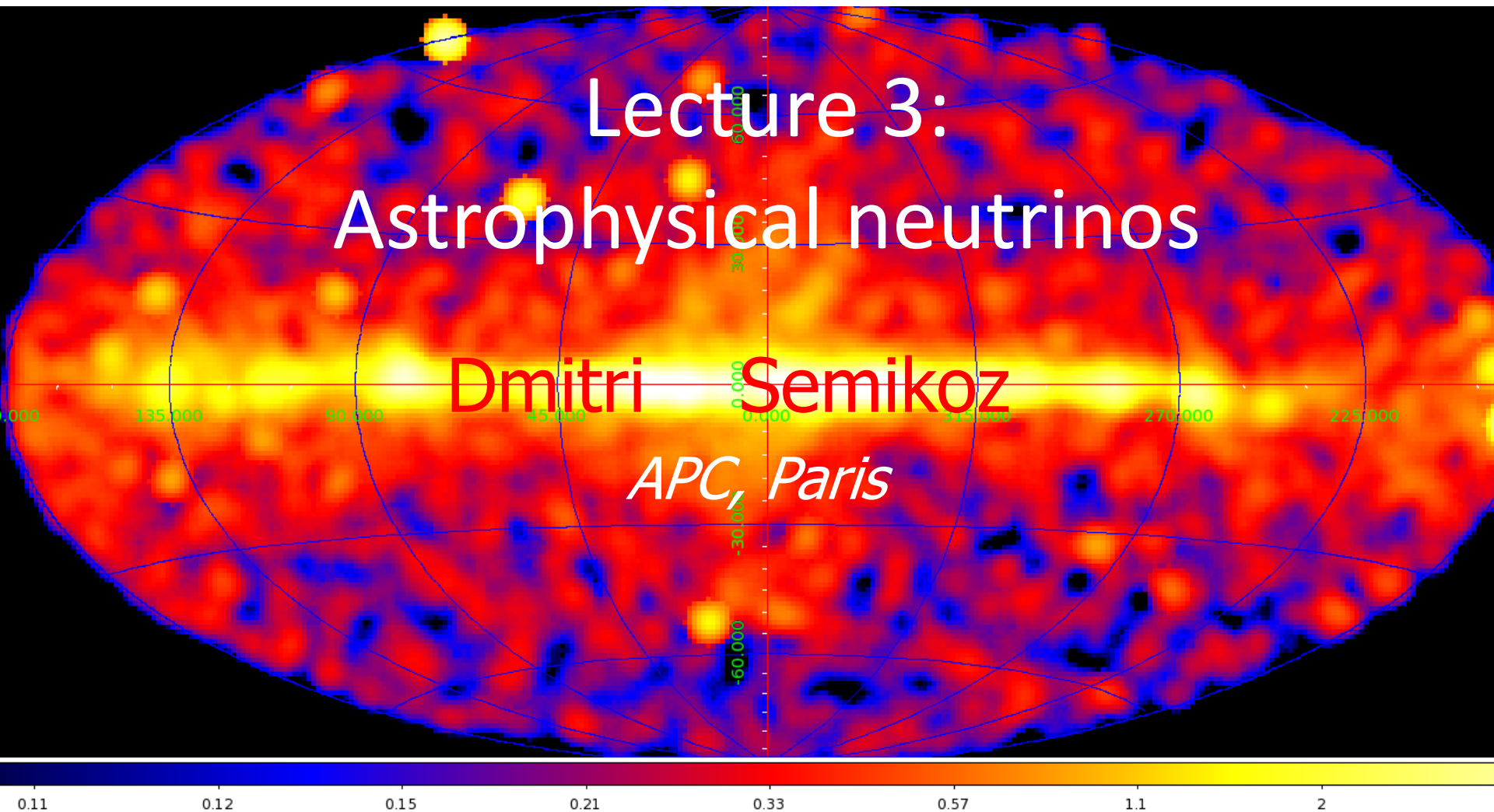


# Lecture 3: Astrophysical neutrinos

Dmitri Semikoz

*APC, Paris*



# Overview:

- *Introduction: neutrinos*
- *Detection technics*
- *Discovery of astrophysical neutrinos by IceCube telescope*
- *Galactic to extragalactic transition of cosmic rays*

# Overview:

- *Neutrino signal from Milky Way Galaxy:*
  - *Theoretical expectations*
  - *Gamma-ray signal*
  - *Significance in IceCube data*
- *Extragalactic sources of neutrinos: AGN's*
- *Gamma-ray counterpart to neutrino signal*
- *Conclusions*

# INTRODUCTION



## Simple facts

The Weak Nuclear Interactions concerns all Quarks and all Leptons

The Weak Interaction takes place whenever some conservation law (isospin, strangeness, charm, beauty, top) forbids Strong or EM to take place

In the Weak Interaction leptons appear in doublets:

Q	L(e) = +1	L( $\mu$ ) = +1	L( $\tau$ ) = +1
0	$\nu_e$	$\nu_\mu$	$\nu_\tau$
-1	$e^-$	$\mu^-$	$\tau^-$

Doublets are characterized by electron, muon, tau numbers (each conserved, except in neutrino oscillations)  $\rightarrow$  whose sum is conserved.

...and the relevant anti-leptons. For instance:

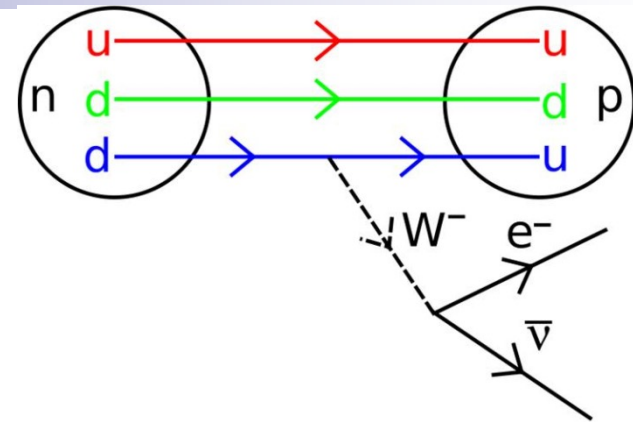
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

## Fermi Theory of the Beta Decay

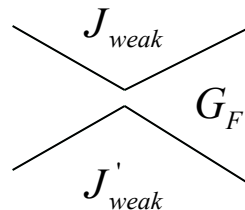
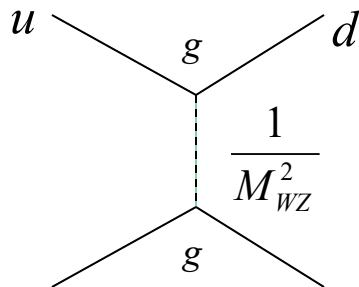
$$A(Z, N) \rightarrow A(Z+1, N-1) + e^- + \bar{\nu}_e$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$d \rightarrow u + e^- + \bar{\nu}_e$$



At the fundamental (constituents) level



$$L_{Fermi} \approx G_F J^\mu J_\mu'^+ = \frac{g^2}{M_W^2} J^\mu J_\mu'^+$$

The rate of decay (transitions per unit time) will be:

$$W = \frac{2\pi}{\hbar} G_F^2 |M|^2 \frac{dN}{dE_0}$$

$$|M|^2$$

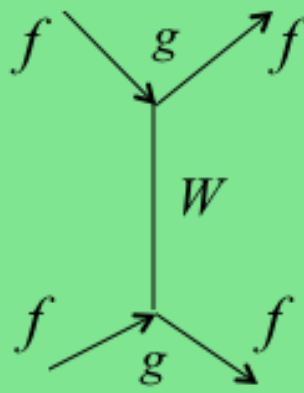
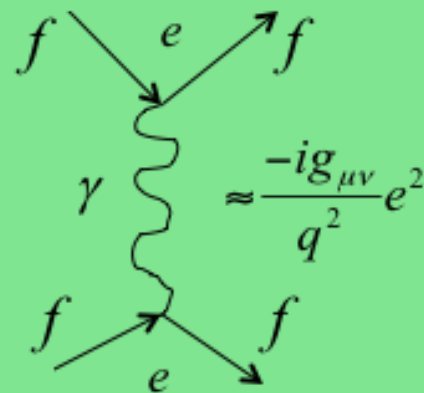
Integration over spins and angles

$$E_0$$

Energy of the final state

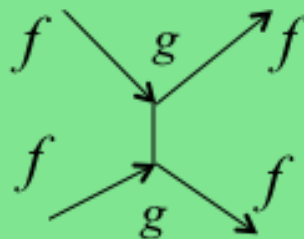
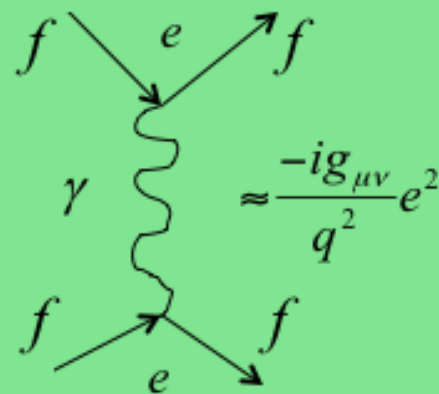
Electromagnetic

Weak



High Energy Matrix Element

$$\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M^2 c^2)}{q^2 - M^2 c^2} g^2$$



Low Energy Matrix Element

$$\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M^2 c^2)}{q^2 - M^2 c^2} g^2 \approx \frac{-ig_{\mu\nu}}{M^2 c^2} g^2 \approx G_F^2$$

## Coupling constants : Electromagnetic and Weak

A reminder :

$$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137} \quad [\alpha] = \left[ \frac{\text{dyne cm cm}}{\text{erg cm}} \right]$$

In rationalized and natural units  
e is adimensional :

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137} \Rightarrow e = 0.09$$

The Weak Fermi constant

$$\frac{G_F}{(\hbar c)^3} = 1.2 \times 10^{-5} \text{ GeV}^{-2}$$

$$G_F = 9.1 \times 10^{-5} \text{ MeV} \cdot \text{fm}^3$$

$$\frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2} g^2}{8 M_W^2 c^4}$$

The Weak Coupling constant is actually bigger than the fine structure constant.

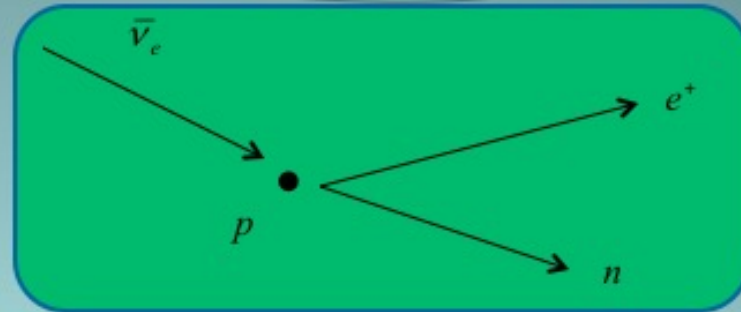
But at low energies it is damped by the W mass into the small  $G_F$  constant

$$g_w^2 = G_F \frac{8}{\sqrt{2}} (M_W c^2)^2 \Rightarrow g_w = 0.65$$

$$\alpha_w = \frac{g_w^2}{4\pi} = \frac{1}{29.5}$$

## Inverse Beta Decay

$$\bar{\nu}_e + p \rightarrow n + e^+$$



$$W = \frac{2\pi}{\hbar} G_F^2 |M|^2 \frac{dN}{dE_0}$$



$$\sigma \approx \frac{1}{\pi} G_F^2 |M|^2 p^2$$

$p$  is the momentum of the neutron/positron system in their CM

This is a mixed (Fermi + Gamow-Teller) transition

$$|M|^2 \cong 4$$

$$\sigma \approx 10^{-43} (cm^2) p^2 (MeV / c)^2$$

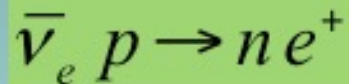
A very small cross section  
The cross section increases with  $E$

## Neutrino discovery:

### Principle of the experiment

In a nuclear power reactor, antineutrinos come from  $\beta$  decay of radioactive nuclei produced by  $^{235}\text{U}$  and  $^{238}\text{U}$  fission. And their flux is very high.

1. The antineutrino reacts with a proton and forms n and  $e^+$



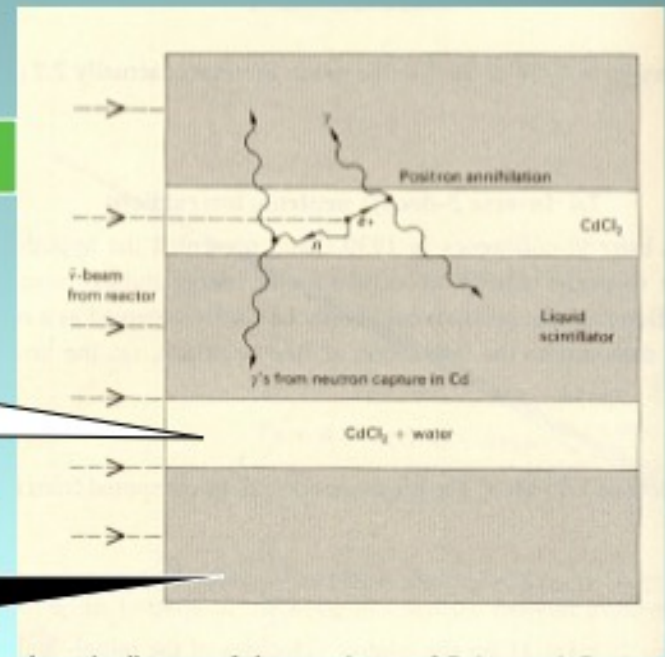
**Inverse Beta Decay**

2. The  $e^+$  annihilates immediately in gammas

3. The n gets slowed down and captured by a Cd nucleus with the emission of gammas (after several microseconds delay)

**Water and cadmium**

**Liquid scintillator**



4. Gammas are detected by the scintillator: the signature of the event is the delayed gamma signal

$$\sigma(\bar{\nu}_e p \rightarrow n e^+) \approx 10^{-43} \text{ cm}^2$$

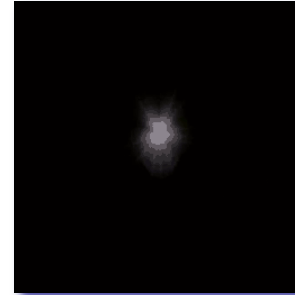
1956: Reines and Cowan at the Savannah nuclear power reactor



# Where do Neutrinos Appear in Nature?



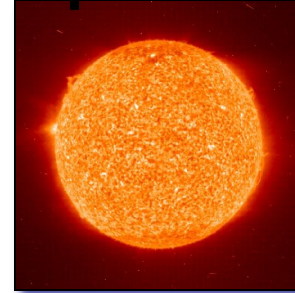
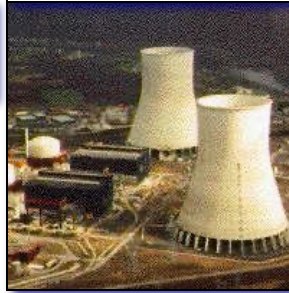
Particle-  
Accelerators



Cosmic Big Bang  
(today  $330 \text{ v/cm}^3$ )  
Indirect BBN, CMBR



Nuclear Reactors



Sun



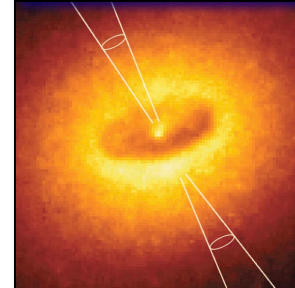
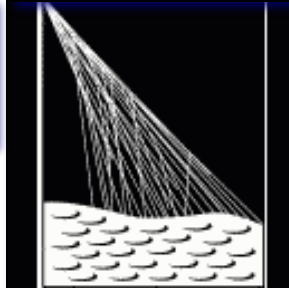
Earth Crust  
(Natural  
Radioactivity)



Supernovae  
(Stellar Collapse)  
SN 1987A ✓



Earth Atmosphere  
(Low energy Cosmic Rays)



Astrophysical  
Accelerators 2013



Sanduleak -69 202

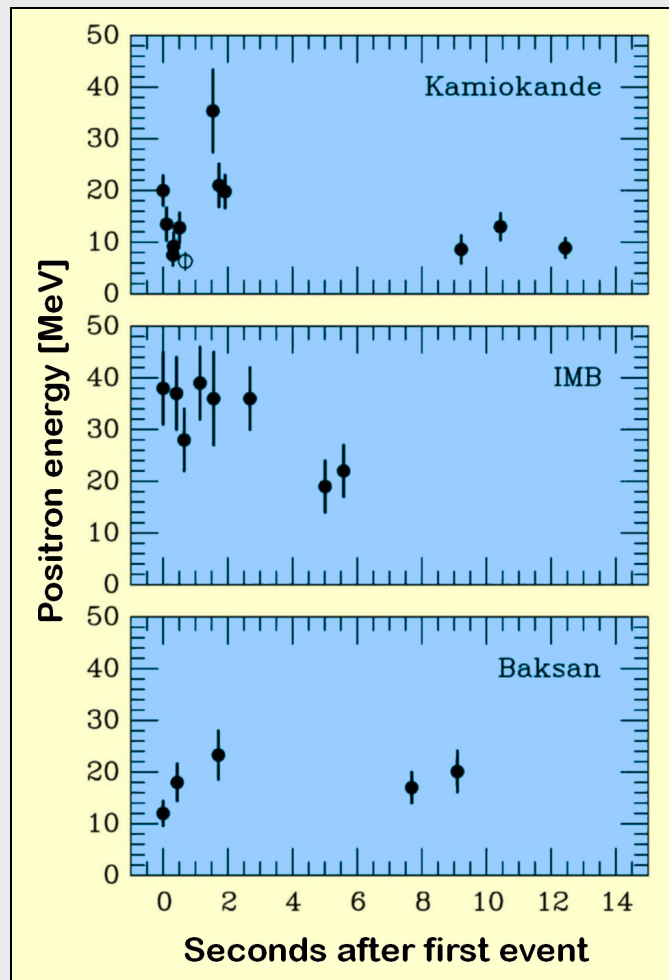


Supernova 1987A 23  
February 1987





# Neutrino Signal from SN 1987A



Kamiokande (Japan)  
Water Cherenkov detector  
Clock uncertainty  $\pm 1$  min

Irvine-Michigan-Brookhaven  
(USA)  
Water Cherenkov detector  
Clock uncertainty  $\pm 50$  ms

Baksan Scintillator Telescope  
(Soviet Union)  
Clock uncertainty  $+2/-54$  s

Within clock uncertainties,  
signals are contemporaneous

# Pion production

$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

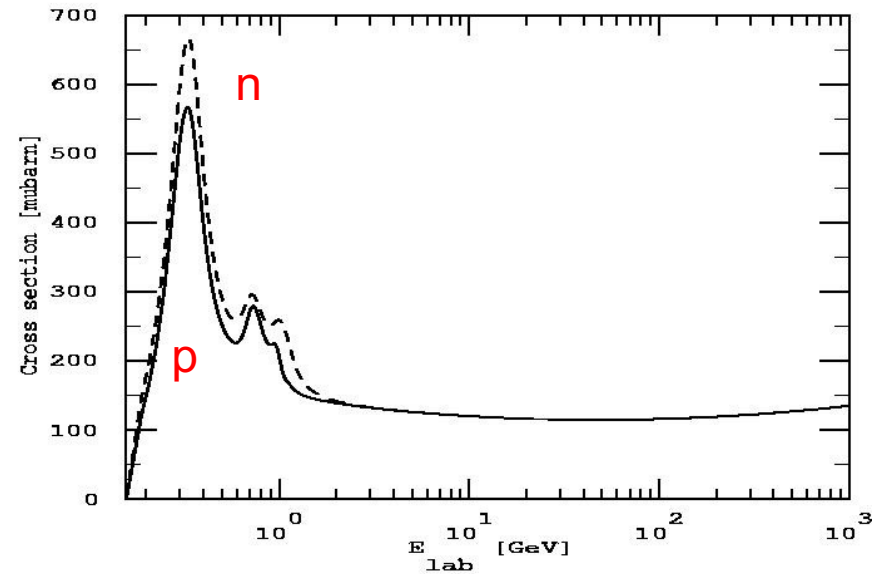
$$N + A_b \Rightarrow N' + \sum \pi^i$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^\pm \Rightarrow \mu^\pm + \nu_\mu$$

$$\mu^\pm \Rightarrow e^\pm + \bar{\nu}_e + \nu_\mu$$

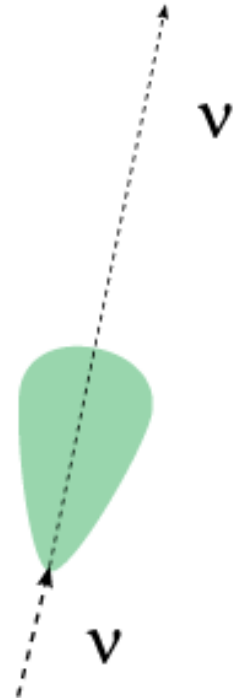
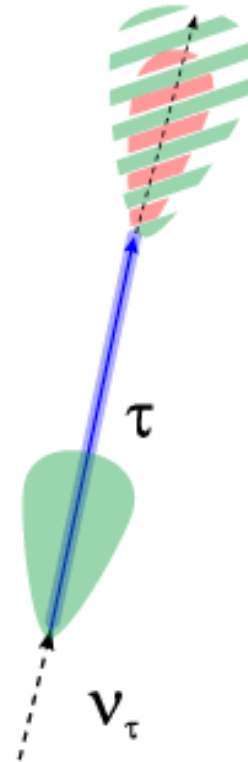
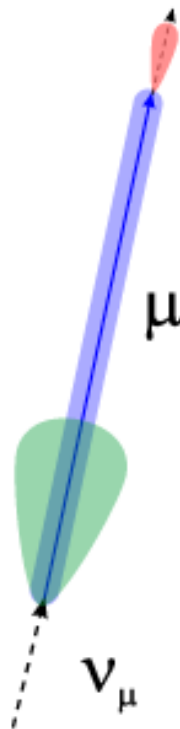
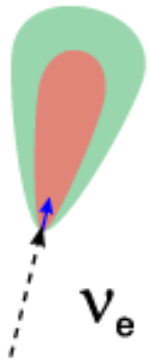
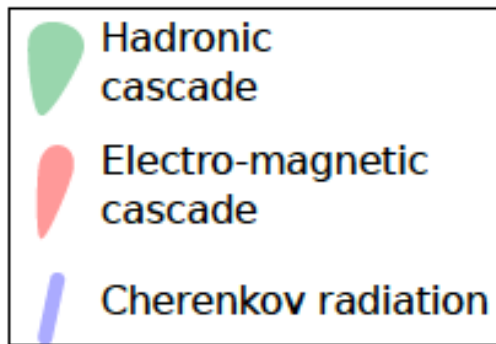
$$n \Rightarrow p + e^- + \bar{\nu}_e$$



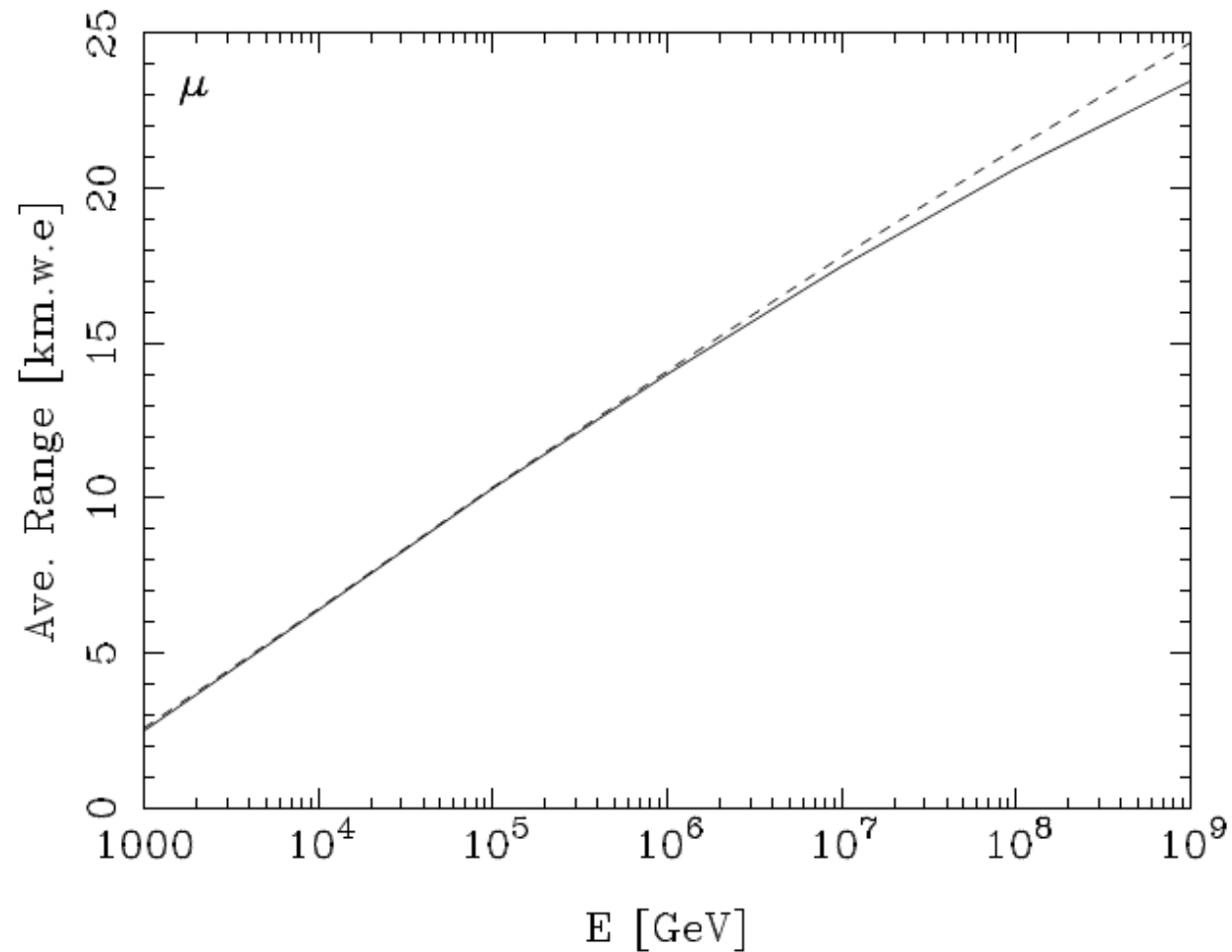
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones:

$$E_\gamma^{tot} \sim E_\nu^{tot}$$

# Detection of neutrino interactions



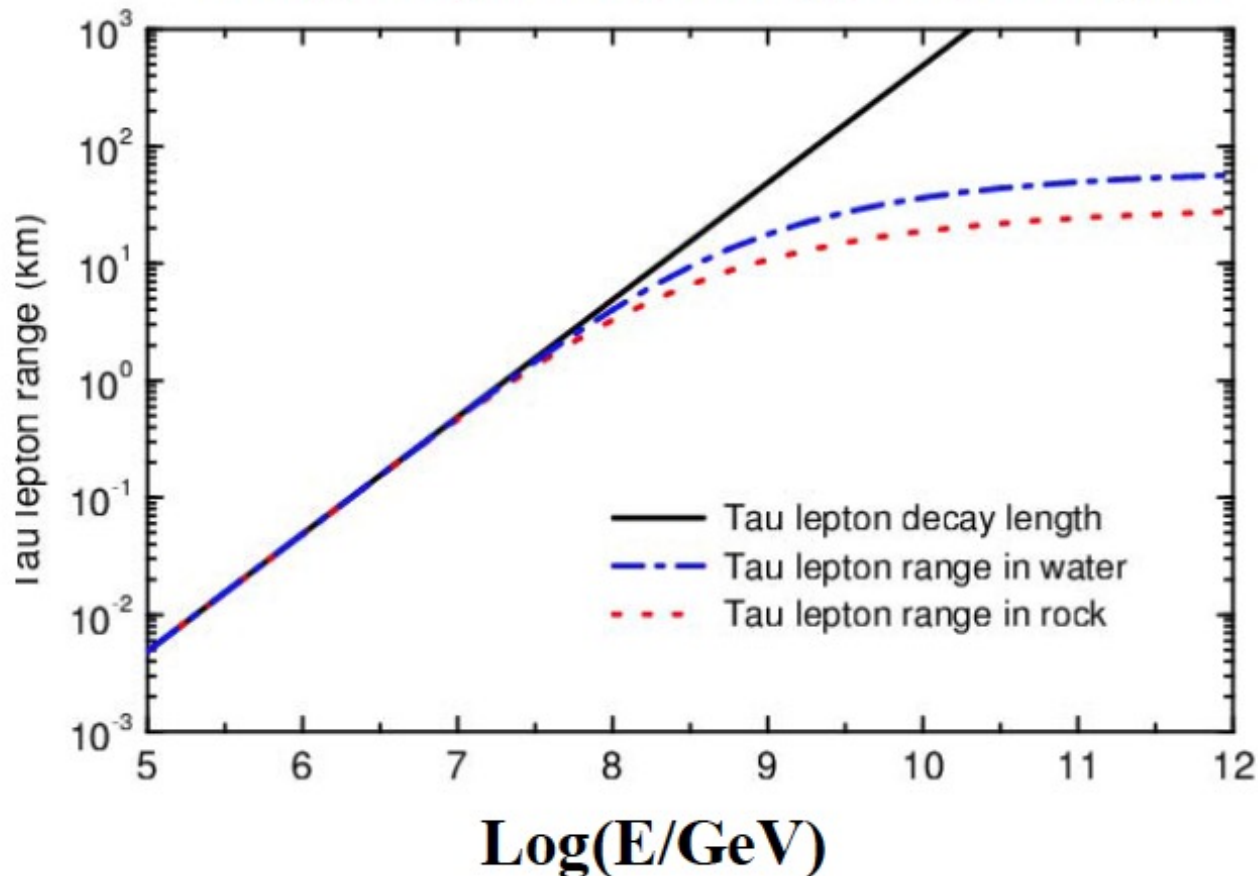
# Muon losses



# Tau energy losses

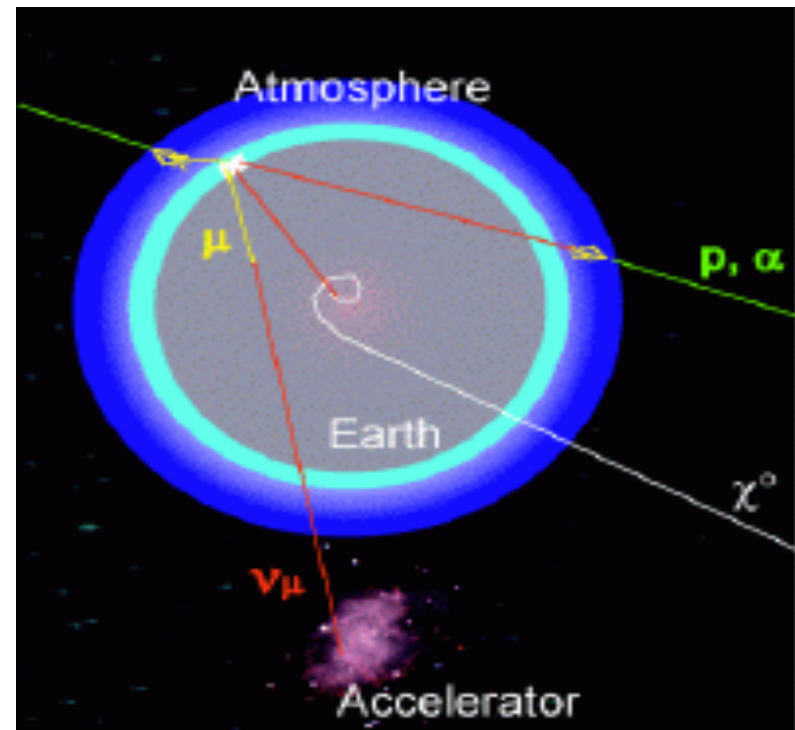
Iyer Dutta, Reno, Sarcevic, & Seckel, 01

Tseng, Yeh, Athar, Huang, Lee, & Lin, 03



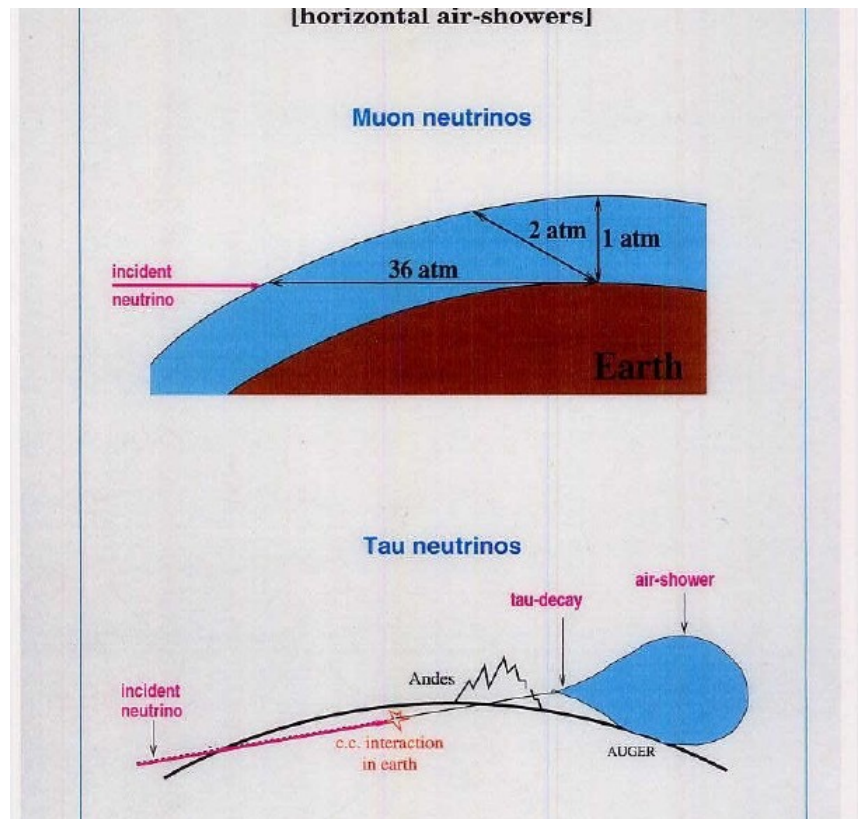
# Experimental detection of $E < 10^{17} \text{eV}$ neutrinos

- Cascade neutrinos coming from above are HE neutrinos from space and secondary from cosmic rays
- Muon neutrinos coming from below are mixture of atmospheric neutrinos and HE neutrinos from space
- Earth is not transparent for neutrinos  $E > 10^{15} \text{eV}$
- Experiments: **MACRO, Baikal, AMANDA, ANTARES, ICECUBE**



# Experimental detection of UHE ( $E > 10^{17}$ eV) neutrinos

- Neutrinos are not primary UHECR
- Horizontal or up-going air showers – easy way to detect neutrinos
- Experiments: Fly's Eye, AGASA, HiRes,
- AUGER



# Radio detection



# Askaryan effect

In 1962 Guren Askaryan suggested that a particle travelling faster than the speed of light in a dense radiotransparent medium such as salt or ice produces a shower of secondary charged particles which contain a charge anisotropy and thus emits a cone of coherent radiation in the radio or microwave part of the electromagnetic spectrum.



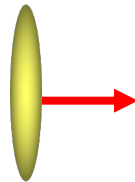
G.Askaryan was the first to note that the outer few metres of the Moon's surface, known as the regolith, would be a sufficiently transparent medium for detecting microwaves from the charge excess in particle showers. The radio transparency of the regolith has since been confirmed by the Apollo missions.



$e^- \rightarrow \dots$  cascade

negative charge is swept into developing shower, which acquires a negative net charge  
 $Q_{\text{net}} \sim 0.25 E_{\text{cascade}} \text{ (GeV)}.$

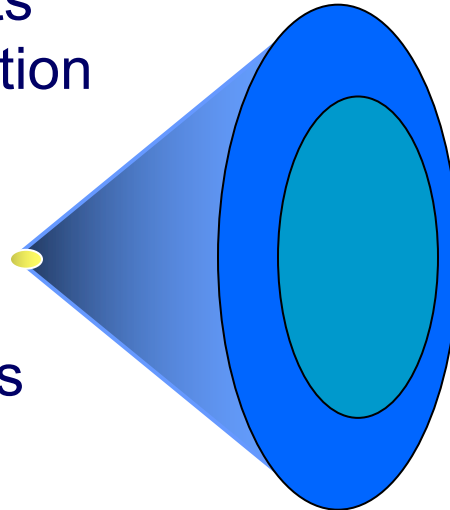
$\Rightarrow$  relativist. pancake  
 $\sim 1\text{cm thick, } \varnothing \sim 10\text{cm}$



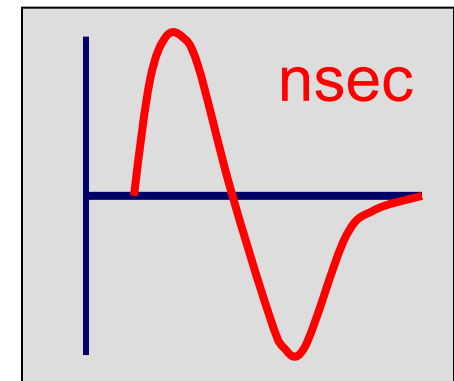
$\Rightarrow$  for  $\lambda \gg 10 \text{ cm (radio)}$   
**coherence**

$\Rightarrow$  each particle emits Cherenkov radiation

$\Rightarrow$  C signal is resultant of overlapping Cherenkov cones



$\Rightarrow$  **C-signal  $\sim E^2$**

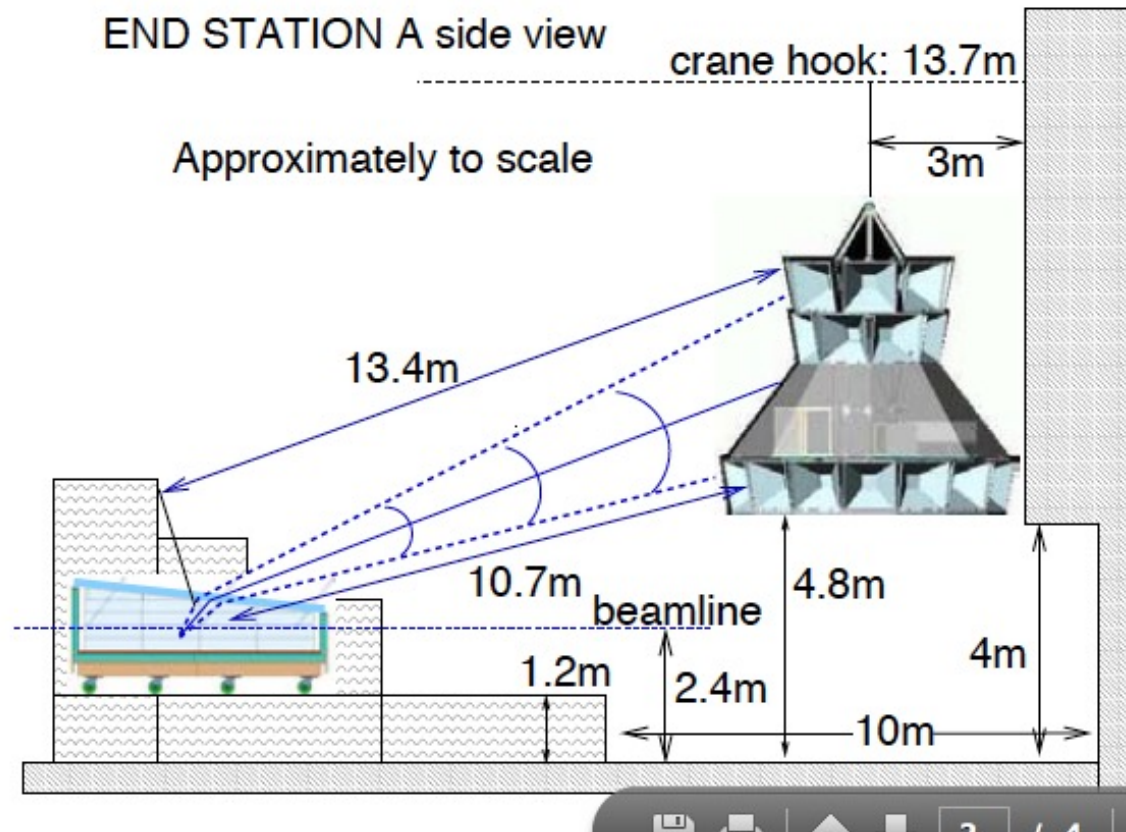


**Experiments:**

**GLUE, RICE, FORTE,  
 ANITA**

**Threshold  $> 10^{16} \text{ eV}$**

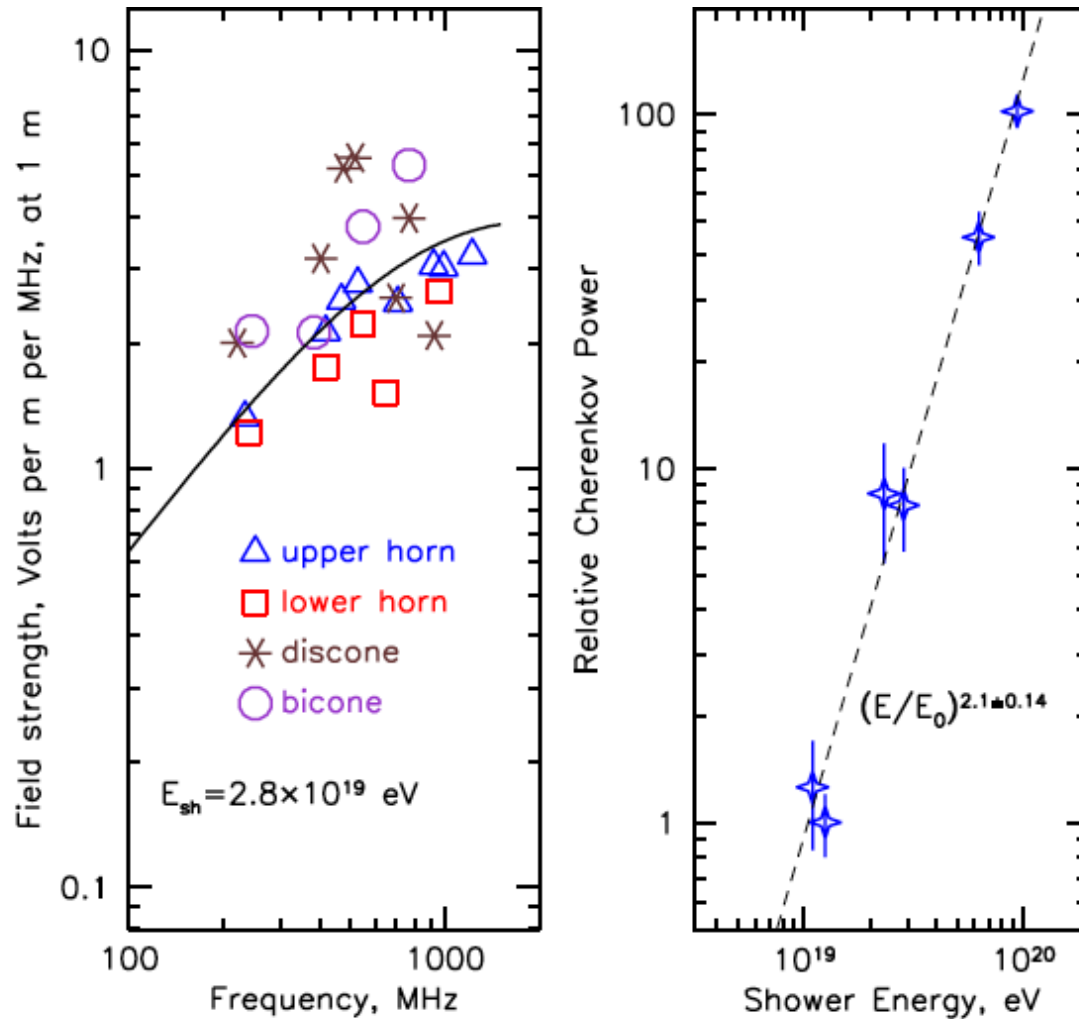
# SLAC 2006: observation of Askarvan effect



# SLAC 2006



# SLAC 2006

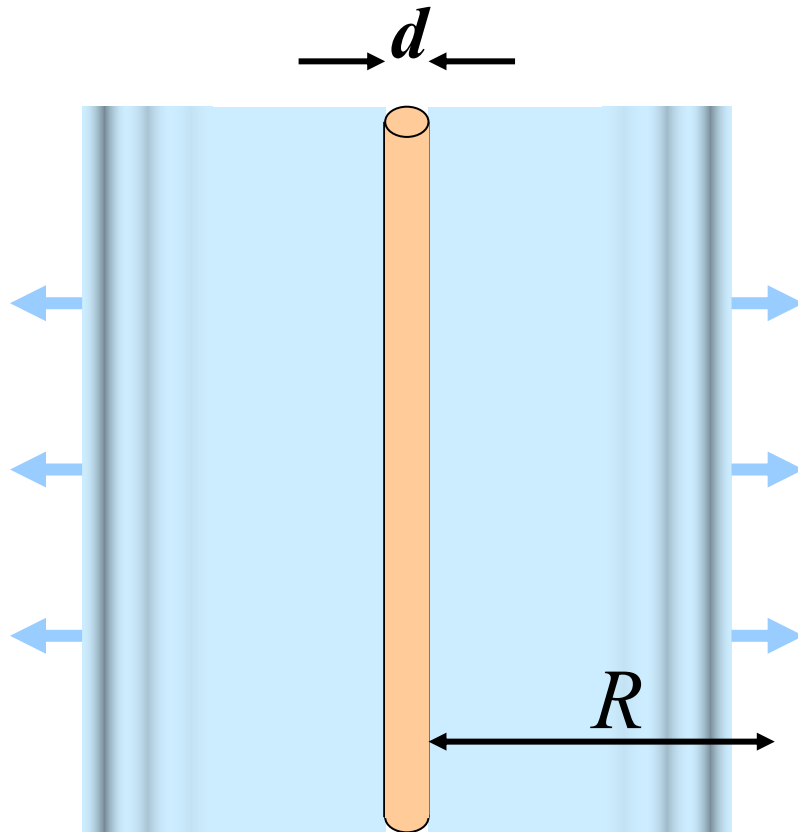
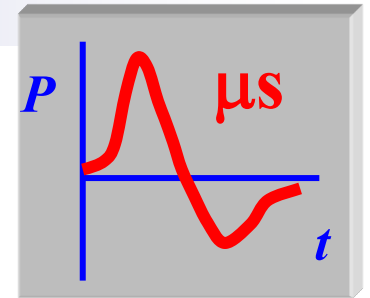


# Acoustic detection

Particle cascade  $\rightarrow$  ionization

$\rightarrow$  heat

$\rightarrow$  pressure wave



Maximum of emission at  $\sim 20$  kHz

Attenuation length of sea water  
at 15-30 kHz: **a few km**  
(light: a few tens of meters)

$\rightarrow$  given a large initial signal,  
huge detection volumes  
can be achieved.

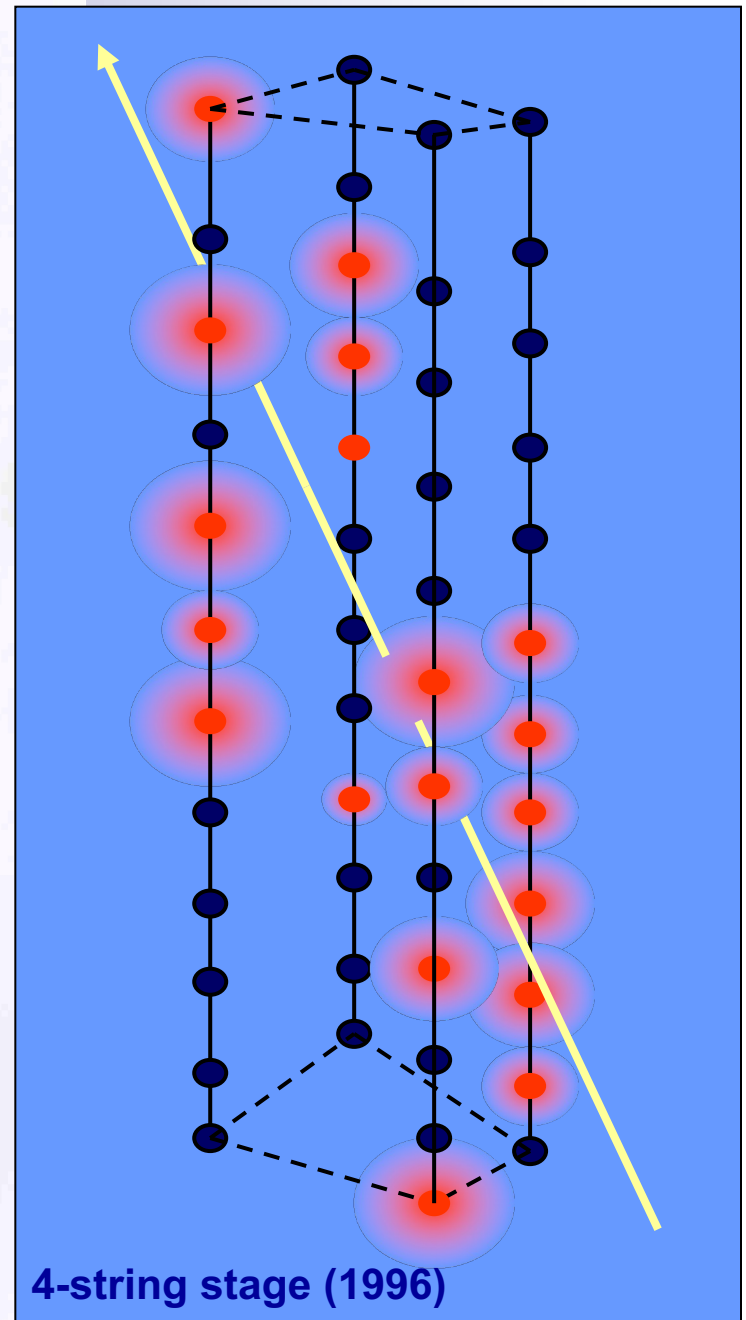
**Threshold  $> 10^{16}$  eV**

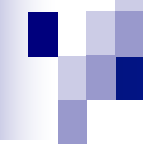
# Historical experiments



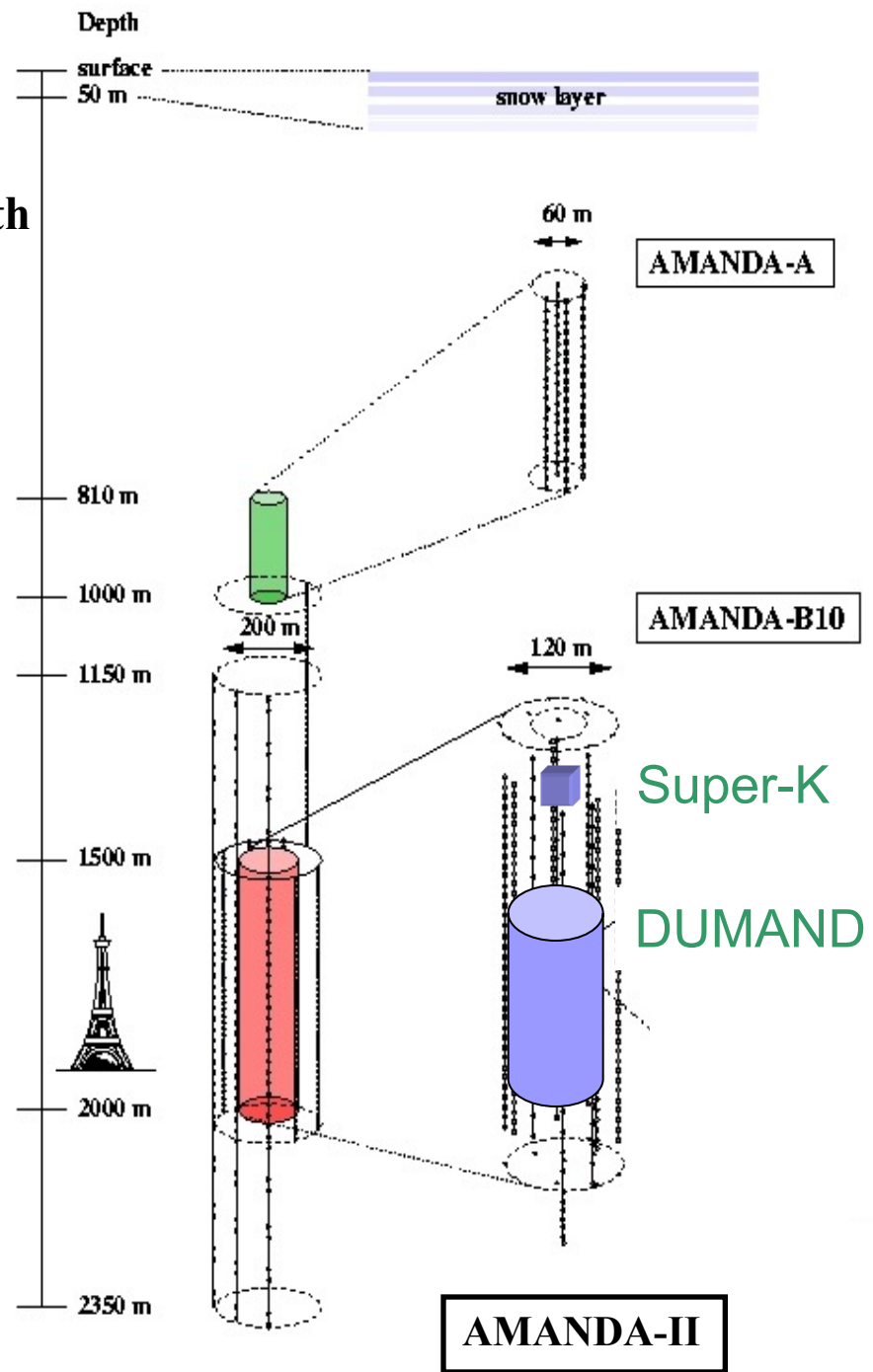
# Lake Baikal

First underwater telescope  
First neutrinos underwater





depth



# AMANDA

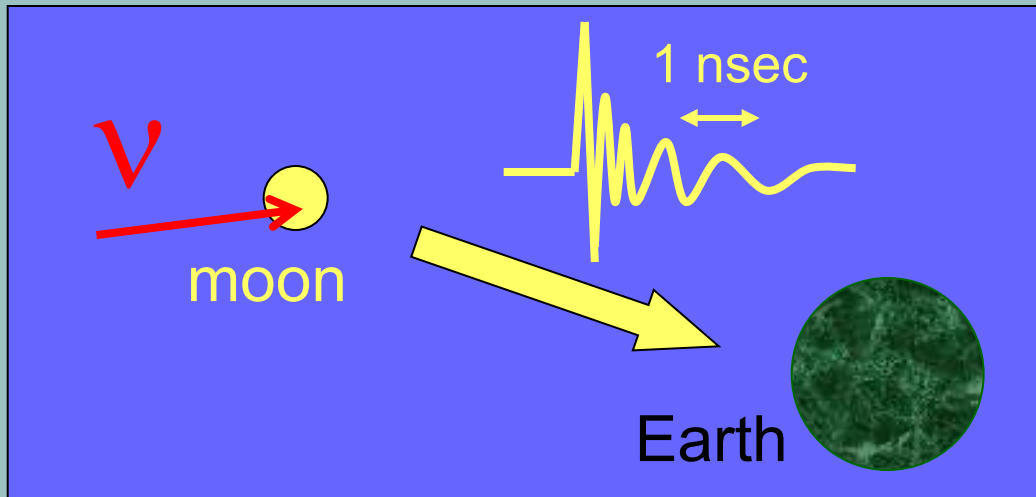


Amanda-II:  
677 PMTs  
at 19 strings  
(1996-2000)

# GLUE Goldstone Lunar Ultra-high Energy Neutrino Experiment

## Lunar Radio Emissions from Interactions of $\nu$ and CR with $> 10^{19}$ eV

Gorham et al. (1999), 30 hr NASA Goldstone  
70 m antenna + DSS 34 m antenna



$$\rightarrow E^2 \cdot dN/dE < 10^5 \text{ eV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$$

