Synergies between Vera C. Rubin Observatory, Nancy Grace Roman Space Telescope, and Euclid Mission: Constraining Dark Energy with Type Ia Supernovae

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ABSTRACT

We review the needs of the supernova community for improvements in survey coordination and data sharing that would significantly boost the constraints on dark energy using samples of Type Ia supernovae from the Vera C. Rubin Observatories, the Nancy Grace Roman Space Telescope, and the Euclid Mission. We discuss improvements to both statistical and systematic precision that the combination of observations from these experiments will enable. For example, coordination will result in improved photometric calibration, redshift measurements, as well as supernova distances. We also discuss what teams and plans should be put in place now to start preparing for these combined data sets. Specifically we re-
quest coordinated efforts in field-selection and survey operations, photometric calibration,
spectroscopic follow-up, pixel-level processing, and computing. These efforts will benefit not
only experiments with Type Ia supernovae, but all time-domain studies, and cosmology with
multi-messenger astrophysics.

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1. INTRODUCTION

Type Ia Supernovae (SNe Ia) are a key probe for measuring dark energy, and currently hold a critical place in two of the three large surveys: the Legacy Survey of Space and Time (LSST) with the Vera C. Rubin Observatories and Nancy Grace Roman Space Telescope. Both LSST and the Roman SN Ia surveys will be unprecedented in their statistical sample size. The LSST optical sample at redshift $0 < z < 1$ will be a factor of $300 \times$ larger than the cumulative sample of SNe Ia today and the Roman NIR sample at $0.3 < z < 3.0$ will discover and measure $50 \times$ more SNe Ia at $z > 1$ than in our sample today and increase the sample of NIR light-curves by a similar magnitude. While Euclid does not have a planned SN Ia survey in its baseline plan (see here for a proposed strategy: Astier et al. 2014), it will revisit deep fields with a regular cadence, which can produce SN Ia detections and be combined with the LSST sample.

The synergy between combined data sets is enormous — especially if the surveys coordinate observations. Combining data sets allows increases in redshift range and wavelength range, boosting the statistical precision and the systematic control. Furthermore, as discussed in other responses to this call, the SN Ia programs will immensely benefit from cross-survey data products to improve calibration and photometric redshifts. Particularly due to the time-dependent nature of SN Ia surveys, planning must be done now for survey coordination and combined analyses. In this response to the DOE/NASA Request for Information, we separate aspects that need decisions now versus those where planning should begin soon to be considered for future synergies.

For the SN Ia programs, it is particularly important that the multiple science agencies who have issued this RFI, continue to work together because the cosmological analyses will be built on SN Ia data that must be obtained using large time allocations from facilities that are run by these (and other) agencies. The quality of the results will also strongly depend on the development of techniques and knowledge that individually may go beyond each different agency’s traditional focus areas. To maximize the science impact of each agency’s investment, scientists must have broad support, including for ways that allow them to work together across agencies’ traditional boundaries. A scientist should only need to apply to a single agency for funding to fully participate in all aspects of the problem.

2. SCIENCE ENHANCEMENTS

a. What are the key dark energy science areas that will be enhanced by these activities? What level of scientific enhancement is expected by carrying them out after the datasets are public?

The LSST and Roman Space Telescope surveys will produce SN Ia samples with significantly different, but overlapping redshift ranges. LSST will discover an enormous ($>300,000$) number of SNe around $z \approx 0.3–0.4$ in its wide survey, and a smaller ($>10,000$) but more cosmologically-constraining number in deep fields out to $z \approx 0.9–1.0$. Roman will discover a
smaller number (>10,000) but reaching to much higher redshifts (z > 2.0). Combining SN Ia samples from LSST and Roman improves the dark energy figure of merit (Albrecht et al. 2006) by up to a factor of two, over independent analyses. In addition, there will be hundreds of strongly gravitationally lensed SNe Ia from these surveys in which joint analysis will greatly improve their cosmological utility in a similar manner as it will for the normal SN Ia population (Goldstein et al. 2019).

