Every Flare, Everywhere: An All-Sky Untriggered Search for Astrophysical Neutrino Transients Using IceCube Data

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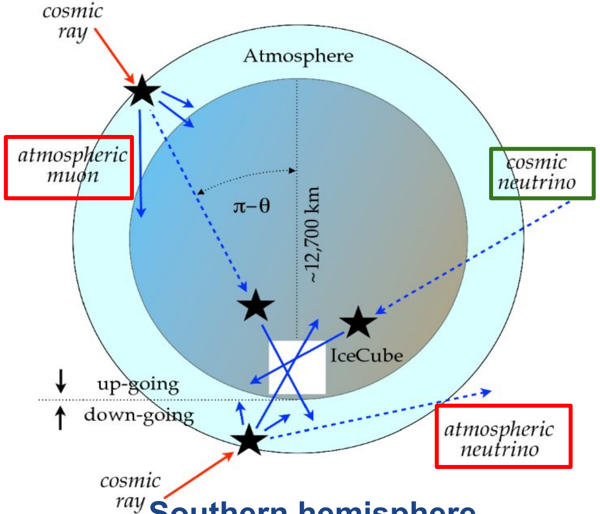
for the IceCube collaboration

IceCube: Signal and Background

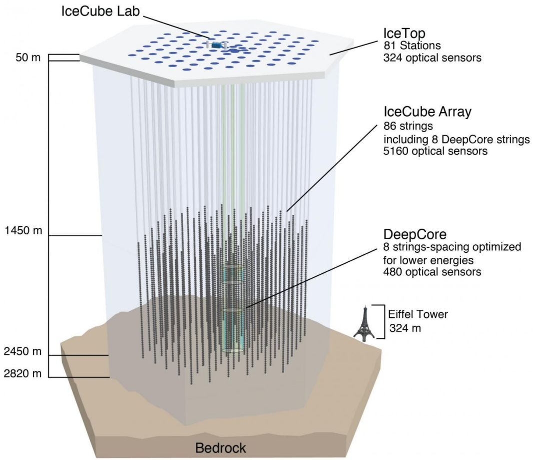
We present an untriggered, unbiased search for multi-flare transient sources of astrophysical neutrinos with IceCube

Northern hemisphere



Southern hemisphere

IceCube is a km^3 high-energy neutrino telescope located at the South Pole



SIGNAL

Muons from astrophysical neutrinos (10 evts/year)

BACKGROUND

- **Muons from atmospheric neutrinos (10 evts/hour)**
  Dominant background in northern hemisphere
- **Atmospheric muons (10^7 evts/hour)**
  Dominant background in southern hemisphere

Analyses Overview

Main Features

Period
10 years (2008-2018),
5 independent samples

Sky
Almost full sky is analyzed
with resolution 0.1° x 0.1°

Northern ($\delta \geq -5°$) and **southern** ($\delta < -5°$) hemispheres **treated separately** due to different background composition

Strategy
Unbinned maximum-likelihood
with multi-flare algorithm

Searches

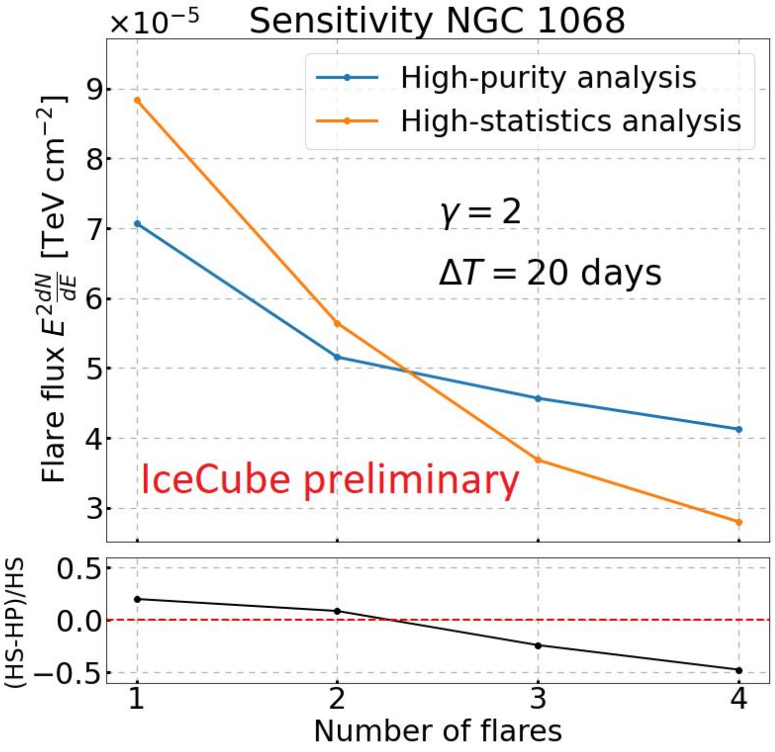
1. Hottest Spot
2. Population Test

Multi-flare Algorithm

Two variants of the multi-flare algorithm are applied:

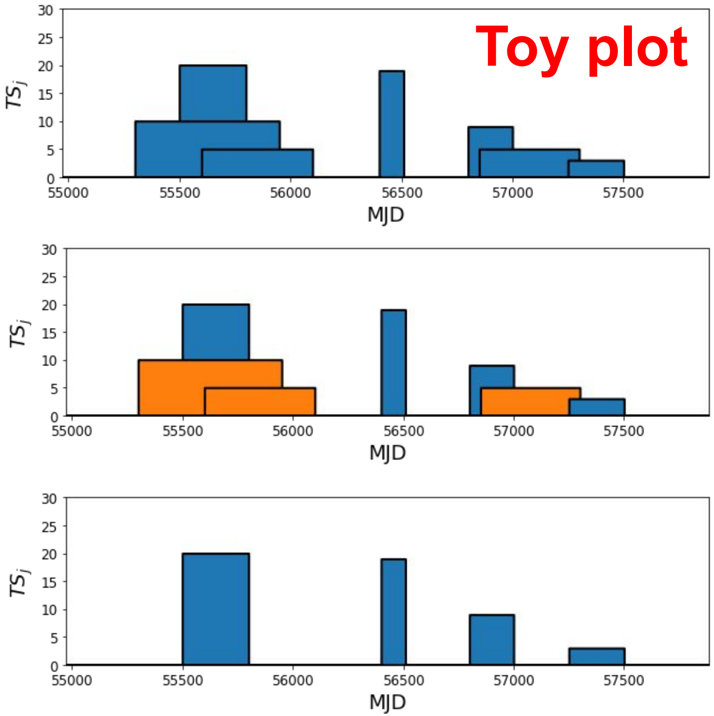
1. **High-statistics**
    - It includes low-significance flares
    - High sensitivity to sources **flaring several times**, low sensitivity to sources **flaring few times**

