Lecture 3: Astrophysical neutrinos

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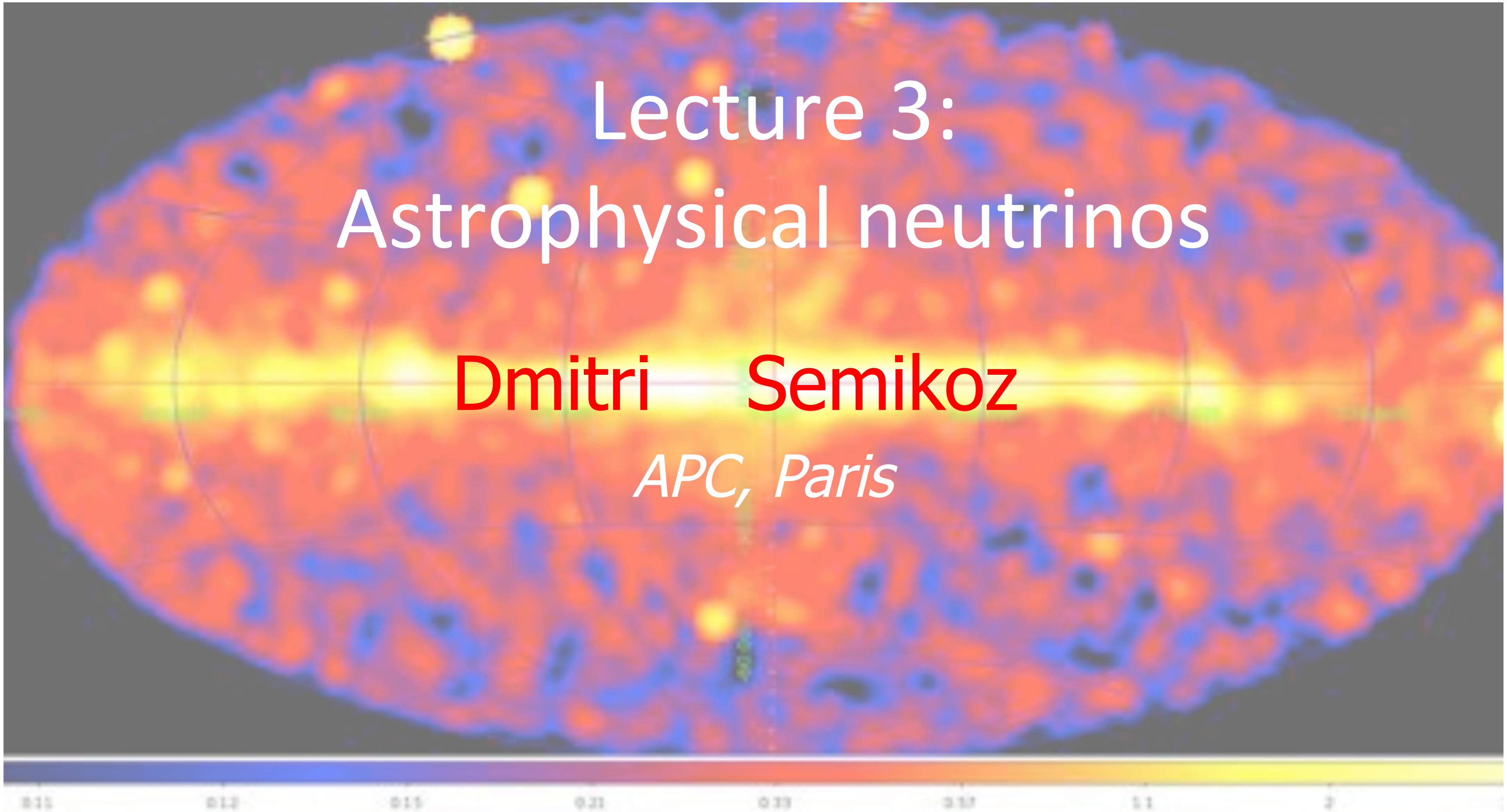


Overview:

- *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 conterpart 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:

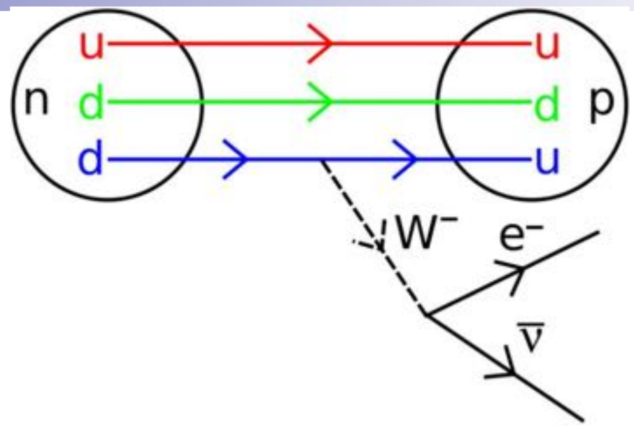
Q	L(e) = +1	L(μ) = +1	L(τ) = +1
0	ν_e	ν_μ	ν_τ
-1	e^-	μ^-	τ^-

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

…and the relevant anti-leptons. For instance:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

Fermi Theory of the Beta Decay

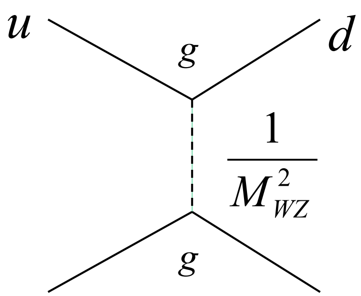


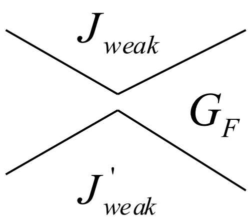
$$A(Z,N) \to A(Z+1,N-1) + e^- + \overline{\nu}_e$$

$$n \to p + e^- + \overline{\nu}_e$$

$$d \to u + e^- + \overline{\nu}_e$$

At the fundamental (constituents) level





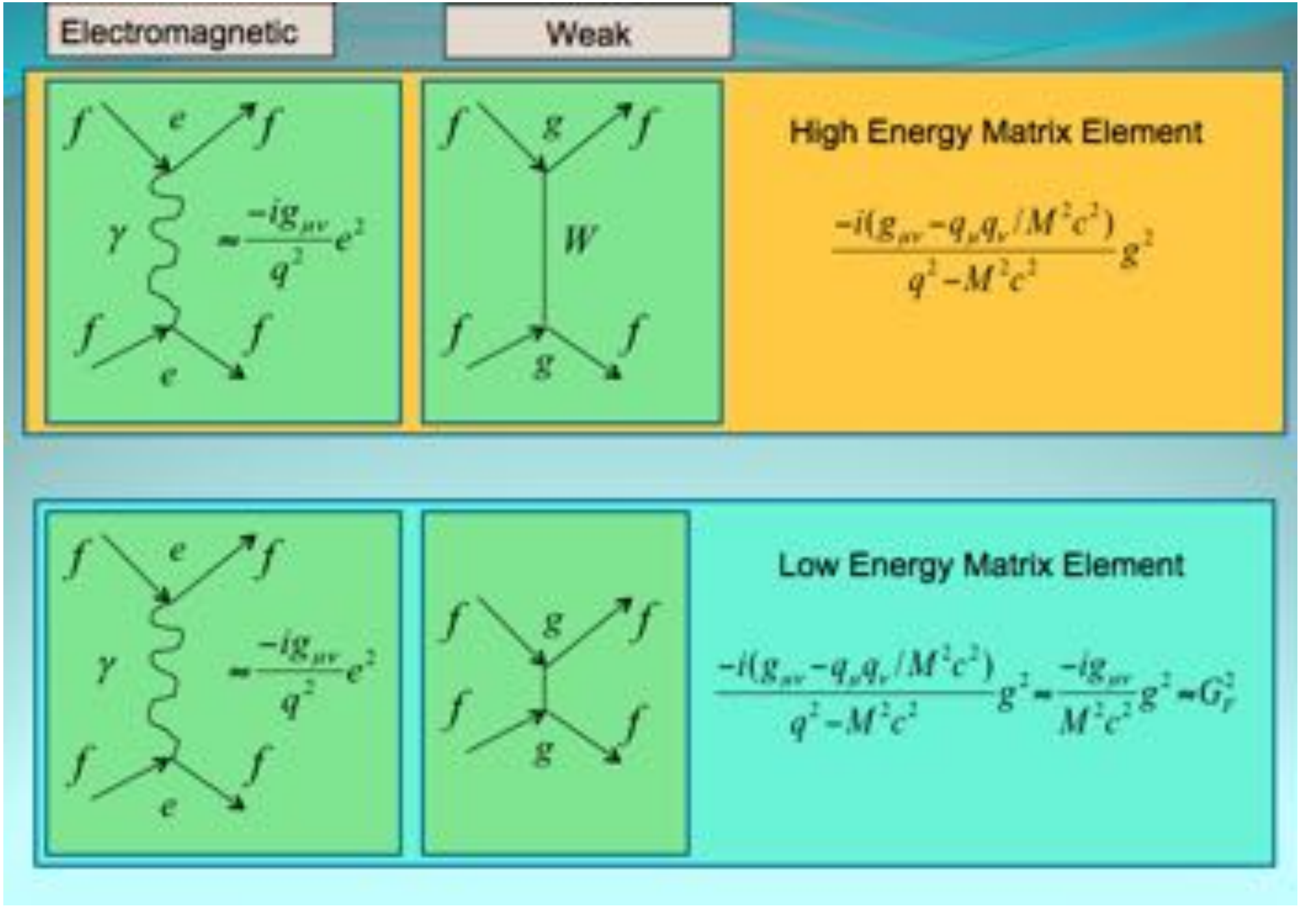
$$L_{Fermi} \approx G_F\, J^{\mu} J'^{+}_{\mu} = \frac{g^2}{M_W^2} J^{\mu} J'^{+}_{\mu}$$

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

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

$\left|M\right|^2$ Integration over spins and angles

E_0 Energy of the final state


Electromagnetic
Weak
High Energy Matrix Element
$\frac{-i(g_{\mu\nu}-q_\mu q_\nu/M^2c^2)}{q^2-M^2c^2}g^2$
$\approx\frac{-ig_{\mu\nu}}{q^2}e^2$
Low Energy Matrix Element
$\frac{-i(g_{\mu\nu}-q_\mu q_\nu/M^2c^2)}{q^2-M^2c^2}g^2\approx\frac{-ig_{\mu\nu}}{M^2c^2}g^2\approx G_F^2$
W
γ

Coupling constants : Eelectromagnetic and Weak

A reminder :

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

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

$$\frac{G_F}{(\hbar c)^3} = 1.2\times10^{-5}\ GeV^{-2}$$

$$G_F = 9.1\times10^{-5}\ MeV \cdot fm^3$$

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

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

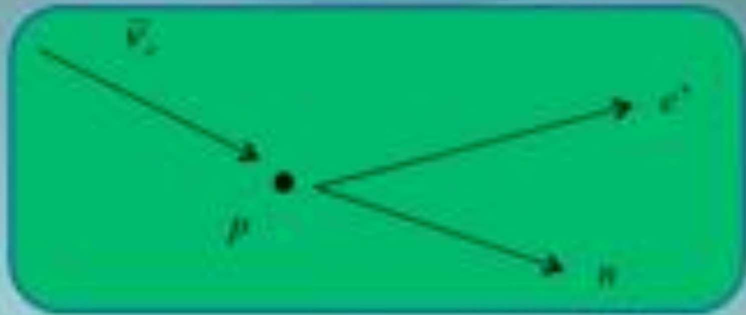
The Weak Coupling constant is actually bigger than the fine structure constant.

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

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

Inverse Beta Decay

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



$$W = \frac{2\pi}{\hbar} G_F^2 |M|^2 \frac{dN}{dE_0} \quad \Rightarrow \quad \sigma = \frac{1}{\pi} G_F^2 |M|^2 p^2$$

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

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

$|M|^2 = 4$

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

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 β decay of radioactive nuclei produced by ^{235}U and ^{238}U fission. And their flux is very high.

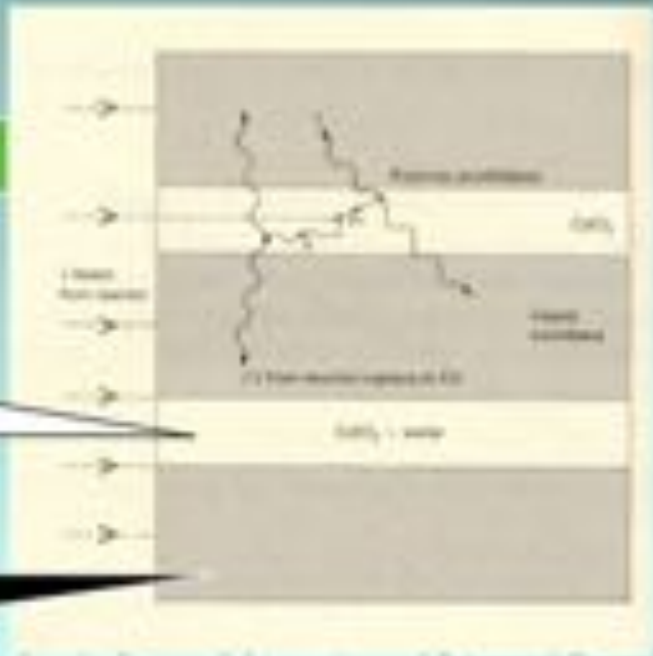
1. The antineutrino reacts with a proton and forms n and e^+

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

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)



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

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

1956: Reines and Cowan at the Savannah nuclear power reactor

Where do Neutrinos Appear in Nature?

✓ Particle-Accelerators

Cosmic Big Bang
(today 330 ν/cm³)
Indirect BBN, CMBR

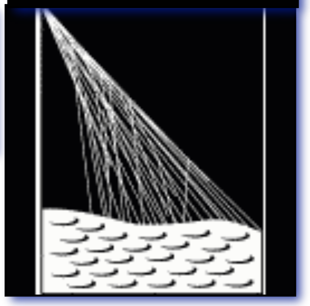
✓ Nuclear Reactors

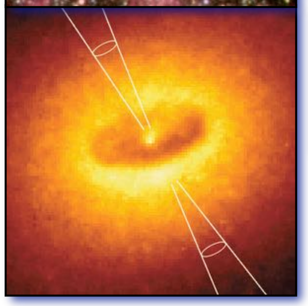
Sun ✓

Earth Crust
(Natural
✓ Radioactivity)

Supernovae
(Stellar Collapse)
SN 1987A ✓

✓ Earth Atmosphere
(Low energy Cosmic Rays)



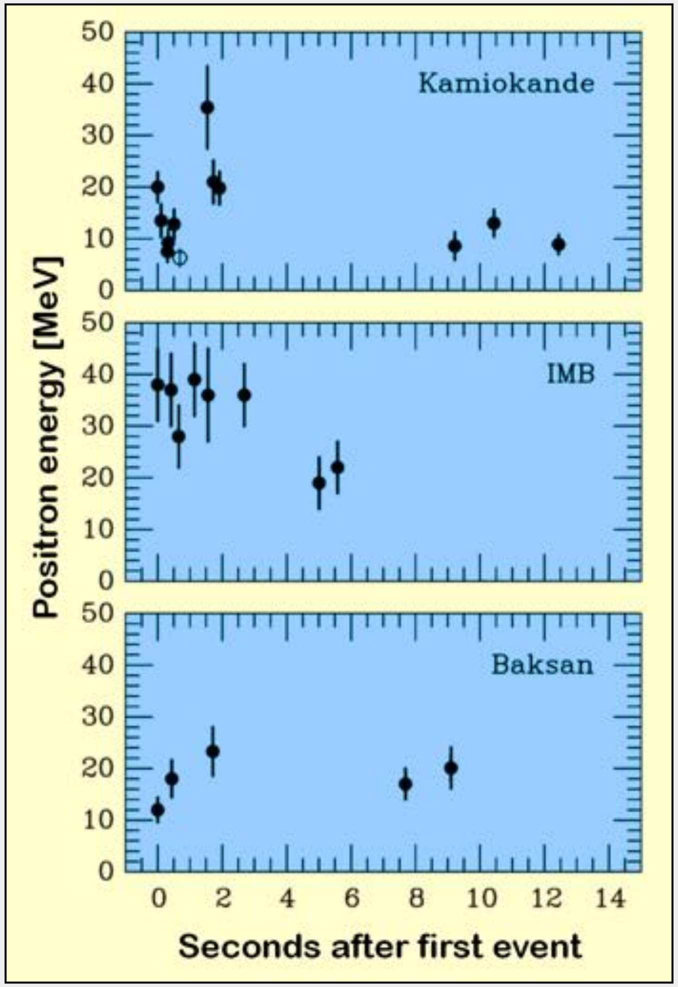


Astrophysical
Accelerators 2013


Sanduleak -69 202


Supernova 1987A
23 February 1987
Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino Signal from SN 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

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

Within clock uncertainties, signals are contemporaneous

Pion production

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

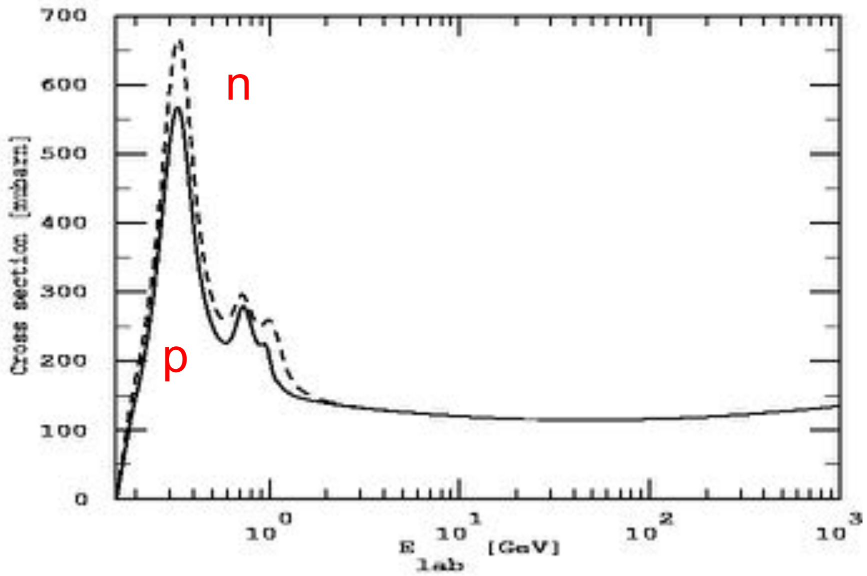
$$N + A_b \Rightarrow N' + \sum \pi^i$$

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

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

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

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

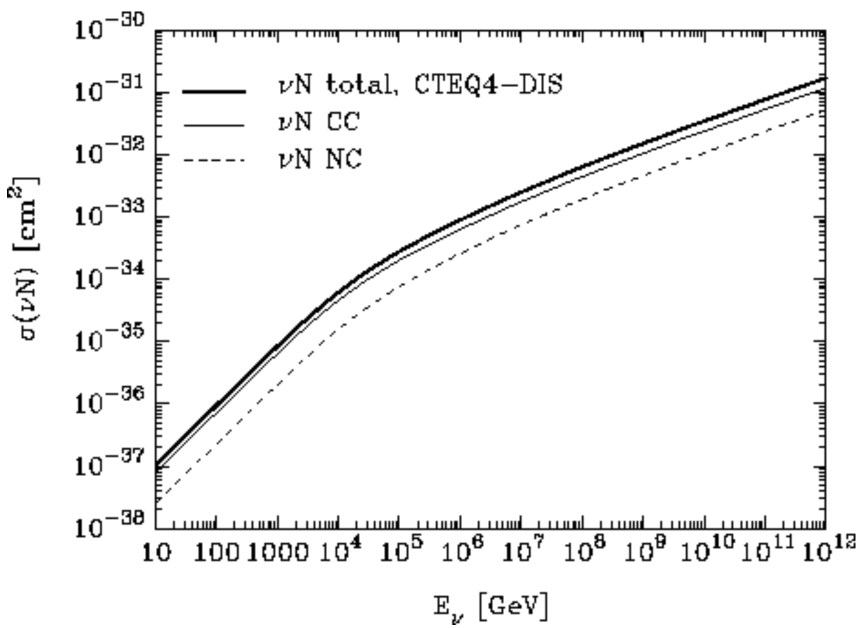


Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

Neutrino flux from sources of gamma-rays

Neutrino cross section:

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



Which fraction of neutrinos interact near/in detector:

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

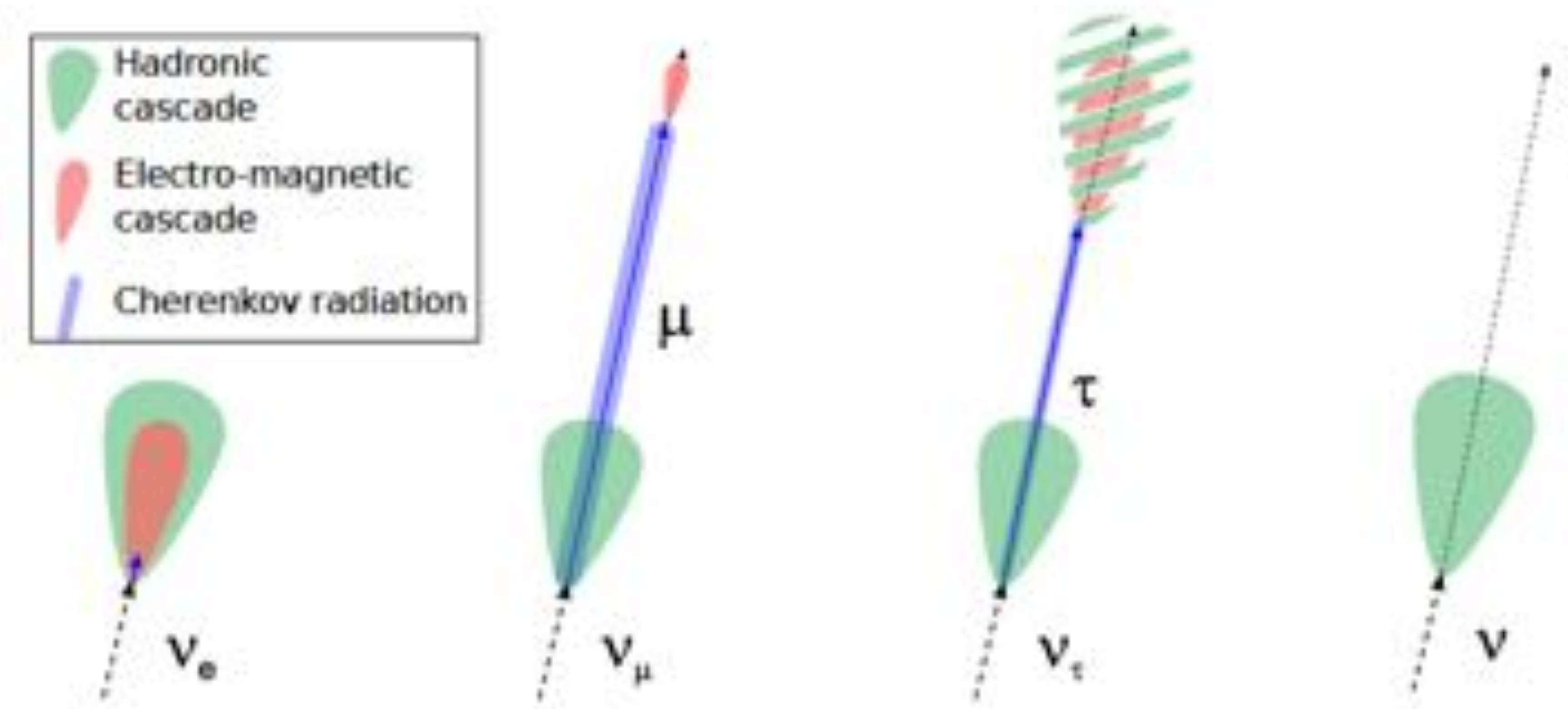
Expected neutrino flux from pp reactions:

$$F_\nu \sim F_\gamma \sim 10^{-12} / cm^2 / s = 3 \cdot 10^5 / km^2 / yr$$

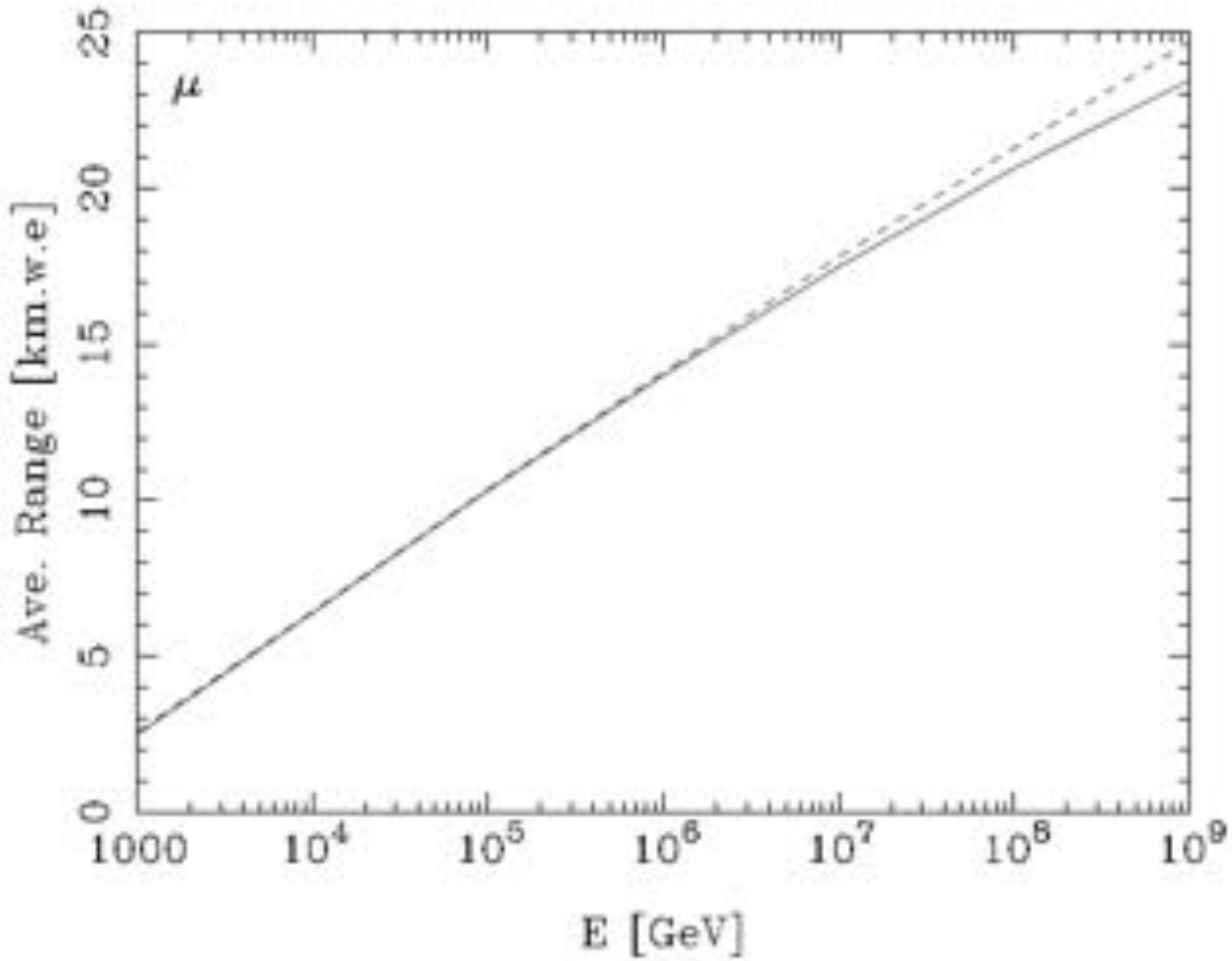
$$N_\nu \sim 10 (F_\gamma / 10^{-12} / cm^2 / s) / yr$$

This means few events per year

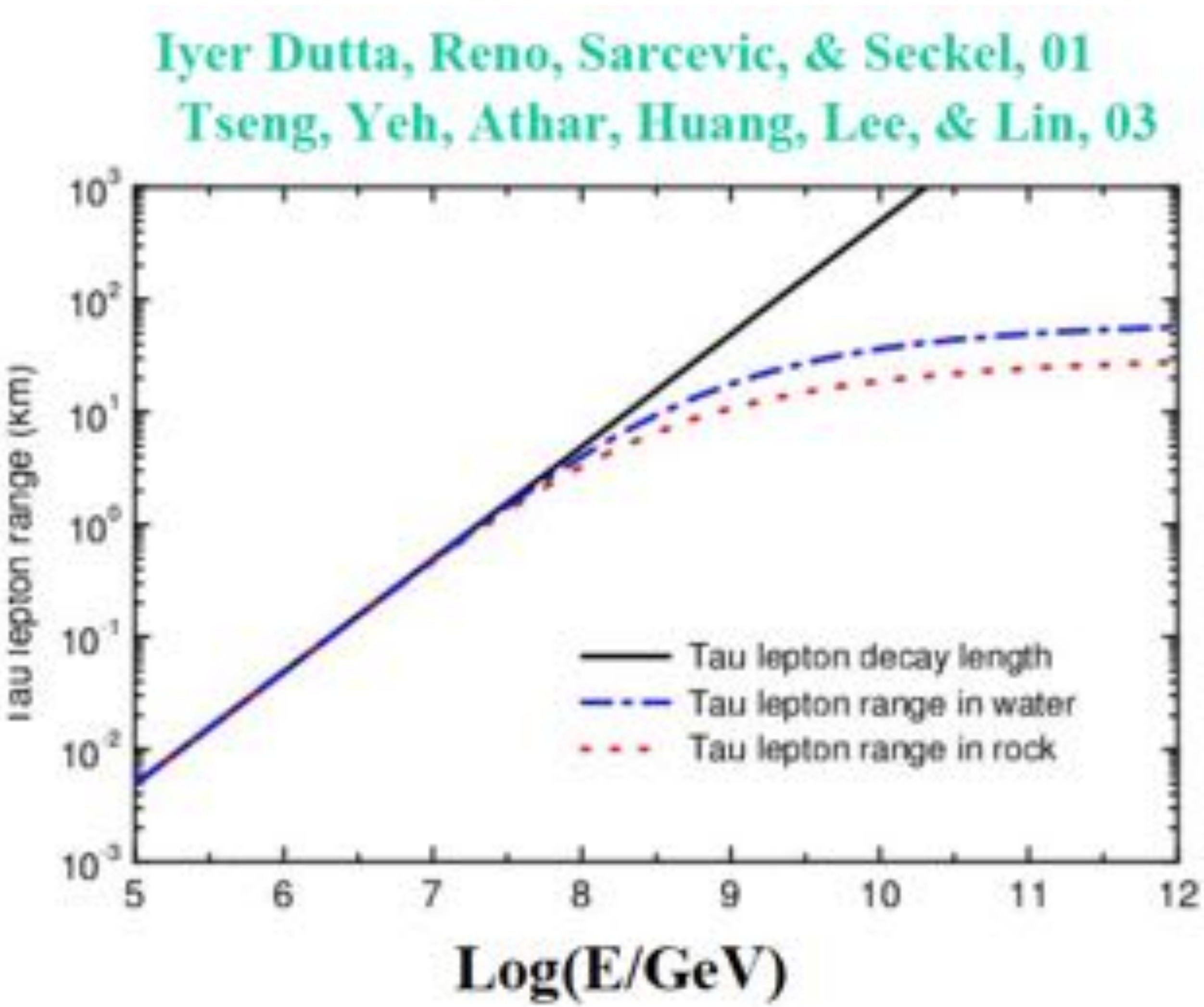
Detection of neutrino interactions



Muon losses

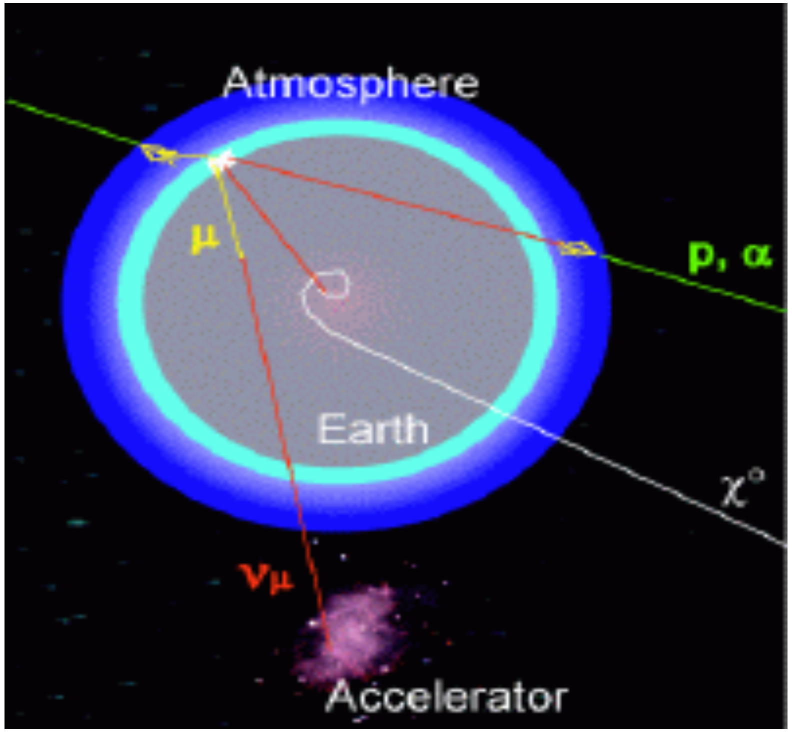


Tau energy losses



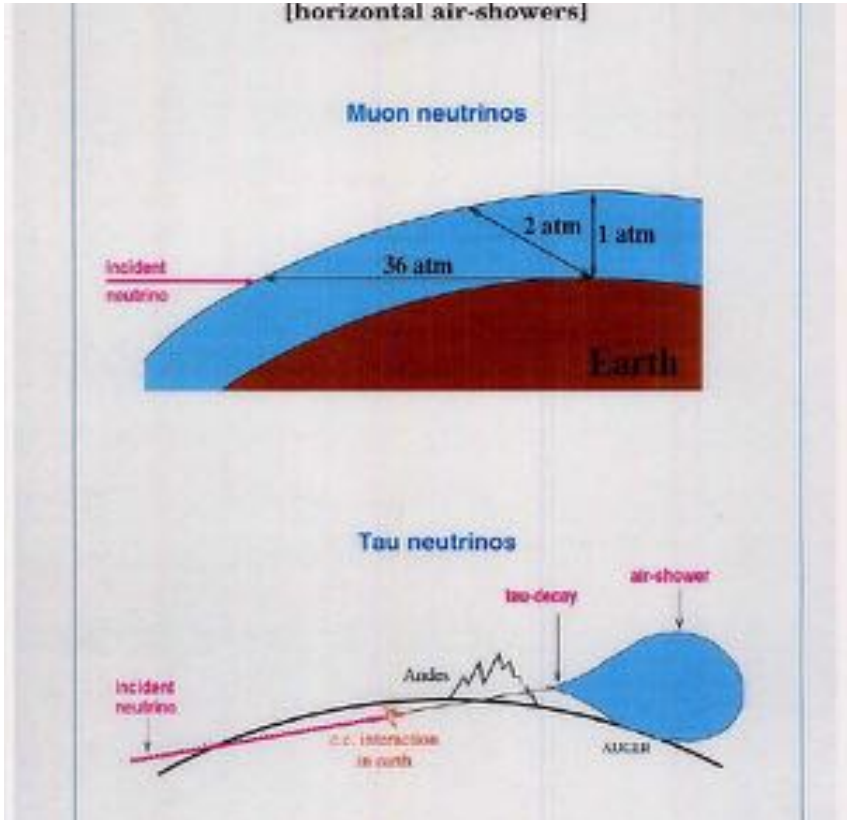
Experimental detection of $E<10^{17}$eV neutrinos

- 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 $E>10^{15}$eV
- Experiments: MACRO, Baikal, AMANDA, ANTARES, ICECUBE



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

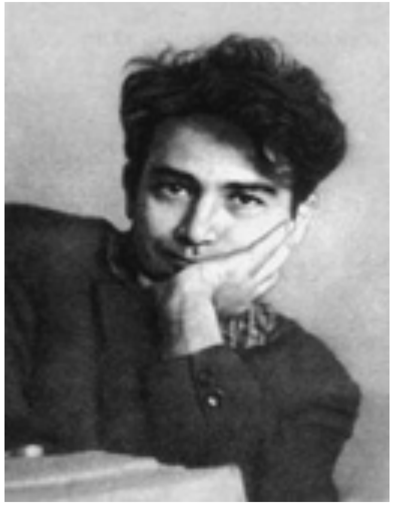
- Neutrinos are not primary UHECR
- Horizontal or up-going air showers – easy way to detect neutrinos
- Experiments: Fly's Eye, AGASA, HiRes,
- AUGER



Radio detection

Askaryan effect

In 1962 Gurgen Askaryan suggested that a particle travelling faster than the speed of light in a dense radiotransparent medium such as salt or 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.



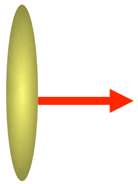
G.Askaryan was the first to note that the outer few metres of the Moon's surface, known as the regolith, would be a sufficiently transparent medium for detecting microwaves from the charge excess in particle showers.
The radio transparency of the regolith has since been confirmed by the Apollo missions.

$\nu_e + n \rightarrow p + e^-$

$e^- \rightarrow$ ... cascade

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

⇒ relativist. pancake
~ 1cm thick, ∅ ~10cm

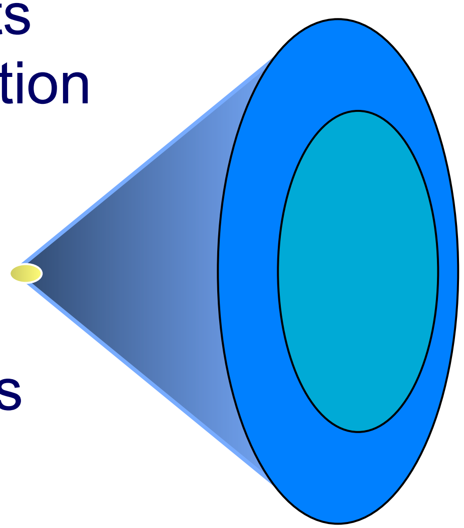


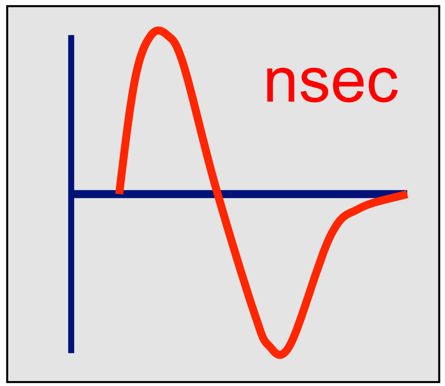
⇒ for λ >> 10 cm (radio)
coherence

⇒ each particle emits Cherenkov radiation

⇒ C-signal ~ E^2

⇒ C signal is resultant of overlapping Cherenkov cones

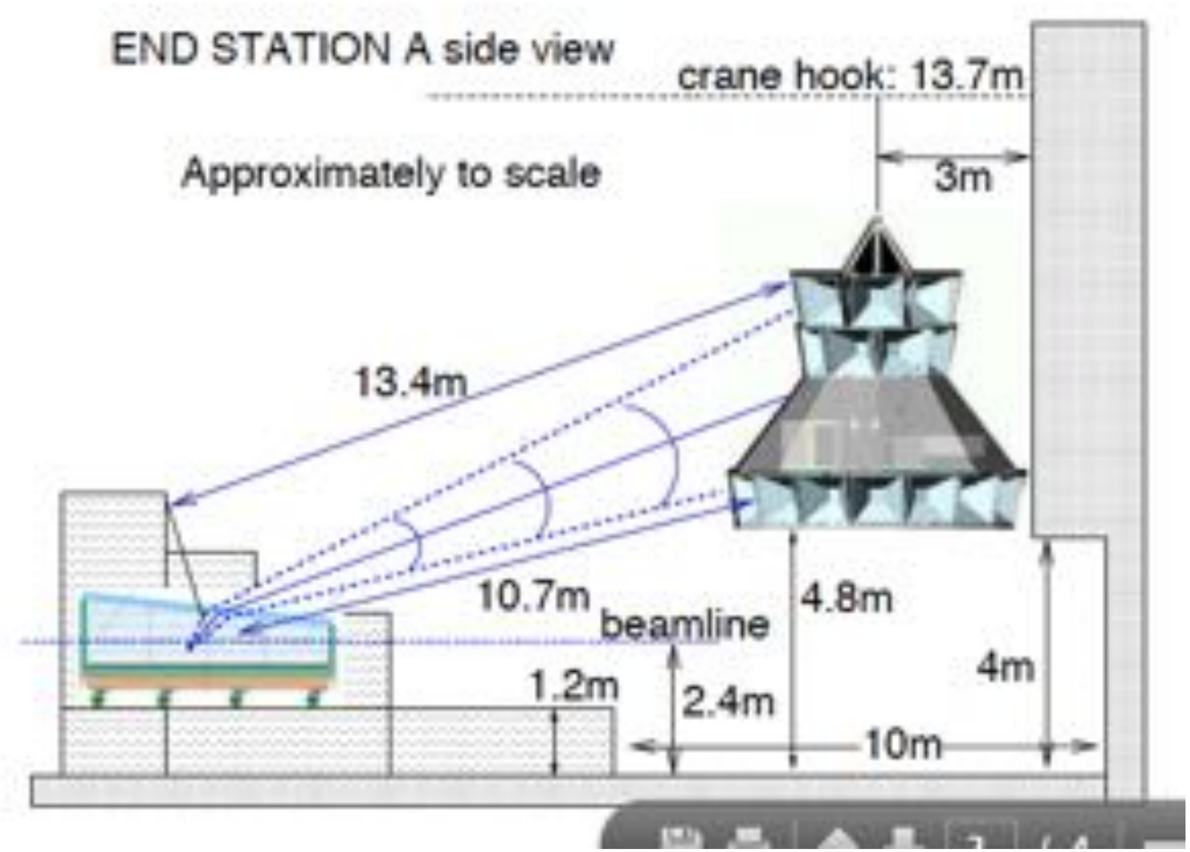




Experiments:
GLUE, RICE, FORTE, ANITA

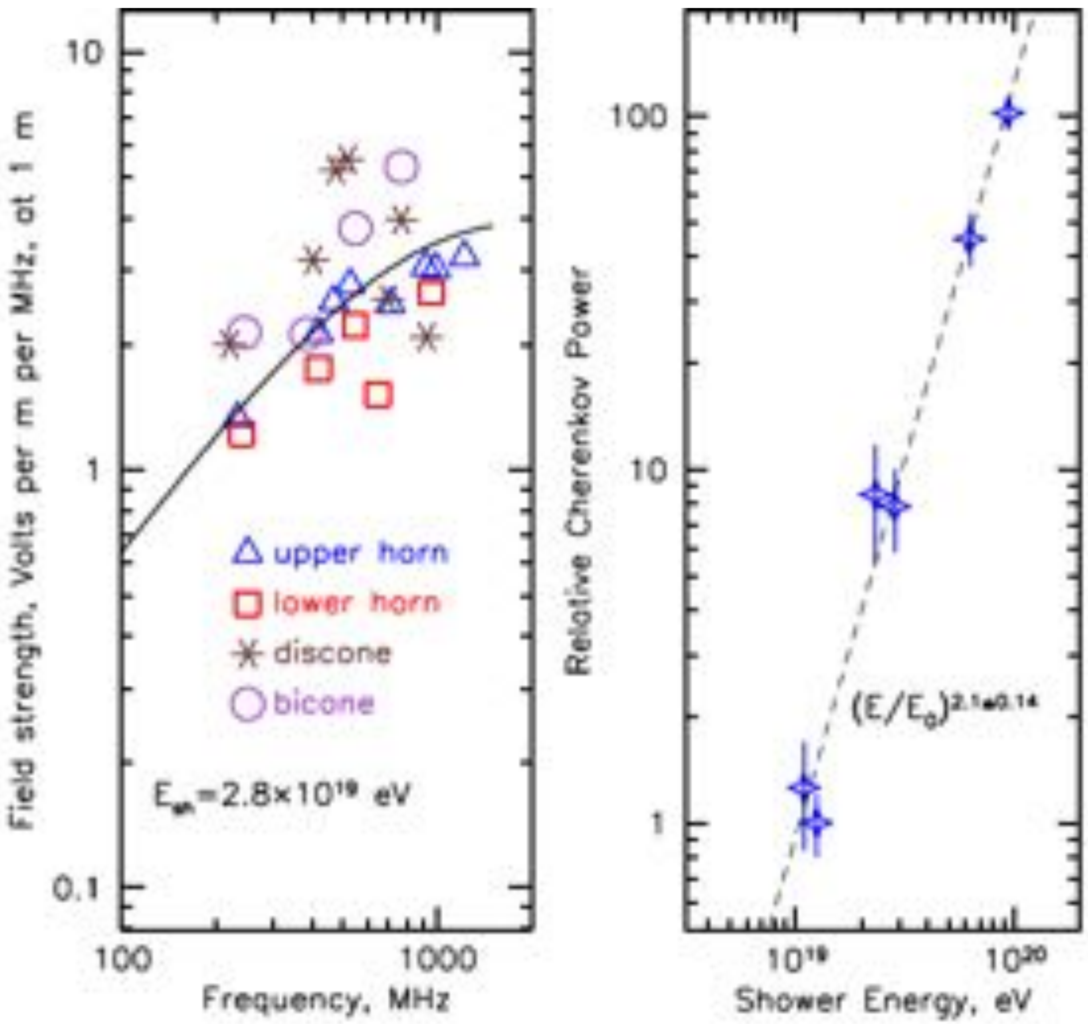
Threshold > 10^{16} eV

SLAC 2006: observation of Askarvan effect



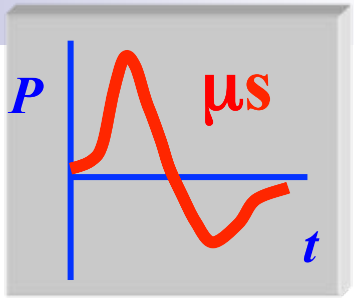
SLAC 2006

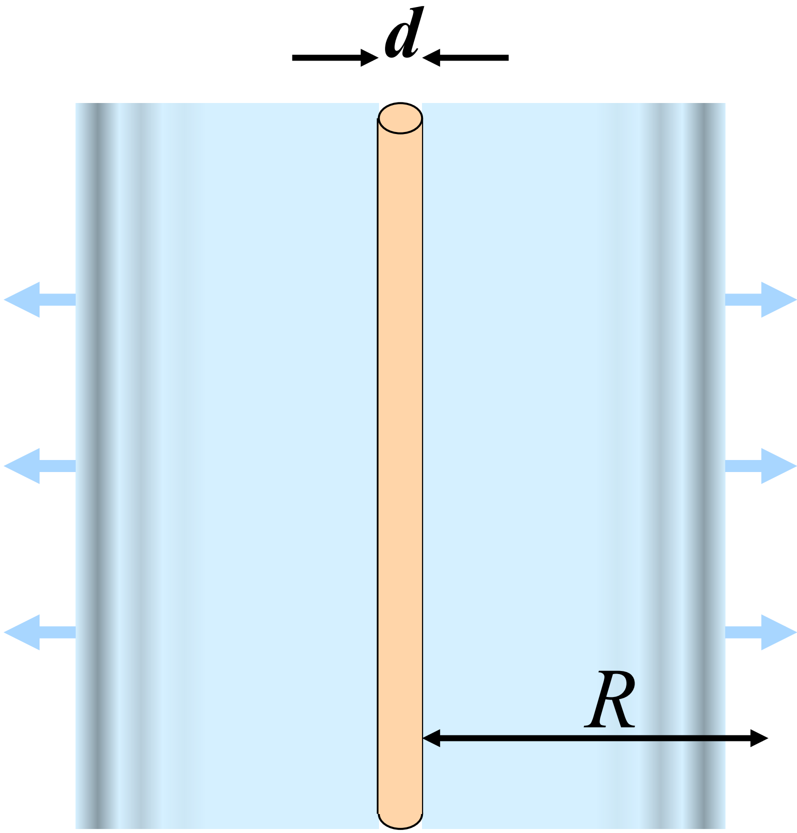
SLAC 2006


Field strength, Volts per m per MHz, at 1 m
Frequency, MHz
upper horn
lower horn
discone
bicone
E_{sh}=2.8×10^{19} eV
Relative Cherenkov Power
Shower Energy, eV
$(E/E_0)^{2.1±0.14}$

