Neutrino background anisotropies

3rd Anisotropic Universe meets Barolo Astrophysical Meeting

04.09.2018, Barolo

René Reimann

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

Credit: IceCube Collaboration/NSF

Multimessenger Astrophysics

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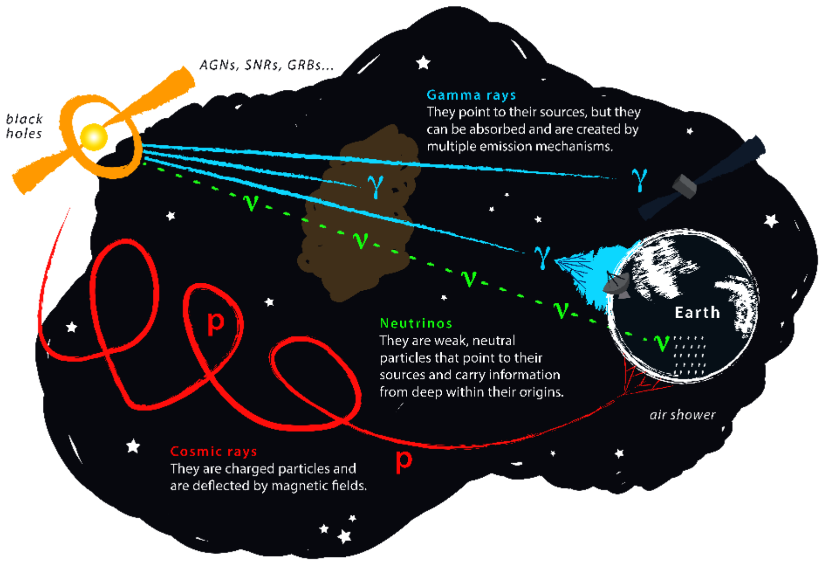
Barolo Astroparticle Meeting
2-5 September 2018



Cosmic Rays interact with photons or matter surrounding the source

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

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

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
- can be produced by leptonic processes

TeV neutrinos
- point back to place of origin
- not absorbed during their propagation
- hard to detect at earth

Gravitational waves
- Produced by extreme gravitational fields

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

Transparency of the Universe

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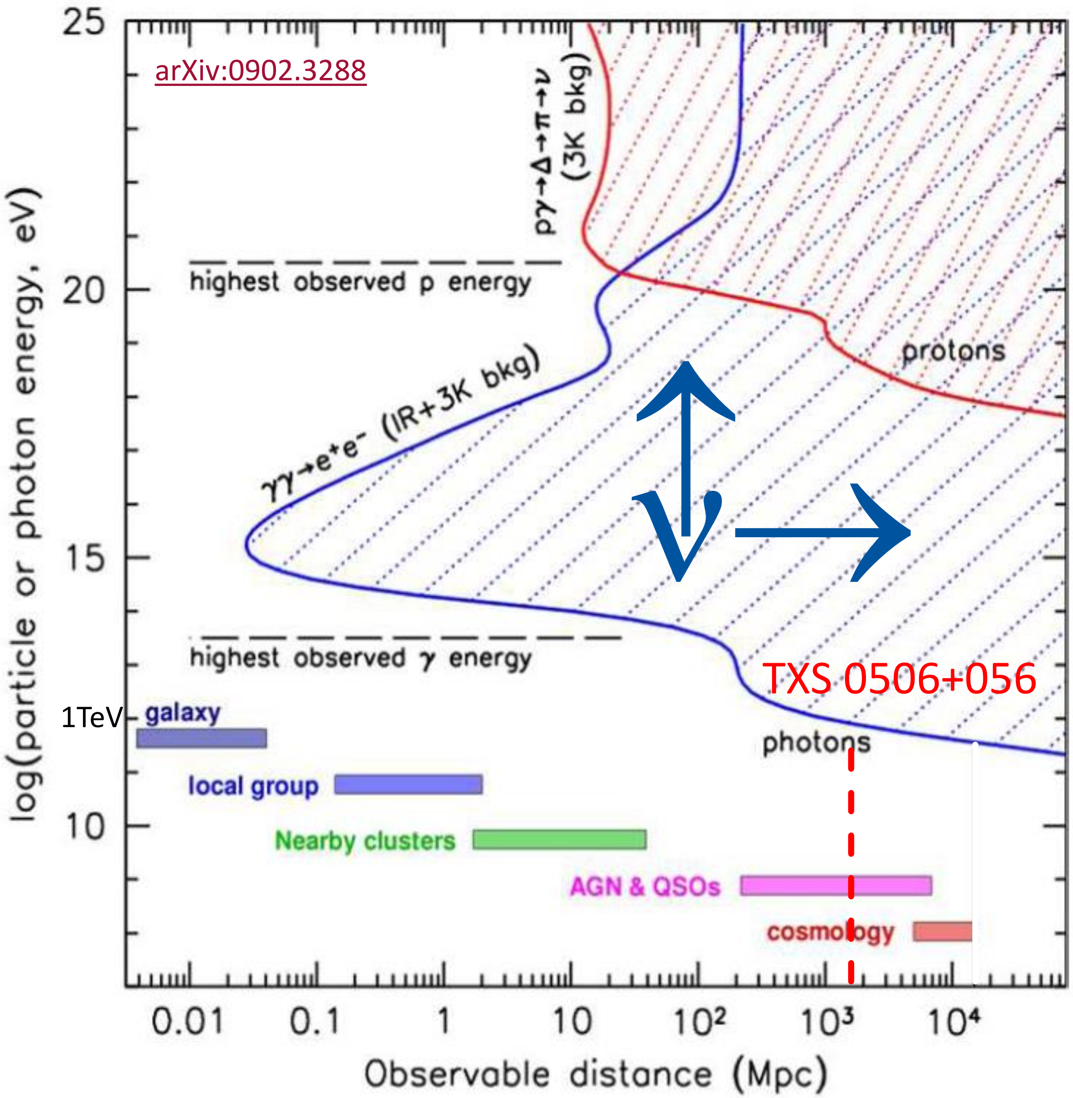


- Photons are absorbed above 10 TeV by interactions with photons
  - CMB
  - Start light
  - …

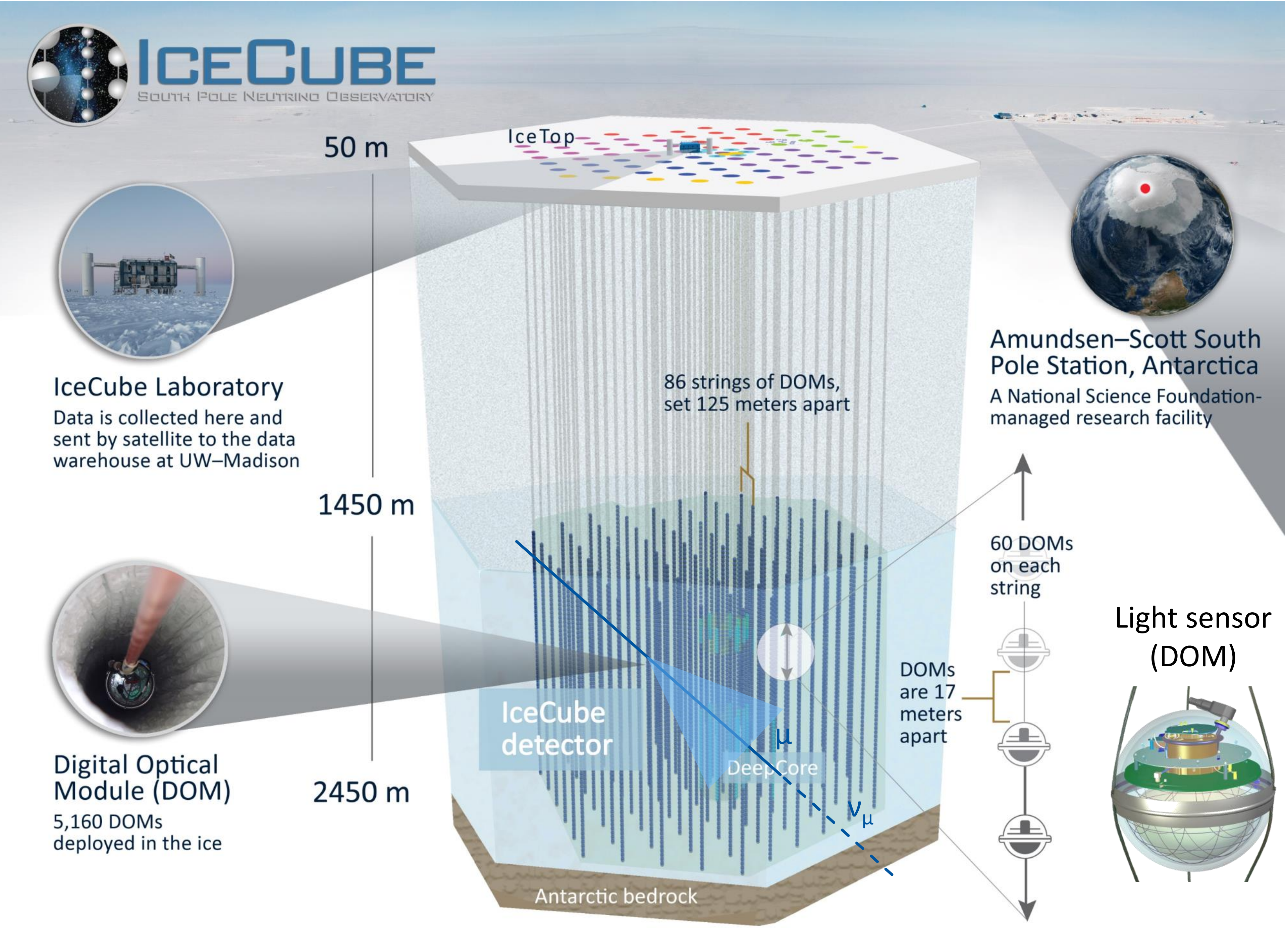
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

- Protons are absorbed by the GZK mechanism

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi + N$$

→ At high energies the observable Universe is limited in cosmic rays and gamma rays

