# A New Method for an Untriggered, Source Stacking Search for Neutrino Flares

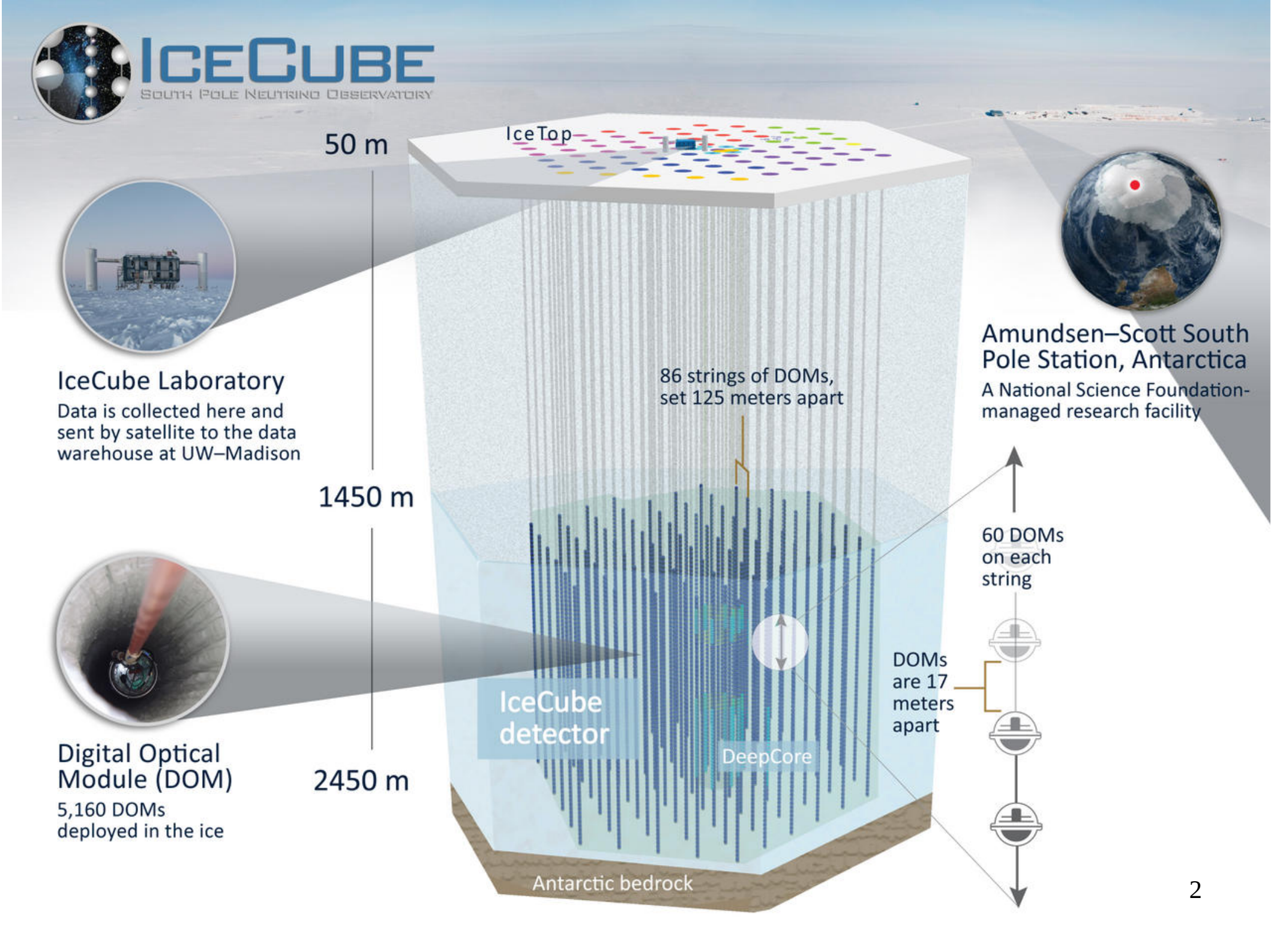
**William Luszczak**, Jim Braun, Albrecht Karle

TeVPA Neutrino Parallel, 12/3/19

IceCube South Pole Neutrino Observatory

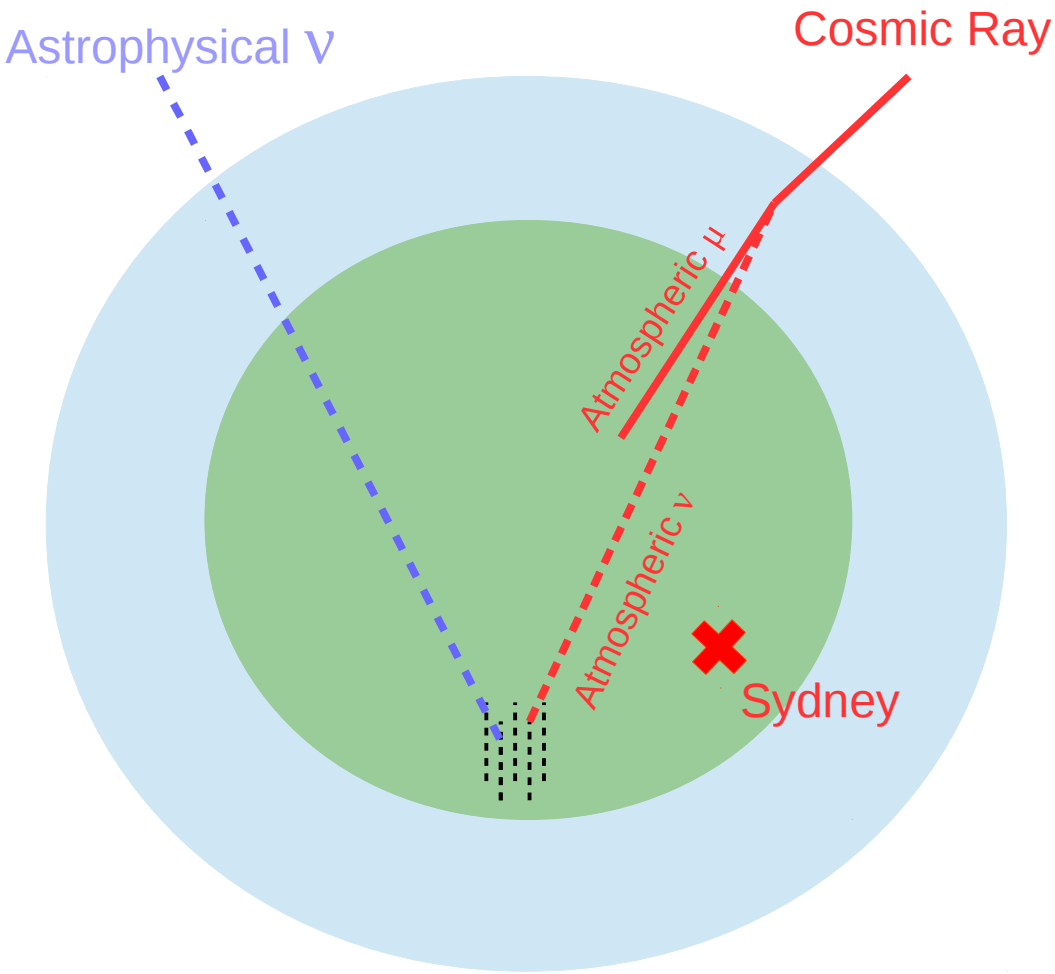
WIPAC

Wisconsin University of Wisconsin-Madison


IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings of DOMs, set 125 meters apart
1450 m
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

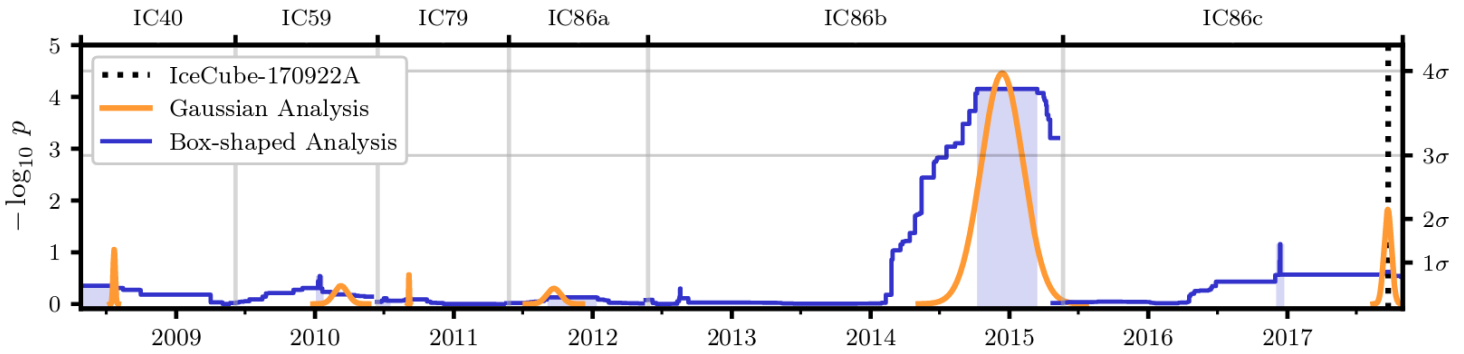
# IceCube Events: Signal and Background

- Northern sky (“upgoing”):
  - Astrophysical neutrinos (signal)
  - Atmospheric neutrinos (background)
- Sample is **high statistics** but **low purity**
- Attempt to distinguish between astrophysical and atmospheric neutrinos on a statistical basis



