IceCube

Search for point-like sources in the astrophysical muon neutrino flux with IceCube

René Reimann for the IceCube Collaboration

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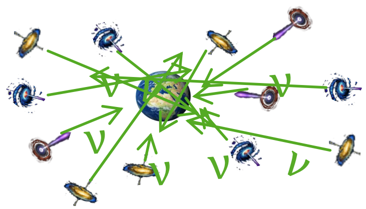
DFG Deutsche Forschungsgemeinschaft

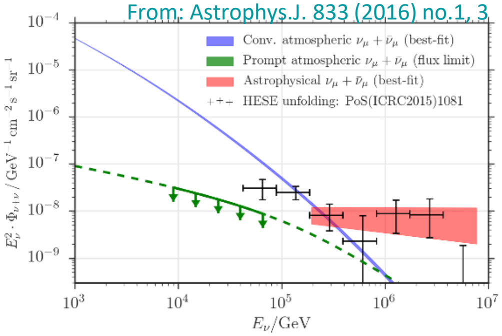
Federal Ministry of Education and Research

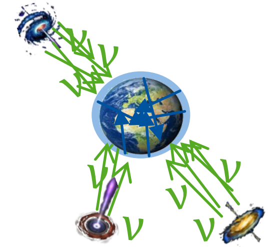
Outline

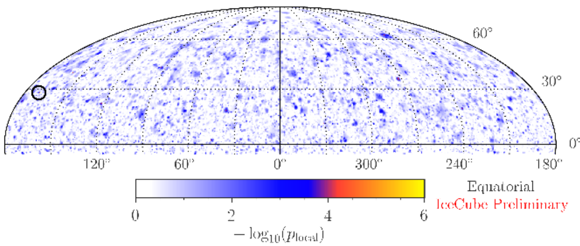
- Sources of Cosmic Rays
- The IceCube Neutrino Observatory
- Measurement of a diffuse muon neutrino flux
- Search for Point sources: An unbinned likelihood analysis
- Results:
  - All sky scan
  - Source Catalog
- Summary and Outlook

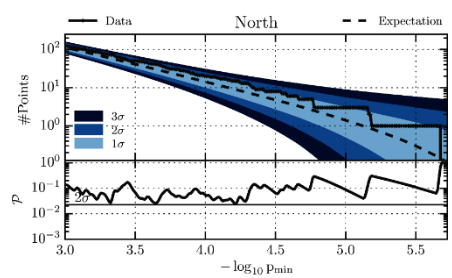


From: Astrophys.J. 833 (2016) no.1, 3









From: Astrophys. J., 835 (2017) no. 2, 151

Sources of HE Cosmic Rays

One major open question in astro-particle physics:

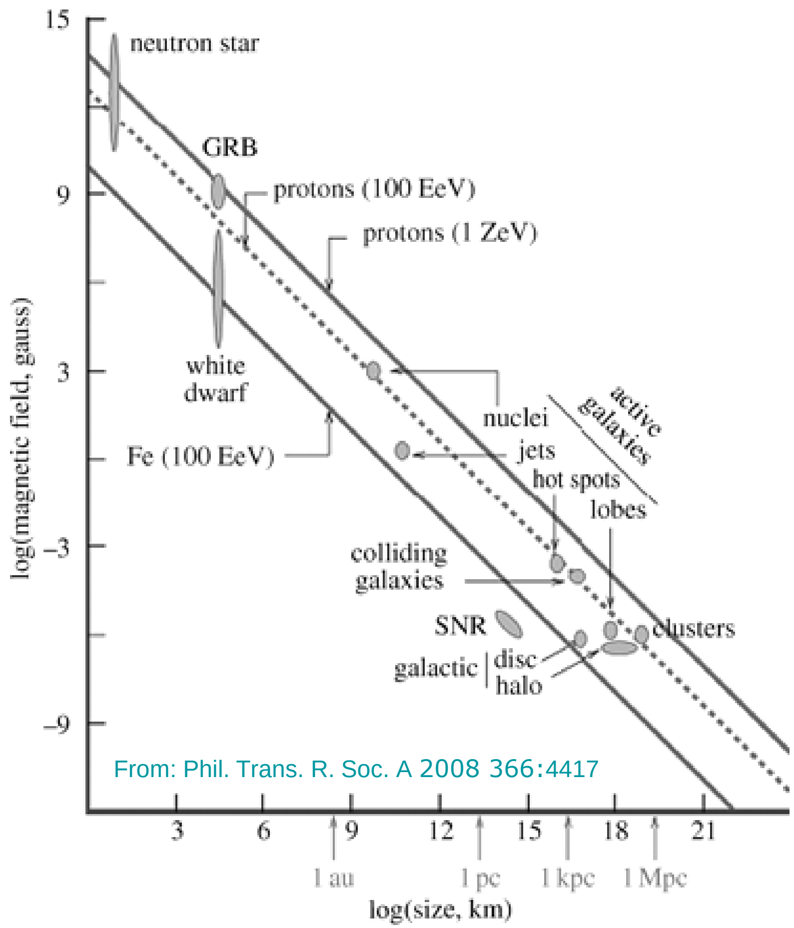
What are source of UHE Cosmic Rays?

What is the acceleration mechanism ?

Maximum energy of particle is constrained by magnetic field strength and size of object

$$E_{\max} \propto \beta_s \cdot z \cdot B \cdot L$$

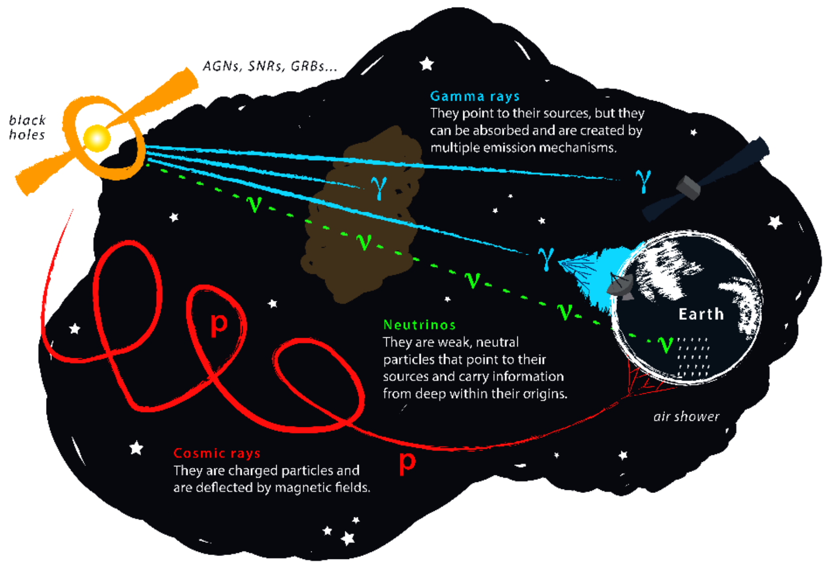
Many different source classes can be responsible including galactic and extra galactic sources



From: Phil. Trans. R. Soc. A 2008 366:4417

Multi-Messenger Particles

- Charged cosmic rays
  - accelerated in astrophysical objects
  - deflected by intergalactic magnetic fields
  - propagation effects energy spectrum
- TeV gamma rays
  - point back to place of origin
  - may not leave the source region because of high density
  - absorbed by interstellar dust clouds
- TeV neutrinos
  - point back to place of origin
  - not absorbed during their propagation through the universe
  - hard to detect at earth



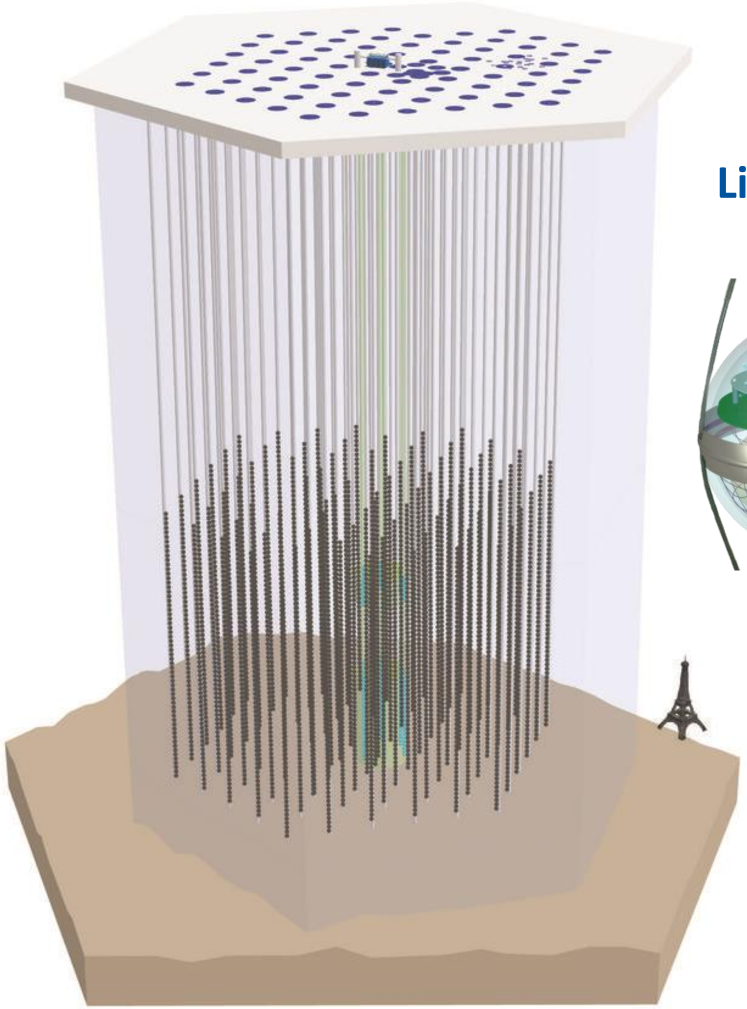
From: http://gallery.icecube.wisc.edu/internal/d/318865-1/physicus.pdf

$$p + \gamma \rightarrow \pi^0 + p$$
$$\rightarrow \boxed{\gamma + \gamma} + \boxed{p}$$
$$\rightarrow \pi^+ + n$$
$$\rightarrow \mu^+ + \nu_\mu + n$$
$$\rightarrow e^+ \boxed{+ \bar{\nu}_\mu + \nu_e + \nu_\mu} + n$$

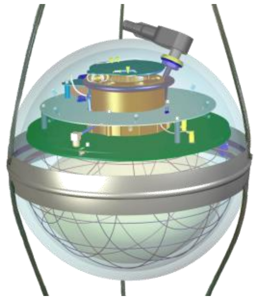
Finding a neutrino point source is smoking gun for hadronic acceleration.

