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

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1 Part I: Summary (1 paragraph)

This proposal is on behalf of the multi-messenger science working group and has three distinct components. Our first goal is to identify high-energy neutrino sources by identifying their optical counterparts. We operate with two complementary search strategies, a ToO program and a correlation study of a large sample of optical sources with the entire IceCube neutrino data set. While the first program has a small SEDm requirement of roughly 20 trigger per year (12h spectroscopic time), the second program is more time-consuming. In case RCF continues we would ask for 190 spectra per year corresponding to 120h of spectroscopy time, while at least 73h (120 spectra) would be common with the RCF program and, hence, only one trigger for both programs is needed. If RCF does not continue we would ask for 240 spectra (145h). Our second goal is to identify optical afterglows of Fermi short gamma-ray bursts. Here, we request 8 hours of SEDM classification spectroscopy, and 3 hours of SEDM photometry in the (unlikely) event of a nearby counterpart. Our third goal is to identify electromagnetic counterparts to gravitational waves from binary neutron star merger and neutron star-black hole mergers. Here, we request 18 hours of SEDM photometry and 12 hours of SEDM spectroscopy.

2 Part II: Team Members / Resources

PI / Point of Contact: Anna Franckowiak
Co-Is: Brad Cenko, Mansi Kasliwal, Marek Kowalski, Jakob Nordin, Ludwig Rauch, Leo Singer, Robert Stein
Science Working Groups: MMA and strong support of the RCF program, GROWTH collaboration
Associated Resources (facilities, etc.): IceCube, Fermi, LIGO/Virgo, GROWTH follow-up network

3 Part III: Science Objectives (1 page)

3.1 Science Case I: Neutrinos

High-energy neutrinos are the key to pinpointing the origin of high-energy cosmic rays (the most powerful accelerators in our Universe). While the gamma-ray blazar, TXS 0506+056 was identified as the first compelling high-energy neutrino source candidates [Aartsen et al., 2018], other studies have limited the overall contribution of *Fermi* blazars to the measured diffuse neutrino flux to $< 30\%$ Aartsen et al. [2017]. Other possible neutrino source classes include choked-jet and interacting supernovae, (low-luminosity) gamma-ray bursts and tidal disruption events. We are aiming to identify high-energy neutrino sources through the detection of their optical counterparts. In particular this is unique probe for the existence of choked jets in supernovae. We follow two complementary strategies:

a) We use the ~ 10 most energetic neutrino track events per year with large ($\sim 50\%$) probability to be of cosmic origin to trigger ToO observations.

b) We search for a statistical excess of neutrinos from entire source populations.

Both programs require SEDm usage to classify potential neutrino counterpart candidates.

3.1.1 ToO (program Ia)

IceCube selects the most interesting neutrino events in realtime at the South pole. Those are either clusters of TeV neutrinos arriving within a short time window or single high-energy ($\sim 100\,TeV$) neutrinos, which have a probability of 50% to be of cosmic origin (in contrast to atmospheric origin). We aim to follow-up those events quickly with ZTF to ensure early photometry is obtained, which is crucial to catch GRB-like afterglows and also to constrain the explosion time of a potential supernovae candidate. These temporal constraints are essential to later establish the coincidence between the neutrino and the optical counterpart. The neutrino events trigger the follow-up marshal, which allows fast scheduling of ZTF observations. Observations will be performed for the first few days, while the MSIP data will be sufficient to trace long-term variability.

The angular error of the IceCube neutrinos are typically of the order of a few square degrees, and can thus be covered by a single pointing. Potentially interesting optical candidates found within the neutrino error circle will be followed up by the SEDm.

3.1.2 Population study (program Ib)

The goal of this second program is to obtain a complete catalog of classified core-collapse SN, up to magnitude of 19, which are spatially and temporally coincident with neutrinos. The main neutrino source scenarios of interest is the choked jet SNe case, where we expect neutrino emission within a day of the explosion time.