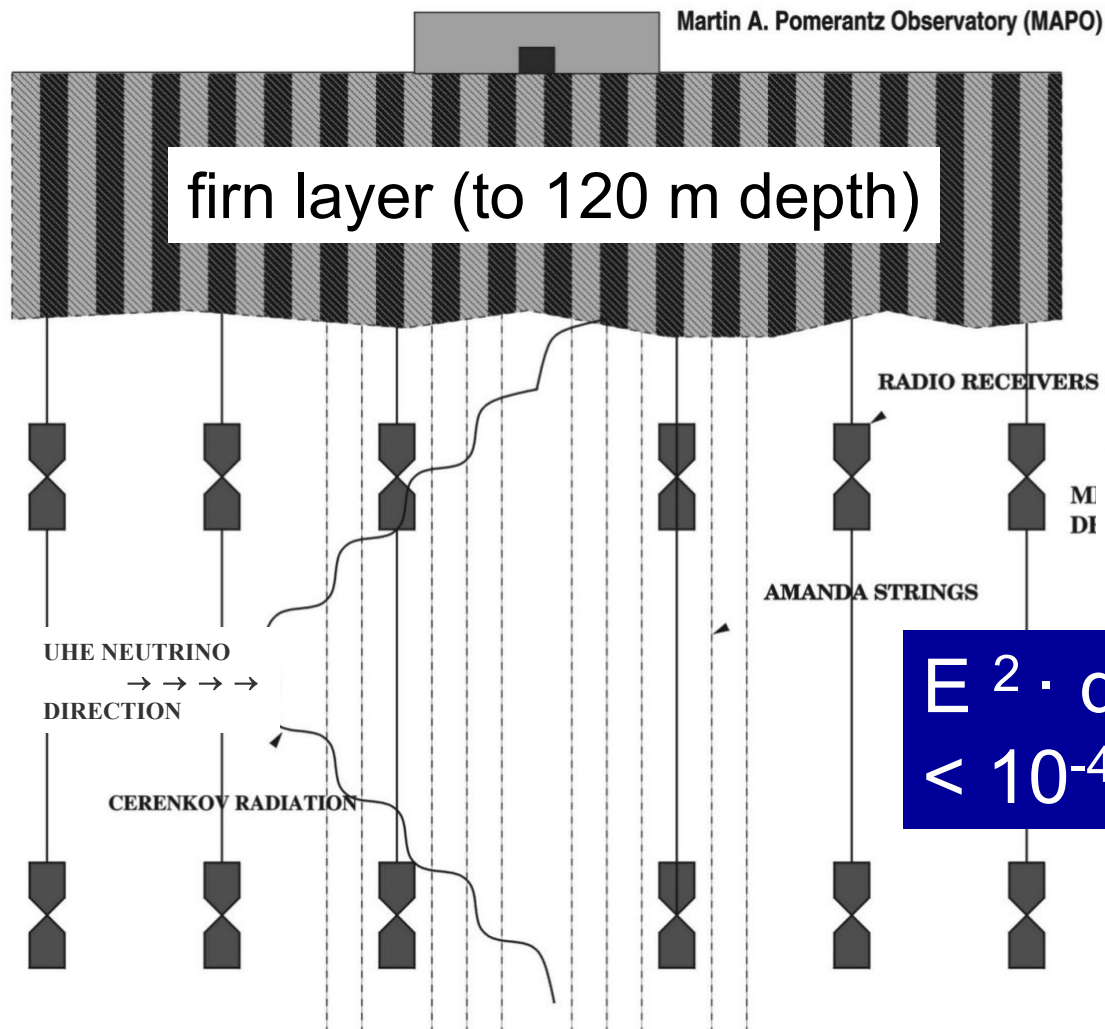
at  $10^{20}$  eV



*Effective target volume*  
 $\sim$  antenna beam ( $0.3^\circ$ )  
 $\times$  10 m layer

$$\rightarrow 10^5 \text{ km}^3$$

# RICE Radio Ice Cherenkov Experiment



South Pole

20 receivers + transmitters

$$E^2 \cdot dN/dE < 10^{-4} \text{ GeV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$$

at  $10^{17}$  eV

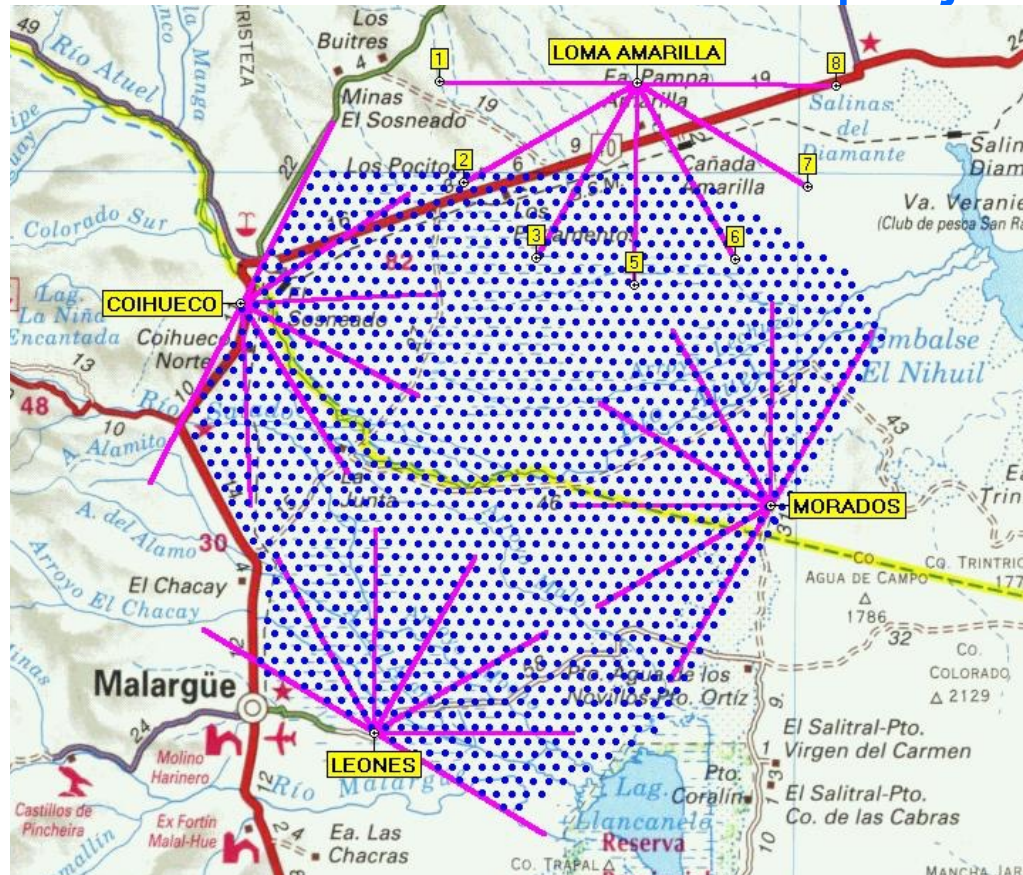
300 METER DEPTH



# Pierre Auger Observatory

South site in Argentina almost finished

North site – project



## Surface Array

**1600 detector stations**  
**1.5 Km spacing**  
**3000 Km<sup>2</sup> (30xAGASA)**

## Fluorescence Detectors

**4 Telescope enclosures**  
**6 Telescopes per enclosure**  
**24 Telescopes total**

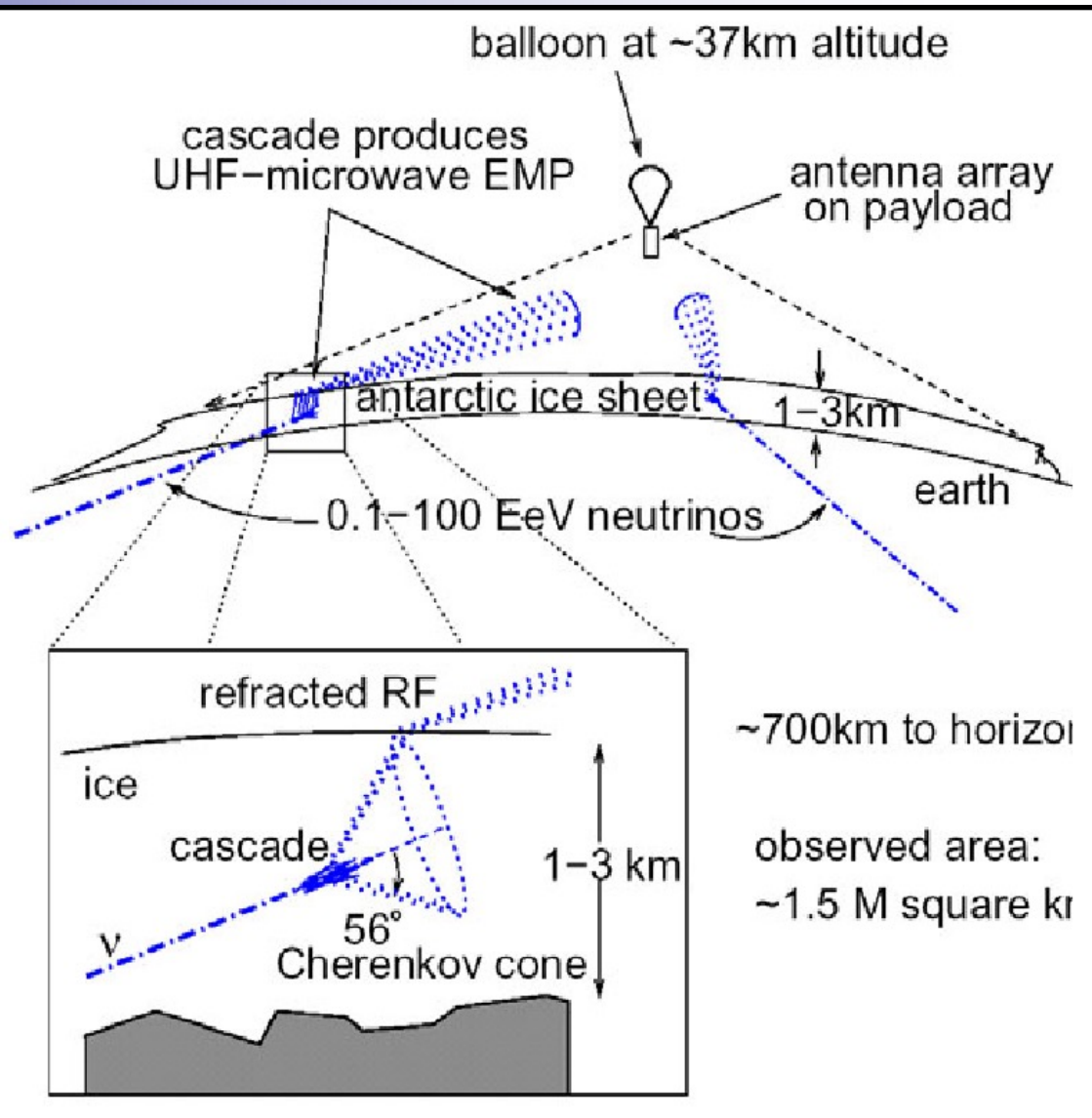
# ANITA

## Antarctic

## Impulsive

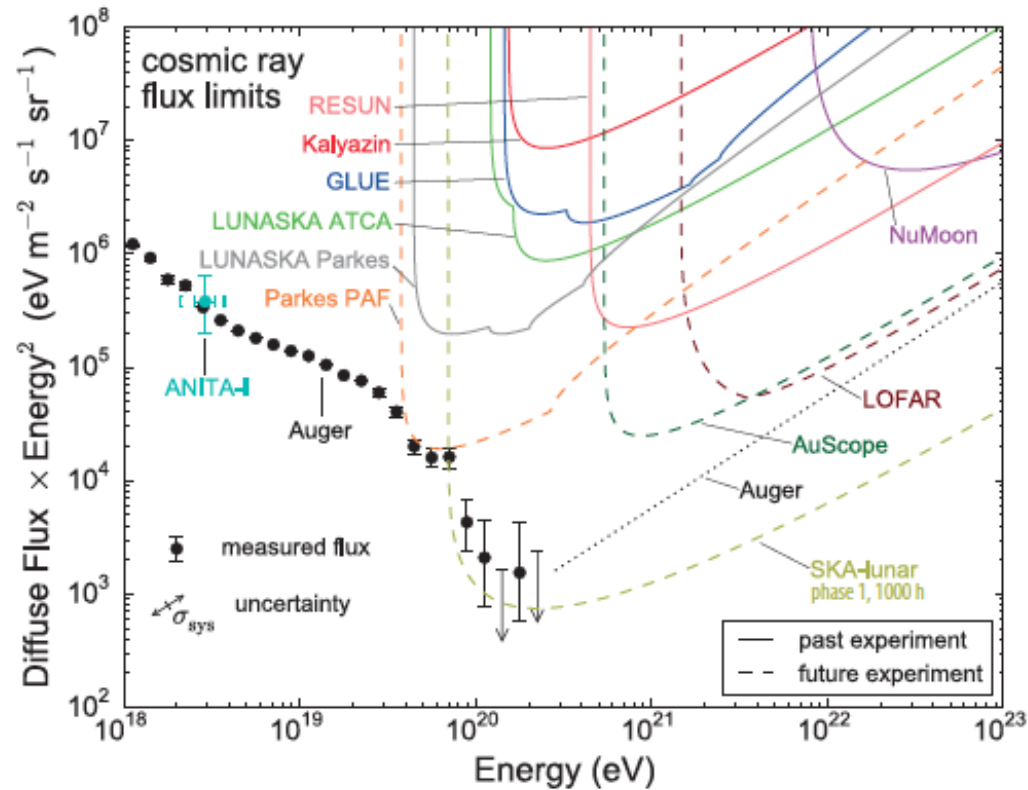
## Transient

## Array

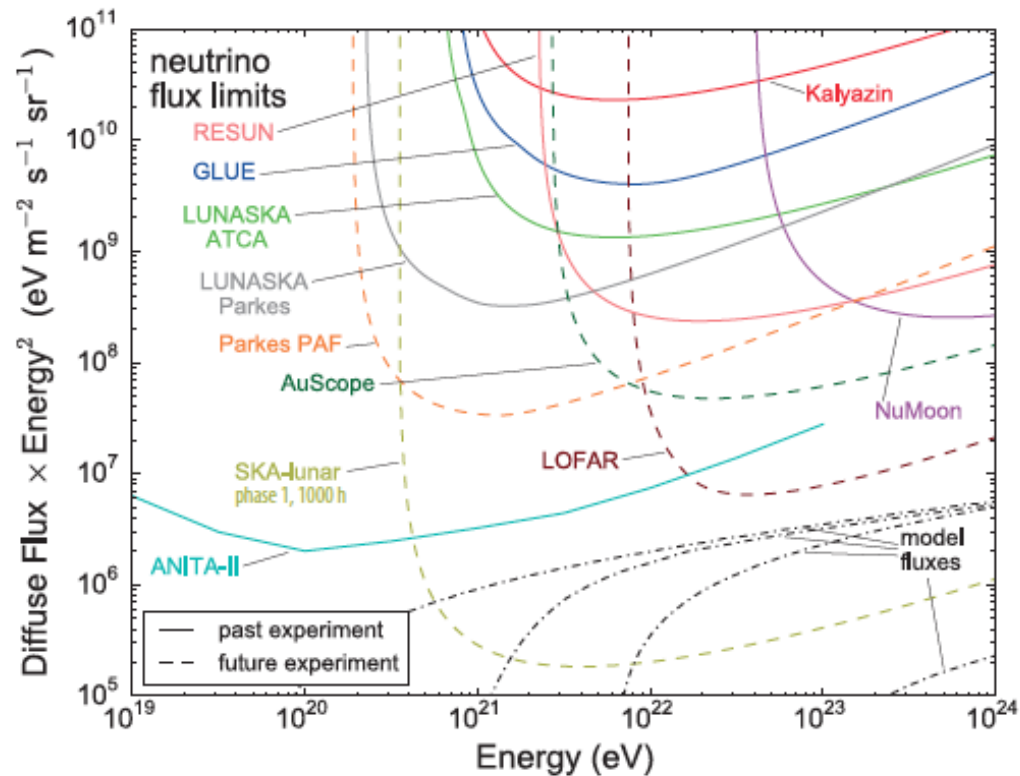


**Flights in 2006, 2007  
(35 days)**

# Radio detection cosmic rays



# Radio detection neutrinos

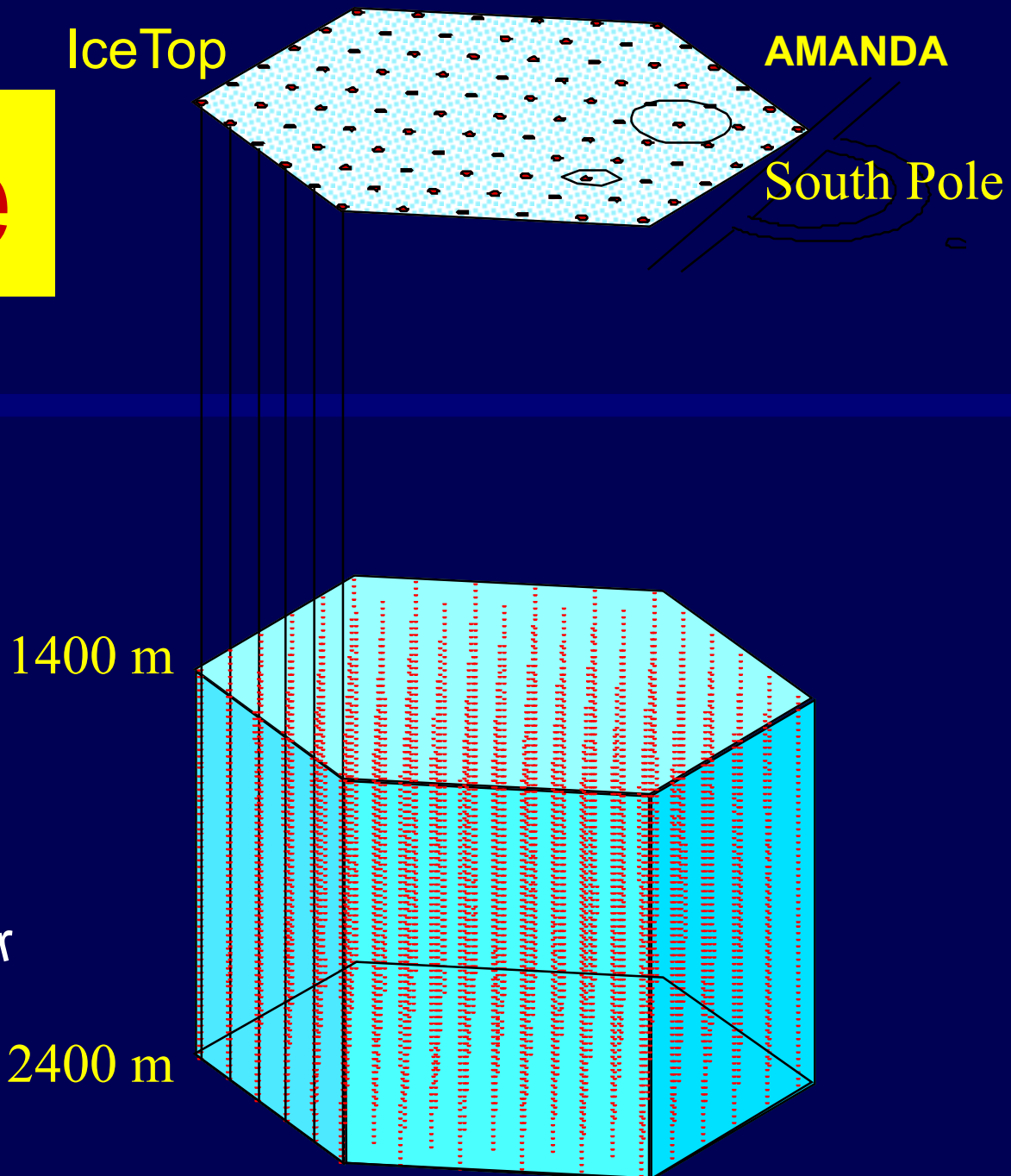




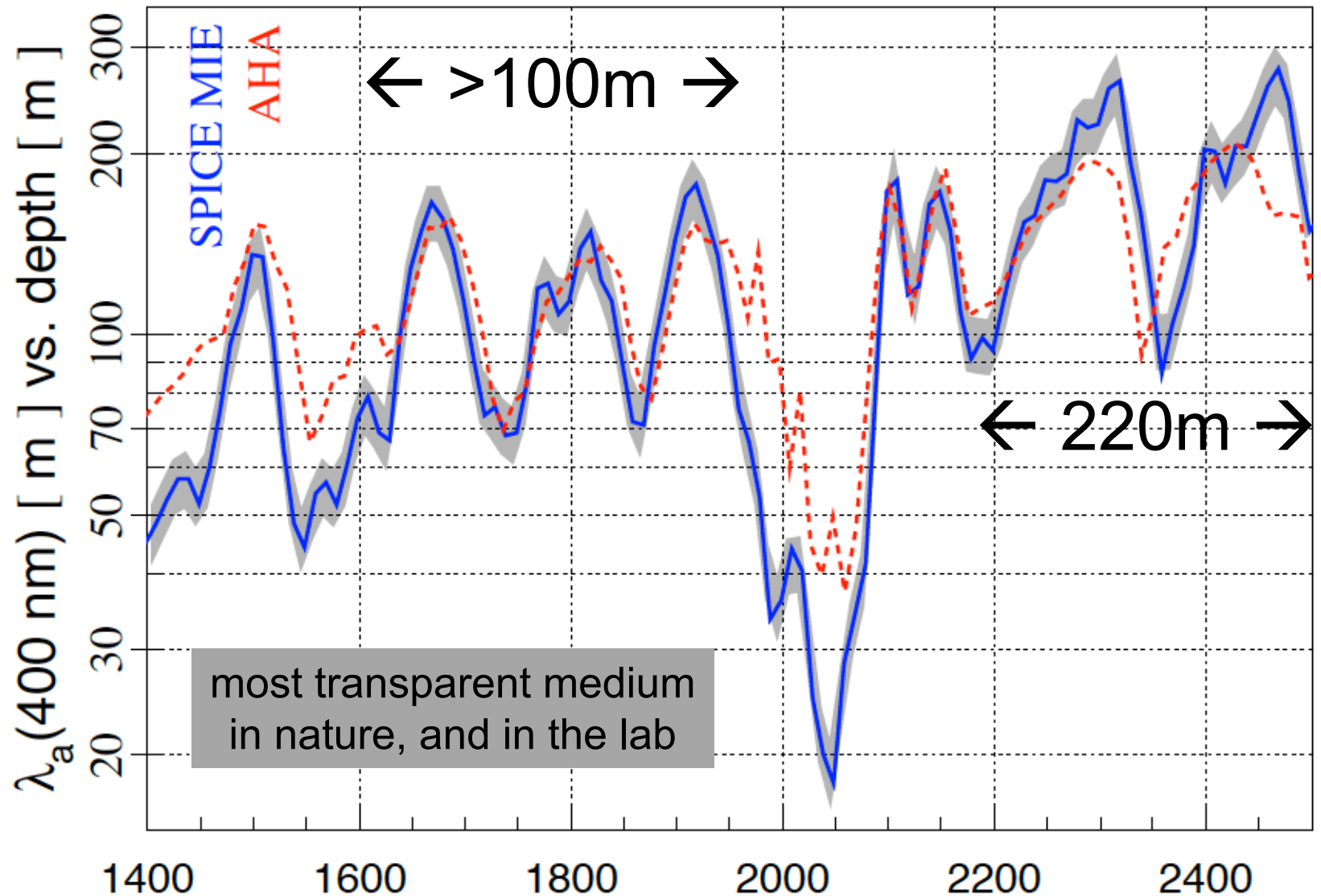
# IceCube

- 80 Strings
- 4800 PMT
- Instrumented volume:  $1 \text{ km}^3$
- Installation: 2004-2010

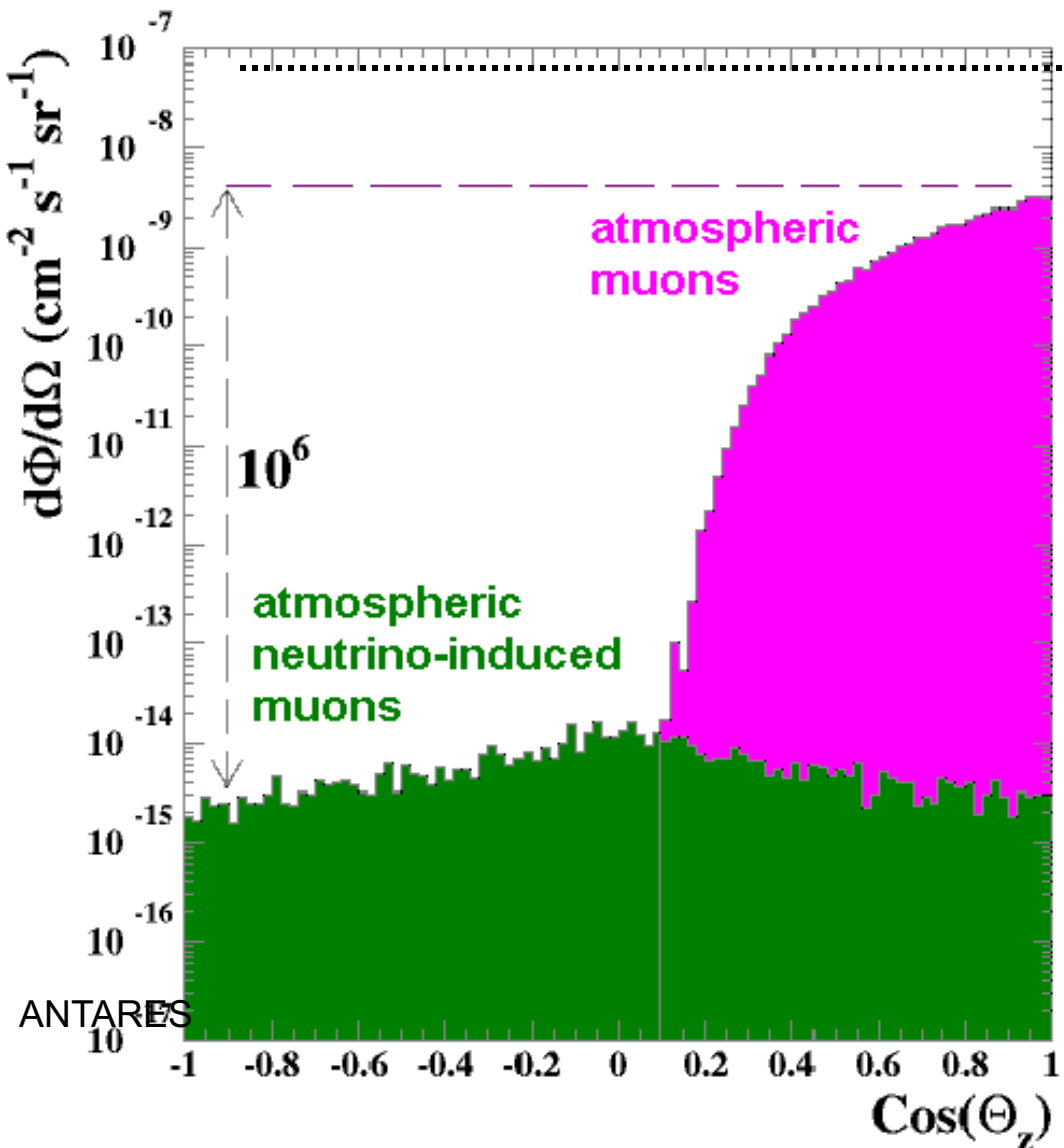
$\sim 80.000 \text{ atm.v per year}$



# absorption length of Cherenkov light



# Backgrounds: atmospheric muons and neutrinos



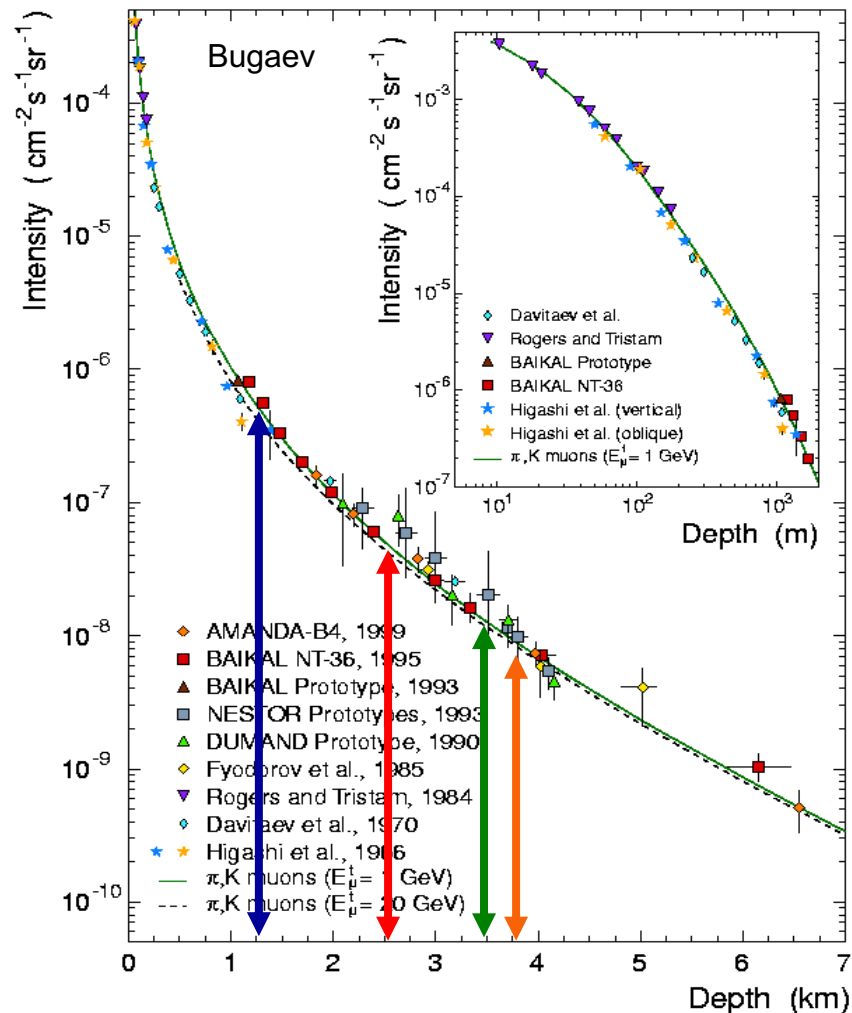
## Atmospheric neutrinos:

- upward tracks are good neutrino candidates;
- event direction and energy criteria can be used to discriminate background from astrophysical signals.

## Atmospheric muons:

- downgoing events background is due to mis-reconstructed (fake) tracks;
- improve analysis filters for atmospheric muon background rejection.

# Atmospheric muon background vs depth



Downgoing muon background is strongly reduced as a function of detector installation depth.

Depth  $> 3000 \text{ m}$  ( $\approx 1 \text{ km}$  rock) is suggested for detector installation

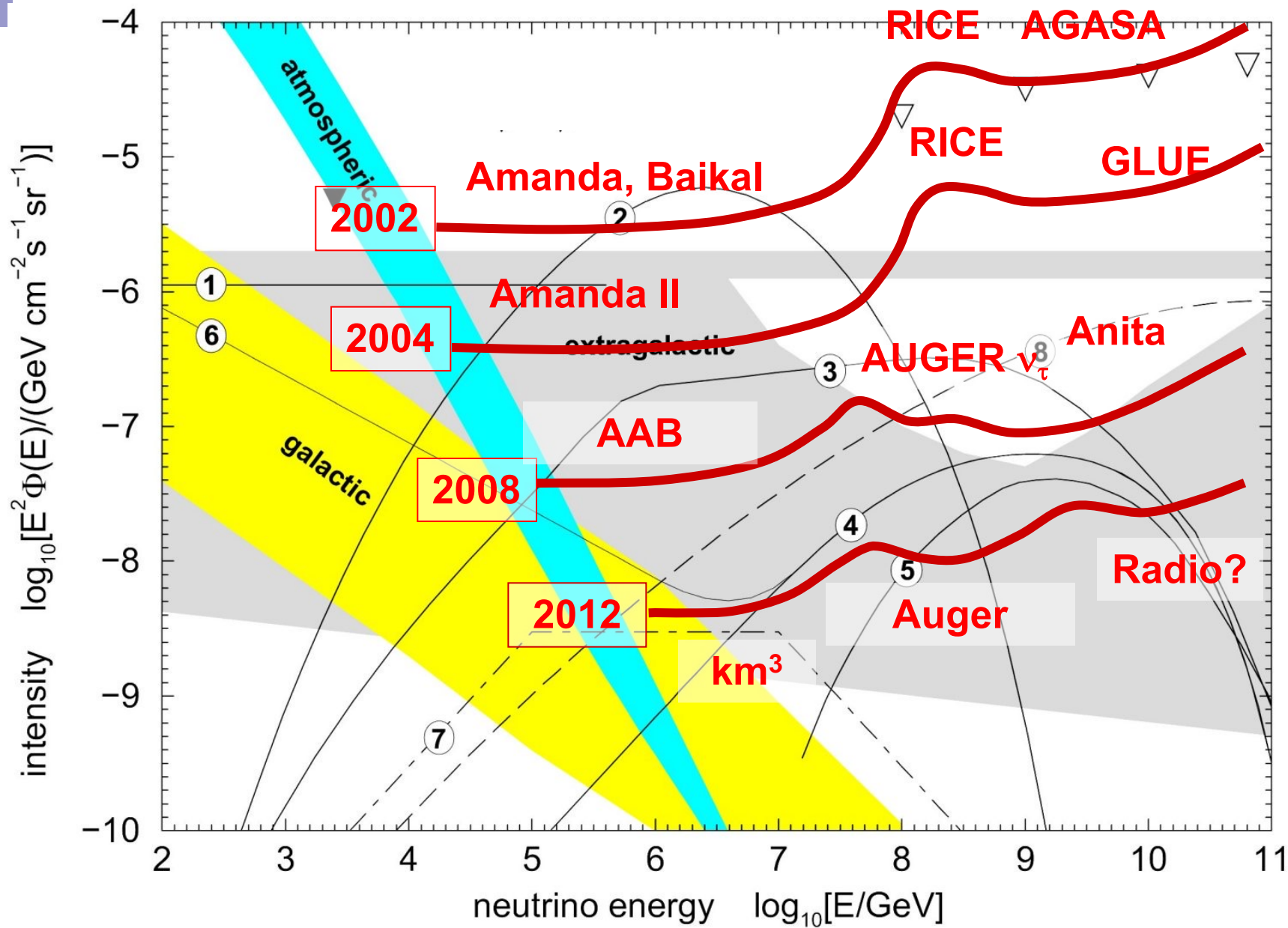
... you looked at 10msec of data !

muons detected per year:

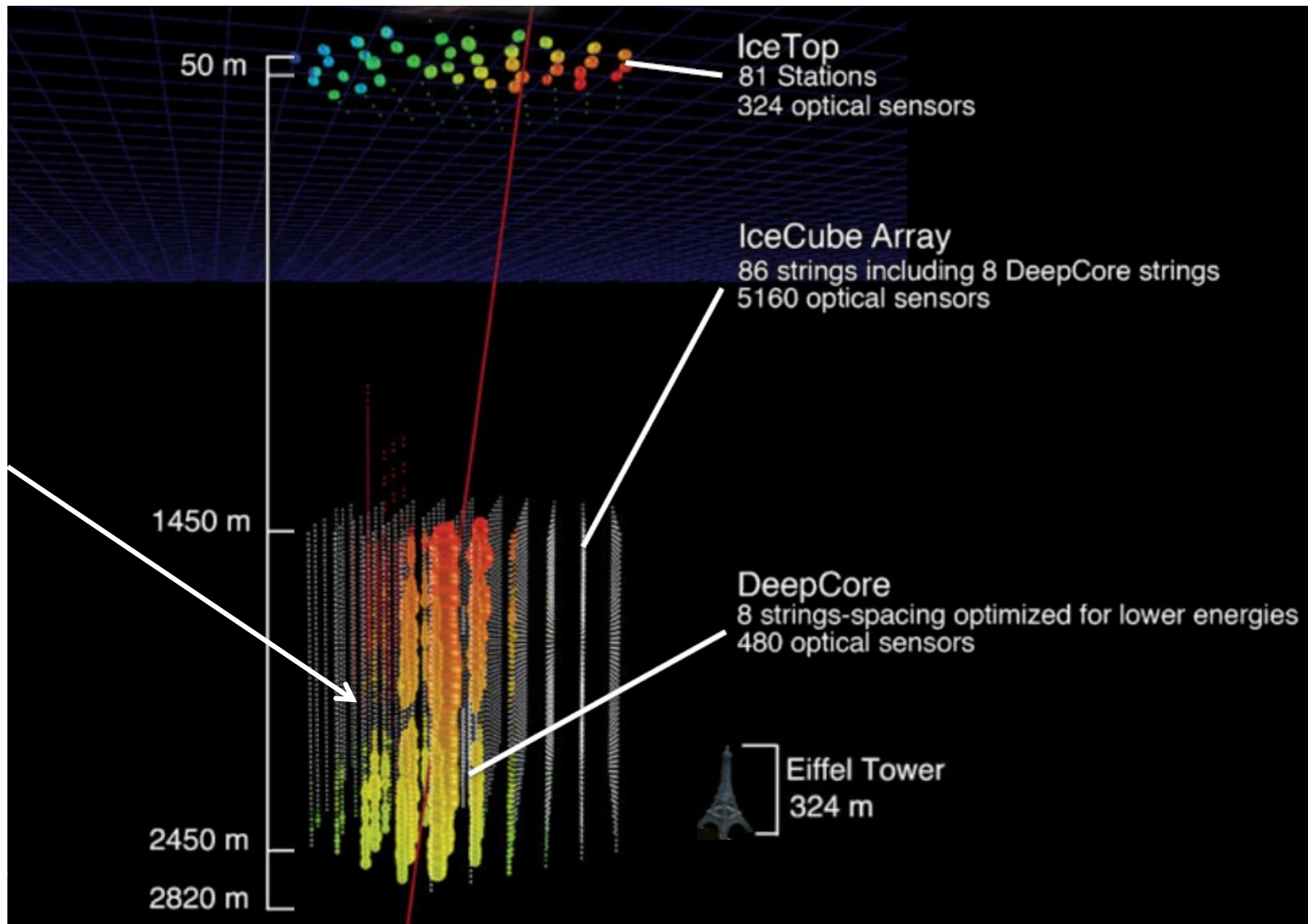
- atmospheric\*  $\mu$   $\sim 10^{11}$
- atmospheric\*\*  $\nu \rightarrow \mu$   $\sim 10^5$
- cosmic  $\nu \rightarrow \mu$   $\sim 10$

\* 3000 per second

\*\* 1 every 6 minutes



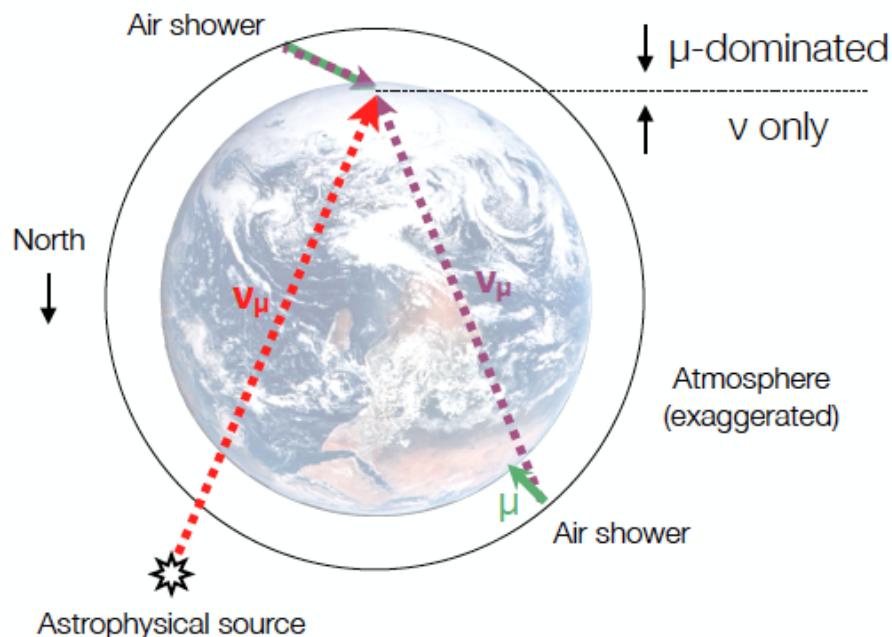
# IceCube discovery of astrophysical neutrinos





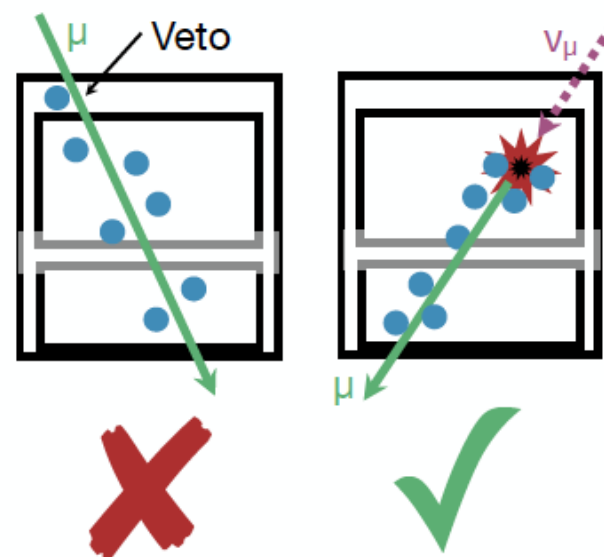
# Isolating neutrino events: two strategies

## Up-going tracks

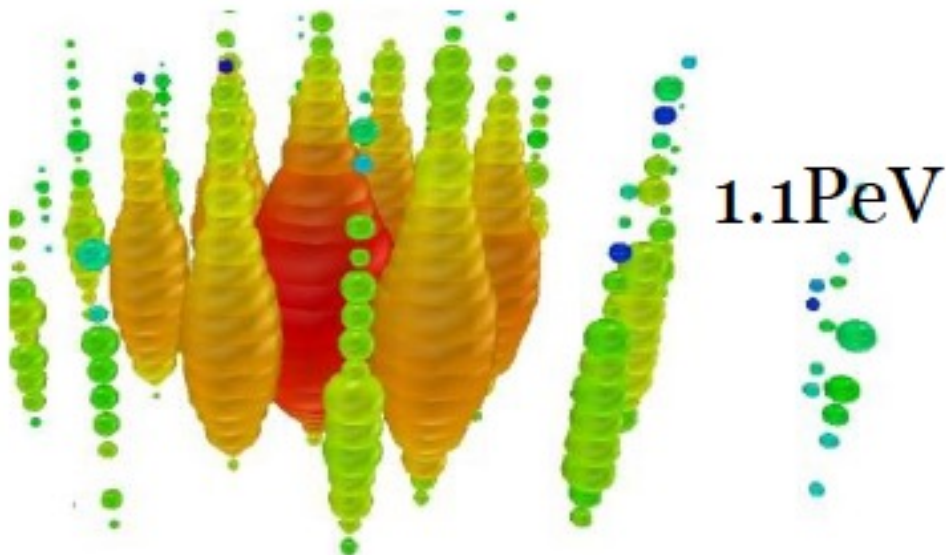
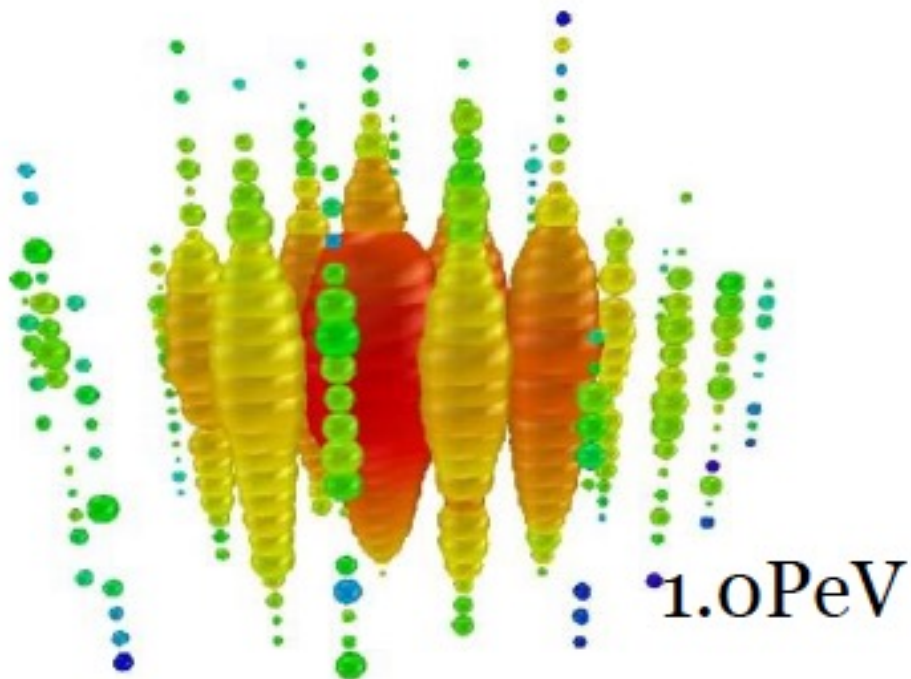


- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to  $\nu_\mu$  only
- Sensitive to half the sky

## Active veto



- Veto detects penetrating muons
- Effective volume smaller than detector
- Sensitive to all flavors
- Sensitive to the entire sky



- energy

1,041 TeV

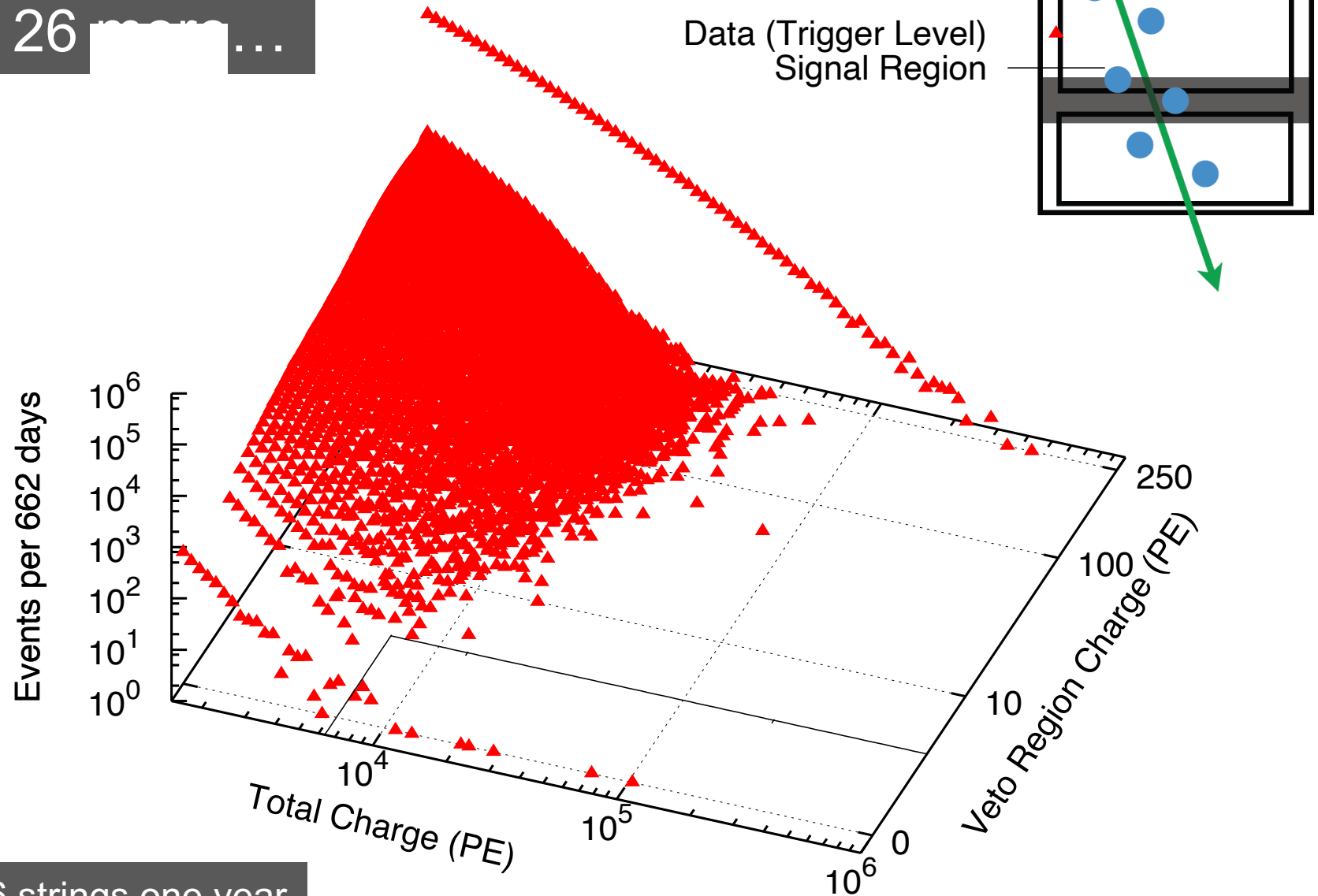
1,141 TeV

(15% resolution)

- not atmospheric:  
probability of  
no accompanying  
muon is  $10^{-3}$  per  
event

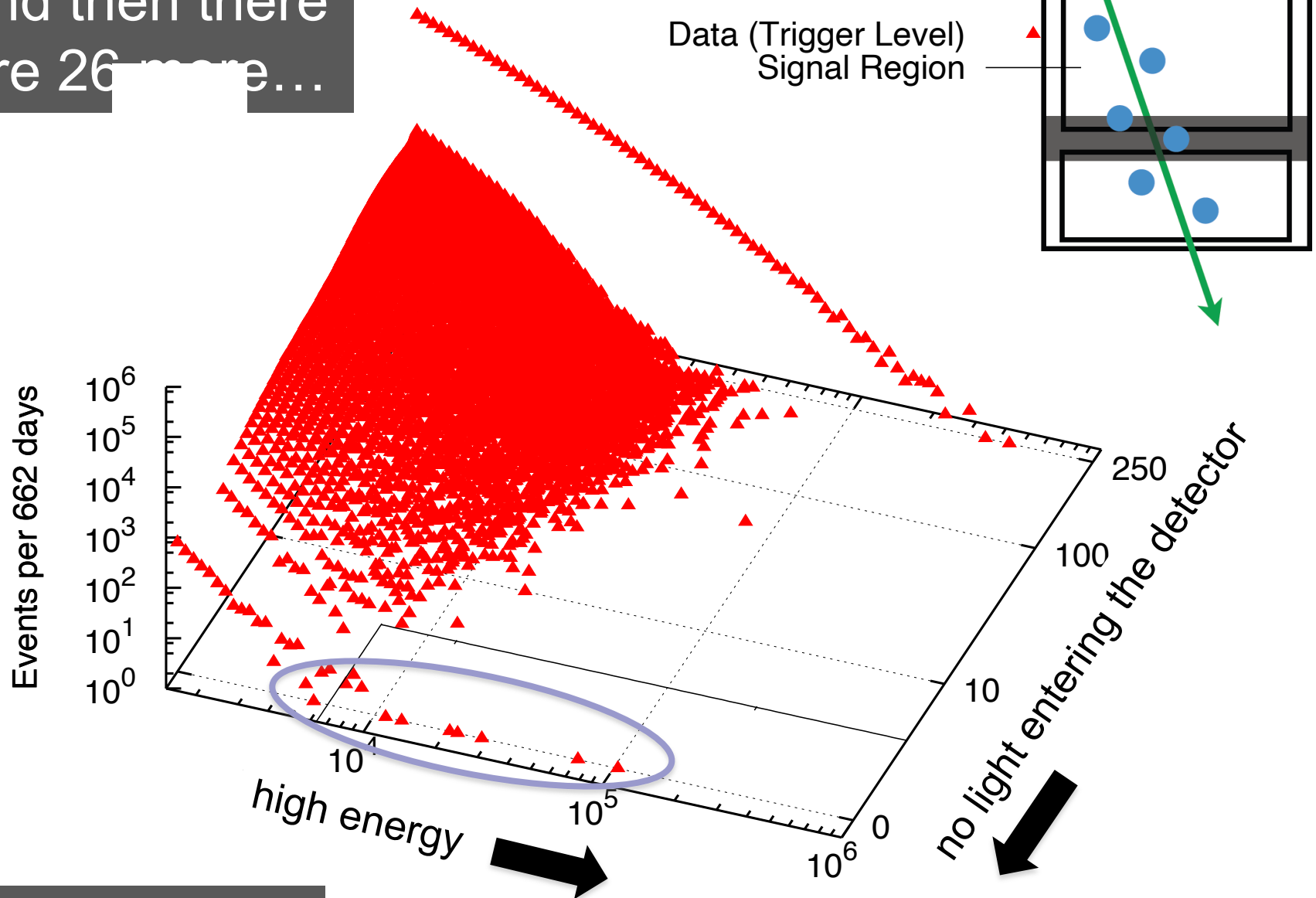
→ flux at present  
level of diffuse  
limit

...and then there  
were 26 ...



data: 86 strings one year

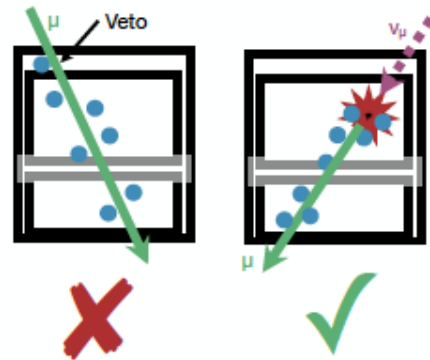
...and then there  
were 26 more...



data: 86 strings one year

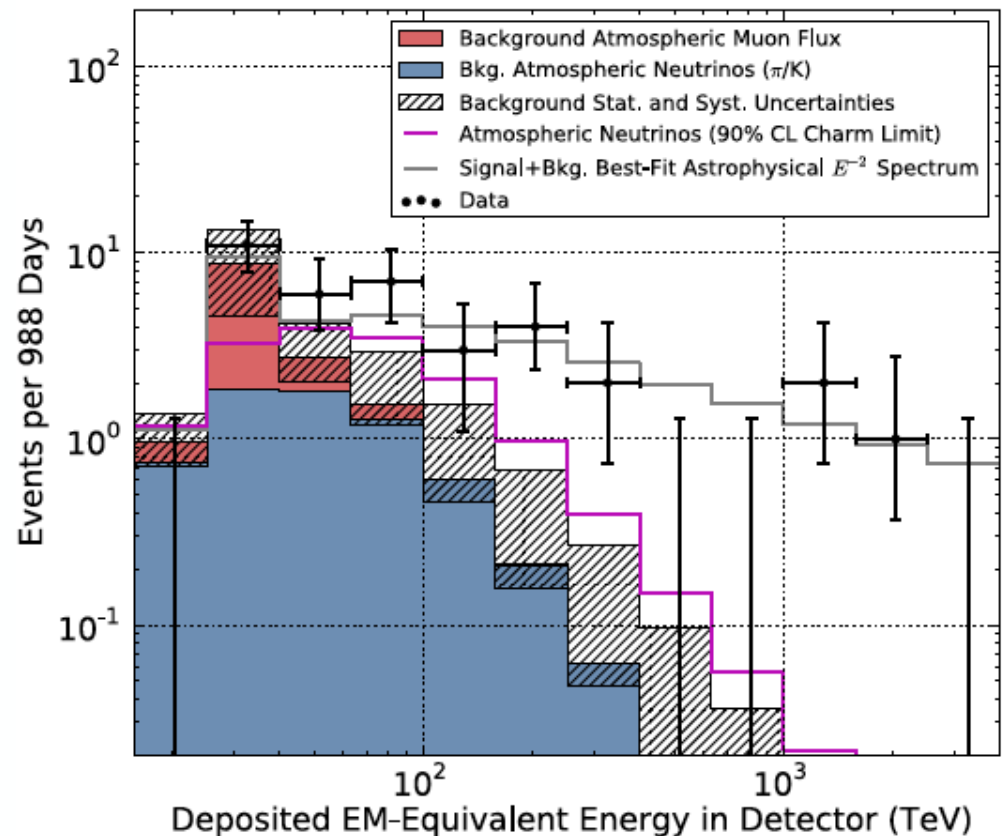
## Evidence for high-energy astrophysical neutrinos

- Selected high-energy starting events in IceCube



- 3 cascades over 1 PeV in 3 years of data
- 5.7  $\sigma$  evidence for astrophysical neutrinos

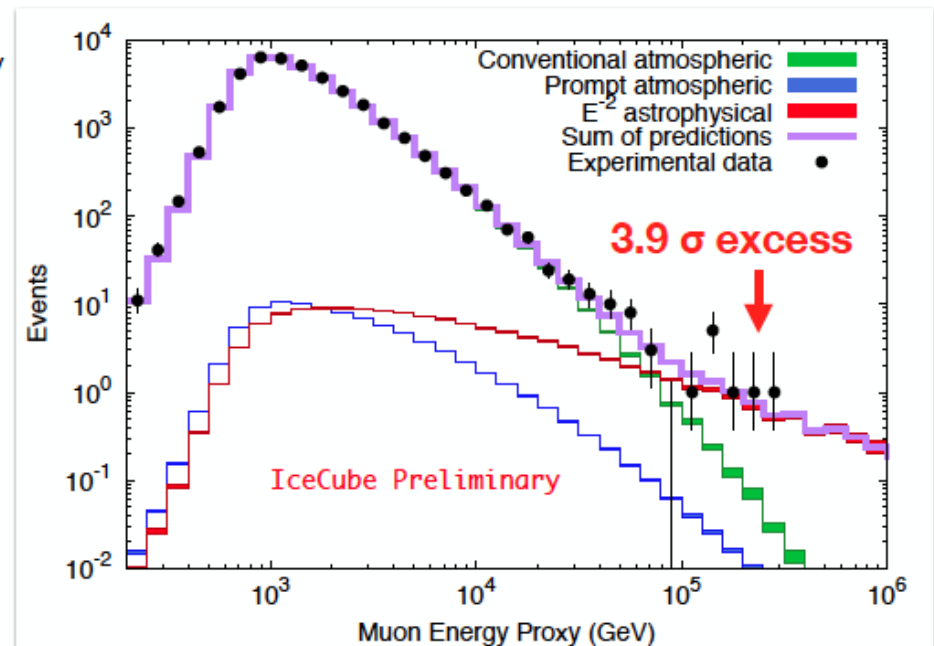
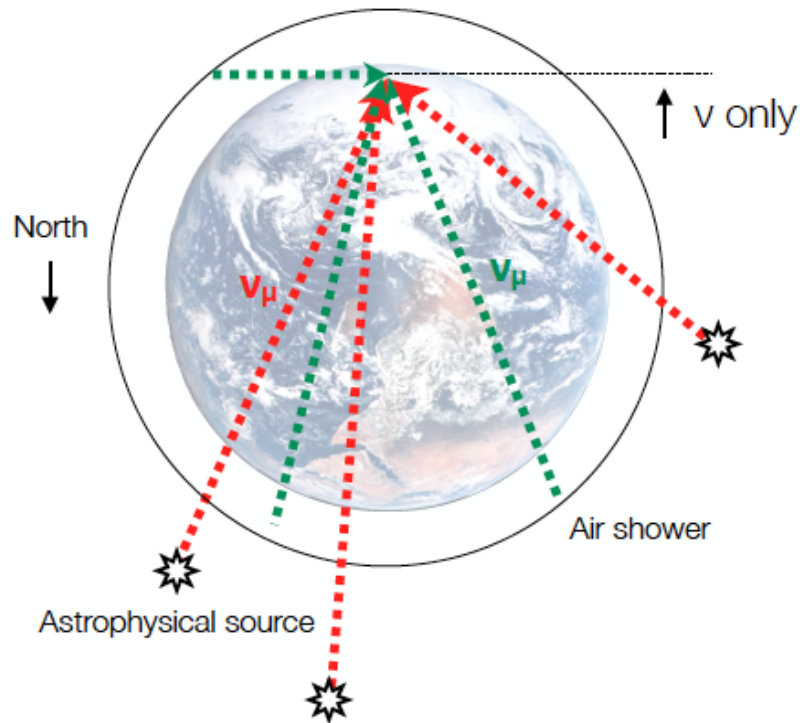
## Deposited energy



arXiv:1405.5303 (accepted for PRL)

# What about the northern sky and $\nu_\mu$ ?

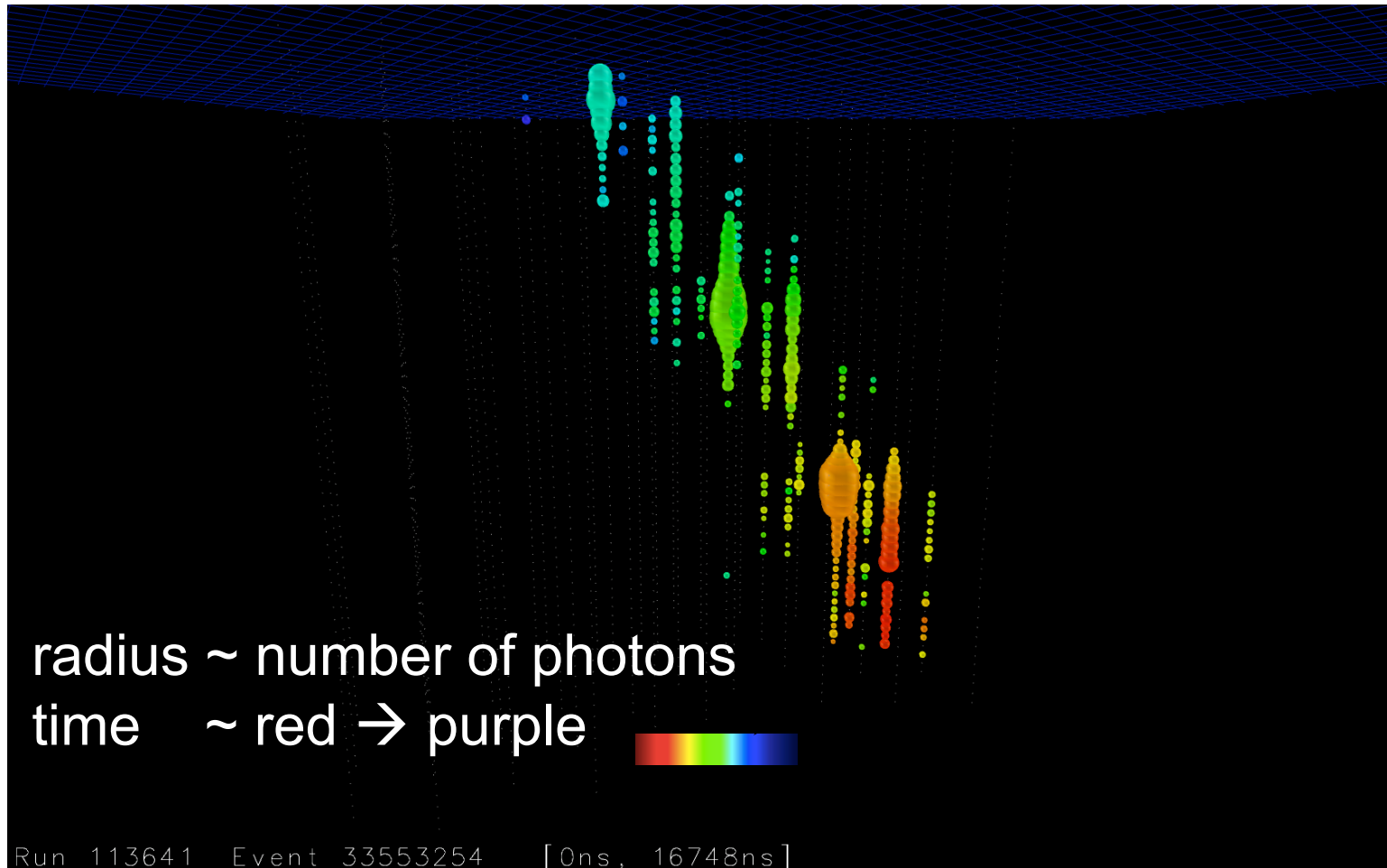
The high-energy starting event sample is dominated by cascades from the southern sky.



