Neutrino Point Source Searches with 10 years of IceCube Data

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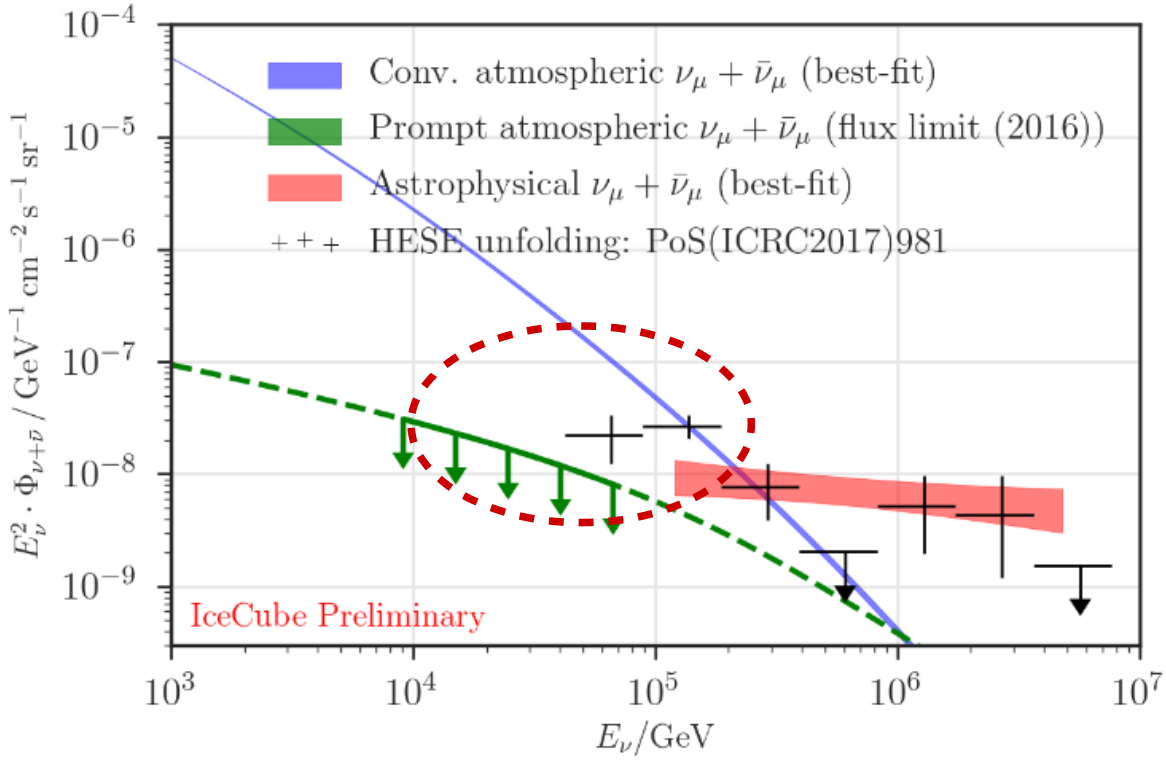
Point Source Searches

- Diffuse astrophysical flux already discovered.
- Data dominated by atmospheric events. However, we expect :

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

  → ***Uniform*** Background
- Blind all-sky Search
- Search Motivated

  Source Locations



Previous Point Source Analyses

- 7 year All-sky search :

  → General search for Neutrino sources

  (M.G. Aartsen et al. 2017)
- 8 year Northern-sky Search :

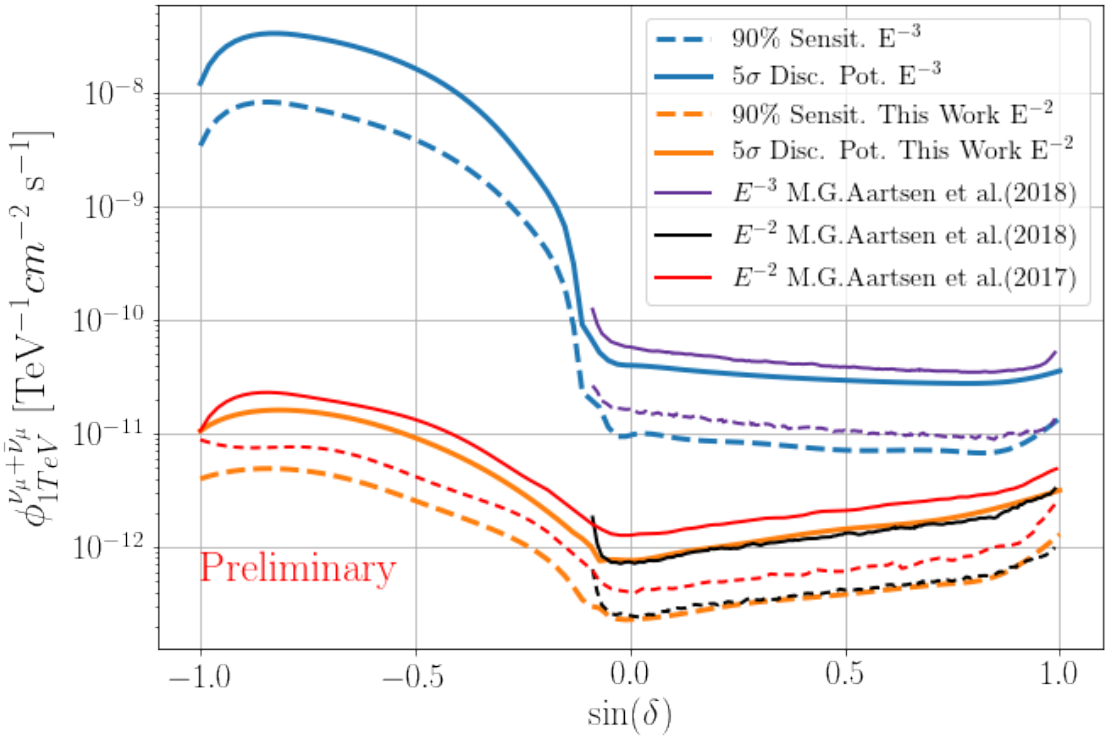
  → Optimised for observed diffuse flux $\propto E^{-2.19}$