Acoustic detection

Particle cascade → ionization
→ heat
→ pressure wave





Maximum of emission at ~ 20 kHz

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

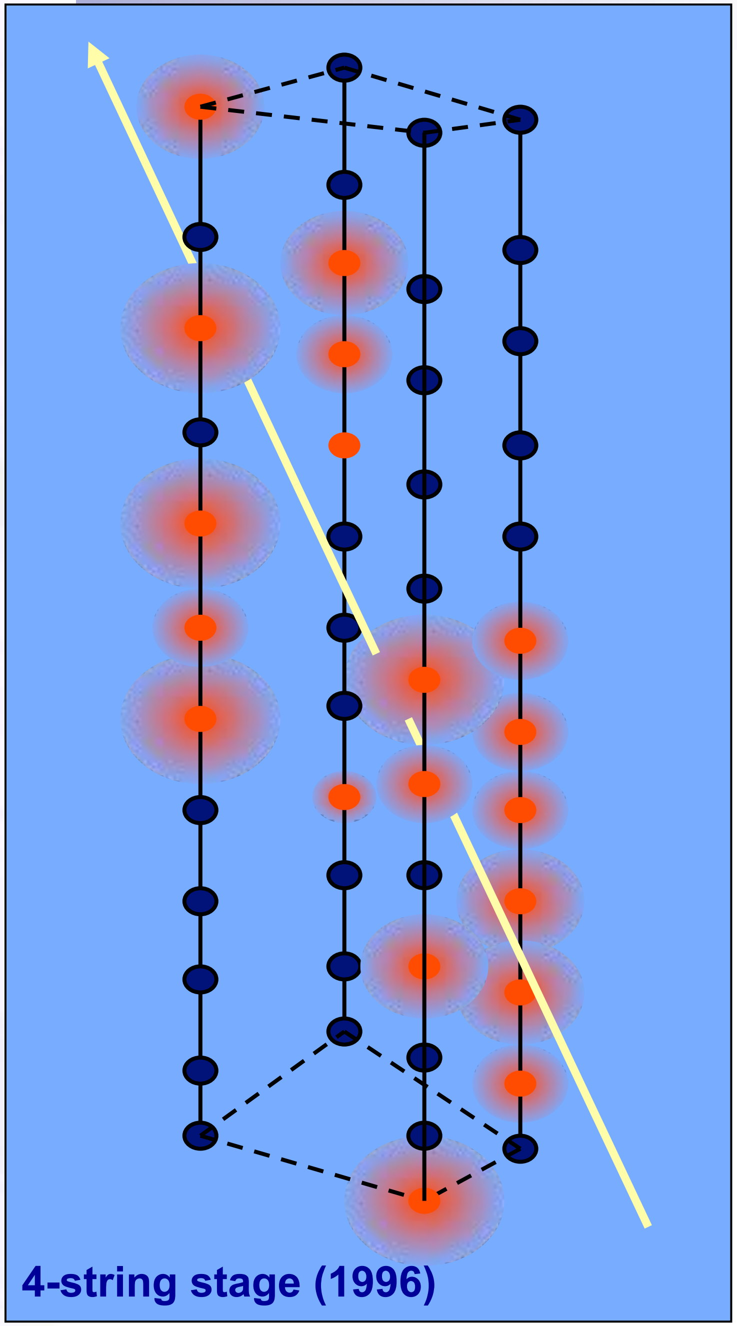
→ given a large initial signal, huge detection volumes can be achieved.

Threshold > 10^{16} eV

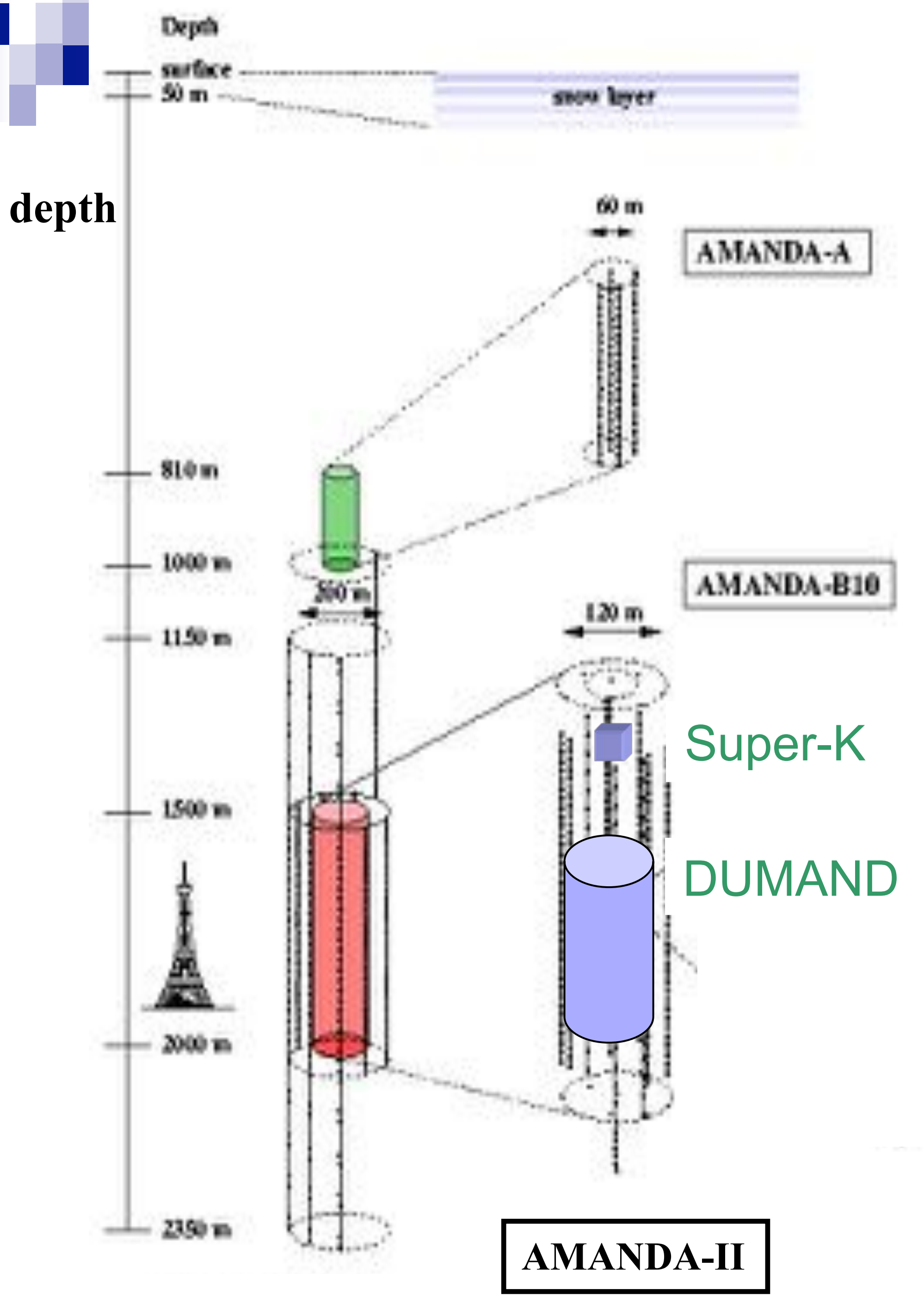
Historical experiments

Lake Baikal

First underwater telescope
First neutrinos underwater



AMANDA



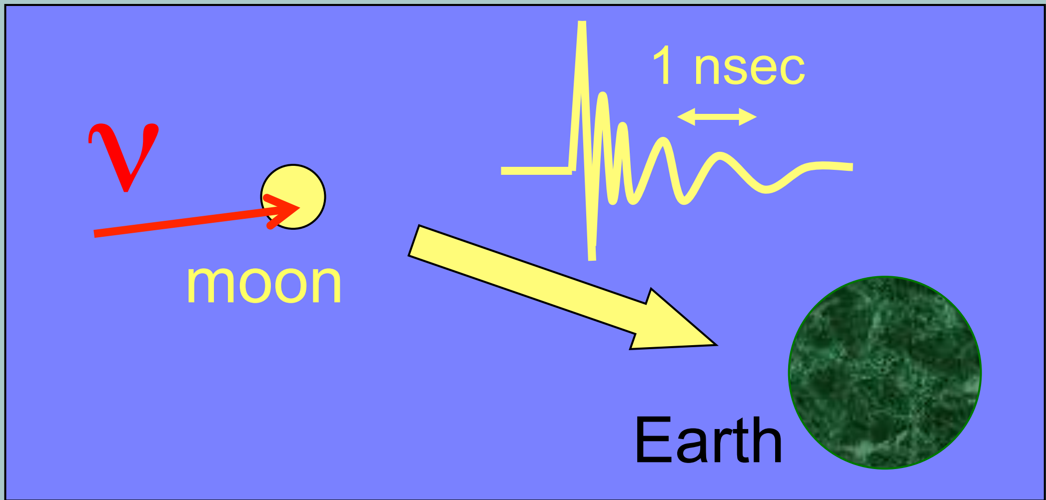
Amanda-II:
677 PMTs
at 19 strings

(1996-2000)

GLUE **G**oldstone **L**unar **U**ltra-high Energy Neutrino **E**xperiment

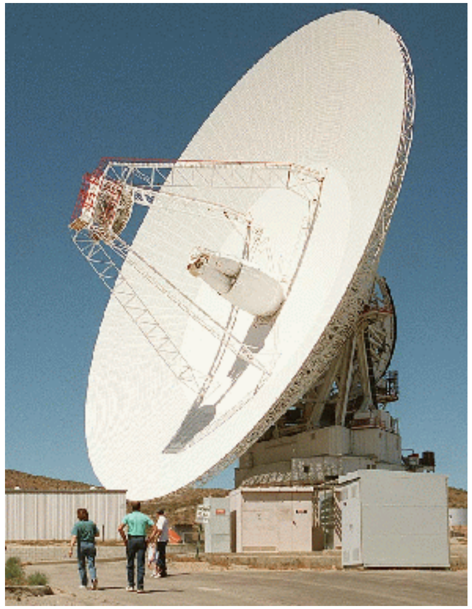
Lunar Radio Emissions from Interactions of ν and CR with $> 10^{19}$ eV

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



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

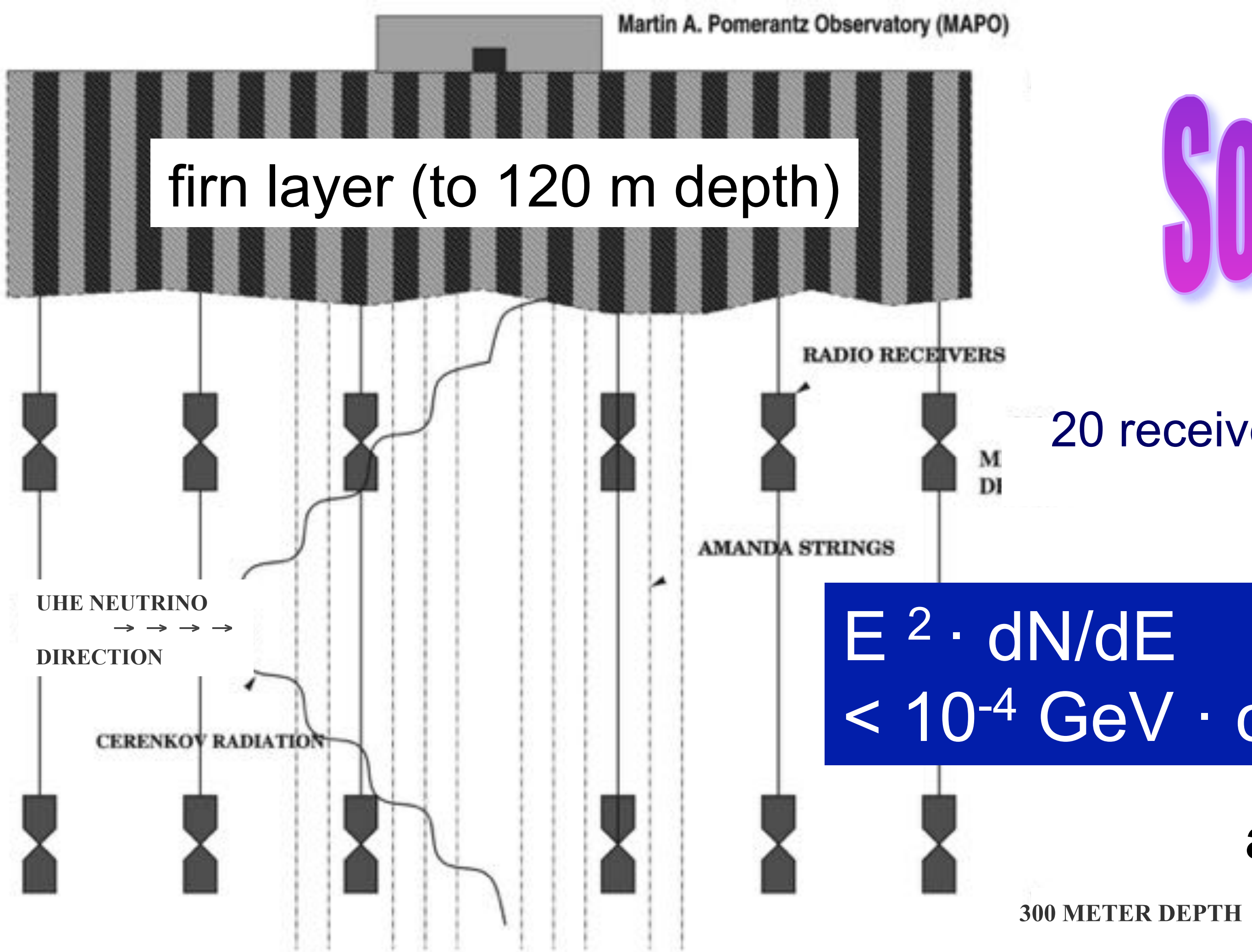
at 10^{20} eV



Effective target volume
~ antenna beam (0.3°)
× 10 m layer

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

RICE Radio Ice Cherenkov Experiment



South Pole

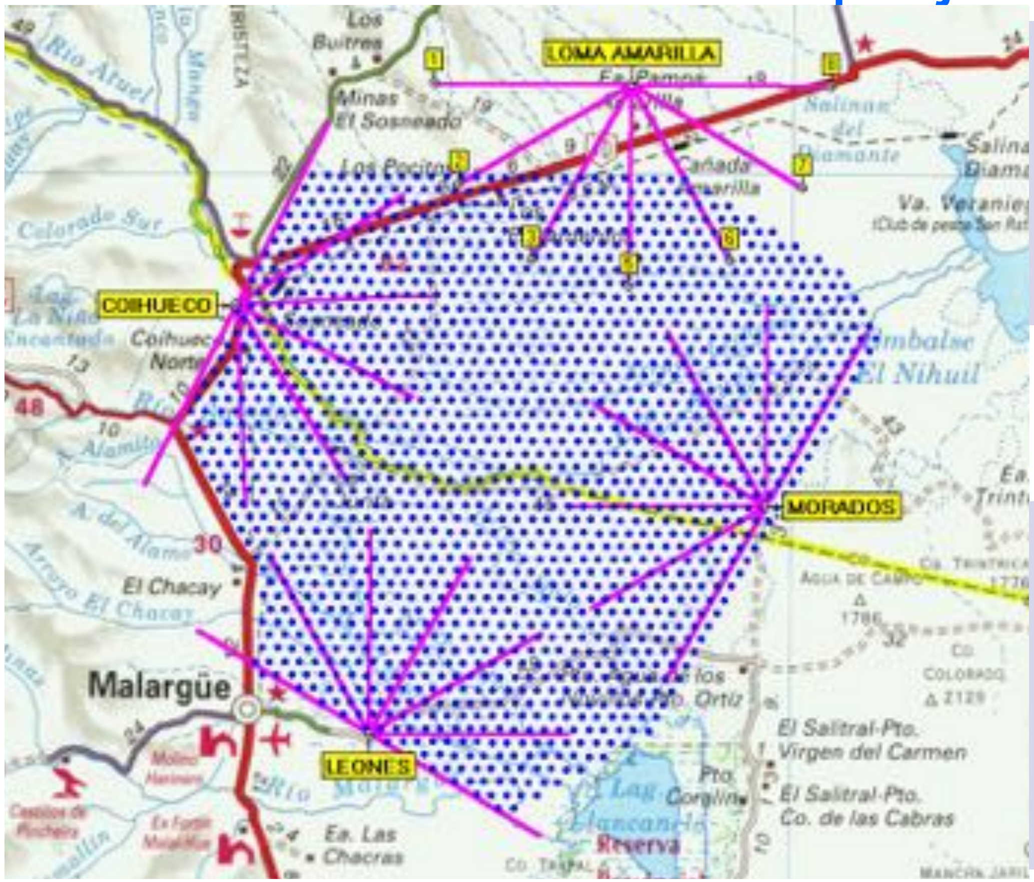
20 receivers + transmitters

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

at 10^{17} eV

Pierre Auger Observatory

South site in Argentina almost finished
North site – project



Surface Array

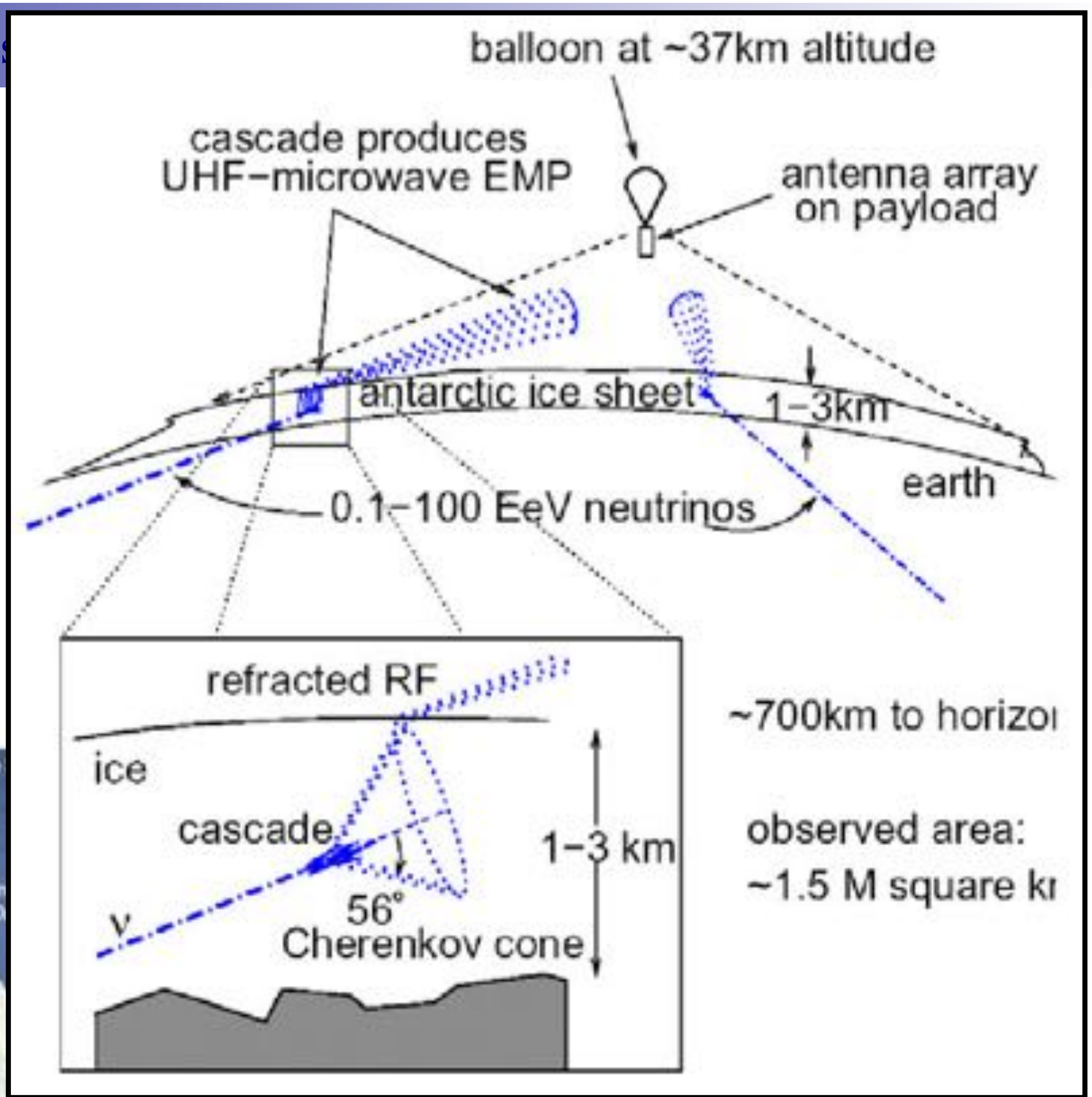
- ***1600 detector stations***
- ***1.5 Km spacing***
- ***3000 Km^2 (30xAGASA)***

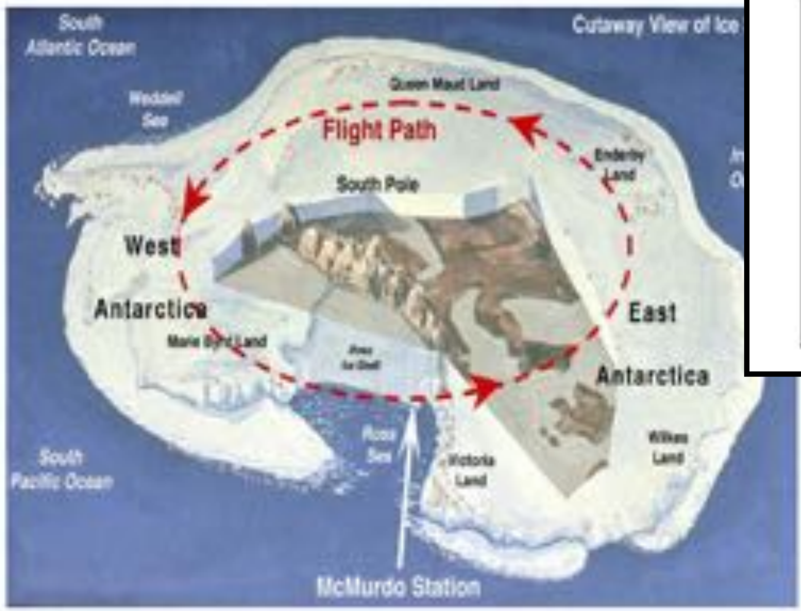
Fluorescence Detectors

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

ANITA

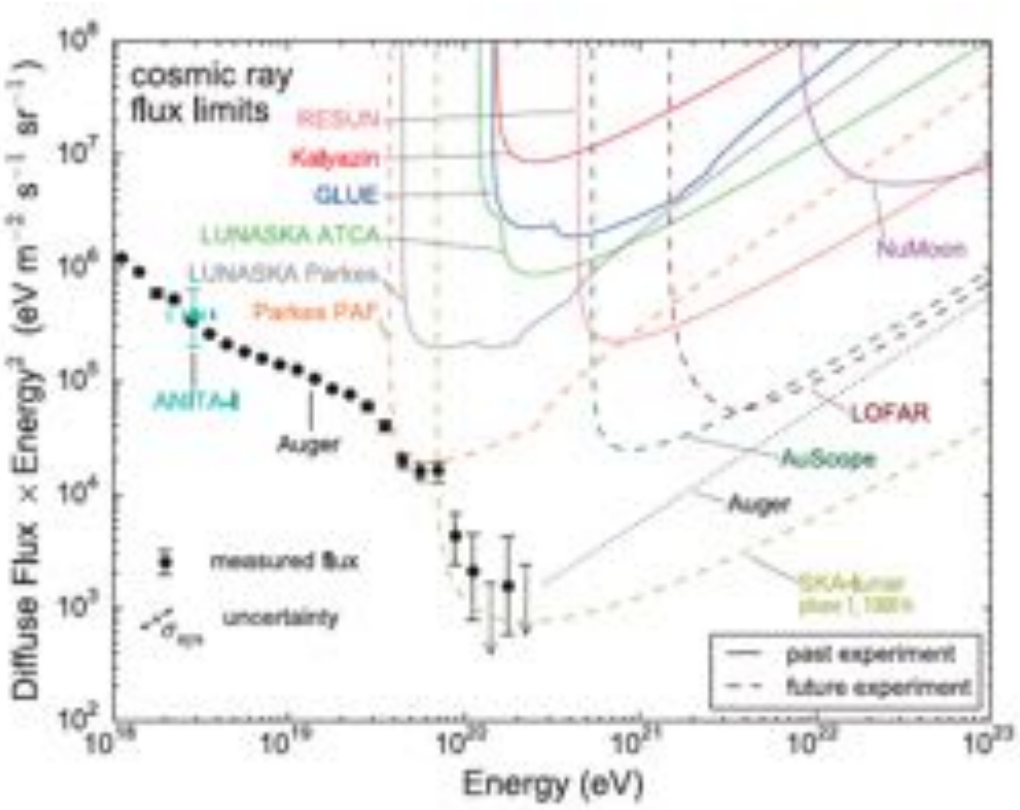
Antarctic
Impulsive
Transient
Array



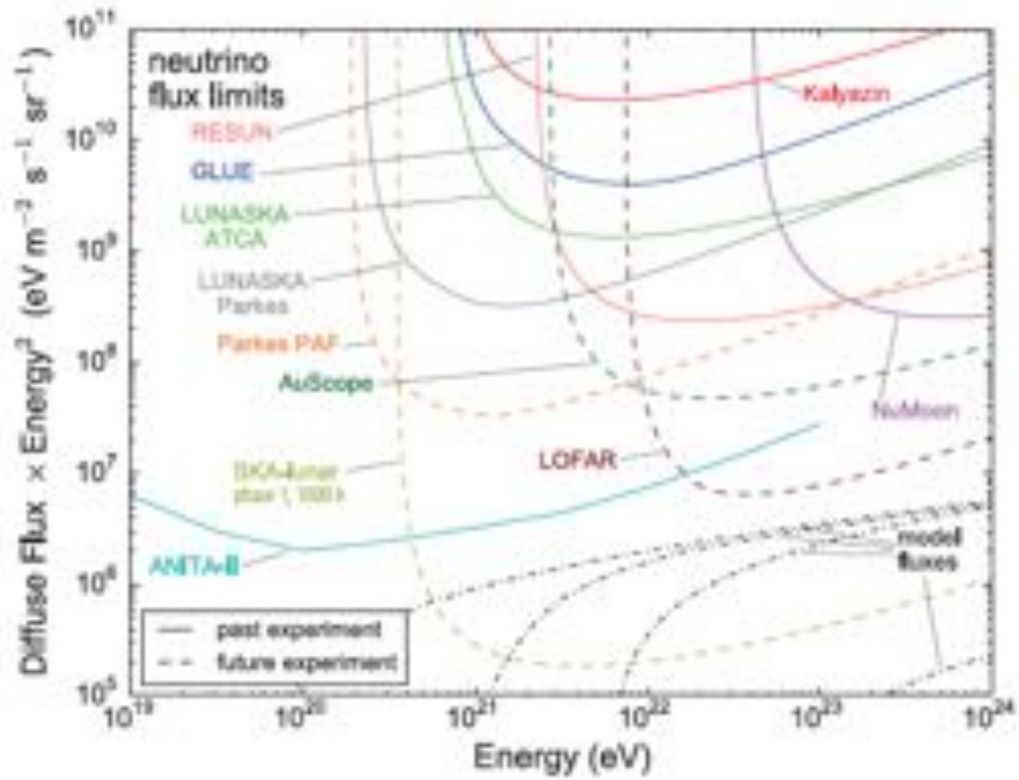


Flights in 2006,2007 (35 days)

Radio detection cosmic rays



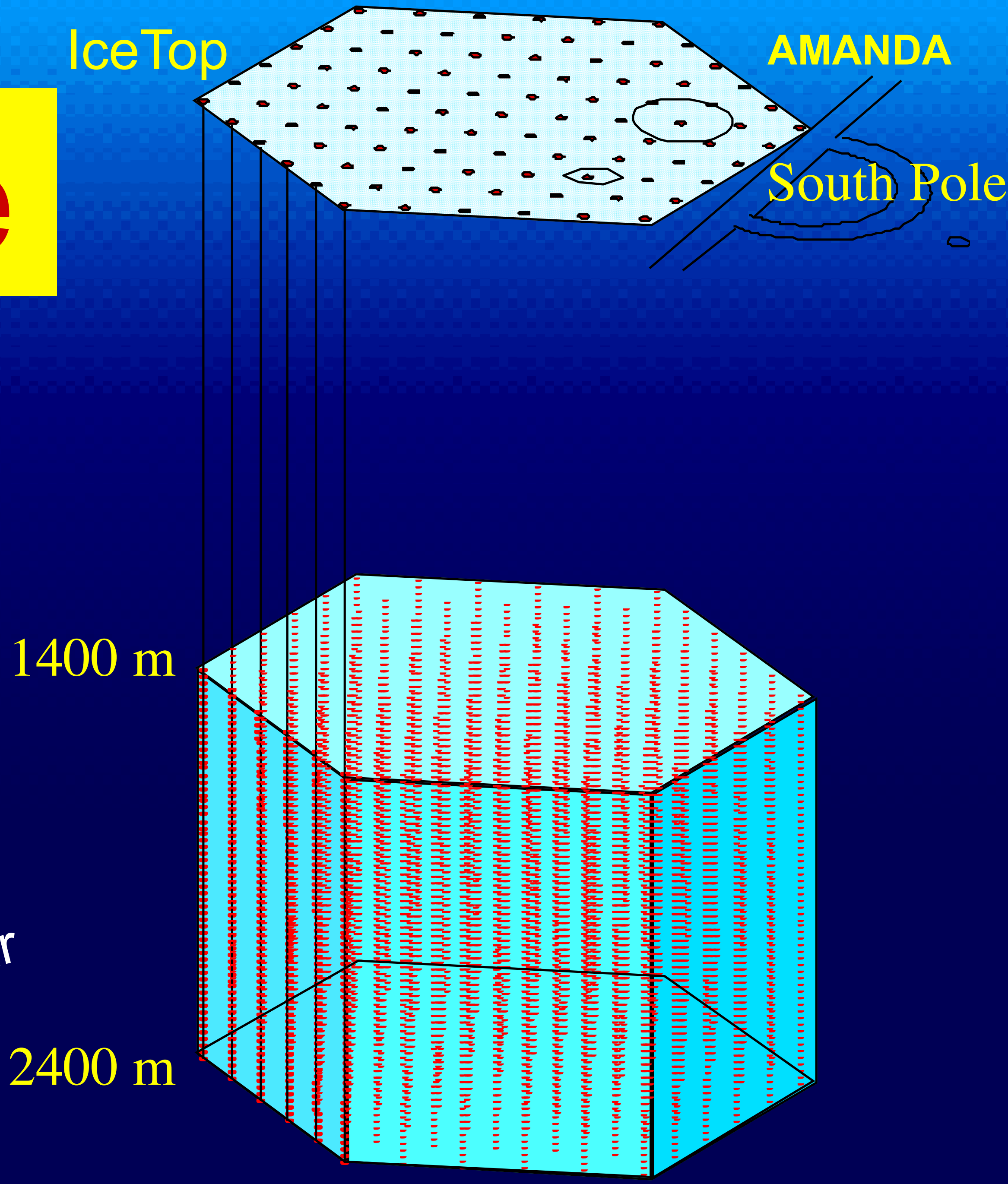
Radio detection neutrinos



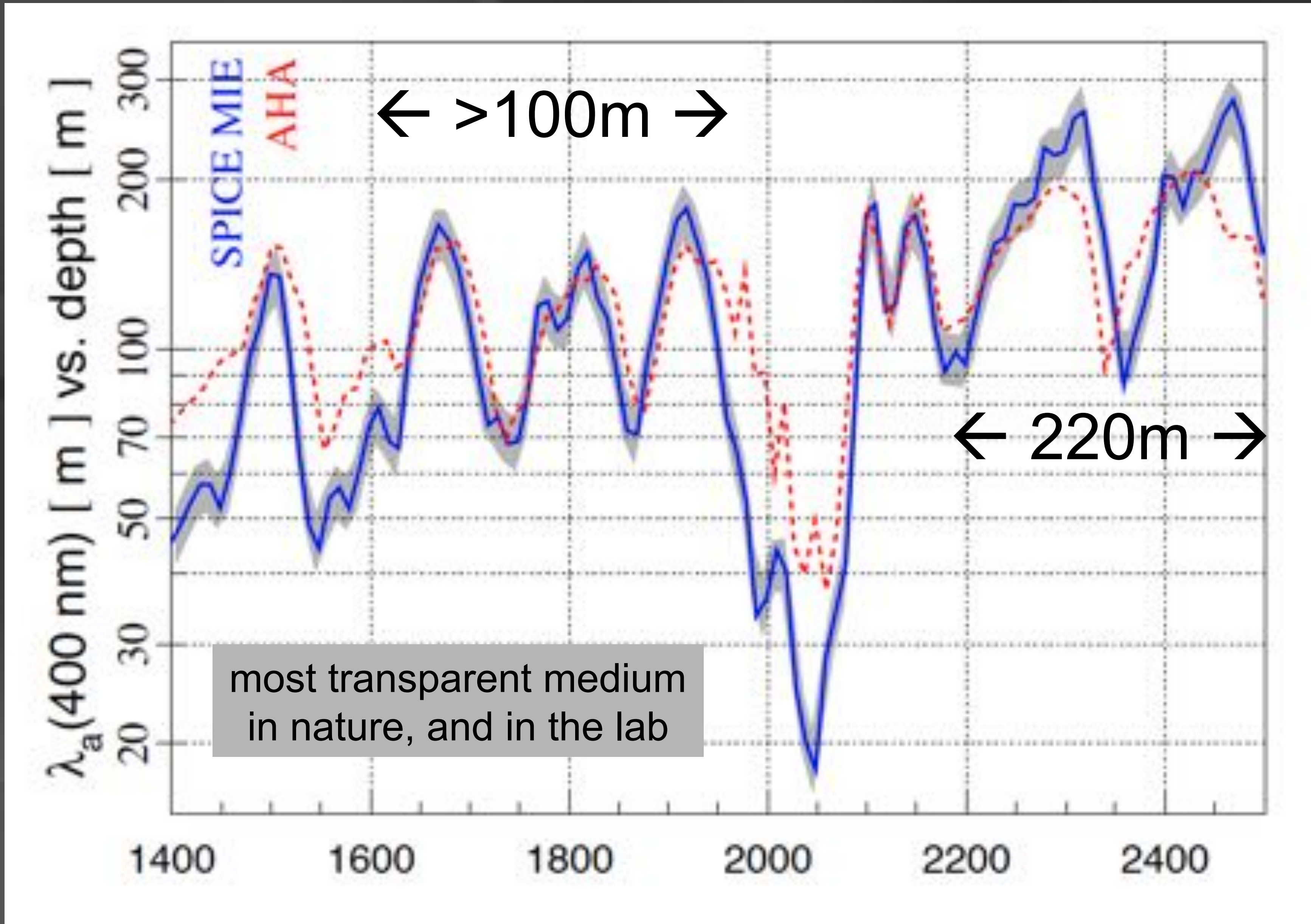
IceCube

- 80 Strings
- 4800 PMT
- Instrumented volume: 1 km^3
- Installation: 2004-2010

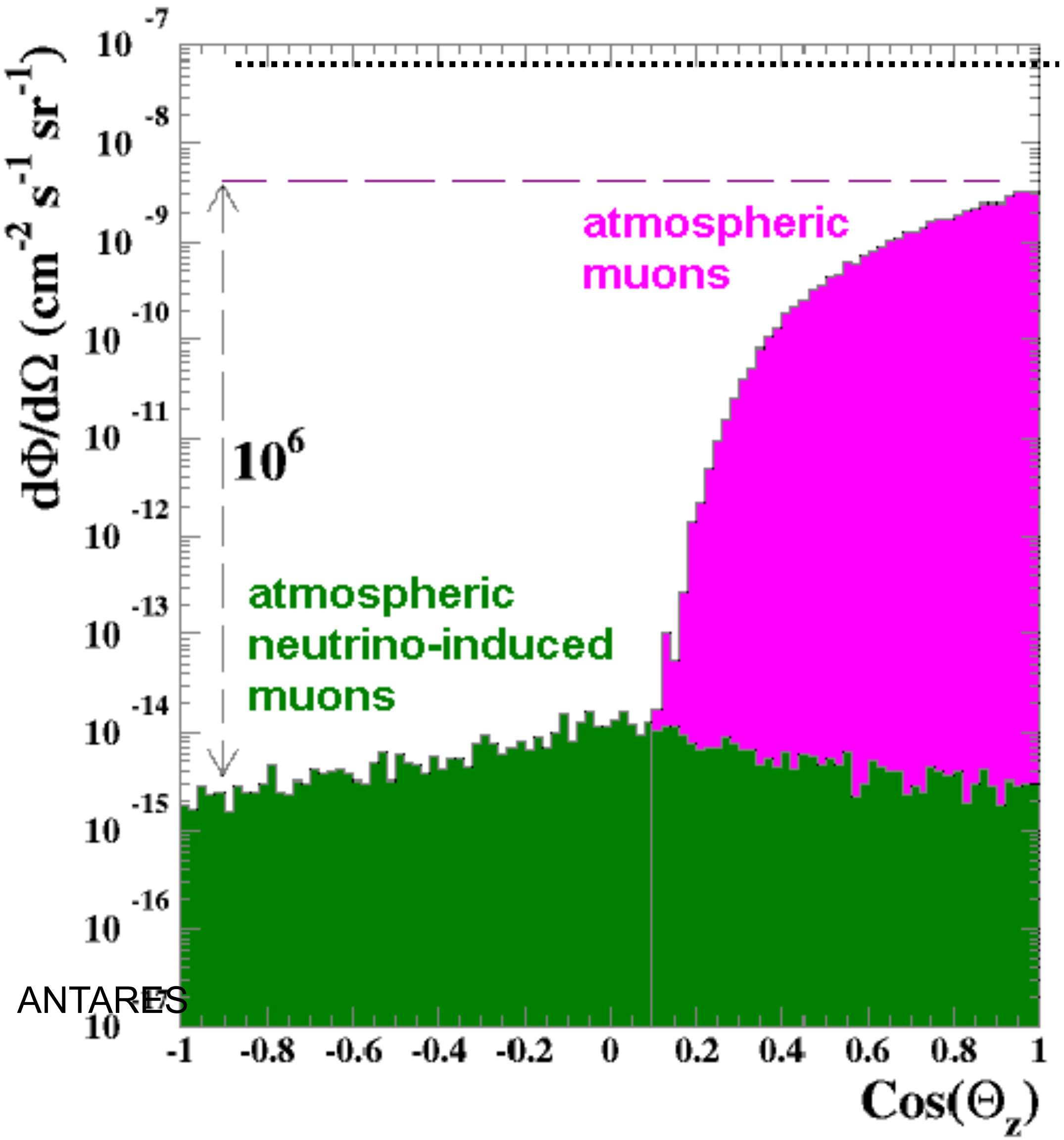
~ 80.000 atm.ν per year



absorption length of Cherenkov light



Backgrounds: atmospheric muons and neutrinos



ANTARES

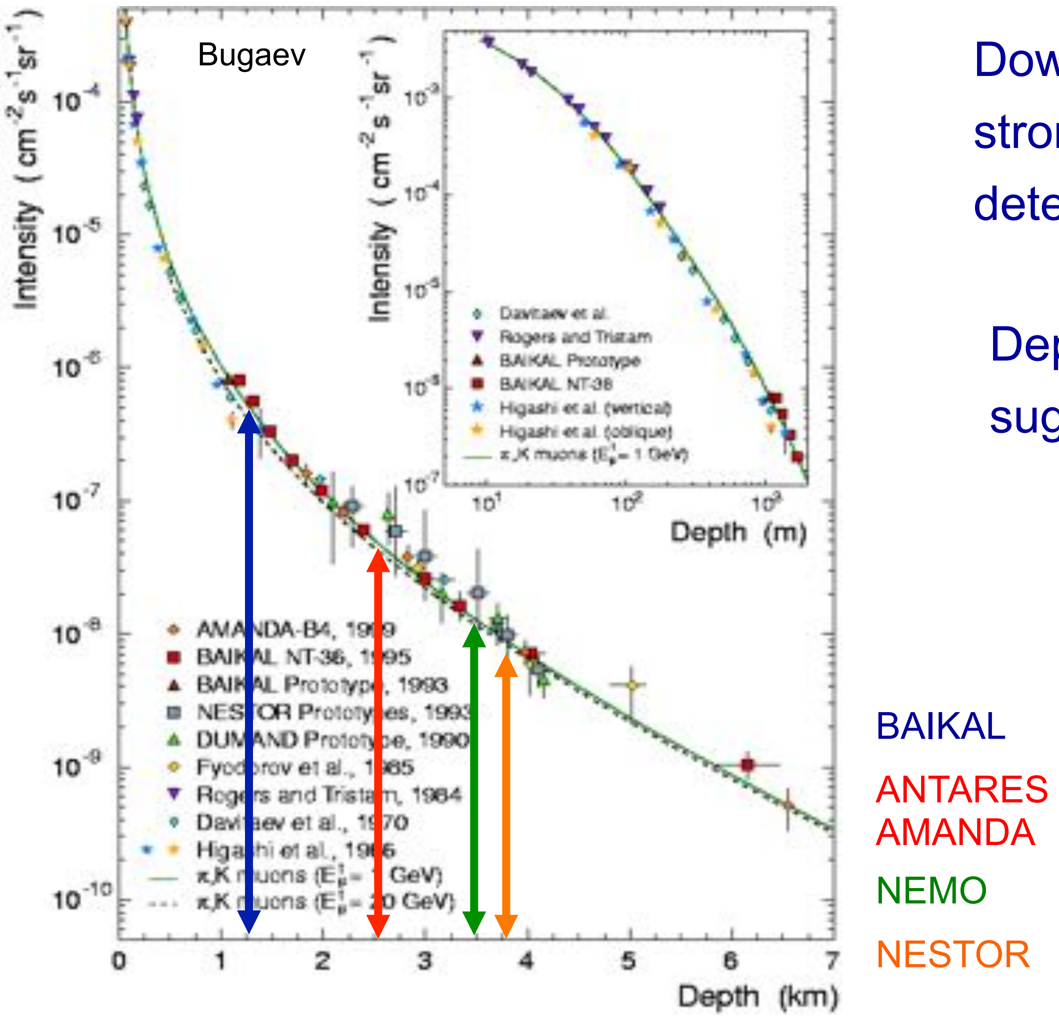
Atmospheric neutrinos:

- 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.