With such high statistical precision, analyses will leverage systematic uncertainty ‘self calibration’ (Kim & Miquel 2006; Rubin et al. 2015; Brout et al. 2020), but will nonetheless be limited by systematic uncertainties. Combining data from Rubin, Roman, and Euclid — as well as complementary spectroscopic follow-up — will greatly improve control of certain systematic uncertainties. There are multiple reasons for this improvement due to both better instrumental calibration and improved knowledge of SN Ia physics. A brief list of the systematic uncertainties that can be improved are:

- **Photometric calibration** A key source of systematic uncertainty for measuring the dark energy equation-of-state is the lack of a common, accurate, chromatic scale referenced to the physics-based International System (SI). The uncertainty in the flux standards, and hence, uncertainty in the photometric zero points are a large contributor to the systematic error budget (Hounsell et al. 2018; Battaglieri et al. 2017). Work to establish such calibration is a focus of several groups — for example, STarDICE, SCALA, NISTStars, Collimated Beam Projector, ORCASat, ORCAS — that are not-accidentally dominated by SN Ia researchers (Lombardo et al. 2017; Aldering et al. 2021; Coughlin et al. 2018). Measurements of dark energy, in particular SN Ia cosmology, require an external calibration error budget, so we must rely on more than one of these paths to be successful. Between them, Roman, Euclid, and LSST span the optical and near-infrared wavelengths, presenting a special challenge. They require not only joint observations of SI-referenced optical-NIR spectrophotometric standard stars, but also must ensure photometric consistency between these experiments through coordinated observations and measurement algorithms for agreed-upon calibration fields. One key activity for achieving the desired cross-mission accuracy is for each mission/experiment to commit the necessary resources towards understanding and tracking instrument performance over time, in addition to wavelength.

- **Spectroscopic follow-up** Combining data from Rubin, Roman, Euclid, and complementary spectroscopic follow-up will greatly improve control of certain systematics. Systematic biases in SN Ia distances can be controlled (or in some cases eliminated) with spectroscopic observations of the supernovae themselves. These observations can remove residual non-Ia contamination and mis-identified redshifts, minimize host-galaxy SN-luminosity dependence, test for population evolutionary drift, and significantly improve the statistical uncertainty of the standardization (Jones et al. 2018; Boone et al. 2021).
• **Photometric redshift measurements** are improved with a broader wavelength coverage (Capak et al. 2019; Rhodes et al. 2019). Photometric redshifts will be an important piece of the overall strategy to obtain SN Ia redshifts. The training of photometric redshift algorithms will also be improved by synergies between observatories, see the response to this RFI “Photometric Redshifts for the Next Generation of Weak Lensing Surveys” by Daniel Masters, et al. for details.

• **Host-galaxy redshifts** In order to measure dark energy with SNe Ia, redshifts are needed. These can come from the SN or its host galaxy. LSST-DESC has baselined obtaining redshifts from host-galaxies due to the multiplex advantage of this approach, and discussions are ongoing to partner with 4MOST for this purpose. But 4MOST will not reach sufficient depth in the LSST Deep-Drilling Fields (DDF), where most of the DESC SN Ia cosmology will be performed. *Roman* will estimate a fraction of its redshifts from the spectra obtained with its prism and grism surveys. *Roman* also has access to 100 nights of time on Subaru, where the PFS instrument could be used to obtain these redshifts for *Roman* SN fields north of declination $-30^\circ$. Simulations by the *Roman* SN SITs show that more than 100 nights on Subaru with PFS could be productively consumed by the *Roman* SN program alone, because there will be a sizable population of intrinsically faint host galaxies of high-redshift *Roman* SNe Ia. Therefore, there is certain to be an unmet need for additional SN host redshifts. A coordinated effort would result in a more efficient follow-up campaign.

