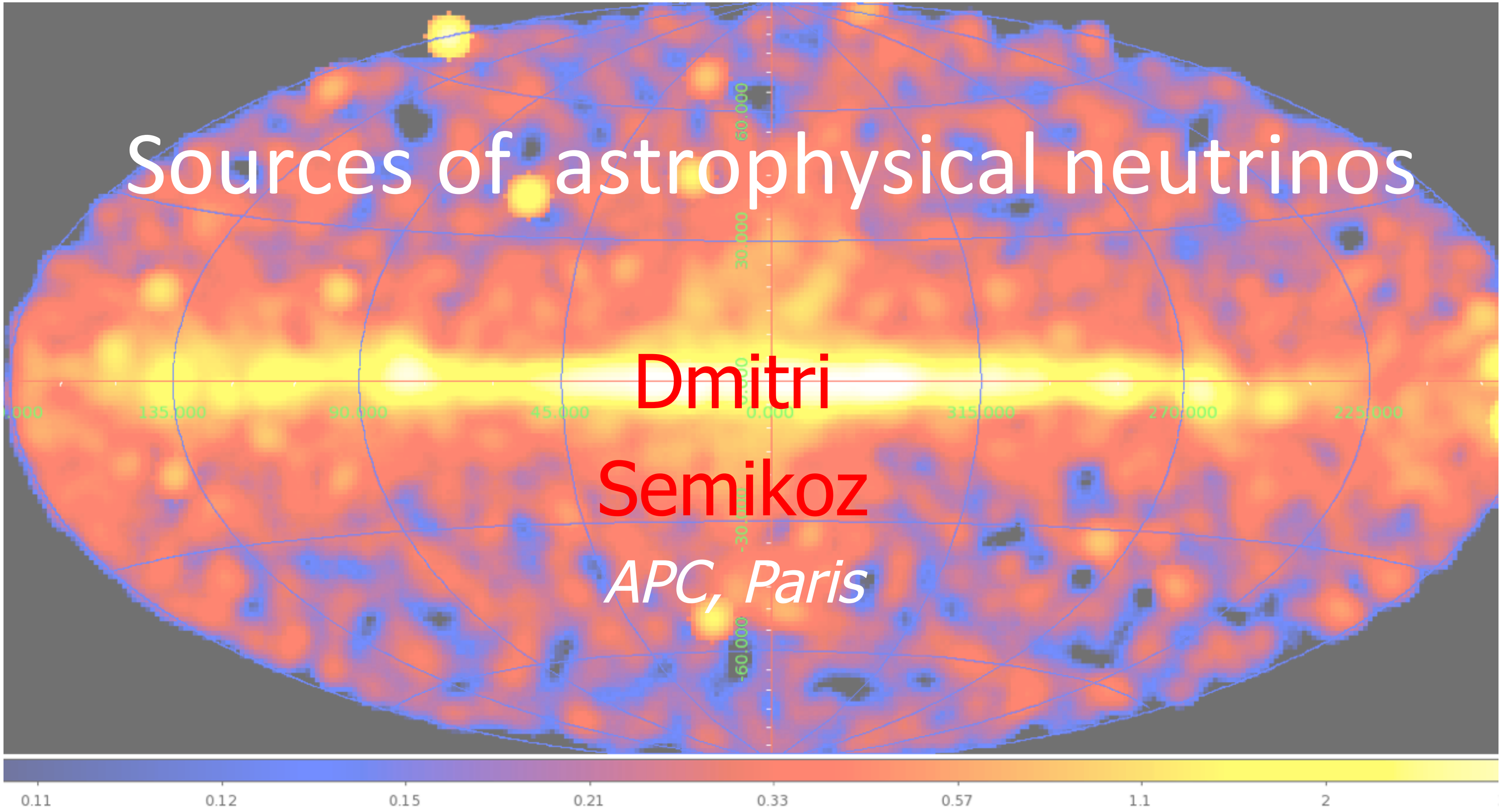
Sources of astrophysical neutrinos



Dmitri

Semikoz

APC, Paris

Overview:

- *Introduction: discovery of astrophysical neutrinos*
- *Future detectors: GVD, km3, upgrade of IceCube*
- *Galactic magnetic field*
- *Galactic cosmic rays*
- *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: BL Lacs, starburst*
- *New information from 6 years of muon neutrino data*
- *Conclusions*

INTRODUCTION

Pion production

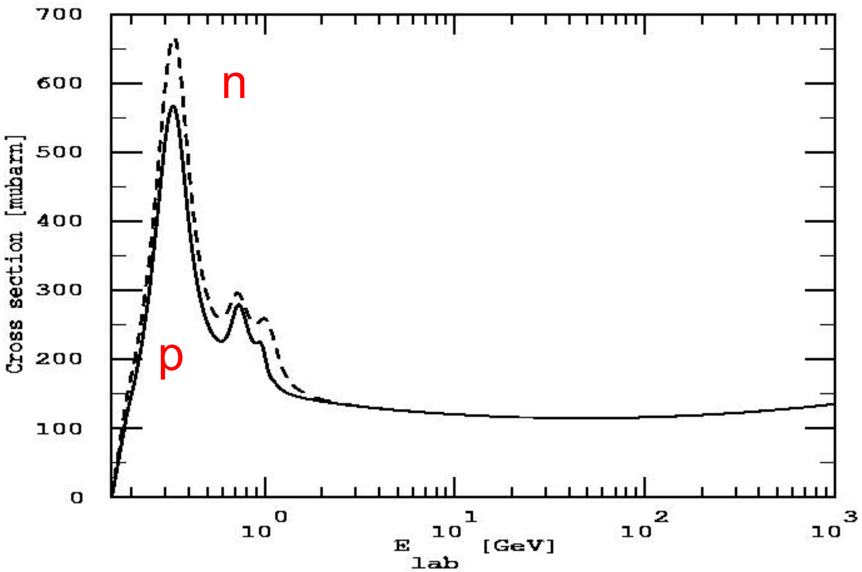
$$N+\gamma_b \Rightarrow N' + \sum \pi^i$$

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

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

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

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



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

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

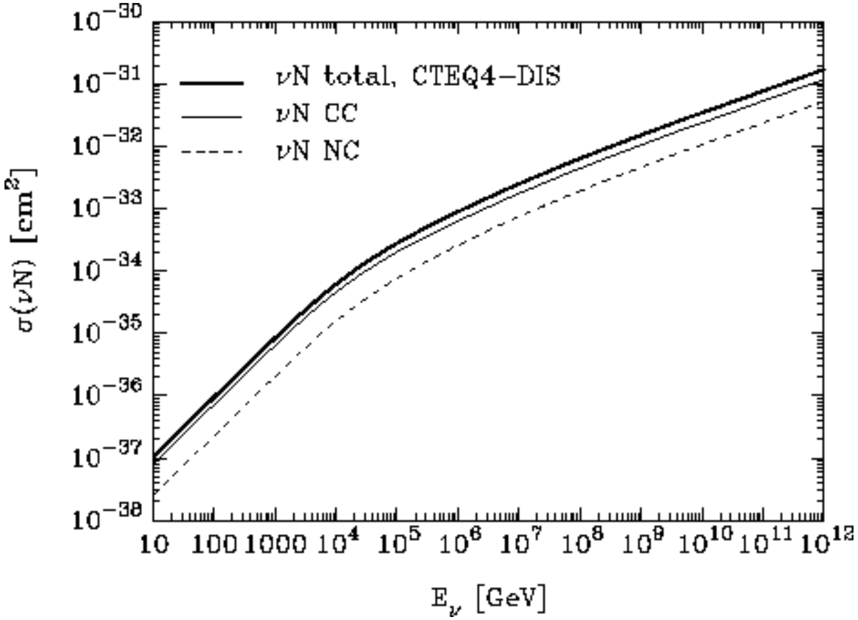
Neutrino flux from sources of gamma-rays

Neutrino cross section:

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

Which fraction of neutrinos
interact near/in detector:

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



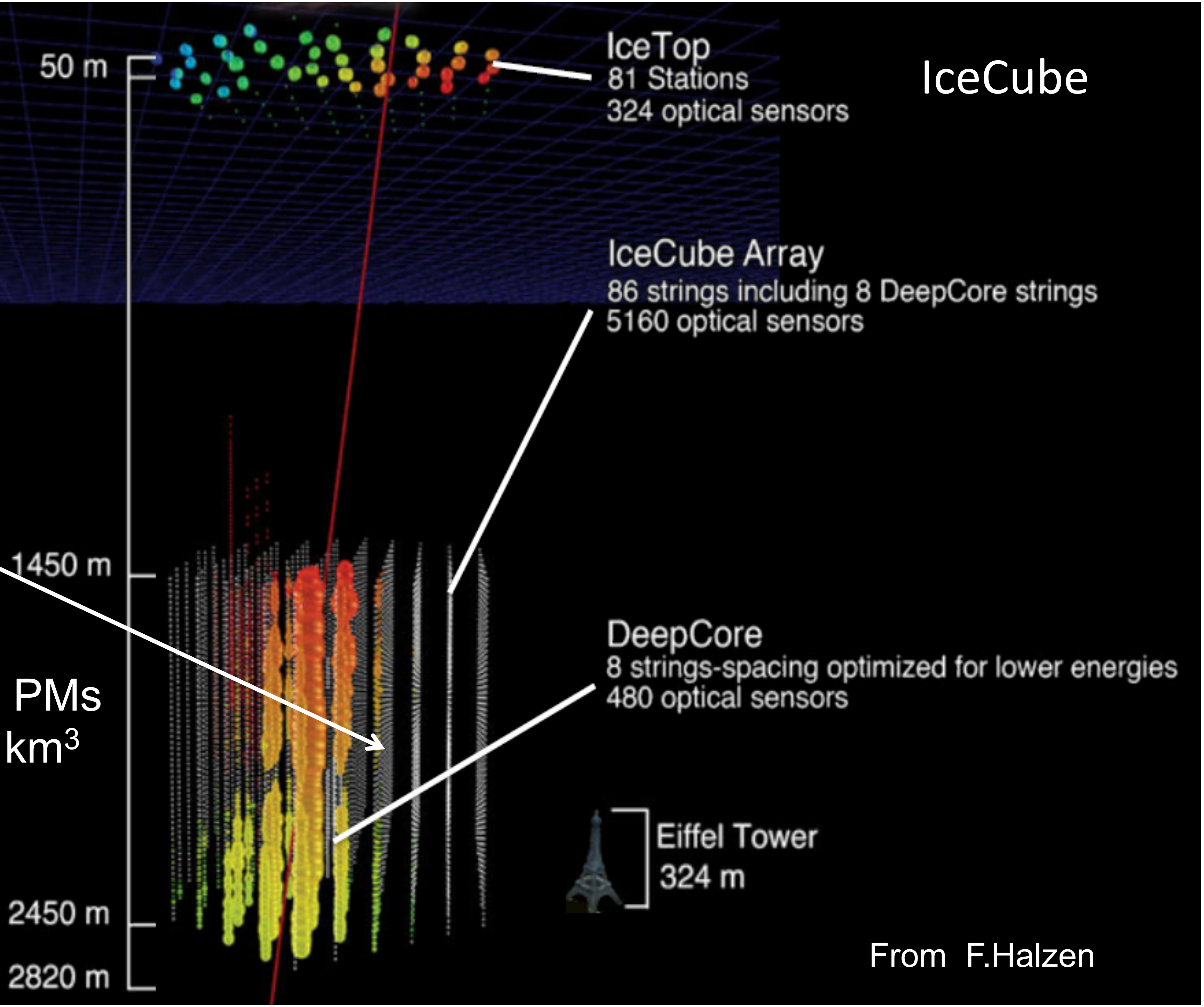
Expected neutrino flux from pp reactions:

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

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

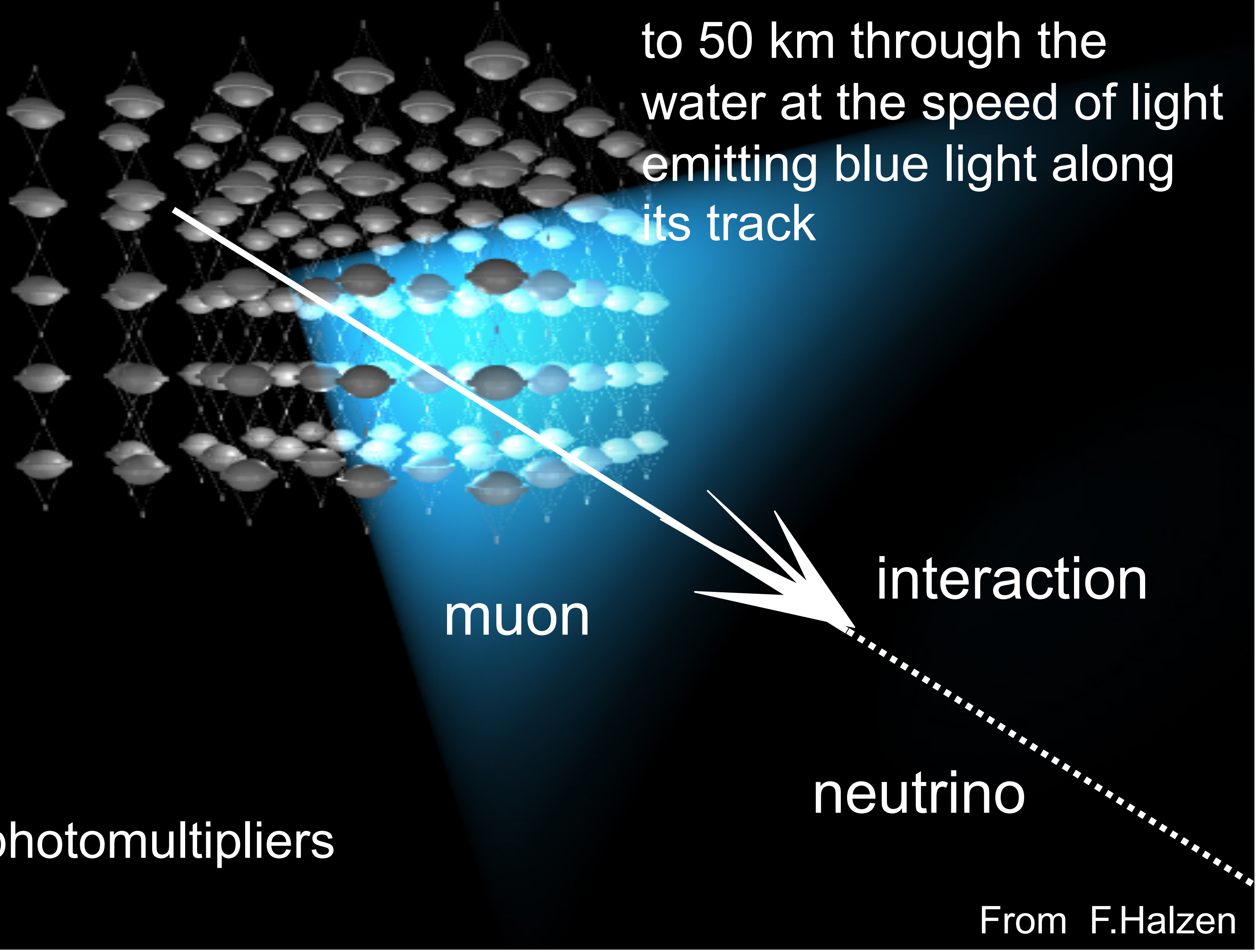
This means few events per year

IceCube



5160 PMs
in 1 km^3

From F.Halzen

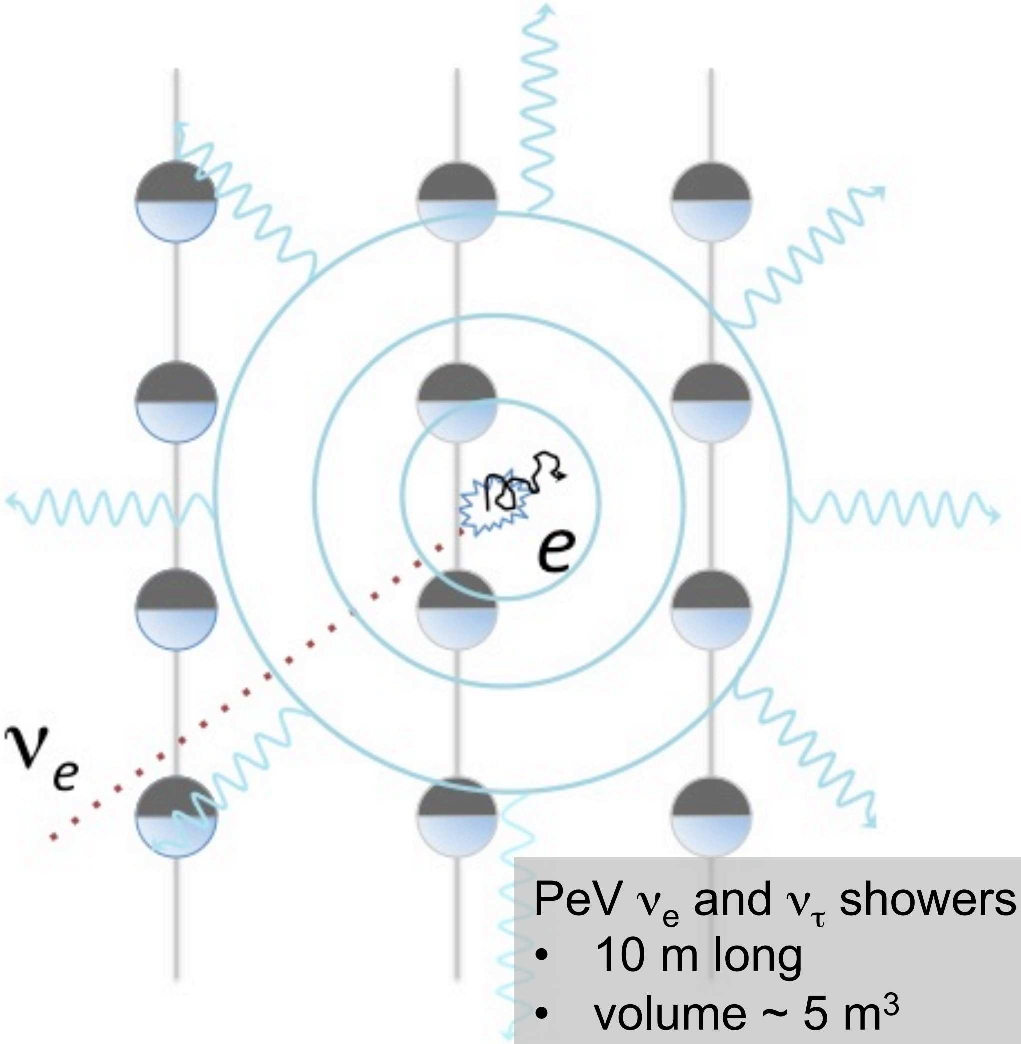


- shielded and optically transparent medium
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track

- lattice of photomultipliers

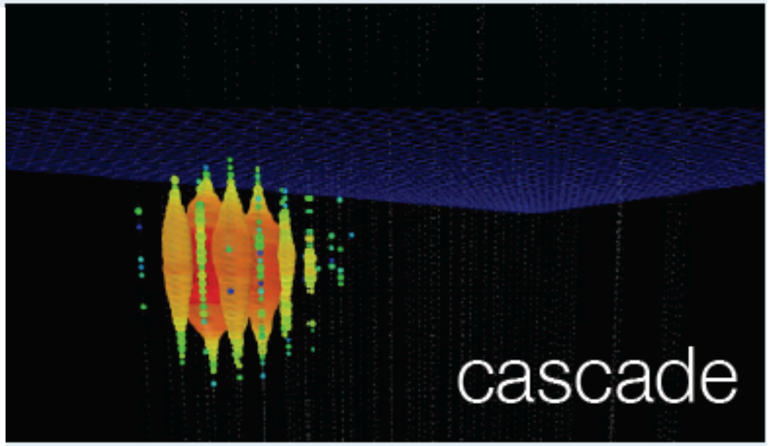
From F.Halzen

tracks and showers



PeV ν_e and ν_τ showers:

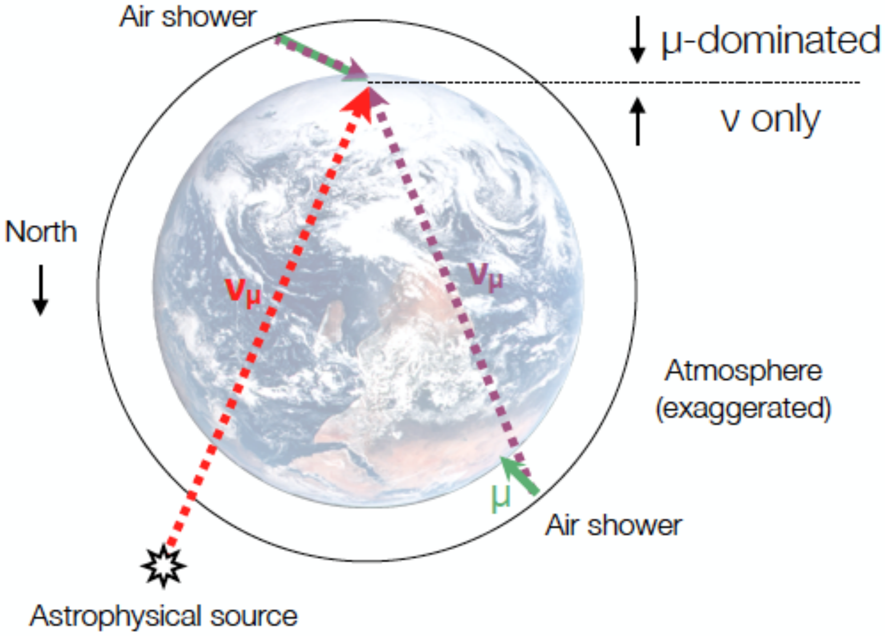
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m



From F.Halzen

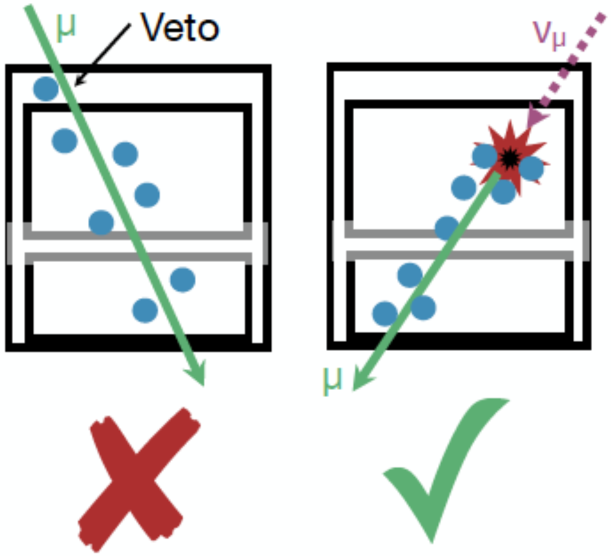
Isolating neutrino events: two strategies

Up-going tracks



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

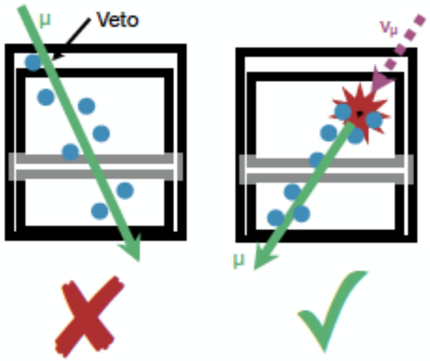
Active veto



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

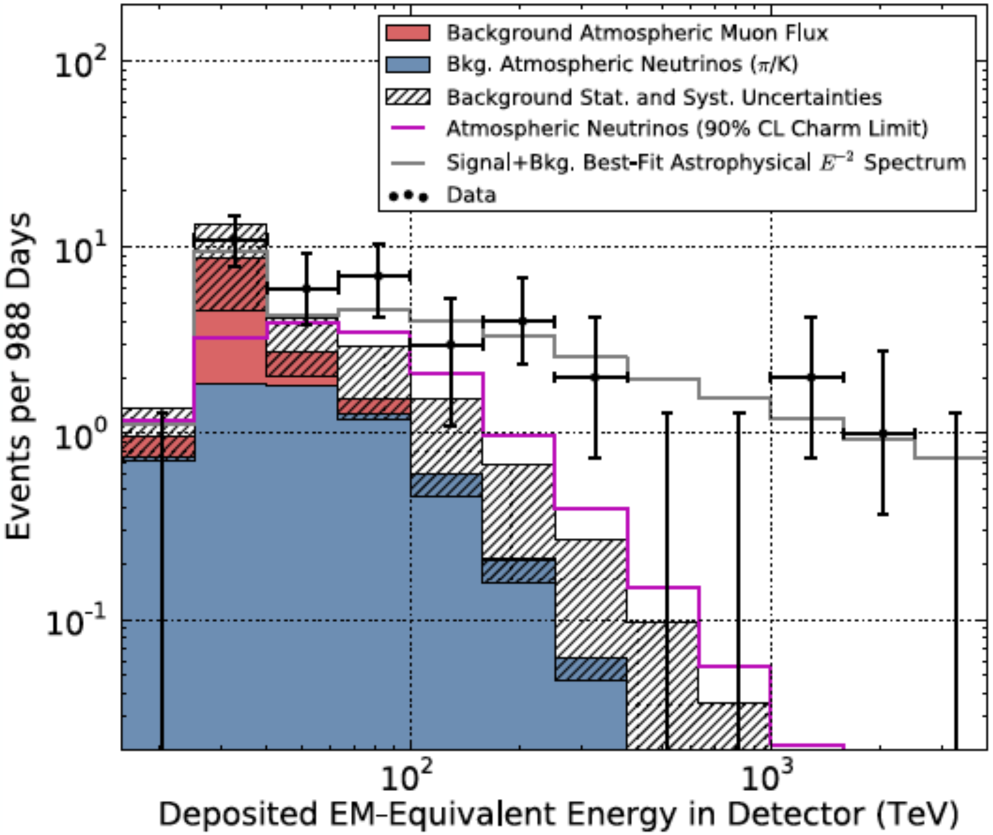
Evidence for high-energy astrophysical neutrinos

- Selected high-energy starting events in IceCube



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

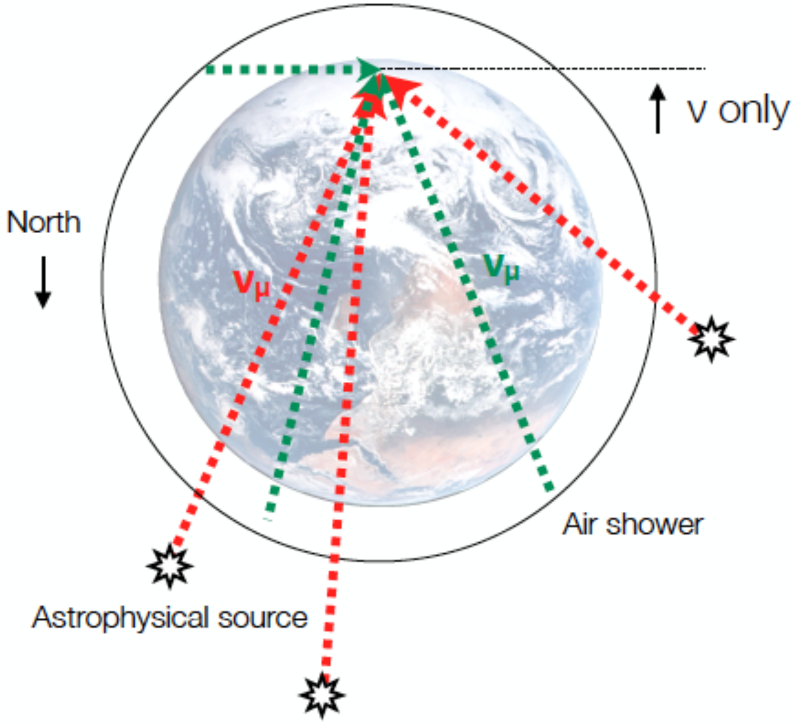
Deposited energy

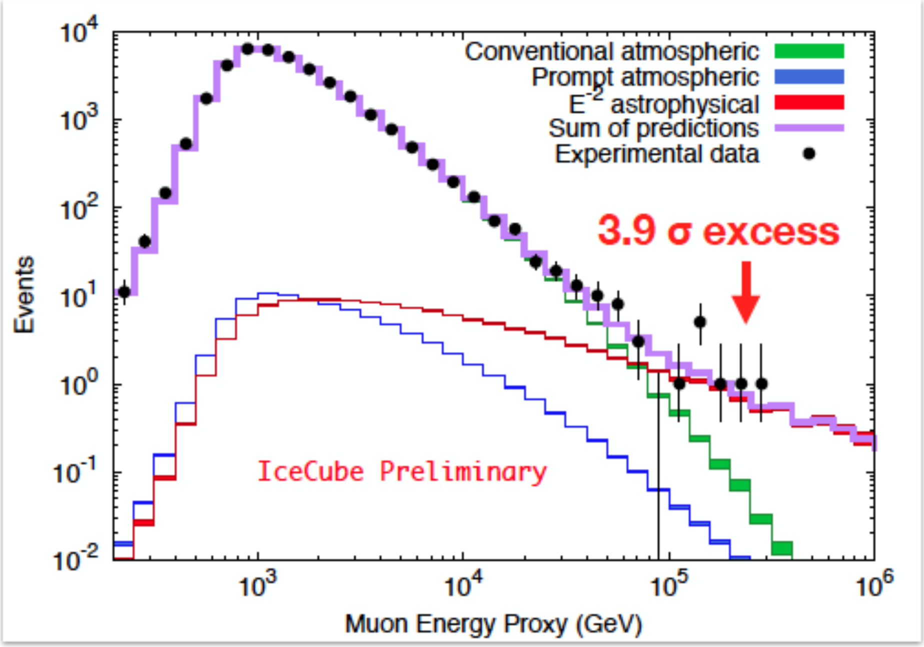


arXiv:1405.5303 (accepted for PRL)

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

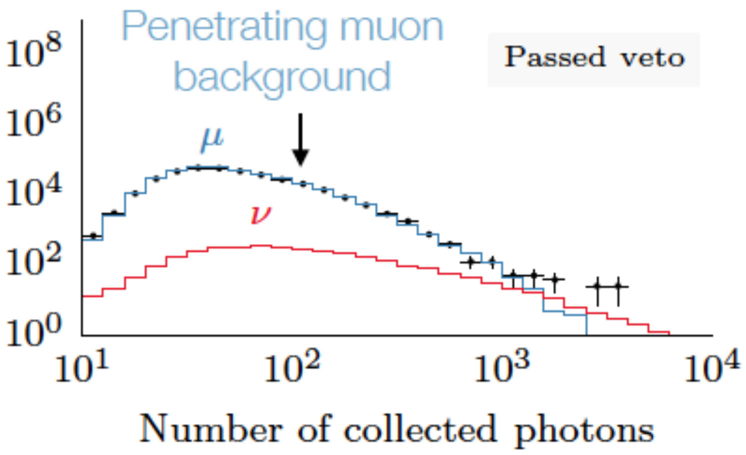
High-energy muons reach the detector from km away → large effective volume