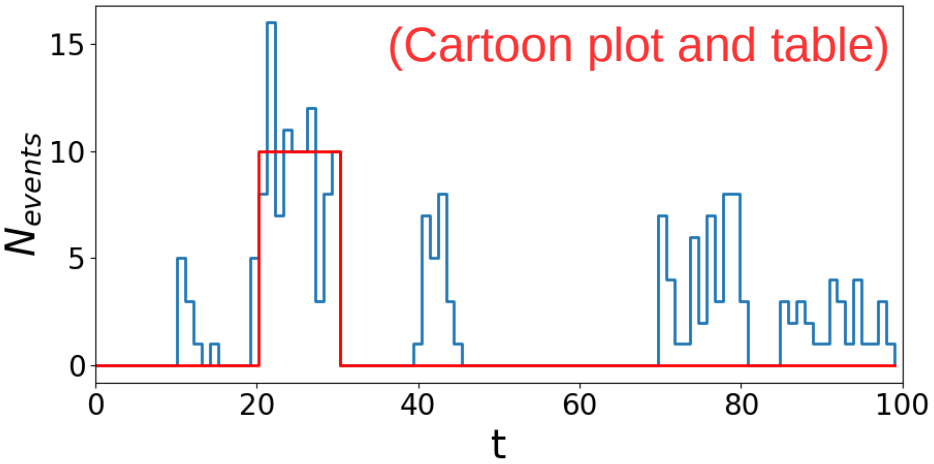
# Existing Clustering Analyses

- September 2017: IceCube observes a high energy neutrino originating from the direction of a flaring blazar (TXS 0506+056)
- ~3 sigma neutrino flare from archival data in 2014-2015
  - No gamma ray counterpart observed for this flare



# A New Method: “Multiflare Stacking”

- A **single flare search (old)** will find the most significant flare for a given source
  - Most sensitive to the case where sources flare 0-1 times on average
- **Multiflare stacking (new)** attempts to use information from <u>all</u> flares
  - Most sensitive to the case where sources flare >2 times on average



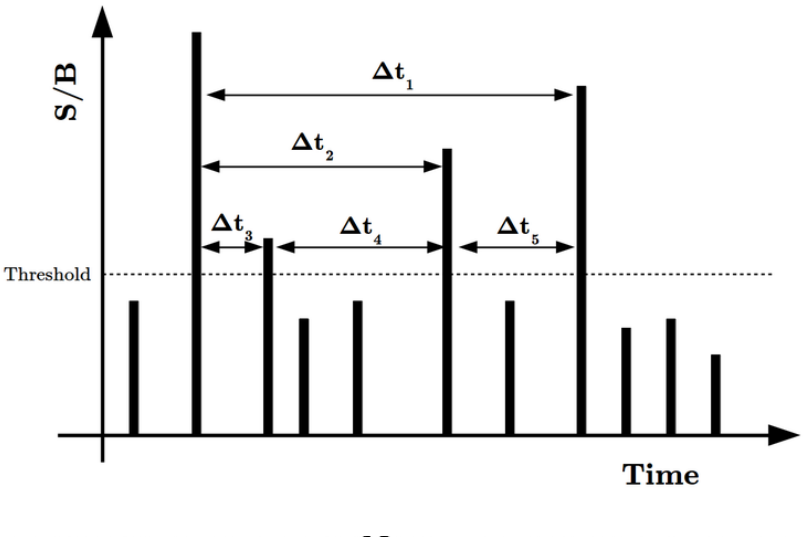

| $t_o$ | Δt | p-val |
|---|---|---|
| 25 | 10 | 1e-3 |
| 43 | 5 | 2e-3 |
| 75 | 10 | 2e-3 |
| 13 | 5 | 3e-3 |
| 94 | 15 | 4e-3 |

A single flare search will only report this value

Multiflare stacking attempts to combine information from all flares

# Multiflare Stacking: Method

- ICRC proceedings:
  - https://pos.sissa.it/358/950/pdf
- Expand on single flare method:
  - Define a set of box-shaped test windows, each starting and ending on an event



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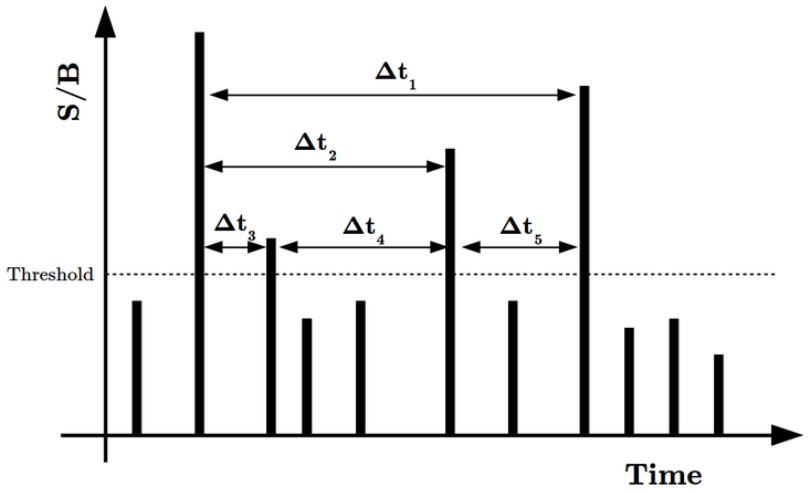
  - Calculate a flare test statistic for each window ($TS_j$)




$$\mathcal{L}(n_s, \gamma, \Delta t_j) = \prod_{i=1}^{N} \frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i$$

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

Spatial PDF ("What is the probability that an event at $\mathbf{r}_i$ originated from $\mathbf{r}_o$")

Energy PDF ("What is the probability that an event with energy $E_i$ originated from a source with spectral index $\gamma$?")

Temporal PDF ("What is the probability that an event at $t_i$ came from a flare at $t_o$, with width $\Delta t$?")

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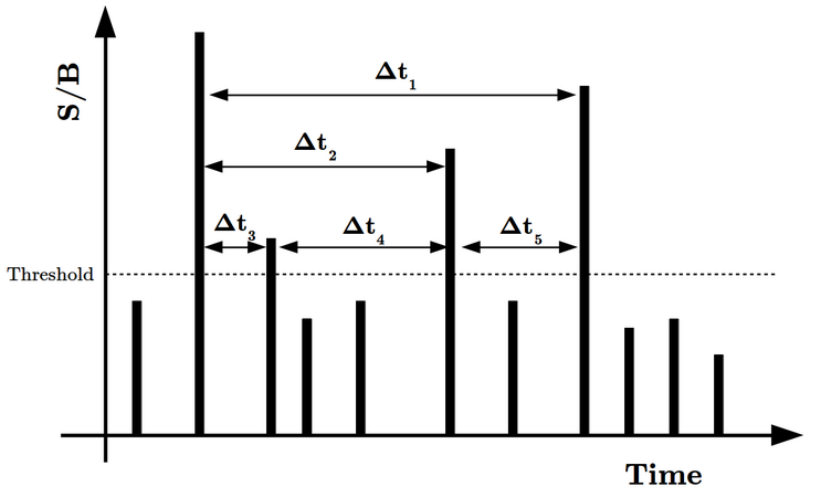


$$\mathcal{L}(n_s, \gamma, \Delta t_j) = \prod_{i=1}^{N} \frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i$$

$$\mathrm{TS}_j|_{\Delta t_j} = -2 \log \left[ \frac{\Delta T_{\mathrm{data}}}{\Delta t_j} \times \frac{\mathcal{L}(\vec{x}_s, n_s = 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma}_s)} \right]$$

# Multiflare Stacking: Method

- ICRC proceedings:
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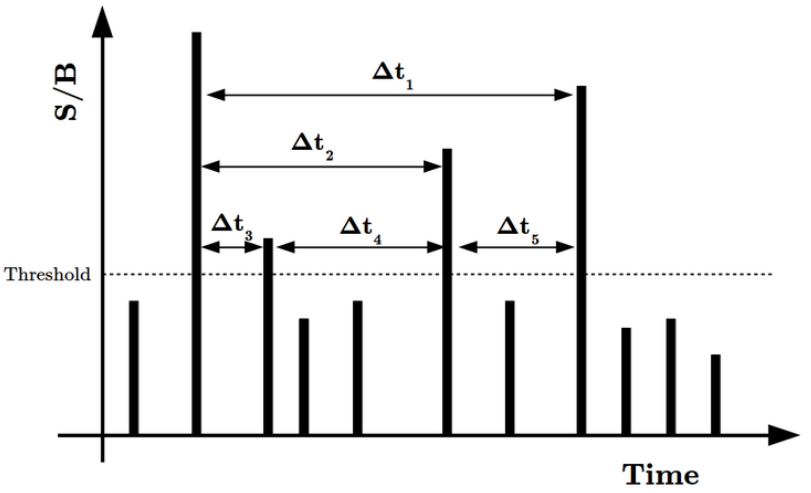
- Expand on single flare method:
  - Define a set of box-shaped test windows, each starting and ending on an event
  - Calculate a flare test statistic for each window ($TS_j$)
  - Sum $TS_j$ associated with **non-overlapping, positive $TS_j$** flares only
    - If two signal-like flares overlap, only take $TS_j$, $ns_j$ from the flare with the **larger** $TS_j$ value

