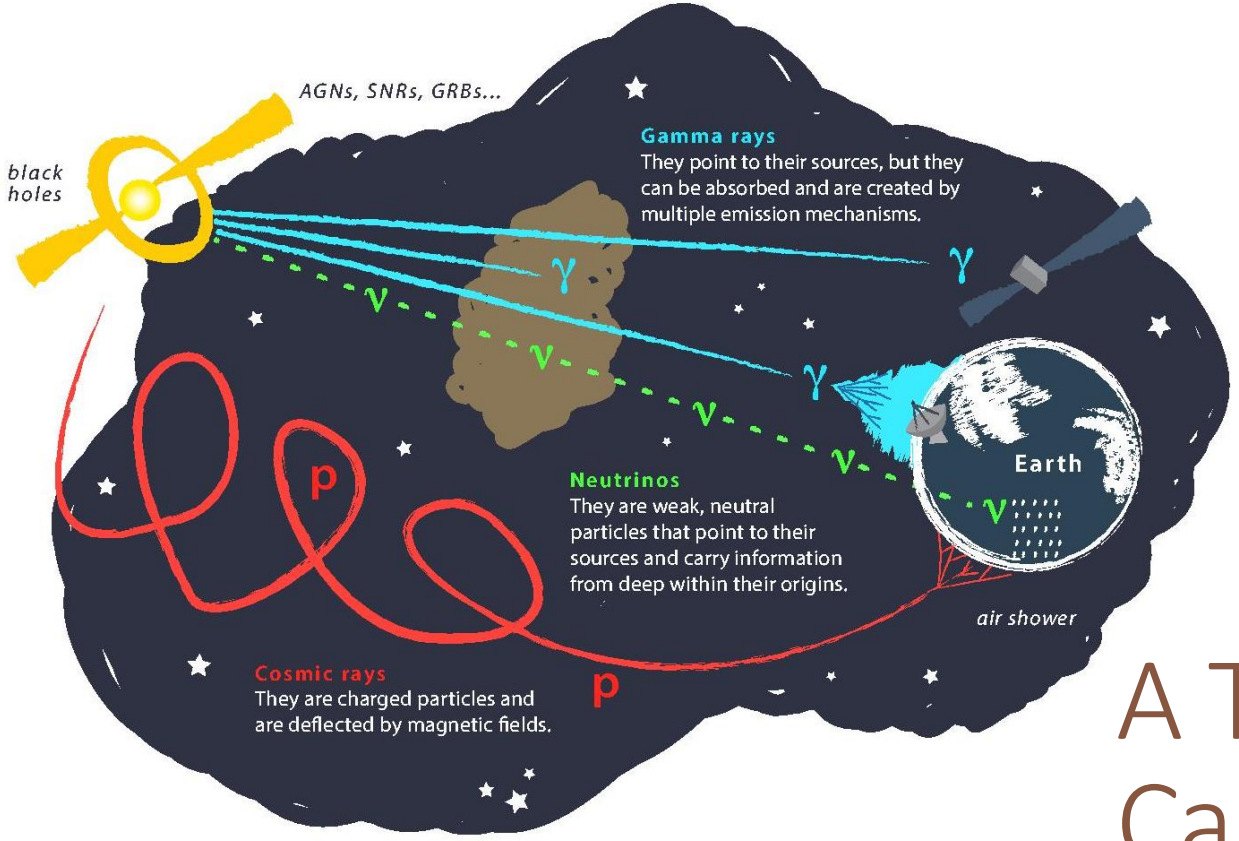


A Time-Variability Test for Candidate Neutrino Sources

PRANAV DAVE (FOR THE ICECUBE COLLABORATION)

