LBL Peculiar-Velocity Program: ZTF2 and LSST

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September 13, 2019

Measuring peculiar velocities using Type Ia supernovae is a primary research topic in the upcoming decade. Peculiar velocities have been cited as a part of the Small Projects Portfolio by the the Cosmic Visions Dark Energy Working Group (Dawson et al., 2018).

A new group is forming ZTF2, a new 3-year survey using the existing ZTF infrastructure. We present the case for LBL joining ZTF2.

1 Probing Gravity With SN Ia Peculiar Velocity Surveys

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 (Hui & Greene, 2006; Davis et al., 2011). The combination fD evolves with redshift; the ΛCDM prediction for the $z = 0$ peculiar velocity power spectrum is shown in Figure 1.

The growth of structure depends on gravity; Linder (2005); Linder & Cahn (2007) find that General Relativity, $f(R)$, and DGP gravity follow the relation $f \approx \Omega_M^\gamma$ with the growth index $\gamma = 0.55, 0.42, 0.68$ respectively (see Huterer et al., 2015, for a review or these models). Using this parameterization, peculiar velocity surveys probe gravity through by modeling $fD = \Omega_M^\gamma \exp\left(-\int_a^1 \Omega_M^\gamma d\ln a\right)$, where $\Omega_M(a)$ also depends on the gravity model~~depends on expansion rate determined by gravity~~[2]. The γ-dependence of $fD(z)$ is shown in Figure 2 of Linder (2013).

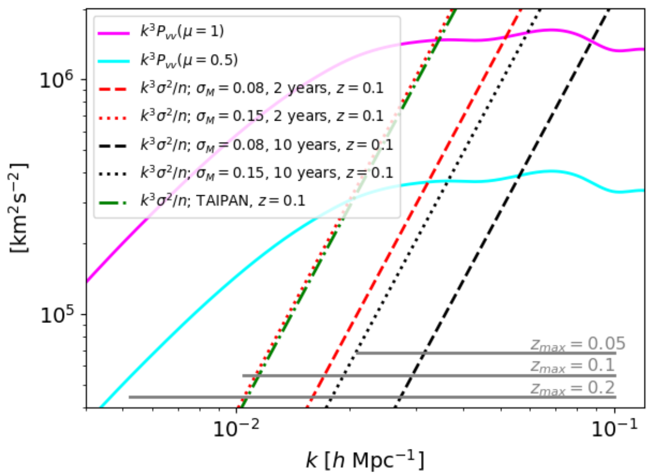

Figure 1: Dimensionless~~Volume-weighted~~[2] peculiar velocity power spectrum $k^3 P_{vv}(z = 0)$ for $\mu \equiv \cos(\hat{k} \cdot \hat{r}) = 1, 0.5$ (magenta, cyan) where $\hat{r}$ is the line of sight, as predicted for General Relativity in the linear regime. Overplotted are peculiar-velocity power-spectrum 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 $z_{\max}$.

The same SNe Ia used to measure peculiar velocities can also serve as tracers of mass overdensities. Overdensities and their motions are connected by the continuity equation, so the SN-overdensity power spectrum also depends on gravity as $P_{\delta\delta} \propto (bD + fD\mu^2)^2$ where b is the SN bias and $\mu \equiv \cos(\hat{k} \cdot \hat{r})$ where $\hat{r}$ is the direction of the line of sight. The bias is a “nuisance” parameter, not present in the velocity power spectrum, which must marginalized out when inferring γ. The same field is responsible for both overdensities and velocities so when combined in a common analysis the sample variance limit is lowered.

A SN Ia peculiar velocity survey is composed of several components:

- Transient Discoveries – Wide-field cadenced imaging surveys detect and localize the angular coordinates of new supernovae.

- Discovery Screening – Galaxy redshift catalogs, supplemental imaging data can provide subsets of the discoveries for classification using relatively expensive follow-up resources.

- SN Ia Classification – Spectroscopy classifies the SN Ia from among the pool of transient discoveries.

- (Host-galaxy) Redshift – Spectroscopy provides redshifts. Host-galaxies generally have more/sharper features that provide more precise redshifts than the supernovae themselves. Resolution $R > 200$ is sufficient~~necessary~~ to ensure that statistical uncertainties are negligible.

