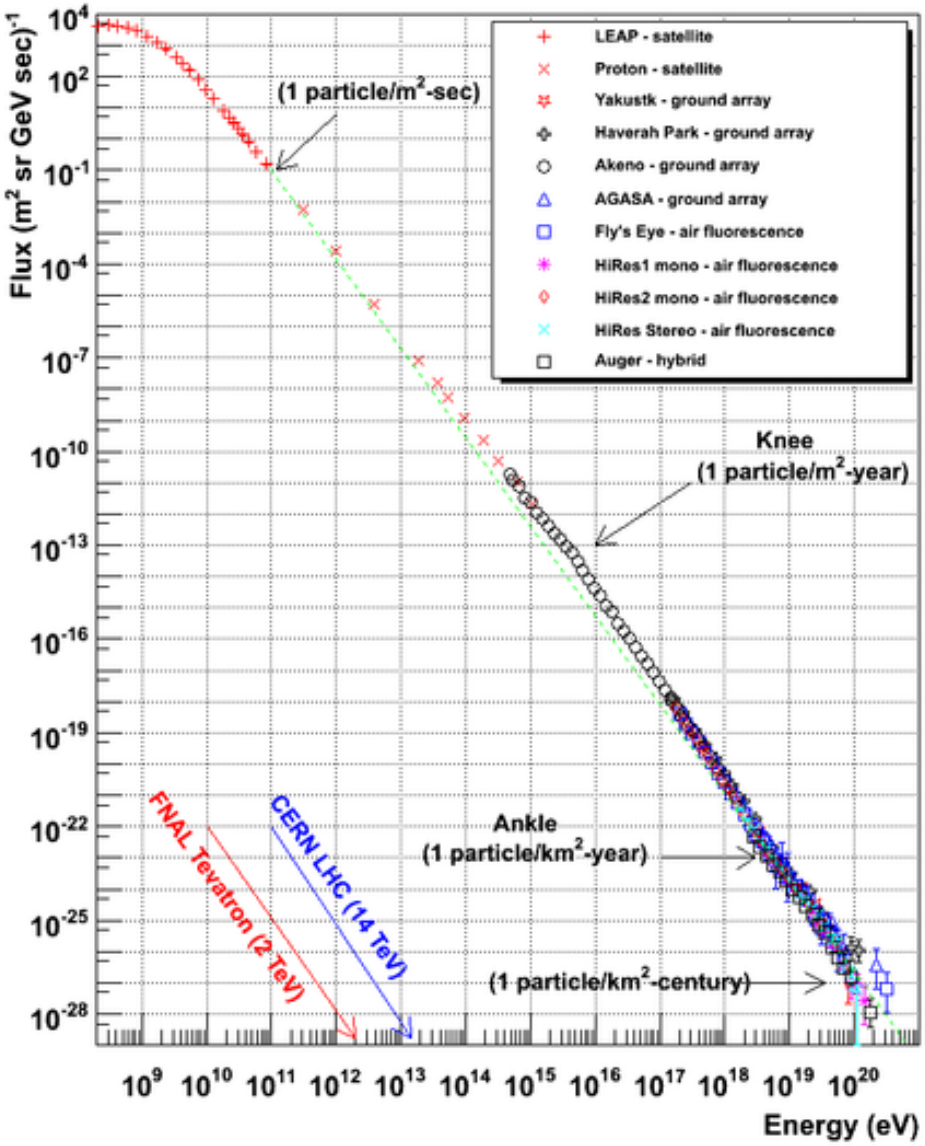
Astrophysical neutrino searches with IceCube

Stéphanie Bron, Teresa Montaruli

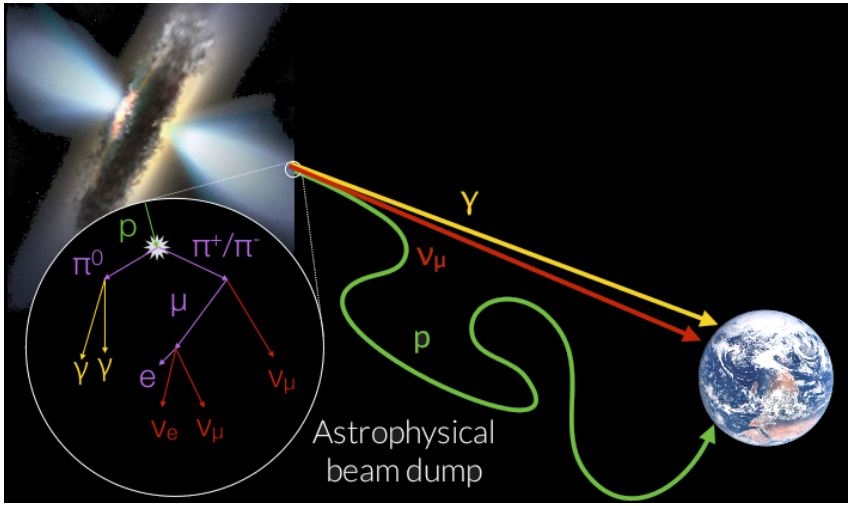
Joint Annual Meeting of SPS and APS
August 24, 2017

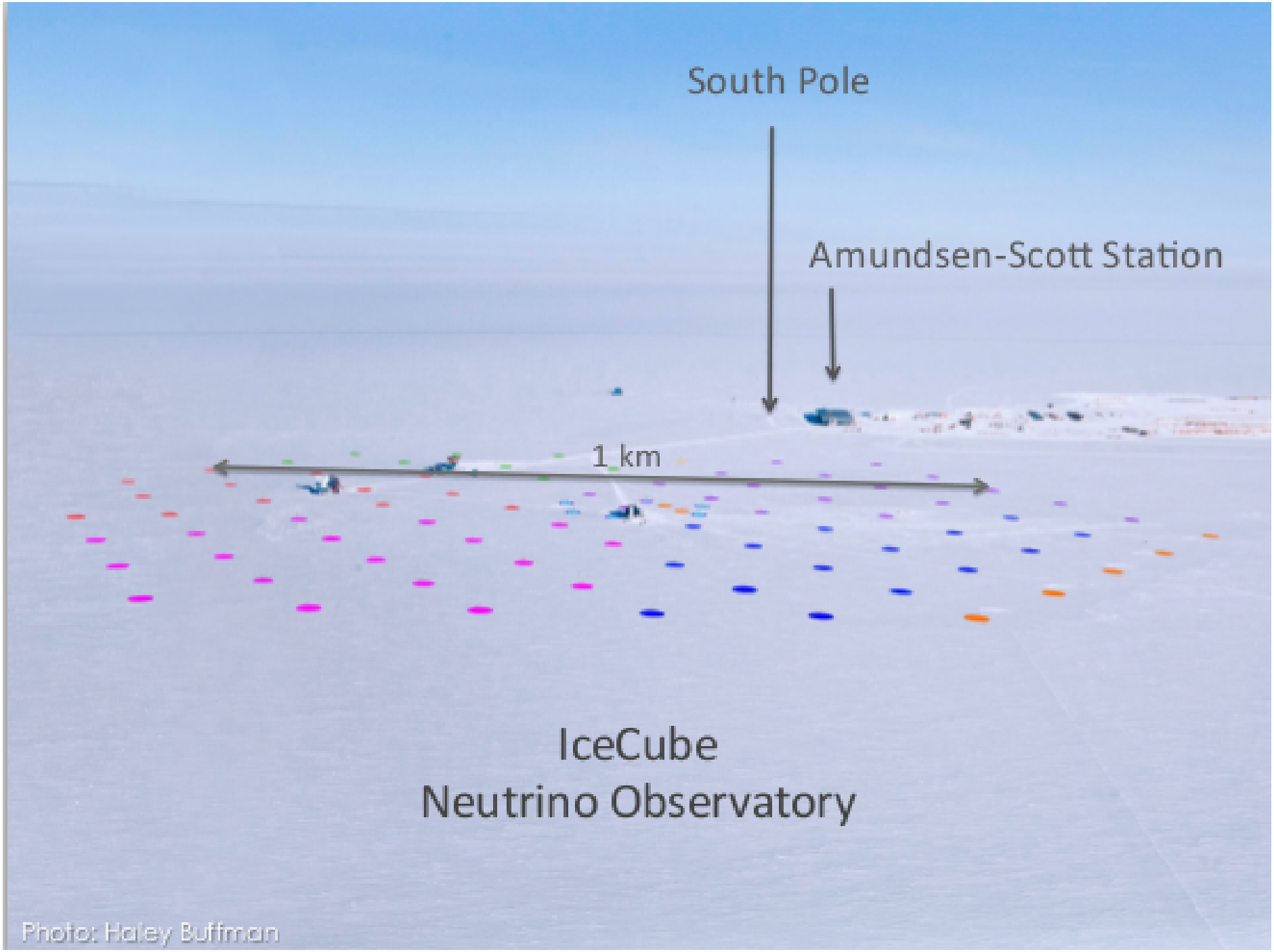
Cosmic ray spectrum



How to find **cosmic ray sources**?

