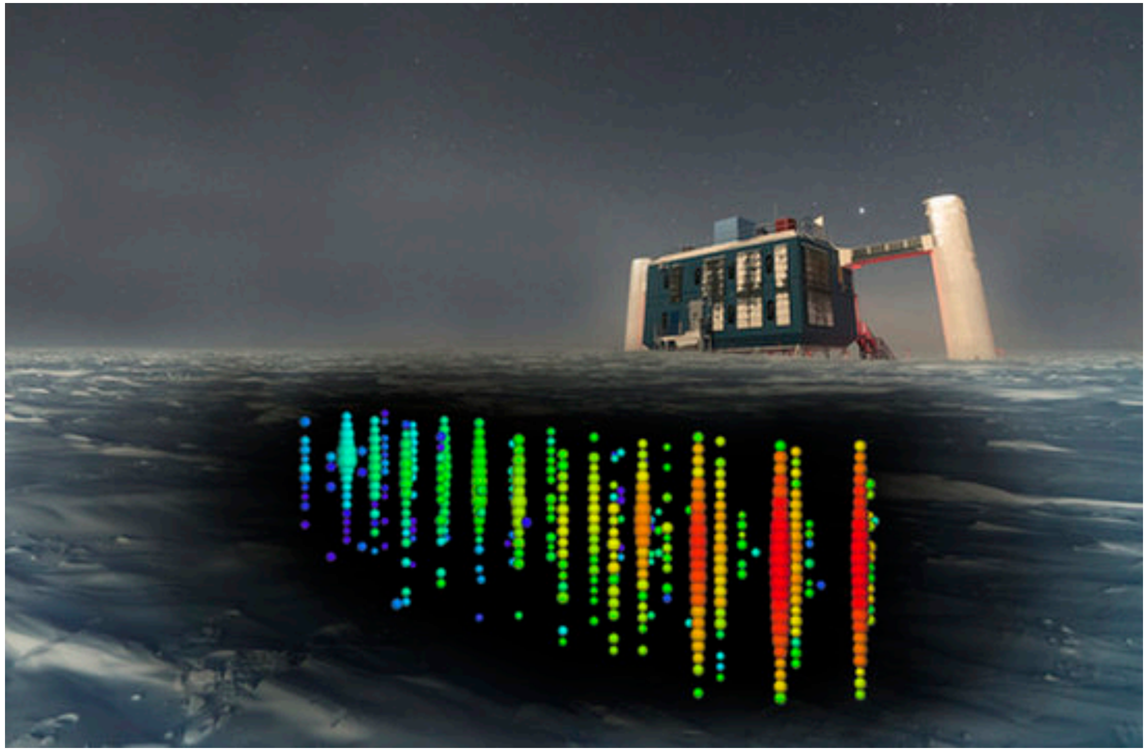
IceCube Follow-up by the Dark Energy Survey

A DECam Search for Explosive Optical Transients Associated with IceCube Neutrinos



Robert Morgan on behalf of the DES Collaboration

arXiv: 1907.07193, Submitted to ApJ

With Keith Bechtol, Rick Kessler, Masao Sako, Zoheyr Doctor, Dan Scolnic, Nacho Sevilla-Noarbe, Marcelle Soares-Santos, Ken Herner, Alyssa Garcia, Antonella Palmese, Dillon Brout, Francisco Paz-Chinchon and Eric Neilsen (from the DES Collaboration); and Naoko Kurahashi Neilson, Marek Kowalski, and Anna Franckowiak (from the IceCube Collaboration)

LSSTC DATA SCIENCE FELLOWSHIP PROGRAM

THE UNIVERSITY of WISCONSIN MADISON

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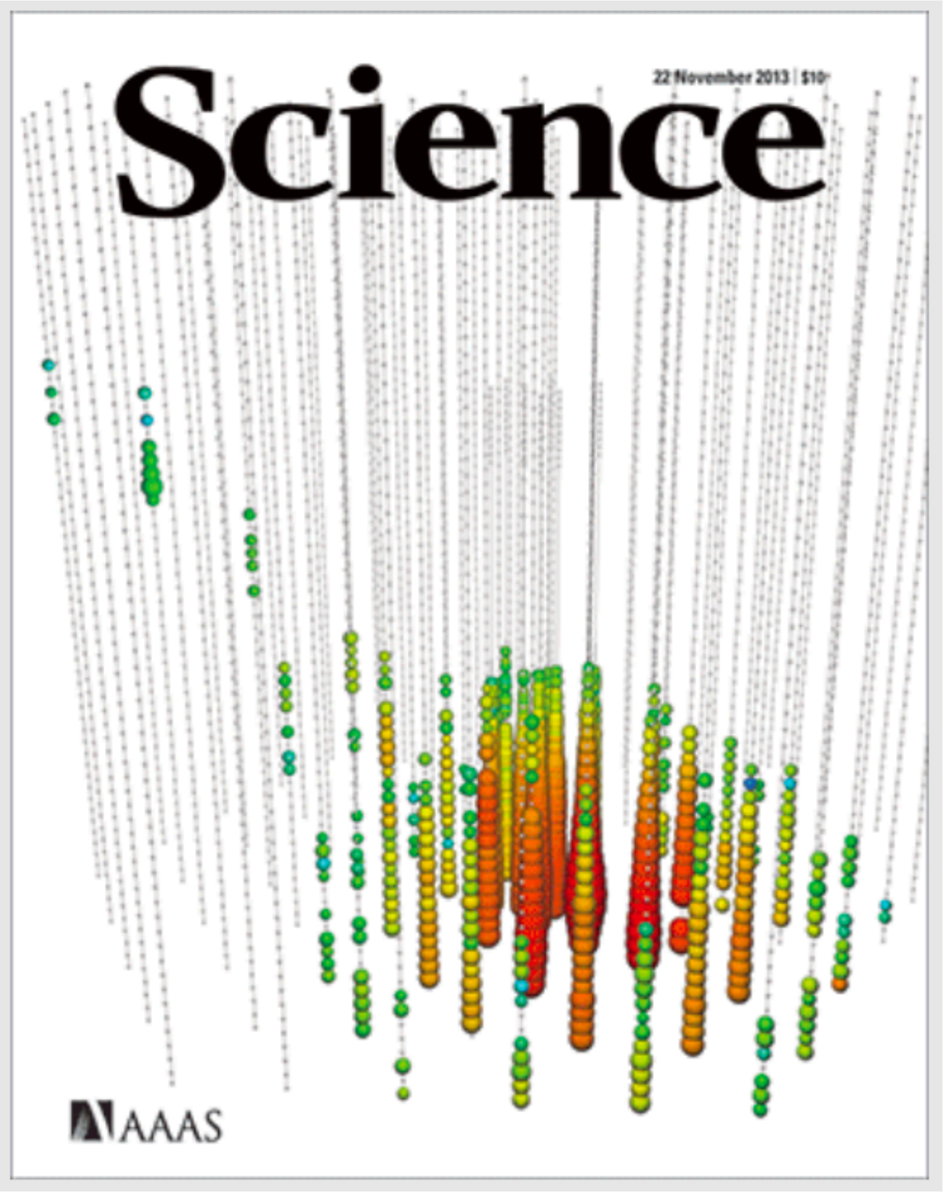
IceCube discovers TeV-Pev neutrinos

- Article: The IceCube Collaboration 2013
- Nearly isotropic neutrino flux
- Not produced in the atmosphere
- Motivated the search for EM counterparts
  - At present, only one out of O(50) high energy neutrinos has convincing evidence for association with an EM counterpart (The IceCube Collaboration et al. 2018)



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Physical Motivations

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IceCube discovers TeV-Pev neutrinos

Current constraints leave a large fraction of the TeV-PeV flux unexplained

Source Class	Maximum Contribution	Reference
Gamma Ray Bursts	1%	Aartsen et al. 2015
Gamma Ray Blazars	19 % - 27 %	Aartsen et al. 2017
Star Forming Galaxies	~30 %	Bechtol et al. 2017

arXiv: 1907.07193

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IceCube discovers TeV-Pev neutrinos

Current constraints leave a large fraction of the TeV-PeV flux unexplained

Several analyses suggest core-collapse supernovae (CC SNe)

- Physical mechanism: A choked relativistic jet during the collapse
- Hadrons accelerated by the jet could produce prompt TeV-PeV neutrino emission
- Associated gamma signal is expected to be blocked by the stellar material
  - Razzaque et al. 2004, Ando & Beacom 2005, Woosley & Janka 2006, Murase & Ioka 2013, among many others

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IceCube discovers TeV-Pev neutrinos

Current constraints leave a large fraction of the TeV-PeV flux unexplained

Several analyses suggest core-collapse supernovae (CC SNe)

This situation has motivated several optical follow-ups

- Some recent papers from the most active collaborations
  - Pan-STARRS1: Kankare et al. 2019
  - MASTER: Aartsen et al. 2017
  - ROTSE and PTF: Aartsen et al. 2015

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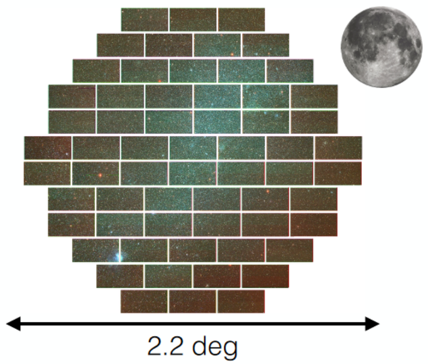
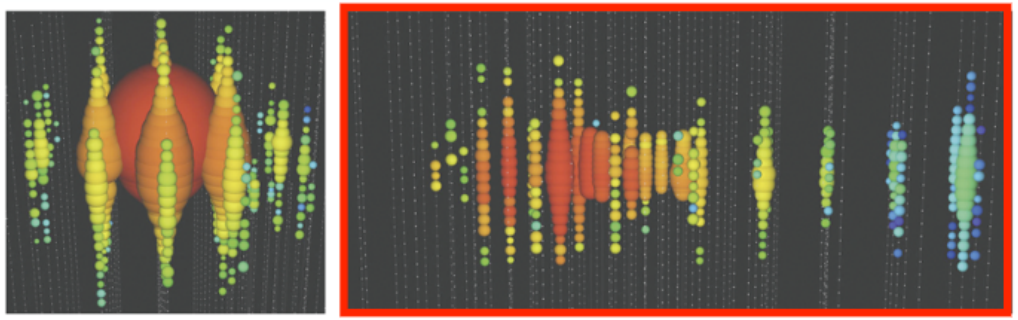
DECam and IceCube:

The best match for optical southern hemisphere neutrino multimessenger studies



Cascade | **Track**

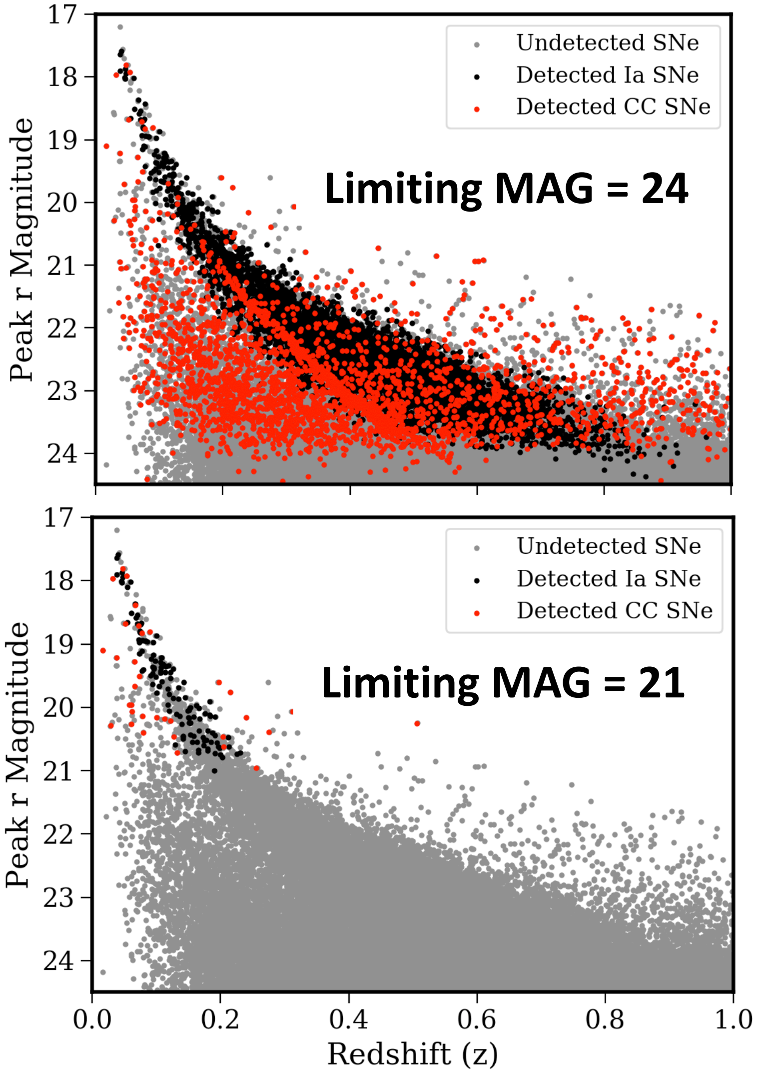


IceCube, arXiv:1406.6757

Angular Resolution

Cascade	Track
~15 deg	~1 deg @ 1 TeV ~0.4 deg @ 100 TeV

Field of view size and imaging depth make DECam the ideal instrument for optical IceCube follow-up in the southern hemisphere