The IceCube Observatory

- IceCube
  - About 1 km^3 of detection volume
  - Measures Cherenkov light from secondary charged particles
  - 5160 light sensors @ 86 strings
  - energy threshold 100 GeV
- DeepCore
  - infill array
  - 8 strings with 60 HQE DOMs each
  - combined with 7 nearest IceCube strings
  - energy threshold 10 GeV
- IceTop
  - Cosmic ray detector at surface
  - 81 stations with 4 DOMs in 2 tanks each
  - 1 km^2 area
  - Cosmic rays: $10^{14} – 10^{18}$ eV



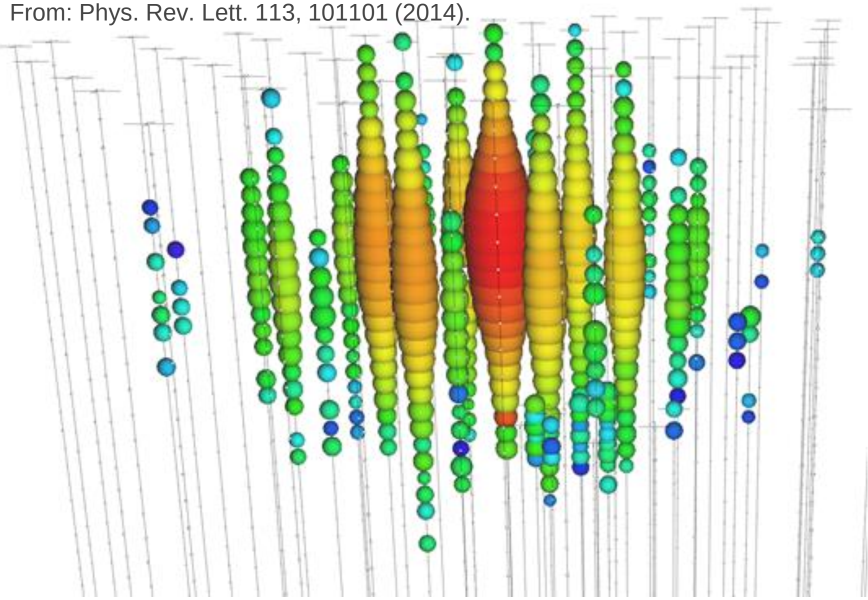
Light sensor (DOM)



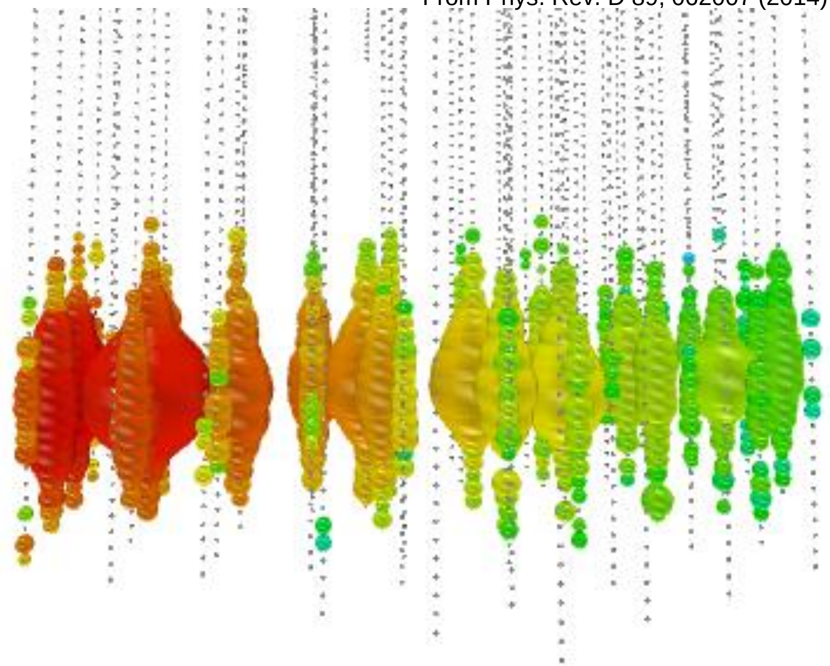
From: http://gallery.icecube.wisc.edu/internal/v/graphics/arraygraphics2011/blueTopArray_001.jpg.html
From: http://gallery.icecube.wisc.edu/internal/v/graphics/dom/DOMNoHarnessWhiteback_lg.jpg.html

Neutrino-Signatures

From: Phys. Rev. Lett. 113, 101101 (2014).



From Phys. Rev. D 89, 062007 (2014)



$$\nu_x + N \rightarrow \nu_x + X$$
$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X \quad \left(E_{\nu_\tau} <\sim PeV\right)$$

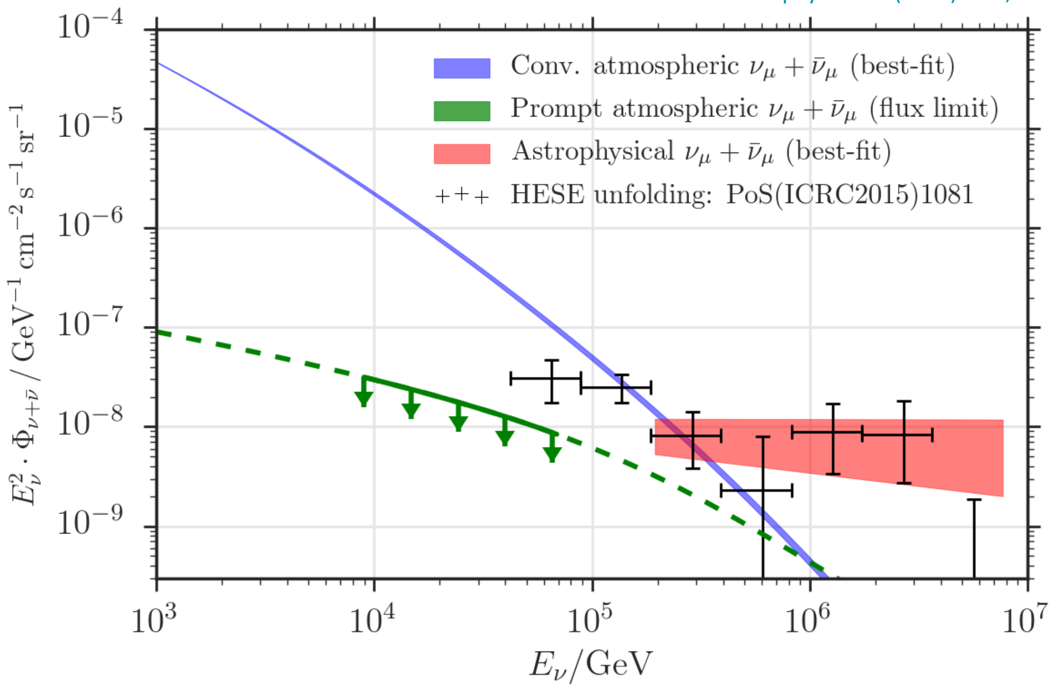
- cascade-like signature
- energy fully contained in most events
  → good energy resolution
- spherical signature
  → bad angular resolution

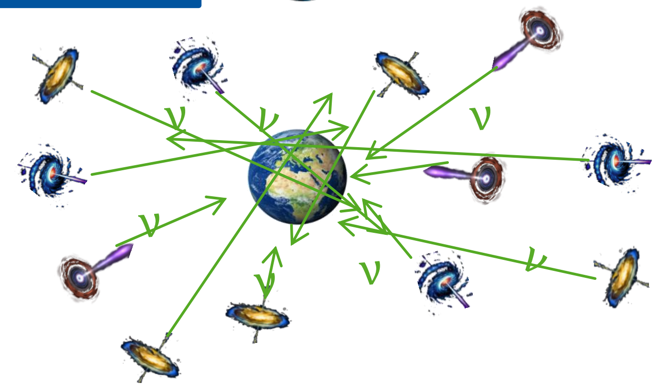
$$\nu_\mu + N \rightarrow \mu + X$$

- track-like signature
- through-going / leaving the detector
  → Bad energy resolution
- long leaver arm
  → Good angular resolution

Measurement of diffuse ν_μ-flux

From: Astrophys.J. 833 (2016) no.1, 3





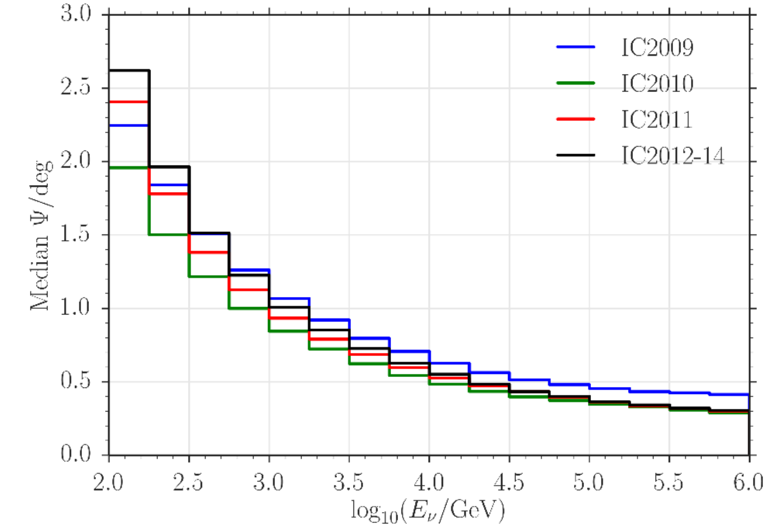
- IceCube has measured diffuse ν_μ-flux
- We know that there are astrophysical neutrinos in this sample.
- ν_μ events have good angular resolution
  → ideal signature to search for point-like sources

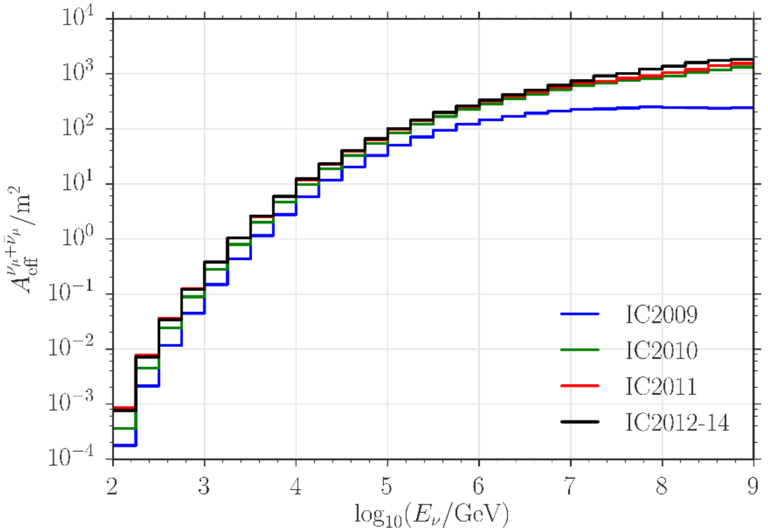
Astrophysical norm.	$0.90_{-0.27}^{+0.3}$ 10^{-18} GeV^{-1}cm^{-2}s^{-1}sr^{-1}
Astro. spectral index	2.13±0.13
Significance	~5.6σ

Still to solve:
What are the sources?

