



UNIVERSITÉ
DE GENÈVE



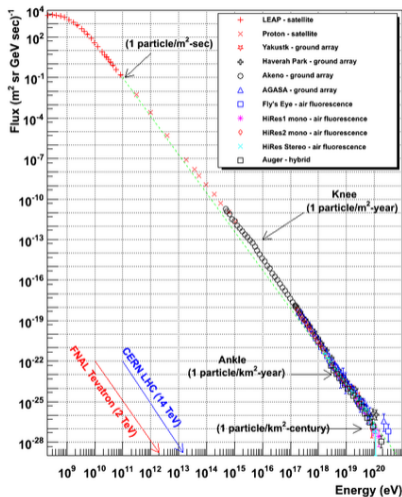
Point-source searches with IceCube

Stéphanie Bron
Rencontres de Blois

June 06, 2018



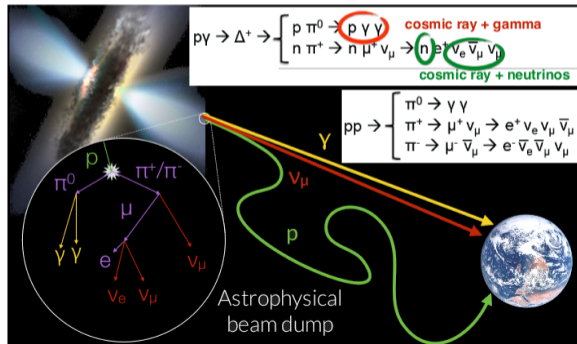
Cosmic ray spectrum



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



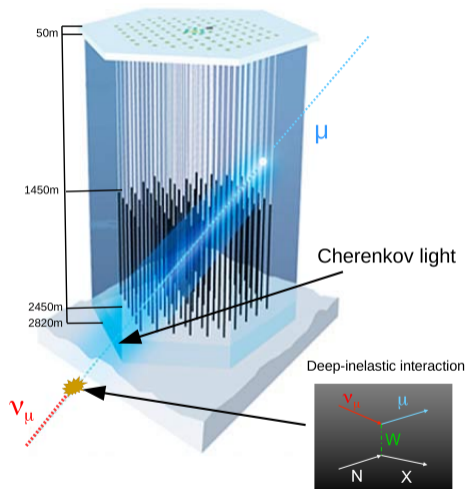
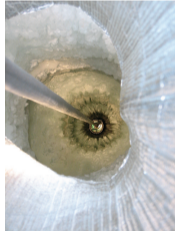
IceCube experiment

- Completed in 2010
- 1 km³ volume
- 86 strings
- 125 m string spacing
- 5160 PMTs
- 17 m vertical spacing

Digital Optical Module (DOM)



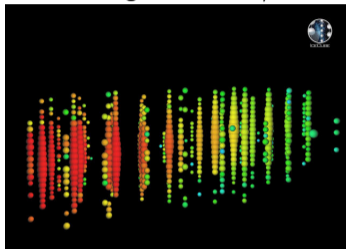
DOM inserted in ice



Neutrino events in the detector

Tracks

Charged-current ν_μ

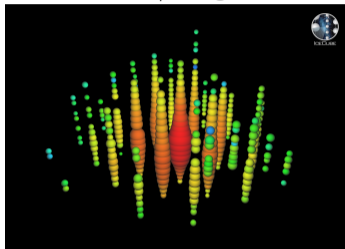


Data (~ 500 TeV)

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

Cascades

Neutral currents/charged-current ν_e

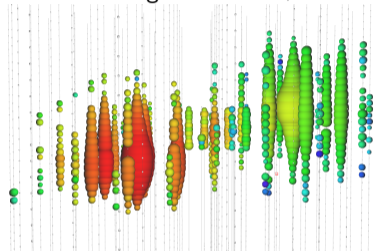


Data (Ernie, 1.14 PeV)

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

"Double-bang"

