Galactic diffuse and isolated source neutrino emission

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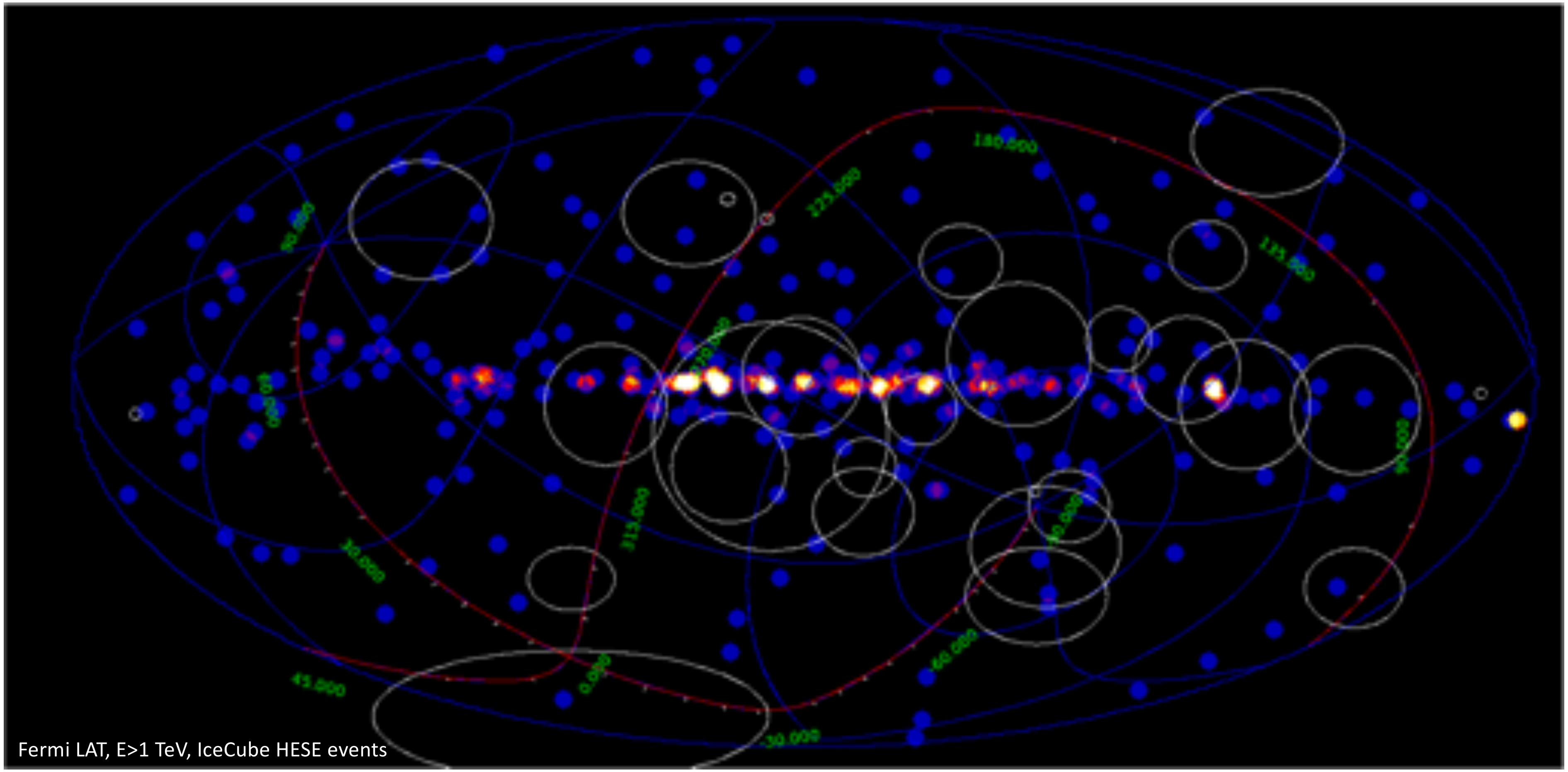
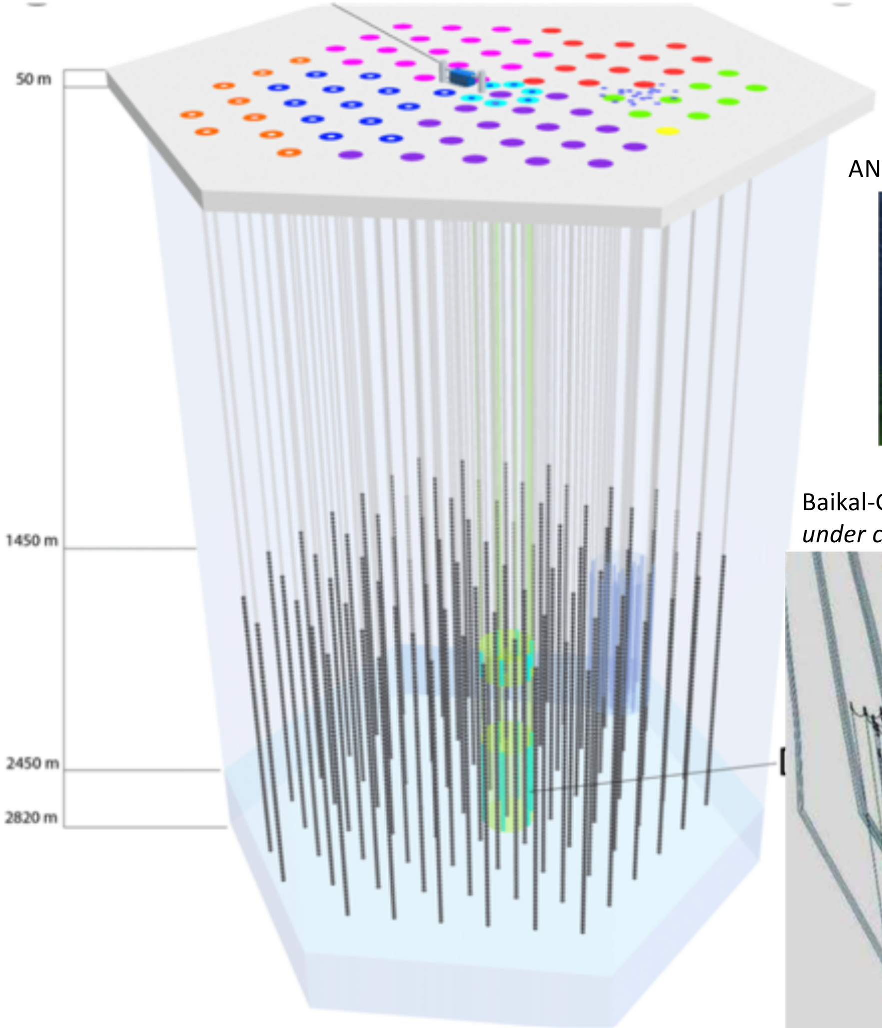


