Looking for the origin of astrophysical neutrinos

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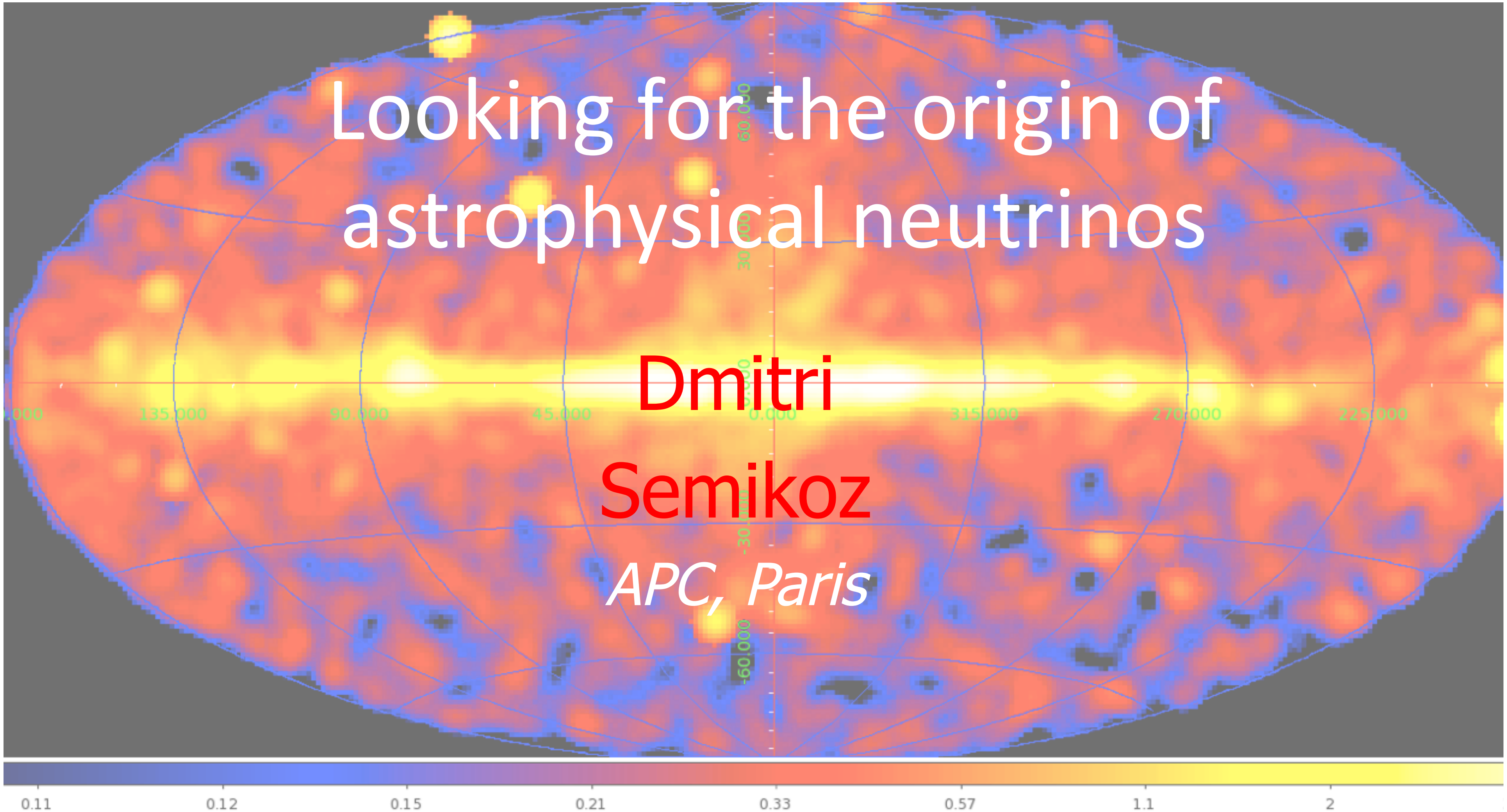


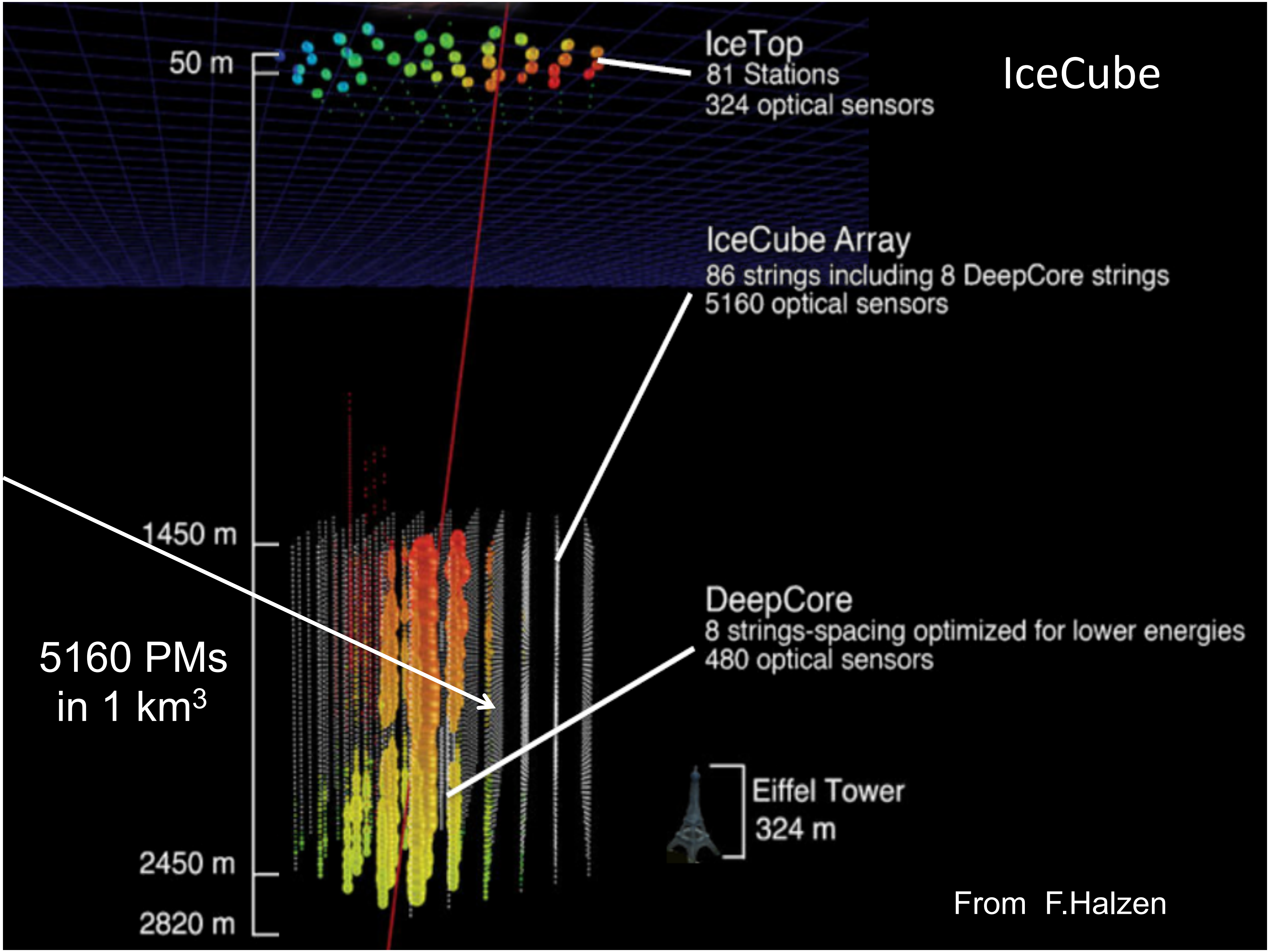
Overview:

- *Introduction: discovery of astrophysical neutrinos*
- *Galactic or extragalactic?*
  - *Galactic magnetic field*
  - *Galactic cosmic rays*
  - *Galactic to extragalactic transition of cosmic rays*
- *Neutrino signal from Milky Way Galaxy:*
  - *Gamma-ray signal*
  - *Significance in IceCube data*

Overview:

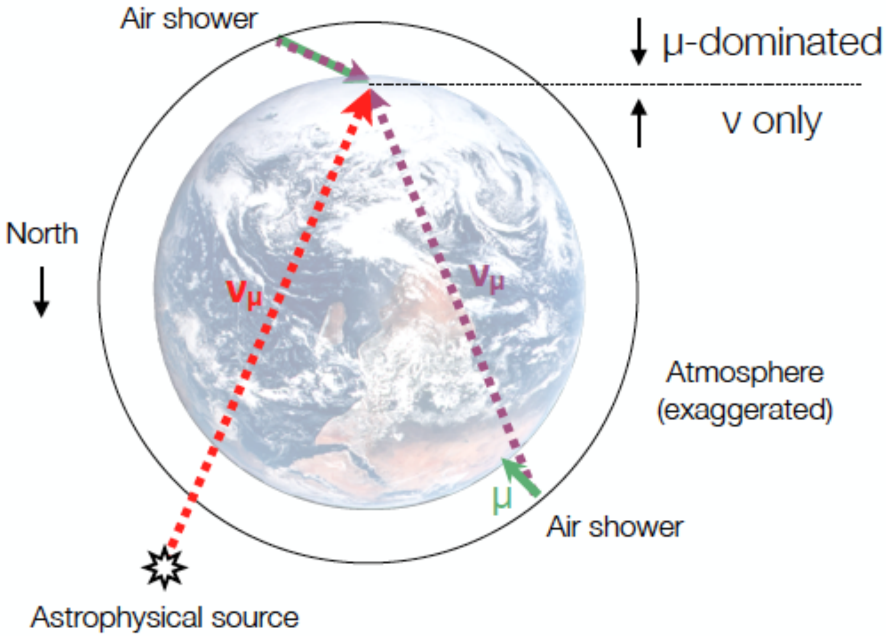
- *Extragalactic source examples: BL Lacs, starburst*
- *New information from 6 years of muon neutrino data*
- *Conclusions*

INTRODUCTION: astrophysical neutrinos


IceCube
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
5160 PMs
in 1 km³
From F.Halzen

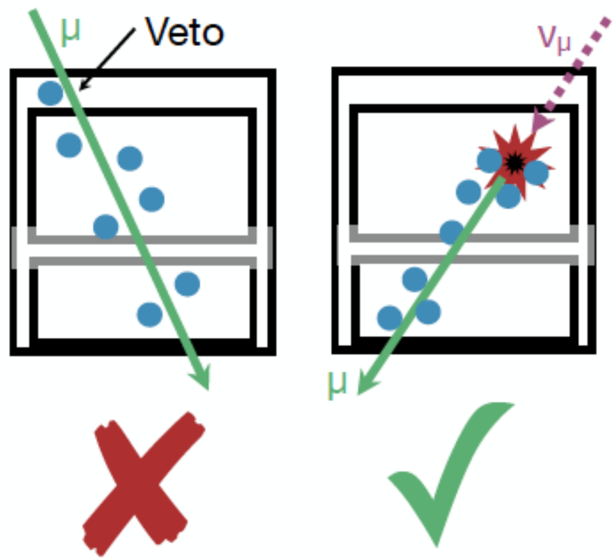
Isolating neutrino events: two strategies

Up-going tracks



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

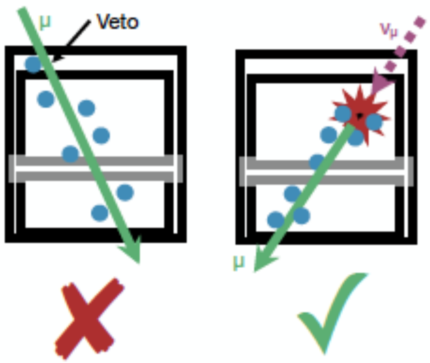
Active veto



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

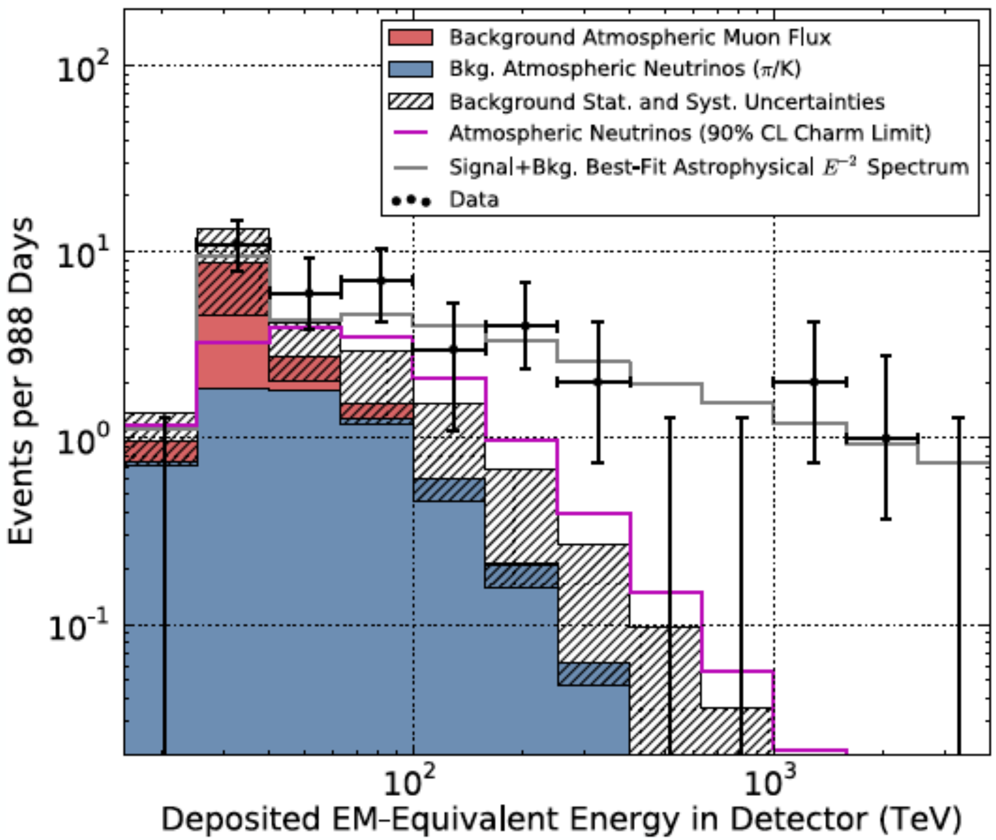
Evidence for high-energy astrophysical neutrinos

- Selected high-energy starting events in IceCube



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

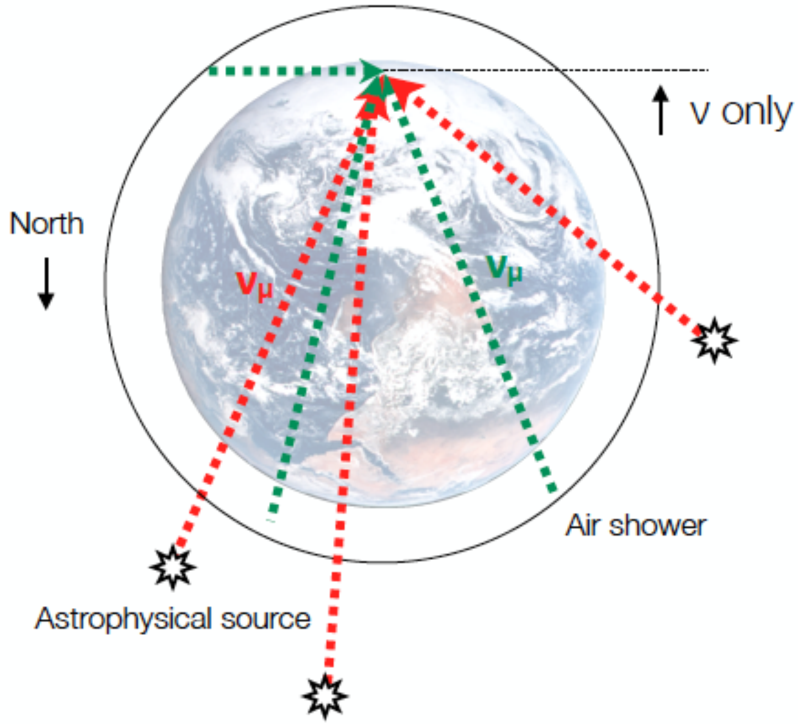
Deposited energy

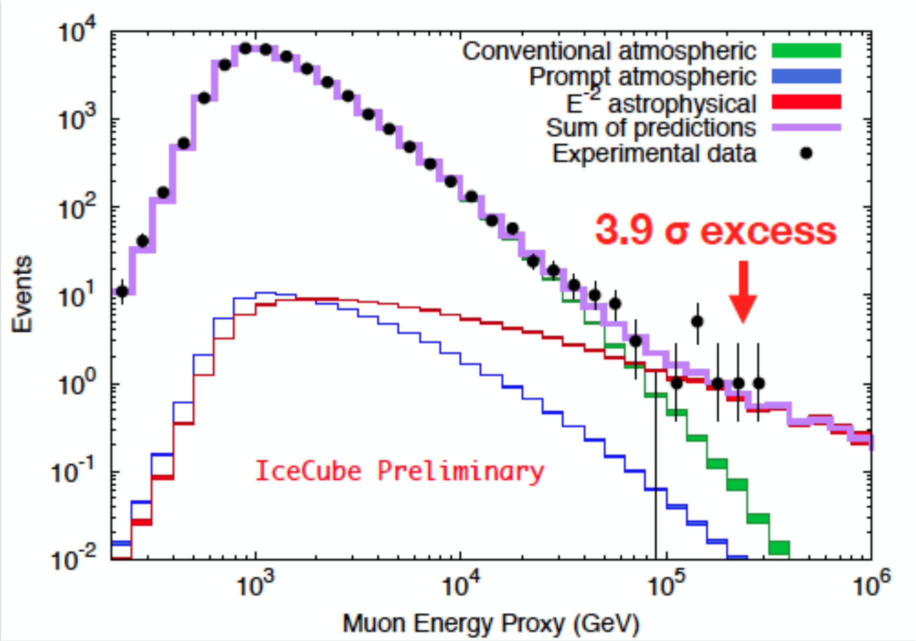


arXiv:1405.5303 (accepted for PRL)

What about the northern sky and ν_μ?