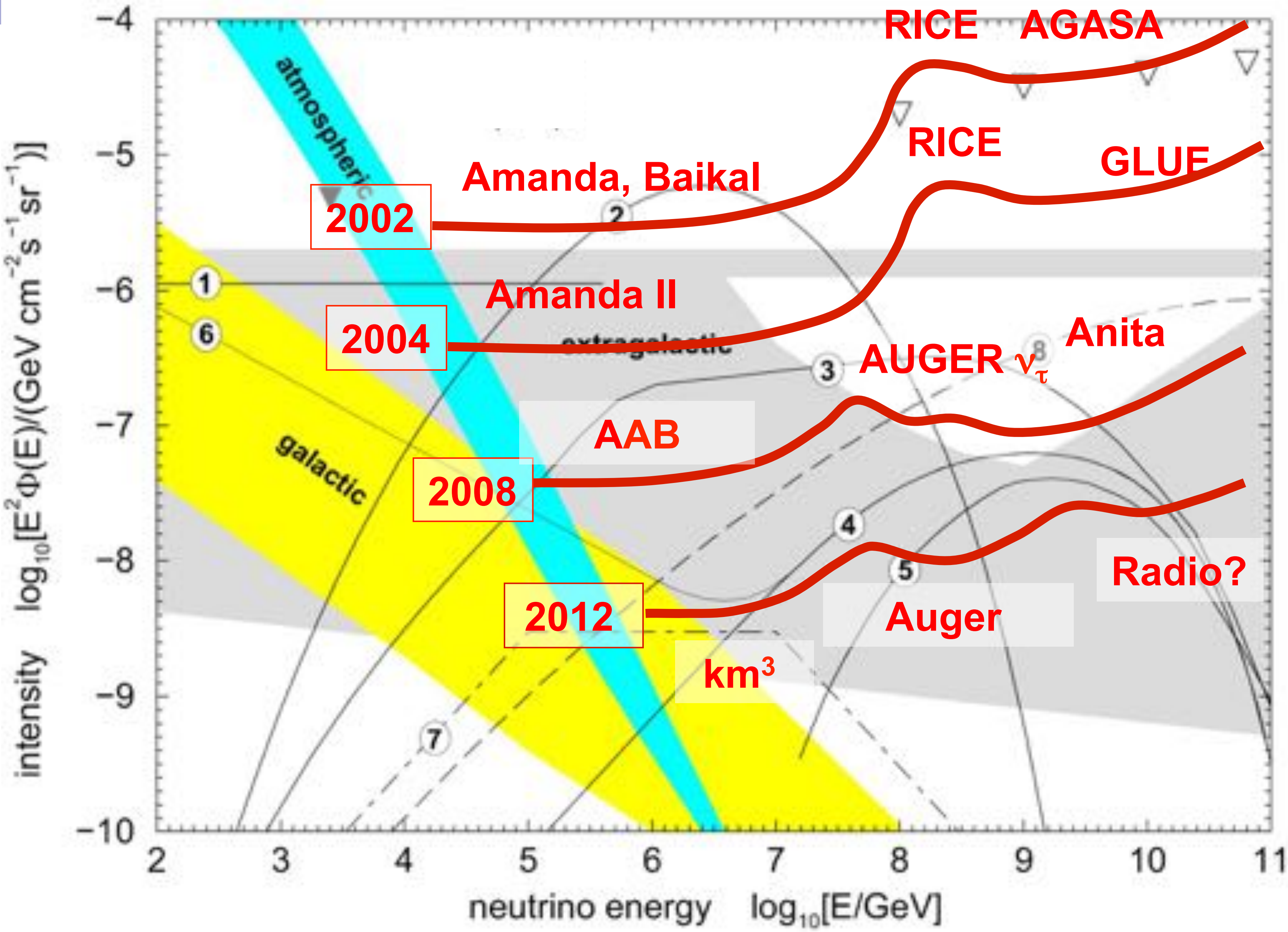
Depth >3000 m (≈1 km rock) is suggested for detector installation

… you looked at 10msec of data !

muons detected per year:

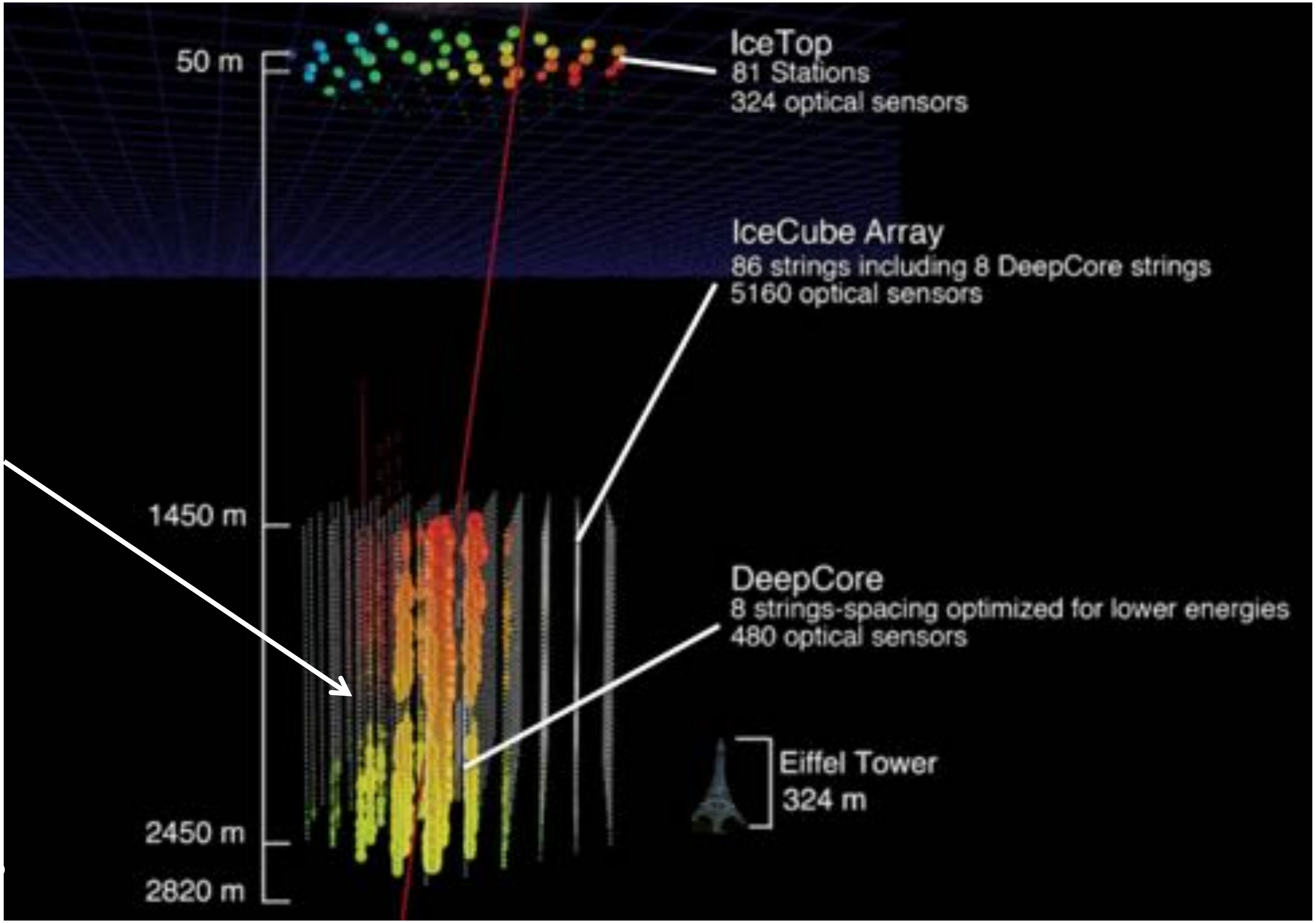
- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second ** 1 every 6 minutes


RICE
AGASA
RICE
GLUE
Amanda, Baikal
2002
Amanda II
2004
extragalactic
AUGER ν_τ
Anita
AAB
2008
galactic
atmospheric
2012
Radio?
Auger
km^3
1
2
3
4
5
6
7
8
−4
−5
−6
−7
−8
−9
−10
2
3
4
5
6
7
8
9
10
11
intensity $\log_{10}[E^2\Phi(E)/(GeV\ cm^{-2}s^{-1}sr^{-1})]$
neutrino energy $\log_{10}[E/GeV]$

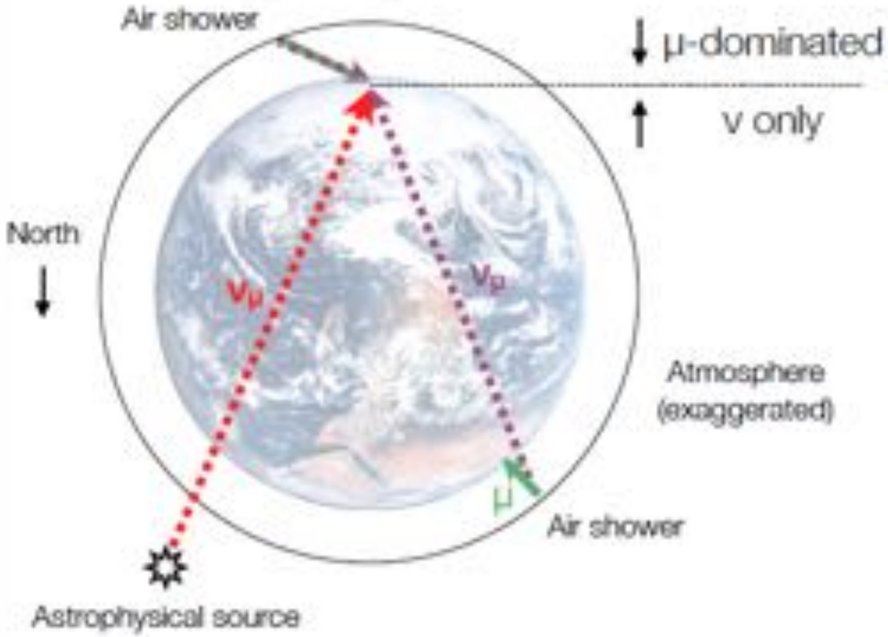
IceCube discovery of astrophysical neutrinos

IceCube


50 m
1450 m
2450 m
2820 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m

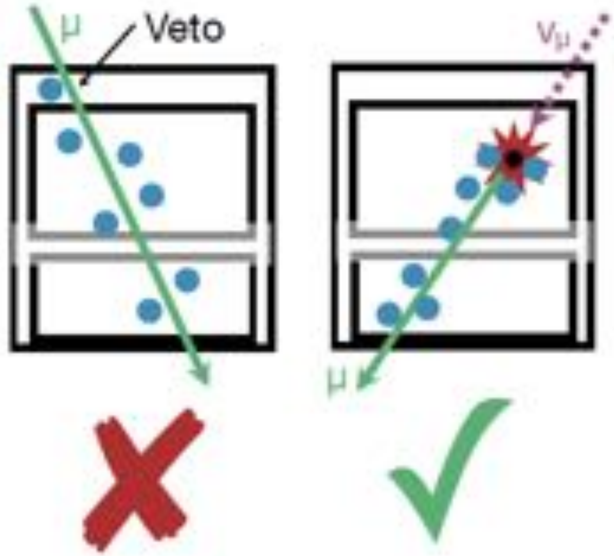
Isolating neutrino events: two strategies

Up-going tracks

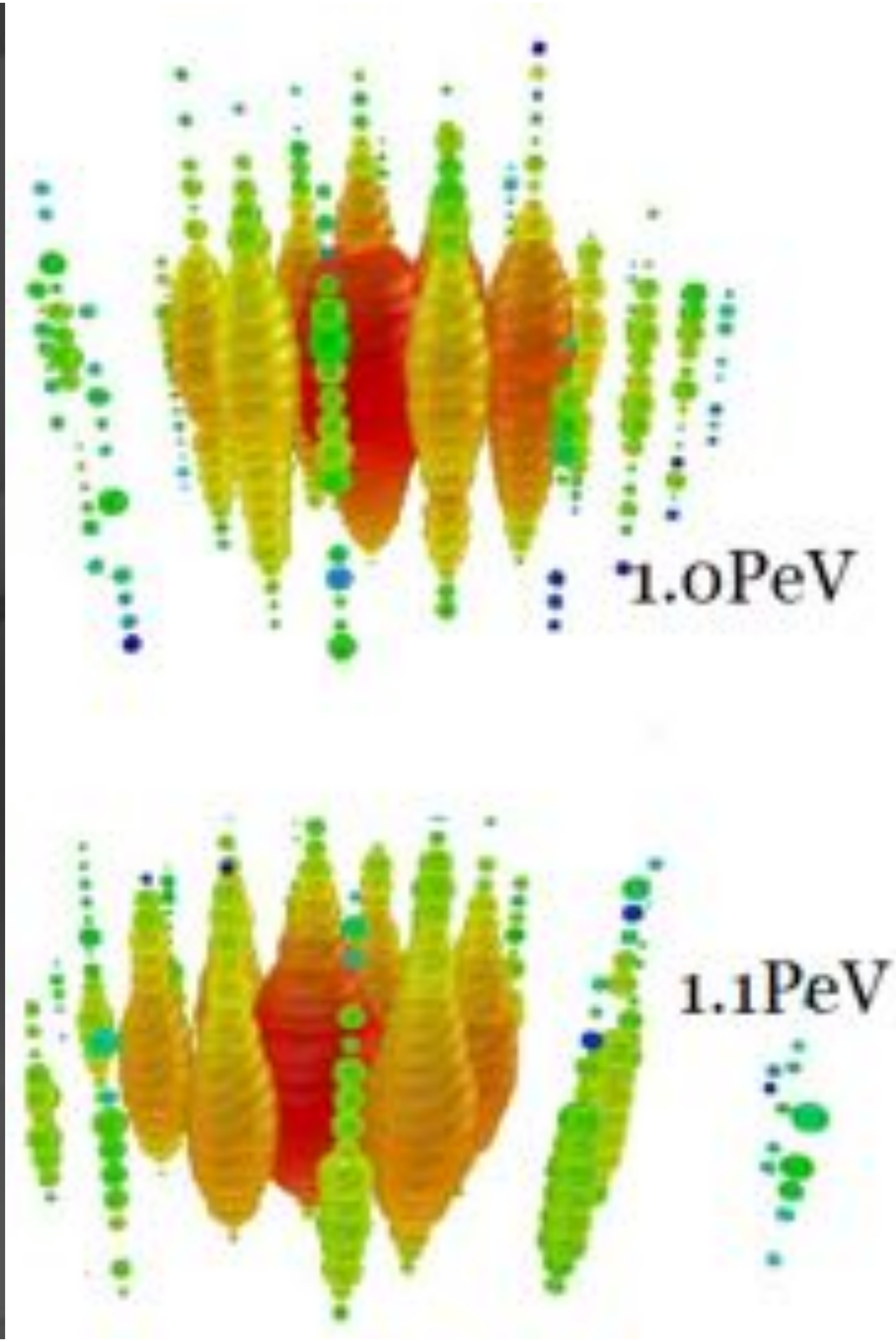


- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to ν_μ only
- Sensitive to half the sky

Active veto



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



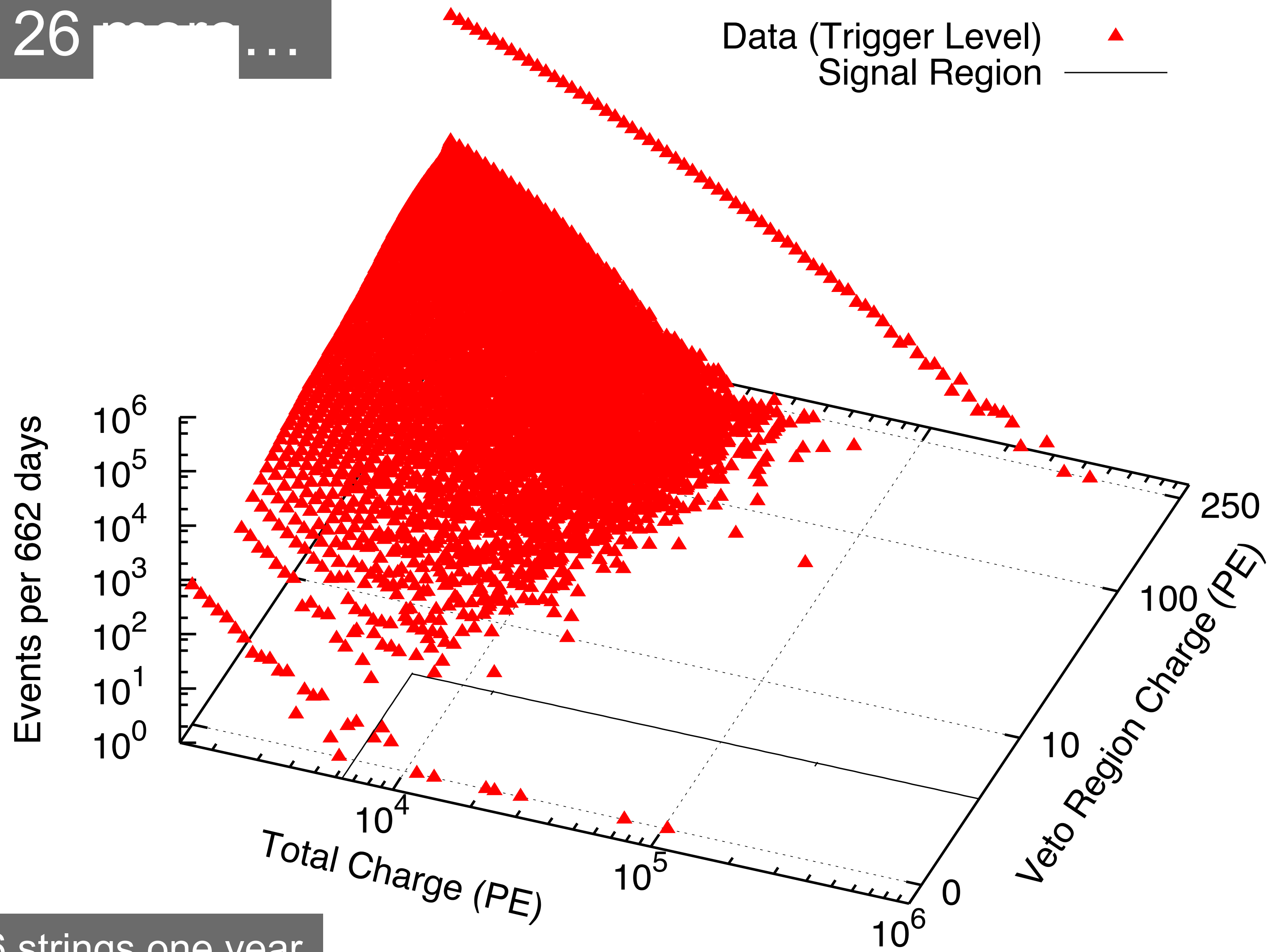
• energy

1,041 TeV
1,141 TeV
(15% resolution)

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

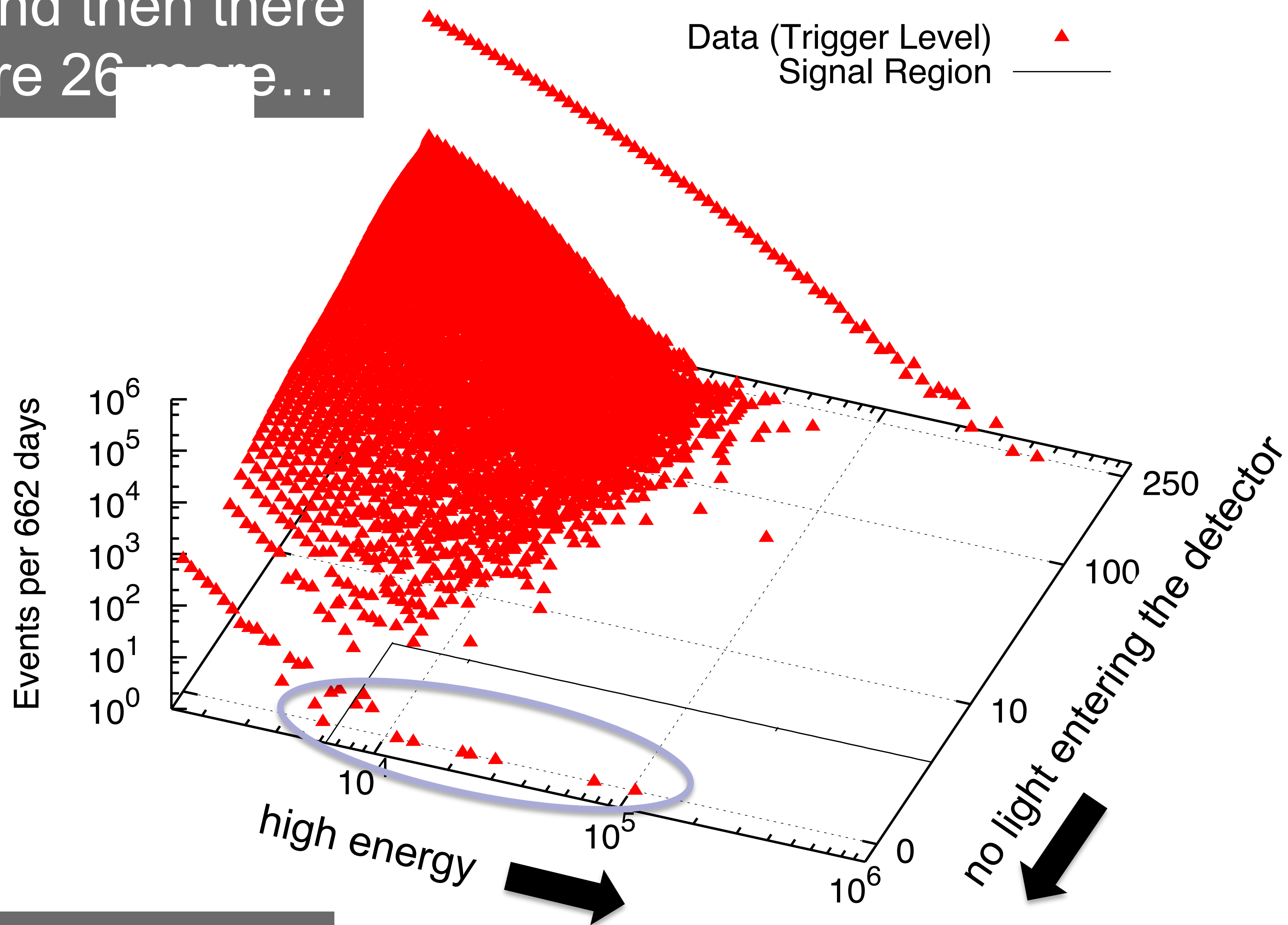
→ flux at present level of diffuse limit

…and then there were 26 more…



data: 86 strings one year

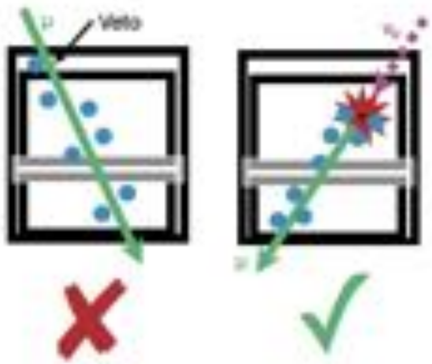
…and then there were 26 more…



data: 86 strings one year

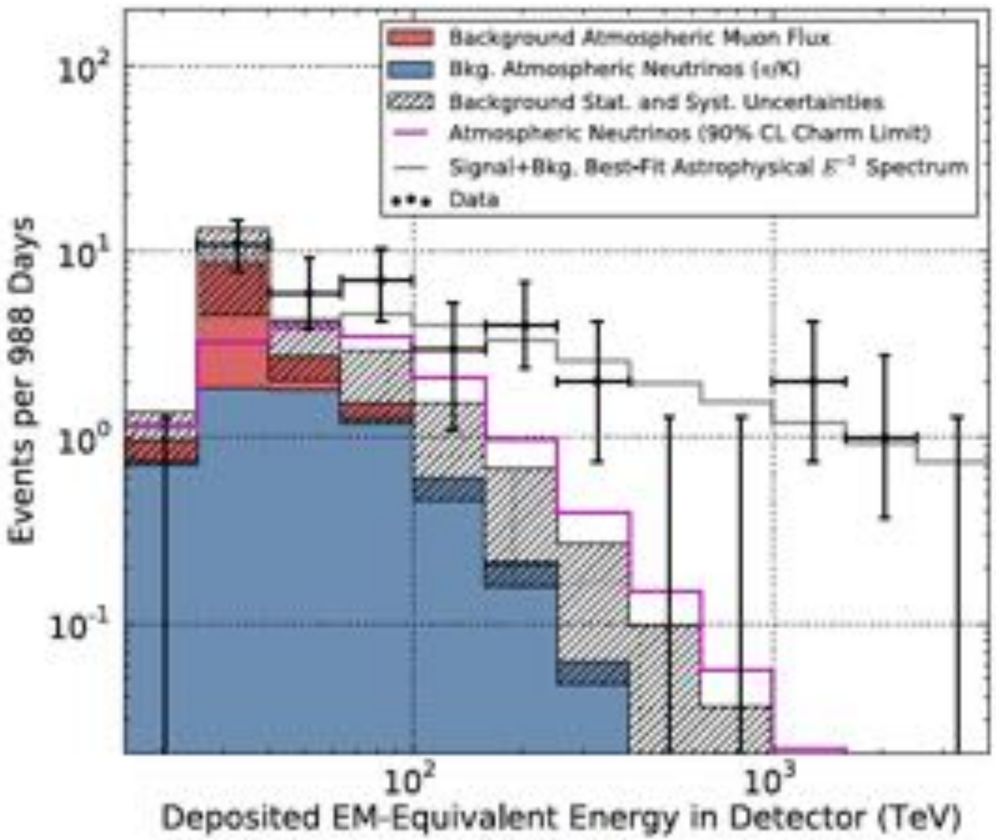
Evidence for high-energy astrophysical neutrinos

- Selected high-energy starting events in IceCube



- 3 cascades over 1 PeV in 3 years of data
- 5.7 σ evidence for astrophysical neutrinos

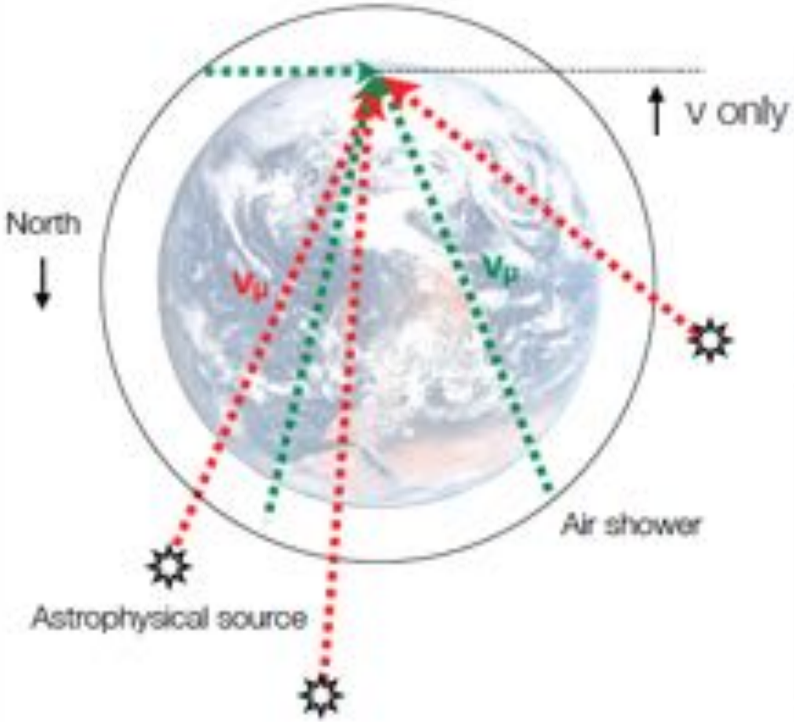
Deposited energy

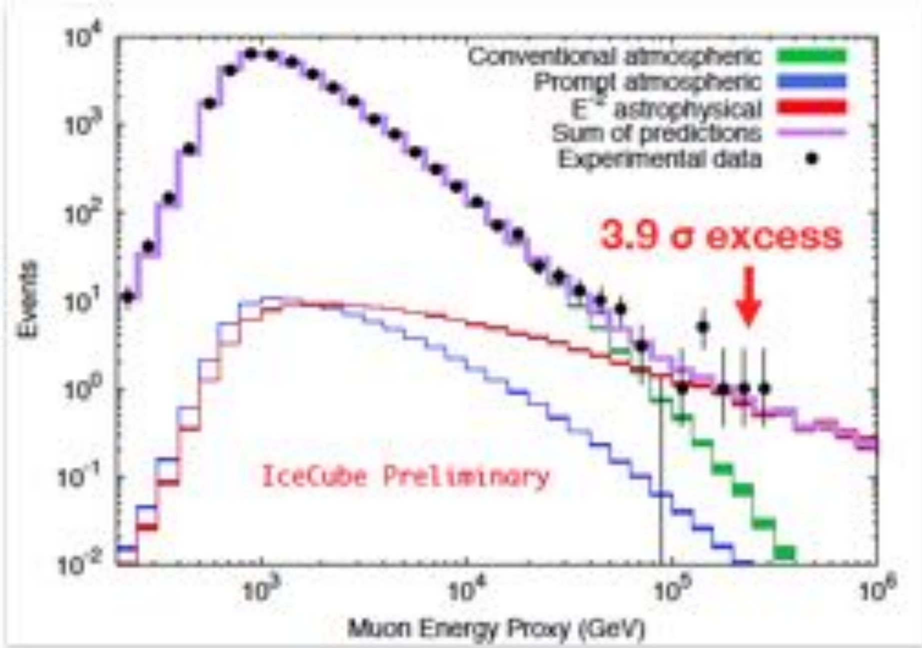


arXiv:1405.5303 (accepted for PRL)

What about the northern sky and ν_μ?

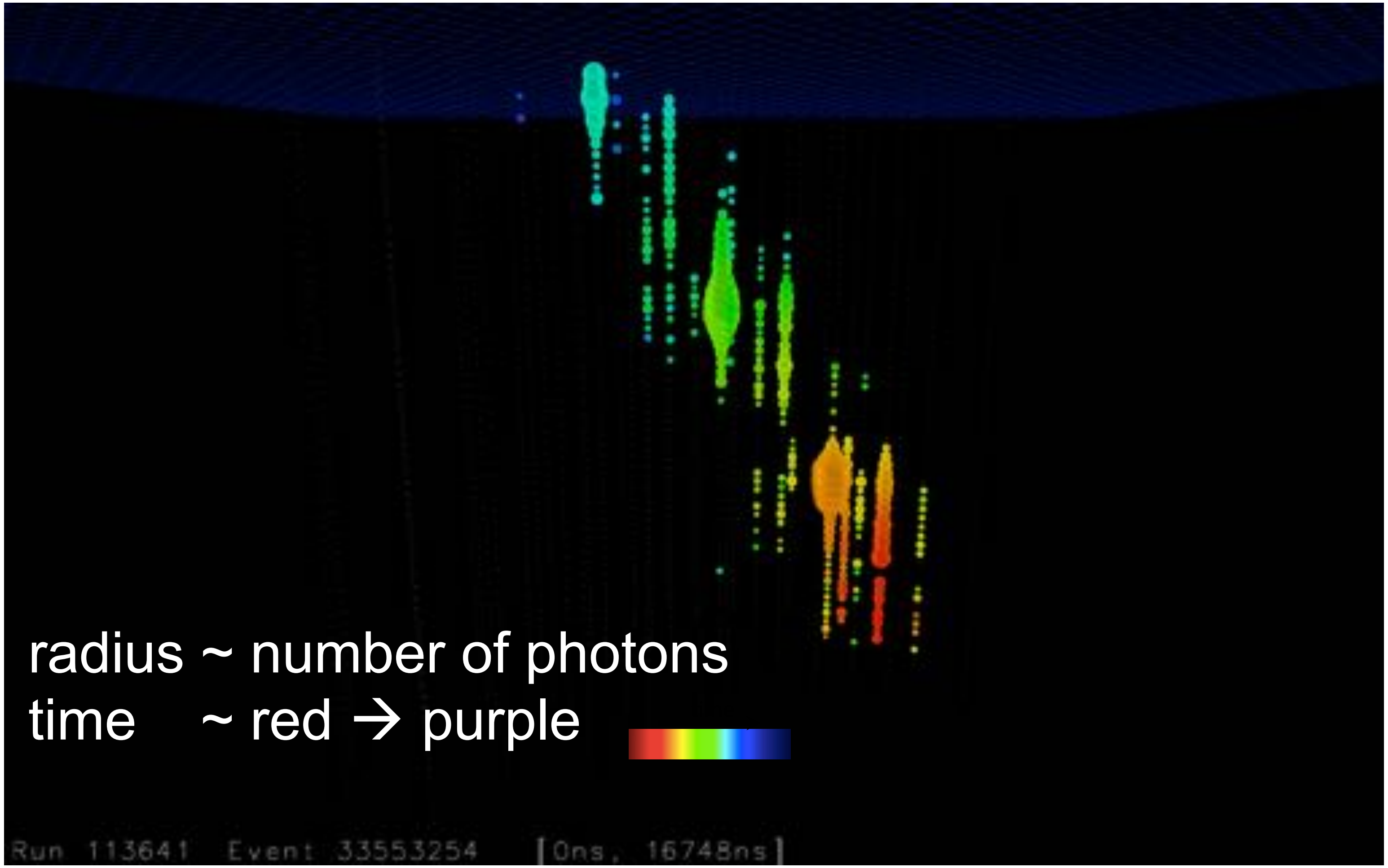
The high-energy starting event sample is dominated by cascades from the southern sky.





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

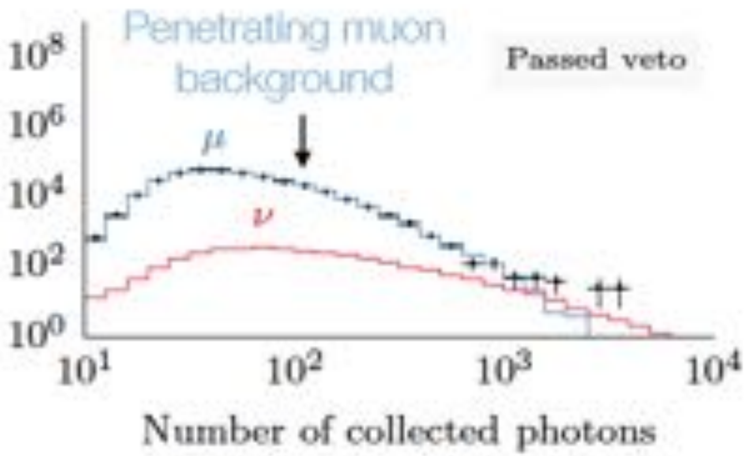
Muon track from 89 TeV neutrino

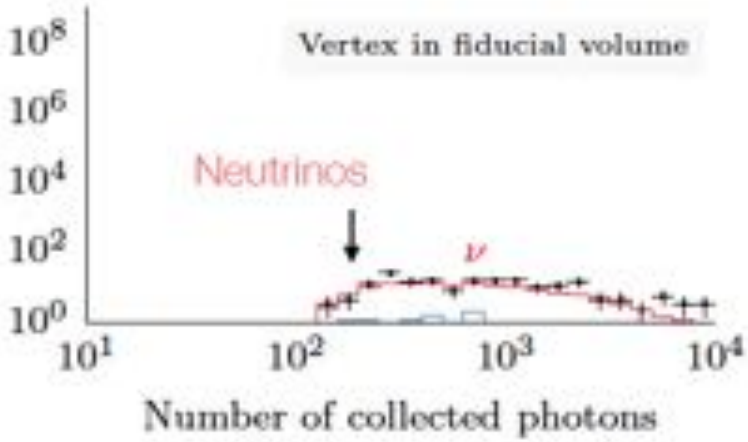


Improved veto techniques

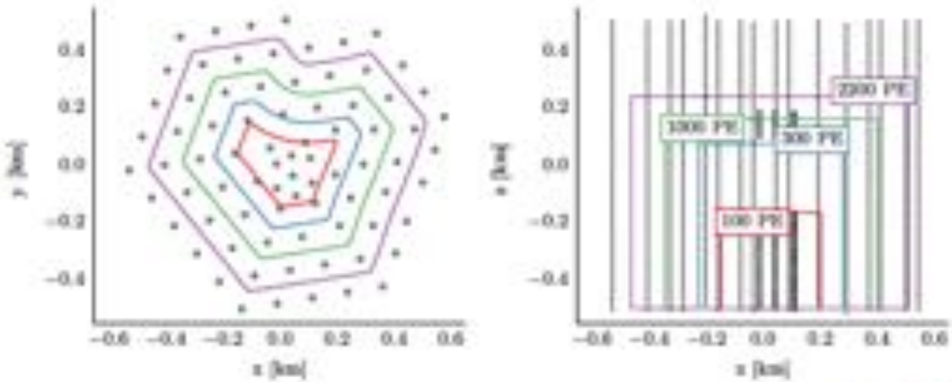
Outer-layer veto → Energy-dependent veto

Neutrino-dominated for E_{dep} > 60 TeV | **Neutrino-dominated for E_{dep} > 1 TeV**

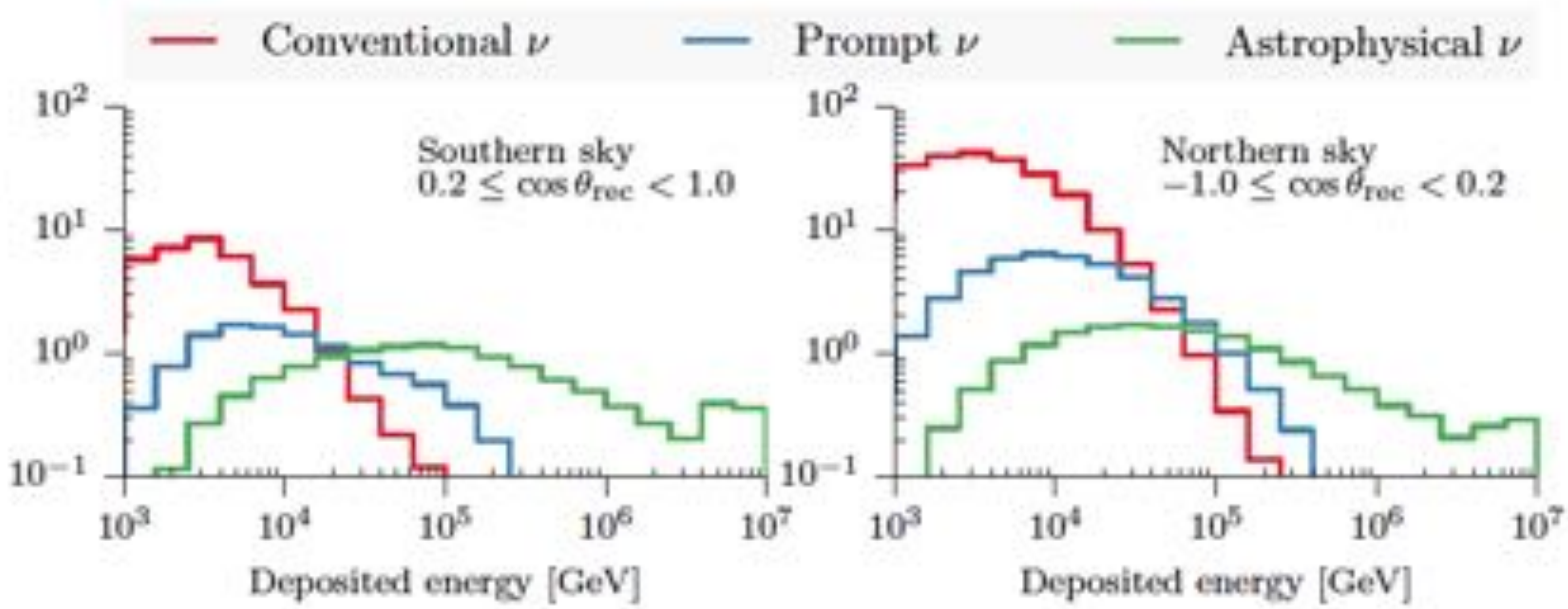




Thicker veto at low energies
suppresses penetrating muons without sacrificing high-energy neutrino acceptance



