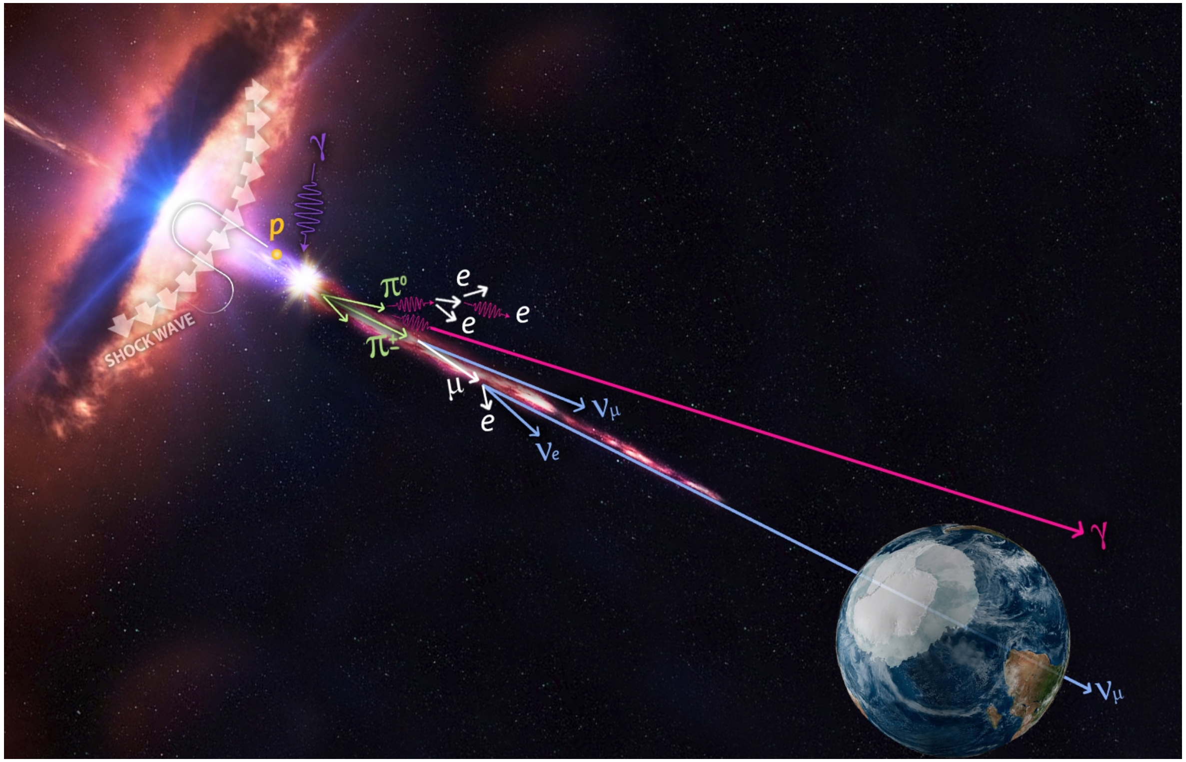
10 years of Neutrino Point-Source Searches

Tessa Carver

Why Neutrinos ?

- **Protons / Cosmic Rays** : directly from the astrophysical sources.
- **Photons** : produced by leptonic and hadronic processes at the source.
- **Neutrinos** : produced only by Hadronic CR interactions.



Hadronic Interactions :

$$pp \Rightarrow \pi^{0} \Rightarrow \gamma\,\gamma$$

$$pp \Rightarrow \pi^{\pm 1} \Rightarrow \mu^{\pm 1} + \nu_{\mu} \Rightarrow \nu_{\mu} + e^{\pm 1} + \bar{\nu}_{e} + \nu_{\mu}$$

- Photons and CRs are attenuated by CMB & surrounding matter
- CRs are deviated due to their charge
- Neutrinos travel unimpeded accross the universe so they can point **directly towards the source**.

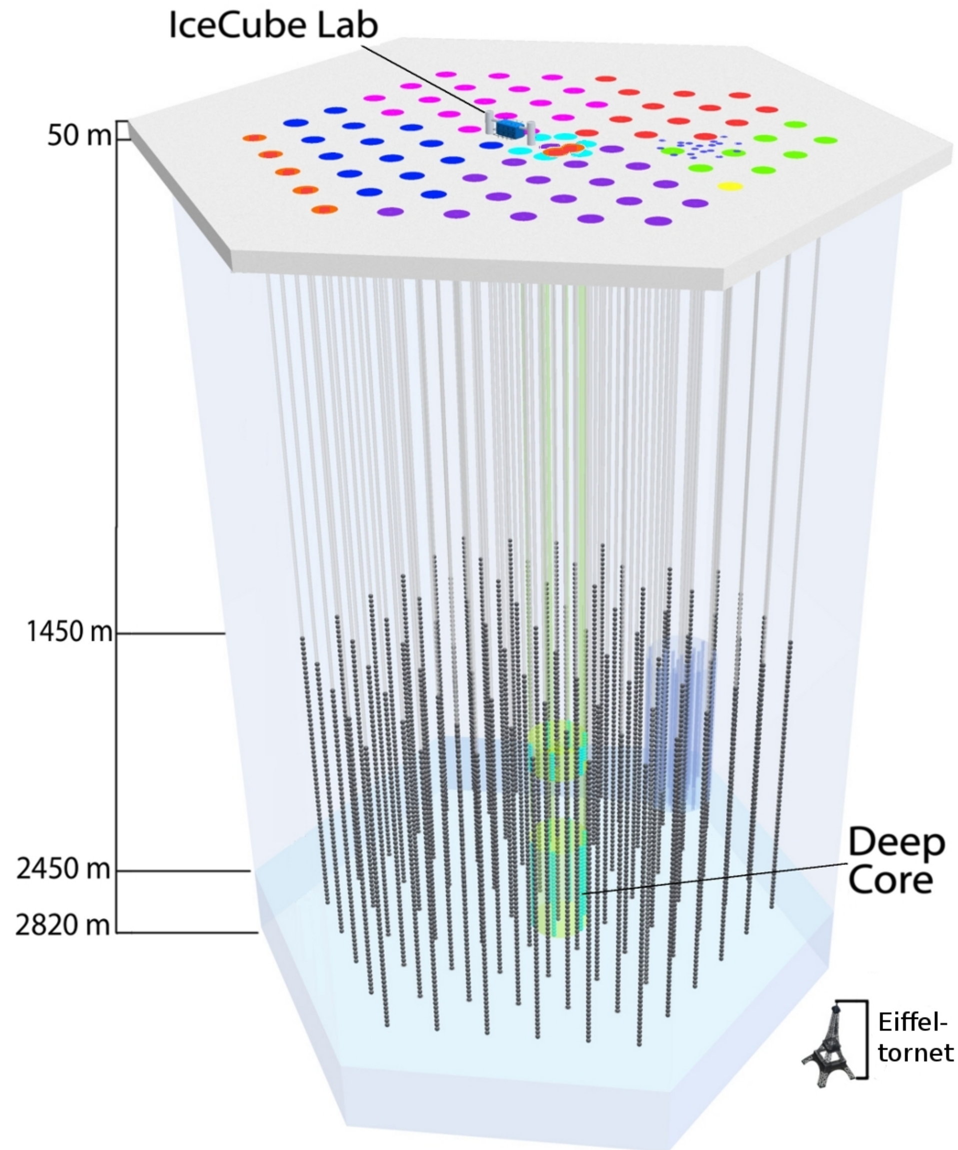
IceCube Detector

<u>What Do We Detect ?</u>

- Neutrinos interact in the ice producing charged leptons.
- Charged leptons induce Cherenkov radiation while traversing the ice.

<u>How ?</u>

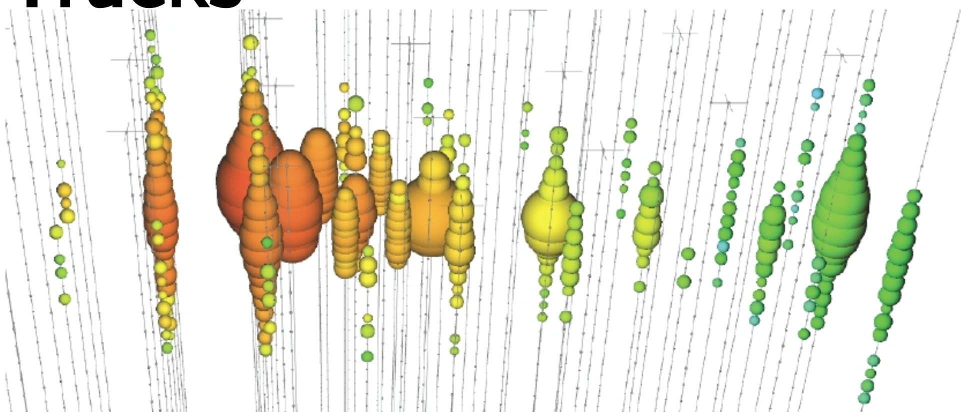
- 86 strings in cubic km of Antarctic Ice over 1.45 km below the surface [1].
- Each string has 60 Digital Optical Modules (DOMs).



[1] Aartsen, M. G., et al. 2017, JINST, 12, P03012

IceCube Events

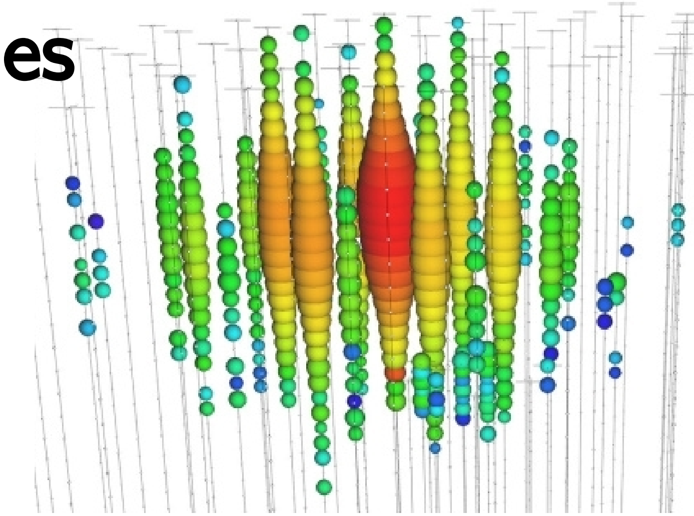
Tracks



Colour : Timing **Earlier** → **Later**
Size of dom : Energy deposited

- High Energy Muons propagate in the ice.
- From: Atmospheric Muons, and Charged Current ν_μ interactions.
- Angular Resolution $< 1^\circ$ [2]
- Poor Energy resolution (factor 2)

Cascades

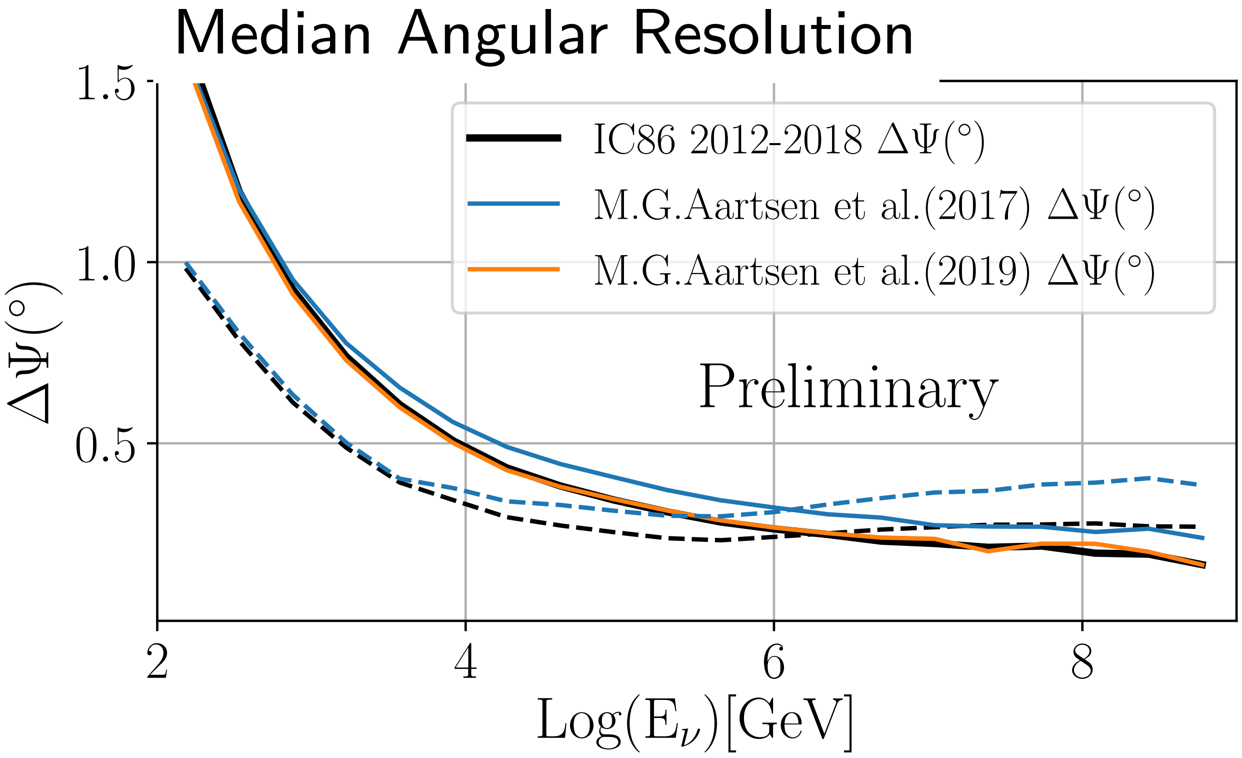


IceCube Big Bird event ~ 2 PeV

- Shower of charged particles in the ice
- From: ν_τ , ν_e, and Neutral Current ν_μ interactions.
- Angular Resolution $\sim 15^\circ$ [3]
- Good Energy Resolution (15%)

[3] Aartsen, M. G., et al. 2017, Astrophys. J., 846, 136
[2] Aartsen, M. G., et al. 2014, Nucl. Instrum. Meth., A736, 143

Updated Direction Reconstruction



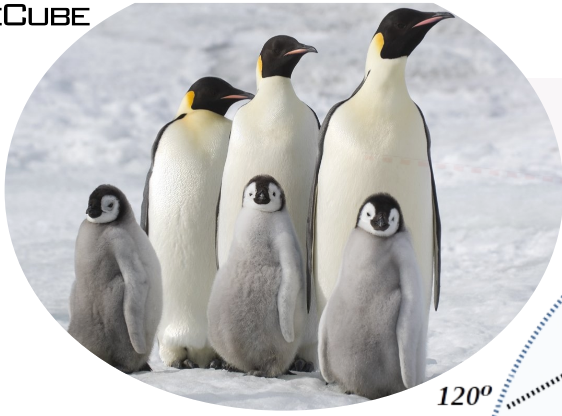
$\Delta\Psi$ = median angular difference between true neutrino direction and reconstructed muon direction.