Charged-current ν_τ

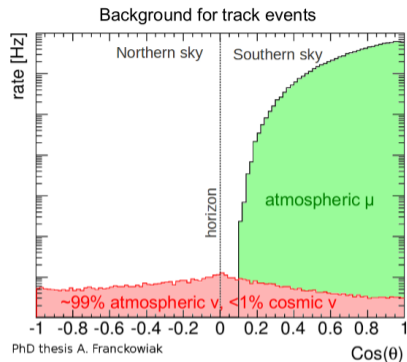
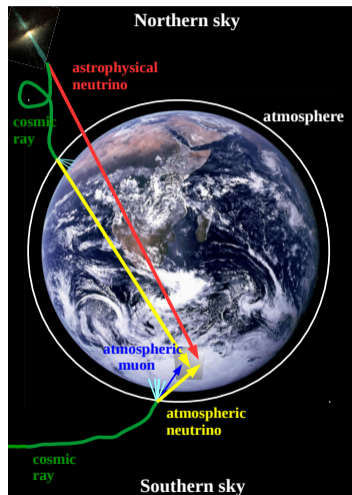


Simulation

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

Early  Late

Background and signal in IceCube



- $E_\nu > 100 \text{ GeV}$ (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

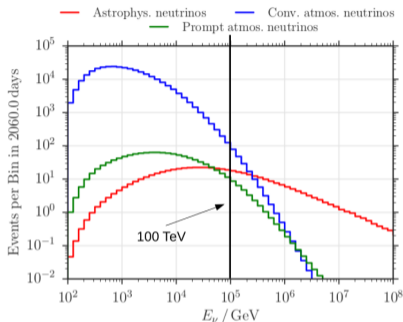
from π/K , dominant < 100 TeV

Prompt atmospheric neutrinos

from charm

Astrophysical neutrinos

dominant > 100 TeV



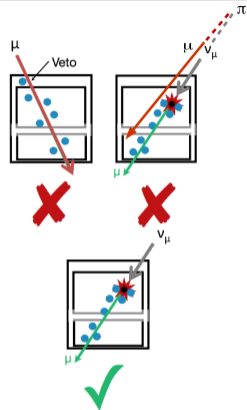
Aartsen et Al., astro-ph.HE (2017)

One possible parametrization:

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

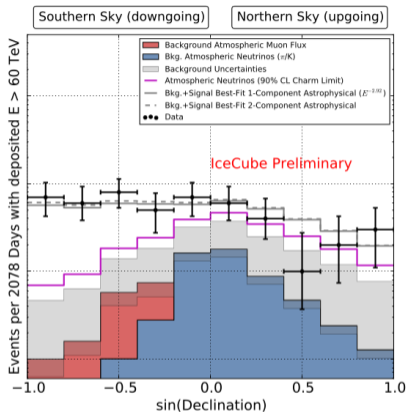
$$\frac{d\phi}{dE} = \phi_0 \cdot \left(\frac{E}{100\text{TeV}} \right)^{-\gamma_{astro}} \quad (\text{free parameters fit in analyses})$$

High Energy Starting Events



- event starts inside detector
→ reduces atmospheric muon background
- energy threshold ~ 60 TeV
→ reduces atmospheric ν background

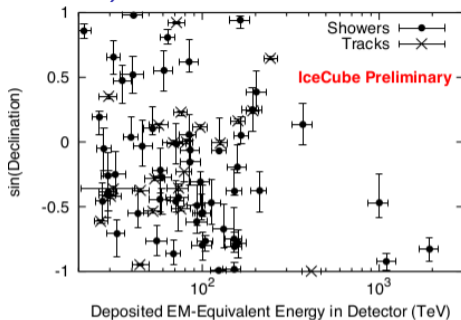
Latest results of HESE (6 years of IceCube data)



ICRC2017

▶ Result of the fit:

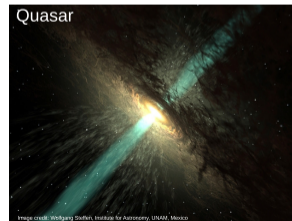
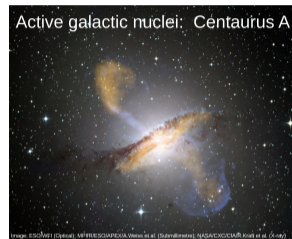
- ▶ $\phi_0 = 2.46 \pm 0.8 [10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}]$
- ▶ $\gamma_{astro} = 2.92^{+0.33}_{-0.29}$



