Lecture 3: Astrophysical neutrinos

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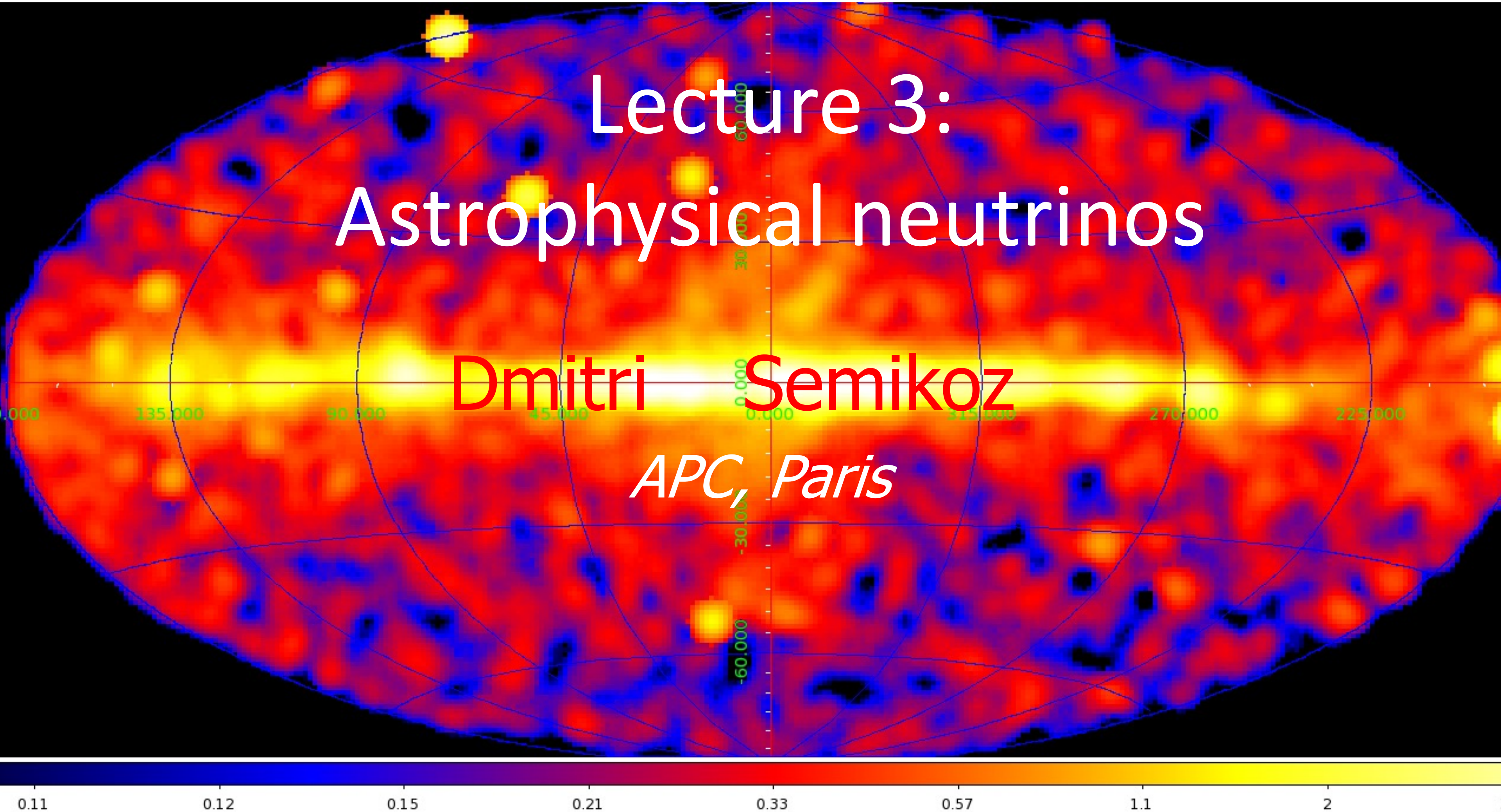


Overview:

- *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:

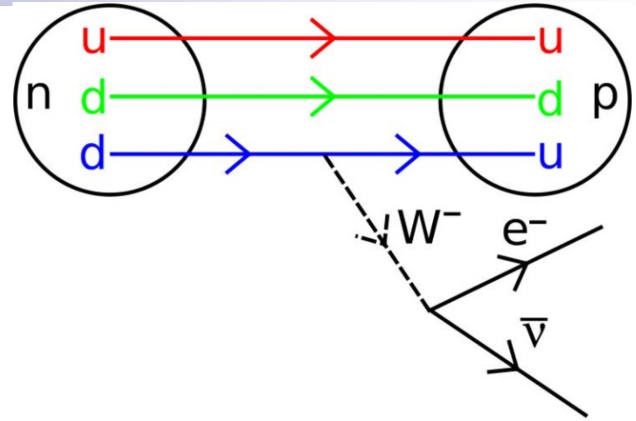
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Fermi Theory of the Beta Decay

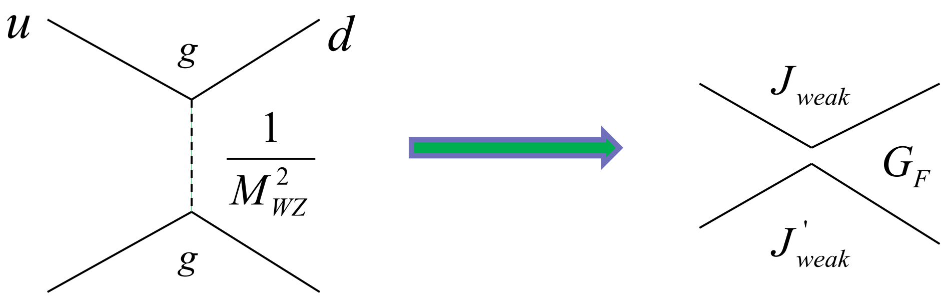
$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \overline{\nu}_e$$

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

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



At the fundamental (constituents) level



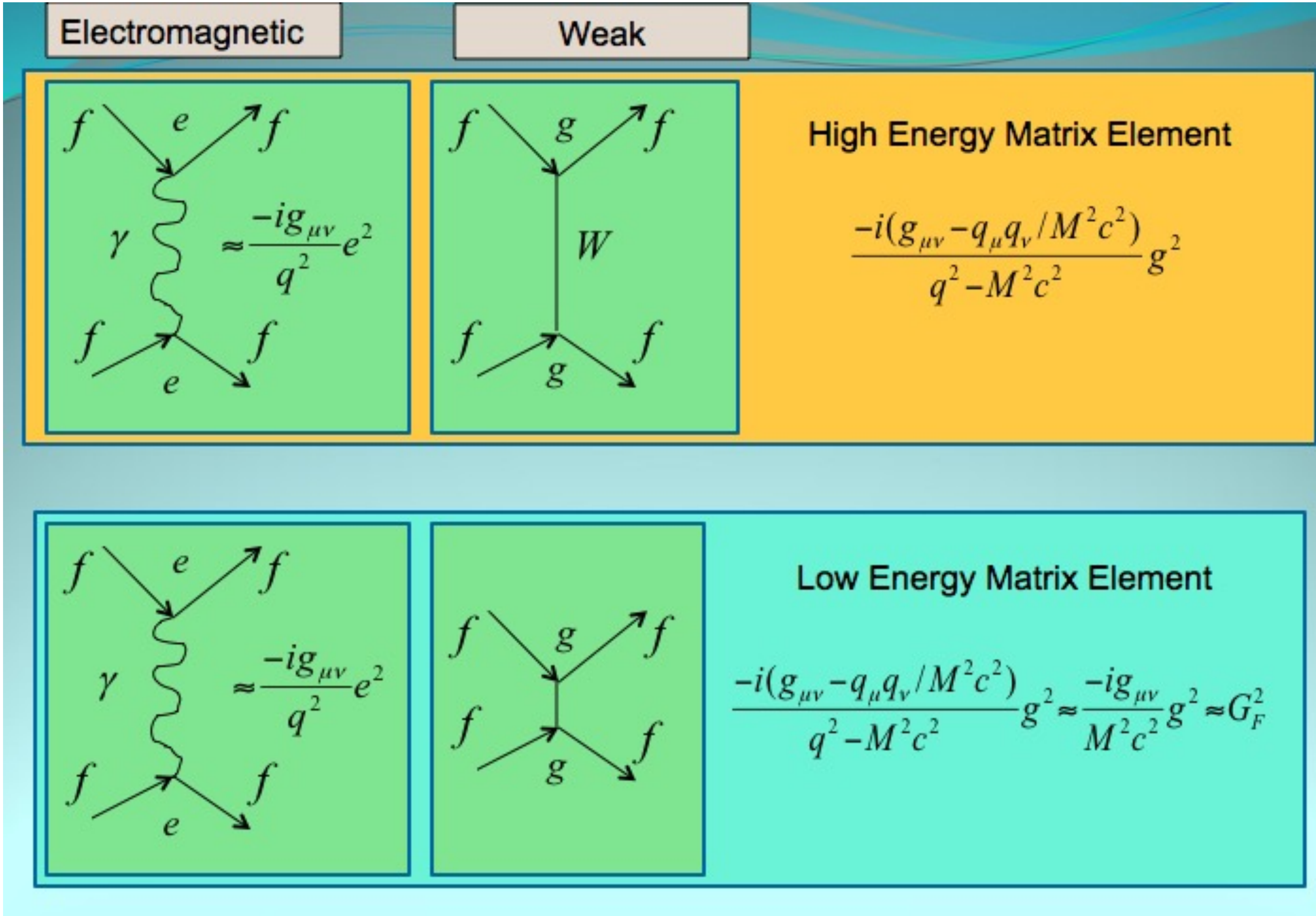
$$L_{Fermi} \approx G_F\, J^{\mu} J'^{+}_{\mu} = \frac{g^2}{M_W^2} J^{\mu} J'^{+}_{\mu}$$

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

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

$|M|^2$ Integration over spins and angles

E_0 Energy of the final state


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

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 :

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

The Weak Fermi constant

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

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

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

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

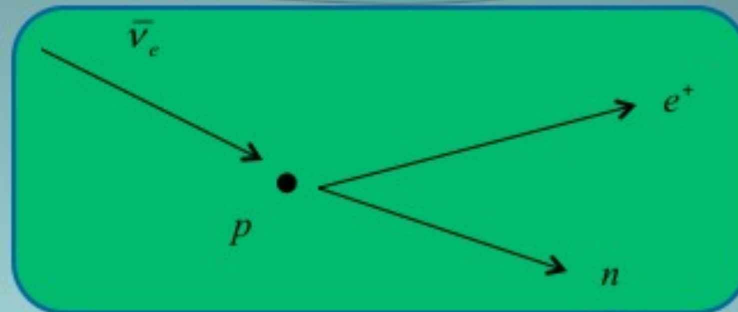
The Weak Coupling constant is actually bigger than the fine structure constant.

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

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



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

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

This is a mixed (Fermi + Gamow-Teller) transition $\quad |M|^2 \cong 4$

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

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 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^+

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

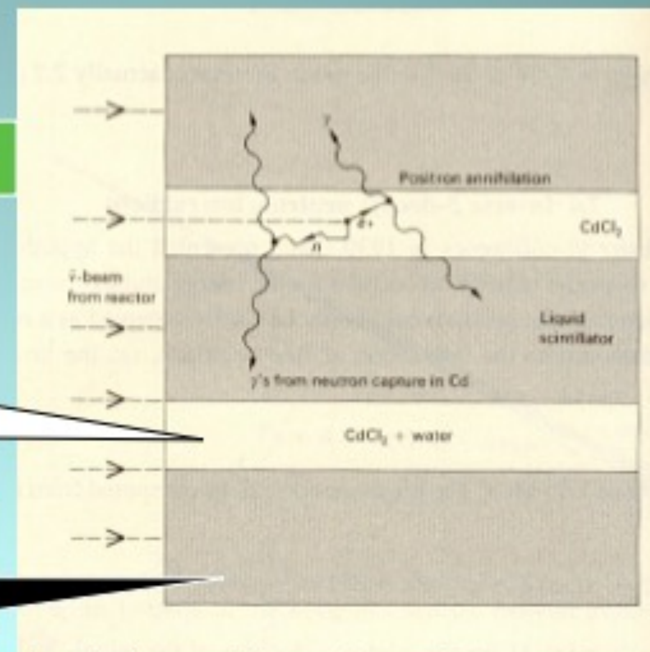
Inverse Beta Decay

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)

Water and cadmium

Liquid scintillator



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

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

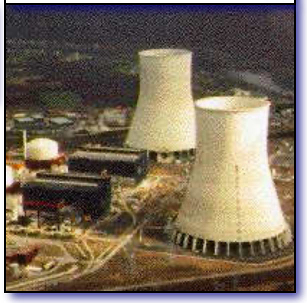
1956: Reines and Cowan at the Savannah nuclear power reactor

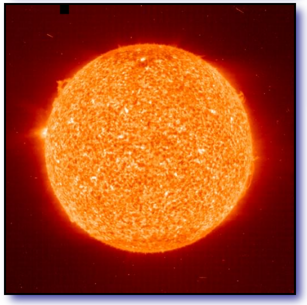
Where do Neutrinos Appear in Nature?

✓ Particle-Accelerators

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

✓ Nuclear Reactors



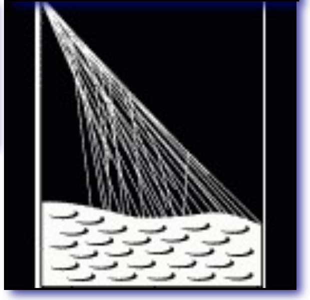


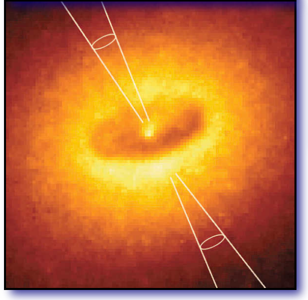
Sun ✓

✓ Earth Crust (Natural Radioactivity)

Supernovae (Stellar Collapse)
SN 1987A ✓

✓ Earth Atmosphere (Low energy Cosmic Rays)



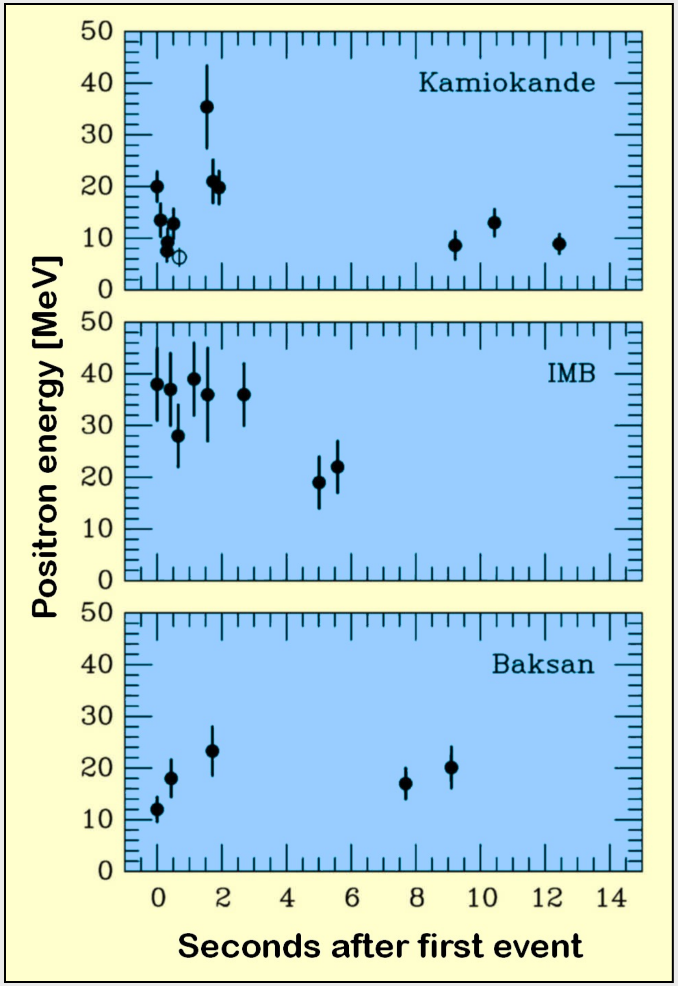


Astrophysical Accelerators 2013


Sanduleak -69 202


Supernova 1987A
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

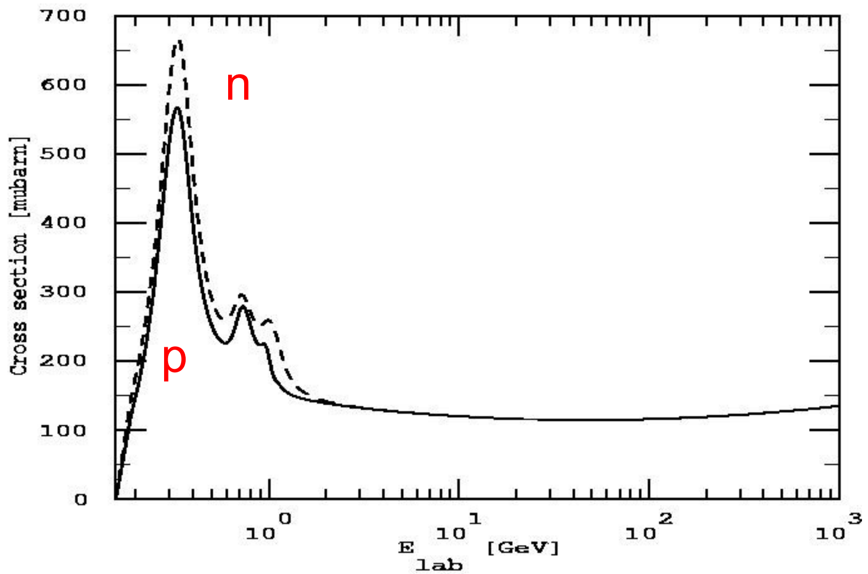
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

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

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

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

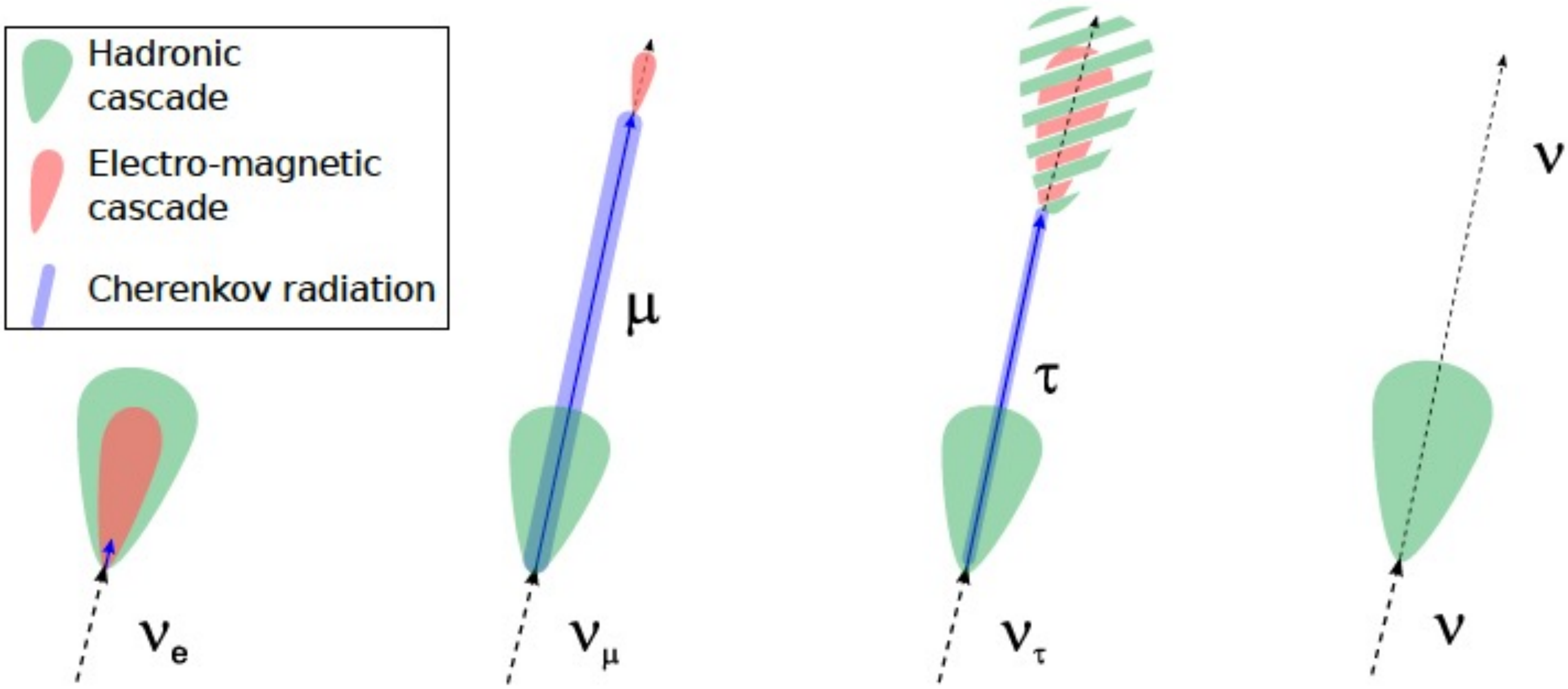
$$\mu^{\pm} \Rightarrow e^{\pm} + \overline{\nu}_e + \nu_{\mu}$$



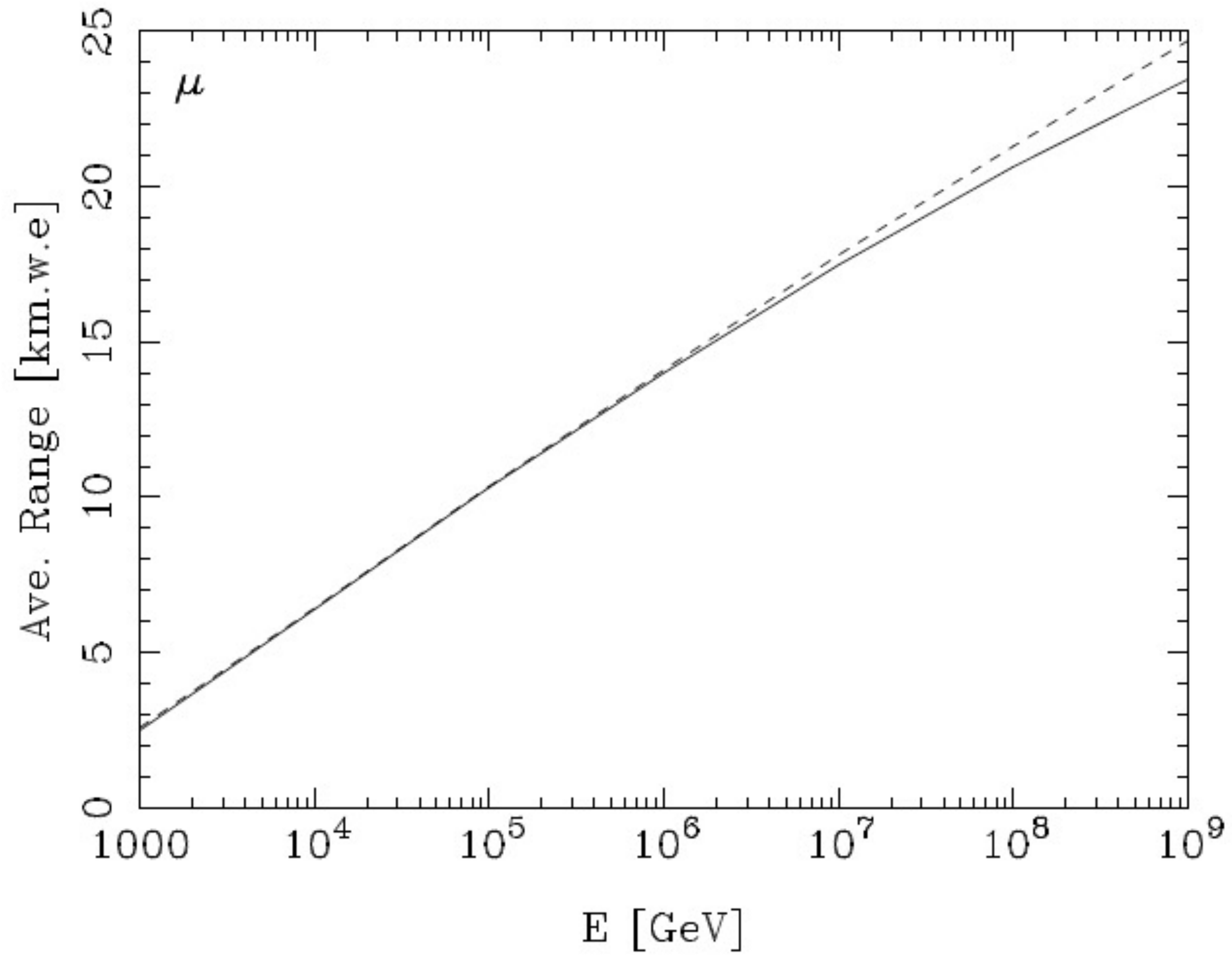
$$n \Rightarrow p + e^- + \overline{\nu}_e$$

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

Detection of neutrino interactions

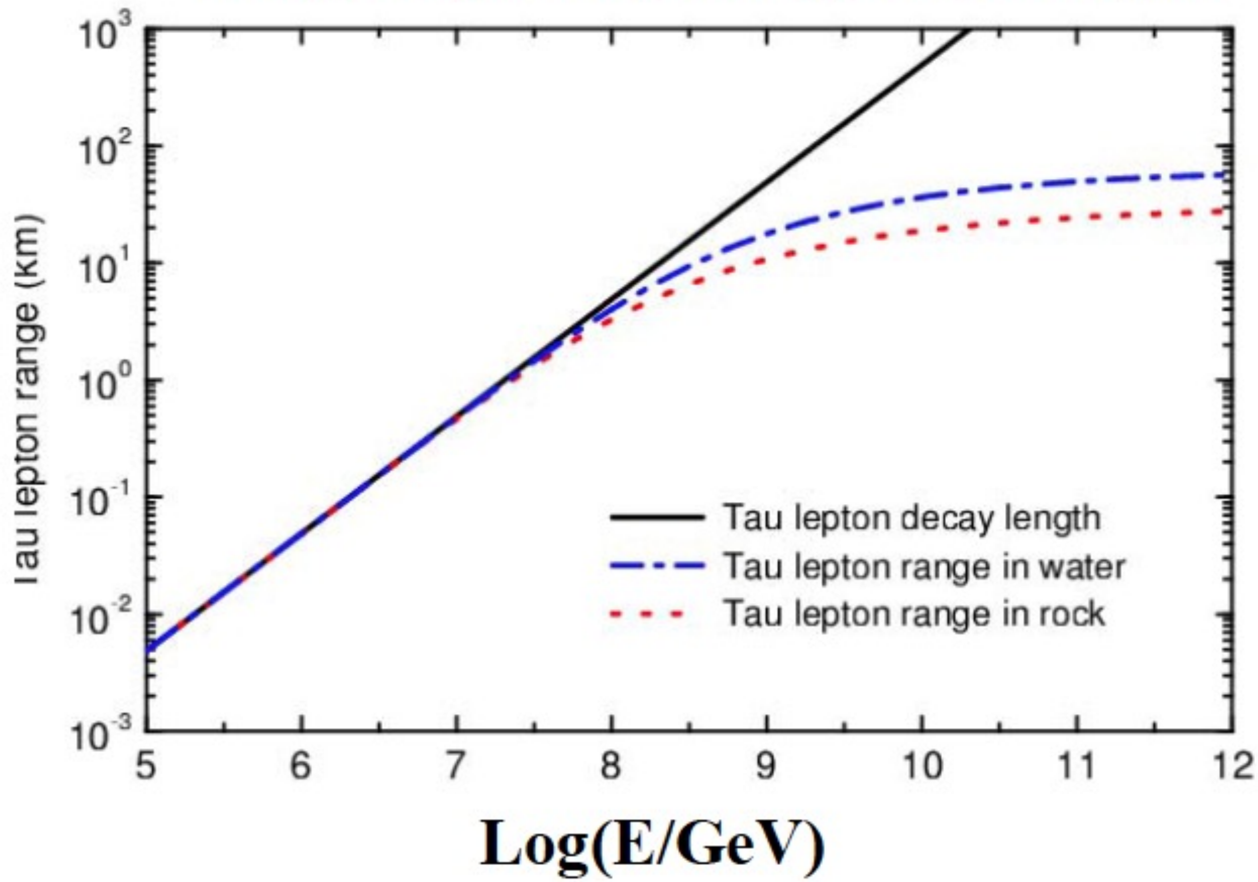


Muon losses



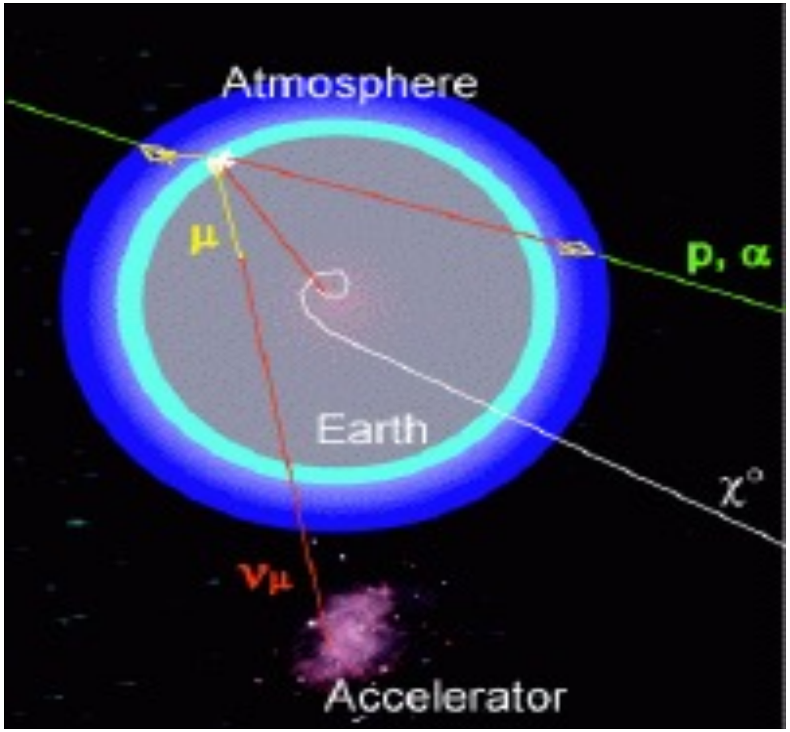
Tau energy losses

Iyer Dutta, Reno, Sarcevic, & Seckel, 01
Tseng, Yeh, Athar, Huang, Lee, & Lin, 03



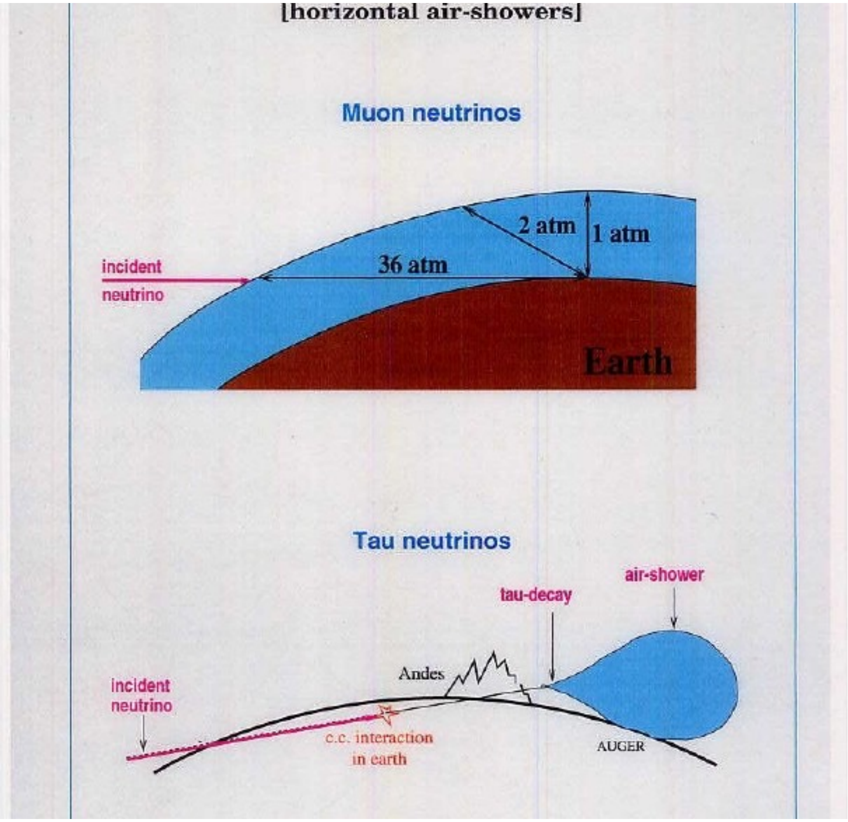
Experimental detection of $E<10^{17}$eV neutrinos

- 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

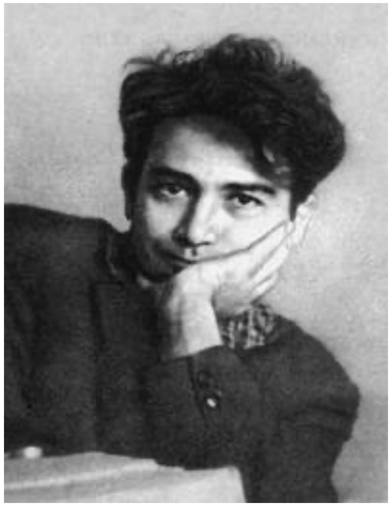
- Neutrinos are not primary UHECR
- Horizontal or up-going air showers – easy way to detect neutrinos
- Experiments: Fly's Eye, AGASA, HiRes,
- AUGER



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.



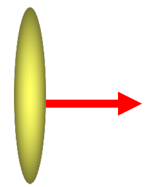
G.Askaryan was the first to note that the outer few metres of the Moon's surface, known as the regolith, would be a sufficiently transparent medium for detecting microwaves from the charge excess in particle showers.
The radio transparency of the regolith has since been confirmed by the Apollo missions.

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

$e^- \rightarrow \ldots$ cascade

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

$\Rightarrow$ relativist. pancake
~ 1cm thick, ∅ ~10cm

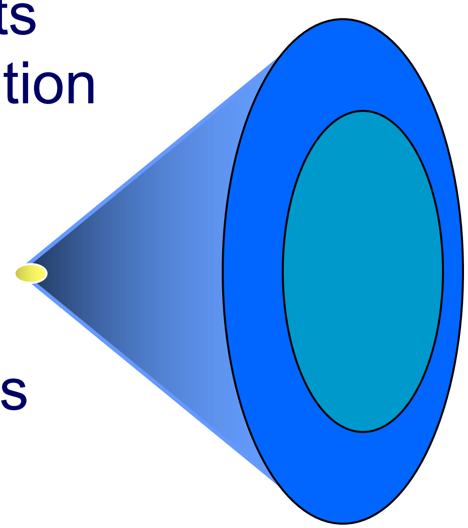


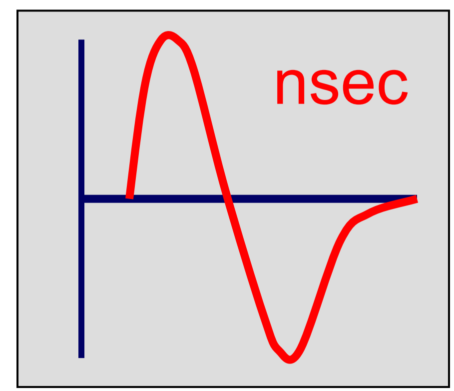
$\Rightarrow$ for λ >> 10 cm (radio)
coherence

$\Rightarrow$ each particle emits
Cherenkov radiation

$\Rightarrow$ C-signal ~ E^2

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

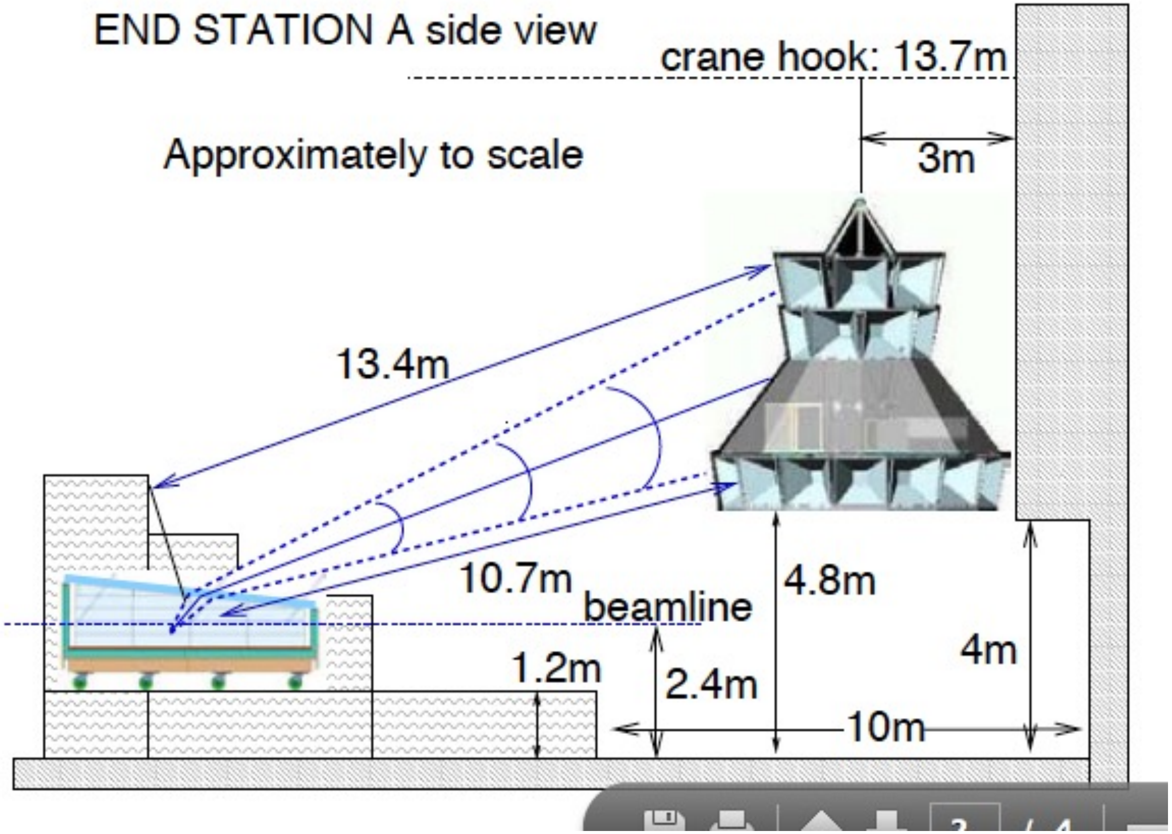




Experiments:
GLUE, RICE, FORTE, ANITA

Threshold > 10^{16} eV

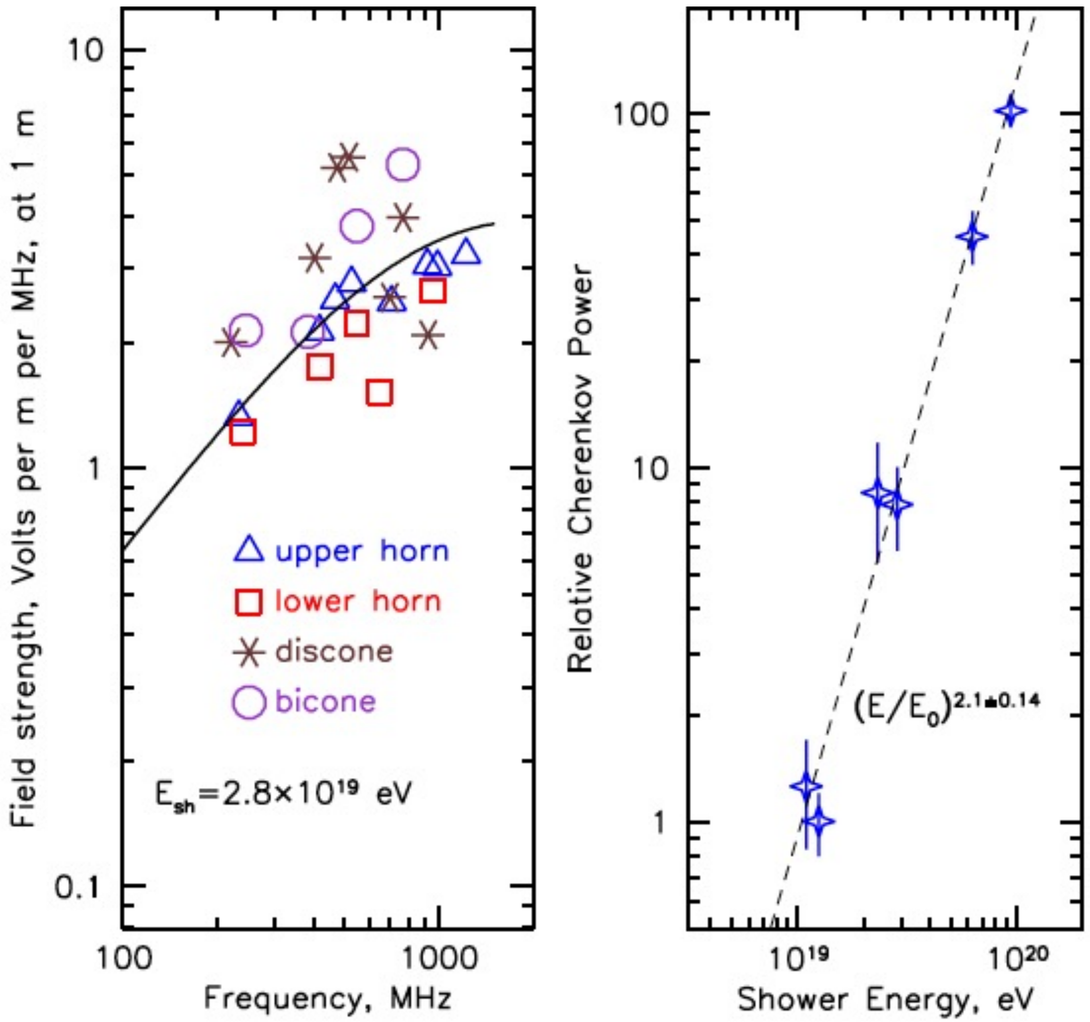
SLAC 2006: observation of Askarvan effect



SLAC 2006



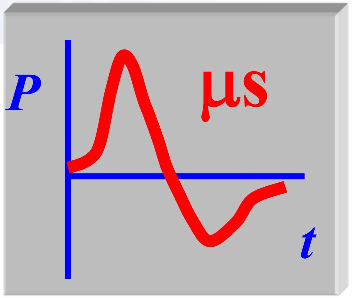
SLAC 2006

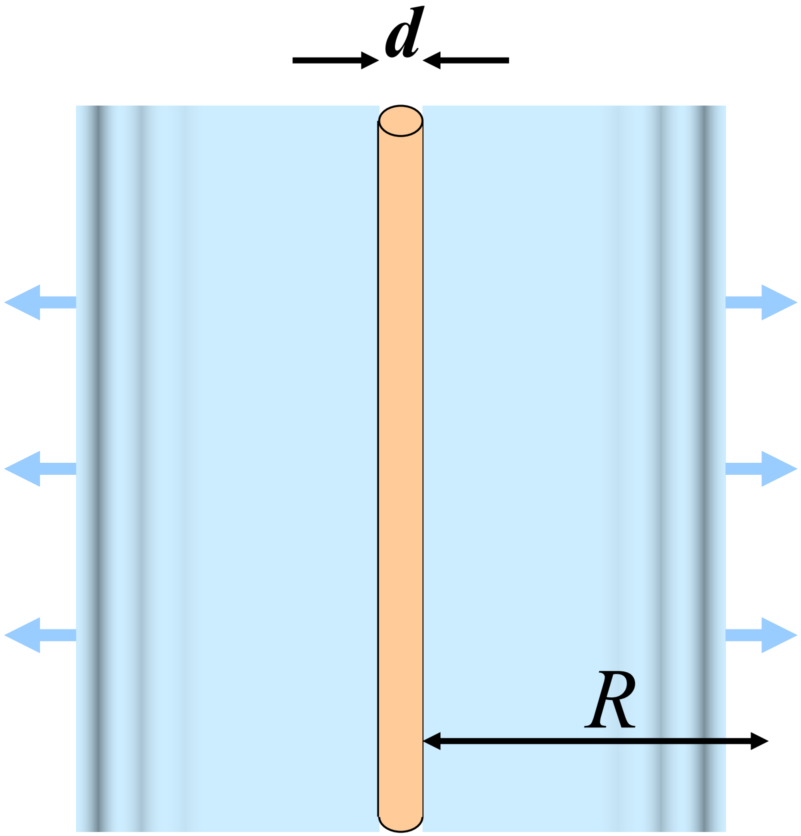


10
1
0.1
100
1000
Frequency, MHz
Field strength, Volts per m per MHz, at 1 m
upper horn
lower horn
discone
bicone
$E_{sh}=2.8\times10^{19}$ eV
100
10
1
10^{19}
10^{20}
Shower Energy, eV
Relative Cherenkov Power
$(E/E_0)^{2.1\pm0.14}$

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)

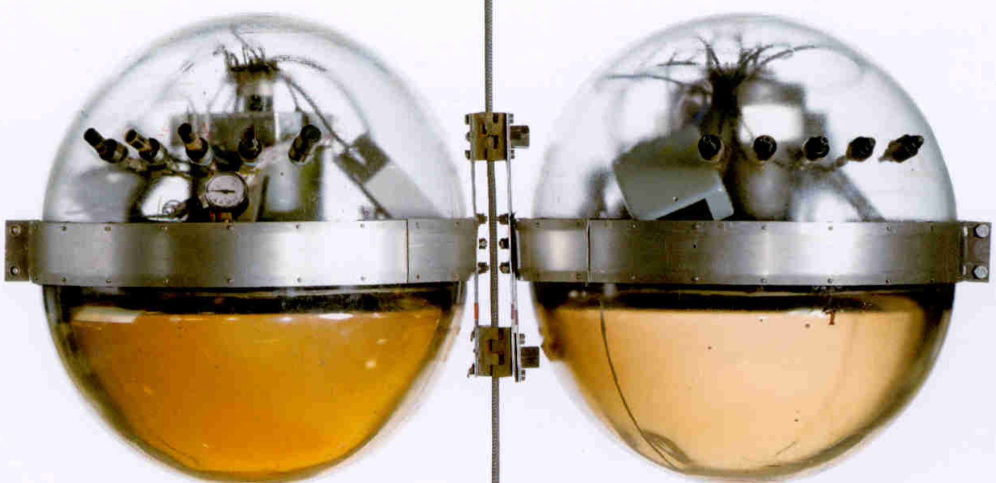
→ given a large initial signal, huge detection volumes can be achieved.