- SN Ia Distance – Imaging produces photometry and colors for light-curve fitting and getting distances. The transient search naturally provides some data for this, of quality that varies depending on the survey strategy. Spectroscopy and NIR photometry have been shown to provide more precise distances than with optical light curves alone.

The above suite of observations provide a pure sample of SNe Ia with observed redshifts and cosmological redshifts (inferred from the distances and the background Hubble law) whose difference is the radial peculiar velocity.

The precision in measuring γ can be projected for different peculiar velocity surveys. The primary parameters that affect the precision are: solid angle Ω, SN number density n, source intrinsic magnitude dispersion σ_M, and for a distance-limited survey the maximum distance $r_{\max}$ (alternatively redshift $z_{\max}$). The dependence is most simply discerned in the Fisher information matrix

$$F_{ij} = \frac{\Omega}{8\pi^2} \int_{r_{\min}}^{r_{\max}} \int_{k_{\min}}^{k_{\max}} \int_{-1}^{1} r^2 k^2 \mathrm{Tr} \left[C^{-1} \frac{\partial C}{\partial \lambda_i} C^{-1} \frac{\partial C}{\partial \lambda_j} \right] d\mu \, dk \, dr \tag{1}$$

where

$$C(k,\mu,a) = \begin{bmatrix} P_{\delta\delta}(k,\mu,a) + \frac{1}{n} & P_{v\delta}(k,\mu,a) \\ P_{v\delta}(k,\mu,a) & P_{vv}(k,\mu,a) + \frac{\sigma^2}{n} \end{bmatrix}, \tag{2}$$

and the peculiar-velocity uncertainty (σ) is related to magnitude uncertainty via $\sigma_M^2 = \left(\frac{5}{\ln 10}\right)^2 \left(1 - \frac{1}{Ha\chi}\right)^2 \sigma^2$.[1] The dependences of γ and other parameters enter through fD in the relations $P_{vv} \propto (fD\mu)^2$, the SN Ia host-galaxy count overdensity power spectrum $P_{\delta\delta} \propto (bD + fD\mu^2)^2$, and the galaxy-velocity cross-correlation $P_{vg} \propto (bD + fD\mu^2) fD\mu$. The density and velocity covariances depend on the parameter set $\lambda \in \{\gamma, \Omega_{M0}, b\}$. Taking ΛCDM as our fiducial model, $\Omega_M = \frac{\Omega_{M_0}}{\Omega_{M_0} + (1-\Omega_{M_0})a^3}$. The uncertainty in the growth index is bounded by $\sqrt{F^{-1}_{\gamma\gamma}}$.

2 Current Results and Projections

2.1 Current Results

Peculiar velocity surveys have already been used to measure the effective fD in redshift bins (referred to as $f\sigma_8$), though not to a level where gravity models can be precisely distinguished. Adams & Blake (2017) use 6dFGS peculiar velocities using Fundamental Plane distances of elliptical galaxies to estimate absolute magnitudes with ~ 0.43 mag precision, yielding a 15% uncertainty in fD at $z \approx 0$. The upcoming TAIPAN survey (da Cunha et al., 2017) will obtain Fundamental Plane galaxies with densities of $n_g \sim 10^{-3}h^3\,\mathrm{Mpc}^{-3}$, and the WALLABY+WNSHS surveys (Johnston et al., 2008) will obtain Tully-Fisher distances (based on the ~ 0.48 mag calibration of absolute magnitude based on the HI 21cm line width) of galaxies with densities $n_g \sim 2 \times 10^{-2} - 10^{-4}h^3\,\mathrm{Mpc}^{-3}$ from $z = 0 - 0.1$ covering 75% of the sky. These surveys combined are projected to have 3% uncertainties in fD (Howlett et al., 2017). 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 (Gordon et al., 2007; Abate & Lahav, 2008; Johnson et al., 2014; Huterer et al., 2015, 2017). SNe Ia discovered by ASAS-SN, ATLAS, and ZTF (Shappee et al., 2014; Tonry et al., 2018; Bellm et al., 2019) over the next several years will provide first probative measures of fD at $z < 0.1$.

