Monitoring & Multi-Messenger Astronomy with IceCube

Monitoring the non-thermal Universe 2018

18.09.2018, Cochem

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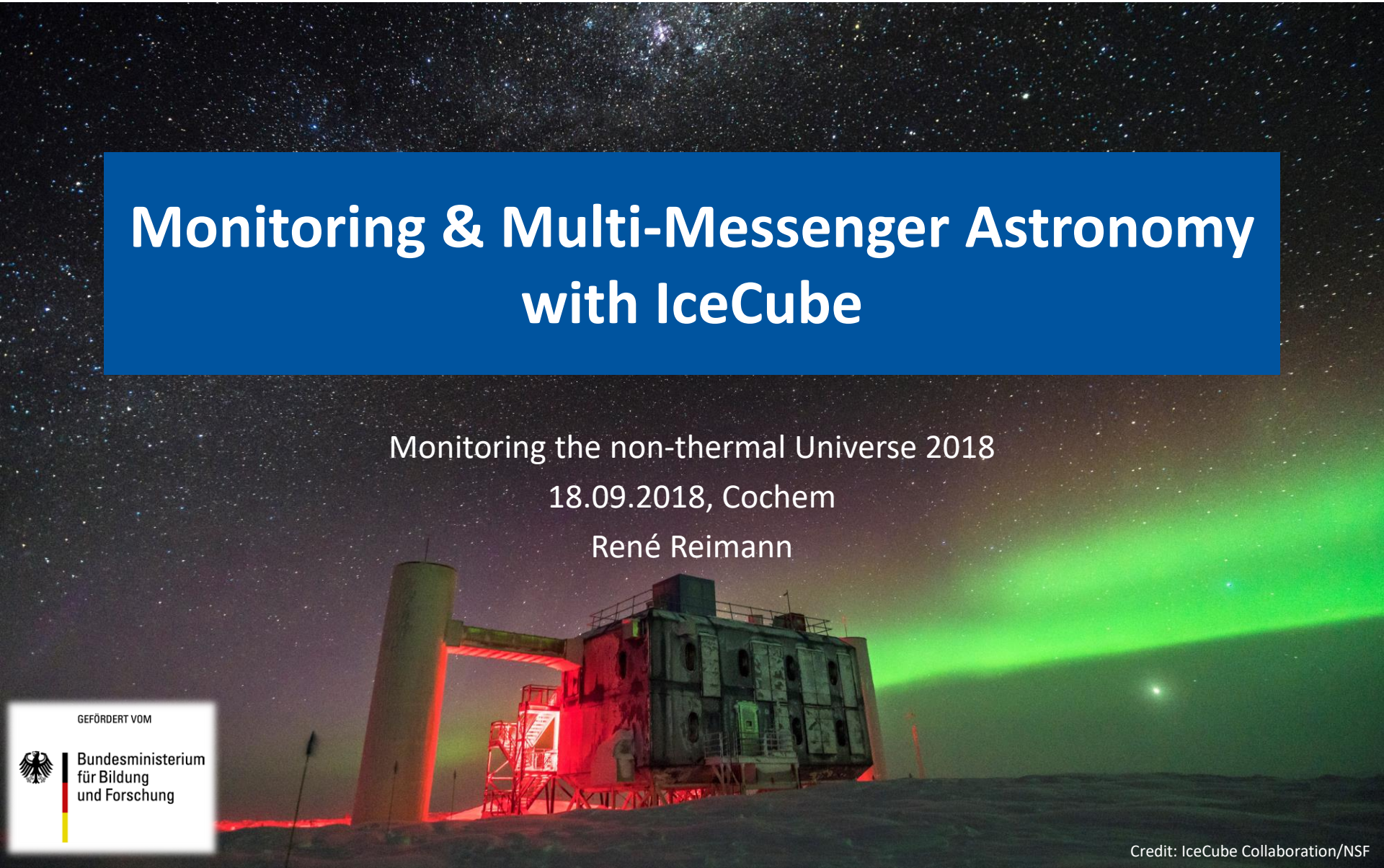
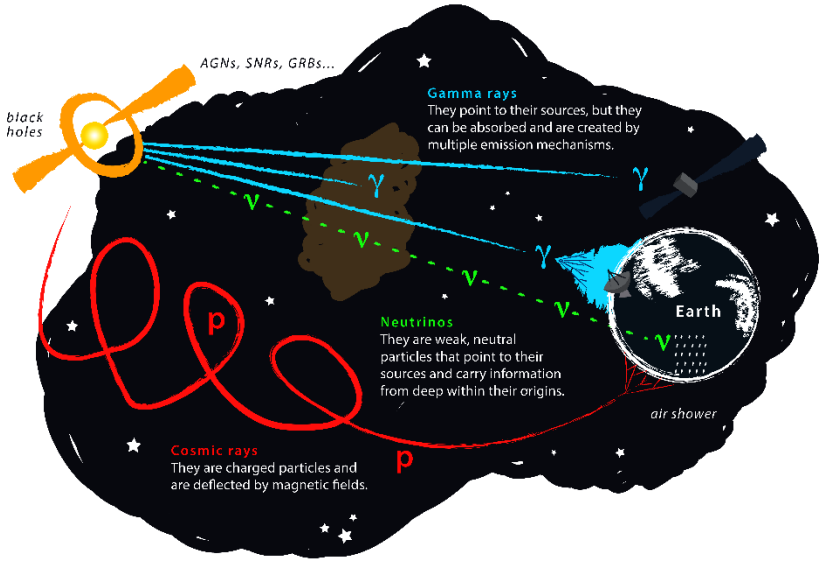


Credit: IceCube Collaboration/NSF

Multimessenger Astrophysics



Cosmic Rays interact with photons or matter surrounding the source

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

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

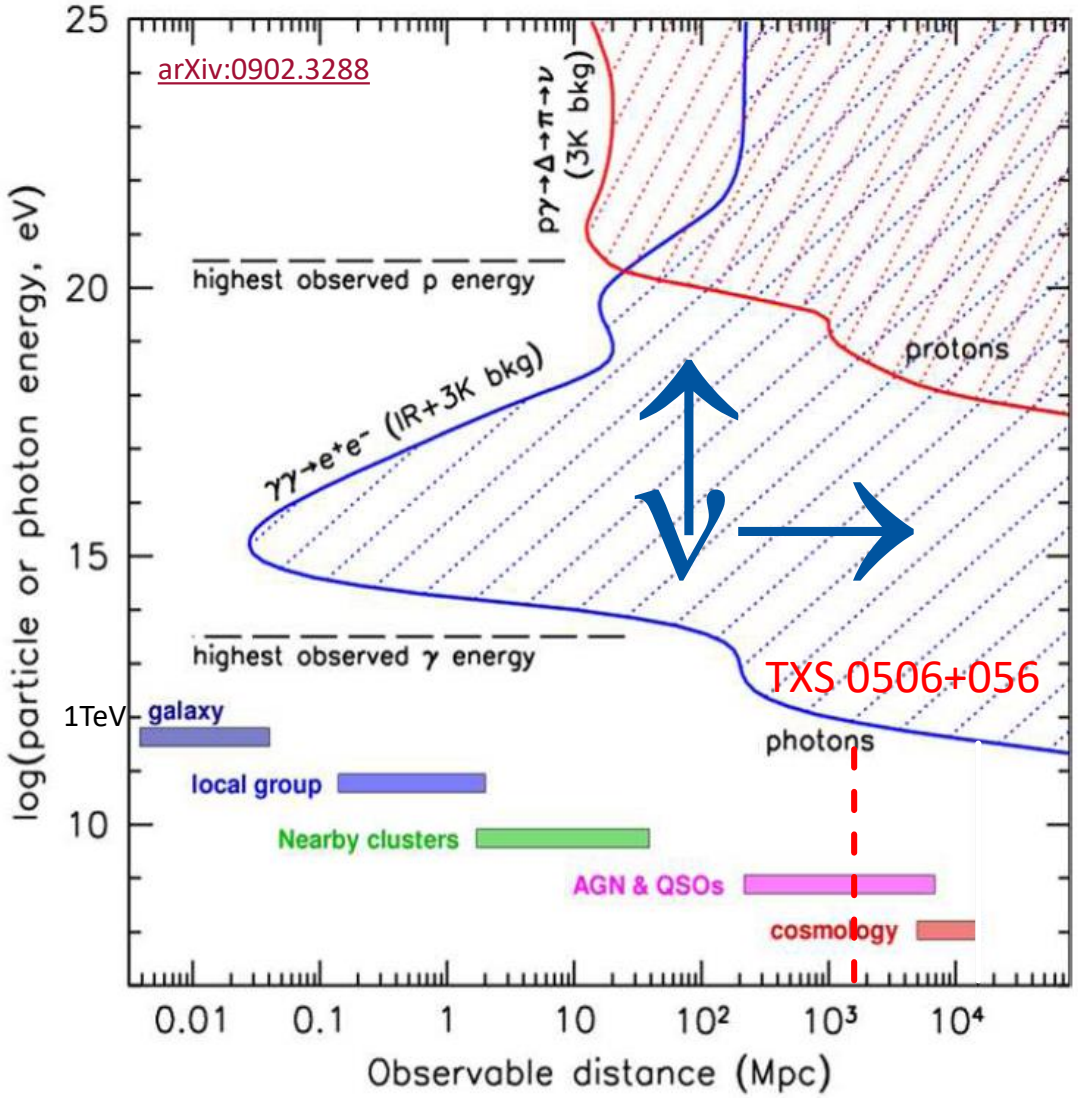
- point back to place of origin
- not absorbed during their propagation
- hard to detect at Earth

Gravitational waves

- Produced by extreme gravitational fields

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

Transparency of the Universe



- 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

IceCube

South Pole Neutrino Observatory

IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

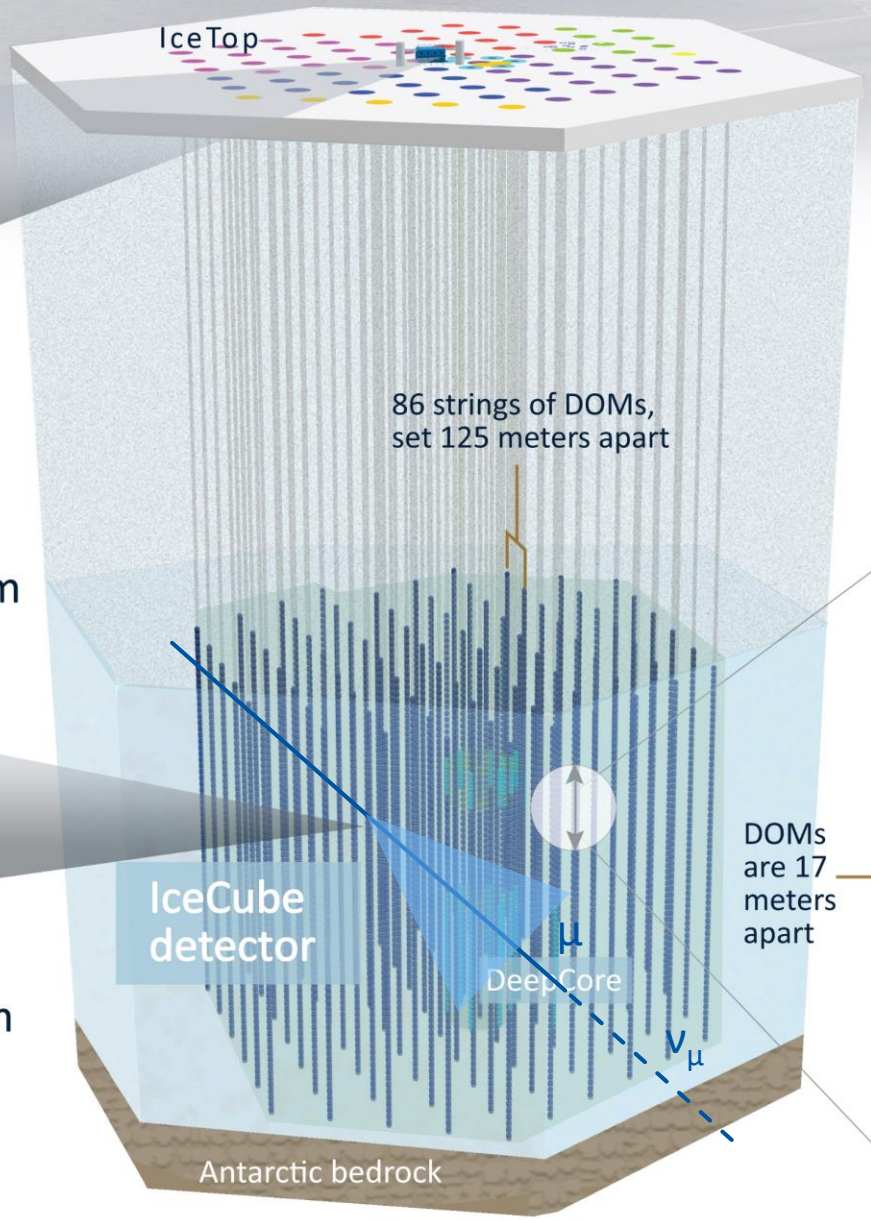
Digital Optical Module (DOM)

