Galactic diffuse gamma-ray and neutrino emission in multi-TeV energy range

Andrii Neronov
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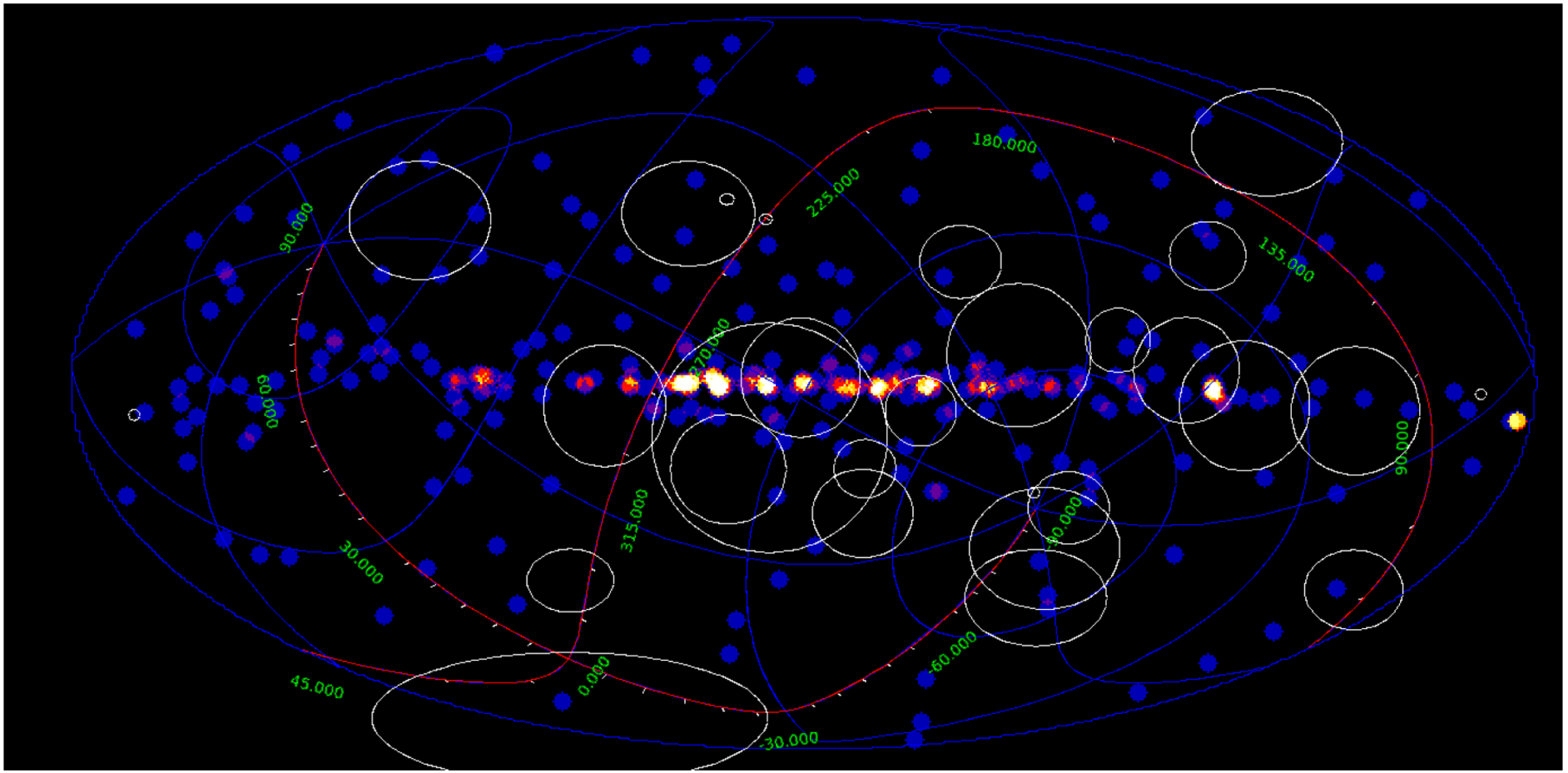
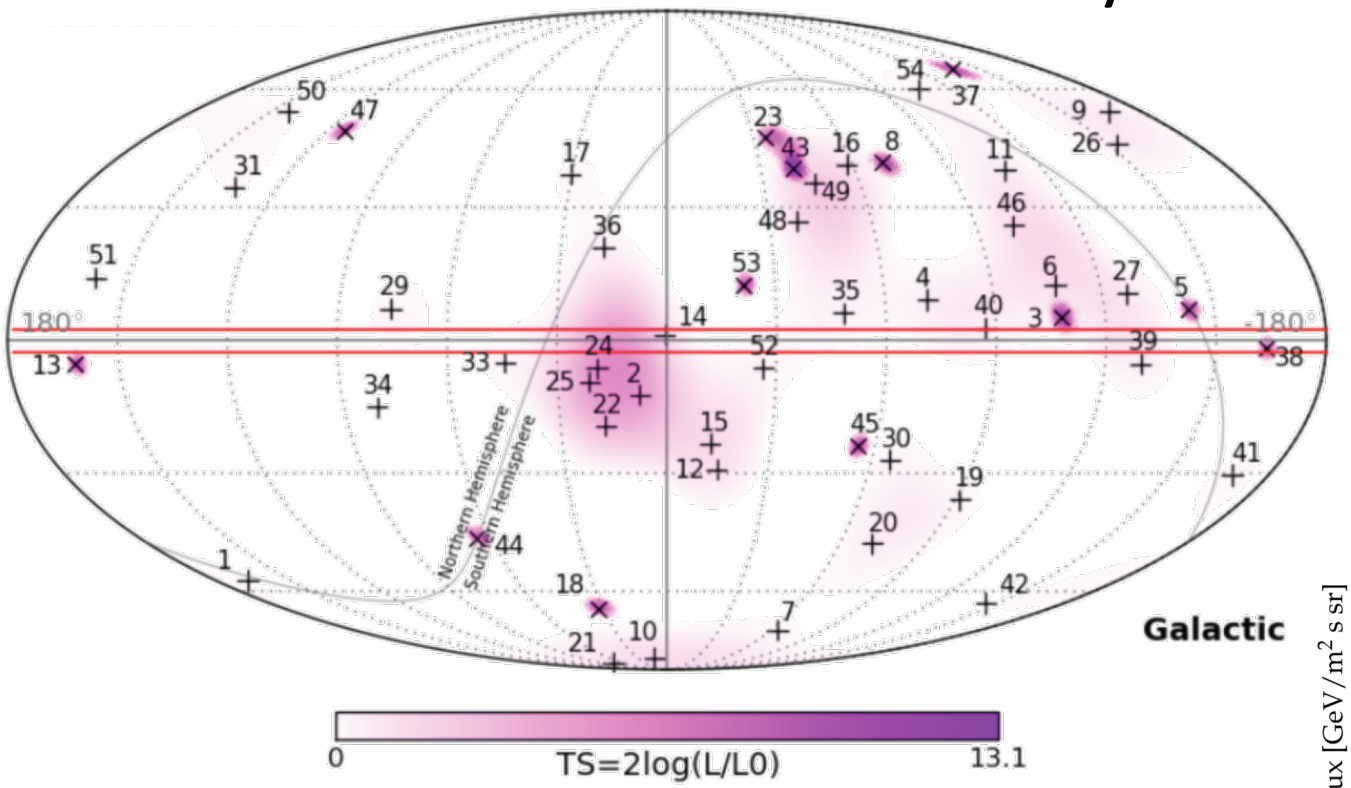


Galactic diffuse gamma-ray and neutrino emission in multi-TeV energy range

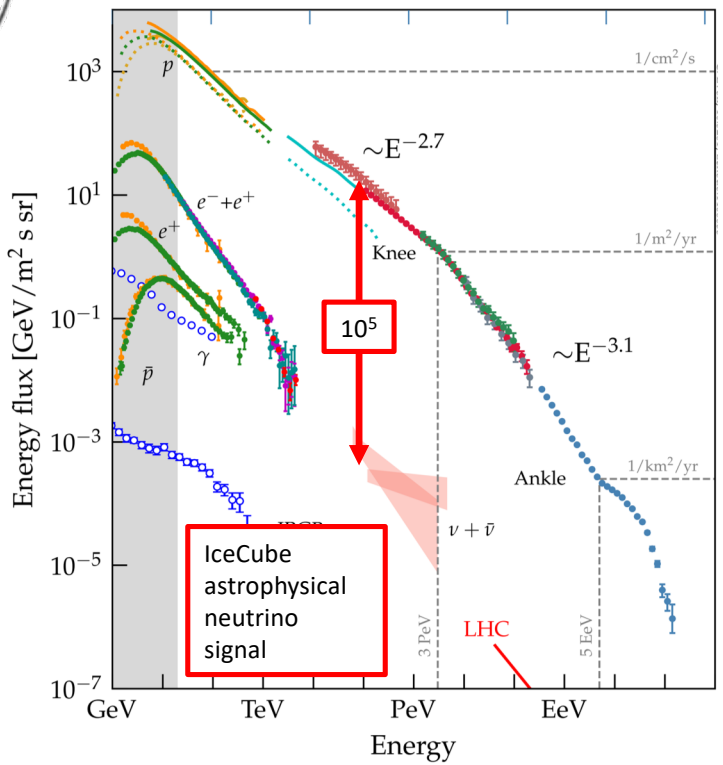
1) Neutrino and gamma-ray sky
2) Gamma-ray diffuse Galactic emission at TeV with Fermi/LAT
3) Multi-TeV Galactic diffuse emission with Cherenkov telescopes

Neutrino sky

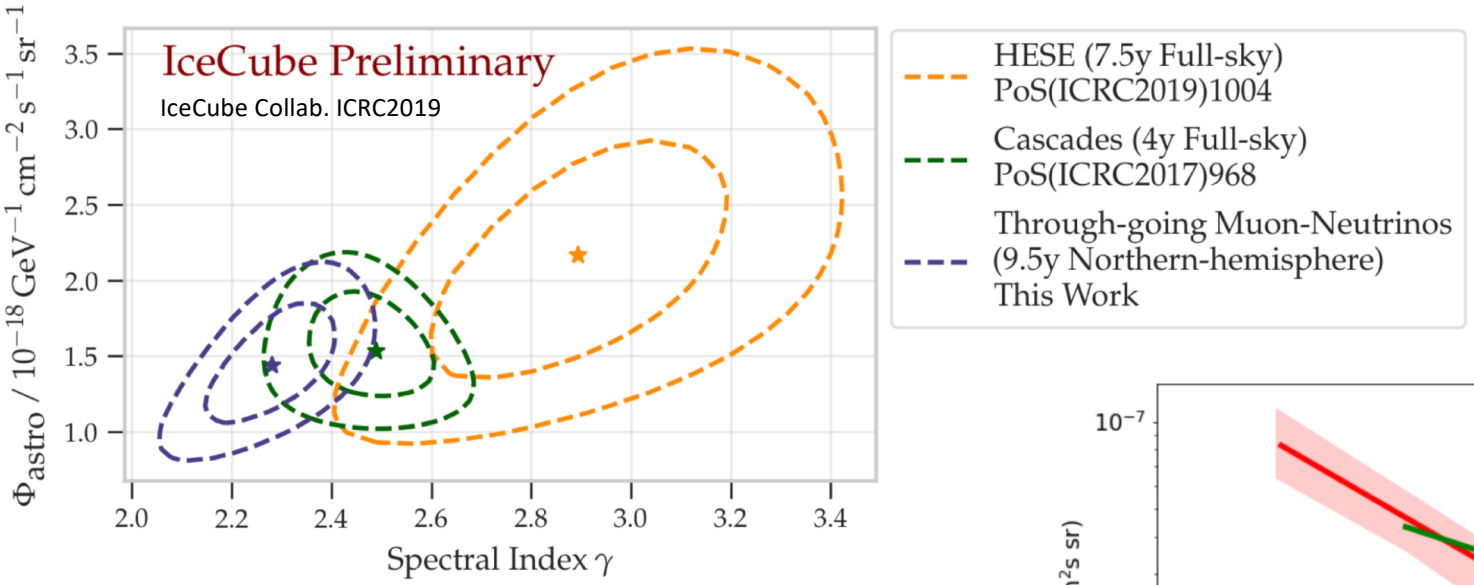


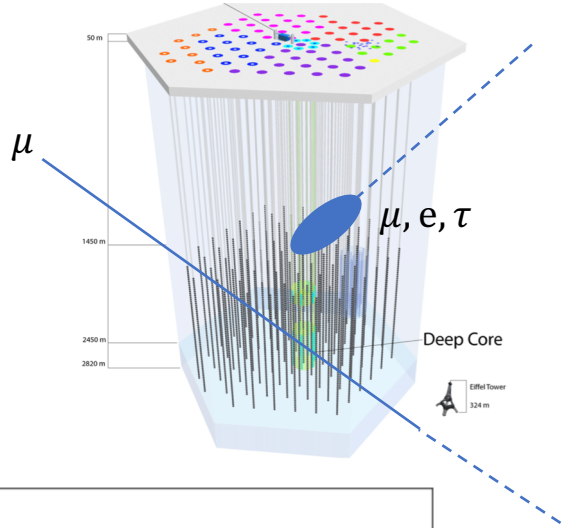
IceCube detects “astrophysical” neutrino signal in the 0.03-10 PeV energy range. Origin of the signal is uncertain.

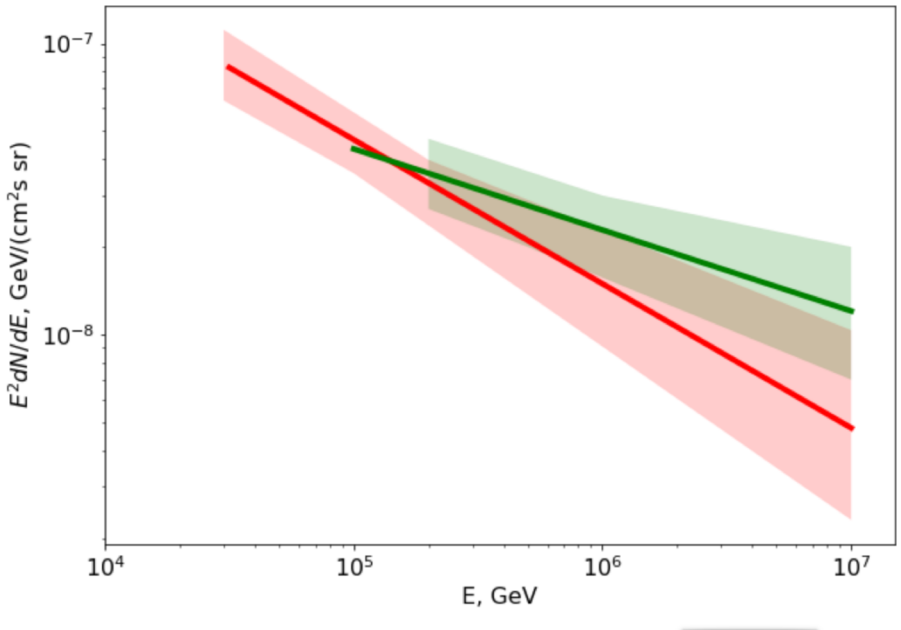
Neutrino event distribution is consistent with being isotropic, which points to extragalactic origin



Neutrino sky





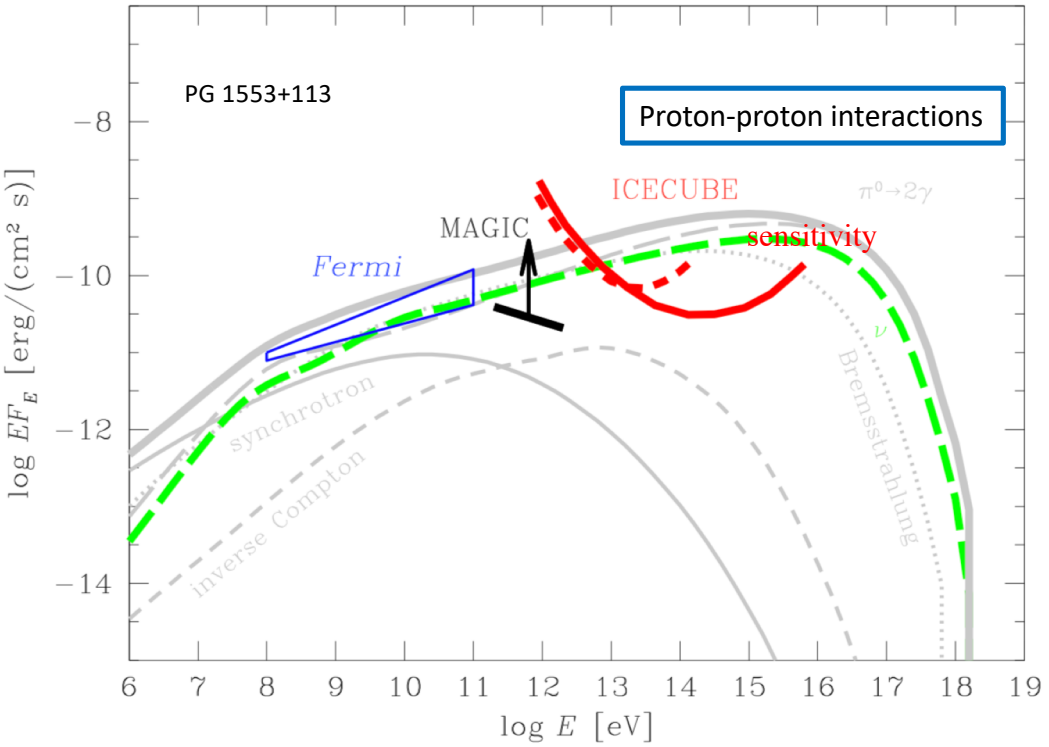


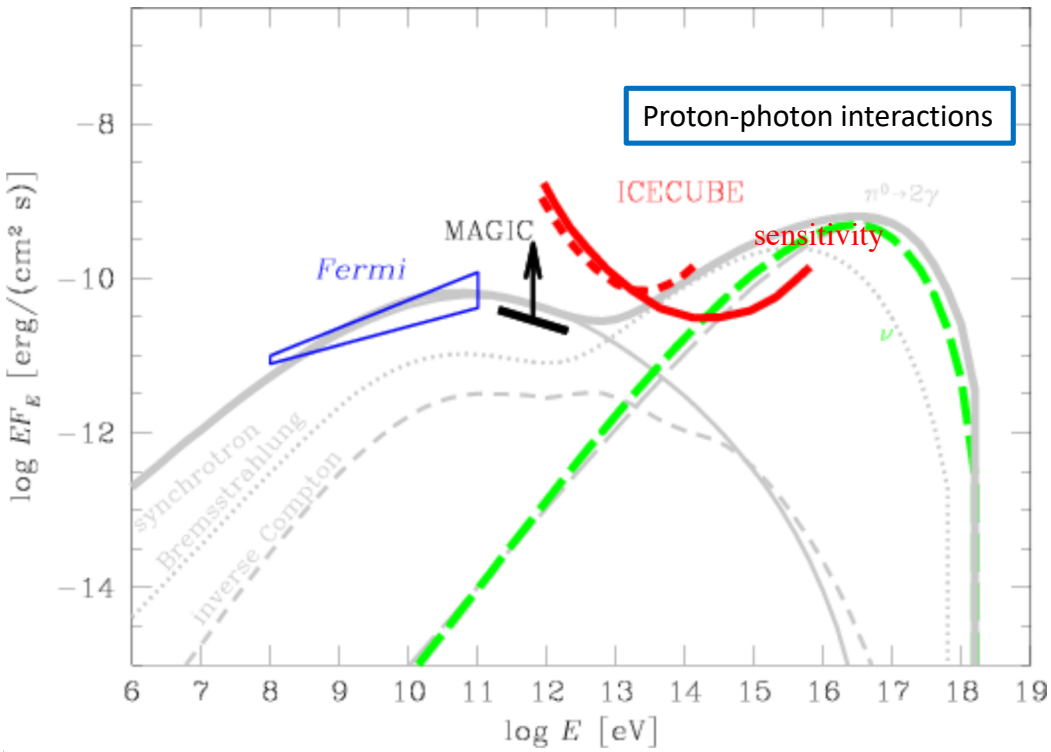
IceCube astrophysical neutrino signal is detected in several "channels": through-going muon tracks, "High-Energy Starting events" (HESE), cascades.

Spectral measurements with different techniques show slight discrepancies (less than 3 sigma).

Spectral measurements with different techniques sample different parts of the sky.