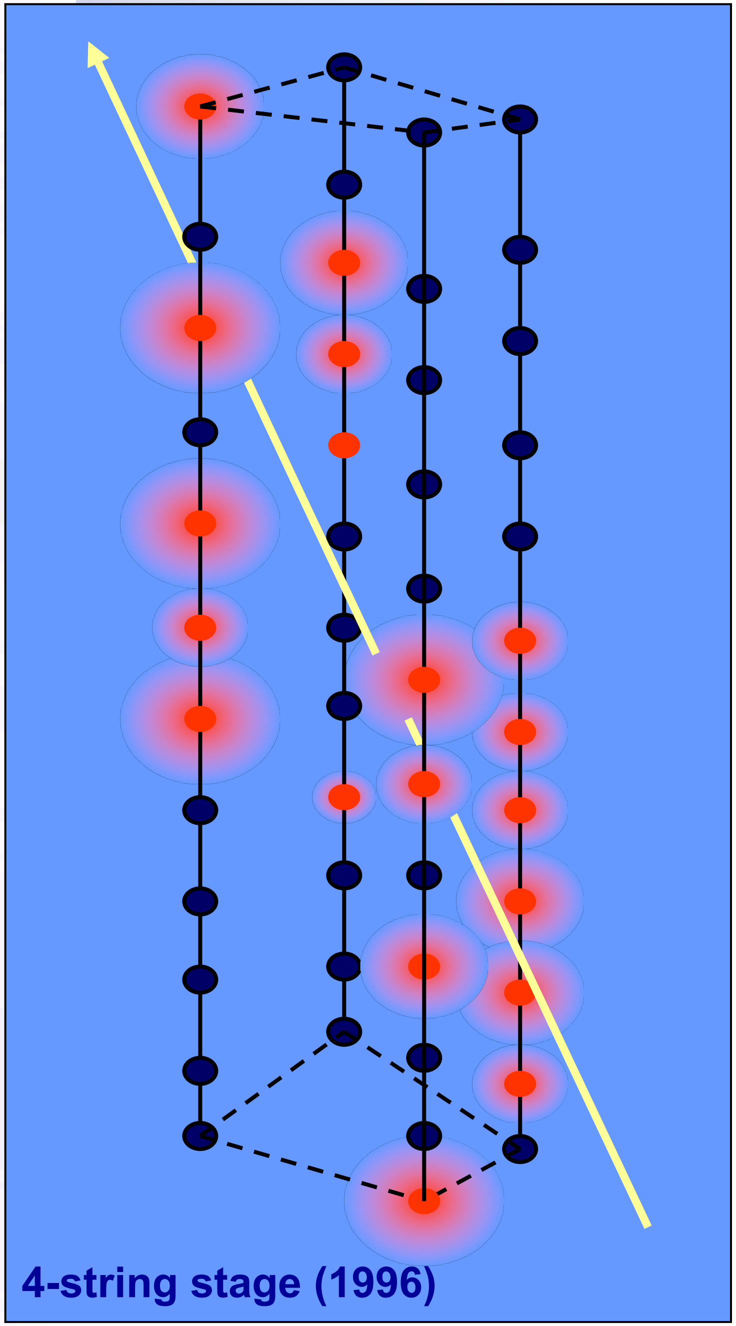
Threshold > 10^{16} eV

Historical experiments

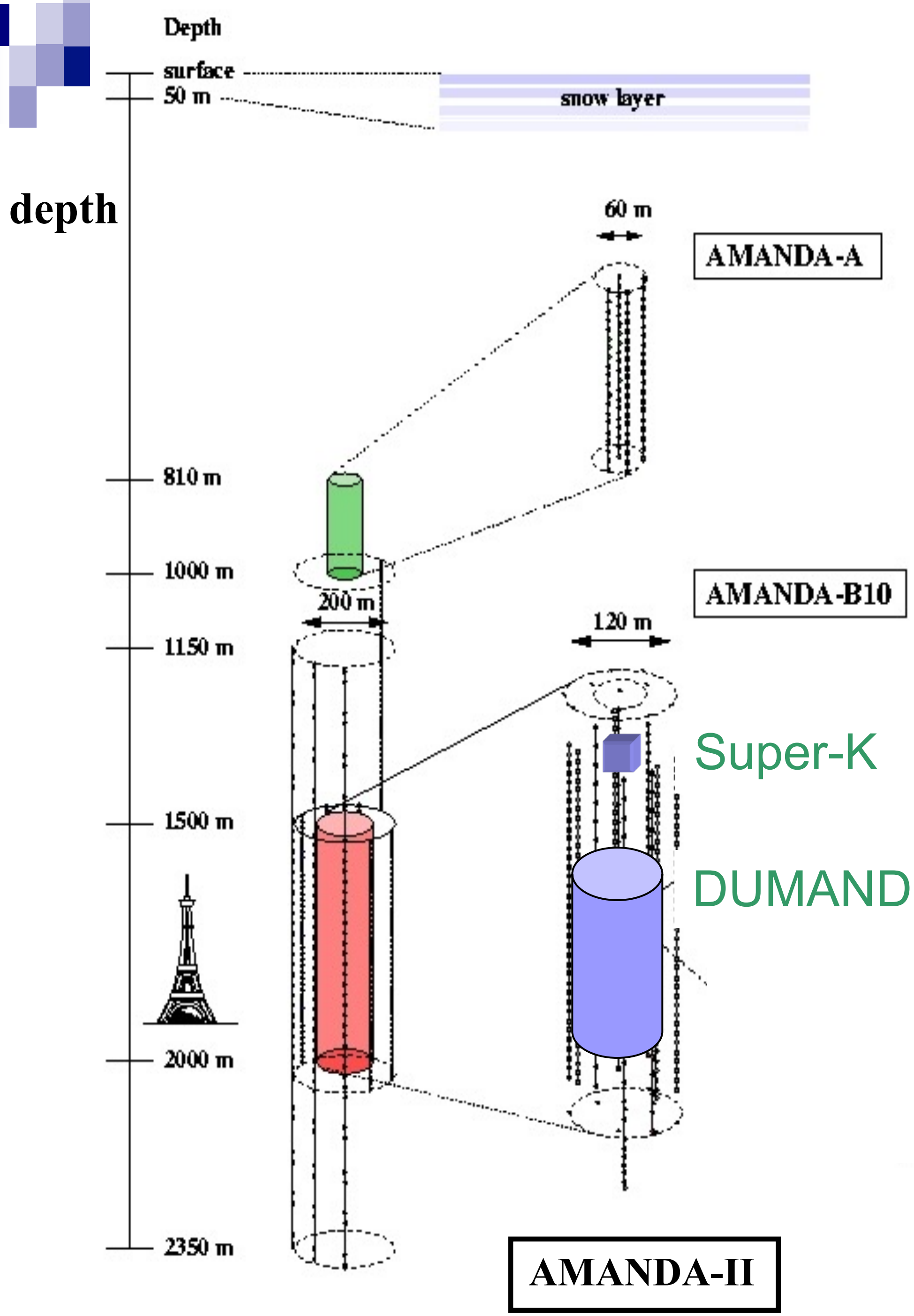
Lake Baikal

First underwater telescope
First neutrinos underwater





AMANDA



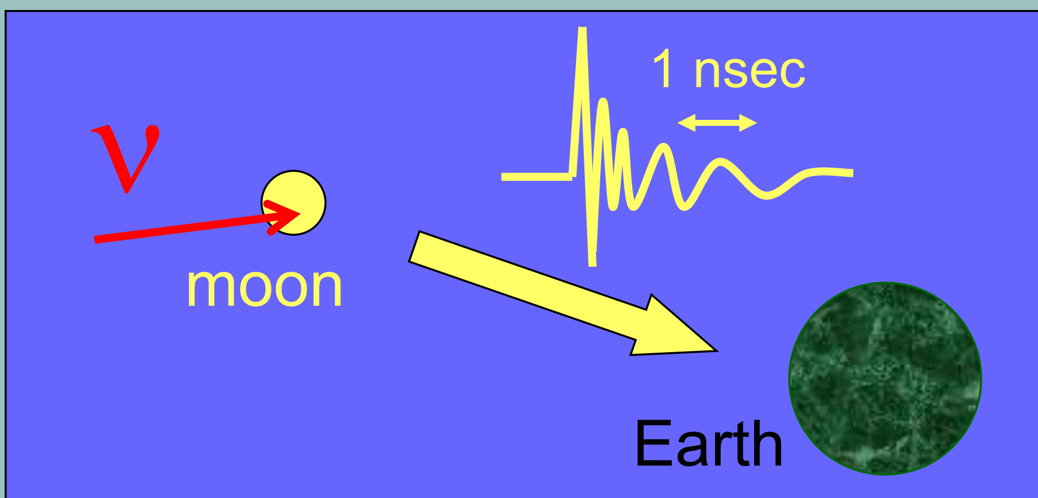
Amanda-II:
677 PMTs
at 19 strings

(1996-2000)

GLUE Goldstone Lunar Ultra-high Energy Neutrino Experiment

Lunar Radio Emissions from Inter-actions of ν and CR with > 10^{19} eV

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



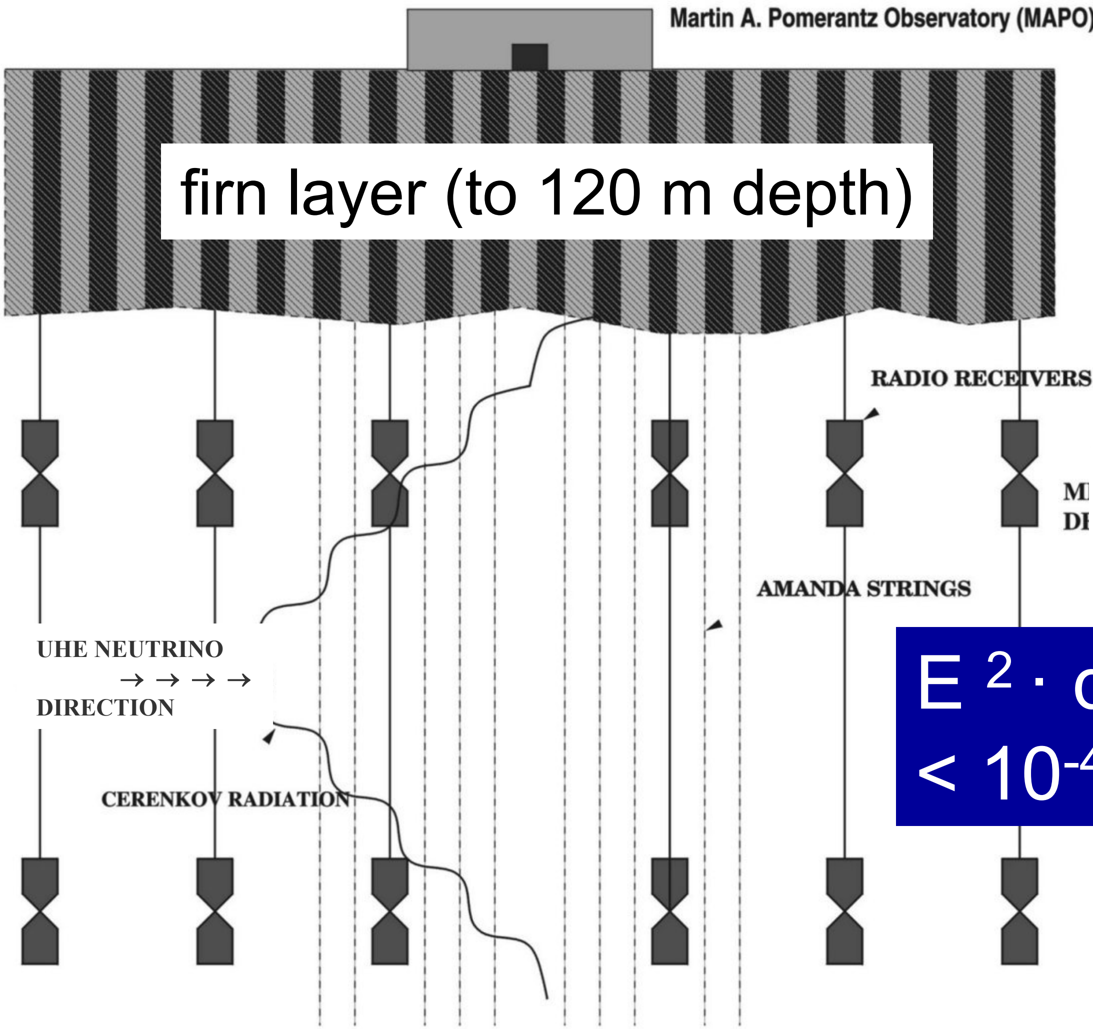
→ $E^2 \cdot dN/dE < 10^5\ eV \cdot cm^{-2} \cdot s^{-1} \cdot sr^{-1}$

at 10^{20} eV

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

→ $10^5\ km^3$

RICE Radio Ice Cherenkov Experiment



South Pole

20 receivers + transmitters

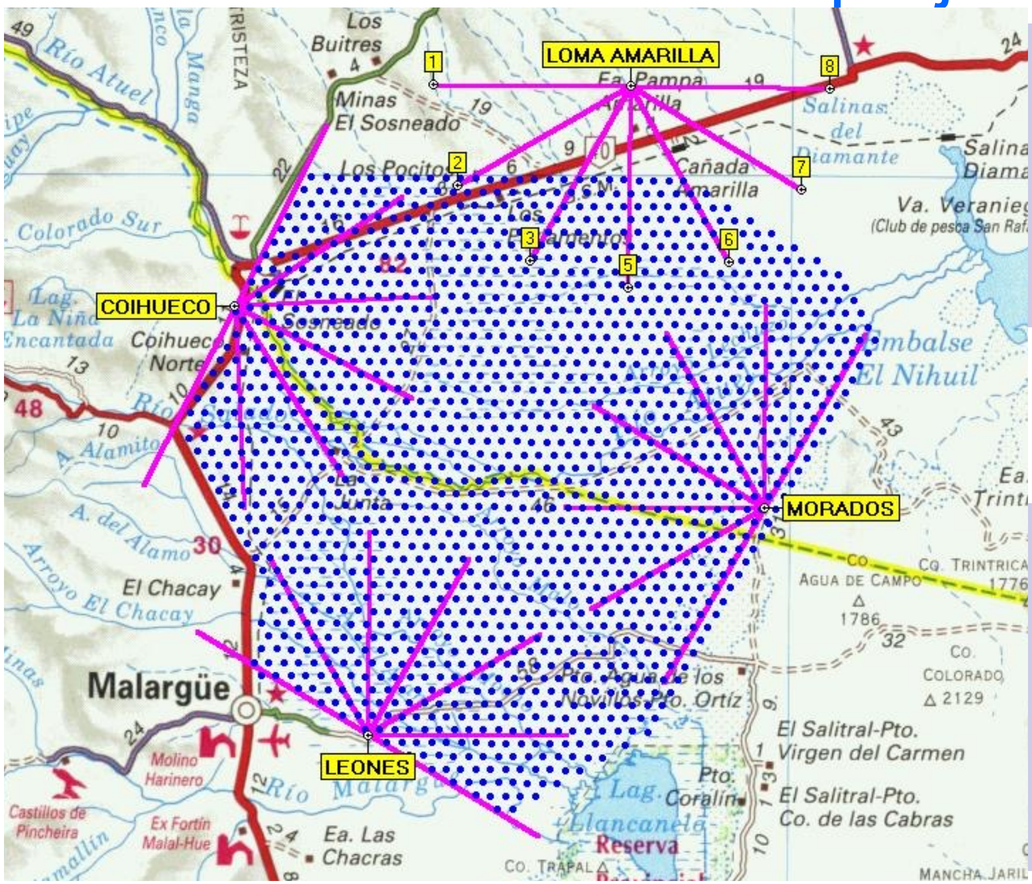
$E^2 \cdot dN/dE$
$< 10^{-4}$ GeV $\cdot$ cm^{-2} $\cdot$ s^{-1} $\cdot$ sr^{-1}

at 10^{17} eV

Pierre Auger Observatory

South site in Argentina almost finished

North site – project



Surface Array

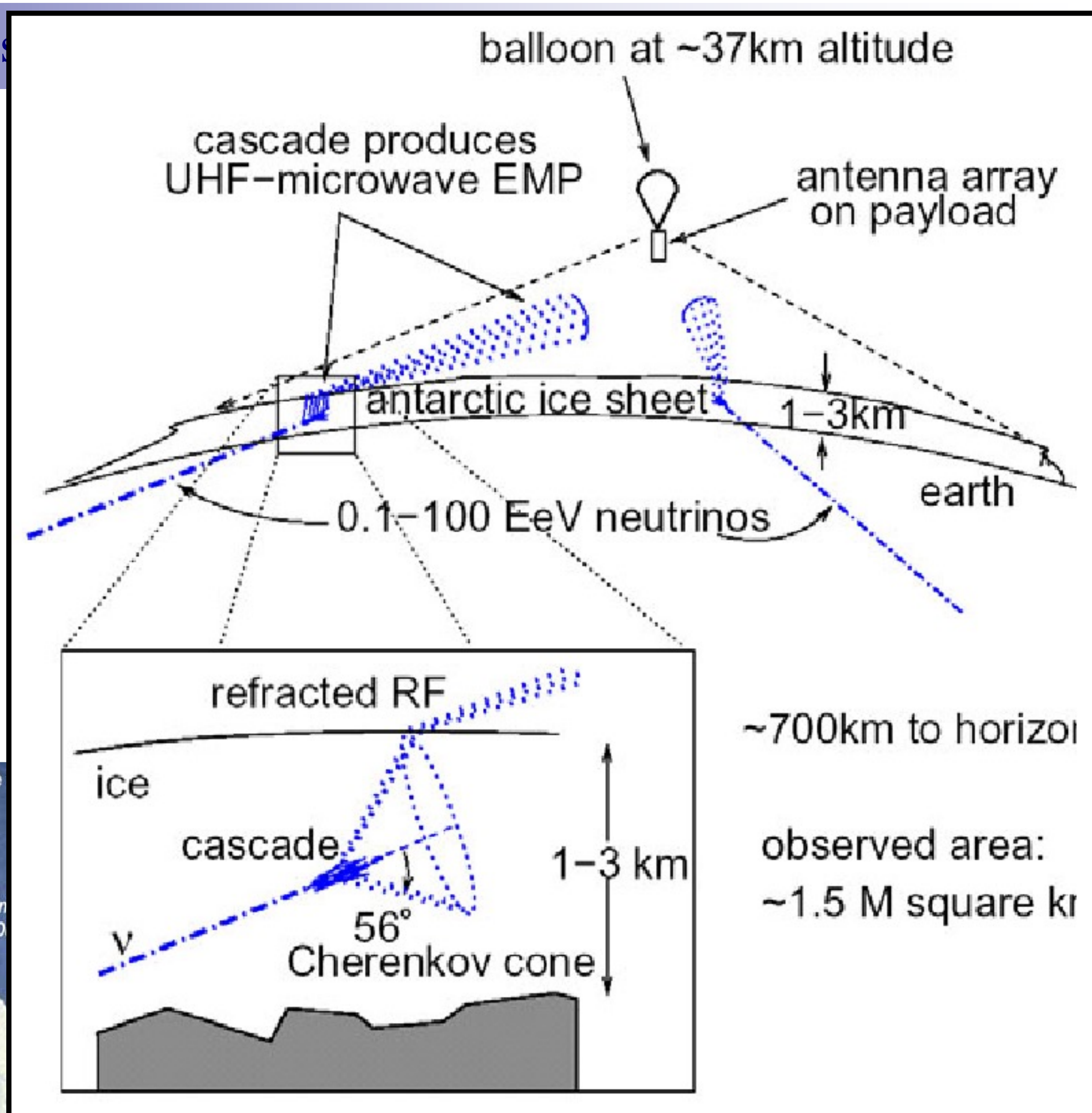
- ***1600 detector stations***
- ***1.5 Km spacing***
- ***3000 Km^2 (30xAGASA)***

Fluorescence Detectors

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

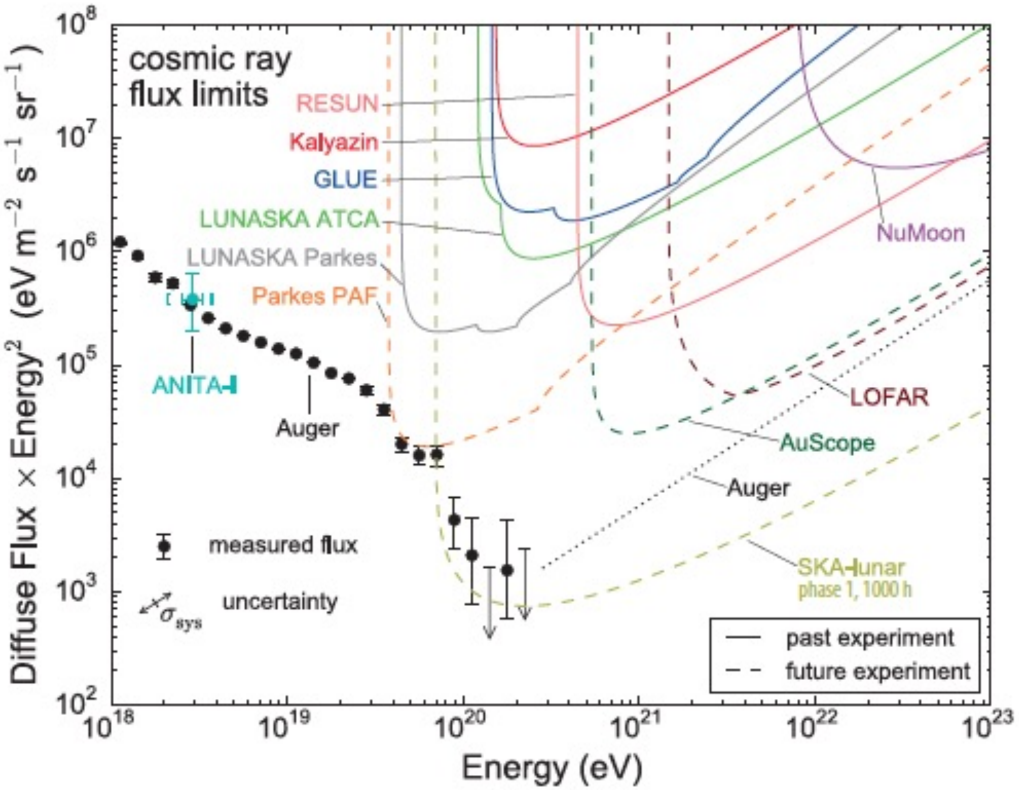
ANITA

Antarctic
Impulsive
Transient
Array

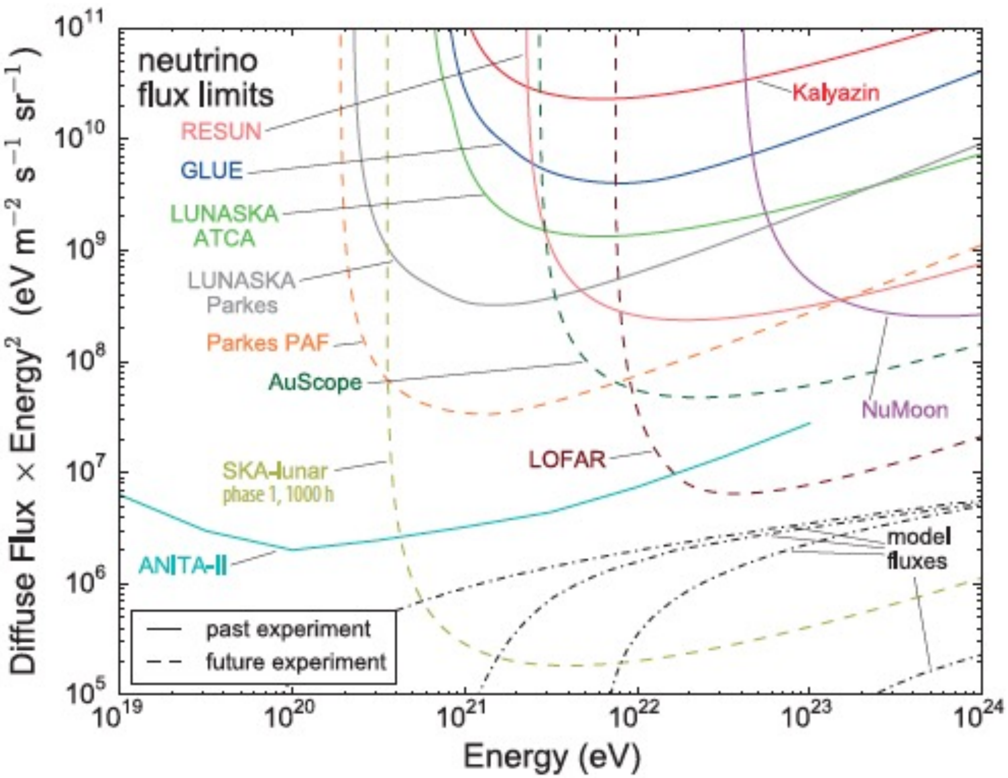


Flights in 2006,2007 (35 days)

Radio detection cosmic rays



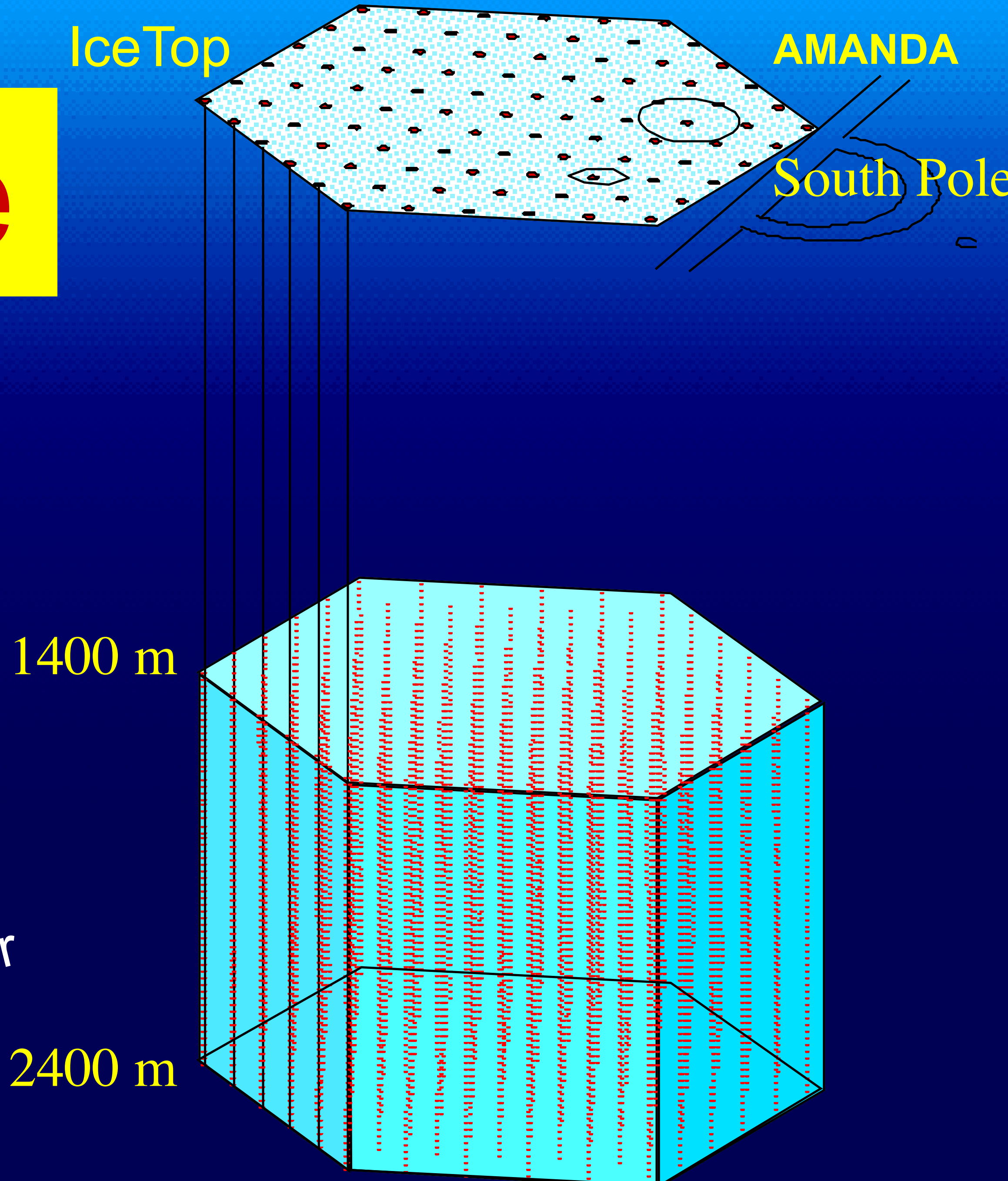
Radio detection neutrinos



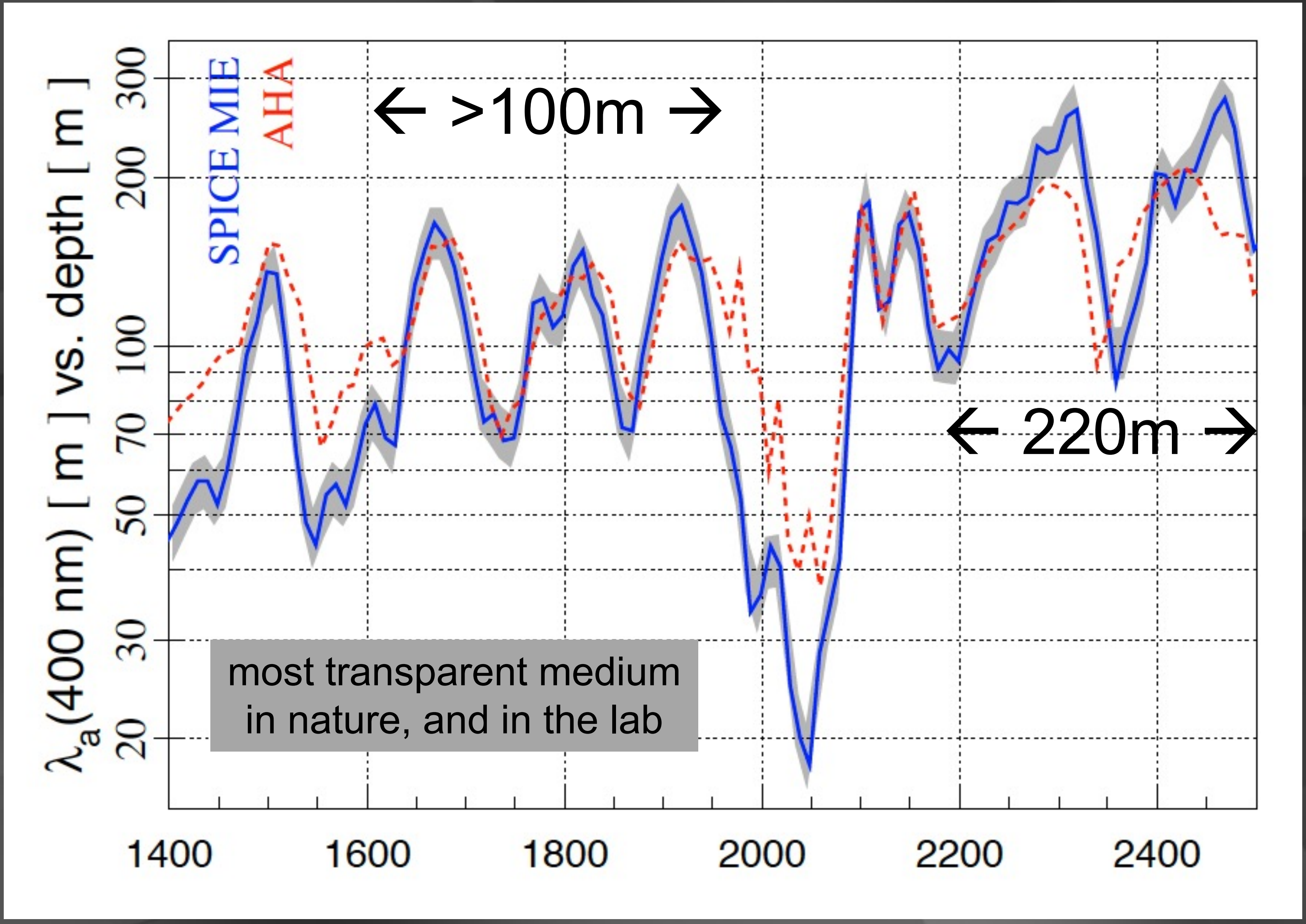
IceCube

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

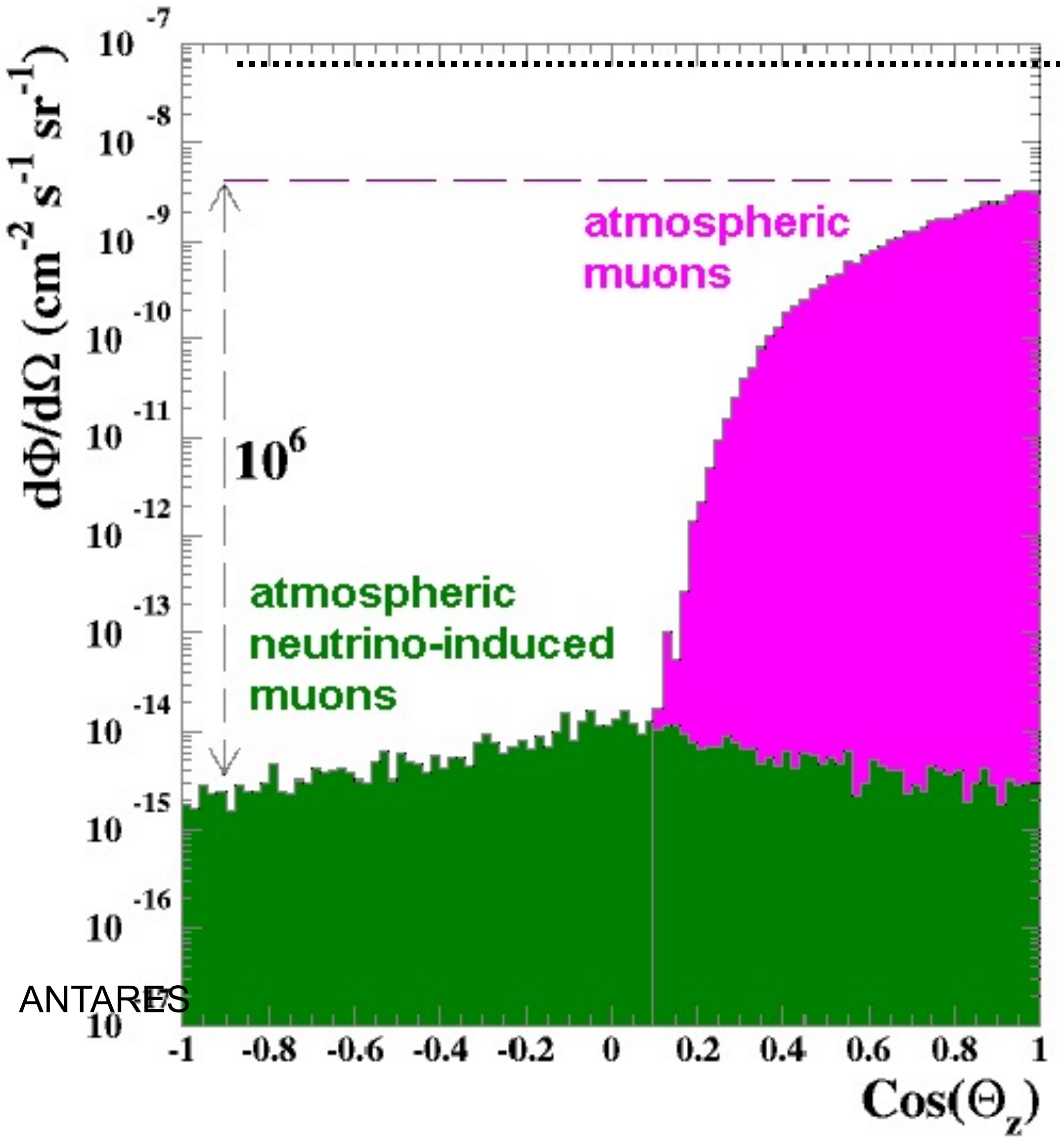
~ 80.000 atm.ν per year



absorption length of Cherenkov light



Backgrounds: atmospheric muons and neutrinos



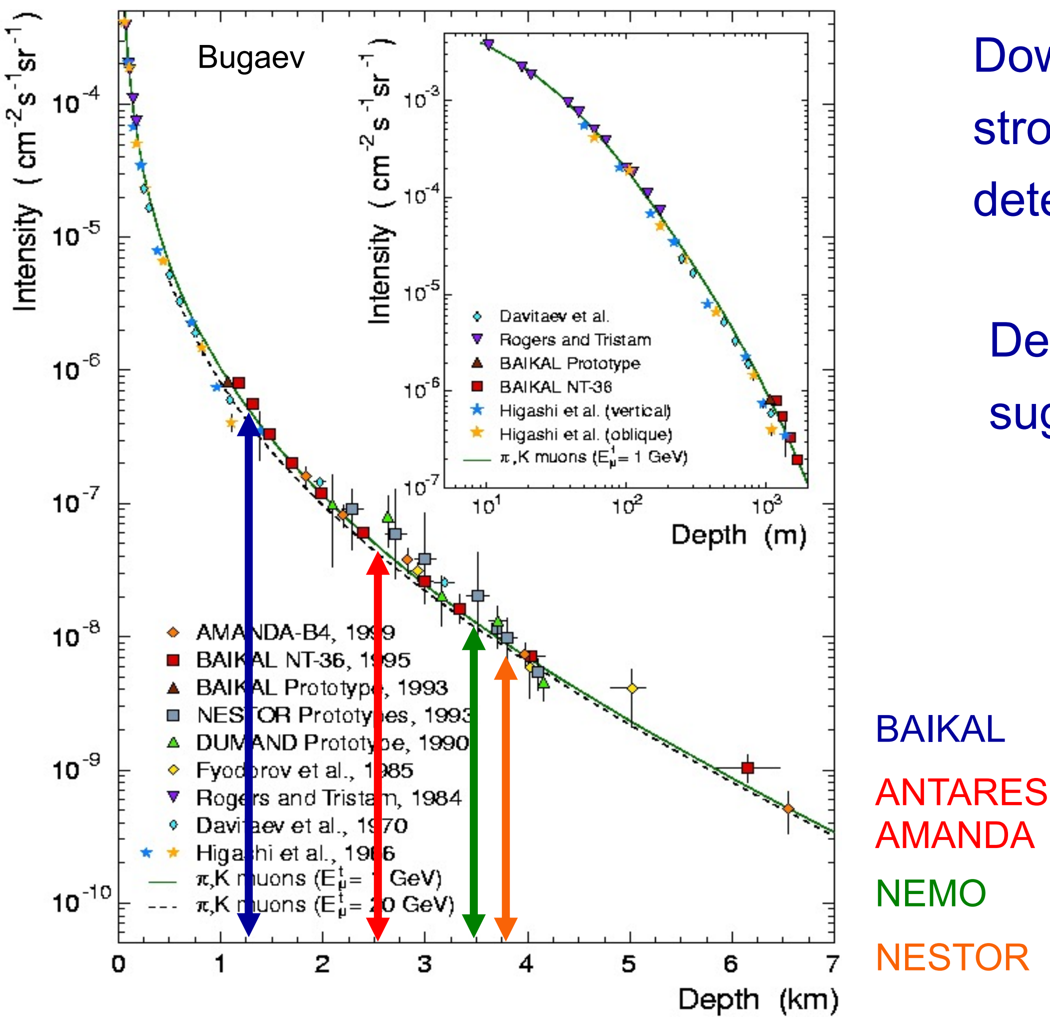
Atmospheric neutrinos:

- 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

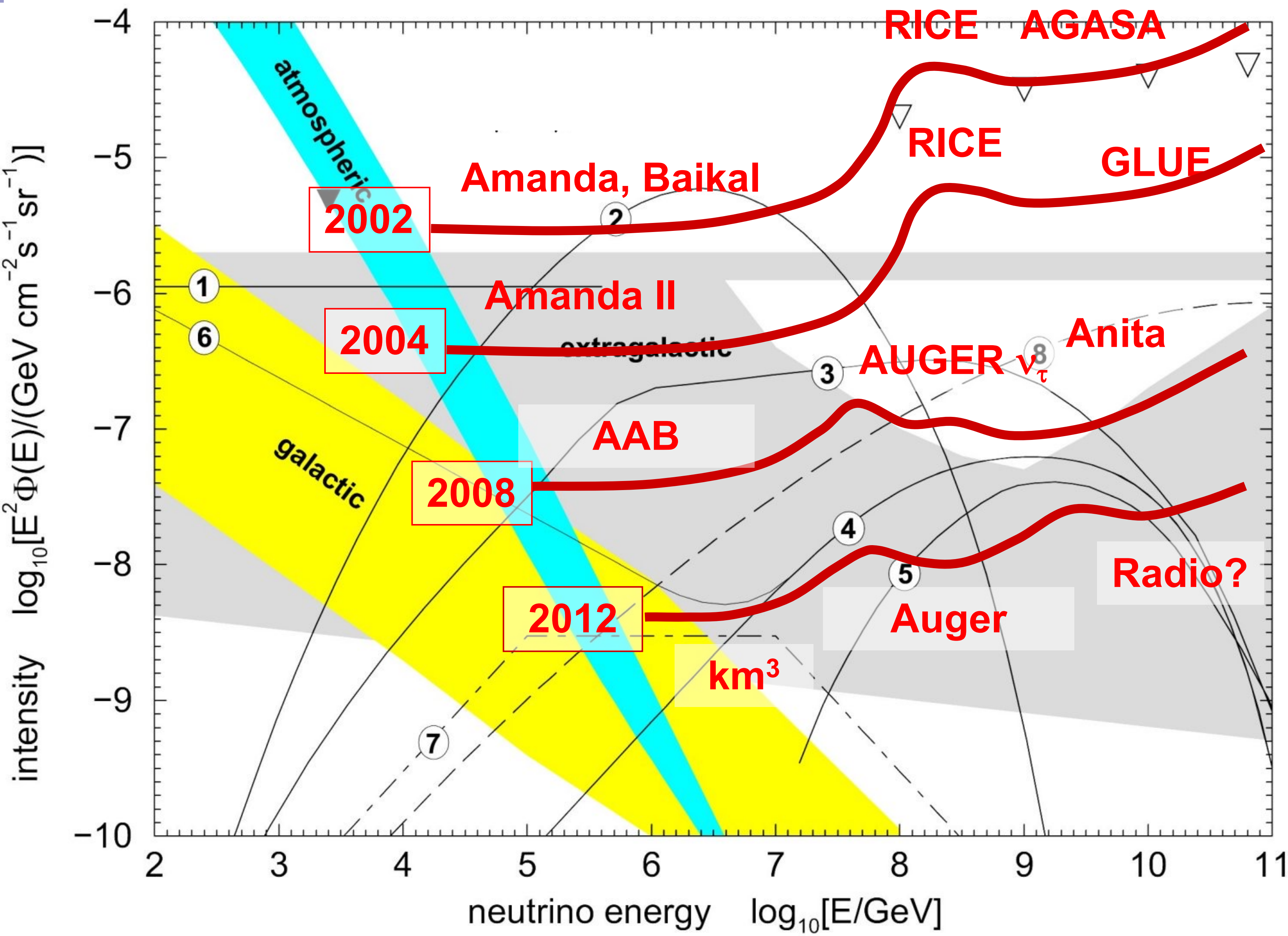
… you looked at 10msec of data !

muons detected per year:

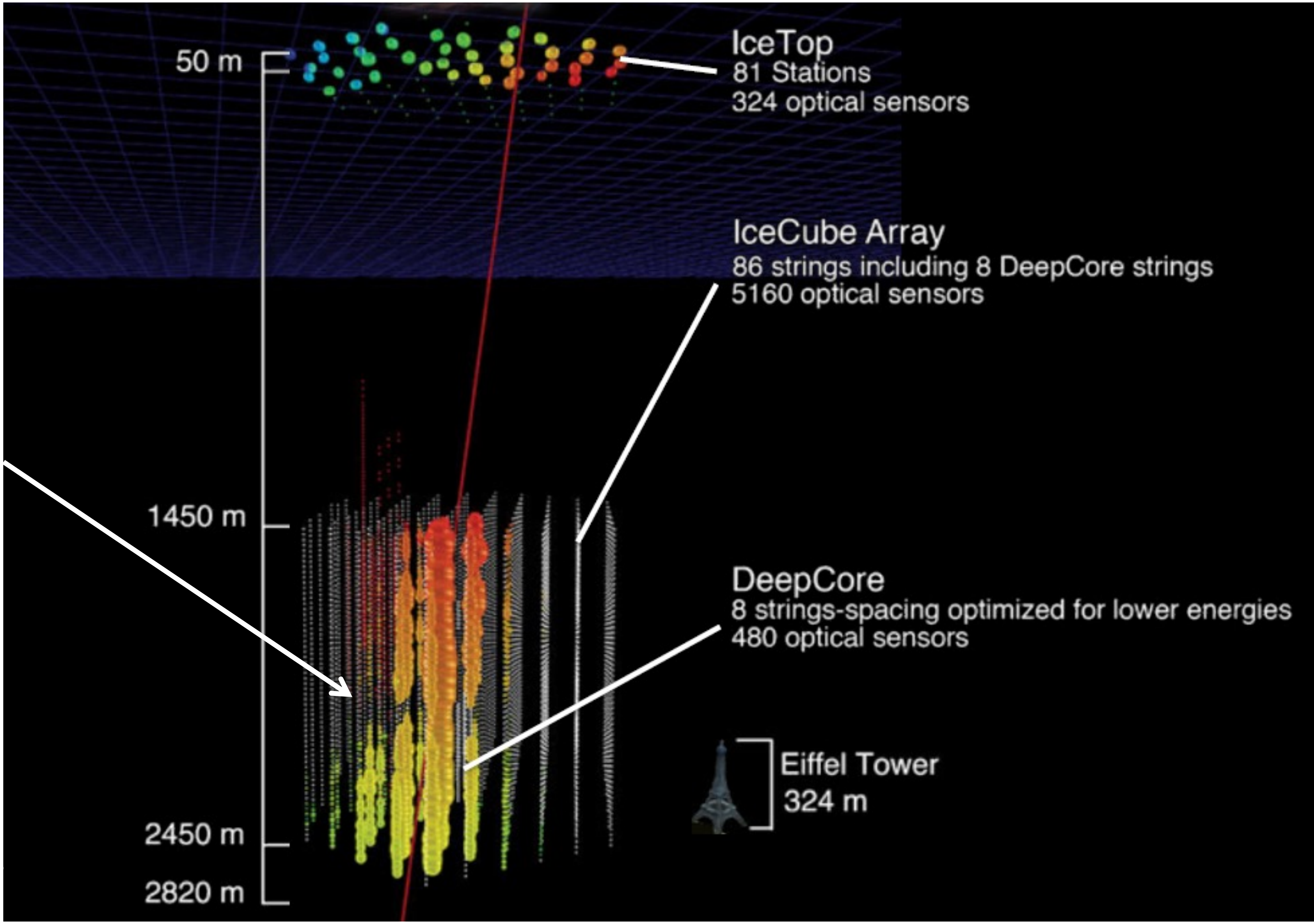
- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second

** 1 every 6 minutes

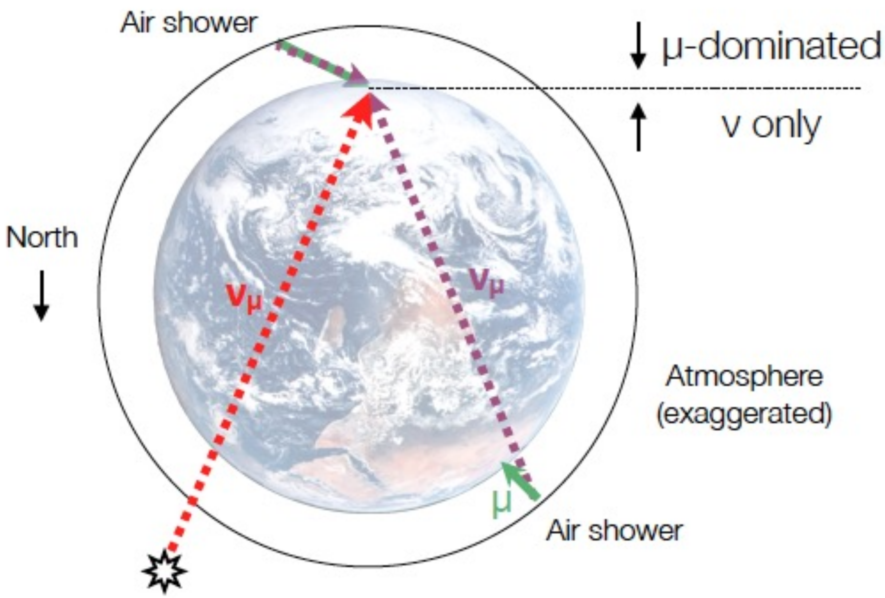

RICE
AGASA
RICE
GLUE
Amanda, Baikal
2002
Amanda II
2004
AUGER ν_τ
Anita
AAB
2008
2012
km³
Auger
Radio?
atmospheric
extragalactic
galactic
intensity log$_{10}$[E$^2\Phi$(E)/(GeV cm^{-2}s^{-1}sr^{-1})]
neutrino energy log$_{10}$[E/GeV]

IceCube discovery of astrophysical neutrinos


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
50 m
1450 m
2450 m
2820 m

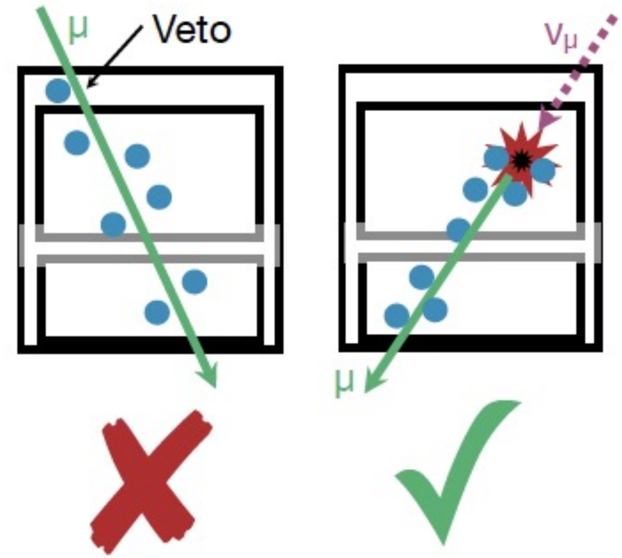
Isolating neutrino events: two strategies

Up-going tracks

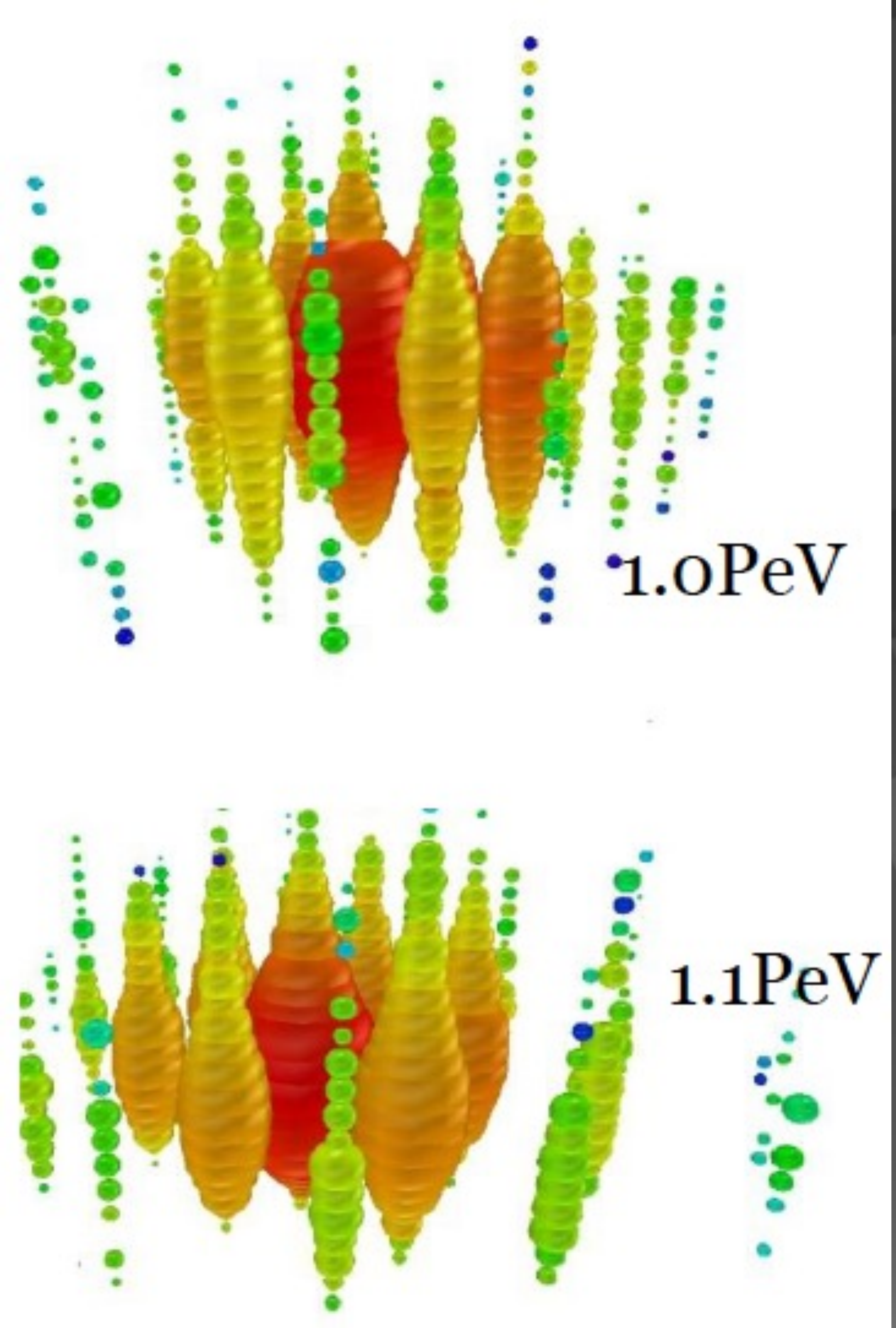


- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to ν_μ only
- Sensitive to half the sky

Active veto



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



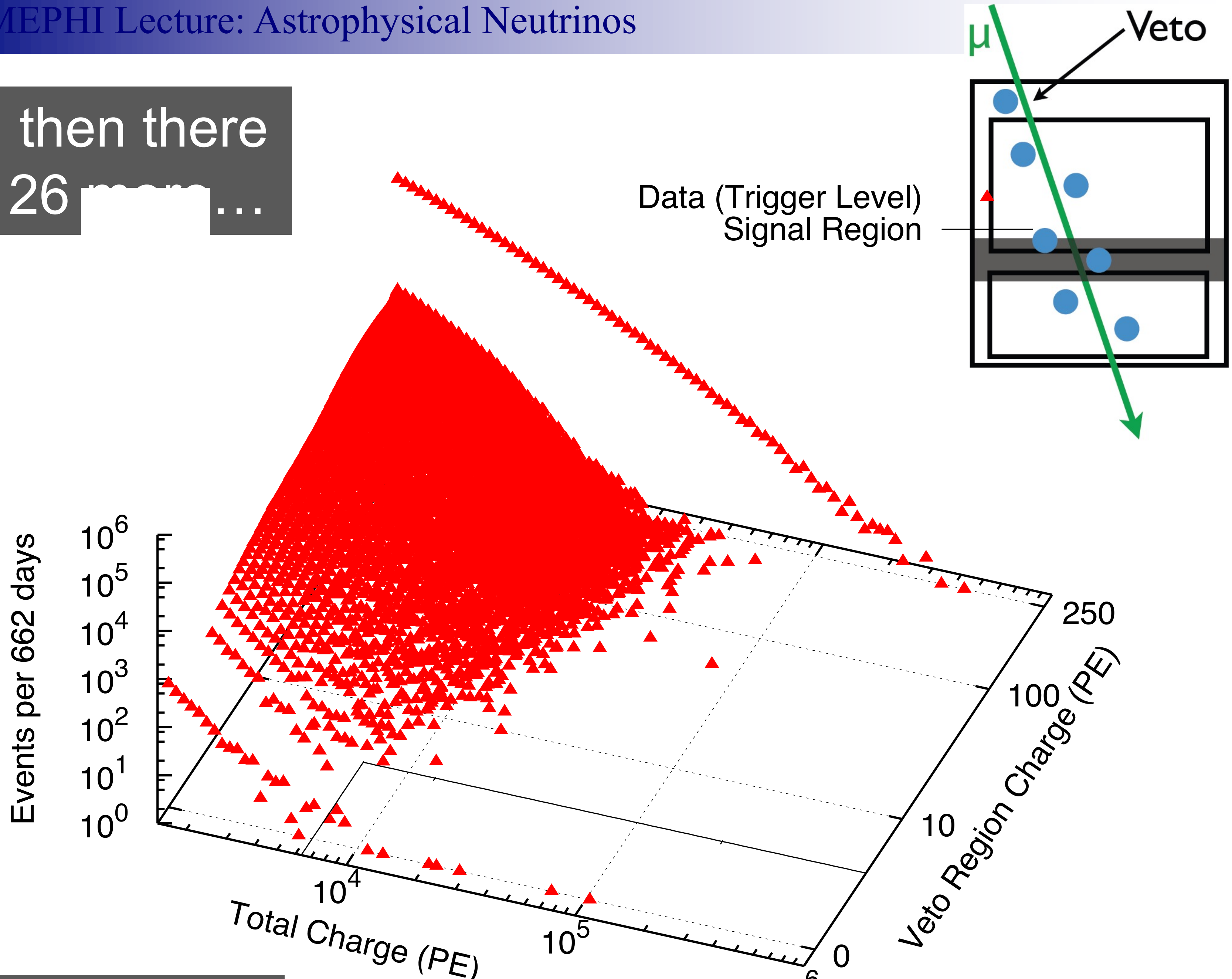
• energy

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

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

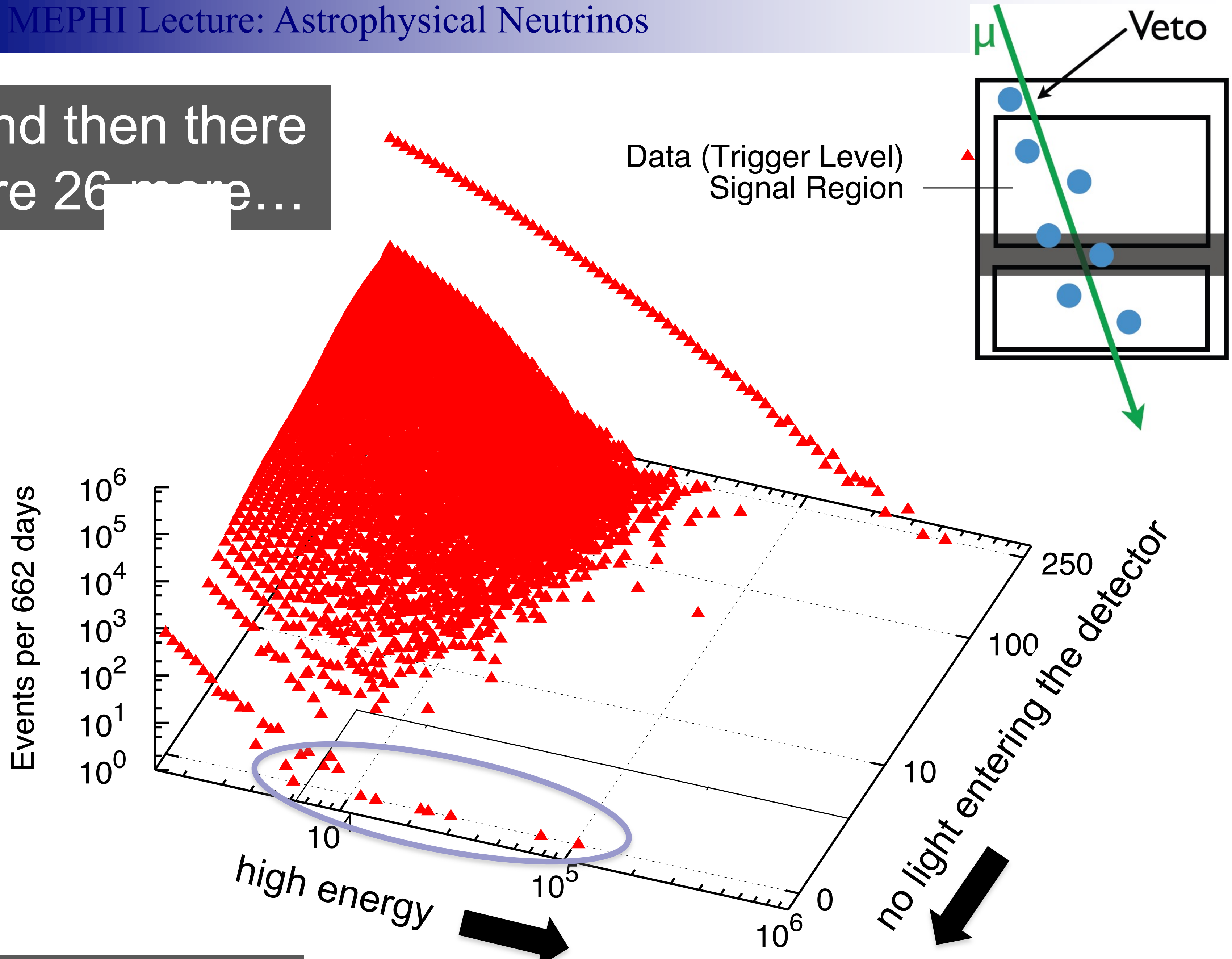
→ flux at present level of diffuse limit

