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Testing Gravity Using Type Ia Supernovae Discovered by Next Generation Wide Field Imaging Surveys

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ABSTRACT

ZTF today and LSST in the upcoming decade will increase the number of identified $z < 0.3$ Type Ia supernovae (SNe Ia) from the hundreds to the hundreds of thousands. The increase in the number density of SNe Ia, in parallel with improvements in the standardization of their absolute magnitudes, now make them competitive probes of the growth of structure. The peculiar velocity power spectrum is sensitive to $f\sigma_8$, the product of the linear growth and amplitude of density perturbations. Cross-correlation with synergistic galaxy surveys further constrains $f\sigma_8$ and the galaxy bias. Thus, in the next decade the peculiar velocities of SNe Ia will provide the growth of structure in the local $z < 0.3$ Universe as a powerful test of General Relativity and other models of gravity.

1. CONNECTION BETWEEN TYPE IA SUPERNOVAE CORRELATIONS AND GRAVITY

In the late 1990's, Type Ia supernovae (SNe Ia) were used as distance probes to measure the homogeneous expansion history of the Universe. 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. It is only appropriate that in the upcoming decade, with their sheer numbers and improved distance precisions, SNe Ia will provide measurements of the *inhomogeneous* motions of structures in the Universe that will provide an unmatched test of whether dark energy or modified gravity is responsible for the accelerating expansion of the Universe.

The growth of structure depends on the expansion history of the Universe, the nature and density of its contents, and gravity. It is therefore a powerful probe of cosmology and dark energy. Growth of structure can be measured from the light-emittting structures in the Universe and from the peculiar velocities of test masses therein. Peculiar velocities are the motions, on top of the cosmological expansion, caused by the gravitational attraction and repulsion of density inhomogeneities in the Universe. The peculiar velocity of an object with a known absolute magnitude can be determined from its observer-frame magnitude and redshift. For a given background cosmology, the observed magnitude provides an estimate of the cosmological redshift, the peculiar velocity is then the difference between the cosmological and CMB-frame redshifts.

Baryonic structures and peculiar velocities provide a measurement of the combination fD. D is the "linear growth factor" that gives the overall amplitude of overdensities, and the "linear growth rate"

$$f \equiv \frac{d\ln D}{d\ln a}$$

is how that amplitude changes with redshift. General Relativity predicts $f \approx \Omega_M^\gamma$ (with D determined accordingly) with $\gamma = 0.55$, whereas other gravity models can be similarly described with different values of γ (Linder & Cahn 2007). The growth of structure, through the measurement of fD, provides a test of General Relativity and breaks degeneracies between gravitational and dark energy models that explain the accelerating expansion of the Universe. Non-GR models may also predict a change in the redshift- and scale-dependence of the growth, such observations provide additional leverage in probing gravity. The parameter σ_8, the standard deviation of overdensities in $8h^{-1}$Mpc spheres, is commonly used in place of D to normalize the overall amplitude of overdensities, so the standard parameterization used by the community is $f\sigma_8$.

Baryonic structures are sensitive to $f\sigma_8$ through redshift space distortions (RSD), which on large scales gives the combination $(b + f\mu^2)\sigma_8$ where b is the bias between the tracer and dark matter and μ gives the angular separation of Fourier modes to the line-of-sight. Correlations between peculiar velocities are sensitive to $f\sigma_8(H_0 d_L)^{-1}$. Although the velocities may be measured off of biased tracers, the tracers' dynamics are driven by all mass (including dark matter) and so are bias-free. As mentioned earlier, peculiar velocities are measured relative to the background cosmological expansion that leads to the dependence on $H_0 d_L$. (Note that the combination $H_0 d_L$ is independent of H_0.) Baryonic structures and peculiar velocities within the same volume are induced by the same overdensities making their cross-correlation insensitive to sample variance (Gordon et al. 2007): galaxy and peculiar velocity surveys provide synergistic constraints more powerful than their naive sum.