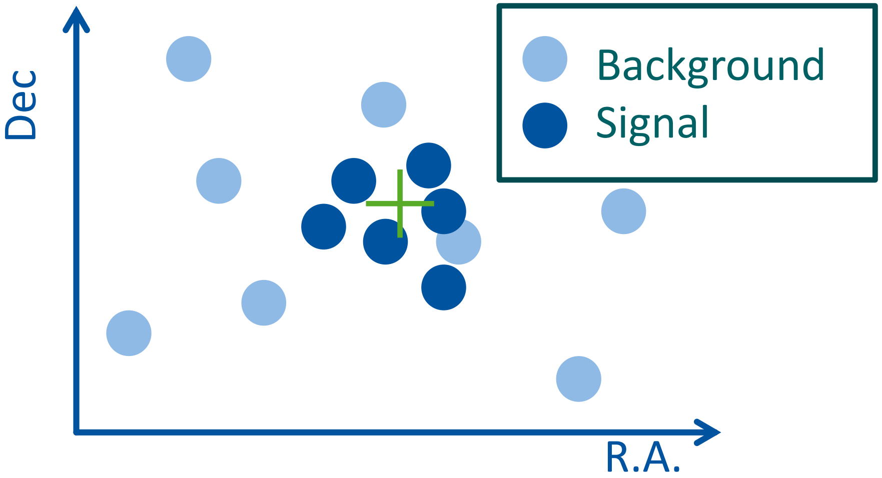
Data Sample

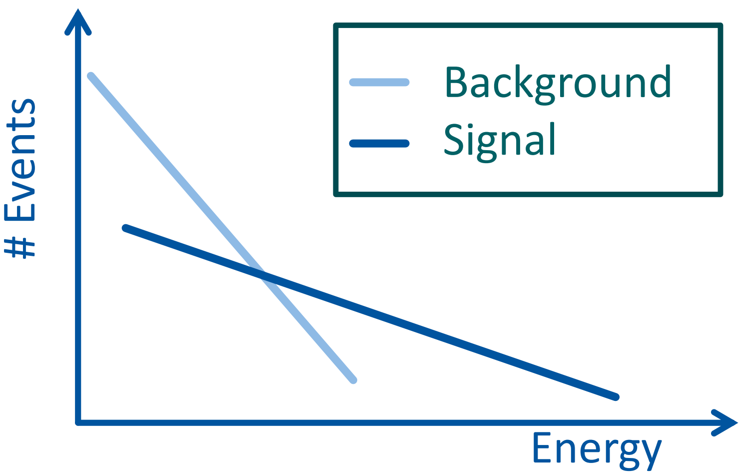
- Muon neutrino candidates selected from Northern hemisphere
- Same sample as for diffuse up-going ν_μ analysis
- 2032 days livetime (IC59-IC86/2014)
- about 340k events
- ν_μ events with good angular resolution
- High purity of more than 99.9% and high efficiency
- Precise parametrization of energy and zenith distribution by diffuse fit





Unbinned Likelihood Analysis





Likelihood function

$$L = \prod_i \left[\frac{n_s}{N} S_{i,spat} S_{i,ener} + \left(1 - \frac{n_s}{N}\right) B_{i,spat} B_{i,ener} \right] + P(\gamma \,|\, \gamma_{astro})$$

Signal: astrophysical ν coming from source location

Background: atmospheric ν & diffuse astrophysical ν

- Spatial signal PDF is a Gaussian with event wise angular resolution
- PDFs derived from parametrization of diffuse fit
- Prior on SI of sources

  → focus search on sources of diffuse flux

Test Statistic

- Likelihood ratio test for fits with $n_s>0$
- Taylor expansion of TS for $n_s=0$ fits to allow for negative TS values

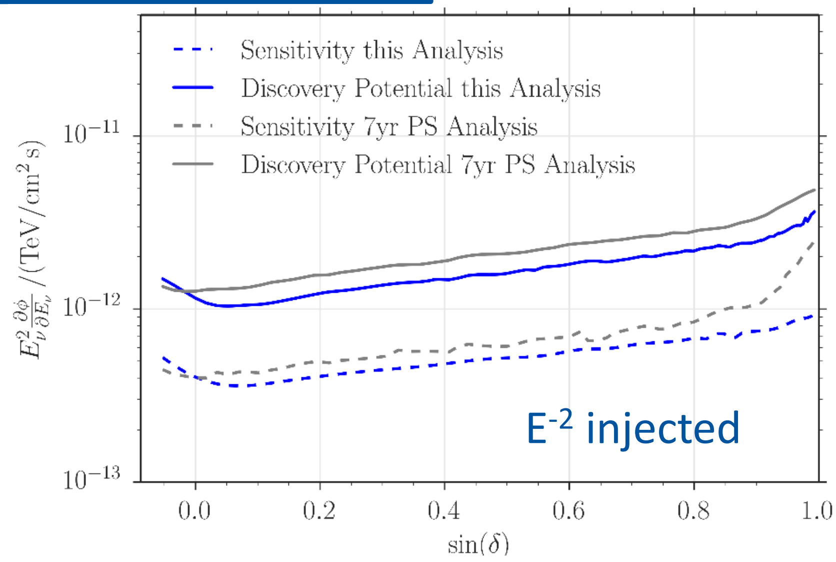
$$TS = -2 \cdot \log \left[\frac{L(\vec{x}_S, 0)}{L(\vec{x}_S, \hat{n}_S, \hat{\gamma})} \right] \qquad n_s > 0$$

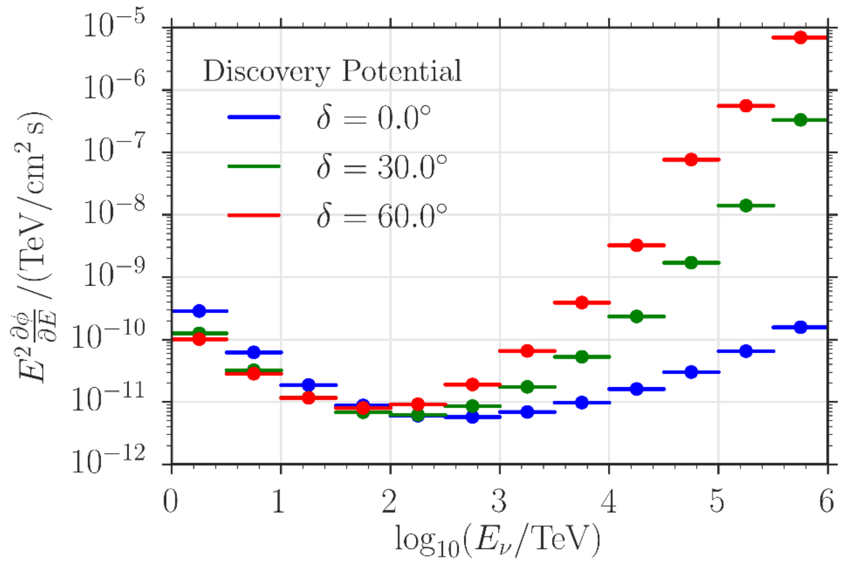
Analysis Performance

Compared to published PS analysis (gray)

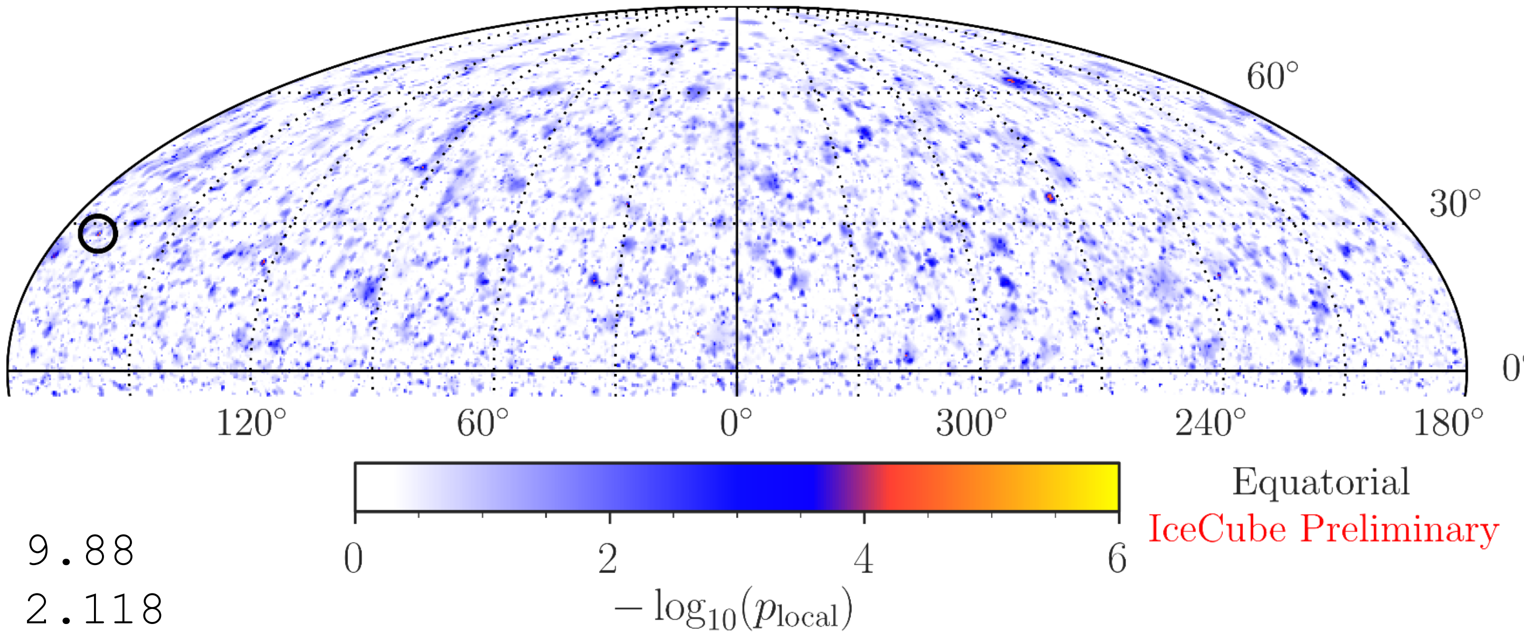
- Astrophys. J., 835 (2017) no. 2, 151
- focus on diffuse muon neutrino flux
- estimation of PDFs from diffuse fit parametrization
- prior on spectral index
- allow for negative TS values
- different event selection (~80% overlap)
- Improved direction reconstruction
- One year less data

→ Focus on diffuse flux gain about ~10-20% in sensitivity and discovery potential