Only sensitive to CC ν_μ → explicit handle on ν_μ flux

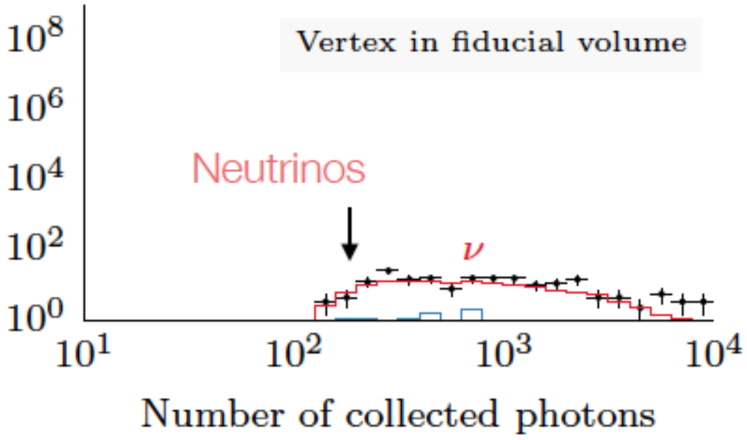
Improved veto techniques

Outer-layer veto → Energy-dependent veto

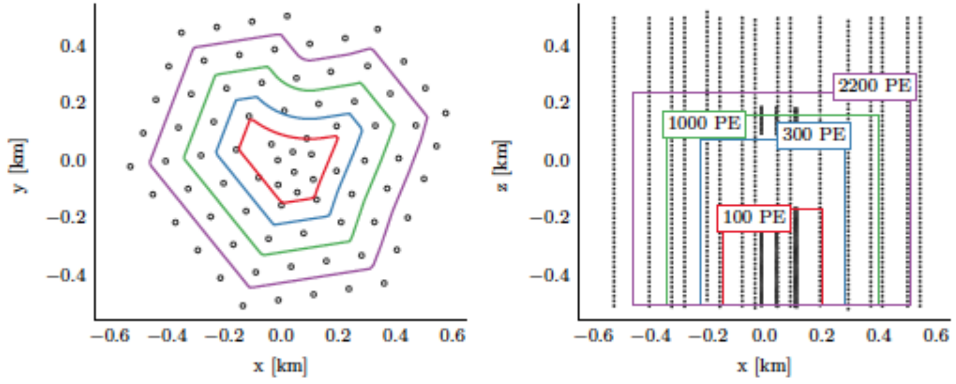
Neutrino-dominated for $E_{dep} > 60$ TeV



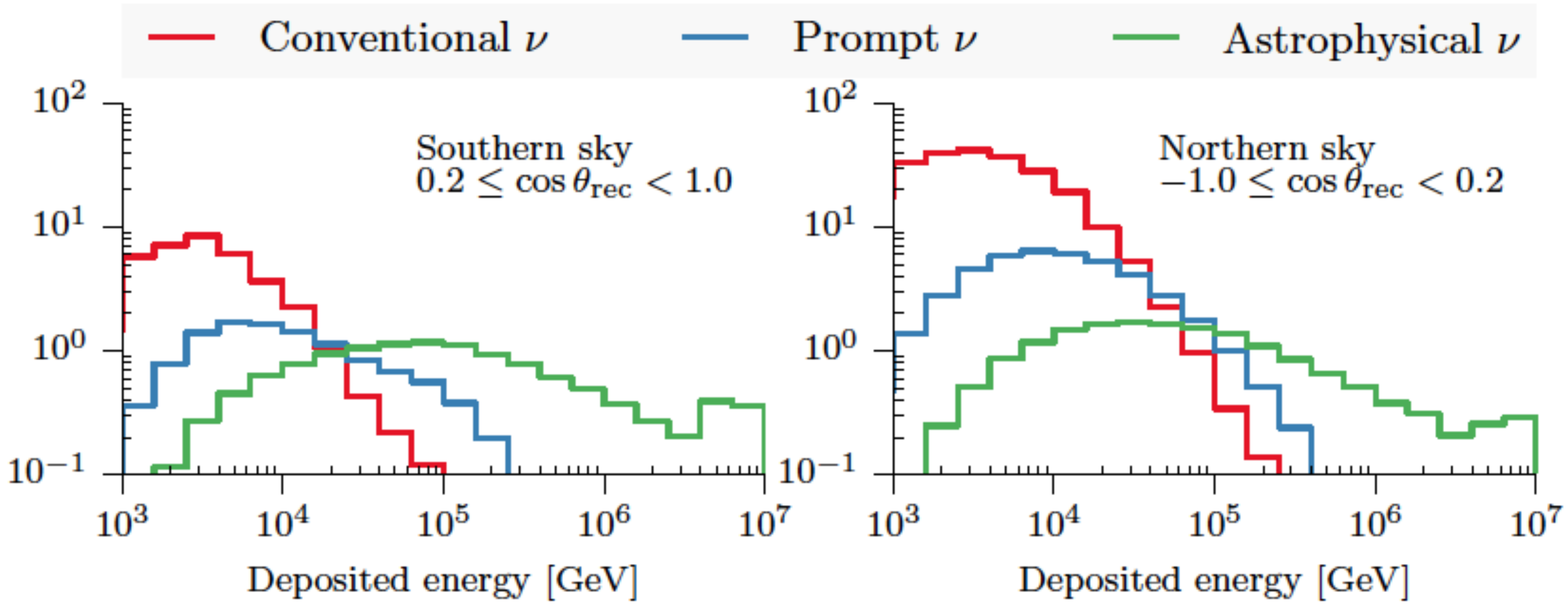
Neutrino-dominated for $E_{dep} > 1$ TeV



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



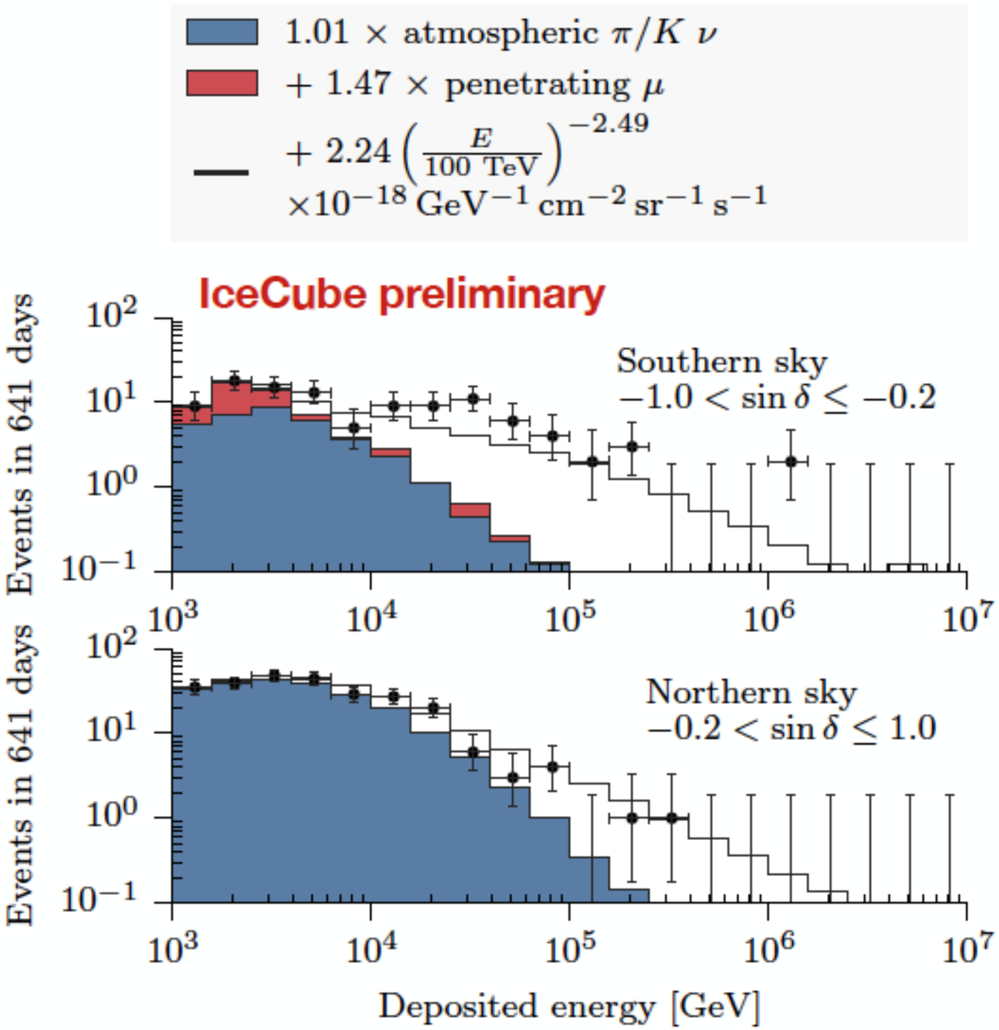
servable energy spectra



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

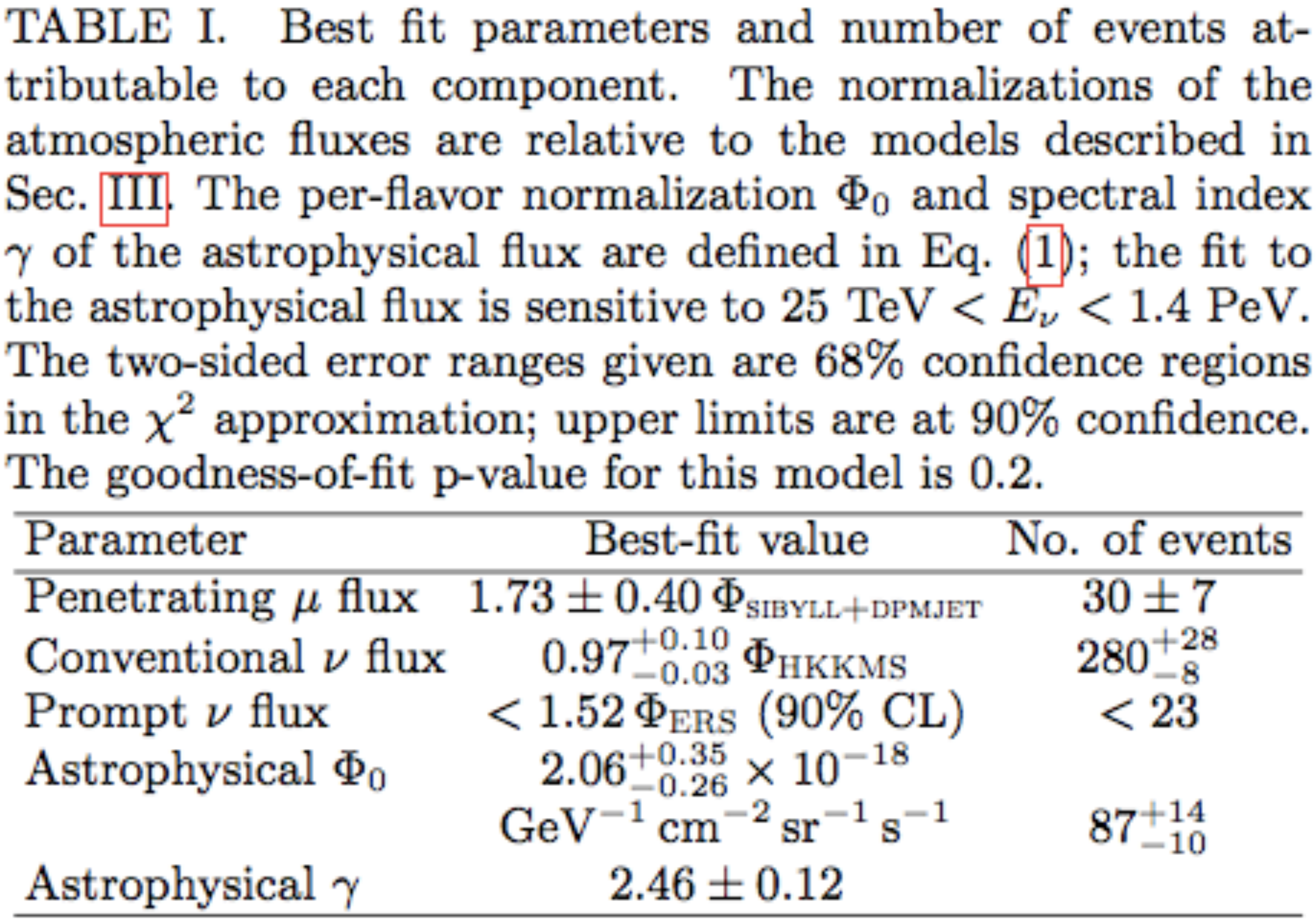
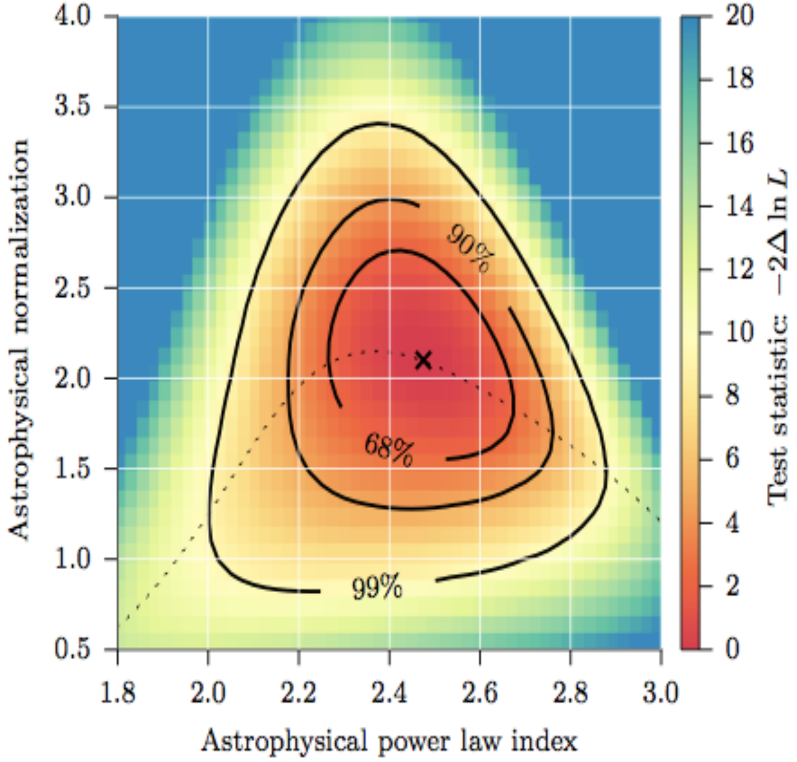


TABLE I. Best fit parameters and number of events attributable to each component. The normalizations of the atmospheric fluxes are relative to the models described in Sec. III. The per-flavor normalization Φ_0 and spectral index γ of the astrophysical flux are defined in Eq. (1); the fit to the astrophysical 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.

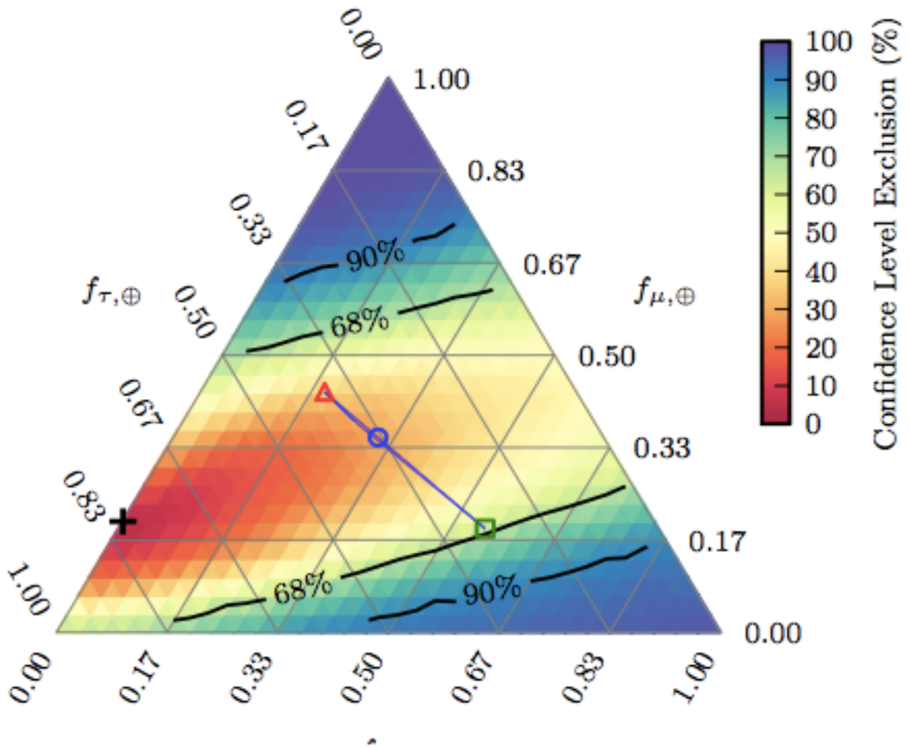
Parameter	Best-fit value	No. of events
Penetrating μ flux	$1.73 \pm 0.40\,\Phi_{\text{SIBYLL+DPMJET}}$	30 ± 7
Conventional ν flux	$0.97^{+0.10}_{-0.03}\,\Phi_{\text{HKKMS}}$	280^{+28}_{-8}
Prompt ν flux	$< 1.52\,\Phi_{\text{ERS}}$ (90% CL)	< 23
Astrophysical Φ_0	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ $\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$	87^{+14}_{-10}
Astrophysical γ	2.46 ± 0.12	

Neutrino spectrum



(a) Likelihood profile in astrophysical power-law index γ and per-flavor normalization $\Phi_0/10^{-18}$ $\mathrm{GeV^{-1}\,cm^{-2}\,sr^{-1}\,s^{-1}}$. $E^{-2.5}$ is strongly favored over E^{-2}.

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 for cascades 1/E^(2.46+-0.14)
- Flux 1/E^2 disfavored with more then 3 sigma significance
- Muon neutrino data favors 1/E^2.06+-0.13 flux !
- Flavor ratio consistent with 1:1:1 as expected
- Cosmogenic neutrinos best constrained by IceCube, but in case of nuclei primaries bigger detector needed to find flux