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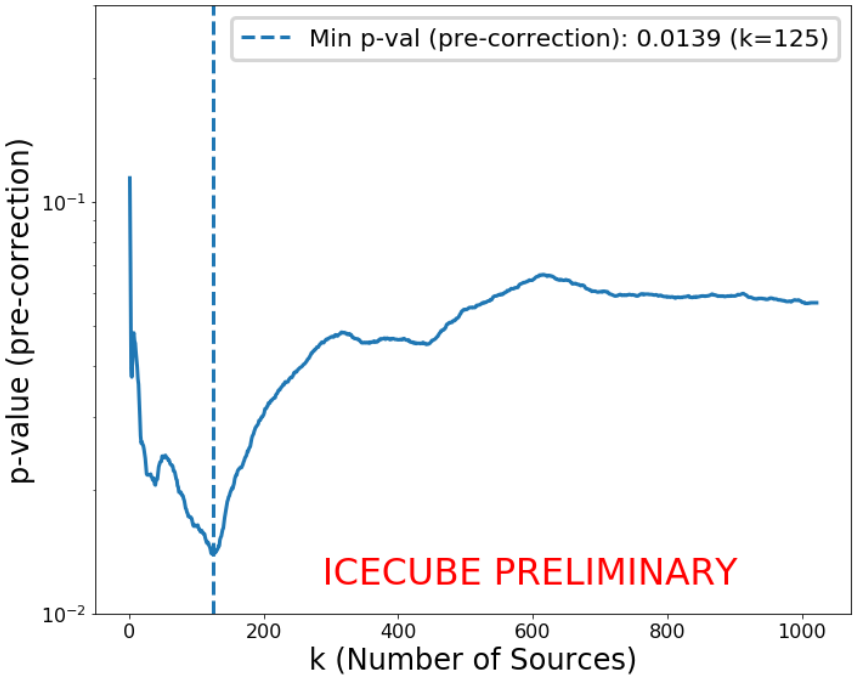
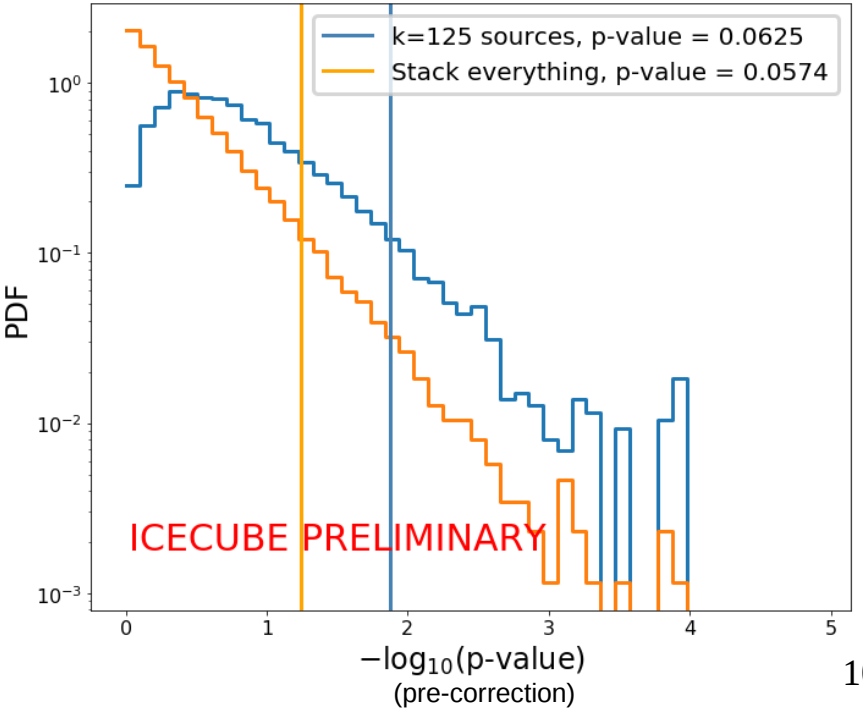
$$\widetilde{TS}_{new} = \sum_{j|TS_j>0} TS_j$$

# 3LAC Blazars: Results

- Northern sky 3LAC blazars (1023 sources)
- Result associated with stacking entire catalog:
  - **p-value = 0.05736 (1.57 sigma)**
- Result associated with optimizing number of sources:
  - **k (best fit number of sources) = 125**
  - **p-value = 0.06254 (1.53 sigma)**



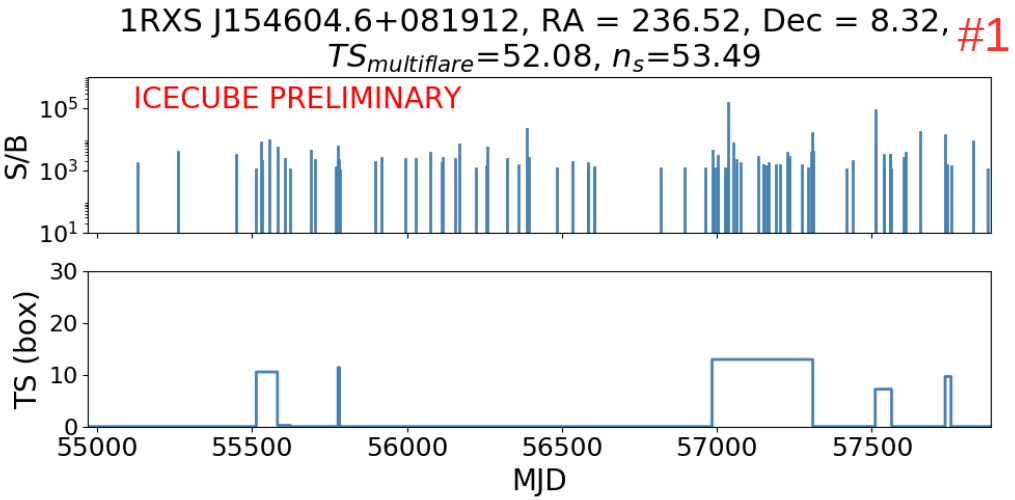



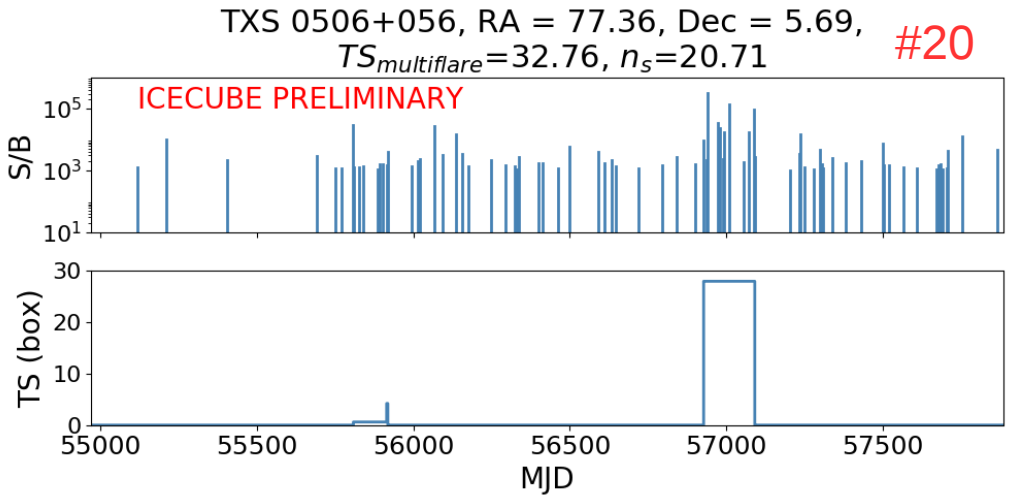
# Blazar Catalog Results: Top 10 Sources

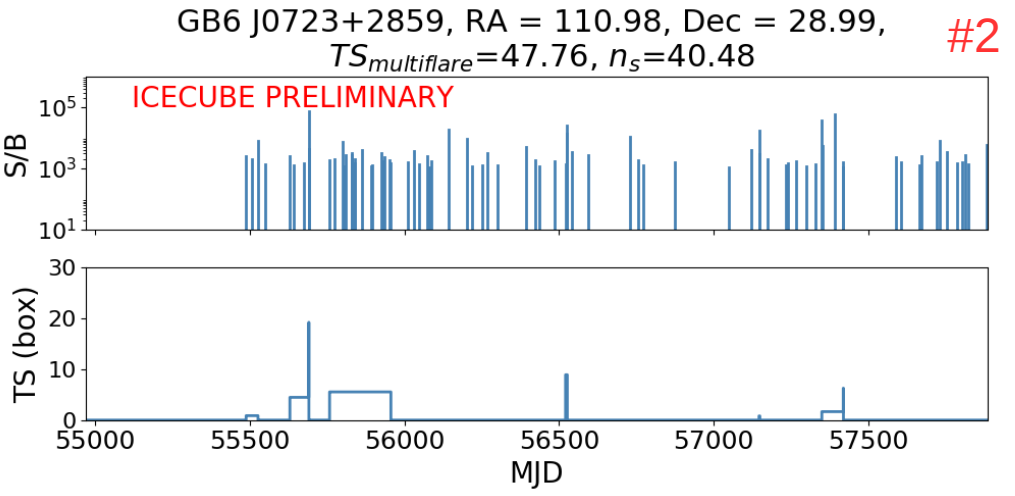
| Name | RA | Dec | Class | TS | ns | p-val (pre-trial) |
|---|---|---|---|---|---|---|
| 1RXS J154604.6+081912 | 236.52 | 8.32 | bll | 52.08 | 53.49 | 8.11e-5 |
| GB6 J0723+2859 | 110.97 | 28.99 | fsrq | 47.75 | 40.48 | 4.58e-4 |
| RBS 1467 | 227.18 | 27.15 | bll | 46.55 | 55.11 | 3.05e-4 |
| RBS 1558 | 241.59 | 56.51 | bll | 41.48 | 28.88 | 1.91e-3 |
| PMN J2324+0801 | 351.18 | 8.03 | bll | 35.40 | 28.15 | 3.11e-3 |
| B2 2214+24B | 334.25 | 24.36 | bll | 39.18 | 36.90 | 3.78e-3 |
| GB6 J0850+4855 | 132.50 | 48.92 | bll | 37.43 | 38.18 | 4.75e-3 |
| 4C +20.25 | 171.49 | 20.10 | fsrq | 37.28 | 27.83 | 5.02e-3 |
| MG2 J094148+2728 | 145.45 | 27.48 | fsrq | 36.01 | 60.58 | 5.12e-3 |
| TXS 2241+406 | 341.05 | 40.95 | bll | 36.12 | 22.61 | 5.22e-3 |
| TXS 0213+619 | 34.26 | 62.19 | bcu III | 37.38 | 30.15 | 5.32e-3 |