2. **High-purity**
    - Tighter quality selection applied to remove low-significant flares
    - High sensitivity to sources **flaring few times**, low sensitivity to sources **flaring several times**



High-Statistics Analysis: Methods

- Box flare hypothesis
- Fit every flare possible, seeded by nearby energetic events
- Remove flares with TS<0
- Remove flare fits that overlap
- Sum the TS of the remaining flares



Total events in sample

Total signal-like events in flare j

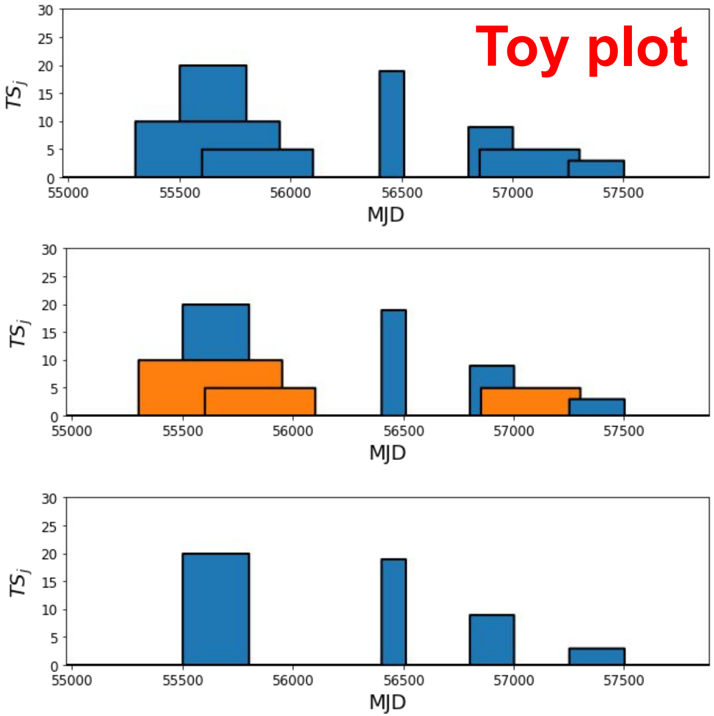
$$\mathcal{L}_j(n_{s,j},\gamma_j,t_{0,j},\Delta t_j)=\prod_{i=1}^{N}\frac{n_{s,j}}{N}S_{i,j}+\left(1-\frac{n_{s,j}}{N}\right)B_{i,j}$$

$$\boxed{S_i=R_i(\vec{r_i}|\vec{r_o})\times\mathcal{E}(E_i|\gamma)\times\mathcal{T}(t_i|t_o,\Delta t)}$$

$$\boxed{B_i=\frac{1}{\Omega\Delta T}\mathcal{E}(E_i|Atm)}$$

High-Statistics Analysis: Methods

- Box flare hypothesis
- Fit every flare possible, seeded by nearby energetic events
- Remove flares with TS<0
- Remove flare fits that overlap
- Sum the TS of the remaining flares



Total events in sample

Total signal-like events in flare *j*

$$\mathcal{L}_j(n_{s,j},\gamma_j,t_{0,j},\Delta t_j)=\prod_{i=1}^{N}\frac{n_{s,j}}{N}S_{i,j}+(1-\frac{n_{s,j}}{N})B_{i,j}$$

$$TS_j=-2\log\left[\frac{\Delta T_{data}}{\Delta t_j}\times\frac{L_j(\mathbf{x_s},n_s=0)}{L_j(\mathbf{x_s},\hat{n}_s)}\right]$$

High-Purity Analysis: Methods

5 independent IceCube samples (different data selection, effective areas)

Likelihood of each sample k:

$$\mathcal{L}^{(k)} = \prod_{i=1}^{\overset{\text{Total events in sample } k}{\uparrow}\, N^{(k)}} \left[\underbrace{\left(\sum_{j=\text{flares}} \frac{\overset{\text{Total signal-like events in flare } j \text{ and sample } k}{\uparrow}\, n_{s,j}^{(k)}}{N^{(k)}} \underset{\text{Single-flare signal PDF}}{\underset{\downarrow}{\mathcal{S}_{ij}^{(k)}}} \right)}_{\text{Multi-flare signal PDF}} + \left(1 - \frac{\sum_j \overset{\uparrow}{n_{s,j}^{(k)}}}{N^{(k)}} \right) \underset{\text{Background PDF}}{\underset{\downarrow}{\mathcal{B}_i^{(k)}}} \right]$$

High-Purity Analysis: Methods

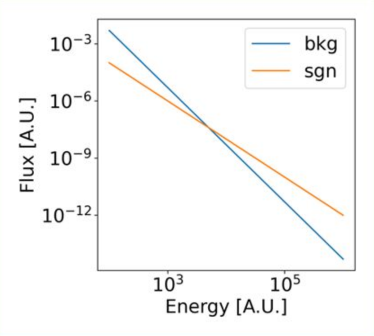
$$\mathcal{L}^{(k)}(\vec{n}_s, \vec{\gamma}, \vec{t}_0, \vec{\sigma}_T) = \prod_{i=1}^{N^{(k)}} \left[\left(\sum_{j=\text{flares}} \frac{n_{s,j}^{(k)}}{N^{(k)}} \mathcal{S}_{ij}^{(k)}(\gamma_j, t_{0,j}, \sigma_{T,j}) \right) + \left(1 - \frac{\sum_j n_{s,j}^{(k)}}{N^{(k)}} \right) \mathcal{B}_i^{(k)} \right]$$

sgn and bkg PDFs =

Energy PDF

Signal: power-law ∝ $E^{-\gamma_j}$

Background: data-driven



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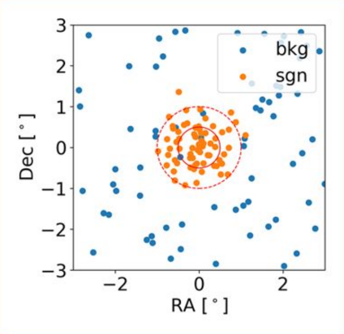
Space PDF

Signal: 2D Gaussian $\frac{1}{2\pi\sigma_i^2}\exp\left[-\frac{|\vec{x}_i-\vec{x}_S|^2}{2\sigma_i^2}\right]$