→ Neutrinos can probe the complete universe



The IceCube Neutrino Observatory: Instrumentation and Online Systems JINST 12 (2017) no.03, P03012, arXiv:1612.05093

https://gallery.icecube.wisc.edu/internal/v/graphics/IceCubeGraphics

The ANTARES neutrino telescope

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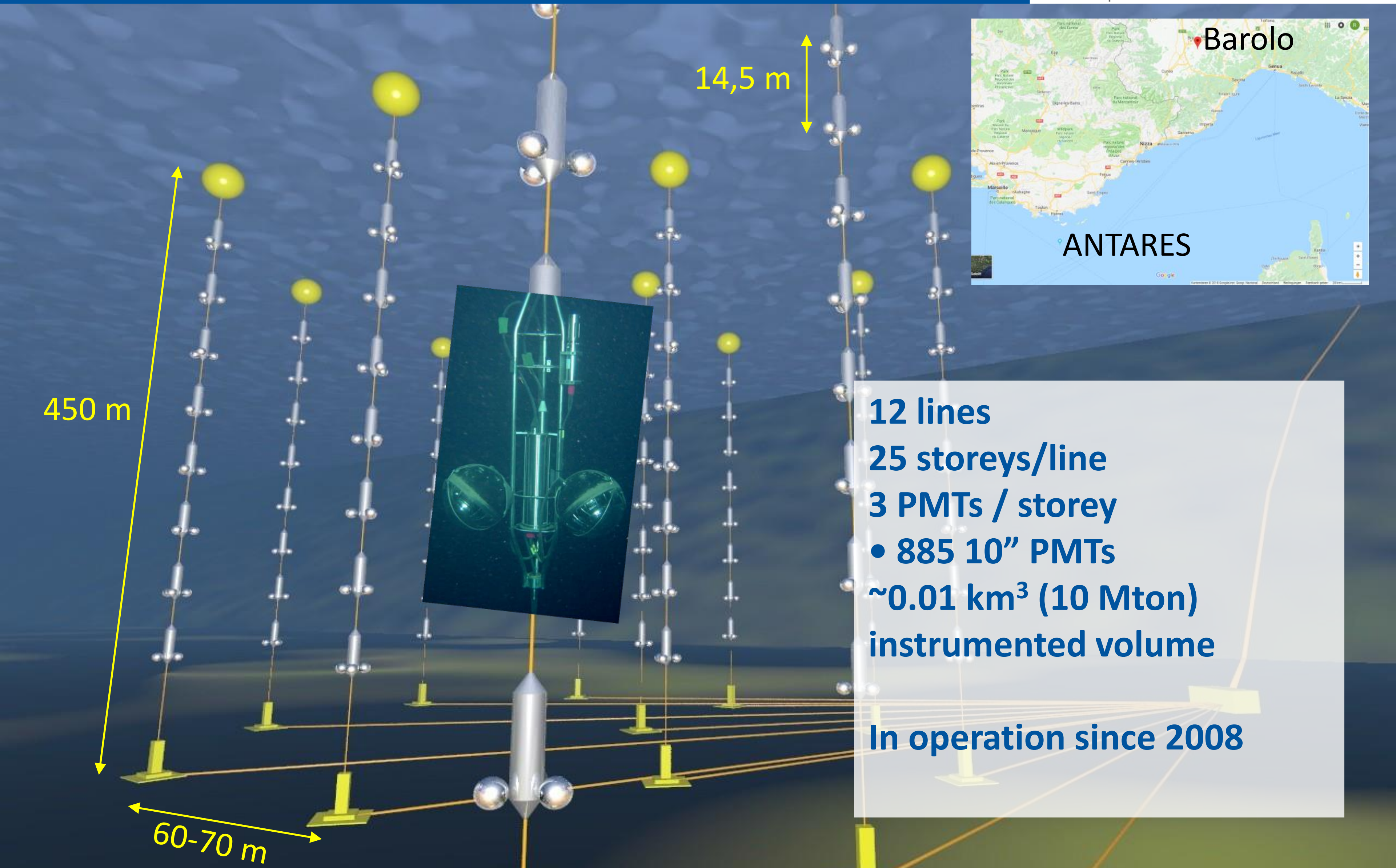


12 lines
25 storeys/line
3 PMTs / storey
- **885 10” PMTs**

~0.01 km^3 (10 Mton) instrumented volume

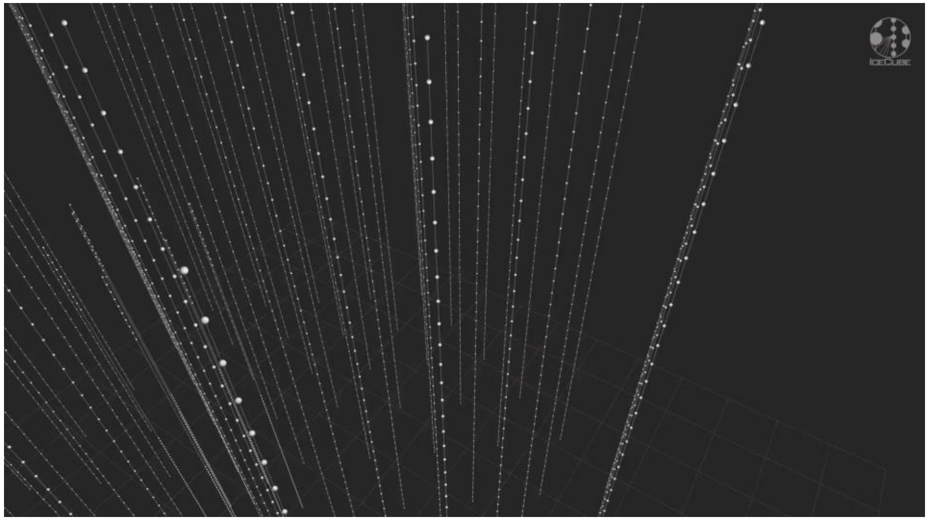
In operation since 2008

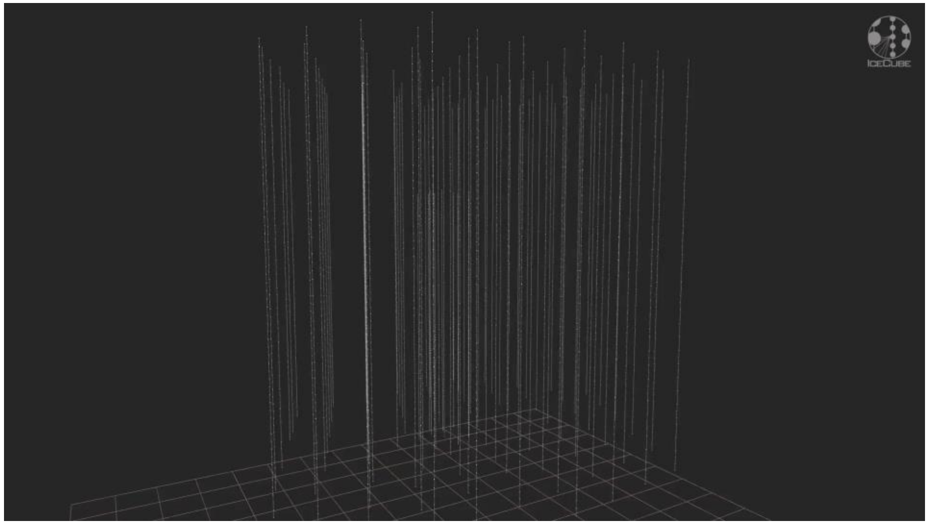
Event Signatures

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

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

Credit: IceCube





- cascade-like signature
- energy fully contained in most events
  → 15% deposited energy resolution
- spherical signature
  → 10-15° angular resolution (>100 TeV)

- track-like signature
- through-going / leaving the detector
  → factor of 2 energy resolution
- long leaver arm
  → < 1° angular resolution

Measurement of astrophysical ν-flux

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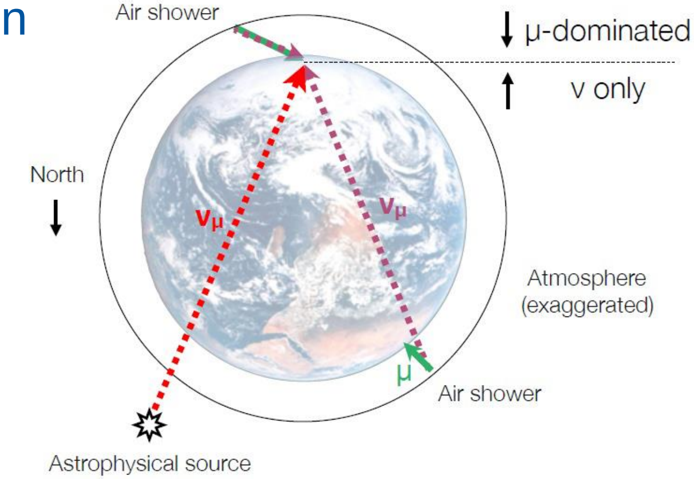
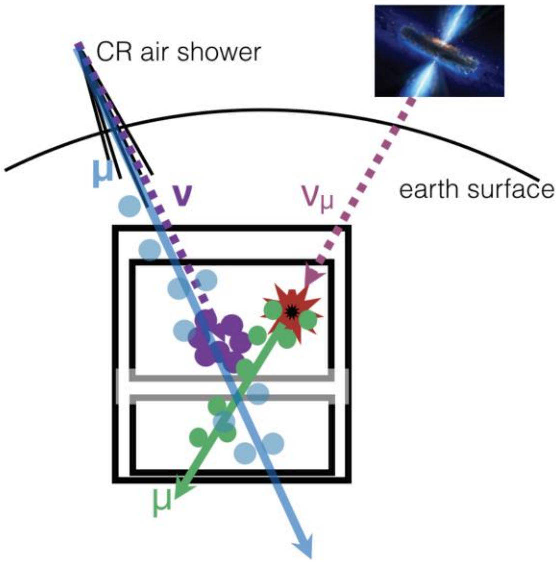
At lower energies, backgrounds dominate detection
- Atmospheric muons (Southern hemisphere)
- Atmospheric neutrinos (Northern hemisphere)

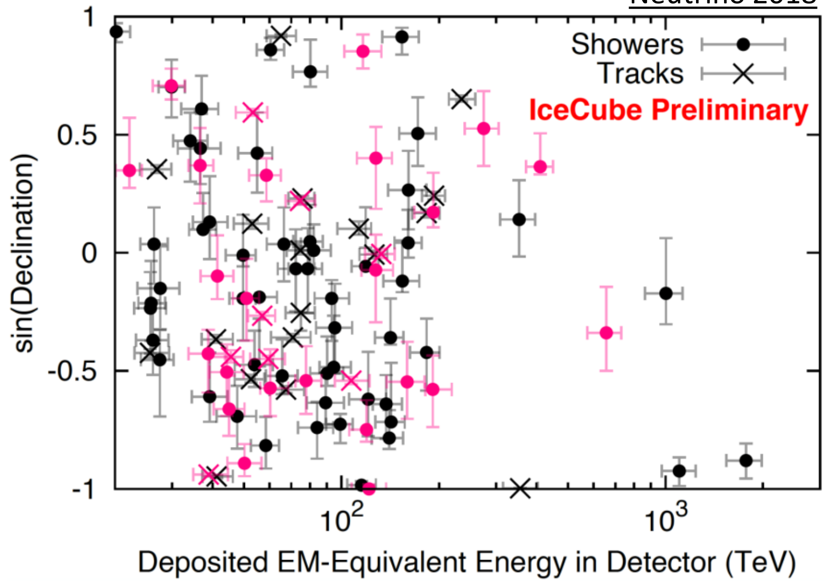
Select high-energy events
- Through-going tracks

