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Testing Gravity using Type Ia Supernovae Discovered by LSST

A. G. Kim,[1] C. Harper,[1] C. Ju,[1] D. Huterer,[2] and others

[1] Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
[2] Department of Physics, University of Michigan, 450 Church Street, Ann Arbor, MI 48109, USA

1. INTRODUCTION

Peculiar velocities provide a measure of $f\sigma_8$, which in turn probes gravity. As precise distance indicators Type Ia supernovae can provide precise peculiar velocities (expressed equivalently as peculiar magnitudes) of their host galaxies (Hui & Greene 2006; Davis et al. 2011). Huterer et al. (2015, 2017) test and ultimately detect correlations in the peculiar velocities of existing SN Ia samples.

Surveys such as ZTF and LSST are and will discover orders of magnitude more nearby SNe Ia than currently available. The motivation of this work is to quantify the probative power of SN Ia-derived peculiar velocities in the LSST era. While there have been a number of articles on the subject, our analysis brings a higher level of fidelity than sought by previous analyses. We simulate SNe Ia hosted by galaxies in a mock galaxy catalog. The numbers of SNe are sufficiently small to allow fast evaluations of the likelihood, which enable the determination of parameter posteriors using MCMC on reasonable computing timescales. We can use our machinery to compare different survey parameters, such as redshift depth, total numbers of supernovae, solid angle/survey geometry, and SN Ia intrinsic magnitude dispersion.

The expected precision of $f\sigma_8$ using LSST-discovered SNe Ia is estimated using the Fisher information matrix of a random Gaussian field with mean zero and covariance $C(k)$ parameterized by λ is

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

The covariance

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

has contributions from the power spectrum, noise in the velocity measurement, and the density of velocity probes. In the sample variance limit for a sample with fixed depth, the variance in $f\sigma_8$ (and other λ parameters) is thus inversely proportional to the survey solid-angle Ω, whereas in the shot-noise limit the variance is inversely proportional to $\Omega n^2 \propto N^2/\Omega$, where n is the number density, and N is the total number of supernovae.

We consider a maximum redshift of $z = 0.2$ because over ten years the noise is not shot-noise dominated, meaning that the differential improvement in the precision of $f\sigma_8$ due to a lower-redshift supernova is greater than that due to a high-redshift supernova. Following all LSST SNe Ia below this redshift likely saturate available follow-up resources. Our calculations are thus based on the number and solid-angle of $z < 0.2$ supernova pre-maximum discoveries for the survey candidates provided by the Project. Based on these numbers we calculate the Figures of Merit in both sample and shot-noise limits, normalized to "baseline2018a". After 10 years, LSST supernovae are at neither extreme; we thus adopt the average of the two FoM's as what we advocate for the survey. These averages for a select set of surveys are shown in Figure **??**.

The cross-correlation between galaxy-count and peculiar-velocity surveys is not yet implemented but is a planned extension of this work. We would like to quantify the suppression of sample variance achieved when considering matter-densities and velocities within the same volume (Gordon et al. 2007).

2. SIMULATED DATA

The Buzzard (v1.6) galaxy catalog is used. This is because it is the survey, with a light cone that covers 10,313.24 sq. deg., that covers the largest solid angle among those currently available in the DESC Generic Catalog Reader. However, the survey geometry is different from that of LSST. The catalog is based on a Flat ΛCDM model with $H_0 = 70$ km s^{-1}, $\Omega_M = 0.286$, $\Omega_B = 0.047$, and $\Omega_\nu = 0$. The catalog contains 140M galaxies with observed redshift

z_{max}	fraction	σ_{SN}	N_{gal}	$\bar{A}$	σ_A	$\sigma_A N_{gal}^{-0.5}$	$\bar{A}\sigma_A^{-1}(12000/760)^{0.5}$
0.20	1.0	0.08	9901	1.18	0.23	0.050	19.91
0.20	0.2	0.08	2021	1.66	0.59	0.062	11.11
0.20	0.3	0.08	3023	1.34	0.43	0.057	12.38
0.20	0.5	0.08	5015	1.13	0.30	0.054	15.13
0.10	1.0	0.08	1294	0.91	0.28	0.091	13.03
0.15	1.0	0.08	3870	1.00	0.24	0.066	16.33
0.20	1.0	0.10	9901	1.06	0.25	0.042	16.60
0.20	1.0	0.12	9901	1.09	0.28	0.040	15.62
0.15	0.3	0.12	1215	1.97	0.92	0.061	8.46
0.12	0.3	0.10	746	1.62	0.70	0.085	9.21
0.07	1.0	0.08	563	1.16	0.36	0.135	12.70

Table 1. .