We look for the same excess in incoming muons from the northern sky  
 High-energy muons reach the detector from km away  $\rightarrow$  large effective volume  
 Only sensitive to CC  $\nu_\mu \rightarrow$  explicit handle on  $\nu_\mu$  flux



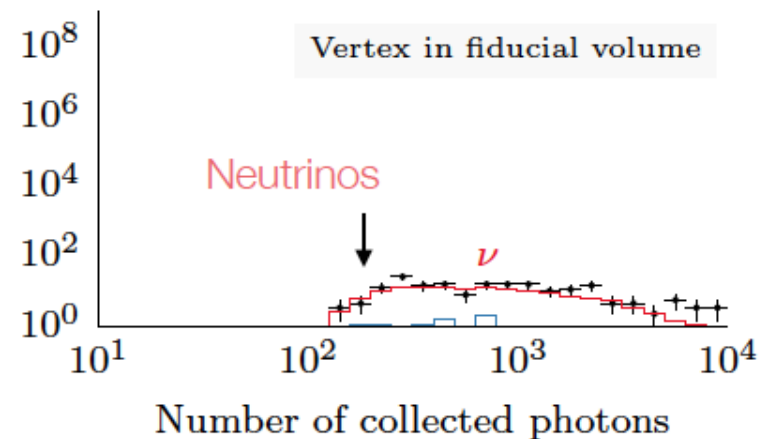
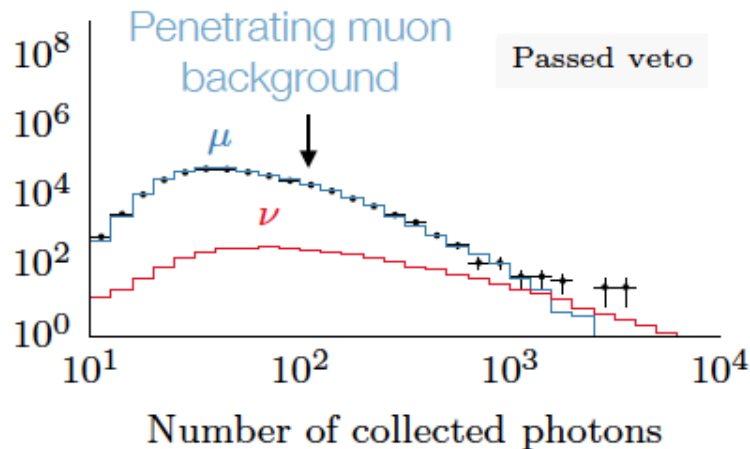
# Muon track from 89 TeV neutrino



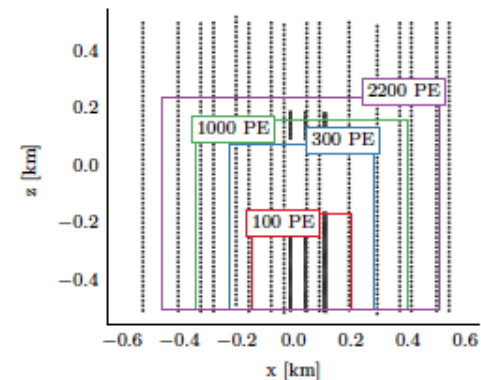
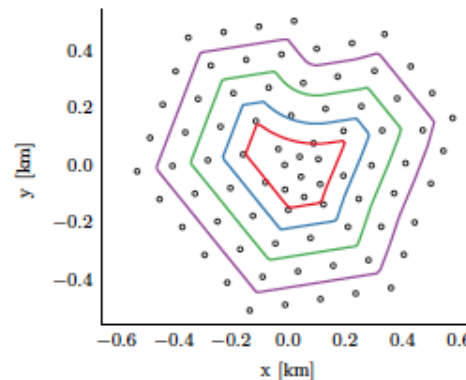


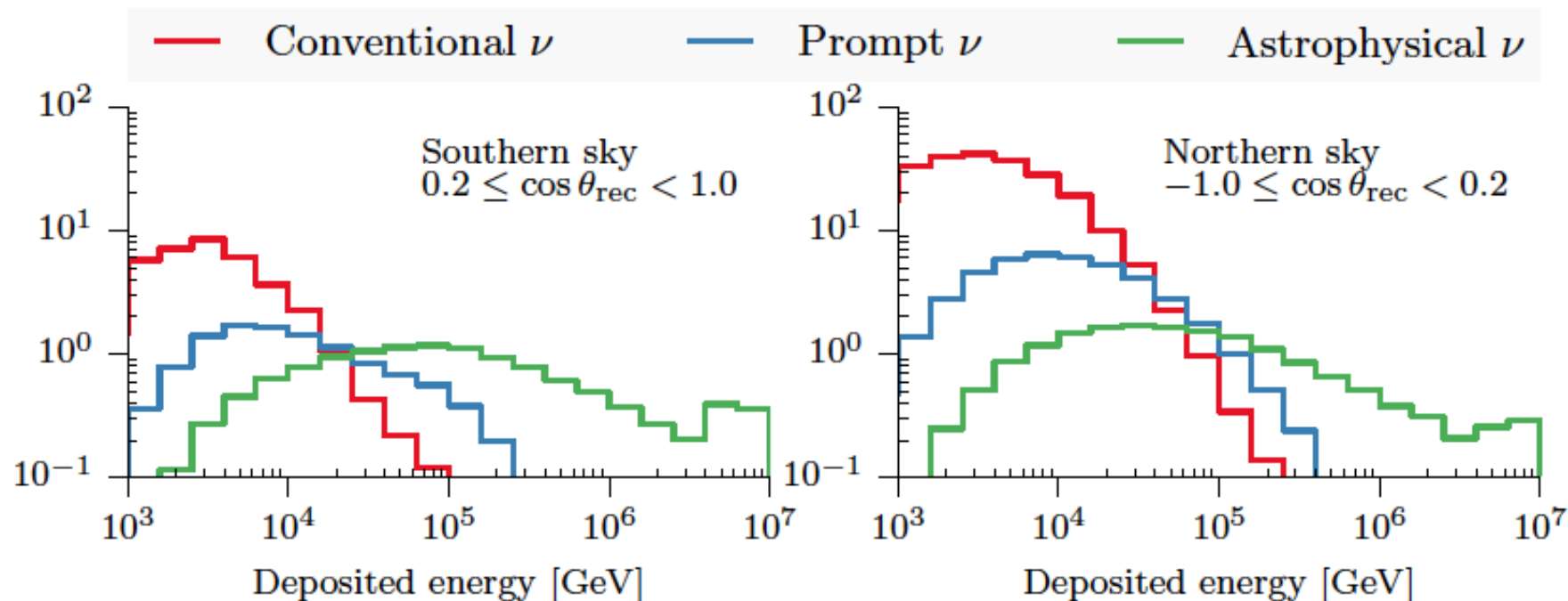
## Improved veto techniques

Outer-layer veto  $\rightarrow$  Energy-dependent veto  
 Neutrino-dominated for  $E_{\text{dep}} > 60 \text{ TeV}$     Neutrino-dominated for  $E_{\text{dep}} > 1 \text{ TeV}$



**Thicker veto at low energies**  
 suppresses penetrating muons  
 without sacrificing high-energy  
 neutrino acceptance





**Conventional** neutrino flux from pion/kaon decay in the atmosphere

determined from low-energy ( $< 3$  TeV) data

**Astrophysical** neutrino flux

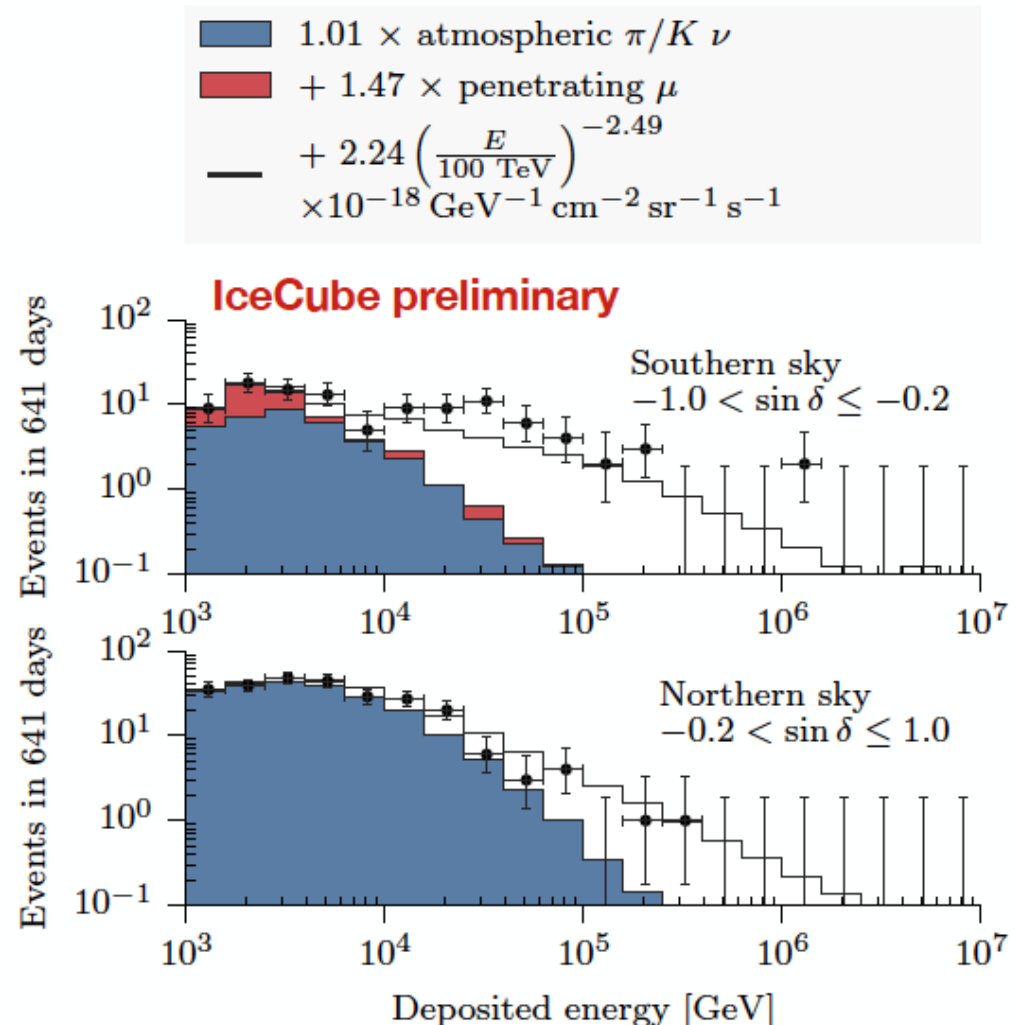
determined from high-energy ( $> 100$  TeV north/ $>50$  TeV south) data

**Prompt** neutrino flux from charmed mesons decay in the atmosphere

constrained by 10-50 TeV data

# Results: energy spectrum

- ▶ 283 cascade and 105 track events in 2 years of data
- ▶ 106 > 10 TeV, 9 > 100 TeV (7 of those already in high-energy starting event sample)
- ▶ Conventional atmospheric neutrino flux observed at expected level with starting events

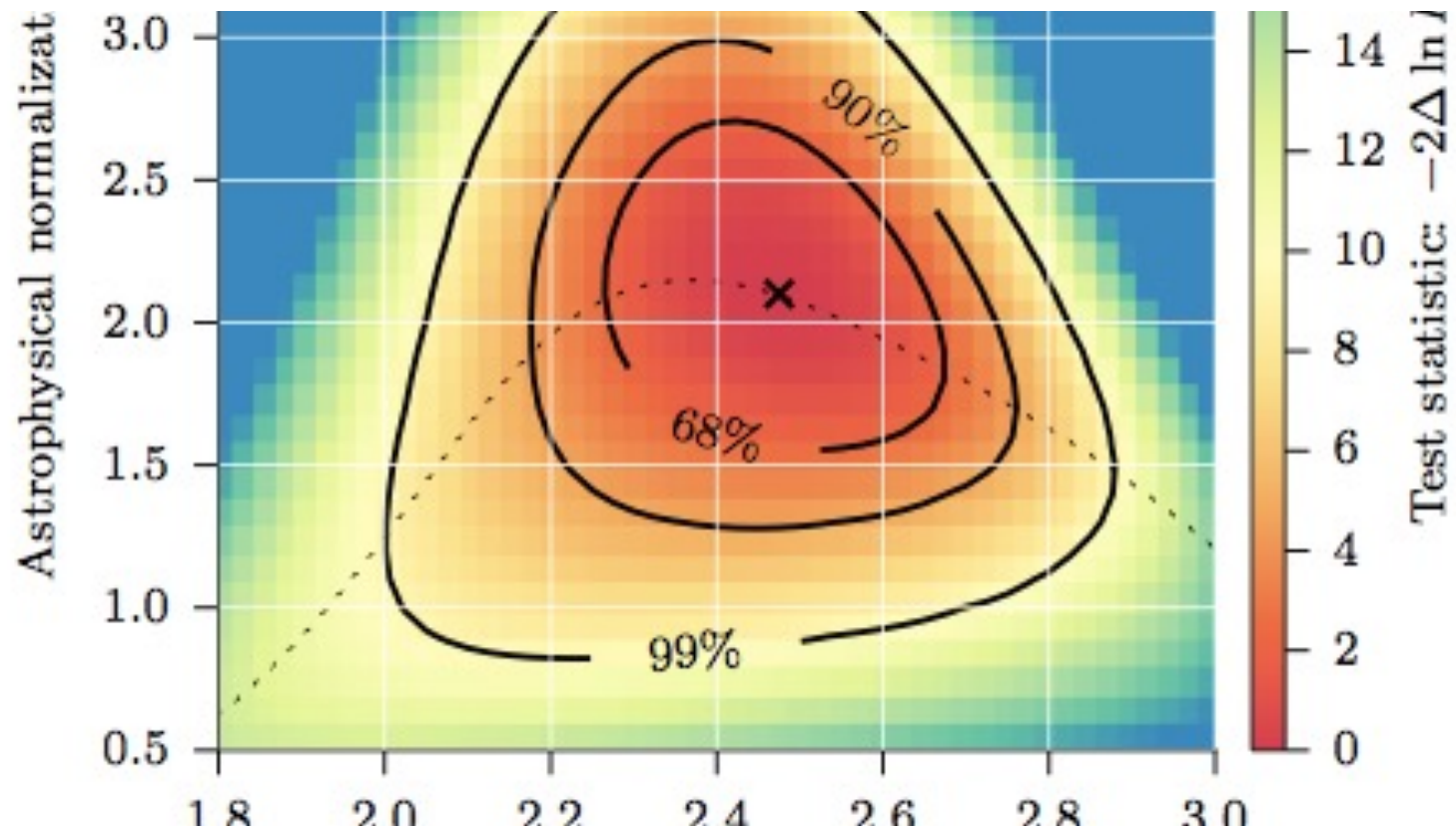


# Best fit parameters

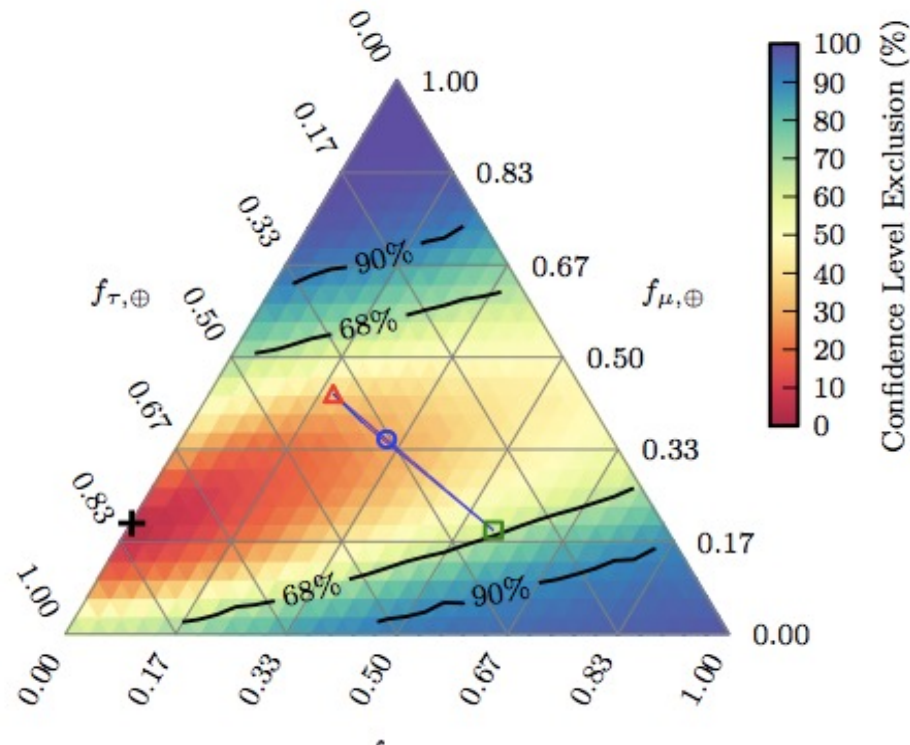
TABLE I. Best fit parameters and number of events attributable to each component. The normalizations of the atmospheric fluxes are relative to the models described in Sec. III. The per-flavor normalization  $\Phi_0$  and spectral index  $\gamma$  of the astrophysical flux are defined in Eq. (1); the fit to the astrophysical flux is sensitive to  $25 \text{ TeV} < E_\nu < 1.4 \text{ PeV}$ . The two-sided error ranges given are 68% confidence regions in the  $\chi^2$  approximation; upper limits are at 90% confidence. The goodness-of-fit p-value for this model is 0.2.

Parameter	Best-fit value	No. of events
Penetrating $\mu$ flux	$1.73 \pm 0.40 \Phi_{\text{SIBYLL+DPMJET}}$	$30 \pm 7$
Conventional $\nu$ flux	$0.97^{+0.10}_{-0.03} \Phi_{\text{HKKMS}}$	$280^{+28}_{-8}$
Prompt $\nu$ flux	$< 1.52 \Phi_{\text{ERS}} \text{ (90\% CL)}$	$< 23$
Astrophysical $\Phi_0$	$2.06^{+0.35}_{-0.26} \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$	$87^{+14}_{-10}$
Astrophysical $\gamma$	$2.46 \pm 0.12$	

# Neutrino spectrum



# Flavor content consistent with 1:1:1



IceCube Collaboration, [arXiv:1502.03376](https://arxiv.org/abs/1502.03376)



# Neutrino astrophysics

- IceCube detected first astrophysical neutrinos. New field started: neutrino astrophysics.
- Best flux  $1/E^{(2.46 \pm 0.14)}$
- Flux  $1/E^2$  disfavored with more than 3 sigma significance
- Muon neutrino data favors  $1/E^{2.1}$  flux !
- Flavor ratio consistent with 1:1:1 as expected
- Cosmogenic neutrinos best constrained by IceCube, but in case of nuclei primaries bigger detector needed to find flux
- Bigger detectors needed for next step

# Future detectors

# Baikal-GVD



## Environmental parameters

Lake Baikal - fresh water

distance to shore  $\sim 6$  km

$L_{\text{abs}} \sim 22\text{-}25$  m

$L_{\text{scat}} \sim 30\text{-}50$  m

depth  $\sim 1360$  m

icefloor during winter

## Telescope design

$\sim 1.5$  km<sup>3</sup>

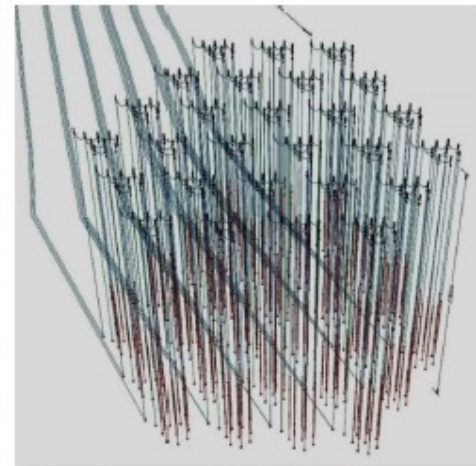
27 shore-cables for 27 clusters

$27 \times 8 = 216$  strings

$216 \times 48 = 10368$  OM<sup>s</sup> ¶

deployment from icefloor

*shallow water* DAQ infrastructure

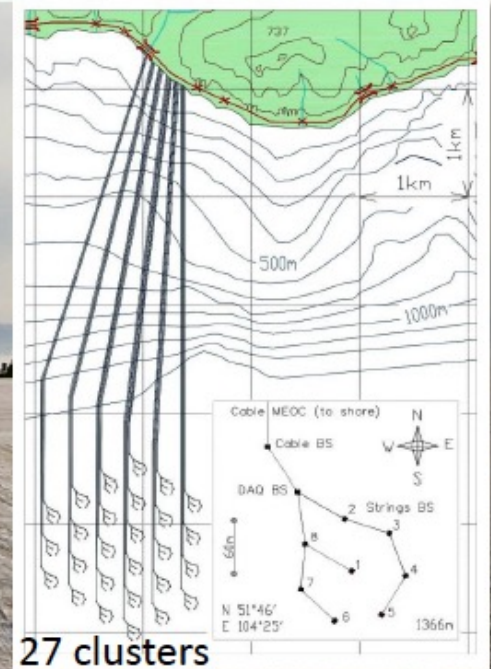
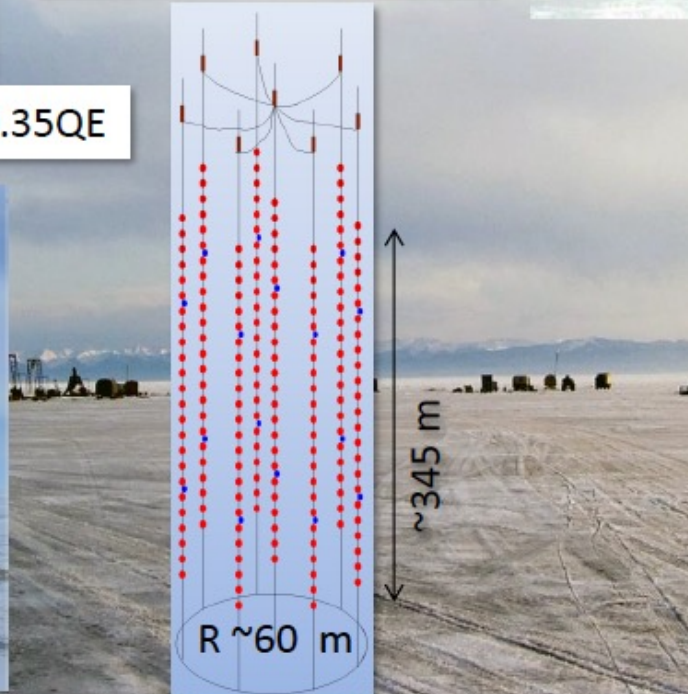
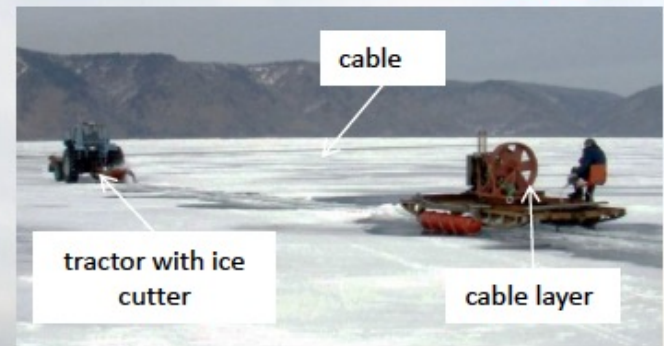
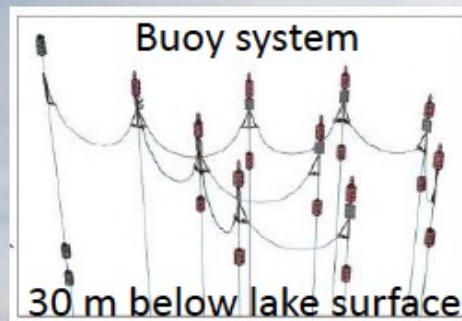


¶ OM – Optical Module

# GVD technology



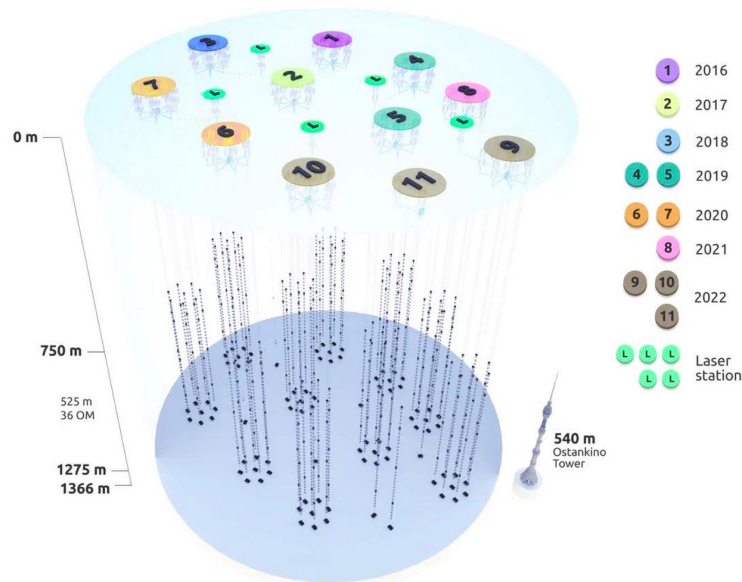
R7081HQE : D=10", ~0.35QE





# Status BAIKAL

## Baikal-GVD construction status 2022 and schedule



10 clusters + 1 special string (laser+36 OM)  
+ 2 experimental strings + 4 laser stations

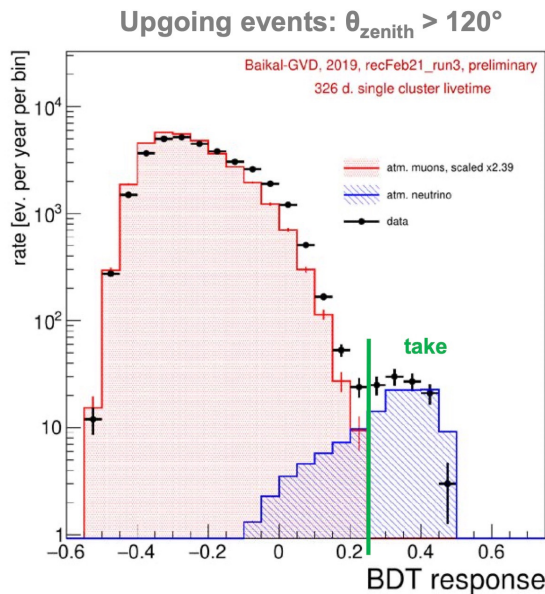
Deployment schedule

Year	Number of clusters	Number of strings	Number of OMs
2016	1	8	288
2017	2	16	576
2018	3	24	864
2019	5	40	1440
2020	7	56	2016
2021	8	64	2304
<b>2022</b>	<b>10</b>	<b>80 + 3</b>	<b>2880 + 84</b>
2023	12	96	3456
2024	14	112	4032

10 clusters is working now, 14 clusters to 2024

# Atmospheric neutrinos

## Track-like events analysis progress



Track-like reconstruction and neutrino selection techniques are being refined

An improvement in sensitivity by a factor of 2 with recent developments

[\[PoS\(ICRC2021\)1063, PoS\(ICRC2021\)1080\]](#)

- Improvement in noise suppression techniques
- More efficient neutrino selection using boosted decision trees (BDT)

**MC expected: 81.2**

**Observed events: 106**

Machine learning application for Baikal water noise suppression: [\[arXiv:2210.04653\]](#)



# Confirmation of astrophysical neutrino flux

## Search for upward moving events [arXiv:2211.09447](https://arxiv.org/abs/2211.09447)

Additional selection requirements:

$$E > 15 \text{ TeV} \ \& \ N_{\text{hit}} > 11 \ \& \ \cos\theta < -0.25$$

Expected:

0.5 events from atm. muons

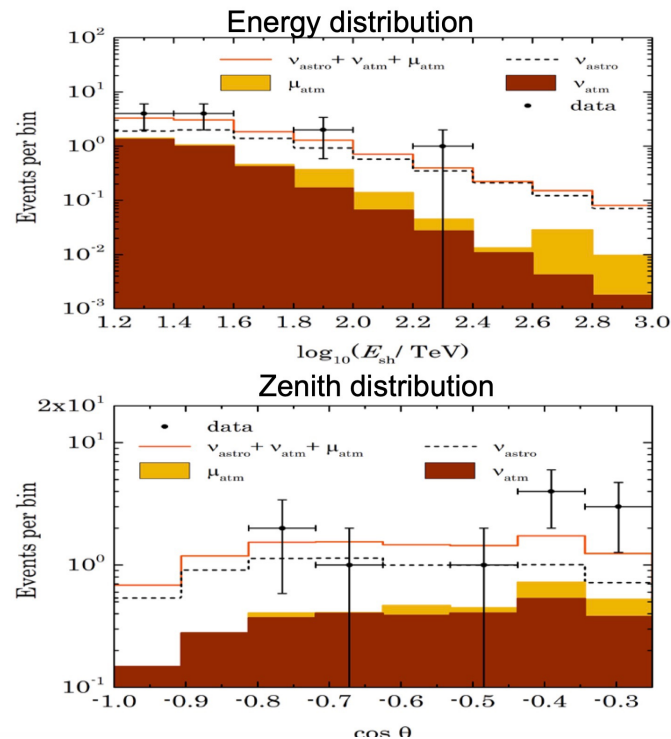
2.7 events from atm. neutrinos

6.3 events for Baikal-GVD best fit  $E^{-2.58}$   
astrophysical flux

Found in data: 11 events

Probability for the background-only hypothesis (stat.+sys.)

**P-value = 0.0024 ( $3.05\sigma$ )**



# Confirmation of astrophysical neutrino flux

Single power-law model of isotropic astrophysical flux:

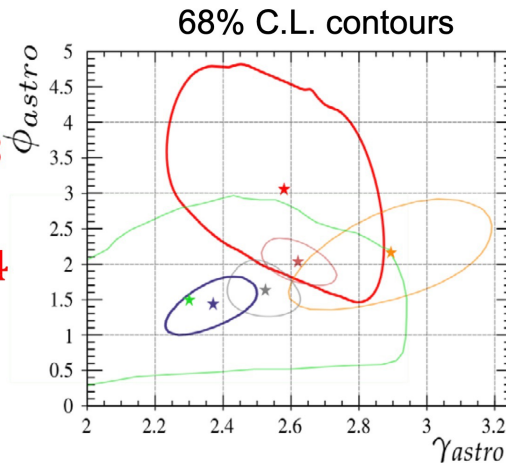
$$(\nu_e : \nu_\mu : \nu_\tau = 1:1:1)$$

$$\Phi^{\nu+\bar{\nu}} = 3 \times 10^{-18} \varphi_{astro} \left( \frac{E}{10^5} \right)^{-\gamma_{astro}} (GeV cm^2 s sr)^{-1}$$

Baikal-GVD best fit parameters:

spectral index  $\gamma_{astro} = 2.58$

One flavor normalization  $\varphi_{astro} = 3.04$



- Baikal-GVD (2018-2021, Upward-going) this study, best fit
- IceCube HESE (7.5y, Full-sky) Phys. Rev. D 104, 022002 (2021)
- IceCube Inelasticity Study (5y, Full-sky) Phys. Rev. D 99, 032004 (2019)
- IceCube Cascades (6y, Full-sky) Phys. Rev. Lett. 125, 121104 (2020)
- IceCube Tracks (9.5y, Northern Hemisphere), The Astrophysical Journal 928, 50 (2022)
- ANTARES Cascades+Tracks (9y, Full-Sky) PoS(ICRC2019) 891 (2020)

[arXiv:2211.09447](https://arxiv.org/abs/2211.09447)

## The Baikal-GVD high-energy cascade sky map (in equatorial coordinates)

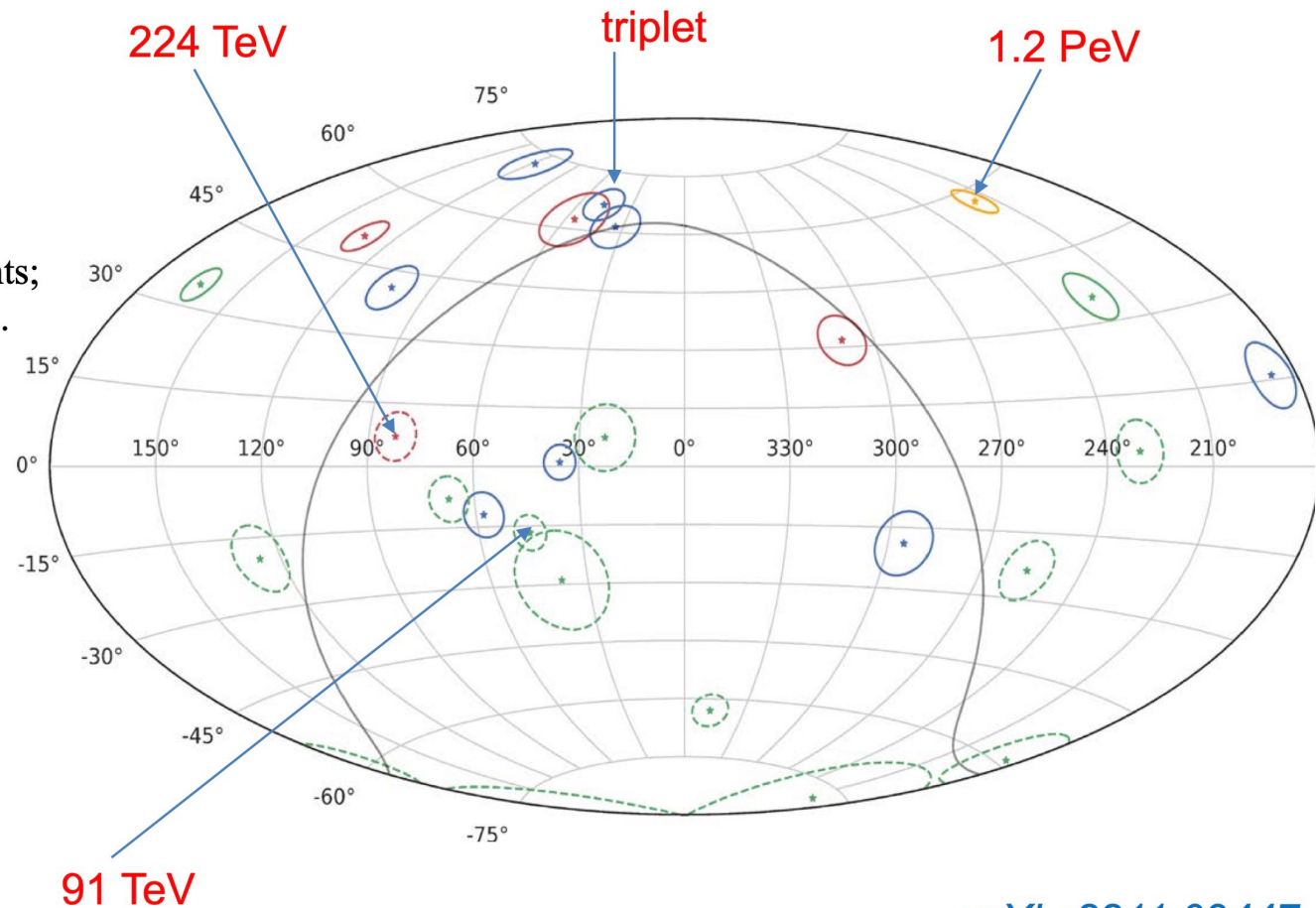
The best-fit positions and 90% angular uncertainty regions:

dashed circles - under-horizon events;  
solid circles - above horizon events.

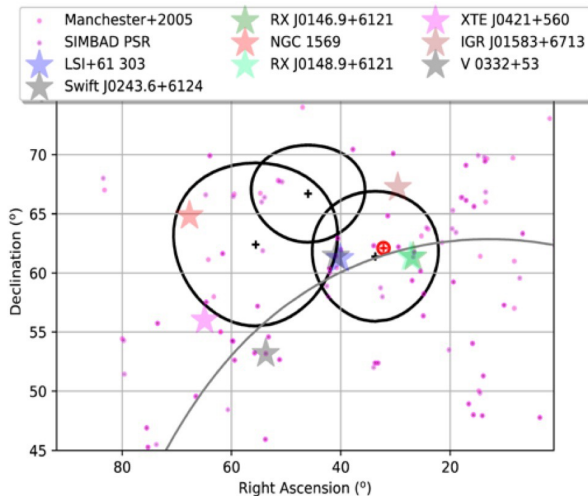
Colour represents event energy:

green –  $E < 100$  TeV,  
blue –  $100 \text{ TeV} < E < 200$  TeV,  
red –  $200 \text{ TeV} < E < 1000$  TeV,  
orange –  $E > 1 \text{ PeV}$ .

The Galactic plane is indicated as a grey curve.



## Event triplet near Galactic plane



Three events (GVD190216CA, GVD190604CA and GVD210716CA) close to the Galactic plane (grey line) and their corresponding 90% errors (black).

The red plus and circle – IC hotspot and  $0.5^\circ$  uncertainty at 90% level (Aartsen & et al. ApJ, 835,151 (2017))

Stars - Several close high-mass X-ray binaries.

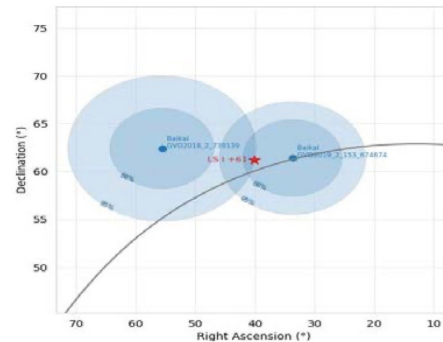
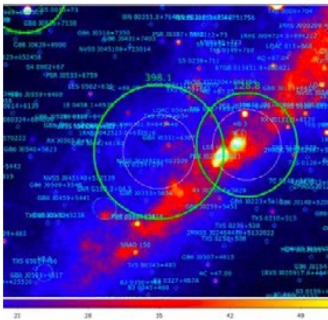
Dots - Galactic pulsars (Manchester et al. 2005, SIMBAD Astronomical Database)



LSI +61° 303  $\gamma$ -ray active binary system

Swift J0243.6+6124 s the only discovered pulsating ultraluminous X-ray source (PULX) in the Galaxy.

## LSI +61 303 and the two Baikal-GVD events



LSI +61 303 –  $\gamma$ -ray microquasar  $3.1^\circ$  from GVD190604CA and  $7.4^\circ$  from GVD190216CA (both are down-going events). Using the PSFs of all 16 HE-events, the chance probability to observe such a doublet near LSI +61 303 was estimated as 0.0187 ( $2.35\sigma$ ) [not corrected for the “look elsewhere effect”]





# KM3NeT in the Mediterranean

## Environmental parameters

Mediterranean Sea – salt water

3 installation sites

distance to shore  $\sim 40\text{-}100$  km

$L_{\text{abs}} \sim 60\text{-}100$  m

$L_{\text{scat}} \sim 50\text{-}70$  m

depths  $\sim 2500\text{-}4500$  m

## Telescope design

$\sim 3.5\text{-}6$  km<sup>3</sup> (depending on spacing)

6 shore-cables for 6 building blocks

$6 \times 115 = 690$  detection units

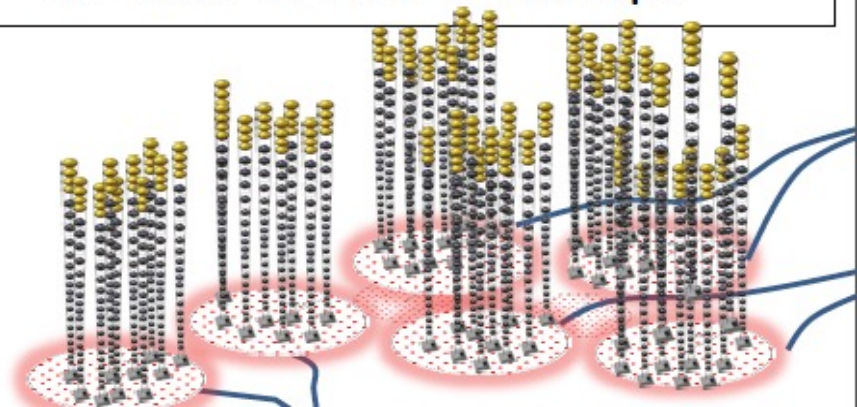
$690 \times 18 = 12420$  OMs

*seabed* data transmission

infrastructure

installation requires ship + ROV

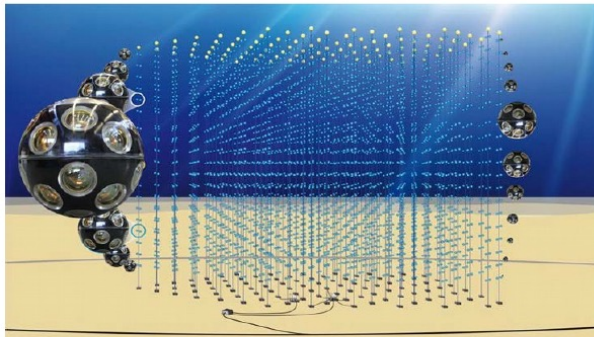
all-data-to-shore concept



# Construction started

## KM3NeT - ARCA

Construction started

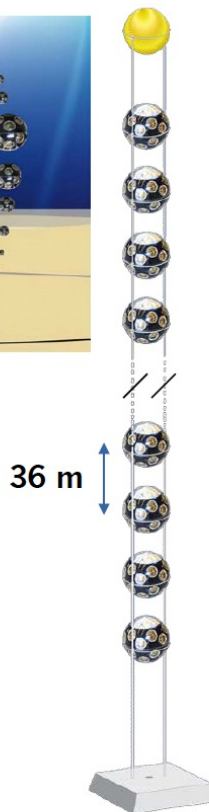


100 km offshore Sicily  
Depth: 3400 m

**2 x 115** strings  
**18** DOMs / string  
**31** PMTs / DOM  
Total: **128 000 PMTs (3")**

Vertical spacing: 36 m  
Horizontal spacing: 90 m

Volume : 1 km<sup>3</sup>



### Digital Optical Module



- 31 x 3" PMTs
- PMT HV
- LED & piezo
- FPGA readout
- DWDM

← 17" →

- ✓ Uniform angular coverage
- ✓ Directional information
- ✓ Digital photon counting
- ✓ All data to shore

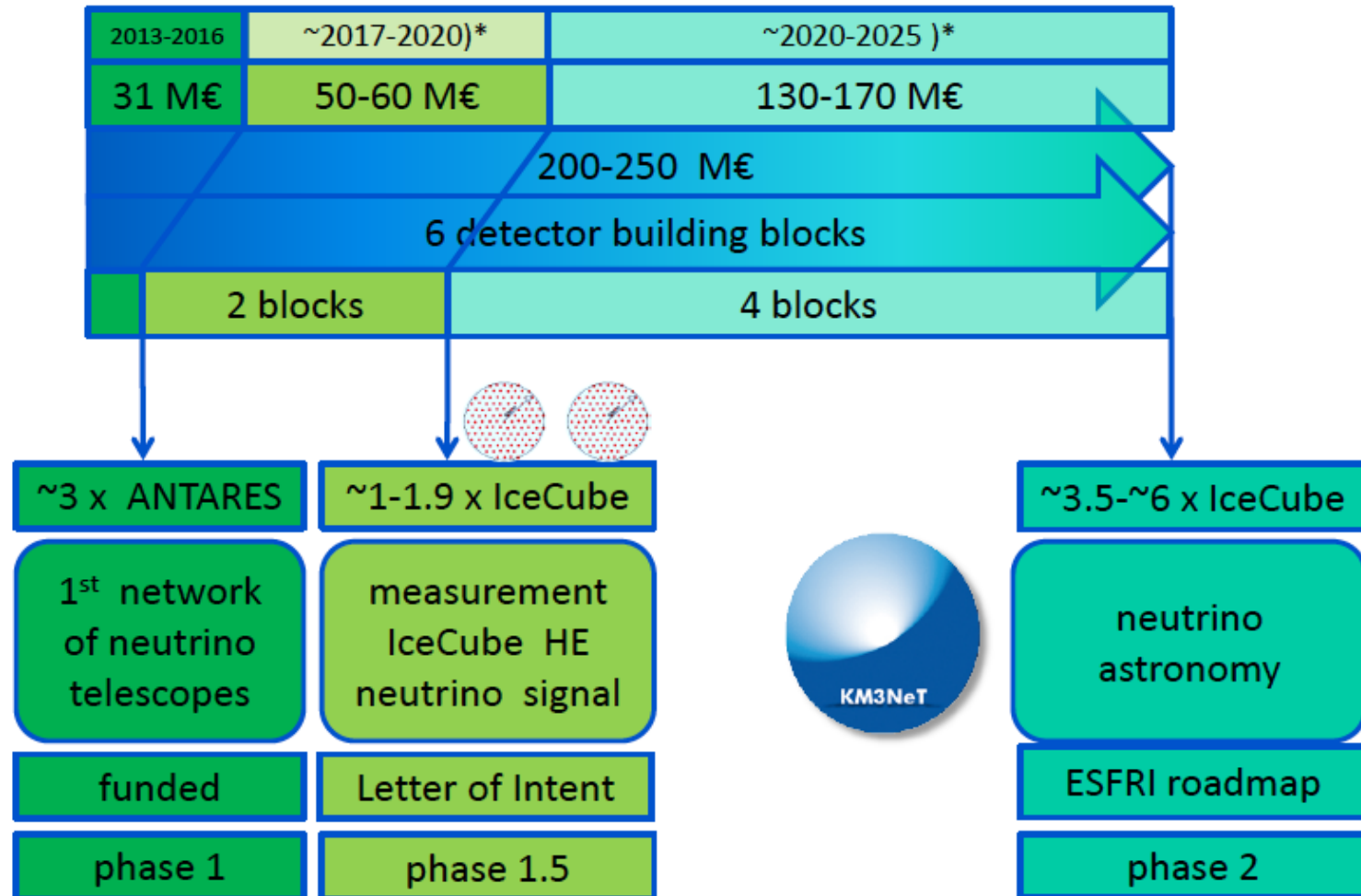
photocathode  
area similar to  
a 17" PMT

Optical background (mainly  
K): 5-10 kHz/PMT

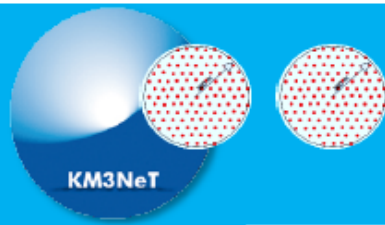




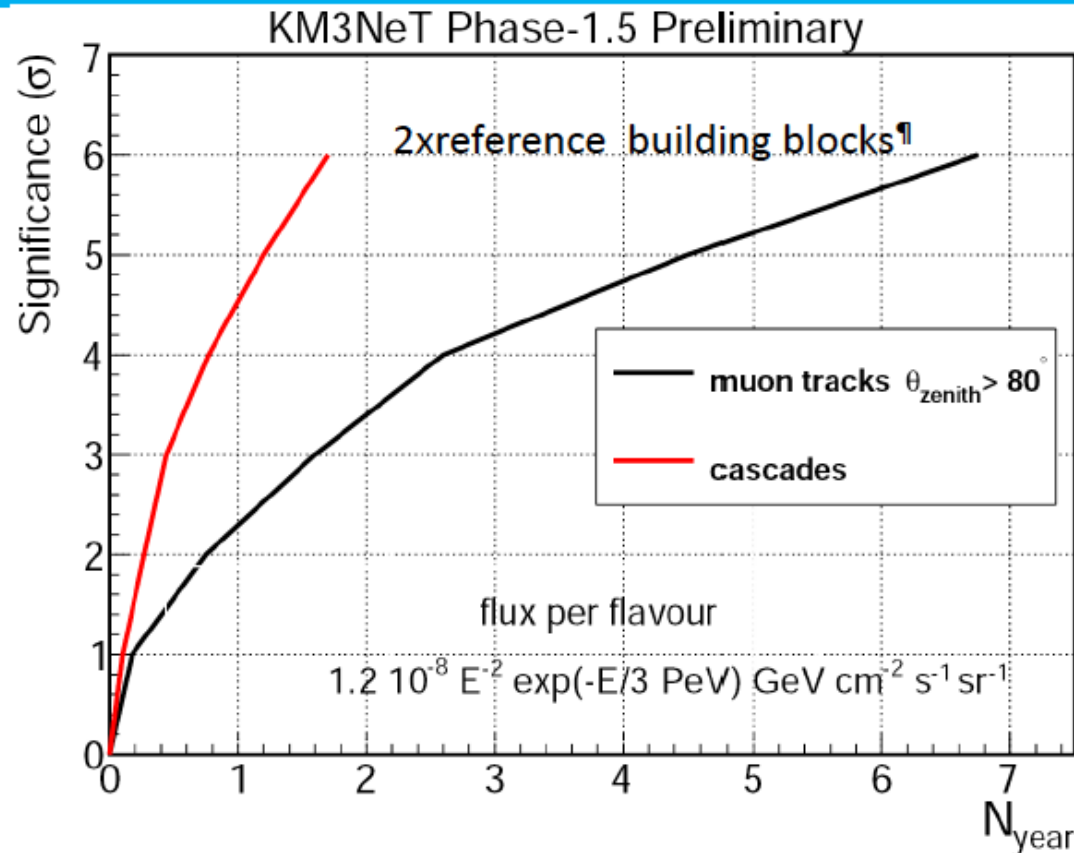
# KM3NeT phased construction



)\* depending on funding



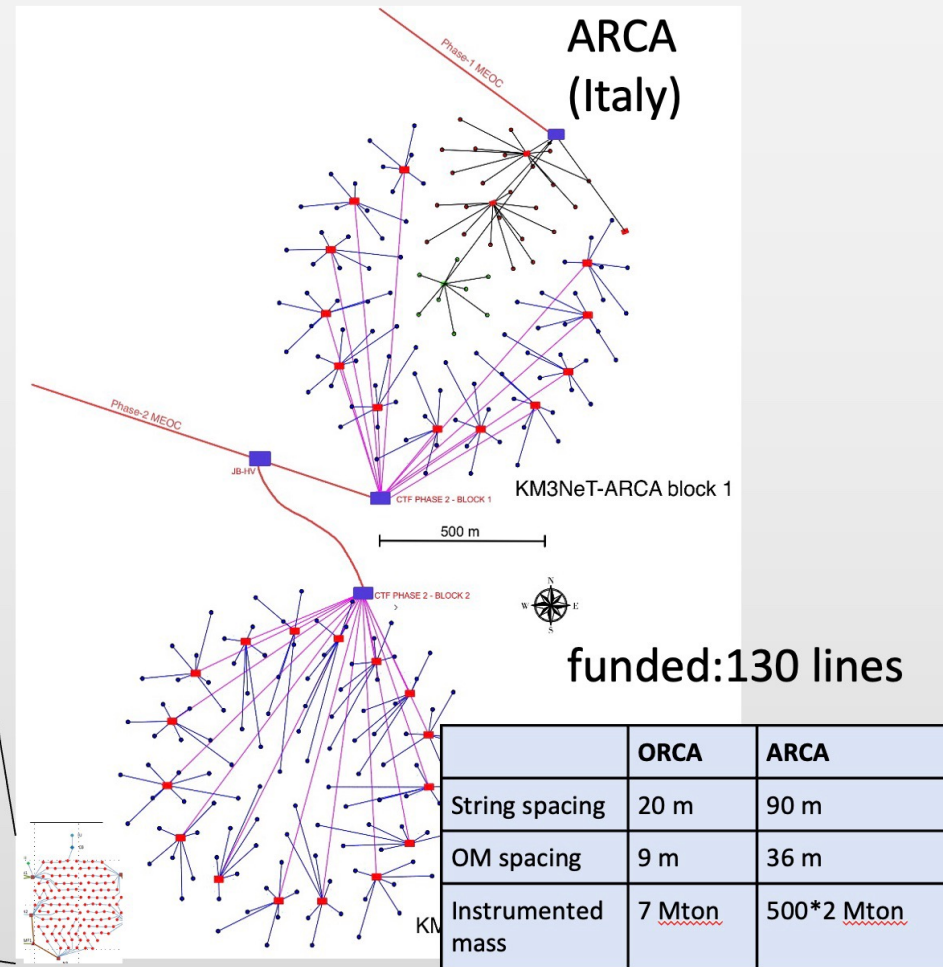
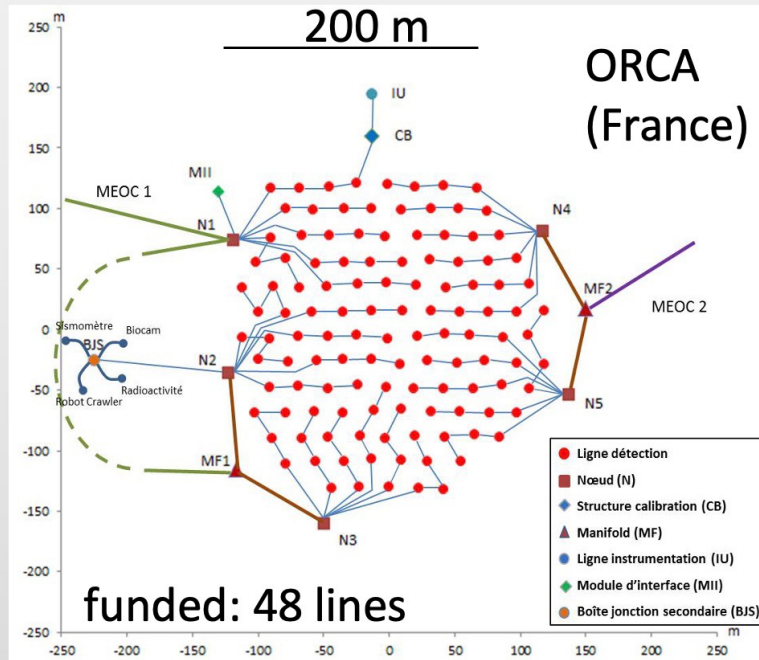
# Performance



Detailed investigation of „IceCube signal“ within a few years, with different *field of view*, different *systematics* and better *angular resolution*

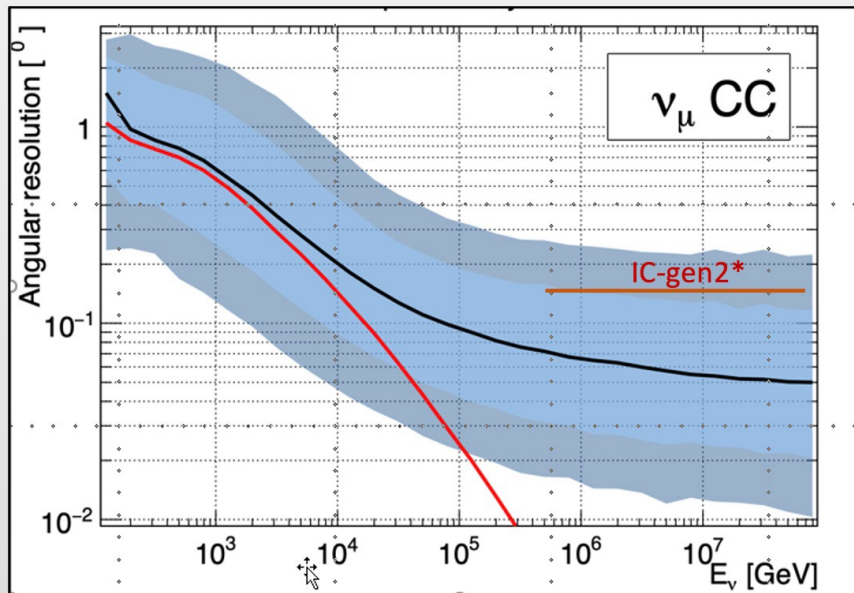
<sup>¶</sup> 30% better FoM with HE blocks with 120 m spacing and R=650 m.