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

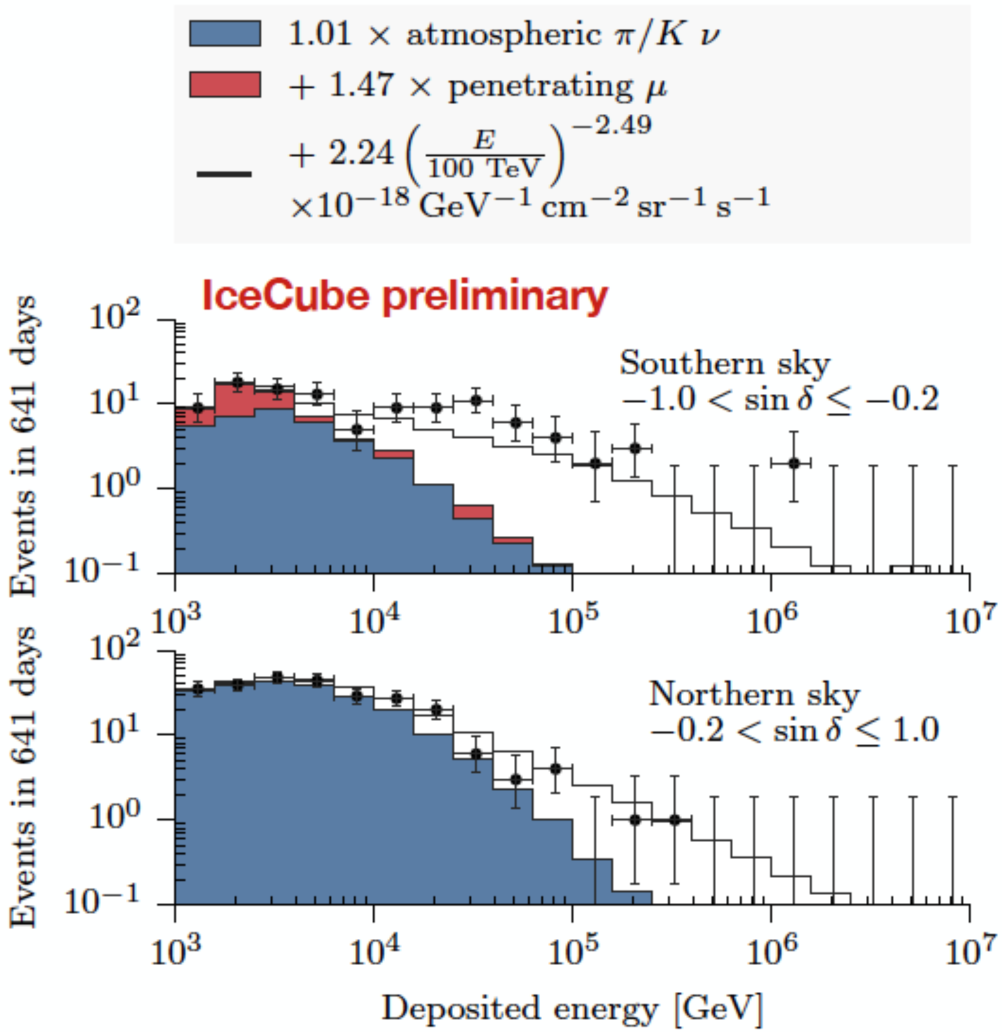




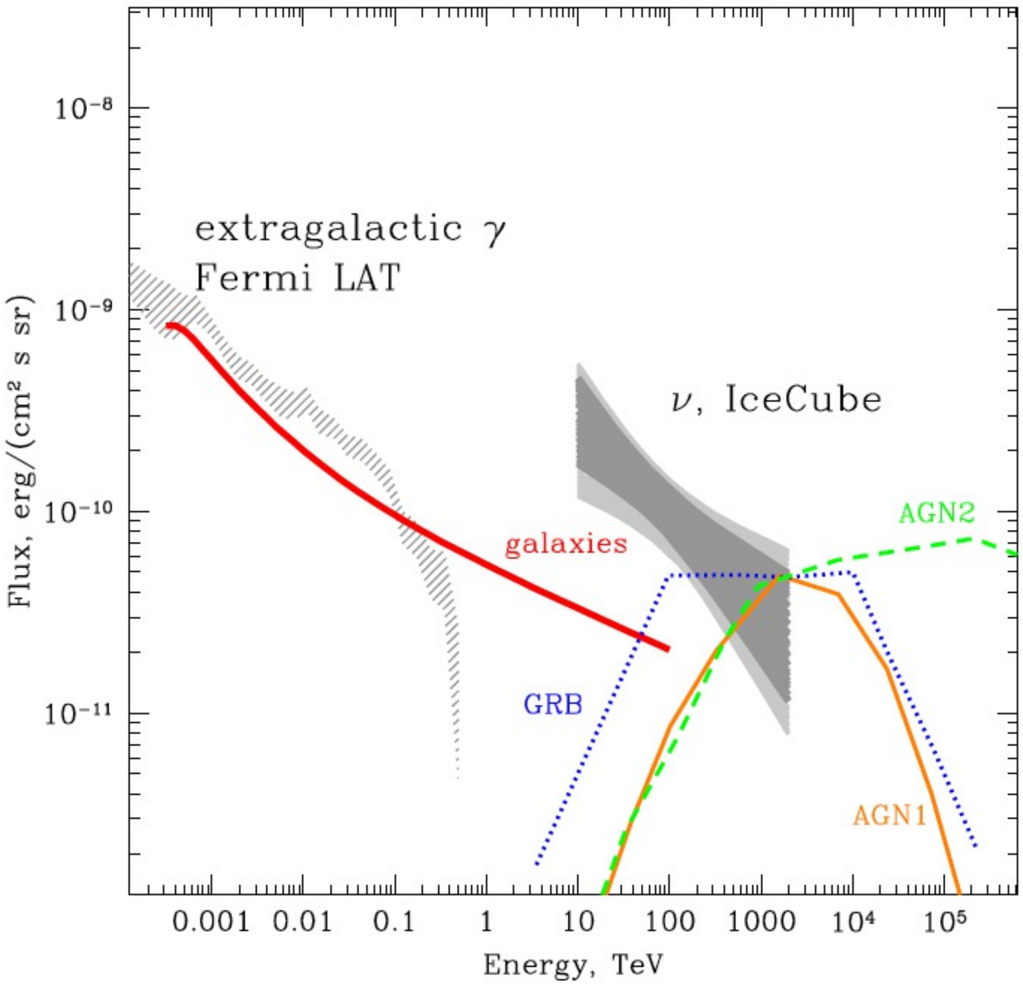
We look for the same excess in incoming muons from the northern sky
High-energy muons reach the detector from km away → large effective volume
Only sensitive to CC ν_μ → explicit handle on ν_μ flux

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



IceCube + Fermi LAT



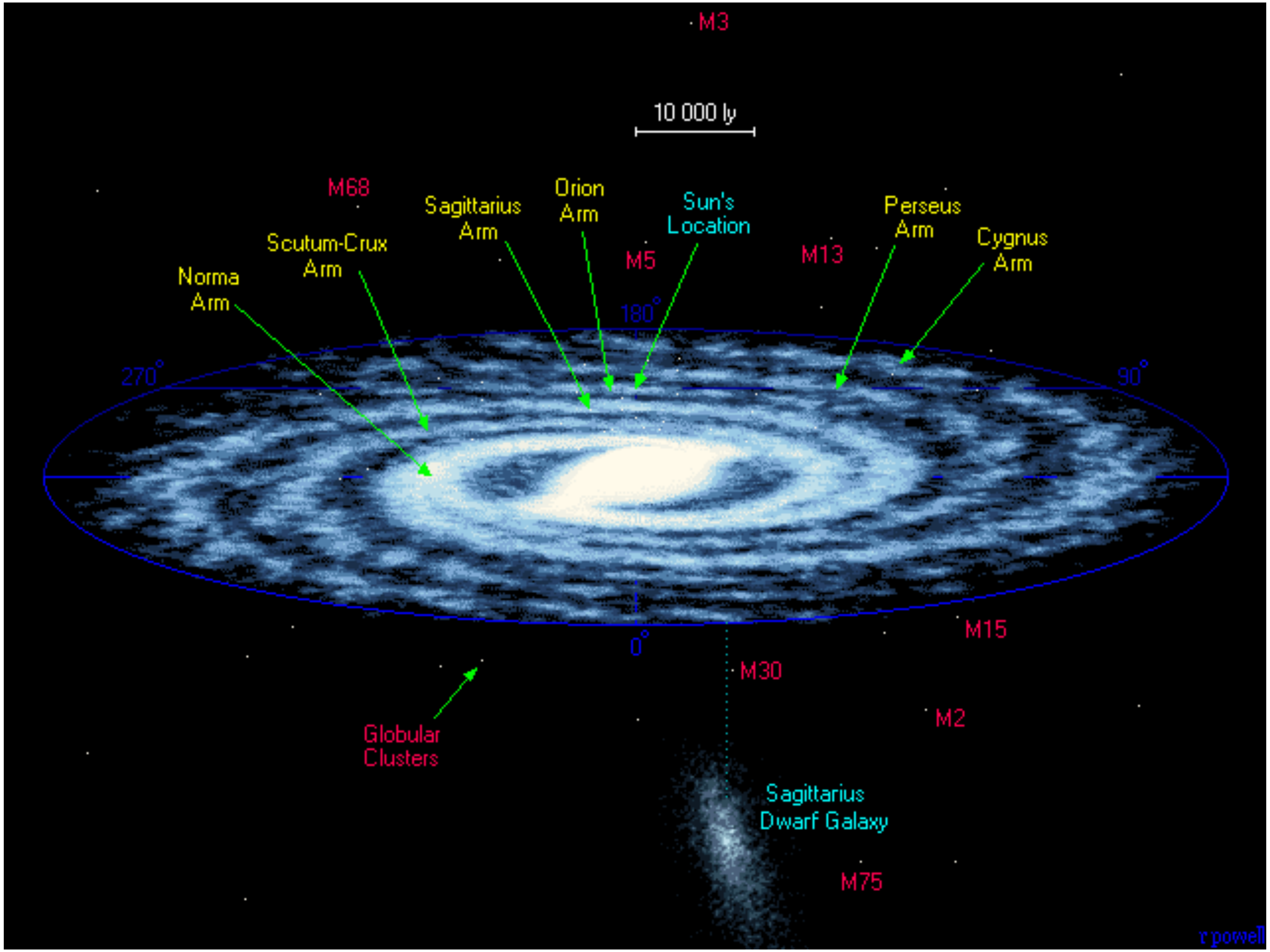
Neutrino astrophysics

- 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 6 years 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

Galactic magnetic field

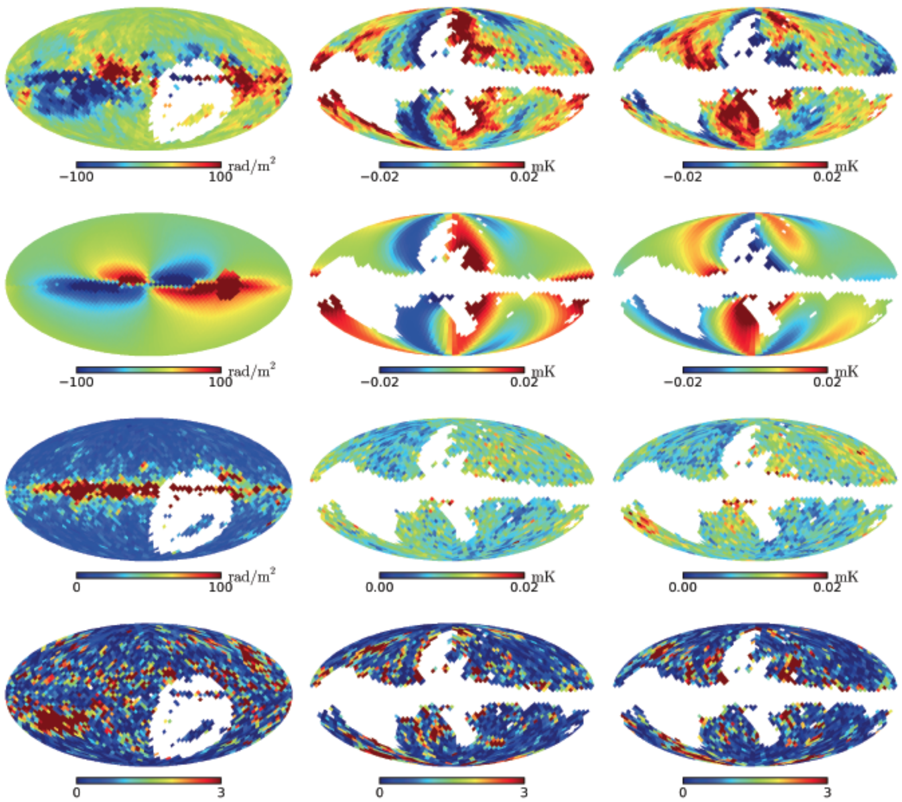
MILKY WAY GALAXY



Galactic magnetic field

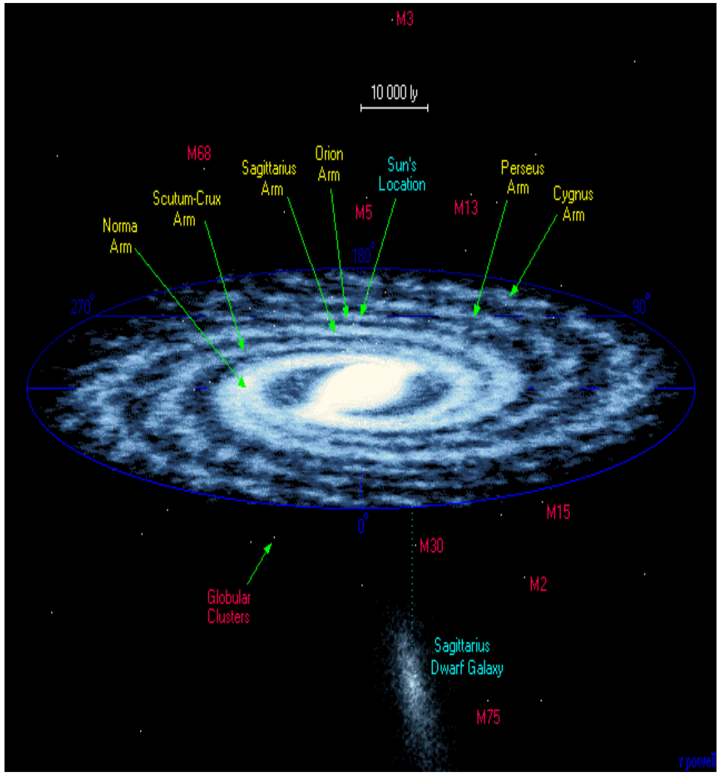
- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

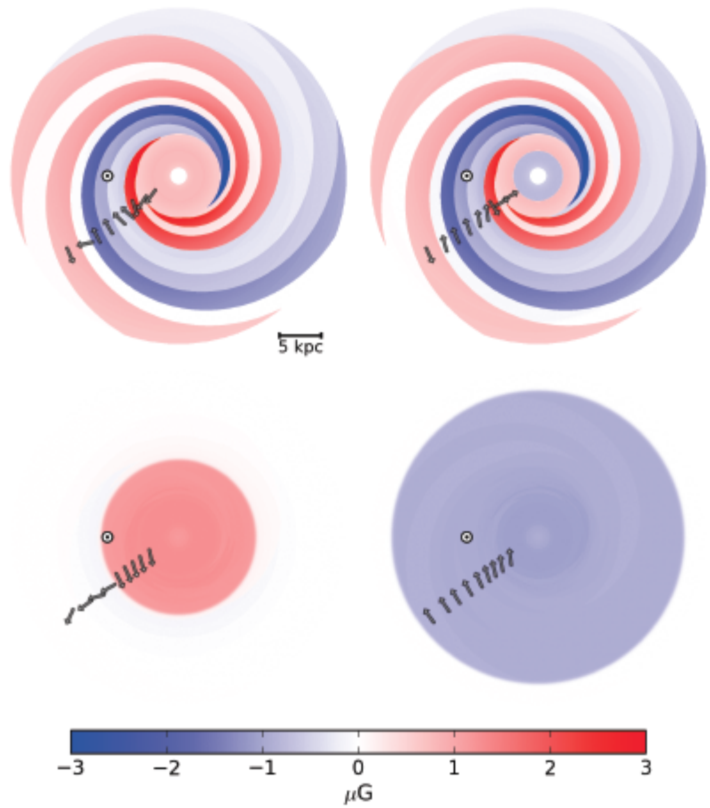
Synchrotron/RM maps



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

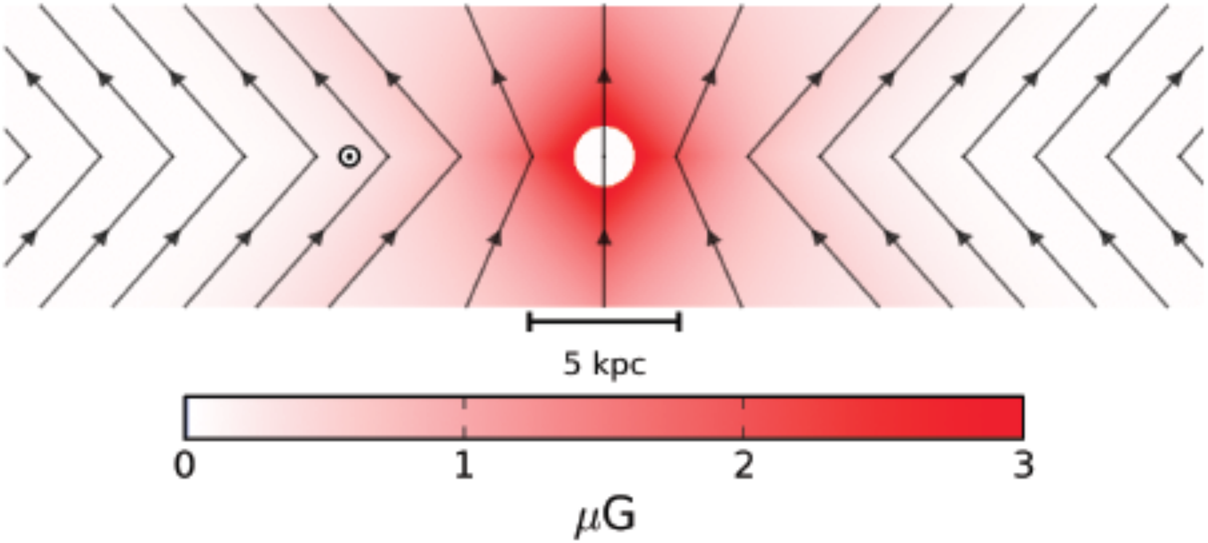
Galactic magnetic field: disk





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)

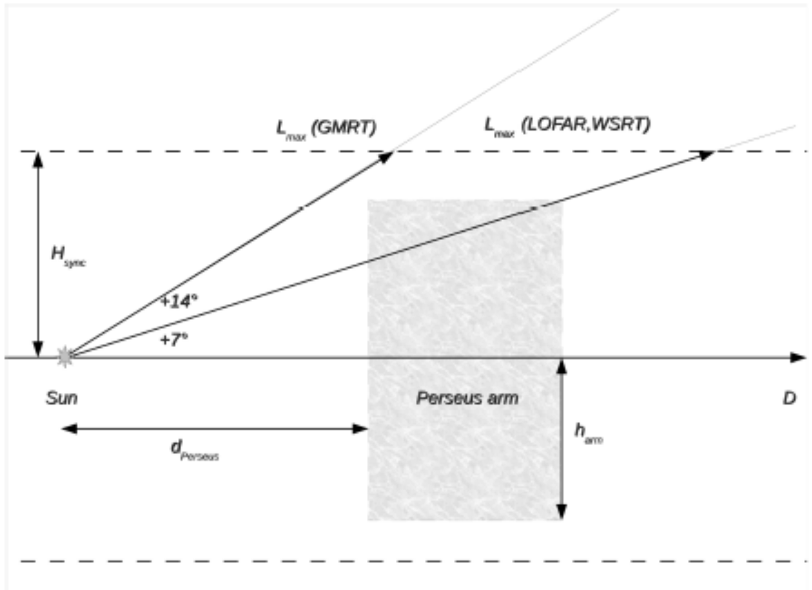
Galactic magnetic field: turbulent component

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

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

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

LOFAR measurement of maximum scale of turbulent GMF in disk



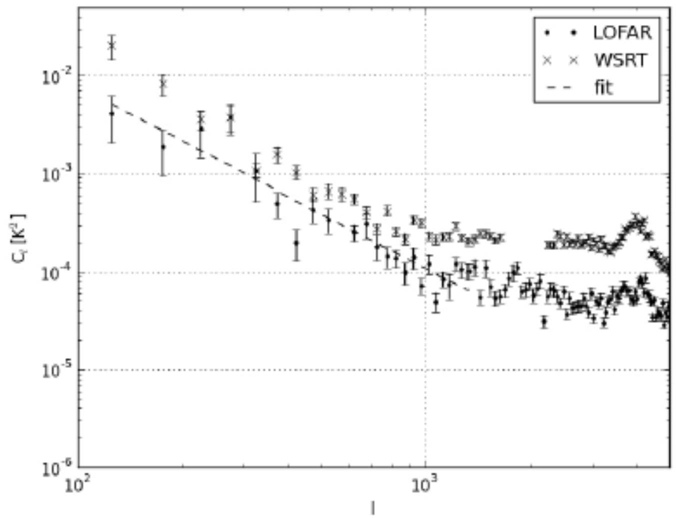


Fig. 9. Power spectra of total intensity from the LOFAR (dots) and WSRT (crosses) observations. The error bars indicate statistical errors at 1σ. The fitted power law (dashed line) with a spectral index $\alpha = -1.84 \pm 0.19$ for $\ell \in [100, 1300]$ is also shown.