…and then there were 26 more…



data: 86 strings one year

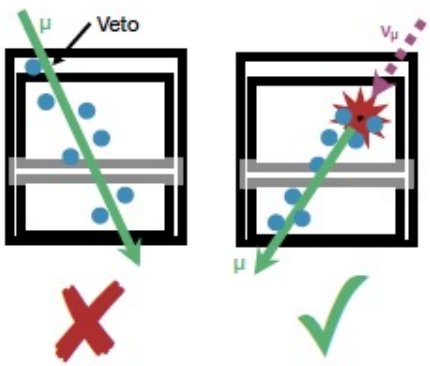
…and then there were 26 more…



data: 86 strings one year

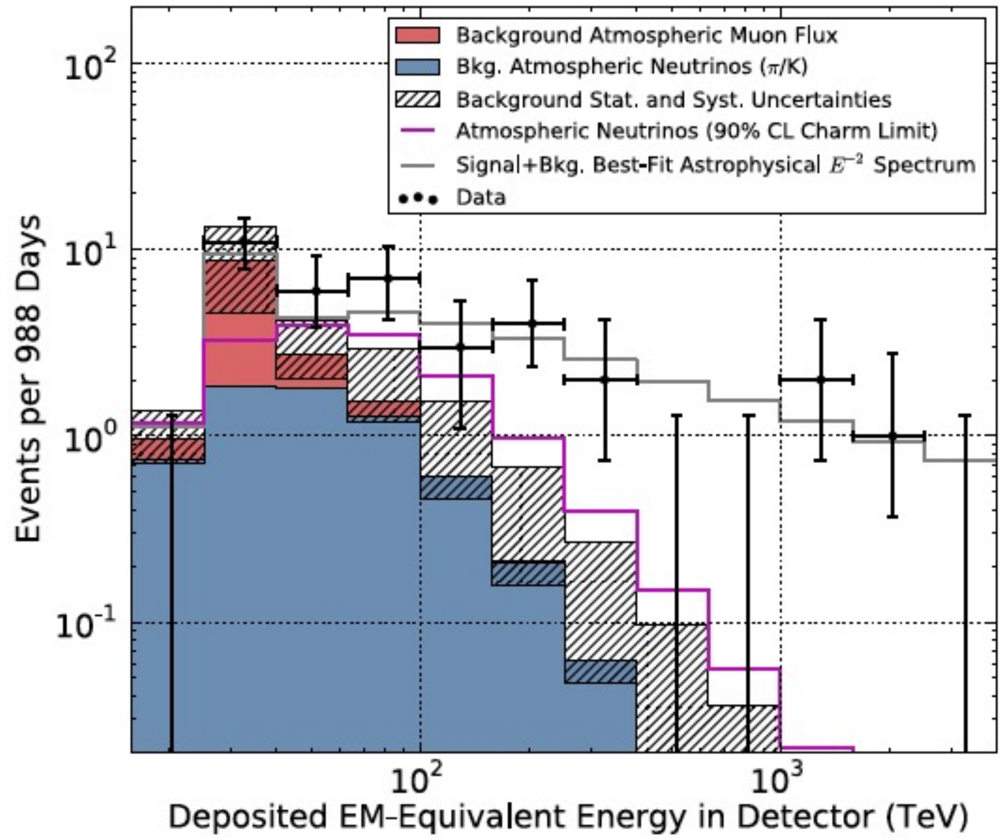
Evidence for high-energy astrophysical neutrinos

- Selected high-energy starting events in IceCube



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

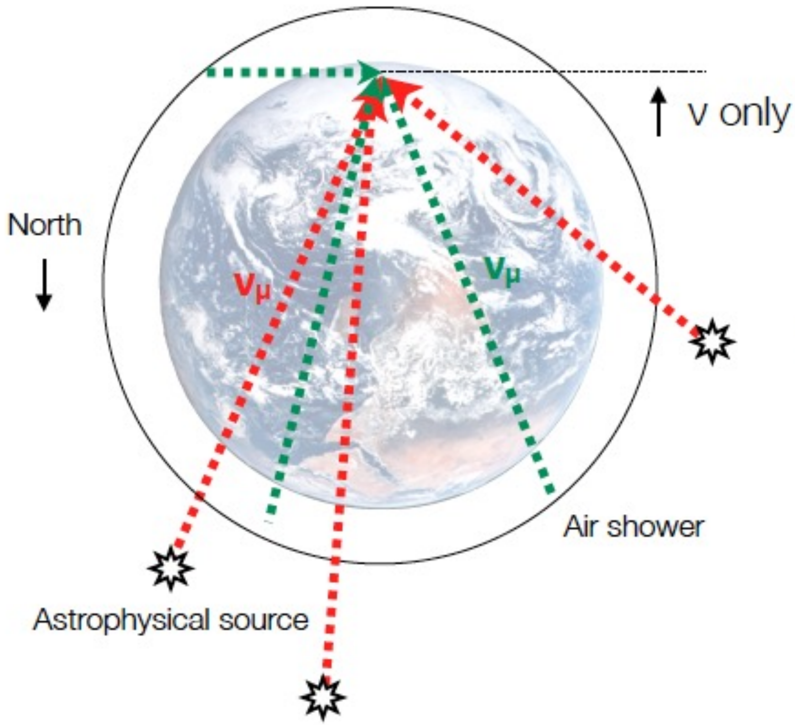
Deposited energy

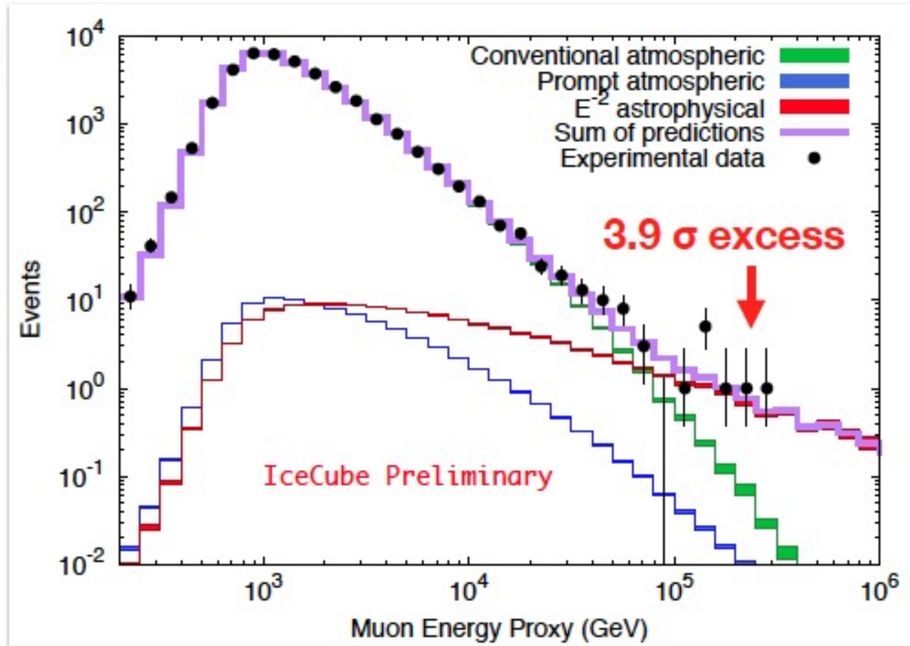


arXiv:1405.5303 (accepted for PRL)

What about the northern sky and ν_μ?

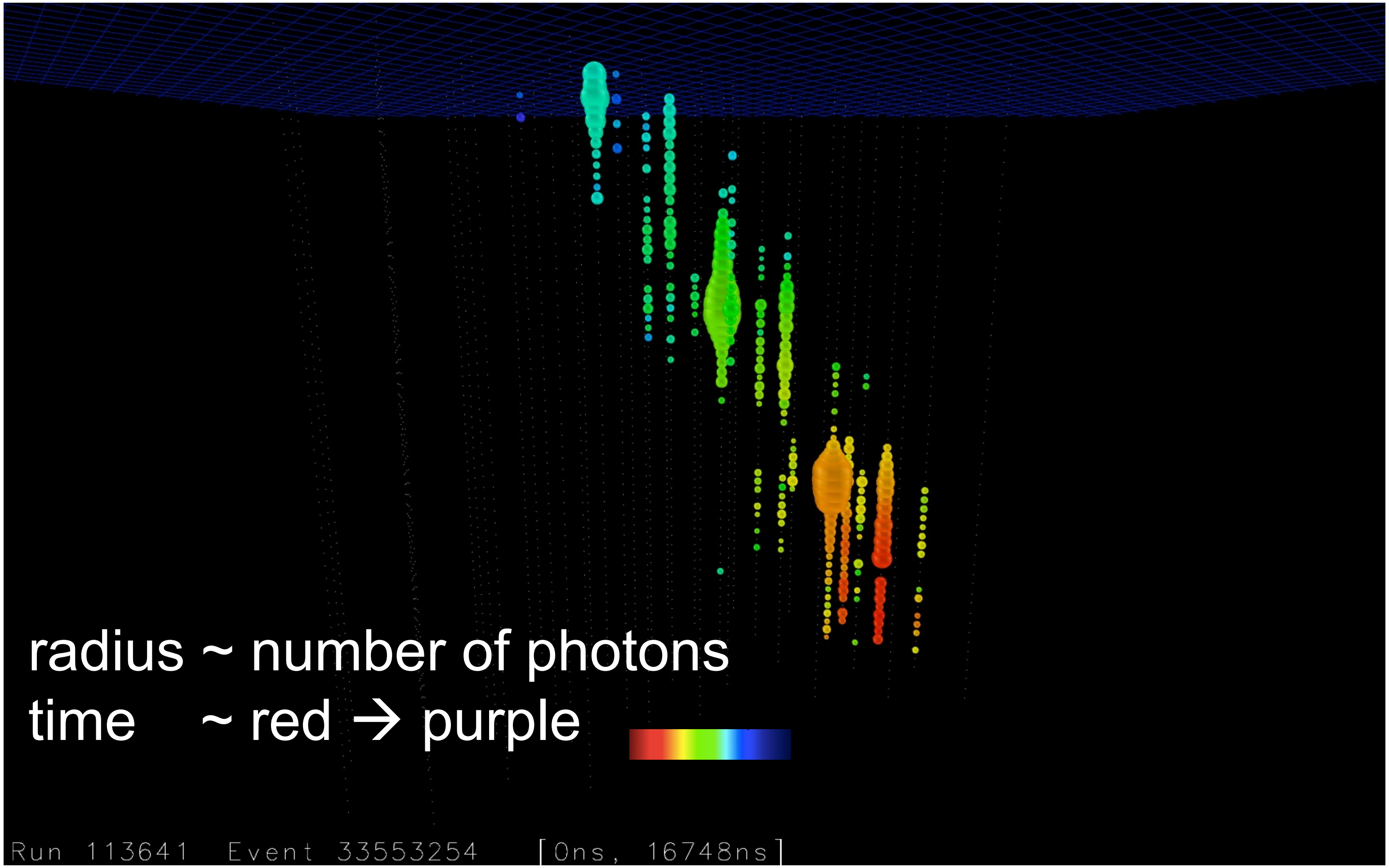
The high-energy starting event sample is dominated by cascades from the southern sky.





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

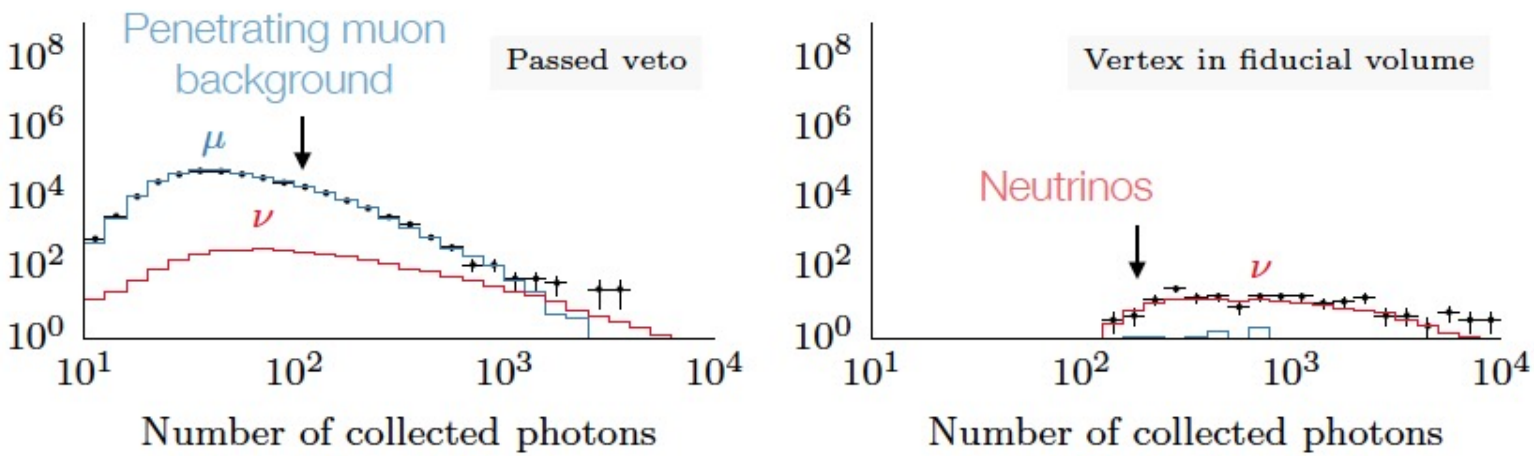
Muon track from 89 TeV neutrino



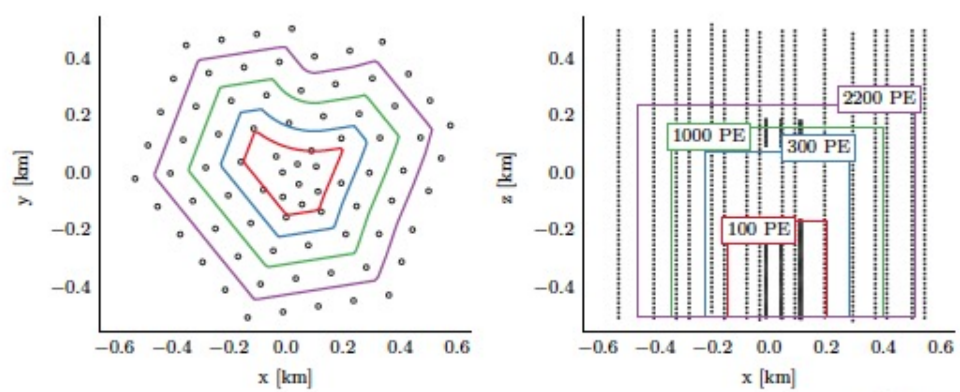
Improved veto techniques

Outer-layer veto → Energy-dependent veto

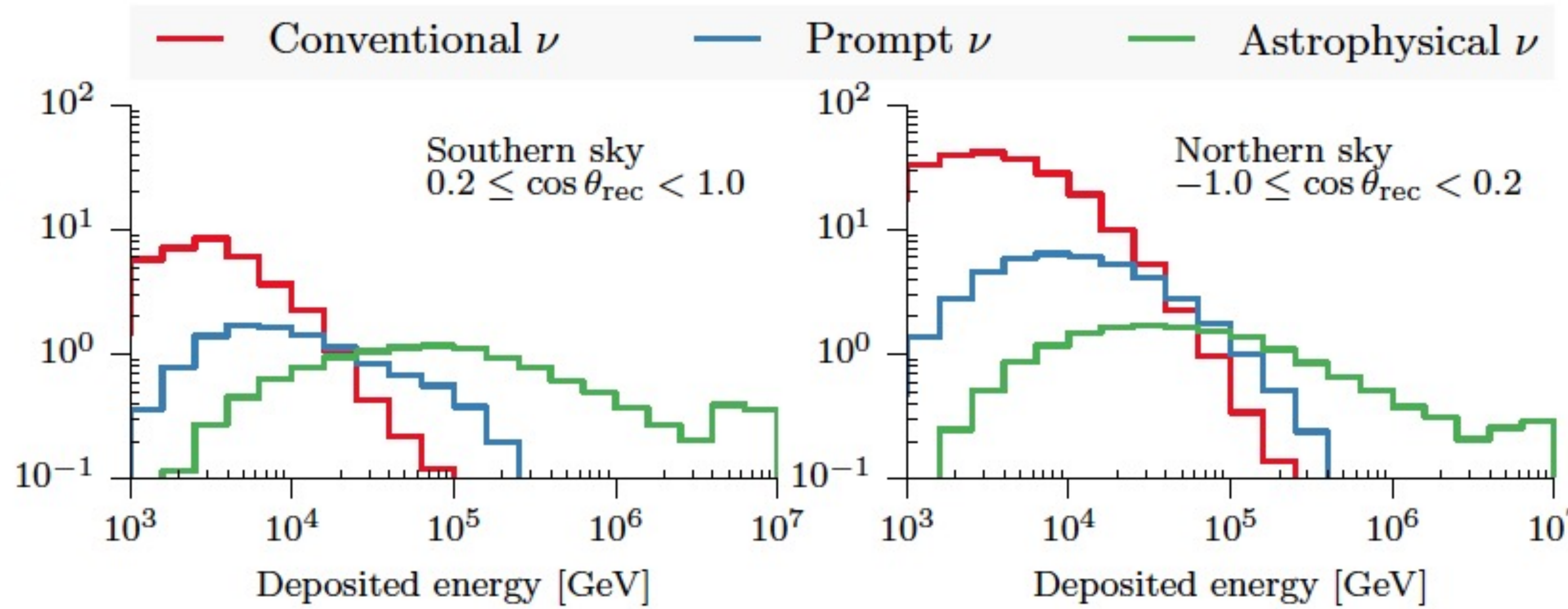
Neutrino-dominated for E_{dep} > 60 TeV | **Neutrino-dominated for E_{dep} > 1 TeV**



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



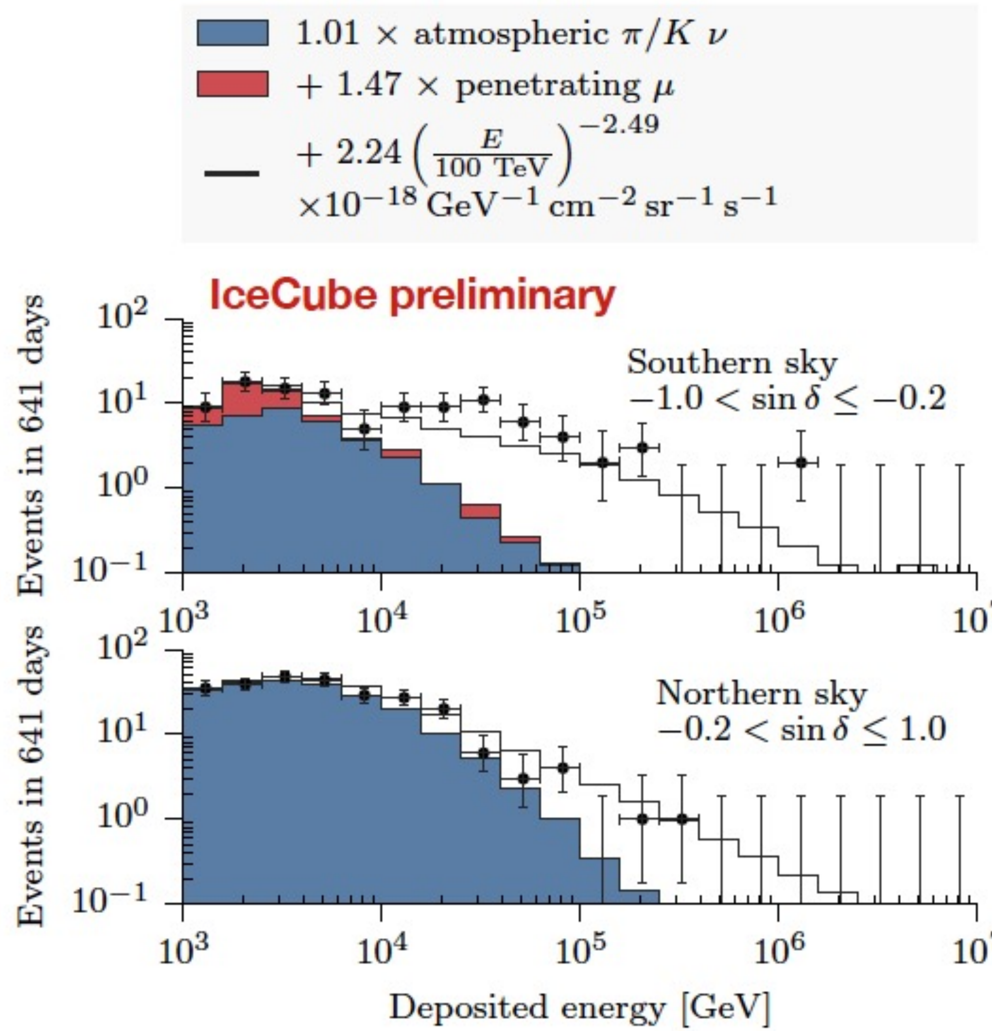
...bservable energy spectra



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

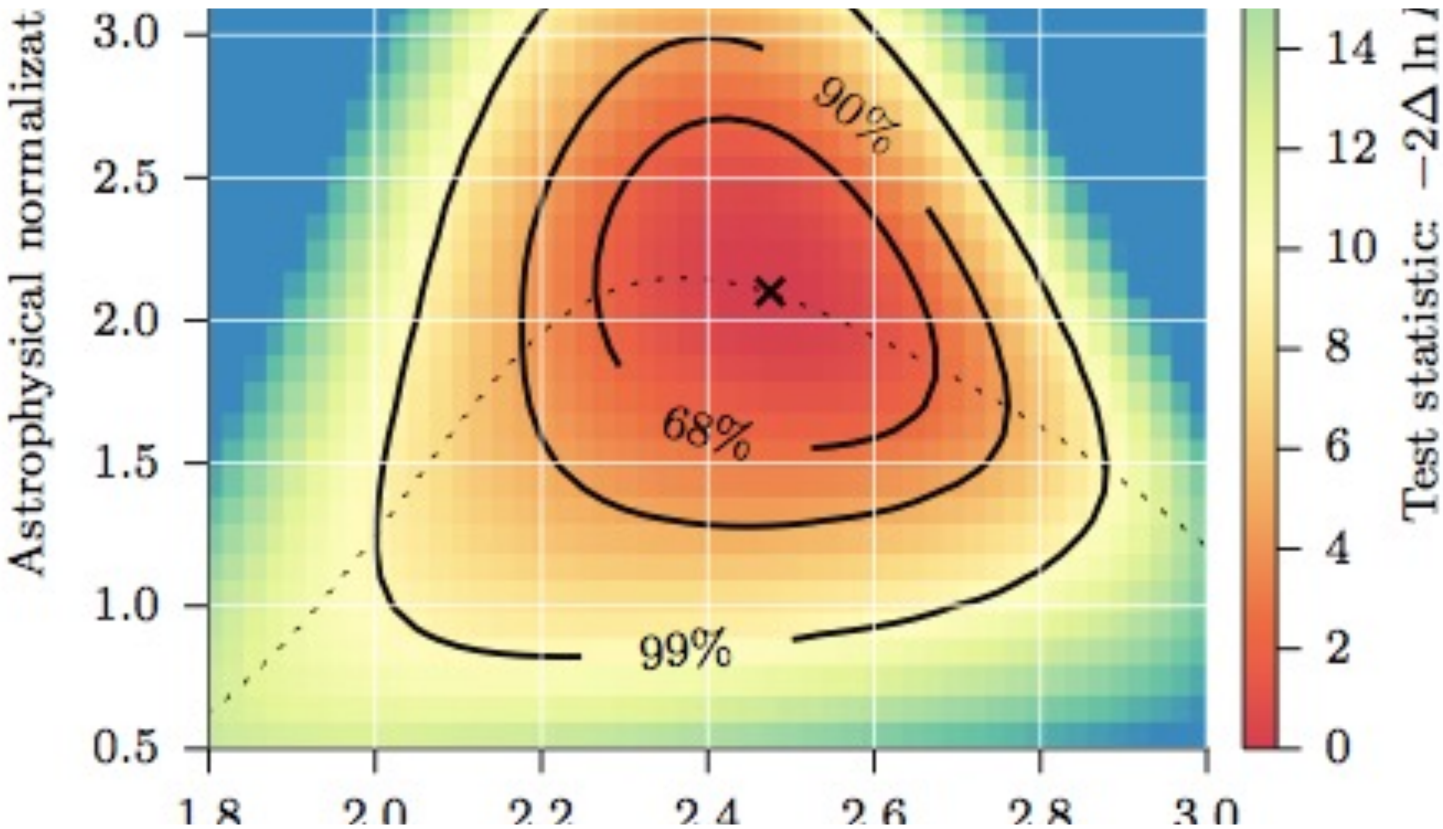


Best fit parameters

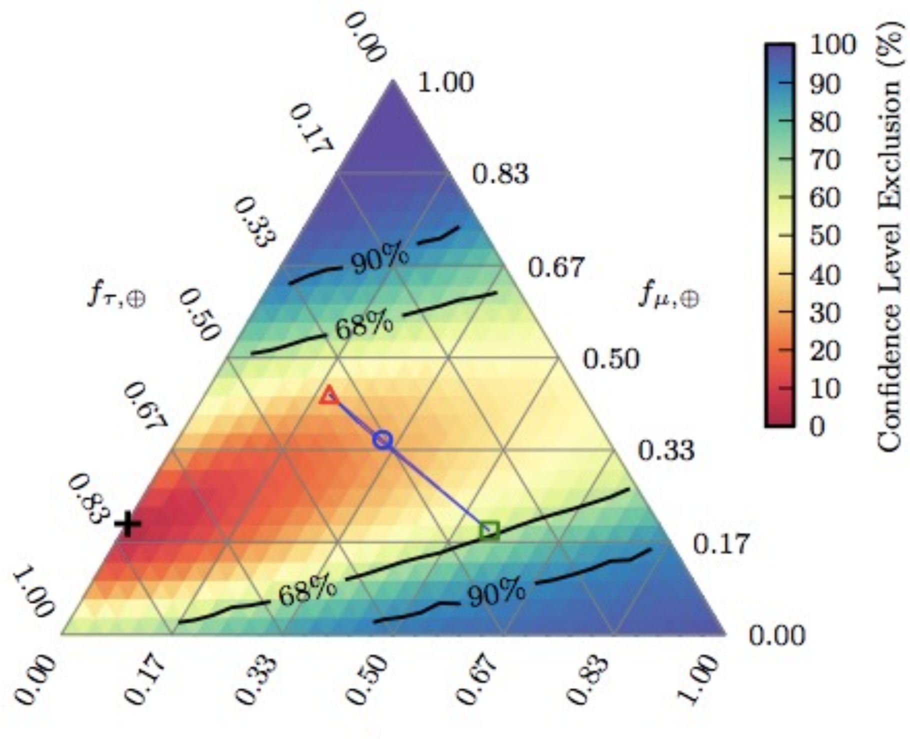
TABLE I. Best fit parameters and number of events attributable to each component. The normalizations of the atmospheric fluxes are relative to the models described in Sec. III. The per-flavor normalization Φ_0 and spectral index γ of the astrophysical flux are defined in Eq. (1); the fit to the astrophysical 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	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ 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**

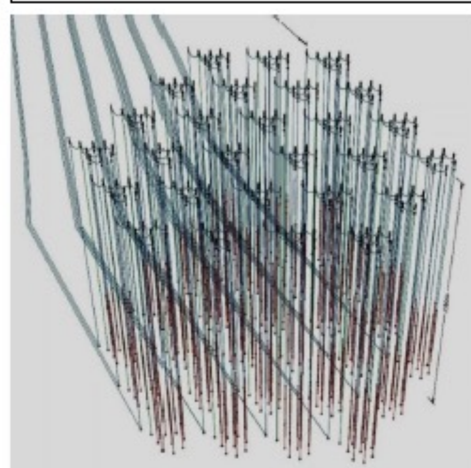
Neutrino astrophysics

- 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

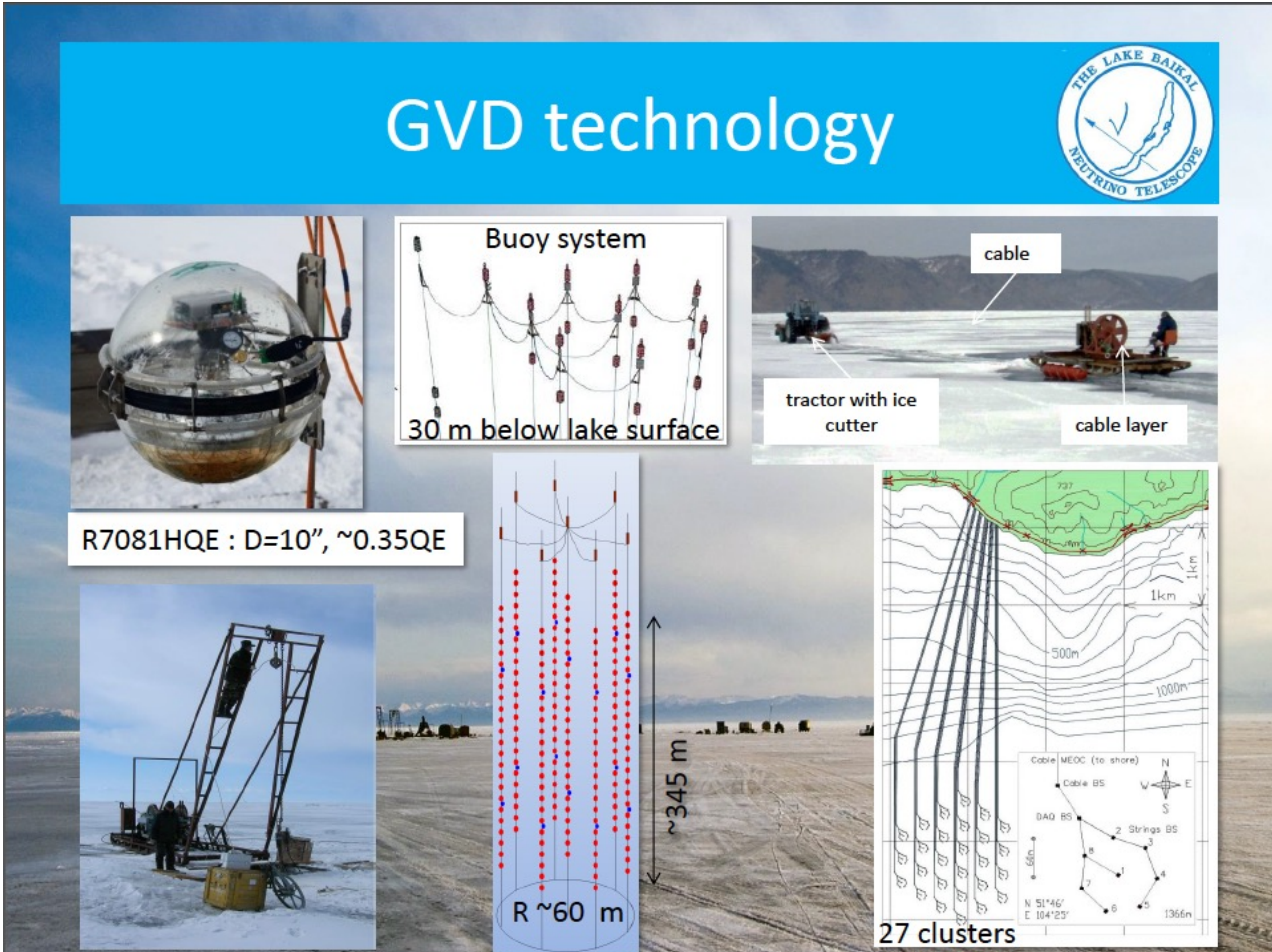
Future detectors

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

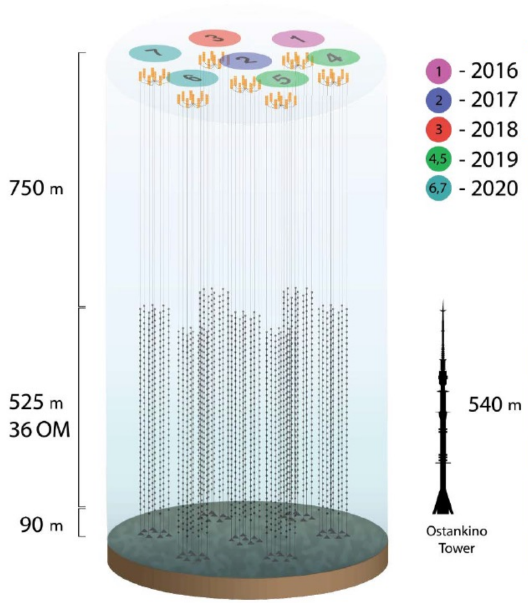


¶ OM – Optical Module


GVD technology
THE LAKE BAIKAL NEUTRINO TELESCOPE
R7081HQE : D=10", ~0.35QE
Buoy system
30 m below lake surface
cable
tractor with ice cutter
cable layer
R ~60 m
~345 m
1km
500m
1000m
Cable MEOC (to shore)
Cable BS
DAQ BS
Strings BS
N
S
W
E
N 51°46'
E 104°25'
1366m
27 clusters

Status BAIKAL

Baikal-GVD construction status and schedule



300 m step between clusters

Deployment schedule

Year	Total number of clusters	Total 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	9	72	2592
2022	11	88	3168
2023	13	104	3744
2024	15	120	4320

Effective volume 2020: 0.35 km^3

1 cluster is working now, 12 clusters to 2020

Event rate BAIKAL

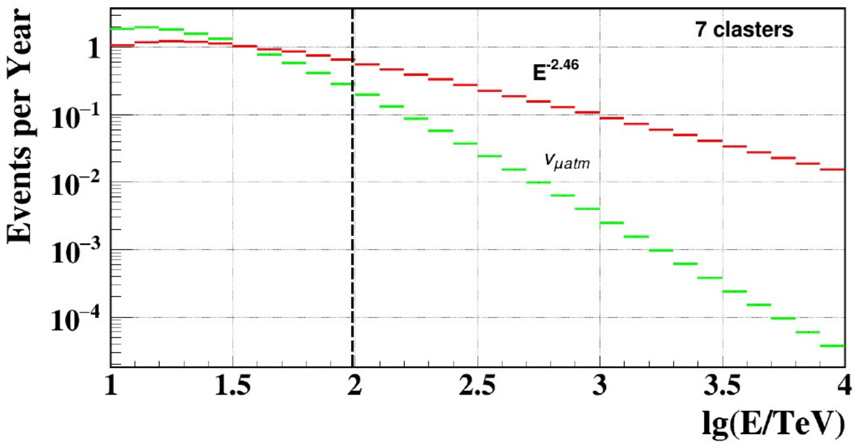
Energy spectrum of astrophysical neutrinos measured by IceCube:
$4.1 \cdot 10^{-6}\, E^{-2.46}\, GeV^{-1}\, cm^{-2}\, s^{-1}\, sr^{-1}$

Event selection criteria
(E_{sh} >100 TeV, N_{hit} >20):

~0.6 events/yr with 1 cluster

~ 3-4 events/yr with 7 clusters

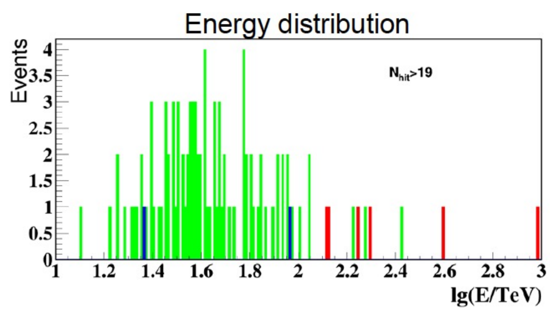
Expected number of detected events in 7 GVD Clusters from astrophysical neutrinos for 1 yr. observation

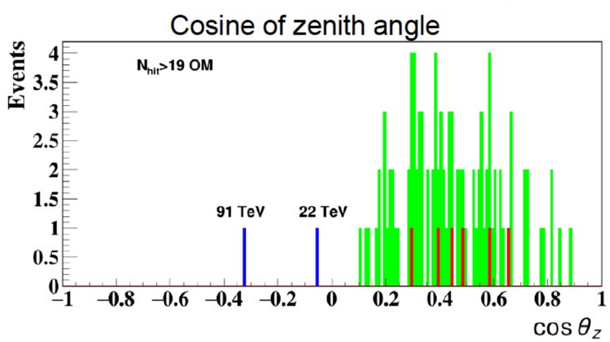


7 clusters are working now

Baikal first stage up to 5 clusters 2016-2019

High energy cascades (data)





Data from 2016, 2018 and 2019 ,
exposition: 2294 days

12 events with E > 100 TeV and Nhit >19:
5 events – cascade events
7 events – cascade events with muon pattern

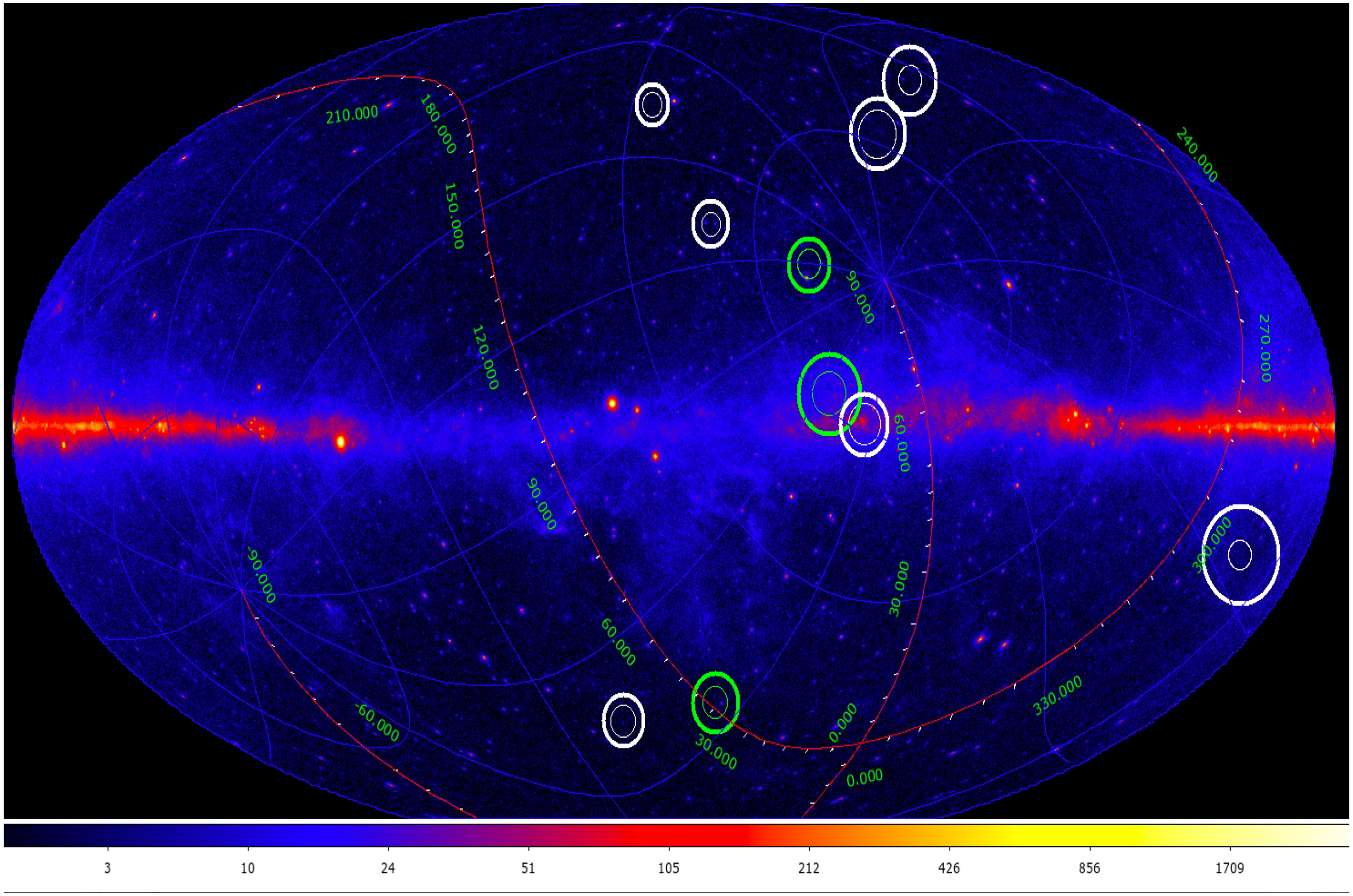
2 upgoing cascades: E ≈ 91 TeV
and E ≈ 23 TeV

of 29

8 events

Preliminary!

BAIKAL: Sky map with 10 events

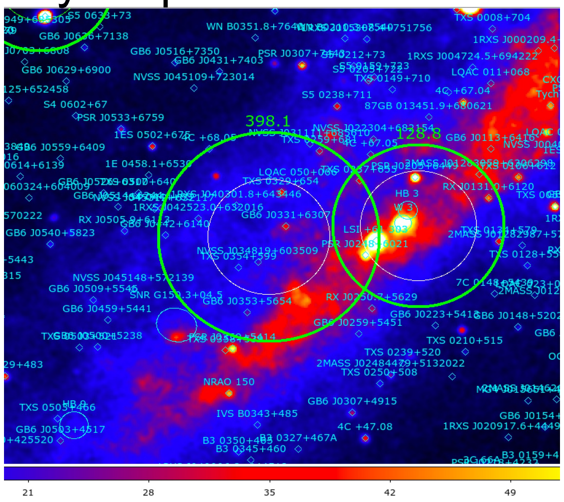


A. NERONOV talk

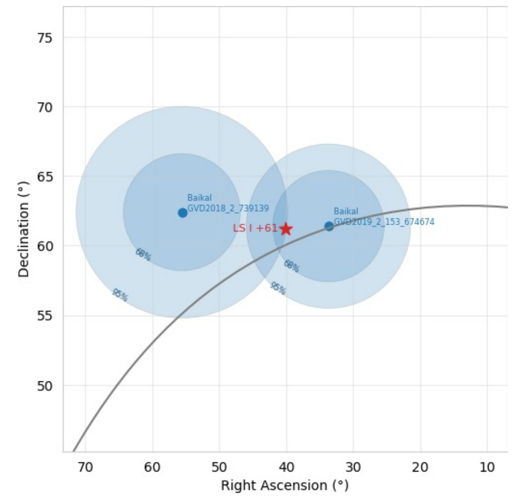
Preliminary!

Two close events at distance 10.3°: GVD_2018_656_N & GVD_2019_153_N

Sky map of Fermi sources



LSI +61 303 and two events



LSI +61 303 – at 3.1° and 7.4° from GVD_2019_153_N and GVD_2018_656_N

LSI +61 303 – microquasar, 26.5 day orbiting period of massive object

Using PSFs of all 10 events chance probability to observe such configuration was estimated:

p-value = 0.007

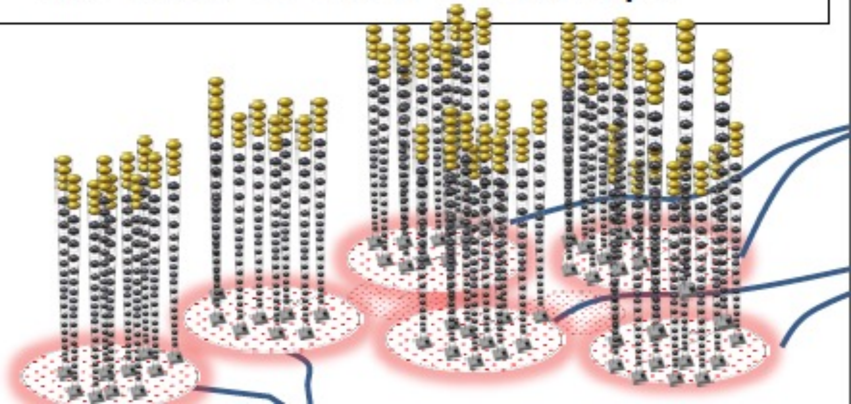
KM3NeT in the Mediterranean

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

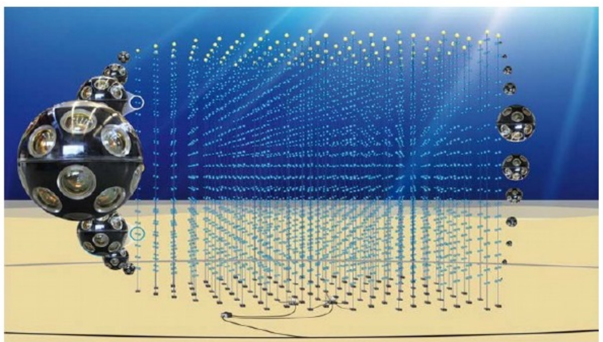
~3.5-6 km³ (depending on spacing)
6 shore-cables for 6 building blocks
6 x 115 = 690 detection units
690 x 18 =12420 OMs
seabed data transmission infrastructure
installation requires ship + ROV
all-data-to-shore concept



Construction started

KM3NeT - ARCA

Construction started

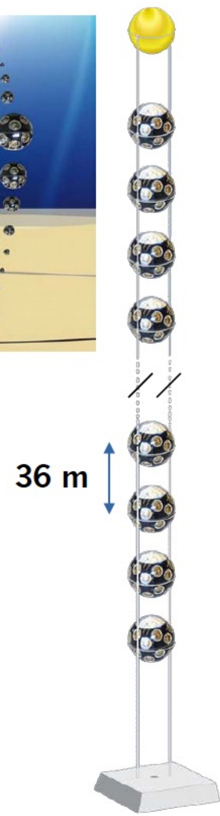


100 km offshore Sicily
Depth: 3400 m

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^3



Digital Optical Module

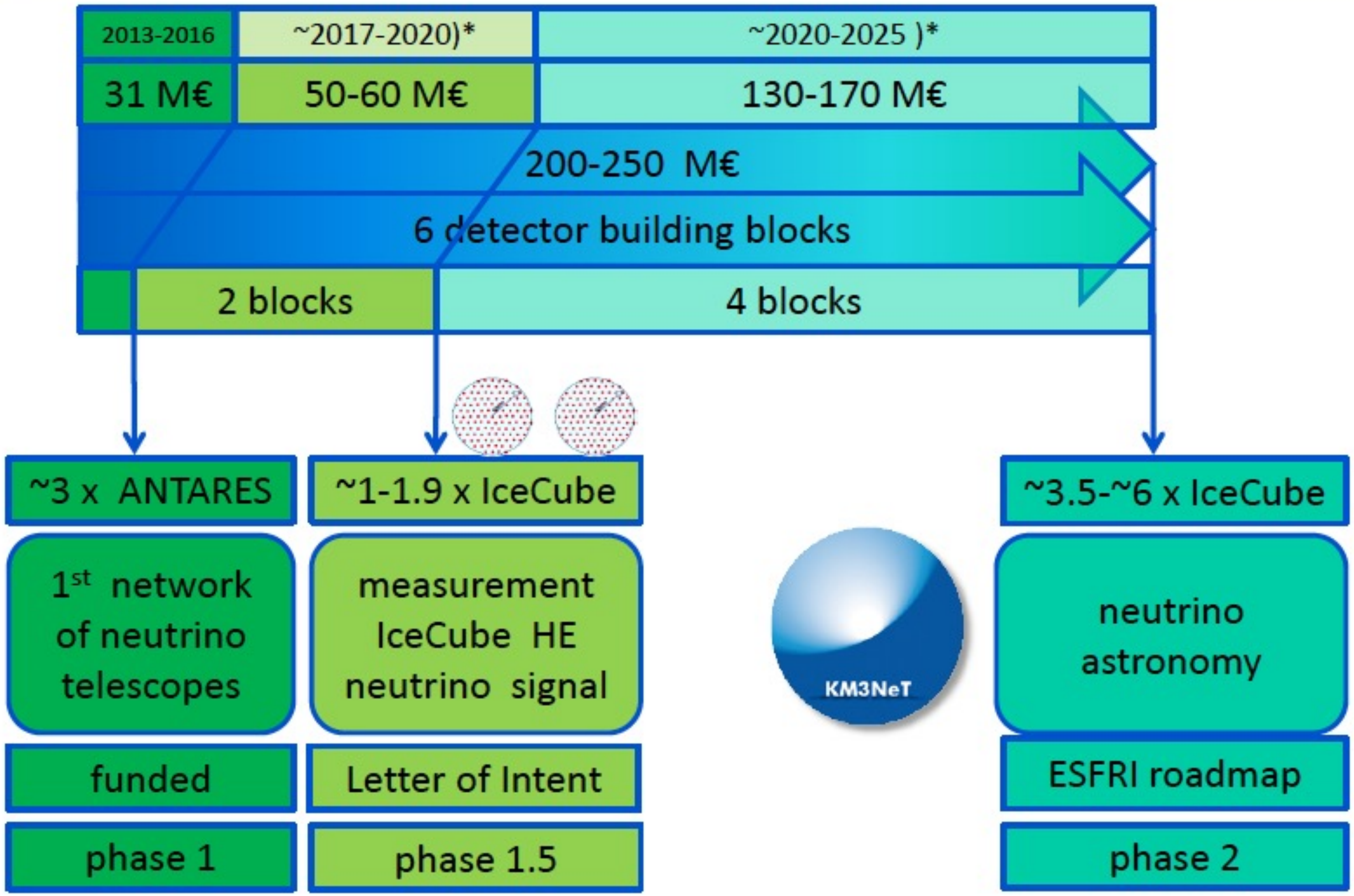
- 31 x 3" PMTs
- PMT HV
- LED & piezo
- FPGA readout
- DWDM