2.2 Projections

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. 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. At this precision the intrinsic velocity dispersion at $z = 0.028$ is 300 $\mathrm{km\,s^{-1}}$, 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 ZTF2 and LSST will increase the number of identified $z < 0.2$ Type Ia supernovae from the hundreds to the hundreds of thousands; over the course of 10-years, LSST will find

$\sim 150,000$ $z < 0.2$ SNe Ia for which good light curves can be measured, 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 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, σ_M^2/n, relative to the Fundamental Plane survey of TAIPAN.

A SN Ia peculiar velocity program hinges on SN discoveries, the number density n of which depends on the cadenced wide-field imaging survey used for the search. It is thus convenient to make projections for upcoming programs based on the imaging survey; the projections here use ZTF2 and LSST as canonical representatives. Keep in mind that other follow-up resources determine the distance precision σ_M, the other important parameter that affects projections.

The primary sources of systematic error in a high-redshift supernova Hubble diagram are not as important for a low-redshift peculiar velocity survey. A Hubble diagram that spans a broad redshift range requires absolute color calibration over the corresponding observer-frame wavelength range and control over the different populations over the span of cosmic time from which SNe are drawn. High-redshift peculiar velocity measurements do not have much sensitivity to γ, and a SN survey confined to lower redshifts is less sensitive to color-calibration uncertainties and population evolution.

Details on the assumptions made for the calculations that follow can be found in Kim et al. (2019).

2.2.1 Near-Term: ZTF2

ZTF2 and TAIPAN are near-term surveys that will measure peculiar velocities, the former using SNe Ia and the latter using Fundamental Plane Galaxies. Both have roughly $z_{\mathrm{max}} = 0.09$ and $\Omega = 2\pi$. Uncertainties in γ for surveys with this depth and solid-angle coverage are shown as a function of number of sources N and σ_M in Figure 2.

The positions of ZTF2 and TAIPAN are marked in the figure, with the former showing both a conservative $\sigma_M = 0.12$ mag and aggressive $\sigma_M = 0.08$ mag. The former is the uncertainty that could be achieved with ZTF2 photometry alone, the latter with additional SN follow-up. ZTF2 and TAIPAN lie in opposite ends of the figure, there are small numbers of ZTF2 SNe with precise distances whereas there are many TAIPAN Fundamental Plane galaxies with imprecise distances. Conservative ZTF2 and TAIPAN are projected to give similar precisions $\sigma_\gamma = 0.060$, whereas aggressive ZTF2 gives a more constraining $\sigma_\gamma = 0.048$. Recall that the difference in γ between GR and the $f(R)$ and DGP gravity is 0.13, meaning that the surveys can already distinguish between these models to $2-3\sigma$.

An important distinction between the surveys is that TAIPAN will observe almost all available Fundamental Plane galaxies in the local volume, meaning that no additional observing can increase the number density n and decrease σ_γ. On the other hand, the number density of supernova increases linearly with time, there is continued room for decreased σ_γ with longer surveys as ZTF2 is not sample-variance limited

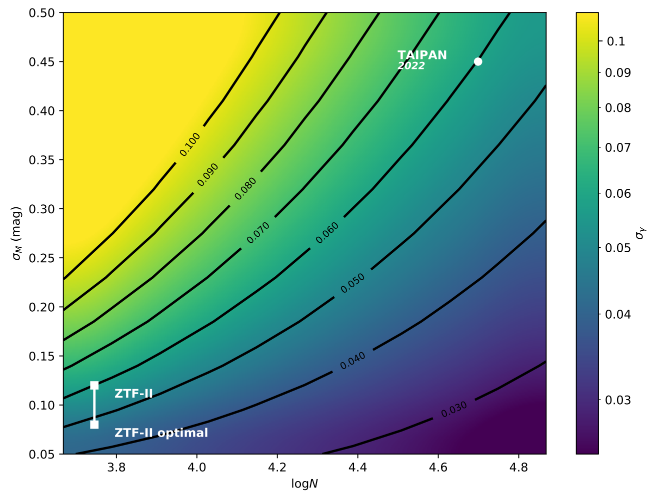

Figure 2: Uncertainties in γ for surveys with $z_{\max} = 0.09$ and $\Omega = 2\pi$ are shown as a function of number of sources N and σ_M. The positions of ZTF2 and TAIPAN are marked, with the former showing both a conservative $\sigma_M = 0.12$ mag and an aggressive $\sigma_M = 0.08$ mag.

