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# IceCube Starting Tracks and Southern Hemisphere

MANTs Meeting | 1-2 October 2016

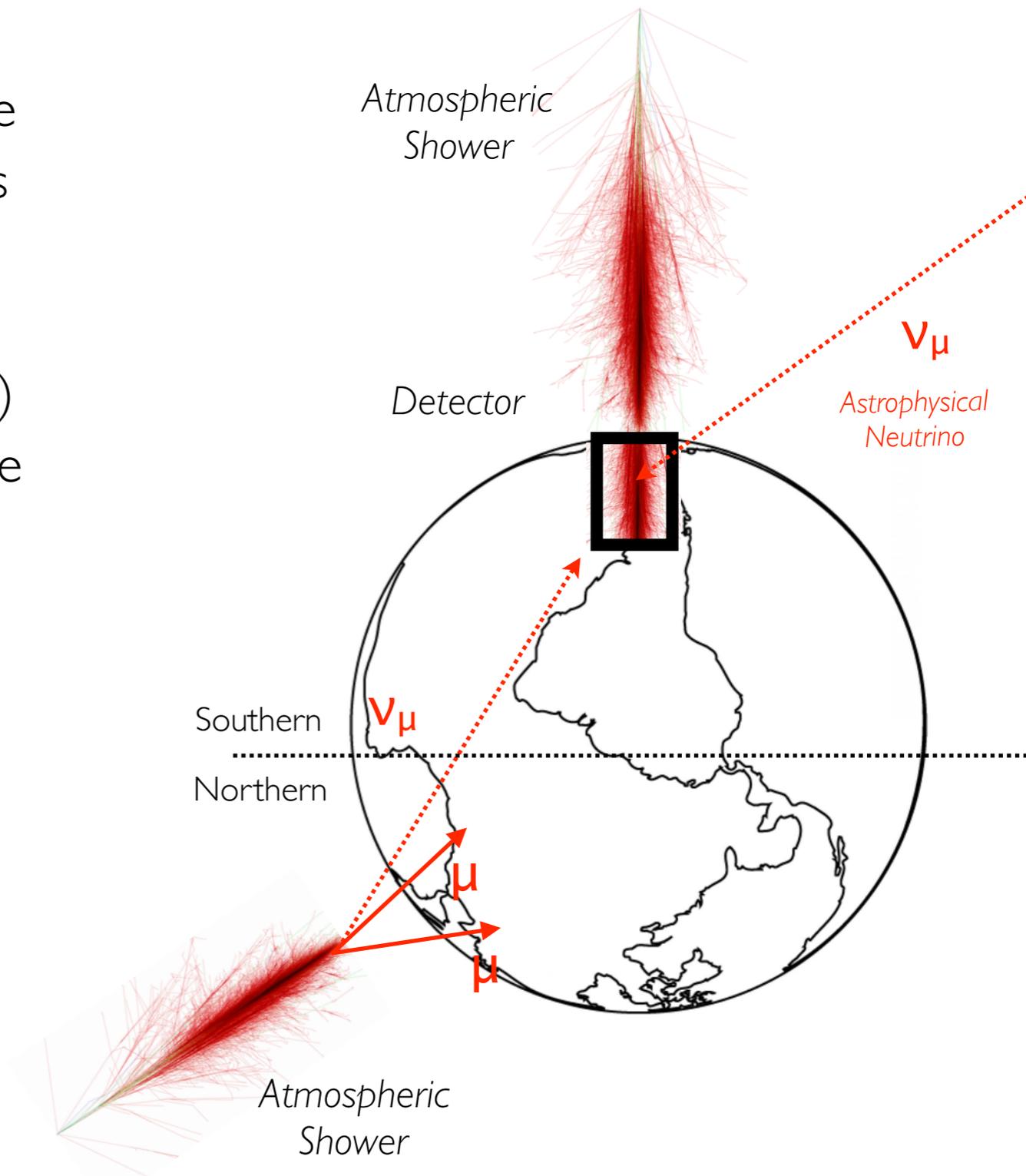


# Outline

- Low-Energy *Time-Independent* Point Source Searches
- Example Veto Method
- Veto-Based Event Selection
- Results from combined search 100 GeV - 100 TeV (4 years)
- Conclusions and Summary

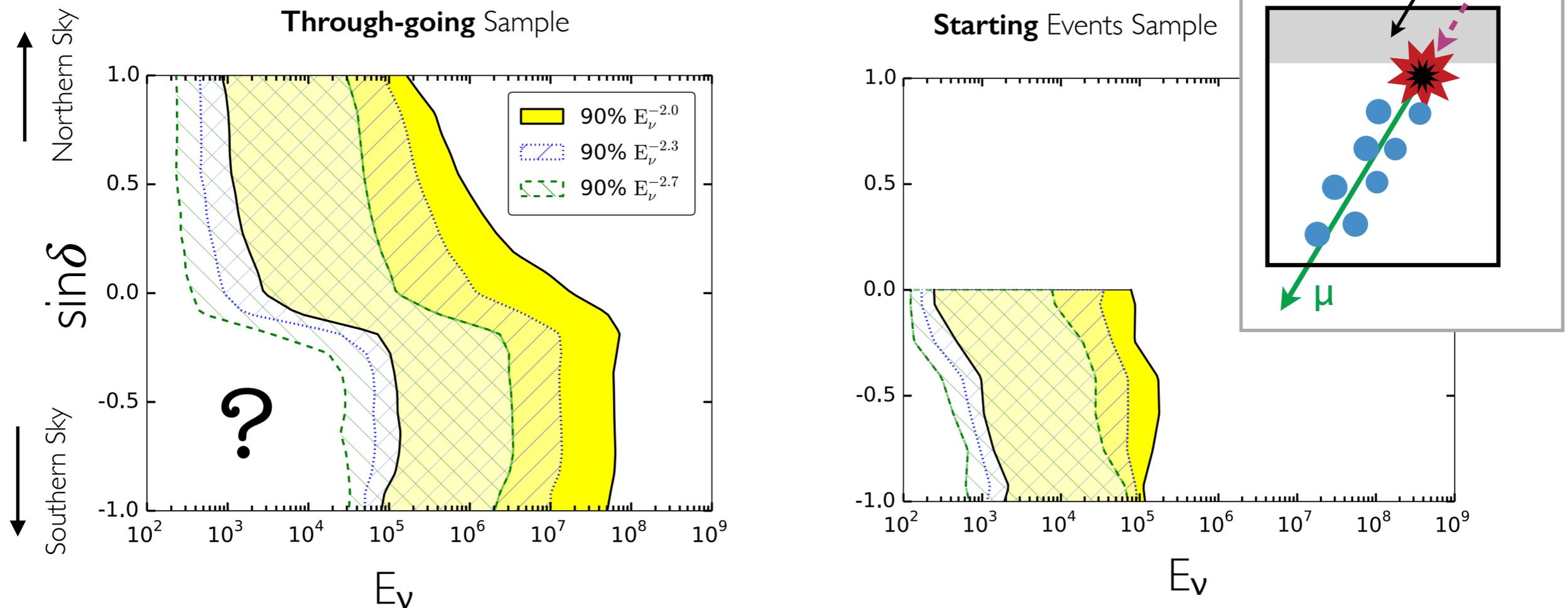
# Low-Energy Point Source Searches

- The Southern sky is “terra incognita” for the search of steady TeV-neutrino point sources in IceCube
- ANTARES has access to the Southern sky at these energies but is smaller (factor  $\sim 60$ )
- Previous Southern sky starting analyses have focused on energies above 100 TeV where the background is low
- Many interesting sources in the Southern sky, potentially at energies below 100 TeV,
- Point source sensitivity down to 100 GeV can be reached by using advanced veto techniques, i.e. looking for events starting inside the detector volume



