White Paper - Searching for Optical Counterparts to High-Energy Neutrino Sources

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Abstract

The IceCube neutrino observatory has detected a flux of likely extragalactic neutrinos. However, the origin of the neutrinos is still unknown. Among the possible candidates are gamma-ray bursts (GRBs), core-collapse supernovae (SNe), active galactic nuclei and tidal disruption events (TDEs) - all are accompanied by a characteristic optical counterpart. Our goal is to identify the neutrino sources by detecting their optical counterpart following two approaches:
a) A target of opportunity (ToO) program, which selects the most interesting astrophysical neutrino candidates in real-time and triggers rapid follow-up observations by ZTF to target rapidly varying transients (e.g. GRB afterglows).
b) All-sky near real-time correlation, where we correlate all optical transients found by ZTF with all neutrino candidates detected by IceCube to target slowly varying transients (e.g. SNe, TDEs).
Fig. 1 shows an illustration of our physics case.

1 Scientific Motivation

1.1 Outline of the goals and competitiveness of ZTF for the project.

The **unique large FoV** of ZTF will allow us for the first time to follow-up astrophysical neutrino candidates with low angular resolution in a target of opportunity program (ToO).
A key aspect is ZTF's **frequent coverage of the full sky**, which will guarantee that recent pre-explosion references are available for ToO observations. Other instruments, like Pan-STARRS, can often cover the neutrino uncertainty region, but it will be very hard to tell which transients are old.
The **large area covered by ZTF** will provide us with catalogs of classified optical transients of unprecedented completeness, which we will use for near real-time cross-correlation studies with a large IceCube neutrino sample.

1.2 Figures of Merit

The ultimate goal is to probe SNe and other optical transients as the sources of high-energy neutrinos.
Most of the ToO alerts will be close to the equator, where IceCube is most sensitive to high-energy neutrinos, and should be observable from Palomar if the weather is good. In a successful ToO program we would be able to follow-up 50-75% of the neutrino alerts within 24h (considering visibility and weather constraints) and find transients in the neutrino error circle down to a magnitude of 20.5 and spectroscopically identify them.
The catalog cross-correlation relies on spectroscopic classification of the relevant sources. The success of the near real-time all-sky correlation study can be measured by the fraction of spectroscopically identified sources with rising light curve within the neutrino error circle.

1.3 Real-Time Discovery

We are interested in sources with a rising light curve consistend with an explosion time coincident with the neutrino arrival time. For the ToO alerts issued for astrophysical neutrino candidates we are additionally interested in sources that show a rapidly declining light curve (e.g. a GRB afterglow).
The project requires human scanning on the same level as the regular survey.

