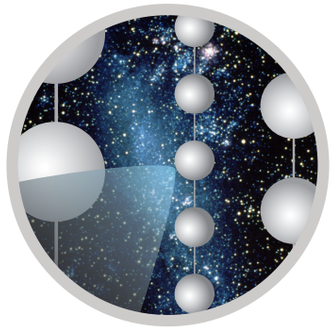


Search for PeV Gamma Rays with IceTop and IceCube

Zach Griffith and Hershal Pandya

The IceCube Collaboration

TeVPA 2017

7 August 2017

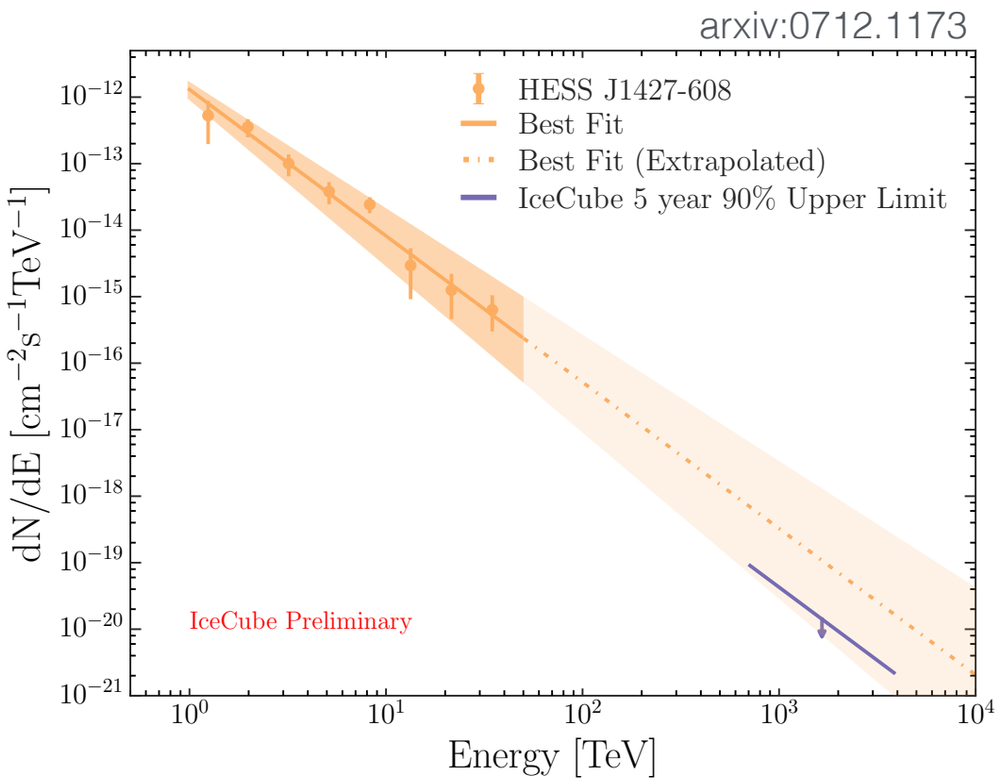
Columbus, Ohio

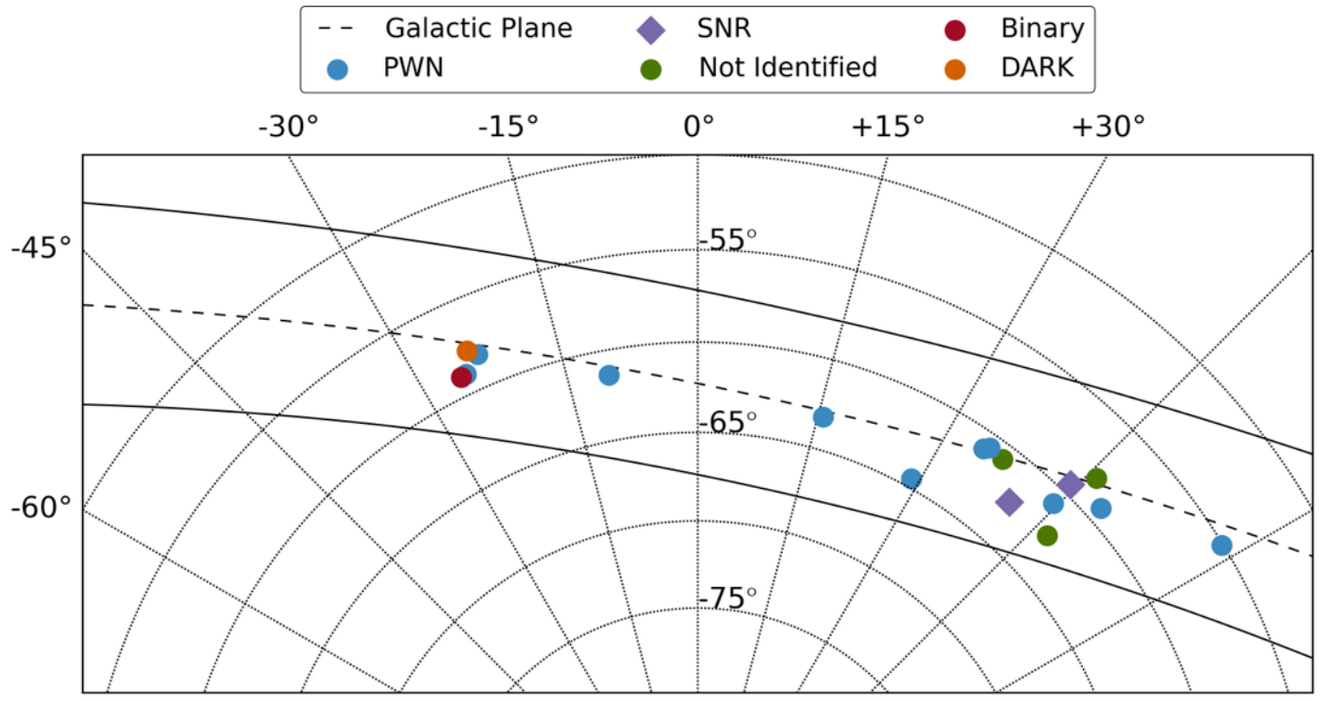
Outline

- Motivation
- Event Selection
- Results
  - Point Source Analyses
    - All-sky scan
    - Search for correlation with known TeV gamma-ray sources (H.E.S.S.)
    - Search for correlations with high-energy IceCube neutrinos
  - Search for excess of PeV gamma rays from the Galactic plane

Motivation

IceCube is the most sensitive southern hemisphere experiment to PeV gamma rays





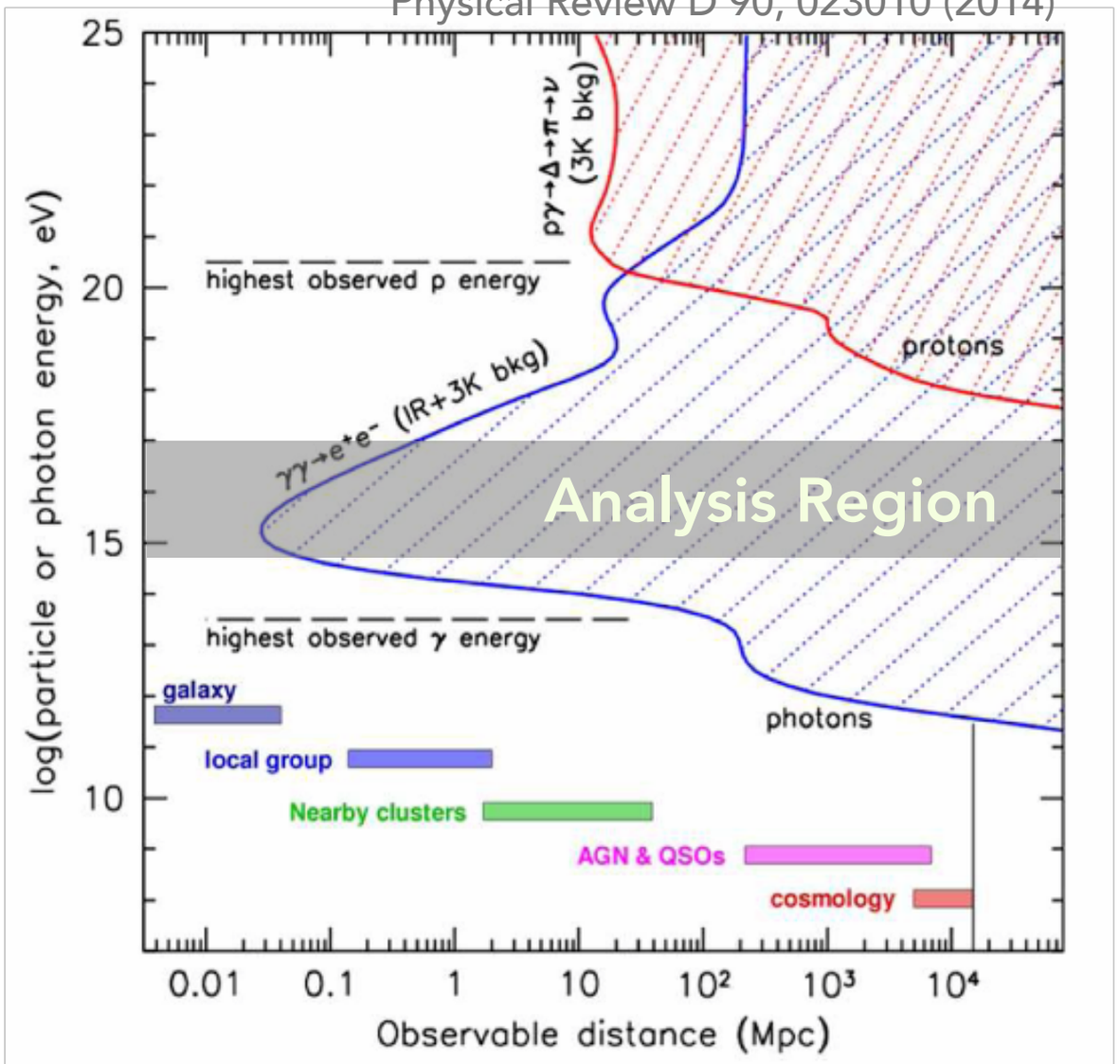
H.E.S.S. sources in the IceCube Field of View