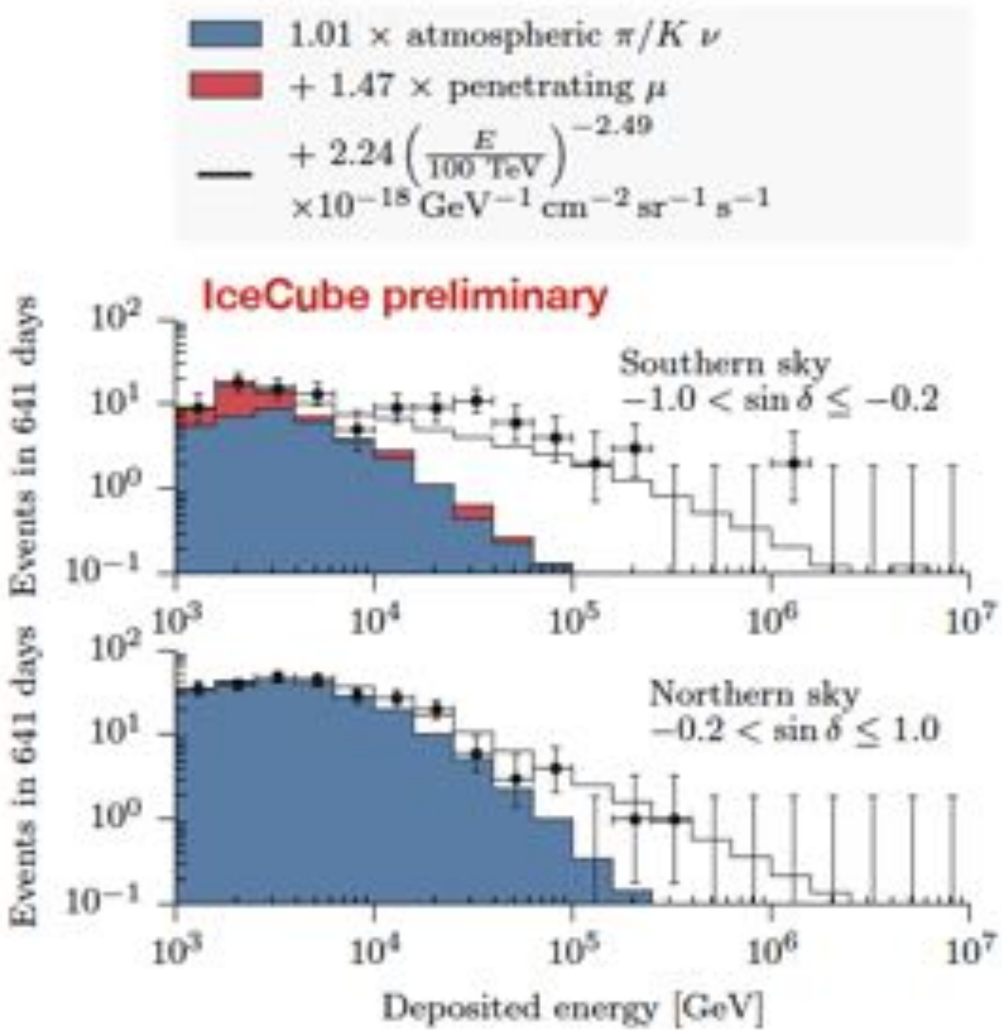
)servable energy spectra



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

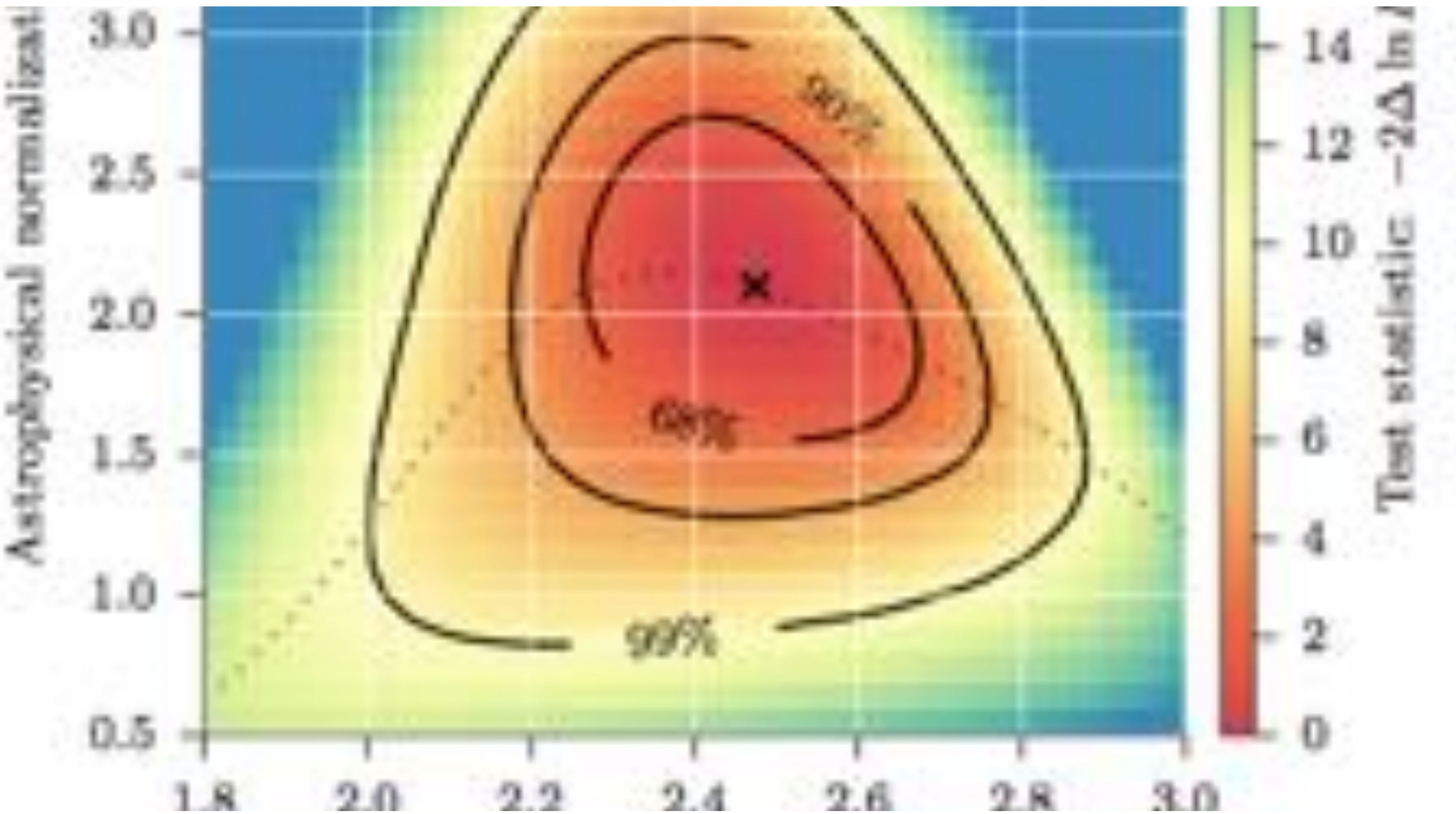


Best fit parameters

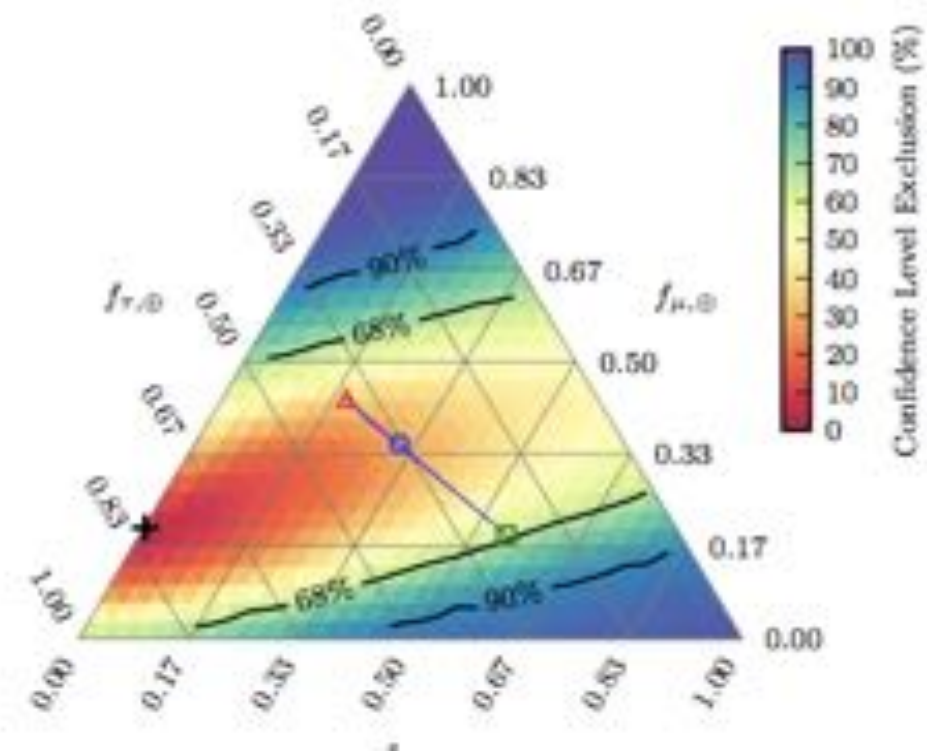
TABLE I. Best fit parameters and number of events attributable to each component. The normalizations of the atmospheric fluxes are relative to the models described in Sec. III. The per-flavor normalization Φ_0 and spectral index γ of the astrophysical flux are defined in Eq. (1); the fit to the astrophysical flux is sensitive to 25 TeV $< E_\nu <$ 1.4 PeV. The two-sided error ranges given are 68% confidence regions in the χ^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 μ flux	$1.73 \pm 0.40\, \Phi_{\mathrm{SIBYLL+DPMJET}}$	30 ± 7
Conventional ν flux	$0.97^{+0.10}_{-0.03}\, \Phi_{\mathrm{HKKMS}}$	280^{+28}_{-8}
Prompt ν flux	$< 1.52\, \Phi_{\mathrm{ERS}}$ (90% CL)	< 23
Astrophysical Φ_0	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ $\mathrm{GeV^{-1}\,cm^{-2}\,sr^{-1}\,s^{-1}}$	87^{+14}_{-10}
Astrophysical γ	2.46 ± 0.12	

Neutrino spectrum



Flavor content consistent with 1:1:1



IceCube Collaboration, **arXiv:1502.03376**

Neutrino astrophysics

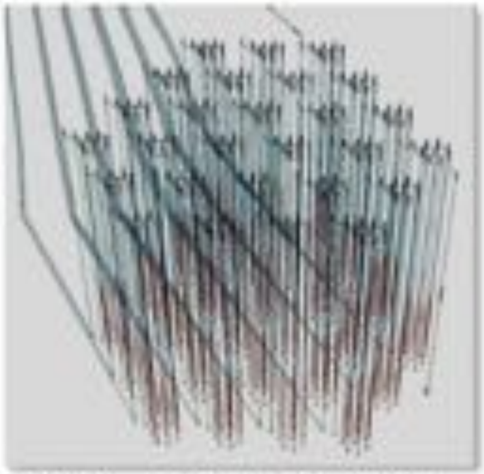
- IceCube detected first astrophysical neutrinos. New field started: neutrino astrophysics.
- Best flux 1/E^(2.46+-0.14)
- Flux 1/E^2 disfavored with more then 3 sigma significance
- Muon neutrino data favors 1/E^2.1 flux !
- Flavor ratio consistent with 1:1:1 as expected
- Cosmogenic neutrinos best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

- Bigger detectors needed for next step

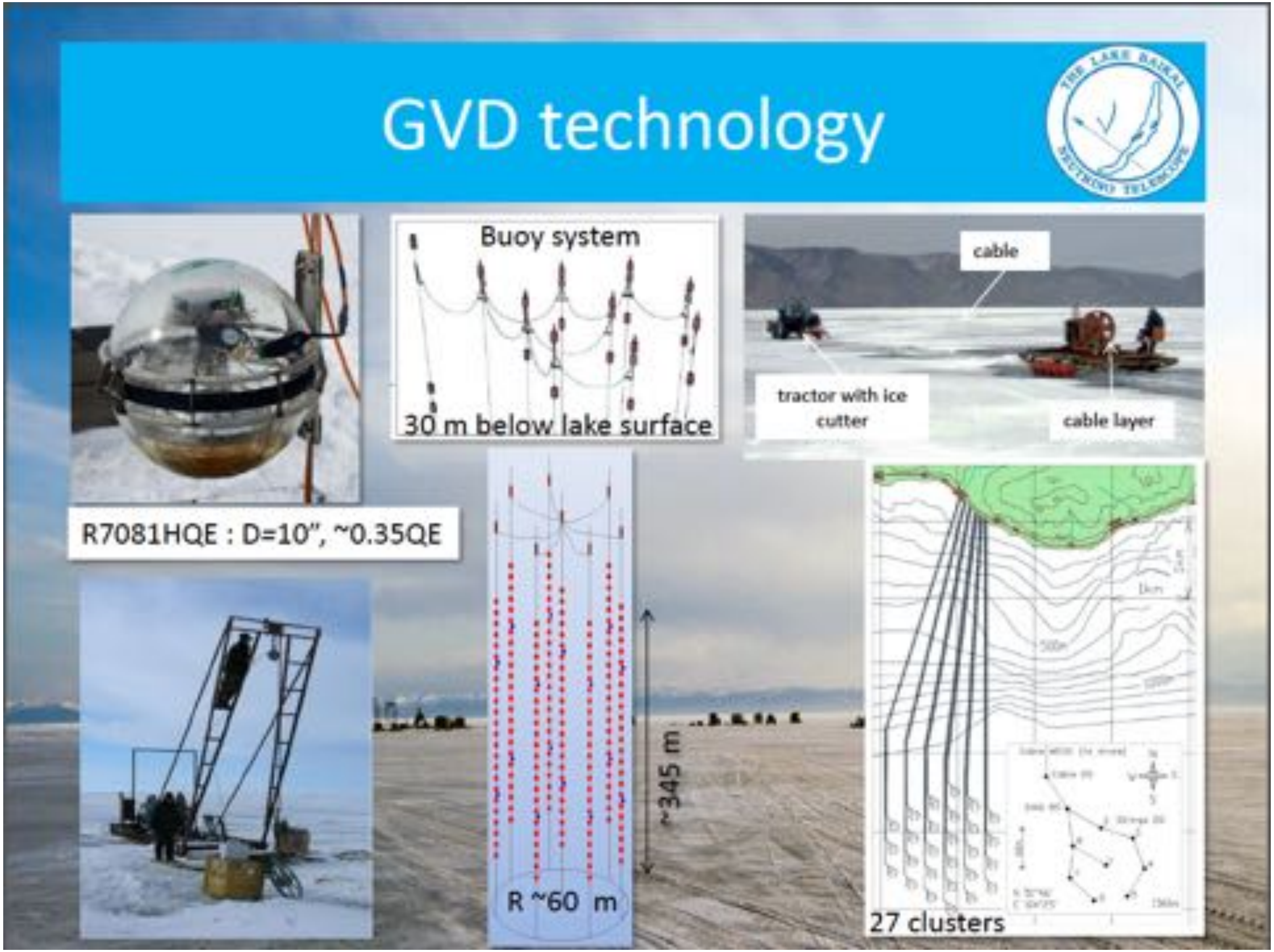
Future detectors

Baikal-GVD

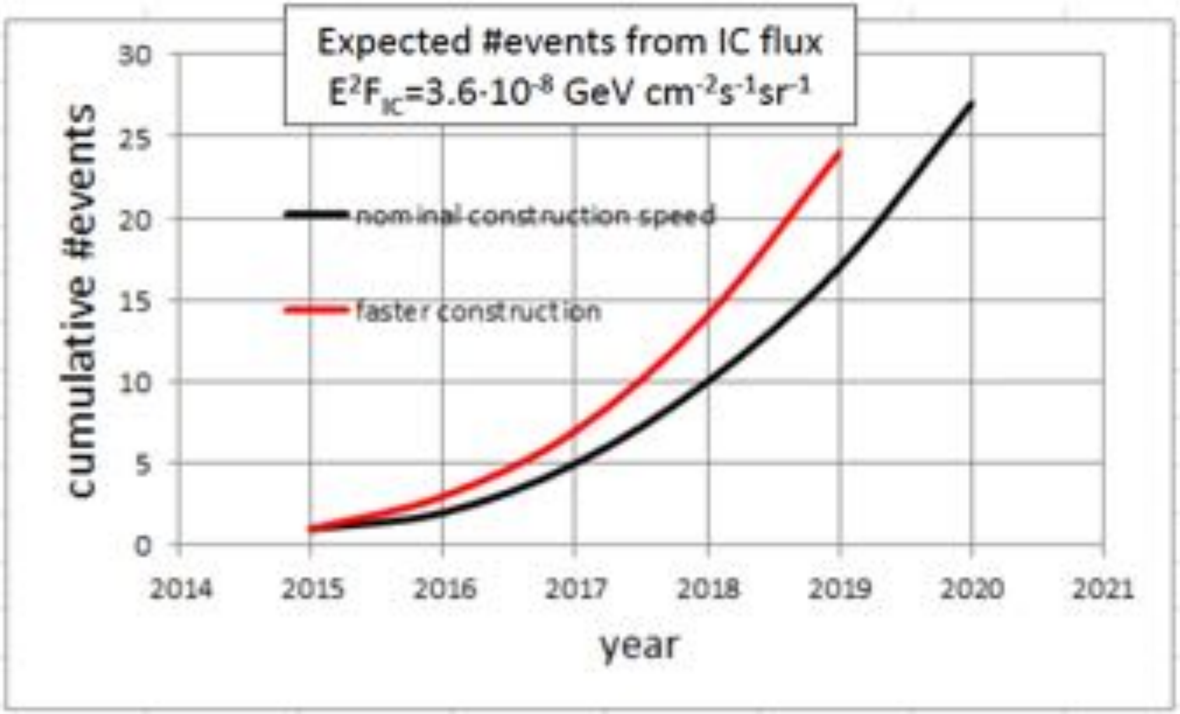
Environmental parameters	Telescope design
Lake Baikal - fresh water	~1.5 km3
distance to shore ~6 km →	27 shore-cables for 27 clusters
L_{abs} ~22-25 m	27*8=216 strings
L_{scat} ~30-50m	216*48=10368 OMs¶
depth ~1360 m	deployment from icefloor
icefloor during winter →	*shallow water* DAQ infrastructure



¶ OM – Optical Module


GVD technology
THE LAKE BAIKAL NEUTRINO TELESCOPE
Buoy system
30 m below lake surface
cable
tractor with ice cutter
cable layer
R7081HQE : D=10", ~0.35QE
~345 m
R ~60 m
27 clusters

Baikal-GVD: performance



E > 100 TeV: ~1 event/cluster/year

1 cluster is working now, 12 clusters to 2020

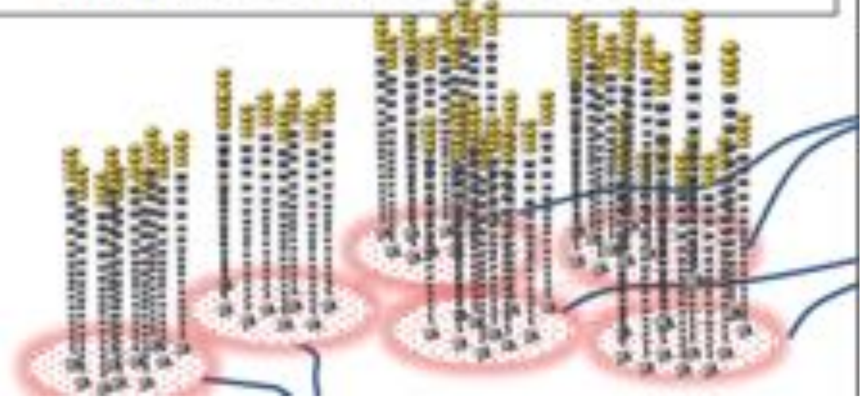
KM3NeT in the Mediterranean

Environmental parameters

Mediterranean Sea – salt water
3 installation sites
distance to shore ~40-100 km
L_{abs} ~60-100 m
L_{scat} ~50-70m
depths ~2500-4500 m

Telescope design

~3.5-6 km^3 (depending on spacing)
6 shore-cables for 6 building blocks
6 x 115 = 690 detection units
690 x 18 =12420 OMs
seabed data transmission infrastructure
installation requires ship + ROV
all-data-to-shore concept



KM3NeT Optical Module

Segmented cathode area: 31 x 3" PMTs

Light concentrator ring

Cathode area: ~ 3 x 10-inch PMT

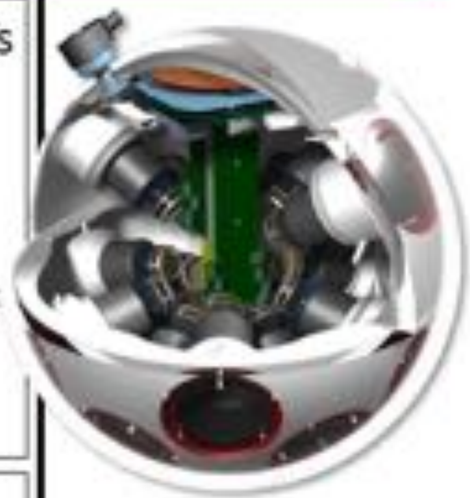
Custom low-power HV bases

LED & piezo inside

Compass and tiltmeter inside

PMT ToT measurements

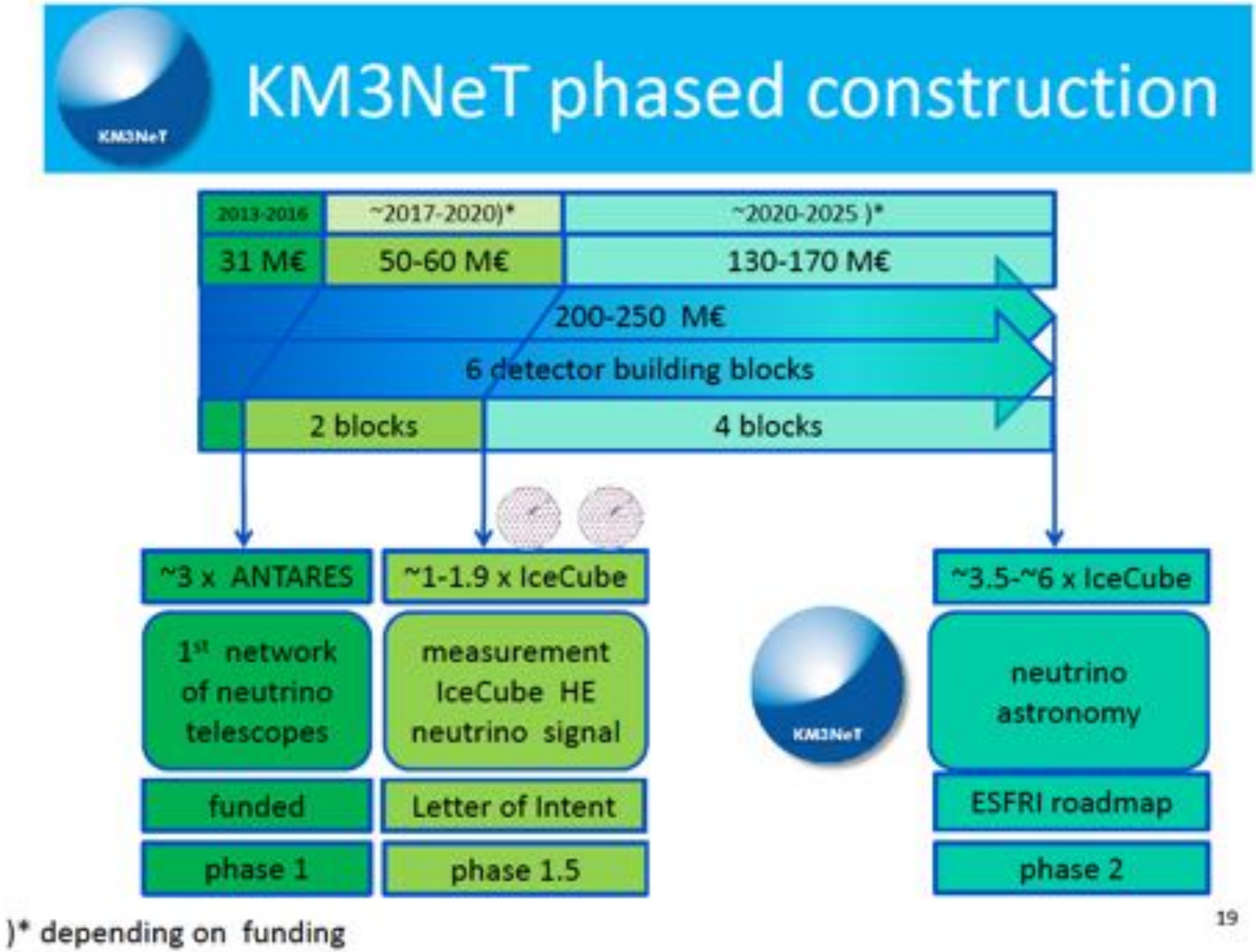
FPGA readout, optical line terminator



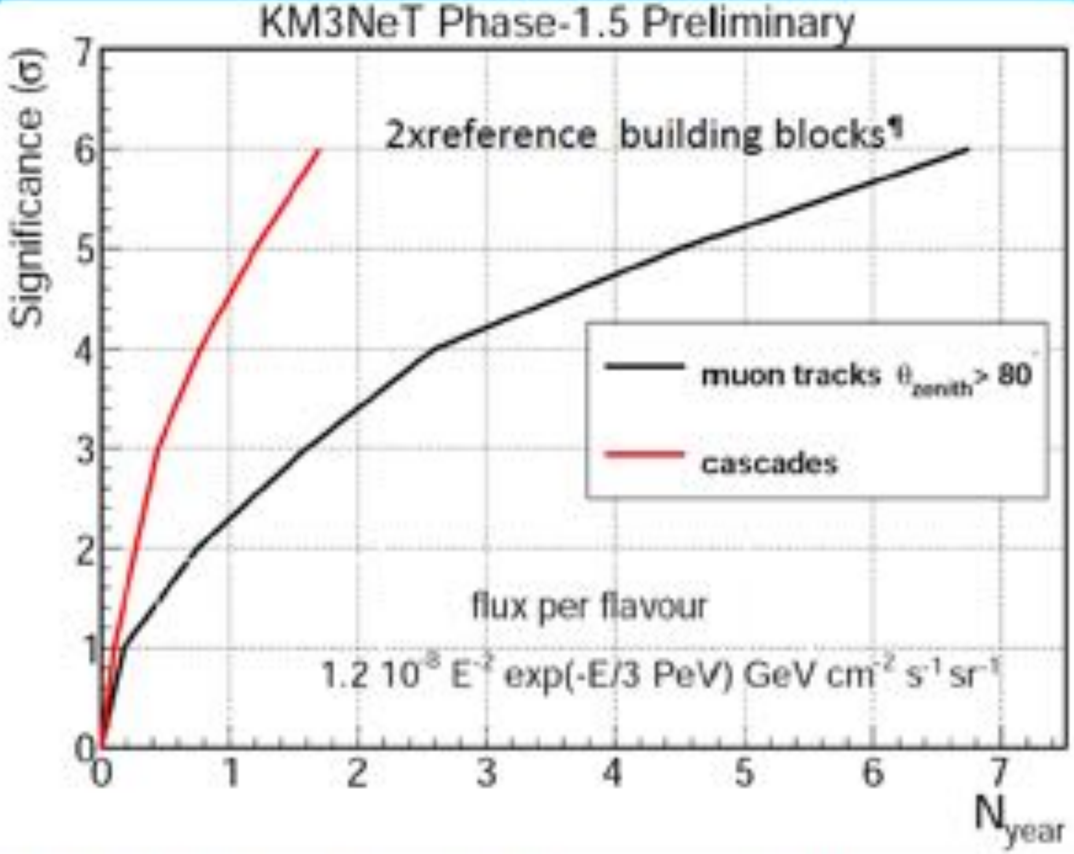
ETEL D792

Hamamatsu R12199

HZC XP53B20


KM3NeT phased construction
KM3NeT
2013-2016
~2017-2020)*
~2020-2025)*
31 M€
50-60 M€
130-170 M€
200-250 M€
6 detector building blocks
2 blocks
4 blocks
~3 x ANTARES
~1-1.9 x IceCube
~3.5-~6 x IceCube
1st network of neutrino telescopes
measurement IceCube HE neutrino signal
neutrino astronomy
KM3NeT
funded
Letter of Intent
ESFRI roadmap
phase 1
phase 1.5
phase 2
19
)* depending on funding

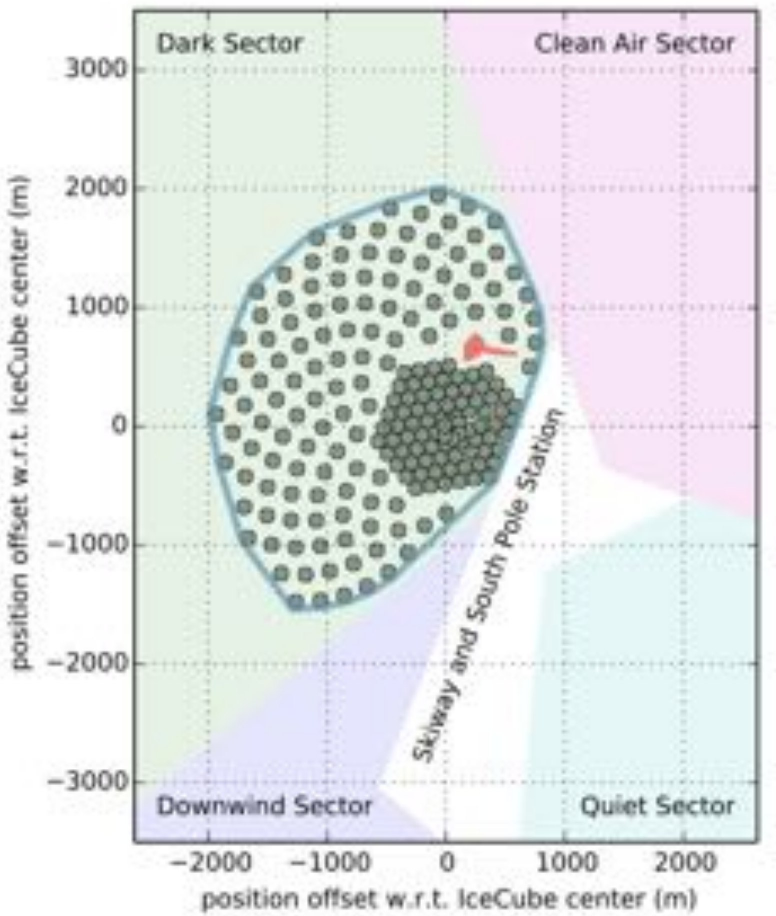
Performance



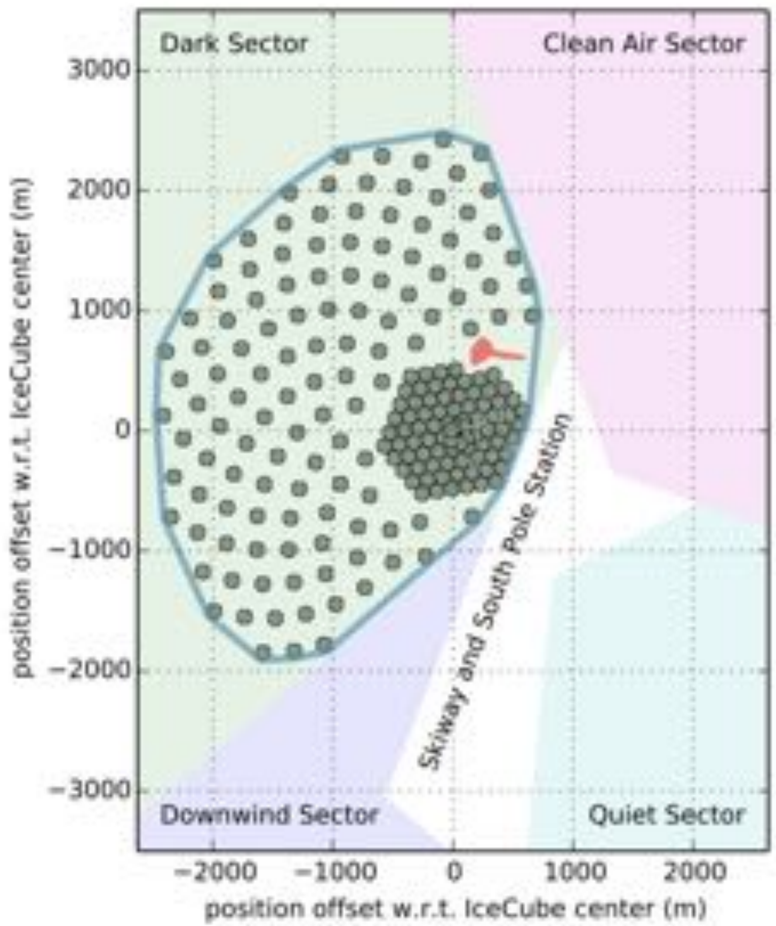
Detailed investigation of „IceCube signal" within a few years, with different *field of view*, different *systematics* and better *angular resolution*

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

86 strings with 240-340 m spacing

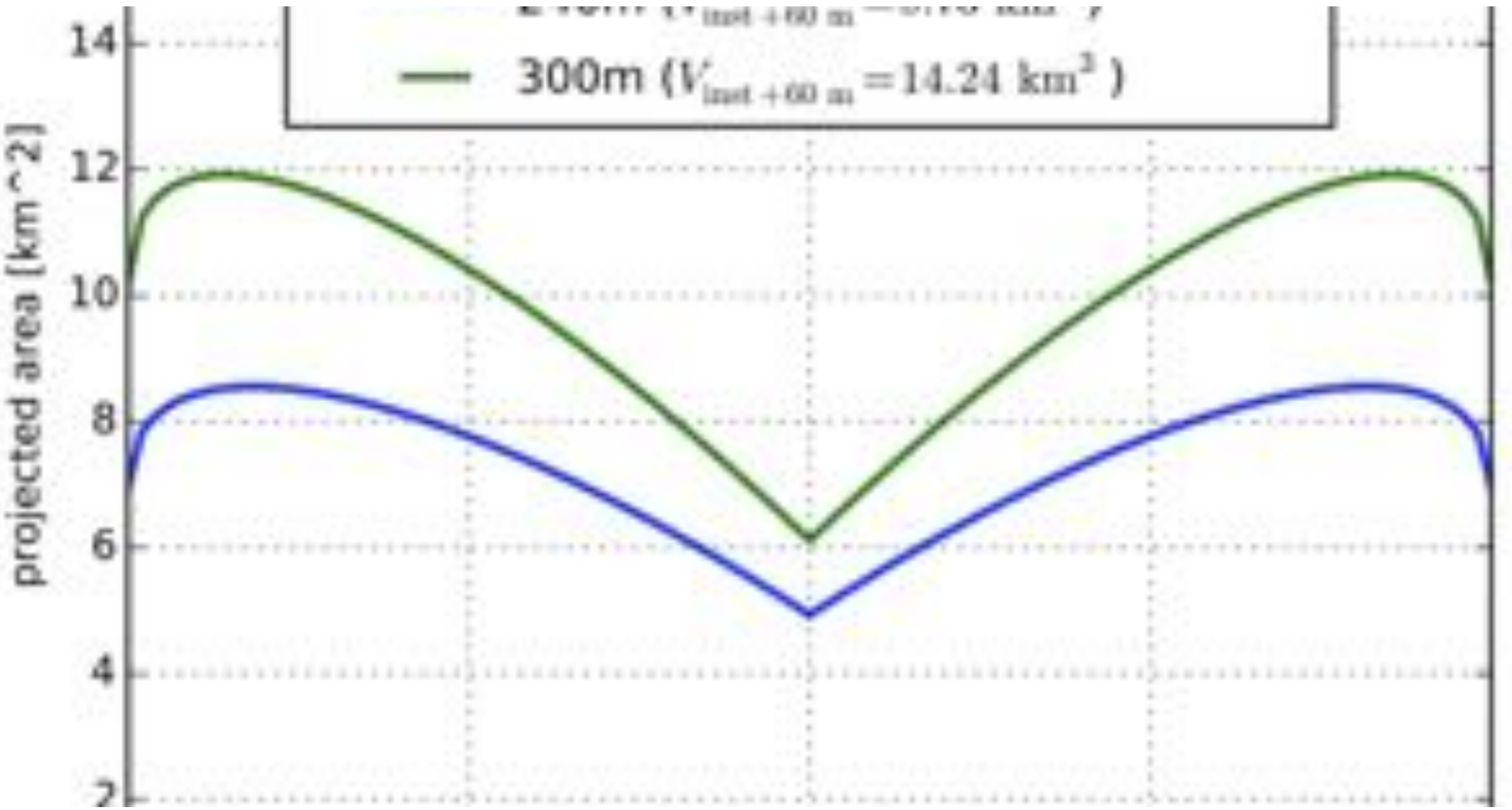


(a) 240 m string spacing ("benchmark")