IceCube South Pole Neutrino Observatory

Georgia Tech

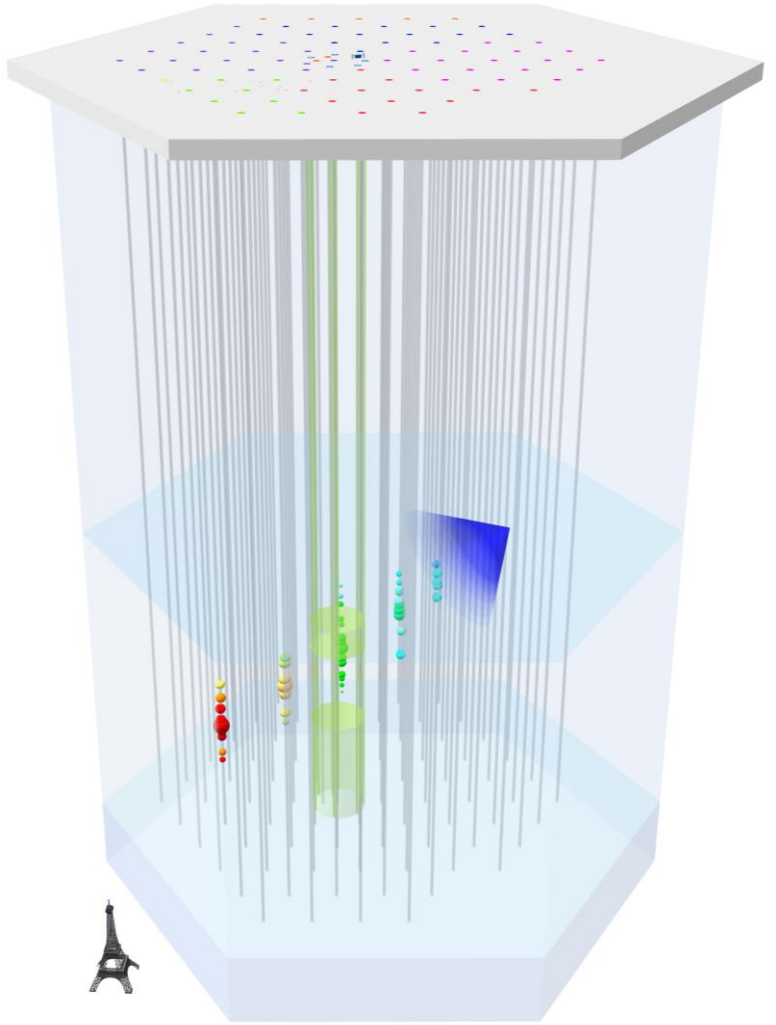
Neutrino Astronomy with IceCube

IceCube is a km^3 high-energy neutrino observatory at South Pole

- 86 strings with 5160 digital optical modules
- 1.45 km below the surface (clear ice)

Background: Atmospheric muons + muons from atmospheric neutrinos (10^7 events per hour)

Signal: Astrophysical neutrinos (10 events per year)

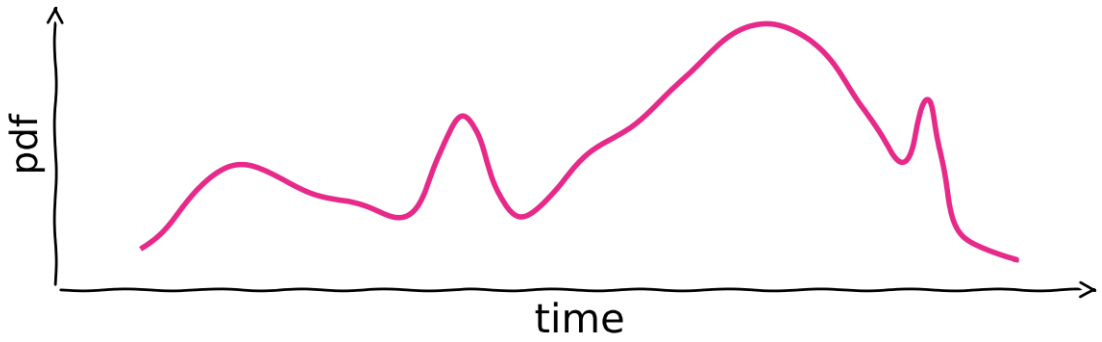


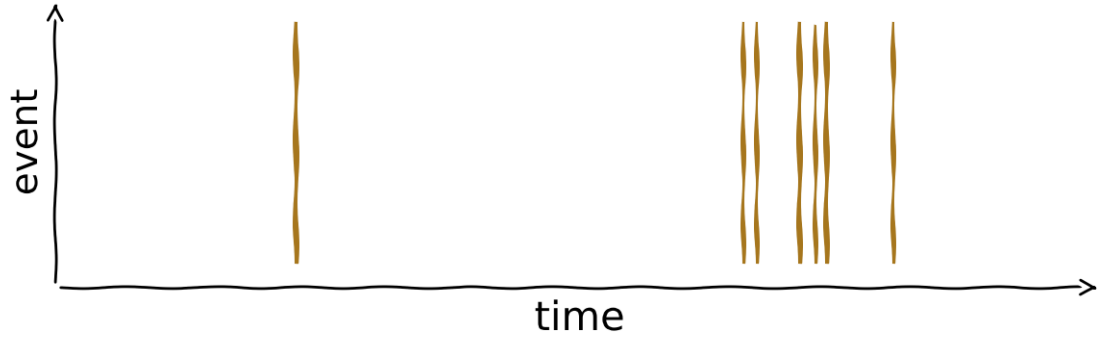
Interesting Results:

- Diffuse astrophysical muon-neutrino spectrum (arXiv:1908.09551)
- Blazar TXS 0506+056 as a candidate neutrino source
  - Best-fit flare: 13 events, spectral index of 2.1, 158-day box
- Seyfert II galaxy NGC 1068 as an interesting source (arXiv:1910.08488)
  - Best-fit time-integrated: 50 events, spectral index of 3.2