Select contained/starting events
- High-Energy Starting Events



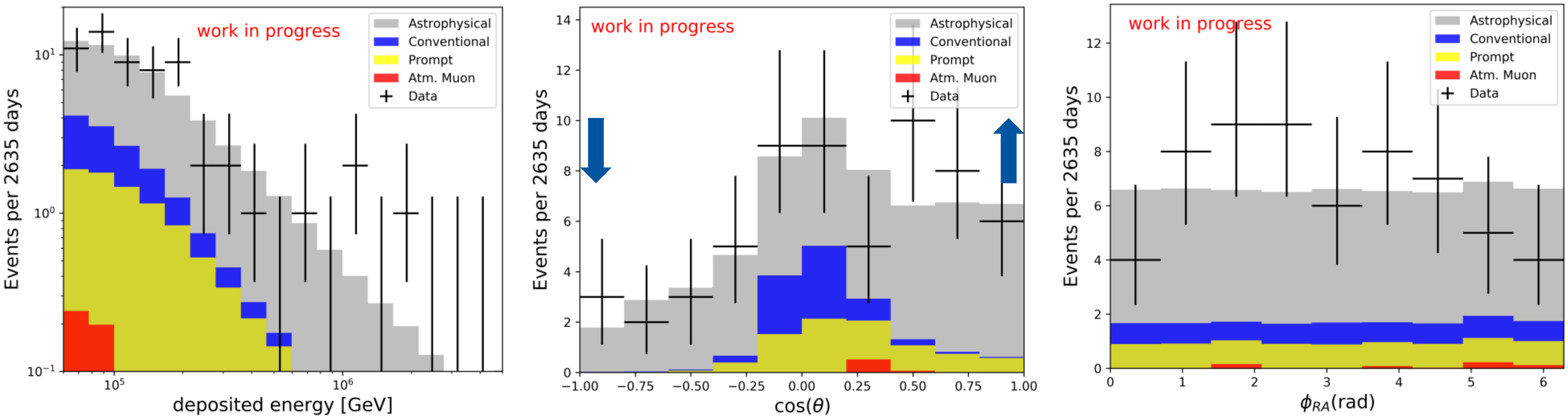


Neutrino 2018



High-Energy Starting Events
7.5 Year result

Neutrino 2018

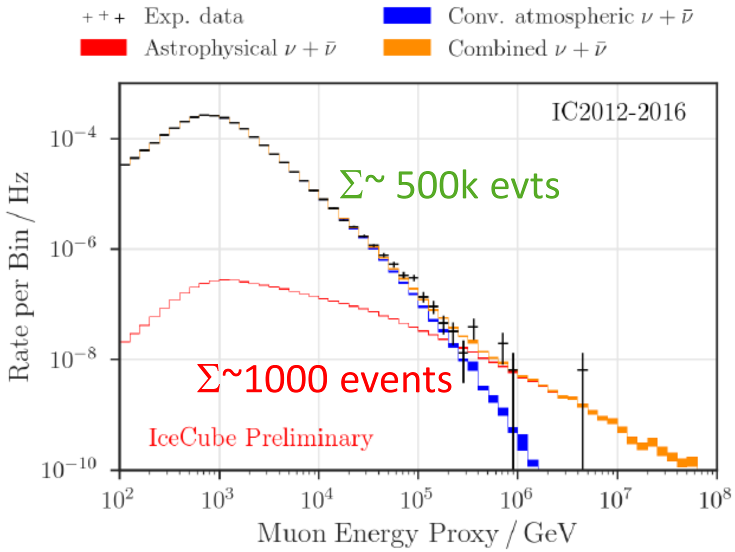


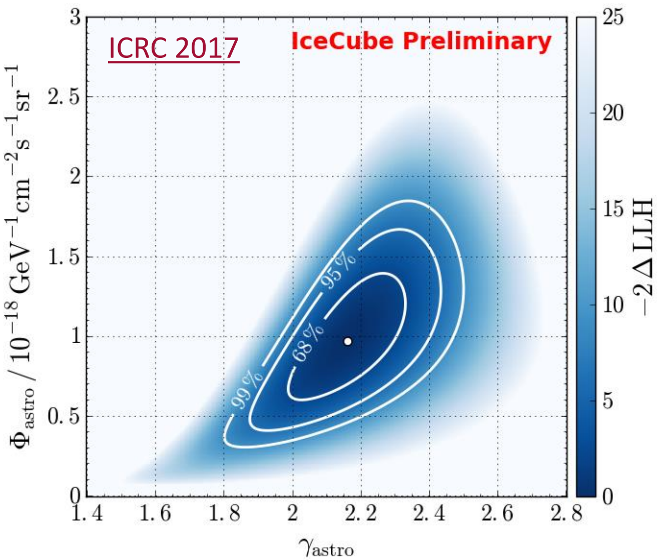
- 103 events total, 60 events with E_{dep} > 60 TeV (>75% astroph. purity)
- Improved calibration and reconstruction
- Fit-Range: 60 events with 60 TeV < E_{dep} < 10 PeV
- Expected background: 0.65±0.2 (atm.μ) , $14.5^{+10.1}_{-8.1}$ (atm.ν, incl. prompt)
- Angular distribution cannot be described by backgrounds
- All flavor flux:

$$E^{-2}\phi = 1.86^{+0.75}_{-0.65} \times 10^{-8} \times (E / 100\text{TeV})^{-0.87}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

- Spectrum relatively soft $\gamma=2.87^{+0.31}_{-0.22}$

Up-going Muons
8 year result





- High statistics
  ~500 000 neutrino events, purity > 99.7%
- Global fit of all data set including systematic uncertainties
  ⇒ Excellent agreement with simulation
  Exclusion of atmospheric origin @ 6.7 σ
- Clear high energy excess above about 200TeV

- Astro Flux $\nu_\mu + \bar{\nu}_\mu$ @ 100TeV:
  $(1.01^{+0.26}_{-0.23}) \times 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$
- Hard Spectral index:
  $\gamma_{astro} = 2.19 \pm 0.10$
- No indication of prompt
- 36 events E_μ> 200TeV (p_{astro} >50%)
- Total ~1000 astrophysical neutrinos with good pointing

High-Energy Neutrino Spectrum

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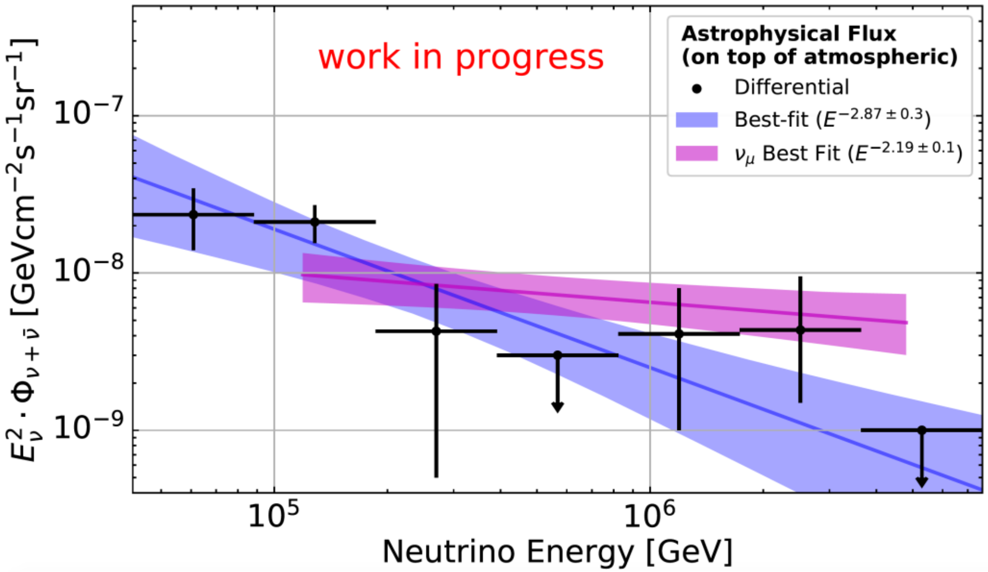
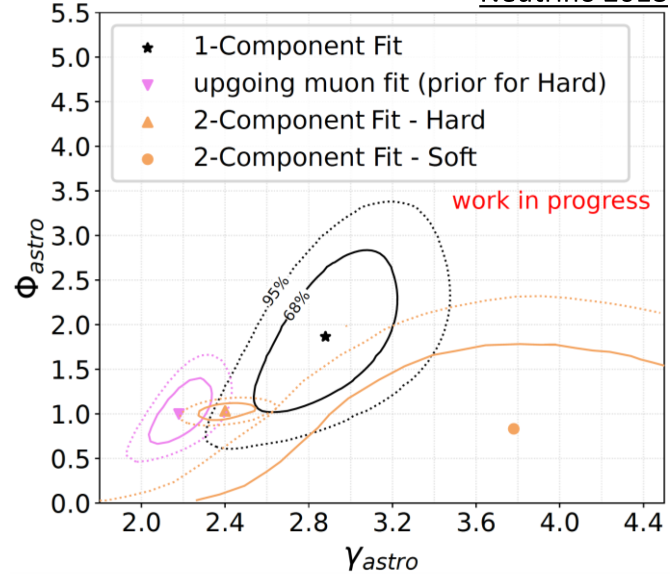
Neutrino 2018





- Overall tension in spectral slope
- Rate of HE events consistent

- Indications of a spectral break?
  - Two component fit of HESE data with muon fit as prior is not yet statistically conclusive
  - Trough-going muons perfers cut-off at 4σ assuming E^{-2}, but <2σ assuming $E^{-2.19}$
- Alternative
  - Indication of different flux from Norther and Southern hemisphere?

The High-Energy Neutrino Sky

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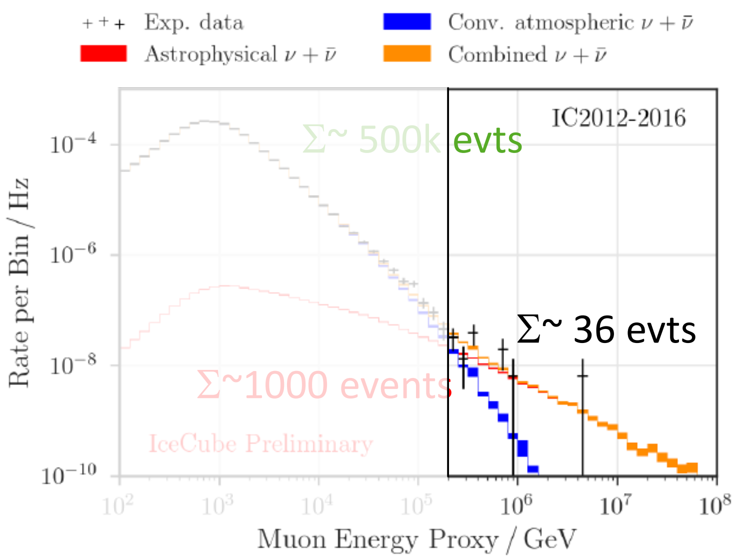