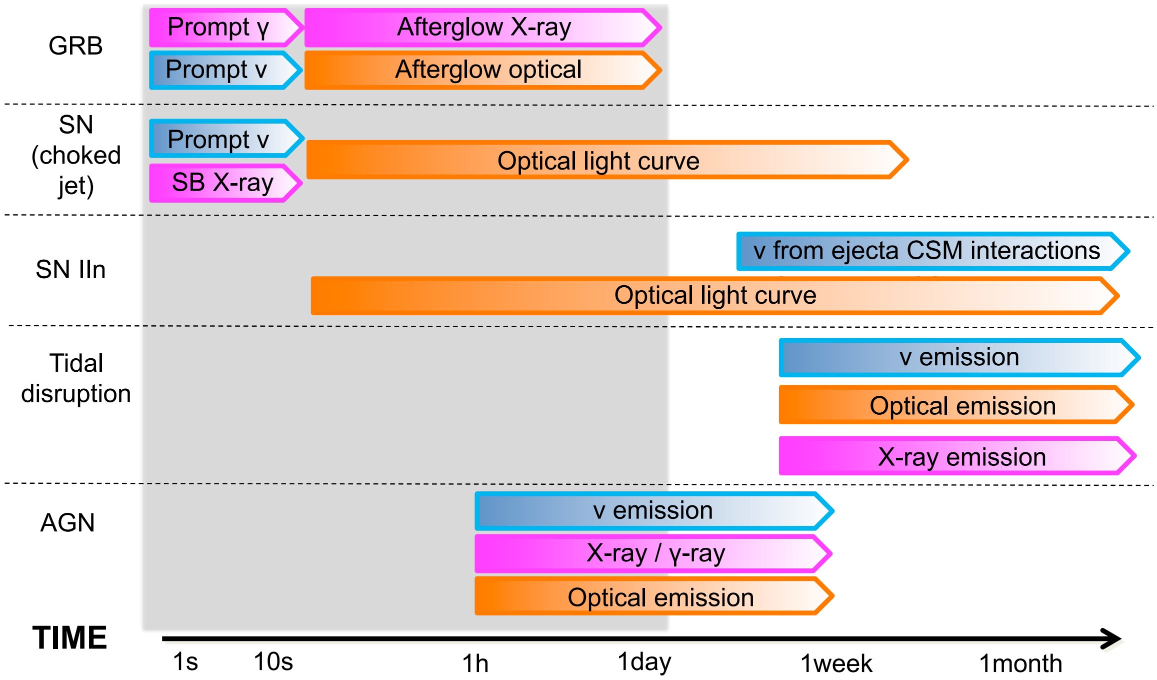


Figure 1: Expected multi-wavelength emission from neutrino source candidates (SB: shock breakout, CSM: circum-stellar material). The shaded gray region indicates where the ToO program will be applied.

2 Proposed Observations

2.1 Pointings, Cadence and Filters

We performed a study showing that the all-sky near real-time cross correlation of neutrinos with optical candidates benefits from a large sky coverage of the ZTF survey (see Appendix A). In the trade-off of sky coverage and cadence, we prefer large sky coverage. Only one filter would be needed to provide the required information on the light curve behavior. Assuming that the public all-sky survey will cover most of the sky every 3 days, this survey would fulfill our requirements. However, the candidates found in the all-sky search need to be classified to collect a sample for a neutrino cross-correlation analysis. We will use the arrival direction of IceCube neutrinos to select optical transients in spatial coincidence with neutrinos and require in addition that the light curves are rising with respect to the neutrino arrival time. The selected candidates need to be spectroscopically classified.
For the ToO we select high-energy neutrino candidates with high probability of being of astrophysical origin. We expect 20 alerts per year, of which 12 have an angular resolution of $\leqslant 1°$ and the remaining 8 have a poor resolution of $1° - 15°$. We suggest immediate re-pointing of the telescope to observe the neutrino position for 5 epoches within the first hour to be sensitive to a GRB-like afterglow. In addition we ask for 2 epochs each in the two following nights. Only one filter is needed. In total we expect 4h of observations time per year including overhead.

2.2 Sensitivity to Calibration and Variations in Cadence and Filters

Only one filter will be necessary for this project. However, additional filters will help with early typing of found candidates. Well calibrated light curves are crucial to identify rising sources. Smaller cadence will help us to pin-point the explosion time more accurately and therefore reduce the background in a cross-correlation study with neutrinos. However in the trade-off of sky coverage and cadence, we prefer large sky coverage.

2.3 Suitable Periods for the Observations

If only a limited region of the Northern sky can be covered in the survey, we prefer to cover parts close to the horizon, where IceCube's sensitivity is highest.

3 Supporting Observations

3.1 Photometric Follow-up

Not needed.

3.2 Cadence/Filter Requirements

The success of this project directly relies on limiting the explosion time for transients. Any reduction in cadence will directly reduce such constraints. Observations in the bluer g filter are preferable as many potential sources are initially blue.

3.3 Spectroscopic Follow-up

We rely on a regular classification of CCSNe. Higher priority can be given to sources, which line up with neutrino directions.

