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

Thematic Areas:

- □ Planetary Systems
- □ Star and Planet Formation
- □ Formation and Evolution of Compact Objects
- ■ Cosmology and Fundamental Physics
- □ Stars and Stellar Evolution
- □ Resolved Stellar Populations and their Environments
- □ Galaxy Evolution
- □ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Alex Kim
Institution: Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
Email: agkim@lbl.gov
Phone: 1-510-486-4621

Co-authors: G. Aldering1, P. Antilogus2, A. Bahmanyar3, S. BenZvi4, H. Courtois5, T. Davis6, H. Feldman7, S. Ferraro1, S. Gontcho A Gontcho4, O. Grau8,9,10, R. Graziani11, J. Guy1, C. Harper1, R. Hložek3,12, C. Howlett13, D. Huterer14, C. Ju1, P.-F. Leget15, E. V. Linder1, P. McDonald1, J. Nordin16, P. Nugent17, S. Perlmutter1,18, N. Regnault15, M. Rigault11,

1Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
2Laboratoire de Physique Nucléaire et de Hautes Energies, Sorbonne Université, CNRS-IN2P3, 4 Place Jussieu, 75005 Paris, France
3Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, Ontario, Canada M5S 3H4
4Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
5Université de Lyon, F-69622, Lyon, France; Université de Lyon 1, Villeurbanne; CNRS/IN2P3, Institut de Physique Nucléaire de Lyon, France
6School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia
7Department of Physics & Astronomy, University of Kansas, Lawrence, KS 66045-7550 USA
8Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
9Department of Astrophysics, American Museum of Natural History, New York, NY 10024, USA
10NSF Astronomy and Astrophysics Postdoctoral Fellow
11Université Clermont Auvergne, CNRS-IN2P3, Laboratoire de Physique de Clermont, F-63000 Clermont-Ferrand, France
12Dunlap Institute for Astronomy and Astrophysics, University of Toronto, ON, M5S 3H4
13International Centre for Radio Astronomy Research, The University of Western Australia, Crawley, WA 6009, Australia
14Department of Physics, University of Michigan, 450 Church Street, Ann Arbor, MI 48109, USA
15Laboratoire de Physique Nucléaire et de Hautes Energies, Sorbonne Université, CNRS-IN2P3, 4 Place Jussieu, 75005 Paris, France
16Institut fur Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany
17Computational Research Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
18Department of Physics, University of California Berkeley, Berkeley, CA 94720
### Endorsers:

