Snowmass2021 - Letter of Interest

A Network to Probe 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, public transient searches will discover sufficient numbers of Type Ia supernovae to make precision measurements of the correlations in the local peculiar velocity field, and hence the growth of structure under the pull of gravity. A follow-up network of properly instrumented telescopes is required to obtain the supplemental redshift, classification, and subclassification data to translate those discoveries into peculiar velocities. A spectrograph similar to those already in operation is a candidate for that instrumentation. Nominal follow-up networks require one 2m-class telescope for a pathfinder project (with additional time from DESI), and several additional 4m-class telescopes to take advantage of the copious deeper discoveries that will be made by the Rubin Observatory. The Snowmass process provides an opportunity for the community to develop a concrete concept for the network and a roadmap for its realization.

Peculiar velocities measured using Type Ia supernovae (SNe Ia) in the local Universe have the power to distinguish between General Relativity and leading models of modified gravity. Measurements with 4-5σ confidence will be possible in the coming decade by exploiting the large numbers of $z < 0.09$ SNe Ia now and soon to be discovered[12;19;22] together with even more out to $z = 0.2$ and beyond to come from the Vera C. Rubin Observatory LSST[21]. Given the anticipated stream of fresh SNe, a coordinated network of follow-up facilities is then required to convert those discoveries into peculiar velocities. The signals the network must provide are deviations from the average Hubble expansion:

Early-Phase Screening: Cadenced wide-field imaging surveys discover SNe Ia together with a background of other transient events. Though not strictly required, screening enables the efficient use of limited telescope resources by identifying a subset of likely active SNe Ia targets for follow-up at peak brightness. Screening is primarily based on the temporal and color evolution during the early post-discovery phases of transient light curves.

SN Ia Classification: Pure SNe Ia samples have lower absolute magnitude dispersion, and hence better velocity precision, relative to samples that suffer from non-Ia contamination. SNe Ia are defined based on their spectroscopic features, so spectroscopic coverage of the relevant features ensures the purity of the analysis sample. Photometric classification dilutes the signal in the scatter of the Hubble diagram, while selection from only early-type hosts has core-collapse contamination and significantly reduced sample size.

Host-Galaxy Precision Redshifts: Peculiar velocities come from the difference between host-galaxy and cosmological redshifts. Fractional host-galaxy redshift uncertainties from moderate-resolution spectroscopy ($R > 100$) do not contribute significantly to the error budget. In many cases the redshifts could come naturally from the galaxy signal in the spectroscopic transient classification. Alternatively, moderate-resolution bright-galaxy redshift surveys can provide multiplexed observations of a significant fraction of nearby SN hosts before discovery or after transient light has faded away.

Precise SN Ia Absolute Magnitudes: SNe Ia are standardizable candles, in that their absolute magnitudes can be inferred from intrinsic observables such as multi-band light-curve shapes, spectroscopic features, and host-galaxy properties. For the same supernova, the absolute magnitude uncertainty derived from a dataset with sparse light curves, a small number of filters, limited wavelength coverage, and lacking spectral-feature measurements is larger than the dispersion derived from a broader dataset with dense light curves, a large number of filters, broad wavelength coverage, and spectral-feature measurements. Surveys with three well-sampled rest-frame optical light curves obtain $\sim 7\%$[18] distance uncertainties; standardization studies show that supplemental infrared data[3;7] or spectrophotometry at peak brightness[5;10] can yield distances as good as $\lesssim 4\%$. Follow-up measurements that give this better precision yield SNe with 3× the peculiar-velocity probative power compared to those with only optical light-curves.

SN Ia Observed Magnitudes: The difference between observed and absolute magnitudes gives the distance to a supernova. Generally the observed magnitudes come from the amplitudes of the same multi-band light curves whose shapes and colors are used to infer absolute magnitudes.

Two reference surveys are introduced to assess the supplemental resources needed for a complete SN peculiar velocity program. The first "pathfinder" survey corresponds to a sample of ~ 5000, $g < 19$ mag, $z < 0.09$ SN Ia discoveries as would be discovered by ASAS-SN+ATLAS, ZTF-II during a three-year survey. The second "legacy" survey is composed of a sample of ~150,000, $r < 20.5$ mag, $z < 0.2$ SN Ia as will be discovered by LSST over the course of ten years.