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DECam Cadence

Candidate Selection

DECam Follow-Ups

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DECam Cadence

- Triggered observations for ~6 epochs spread over 2-3 weeks after an alert
- 2 x 150 second exposures in *gri*
- Half-chip dither to fill in CCD gaps
- 5σ limiting magnitude *g*,*r*,*i* = 23.6, 23.7, 23.3 mag
- Process images with DES Difference Imaging Pipeline
  - Reference: Kessler et al. 2015

arXiv: 1907.07193

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DECam Cadence

Candidate Selection

- Largest expected contaminants:
  - Noise, AGN / QSO, Asteroids, Type Ia SNe, Unassociated CC SNe
- Cuts on data
  - Optical quality and detectability
  - Increasing brightness
  - Light curve fitting for the date of peak brightness
  - Random forest classification for CC versus Ia
  - Catalog lookup to exclude AGN / QSO

arXiv: 1907.07193

Observations

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DECam Cadence

Candidate Selection

DECam Follow-Ups

- Two alerts with completed analysis
  - IC170922A (GCN) and IC171106A (GCN)
  - 1 candidate passed selection for each follow-up

arXiv: 1907.07193

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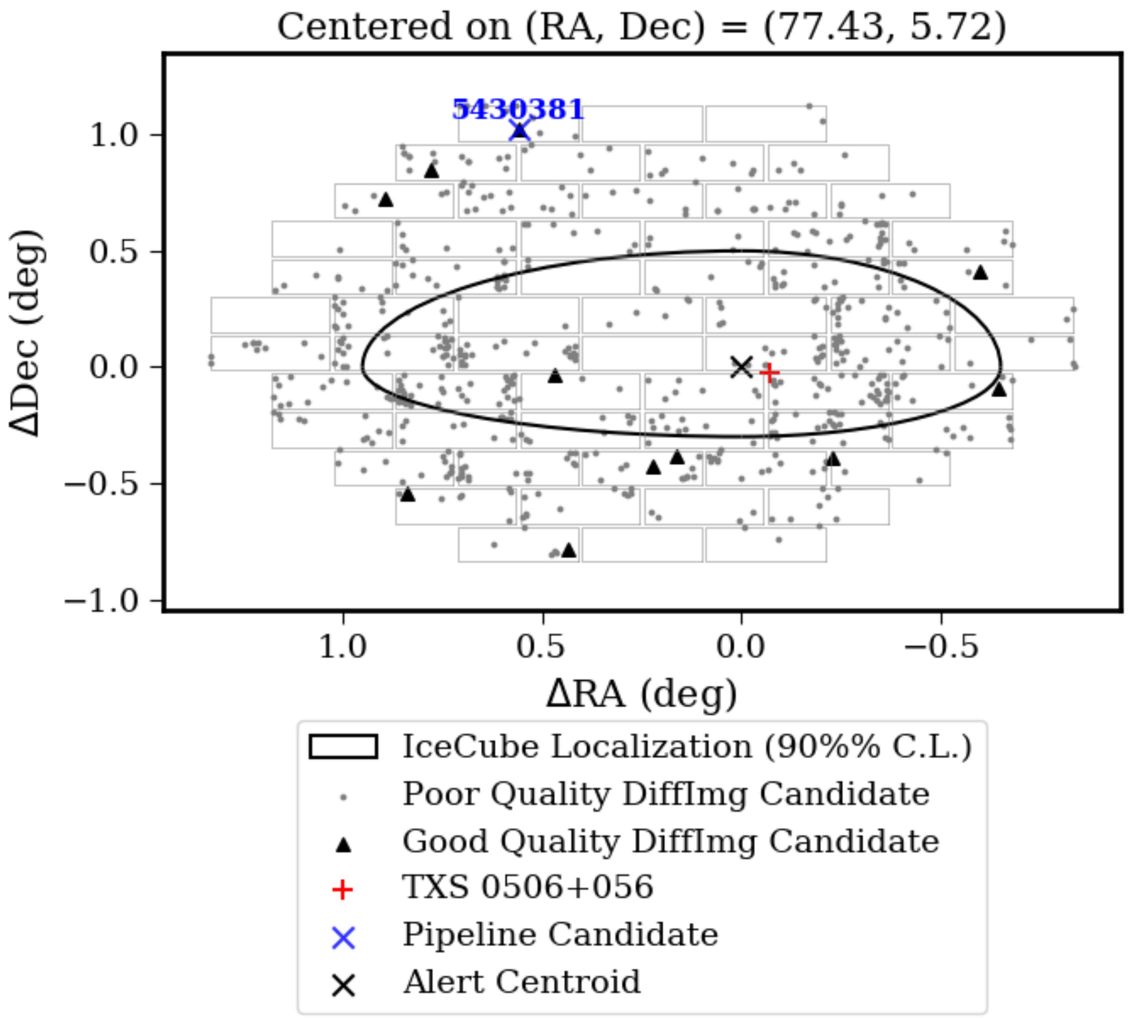
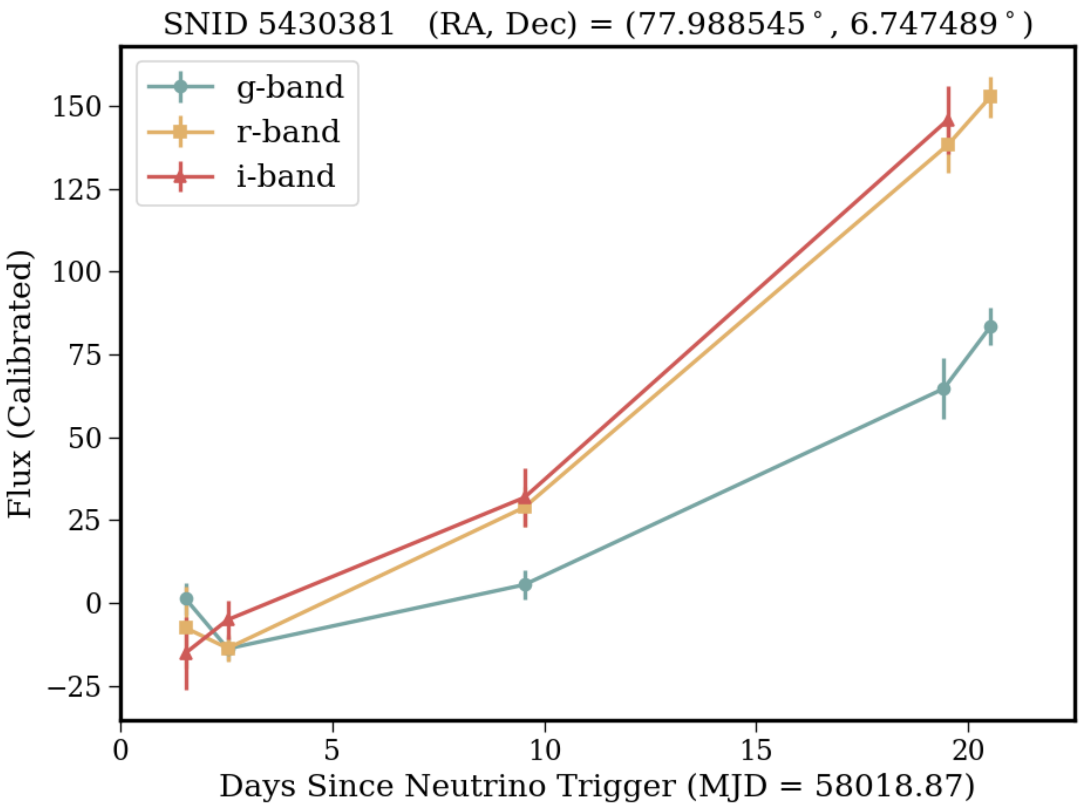
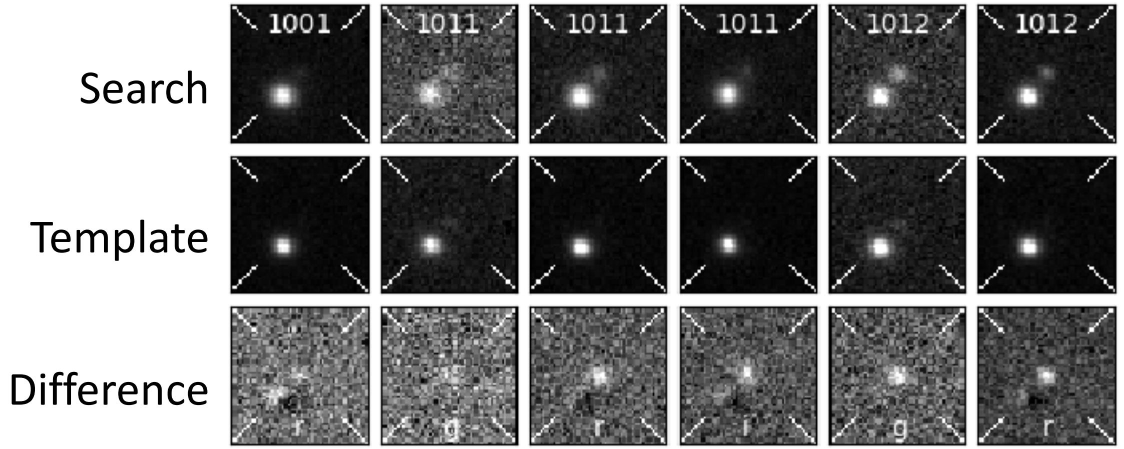
DES-5430381

(g, r, i) mag = (22.7, 22.0, 22.1)







Candidate for IC171106A

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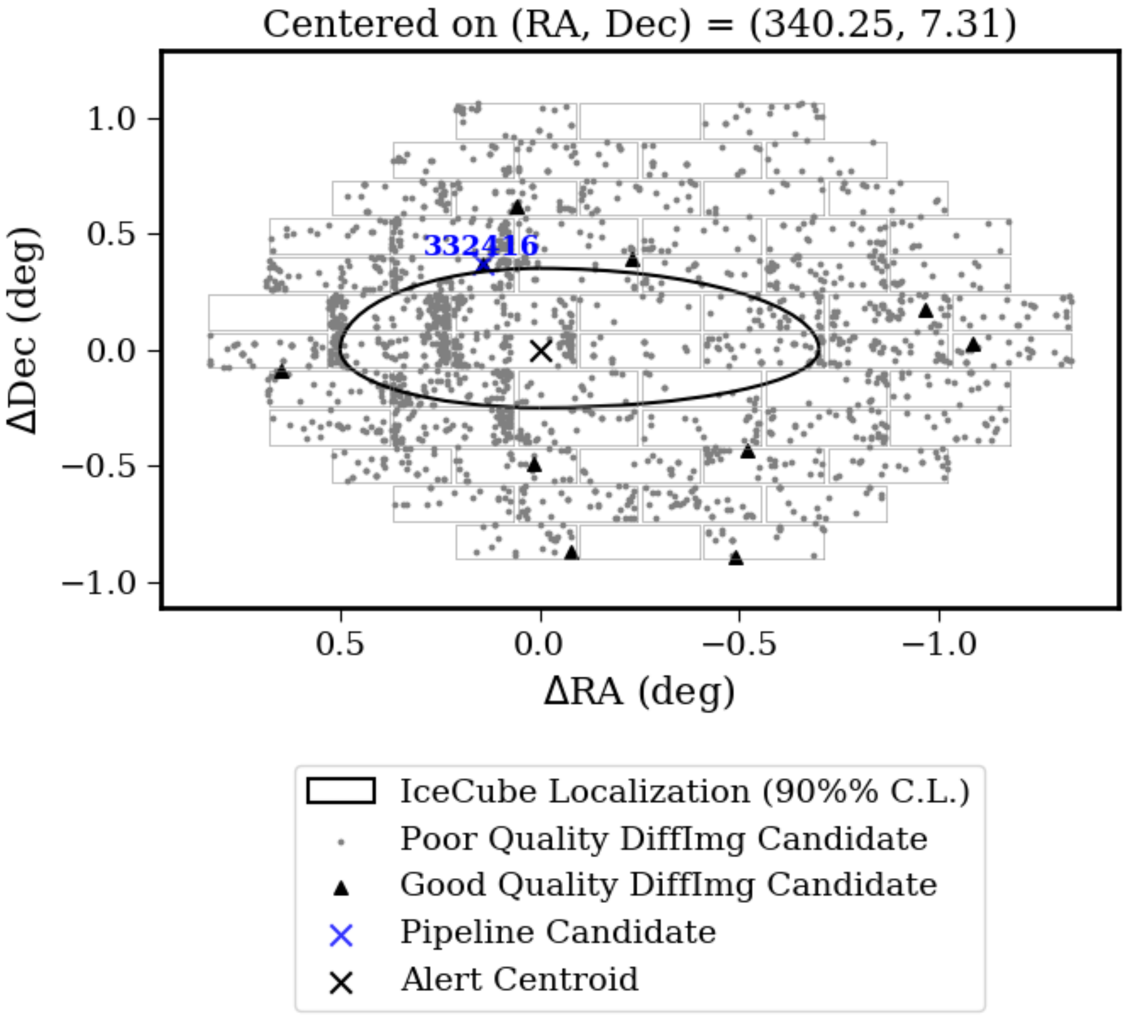
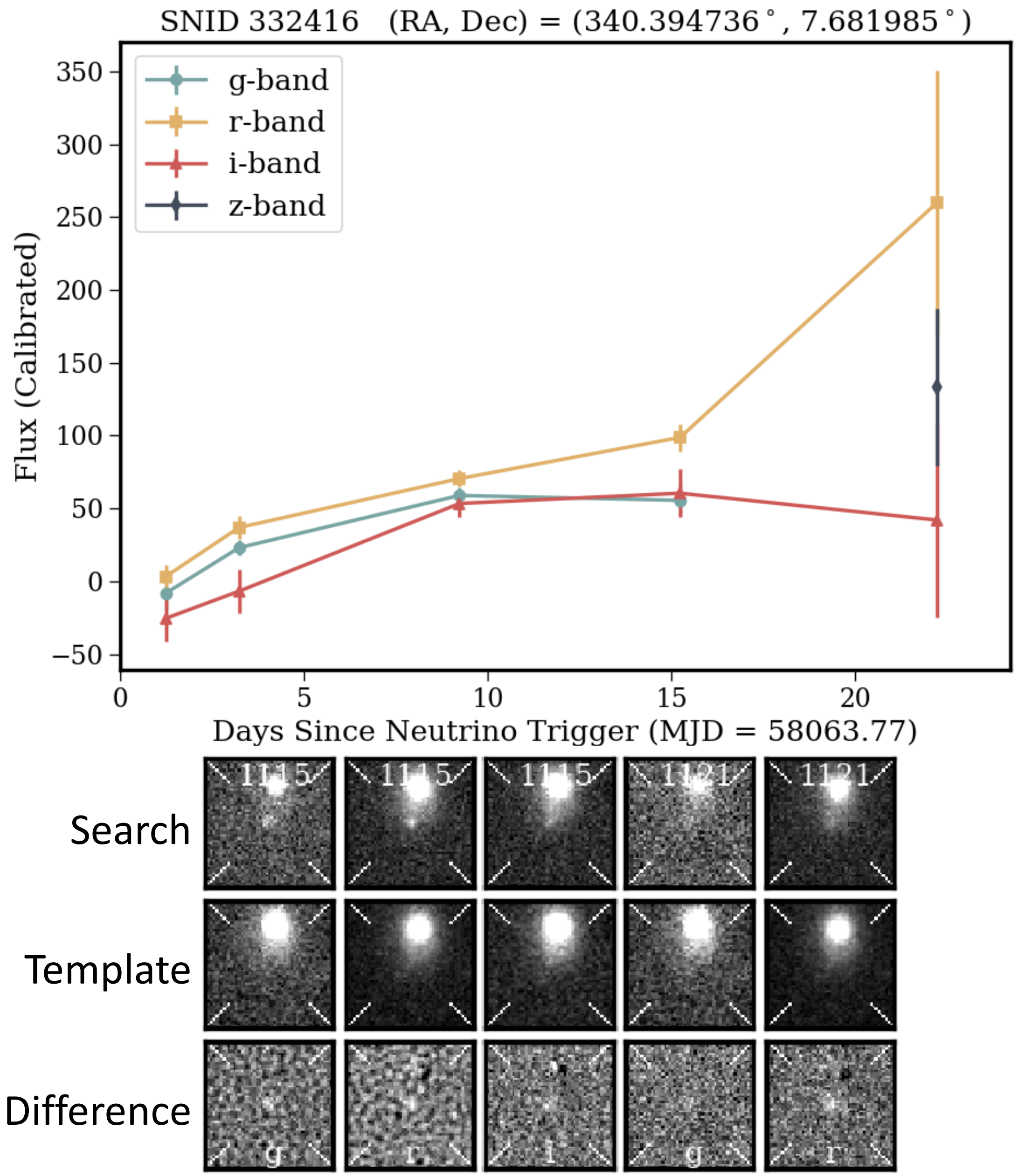
DES-332416