- Behzad Ansarinejad
- Robert Armstrong
- Jacobo Asorey
- Carlo Baccigalupi
- Maciej Bilić
- Julian Borrell
- Elizabeth Buckley-Geer
- Kelly A. Dougall
- Cora Dvorkin
- Simon Foreman
- Jacobo Asorey
- Carlo Baccigalupi
- Maciej Bilicki
- Julian Borrill
- Elizabeth Buckley-Geer
- Kelly A. Douglass
- Cora Dvorkin
- Simon Foreman
- Lluís Galbany
- Juan García-Bellido
- Martina Gerbino
- Mandeep S.S. Gill
- Larry Gladney
- Saurabh W. Jha
- Johann Cohen-Tanugi
- D. O. Jones
- Marc Kamionkowski
- Ryan E. Keeley
- Robert Kehoe
- Savvas M. Koushiappas
- Ely D. Kovetz
- Kazuya Koyama
- Benjamin L’Huillier
- Ofer Lahav
- Chien-Hsiu Lee
- Michele Liguori
- Axel de la Macorra
- Joel Meyers
- Surhud More
- Jeffrey A. Newman
- Gustavo Niz
- Antonella Palmese
- Francesco Piacentini
- Korea Astronomy and Space Science Institute, Yuseong-gu, Daedeok-daero 776, Daejeon 34055, Korea
- Brookhaven National Laboratory, Physics Department, Upton, NY 11973, USA
- Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
- Texas A&M University, College Station, TX 77843
- PITP PACC, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
- Department of Physics, Lower Mountjoy, South Rd, Durham DH1 3LE, United Kingdom
- Lawrence Livermore National Laboratory, Livermore, CA, 94550
- SISSA - International School for Advanced Studies, Via Bonomea 265, 34136 Trieste, Italy
- IFPU - Institute for Fundamental Physics of the Universe, Via Beirut 2, 34104 Trieste, Italy
- INFN - National Institute for Nuclear Physics, Via Valerio 2, I-34127 Trieste, Italy
- Center for Theoretical Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668, Warsaw, Poland
- Fermi National Accelerator Laboratory, Batavia, IL 60510
- Department of Physics, Harvard University, Cambridge, MA 02138, USA
- Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
- Instituto de Física Teorica UAM/CSIC, Universidad Autónoma de Madrid, 28049 Madrid, Spain
- Universidad Autónoma de Madrid, 28049, Madrid, Spain
- HEP Division, Argonne National Laboratory, Lemont, IL 60439, USA
- Kavli Institute for Particle Astrophysics and Cosmology, Stanford 94305
- Stanford University, Stanford, CA 94305
- SLAC National Accelerator Laboratory, Menlo Park, CA 94025
- Department of Physics, Yale University, New Haven, CT 06520
- Department of Physics and Astronomy, Rutgers, the State University of New Jersey, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA
- Laboratoire Univers et Particules de Montpellier, Univ. Montpellier and CNRS, 34090 Montpellier, France
- University of California at Santa Cruz, Santa Cruz, CA 95064
- Johns Hopkins University, Baltimore, MD 21218
- Southern Methodist University, Dallas, TX 75275
- Brown University, Providence, RI 02912
- Department of Physics, Ben-Gurion University, Be’er Sheva 84105, Israel
- Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth PO1 3FX, UK
- University College London, WC1E 6BT London, United Kingdom
- National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719 USA
- Dipartimento di Fisica e Astronomia “G. Galilei”, Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy
- IFUNAM - Instituto de Física, Universidad Nacional Autónoma de México, 04510 CDMX, México
- The Inter-University Centre for Astronomy and Astrophysics, Pune, 411007, India
- División de Ciencias e Ingenierías, Universidad de Guanajuato, León 37150, México
- Dipartimento di Fisica, Università La Sapienza, P. le A. Moro 2, Roma, Italy
- Istituto Nazionale di Fisica Nucleare, Sezione di Roma, 00185 Roma, Italy
Abstract: In the upcoming decade cadenced wide-field imaging surveys 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 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. The peculiar velocity power spectrum is sensitive to the growth index $\gamma$, which captures the effect of gravity on the linear growth of structure through the relation $f = \Omega_M^{\gamma}$. We present the first projections for the precision in $\gamma$ for a range of realistic SN peculiar-velocity survey scenarios. In the next decade the peculiar velocities of SNe Ia in the local $z < 0.3$ Universe will provide a measure of $\gamma$ to $\pm 0.01$ precision that can definitively distinguish between General Relativity and leading models of alternative gravity.

56 The University of South Carolina, Columbia, SC 29208
57 Space Telescope Science Institute, Baltimore, MD 21218
58 Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
59 Kansas State University, Manhattan, KS 66506
60 Stony Brook University, Stony Brook, NY 11794
61 Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
62 Syracuse University, Syracuse, NY 13244
63 National Astronomical Observatories, Chinese Academy of Sciences, PR China
64 School of Physics, Korea Institute for Advanced Study, 85 Hoegiro, Dongdaemun-gu, Seoul 130-722, Korea
1 Introduction

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, solid-angle coverage, 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.

In the next decade, SNe Ia will be used as peculiar-velocity probes to measure the influence of gravity on structure formation within the Universe. Peculiar velocities induce scatter along the redshift axis of the SN Hubble diagram, which is pronounced at low redshifts and when the magnitude scatter (e.g. due to intrinsic magnitude dispersion) is small. The peculiar velocity power spectrum is sensitive to the growth of structure as \( P_{vv} \propto (fD)^2 \), where \( D \) is the spatially-independent “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 [12, 7].

The \( \Lambda \)CDM prediction for the \( z = 0 \) peculiar velocity power spectrum is shown in Figure 1. The growth of structure depends on gravity; [18] find that General Relativity, \( f(R) \), and DGP gravity follow the relation \( f \approx \Omega_\Lambda^\gamma \) with \( \gamma = 0.55, 0.42, 0.68 \) respectively (see [15] for a review of these models). Using this parameterization to model gravity, peculiar velocity surveys probe \( \gamma \) through \( fD \), whose \( \gamma \)-dependence is plotted in Figure 2 of [19].