  (M. G. Aartsen et al. 2018)
- 10 year search :

  → same method as 7 year all-sky

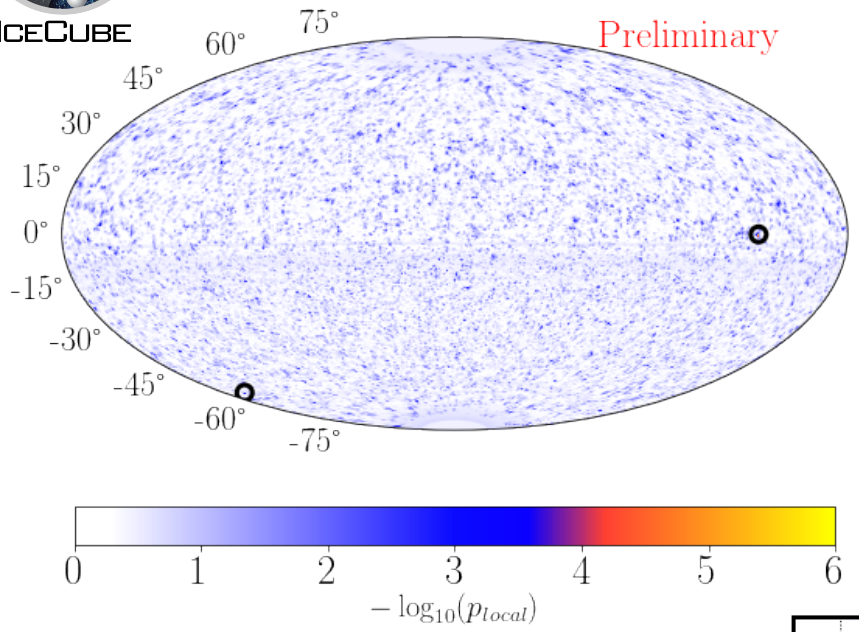
  1) new source catalog

  2) updated event selection



Analysis	Data Selection	All-Sky Scan Hotspots	Source List Results
All-Sky Search	7 years μ tracks	North: $p_{\text{post-trial}} = 29\%$ South: $p_{\text{post-trial}} = 17\%$	2 ~1% pre-trial p-values North : 1ES 1959+650, $p_{\text{post-trial}} = 54\%$ South : PKS 1406-076, $p_{\text{post-trial}} = 37\%$
Northern Sky search	8 years diffuse μ tracks	North: $p_{\text{post-trial}} = 27\%$	4 ~1% pre-trial p-values 4C 38.41, $p_{\text{post-trial}} = 23.7\%$ (post-trial)

10 year All-Sky Scan Results



- Evaluate likelihood of signal over background for grid over entire sky.
- **Hottest point** = position with smallest p-value in each hemisphere.