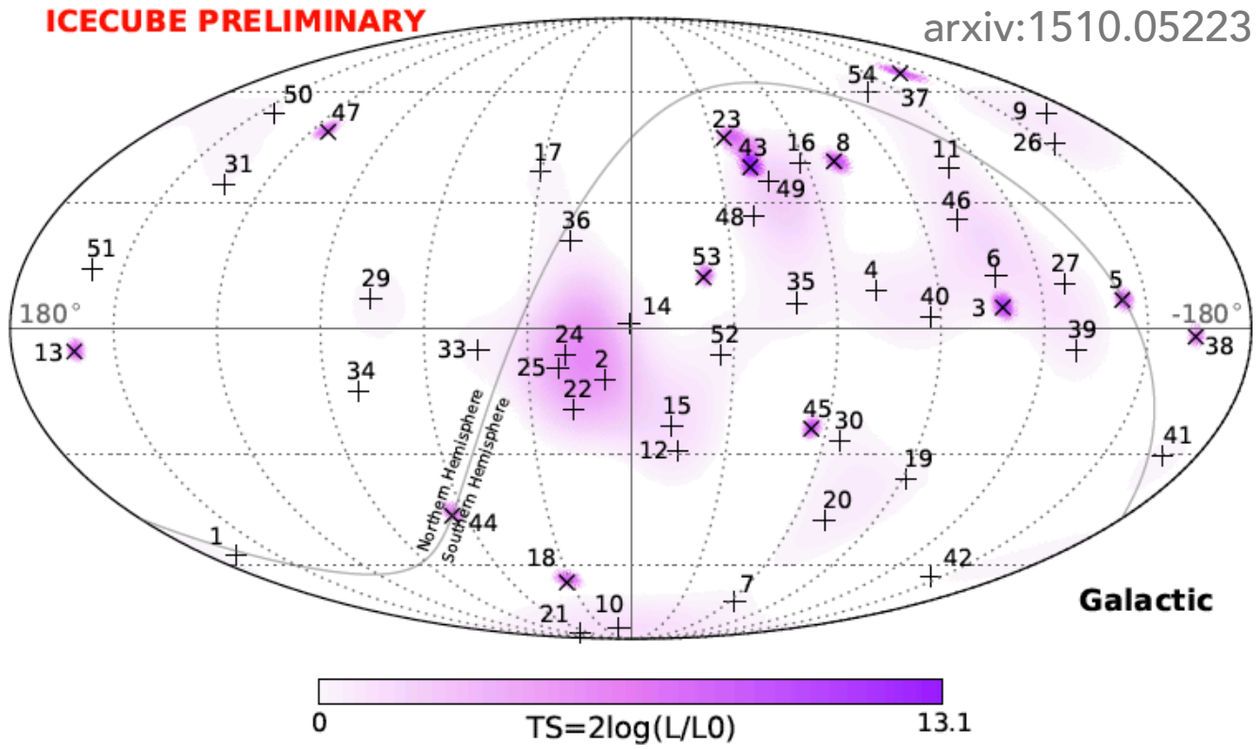
IceCube can test whether the spectra of known TeV sources extend up to PeV energies without a cut-off

ICECUBE

Motivation

Physical Review D 90, 023010 (2014)





$$\text{primary process} \rightarrow \pi^0\,(+\pi^\pm) + \ldots \rightarrow \gamma_{\text{UHE}}\,(+\nu_{\text{UHE}}) + \ldots$$

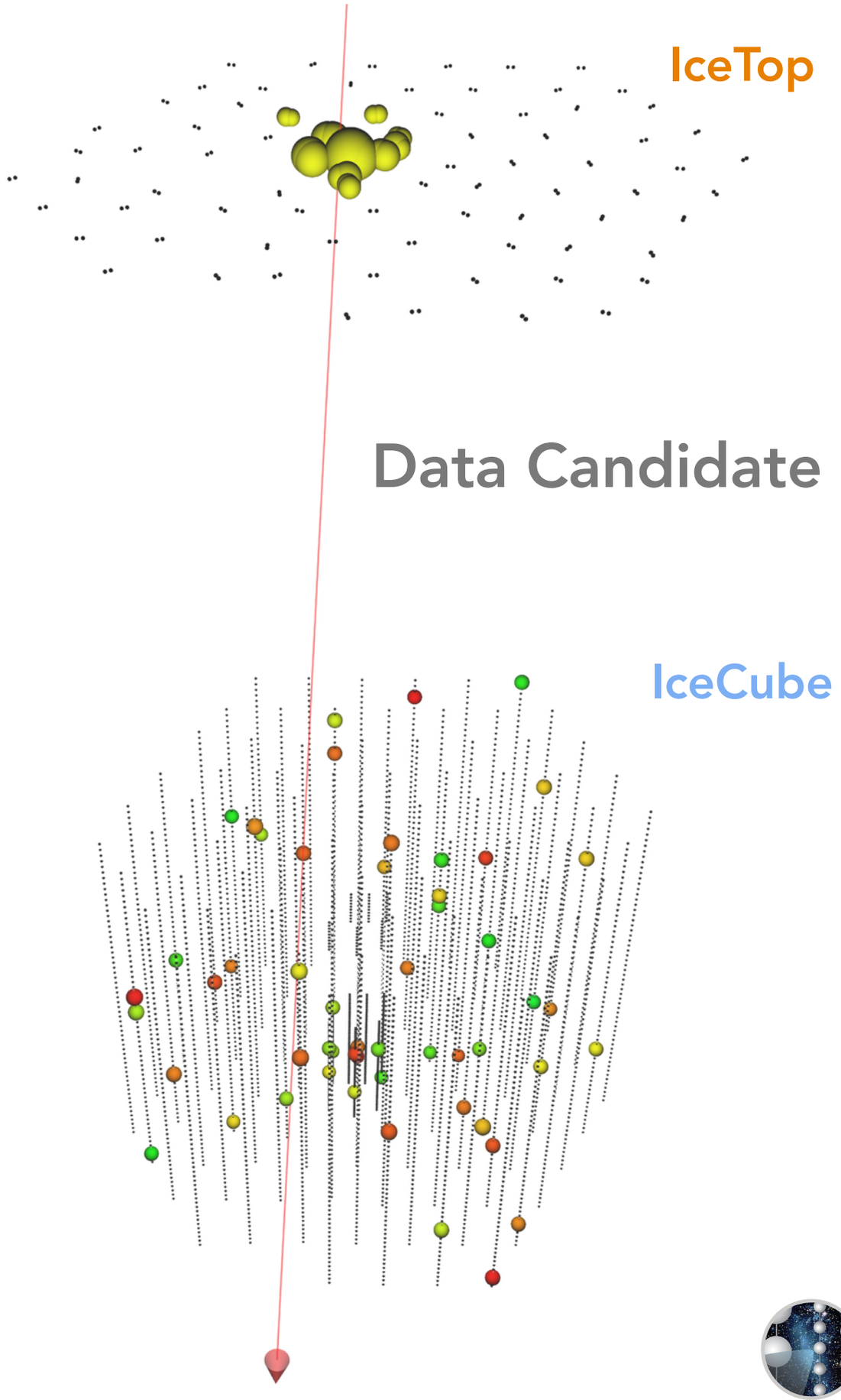
Observation of PeV Gamma-rays can indicate galactic origin of some of the IceCube neutrinos

Gamma Hadron Discrimination

- Gamma-ray air showers have ~10 times fewer muons, less local fluctuations, and younger shower age compared to cosmic-ray showers

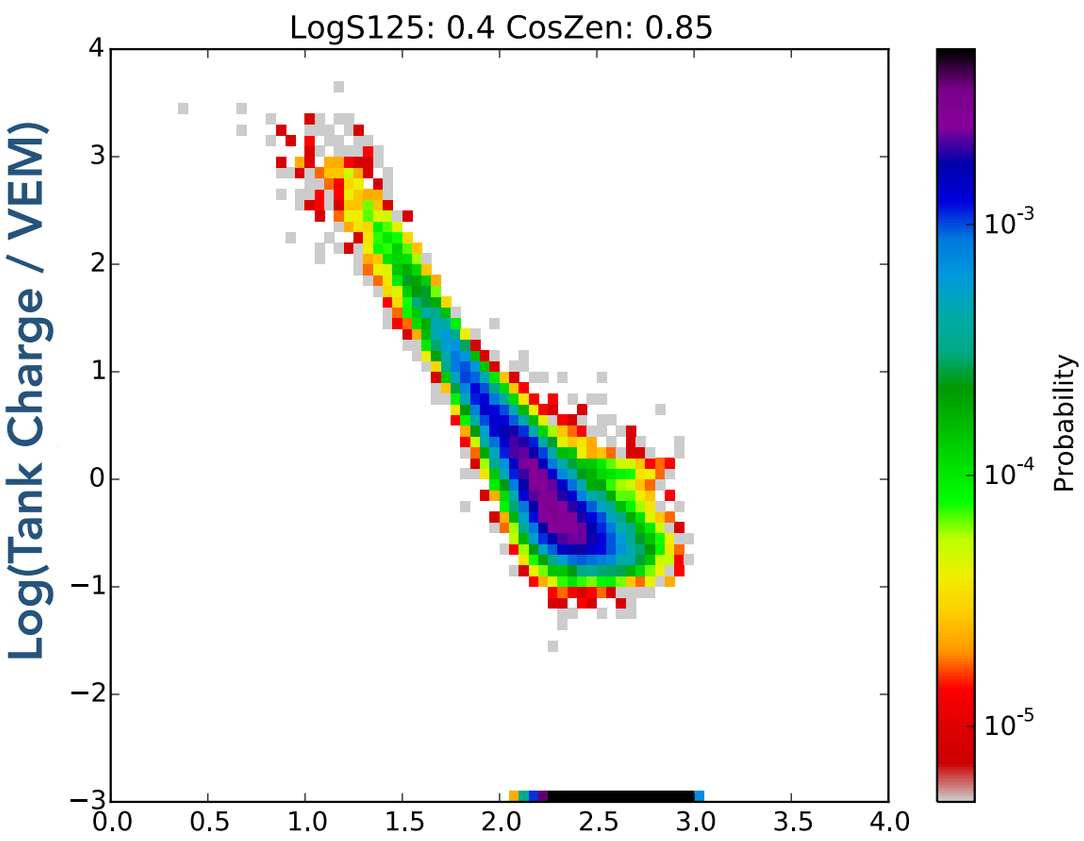
- IceTop measures:
  - Shower energy
  - Shower core and direction
  - Peripheral GeV muons
  - Lateral distributions of energy and timing