# Building blocks

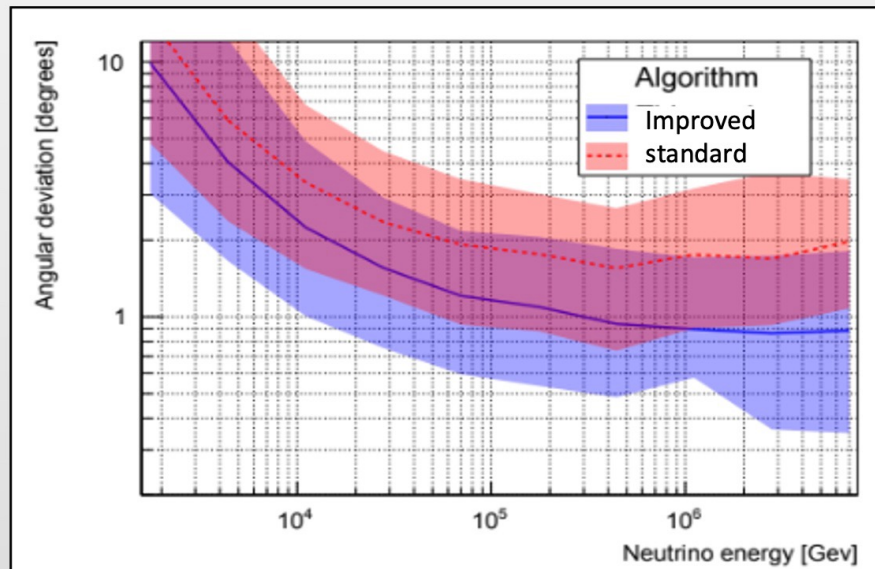


# KM3NeT Resolutions

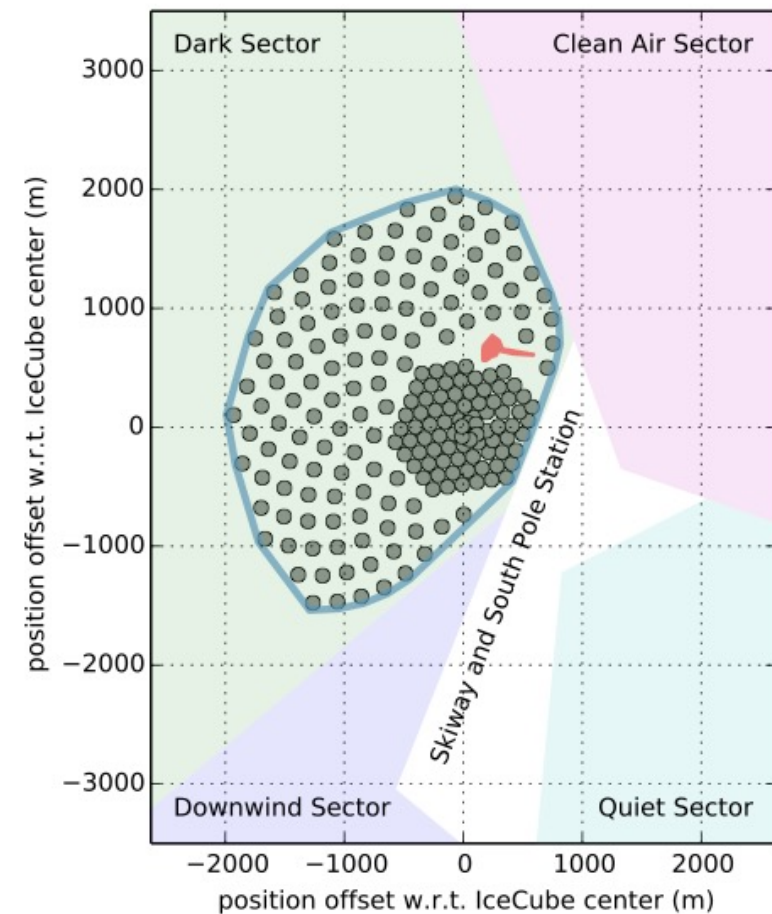
## Tracks



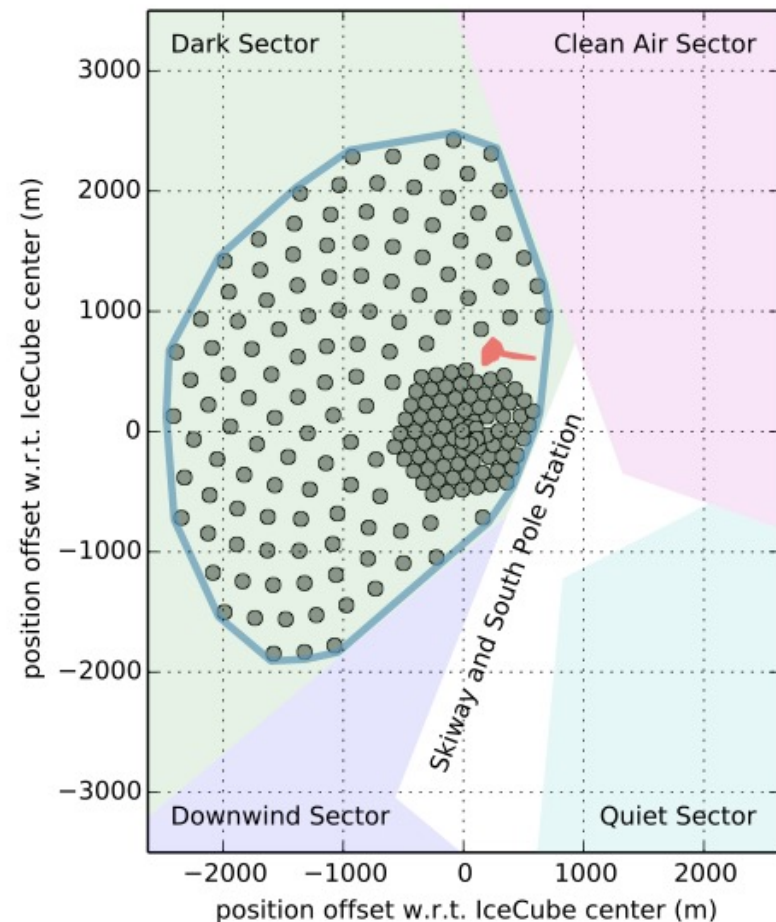
## Cascades



# 86 strings with 240-340 m spacing



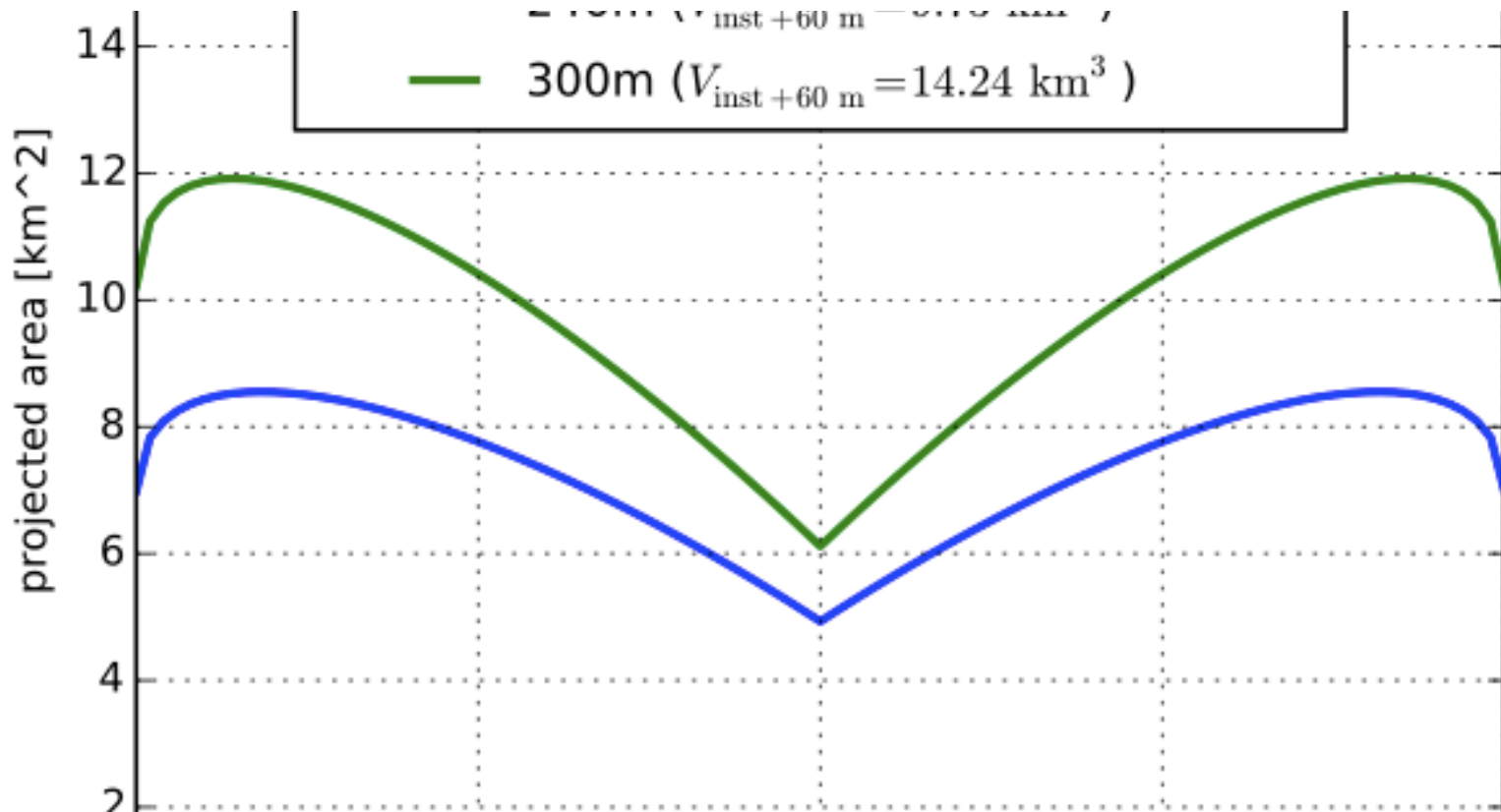
(a) 240 m string spacing ("benchmark")



(b) 300 m string spacing

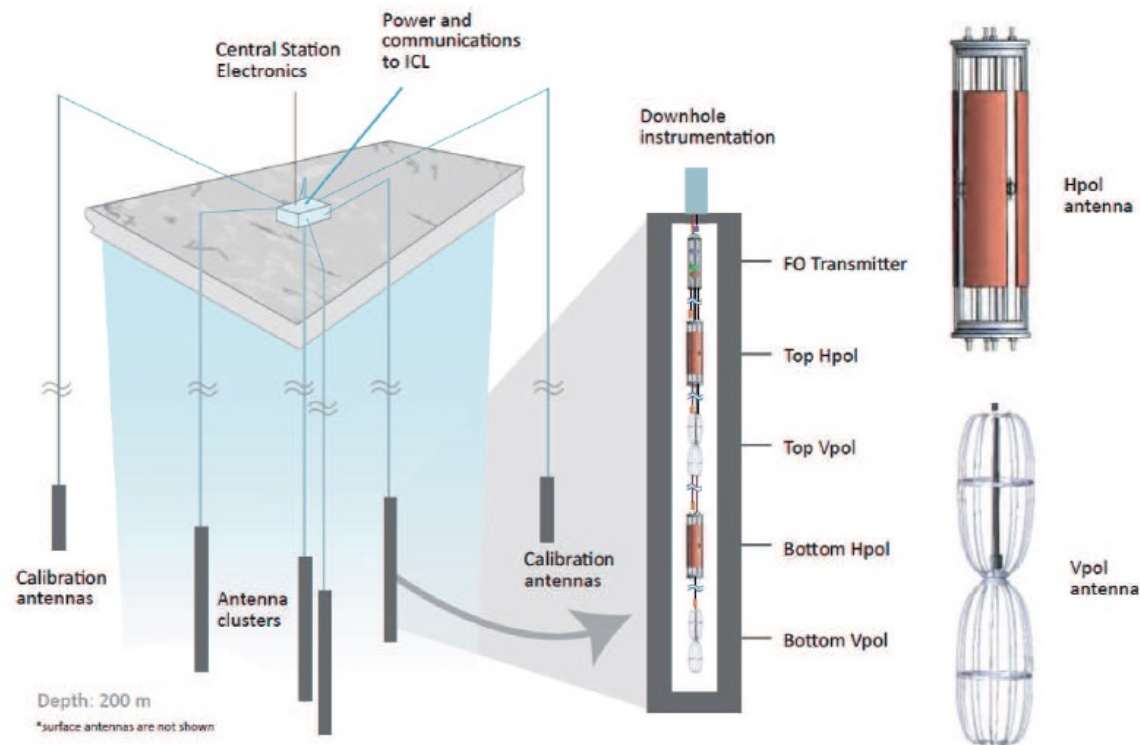


# Effective volume

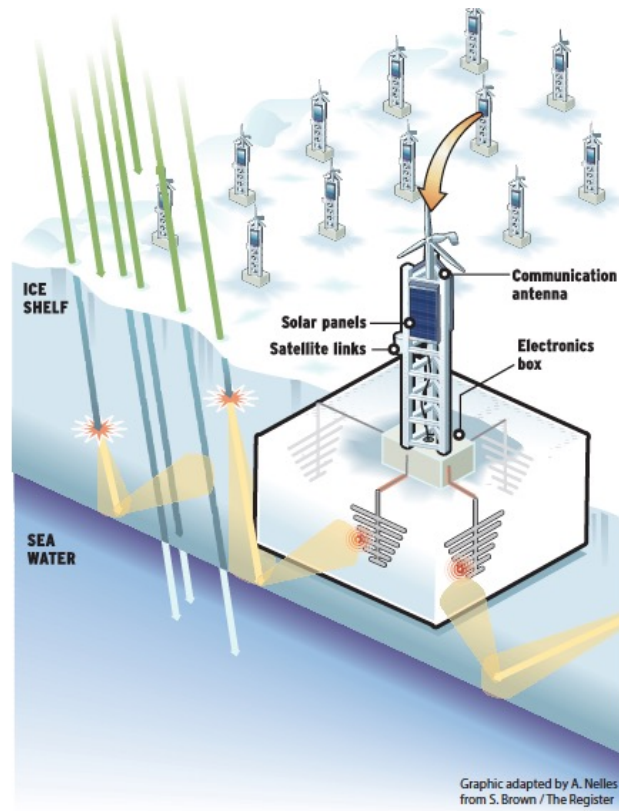




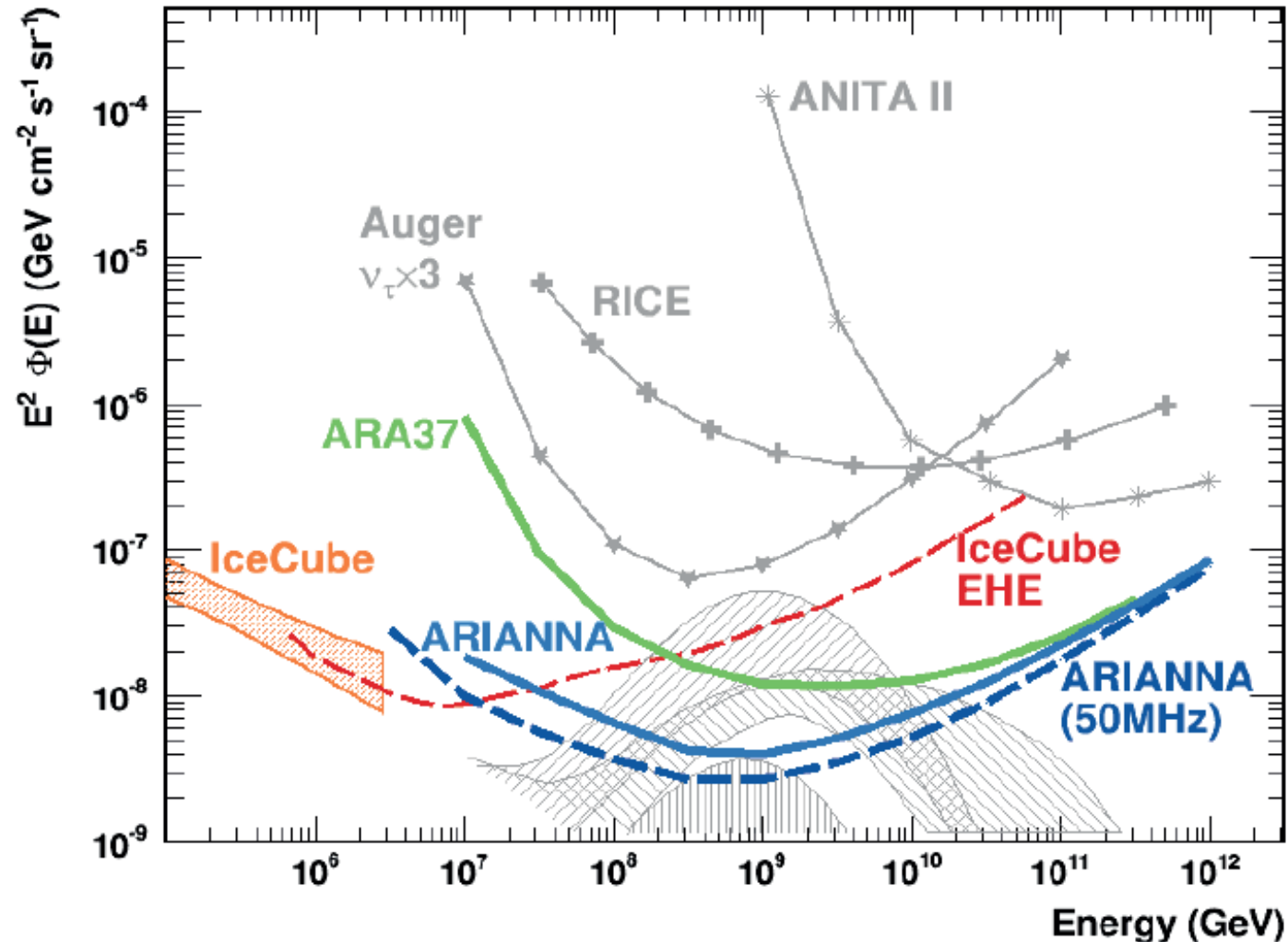
# ARA radio detector South pole



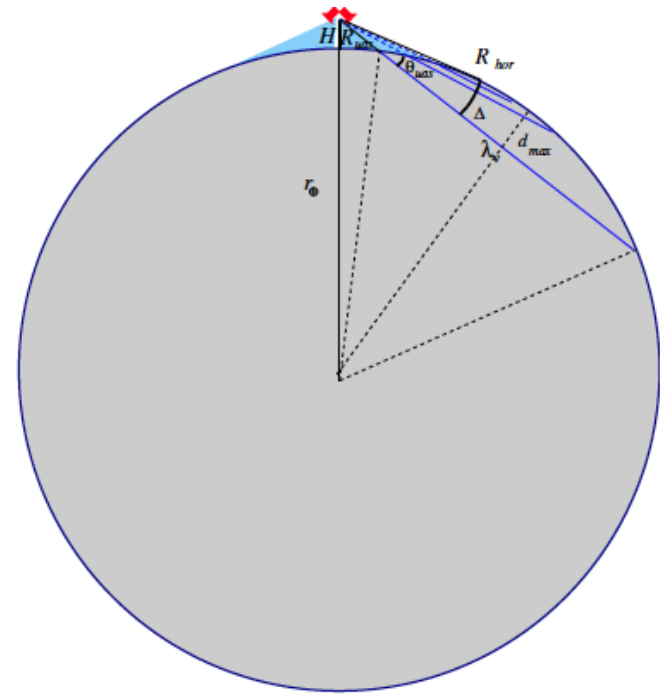
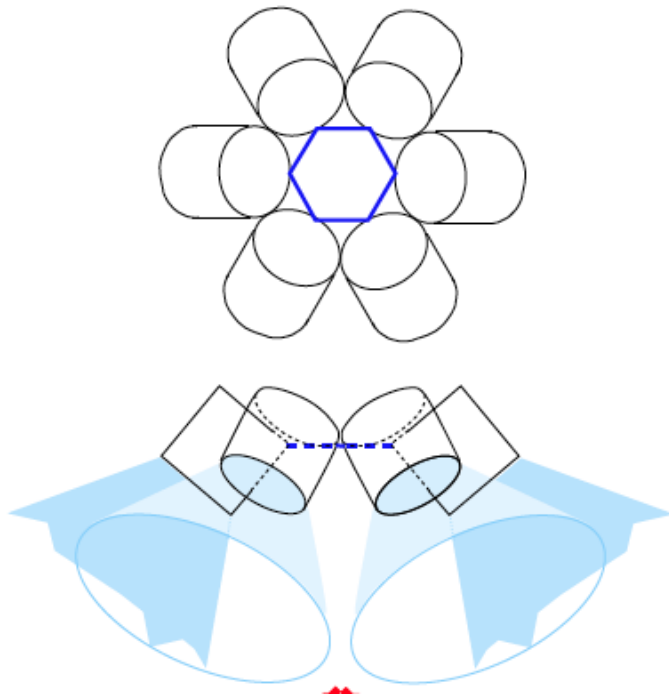
# ARIANNA radio detector Antarctica



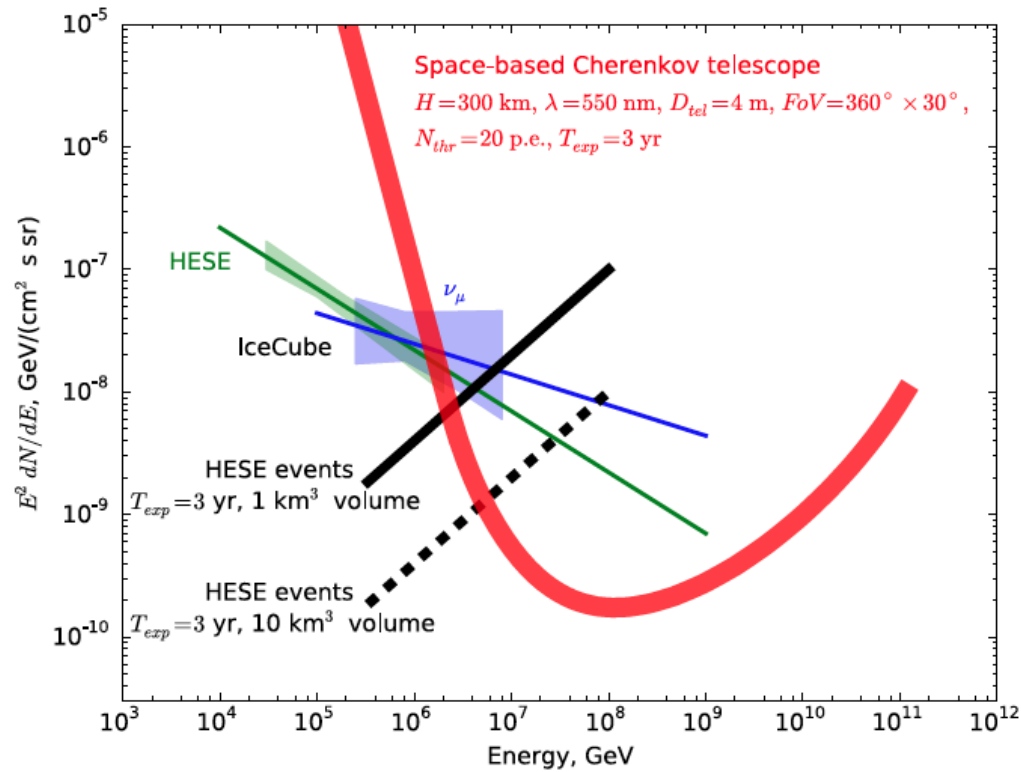
# Future radio detection



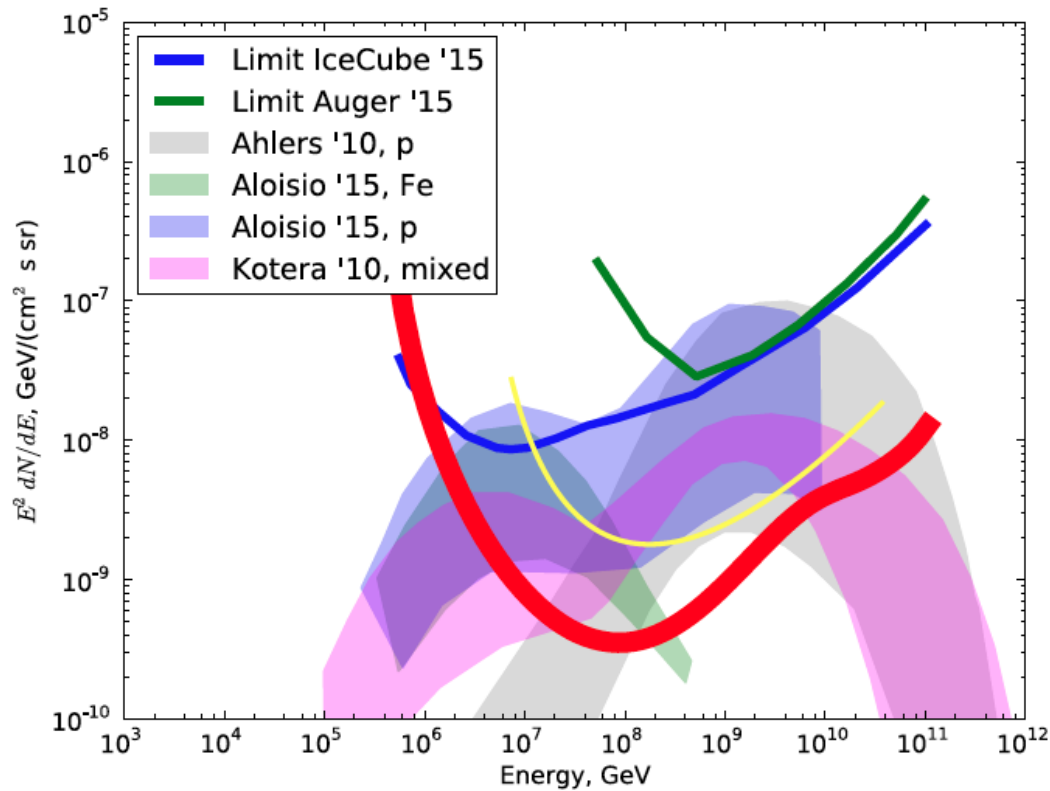
# Detection of neutrinos from space



# Space telescope project



# Detection of GZK neutrinos

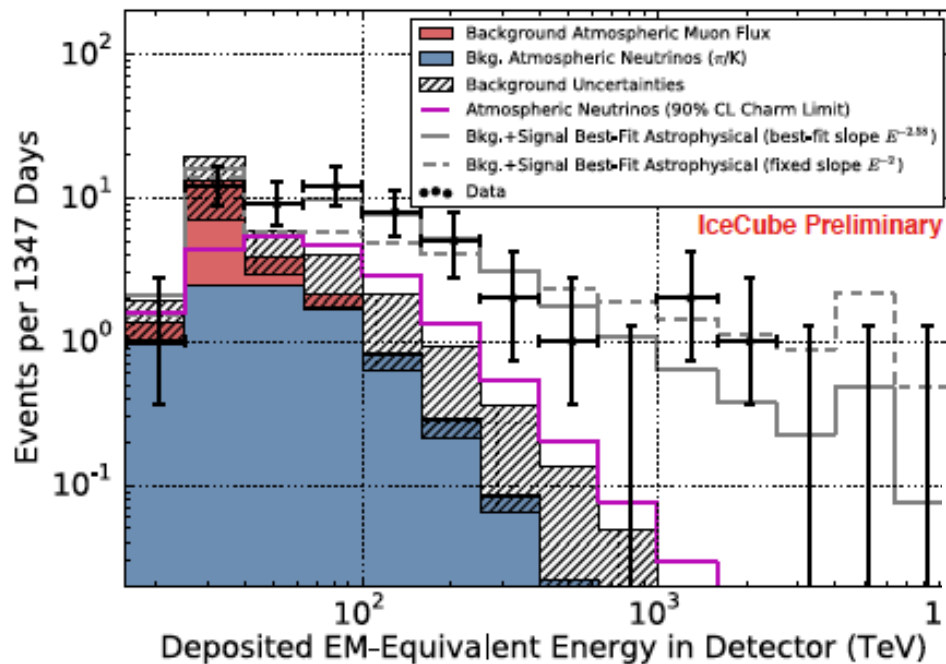




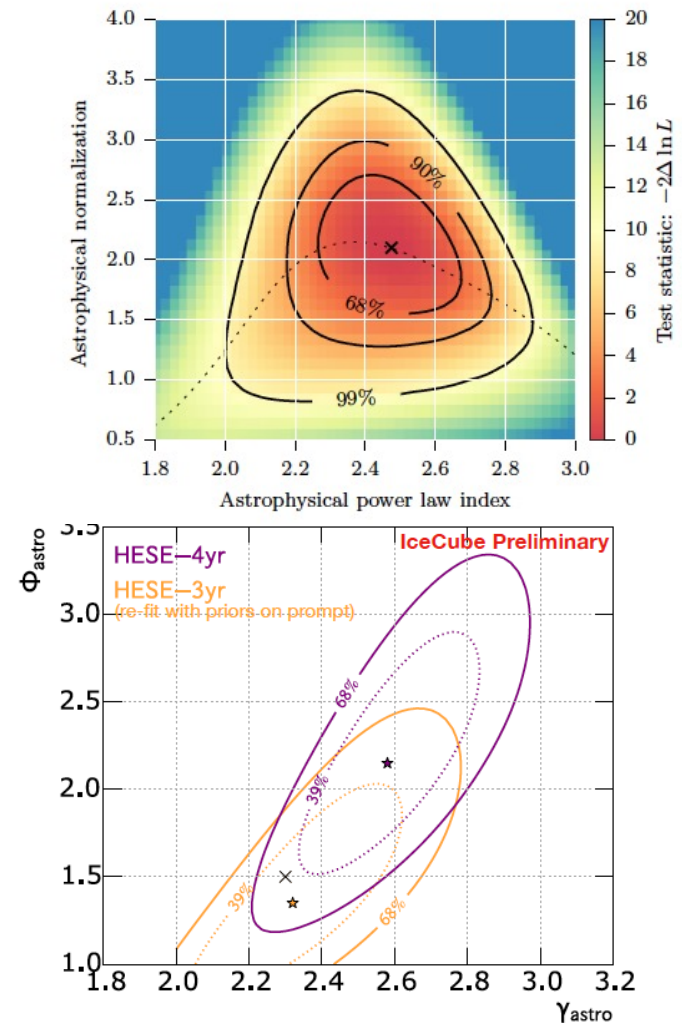
# What we can expect from future detectors

- Split Galactic and extragalactic contribution in diffuse flux
- Find first point/extended sources
- Limit or find extragalactic flux above PeV
- Help to find sources of PeV Galactic cosmic rays

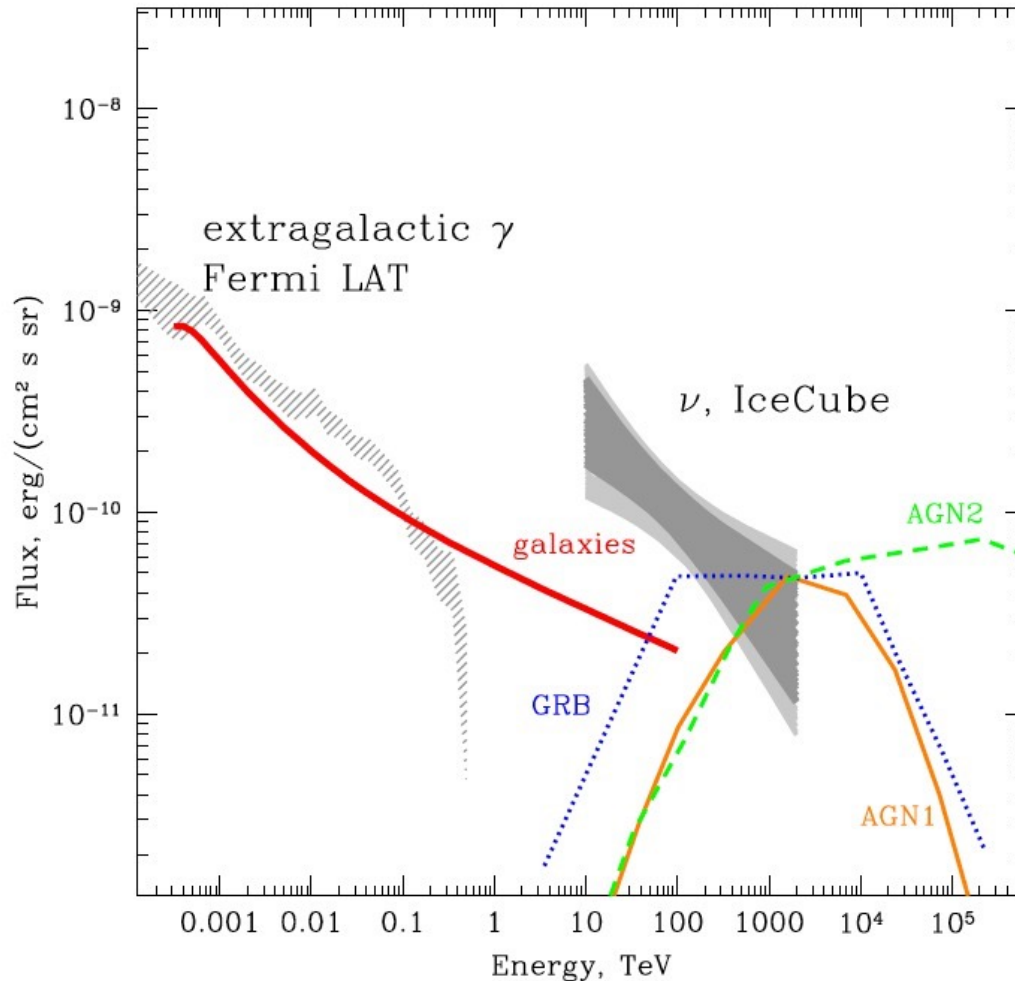
# IceCube data 4 yrs



IceCube, ICRC 2015



# IceCube + Fermi LAT



A.Neronov, D.S. arXiv:1412.1690

# Theoretical predictions of neutrino flux

# EXPECTED NEUTRINO FLUXES

Local optical depth of protons:

$$\tau(\text{PeV})=0.003$$

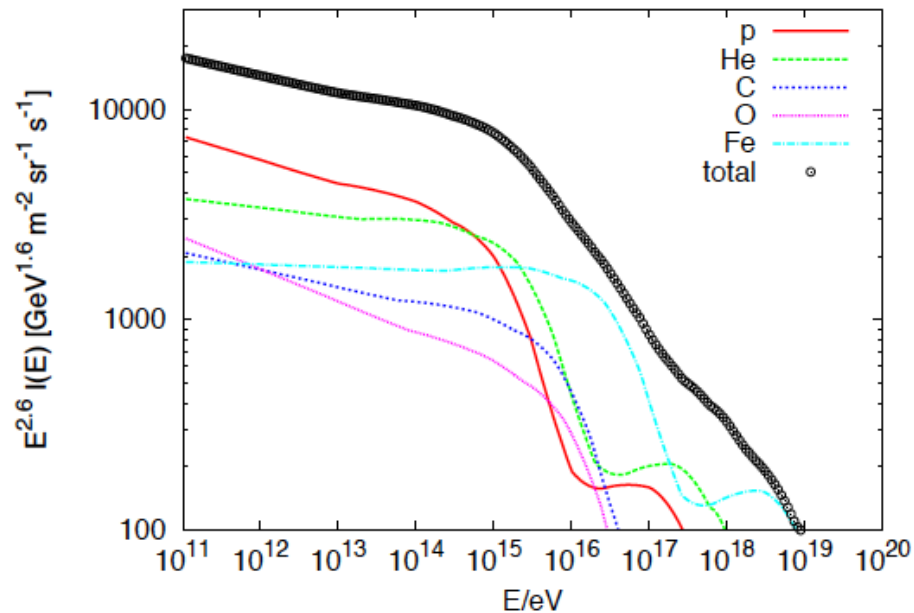
$$\tau(10 \text{ PeV})=0.0002$$

$$E^2 F_\nu(\text{PeV})=0.2 \text{ eV/cm}^2/\text{s/sr}$$

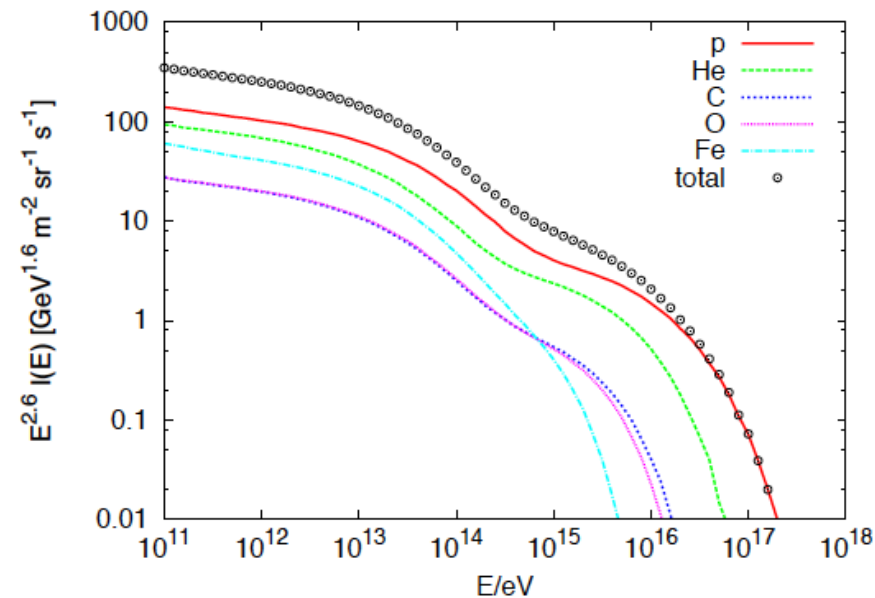
$$E^2 F_\nu(100 \text{ TeV})=3 \text{ eV/cm}^2/\text{s/sr}$$

# EXPECTED NEUTRINO FLUXES

Local CR



Neutrino from local CR



Contribution of local CR sea assuming local CR holds for all galaxy

M.Kachelriess and S.Ostapchenko, arXiv:1405.3797



# EXPECTED NEUTRINO FLUXES

Flux from GMC with mass  $M_{\text{cl}}$  at distance  $d$ :

$$\phi_{\nu}(E) = \tilde{\varepsilon}_{\text{M}} \frac{c \sigma_{\text{inel}}}{4\pi d^2} \frac{M_{\text{cl}}}{m_p} n_{\text{CR}}(E) Y_{\nu}(E) .$$

Flux from GMC  $10^5 \text{ Msun}$  at 1 kpc:

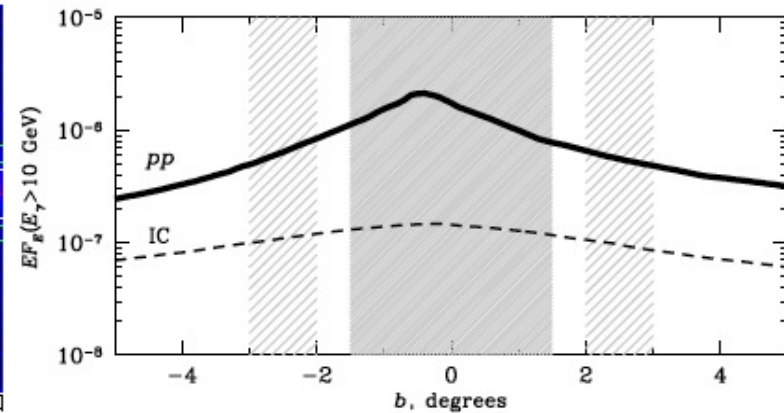
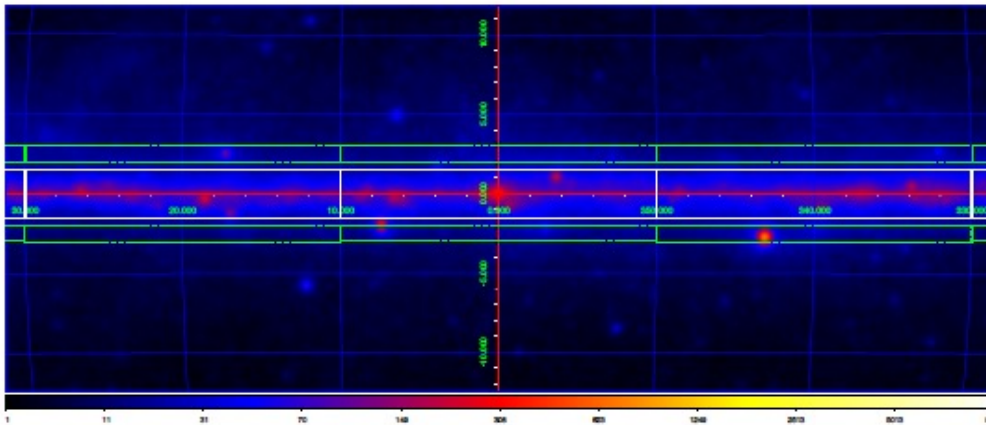
$$E^2 \phi_{\nu}(E) \simeq 140 \text{ eV cm}^{-2} \text{ sr}^{-1}$$

# Galactic neutrino fluxes

- Point sources (isolated) give small contribution
- Diffuse flux normalized to local CR flux give too small contribution
- Something new?

# CR spectrum in MW and LMC from gamma-rays

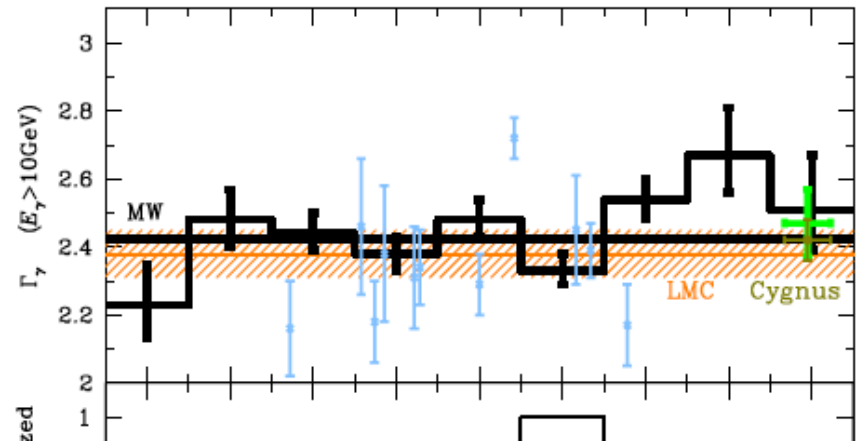
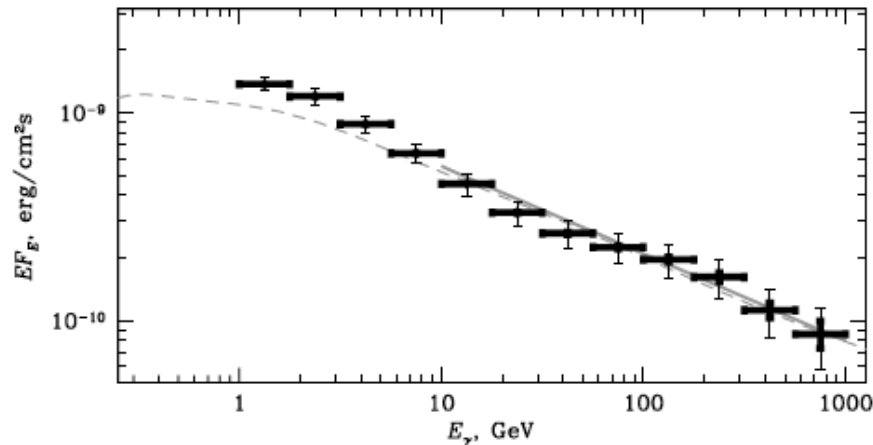
# Milky Way inner Galaxy Fermi $E > 10$ GeV



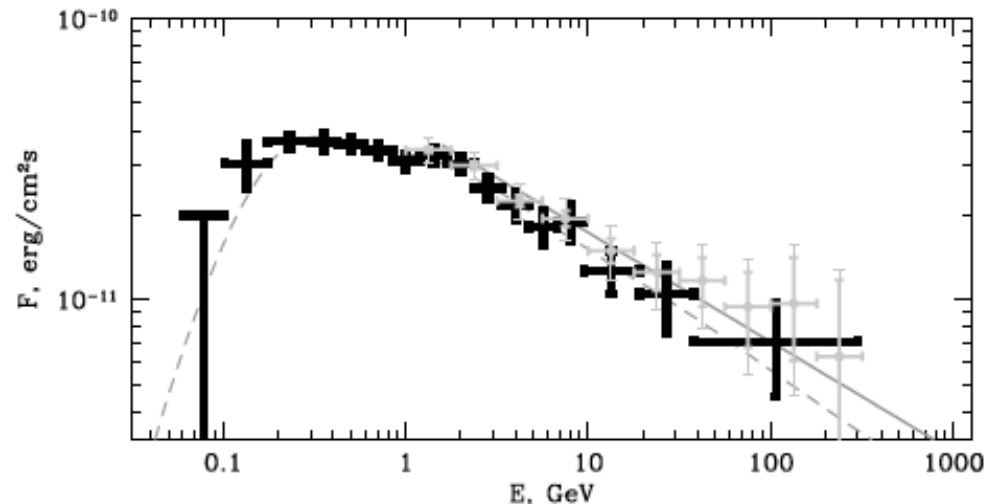
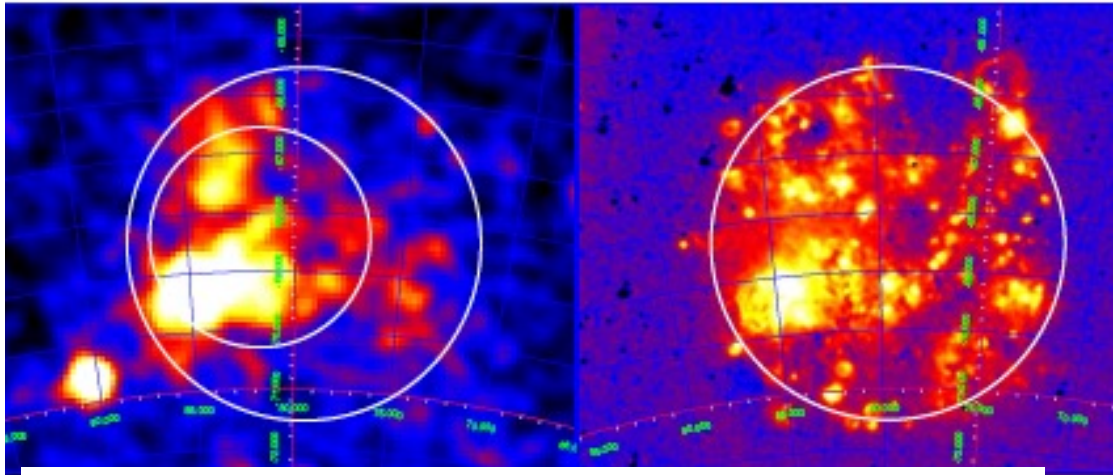
**A.Neronov and D.Malishev, arXiv: 1505.07601**

# Milky Way inner Galaxy

## Fermi $E > 10$ GeV: spectrum 2.45



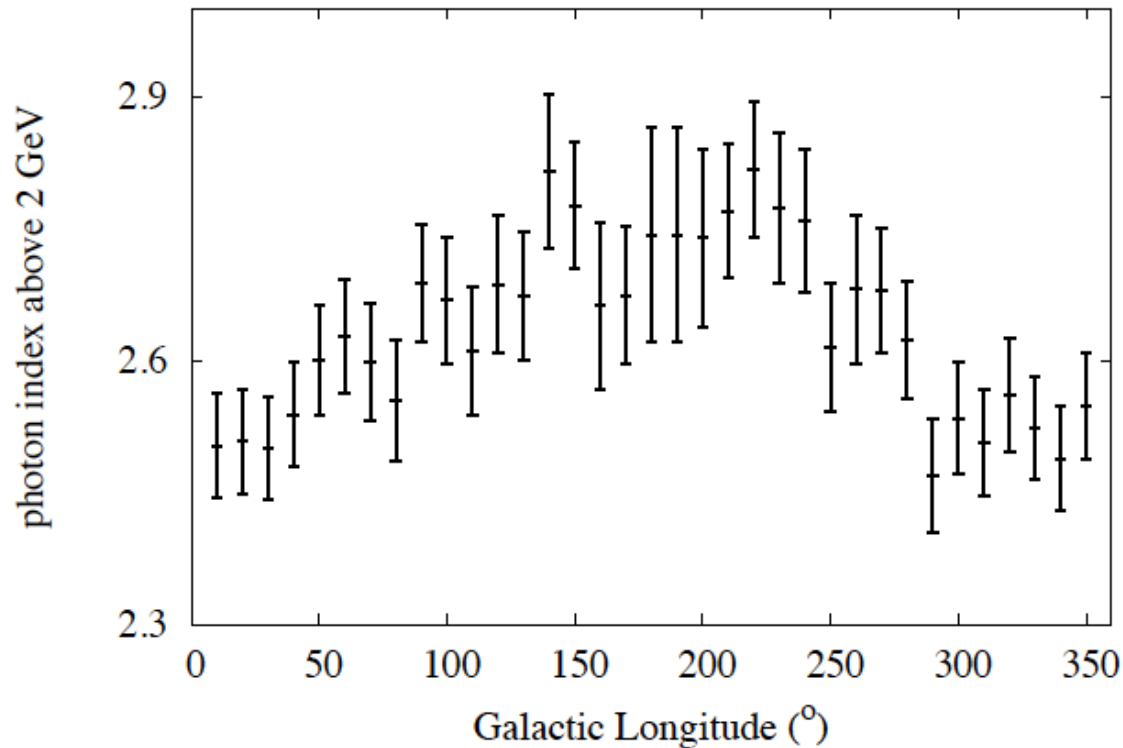
# In LMC average proton spectrum 2.45



**A.Neronov and D.Malishev, arXiv: 1505.07601**

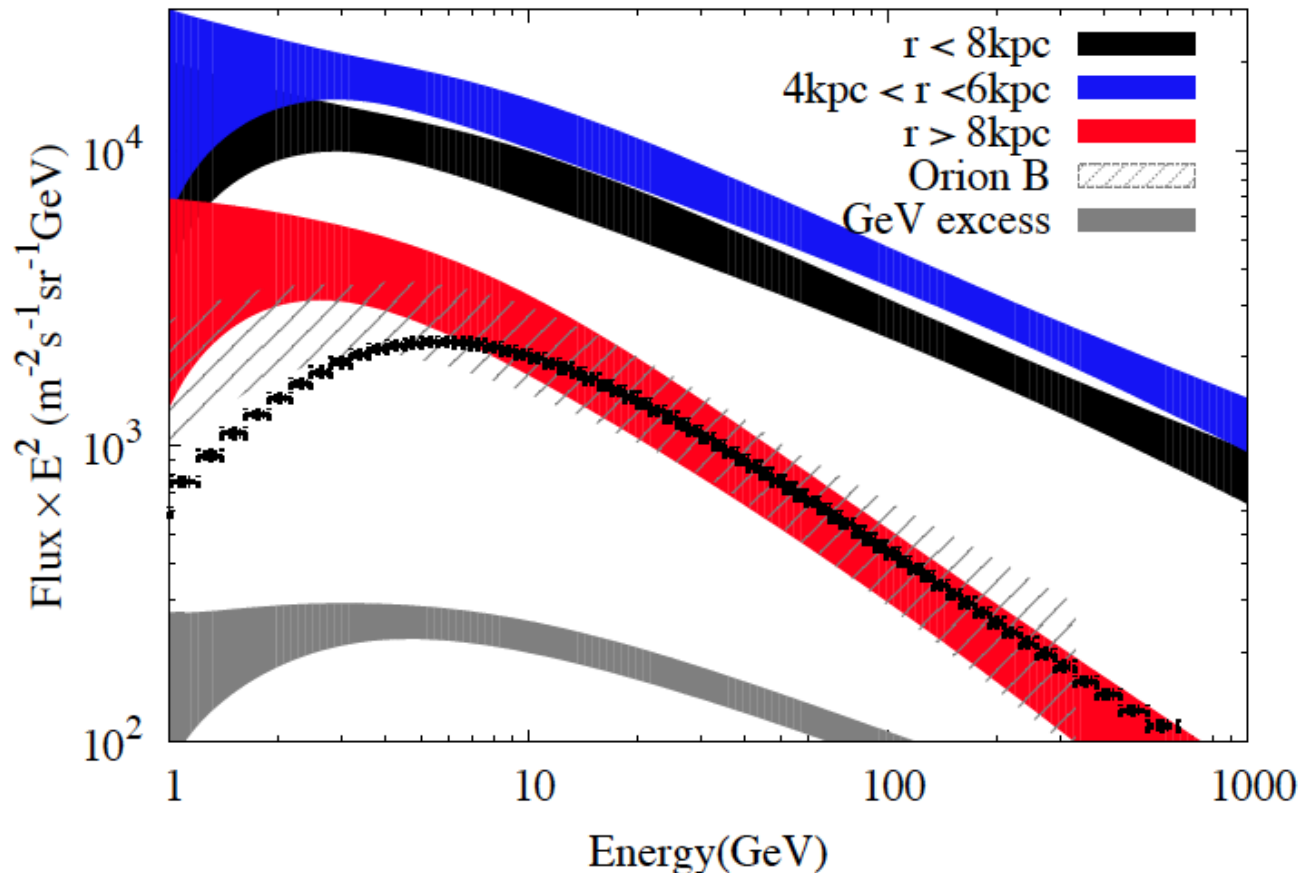


# Proton flux above 2 GeV



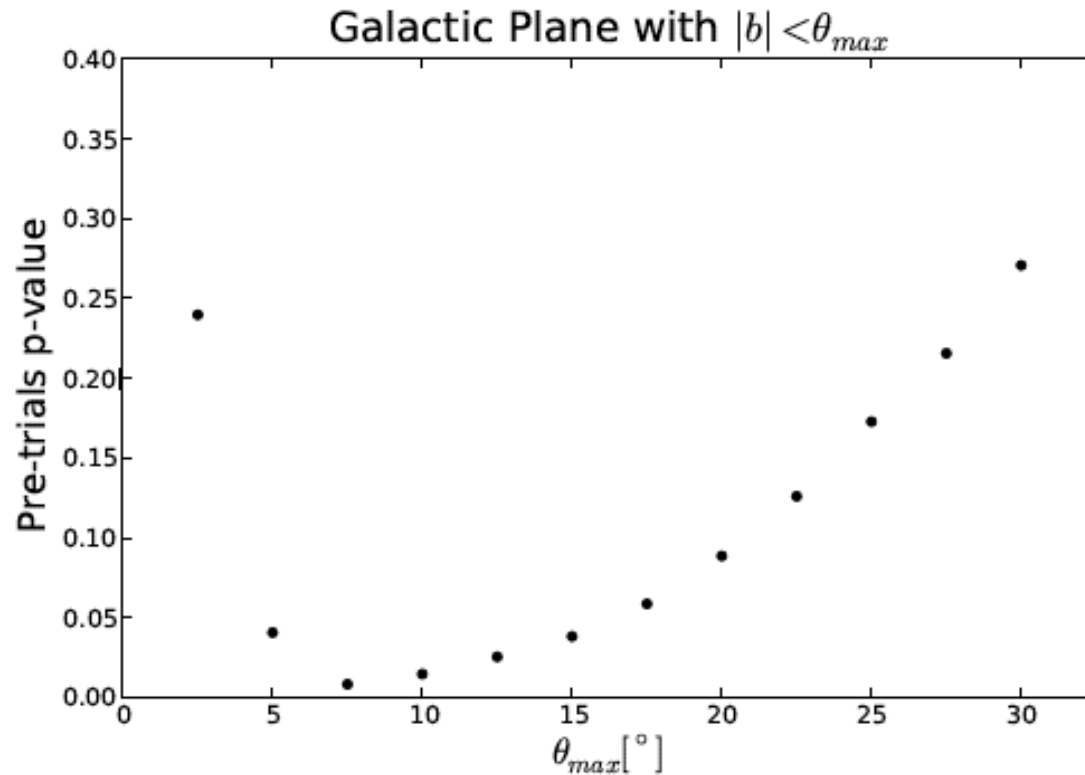
## Fit with gas ring template

CRs SED in different rings.