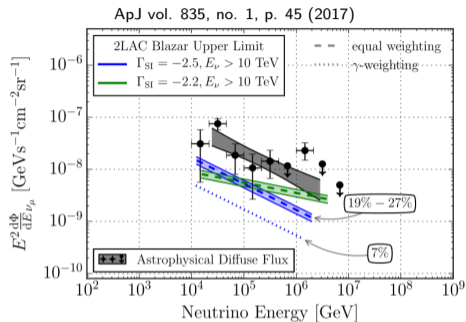
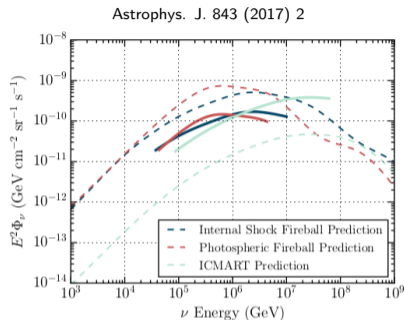
- Excess in neutrinos first measured in 2013 (see **Science 342, 1242856 (2013)**)
- At ICRC 2017: 80 events observed
- $15.6^{+11.4}_{-3.9}$ atmospheric neutrinos
- 25.2 ± 7.3 atmospheric muons
- can't discriminate between unbroken/broken power law

There is an astrophysical flux...

So what produces it?



Extragalactic source candidates



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

$\leq 27\%$ 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

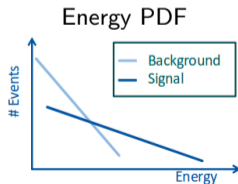
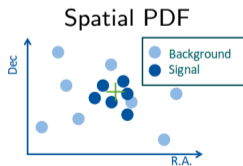
	Time independent	Time dependent
Untriggered	all-sky scan	all-sky flare analysis
Triggered	–	gamma-ray lightcurve analysis

Unbinned likelihood analysis method <https://doi.org/10.1016/j.astropartphys.2008.02.007>

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

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

Signal PDF Background PDF



Time independent: All-sky scan

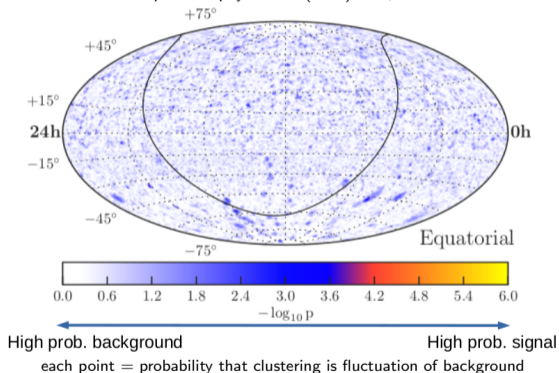
- Hypothesis: neutrino source = clustering of events in the sky
- tracks with $E_\nu > 1$ TeV

Signal PDF: time integrated

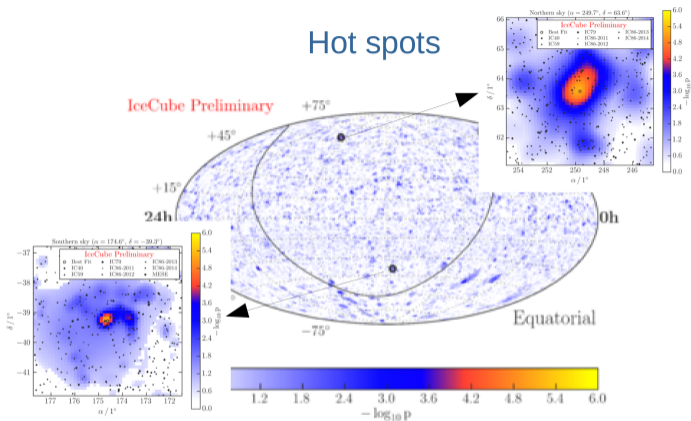
- ▶ $S_i = P_i^{sig}(\sigma_i, \vec{r}_i | \vec{r}_{src}) \cdot \epsilon_i^{sig}(E_i, \delta_i | \gamma)$
- ▶ 2 free params: n_s, γ

7 years of IceCube data

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



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!