- Bigger detectors needed for next step

Future detectors

Baikal-GVD

Environmental parameters

Lake Baikal - fresh water

distance to shore ~6 km →

L_{abs} ~22-25 m

L_{scat} ~30-50m

depth ~1360 m

icefloor during winter →

Telescope design

~1.5 km3

27 shore-cables for 27 clusters

27*8=216 strings

216*48=10368 OMs¶

deployment from icefloor

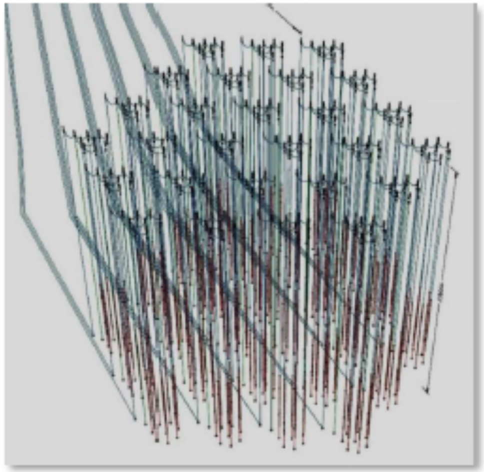
shallow water DAQ infrastructure

The Baikal-GVD Collaboration

7 institutes

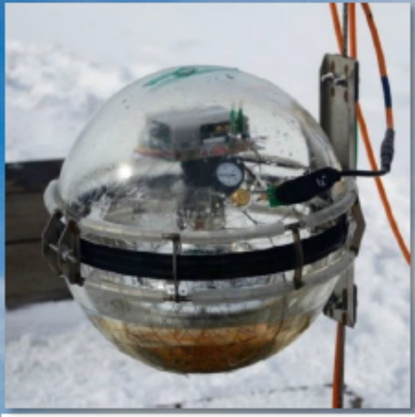
~55 scientists

baikalweb.jinr.ru

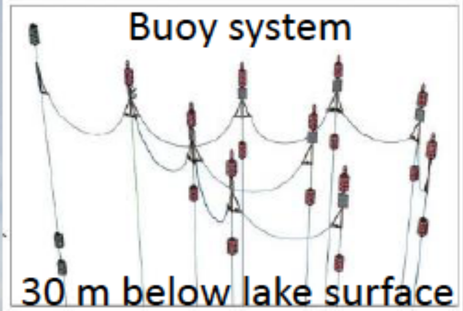


¶ OM – Optical Module

GVD technology

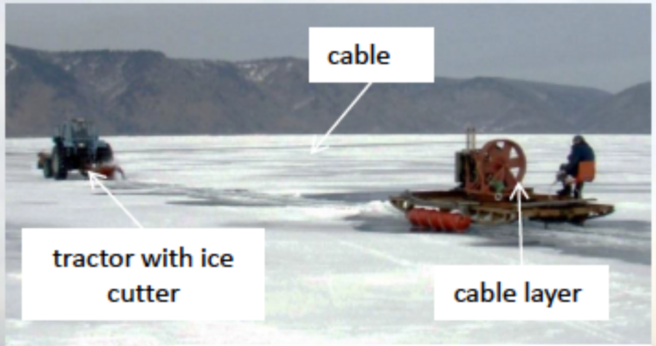


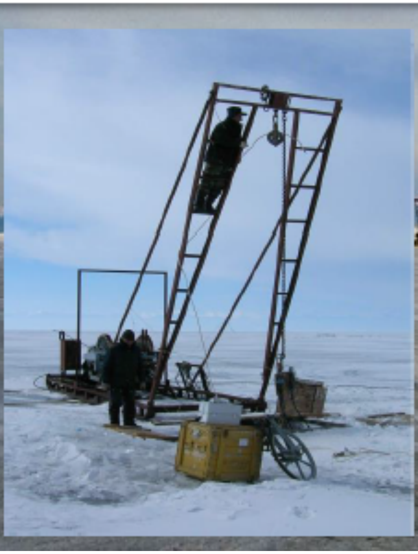
R7081HQE : D=10”, ~0.35QE

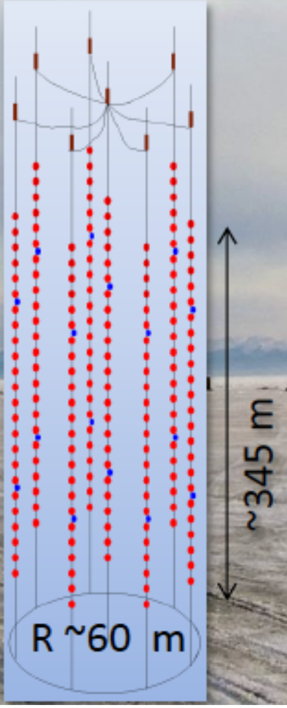


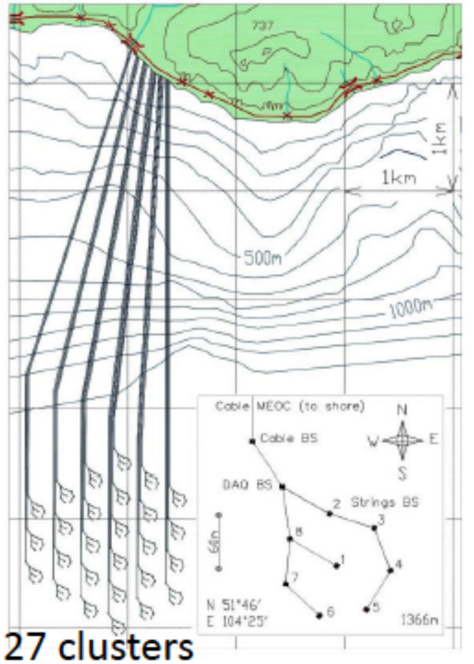
Buoy system

30 m below lake surface



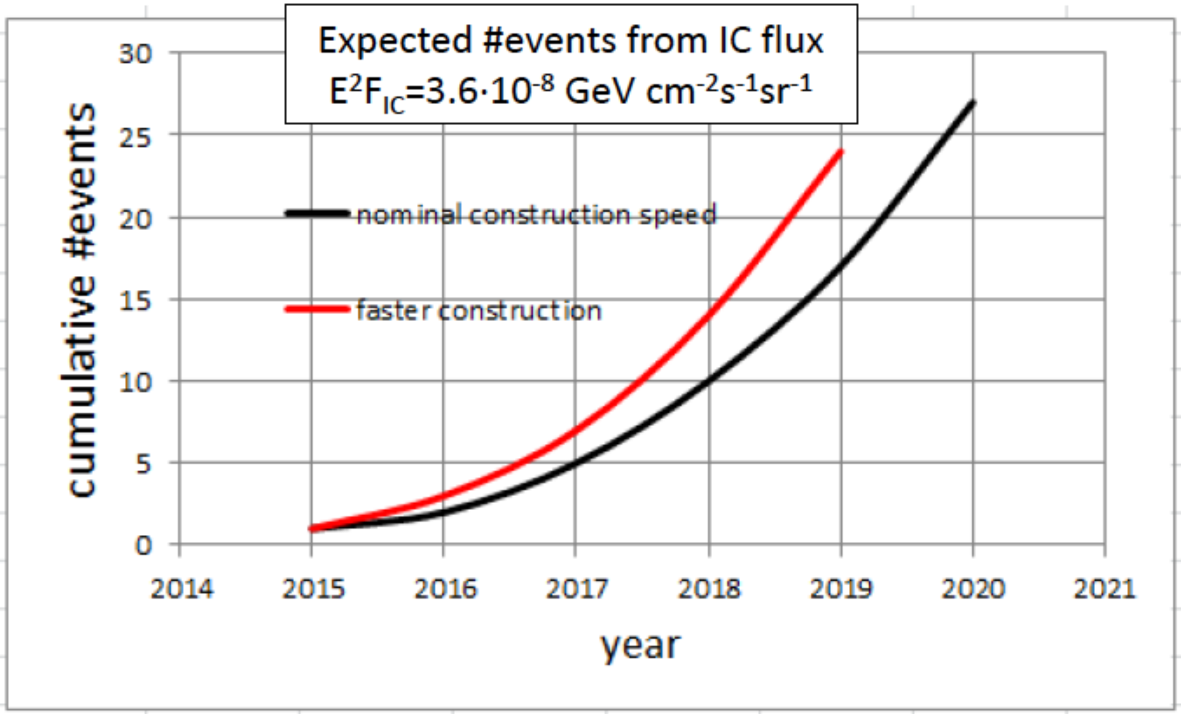






27 clusters

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

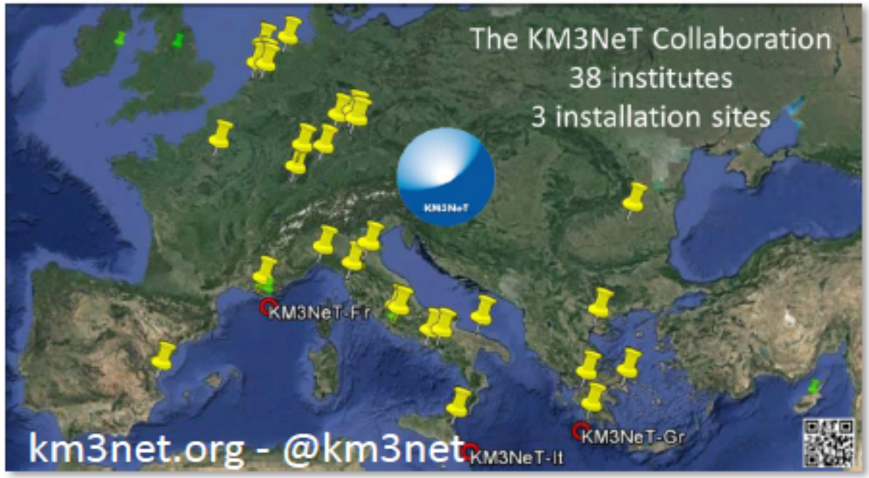
6 x 115 = 690 detection units

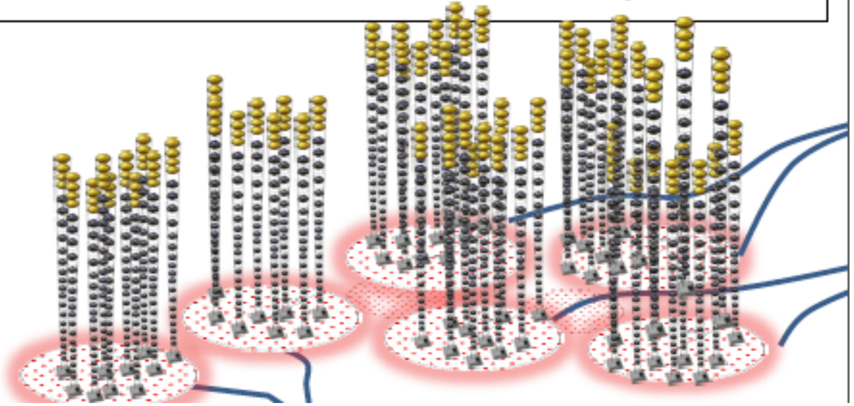
690 x 18 =12420 OMs

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

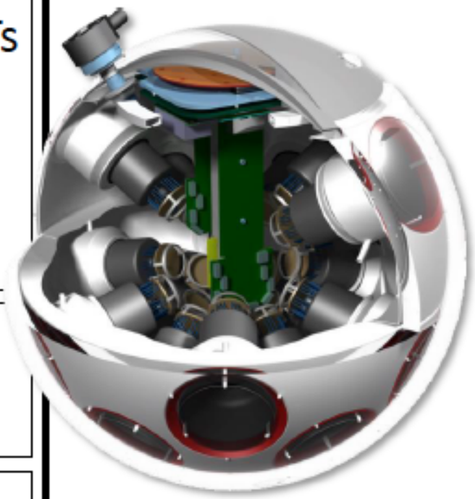
Custom low-power HV bases

LED & piezo inside

Compass and tiltmeter inside

PMT ToT measurements

FPGA readout, optical line terminator

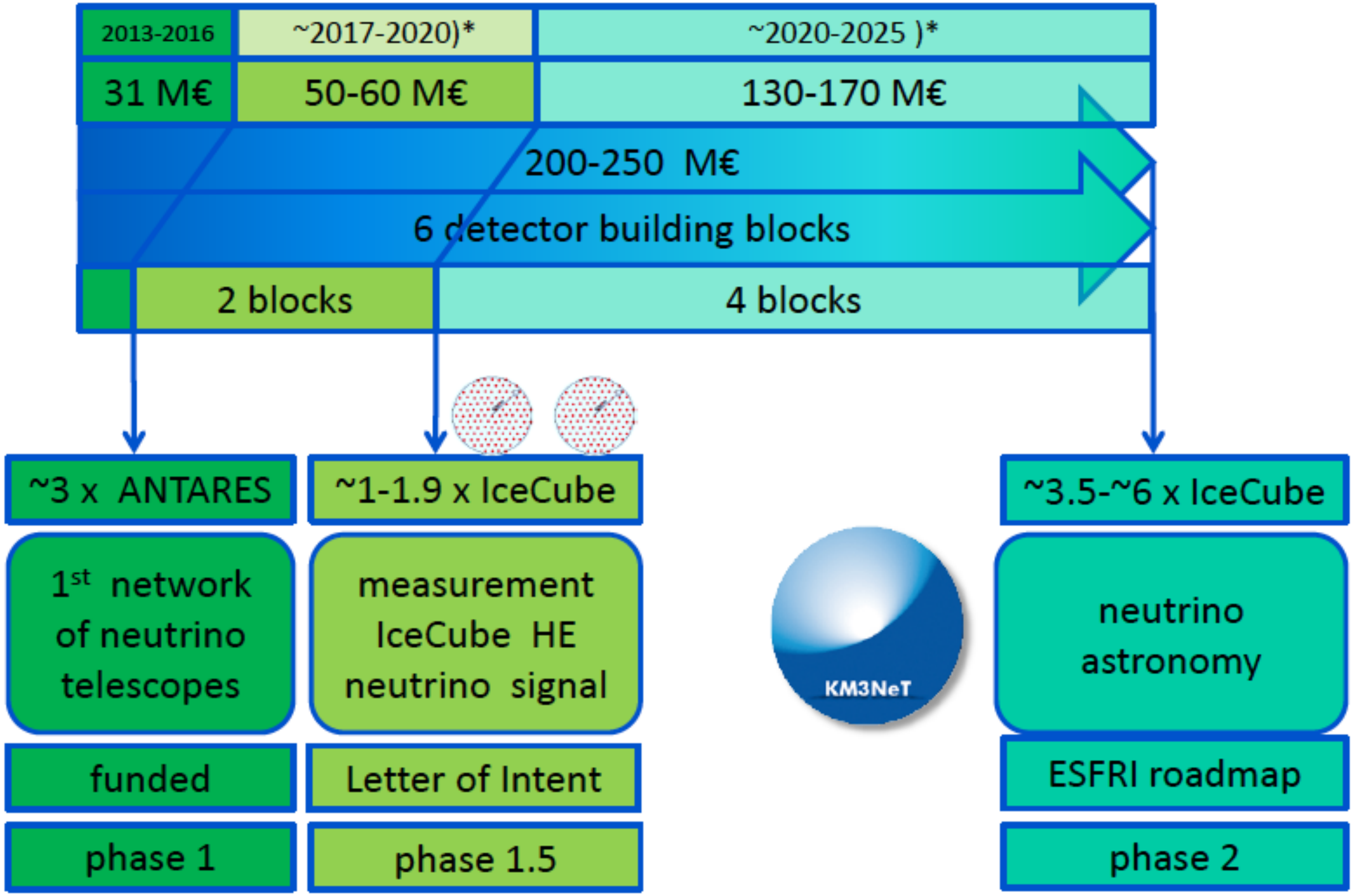


ETEL D792

Hamamatsu R12199

HZC XP53B20

KM3NeT phased construction



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

1st network
of neutrino
telescopes

funded

phase 1

~1-1.9 x IceCube

measurement
IceCube HE
neutrino signal

Letter of Intent

phase 1.5

~3.5-~6 x IceCube

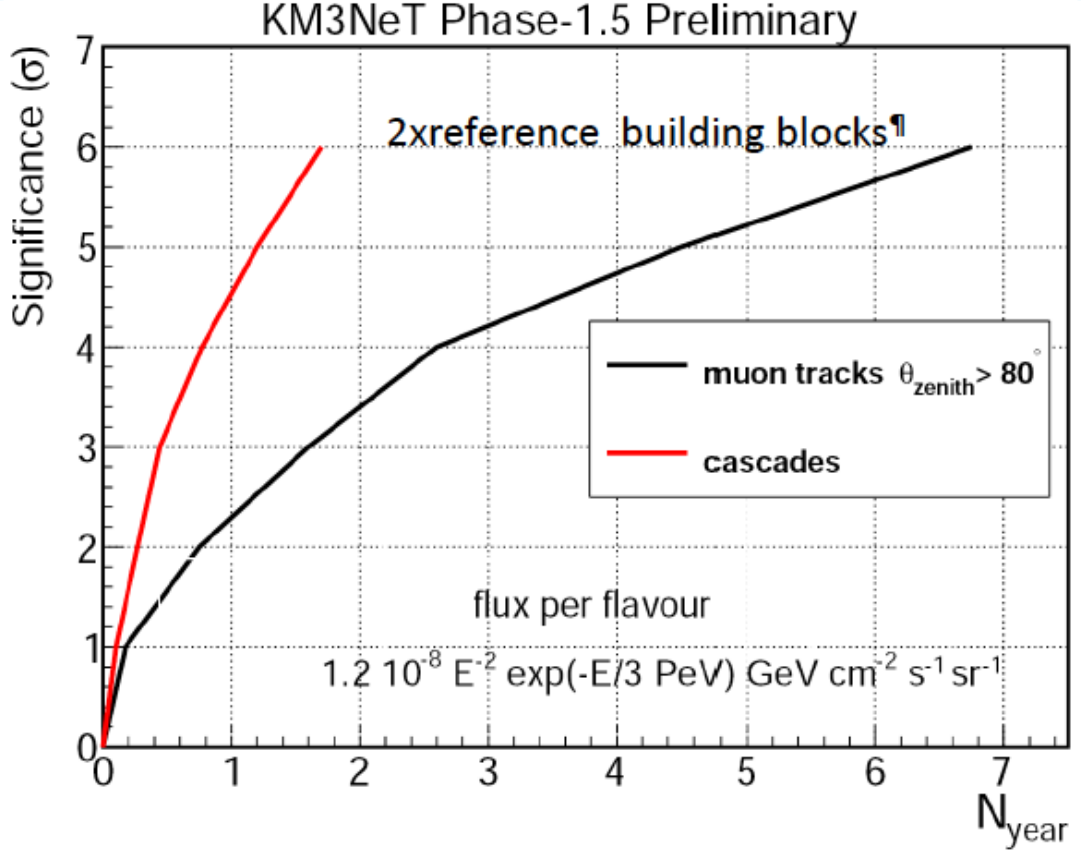
neutrino
astronomy

ESFRI roadmap

phase 2

)* depending on funding

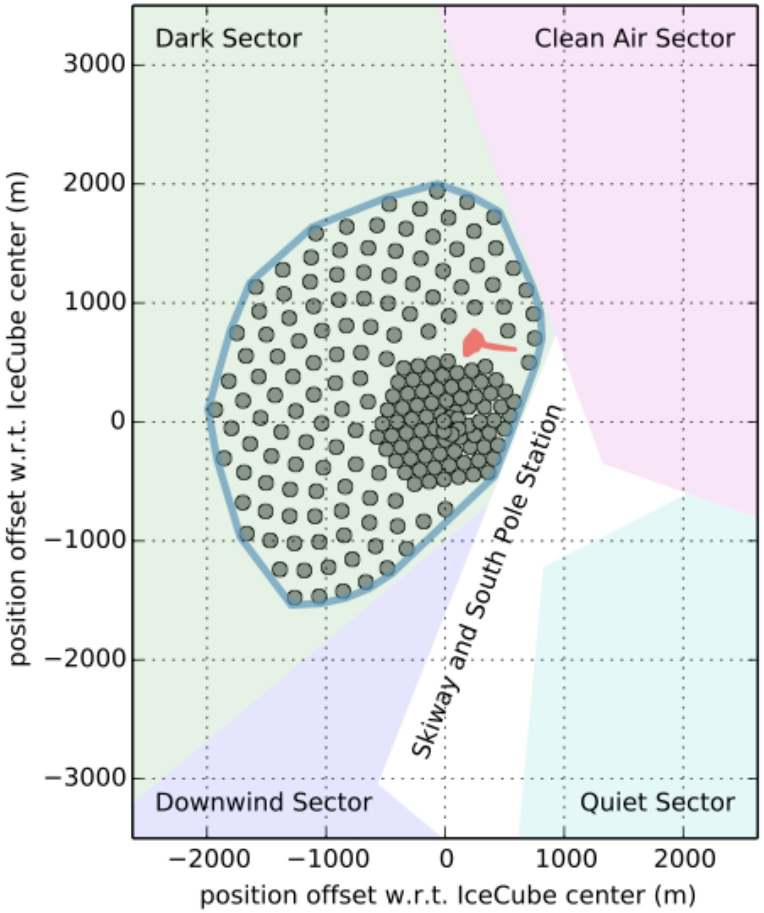
Performance



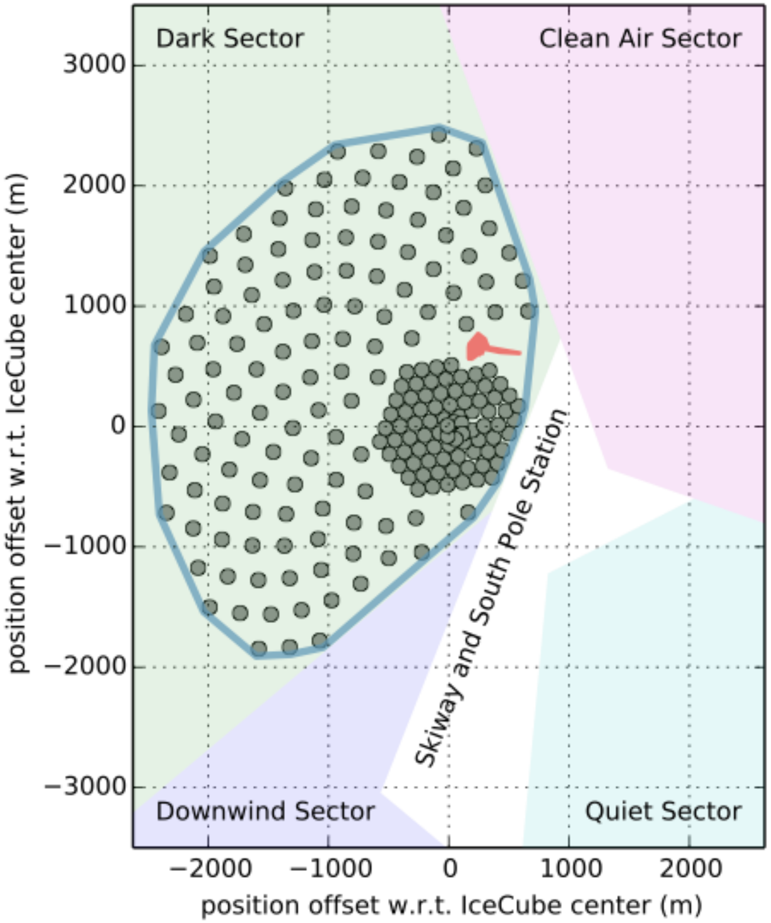
Detailed investigation of „IceCube signal" within a few years, with different *field of view*, different *systematics* and better *angular resolution*

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

86 strings with 240-340 m spacing

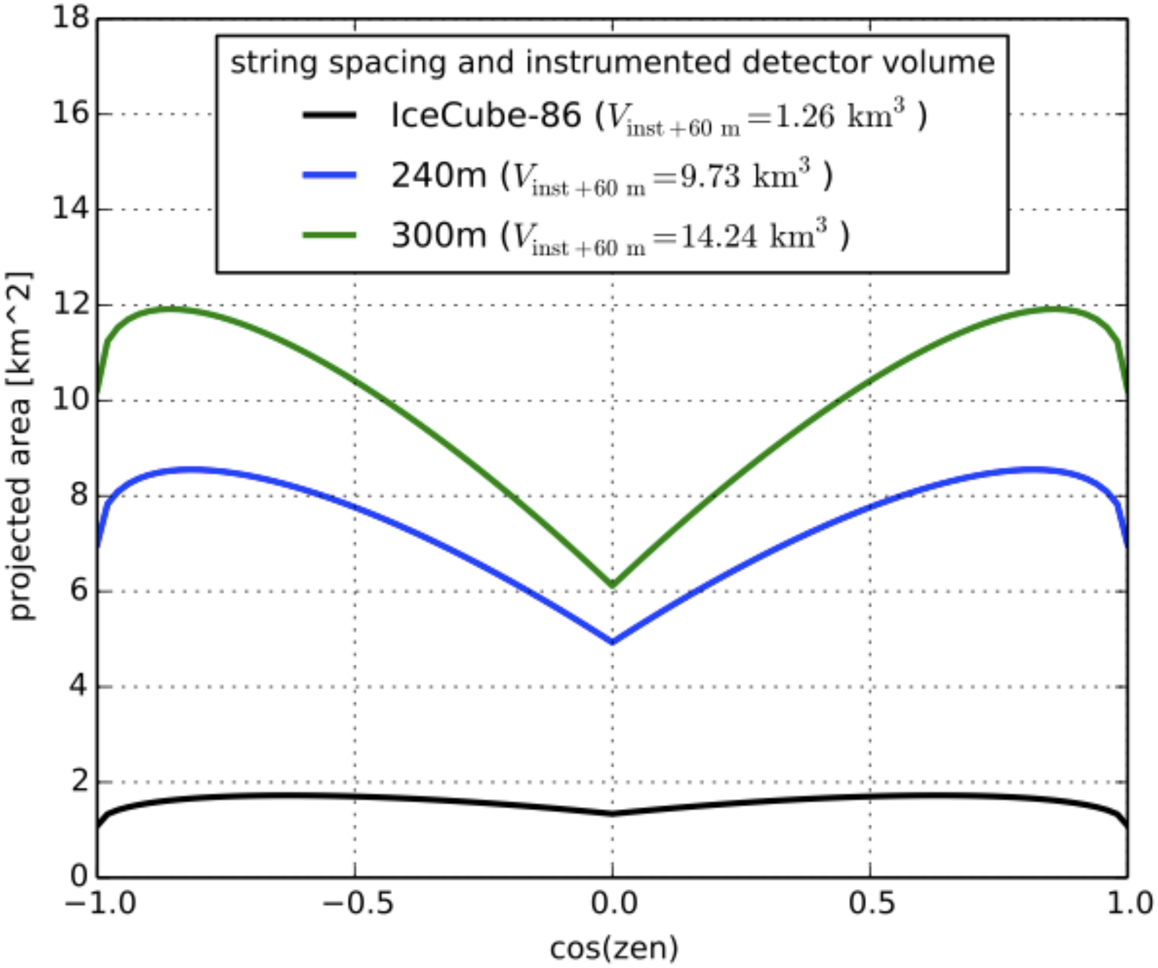


(a) 240 m string spacing ("benchmark")



(b) 300 m string spacing

Effective volume

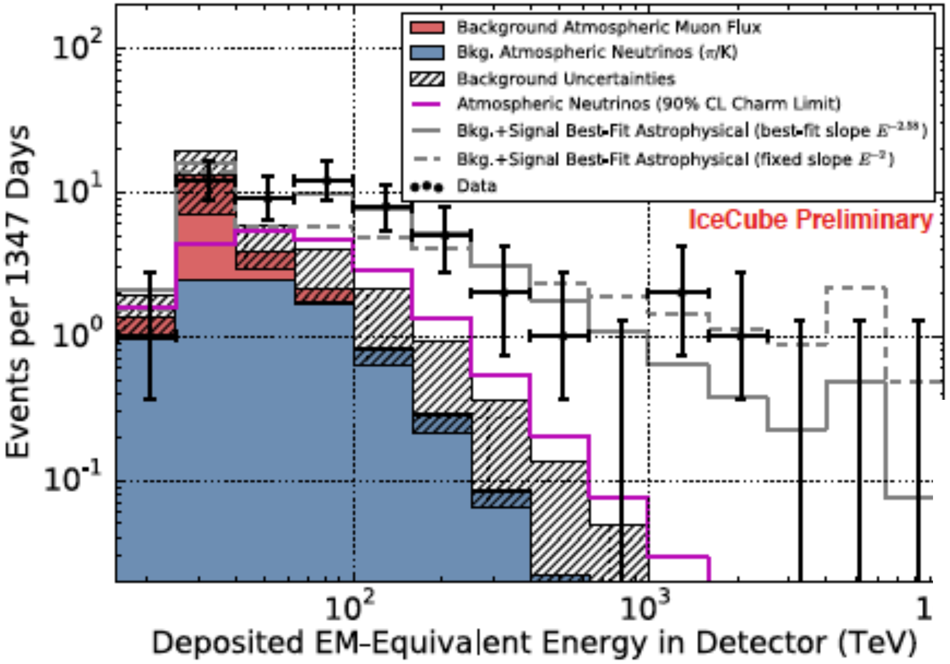


IceCube Collaboration, **arXiv:1412.5106**

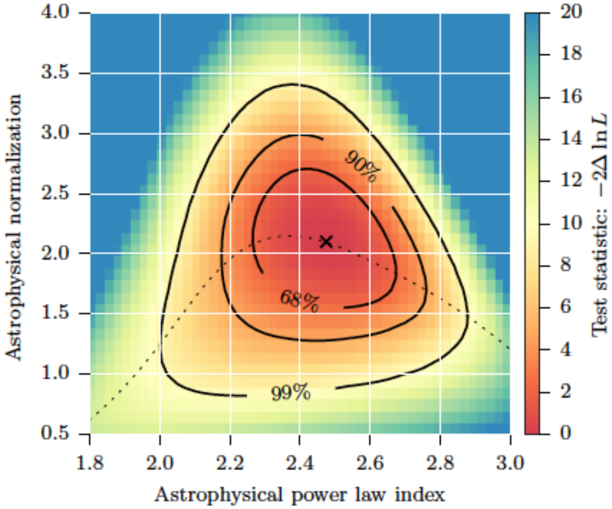
What we can expect from future detectors

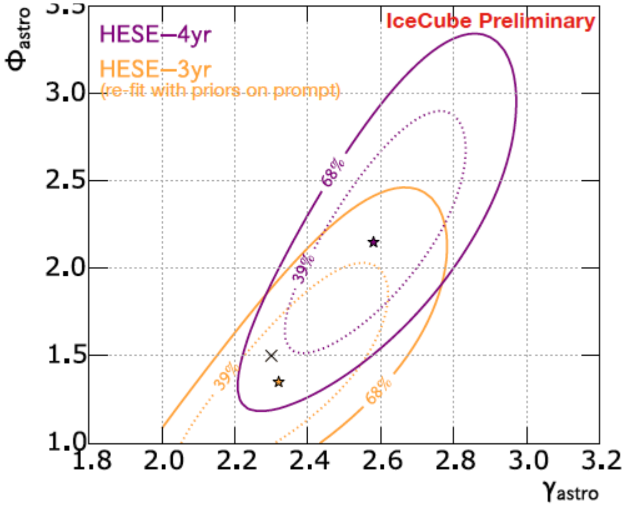
- Split Galactic and extragalactic contribution in diffuse flux
- Find first point/extended sources
- Constrain or find extragalactic flux above PeV
- Help to find sources of PeV Galactic cosmic rays

Present situation: IceCube data 4 yrs

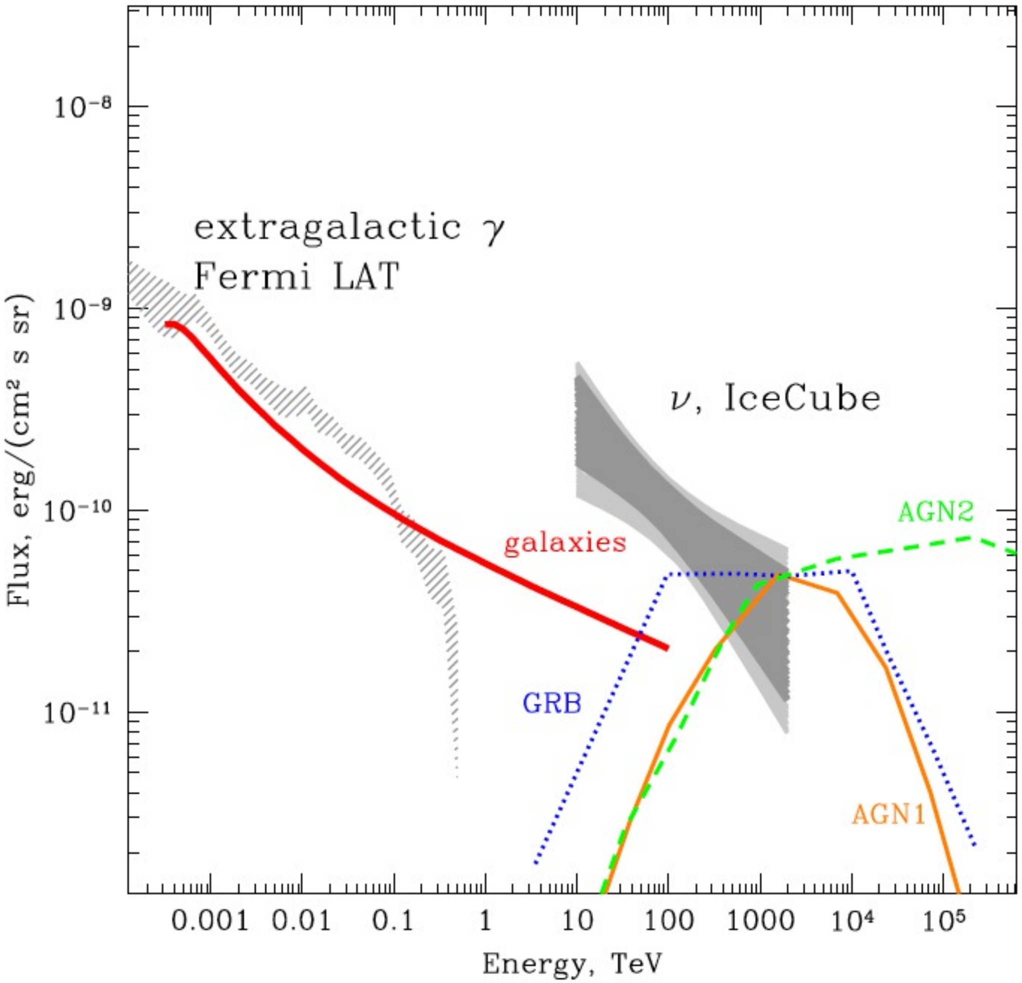


IceCube, ICRC 2015





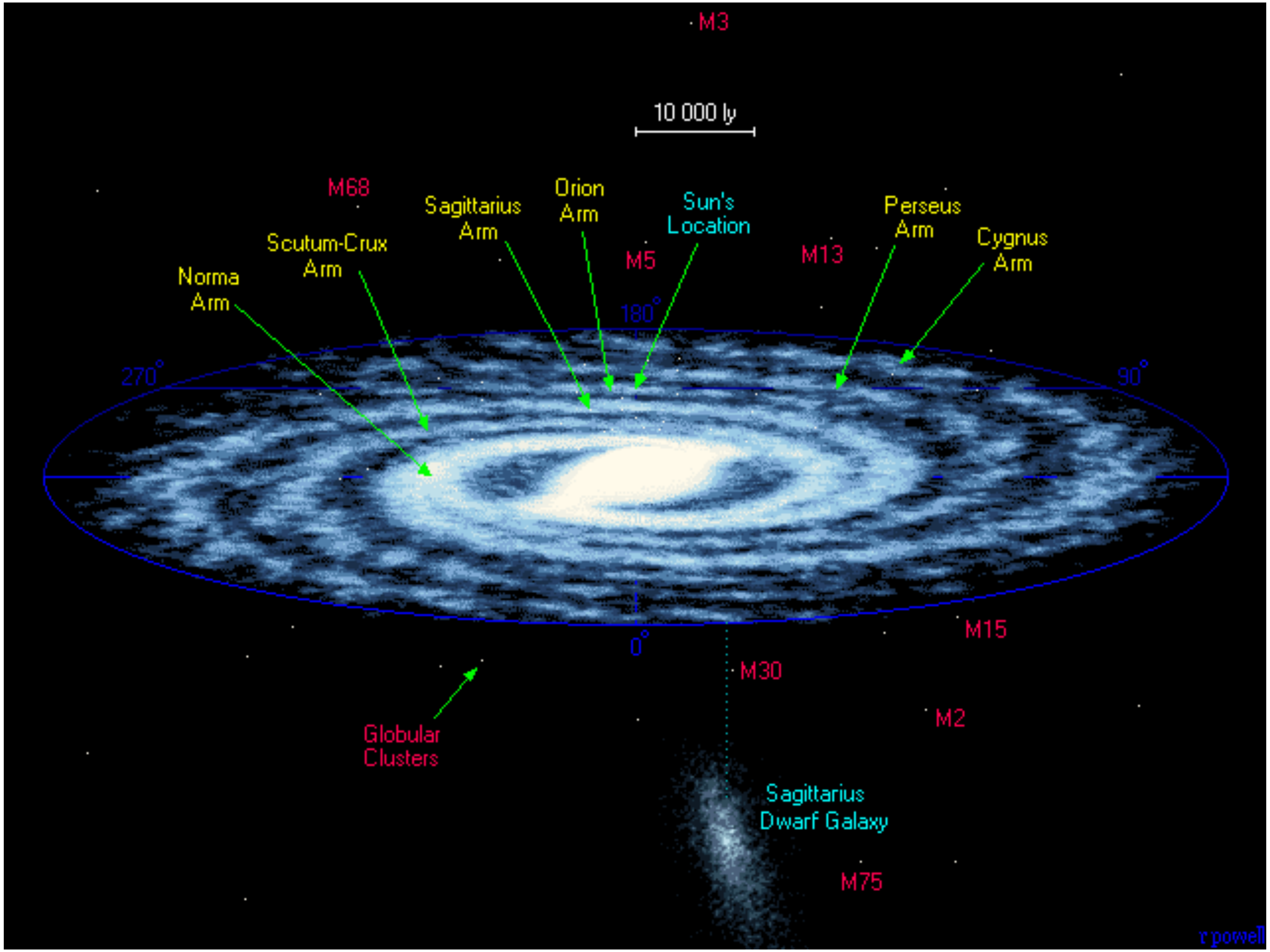
IceCube + Fermi LAT



A.Neronov, D.S. arXiv:1412.1690

Galactic magnetic field

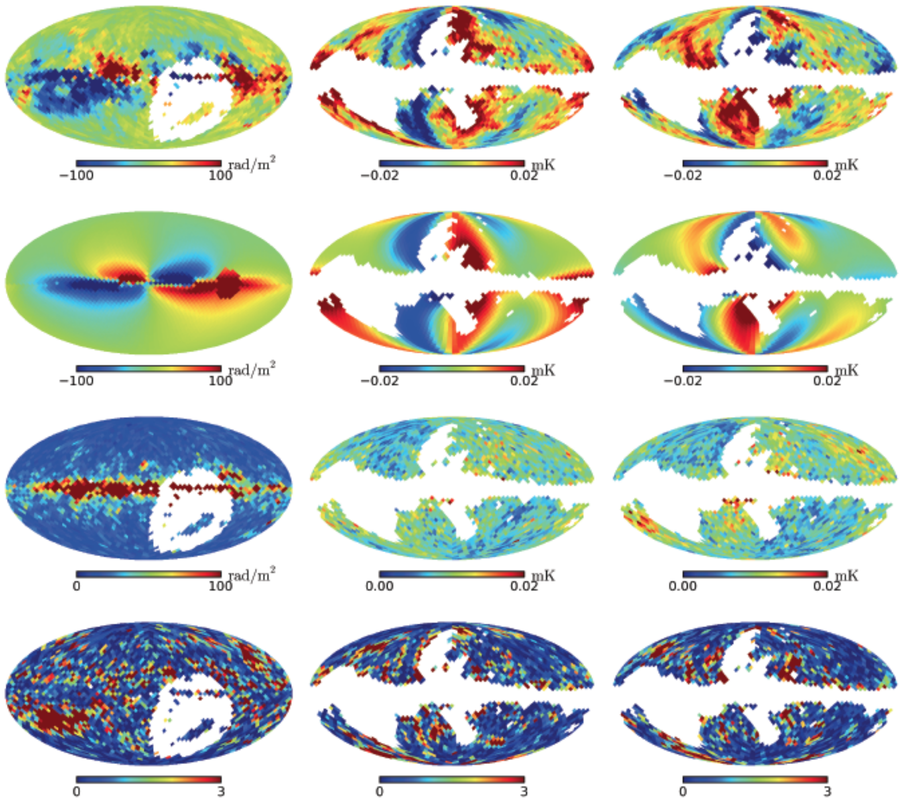
MILKY WAY GALAXY



Galactic magnetic field

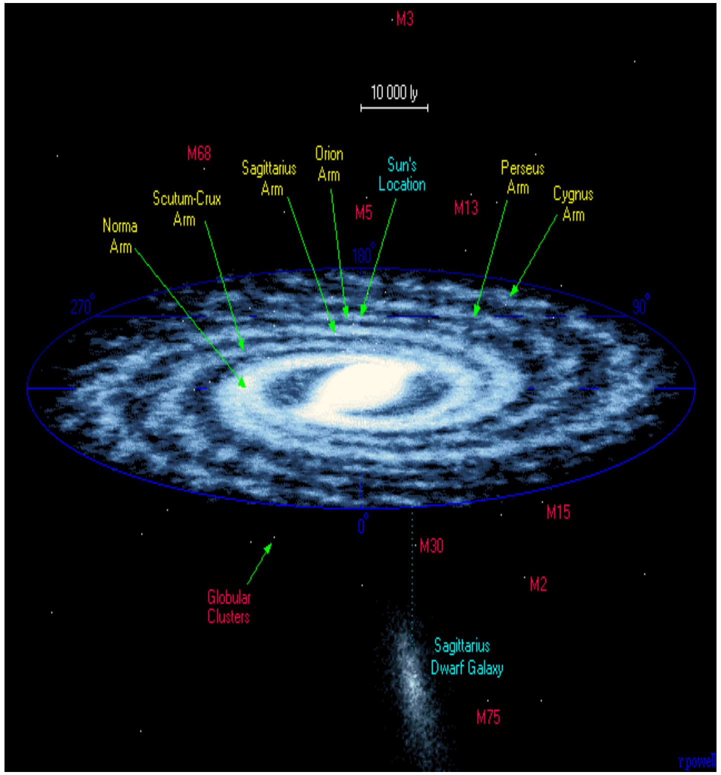
- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