Background: data-driven



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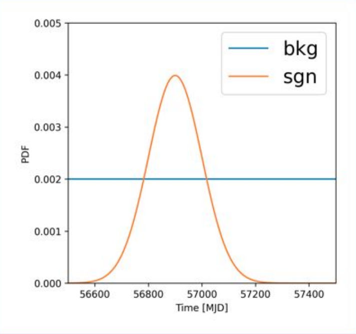
Time PDF

Signal: Gaussian ∝ $\exp\left[\frac{(t_i-t_{0,j})^2}{2\sigma_{T,j}^2}\right]$

Background: uniform



High-Purity Analysis: Methods

10-year likelihood: $\mathcal{L} = \prod_{k} \mathcal{L}^{(k)}$

Test Statistic:

10-year livetime

Background likelihood

$$\mathrm{TS} = -2\log\left[\frac{1}{2}\left(\prod_{j=\mathrm{flares}} \frac{T_{live}}{\hat{\sigma}_{T,j} I\left[\hat{t}_{0,j}, \hat{\sigma}_{T,j}\right]}\right) \times \frac{\mathcal{L}(\vec{n}_s = \vec{0})}{\mathcal{L}(\hat{\vec{n}}_s, \hat{\vec{\gamma}}, \hat{\vec{t}}_0, \hat{\vec{\sigma}}_T)}\right]$$

$$\int_{T_{live}} \frac{1}{\sqrt{2\pi}\sigma_{T,j}} \exp\left[-\frac{(t-t_{0,j})^2}{2\sigma_{T,j}^2}\right] dt$$

Maximum likelihood

The number of flares is selected similarly to the high-stat analysis, but requiring single-flare TS>2

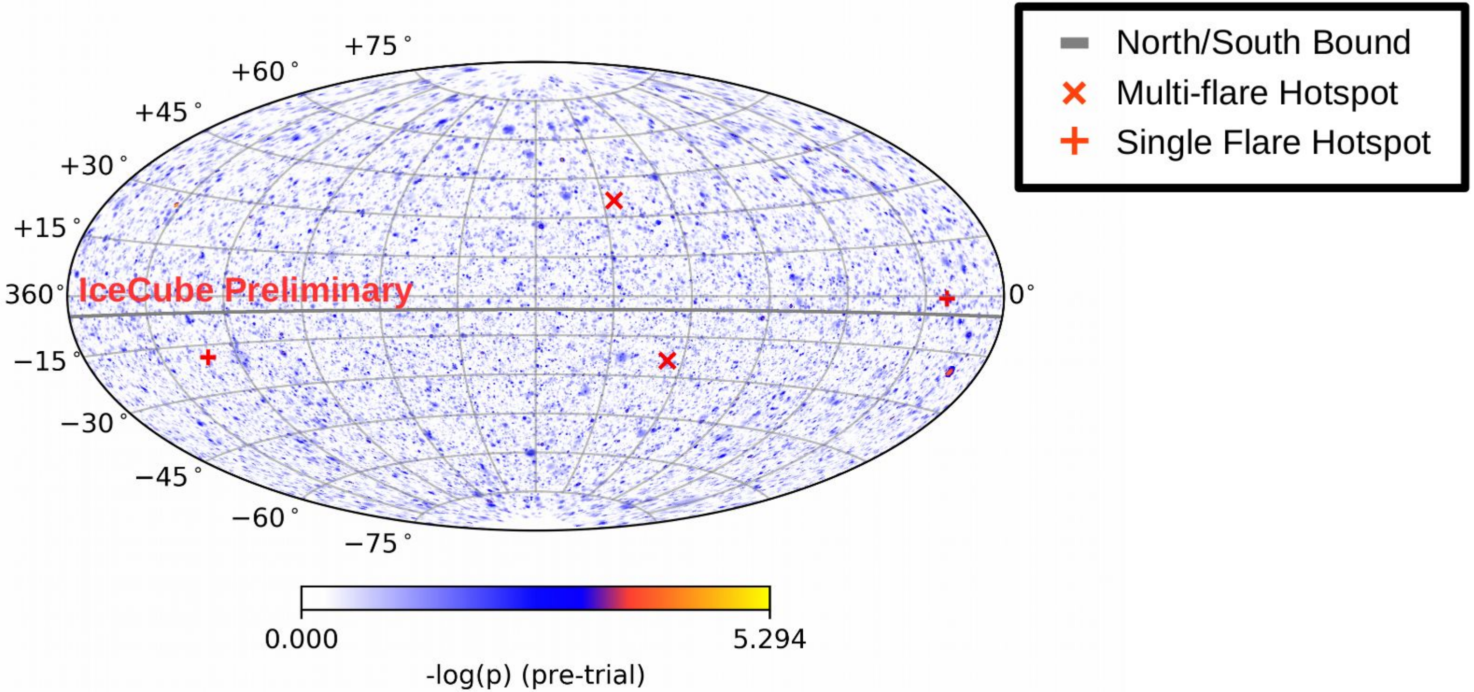
All-sky Searches

The two multi-flare variants are each used for two searches in each hemisphere:

- **Hottest spot search**
  It looks for the most significant spot (hottest spot):
    a. A p-value p_{val} is calculated from all pixels in the sky
    b. The smallest p_{val} in each hemisphere is selected and corrected for trials

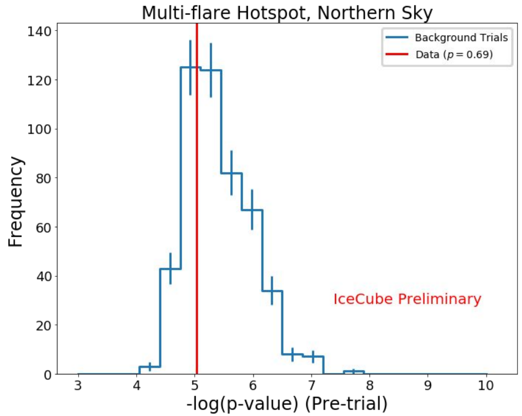
- **Population test**
  It looks for an excess of sub-threshold hot spots
    a. Cumulative number of hot spots with $p_{val} < p_{thr}$ is calculated
    b. A p-value for this test is calculated for several p_{thr} assuming binomial (high stat variant) or Poissonian (high-purity variant) statistics
    c. The smallest p-value in each hemisphere is selected and corrected for trials