# Low-Energy Point Source Searches

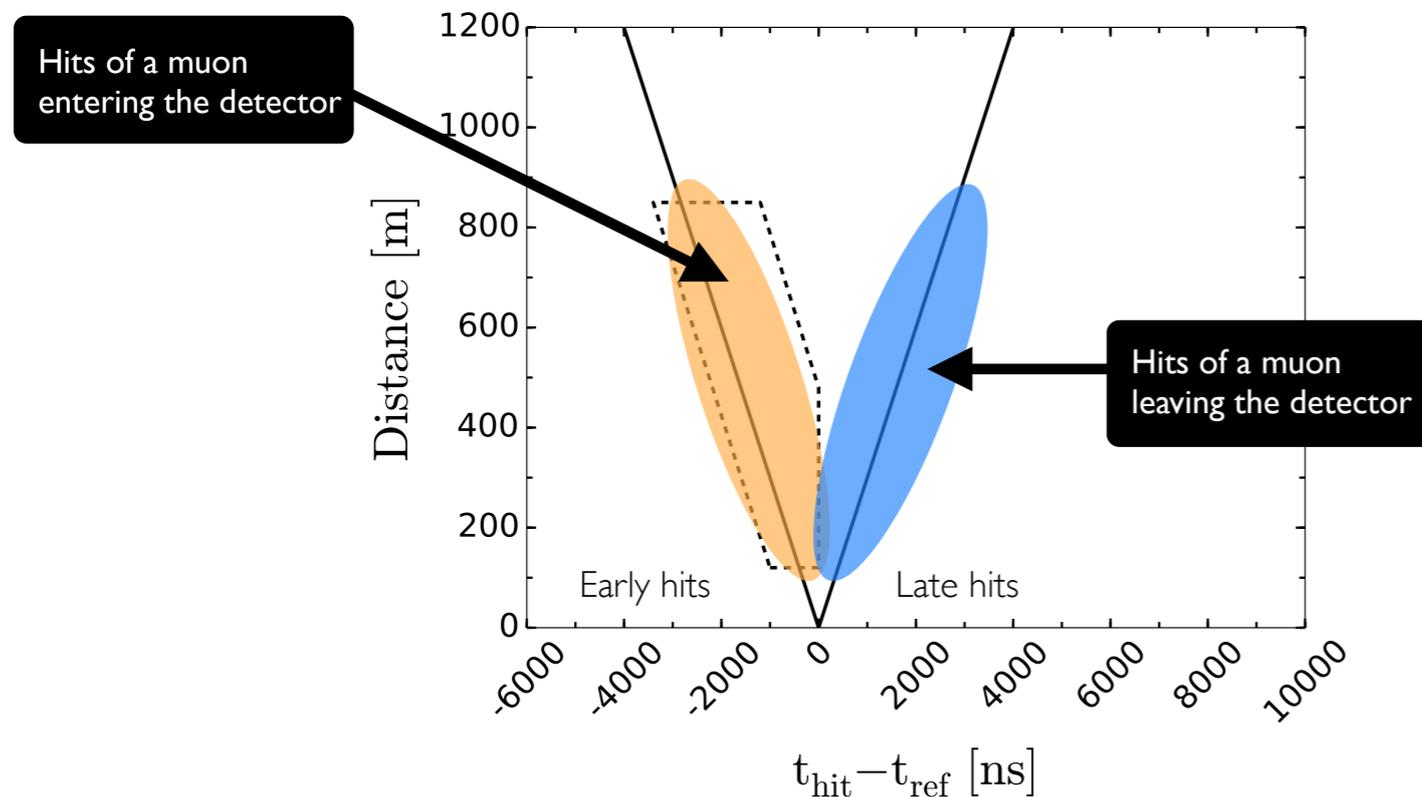
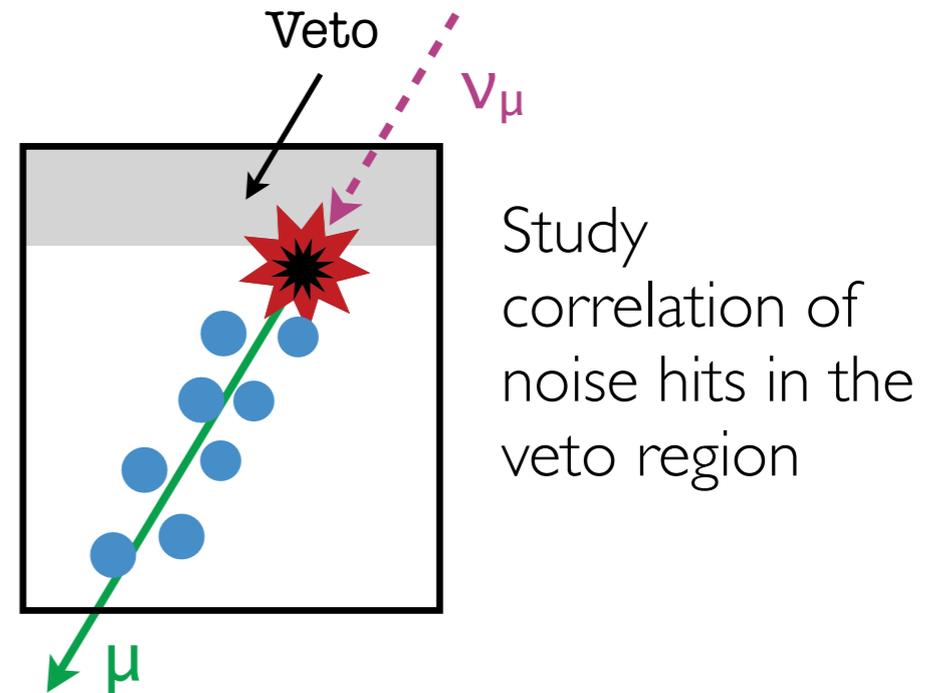
Simulated signal event distributions in final event samples:



- Improved point source sensitivity for IceCube in the Southern sky
- Identify starting events - search for clustering of events