Extragalactic neutrinos from AGN





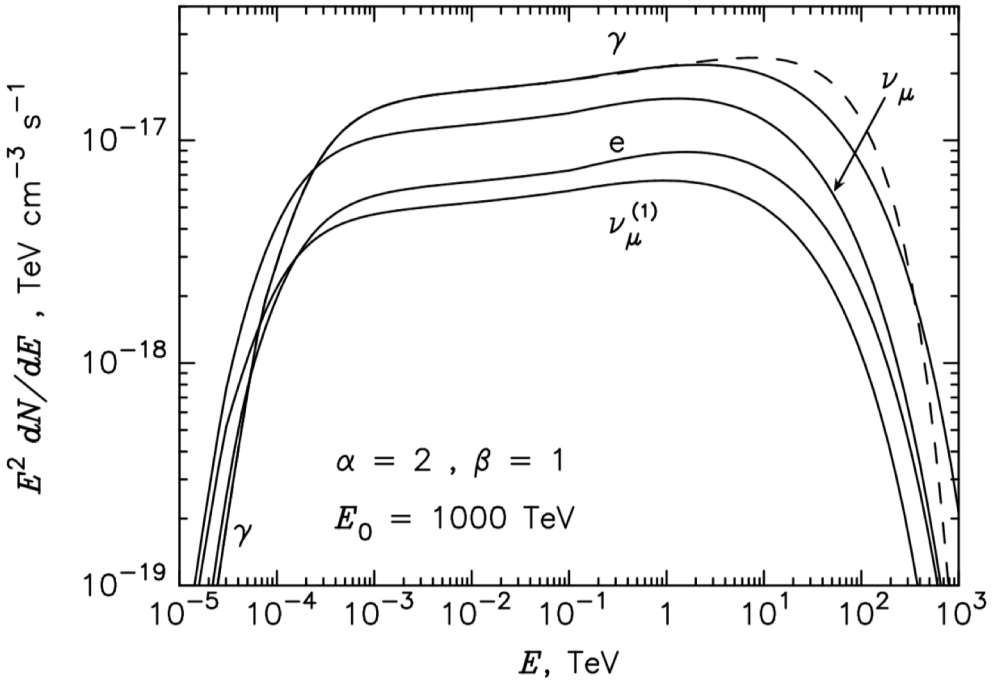
Radio-loud active galactic nuclei and more specifically blazars are considered as viable extragalactic source candidates. High-energy proton interactions in the AGN jet with

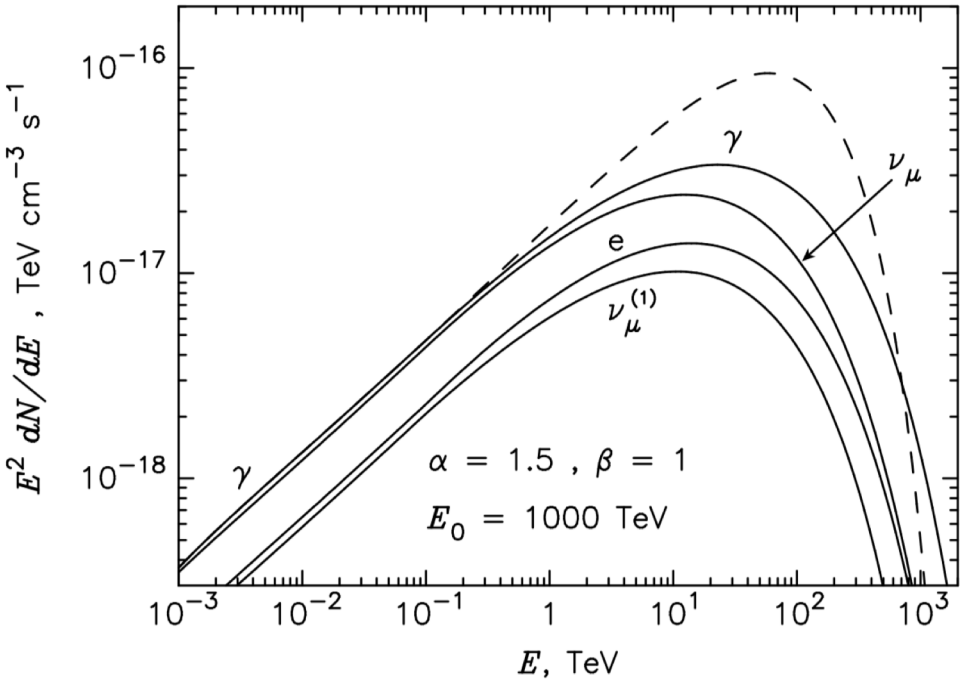
– low-energy protons from the accretion flow or circumnuclear medium and
– low-energy radiation fields from the accretion disk or jet

Result in production and decays of pions with emission of neutrinos and gamma-rays.

Biermann, Mannheim, Stecker et al, '90th, ……..
Figure from Neronov, Ribordy '09

Neutrino and gamma-ray production in high-energy proton interactions

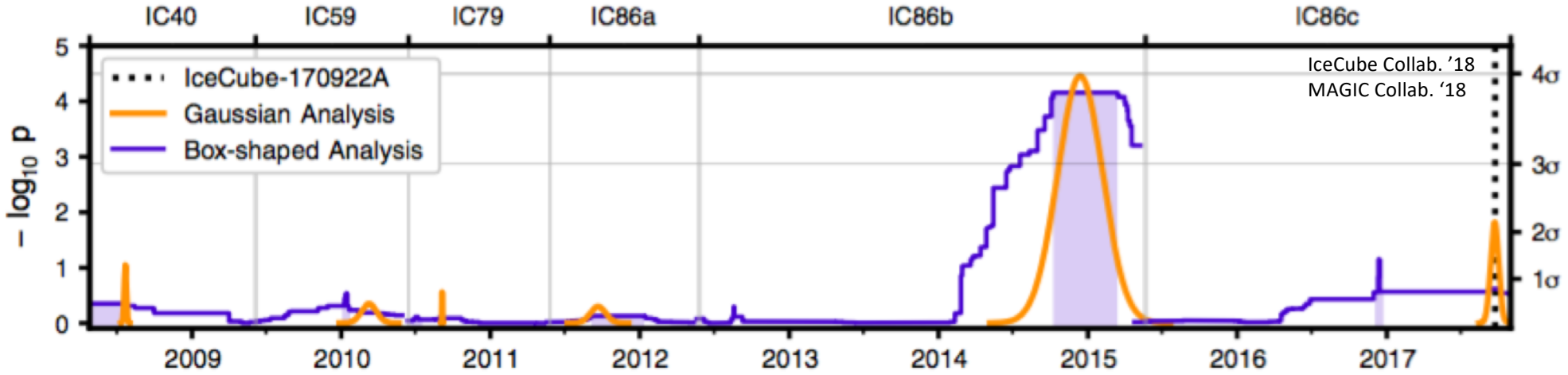




Pion production in proton-proton interactions is characterized by energy threshold $E_{thr} \simeq 100$ MeV. Typical energy of neutrinos is $E_\nu \sim 0.03\, E_{thr}$. Total power emitted in neutrinos is comparable to the total power output in electromagnetic component (electrons plus gammas). Spectra of gamma and neutrinos nearly repeat the spectrum of parent protons.

Kelner, Aharonian 2006

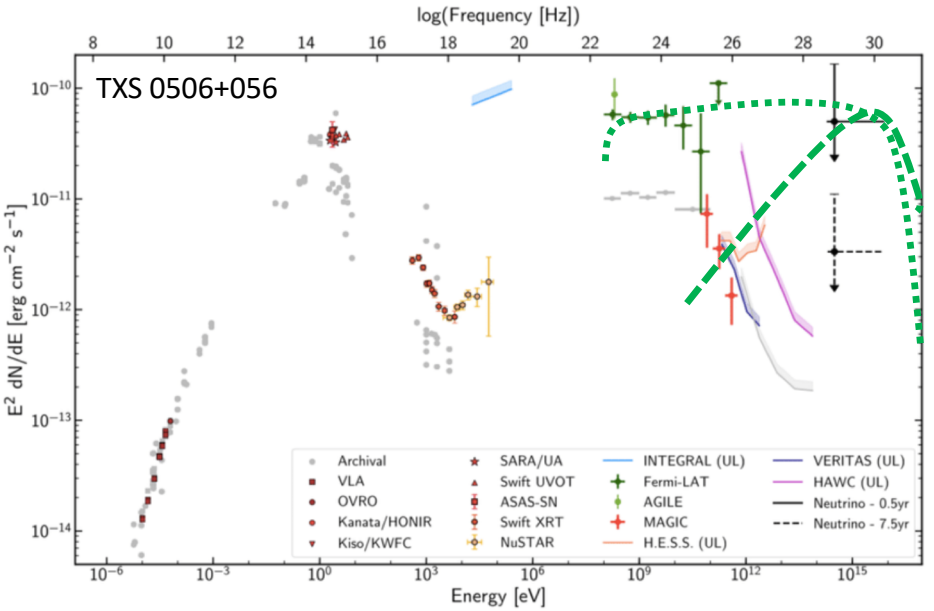
Extragalactic neutrinos from AGN



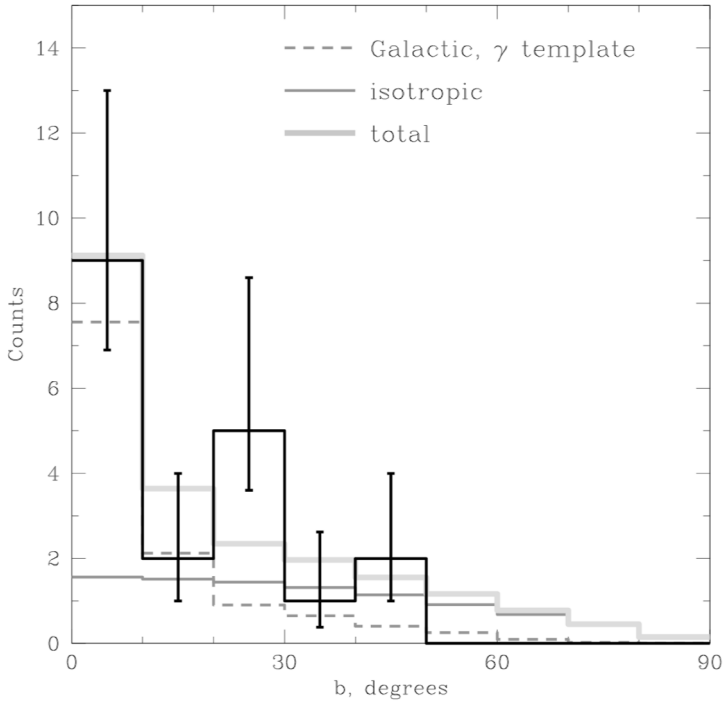
3-sigma evidence for neutrino emission from a blazar (TXS 0506+056) has been reported.

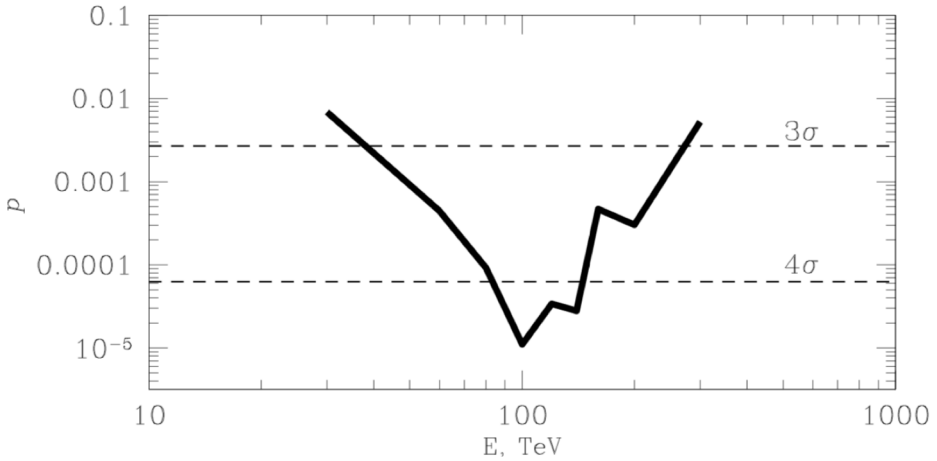
Gamma-ray emitting AGN which dominate Fermi/LAT extragalactic sky are not responsible for the production of the bulk of the IceCube signal.

It is still possible that the "neutrino loud" blazar AGN population exists, but neutrino flux from an AGN is not proportional to its gamma-ray flux.



Galactic neutrino sources (?)





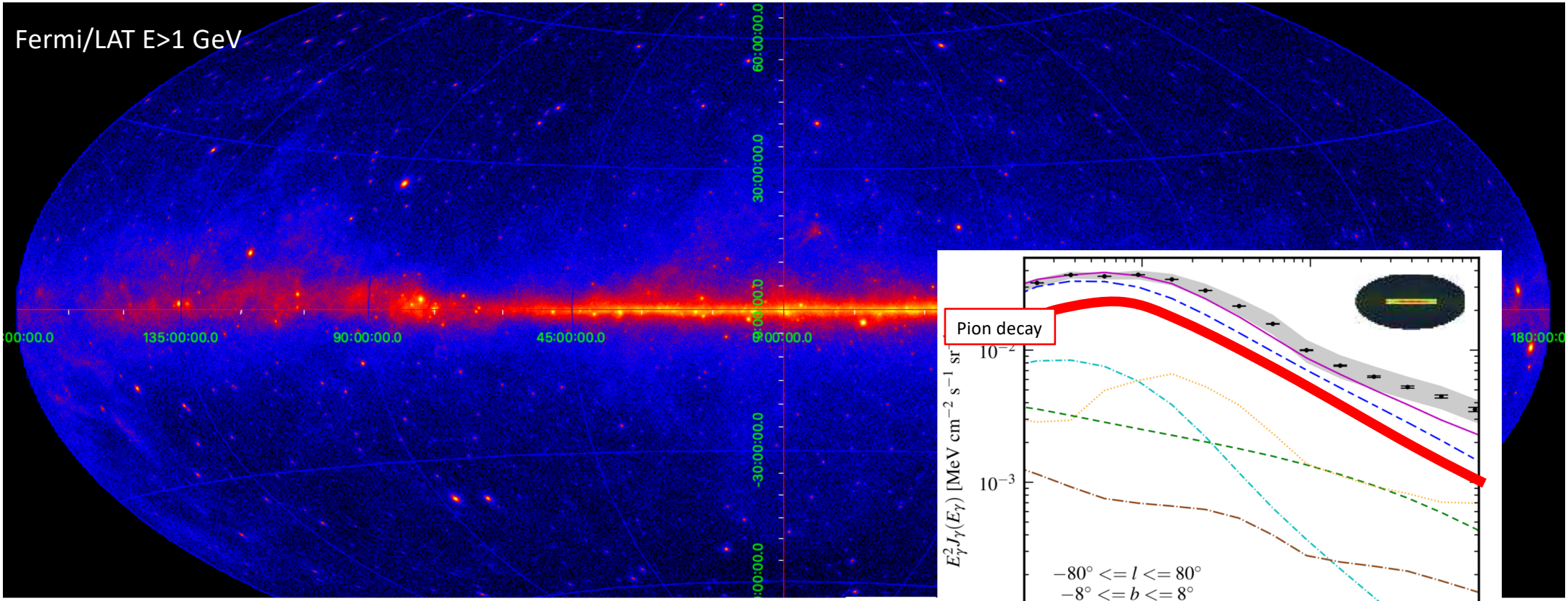
	7yr Cascades				Previous Work			
Template	p-value	Sensitivity	Fitted Flux	UL	p-value	Sensitivity	Fitted Flux	UL
KRA_γ^5	0.021	0.58	0.85	1.7	0.29	0.81	0.47	1.19
KRA_γ^{50}	0.022	0.35	0.65	0.97	0.26	0.57	0.37	0.90
Fermi-LAT π^0	0.030	2.5	3.3	6.6	0.37	2.97	1.28	3.83

Mild evidence for anisotropy of neutrino signal exists: there are more events at lower Galactic latitudes. Deficit of neutrino events at high Galactic latitude and excess at low Galactic latitude amount to 3σ evidence post-trial for anisotropy (with 5 year HESE event set).

A 2.3σ excess is found in the IceCube likelihood sky template fitting (KRAγ model of Galactic pion decay emission) in cascade events.

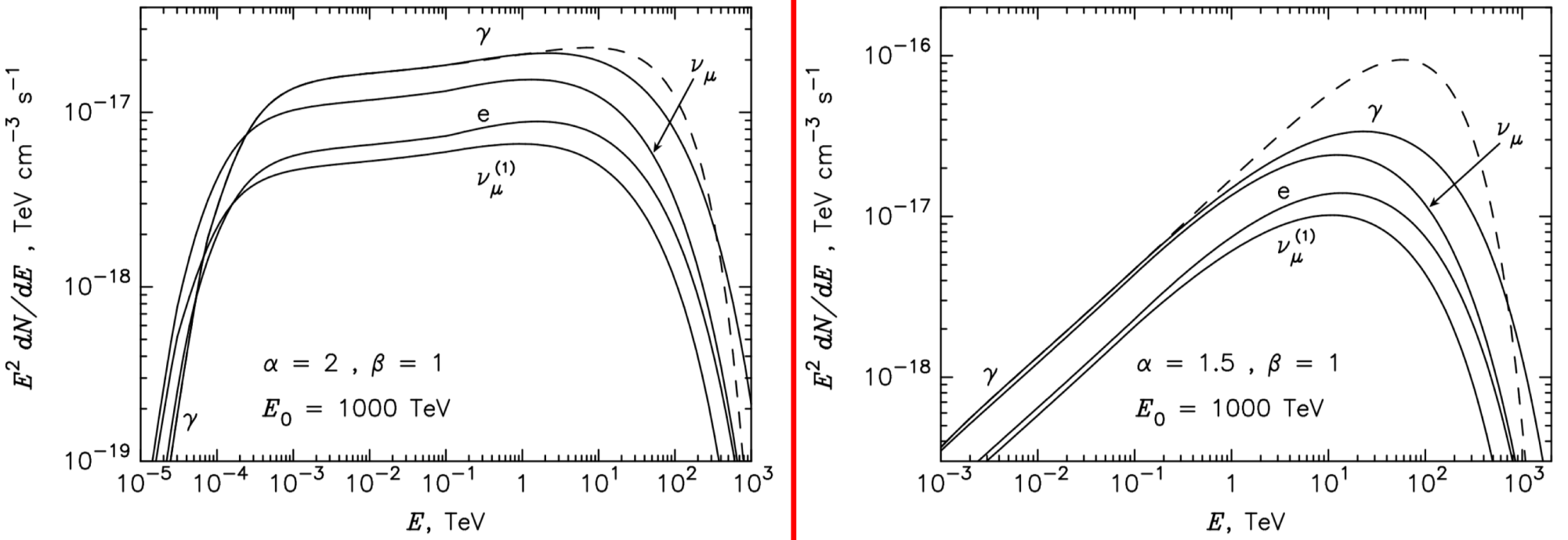
Neronov, Semikoz '16
IceCube Collab. arXiv:1907.06714

Gamma-ray sky



Galactic diffuse emission is dominated by pion decay flux from cosmic ray interactions in the interstellar medium.

Neutrino and gamma-ray production in cosmic ray interactions



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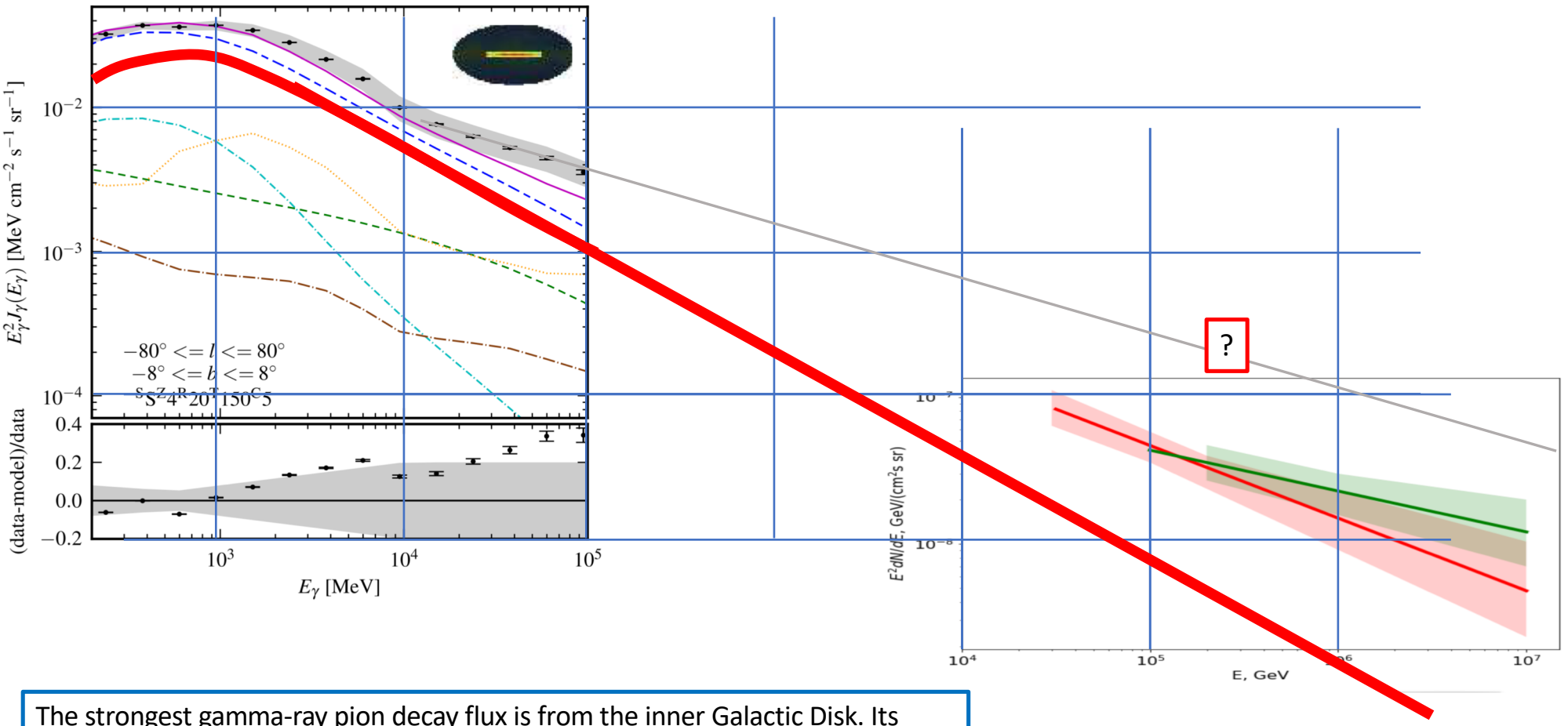
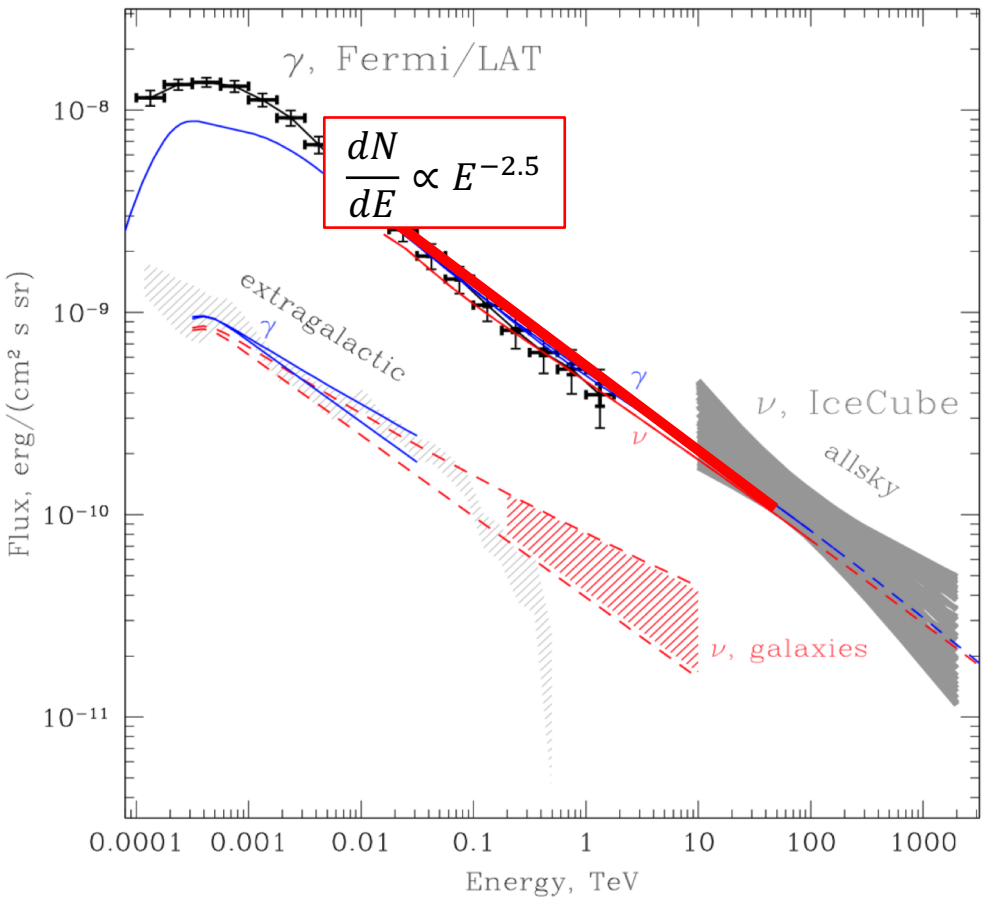
Kelner, Aharonian 2006

Gamma-ray + neutrino sky



The strongest gamma-ray pion decay flux is from the inner Galactic Disk. Its extrapolation to 100 TeV range is below the observer sky-averaged neutrino flux.