• **SN Ia standardization** Systematic biases in SN Ia distances are better understood when combining light-curve data across broad wavelengths, such as LSST+ NIR from Rubin and *Euclid* (Ponder et al. 2020; Uddin et al. 2020). These observations would need to be coordinated so all surveys could observe the same transients. While rest-frame optical (and rest-frame NIR) bands are highly correlated among themselves, optical and NIR bands are relatively uncorrelated, indicating unique information when observing across this wide wavelength range (Mandel et al. 2011). Additionally, a broader wavelength range provides a larger lever arm to constrain dust reddening and perhaps disentangle the effects of intervening dust from intrinsic color (Brout & Scolnic 2020; Mandel et al. 2020). In addition, SNe Ia have a lot of diversity in the rest-frame UV, which can help to perform better standardization if it can be exploited (Ellis et al. 2008; Cooke et al. 2011; Foley et al. 2012; Léget et al. 2020; Boone et al. 2021). The complimentary observed wavelengths of *Roman* and Rubin allow for improved SNe Ia standardization at a broader redshift, resulting in better constraints on dark energy. Furthermore, many studies have shown that properties of SNe correlate with properties of the host-galaxy properties, and these correlations can be used to better standardize SNe Ia. Combined photometry from the different missions will allow for greater wavelength range to determine host-galaxy properties and significantly improve these studies.
• **Selection functions** When combining surveys that target different redshifts, one can better characterize selection effects and faint source photometry by comparing photometry of different surveys with different depths (Rubin et al. 2015; Kessler & Scolnic 2017).

b. What is the scope of work required, as well as the opportunities and costs?

There are a number of work items that fall under the theme of “survey coordination.” Due to the timeline of LSST, much of this needs to be done now. A TAG survey coordination task-force is already in place, though their charge has been mainly limited to sky-area selection (deep and wide fields). While there are currently groups in place to discuss survey strategy coordination, a key obstacle is different timelines between when decisions need to be made by each survey. What needs to be coordinated now:

- A coordinated selection of overlapping deep field location, time, season length, and filters.

- Establishment of an all-sky calibration network: to make sure all surveys can observe standard stars from same network. This includes ensuring that SI-traceable, calibrated standard stars are available at multiple locations around the sky, as well as establishing a set of “touchstone” fields suitable for survey facilities. Stable stars in these fields should be identified, and if possible, subjected to the same vetting process as the traditional, individual flux standards, as in the CALSPEC (Bohlin et al. 2014) data base. There have been a few independent efforts, the most recent and extensive being faint, northern white dwarf standards placed on the CALSPEC system (Narayan et al. 2019; Calamida et al. 2019).

What needs to be planned soon:

- Forced-position photometry on subtracted images from surveys with faint detection.

- Prioritized spectroscopic follow-up for supernovae and host-galaxies.

- Artificial source injection on real images for measuring detection efficiency and validating photometric pipeline.

**Forced-position photometry on subtracted images.** In terms of forced-position photometry, while all surveys have plans for forced photometry at specific locations, there is no plan in place for coordination across surveys. There should be a system to share lists of SN positions and peak dates (for building templates). Furthermore, it is unclear if Euclid plans to perform image subtraction, and a separate agency/survey may be necessary to provide the software necessary to perform this task. Archive access, between science analysis platforms, is needed to allow reprocessing for consistency and homogeneity will be critical, particularly
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for transient detection and classifications. This would enable, for example, using SN locations determined from one survey to perform forced-position photometry on data from a second survey.

Consistent observation and modeling of SNe Ia in their host galaxies will require forced-position photometry or scene modeling of pixel data based on recorded positions of detected supernovae. Specifically, SNe detected by Roman should be photometered in the Rubin data, even in cases where the SN is below the detection threshold.

