Cosmology with Type Ia supernovae

Amanullah, R., Nordin. J., Feindt, U., Goobar, A. Hangard, L., Kowalski, M., Nugent, P., Rigault, M., Paech, K., Papadogiannakis, S.

1 Scientific motivation

Understanding the nature of dark energy by constraining its equation of state parameter, $w(z) = w_0 + w_a \cdot z/(1+z)$ where w_0 and w_a are constants, is one of the key goals in contemporary science.

1.1 SNe Ia cosmology with ZTF

Cosmological constraints from SNe Ia come from comparing the *relative* brightnesses of high-z SNe with those at low-z. In other words, in order for the high-z SN Ia campaigns of e.g. LSST and WFIRST to reach their full potential, equally ambitious programs are required at low-z. In Fig. a) we show that the predicted[1] constraints of $w(z)$ can be improved with up to a factor of three if future WFIRST [1] and existing [2] data are combined with a nearby ZTF sample. From Fig. b) the impact of the ZTF sample can be better understood. The uncertainties at low-z are dominating the error budget of current cosmological analyses.

ZTF is the only survey that will provde a *complete* and *unbiased* SN Ia sample for $z < 0.1$. A complete set will allow us to understand selection effects and host environment dependencies (that has recently been discovered) not only relative to the survey, but in an absolute sense. ZTF will thus provide a unique sample with which to quantify the key systematic uncertainties that will limit future high-z surveys.

Other current and planned all-sky surveys, such as ASAS-SN and ATLAS, only provide unbiased detections in the very nearby region where SN Ia distances are strongly affected by peculiar velocities. Competing campaigns that plan to use the ZTF MSIP survey for discovery, and other resources for follow-up, will not be able to reach our sample size and completeness unless they invest a vast amount of time in both spectroscopic and photometric follow-up.

Ancillary SN Ia science A low-z SN Ia sample, homogeneously distributed over the northern sky will allow us to study any spatial variability of H_0 and address the tension between the local and CMB values, as well as more general studies of anisotropies in the local universe [3]. Further, the ZTF SN Ia sample can be used to answer astrophysical questions regarding SN Ia progenitors, the diversity in the SN Ia population [4], the dependence of SN Ia properties with host galaxy environments [5, 6] and extragalactic extinction [7]. The ZTF sample of spectroscopically classified transients will also be critical for training the LSST photometric typing algorithms.

In conclusion, ZTF has an opportunity to play a key role both for providing a legacy sample for future SN Ia Hubble diagrams, and for determining the limits and feasibility for future SN Ia programs with the LSST and WFIRST.

1.2 Figures of merit

To match the target precision, every individual SN Ia in our core sample needs to be (i) discovered before peak brightness, (ii) spectroscopically classified, (iii) observed in *at least three filters* (see § 2) and (iv) continuously observed until +40 days past maximum.

With the requirements (i), (iii) and (iv) above the *measurement precision* for each object will reach the level needed for current, and future, SN Ia standardization techniques, while (ii) is needed to secure the purity of the sample. The minimum requirement to sub classify objects as normal SNe Ia is one SEDM spectrum close to peak with $S/N \geq 10$.

[1] Details for our simulations are found at `http://www.oir.caltech.edu/twiki_ptf/bin/view/ZTF/SNeSimulations`

Required sample size If the empirical correction laws used to standardize SNe Ia were perfect, and the nature of all systematic errors were observational, a total sample size of ~ 500 SNe Ia would be sufficient to reach the statistical precision required. However, due to known astrophysical diversities, where the color law of SNe Ia is the most important, a larger sample will be needed. Assuming the observed color distribution of SNe Ia [8], and that individual color laws are randomly drawn from the full range of known SN Ia laws [7], we can conclude that a total sample of ~ 2000 SNe Ia is required in order to meet the target precision once the uncertainty of the average color law has been propagated to the distance moduli for the sample. This sample size is also large enough for identifying SN Ia subclasses with different properties and/or hosted in different environments.

1.3 Real-time discoveries

Real-time discoveries will *not* be necessary. Potential SNe Ia need to be identified and photometrically classified in order to plan spectroscopic observation around the predicted maximum. At $z \sim 0.1$, a normal SN Ia is expected to rise above the detection threshold, $r = 20.5$ mag (AB), ~ 10 days before maximum.