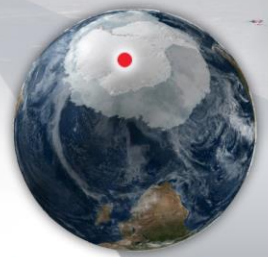
5,160 DOMs deployed in the ice

50 m

1450 m

2450 m





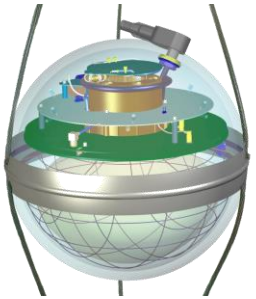
Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart

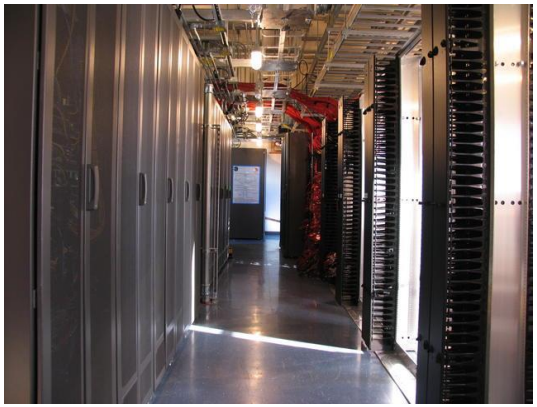
Light sensor (DOM)

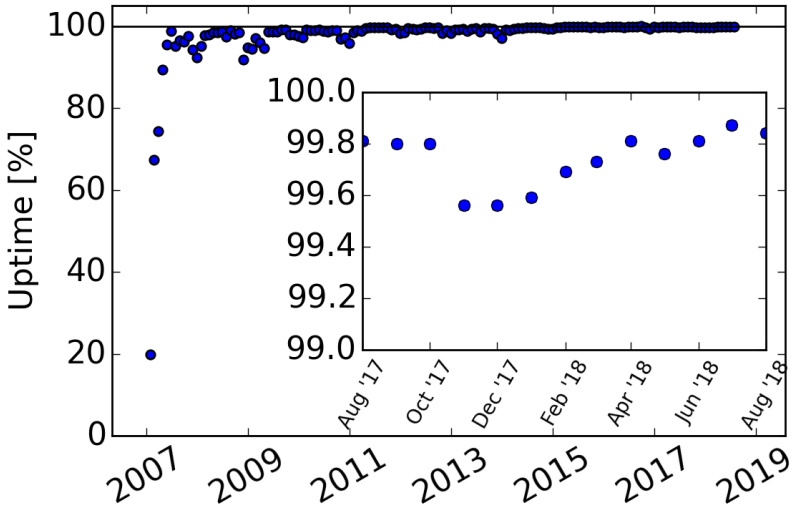


The IceCube Neutrino Observatory: Instrumentation and Online Systems JINST 12 (2017) no.03, P03012, arXiv:1612.05093

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

IceCube Data Taking





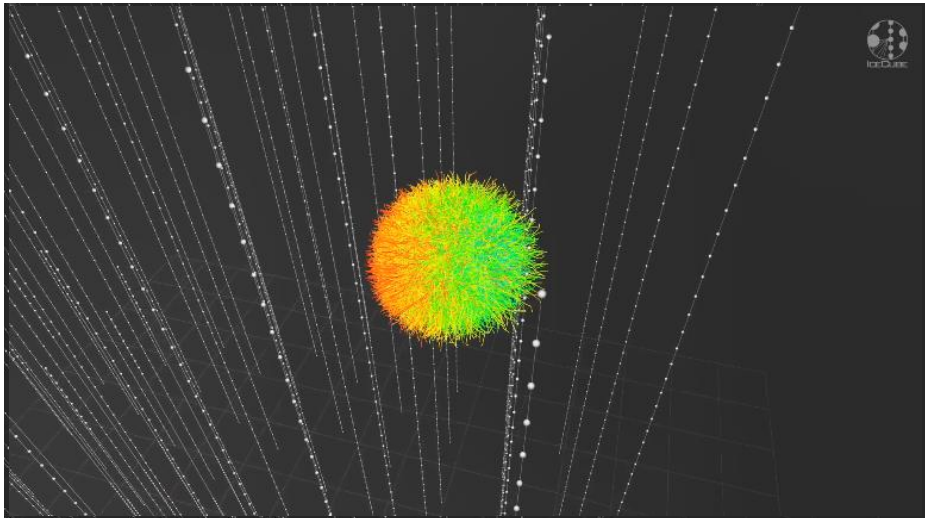
- Digital data acquisition at the surface
- Automated detector calibration
- Automated data processing and transmission by satellite north
- Special real-time systems for Alerts
- Operation-time > 99.7 %
- Physics data > 98.9%
- 1 neutrino (>TeV) every 7 minutes

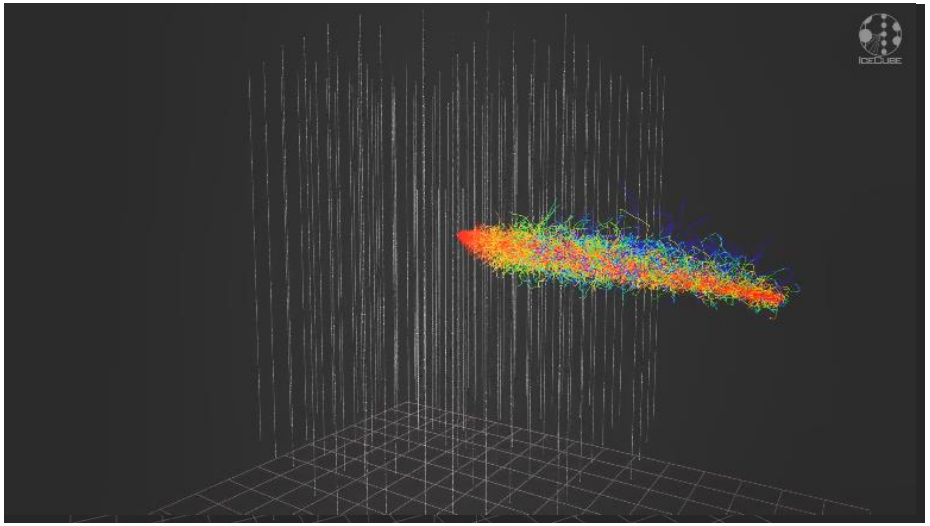
Event Signatures

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

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

Credit: IceCube





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

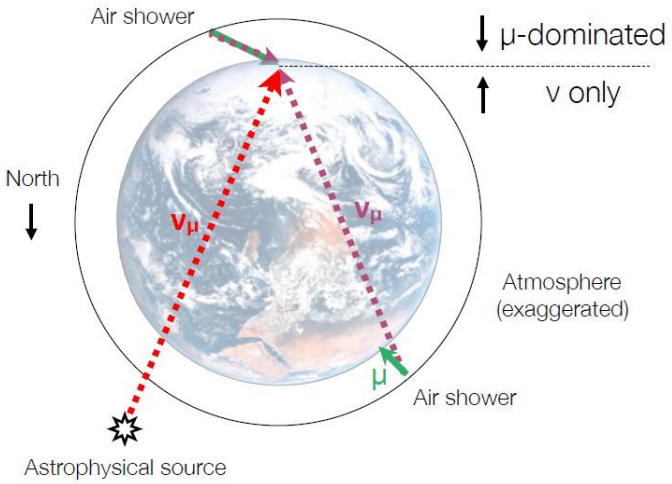
- track-like signature
- through-going / leaving the detector
  → factor of 2 energy resolution
- long leaver arm
  → < 1° angular resolution

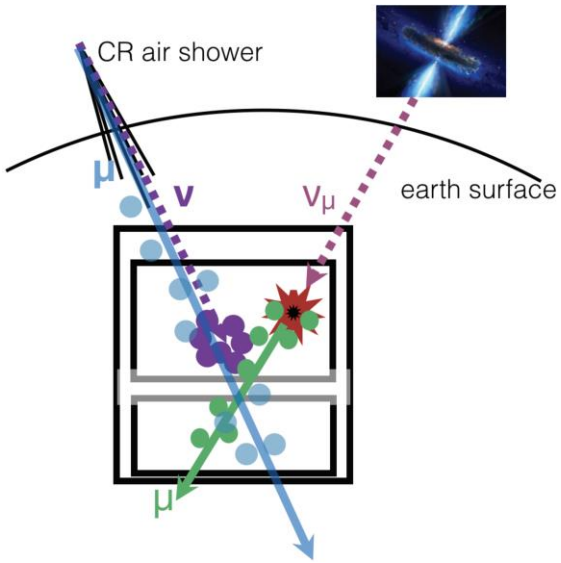
Measurement of astrophysical ν-flux

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

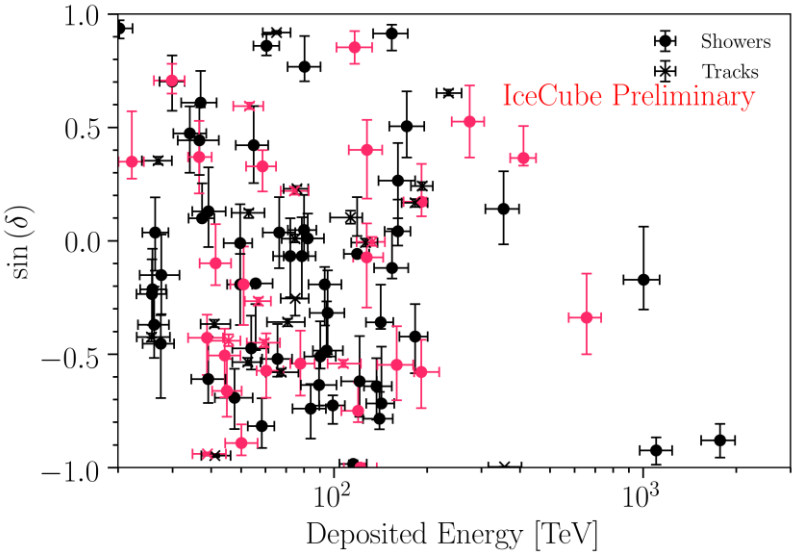
Select high-energy events
- Through-going tracks (~2π FoV)

Select contained/starting events
- High-Energy Starting Events (4π FoV)



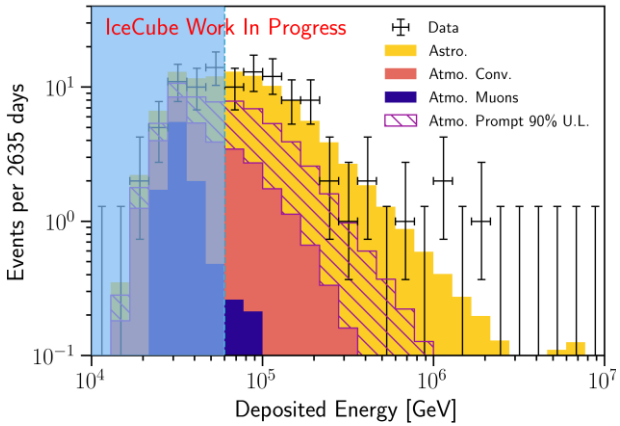


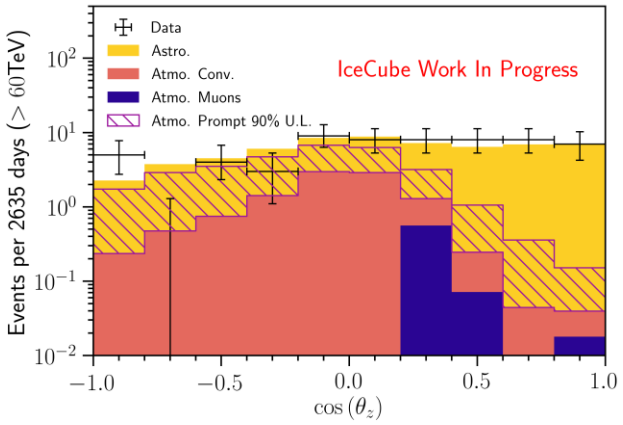
Neutrino 2018

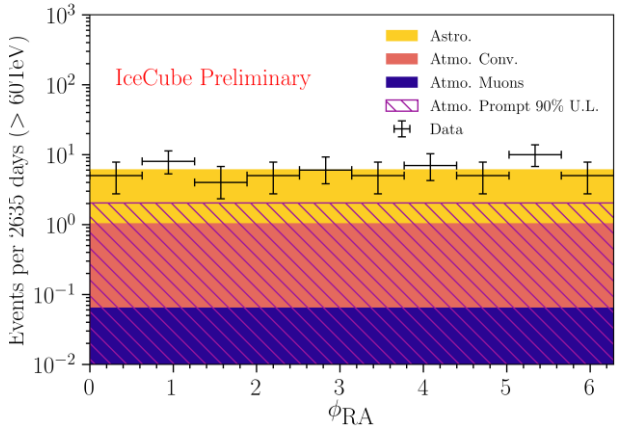


High-Energy Starting Events
7.5 Year result

TeVPA 2018





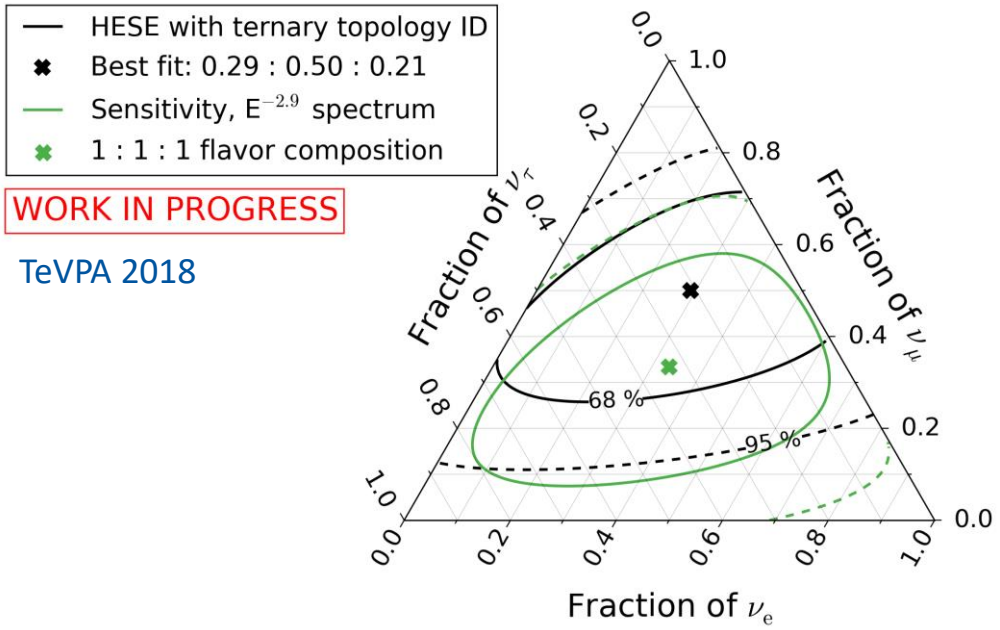


- 102 events total, 60 events with E_{dep} > 60 TeV (>75% astroph. purity)
- Improved calibration and reconstruction
- Fit-Range: 60 TeV < E_{dep} < 10 PeV
- Expected background: 0.65±0.2 (atm.μ) , $14.5^{+10.1}_{-8.1}$ (atm.ν, incl. prompt)
- Angular distribution cannot be described by backgrounds
-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

