UNIVERSITÉ DE GENÈVE

IceCube
SOUTH POLE NEUTRINO OBSERVATORY

Point-source searches with IceCube

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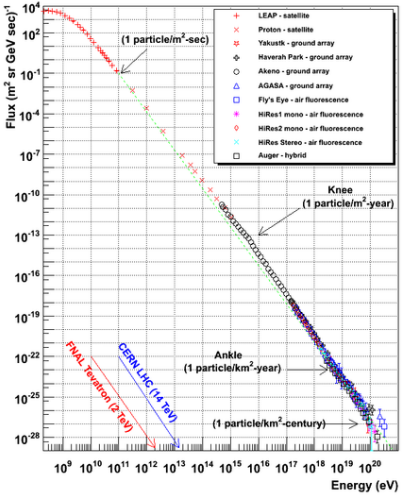
June 06, 2018

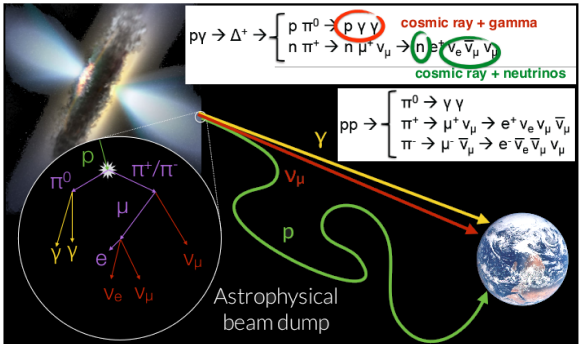
Cosmic ray spectrum



Sources of cosmic rays are **unknown**

How to find **cosmic ray sources**?

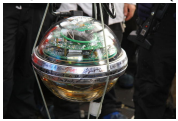
- Cosmic rays (= nuclei) are deflected by magnetic fields
- Gamma rays are absorbed
- Neutrinos travel undeflected, only candidate messenger to point back at sources



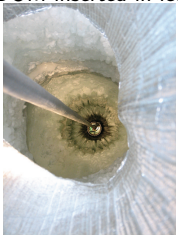
IceCube experiment

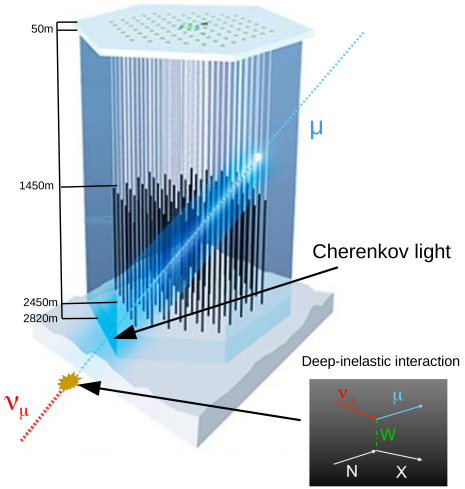
- Completed in 2010
- 1 km^3 volume
- 86 strings
- 125 m string spacing
- 5160 PMTs
- 17 m vertical spacing

Digital Optical Module (DOM)



DOM inserted in ice

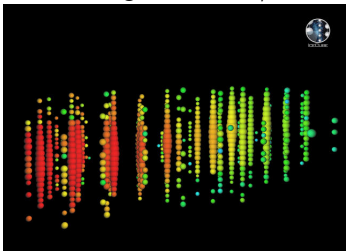




Neutrino events in the detector

Tracks

Charged-current ν_μ

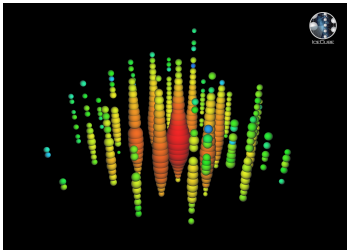


Data ($\sim$ 500 TeV)

- angular resolution $\sim 1^\circ$
- factor of ≈ 2 energy resolution

Cascades

Neutral currents/charged-current ν_e

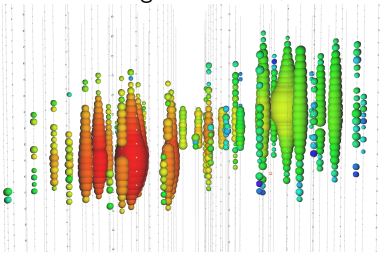


Data (Ernie, 1.14 PeV)