Nominal follow-up networks that collect the requisite peculiar-velocity data for the above reference surveys are now described. The follow-up strategies presented have the advantage of being based on successful precedents, but do not represent the only viable strategy.

Wide-field ($\gtrsim 1$ sq. deg.) Imaging Survey on a $\lesssim 2$m Telescope: Early-phase screening ideally would come from this search. The observing strategy of ZTF (and presumably ZTF-II) is highly cadenced and so provides good early photometric classification[15]. However, the original LSST Wide Fast Deep (WFD) survey produces sparse per-band light curves with little early-time data and poor distance determinations[14]. The ultimate LSST WFD strategy is currently unspecified; hence its capability for early typing remains unknown. The Rubin Observatory has convened the Survey Cadence Optimization Committee, which is currently slated to give its recommendations by Dec. 31, 2021. This source of risk is mitigated by planning for a wide-field imaging survey on a different telescope designed to 1) fill in the temporal gaps of the WFD survey to enable early classification; 2) implement an observing strategy optimized for low redshift peculiar velocities, e.g. favor larger solid angle and shallower depth than envisioned for WFD. The LS4 project[16], a next-generation transient search on the La Silla Schmidt Telescope with an upgraded camera, satisfies these needs. Other options include the VST/OmegaCam[8] and DECam.

Targeted (IFU) Spectroscopy of Active SNe: Spectroscopic follow-up with moderate spectral resolution of likely SNe Ia provides 1) classification; 2) host-galaxy redshifts; 3) precision SN Ia absolute magnitudes. The SNIFS Integral Field Unit (IFU) spectrograph[13] mounted on the UH-88" is a proof of concept, having generated a time series of ~ 300 SNe Ia[1] at $z < 0.08$. (Other IFU designs[2;6] are also viable.) The IFU allows for the subtraction of a host-galaxy reference yielding a spectrophotometric SN-only spectrum. For the "pathfinder survey", a 2.2m telescope requires an average 20 minute exposure to measure the spectral features of one SN Ia near maximum light, which translates to ~ 160 clear nights per year for three years to get the full sample. Total clock time includes overheads for poor weather and non-Ia contamination. In addition, a comparable amount of non-time-critical reference spectra must be obtained at least a year after the SN light has faded. The "legacy" survey of 150,000 SNe Ia requires added 4m-class telescopes with 7× the open-shutter time per year (3 telescope years per year plus weather overhead) for ten years plus additional time for references.

Targeted Spectroscopy of Host Galaxies: The redshifts of a subset of hosts will not be accessible from the IFU data. In these cases redshifts of host galaxies can be efficiently obtained using wide-field multi-object spectroscopy with DESI[9] or 4MOST[20] even after the supernova light has faded.

There are other approaches for designing the network that can be evaluated during the Snowmass Process. One option is to focus on NIR photometry to improve SN Ia distances, e.g. at UKIRT. Another is to decouple the classification and redshifting instruments by obtaining (sub)classifications using $R < 100$ spectroscopy that cannot deliver a precision redshift, e.g., SED Machine[4], and getting redshifts from dedicated host-galaxy spectroscopy; indeed this approach is being applied to the shallow discoveries of ZTF[11]. Another option is to use photometry only, without supplemental spectroscopy, to calibrate SN absolute magnitudes; the probative power of each SN drops significantly in this case, but still remains much better than competing Fundamental Plane and Tully-Fisher distances. Similarly, follow-up of a reduced subset of SNe with scaled-back follow-up resources, while not taking full advantage of all the discoveries, can still outperform galaxy-derived distance surveys.

We advocate an SN Ia Follow-up Network designed for peculiar velocity science. While SN discoveries will come for "free" in the next ten plus years, resources are required to get the full suite of information needed for accurate measurement to reach the discovery potential of 4-5σ for modified gravity. A pathfinder survey requires one 2m-class telescope whereas a legacy survey requires 3+ 4m telescopes. IFU spectrographs meeting our requirements have already been built, though there are avenues by which modest R&D can lower total costs and risk. A homogeneous SN sample and data significantly simplify the hardware, processing, and science analysis. This Network represents one of several efforts for following up transient discoveries. Coordination with other follow-up programs[17] can allow for optimized use of resources and open an expanded science program for the Network.

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