Hottest Point in North : δ ≥ -5°

RA = 40.87° , Dec = -0.30°

n_{signal} = 61.5 , γ= 3.4, TS = 25.3

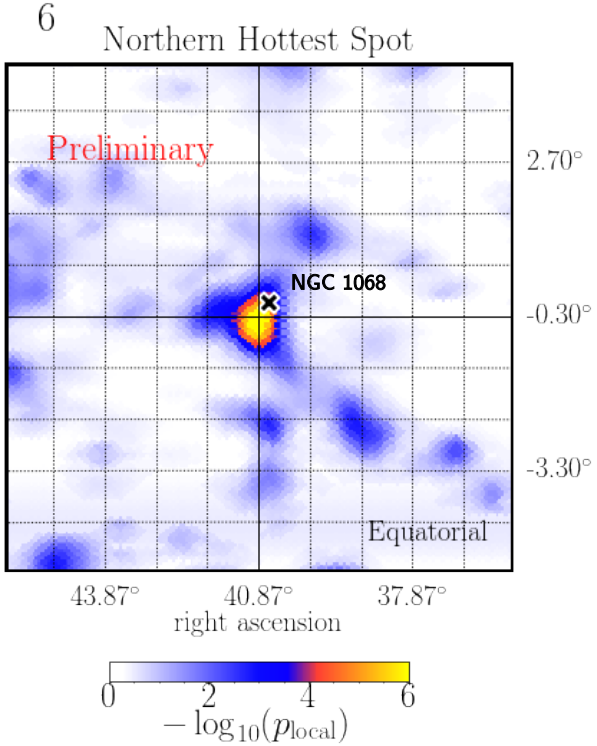
-log10(pval)= 6.45 ⇒ 9.9% post-trial

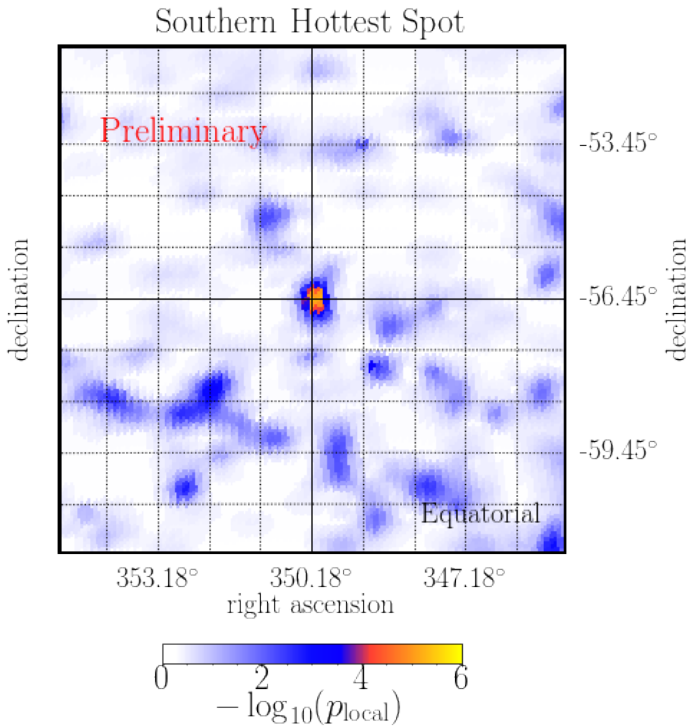
Hottest Point in South : δ< -5°

RA = 350.18° , Dec -56.45°

n_{signal} =17.8, γ = 3.3, TS= 20.0

-log10(pval) =5.37 ⇒ 75% post-trial





Updated Individual Source List

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

- Top 5% of extra-galactic sources organised by Flux-integral >1 GeV from *Fermi*-LAT 3FGL catalog :

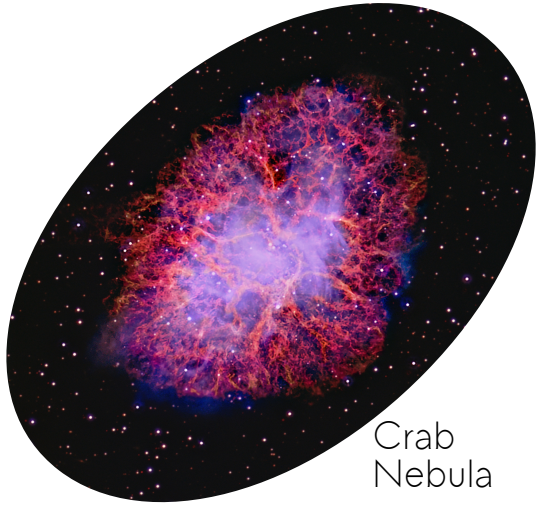
  → BL Lac, Flat-spectrum radio quasar (FSRQ), Starburst galaxies, other Active Galactic Nuclei (AGN).

- 8 *Fermi*-LAT galaxies identified with known starburst activity → all kept.
- Galactic sources: model flux from γ-ray obervations > 50% of the sensitivity flux.
- Result :

  → Northern Sources (87 extra-galactic, 10 Galactic)

  → Southern Sources (11 extra-galactic, 2 Galactic)


AGN


Crab Nebula

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

- 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°** from the hottest point in the sky.