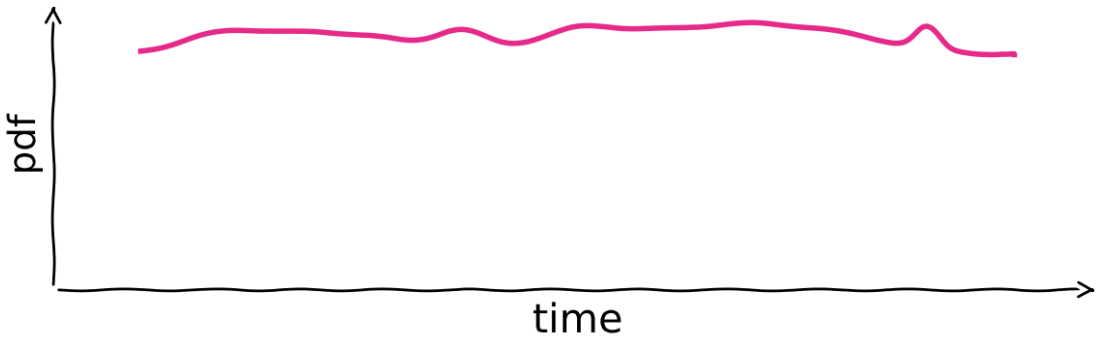
Time-Variability of Neutrino Sources

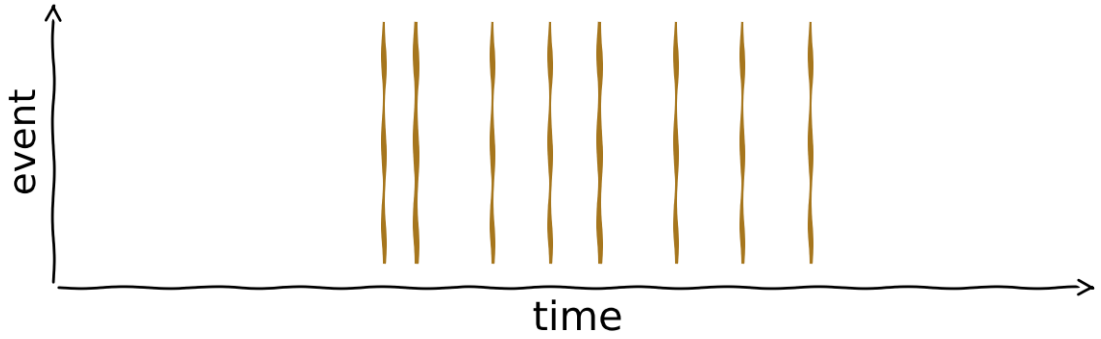
What does a neutrino light-curve from an astrophysical source look like?





generic time-variable





steady

Characterizing a Neutrino Source

Events in IceCube can be weighted by probabilities:

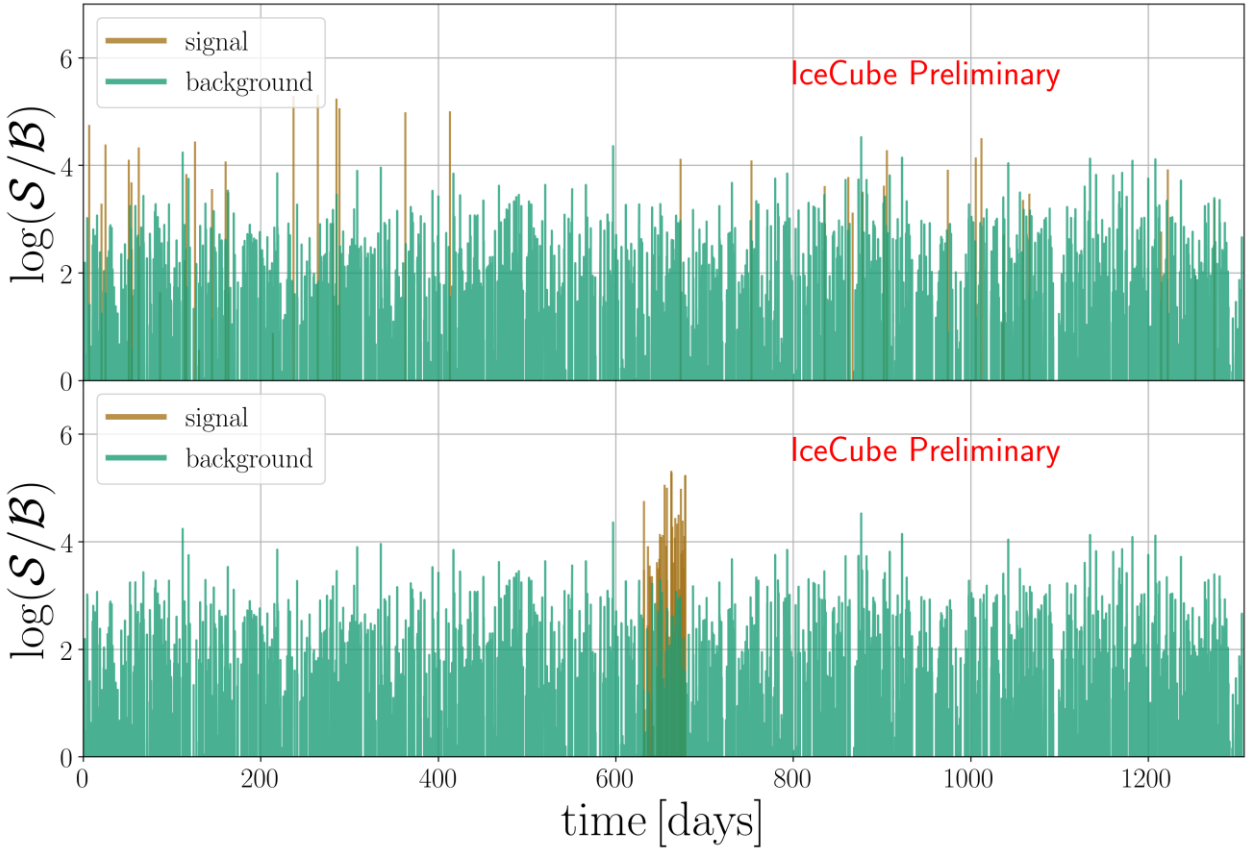
$$\mathcal{S}_i = \mathcal{P}_i^{\mathrm{sig}}(\sigma_i, \vec{r}_i|\vec{r}_o) \cdot \mathcal{E}_i^{\mathrm{sig}}(E_i, \delta_i|\gamma), \quad \mathcal{B}_i = P_i^{\mathrm{bkg}}(\delta_i) \cdot \mathcal{E}_i^{\mathrm{bkg}}(E_i, \delta_i)$$