$$E^{-2}\phi = 2.19^{+1.10}_{-0.55} \times 10^{-8} \times (E / 100\text{TeV})^{-0.91}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

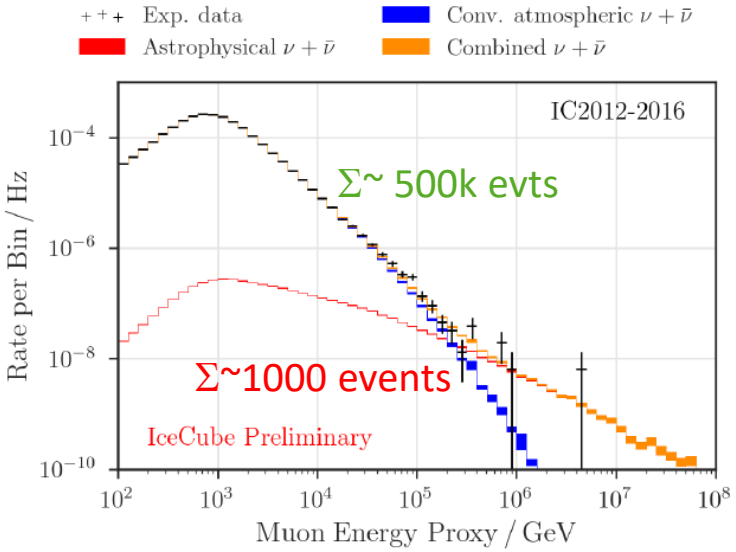
- Spectrum relatively soft $\gamma = 2.91^{+0.33}_{-0.22}$

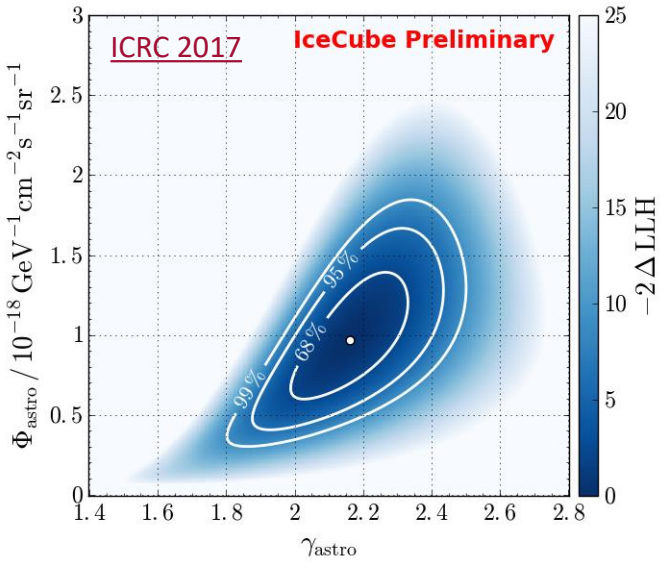
Flavor analysis of HESE data



- Two tau-neutrino candidate under investigation
- Result consistent with full 1:1:1 mixing
- Neutrino oscillations over >Mpc baselines
- Single flavor fluxes excluded
- Neutron decay scenario disfavored

Up-going Muons
8 year result

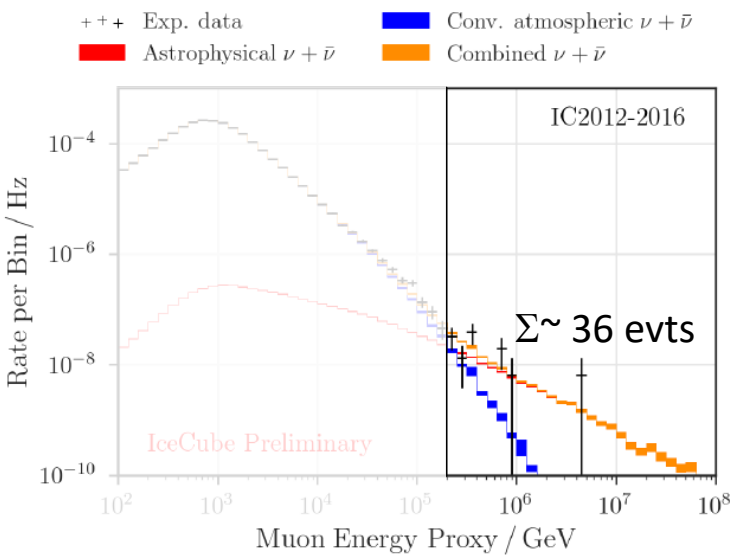


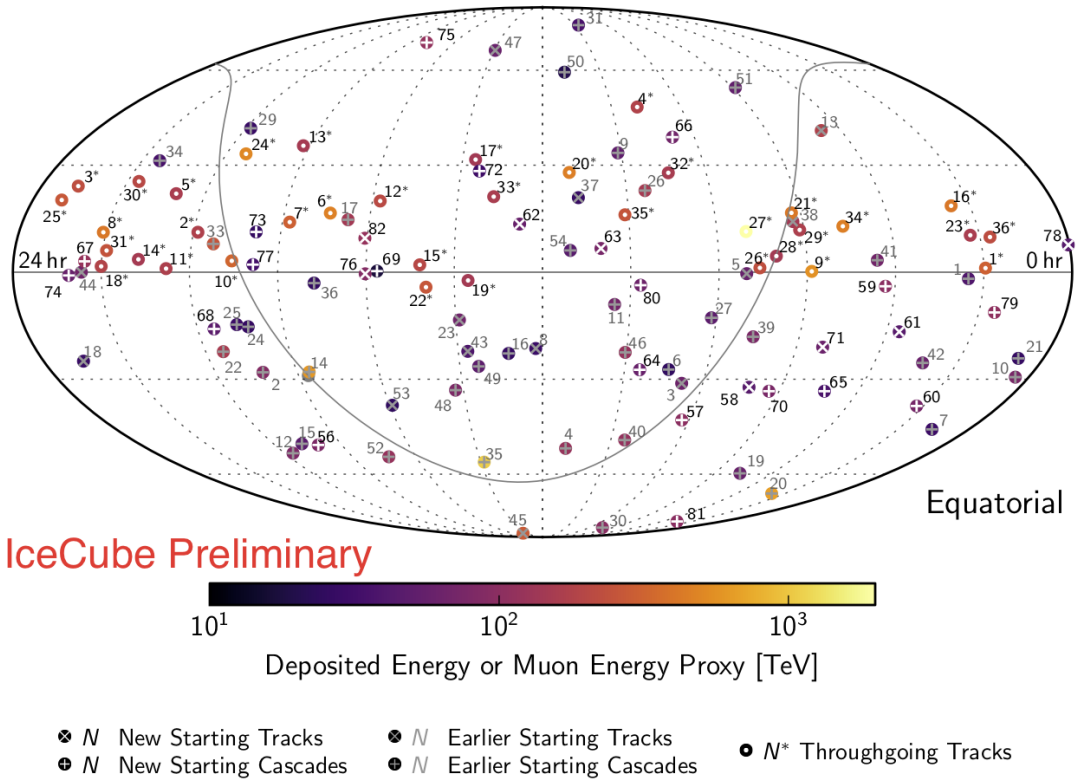


- High statistics
  ~500 000 neutrino events, purity > 99.7%
- Global fit of all data set including systematic uncertainties
  ⇒ Excellent agreement with simulation
  Exclusion of atmospheric origin @ 6.7 σ
- Clear high energy excess above about 200TeV

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

The High-Energy Neutrino Sky





- 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

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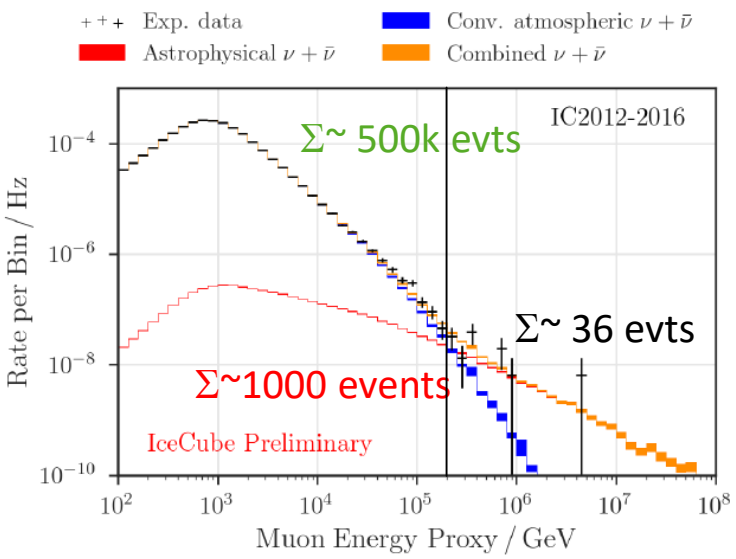