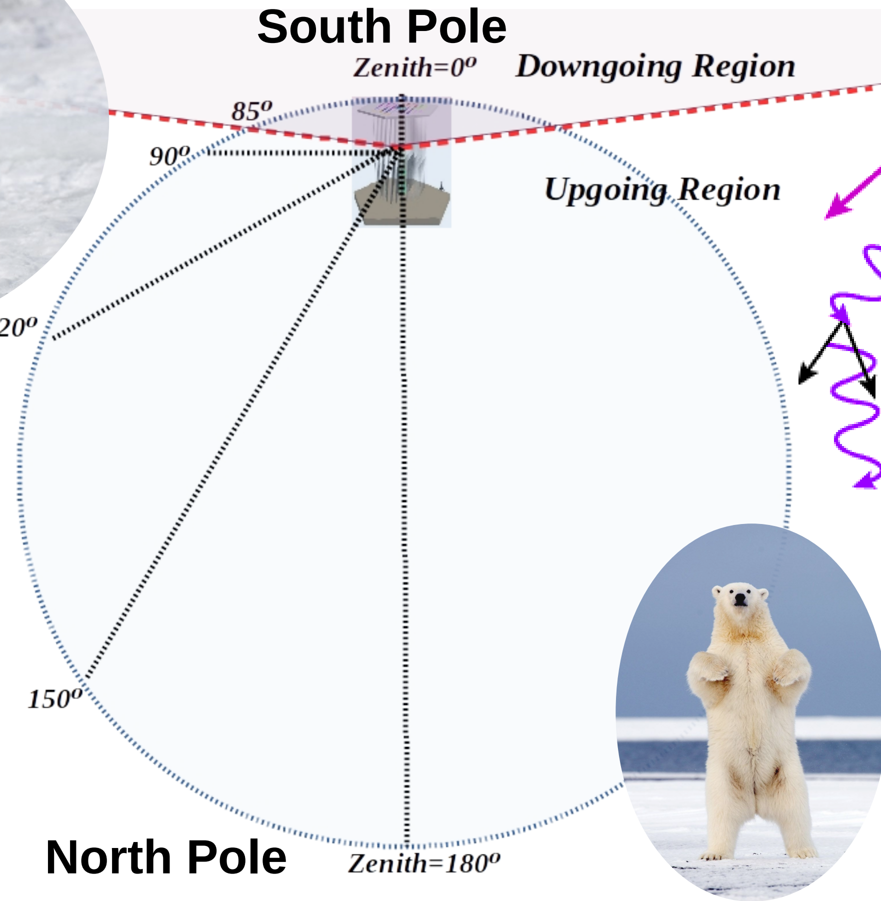
- Angular Resolution : ~1^0 at 1TeV to ~0.2^0 > 100 TeV.
- New direction reconstruction re-applied to both hemispheres. Inspired by improved sensitivity of northern sky analysis [9]

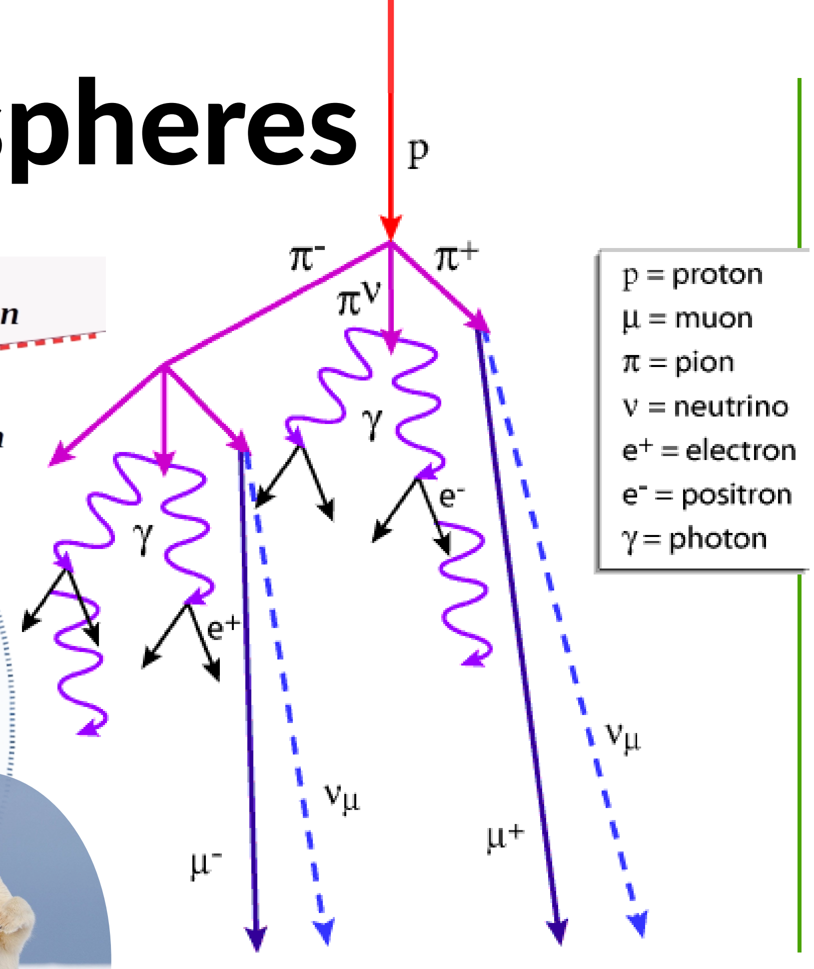
→ Over 10% improvement for events > 10 TeV compared to 7 year all-sky selection [10].

[9] Aartsen, M. G., et al. 2019, Eur. Phys. J. C., arXiv:1811.07979 [10] Aartsen, M. G., et al. 2017, Astrophys. J., 835, 151

Different Hemispheres





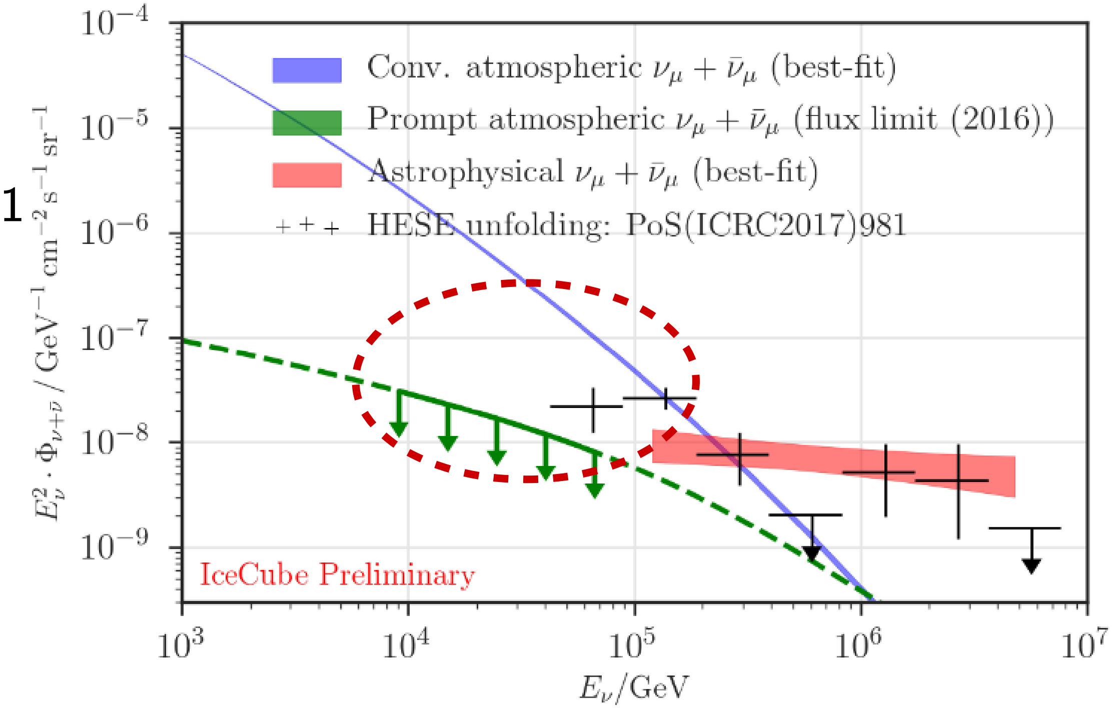


- Southern hemisphere heavily contaminated by atmospheric neutrinos & muons
- Muons produced in the northern atmosphere cannot reach IceCube

Analysis Motivation

- IceCube discovered diffuse astrophysical flux.
- Evidence has been presented for only 1 neutrino source. (TXS 0506+056 [4])

$\rightarrow \sim$1% of the diffuse flux.



[4] M. G. Aartsenet al.(IceCube), Science361, 147–151 (2018),

Analysis Motivation

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- Evidence has been presented for only 1 neutrino source. (TXS 0506+056 [4])

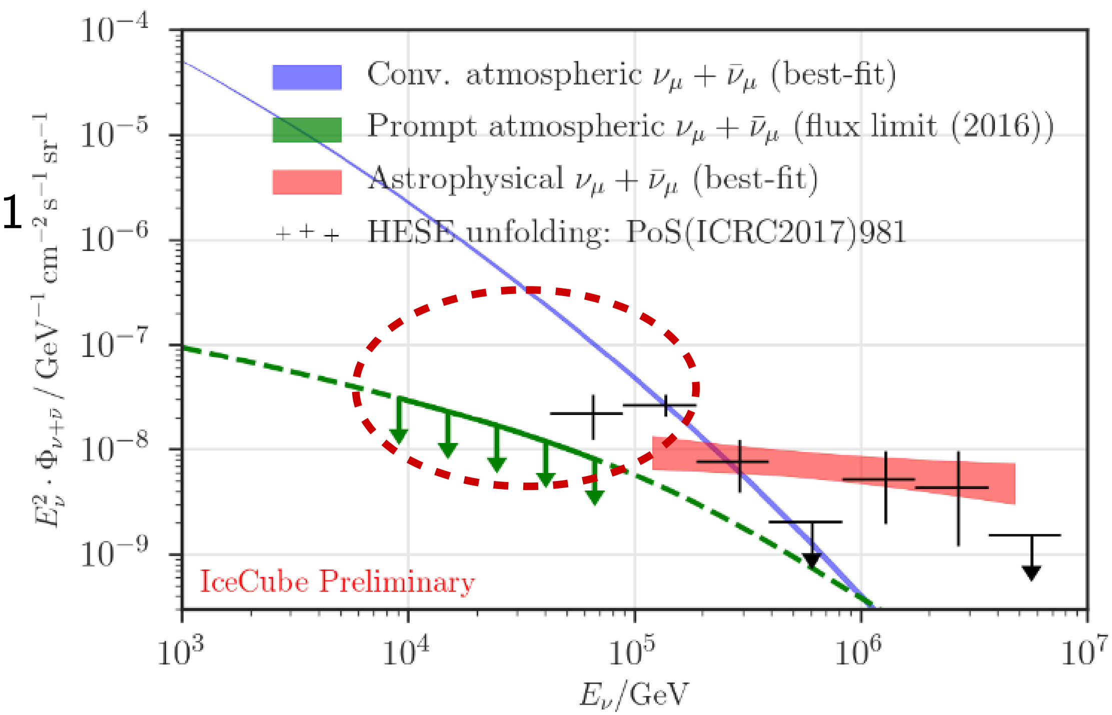
  → ~1% of the diffuse flux.