- IceCube measures:
  - Thoroughgoing (>300 GeV) muons from shower core

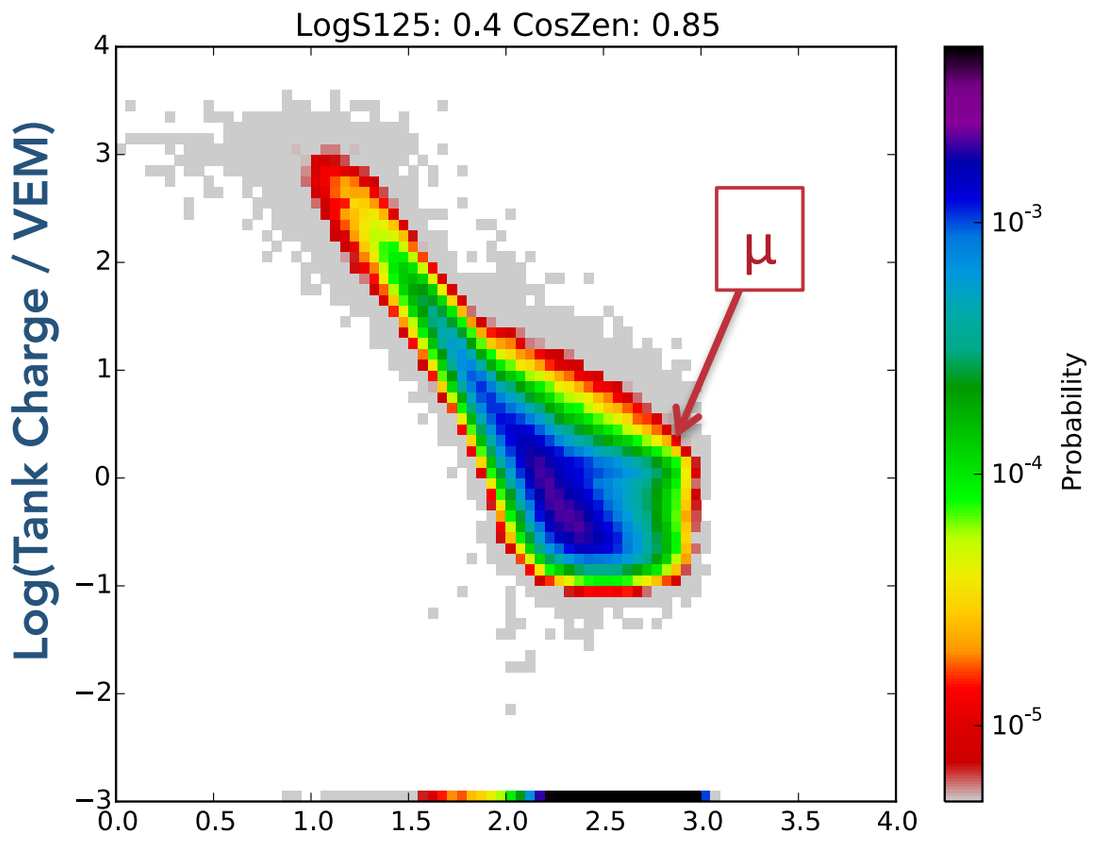


IceTop Gamma/Hadron Discrimination

Gamma Ray Simulation



Cosmic Ray Data



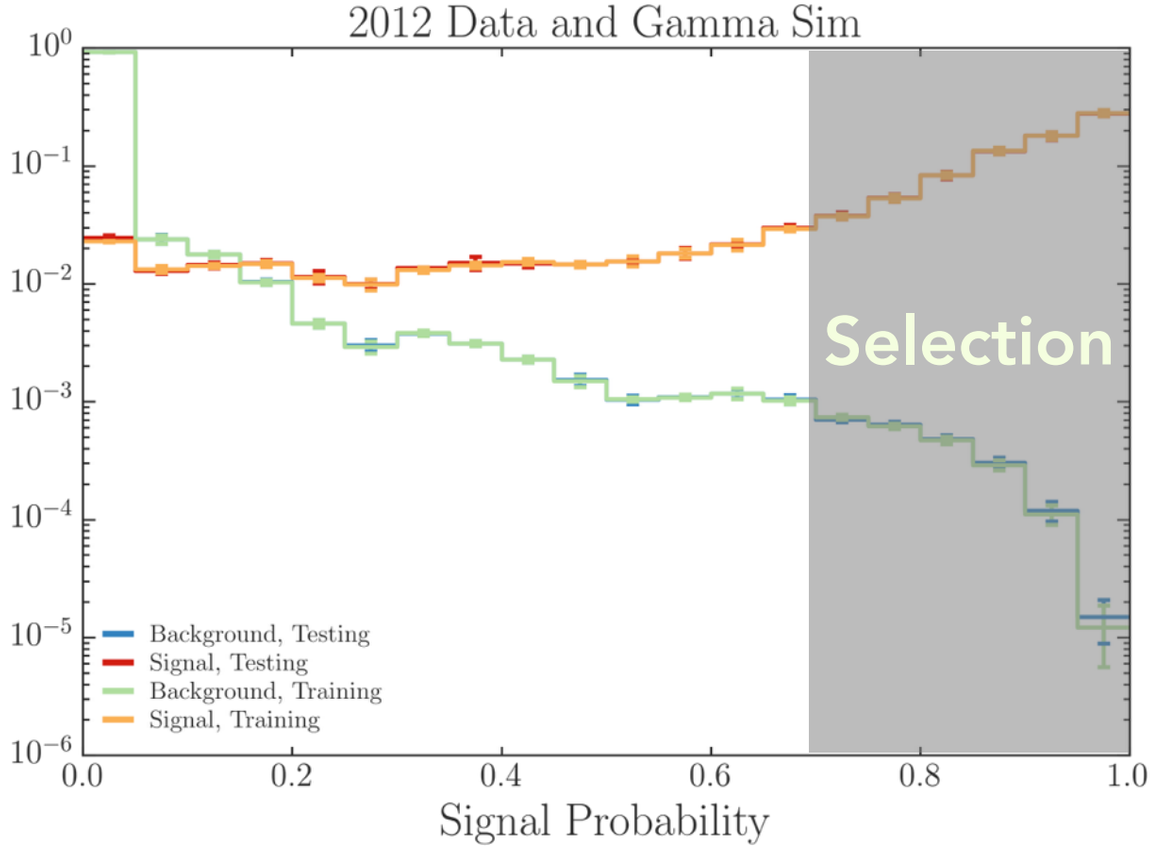
Plots from Hershal Pandya

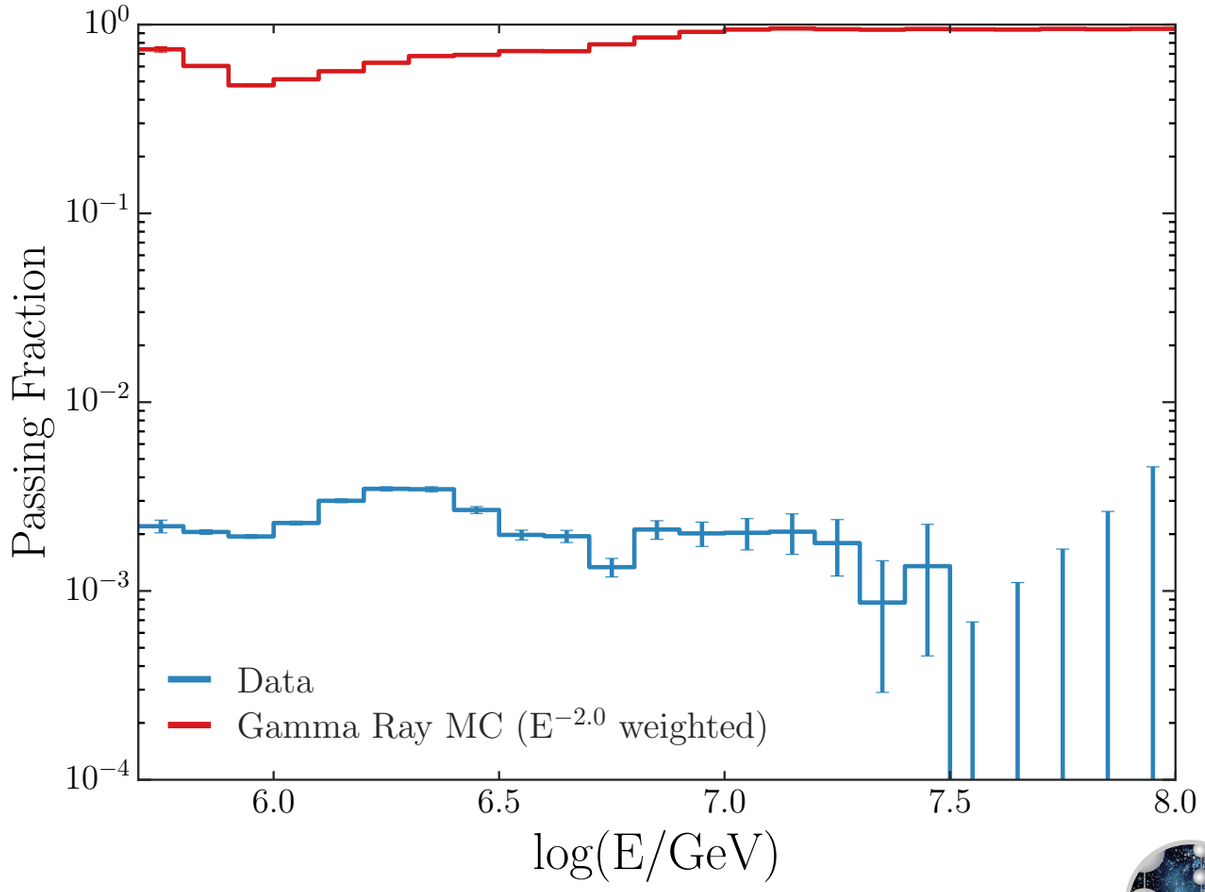
$$LLHR = Log_{10}\left(\frac{L(\{(Q_i\,R_i)\}\,|\,H_\gamma)}{L(\{(Q_i\,R_i)\}\,|\,H_{CR})}\right);\ i = 1\ to\ 162\ IT\ Tanks$$

IceCube

Random Forest Classifier

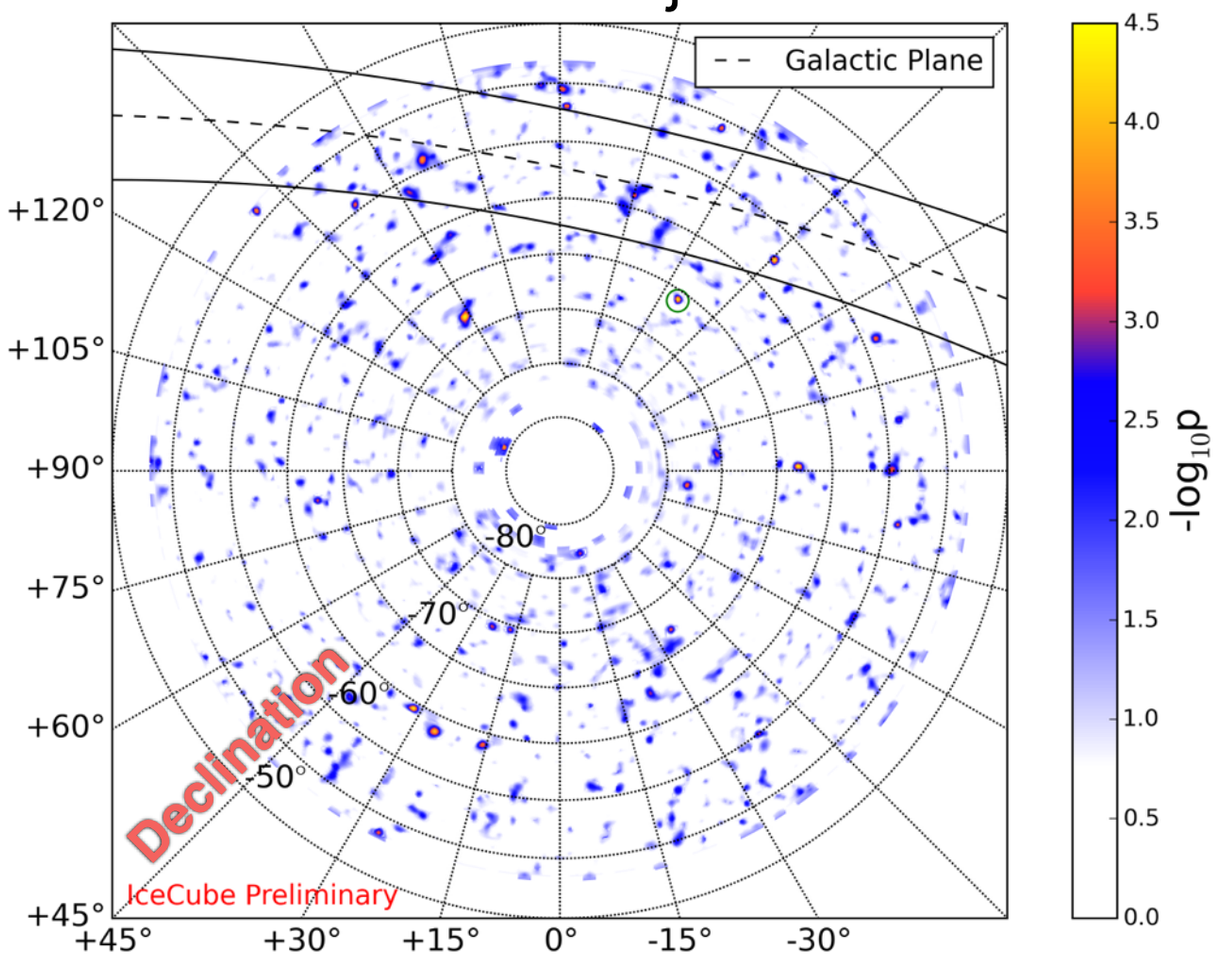
- Features
  - IceCube Charge
  - IceTop LLHRatio
  - $\log_{10}(S_{125})$ (IceTop energy proxy)
  - sin(Declination)
  - IceCube Containment
- Point source selection
  - Classifiers constructed with gamma simulation weighted to relatively hard ($E^{-2.0}$) and soft ($E^{-2.7}$) spectral bounds
- Diffuse galactic plane selection
  - Classifier constructed with softer ($E^{-3.0}$) spectrum