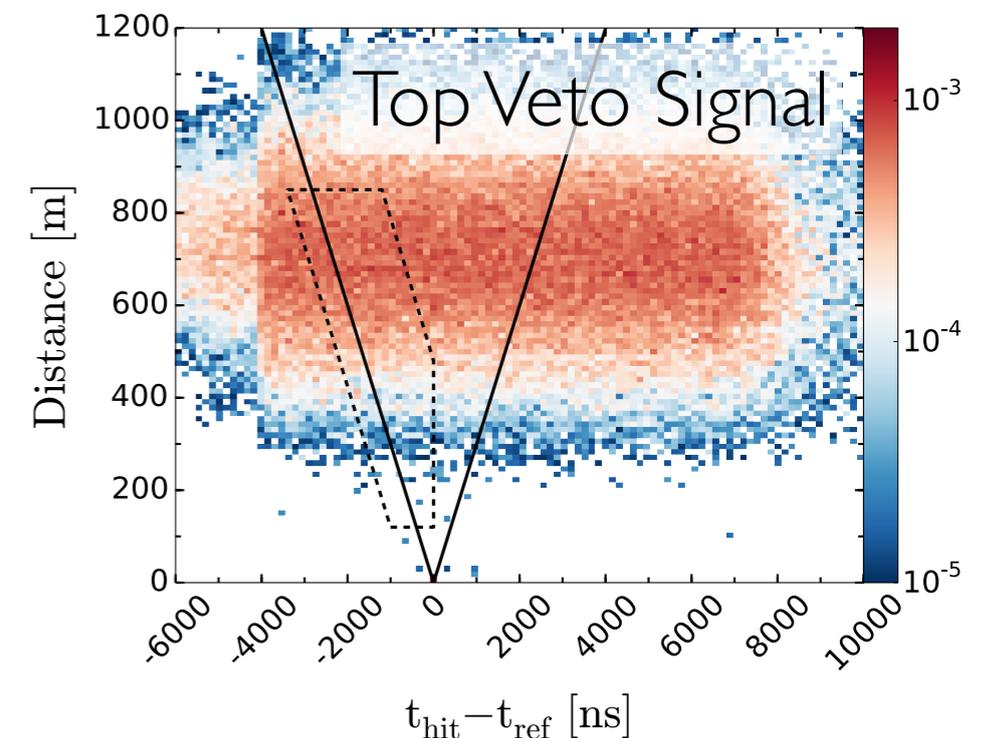
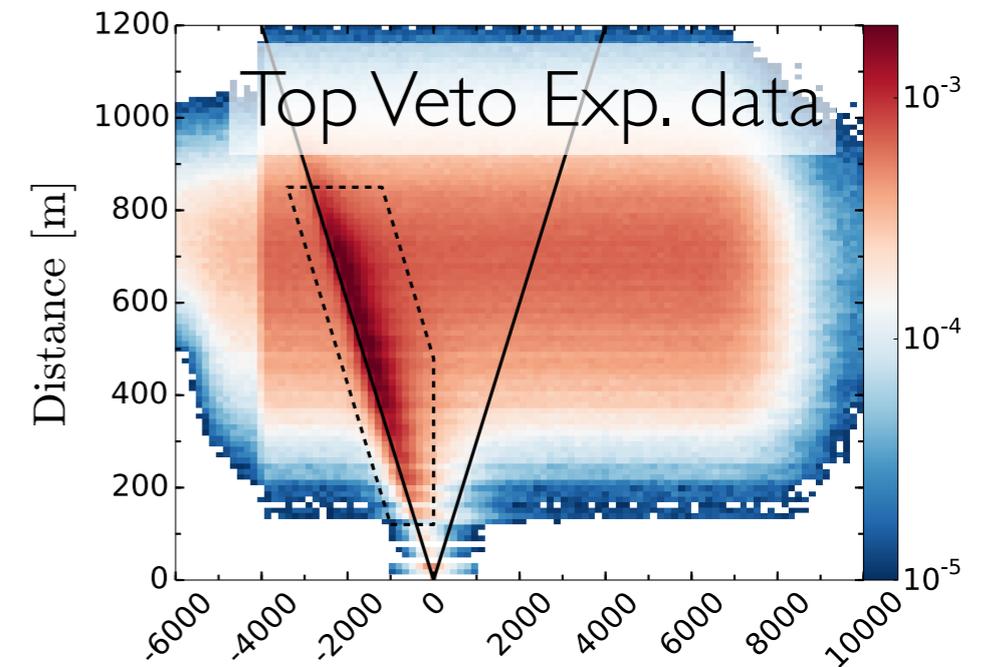
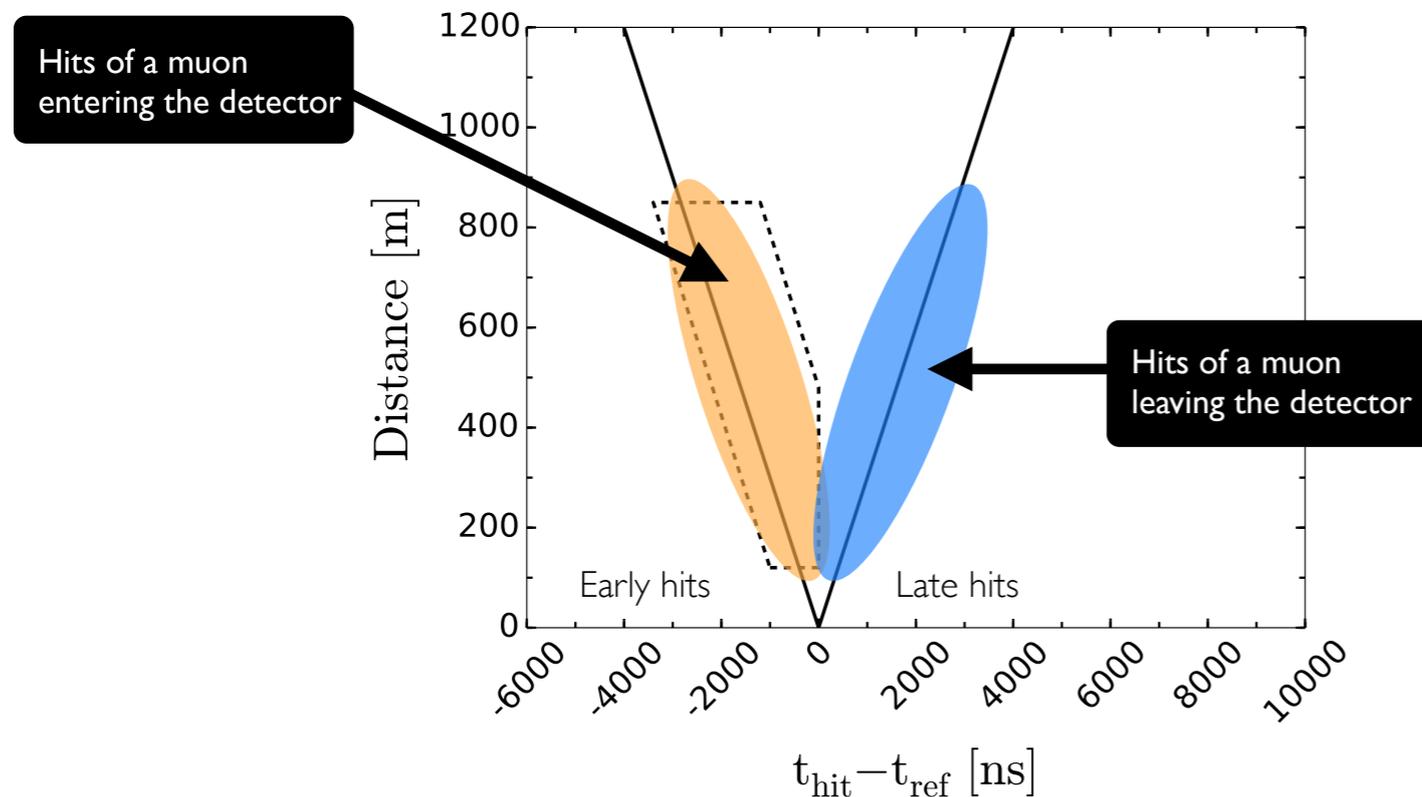
# Example Method - Causality Study in Veto

- Study causality of noise hits in outer layers relative to first coincident hit (reference) in the fiducial volume.
- Are the veto noise hits consistent with a particle traveling with the speed of light through the detector?
- Causality is studied for all pulses in two veto regions: top and side.