We expect that human scanning will be necessary initially, but we will require that each candidate is rising, has been detected in multiple epochs and in all three bands, and that the lightcurve, colors and photo-z of the presumable host is consistent with a SN Ia at $z < 0.1$, before it is passed to a scanner. In order to do photometric typing we will need information about the host-galaxy, primarily from the Pan-STARRS catalog.

2 Proposed observations

The depth and cadence for the $g + r$ MSIP survey are well matched to our needs, assuming ZTF exposure times of 30 s. SN Ia distances are obtained from an empirical relation where the peak SN brightness, the lightcurve width and color are combined. SNe Ia observed in only one color require the application of an assumed color law, providing insufficient verification of the standardization for modern SN Ia cosmology. In order to *both* measure the color of each individual SN Ia *and* to fit for the average, empirical, color law of the full sample, at least two colors are needed. For this program, *we therefore request cadenced i-band observations from the ZTF partnership* of the MSIP fields. The i-band data are also required for photometric typing and the ancillary SN Ia science topics listed above.

2.1 Pointings, cadence and filters

Assuming a depth of $g, r \sim 20.5$ mag we find that the MSIP survey will discover and provide g, r lightcurves that fulfill our requirements (i) and (iv) for ~ 800 SNe Ia per year, where weather has been taken into account.

The exact strategy for i-band follow-up will have to be adjusted once the details for the MSIP survey is fixed, but assuming it covers 15 000 sq. deg. using a fixed 3-day cadence, *we propose that the ZTF partnership also survey the fields with a 4-day cadence.* This would require ≈ 50 min per night (assuming that areas with high Galactic extinction, $\sim 10\,\%$ of the sky, are not surveyed).

The chosen cadence is required to obtain pre-max i-band data and to sample the second peak visible in wavelengths redder than the r-band. The latter is a unique feature for SNe Ia, where the time difference between the peaks can be used to measure the ^{56}Ni mass of each object [9] – yet another tool for studying SN Ia physics. In addition to measuring the colors and color law, the data will allow us to build an i-band Hubble diagram where the dispersion is tighter and the effect of extinction is significantly lower.

2.2 Sensitivity to calibration and variations in cadence of filters

Calibration In Fig a) we have studied how different calibration offsets between ZTF and WFIRST would affect the measured (w_0, w_a) parameters, and we can conclude that the propagated bias will exceed the statistical uncertainty for offsets $> 1\,\%$. The measured SN brightness will be directly biased by errors in the applied flat-field/sensitivity corrections and/or atmospheric extinction model.

Effects of a reduced i-band cadence With a cadence of 6-days we would still be able to estimate the average color-law (with higher uncertainty). However, it would (1) degrade our ability to photometrically type the candidates on the rise, (2) significantly reduce the ability to characterize the second peak, and (3) prevent measurements of the second color to a higher precision than the currently known intrinsic dispersion. Here, (1) would increase the load on the SEDM (see § 3.3), (2) would prevent classification of the vast number of transients in ZTF that will never be spectroscopically confirmed and affect the ancillary science, and (3) means that future standardization techniques could make the ZTF sample obsolete.

2.3 Sky coverage

One of our science goals is to do directional measurements of H_0 and anisotropies in the local universe which requires coverage of the whole northern sky.

3 Supporting observations

3.1 Use of other photometric facilities and feasibility of relaxed cadence and filter requirements[2]

Obtaining the i-band using another facility is a major undertaking and would require 1–1.5 hours per night using a $\lesssim 2\,$m telescope, together with a complete system calibration. The SNe would need to be spectroscopically classified earlier, based on less reliable photometric typing, in order to obtain the required pre-max i-band observations, which would increase the load on the SEDM. Further, the majority of transients discovered by ZTF will never be spectroscopically classified. With the proposed i-band observations, we will be able to photometrically type the majority of the ZTF transient sample as most SNe Ia show the characteristic second peak in their i-band lightcurves.

3.3 Spectroscopic classification

We plan to use the SEDM for classification. The spectroscopic classification can be obtained at maximum and planned in advance, thus minimizing the load of the SEDM. Photometric typing, based on three filters, in combination with photo-z of the presumed host will be used to determine the nature and redshift of each discovered transient. The combination is necessary since only using photo-z will result in a contamination of $\sim 50\,\%$ from SNe Ia at $z > 0.1$.

For the SEDM we need S/N> 10 (mean) per spectral element in order to sub classify our object at maximum as normal SNe Ia. In total we need to target ~ 2 candidates per night, each with an average exposure time of 2700 s (split in A/B pairs). Using the first year data we will investigate the feasibility of sub-classifying (normal, 91bg, 91T, etc.) SNe Ia using photometry only.