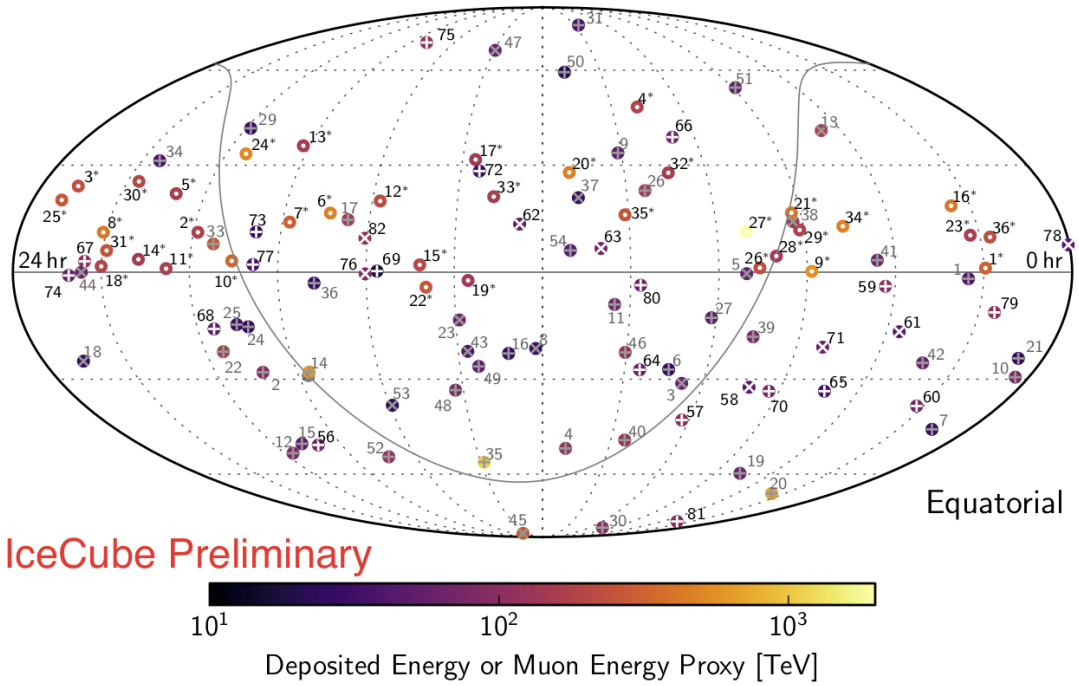

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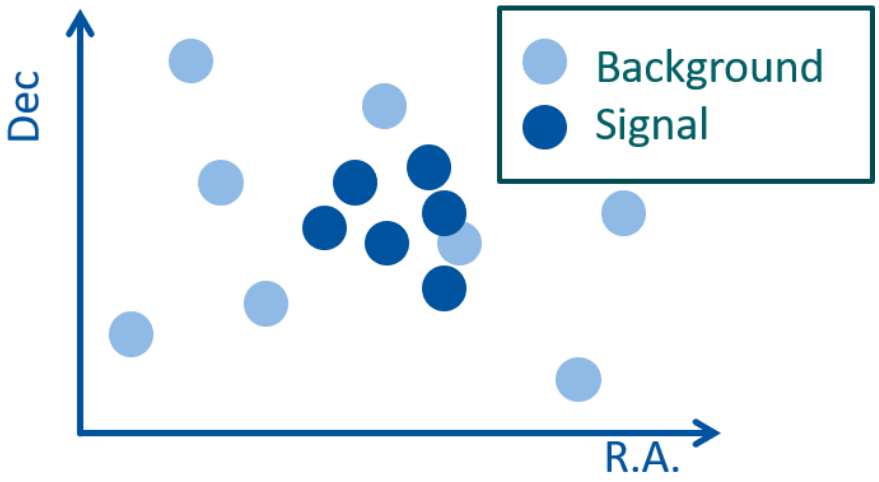
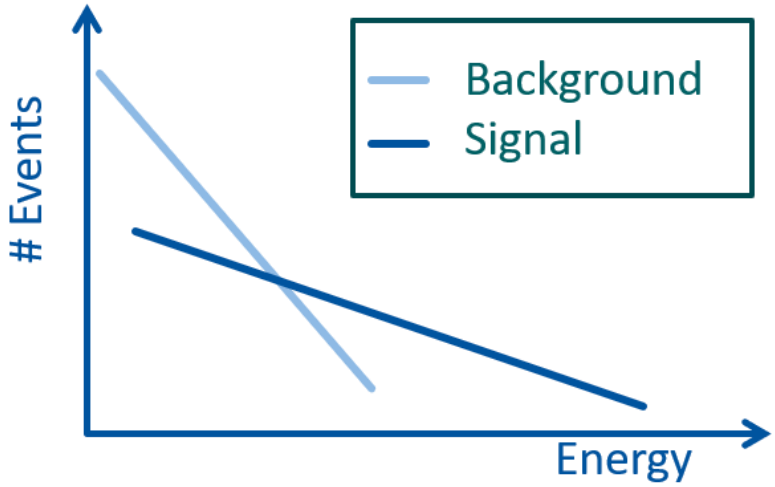
Unbinned likelihood analysis





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

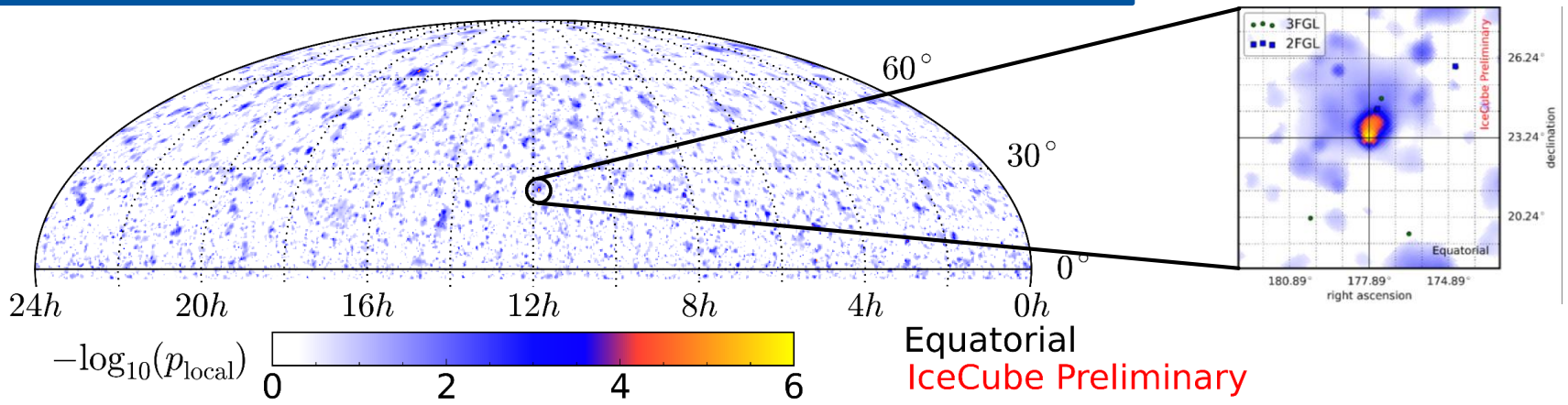
$\rightarrow$ $S_i = S_{spat,i} \cdot S_{ener,i}$

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

Likelihood ratio test as test statistic

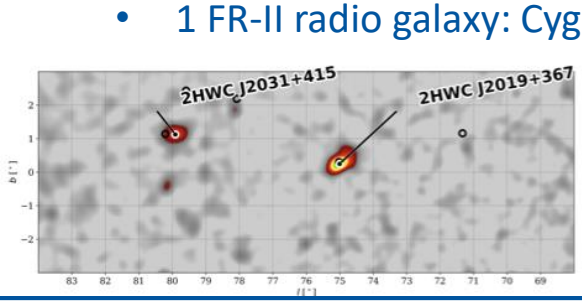
$$TS = -2 \cdot \log\left[\frac{L(\vec{x}_s, n_s = 0)}{L(\vec{x}_s, \hat{n}_s, \hat{\gamma})}\right]$$

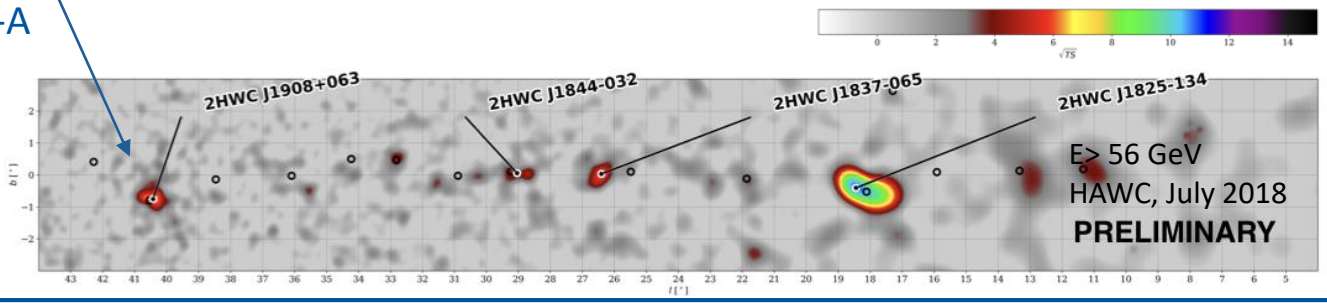
Search for Point-Like Sources



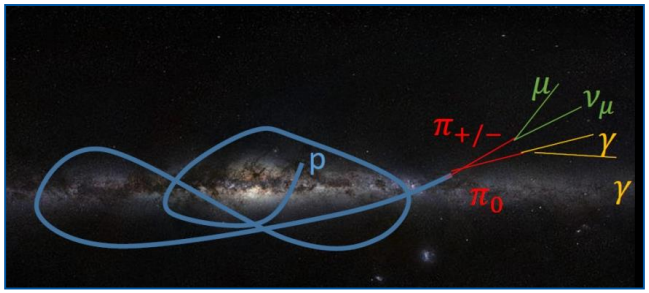
- Time integrated unbinned point source hot spot search
- ~500k events from 8 years (NH) of data, energy-weighted to distinguish atmospheric (isotropic) and astrophysical neutrinos
- IceCube & ANTARES a-priori source catalog with 34 source on NH based on γ-observations
  4 sources in catalog have local p-value ~1%
  - 1 galactic: MGRO J1908
  - 2 FSRQ: 4C38.41, 3C454.3
  - 1 FR-II radio galaxy: Cyg-A

→ **Compatible with background**

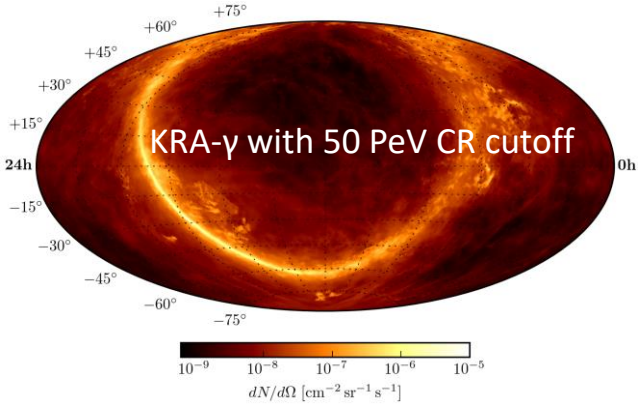




Large Scale Structure
Galactic plane

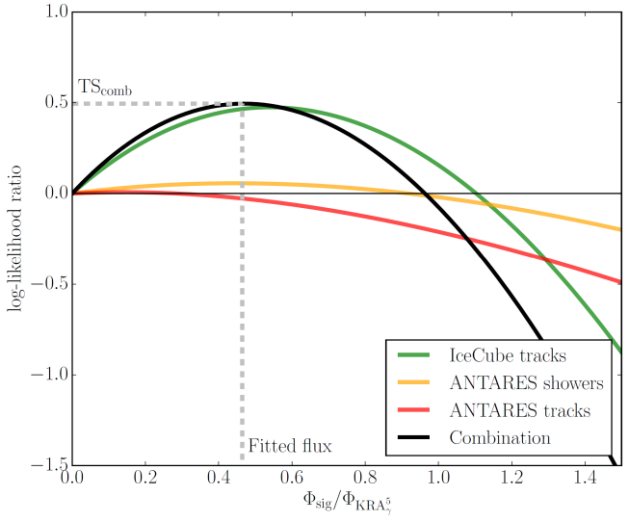


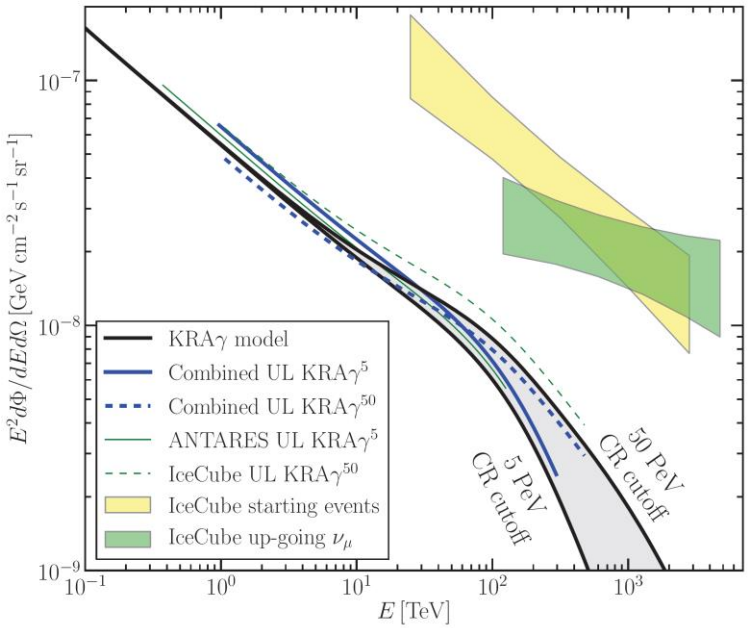
ANTARES & IceCube Combined result arXiv:1808.03531



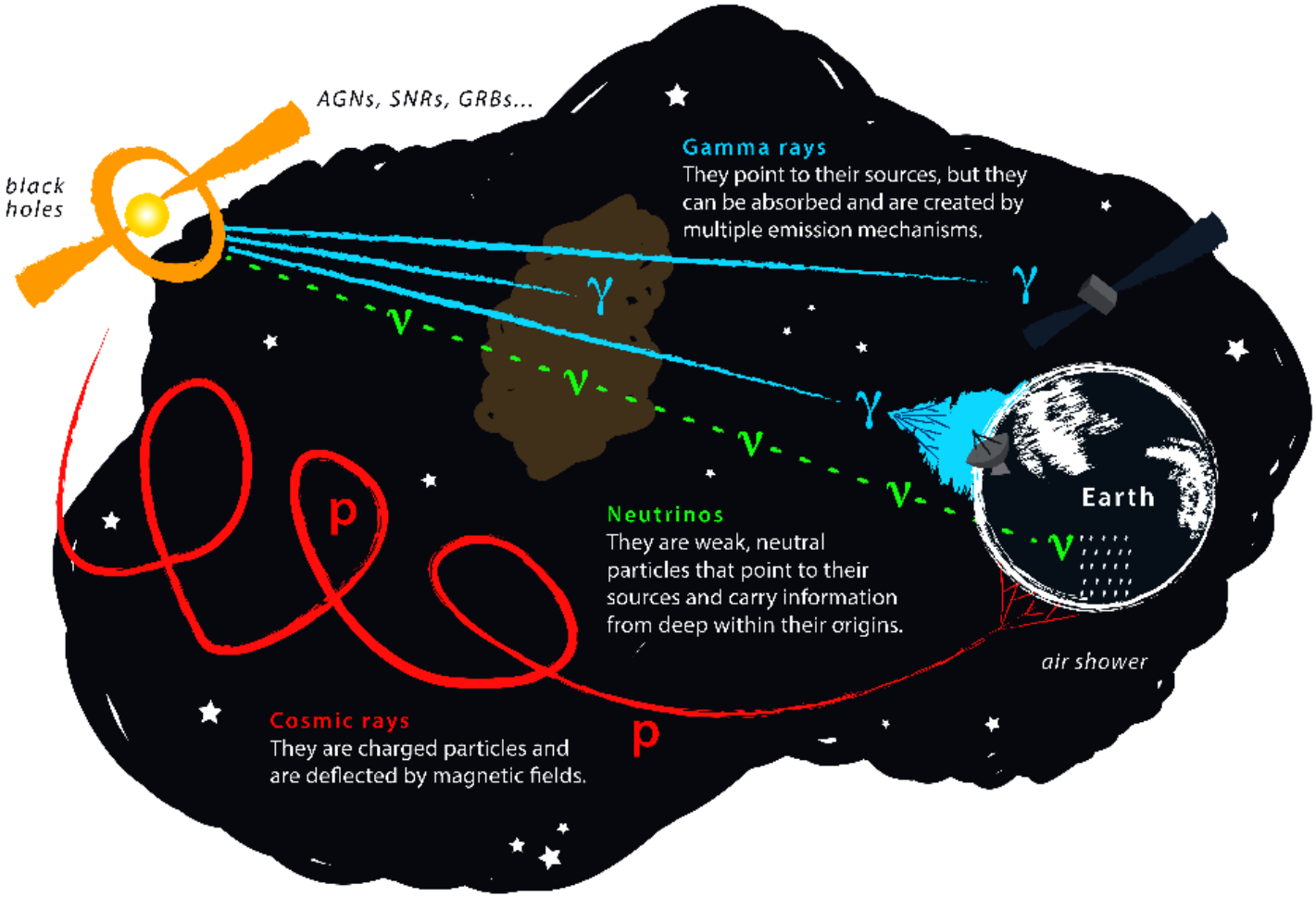
Guaranteed (but weak) flux from galactic plane due to CR interactions with the ISM