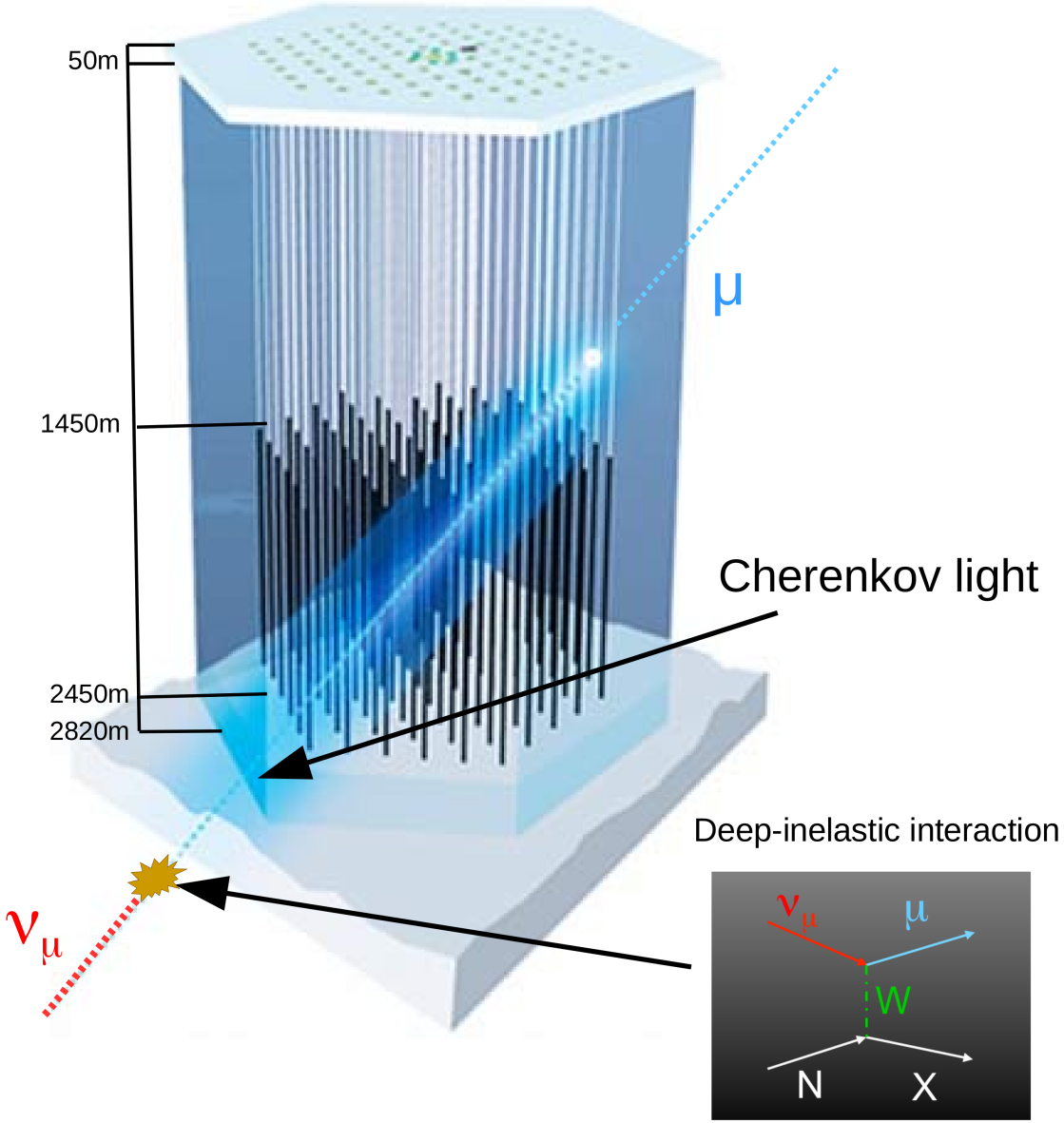
- Cosmic rays (= nuclei) are deflected by magnetic fields
- Gamma rays are absorbed
- Neutrinos travel undeflected, only candidate to point back at sources




South Pole
Amundsen-Scott Station
1 km
IceCube
Neutrino Observatory
Photo: Haley Buffman

IceCube experiment

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



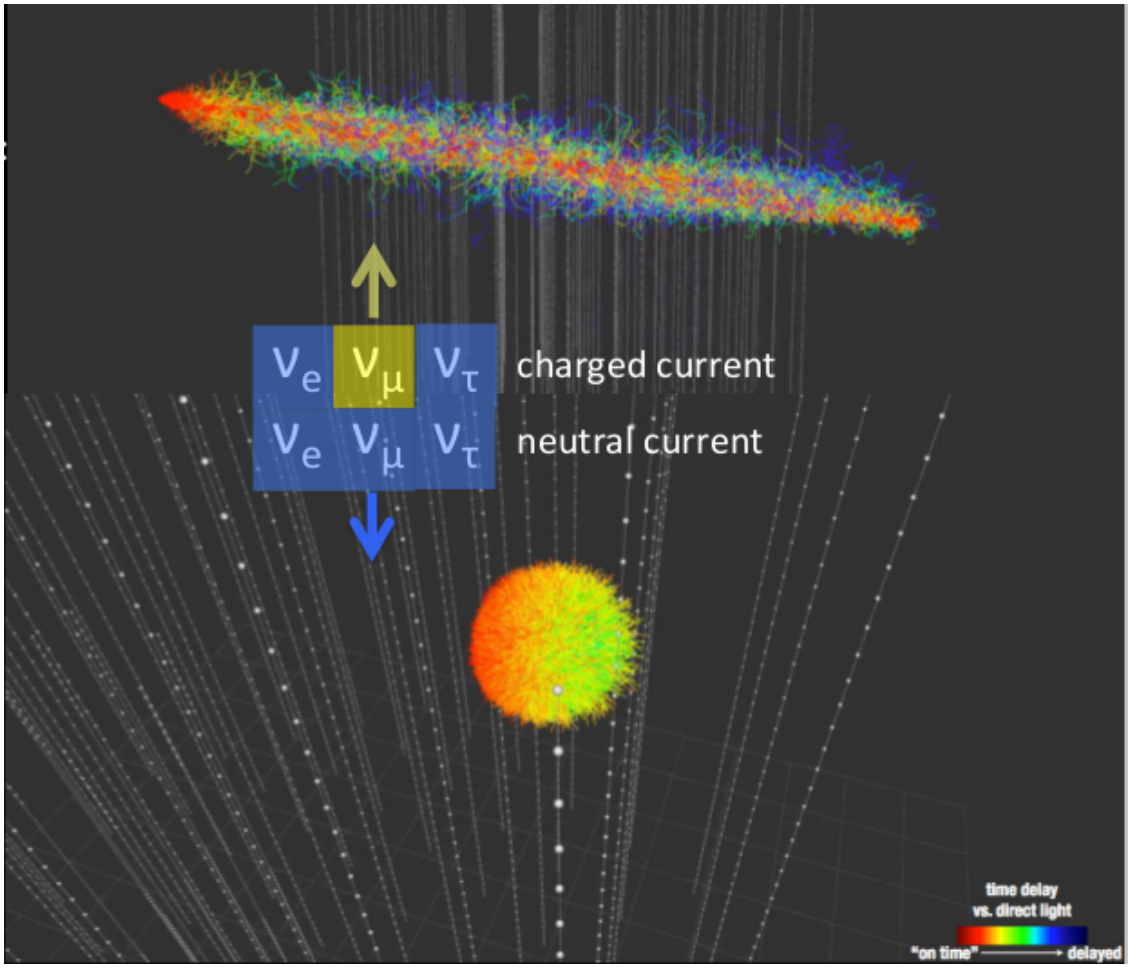
Neutrino events in the detector

Tracks

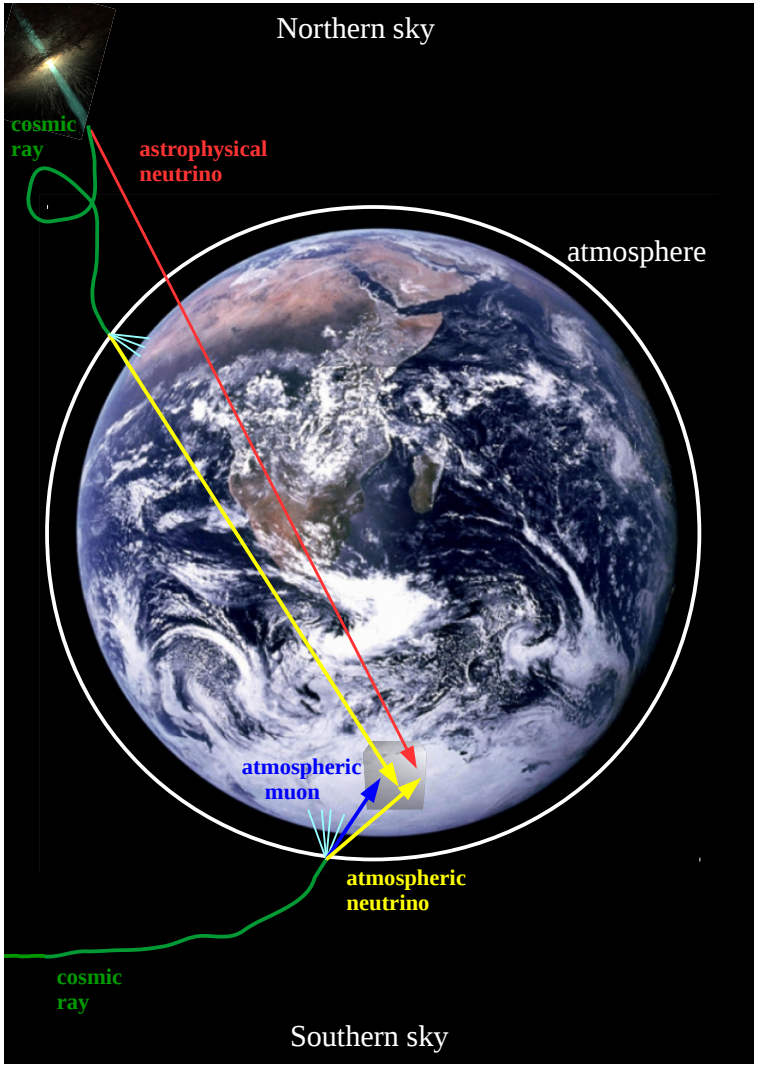
- angular resolution $\sim 1^\circ$
- poor energy resolution