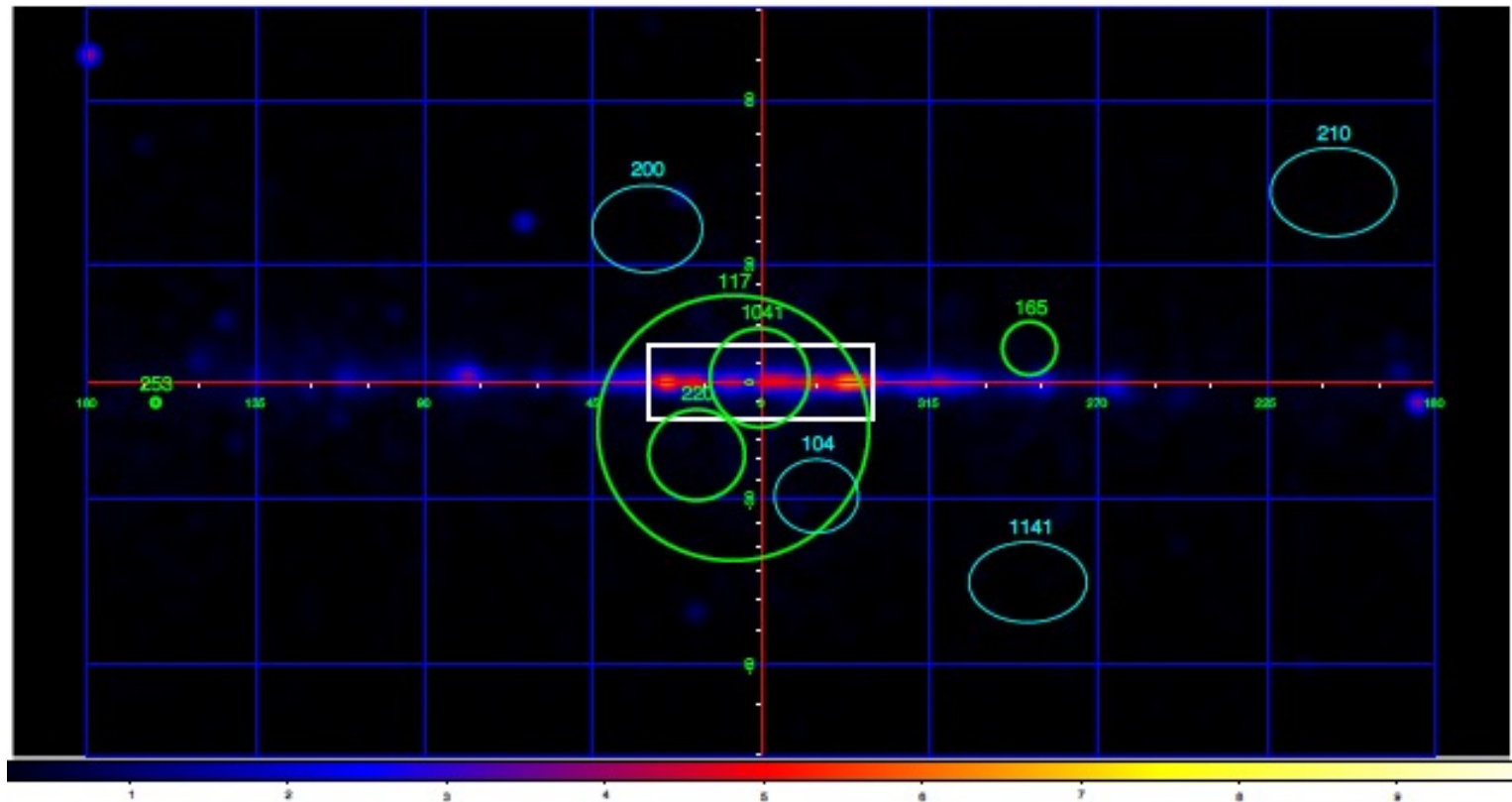


# Neutrino flux from Milky Way

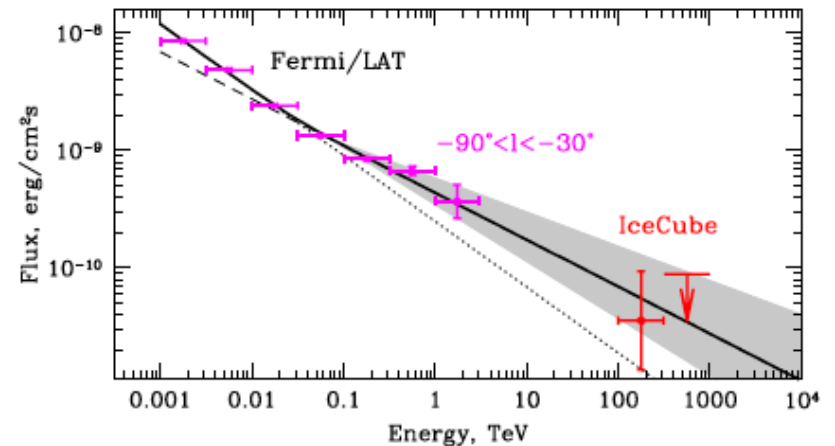
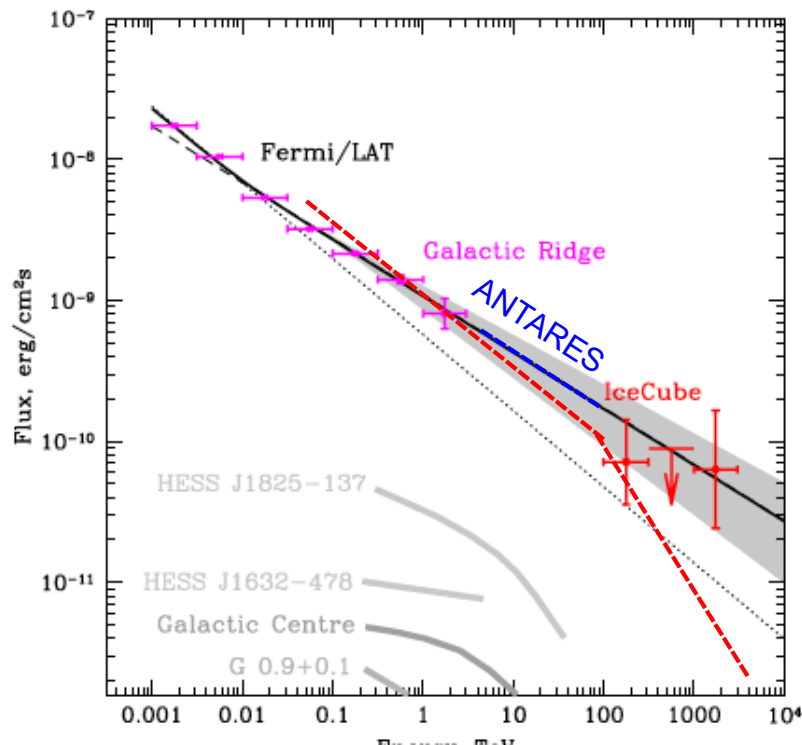
## Galactic plane: 2% by chance



Half of ICECUBE events  $E > 100$  TeV are in Galactic plane. Are they correlate with gamma-rays?



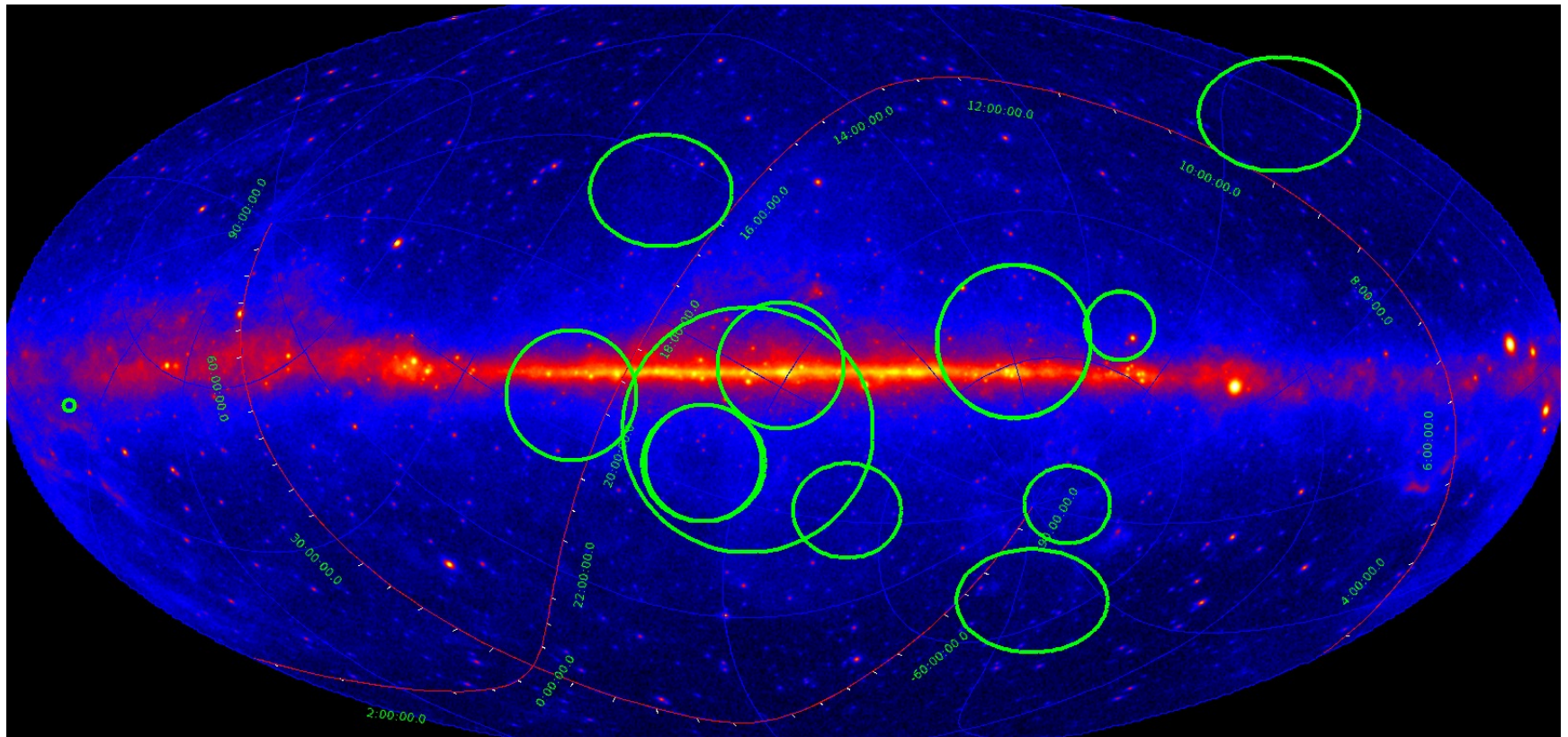
# Real multimessenger fluxes, $\alpha=2.5$



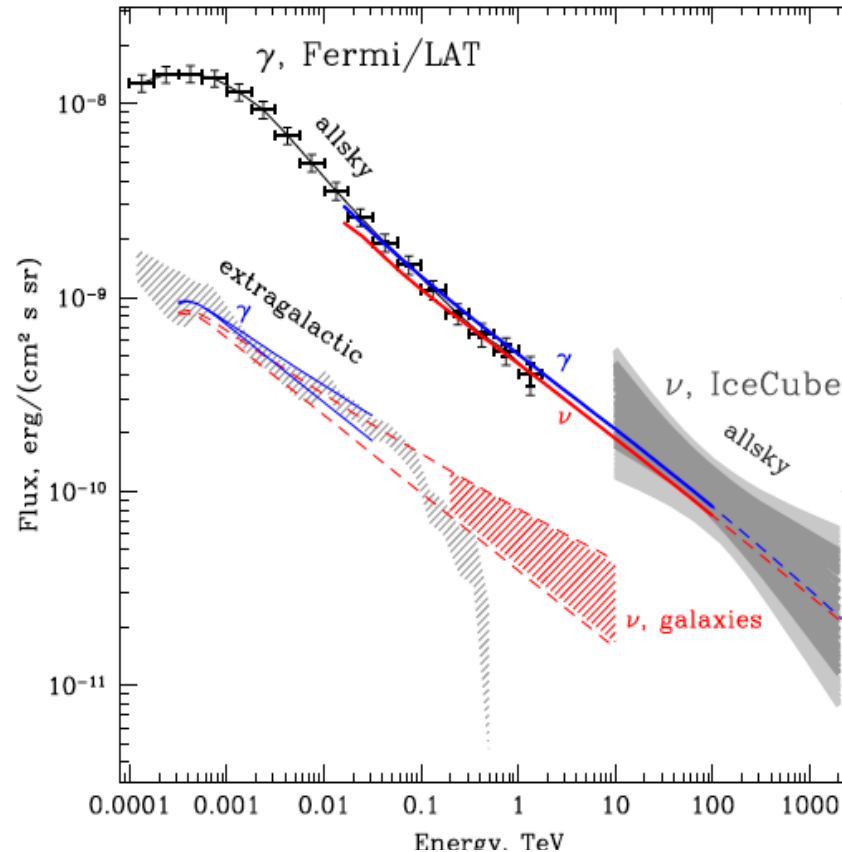
V.Berezinsky & A.Smirnov 1975



# IceCube neutrino sky map 3 years $E > 100$ TeV

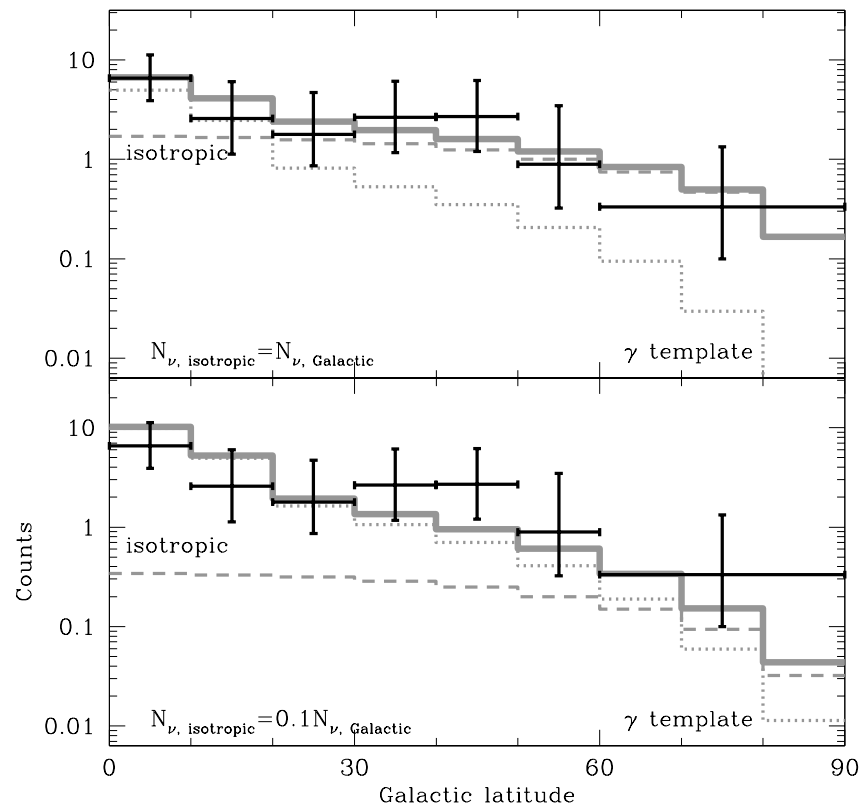


# IceCube + Fermi LAT all sky: protons $1/E^{2.5}$



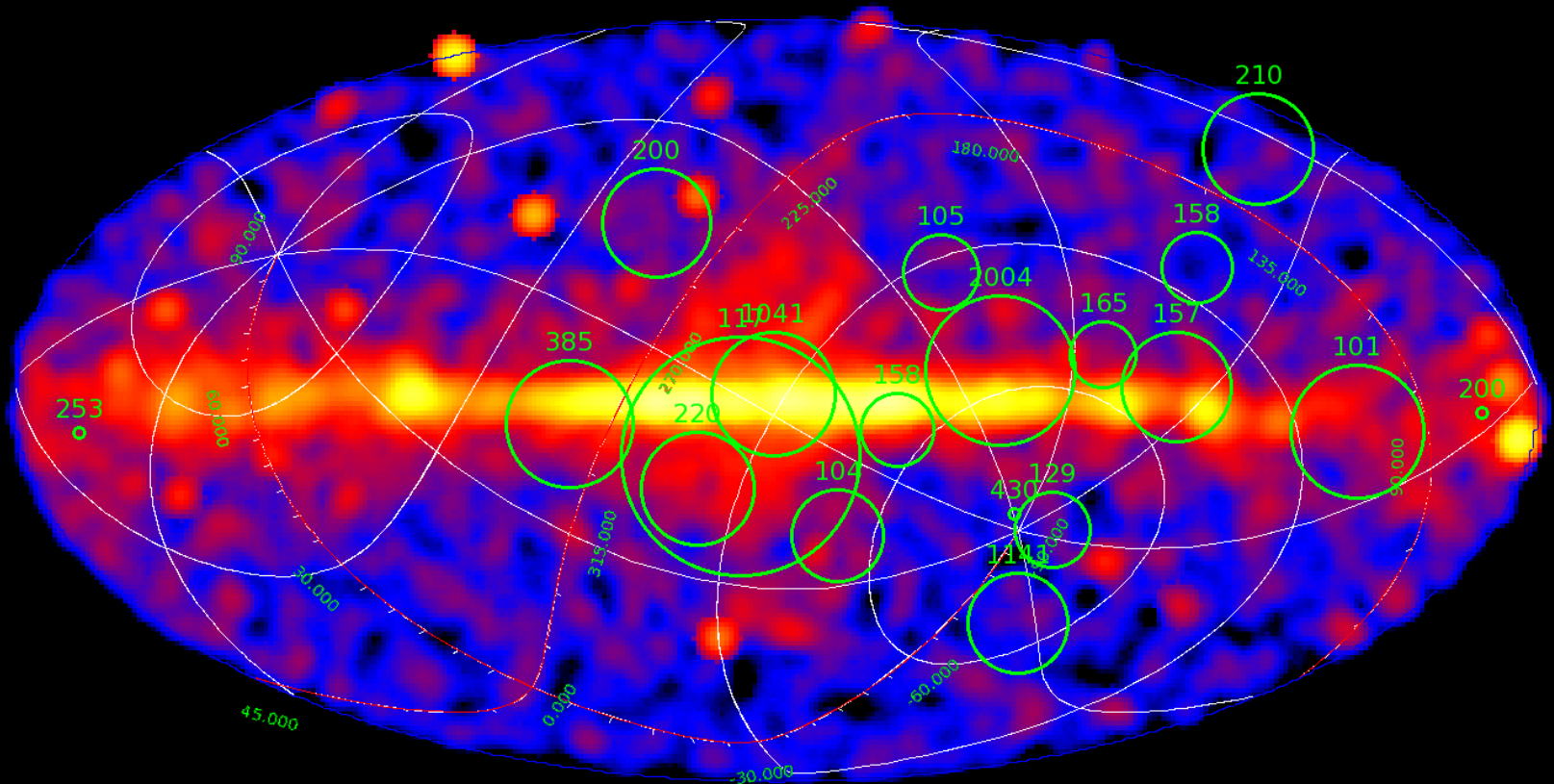
A.Neronov, D.S. arXiv:1412.1690

# Neutrino flux as function of $|b|$

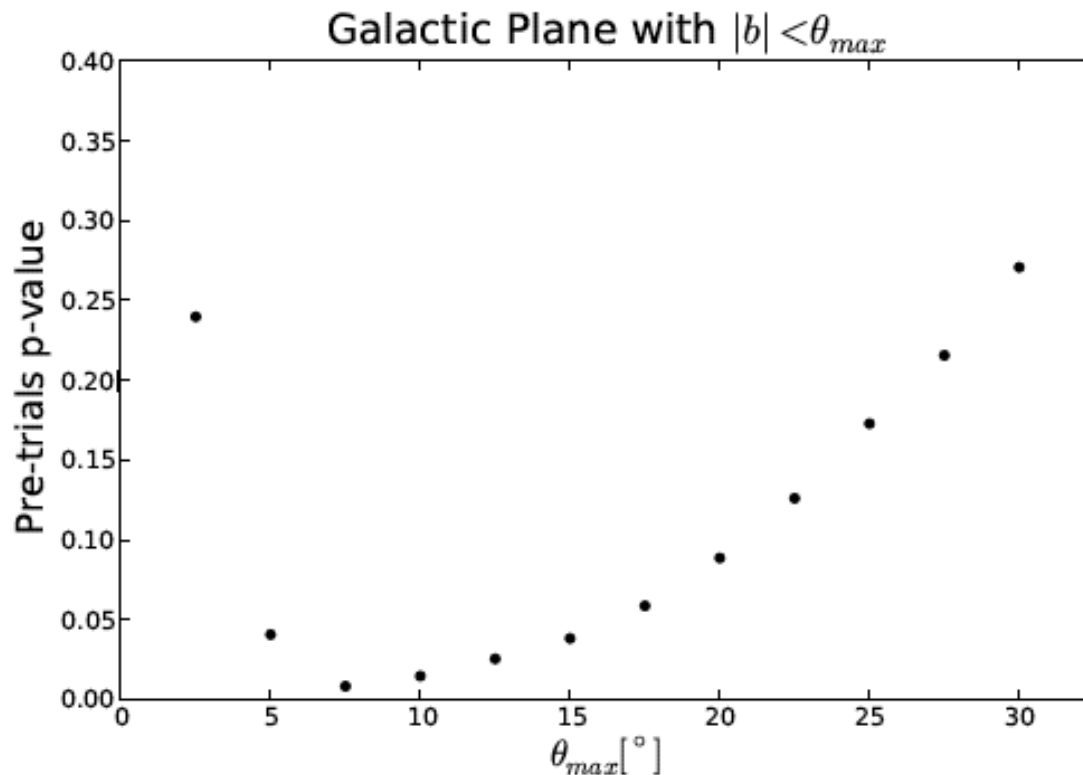


# IceCube neutrino sky map

4 years  $E > 100$  TeV and Fermi  $E > 100$  GeV 5 degree smoothed

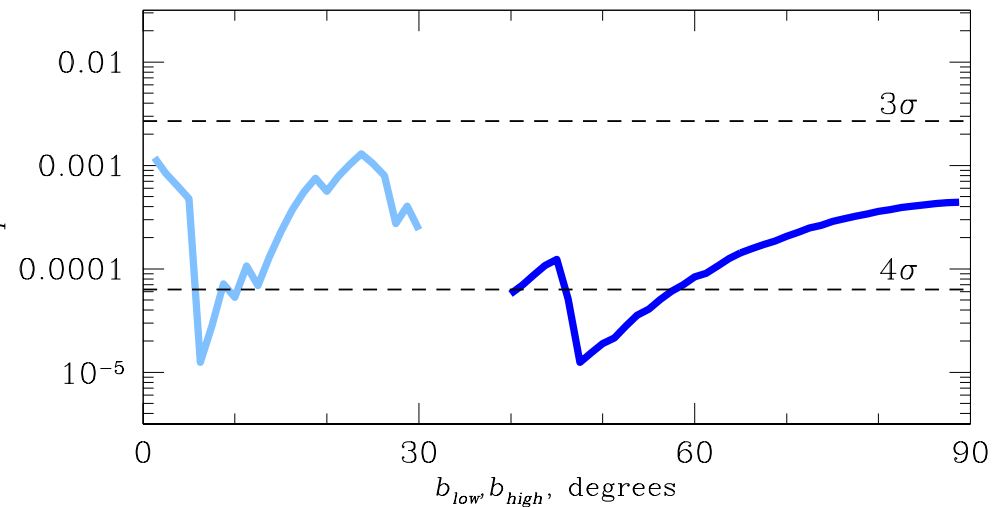
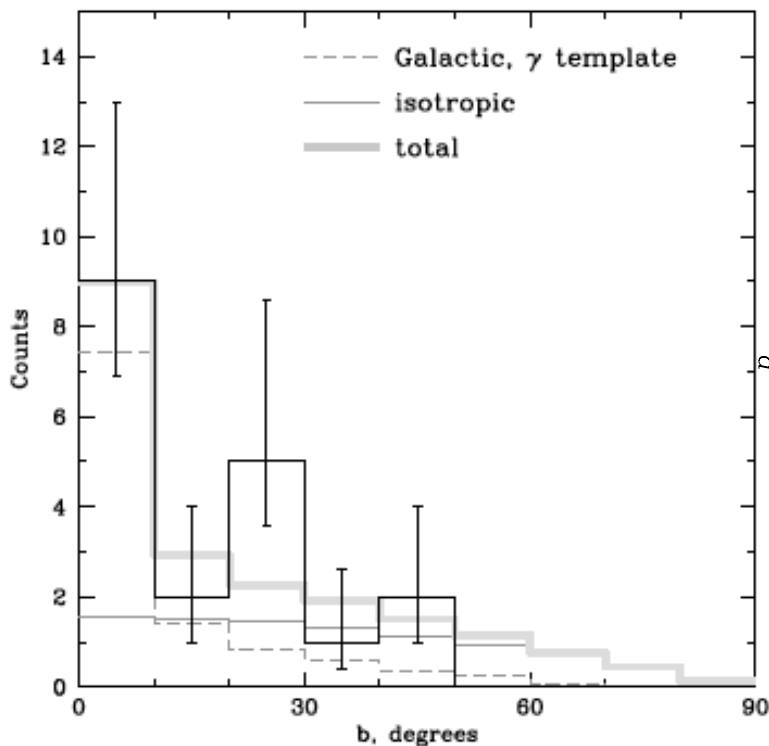


# IceCube galactic plane 3 years: 2% by chance – small statistics



ICECUBE collaboration, arXiv:1405.5303

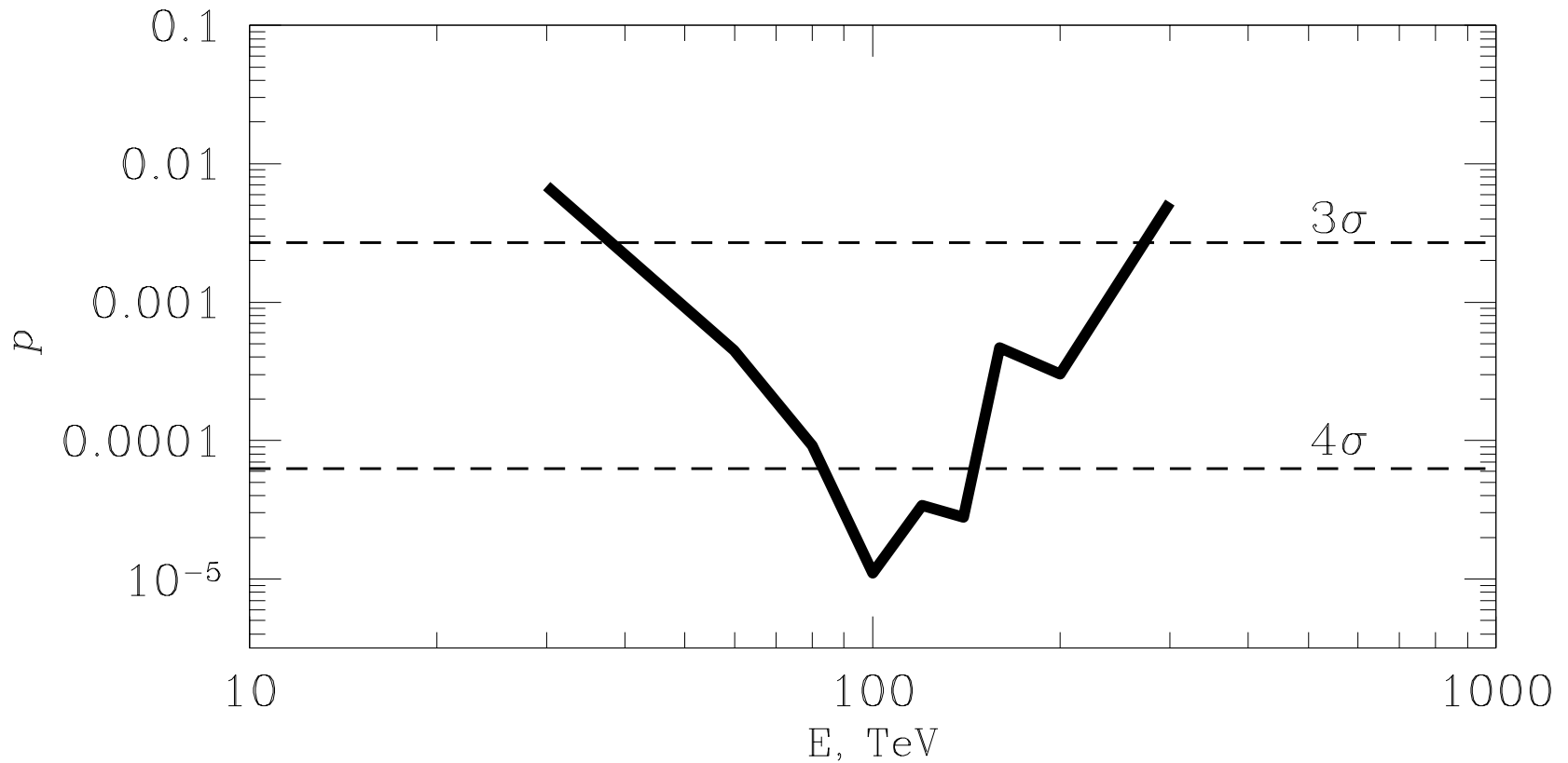
# Evidence of Galactic component in 4 year IceCube data $E > 100$ TeV



**A. Neronov & D.S. arXiv: 1509.03522**

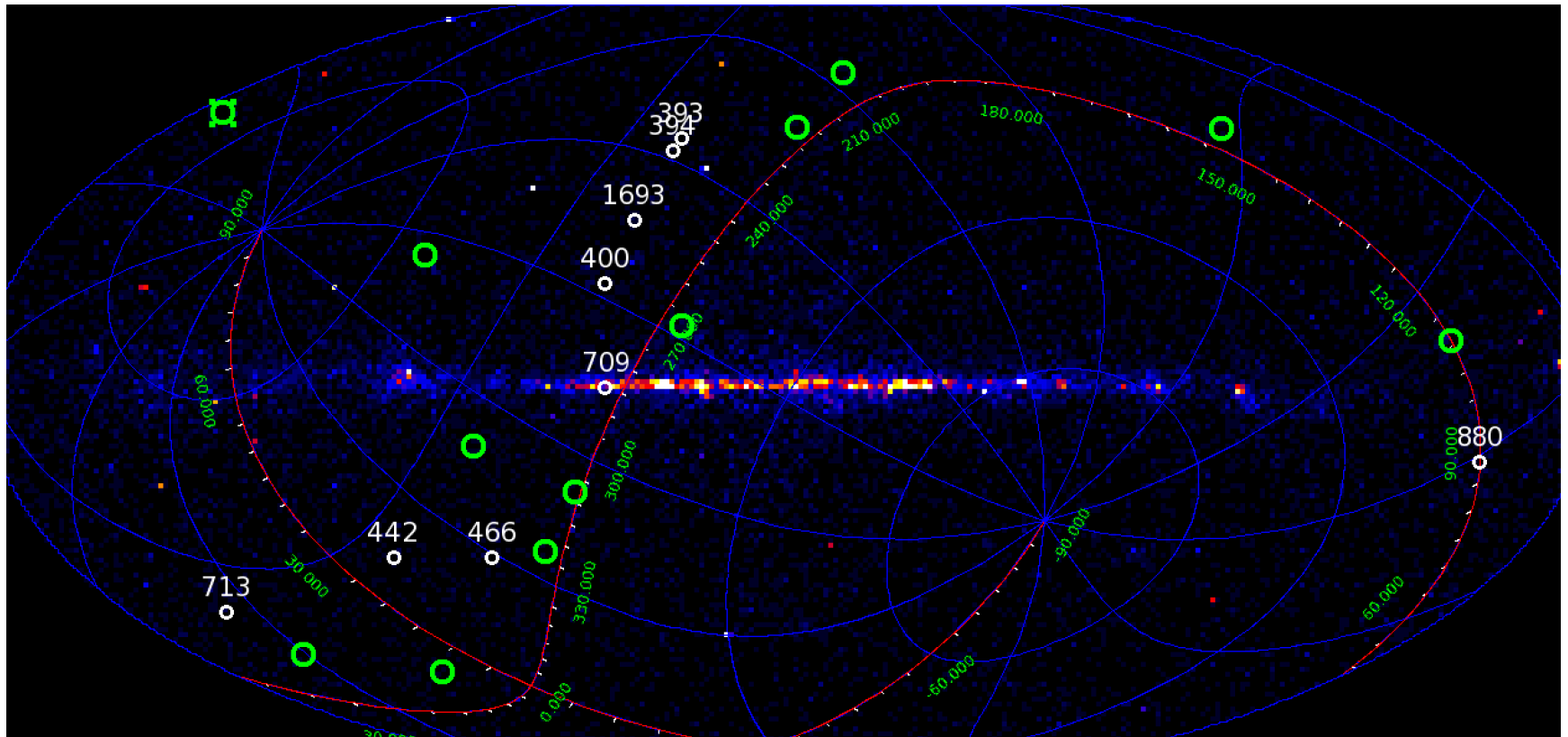


Post-trial probability is  $1.7 \cdot 10^{-3}$



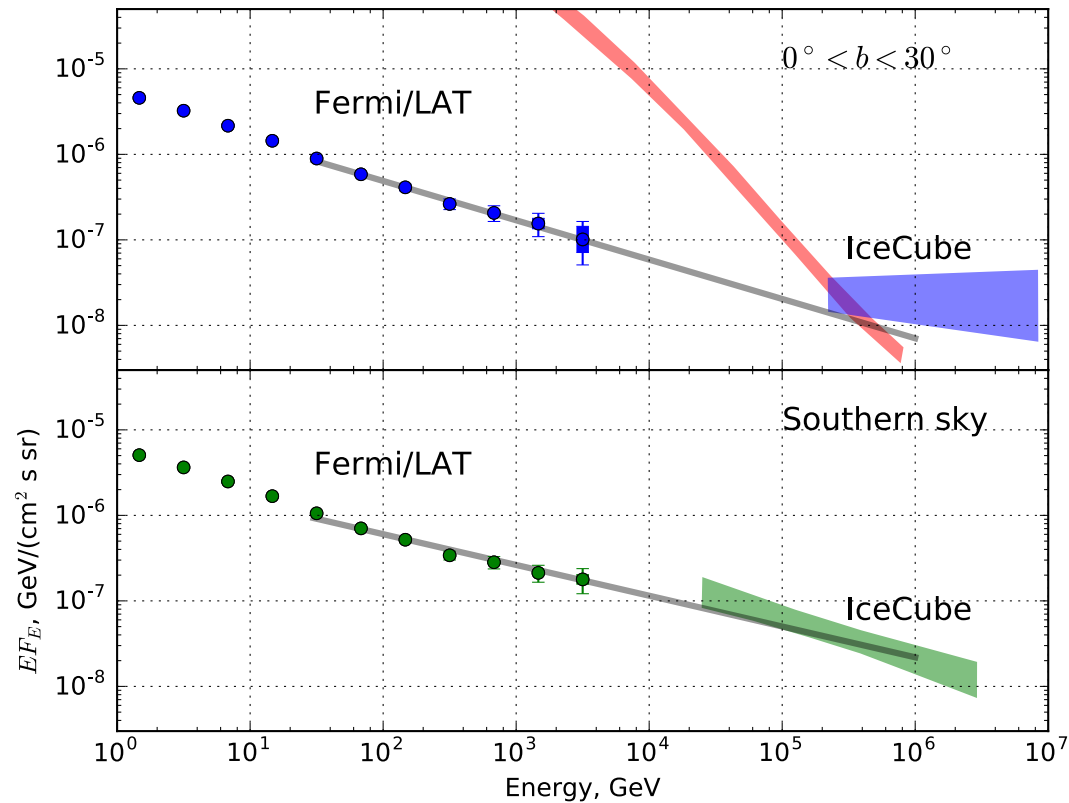
**A. Neronov & D.S. arXiv: 1509.03522**

# Muon neutrinos



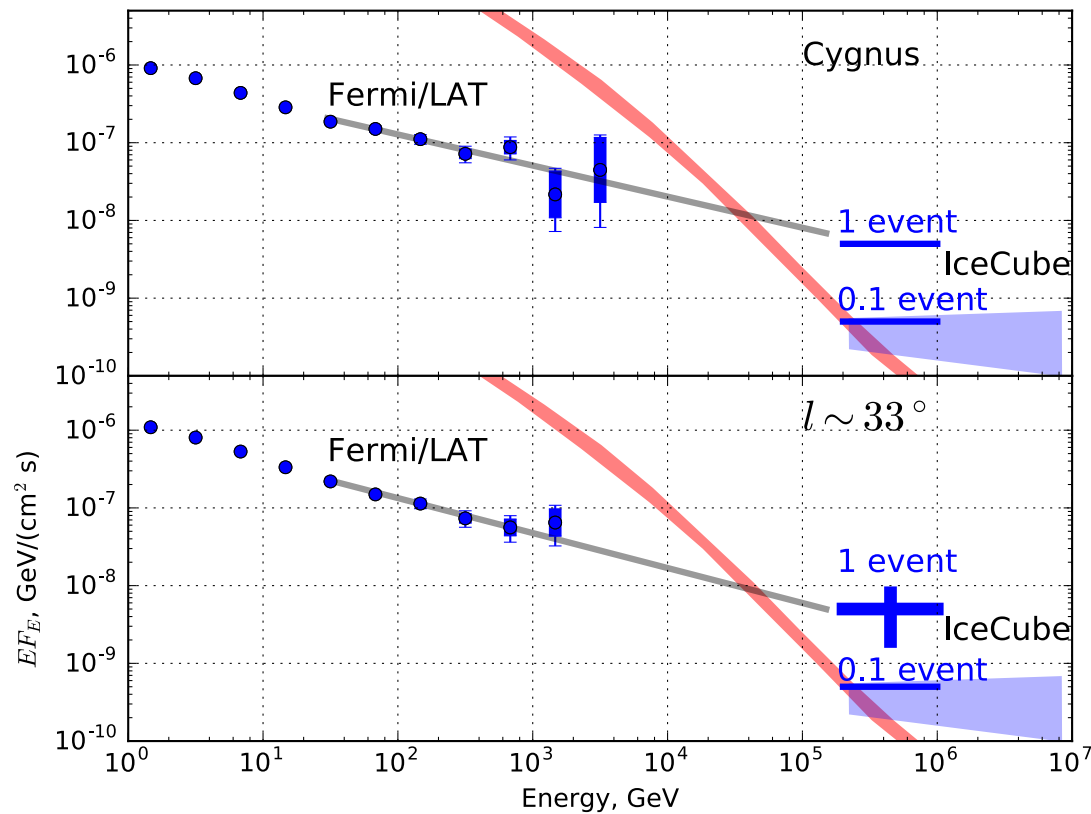
**IceCube, ICRC 2015**

# North and South sky: IceCube



**A. Neronov & D.S. arXiv: 1603.06733**

# First galactic diffuse sources

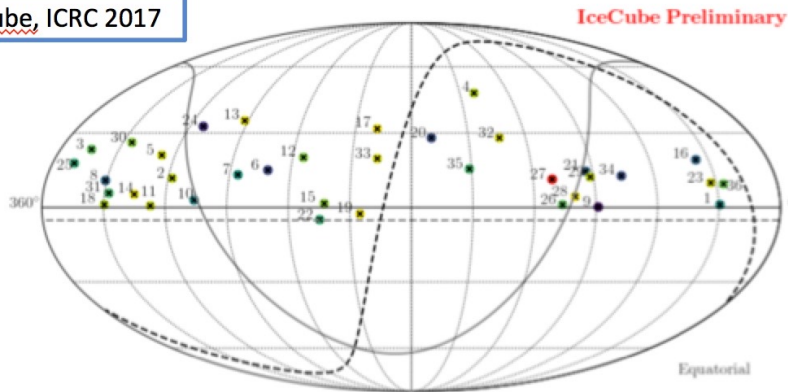


**A. Neronov & D.S. arXiv: 1603.06733**

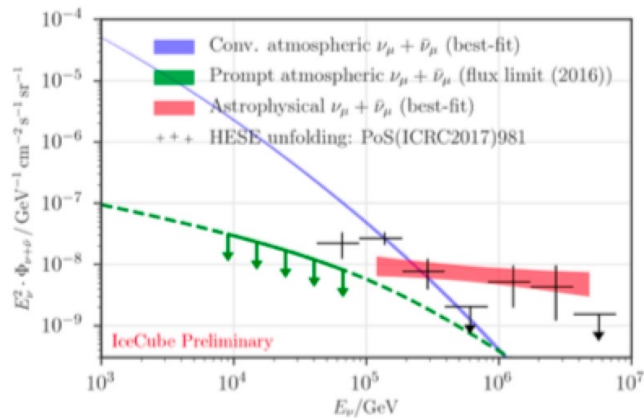
## IceCube ICRC 2017

## Astrophysical neutrino signal

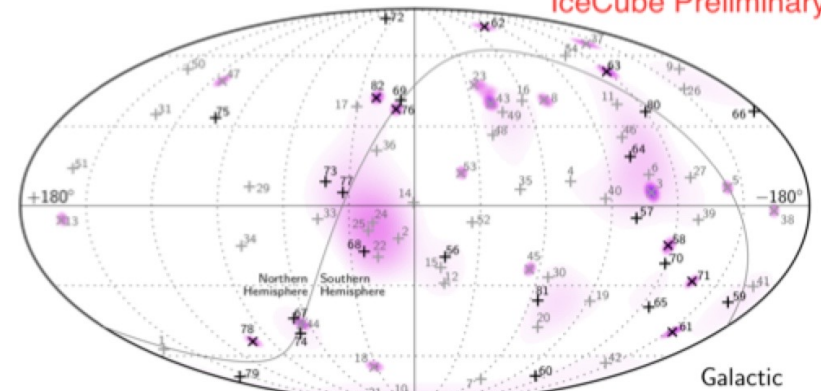
IceCube ICRC 2017



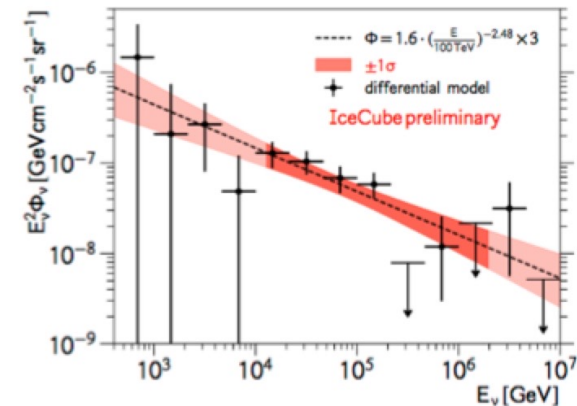
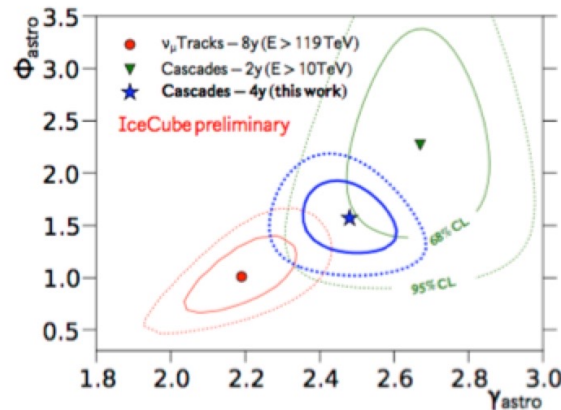
Muon neutrino sample



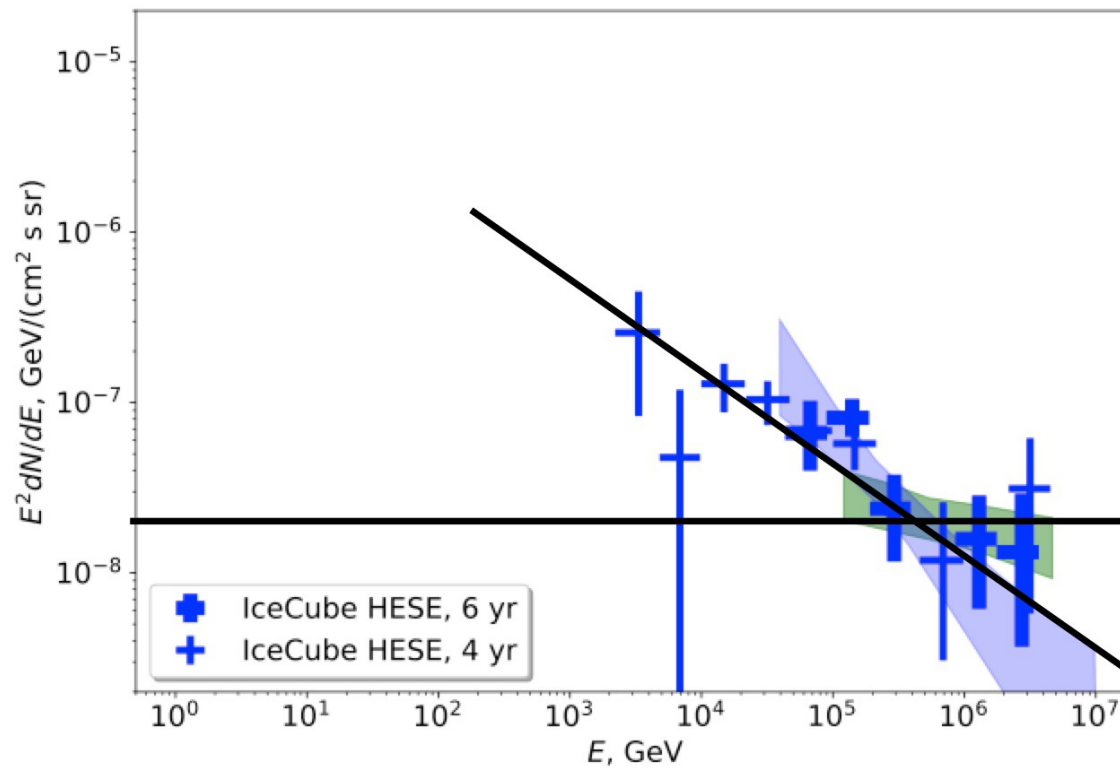
IceCube Preliminary



High Energy Starting Event neutrino sample



# IceCube data





# Diffuse gamma-ray background

# Pion production

$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

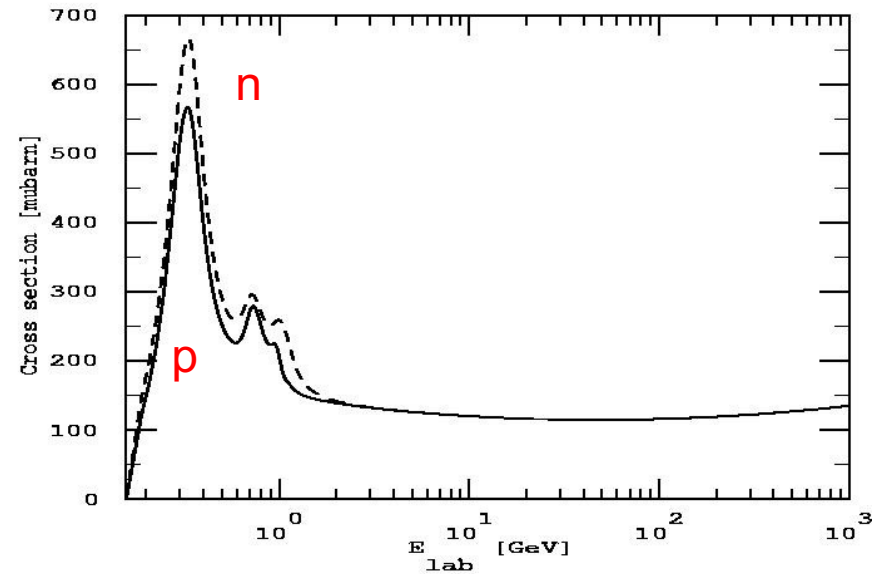
$$N + A_b \Rightarrow N' + \sum \pi^i$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^\pm \Rightarrow \mu^\pm + \nu_\mu$$

$$\mu^\pm \Rightarrow e^\pm + \bar{\nu}_e + \nu_\mu$$

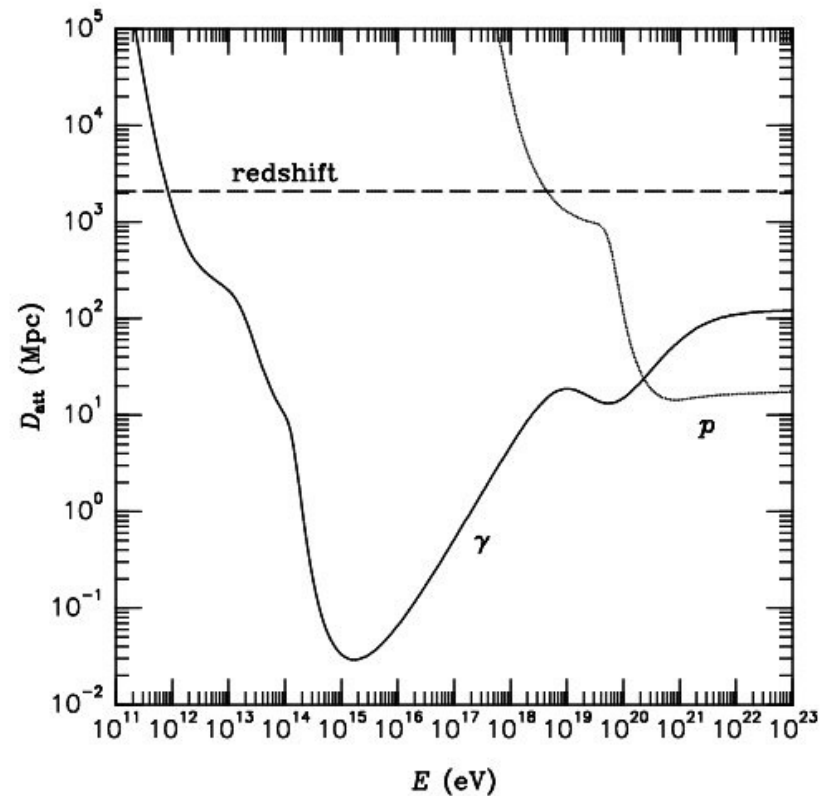
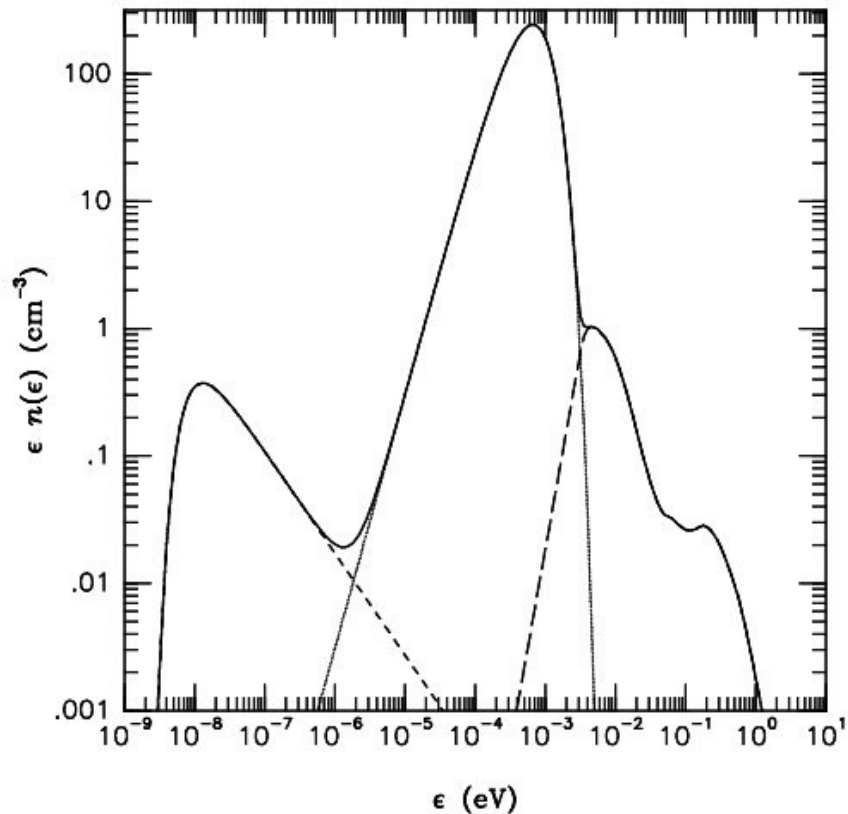
$$n \Rightarrow p + e^- + \bar{\nu}_e$$