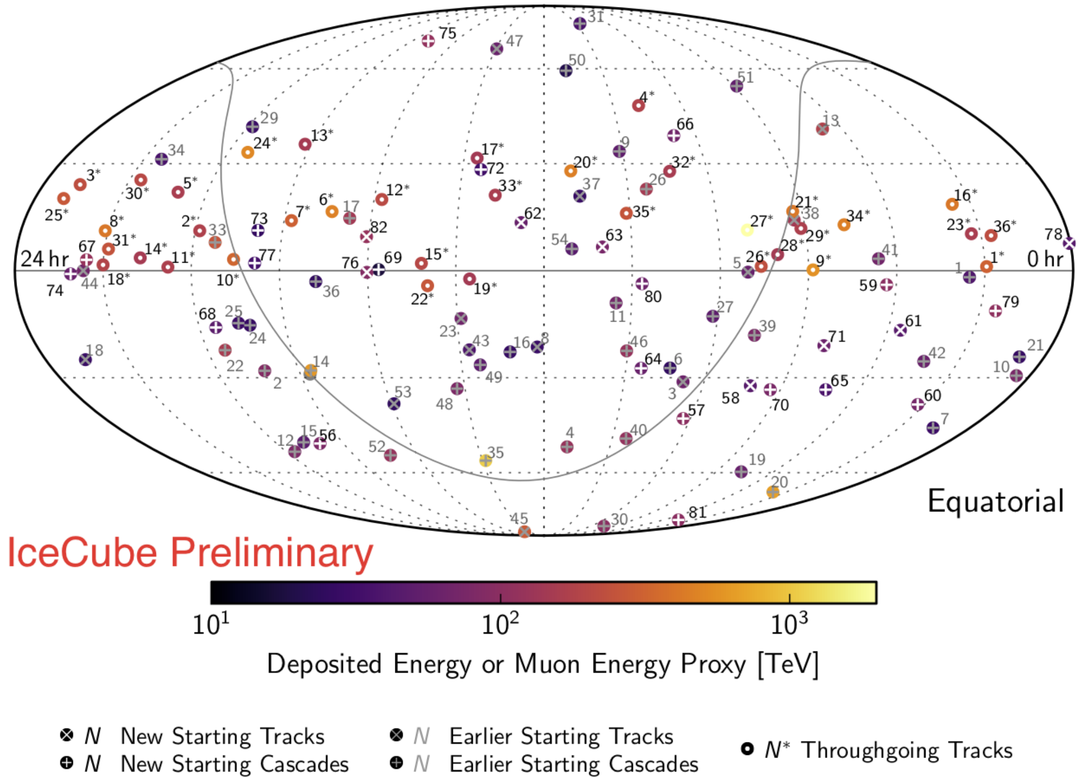

- Skymap of HESE+HEMU with P(astro)>50% (2017)
- No anisotrpy found in ~100 events
- Large amount of astrophysical neutrinos at lower energies ~1000
  - →Use the full sample
- Background events from atmosphere do not cluster

Large Scale Structure
Galactic plane

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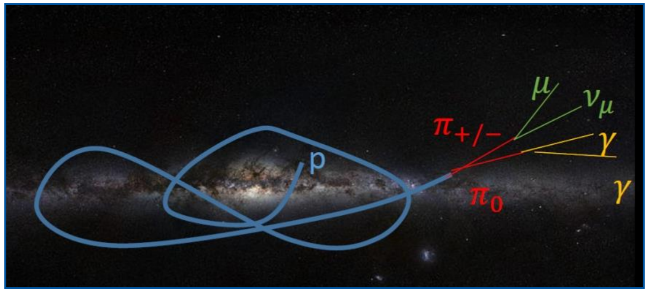
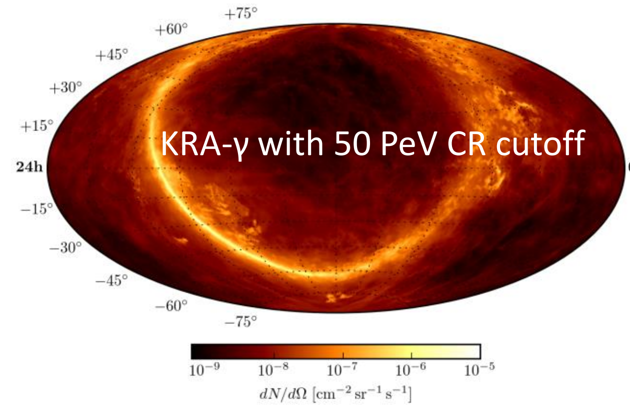
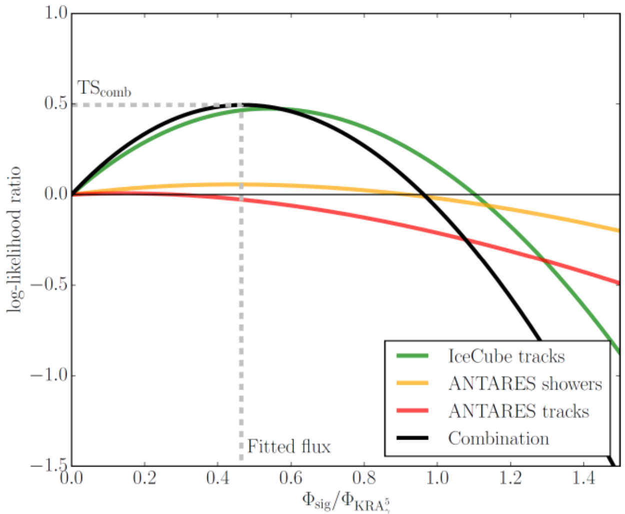


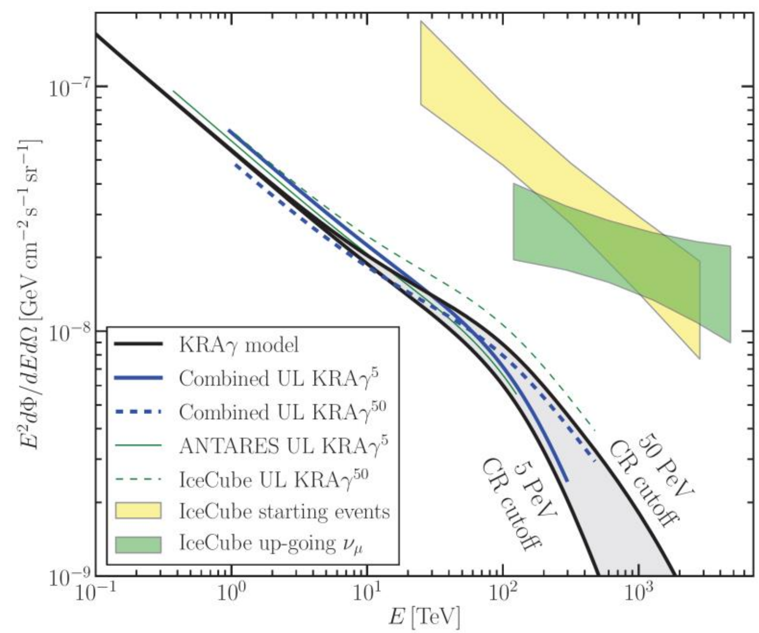
ANTARES & IceCube Combined result arXiv:1808.03531



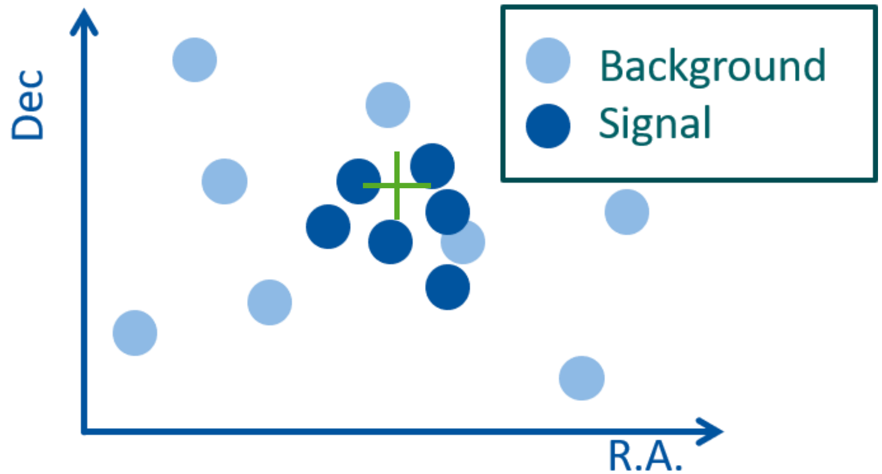
Guaranteed (but weak) flux from galactic plane due to CR interactions with the ISM

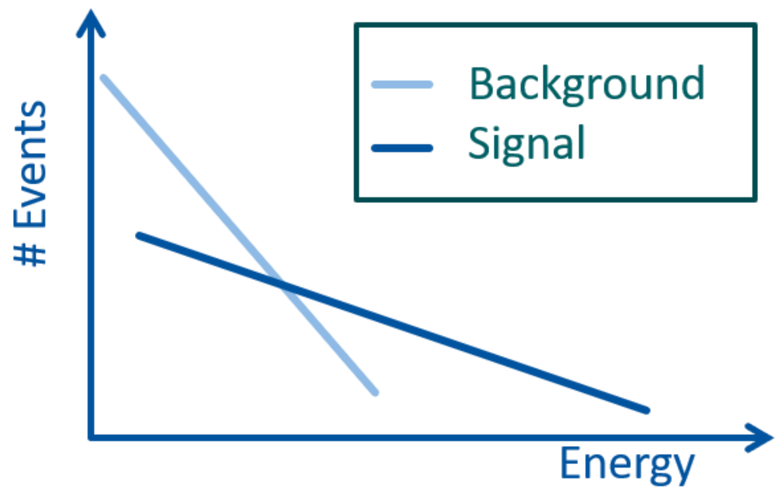
- Expect ~40 ν/a
- Measurement observes slight overfluctuation
- Upper limit very close to realistic estimate





Search for Point Sources





Unbinned Likelihood:

$$L = \sum_i \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i\right]$$

where:

N number of events in sample

n_s number of signal events $\rightarrow \phi_{100\,TeV}$

S_i Signal probability

B_i Background probability

also use Spatial and Energy distribution

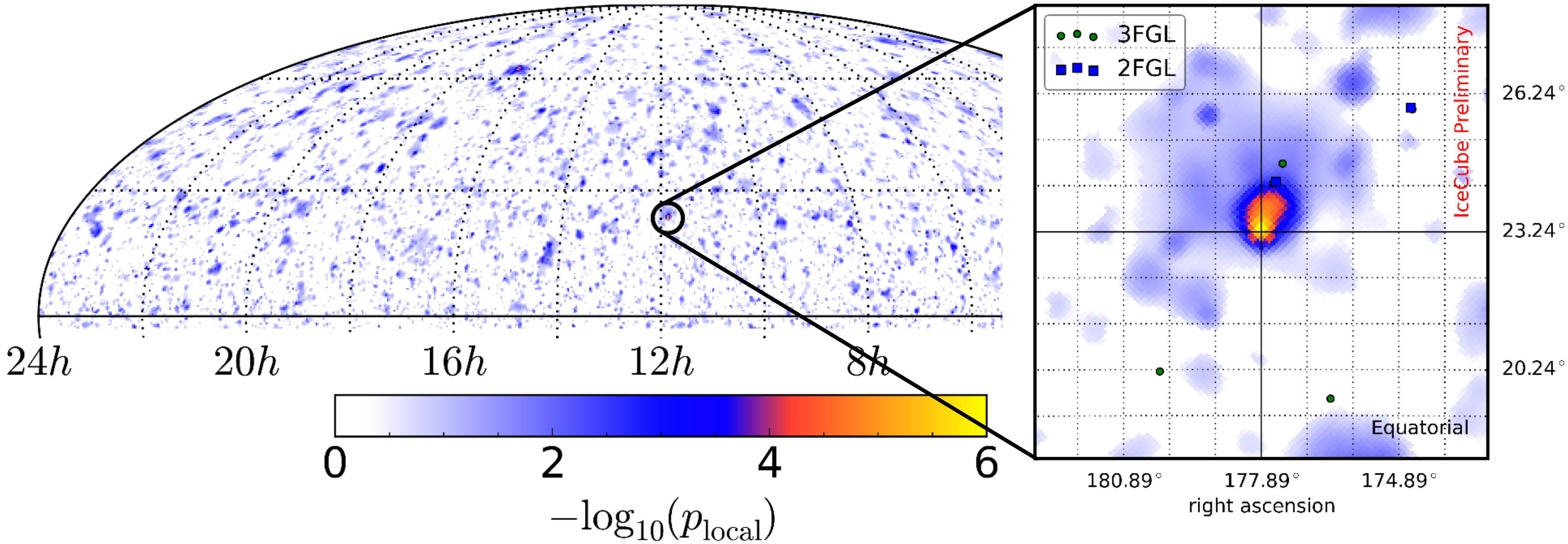
$\rightarrow \quad S_i = S_{spat,i} \cdot S_{ener,i}$