The probative power of a specific peculiar-velocity tracer primarily depends on its number density and the precision to which its absolute magnitudes are known. The current generation of peculiar velocity studies uses $10^3 - 10^5$ galaxies with Fundamental Plane and Tully-Fisher distances (Masters et al. 2008; Springob et al. 2014; Tully et al. 2016). These galaxies have absolute magnitude uncertainties of ~ 0.4 mag. Next generation surveys WALLABY (Johnston et al. 2008) and TAIPAN (da Cunha et al. 2017) are designed to increase these sample sizes by an order of magnitude over 75% of the sky to a maximum depth of $z = 0.1$.

The current sample of SNe Ia has a low number density compared to Fundamental Plane and Tully-Fisher galaxies. Nevertheless, their low intrinsic-magnitude uncertainties can provide peculiar velocities (expressed equivalently as peculiar magnitudes) of their host galaxies (Hui & Greene 2006; Davis et al. 2011). Existing SN Ia samples have been used to test and ultimately find spatial correlations in peculiar velocities that may be attributed to the growth of structure (Abate & Lahav 2008; Johnson et al. 2014; Huterer et al. 2015, 2017). However, the signal-to-noise is currently insufficient to perform a meaningful test of GR.

Two advances in the upcoming decade will make SNe Ia important probes of $f\sigma_8$. First, the precision of SN Ia distances can be improved. The commonly-used empirical 2-parameter SED model yields $\sigma_M \gtrsim 0.12$ mag absolute magnitude dispersion. However, SNe transmit more information than just the light-curve shape and single color used in current SN models. Recent studies indicate that with the right data, SNe absolute magnitudes can be calibrated to $\sigma_M \lesssim 0.08$ mag (see e.g. Barone-Nugent et al. 2012; Fakhouri et al. 2015). Though not yet established, it is anticipated that such a reduction in intrinsic dispersion comes with a reduction in the magnitude bias correlated with host-galaxy properties that is observed using current calibrations. One such SN is worth $\gtrsim 25$ galaxies with 0.4 mag absolute magnitude uncertainty. Secondly, ZTF today and LSST in the upcoming decade will increase the number of identified $z < 0.3$ Type Ia supernovae (SNe Ia) from the hundreds to the hundreds of thousands, over the course of 10-years, LSST will find $\sim 150,000$ $z < 0.2$, $\sim 520,000$ $z < 0.3$ SNe Ia for which good light curves can be measured. This is a sample size with more galaxies at deeper redshifts than projected by WALLABY and TAIPAN. Measurement of the velocity field using LSST-discovered SNe Ia has been previously quantified by Bhattacharya et al. (2011); Odderskov & Hannestad (2017).

The precision in $f\sigma_8$ derived from the baseline WFD ten-year SN Ia discoveries has been projected by Howlett et al. (2017a), from both their RSD and peculiar velocities. The results are summarized in Table 1, where a 5% distance (0.1 mag) uncertainty is assumed for each supernova. SNe Ia alone can provide a 2% measurement of $f\sigma_8$ at $z < 0.3$ redshifts lower than where galaxy and cluster (through the kinematic S-Z effect) RSD measurements are sensitive. A joint galaxy RSD and SN peculiar velocity will be even more powerful. SNe Ia peculiar velocities will measure $f\sigma_8$ at $z < 0.3$ as well as galaxy surveys will at $z \sim 0.6$ using RSD. This can be compared to the current 15% uncertainty from 6dF (Adams & Blake 2017), 3% uncertainty projected for the combined TAIPAN and WALLABY+WNSHS surveys (Howlett et al. 2017b) for low-redshift measurements of $f\sigma_8$. At larger $z > 0.3$ redshifts DESI projects 10% accuracies.