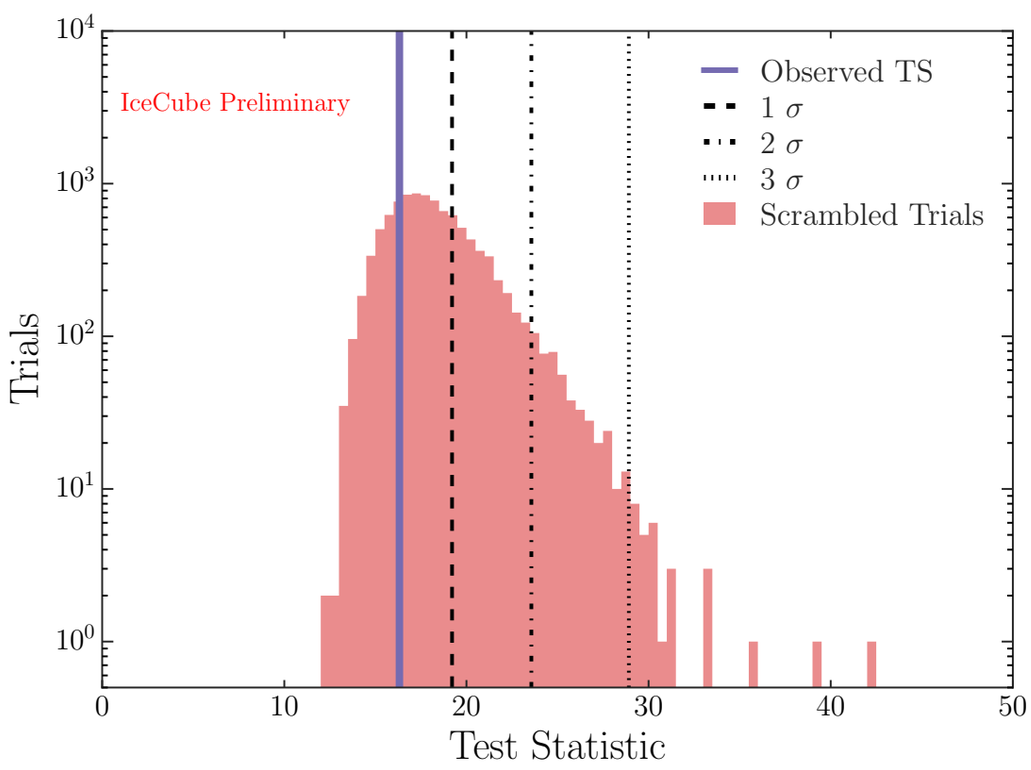




All-Sky Scan

- Implemented with 5 years of full detector data
- Test over entire sky using standard unbinned likelihood method
  - with energy weights
  - fitting to spectral index
- Significance of hottest spot determined by background trial comparison
- **hottest spot post-trial p-value: 77%**





Hottest Spot

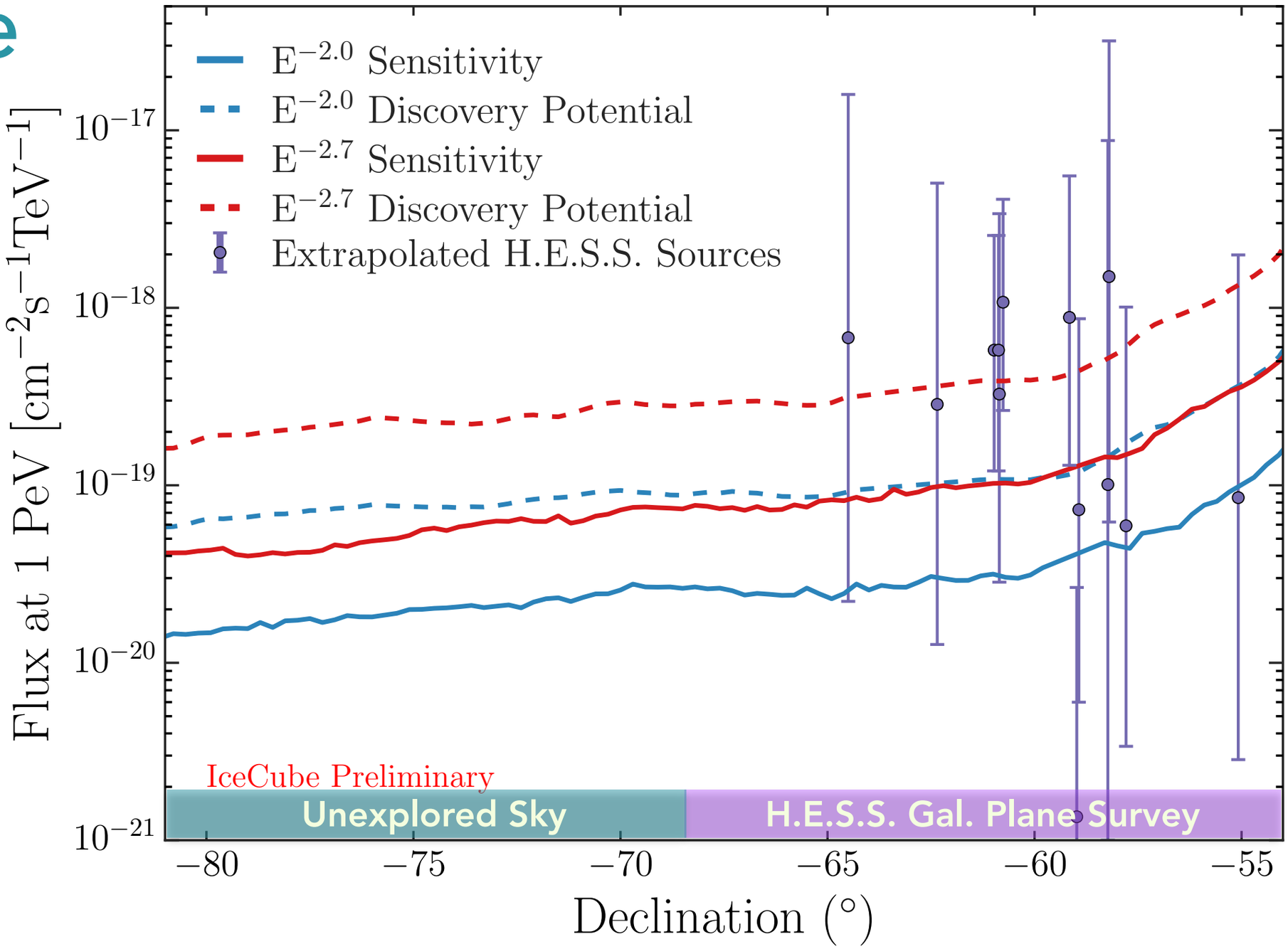
- $\delta = -63.5°$
- $\alpha = 28.5°$
- $\gamma = 3.21$
- $n_s = 11.22$

Flux: 1.75×10^{-19} GeV^{-1}cm^{-2}s^{-1}

ICECUBE

Point Source Sensitivity

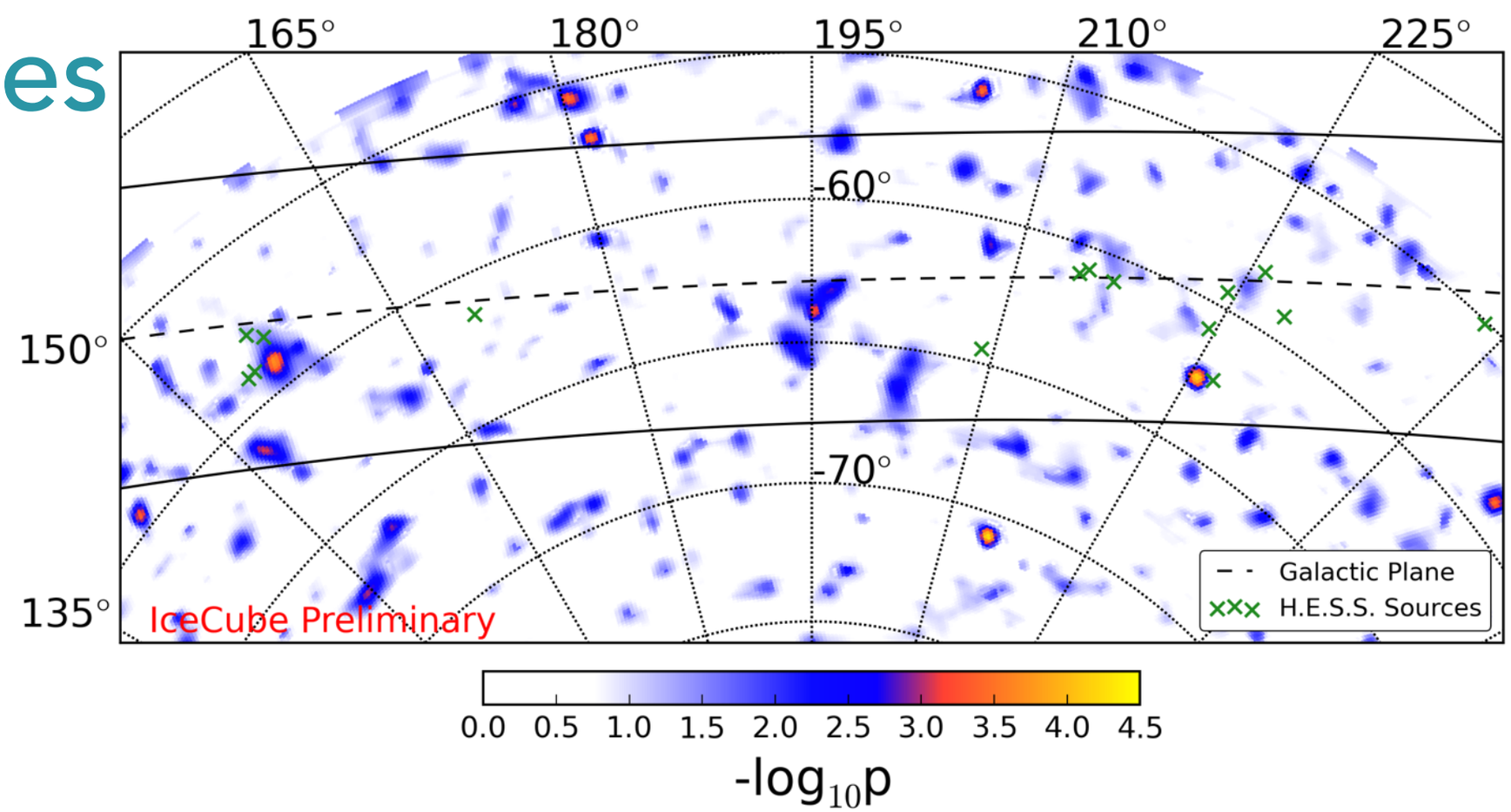
- Sensitivity:
  - 90% C.L. upper limit
- Discovery Potential:
  - 5σ detection 50% of the time