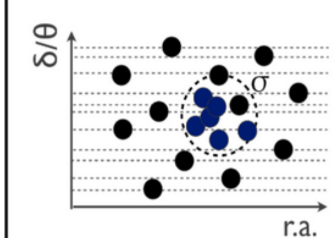
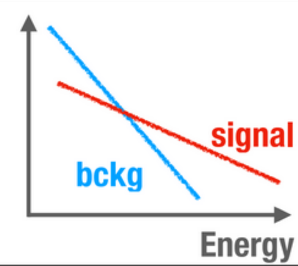
- Data dominated by atmospheric events. However, we expect :

  → ***Clustered*** or **correlated** signal (in space and/or time)

  → ***Uniform*** Background

- Astrophysical spectrum expected to be harder : $dN/dE \propto E^{-\gamma}$, $1<\gamma<4$



Method	Spatial PDF	Energy PDF
Time-integrated		

[4] M. G. Aartsenet al.(IceCube), Science361, 147–151 (2018),

ICECUBE

Updated Point Source Searches

Search	Advantages	Disadvantages
All Sky Scan	• Allows for sources not well observed by other messengers including unexpected source candidates	• Large penalty from trials. • Requires a very strong source to be more significant than any possible background fluctuation.
Source List Search	• Provides significance and fit information specific to individual sources.	• Limited to low number of possible candidates. • Limited by sensitivity at the source location.
Stacking Search	• Gain large factors in sensitivity especially in regions where IceCube is less sensitive (Southern Hemisphere)	• Requires more source knowledge. • Most stacked locations should emit a neutrino flux $\rightarrow$ strong penalty if an inaccurate weighting scheme is implemented.

Less Required Source Knowledge

Less sensitivity

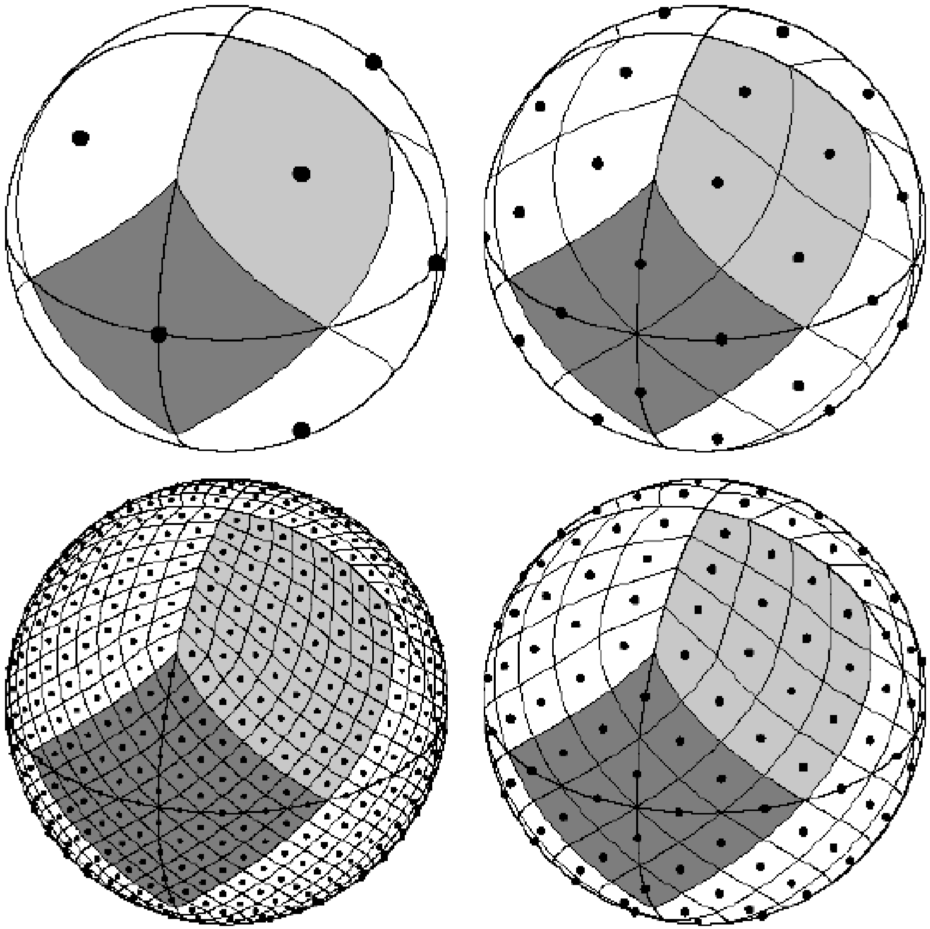
↓

Increasing Knowledge & Sensitivity

1)

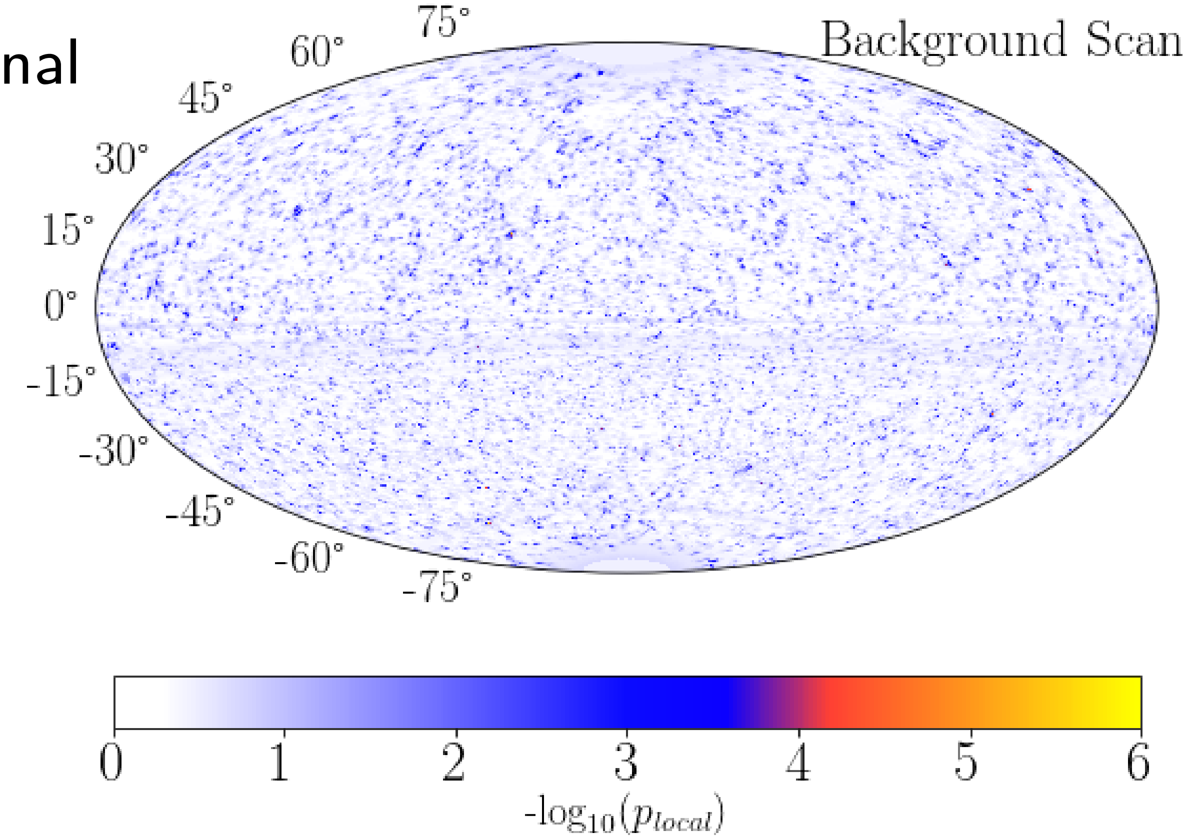
All-Sky Scan

1) Create grid of points with ~0.9° binning across the entire sky.
2) Exclude regions around poles due to low statistics.
3) Maximize Signal/Background likelihood ratio (TS) at every point.
4) Re-iterate with finer binning
5) Repeat until evaluated for ~0.1° binning
6) Use TS to calculate pre-trial p-value



All-Sky p-value map

- Most significant pre-trial p-value in each hemisphere. → **Hotspots.**
- post-trial p-values calculated by comparing hotspots from different scans of background with final true scan.

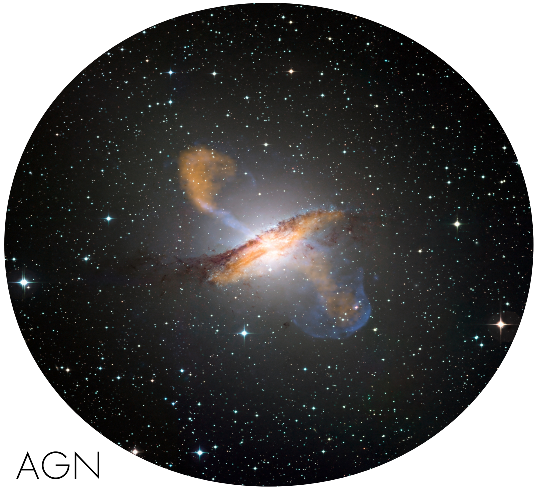


Updated Individual Source List

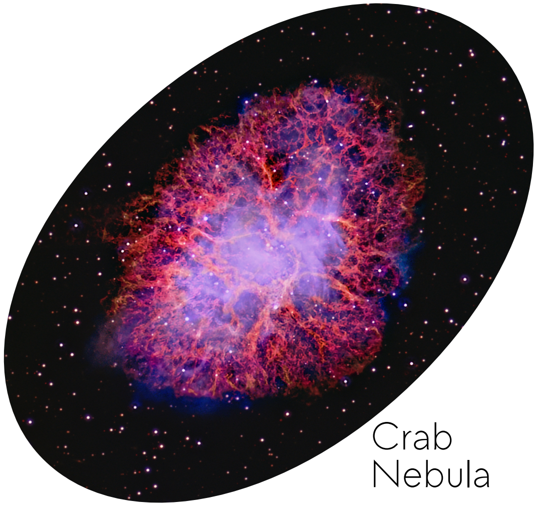
2)

New source candidates list of 110 Galactic & Extra-galactic sources :

- The top 5% of extra-galactic sources organised by Flux integral from Fermi catalog : BL LAC, Flat-spectrum radio quasar (FSRQ), Starburst galaxies, AGN.
- From the Fermi catalog only 8 galaxies were identified with known starburst activity so they were all kept.
- For Galactic sources criteria was applied where model flux $>$ 50% of the sensitivity flux for each source.



AGN



Crab Nebula

3) Catalog Population Analysis

- Search for excess in rate of hotspots in the catalog.
- Assume a binomial distribution.

  → Probability of k out of N sources passing a threshold (p_k) :

$$P_{\text{binom}}(k|p_k,N) = \binom{N}{k} p_k^k (1-p_k)^{N-k}$$

  → Iterate the threshold to test k=1,2,3,...,N.

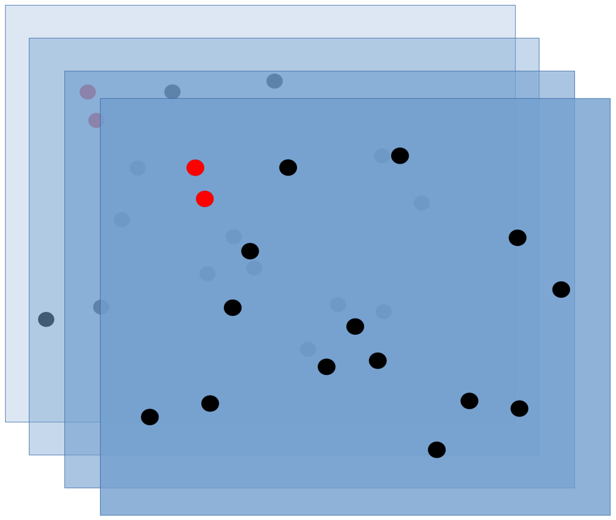
- Example :

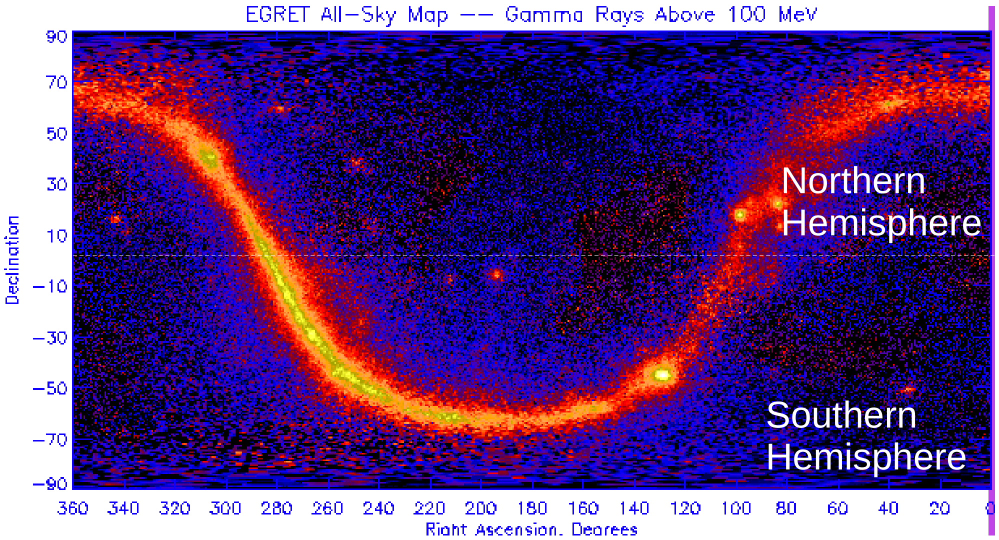
  → 1 x 2σ source out of 100 : P_{binom} (1|0.02,100)=0.87 (Under-fluctuation.)

  → 10 x 2σ sources out of 100 : P_{binom} (10|0.02,100)= 4σ

Stacking Searches

- Galactic source flux alone < sensitivity flux → large section of the Galactic plane in the southern hemisphere.
- Optimal for sources with similar spectra → single fit spectral index.