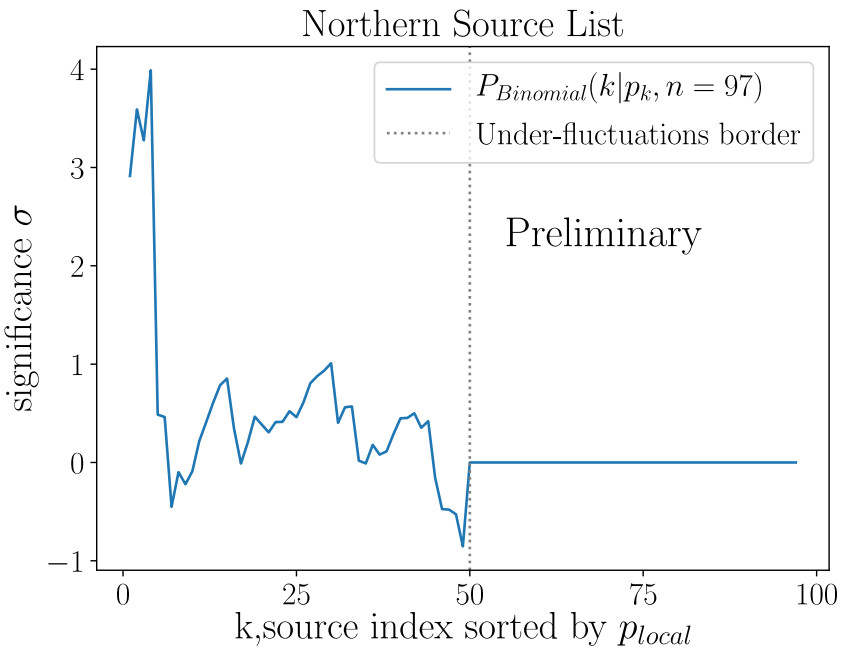
Source Population Results

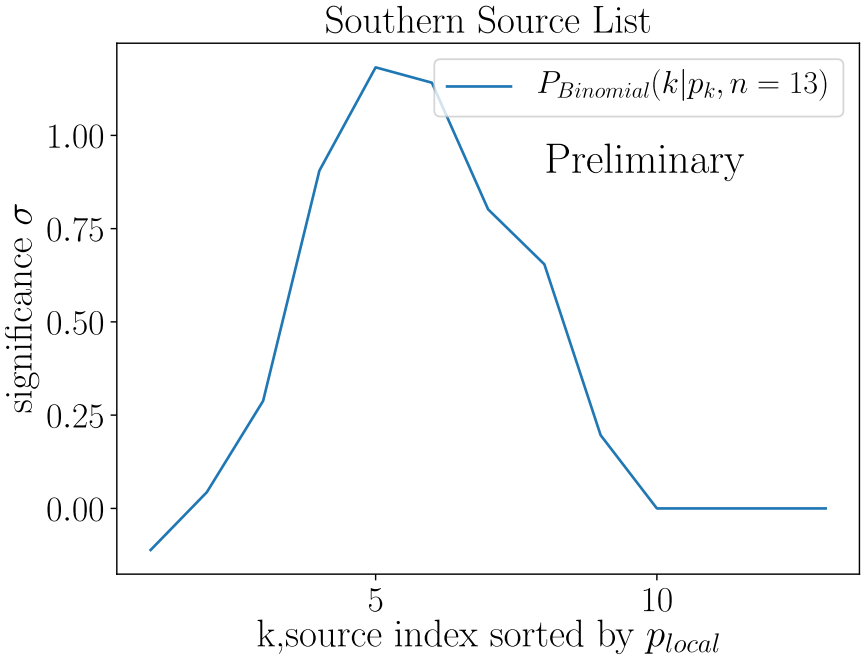
Search for excess of hotspots → A significant p-value demonstrates inconsistency with background-only for entire catalog.

- Probability of k or more sources passing a threshold out of a catalog of N.
- 4σ pre-trial where k=4 in Northern Catalog.

  → 3.3σ post-trial. (2.25σ w/o TXS 0506+056) to account for N other possible excesses

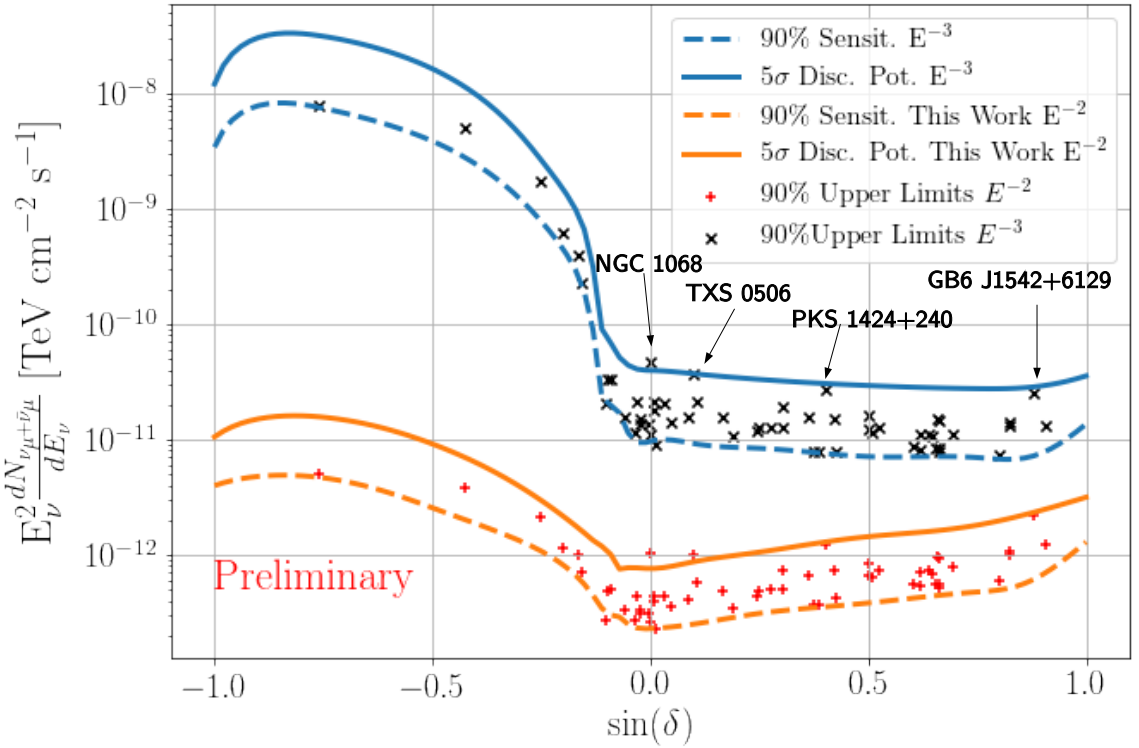
- Includes NGC 1068, TXS 0506+056, PKS 1424+240,GB6 J1542+6129