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

photocathode area similar to a 17" PMT

Optical background (mainly ^{40}K): 5-10 kHz/PMT

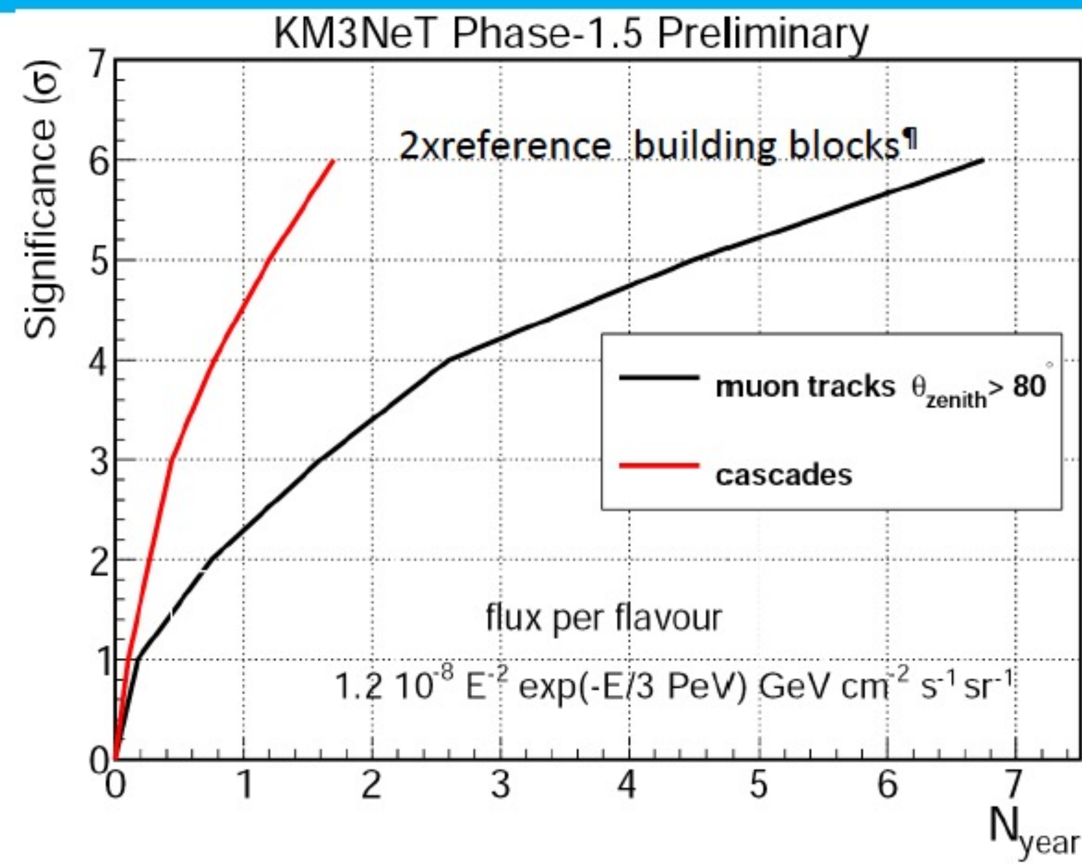
KM3NeT phased construction



)* depending on funding

KM3NeT

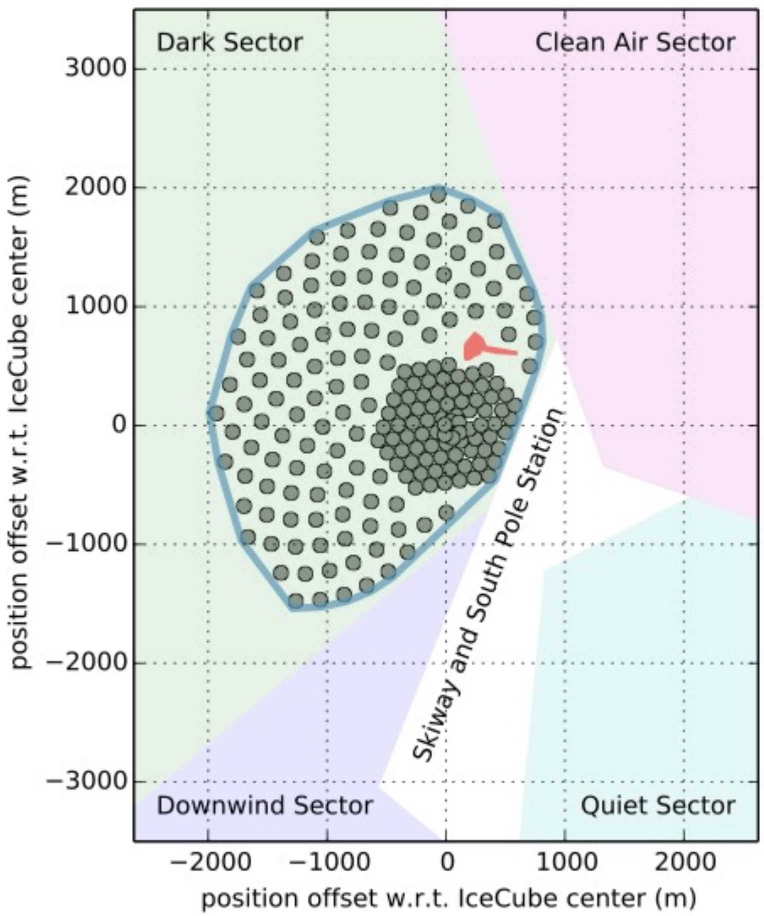
Performance



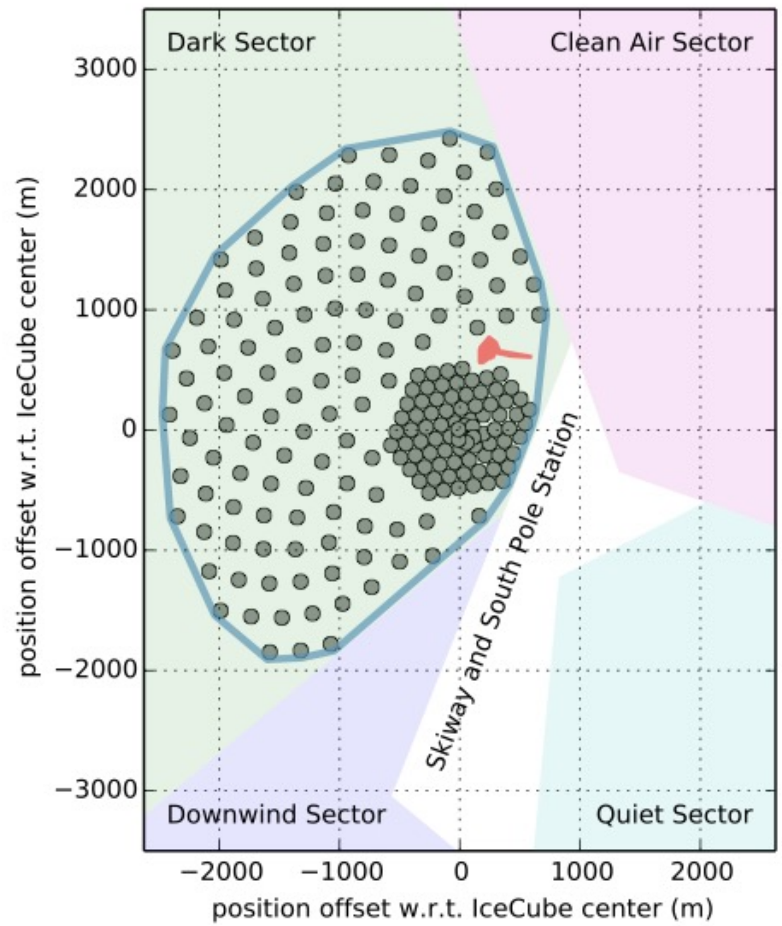
Detailed investigation of „IceCube signal“ within a few years, with different *field of view*, different *systematics* and better *angular resolution*

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

86 strings with 240-340 m spacing

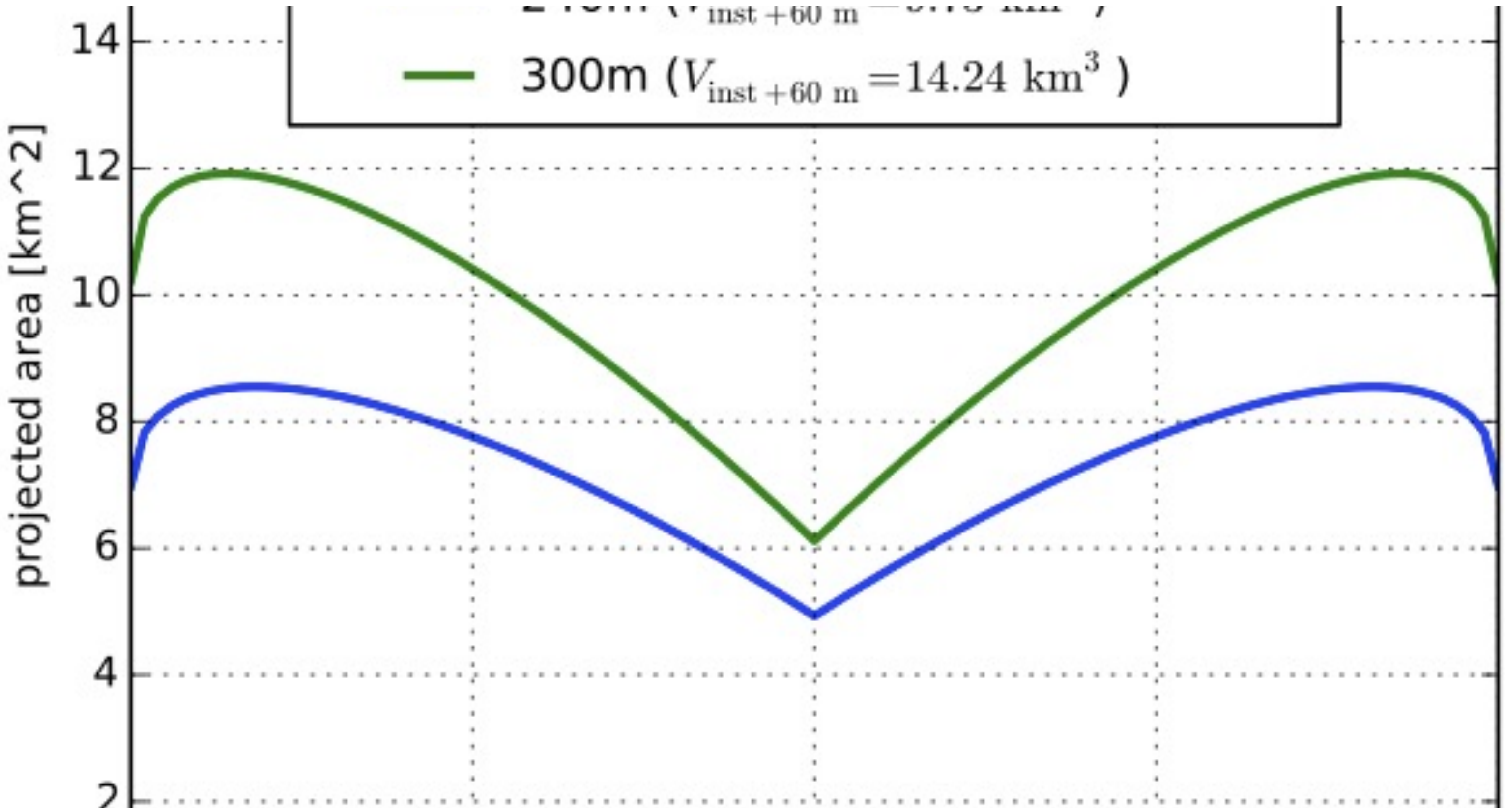


(a) 240 m string spacing ("benchmark")



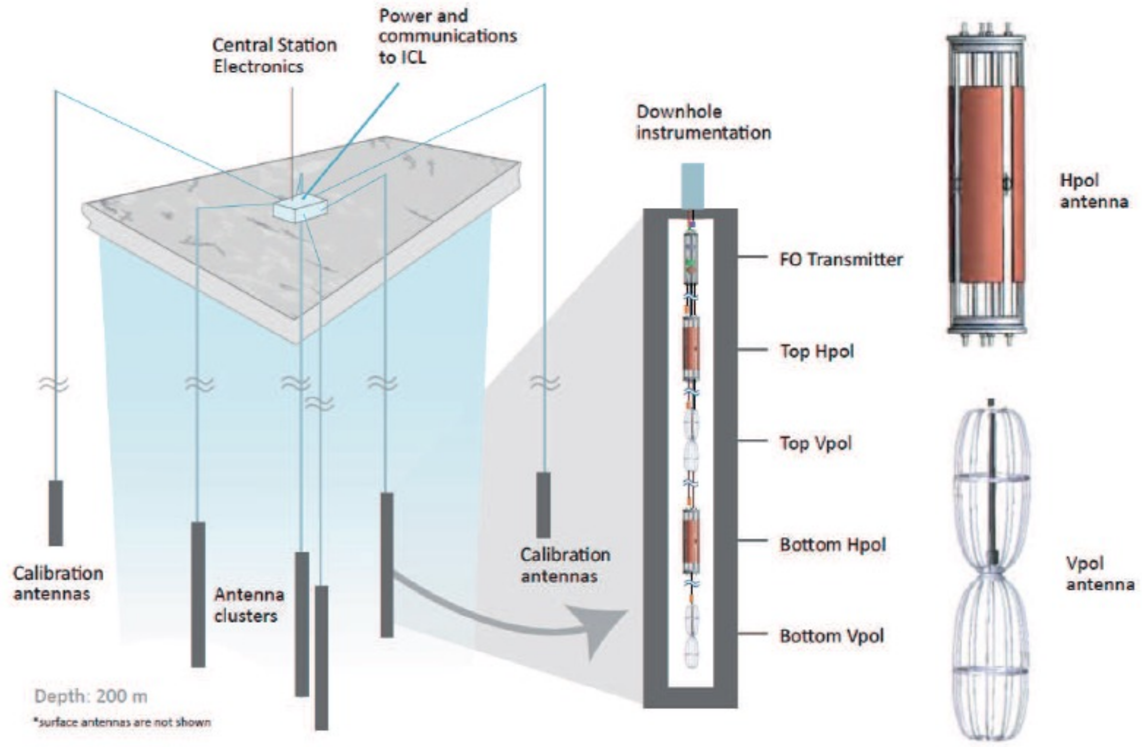
(b) 300 m string spacing

Effective volume

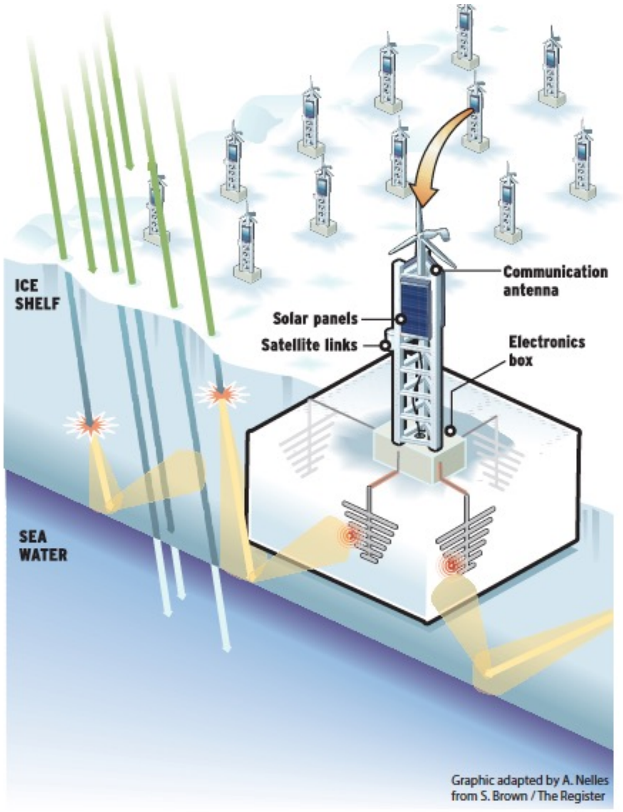


IceCube Collaboration, **arXiv:1412.5106**

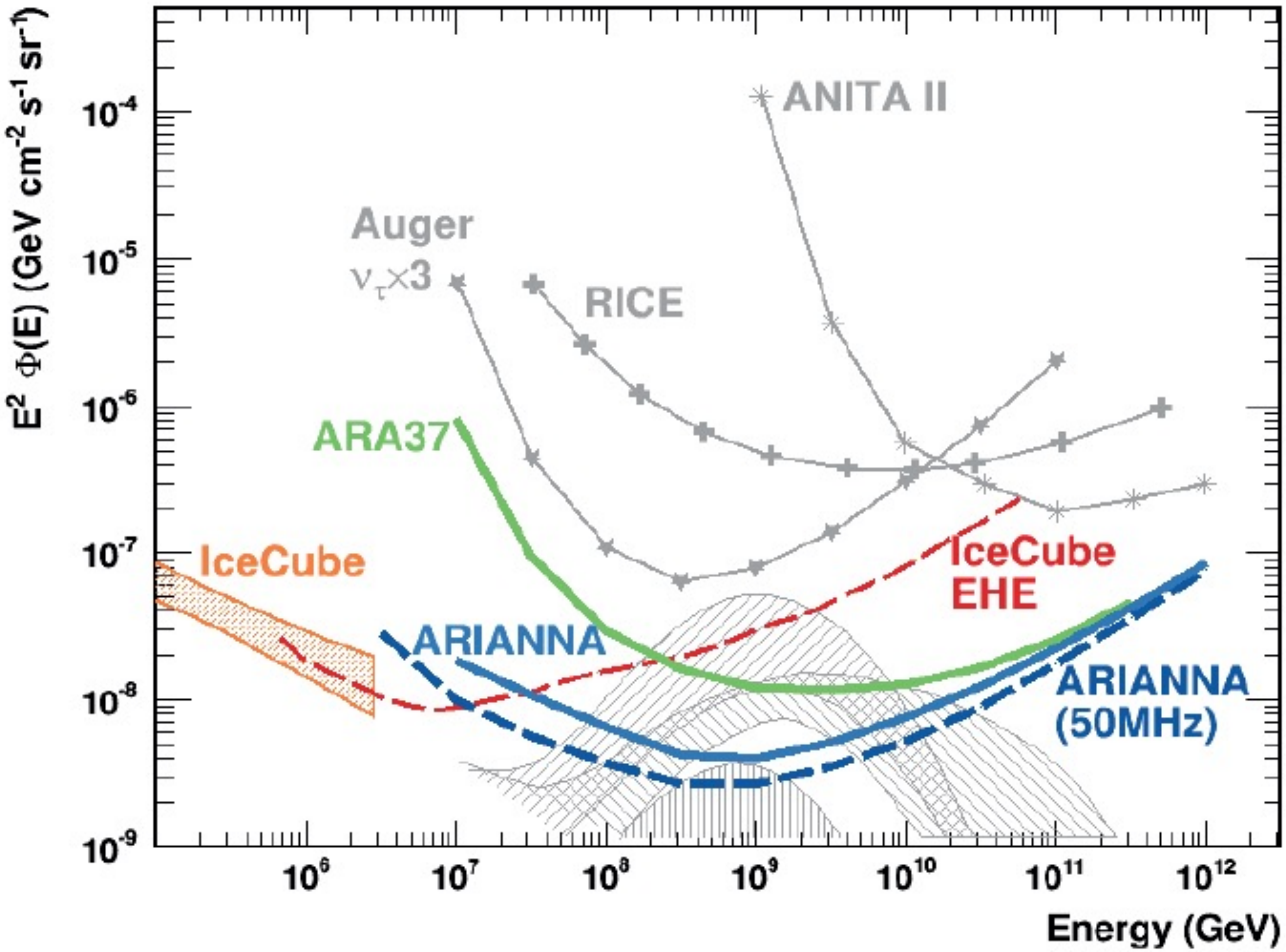
ARA radio detector South pole



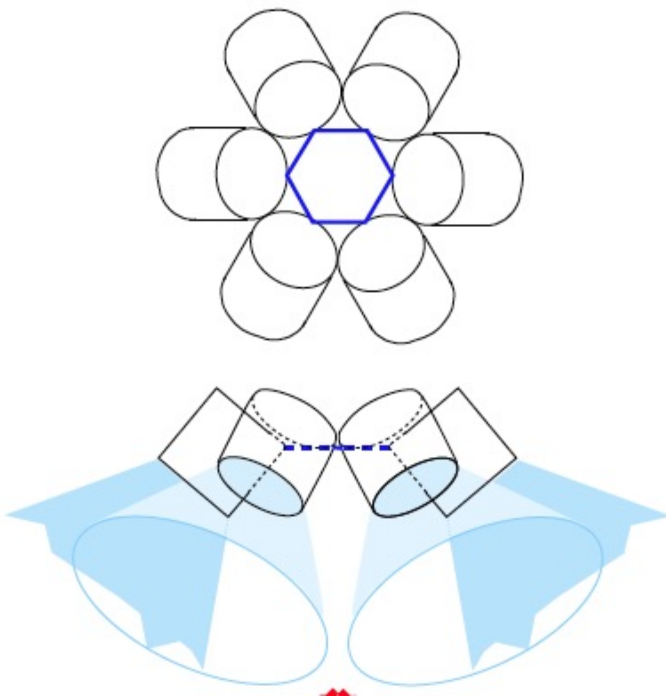
ARIANNA radio detector Antarctics

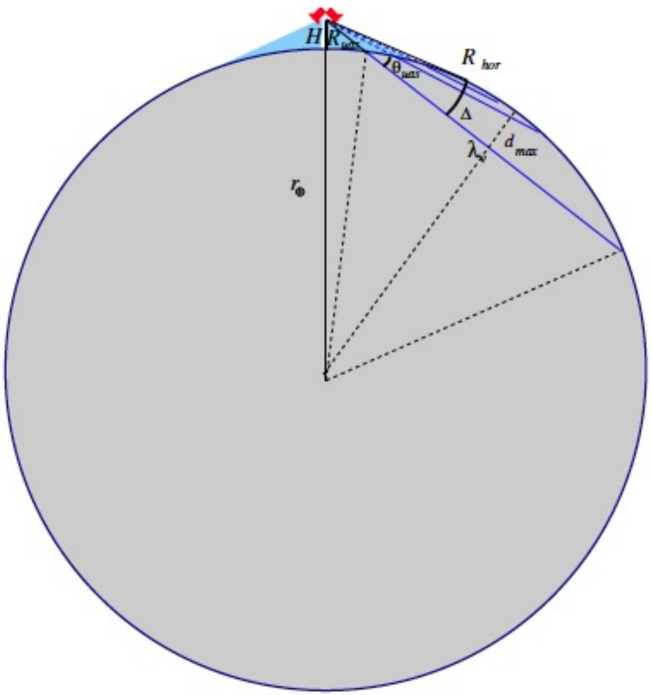


Future radio detection

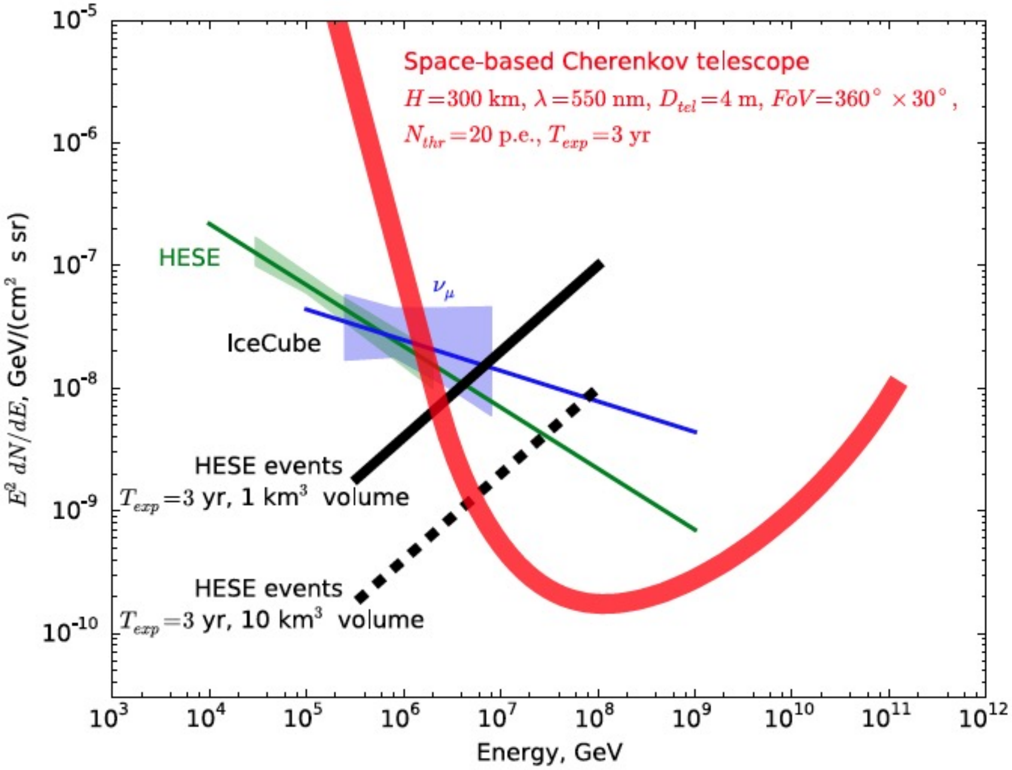


Detection of neutrinos from space

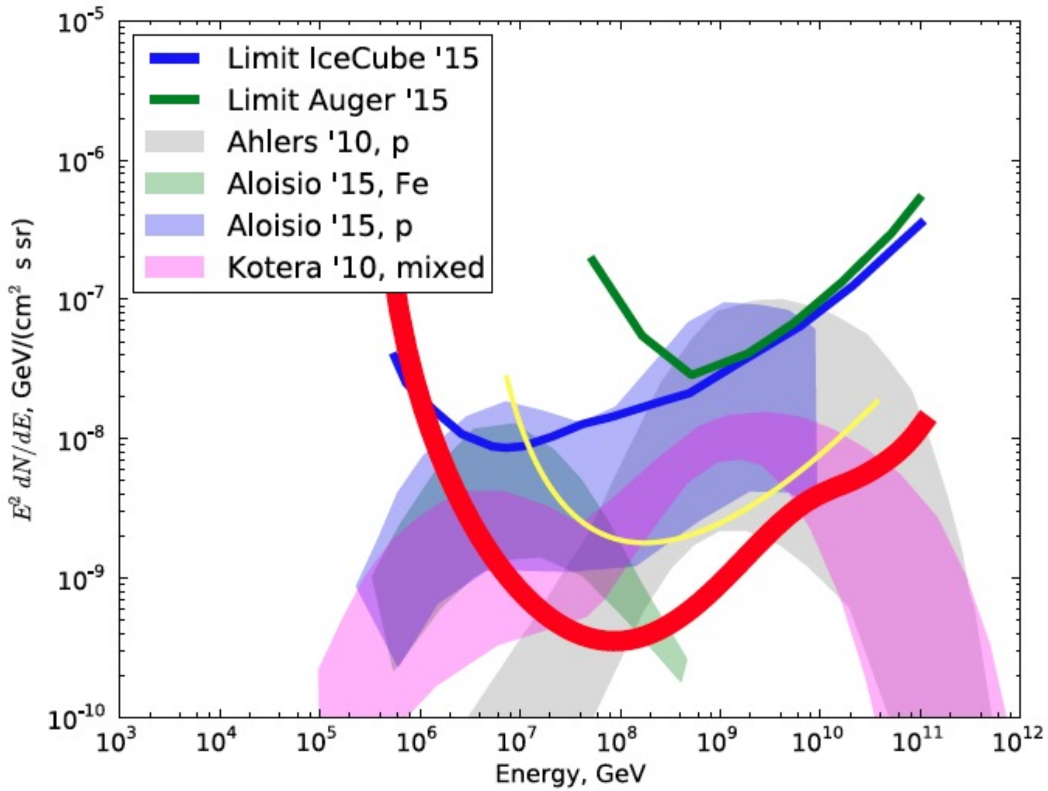




Space telescope project



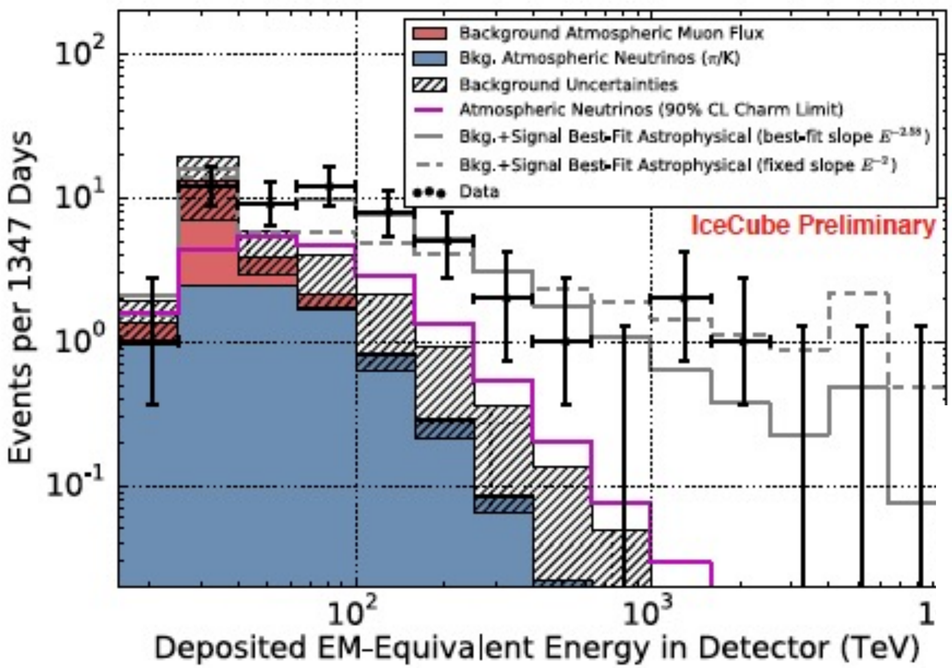
Detection of GZK neutrinos



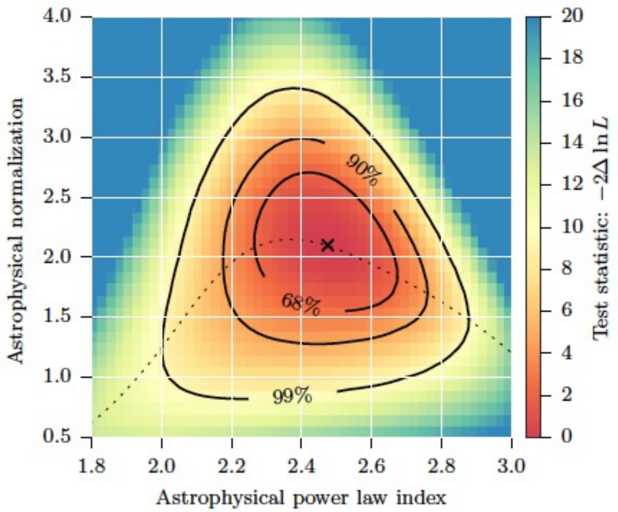
What we can expect from future detectors

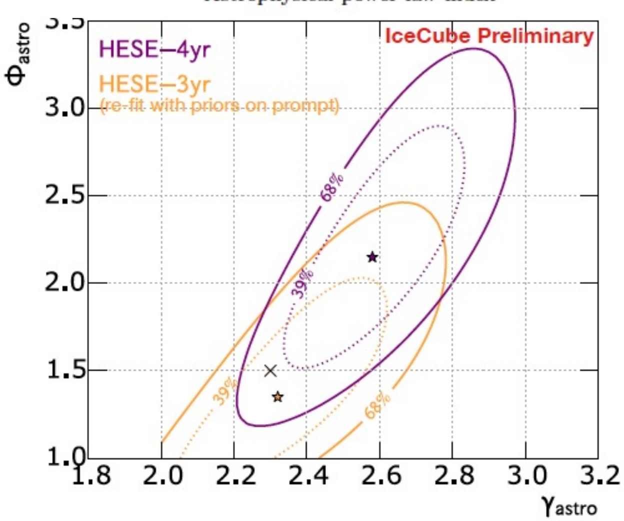
- Split Galactic and extragalactic contribution in diffuse flux
- Find first point/extended sources
- Limit or find extragalactic flux above PeV
- Help to find sources of PeV Galactic cosmic rays

IceCube data 4 yrs

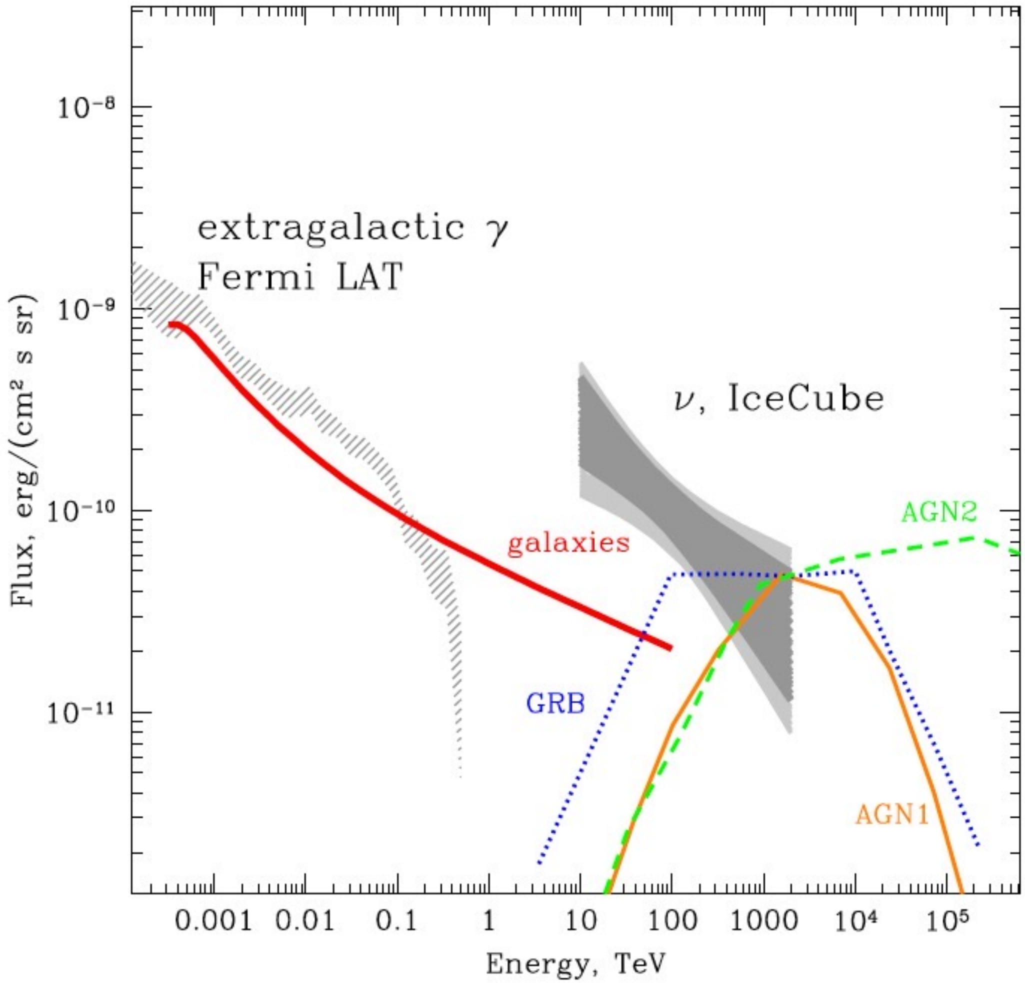


IceCube, ICRC 2015





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

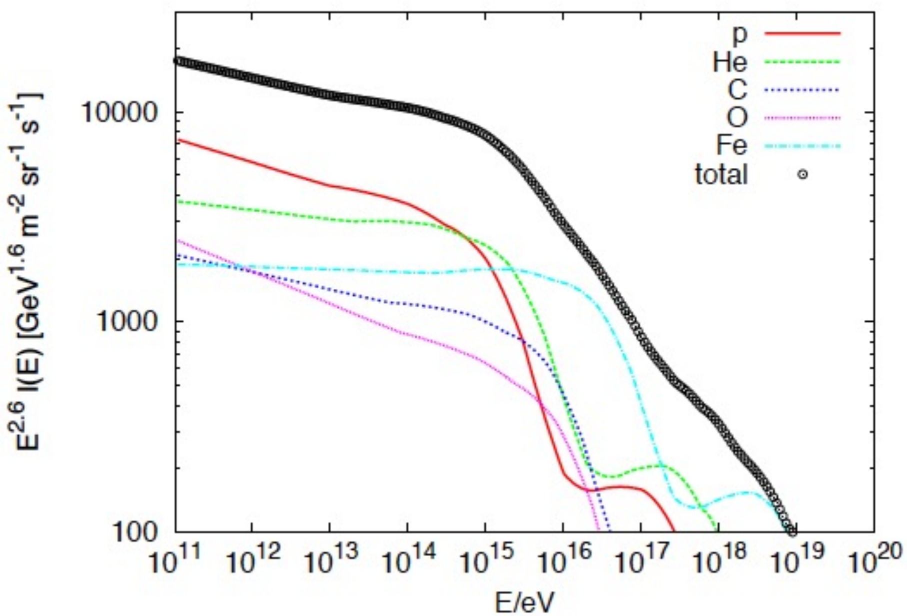
τ(10 PeV)=0.0002

E^2F_ν(PeV)=0.2 eV/cm^2/s/sr

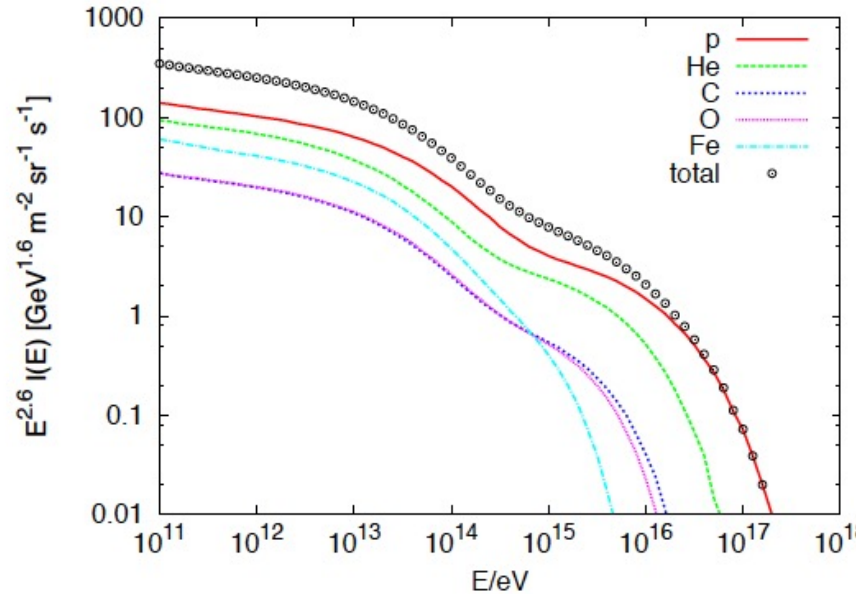
E^2F_ν(100 TeV)=3 eV/cm^2/s/sr

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:

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

Flux from GMC 10^5 Msun at 1 kpc:

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

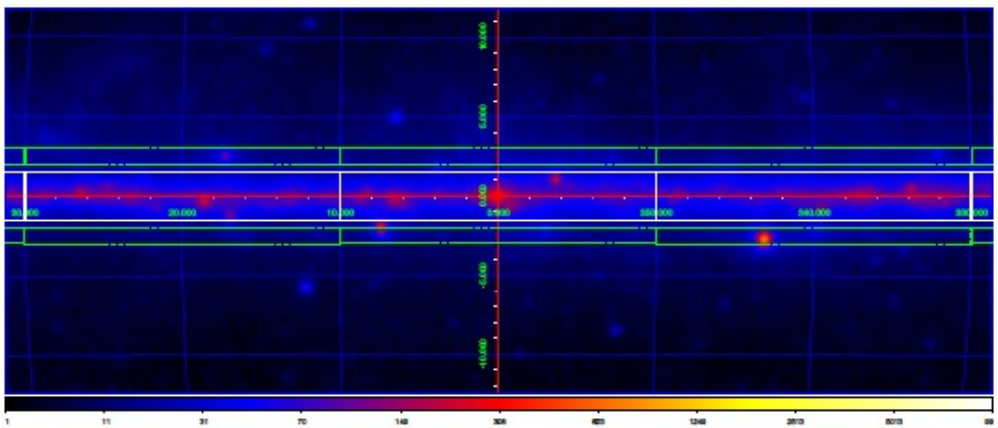
M.Kachelriess and S.Ostapchenko, arXiv:1405.3797

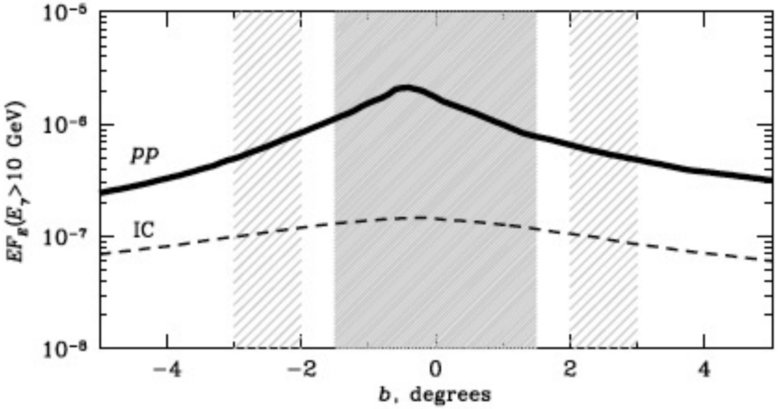
Galactic neutrino fluxes

- 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

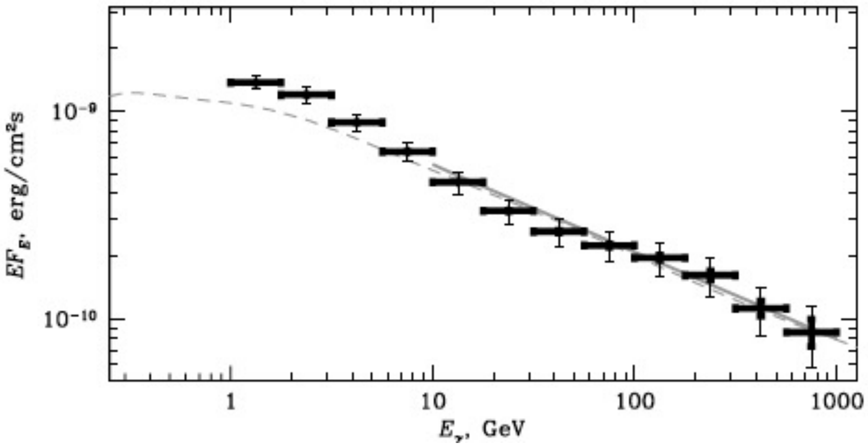
Milky Way inner Galaxy Fermi E>10 GeV

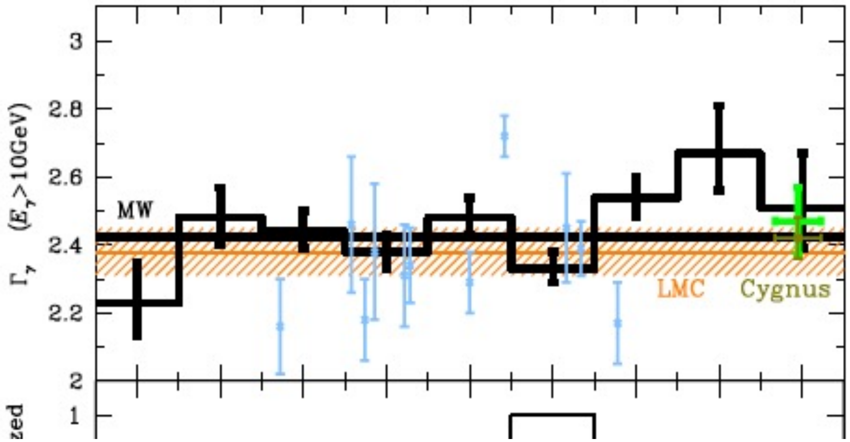




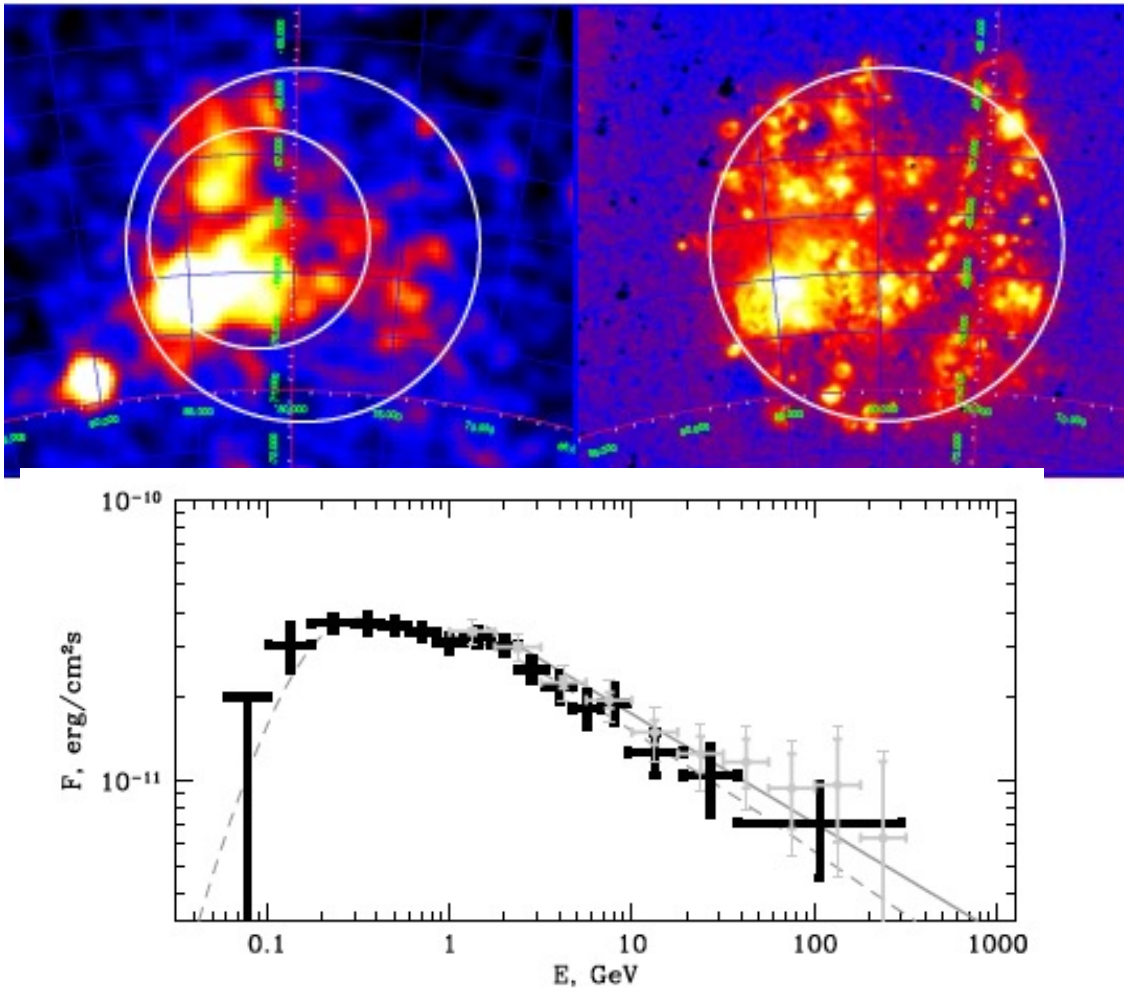
A.Neronov and D.Malishev, arXiv: 1505.07601

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



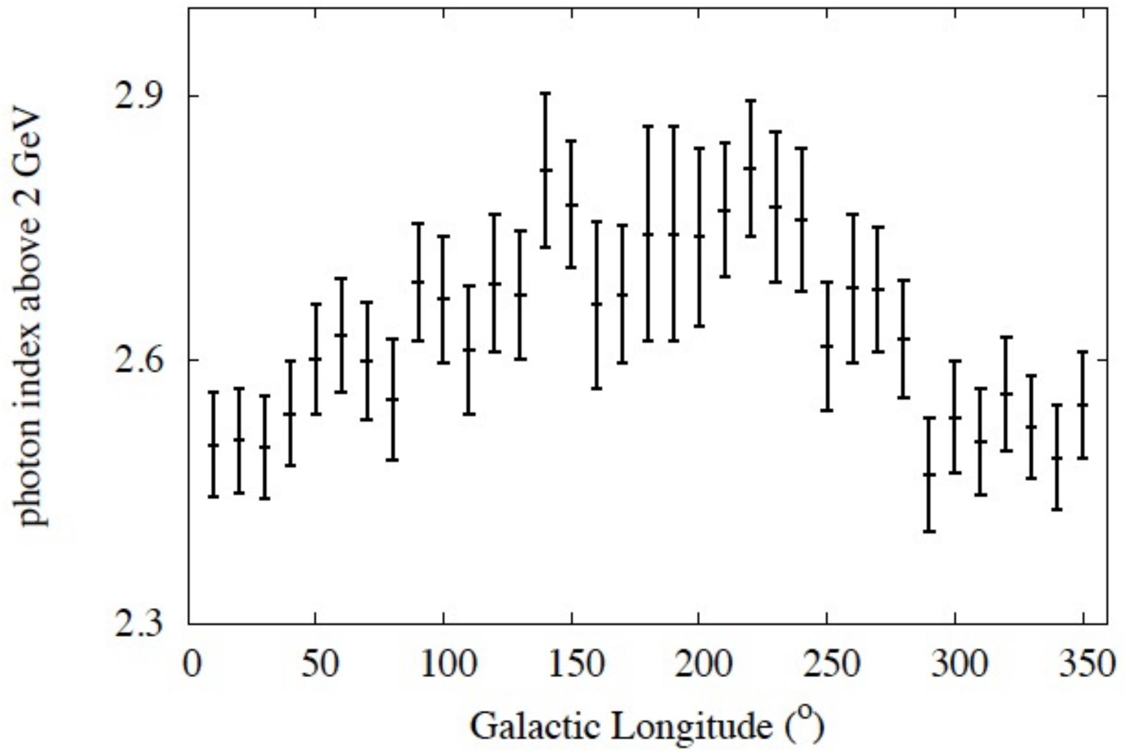


In LMC average proton spectrum 2.45



A.Neronov and D.Malishev, arXiv: 1505.07601

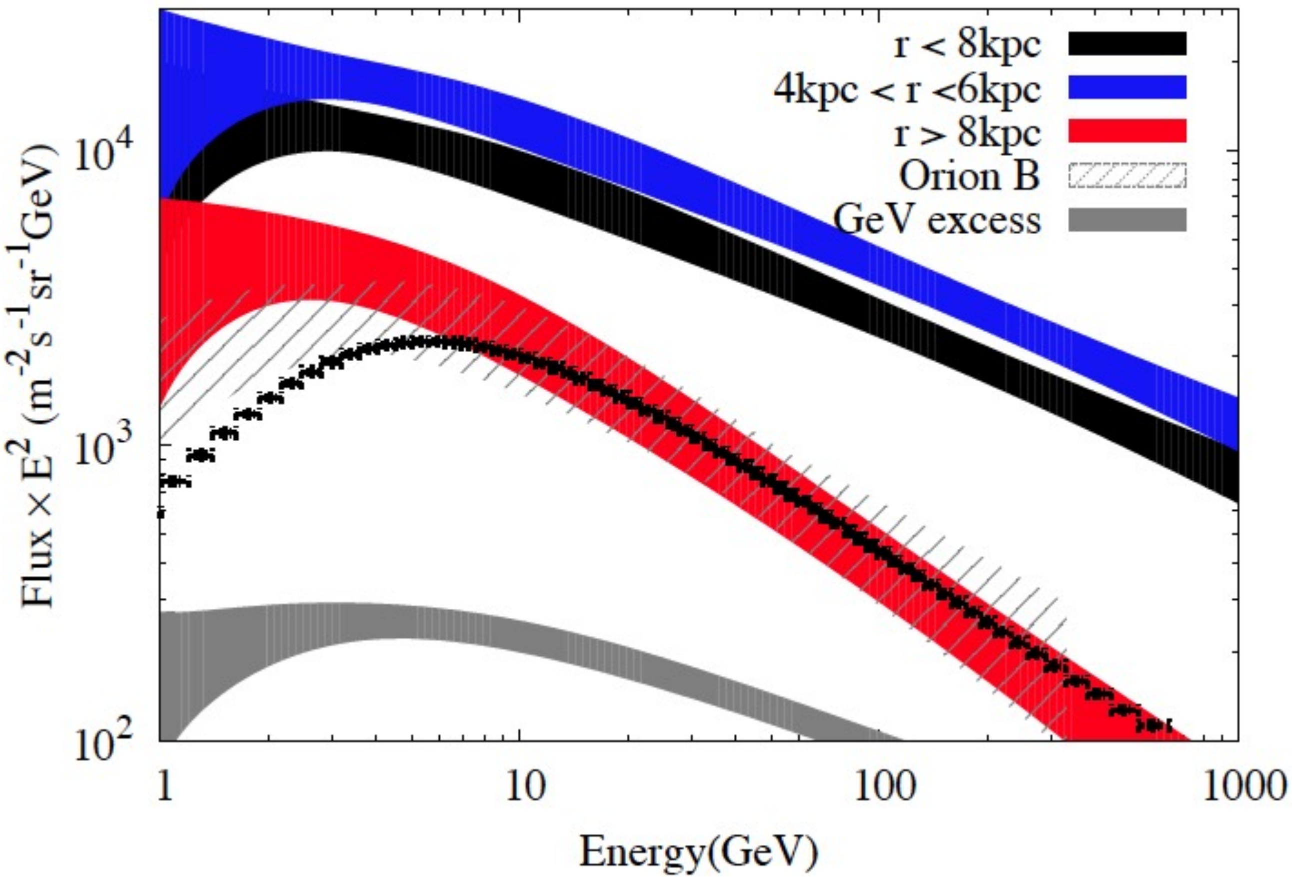
Proton flux above 2 GeV



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

Fit with gas ring template

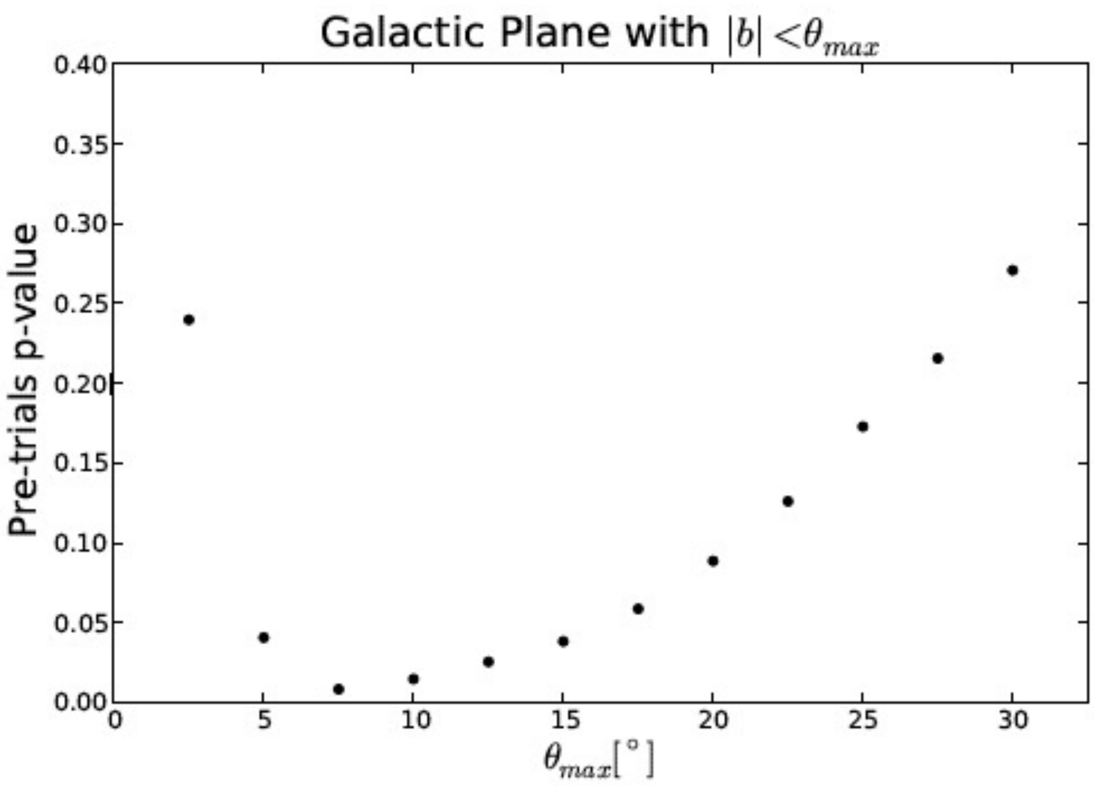
CRs SED in different rings.