$z < 0.2$. Each galaxy has its cosmological redshift, the x-, y-, z-components of its peculiar velocity from which the radial peculiar velocity is determined, and its star formation rate and stellar mass from which the supernova rate of each host is determined using Smith et al. (2012). Supernovae are realized for a span of 10 observer-years yielding 17,205 objects. This total supernova production underestimates the expected discovery of 130,000 supernovae in 10 observer-years based on the volumetric rate of Dilday et al. (2010). The volumetric rate is more robust, so the sample under consideration in this article corresponds to 1.3 years worth of discoveries.

Each supernova is assigned a magnitude based on the distance modulus of its cosmological redshift plus a random term drawn from a Normal distribution σ_M, which for simplicity is the same for all supernovae and captures both intrinsic magnitude dispersion and measurement uncertainty. No other corrections are applied to the observed magnitude. Dipole effects of the heliocentric motion with respect to the CMB and of the galaxies with respect to the CMB are ignored: referring to Davis et al. (2011), the effects in Eq. 18 are ignored.

3. ANALYSIS

The analysis of this article is almost identical to that of Huterer et al. (2015, 2017). The peculiar magnitude correlation function $\xi_{\delta m \delta m}$ expected from General Relativity starting with the CMB matter density power spectrum is calculated using CAMB (Lewis & Bridle 2002) assuming the same cosmological parameters used for the Buzzard catalog. Our model for the data covariance is

$$C_{ij} = A\xi_{\delta m \delta m}(\mathbf{r_i}, \mathbf{r_j}) + \frac{\sigma_M^2}{N_i}\delta_{ij} + \sigma_{NL}^2(z_i; \sigma_v)\delta_{ij}. \tag{3}$$

In this model, we treat the shape of the power spectrum ξ as fixed and use the parameter A to represent deviations from General Relativity $A = 1$. This model is not sensitive to the shape of the power spectrum between gravitational models. Nevertheless, for convenience we say that our model gives $f\sigma_8 = A(f\sigma_8)^{GR}$, where $(f\sigma_8)^{GR}$ is the expectation from General Relativity. Special cases of modified gravity could give $A = 1$, but inconsistency with $A = 1$ is is evidence against General Relativity. The final term includes extra magnitude dispersion produced by non-linear effects on velocity, parameterized with σ_v, such that

$$\sigma_{NL} = \frac{5}{\ln 10}\frac{1+\bar{z}}{\bar{z}}\sigma_v, \tag{4}$$

where $\bar{z}$ is the cosmological redshift of the host galaxy.

4. RESULTS OF SUBSETS

For all analyses we remove supernovae below observed $z_{min} = 0.01$ in order to reduce errors made in the first-order transformation between velocity and magnitude. This cut removes a small volume relative to the full survey.

The

We consider two different scenarios cutting at different redshift depths $z_{max} = 0.1$ and $z_{max} = 0.15$. All the objects in the first scenario are in the second scenario. The results are shown in Fig. 3. The points of interest are:

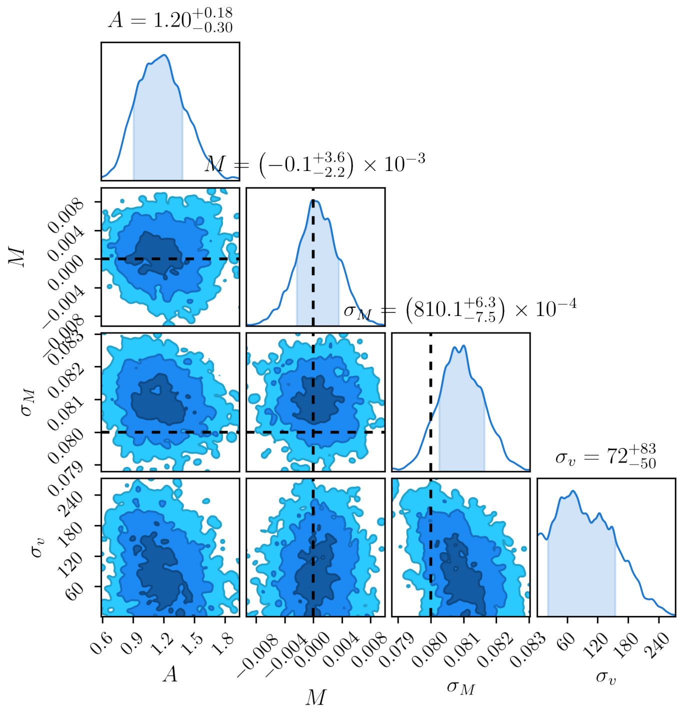

Figure 1. Confidence regions for the model parameters. $A = (f\sigma_8)/(f\sigma_8)_{GR}$, M is the supernova absolute magnitude, σ_M is the magnitude dispersion, and σ_v is the non-linear contribution to peculiar velocity. The parameters for which I controlled the input, $M = 0$ and $\sigma_M = 0.08$ mag, are shown in dotted lines. Left: A survey truncated at $z_{max} = 0.1$. Right: A survey truncated at $z_{max} = 0.15$.