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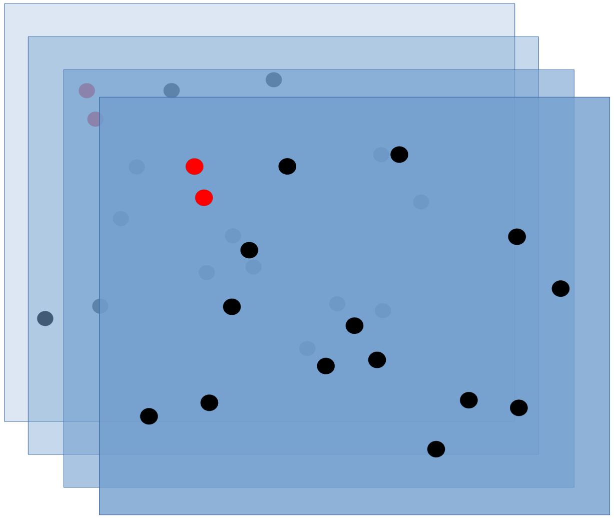
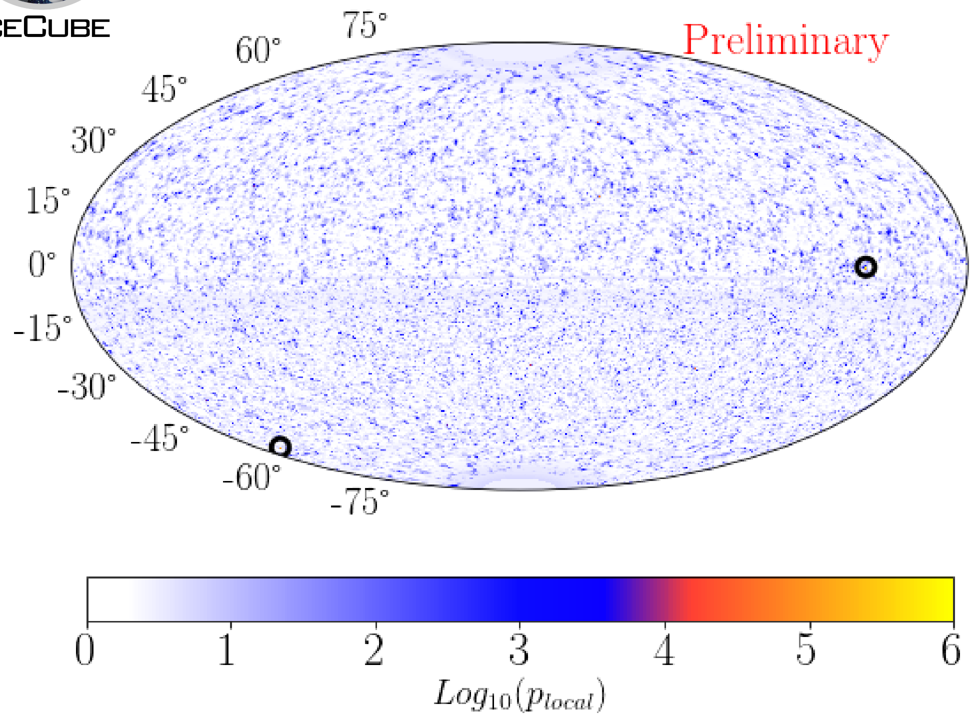


- 3 catalogs :
  → 58 Unidentified sources (UNID)
  → 33 Pulsar Wind Nebula (PWN)
  → 23 Supernova Remnant (SNR)

Casseopia A


Results

10 year All-Sky Scan Results



- Scan the entire sky and evaluate the likelihood of signal over background.
- The position with the smallest p-value in each hemisphere is taken as the hottest spot.

Hottest Point in Northern Hemisphere : δ ≥ -5º

RA = 40.87° , Dec = -0.30°

n_{signal} = 61.45 , γ= 3.411

-log(p) = 6.45, TS = 25.34 ⇒ 9.9 % post-trial

Hottest Point in Southern Hemisphere : δ< -5º

Ra = 350.18° , dec -56.45°

n_{signal} =17.75, γ = 3.34

-log(p) =5.37, TS= 19.95 ⇒ 75 % post-trial

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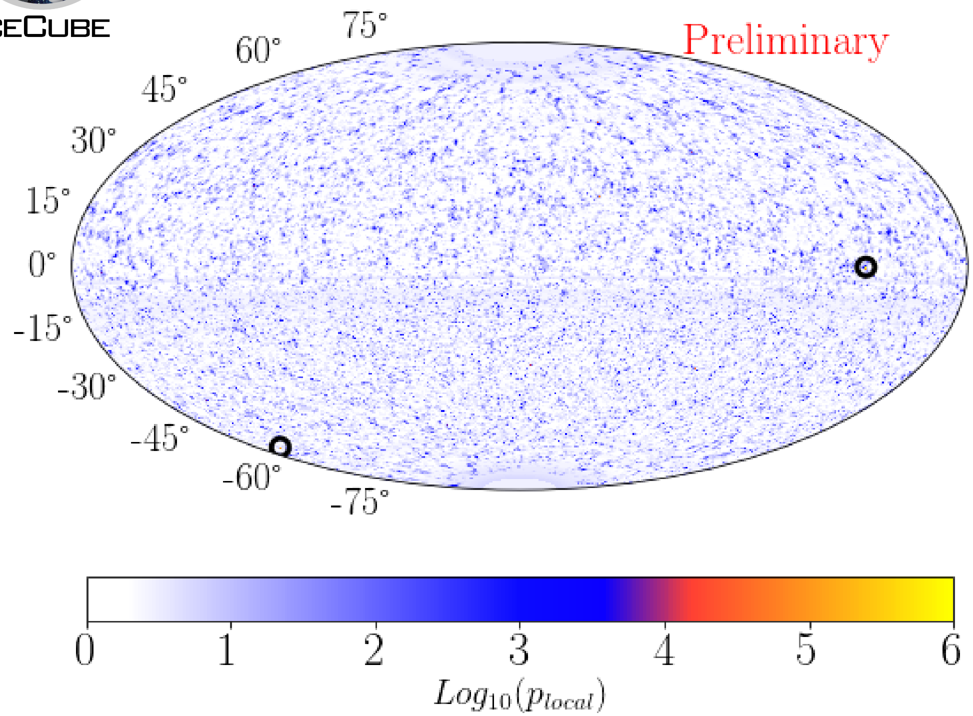

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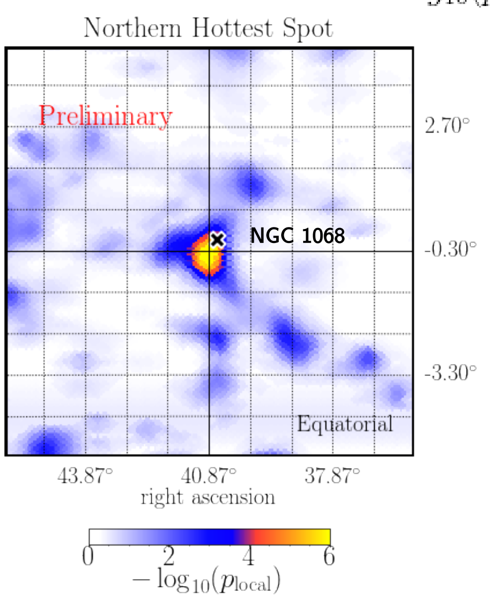

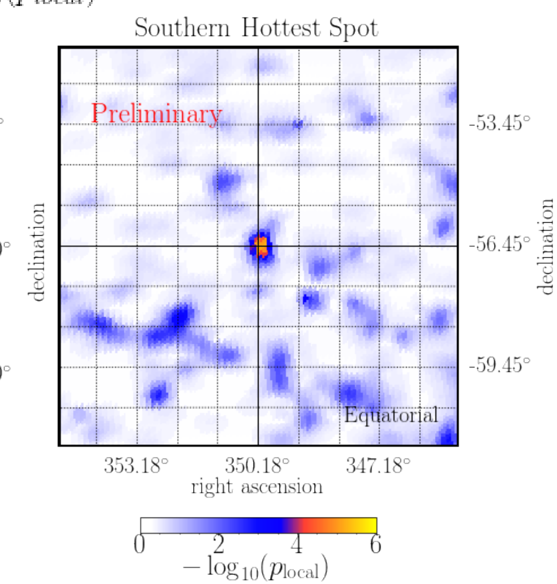

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Most significant Source List Results

Name	Ra (°)	Dec (°)	TS	n_{signal}	γ	$-\log_{10}(p_{local})$	Pre-trial σ
NGC 1068	**40.67**	**-0.01**	**17.04**	**50.4**	**3.16**	**4.74**	**4.13**
TXS 0506+056	**77.35**	**5.70**	**13.05**	**12.32**	**2.08**	**3.72**	**3.55**
PKS 1424+240	**216.76**	**23.8**	**9.88**	**41.47**	**3.94**	**2.8**	**2.95**
GB6 J1542+6129	**235.75**	**61.50**	**9.29**	**29.72**	**3.02**	**2.74**	**2.91**
MGRO J1908+06	287.17	6.18	3.48	4.22	1.96	1.42	1.77
PKS 1717+177	259.81	17.75	2.96	19.82	3.65	1.32	1.66
PKS 2233-148	339.14	-14.56	2.8	5.32	2.80	1.26	1.6
B2 1215+30	184.48	30.12	2.67	18.60	3.39	1.09	1.4
M 31	10.82	41.24	2.11	10.99	4.0	1.09	1.4
4C +55.17	149.42	55.38	1.61	11.88	3.27	1.02	1.31

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- Evidence for a flaring Blazar from a flare in 2014. (M. G. Aartsen et al. 2018)

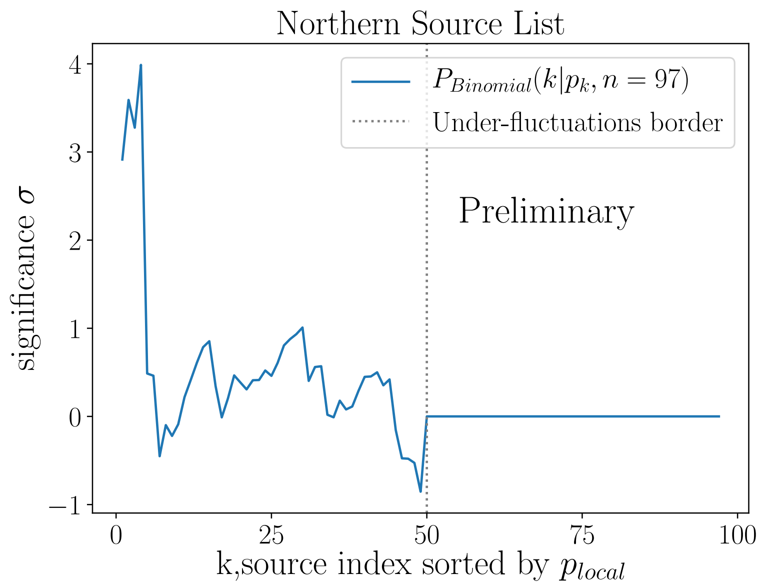
- Most signifcant excess in the Northern Source List. → **2.9σ post-trial**
- **0.35^0** from the hottest point in the sky.

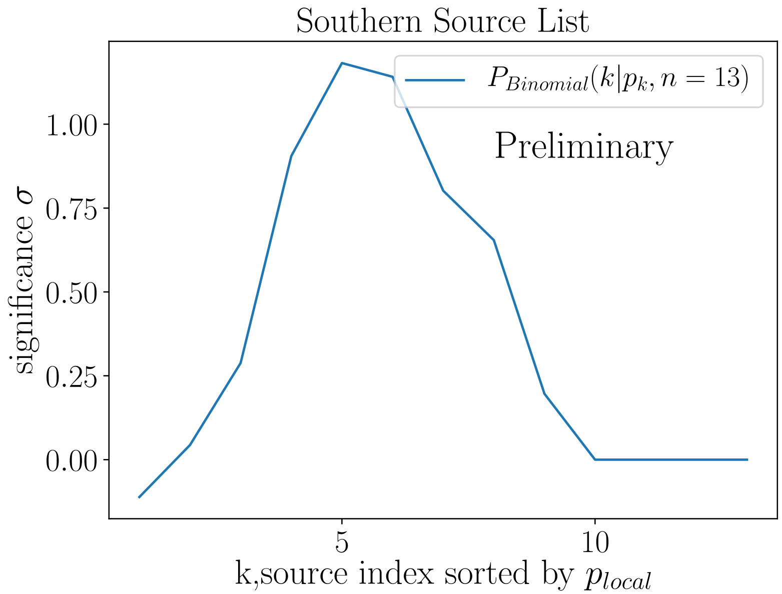
Source Population Results

Search for an excess of hotspots → A significant p-value could demonstrate inconsistency with background only for entire catalog.