arXiv: 1308.2804

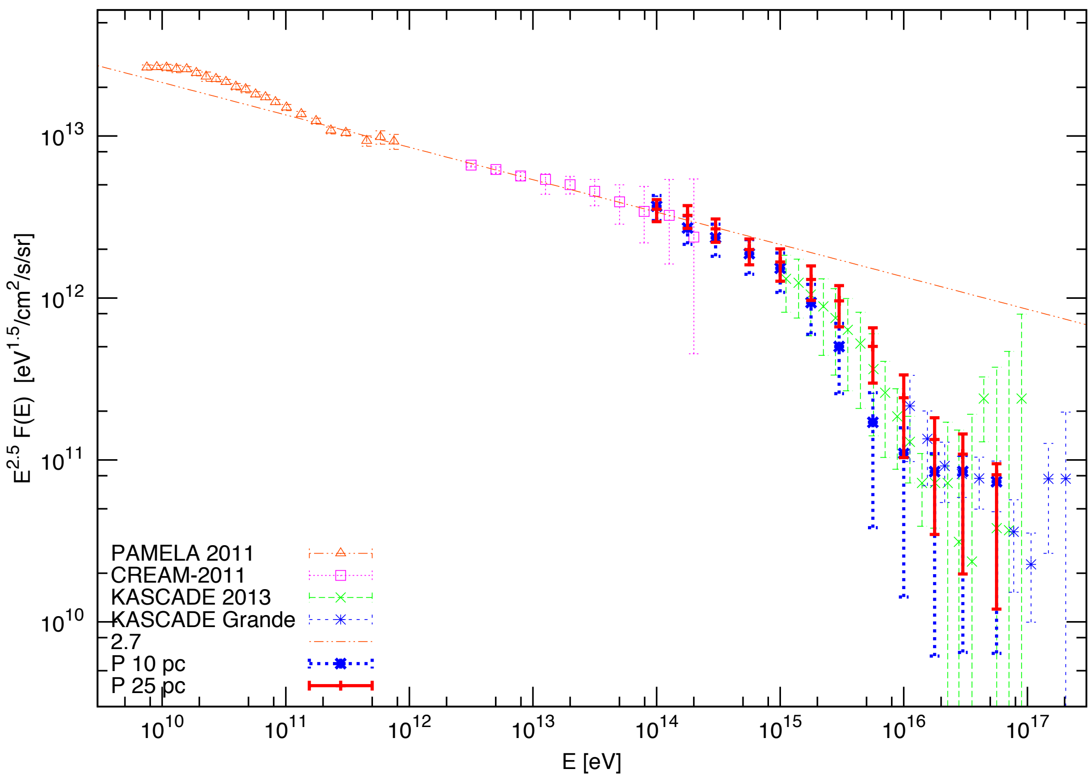
Lmax ~ 20 pc +-6 pc in disk

Galactic cosmic ray model

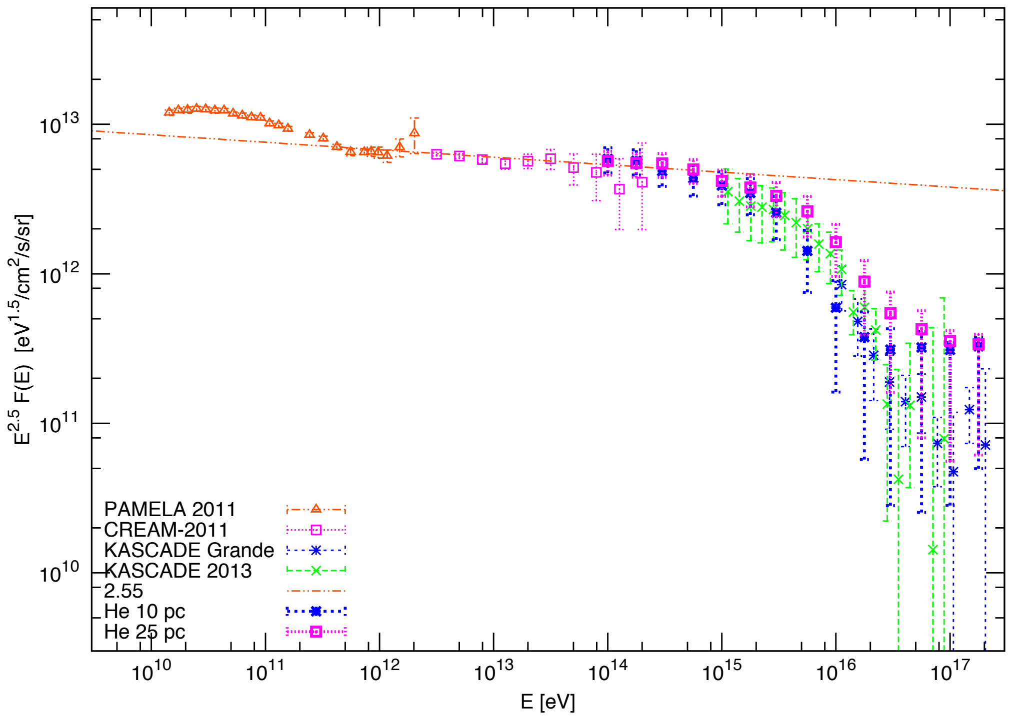
ESCAPE MODEL:

- 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*

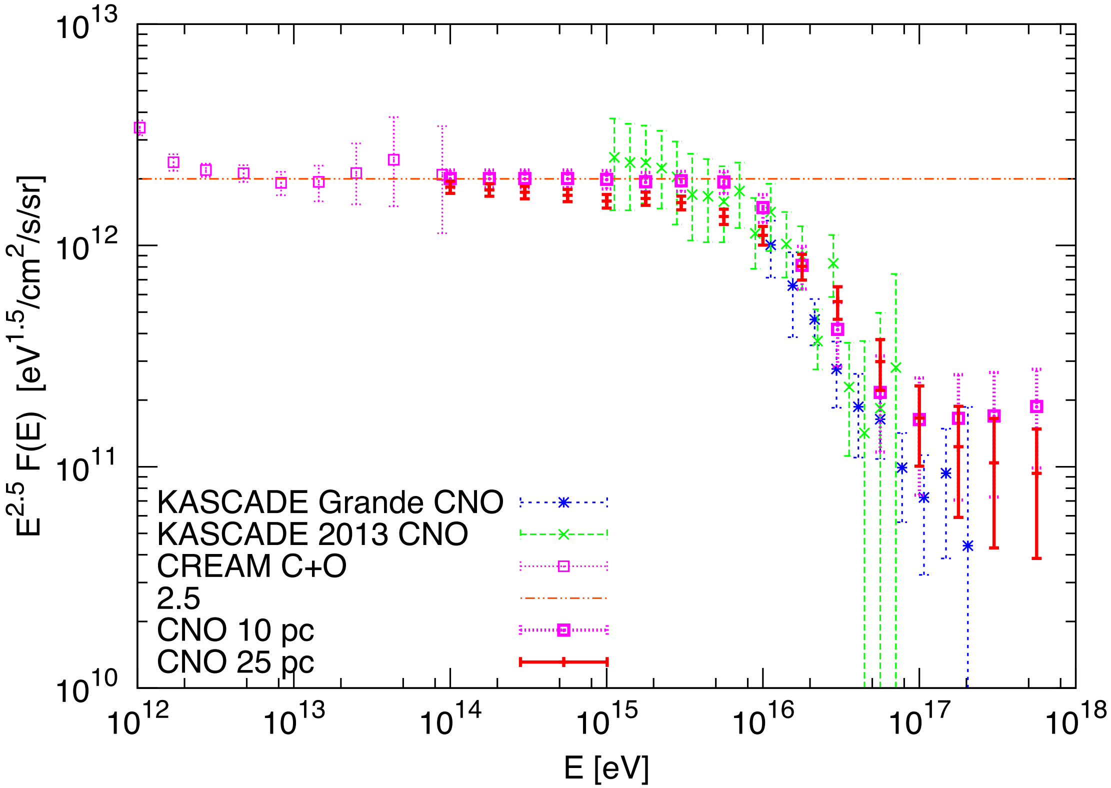
Cosmic Ray Knee: protons



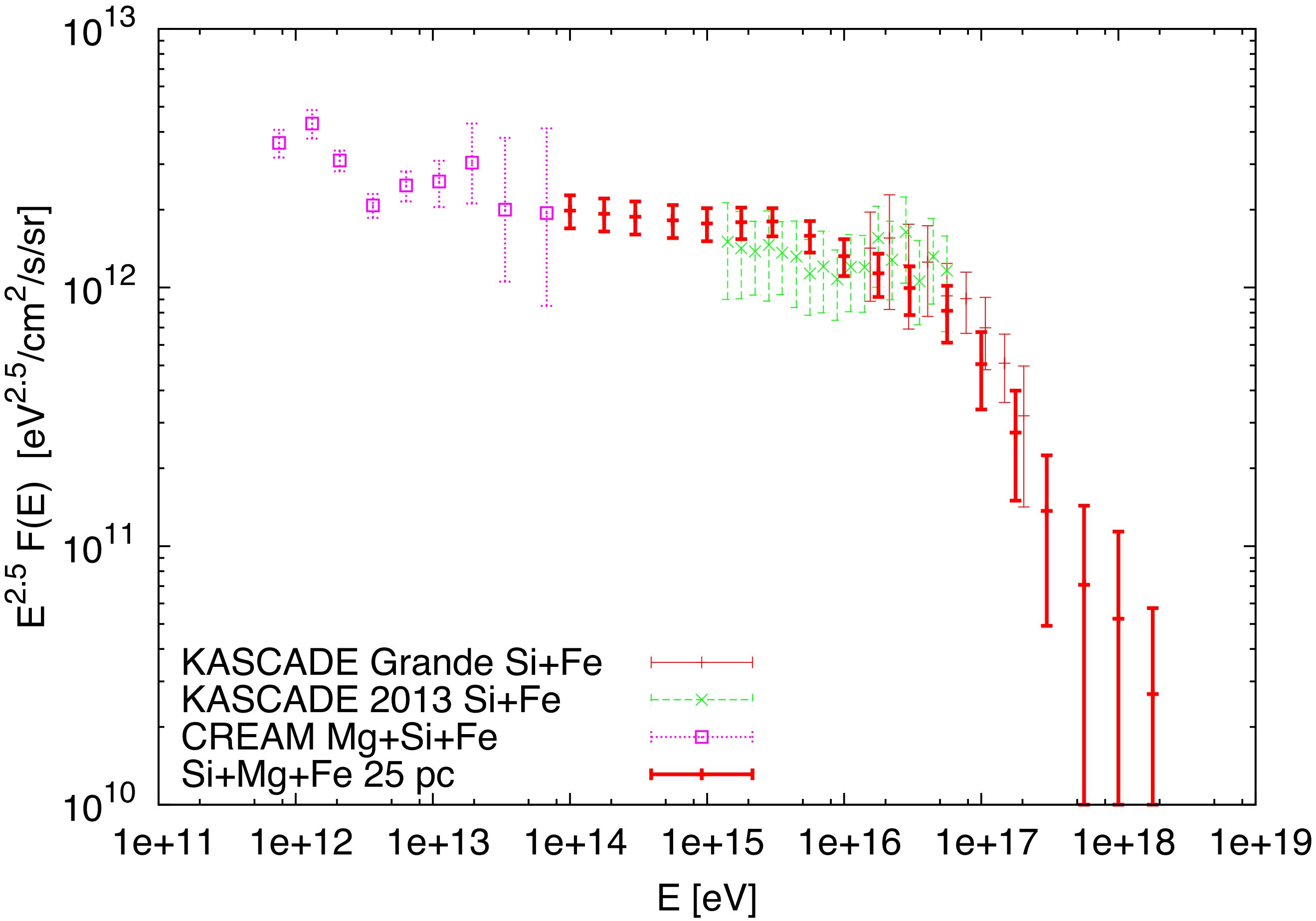
Cosmic Ray Knee: He



Cosmic Ray Knee: CNO

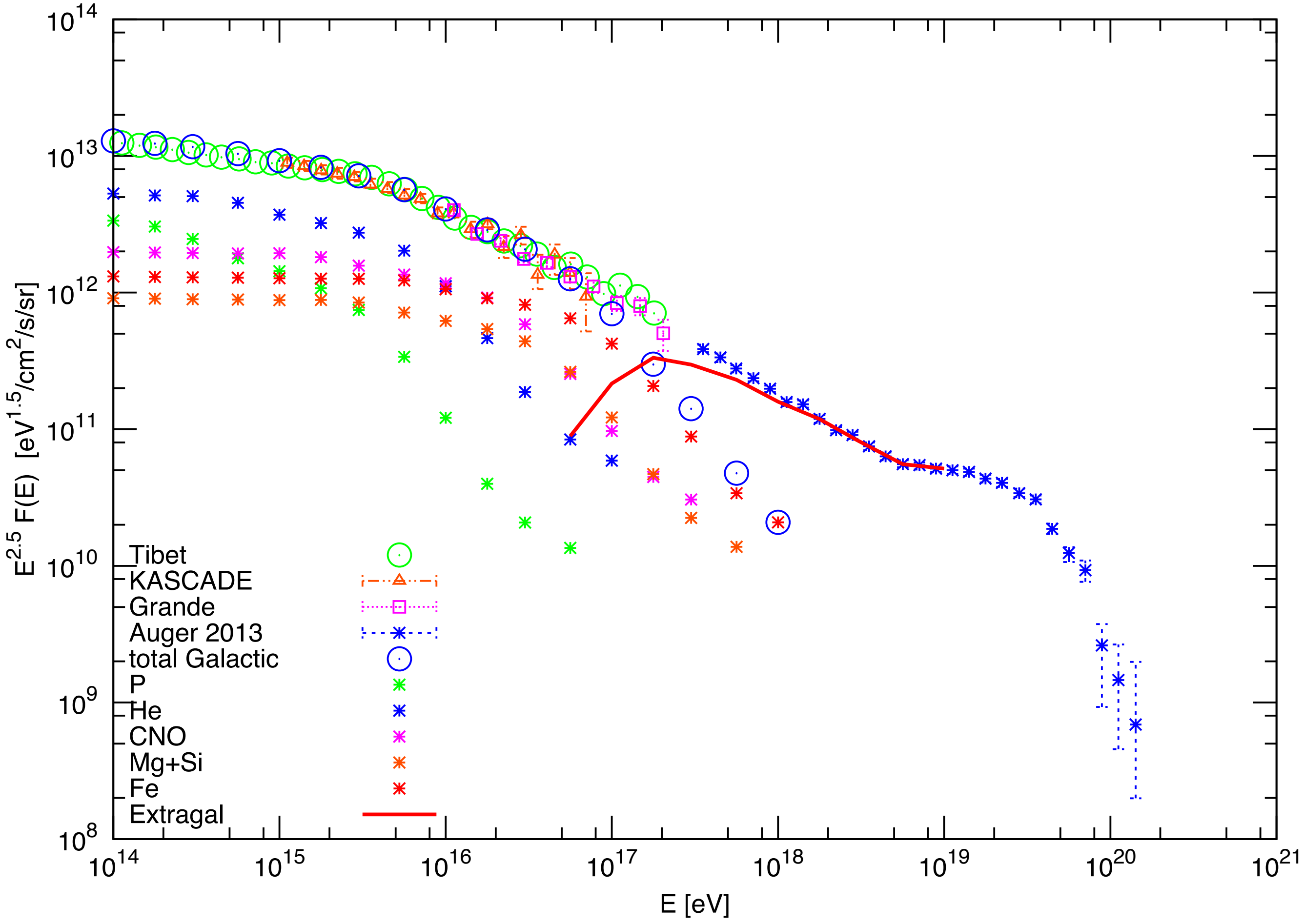


Cosmic Ray Knee: Mg+Si+Fe



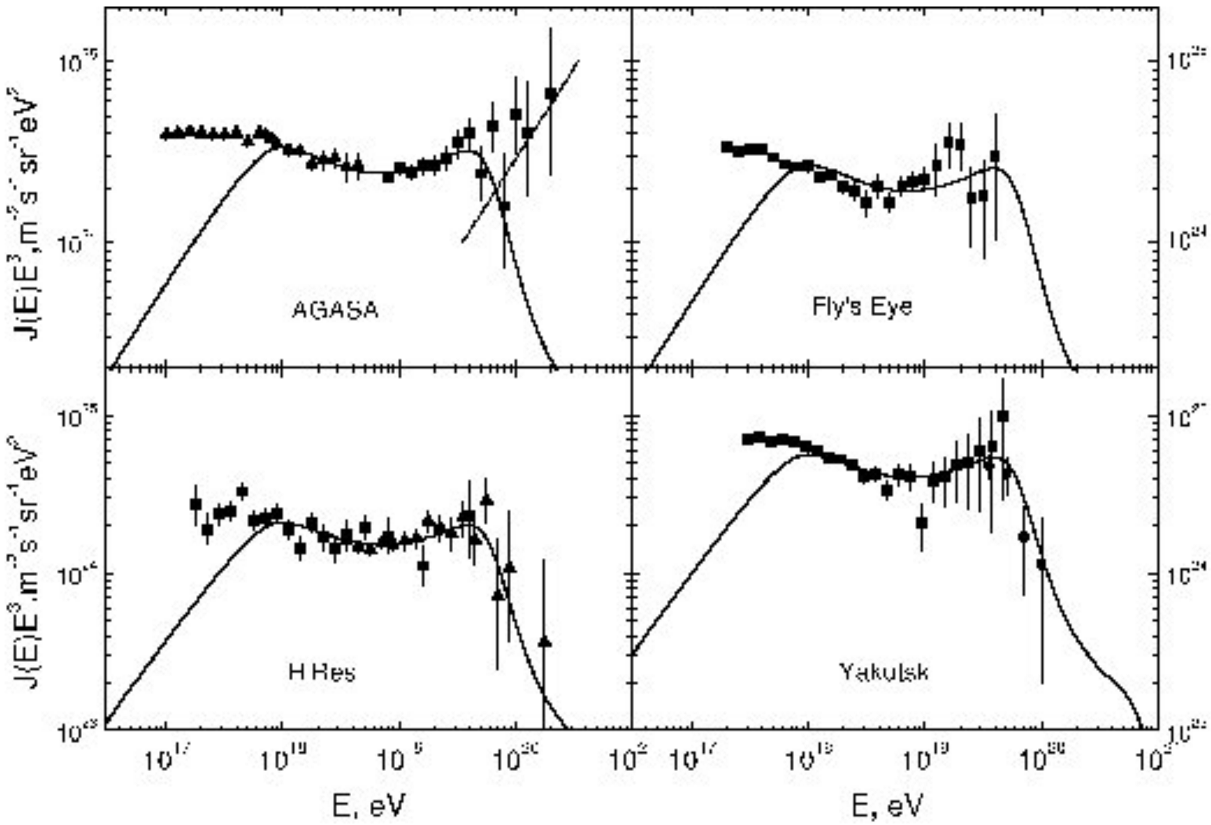
Thanks to Andreas Haungs for discussion

Cosmic Ray Knee: all particles



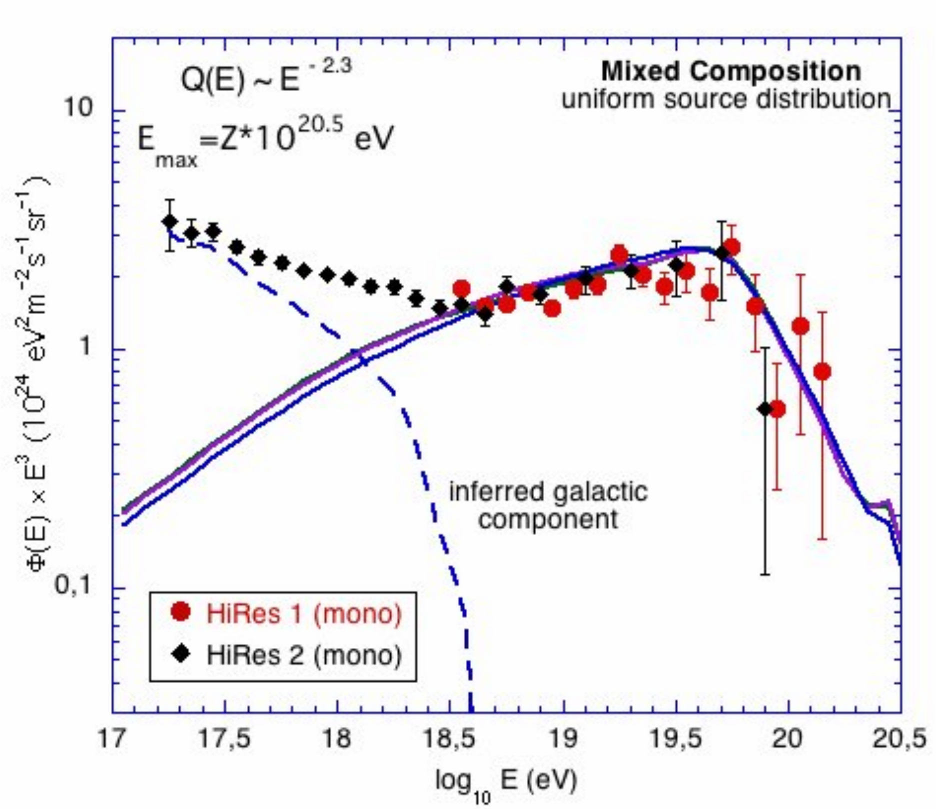
Transition from galactic to extragalactic cosmic rays