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

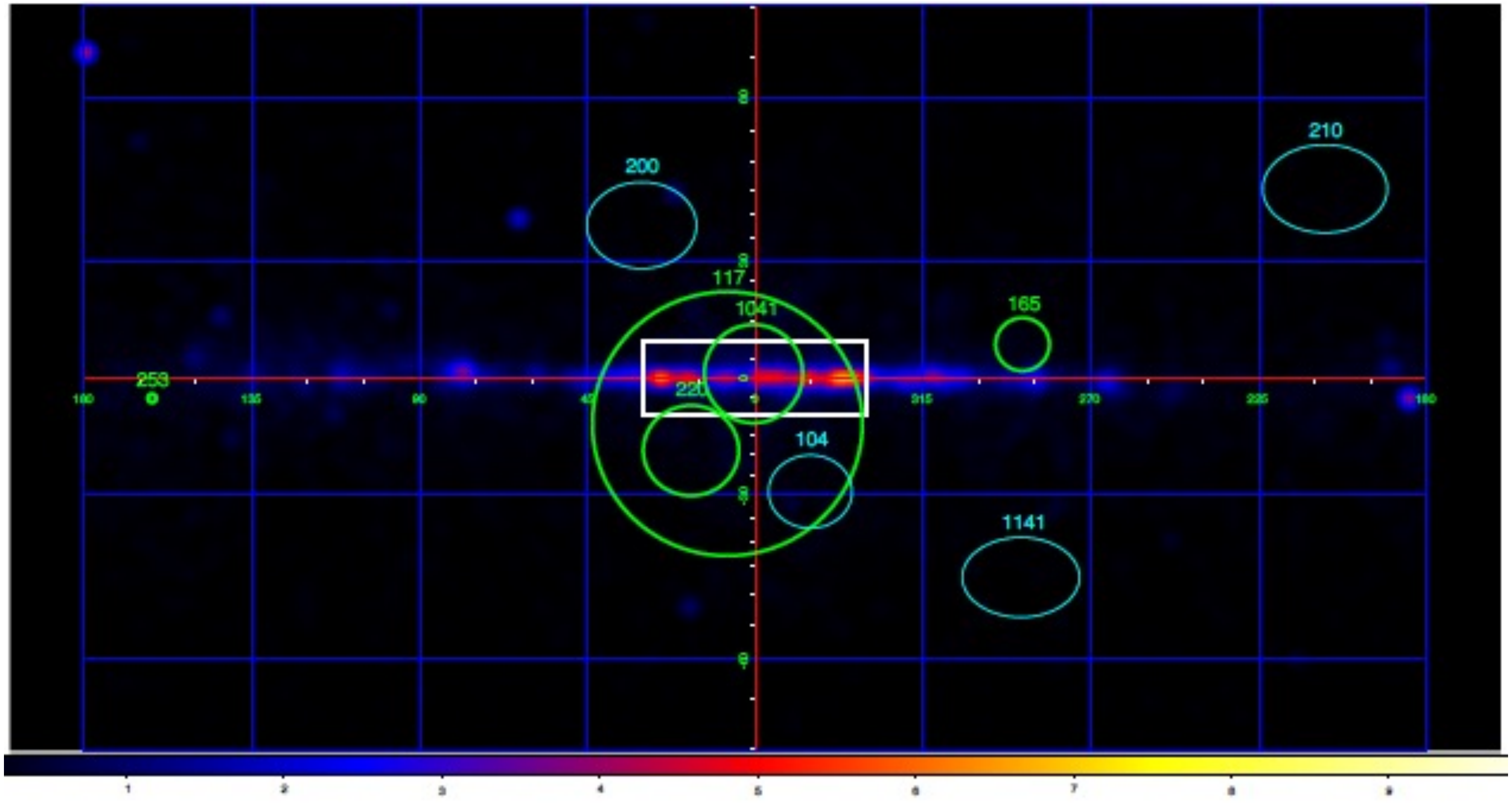
Neutrino flux from Milky Way

Galactic plane: 2% by chance



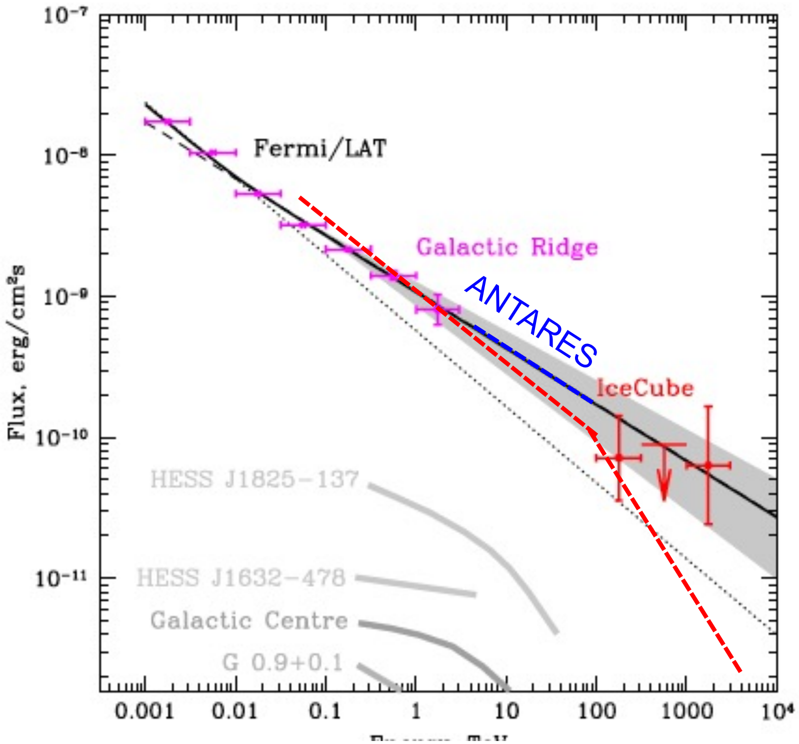
ICECUBE collaboration, 1405.5303

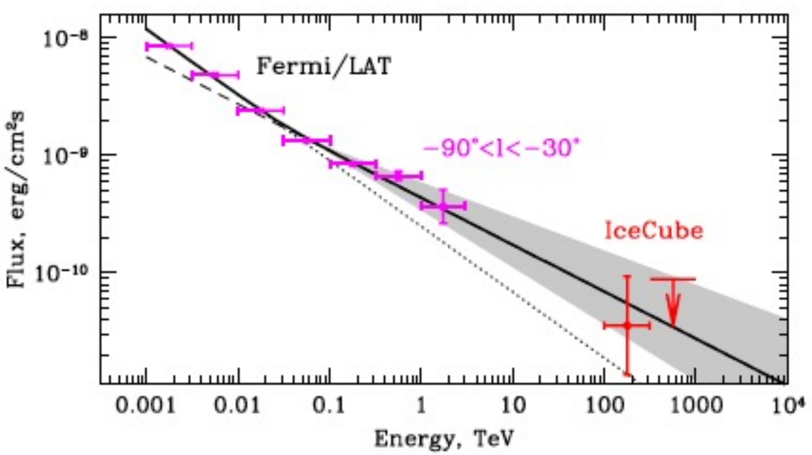
Half of ICECUBE events E>100 TeV are in Galactic plane. Are they correlate with gamma-rays?



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

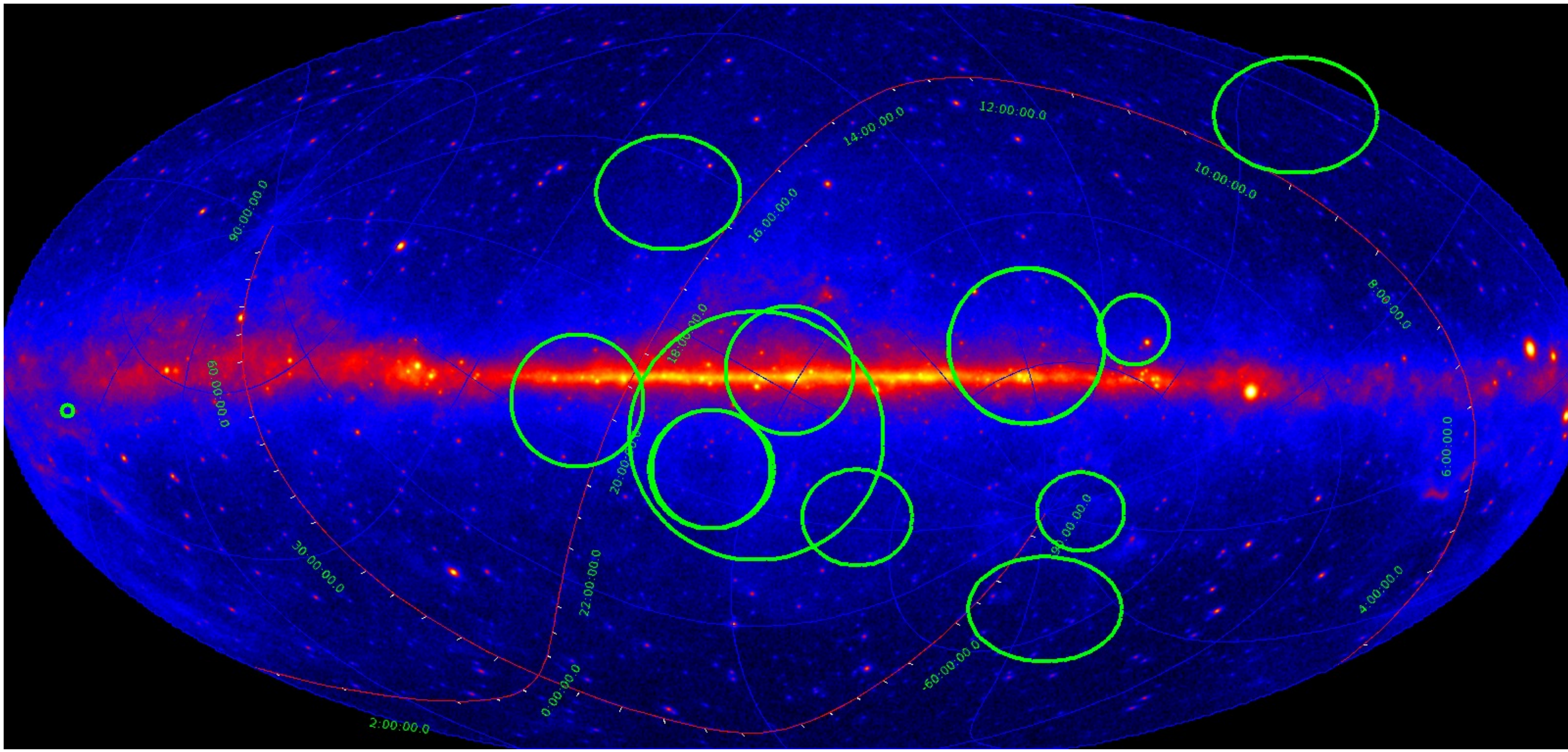
Real multimessenger fluxes, alpha=2.5



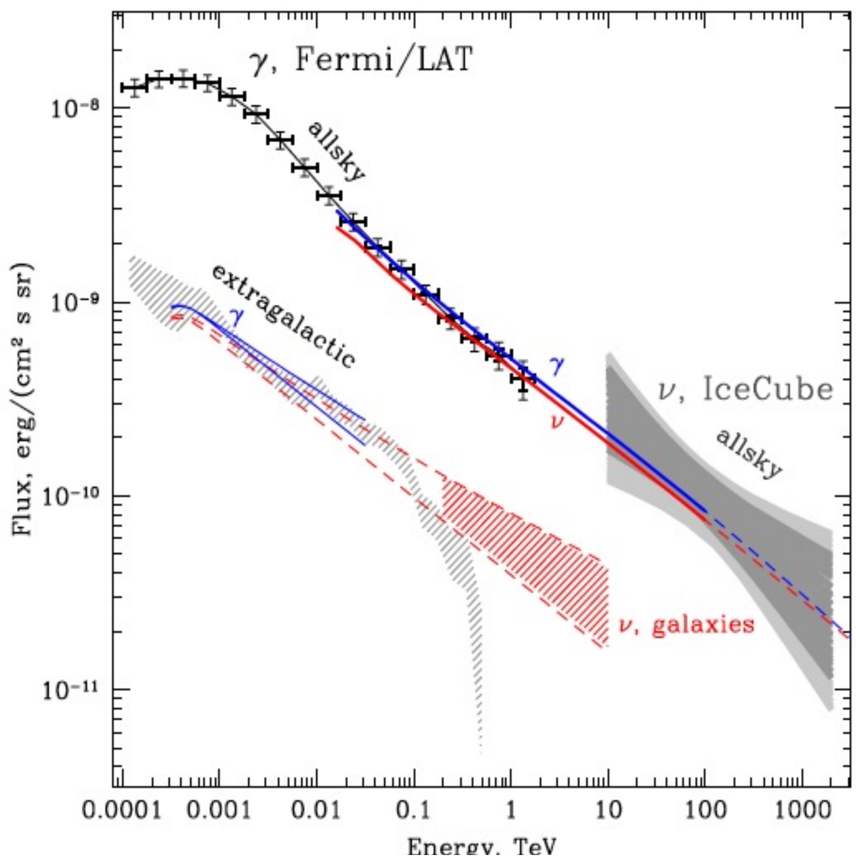


V.Berezinsky & A.Smirnov 1975

IceCube neutrino sky map
3 years E> 100 TeV

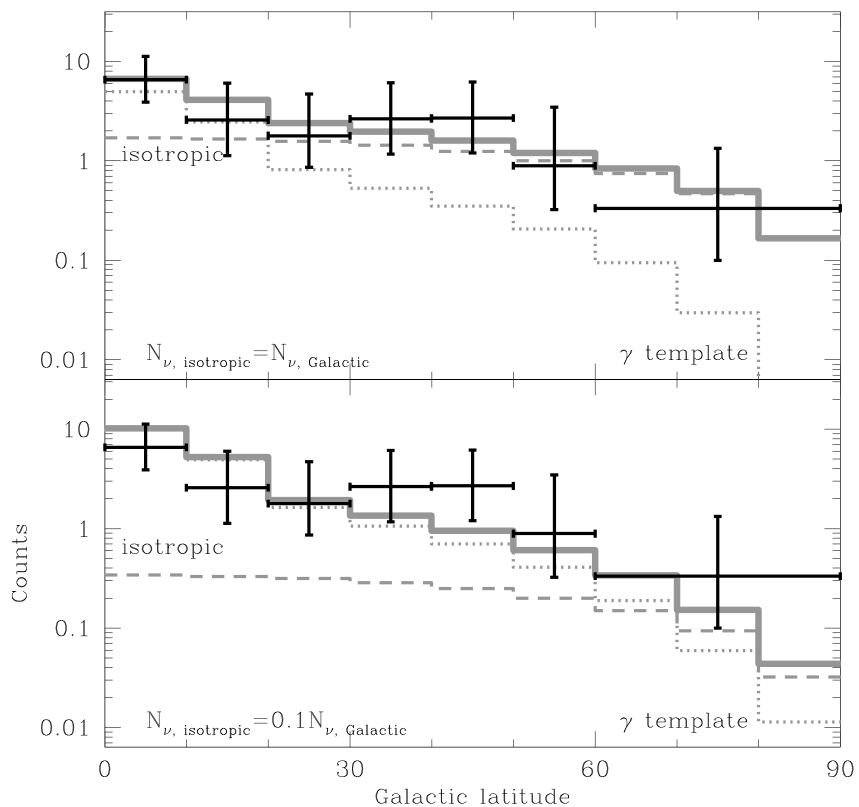


IceCube + Fermi LAT all sky: protons 1/E^2.5

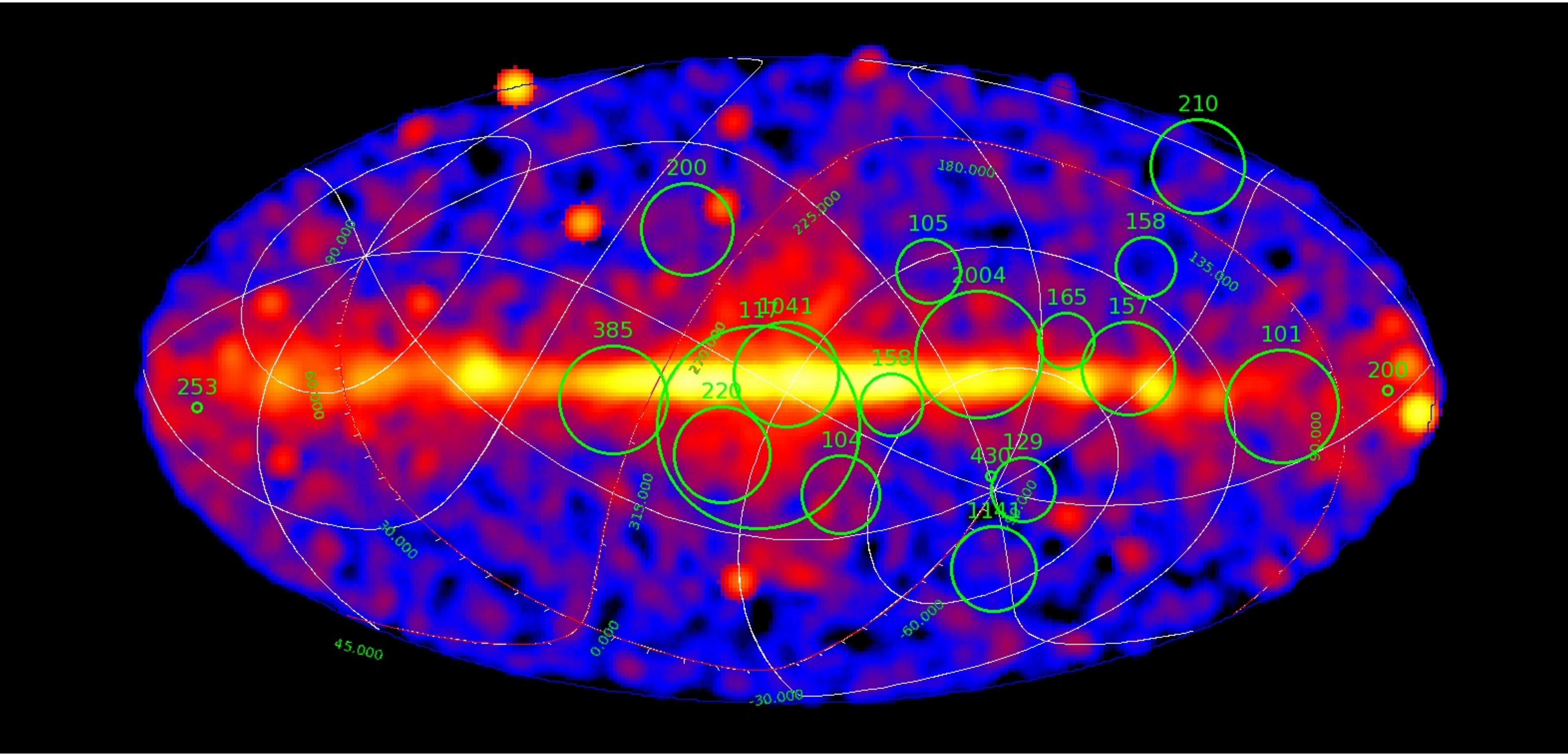


A.Neronov, D.S. arXiv:1412.1690

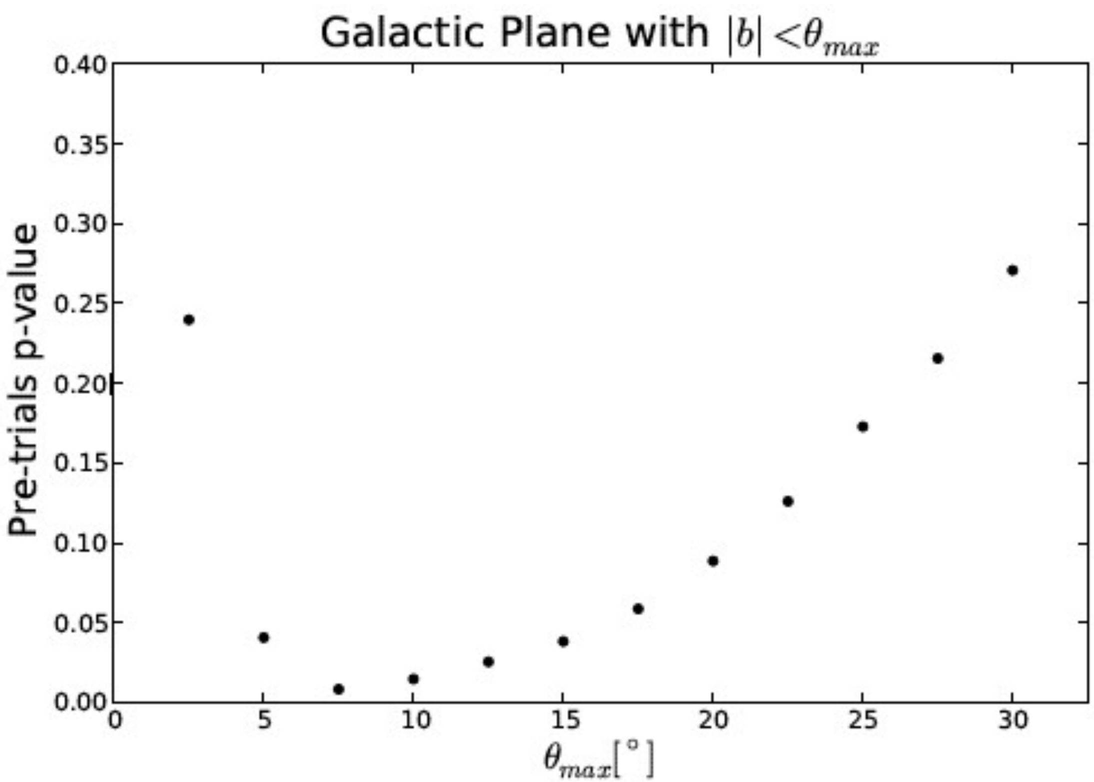
Neutrino flux as function of |b|



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

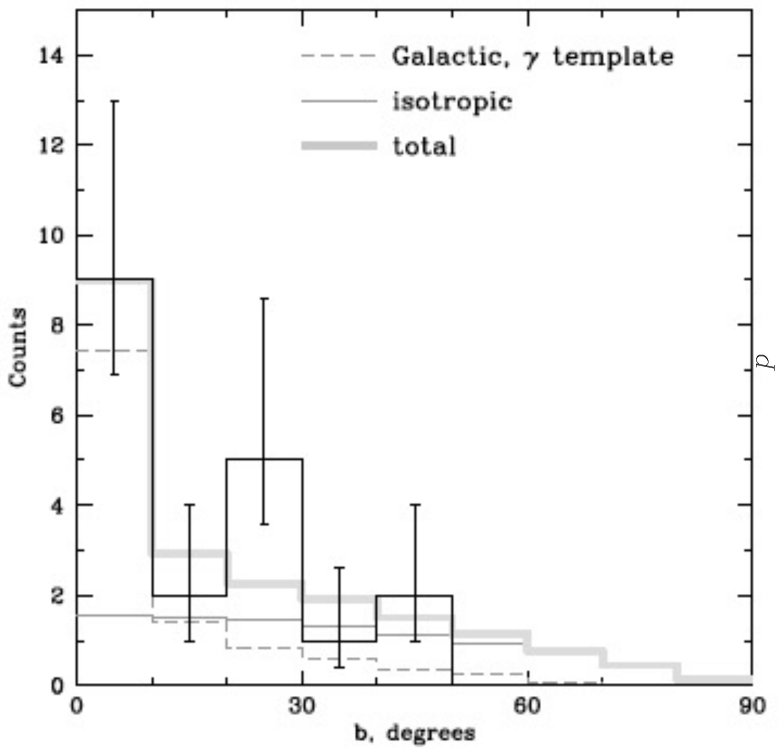


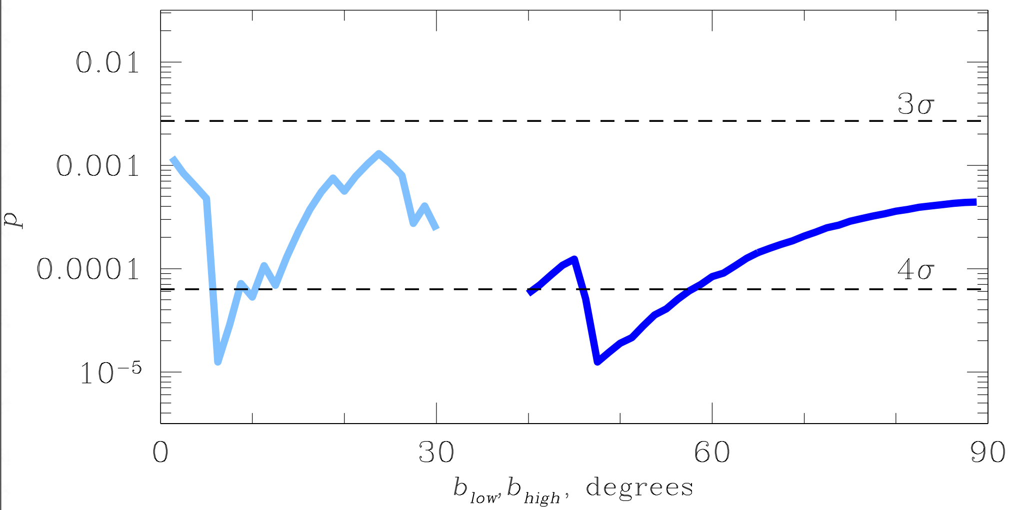
IceCube galactic plane 3 years: 2% by chance – small statistics



ICECUBE collaboration, arXiv:1405.5303

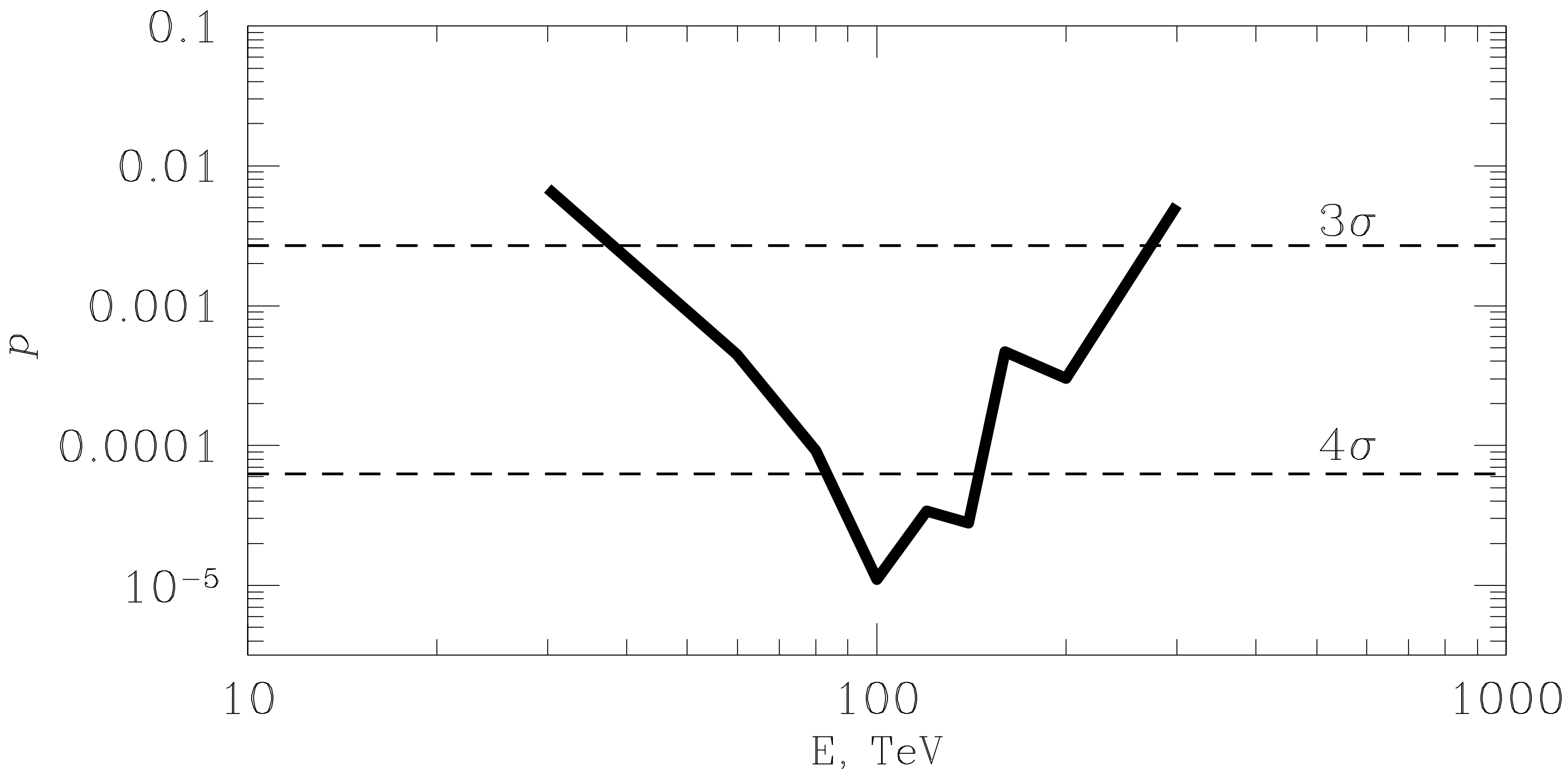
Evidence of Galactic component in 4 year IceCube data E>100 TeV





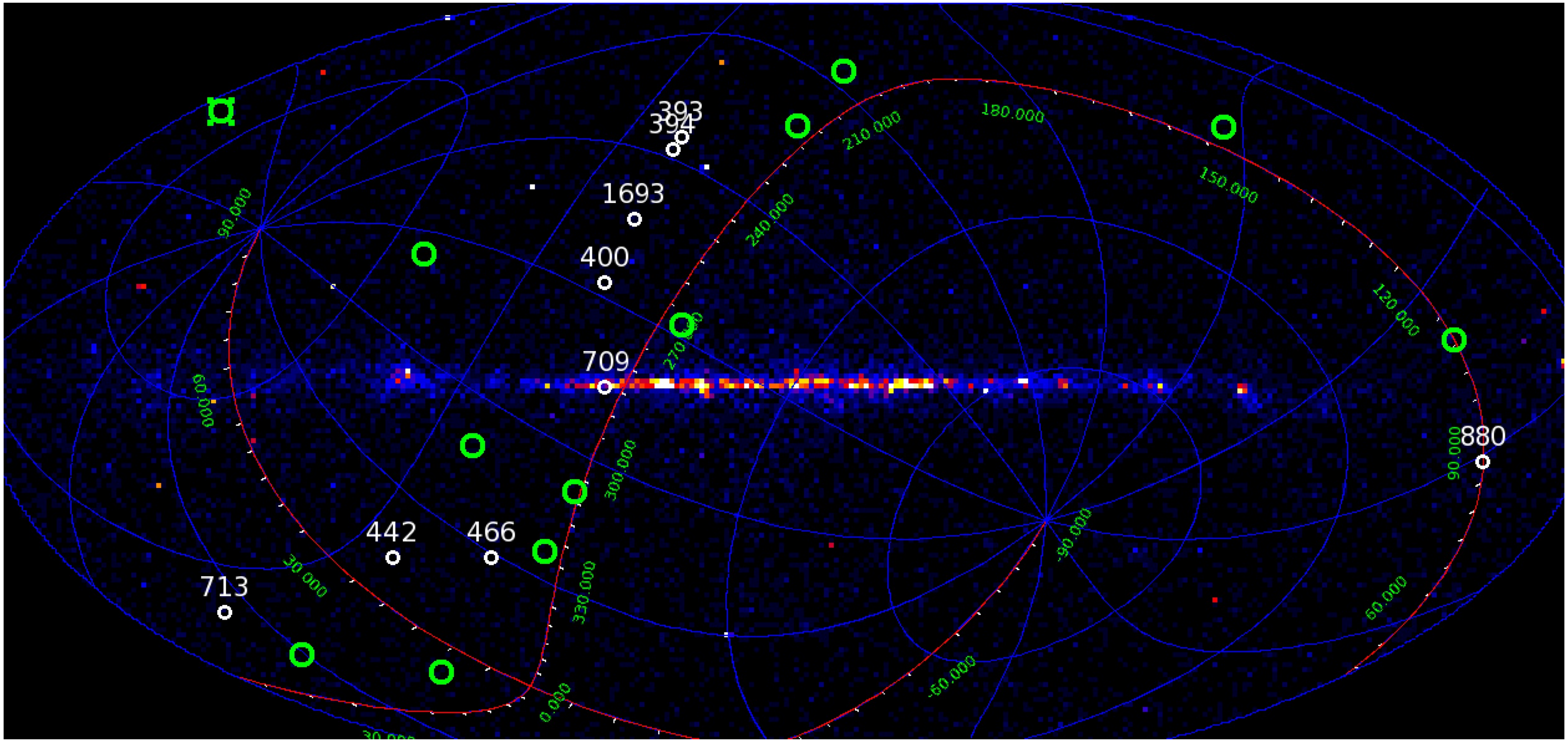
A. Neronov & D.S. arXiv: 1509.03522

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



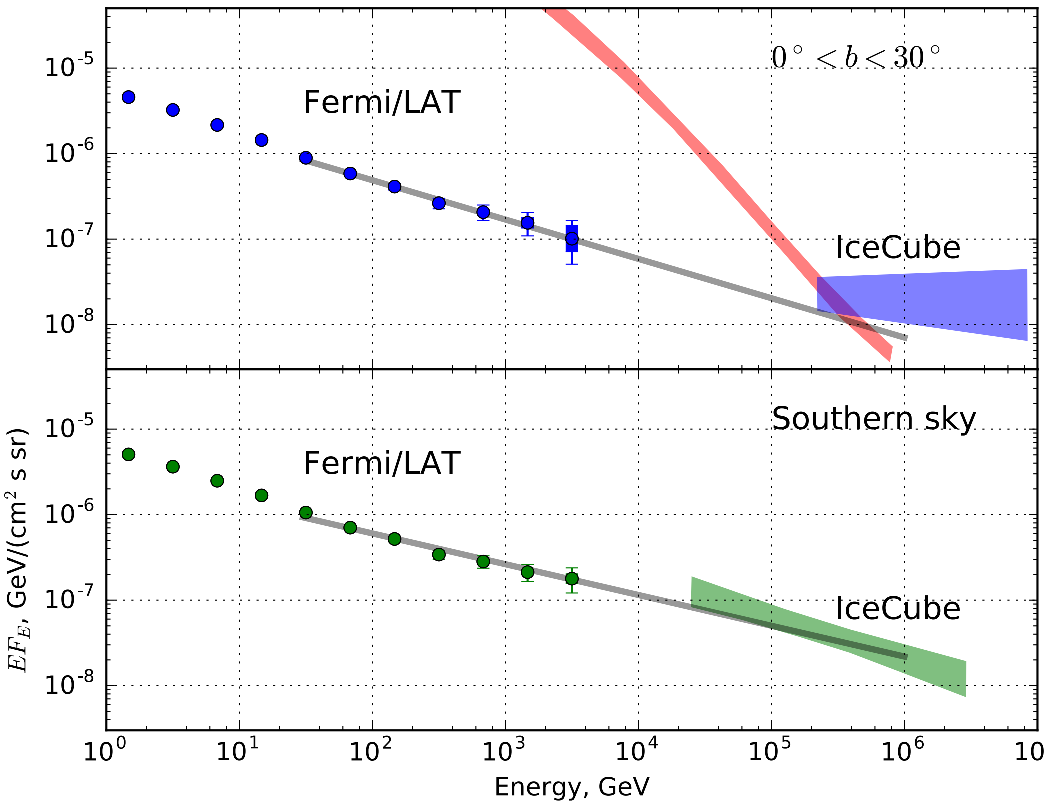
A. Neronov & D.S. arXiv: 1509.03522

Muon neutrinos



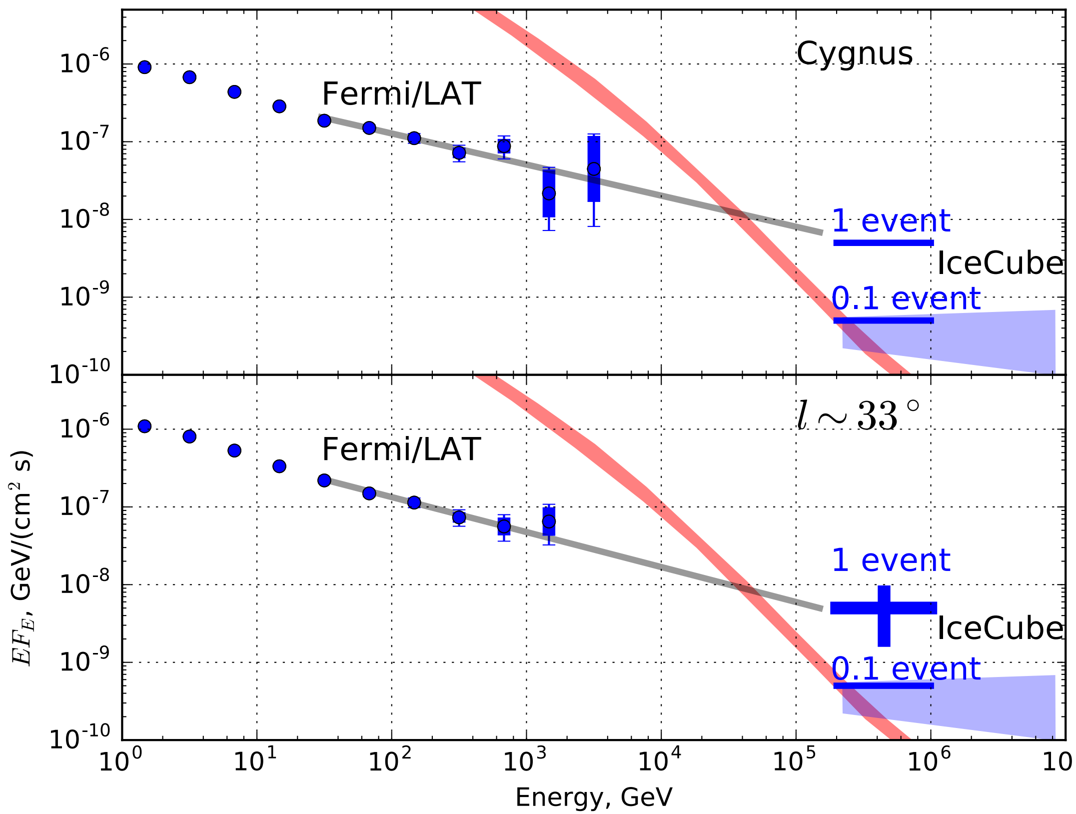
IceCube, ICRC 2015

North and South sky: IceCube



A. Neronov & D.S. arXiv: 1603.06733

First galactic diffuse sources

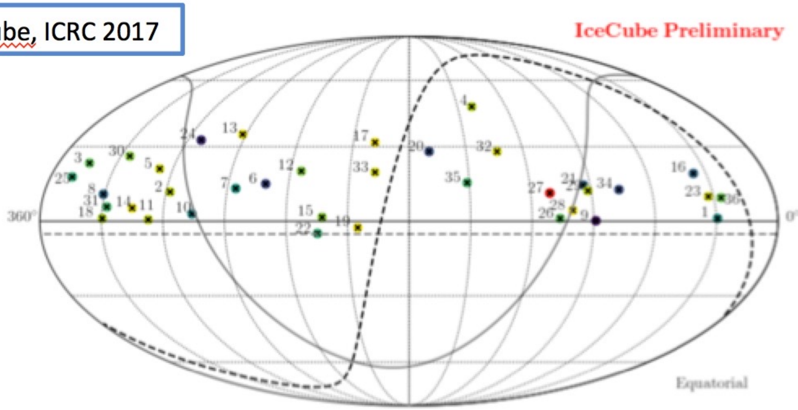


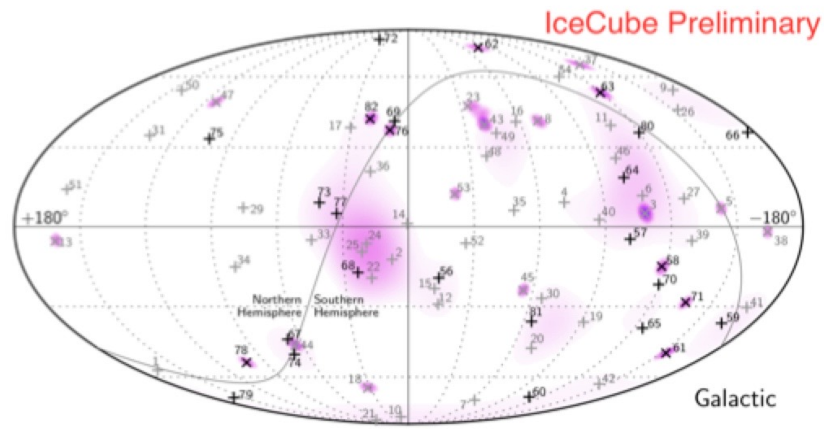
A. Neronov & D.S. arXiv: 1603.06733

IceCube ICRC 2017

Astrophysical neutrino signal

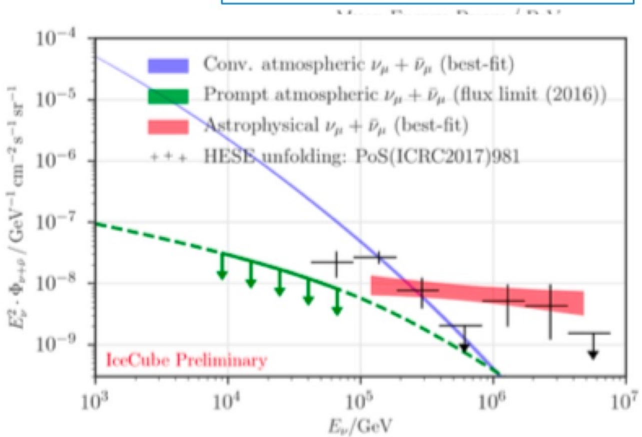
IceCube, ICRC 2017

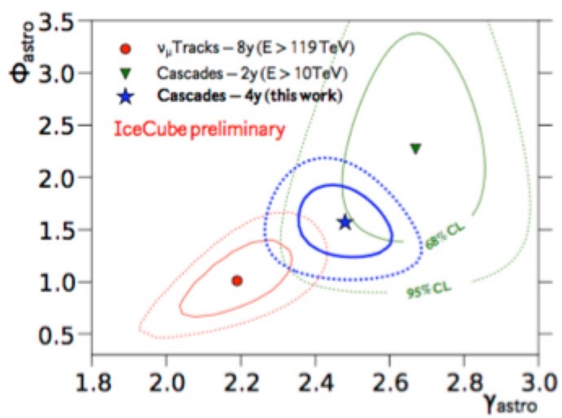


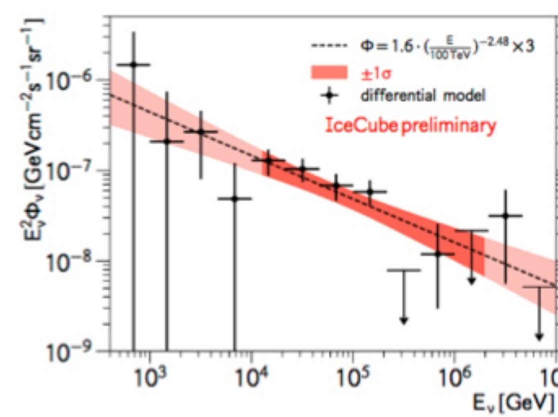


Muon neutrino sample

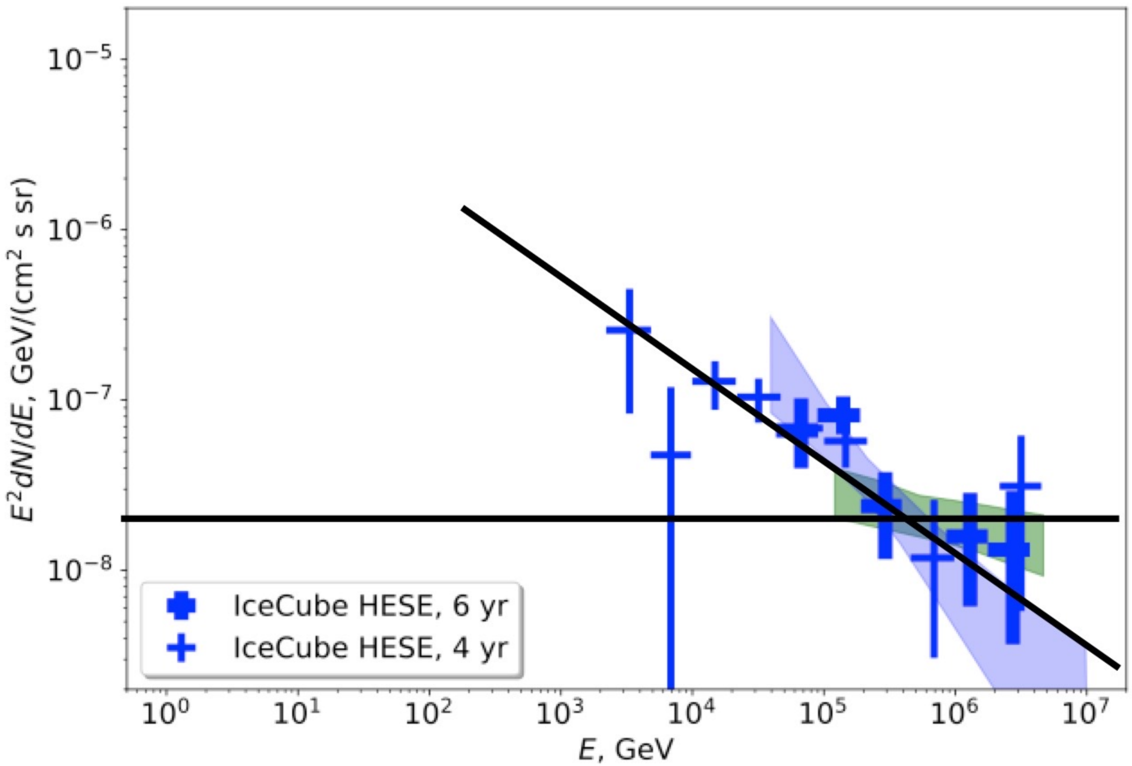
High Energy Starting Event neutrino sample







IceCube data



Diffuse gamma-ray background

Pion production

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

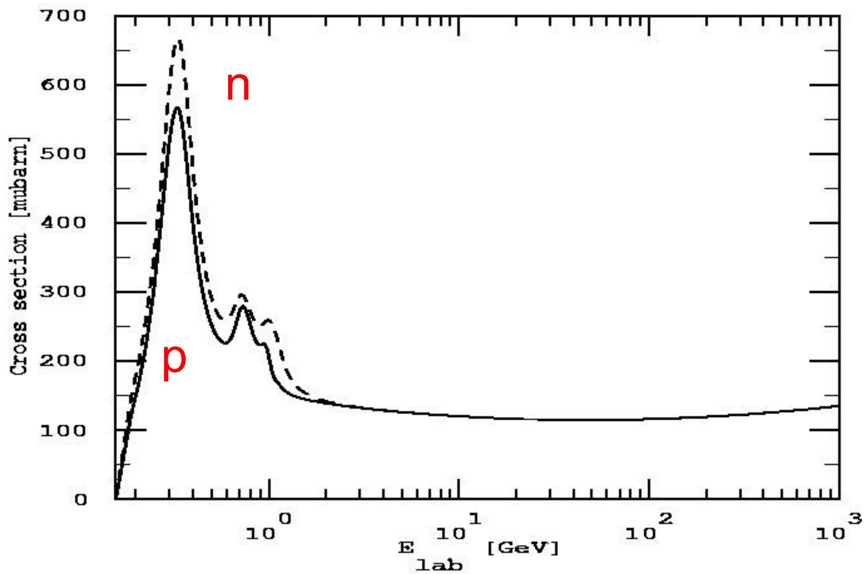
$$N + A_b \Rightarrow N' + \sum \pi^i$$

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

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

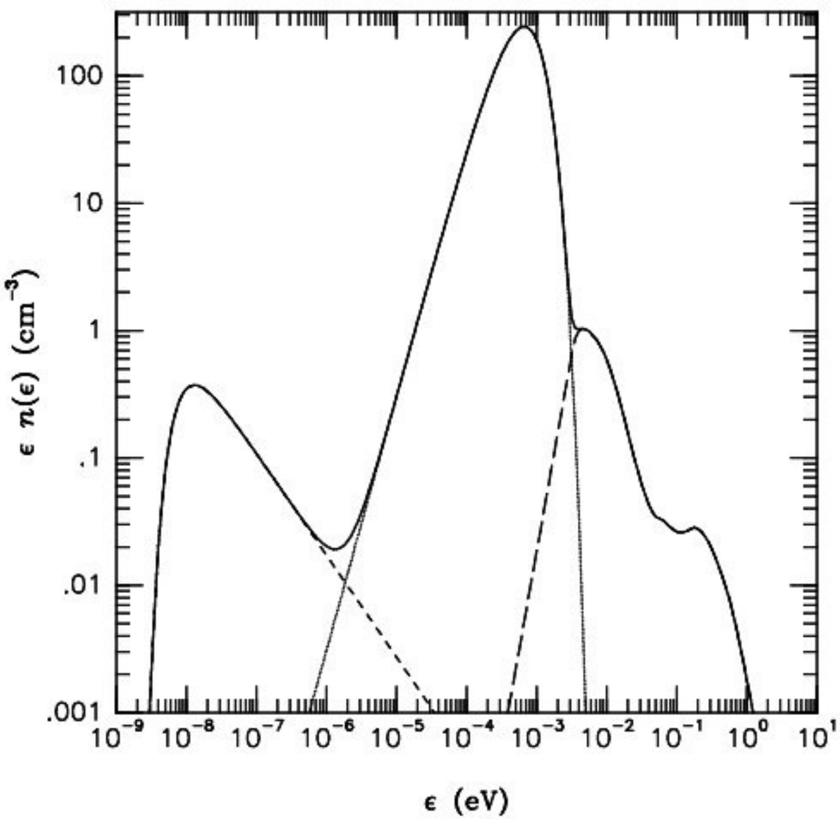
$$\mu^\pm \Rightarrow e^\pm + \overline{\nu}_e + \nu_\mu$$