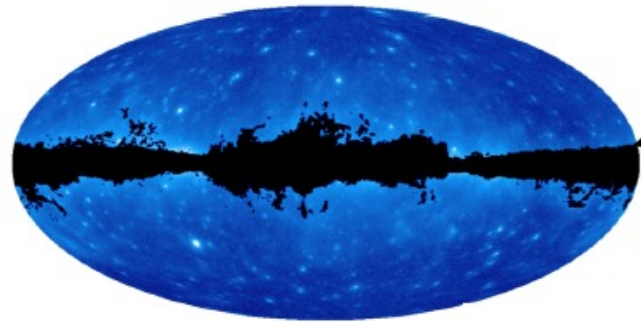
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones:

$$E_\gamma^{tot} \sim E_\nu^{tot}$$

# Diffuse backgrounds



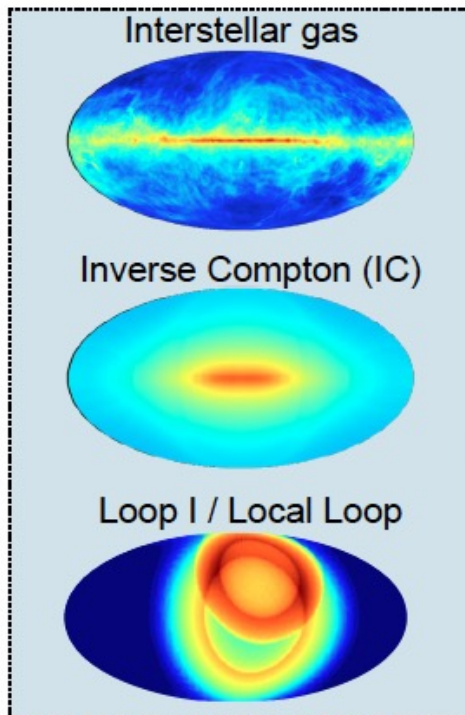
## Derivation of the isotropic gamma-ray background



**Not used in this analysis:**

- > Galactic plane
- > Regions with dense molecular clouds
- > Regions with non-local atomic hydrogen clouds

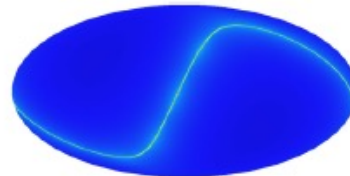
=



Galactic diffuse emission

+

Solar disk and IC



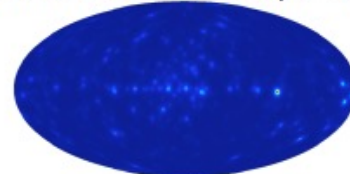
+

Isotropic emission

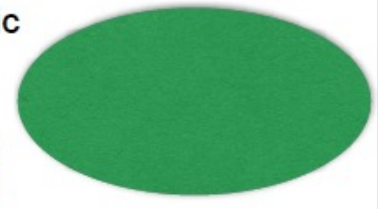


+

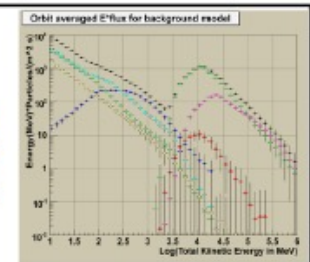
Resolved sources (2FGL)

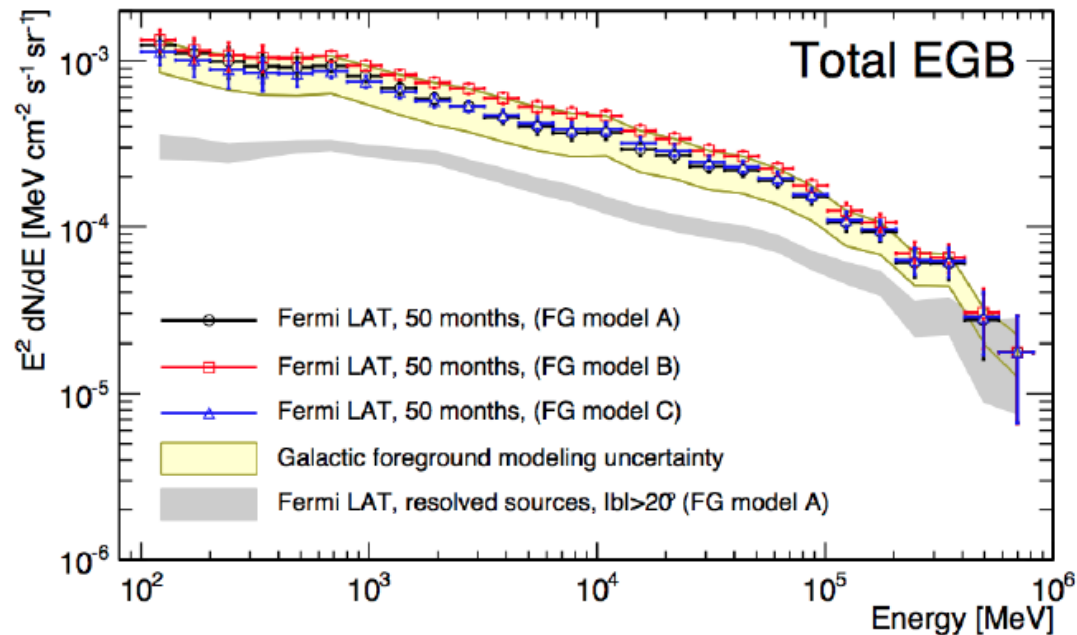


Isotropic  
γ-ray  
back-  
ground  
(IGRB)



Contami-  
nation from  
CR induced  
background





- > **Sum of the intensities** of IGRB and the resolved high-latitude sources.
- > Contribution of high-latitude Galactic sources **<< 5%**.
- > Spectrum can be parametrized by **power-law with exponential cutoff**.
- > Spectral index **~ 2.3**, cutoff energy **~ 350 GeV**.

# Pion production

$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

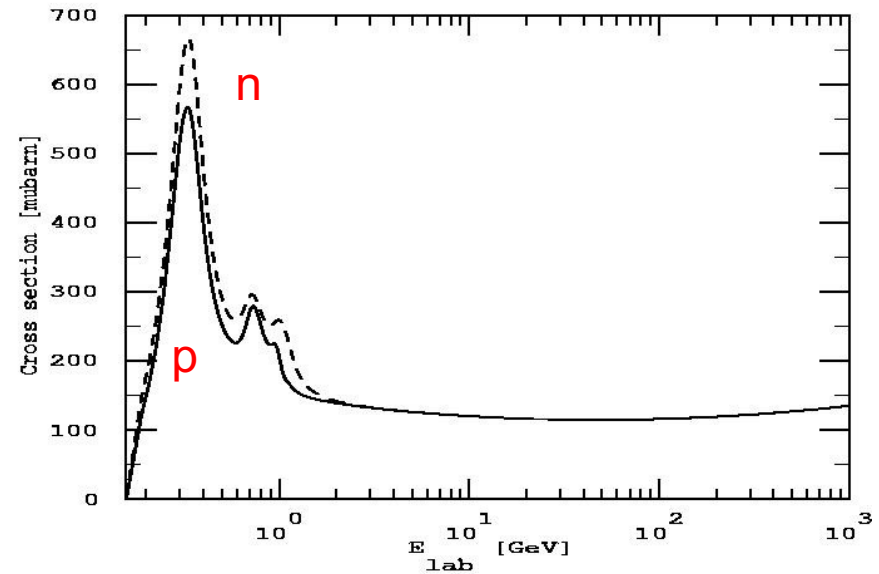
$$N + A_b \Rightarrow N' + \sum \pi^i$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^\pm \Rightarrow \mu^\pm + \nu_\mu$$

$$\mu^\pm \Rightarrow e^\pm + \bar{\nu}_e + \nu_\mu$$

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

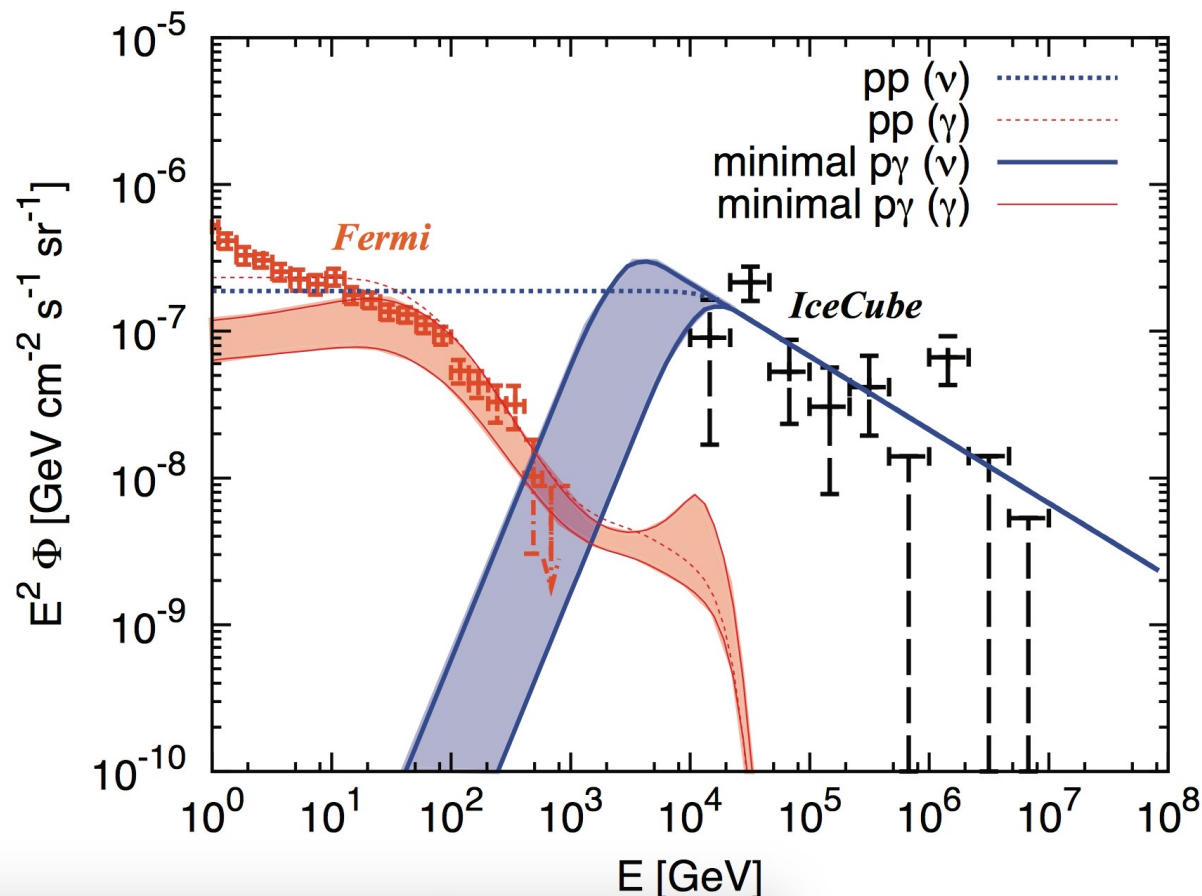


Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones:

$$E_\gamma^{tot} \sim E_\nu^{tot}$$

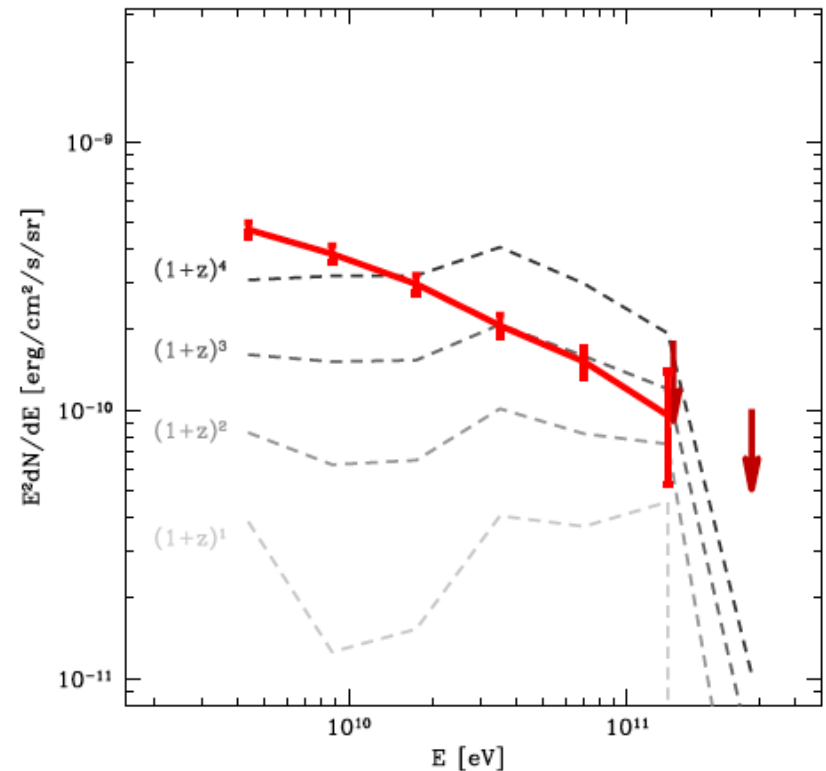
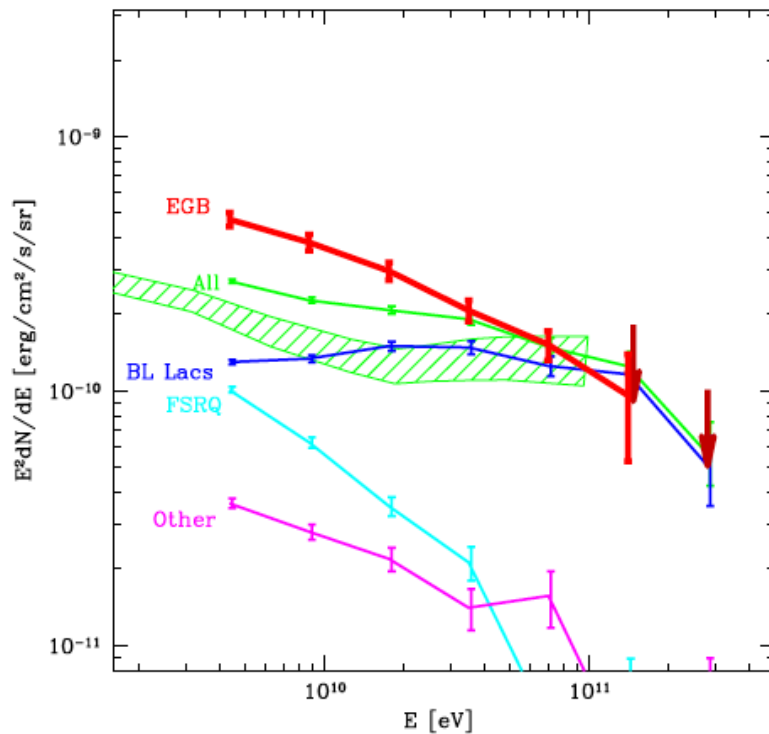


# Self-consistent extragalactic sources

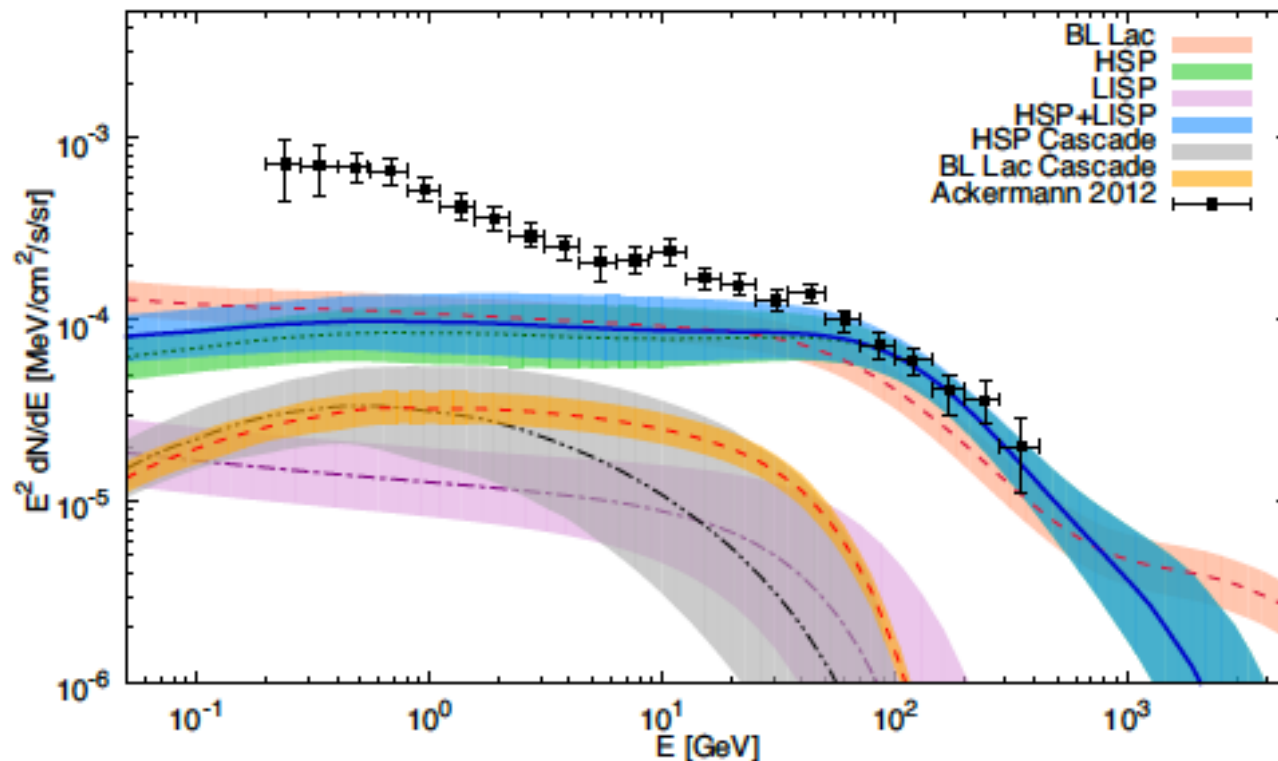


# *Astrophysical neutrinos from BL Lacs*

# Unresolved BL Lacs give main contribution to diffuse gamma-ray



# BL Lacs give main contribution to high energy part of diffuse gamma-ray flux

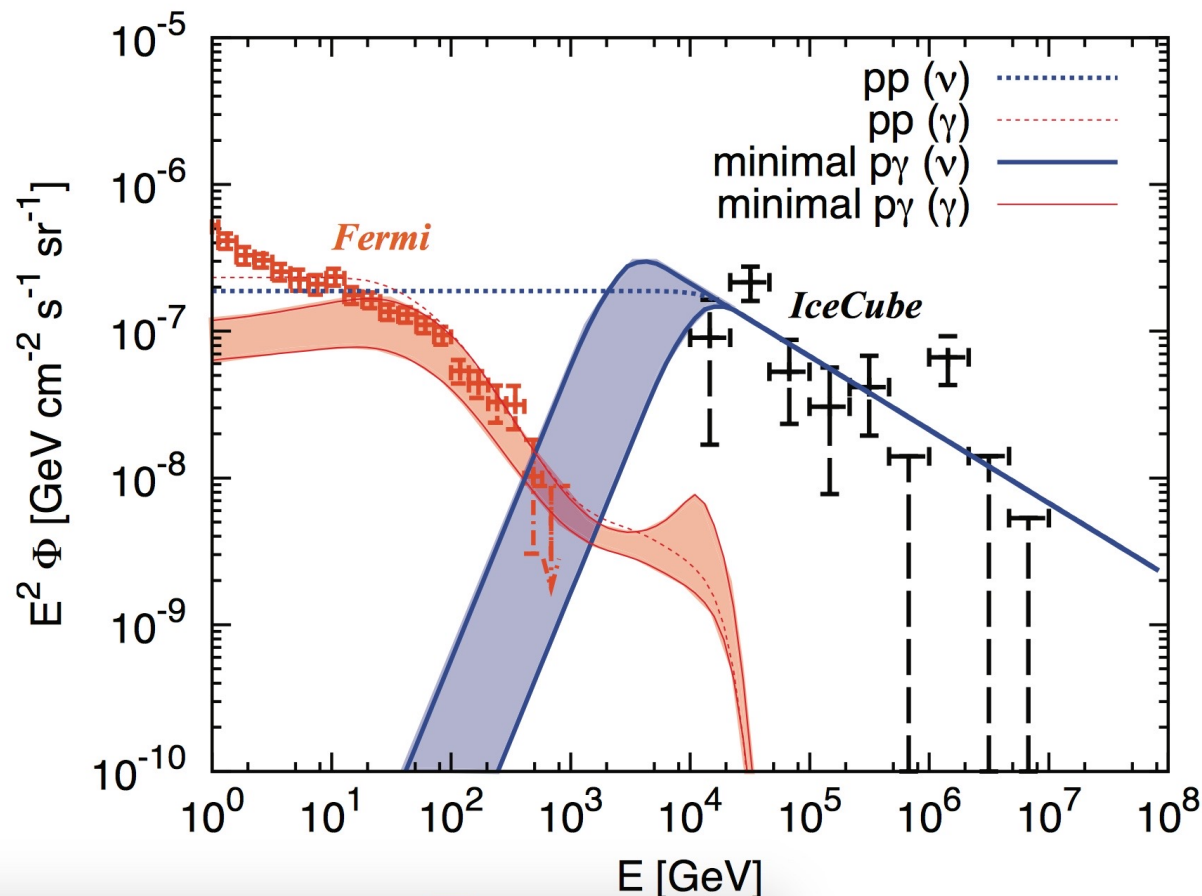


**M. Di Mauro et al, arXiv:1311.5708**

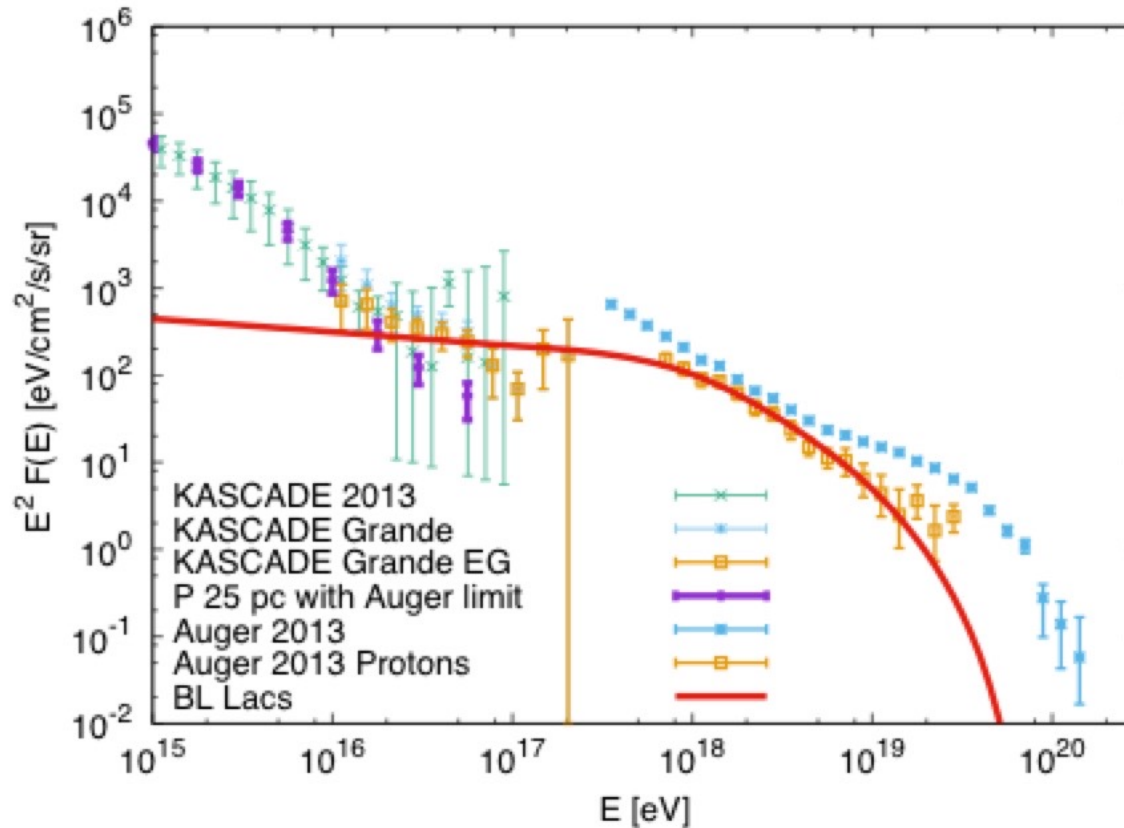
# Fermi confirmed resolution of BL Lac sources above 50 GeV

$\text{cm}^{-2} \text{s}^{-1}$ ). We employ a one-point photon fluctuation analysis to constrain the behavior of  $dN/dS$  below the source detection threshold. Overall the source count distribution is constrained over three decades in flux and found compatible with a broken power law with a break flux,  $S_b$ , in the range  $[8 \times 10^{-12}, 1.5 \times 10^{-11}] \text{ ph cm}^{-2} \text{s}^{-1}$  and power-law indices below and above the break of  $\alpha_2 \in [1.60, 1.75]$  and  $\alpha_1 = 2.49 \pm 0.12$  respectively. Integration of  $dN/dS$  shows that point sources account for at least  $86^{+16}_{-14}\%$  of the total extragalactic  $\gamma$ -ray background. The simple form of the derived source count distribution is consistent with a single population (i.e. blazars) dominating the source counts to the minimum flux explored by this analysis. We estimate the density of sources

# Are neutrino sources blazars?



# UHECR proton flux from BL Lacs



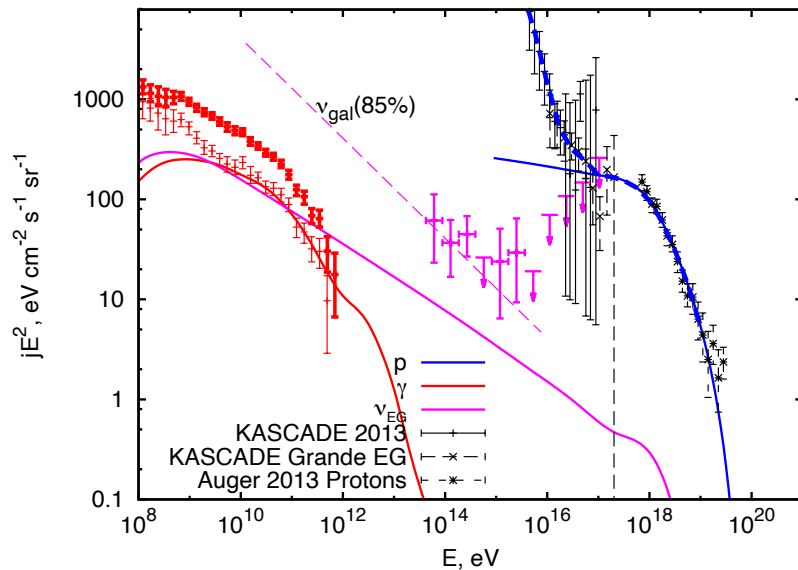


## Protons in sources

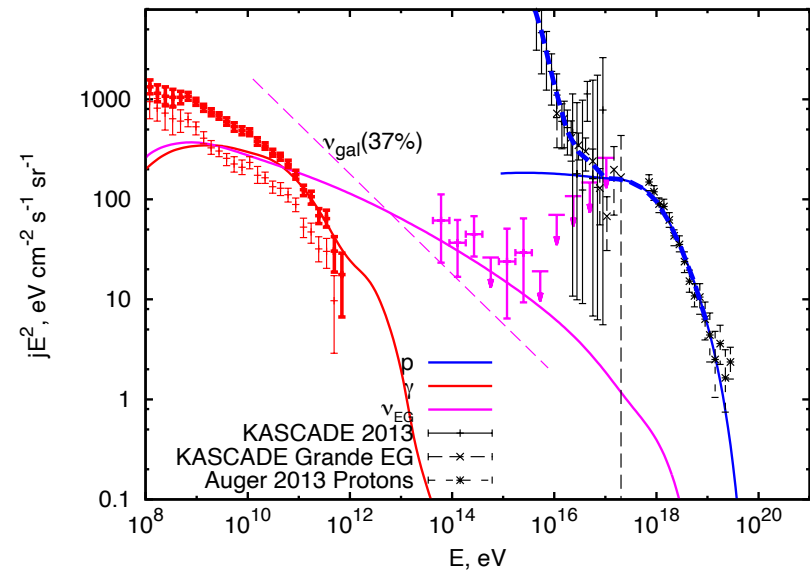
- $E < E_1$  ( $\tau = 1$ ) conversion to neutrino and gamma-rays. Neutrino flux = Proton flux
- $E > E_{\text{esc}}$  ( $\tau \ll 1$ ) protons go away Neutrino flux = Proton flux
- $E_1 < E < E_{\text{esc}}$  diffusion of protons Neutrino flux is softer

# Multimessenger signal from BL Lacs: dependence on escape energy

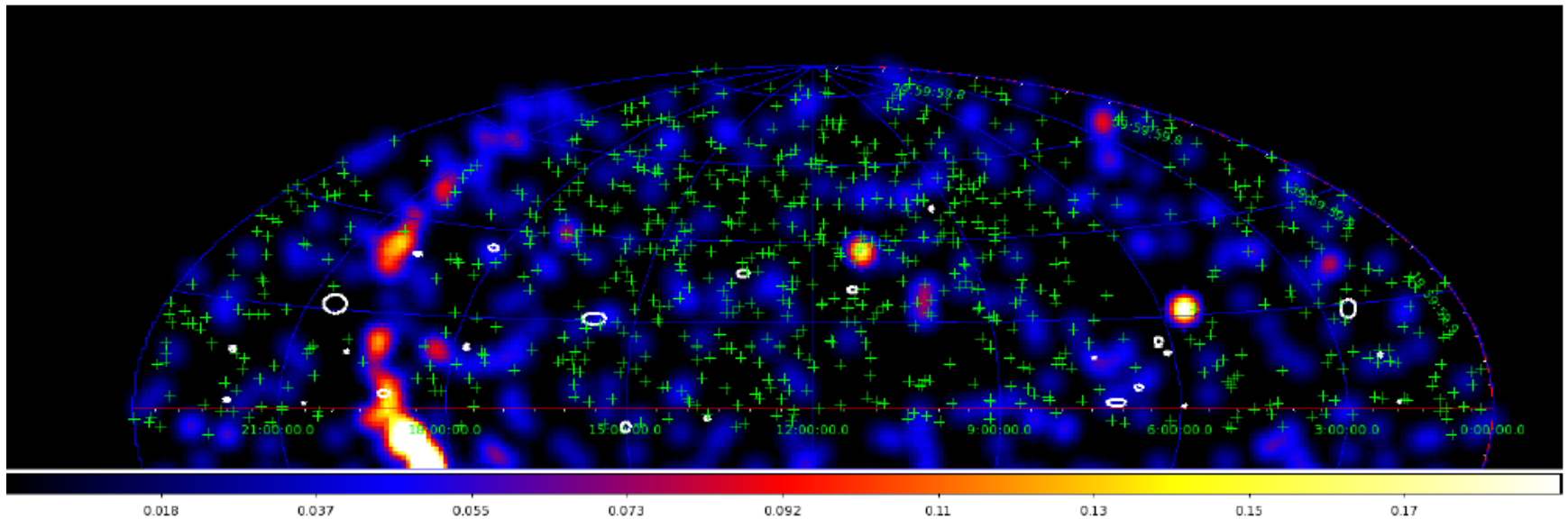
0.3 TeV



100 TeV

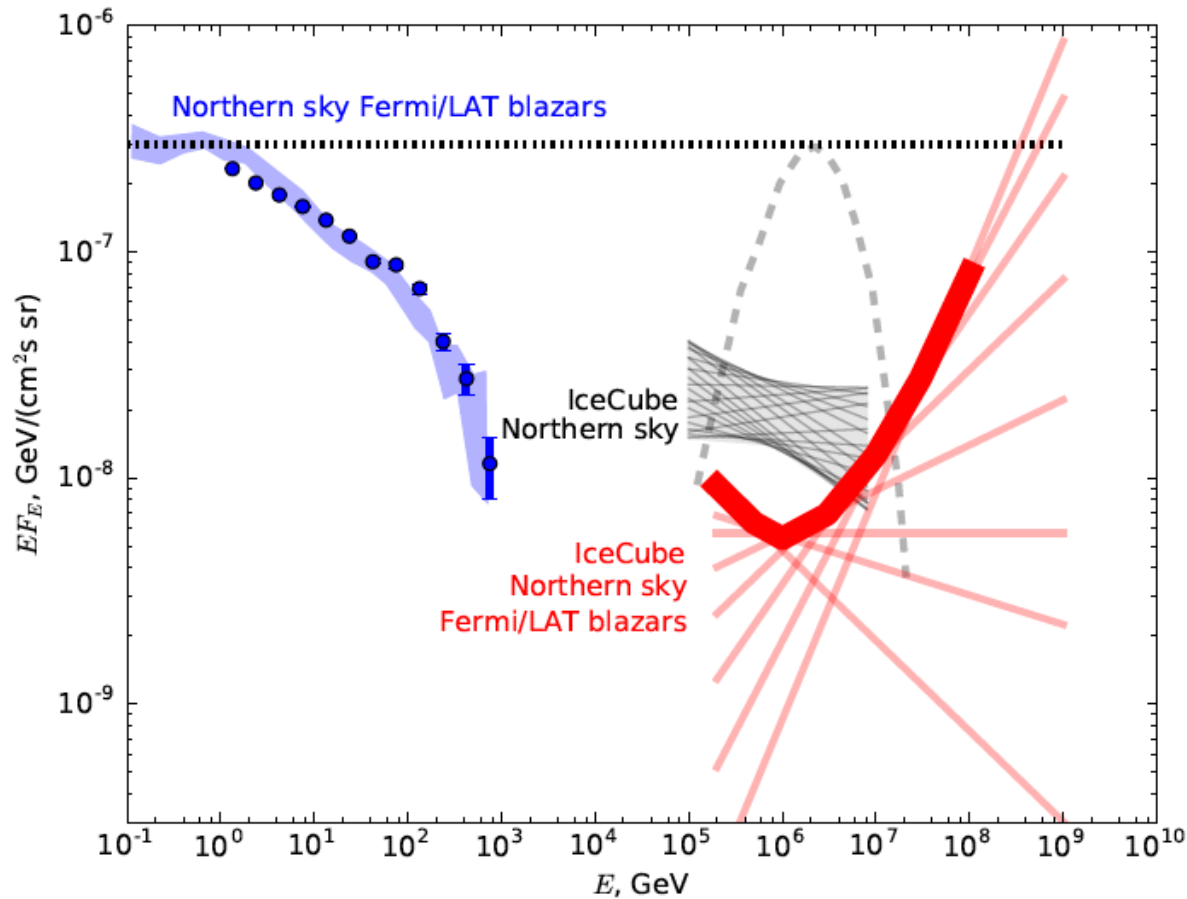


# Fermi blazars and IceCube neutrinos



A.Neronov, K.Ptitsyna and D.S, arXiv:1611.06338

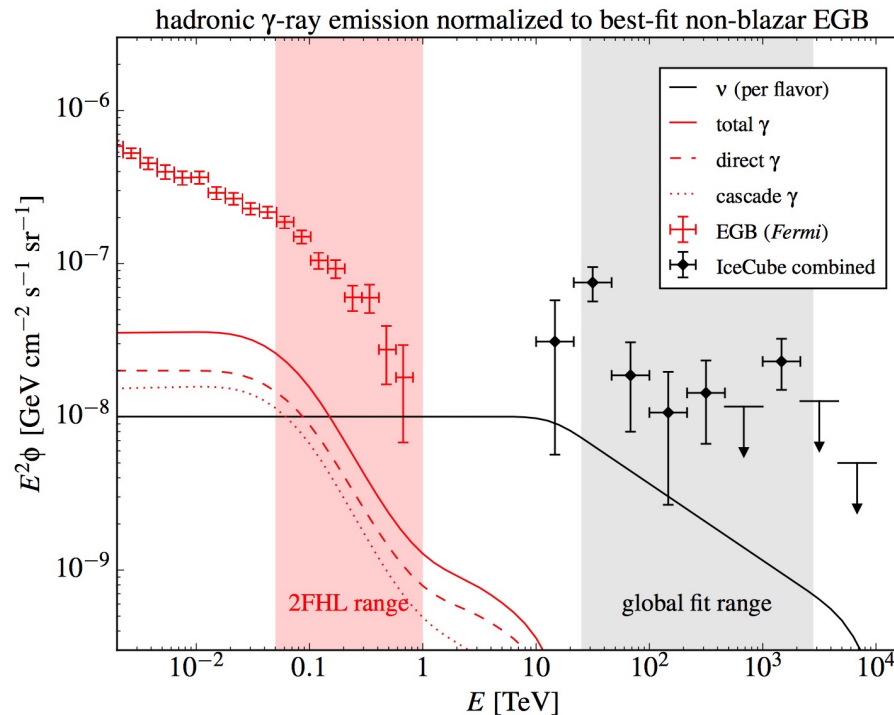
# Neutrinos not from blazars



IceCube    arXiv:1611.03874

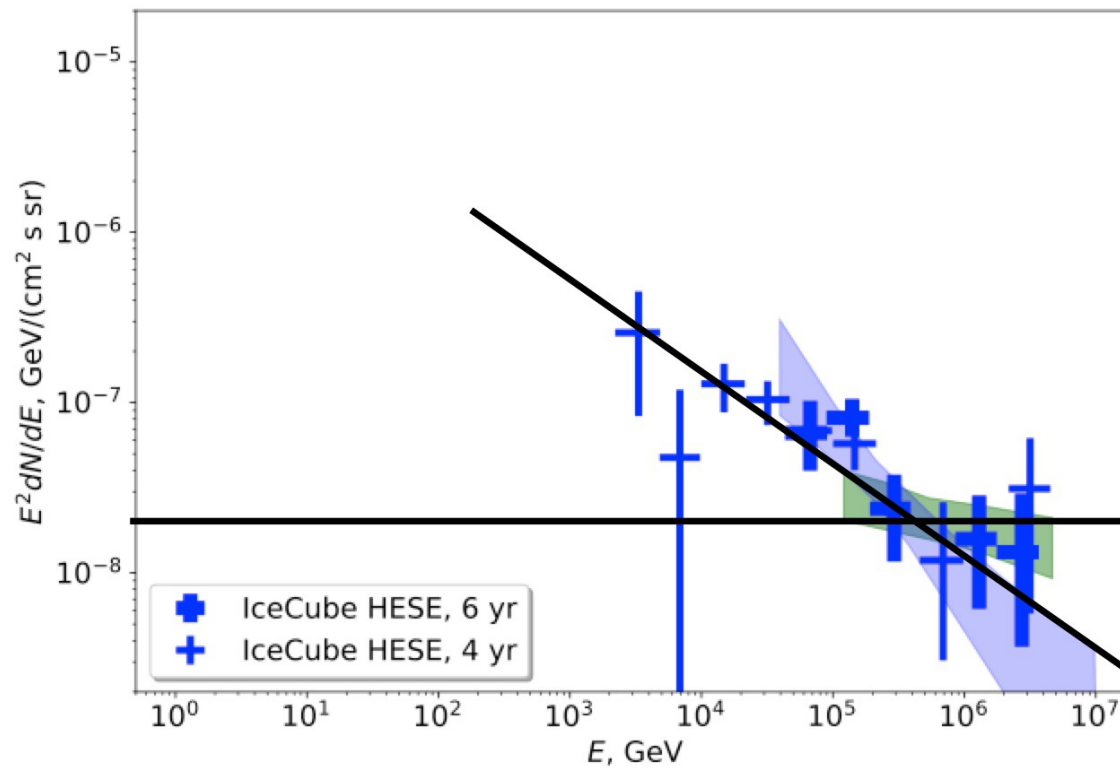
A.Neronov, K.Ptitsyna and D.S., arXiv:1611.06338

# Self-consistent extragalactic sources: no nearby blazars

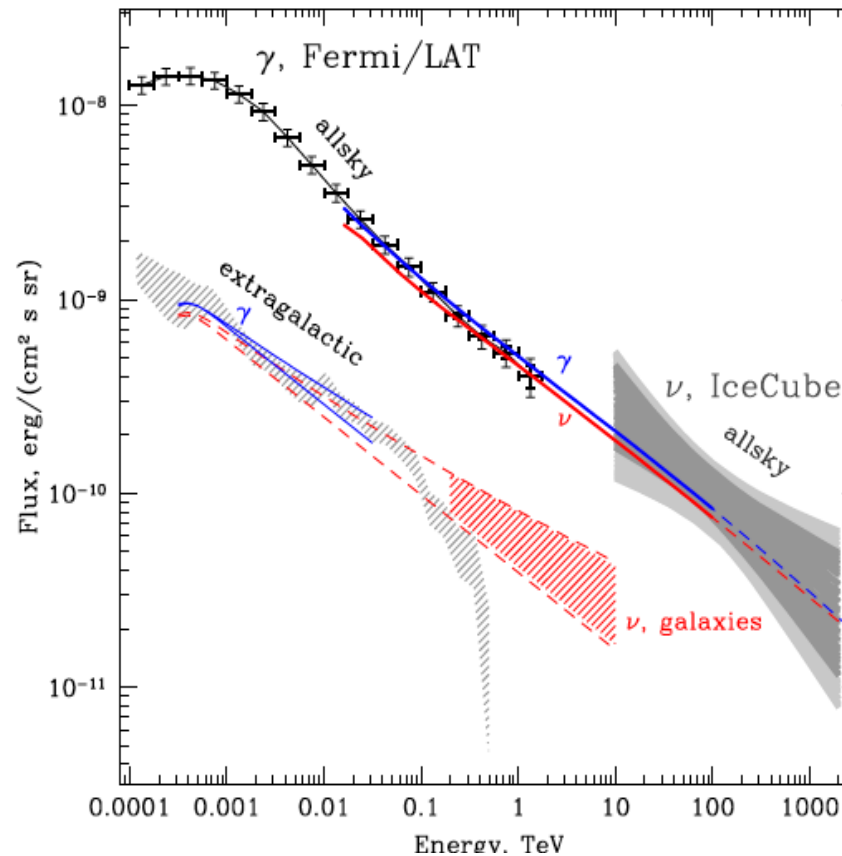


[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

# IceCube data



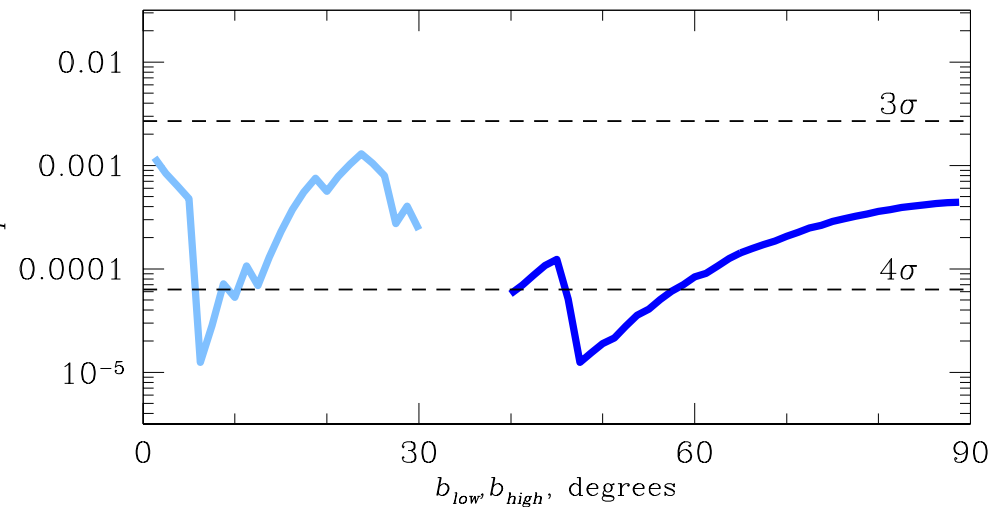
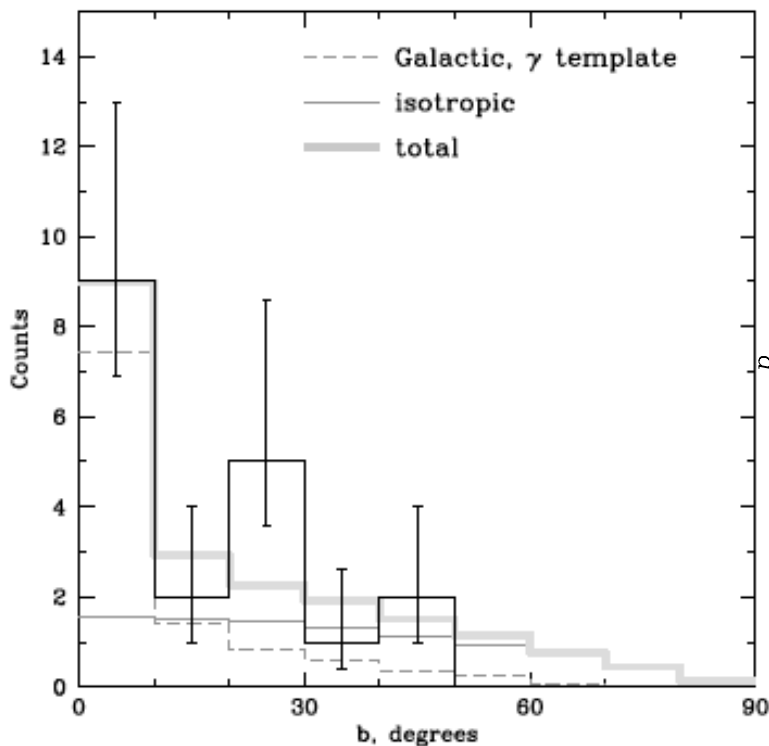
# IceCube + Fermi LAT all sky: protons $1/E^{2.5}$



A.Neronov, D.S. arXiv:1412.1690

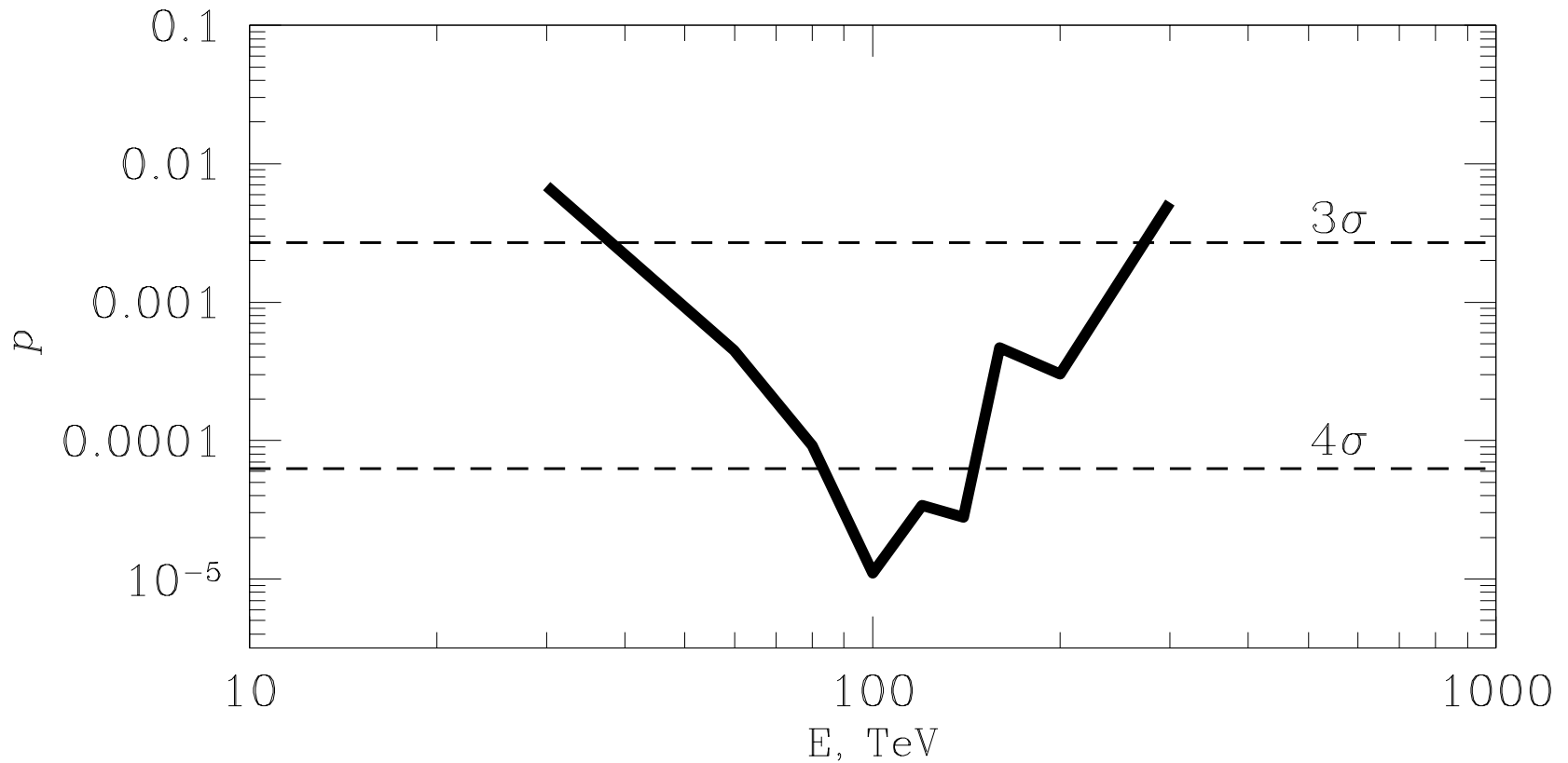


# Evidence of Galactic component in 4 year IceCube data $E > 100$ TeV



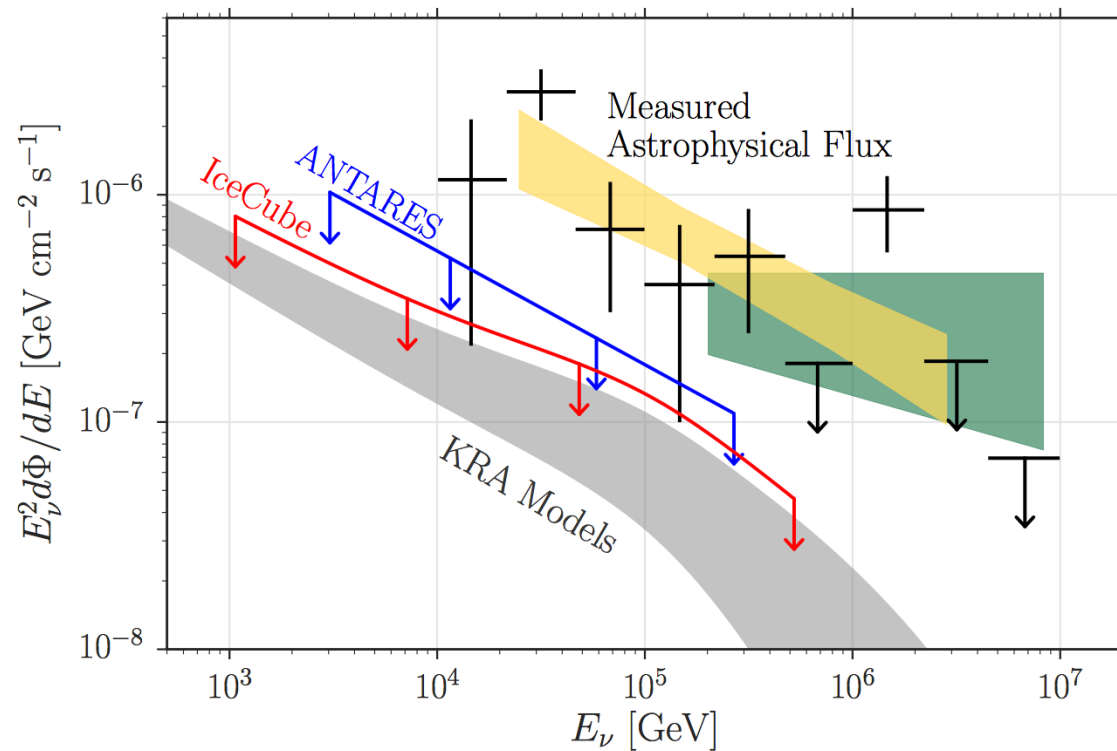
**A. Neronov & D.S. arXiv: 1509.03522**

Post-trial probability is  $1.7 \cdot 10^{-3}$

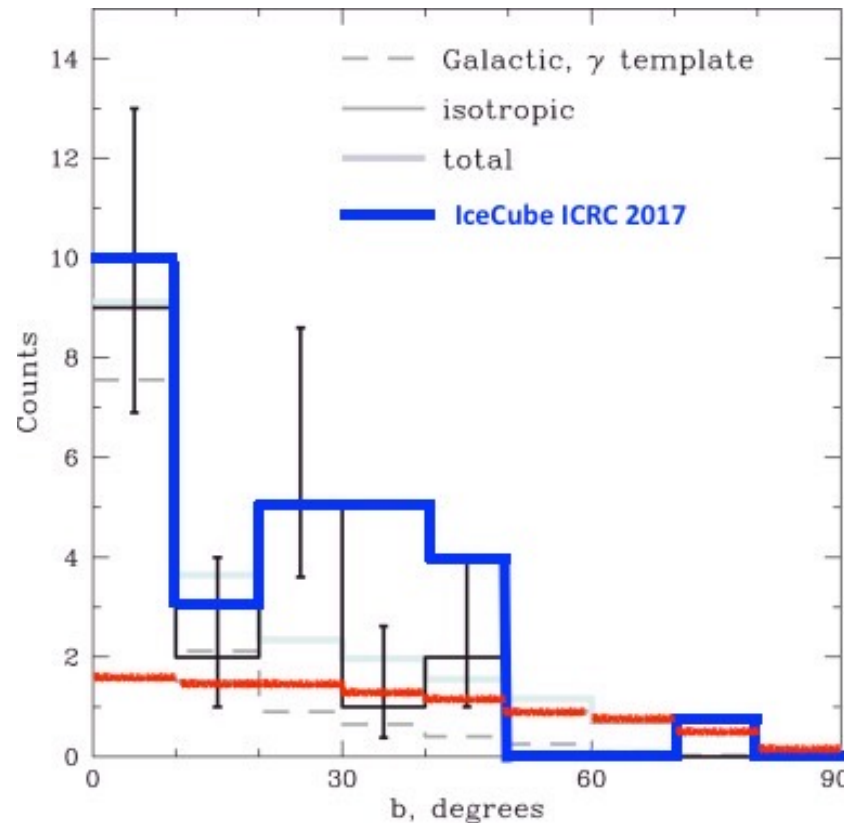


**A. Neronov & D.S. arXiv: 1509.03522**

# IceCube and ANTARES galactic plane



# Anisotropy at $E > 100$ TeV



**A. Neronov, M.Kachelriess and D.S. 2018**

# Point source searches

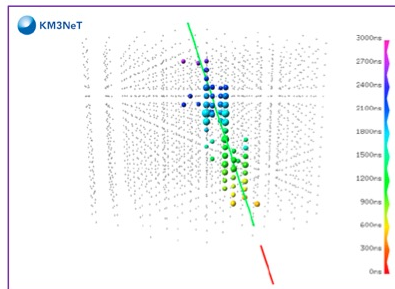
# Point-source samples: angular resolution