Dip model: Protons can fit UHECR data



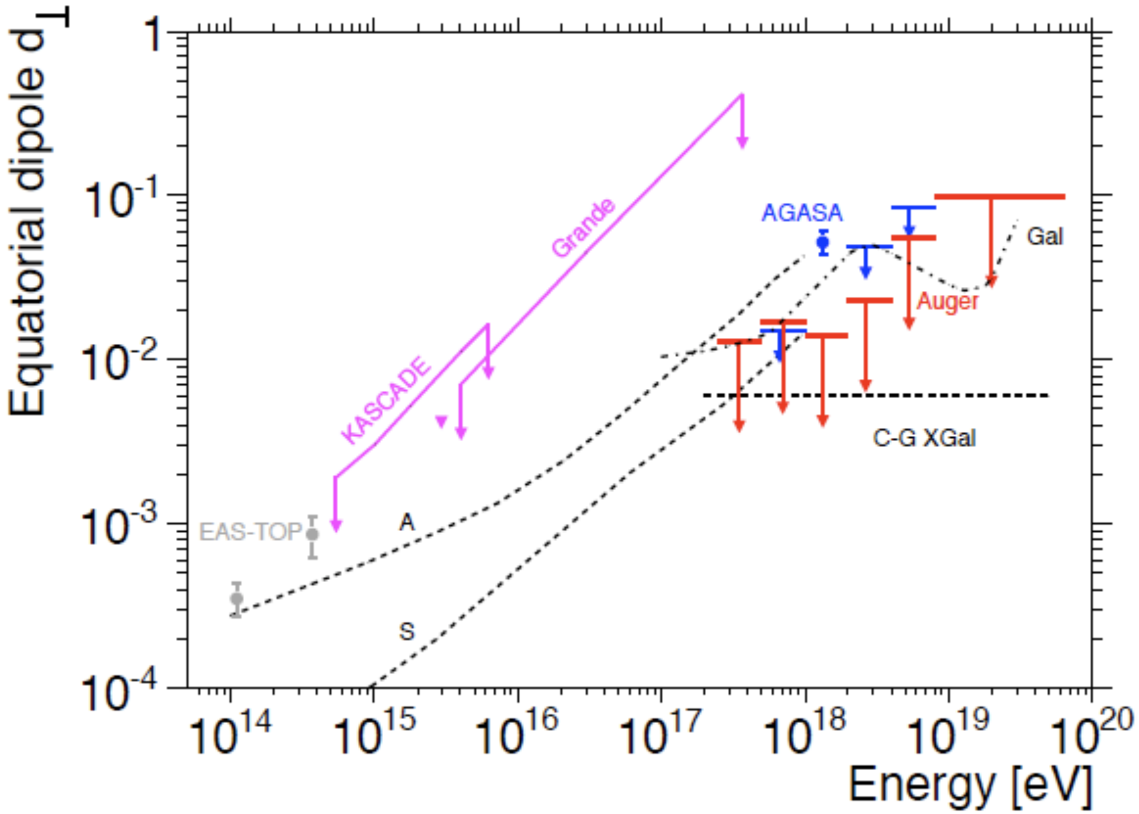
V.Berezinsky , astro-ph/0509069

Mixed composition model



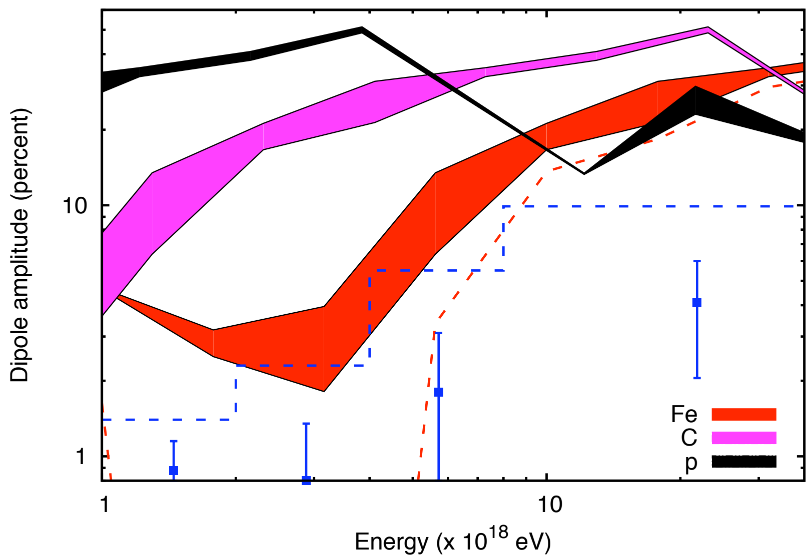
D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