# 3LAC Blazars: Flare Curves

- Can use this to produce neutrino “light curves” (“flare curves”)
- TXS 0506+056 is #20 in terms of multiflare significance
  - 3.5 sigma untriggered flare in 2014/15
  - DOI:10.1126/science.aat2890



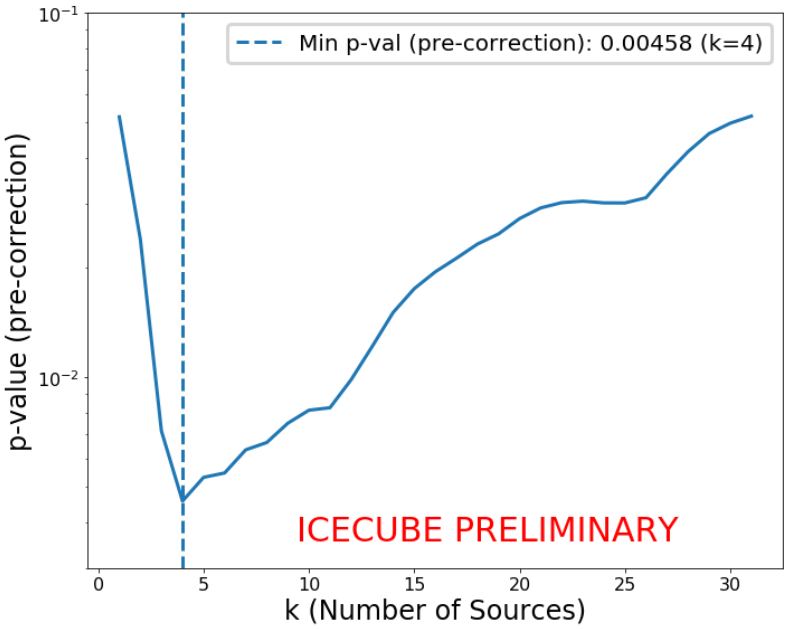



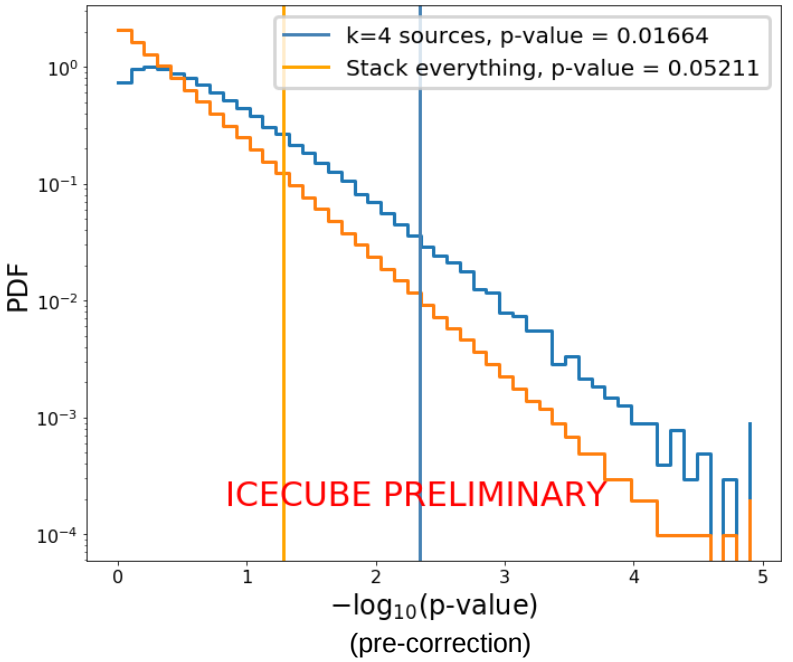



# “Self-Triggered” Catalog: Results

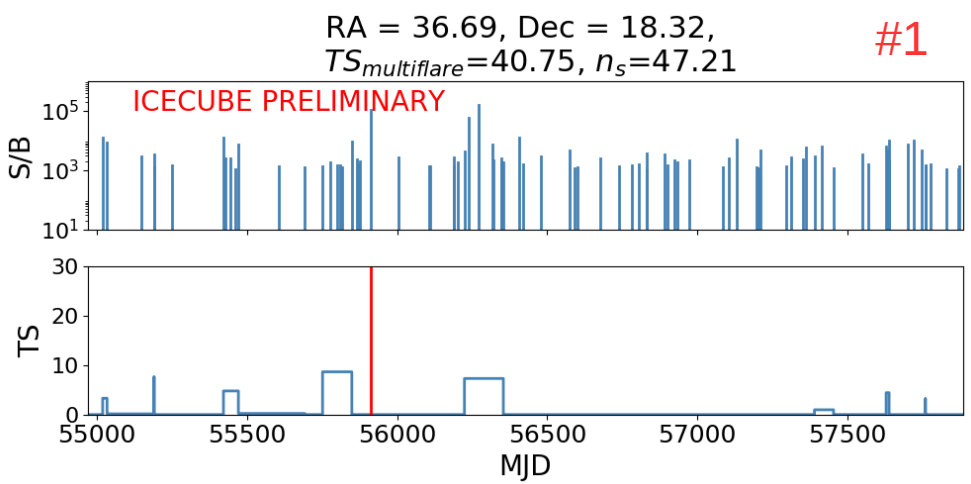
- Use locations of northern sky IceCube events with reconstructed energy > 200 TeV as “sources” (32 locations)
  - Similar to analysis done by Martina Karl: https://pos.sissa.it/358/929/pdf
- Result associated with stacking entire catalog:
  - **p-value = 0.05211 (1.62 sigma)**
- Result associated with optimizing number of sources:
  - **k (best fit number of sources) = 4**
  - **p-value: 0.01664 (2.13 sigma)**

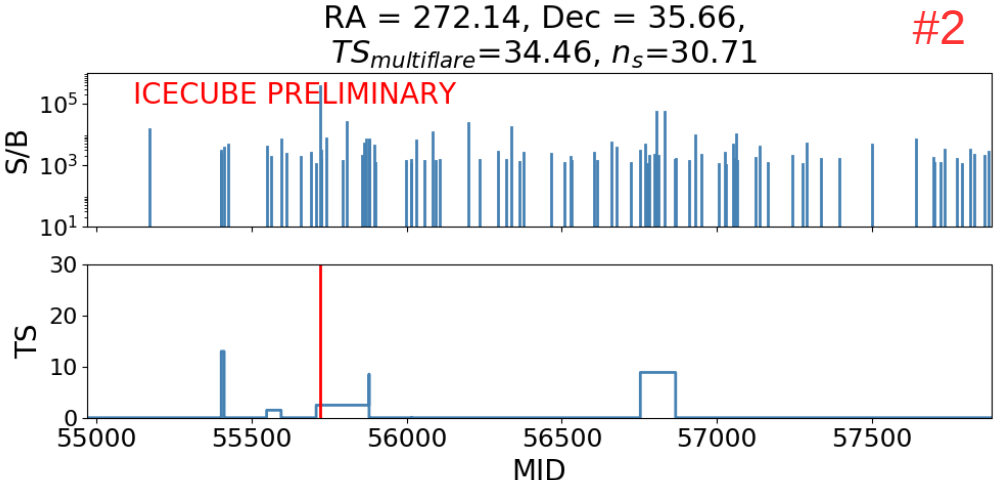
| RA | Dec | TS | ns | P-value (pre-trial) |
|---|---|---|---|---|
| 36.69 | 18.32 | 40.75 | 47.21 | .00197 |
| 272.14 | 35.66 | 34.36 | 30.71 | .00729 |
| 170.19 | 27.85 | 34.30 | 45.75 | .00834 |
| 93.26 | 16.33 | 28.70 | 30.02 | .02667 |