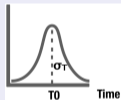
- **Coming soon:** improved sample being finalized, 10 years of tracks will be used for an update

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

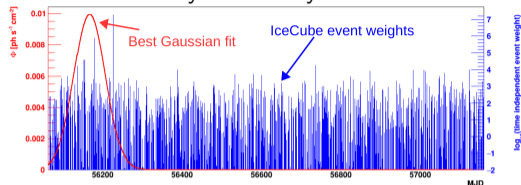
- ▶ $S_i = P_i^{sig}(\sigma_i, \vec{r}_i | \vec{r}_{src}) \cdot \epsilon_i^{sig}(E_i, \delta_i | \gamma) \cdot T_i^{sig}$
- ▶ 4 free params: $n_s, \gamma, T_0, \sigma_T$



→ no significant time clustering found!

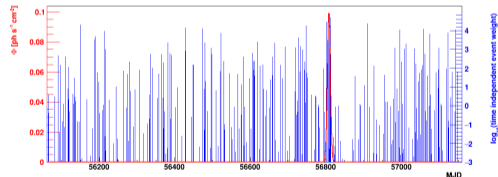
Coming soon: update of analysis covering 2015-2017

May 2013-May 2015



Best Gaussian fit - North Hemisphere

▶ p-value: 16%

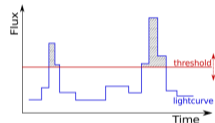


Best Gaussian fit - South Hemisphere

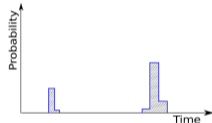
▶ p-value: 23%

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: ~ 100 MeV-300 GeV
- Add time PDF, T_i^{sig}



(a) Lightcurve and threshold



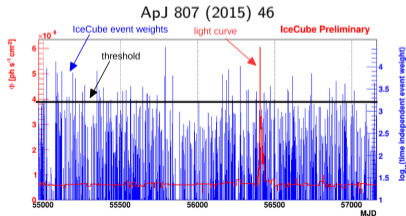
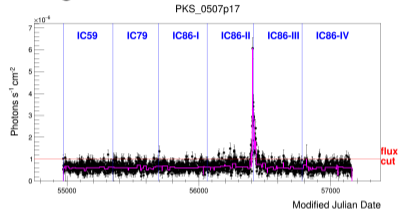
(b) Time PDF

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

→ no significant correlation found!

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

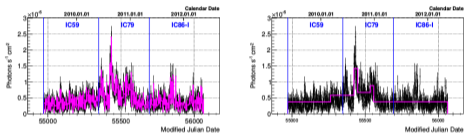


→ p-value: 30.18%

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

Monthly Time-Dependent Analysis

Navigation

The Documentation

Analysis Results

- MJD 56150.0 to 56230.0 (2012-08-11 to 2012-10-10)
- MJD 56180.0 to 56260.0 (2012-09-10 to 2012-11-09)
- MJD 56210.0 to 56270.0 (2012-10-10 to 2012-12-08)

Quick search

Enter search term(s) or a modified, class or function name.

