Transients in the Local Universe

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Disclosures

This white paper was circulated to two groups: the Palomar Transient Factory (PTF)[1] and the Science Working Group on Transients of the Large Synoptic Survey Telescope (LSST)[2]. The two authors have incorporated most of the feedback. However, the final version is the responsibility of the two authors and is not legally binding on the PTF and LSST collaborations.

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The first author is the Principal Investigator of PTF project and the Chair of the Science Working Group on Transients of LSST. The second author is a graduate student whose thesis is centered around the topic of this white paper.

[1]PTF is a project whose only goal is a systematic investigation of variables and transients in the optical sky. It is based around the Palomar 48-inch Oschin Schmidt telescope with a 96-million pixel detector and 7.8 square degrees field of view. PTF partners include California Institution of Technology, Columbia University, Infrared Processing & Analysis Center, Lawrence Berkeley Laboratory, Las Cumbres Observatory Global Telescope, Weizmann Institute of Science & UC Berkeley. PTF achieved first light in December 2008 and expects to be in routine operation by May 2009.

[2]The LSST project is based around a 8.4-m telescope coupled to a 3-billion pixel camera. LSST plans to survey the entire sky visible from Chile in multiple colors every week. The goals range from near-Earth asteroids to cosmology. Twenty eight institutions are members of this consortium. LSST hopes to see first light in 2014 and start transient search in 2015.

Abstract

Two different reasons make the search for transients in the nearby Universe (d$\lesssim$ 200 Mpc) interesting and urgent. First, there exists a large gap in the luminosity of the brightest novae (-10 mag) and that of sub-luminous supernovae (-16 mag). However, theory and reasonable speculation point to several potential classes of objects in this "gap". Such objects are best found in the Local Universe. Second, the nascent field of Gravitational Wave (GW) astronomy and the budding fields of Ultra-high energy cosmic rays, TeV photons, astrophysical neutrinos are likewise limited to the Local Universe by physical effects (GZK effect, photon pair production) or instrumental sensitivity (neutrino and GW). Unfortunately, the localization of these new telescopes is poor and precludes identification of the host galaxy (with attendant loss of distance and physical diagnostics). Both goals can be met with wide field imaging telescopes acting in concert with follow-up telescopes. Astronomers must also embark upon completing the census of galaxies in the nearby Universe.

1 A Historical Summary

Variable objects have played a major role in the history of astronomy. At the beginning of the previous century, the pulsating Cepheids showed that the Galaxy was much larger than had been assumed before. Hubble's discovery of Cepheids in the Andromeda nebula showed that it was a galaxy similar in size to our own.

F. Zwicky's 18-inch Palomar Schmidt program was the first systematic study of the transient sky. Zwicky laid the foundation of the field of supernovae which in turn touched upon the origin of cosmic rays, the synthesis of Iron and higher-(A, Z) elements and the collapse of stellar cores. This success led to the 48-inch Palomar Oschin Schmidt telescope, famous for two Sky Surveys.

At the end of the previous century, supernovae came back into main stream. The first indication of a new constituent of the Universe, dark energy, was deduced from the dimming of Ia supernovae located at cosmological distances (Perlmutter et al. 1999, Riess et al. 1998). The last decade saw a veritable explosion in the field of gamma ray bursts – the most relativistic explosions in Nature.

The purpose of this white paper is to explicitly draw attention to the importance of a systematic study of transients in the local Universe (defined here as distance $\lesssim$ 200 Mpc). The rationale for this myopic view is laid in §2 and §3. We argue that the path to discovery necessarily lies through identification and elimination of fore- and background transient events (§4). We discuss upcoming facilities in (§5). While detection of any cosmic source by LIGO constitutes a major step there is wide-spread agreement of the necessity of arc-second localization (which means in essence detecting an electromagnetic counterpart). We end with a proposed plan to identify electromagnetic counterparts to LIGO sources (§6).

Here, we limit the discussion to transients in the local Universe. We refer the reader to the following white papers: Cosmological explosions (Wozniak et al.), gravitational wave sources (Bloom et al., Phinney et al.) and Galactic variable stars (Becker et al.).