Unbinned likelihood method fits signal:

- number of signal events: $\hat{n}_s$
- spectral index of unbroken power-law: $\hat{\gamma}$

A *characterization* tool can be built based on temporal distribution of events

- test example flare(s) for a variety of signal



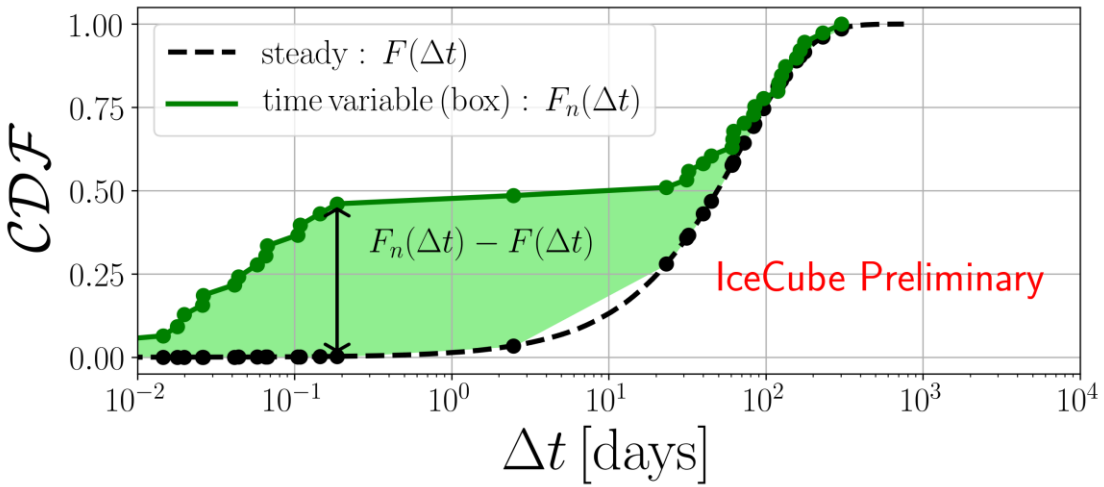
Testing the Steady Hypothesis

Method to test time-variability using single-hypothesis, based on Cramér-von Mises test:

- Perform time-integrated fit at candidate source location
- Weight events based on fitted spectrum ($\hat{\gamma}$)
- Select highest fit-bias corrected number of events with **S/B**
- Compare consecutive-pair distribution to expectation from a *steady source*

TS distributions can be compared to steady or variable injection

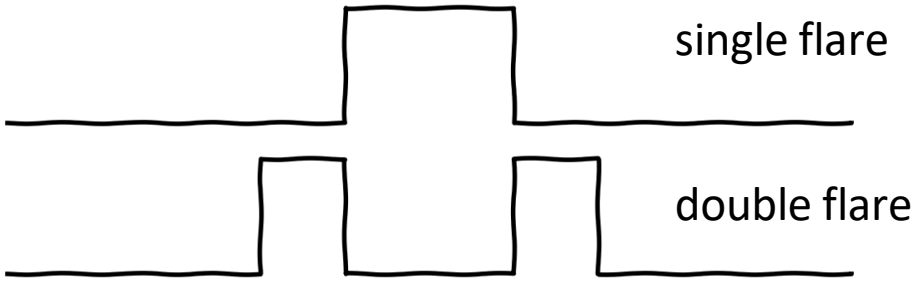
$$TS = \sqrt{\int_0^1 (F(\Delta t) - F_n(\Delta t))^2 dF}$$