We expect roughly 160 neutrinos per day in the Northern hemisphere with an angular resolution of 1 square degree. Per square degree we expect on average 2.0 CCSNe with distance $z < 0.08$ and 4.7 Type Ia SNe detectable at 20.5 mag (corresponding to a redshift of 0.08 and 0.16, assuming a peak magnitude of -17 and -19 respectively). We are only interested in sources which rise starting at the neutrino arrival time. We assume that this requirement reduces the number of CCSNe by $\Delta T/365$ assuming an uncertainty of the explosing time of $\Delta T = 5\,$days. This results in roughly 6 supernovae per night lining up with a neutrino event by chance in the entire Northern hemisphere. Assuming that 1/3 of the Northern sky will be surveyed we expect to select 2 sources per night for spectroscopic follow-up.
Bright sources can be followed up with the SEDM, while fainter sources can be targeted by the Liverpool telescope (they've showed interest in following up potential neutrino sources, but an agreement needs to be made). We expect that roughly 10% of the sources will be brighter than magnitude 19 and observable with the SEDM, that would be one source every 5-6 days, requiring 1h of observation time.

3.4 Other External Resources

The IceCube team has some Swift time to search for X-ray counterparts to high-energy neutrinos.

4 Expertise to Undertake the Project

4.1 Expertise and External Collaborators

We need experience in transient classification (Jakob Nordin) and fast processing of neutrino data (Jakob van Santen, Anna Franckowiak). We are in the process of hiring a new postdoc and PhD student to join this effort. Mansi Kasliwal will help with automated ToO triggering, candidate vetting and follow-up with the GROWTH network.

4.2 Specify tools required to deliver science products.

We need to include the neutrino stream information into the ZTF marshal to allow for automatic identification of optical candidates in the neutrino error circles. In addition rising sources need to be identified to select the interesting candidates for spectroscopic follow-up. Fields close to neutrino signals need to be monitored for 10-20 days to allow distant SNe to brighten. Software will be developed to allow this monitoring, including human scanning of potential candidates.
A tool for ToO observations (similar to GW follow-up) will be needed to follow-up neutrino alerts.

5 Manpower and Time-line

5.1 Specify the people that will carry out the project as well as milestones for the publication plan.

Jakob van Santen and Anna Franckowiak will provide the neutrino stream and work on the selection of optical candidates for spectroscopic follow-up.
The collected catalog of identified sources will be input to a non-real time all-sky correlation study using

a large sample of neutrino data (see also Appendix A). A correlation study will be applied for various source classes (e.g. different types of CCSNe, TDEs). After one year of science data taking with ZTF the cross-correlation study with neutrino data will be performed and upper limits (or the first detection of neutrino production in CCSNe) will be published.

A Appendix

The appendix provides more details on the project outlined above and explains how we derived the given numbers.

A.1 High-Energy Neutrino Sources

High-energy neutrinos are unique messengers from the high-energy Universe. Produced in hadronic interaction in the most violent sources in the Universe they provide a smoking gun signature for the origin of cosmic rays. Furthermore, neutrinos are capable to escape even the densest environments such as stellar cores and black hole accretion disks. They thus carry information that no other messenger can provide.

After the first detection of a diffuse flux of astrophysical neutrinos [Aartsen et al., 2013] the most pressing question in the field of neutrino astronomy is where those neutrinos come from. No significant cluster in space or time was found in neutrino data yet [Aartsen et al., 2016] and the isotropic distribution of the neutrinos points to an extra-galactic origin.

Gamma-ray bursts (GRB) have been suggested as source candidates for the highest-energy cosmic rays and high-energy neutrinos [Waxman, 1995, Waxman and Bahcall, 1997]. Recently gamma-ray bright bursts could be excluded as the main contributor to the diffuse neutrino flux [Aartsen et al., 2016]. However, a large population of low-luminosity gamma-ray burst might contribute significantly to the observed flux. While highly relativistic jets can explain gamma-ray bright bursts, choked jets may explain trans-relativistic supernovae (SNe) and low-luminosity GRBs, giving a unified picture of GRBs and GRB-SNe [Senno et al., 2016]. This scenario can be probed by high-energy neutrinos.