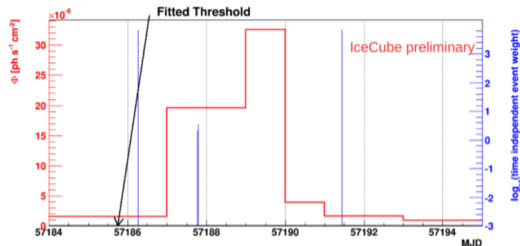
Analysis Results

Source	Type	Dist [kpc]	RA [h:m:s]	Dec [d:m:s]
0220+508	?	16.616	09:02	09:02
0827+243	?	24.22	127:49	
09UGLJ0910-2-5044	gamma-ray source	-50.743	137:568	
09UGLJ2146L4+3830	Chesear	39.666	250:355	
1ES 1509+659	BL Lac	65.149	300.0	
1ES 2322-509	BL Lac	-40.68	351:186	
1ES 2344+514	BL Lac	51.705	356:77	
1H 0323+344	Seyfert 1 Galaxy	54.779	51:372	
3C 120	Seyfert 1 Galaxy	5.354	68:298	
3C 273	Seyfert 1 Galaxy	2.052	187:278	
3C 279	Chesear	5.789	194:047	
3C 686	BL Lac	-4.95	336:447	
3C 654.3	Chesear	16.148	343:491	

Analyzed time windows

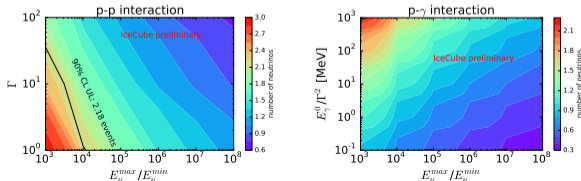
Sortable table

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

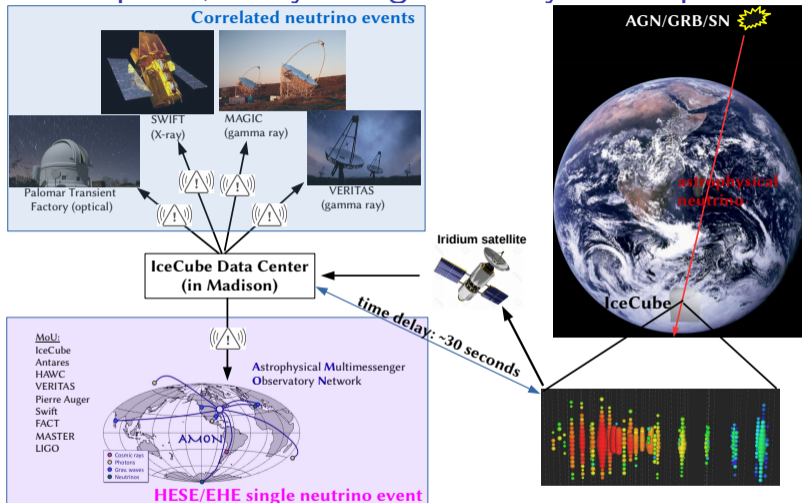


no significant result, p-value 19%
→ constraints on hadronic model

<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

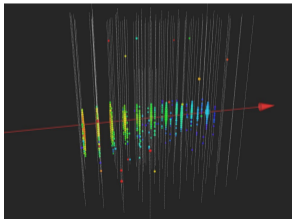
IceCube-170922A: Extremely High Energy event detected by IceCube on 22nd September 2017

→ EHE alert sent to AMON via GCN

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

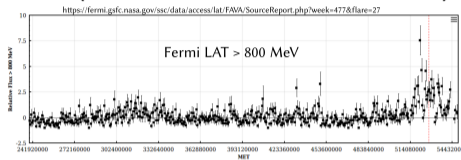
Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

E proxy of about 120 TeV



- Paper in preparation

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



Apple Podcasts
GCN BUCS
Other
ATel on Twitter and Facebook
ATel on LinkedIn
ATel Community Site

The Astronomer's Telegram
Post | Search | Policies
Credential | Needs | Email
23 May 2018: 12:49 UT
This space is free for your conference.

[Previous | Next | ADS]

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817: **Razmik Mirzoyan for the MAGIC Collaboration** on **4 Oct 2017; 17:17 UT**
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Twitter | ResearchGate

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), Lami et al., *Astron. J.*, 139, 1695-1712 (2010)), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event.

