Snowmass2021 - Letter of Interest

Probing Gravity with Type Ia Supernova Peculiar Velocities

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract: In the upcoming decade cadenced wide-field imaging surveys will increase the number of identified Type Ia supernovae (SNe Ia) at $z < 0.2$ from hundreds up to one hundred thousand. The increase in the number density and solid-angle coverage of SNe Ia, in parallel with improvements in the standardization of their absolute magnitudes, now make them competitive probes of the growth of structure and hence of gravity. Each SN Ia can have a peculiar velocity $S/N \sim 1$ with the distance probative power of $30 - 40$ galaxies, so a sample of 100,000 SNe Ia is equivalent to a survey of 3 million galaxies, in a redshift range where we currently have $\lesssim$100,000 galaxies. The peculiar velocity power spectrum is sensitive to the effect of gravity on the linear growth of structure. In the next decade the peculiar velocities of SNe Ia at $z < 0.2$ can distinguish between General Relativity and leading models of alternative gravity at 4-5σ confidence. These constraints have the same statistical significance as those from DESI or Euclid, but are measured essentially at a given cosmic time rather than averaged over a broad range $z \sim 1 - 2$, and at low redshift where modifications of gravity may be most apparent. Together, SNe Ia and high-redshift peculiar velocity tracers are sensitive to physics beyond the standard ΛCDM cosmology.

In the late 1990's, Type Ia supernovae (SNe Ia) were used as distance probes to measure the homogeneous expansion history of the Universe[20;21]. The remarkable discovery that the expansion is accelerating has called into question our basic understanding of the gravitational forces within the Universe. Either it is dominated by a "dark energy" that is gravitationally repulsive, or General Relativity is inadequate and needs to be replaced by a modified theory of gravity. In the upcoming decade, with their sheer numbers, solid-angle coverage, and improved distance precisions, SNe Ia will provide measurements of the *inhomogeneous* motions of structures in the Universe that will provide a novel test of whether dark energy or modified gravity is responsible for the accelerating expansion of the Universe.

Peculiar velocities are the motions of galaxies that are superimposed on top of the homogeneous expansion of the Universe. They are caused by the gravitational attraction of surrounding mass-density inhomogeneities. The strength of the gravitational pull can be inferred from peculiar velocities if those inhomogeneities are known.

There are two observational approaches to access peculiar velocities, Redshift Space Distortions (RSD) and distance indicators. Both hinge on the measurement of redshift, whose signal is a mix of the cosmological expansion and line-of-sight peculiar velocity. For RSD[12] (RSD), correlations in galaxy positions, which are isotropic in real space, appear distorted when redshift is used as a distance proxy along the line-of-sight. In this letter we highlight the use of distance indicators to measure peculiar velocity[19]. Given the background expansion (e.g. the linear Hubble law at low redshift), a distance corresponds to a cosmological redshift. The difference between the cosmological and the observed redshifts is attributed to peculiar velocity. An alternative perspective is that peculiar velocity appears as a "peculiar distance" on a Hubble diagram if the redshift measurement is taken at face value. Peculiar distance measurements are particularly sensitive at low-redshift, since velocity uncertainties scale with redshift given a fixed distance uncertainty. This is precisely the regime where RSD lacks sensitivity, due to the limited volume and sources with which to measure galaxy correlations.

Mass inhomogeneities must be mapped in order to measure the strength of gravity from peculiar velocities. One approach is to measure peculiar velocities and galaxy overdensities in the same volume. Direct comparison of the two fields then gives the strength of the gravitational pull. Alternatively, the statistical properties of local peculiar velocities can be compared with those of the mass overdensities at the CMB, since gravity models can connect the temporal evolution between the two.

The amplitude of peculiar velocities as measured with distance indicators is sensitive to the combination fD, where D is the spatially-independent, redshift-dependent "growth factor" in the linear evolution of density perturbations and $f \equiv \frac{d \ln D}{d \ln a}$ is the linear growth rate where a is the scale factor[6;11]. The redshift-dependent fD depends on gravity; General Relativity, $f(R)$, and DGP gravity follow the empirical relation $f \approx \Omega_M^\gamma$ with constant $\gamma = 0.55, 0.42, 0.68$ respectively, where Ω_M is the normalized mass density[16;17]. Fixing the normalization of fD to the CMB, the predicted values of fD for different values of γ's splay out at low redshift[18], meaning that for a fixed fD uncertainty, it is the local universe that has the strongest probative power to resolve gravity models. This is the regime where peculiar distances are more effective than RSD in measuring peculiar velocities. Moreover, in many theories modifications of gravity are most prominent at low redshift.