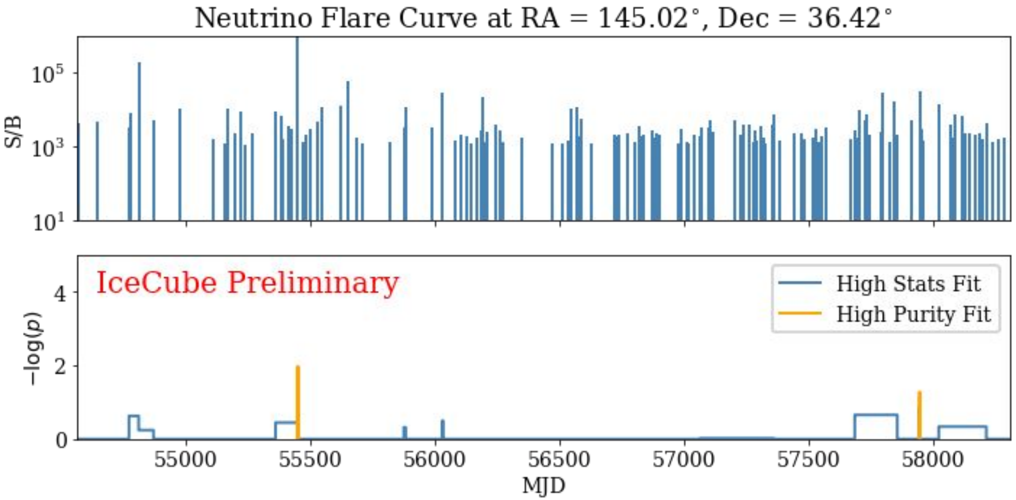
High-Statistics Analysis: Skymap

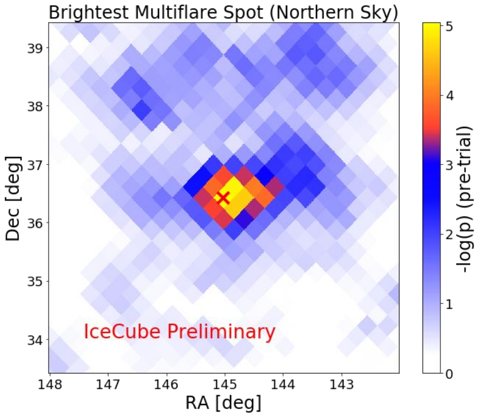


High-Statistics Analysis: Hottest Spot

- Most significant northern sky pixel:
    - RA, dec = 145.02°, 36.42°
    - p (pre-trial) = 9.16×10^{-6}
    - p (post-trial) = 0.69

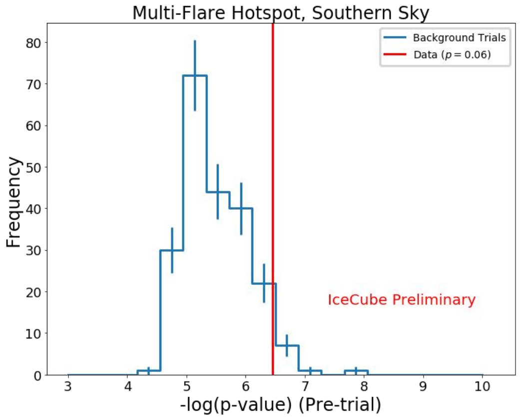

Multi-flare Hotspot, Northern Sky

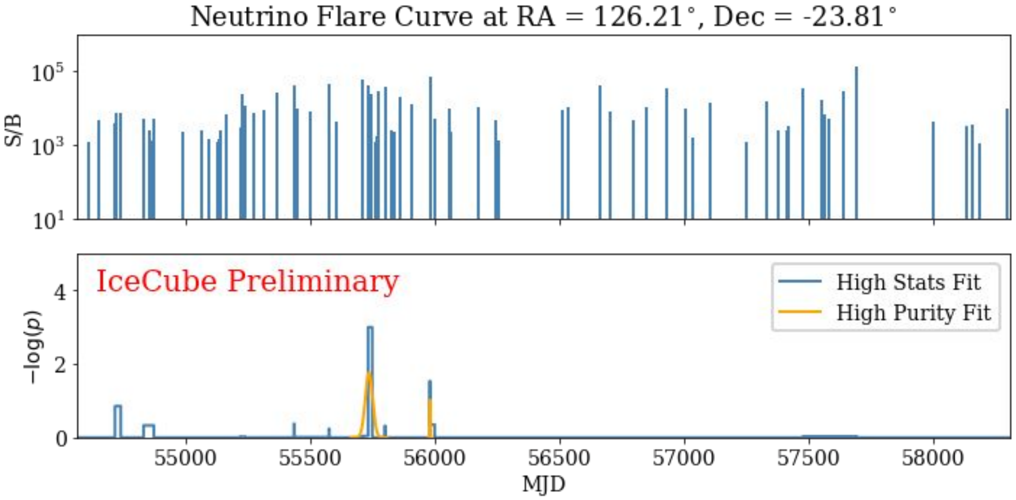

Neutrino Flare Curve at RA = 145.02°, Dec = 36.42°

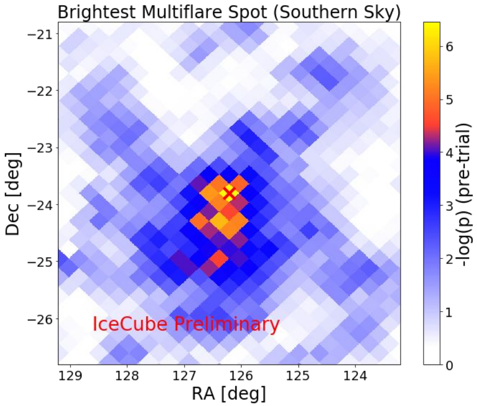

Brightest Multiflare Spot (Northern Sky)

High-Statistics Analysis: Hottest Spot

- Most significant southern sky pixel:
  - RA, dec = 126.21°, -23.81°
  - p (pre-trial) = 3.54×10^{-7}
  - p (post-trial) = 0.06