The projected precisions for LSST-discovered SNe Ia have a number of interesting features. Despite the significant gain in volume and numbers of supernovae, the $f\sigma_8$ uncertainty in increasing redshift bins asymptotes such that there is little benefit in going beyond $z = 0.3$. At $z < 0.2$ the constraining power on $f\sigma_8$ comes primarily from peculiar velocities but by $z = 0.3$ RSD is more important. It turns out that for $z > 0.1$, the volume is sufficiently large that the LSST sample is not yet sample variance limited.

Redshift	RSD (z-bin)	RSD + PV (z-bin)	RSD+PV (cumulative)
$0.00 < z < 0.05$	66.3	13.9	13.9
$0.05 < z < 0.10$	24.6	7.3	6.5
$0.10 < z < 0.15$	14.8	5.8	4.3
$0.15 < z < 0.20$	10.6	5.0	3.3
$0.20 < z < 0.25$	8.3	4.4	2.6
$0.25 < z < 0.30$	6.8	4.0	2.2

Table 1. Projected percent uncertainties in $f\sigma_8$ from a 10-year LSST SN survey with 5% distance uncertainties from Howlett et al. (2017a). RSD is from clustering, and RSD + PV is from joint clustering and peculiar velocities. The cumulative column shows the effective uncertainty from combining its and all other shallower redshift bins.

2. DESIGNING A SUPERNOVA SURVEY TO MEASURE $f\sigma_8$

2.1. *Survey Parameters that Determine Scientific Performance*

Howlett et al. (2017a) project how well peculiar velocity surveys can measure $f\sigma_8$. They perform their analysis in Fourier space, where the Fisher information matrix of parameters λ_i from random Gaussian field with mean zero and covariance $C(k)$ is

$$F_{ij} = \frac{V}{2}\int \frac{d^3k}{(2\pi)^3}\mathrm{Tr}\left[C^{-1}\frac{\partial C}{\partial \lambda_i}C^{-1}\frac{\partial C}{\partial \lambda_j}\right], \tag{1}$$

where the covariance for the velocity-velocity correlation

$$C = P_{vv}(k) + \frac{\sigma^2}{n} \tag{2}$$

is dependent on the power spectrum, noise in the velocity measurement dominated by the intrinsic velocity dispersion σ, and the density of velocity probes (Howlett et al. 2017b). The primary dependence on the growth of structure is through the normalization of the velocity power spectrum, such that

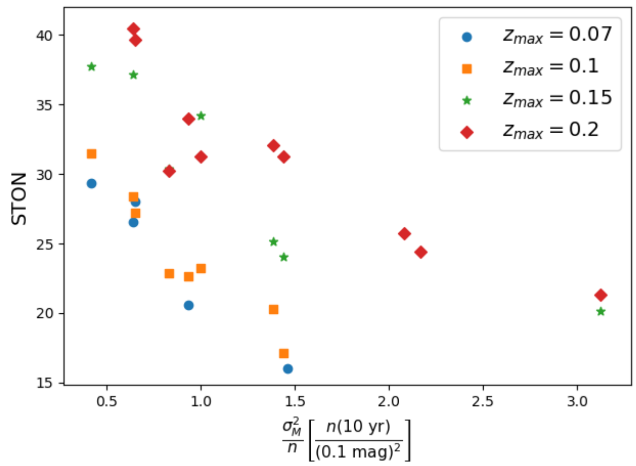
$$\frac{\partial P_{vv}}{\partial \lambda} = \text{constant} \tag{3}$$

for the parameter choice $\lambda = (f\sigma_8)^2$. In the sample-variance limit, $F_{\lambda\lambda} \propto V$ whereas in the shot noise limit $F_{\lambda\lambda} \propto Vn^2\sigma^{-4}$.

The survey parameters that enter the Fisher matrix are the volume V, which in turn can be parameterized by the survey solid angle Ω and the redshift depth z_{max} ; the number density of sources n; and the intrinsic magnitude dispersion σ_M, where magnitude and velocity dispersions are related at low-redshift by $\sigma_M \approx \frac{5}{\ln 10}\frac{1+z}{z}\sigma$. LSST is expected to discover all $z < 0.3$ SNe Ia before maximum light in its active Wide Fast Deep (WFD) survey area. Equating LSST discovery with having a meaningful peculiar velocity, the number density n is thus a fixed parameter, which only increases with survey duration. Thus Ω, z_{max}, and σ_M are left as the relevant parameters.