Related:
11409 Optical and near-infrared polarimetric observations of the IceCube-170922A counterpart candidate TXS 0506+056
11430 Optical polarimetry of TXS 0506+056 (possible counterpart of IceCube-170922A)
11410 Fermi-LAT detection of enhanced gamma-ray activity and hard spectrum of TXS 0506+056, located inside the IceCube-170922A error region
10942 IceCube-171106A Swift observations
10890 Subaru/FOCAS Optical Spectroscopy for a possible IceCube-170922A counterpart TXS 0506+056
10861 VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event
10845 Jlist Swift XRT and NuSTAR Observations of TXS 0506+056
10844 Kanata optical imaging and spectroscopy

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

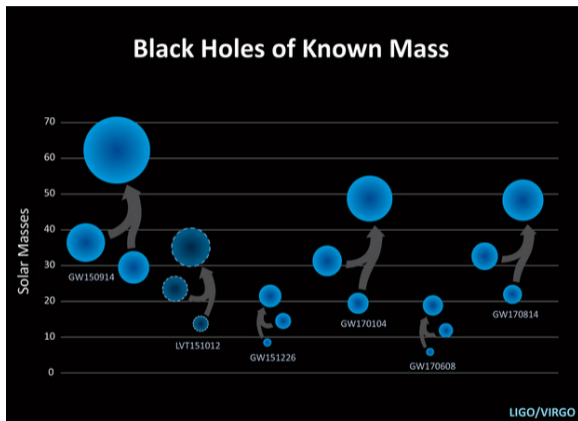
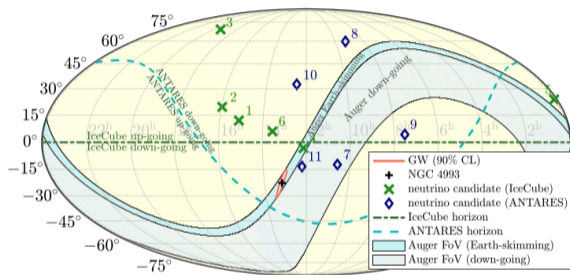


Image credit: www.ligo.caltech.edu/images

→ 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. D*93, 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

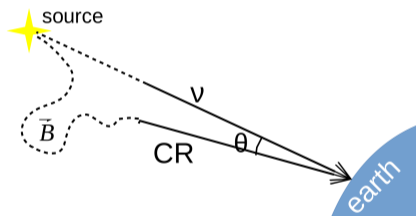
Pierre Auger results:

- 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

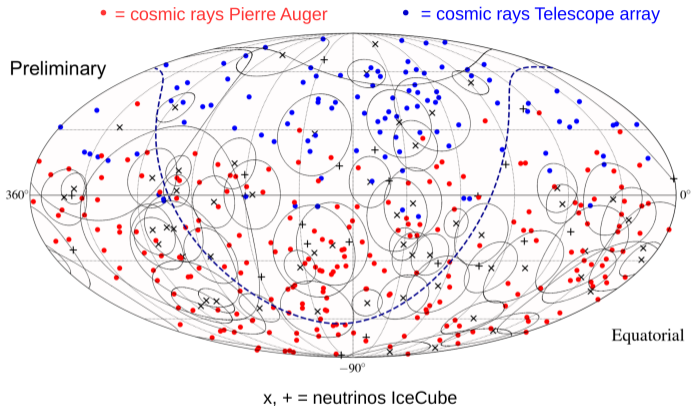


Data sample		
cosmic rays	Telescope array Pierre Auger	$E_{CR} > 50 \text{ EeV}$
neutrinos	IceCube	$E_{\mu} > 200 \text{ TeV}$

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

→ most significant result

Correlation with ultrahigh-energy cosmic rays

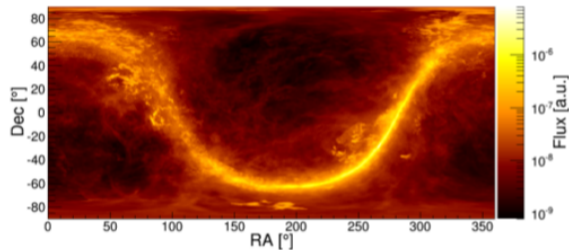


- ▶ previous analysis: $\sim 3\sigma$
- ▶ This analysis = addition of 2 years of IceCube data: $\sim 2\sigma$

→ 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**?