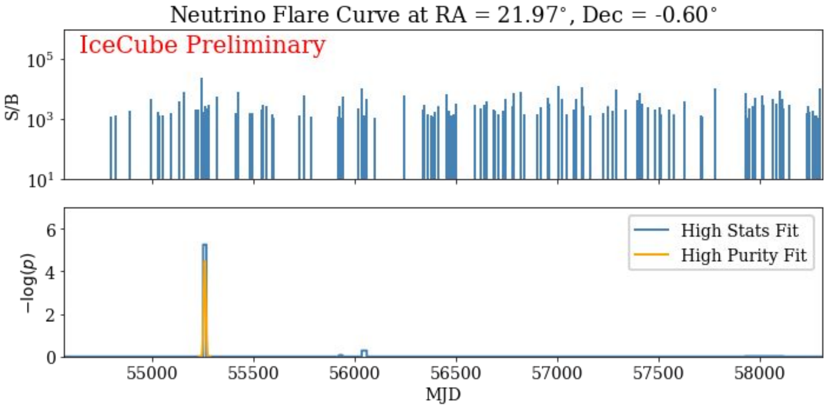


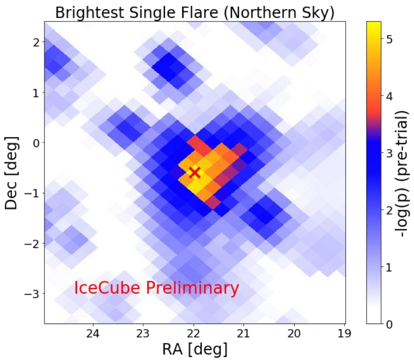


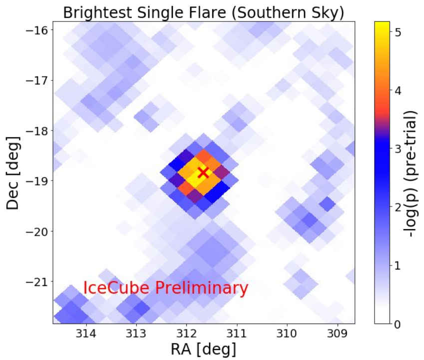


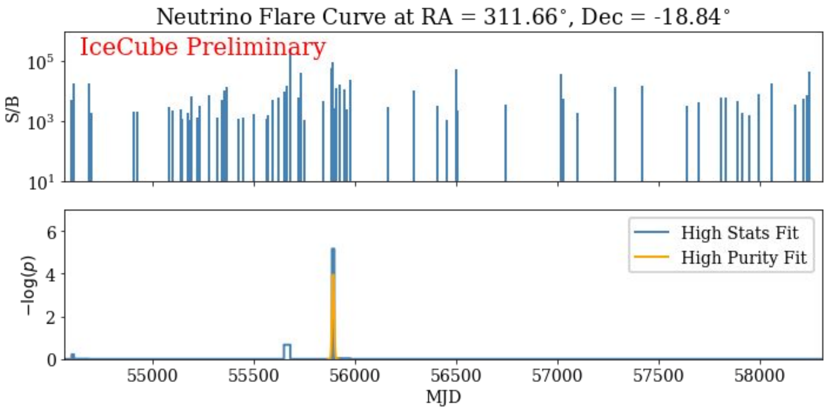
High-Statistics Analysis: Brightest Individual Flares

- Since we fit everything, we can easily extract the standard single flare results
- Northern sky:
  - ○ RA, Dec = 21.97°, -0.60°
  - ○ p (pre-trial) = 5.09×10^{-6}
  - ○ p (post-trial) = 0.82
- Southern sky:
  - ○ RA, Dec = 311.66°, -18.84°
  - ○ p (pre-trial) = 3.55×10^{-7}
  - ○ p (post-trial) = 0.53

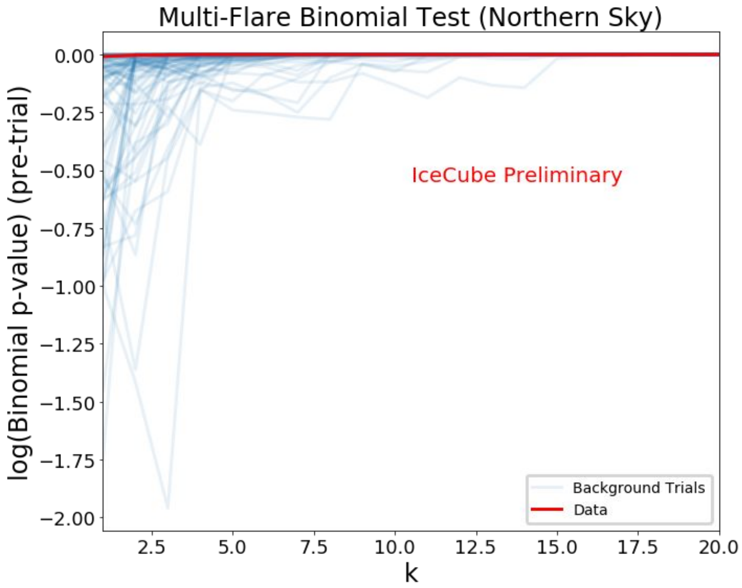

Neutrino Flare Curve at RA = 21.97°, Dec = -0.60°

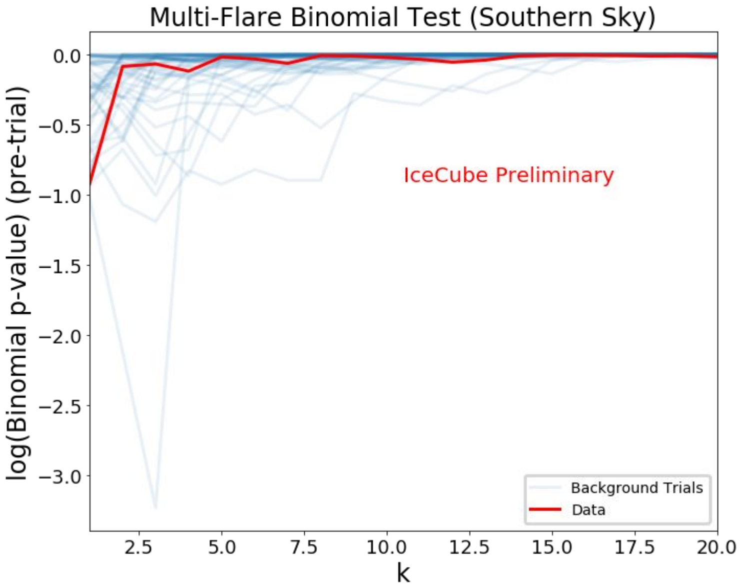

Brightest Single Flare (Northern Sky)


Brightest Single Flare (Southern Sky)