2 Rationale & Motivation: Events in the Gap

A plot of the peak luminosity versus a duration that is characteristic (based on physics or convention) is a convenient way to summarize

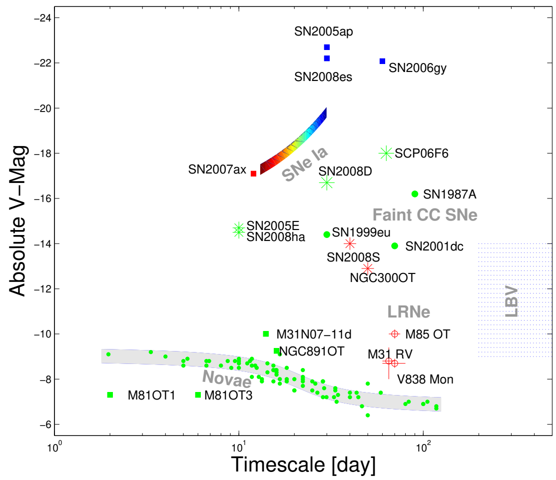

Figure 1: The phase space of cosmic transients : peak V-band luminosity as a function of duration, with color a measure of the true color at maximum. Shown are the known explosive (supernovae) and eruptive (novae, luminous blue variables [LBV]) transients. Also shown are new types of transients (all found over the last two years): the peculiar transients M 85 OT2006-1, M31-RV and V838 Mon, which possibly form a new class of "luminous red novae"; almost every scenario has been suggested – core collapse, common envelope event, planet plunging into star, a peculiar nova and a peculiar AGB phase; the baffling transient with a spectrum of a red-shifted Carbon star, SCP 06F6 (Barbary et al 2008; see also Soker et al 2008); a possible accretion induced collapse event SN 2005E (Perets et al. 2009); the extremely faint, possibly Type Ibc, SN 2008ha (Valenti et al. 2008); and peculiar eruptive events with extremely red progenitors SN 2008S and NGC300-OT (Thompson et al. 2008, Smith et al. 2008, Bond et al. 2009). [Figure adapted from Kulkarni et al. (2007).]

explosive events. We first focus on novae and supernovae of type Ia (SN Ia). As can be seen from Figure 1 novae and SN Ia form a distinctly different locus. Brighter supernovae take a longer time to evolve (the "Phillips" relation; Phillips 1993) whereas the opposite is true of novae: the faster the nova decays the higher the luminosity (the "Maximum Magnitude Rate of Decline", MMRD relation; see, for example, Della Valle and Livio 1995, Downes and Duerbeck 2000).

The primary physical parameter in SN Ia is the amount of Nickel that was synthesized. There is almost a factor of 10 variation between the brightest ("1991T-like") and the dimmest ("1991bg-like") SN Ia. The Phillips relation has been quantified with high precision and the theory is well understood. In contrast, the MMRD does not enjoy the same quantity or quality of light curves as those of Ia supernovae. Fortunately, dedicated ongoing nova searches in M31 and the P60-FasTING project (see §4) has vastly increased the number of well-sampled light curves.

The large gap between the brightest novae (say $M_{\rm V} \sim -10$) and the faintest supernovae ($M_{\rm V} \sim -16$), especially on timescale shorter than thirty days, is hard to miss. The gap beckons astronomers to search the heavens for new populations.

A discussion of potential new classes of events in the gap would benefit from a review of the basic physics of explosions. An important complication is a potential heat source at the center: a hot white dwarf (novae) or gradual release of radioactive energy (supernovae).

The primary physical parameters are: the mass of the ejecta ($M_{\rm ej}$), the velocity of the ejecta (v_s), the radius of the progenitor star (R_0) and the total energy of the explosion ($\mathcal{E}_0$). Two distinct sources of energy contribute to the explosive energy: the kinetic energy of the ejecta, $\mathcal{E}_{\rm k} \equiv (1/2)M_{\rm ej}v_s^2$ and the energy in the photons (at the time of the explosion), $\mathcal{E}_{\rm ph}$.

Assuming spherical symmetry and homogeneous density, the following equation describes the gains and losses suffered by the store of heat (E):

$$\dot{E} = \varepsilon(t)M_{\rm ej} - L(t) - 4\pi R(t)^2 P v(t). \quad (1)$$

Here, $L(t)$ is the luminosity radiated at the surface and $\varepsilon(t)$ is heating rate (energy per unit time) per gram from any source of energy (e.g. radioactivity or a long-lived central source). P is the total pressure and is given by the sum of gas and photon pressure.