- Solid Angle Ω: The variance in $f\sigma_8$ is inversely proportional to solid angle Ω. The baseline LSST survey covers 18,000 sq. deg, at $-75 \lesssim \delta \lesssim 15$ avoiding the Galactic plane. Larger solid-angle coverage for $z < 0.3$ SN Ia searches, beyond the LSST baseline, benefits peculiar-velocity science. Complementary northern-hemisphere surveys and LSST-expanded or independent coverage of the southern equatorial pole, could significantly increase the sky coverage with a corresponding decrease in the variance of $f\sigma_8$.

- Redshift Depth z_{max}: For the number densities generated by LSST and the SN Ia intrinsic magnitude dispersion, the noise is not sample-variance limited. We have run simulations of LSST SN surveys and calculated the signal-to-noise (STON) of $f\sigma_8$ from the peculiar-velocity correlations. These simulations show, as seen in the left plot of Figure 1, that an increase in the number density of tracers leads to a significant improvement in STON. It is also worth noting that sample variance is not negligible, as seen by the non-linear dependence of the STON on σ_M^2/n.



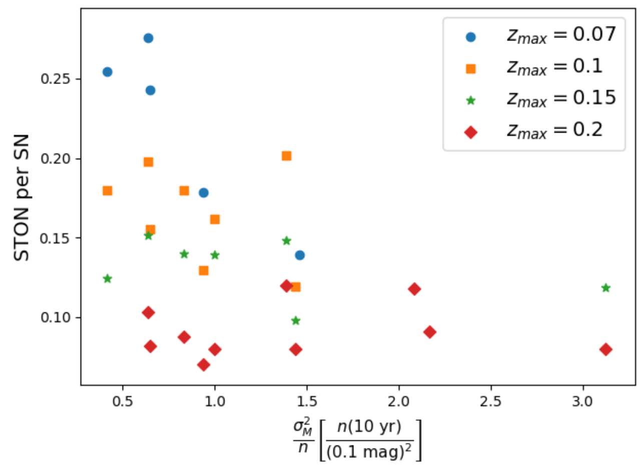


Figure 1. Left: STON of $f\sigma_8$ from simulated LSST SN peculiar-velocities only (no RSD). There is a small level of scatter in the plots idue to the random realizations made in simulating the surveys. For several limiting redshift depths, the STON is plotted as a function of σ_M^2/n, normalized to intrinsic magnitude dispersion $\sigma_M = 0.1$ mag and 10-year LSST number densities. Right: The effective contribution to the STON per supernova, quantified as STON divided by the root of the number of tracers.

The effective contribution to the STON per supernova, quantified as STON divided by the root of the number of tracers, is higher for lower z_{max}. This is shown in the right plot of Figure 1.

A low-redshift tracer is more valuable than one at higher redshift.

- Intrinsic Magnitude Dispersion σ_M: A decrease in the supernova intrinsic magnitude dispersion leads to a significant improvement in the STON of $f\sigma_8$, as shown in Figure 1 in parallel to our earlier discussion of the dependence of n. We are not sample-variance limited so the σ_M^2/n-term in the Fisher matrix is important. Survey follow-up strategy, which determines which data are available per SN Ia, influences the accuracy to which their distances can be determined. This dependence is non-trivial: the improvement between $\sigma_M = 0.08$ and 0.15 mag dispersions is equivalent to a factor of 3.52 in number density, or equivalently in survey duration.