(g, r, i, z) mag = (23.1, 21.5, 23.4, 22.2)





Simulation Components

- SNe light curves simulated in SNANA (Kessler et al. 2009)
- Signal sample:
  - CC SNe with explosion time set to date of neutrino trigger
- Background sample:
  - Type Ia SNe and CC SNe with PeakMJD in [Trigger – 30 days, Trigger + 100 days]
    - Type Ia rate from Dilday et al. 2008
    - CC SNe rate from Bernstein et al. 2012

Procedure: Apply selection criteria to simulations and quantify the expected numbers of signal and background events as functions of redshift

arXiv: 1907.07193

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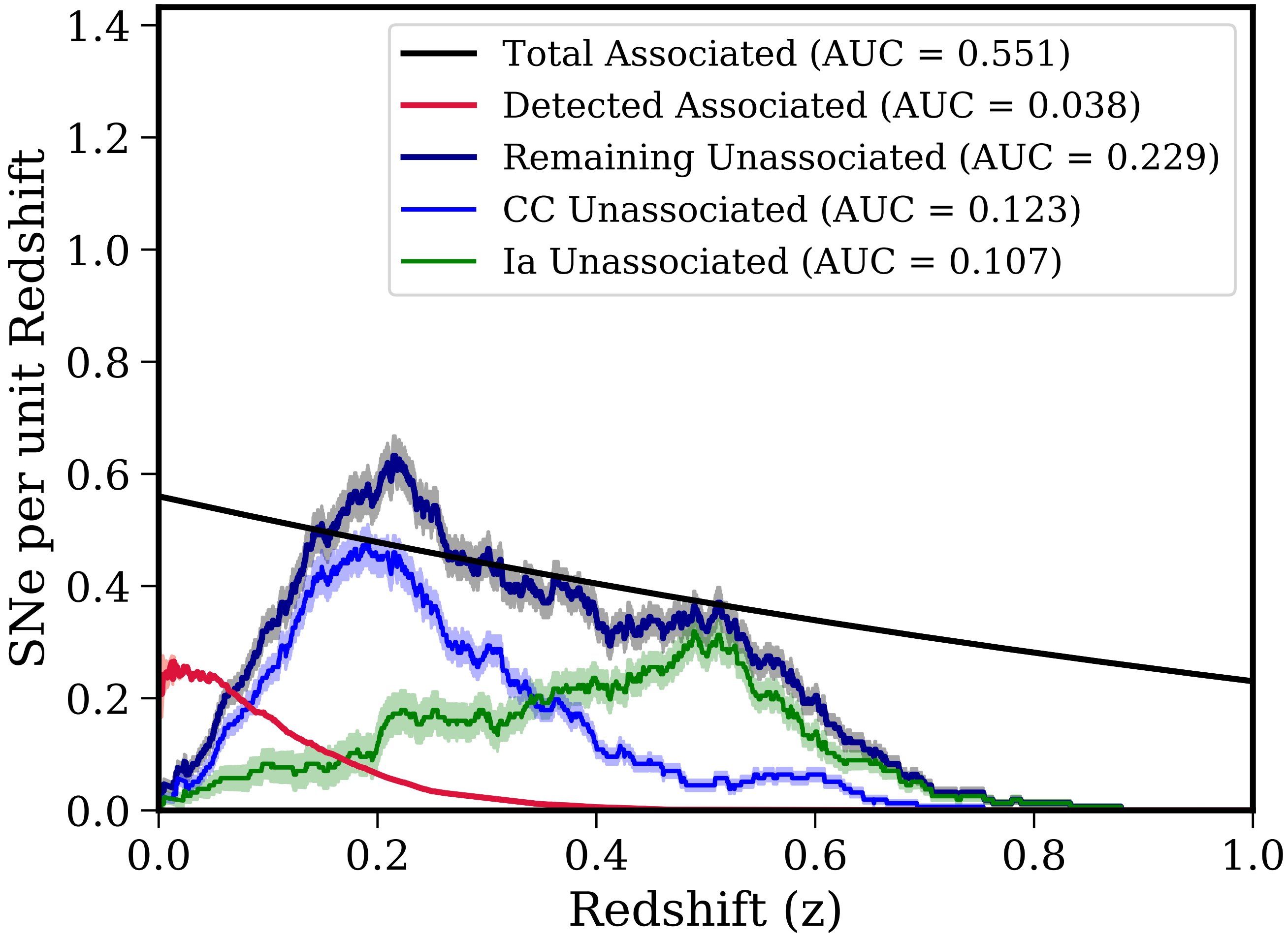
Simulations show a large unremovable SNe background and comparatively low detectable signal

- Very unlikely to be able to confidently associate a single SN with a single neutrino
- With repeated observations, one could observe a statistically significant excess of SNe over time



Distributions show the expected SNe per unit redshift within the IceCube 90% confidence region for the IC170922A follow-up

arXiv: 1907.07193

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We perform 1000 realizations of dedicated follow-up campaigns.

Figure: TS distributions of 1000 realizations of the follow-up of 60 IceCube alerts.
The parameter λ represents the true fraction of the IceCube TeV-PeV flux caused by CC SNe

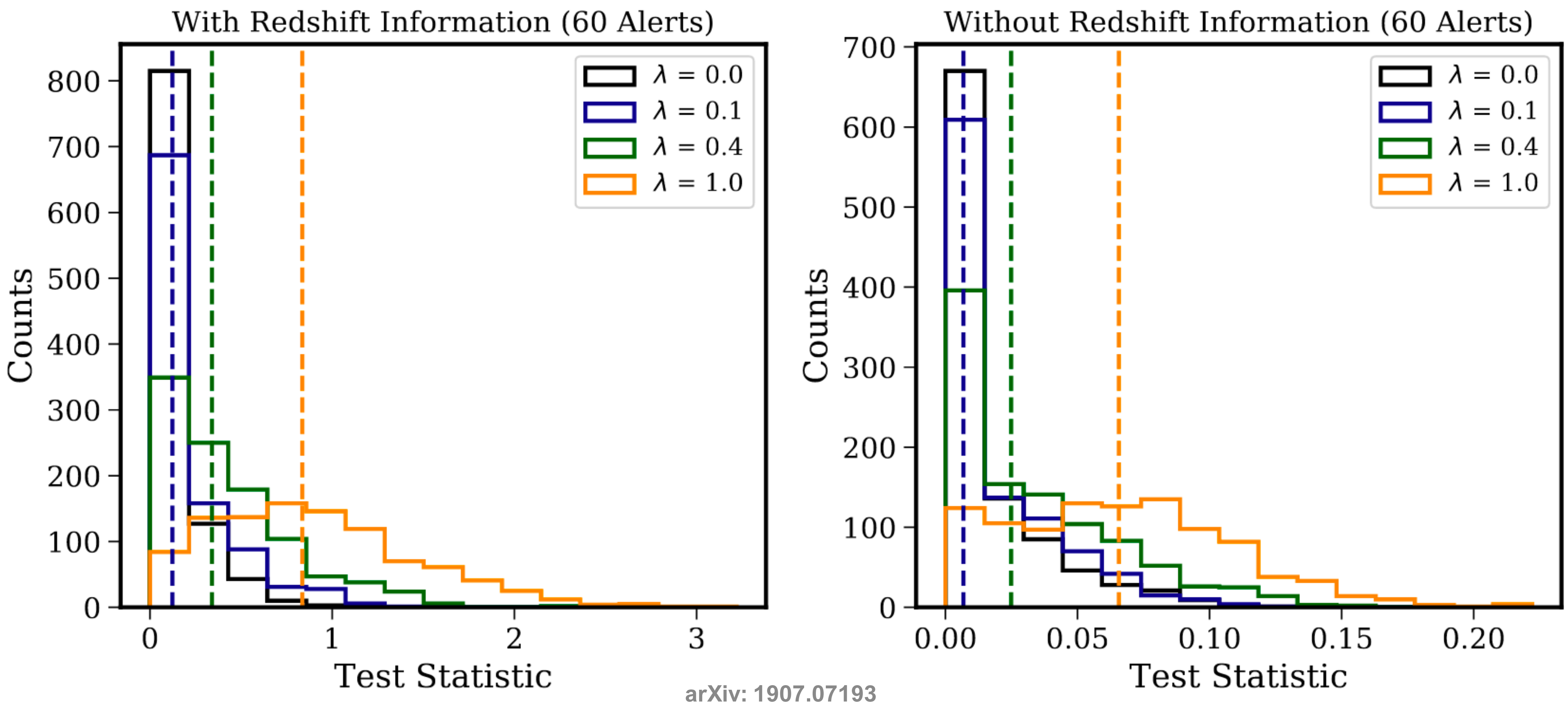

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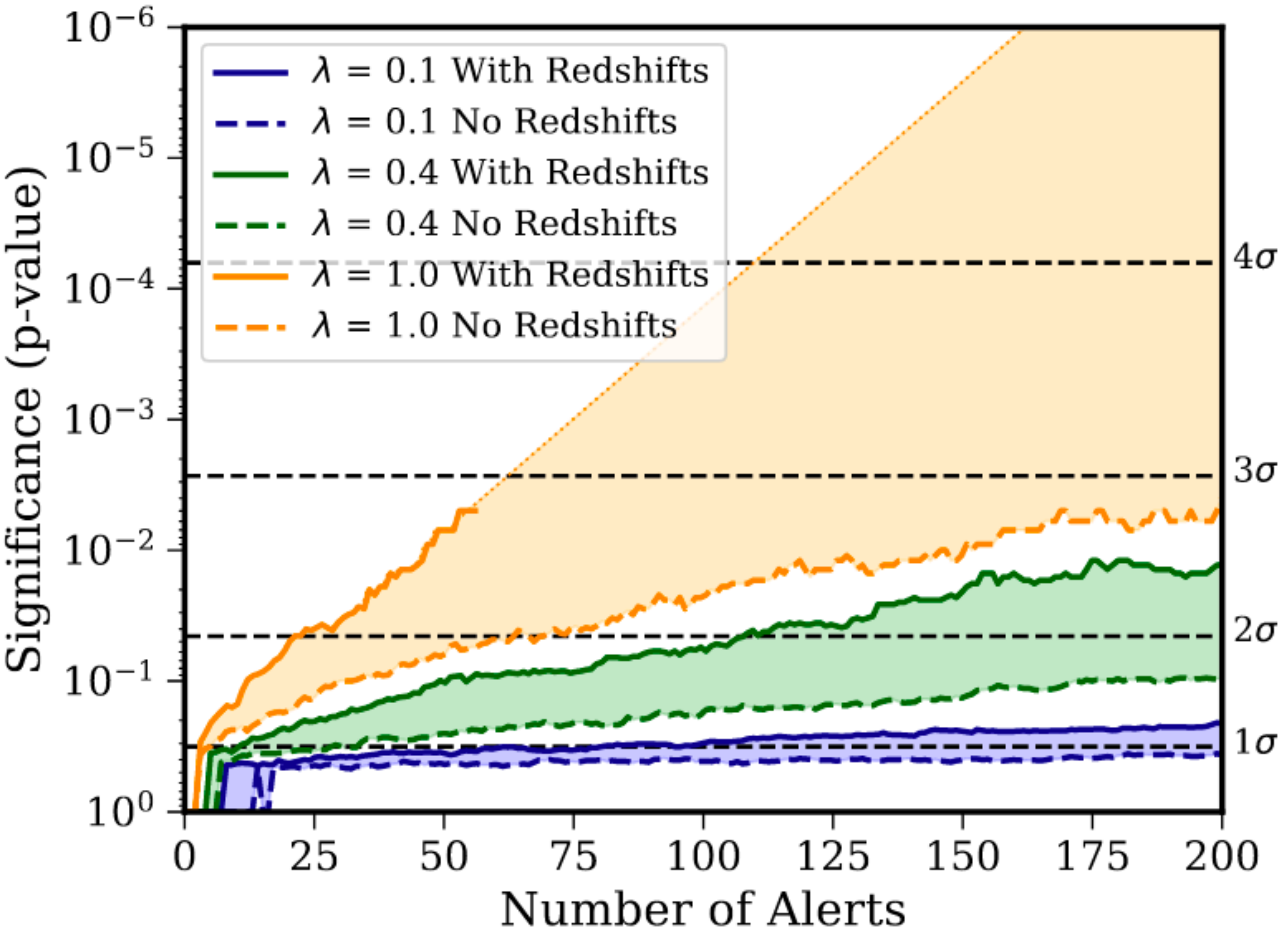
Figure:

Confidence level at which one can claim CC SNe contribute to the TeV-PeV IceCube neutrino flux

Performance depends on:

- Observing conditions
- Availability of redshift information
- Number of alerts targeted
- True fraction of IceCube flux caused by CC SNe (λ)



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Application to Observations

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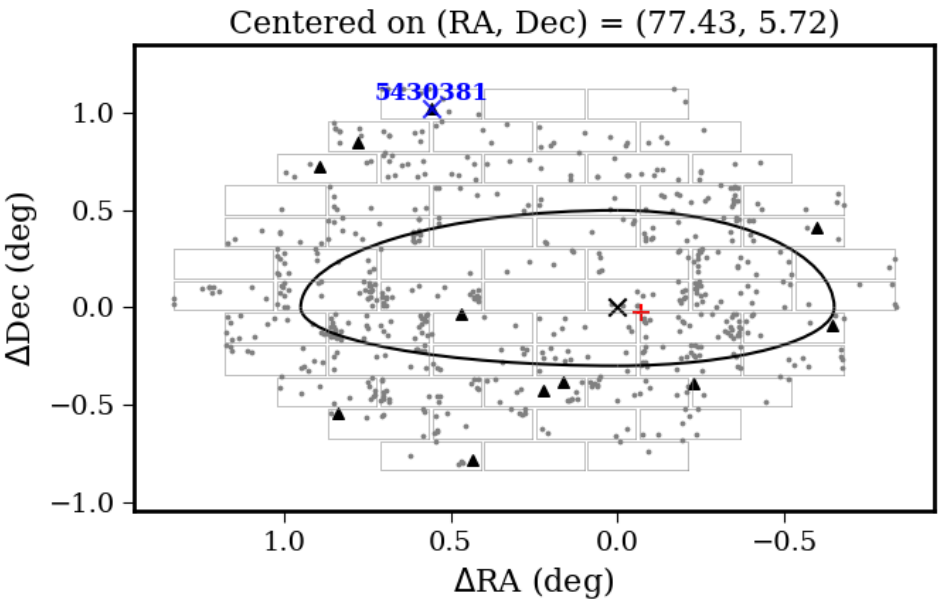
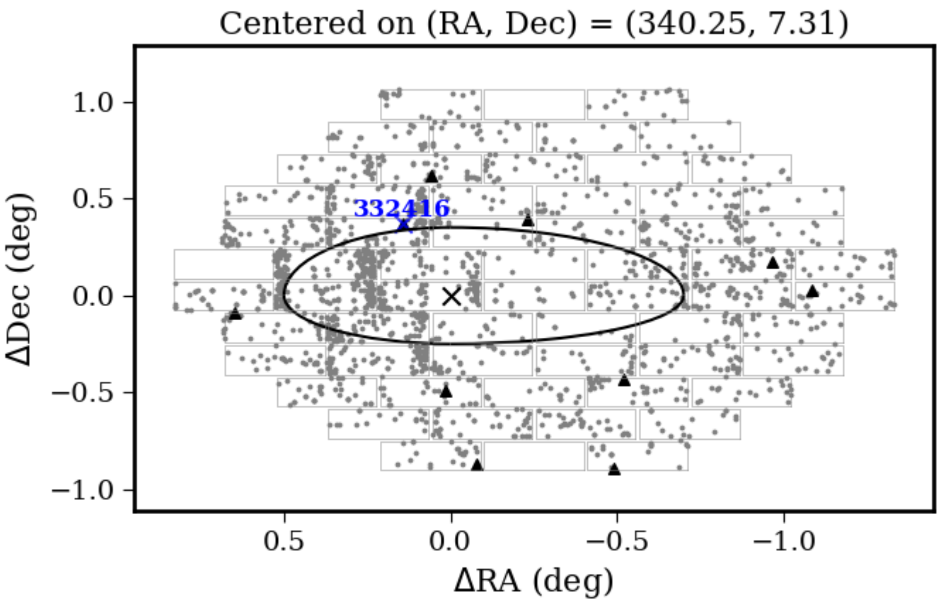
Based on the 1000 realizations of DECam follow-ups, we calculate p-values for the association of each candidate with the corresponding neutrino alert

DES-5430381 and IC170922A:	p-value = 1.00
DES-332416 and IC171106A:	p-value = 0.03
Joint result:	p-value = 0.09

Based on the simulations, we shouldn't expect to be able to make a significant claim after only two follow-ups.





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Components of a Successful Follow-Up Campaign

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Based on our pilot observations, the necessary components of a successful follow-up campaign are:

1. Triggered follow-up
2. Deep imaging
3. Redshift information
4. The follow-up of many alerts

arXiv: 1907.07193

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3. Redshift information
4. The follow-up of many alerts

Looking Forward:

- DECam will likely remain the best instrument for this campaign
  - Deep imaging
  - Fild of view size
  - Availability of triggered observations
- IceCube Gen2
  - Increased neutrino event rate
  - Improved angular resolution
- LSST
  - Host galaxy photo-z measurements

arXiv: 1907.07193

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CC SNe are frequent enough that we expect an unremovable background to be present in optical follow-ups

Obtaining redshifts of candidates / host galaxies helps to reduce backgrounds significantly

If CC SNe make up a significant fraction of the TeV-PeV neutrino flux, it will take dedicated and methodological follow-up of several of IceCube alerts to observe a statistically significant excess of CC SNe.

arXiv: 1907.07193

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Thank you!

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Supplemental Material

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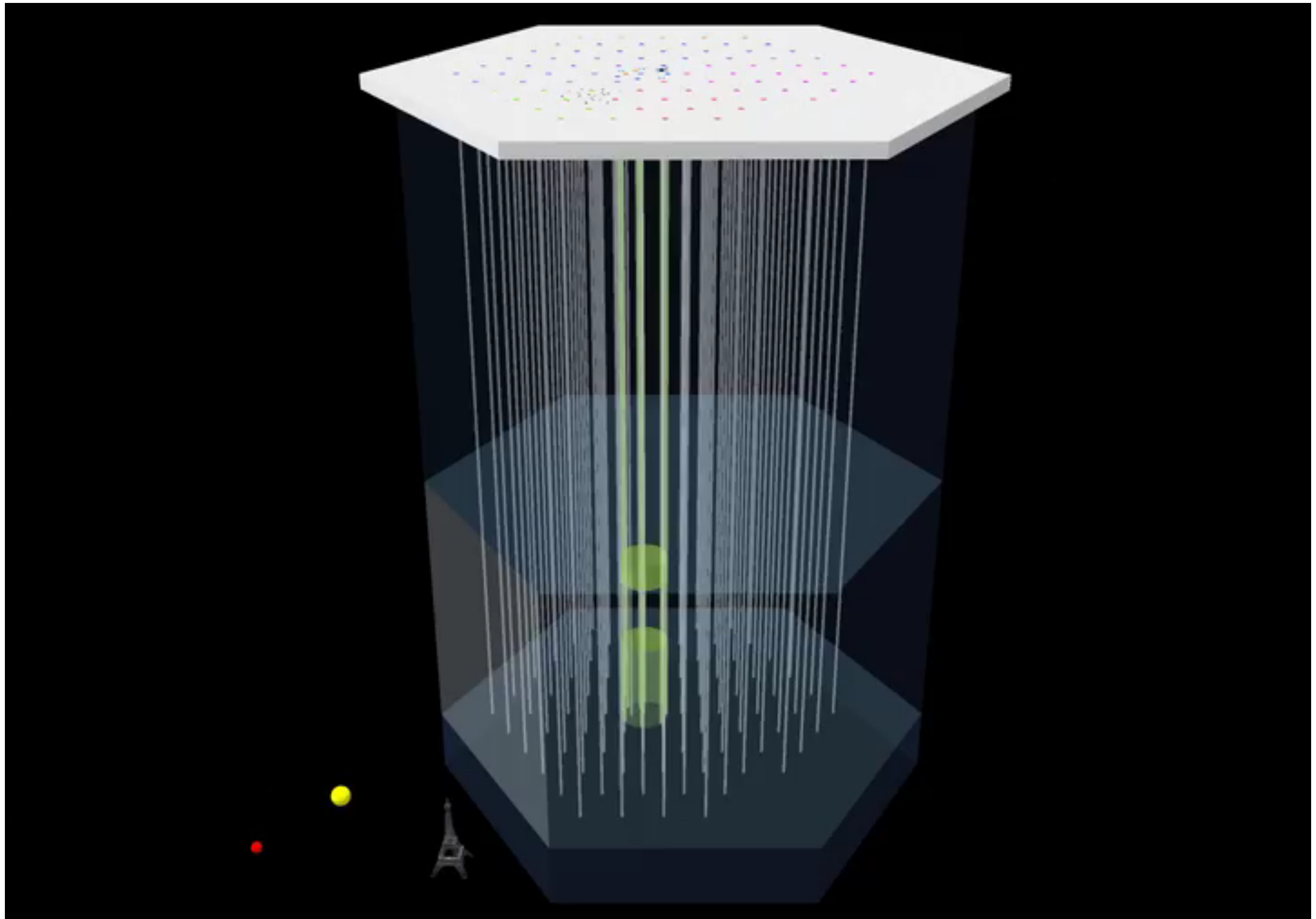
The IceCube Neutrino Observatory

- Cubic km scale detector built into the South Pole ice
- Over 5000 optical modules to detect Cherenkov radiation
- Event reconstruction
- Realtime alert system


The IceCube Collaboration

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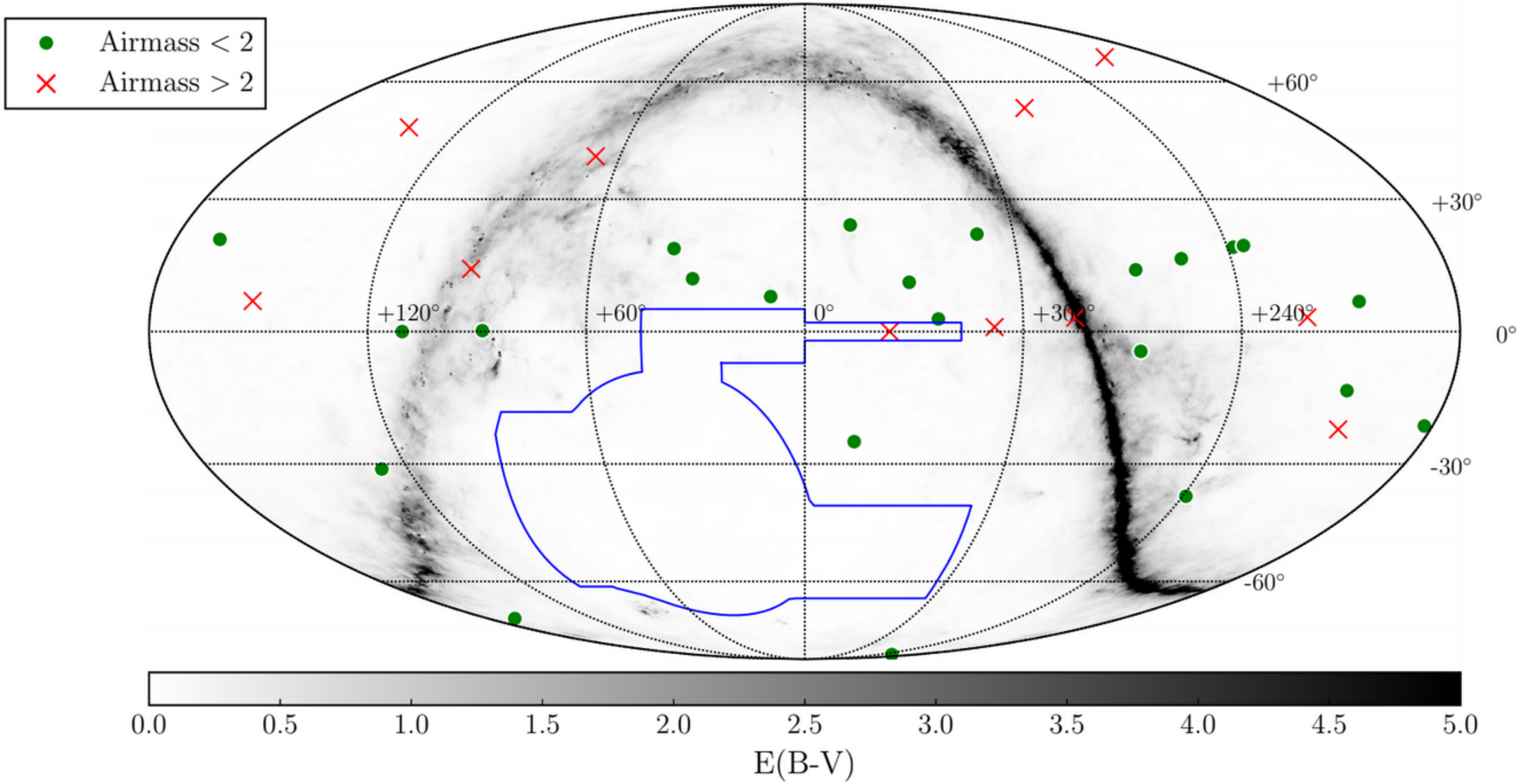

Figure: Population of the best-localized high energy neutrino track events detected by IceCube