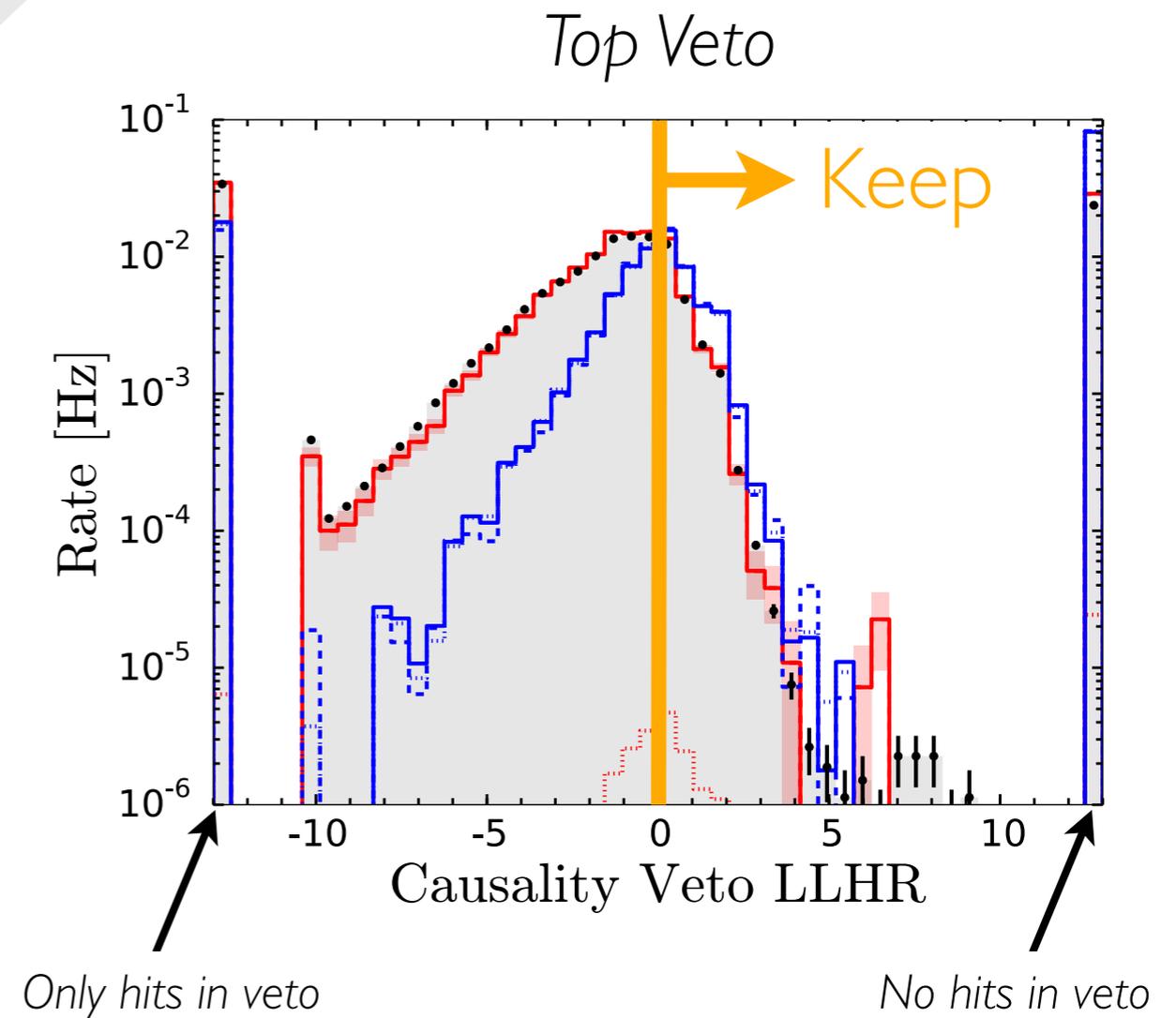
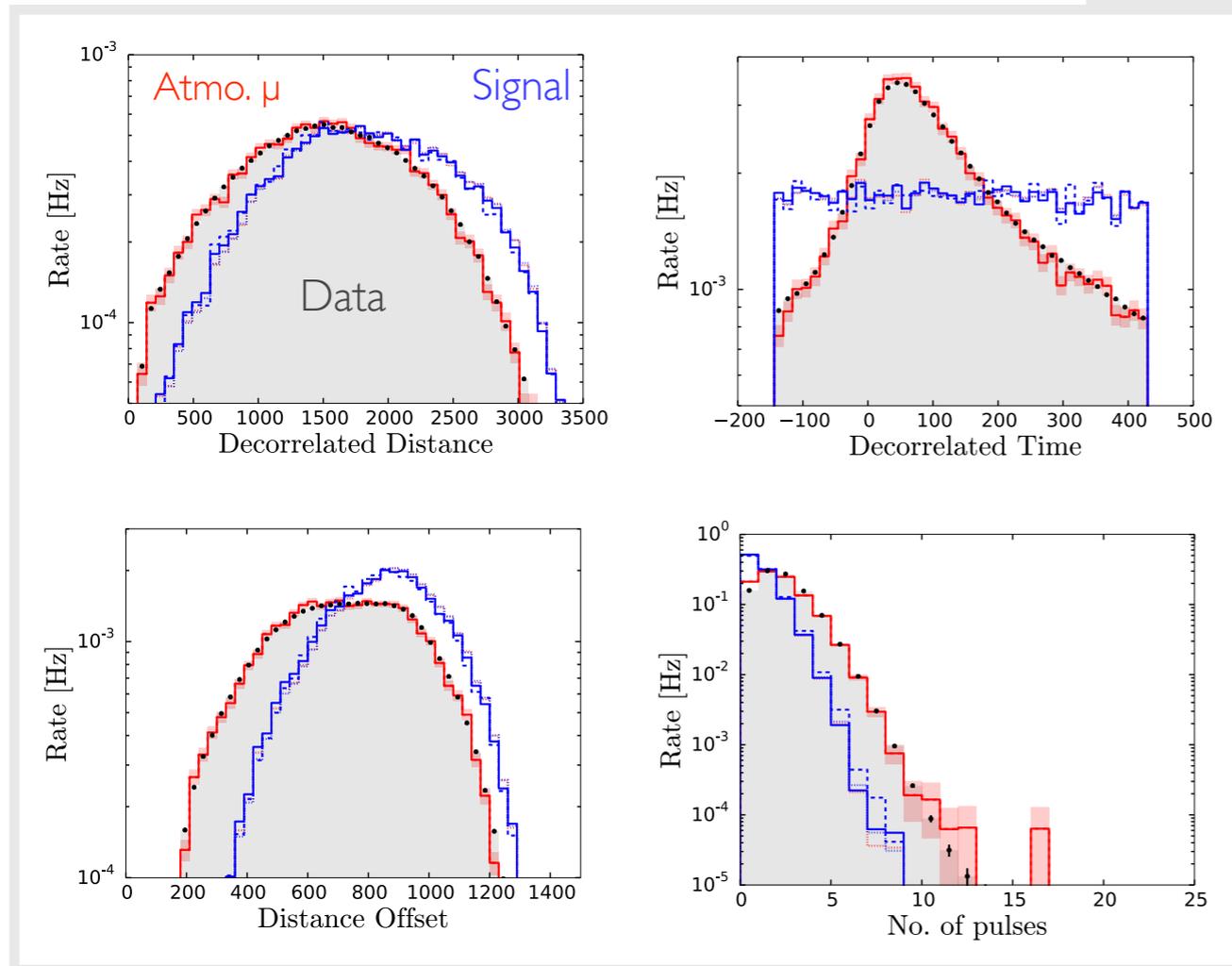