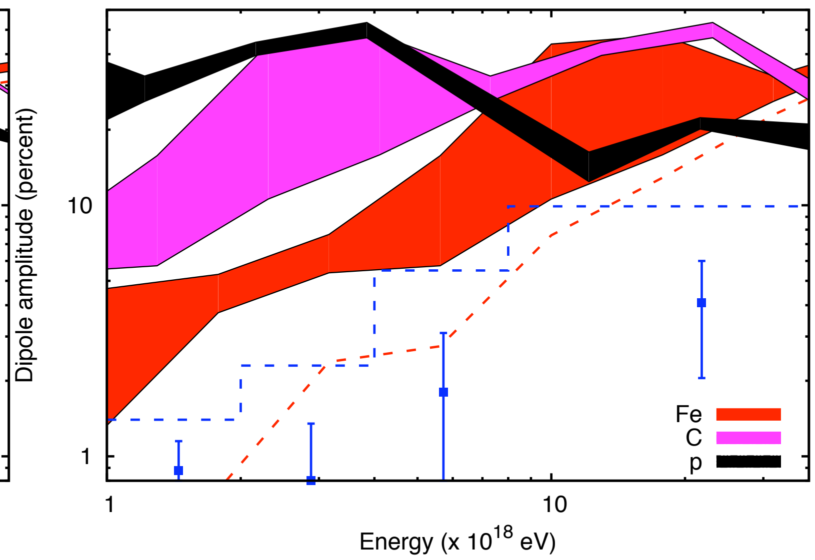
Anisotropy dipole



Pierre Auger Collaboration, arXiv:1103.2721

Galactic sources: dipole calculation



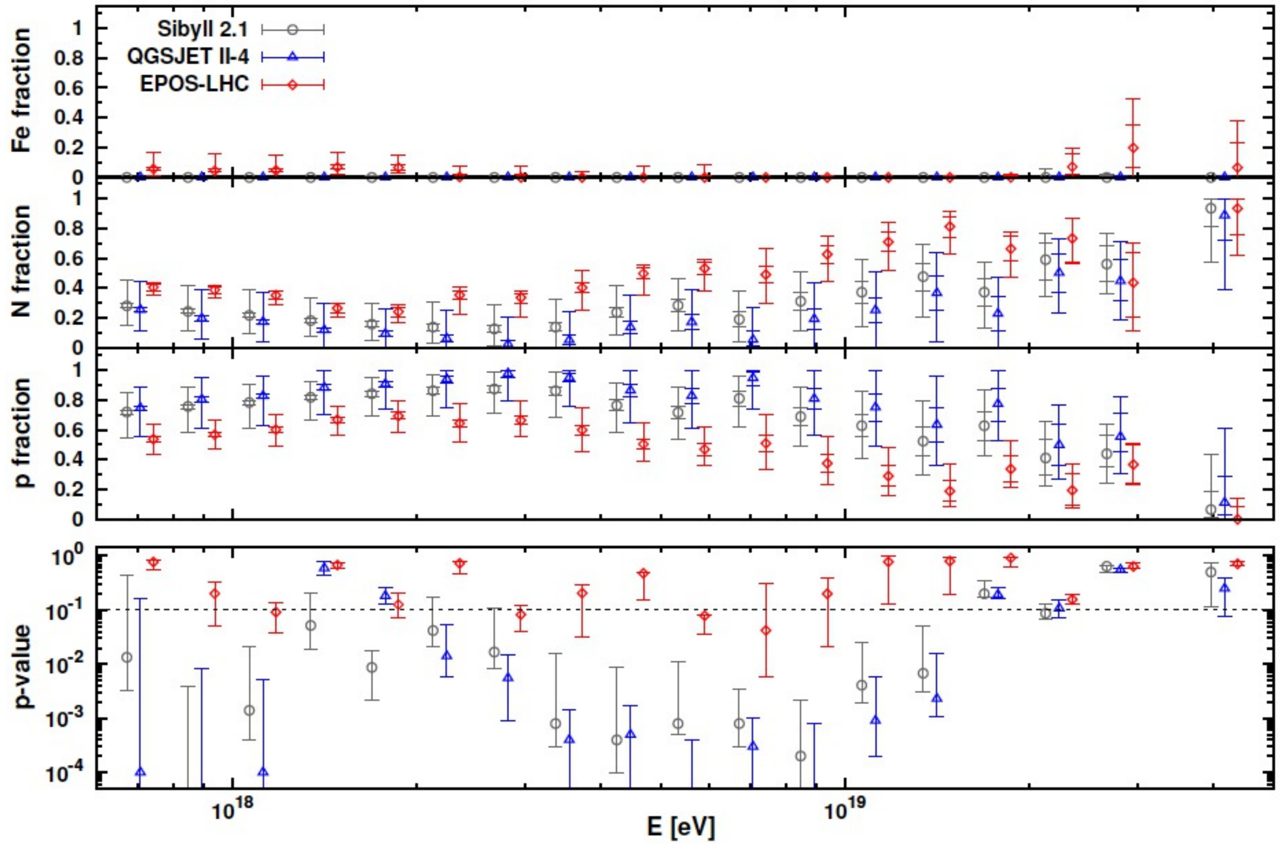


Turb. Magn. Field spectrum
Kolmogorov/Kraichnan

Lmax = 100-300 pc

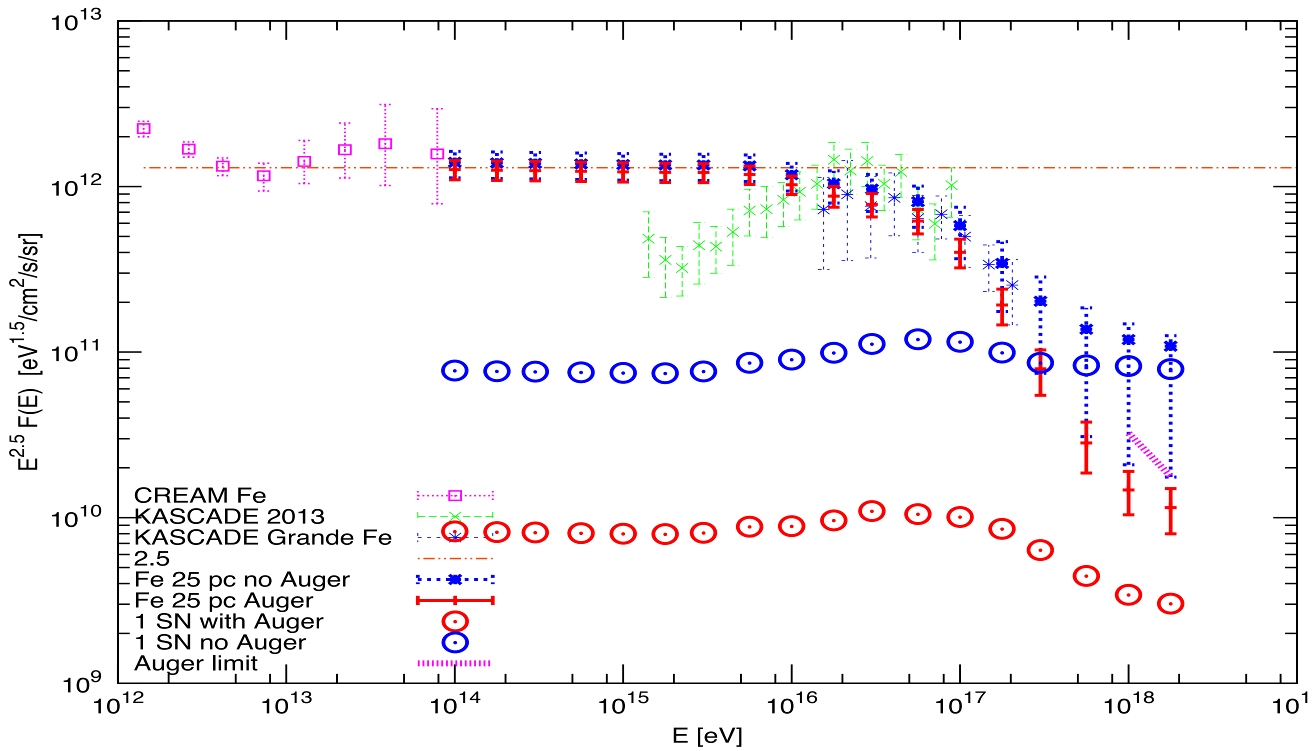
G.Giacinti et al, **arXiv:1112.5599**

Auger cosmposition measurements

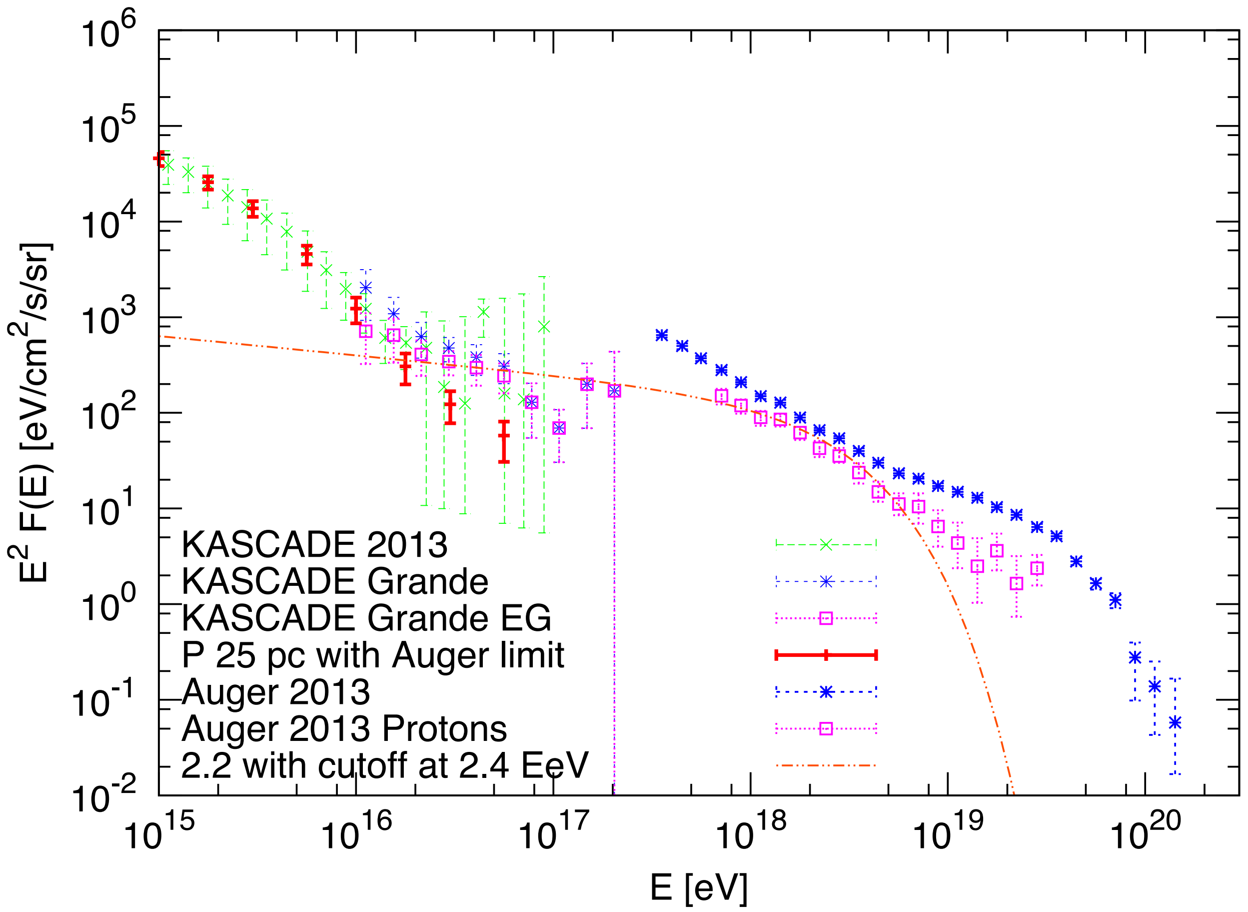


Auger Collaboration, **arXiv:1409.5083**

Auger limit on Fe fraction



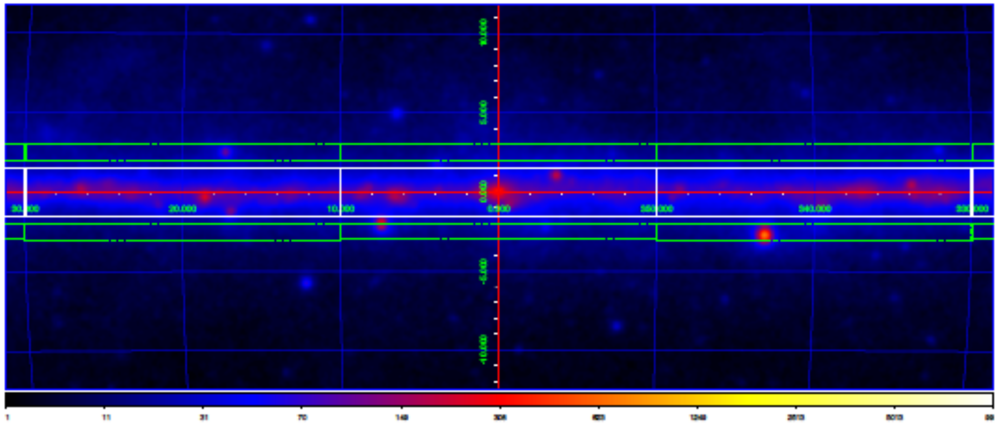
Extragalactic proton sources

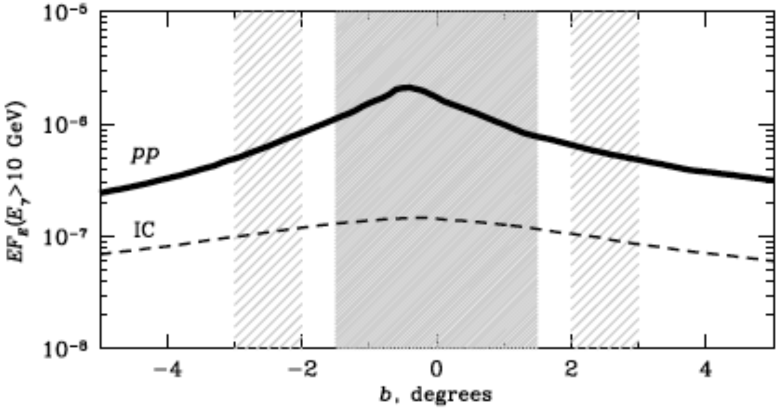


G.Giacinti et al,1502.01608

CR spectrum in MW and LMC from gamma-rays

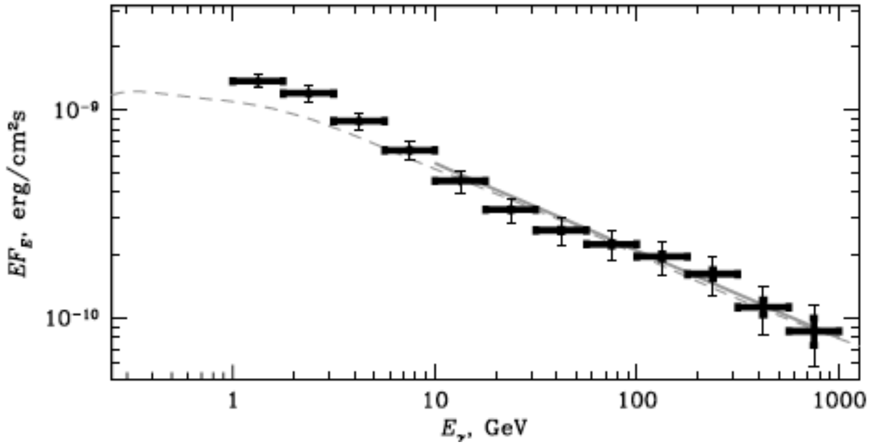
Milky Way inner Galaxy
Fermi E>10 GeV

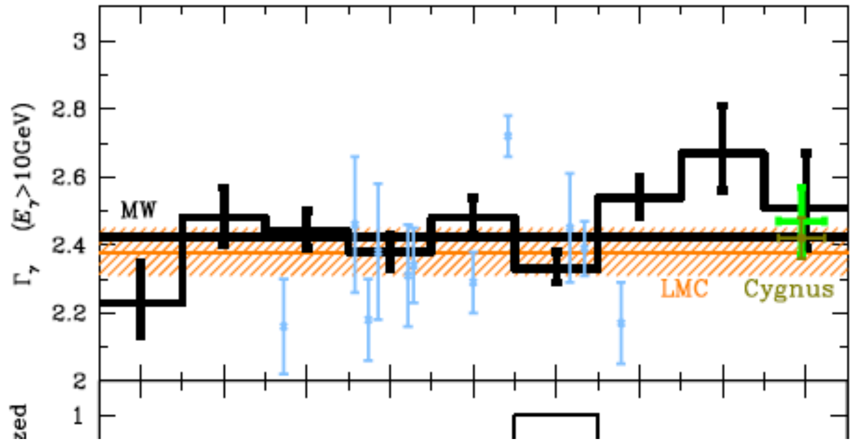




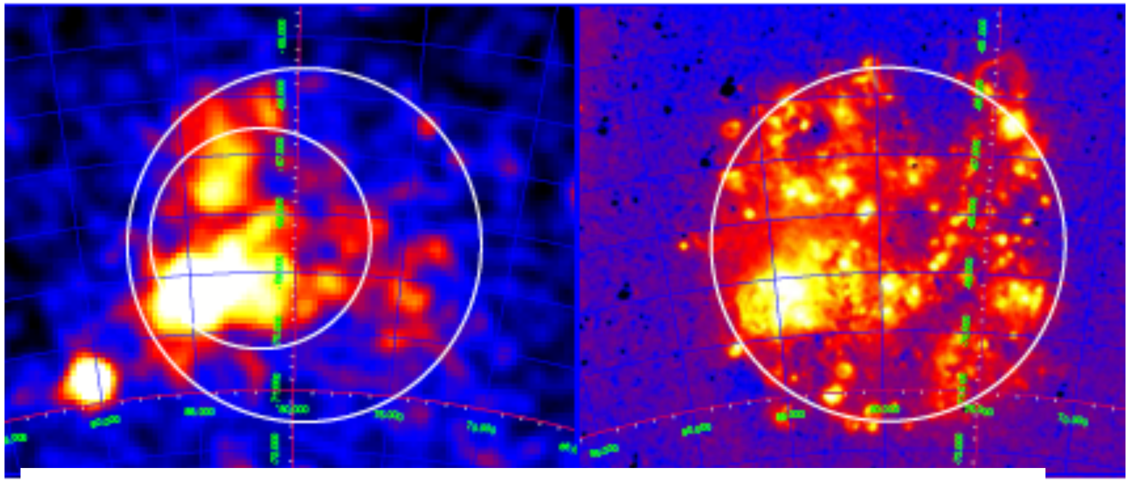
A.Neronov and D.Malishev, arXiv: 1505.07601

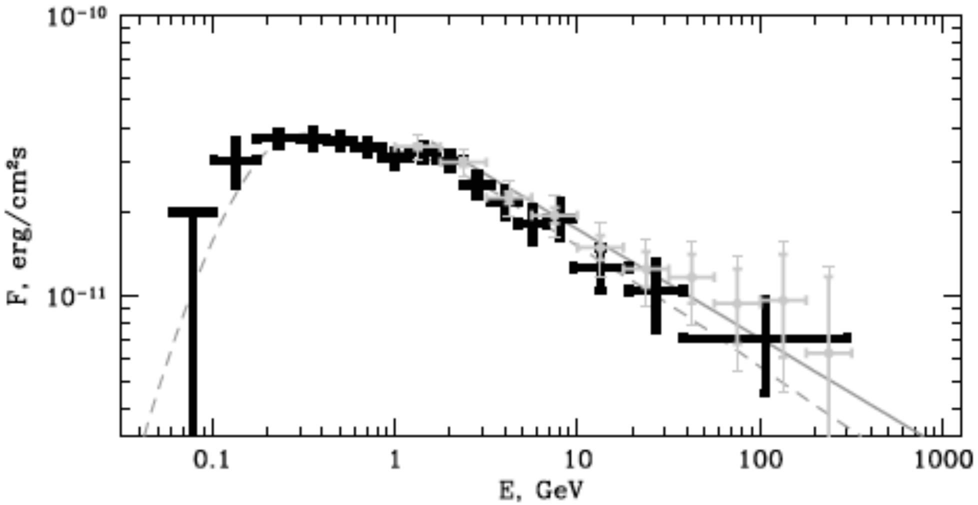
Milky Way inner Galaxy
Fermi E>10 GeV: spectrum 2.45





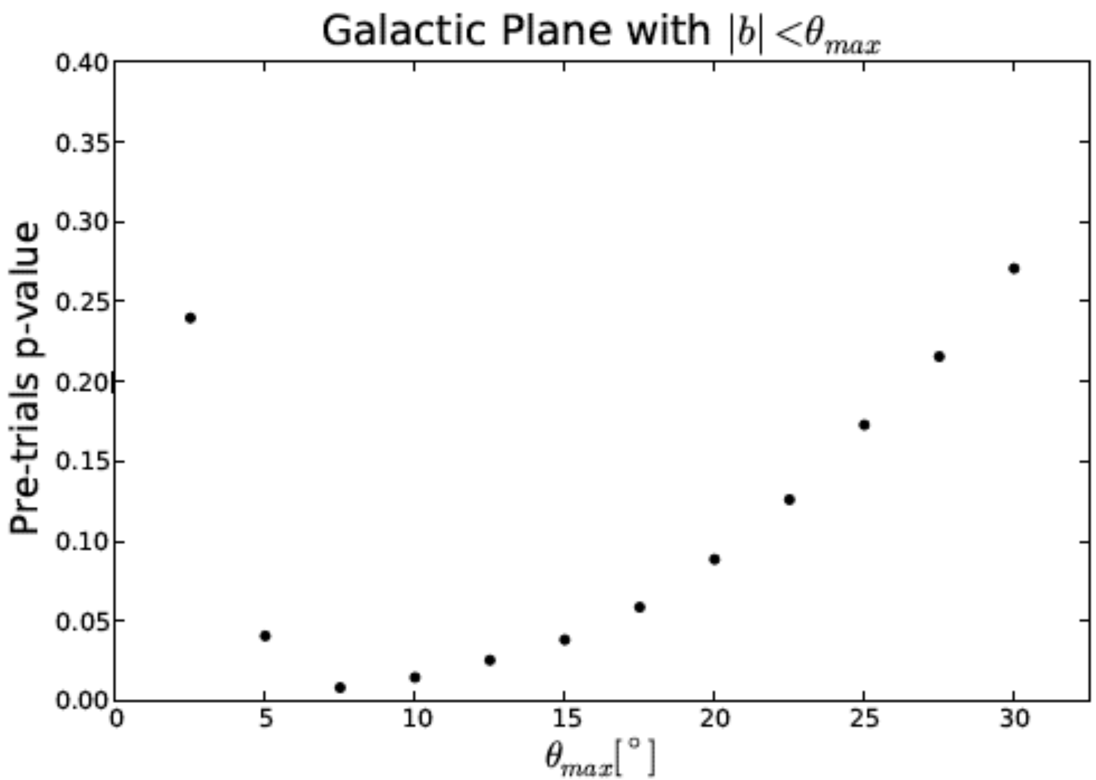
In LMC average proton spectrum 2.45





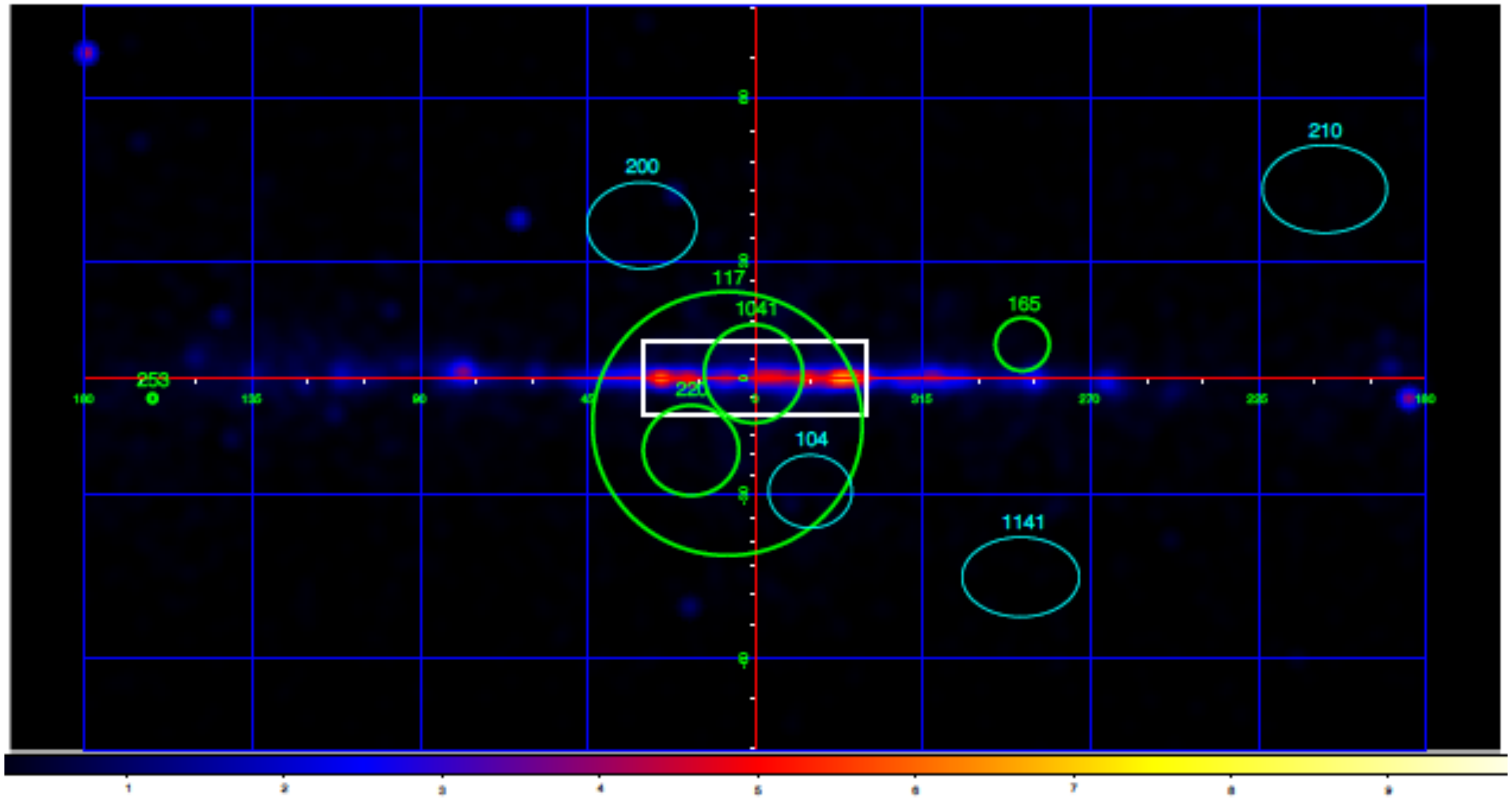
Neutrino flux from Milky Way

Galactic plane: 2% by chance



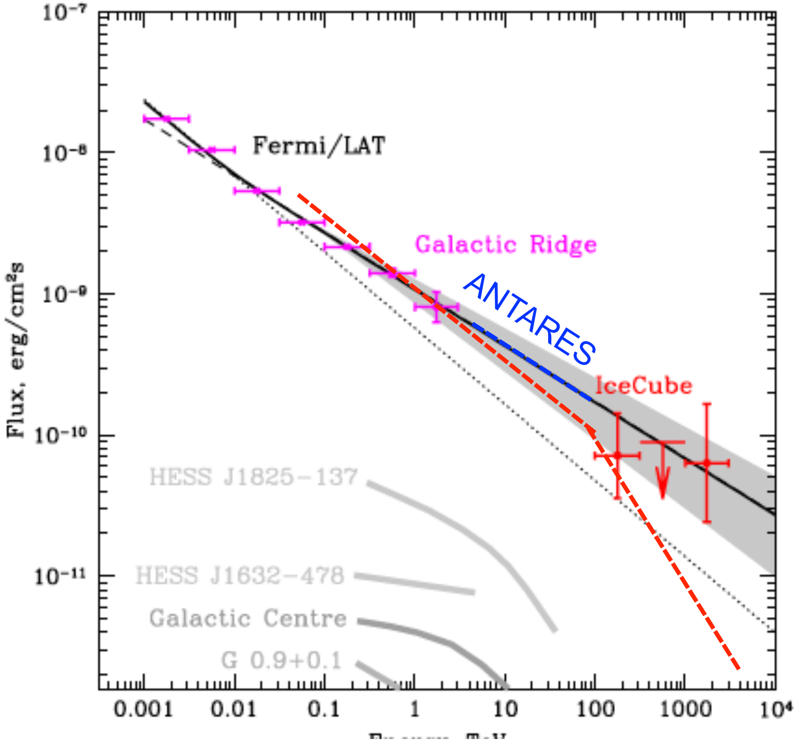
ICECUBE collaboration, 1405.5303

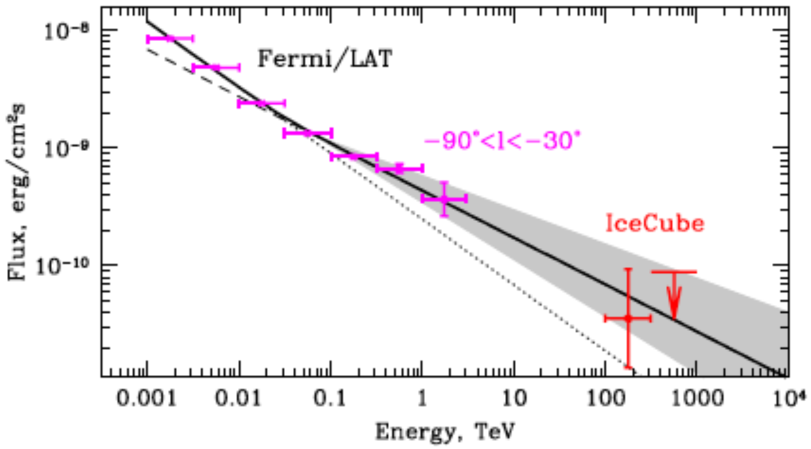
Half of ICECUBE events E>100 TeV are in Galactic plane. Are they correlate with gamma-rays?