Importance of Deep Imaging

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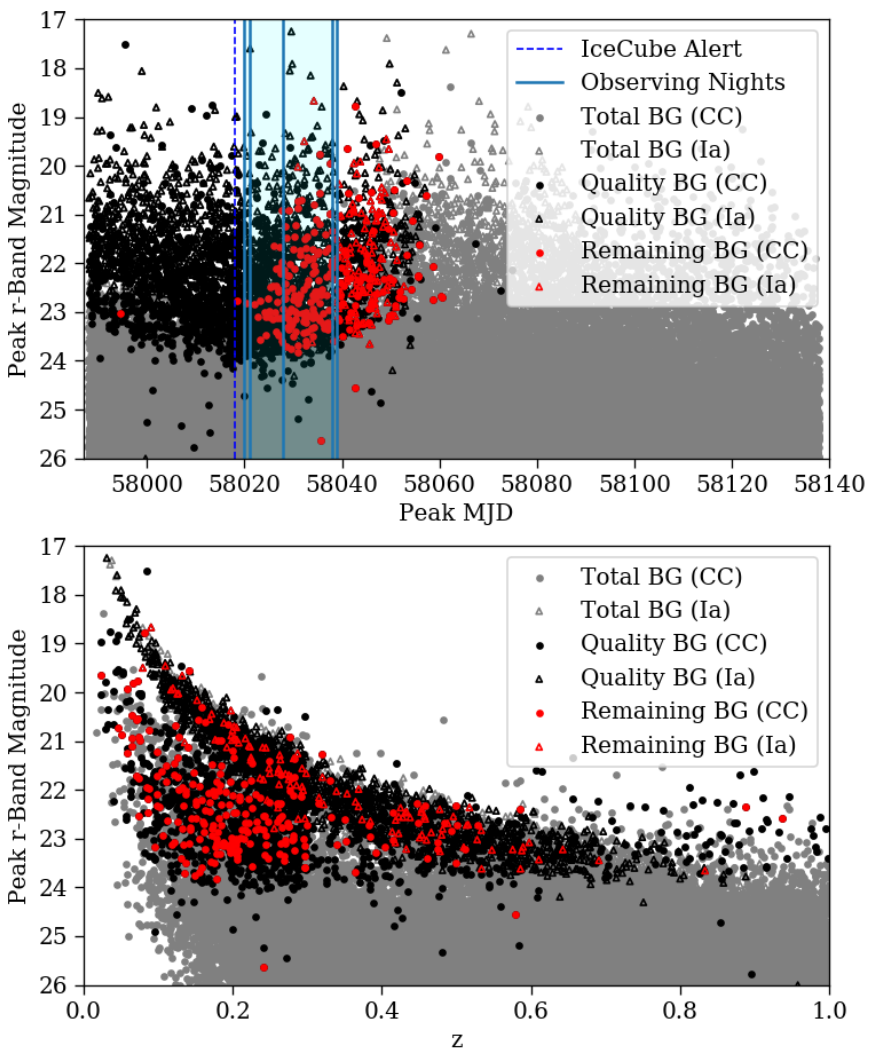
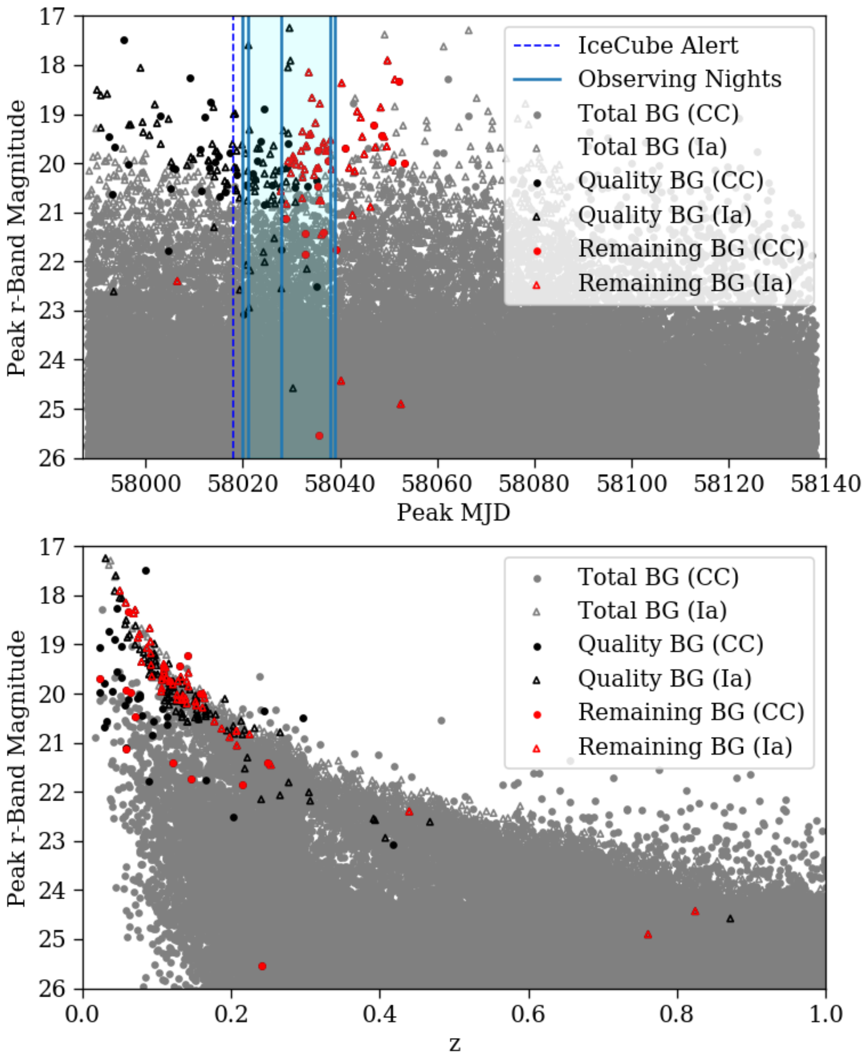


Limiting Magnitude = 24
(DES)



Limiting Magnitude = 21
(Previous Efforts)

Observational Results

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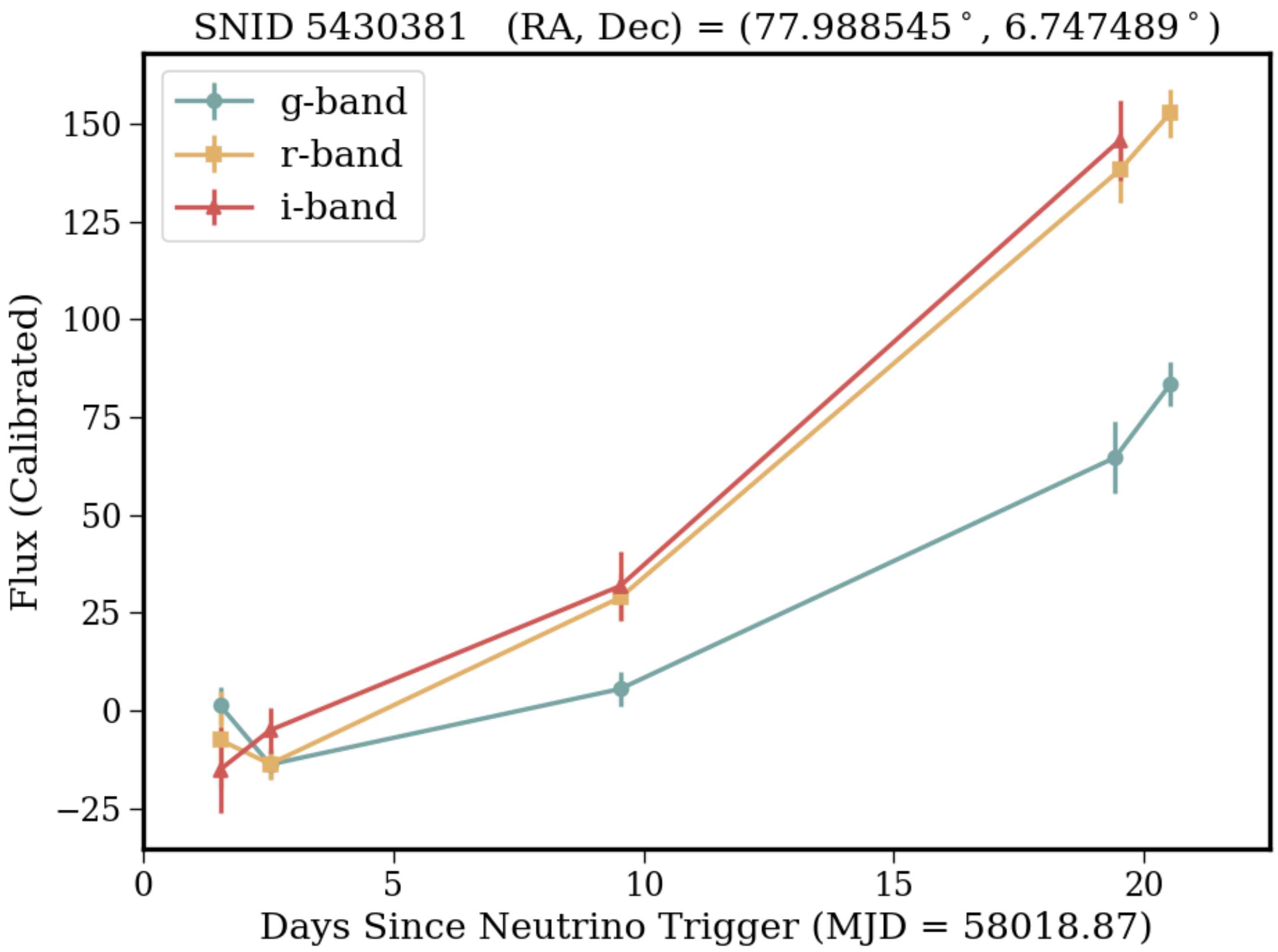