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

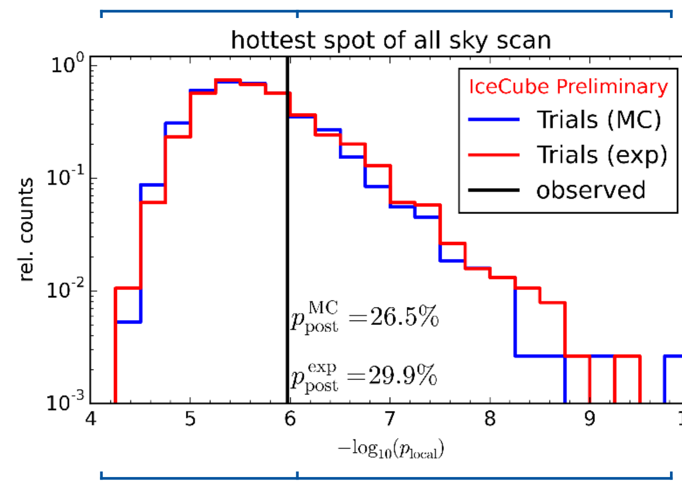
Likelihood ratio test as test statistic

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

Northern Hemisphere Scan

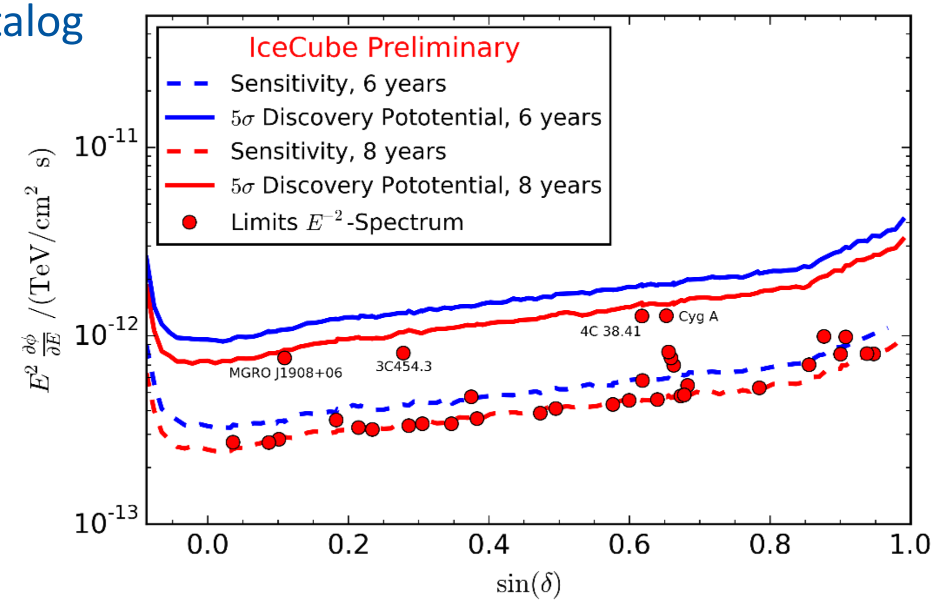


- Most unbiased test for a point source
  → scan of complete visible sky (Northern hemisphere)
- Scan Grid width of about 0.1°
- About 130 000 independent trials
- Most significant point indicated by black circle
- Trial corrected p-value 26.5% (29.9%) using background simulation (scrambled experimental data)
  → **Compatible with background only**



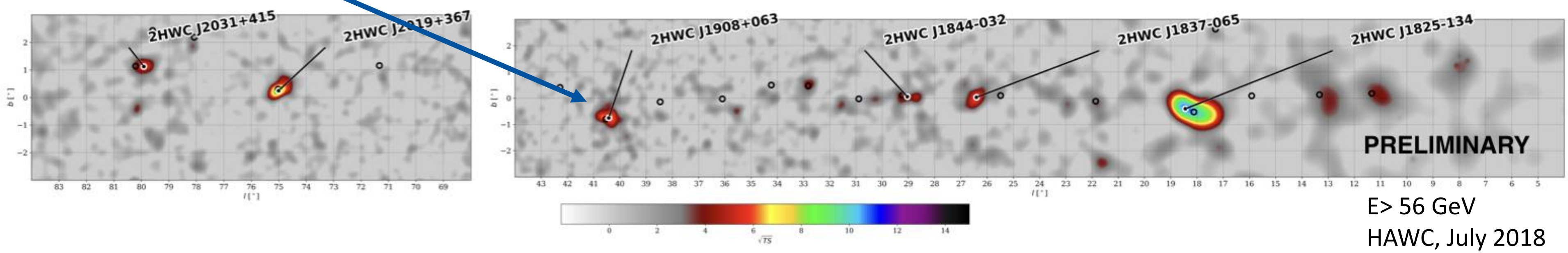
Catalog Result

- Select source candidates based on γ-observations
- IceCube & ANTARES pre-defined a source catalog with 34 source on Northern hemisphere
- Most significant source 4C 38.41 (0.8%)
- post-trial p-value of 23.7% (20.3%)
  → **Compatible with background only**



- 4 sources in catalog have local p-value ~1%
  - 1 galactic: MGRO J1908
  - 2 FSRQ: 4C38.41, 3C454.3
  - 1 FR-II radio galaxy: Cyg-A

- MGRO J1908 is a known γ-source observed by HAWC >50TeV



E> 56 GeV
HAWC, July 2018

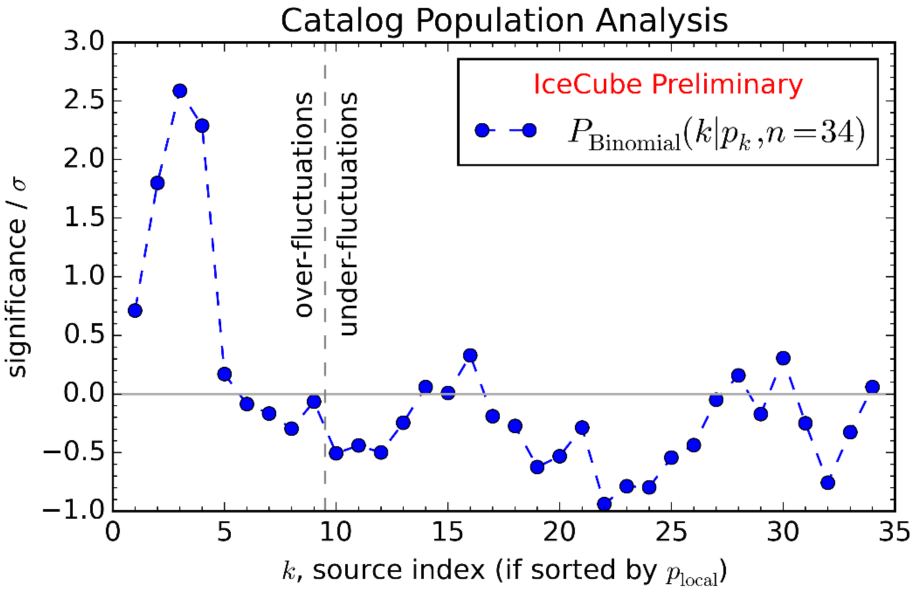
Catalog Population Analysis

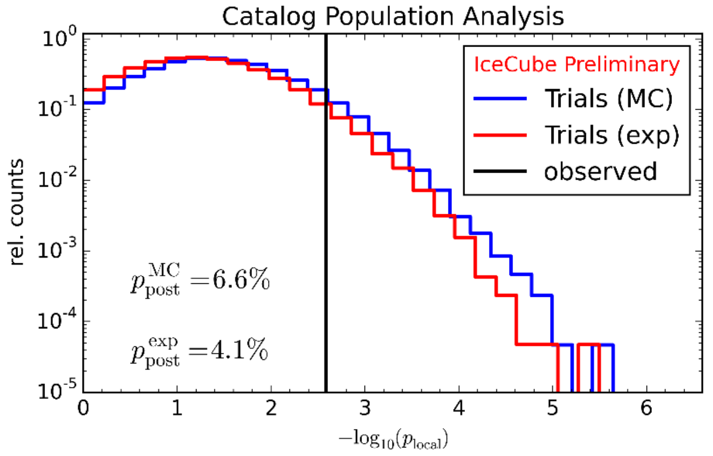
- No observation of single significant source.
- Test for multiple sub-threshold sources.
- Combine p-values of k most significant sources from the catalog:

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

- Most significant combination for k=3 with 2.59σ local significance
- Trial correction gives a post-trial p-value of 6.6% (4.1%) using background simulation (scrambled experimental data)

→ **Compatible with background only**





Hotspot Population Analysis

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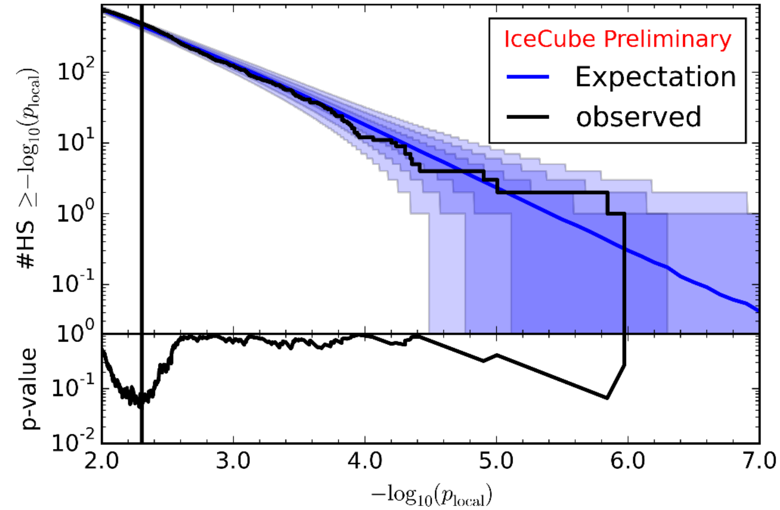
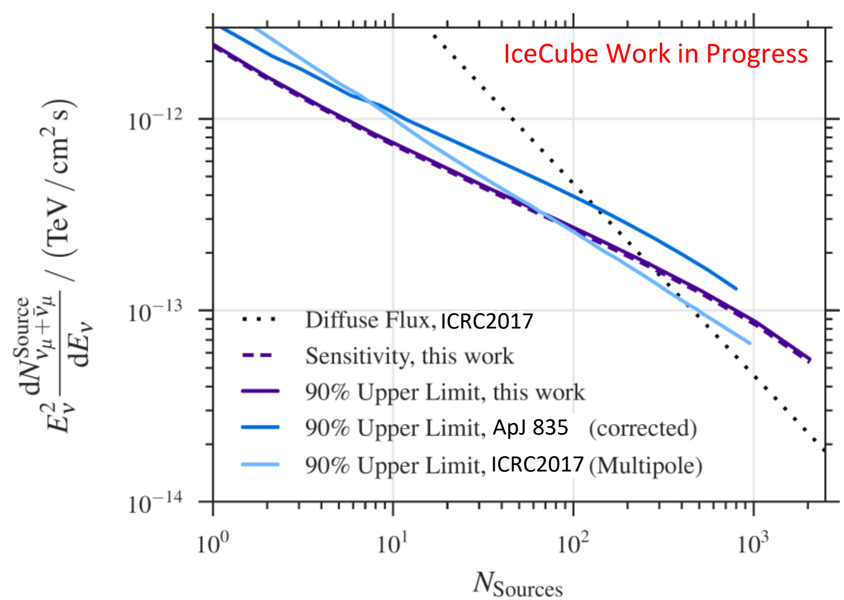
- Count number of local warm spots with p-value smaller $p_{threshold}$
- Compare with background expectation
- Number of expected local warmspots is Poisson distributed.