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





Multi-Messenger



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

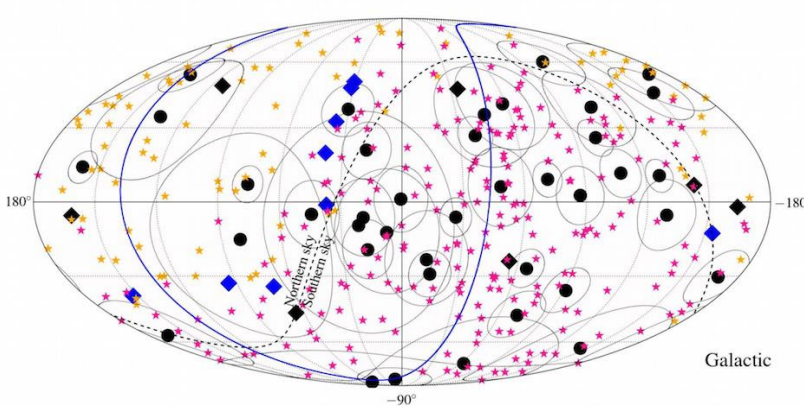
UHECR correlation

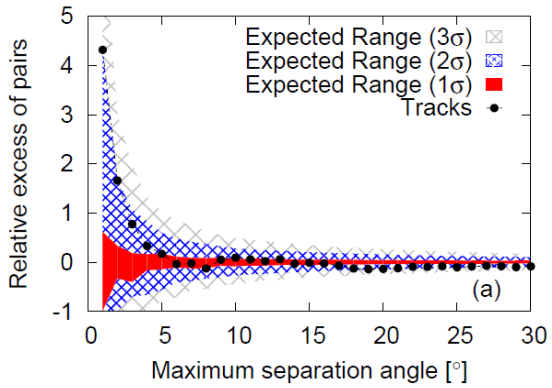
- 300 cosmic ray events > 50 EeV (magnetic deflection small) from the Telescope Array and Pierre Auger

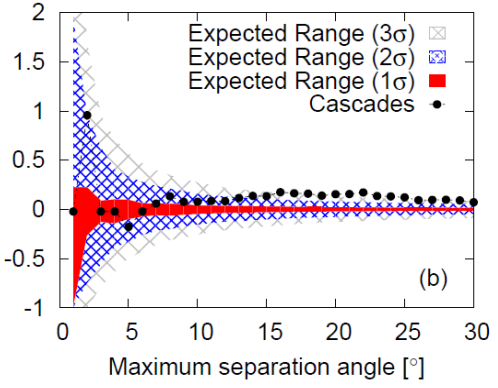
- HESE neutrinos + ~ a dozen events from other samples

- Cross correlation analysis of cosmic ray and neutrino arrival directions
- Stacking analysis with an assumed magnetic deflection of 6°

→ over a variety of tests no observed significance > 3.3σ



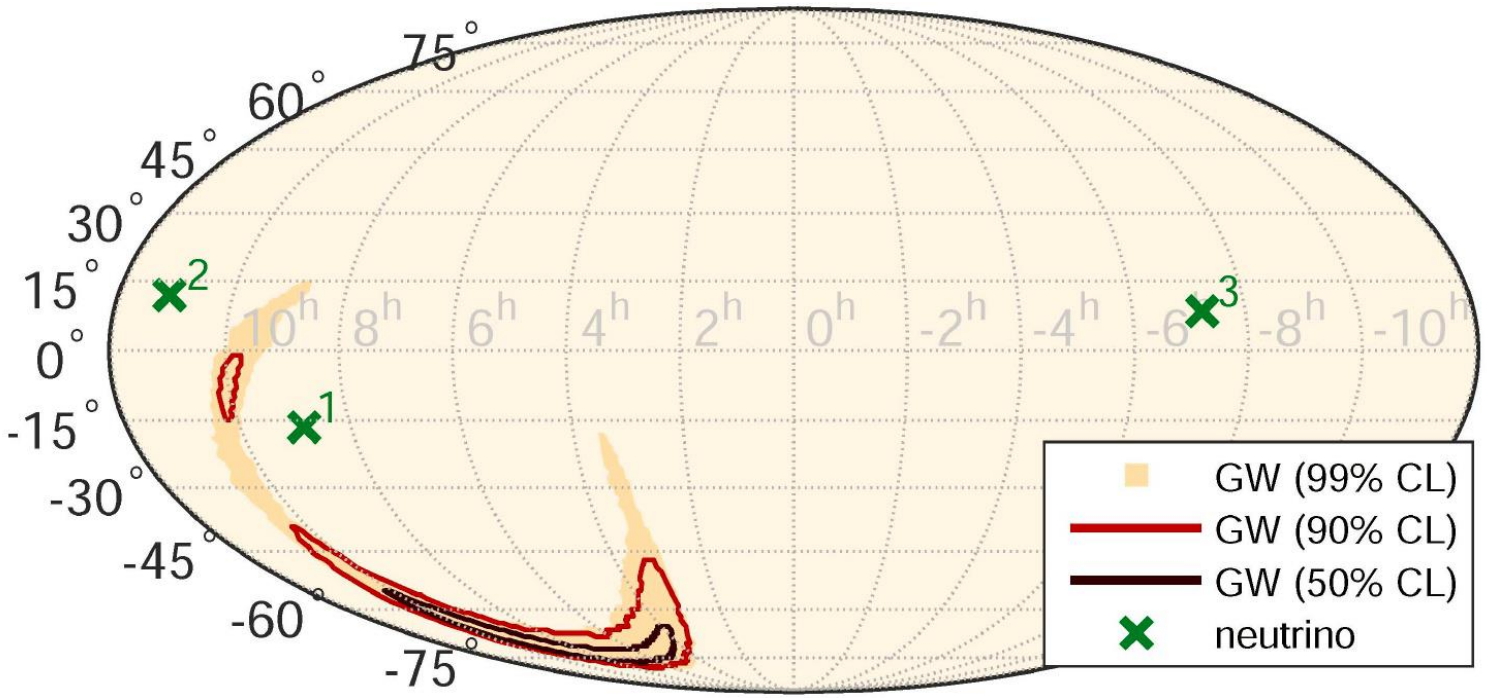




JCAP 1601 (2016) no.01, 037

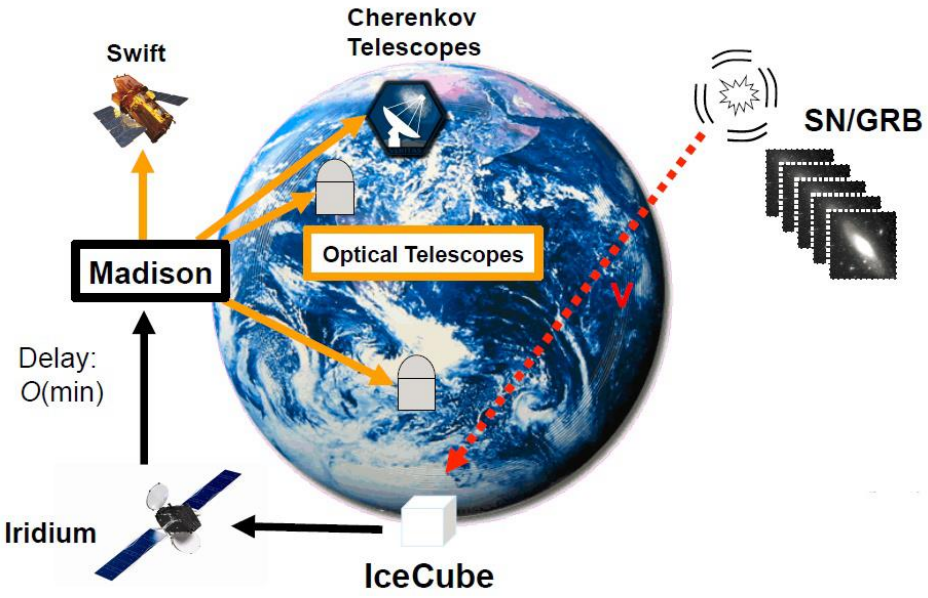
Gravitational Wave correlation

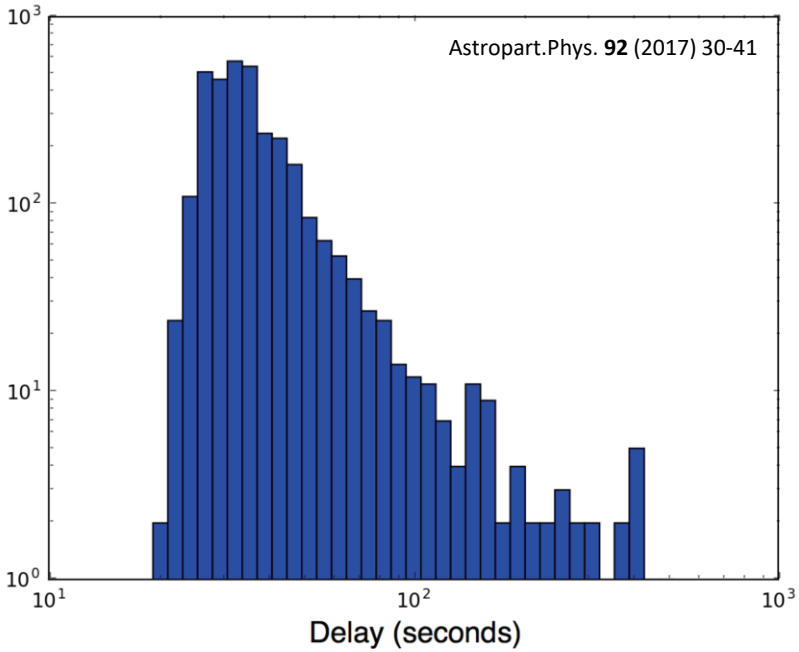
- First black hole merger GW150914, observed by LIGO on Sep. 2015
- IceCube and Antares observed 3 and 0 neutrino candidates within ±500s
- consistent with the atmospheric expectation
- No SN alert triggered in IceCube (monitors average detector rate)



arXiv:1602.05411v3

Realtime Alert System





Focus on well reconstructed track-like events

Use Iridium satellite to send data (2.4 kbps bandwidth, 24h available)

Send alert data in two stages:

1. minimal message with alert stream, direction and few key parameters
2. full event data for follow-up program in Northern hemisphere

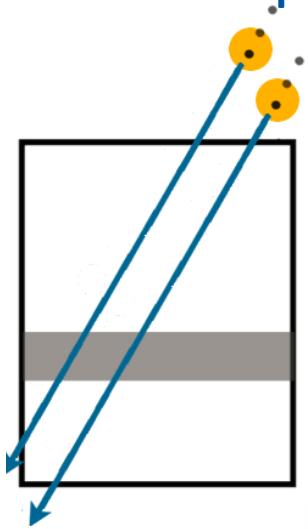
Latency from detection to alert typically less than 1 minute (median 33 second)

Program since April 2016

First alert follow up by PTF, ZTF, HAWC, VERITAS, MAGIC, HESS, Fermi LAT, Fermi GBM, Swift, …