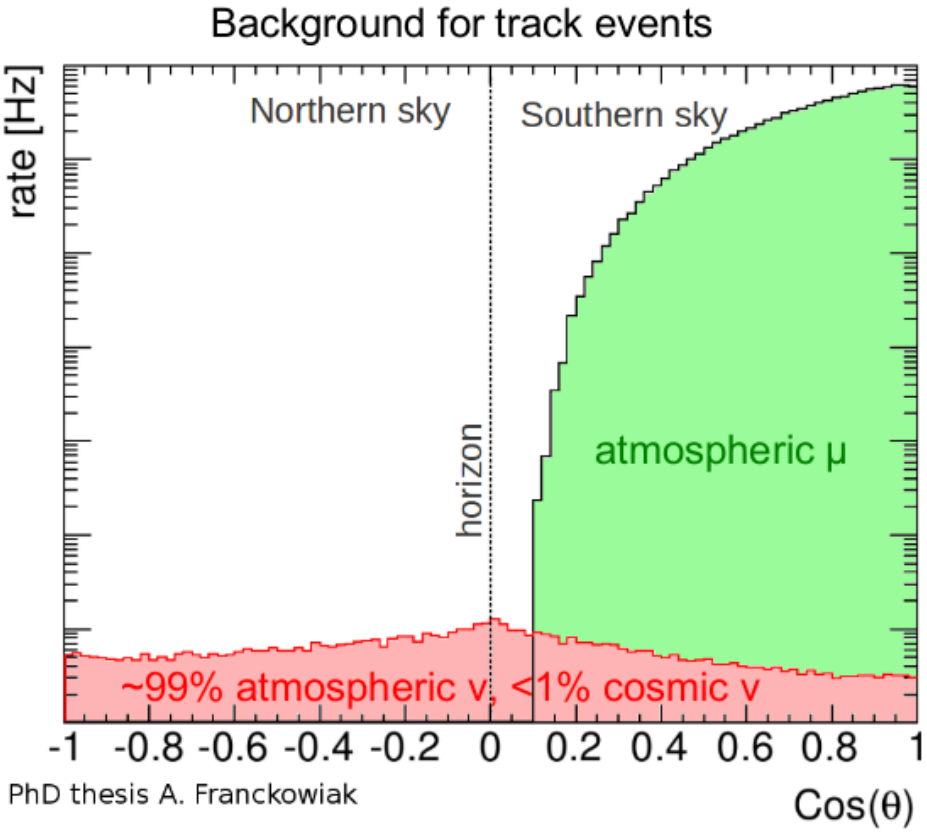
Cascades

- angular resolution $\sim 10^\circ$
- good energy resolution



Background and signal in IceCube





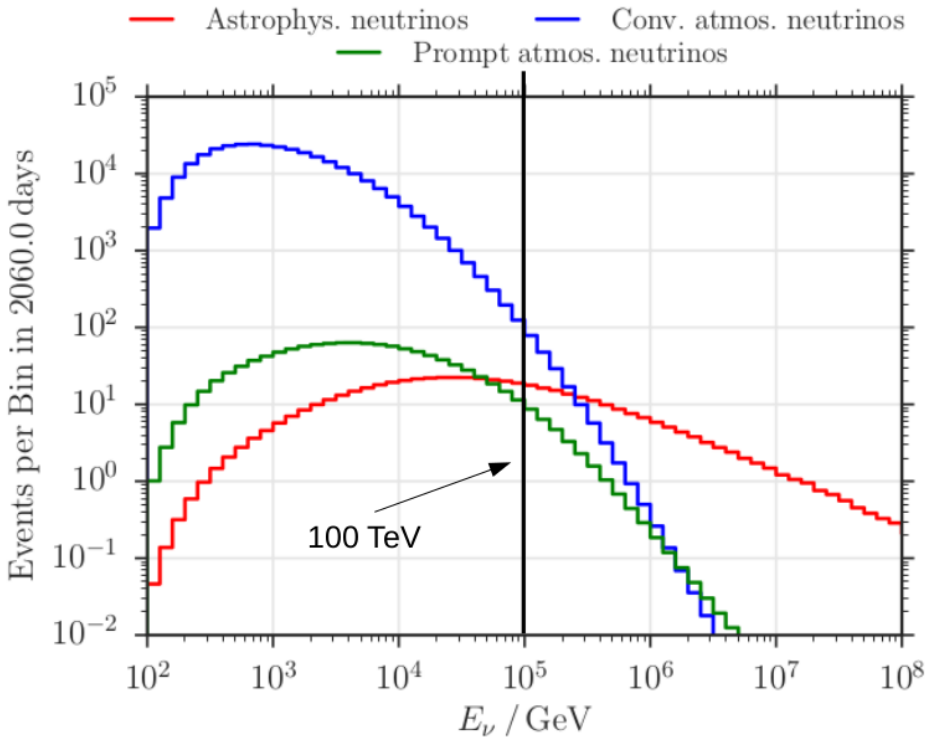
- $E_\nu > 10$ GeV
- μ rate: 2.5 kHz - ν rate $\sim$ mHz
- $\sim$ 100'000 high energy ν/year

The IceCube neutrino flux

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

Prompt atmospheric neutrinos
from charm

Astrophysical neutrinos
dominant > 100 TeV



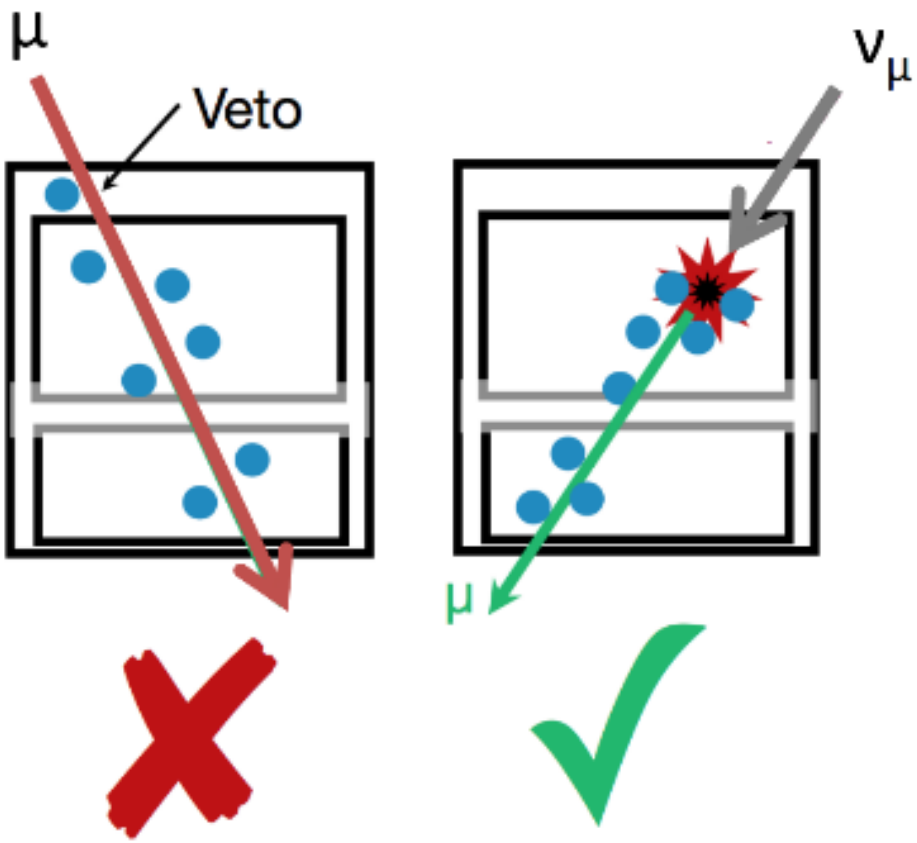
Aartsen et Al., astro-ph.HE (2017)

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

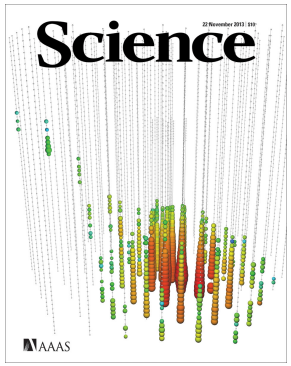
$$\frac{d\phi}{dE} = \phi_0 \cdot \left(\frac{E}{100\text{TeV}}\right)^{-\gamma_{astro}}$$