Other possible sources are active galactic nuclei (AGN) or tidal disruption events (TDEs). Gamma-ray bright blazars have been disfavored as the main contributor to the diffuse neutrino flux by a recent blazar source stacking, which limits the contribution of blazars detected by *Fermi* to the total astrophysical neutrino flux to $\sim 30\%$ [Aartsen and et al., 2016]. However, Kadler et al. [2016] found an interesting correlation of the PeV neutrino event "Big Bird" with a high-fluence blazar outburst, hinting to a possible origin of at least a fraction of high-energy neutrinos in blazar flares. Jets produced by the transient accretion of the disrupted material in TDEs could be efficient neutrino factories [Wang and Liu, 2016, Lunardini and Winter, 2016, Senno et al., 2016, Dai and Fang, 2016].

We expect transient or variable neutrino signals from the candidate source classes listed above, which will be accompanied by transient or variable electro-magnetic (EM) counterparts. The duration of the neutrino and EM emission varies for different sources and is illustrated in Fig. 1.

A.2 Neutrino Detection

The IceCube neutrino detector located at the geographic South Pole comprises a volume of $1\,\mathrm{km}^2$ and is capable to detect neutrinos with energies above $100\,\mathrm{GeV}$ and beyond. We distinguish two signal signatures: track and shower events. Track events are produced in charged-current interactions of muon-neutrinos and typically have an angular resolution of less than 1°, while shower events are produced by neutral-current interactions of all neutrino flavors and charged-current interactions of electron and tau-neutrinos and have a poor angular resolution of $\mathcal{O}(10^\circ)$.

A.3 Search for Optical Counterparts

Our goal is to identify the sources of high-energy neutrinos by detecting their optical counterparts. We are planning to follow two complementary approaches. First, to target rapidly varying transients (duration less than 1 day, indicated as gray shaded region in Fig. 1), we are planning to run a target of opportunity program, which selects the most interesting astrophysical neutrino candidates in real-time and triggers rapid follow-up observations by ZTF. Second, targeting slowly varying transients, we will correlate all optical transients found by ZTF with all neutrino candidates detected by IceCube.

A.3.1 Target of Opportunity Program (ToO)

Astrophysical neutrino candidates can be selected from the large background of atmospheric background by a) selecting the most energetic events or b) looking for clusters of events in time and space. The latter program has been running since 2008 and delivered alerts to PTF since 2011 [Abbasi and et al., 2012, Aartsen and et al., 2015]. However, it was so far only sensitive to transients lasting $< 100\,\mathrm{s}$. A planned extension will offer sensitivity to longer transients and additionally improve the sensitivity. Single high-energy neutrino alerts are released to the public through the Astrophycial Multimessenger Observatory Network (AMON) Smith et al. [2013] via the Gamma-Ray Coordinates Network (GCN[1]) since 2016.

We expect a rate of one neutrino alert per month with angular resolution of $\lesssim 1°$ and 8 with poor resolution of $1 - 15°$. Roughly 50-75% will be observable by ZTF within the first night. For those we suggest immediate re-pointing of the telescope to observe the neutrino position for 5 epoches within the first hour to be sensitive to a GRB-like afterglow. In addition we ask for 2 epochs each in the two following nights.

Candidates within the neutrino error circle have to be identified as soon as possible to be able to request a spectroscopic follow-up. In the first night we focus on rapidly fading candidates (such as GRB afterglows). Sources that rise over the following two nights could be young supernovae, which produced high-energy neutrinos at their explosion time.

A.3.2 Catalog Correlation Studies

Transient neutrino sources with a slower evolving optical counterpart (e.g. supernovae) do not require an immediate re-pointing of the telescope. However, to ensure statistically significant correlation of neutrinos with the found optical counterparts we rely on closely-sampled optical light curves and the classification of the source. For example, in case of a choked-jet SN, the neutrino production is expected at the explosion time and an accurate estimate of the explosion time is crucial to establish the correlation of the neutrino signal and the SN and distinguish it from a chance coincidence.

In the following we will present a simple model of a stacked search for neutrinos from core-collapse supernovae, and use it to study how the sensitivity of such a search would depend on the cadence and angular coverage of a ZTF survey.