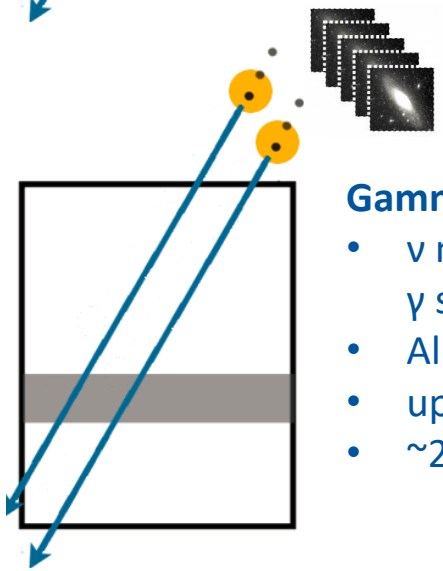
IceCube Alert Streams

Multiple Event Streams



Optical Follow-Up

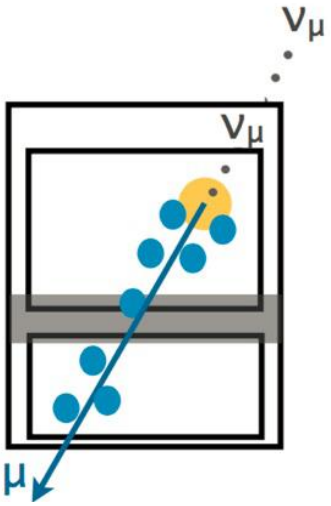
- Neutrino doubles (2+)
- Northern hemisphere
- spatial & temporal clustered
- ~3 alerts/year



Gamma Follow-Up

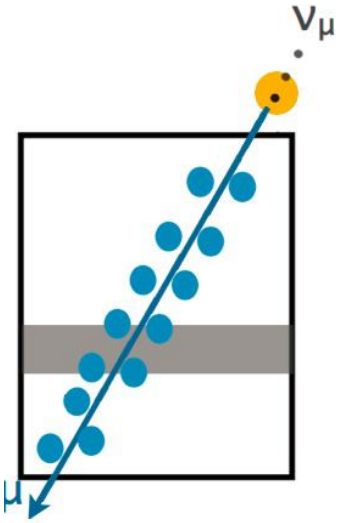
- ν multiplet from known γ sources
- All sky
- up to 3 weeks apart
- ~2 alerts/year

Single Event Streams



High Energy Starting Events

- High energy (>6000 PE)
- Veto of atmospheric muons
- Just tracks
- All sky tracks
- ~3-4 alerts/year



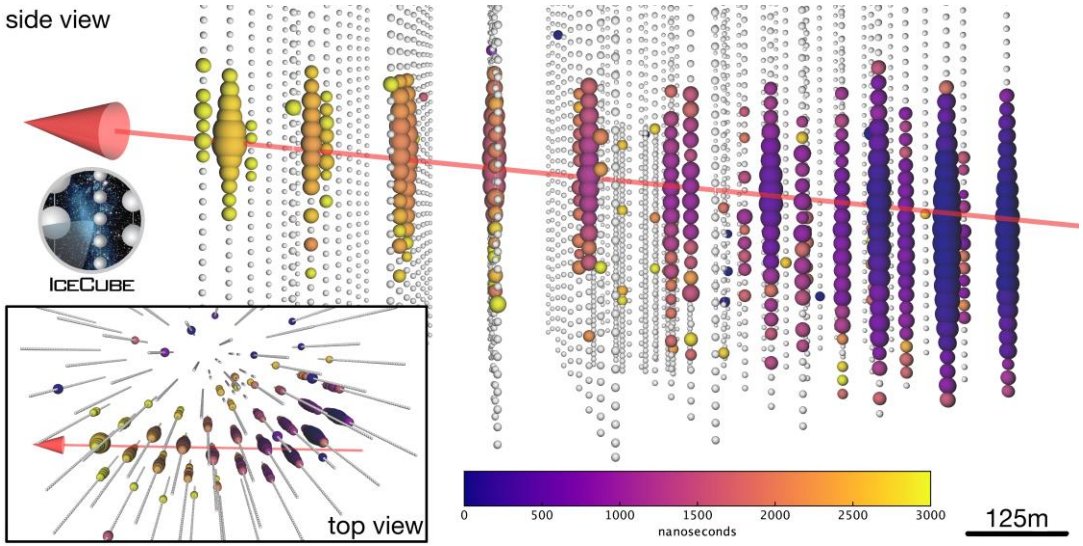
Extreme High Energy

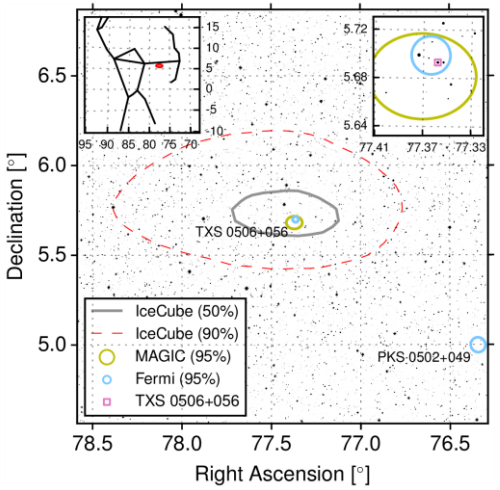
- Optimized for GZK-ν
- VHE through-going tracks
- PE > 3000, Hit DOMs > 300
- Good track reconstruction
- All sky
- ~4-5 alerts/year

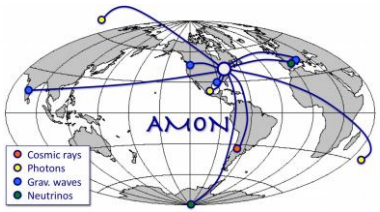
Aartsen *et al* Astropart. Phys. 92, 30-41 (2017)