Next, we resort to the so-called "diffusion" approximation (see Arnett 1996; Padmanabhan 2000, volume II, §4.8),

$$L = E_{\rm ph}/t_{\rm d}, \tag{2}$$

where $E_{\rm ph} = aT^4V$ is the energy in photons [V is the volume, $(4\pi/3)R^3$], and

$$t_d = B\kappa M_{\rm ej}/cR \tag{3}$$

is the timescale for a photon to diffuse from the center to the surface. The pre-factor B in Equation 3 depends on the geometry and, following Padmanabhan, we set $B = 0.07$. κ is the mass opacity.

We will make one simplifying assumption: most of the acceleration of the ejecta takes place on the initial hydrodynamic timescale, $\tau_h = R_0/v_s$, and subsequently coasts at $R(t) = R_0 + v_{\rm s}t$.

First, let us consider a "pure" explosion i.e. no subsequent heating [$\varepsilon(t) = 0$]. If photon pressure dominates then $P = 1/3(E/V)$ and an analytical formula for $L(t)$ can be obtained (Padmanabhan, *op cit*):

$$L(t) = L_0 \exp\Big(-\frac{t\tau_h + t^2/2}{\tau_h\tau_d}\Big); \tag{4}$$

here, $\tau_d = B(\kappa M_{\rm ej}/cR_0)$ is the initial diffusion timescale and $L_0 = \mathcal{E}_{\rm ph}/\tau_d$.

From Equation 4 one can see that the light curve is divided into (1) a plateau phase which lasts until about $\tau = \sqrt{\tau_d\tau_h}$ after which (2) the luminosity undergoes a (faster than) exponential decay. The duration of the plateau phase is

$$\tau = \sqrt{\frac{B\kappa M_{\rm ej}}{cv_s}} \tag{5}$$

and is independent of R_0. The plateau luminosity is

$$L_p = \mathcal{E}_{\rm ph}/\tau_d = \frac{cv_s^2R_0}{2B\kappa}\frac{\mathcal{E}_{\rm ph}}{\mathcal{E}_{\rm k}}. \tag{6}$$

As can be seen from Equation 6 the peak luminosity is independent of the mass of the ejecta but directly proportional to R_0. To the extent that there is rough equipartition[3] between the kinetic energy and the energy in photons, the luminosity is proportional to the square of the final coasting speed, v_s^2.

Pure explosions satisfactorily account for supernovae of type IIp. Note that since $L_p \propto R_0$ the larger the star the higher the peak luminosity. SN 2006gy, one of the brightest supernovae, can be explained by invoking an explosion in a "star" which is much larger (160 AU) than any star (likely the material shed by a massive star prior to its death; see Smith & McCray 2007).

Conversely, pure explosions resulting from the deaths of compact stars (e.g. neutron stars, white dwarfs or even stars with radius similar to that of the Sun) will be very faint. For such progenitors visibility in the sky would require some sort of additional subsequent heat input and discussed next.

First we will consider "supernova"-like events i.e. events in which the resulting debris is heated by radioactivity. One can easily imagine a continuation of the Ia supernova sequence. We consider three possible examples for which we expect a smaller amount of radioactive yield and a rapid decay (timescales of days): coalescence of compact objects, accreting white dwarfs (O-Ne-Mg) and final He shell flash in AM CVn systems.

Following Li & Paczynksi (1998), Kulkarni (2005) considers the possibility of the debris of neutron star coalescence being heated by decaying neutrons. Amazingly (despite the 10-min decay time of free neutrons) such events (dubbed as "macronovae") are detectable in the nearby Universe over a period as long as a day, provided even a small

[3] This is a critical assumption and must be checked for every potential scenario under consideration. In a relativistic fireball most of the energy is transferred to matter. For novae, this assumption is violated (Shara, pers. comm.).

amount ($\sim> 10^{-3}\,M_\odot$) of free neutrons is released in such explosions.

Bildsten et al. (2007) consider a Helium nova (which arise in AM CVn systems). For these events (dubbed ".Ia" supernovae), not only radioactive Nickel but also radioactive Iron is expected.

Intermediate mass stars present two possible paths to sub-luminous supernovae. The O-Ne-Mg cores could either lead to a disruption (bright SN but no remnant) or a sub-luminous explosion (Kitaura et al. 2006). Separately, the issue of O-Ne-Mg white dwarfs accreting matter from a companion continues to fascinate astronomers. The likely possibility is a neutron star but the outcome depends severely on the unknown effects of rotation and magnetic fields. One possibility is an explosion with low Nickel yield (see Metzger et al. 2008 for a recent discussion and review of the literature).