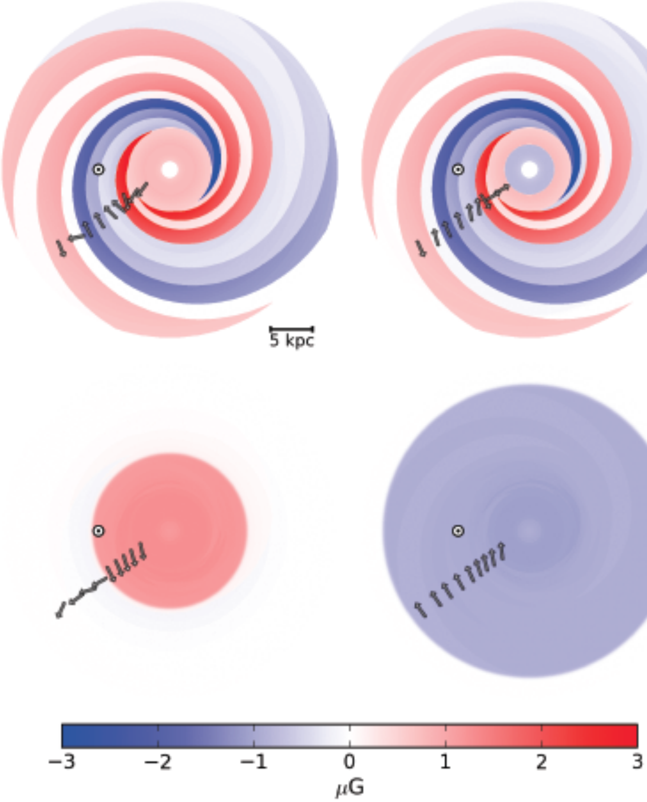
Synchrotron/RM maps



From R.Jansson & G.Farrar, arXiv:1204.3662

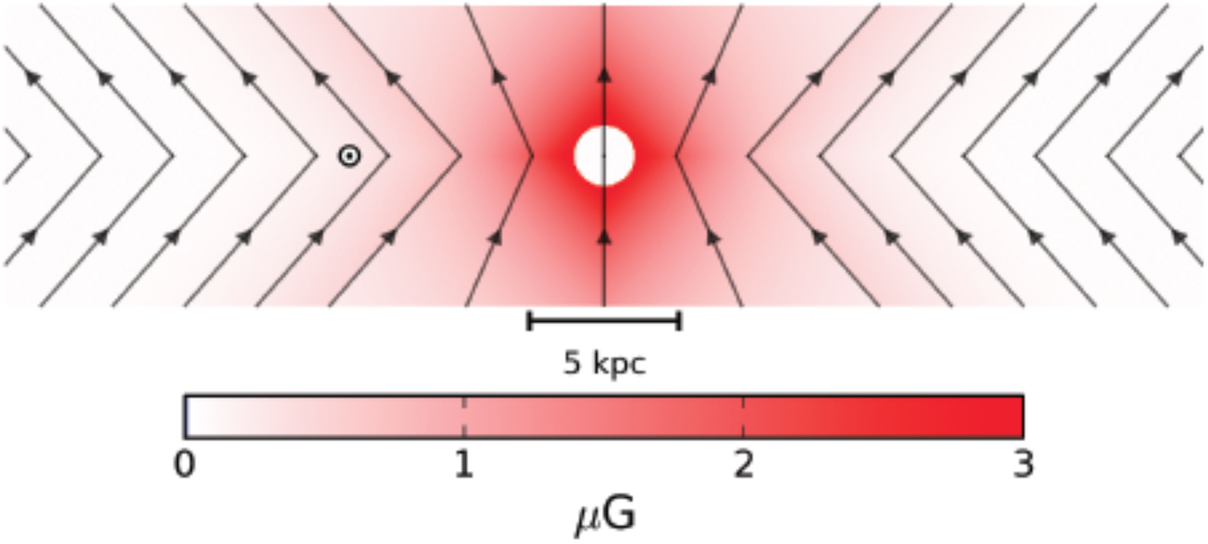
Galactic magnetic field: disk





R.Jansson & G.Farrar, arXiv:1204.3662

Galactic magnetic field halo: x-shape



R.Jansson & G.Farrar, arXiv:1204.3662

GMF regular field parameters

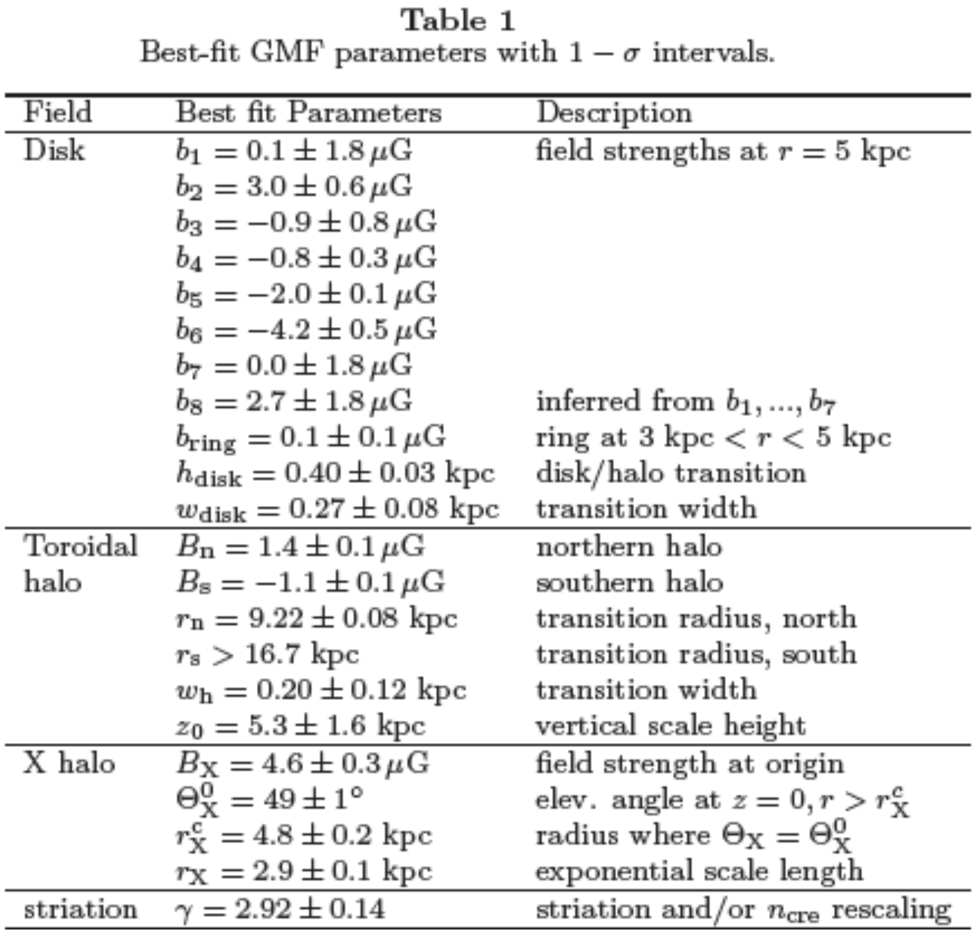


Table 1
Best-fit GMF parameters with $1-\sigma$ intervals.

Field	Best fit Parameters	Description
Disk	$b_1 = 0.1 \pm 1.8\,\mu$G	field strengths at $r = 5$ kpc
	$b_2 = 3.0 \pm 0.6\,\mu$G	
	$b_3 = -0.9 \pm 0.8\,\mu$G	
	$b_4 = -0.8 \pm 0.3\,\mu$G	
	$b_5 = -2.0 \pm 0.1\,\mu$G	
	$b_6 = -4.2 \pm 0.5\,\mu$G	
	$b_7 = 0.0 \pm 1.8\,\mu$G	
	$b_8 = 2.7 \pm 1.8\,\mu$G	inferred from $b_1, ..., b_7$
	$b_{\rm ring} = 0.1 \pm 0.1\,\mu$G	ring at 3 kpc $< r <$ 5 kpc
	$h_{\rm disk} = 0.40 \pm 0.03$ kpc	disk/halo transition
	$w_{\rm disk} = 0.27 \pm 0.08$ kpc	transition width
Toroidal halo	$B_{\rm n} = 1.4 \pm 0.1\,\mu$G	northern halo
	$B_{\rm s} = -1.1 \pm 0.1\,\mu$G	southern halo
	$r_{\rm n} = 9.22 \pm 0.08$ kpc	transition radius, north
	$r_{\rm s} > 16.7$ kpc	transition radius, south
	$w_{\rm h} = 0.20 \pm 0.12$ kpc	transition width
	$z_0 = 5.3 \pm 1.6$ kpc	vertical scale height
X halo	$B_{\rm X} = 4.6 \pm 0.3\,\mu$G	field strength at origin
	$\Theta^0_{\rm X} = 49 \pm 1^\circ$	elev. angle at $z = 0, r > r^c_{\rm X}$
	$r^c_{\rm X} = 4.8 \pm 0.2$ kpc	radius where $\Theta_{\rm X} = \Theta^0_{\rm X}$
	$r_{\rm X} = 2.9 \pm 0.1$ kpc	exponential scale length
striation	$\gamma = 2.92 \pm 0.14$	striation and/or $n_{\rm cre}$ rescaling

R.Jansson & G.Farrar, arXiv:1204.3662

Galactic magnetic field

- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

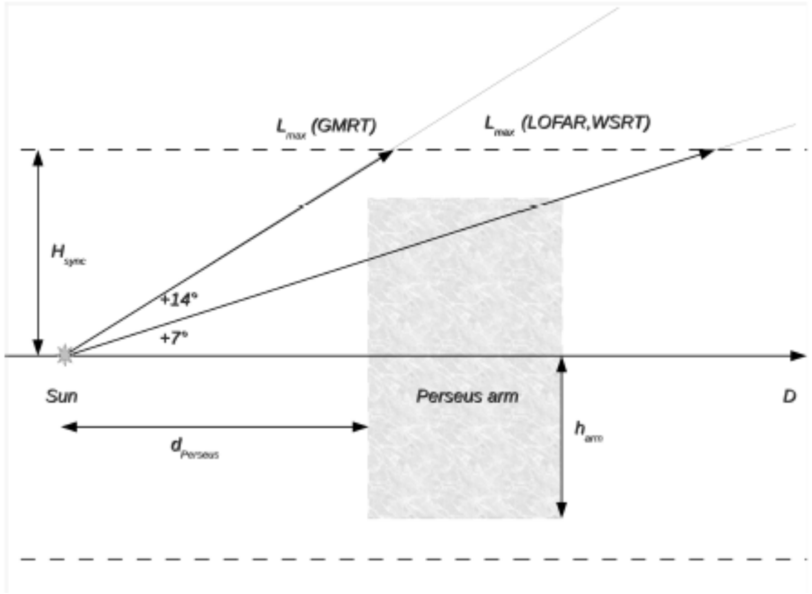
Galactic magnetic field: turbulent component

- Field with $\langle \boldsymbol{B}(\boldsymbol{r})\rangle = 0$ $\langle \boldsymbol{B}(\boldsymbol{r})^2\rangle \equiv B_{\mathrm{rms}}^2 > 0.$
- Power spectrum $\mathcal{P}(k) \propto k^{-\alpha},$ $|\boldsymbol{B}(\boldsymbol{k})|^2 \propto k^{-\alpha-2}$
- With index $\alpha = 5/3,\ 3/2$ for Kolmogorov/Kraichnan cases
- Correlation length

$$L_{\mathrm{c}} = \frac{L_{\max}}{2}\,\frac{\alpha-1}{\alpha}\,\frac{1-(L_{\min}/L_{\max})^{\alpha}}{1-(L_{\min}/L_{\max})^{\alpha-1}}\,.$$

- Where
- $L_{\min} = 1\,\mathrm{AU}$ Lmax=25-100 pc

LOFAR measurement of maximum scale of turbulent GMF in disk



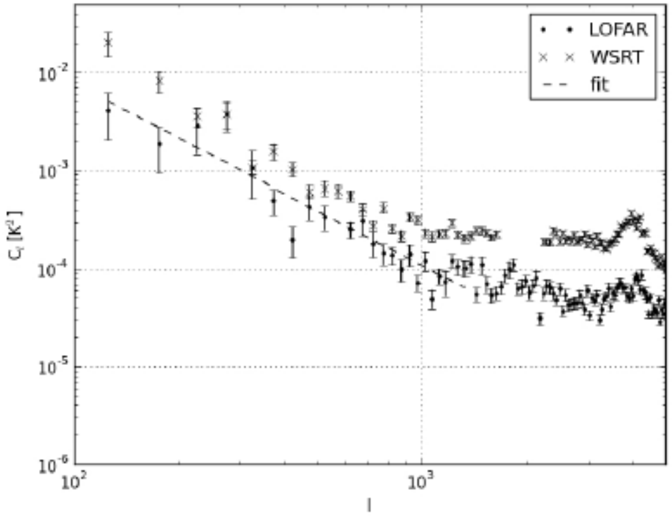


Fig. 9. Power spectra of total intensity from the LOFAR (dots) and WSRT (crosses) observations. The error bars indicate statistical errors at 1σ. The fitted power law (dashed line) with a spectral index $\alpha = -1.84 \pm 0.19$ for $\ell \in [100, 1300]$ is also shown.

arXiv: 1308.2804

Lmax ~ 20 pc +-6 pc in disk

Galactic cosmic ray model

ESCAPE MODEL:

- Idea: V. L. Ginzburg and S. I. Syrovatskii, *1962-1964; small angle diffusion approximation*
- Developement: V. S. Ptuskin et al., Astron. Astrophys. 268, 726 (1993); J. Candia, E. Roulet and L. N. Epele, JHEP 0212, 033 (2002); J. Candia, S. Mollerach and E. Roulet, JCAP 0305, 003 (2003). *Hall diffusion approximation*

Cosmic Ray Knee

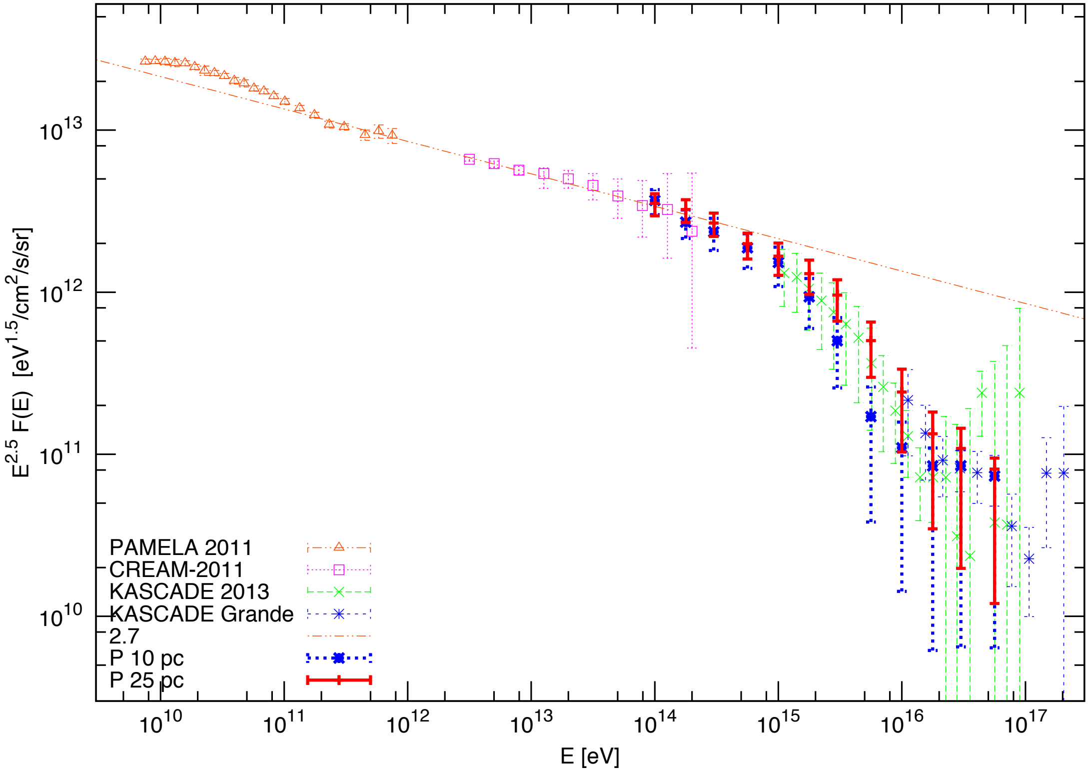
- change of interactions at multi-TeV energies: excluded by LHC
- maximal energy of dominant CR sources – Hillas model
- knee at $R_L(E/Z) \simeq l_{\rm coh}$:

  $\Rightarrow$ change in diffusion from $D(E) \sim E^{1/3}$ to
  - Hall diffusion $D(E) \sim E$
  - small-angle scattering $D(E) \sim E^2$
  - something intermediate?

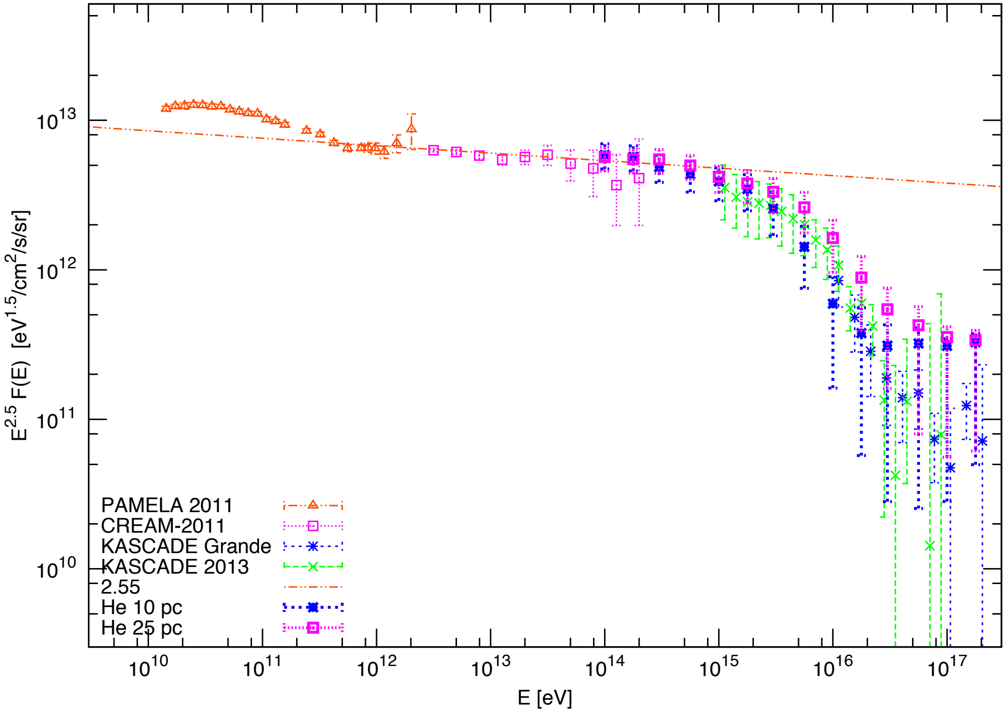
our approach:

- use model for Galactic magnetic field
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.

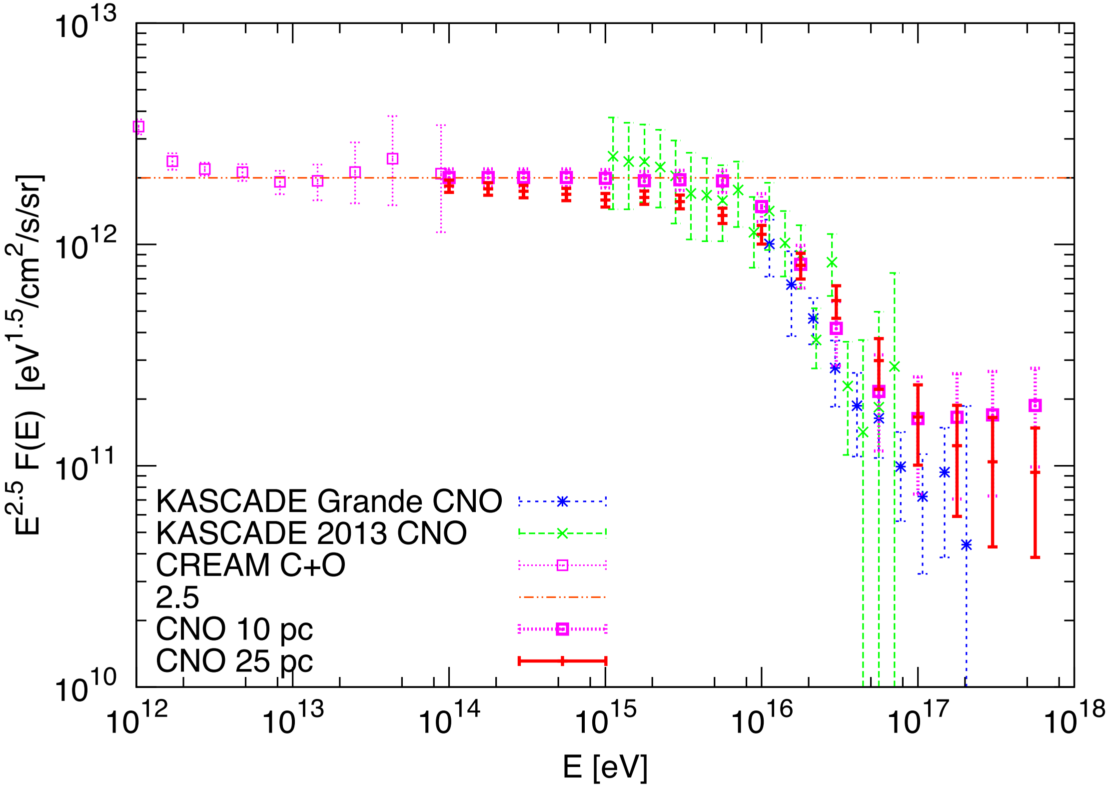
Cosmic Ray Knee: protons



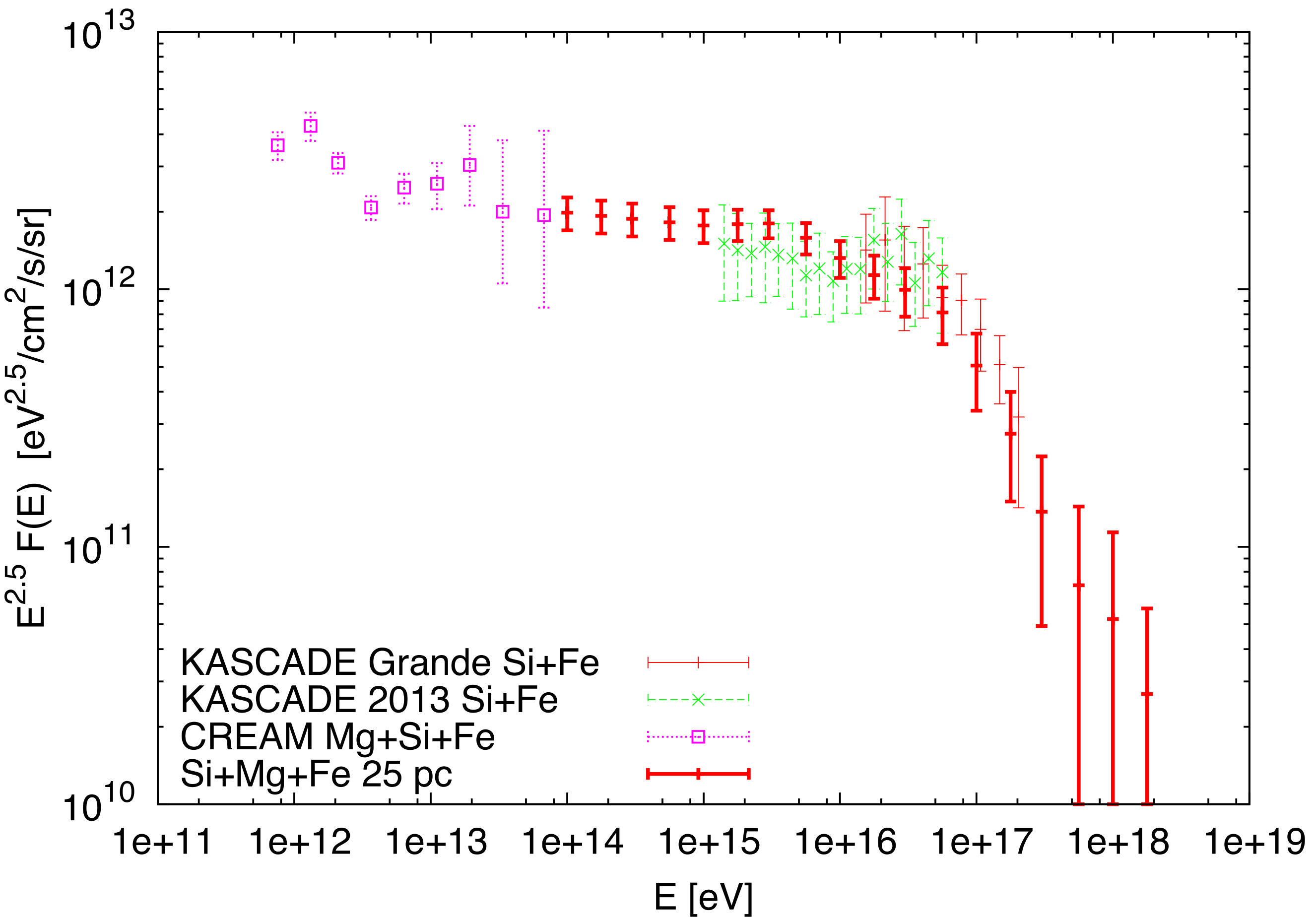
Cosmic Ray Knee: He



Cosmic Ray Knee: CNO

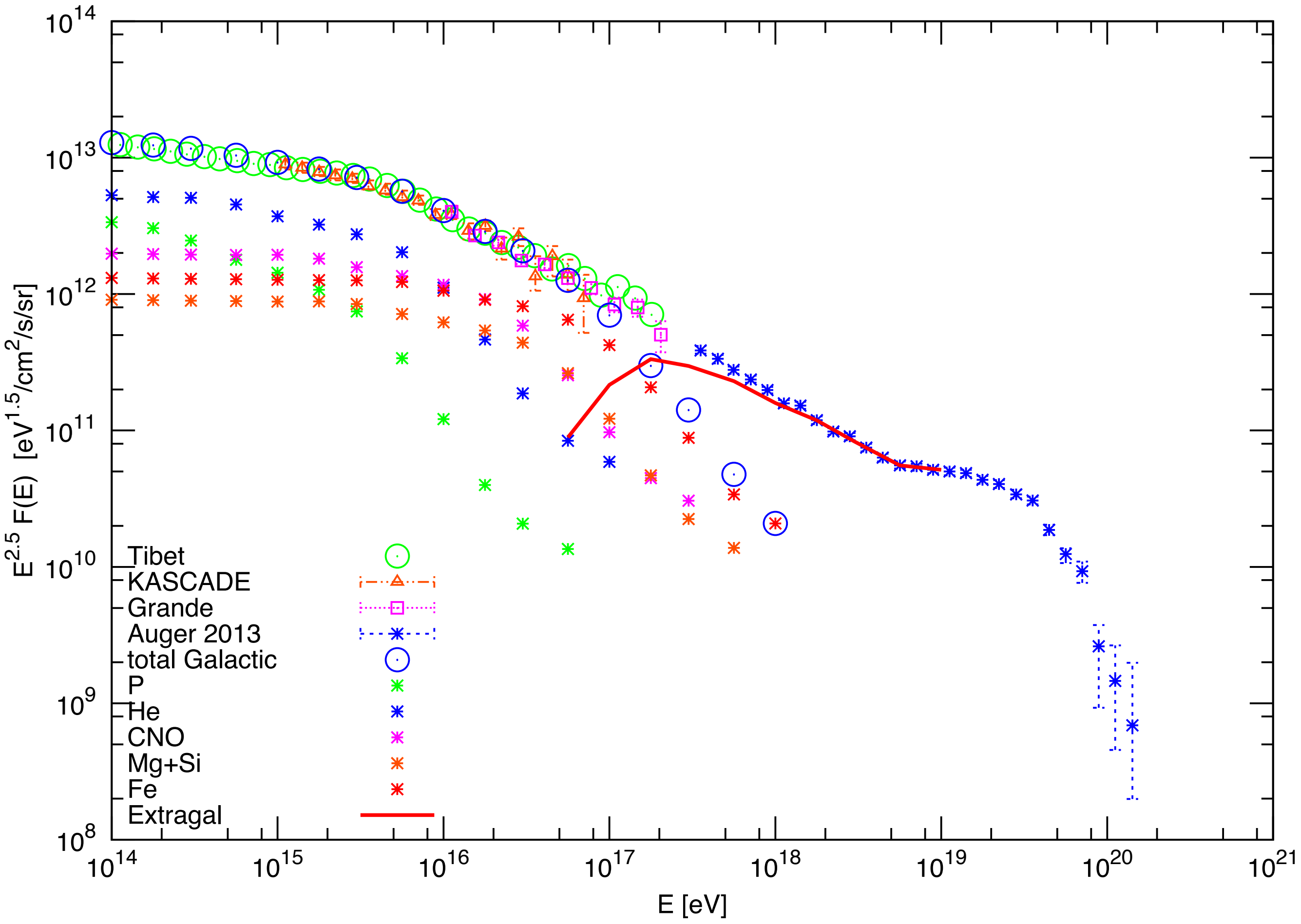


Cosmic Ray Knee: Mg+Si+Fe



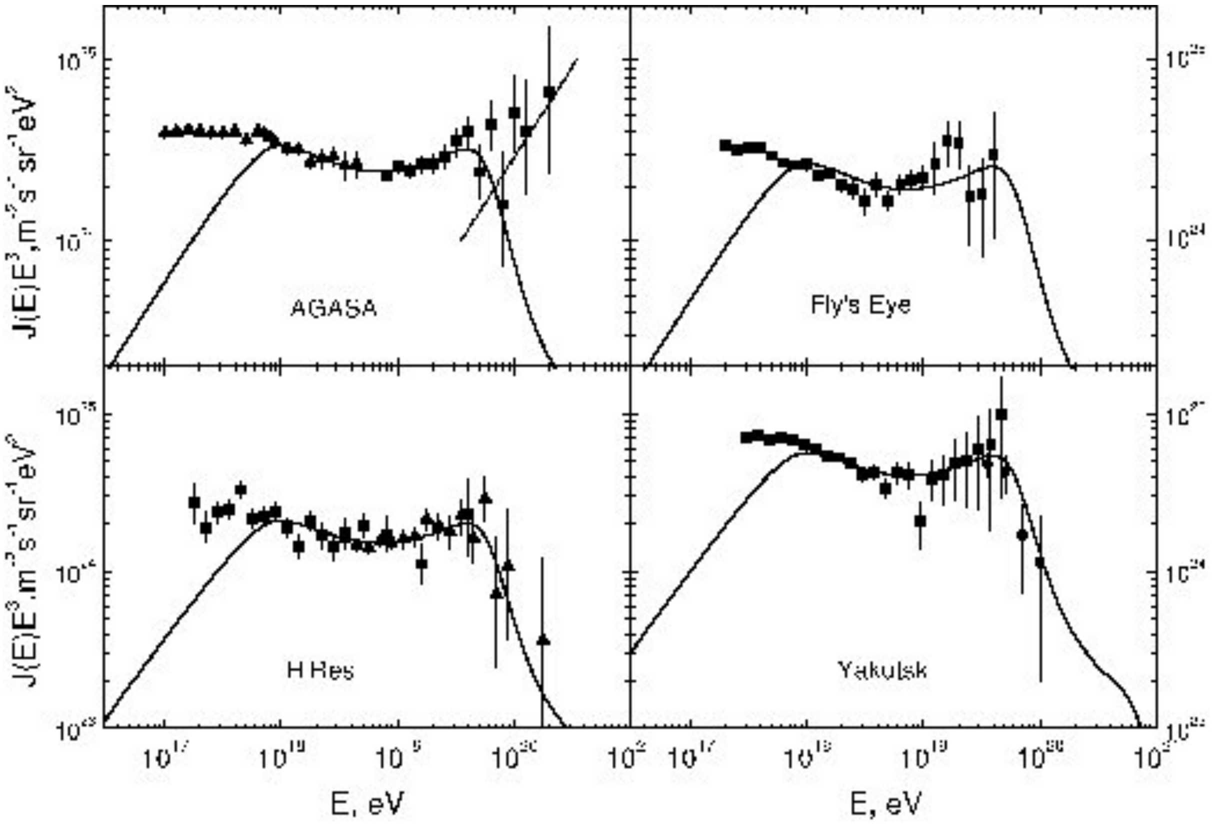
Thanks to Andreas Haungs for discussion

Cosmic Ray Knee: all particles



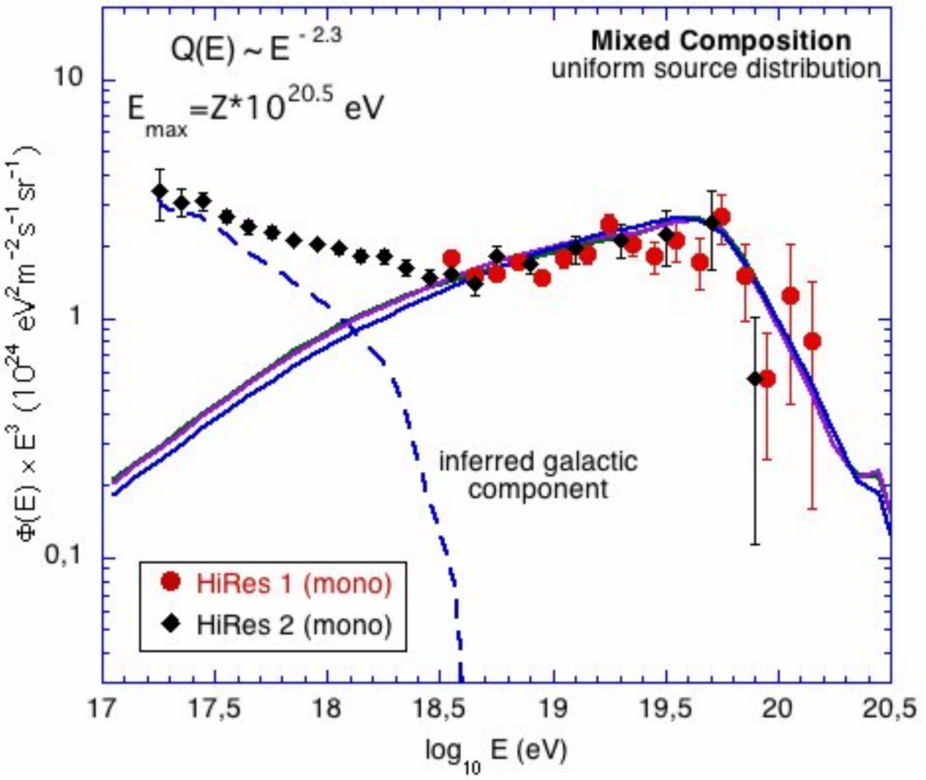
Transition from galactic to extragalactic cosmic rays