Neutrino Flare Curve at RA = 311.66°, Dec = -18.84°

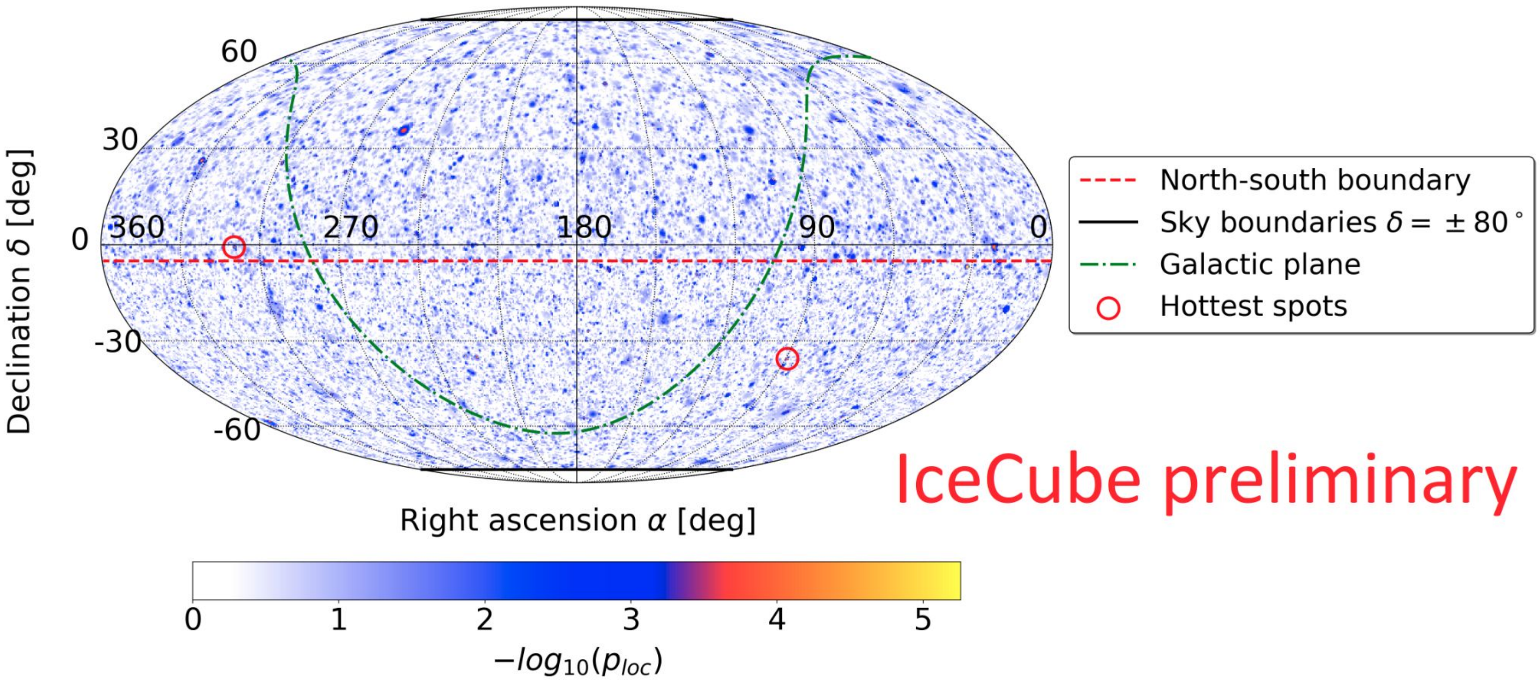
High-Statistics Analysis: Population Analysis





- Binomial tests of multiflare hot spots (>1 degree separation) reveal no significant population excess
    - North: k = 1, p = 0.98
    - South: k = 1, p = 0.12

High-Purity Analysis: Sky Map

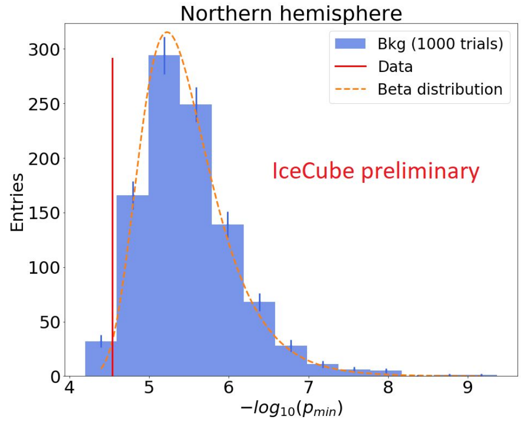


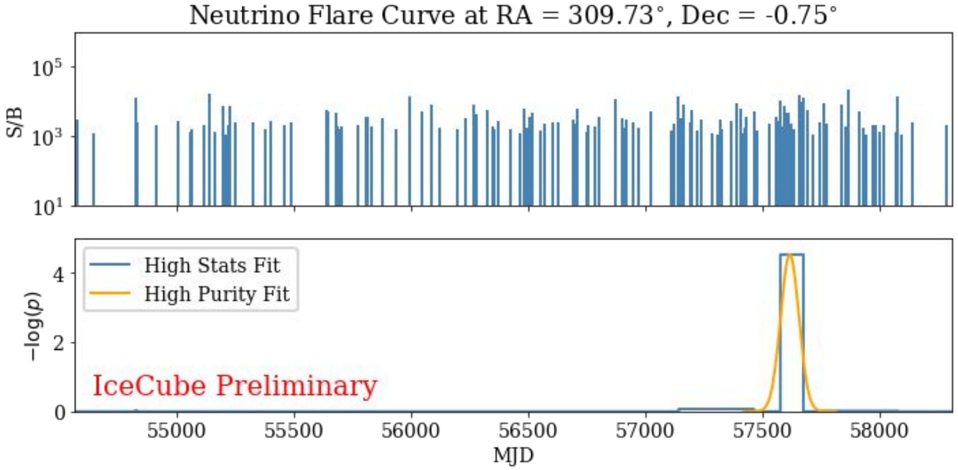
IceCube preliminary

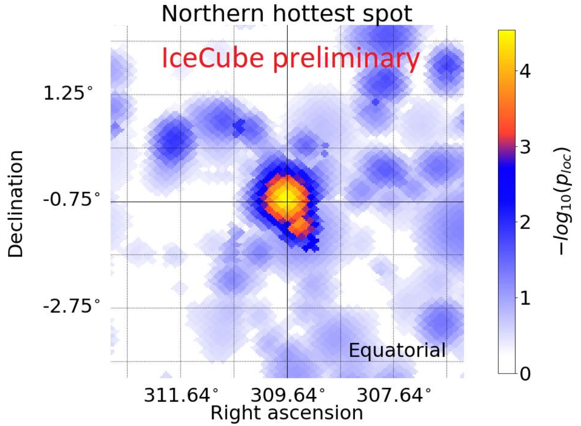
High-Purity Analysis: Northern Hottest Spot

Most significant northern sky pixel:

R.A.	dec	Pre-trial p_{val}	Post-trial p_{val}
309.64°	-0.75°	2.9×10^{-5}	0.98



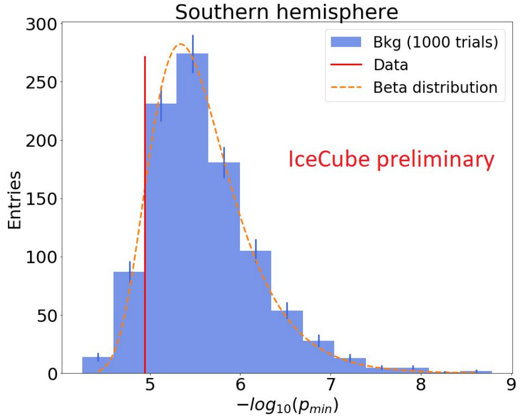


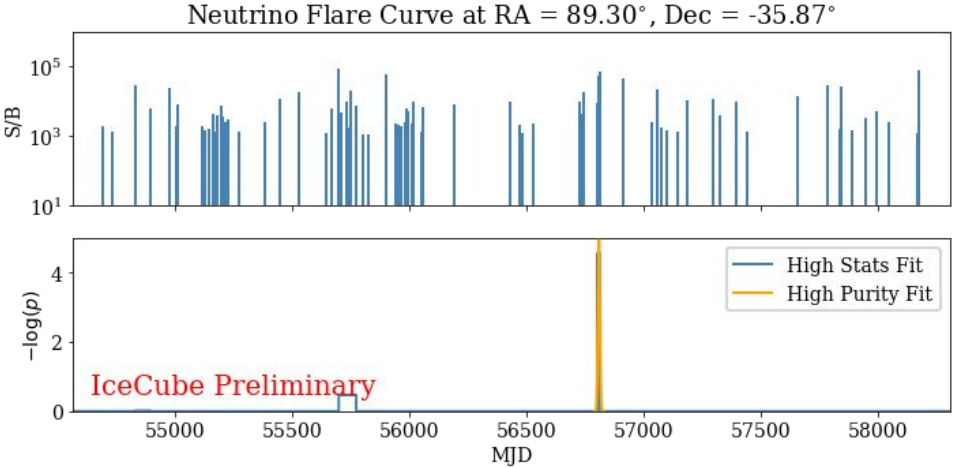


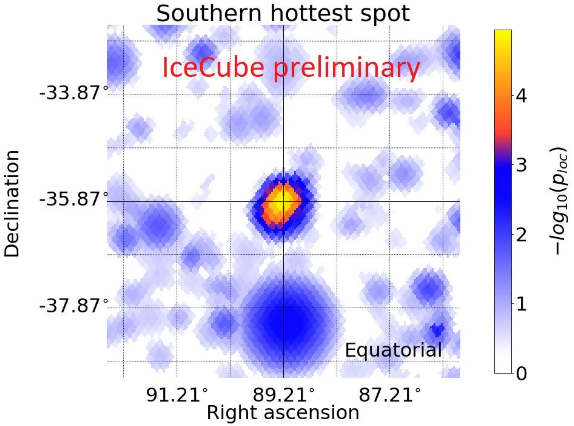
High-Purity Analysis: Southern Hottest Spot

Most significant southern sky pixel:

R.A.	dec	Pre-trial p_{val}	Post-trial p_{val}
89.21°	-35.87°	1.1×10^{-5}	0.90







High-Purity Analysis: Population Test

Based on Poissonian statistics:

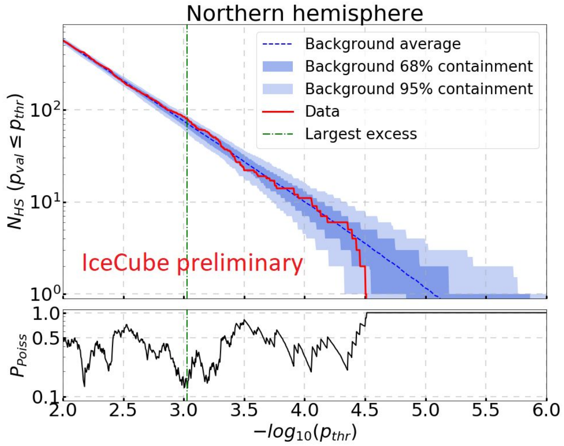
Expected hot spots from background

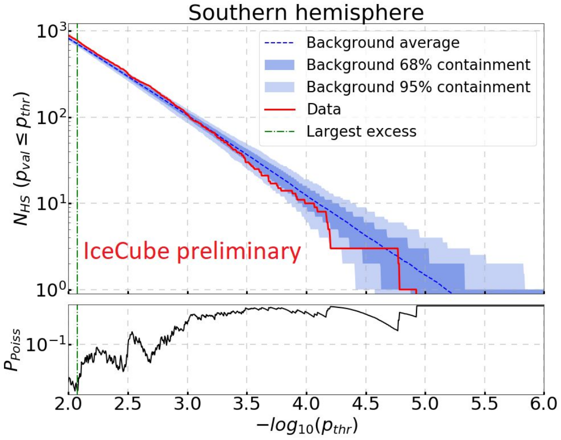
$$P_{Poiss}(p_{thr}) = e^{-\lambda(p_{thr})} \sum_{m=k(p_{thr})}^{\infty} \frac{\lambda(p_{thr})^{m}}{m!}$$

Observed hotspots

No significant excess:

Hemisphere	Pre-trial P_{Poiss}	Post-trial P_{Poiss}
North	0.13	0.85
South	6.0×10^{-3}	0.22