An entirely different class of explosive events are expected to arise in massive or large stars: birth of black holes (which can range from very silent events to GRBs and everything in between), strong shocks in supergiants (van den Heuvel 2008) and common envelope mergers. Equations 5 and 6 provide a guidance to the expected appearance of such objects. Fryer et al. 2007 develop detailed model for faint, fast supernovae due to Nickel "fallback" into the black hole. For the case of the birth of a black hole with no resulting radioactive yield (the newly synthesized material could be advected into the black hole) the star will slowly fade away on a timescale of $\min(\tau_d, \tau)$. Modern surveys are capable of finding such wimpy events (Kochanek et al. 2008).

In the spirit of this open-ended discussion of new transients we also consider the case where the gas pressure could dominate over photon pressure. This is the regime of weak explosions. If so, $P = 2/3(E/V)$ and Equation 1 can be integrated to yield

$$L(t) = \frac{L_0}{(t/\tau_h + 1)} \exp\Big(- \frac{\tau_h t + t^2/2}{\tau_h \tau_d}\Big). \quad (7)$$

In this case the relevant timescale is the hydrodynamic timescale. This regime is populated by Luminous Blue Variables and Hypergiants. Some of these stars are barely bound and suffer from bouts of unstable mass loss and photometric instabilities.

As can be gathered from Figure 1 the pace of discoveries over the past two years gives great confidence to our expectation of filling in the phase space of explosions.

3 Rationale & Motivation: New Astronomy

Four entirely different fields of astronomy are now being nurtured by physicists. For these fields all that matters is transients in the local Universe.

Cosmic rays with energies exceeding 10^{20} eV are strongly attenuated owing to the production of pions through interaction with the cosmic micro-wave background (CMB) photons [the famous Greisen-Zatsepin-Kuzmin (GZK) effect]. Recently, the Pierre Auger Observatory (PAO 2007) has found evidence showing that such cosmic rays with energies above 6×10^{19} eV are correlated with distribution of matter in the local 75-Mpc sphere.

Similarly very high energy (VHE) photons (TeV and PeV) have a highly restricted horizon. The TeV photons interact with CMB photons and produces electron-positron pairs. A number of facilities are now routinely detecting extra-galactic TeV photons from objects in the nearby Universe (Veritas, MAGIC, HESS, CANGAROO).

Neutrino astronomy is another budding field with an expected vast increase in sensitivity. The horizon here is primarily limited by sensitivity of the telescopes (ICECUBE).

Gravitational wave (GW) astronomy suffers from both poor localization (small interferometer baselines) and sensitivity. The horizon radius is 50 Mpc for `enhanced` LIGO (e-LIGO) and about 200 Mpc for `advanced` LIGO (a-LIGO) to observe neutron star coalescence. There is wide spread agreement that the greatest gains will require electromagnetic localization of the event.

Progress in these areas, especially GW astronomy, *require* arc-second localization. Unfortunately, all sorts of foreground and background transients *will* be found within the several to tens of sq deg of expected localizations. Studying each of these transients will result in significant "opportunity cost". This issue is addressed in §6.

4 Foreground Fog & Background Haze

Ongoing projects of modest scope offer a glimpse of the pitfalls on the road to achieving the grand goals summarized in §2 and §3. Nightly monitoring of M31 for novae (several groups) and our Palomar 60-inch program of nearby galaxies already show high variance in the MMRD relation (Figure 2). The large scatter of the new novae suggests that in addition to the mass of the white dwarf, other physical parameters play a role (such as accretion rate, white dwarf luminosity, e.g. Shara 1981).

A nightly targeted search of nearby rich clusters (Virgo, Coma and Fornax) using the CFHT (dubbed "COVET") and the 100-inch du Pont (Rau et al. 2008a) telescopes uncover the extensive fore-ground fog (asteroids, M dwarf flares, dwarf novae) and the background haze (distant, unrelated SN). The pie-chart in Figure 3 dramatically illustrates that *new discoveries require efficient elimination of fore- and back-ground events.*