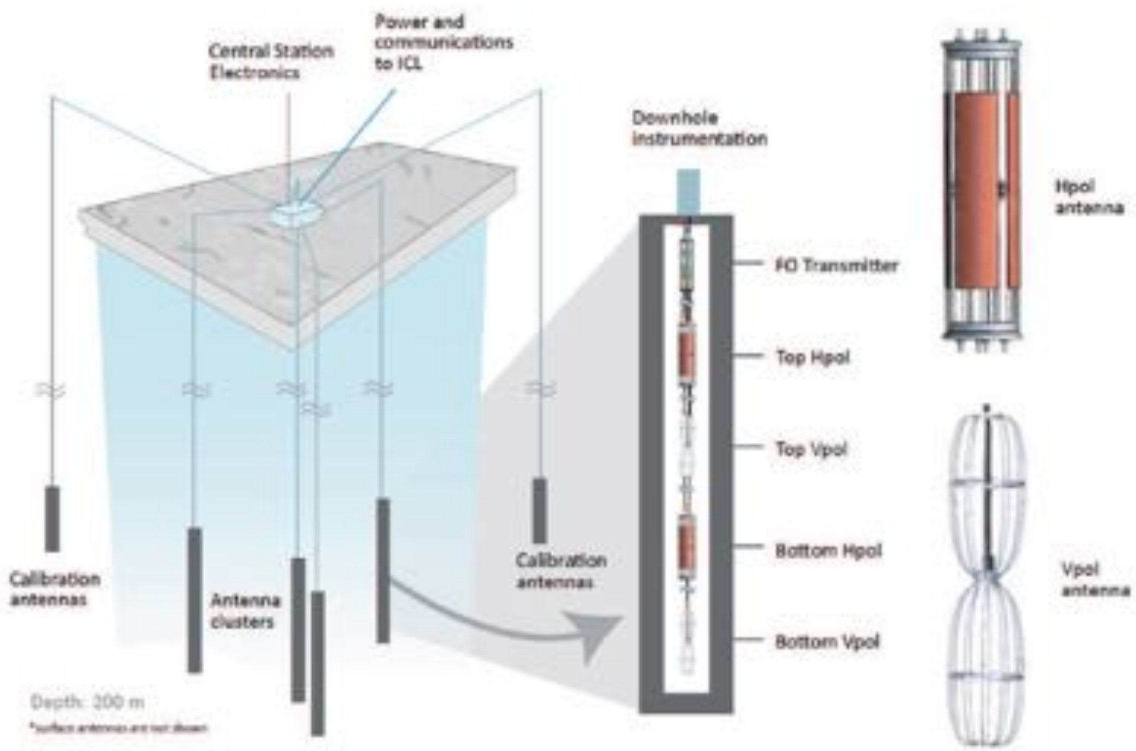
(b) 300 m string spacing

Effective volume

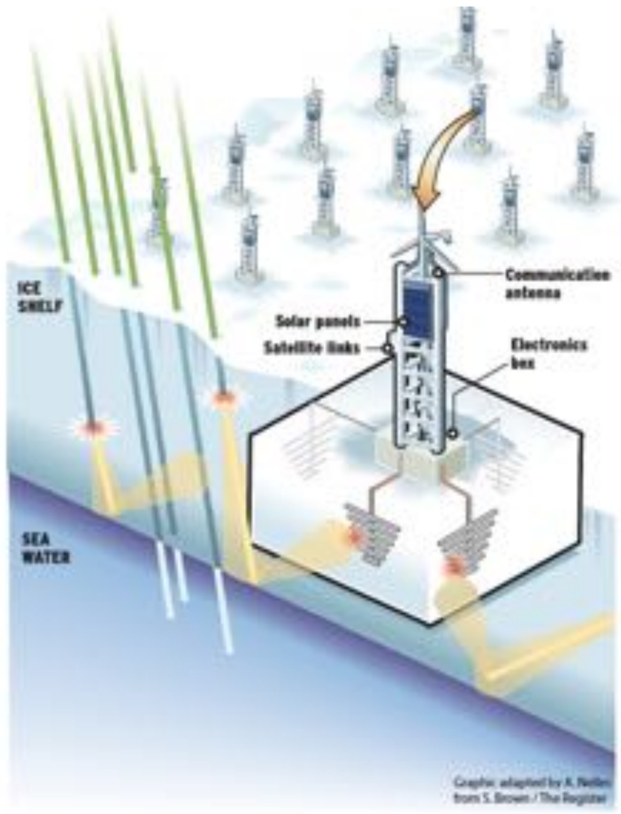


IceCube Collaboration, **arXiv:1412.5106**

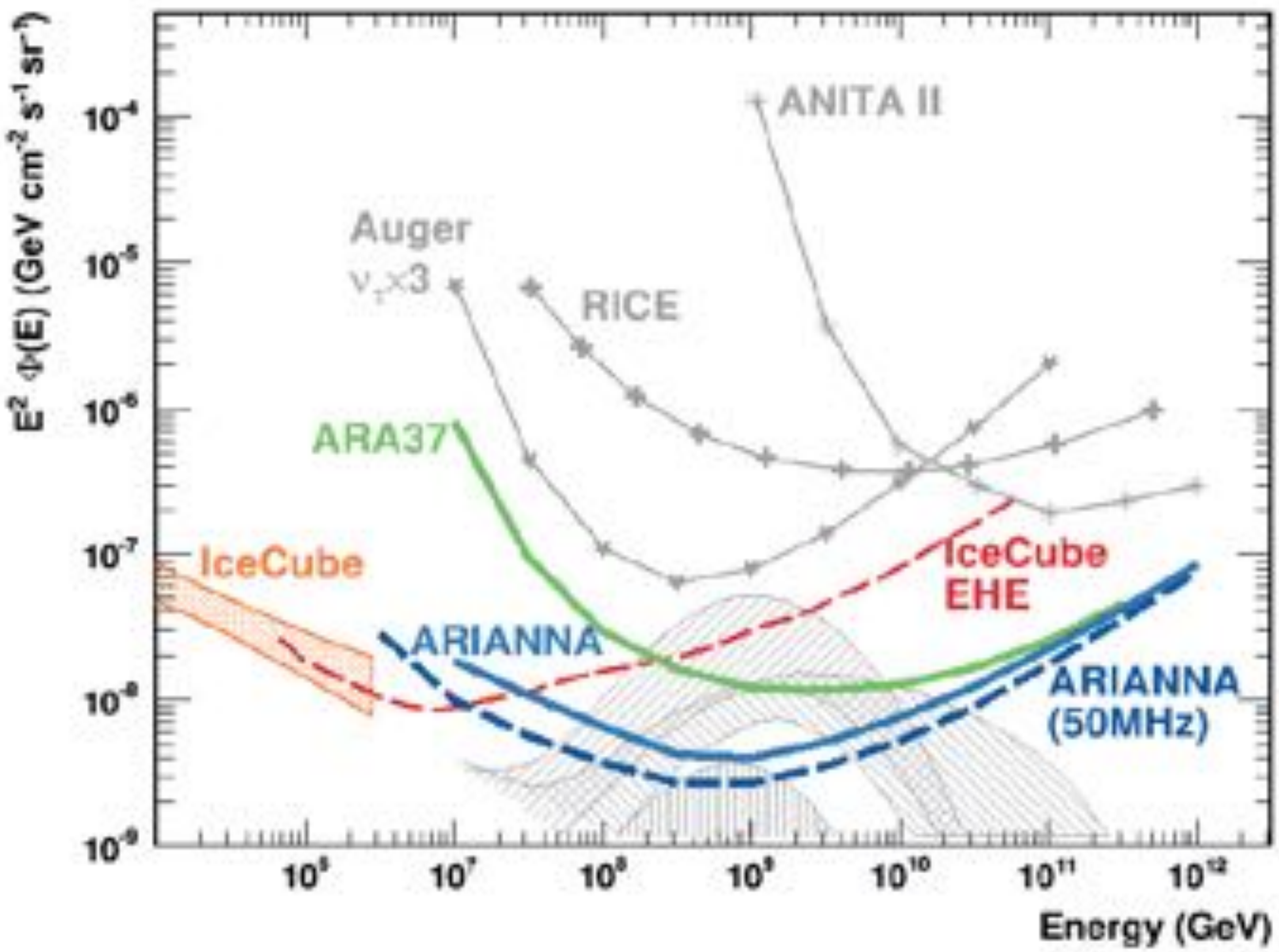
ARA radio detector South pole



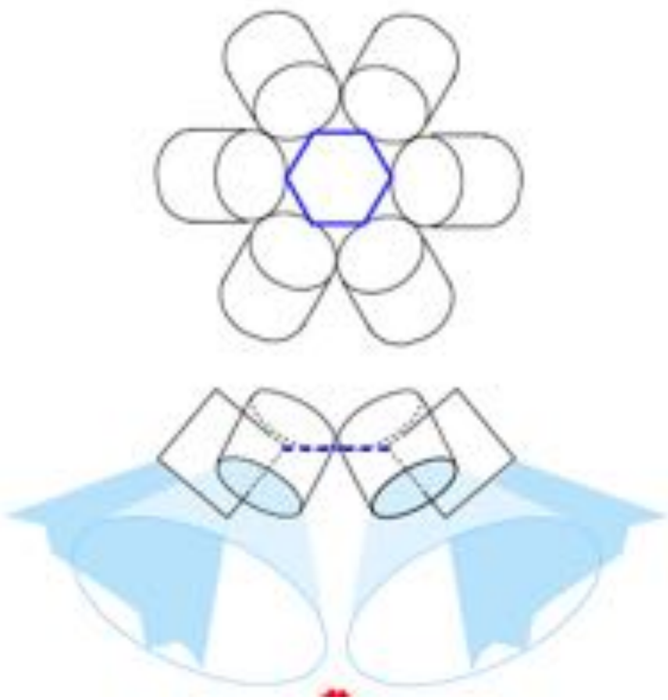
ARIANNA radio detector Antarctics

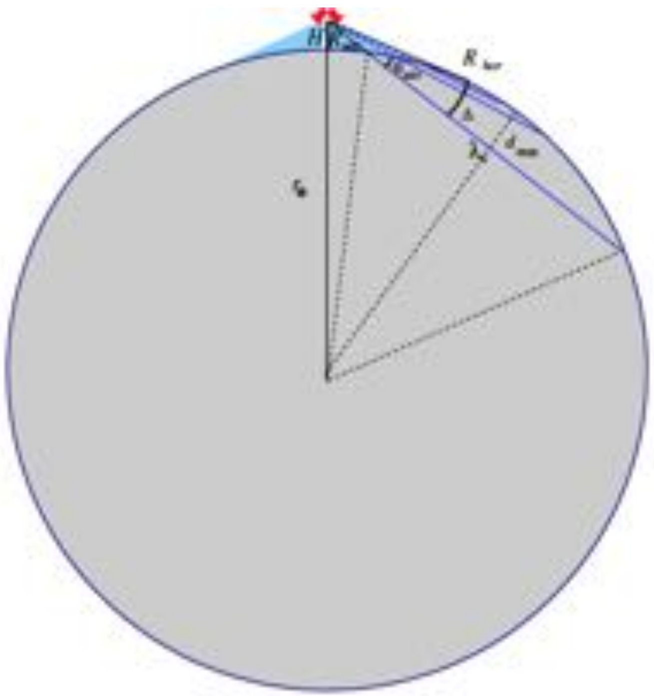


Future radio detection

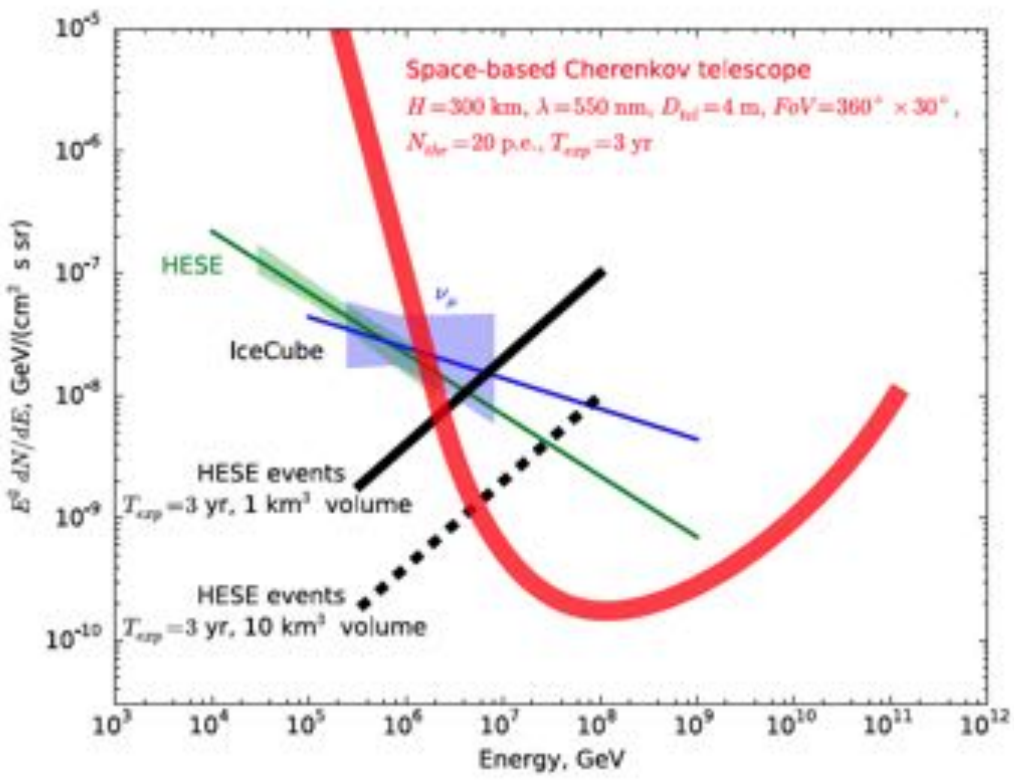


Detection of neutrinos from space

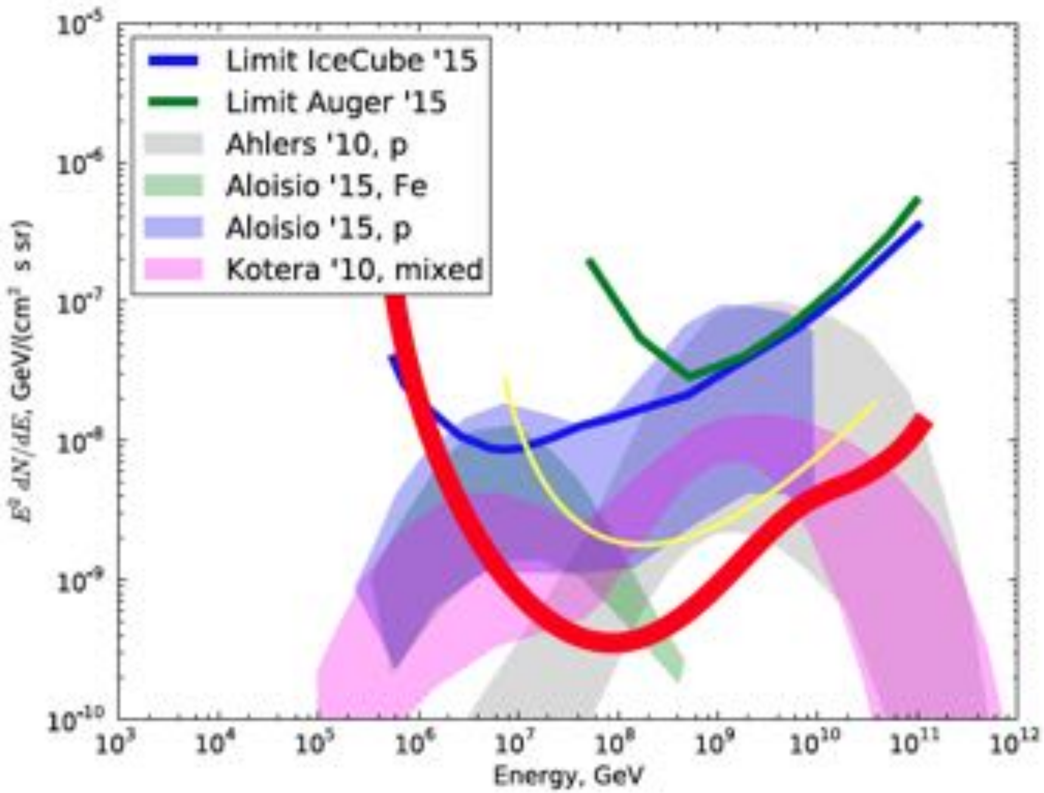




Space telescope project



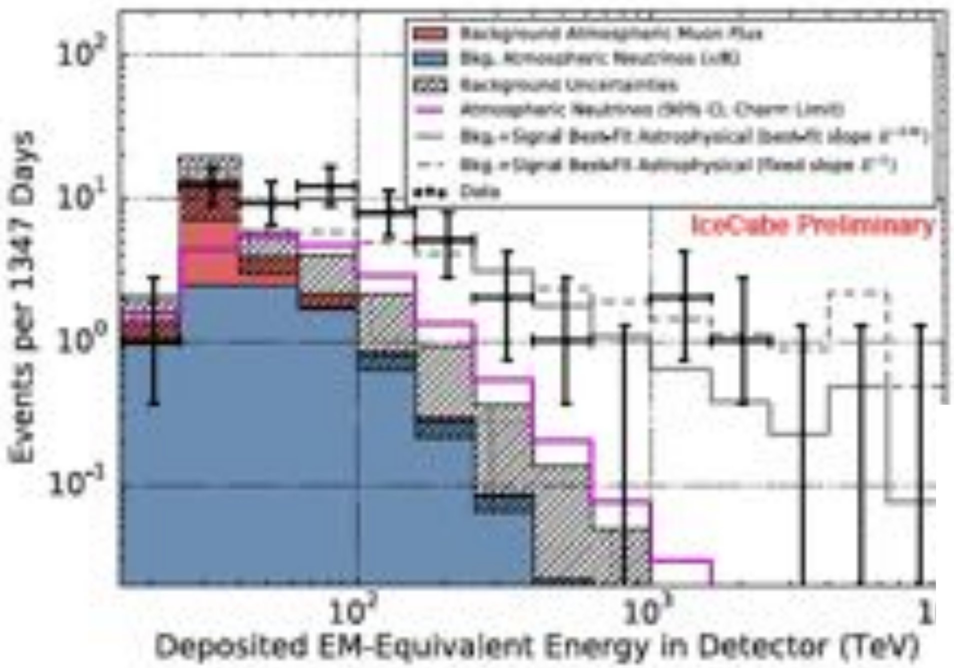
Detection of GZK neutrinos



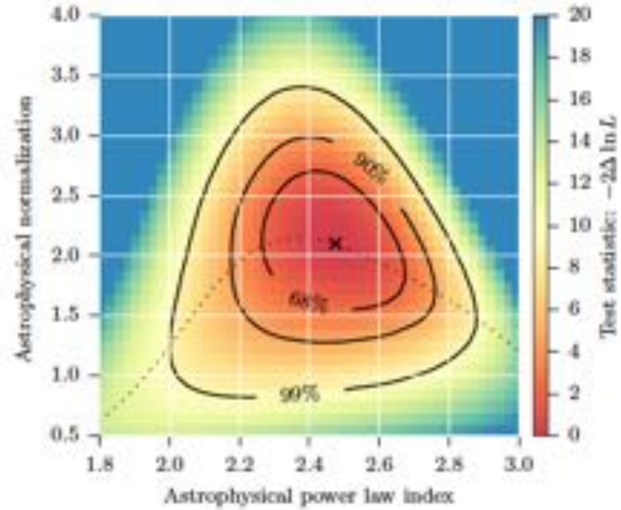
What we can expect from future detectors

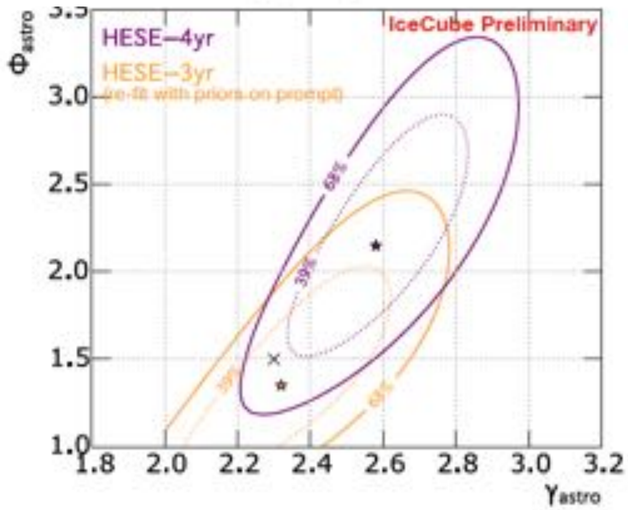
- Split Galactic and extragalactic contribution in diffuse flux
- Find first point/extended sources
- Limit or find extragalactic flux above PeV
- Help to find sources of PeV Galactic cosmic rays

IceCube data 4 yrs

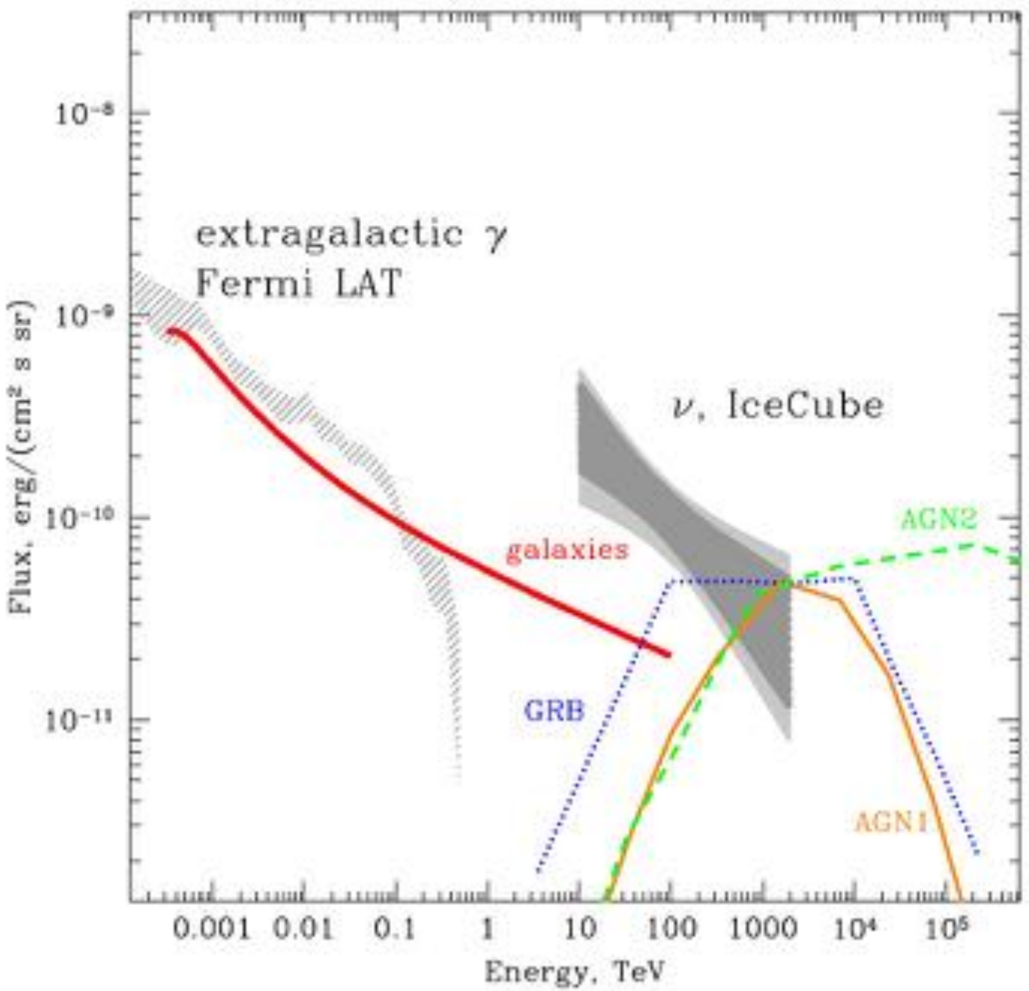


IceCube, ICRC 2015





IceCube + Fermi LAT



A.Neronov, D.S. arXiv:1412.1690

Theoretical predictions of neutrino flux

EXPECTED NEUTRINO FLUXES

Local optical depth of protons:

τ(PeV)=0.003

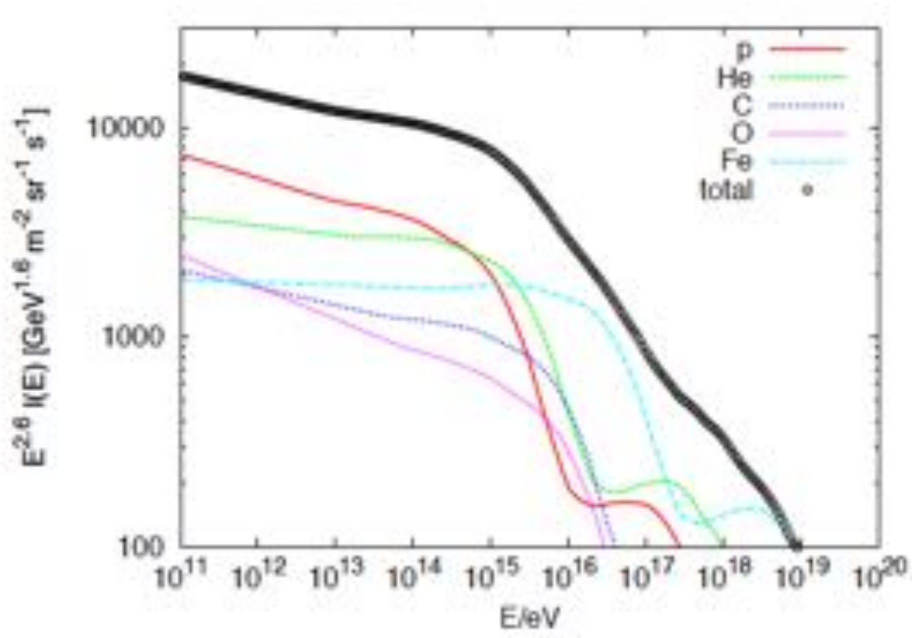
τ(10 PeV)=0.0002

E^2F_ν(PeV)=0.2 eV/cm^2/s/sr

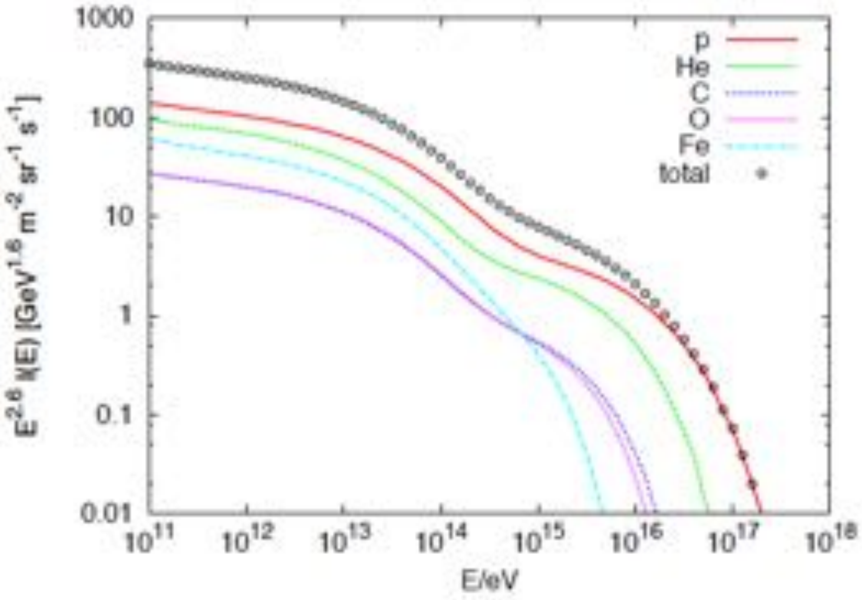
E^2F_ν(100 TeV)=3 eV/cm^2/s/sr

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_{cl} at distance d:

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

Flux from GMC 10^5 Msun at 1 kpc:

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

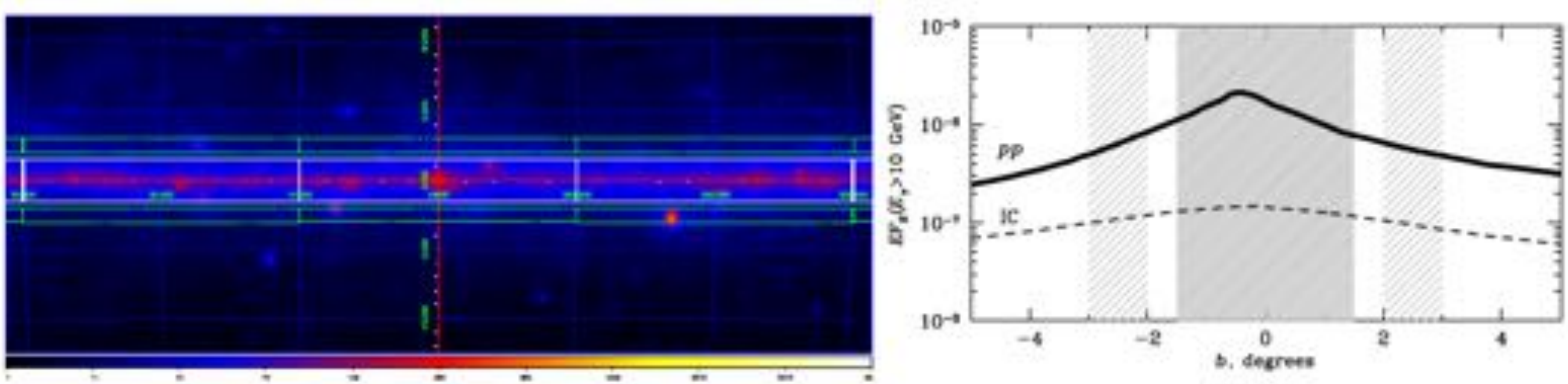
M.Kachelriess and S.Ostapchenko, arXiv:1405.3797

Galactic neutrino fluxes

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

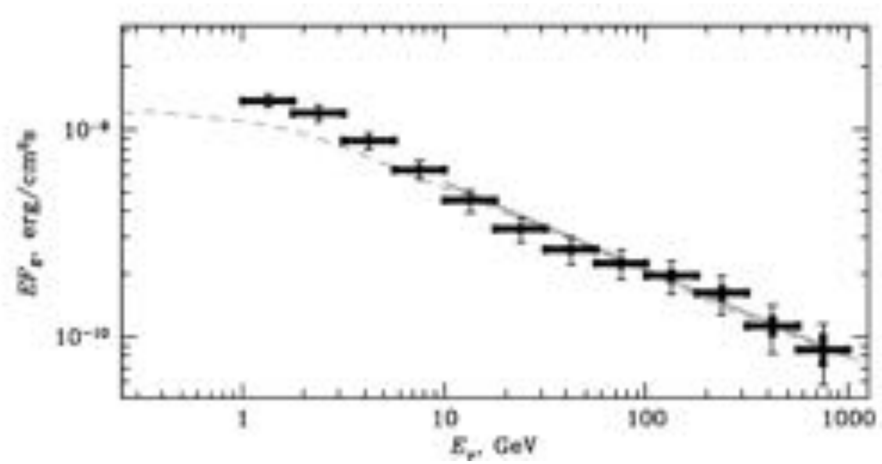
CR spectrum in MW and LMC from gamma-rays

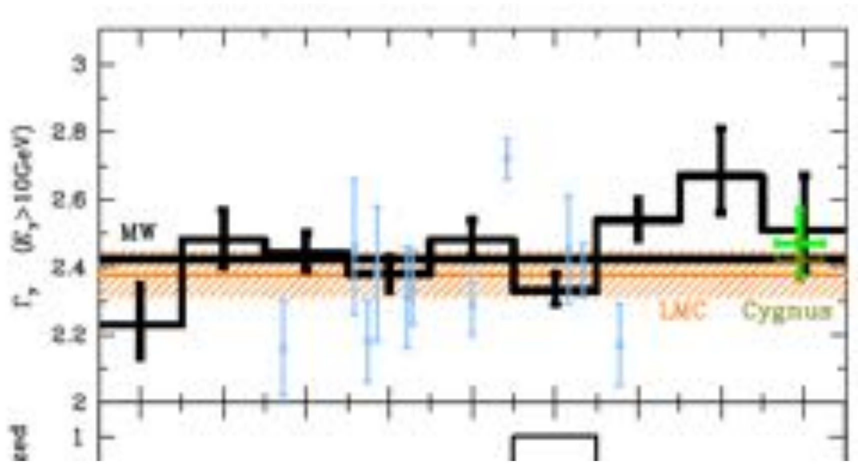
Milky Way inner Galaxy Fermi E>10 GeV



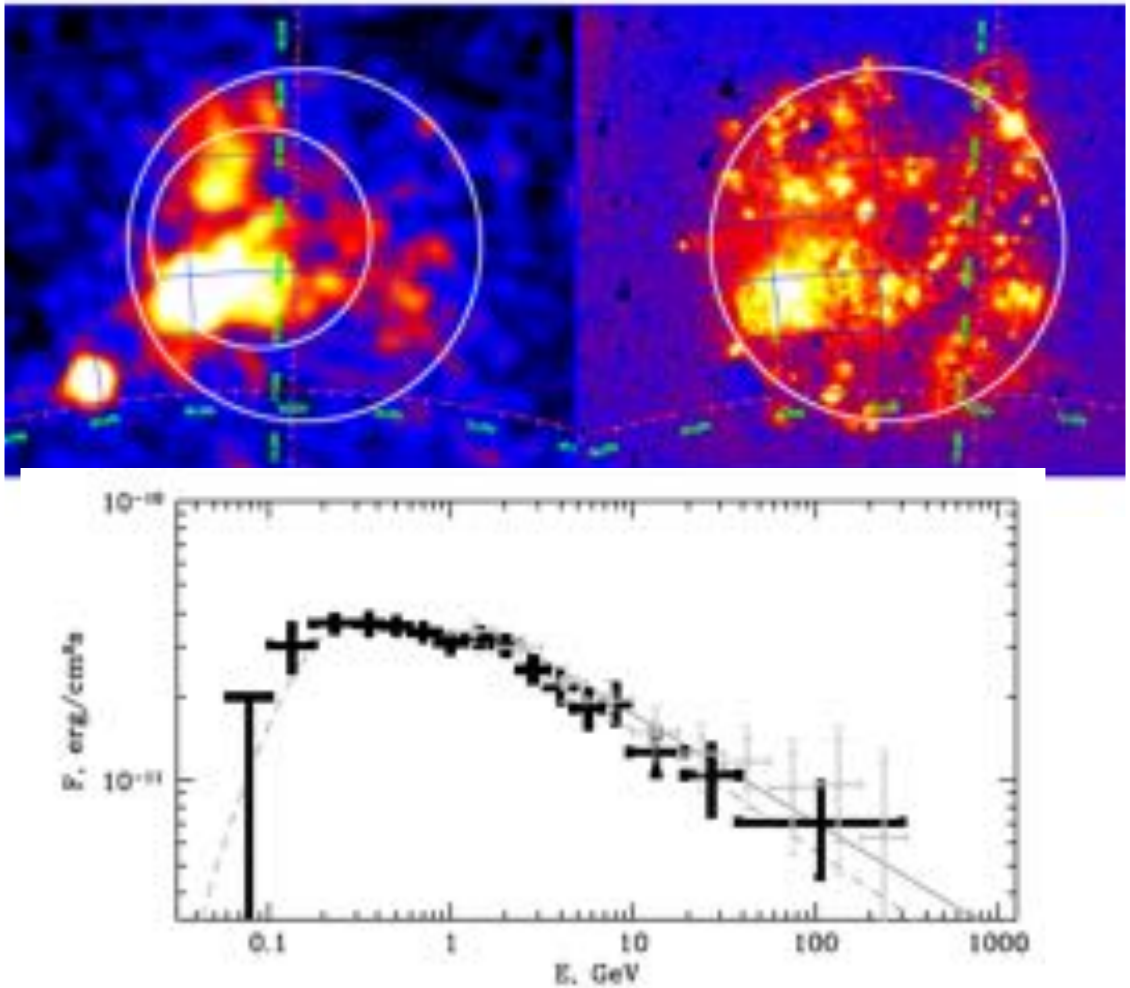
A.Neronov and D.Malishev, arXiv: 1505.07601

Milky Way inner Galaxy
Fermi E>10 GeV: spectrum 2.45



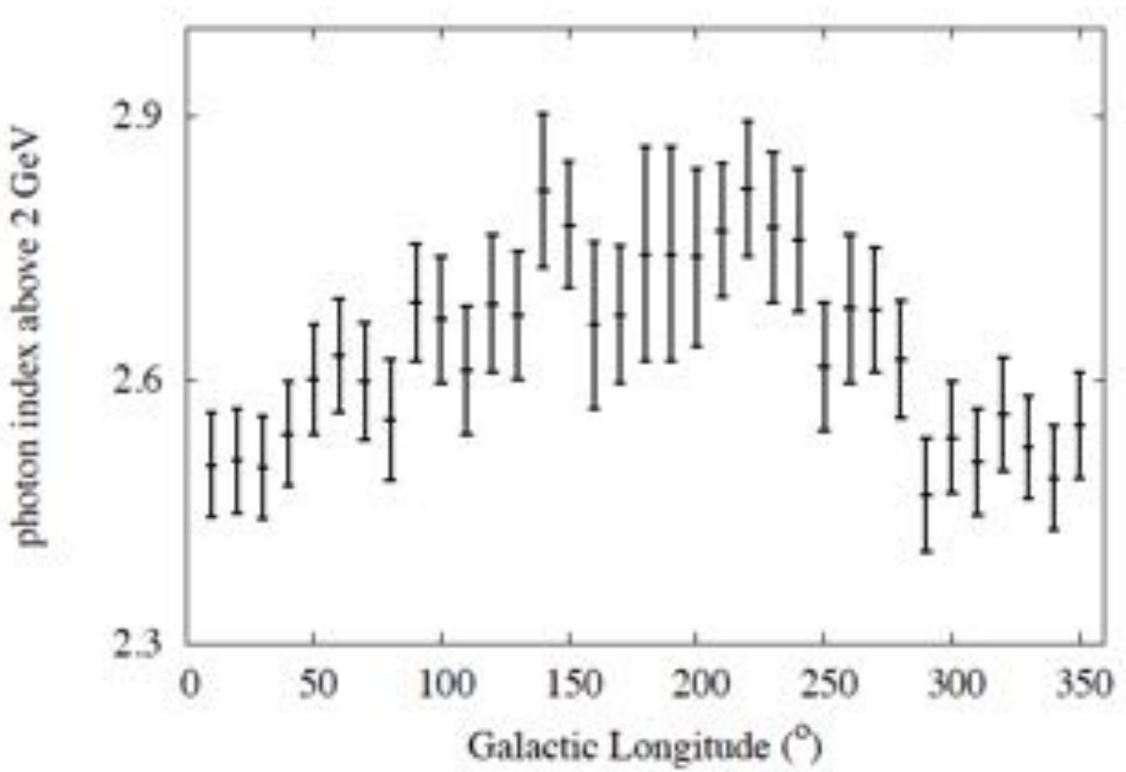


In LMC average proton spectrum 2.45



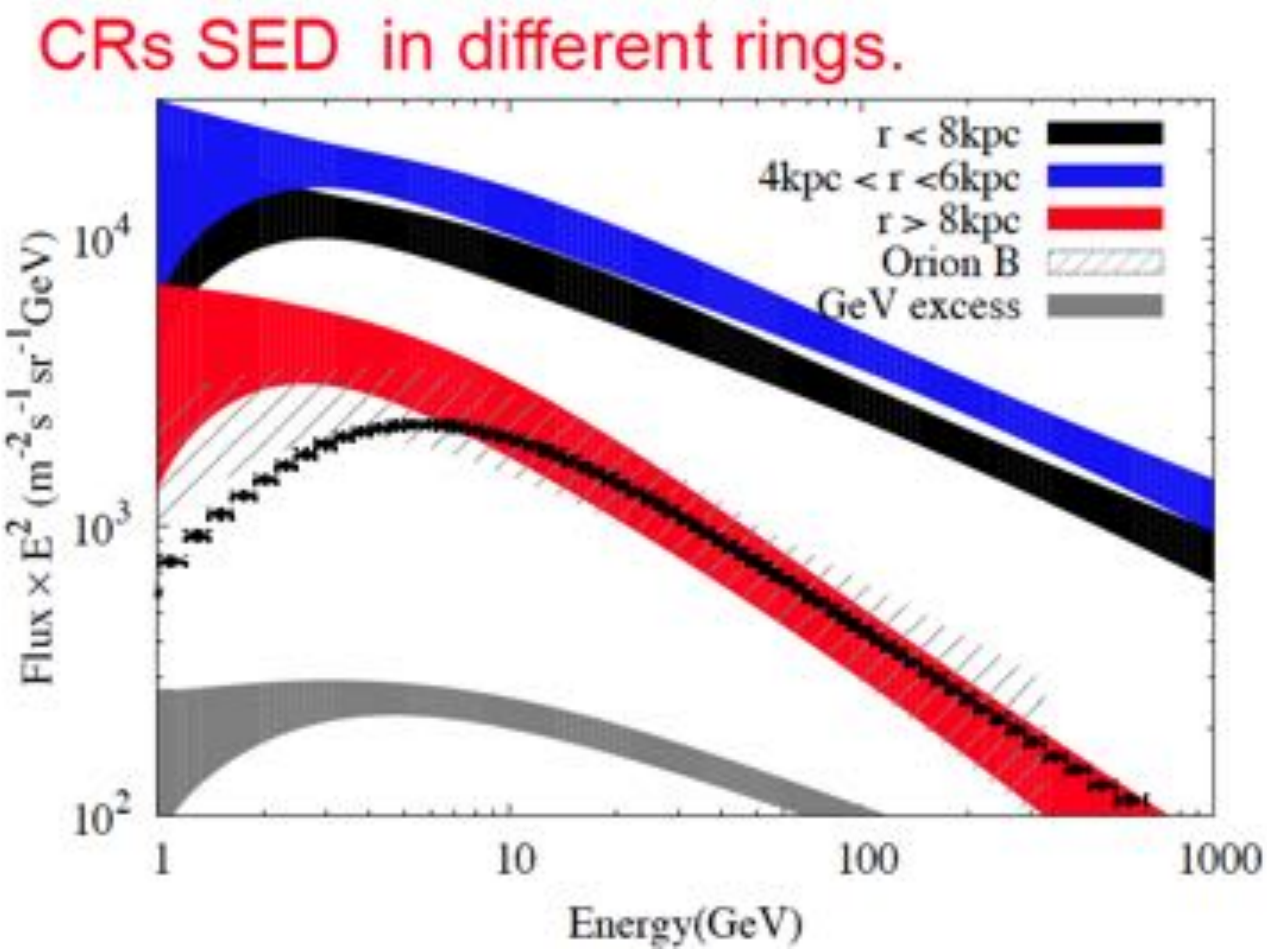
A.Neronov and D.Malishev, arXiv: 1505.07601

Proton flux above 2 GeV



R.Yang, F.Aharonian and C.Evoli PRD 93, 123007, 2016

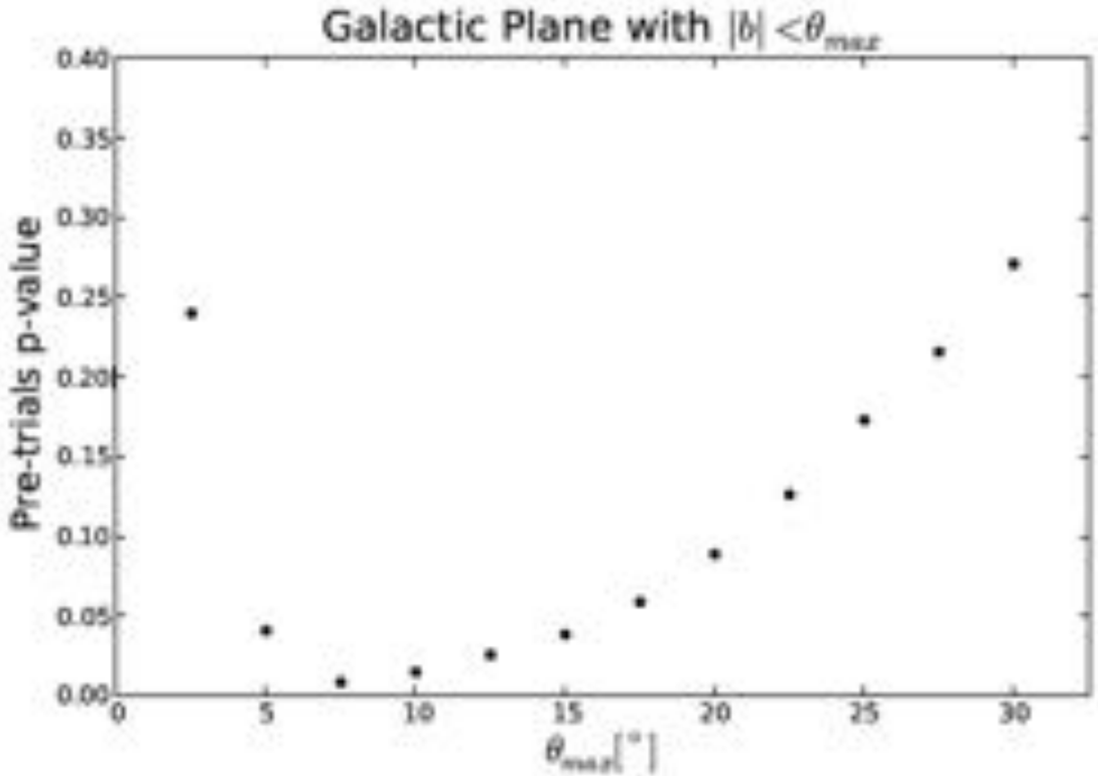
Fit with gas ring template



R.Yang, F.Aharonian and C.Evoli PRD 93, 123007, 2016

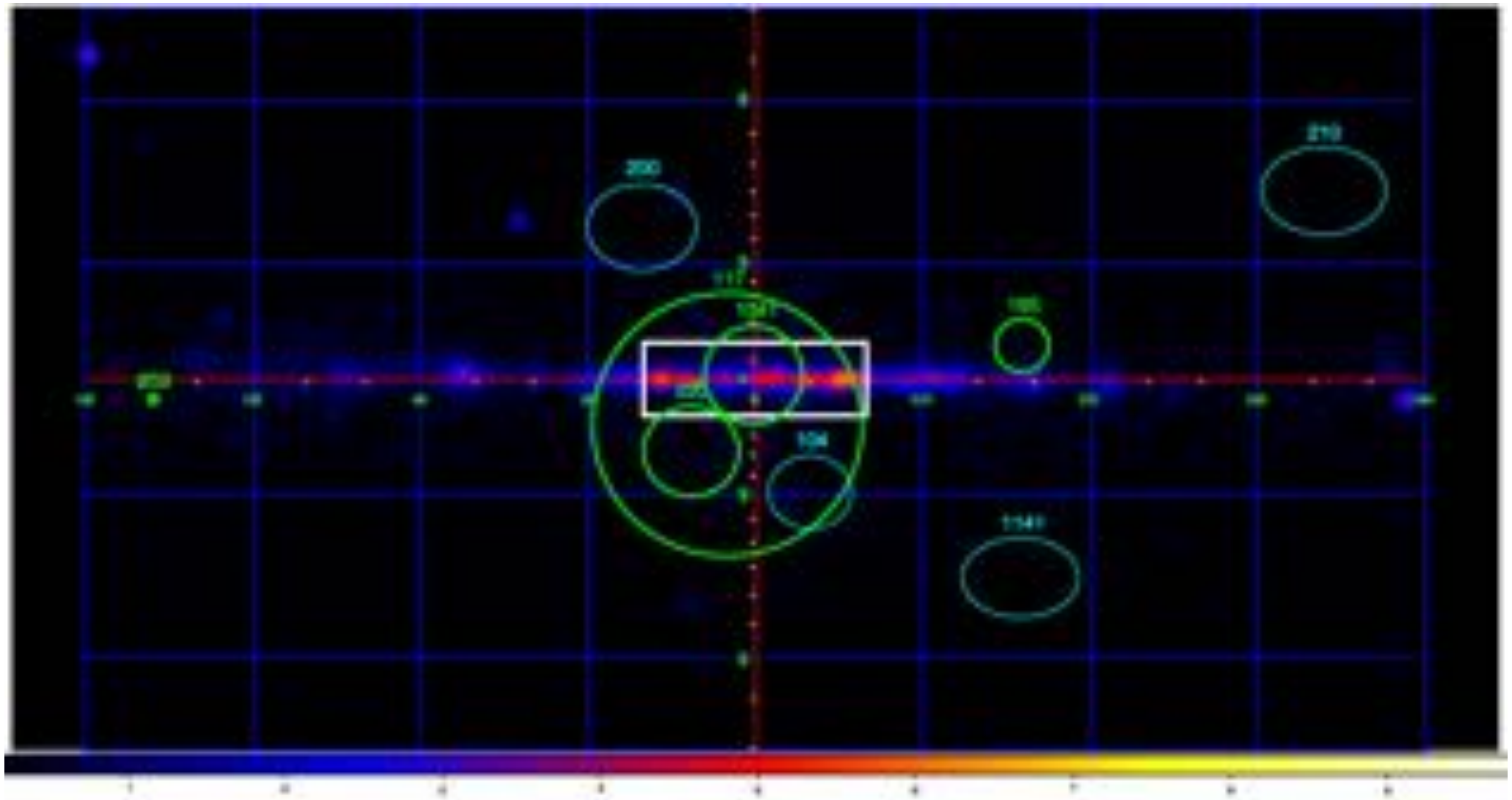
Neutrino flux from Milky Way

Galactic plane: 2% by chance



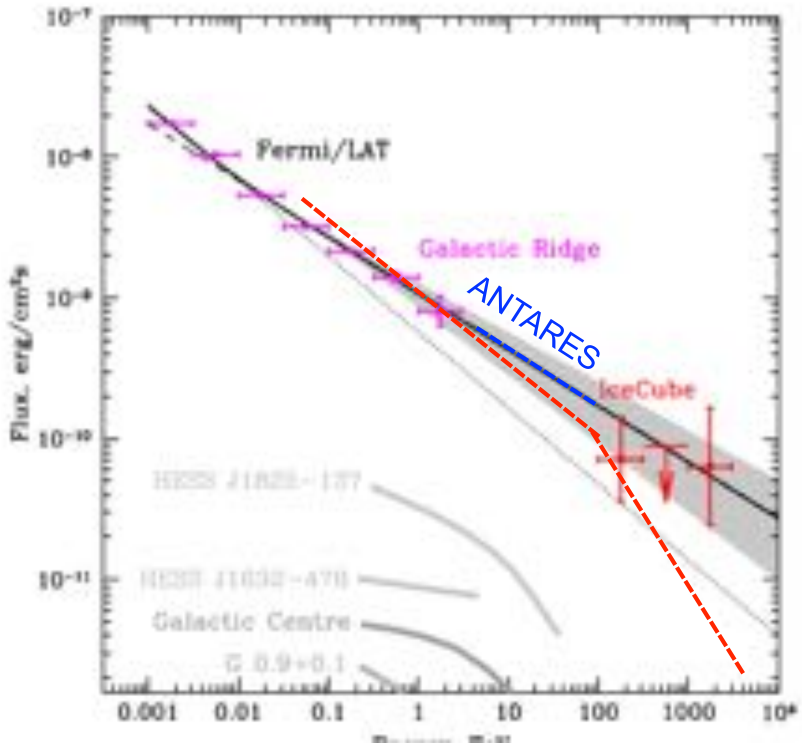
ICECUBE collaboration, 1405.5303

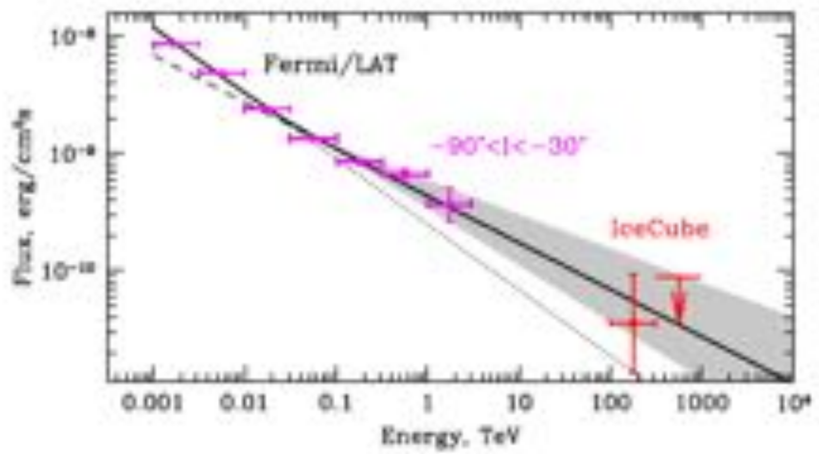
Half of ICECUBE events E>100 TeV are in Galactic plane. Are they correlate with gamma-rays?