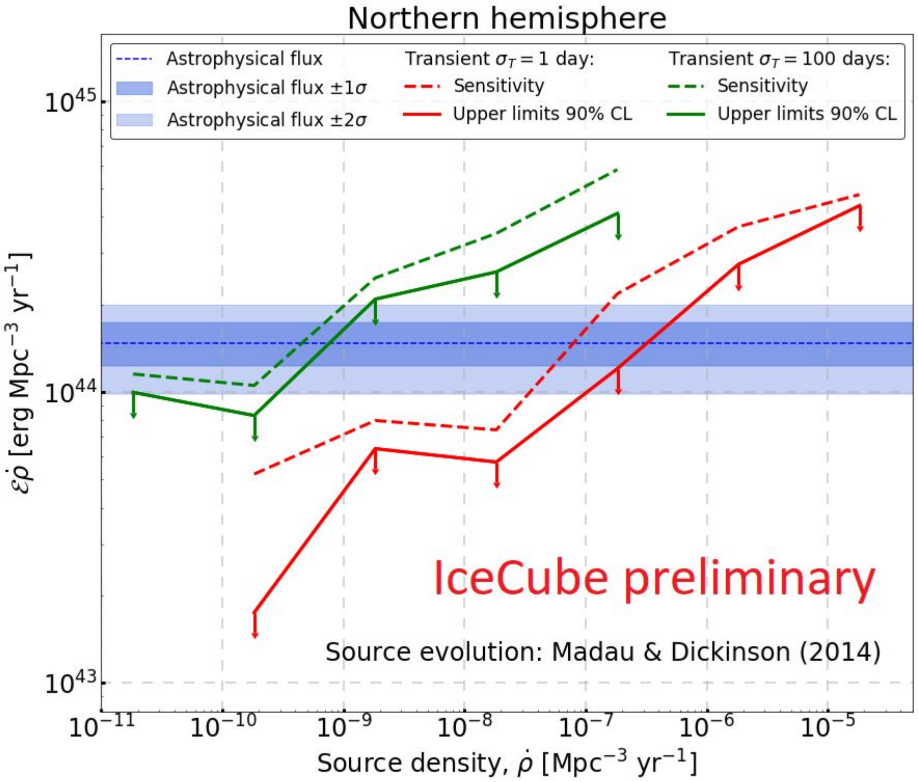


Constraints on Northern Sky Population

Population test in high-purity analysis is used to constrain the luminosity and density of a population of transient sources in northern hemisphere, assuming:

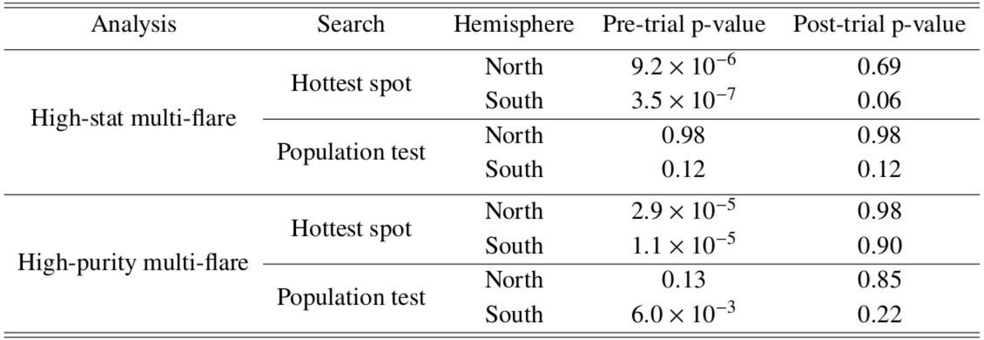
- Isotropic distribution
- Single flares
- Energy dependence $dN/dE \propto E^{-2.28}$
- Time-scale of 1 or 100 days
- Source evolution: Madau & Dickinson (2014)

Simulations of flare intensity and source declinations are made with FIRESONG



Conclusions

- No significant transients are observed
- Constraints are set on transient population in northern sky
- Neutrino lightcurves are produced from all directions in the sky



Analysis	Search	Hemisphere	Pre-trial p-value	Post-trial p-value
High-stat multi-flare	Hottest spot	North	9.2×10^{-6}	0.69
		South	3.5×10^{-7}	0.06
	Population test	North	0.98	0.98
		South	0.12	0.12
High-purity multi-flare	Hottest spot	North	2.9×10^{-5}	0.98
		South	1.1×10^{-5}	0.90
	Population test	North	0.13	0.85
		South	6.0×10^{-3}	0.22

Summary of results

We wish to acknowledge the National Science Foundation and the Fonds National Suisse for their support in this and other IceCube analyses

BACKUP

High-Purity Analysis: Hottest Spot’s Flare Parameters

Northern Hottest Spot

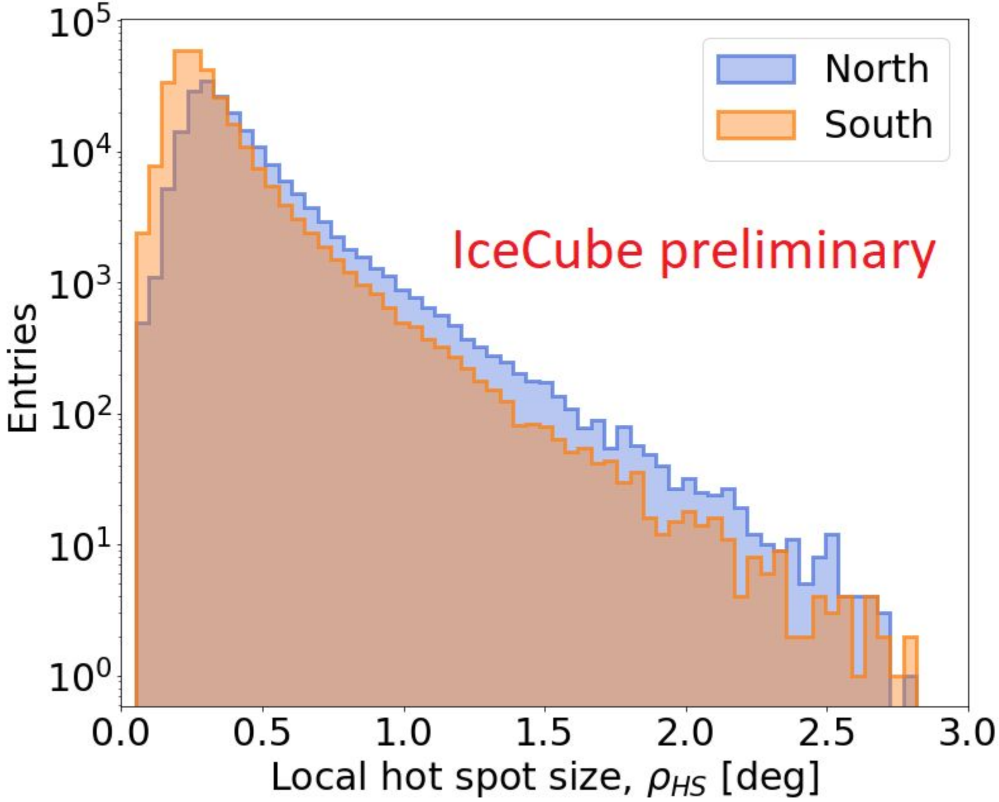
R.A.	dec	n_s	γ	t_0 [MJD]	σ_T [days]	*Pre-trial* p_{val}	*Post-trial* p_{val}
309.64°	-0.75°	21.7	3.0	57615	39	2.9×10^{-5}	0.98

Southern Hottest Spot

R.A.	dec	n_s	γ	t_0 [MJD]	σ_T [days]	*Pre-trial* p_{val}	*Post-trial* p_{val}
89.21°	-35.87°	6.5	2.8	56808.6	4.2	1.1×10^{-5}	0.90

Both hottest spots are single-flare

Local Hot Spots



High-Purity Analysis: Post-Trial p-value Population Test