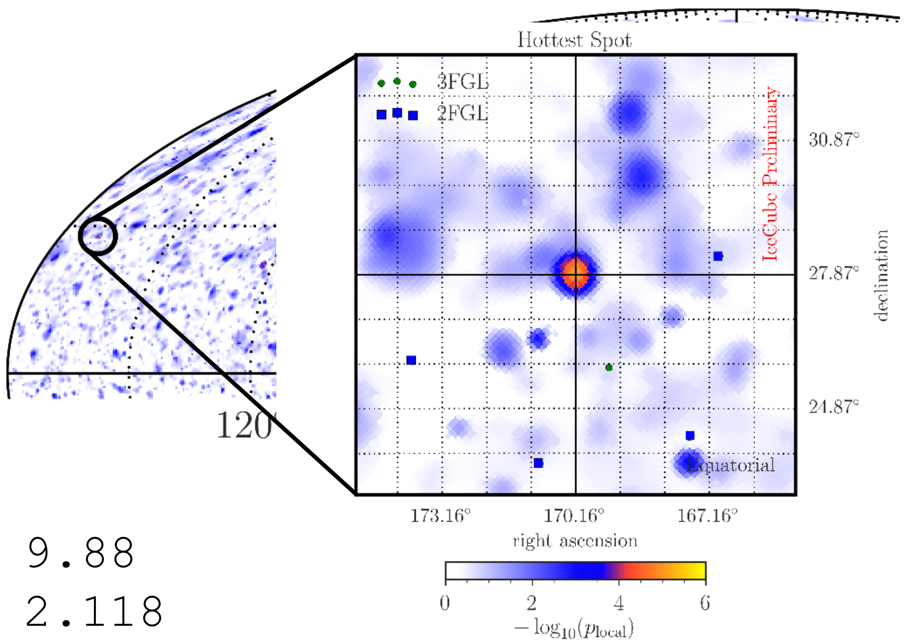
Results: All-Sky Scan

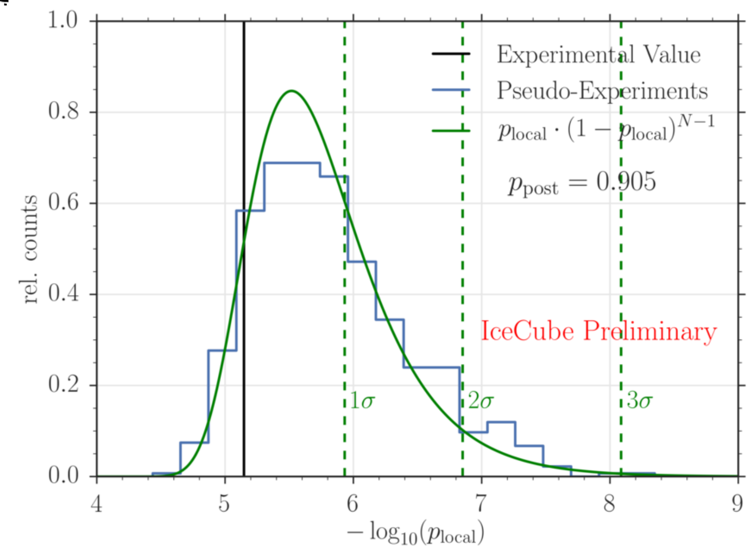


n_s:	9.88
γ:	2.118
TS:	17.36
pVal:	$10^{-5.13}$
ra:	170.16°
dec:	27.91°
b_{gal}:	69.88°
l_{gal}:	205.45°

- We scanned of the whole Northern hemisphere down to -5 deg declination
- Hottest spot has a local p-value of $10^{-5.13}$ (black circle)
- Position and fit-parameters are given at left hand

Results: All-Sky Scan





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- Trial corrected p-value: 90.5%
  → **Compatible with background only hypothesis**
- Zoom into Hot Spot region
  - No correlation with source position from second and third Fermi-LAT catalog
  - Does not coincide with locations from previous analysis

Catalog Search

Table 1: Results of the pre-defined source list.

Source	Type	α [deg]	δ [deg]	p-Value	TS	n_s	Φ_0 [TeV cm^{-2} s^{-1}]
PKS 0235+164	BL Lac	39.66	16.62	0.7355	-0.400	0.00	$2.04 \cdot 10^{-13}$
1ES 0229+200	BL Lac	38.20	20.29	0.4762	-0.059	0.00	$4.47 \cdot 10^{-13}$
W Comae	BL Lac	185.38	28.23	0.4420	-0.055	0.00	$5.37 \cdot 10^{-13}$
Mrk 421	BL Lac	166.11	38.21	0.2433	0.029	0.48	$8.68 \cdot 10^{-13}$
Mrk 501	BL Lac	253.47	39.76	0.6847	-0.172	0.00	$3.51 \cdot 10^{-13}$
BL Lac	BL Lac	330.68	42.28	0.5104	-0.028	0.00	$5.58 \cdot 10^{-13}$
H 1426+428	BL Lac	217.14	42.67	0.7890	-0.243	0.00	$1.96 \cdot 10^{-13}$
3C66A	BL Lac	35.67	43.04	0.3306	-0.001	0.00	$7.50 \cdot 10^{-13}$
1ES 2344+514	BL Lac	356.77	51.70	0.9264	-0.808	0.00	$1.58 \cdot 10^{-13}$
1ES 1959+650	BL Lac	300.00	65.15	0.2069	0.124	1.69	$1.17 \cdot 10^{-12}$
S5 0716+71	BL Lac	110.47	71.34	0.7230	-0.380	0.00	$3.84 \cdot 10^{-13}$
3C 273	FSRQ	187.28	2.05	0.3807	-0.014	0.00	$4.42 \cdot 10^{-13}$
PKS 1502+106	FSRQ	226.10	10.52	0.2322	-0.000	0.00	$5.98 \cdot 10^{-13}$
PKS 0528+134	FSRQ	82.73	13.53	0.2870	-0.002	0.00	$5.74 \cdot 10^{-13}$
3C454.3	FSRQ	343.50	16.15	0.0072	5.503	5.98	$1.26 \cdot 10^{-12}$
4C 38.41	FSRQ	248.81	38.13	0.0055	5.686	6.62	$1.72 \cdot 10^{-12}$
MGRO J1908+06	NI	286.99	6.27	0.0032	6.284	3.28	$1.13 \cdot 10^{-12}$
Geminga	PWN	98.48	17.77	0.9754	-2.424	0.00	$1.16 \cdot 10^{-13}$
Crab Nebula	PWN	83.63	22.01	0.1188	0.709	4.32	$8.65 \cdot 10^{-13}$
MGRO J2019+37	PWN	305.22	36.83	0.9884	-3.191	0.00	$1.39 \cdot 10^{-13}$
Cyg OB2	SFR	308.09	41.23	0.3174	-0.002	0.00	$7.53 \cdot 10^{-13}$
IC443	SNR	94.18	22.53	0.8153	-0.457	0.00	$1.22 \cdot 10^{-13}$
Cas A	SNR	350.85	58.81	0.2069	0.033	0.88	$1.05 \cdot 10^{-12}$
TYCHO	SNR	6.36	64.18	0.4471	-0.019	0.00	$8.14 \cdot 10^{-13}$
M87	SRG	187.71	12.39	0.6711	-0.256	0.00	$2.85 \cdot 10^{-13}$
3C 123.0	SRG	69.27	29.67	0.9055	-0.747	0.00	$1.30 \cdot 10^{-13}$
Cyg A	SRG	299.87	40.73	0.0049	6.335	4.30	$1.78 \cdot 10^{-12}$
NGC 1275	SRG	49.95	41.51	0.2582	0.007	0.25	$8.31 \cdot 10^{-13}$
M82	SRG	148.97	69.68	0.8887	-0.888	0.00	$1.83 \cdot 10^{-13}$
SS433	XB/mqso	287.96	4.98	0.8738	-1.085	0.00	$1.01 \cdot 10^{-13}$
HESS J0632+057	XB/mqso	98.24	5.81	0.8359	-0.917	0.00	$1.01 \cdot 10^{-13}$
Cyg X-1	XB/mqso	299.59	35.20	0.5422	-0.106	0.00	$4.93 \cdot 10^{-13}$
Cyg X-3	XB/mqso	308.11	40.96	0.3230	-0.003	0.00	$7.28 \cdot 10^{-13}$
LSI 303	XB/mqso	40.13	61.23	0.2843	0.001	0.17	$1.01 \cdot 10^{-12}$
Hottest spot of the all-sky search							
—	—	170.16	27.87	$10^{-5.14}$	17.271	10.28	—

Catalog based on the standard IceCube and ANTARES source list.

The source list has been unchanged for years now.

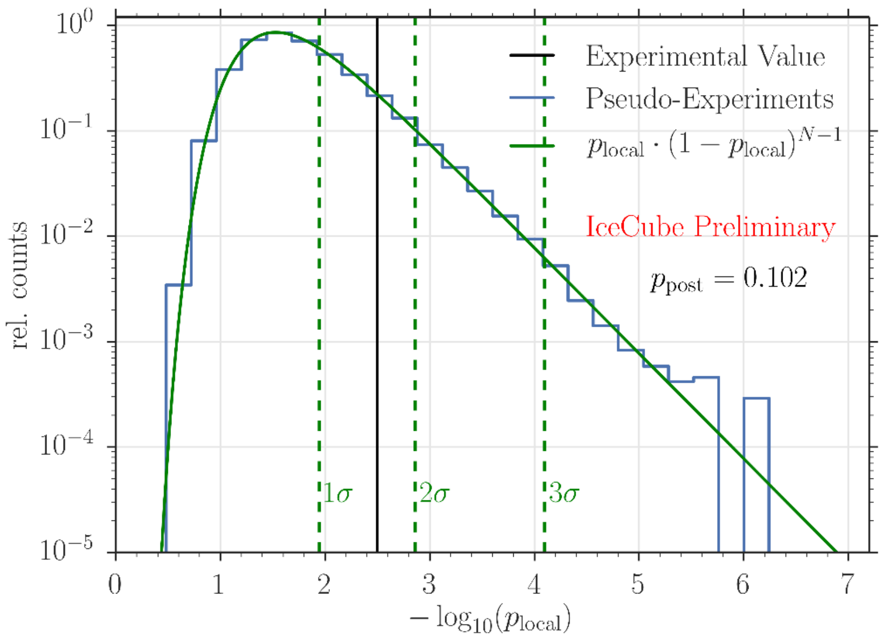
Here we consider the 34 sources on Northern hemisphere.

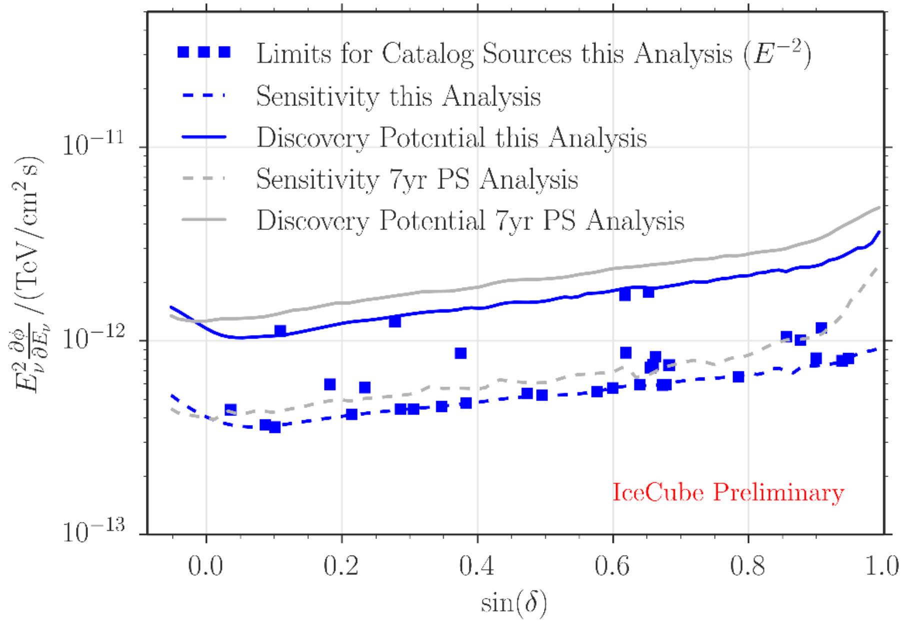
For each source the best fit ns, TS, local p-value and the 90% upper flux limit is shown.

The SI is not shown as it is effectively fixed to be about 2.13.

MGRO J1908+06 is source with smallest local p-value

Catalog Search





- p-value of the most significant source in the list is 10.2%
  → **Compatible with background only hypothesis**
- flux limits on 90% C.L. for E^{-2} fluxes have been calculated
  - Limits below the sensitivity of the analysis are set to sensitivity level
  - 90% upper limits can be still above discovery potential as long as best fit flux is below.
- For comparison 7yr PS Analysis (Astrophys. J., 835 (2017) no. 2, 151) is shown

Interesting Sources

Table 1: Results of the pre-defined source list.