A.Neronov, D.S. and C.Tchernin, arXiv:1307.2158

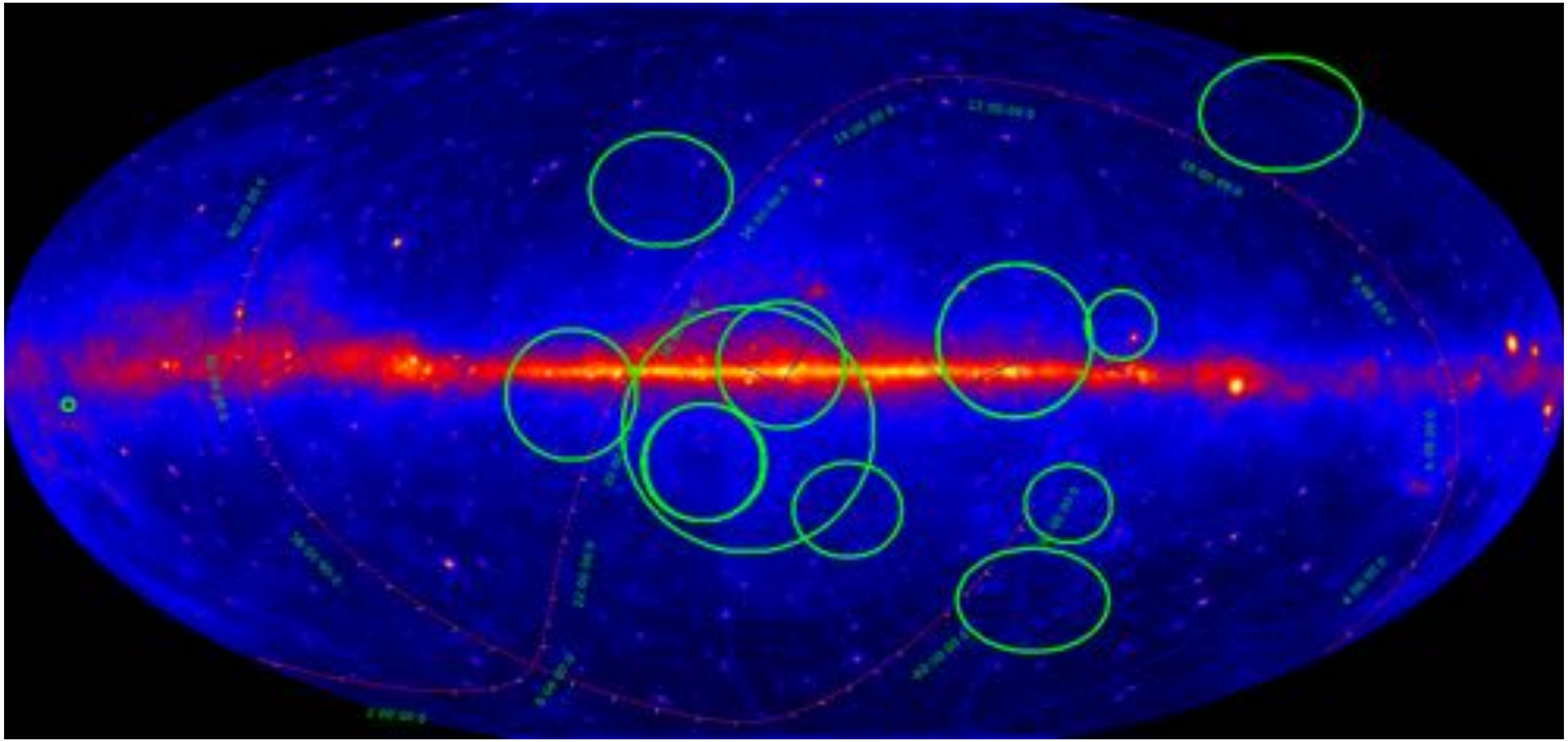
Real multimessenger fluxes, alpha=2.5



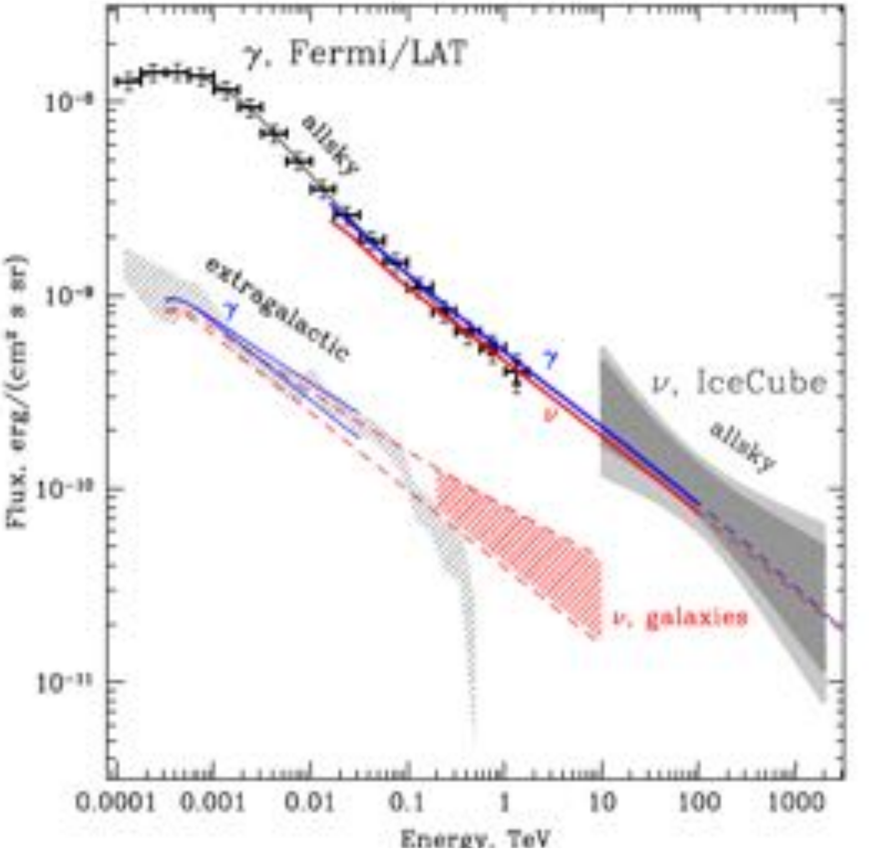


V.Berezinsky & A.Smirnov 1975

IceCube neutrino sky map
3 years E> 100 TeV

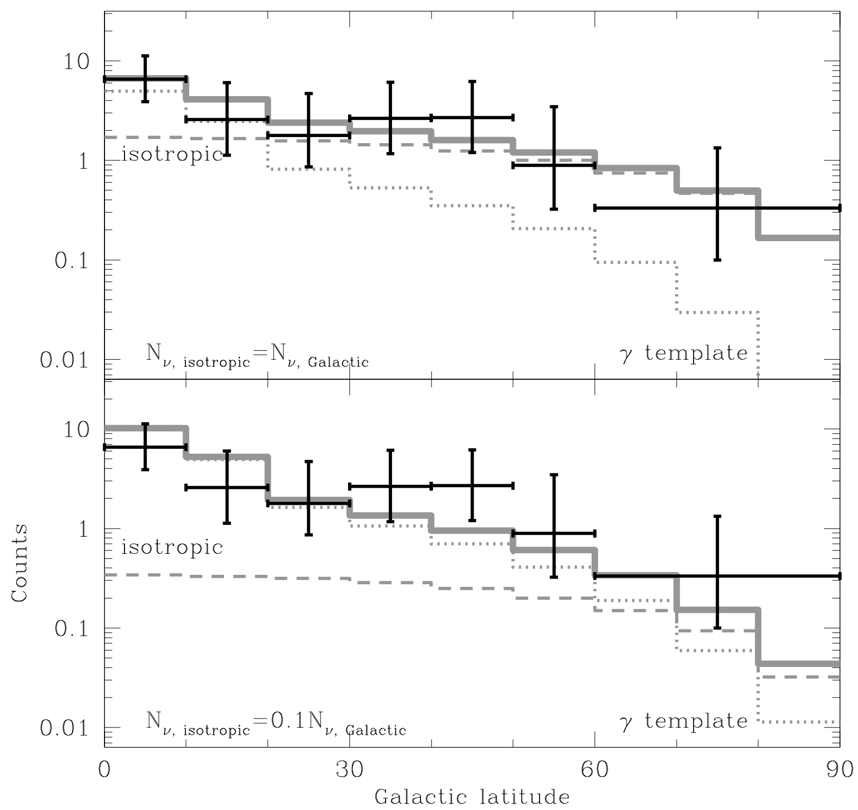


IceCube + Fermi LAT all sky: protons 1/E^2.5

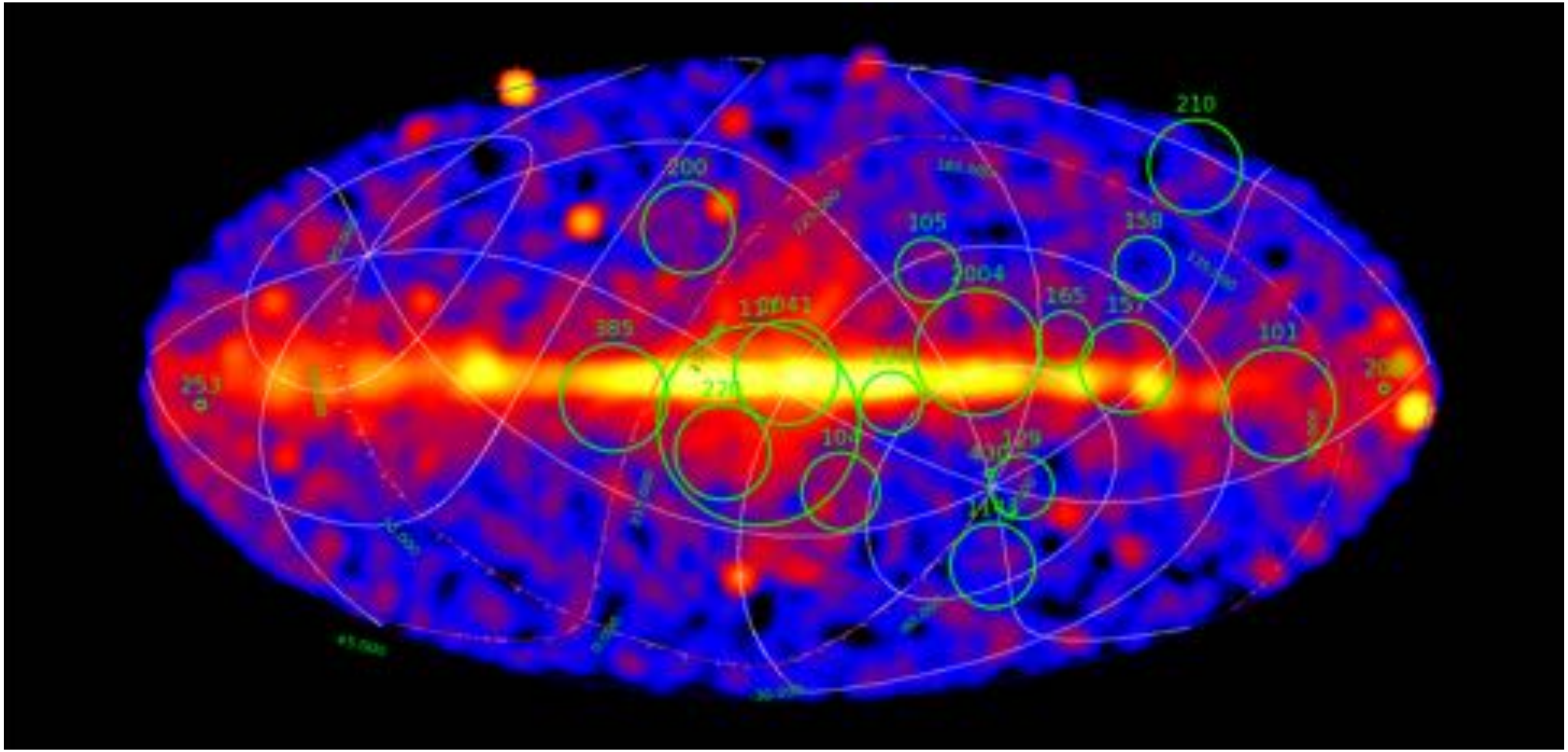


A.Neronov, D.S. arXiv:1412.1690

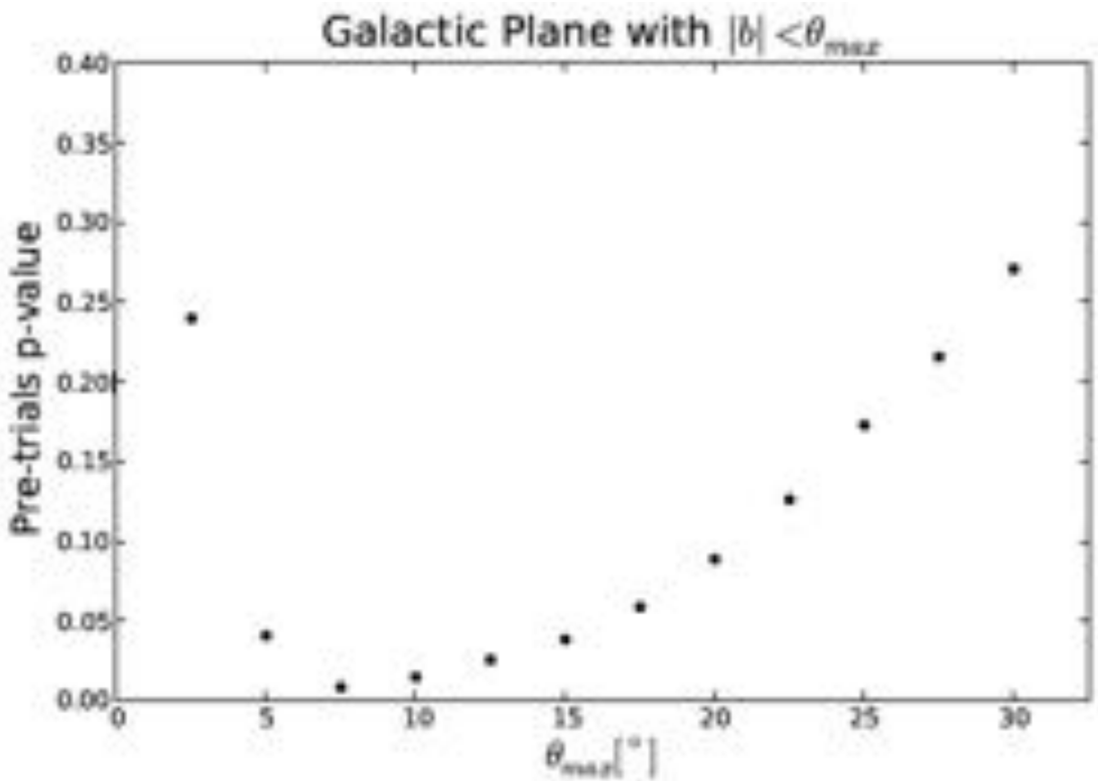
Neutrino flux as function of |b|



IceCube neutrino sky map 4 years E> 100 TeV and Fermi E>100 GeV 5 degree smoothed

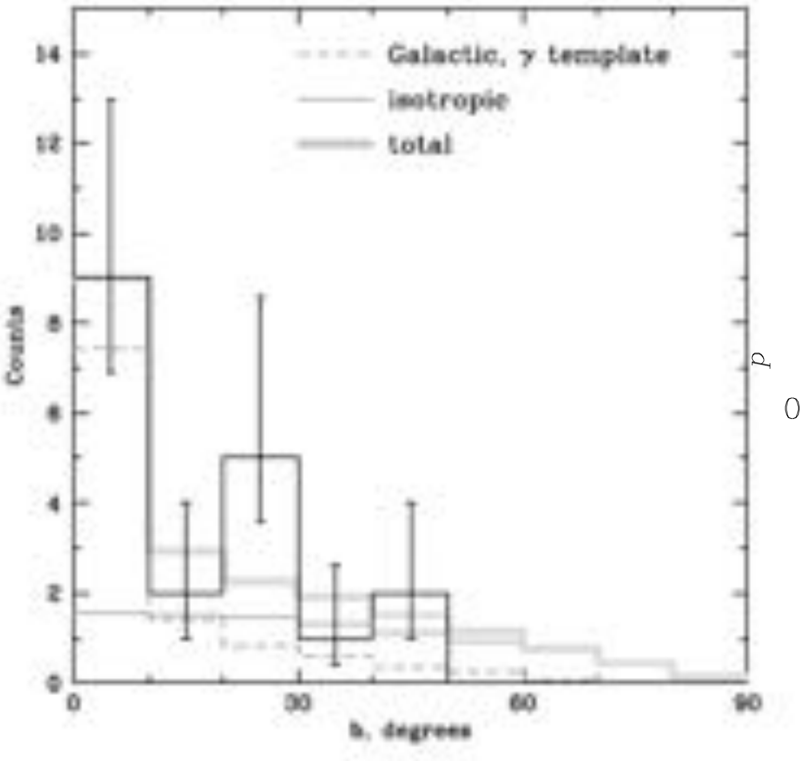


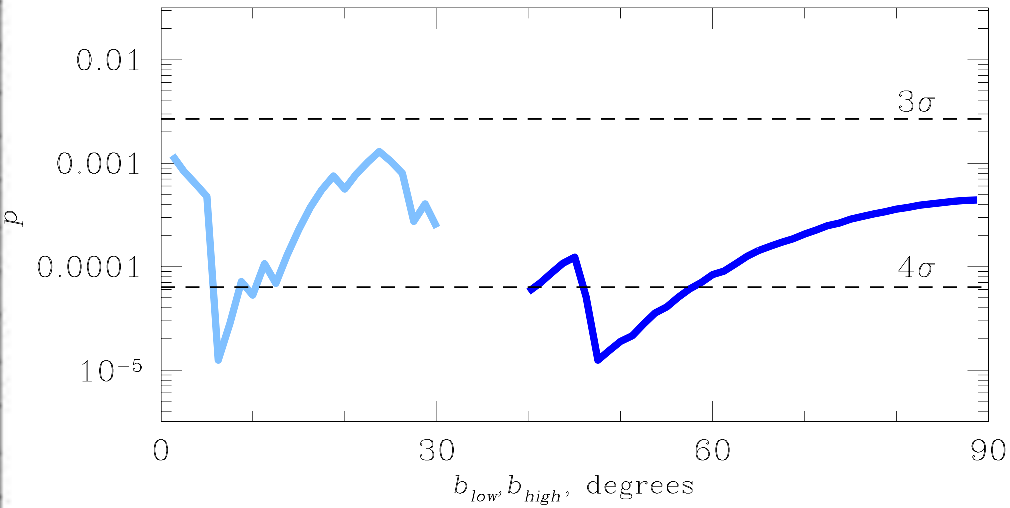
IceCube galactic plane 3 years: 2% by chance – small statistics



ICECUBE collaboration, arXiv:1405.5303

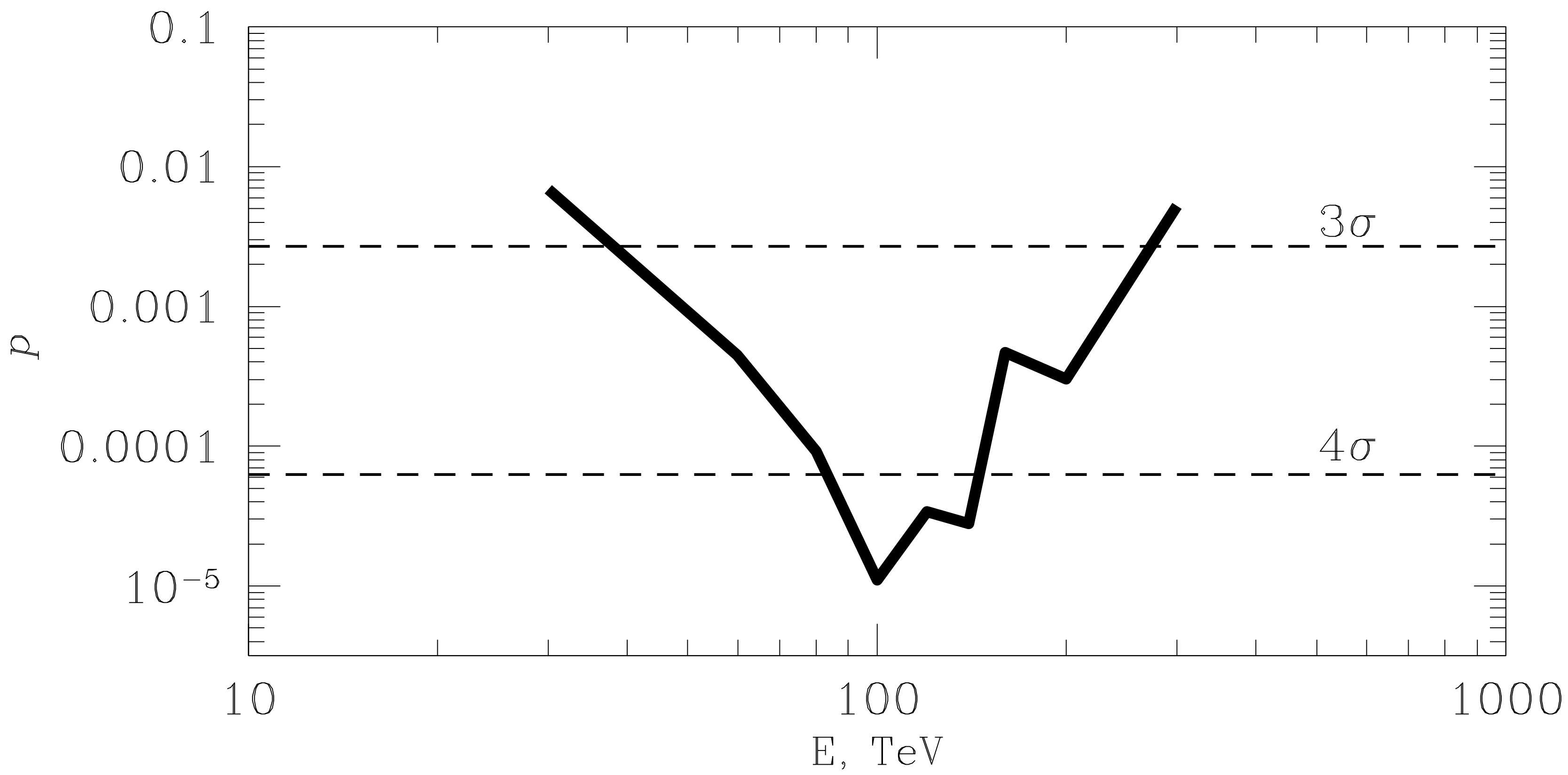
Evidence of Galactic component in 4 year IceCube data E>100 TeV





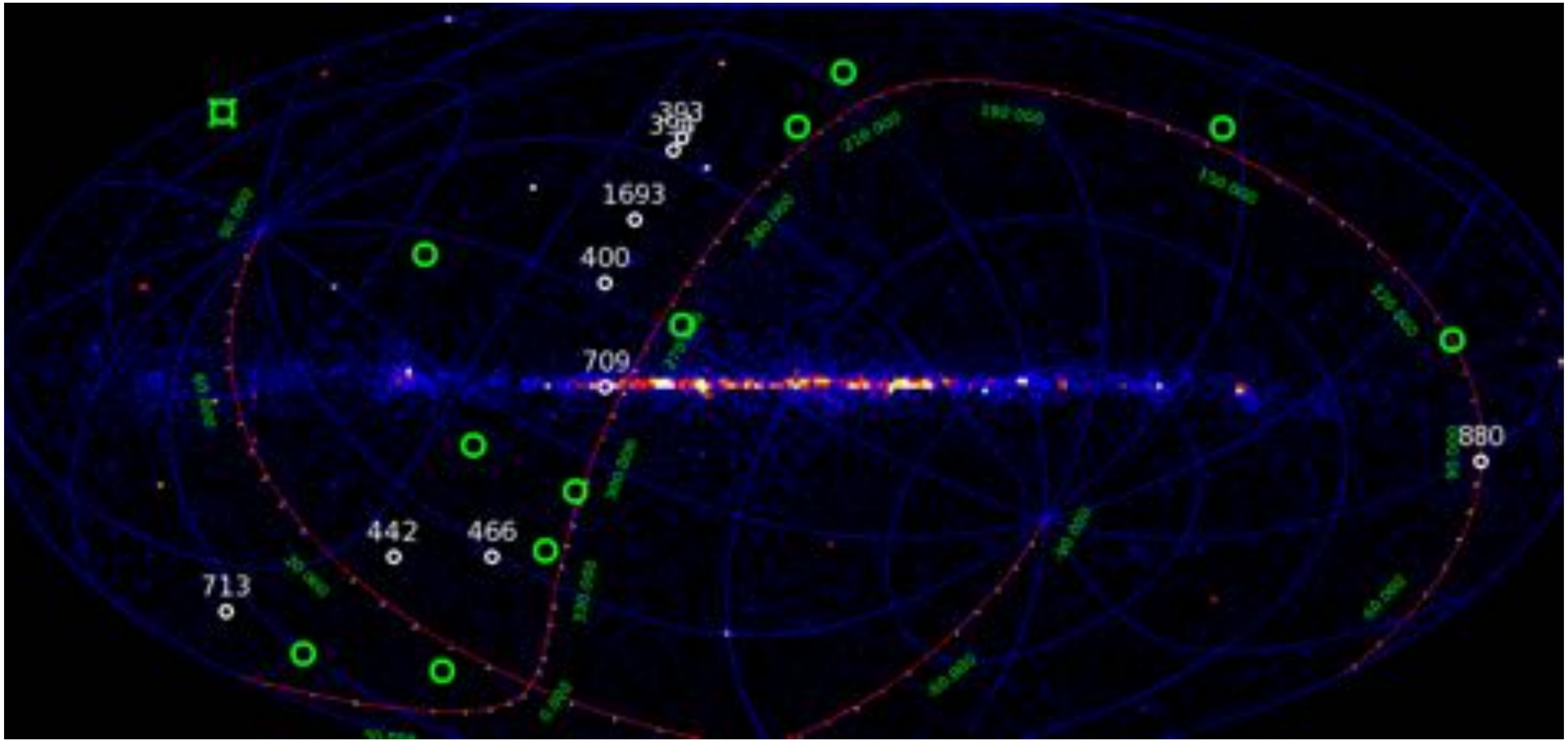
A. Neronov & D.S. arXiv: 1509.03522

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



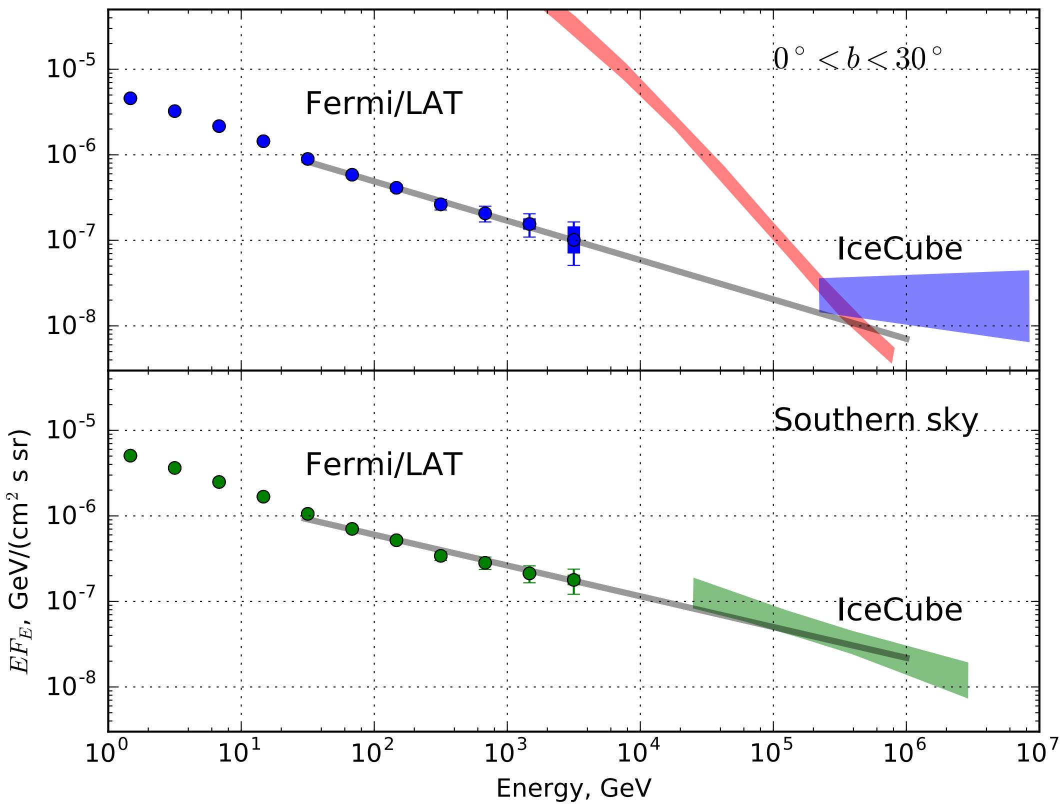
A. Neronov & D.S. arXiv: 1509.03522

Muon neutrinos



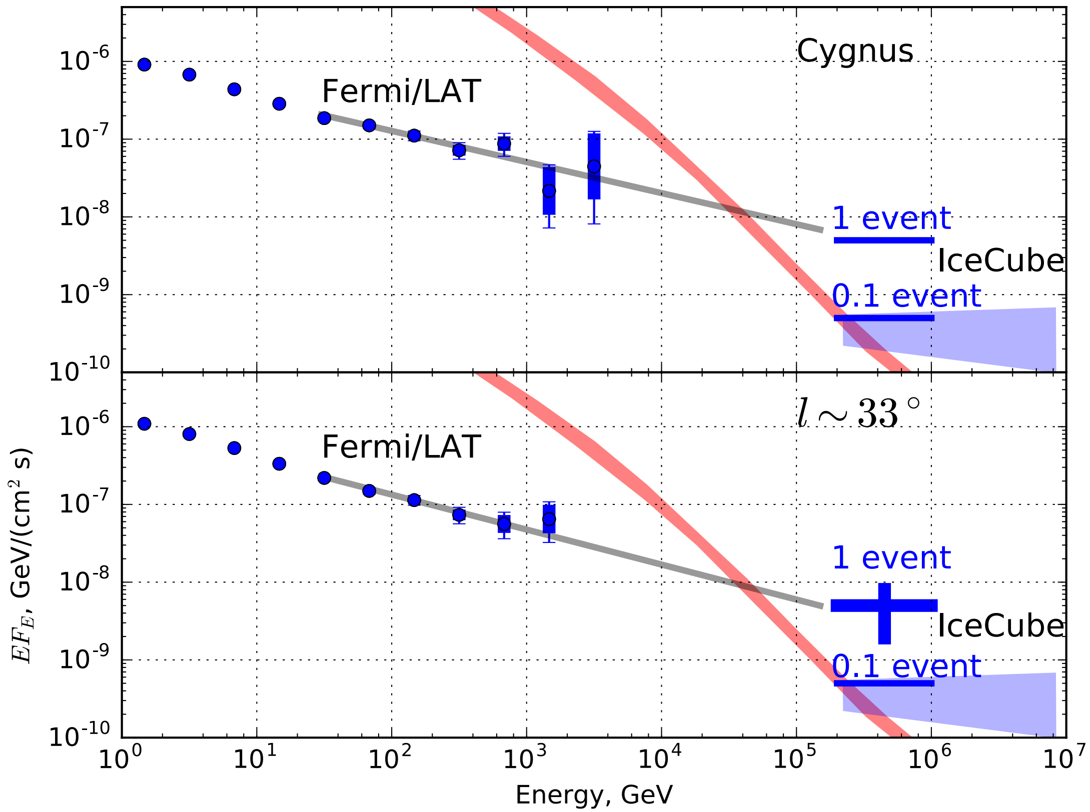
IceCube, ICRC 2015

North and South sky: IceCube



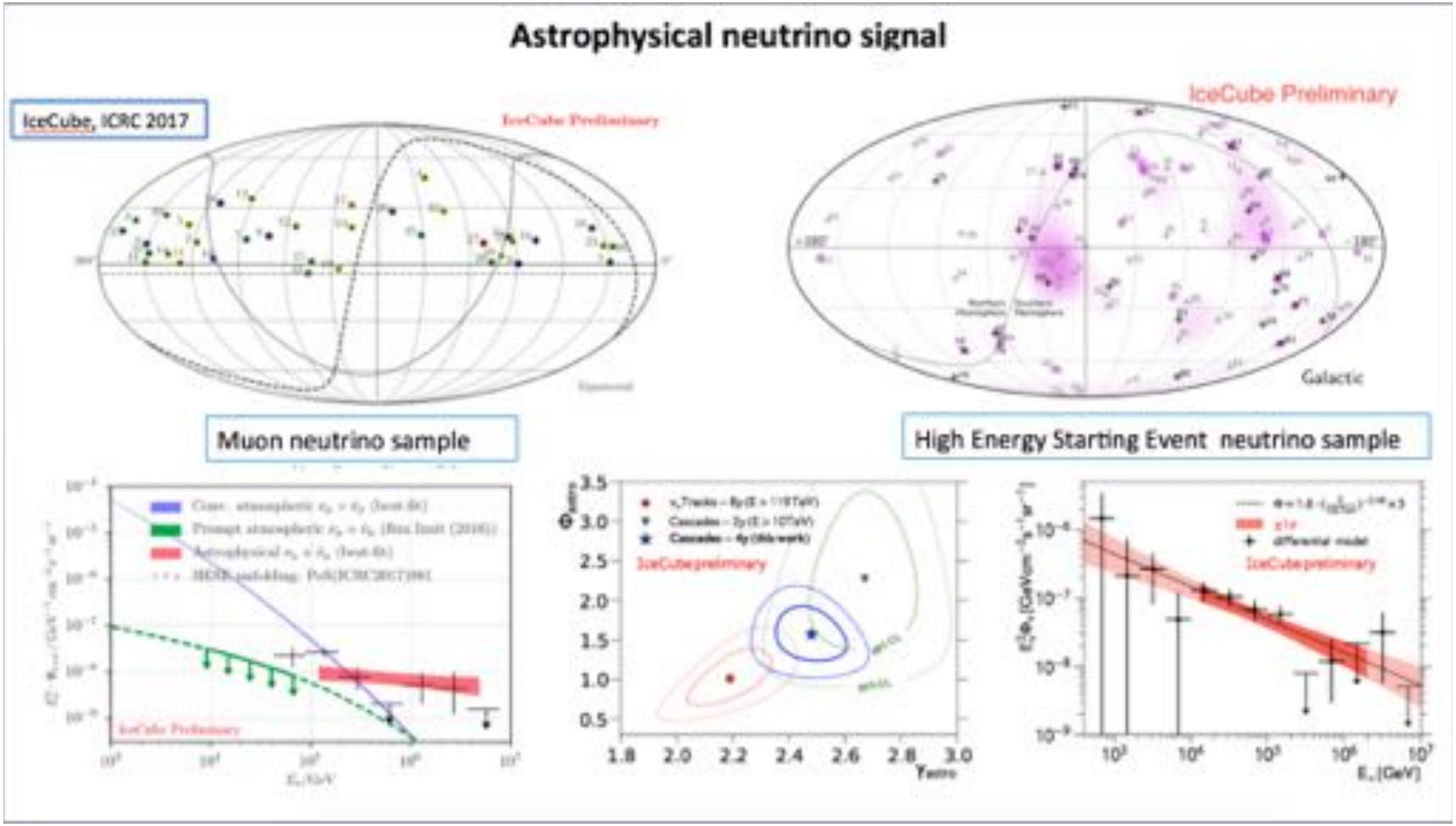
A. Neronov & D.S. arXiv: 1603.06733

First galactic diffuse sources

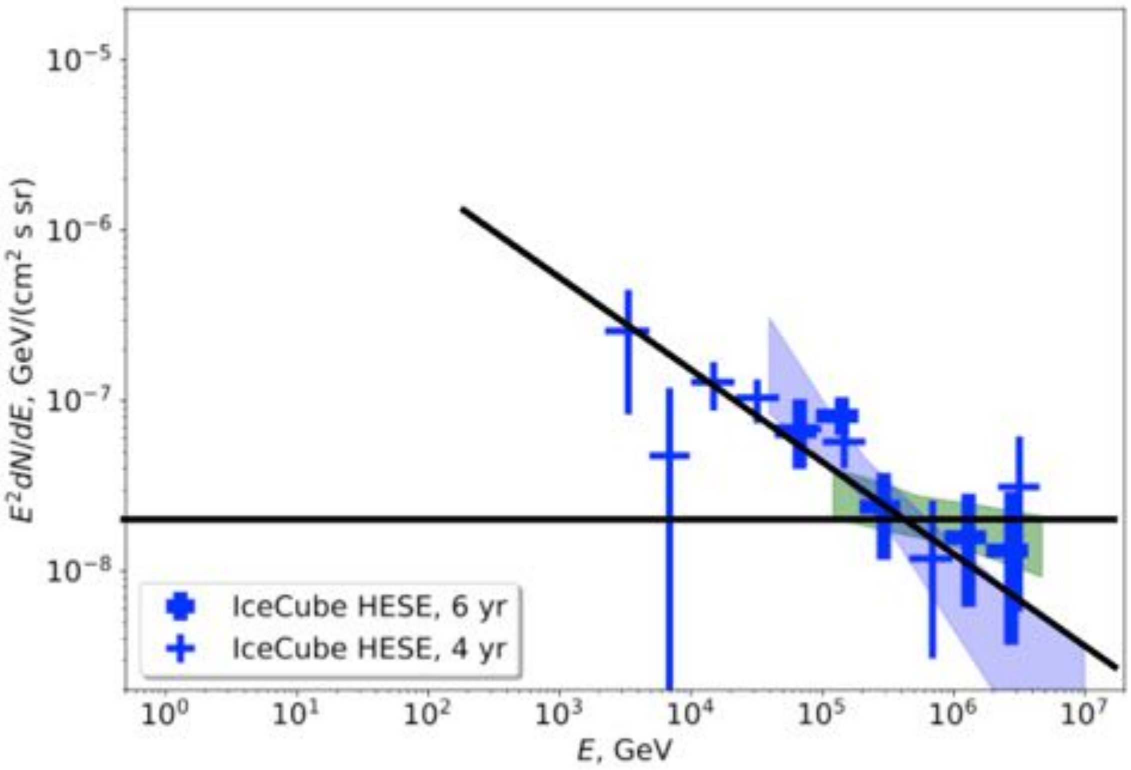


A. Neronov & D.S. arXiv: 1603.06733

IceCube ICRC 2017



IceCube data



Diffuse gamma-ray background

Pion production

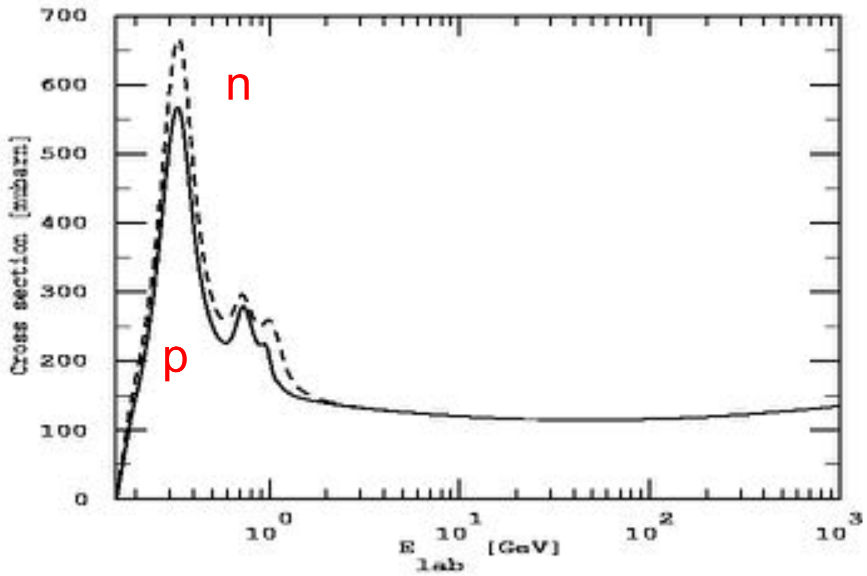
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

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

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

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

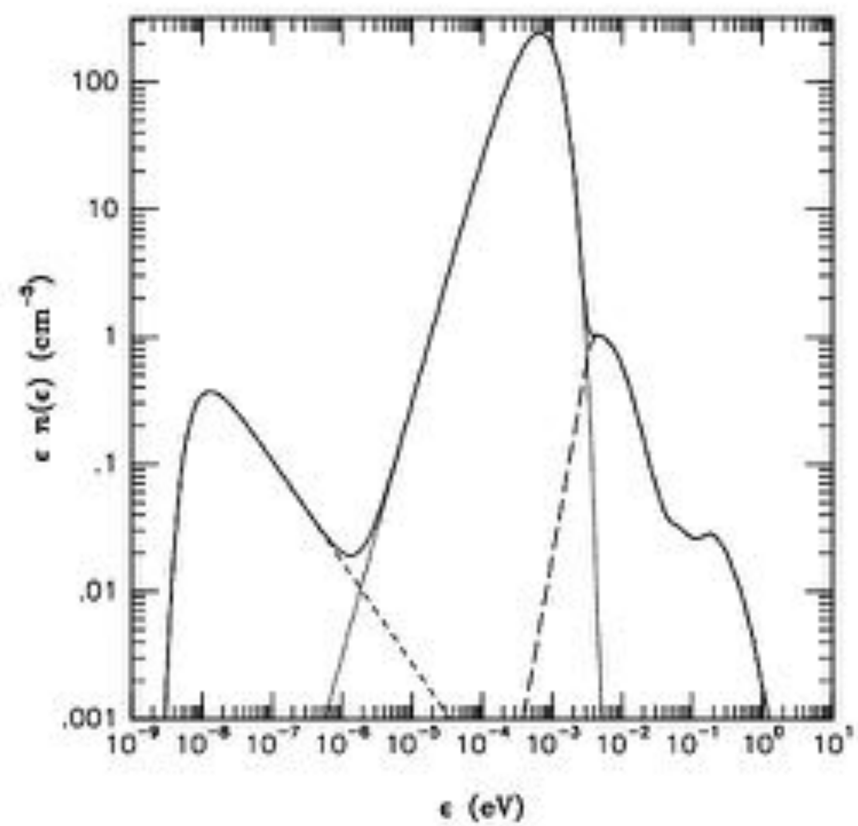
$$\mu^\pm \Rightarrow e^\pm + \bar{\nu}_e + \nu_\mu$$

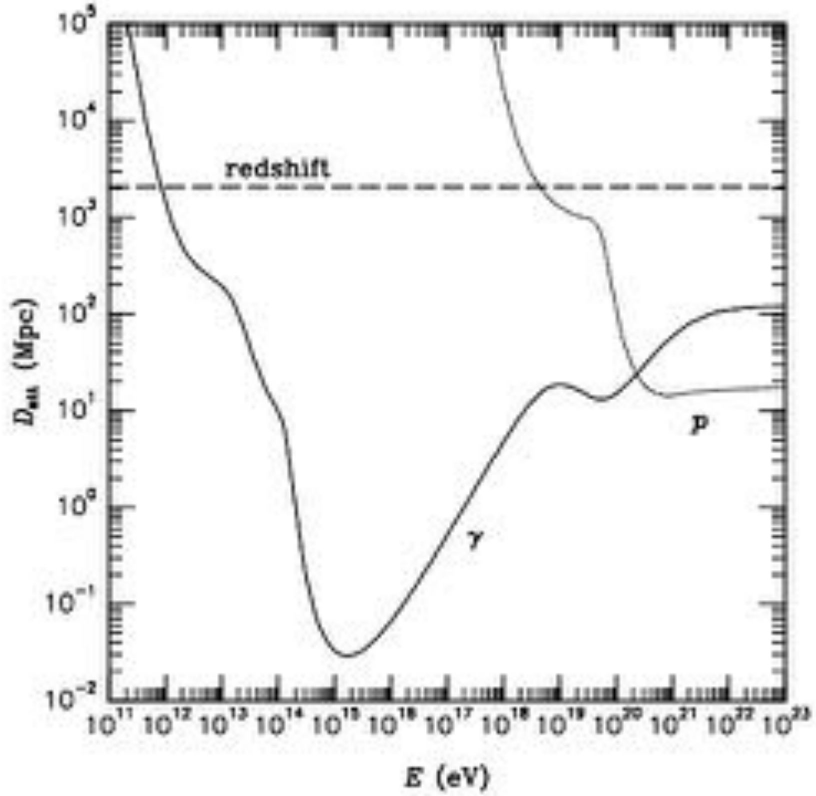


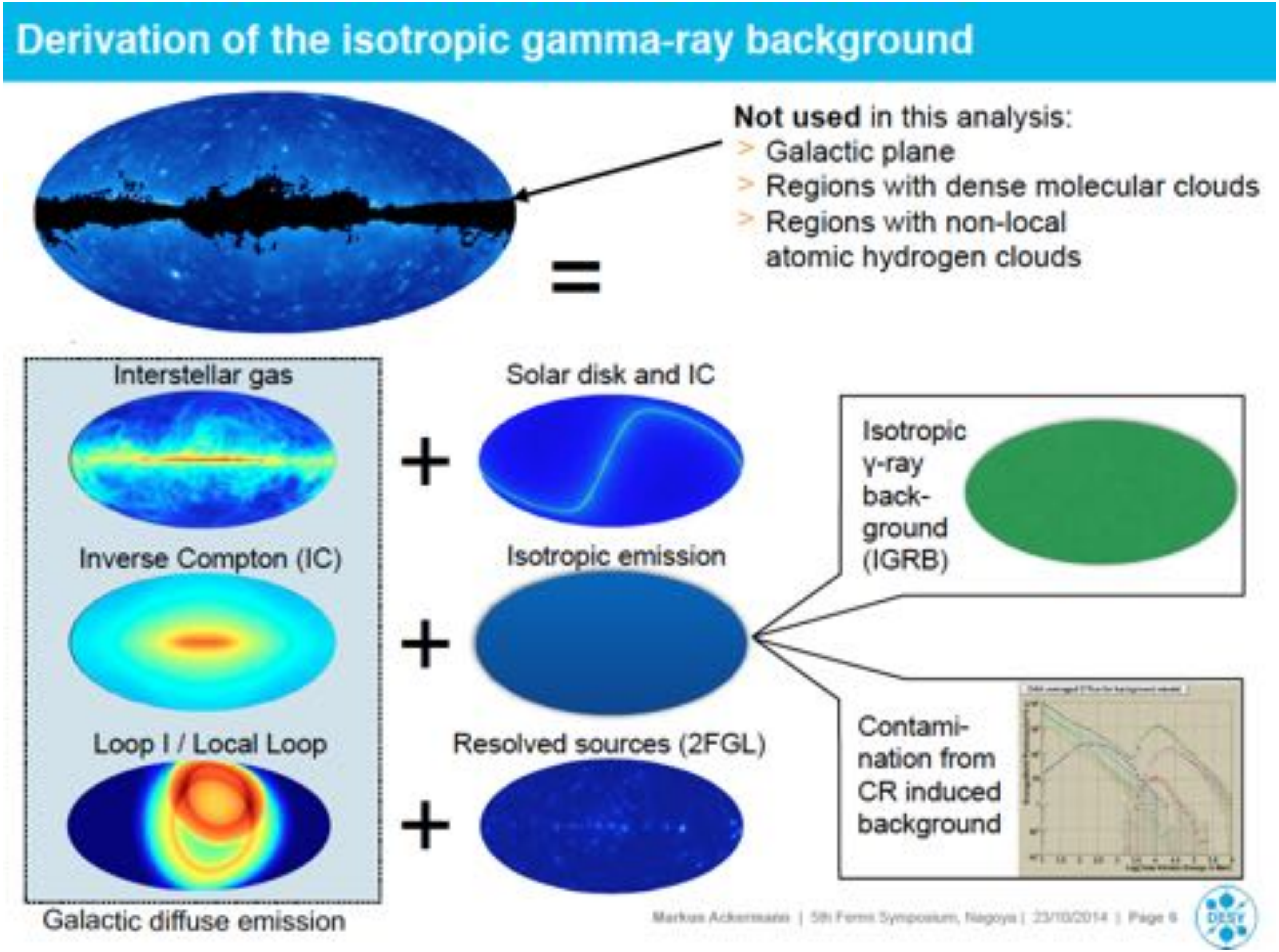
$$n \Rightarrow p + e^- + \bar{\nu}_e$$

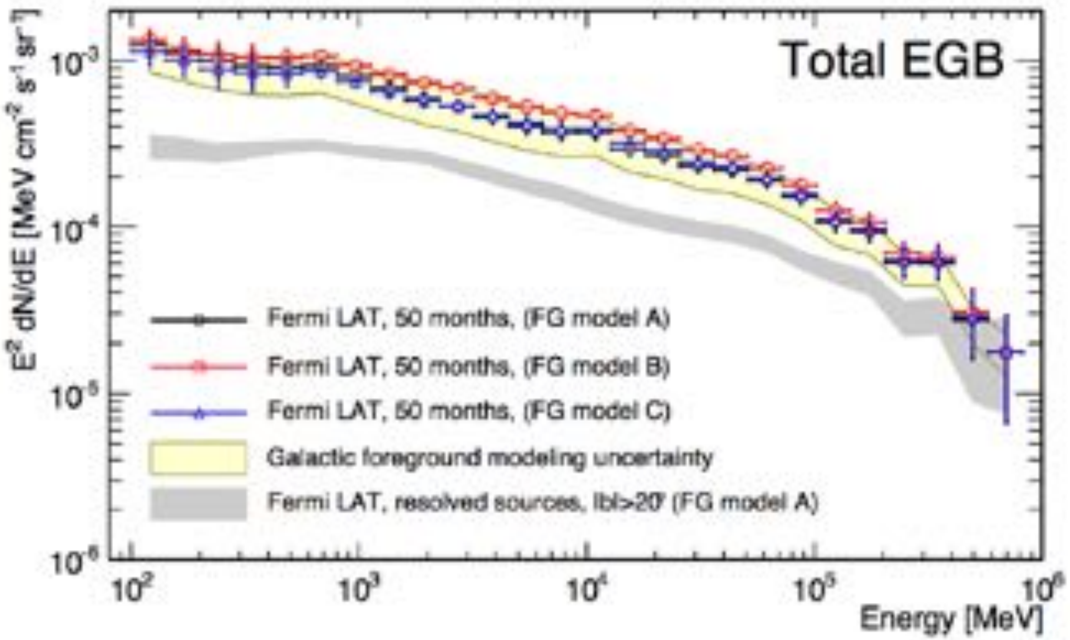
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