- angular resolution $\sim 10^\circ$
- $\pm$ 10-15% deposited energy resolution

"Double-bang"

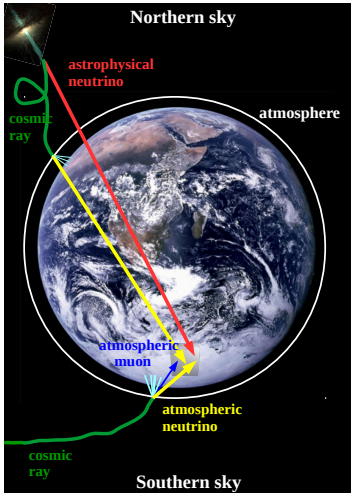
Charged-current ν_τ

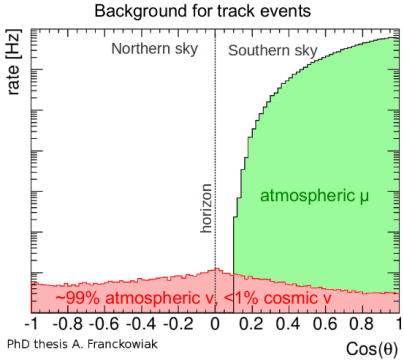


Simulation

- none observed yet
- τ decay length = 50m/PeV

Background and signal in IceCube





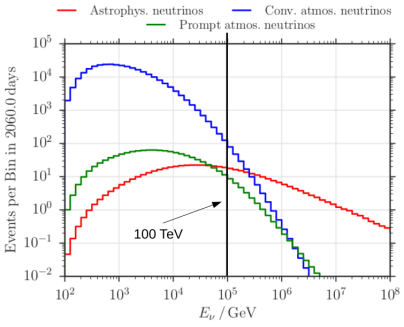
- $E_\nu > 100$ GeV (10 GeV DeepCore)
- μ rate: 2.5 kHz - ν rate $\sim$ mHz
- $\sim$ 200'000 up-going atmospheric ν/year
- $\sim \mathcal{O}(10)$ astrophysical ν/year that we can isolate (much more at lower energy)

Isolating astrophysical signal

Conventional atmospheric neutrinos
from π/K, dominant $<$ 100 TeV

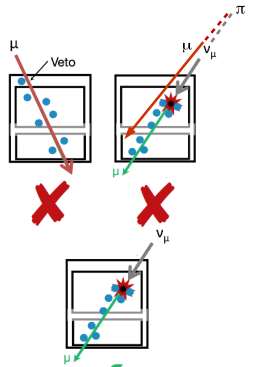
Prompt atmospheric neutrinos
from charm

Astrophysical neutrinos
dominant $>$ 100 TeV



Aartsen et Al., astro-ph.HE (2017)

High **E**nergy **S**tarting **E**vents



One possible parametrization:

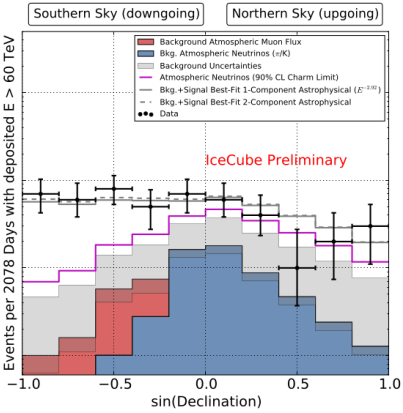
Astrophysical flux: unbroken powerlaw with ϕ_0, γ_{astro}

$$\frac{d\phi}{dE} = \phi_0 \cdot \left(\frac{E}{100\text{TeV}}\right)^{-\gamma_{astro}}$$

(free parameters fit in analyses)