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

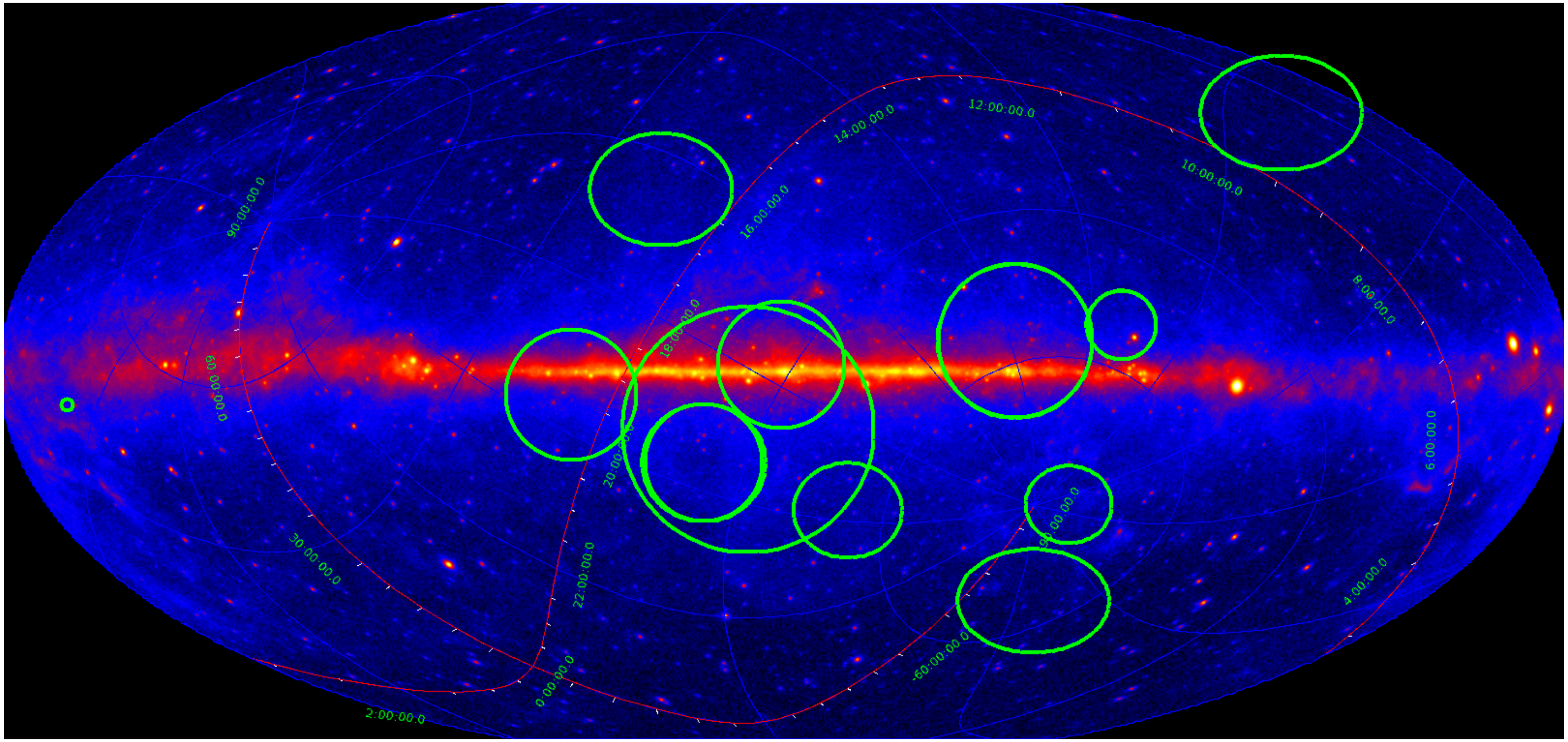
Real multimessenger fluxes, alpha=2.5



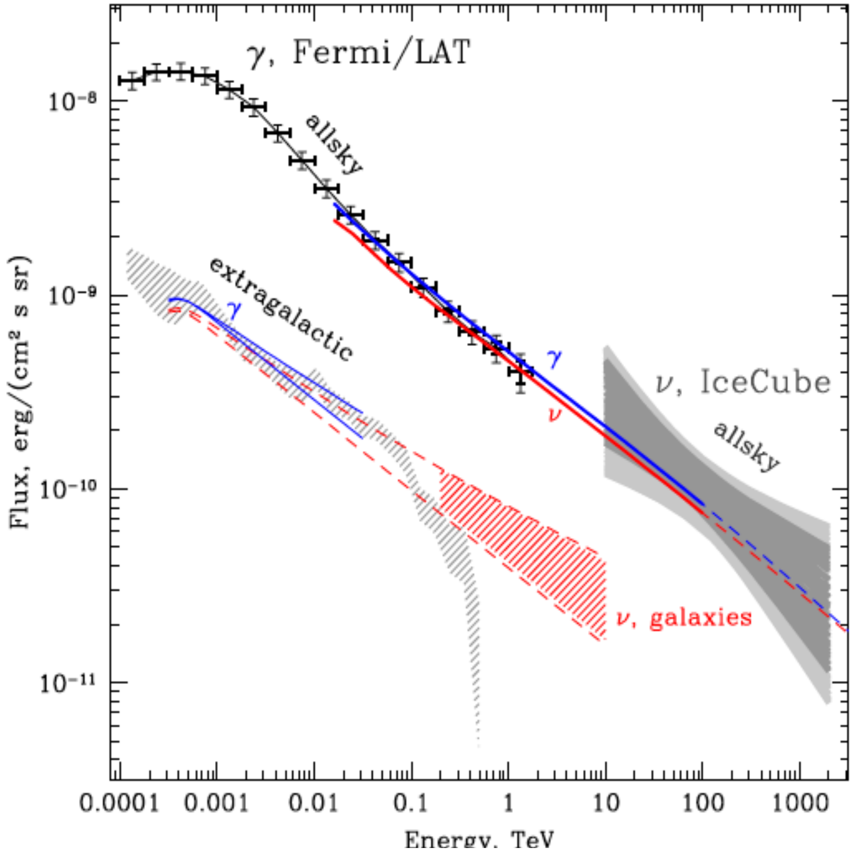


V.Berezinsky & A.Smirnov 1975

IceCube neutrino sky map
3 years E> 100 TeV

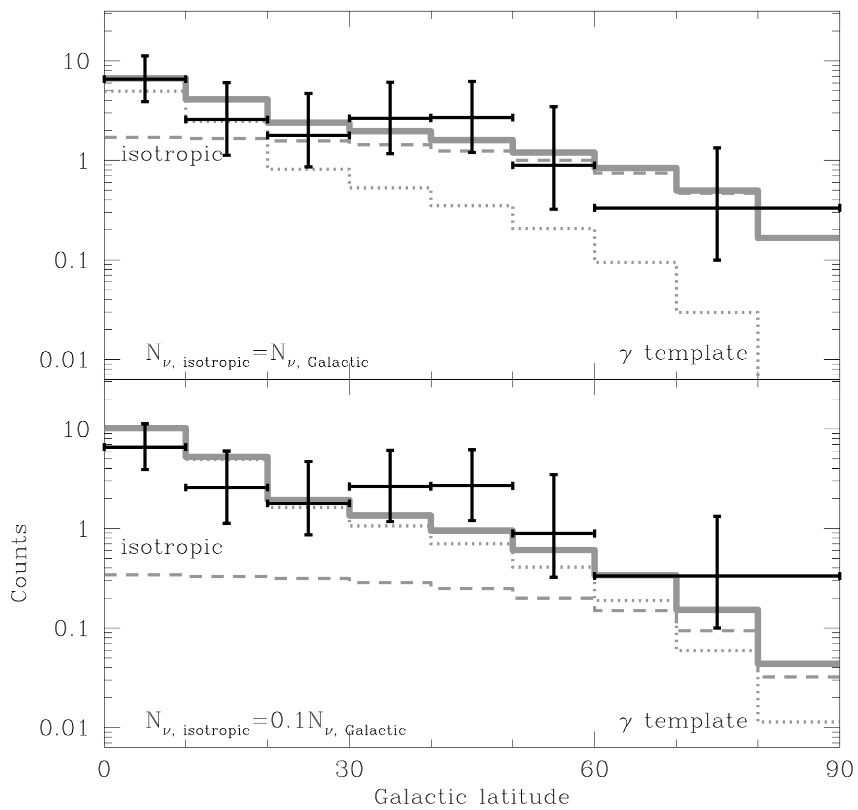


IceCube + Fermi LAT all sky: protons 1/E^2.5

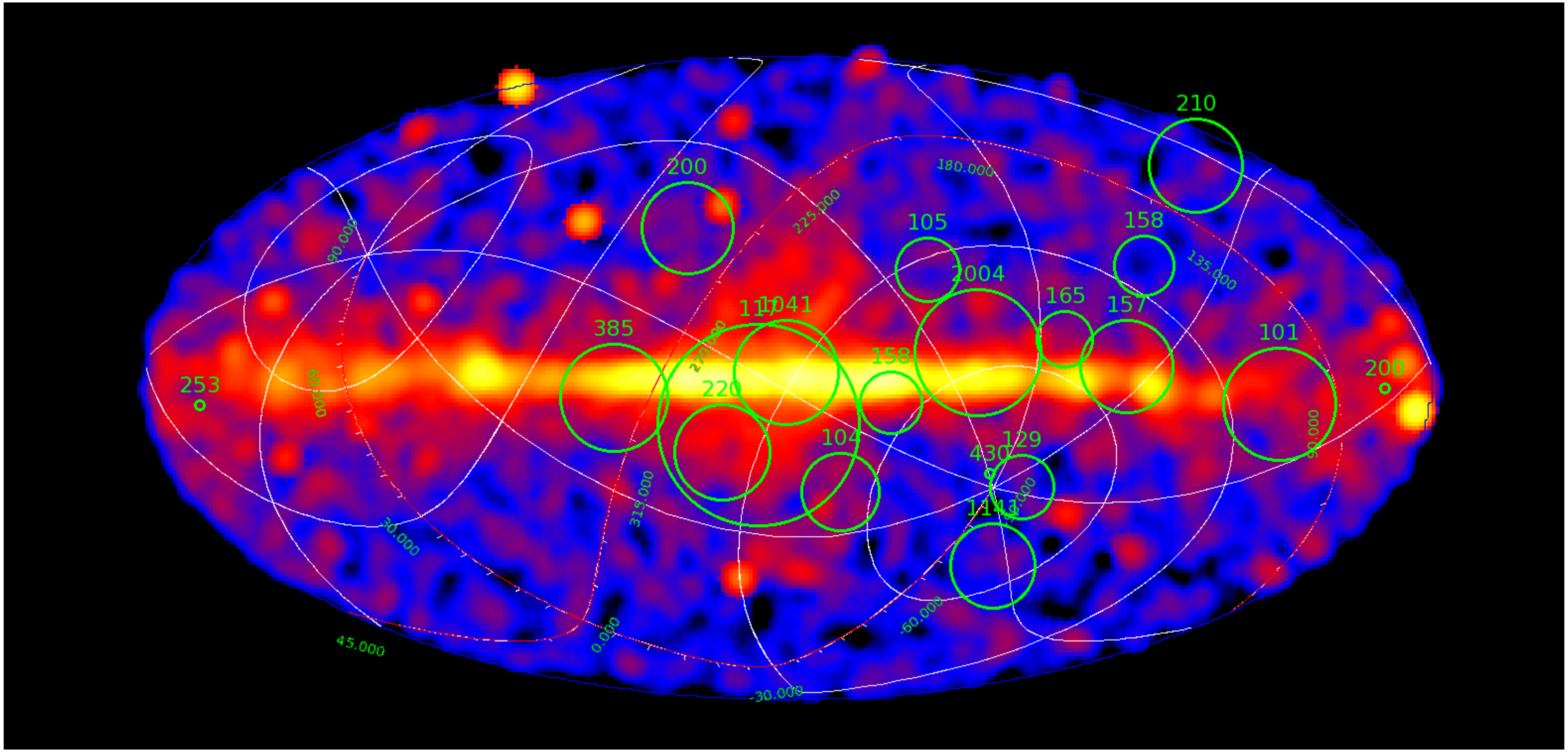


A.Neronov, D.S. arXiv:1412.1690

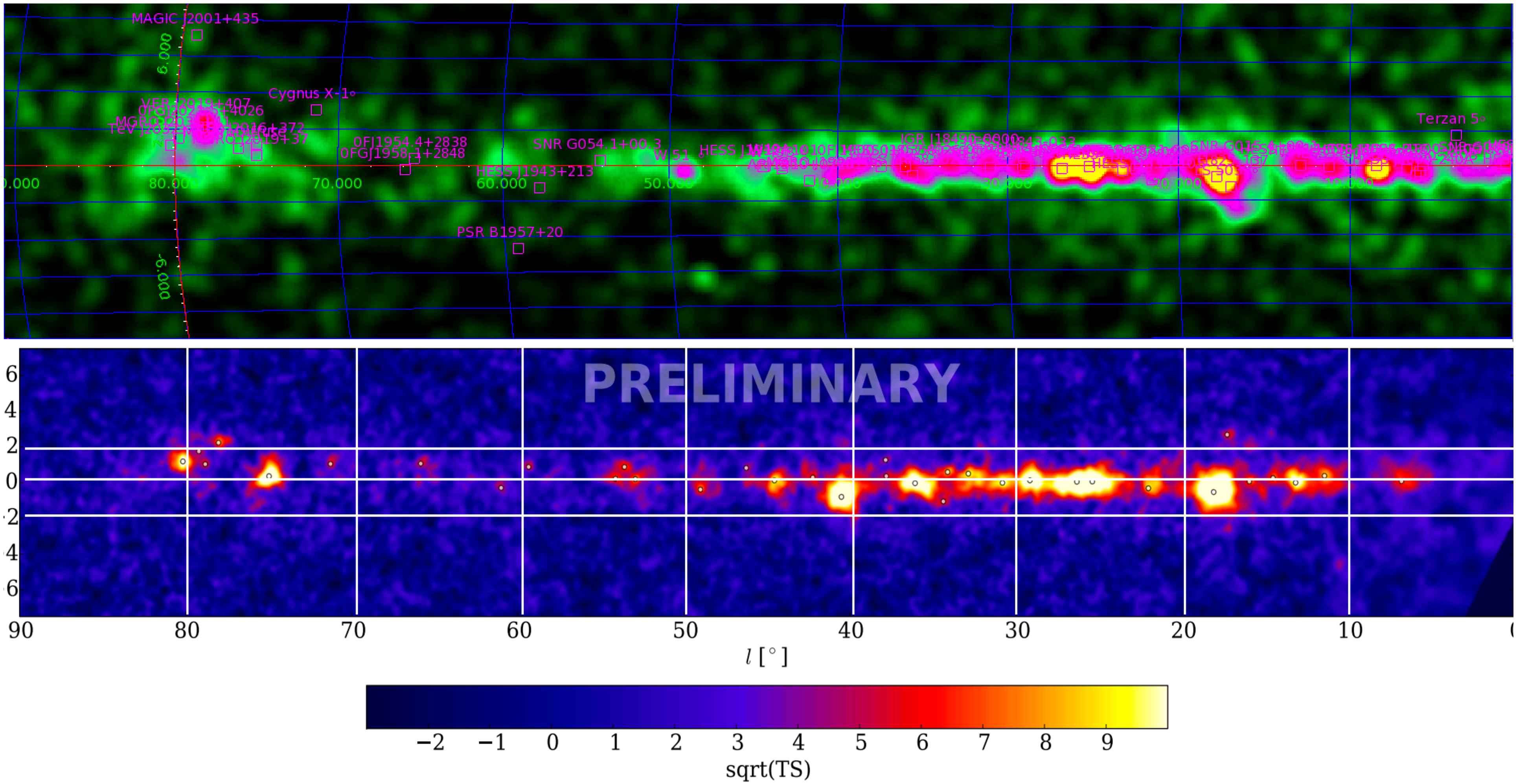
Neutrino flux as function of |b|



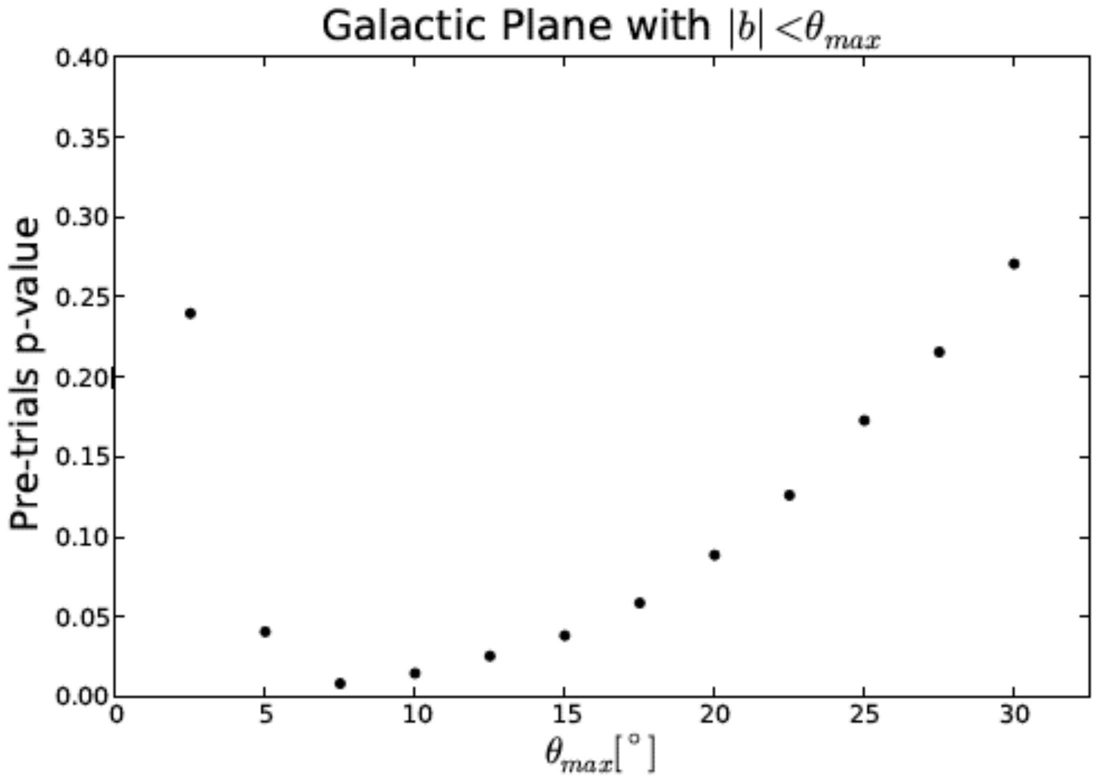
IceCube neutrino sky map 4 years E> 100 TeV and Fermi E>100 GeV 5 degree smoothed



First HAWC results: E> 4 TeV gamma-rays

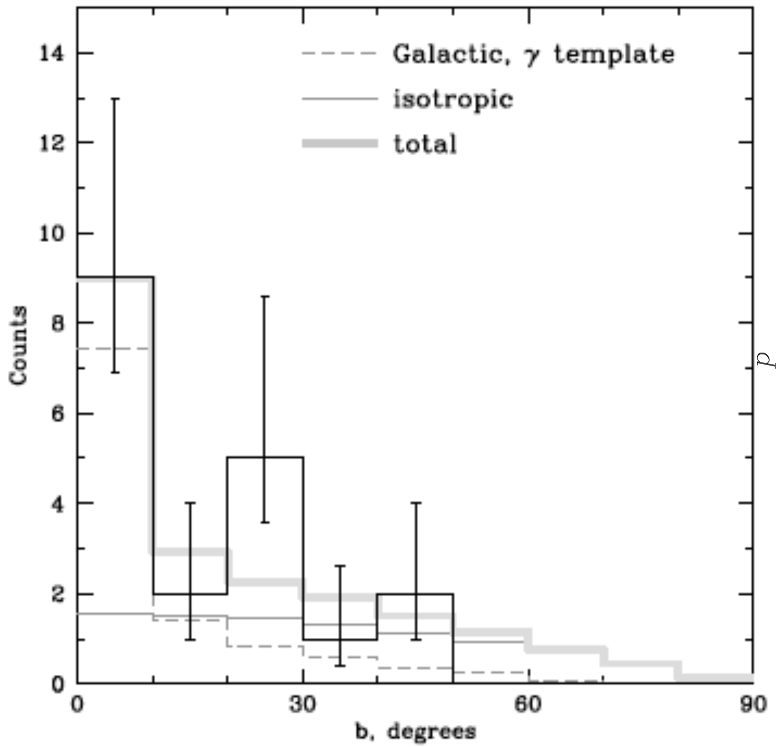


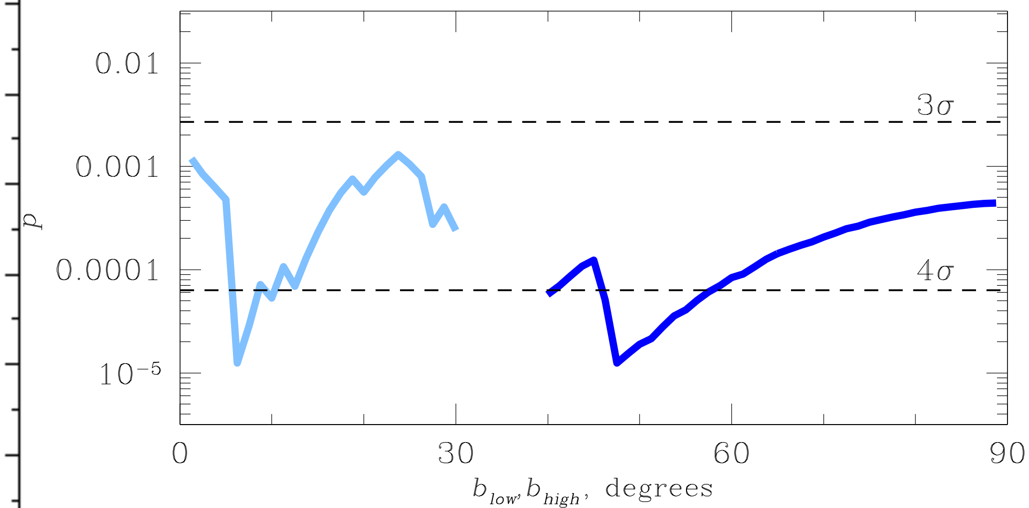
IceCube galactic plane 3 years: 2% by chance – small statistics



ICECUBE collaboration, arXiv:1405.5303

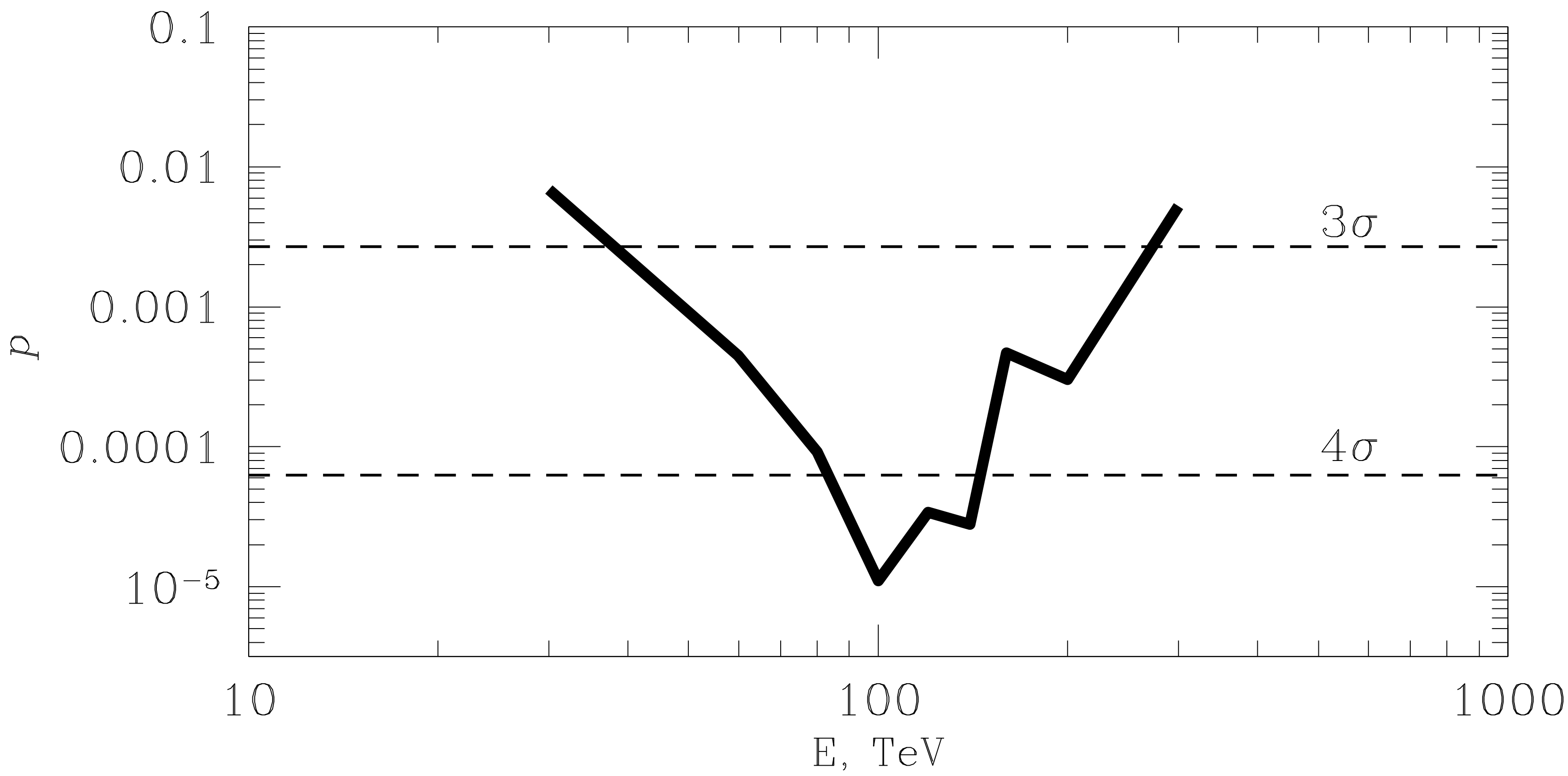
Evidence of Galactic component in 4 year IceCube data E>100 TeV