- Probability of k or more sources passing a threshold out of a sample of N.
- Most significant result: 4σ pre-trial where k=4.
- → 3.3σ post-trial. (2.25σ w/o TXS 0506+056) to account for N other possible excesses

- Includes NGC 1068, TXS 0506+056, PKS 1424+240,GB6 J1542+6129

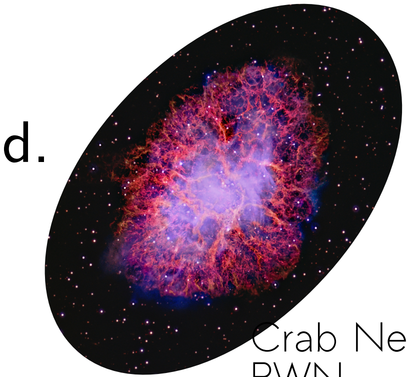




10 year Stacking Results

Cassiopeia A : SNR

- 3 Galactic catalogs updating published results [12]
- Weighted the sources in each catalog by the integral flux above 10 TeV as estimated by Gamma ray observations.
- All catalogs consistent with background.



Crab Nebula: PWN

- 90% upper-limits calculated for emission from each catalog parametrized as :

$d\varphi_{\nu+\bar{\nu}}/dE = \varphi_{90\%} x(E/1TeV)^{-2}\ GeV^{-1}cm^{-2}s^{-1}$

Source Catalog	Number of sources	p-value	n_s	γ	$\phi_{90\%}$
Supernovae Remnants	23	0.11	23.9	3.55	4.96×10^{-15}
Unidentified Objects	58	0.4	3.28	2.39	1.56×10^{-15}
Pulsar Wind Nebula	33	1.0	-	-	2.64×10^{-15}

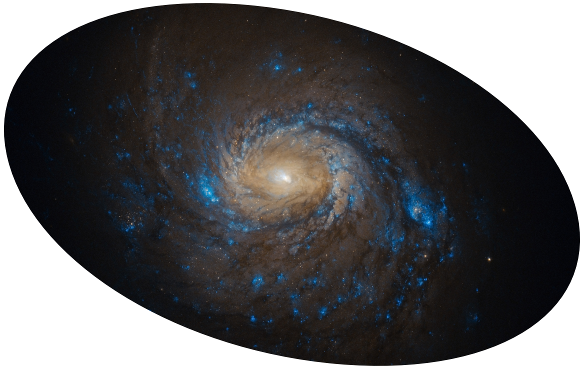
[12] M. G. Aartsen Astrophys.J. 849 (2017) 67

Summary

- No new neutrino steady state source has been discovered.
- NGC 1068 in coincidence with Northern Hotspot. 2.9σ post-trial pvalue.
- Source List Catalog is inconsistent with background only hypothesis at 3.3σ

  → Includes: NGC 1068, TXS 0506+056, PKS 1424+240,GB6 J1542+6129

- The best fit neutrino flux for NGC 1068 is greater than current Gamma ray observations.
- Results demonstrate a strong motivation to continue to analyse the objects in these catalogs.



M77/NGC 1068

https://www.flickr.com/groups/hubblehiddentreasures_advanced/

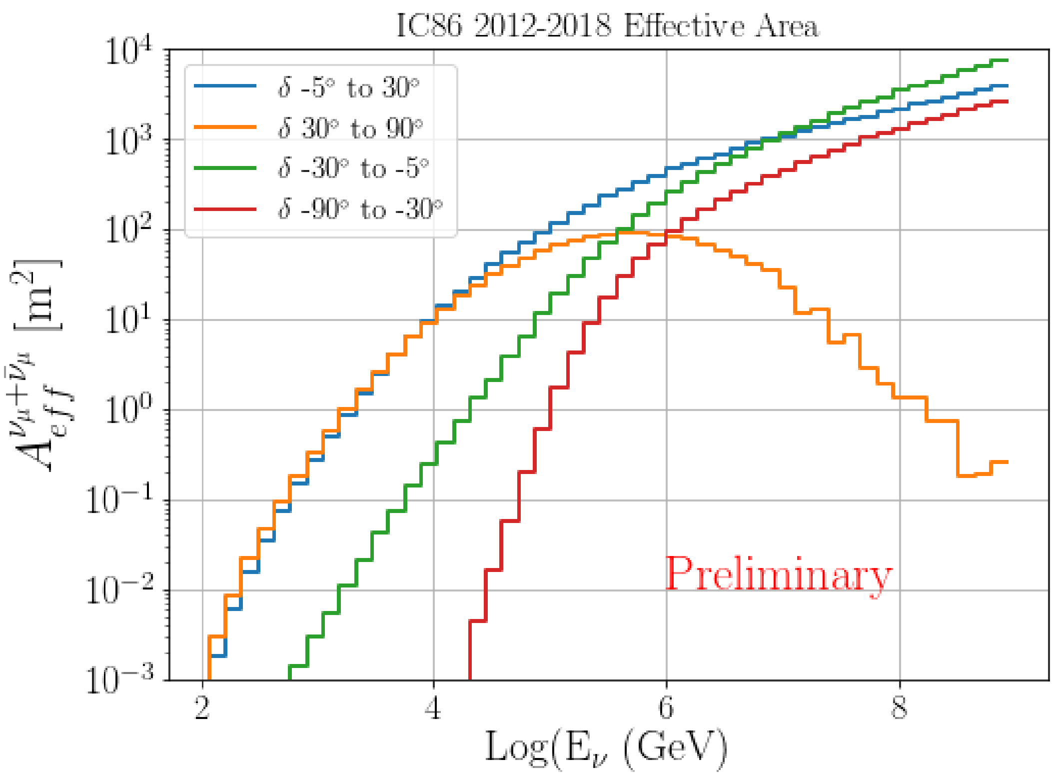
Back up

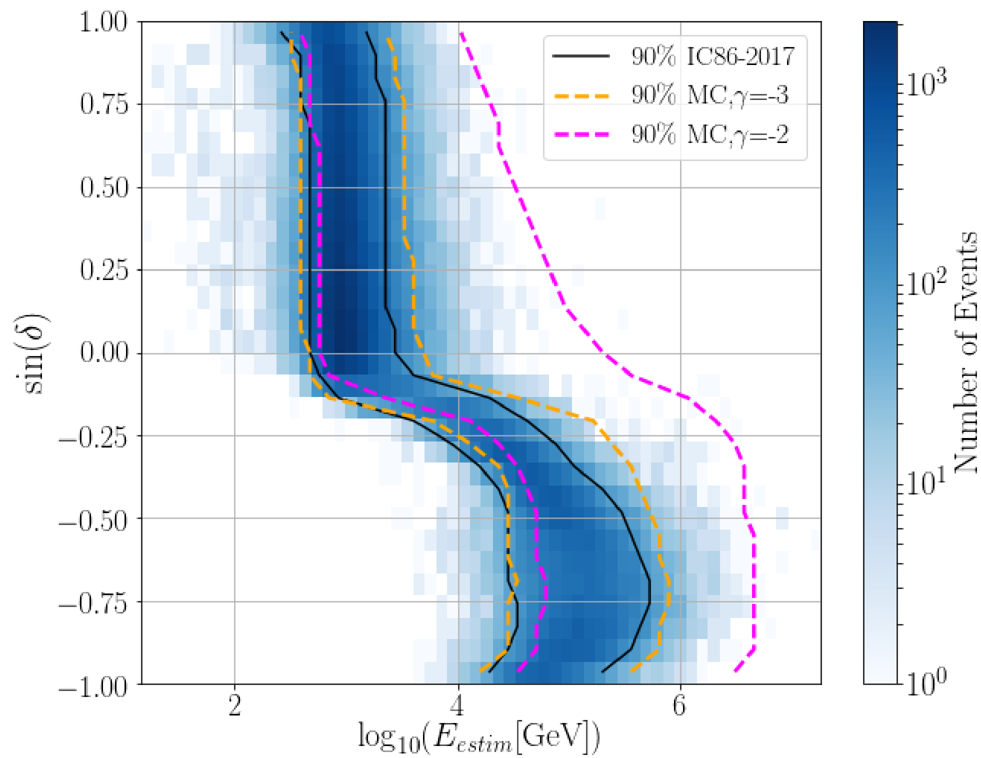
Selection Effective Area

- Effective Area comparable to previous event selection.
- Rate of ν depends on Energy & Declination

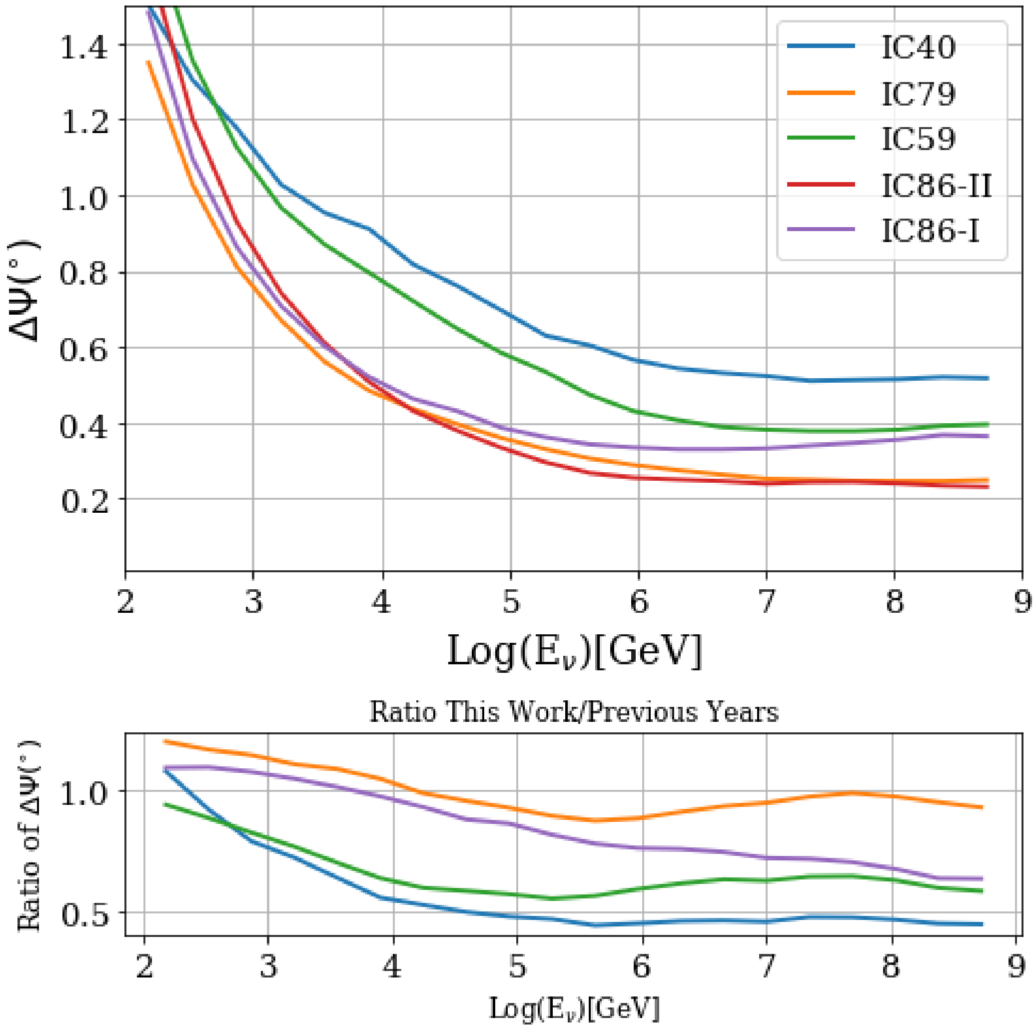
  → Southern events must have higher energy due to strict cuts.

  → Northern events can be filtered by Earth.

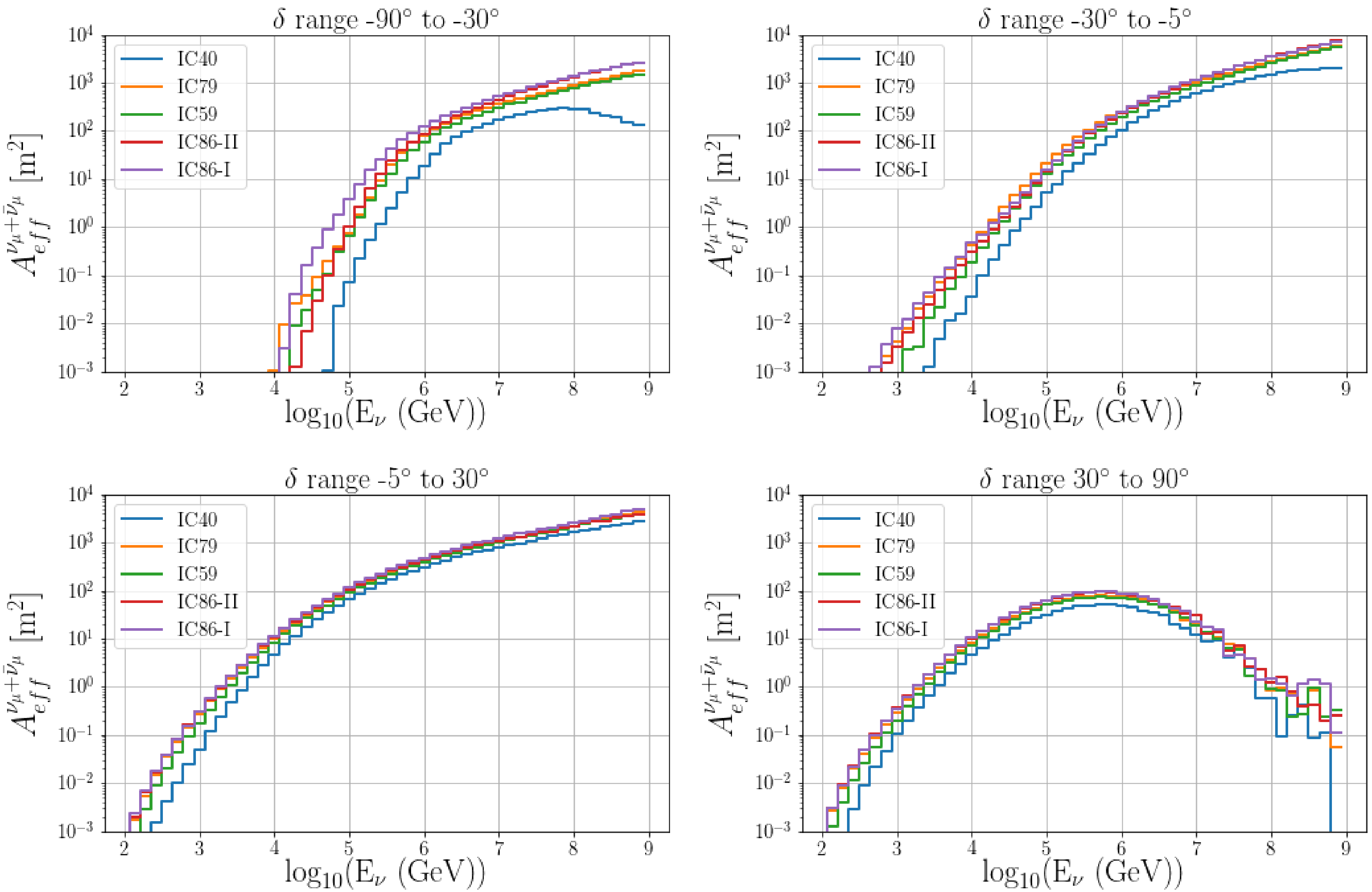




Point Spread Function : All Years



Effective area : All Years



Likelihood Method

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- Maximize signal-over-background likelihood [11]:

$$\mathcal{L}(n_s, \gamma_s, \vec{x_s}) = \prod_{i=1}^{N_\nu} \left(\frac{n_s}{N_\nu} \mathcal{S}_i(\gamma_s, \vec{x_s}) + \left(1 - \frac{n_s}{N_\nu}\right) \mathcal{B}_i \right)$$

Spatial Clustering Energy Spectra

$$\mathcal{S}(E_i, \vec{x_i}) = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|x_s - x_i|^2}{2\sigma_i^2}} \times \mathcal{E}_\mathcal{S}(E_i, sin\delta_i, \gamma)$$

$$\mathcal{B}(E_i, \vec{x_i}) = \frac{\mathcal{P}_\mathcal{B}(sin\delta_i)}{2\pi} \times \mathcal{E}_\mathcal{B}(E_i, sin\delta_i)$$

- Probability Density Function (PDF) contains spatial & energy component:

  1) $\rightarrow$ Spatial clustering Signal according to a 2D Gaussian distribution

  $\rightarrow$ Atmospheric background uniform in Right Ascension.

  2) Signal events and background events to follow different spectra.

- Maximize Test Statistic (TS):

$$\text{TS} = 2log\left[\frac{\mathcal{L}(\hat{n_s}, \hat{\gamma})}{\mathcal{L}(n_s = 0)}\right]$$

$\rightarrow$ n_s,γ are free parameters.

[11] Abbasi, R., et al. 2011, Astrophys. J., 732, 18

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Spatial Clustering Energy Spectra

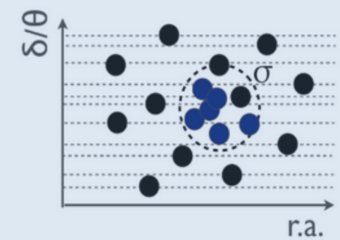
$$\mathcal{S}(E_i,\vec{x_i}) = \frac{1}{2\pi\sigma_i^2}e^{-\frac{|x_s-x_i|^2}{2\sigma_i^2}} \times \mathcal{E}_{\mathcal{S}}(E_i, sin\delta_i, \gamma)$$

$$\mathcal{B}(E_i,\vec{x_i}) = \frac{\mathcal{P}_{\mathcal{B}}(sin\delta_i)}{2\pi} \times \mathcal{E}_{\mathcal{B}}(E_i, sin\delta_i)$$

- Probability Density Function (PDF) contains spatial & energy component:

1) $\rightarrow$ Spatial clustering Signal according to a 2D Gaussian distribution

$\rightarrow$ Atmospheric background uniform in Right Ascension.



2) Signal events and background events to follow different spectra.

- Maximize Test Statistic (TS):

$$\mathrm{TS} = 2log\left[\frac{\mathcal{L}(\hat{n_s},\hat{\gamma})}{\mathcal{L}(n_s=0)}\right]$$

$\rightarrow$ n_s,γ are free parameters.

[11] Abbasi, R., et al. 2011, Astrophys. J., 732, 18

Likelihood Method

ICECUBE

- Maximize signal-over-background likelihood [11]:

$$\mathcal{L}(n_s,\gamma_s,\vec{x_s}) = \prod_{i=1}^{N_\nu}\left(\frac{n_s}{N_\nu}\mathcal{S}_i(\gamma_s,\vec{x_s}) + \left(1-\frac{n_s}{N_\nu}\right)\mathcal{B}_i\right)$$

Spatial Clustering　　Energy Spectra

$$\mathcal{S}(E_i,\vec{x_i}) = \frac{1}{2\pi\sigma_i^2}e^{-\frac{|x_s-x_i|^2}{2\sigma_i^2}} \times \mathcal{E}_{\mathcal{S}}(E_i, sin\delta_i, \gamma)$$

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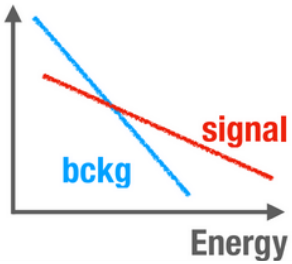

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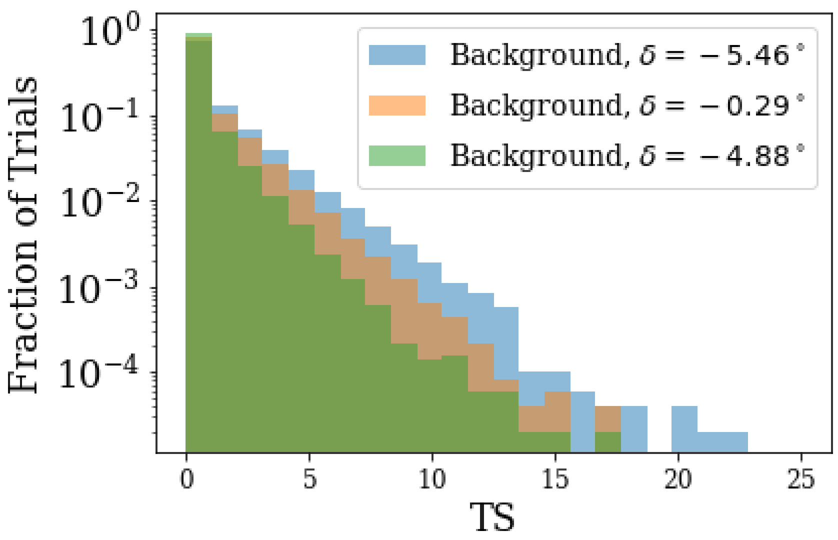
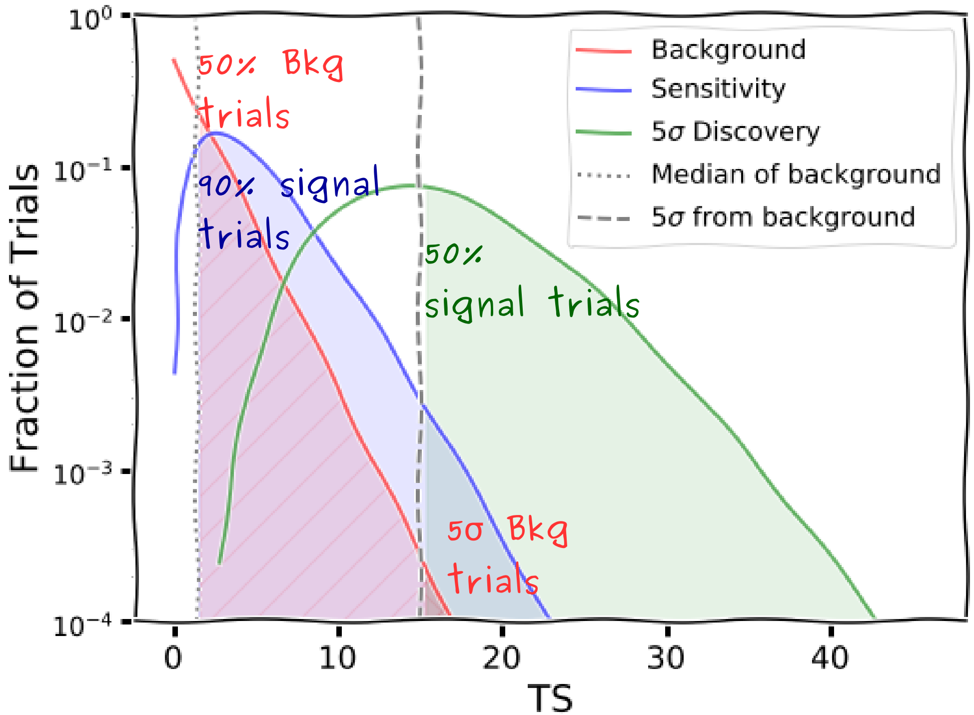
P-value calculation

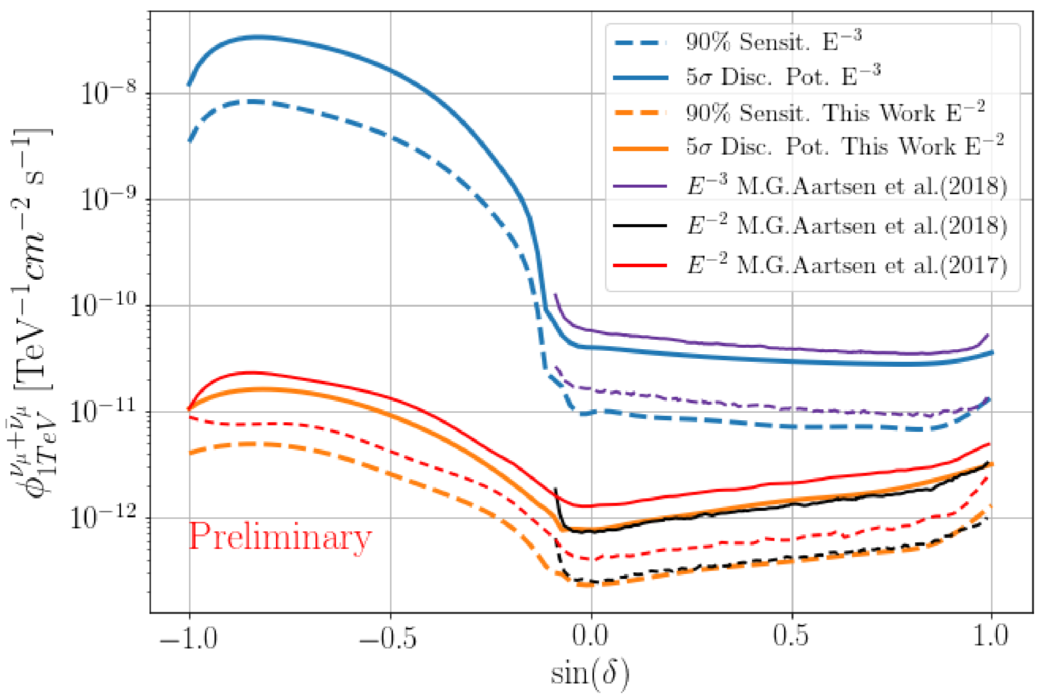


- Maximize TS at the same point using 1 million trials → TS distribution.
- Fit TS distribution with χ^2
- Pre-trial p-value = Fraction of trials > $TS_{unblinded}$

New Selection Performance

- Estimate signal flux for analysis to be sensitive to/discover a source.
  → ~35% improvement in sensitivity wrt to previous 7 year analysis [10]
- 8 year northern sky analysis [9] optimised for $E^{-2.19}$ spectra
  → Comparable sensitivity for E^{-2}
  → New analysis shows ~30 % improvement for soft spectra ~ E^{-3}.