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
=
Interstellar gas
Inverse Compton (IC)
Loop I / Local Loop
Galactic diffuse emission
+
Solar disk and IC
+
Isotropic emission
+
Resolved sources (2FGL)
Isotropic γ-ray back-ground (IGRB)
Contami-nation from CR induced background
Markus Ackermann | 5th Fermi Symposium, Nagoya | 23/10/2014 | Page 6
DESY



- **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

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

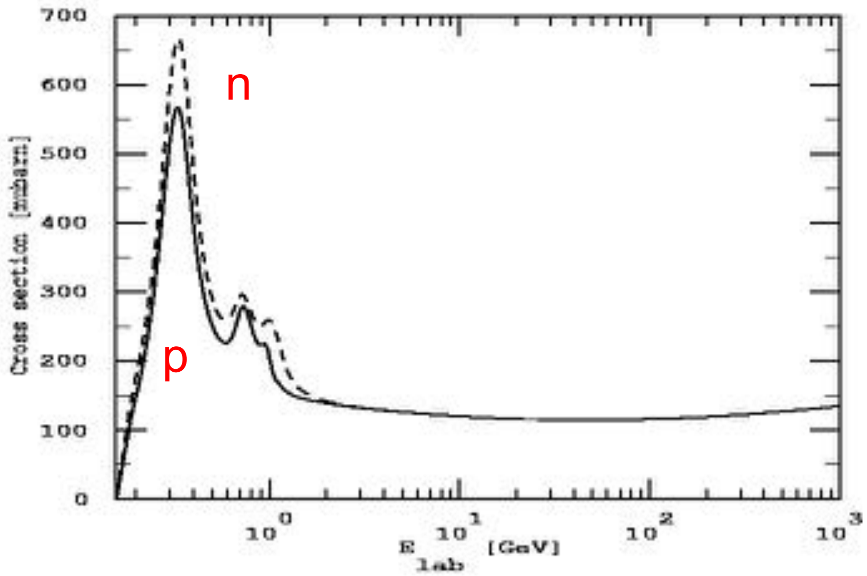
$$N + A_b \Rightarrow N' + \sum \pi^i$$

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

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

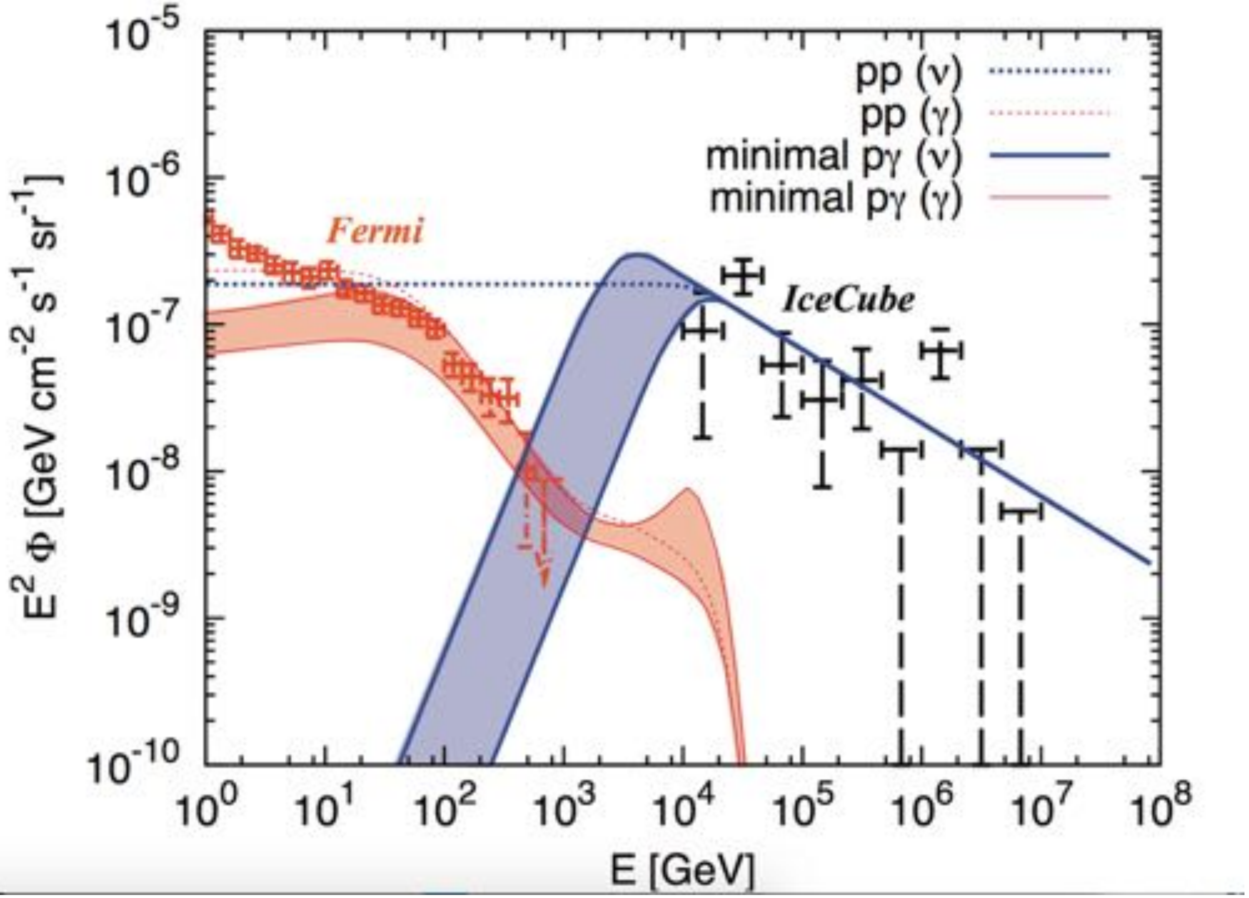
$$\mu^{\pm} \Rightarrow e^{\pm} + \overline{\nu}_e + \nu_\mu$$

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



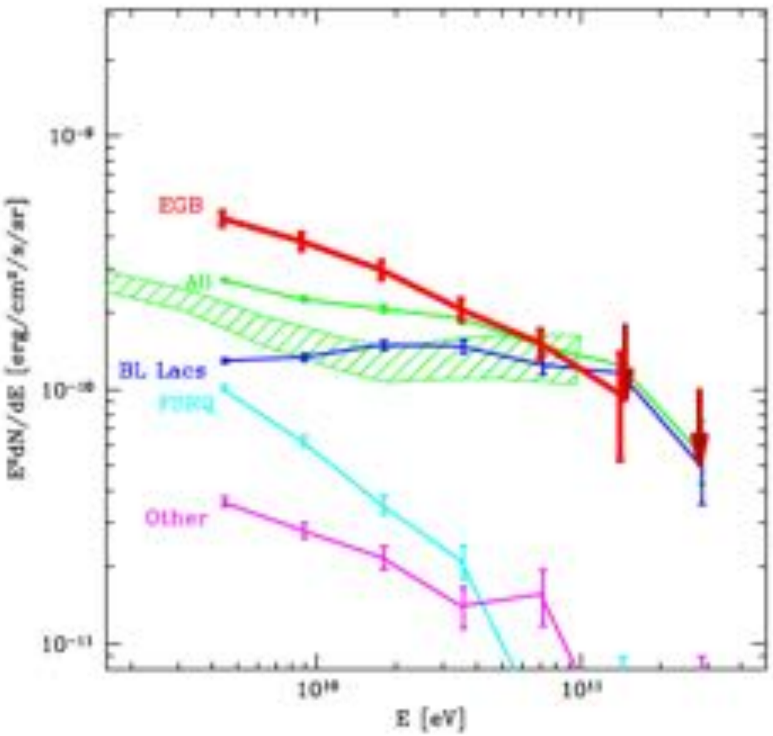
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

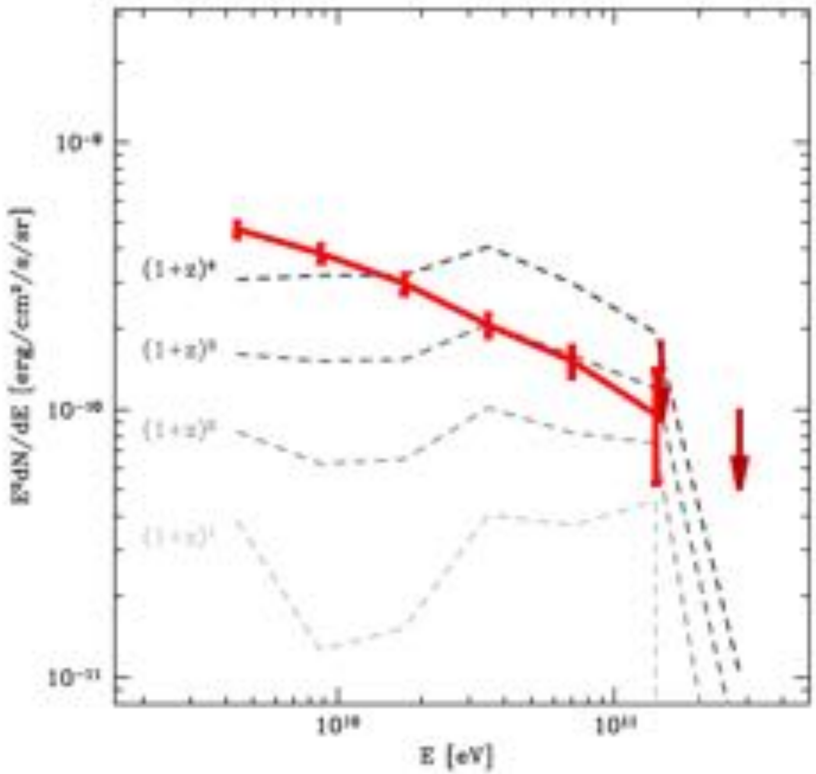
Self-consistent extragalactic sources



Astrophysical neutrinos from BL Lacs

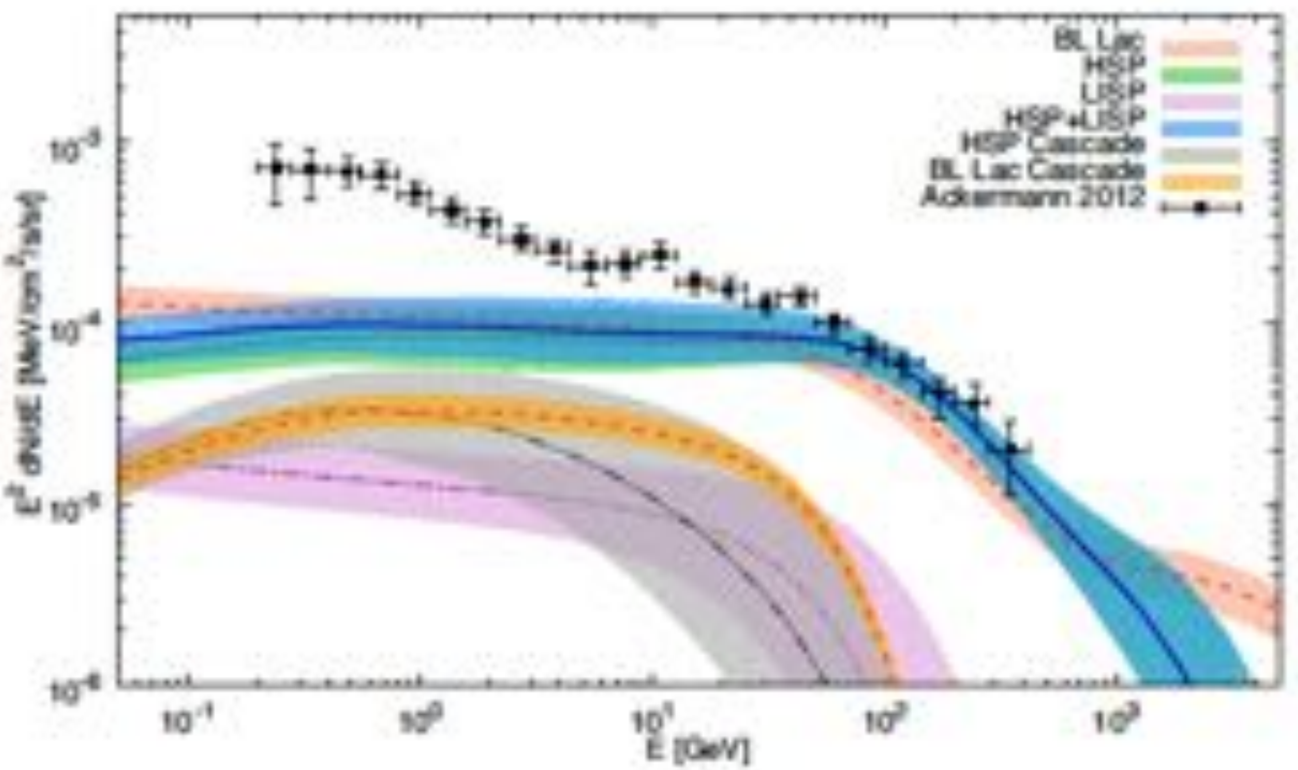
Unresolved BL Lacs give main contribution to diffuse gamma-ray





A.Neronov, D.S. Astrophys.J. 757 (2012) 61

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



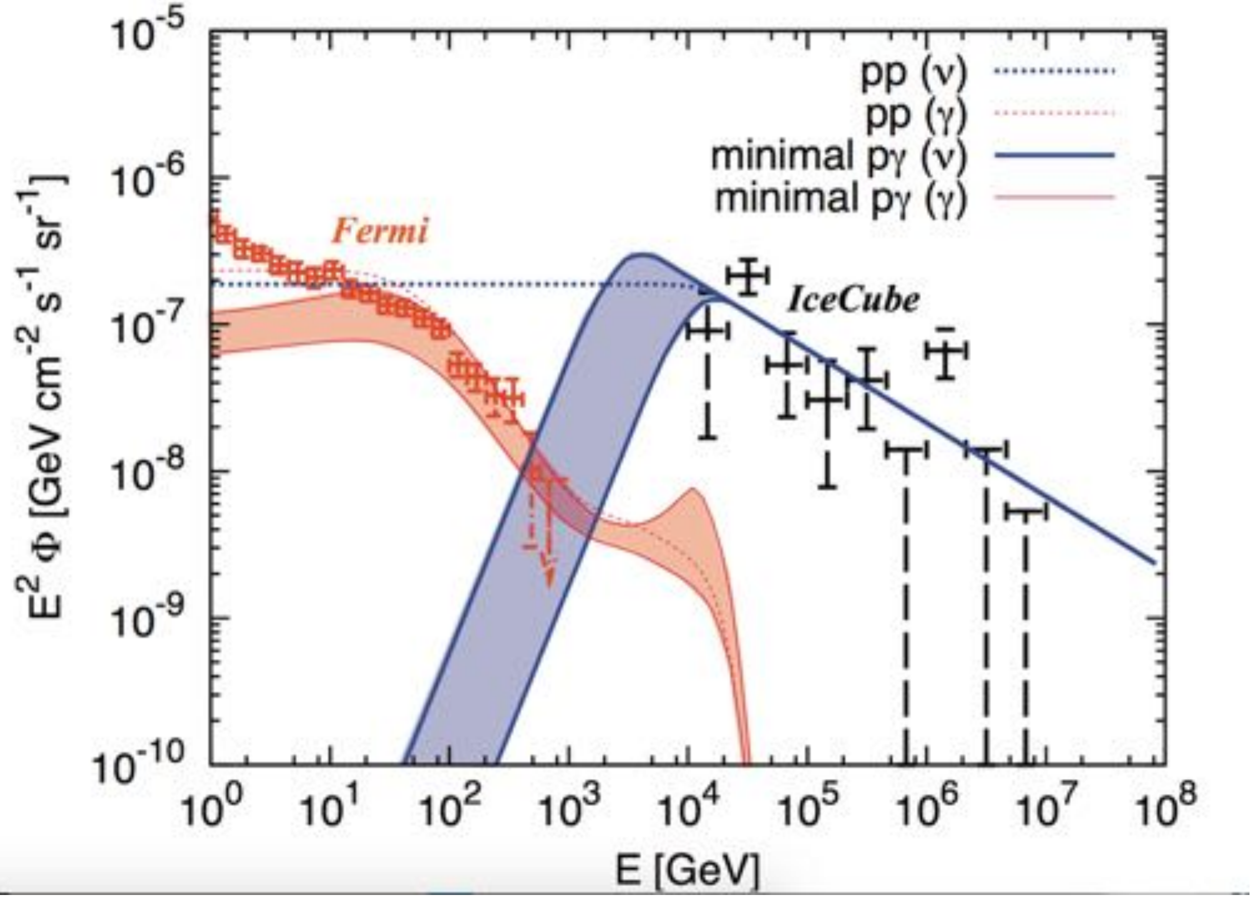
M. Di Mauro et al, arXiv:1311.5708

Fermi confirmed resolution of BL Lac sources above 50 GeV

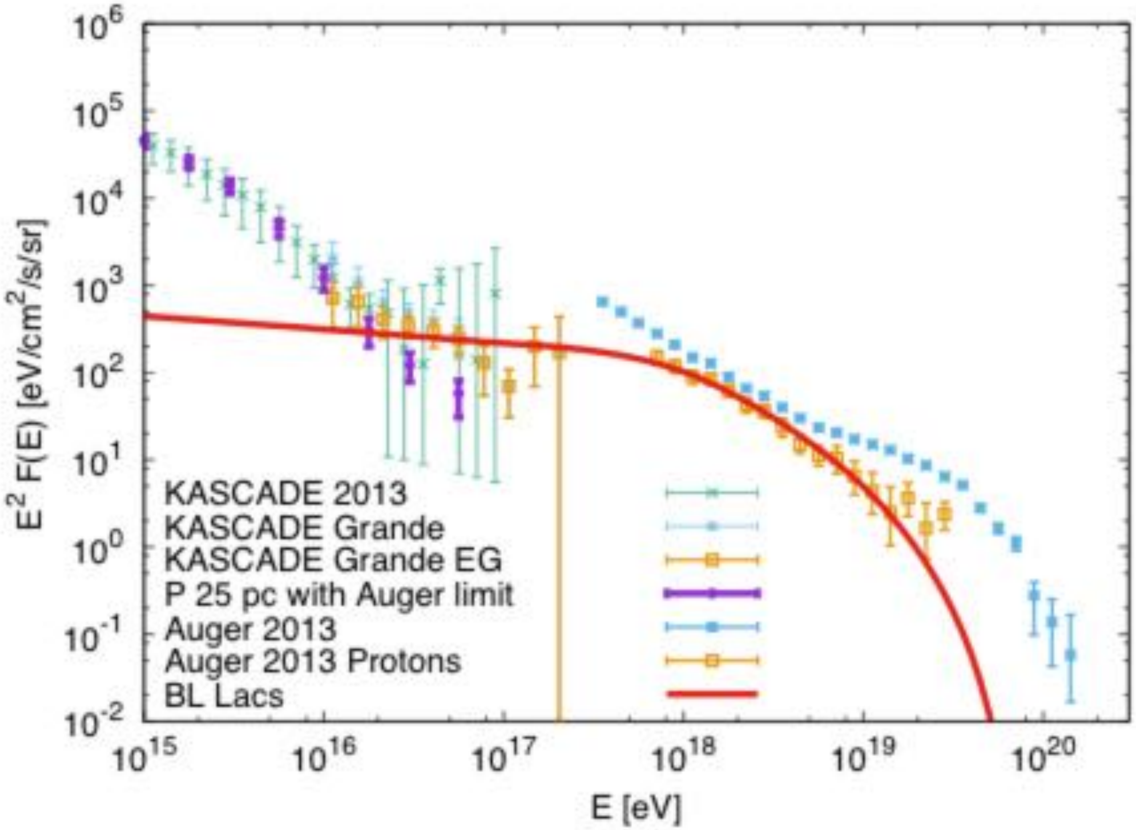
cm^{-2} s^{-1}). We employ a one-point photon fluctuation analysis to constrain the behavior of dN/dS below the source detection threshold. Overall the source count distribution is constrained over three decades in flux and found compatible with a broken power law with a break flux, S_b, in the range $[8 \times 10^{-12}, 1.5 \times 10^{-11}]$ ph cm^{-2} 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 γ-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

Fermi collaboration, arXiv:1511.00693

Are neutrino sources blazars?



UHECR proton flux from BL Lacs



G.Giacinti, M.Kachelriess, O.Kalashev, A.Neronov and D.S., **arXiv: 1507.07534**

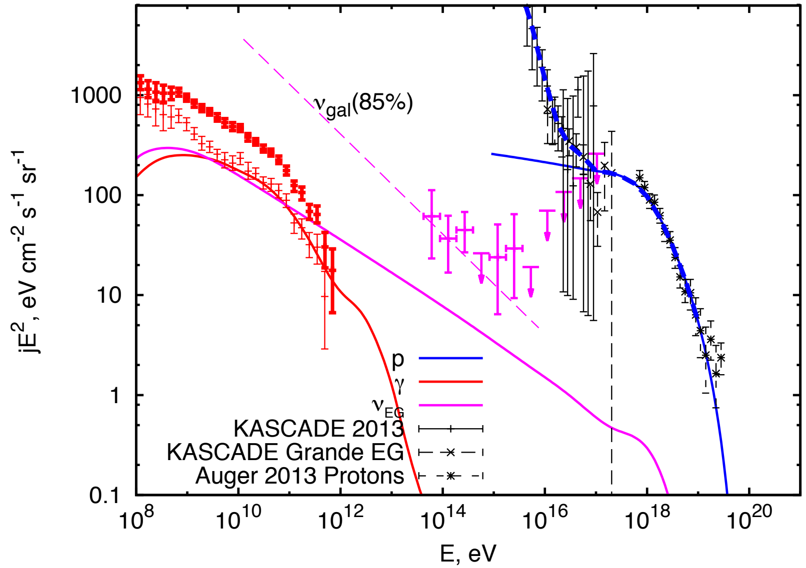
Protons in sources

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

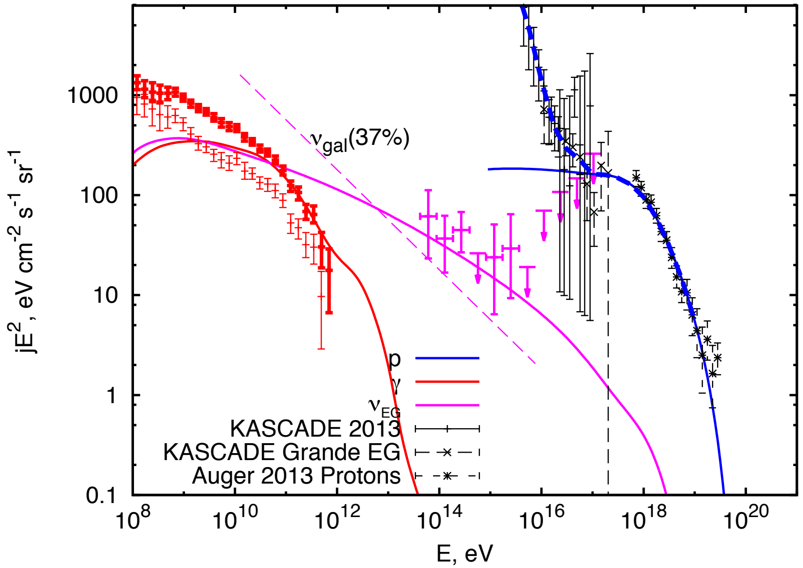
G.Giacinti, M.Kachelriess, O.Kalashev, A.Neronov and D.S., **arXiv: 1507.07534**

Miltimessenger signal from BL Lacs: dependence on escape energy

0.3 TeV

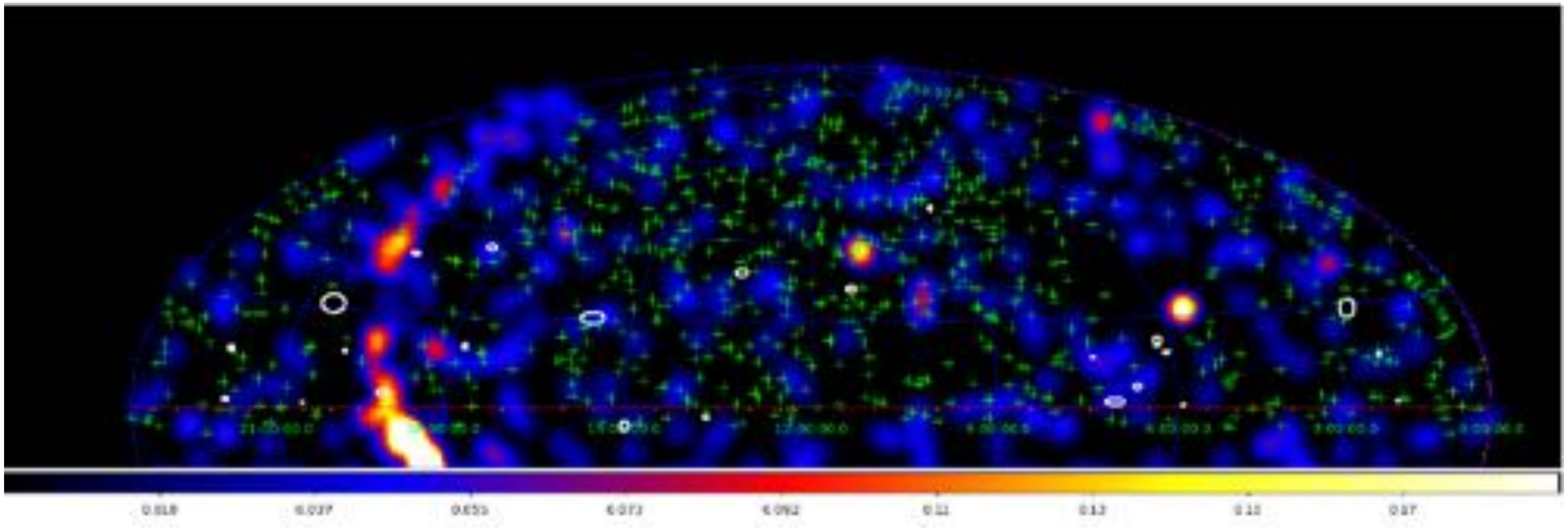


100 TeV



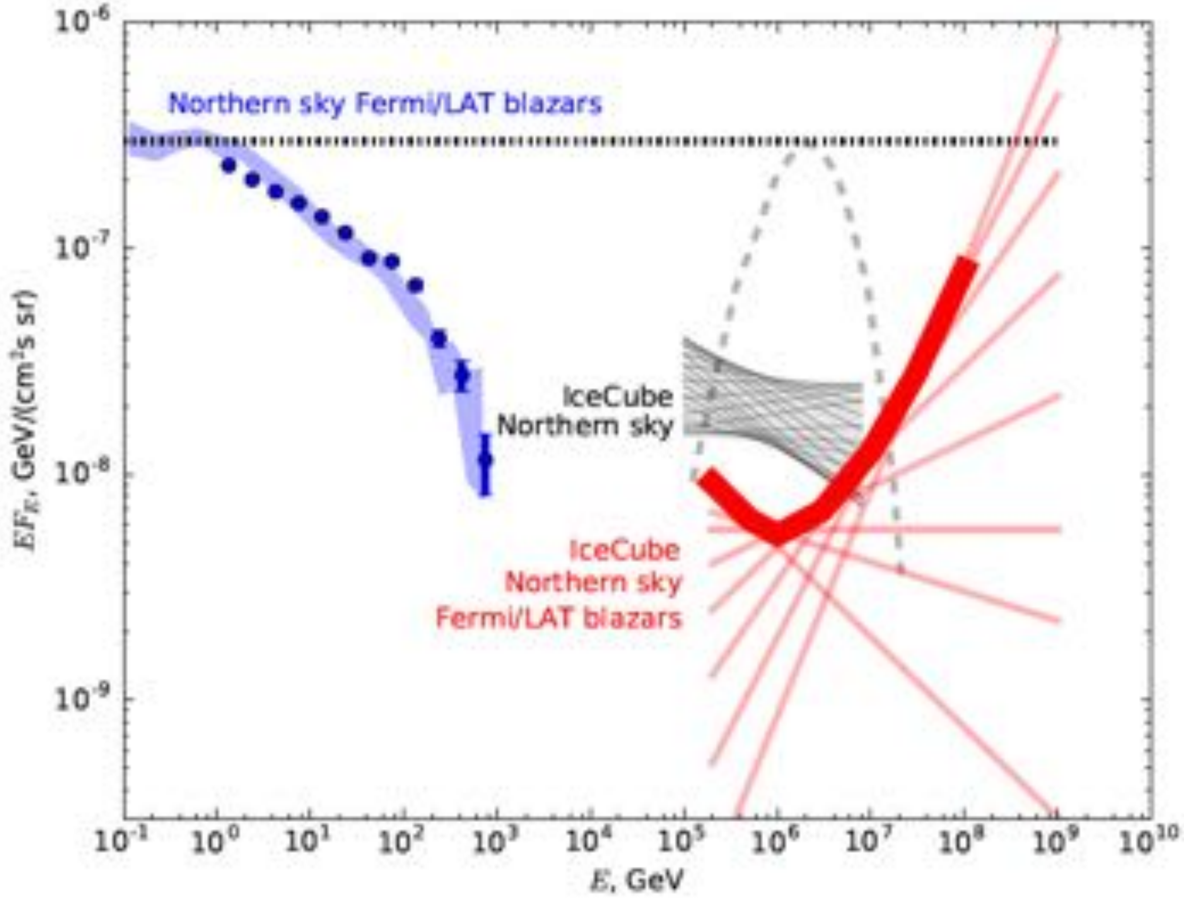
G.Giacinti, M.Kachelriess, O.Kalashev, A.Neronov and D.S., **arXiv: 1507.07534**

Fermi blazars and IceCube neutrinos



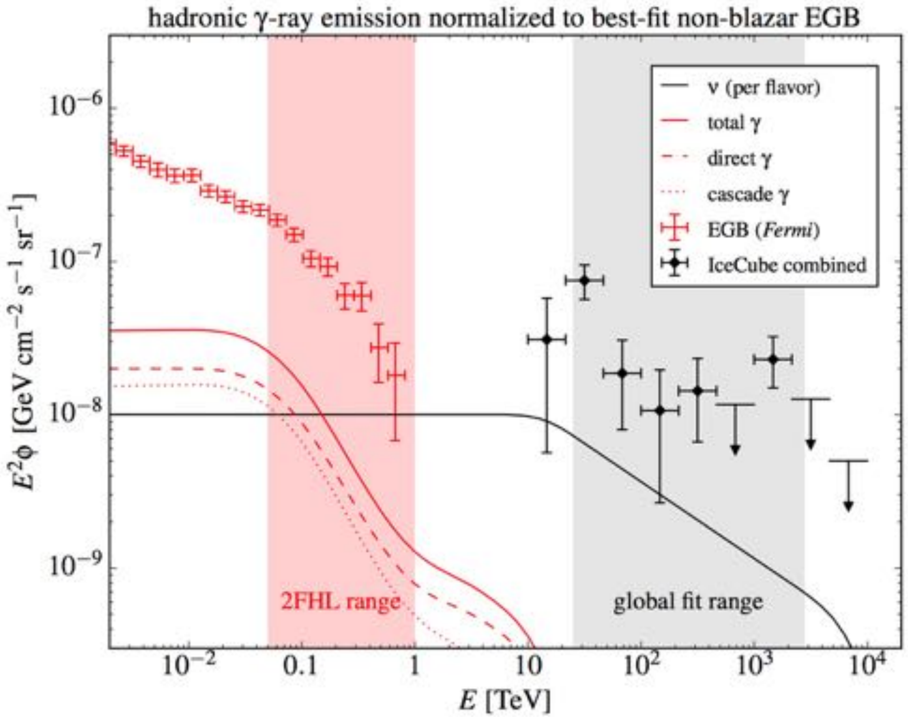
A.Neronov, K.Ptitsyna and D.S, arXiv:1611.06338

Neutrinos not from blazars



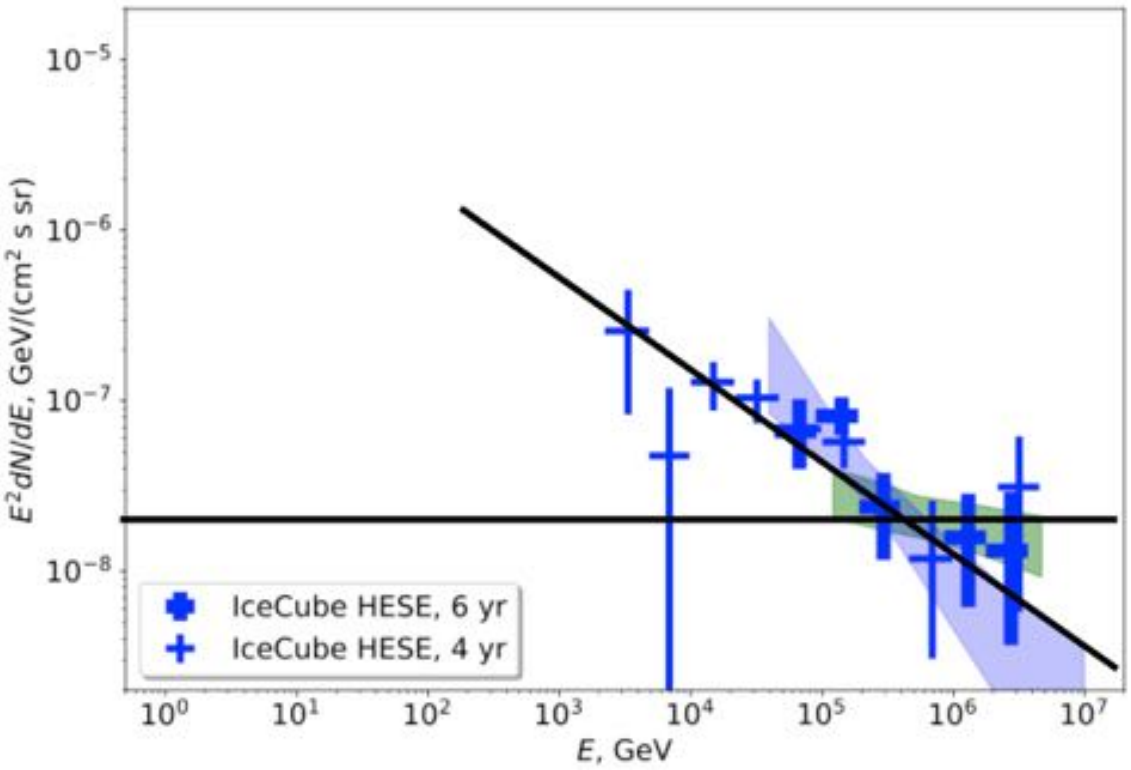
IceCube arXiv:1611.03874
A.Neronov, K.Ptitsyna and D.S., arXiv:1611.06338

Self-consistent extragalactic sources: no blazars

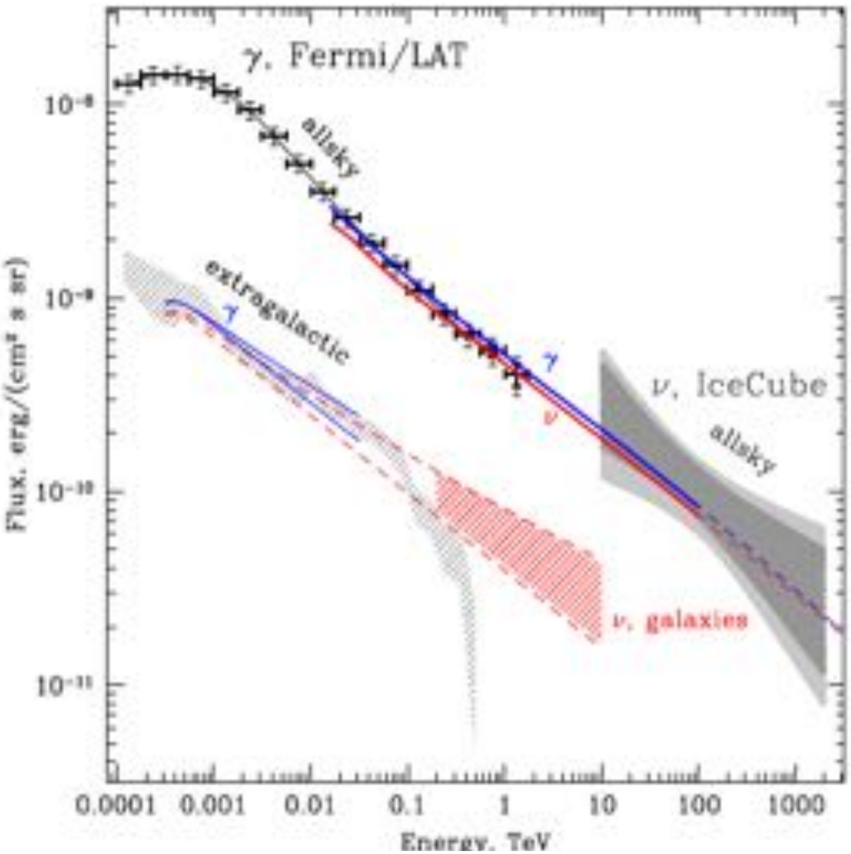


[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

IceCube data

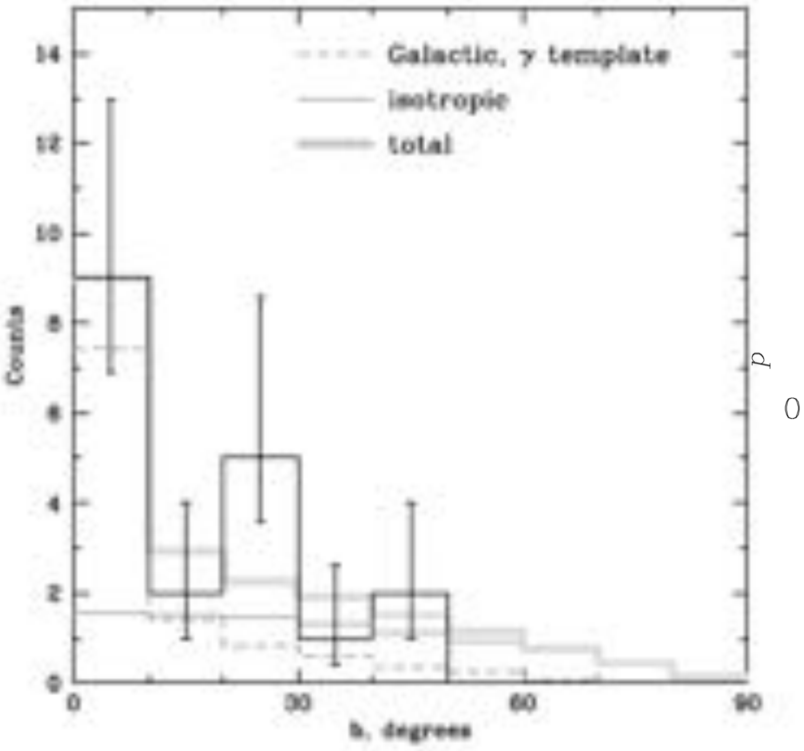


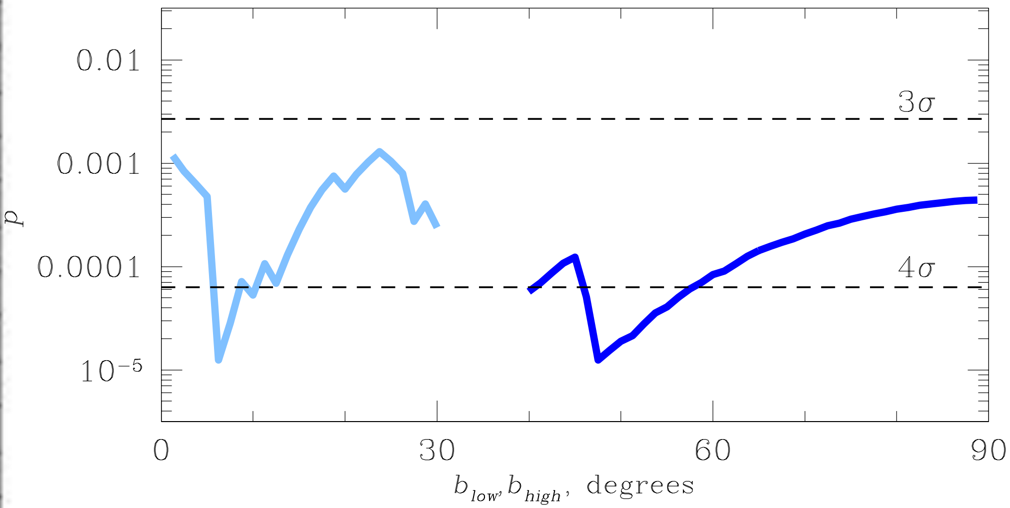
IceCube + Fermi LAT all sky: protons 1/E^2.5