Based on a pre-defined event selection from IceCube, we expect $\mathcal{O}(160)$ muon neutrino events per day in the Northern hemisphere with an average angular uncertainty of 1 sqrdeg. To find optical transients in the vicinity of the neutrino positions, we use the software package AMPEL[1] to select all ZTF alerts in spatial coincidence and monitor the light curves on a daily basis. The decision to take a spectrum of a transient will then be based on a maximum likelihood analysis to increase the probability to target viable neutrino sources. Once a sample of classified sources is collected, we apply a neutrino stacking analysis to search for a statistical excess of neutrinos from the entire source population. To derive meaningful limits, or to estimate the total contribution of a source class to the diffuse neutrino flux, we have to know the estimate the completeness of our source sample

In this direction, we find large overlaps between our program and the RCF. In the following we discuss two scenarios, depending if the RCF continues or not.

3.1.3 Scenario I: RCF continues

In our preferred case, the RCF program is operated in parallel to the neutrino program. We would share the majority of our spectroscopic time with the RCF program, as the intersection of selected transients for classification is substantial. Hence, for all transients which are common to both programs only one SEDm trigger for both programs is needed. Moreover, transients which did not show a time correlated neutrino detection but are present in the RCF program are crucial not only for our background estimates but also essential to quantify the completeness of our selection of neutrino sources.

3.1.4 Scenario II: RCF does not continue

In this case, we would need to split our spectroscopic time between classify neutrino counterparts and creating a control sample to estimate our background sample. Hence, this would result in lowering our limiting magnitude to 18.5, reducing the expected number of detectable neutrino sources. This would reduce our sensitivity compared to Scenario I.

3.2 Science Case II: Short GRBs

The recent discovery of a low-luminosity gamma-ray burst (GRB 170817A) in coincidence with the binary neutron star merger GW170817A begs a critical question: are there more nearby short GRBs in the *Fermi* (and potentially *Swift*) sample that are unidentified because of faint/off-axis afterglow emission? To address this issue, we have begun a program to follow-up poorly localized short GRBs from the Gamma-Ray Burst Monitor (GBM) on *Fermi* to search for optical counterparts. While our primary objective has been to find counterpoarts (particularly for nearby events, i.e., kilonovae), we have also used these ToO observations as dry runs for the large gravitational wave localizations that are anticipated in O3.

3.3 Science Case III: Gravitational Waves

The joint discovery of gravitational waves and electromagnetic radiation from the binary neutron star merger GW170817 was a watershed moment for astrophysics - it solved the decades old mystery of the origin of short GRBs, it demonstrated that binary neutron star mergers could produce the bulk of the heavy elements in the universe, and it suggests that these events may be utilized to probe the cosmology of the universe independent of the local distance ladder. The key to nearly all these discoveries was the identification

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

Type	date	RA	Dec	Error	Comments
Doublet	2018-06-11 23:36:04.87	255.63	13.32	0.90	observed
EHE	2018-09-08 19:59:31.84	145.77	-2.52	0.34	Sun distance 22.68 deg
HESE	2018-10-14 11:52:19.07	225.18	-34.79	1.22	Sun distance 35.73 deg
EHE	2018-10-23 16:37:32.65	269.84	-8.89	0.29	camera down
HESE	2018-10-31 02:02:51.41	182.79	-68.39	1.22	retracted

Table 1: ToO triggers received from IceCube

(and precise localization) of an electromagnetic counterpart - here we aim to detect and characterize optical counterparts to gravitational wave detections in the O3 observing run.

4 Part IV: Past Usage (1 page)

4.1 Neutrino ToO (program Ia)

Since ZTF began operations, we have received five IceCube alerts (see Tab. 1). Only one could be followed-up with ZTF, and no interesting candidate was identified in the data. Therefore, no SEDm time was used.

4.1.1 Neutrino Doublet

A neutrino doublet (two or more neutrinos within 100 sec and separated by less than 3.5 deg) arrived on 2018-06-11 23:36:05 UTC. The two neutrinos had $\sim$ 1TeV energies, and were separated by 0.3 sec in time and 3 deg in space. The 90% angular uncertainty on the combined direction was 0.9 deg. We expect $\sim$4 more significant doublets per year. Observations were scheduled by hand for the following night for one field (535). Two 300s exposures were taken on June 12 and another two 300s exposures on June 13. There was another 60s exposure on June 12 and 30s exposures on June 13, 16, 17 and 19. This was the first time we took 300s exposures. The reference image should be deep enough (combines at least 15 images). Image quality looked good, even without guiding.