Real-Time Multi-Messenge IceCube170922A

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



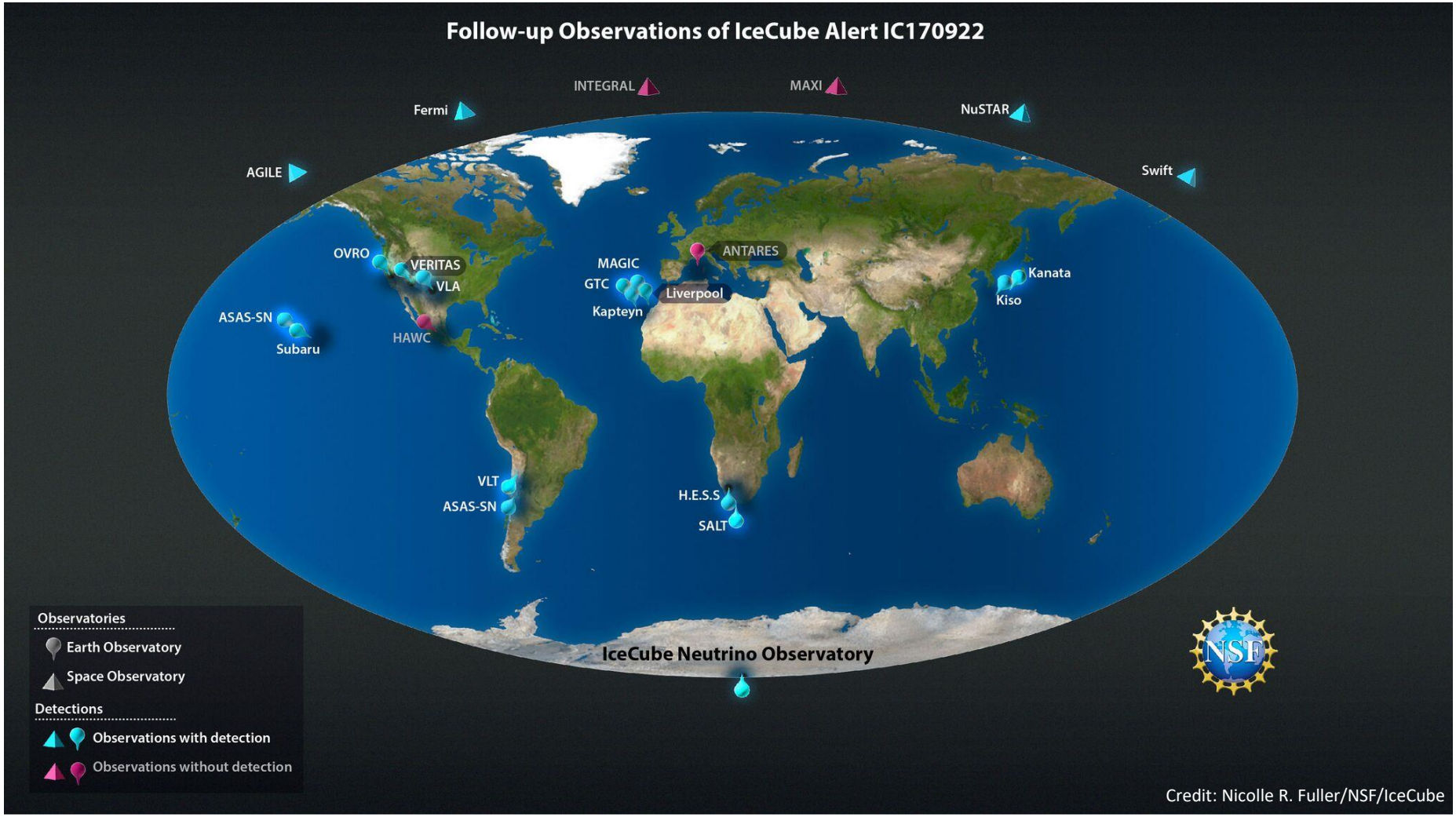




- Extreme-High Energy Alert
- on September 22, 2017
- uncertainty <1 deg² at 90% CL
- sent alert 43 seconds after detection
- 290 TeV neutrino energy assuming $E^{-2.13}$
- Signalness 56.5% (energy and declination)

```
////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```

Follow-up Observatories

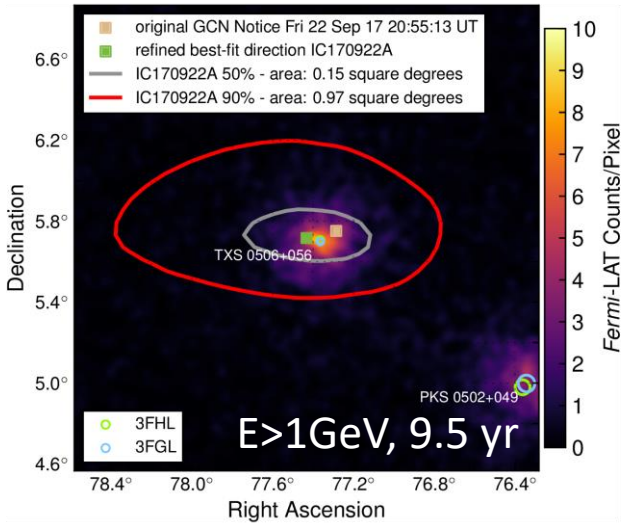


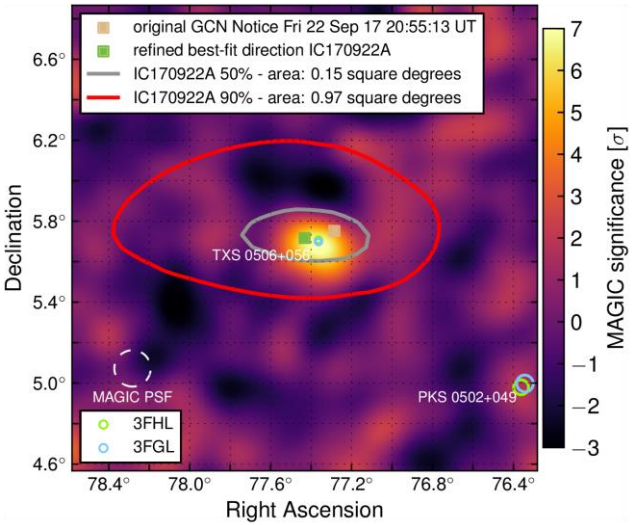
Follow-up Observatories

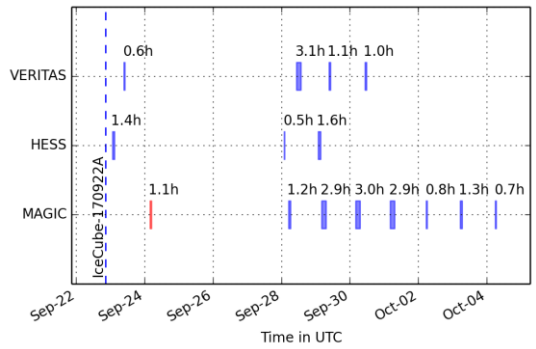
- Fermi Large Area Telescope (LAT) detected counter part
- Blazar TXS 0506+056
- 0.16° from neutrino direction
- Blazar shows strong gamma-ray flare
- Detected by to separate Fermi online analysis

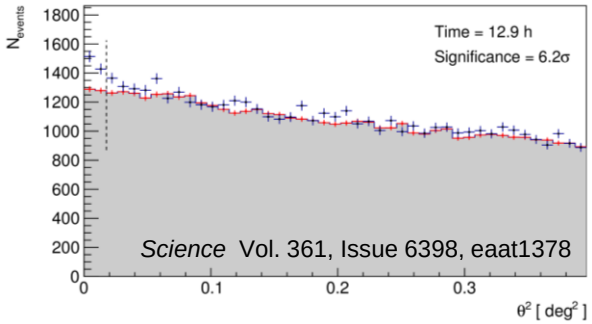
- HESS, VERITAS, MAGIC made follow-up observations
- No detection in the nights after neutrino alert
- Resumed follow-up after Fermi-LAT observation
- MAGIC found 374±62 excess photons
- MAGIC found γ-rays up to 400 GeV energy

Science Vol. 361, Issue 6398, eaat1378

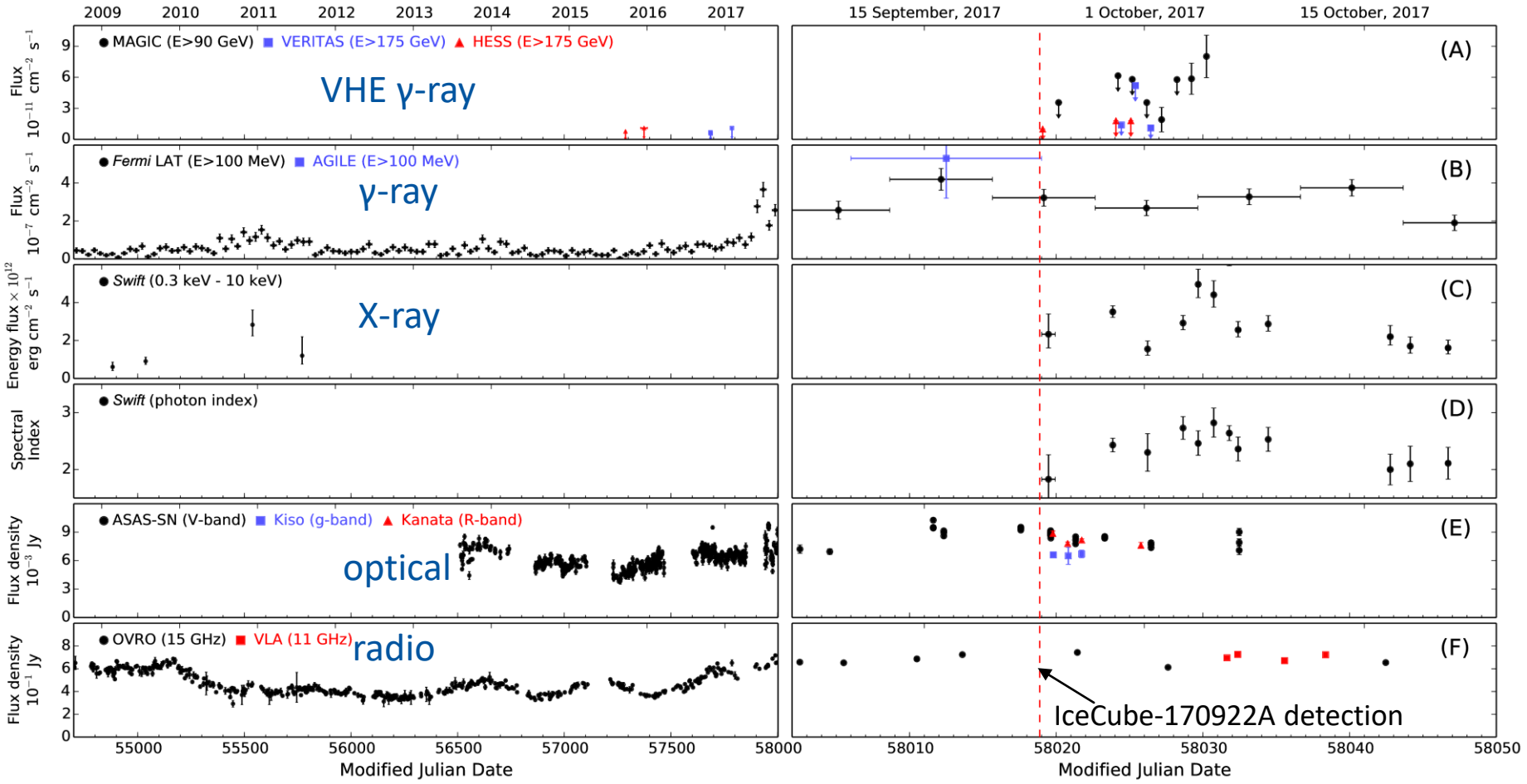






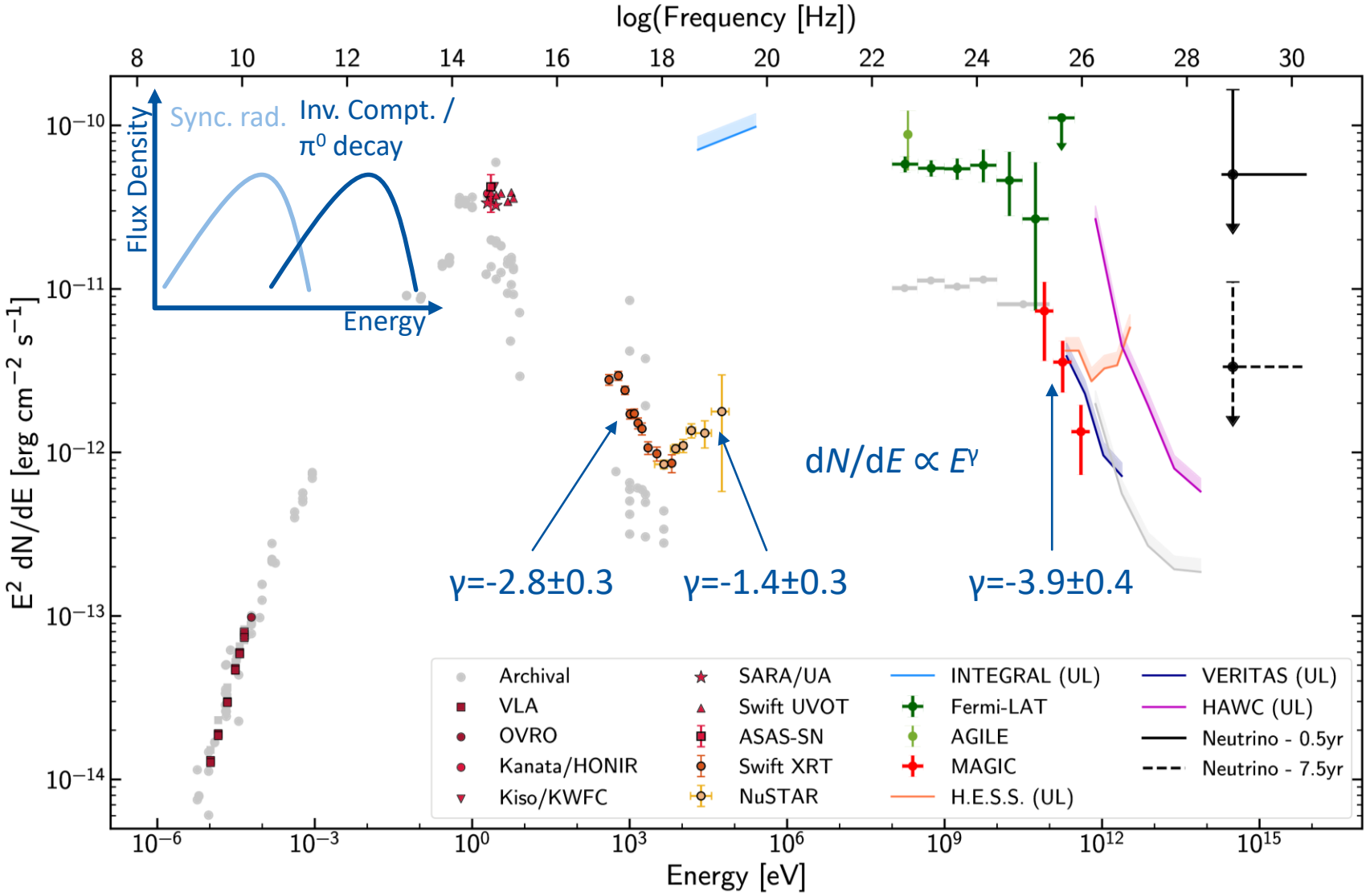


Multi-Wavelength Observation

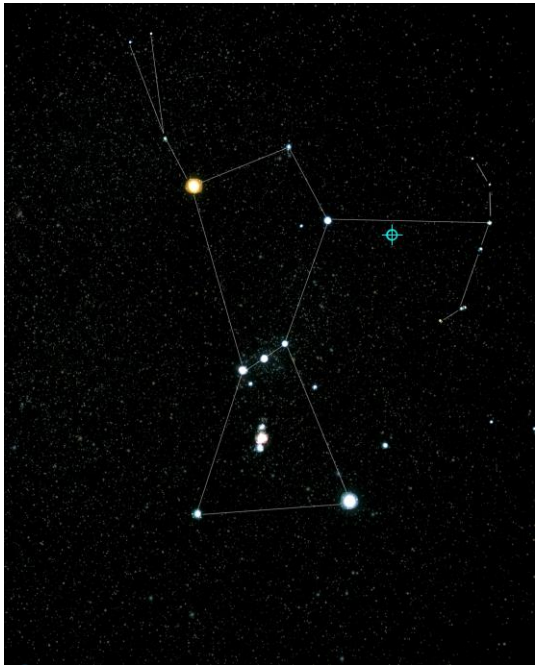


- high emission state
- significant variability
- spectral variability
- correlation of VHE gamma-ray and X-ray

Differential Photon Spectrum



Blazar TXS 0506+056



TXS 0506+056

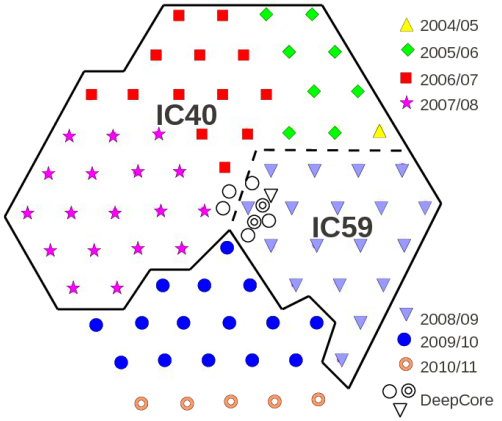
- not much known about blazar before alert
- Type: BL Lac
- RA: 5h 9‘ 25.96‘‘ (77.36°), Dec: +5° 41‘ 35.32‘‘ (5.69°)
- z= 0.3365 ± 0.0010 (Pianno, et al. ApJ **854** (2018) 2)
- one of the most luminous blazars

But how often does this happen by chance?

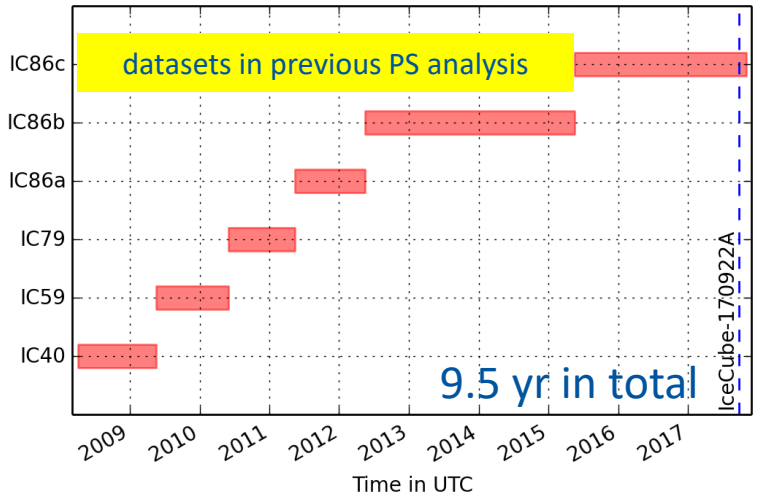
- 2257 cataloged extragalactic Fermi-LAT sources
- Light curves above 1 GeV in monthly bins
- Likelihood ratio test comparing random coincidence (H0) to correlation between γ-ray flux & neutrino-flux for several models
  - Energy flux, Flux variability, VHE detection
  - 4.1σ preference for correlated emission
- Trials corrected:
- previous alerts + 41 additional events that *would* have generated alerts, had they been operational