Galactic (?) Gamma-ray + neutrino sky

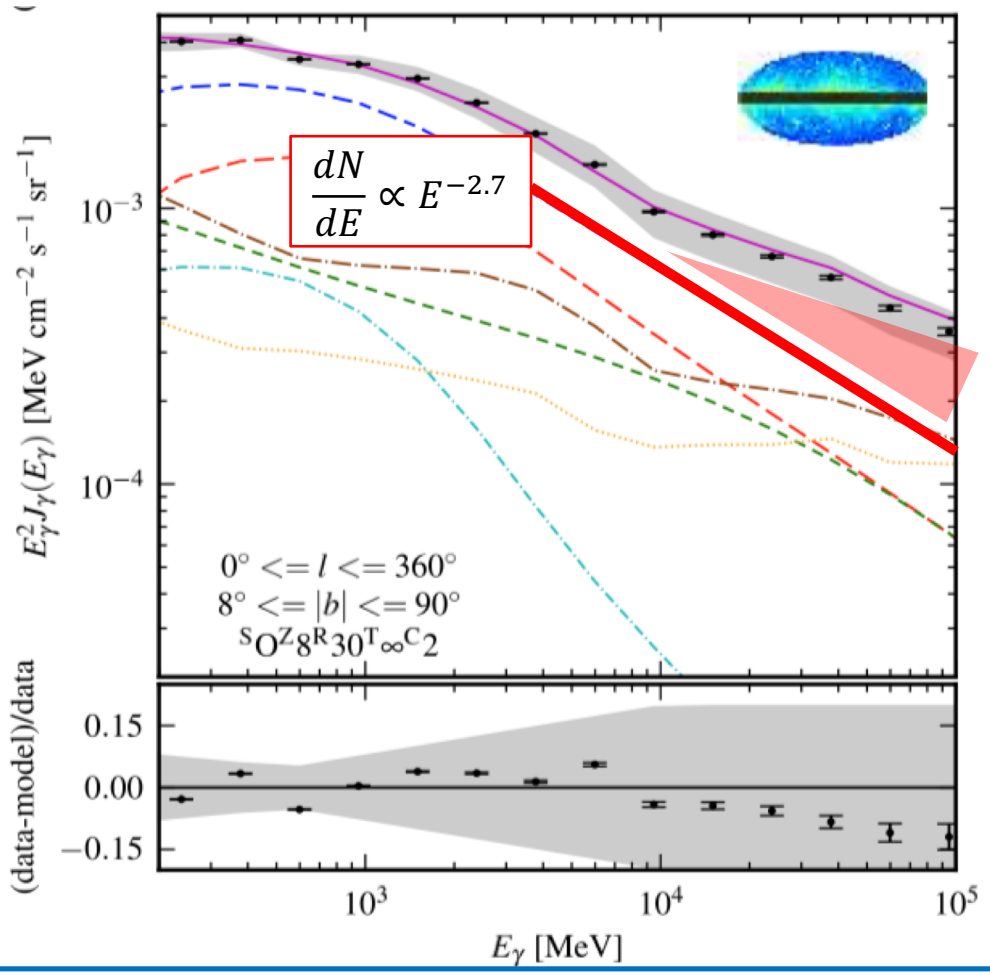


All-sky gamma-ray and neutrino spectra are consistent with each other.

Is there a Galactic component in the astrophysical neutrino signal?

AN, Semikoz, 2014

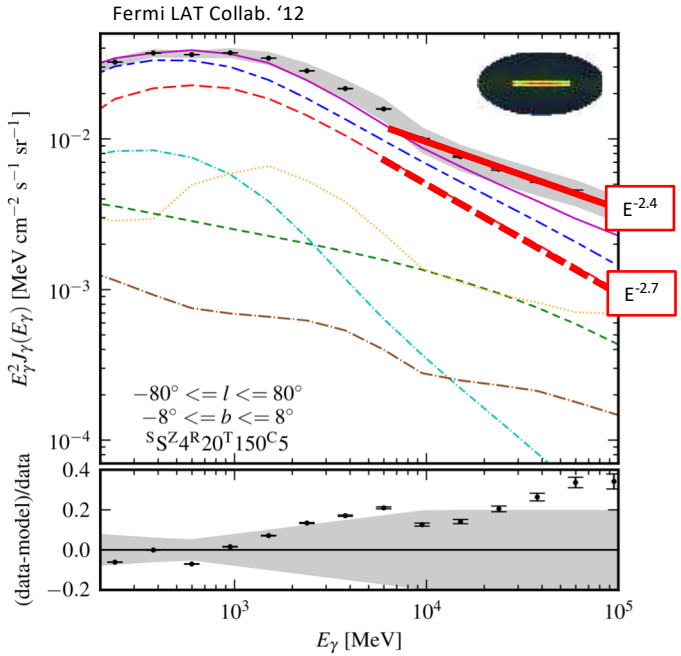
Gamma-ray + neutrino sky

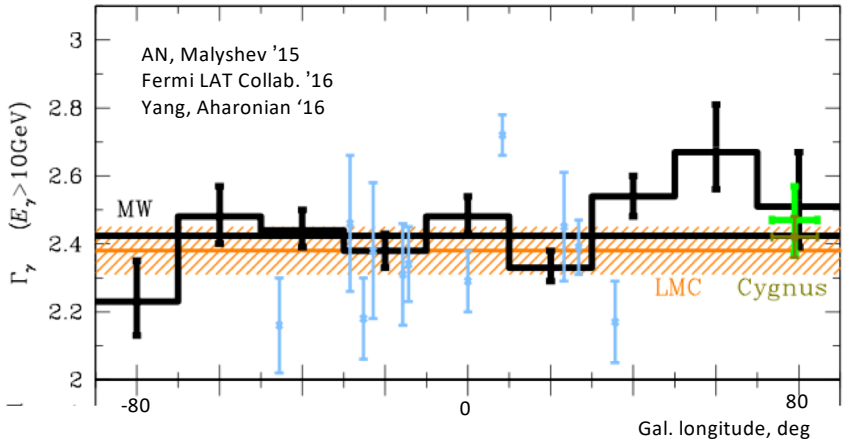


Conventional models of pion decay emission from cosmic ray interactions would assume the spectral slope -2.7 of the locally observed cosmic ray spectrum (e.g. Fermi diffuse emission model of 2012).

Ackermann et al. (2012)

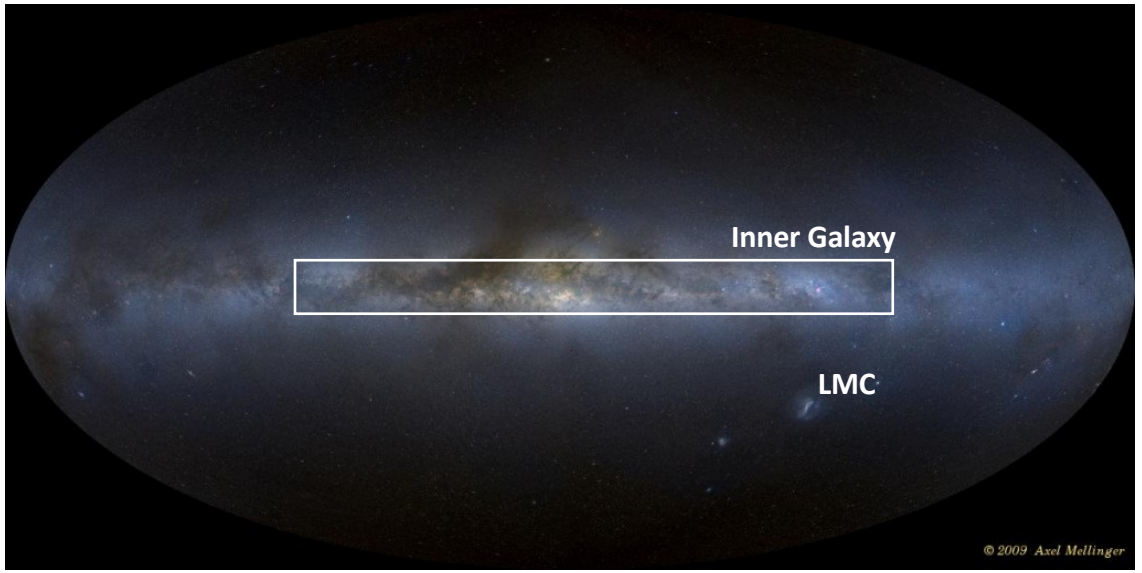
Average Galactic cosmic ray spectrum



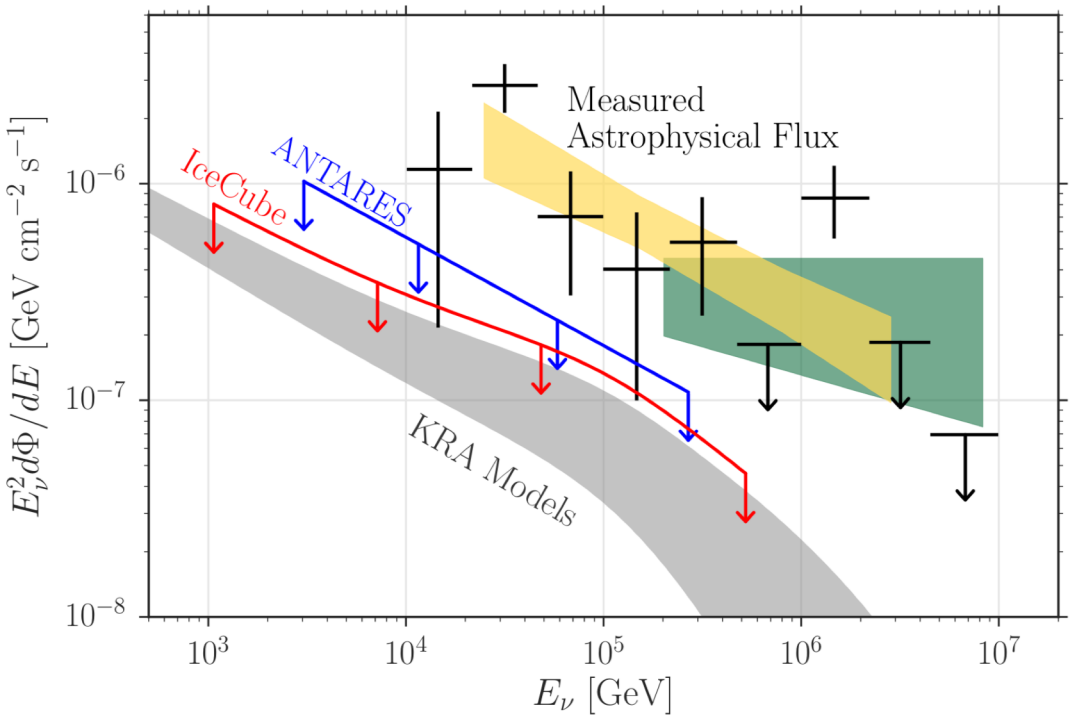


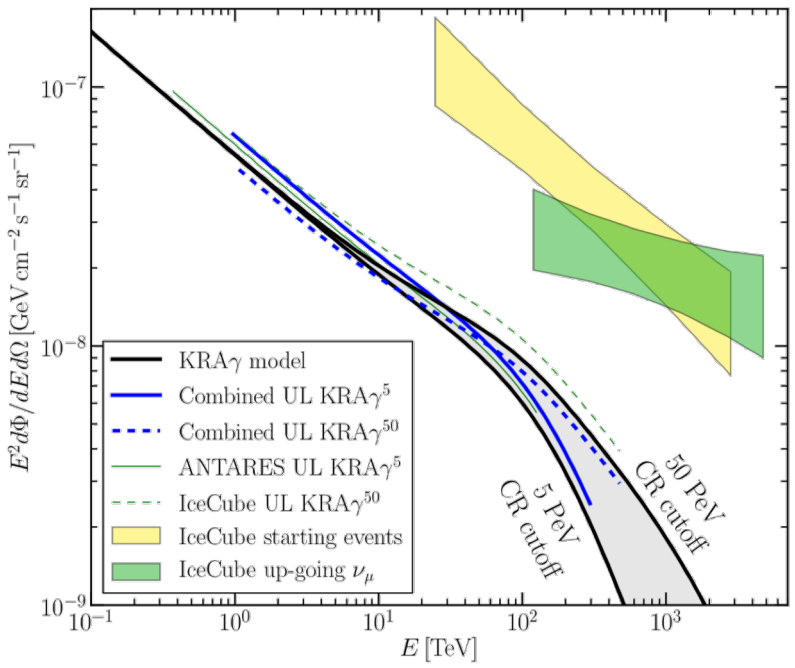
Fermi/LAT gamma-ray data suggest that average cosmic ray spectrum in the Galactic Disk is different from the locally measured one. Average spectrum of cosmic rays residing in the Galactic Disk has the slope $\frac{dN}{dE} \propto E^{-\Gamma}$, $\Gamma = 2.4 \ldots 2.5$, rather than $\Gamma \simeq 2.7$.

Similar slope is found for cosmic rays residing in the Large Magellanic Cloud.



Galactic (?) Gamma-ray + neutrino sky





IceCube and ANTARES telescopes have reported tight limits on Galactic contribution to the astrophysical neutrino flux.

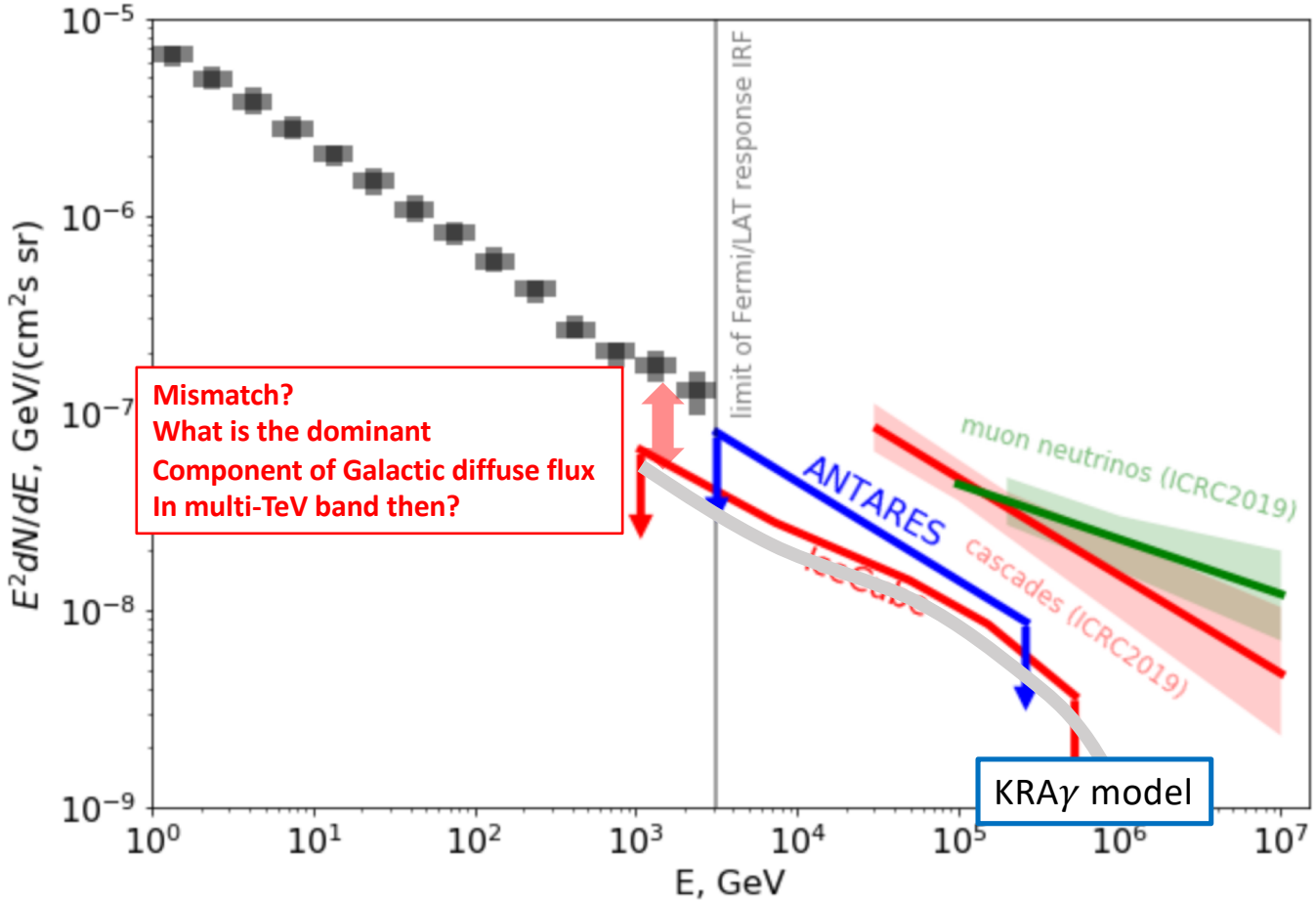
The analysis is based on “non-observation of the excess” along the Galactic Plane.

The analysis method uses a template of Galactic neutrino flux derived from modelling of cosmic ray propagation in the Galaxy.

IceCube Collab. ’17, ’18 ANTARES Collab. 17, ’18 Denton, Marfatia, Weiler ’17

Galactic (?)

All-sky multi-messenger (neutrino +gamma-ray) spectrum



IceCube Collab. ’17, ’18 ANTARES Collab. 17, ’18 Denton, Marfatia, Weiler ’17
AN, Semikoz, 2014

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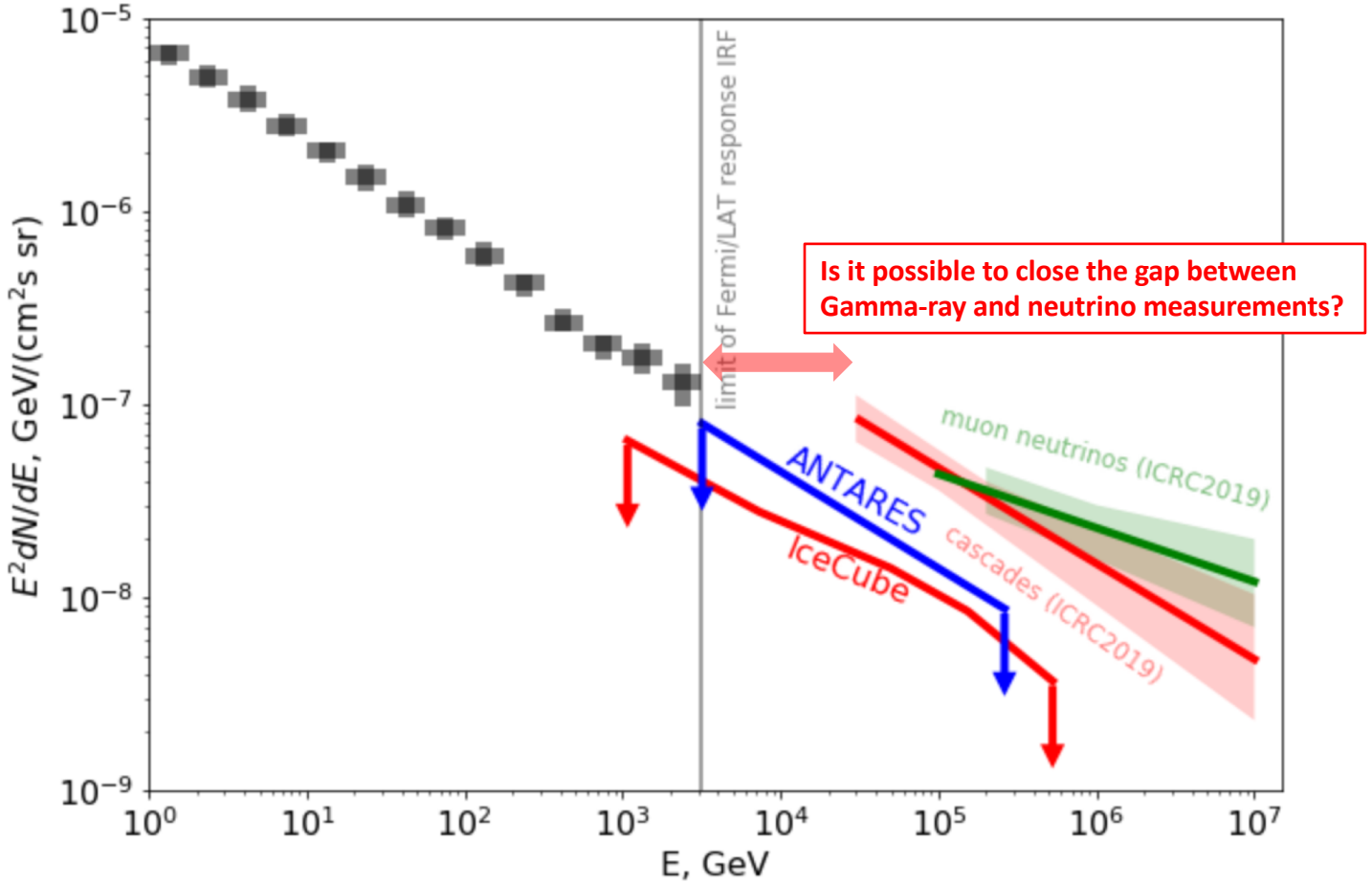
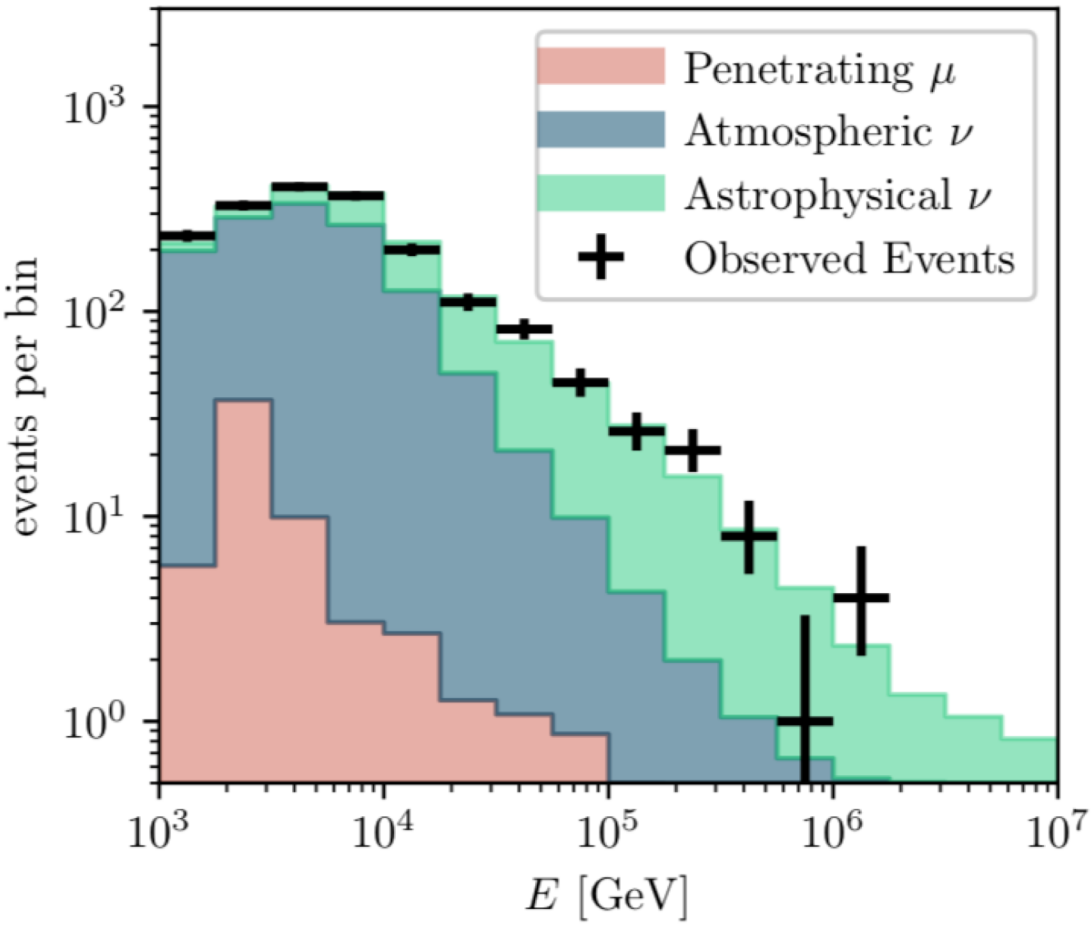