The quasi-diffuse astrophysical neutrino flux observed by IceCube can be described by a spectrum $E^2\Phi_\nu = 1.5 \times 10^{-8}(E_\nu/100\mathrm{TeV})^{-0.3}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$, or $\sim$163 muon neutrino events of energy $E_\nu > 1\,\mathrm{TeV}$ per hemisphere and year. If these are produced by sources whose luminosity evolves with the star formation rate, we expect 15% of this flux to come from sources within 1 Gpc. If we exclude the area within 5° of the Galactic plane, then we expect $\sim$22 events from nearby sources at declinations greater than -3°.

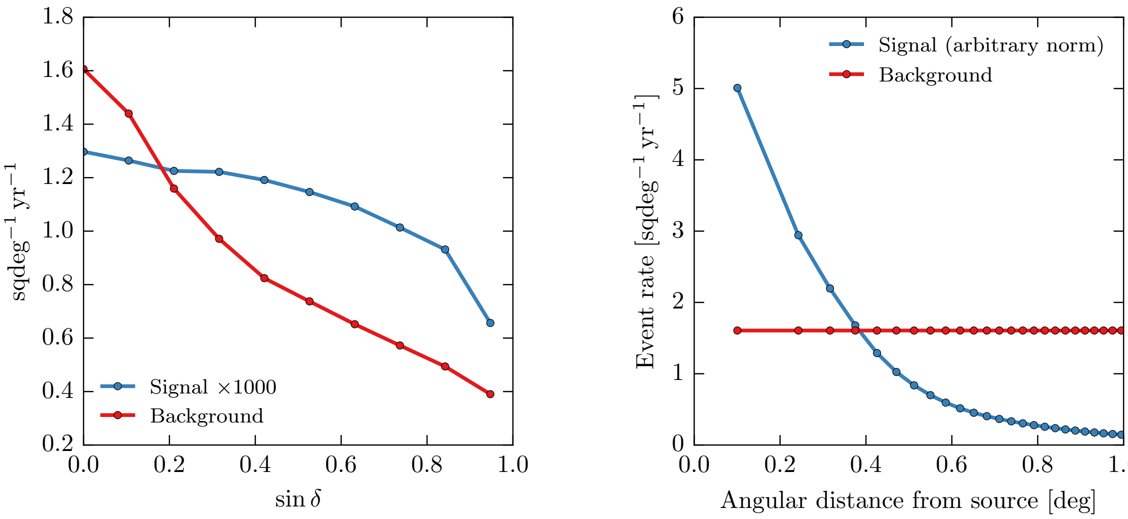
For this study, we assume that SNIbc are the sole source of the quasi-diffuse astrophysical neutrino flux. Furthermore, we assume a constant absolute optical magnitude of -18, making them detectable out to $\sim$480 Mpc in a single 30-second exposure. Considering the density of SNIbc, $\sim 5 \times 10^{-6}\,\mathrm{Mpc^{-3}\,yr^{-1}}$ Mannucci et al. [2005], Cappellaro et al. [1999], we expect roughly 1150 candidate sources per hemisphere and year. Together these visible sources should produce 10.3 neutrino events per year that have to be distinguished from a foreground of rougly 1 event per square degree and year, as shown in Figure 2. We model the search as a simple counting experiment, and score the median significance of the excess above background in each bin with a Poisson test statistic,

$$-2\Delta \ln L = -2 \sum \left[(n_s + n_b) \ln \frac{n_s + n_b}{n_b} - n_s \right], \tag{1}$$

where n_b is the average number of background events, n_s the average number of signal events, and the sum runs over angular bins centered on each source candidate. The background is integrated over the uncertainty on the explosion date, given by the survey cadence. The sensitivity of such a search is thus a balance between sky coverage (to detect the largest number of candidate sources) and cadence (to avoid picking up too much background).