Dip model: Protons can fit UHECR data



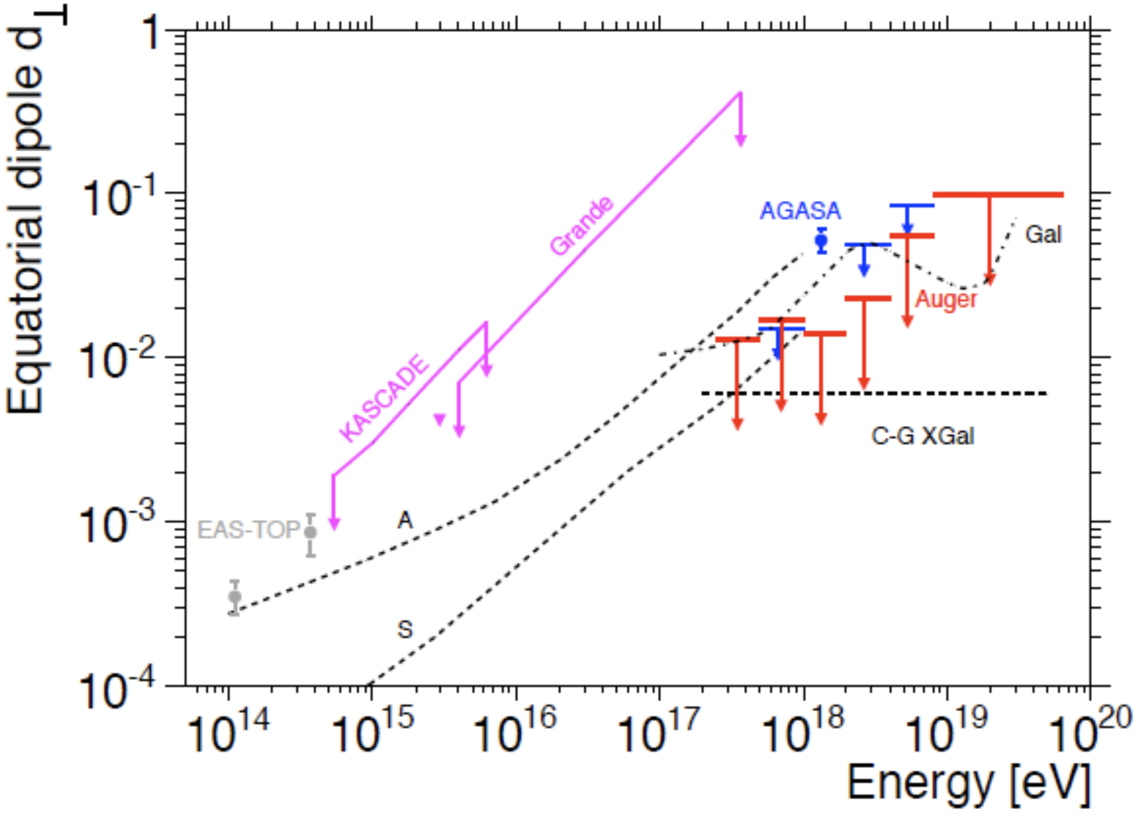
V.Berezinsky , astro-ph/0509069

Mixed composition model



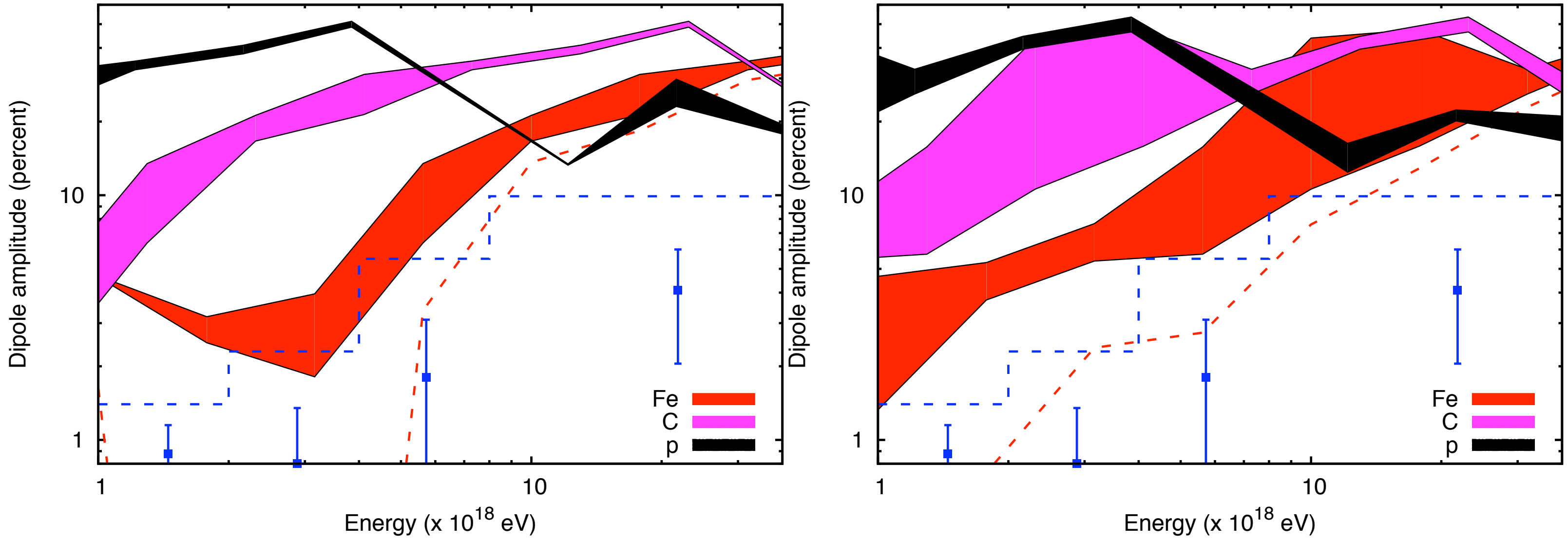
D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Anisotropy dipole



Pierre Auger Collaboration, arXiv:1103.2721

Galactic sources: dipole calculation

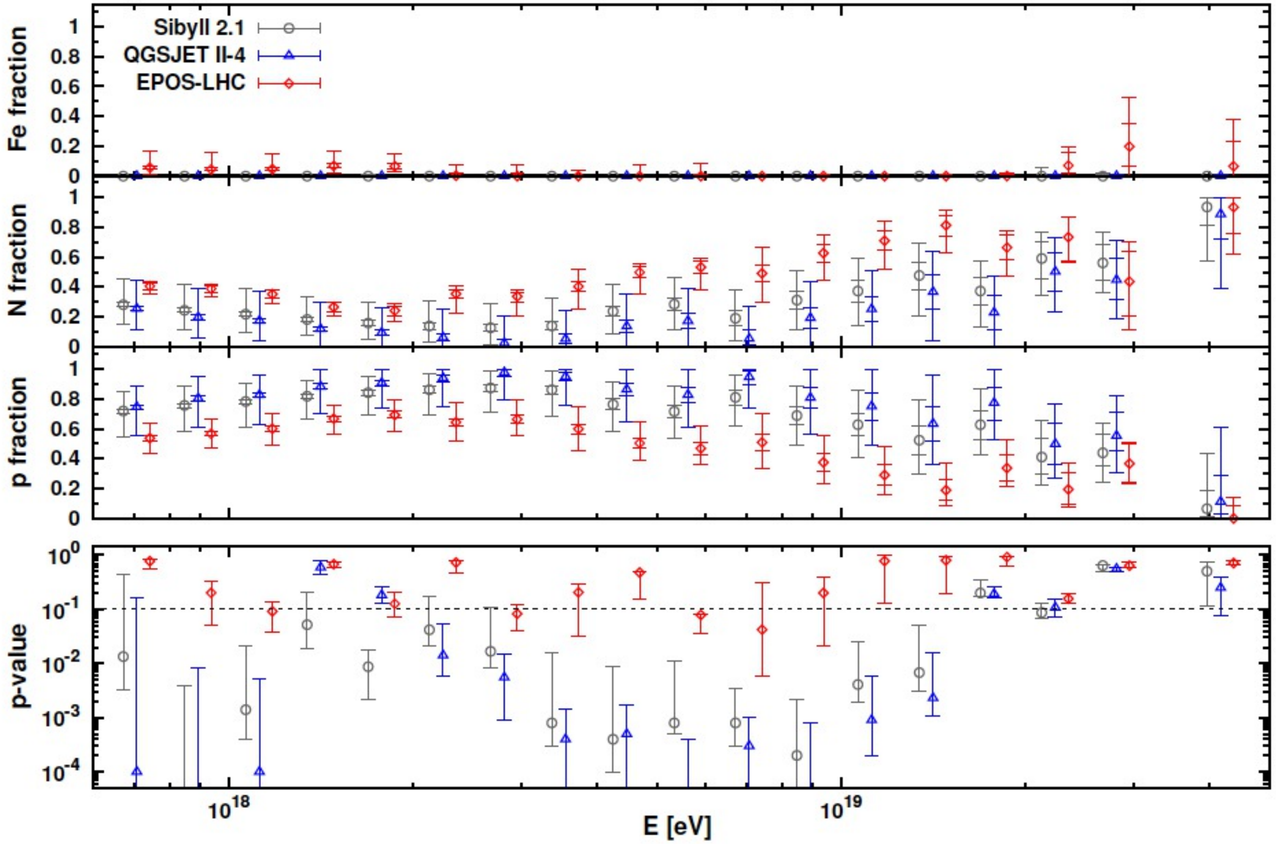


Turb. Magn. Field spectrum
Kolmogorov/Kraichnan

Lmax = 100-300 pc

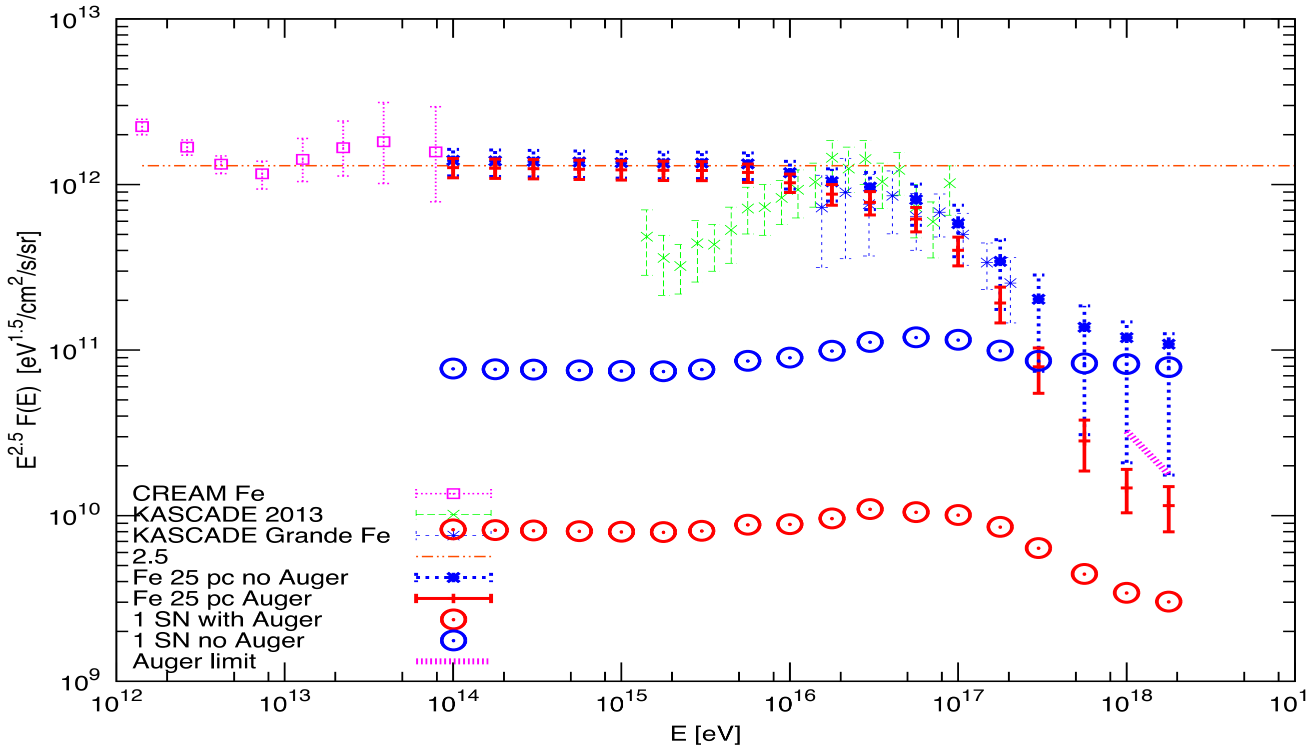
G.Giacinti, M.Kachelriess, D.S. and G.Gigl, **arXiv:1112.5599**

Auger cosmposition measurements

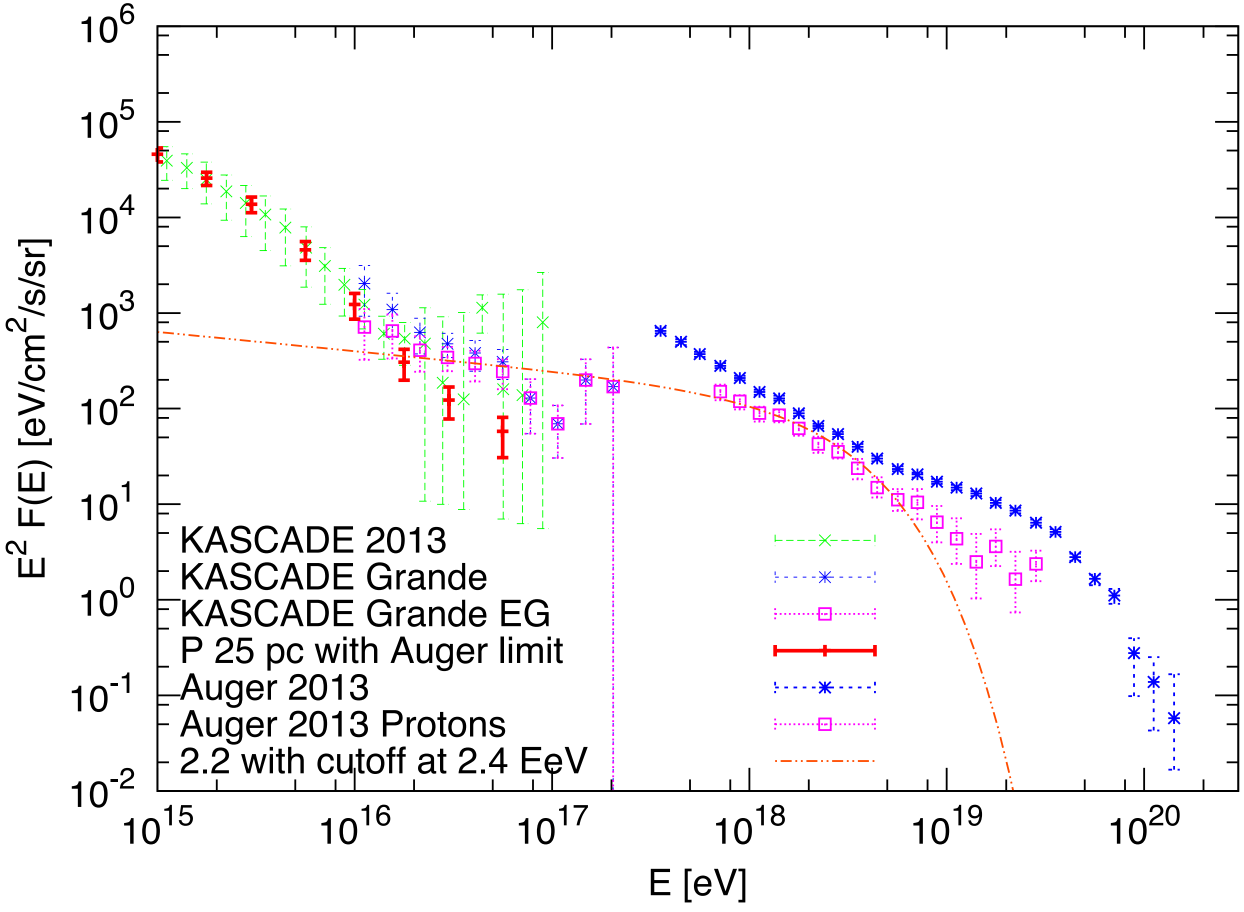


Auger Collaboration, **arXiv:1409.5083**

Auger limit on Fe fraction



Extragalactic proton sources



G.Giacinti et al,1502.01608

Theoretical predictions of neutrino flux

EXPECTED NEUTRINO FLUXES

Local optical depth of protons:

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

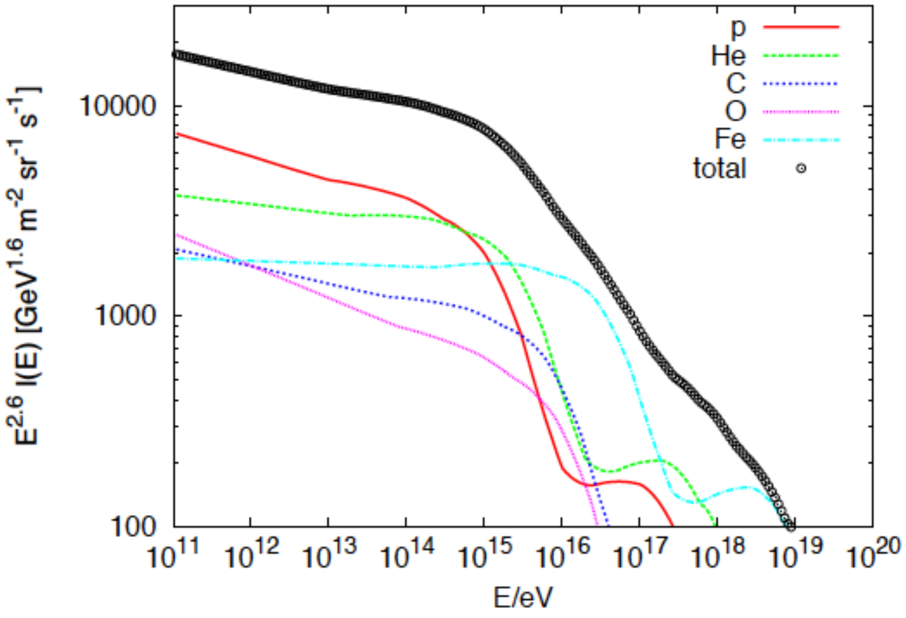
$\tau(10\ \mathrm{PeV})=0.0002$

E^2F_ν(PeV)=0.2 eV/cm^2/s/sr

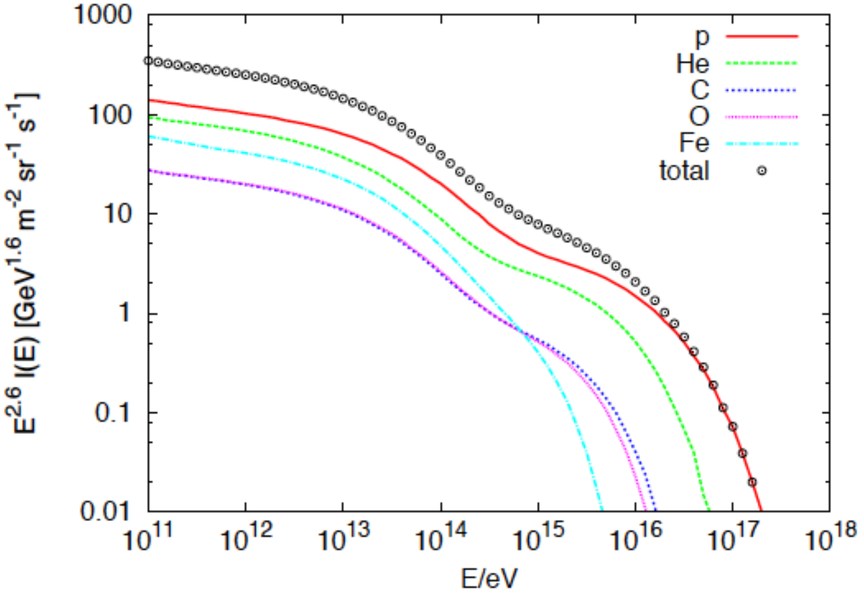
E^2F_ν(100 TeV)=3 eV/cm^2/s/sr

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:

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

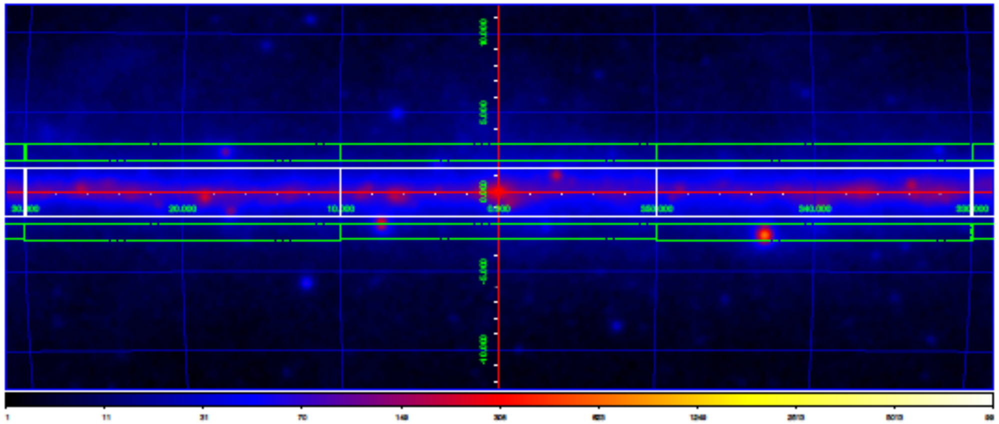
M.Kachelriess and S.Ostapchenko, arXiv:1405.3797

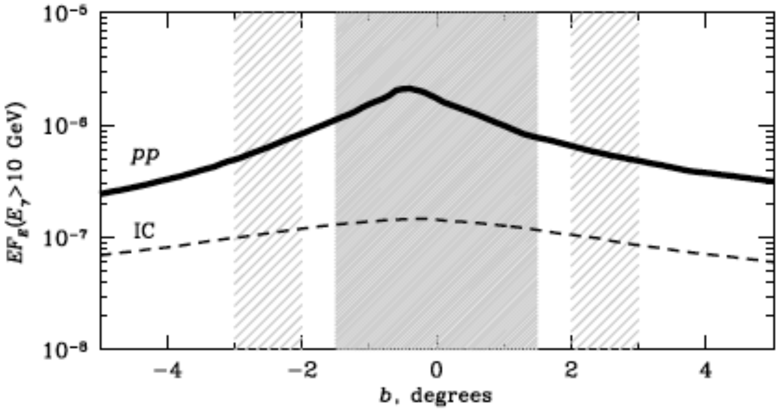
Galactic neutrino fluxes

- Point sources (isolated) give small contribution
- Diffuse flux normalized to local CR flux give too small contribution
- Flux in the arms dominates: GMC with larger magnetic fields and larger gas density, recent sources

CR spectrum in MW and LMC from gamma-rays

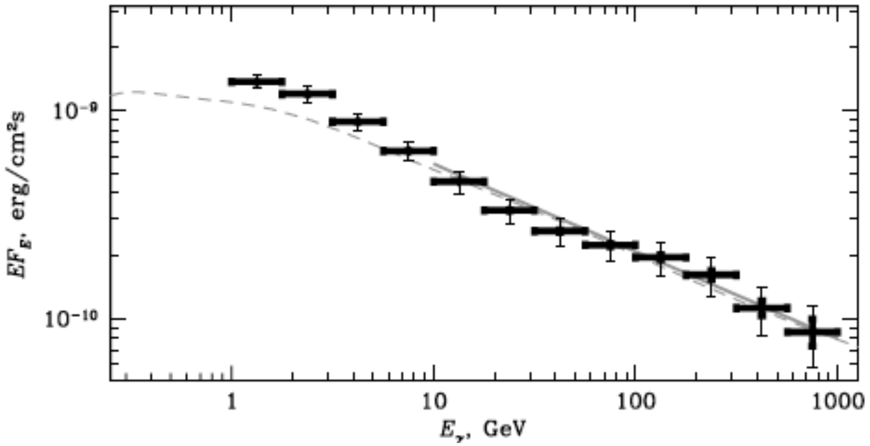
Milky Way inner Galaxy
Fermi E>10 GeV

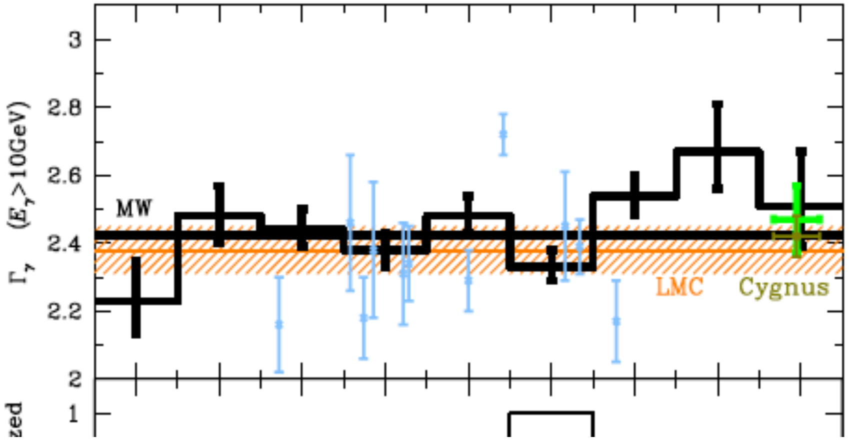




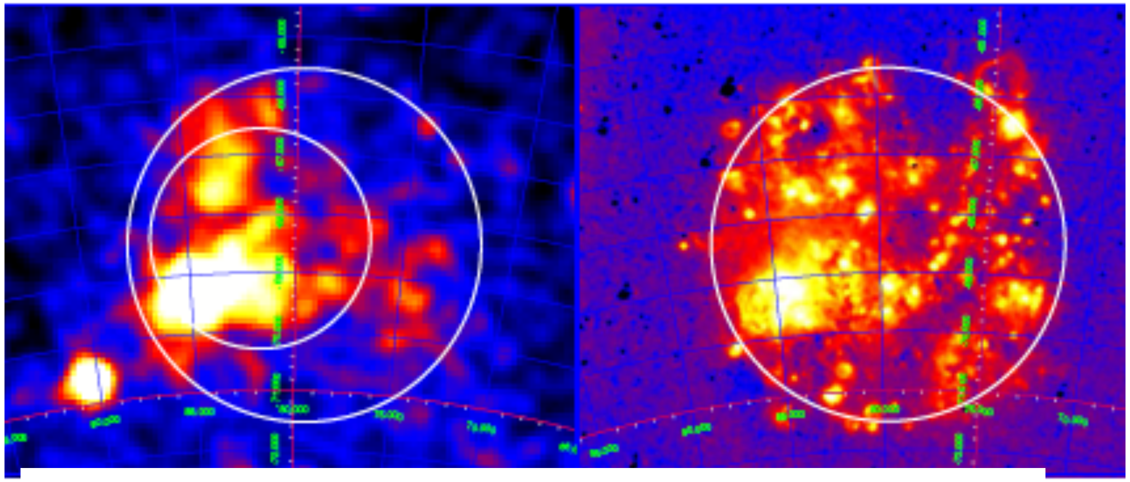
A.Neronov and D.Malishev, arXiv: 1505.07601