**Follow-up spectroscopy** Due to the time-sensitive nature of transient science, combining information across surveys must be done quickly. This is particularly important if one wants to include interesting transients or observe SNe Ia early in their evolution. For spectroscopic programs, there are multiple options including Subaru/PFS and The Dark Energy Spectroscopic Instrument (DESI). Priority should be given to targets in fields from multiple telescopes. DOE’s DESI instrument could help fulfill this need for any Roman fields or LSST DDF fields it can reach. For any blocks of the Roman wider-field tier that are contiguous over more than 7 sq. deg, DESI will be as efficient as PFS (in terms of host redshifts per hour). Trial observations with DESI – requiring total exposure on a field in the neighborhood of 25 hr – could test the power of DESI for this application. The result could influence the selection of the sky regions for the Roman SN program. Field selection will take place over the next few years.

To facilitate the coordination of spectroscopic follow-up, multiple ‘Broker’ groups are studying optimal prioritization. This includes a joint effort between DESC and the Cosmostatistics Initiative (COIN) to develop a Recommendation System for Spectroscopic Follow-up (RESSPECT; Kennamer et al. 2020), which will optimize follow-up taking into account multiple metrics including photometric classification uncertainty and availability of telescope time for spectroscopic follow-up. With collaboration between the three experiments, we can construct different metrics to optimize combined science goals.

**Artificial source injection** Artificial source injection on real images is used to measure single-visit detection efficiency vs. S/N in each bandpass (Pain et al. 1996; Kessler et al. 2019), measure efficiency vs. S/N for machine-learning used to reject subtraction artifacts (Bailey et al. 2007; Goldstein et al. 2015), and to characterize anomalous noise on bright galaxies (Sec. 6.4 of Kessler et al. 2019; Sec. 4.4 of Brout et al. 2019b). The resulting efficiency and anomalous-noise maps are used to measure biases in simulated data to correct for expected biases in real data. Artificial source magnitudes should span from near saturation to \( \sim 2 \) mag beyond the detection limit. Artificial sources need not be associated with realistic light curves, but should be placed near galaxies following their light profile. Ultimately, artificial light-curve injection is useful to check the entire cosmology analysis as shown in Sec. 6 of Brout et al. (2019a). From experience with this data set, artificial SN light curves provide an adequate flux range to measure a single-visit detection efficiency.

Rubin and Roman will have the bulk of their SNe at different redshifts. Analyses that are sensitive to potential SN Ia population drift and detection efficiency will be greatly improved
and less total work if done consistently for both Rubin and Roman. This can be done both on the real data once available, but should also be done on consistent, simulated images. In particular, the part of the pixel processing that matters for SN sensitivity is the distribution of SN light on top of different host galaxy types and local surface brightness. An effort to do this correctly and consistently across Euclid, Rubin, and Roman will (1) be much simpler to understand and compare across analyses; and (2) be less total effort to do jointly than for each team to re-do and then have to re-interpret across different teams.

c. What are key obstacles, impediments, or bottlenecks to advancing development of these plans?

The key operational obstacles are communication and timeliness. Since SNe Ia reach peak only a few weeks after discovery, communication must be done both proactively and in real time. Speed is even more important for ancillary science with rare transients where their evolution is unknown. Furthermore, it is still unclear which data can be shared and with what latency. This will complicate efforts to optimally yield the best cosmological constraints from joint observations and joint analyses. The key structural challenge is giving teams authority to work on topics across projects. Many endeavors will work best when a team working on a topic under one project is encouraged to make the connection to complementary projects. However, this will requires agencies to be willing and able to coordinate.

There are also some potential challenges with the proprietary nature of the Rubin Observatory LSST data. The Roman data are fully public, while the LSST data have a 2-year proprietary period. The Roman science collaborations will be international, and unlikely to precisely match up with international data rights in LSST. Thus if one wanted to do a joint Roman+LSST analysis of the first year of Roman data, the LSST data on those same supernovae would not be available to the full Roman community until 2 years later. However, the LSST data rights community could do a full analysis of the LSST + Roman data.

d. Are there other science topics besides dark energy that drive the requirements for joint data processing or analysis?