We assume that a single exposure and readout will take 45 seconds, and that there will be an average of 6 clear hours per night, 40% of which will be available for the private survey. With 2 epochs per band and field, this means that 2256 square degrees can be surveyed each night, or the entire Northern sky every 9 nights. Figure 3 shows the median significance of the neutrino excess in the directions of detected supernovae as a function of depth for each of 10 equal-area declination bands. The search nearly reaches

[1] `http://gcn.gsfc.nasa.gov/`



(a) Averaged by declination band

(b) Near a point source

Figure 2: Neutrino event rates in IceCube. The effective area of the detector is largest at 0° declination, and decreases towards the North Pole. The atmospheric neutrino background is nearly isotropic, while the rate from a genuine point source is concentrated at one point in the sky (50% $< 0.5°$ from the source).

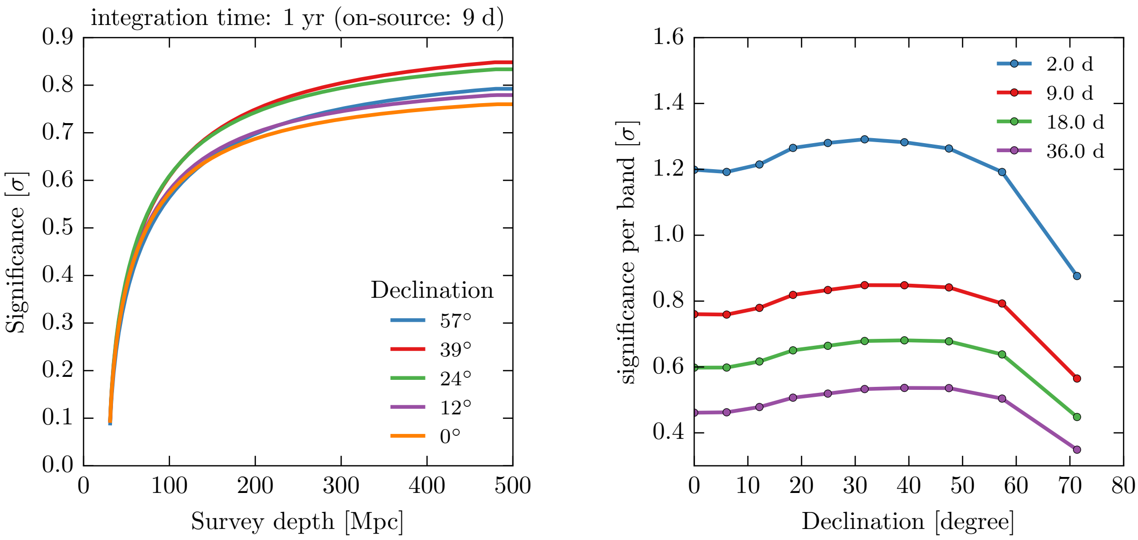
its asymptotic sensitivity at the limiting depth of the survey; going deeper would add more background than additional signal. The largest contribution to the significance comes from small declinations. This gives us a natural way to prioritize fields. If a full-hemisphere survey can not be performed with a ~10 day cadence, then the most weight should be given to areas at middle declinations and near the equator, as illustrated in Figure 4.

A 10 day cadence may also be too long to be useful for all consumers. To survey most of the Northern sky every two nights, for example, the area surveyed per night would have to be quadrupled. This can be accomplished by any three of:

1. Using the public survey to augment the private survey (i.e. assuming that 80% of good observing time will be available for the total survey)
2. Taking only one epoch per field instead of two
3. Using only one filter per epoch

With 9024 square degrees surveyed per night, the Northern sky up to 63 degrees declination can be surveyed every two nights, or up to 25 degrees every night. As in other cases, the larger area is preferable for this kind of correlation study.