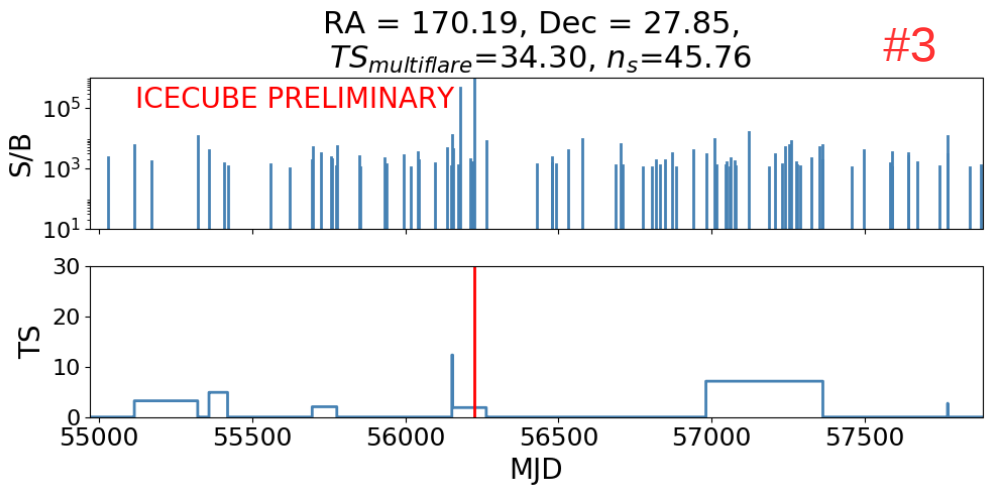


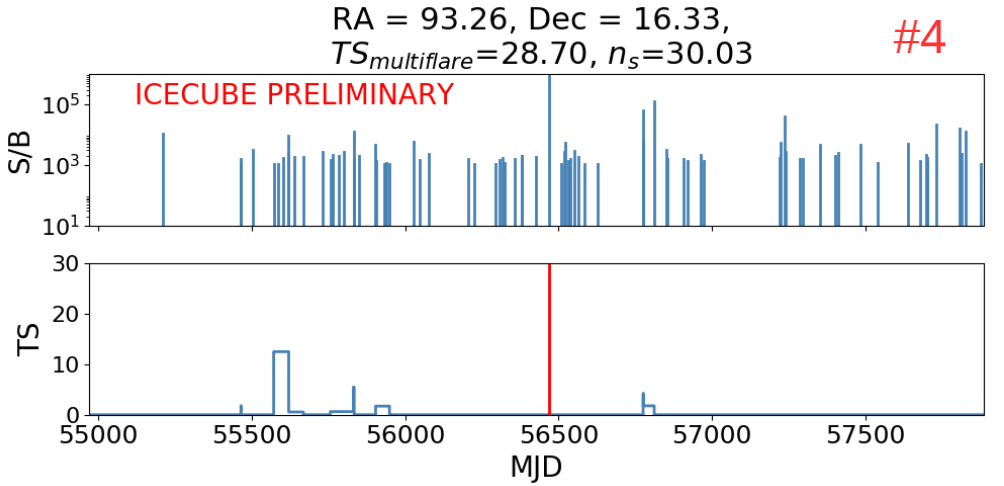



# “Self-Triggered” Catalog: Flare Curves




*Red line marks the arrival time of the high-energy “seed” event that defines the “source” location

# Existing Clustering Analyses

| | **Time Independent** | **Untriggered Time-Dependent** |
|---|---|---|
| **Single-Source Searches** | “Standard” PS analysis (DOI: 10.3847/1538-4357/835/2/151) | Single flare analysis (DOI:10.1126/science.aat2890) |
| **Source Stacking** | Blazar catalog analysis (DOI:10.3847/1538-4357/835/1/45) | This analysis! (Multiflare stacking) |

# Summary and Conclusion

- New method (multiflare stacking) allows us to perform an untriggered, time-dependent, source stacking search for neutrino flares
- New method applied to two different catalogs:
  - Northern sky 3LAC blazars:
    - **p=0.05736 (full catalog)**
    - **p=0.06254 (k=125 sources)**
  - “Self-triggered” catalog:
    - **p=0.05211 (full catalog)**
    - **p=0.01664 (k=4 sources)**
- Paper in progress, plan to publish in ApJ in early 2020
  - “Flare curves” produced for each source, planned for release alongside paper
- Full multiflare skymap in the works
  - Every flare, everywhere

Thanks for listening!

# Backup Slides

# Hypothesis Testing for Flares

Past analyses use a likelihood based construction to attempt to fit a **single flare** to the data:

$$\mathcal{L}(n_s, \gamma, t_o, \Delta t) = \prod_{i=1}^{N} \left[ \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right]$$

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

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

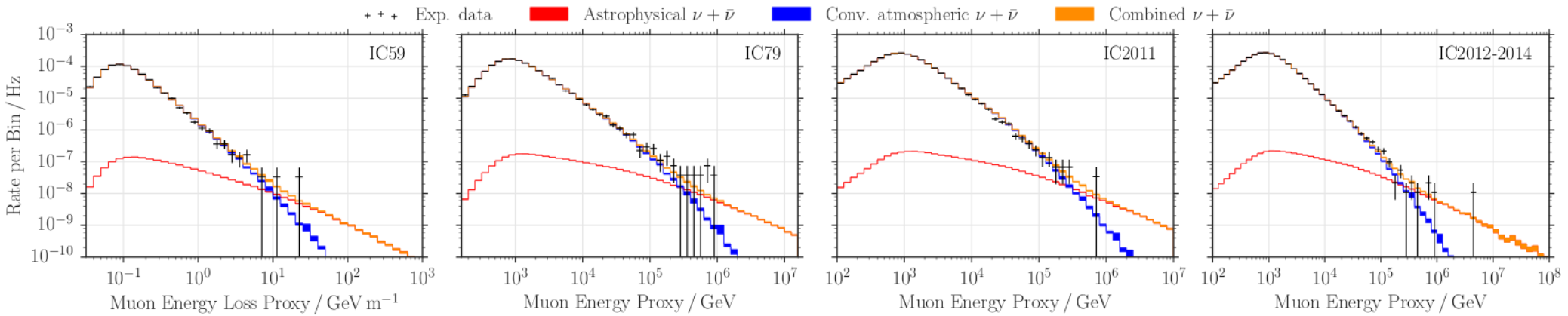
Spatial PDF ("What is the probability that an event at $\mathbf{r}_i$ originated from $\mathbf{r}_o$")

Energy PDF ("What is the probability that an event with energy $E_i$ originated from a source with spectral index $\gamma$?")

Temporal PDF ("What is the probability that an event at $t_i$ came from a flare at $t_o$, with width $\Delta t$?")

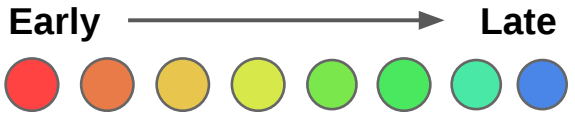
Same questions, but assuming the event is a background (atmospheric) event

$$TS = -2log\left[\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(n_s = \hat{n}_s)}\right]$$

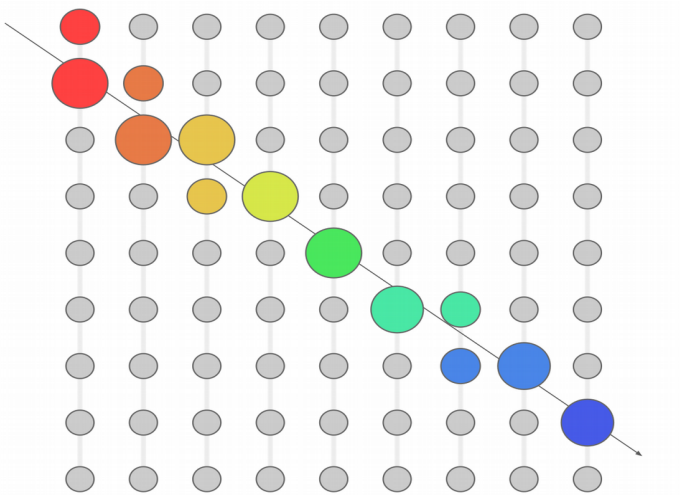



- "Observation and Characterization of a Cosmic Muon Neutrino Flux from the Northern Hemisphere using six years of IceCube data", DOI: 10.3847/0004-637X/833/1/3