IceCube Collab. ’17, ’18 ANTARES Collab. 17, ’18 Denton, Marfatia, Weiler ’17
AN, Semikoz, 2014

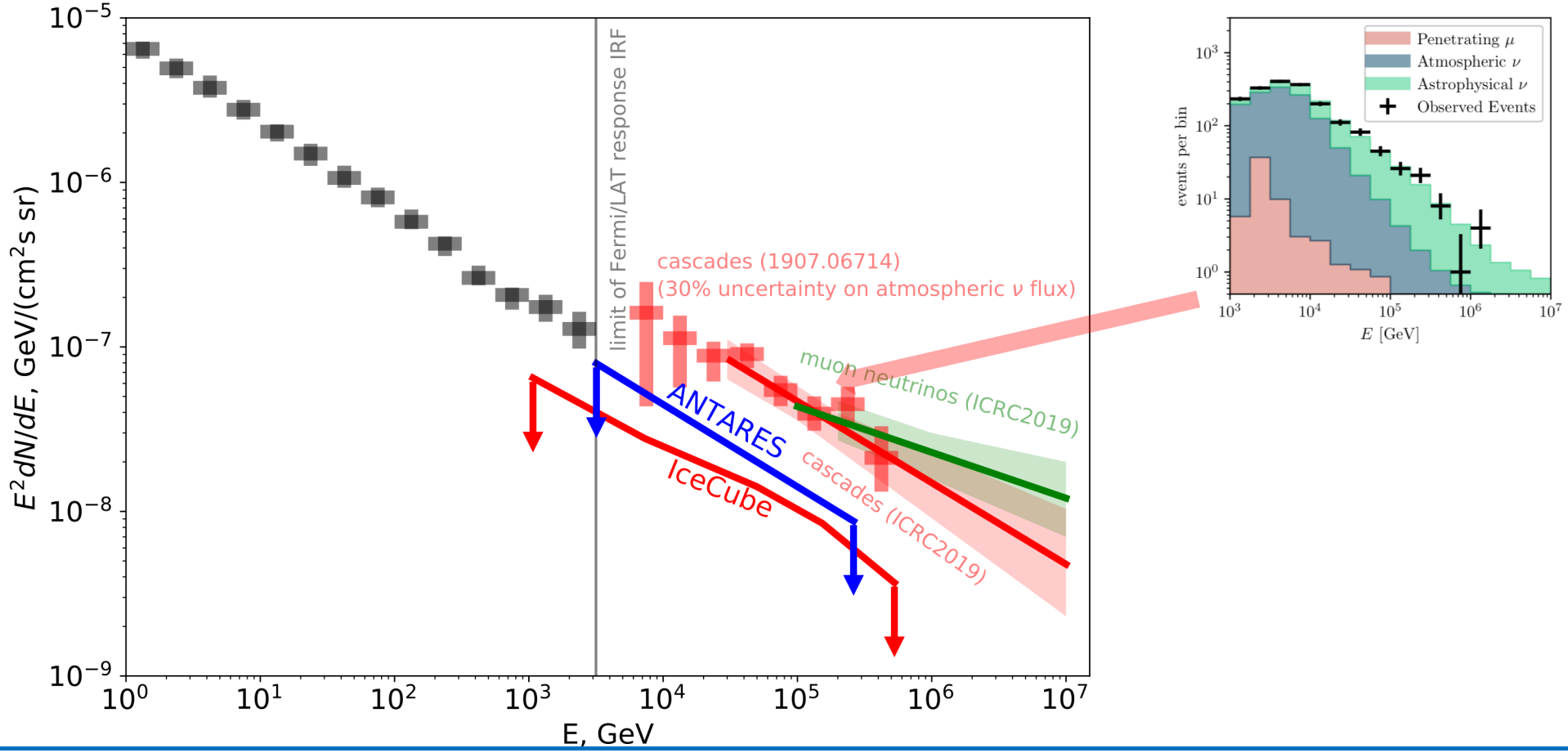
All-sky neutrino signal in multi-TeV band



Data points down to 1 TeV in the “cascade” event sample have been shown in a recent IceCube publication.
The astrophysical neutrino flux is detectable down to TeV energy.

IceCube Collab. 1907.06714

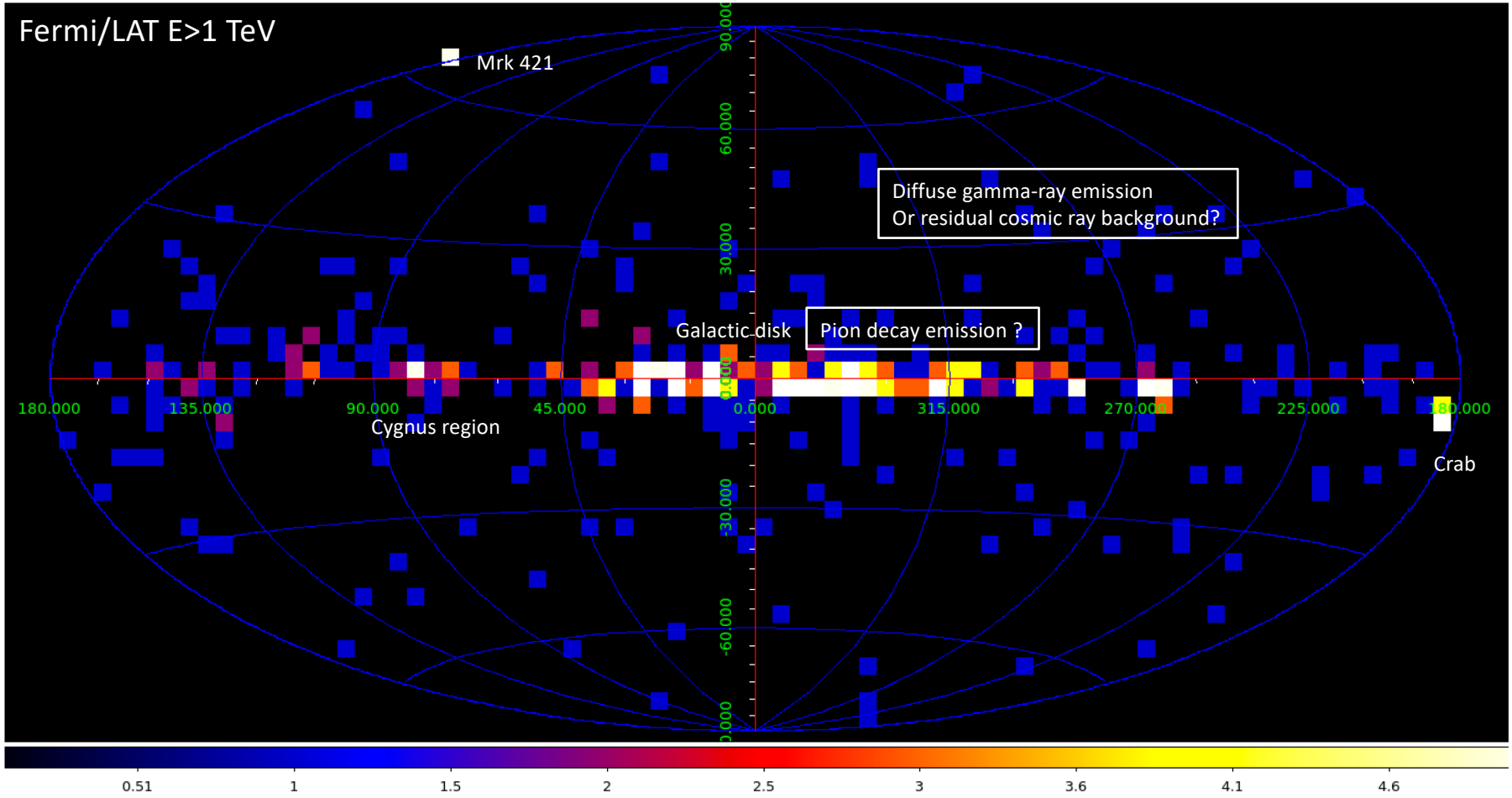
All-sky neutrino signal in multi-TeV band



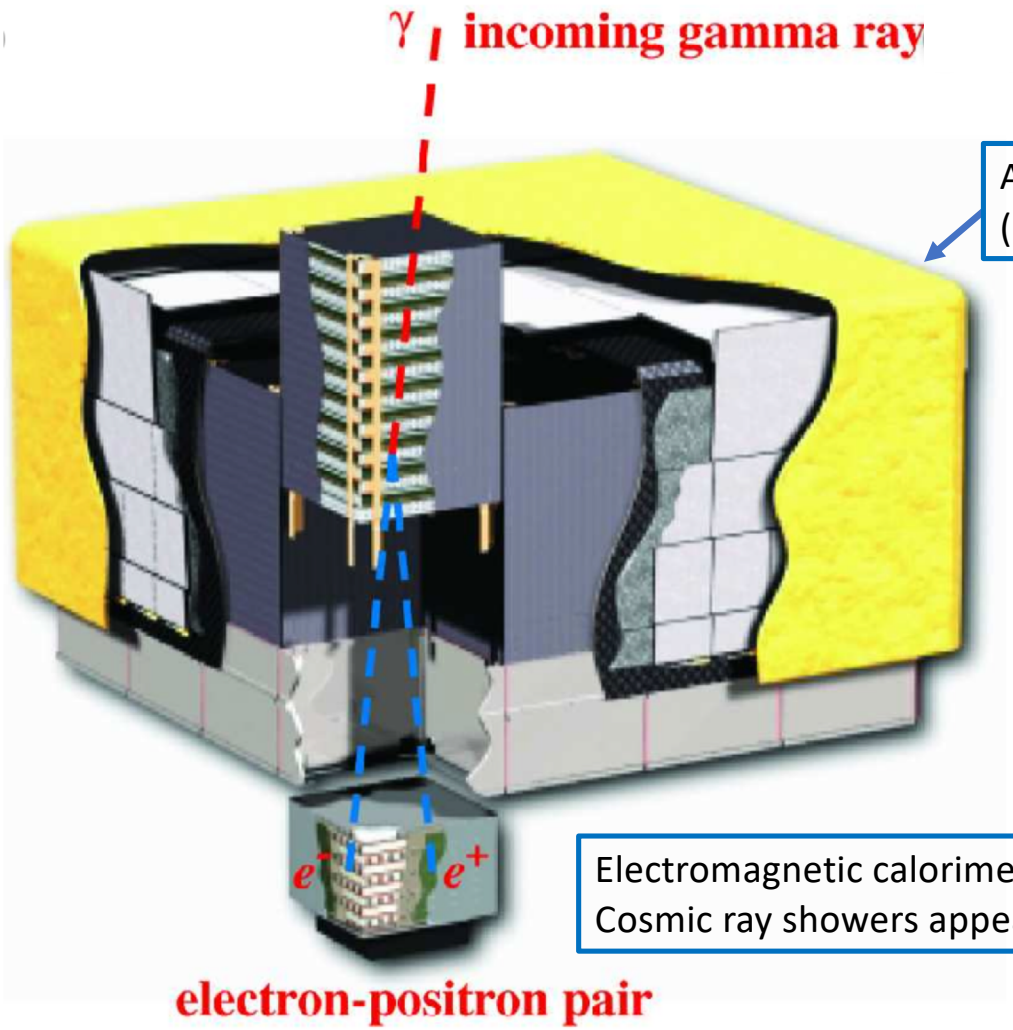
Statistics of IceCube signal in the TeV band is high enough.
The errorbars (not from the quoted IceCube paper) in the TeV band are dominated by the uncertainty of the dominant atmospheric neutrino flux component. Progress is possible via improved measurement / modelling of the atmospheric neutrino flux.

IceCube Collab. 1907.06714

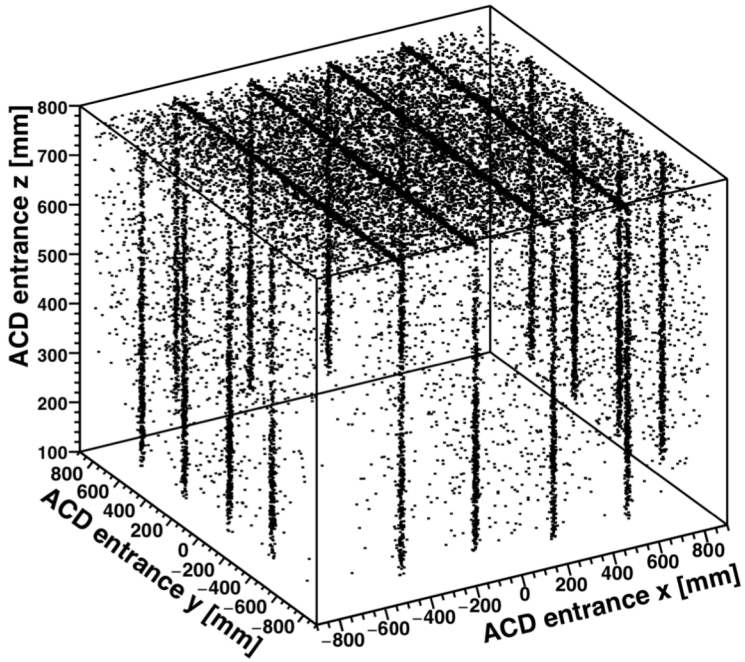
All-sky gamma-ray signal in multi-TeV band



Residual cosmic ray background in Fermi/LAT data

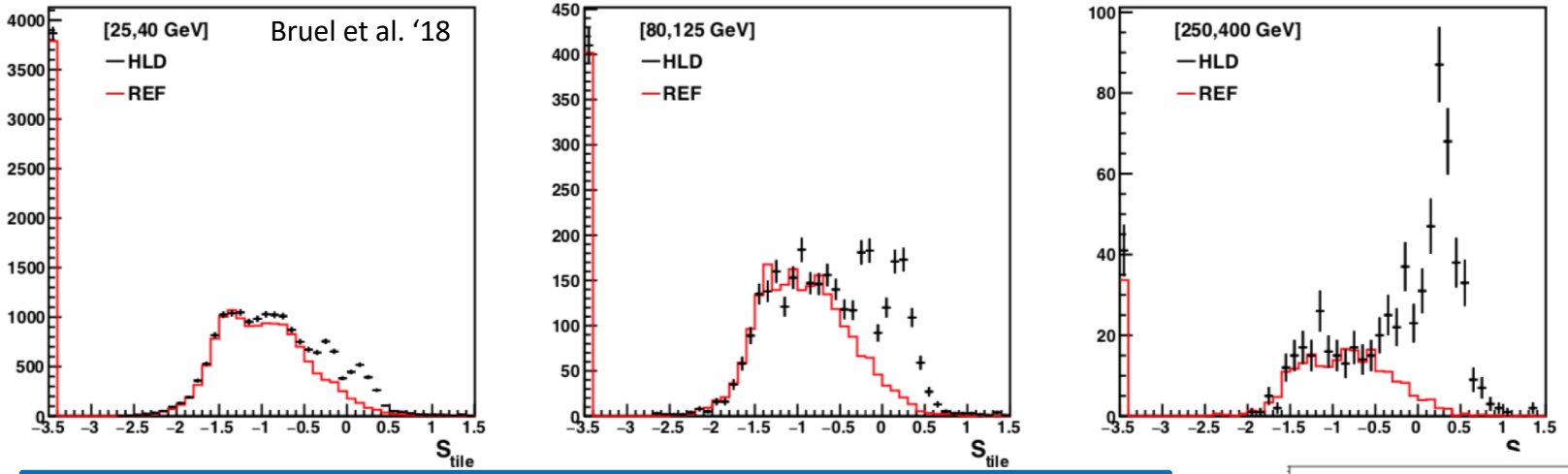


Bruel et al. '18



Starting points of residual events leaking through the ACD tiles in the SOURCE class event selection

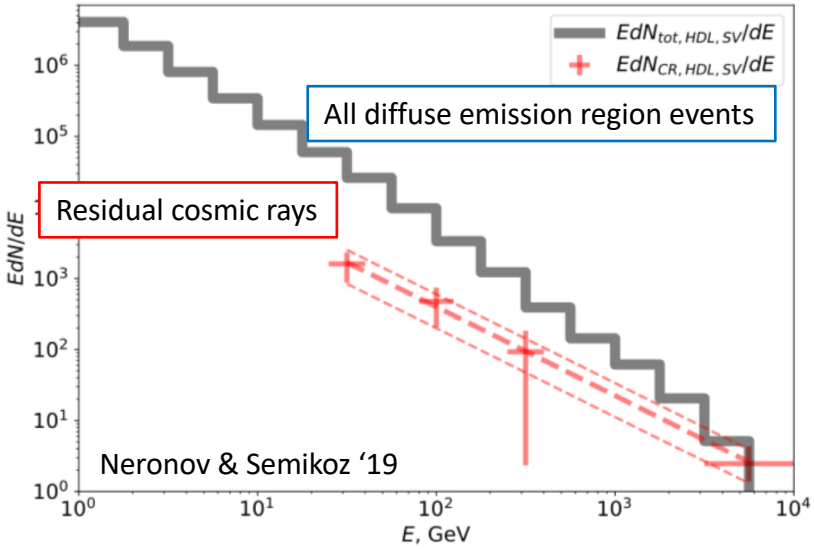
Residual cosmic ray background in Fermi/LAT data



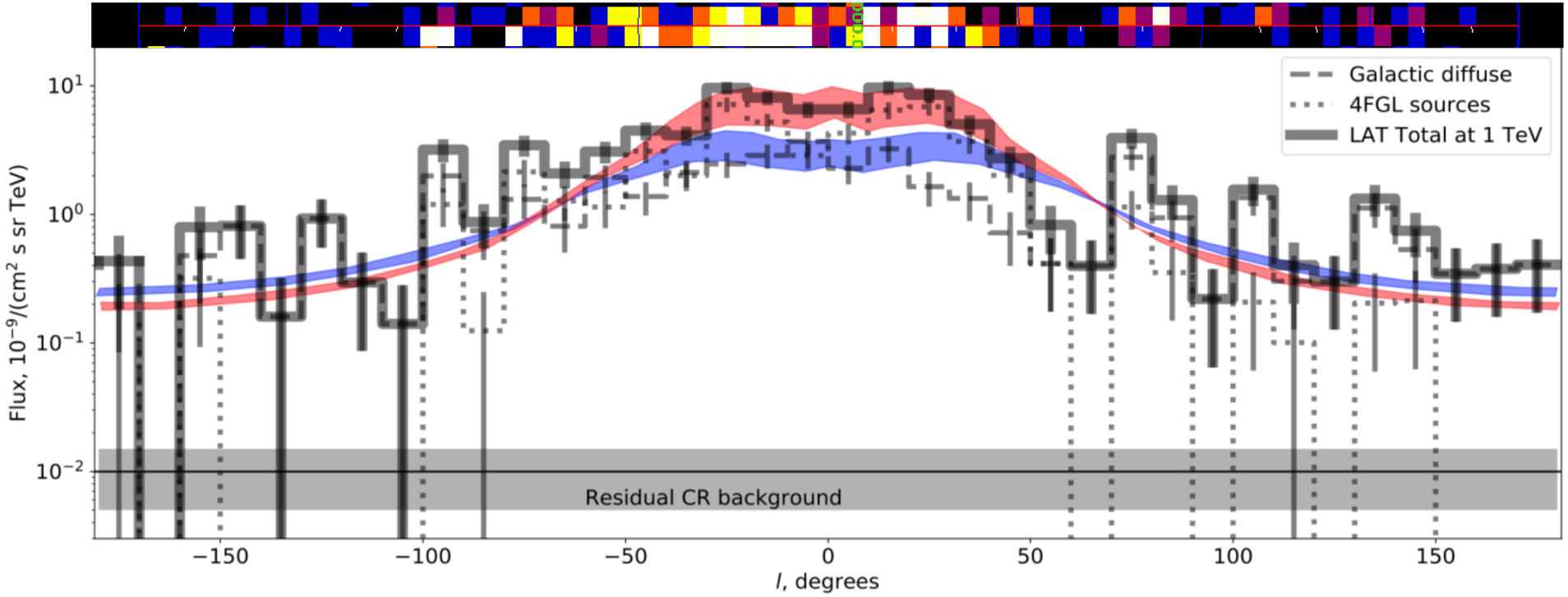
Comparison of photon dominated (red) and “high Galactic latitude diffuse” event sample signals in the ACD tiles (S_{tile}) through which the event should have passed in SOURCE event class (Bruel et al. ‘18).