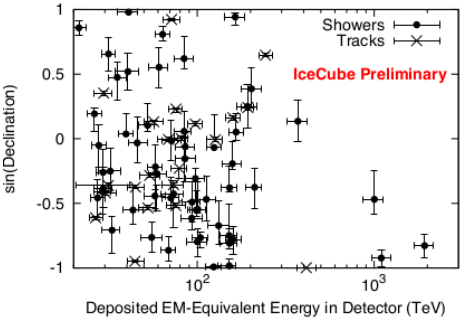
- event starts inside detector
  $\rightarrow$ reduces atmospheric muon background
- energy threshold $\sim$ 60 TeV
  $\rightarrow$ reduces atmospheric ν background

Latest results of HESE (6 years of IceCube data)



ICRC2017

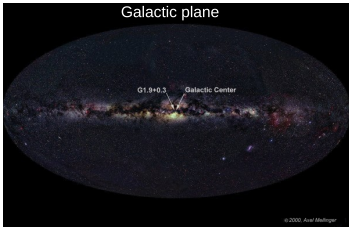
- Result of the fit:
  - $\phi_0 = 2.46 \pm 0.8$ [10^{-8} GeV cm^{-2}s^{-1}sr^{-1}]
  - $\gamma_{astro} = 2.92^{+0.33}_{-0.29}$

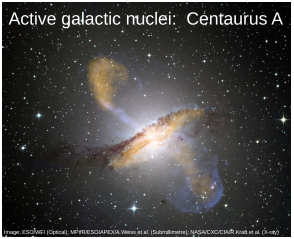


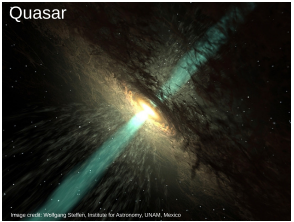
- Excess in neutrinos first measured in 2013 (see **Science 342, 1242856 (2013)**)
- At ICRC 2017: 80 events observed
- $15.6^{+11.4}_{-3.9}$ atmospheric neutrinos
- 25.2 ± 7.3 atmospheric muons
- can't discriminate between unbroken/broken power law

There is an astrophysical flux...

So what produces it?

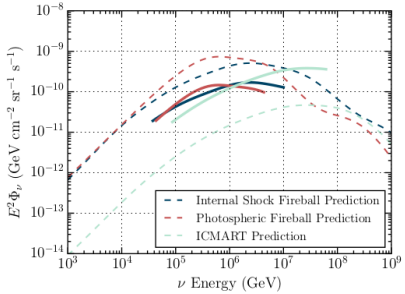






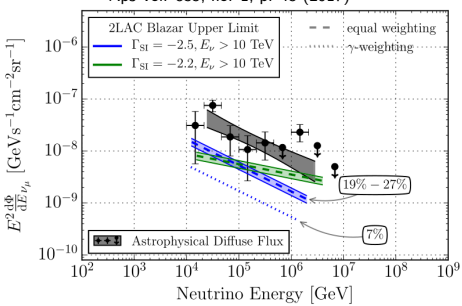
Extragalactic source candidates

Astrophys. J. 843 (2017) 2



$\leq$ **1% of astrophysical flux can come from GRBs**

ApJ vol. 835, no. 1, p. 45 (2017)



$\leq$ **27% of astrophysical flux can come from blazars**

- Neutrino emission from obvious source candidates well constrained
- But there are lots of sources we don't know well or not observed (too far away, GRBs with choked jets, ...)

We can use hypothesis that signal is clustered while background is isotropic to look in lower energy IceCube data and to find out sources

Method for point-source searches in IceCube

Point-source analyses

	Time independent	Time dependent
Untriggered	all-sky scan	all-sky flare analysis
Triggered	–	gamma-ray lightcurve analysis

Unbinned likelihood analysis method

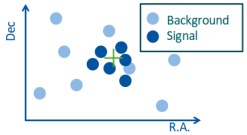
https://doi.org/10.1016/j.astropartphys.2008.02.007

$$TS = -2\log\left(\frac{\mathcal{L}(n_s=0)}{\mathcal{L}(\hat{n}_s,\hat{\gamma}_s,...)}\right)$$

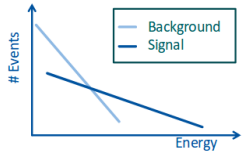
$$\mathcal{L}(\vec{r}_{src}, n_s, \gamma_s, ...) = \prod_N \left(\frac{n_s}{N} S_i + \frac{N-n_s}{N} B_i\right)$$