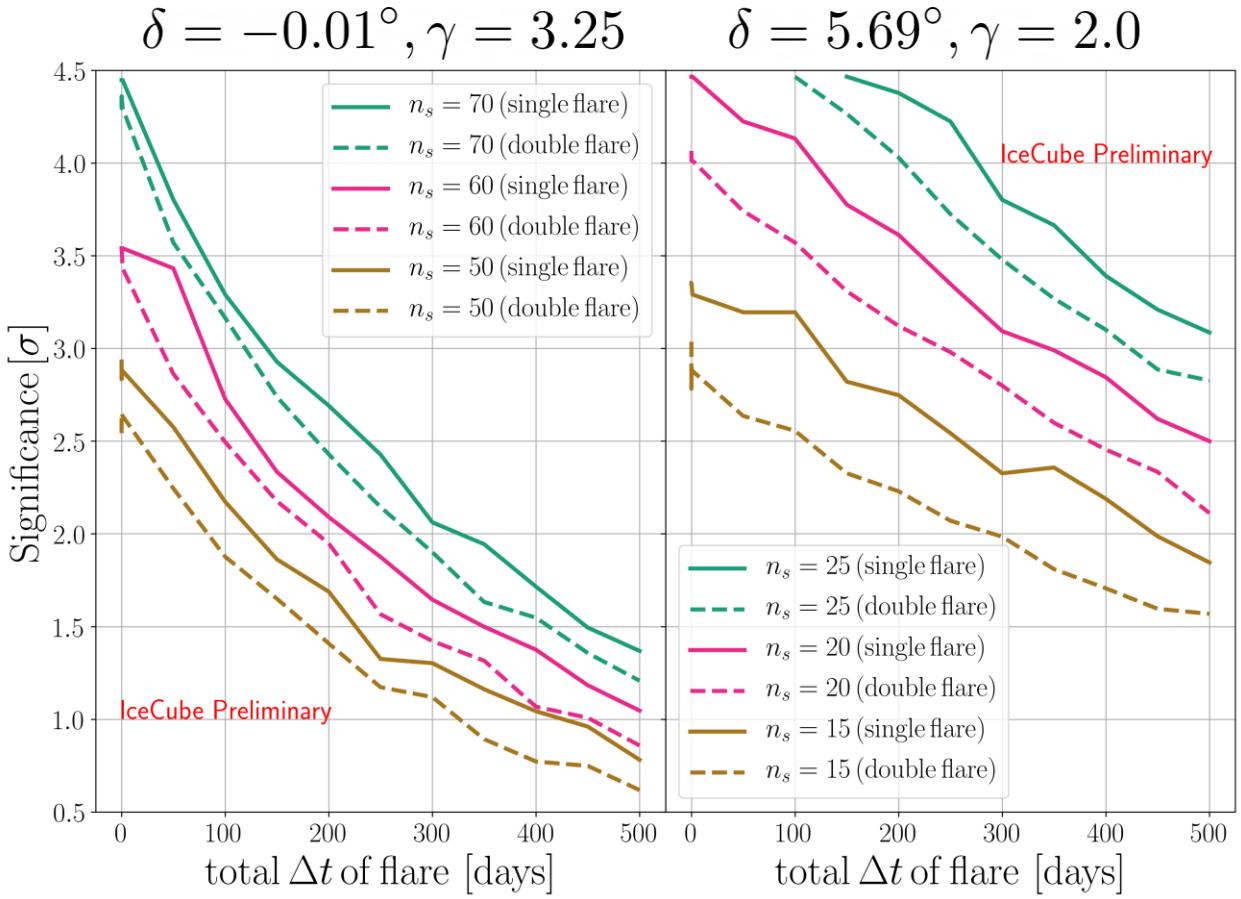


Black: The Hypothesis we test (injected steady signal + background)
Green: Example variable data (injected box signal + background)

Single and Double Flare Sensitivity

- Longer flares asymptote to steady hypothesis
- More signal events -> more high-weighted event pairs
- Double-flares constructed by splitting a single flare, keeping **signal strength** and **total flare active time** constant
  - Example: 100-day flare of 50 events compared to two 50-day flares of 25 events each





Results using 7.5 years of IceCube Data

- 7.5 years of track-like events used by IceCube's alert system*
- Test applied to 4 most-significant sources from 10-year time-integrated point-source search^ as an *a posteriori* test
- All sources found consistent with steady emission
- Future: very bright neutrino sources can be characterized

Name of Source	RA (deg)	Dec. (deg)	p-value
TXS 0506+056	77.35	5.7	0.62
NGC 1068	40.67	-0.01	0.4
PKS 1424+240	216.76	23.8	0.53
GB6 J1542+6129	235.75	61.5	0.34

All 4 sources consistent with steady emission

* Astropart. Phys., 92 (June 2017) – IceCube collaboration

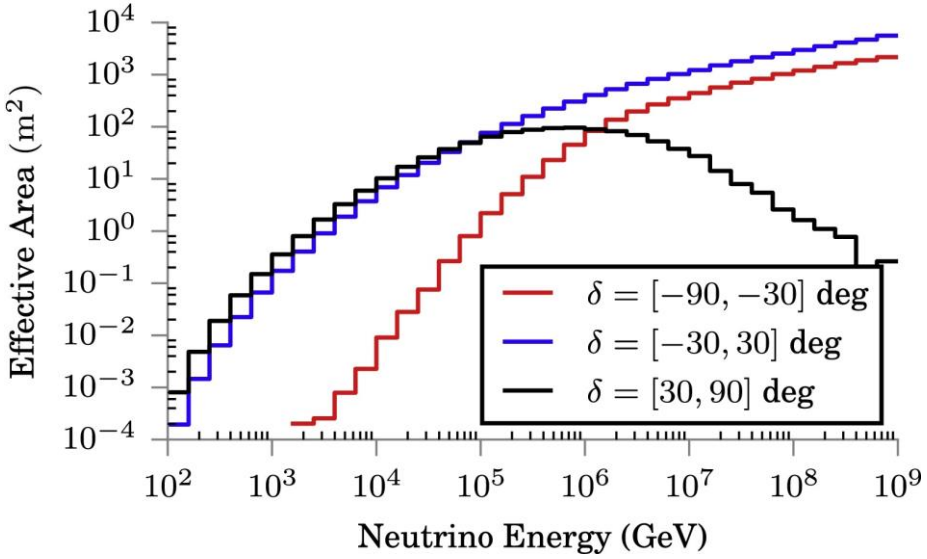
^ PRL 124 (Feb 2020) – IceCube collaboration