Simultaneous observations with Rubin and Roman will result in a large sample of transients beyond SNe Ia. Combined optical/NIR observations will constrain dust properties of extinguished supernovae and reveal other exotic transients whose emission peaks at $\sim 1 \mu m$ such as luminous red novae and kilonovae. Core-collapse supernova rates, which constrain the cosmic star-formation rate, can be more accurately determined without requiring a dust-obscured correction.

The hundreds of strongly gravitationally lensed SNe Ia observed from these surveys, though not a part of typical cosmological analyses, would benefit from joint analysis and result in a significant improvement to their cosmological utility (Goldstein et al. 2019). Furthermore, multi-wavelength follow-up of gravitational wave counterparts is necessary to constrain the composition of the ejected material.
3. COLLABORATION AND PARTNERSHIPS

k. What cooperation or partnerships between DOE and NASA could further the scientific and technology advances?

- While a TAG Survey Coordination group is already formed (led by Dan Scolnic and Daniel Stern), communication between this group and the collaborations should be formalized and the charge expanded to improve survey operations to further coordination between survey planners, specifically with the authority and ability to tweak the strategies before and during the multiple surveys. We advocate that all survey strategies be reviewed and adjusted periodically during operations, in order to further optimize synergies based on what is learned from initial data sets, and based on what new observing facilities become available.

- The creation of a joint survey calibration task force to establish communication across the missions, identify common algorithms, and ensure coordination so that uncertainties in photometric calibration are not the limiting factor in achieving Stage IV dark energy figure of merit (Albrecht et al. 2006).

- Spectroscopic follow-up task force to ensure that access to sufficient follow-up spectroscopy resources is obtained, through different TACs, MoUs with external groups in exchange for data rights, and through the construction of new facilities and instruments. There will be multiple types of spectroscopic follow up to achieve the different goals of SN identification, redshift determination, and statistical and systematic error constraints, and to follow SN targets that are visible in different hemispheres at different times. Moreover, systems (and pipelines) will need to be planned, organized, and developed to ensure rapid and efficient use of all available spectroscopic resources. As an example of a prioritization issue that this planning should address: if a SN is observed by multiple surveys, it should be preferentially allocated appropriate follow-up resources, while avoiding duplication of observations to maximize science return.

- Expansion of in-place joint pixel-processing task force to generate a plan for all surveys to grant access of pixel-level data associated with transients, in less than one day turn round, and with oversight of the development of the necessary infrastructure to realize this goal. Many images will be crowded and confusion-limited, making catalog-only data of limited utility relative to the previous generation of ground-based surveys. A joint pixel-processing facility will be necessary to provide postage stamps generated from the images taken from the different surveys, together with a probabilistic source separation, and probability density functions of photometric redshift. The same facility will be useful for understanding the host environments of transients of all varieties, and in particular how galaxy evolution impacts transient explosions. Deep multi-survey images of the host will also be useful for early classification, and to detect rare strongly-lensed supernovae which will need prioritized followup.
Joint pixel-processing of data from different surveys will also be necessary for multi-messenger astrophysics (e.g. detecting the optical counterparts of events seen in future surveys such as CMB-S4). Services and standards to deliver alerts for detections in multi-messenger missions such as HopSkotch are being developed by the SCiMMA group\(^1\), and coordination between these groups would be a major responsibility of such a joint processing task force. A joint pixel processing facility is also crucial to several other probes of dark energy, detailed in a response to this RFI from LSST DESC in Annis et al., “Response from the Rubin Observatory LSST Dark Energy Science Collaboration: Extending LSST Studies of Dark Energy and Dark Matter with Roman and Euclid”.