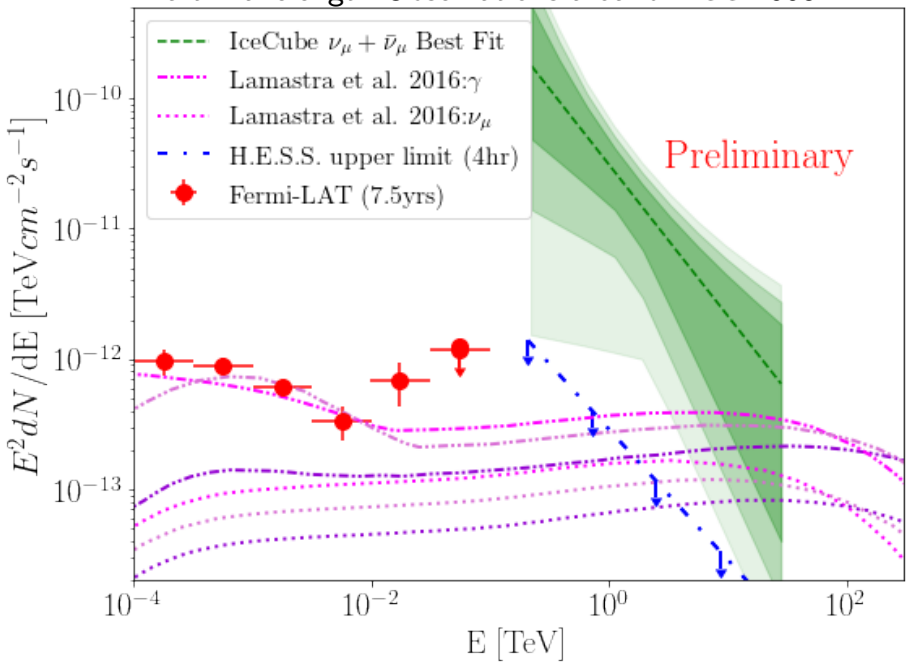


Outlook on Results

- 2.9σ deviation from background @ coordinates of NGC 1068.
- All-sky hotspot ~ 1^0 diameter : center offset 0.35° from NGC 1068.
- Offset & size of hotspot consistent with simulated tests for a soft-flux at a point-source.



Multi-wavelength Observations around NGC 1068



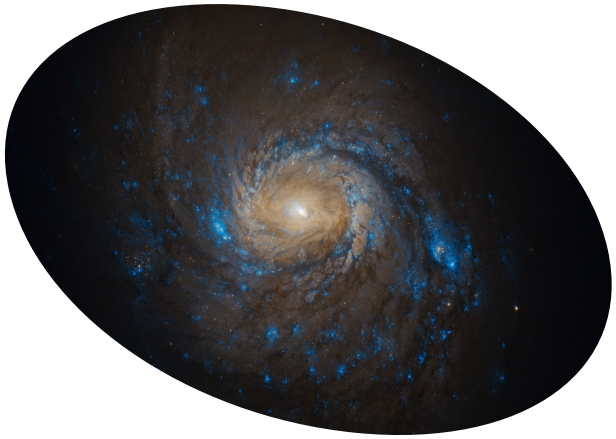
NGC 1068 best-fit flux normalisation > current γ-ray observations.

→ Best-fit spectrum ∝ $E^{-3.2}$

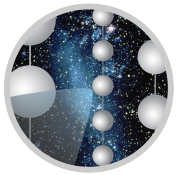
Summary

- No new neutrino steady-state source discovered.
- NGC 1068 in coincidence with Northern Hotspot $\rightarrow$ 2.9σ post-trial p-value.
- Source List Catalog is inconsistent with background only hypothesis at 3.3σ

  $\rightarrow$ Includes: NGC 1068, TXS 0506+056, PKS 1424+240,GB6 J1542+6129
- Best-fit neutrino flux for NGC 1068 $>$ current γ-ray observations.
- Results demonstrate a strong motivation to continue to analyse the objects in these catalogs.



