact pair conservation equation and non-linear matter clustering, validated against the Quijote and TNG300-3 simulations. Extending the analysis from a linear-regime baseline of 50 Mpc/h down to 4 Mpc/h at z=0.5 reduces the uncertainty on fσ8 by up to 86%, while the joint Ωm–fσ8 Figure-of-Merit improves by up to a factor of 9.1.

These gains motivate asking how much of this non-linear information can be recovered with LSST-era datasets. LSST will provide dense photometric samples for cross-correlation with spectroscopic and CMB surveys, while photometric redshift uncertainties, tracer selection and galaxy velocity bias complicate the interpretation of small-scale pairs. Our framework provides a controlled starting point for quantifying these effects and determining the scales on which non-linear pairwise motions can become a practical cosmological probe.

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