**ANTARES**  
tracks  
CC  $\nu_\mu$

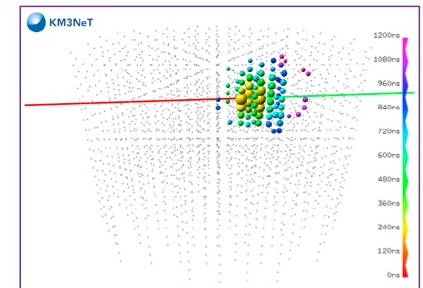
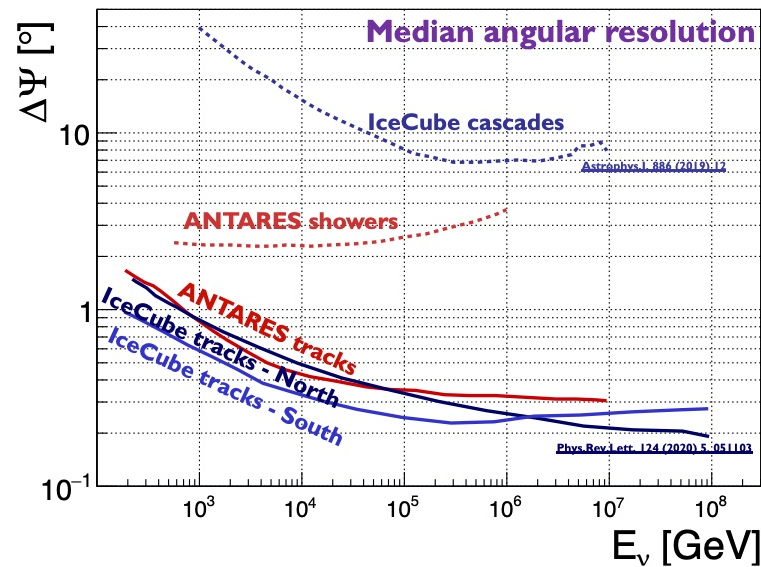
**ANTARES**  
showers  
NC  $\nu_x$  + CC  $\nu_e, \nu_\tau$

**IceCube**  
through-going tracks  
CC  $\nu_\mu$

**IceCube**  
cascades  
NC  $\nu_x$  + CC  $\nu_e, \nu_\tau$



Track event  
in a neutrino telescope



Shower/cascade event  
in a neutrino telescope

# IceCube 10-year: point-source with tracks

**All-sky search North/South**

**p-value:  $4.3 \times 10^{-6} \rightarrow 4.4\sigma$  (pre-trial)**  
**75% (post-trial)**

**p-value:  $3.5 \times 10^{-7} \rightarrow 5.0\sigma$  (pre-trial)**  
 **$9.9 \times 10^{-2} \rightarrow 1.3\sigma$  (post-trial)**

**$(\hat{\alpha}, \hat{\delta}) = (350.2^\circ, -56.5^\circ)$**   
 **$\hat{n}_s = 17.8$**   
 **$\hat{\gamma}_s = 3.3$**

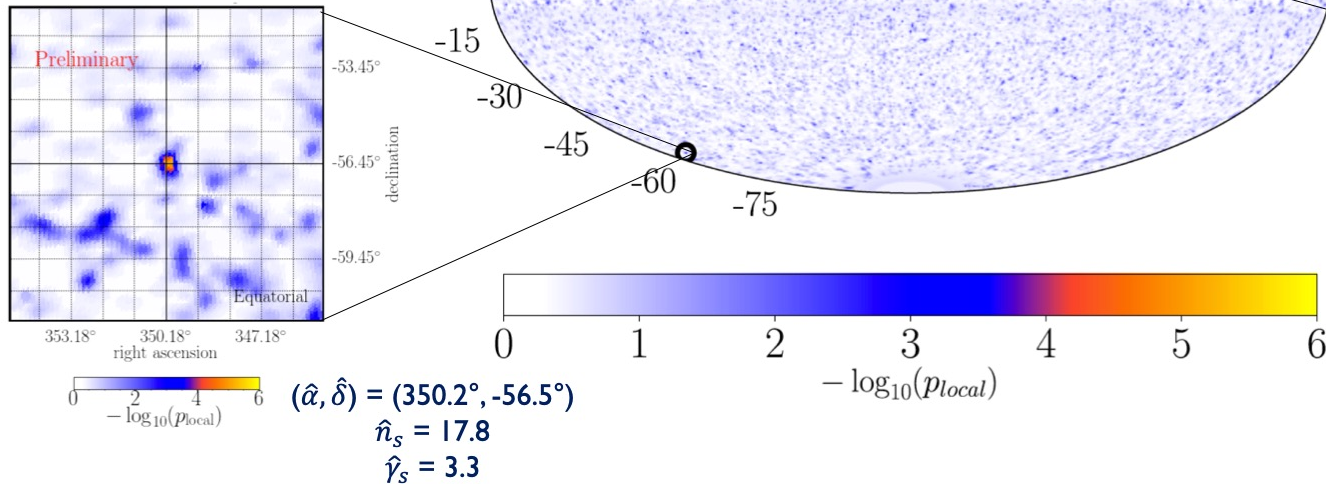
**$(\hat{\alpha}, \hat{\delta}) = (40.9^\circ, -0.3^\circ)$**   
 **$\hat{n}_s = 61.5$**   
 **$\hat{\gamma}_s = 3.4$**

**Active Galaxy NGC 1068 (aka M77)**  
**0.35° from the hotspot**

**Offset consistent with IceCube angular resolution**

$(\hat{\alpha}, \hat{\delta}) = (40.9^\circ, -0.3^\circ)$      $9.9 \times 10^{-2} \rightarrow 1.3\sigma$  (post-trial)  
 $\hat{n}_s = 61.5$   
 $\hat{\gamma}_s = 3.4$

p-value:  $4.3 \times 10^{-6} \rightarrow 4.4\sigma$  (pre-trial)  
75% (post-trial)



Active Galaxy  
**NGC 1068** (aka M77)  
0.35° from the hotspot  
Offset consistent with IceCube angular resolution



# IceCube 10-year: point-source with tracks

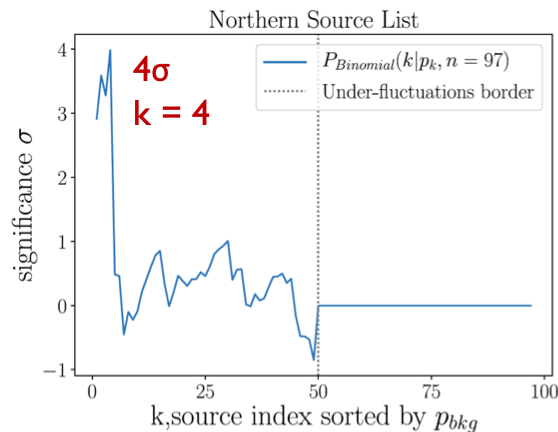
## Population study:

A binomial test is used to search for a significant **excess** of small p-values obtained in the source-catalog search compared to the uniform background expectation:

$$p_{\text{bkg}} = \sum_{i=k}^N P_{\text{binom}}(i|p_k, N) = \sum_{i=k}^N \binom{N}{i} p_k^i (1-p_k)^{N-i}$$

Number of sources  
in the catalog

Number of sources with  
p-value smaller than  $p_k$



## Best sources

Ranking	Source	Type	RA	$\delta$	$\hat{n}_s$	$\hat{\gamma}_s$	# $\sigma$ pre-trial
1st	NGC 1068	SBG	40.67°	-0.01°	50.4	3.2	4.1
2nd	TXS 0506+056	BLL	77.35°	5.70°	12.3	2.1	3.6
3rd	PKS 1424+240	BLL	216.76°	23.80°	41.5	3.9	3.0
4th	GB6 J1542+6129	BLL	235.75°	61.50°	29.7	3.0	2.9
5th							<2

$k = 4$  most significant sources

**4 $\sigma$  pre-trial**

**→ 3.3 $\sigma$  post-trial (2.3 $\sigma$  without TXS 0506+056)**

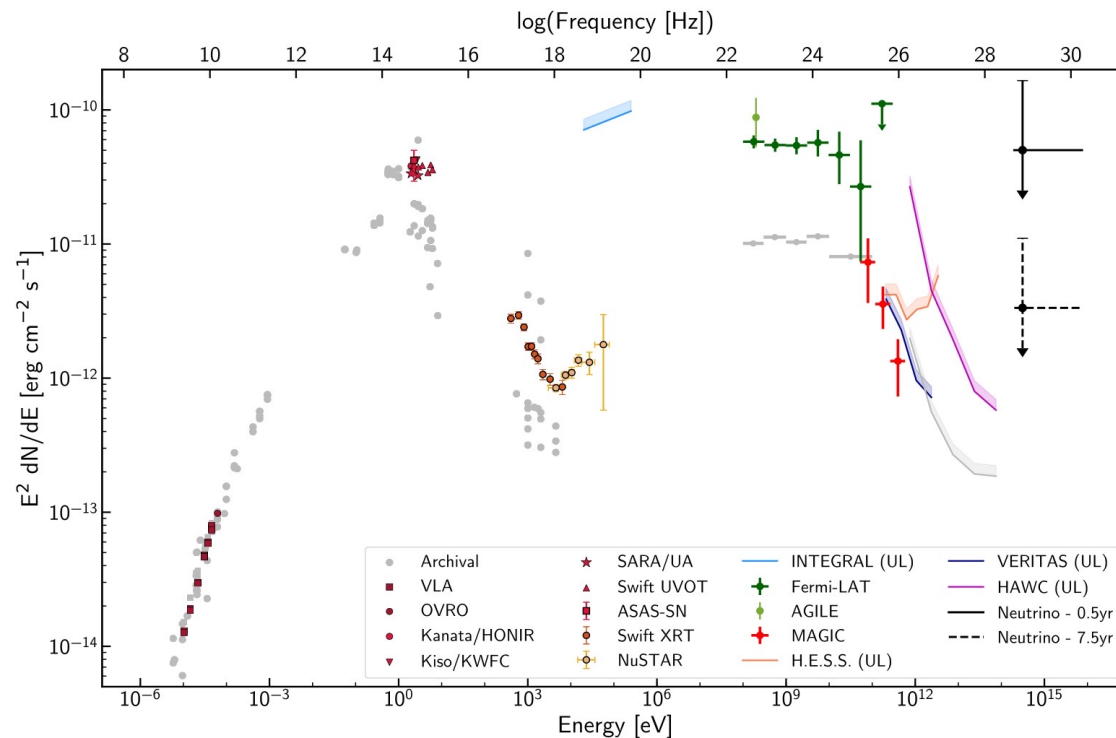
First candidate  
neutrino source  
TXS 0506+056

# First neutrino source candidate

## TXS 0506+056

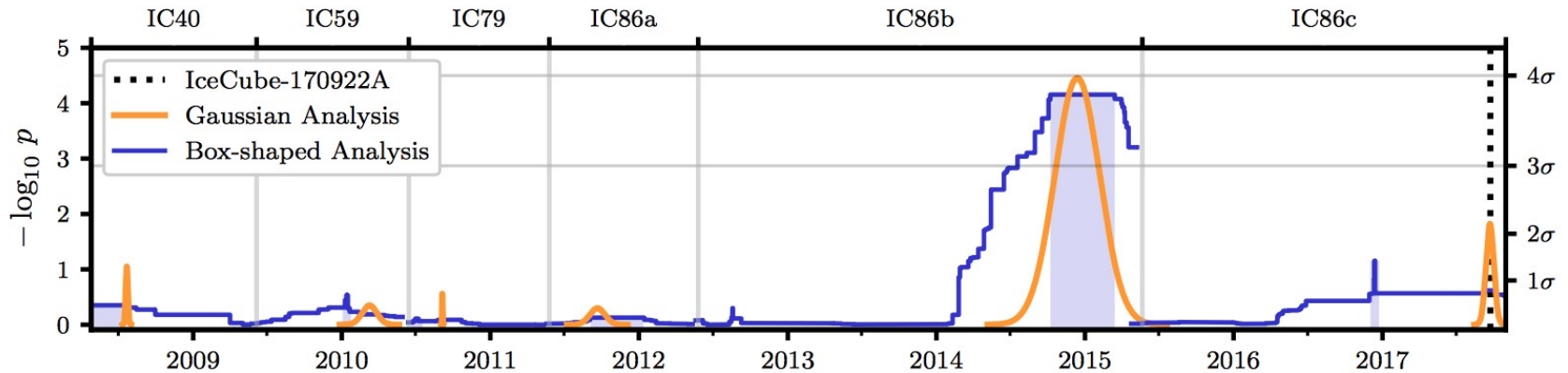
- Blazar TXS 0506+056 is Fermi source, one of 50 bright sources , but not in first 20.
- Icecube event: IceCube-170922A Sept 22 2017
- TXS 0506+056 has redshift  $z=0.3365$
- MAGIC detected flair Sept 28 2017
- Fermi detected activity of source in the same period.

# TXS 0506+056 multi-messenger



IceCube collab 1807.08794

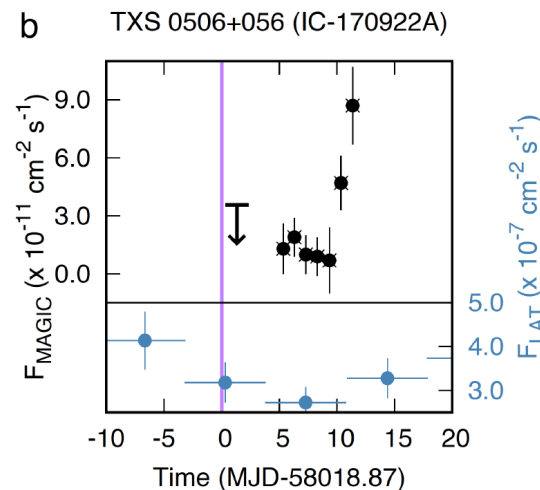
# TXS 0506+056 neutrino flare 3 sigma



IceCube collab 1807.08794.

# TXS 0506+056 multi-messenger

no TeV gamma rays at the time the neutrino



- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

# TXS 0506+056 multi-messenger

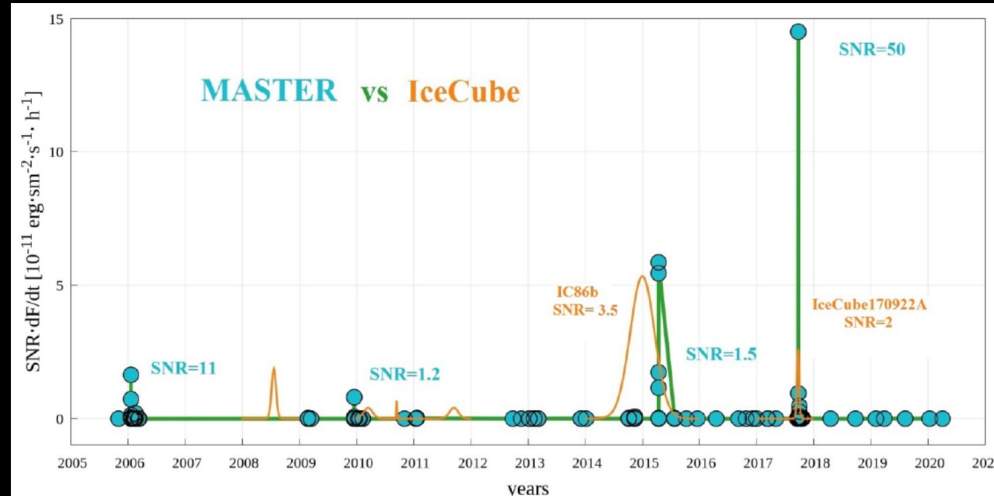
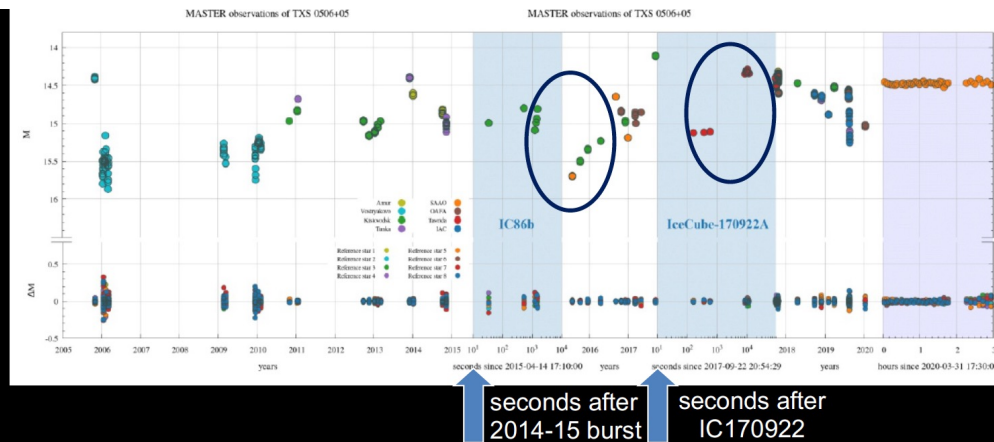
**MASTER**  
robotic network

optical observations  
TXS 0506+056  
since 2005

blue panels:  
expanded time axis  
years  $\rightarrow$  seconds

time variation of flux  
times  
signal-to-noise

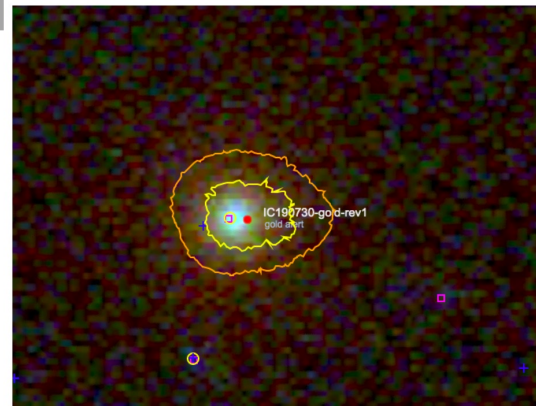
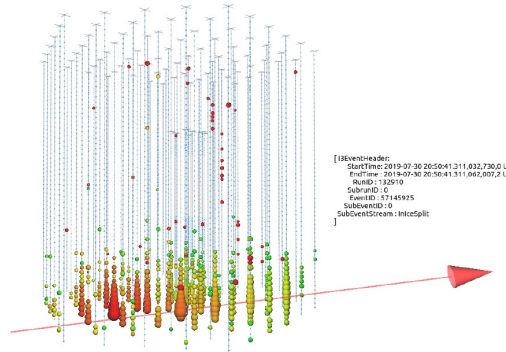
hour-scale  
variability of the  
source after  
neutrino emission





# PKS 1502+106

a second cosmic ray source



IC 190730: 300 TeV

- coincident with PKS 1502+106
- radio burst

[ Previous | Next ]

## Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996: *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. Würzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)* on 7 Aug 2019; 12:31 UT

Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar



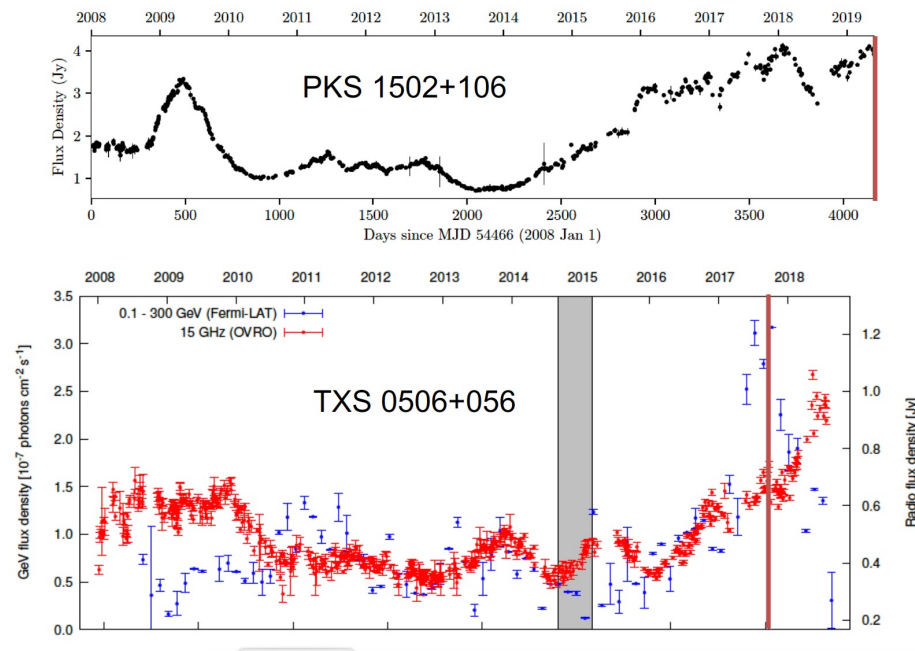
On 2019/07/30 8:68:53 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

### Related

- 12996** Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
- 12985** IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
- 12983** Optical flares of candidate neutrino blazar PKS 1502+106
- 12981** ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
- 12974** Optical follow-up of IceCube-190730A with ZTF
- 12971** IceCube-190730A: MASTER alert observations and analysis
- 12967** IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
- 12926** VLA observations reveal increasing brightness of 180GJ-zJ04516.3-273333, a potential source of IC190704A

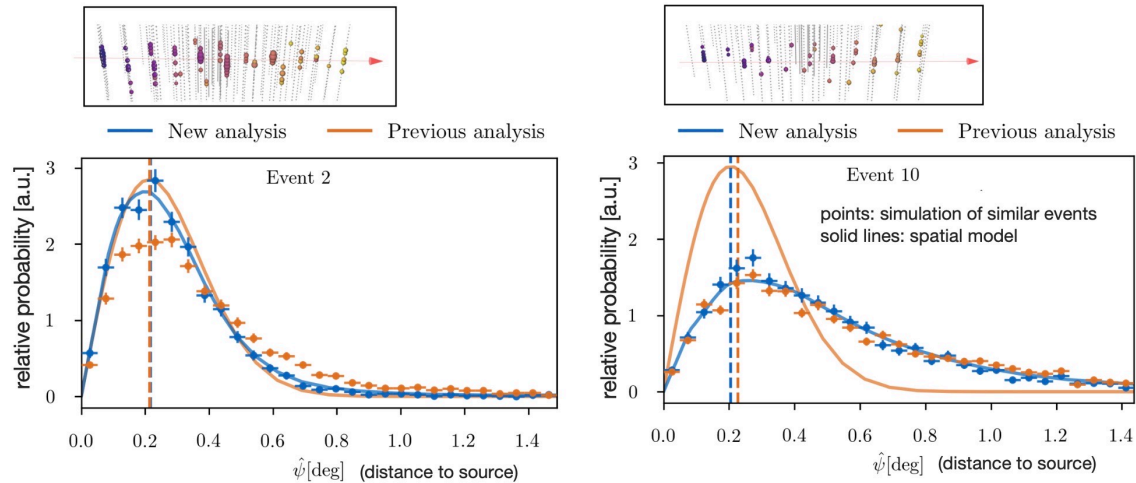
# TXS 0506+056 multi-messenger

the two highest energy (300 TeV  $\nu_\mu$ ) IceCube neutrino alerts are coincident with radio flares



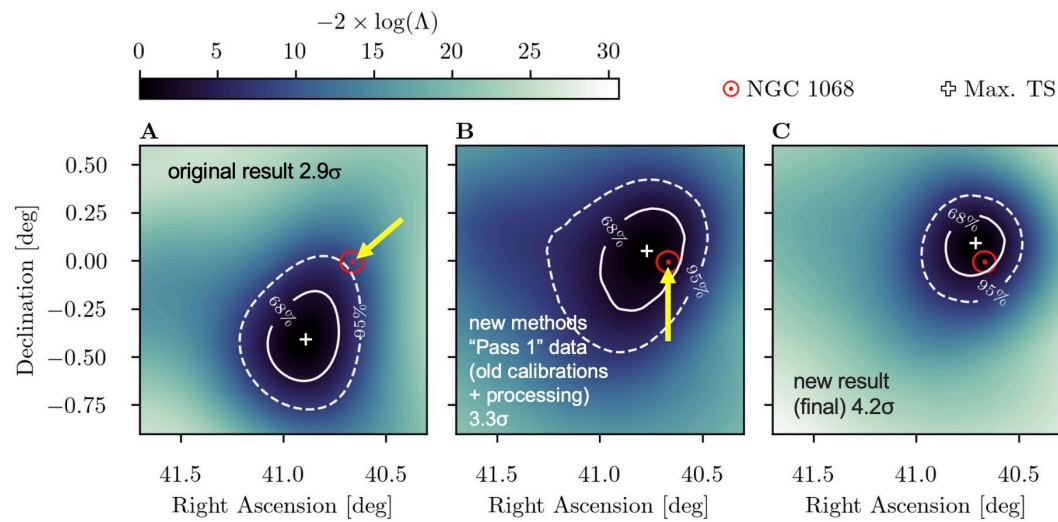
# First TeV neutrino source AGN NGC 1068

pointing with neutrinos:



directional distributions:

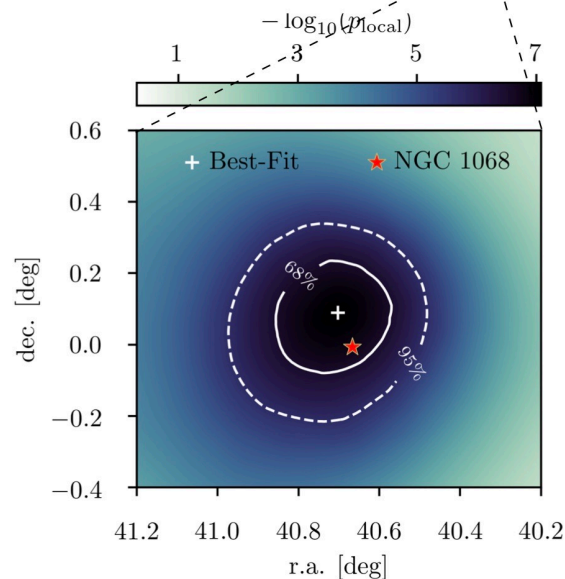
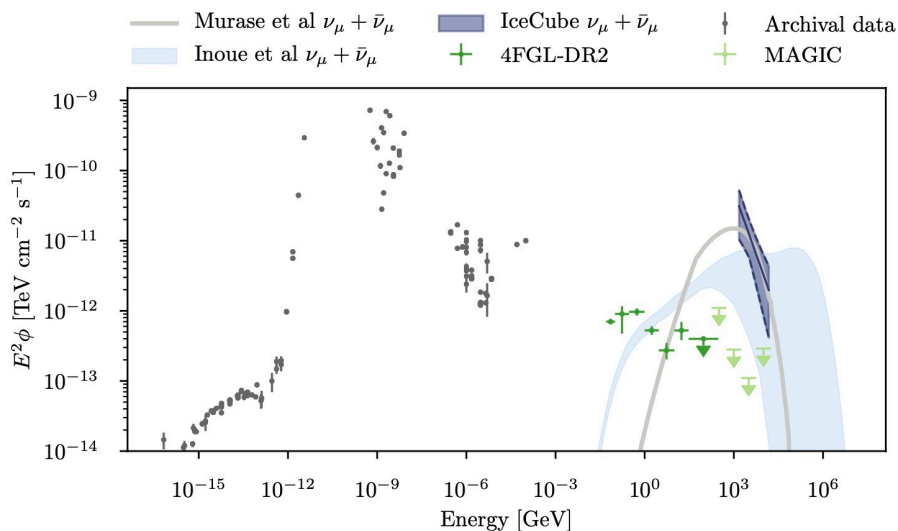
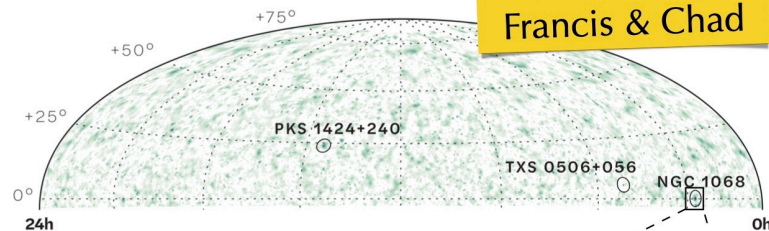
- better modeling of the directional distribution of neutrinos
- consistent with full Monte-Carlo simulations of the detector



# Excess from NGC 1068

Northern hot spot in the vicinity of Seyfert II galaxy **NGC 1068** has now a **significance of  $4.2\sigma$**  (trial-corrected for 110 sources).

see talks by Francis & Chad

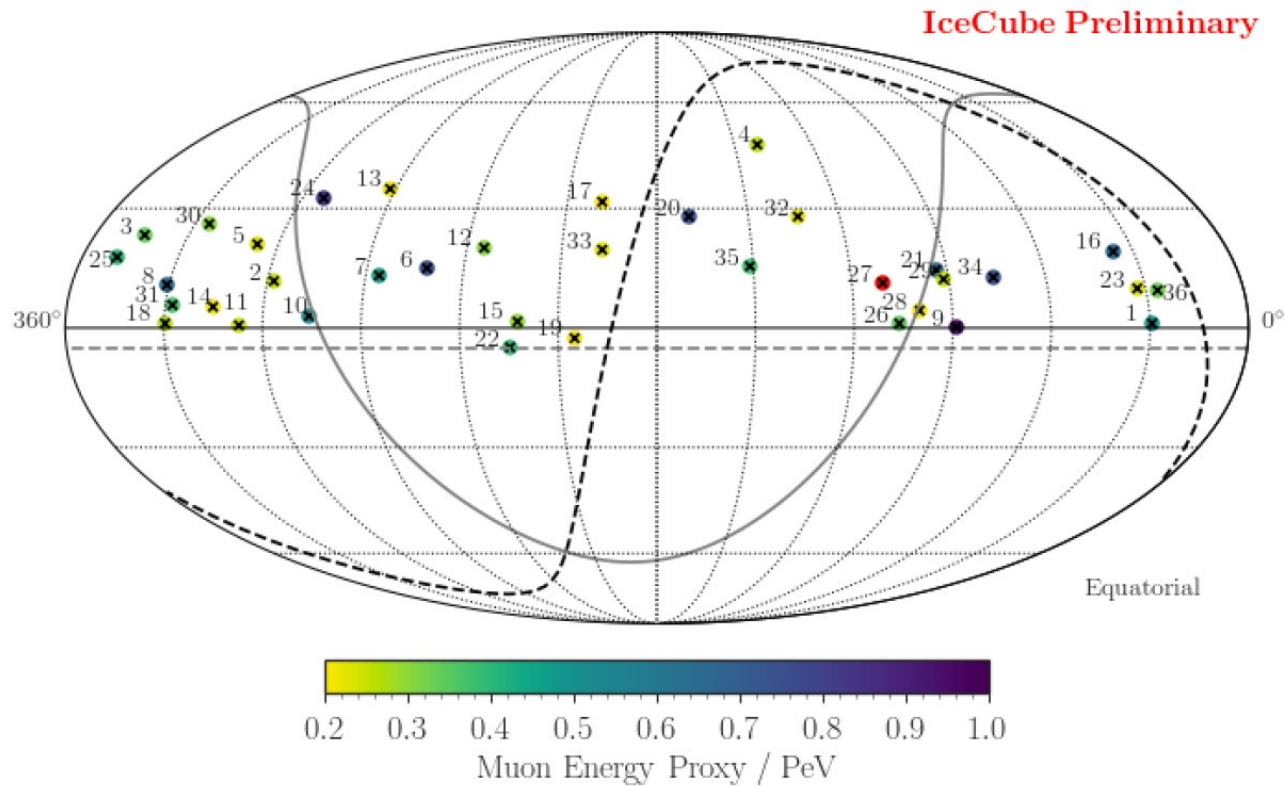


[IceCube, PRL 124 (2020) 5 ( **$2.9\sigma$  post-trial**); Science 378 (2022) 6619 ( **$4.2\sigma$  post-trial**)]

# Bright neutrino source populations

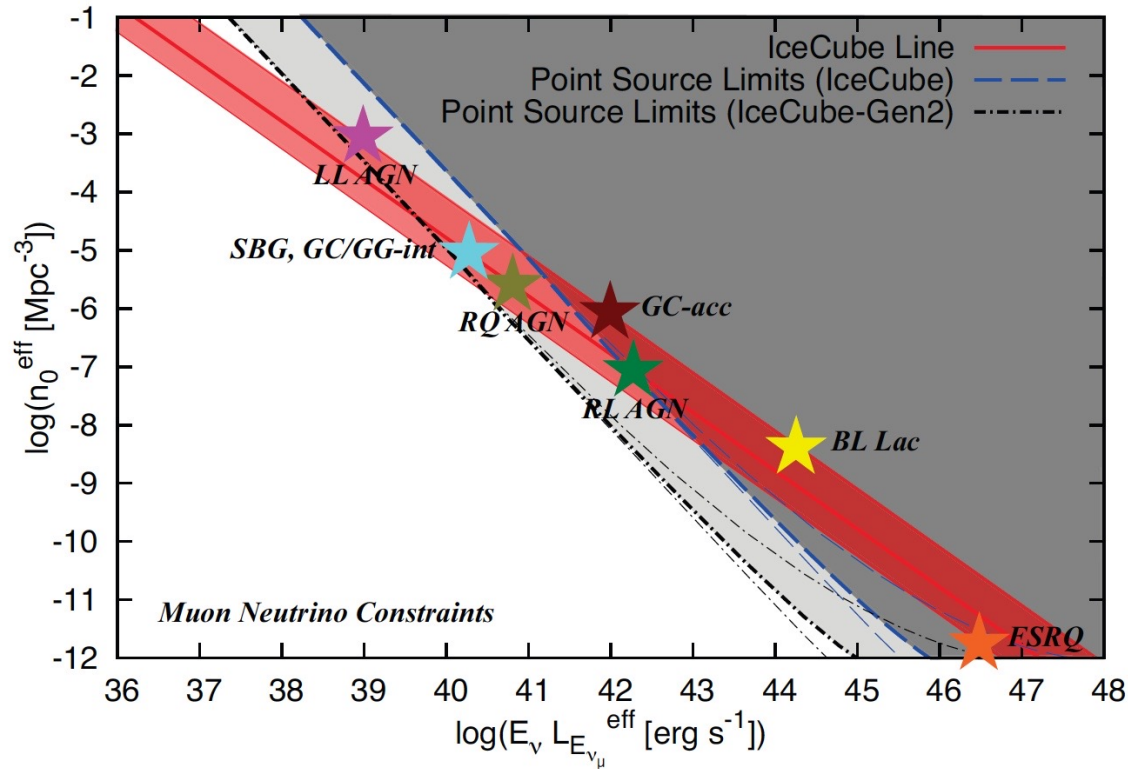


# Icecube 8 years muon neutrinos



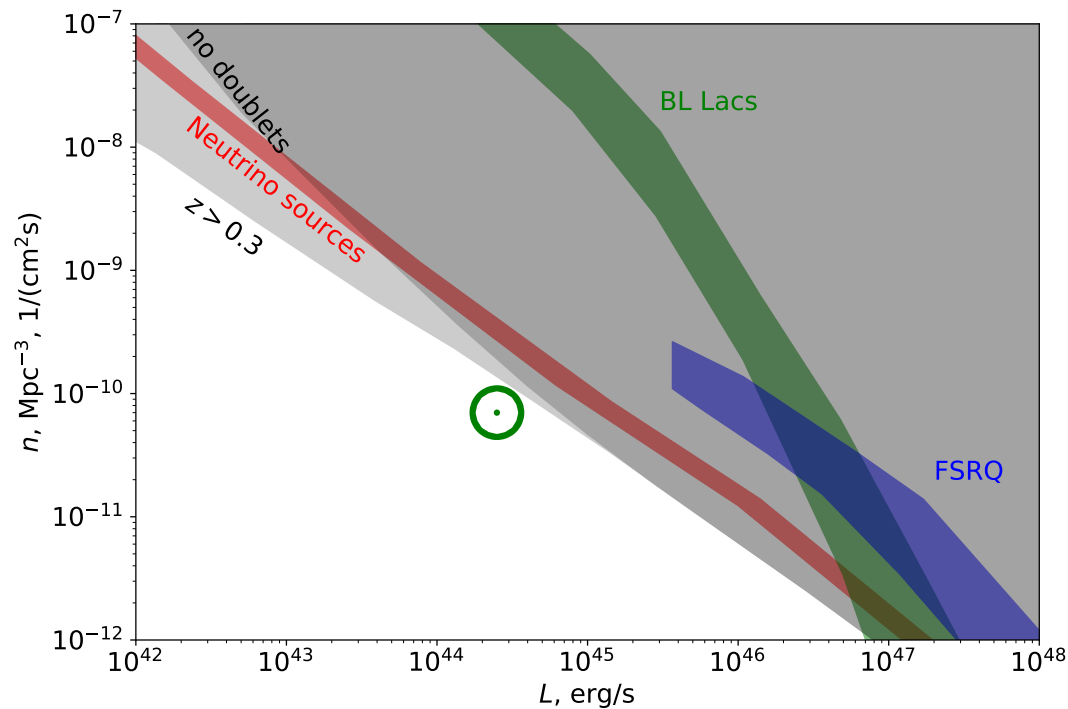
IceCube ICRC 2017

# No doublets put limit on density of sources



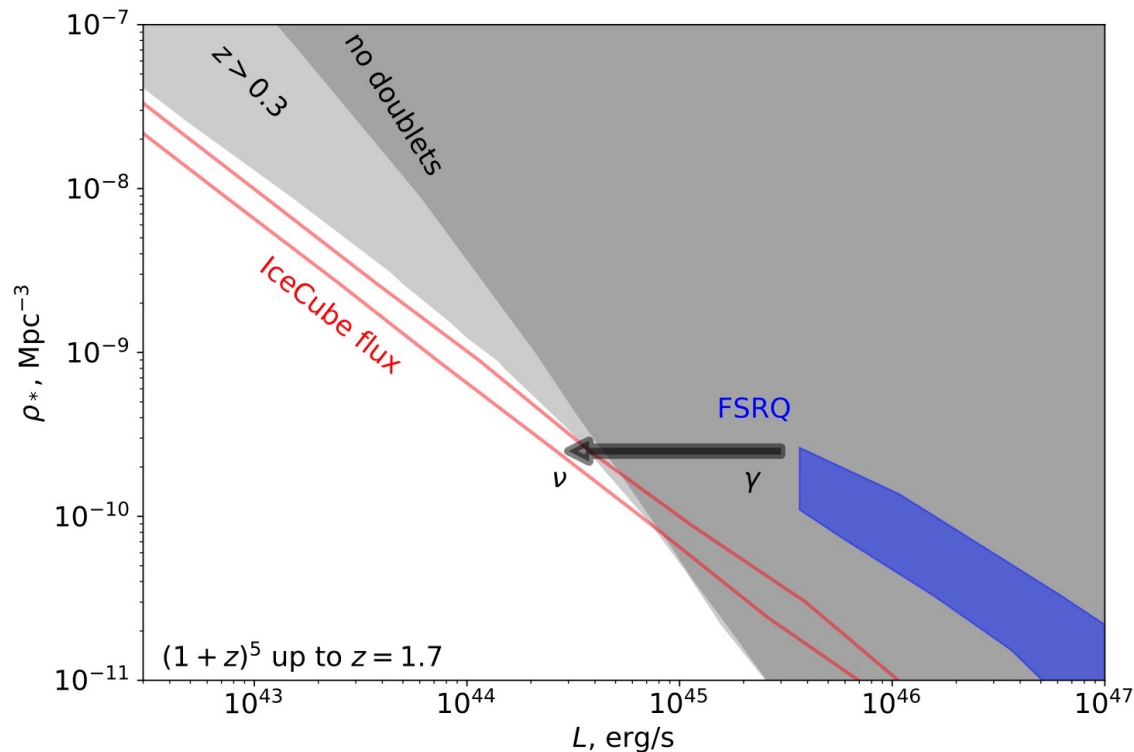
K.Murase, E.Waxman, 1607.01601

# Neutrinos from not evolving sources+TXS 0506+056



A.Neronov, D.S. 1811.06356

# Neutrino from strongly evolving sources: neutrino flux small compared to gamma-ray flux

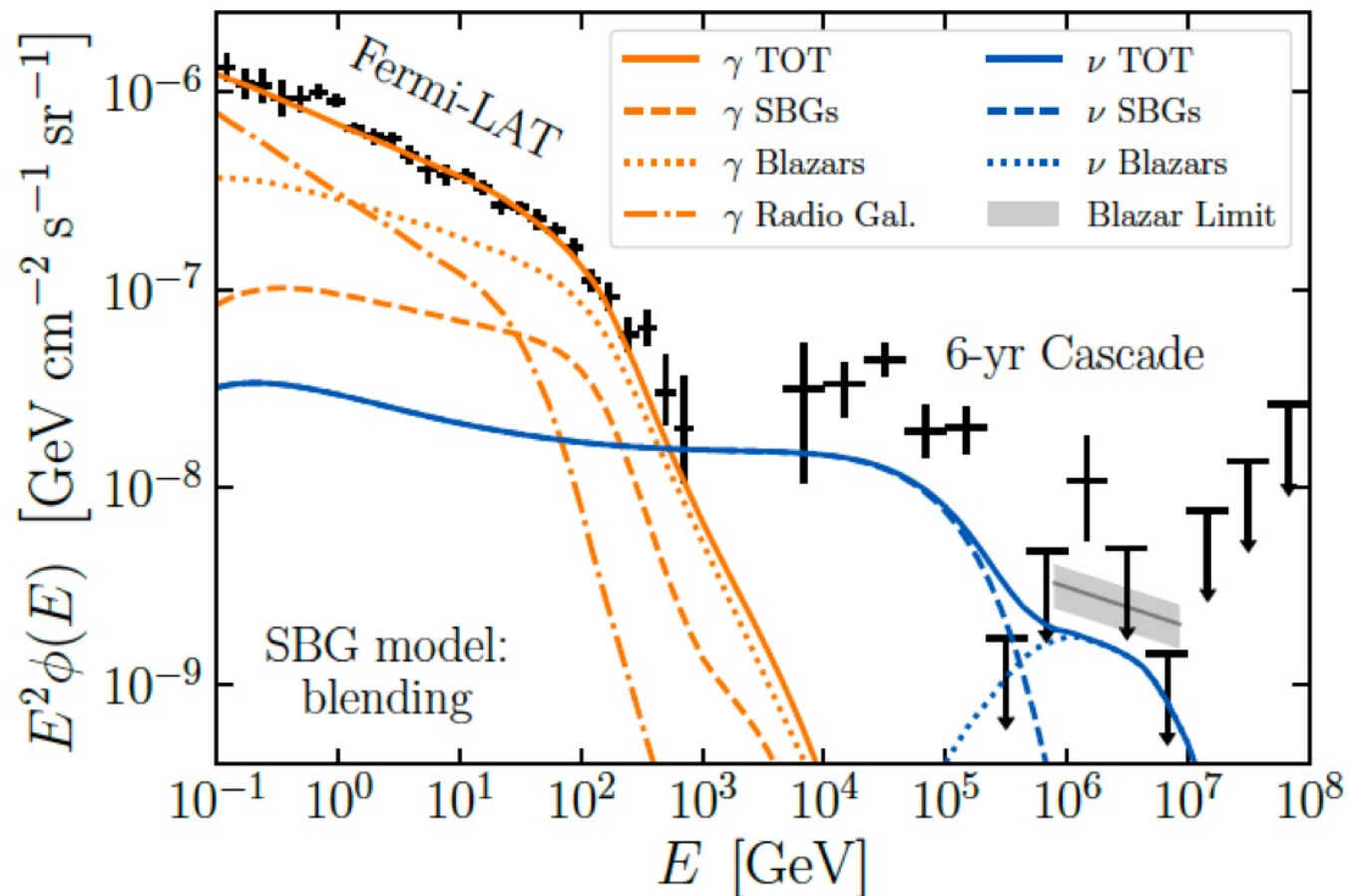


A.Neronov, D.S 1811.06356

# Source populations searches

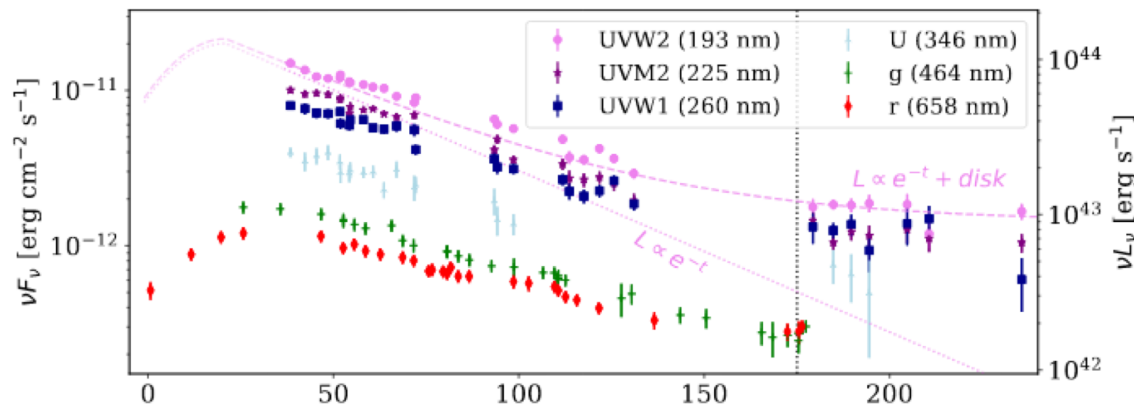
## Star Burst Galaxies 1%

ArXiv:2011.02483



# Tidal disruption event 0.5%

## IC191001A + AT2019dsg

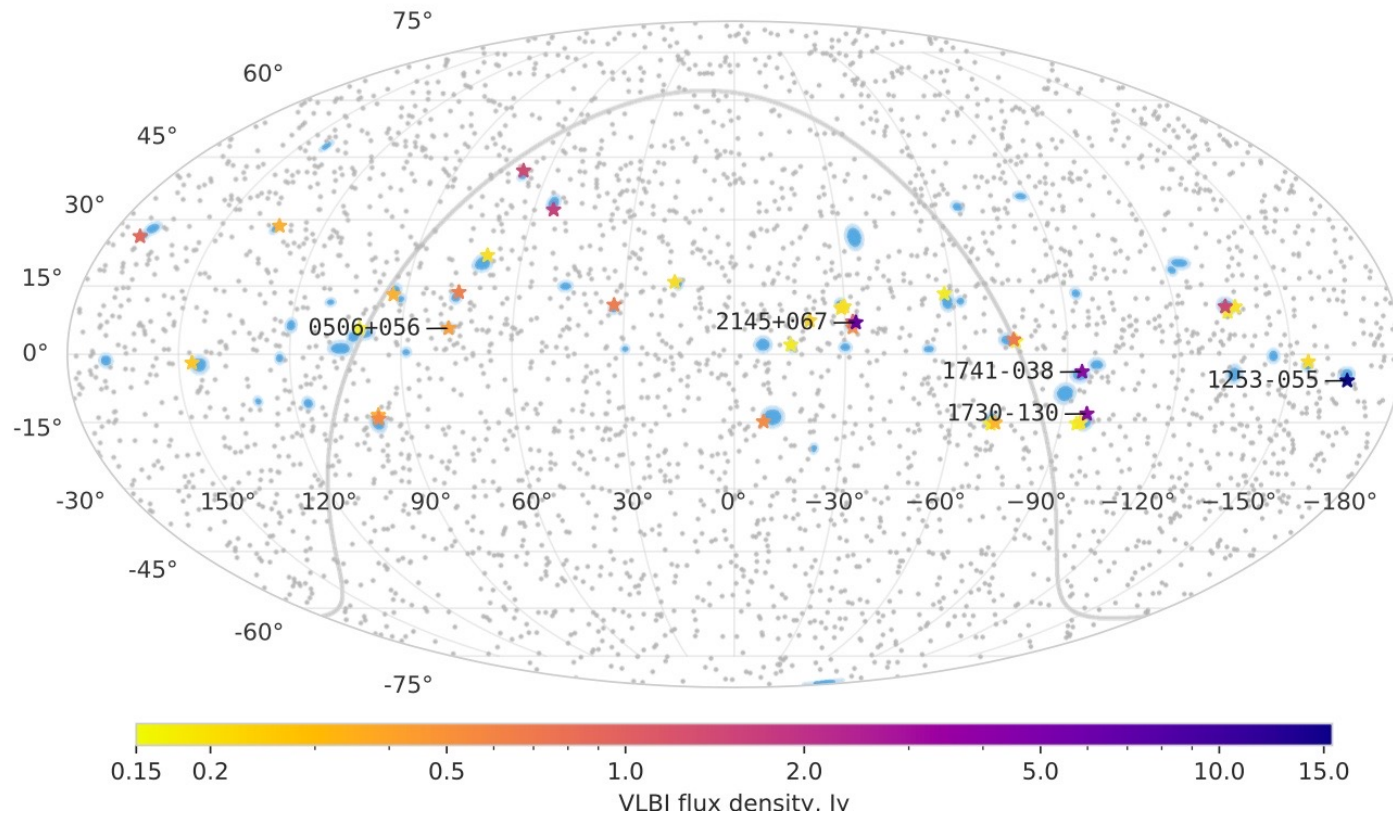
<https://arxiv.org/abs/2005.05340>


Bright, radio-emitting TDE found coincident with IC191001A.

TDEs are rare. Accounting for all 8 neutrino campaigns and ZTF RE TDE density (1 per 10000 sq. deg.), the probability to find any coincident radio-emitting TDE is 0.5%.



# VLBI Radio/neutrino 4/7 sources in IceCube field of view (3 sigma after penalty)



Plavin et al, 2000.00930

# Neutrino – Blazar Association

Testing hypothesis:

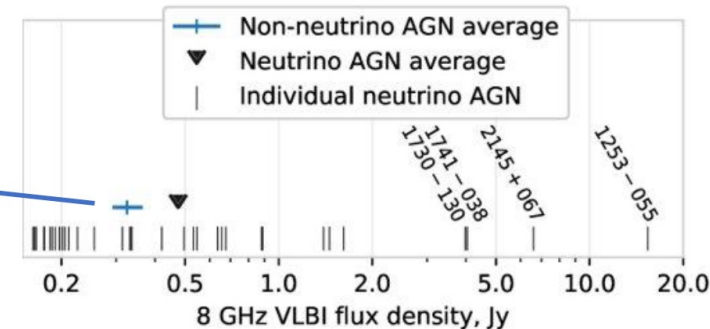
- Bright blazars commonly coincide with neutrino arrival directions?
- Neutrinos commonly arrive from directions of bright blazars?

(Plavin+2020)

**Result:** yes, this correlation is present!  $\Rightarrow$  Neutrinos are emitted by blazars!

Events  $\geq 200$  TeV: p-value = 0.2%

Test: blazars within neutrino error regions are brighter than average.