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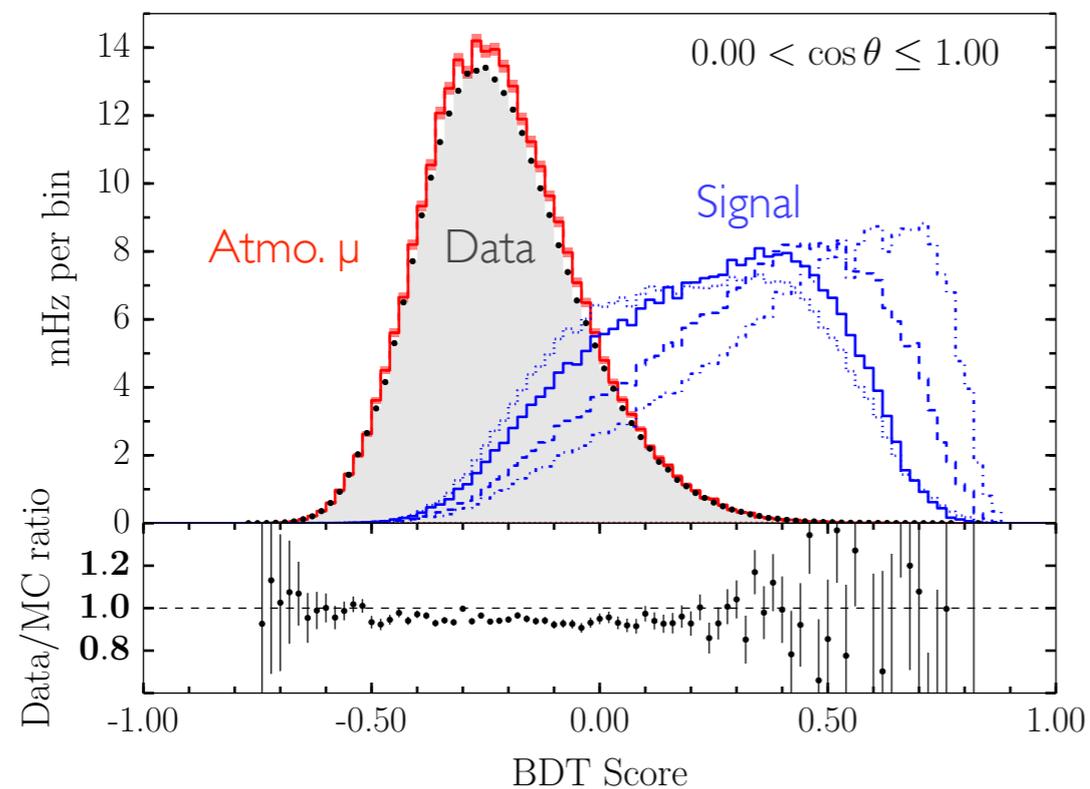


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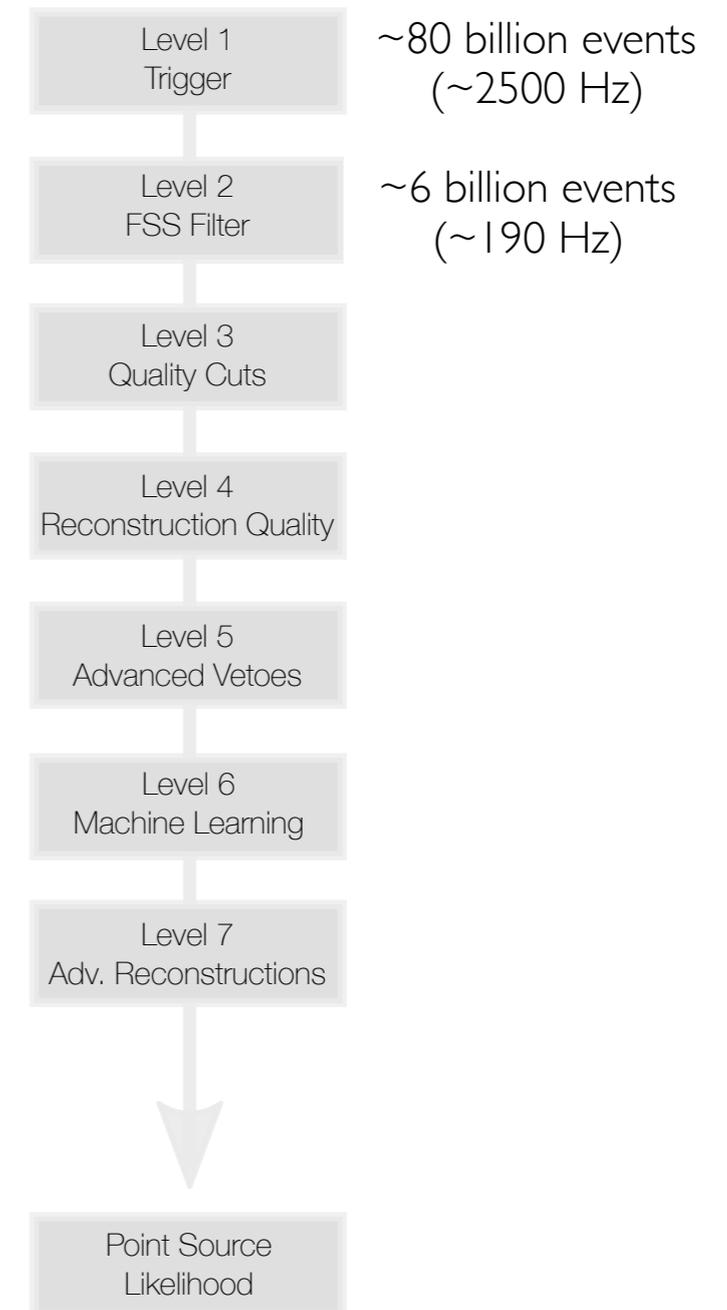


# Veto-Based Event Selection

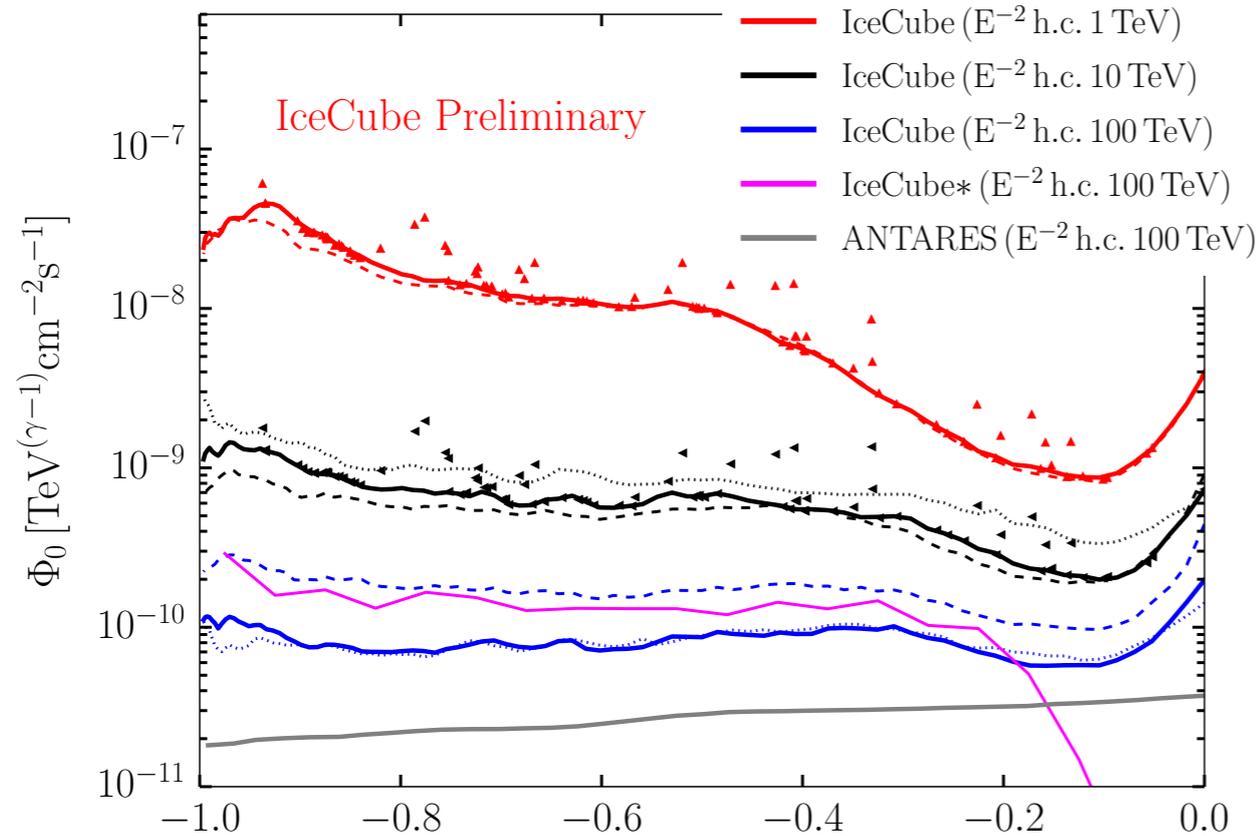
- Challenge: Reject background while still keeping low-energy events with a reasonable pointing  $\sim(1-2)^\circ$
- Two selections:
  - 100 GeV - 10 TeV (2011-2014)
  - 10 TeV - 100 TeV (2012-2014)
- Analyses combined using simple cut on reconstructed energy