- H.E.S.S. sources shown assume optimistic scenario:
  - no break in the fitted power law at TeV energies
  - no absorption

H.E.S.S. Sources

Source	pre-trial p-value
HESS J1356-645	>0.50
HESS J1507-622	0.28
SNR G292.2-00.5	0.39
Kookaburra (Rabbit)	0.35
HESS J1458-608	0.20
HESS J1427-608	0.11
Kookaburra (PWN)	>0.50
SNR 6318.2+00.1	>0.50
MSH 15-52	0.47
HESS J1018-589 B	0.09
HESS J1018-589 A	0.12
HESS J1503-582	0.24
HESS J1026-582	0.04
Westerlund 2	0.07
SNR G327.1-01.1	>0.50

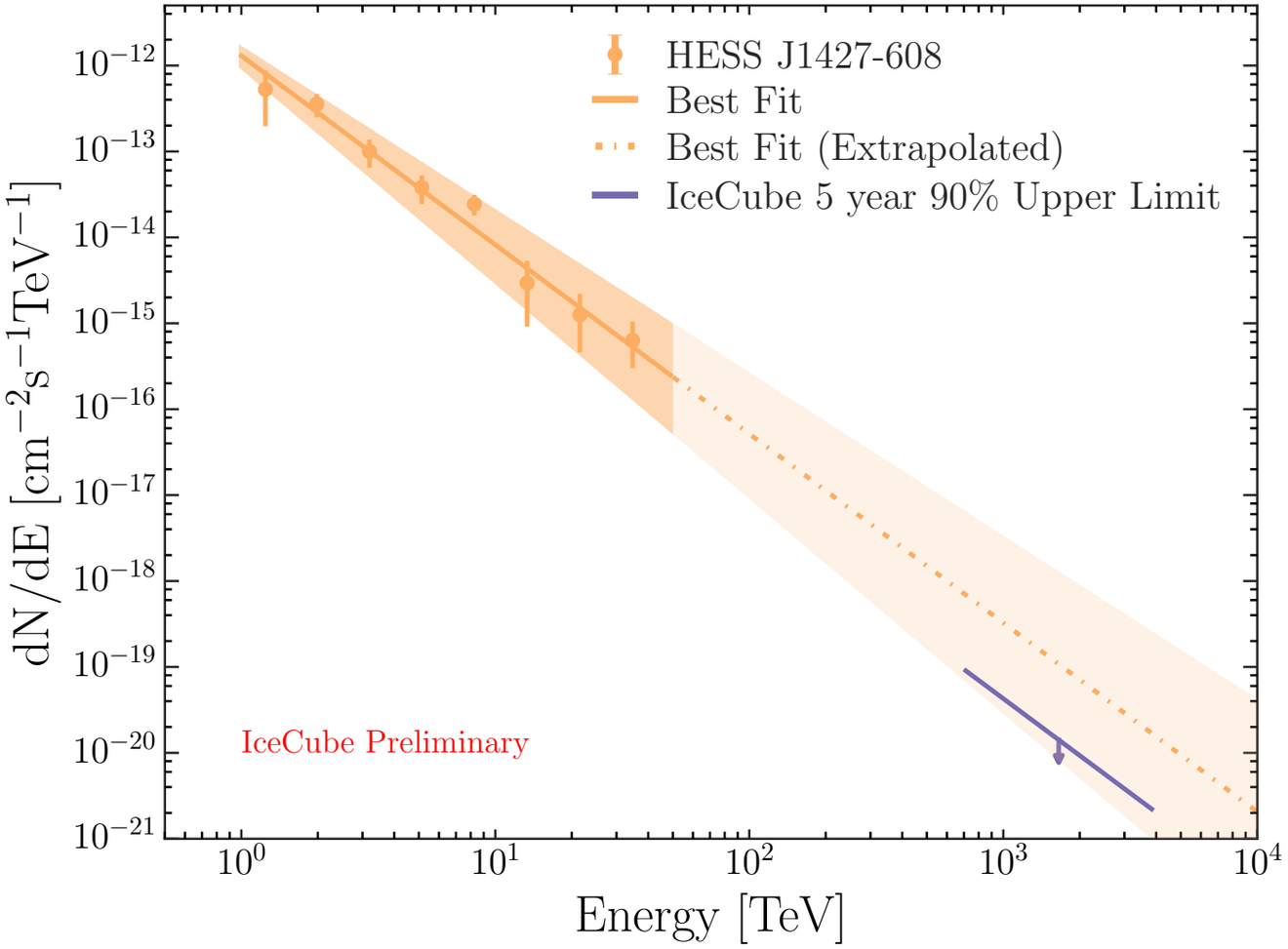


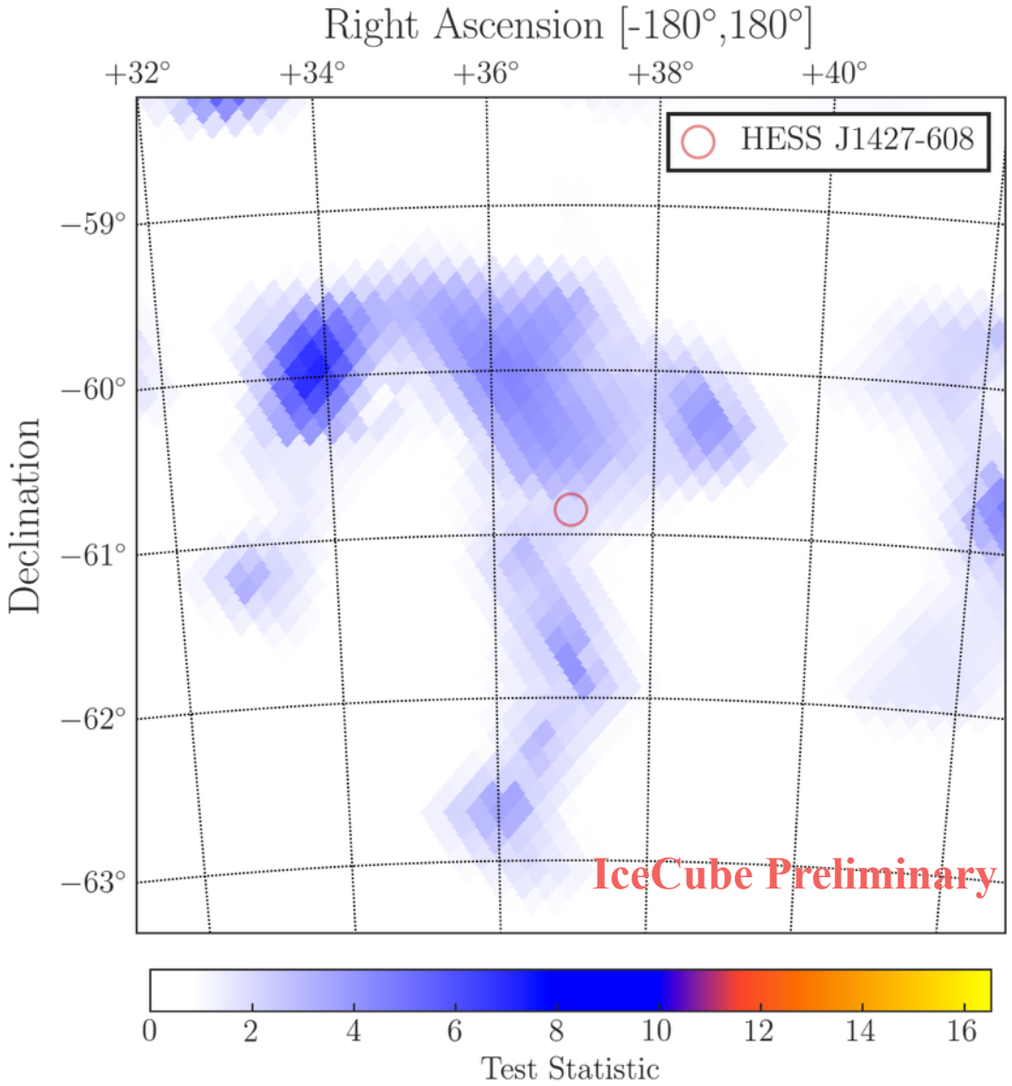
- 15 total in FOV with no evidence of a cutoff at TeV energies
- Hottest individual H.E.S.S. source: H.E.S.S. J1026-582
  - post-trial p-value of hottest source: 45%
- Stacked likelihood test also performed with catalog
  - stacking test p-value: 5%

IceCube

H.E.S.S. J1427-608

arxiv:0712.1173



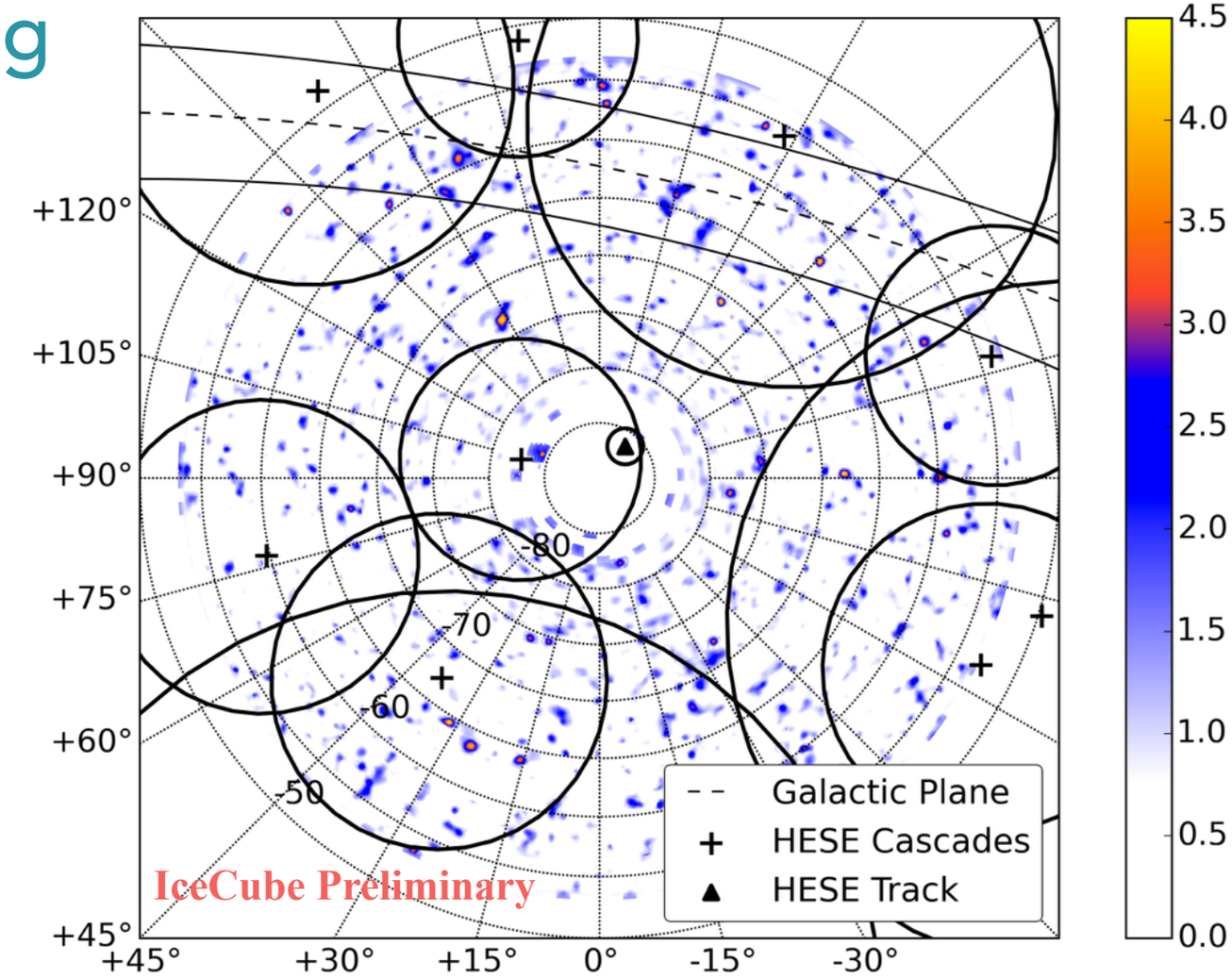


- Unidentified source with confirmed counterpart at GeV energies by Fermi (Guo et al. 2016)
- Well fit to E^{-2} over 4 orders of magnitude (GeV-TeV) with no cut-off, unique among known TeV sources
- IceCube limit is first at PeV energies