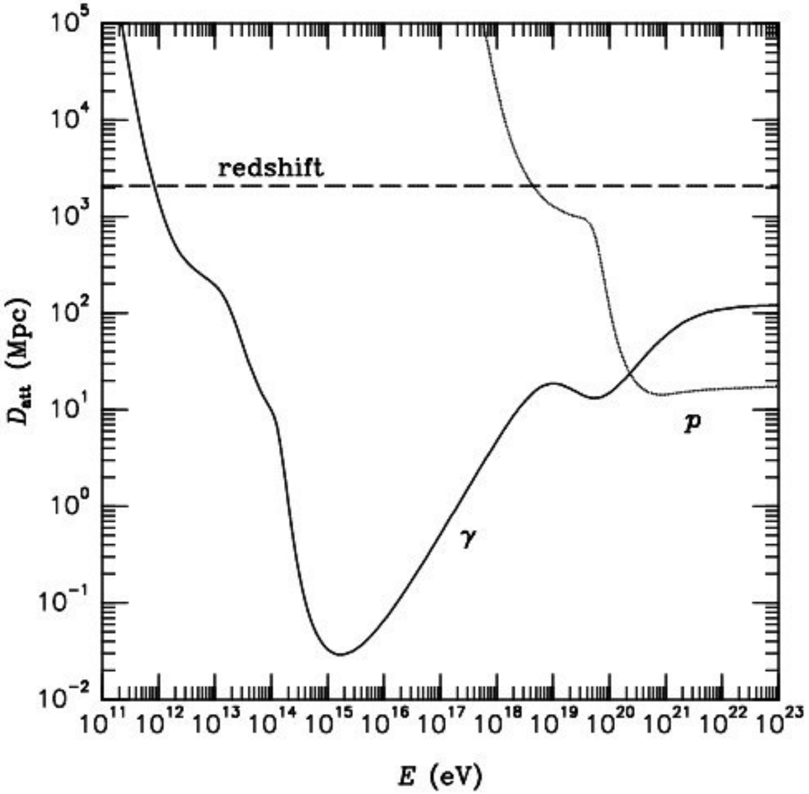
$$n \Rightarrow p + e^- + \overline{\nu}_e$$



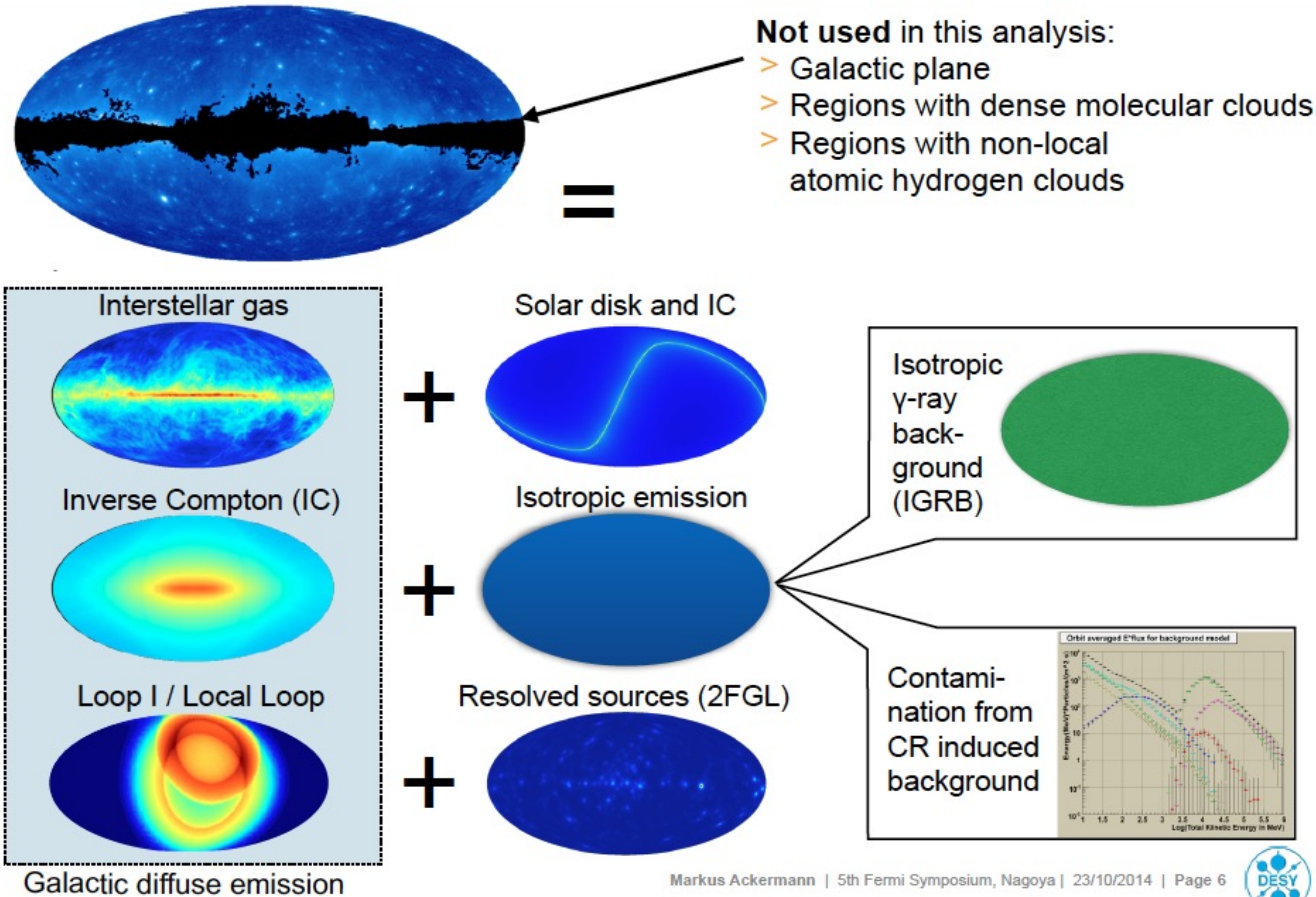
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

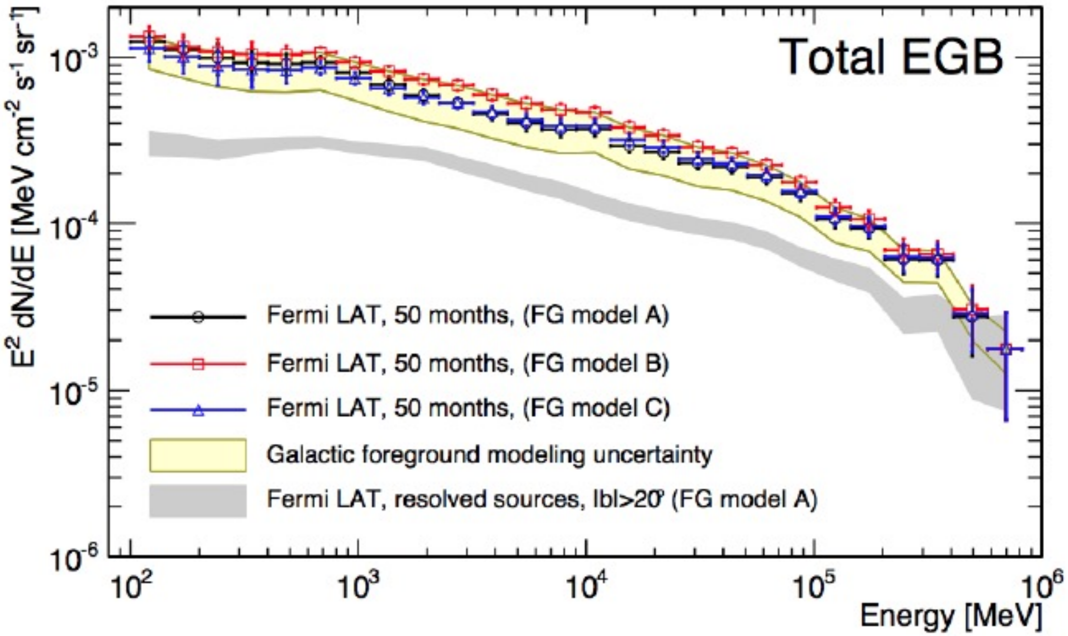
Diffuse backgrounds





Derivation of the isotropic gamma-ray 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

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

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

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

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

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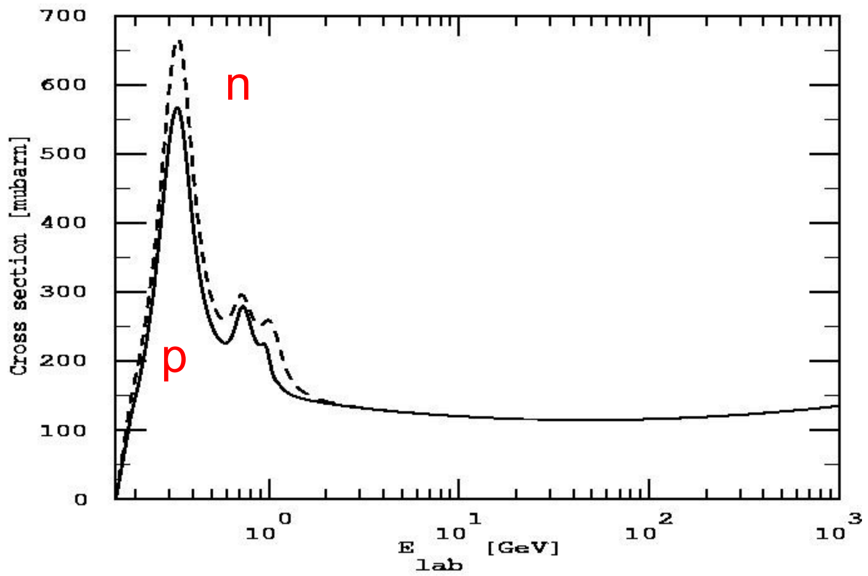
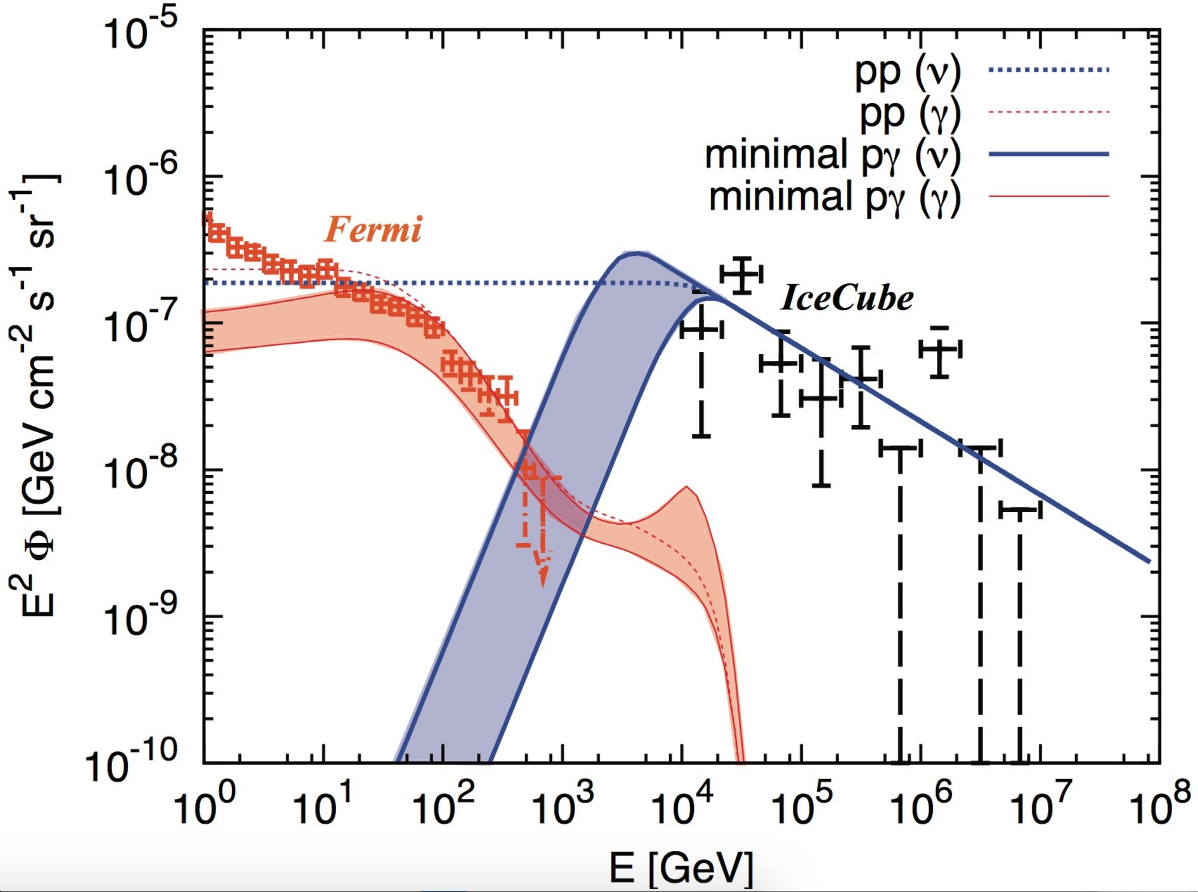
$$n \Rightarrow p + e^- + \overline{\nu}_e$$



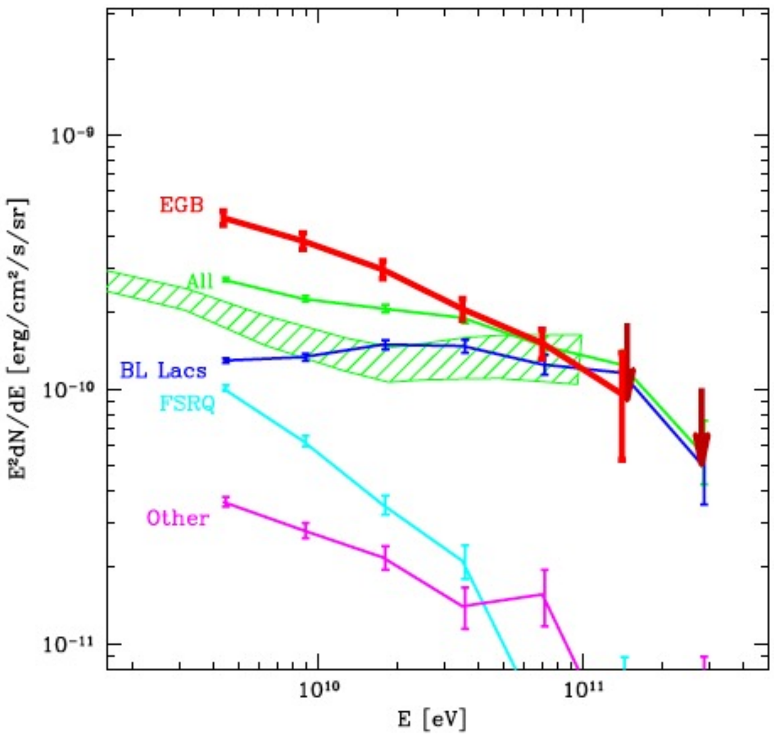
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

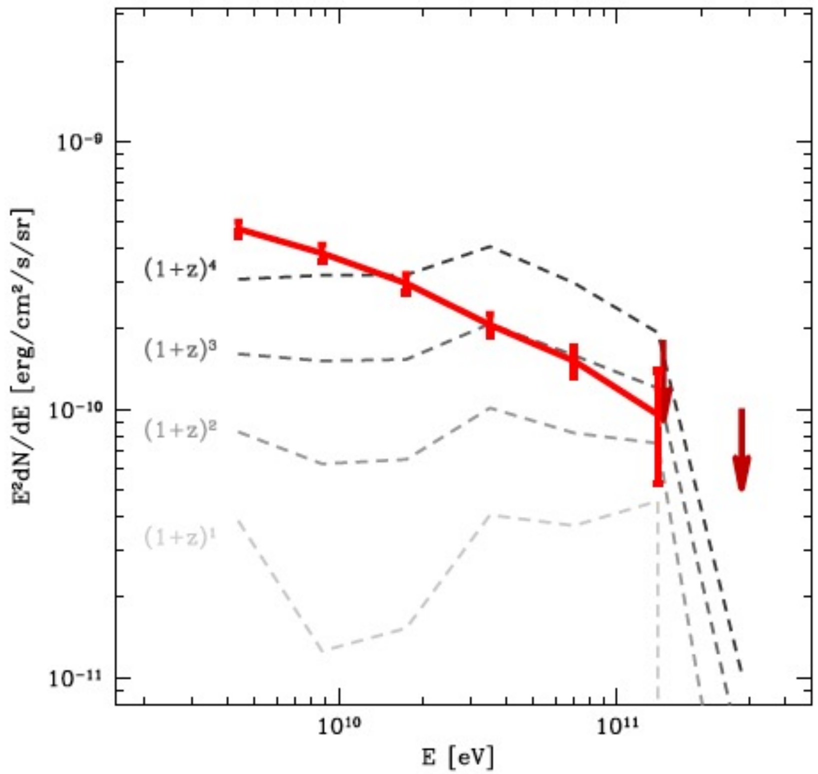
Self-consistent extragalactic sources



Astrophysical neutrinos from BL Lacs

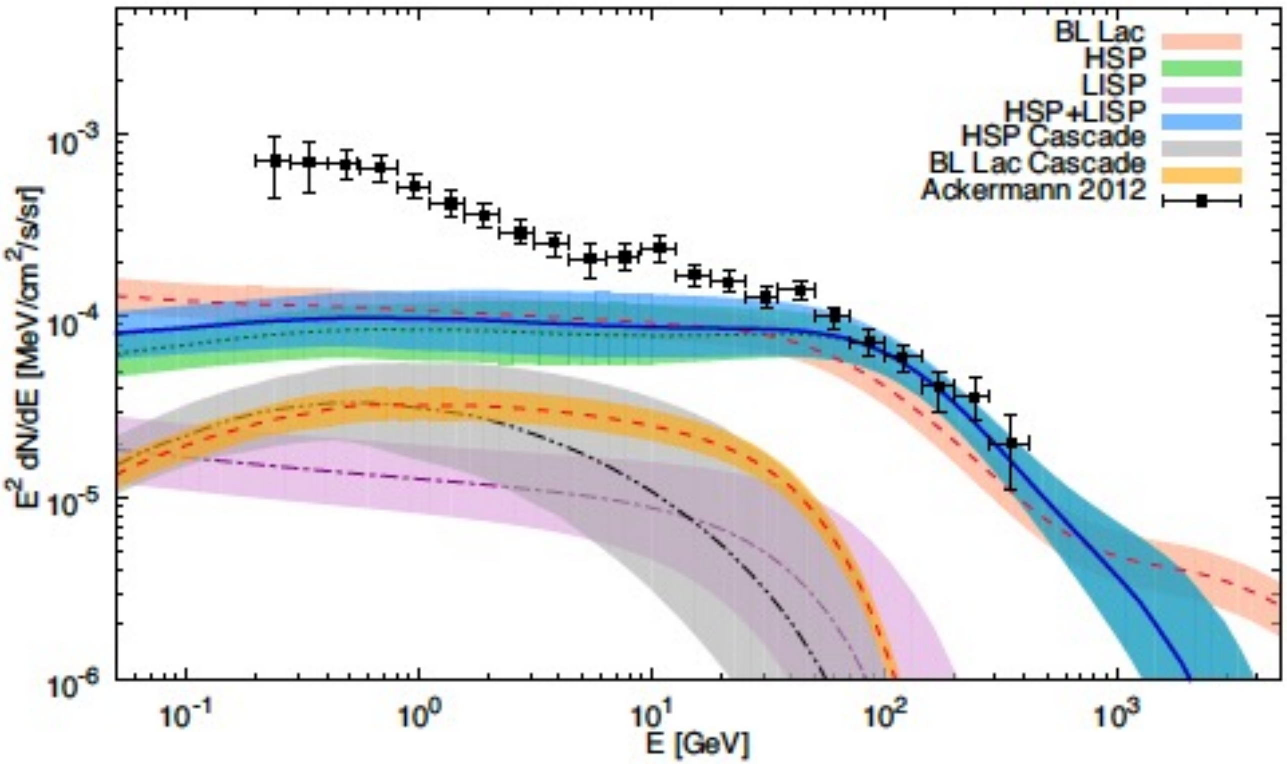
Unresolved BL Lacs give main contribution to diffuse gamma-ray





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

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



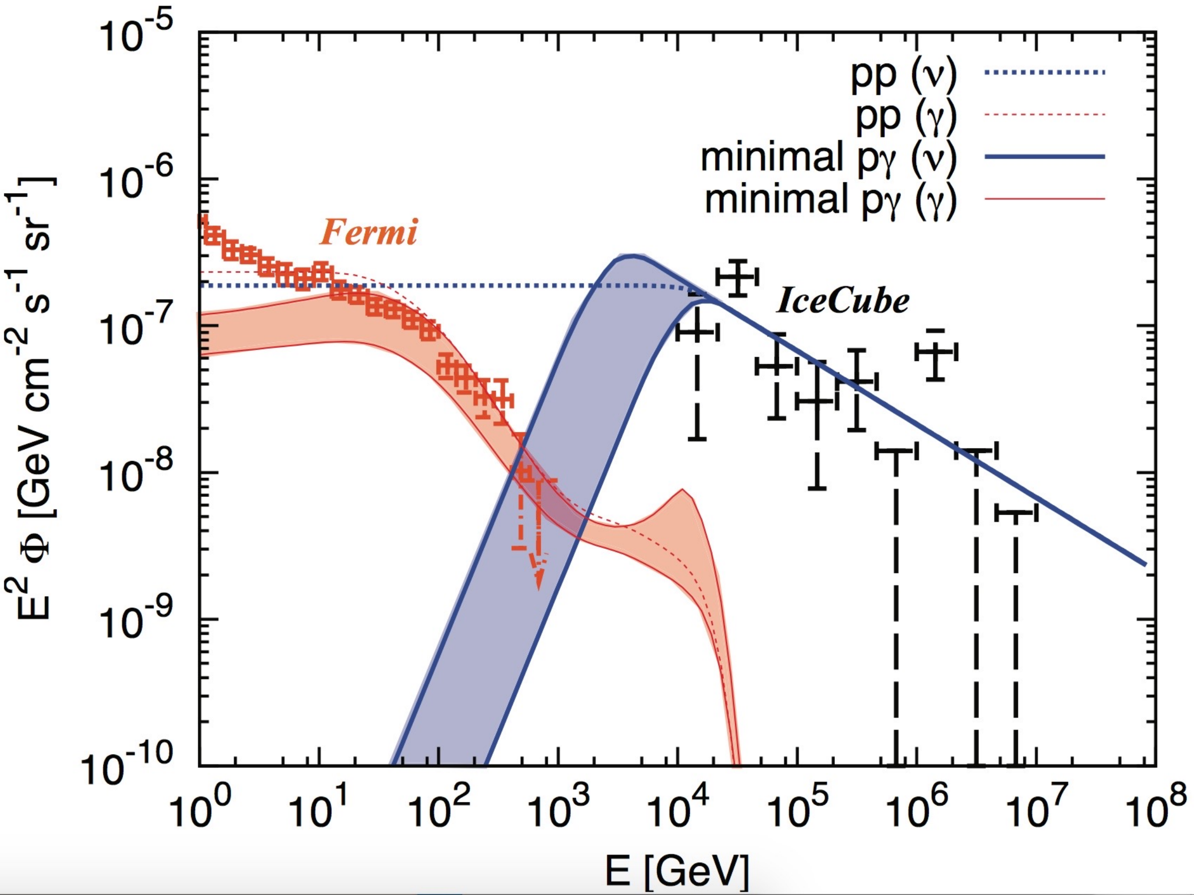
M. Di Mauro et al, arXiv:1311.5708

Fermi confirmed resolution of BL Lac sources above 50 GeV

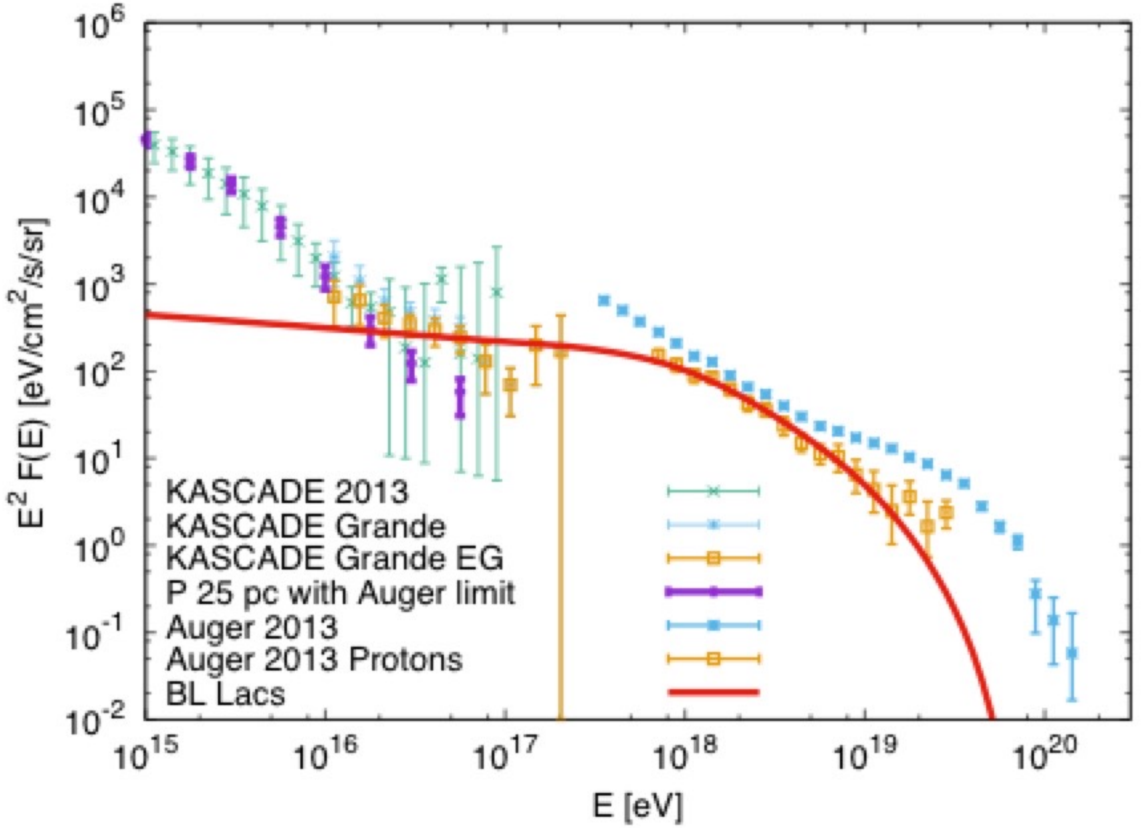
cm^{-2} s^{-1}). We employ a one-point photon fluctuation analysis to constrain the behavior of dN/dS below the source detection threshold. Overall the source count distribution is constrained over three decades in flux and found compatible with a broken power law with a break flux, S_b, in the range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

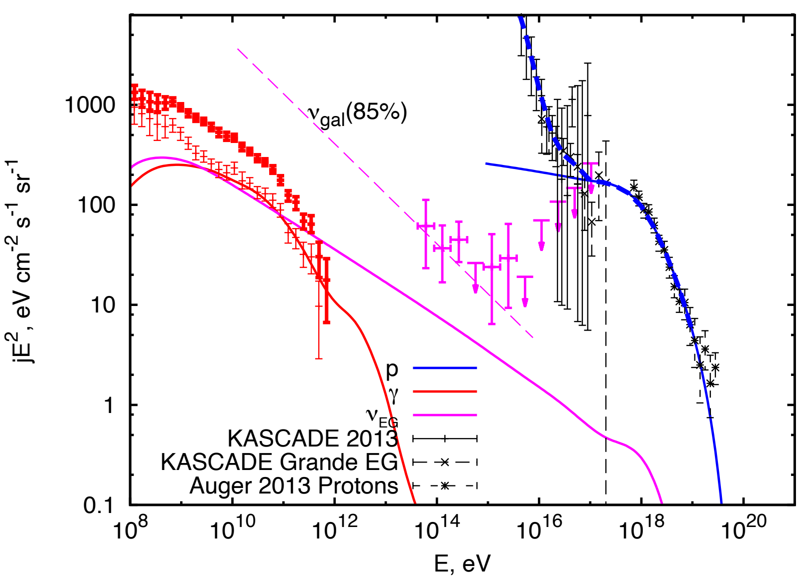
Protons in sources

- $E<E_1(\tau=1)$ 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

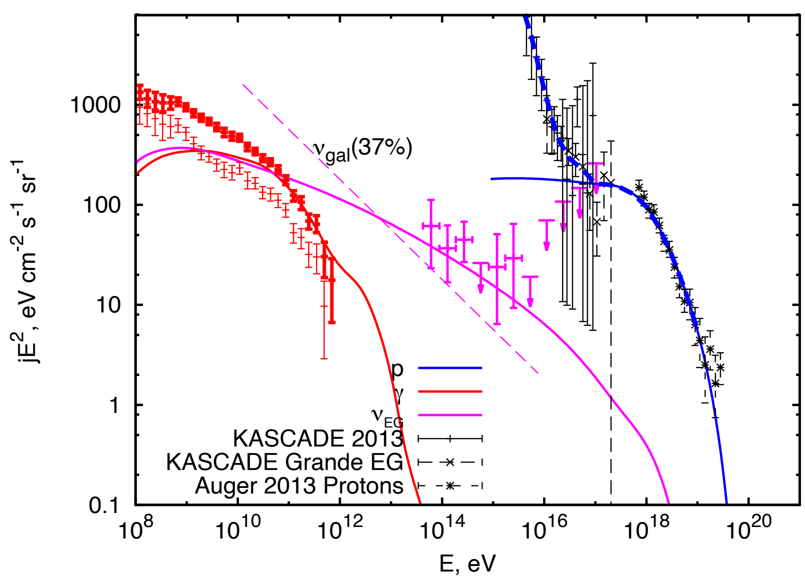
G.Giacinti, M.Kachelriess, O.Kalashev, A.Neronov and D.S., **arXiv: 1507.07534**

Miltimessenger signal from BL Lacs: dependence on escape energy

0.3 TeV

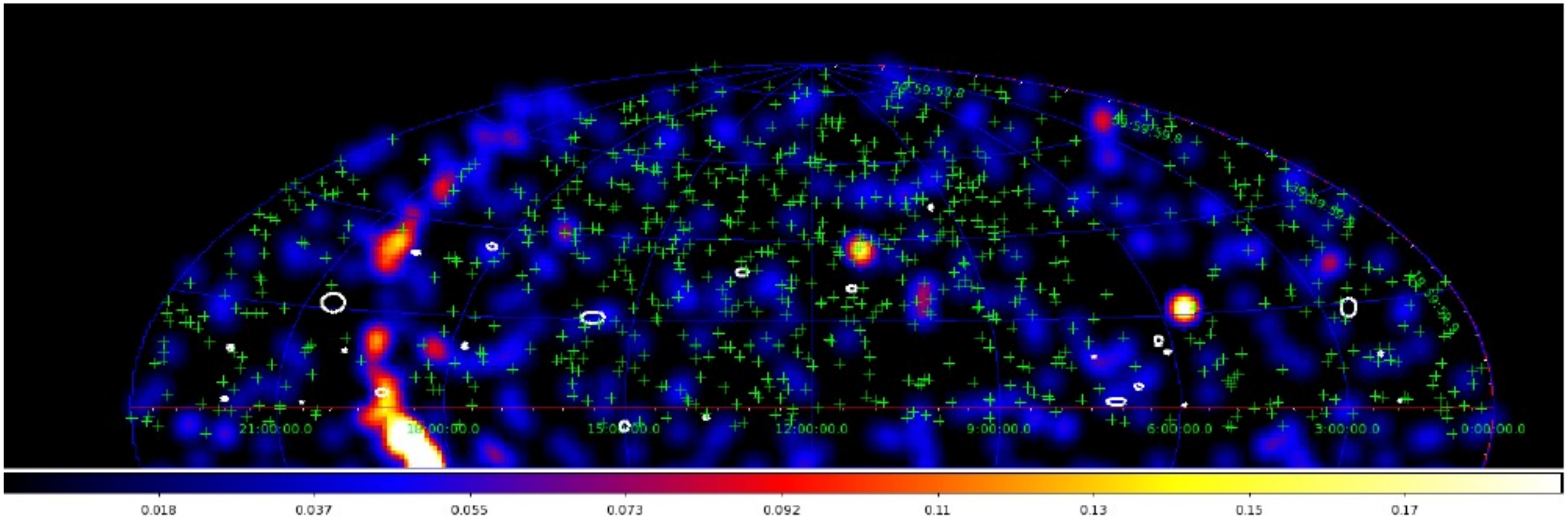


100 TeV



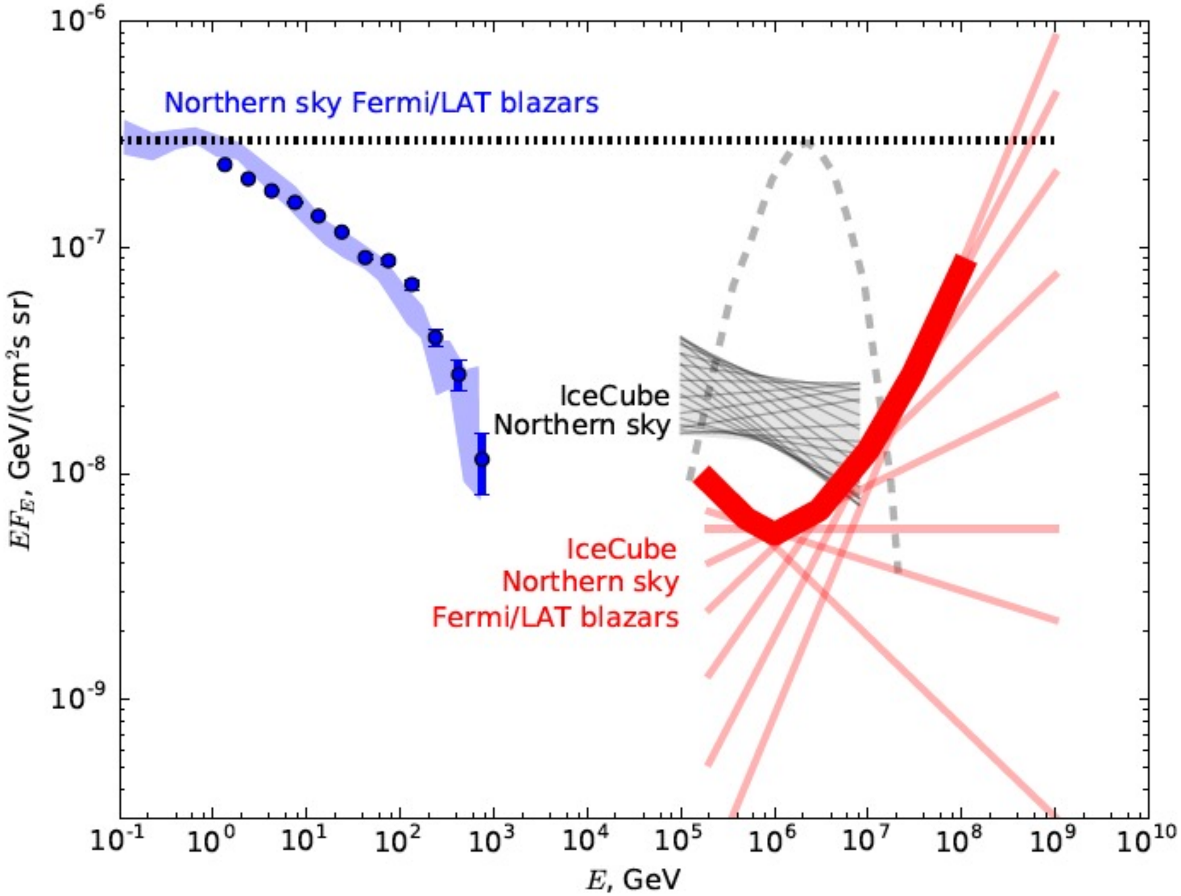
G.Giacinti, M.Kachelriess, O.Kalashev, A.Neronov and D.S., **arXiv: 1507.07534**

Fermi blazars and IceCube neutrinos



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

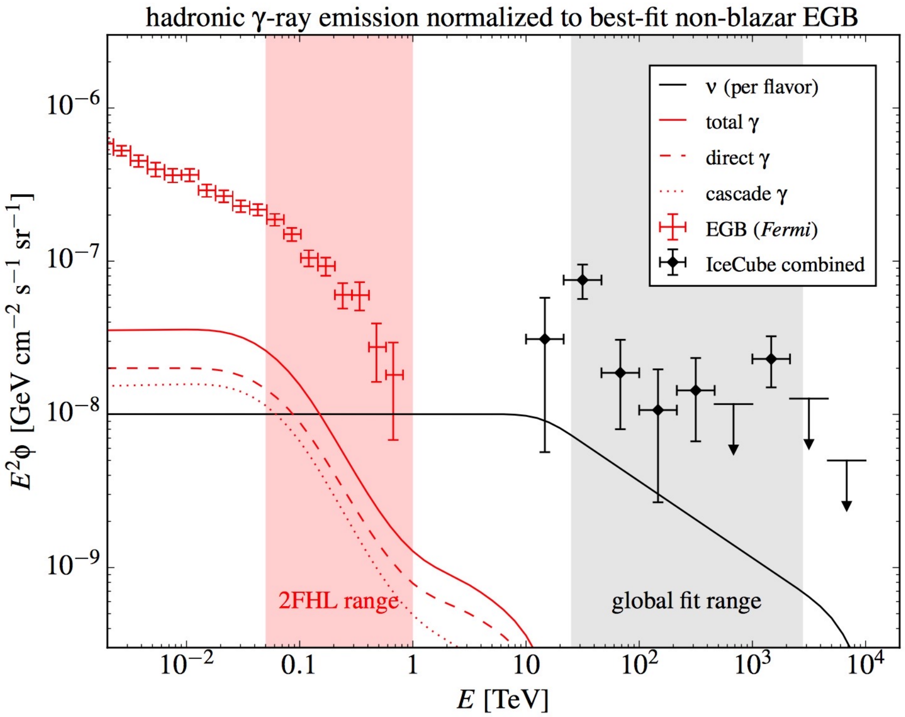
Neutrinos not from blazars



<u>**IceCube arXiv:1611.03874**</u>

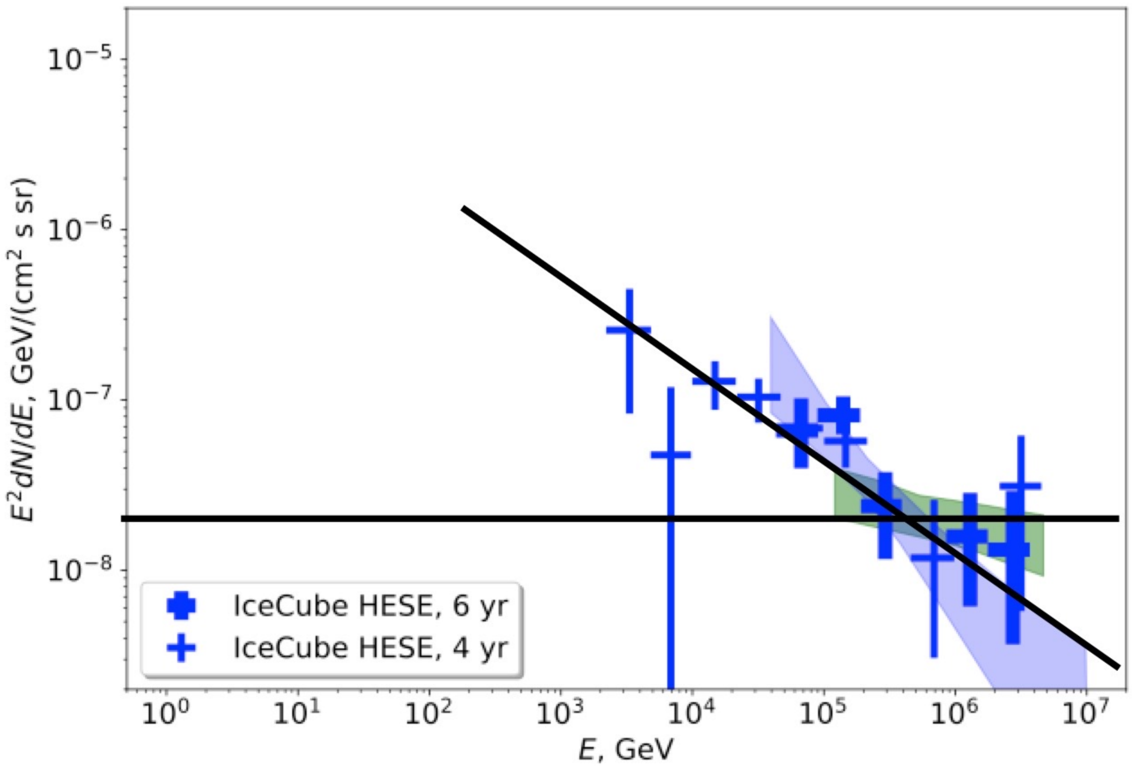
<u>**A.Neronov, K.Ptitsyna and D.S., arXiv:1611.06338**</u>

Self-consistent extragalactic sources: no nearby blazars

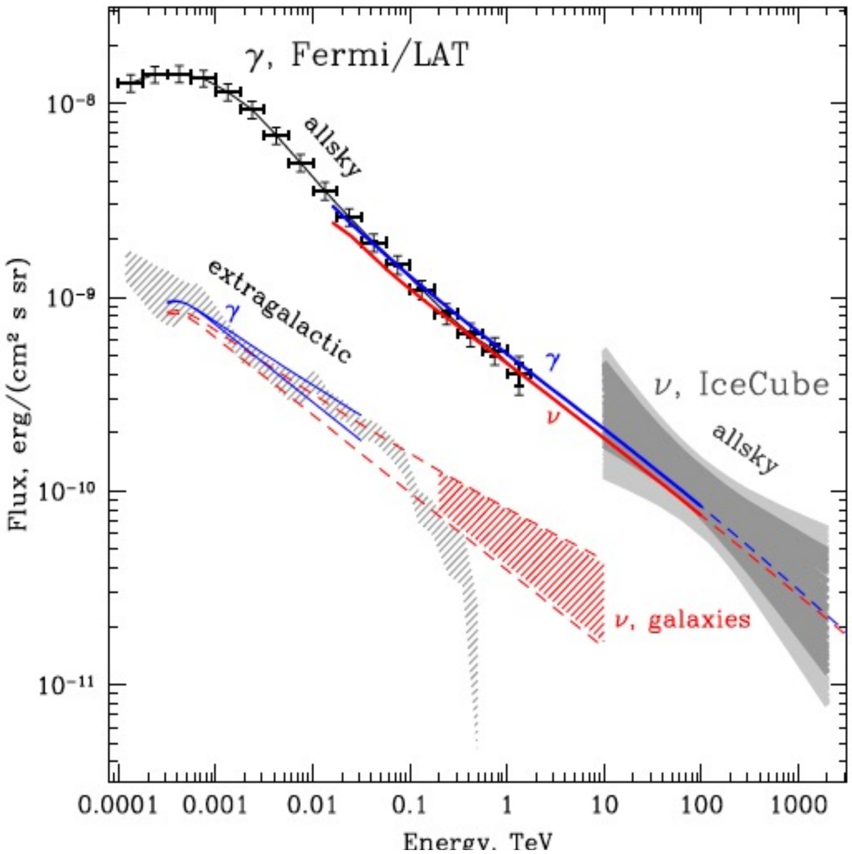


[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

IceCube data

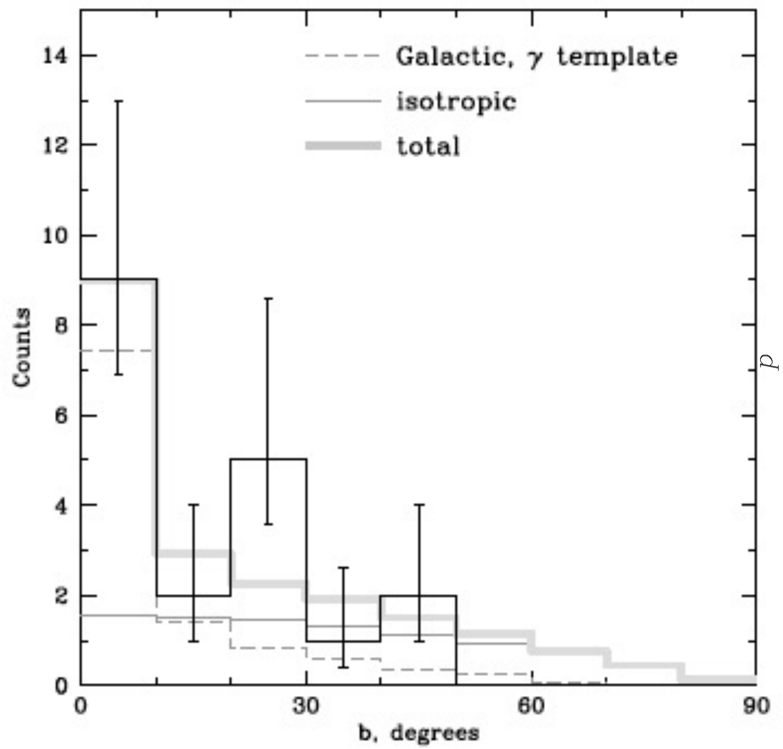


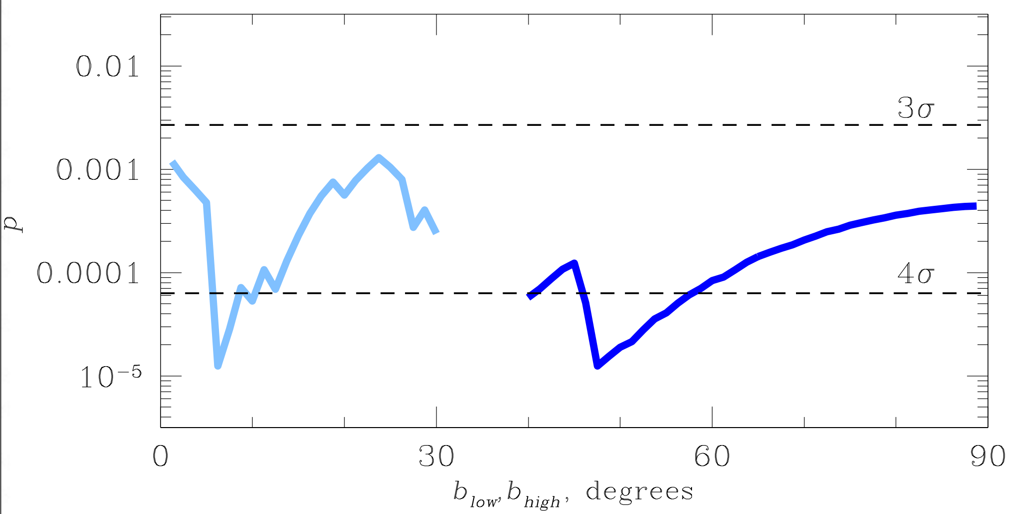
IceCube + Fermi LAT all sky: protons 1/E^2.5



A.Neronov, D.S. arXiv:1412.1690

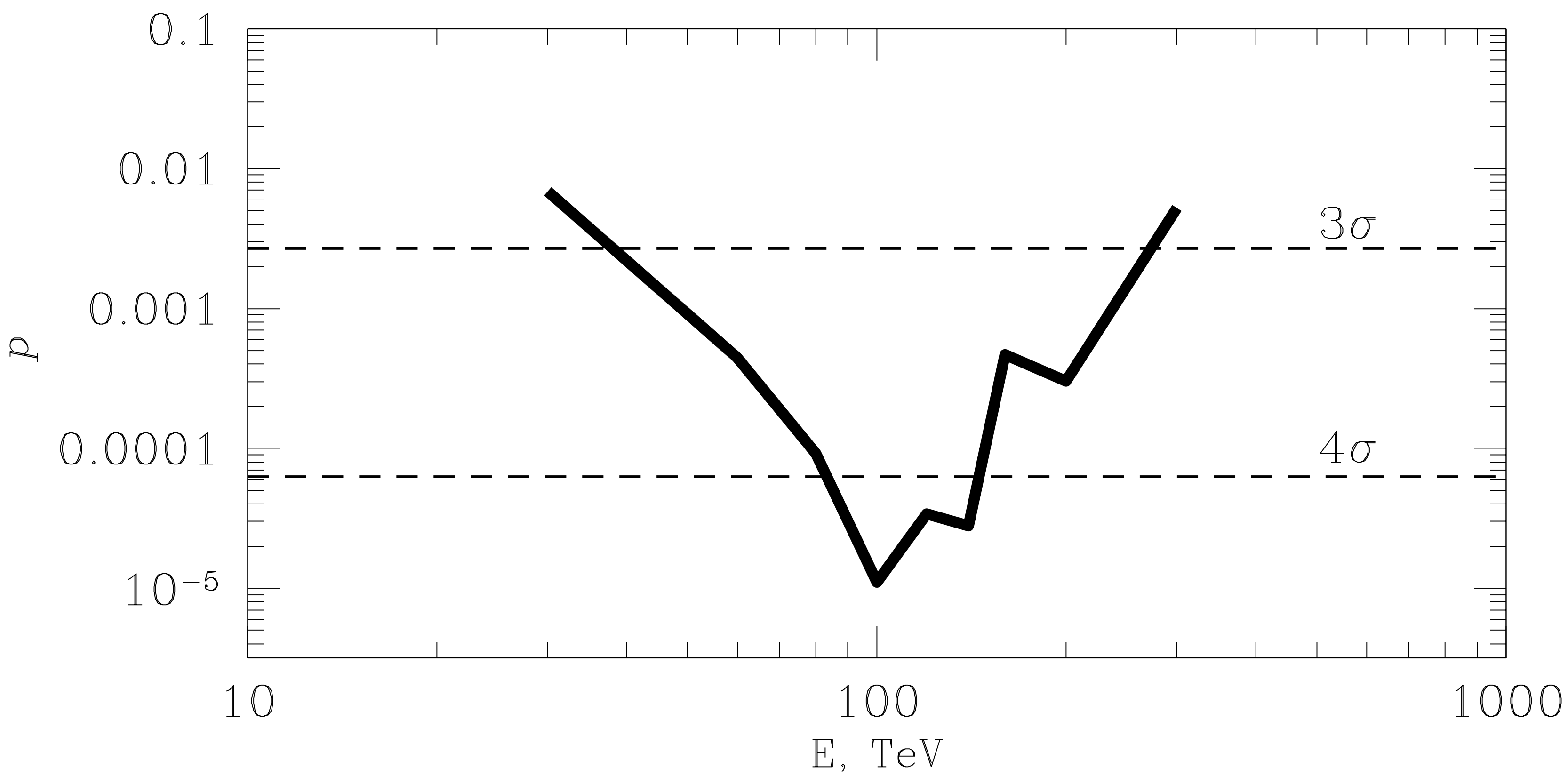
Evidence of Galactic component in 4 year IceCube data E>100 TeV