*ϕ_0, γ_{astro} = free parameters that are fit in analyses

Isolating astrophysical signal

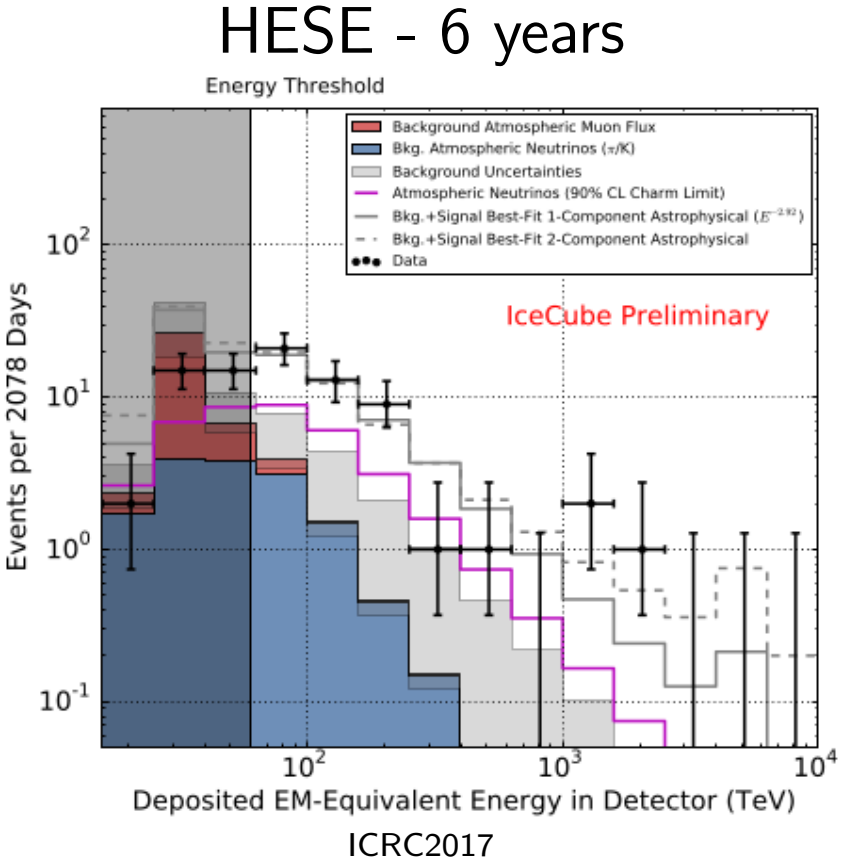


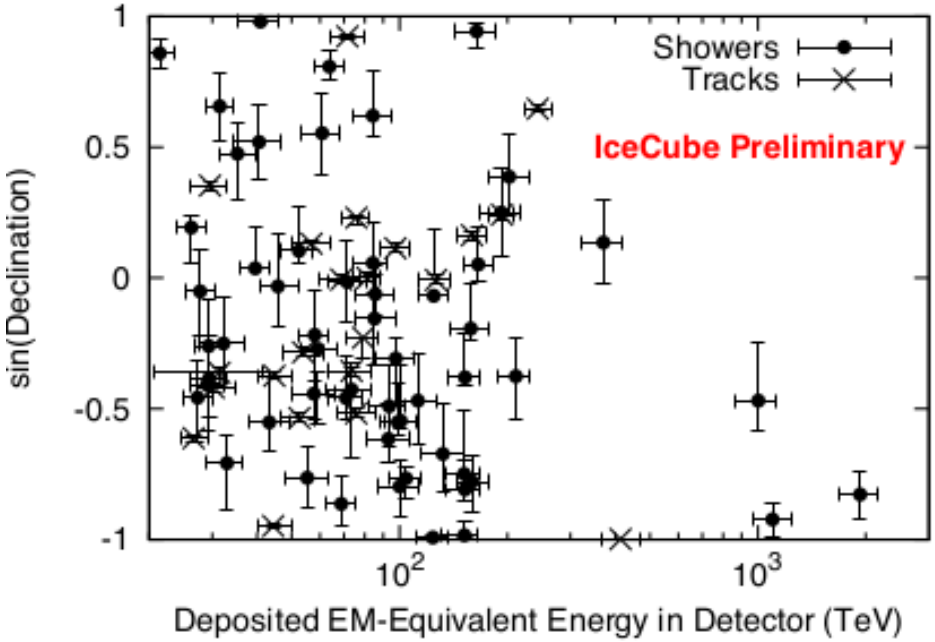
- event starts inside detector
  $\rightarrow$ reduces muon background
- energy threshold $\sim$ 60 TeV
  $\rightarrow$ increases purity
- this selection is called **H**igh **E**nergy **S**tarting **E**vents (**HESE**)



https://arxiv.org/abs/1311.5238

Latest results of HESE



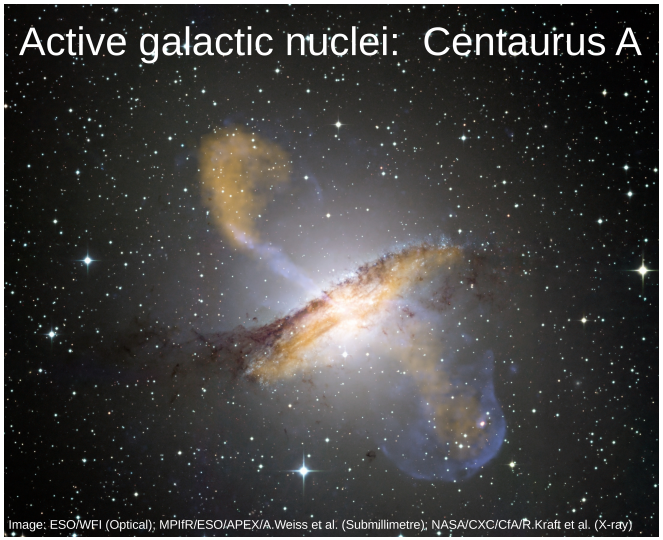


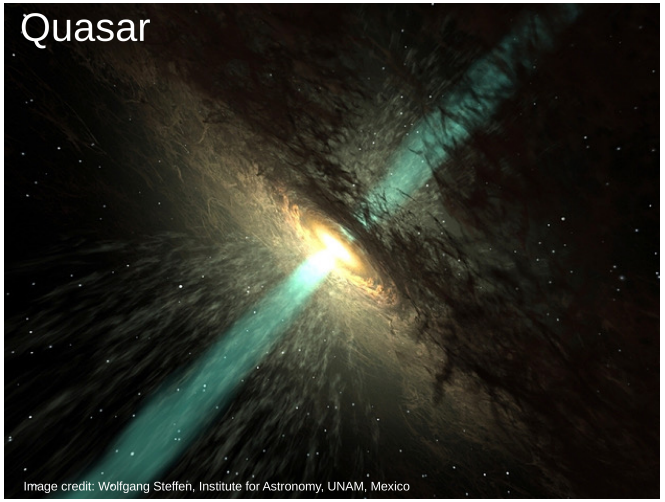
- 80 events observed
- $15.6^{+11.4}_{-3.9}$ atmospheric neutrinos
- 25.2 ± 7.3 atmospheric muons

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

There is an astrophysical flux...

So what produces it??





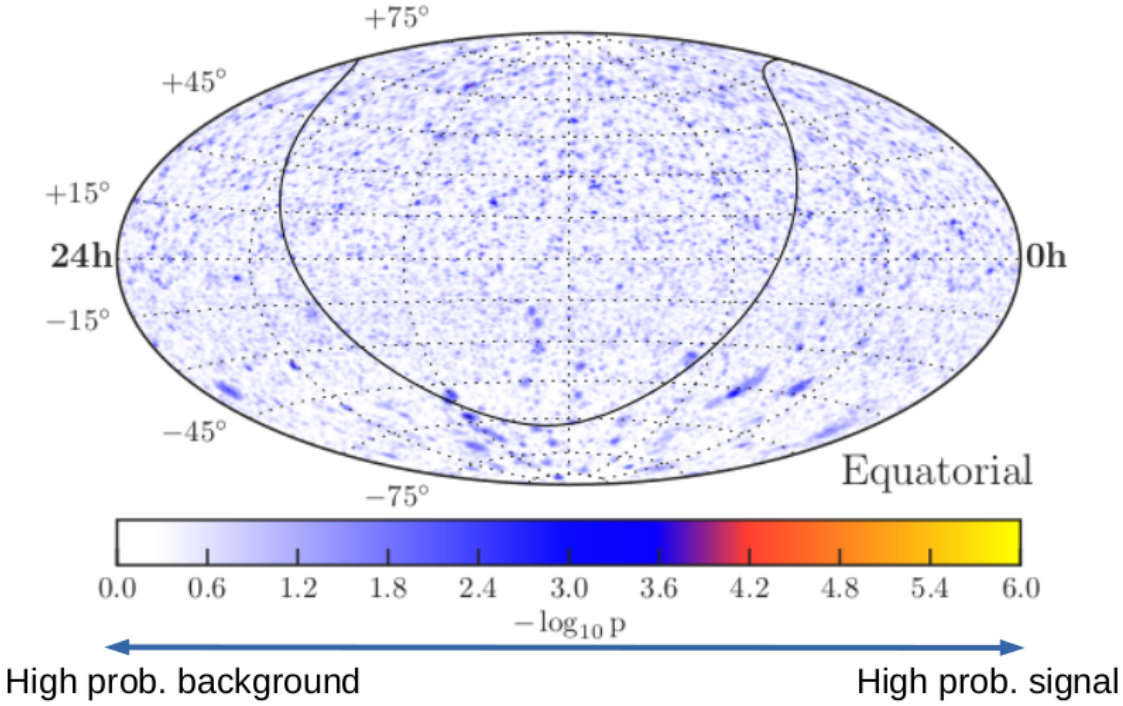
Search for point sources

Time integrated

- Hypothesis: neutrino source = clustering of events in the sky
- HESE: strict constraint on energy → few events
- Use bigger sample starting from $E_\nu > 1$ TeV
- need the best pointing: tracks

7 years of IceCube data

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



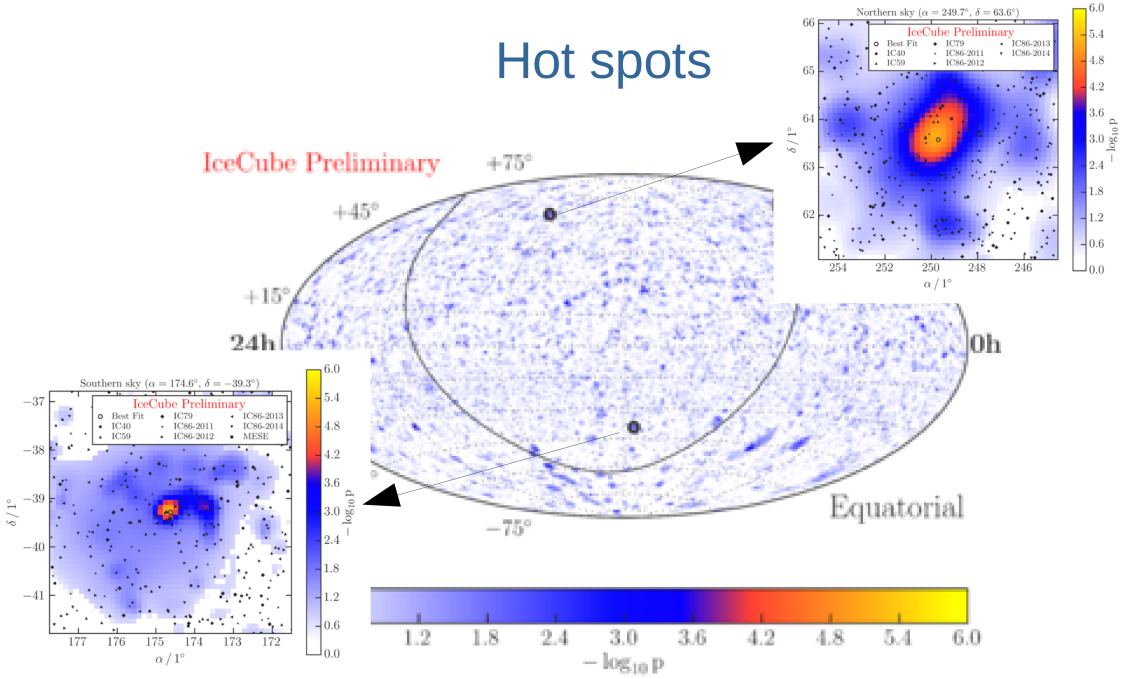
each point = probability that clustering is fluctuation of background

Unbinned likelihood method: Point source searches

- data = mixture of signal and background:
  $\mathcal{L}(\vec{r}_{src}, n_s, \gamma) = \sum_N (\frac{n_s}{N} S_i + \frac{1-n_s}{N} B_i)$, n_s=number of signal event

Search for point sources

Time integrated



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

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

→ no significant spatial clustering found!