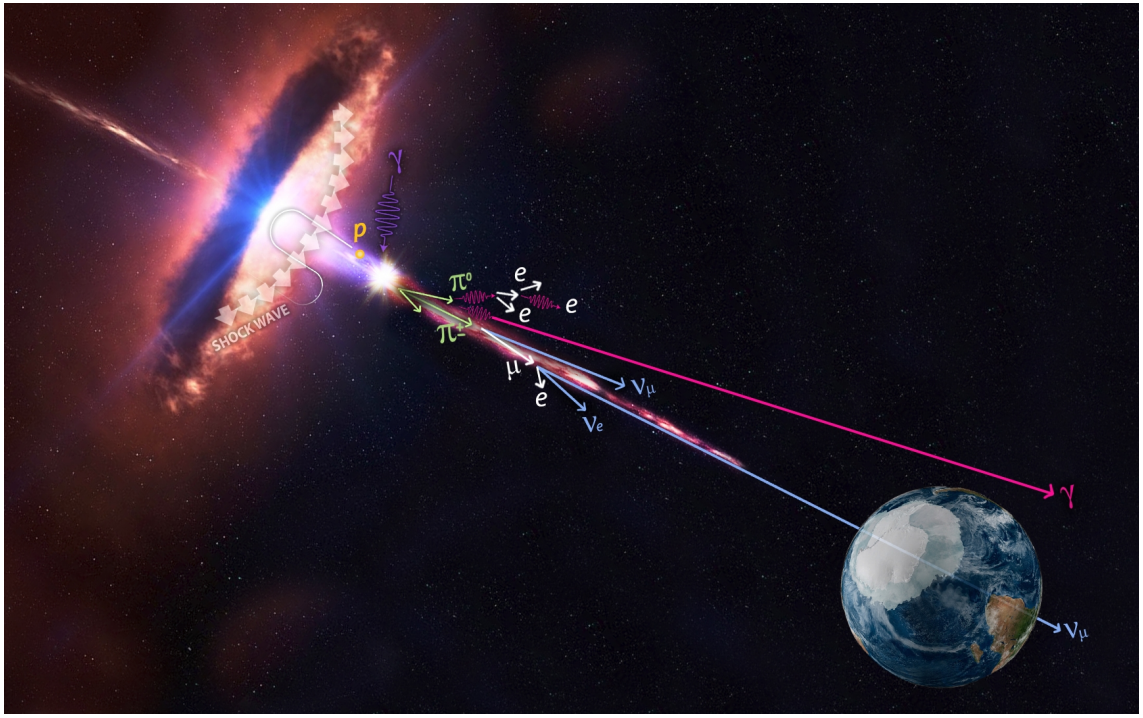
M77/NGC 1068
https://www.flickr.com/groups/hubblehiddentreasures_advanced/



Back up

Messenger Particles

- **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 :

$$pp \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$

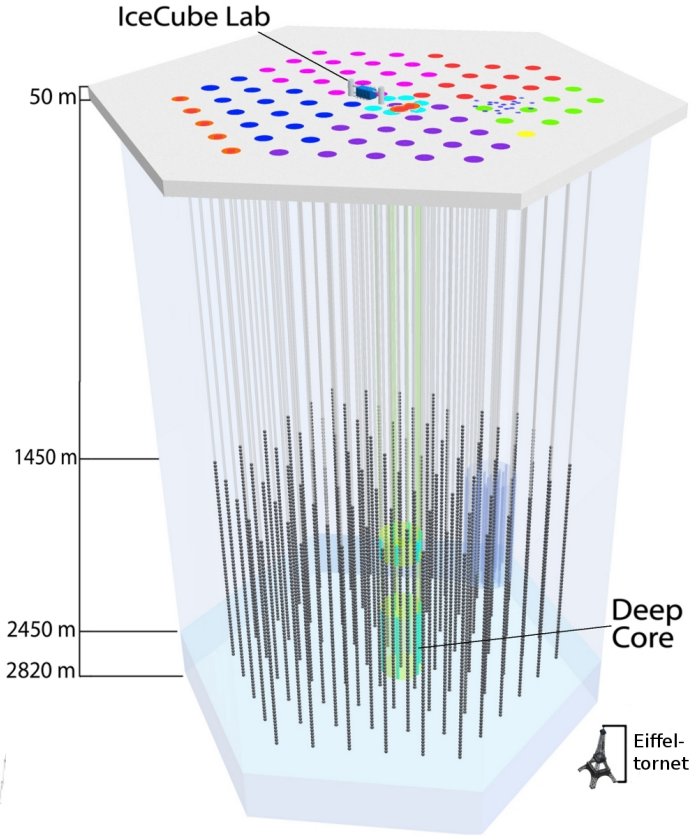
$$pp \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

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

Photons and CRs particles are attenuated and/or **deviated** on their journey towards the earth.

Neutrinos travel unimpeded accross the universe so they can point **directly towards the source**.