Signal PDF Background PDF

Spatial PDF



Energy PDF



Time independent: All-sky scan

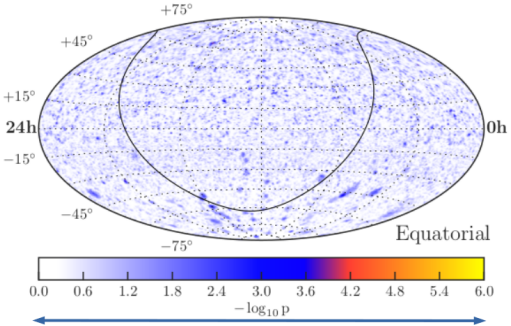
- Hypothesis: neutrino source = clustering of events in the sky
- tracks with $E_\nu > 1$ TeV

Signal PDF: time integrated

- $S_i = P_i^{sig}(\sigma_i, \vec{r}_i|\vec{r}_{src}) \cdot \epsilon_i^{sig}(E_i, \delta_i|\gamma)$
- 2 free params: n_s, γ

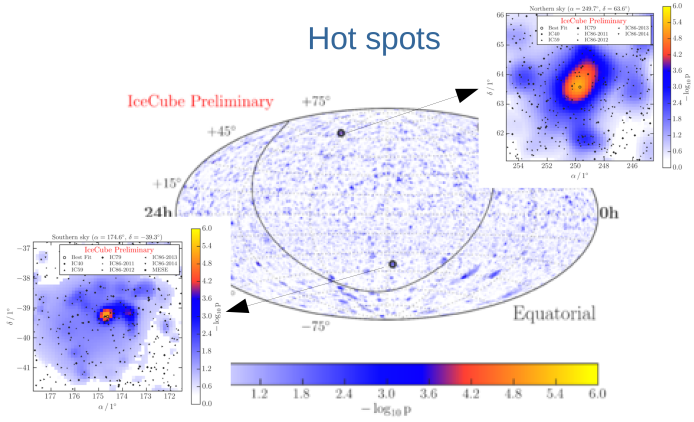
7 years of IceCube data

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



each point = probability that clustering is fluctuation of background

Time independent: All-sky scan



Hemisphere	North	South
n_s	27.22	15.54
γ	1.95	2.84
p-value	44%	39%

→ no significant spatial clustering found!

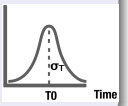
- **Coming soon**: improved sample being finalized, 10 years of tracks will be used for an update

Time dependent: All-sky gaussian flare analysis

- Hypothesis: time clustering of events at time T_0 around a Gaussian with width σ_T (Astropart.Phys. 33 (2010) 175-181)
- Add time PDF, T_i^{sig}

Signal PDF: time dependent

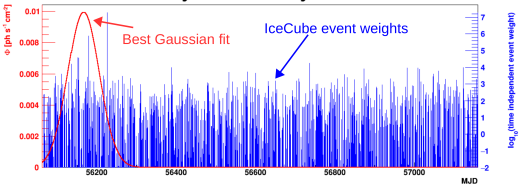
- $S_i = P_i^{sig}(\sigma_i, \vec{r}_i|\vec{r}_{src}) \cdot \epsilon_i^{sig}(E_i, \delta_i|\gamma) \cdot T_i^{sig}$
- 4 free params: n_s, γ, T_0, σ_T



→ no significant time clustering found!

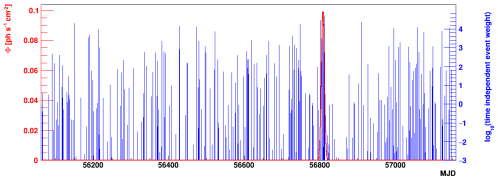
Coming soon: update of analysis covering 2015-2017

May 2013-May 2015



Best Gaussian fit - North Hemisphere

- p-value: 16%

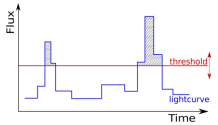


Best Gaussian fit - South Hemisphere

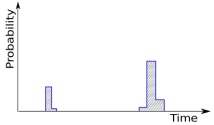
- p-value: 23%

Time dependent: Gamma-ray lightcurve analysis

- Hypothesis: time clustering of events in coincidence with gamma-ray flare of selected transient sources from Fermi-LAT
- E_γ range: $\sim$ 100 MeV-300 GeV
- Add time PDF, T_i^{sig}