Astrophys.J. 849 (2017) 67

Analysis method:

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

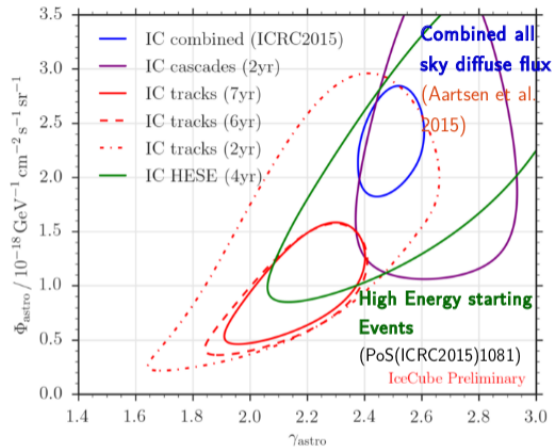
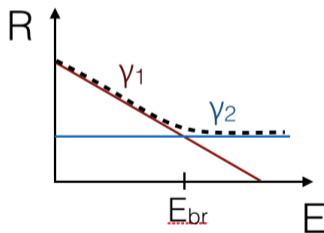
< 14% of astrophysical flux can come from Galactic plane

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

Spectral index γ_{astro}

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

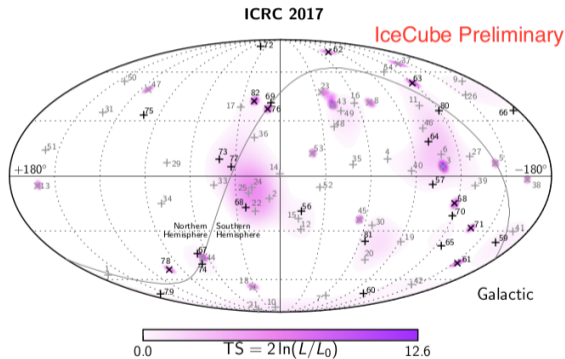
→ tension : could indicate a
broken power law



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

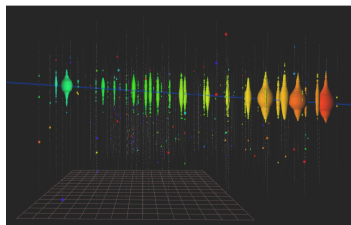
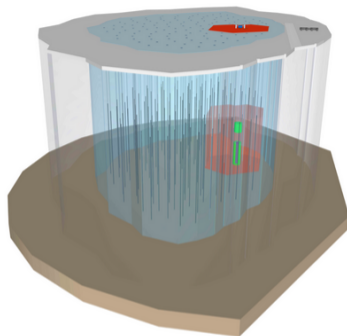
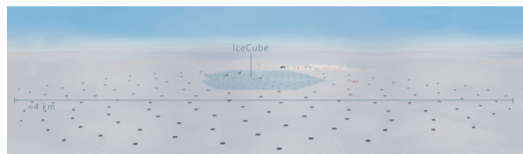
Looking for sources with HESE

- 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

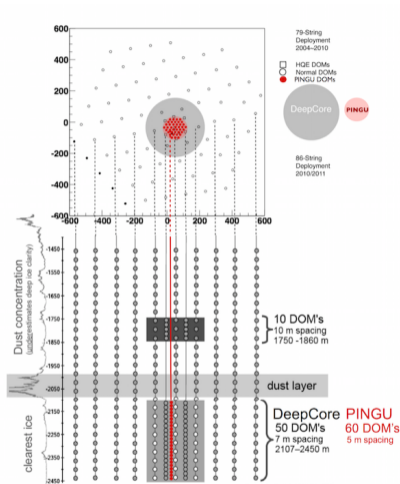


No significant result: p-values of 44% and 77% for the shower-only and the all-events test → constraint on energy is very strict: too few events

IceCube-Gen2



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



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