Source	Type	α [deg]	δ [deg]	p-Value	TS	n_s	Φ_0 [TeV cm^{-2} s^{-1}]
MGRO J1908+06	NI	286.99	6.27	0.0032	6.284	3.28	$1.13\cdot10^{-12}$
Cyg A	SRG	299.87	40.73	0.0049	6.335	4.30	$1.78\cdot10^{-12}$
4C 38.41	FSRQ	248.81	38.13	0.0055	5.686	6.62	$1.72\cdot10^{-12}$
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LSI 303	XB/mqso	40.13	61.23	0.2843	0.001	0.17	$1.01\cdot10^{-12}$
…	…	…	…	…	…	…	…

There's no evidence of anything here - but let's look at these anyway

- Each source in the catalog was non significant on its own.
- However we have 4 sources with p-value smaller than 1%.
- These sources are related to 3 different source classes.

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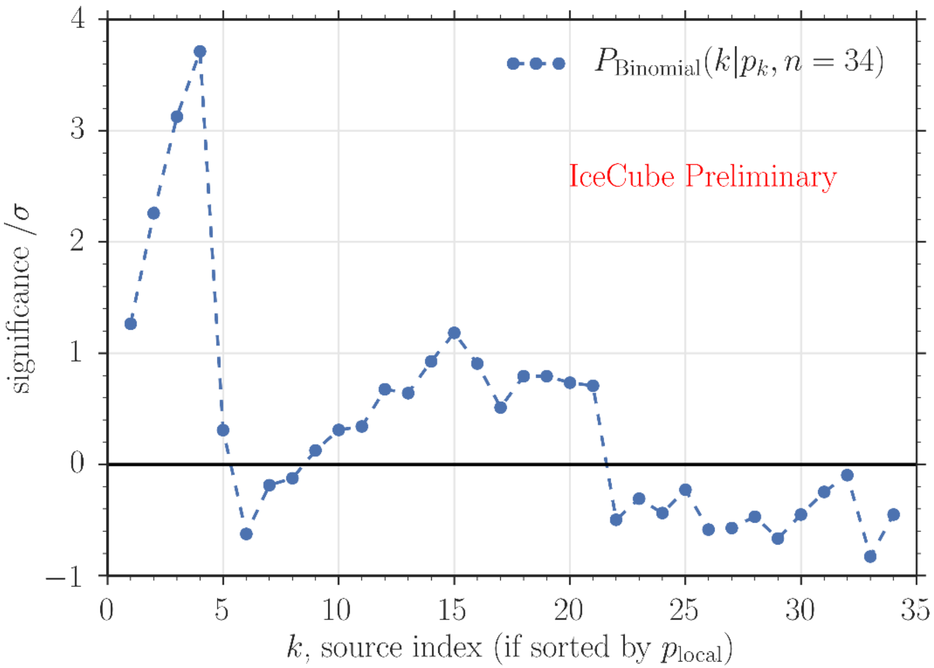
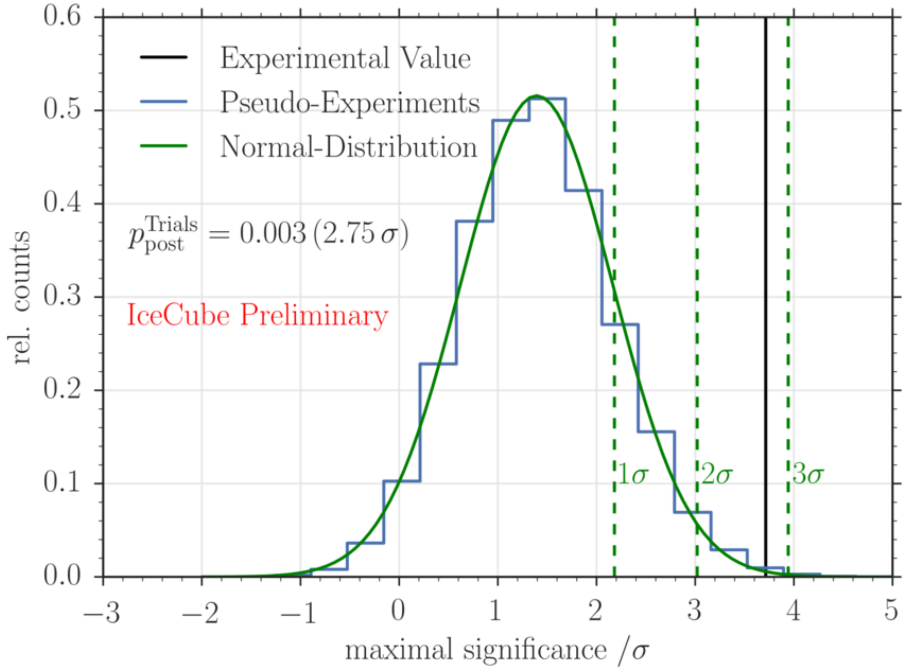
There's no evidence of anything here - but let's look at these anyway

- Each source in the catalog was non significant on its own.
- However we have 4 sources with p-value smaller than 1%.
- These sources are related to 3 different source classes.
- Combining sources, when sorted by local p-value
- Binomial-probability to find k sources with p-value smaller than p_k of N

$$\binom{N}{k} p_k^{\,k} (1 - p_k)^{N-k}$$

Combination of source from source list





Significance of binomial combination of p-values of sources.
We have to correct for the choice of number of sources we chose to combine.
Trial correction significance is 2.75σ.
Note:

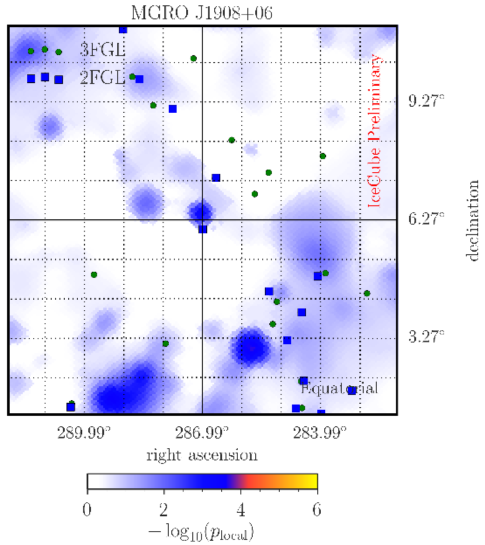
- This test has been introduced post unblinding.
- Combination not physical motivated, as sources not from same source class.

Interesting Sources

Local p-value landscape around source with sources of the 2/3 FGL

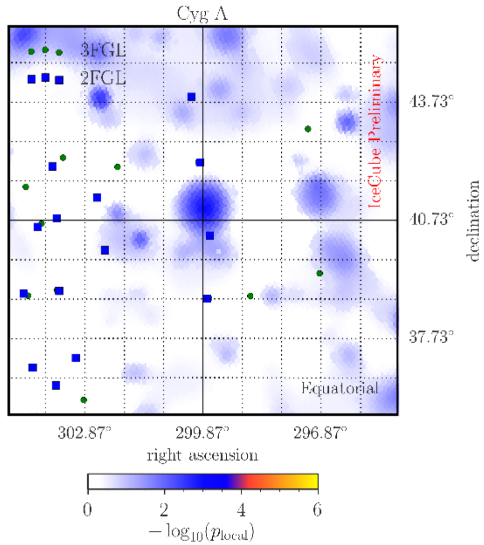
MGRO J1908+06

- MGRO J1908+06 is an extended TeV gamma ray source (σ=~0.4°)
  - Measured position varies from experiment to experiment.
  - We use the position as in the previous PS publications.
- Source is classified as “not identified”
- Associated with Pulsar Wind Nebular (and SNR)
- Gamma ray flux is 80% of crab at 20TeV



Cygnus A

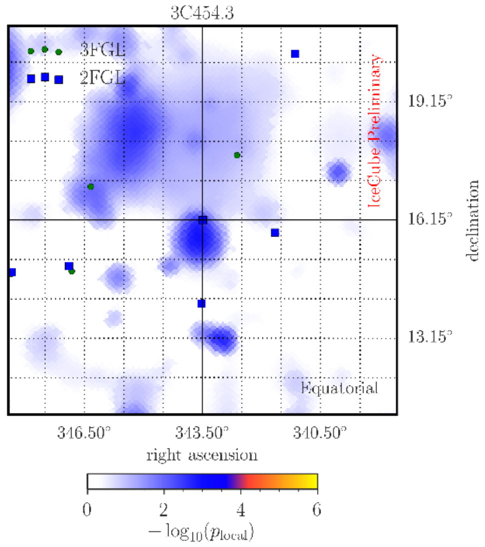
- FRII / Starburst Radio Galaxy
- z=0.056
- viewing angle of 50-85 deg to jets
- Cygnus A has not yet been measured in gamma-rays
- the Fermi source near the center is not Cygnus A



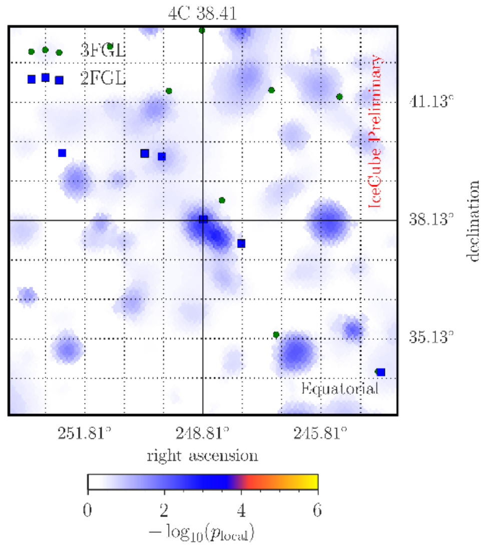
Interesting Sources

Local p-value landscape around source with sources of the 2/3 FGL

3C454.3
- Flat Spectrum Radio Quasars / FR-II
- strong variable gamma ray source

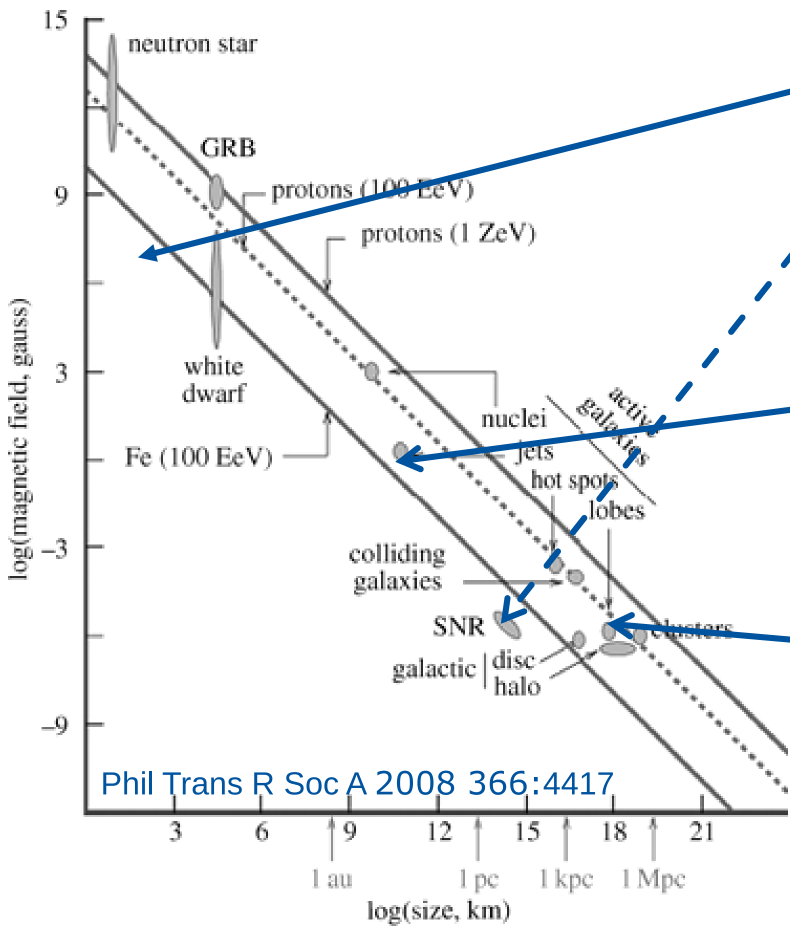


4C 38.41
- Flat Spectrum Radio Quasars
- optical violent variable
- gamma ray flux varies significantly on daytime scale
- z=1.814
- large out burst in 2011 visible over the entire EM spectrum