(a) Lightcurve and threshold



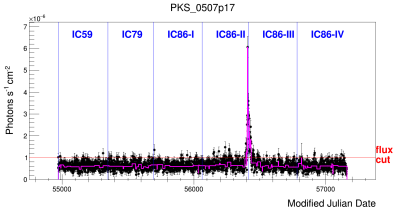
(b) Time PDF

Signal PDF: time dependent

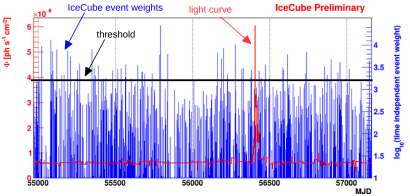
- $S_i = P_i^{sig}(\sigma_i, \vec{r}_i|\vec{r}_{src}) \cdot \epsilon_i^{sig}(E_i, \delta_i|\gamma) \cdot T_i^{sig}$
- 4 free params: n_s, γ, threshold, lag

$\rightarrow$ no significant correlation found!

May 2009-May 2015
Most significant source: blazar PKS 0507+17



ApJ 807 (2015) 46

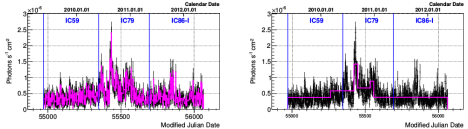


$\rightarrow$ p-value: 30.18%

Monthly gamma-ray lightcurve analysis

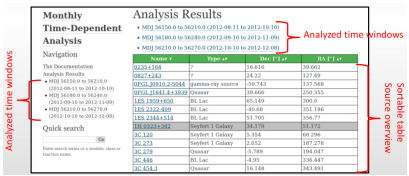
- Same analysis on shorter time scale: 1 month
- Flare selection currently checked → Bayesian blocks method

(`http://stacks.iop.org/0004-637X/764/i=2/a=167`)

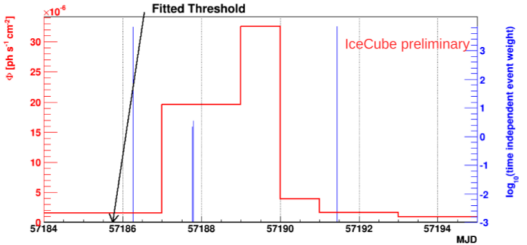


(a) F_B=0.5 (b) F_B=50

- Automatic analysis from source selection to results on webpage

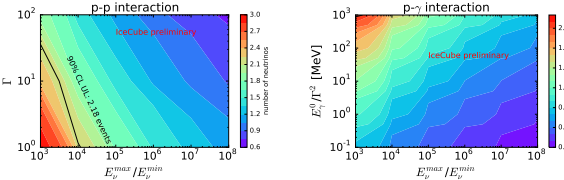


Analysis recently tested on an huge flare of blazar 3C 279 (11-days analysis)

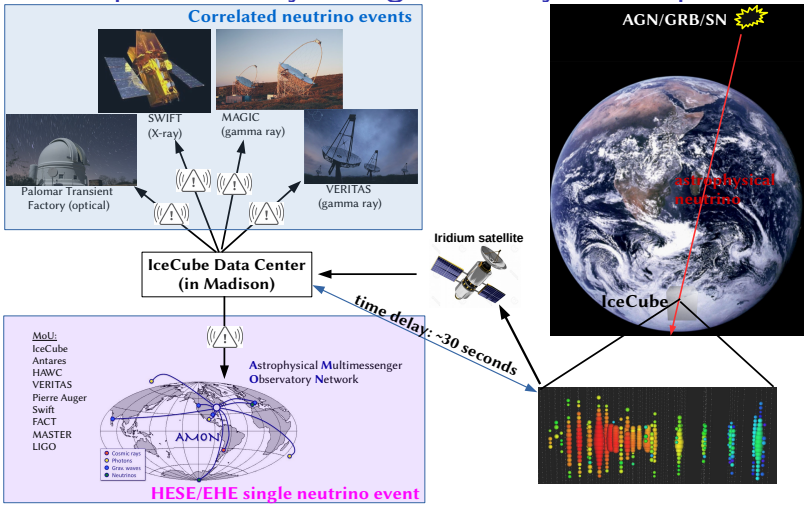


no significant result, p-value 19%
→ constraints on hadronic model

`http://iopscience.iop.org/article/10.3847/0004-637X/831/1/12/pdf`



IceCube alerts to optical, X-ray and gamma-ray telescopes



The IceCube Realtime Alert System. Astroparticle Physics. 92. 10.1016/j.astropartphys.2017.05.002