IceCube

IceCube High Energy Starting Event (HESE) Neutrinos

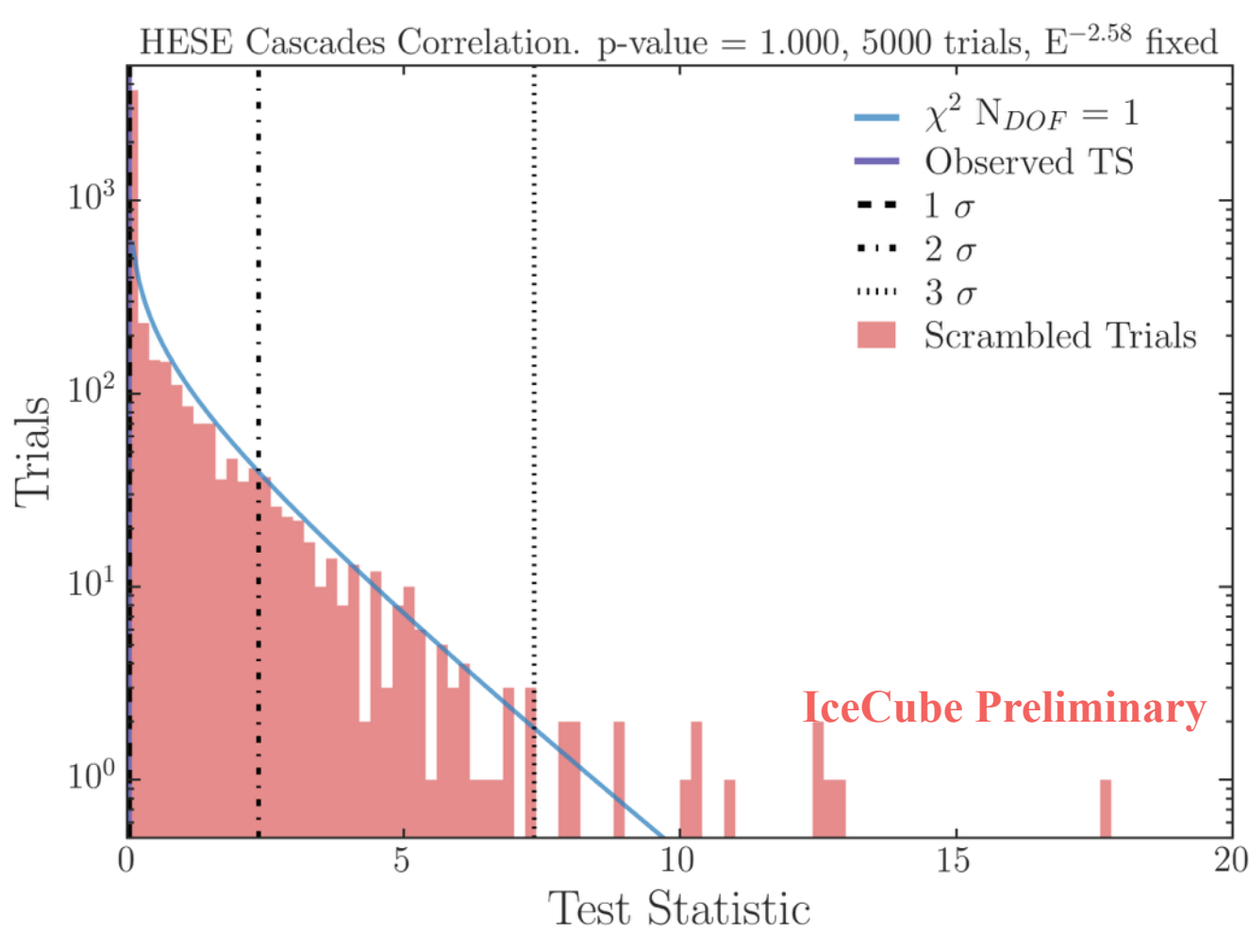
- Pure sample of neutrino events with strong astrophysical evidence
- Using 4-year sample, where 11 total events have a reconstructed direction within 1σ of FOV
- Event types:
  - **Cascades**: good energy resolution, poor angular resolution
  - **Tracks**: poor energy resolution, good angular resolution



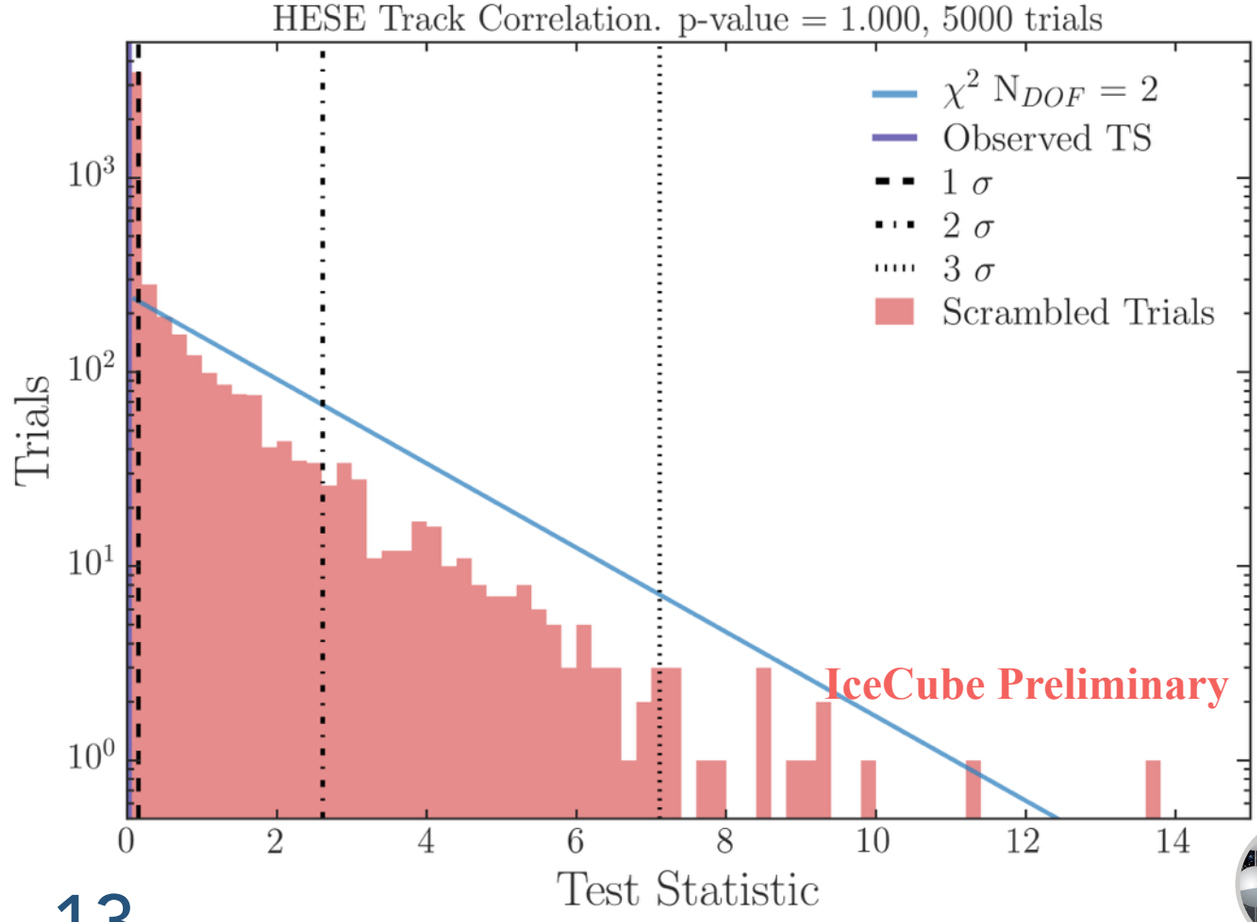
IceCube

IceCube High Energy Starting Event (HESE) Neutrinos

- Cascades
  - Broad spans in declination require convolution of detector acceptance - use template method
  - Spectral index fixed at 4-yr best fit of HESE data: $E^{-2.58}$
  - **p-value > 49%**

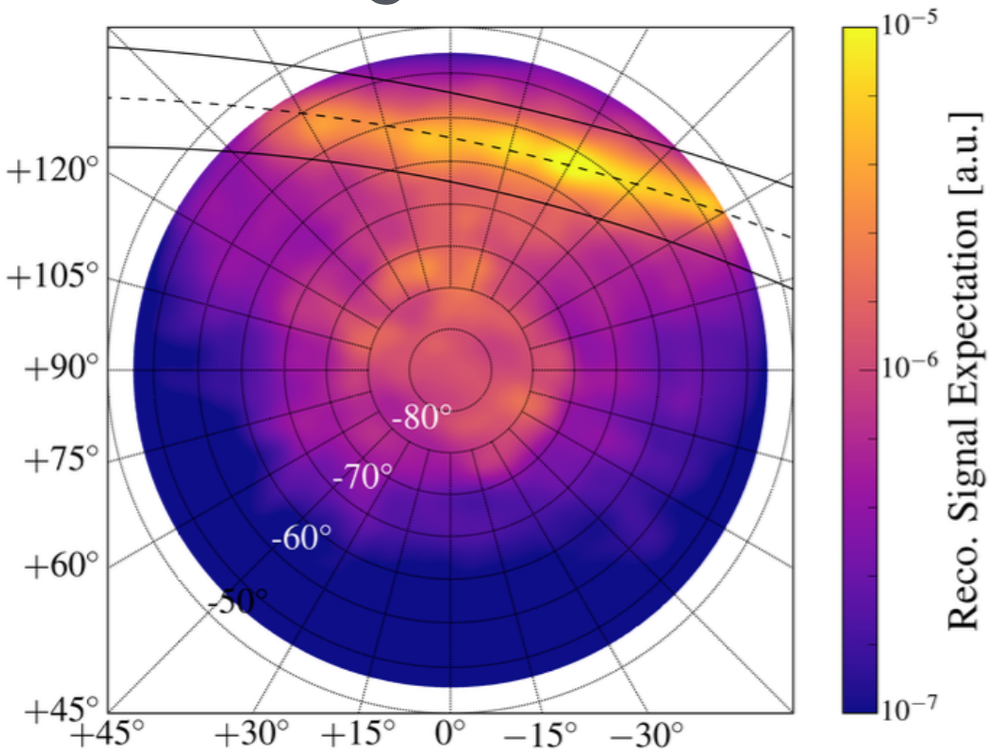


- Tracks
  - Vertical location of track limits right ascension only scrambling
  - For <5° zenith, scramble in right ascension and declination
  - **p-value > 71%**