Sources of HE Cosmic Rays

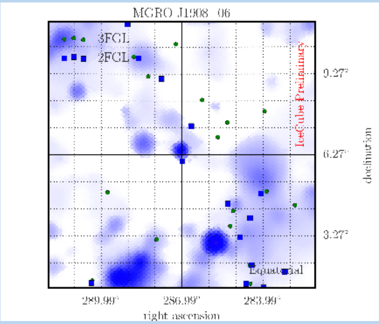
There is no physical motivation
to combine these sources.



Phil Trans R Soc A 2008 366:4417

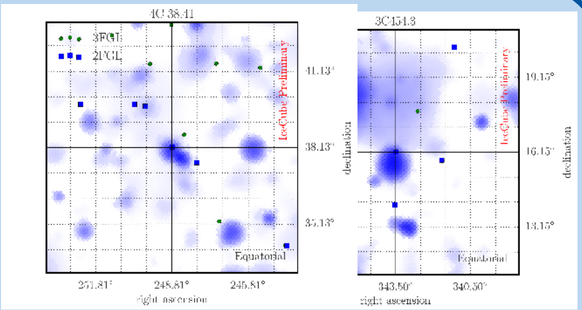
MGRO J1908+06

Pulsar Wind Nebular (& SNR)



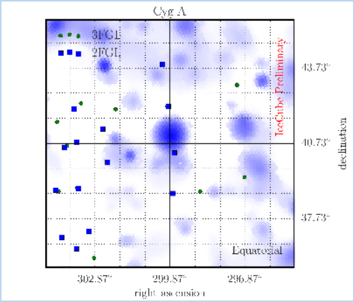
3C454.3
4C 38.41

FSRQ



Cygnus A

Starburst Radio Galaxy



Summary

- IceCube measured an all-flavor and a diffuse muon neutrino flux
- We performed a search for point-like neutrino sources that focused on sources of the diffuse muon neutrino flux
- Improvements in method due to focus on diffuse flux gain about ~10-20% sensitivity
- The trial corrected p-value of the all-sky scan was 90.5% with the point with the smallest p-value at RA 170.16°, Dec 27.91°
- MGRO J1908+06 is the source with the smallest p-value of 0.32% in a pre-selected list of 34 sources with a trial corrected p-value of 10.2%
- A posterior binomial probability to find 4 sources with p-value < 0.72% in source catalog is 0.3% (2.75σ)
  - A combination of these sources is physically not motivated.

Outlook
Additional Year of Data

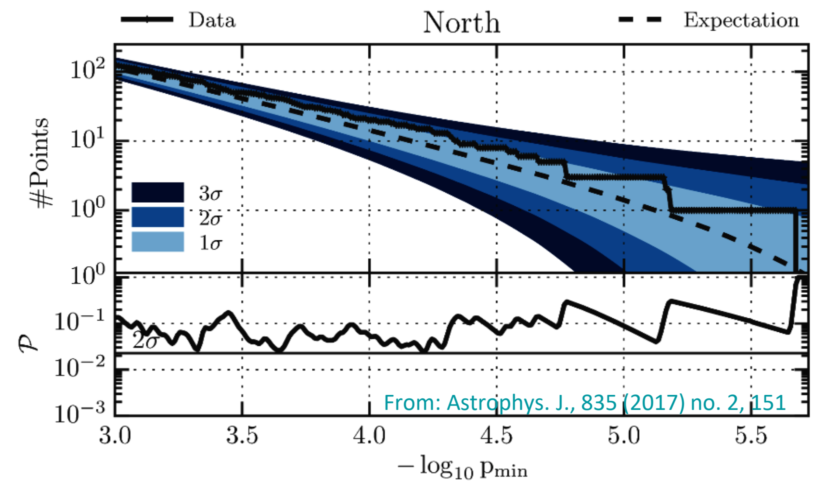
Another year are read to be analyzed.

The sensitivity for single point sources increases again by about 10%.

We will also include a search for a population of sub-threshold sources in the all sky scan, similar to the one shown in Astrophys. J., 835 (2017) no. 2, 151

There the number of spots with local p-value below a threshold is compared to the expectation

$$\lambda\left(-\log_{10}\left(p_{\min}\right)\right) \qquad P = e^{-\lambda} \sum_{m=n}^{\infty} \frac{\lambda^m}{m!}$$



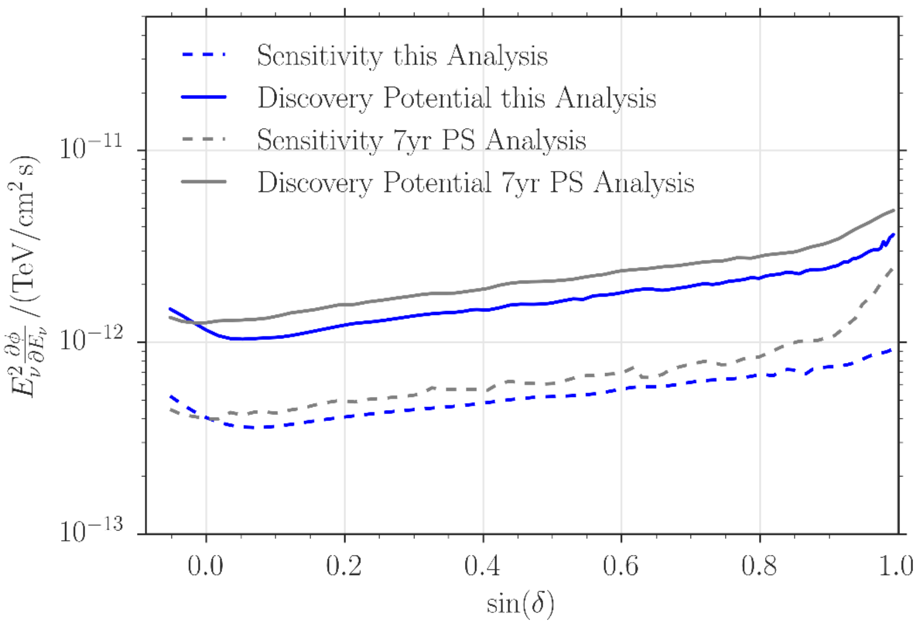
Results will be hopefully ready by ICRC. Stay tuned.