A near real-time correlation of ZTF transients with IceCube neutrinos could help to identify potentially interesting candidates and therefore help to preselect candidates for spectroscopic follow-up. We expect roughly 160 neutrinos per day in the Northern hemisphere with an angular resolution of 1 square degree. Per square degree we expect on average 2.0 CCSNe with distance $z < 0.08$ and 4.7 Type Ia SNe detectable at 20.5 mag (corresponding to a redshift of 0.08 and 0.16, assuming a peak magnitude of -17 and -19 respectively). We are only interested in sources which rise starting at the neutrino arrival time. We assume that this requirement reduces the number of CCSNe by $\Delta T/365$ assuming an uncertainty of the explosing time of $\Delta T = 5$ days. This results in roughly 6 supernovae per night lining up with a neutrino event by chance in the entire Northern hemisphere. Assuming that 1/3 of the Northern sky will be surveyed we expect to select 2 sources per night for spectroscopic follow-up.



(a) By catalog depth

(b) By declination

Figure 3: Significance of neutrino excess in the directions of detected supernovae after 1 year, assuming a cadence (and thus per-source integration time) of 9 days. The right panel shows how the maximum-depth contribution from each band contributes as the cadence is reduced. The estimate of the explosion time becomes more accurate with increased cadence.

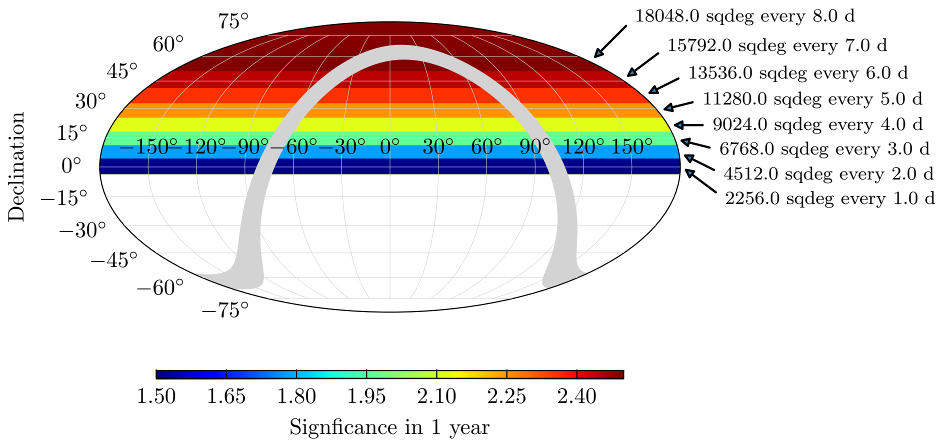


Figure 4: Different survey strategies given a total area of 2256 square degrees per night. Each band shows the area to be surveyed, with the color denoting the significance of high-energy neutrino emission from SNIbc detected in that band. The best significance is obtained by surveying all but the northernmost 10% of the sky every 8 days.

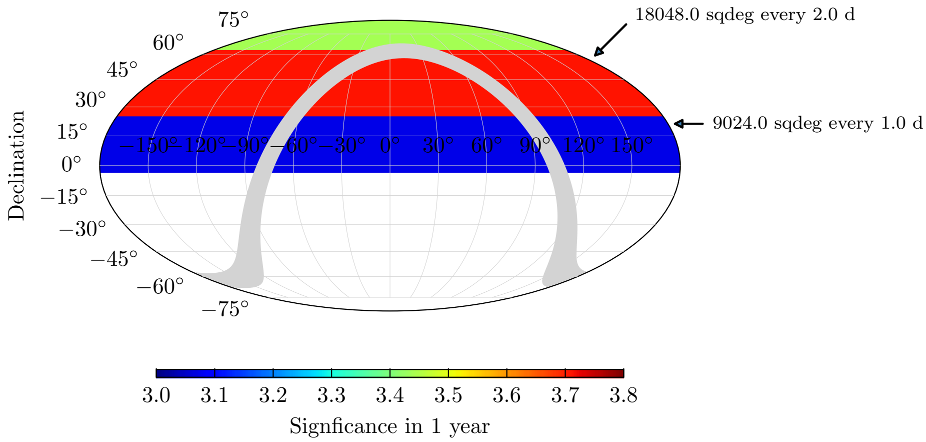


Figure 5: Different survey strategies given a total area of 9024 square degrees per night. The best significance is obtained by surveying all but the northernmost 10% of the sky every 2 days.

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