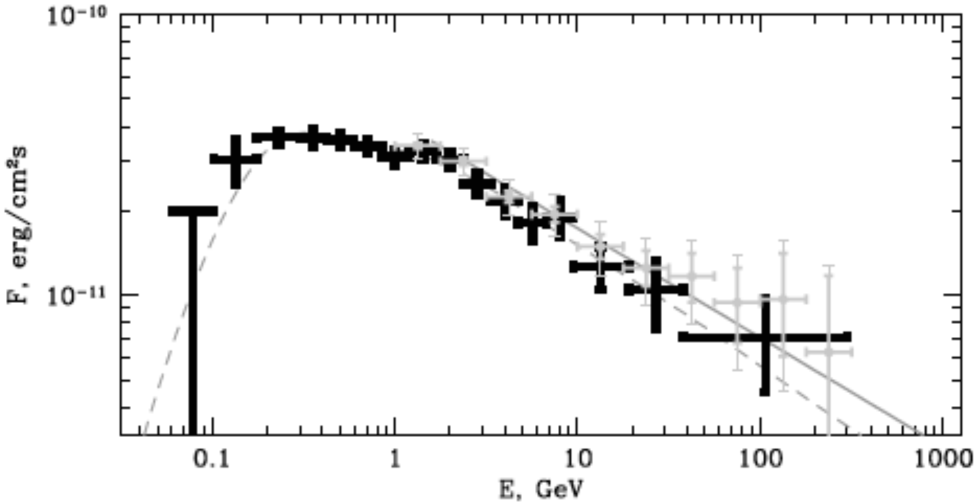
Milky Way inner Galaxy
Fermi E>10 GeV: spectrum 2.45





In LMC average proton spectrum 2.45

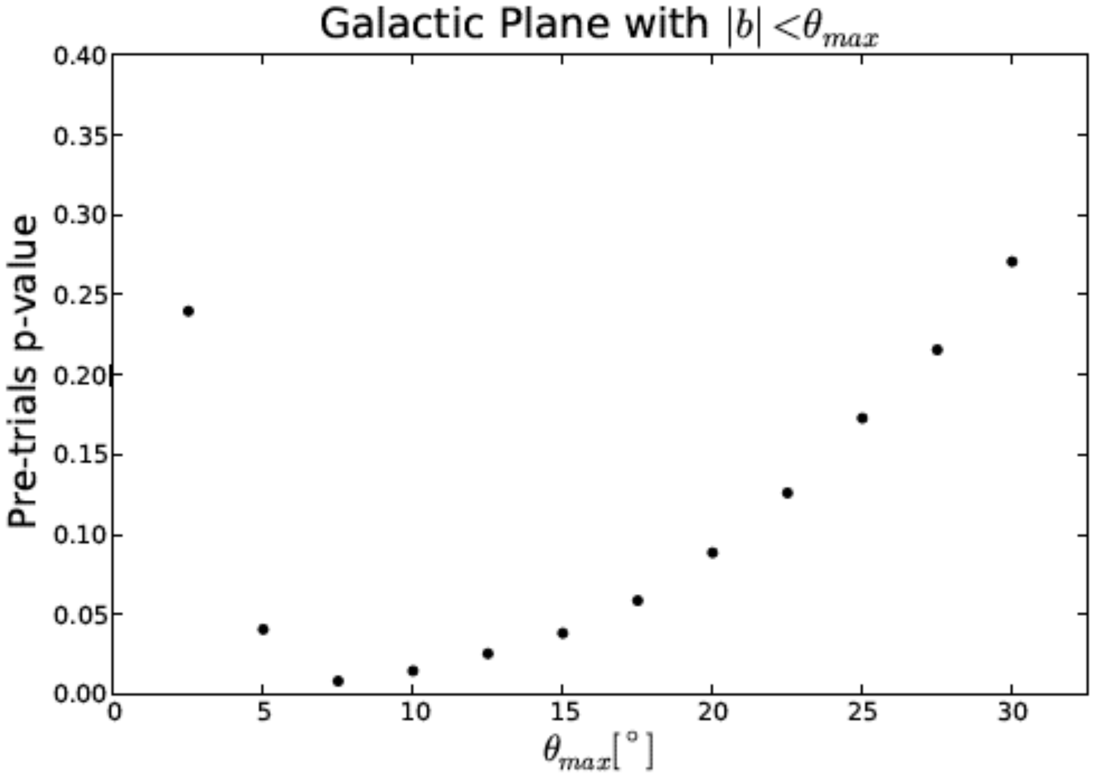




A.Neronov and D.Malishev, arXiv: 1505.07601

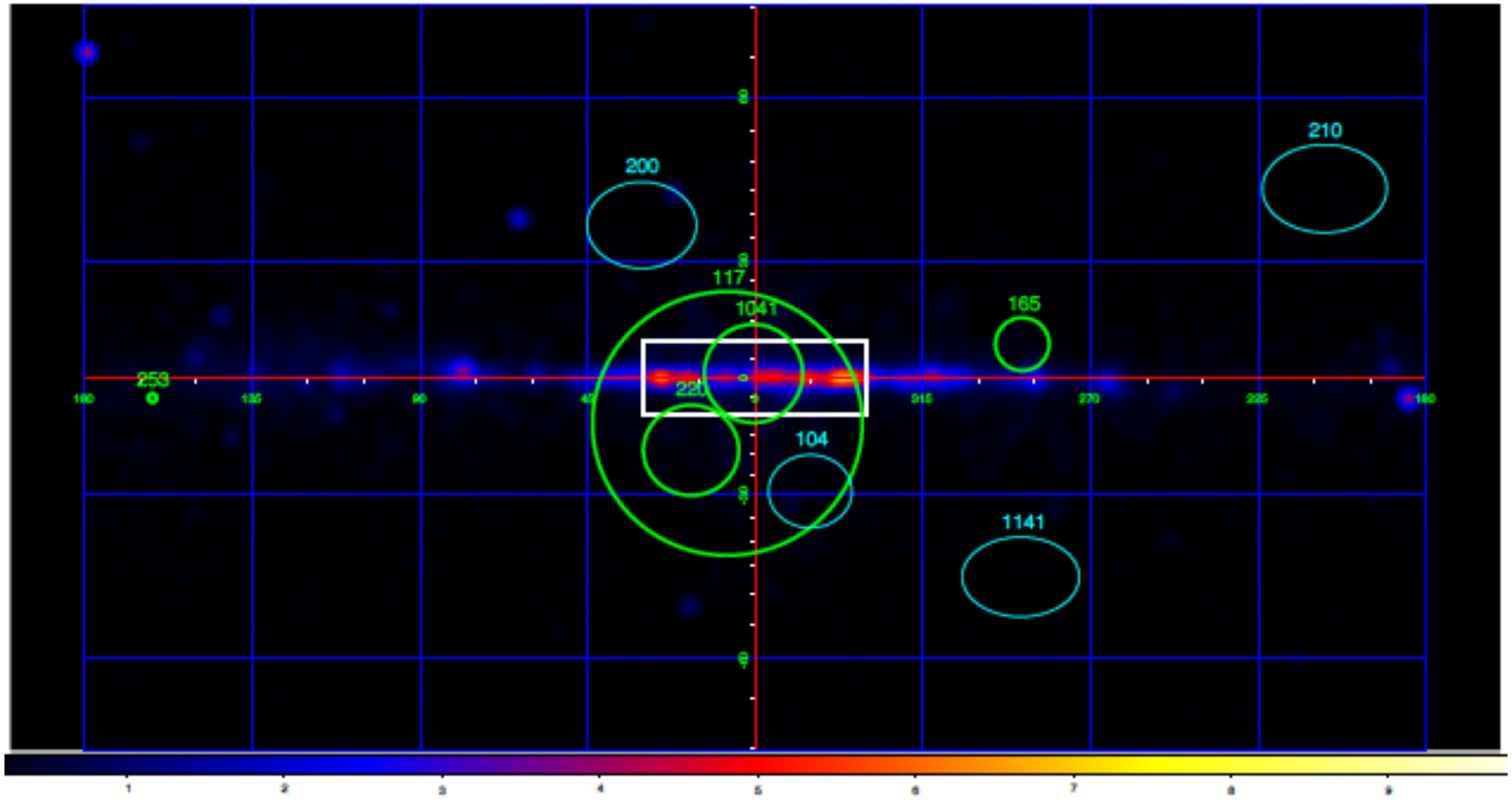
Neutrino flux from Milky Way

Galactic plane: 2% by chance



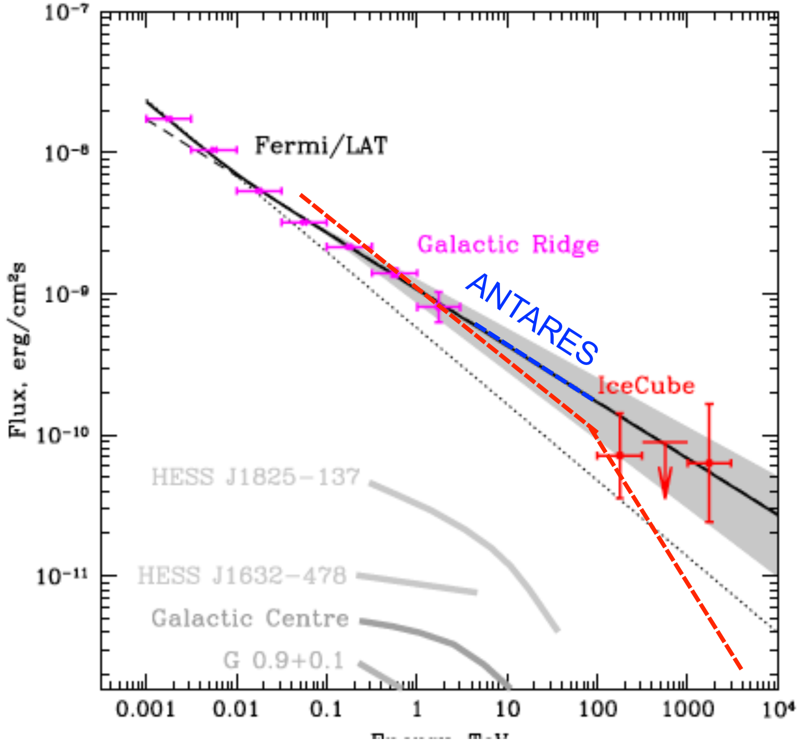
ICECUBE collaboration, 1405.5303

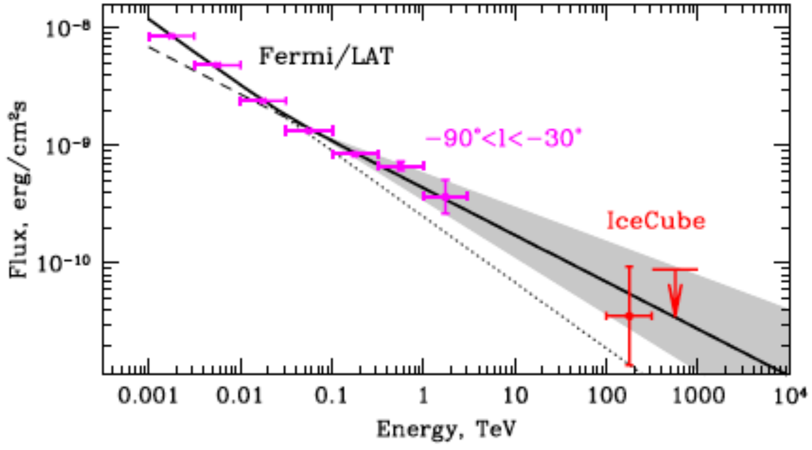
Half of ICECUBE events E>100 TeV are in Galactic plane. Are they correlate with gamma-rays?



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

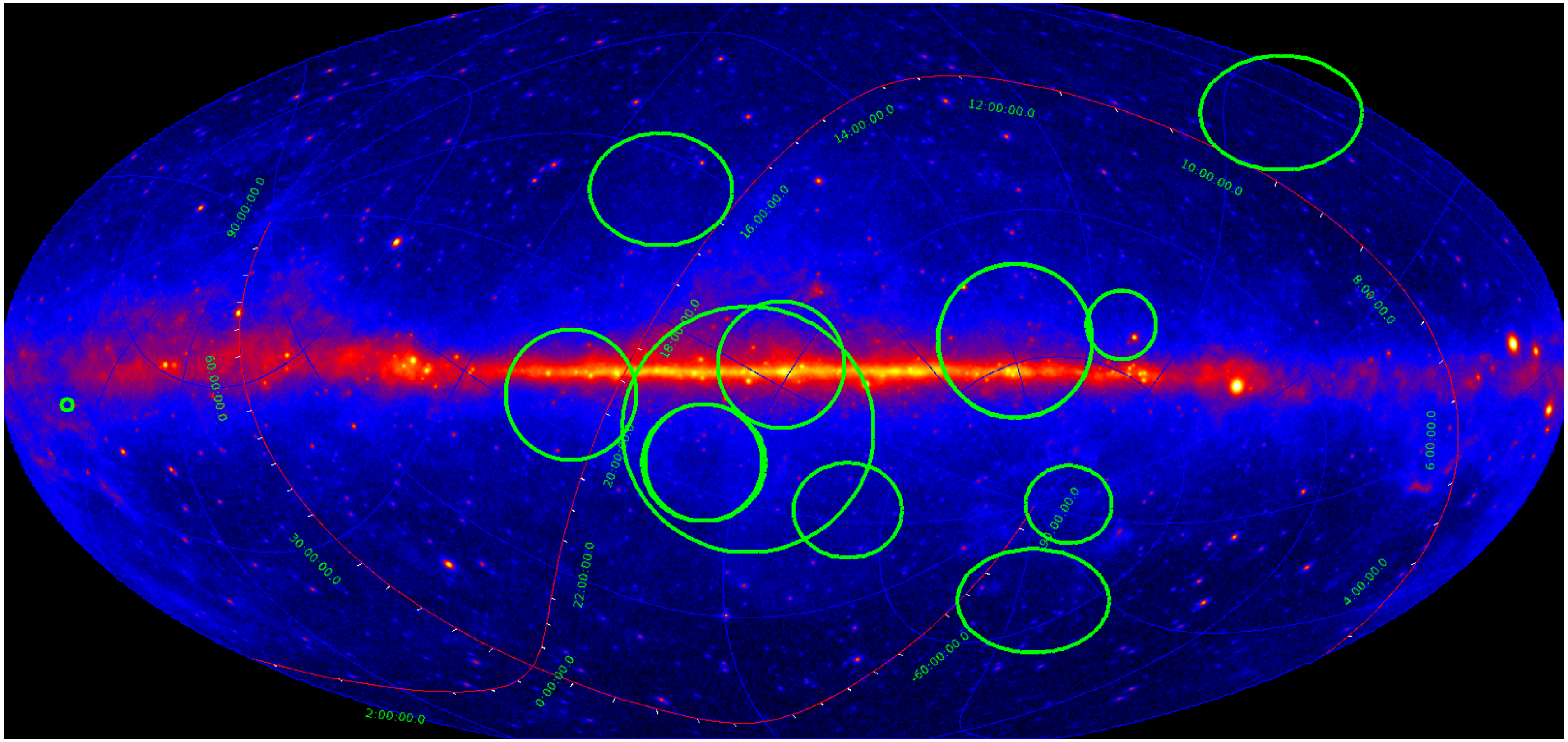
Real multimessenger fluxes, alpha=2.5



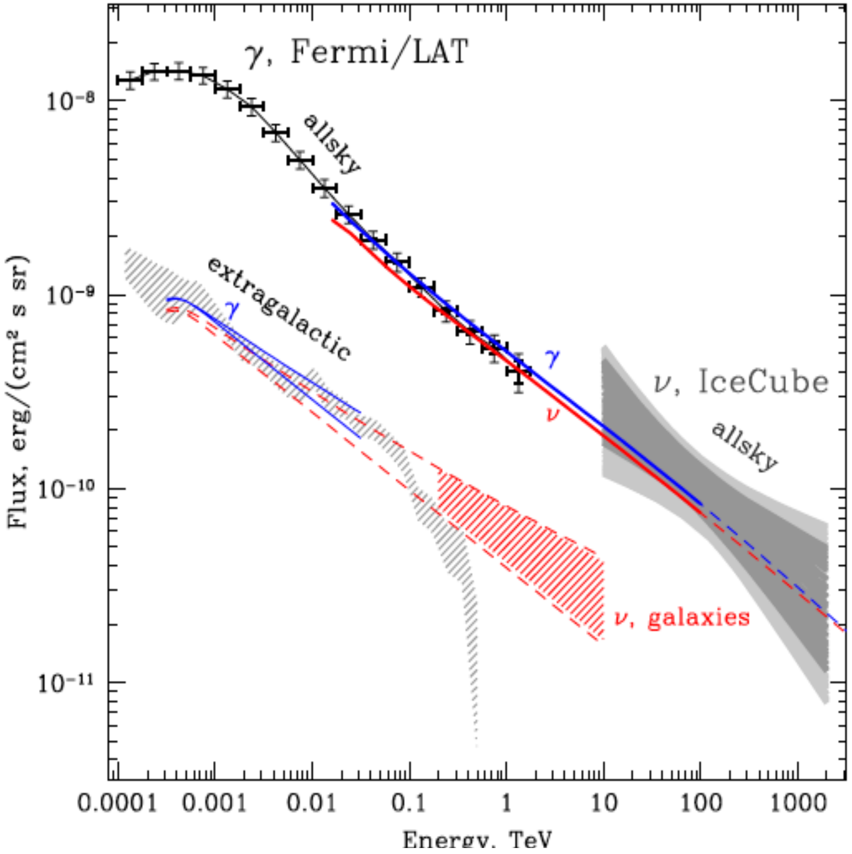


V.Berezinsky & A.Smirnov 1975

IceCube neutrino sky map
3 years E> 100 TeV

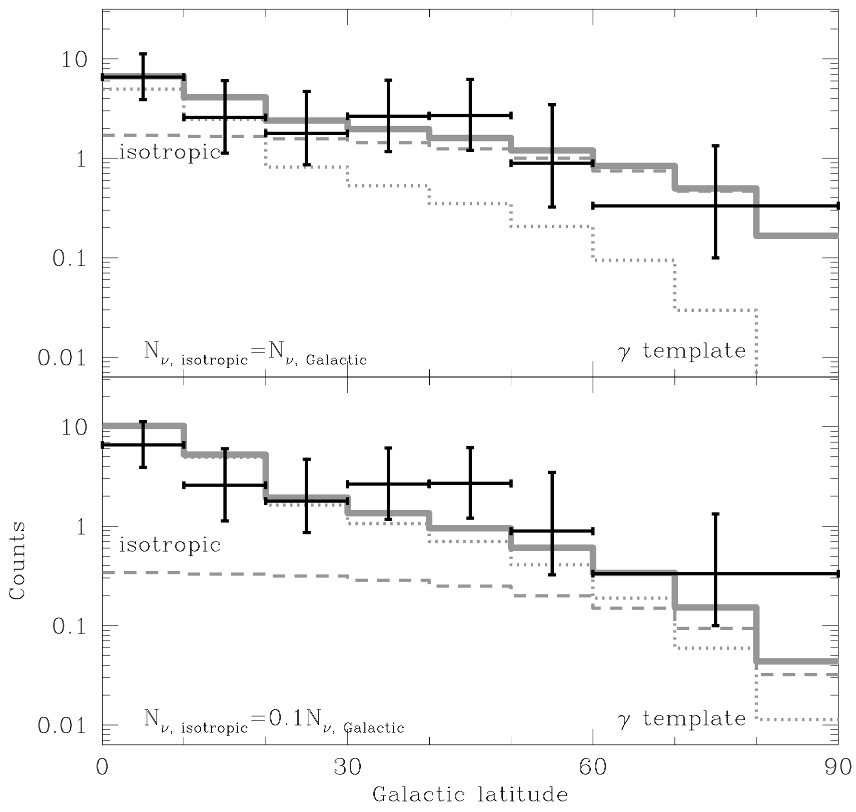


IceCube + Fermi LAT all sky: protons 1/E^2.5

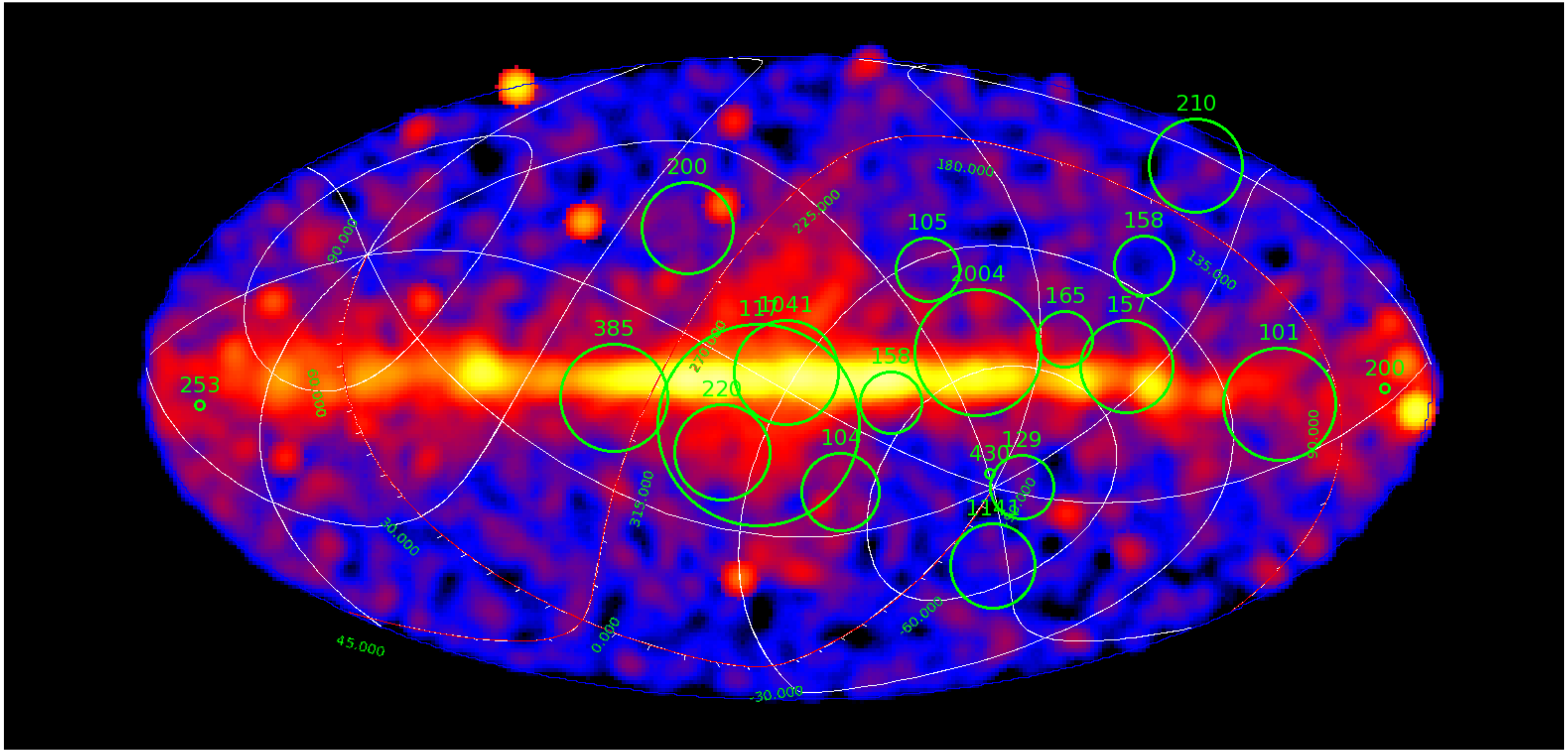


A.Neronov, D.S. arXiv:1412.1690

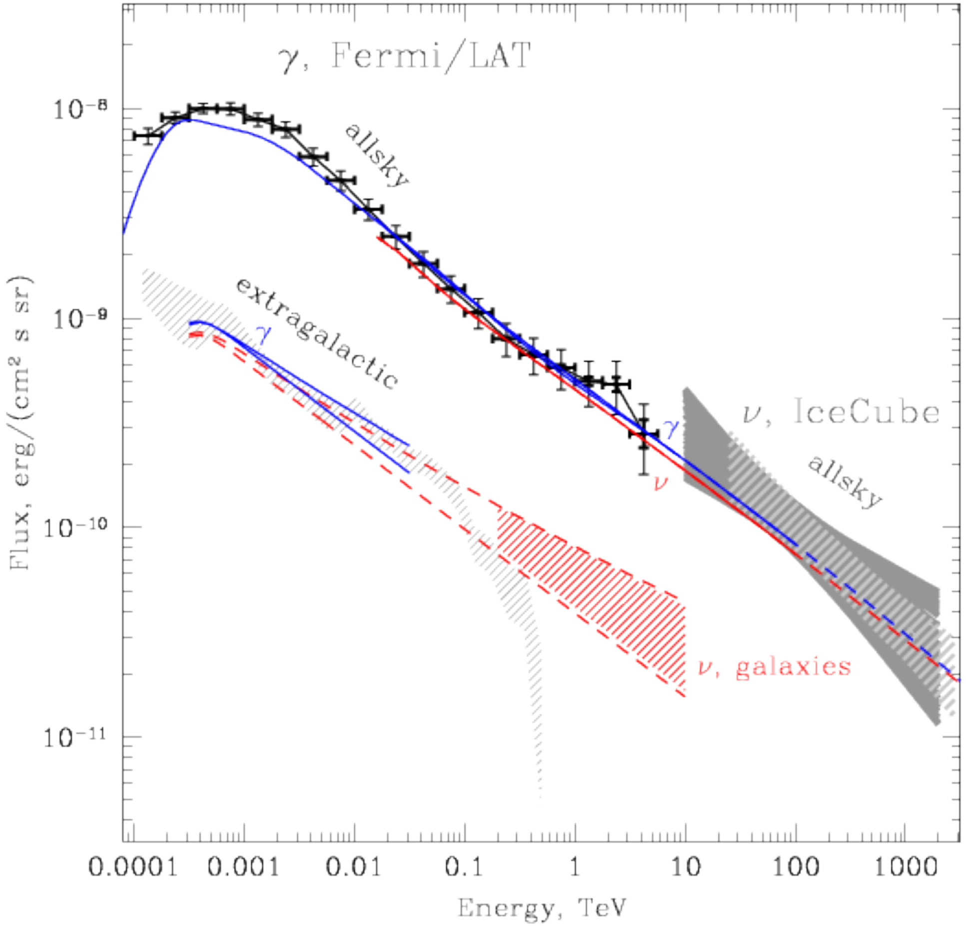
Neutrino flux as function of |b|



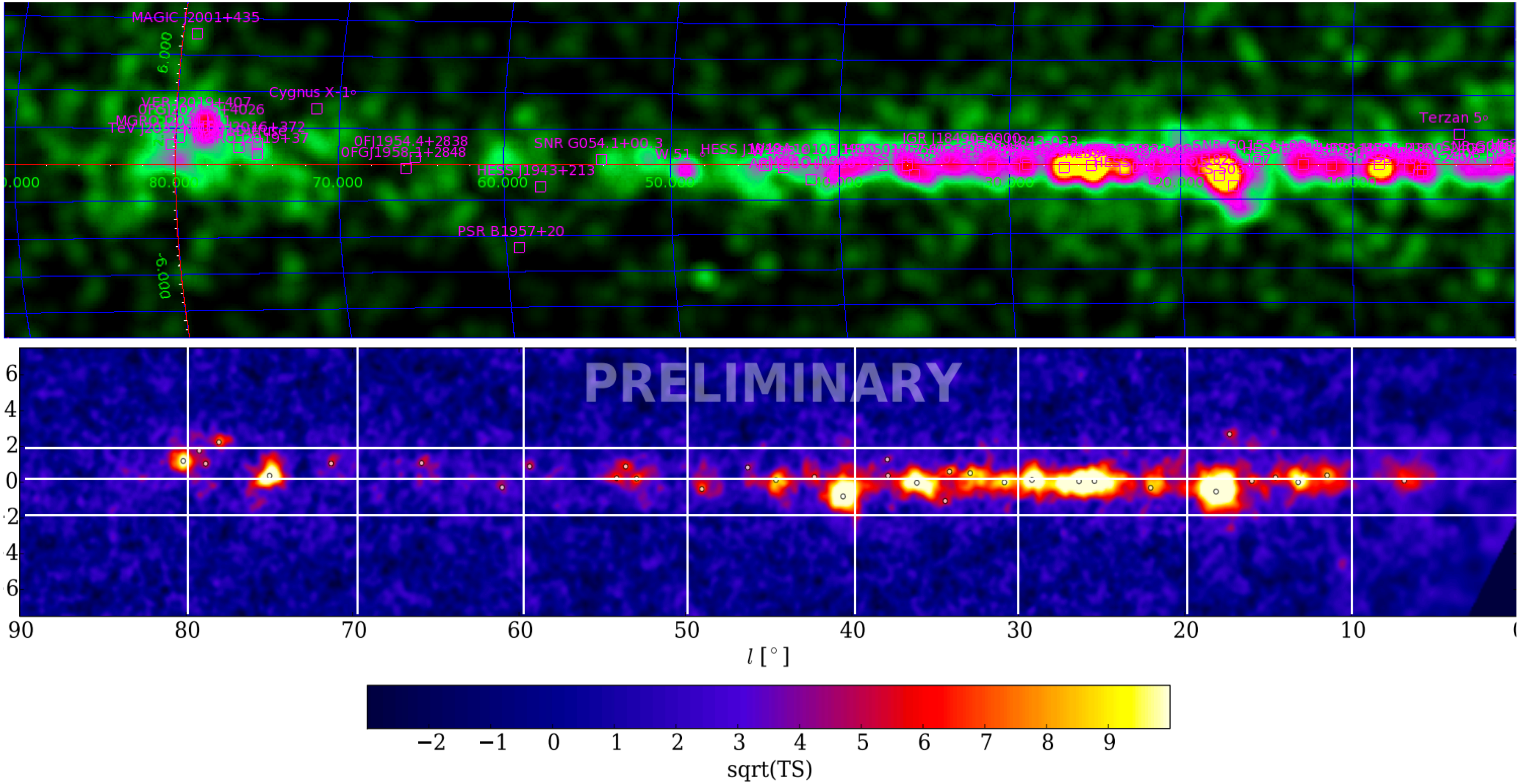
IceCube neutrino sky map 4 years E> 100 TeV and Fermi E>100 GeV 5 degree smoothed