The IceCube Collaboration

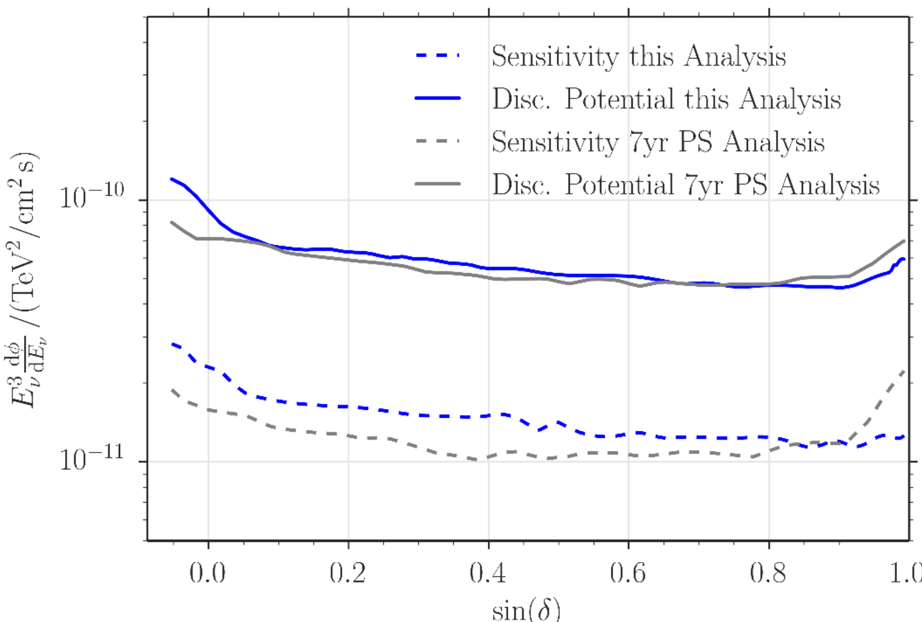
Backup

Sensitivity to different source spectra

Sensitivity and discovery potential

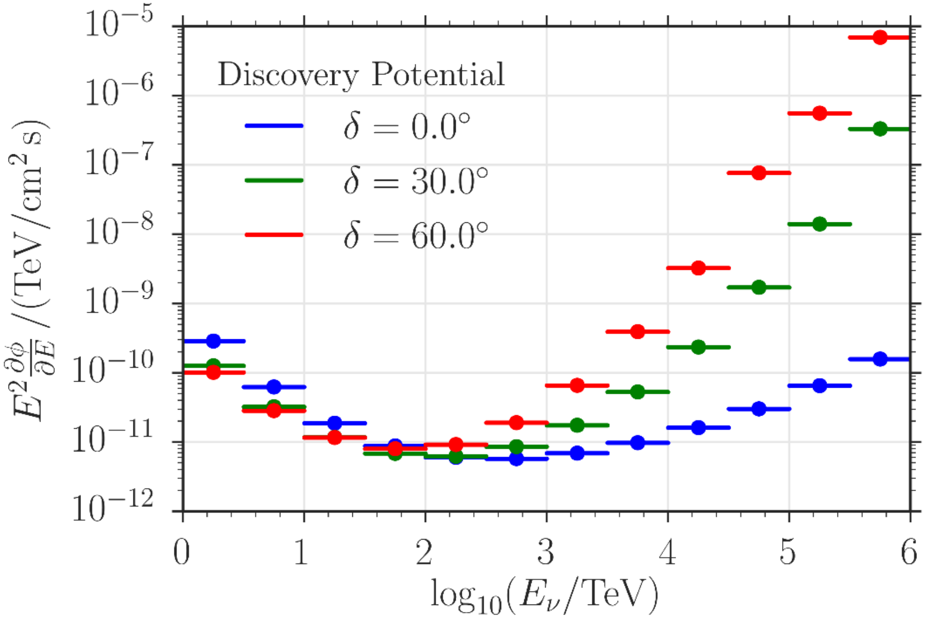


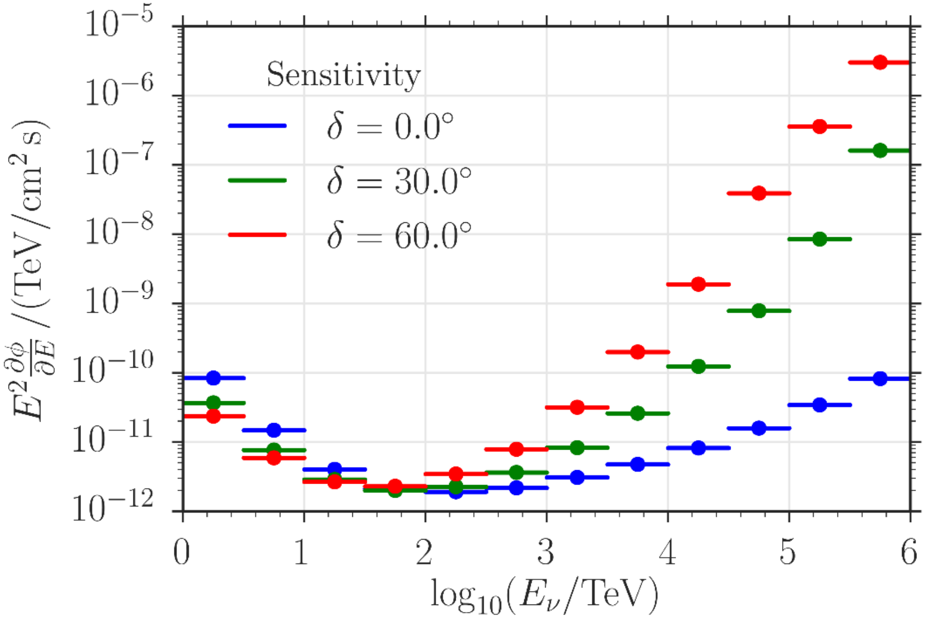
for an E^{-2} spectrum



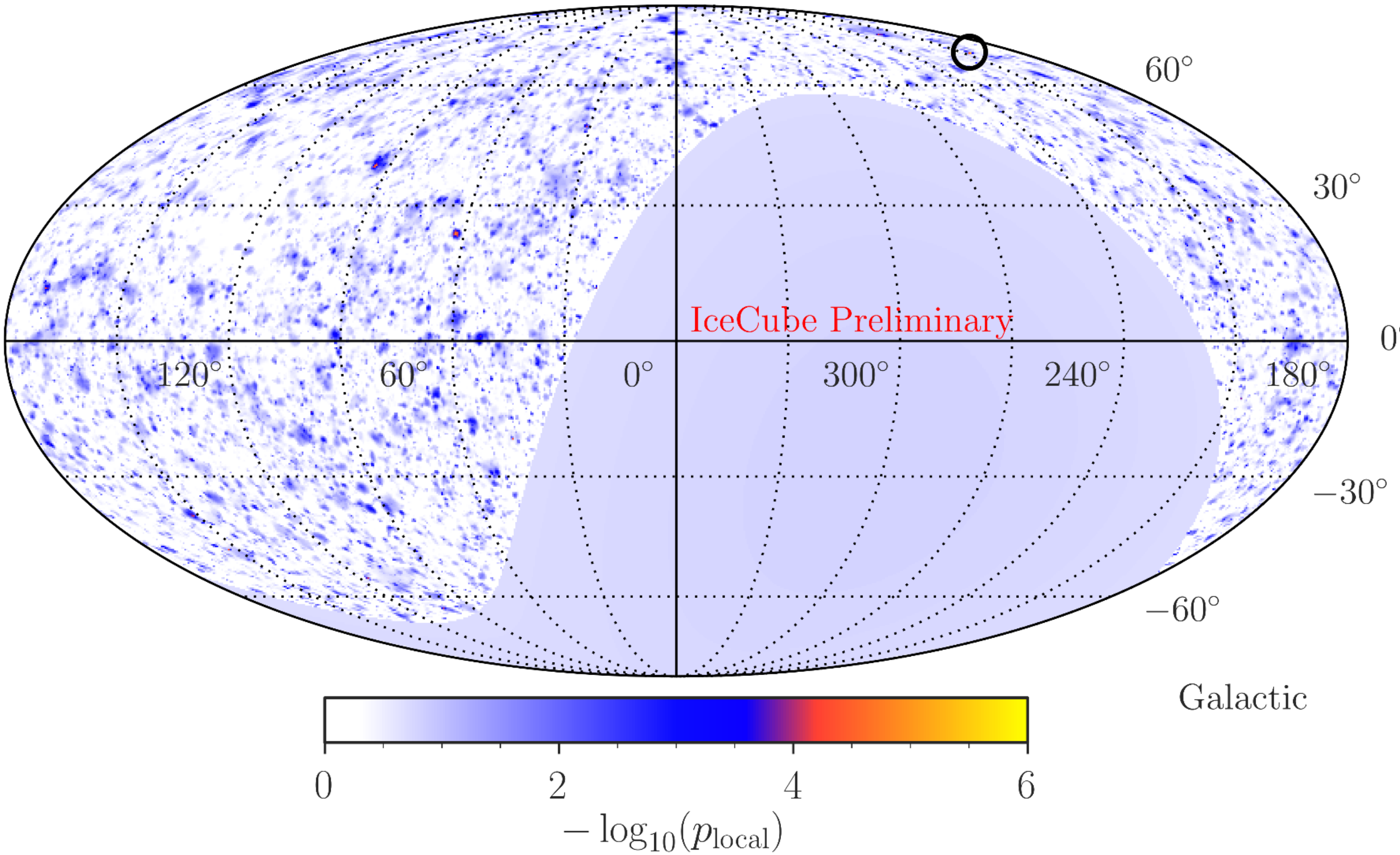
for an E^{-3} spectrum

Differential Sensitvity and Discovery Potential



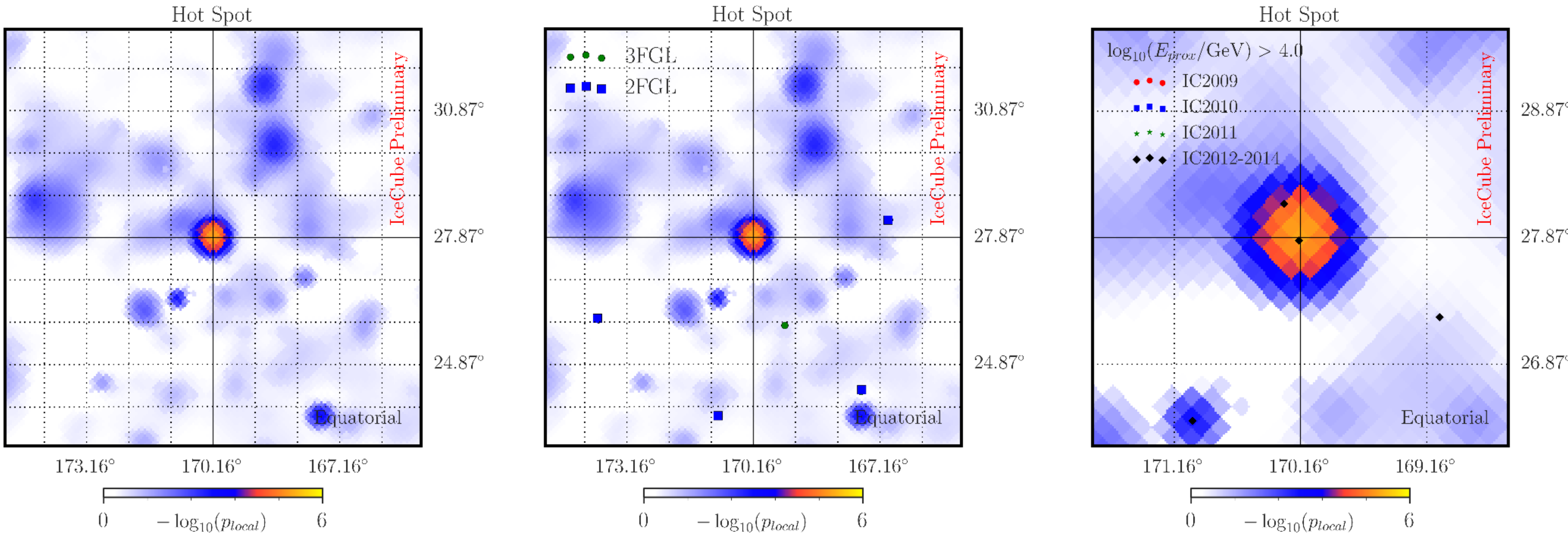


All sky scan in galactic coordinates



Local p-value of the all sky scan in galactic coordinates.

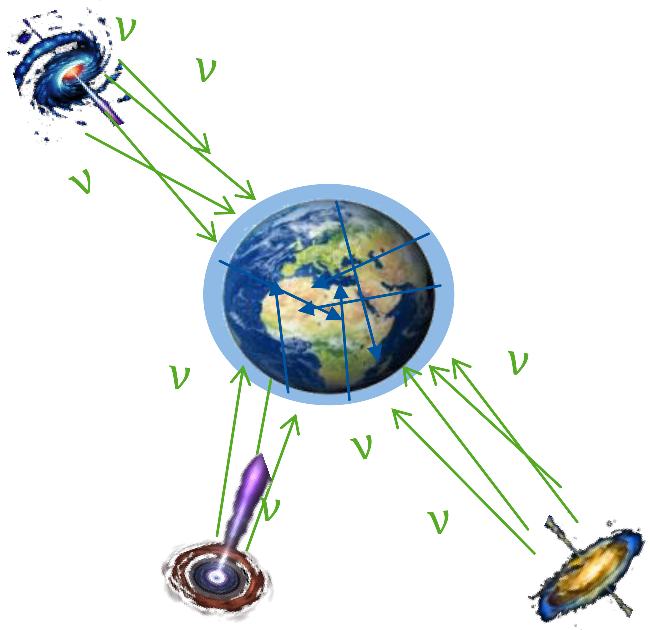
Hottest Spot



Zoom into region of the hottest spot.