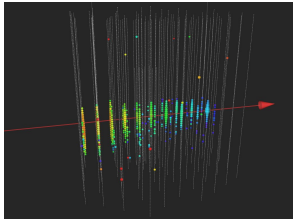
See talk from Konstancja Satalecka on Friday 9am

An interesting IceCube alert

IceCube-170922A: Extremely High Energy event detected by IceCube on 22nd September 2017 → EHE alert sent to AMON via GCN

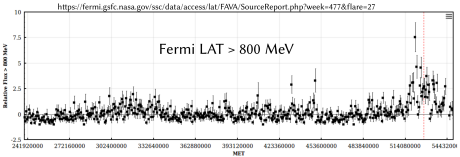
(https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3?)

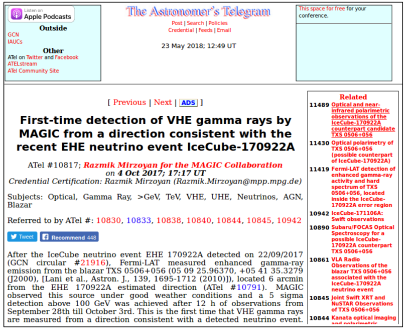
```
Date: 22 Sep, 2017                E proxy of about 120 TeV
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000
```



- Paper in preparation

Fermi-LAT reports blazar TXS 0506+056 in flaring state (RA = 77.43°, Dec = 5.72°, J2000)





Summary and outlook

- Diffuse astrophysical flux detected with more than 7σ significance
- Searches for sources
  - scanning the whole sky and looking for spatial clustering
  - scanning the whole sky and looking for spatial and time clustering
  - correlations in space and time with gamma rays
- Searches for sources targeting shorter time scales:
  - monthly correlation with gamma-rays
  - real time alerts send IceCube events details to a global telescope network for follow-up
- A brilliant mutli-messenger program is now active with IceCube.
  Stay tuned for interesting results coming soon!


Thank you!

Additional slides

Gravitational waves

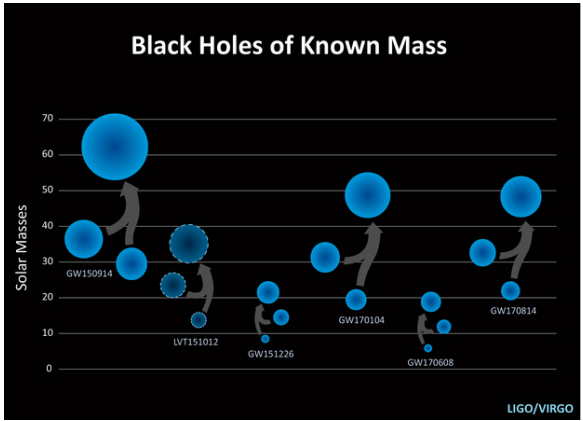
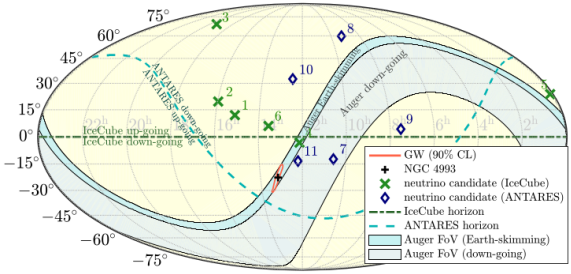


Image credit: `www.ligo.caltech.edu/images`

$\rightarrow$ neutrinos may be emitted if the merger happens in a sufficiently baryon-dense environment and a black hole + accretion disk system is formed