A. Neronov & D.S. arXiv: 1509.03522

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



A. Neronov & D.S. arXiv: 1509.03522

Diffuse gamma-ray background

Pion production

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

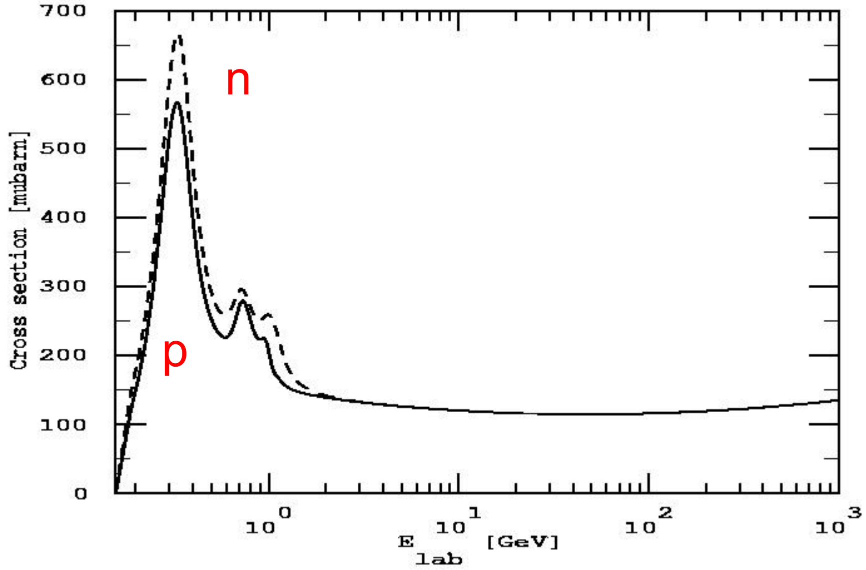
$$N + A_b \Rightarrow N' + \sum \pi^i$$

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

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

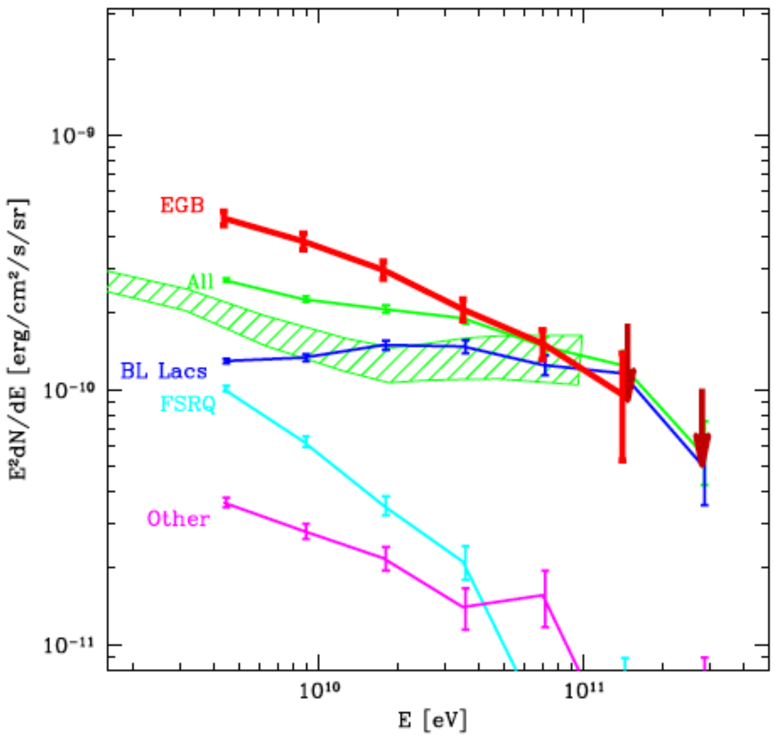
$$\mu^\pm \Rightarrow e^\pm + \bar{\nu}_e + \nu_\mu$$

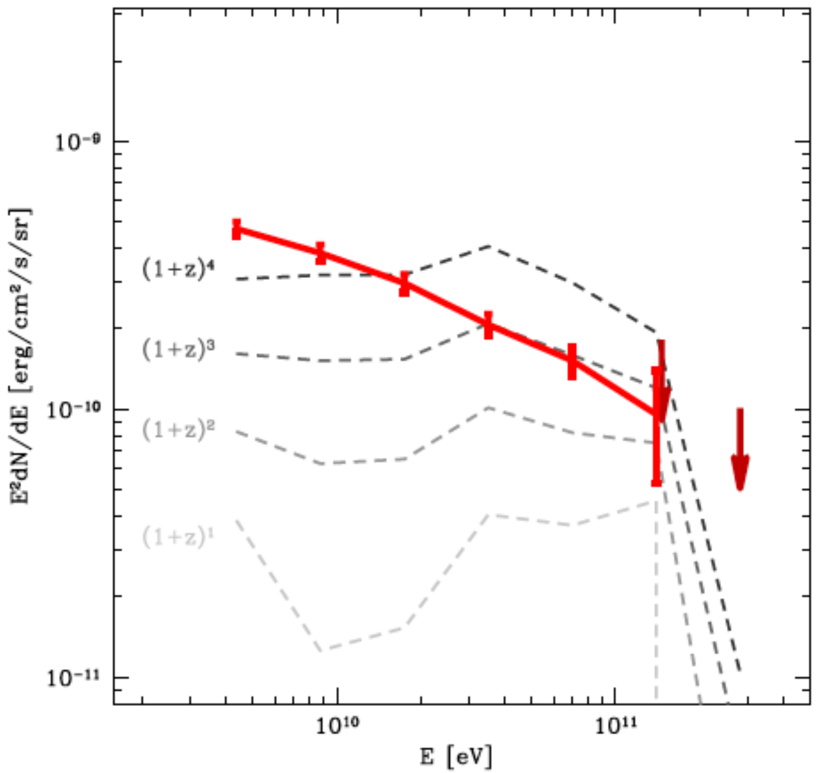
$$n \Rightarrow p + e^- + \bar{\nu}_e$$



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

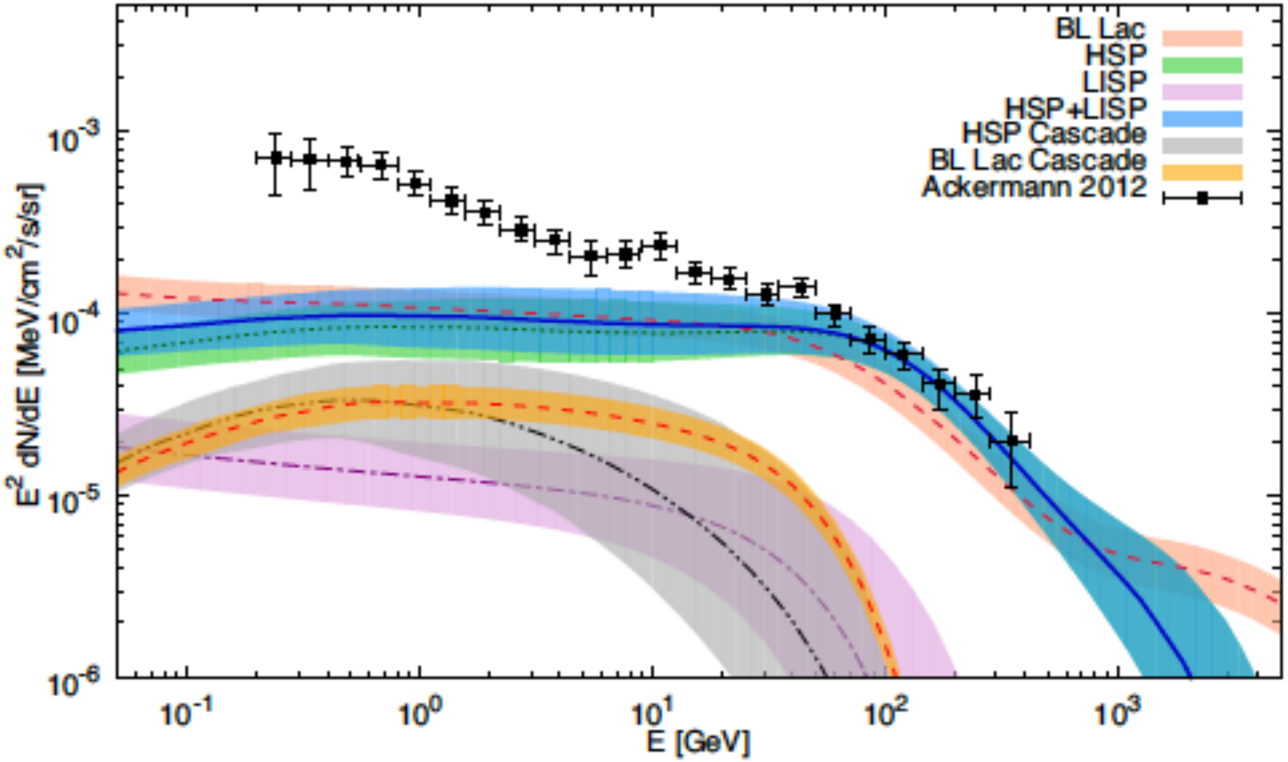
BL Lacs give main contribution to high energy part of diffuse gamma-ray flux





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

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



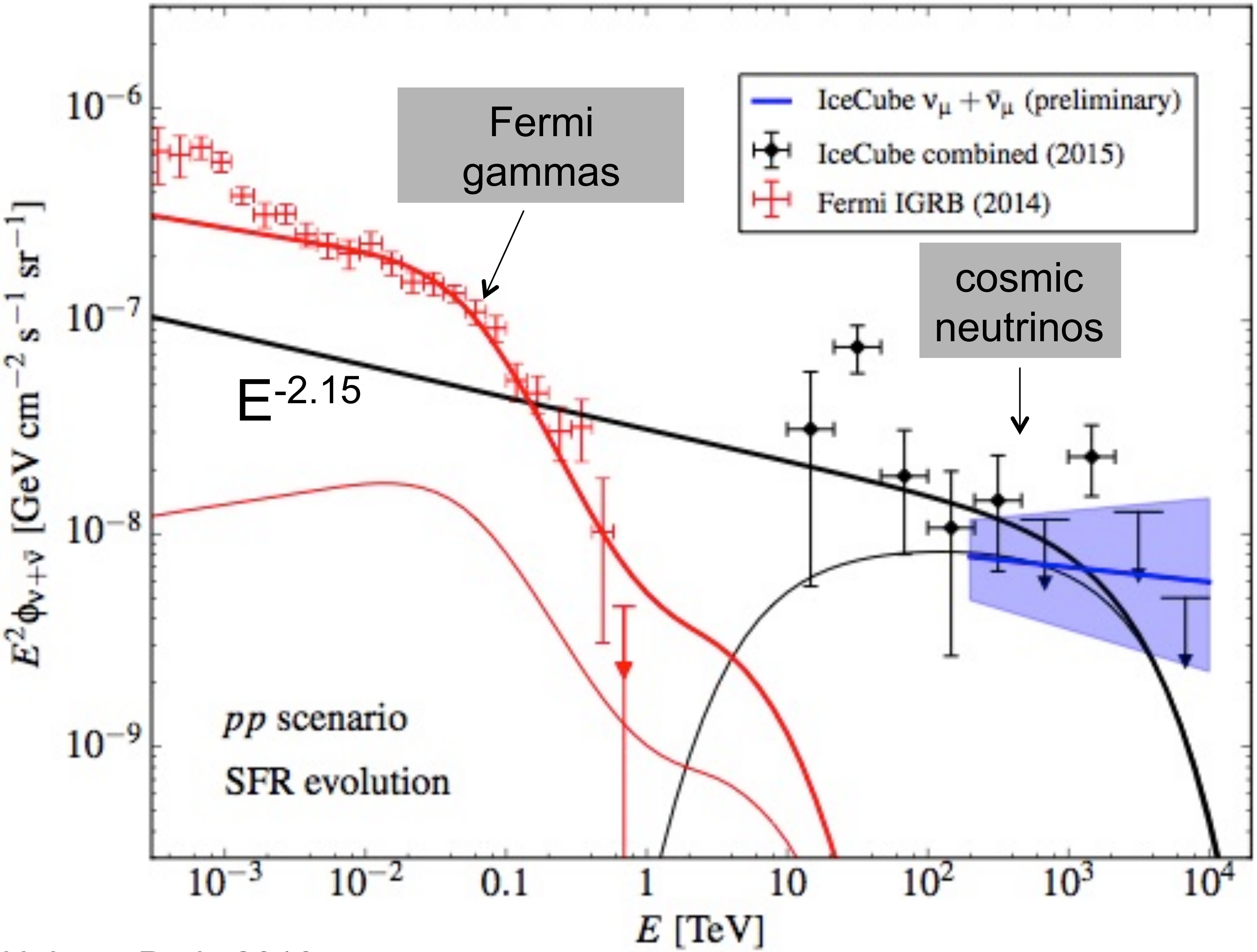
M. Di Mauro et al, arXiv:1311.5708

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

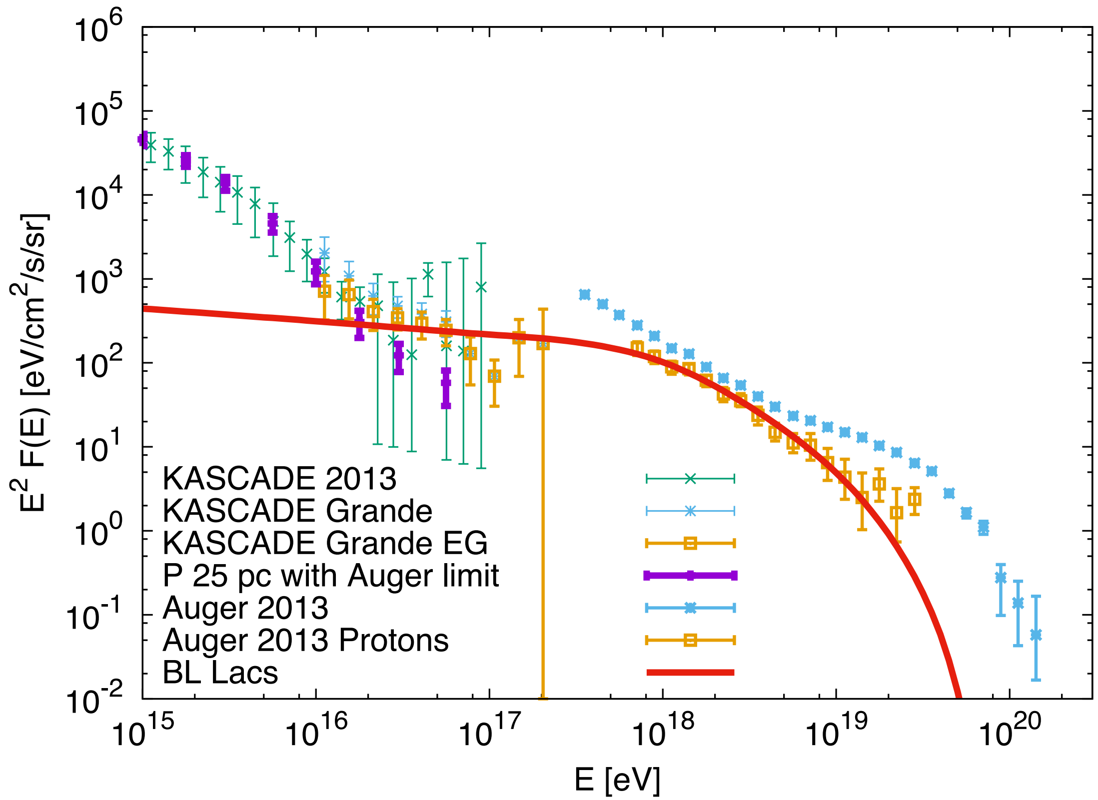
$\pi^+ = \pi^- = \pi^0$



From F.Halzen, Paris 2016

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**

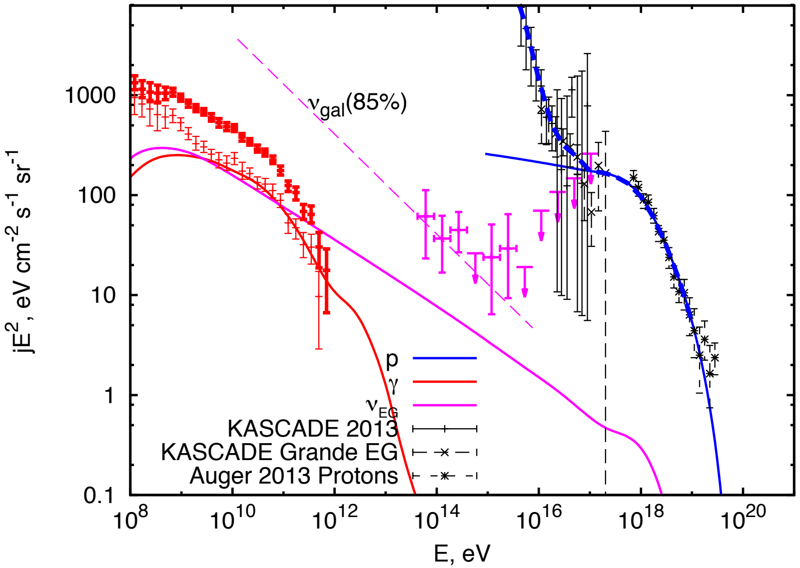
Protons in sources

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

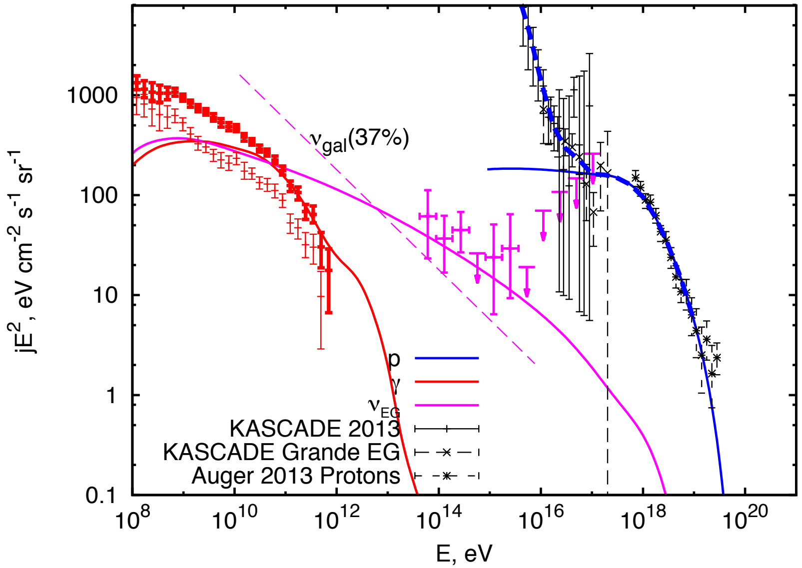
G.Giacinti, M.Kachelriess, O.Kalashev, A.Neronov and D.S., **arXiv: 1507.07534**