IceCube Detector

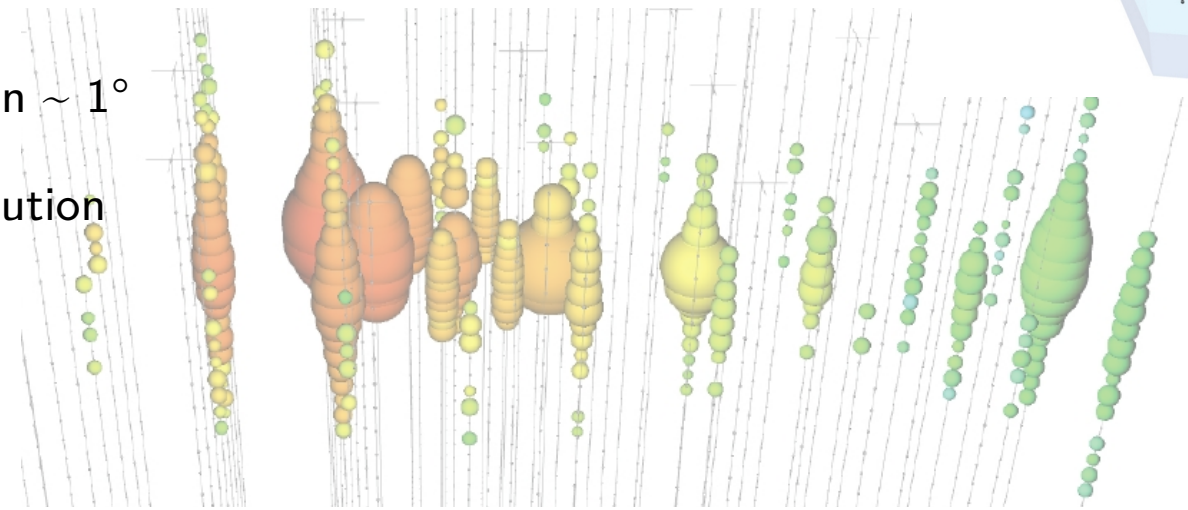


What Do We Detect ?

- Neutrinos interact in the ice producing charged leptons.
- Charged leptons then induce Cherenkov radiation during their propagation through the ice.

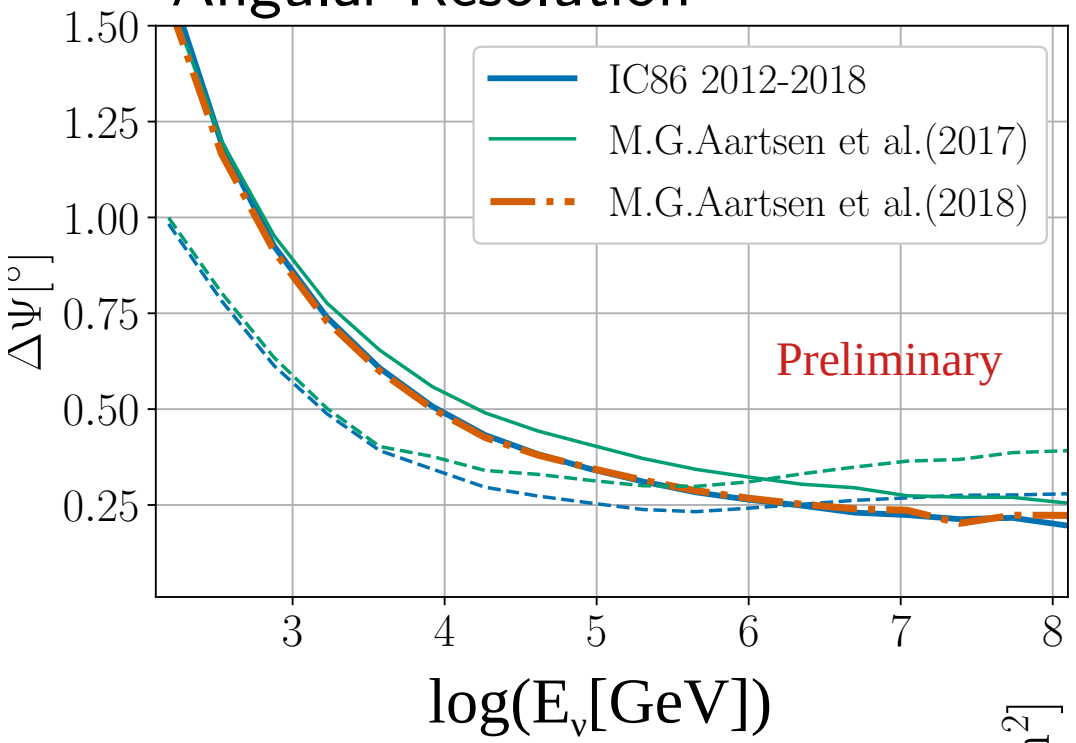
IceCube Events ?