$p_{threshold}$	$10^{-2.30}$
# observed (# expected)	492 (454.3)
$p_{poisson}$	4.17%
p_{post}^{MC} (p_{post}^{exp})	42.0% (54.3%)

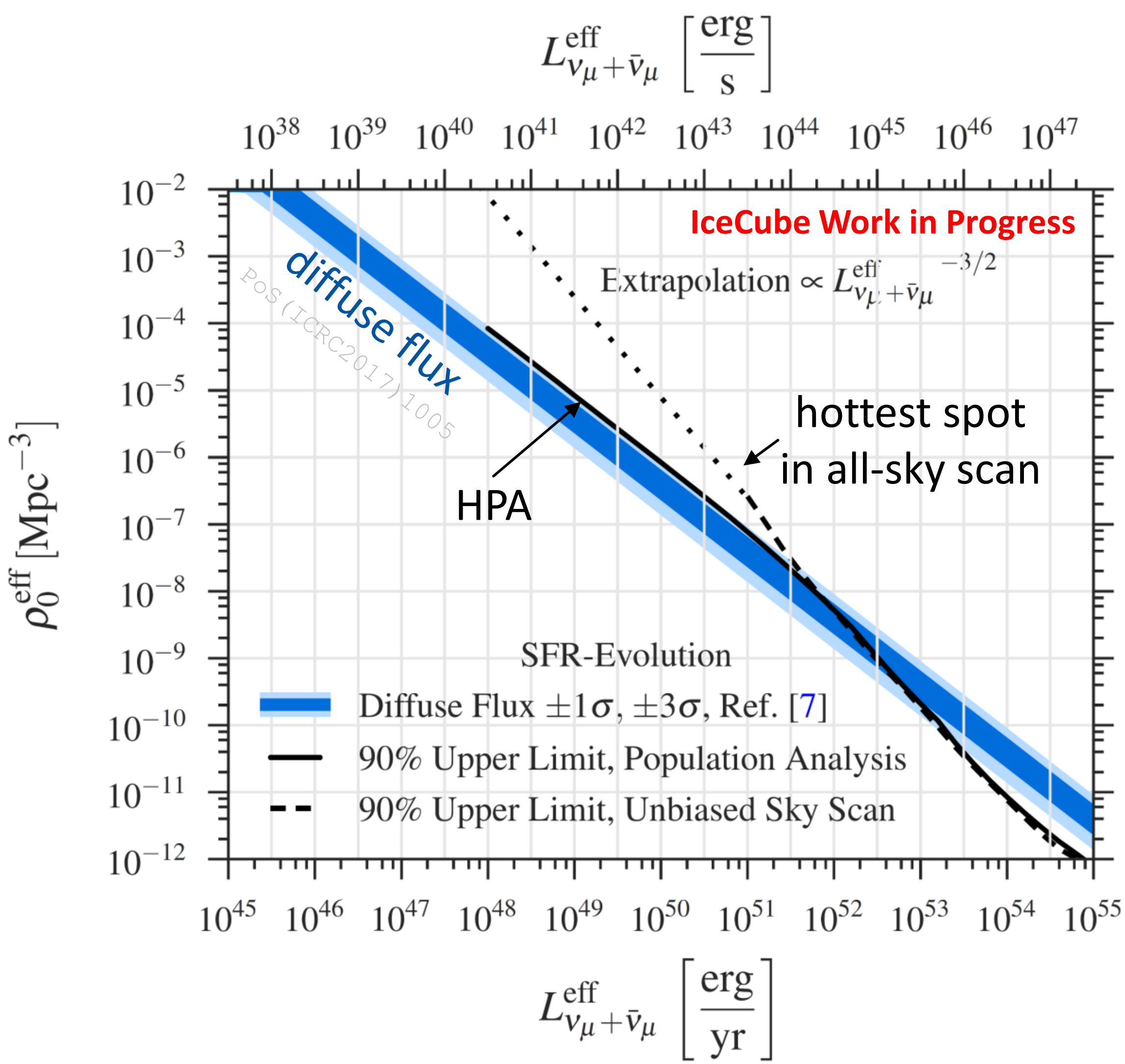
→ **Compatible with background only**

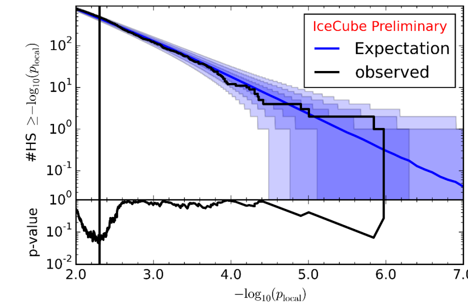


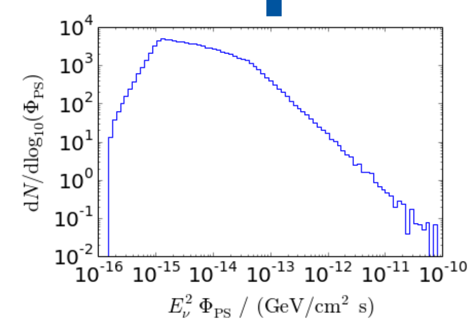


- 90% UL flux per source
- equal-strength sources (E^{-2}-spectrum)
- benchmark scenario

Hotspot Population Analysis
Source Populations







Flux distribution generated with FIRESONG

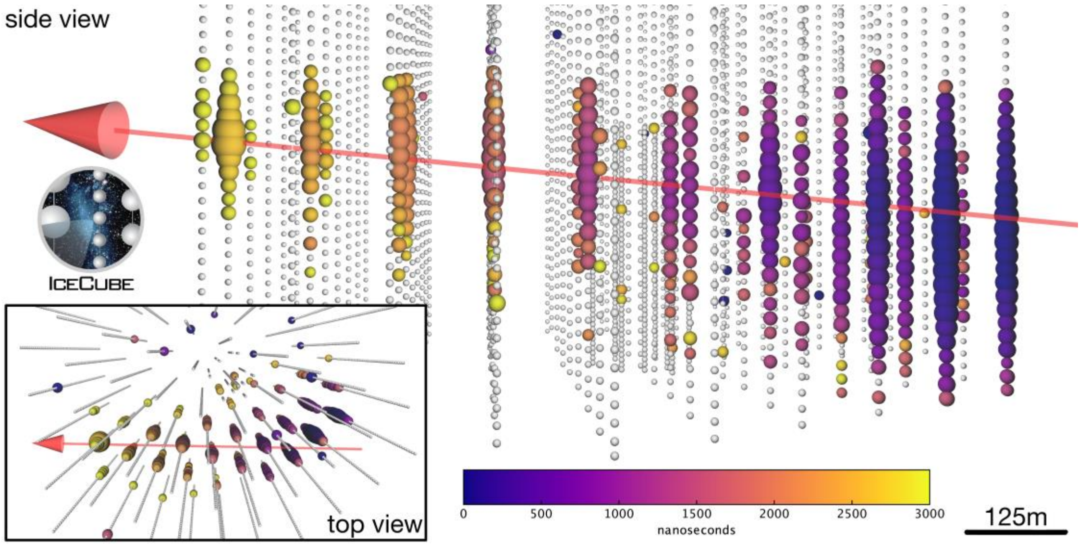
Assumptions:

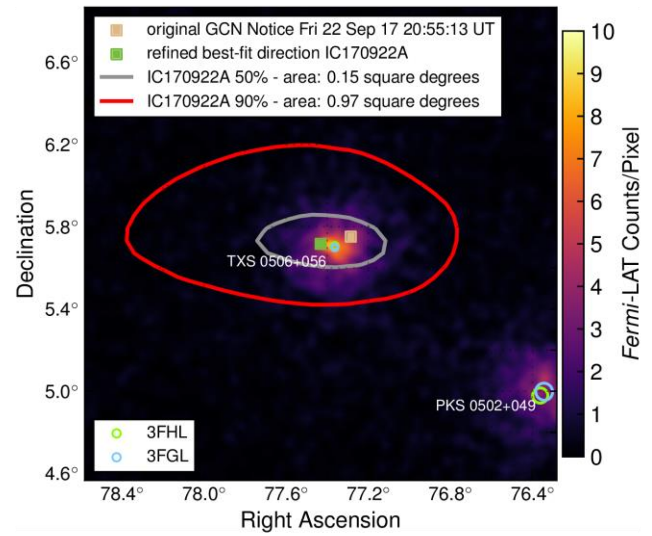
- Standard Candle Luminosity
- SFH (Hopkins & Beacom 2006)
- Energy Range: 10 TeV - 10 PeV
- Cosmology: Planck 2015

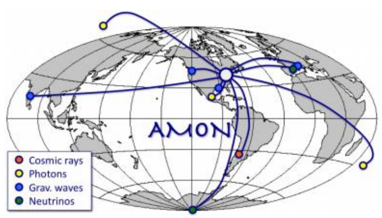
FIRst Extragalactic Simulation Of Neutrinos and Gamma-rays (FIRESONG), https://github.com/ChrisCFTung/FIRESONG