## Example Event Selection



# Point Source Sensitivity

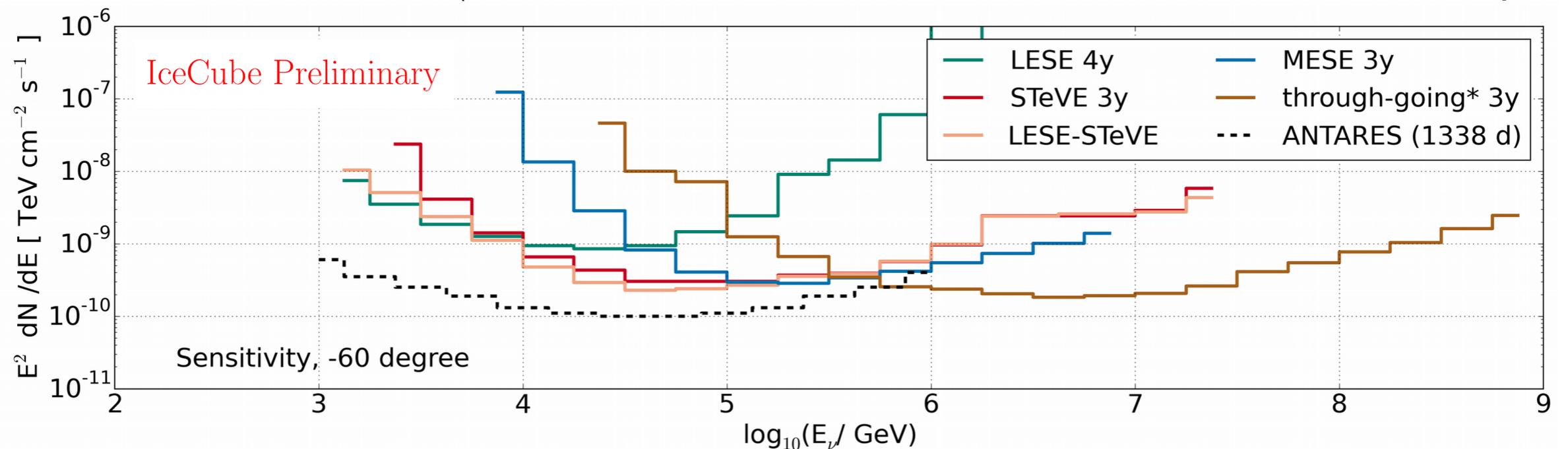


## Integrated Sensitivity

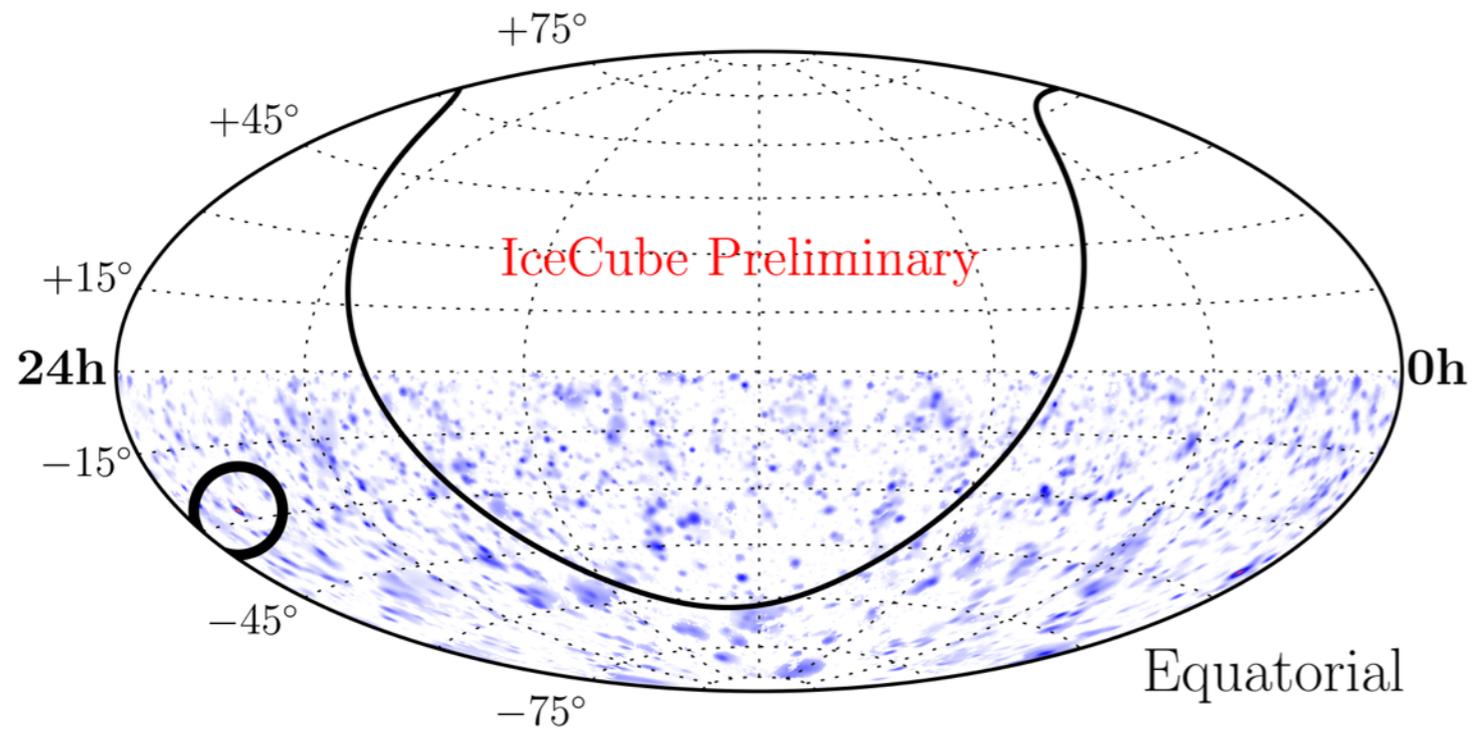
**Dashed:** Selection 100 GeV - 10 TeV  
**Dotted:** Selection 10 TeV - 100 TeV  
**Solid:** Combined Selection

IceCube\* = MESE (3y) + Through-going (4y)

