SEDM White Paper from the Multi-Messenger Astrophysics Science Working Group

A. Franckowiak, M. Kowalski, L. Rauch, S. B. Cenko, L. P. Singer and M. M. Kasliwal on behalf of the ZTF SWG on MMA

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The ZTF Science Working Group on Multi-Messenger Astrophysics is undertaking three projects that request the use of SEDM. Every night, on average, we expect one target coincident with a neutrino localization. Every fortnight, on average, we expect to have either a GRB or GW or very high energy neutrino trigger. On a night with either a GW or a GRB or a high-energy neutrino trigger, follow-up of potentially fast-fading optical counterparts will take precedence over our nightly neutrino follow-up program.

1 Neutrino Follow-Up

The goal of the neutrino ToO program is to obtain a complete catalog of classified core-collapse SN up to magnitude of 19, if they lie close to a neutrino in space and time. Two main scenarios of neutrino sources are in the following of interest: a) choked jet SNe, where we expect neutrino emission within one day of the explosion time, b) circum-stellar medium (CSM) interacting SNe, where neutrinos are produced in collisions of the ejecta with the CSM and neutrino emission is expected on time scales of 30-100 days.

1.1 Neutrino Stream and Trigger

Based on a pre-defined event selection of IceCube we expect $\mathcal{O}(160)$ muon neutrino events per day in the Northern hemisphere ($N_\nu = 115$ in 15000 sqrdeg) with an average angular uncertainty of 1 sqrdeg. To find optical transients in vicinity of the neutrino positions we will use the software package AMPEL[1] to select all ZTF alerts in spatial coincidence and monitor the light curve on a daily basis. AMPEL enables a continuous tracking and fitting of light curves which will steadily increase the precision of the estimated explosion time and peak magnitude for a given transient. Combined with a condition for a temporal overlap between the transient properties and neutrino detection, photometric redshift as well as the energy information of the neutrino, the decision to take a spectrum of a transient will be based on a maximum likelihood analysis to increase the probability to target viable neutrino sources.

1.2 Estimation: Number of SEDM Spectra

We assume that these requirements described above reduce the number of sources by $\Delta T/365$, where ΔT is the time window in which we consider a neutrino-optical-transient coincidence. We require at least 3 detections with $m < 20.5$. We estimate the numbers of spectra required from the SED machine based on SNe light curves simulated by Uli.

We assume that 15000 sqrdeg of the Northern sky will be scanned in the public survey. The number of expected spectral follow-ups per day is given by:

$$N_{\rm spec} = \frac{N_{\rm SN}}{365/2\,{\rm days}} \Delta T \frac{N_\nu}{15000}, \tag{1}$$

$N_{\rm SN}$ is the number of SNe given by Uli's simulation over 6 months.

The following table shows the number of CC and Type Ia SNe we expect to randomly line up with one of the N_ν neutrino candidates. We list the numbers for different magnitude thresholds, which are the brightest detections for the simulated sources. Figure 1 illustrates the impact of limiting the magnitude of the survey on the neutrino signal significance with respect to the survey depth assuming one year of data. Here we assume that 1% of all core-collapse SNe produce the observed diffuse neutrino flux and those SNe have an absolute magnitude of -17. At a limiting magnitude of 21 (red line) a significance of $3.7\,\sigma$ is expected at 400 Mpc survey depth, however, by reducing the magnitude to 19.0, hence, reducing the total number of transients and number of necessary spectra, the max. significance is reduced by only approx. 10 % ($3.3\,\sigma$).

We propose to observe all sources, which get brighter than magnitude 19 with the SEDm. To do this we require 1 spectrum per day. Note that many of those transients will already be typed by other groups (i.e. the Type Ia group) and hence the requested number of spectra are only an upper limit.

Note that for CSM interacting SNe, an extended emission time scale of 30 days will allow to distinguish the candidates through their light curve shape, which allows us to trigger only on a subset of IIn, which would be 0.24 per day if we extend the time window to 100 days. In total we require 1.24 spectra per day.

[1] http://noir.caltech.edu/twiki_ptf/bin/viewauth/ZTF/CosmoAMPEL

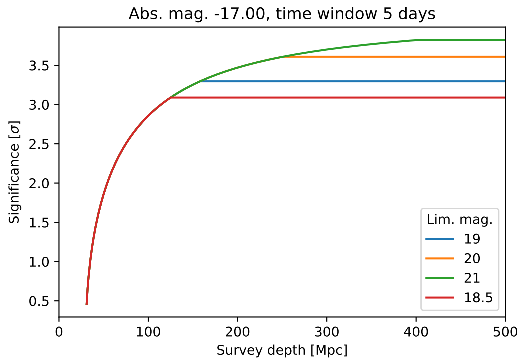

Figure 1: The figure shows the significance of the correlation between neutrino events and core-collapse supernovae with one year of observations assuming that 1% of the SNe produce the detected astrophysical neutrino flux. The maximal significance depends on the depth out to which the survey and SN classification is complete.

type	$\Delta T = 5$ days	$\Delta T = 30$ days
	mag < 18.5	
Ia	0.050	0.298
Ibc	0.009	0.055
IIn	0.006	0.037
IIp	0.016	0.093
total	0.080	0.483
	mag < 19.0	
Ia	0.098	0.590
Ibc	0.018	0.110
IIn	0.012	0.071
IIp	0.031	0.184
total	0.159	0.954

Table 1: Expected number of SNe randomly lining up with a neutrino in space and time for different time windows ΔT defining the temporal coincidence and different apparent peak magnitudes.