![Figure 1: Volume-weighted peculiar velocity power spectrum](image)

Figure 1: Volume-weighted peculiar velocity power spectrum \( k^3 P_{vv}(z = 0) \) for \( \mu \equiv \cos (\hat{k} \cdot \hat{r}) = 1, 0.5 \) (magenta, cyan) where \( \hat{r} \) is the line of sight, as predicted for General Relativity in the linear regime. Overplotted are peculiar-velocity power-spectrum shot noise (diagonal lines) for various observing parameters. Red shows the shot noise expected from a 2-year LSST survey while black shows a 10-year LSST survey. The dotted and dashed lines indicate the assumed intrinsic magnitude dispersion, using 0.08 (dashed) or 0.15 mag (dotted). The expected shot noise from TAIPAN is shown in green (dash-dotted). The bottom solid grey horizontal lines show the approximate range of \( k \) expected to be used in surveys with corresponding redshift depths \( z_{\text{max}} \).

Peculiar velocity surveys have already been used to measure \( fD \) (also referred to as \( f\sigma_8 \)),

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though not to a level where gravity models can be precisely distinguished. [2] use 6dFGS peculiar velocities using Fundamental Plane distances of elliptical galaxies to estimate absolute magnitudes with \( \sim 0.43 \) mag precision, yielding a 15% uncertainty in \( fD \) at \( z \approx 0 \). The upcoming TAIPAN survey [6] will obtain Fundamental Plane galaxies with densities of \( n_g \sim 10^{-7}h^3\text{Mpc}^{-3} \), and the WALLABY+WNSHS surveys [17] will obtain Tully-Fisher distances (based on the \( \sim 0.48 \) mag calibration of absolute magnitude based on the HI 21cm line width) of galaxies with densities \( n_g \sim 2 \times 10^{-2} - 10^{-4}h^3\text{Mpc}^{-3} \) from \( z = 0 - 0.1 \) covering 75% of the sky. These surveys combined are projected to have 3% uncertainties in \( fD \) [11]. For reference, DESI projects a 10% precision of \( fD \) at \( z \approx 0.3 \) by looking for signatures (Redshift Space Distortions; RSD) expected from galaxies infalling toward mass overdensities.

Relative to galaxies with Fundamental Plane or Tully-Fisher distances, SN Ia host galaxies currently have significantly lower number density but have better per-object peculiar velocity precision. 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 [9, 1, 16, 13, 14]. SNe Ia discovered by ASAS-SN, ATLAS, and ZTF [20, 21, 4] over the next several years will provide first probative measures of \( fD \) at \( z < 0.1 \).

Two advances in the upcoming decade will make SN Ia peculiar velocities more powerful. First, the precision of SN Ia distances can be improved. The commonly-used empirical 2-parameter spectral model yields absolute magnitude dispersion \( \sigma_M \gtrsim 0.12 \) mag. 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, SN absolute magnitudes can be calibrated to \( \sigma_M \lesssim 0.08 \) mag [?, see e.g.] [2012MNRAS.425.1007B, 2015ApJ...815...58F]. 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. At this precision the intrinsic velocity dispersion at \( z = 0.028 \) is 300 km s\(^{-1}\), i.e. a single SN Ia is of such quality as to measure a peculiar velocity with \( S/N \sim 1 \). If corrections of all SNe Ia are not possible, the use of SN Ia subclasses is an option though at the expense of reducing the numbers of velocity probes. Secondly, in the upcoming decade cadenced wide-field imaging surveys such as ZTF and LSST will increase the number of identified \( z < 0.3 \) Type Ia supernovae 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, corresponding to a number density of \( n \sim 5 \times 10^{-4}h^3\text{Mpc}^{-3} \). This sample has comparable number density and more galaxies at deeper redshifts than projected by WALLABY and TAIPAN. With similar densities, the (two) ten-year SN Ia survey will have a (6) 29\( \times \) reduction in shot-noise, \( \sigma_M^2/n \), relative to the Fundamental Plane survey of TAIPAN.