## Differential Sensitivity

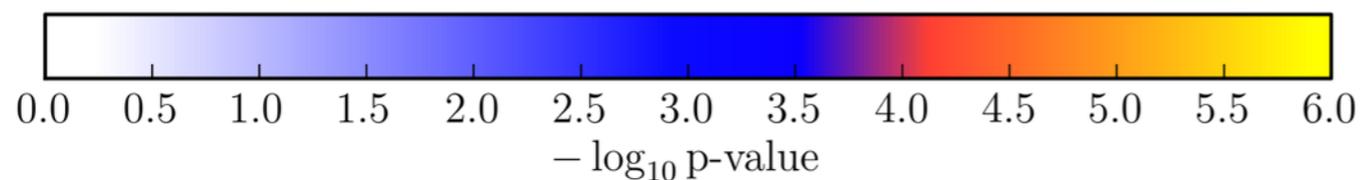


# Combined Results - Unbinned Likelihood



Top 5 out of 96

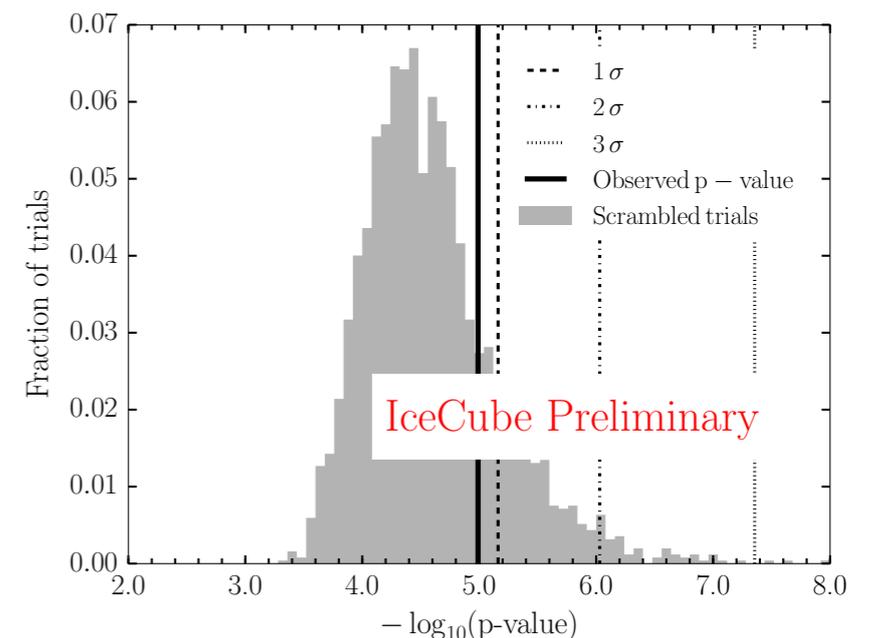
Source	RA	dec	Pre-trial -log10(pval)
<b>HESS_J1616_508</b>	<b>243.6</b>	<b>-50.9</b>	<b>2.74</b>
<b>KUV_00311_1938</b>	8.4	-19.2	2.50
<b>HESS_J1614_518</b>	243.3	-51.6	2.13
<b>PKS_0301_243</b>	45.7	-24.3	1.88
<b>NGC_253</b>	11.6	-25.3	1.46



Hottest spot:

- R.A. 340°, Dec. -28° (best-fit  $n_s = 14.6$ ,  $\gamma = 2.63$ ),
- pre-trial p-value  $1.02e-5$  ( $-\log_{10} \rightarrow 4.99$ ),
- post-trial p-value 21.6 % (**preliminary**)

Trial correction



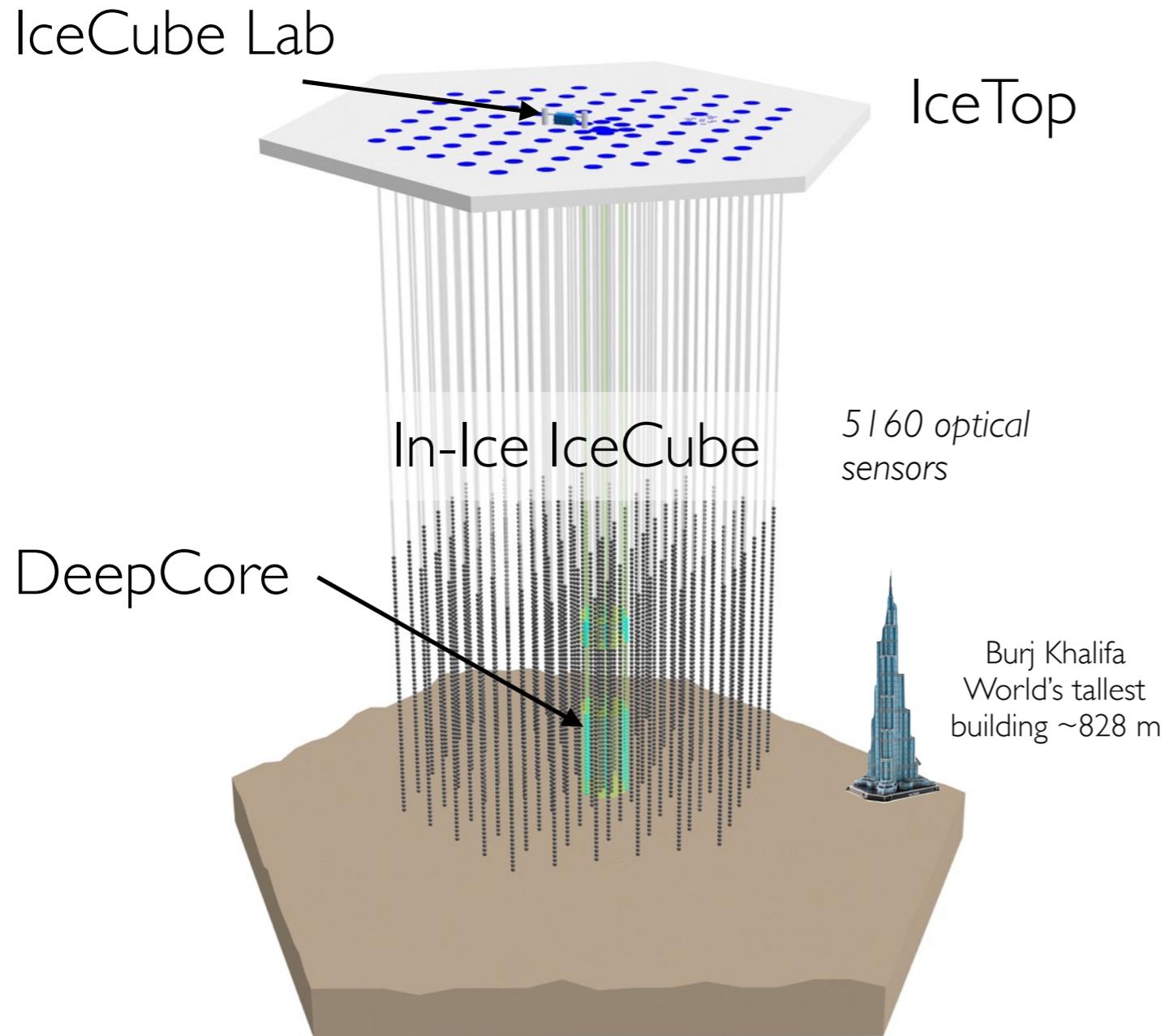
# Conclusions and Summary

- Southern sky is a challenge for IceCube, especially at low-energies
- A new data stream and two event selections were developed to select starting track events, utilizing veto methods.
- Application: IceCube point source searches in the Southern sky at energies as low as 100 GeV
  - Searching for a clustering of starting events
  - No evidence for localized neutrino sources found in data taken between 2011-2014