Real-Time Multi-Messenge IceCube170922A

Science Vol. 361, Issue 6398, eaat1378 DOI: 10.1126/science.aat1378







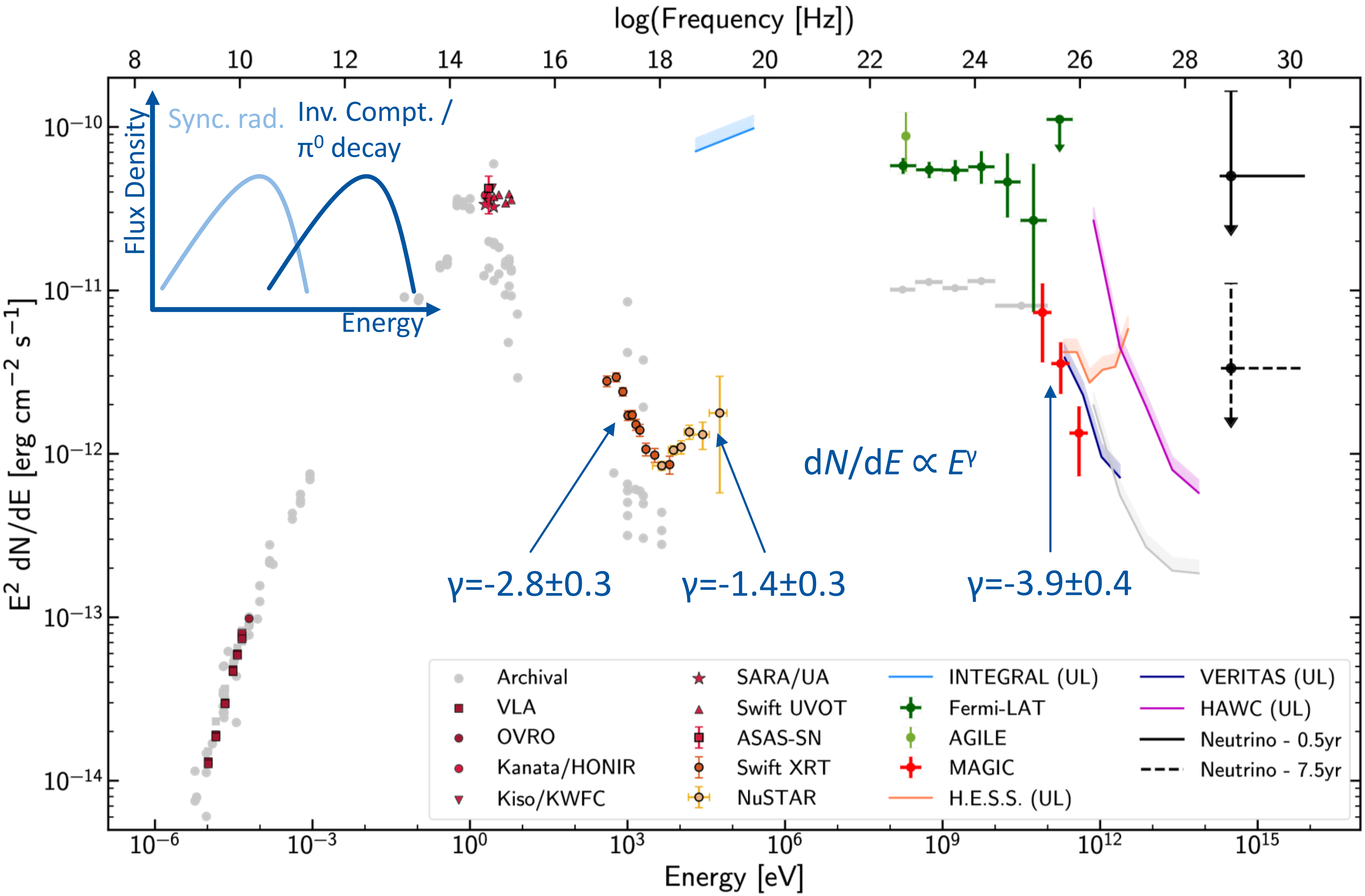
- Extrem-High Energy Alert
- on September 22, 2017
- uncertainty <1 deg² at 90% CL
- send alert 43 seconds after detection
- 290 TeV neutrino energy assuming $E^{-2.13}$
- Signalness 56.5% (energy and declination)

- Follow-up by 18 Observatories
- Fermi LAT found strong flaring counter part
- MAGIC observed γ-rays up to 400 GeV
- Chance coincidence rejected at 3σ

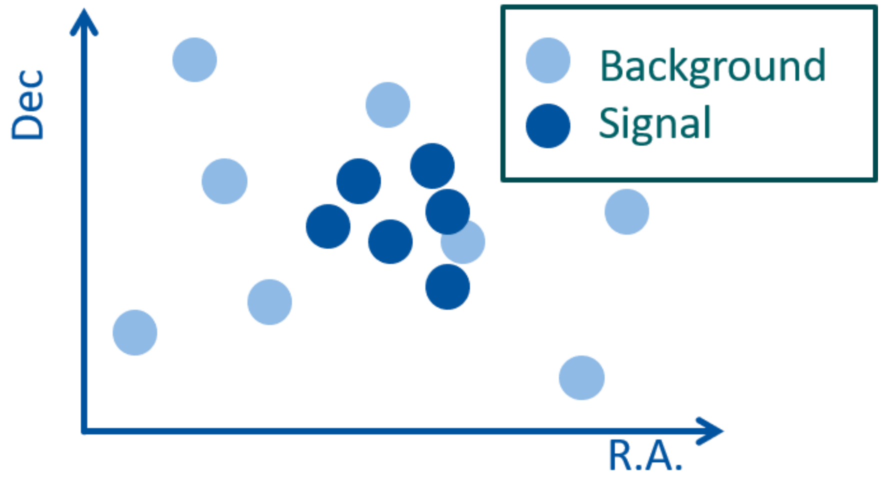
TXS 0506+056 (BL Lac)

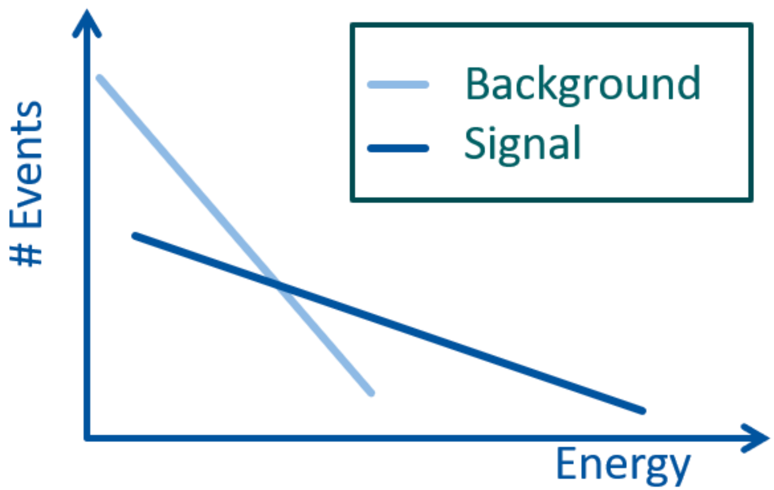
- RA: 5h 9‘ 25.96“, Dec: +5° 41‘ 35.32“
- redshift ≈0.3
- one of the most luminous blazar

Differential Photon Spectrum



Unbinned likelihood analysis





Unbinned Likelihood:

$$L = \sum_i \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i\right]$$

where:

- N number of events in sample
- n_s number of signal events $\rightarrow \phi_{100\ TeV}$
- S_i Signal probability
- B_i Background probability

also use Spatial and Energy distribution

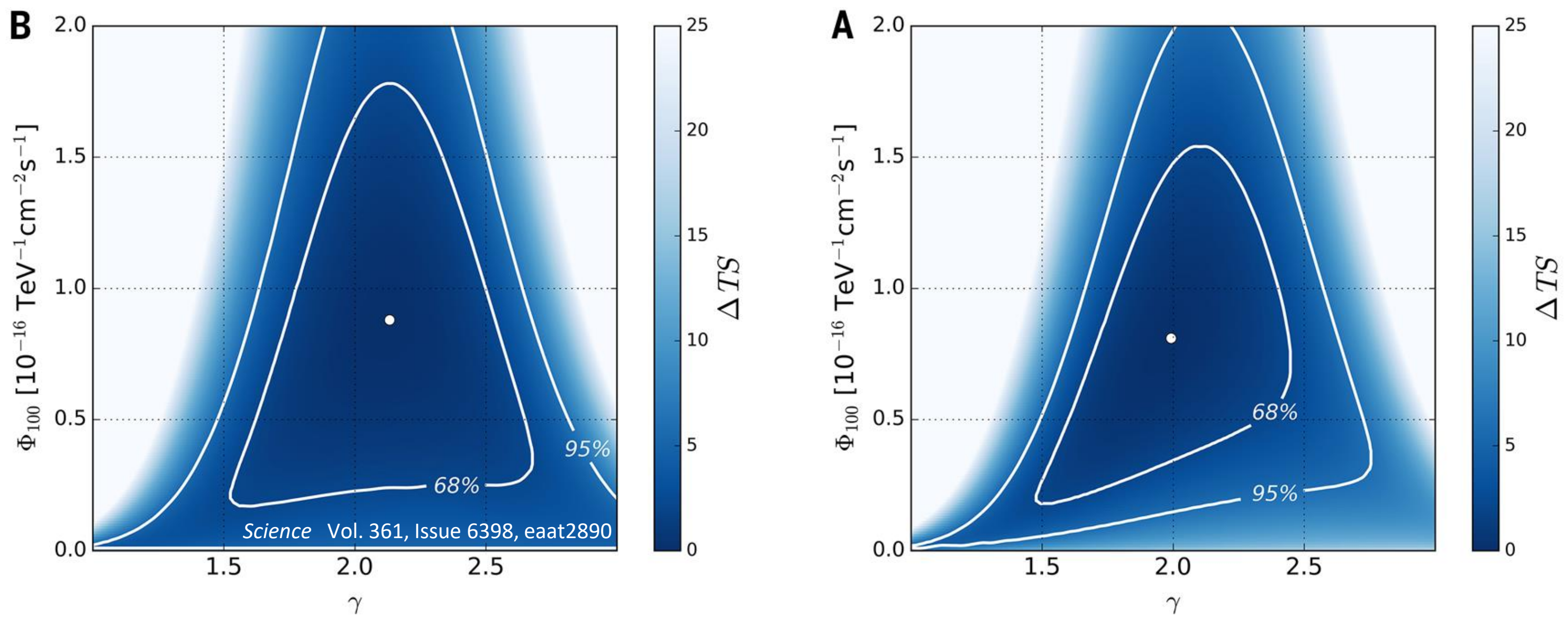
$\rightarrow \quad S_i = S_{spat,i} \cdot S_{ener,i}$

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

Likelihood ratio test as test statistic

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

Time Integrated Result



	7 years (2008-2015)	9.5 years (2008-2017)
Normalization @ 100 TeV [TeV^{-1}cm^{-2}s^{-1}]	$\left(\mathbf{0.9^{+0.6}_{-0.5}}\right)\cdot\mathbf{10^{-16}}$	$\left(0.8^{+0.5}_{-0.4}\right)\cdot 10^{-16}$
Spectral index	$\mathbf{2.1 \pm 0.3}$	2.0 ± 0.3
p-value	**1.6% (2.1σ)**	0.002% (4.1σ)

- Search at exact TXS position
  → Single trial
- 9.5 years includes alert event
  → a posteriory
- 7 year result independent data

Time Dependend analysis

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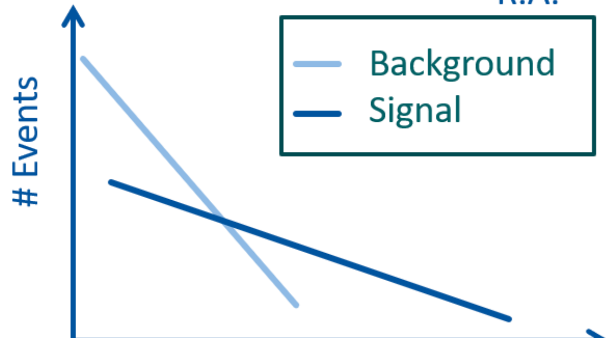