Search for point sources

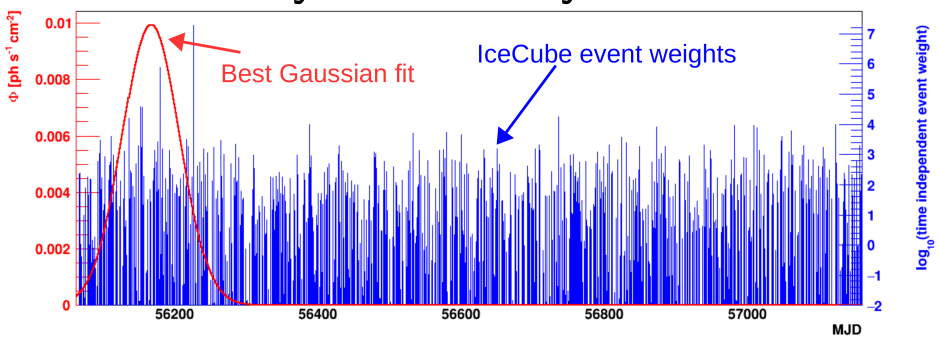
Time dependent - Gaussian flare

- Hypothesis: time clustering of events at time T_0 around a Gaussian with width σ_T
- Add time PDF, T_i^{sig}

Signal PDF: time dependent

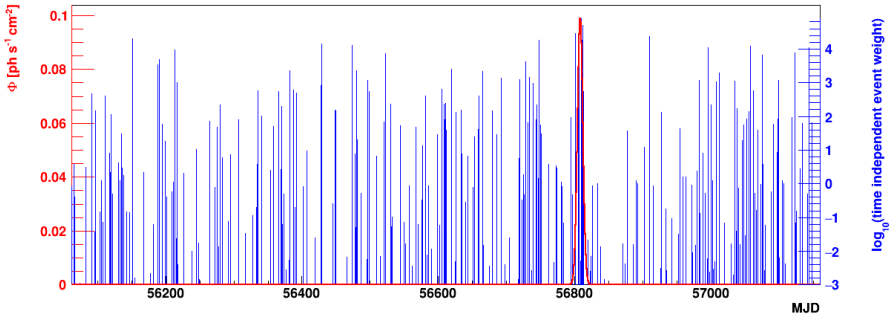
- $S_i = P_i^{sig}(\sigma_i, \vec{r}_i | \vec{r}_{src}) \cdot \epsilon_i^{sig}(E_i, \delta_i | \gamma) \cdot T_i^{sig}$
- 4 free params: n_s, γ, T_0, σ_T

May 2013-May 2015



Best Gaussian fit - North Hemisphere

- p-value: 16%



Best Gaussian fit - South Hemisphere

- p-value: 23%

→ no significant time clustering found!

Search for point sources

Time dependent - Gamma-ray flare

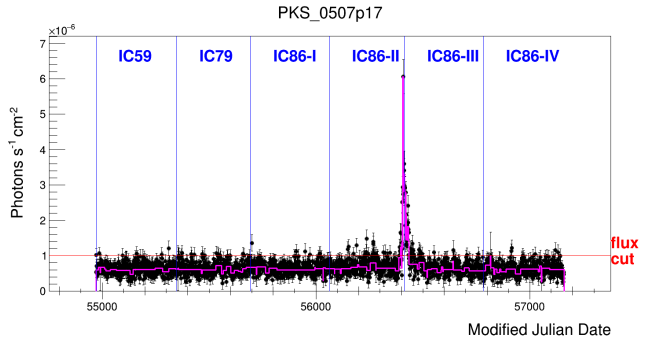
- Hypothesis: time clustering of events in coincidence with gamma-ray flare of selected transient sources from Fermi-LAT
- E_γ range: $\sim$ 100 MeV-300 GeV
- Add time PDF, T_i^{sig}

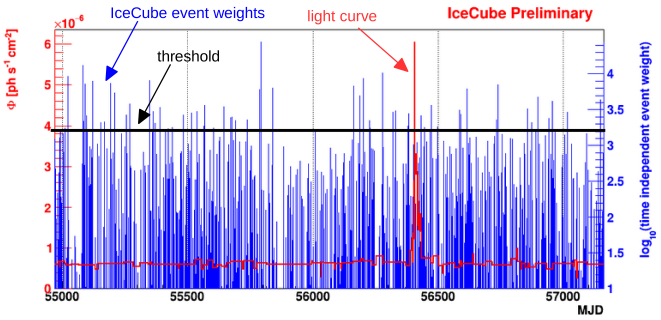
Signal PDF: time dependent

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

$\rightarrow$ no significant correlation found!

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





$\rightarrow$ p-value: 30.18%

Search for point sources

Time dependent - Gamma-ray flare

- 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}

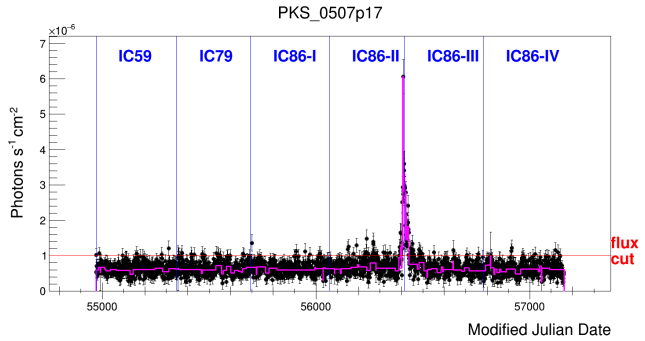
Signal PDF: time dependent

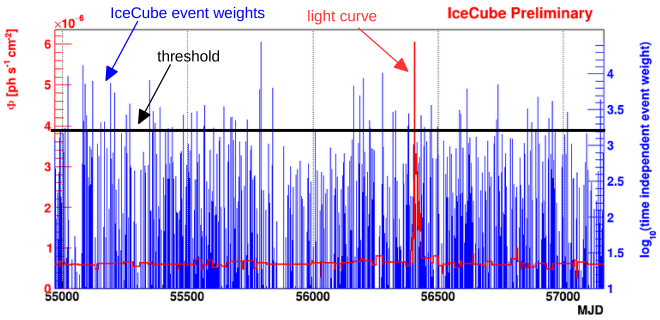
- $S_i = P_i^{sig}(\sigma_i, \vec{r}_i | \vec{r}_{src}) \cdot \epsilon_i^{sig}(E_i, \delta_i | \gamma) \cdot T_i^{sig}$
- 4 free params: n_s, γ, threshold, lag

$\rightarrow$ no significant correlation found!

- Same analysis on shorter time scale: 1 month
- Automatic analysis from source selection to results on webpage
- Ongoing analysis: no results yet

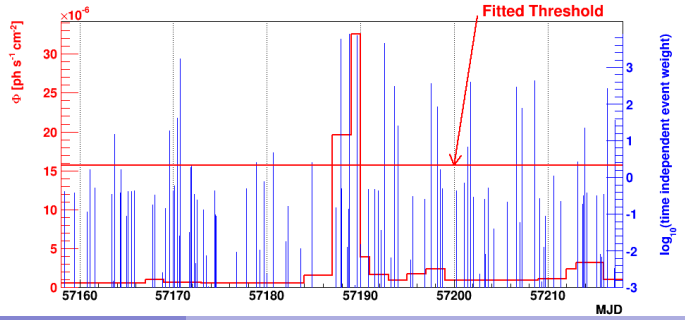
May 2009-May 2015
Most significant source: blazar PKS 0507+17