# IceCube Event Types



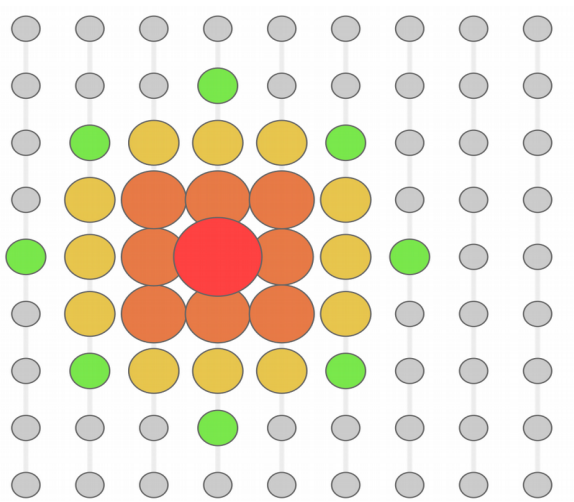

Track



$$\nu_\mu + X \rightarrow \mu^+ + Hadrons$$

- Factor of ~2 energy resolution
- < 1 degree angular resolution

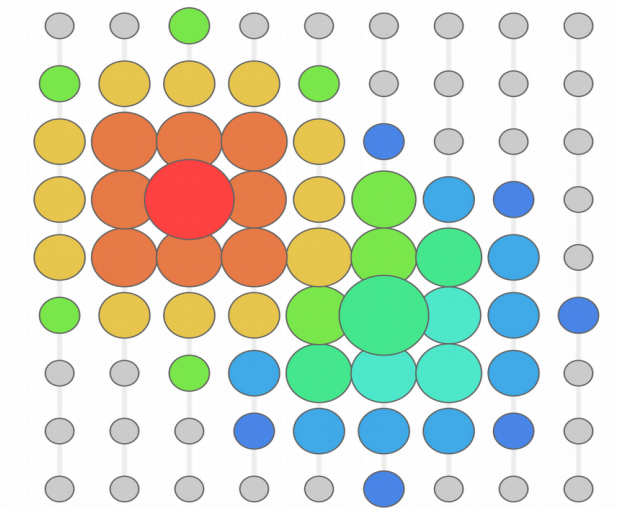
Cascade



$$\nu_e + X \rightarrow e^+ + Hadrons$$

- 15% deposited energy resolution
- ~10 degree angular resolution above 100 TeV

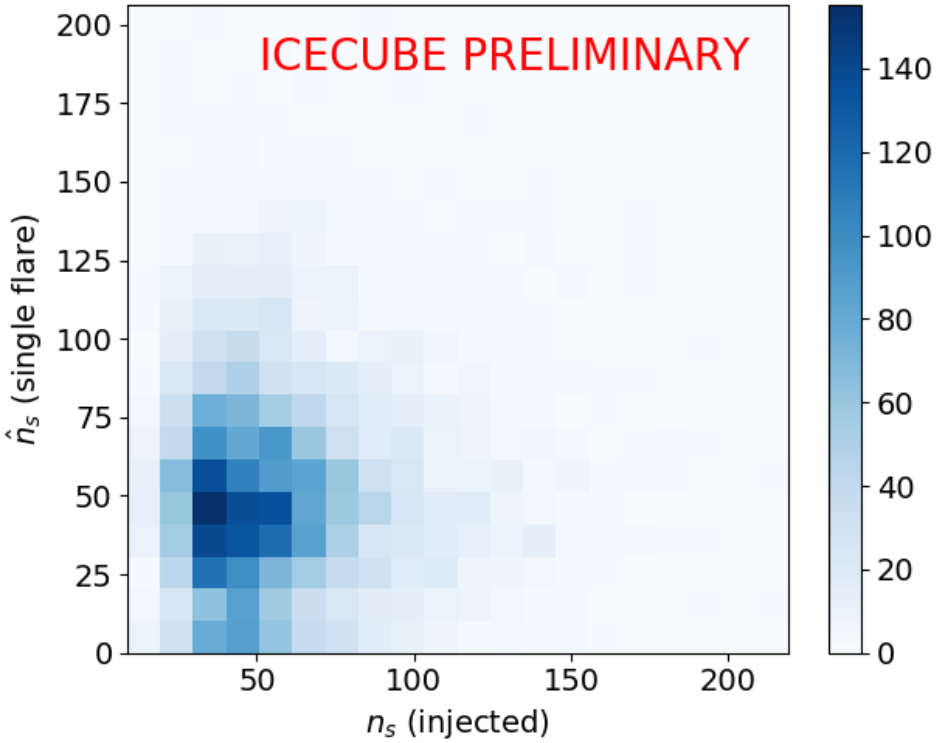
Double Cascade

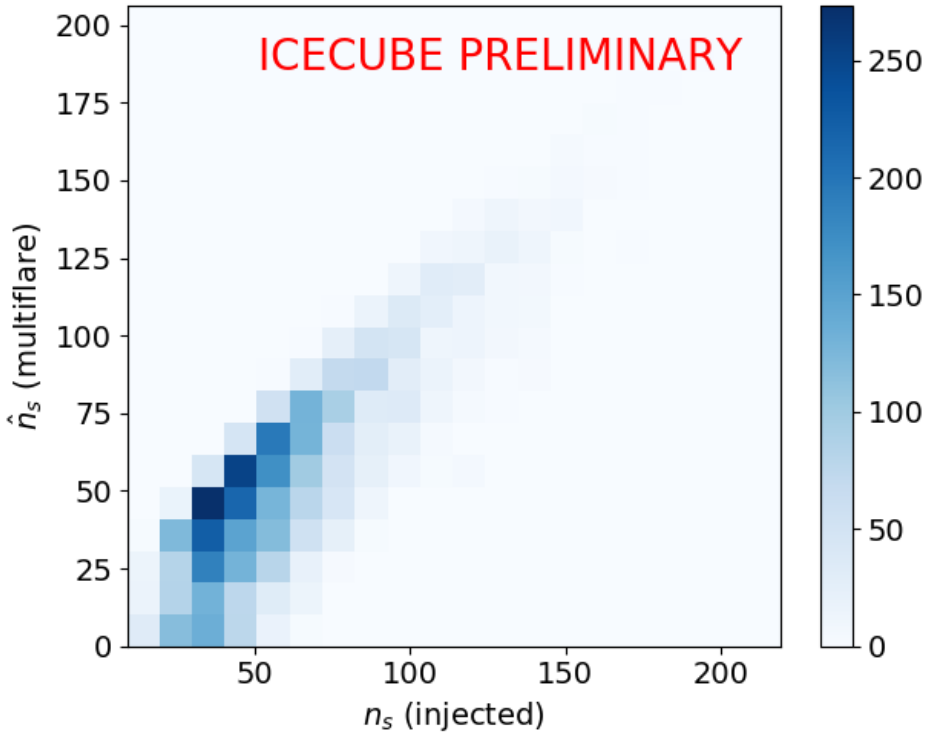


$$\nu_\tau + X \rightarrow \tau^+ + Hadrons$$
$$\tau^+ \rightarrow \bar{\nu}_\tau + \pi^+ + \pi^o$$