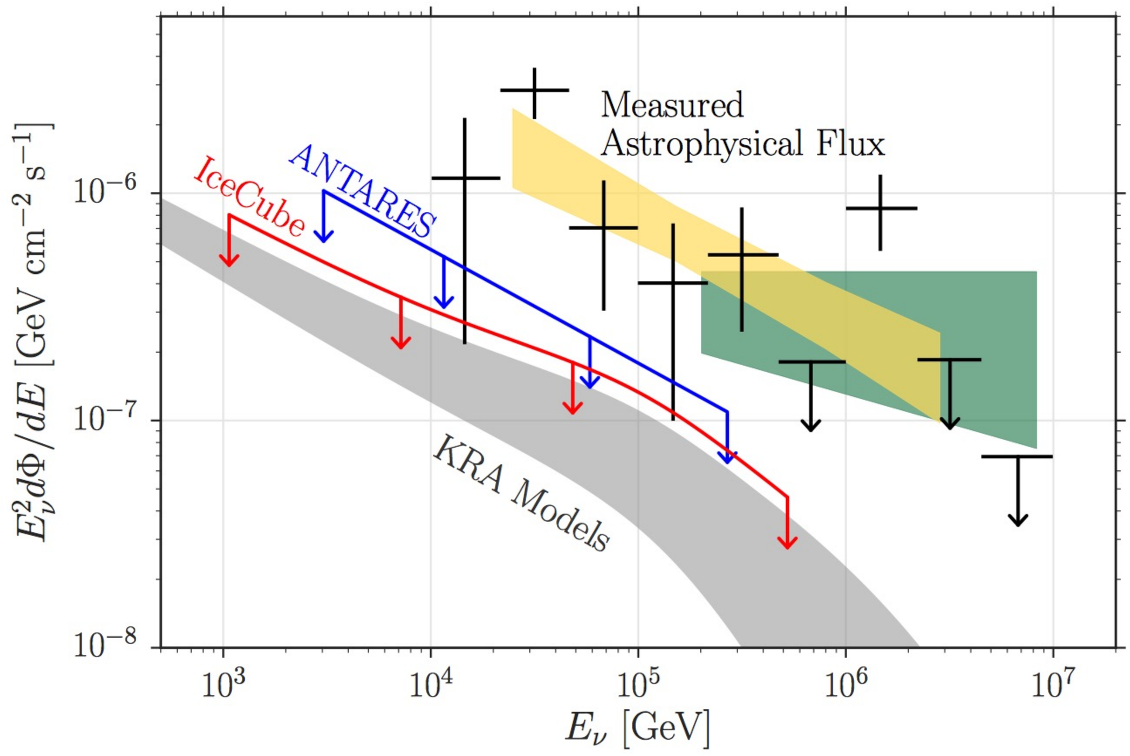
A. Neronov & D.S. arXiv: 1509.03522

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



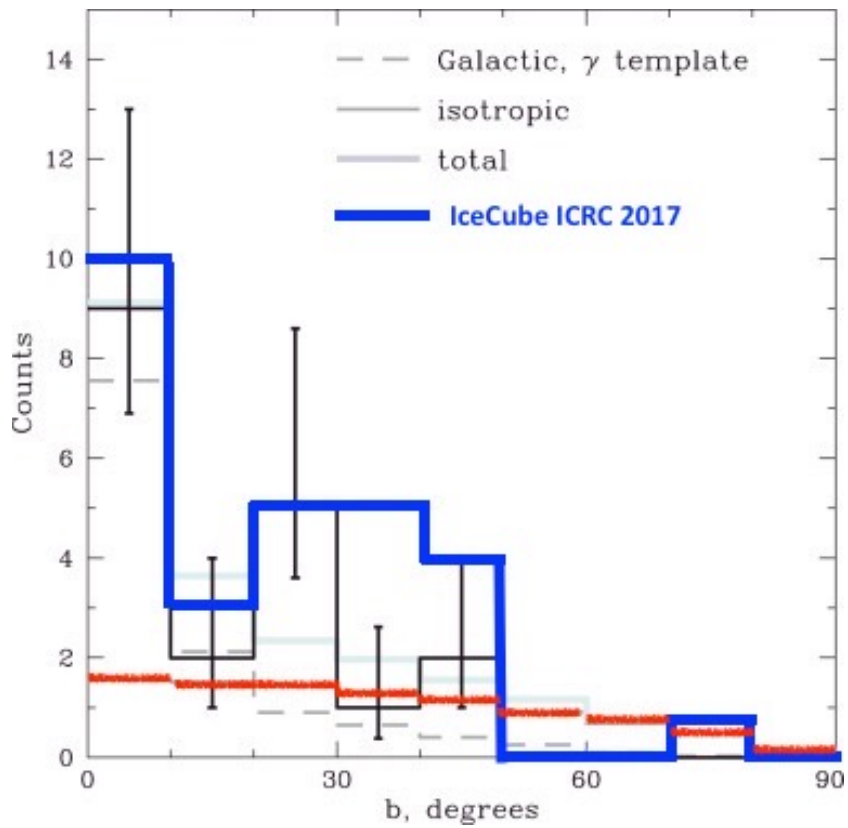
A. Neronov & D.S. arXiv: 1509.03522

IceCube and ANTARES galalactic plane



ICRC 2017

Anisotropy at E>100 TeV



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

Point source searches

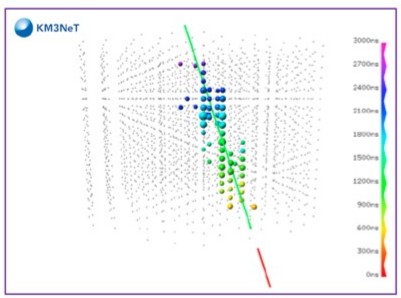
Point-source samples: angular resolution

ANTARES
tracks
CC ν_μ

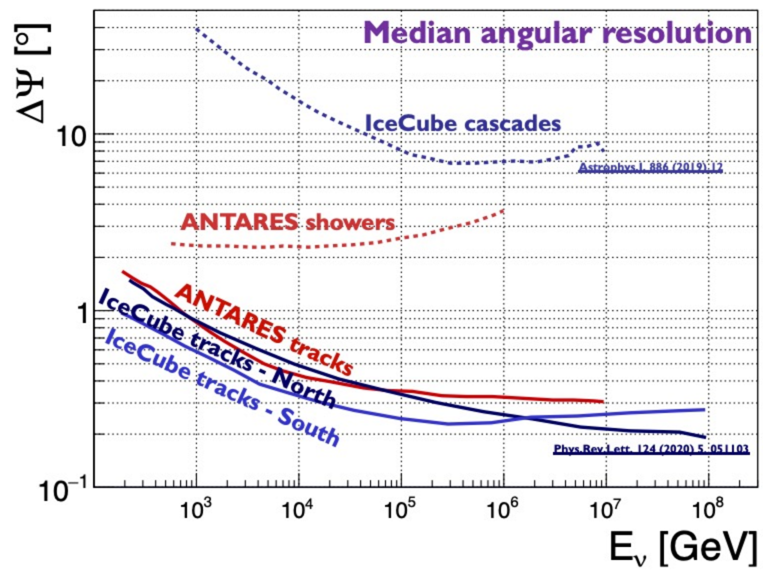
ANTARES
showers
NC ν_x + CC $\nu_{e,}\nu_\tau$

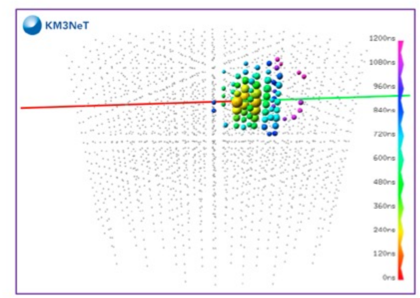
IceCube
through-going tracks
CC ν_μ

IceCube
cascades
NC ν_x + CC $\nu_{e,}\nu_\tau$

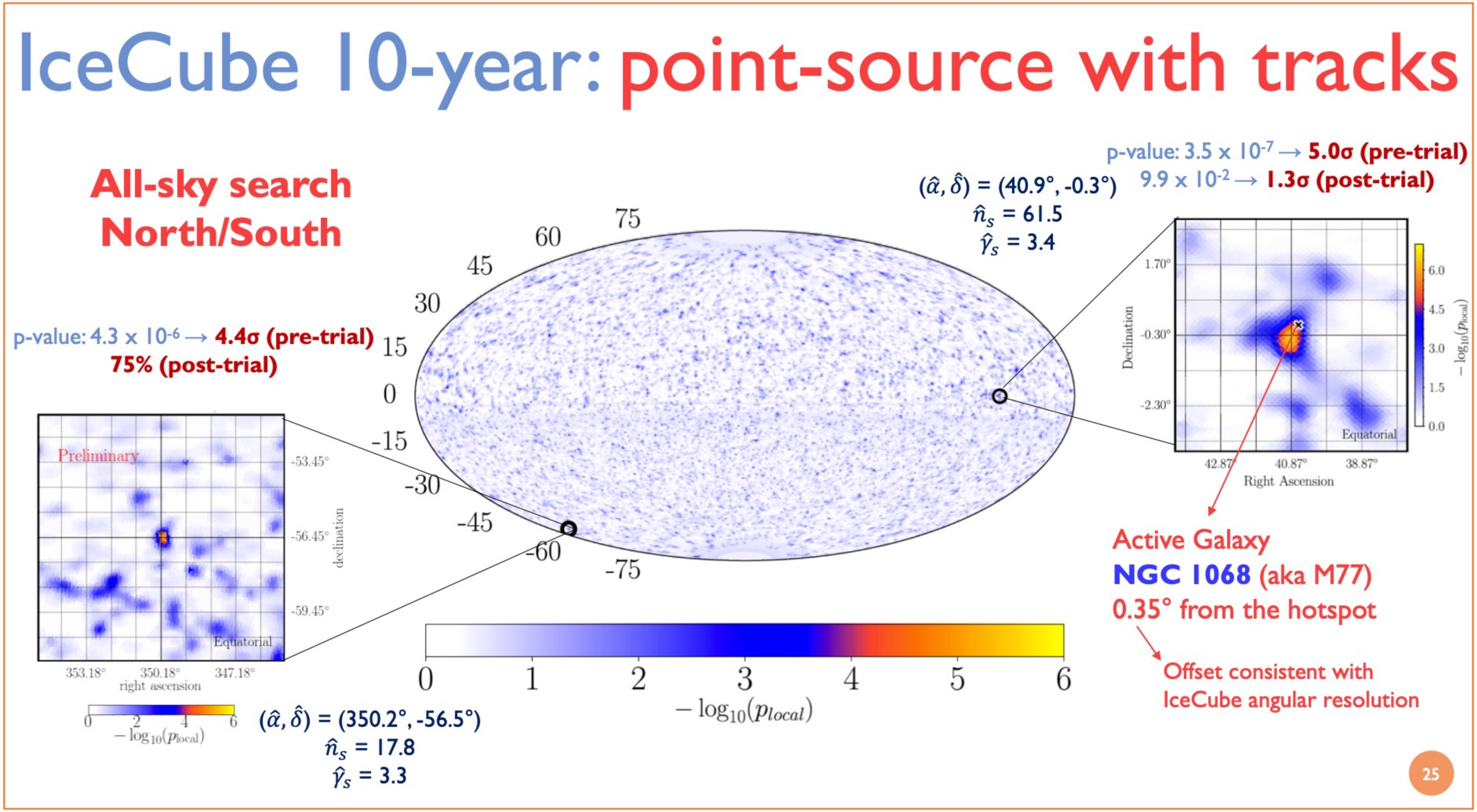


Track event
in a neutrino telescope





Shower/cascade event
in a neutrino telescope


IceCube 10-year: point-source with tracks
All-sky search
North/South
p-value: 4.3 x 10^-6 → 4.4σ (pre-trial)
75% (post-trial)
Preliminary
Equatorial
-53.45°
-56.45°
-59.45°
declination
353.18°
350.18°
347.18°
right ascension
0 2 4 6
− log10(plocal)
(α̂, δ̂) = (350.2°, -56.5°)
n̂s = 17.8
γ̂s = 3.3
75
60
45
30
15
0
-15
-30
-45
-60
-75
0 1 2 3 4 5 6
− log10(plocal)
(α̂, δ̂) = (40.9°, -0.3°)
n̂s = 61.5
γ̂s = 3.4
p-value: 3.5 x 10^-7 → 5.0σ (pre-trial)
9.9 x 10^-2 → 1.3σ (post-trial)
1.70°
-0.30°
-2.30°
Declination
42.87°
40.87°
38.87°
Right Ascension
Equatorial
6.0
4.5
3.0
1.5
0.0
− log10(plocal)
Active Galaxy
NGC 1068 (aka M77)
0.35° from the hotspot
Offset consistent with
IceCube angular resolution
25

IceCube 10-year: point-source with tracks

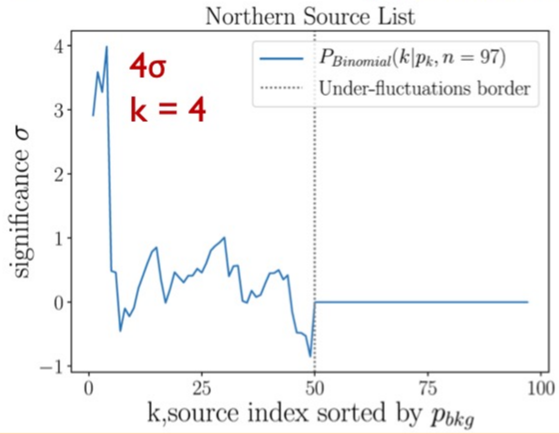
Population study:

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:

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

Number of sources in the catalog (N)

Number of sources with p-value smaller than p_k (k)



Best sources

Ranking	Source	Type	RA	δ	$\hat{n}_s$	$\hat{\gamma}_s$	#σ 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

4σ pre-trial

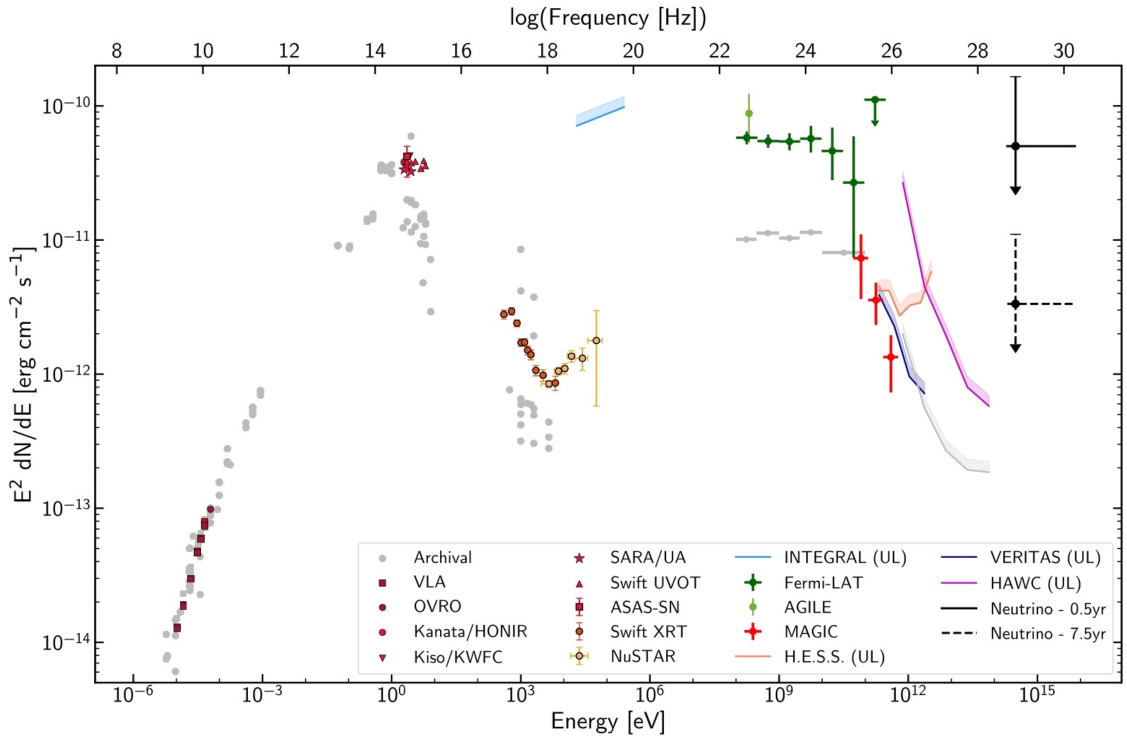
→ **3.3σ post-trial** (2.3σ without TXS 0506+056)

First candidate neutrino source TXS 0506+056

First neutrino source candidate TXS 0506+056

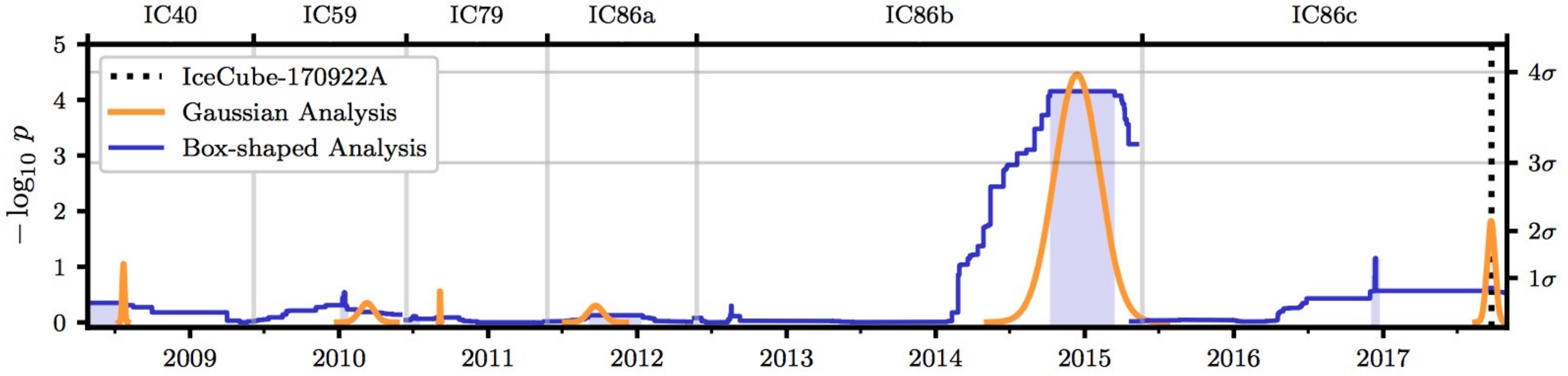
- Blazar TXS 0506+056 is Fermi source, one of 50 bright sources , but not in first 20.
- Icecube event: IceCube-170922A Sept 22 2017
- TXS 0506+056 has redshift z=0.3365
- MAGIC detected flair Sept 28 2017
- Fermi detected activity of source in the same period.

TXS 0506+056 multi-messenger



IceCube collab 1807.08794

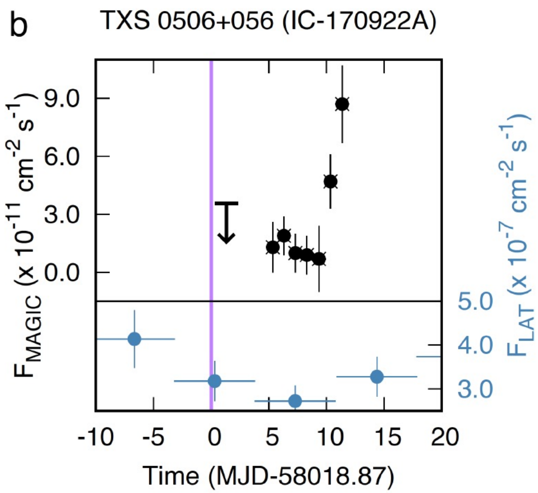
TXS 0506+056 neutrino flair 3 sigma



IceCube collab 1807.08794.

TXS 0506+056 multi-messenger

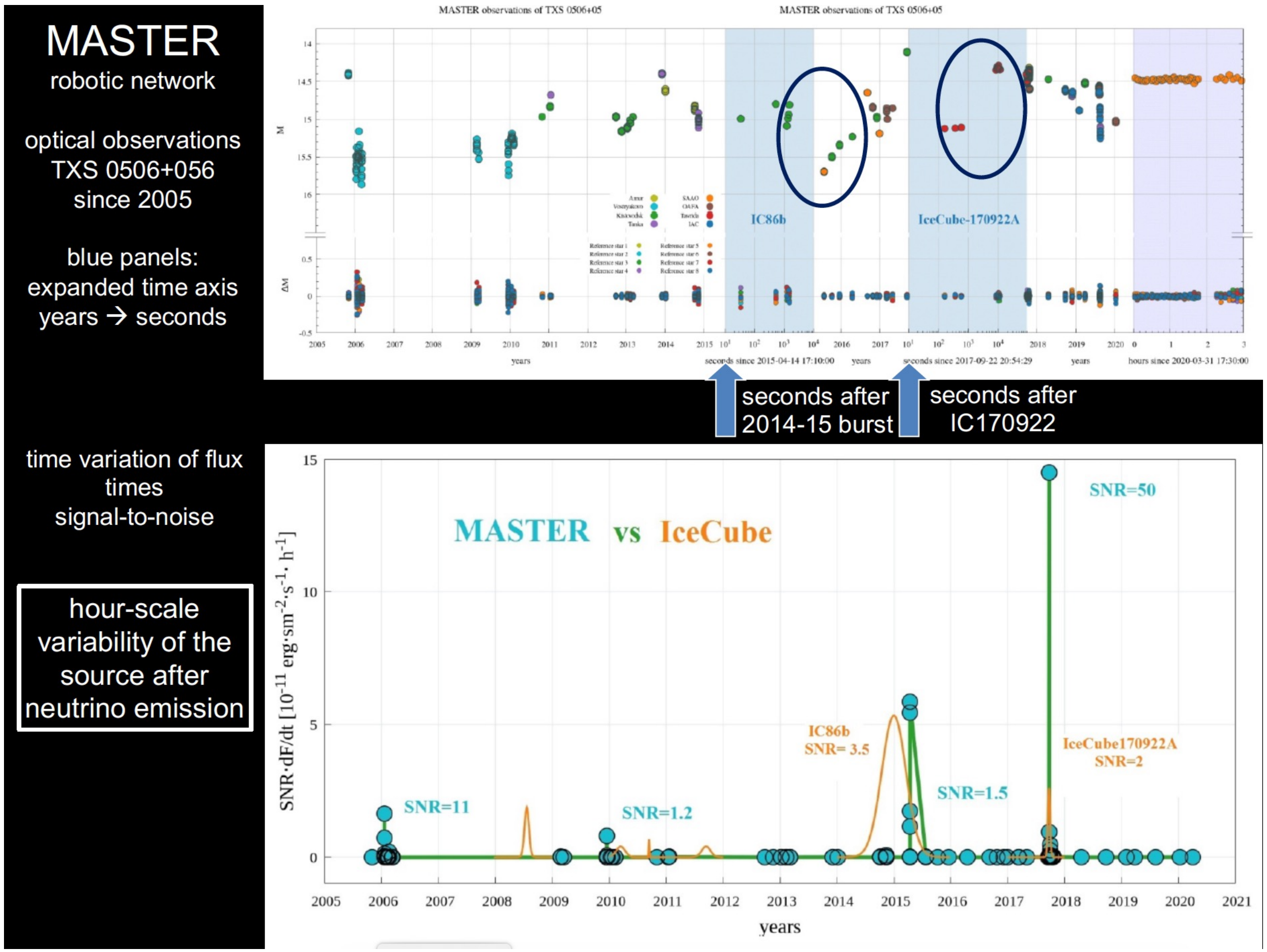
no TeV gamma rays at the time the neutrino



- 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

F.Halzen talk Paris Dec 2020

TXS 0506+056 multi-messenger



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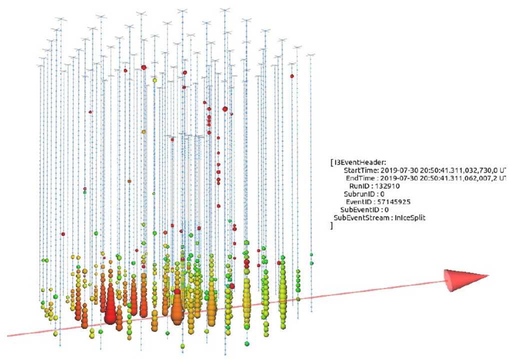
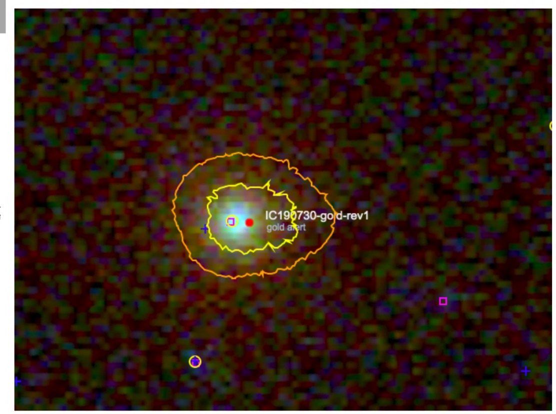
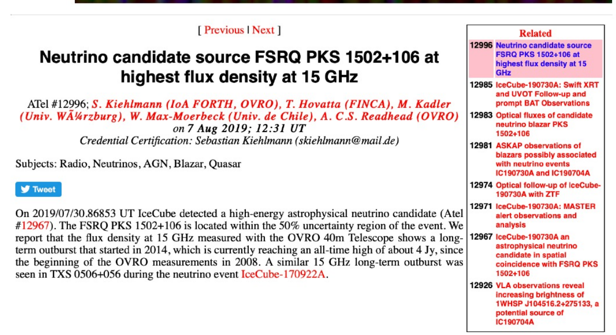
PKS 1502+106

a second cosmic ray source





IC 190730: 300 TeV
- coincident with PKS 1502+106
- radio burst



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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. WÃ¼rzburg), 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

Tweet

On 2019/07/30.86853 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 fluxes 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 1WHSP J104516.2+275133, a potential source of IC190704A

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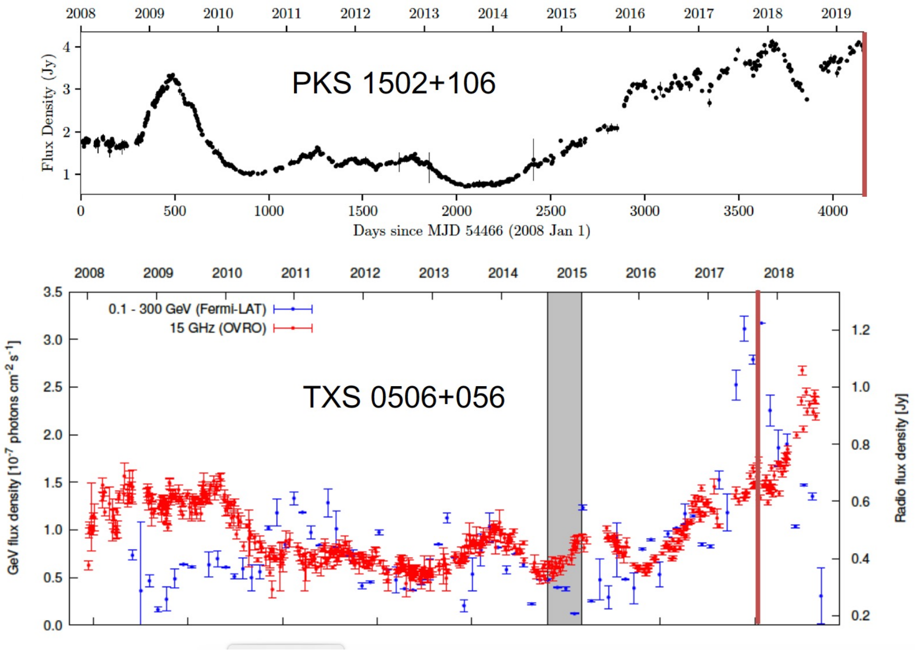
TXS 0506+056 multi-messenger

the two highest energy (300 TeV ν_μ) IceCube neutrino alerts are coincident with radio flares



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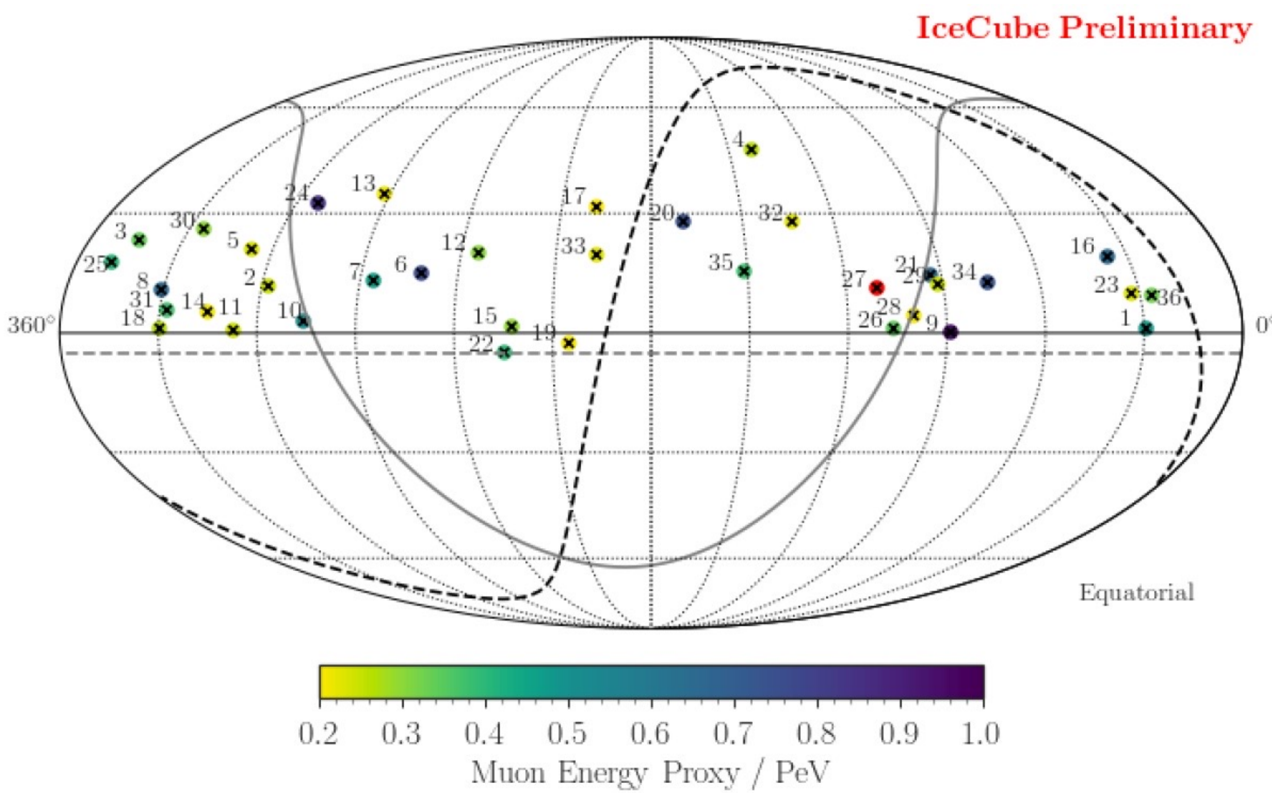
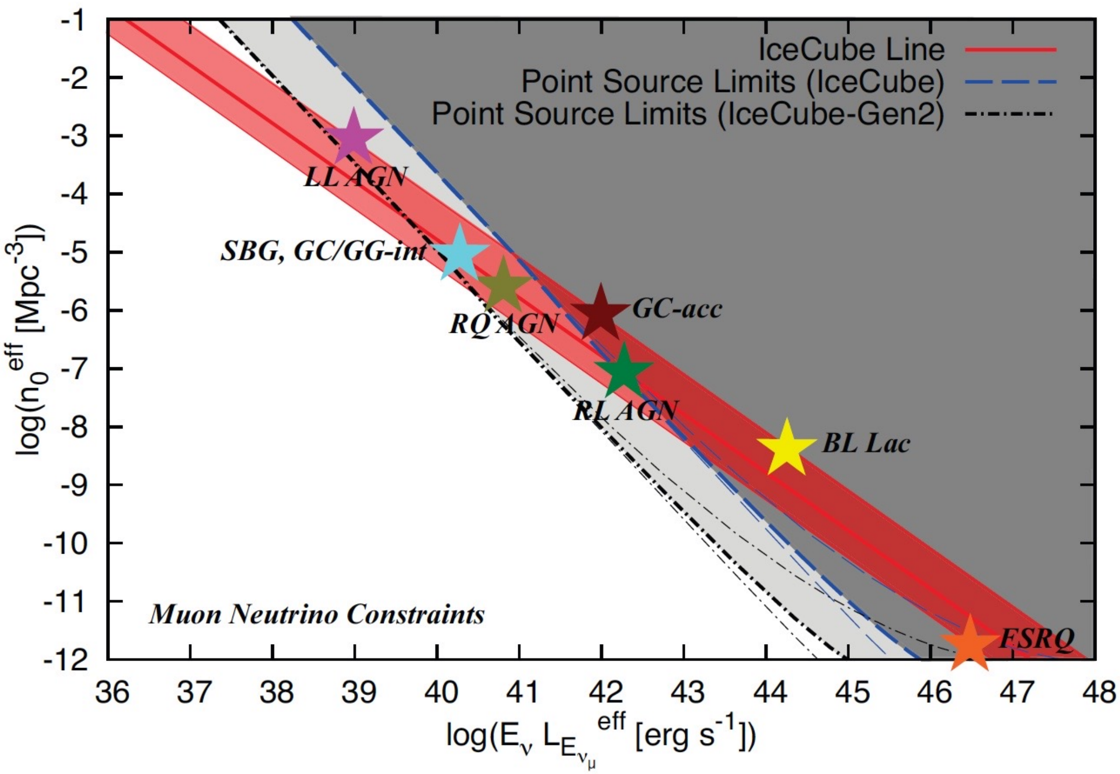
Bright neutrino sources

Icecube 8 years muon neutrinos



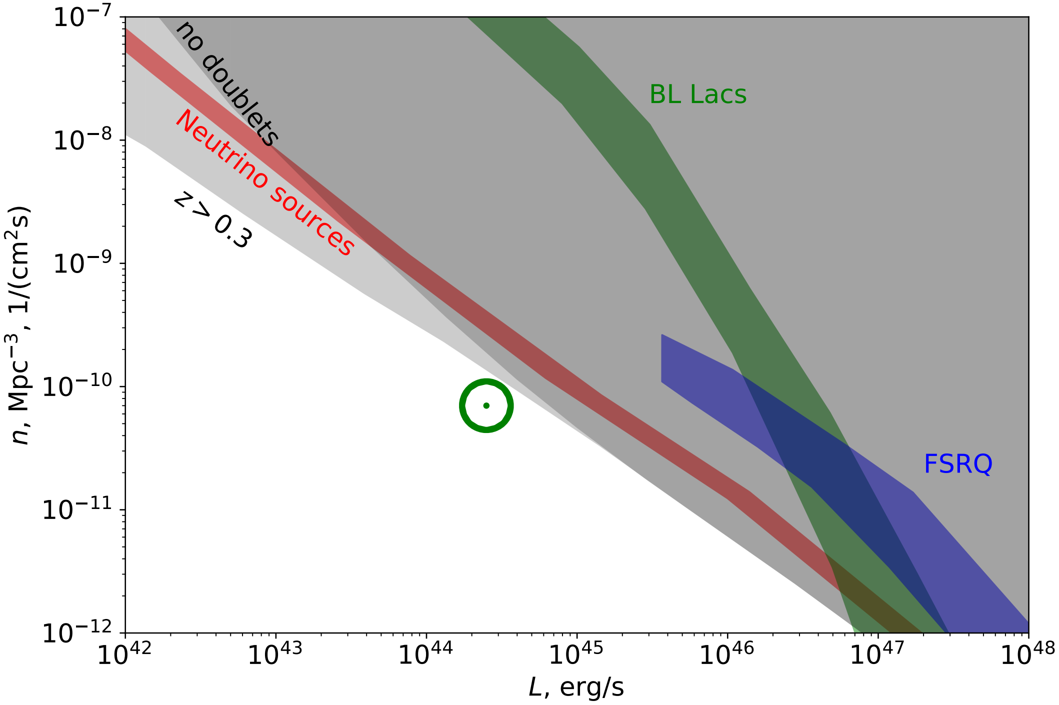
IceCube ICRC 2017

No doublets put limit on density of sources



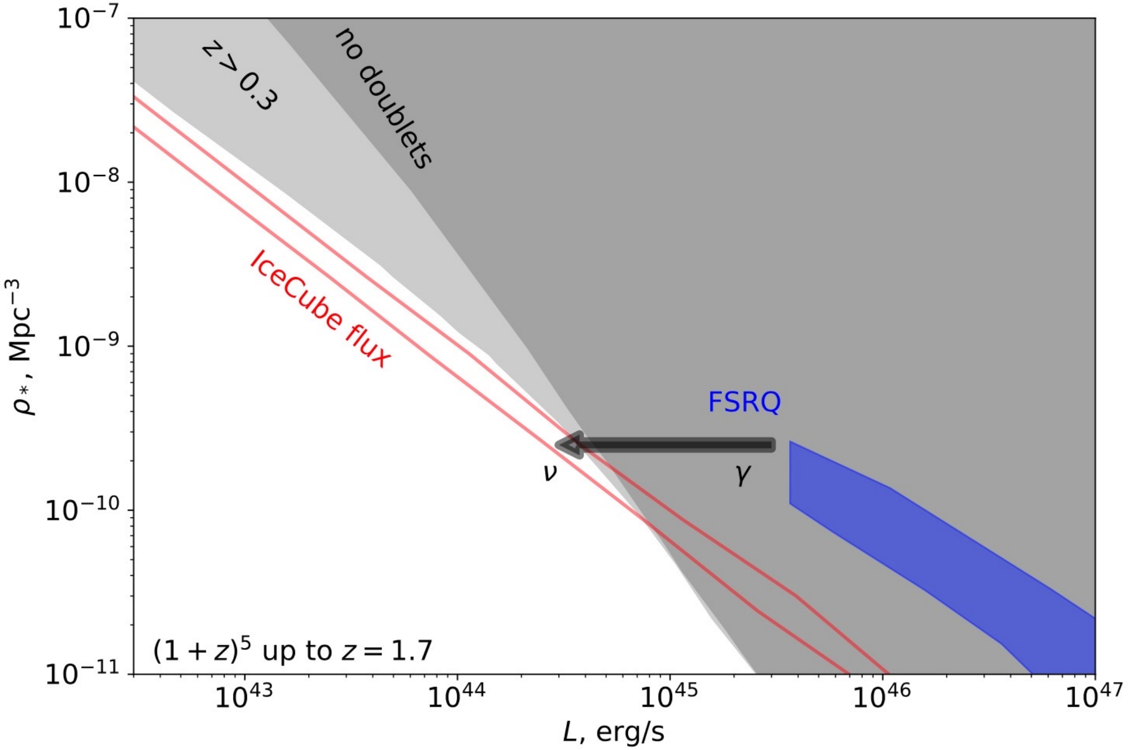
K.Murase, E.Waxman, 1607.01601

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

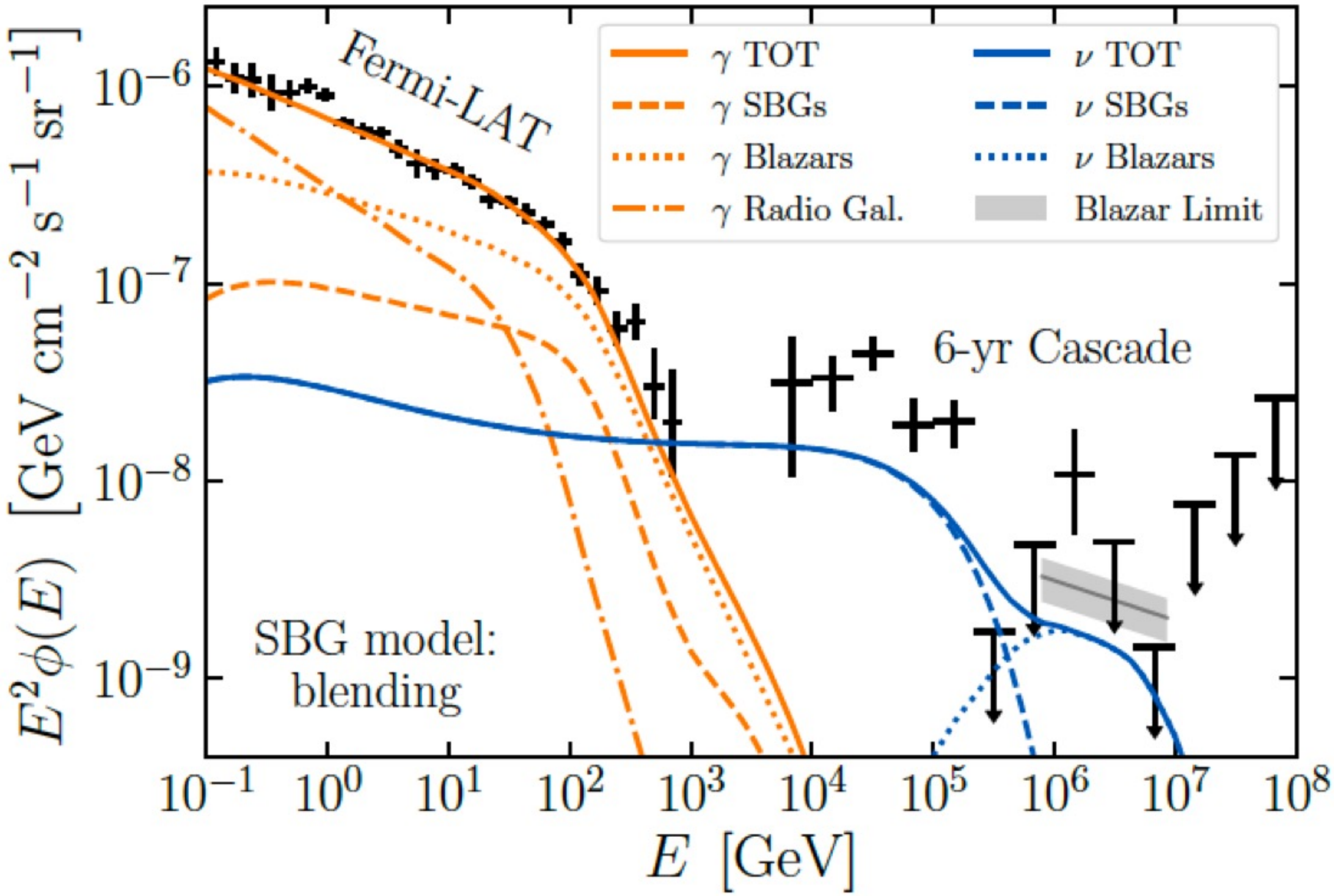


A.Neronov, D.S 1811.06356

Source populations searches

Star Burst Galaxies 1%

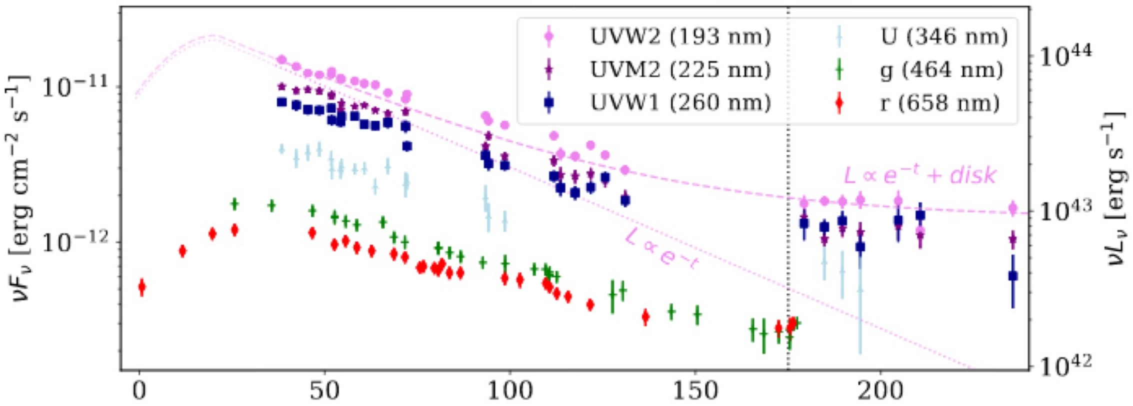
ArXiv:2011.02483



Tidal disruption event 0.5%

IC191001A + AT2019dsg

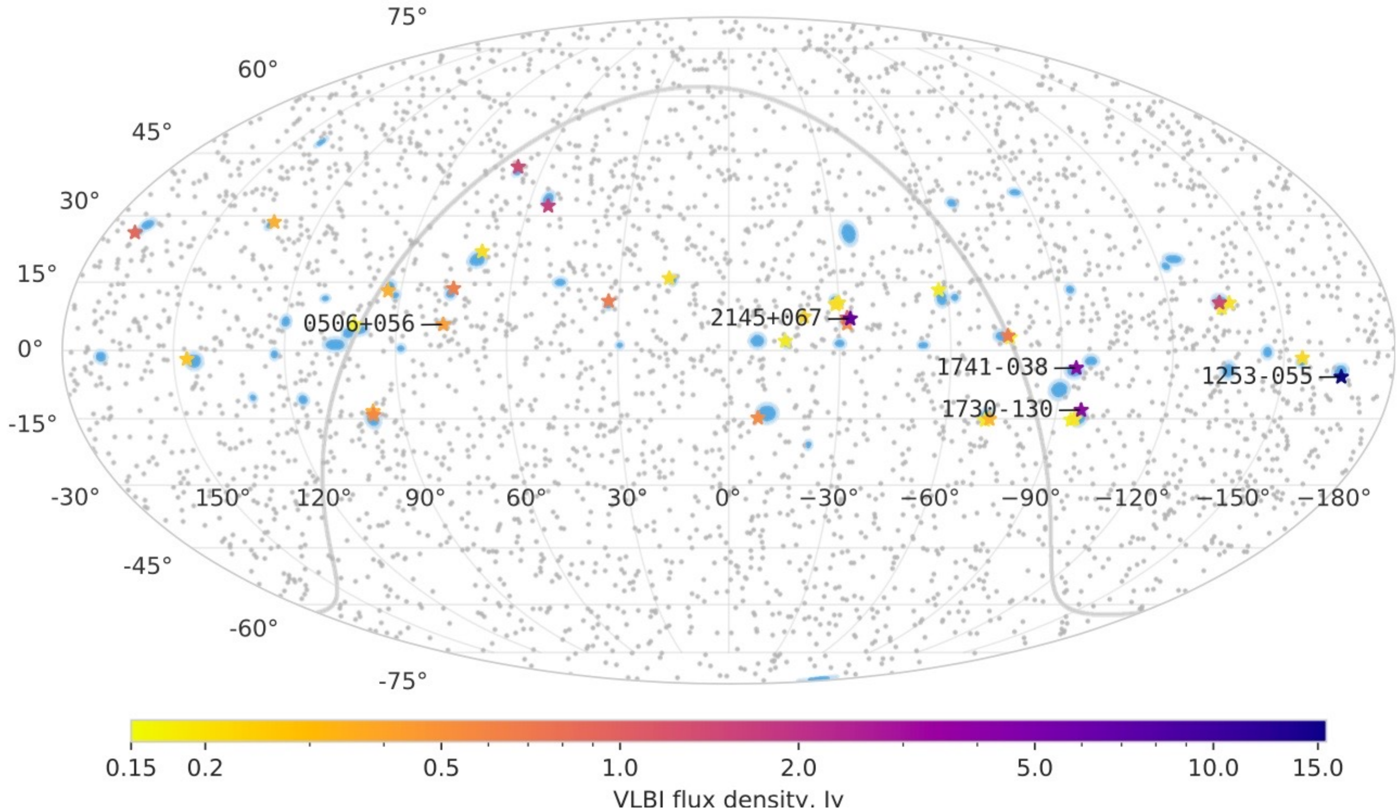
https://arxiv.org/abs/2005.05340



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

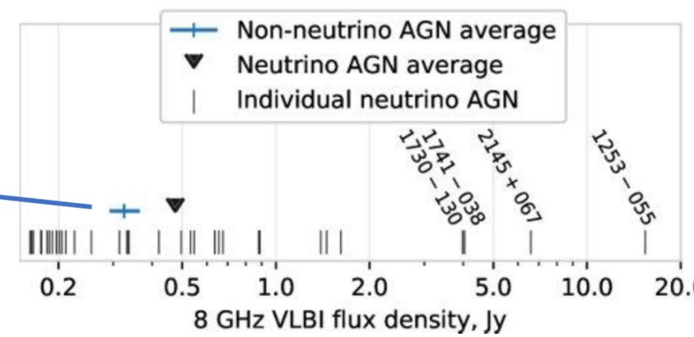
Testing hypothesis:

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

(Plavin+2020)

Result: yes, this correlation is present! ⇒ Neutrinos are emitted by blazars!

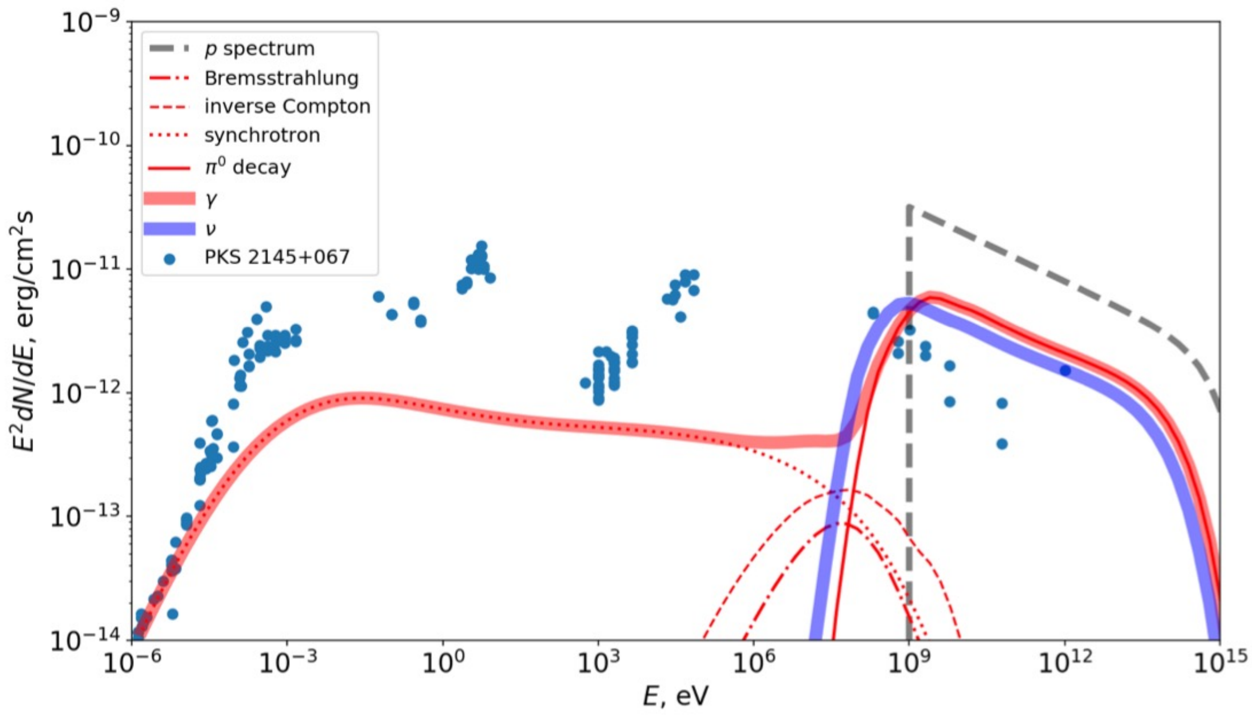
Events ≥ 200 TeV: p-value = 0.2%
Test: blazars within neutrino error regions are brighter than average.