A.Neronov, D.S. arXiv:1412.1690

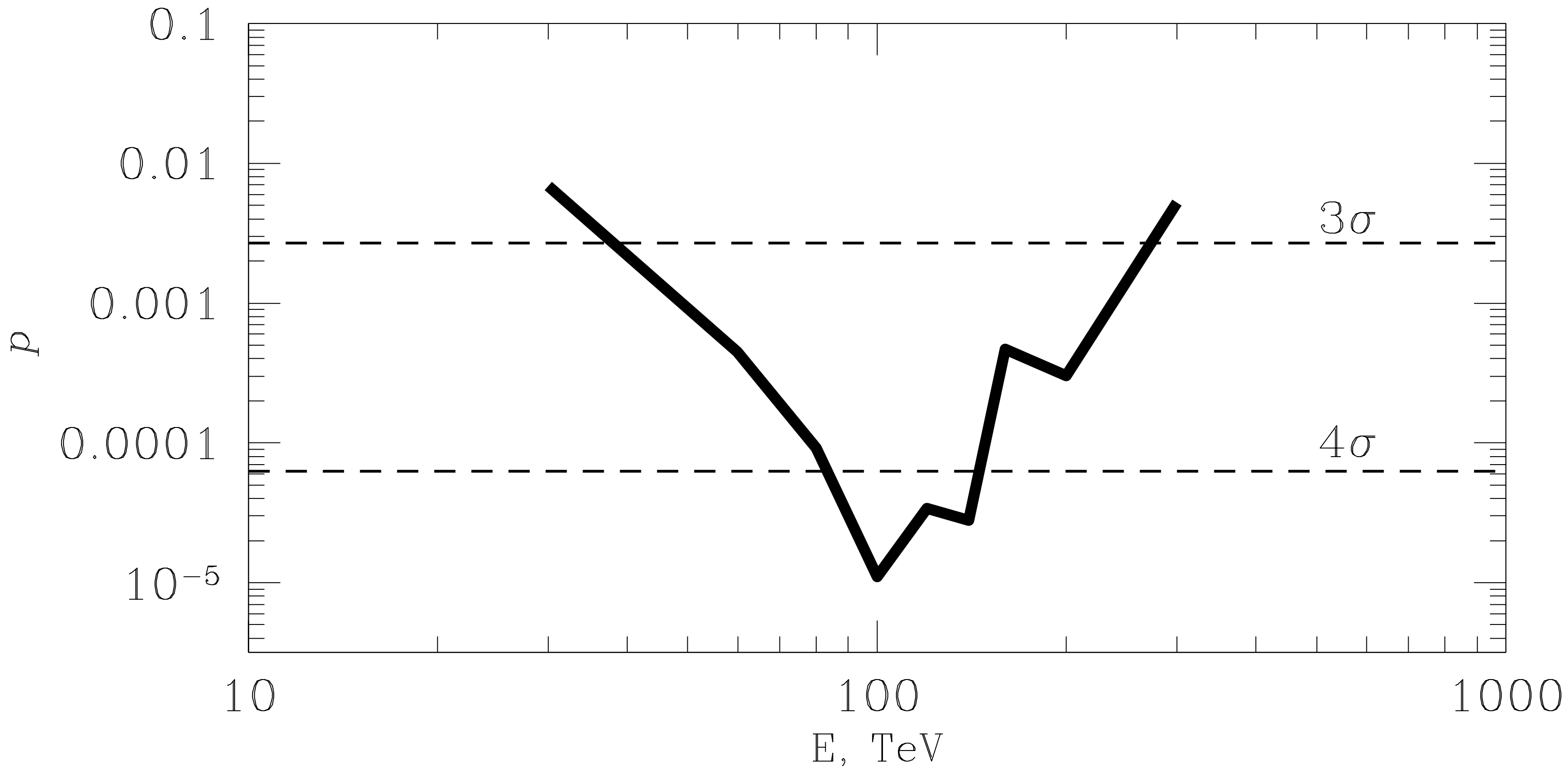
Evidence of Galactic component in 4 year IceCube data E>100 TeV





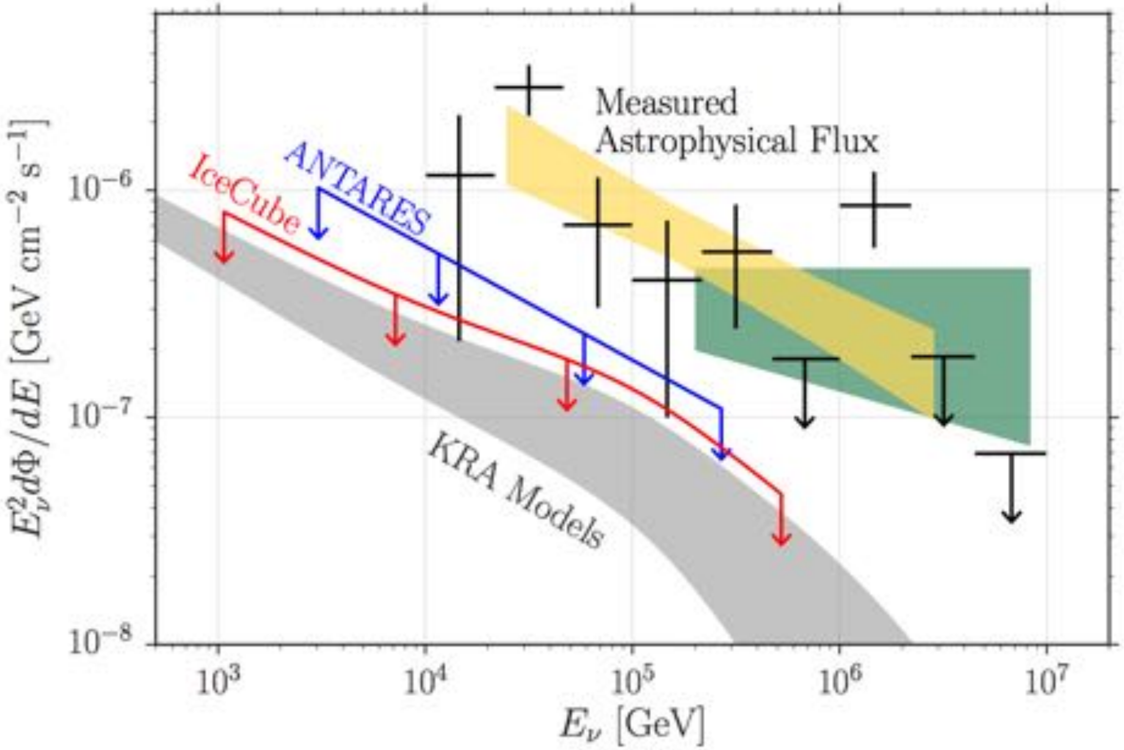
A. Neronov & D.S. arXiv: 1509.03522

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



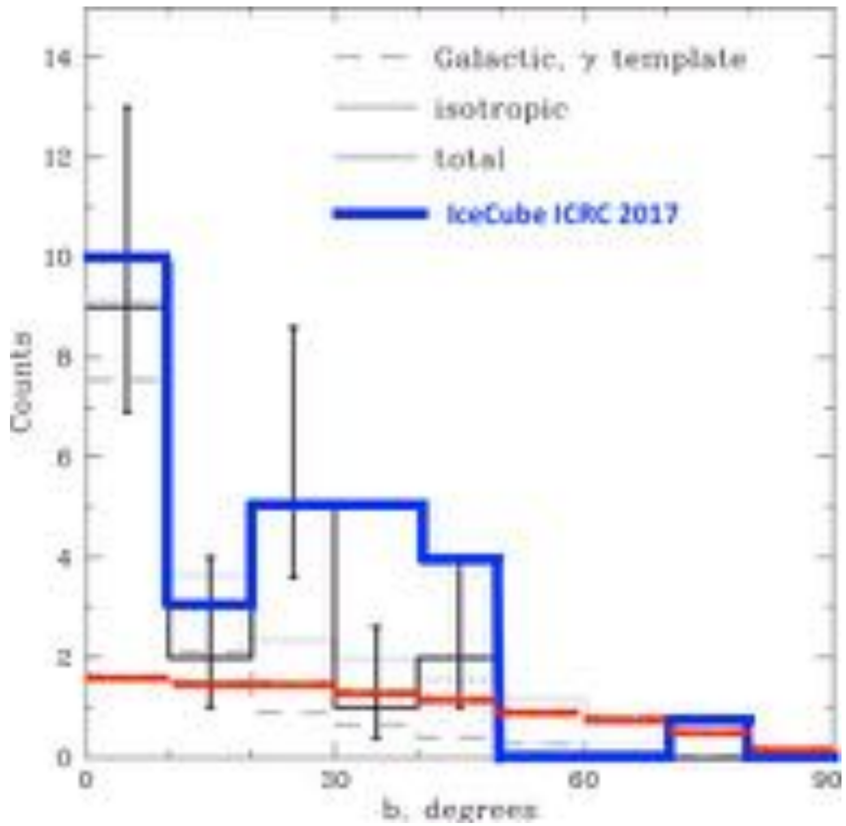
A. Neronov & D.S. arXiv: 1509.03522

IceCube and ANTARES galalactic plane



ICRC 2017

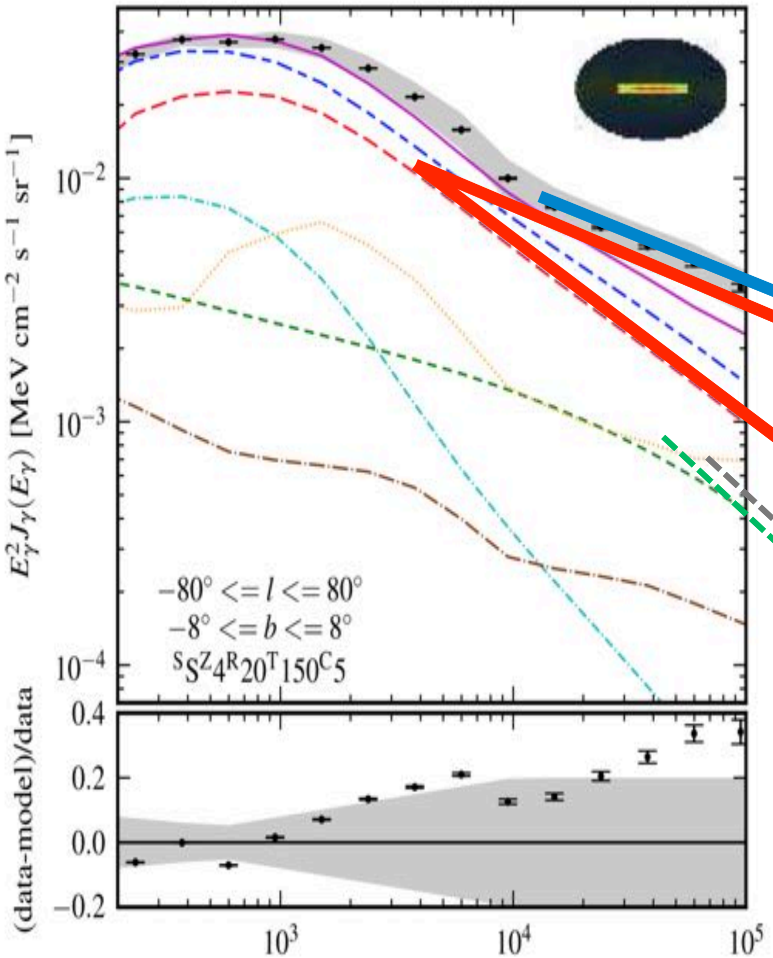
Anisotropy at E>100 TeV



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

Discovery of gamma-ray conterpart

Multi-messenger spectrum of the Galactic Plane



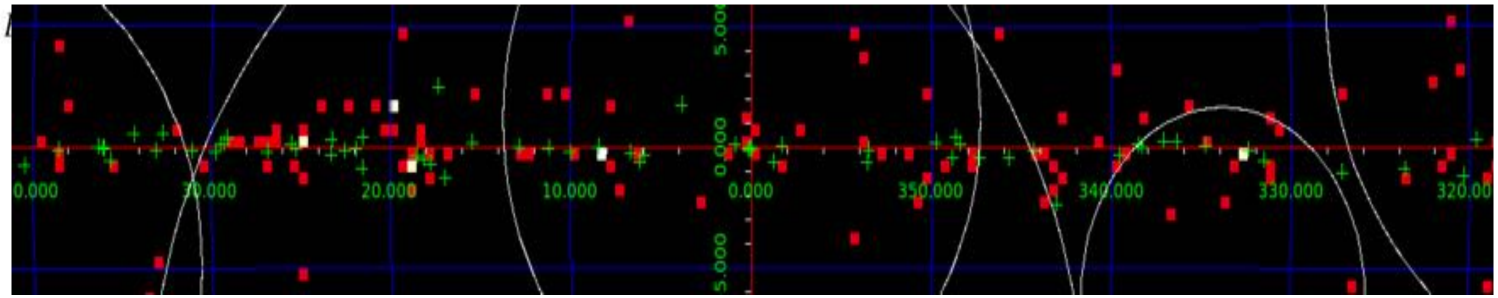
Fermi/LAT multi-TeV emission from the Galactic Plane could hardly be dominated by diffuse emission process which does not generate neutrinos.

It also does not come from known isolated sources

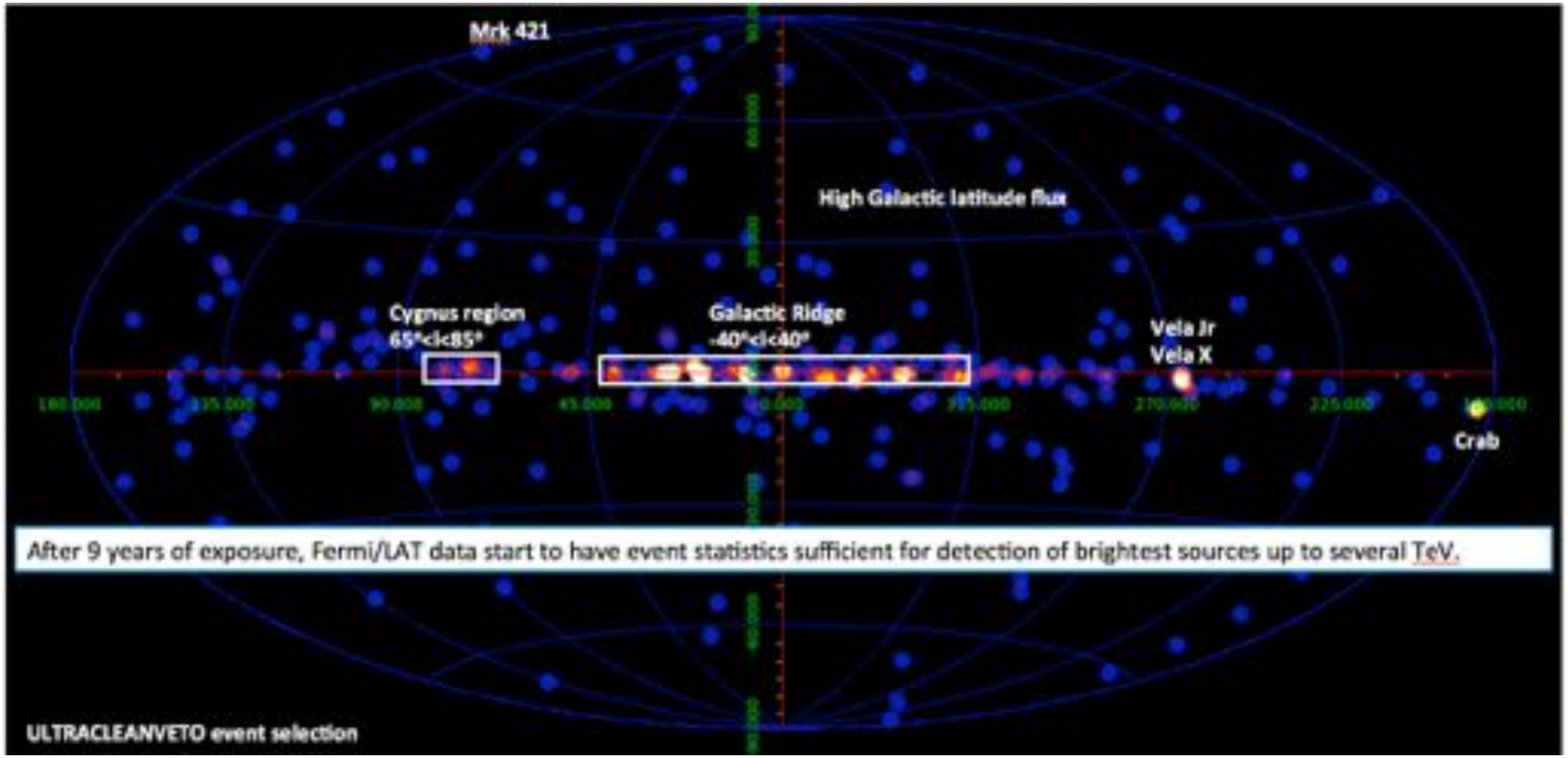
π^0 decays

Inverse Compton

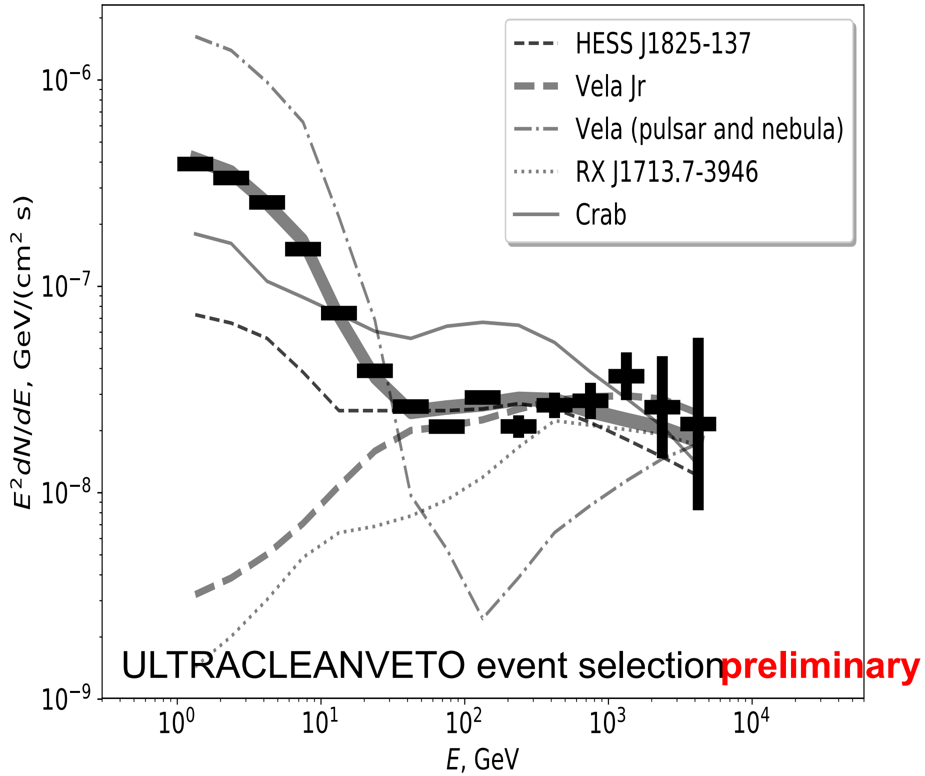
atalog sources



Fermi sky map E> 1 TeV



Fermi/LAT multi-TeV sky



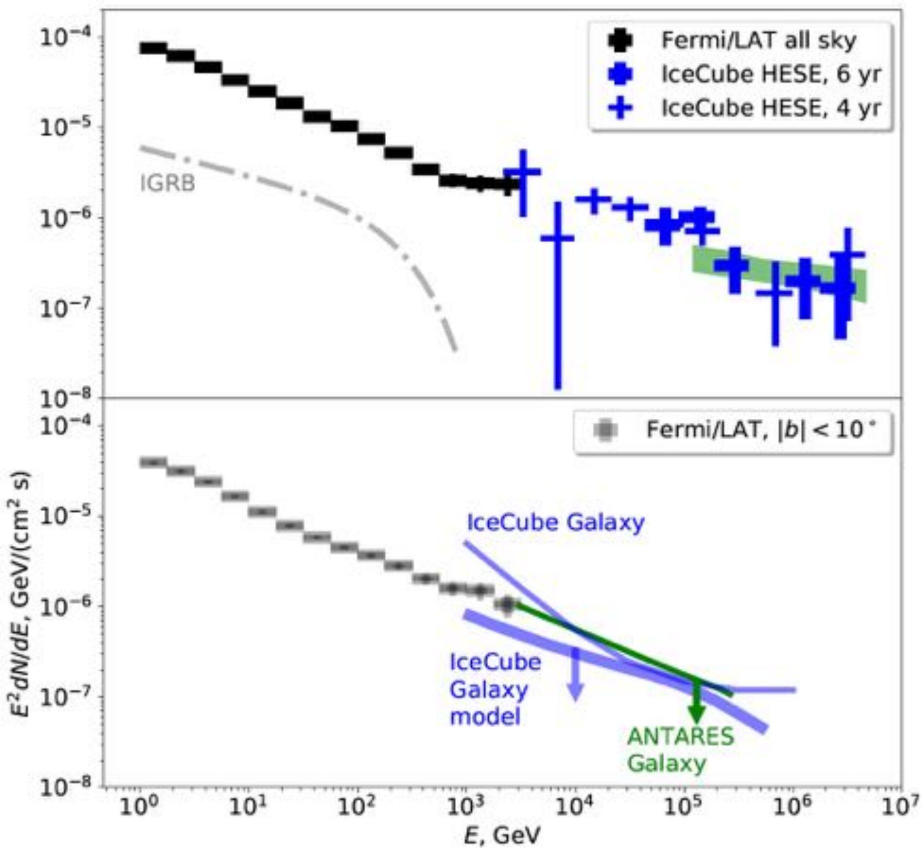
After 9 years of exposure, Fermi/LAT data start to have event statistics sufficient for detection of brightest sources up to several TeV.

Fermi /LAT calibration is not assured above 1 TeV (https://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html). Those need to be derived / verified.

This could be done via cross-calibration with the ground-based gamma-ray telescopes (HESS, MAGIC, VERITAS) and air shower arrays (MILAGRO, HAWC, ARGO-YBJ)

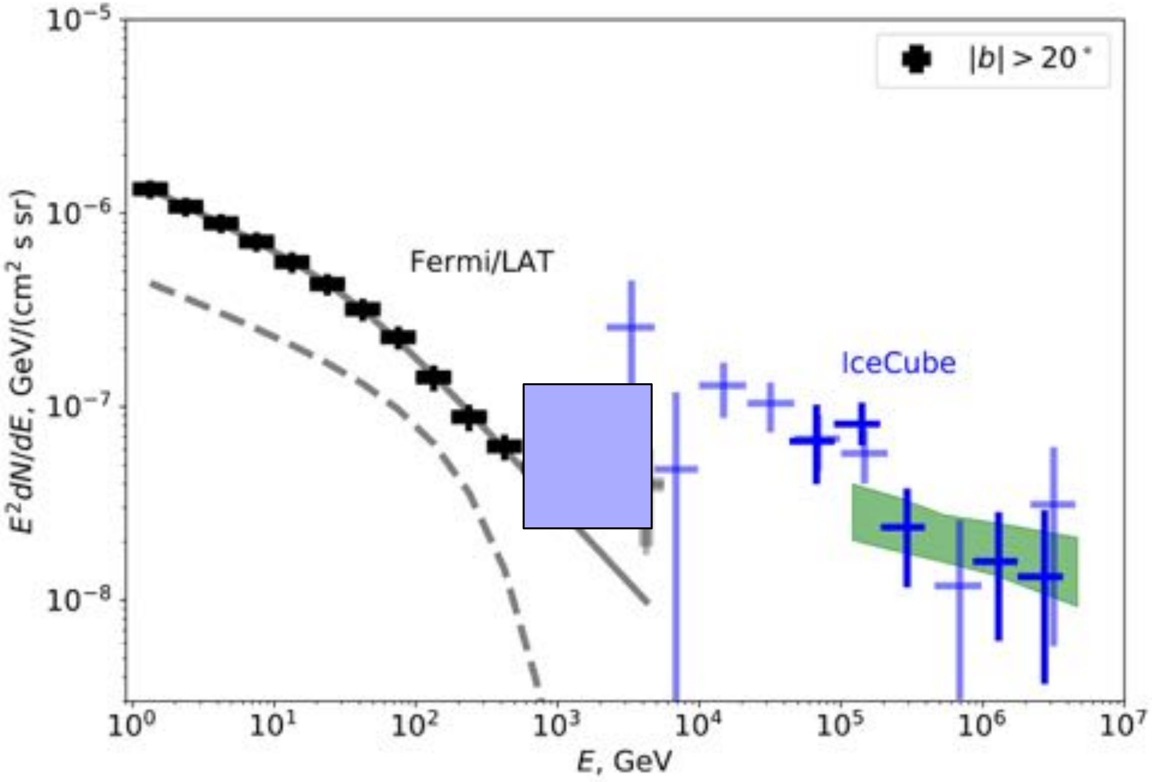
AN, Kachelriess, Semikoz

IceCube + Fermi LAT all sky



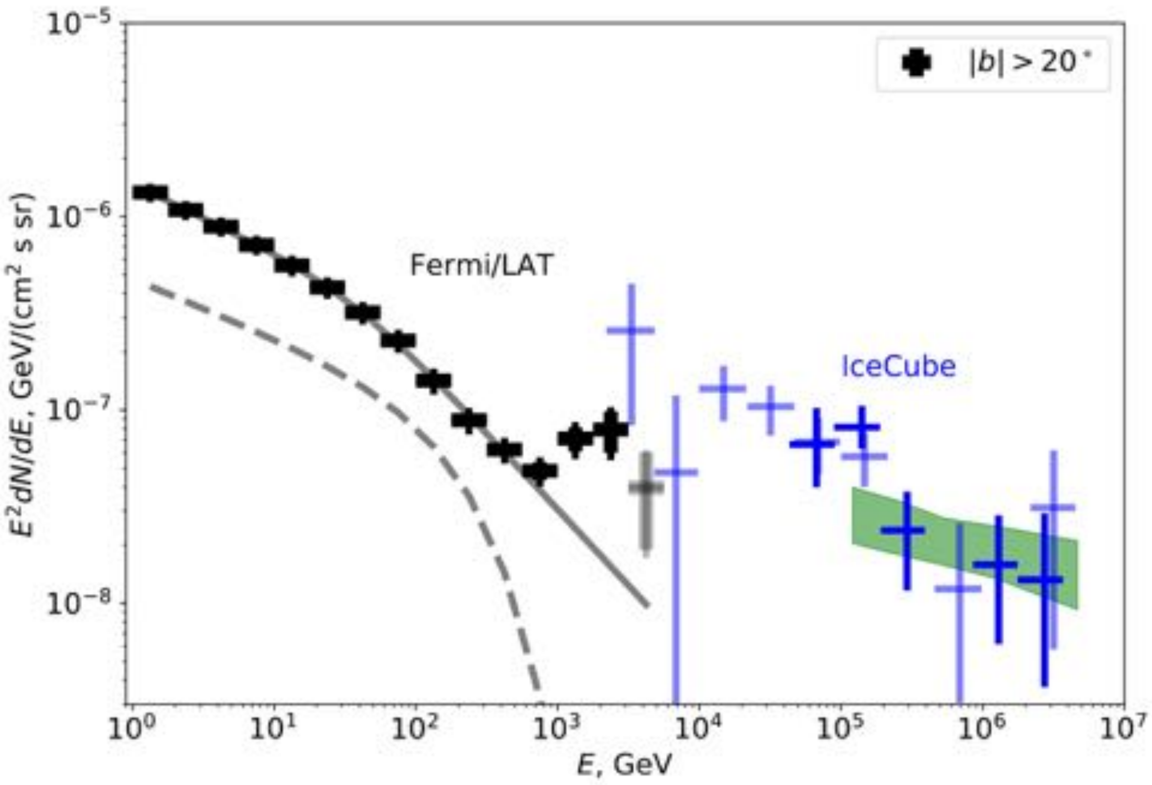
A.Neronov, M.Kachelriess and D.S. arXiv:1802.09983

IceCube + Fermi LAT high galactic latitude



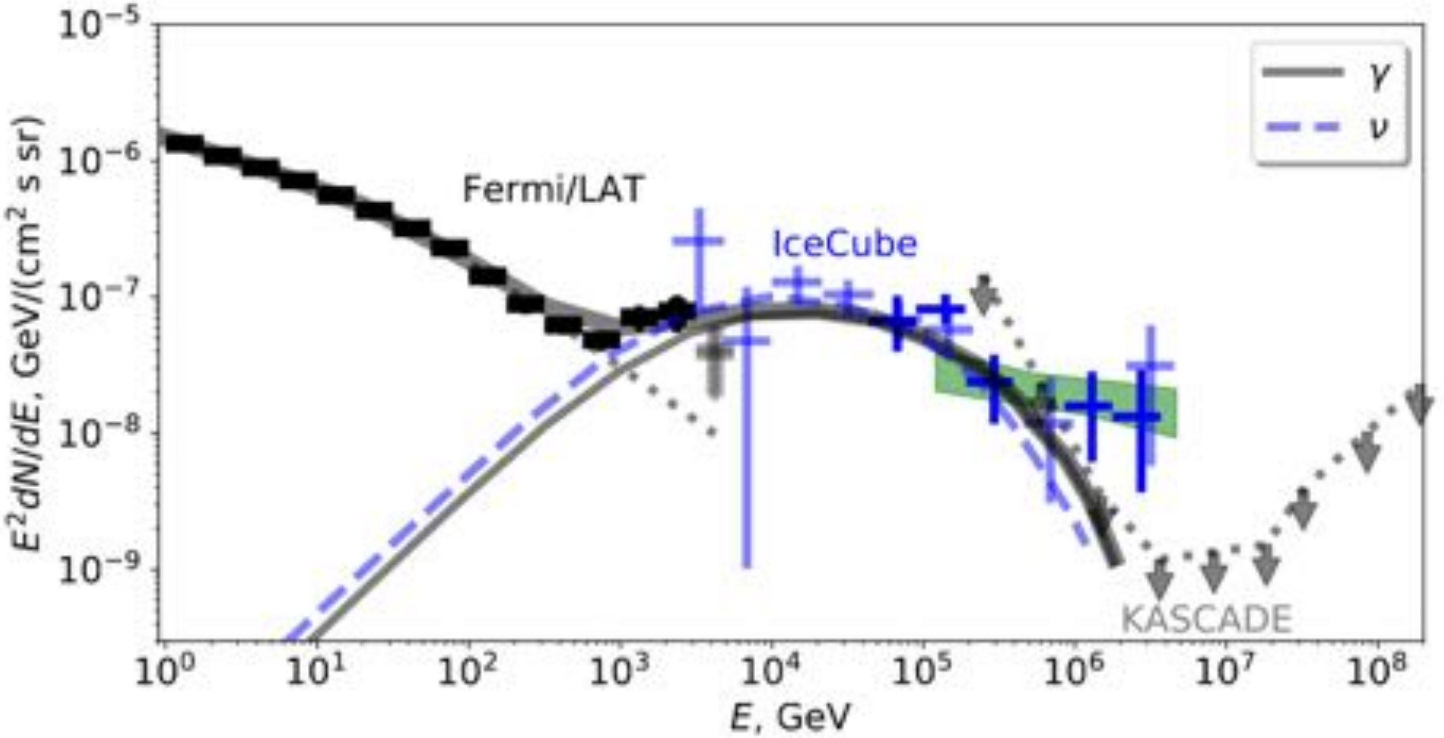
A.Neronov, M.Kachelriess and D.S. 2018

IceCube + Fermi LAT high galactic latitude



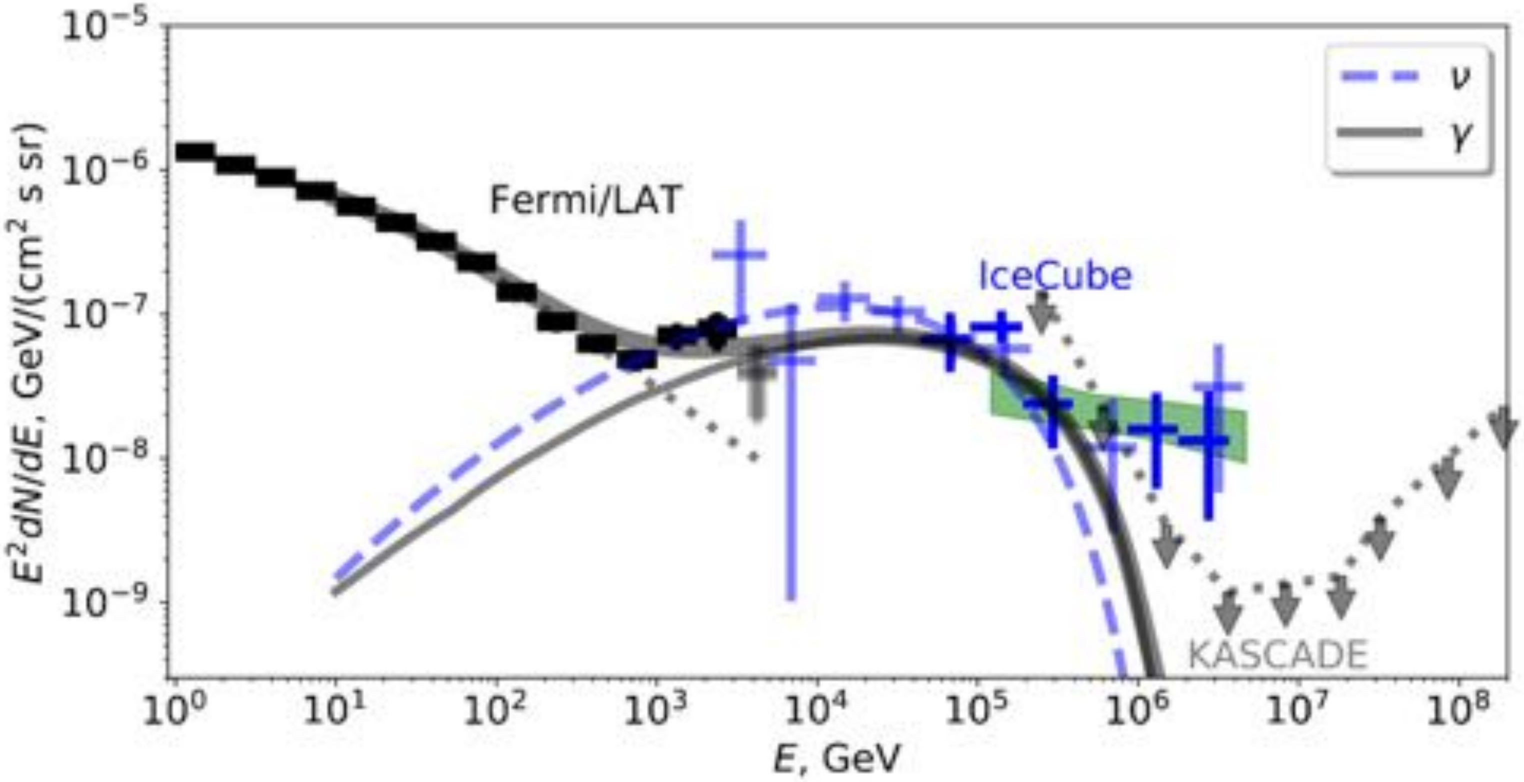
A.Neronov, M.Kachelriess and D.S. arXiv:1802.09983

IceCube + Fermi LAT : local source



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

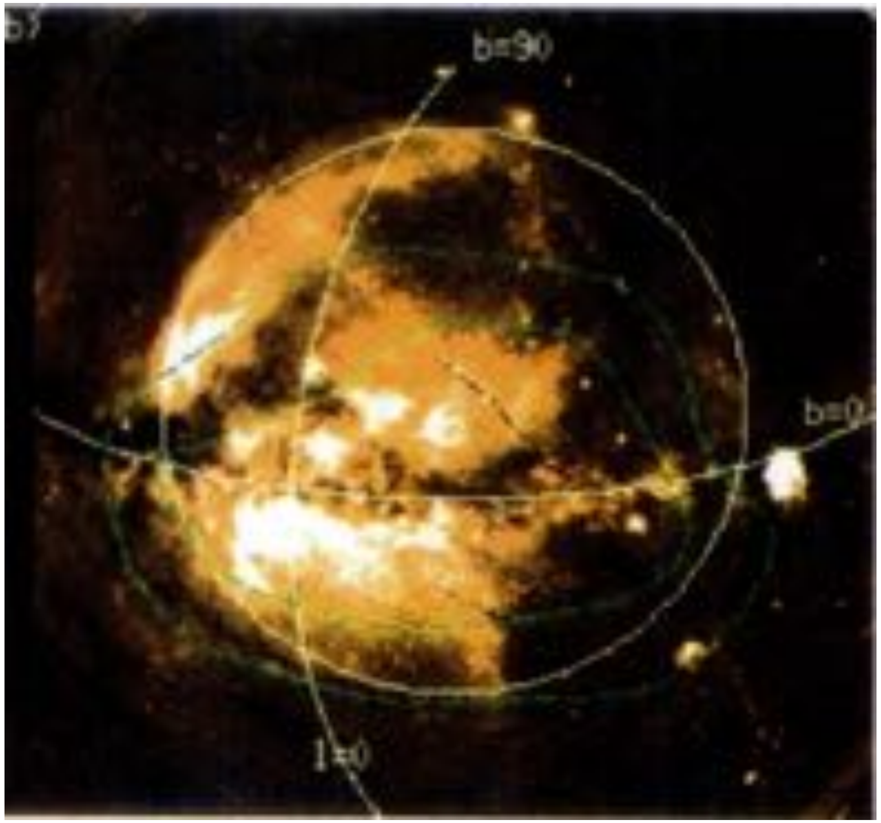
IceCube + Fermi LAT Dark Matter m=5 PeV



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

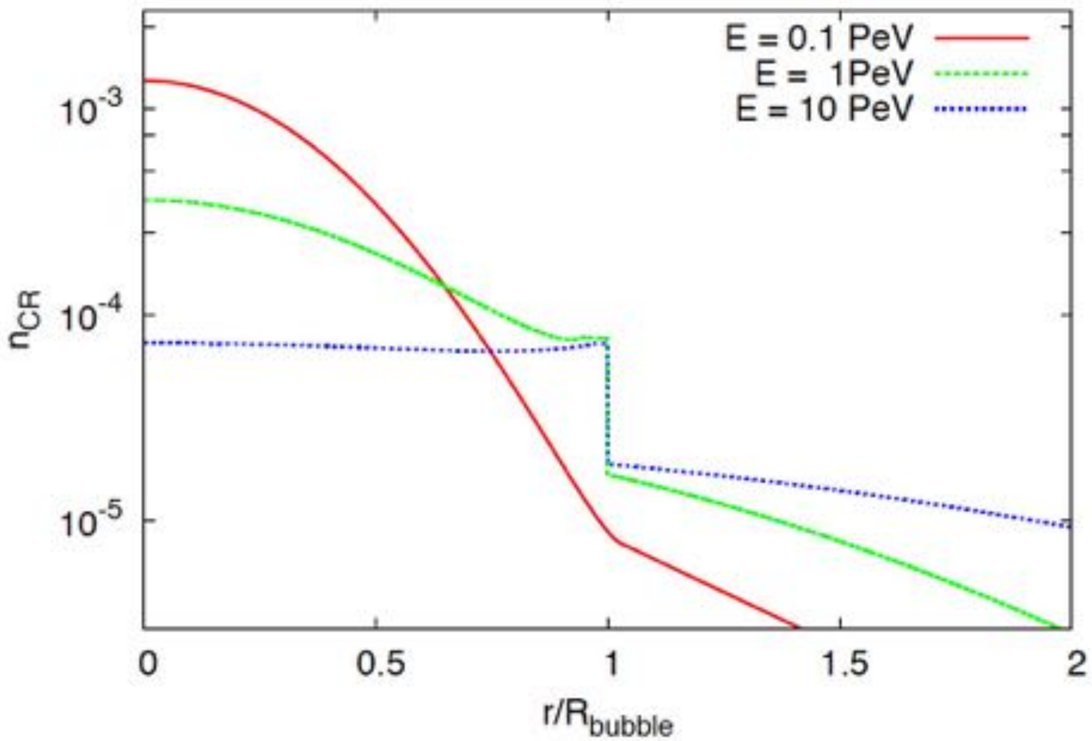
Out-of-plane Galactic sources: Local and Loop I superbubbles

Loop I



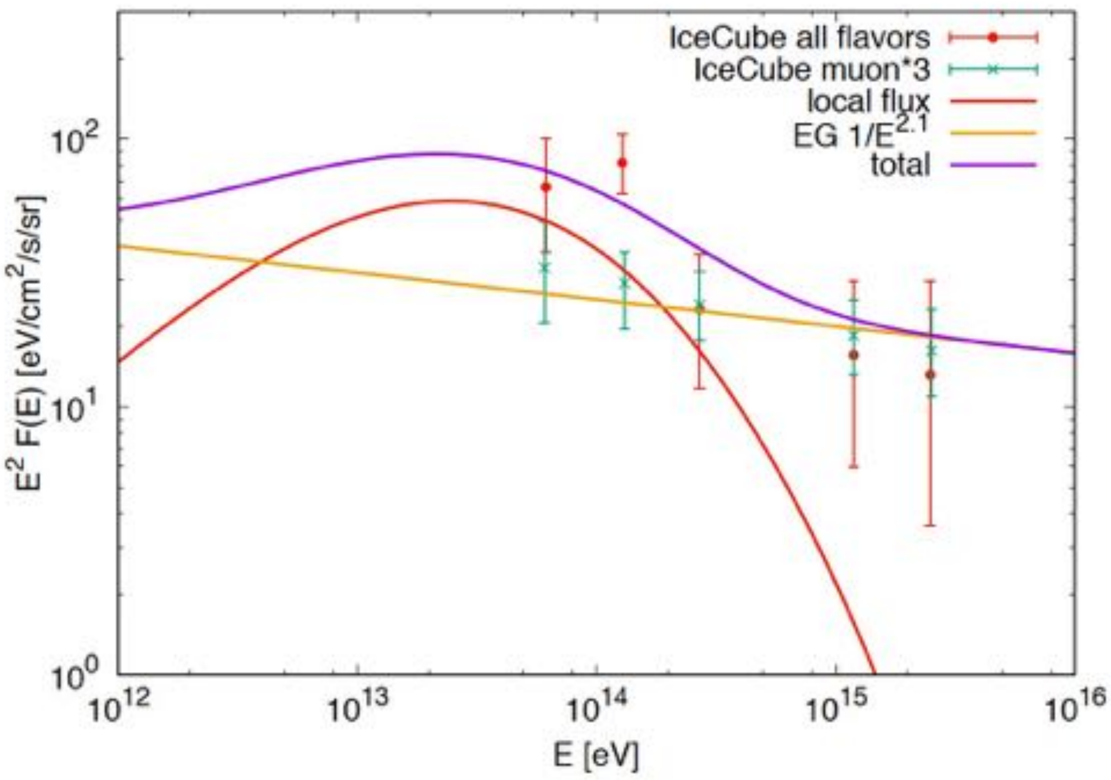
K.Andersen, M.Kachelriess and D.Semikoz, arXiv:1712.03153

Cosmic ray density



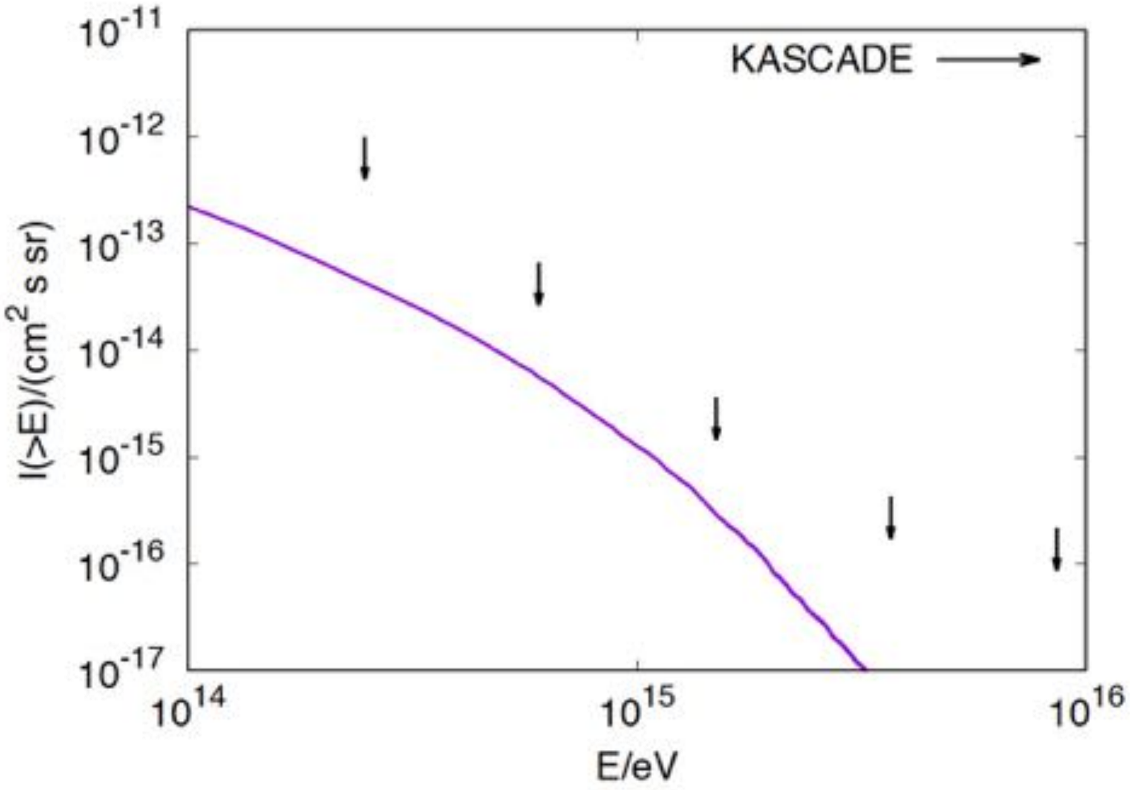
K.Andersen, M.Kachelriess and D.Semikoz, arXiv:1712.03153

Loop I neutrino flux



K.Andersen, M.Kachelriess and D.Semikoz, arXiv:1712.03153

Loop I gamma-ray flux



K.Andersen, M.Kachelriess and D.Semikoz, arXiv:1712.03153

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-km3 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 unknown sources, AGN's are good candidates.*