- P-Value landscape
- P-Value landscape with sources of the 2/3 FGL
- P-Value landscape with events above 10 TeV

Unbinned likelihood analysis



Likelihood for event i:

$$L_i = \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i$$

where:

- N number of events in sample
- n_s number of signal events
- S_i Signal probability
- B_i Background probability

Unbinned likelihood analysis

$$S_i = S\left(|\vec{x}_i - \vec{x}_s|, \sigma_i, \delta_i\right) = \frac{1}{2\pi\sigma_i}\exp\left(-\frac{|\vec{x}_i - \vec{x}_s|}{2\sigma_i}\right)$$

Likelihood for event i:

$$L_i = \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i$$

where:

- N number of events in sample
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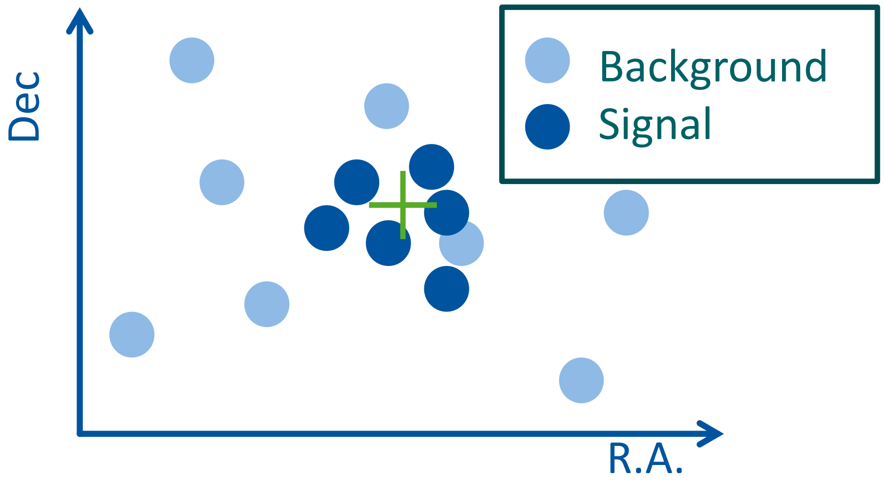
Unbinned likelihood analysis



$$B_i = B(\delta_i) = \frac{1}{2\pi} B(\delta_i)$$

Likelihood for event i:

$$L_i = \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i$$

where:

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- n_s number of signal events
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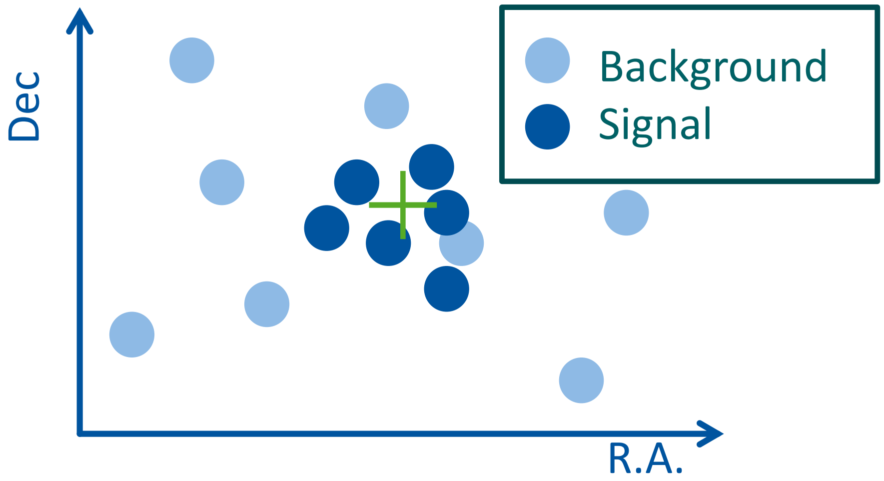
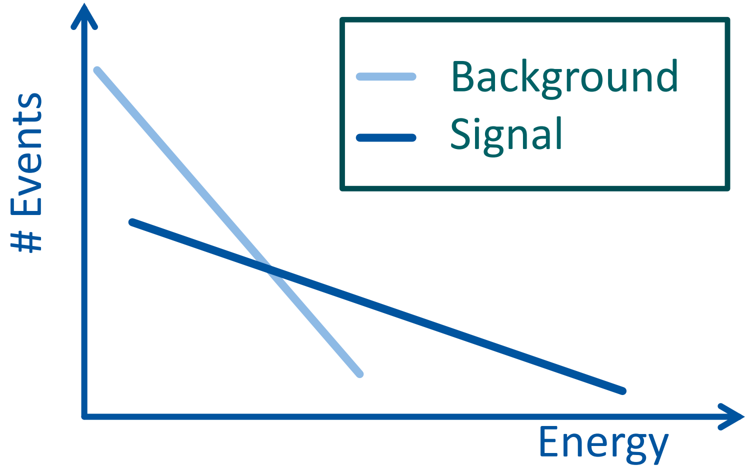
Unbinned likelihood analysis





Likelihood for event i:

$$L_i = \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i$$

where:

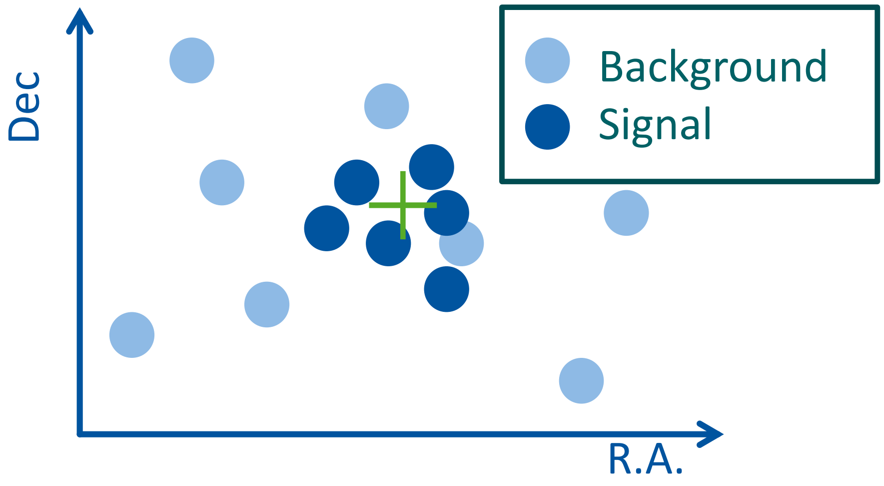
- N number of events in sample
- n_s number of signal events
- S_i Signal probability
- B_i Background probability

also use Spatial and Energy distribution

→ $S_i = S_{spat,i} \cdot S_{ener,i}$

→ $B_i = B_{spat,i} \cdot B_{ener,i}$

Unbinned likelihood analysis

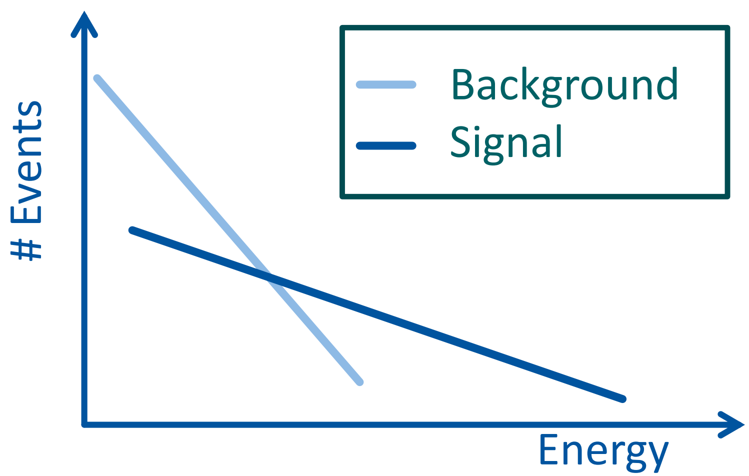


Likelihood for event i:

$$L_i = \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i$$

where:

- N number of events in sample
- n_s number of signal events
- S_i Signal probability
- B_i Background probability



also use Spatial and Energy distribution

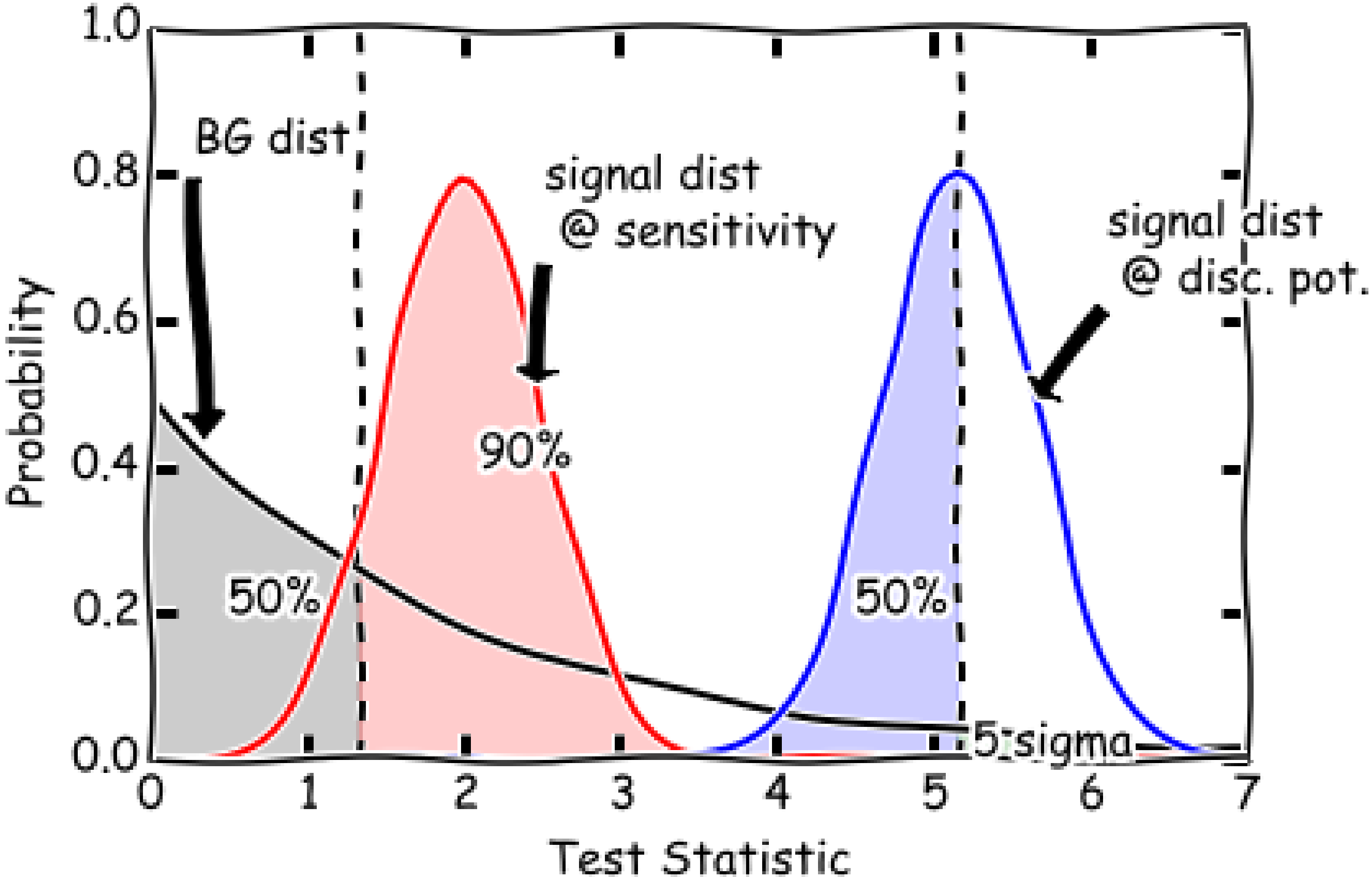
$\rightarrow$ $S_i = S_{spat,i} \cdot S_{ener,i}$

$\rightarrow$ $B_i = B_{spat,i} \cdot B_{ener,i}$

Likelihood for ensemble of events

$$L = \prod_i \left[\frac{n_s}{N} S_{i,spat} S_{i,ener} + \left(1 - \frac{n_s}{N}\right) B_{i,spat} B_{i,ener} \right]$$

Sensitivity & Discovery Potential



Sensitivity and Discovery potential declination dependent but not R.A. dependent