This was the first ZTF ToO trigger, and automatic scheduling was not in place yet. Scheduling observations came at a large overhead. In the future candidates from neutrino ToOs will be automatically processed by AMPEL, and interesting candidates pushed into the marshal. AMPEL was only running in beta mode at the time of the alert, but we nonetheless managed to filter candidates with AMPEL by hand and push them into the marshal. No interesting candidate was found. Fewer dim candidates than expected were found in the deep images (note that this was the first time such deep observations were performed). This problem was investigated and fixed by IPAC.

Since the doublet stream is a private GCN stream from IceCube, we could not report our results in an ATel.

4.1.2 Other Triggers

We were unlucky with the other four IceCube alerts. Two were too close to the Sun to be followed up. One was revealed as a likely atmospheric background events after further checks by IceCube and therefore retracted. Another arrived when the camera was not installed.

4.2 Neutrino Population study (program Ib)

The neutrino correlation program entered commissioning phase in August 2018. It required substantial software development (AMPEL) to automatically correlate neutrinos with optical transients. In a primary selection step, all transients with at least 3 observations, where the first and last detection are more than 1 day apart, are identified. In addition, a match to the GAIA catalog is performed to reduce stellar contamination. A galactic latitude cut of 10° latitude is also applied. The second transient selection step is based on a maximum likelihood approach, where for each transient and neutrino detection we calculate a test statistic (TS). A high value of the test statistic indicates a low probability of the association being a background

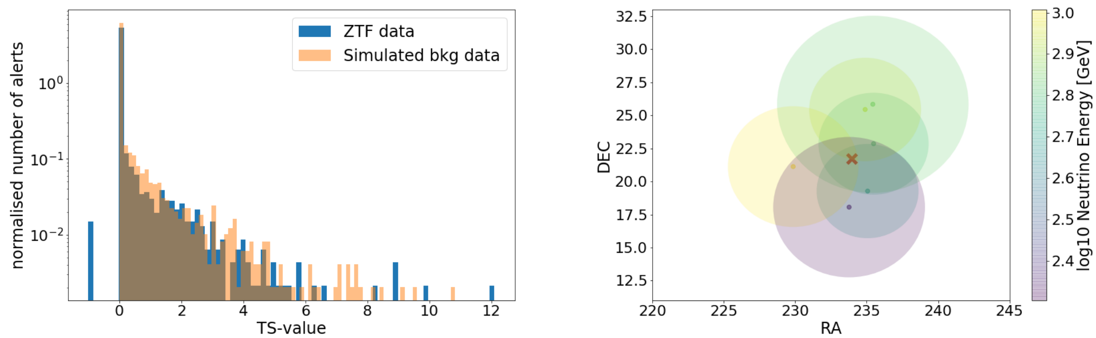

Figure 1: Left: The transient selection is based on the result of a maximum likelihood optimization. The calculated test statistic (TS) is shown for ZTF data in blue and simulated data in red which agree well during the commissioning phase. Right: The red cross indicates the position of a selected transient and the colored circles represent the uncertainty of the reconstructed neutrino origins. The color coded scale displays the neutrino energy.

fluctuation. The left plot in figure 1 shows the distribution of test statistic values. Our simulation is based on a SNCosmo simulation of transients detected with ZTF and scrambled directions of IceCube neutrino events. The distribution of computed TS values of the simulation and ZTF data agree well, which indicates that AMPEL is operating correctly (right plot in figure 1). We follow up transients which show a TS value that is greater than 1. The value is optimized to avoid on the one hand to follow up too many accidental coincidences, while still keeping as many neutrino source candidates as possible.

The optical alerts collected by the neutrino program filter since the start of the commissioning phase in August is shown in figure 2. The blue histogram shows the number of new transients per day which pass our cut criteria (an average of 0.79 new alerts per day). Out of the selected transients, on average 0.52 spectra per day (black) were triggered by the RCF program. Most of the remaining candidates are fainter than 18.5 mag or are of stellar origin (e.g. CVs). Hence, all transients in our program below 18.5 mag also pass the RCF filter and both programs can share their spectroscopic time.