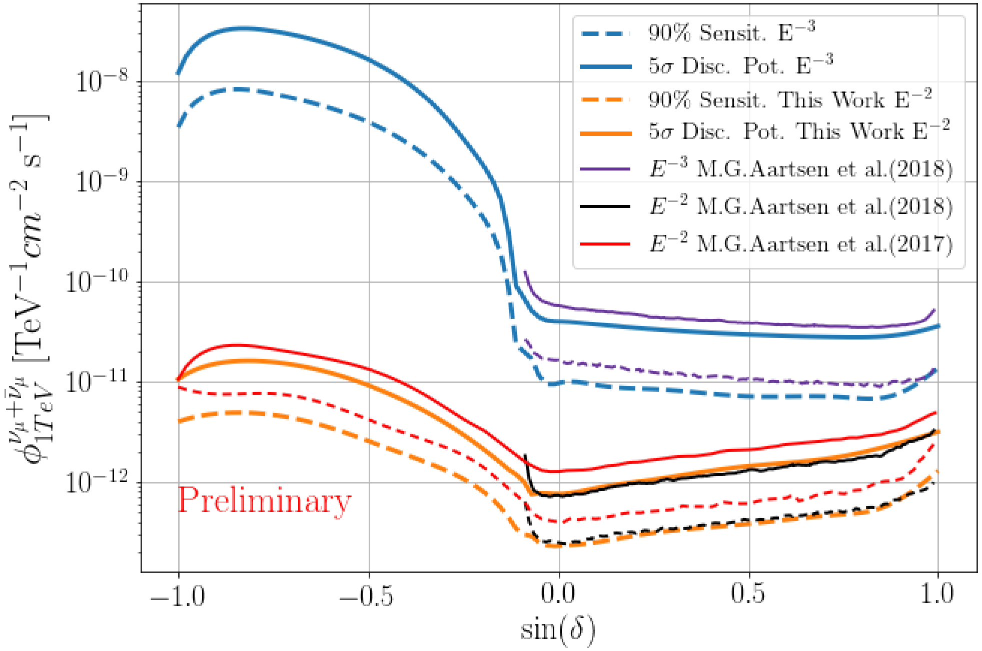


[9] Aartsen, M. G., et al. 2019, Eur. Phys. J. C., arXiv:1811.07979 [10] Aartsen, M. G., et al. 2017, Astrophys. J., 835, 151

Previous Point Source Analyses

ICECUBE

- 7 year All sky search
  → General search for Neutrino sources
  (M.G. Aartsen et al. 2017)
- 8 year Northern sky Search :
  → Optimised for observed diffuse flux $E^{-2.19}$
  (M. G. Aartsen et al. 2018)
- 10 year search : same method as 7 year all-sky
  1) new source catalog
  2) updated event selection for the final 6 years.

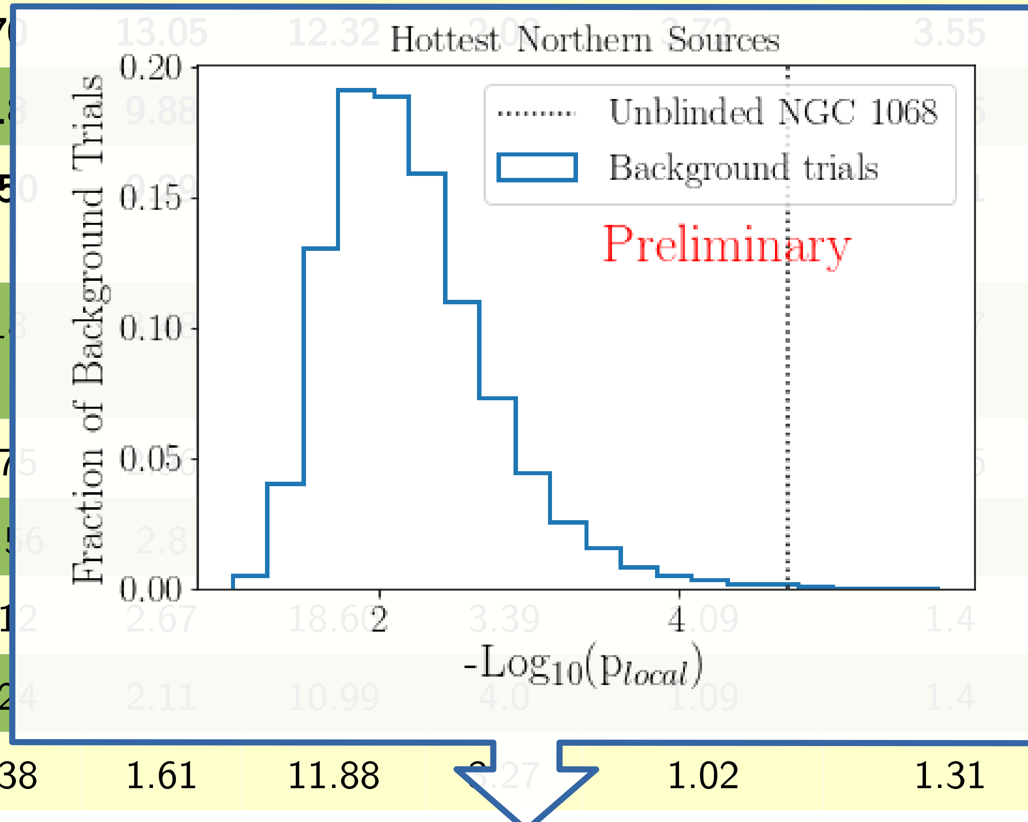


Analysis	Data Selection	All-Sky Scan	Source List Results
All-Sky Search	7 years μ tracks	North: 1.82×10^{-6} → 29% (post-trial) South: 0.93×10^{-6} → 17% (post-trial)	2 ~1% p-values North : 1ES 1959+650 1.8% → 54% (post-trial) South : PKS 1406-076 5.3%→ 37% (post-trial)
Northern Sky search	8 years diffuse μ tracks	North: 1.07×10^{-6} → 26.5% (post-trial)	4 ~1% p-values 4C 38.41 : 0.8% → 23.7% (post-trial)

Most significant Source List Results

ICECUBE

Name	Ra (°)	Dec (°)	TS	n_{signal}	γ	$-\log_{10}(p_{local})$	Pre-trial σ
NGC 1068	**40.67**	**-0.01**	**17.04**	**50.4**	**3.16**	**4.74**	**4.13**
TXS 0506+056	**77.35**	**5.70**	13.05	12.32	[illegible]	[illegible]	3.55
PKS 1424+240	**216.76**	**23.8**	9.88	[illegible]	[illegible]	[illegible]	[illegible]
GB6 J1542+6129	**235.75**	**61.50**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MGRO J1908+06	287.17	6.18	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PKS 1717+177	259.81	17.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PKS 2233-148	339.14	-14.56	2.8	[illegible]	[illegible]	[illegible]	[illegible]
B2 1215+30	184.48	30.12	2.67	18.62	3.39	[illegible]	1.4
M 31	10.82	41.24	2.11	10.99	4.0	1.09	1.4
4C +55.17	149.42	55.38	1.61	11.88	[illegible]	1.02	1.31

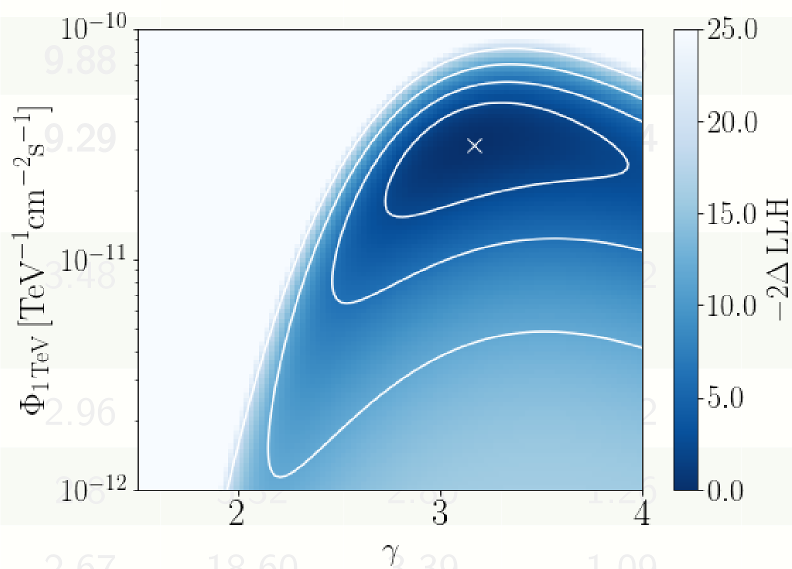


- Evidence for a flaring Blazar from a flare in 2014. (M. G. Aartsen et al. 2018)

- Most signifcant excess in the Northern Source List. → **2.9σ post-trial**
- **0.35^0** from the hottest point in the sky.

Most significant Source List Results

Name	Ra (°)	Dec (°)	TS	n_{signal}	γ	$-\log_{10}(p_{local})$	Pre-trial σ
NGC 1068	**40.67**	**-0.01**	**17.04**	**50.4**	**3.16**	**4.74**	**4.13**
TXS 0506+056	**77.35**	**5.70**	**13.05**	**12.32**	**2.08**	**3.72**	**3.55**
PKS 1424+240	**216.76**	**23.8**	9.88	[illegible]	[illegible]	[illegible]	2.95
GB6 J1542+6129	**235.75**	**61.50**	9.29	[illegible]	[illegible]	[illegible]	2.91
MGRO J1908+06	287.17	6.18	3.48	[illegible]	[illegible]	[illegible]	1.77
PKS 1717+177	259.81	17.75	2.96	[illegible]	[illegible]	[illegible]	1.66
PKS 2233-148	339.14	-14.56	[illegible]	[illegible]	[illegible]	[illegible]	1.6
B2 1215+30	184.48	30.12	2.67	18.60	3.39	1.09	1.4
M 31	10.82	41.24	2.11	10.99	4.0	1.09	1.4
4C +55.17	149.42	55.38	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



- Soft Spectrum ~ $E^{-3.16}$ → Close to background spectrum.
- Large uncertainties in γ and flux normalization. (Φ)

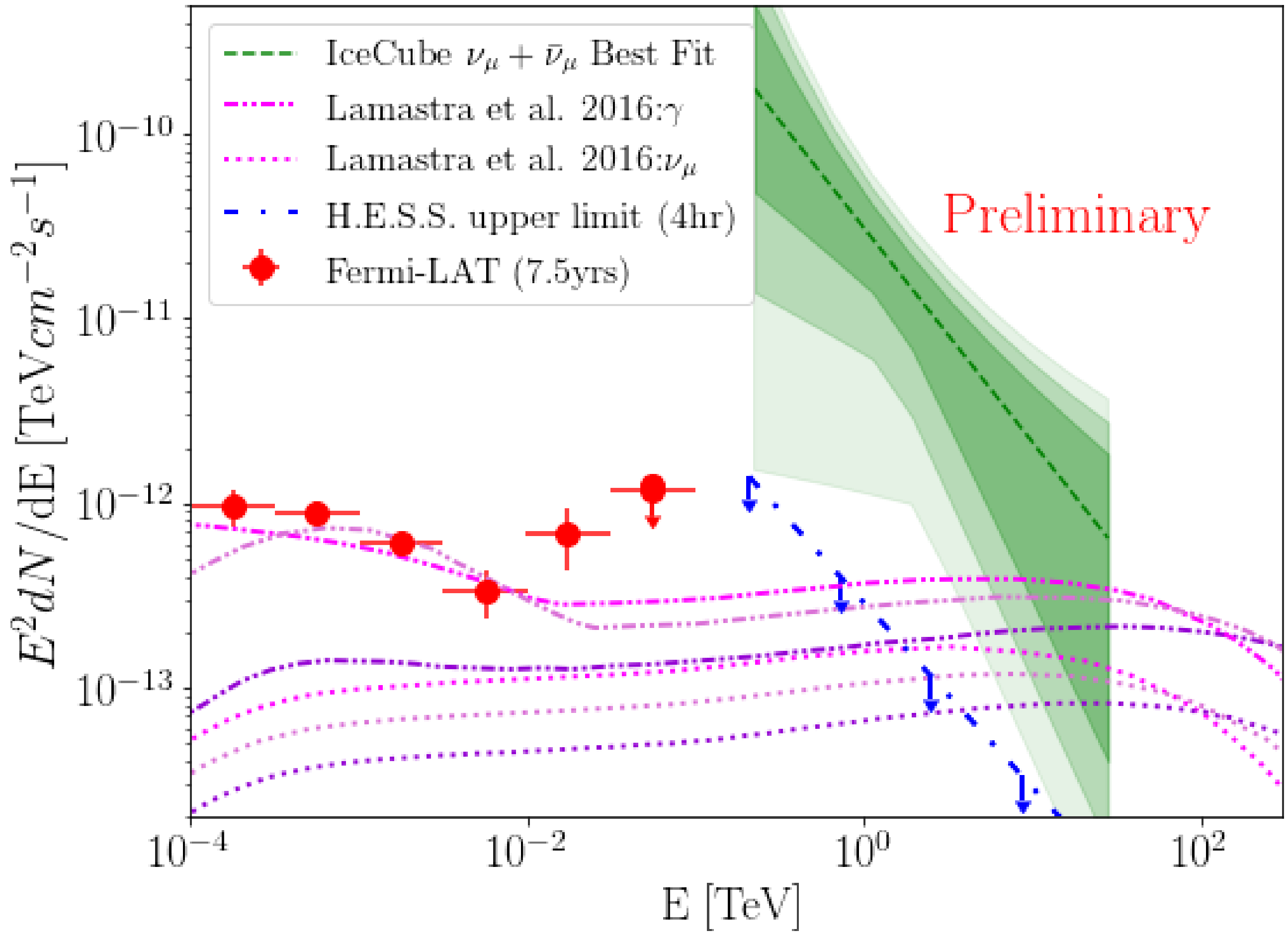
- Evidence for a flaring Blazar from a flare in 2014. (M. G. Aartsen et al. 2018)

- Most signifcant excess in the Northern Source List. → **2.9σ post-trial**
- **0.35⁰** from the hottest point in the sky.