Diffuse Galactic Plane Template Analysis

Signal PDF



Ref: PoS(ICRC2017) 1011

$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i(\mathbf{x}_i, \sigma_i, E_i; \gamma) + \widetilde{D}_i(\sin\delta_i, E_i) - \frac{n_s}{N} \widetilde{S}_i(\sin\delta_i, E_i) \right)$$

Signal PDF

Signal subtracted background PDF generated from observed data

- Signal PDF constructed from the pion decay component of the Fermi-LAT diffuse emission model
- Fermi template is multiplied with detector acceptance and convolved with point spread function of reconstructed events
- Unbinned maximum likelihood analysis performed with the likelihood function described above
- **No significant evidence found to exclude null hypothesis**

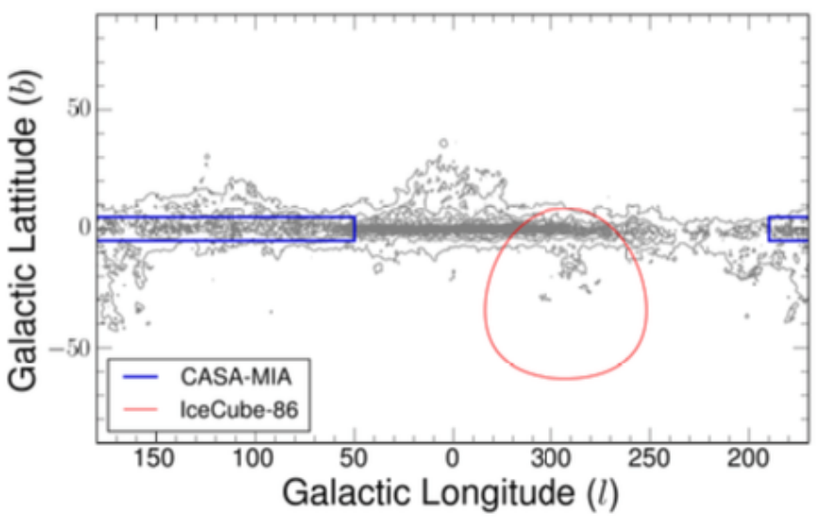
Galactic Plane Upper Limit

- Template analysis yields normalization ***A*** to spectral energy distribution of the angular-integrated flux from the entire field of view

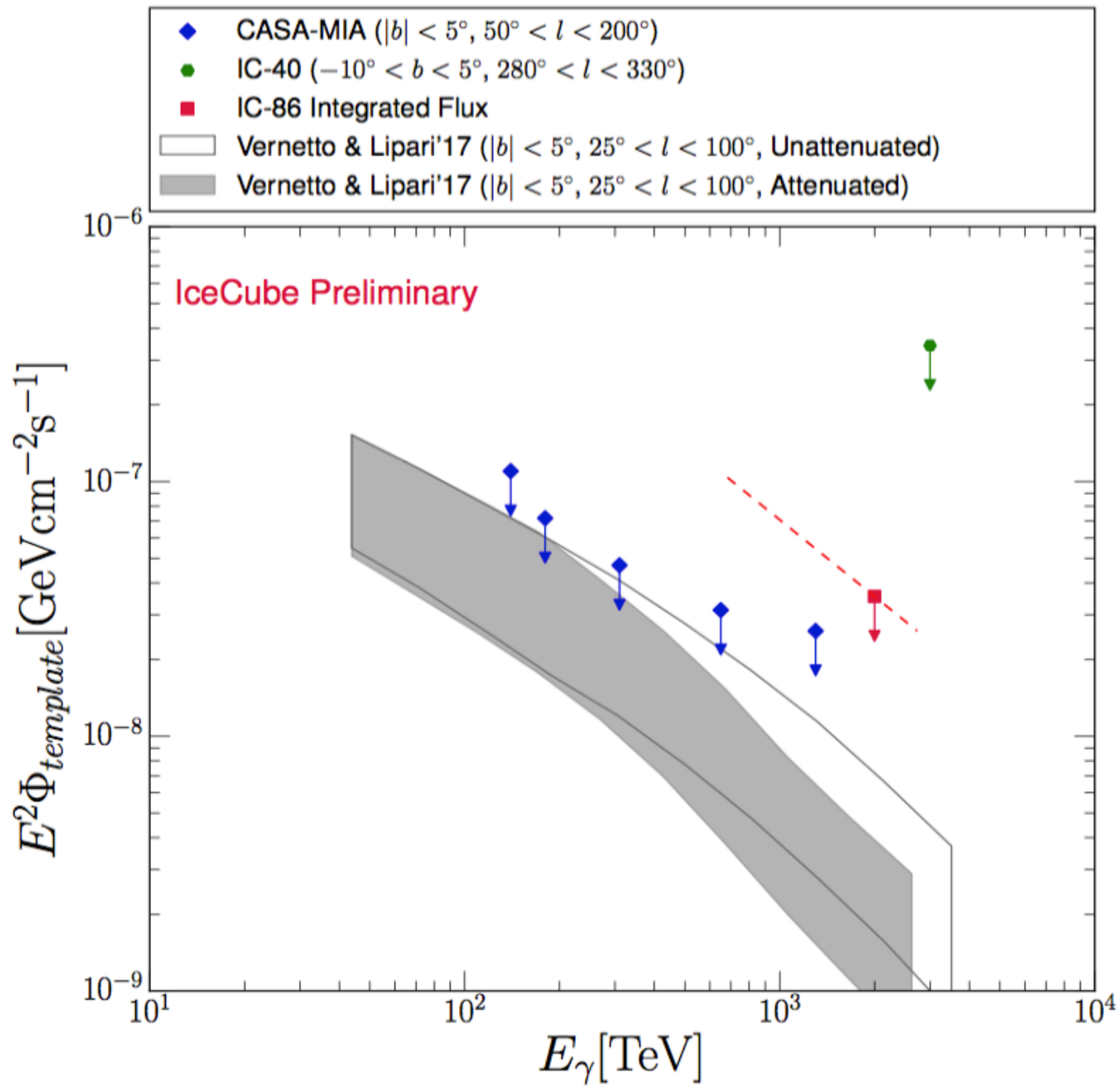
$$E^2\,\phi'(E) = A\left(\frac{E}{E_0}\right)^{2-\gamma}$$

- We compare with CASA-MIA, the previous IceCube analysis, and models by comparing "scaled angular-integrated" fluxes:

$$\Phi_{template} = \Phi\Delta\Omega\frac{\int_{all\ sky} S_{Fermi}\,d\Omega}{\int_{\Delta\Omega} S_{Fermi}\,d\Omega}$$



Scaled Angular-Integrated Flux



IceCube

Conclusion

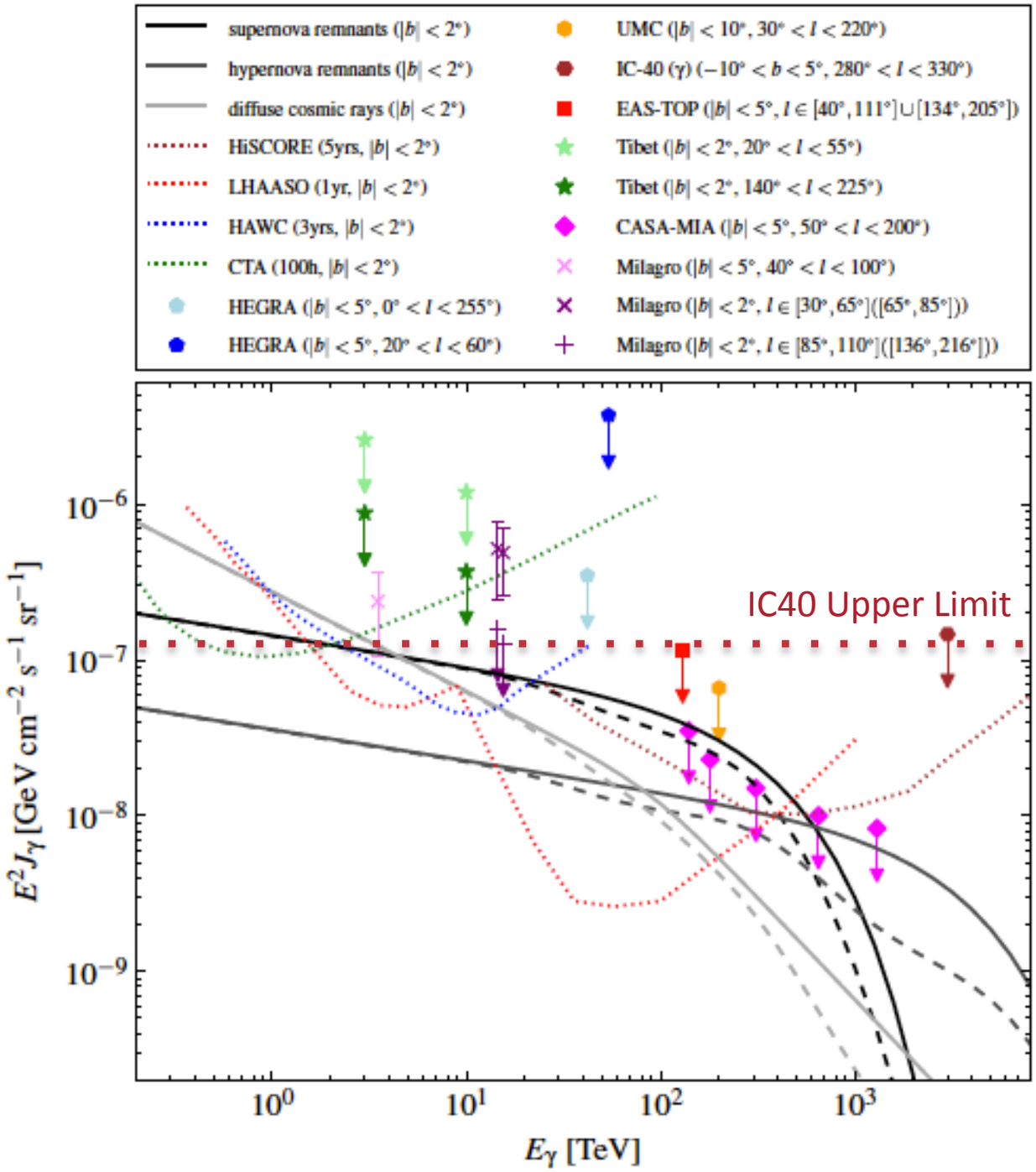
- No evidence for PeV gamma-ray sources was found in 5 years of IceCube/IceTop data
  - Point Source Analyses
    - All-sky scan
    - Search for correlation with known TeV gamma-ray sources (H.E.S.S.)
    - Search for correlations with high-energy IceCube neutrinos
  - Search for excess of PeV gamma rays from the Galactic plane
- Limits set most stringent yet to PeV gamma-rays in southern hemisphere

Thank you!