ZTF2 and TAIPAN are not in competition but are complementary. Being in different hemispheres, the two surveys cover different parts of sky, meaning that their two independent results can be combined quadratically to produce a reduced joint uncertainty.

2.2.2 Long-Term: LSST

A long-term supernova peculiar-velocity survey can be performed with SNe Ia discovered by LSST. As a 10-year survey, LSST generates higher supernova number densities to fainter limiting magnitude than ZTF2, making possible significantly improved constraints on the growth index. All the proposed LSST surveys have complete SN Ia discovery out to $z = 0.3$. The expected distance uncertainties derived from LSST light curves vary greatly depending on observing strategy, but at best is expected to be $\sigma_M = 0.12$ mag. Some strategies provide SN discovery but much poorer light curves and distances. As with the ZTF2 survey, lower magnitude uncertainties can be achieved with supplemental data.

Uncertainties in γ for surveys with a 10-year duration and $\Omega = 2\pi$ sky coverage, applicable to the LSST WFD survey, are shown as a function of limiting redshift z_{max} and σ_M in Figure 3. The redshift depth afforded by LSST provides significant improvement relative to the shallower ZTF2 survey. After 10 years, the region with $z_{max} < 0.1$ has σ_γ that is only weakly σ_M-dependent, which reflects the relatively strong sample variance in the small local survey volume. As σ_γ quickly increases for surveys shallower than the $z_{\max} = 0.09$ of

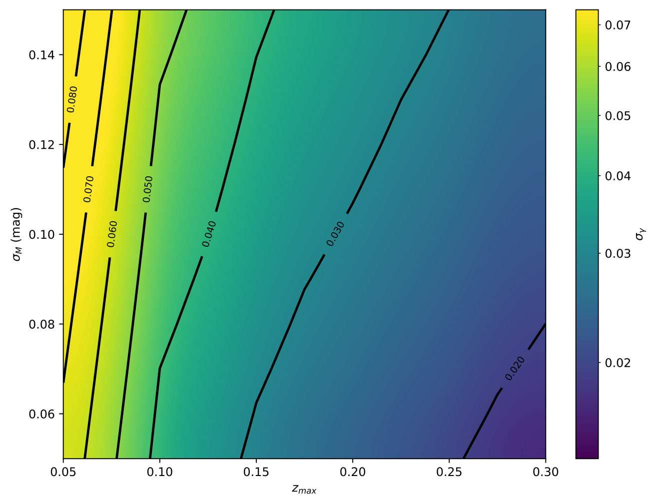

Figure 3: Uncertainties in γ for surveys with a 10-year duration and and $\Omega = 2\pi$ sky coverage are shown as a function of limiting redshift z_{max} and σ_M.

ZTF2, better growth index constraints are achieved by going to $z_{max} > 0.1$. The gradient in decreasing σ_γ does shallow out with increasing redshift despite the increased survey volume, as the velocity uncertainties degrade with redshift for a fixed σ_M.

2.3 Complementarity with High-z redshift surveys

Combined low-redshift peculiar velocity and high-redshift RSD fD measurements (i.e. from DESI) are highly complementary as together they probe the γ-dependent shape of $fD(z)$ (not just its normalization) and potential scale-dependent influence of gravitational models. The latter is true because the $k_{\max}$ of linear modes for the RSD measurement is higher than that of the low-redshift peculiar velocity measurement.[2]

3 Plan for a Peculiar Velocity Program

The projections for measuring γ with ZTF2 and LSST SN Ia discoveries show the power of peculiar velocities surveys at low redshift. This tracer provides an unmatched new window with which to test gravity and the source of the accelerating expansion of the Universe. We propose the following course of research for the upcoming decade.

3.1 Present

The current goals are to provide a proof of concept of a SN peculiar velocity survey while developing domain expertise and pipelines that can be used in future experiments.

Kim has developed a SNFactory/ZTF peculiar-velocity analysis framework with a post-doc. Its distinguishing features is that it is likelihood-based including both density and peculiar velocities. The complexity of including fitting the underlying mass density field in the model is addressed through Hamiltonian Monte Carlo. Analytic expressions for the partial derivatives of the likelihood are coded, avoiding the computational limitations of *autodiff* in STAN. A end-to-end implementation is complete, validation of it is ongoing.