Comparison of statistics of “pure photon” (0.3 degree circles around 4FGL catalog sources, the Earth limb and the Galactic Ridge) events in the SOURCE and new SOURCEVETO class, and of events in the “High latitude diffuse emission” (HLD) (outside 0.3 degrees around 4FGL sources, Galactic latitude >20 degrees) regions allows to……..

estimate of the residual cosmic ray background fraction in SOURCEVETO class (Neronov & Semikoz ‘19)



Galactic Plane in multi-TeV band



The residual cosmic ray background is largely sub-dominant compared to the multi-TeV gamma-ray signal all along the Galactic Plane (inner and outer galaxy).

Neronov, Semikoz, arXiv:1907.06061 (A&A accepted)

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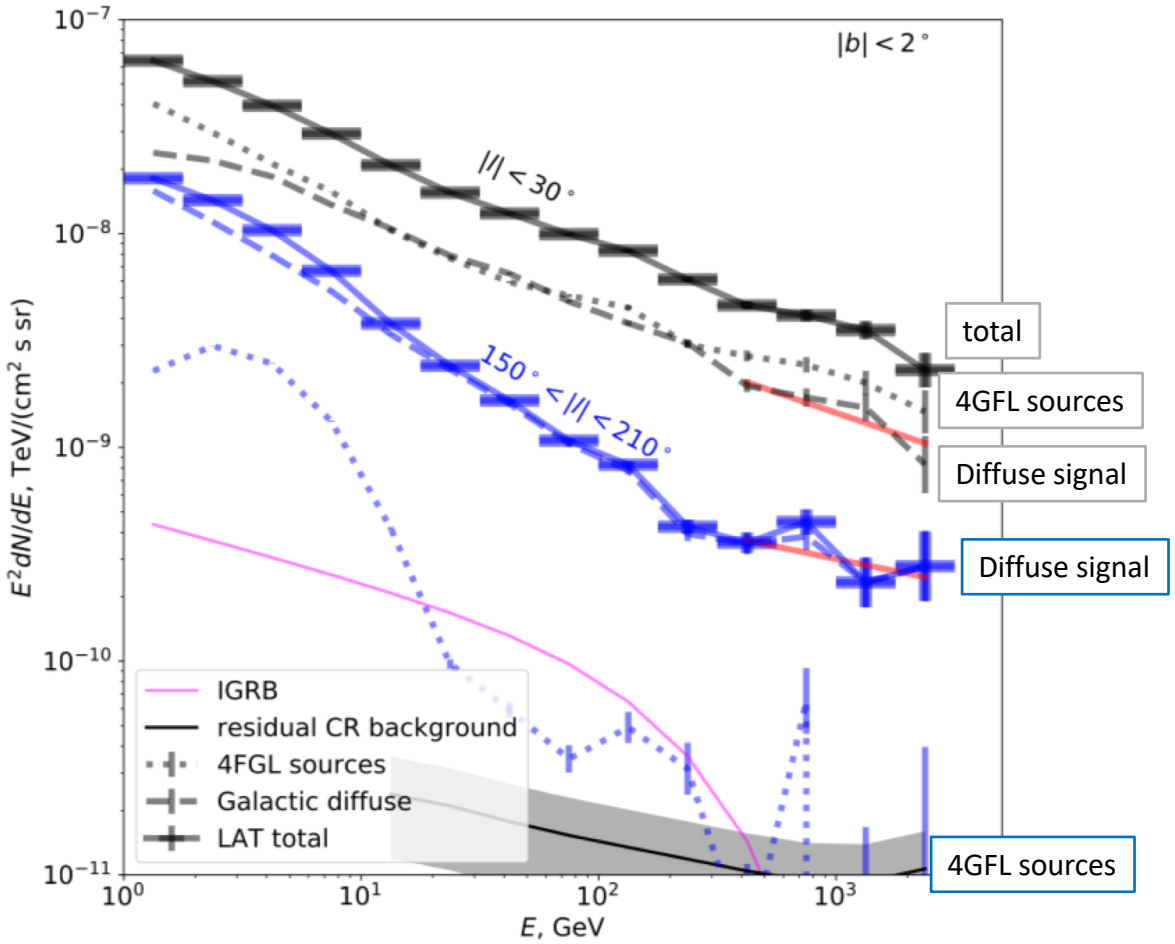

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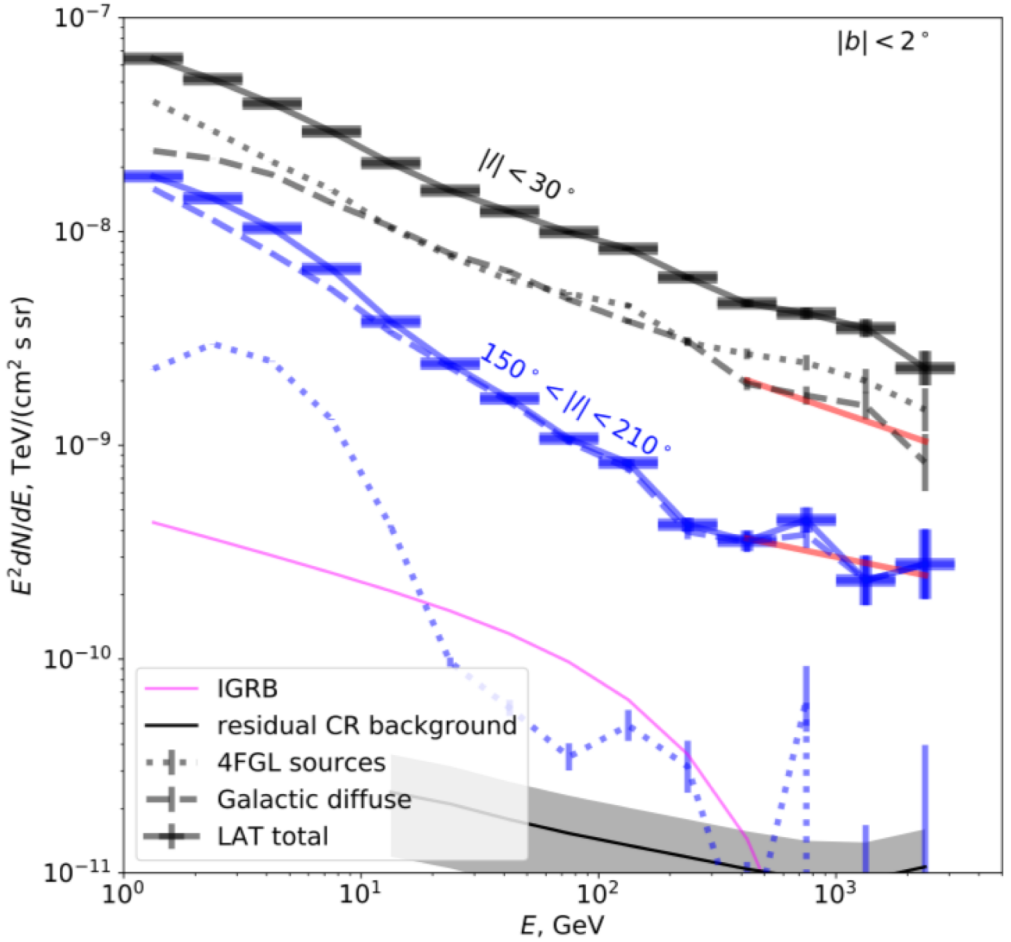

Galactic Plane is visible well able 3 TeV

Spectrum is not shown At higher energy because instrument response is not known

The residual cosmic ray background is largely sub-dominant compared to the multi-TeV gamma-ray signal all along the Galactic Plane (inner and outer galaxy).

Neronov, Semikoz, arXiv:1907.06061

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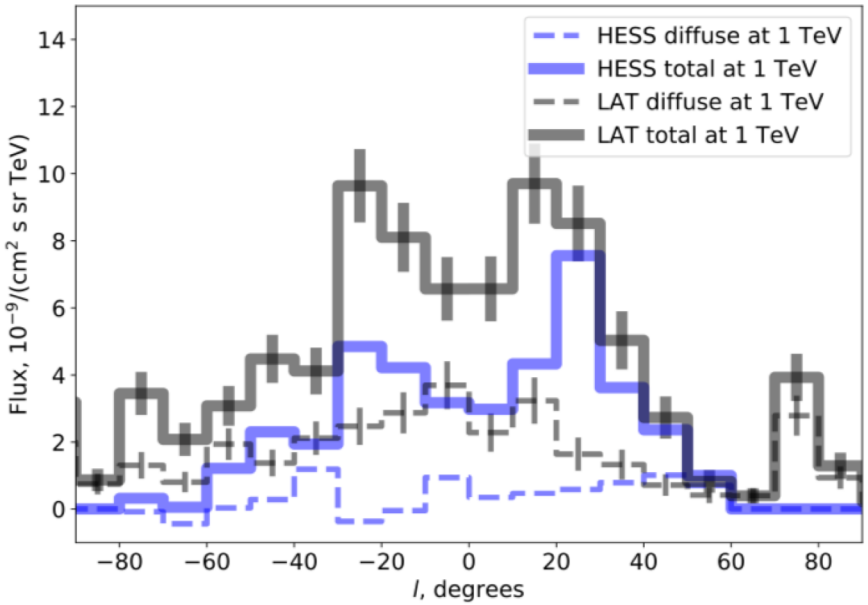
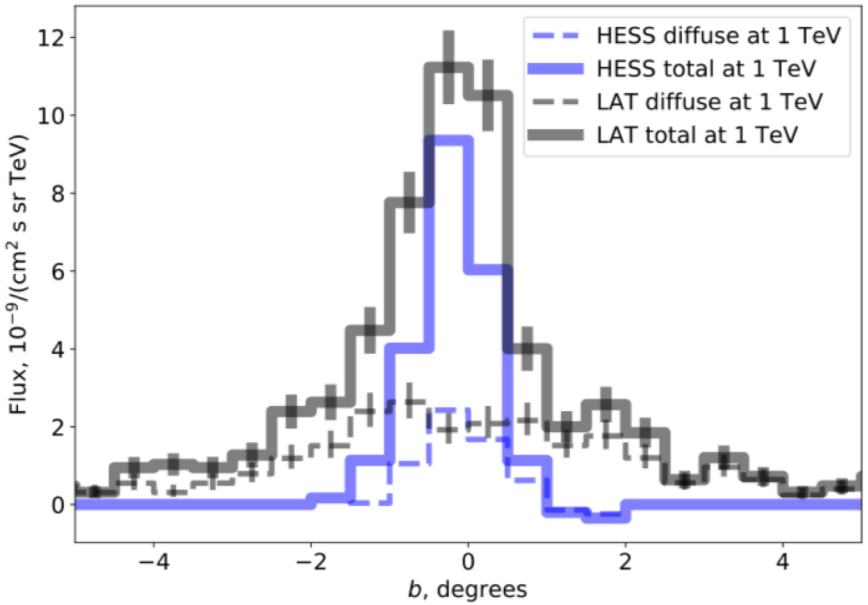
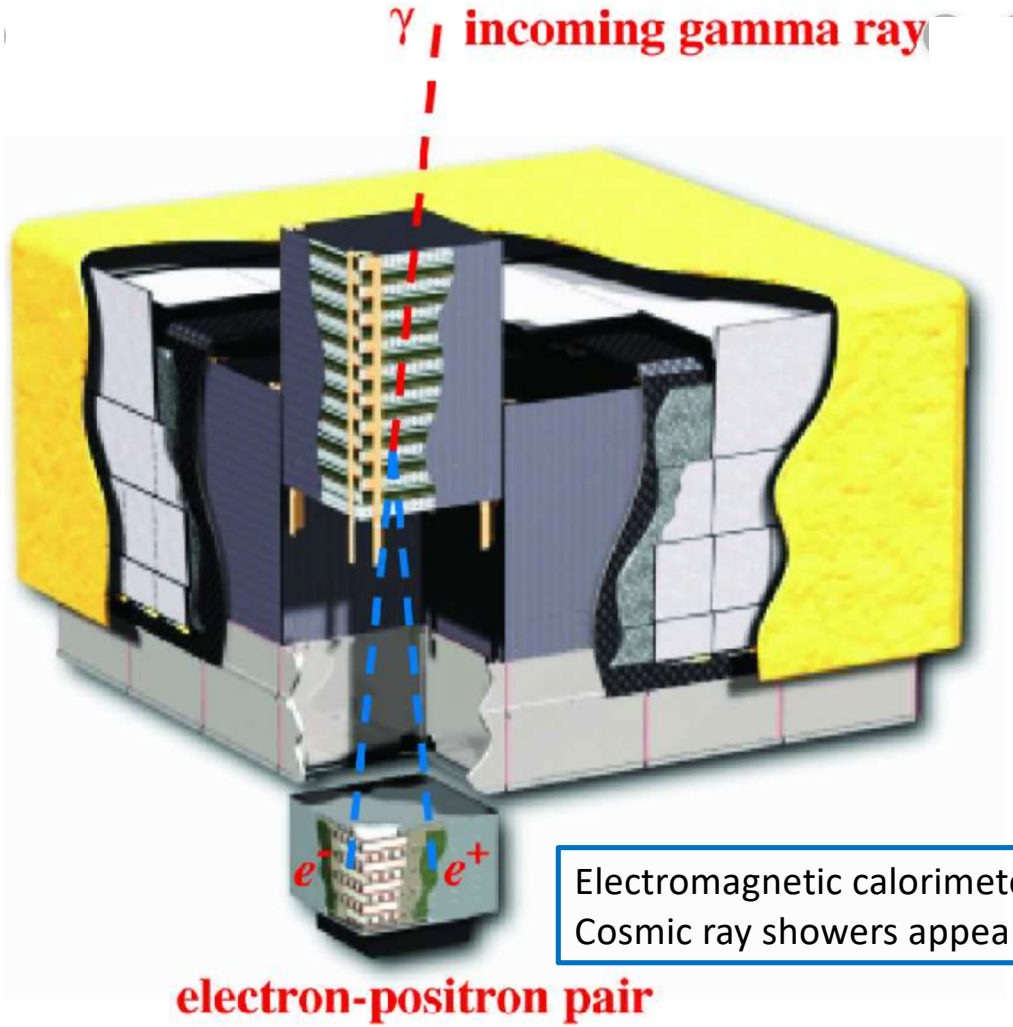


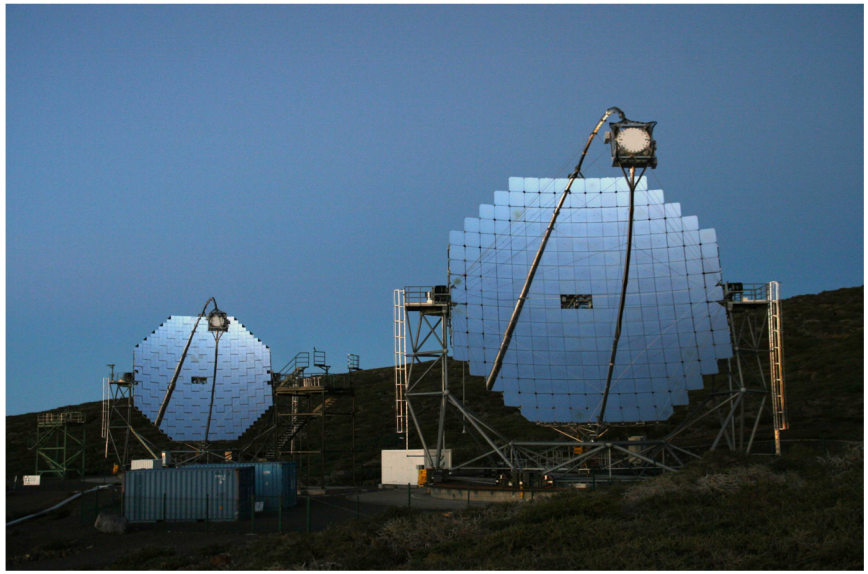


LAT measurements of the Galactic Plane signal at TeV are systematically higher than those of HESS (which should be considered as lower bound on the flux, as stated in the HESS paper).

Neronov, Semikoz, arXiv:1907.06061

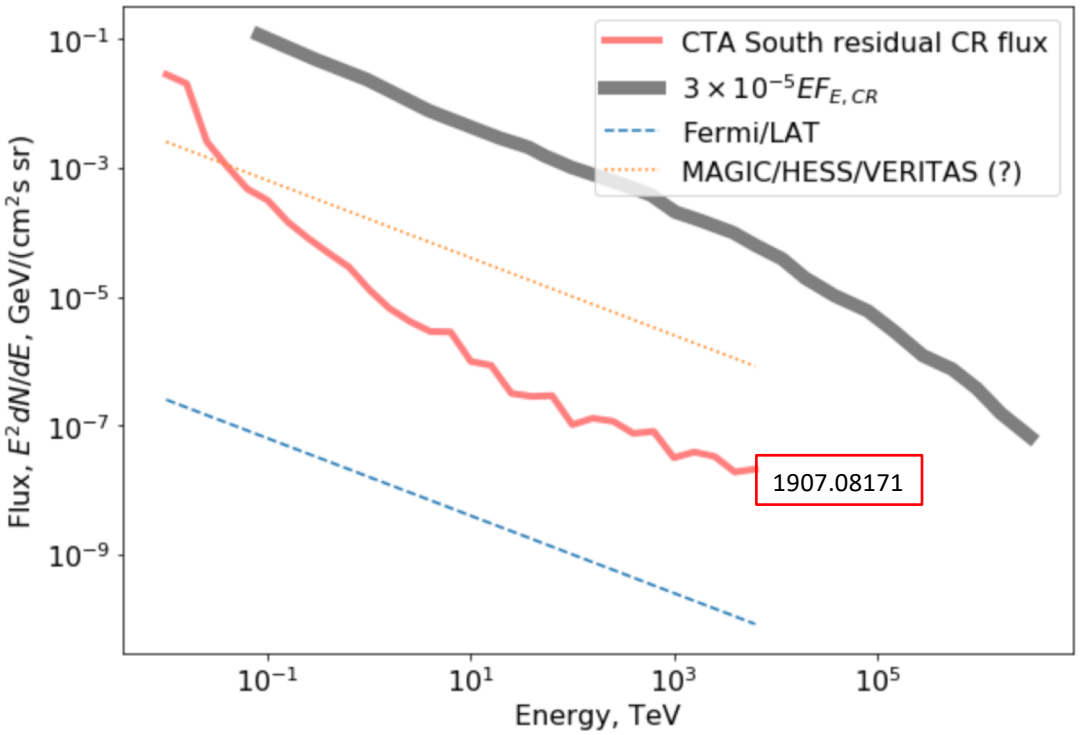
The challenge of observing diffuse emission with Cherenkov telescopes

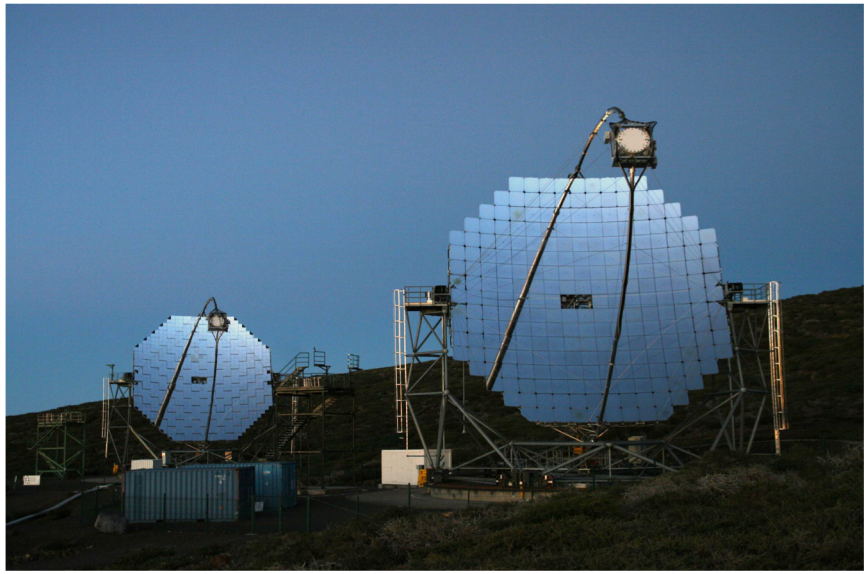




Electromagnetic calorimeter (CAL)
Cosmic ray showers appear wider here)

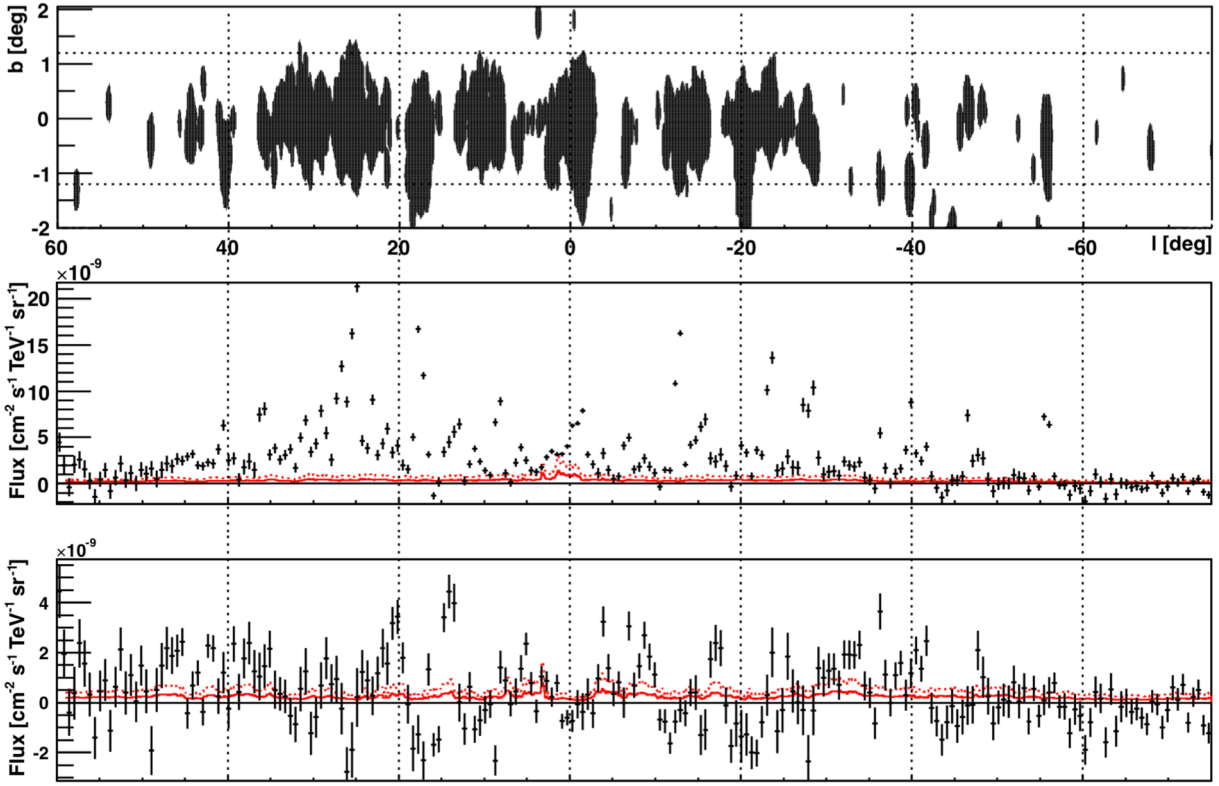
The challenge of observing diffuse emission with Cherenkov telescopes