4.3 Short Gamma-Ray Bursts

We have followed up 6 *Fermi*-GBM short GRBs since the beginning of ZTF. While no clear counterparts were identified for any of these events, it has been an extremely useful dry run for the anticipated localizations from LIGO and Virgo in O3. In each of these cases we identified a small but significant number of new transients in the GRB localization (typically ~ 10 events in $\sim$ few hundred square degrees); however, most of these are too faint for realistic classification with SEDM ($> 20\,\mathrm{mag}$). We have executed 3 SEDM triggers for classification of sufficiently bright targets as part of this effort - two of these objects turned out to be type Ia supernovae, while the third was a previously undiscovered CV. The total time usage is ~ 2.5 hours.

4.4 Gravitational Waves

No usage in the year 2018. No triggers were received from Ligo/Virgo.

5 Part V: Observing Details (1 page)

5.1 Ib. Neutrino Population study

We would like to continue our program without major changes to obtain a uniform data set. As it is not clear if we can rely on the continuity of the RCF program, we consider two cases below.

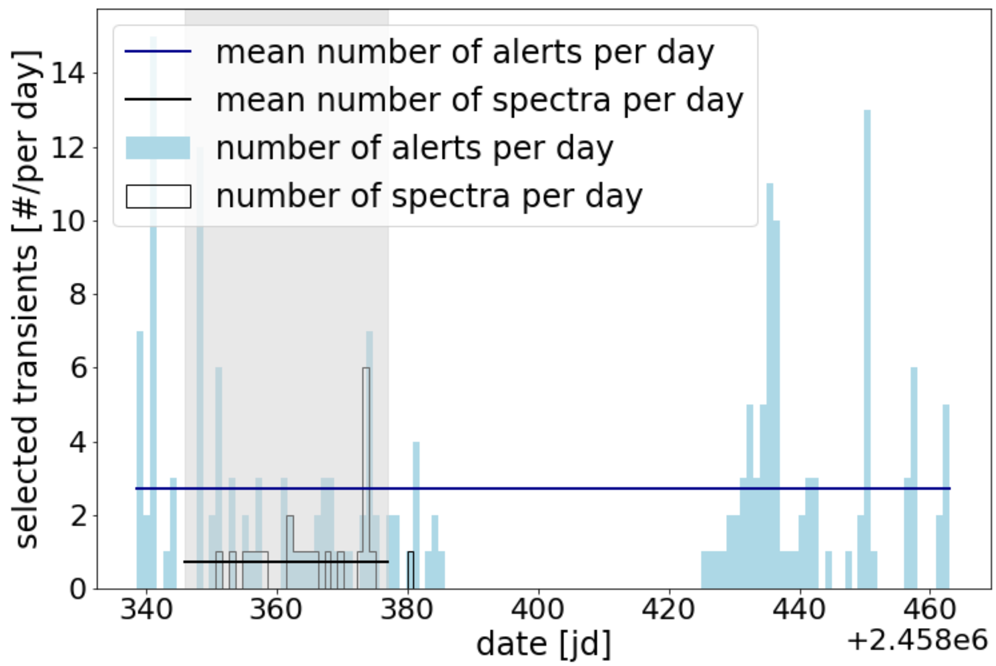

Figure 2: Number of new transients per day. The blue line shows the average of 0.79 new alerts per day. Out of those we were able with the help of the RCF program to type 0.52 transients per day (black line).

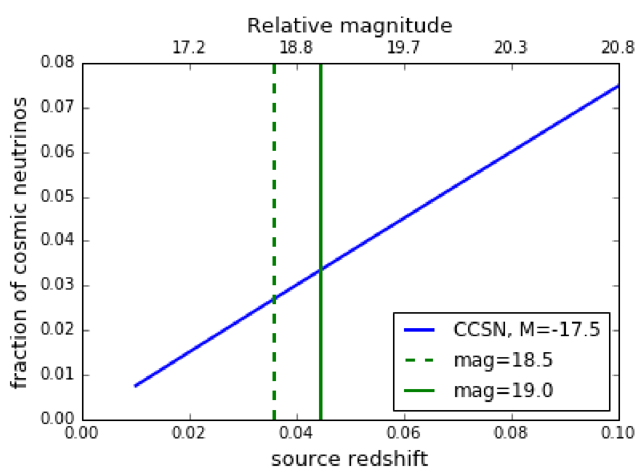

Figure 3: Expected fraction of supernovae counterparts visible up to a given redshift assuming the sources follow the star formation rate. Limiting magnitudes of 18.5 and 19 are marked as green vertical lines. By reducing our program to 18.5 mag we reduce the number of visible neutrino counterparts from 3.4% to 2.7%.