Multi-wavelength Observations around NGC 1068

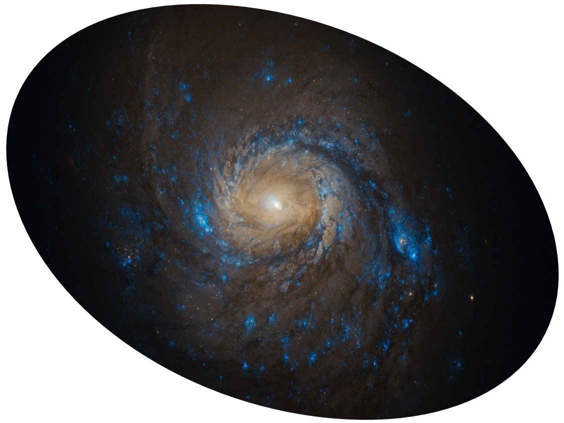
ICECUBE

- Barred spiral galaxy with AGN → brightest seyfert II galaxy.
- Dense clouds of matter around central AGN, regions of intense star-formation.
- 47 million light years away (redshift 0.003)



- These results show large uncertainties in spectral index & flux normalization.

  → Best-fit normalisation is greater than current Gamma-ray observations.

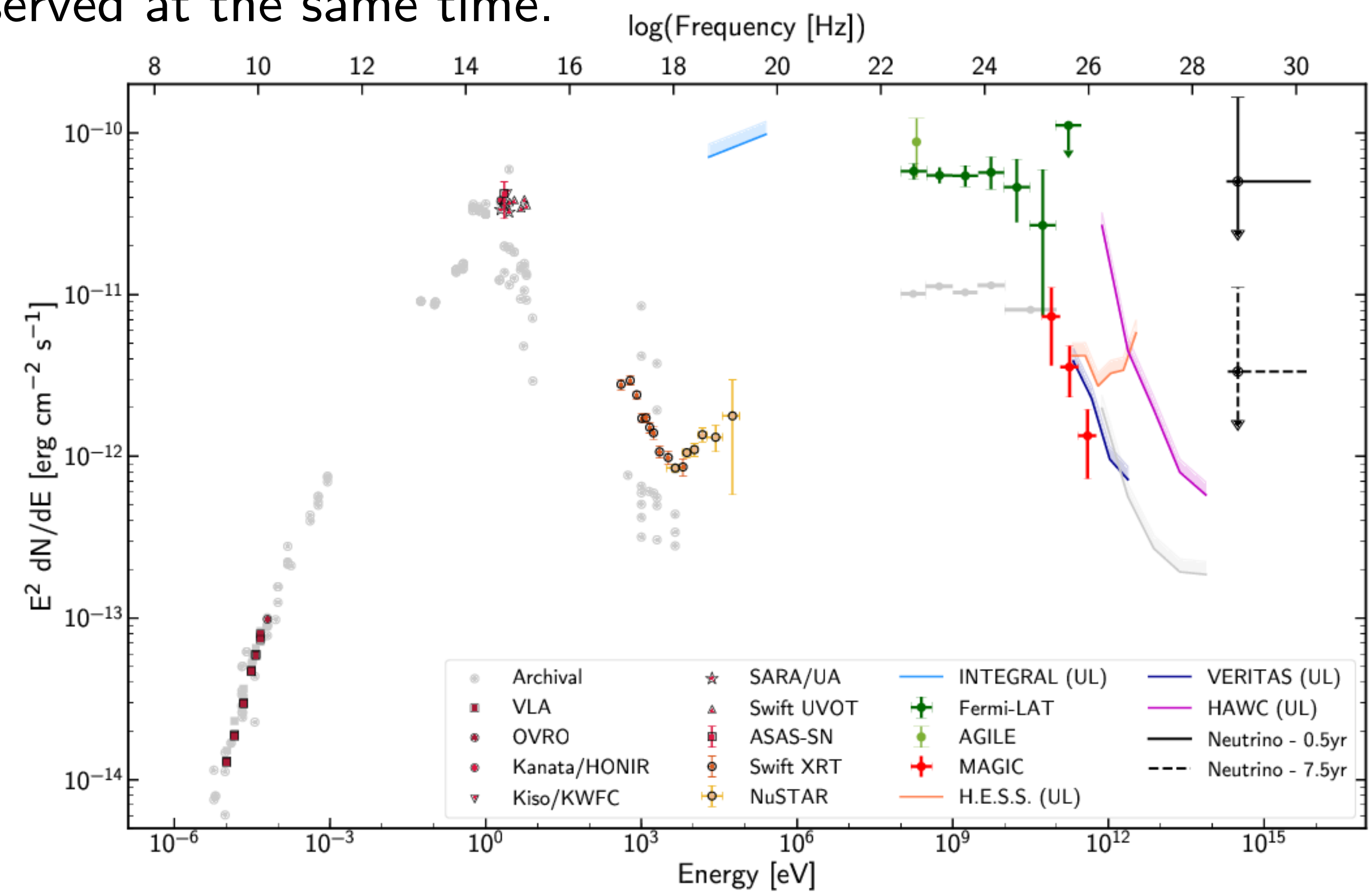


M77/NGC 1068

https://www.flickr.com/groups/hubblehiddentreasures_advanced/

Gamma-ray & Neutrino Sources

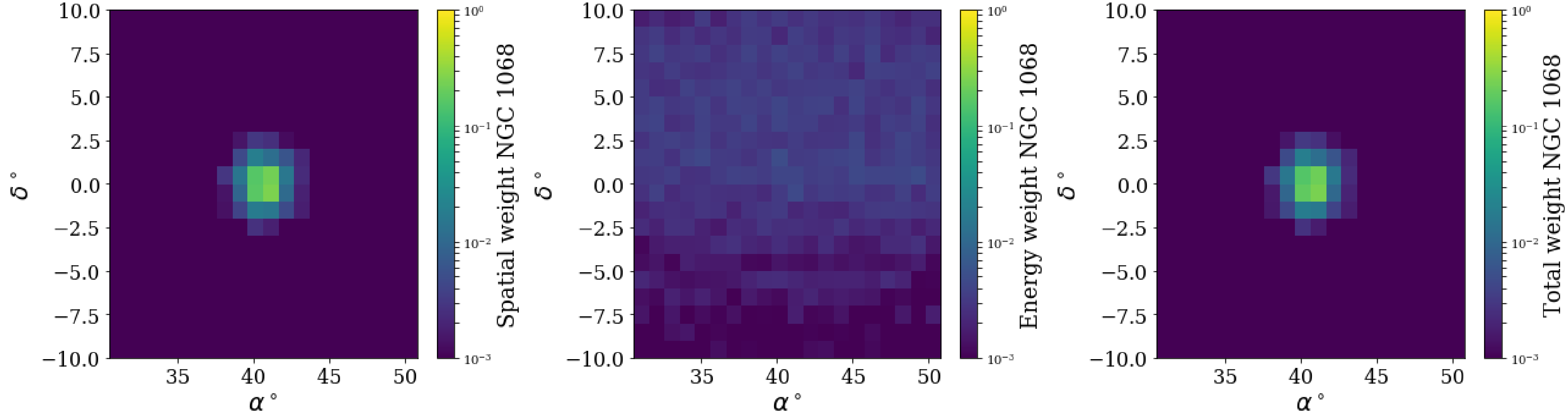
- TXS 0506 identified with neutrinos: High energy alert in coincidnce with a flaring blazar.
- Archival search found neutrino flare in 2014.
- No flare in Gamma observed at the same time.

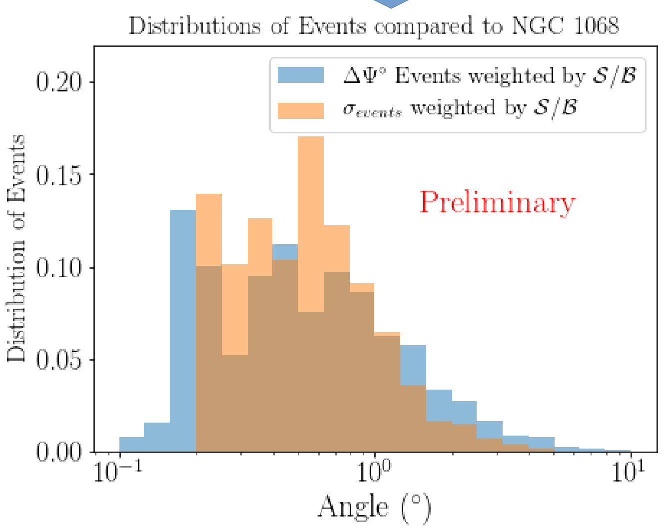


A closer look around NGC 1068

- Weighted event distribution assuming source @ NGC 1068 :

  → dominated by spatial contribution.





- Most contributing events within 1^0 & angular uncertainity $< 1^0$.

IceCube

A closer look around NGC 1068

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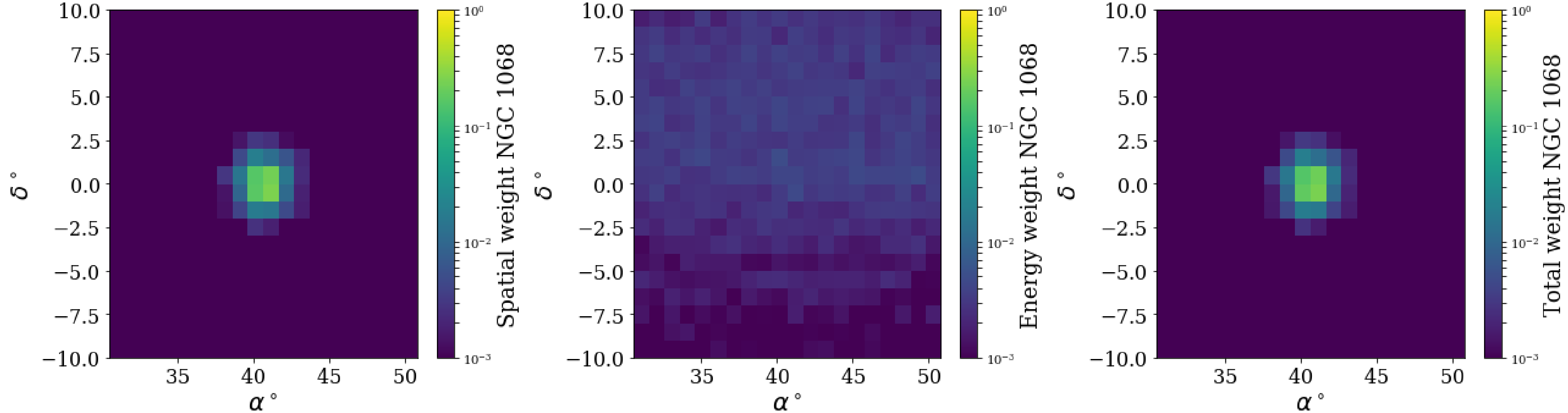

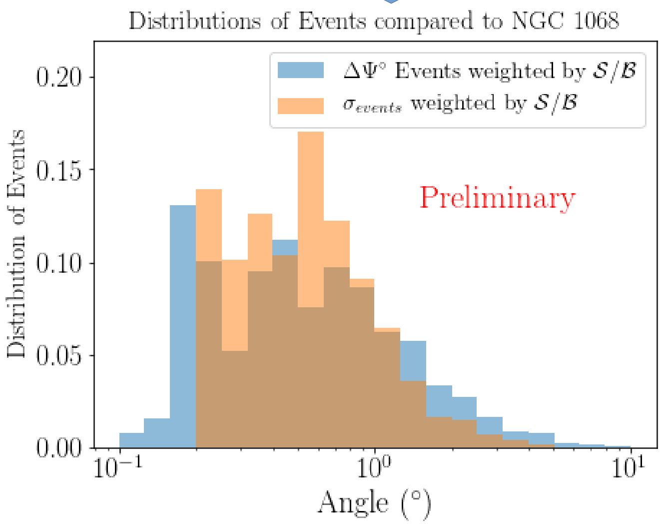

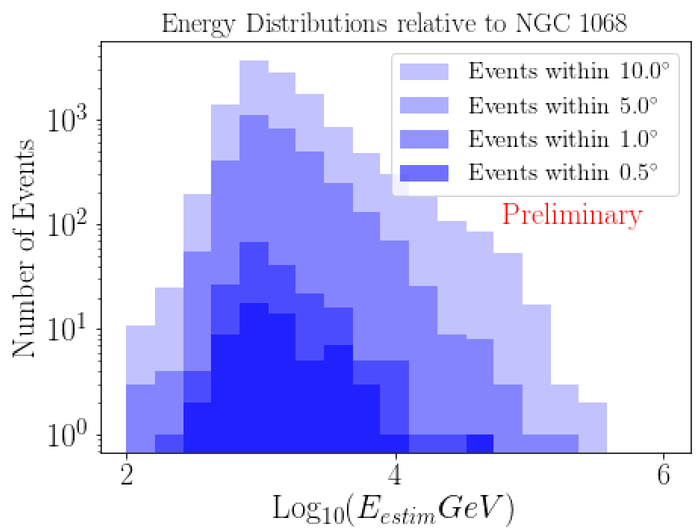

- Most contributing events within 1^0 & angular uncertainity $< 1^0$.
- Only 1 event deposited $>$ 10TeV in detector within 0.5^0 of NGC 1068.

Simulating NGC 1068

1) Create background trial (scrambling event RA)

2) Inject simulation of best-fit ν flux @ NGC 1068.

3) Scan $\pm 5^0$ around coordinates.

4) Fit most significant p-value.

- Hotspot $> 1^0$ away from NGC 1068 implies failed fit.

Can hotspot be shifted from true source location ?

- $\sim$70% within 1^0, $\sim$51% within 0.35^0, peaked at 0.2^0.

When the hotspot is shifted, is it extended ?

- shift $= 0.35^0$

$\rightarrow$ typical $\sim$35% drop in TS hotspot$\rightarrow$ source.

(Drop in TS for unblinded map was $\sim$30%)