- **3.0σ** preference for correlated emission

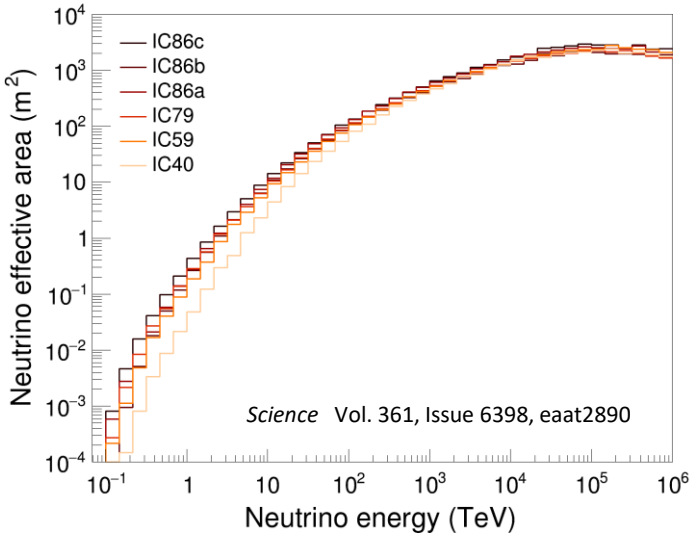
Archival Data

- IceCube has about 10 years of data
- Use selection developed for PS searches
- About 70000 muon tracks pre year
- Dominated by atmospheric muons and neutrinos
- Added all available data up to October 2017
- Run previous developed point source analysis

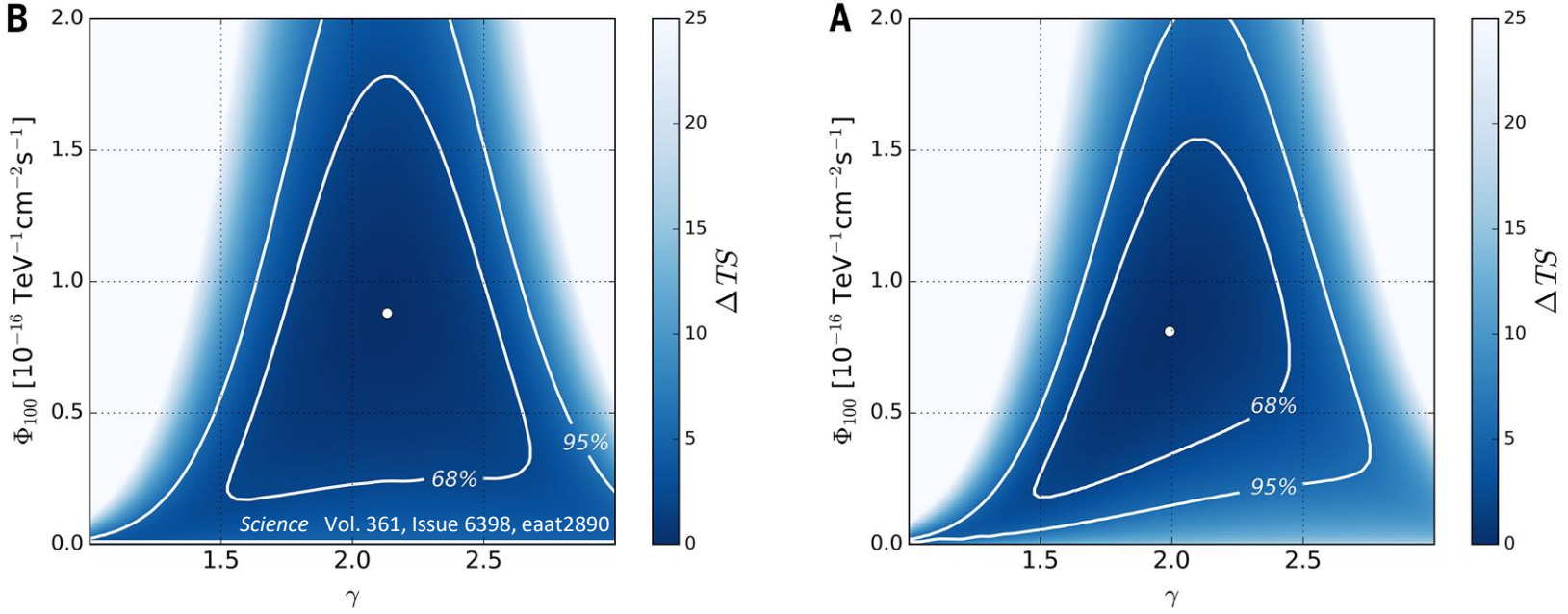


Astron.Astrophys. 539 (2012) A60





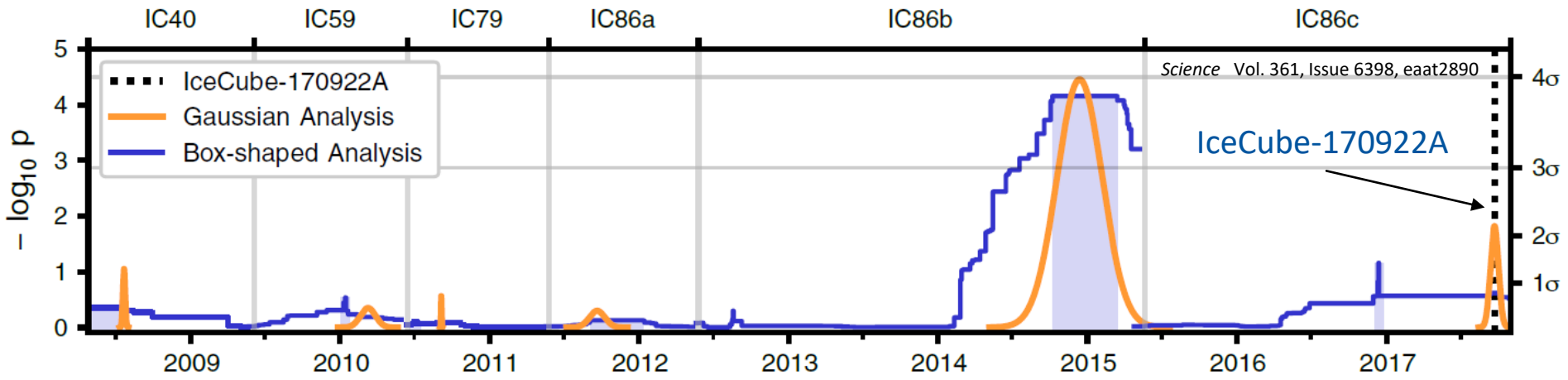
Time Integrated Result



	7 years (2008-2015)	9.5 years (2008-2017)
Normalization @ 100 TeV [TeV^{-1}cm^{-2}s^{-1}]	$\mathbf{(0.9^{+0.6}_{-0.5}) \cdot 10^{-16}}$	$(0.8^{+0.5}_{-0.4}) \cdot 10^{-16}$
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

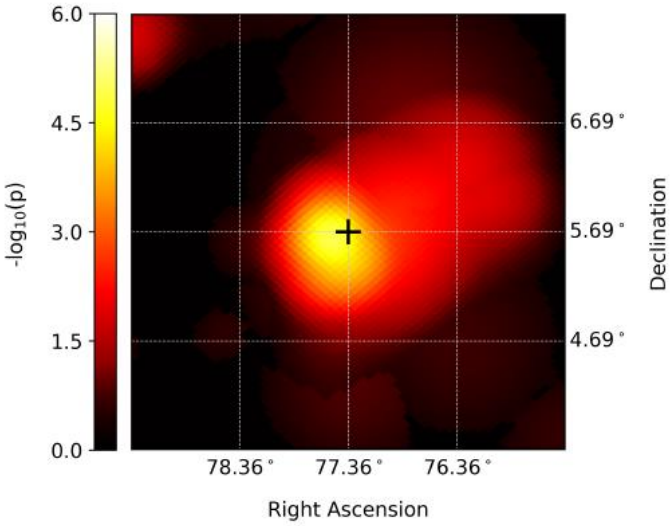
Time Dependent Result



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

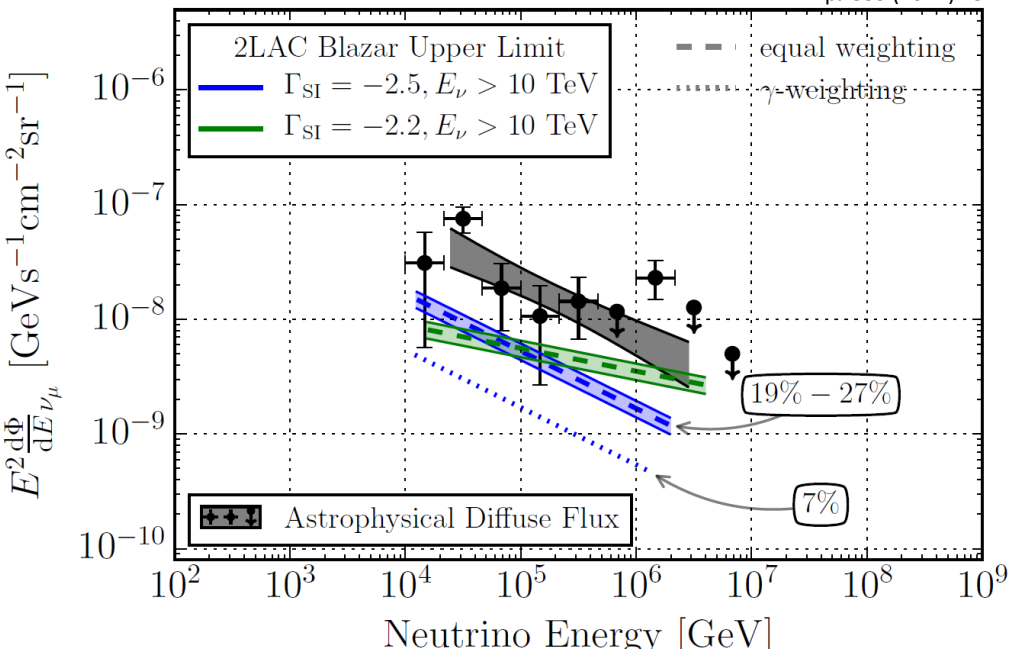
- IceCube published limit on blazar contribution to diffuse astrophysical neutrino flux

- 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)

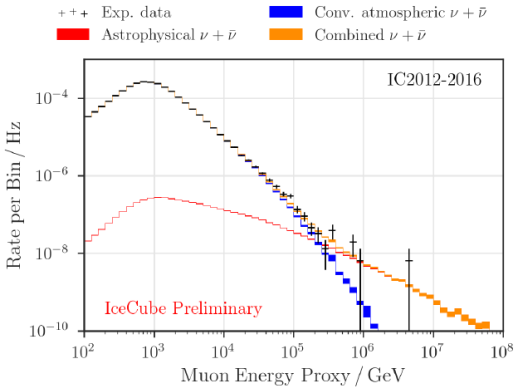
- TXS flux is 1% of 9.5 year diffuse flux

ApJ 835 (2017) 45



Conclusions

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



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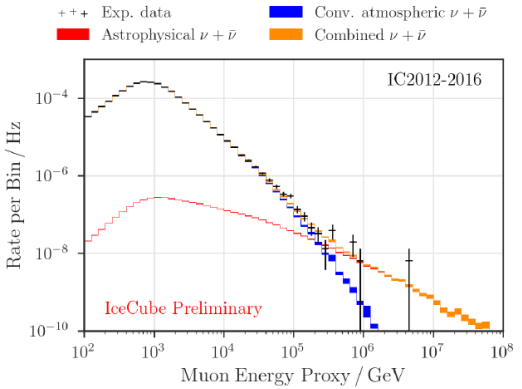
- No significant identification of an individual point-like source
- No significant identification of a neutrino UHECR correlation
- No significant identification of a neutrino GW correlation



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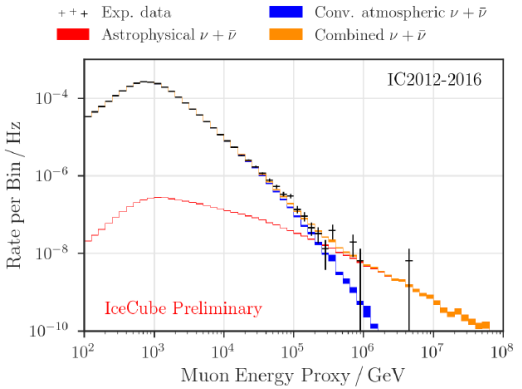
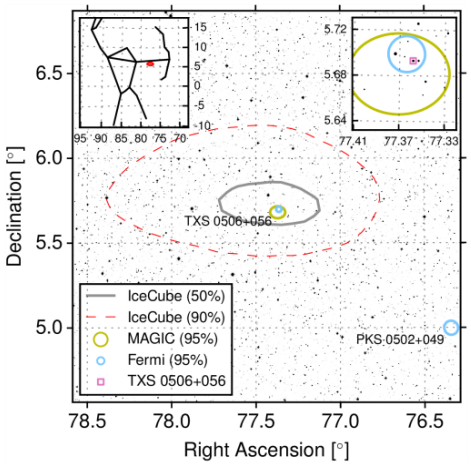
- Found strongly flaring gamma-ray counterpart TXS 0506+056
  - →3.0σ evidence for correlated emission
  - →one of the most luminous known Blazars
- Search for neutrino emission in IceCube archival data
  - → 3.5σ evidence for a neutrino flare at end of 2014 from the same source





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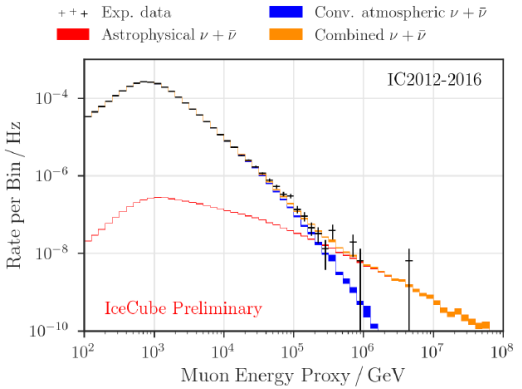
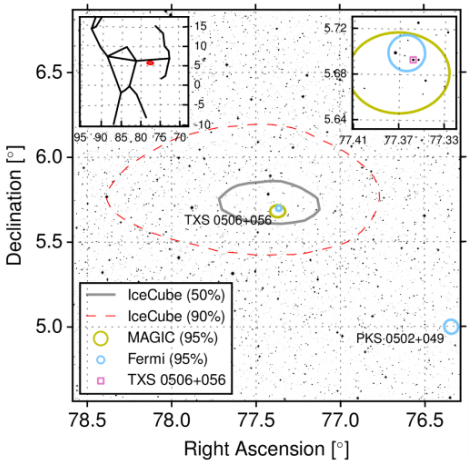
  - → **Starting to become interesting, stay tuned**





Backup