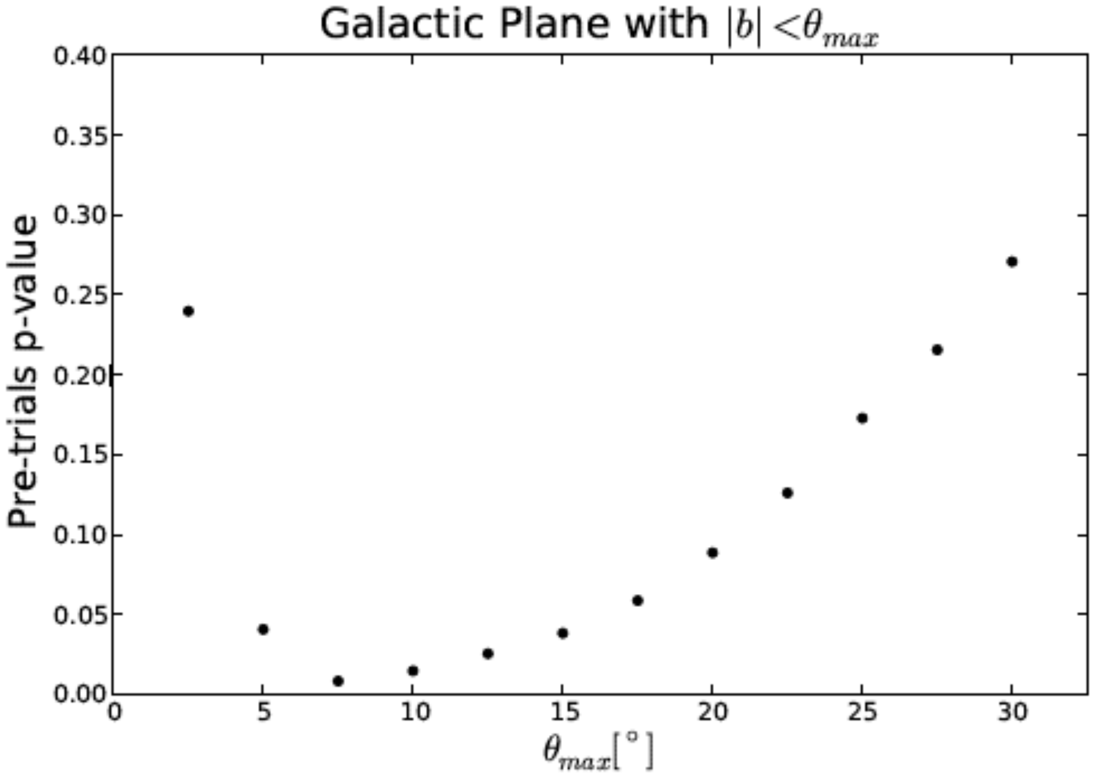
IceCube + Fermi LAT all sky: update



First HAWC results: E> 4 TeV gamma-rays

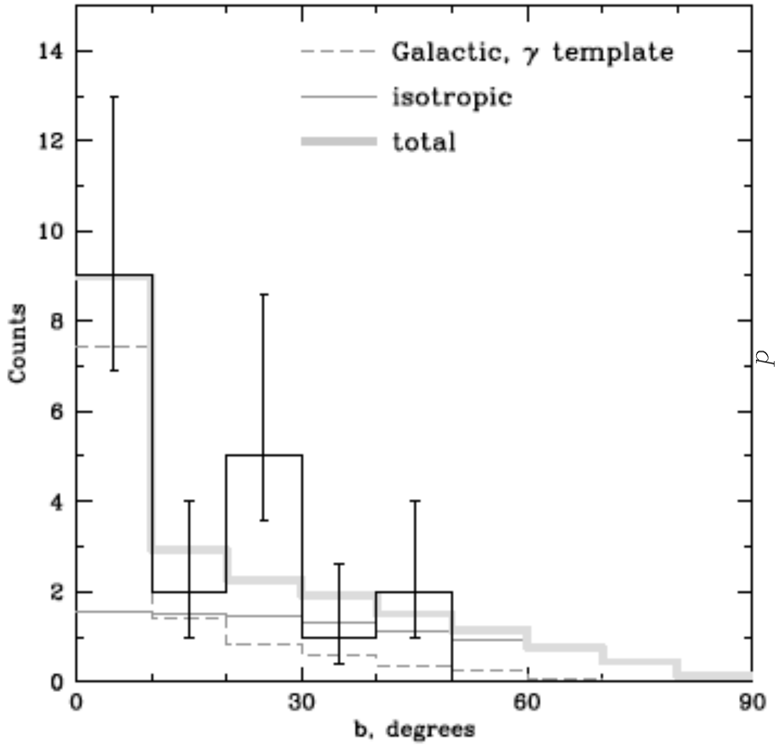


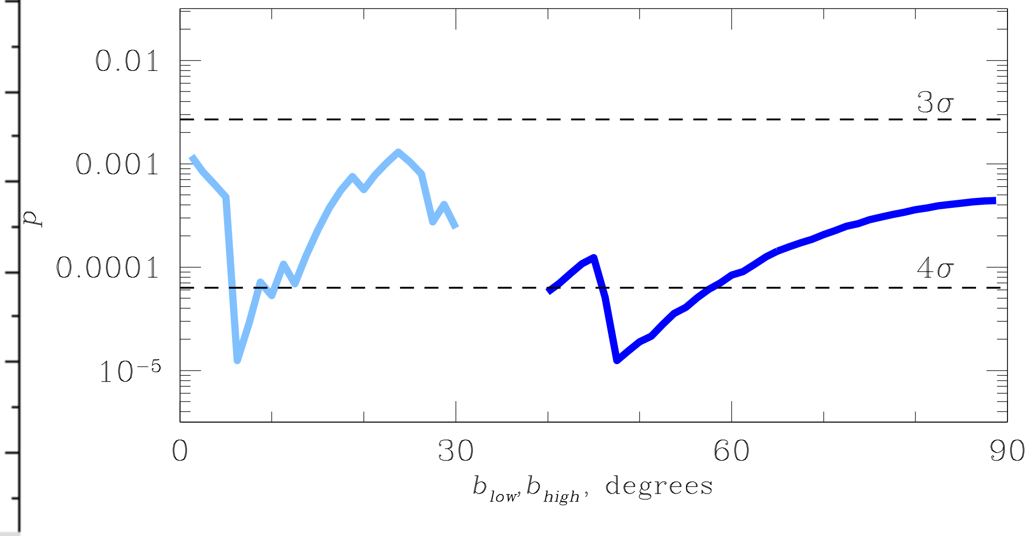
IceCube galactic plane 3 years: 2% by chance – small statistics



ICECUBE collaboration, arXiv:1405.5303

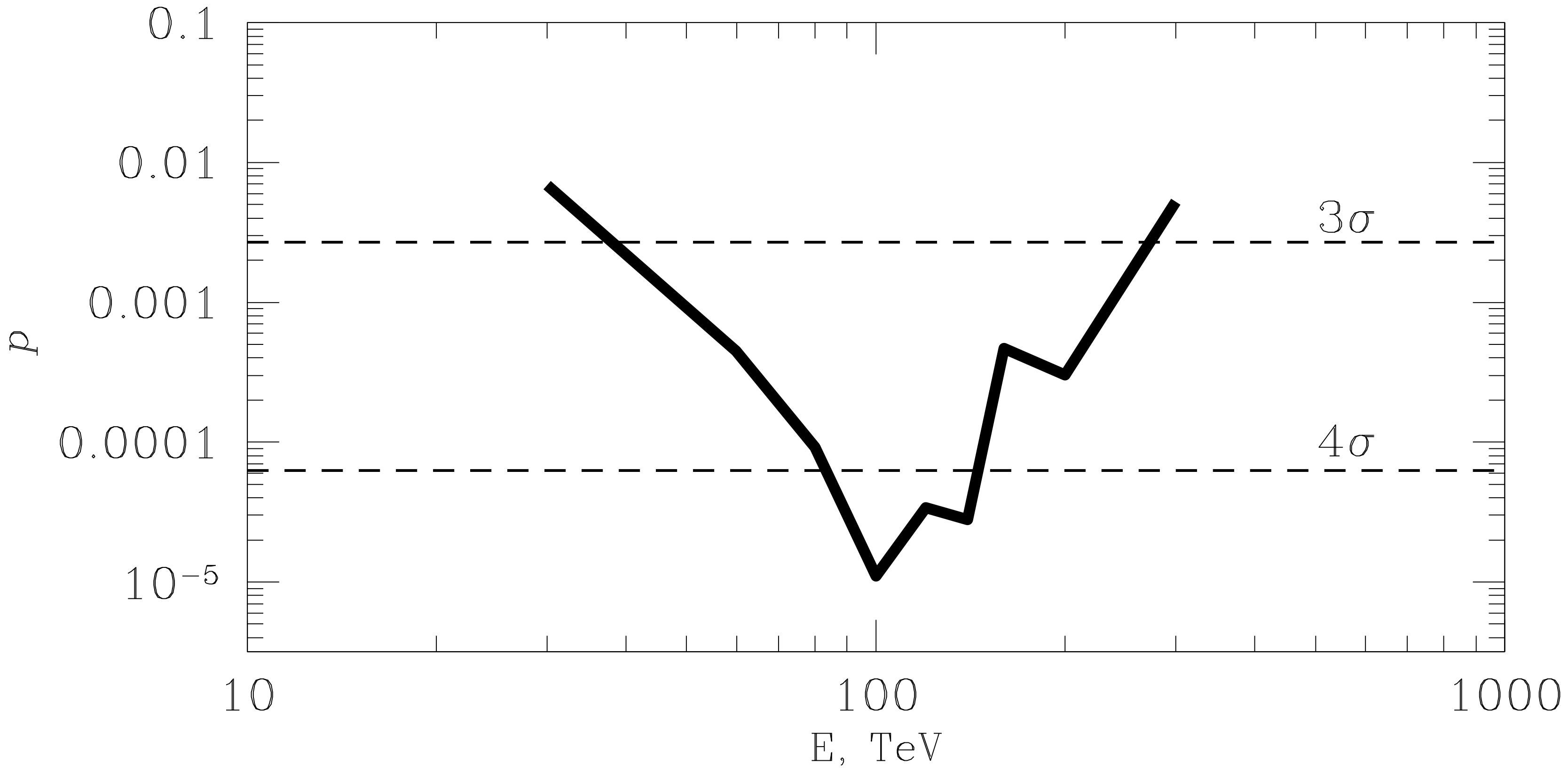
Evidence of Galactic component in 4 year IceCube data E>100 TeV





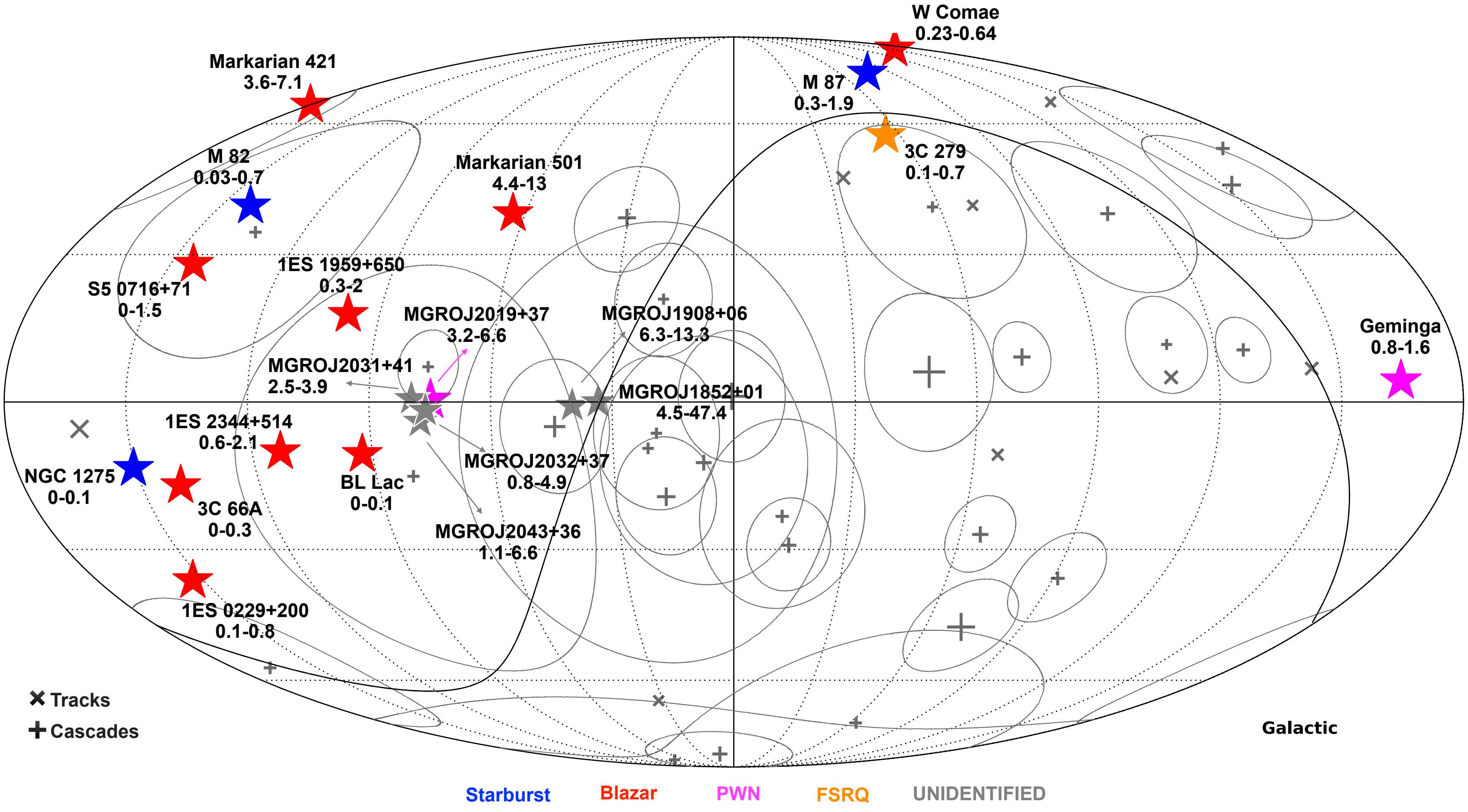
A. Neronov & D.S. arXiv: 1509.03522

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



A. Neronov & D.S. arXiv: 1509.03522

number of neutrino events from gamma ray sources in 5 years



Diffuse gamma-ray background

Pion production

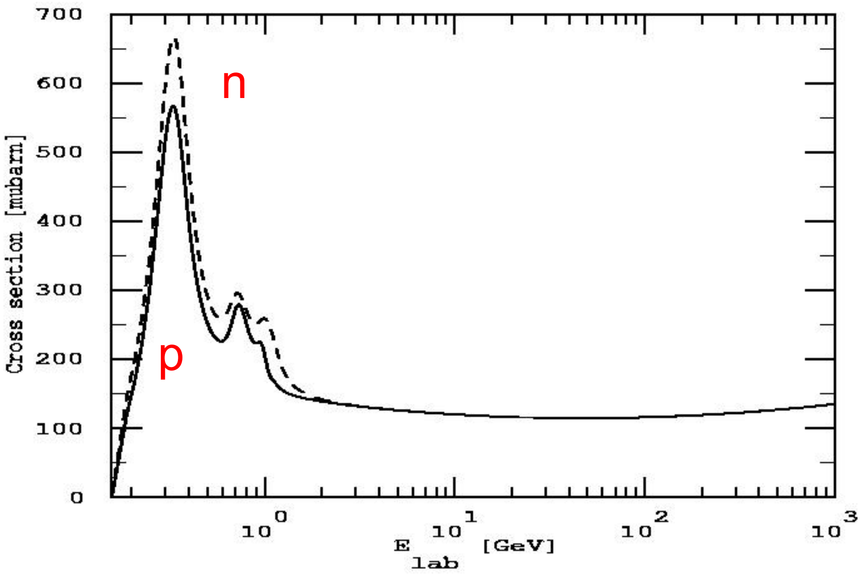
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

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

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

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

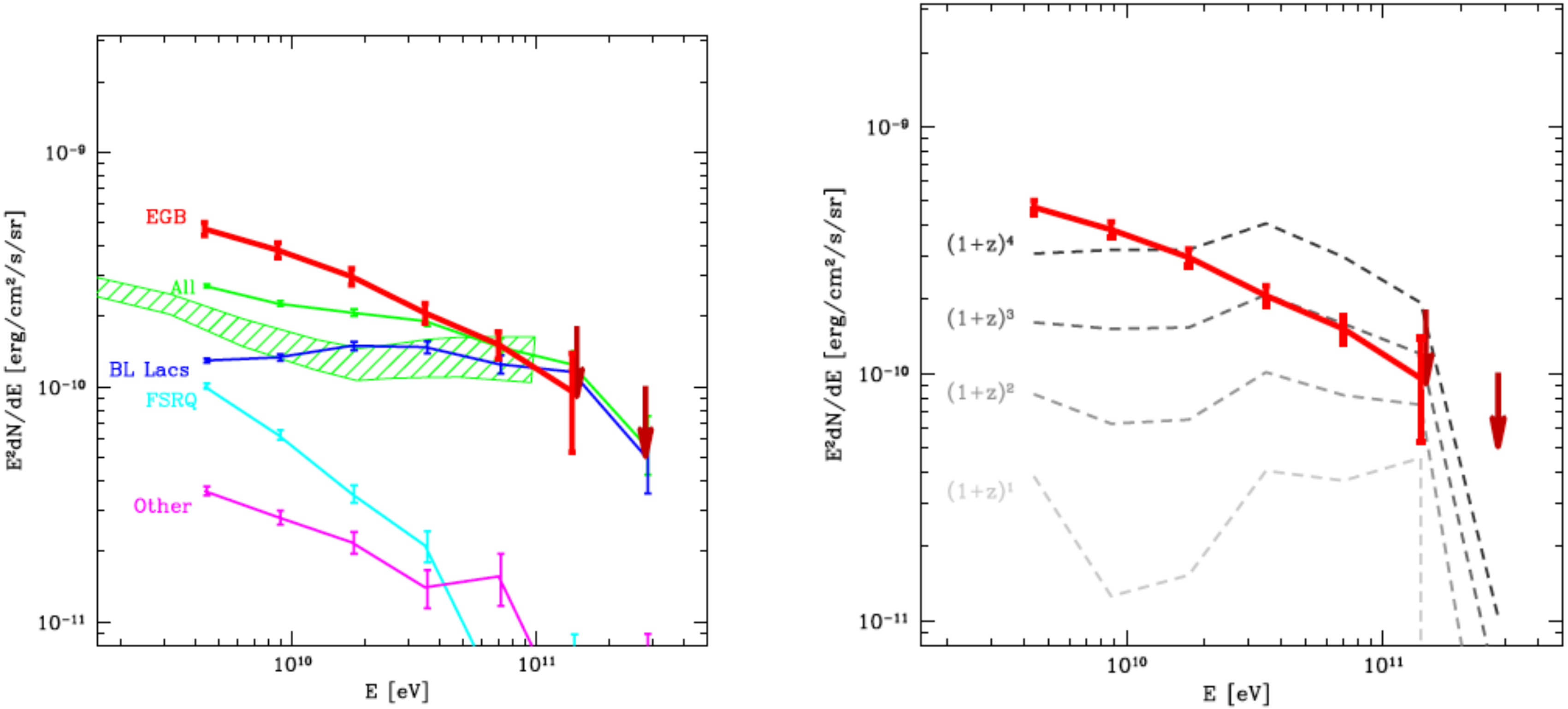
$$\mu^\pm \Rightarrow e^\pm + \overline{\nu}_e + \nu_\mu$$



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

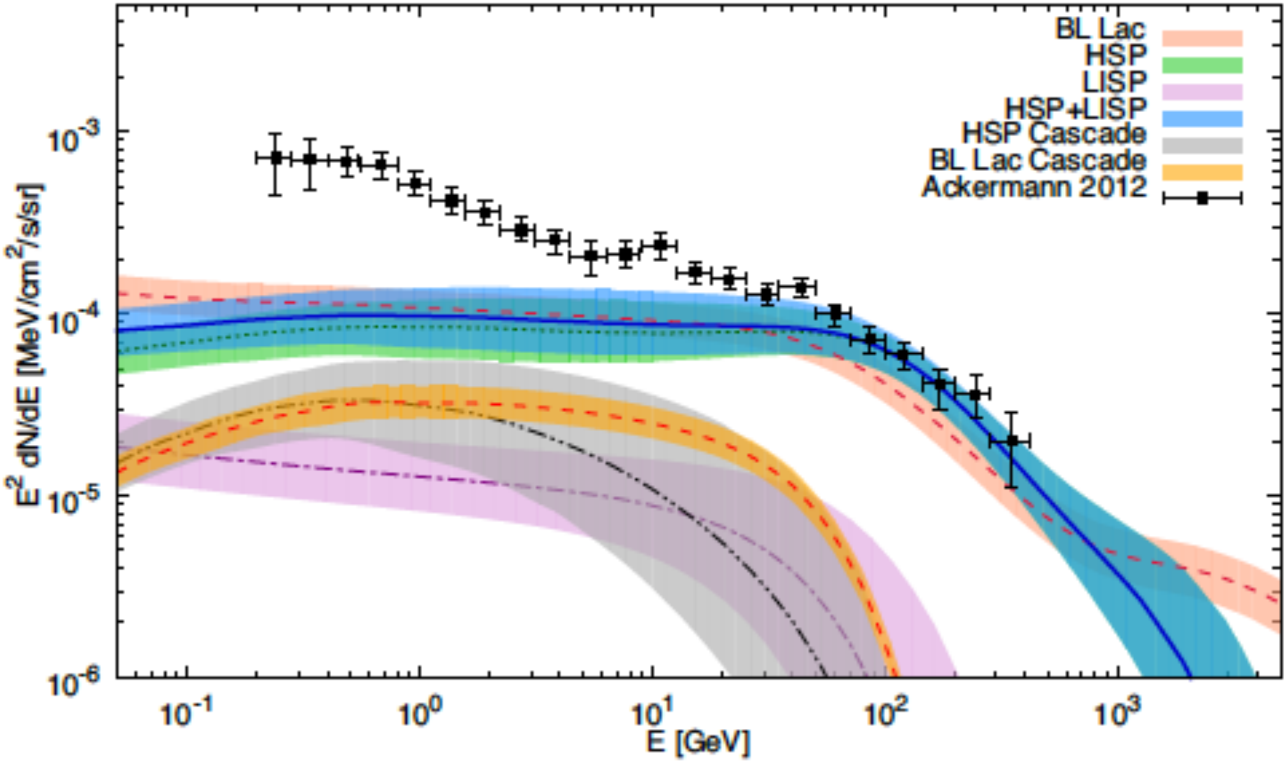
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

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



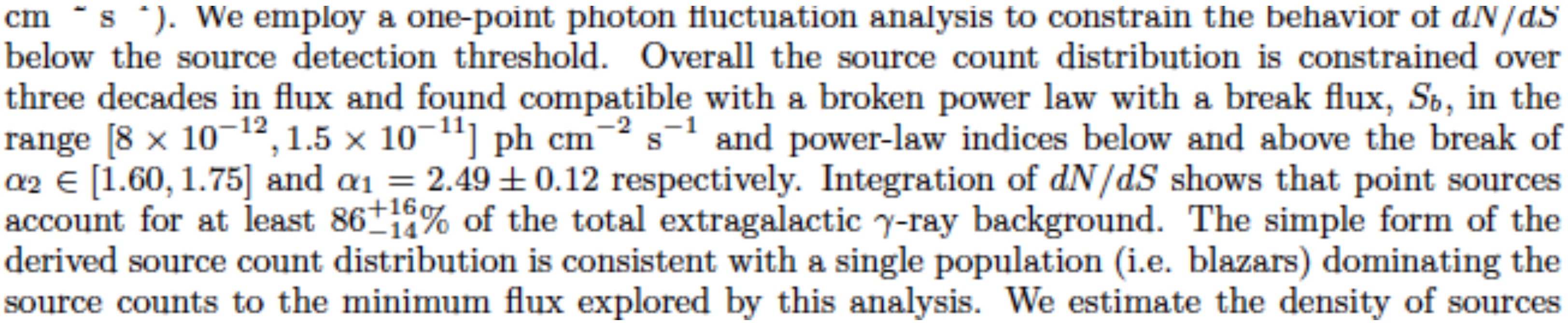
A.Neronov and D.S., arXiv:1103.3484

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



M. Di Mauro et al, arXiv:1311.5708

Fermi just confirmed resolution of BL Lac sources above 50 GeV

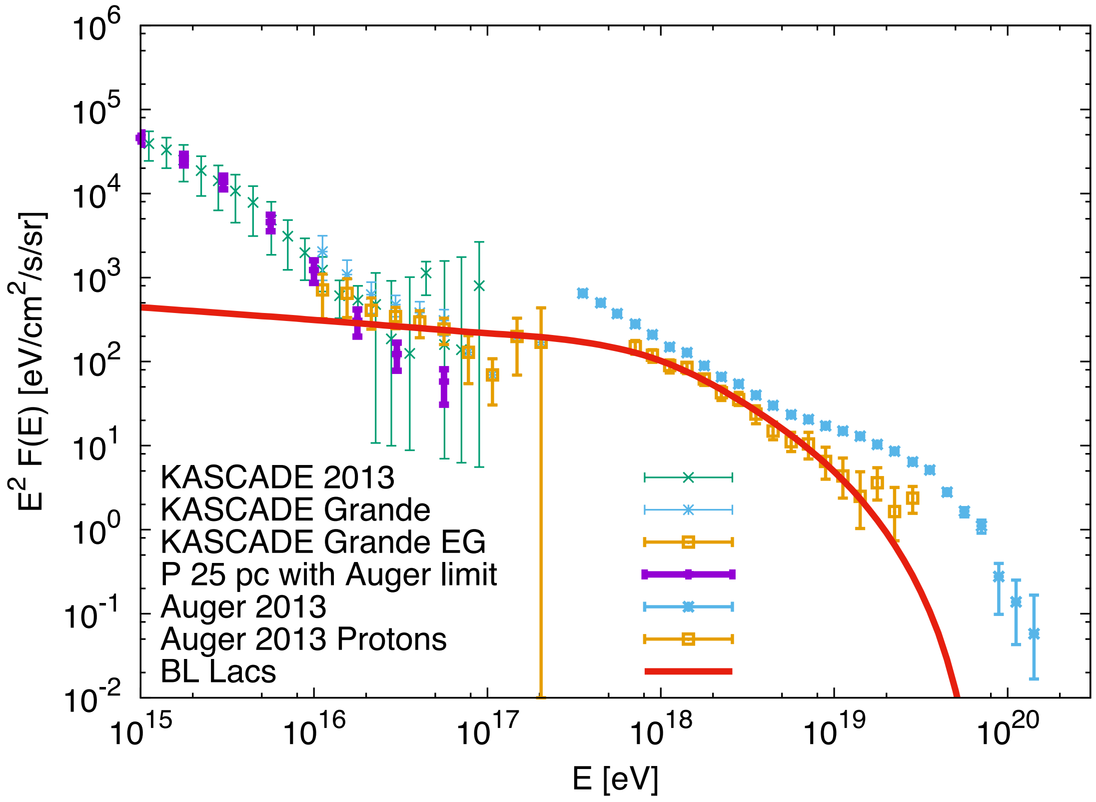


cm^{-2} s^{-1}). We employ a one-point photon fluctuation analysis to constrain the behavior of dN/dS below the source detection threshold. Overall the source count distribution is constrained over three decades in flux and found compatible with a broken power law with a break flux, S_b, in the range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

BL Lacs as UHECR, neutrino and gamma-ray sources

UHECR proton flux from BL Lacs



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

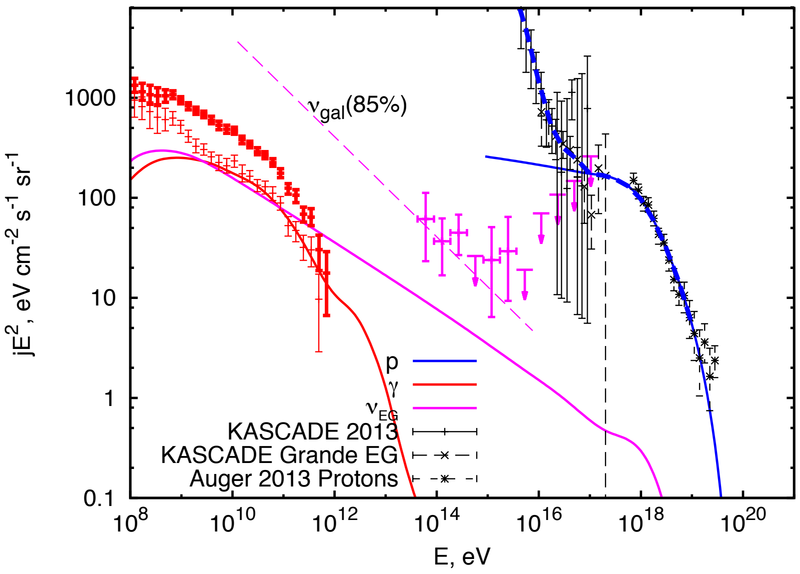
Protons in sources

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

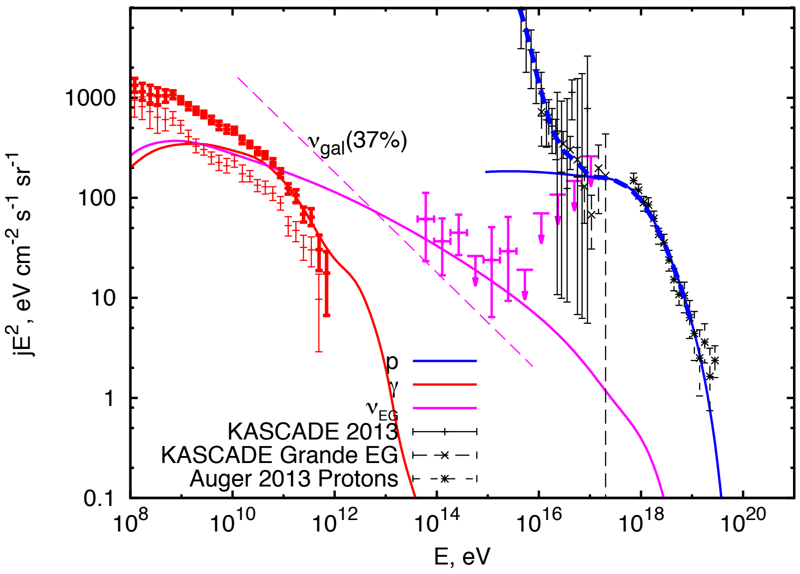
G.Giacinti, M.Kachelriess, O.Kalashev, A.Neronov and D.S., **arXiv: 1507.07534**