Current and upcoming distance-based measurements of fD are based primarily on galaxies, which though plentiful have fairly imprecise distance precisions of $\sim$ 22-26% per-object. Measurements of fD made from comparing velocity and density fields in the local Universe with an effective redshift $z = 0.035$ have 12% precision[22]. Using the same approach, SKA is projected to give a 3% precision[15] using Tully-Fisher (T-F) distances. Recent measurements[1] of fD using the statistical properties of 6dFGS Fundamental Plane (FP) peculiar velocities give 13.5% precision on fD at $z < 0.057$ (truncating at smaller scales than the preceding citations). In the near future, the TAIPAN survey[5] (with densities of $n_g \sim 10^{-3} h^3\,\mathrm{Mpc}^{-3}$)

and the WALLABY+Apertif Shallow surveys ($n_g \sim 2 \times 10^{-2} - 10^{-4} h^3\,\mathrm{Mpc}^{-3}$), each covering 75% of the sky out to $z =$0–0.1, are together projected[10] to yield 3% uncertainties in fD.

Two advances in the upcoming decade will make SN Ia peculiar velocities a competitive probe of the growth of structure and gravity. First, the precision of SN Ia distances can be improved. The commonly-used empirical 2-parameter spectral model yields absolute magnitude dispersion $\sigma_M \gtrsim 0.14$ mag (7% distance uncertainty). However, SNe transmit more information than just the light-curve shape and single color used in current SN models. Recent studies[3;4;8] indicate that with the right data, SN absolute magnitudes can be calibrated to $\sigma_M \lesssim 0.08$ mag (4% distance uncertainty). At this precision one supernova has the probative power of 30(42) T-F (FP) galaxies (or 10(14) galaxies for $\sigma_M = 0.14$), and can measure a peculiar velocity with $S/N \sim 1$. Second, in the upcoming decade cadenced wide-field imaging surveys such as ASAS-SN, ATLAS, ZTF-II and the Vera C. Rubin Observatory LSST will increase the number of identified Type Ia supernovae from the hundreds to the hundreds of thousands; over the course of 10-years, LSST will find ∼150,000 at $z < 0.2$, and ∼520,000 at $z < 0.3$ SNe Ia, corresponding to a number density of $n \sim 5 \times 10^{-4} h^3\,\mathrm{Mpc}^{-3}$. This sample has comparable number density and more SN-host galaxies at deeper redshifts than projected by WALLABY and TAIPAN. Even with half the number density, a ten-year SN Ia survey will have a $\sim 20\times$ reduction in shot-noise relative to TAIPAN[13].

Given these advances, supernovae discovered by wide-field searches in the next decade will be able to tightly constrain the growth of structure in the low-redshift Universe. For example, over the course of a decade a SN survey relying on LSST discoveries plus spectroscopic redshifts can produce 4–14% uncertainties in fD in 0.05 redshift bins from $z = 0$ to 0.3, cumulatively giving 2.2% uncertainty on fD within this interval, where at $0 < z < 0.2$ most of the probative power comes from peculiar velocities and at higher redshifts from RSD[9]. Systematics affecting high-z analysis are suppressed in this restricted redshift range. For reference, DESI projects a 10% precision of fD at $z \approx 0.3$ using RSD[7].

In the short to medium term, SN Ia discoveries by ASAS-SN, ATLAS, ZTF-II (or beginning LSST) can reach completeness at a depth of $z_{\text{max}} = 0.09$ and cover $\Omega \approx 2\pi$ of extragalactic sky. With follow-up that gets 4% per-object distance uncertainties, these SNe Ia can distinguish between the above gravity models (i.e. $\Delta\gamma = 0.13$) to 2–3σ. A long-term supernova peculiar-velocity survey can be performed with SNe Ia discovered in the LSST Wide Fast Deep survey. As a 10-year survey, LSST generates higher supernova number densities to fainter limiting magnitude, making possible significantly improved constraints on the growth index. Uncertainties in γ for surveys with a 10-year duration, redshift depth of 0.2, and $\Omega = 2\pi$ sky coverage, with appropriate follow-up, are ± 0.02[14]. LSST-discovered supernovae can thus distinguish between the aforementioned modified gravity models to 4–5σ. The redshift depth afforded by LSST provides significant improvement relative to the shallower surveys. Although the probative power per object decreases with redshift, as does the leverage on γ, the additional volume provided by LSST is needed to overcome the slow gain that comes from increased numbers of SNe at $z < 0.1$ after several years.

High-redshift peculiar velocity measurements from RSD highly complement those from distance indicators. RSD has higher signal-to-noise at high redshift, and can probe both shorter and longer length scales than those easily modeled or available in the more evolved, smaller volume of the local Universe. This synergy is particularly powerful when testing for physics beyond ΛCDM. For example, the area of the Ω_M–γ error contour when marginalizing over the dark energy of state with w_0–w_a is reduced by a factor of several in a joint SN Ia–RSD analysis versus treating them independently[14].

We advocate that SN Ia Peculiar Velocity surveys be included in the long-term planning of the HEP program. It will provide a unique and powerful low-redshift probe of modified gravity and help distinguish theories beyond the cosmological ΛCDM standard model[2;14]. The survey is enabled by upcoming wide-field long-term transient searches such as ZTF-II and the LSST, and is synergistic with current (DESI) and high-redshift redshift surveys also being put forward as part of the Snowmass process.

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