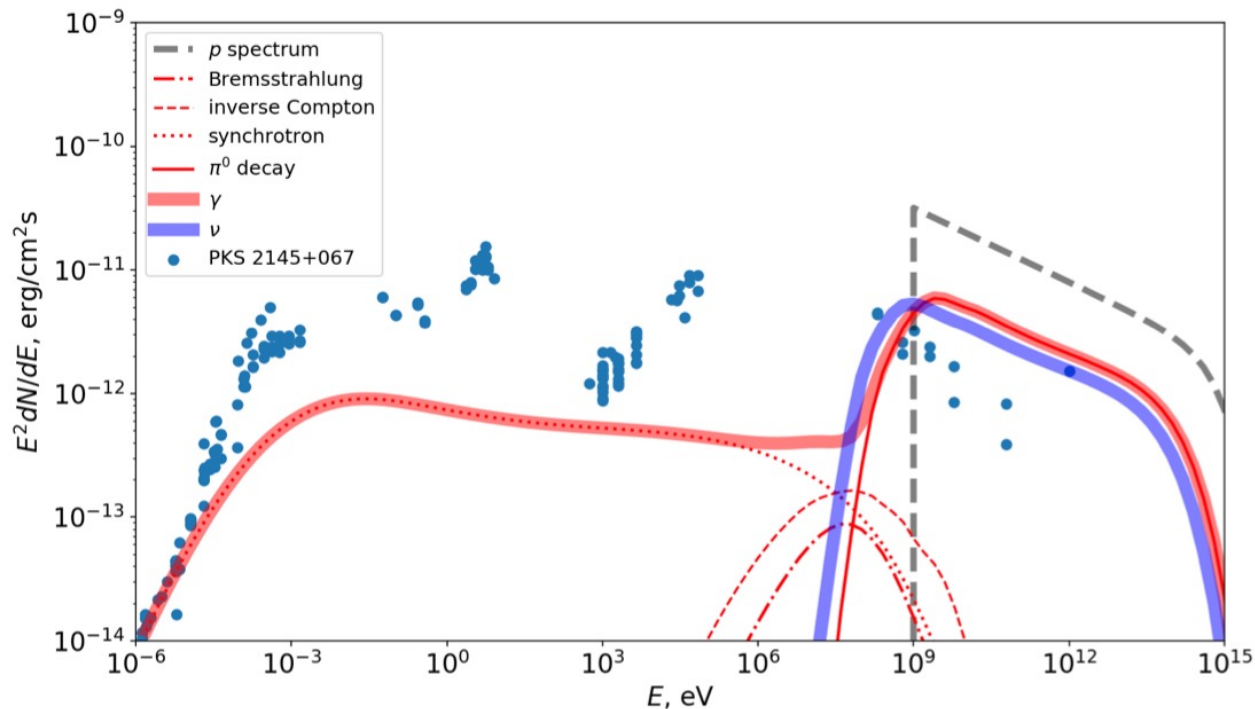


Lower energies, likelihood map: p-value = 0.3%

Test: higher than average IceCube likelihoods in the directions of blazars

Combined: p-value =  $4 \times 10^{-5}$ ,  $4.1\sigma$

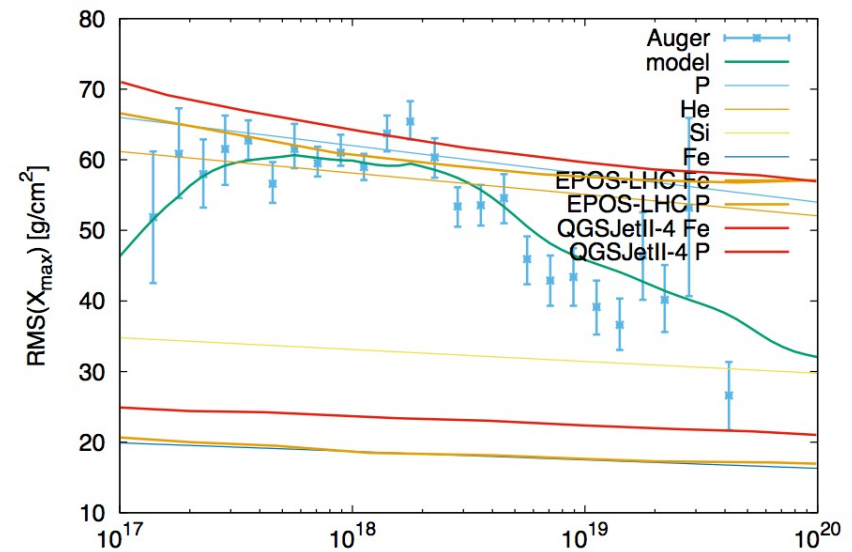
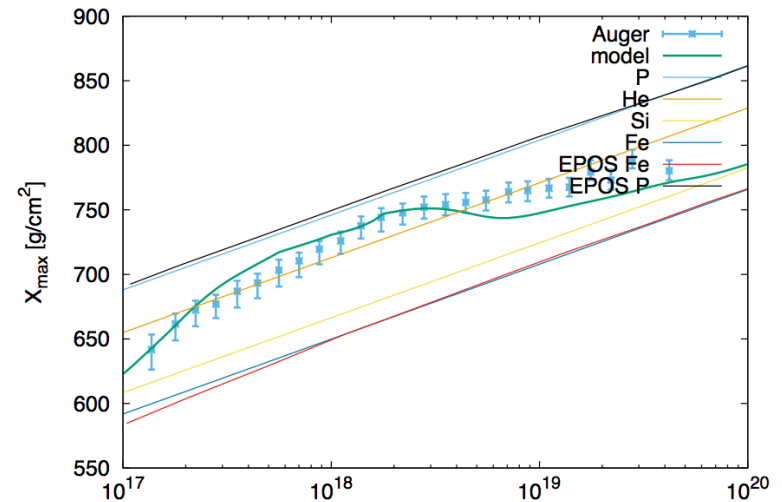
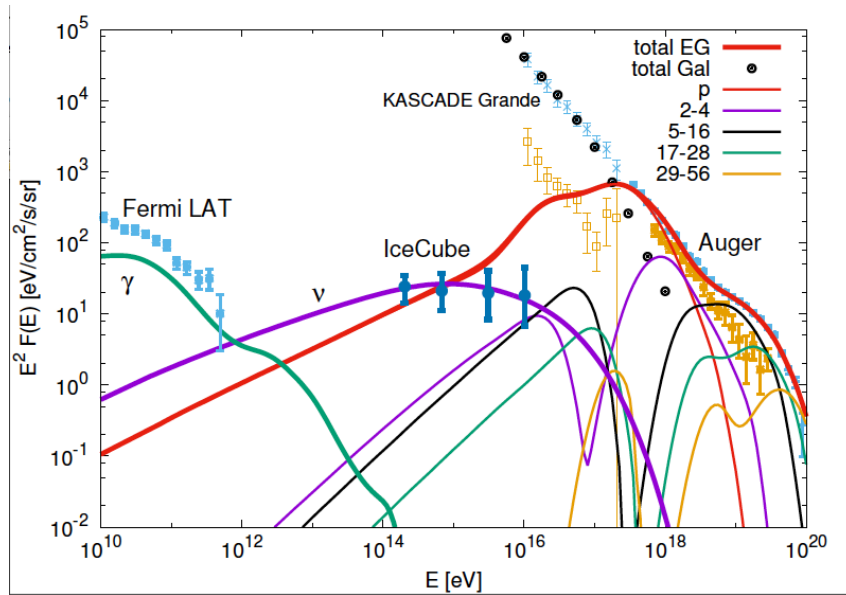
# P-P in jet can produce radio flux connected with protons



Neronov and DS, JETP Lett, arxiv: 2012.04425

## UHECR sources

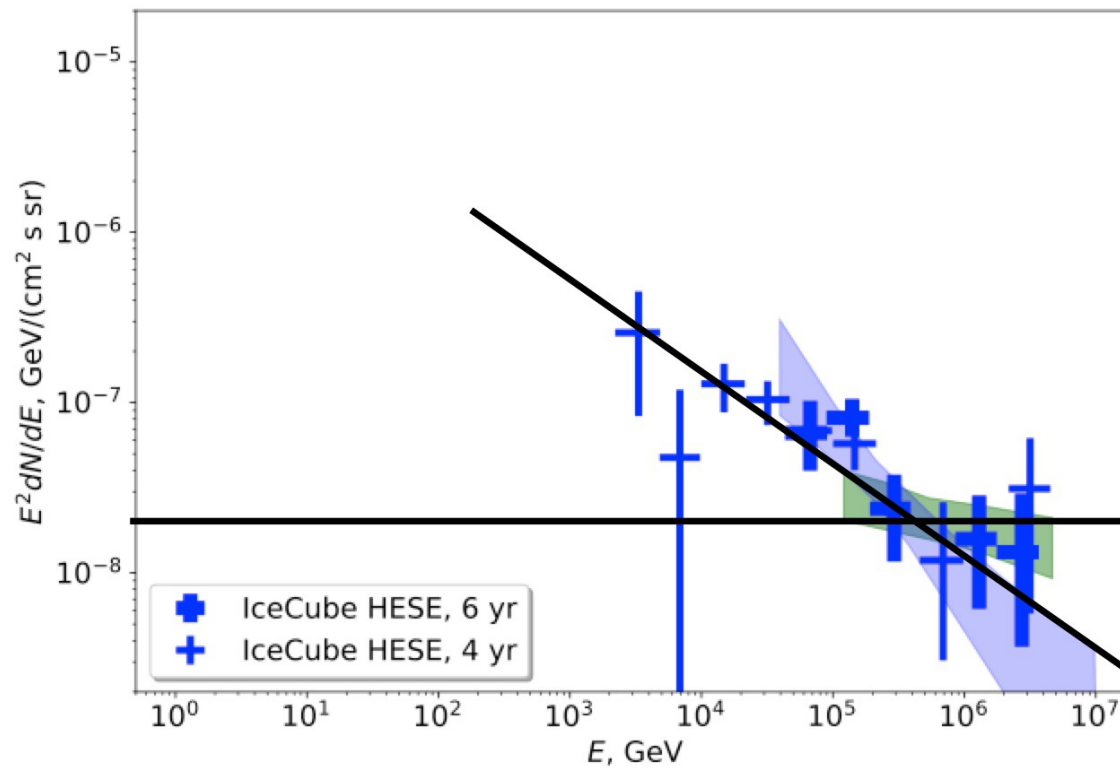
AGN's: P-gamma + Proton-proton interactions in the source region



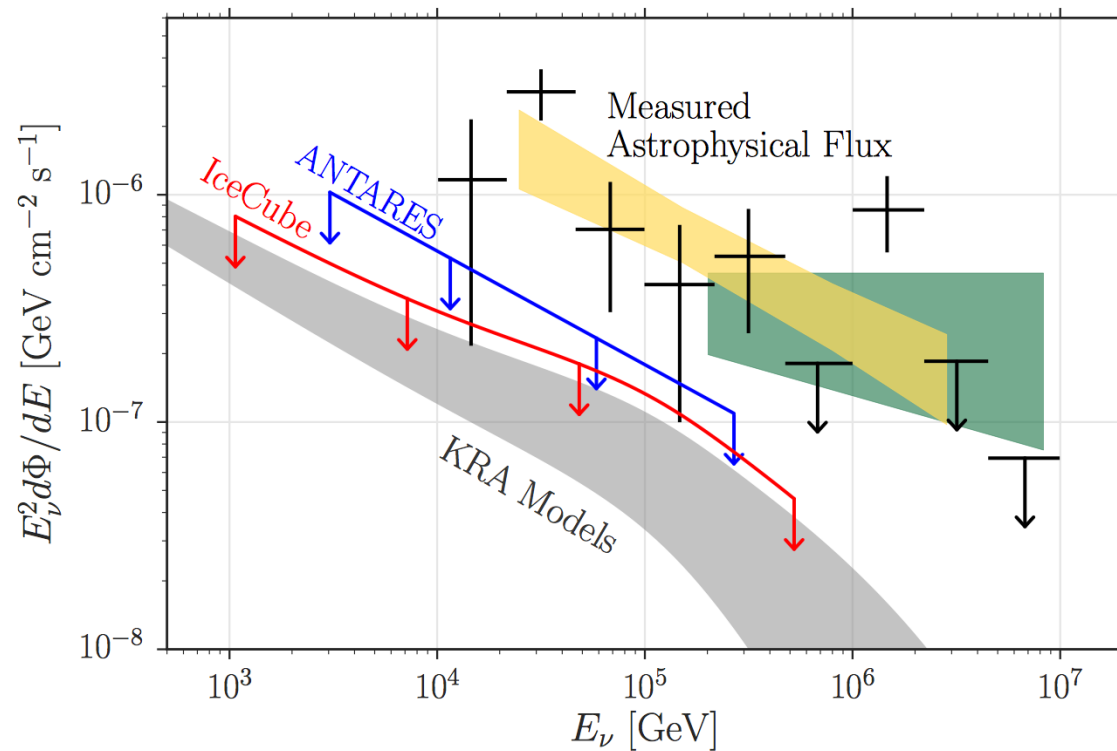
**M.Kachelriess, O.Kalashev,**  
**S.Ostapchenko and D.S., 1704.06893**

# *Low energy excess*

# IceCube data

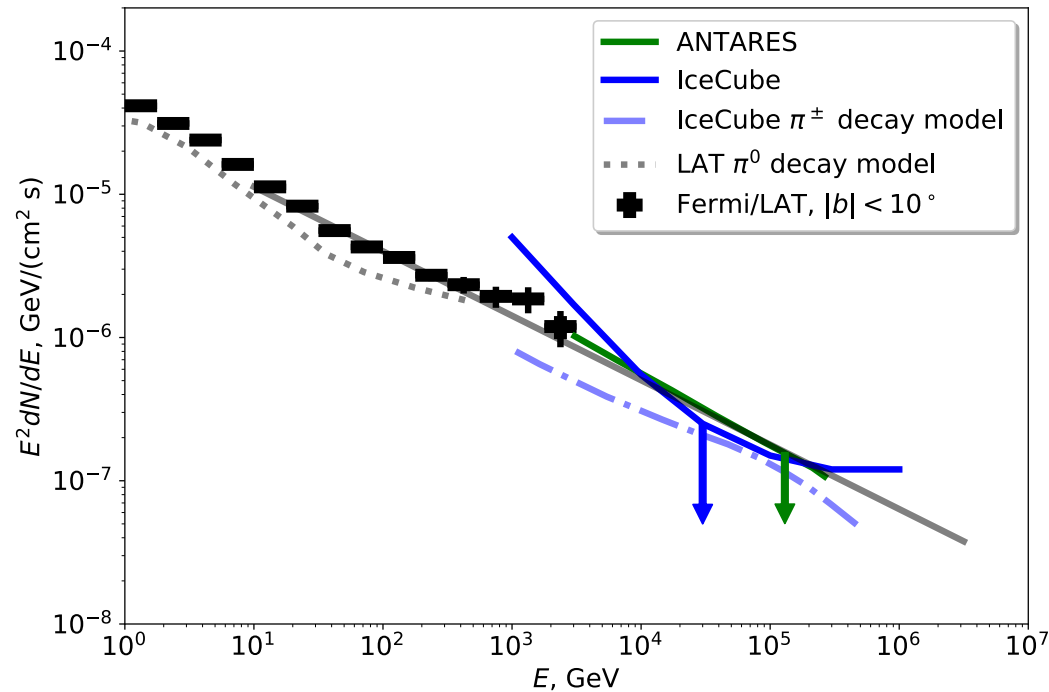


# IceCube and ANTARES galactic plane



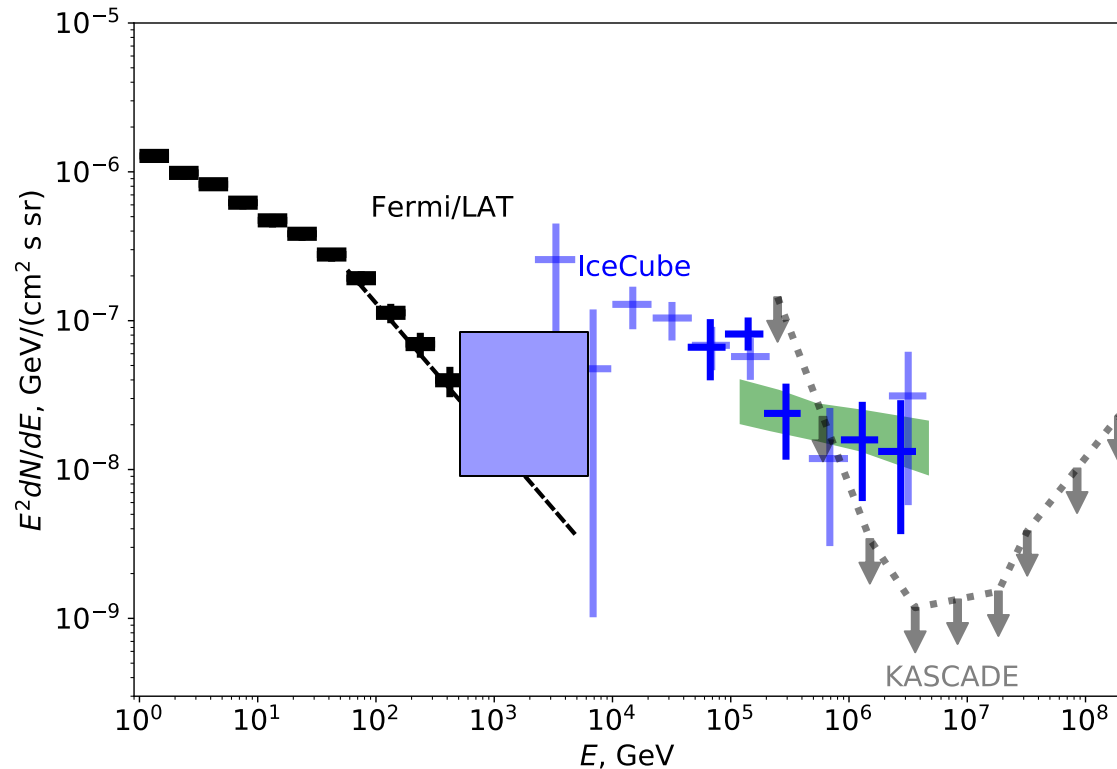


# IceCube + Fermi LAT Galactic plane



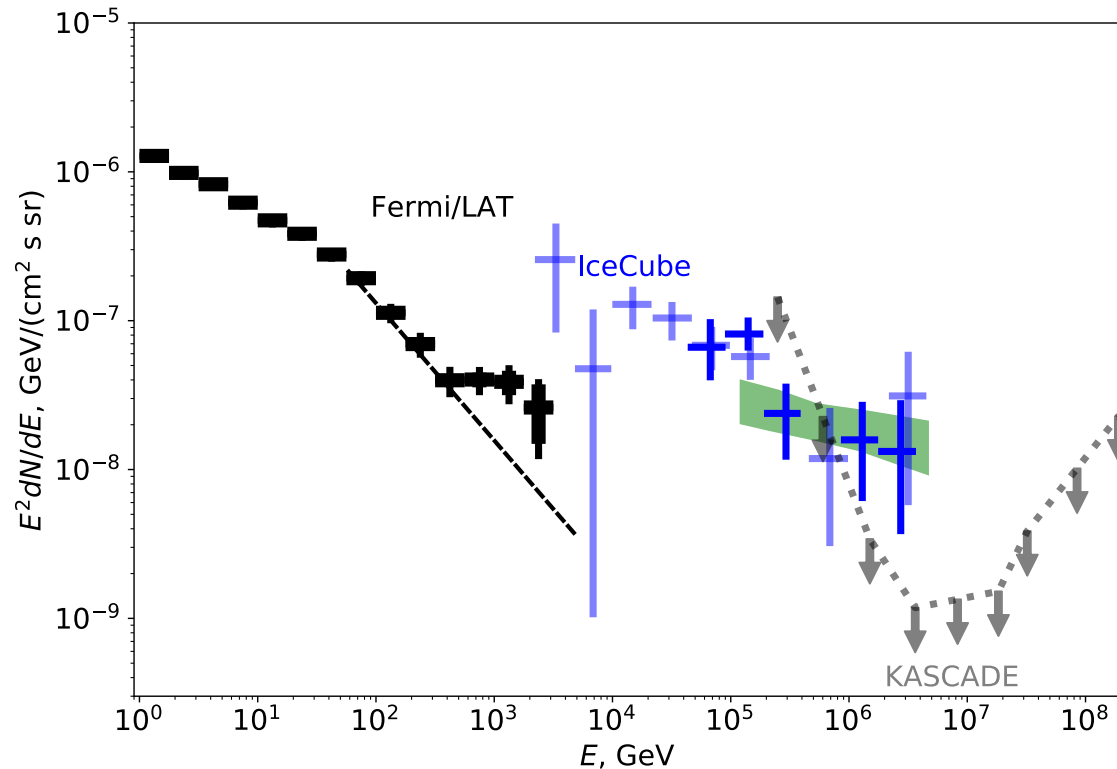
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

# IceCube + Fermi LAT high galactic latitude $|b| > 20^\circ$



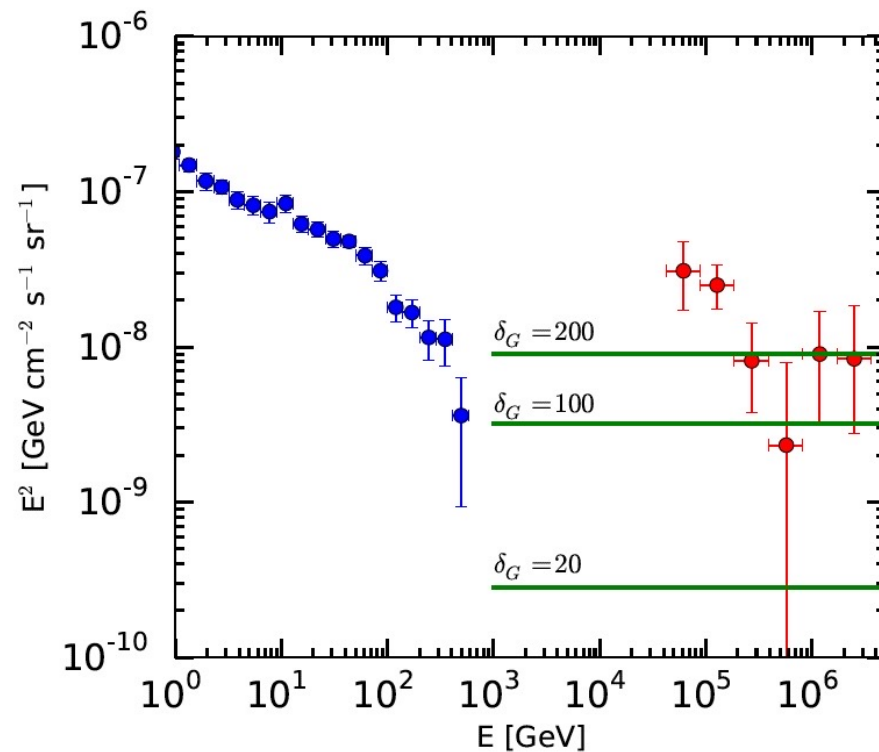
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

# IceCube + Fermi LAT high galactic latitude $|b| > 20^\circ$



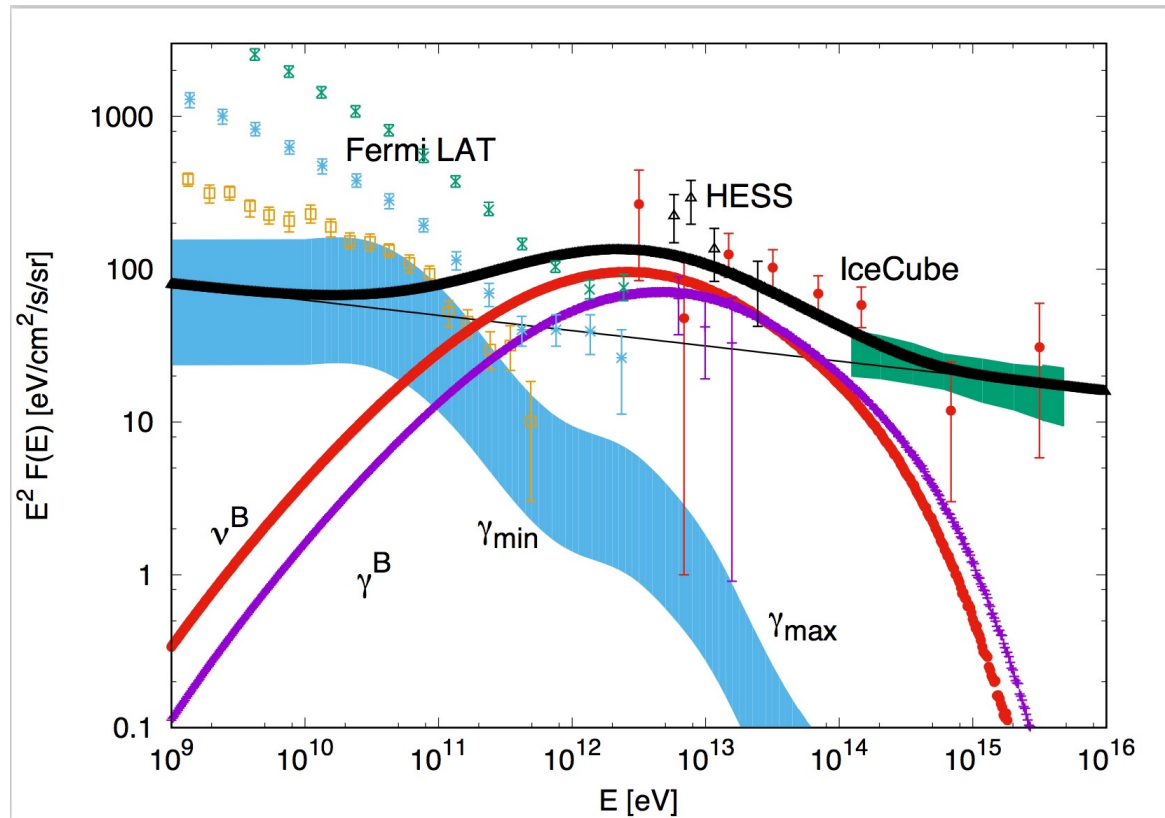
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

# Neutrinos from cosmic ray interactions in Galactic Halo



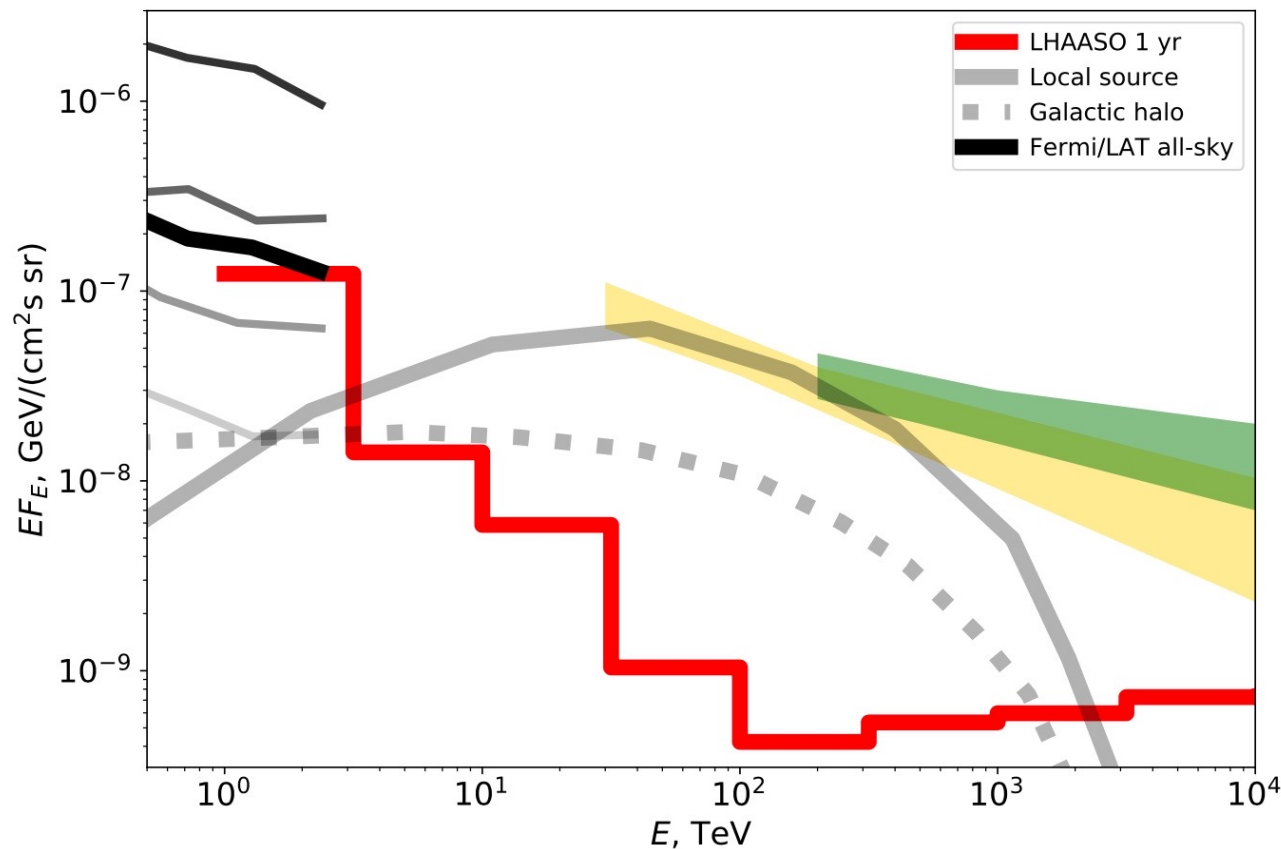
A.Taylor, S.Gabici and F.Aharonian, 1403.3206  
 P.Biasi and E.Amato, 1901.03609

# IceCube + Fermi LAT+HESS : local source



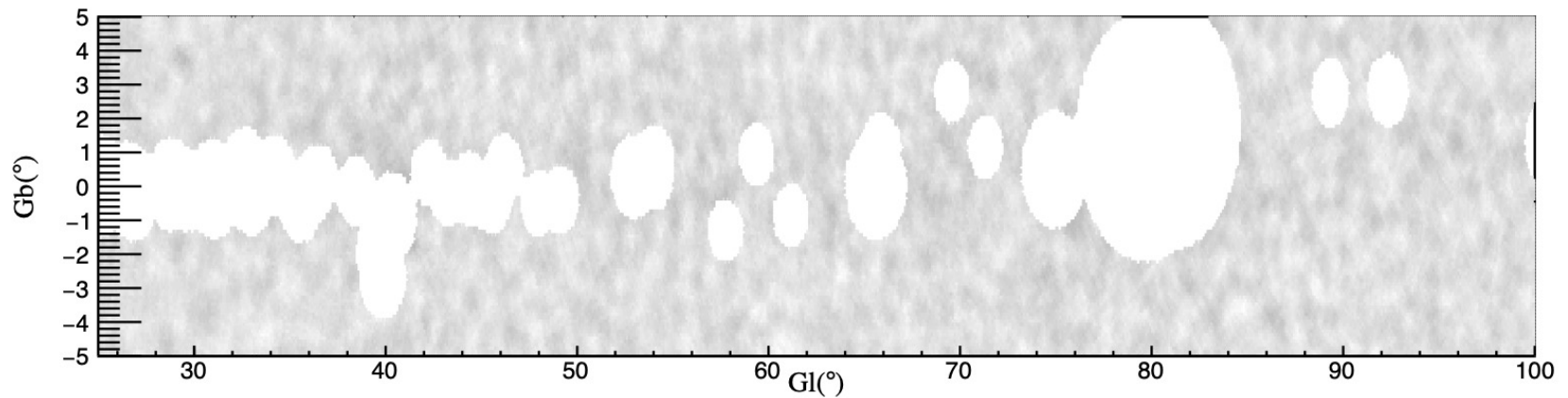
M.Bouyahiaoui, M.Kachelriess and D.S. , arXiv:2001.00768

# LHAASO sensitivity Local SuperBubble and Galactic Halo



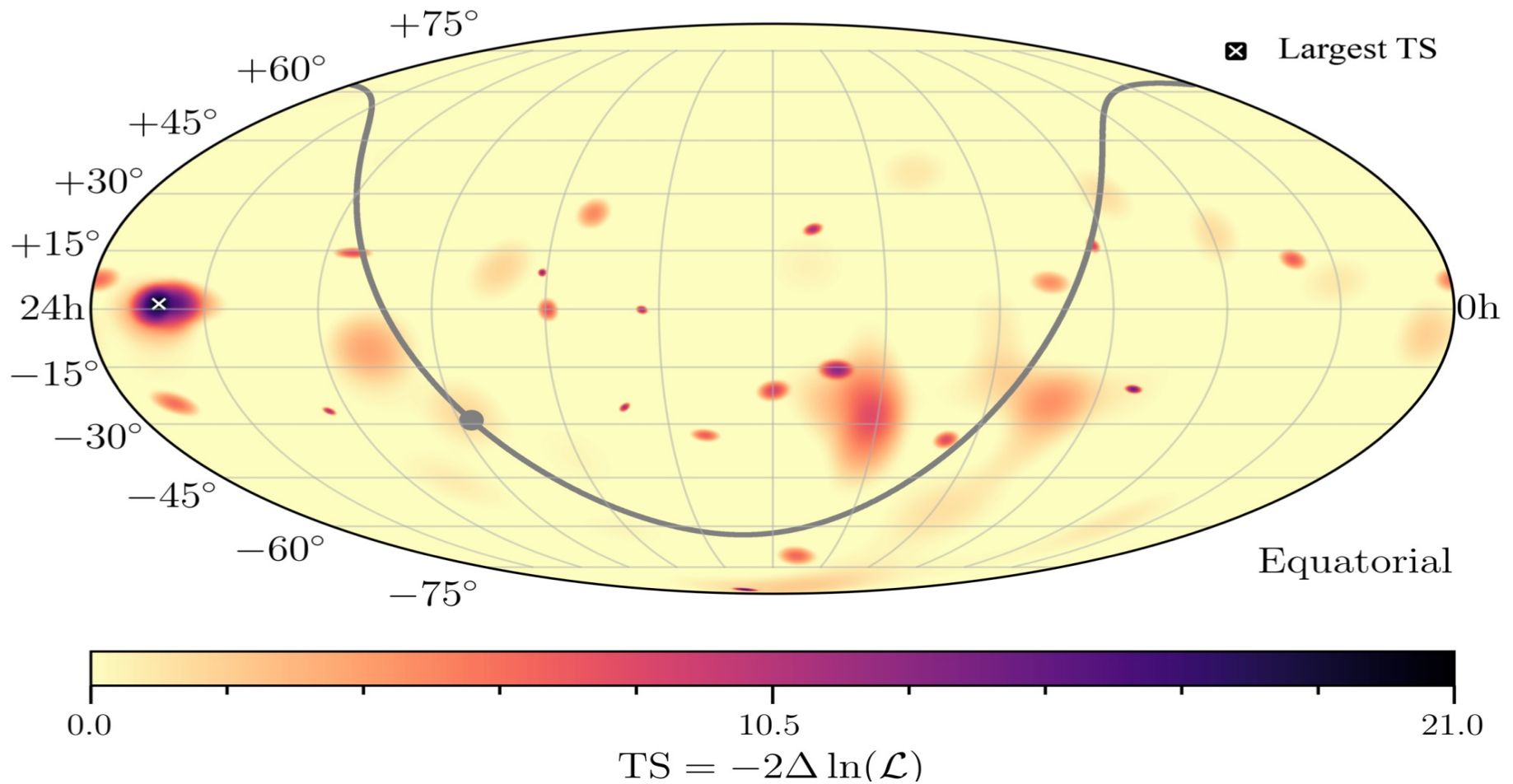
A.Neronov and D.S. , astro-ph/2001.11881

# LHAASO cut sources



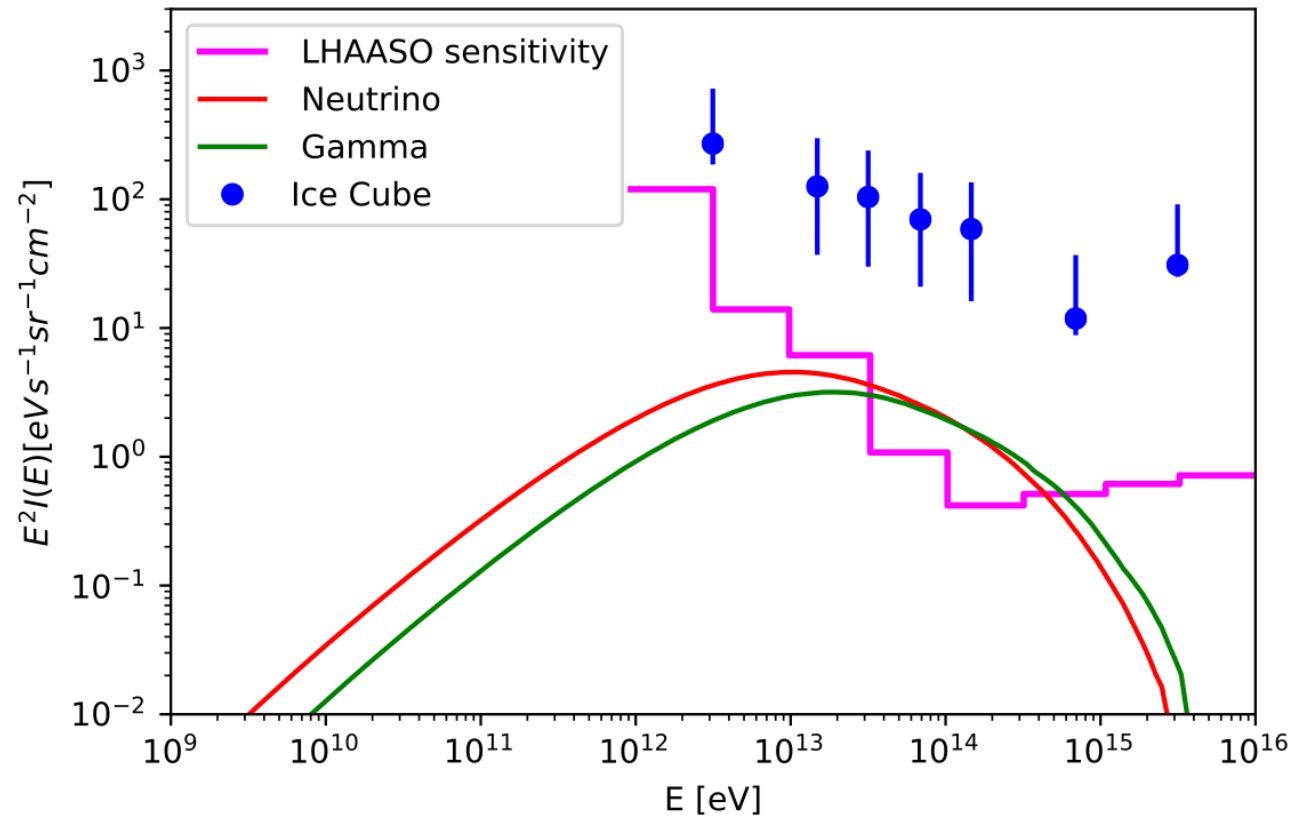


# Sky map HESE 7.5 years



IceCube, [astro-ph/2011.03545](https://arxiv.org/abs/astro-ph/2011.03545)

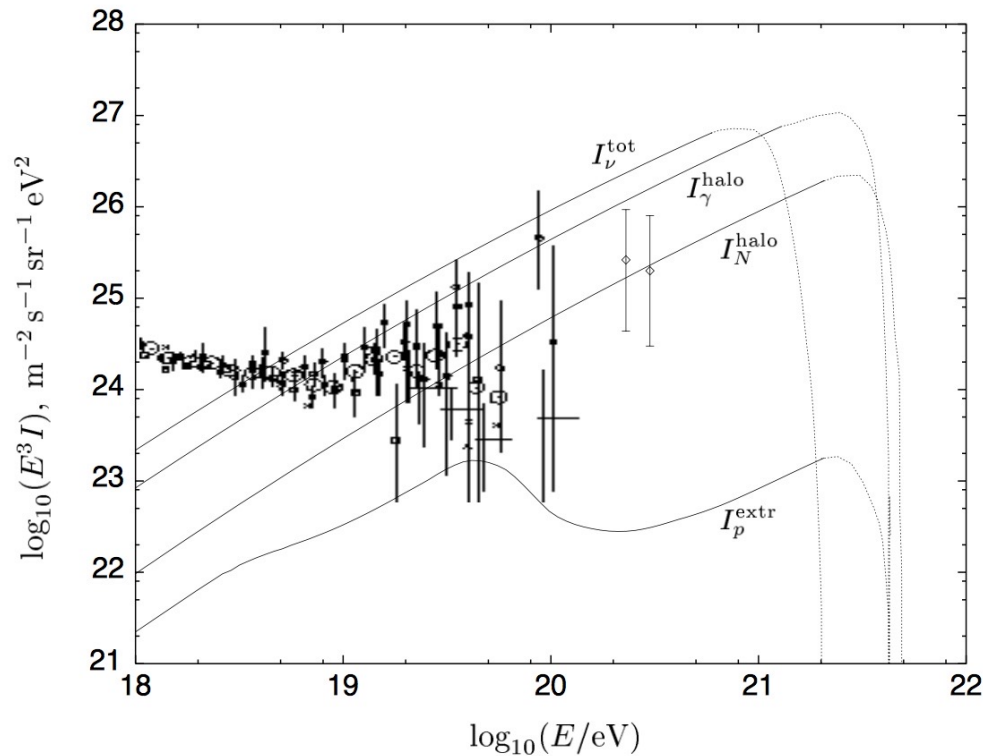
# Cygnus loop neutrinos



M. Bouyahiaoui, M. Kachelriess, and. D.S. , astro-ph/2105.13378

# Super-Heavy Dark Matter

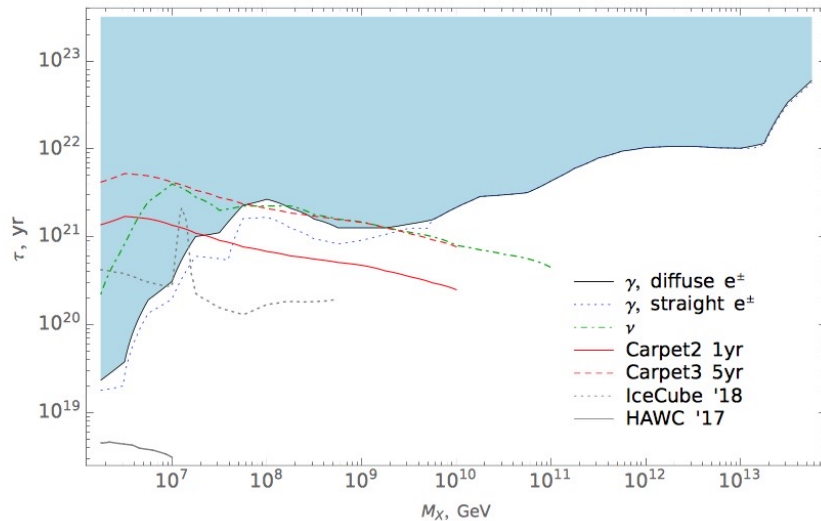
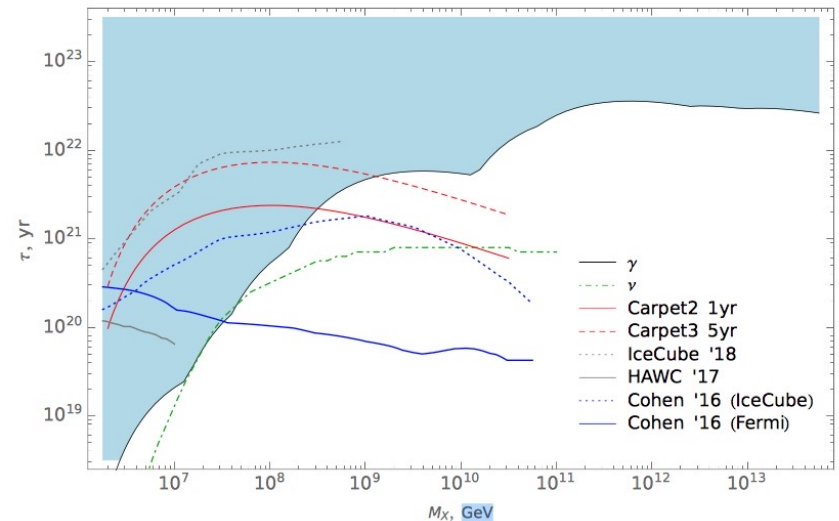
# For SHDM galactic flux dominates in neutrinos and gamma-rays



V.Berezinsky, M.Kachelriess and A.Vilenkin, 1997

V.Kuzmin and V.Rubakov, 1998

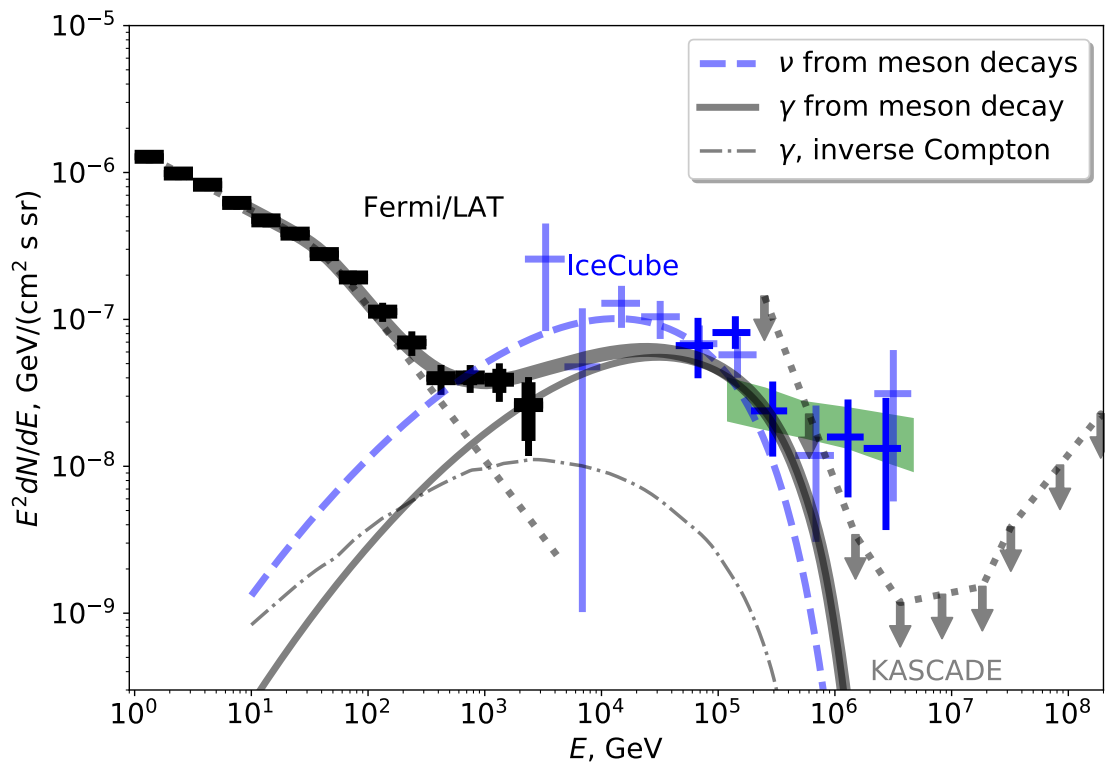
# Modern constraints on SHDM

(a)  $X \rightarrow \nu\bar{\nu}$ (b)  $X \rightarrow q\bar{q}$ 

M. Kachelriess, O. E. Kalashev and M. Yu. Kuznetsov, 1805.04500

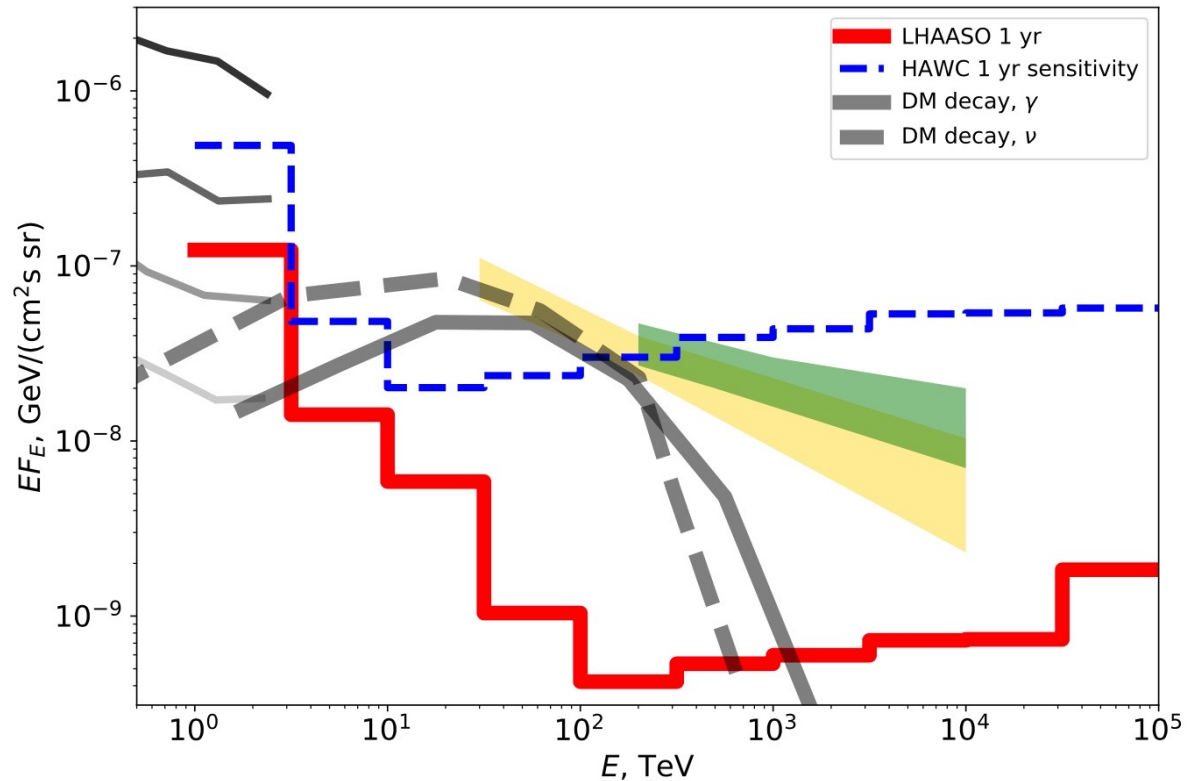
# IceCube + Fermi LAT

## Dark Matter $m=5$ PeV



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

## LHAASO sensitivity DM



A.Neronov and D.S. , astro-ph/2001.11881



# Summary

- *Atmospheric neutrinos dominate measured neutrino flux up to 100 TeV*
- *Neutrino astronomy started in 2013 with detection of  $E > 100$  TeV neutrinos*
- *New multi-km<sup>3</sup> detectors are needed to find first point sources*

# Summary

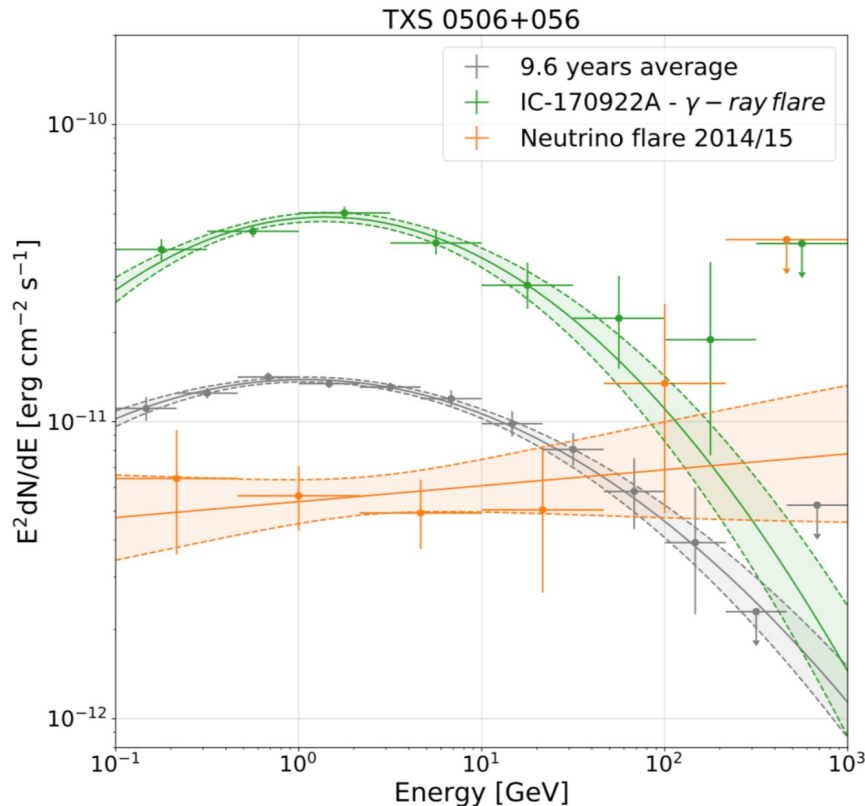
- *Astrophysical neutrino flux with power law  $1/E^{2.5}$  was surprise to theoreticians.*
- *Galactic to extragalactic transition is around 10 PeV in protons, i.e. one expects both contributions for 1 PeV neutrinos*
- *We have clear pp signal in Fermi gamma-rays all the way up to 10 TeV. This signal dominated by Galaxy contribution with  $1/E^{2.5}$ . This predicts unavoidable galactic neutrino flux*

# Summary

- *First diffuse neutrino flux measurements contain both galactic and extragalactic components. Evidence of Galactic component come in 4 years of IceCube data*
- *Galactic component give 50%-90% of flux at lower energies  $E < 100$  TeV*
- *Fermi at TeV energies have new Galactic component*
- *Extragalactic component can come from blazars, but models should be refined*

# SEMINAR

# TXT 0506+056



$$1 \text{ erg} = 0.624 \text{ TeV} = 6.24 \times 10^{11} \text{ eV}$$

$$E^2 F(E) = 6 \text{ eV/cm}^2/\text{s}$$

$$EF(E) = 6 \text{ (eV/E) /cm}^2/\text{s}$$

$$N = EF(E) * A * T$$

$$N(100 \text{ TeV}) = 6 * 10^{-14} * 10^{10} \text{ cm}^2 * 3 * 10^7 \text{ s} \text{ /km}^2/\text{yr}$$

$$N(100 \text{ TeV}) = 2 * 10^4 \text{ /km}^2/\text{yr}$$

$$N(100 \text{ TeV}) = (0.5-5) 2 * 10^4 \text{ /km}^2/\text{yr}$$

# Neutrino detection

Neutrino cross section:

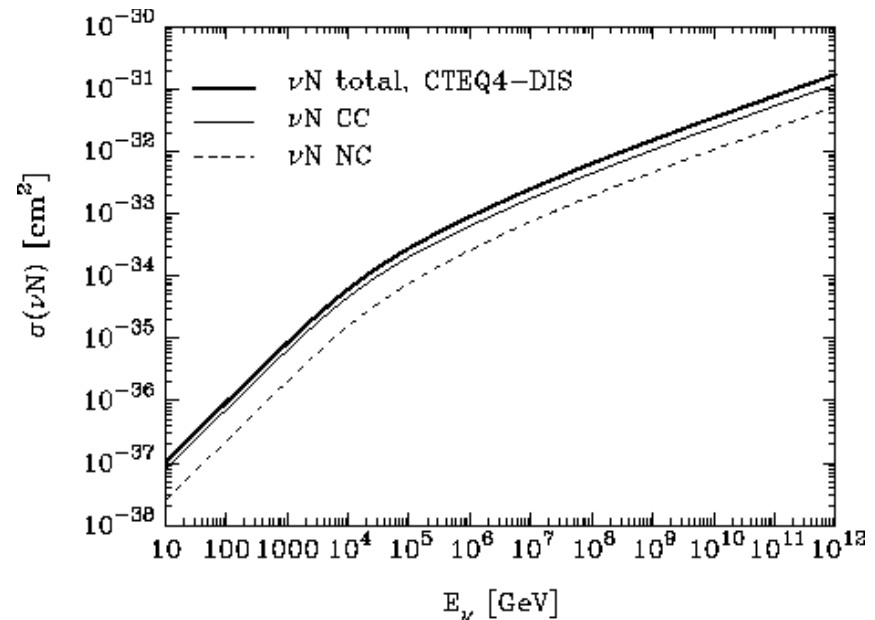
$$\sigma_{\nu p}(100 \text{ TeV}) = 3 \cdot 10^{-34} \text{ cm}^2$$

Optical depth: which fraction of neutrinos interact near/in detector:

$$\tau = \sigma n_{ICE} R$$

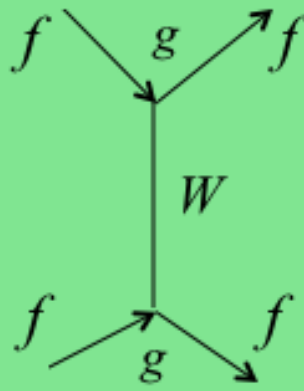
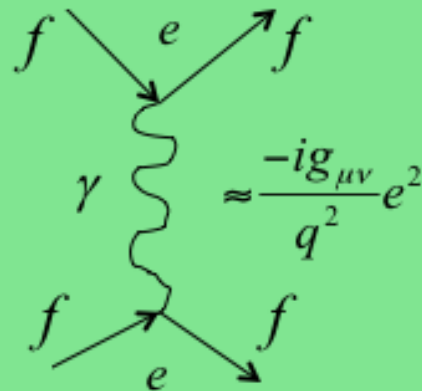
$$n_{ICE} \sim 1 \text{ g} / \text{cm}^3 = 10^{24} / \text{cm}^3$$

$$\tau = \sigma n_{ICE} R \sim 3 \cdot 10^{-5}$$



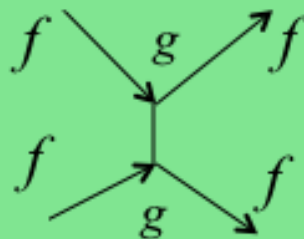
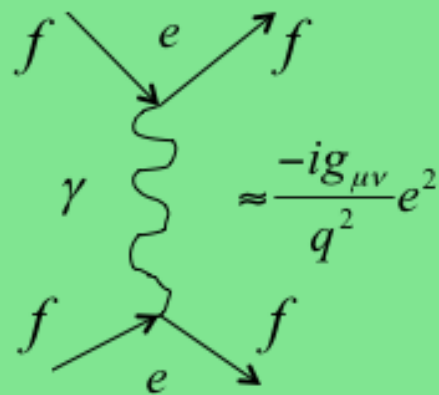
Electromagnetic

Weak



High Energy Matrix Element

$$\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M^2 c^2)}{q^2 - M^2 c^2} g^2$$



Low Energy Matrix Element

$$\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M^2 c^2)}{q^2 - M^2 c^2} g^2 \approx \frac{-ig_{\mu\nu}}{M^2 c^2} g^2 \approx G_F^2$$

# Neutrino flux from sources of gamma-rays

Neutrino cross section:

$$\sigma_{\nu p}(100 \text{ TeV}) = 3 \cdot 10^{-34} \text{ cm}^2$$

Which fraction of neutrinos  
interact near/in detector:

$$\tau = \sigma n_{ICE} R \sim 3 \cdot 10^{-5}$$

Expected neutrino flux from pp reactions:

$$N_{\nu} \sim 0.6 / \text{km}^2 / \text{yr}$$