Selecting candidates based on a maximum likelihood, which will be implemented by the start of the public survey, will allow us to reduce this number.

In addition, we trigger ZTF observations for very-high energy neutrino events at a rate of approximately 20 per year. Given the spatial and temporal coincidence requirements outlined above the number of random coincidences is small and we expect less than 1 trigger SED machine trigger per months.

2 Short GRB Follow-Up

The goal of this program is to identify optical counterparts of short gamma-ray bursts (GRBs). Our P48 searches will likely be most sensitive to the "afterglow" emission from ultra-relativistic ejecta viewed within a collimated jet. However, we will also search for the more isotropic "kilonova" emission from events like the recent watershed GW170817, for which we will be sensitive out to distances of at least 150 Mpc (30 s exposures; we are still exploring how long integrations we can obtain reliably without the guider camera installed).

2.1 GRB Stream and Trigger

The primary source of short GRB triggers for our program will be the Gamma-Ray Burst Monitor (GBM) on the *Fermi* satellite. While *Swift* is (slightly) more sensitive and provides arcminute localizations, the *Fermi*-GBM has a much larger field-of-view (factor of ~ 5) and so triggers on-board on ≈ 40 short GRBs each year. Additionally, more sensitive searches of *Fermi*-GBM data via ground processing uncover a comparable number of "weak" short GRBs, and these may be more promising candidates for the golden nearby events (given the low isotropic energy release of GRB170817A). Given visibility constraints, weather losses, etc., we expect to follow ~ 2 *Fermi*-GBM short GRBs per month with P48. Short GRB localizations vary from $\sim 100\,\mathrm{deg}^2$ to $\sim 1000\,\mathrm{deg}^2$ depending on the gamma-ray fluence and spacecraft orientation. Here we adopt a typical value of $500\,\mathrm{deg}^2$ for our SEDM usage estimates.

2.2 Estimation: Number of SEDM Spectra

For each P48 trigger, we will utilize standard IPAC data products to identify new transient sources in the GBM localization regions. Here we request P60 SEDM classification spectra for sources brighter than 19 mag discovered as part of these searches. Classification spectra for fainter sources will be covered by target-of-opportunity programs at the Discovery Channel Telescope, Palomar, and Keck via our team members (Cenko, Singer, and Kasliwal).

To estimate the number of sources requiring SEDM spectra, we have re-examined searches for optical counterparts to long-duration *Fermi*-GBM GRBs performed with the Intermediate Palomar Transient Factory (Singer et al., 2013, ApJL, 776, 34; Singer et al., 2015, ApJ, 806, 52). From these empirical data sets, we find that the rate of transients with $r < 19\,\mathrm{mag}$ in long-duration GRB error circles is $\leqslant 1$ per $100\,\mathrm{deg}^2$. For the typical search region described above, this corresponds to $\leqslant 5$ sources requiring SEDM classification spectra, or ~ 10 per month. We note that this is a relatively conservative (i.e., large) estimate, since with the $15{,}000\,\mathrm{deg}^2$ ZTF MSIP survey, many of these can be ruled out as candidate counterparts via pre-outburst detections.

For classification purposes, we anticipate 40 minute integrations will yield sufficient SNR (≈ 5 based on Blagorodnova et al. 2017). So our total request for spectroscopic classification amounts to ≈ 7 hours per month.

In addition, we also request permission to obtain multi-color photometry for any extremely nearby ($d \leqslant 200\,\mathrm{Mpc}$) candidate counterparts, to characterize the (rapid) early color evolution as was seen in GW170817. The rates of such sources are sufficiently low we expect at most one of these over the course of the 6 months covered by this proposal call. But an additional several hours of imaging would be extremely critical to map the early evolution were such a source found.

In total then, for the full six months covered here, we request 45 hours of SEDM data (42 hours classification spectra, 3 hours Rainbow camera imaging).

3 Gravitational Wave Follow-Up

The goal of this program is to identify optical counterparts to gravitational waves (GW), in particular, mergers of two neutron stars or merger of a neutron star with a black hole. During semester 2018A, the LIGO and Virgo GW interferometers are mostly offline for upgrades and the next GW observing run O3 doesn't begin until 2018B. However, there is still some chance that a trigger or two is sent during commissioning (cf GW150914 which was sent a few days before the official start of O1). The expected median localization is 250 square degrees and our search will be to a depth of 22 mag. SEDM photometry can help with filtering which sources have the characteristic red evolution of GW170817 and more likely to be associated with the GW. We anticipate needing photometry of 10 sources x 3 min per exposure x 3 filters x 3 epochs per GW trigger i.e. 4.5 hours. We are unlikely to need SEDM spectroscopy as unrelated sources brighter than 19 mag will likely be flagged by their tell-tale light curves in the all-sky MSIP survey.