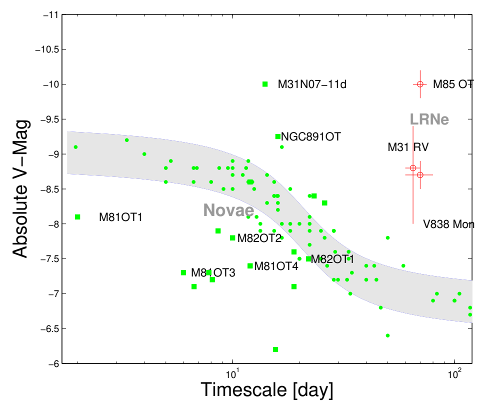

Figure 2: A plot of the peak absolute magnitudes versus decay timescale of novae discovered by the Palomar P60-FasTING project. The shaded grey region represents the Maximum Magnitude Rate of Decline relationship bounded by $\pm 3\sigma$ (Della Valle and Livio 1995). The data that defined this MMRD are shown by green circles. Squares indicate novae discovered by P60-FasTING in 2007-2008 (unlabelled if in M31). [Preliminary results from Kasliwal et al. 2009b, in prep.]

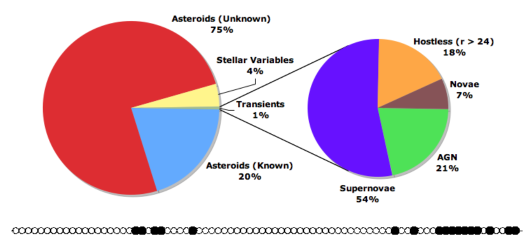

Figure 3: 28 COVET transients were discovered during our pilot run in 2008A (7 hours) – two novae and the remainder background supernovae and AGN. Transients with no point source or galaxy host to a limiting magnitude of r>24 are classified as hostless. Of the 2800 candidates, our pipeline automatically rejected 99% as solar-system or galactic. [Preliminary version from Kasliwal et al. 2009c, in prep.]

5 The Era of Synoptic Imaging Facilities

There is widespread agreement that we are now on the threshold of the era of synoptic and wide field imaging at optical wavelengths. This is best illustrated by the profusion of operational (Palomar Transient Factory, PanSTARRS), imminent (SkyMapper, VST, ODI) and future facilities (LSST) in optical and SASIR in infrared.

In Table 1 and Figure 4 we present current best estimates for the rates of various events and the "grasp" of different surveys.

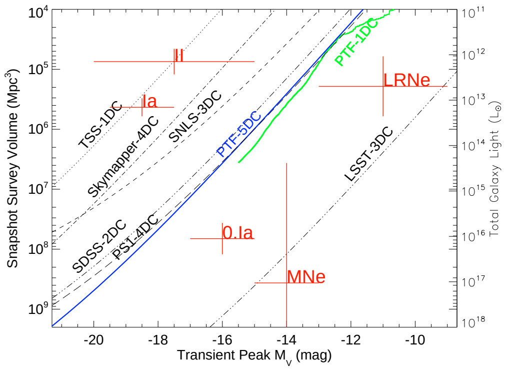

Figure 4: Volume probed by various surveys (in a single specified cadence period) as a function of transient absolute magnitude. Red plusses represent the minimum survey volume needed to detect a single transient event (the uncertainty in the y-axis is due to uncertainty in rates). PTF-5d (blue-solid) is more sensitive than TSS (dotted), Skymapper (dot-dashed), Supernova Legacy Survey (SNLS, dashed) and SDSS-SN (double-dot dashed) and competitive with PanSTARRS-1 (PS1-MD, long dashed). Lines for each survey represent one transient event in specified cadence period. PTF-1d (green solid line) represents a targeted 800 sq deg survey probing luminosity concentrations in the local Universe, with a factor of three larger effective survey volume than a blind survey with same solid angle. PTF will discover hundreds of supernovae and possibly several rare events such as "0.Ia", Luminous Red Novae (LRNe) and Macronovae (MNe) per year. The LSST (Wide Fast Survey) will discover hundreds of these rare events. [Adapted from figure by Bildsten et al. 2009.]

The reader should be cautioned that many of these rates are very rough. Indeed, the principal goal of the Palomar Transient Factory is to accurately establish the rates of the fore- and back-ground events. It is clear from Figure 4 that *the impressive grasp of LSST is essential to the discovery of rare events.*

6 Localizing LIGO events

We simulated a hundred GW events (Kasliwal et al. 2009a, in prep) and compute the exact localization on sky (assuming a neutron-star neutron-star merger waveform and triple coincidence data from LIGO-Hanford, LIGO-Louisiana and Virgo). The localizations range between 3–700 sq deg for e-LIGO and 0.2–300 sq deg for a-LIGO (range quoted between 10th and 90th percentile). The Universe is very dynamic and the number of false positives in a single snapshot is several tens for a median localization (see Figure 5).