$\rightarrow$ p-value: 30.18%

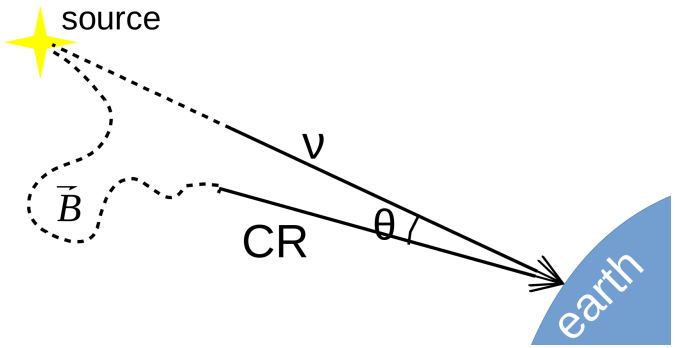
May-July 2015



Search for point sources

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

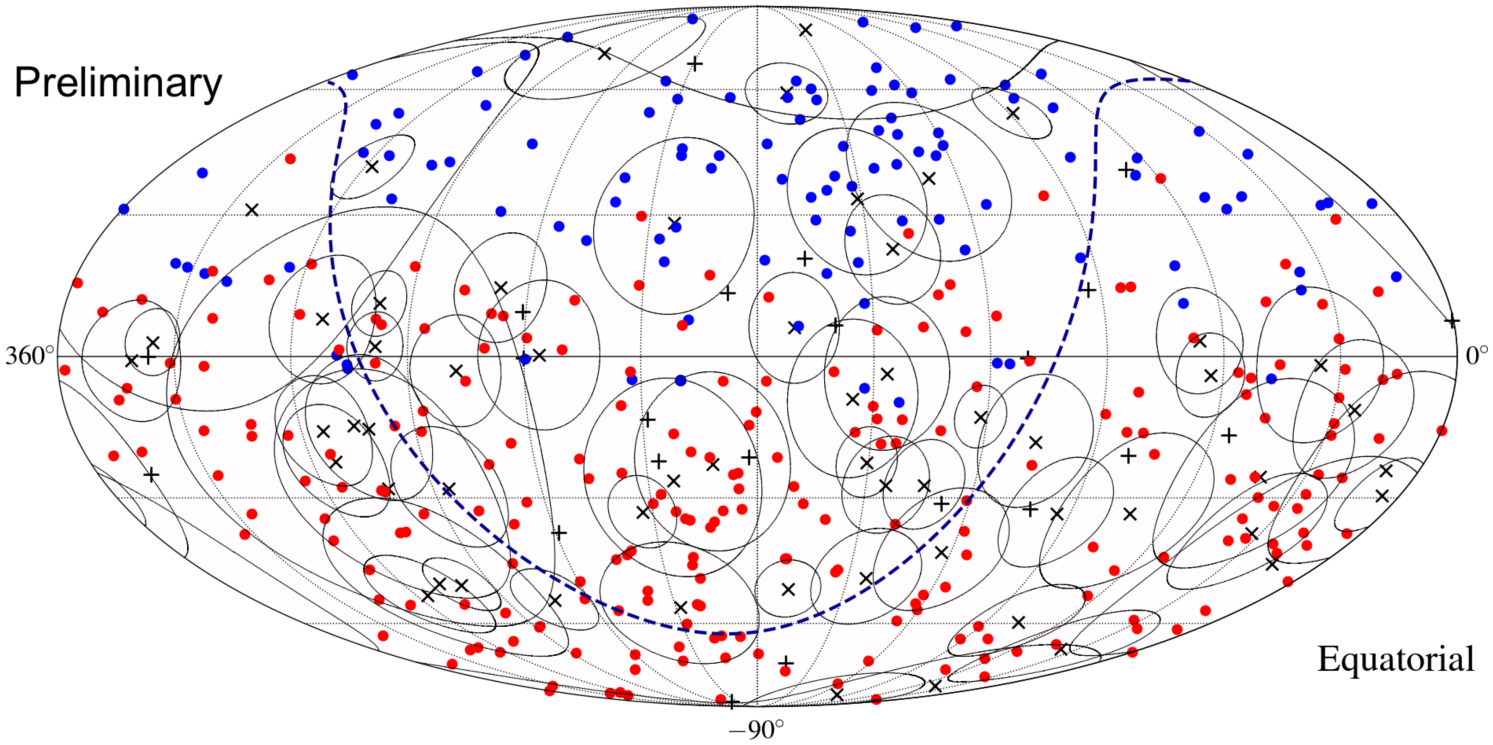
Tested deflection hypotheses: $\theta = [3^\circ, \boxed{6^\circ}, 9^\circ] \cdot 100\ \mathrm{EeV}/E_{CR}$

$\rightarrow$ most significant result

Search for point sources

Correlation with ultrahigh-energy cosmic rays

• = cosmic rays Pierre Auger • = cosmic rays Telescope array



x, + = neutrinos IceCube

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

$\rightarrow$ no significant correlation found!

Summary and outlook

- Diffuse astrophysical flux detected with more than 5σ significance

Summary and outlook

- Diffuse astrophysical flux detected with more than 5σ significance
- Sources of astrophysical neutrinos still unknown

Summary and outlook

- Diffuse astrophysical flux detected with more than 5σ significance
- Sources of astrophysical neutrinos still unknown
- Searches for sources
  - scanning the whole sky
  - correlations in space and time with gamma rays
  - correlations in space with cosmic rays

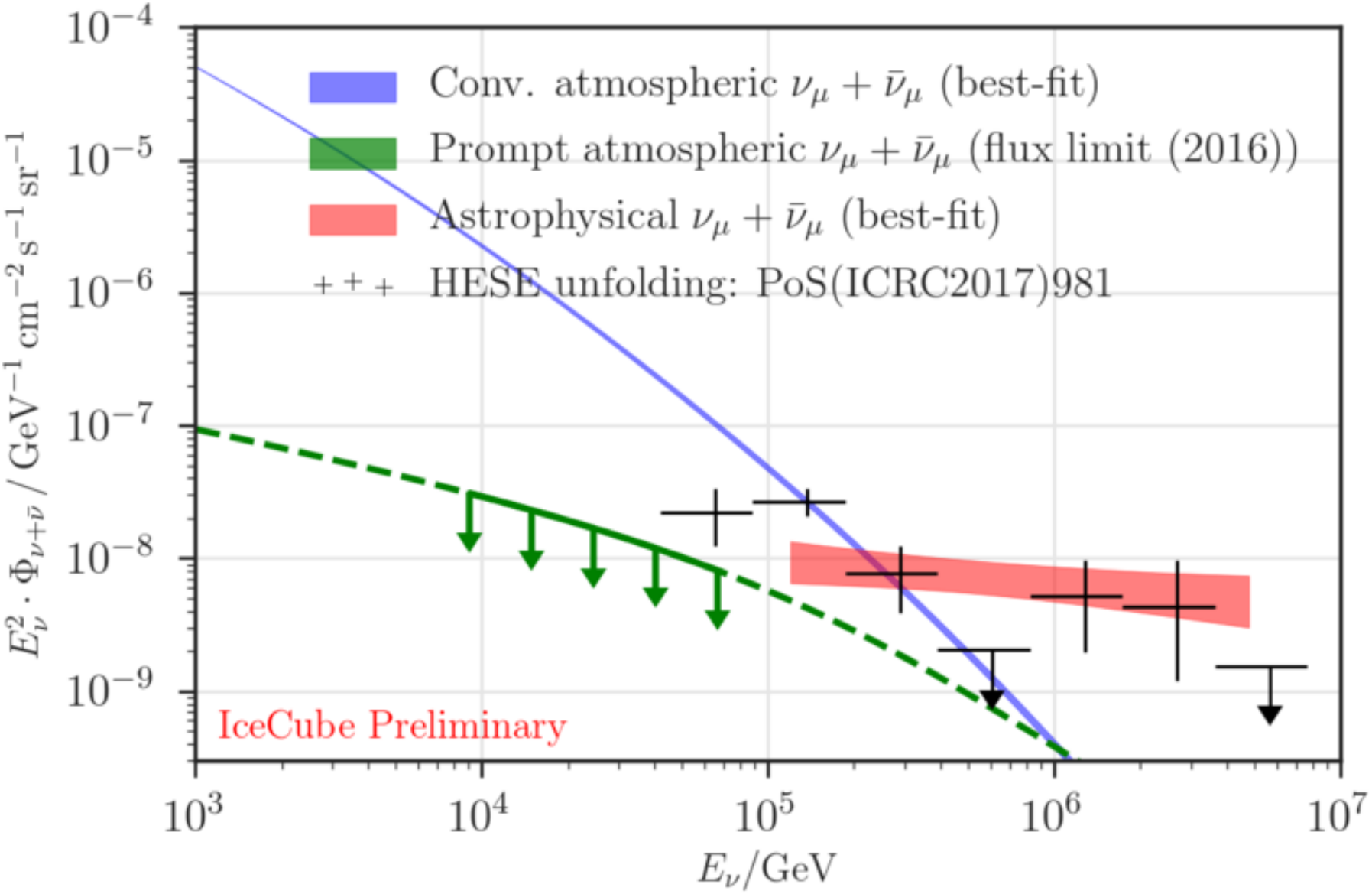
Summary and outlook

- Diffuse astrophysical flux detected with more than 5σ significance
- Sources of astrophysical neutrinos still unknown
- Searches for sources
  - scanning the whole sky
  - correlations in space and time with gamma rays
  - correlations in space with cosmic 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

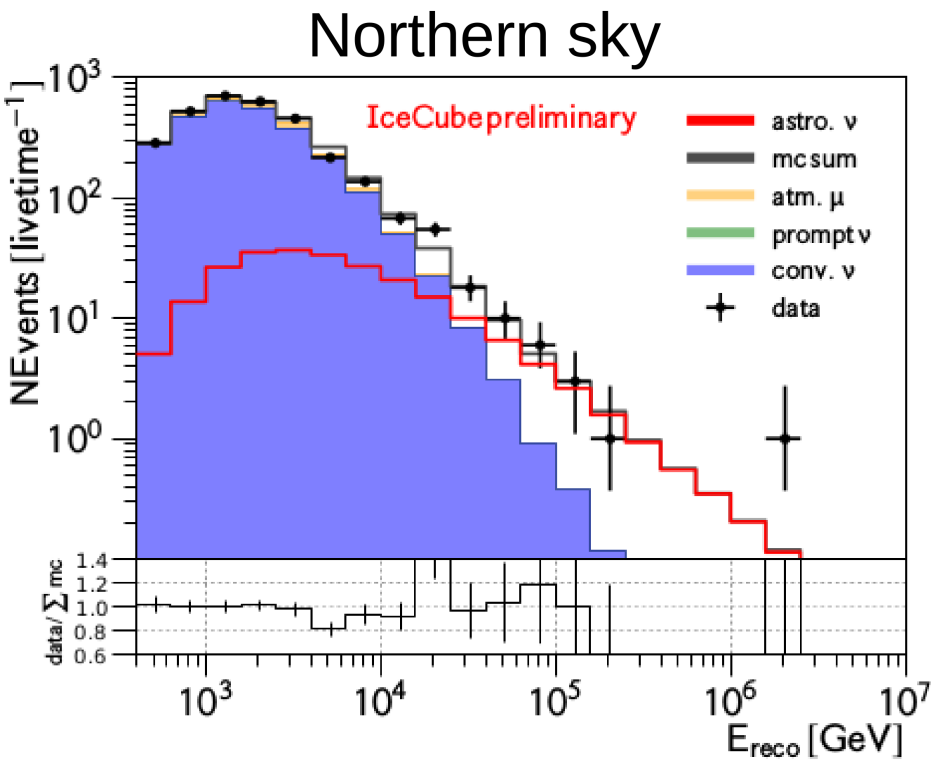
Thank you!