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 [10].
2 Testing Gravity with Peculiar Velocity Surveys

While the growth rate \( fD \) can be used to test several aspects of physics beyond the standard cosmological model (e.g. dark matter clustering, dark energy evolution), our scientific interest is in probing gravity, so here we focus on the growth index \( \gamma \). To illustrate the distinction, \( \frac{d \ln fD}{d \gamma} \) is the galaxy bias and \( \lambda \) is imposed as our analysis assumes that peculiar velocities are significantly smaller than the cosmological redshift. The sample-selection efficiency \( \epsilon \) is redshift-independent, \( \Omega = 3 \) \( \Omega_M \)\(, \Omega_{M_0}, \gamma \)\(, bD, \Omega_{M_0} \)\(, fD \) are the observed-frame SN Ia rate and \( \epsilon \) is the sample-selection efficiency, and the intrinsic SN Ia magnitude dispersion through the resulting peculiar velocity intrinsic dispersion \( \sigma \approx \left( \frac{5}{\ln \frac{1+z}{2}} \right)^{-1} \sigma_M \)

The uncertainty in \( \gamma \) is \( \sigma_\gamma = \sqrt{(F^{-1})_{\gamma\gamma}} \). Non-GR models may also predict a change in the scale-dependence of the growth or non-constant \( \gamma \), such observations provide additional leverage in probing gravity but are not considered here.

The uncertainty \( \sigma_\gamma \) of a survey depends on its solid angle \( \Omega \), depth given by the comoving distance out to the maximum redshift \( r_{\text{max}} = r(z_{\text{max}}) \), duration \( t \) through \( n = \epsilon \phi t \) where \( \phi \) is the observer-frame SN Ia rate and \( \epsilon \) is the sample-selection efficiency, and the intrinsic SN Ia magnitude dispersion through the resulting peculiar velocity intrinsic dispersion \( \sigma \approx \left( \frac{5}{\ln \frac{1+z}{2}} \right)^{-1} \sigma_M \).

We consider SN peculiar velocity surveys for a range of redshift depths \( z_{\text{max}} \) for durations of \( t = 2 \) and 10 years. The other survey parameters \( \Omega = 3 \pi, \epsilon = 0.65, \sigma_M = 0.08 \) mag are fixed. The \( k \)-limits are taken to be \( k_{\text{min}} = \pi/r_{\text{max}} \) and \( k_{\text{max}} = 0.1 \ h \text{Mpc}^{-1} \). A minimum distance \( r_{\text{min}} = r(z = 0.01) \) is imposed as our analysis assumes that peculiar velocities are significantly smaller than the cosmological redshift. The sample-selection efficiency \( \epsilon \) is redshift-independent, i.e. the native redshift distribution is not sculpted. The input bias of SN Ia host galaxies is set as \( b = 1.2 \). An independent measurement of \( \Omega_{M_0} = 0.3 \pm 0.005 \) is included and is a non-trivial contributor to the \( \gamma \) constraint. Number densities are taken to be direction-independent, neglecting the slight declination-dependence of SN-survey time windows.

All the surveys considered provide meaningful tests of gravity. The projected uncertainty in \( \gamma \) achieved by the suite of surveys are shown in Figure 2. The primary result is for the cross-correlation analysis that uses overdensities (RSD), peculiar velocities, and their cross-correlations.
The projected uncertainty in $\gamma$, $\sigma_\gamma$, achieved by two-year (red) and ten-year (black) SN Ia surveys of varying depth $z_{\text{max}}$. For each survey uncertainties are based on three types of analyses: using only peculiar velocities (dashed); using both RSD and peculiar velocities independently (dotted); using both RSD, peculiar velocities, and their cross-correlation (solid).

The short and shallow, 2-year, $z_{\text{max}} = 0.11$ survey has $\sigma_\gamma \sim 0.038$, which can distinguish between General Relativity, $f(R)$, and DGP gravities at the $> 3\sigma$ level. The 10-year survey performance asymptotes at $z_{\text{max}} \sim 0.2$ at a precision of $\sigma_\gamma \sim 0.01$. Figure 2 also shows uncertainties based on two other analyses, one that only uses peculiar velocities, and one that combines independent RSD and peculiar velocity results. Peculiar velocities alone account for much of the probative power of the surveys. RSD alone do not provide significant constraints. However, considering RSD and velocity cross-correlations decreases $\sigma_\gamma$ by $\sim 20\%$. The implication is that there are important $k$-modes that are sample variance limited either in overdensity and/or peculiar velocity who benefit from the sample-noise suppression engendered by cross-correlations.