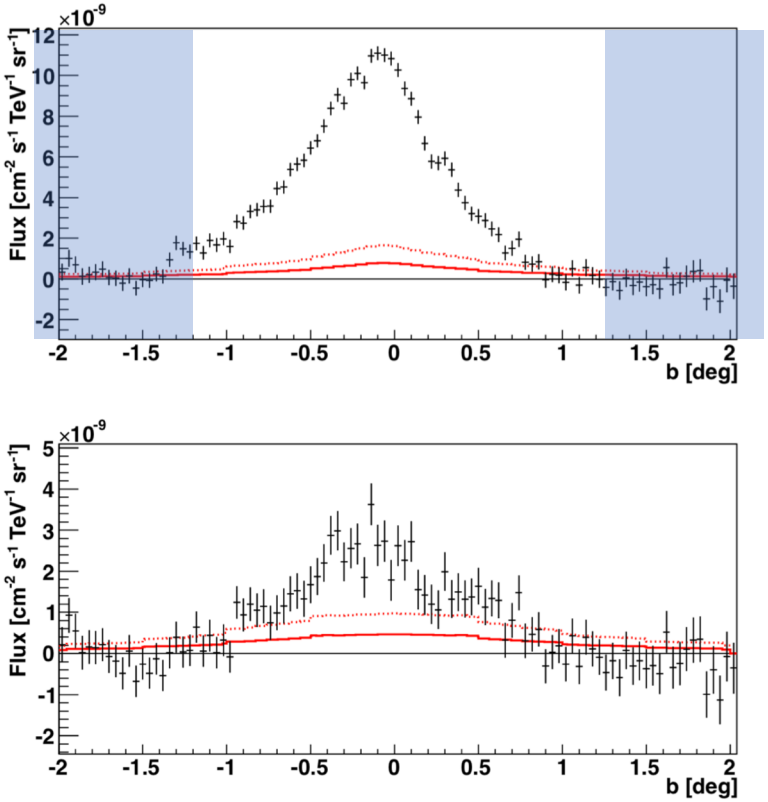




Residual cosmic ray backogrund in Cherenkov telescopes is much above the diffuse sky flux level.

The challenge of observing diffuse emission with Cherenkov telescopes



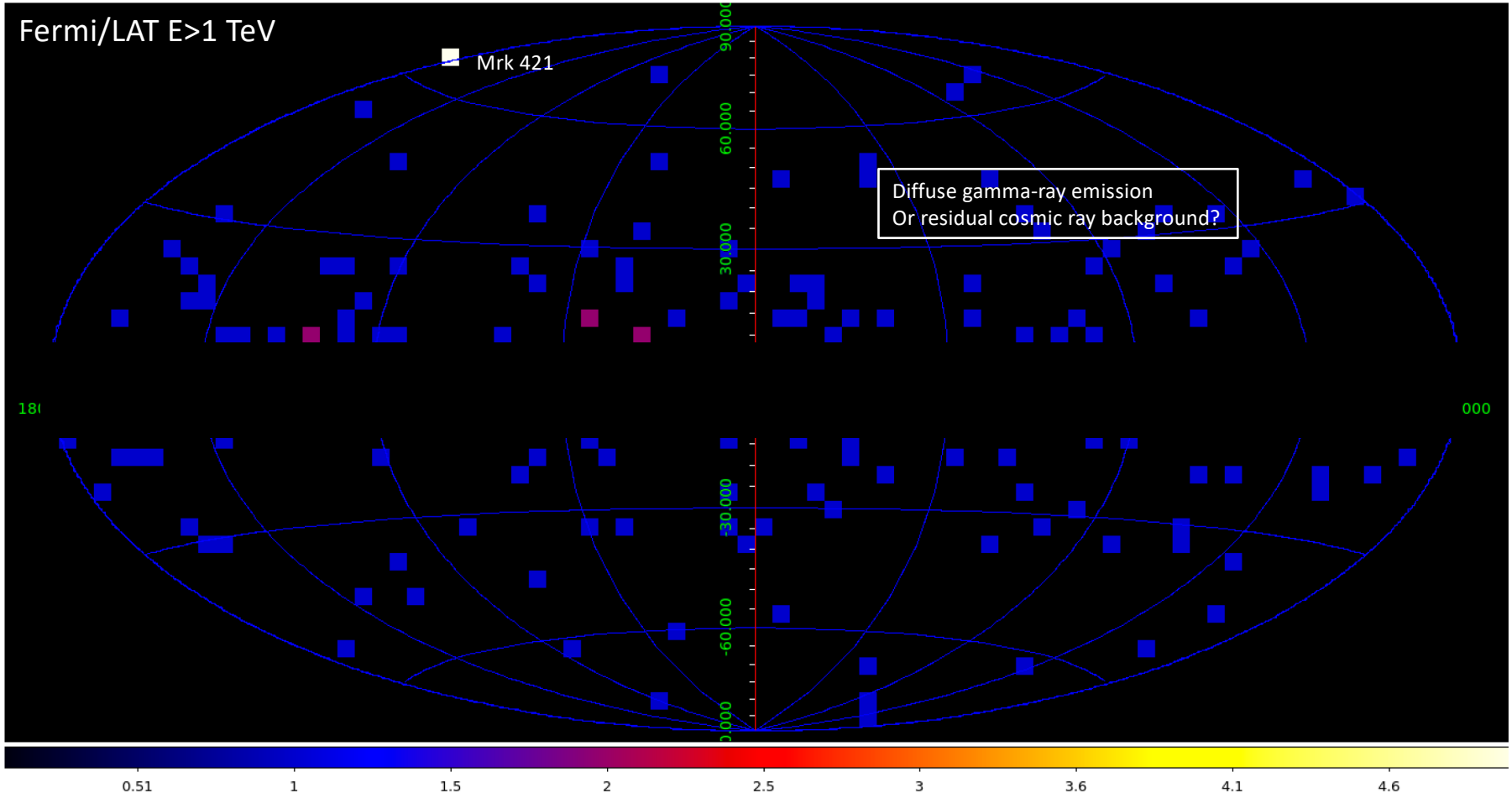


HESS colaboration was able to partially overcome the problem of high residual cosmic ray backogrund by defining backgorund estimate regions within wide enough Galactic Plane survey region.

These background estimate regions are, however, not signal-free.

HESS Collab. ‘14

High Galactic latitude signal in multi-TeV band



Neronov, Semikoz, arXiv:1907.06061

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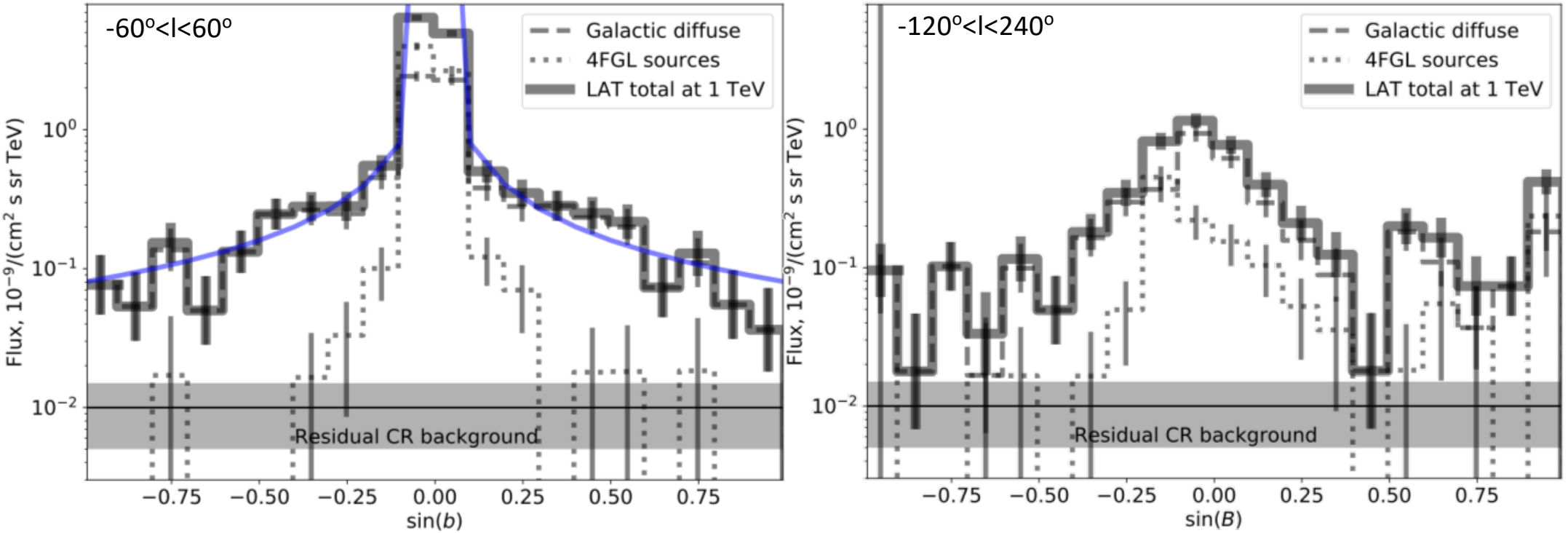
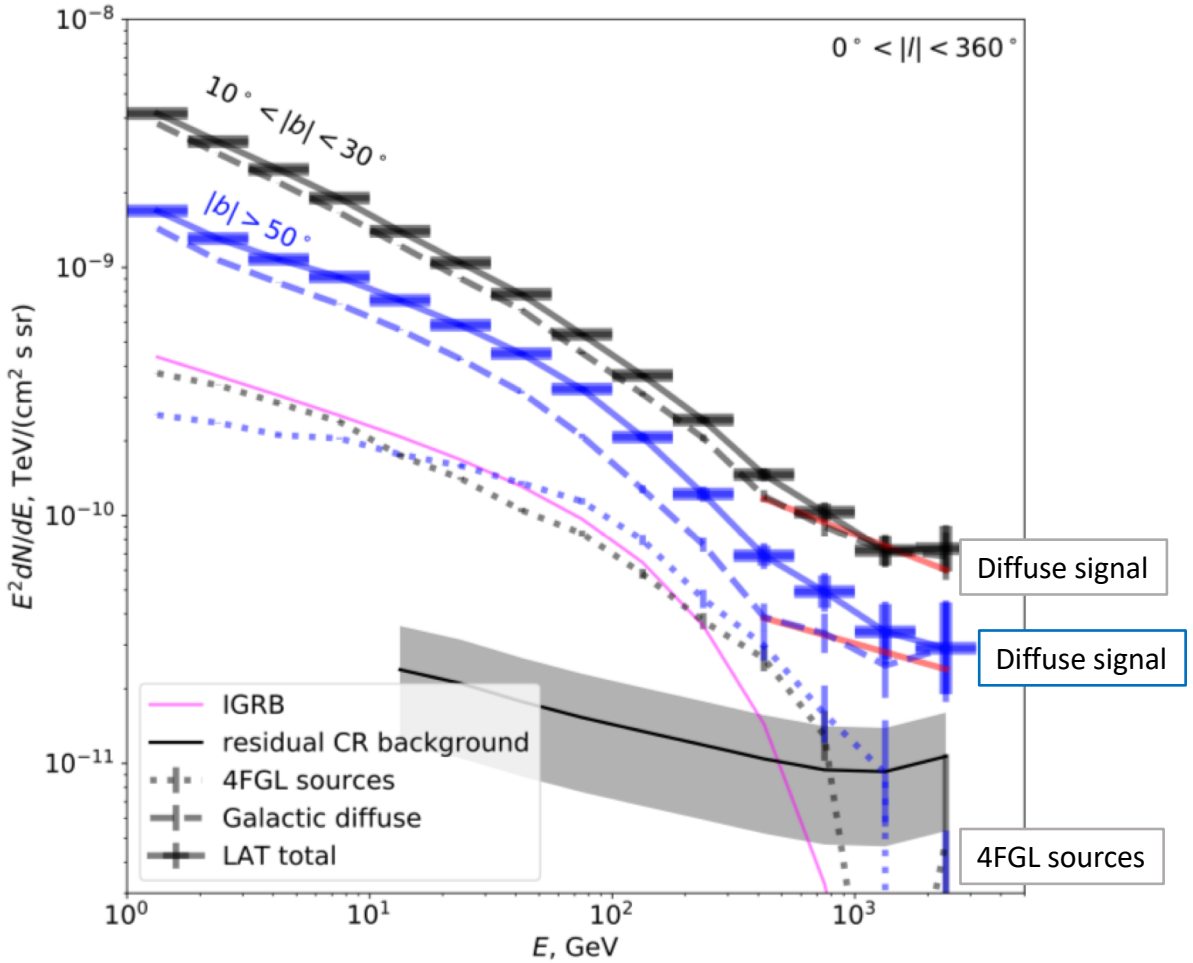


Residual cosmic ray background is also lower than the observed flux at high Galactic latitude. This means that large part of the high-latitude counts are photons.

Neronov, Semikoz, arXiv:1907.06061

High Galactic latitude signal in multi-TeV band



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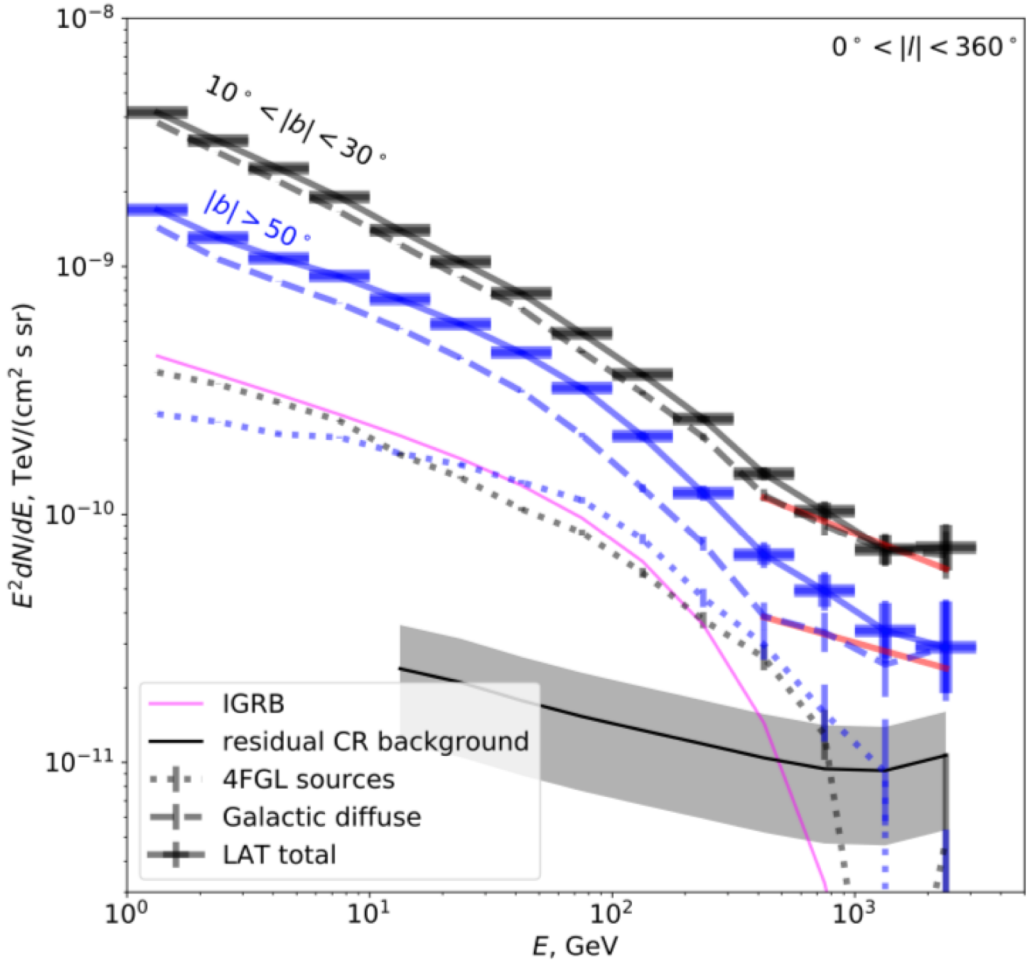


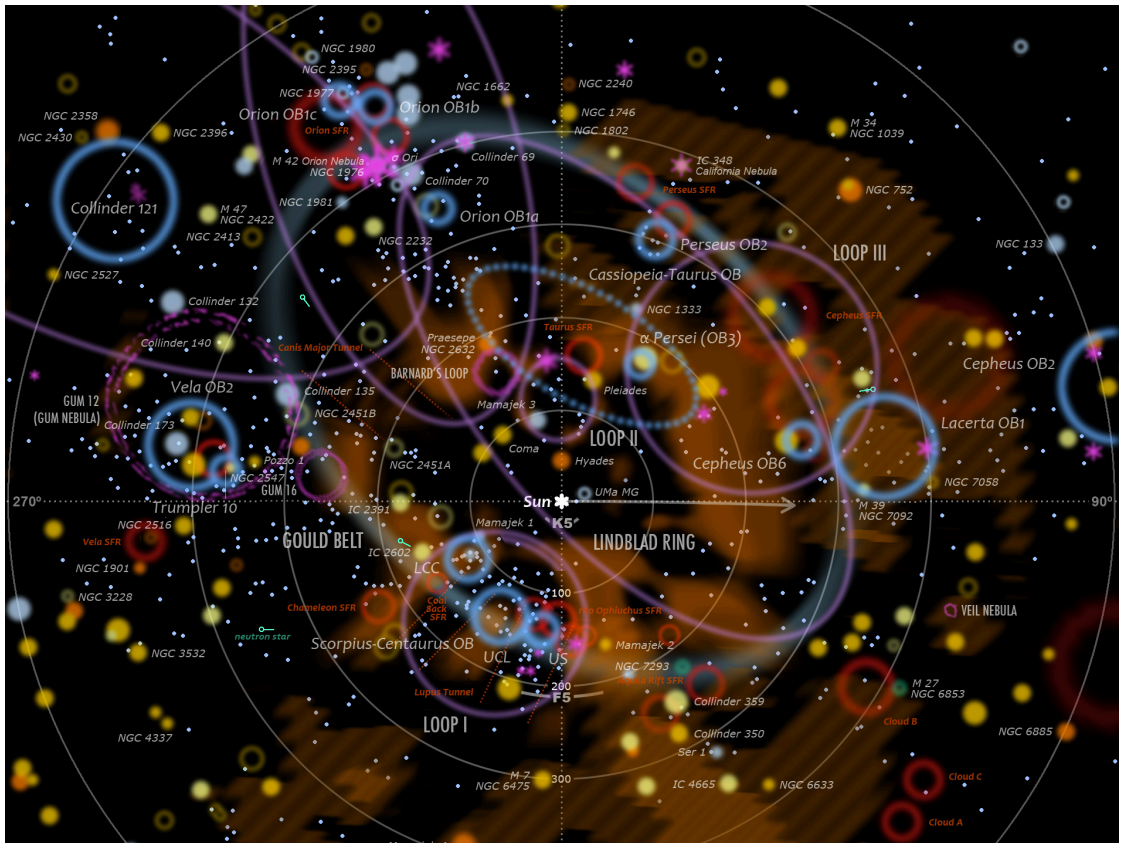
High Galactic latitude emission in multi-TeV region is of Galactic origin, because extragalactic flux is suppressed by absorption on EBL.

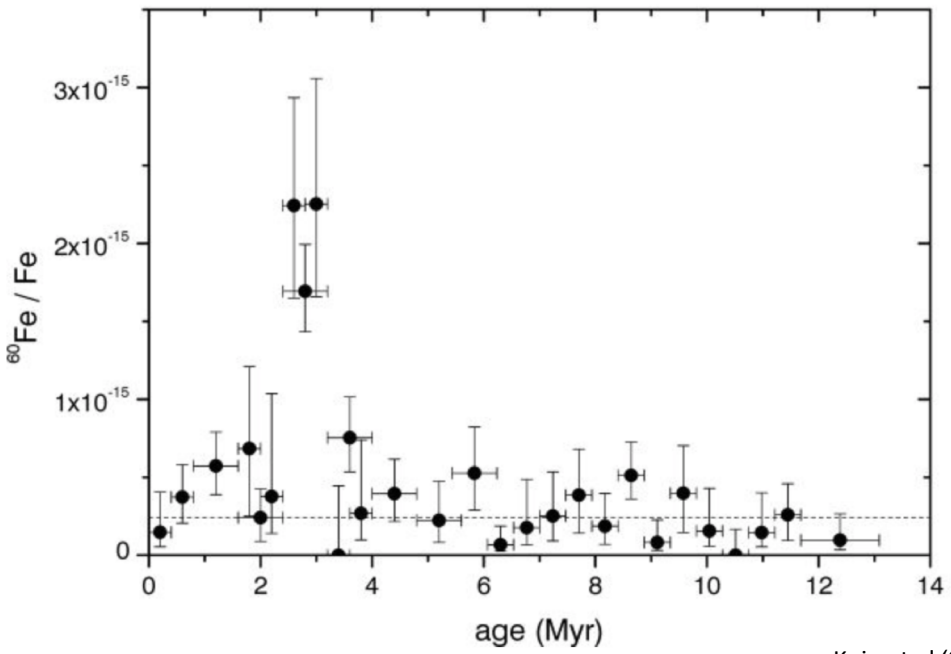
The Galactic diffuse spectrum appears to harden at the highest energy.