- Neutrino correlation searches with IceCube and ANTARES: **Phys. Rev. D93, 122010 (2016), Phys. Rev. D 96, 022005 (2017)**
- No significant neutrino detection in correlation with GW

Search for correlation with GW170817



The Astrophysical Journal Letters, vol 850, 2, (2017)

search for coincident neutrinos using a time window of ± 500 s around GW and 14 days after GW

IceCube results:

- 6 ν candidate events $\rightarrow$ no directional correlation, consistent with atmospheric background
- 0 HESE event

Antares results:

- 0 ν candidate events within ± 500 s, 0 spatially coincident event in 14 days search

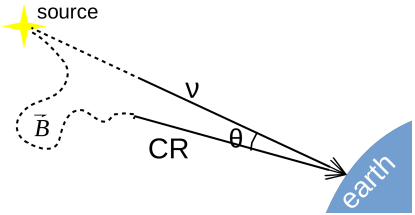
Pierre Auger results:

- 0 ν candidate events within ± 500 s or in 14 days search

$\rightarrow$ consistent with our expectations from a typical GRB observed off-axis, or with a low-luminosity GRB

Correlation with ultrahigh-energy cosmic rays

- Unbinned likelihood analysis
- Test correlation between neutrinos and ultrahigh-energy cosmic rays

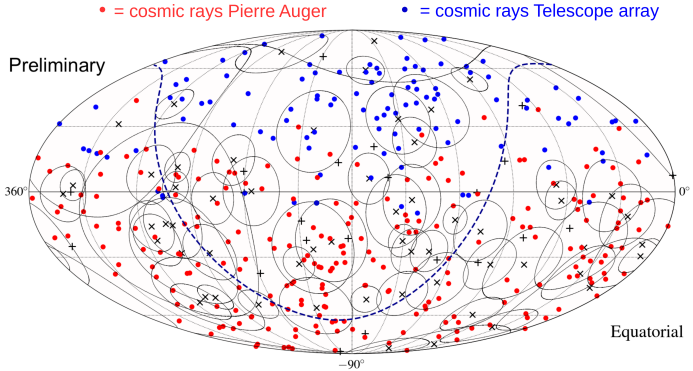


Data sample

cosmic rays	Telescope array Pierre Auger	$E_{CR} > 50$ EeV
neutrinos	IceCube	$E_{\mu} > 200$ TeV

Tested deflection hypotheses: $\theta = [3^\circ, \boxed{6^\circ}, 9^\circ] \cdot 100\ \text{EeV}/E_{CR}$
$\rightarrow$ most significant result

Correlation with ultrahigh-energy cosmic rays

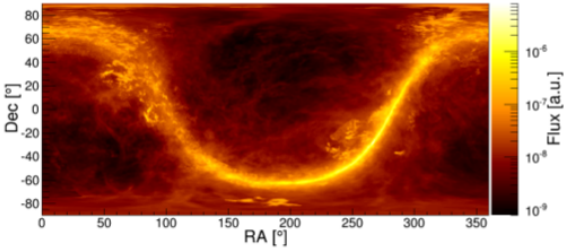


- previous analysis: $\sim 3\sigma$
- This analysis = addition of 2 years of IceCube data: $\sim 2\sigma$

$\rightarrow$ no significant correlation found!

Galactic plane emission template

How much from the diffuse neutrino flux we observe comes from interaction of cosmic rays with the **interstellar gas of our Galaxy**?



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Analysis method:

- take models of gamma-ray emission: KRA-γ (50 PeV cutoff) model
- search for anisotropy corresponding to model in neutrino arrival directions

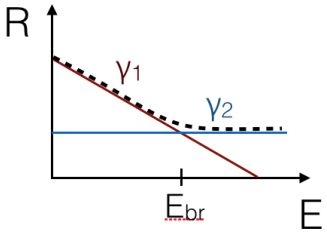
$<$ 14% of astrophysical flux can come from Galactic plane