- A real-time forced-position photometry task force to recover measurements for SN detected in other surveys. As missions detect SNe, it can be very valuable to recover sub-threshold measurements from other surveys. It is possible to study the earliest phases of a potentially strongly-lensed SNe detected in LSST several days after explosion if it is possible to extract forced photometry at the location of other lensed images from Roman observations. A forced photometry service should also be capable of working together with a pixel processing facility to allow reprocessing of data, as well as fake source injection to model the joint survey selection function. This will be essential to understand the demographics of novel and rare classes of transients such as pair-instability supernovae, as well as to propagate measurements from each of these missions into joint cosmological constraints on the properties of dark energy.

- Joint computational task force to manage shared computing of these multi-mission datasets, including common simulations (e.g. simulating the multi-mission sky to include the effect of a novel dark energy model, to ensure its effects are correctly propagated through all three surveys), and tools for data access and processing (e.g. a shared JupyterHub environment that scientists working on any of these missions can use). Computing is the central nexus between observers, theorists, and instrumentalists, and now encompasses astrostatistics and data science, in addition to computational physics. A research platform facility that collocates (or provides transparent access to) data holdings and provides computing will also be essential for multi-messenger astrophysics, which has a similar need to combine observations from several different observatories (e.g. LIGO-VIRGO-Kagra, IceCube and ngVLA) together with Euclid, Roman and Rubin.

1. What mix of institutions or collaboration models could best carry out the envisioned research and/or development?

We advocate the use of cross-survey (and agency) task forces to plan and coordinate the above synergistic activities. These task forces should have both sufficient scientific expertise

\(^1\) https://scimma.org/
and authority to be able to address specific issues, such as synergistic survey strategies, calibration networks, and spectroscopic follow-up.

**m. What resources, capabilities and infrastructure at DOE National Laboratories or the NASA Centers would be beneficial for and could accelerate or facilitate research in this topic?**

DOE National Laboratories and the NASA Centers can jointly support mutually beneficial resources such as long-term computing infrastructure personnel, who have different skill sets and career paths than typical academics. This can be important to ensure the access to technically focused long-term joint processing and simulation efforts. Storage and computational time in the Rubin and *Roman* analysis pipelines and user spaces to do these tasks. Many of the previously mentioned task forces can be coordinated out of one or more DOE National Lab or NASA Center.

**n. Are there other factors, not addressed by the questions above, which should be considered in planning HEP and APD activities in this subject area?**

No answer.

4. **CONCLUSION**

Type Ia supernovae (SNe Ia) are a key cosmological probe, and the supernovae that the three great observatories - *Euclid*, *Nancy Grace Roman Space Telescope* and the Vera C. Rubin Observatory - will discover promise to revolutionize our understanding of the nature of dark energy. These transients are already key science drivers for two of the three large surveys of the 2020s: LSST and *Roman*, which have large and active communities involved in all aspects of these missions. Combining data sets allows increases in redshift range and wavelength range, boosting the statistical precision and the systematic control. We discussed improvements to both statistical and systematic precision that combinations of data sets will enable such as improved photometric calibration, SN Ia standardization, and redshift measurements. Other science cases will also benefit from these synergies. In particular, the photometric redshift improvements will benefit cosmological measurements from weak lensing. Also the discovery and confirmation of strong-lensing systems, galaxy clusters, and gravitational wave counterparts.

While the community will benefit from combining data from these observatories, orchestrating them to act in concert with one another will yield the greatest scientific benefits. Particularly due to the time-dependent nature of SN surveys, planning must be done both prior to and during the surveys. We have discussed what teams and plans should be put in place now to start preparing for these combined sets by setting up cross-agency task forces. These task forces will allow for the needed communication to improve survey operations, calibration, spectroscopic follow-up, joint pixel-processing, and analysis. By working together,
the DOE and NASA, can improve their investments with an increase of scientific output, and in particular, a deeper understanding of the nature of dark energy and our Universe.

The Roman Supernova Science Investigation Teams and the LSST DESC Supernova Working Group endorse this response.

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