- Morphology observed recently (2017)
- Decay length is 50m/PeV

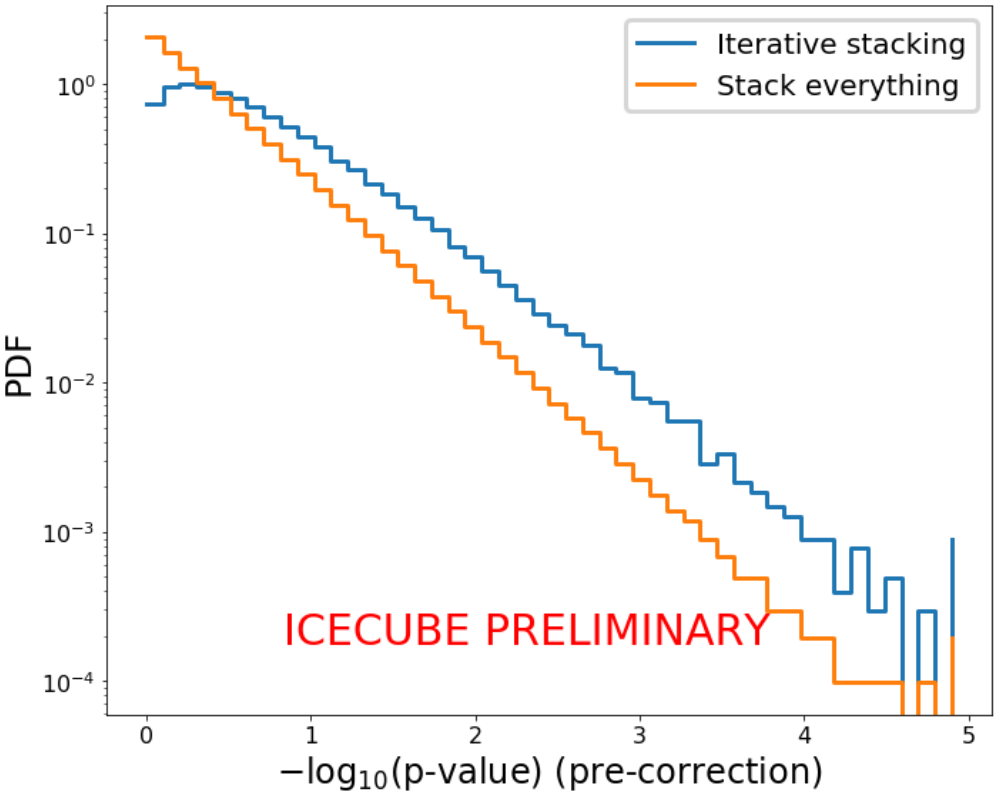
# Recovering Injected Signal



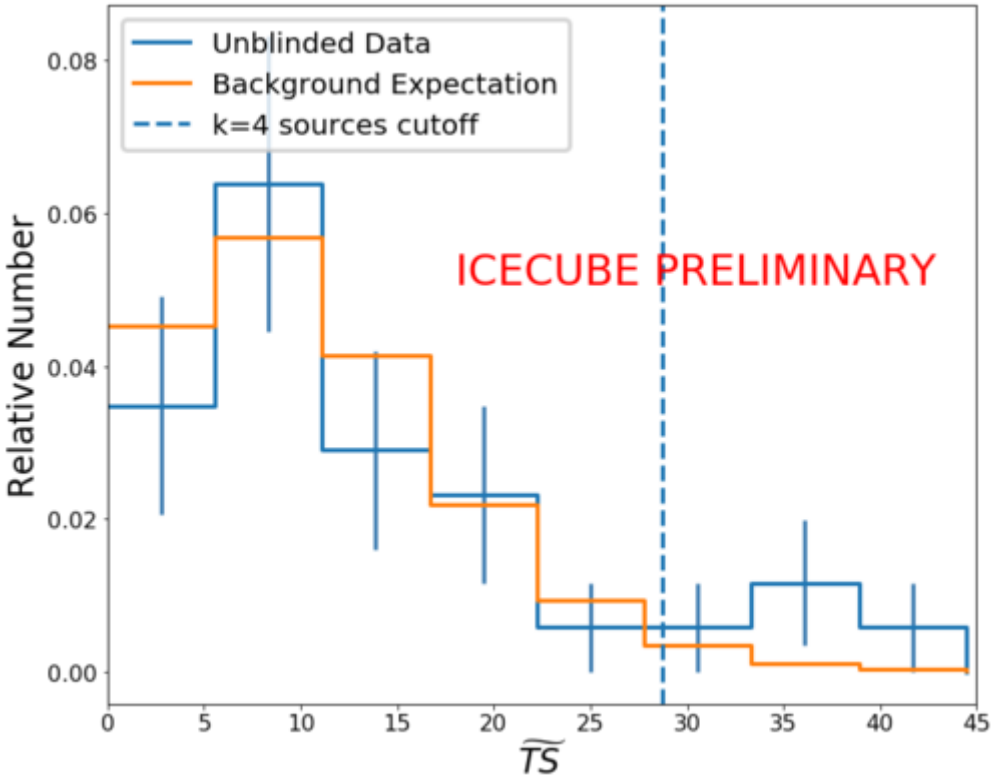



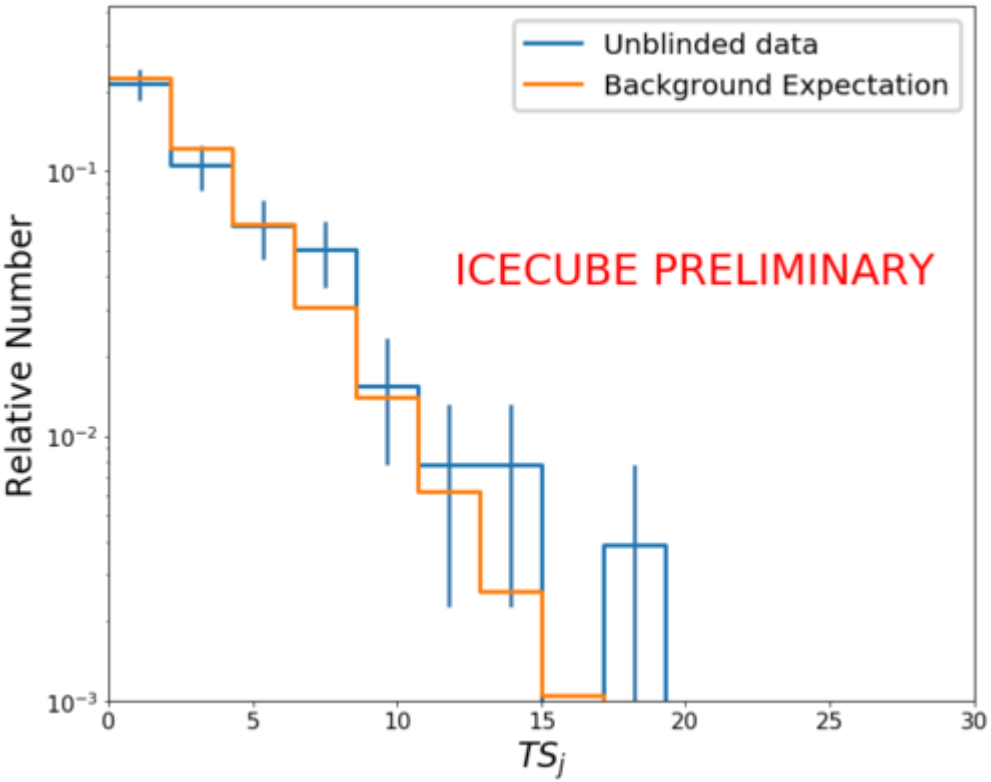
# “Iterative” Stacking

- Problem: Stacking too many sources is likely to drown out signal
- Solution: Stack only the k most significant sources
  - Iterate over k to find minimum p-value
  - Account for correlations and trial factor with background scrambles

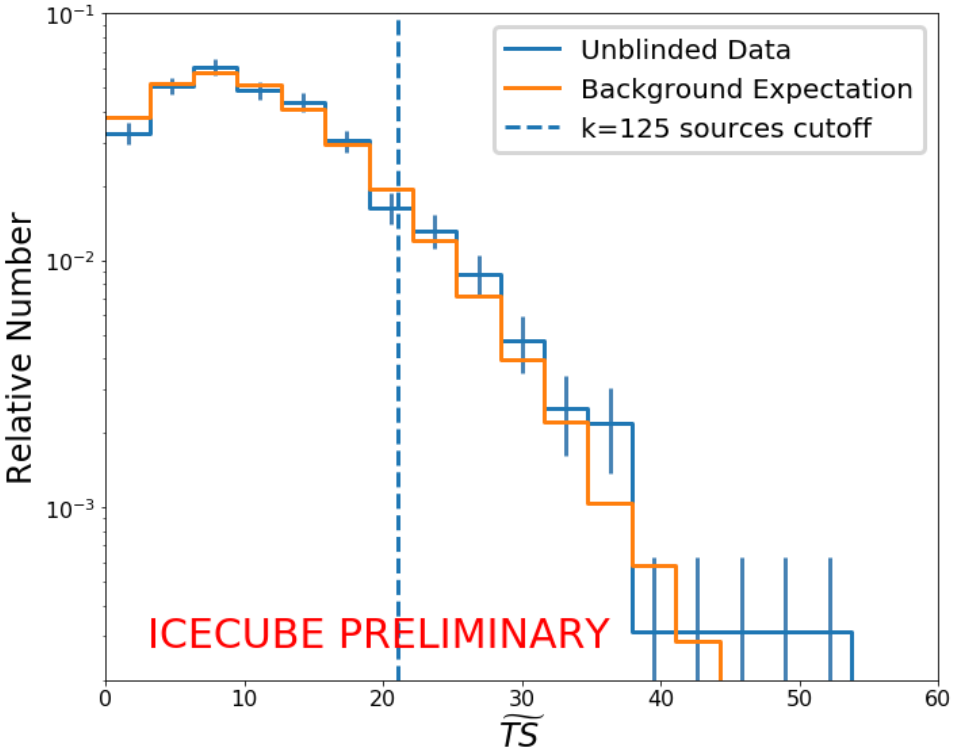


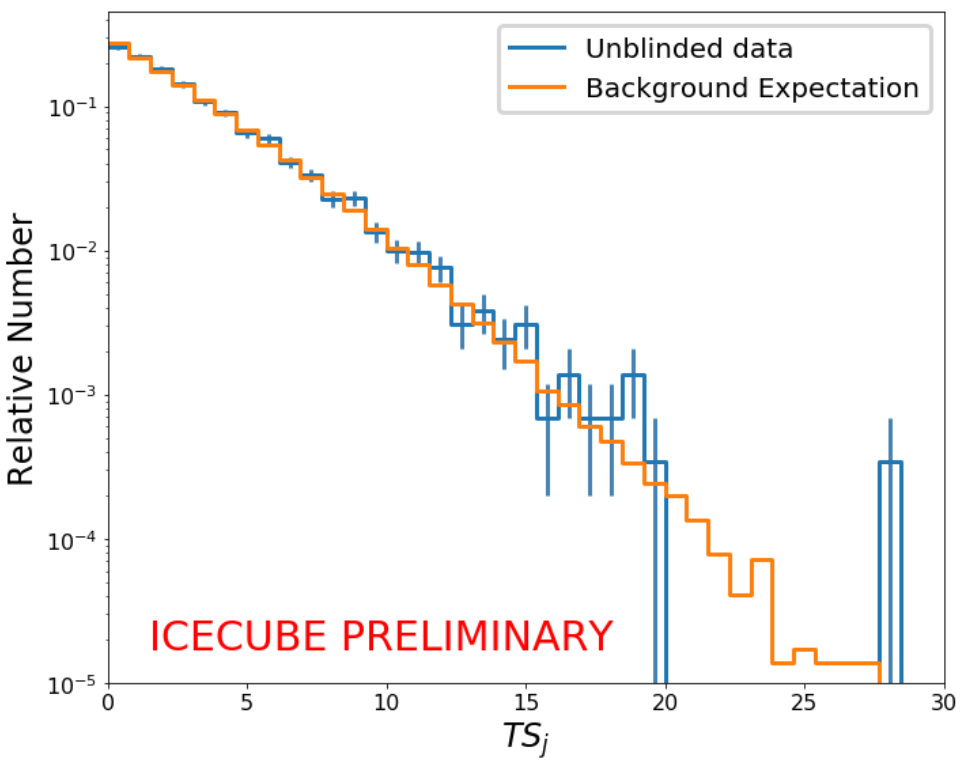
# Self-Triggered Catalog: TS Distributions