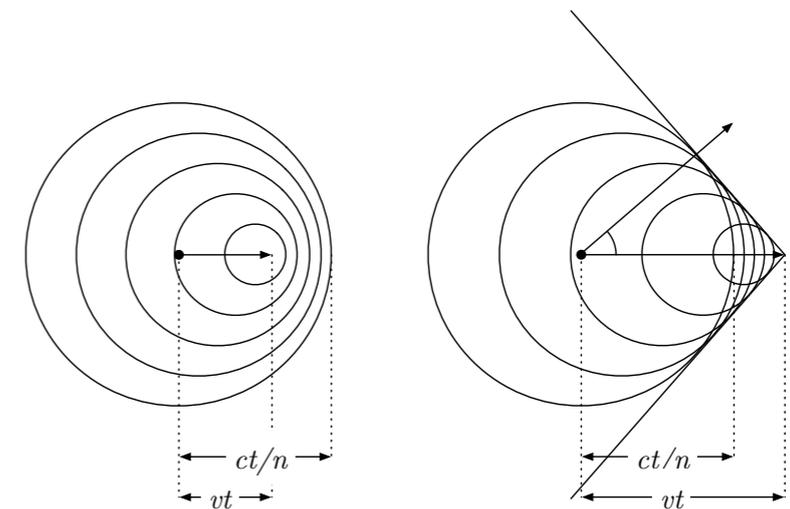
# Backup



# The IceCube Neutrino Observatory



- IceCube is a cubic-kilometer sized detector,
- Located in the ice cap at the South Pole, Antarctica,
- Monitors over 1 billion tons of ultra-clear glacial ice,
- Operates in  $4\pi$  mode,
- Detects Cherenkov radiation of neutrino induced charged particles traversing the ice.



# Search for Clustering of Neutrino Candidate Events

- Unbinned maximum likelihood algorithm using 3 observables:  
Angular reconstruction, Angular uncertainty estimate, Energy proxy

$$\mathcal{L}(n_S, \gamma) = \prod_i^N \left[ \underbrace{\frac{n_S}{N} \mathcal{S}(\vec{x}_i, \sigma_i, \mathbf{E}_i; \vec{x}_S, \gamma)}_{\text{Signal}} + \underbrace{\left(1 - \frac{n_S}{N}\right) \mathcal{B}(\delta_i; \mathbf{E}_i)}_{\text{Background}} \right]$$

$$\mathcal{S} = S(|\vec{x}_i - \vec{x}_S|, \sigma_i) \times \mathcal{E}(\mathbf{E}_i, \delta_i, \sigma_i; \gamma)$$

$$\mathcal{B} = S_{\text{bkg}}(\delta_i) \times \mathcal{E}_{\text{bkg}}(\mathbf{E}_i, \delta_i, \sigma_i, \gamma)$$

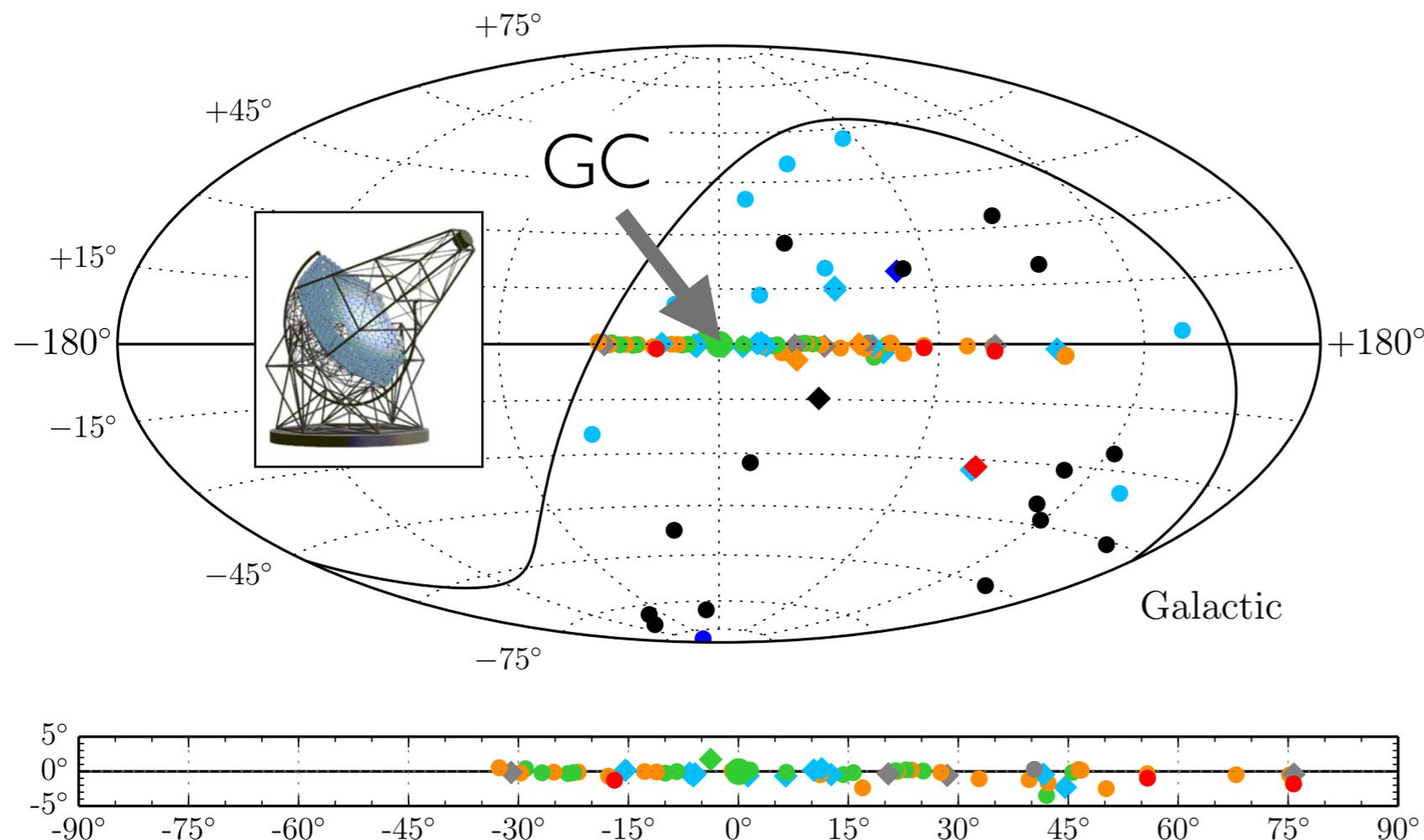
- The total likelihood of the combined samples is the product of the individual likelihoods
- The total number of signal events is split evenly among the samples given their exposure time and expected signal statistics derived from the effective area

$$n_S^j = n_S \times \frac{\int_0^\infty dE A_{\text{eff}}^j(E, \sin \delta) E^{-\gamma}}{\sum_i \int_0^\infty dE A_{\text{eff}}^i(E, \sin \delta) E^{-\gamma}}$$

Test Statistics:  $\mathcal{TS} = 2 \ln \left[ \frac{\mathcal{L}(\hat{n}_S, \hat{\gamma})}{\mathcal{L}(n_S = 0)} \right]$

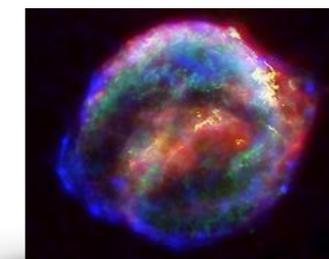
Wilks' theorem:  $\chi^2$  with 2 d.o.f. as sample approaches  $\infty$

# Source List of Known Gamma-Ray Emitters



## Source list definition (total of 96 sources):

- All 84 Southern sky TeVCat sources in the stable catalogs 'Default Catalog' and 'Newly Announced',
- 12 additional source traditionally investigated by IceCube,
- Known gamma-ray emitting sources as observed by ground-based experiments such as VERITAS, MAGIC, and HESS.



Supernova Remnants



Pulsars