The first application o the analysis pipeline will be for SNFactory supernovae. A next analysis will be of ZTF-discovered SNe when those data are ready. The plan is for a subset of the required data, precision redshifts of SN host galaxies, to be provided by DESI. Additional DESI data contributions are being discussed.

3.2 Near Term: DESI as TAIPAN-North

There has been talk of using BGS for a peculiar-velocity survey. There is some question as to how deep the BGS achieves. This should be dug into.

3.3 Near Term: ZTF2 + DESI

A near-term peculiar velocity program can already provide the most competitive measurements of γ at low redshift. Engaging in science now positions LBL for domain leadership in the LSST era. For its near-term peculiar-velocity program, we advocate a survey using SN Ia discoveries from ZTF2, rather than other possible surveys, for the following reasons:

- A peculiar-velocity survey is already being touted as a primary science driver. As such, the observing strategy should accommodate our needs.
- It would be ready to start at the end of ZTF in 2021.
- It is cheap, with a cost ranging from zero to access public data, to an amount ($300k?) smaller than building a new facility.
- ZTF2 includes SEDMachine for classification of $m < 18.5$ mag transients.
- It is in the Northern Hemisphere, which complements and is not superseded by LSST. Even after the nominal 3-year survey and simultaneous with LSST, the facility remains important for peculiar-velocity studies.
- It is anticipated that the public plus private collaboration surveys can be designed to generate distance precisions of $\sigma_M = 0.12$ mag, which allow good velocity measurements with SNe Ia. (Additional follow-up can lower this uncertainty further.)
- The limiting redshift $z_{\mathrm{max}} = 0.09$ is sufficiently deep to have a scientifically interesting result $\sigma_\gamma < 0.053$. There are other SN searches that do not achieve this depth.

ZTF2 SN Ia discoveries are combined with data from other facilities to form a complete PV program. We propose:

- DESI will provide the following components of the survey:
  - Discovery Screening – Provides redshifts for probable host galaxies of new transients, for use in early classification. A host galaxy may already have a DESI redshift, may be a BGS target without a redshift but whose observation could be prioritized, or non-DESI target for which we make a secondary-target fiber allocation.
  - SN Ia Classification – Spectroscopy of active transients through secondary-target fiber allocations within DESI survey pointings. There will be ~ 1 active $r < 21.5$ SN Ia in every three DESI pointings. Coordinating DESI pointings such that "every" pointing contains a ZTF2 discovery can significantly increase the number of classifications, relative to the random (from the transient perspective) default DESI pointings. Triggered observations of non-DESI pointings is possible, though does not take advantage of DESI multiplexing.
  - Host-galaxy redshift – Some precise galaxy redshifts may not be available at the end of the ZTF2 survey. Mopping up of ZTF2 host-galaxy redshifts can be done efficiently with a single sweep of DESI's MOS.

  The $R > 2000$ resolution provides sufficiently precise redshifts so as to make their uncertainties negligible in the γ error budget. Its BGS targets will host a large fraction of ZTF2-discovered SNe Ia.

- SNIFS at the UH-88 is used to spectroscopically observe a subset of active likely-SN Ia transients. SNIFS provides simultaneously
  - SN Ia Classification – SNIFS can supplement SED Machine to go toward 100% SN Ia classifications while going deeper than the nominal 18.5 mag limit of SED Machine.
  - Host-galaxy redshift.
  - SN Ia Distance – SNIFS has already been used to standardize SNe Ia magnitudes to $\sigma_M = 0.08$ mag. SNIFS observations will be designed to obtain this precision. This SN subset will have relatively smaller peculiar-velocity uncertainties relative to those with only ZTF2 photometry. The SNIFS IFU provides local host-galaxy properties, which may also improve SN distance precisions.

  The University of Hawaii must allocate time and resources into the program. There is already UH expertise in supernovae and peculiar velocities and an existing relationship with LBL.

- NIR – Something through UH?

– SN Ia Distance – NIR observations are designed to get $\sigma_M = 0.08$ mag. These SNe will be more sensitive probes of velocity than those with only ZTF2 photometry.

The active SN spectrophotometric and NIR follow-up provide significant distances estimates over what ZTF2 photometry can do alone.