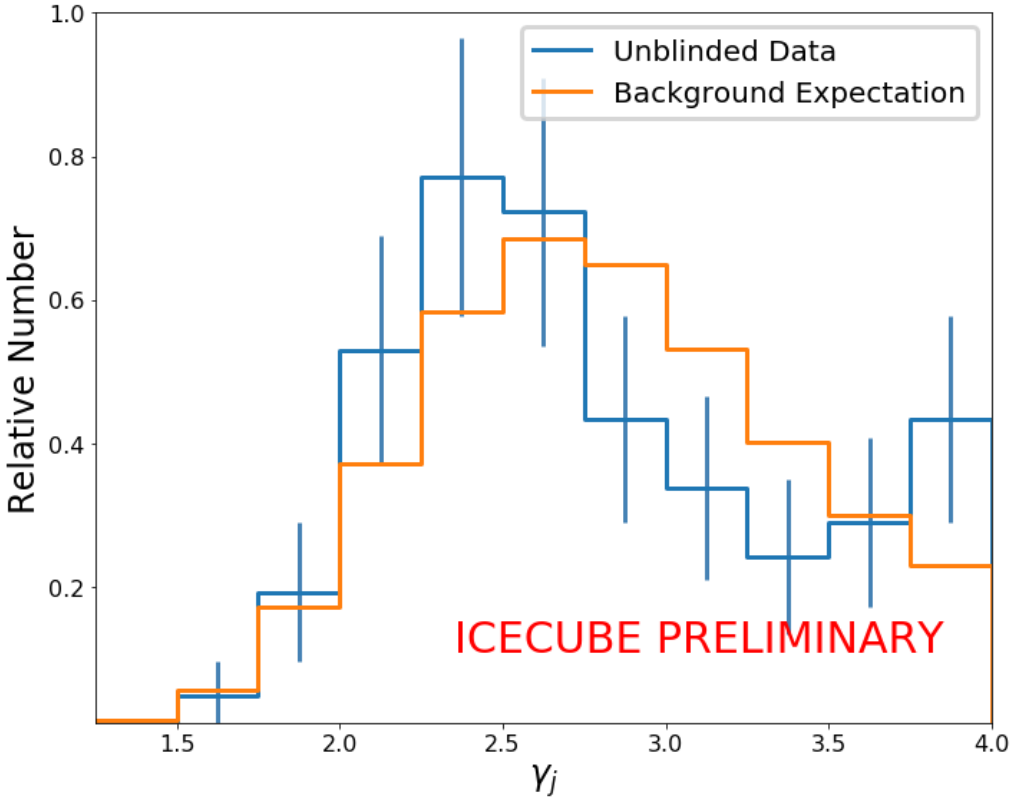



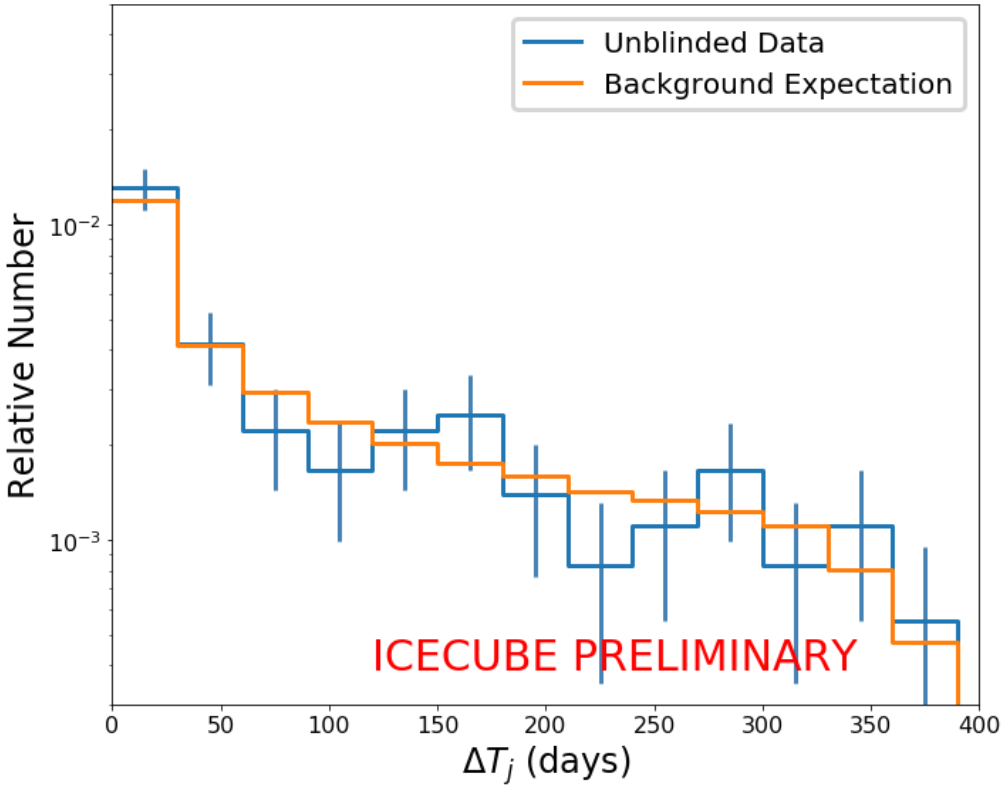
# 3LAC Blazars: TS Distributions



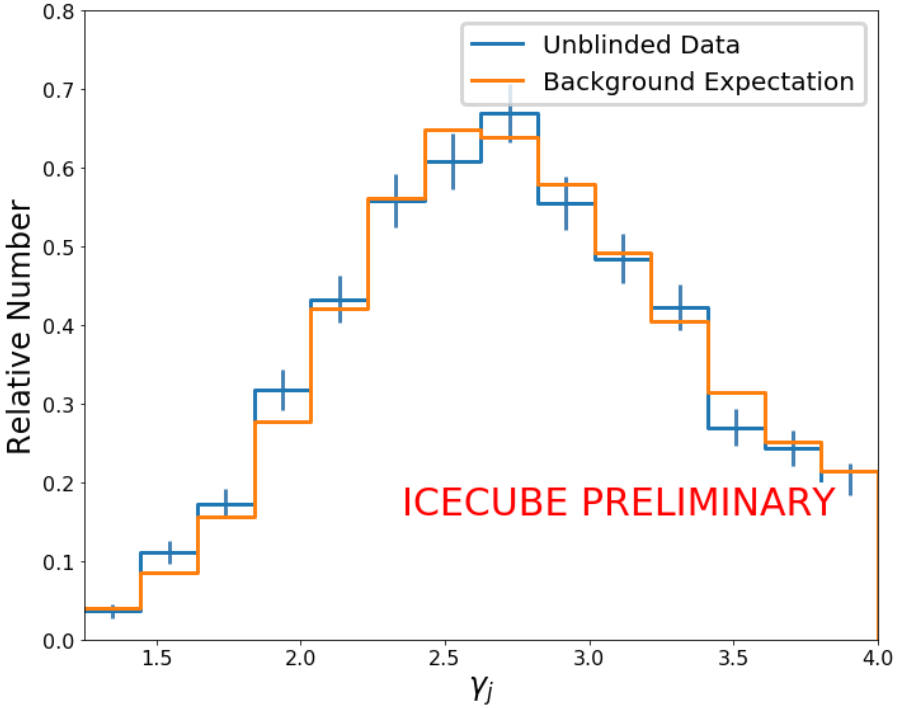



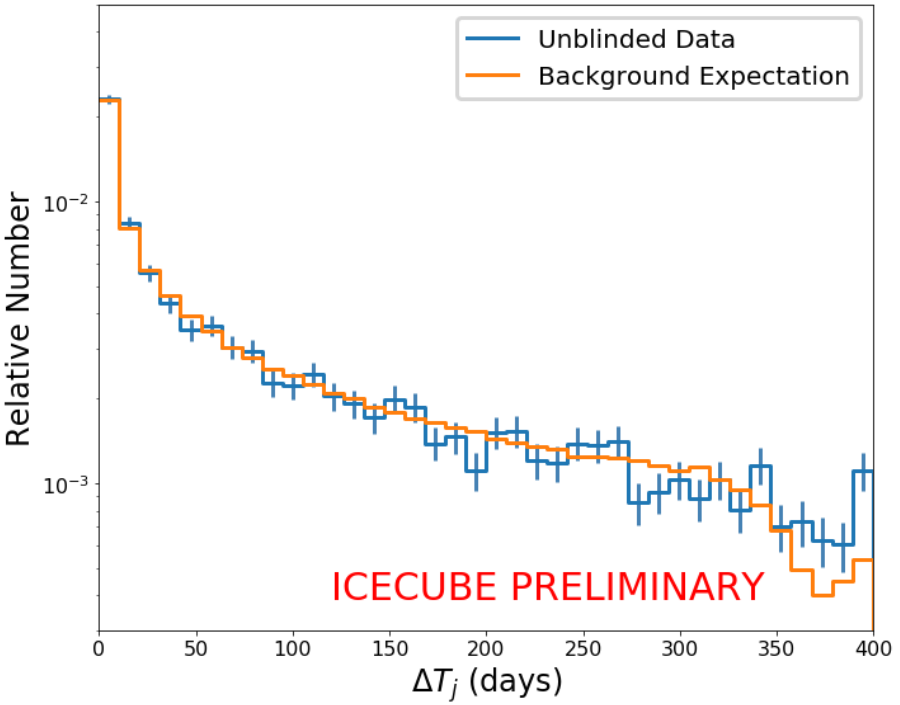
# Self Triggered Catalog: Flare Parameter Distributions



# Blazar Catalog: Flare Parameter Distributions



# Some Other Interesting Flare Curves

- A few sources with seed events on top of flares
- 7 seed event/flare correlations (out of 32 sources)
- Likely triplets of events where 1 event is very high energy
- Some quick background scrambles give a correlation significance of around 11%
  - 11% of background trials with random seed event times produce 7 or more sources with correlations