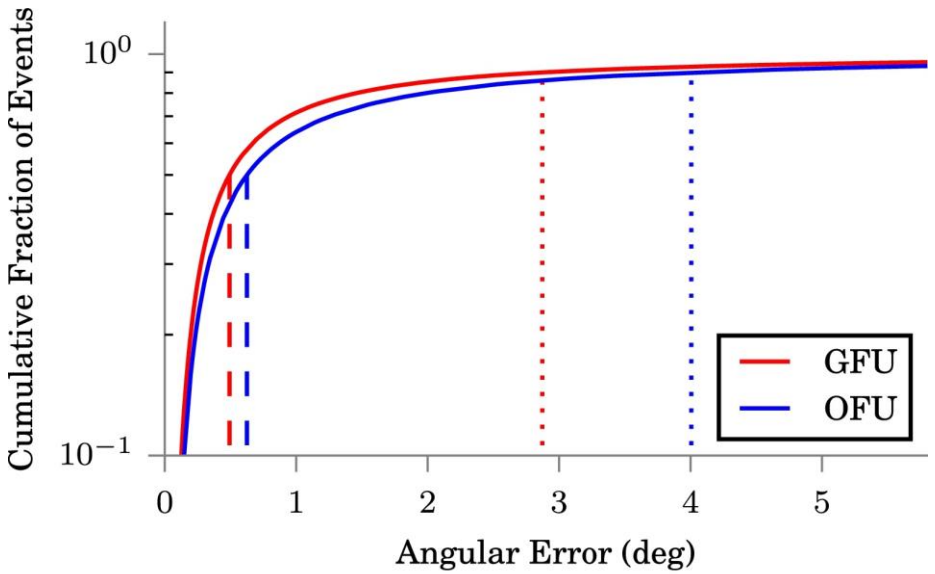
Summary

- New characterization tool to test time-variability of candidate neutrino sources
- Method is model-independent and does **not** assume a temporal shape for variable sources
- Tested example injections of a flaring source, performs better for very strong signal
- Applied to 4 most-significant sources in IceCube using 7.5 years of track-like events
- All 4 sources found consistent with steady emission, including NGC 1068 and TXS 0506+056