- There is a bias toward low $f\sigma_8$ for low-redshift ($z_{max} = 0.1$). Adding more supernova with increasing redshift decreases the bias ($z_{max} = 0.15$), and A eventually approaches 1 ($z_{max} = 0.2$ not shown).
- Based on the analysis of Howlett et al. (2017), I added an intrinsic velocity dispersion σ_v (km s^{-1}) due to non-linear effects. This was not in Dragan's model. My fit finds that this dispersion is consistent with zero, not well constrained, and not strongly correlated with A. The lack of covariance is consistent with Dragan's own tests.
- The fit intrinsic magnitude dispersion, on the other hand, is larger than the input $\sigma_M = 0.08$ mag. This indicates that the catalogs contain extra velocity dispersion better attributed to intrinsic magnitude dispersion rather than correlated peculiar velocities.

- Dragan: Is there some way that the formalism in your article breaks down at low-redshift? I do remove very low-redshift objects at $z < 0.01$, which I think is conservative.
- Risa/Joe: Is there any reasons for the Buzzard catalog to not capture correlated peculiar velocities on small scales (box size to large?) nor capture non-linear velocities? (I don't know how to translate a mass resolution of 2.7e10 $M_\odot/h$ into a spatial resolution!)

REFERENCES

Davis, T. M., Hui, L., Frieman, J. A., et al. 2011, ApJ, 741, 67, doi: 10.1088/0004-637X/741/1/67

Dilday, B., Smith, M., Bassett, B., et al. 2010, ApJ, 713, 1026, doi: 10.1088/0004-637X/713/2/1026

Gordon, C., Land, K., & Slosar, A. 2007, PRL, 99, 081301, doi: 10.1103/PhysRevLett.99.081301

Howlett, C., Staveley-Smith, L., Elahi, P. J., et al. 2017, MNRAS, 471, 3135, doi: 10.1093/mnras/stx1521