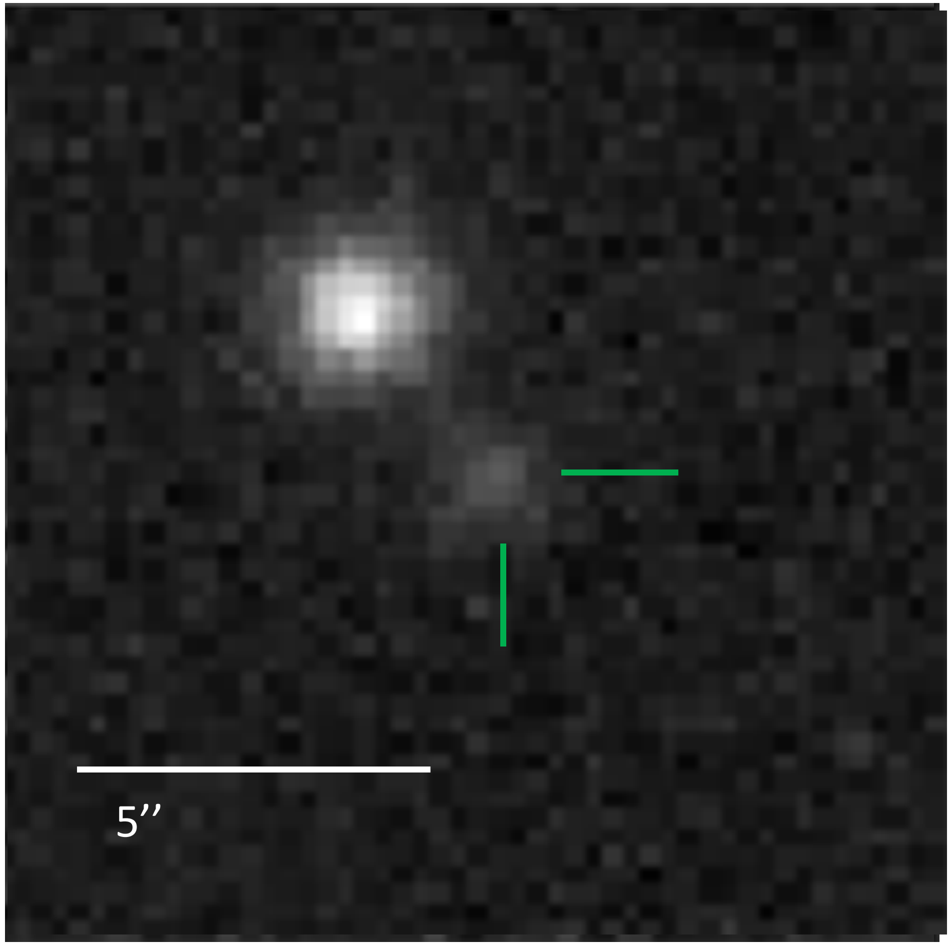

Observational Results Part 2

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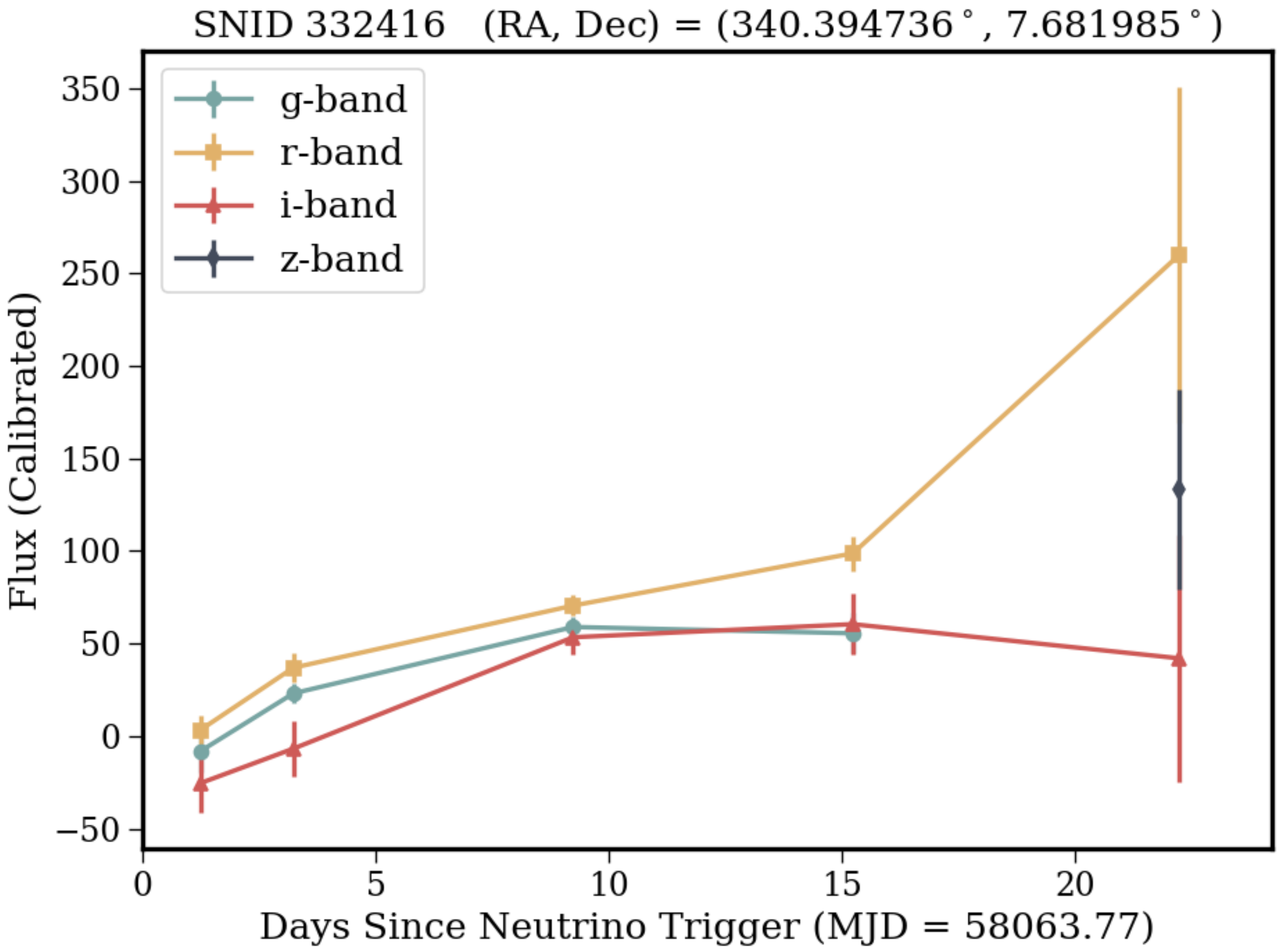

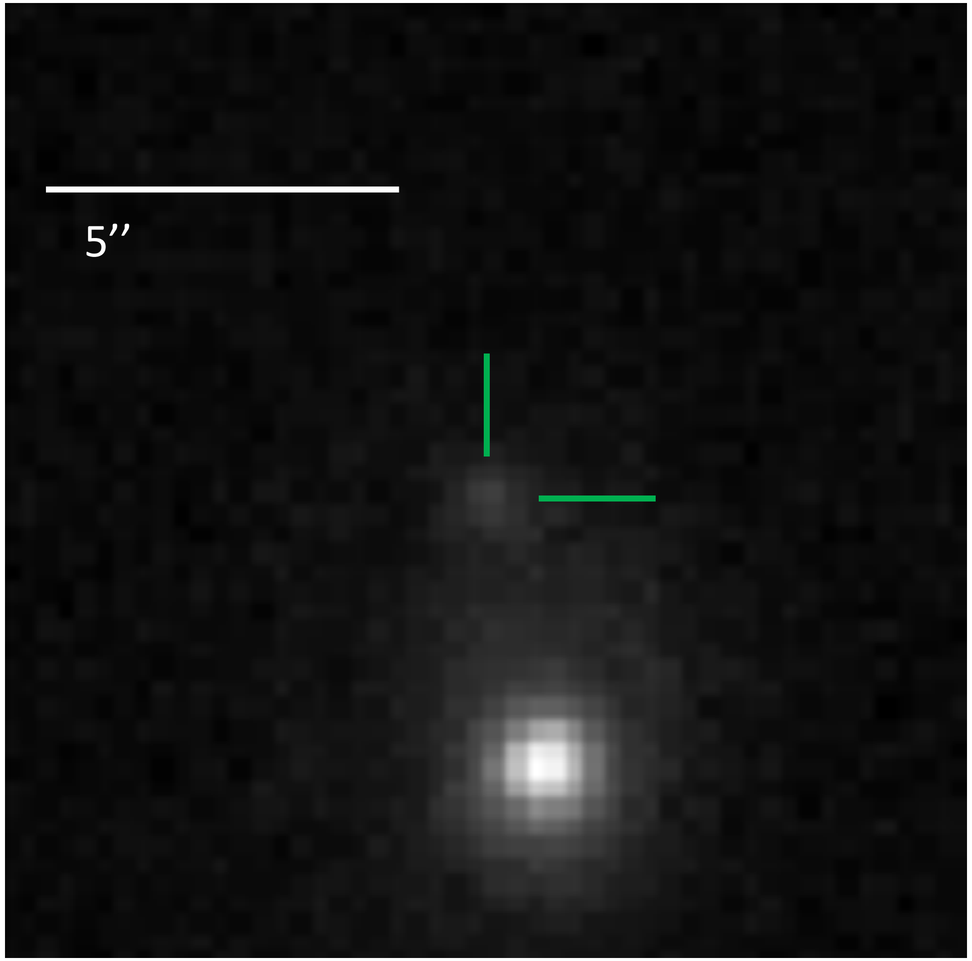

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Signal Sample

CC SNe with the explosion time set to the date of the neutrino trigger

Background Sample

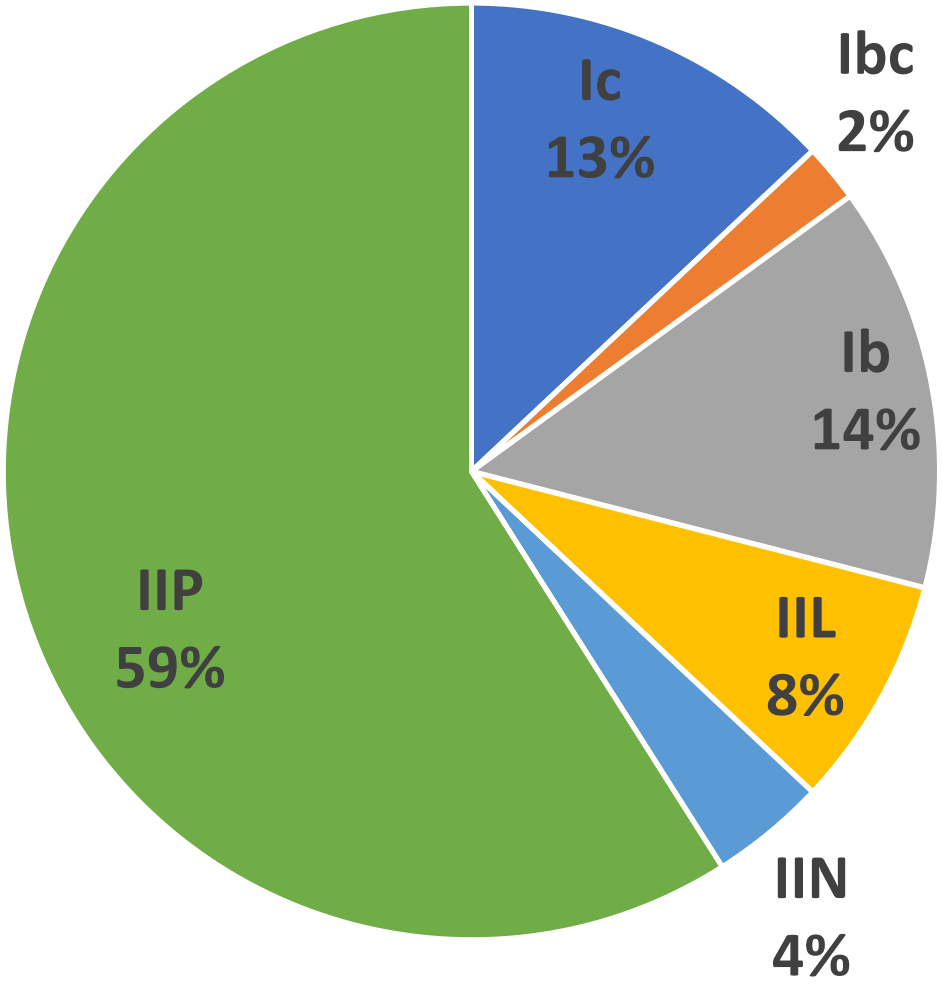
Type-Ia and CC SNe within the range

Trigger – 30 days < PEAKMJD < Trigger + 100

Notes

- Trying to select against Type Ia SNe, out-of-phase CC SNe
- Purposeful inclusion of in-phase CC SNe in background sample

Signal Sample Type Distribution



Candidate Selection

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Selection Criteria Effectiveness on Signal versus Background Samples

Criterion	Description	Signal Efficiency	Background Efficiency
Light Curve Quality	Detected in two separate epochs regardless of filter	19.9 %	16.0 %
Increasing Flux	No detection on first night, or if detected, an increase in flux by at least 1 mag over the first two nights	19.8 %	10.8 %
Best-Fit Peak MJD	PSNID fitting to type-II and type-Ibc templates has best-fit peak MJD 16 and 6 nights after trigger, respectively	17.9 %	5.5 %
Random Forest Classifier	RFC trained on SNANA simulations to select temporally-coincident and low-z CC SNe from background SNe	12.1 %	1.3 %

Efficiencies based on $z < 0.3$ simulations of IC170922A

Sensitivity Analysis

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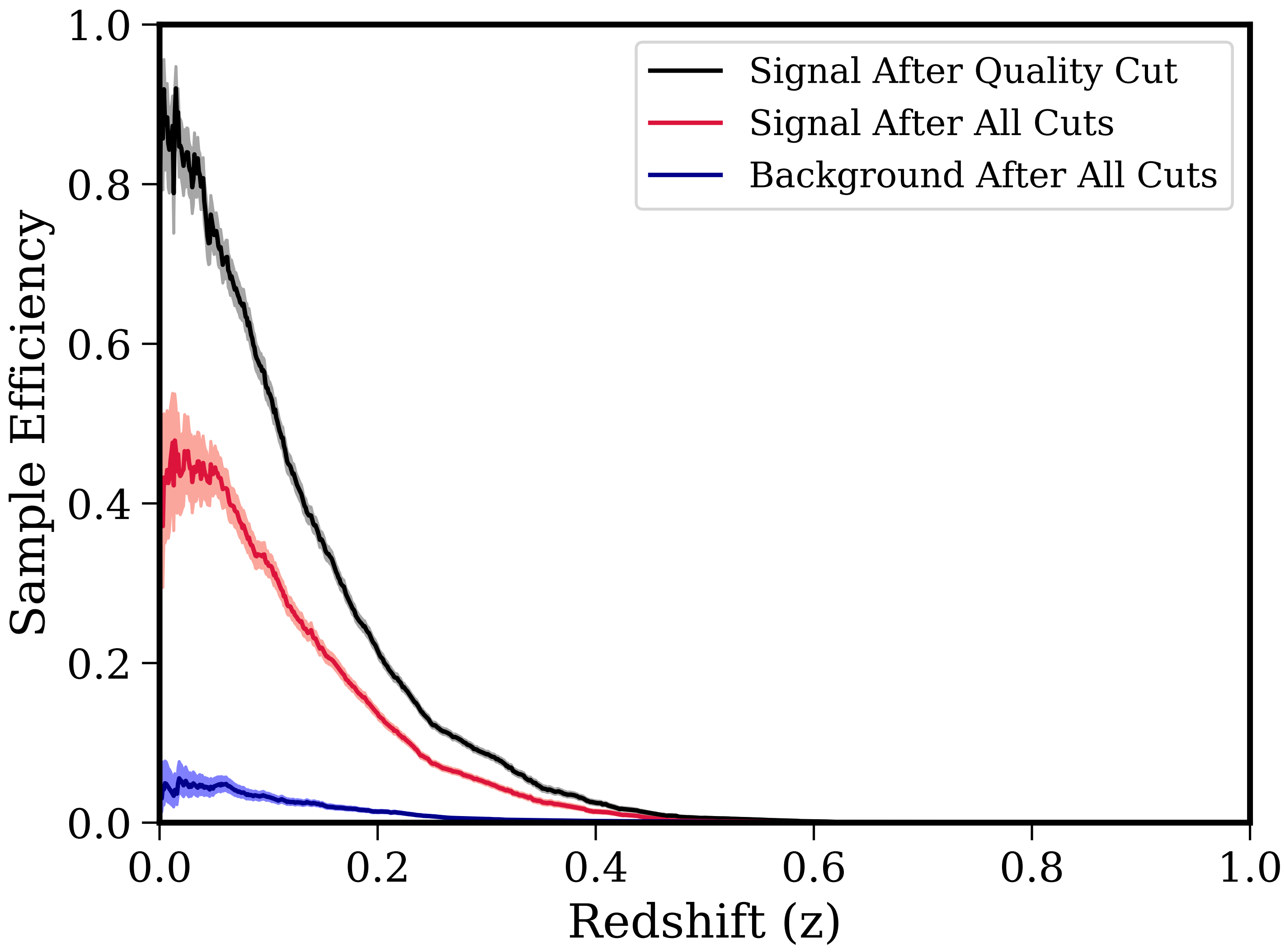

Simulation-Based Sensitivity Analysis

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Signal rate determination:

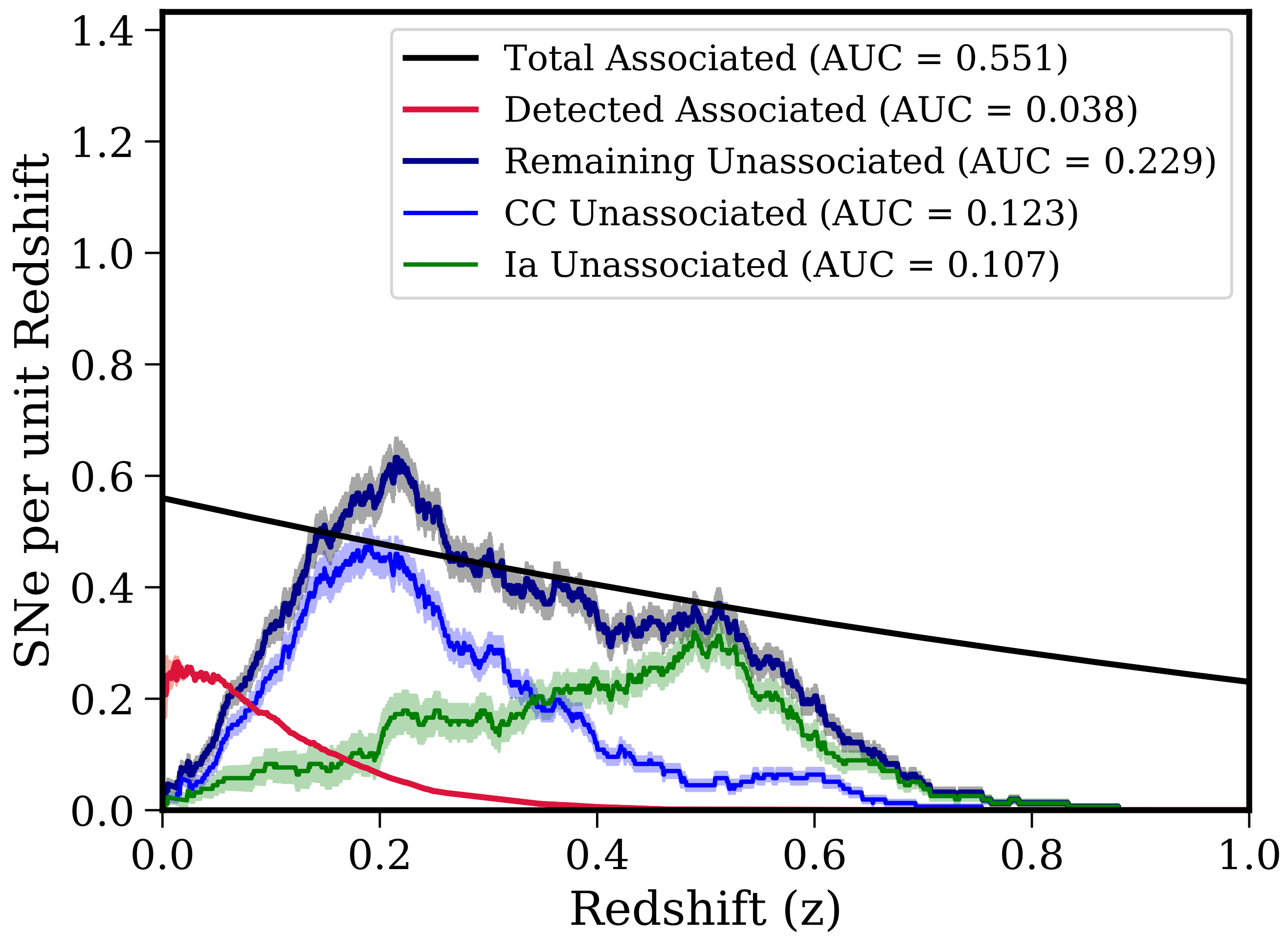
- Obtain signal efficiency as a function of redshift
- Fold signal efficiency with massive star formation rate to obtain neutrino intensity from CC SNe PDF

Cumulative intensity · Luminosity distance · Time dilation

$$\frac{dN_\nu(E_\nu)}{dE_\nu d\Omega dt_{\mathrm{obs}} dA} = \int_0^{z_{\max}} \frac{dV}{dz d\Omega} \frac{1}{4\pi D_L^2} \frac{dN_\nu(E_\nu(1+z))}{dE_\nu} \frac{1}{1+z} \mathcal{R}(z) dz$$

Comoving volume · Emission spectrum · Star formation rate

Background rate is obtained directly from simulations



Distributions show the expected SNe per unit redshift within the IceCube 90% confidence region for the IC170922A follow-up

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A Monte Carlo Approach to forecasting follow-up feasibility

Details:

- Parameterize the signal by the fraction of high energy neutrinos that are produced by CC SNe (call this fraction λ)
- Define a test statistic

$$\mathcal{L} = Poisson\ (Observed \mid Expected\ Background)$$

$$TS = \log(\mathcal{L})|_{\lambda=\hat{\lambda}} - \log(\mathcal{L})|_{\lambda=0}$$

- Perform 1000 realizations of the problem with $\lambda = 0$
  - This is our "null-hypothesis test statistic distribution"
- Perform 1000 realizations of the problem with $\lambda \neq 0$
  - This is our "signal-hypothesis test statistic distribution"

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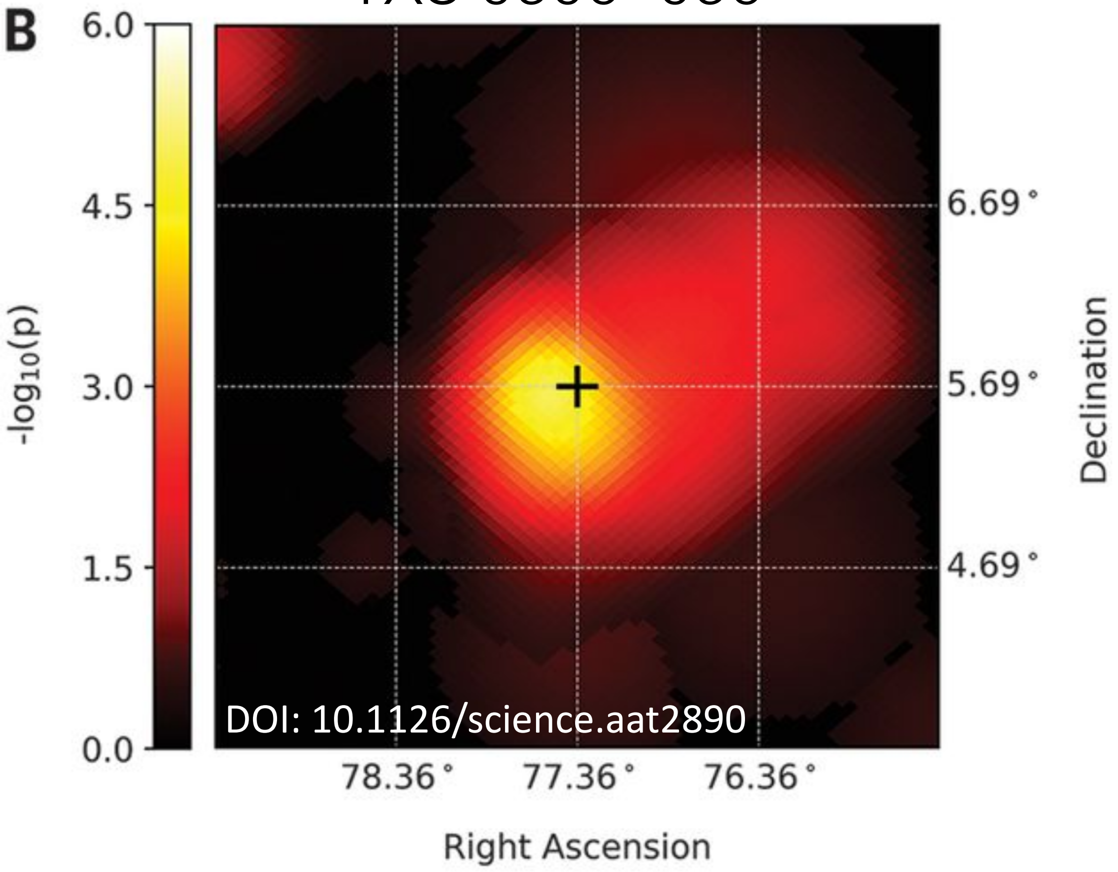
Identifying high-energy neutrino sources is a current focus of multimessenger studies and a necessity for the field of neutrino astronomy

Proposed Sources
Gamma Ray Blazars
Gamma Ray Bursts
Star-forming Galaxies
Core Collapse SNe

TXS 0506+056



Frequently Asked Questions About TXS

IC-170922A was associated to TXS0506+056; Why didn't DECam find it?

- At the time of the alert, TXS 0506+056 was V ~ 14 mag and therefore would be saturated in our DECam images. Our search was optimized for **faint transients**
- Optical imaging, spectroscopy, and polarimetry obtained from combination of ASAS-SN, Kanata/HONIR, Kiso/KWFC, Liverpool Telescope, Subaru/FOCAS

Are continued searches for *other source classes* besides gamma-ray blazars in association with IceCube neutrinos still well motivated?

- YES – gamma-ray blazars likely contribute a small fraction of the total diffuse flux
- 51 total events pass IceCube realtime alert criteria; 1 coincident gamma-ray bright blazar → consistent with ~5% overall contribution from blazars, taking into account purity of realtime alert stream
- Previous cross-correlation studies using a larger neutrino event sample found upper limits on the gamma-ray blazar contribution of < 10-30% (arXiv:1611.03874)

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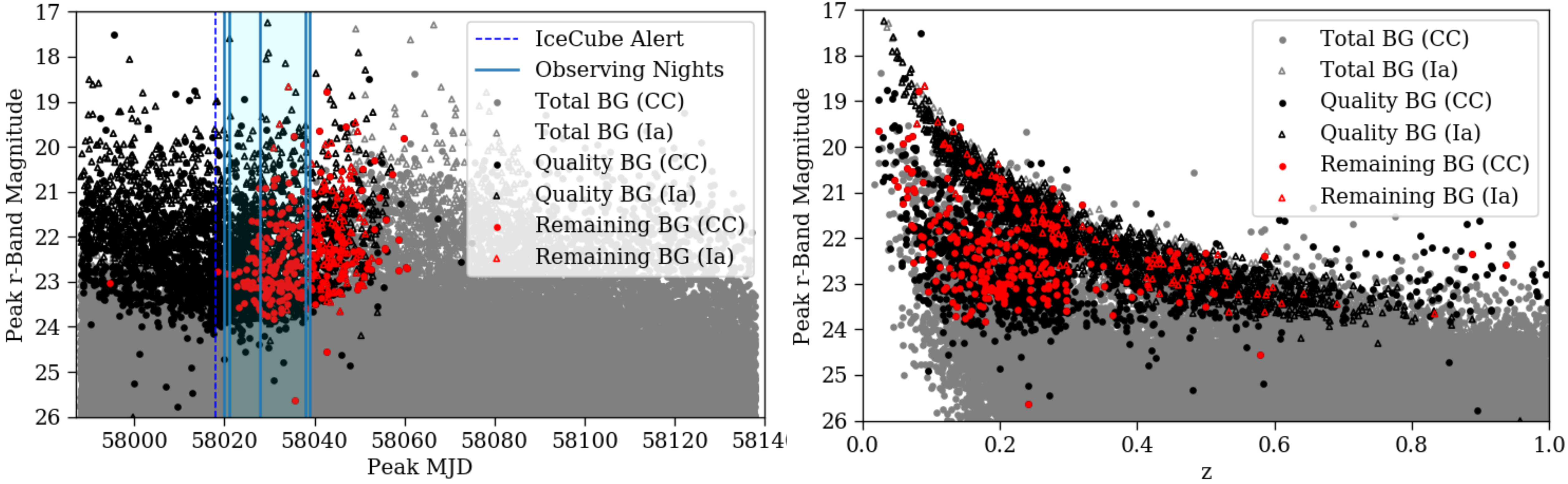

Figure: Magnitude and Redshift distributions of events after cuts

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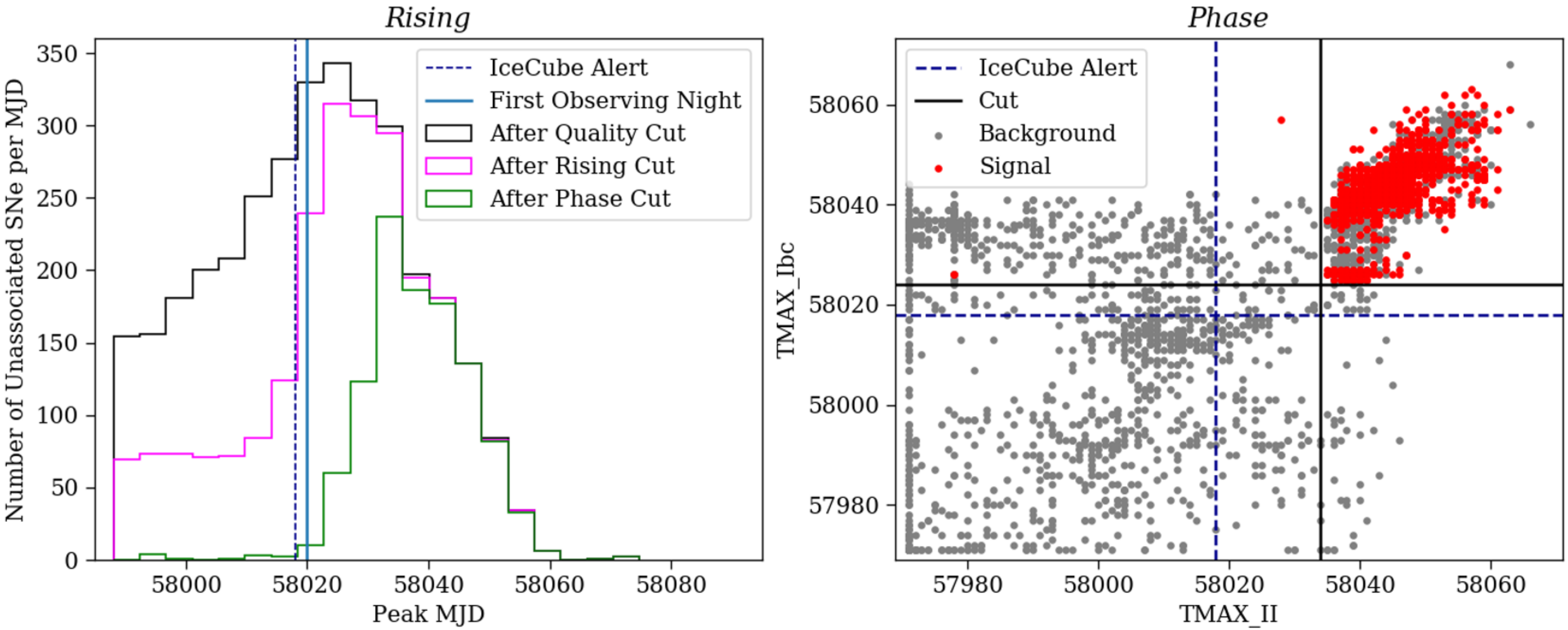