ZTF2 will have public, private collaboration, and CalTech surveys. In ZTF, the private time was used to survey in the i-band (supplementing the g and r-bands of the public survey), that turns out to be useful in transient classification and SN Ia distance determination. Nevertheless, we should monitor whether the public data is sufficient for our needs. It could be that we do not need to buy into ZTF2 in order to have a ZTF2-discovery peculiar velocity survey. (Input from current ZTF folks should be solicited.)

3.4 Long Term: LSST +

The DESC SN Ia Working Group is interested in peculiar velocity science. There is an official peculiar-velocity project. A peculiar-velocity metric was included in the DESC response to the Project call for white papers on observing strategies. Informal meetings have been held by DESC members.

3.5 A New Project

The scope of ZTF2 and the coordination of follow-up of LSST discoveries extend beyond the confines of current DOE projects. The recommendations of the Small Projects Portfolio by the Cosmic Visions Dark Energy Working Group provides an path by which LBL could lead an international collaboration, supported by the Office of Science, in the study of Peculiar Velocities.

The new peculiar velocity project would focus on two topics: the use of DESI (and future spectroscopic surveys such as DESI2) for measuring distances of fundamental plane galaxies; the mobilization of follow-up resources and data management that are required or enhance the probative power of transient discoveries by ZTF2/LSST. Ideas being discussed for the latter include refurbishment and use of the UH-88 + SNIFS, DESI, 4MOST, a proposed French spectrograph mounted at ESO, a network of identical spectrographs (e.g. the DESI design) distributed around the world. There is expressed interest from South Africa and Australia in using their resources for peculiar-velocity follow-up observations.

LBL, through the project, would support a broad community interested in peculiar velocities. There are interested groups at the University of Hawaii, the University of Michigan, the University of Pittsburgh, the University of Rochester, Yale University, Brookhaven National Laboratory, the Carnegie Observatories, several IN2P3 labs, Humboldt University, the University of Toronto, the University of Queensland, African Institute for Mathematical Sciences.

4 ZTF2 Collaboration Buy In

While a successful peculiar velocity survey is possible from public ZTF2 alerts, there are benefits to joining the private survey, including having the power to design both public and private surveys and access to data that gives better early classification and SN distances. ZTF2 requires buy-in: here are some options for LBL

4.1 Through DESI

DESI could try to negotiate buy-in through in-kind contributions of galaxy redshift catalogs and observations. DESI members, including interested LBL and non-LBL collaborators, would gain access to the ZTF2 collaboration.

DESI would offer some of the following

- Early access to spectra of transient host-galaxies taken as part of its surveys, the BGS in particular.
- Prioritize observations of those DESI targets that happen to be of interest to ZTF2.
- Secondary science fiber overrides in DESI pointings.
- DESI pointing overrides for objects in fields with no planned near-term observations.
- Galactic time allocation, in anticipation that at some seasons DESI will not have many extra-galactic pointings.
- Redshifts of "all" transient hosts at the conclusion of ZTF2
- Joint DESI-ZTF2 density plus peculiar-velocity analysis.

Toward the end of the DESI survey there will be an opportunity for pilot studies for an extension or next-generation DESI. We can develop and advocate such a study beneficial to ZTF2.

4.2 Through NERSC

Current plans call for IPAC to perform ZTF2 data management. There is a constituency of current ZTF stakeholders who would like for NERSC to take on this responsibility for ZTF2, as IPAC has not delivered desired photometric accuracies.

Peter, beyond running code at NERSC, what more could LBL commit to?

4.3 LSST In-Kind Contribution

The new "open data" model for LSST has non-US scientists looking for in-kind contributions to buy into LSST. International scientists are informally asking LBL folks whether ZTF2 could be a contribution. Through the process initiated by DESC, we plan to advocate for ZTF2-LSST collaboration. Any such dealing would be done at the funding agency level with input from the LSST Project, it is doubtful that LBL could play a leadership role in such negotiations.

5 Conclusions

In the next decade, the high number of SN discoveries together with improved precision in their distance precisions will make $z < 0.2$ SNe Ia, more so than galaxies, powerful probes of gravity through their effect on the growth of structure. No other probe of growth of structure or tracer of peculiar velocity can alone provide comparable precision on γ 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. TAIPAN and a TAIPAN-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.

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