Backup Slides

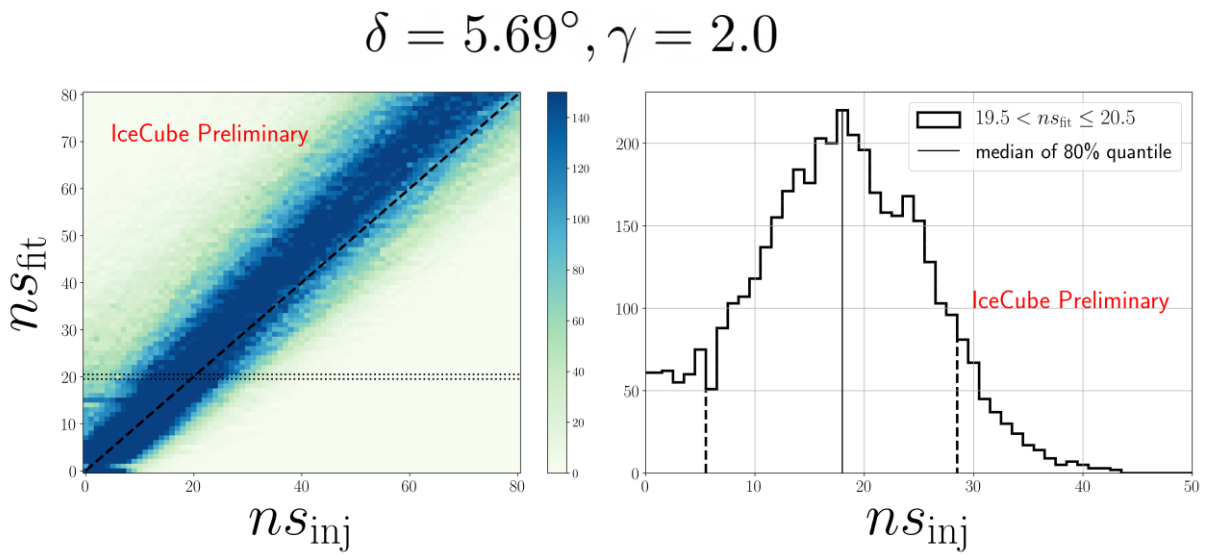
Effective Area of Sample Used

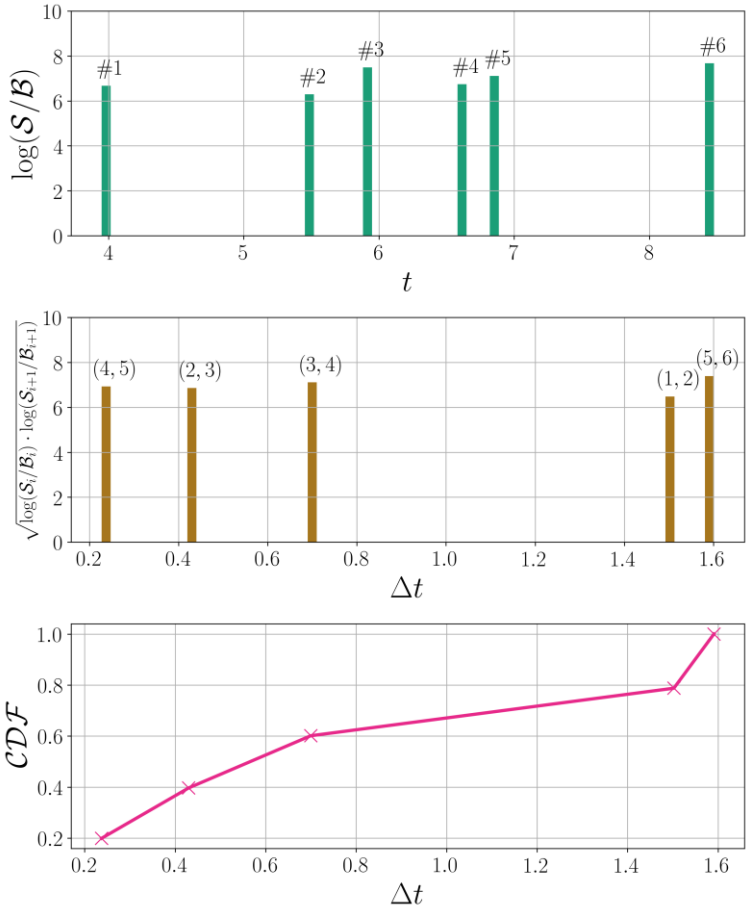




Astropart. Phys., 92 (June 2017) – IceCube collaboration

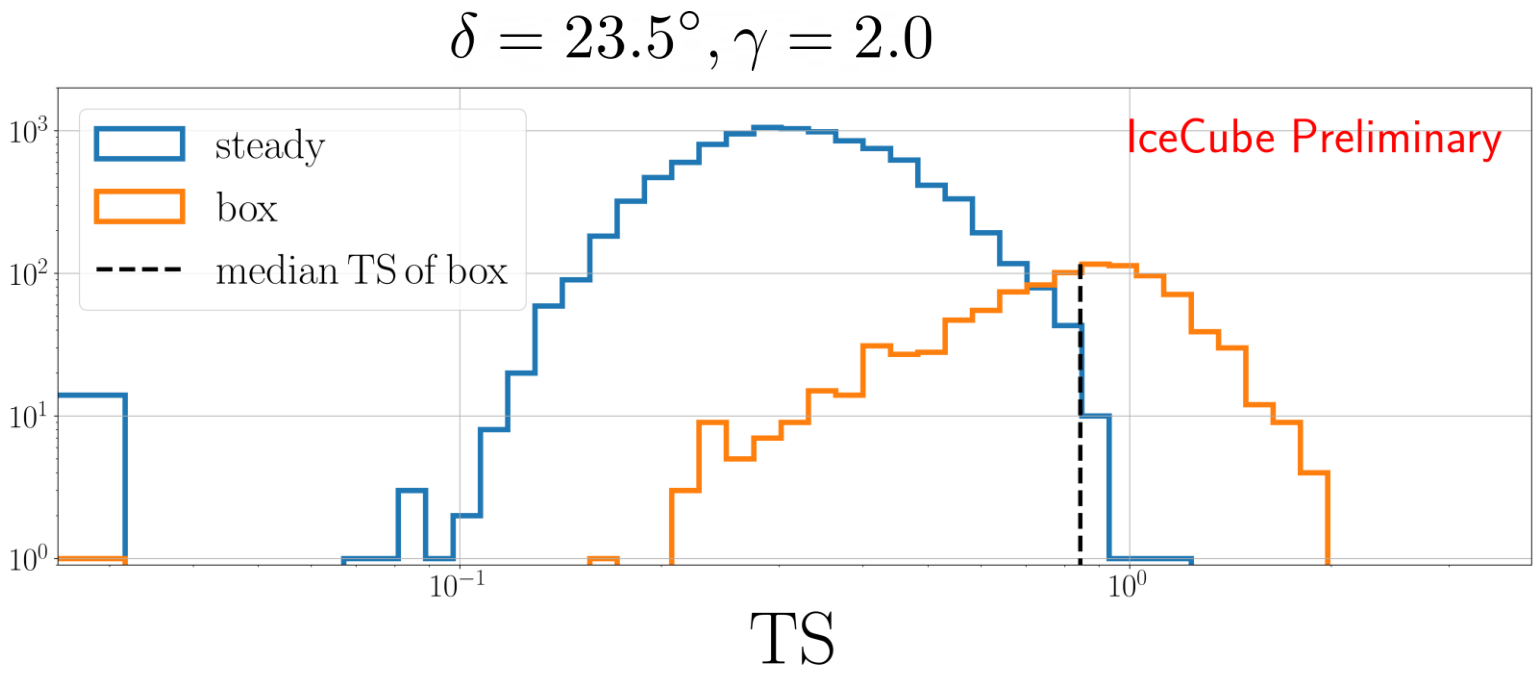
Event-Pair Selection





- Fit-bias correction of event selection around source (top)
- Construction of weighted CDF for highest S/B events (right)