Survey performance is examined in more detail by considering how $\sigma_\gamma$ in the cross-correlation analysis changes with respect to the survey parameters $\Omega$, $z_{\text{max}}$, $t$, and $\sigma_M$, and also with respect to differential redshift bins within a given survey. Though not directly a survey parameter, we also examine changes with respect to our fiducial choice of $k_{\text{max}}$.

Solid Angle $\Omega$: The Fisher Matrix $F$ is proportional to the survey solid angle $\Omega$ so $\sigma_\gamma \propto \Omega^{-1/2}$.

Differential Redshift Bin $z$: Certain redshifts constrain $\gamma$ more strongly than others. If at a given moment of a survey we had a set of SNe Ia from which to choose, it turns out the one with the lowest $z_{\text{max}}$ would be preferred. This is demonstrated to be the case at the end of both 2- and 10-year surveys with $z_{\text{max}} = 0.2$. The left panel of Figure 3 shows $|\partial \sigma_\gamma / \partial z|$, which for both surveys monotonically decreases from $z = 0.01$ out to $z = 0.2$. If we had to sculpt the distribution, the preference would be to cut out the highest redshift bins resulting in a decreased $z_{\text{max}}$. The optimal redshift distribution is thus the unsculpted SN-discovery distribution truncated by $z_{\text{max}}$.

Redshift Depth $z_{\text{max}}$: Increasing the survey redshift depth increases the $\gamma$ precision. The differential improvement in $\sigma_\gamma$ plateaus at $z_{\text{max}} \sim 0.2$ as seen in Figure 2.

Survey duration $t$; Intrinsic Magnitude Dispersion $\sigma_M$: An increased survey duration accumulates more supernovae, decreasing shot noise and increasing the precision in $\gamma$ for all the surveys considered. The surveys we consider have varying relative contributions of sample variance and shot noise: those that have a larger shot-noise contribution (i.e. shorter surveys and those with higher $z_{\text{max}}$) benefit more from extending the survey duration. Like survey duration, intrinsic magnitude...
 dispersion is related to survey performance through the shot noise and thus has a similar relationship with \(\sigma_{\gamma}\); the effect of duration and magnitude dispersion are shown in the right-panel plot of Figure 3 as \(\sigma_{\gamma}^{-1}\partial\sigma_{\gamma}/\partial \ln t\) and \(\sigma_{\gamma}^{-1}\partial\sigma_{\gamma}/\partial\sigma_M\) as a function of \(z_{\text{max}}\) for two- and ten-year surveys.

**Minimum length scale, maximum wavenumber \(k_{\text{max}}\):** There is a minimum length scale at which density and velocity distributions are reliably predicted from theory. Changes in this scale engender fractional changes in the \(\gamma\) precision as \(\sigma_{\gamma}^{-1}\partial\sigma_{\gamma}/\partial k_{\text{max}} = 0.0050\) at \(k_{\text{max}} = 0.1 h \text{ Mpc}^{-1}\), which is survey-independent.

## 3 Conclusions

In the next decade, the high number of SN discoveries together with improved precision in their distance precisions will make \(z < 0.3\) SNe Ia, more so than galaxies, powerful probes of gravity through their effect on the growth of structure. Different survey strategies can be adopted to take advantage of these supernovae, and in this White Paper we present a formalism and code (available at [http://tiny.cc/PVScience](http://tiny.cc/PVScience)) by which their scientific merits can be assessed and present results for a range of options.

No other probe of growth of structure or tracer of peculiar velocity can alone provide comparable precision on \(\gamma\) in the next decade. At low redshift, the RSD measurement is quickly sample variance limited (as are the planned DESI BGS and 4MOST surveys) making peculiar velocities the only precision probe of \(fD\). TAPIAN and a TAPIAN-like DESI BGS will be able to measure FP distances for nearly all usable nearby galaxies, so at low-\(z\) the Fundamental Plane peculiar-velocity technique will saturate at a level that is not competitive with a 2-year SN survey.

Combined low-redshift peculiar velocity and high-redshift RSD \(fD\) measurements are highly complementary as together they probe the \(\gamma\)-dependent shape of \(fD(z)\) (not just its normalization) and potential scale-dependent influence of gravitational models, since low- and high-redshift surveys are weighted by lower and higher \(k\)-modes respectively. SN Ia peculiar velocity surveys are of the highest scientific interest and we encourage the community to develop aggressive surveys in the pursuit of testing General Relativity and probing gravity.
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