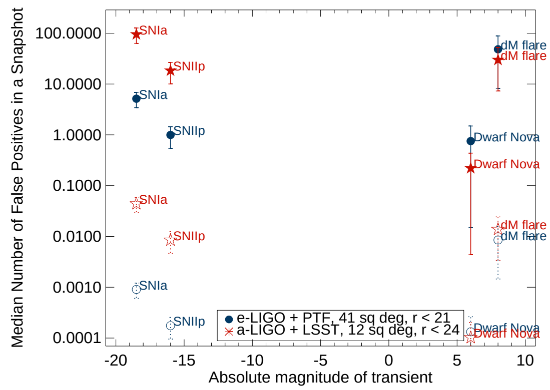

Figure 5: Number of false positives in a single snapshot. For e-LIGO (blue circles), we use the median localization of 41 sq deg and follow-up depth of r<21 is assumed. For a-LIGO (red stars), we use the median localization of 12 sq deg and follow-up depth of r<24. Filled symbols denote false positives in the entire error circle and empty symbols show false positives that are spatially coincident with nearby galaxies. Dwarf novae and M-dwarf (dM) flares constitute the foreground fog and the "error bars" on numbers represents the dependence on galactic latitude. Supernovae (Ia,IIp) constitute background haze.

Fortunately, the sensitivity-limited < 200 Mpc horizon of GW astronomy is a blessing in disguise. The opportunity cost (§4) can be substantially reduced by restricting follow-up to those transients that are spatially coincident with galaxies within 200 Mpc. Limiting the search to the area covered by galaxies within a LIGO localization reduces a sq deg problem to a sq arcmin problem — a reduction in false positives by three orders of magnitude!

Given the total galaxy light in the localization, we also find that the number of false

Table 1: Properties and Rates for Optical Transients[a]

Class	M_v [mag]	τ^b [days]	Universal Rate (UR)	PTF Rate [yr^{-1}]	LSST Rate [yr^{-1}]
Luminous red novae	$-9..-13$	20..60	$(1..10)\times10^{-13}\,yr^{-1}\,L_{\odot,K}^{-1}$	0.5..8	80..3400
Fallback SNe	$-4..-21$	0.5..2	$<5\times10^{-6}\,Mpc^{-3}\,yr^{-1}$	<3	<800
Macronovae	$-13..-15$	0.3..3	$10^{-4..-8}\,Mpc^{-3}\,yr^{-1}$	0.3..3	120..1200
SNe .Ia	$-15..-17$	2..5	$(0.6..2)\times10^{-6}\,Mpc^{-3}\,yr^{-1}$	4..25	1400..8000
SNe Ia	$-17..-19.5$	30..70	$^c\ 3\times10^{-5}\,Mpc^{-3}\,yr^{-1}$	700	200000[d]
SNe II	$-15..-20$	20..300	$(3..8)\times10^{-5}\,Mpc^{-3}\,yr^{-1}$	300	100000[d]

[a]Table from Rau et al. 2008b; see references therein. [b]Time to decay by 2 magnitudes from peak. [c]Universal rate at z< 0.12. [d]From M. Wood-Vassey, pers. comm.

Table 2: Galaxy Characteristics in LIGO Localizations

	E-LIGO			A-LIGO		
	10%	50%	90%	10%	50%	90%
GW Localization (sq deg)	3	41	713	0.2	12	319
Galaxy Area (sq arcmin)	4.4	26	487	0.15	20.1	185
Galaxy Number	1	31	231	1	76	676
Galaxy Luminosity (Log)	10.3	11.2	12.1	10.9	12.0	13.0

positives due to unrelated supernovae or novae within the galaxy is negligible. To be sensitive to transients as faint at peak as $M<-13$ (fainter than the faintest observed short hard gamma ray burst optical afterglow), e-LIGO needs at-least a 1-m class telescope for follow-up ($m<21$, 50 Mpc) and a-LIGO an 8-m class ($m<24$, 200 Mpc). Given the large numbers of galaxies within the localization (Table 2), a large field of view camera (>5 sq deg) will help maximize depth and cadence as compared to individual pointings. Thus, PTF is well-positioned to follow-up e-LIGO events and LSST to follow-up a-LIGO events.

The feasibility hinges on a complete galaxy catalog. We compiled all available distances to nearby galaxies and find that this catalog is only 70% complete at e-LIGO distance and 55% complete at a-LIGO distance. It is important that astronomers embark upon completing the census of galaxies within 200 Mpc.

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