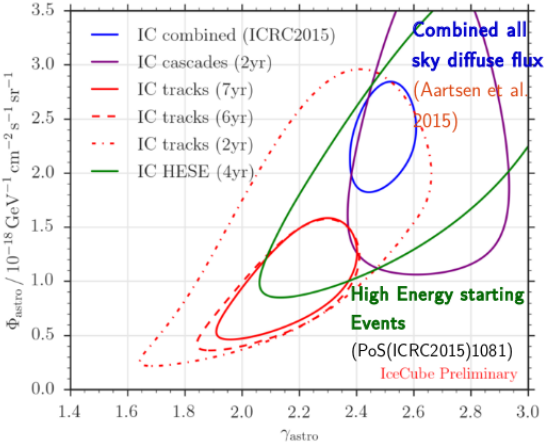
Paper in preparation: New joint Galactic plane analysis between IceCube and Antares, using KRAγ template, 5 PeV cosmic-ray cutoff, expect better limits

Spectral index γ_{astro}

90% confidence level regions
for
the value of γ_{astro}

$\rightarrow$ tension : could indicate a broken power law

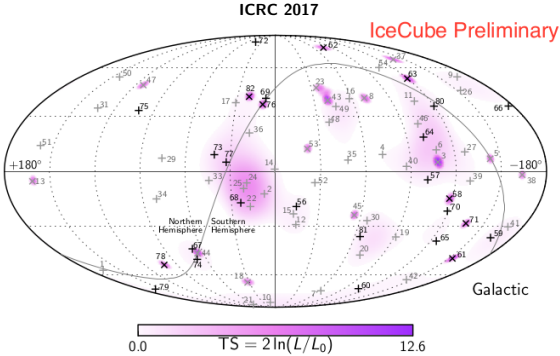




Analysis	ϕ_0 [10^{-8} GeV cm^{-2}s^{-1}sr^{-1}]	γ_{astro}
HESE-6yrs	2.46 ± 0.8	$2.92^{+0.33}_{-0.29}$
Tracks-8yrs	$1.01^{+0.25}_{-0.23}$	2.19 ± 0.10
Cascades-4yrs	$1.57^{+0.23}_{-0.22}$	2.48 ± 0.08

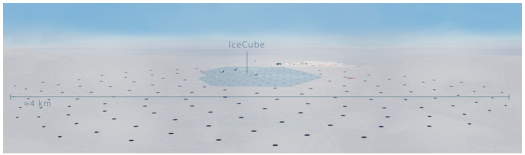
Looking for sources with HESE

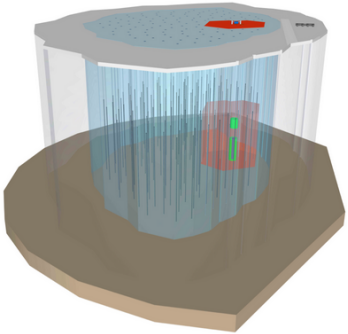
- events directions from HESE sample put on a skymap
- neutrino source = clustering of events in the sky
- maximum-likelihood method with two free parameters: number of source events, spectral index

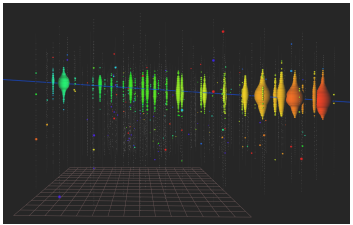


No significant result: p-values of 44% and 77% for the shower-only and the all-events test → constraint on energy is very strict: too few events

IceCube-Gen2

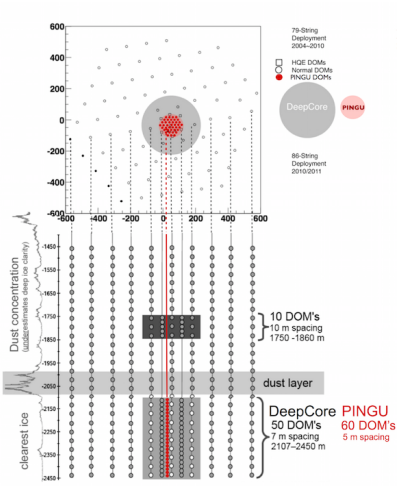






- 10 km^3
- 1 order of magnitude increase in neutrino detection rates $\rightarrow$ statistically significant samples in the PeV to EeV range

PINGU



main goal: distinguish between the normal and inverted NMH $\rightarrow 3\sigma$ significance with ~ 3.5 years of data