- High Energy Muon tracks in the ice.
- From: Atmospheric Muons, and Charged Current ν_μ interactions.
- Angular Resolution $\sim 1°$
- Poor Energy resolution

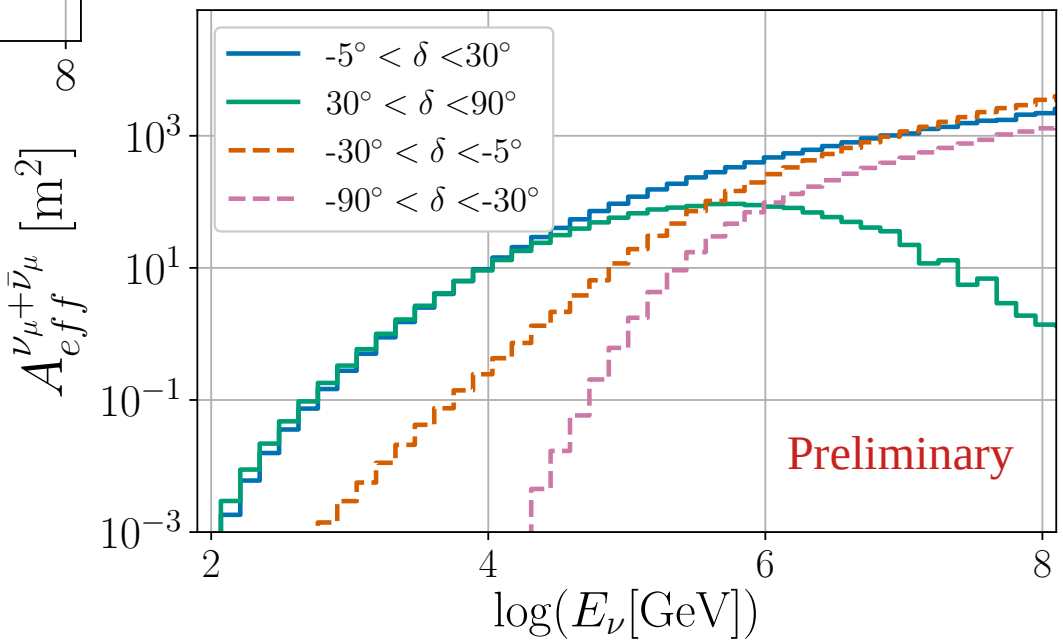


New Selection Performance

Angular Resolution



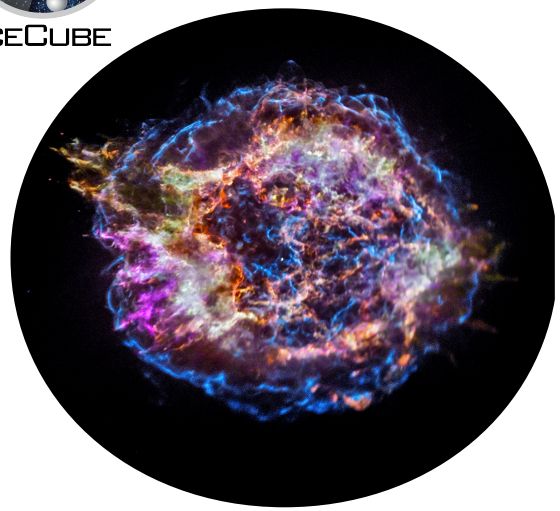
Effective Area 2012-2018



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.

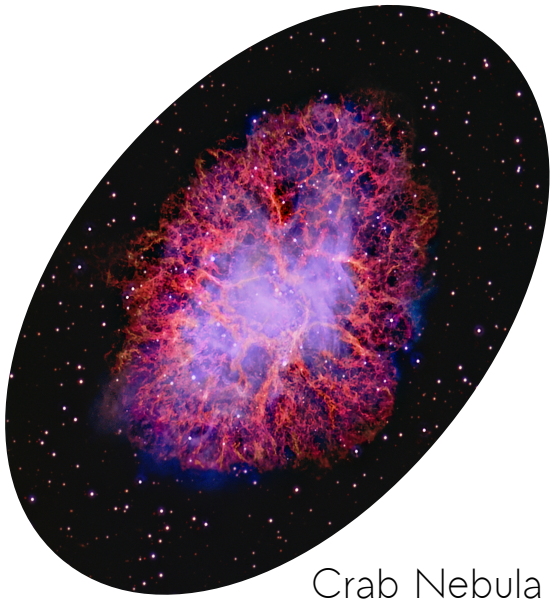
Stacking Results



Cassiopeia A : SNR

- Stacked 3 catalogs of Galactic objects
- Weighted the sources in each catalog by the integral flux above 10 TeV as estimated by Gamma ray observations.
- All consistent with background.

Catalog	Number of sources	TS	γ	n_{signal}	p-value
Super Nova Remnants (SNR)	23	1.49	3.55	23.9	0.11
Pulsar Wind Nebula (PWN)	33	0	-	-	1.0
Unidentified Objects (UNID)	58	0.09	2.39	3.28	0.4



Crab Nebula : PWN