  The intrinsic magnitude dispersion depends on the purity of the sample. Conservatively, we consider a pure SN Ia sample obtained through spectroscopic classification; the requisite follow-up resources needed for complete $z < 0.3$ coverage is conceivable. The feasibility of using photometric classification is an important subject of research that can have implications for survey planning, particularly in extending the redshift range.

2.2. *Designing an SN Ia Peculiar Velocity Survey*

There are different options to consider in the design of a SN Ia peculiar velocity survey, though at this point it is difficult to assess which is optimal or most cost effective. While there are a variety of recently identified indicators of SN Ia diversity that improve upon the 2-parameter model (SALT2) currently used to determine distances, there is not yet an umbrella model that simultaneously captures all indicators, their correlations, and characterizes the model residuals. Here we make several general conclusions based upon the above findings, while noting that constructing such a model is a parallel endeavor that will benefit peculiar-velocity and other SN Ia science.

- Spectroscopic transient classification: SNe Ia are defined through the absence of Hydrogen and the presence of the 6150 Å Silicon P-Cygni feature.

- Spectroscopic redshifts: Peculiar velocities are extracted directly from redshift measurements. Redshift uncertainties of > 0.5% contribute significantly to the error budget. We thus conclude that there is the need for spectroscopic $R > 200$ host-galaxy redshifts. In most cases this redshift will be available in the classification spectrum. Planned bright-galaxy redshift surveys can also observe a significant fraction of nearby SN hosts.

- Role of LSST: LSST can be taken to be a SN Ia discovery and distance machine, or a discovery machine only. The nominal cadence produces sparse per-band light curves, which limits the intrinsic magnitude dispersion possible with LSST data alone to $\sigma_M \approx 0.15$ mag. The wide-field of LSST is well suited for discoveries over a larger area of sky, but does not provide significant multiplex advantage for the low surface-density of active $z < 0.3$ SNe Ia. LSST is suited for maximizing Ω while other (cheaper) resources that supplement LSST photometry can improve σ_M. The ultimate WFD observing strategy determines how well σ_8 can be determined with LSST data alone, and the amount of external resources needed (if any) to reach a targeted σ_M.

- Follow-up resources to determine per-SN distances: Supplemental non-LSST follow-up data in the form of improved temporal light-curve sampling (accurate rise and decline times), expanded (UV, NIR) wavelength coverage, and spectral features can access high-fidelity SN Ia models with lower intrinsic magnitude dispersion and residual systematic bias. For example, infrared data (Barone-Nugent et al. 2012) or spectrophotometry at peak brightness (Fakhouri et al. 2015) are projected to give $\sigma_M \lesssim 0.08$ mag.

  Scientific leverage dictates that low-redshift sources are most valuable. This aligns with observational considerations, for which closer and hence brighter objects require more modest follow-up resources. Therefore, z_{max} depends on the follow-up program as the redshift where complete follow-up saturates resources.

  A follow-up survey with $z_{max} = 0.2$ would have $\sim 150,000$ targets over 10 years. These sources will be observed when brighter than $r \sim 20.5$ mag and so will be accessible to 2–4m-class telescopes.

3. CONCLUSIONS

SNe Ia are already powerful probes of the homogeneous cosmological expansion of the Universe. In the next decade. high-cadence, wide-field imaging surveys, together with improved precision in their distance determinations, will make SNe Ia powerful probes of the gravity induced-motion caused by the inhomogeneous Universe. SNe Ia peculiar velocities at $z < 0.3$ will measure $f\sigma_8$ significantly better than galaxy surveys, at lower redshifts that provide better leverage to test gravity models. While imaging surveys will provide a steady stream of SNe Ia, a coordinated plan of follow-up is required to take advantage of their probative power. The resources necessary to follow hundreds of thousands of SNe depend on specific follow-up choices, and access to those resources will define the redshift limits of the survey. Fortunately, the lowest-redshift, and hence brightest, supernovae are of the highest interest, so that a modest suite of ~ 5 2–4m telescopes should be capable of providing leading measurements of $f\sigma_8$ at $z \sim 0.1$.

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