Residual cosmic ray background is also lower than the observed flux at high Galactic latitude. This means that large part of the high-latitude counts are photons.

Neronov, Semikoz, arXiv:1907.06061

Local Galactic environment

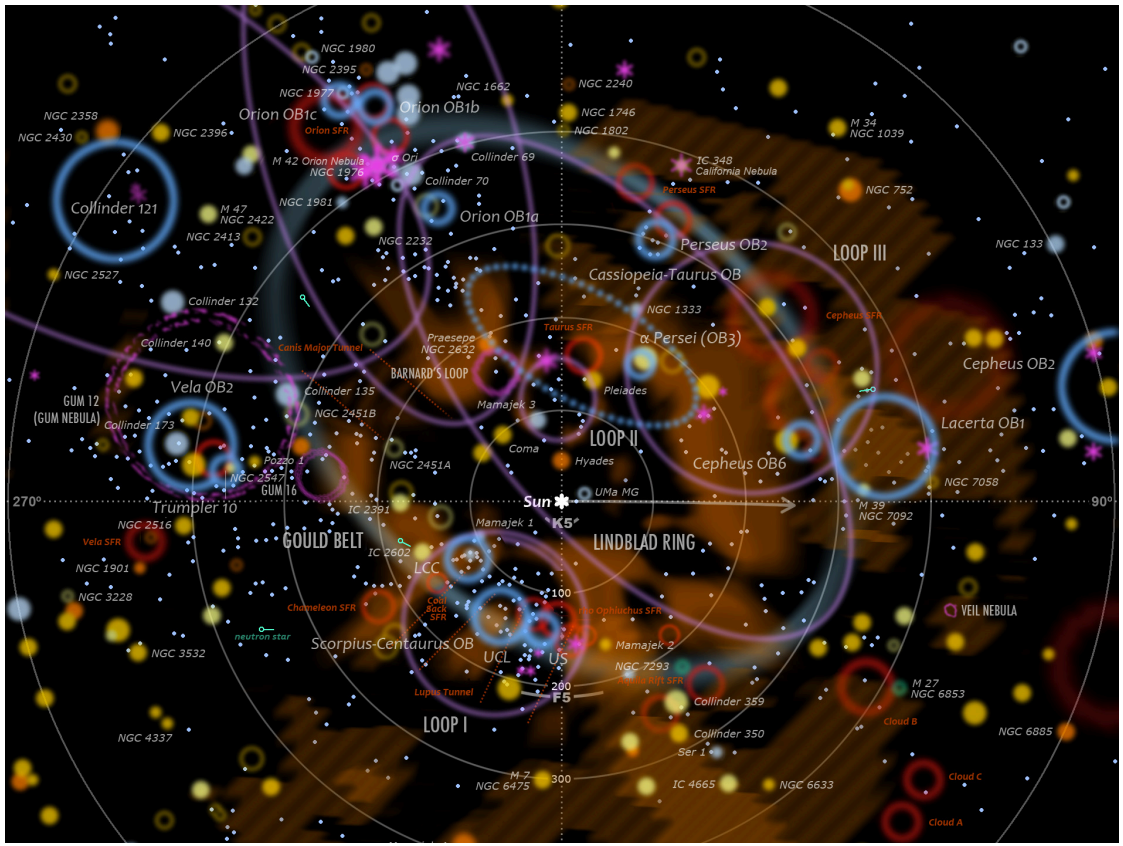


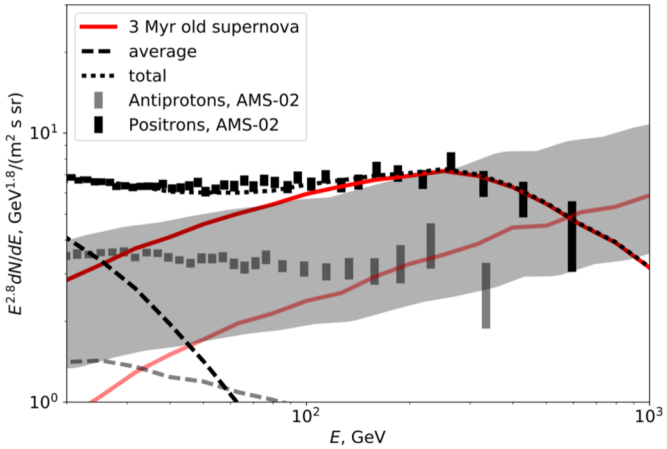


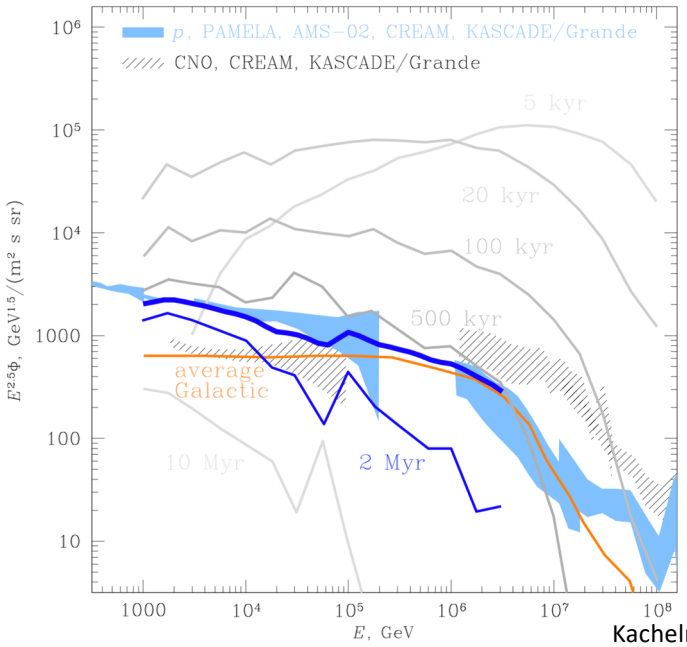
Some 2 Myr ago a supernova shell hass passed through the Earth and deposited radioactive ^{60}Fe isotopes in the deep ocean sediments.

Knie et al '04

Local Galactic environment



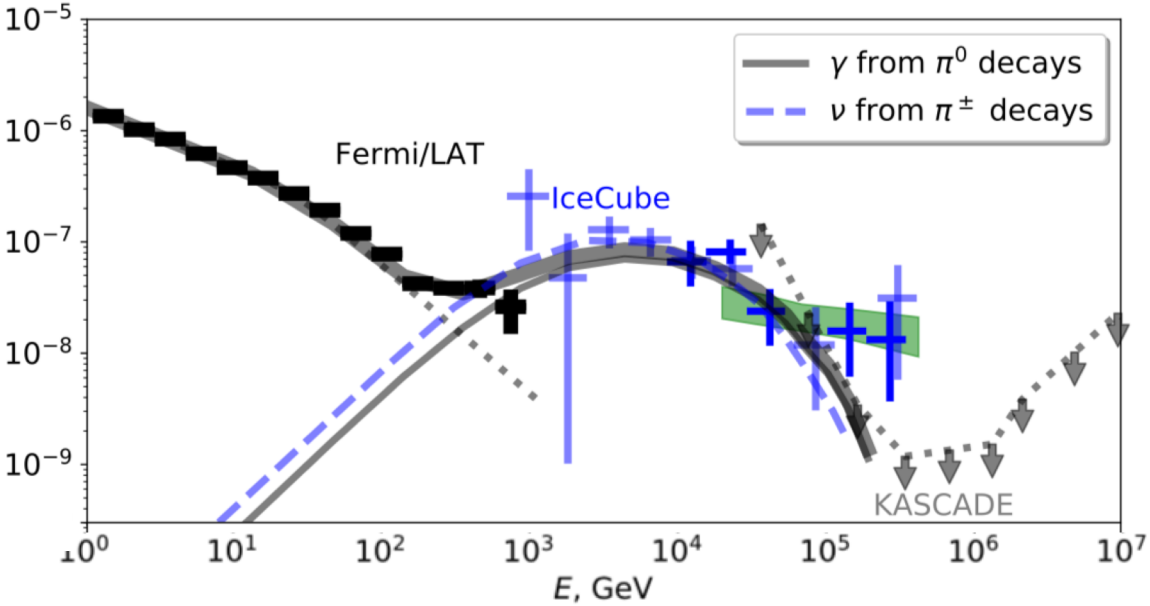




Peculiarities of the local measurements of cosmic ray spectrum (positron and antiproton spectra, feature at 1

Kachelriess, AN, Semikoz ’15, ‘17

High-latitude Galactic gamma-ray and neutrino flux: possible models

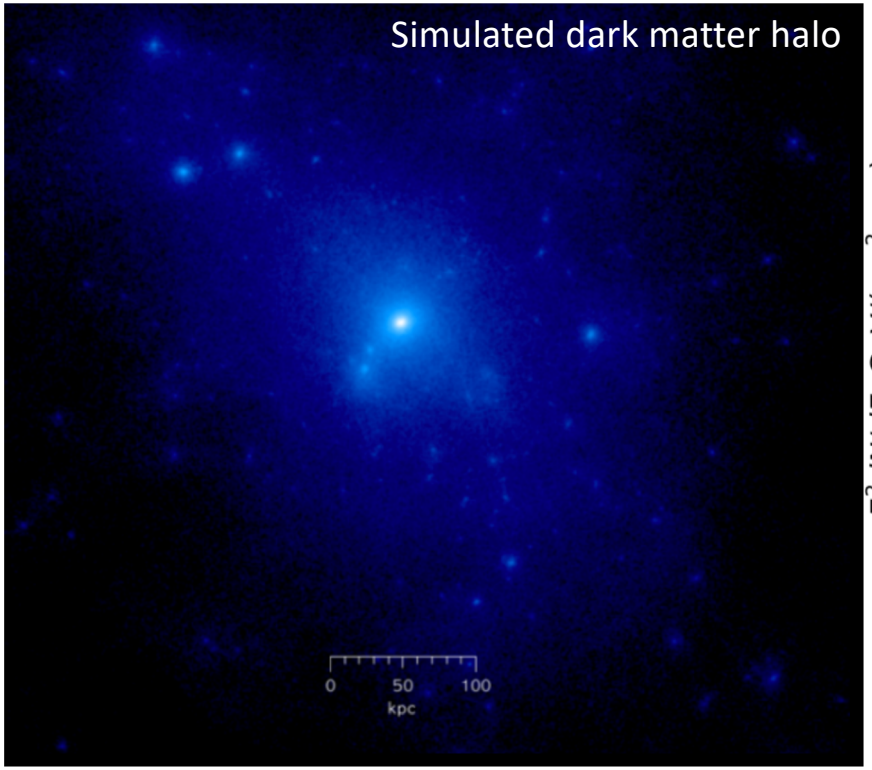


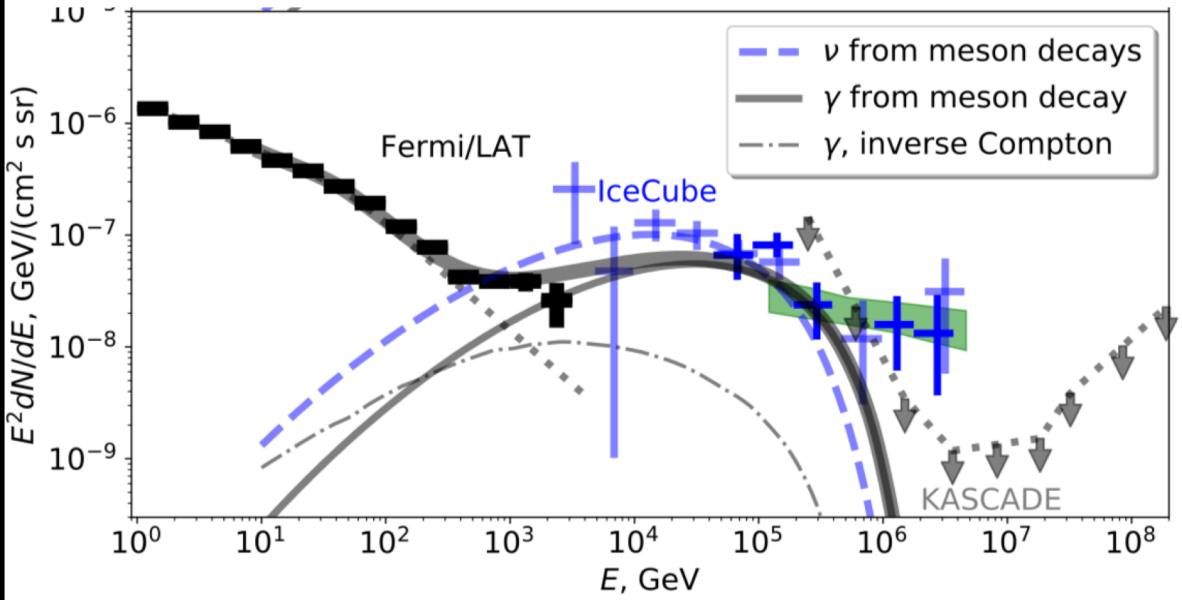
Cosmic rays with total energy $\mathbf{10^{50}}$ **erg** which have escaped nearby recent (within the escape time of PeV particles) source loose energy into neutrino and gamma-rays on time scale $t_{pp}\sim 10^{8}\ (n_{ISM}/0.5\ \mathrm{cm}^{-3})$ yr.
This might result in very extended emission with a flux

$$F\sim 10^{-10}\ (n_{ISM}/0.5\ \mathrm{cm}^{-3})\ (d/0.5\ \mathrm{kpc})^{-2}\ \mathrm{erg}/(\mathrm{cm}^2\ \mathrm{s})$$
$$\sim 10^{-7}\mathrm{GeV}/(\mathrm{cm}^2\ \mathrm{s})$$

Neronov, Semikoz, Kachelriess 2018

High-latitude Galactic gamma-ray and neutrino flux: possible models

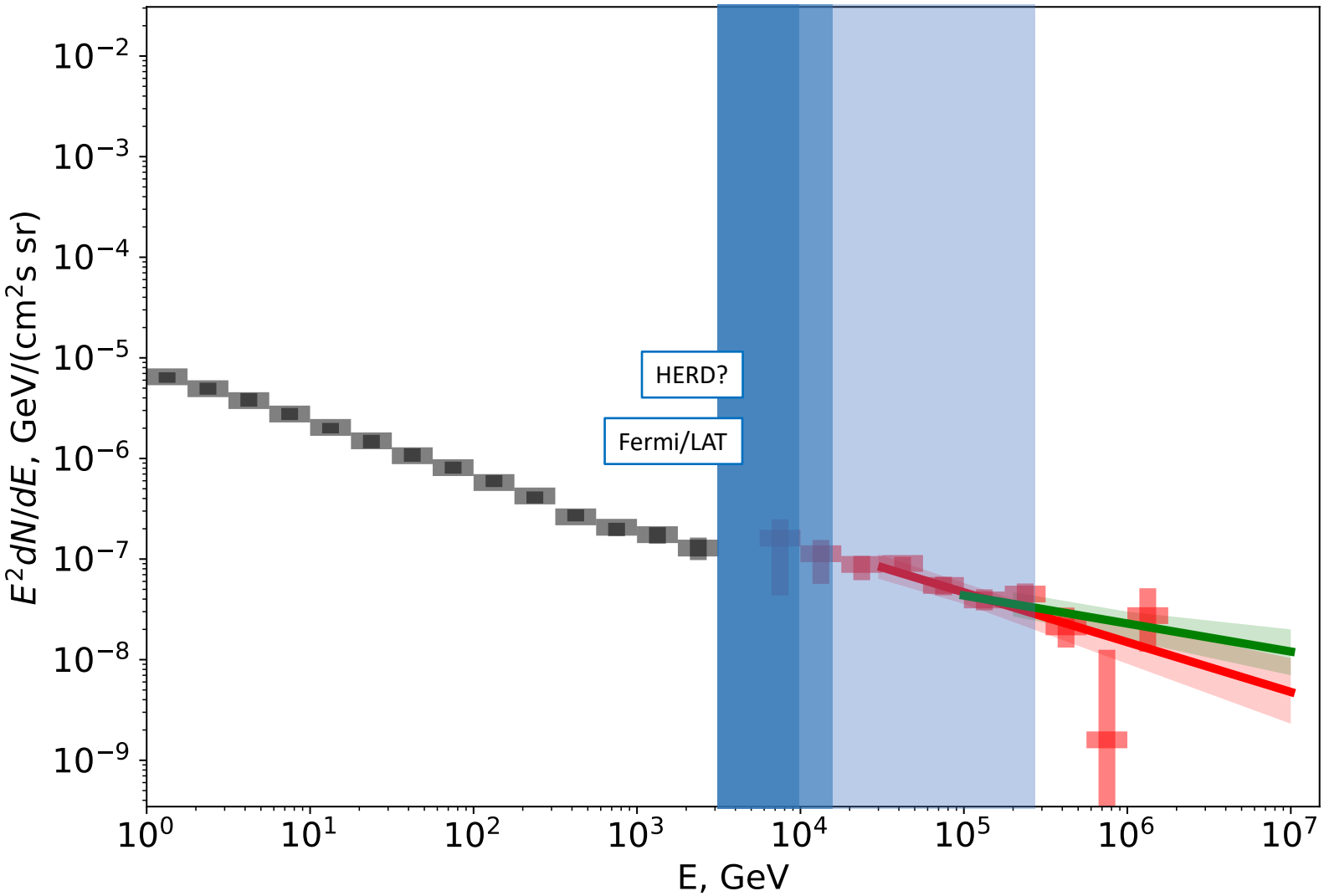




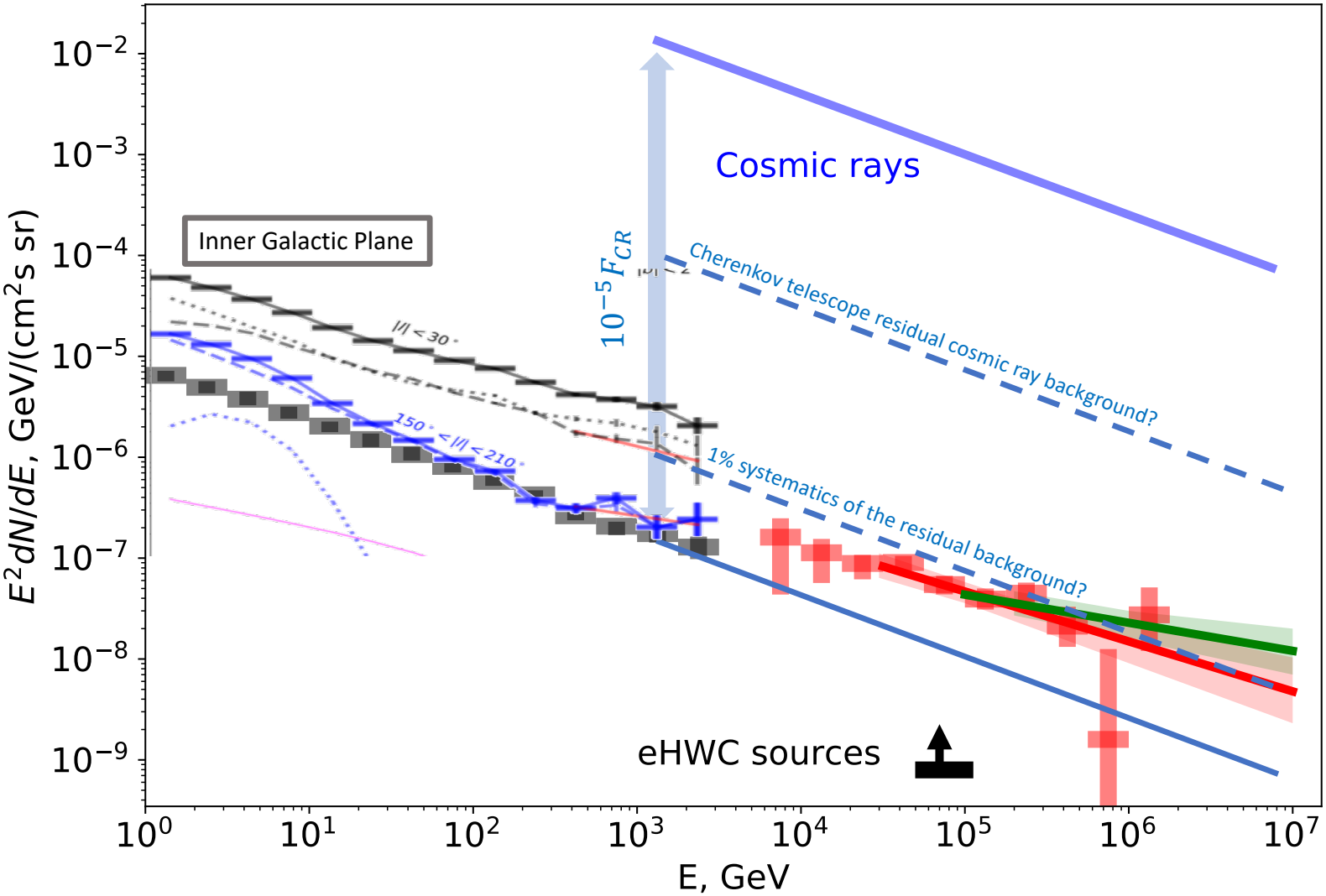
Decays of heavy dark matter particles with lifetime $\sim 10^{28}$ s into pions or directly into neutrinos and gamma-rays could provide the required multi-messenger flux at high Galactic latitude.