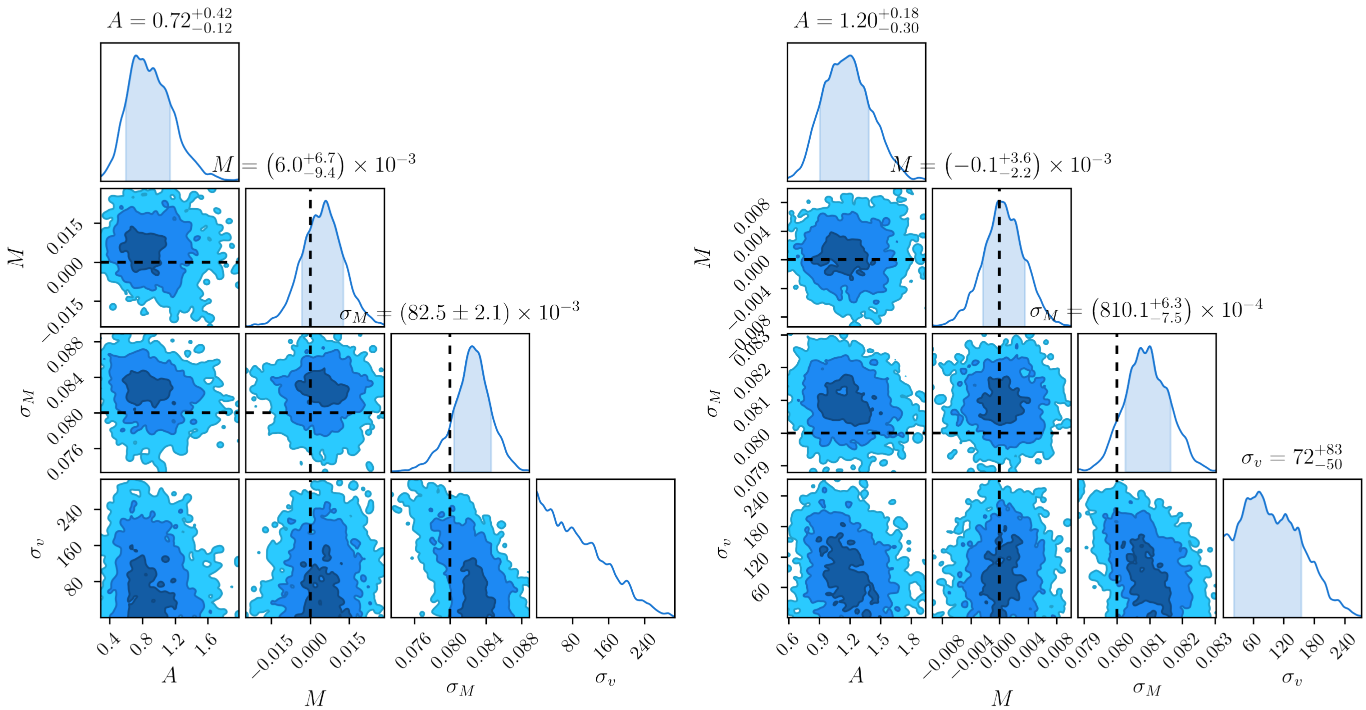

Figure 2. Confidence regions for the model parameters. $A = (f\sigma_8)/(f\sigma_8)_{GR}$, M is the supernova absolute magnitude, σ_M is the magnitude dispersion, and σ_v is the non-linear contribution to peculiar velocity. The parameters for which I controlled the input, $M = 0$ and $\sigma_M = 0.08$ mag, are shown in dotted lines. Left: A survey truncated at $z_{max} = 0.1$. Right: A survey truncated at $z_{max} = 0.2$.

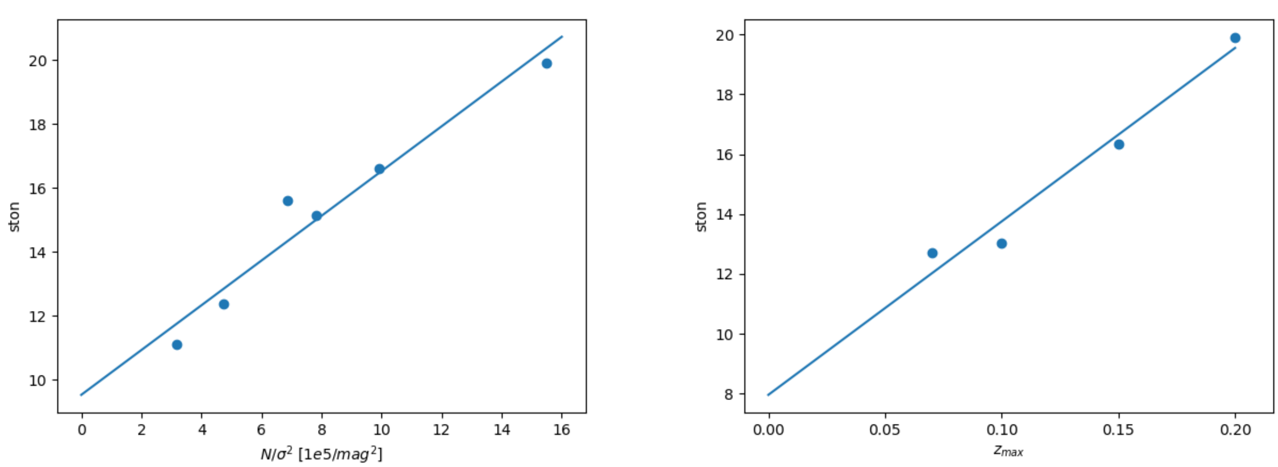

Figure 3. Confidence regions for the model parameters. $A = (f\sigma_8)/(f\sigma_8)_{GR}$, M is the supernova absolute magnitude, σ_M is the magnitude dispersion, and σ_v is the non-linear contribution to peculiar velocity. The parameters for which I controlled the input, $M = 0$ and $\sigma_M = 0.08$ mag, are shown in dotted lines. Left: A survey truncated at $z_{max} = 0.1$. Right: A survey truncated at $z_{max} = 0.15$.

Hui, L., & Greene, P. B. 2006, PRD, 73, 123526, doi: 10.1103/PhysRevD.73.123526

Huterer, D., Shafer, D. L., & Schmidt, F. 2015, JCAP, 12, 033, doi: 10.1088/1475-7516/2015/12/033

Huterer, D., Shafer, D. L., Scolnic, D. M., & Schmidt, F. 2017, JCAP, 5, 015, doi: 10.1088/1475-7516/2017/05/015

Lewis, A., & Bridle, S. 2002, PhRvD, 66, 103511, doi: 10.1103/PhysRevD.66.103511

Smith, M., Nichol, R. C., Dilday, B., et al. 2012, ApJ, 755, 61, doi: 10.1088/0004-637X/755/1/61