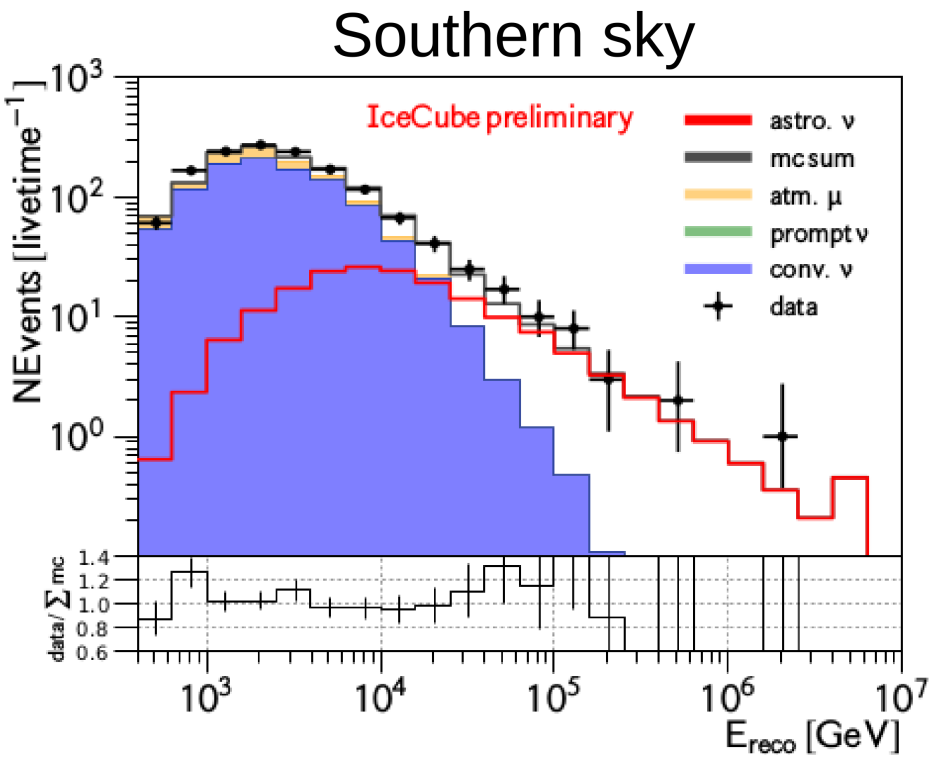
Additional slides

Tracks - 8 years



Cascades - 4 years

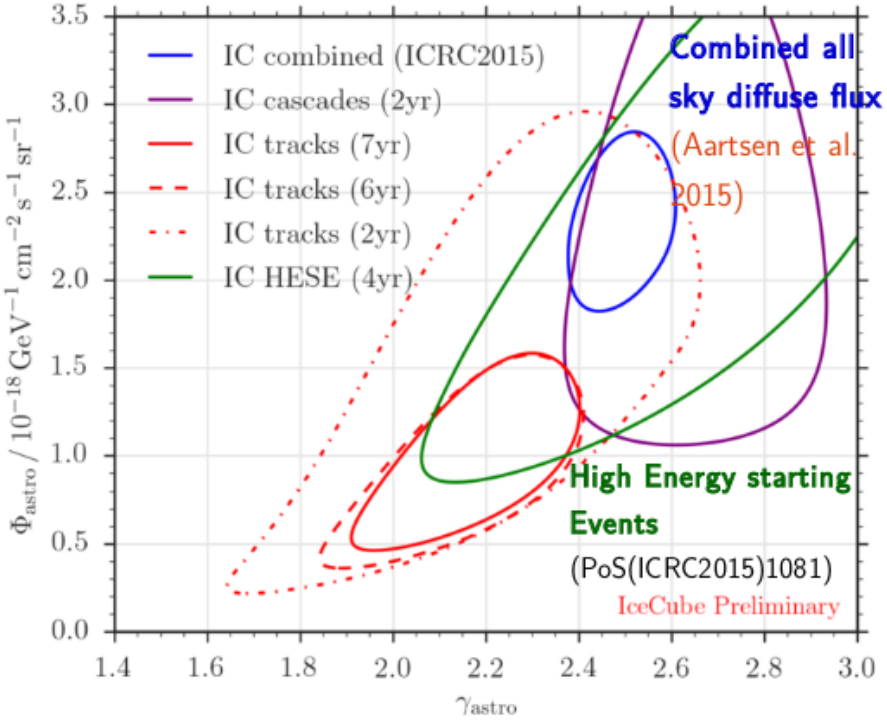




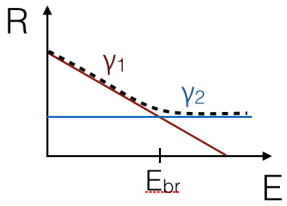
Fit comparison: spectral index γ_{astro}

Warning: Plot made with older data than just presented!

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



$\rightarrow$ tension : broken power law??

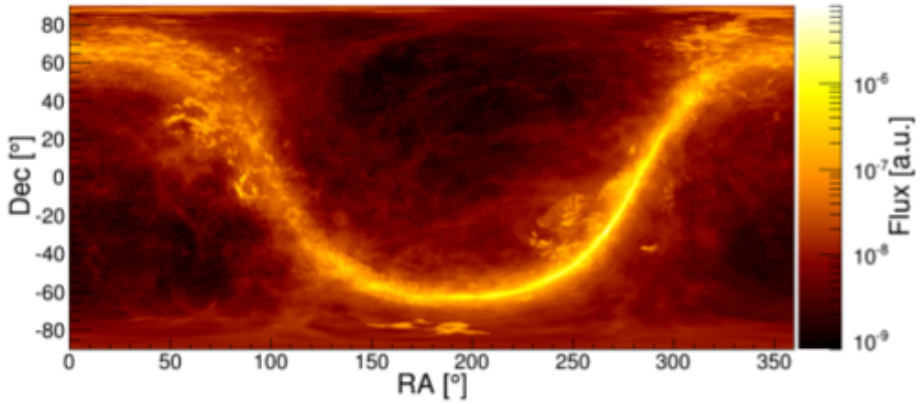


Results of the fit

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

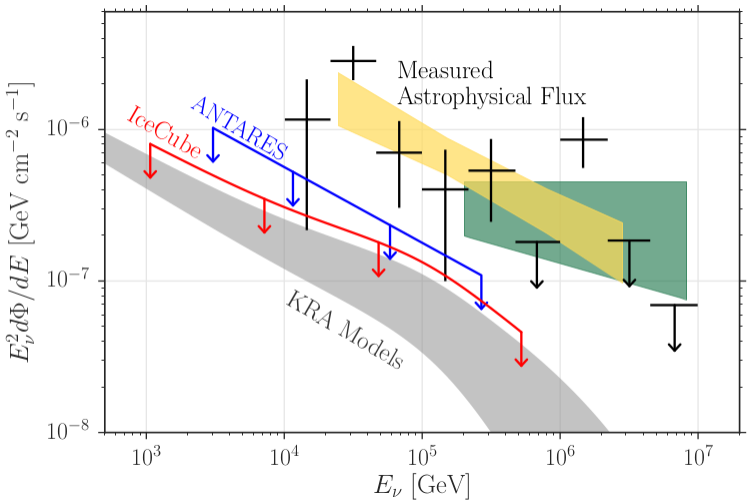
Correlation with galactic plane

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



Analysis method:

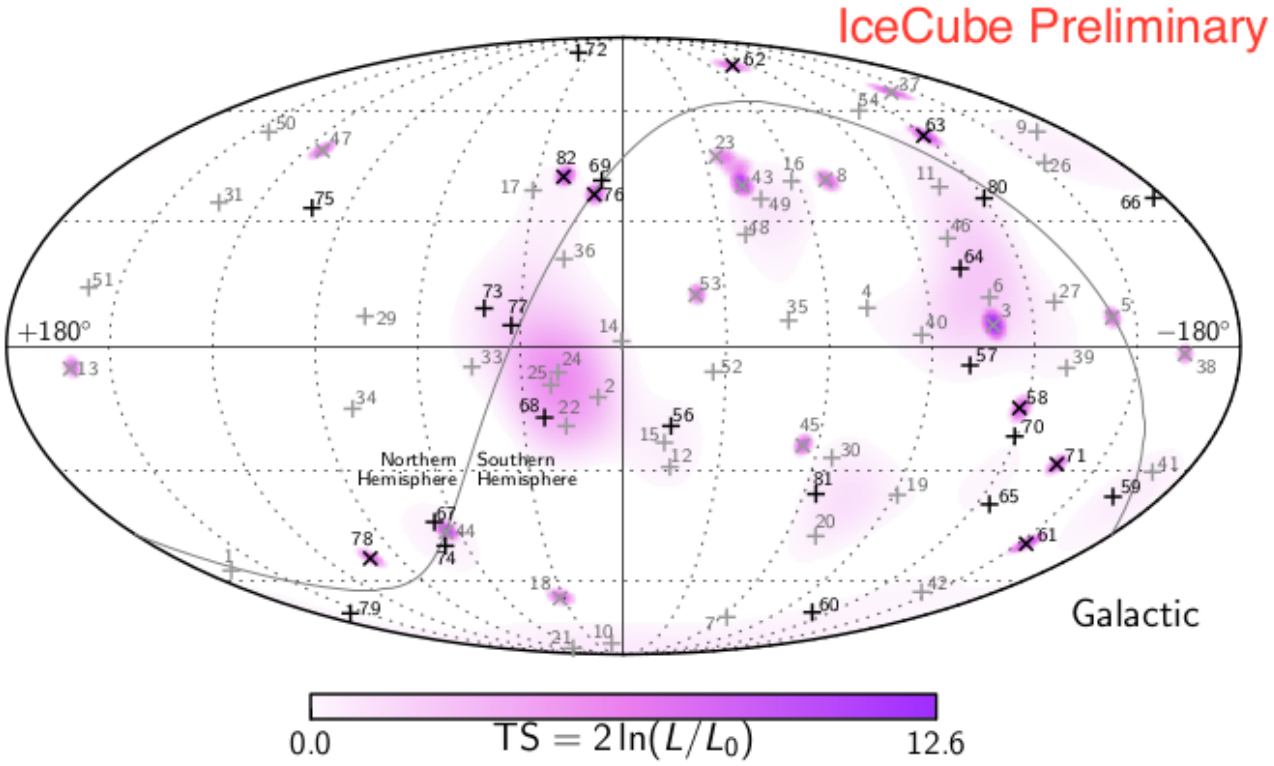
- take models of gamma-ray emission: KRA-γ (50 PeV cutoff) model
- search for anisotropy corresponding to model in neutrino arrival directions