Lim. Mag	Alerts [1/d]	Trigger [1/d]	Trigger per year
19	0.79	0.52	190
18.5	0.54	0.32	120
18	0.4	0.1	35

Table 2: Number of necessary spectra with respect to the limiting magnitude of the program

5.1.1 Scenario I: RCF continues

We would continue to limit our program to apparent magnitudes below 19. On average, we receive 0.79 alerts per day in our program, with on average 0.52 transients per day which need to be followed up. This results in 188 spectra which we would need in 2019 to classify transients which are correlated to a neutrino detection. Out of those, at least 120 transients would be common with the RCF program. Hence, only 70 trigger in 2019 would be needed for the neutrino program to be complete up to 19 mag. The estimated numbers for various limiting magnitudes are shown in figure 2.

In total we ask for 210 spectra (120h) where at least 120 spectra (73h) would be shared with RCF.

5.1.2 Scenario II: RCF does not continue

In case RCF ceases operating, our program would need to change its observing plan substantially. We would be forced to limit our program to 18.5 mag requiring 120 spectra (73h). This would reduce our signal by 20%, as can be seen in Fig. 3. It is essential to our program to keep the signal acceptance as high as possible due to the small number of high energy neutrinos detected with IceCube. In addition, we must build a similar sized control sample of approximately 120 classified transients (73h) to have a reliable background estimate of accidentally coincident neutrinos to each source class and to study the completeness of the neutrino selection. In sum we ask, in this scenario, for 240 spectra (145h).

5.2 Ia. Neutrino ToO

We expect 10 “gold” sample neutrino alerts with a probability to be of cosmic origin of at least 50% and additional 25 “bronze” neutrino alerts with a signalness of at least 30%. While we apply a ToO follow-up for all gold alerts, we will rely on the standard MSIP cadence for the bronze alerts. We are aiming to classify all potentially interesting candidates found in within the neutrino error circle with an average area of 3 sqrdeg. We assume that 15% of the alerts will be too close to the sun. Thus, in total, we cover an area of roughly 85 sqrdeg per year. Assuming the rate of young supernovae (assuming an explosion time within 5 days of the neutrino arrival) with a peak magnitude of < 19 of 0.12 per sqrdeg this yields roughly 10 SEDm trigger per year from SNe. We assume that we will trigger on other variable such as AGN core activity with a similar rate leading to a total rate of 20 per year (12h).

5.3 II. Short Gamma-Ray Bursts

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 targetof-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 utilize our experience from Year 1 in ZTF. We find ~ 1 previously unknown source with $r < 19$ mag per ToO trigger. Assuming a rate of 1 trigger per month, and a total clock time of 2430 s per trigger (appropriate for sources of this brightness), this corresponds to 8 hours of SEDM spectroscopy.

In addition, we also request permission to obtain multi-color photometry for any extremely nearby ($d <$ 200 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 year covered by this proposal call. But an additional several (3) hours of imaging would be extremely critical to map the early evolution were such a source found.

5.4 III. 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. Starting March 2019, the LIGO and Virgo GW interferometers are expected to being their third observing run with sensitivity to binary neutron star mergers out to 120 Mpc. The expected event rate is 2-4 events per year. The expected median localization is 250 square degrees and our ZTF 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. However, since the RCF survey only focuses on transients brighter than 18.5 mag, we may still have a few events. So we request spectroscopy for 3 sources x 1 hour per GW trigger. Our total request is 18 hours of SEDM photometry and 12 hours of SEDM spectroscopy.

6 Part VI: Publication Plans (0.5 page)

We are planning to write several joint IceCube-ZTF papers. First, we plan to write one technical paper explaining our neutrino program including a sensitivity curve. This paper will compare the performance of program a) and b). After one year of data collection with RCF we will perform a neutrino stacking analysis with that sample, which will result in a publication. A deeper search beyond the RCF sample will follow in a second paper.

Each component of the three ToO programs will result in ATels/GCNs for each successful follow-up observation. In the case of non-detections, after one year, each of the the three ToO programs will summarize results in papers. In the case of detections, each individiual trigger will likely lead to multiple publications.

References

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