Lower energies, likelihood map: p-value = 0.3%
Test: higher than average IceCube likelihoods in the directions of blazars

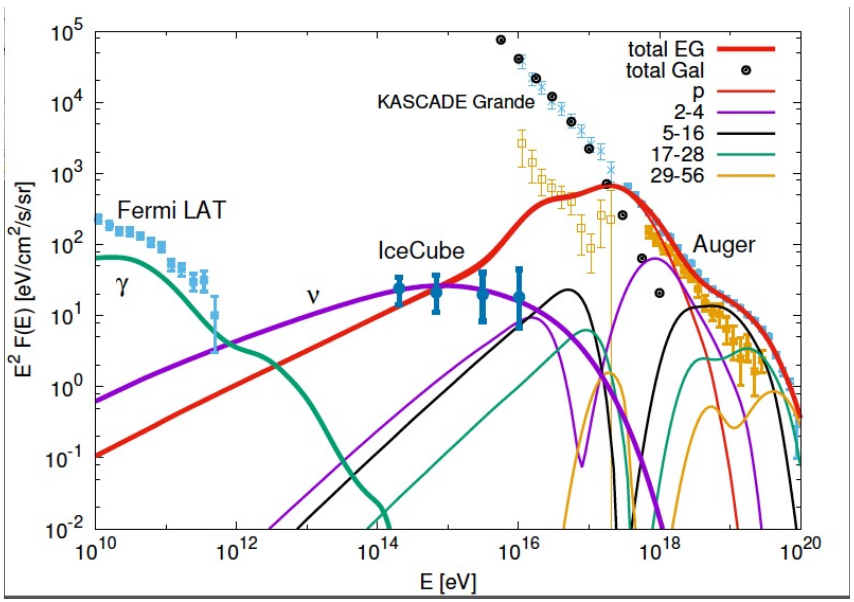
Combined: p-value = 4×10^{-5}, 4.1σ

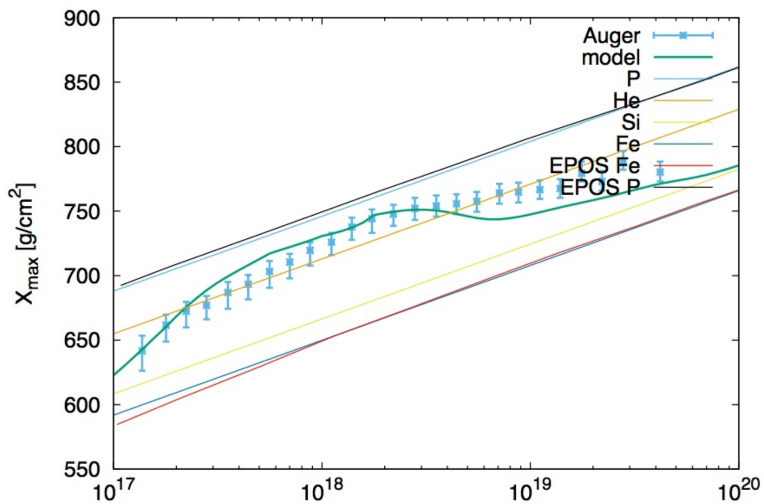
P-P in jet can produce radio flux connected with protons

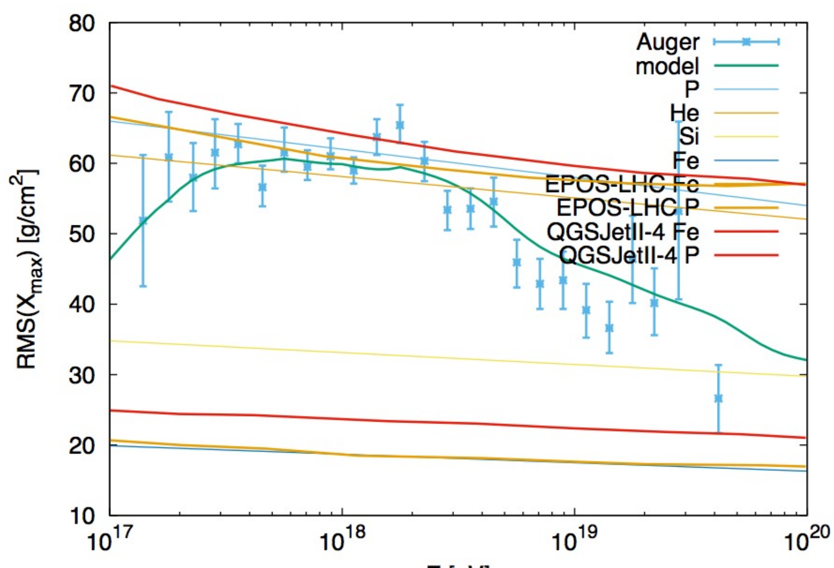


Neronov and DS, JETP Lett, arxiv: 2012.04425

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



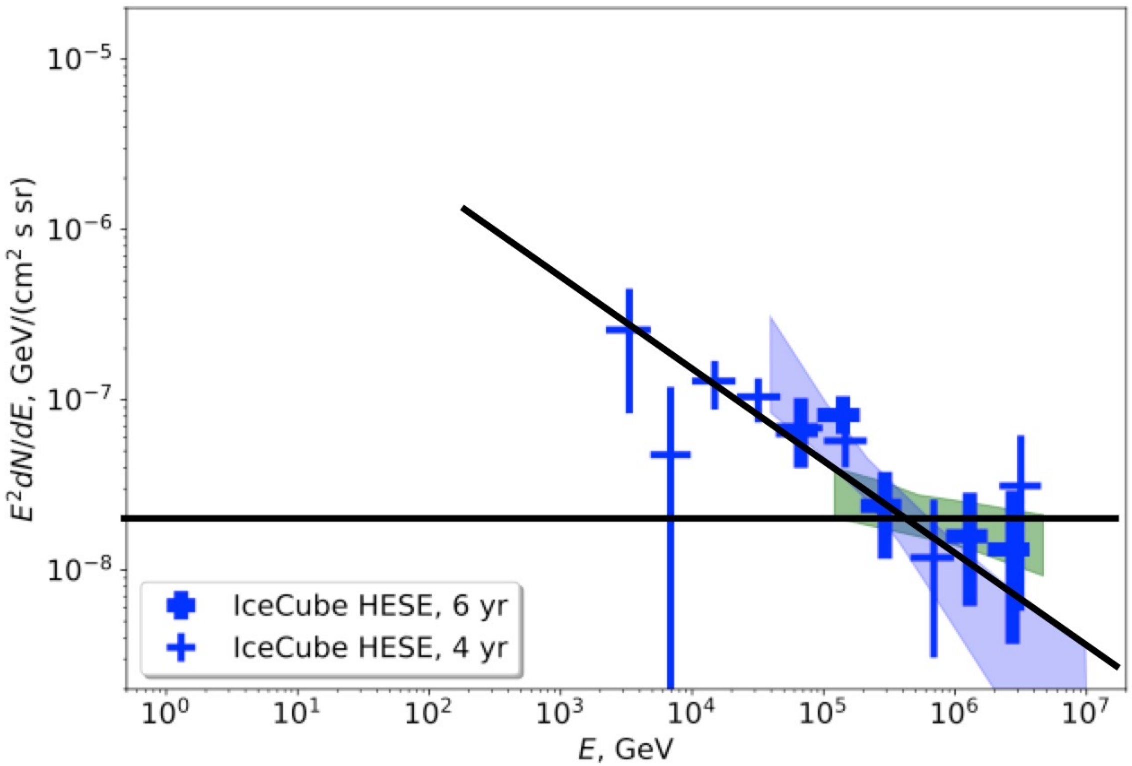




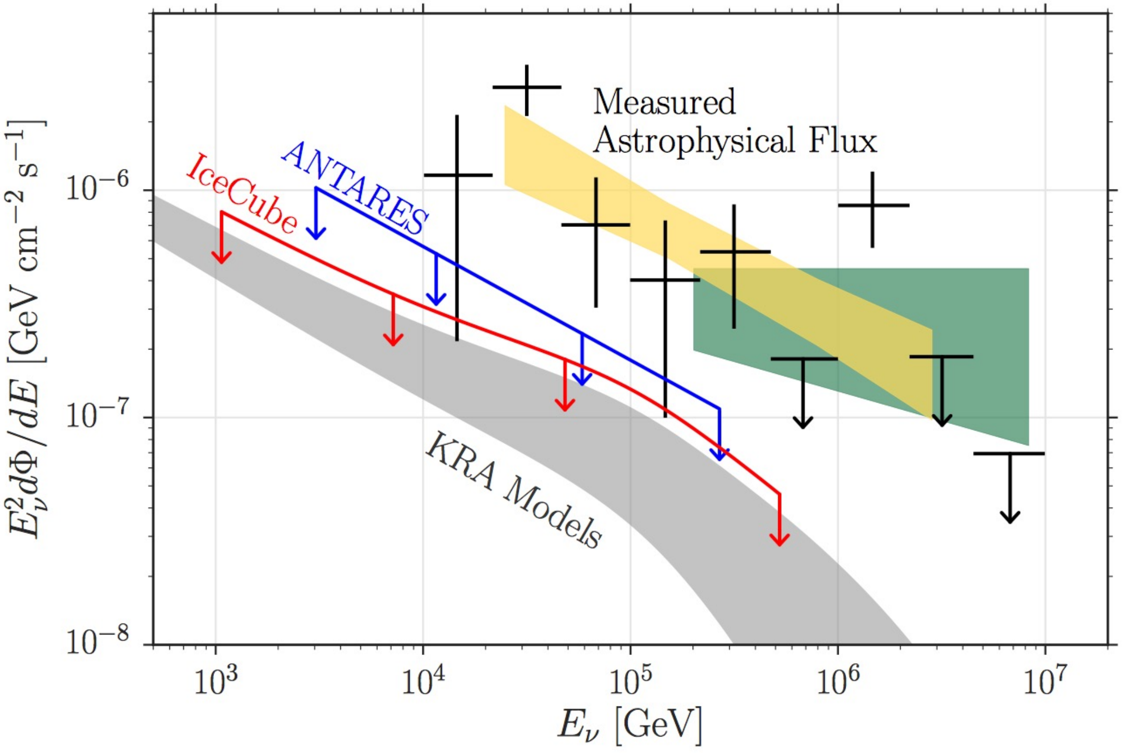
M.Kachelriess, O.Kalashev, S.Ostapchenko and D.S., 1704.06893

Low energy excess

IceCube data

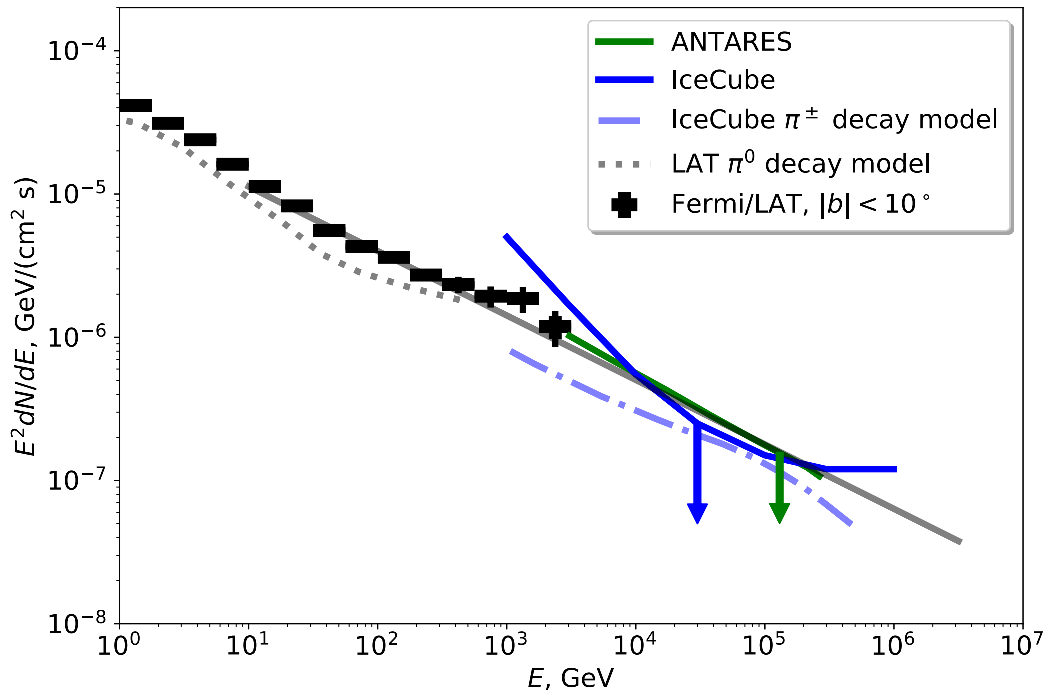


IceCube and ANTARES galalactic plane



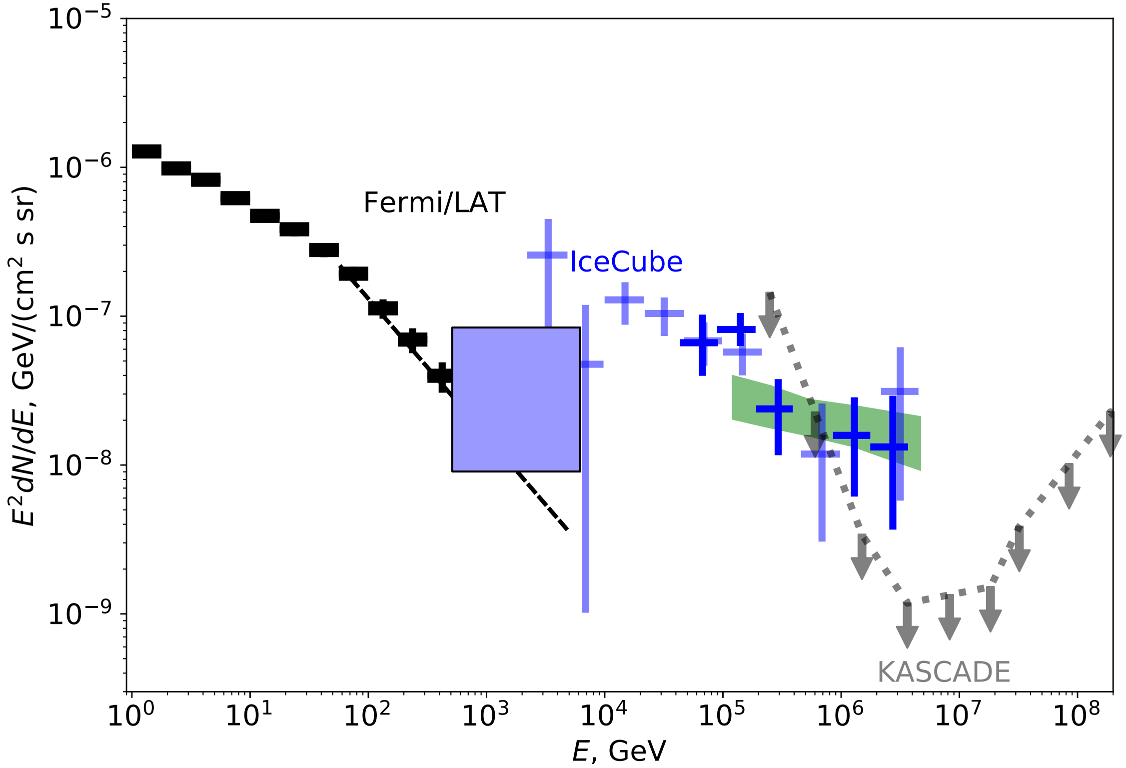
ICRC 2017

IceCube + Fermi LAT Galactic plane



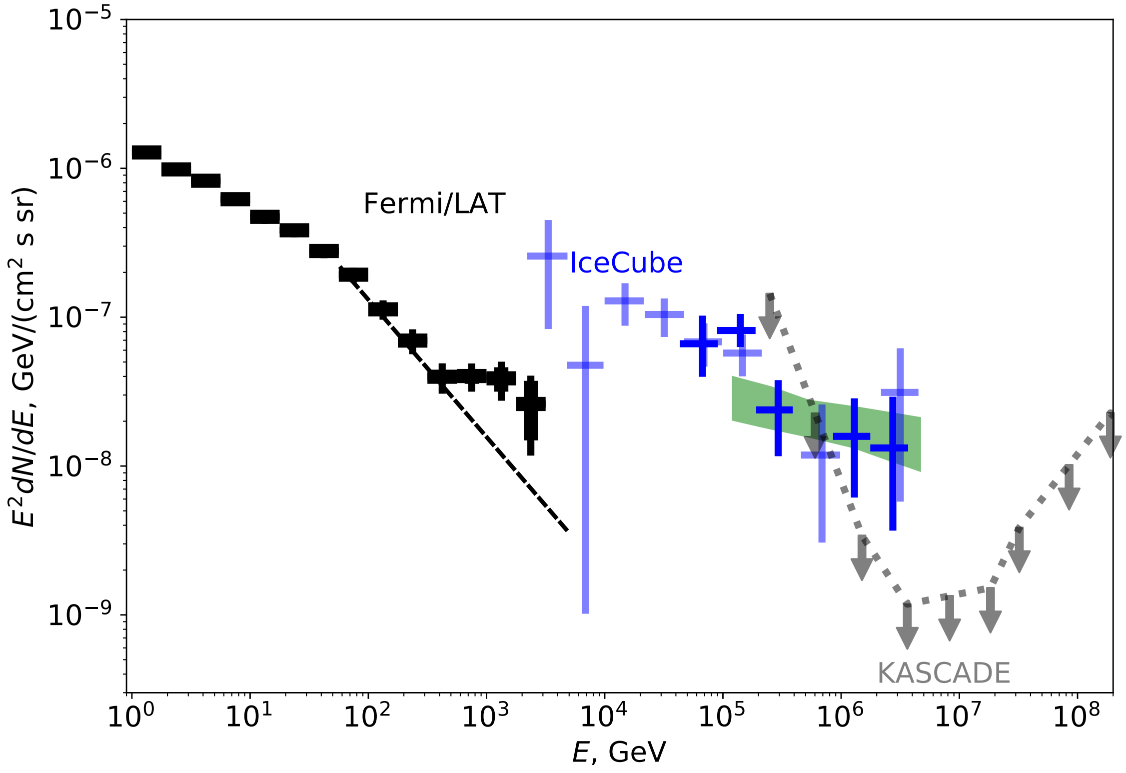
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

IceCube + Fermi LAT high galactic latitude ÌbÌ>20 deg



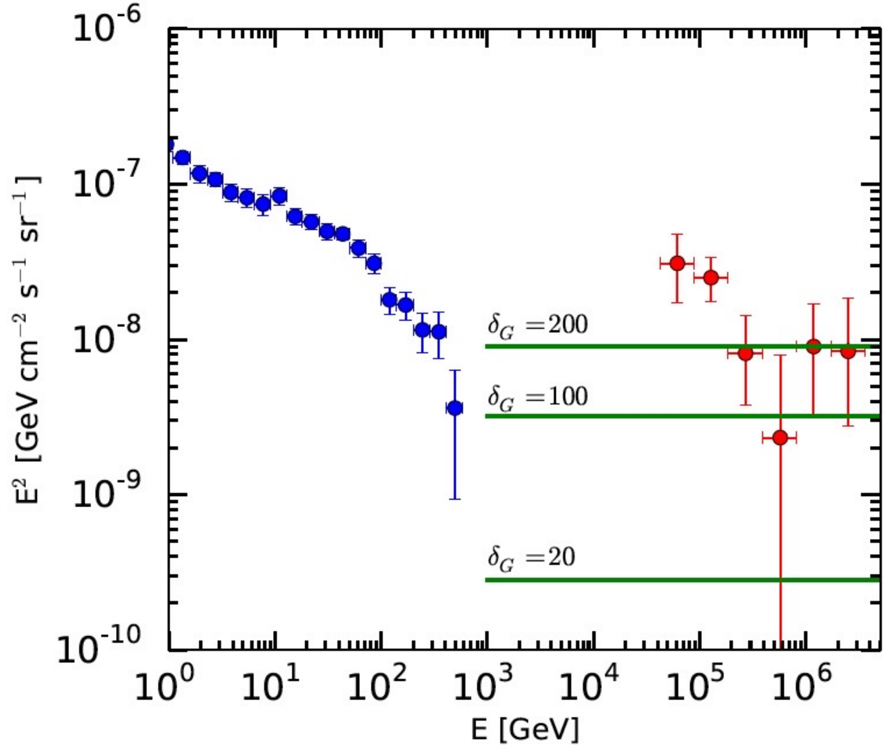
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

IceCube + Fermi LAT high galactic latitude ÌbÌ>20 deg



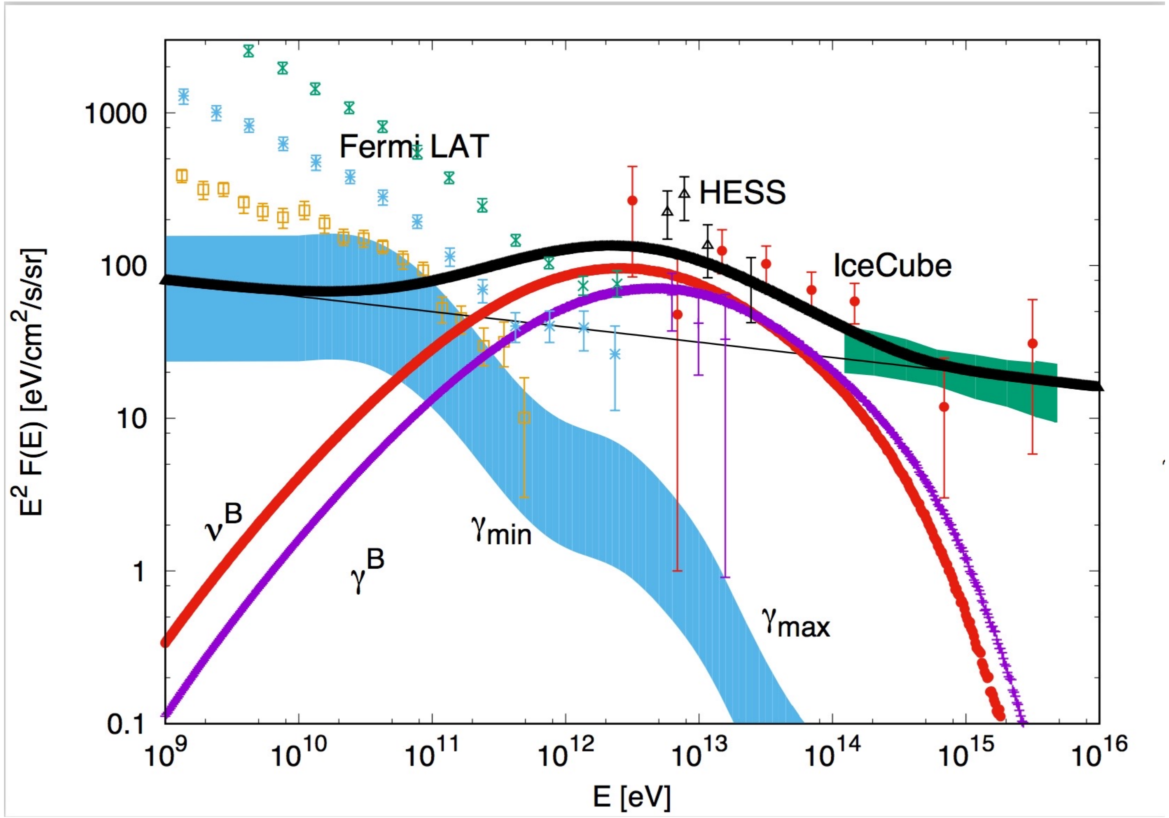
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

Neutrinos from cosmic ray interactions in Galactic Halo



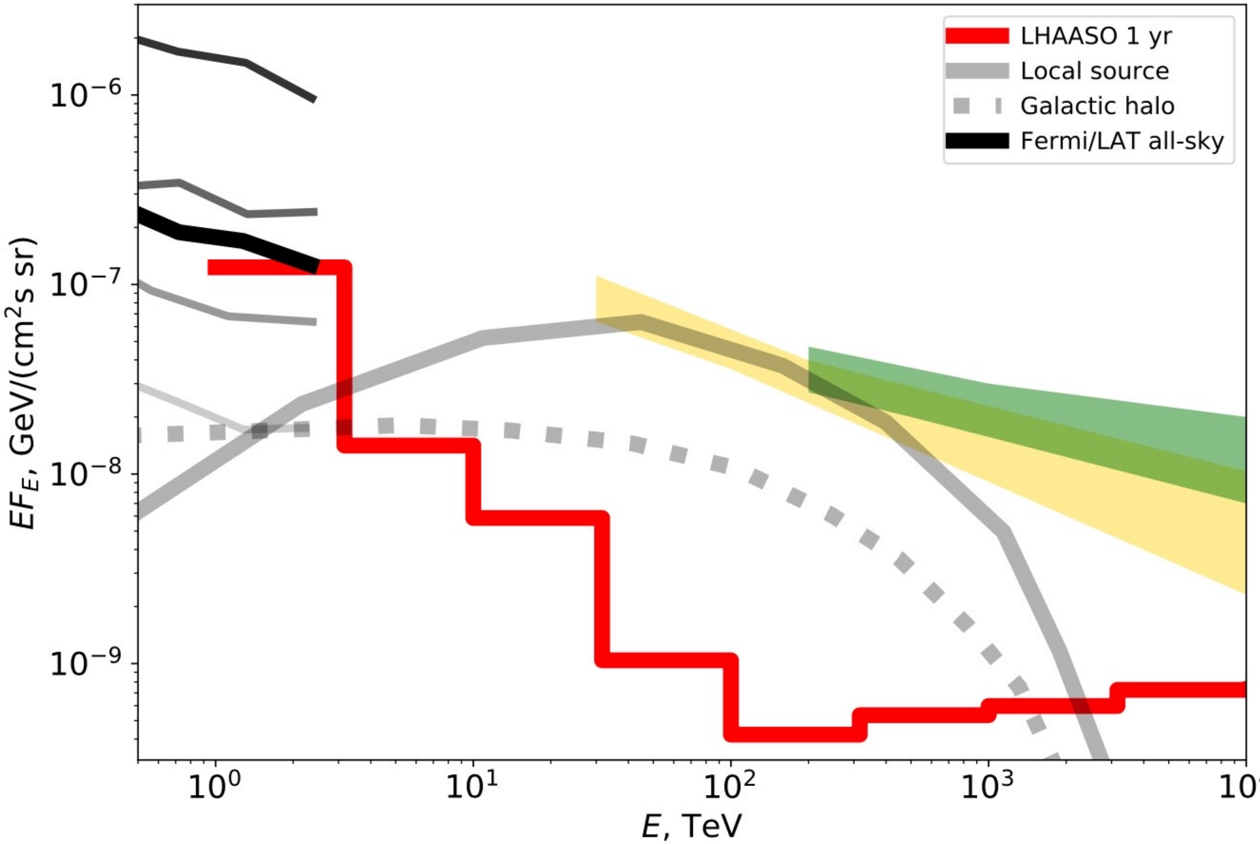
A.Taylor, S.Gabici and F.Aharonian, 1403.3206
P.Blasi and E.Amato , 1901. 03609

IceCube + Fermi LAT+HESS : local source



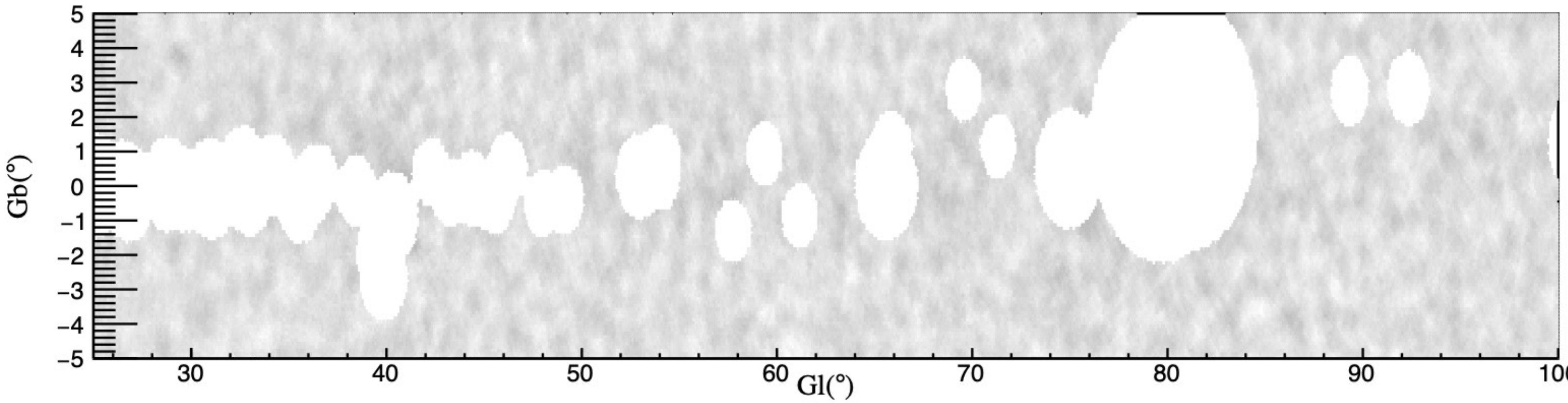
M.Bouyahiaoui, M.Kachelriess and D.S. , arXiv:2001.00768

LHAASO sensitivity Local SuperBubble and Galactic Halo



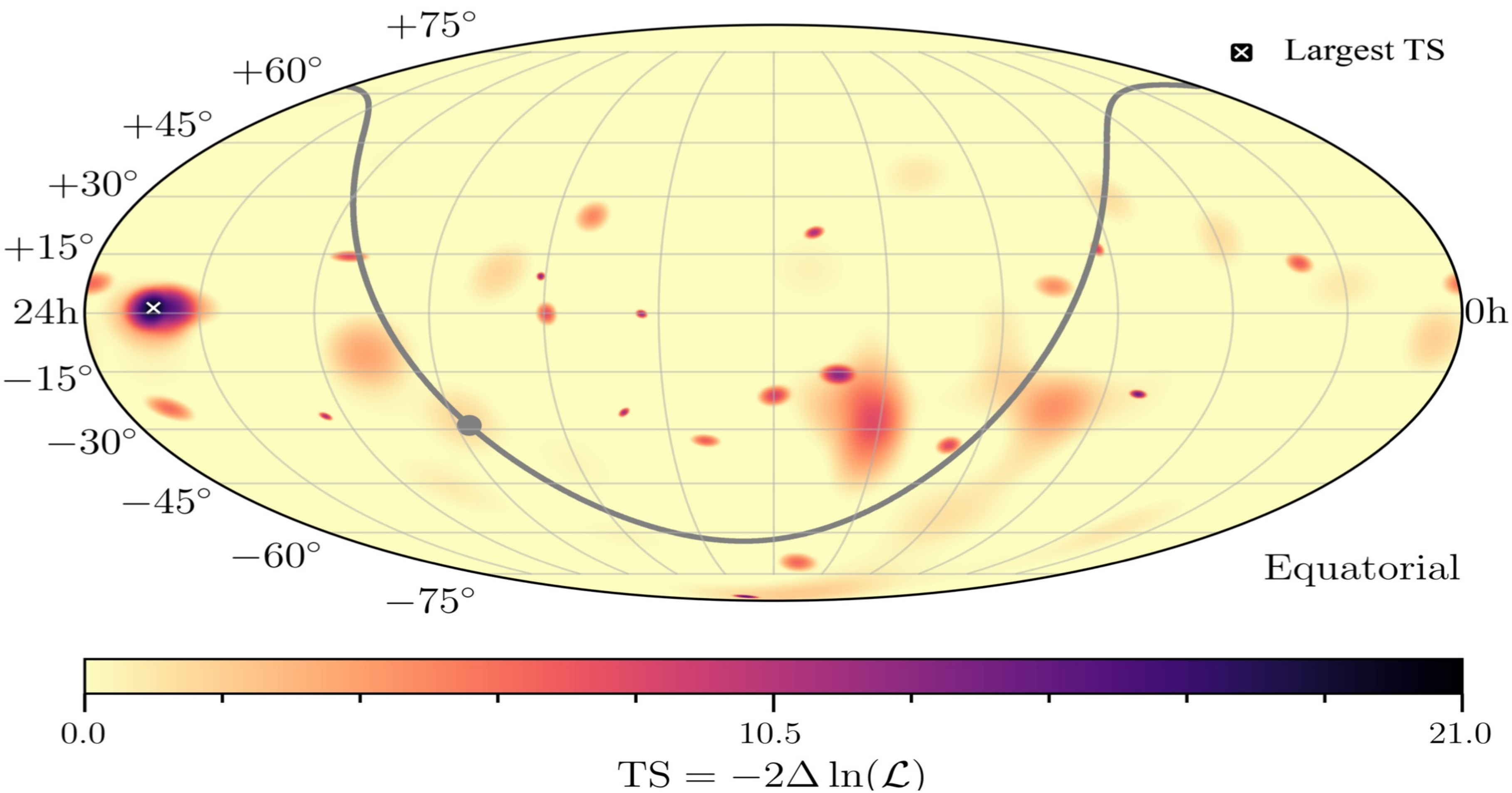
A.Neronov and D.S. , astro-ph/2001.11881

LHAASO cut sources



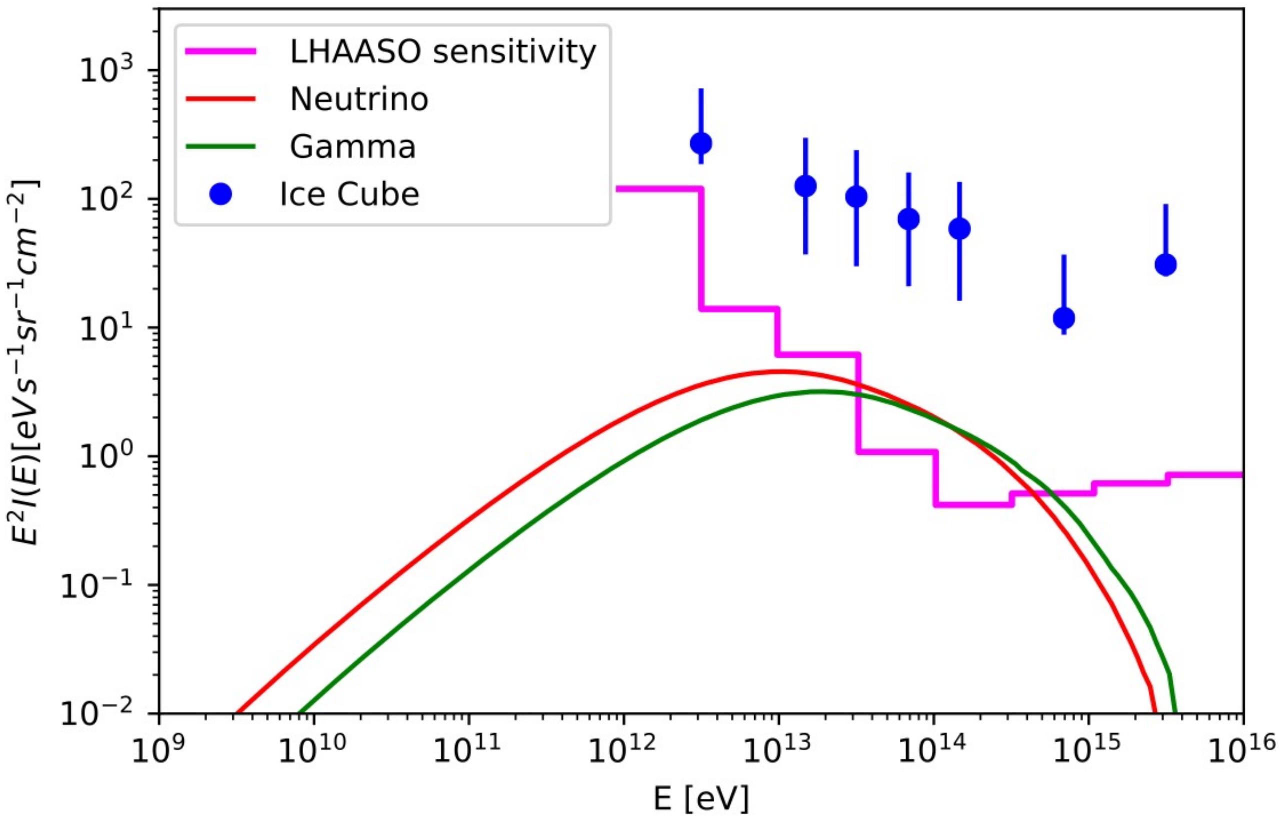
LHAASO talk ICRC Jul 2021

Sky map HESE 7.5 years



IceCube, astro-ph/2011.03545

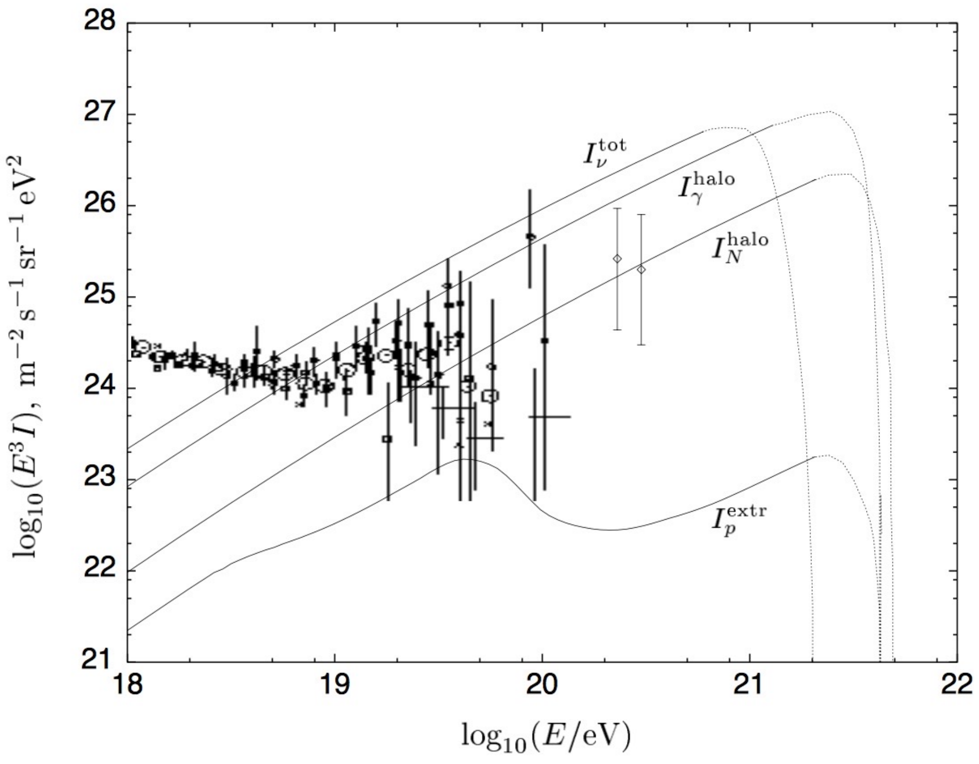
Cygnus loop neutrinos



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

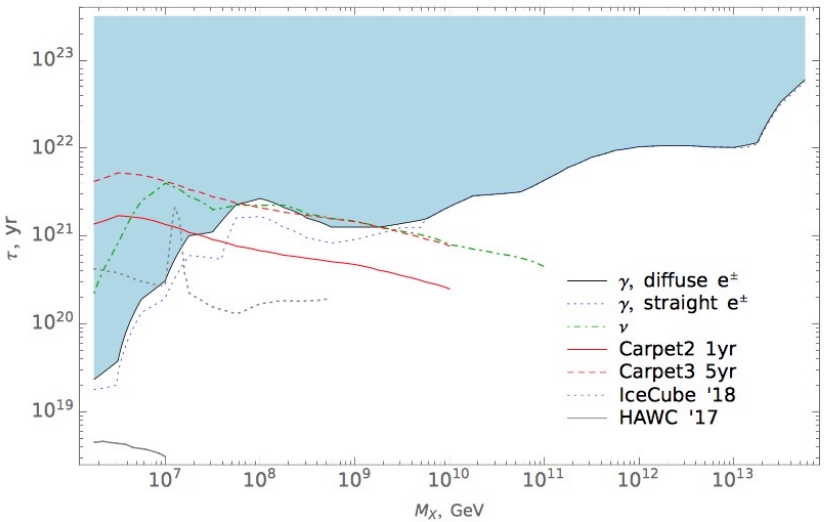
Super-Heavy Dark Matter

For SHDM galactic flux dominates in neutrinos and gamma-rays

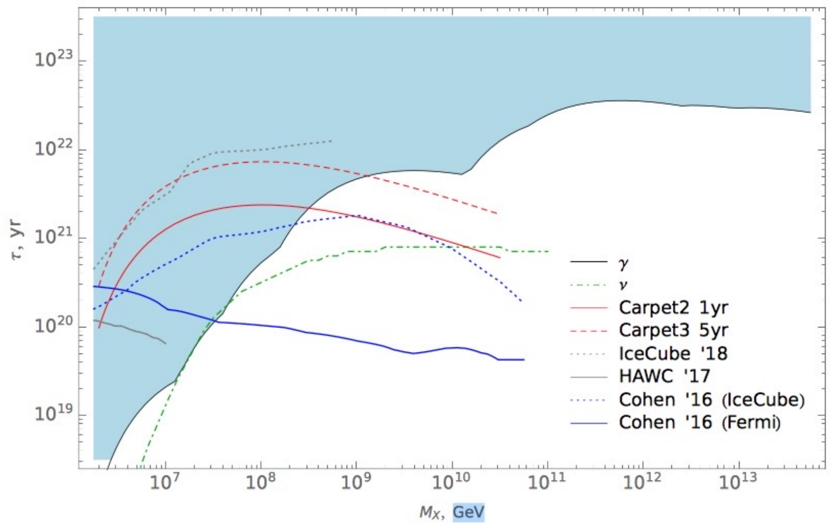


V.Berezinsky, M.Kachelriess and A.Vilenkin, 1997
V.Kuzmin and V.Rubakov, 1998

Modern constraints on SHDM



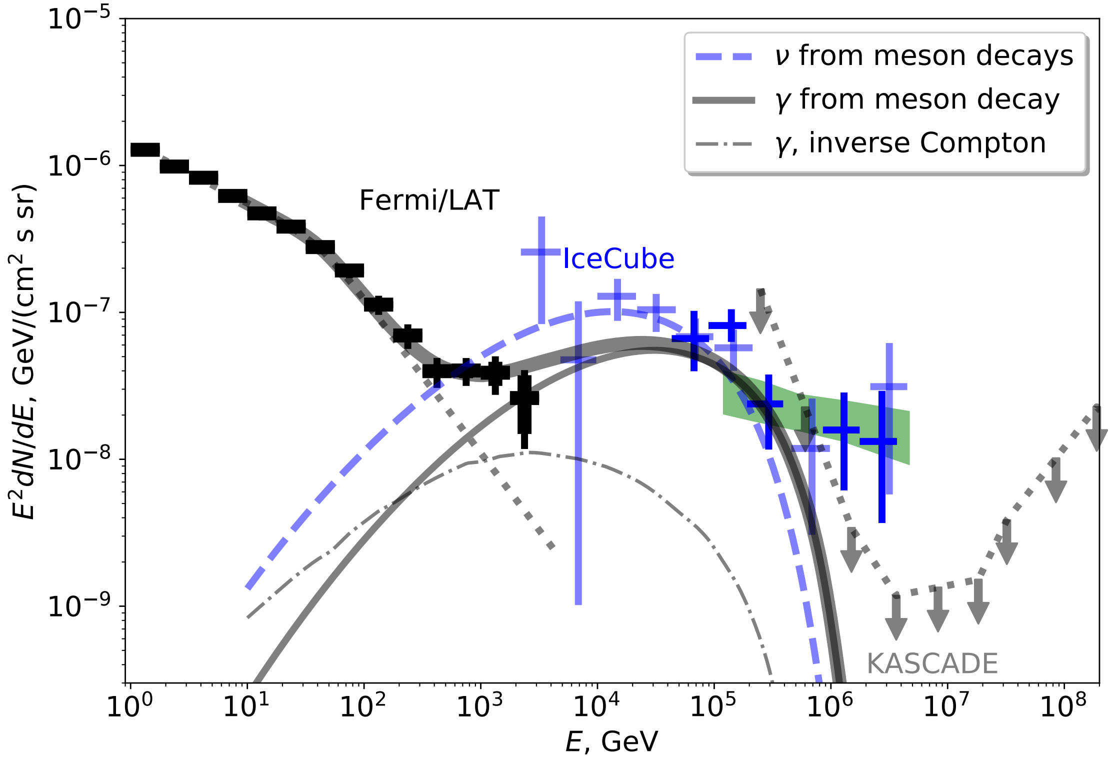
(a) $X \to \nu\bar{\nu}$



(b) $X \to q\bar{q}$

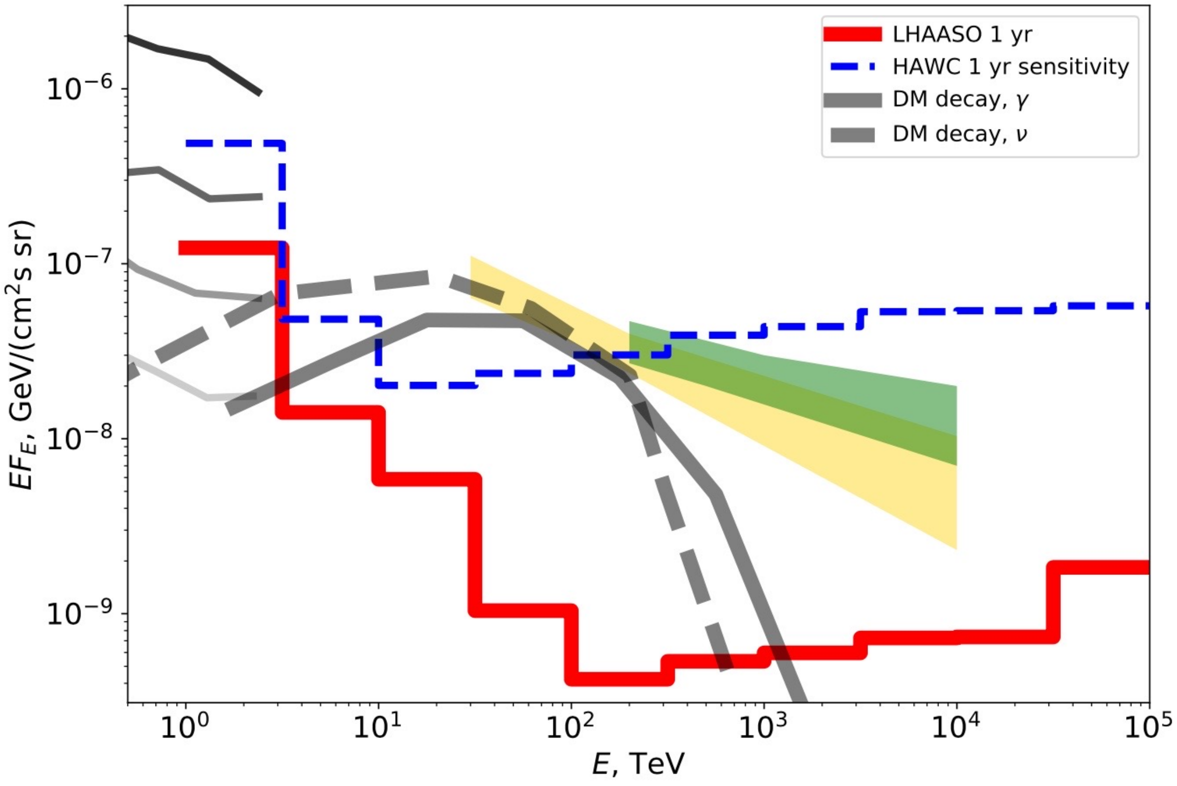
M. Kachelriess, O. E. Kalashev and M. Yu. Kuznetsov, 1805.04500

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-km3 detectors are needed to find first point sources*

Summary

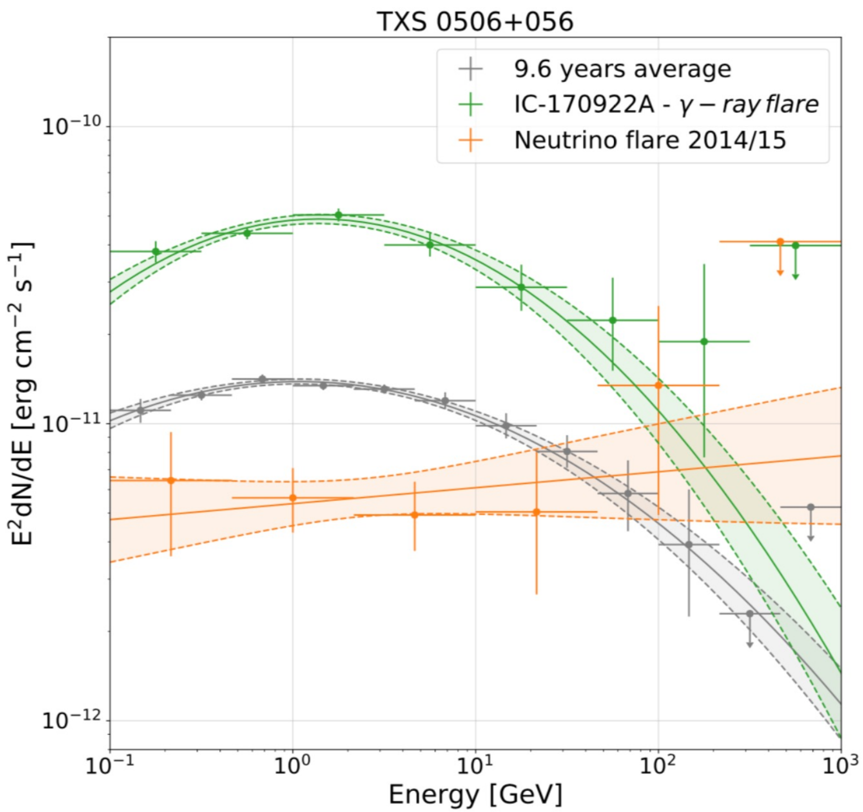
- *Astrophysical neutrino flux with power law $1/E^{2.5}$ was surprise to theoreticians.*
- *Galactic to extragalactic transition is around 10 PeV in protons, i.e. one expects both contributions for 1 PeV neutrinos*
- *We have clear pp signal in Fermi gamma-rays all the way up to 10 TeV. This signal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

SEMINAR

TXT 0506+056



1 erg =0.624 TeV =6.24e11 eV

E^2 F(E) = 6 eV/cm^2/s
EF(E) =6 (eV/E) /cm^2/s

N=EF(E)*A*T

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

N(100 TeV) =$2*10^4$ /km^2/yr

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

Neutrino detection

Neutrino cross section:

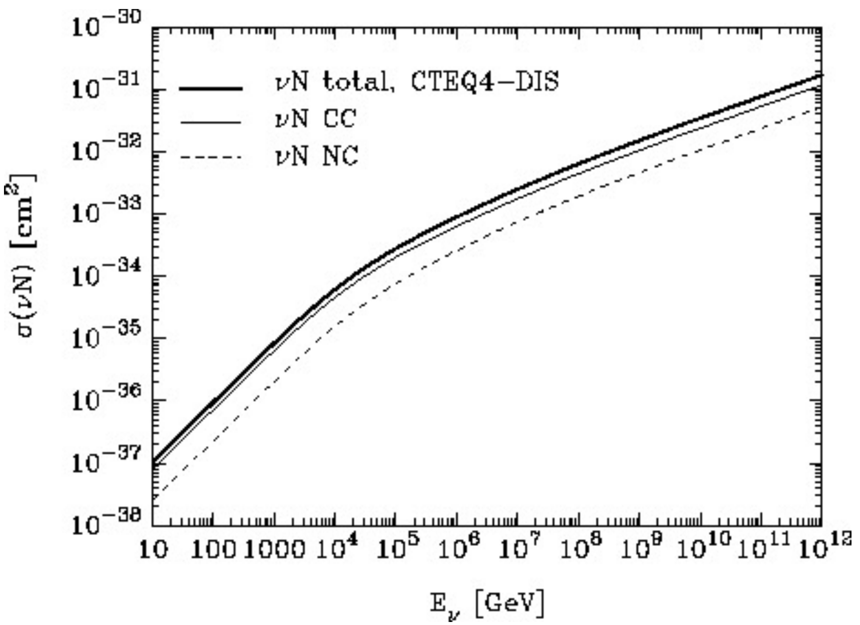
$$\sigma_{\nu p}(100\ TeV) = 3\cdot 10^{-34}\, cm^2$$

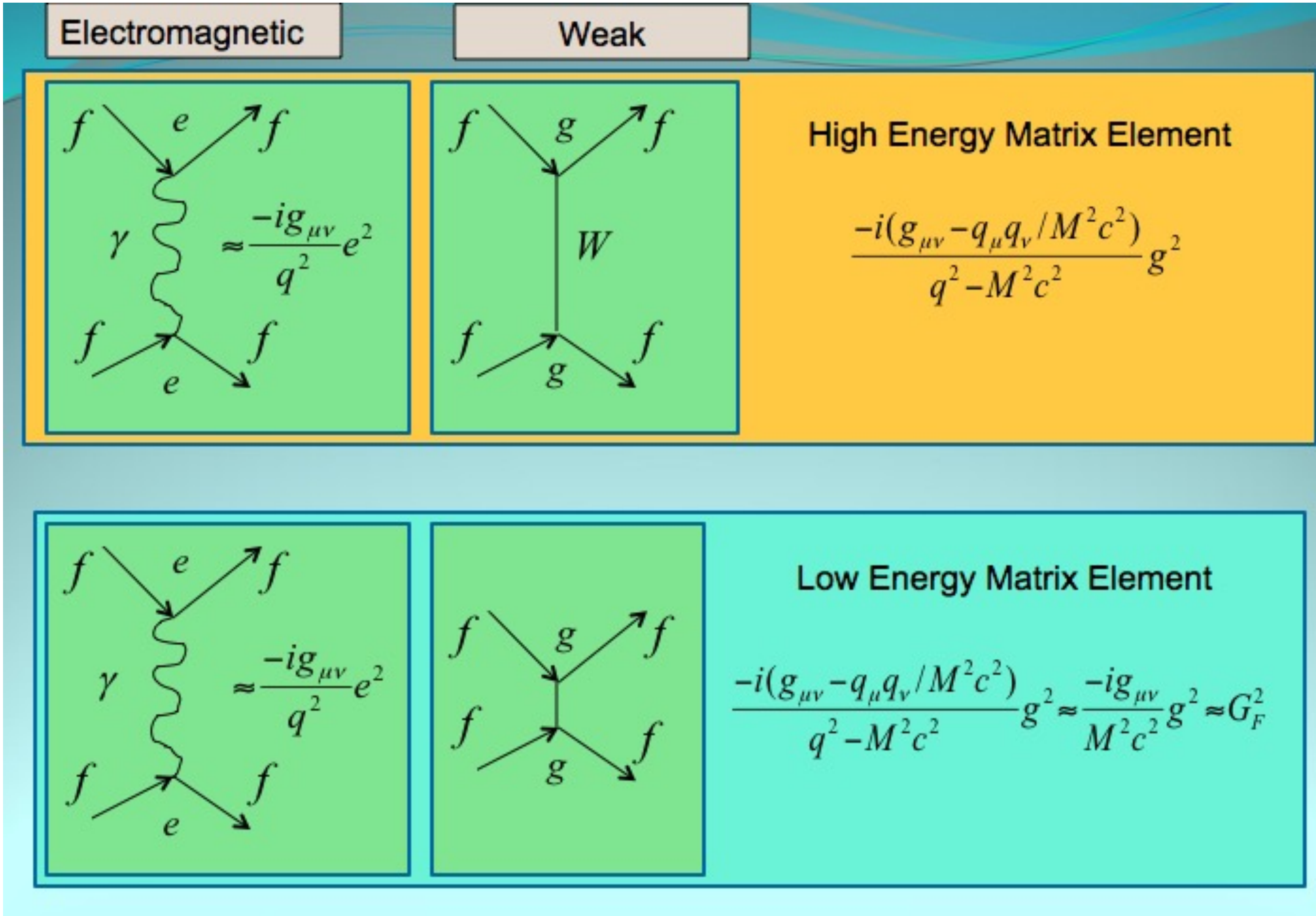
Optical depth: which fraction of neutrinos interact near/in detector:

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

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

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




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

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:

$$N_\nu \sim 0.6 / km^2 / yr$$