3.4 Additional follow-up

At the end of the survey we will have to obtain spectroscopic redshifts of the host galaxies in order to put the SNe Ia on the Hubble diagram (the resolution of the SEDM is not sufficient for this). This is not time-critical and we are currently investigating the possibility of piggy-backing on planned MOS surveys.

[2] This section also addresses § 3.2

A subset of our sample, e.g. heavily reddened or hostless SNe Ia, will require additional spectroscopic follow-up while they are active. We will use our time at NOT for this.

4 Expertise and tools

Expertise We have the expertise within our groups (OKC and HU) to carry out this program.

Tools The specific requirements for SN Ia candidate vetting (§ 1.3) and photometric typing needs to be implemented, or added to, the general ZTF treasurer. Tools that may require improvement for our science case depending on their performance are the photometry and the SEDM reduction pipelines.

5 Manpower

Manpower and time-line This project will be led and carried out by the SN Ia groups at HU and OKC. We intend to first publish studies on: comparing the SN Ia properties to their host environment, the feasibility of typing only based on the i-band and the spatial variability of H_0. These topics can be done with only relative photometry, with first publications planned using only the first-year data.

Thesis projects One of the students at OKC will work on ZTF data, Laura Hangard. She is currently studying how SN Ia properties are related to their host environments with natural extensions to ZTF. At HU, one student, Valery Brinnel, will start this year, with the ZTF SN Ia program being the core of his work.

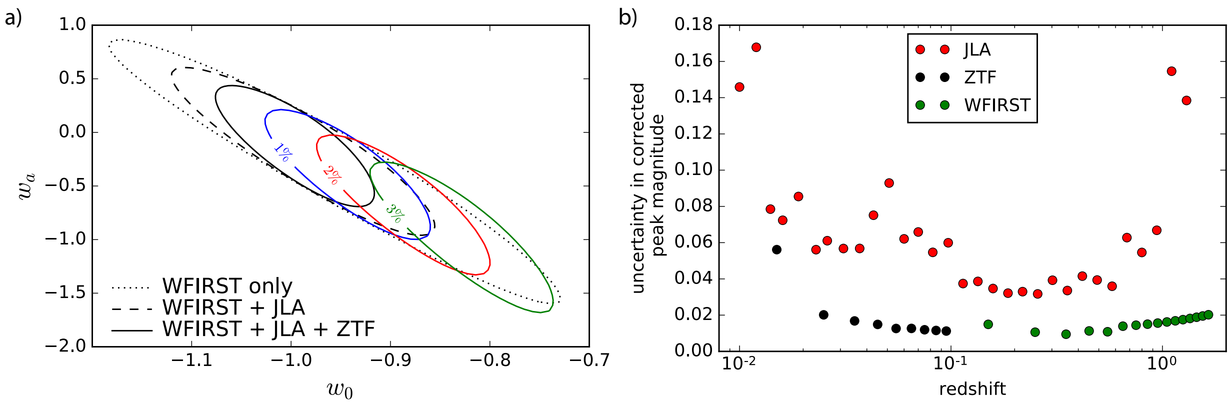

Figure a) Simulated 68 % confidence contours for the (w_0, w_a)-plane. The data were generated assuming a cosmological constant, Λ, which corresponds to $(w_0, w_a) = (-1, 0)$. The black contours show the expected WFIRST constraints (dotted), when this data are combined with the current JLA sample (dashed), and the ZTF data (black). The color contours illustrate the impact of a systematic magnitude offset between the ZTF sample and the other data sets of 1 % (blue), 2 % (red) and 3 % (green), respectively. **b)** The corrected SN Ia peak magnitude uncertainties for different redshift bins that were used to derive the black contours in a). The uncertainties for the existing data sets are large at the end-points of the Hubble diagram. While redshifts at $z > 0.1$ will be covered by future facilities such as LSST and WFIRST, neither of these surveys will cover the lowest redshift bins that are particularly important for anchoring the Hubble diagram.

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[4] Nordin, J., et al. 2011, A&A, 526, 119
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[6] Rigault, M., et al. 2015, ApJ, 802, 20
[7] Amanullah, R., et al. 2015, MNRAS, 453, 3300
[8] Stanishev, V. et al., Submitted to A&A, *arXiv:1505.07707*
[9] Dhawan, S., et al. 2016, A&A, 588, 84