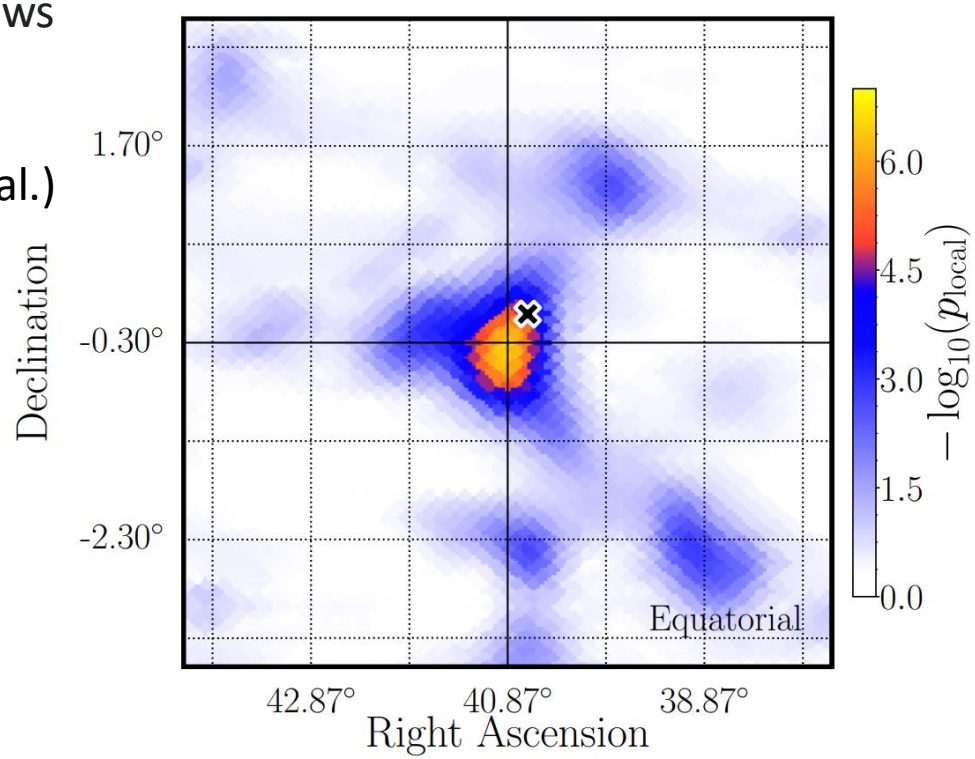
Test Statistic Comparison



- Histograms comparing test statistic distributions for:
  - injected steady and variable (flare-width = 200 days) signal
- Box-flare rejects the steady hypothesis at 2.97σ

NGC 1068 in IceCube

- Time-integrated catalog search using 10 years of IceCube data shows excess from Seyfert II galaxy NGC 1068 at 2.9σ
- Catalog composed of select sources from Fermi-LAT 4FGL (extra-gal.) and TeVCat, gammaCat (gal.)
- Best-fit parameters from catalog search:
  - Signal excess: 50 events
  - Spectral index: 3.2



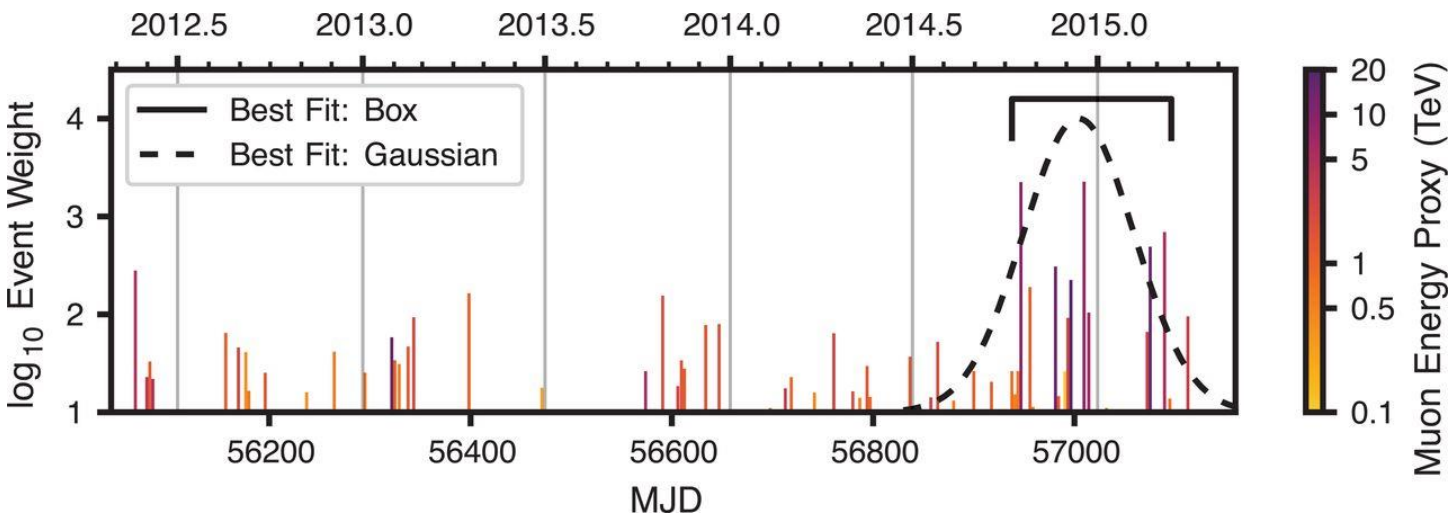
PRL 124 (Feb 2020) – IceCube collaboration

TXS 0506+056 in IceCube

- IC170922A neutrino alert event found in spatial coincidence with blazar TXS 0506+056

- Archival search in that direction finds a time-dependent flare fit of 3.5σ in 2014-2015

- Best-fit parameters:
  - Signal excess: 13 events
  - Spectral index: 2.1
  - Flare-width (box hypothesis): 158 days



Science 361 (July 2018) – IceCube collaboration