Maximum of 14% of the diffuse flux comes from Galactic plane

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

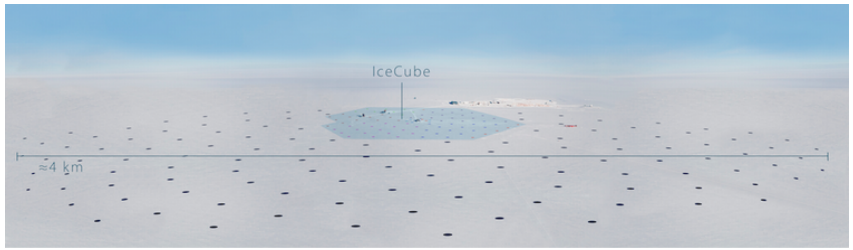


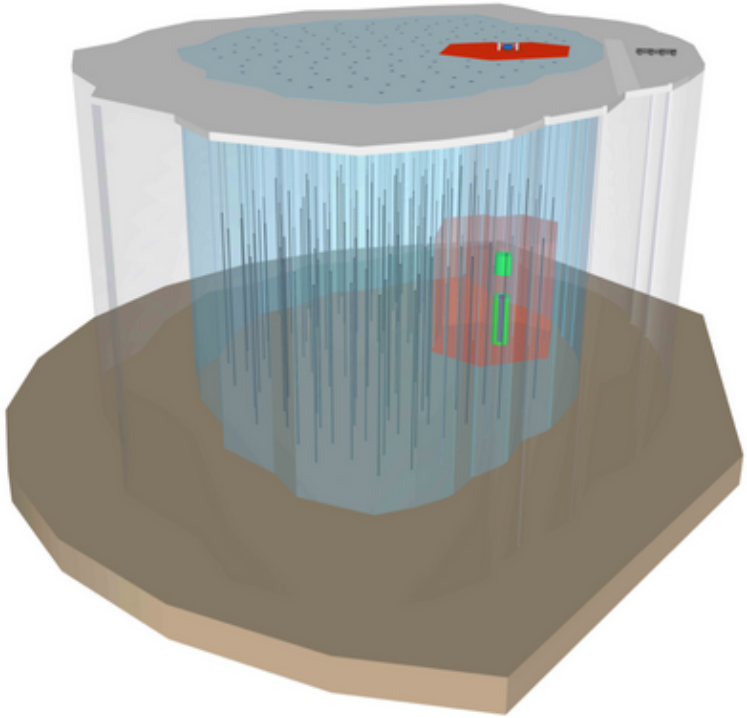
→ constraint on energy is very strict: too few events

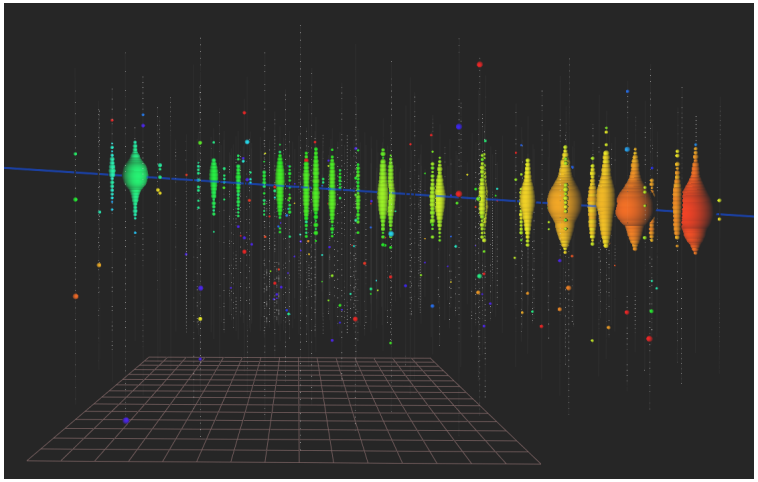
Real time alerts

- HESE/EHE: Single event over a certain energy threshold reconstructed to high level and details sent to Astrophysics Multimessenger Observatory Network
- Optical follow up : Accumulation of events coming from a single point in the sky within 100s targeting SN or GRB. Information sent to PTF, SWIFT and XRT
- Gamma follow up : Accumulation of events coming from a single point in the sky up to 3 weeks from a selection of known AGNs. Information sent to Magic and Veritas.

IceCube-Gen2







→ statistically significant samples

in the PeV to EeV range

Systematic uncertainties

- neutrino detection uncertainties
  - optical efficiency of the detector
  - neutrino-nucleon cross section
  - muon energy loss cross section
  - optical properties of Antartic ice
- atmospheric flux uncertainties
  - flux normalizations
  - spectral shape
  - composition of cosmic-ray spectrum in the knee region
  - spectral index of primary cosmic-ray spectrum
  - relative production of pions and kaons in the atmosphere

Muon energy losses

- Muon energy infered from muon energy losses along its track inside detector
- Below 1 TeV: ionization dominating, cst, Cherenkov light produced $\approx$ independant of energy
- Above 1 TeV: stochastic interactions, most of Cherenkov light produced from secondary particles along the muon's path

Average energy loss of muon

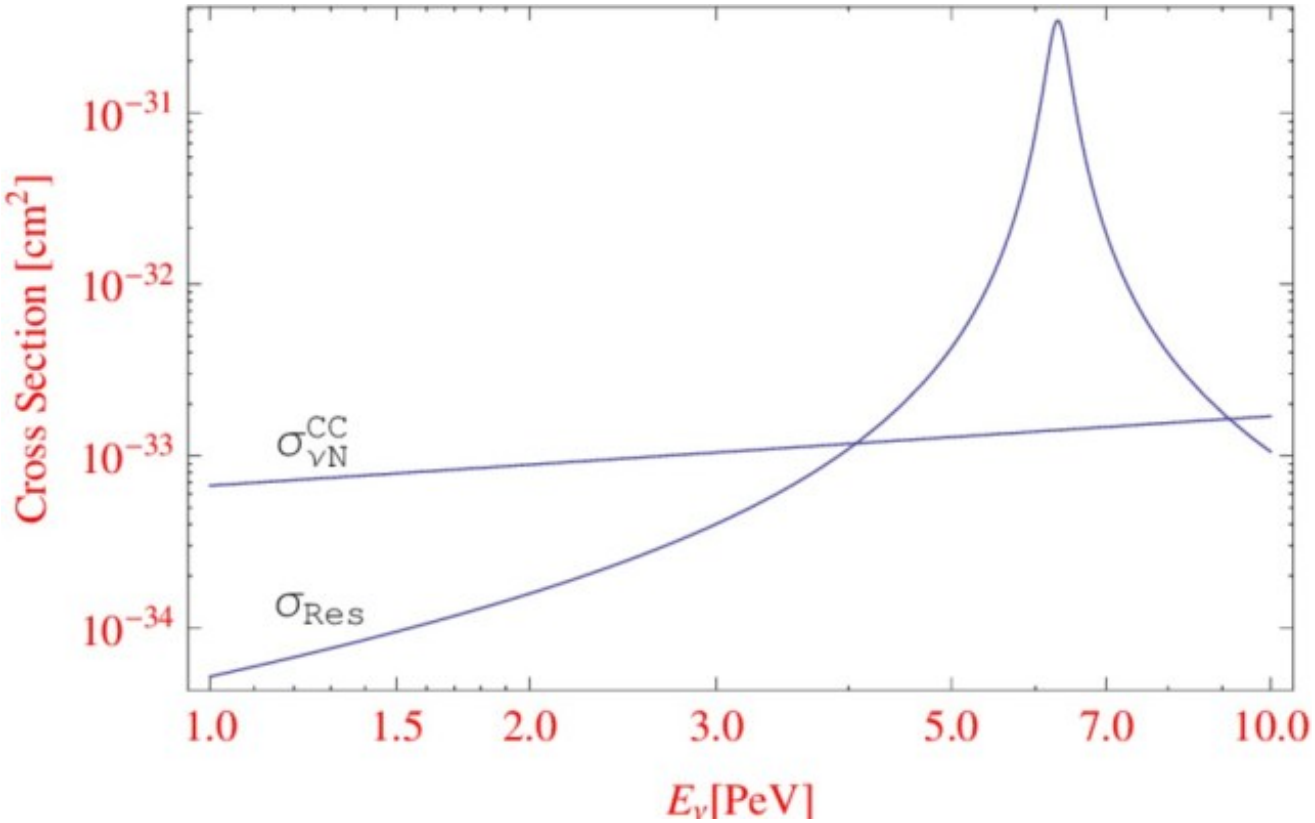
$$\frac{dE_\mu}{dx} = A + BE_\mu$$

$$A = 0.0024\text{GeV } (\text{g/cm}^2)^{-1}, B = 0.000032\text{GeV}(\text{g/cm}^2)^{-1}$$

Compared to expected number of photoelectrons for a fixed energy loss of 1 GeV/m

At TeV energies, muons travel several kilometers in the ice.

Glashow resonance



http://arxiv.org/abs/1407.3255

$\rightarrow$ Glashow resonance events contribute to high energy ν_μ events