Neronov, Semikoz, Kachelriess 2018

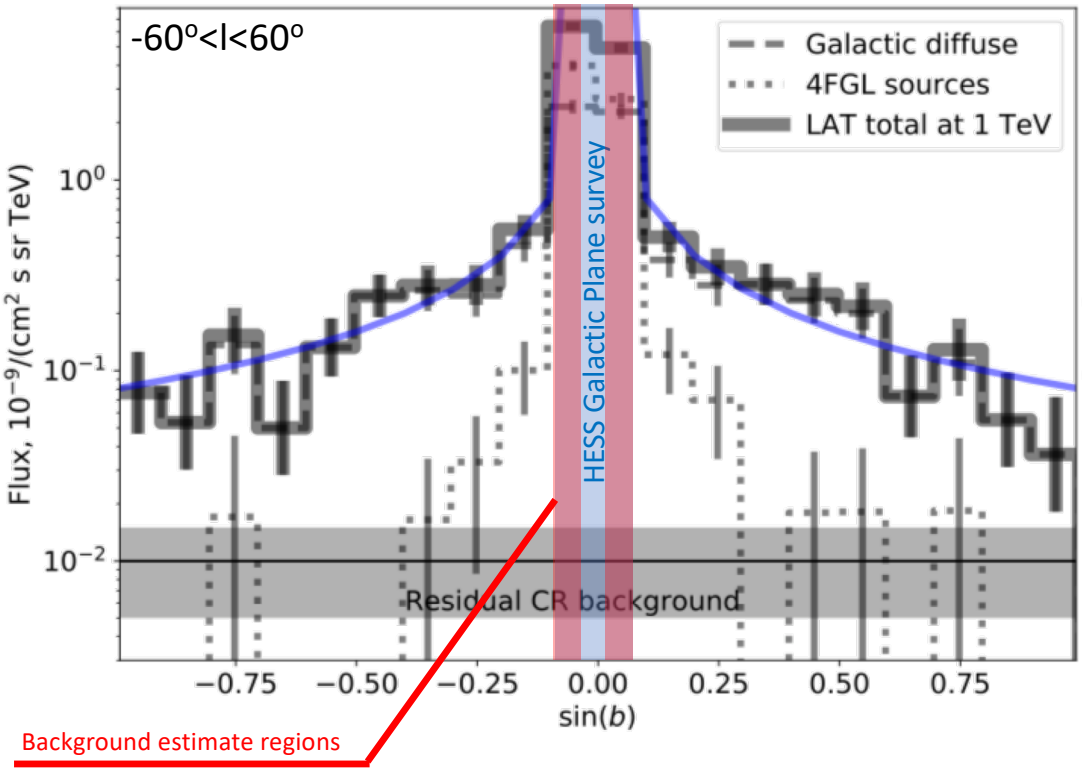
Measurement of Galactic diffuse emission at E>3TeV?

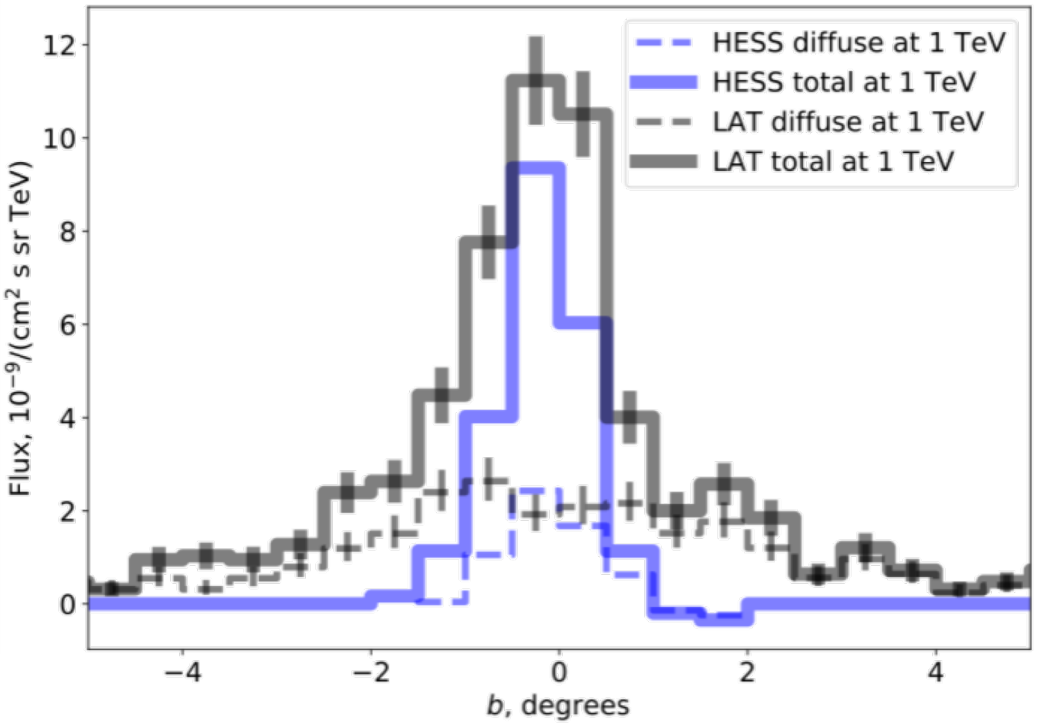


Galactic diffuse emission at E>3TeV?

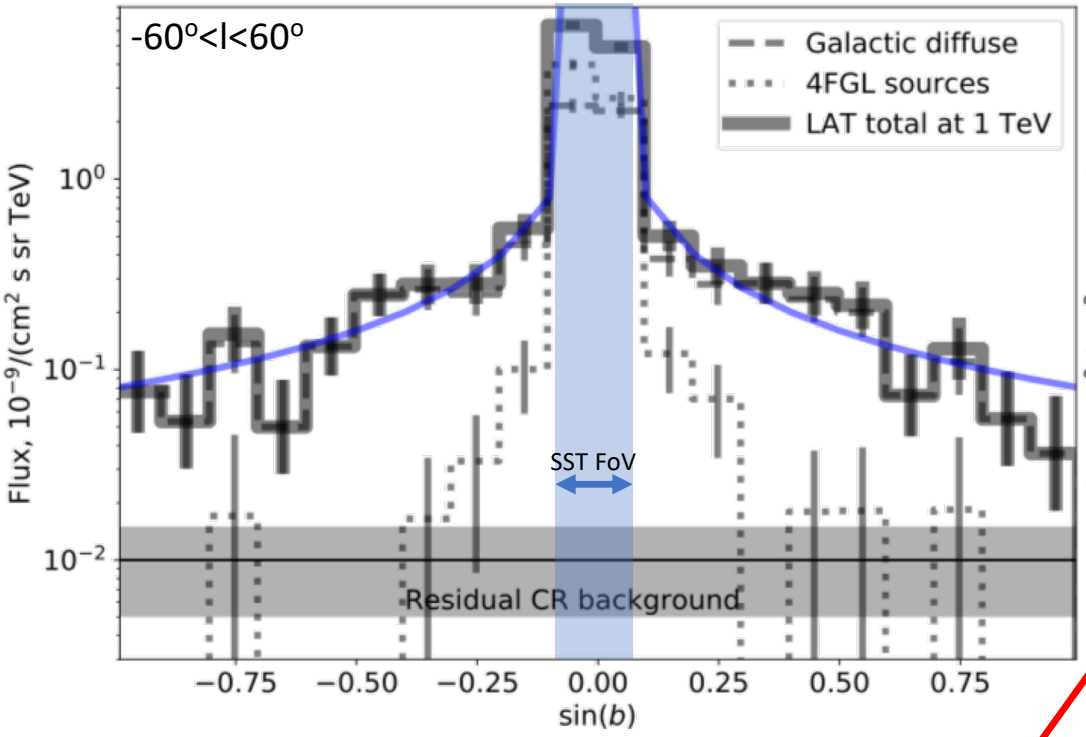


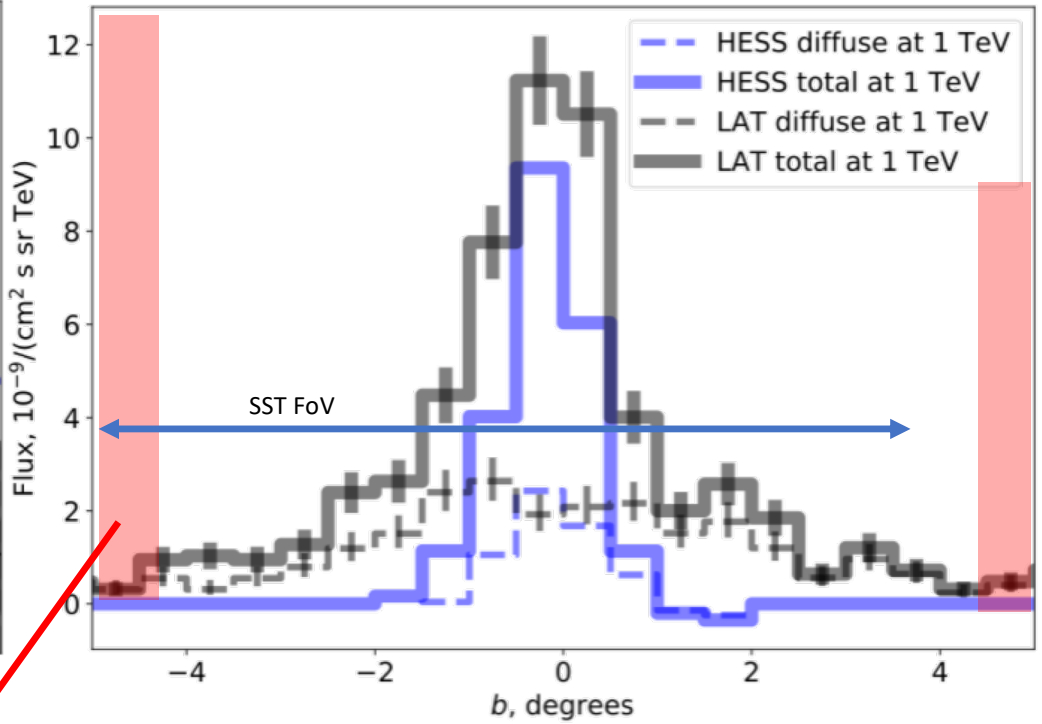
Re-using HESS approach: Galactic diffuse emission with CTA





Galactic diffuse emission with CTA

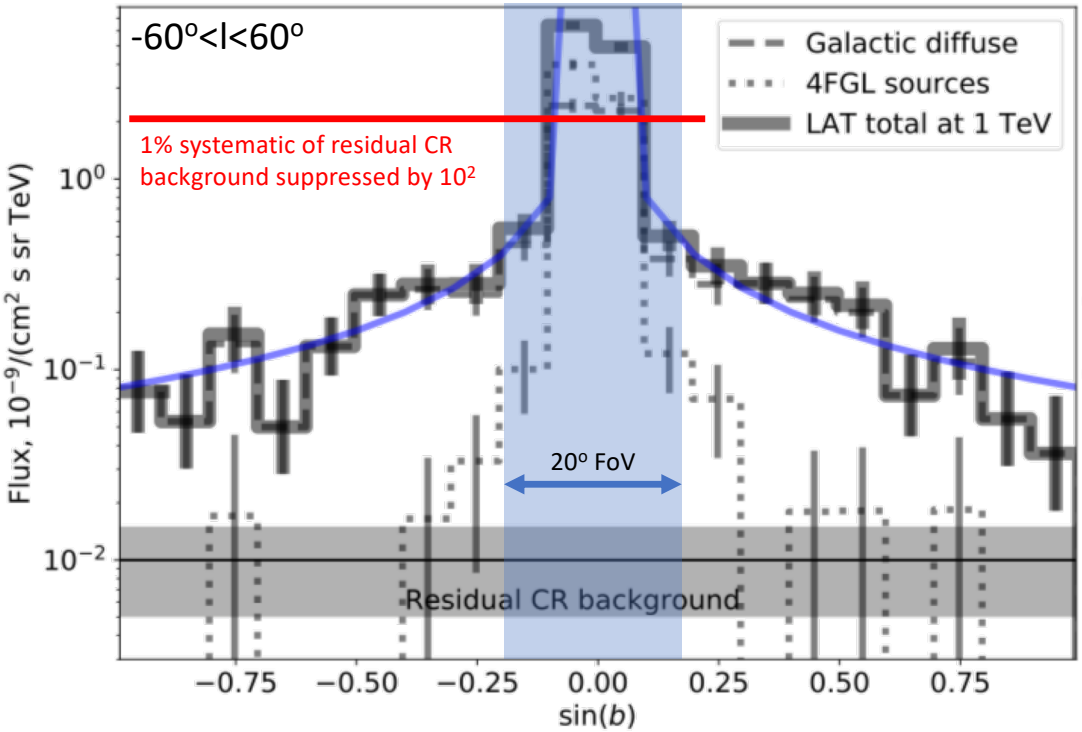


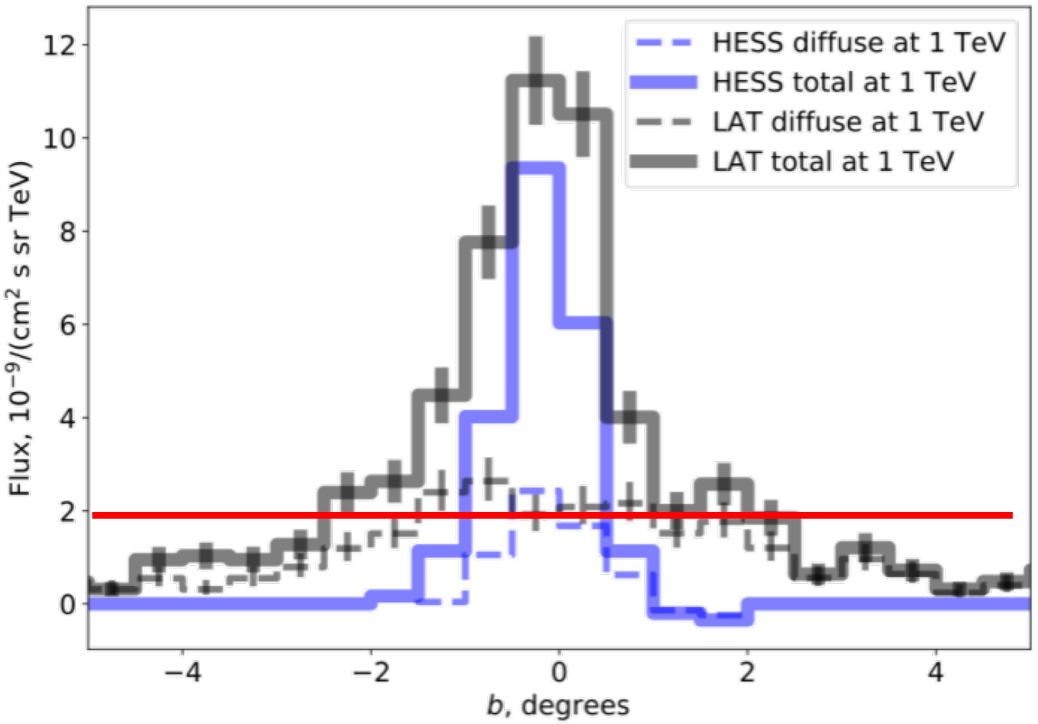


Background estimate regions

Larger FoV of CTA SST will provide an improvement for the measurement of the Galactic Disk diffuse emission in multi-TeV range

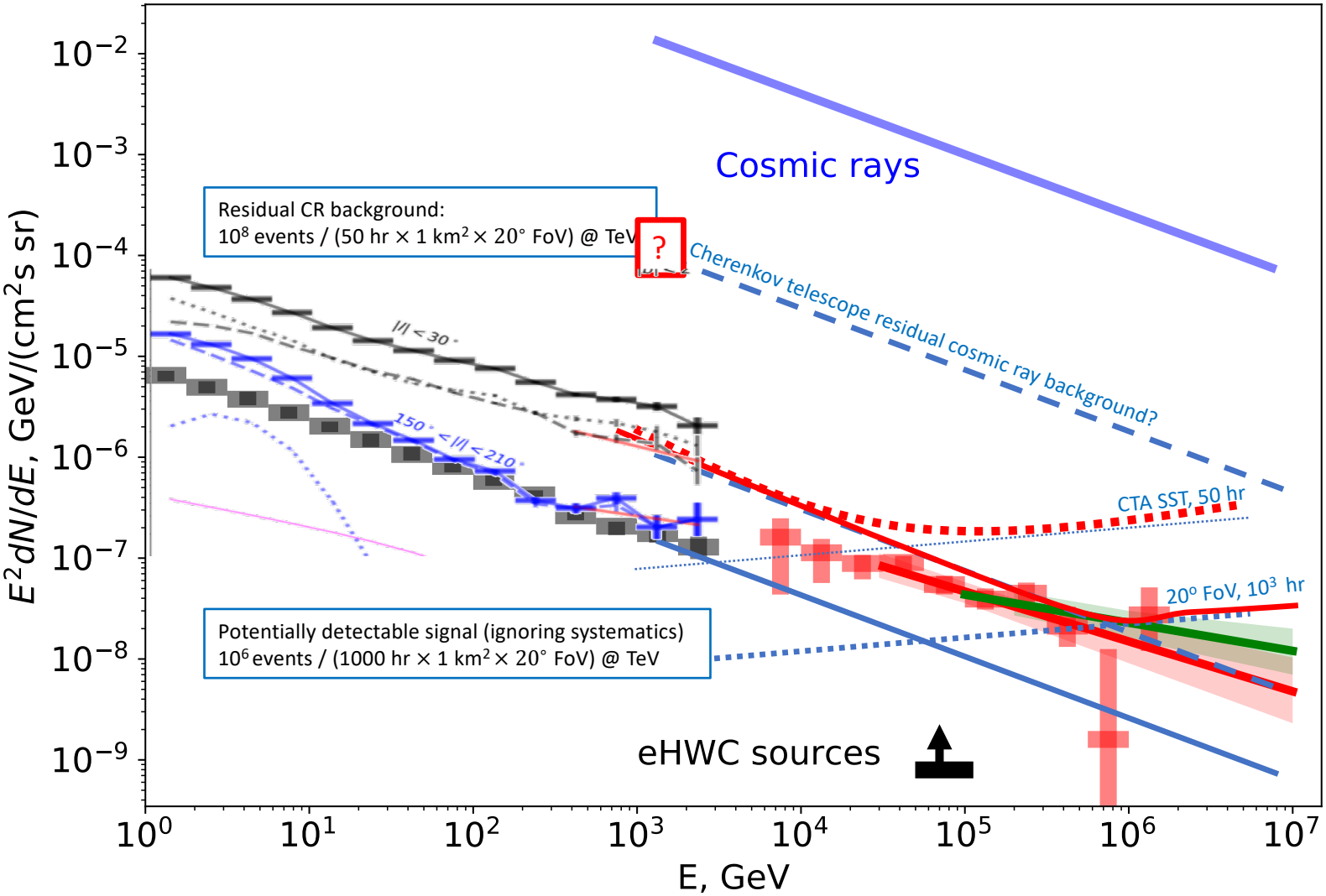
Re-using HESS approach: Galactic diffuse emission with 20º FoV telescope





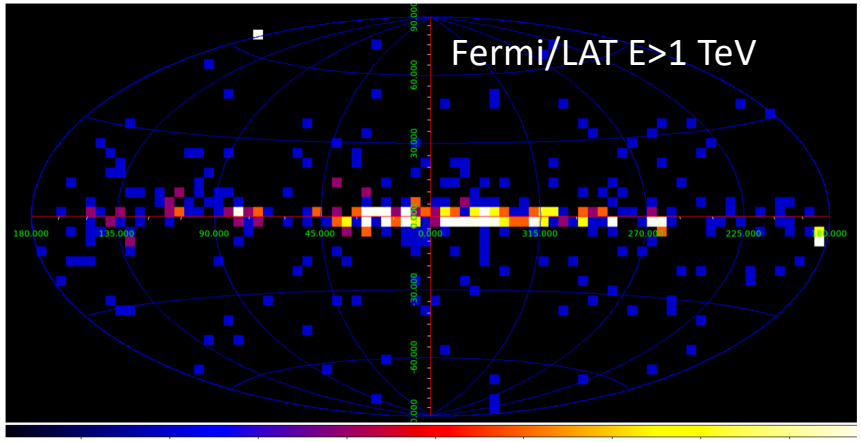
Larger FoV telescopes would allow a measurement of the diffuse emission up to larger Galactic latitudes, via measurements of the gradient of event count rates along the Galactic latitude direction in long stacked images aligned along Galactic longitude.

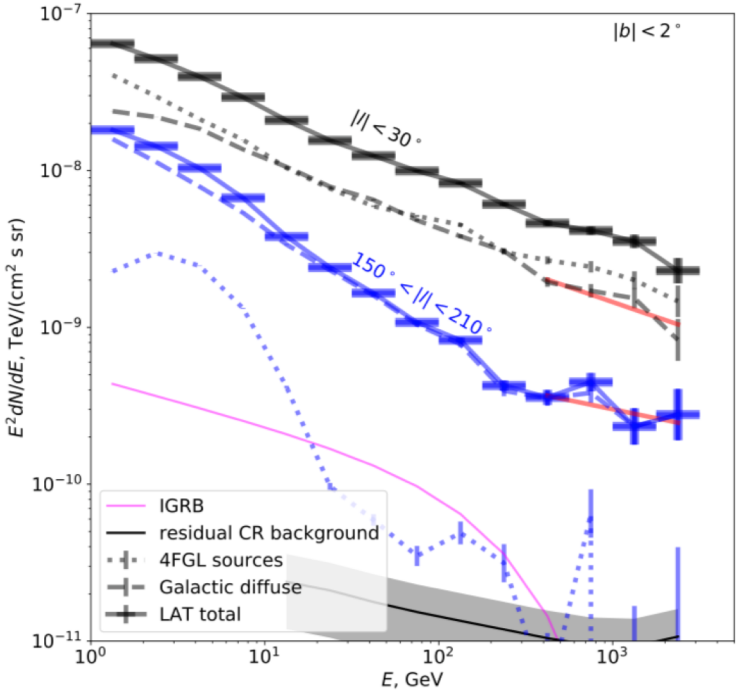
Re-using HESS approach: Galactic diffuse emission with dedicated 20º FoV telescope

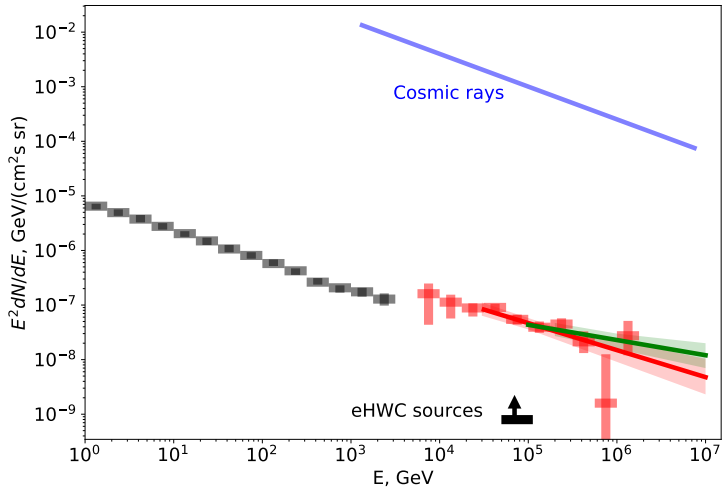


Summary

Galactic diffuse emission spectrum is measured up to E=3 TeV







Measurement of multi-messenger (gamma+neutrino) signal in 10-100 TeV band is possible.