Figure: Efficacy of Rising and Phase Cuts

Random Forest Classification

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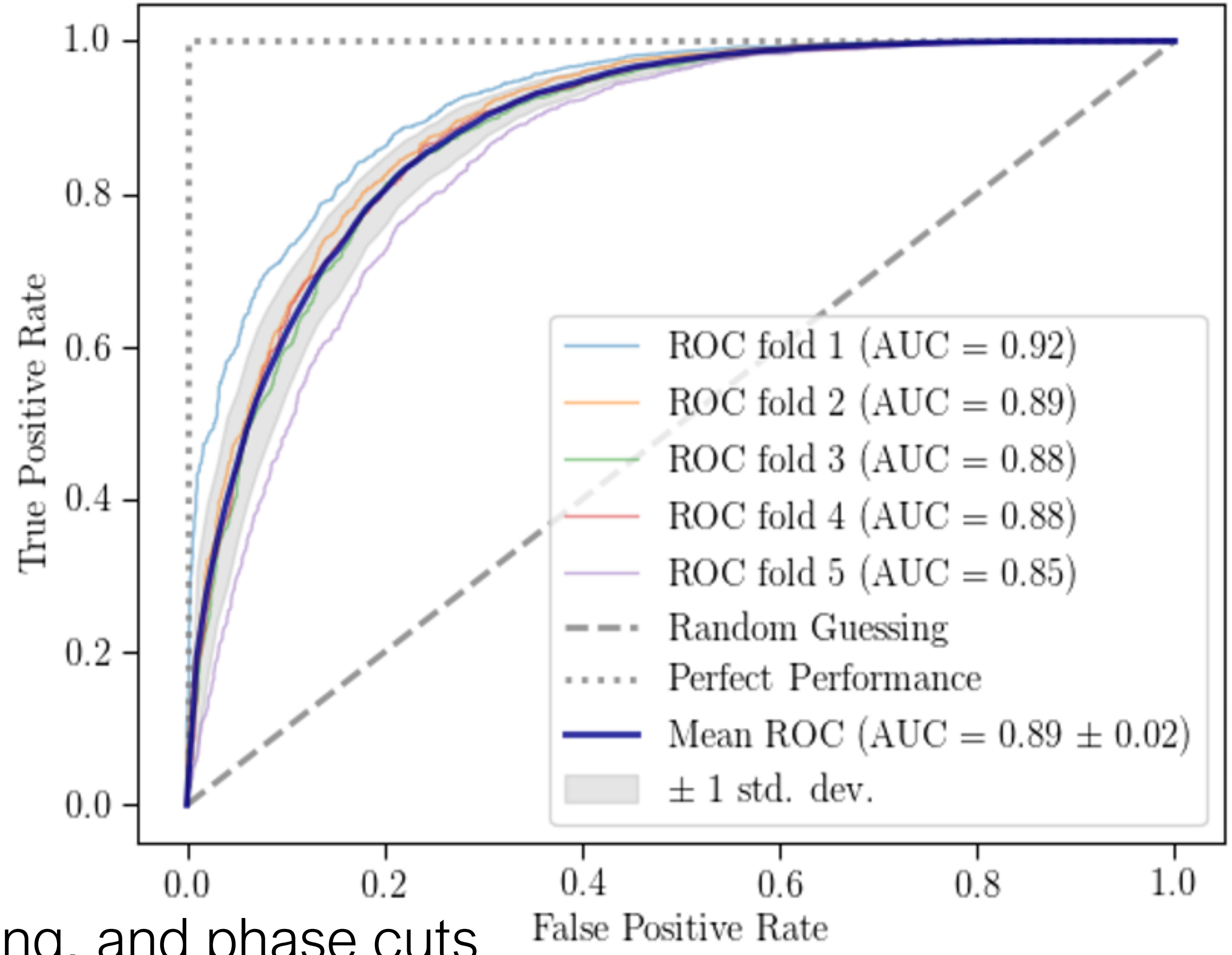
Classification pipeline

- Use PSNID to fit light curves to Ia, Ibc, and II templates
- Principal Component Analysis
  - 8 components
- Random Forest Classifier
  - 1000 estimators
  - No max-depth restriction
  - Decisions based on entropy
- Five-fold Cross Validation



Training set

- All light curves pass the quality, rising, and phase cuts
- Good: Signal sample SNe with $z < 0.3$
- Bad: Background sample SNe and Signal sample SNe with $z > 0.3$

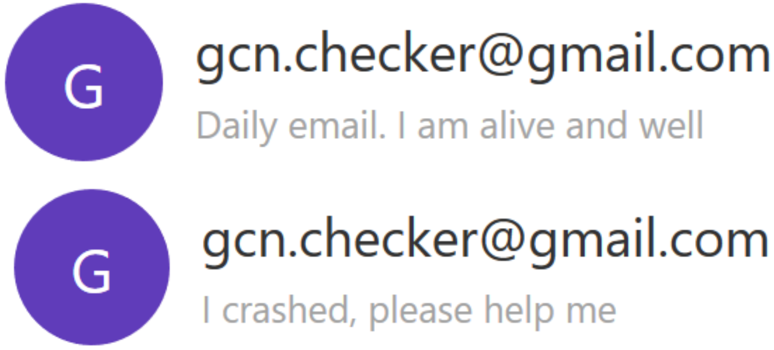
IceCube Alert Monitoring

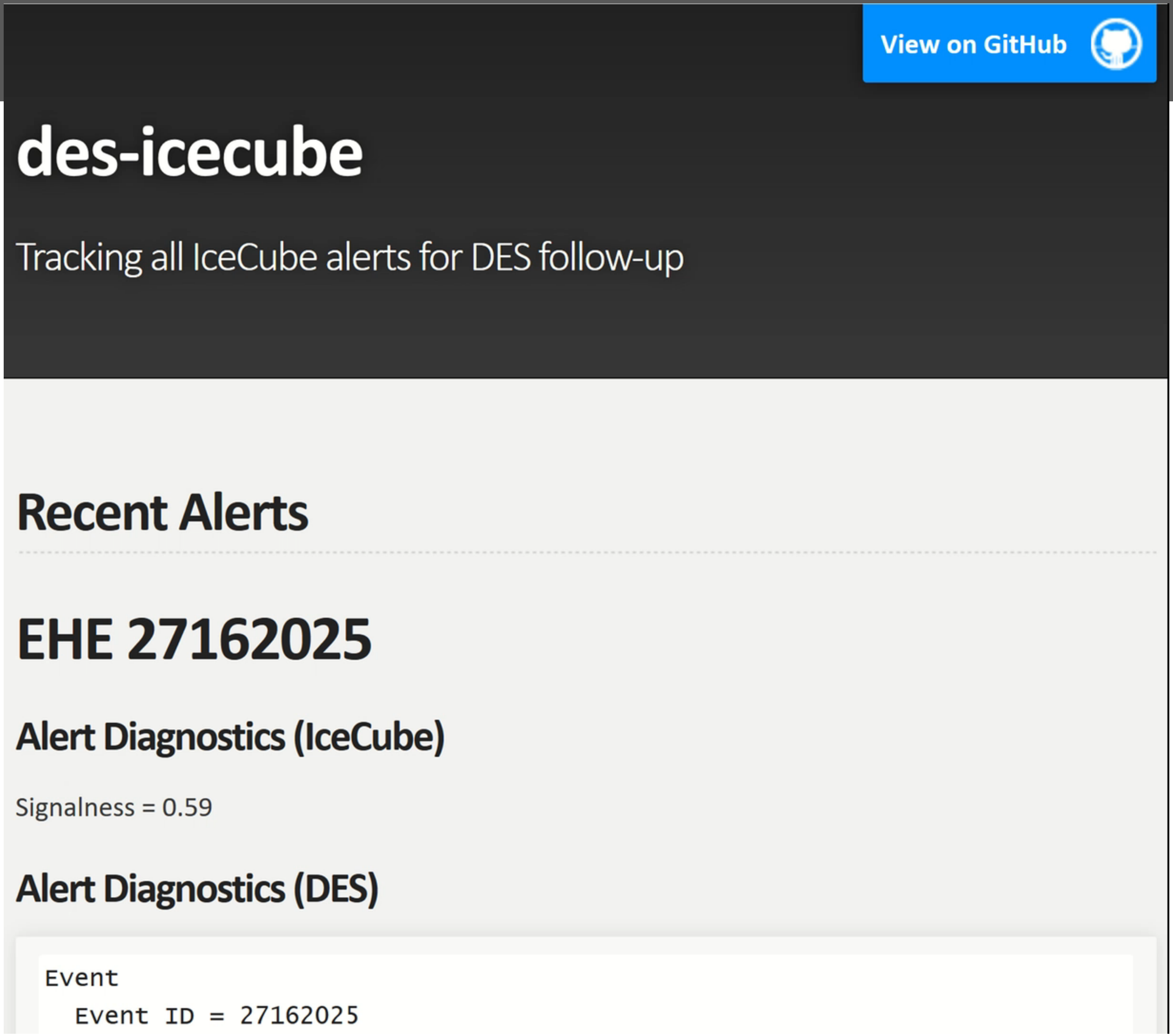
https://rmorgan10.github.io/des-icecube/

Complete alert observability diagnostics within minutes

Notifies users via email

Stable and running at Fermilab





IceCube Angular Resolution

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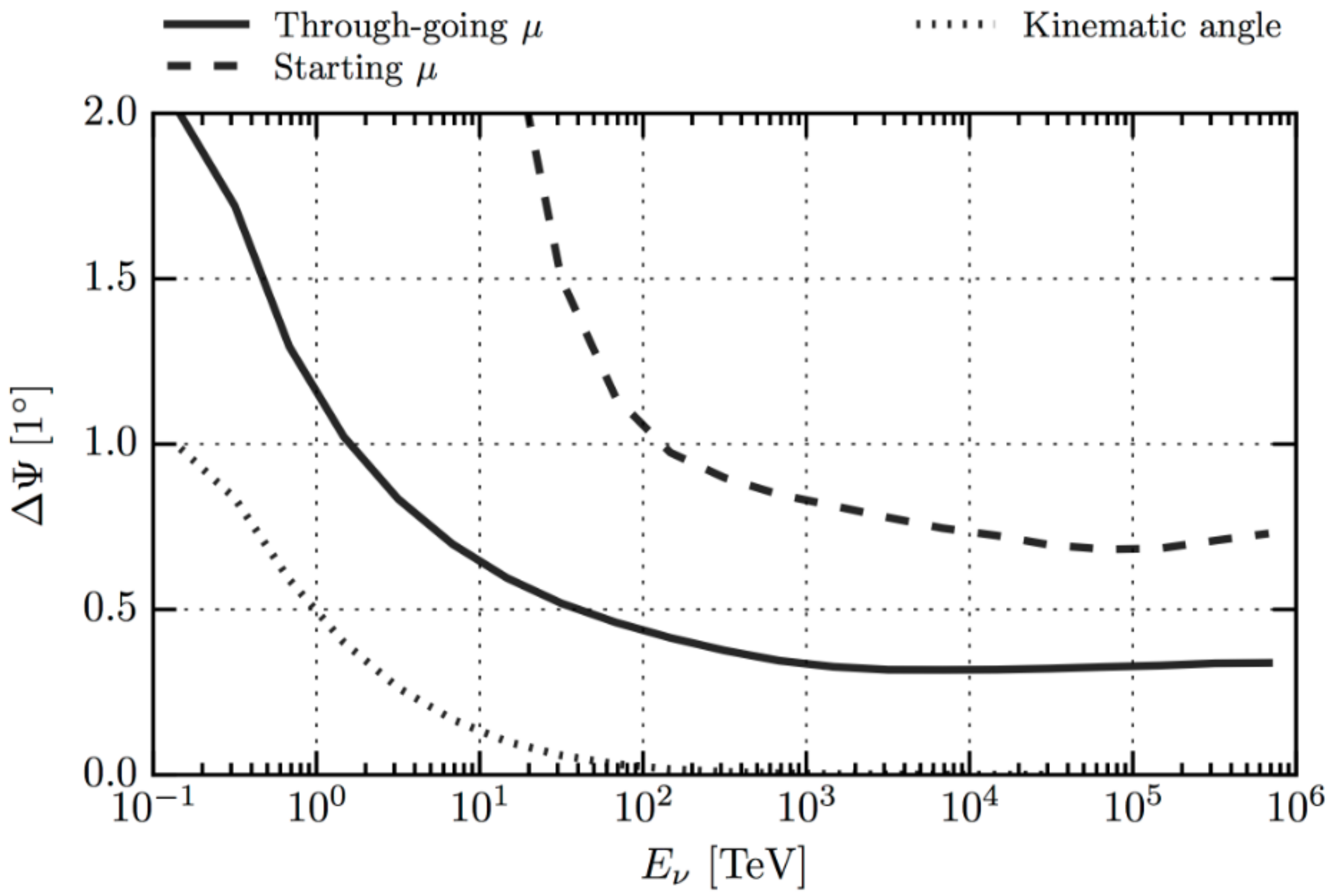

IceCube, arXiv:1609.04981

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Neutrino Intensity Redshift Integral Incorporating Star-Formation Rate

Cumulative intensity

Luminosity distance

Time dilation

$$\frac{dN_\nu(E_\nu)}{dE_\nu d\Omega dt_{\rm obs} dA} = \int_0^{z_{\rm max}} \frac{dV}{dz d\Omega} \frac{1}{4\pi D_L^2} \frac{dN_\nu(E_\nu(1+z))}{dE_\nu} \frac{1}{1+z} \mathcal{R}(z) dz$$

Comoving volume

Emission spectrum

Star formation rate