Backup Slides

Comparison to Prior Analysis

arxiv:1309.4077v3



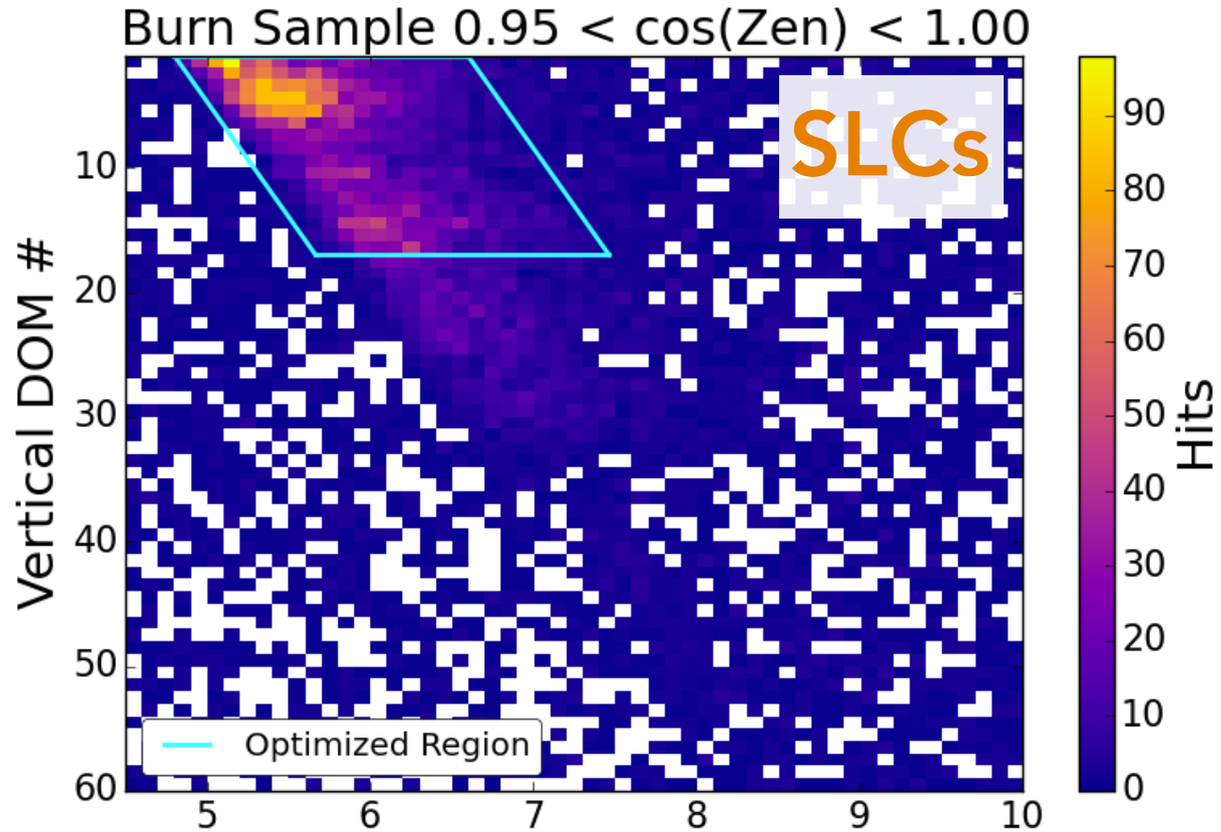
- IC40 Analysis:
  - IceCube used as veto
  - No point sources were found
  - Upper limit on the diffuse gamma-ray flux from the Galactic Plane in the energy range 1.2 - 6.0 PeV

- Current Analysis Details:
  - 5 years of IC86 data
  - Energy range of ~1 PeV - 100 PeV
  - Random forest for event selection
  - Cleaned and optimized In-Ice charge
  - Composition sensitive IceTop LLH ratio

IceCube Charge

- The IC-40 analysis required 0 HLC hits in IceCube.

- This analysis uses the total charge in IceCube as a separating feature, a sum of:

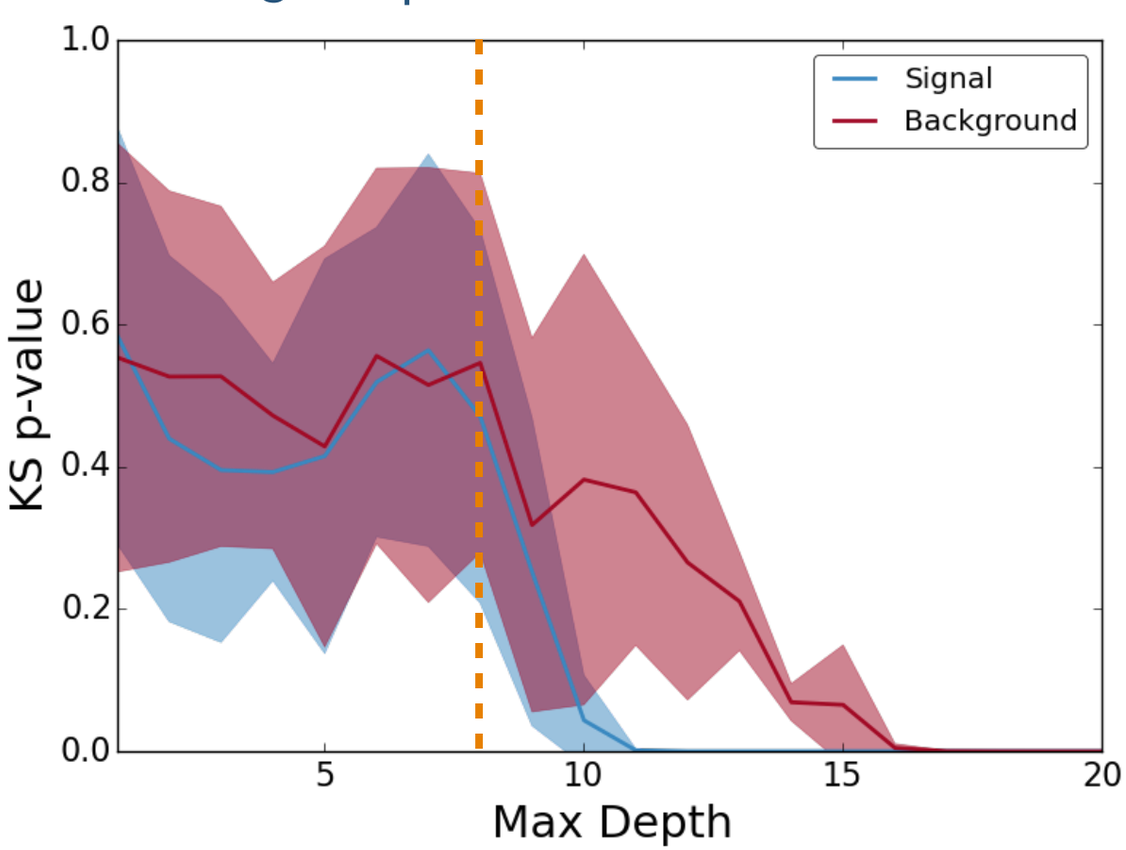


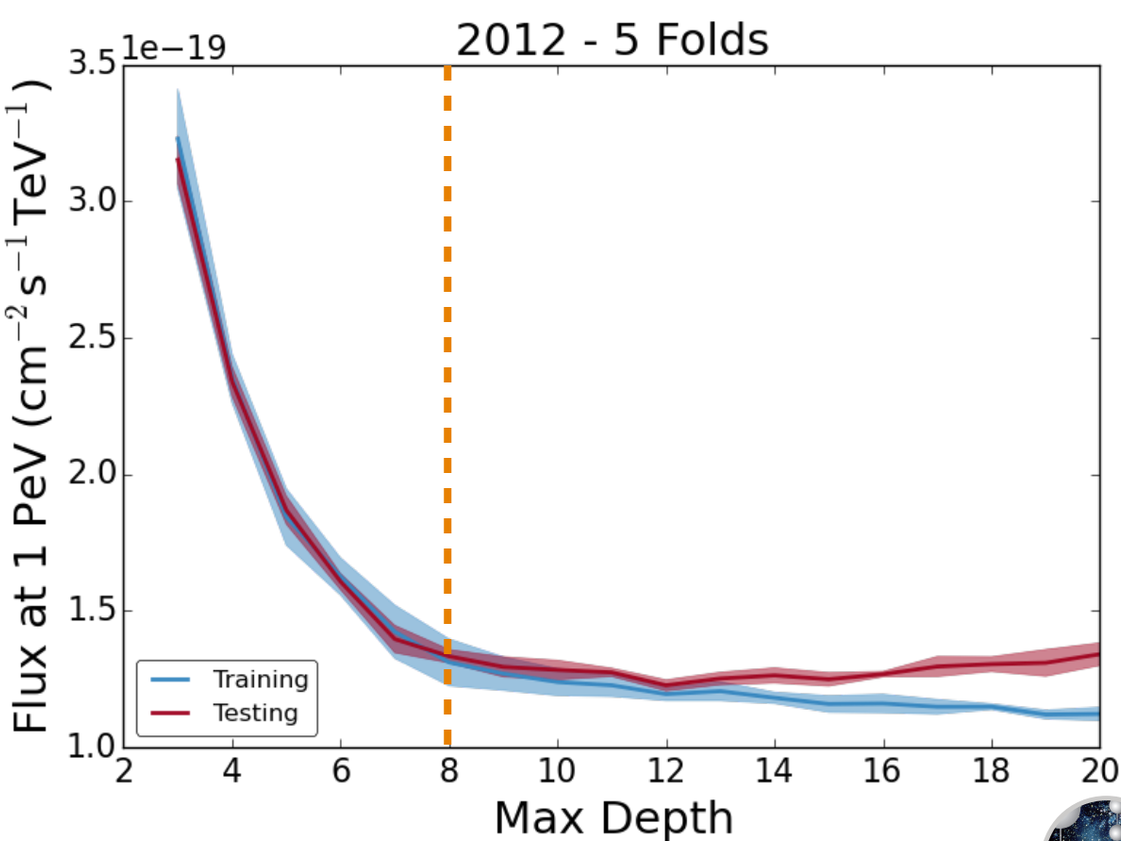
  - Charge in HLC hits
    - Keep pulses with 3.5 μs < t_{pulse}-$t_{ITtrigger}$ < 11.5 μs for events with no IceCube trigger
    - Clean with SeededRT for events with IceCube trigger
  - Charge in SLC hits
    - within 130 meters of reconstructed track
    - Top 16 DOMs
    - 1.8 μs time window
    - Starting Time = (4.8 μs + depth/c)/cos(Zenith)

Random Forest Classifier

- Implemented using scikit-learn
- Data used for background
  - 10% of each year dedicated as burn sample for training
- Gamma simulation used for signal
  - 80% used for training, remaining 20% kept for final sensitivity
- 5-fold cross-validation used for hyper-parameter optimization
- Overtraining tested with KS test and validation curves of training and testing samples

Parameter	Setting
min_samples_split	2
min_samples_leaf	1
min_weight_fraction_leaf	0
max_leaf_nodes	None
max_depth	8
n_estimators	1000





IceCube