Miltimessenger signal from BL Lacs: dependence on escape energy

0.3 TeV

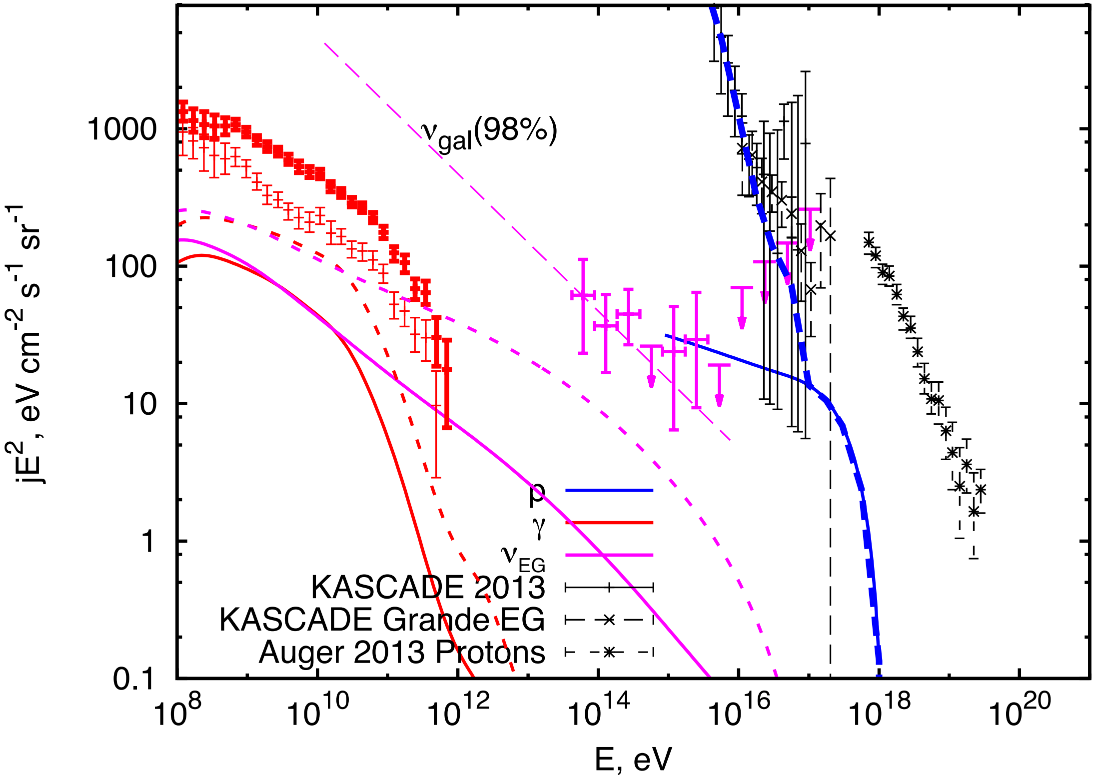


100 TeV



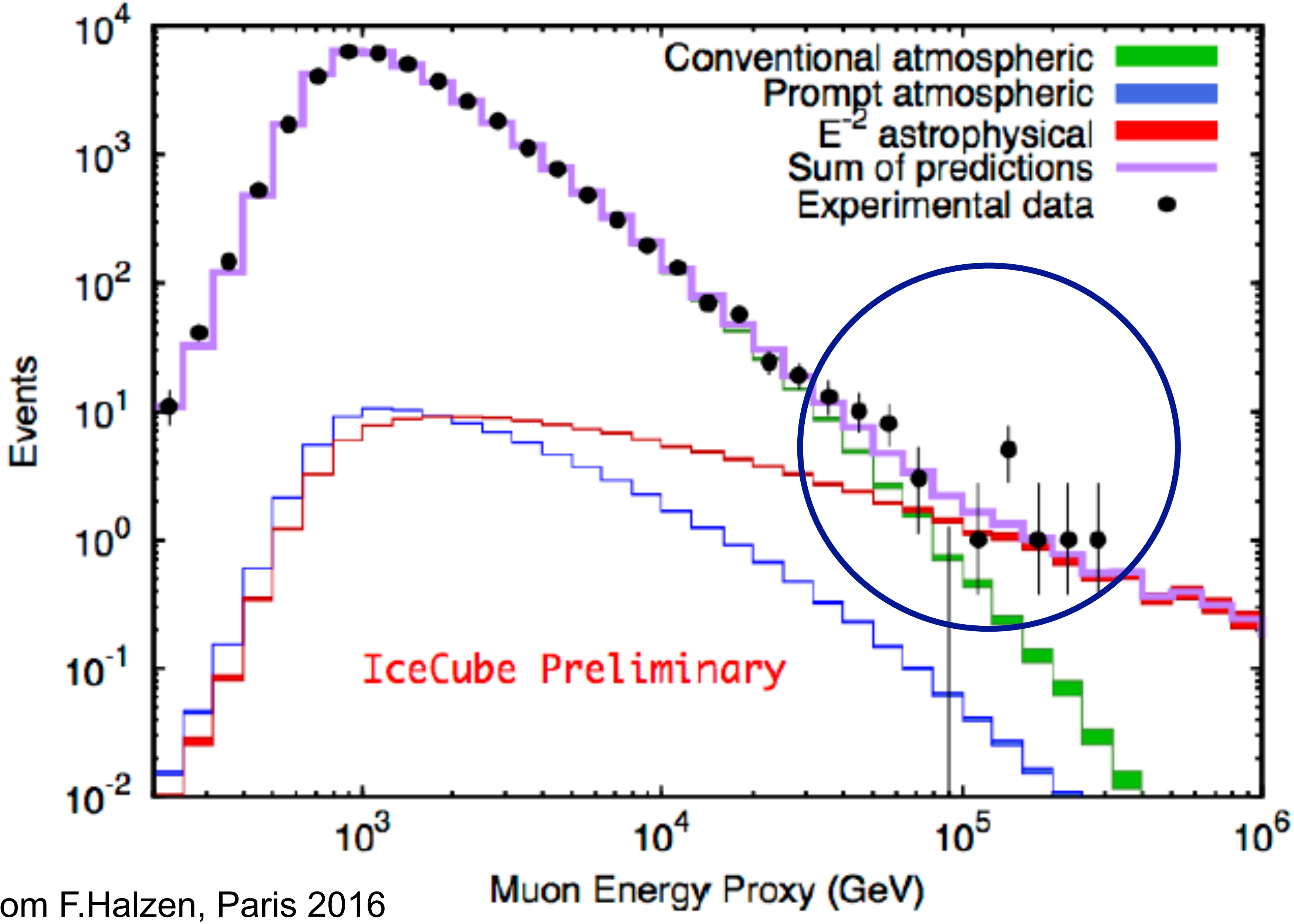
G.Giacinti, M.Kachelriess, O.Kalashev, A.Neronov and D.S., **arXiv: 1507.07534**

UHECR proton flux from Star Burst galaxies



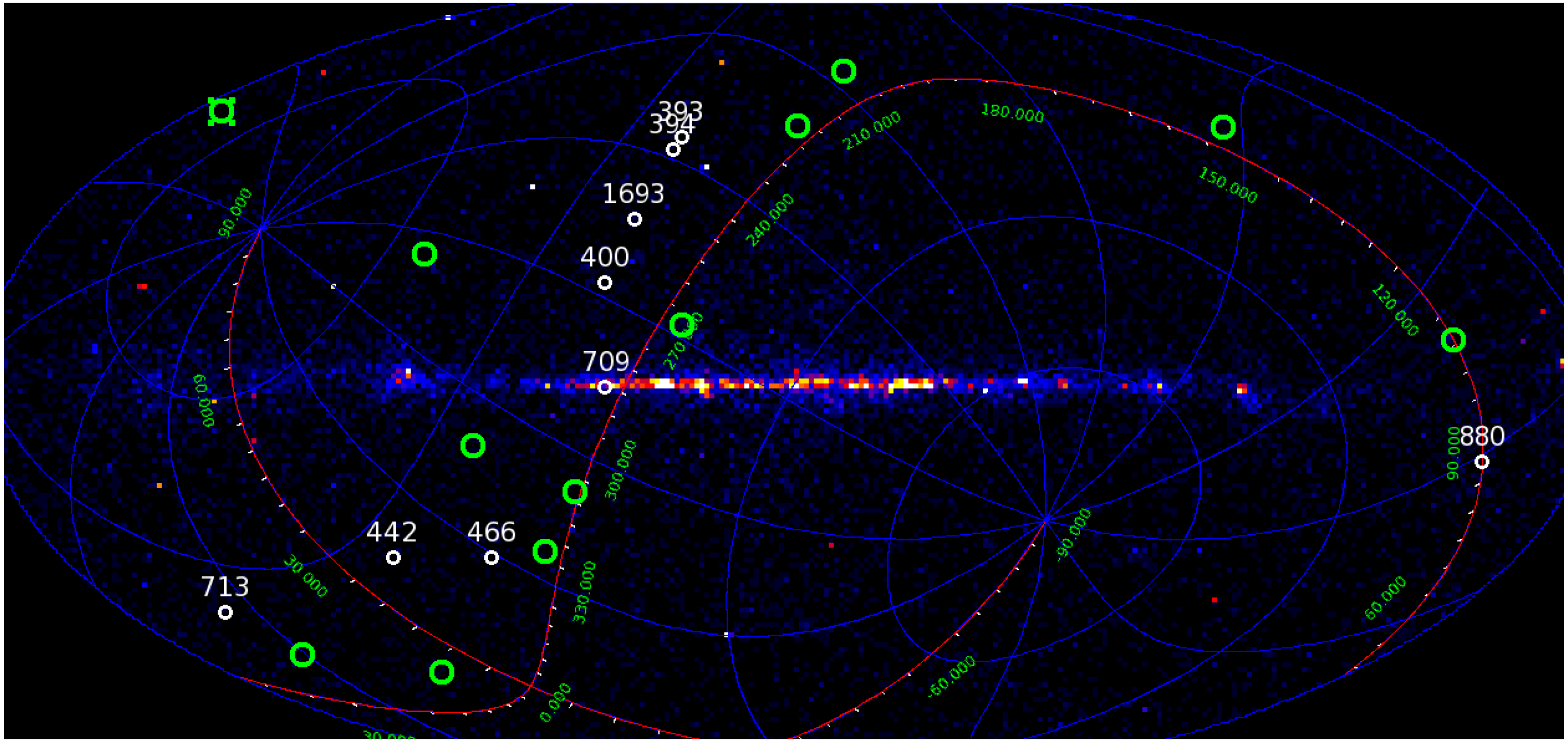
Extragalactic neutrino flux from 6 years of muon neutrinos

cosmic neutrinos in 2 years of data at 3.7 sigma



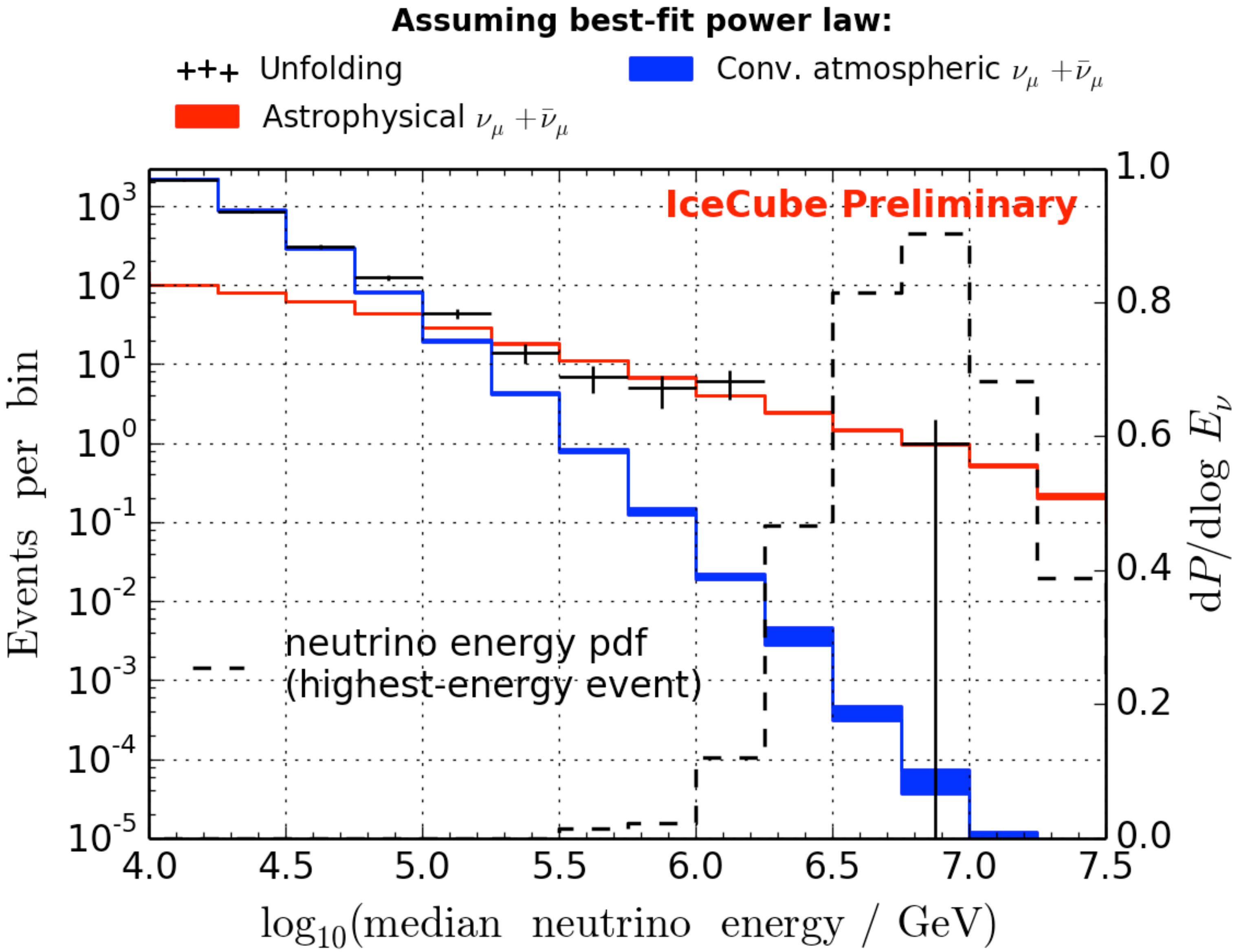
From F.Halzen, Paris 2016

Muon neutrinos



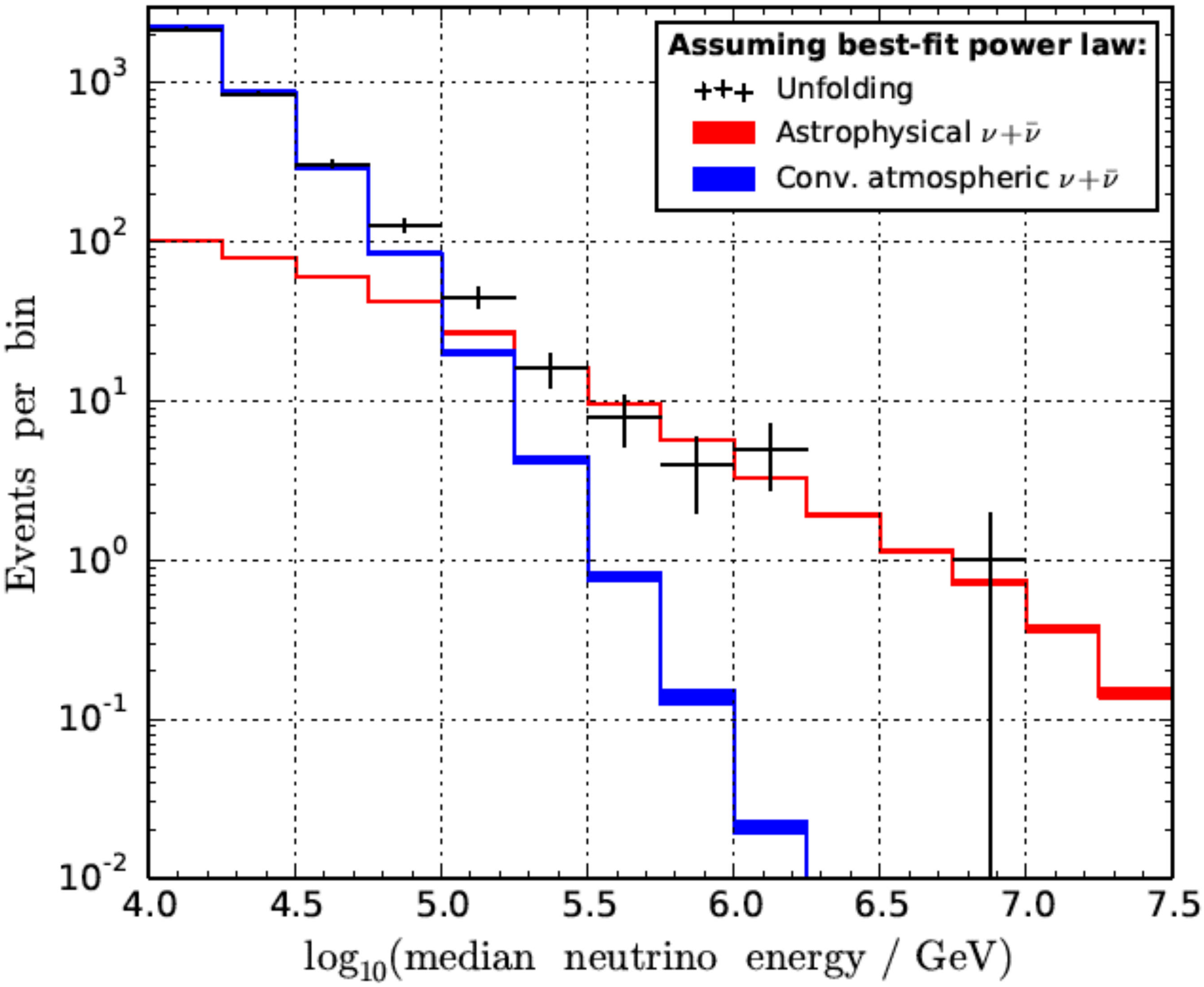
IceCube, ICRC 2015

muon neutrinos through the Earth → 6 sigma



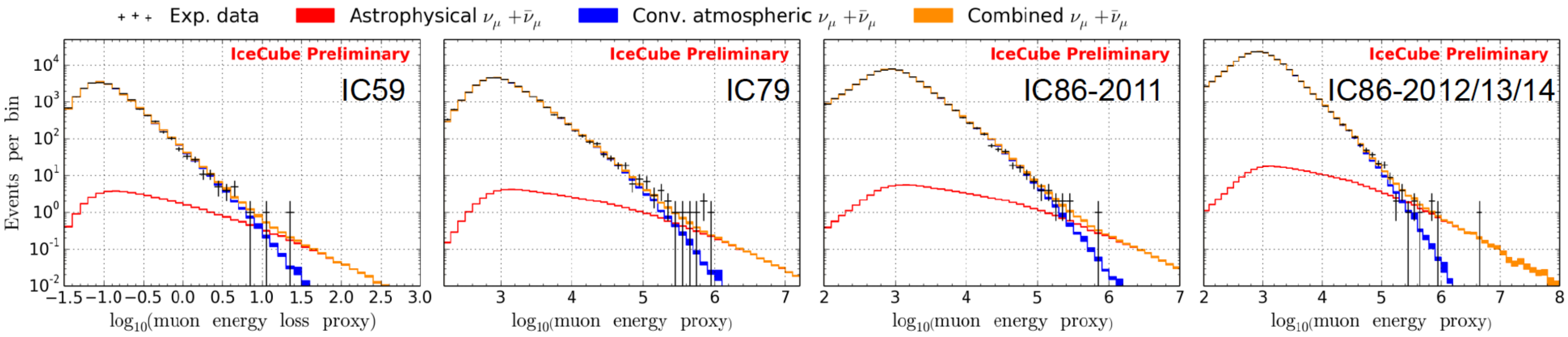
From F.Halzen, Paris 2016

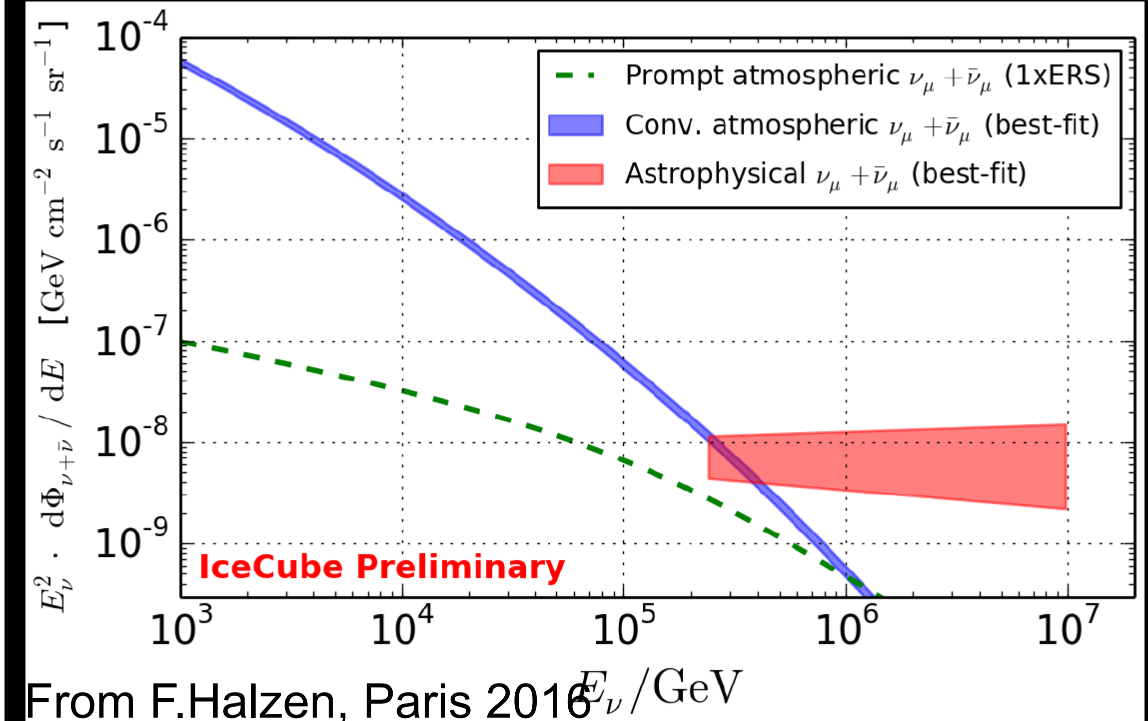
muon neutrinos through the Earth → 5.6 sigma



From F.Halzen, Paris 2016

for 5.5 years of data: 3.7→ 5.6 sigma and E^{-2} above 200 TeV !





From F.Halzen, Paris 2016

- Best-fit astrophysical normalization:

$$(0.78^{+0.29}_{-0.25}) \times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

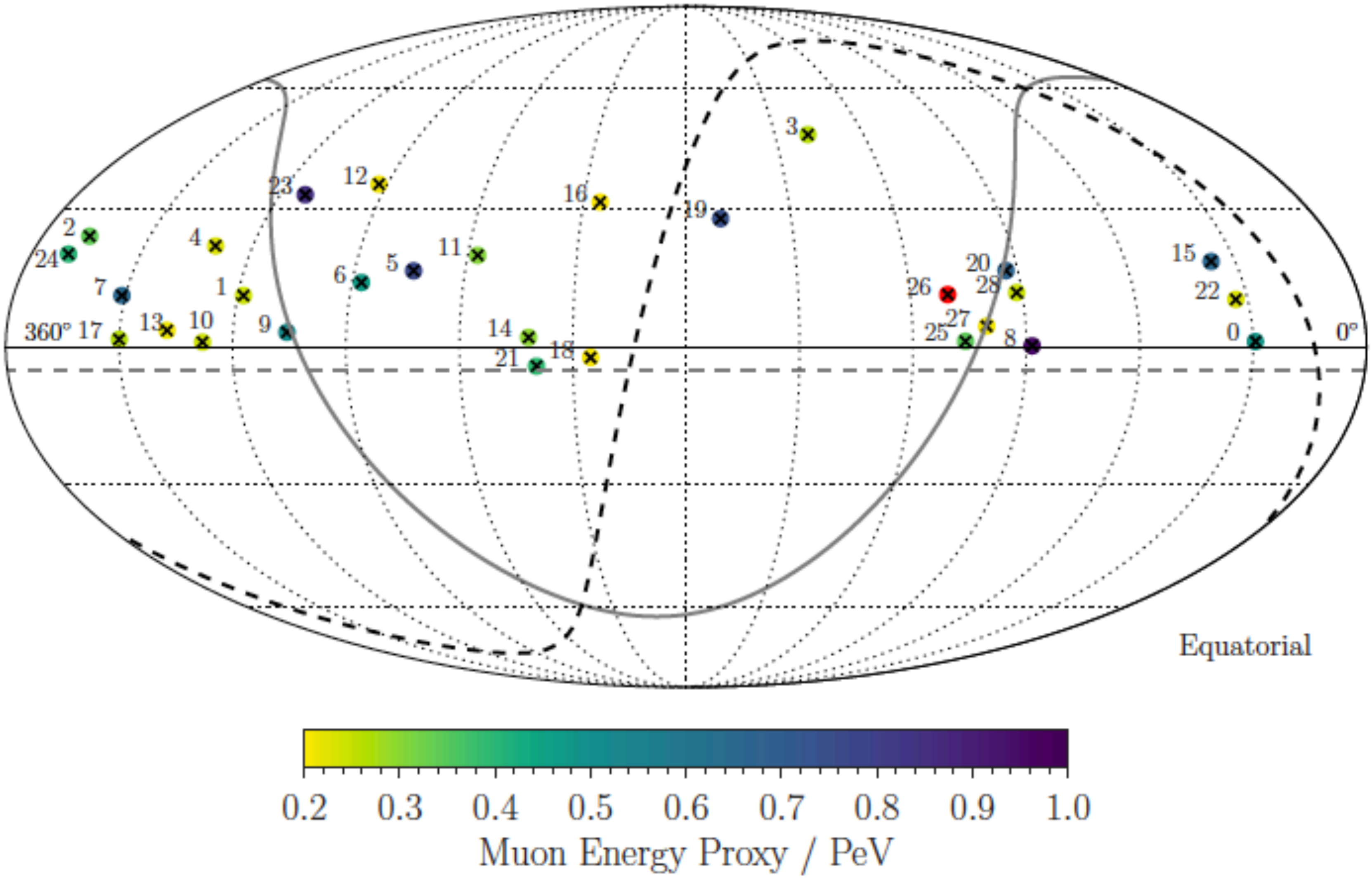
- Best-fit spectral index:

$$\gamma_{\mathrm{astro}} = 2.06 \pm 0.13$$

- Energy ranges:

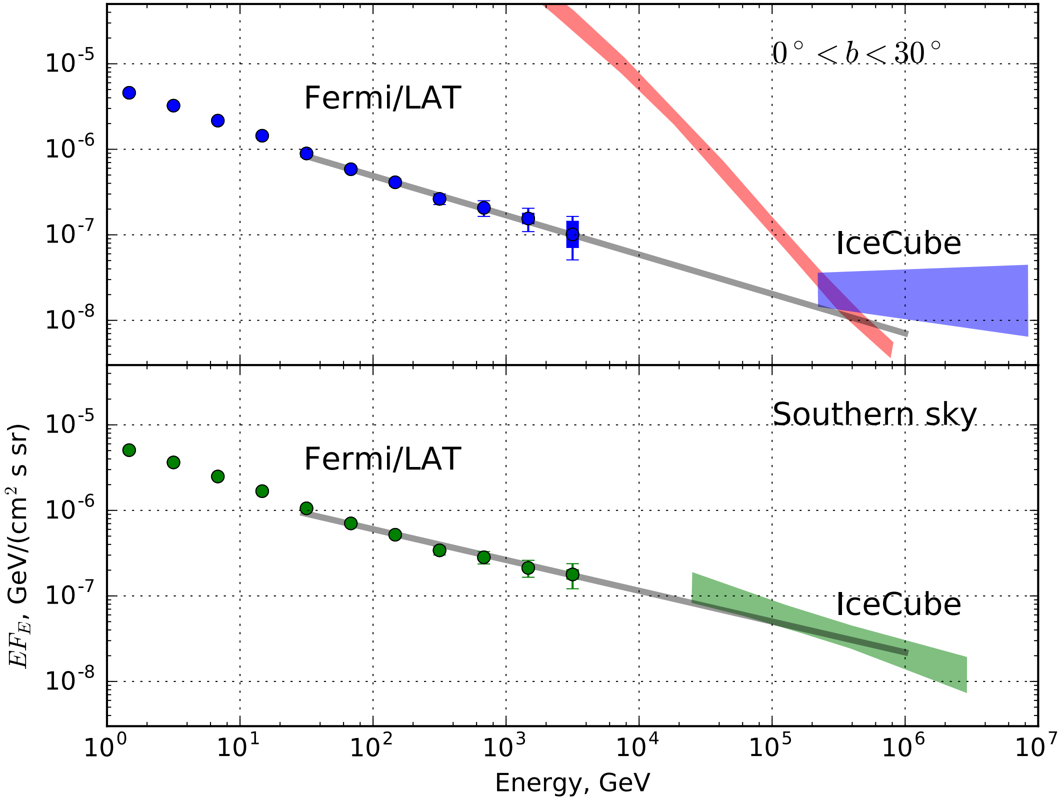
$$240\ \mathrm{TeV} - 10\ \mathrm{PeV}$$

- Atmospheric-only hypothesis excluded by 6.0σ



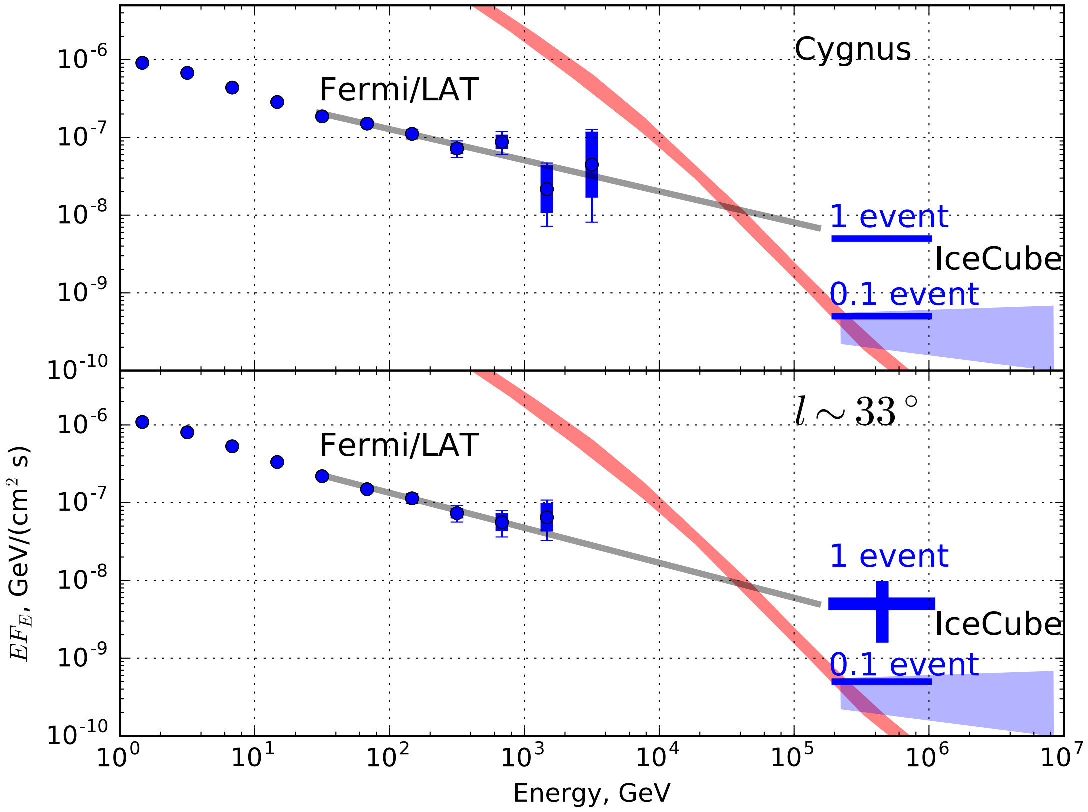
From F.Halzen, Paris 2016

North and South sky: IceCube



A. Neronov & D.S. arXiv: 1603.06733

First galactic diffuse sources



A. Neronov & D.S. arXiv: 1603.06733

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. HAWC results at 10 TeV will be important!*

Summary

- *First diffuse neutrino flux measurements contain both galactic and extragalactic components. Evidence of Galactic component come in 4 years of IceCube cascade data*
- *Galactic component give at least 50% of total flux, but can be as low as 10% in the north sky*
- *Extragalactic component was measured with 6 years of muon neutrino data. It has flux 1/E^2.1 above 200 TeV and unknown origin, but connected to diffuse gamma-ray flux measured by Fermi and probably to UHECR flux*