Miltimessenger signal from BL Lacs: dependence on escape energy

0.3 TeV



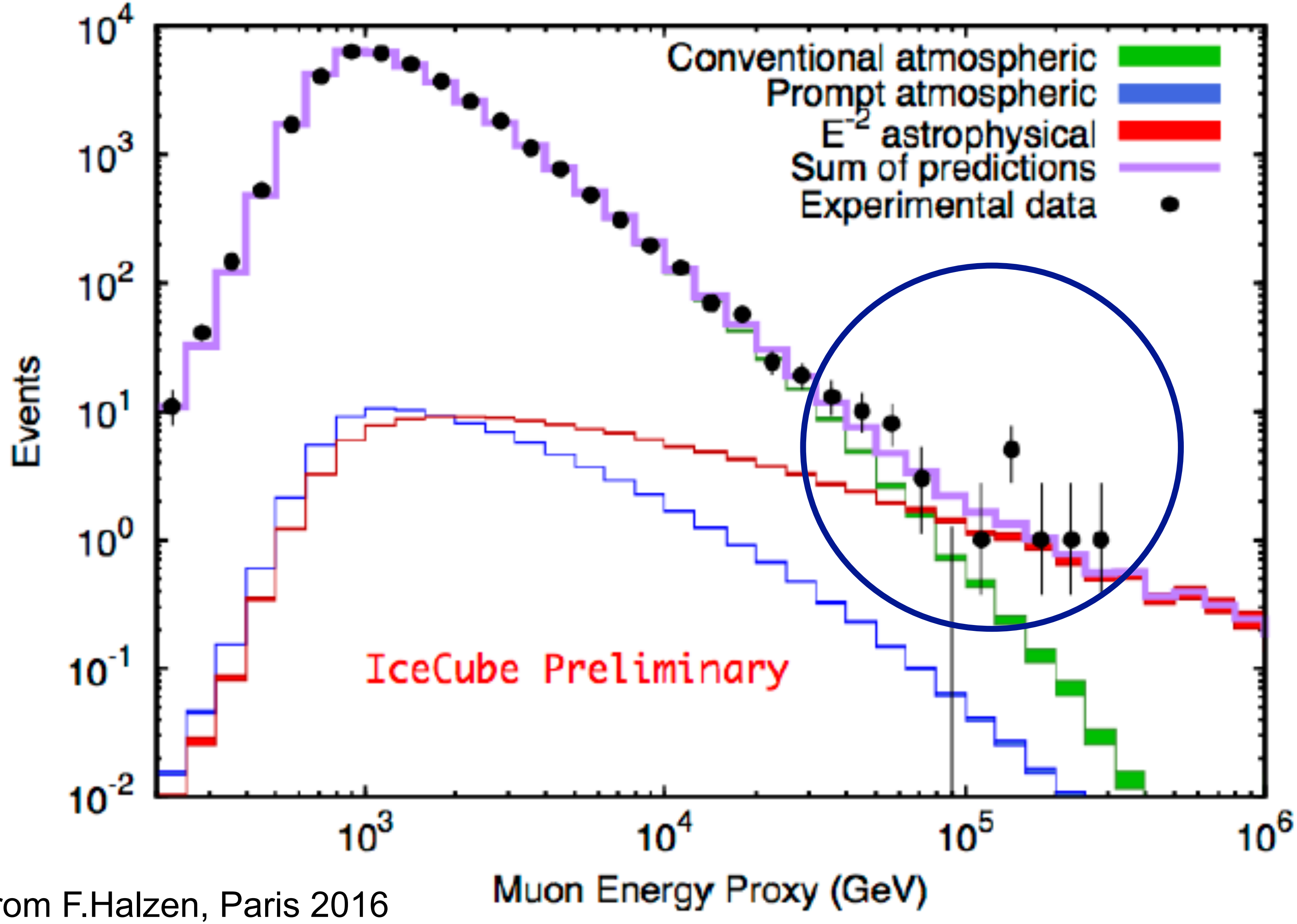
100 TeV



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

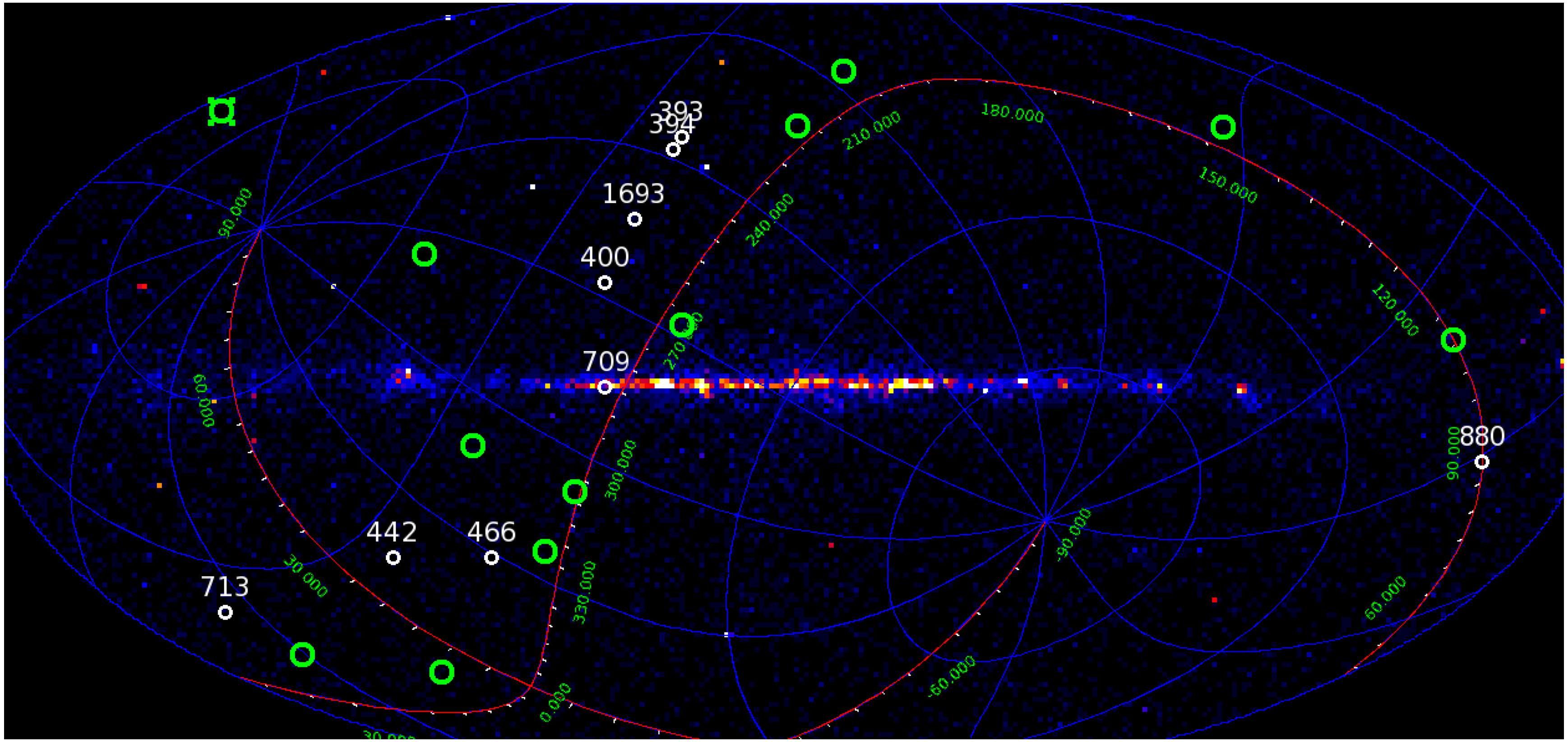
Extragalactic neutrino flux from 6 years of muon neutrinos

cosmic neutrinos in 2 years of data at 3.7 sigma



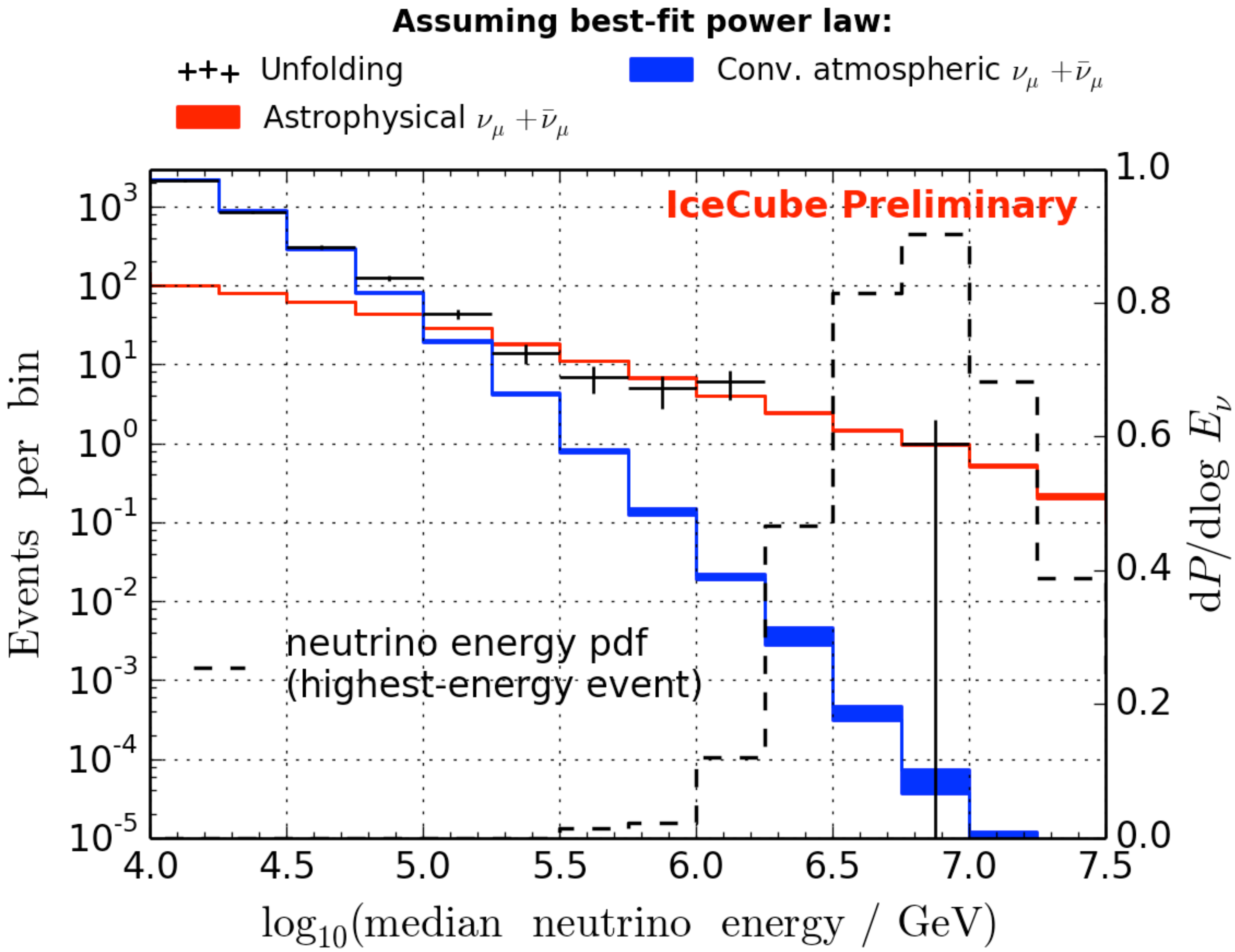
From F.Halzen, Paris 2016

Muon neutrinos

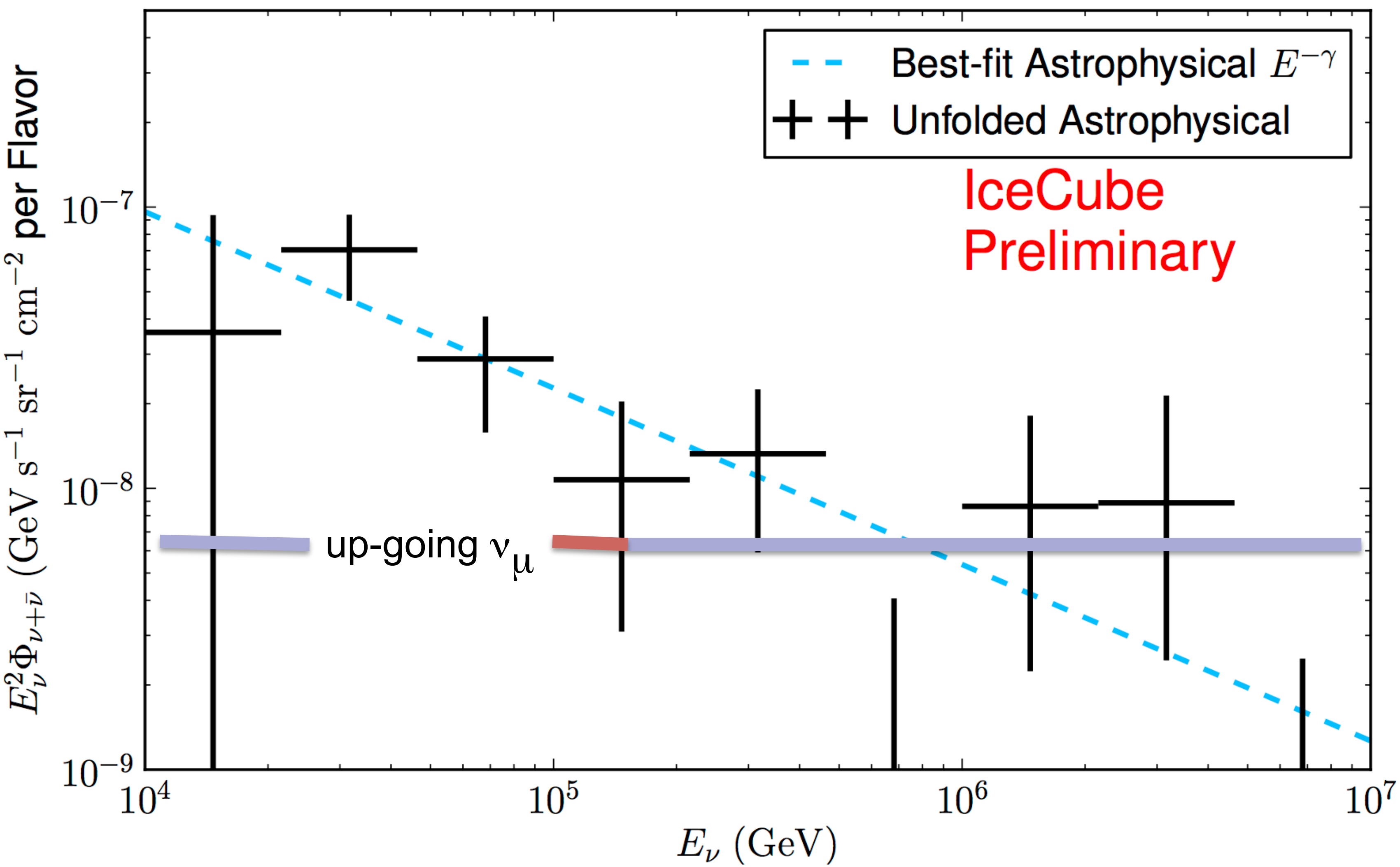


IceCube, ICRC 2015

muon neutrinos through the Earth → 6 sigma

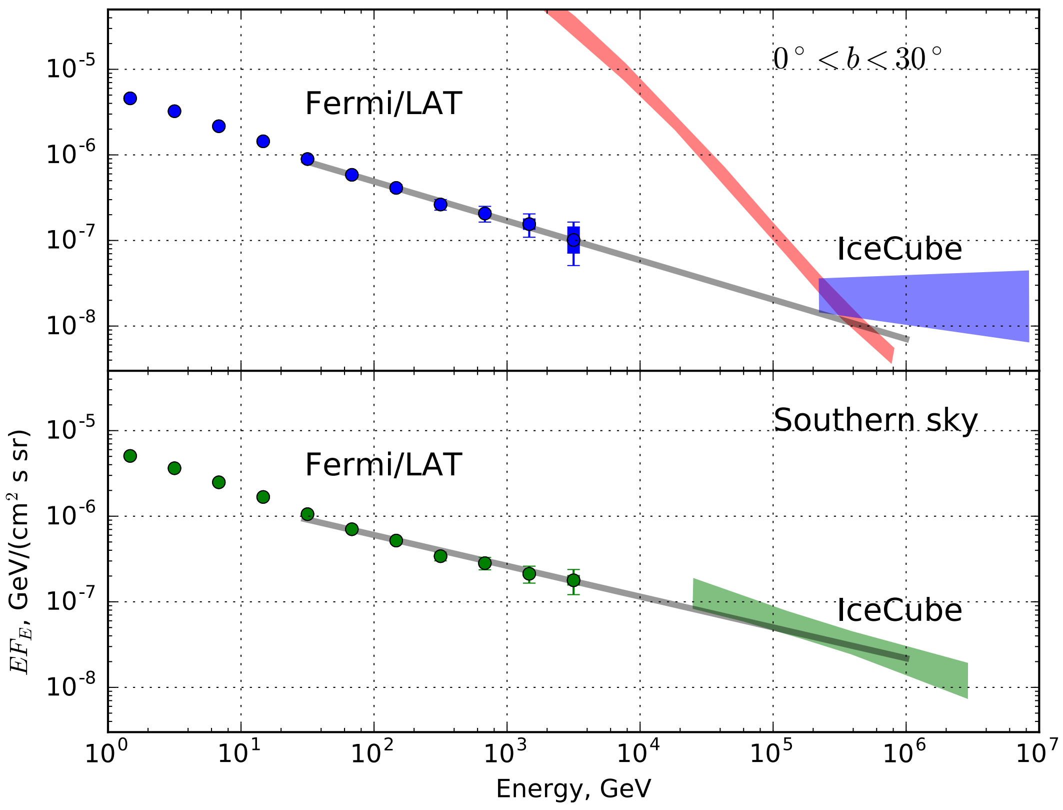


From F.Halzen, Paris 2016



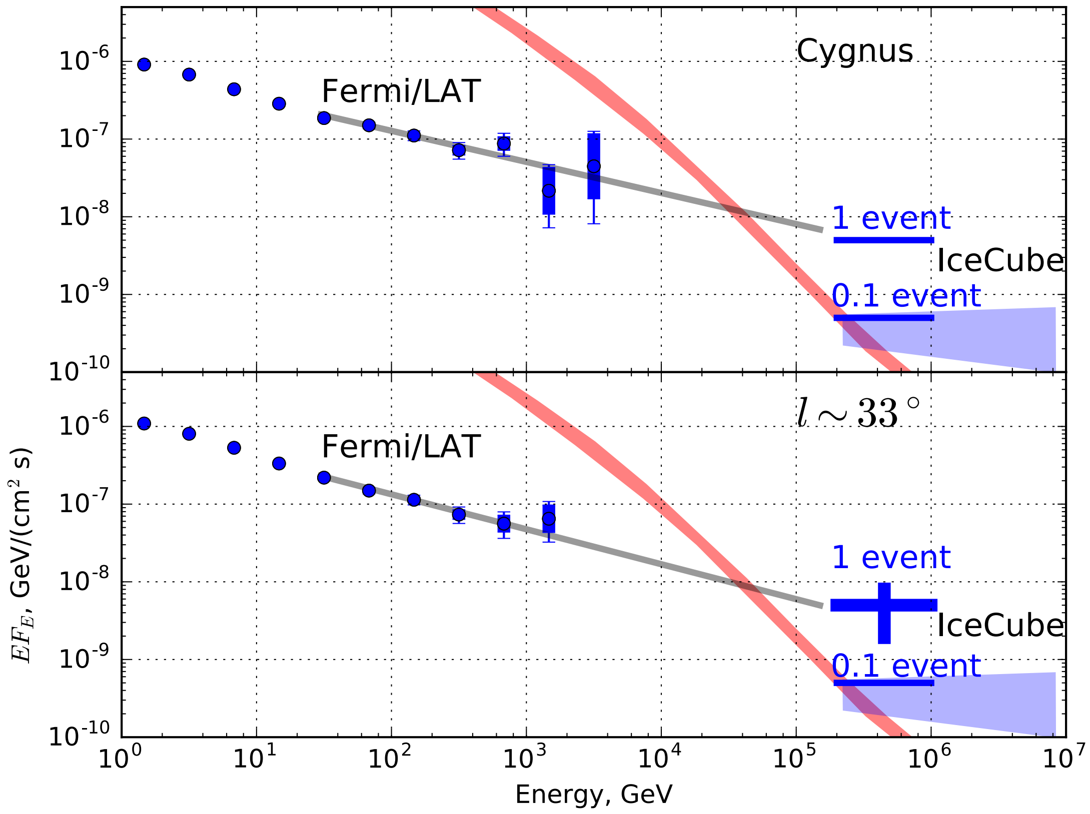
From F.Halzen, Paris 2016

North and South sky: IceCube



A. Neronov & D.S. arXiv: 1603.06733

First galactic diffuse 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 few 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*