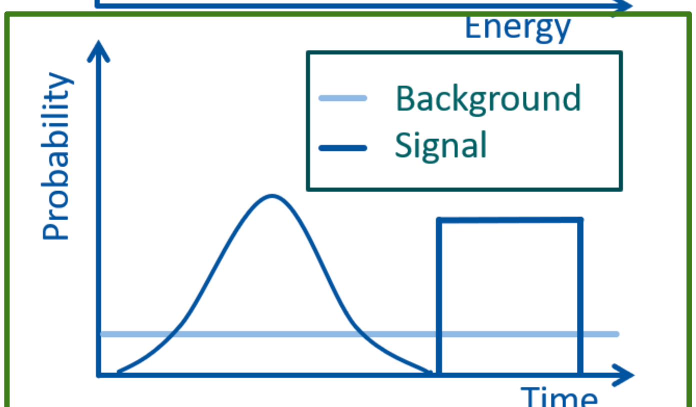

Unbinned Likelihood:

$$L = \sum_i \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i\right]$$

where:

- N number of events in sample
- n_s number of signal events $\rightarrow \phi_{100\ TeV}$
- S_i Signal probability
- B_i Background probability

also use Spatial, Energy and Time distribution

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

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

Likelihood ratio test as test statistic

$$TS = -2 \cdot \log\left[\frac{T}{T_w} \times \frac{L(\vec{x}_s, n_s = 0)}{L(\vec{x}_s, \hat{n}_s, \hat{\gamma}, T_0, T_w)}\right]$$

Time Dependent Result

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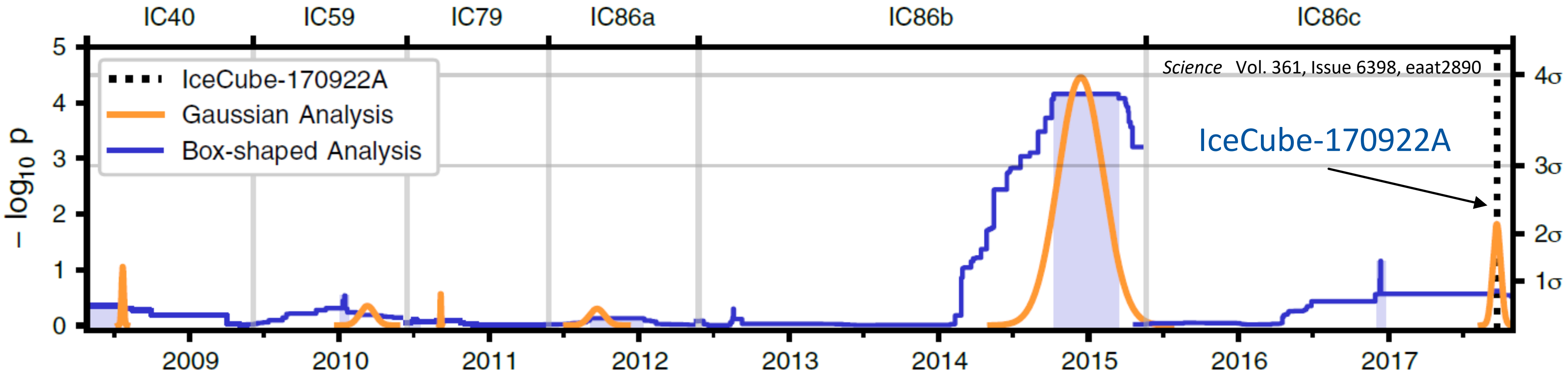
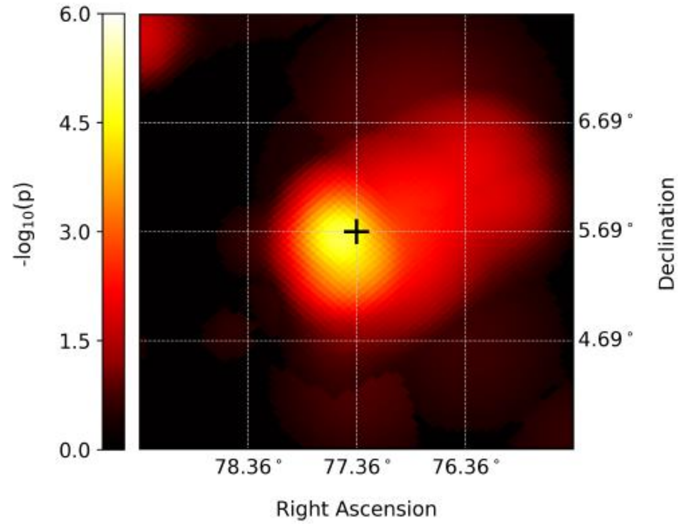


Evidence of time-dependent emissions:

- 13 ± 5 events over background (5.8 events, in 1° radius, 158 days)
- Independent of, and prior to neutrino alert

	Gaussian	Box
T_0	13 Dec 2014 ± 21 days	26 Dec 2014
T_w	110^{+35}_{-24} days	158 days
p_{val} (season)	3×10^{-5}	7×10^{-5}
p_{val} (overall)	1×10^{-4} (3.7σ)	2×10^{-4} (3.5σ)



Best of both with trial factor of 2 → 3.5σ

ν-directional correlation with Blazars

- IceCube published limit on blazar contrinution to diffuse astrophysical neutrino flux

- Using 2nd Fermi LAT catalog of 862 Blazars
- Stacking of all neutrino directions
- No significant excess in 4 year IceCube data

- 2LAC blazars < 27% observed astrophysical neutrino flux (assuming $E^{-2.5}$)
- < 40% - 80% (assuming E^{-2}, > 200 TeV)

- TXS flux is 1% of 9.5 year diffuse flux

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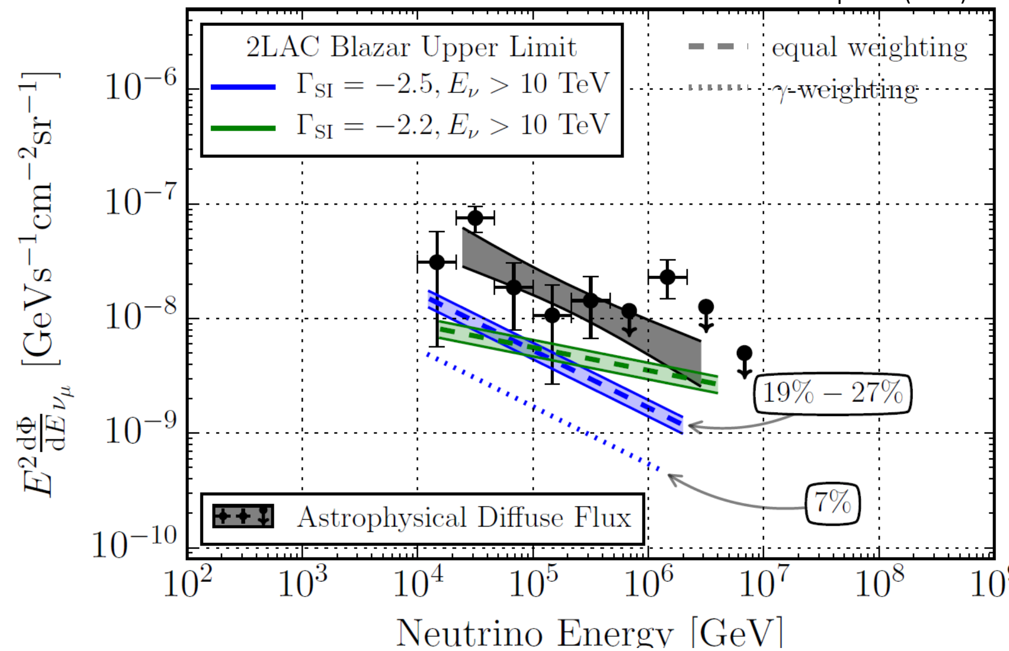
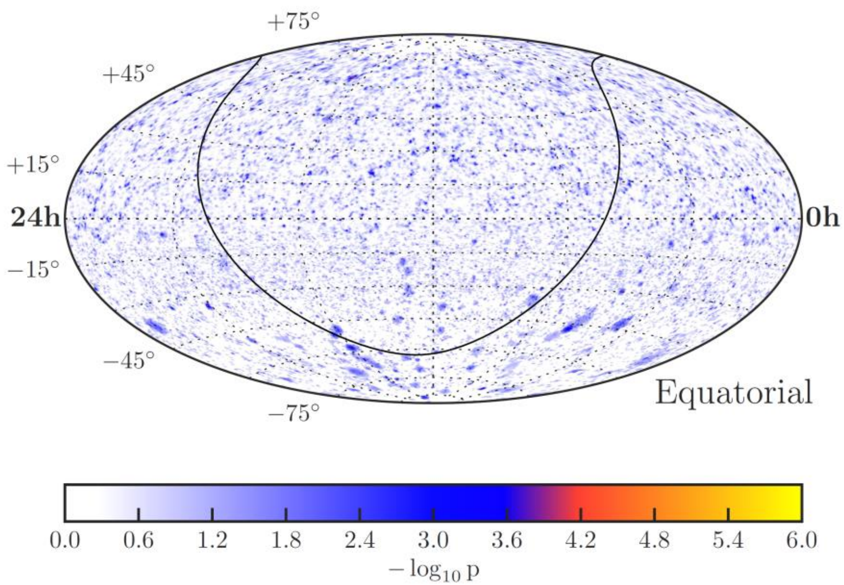


Further Searches for Neutrino Sources

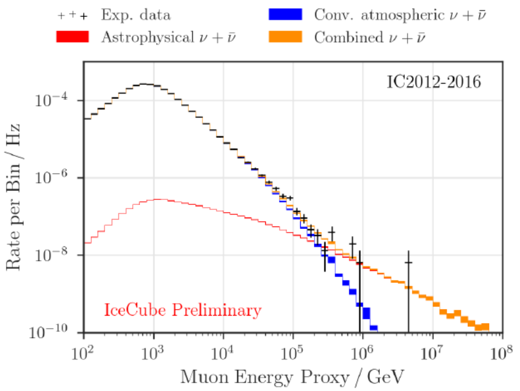


Hemisphere	North	South
n_{source}	32.6	15.4
γ	2.8	2.9
p_{local}	1.82×10^{-6}	0.93×10^{-6}
p_{post}	29%	17%

Total events: 424,000 (upgoing)
+ 289,000 (downgoing)
+ 1,700 (starting)
Live-time: 7 year data, 2431 days

- No significant excess in full sky search
- No significant time variability
- No spot of increasing significance with time
- No significant correlation with known TeV gamma sources
- No significant extended sources
- No signal from GRB
- No signal from 2LAC Blazar catalog
- No Dark Matter
- …

Conclusions



- IceCube has observed a astrophysical neutrino flux
  - With High Energy Starting Events
  - With through-going Muons

- No positive identification of galactic plane (yet)
- No positive identification of an individual point-like source
- No positive identification of a population of sub-threshold sources

- On September 22 2017 IceCube send an alert of a well localized high-energy track-like event: IC170922A (signalness = 56%)
- Found strongly flaring gamma-ray counterpart TXS 0506+056
  - → 3.0σ evidence for correlated emission
  - → one of the most luminous known Blazars
- Search for neutrino emission in IceCube archival data
  - → 3.5σ evidence for a neutrino flare at end of 2014 from the same source

→ **Starting to become interesting, stay tuned**