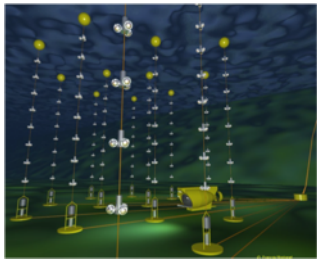
Fermi LAT, E>1 TeV, IceCube HESE events

Neutrino telescopes

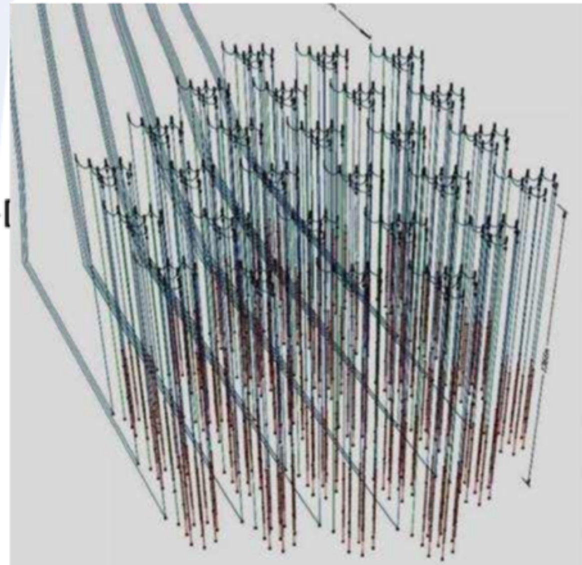


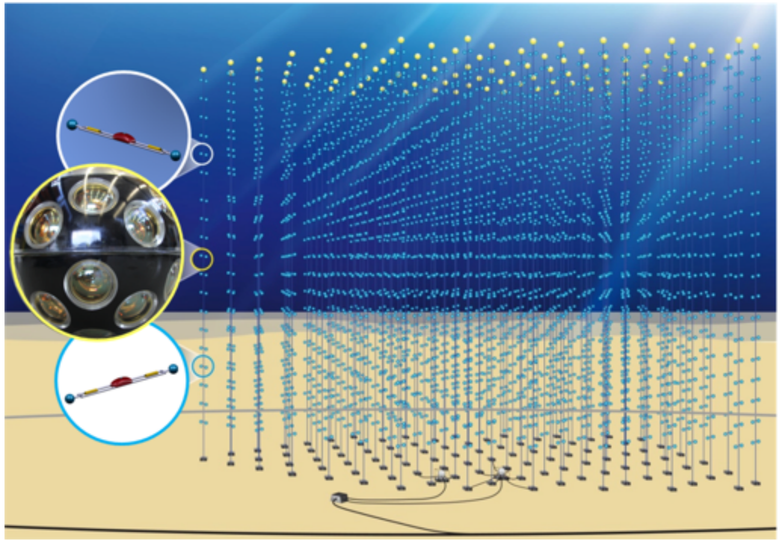
IceCube at the South Pole

ANTARES in Mediterranean Sea



Baikal-GVD in lake Baikal
under construction





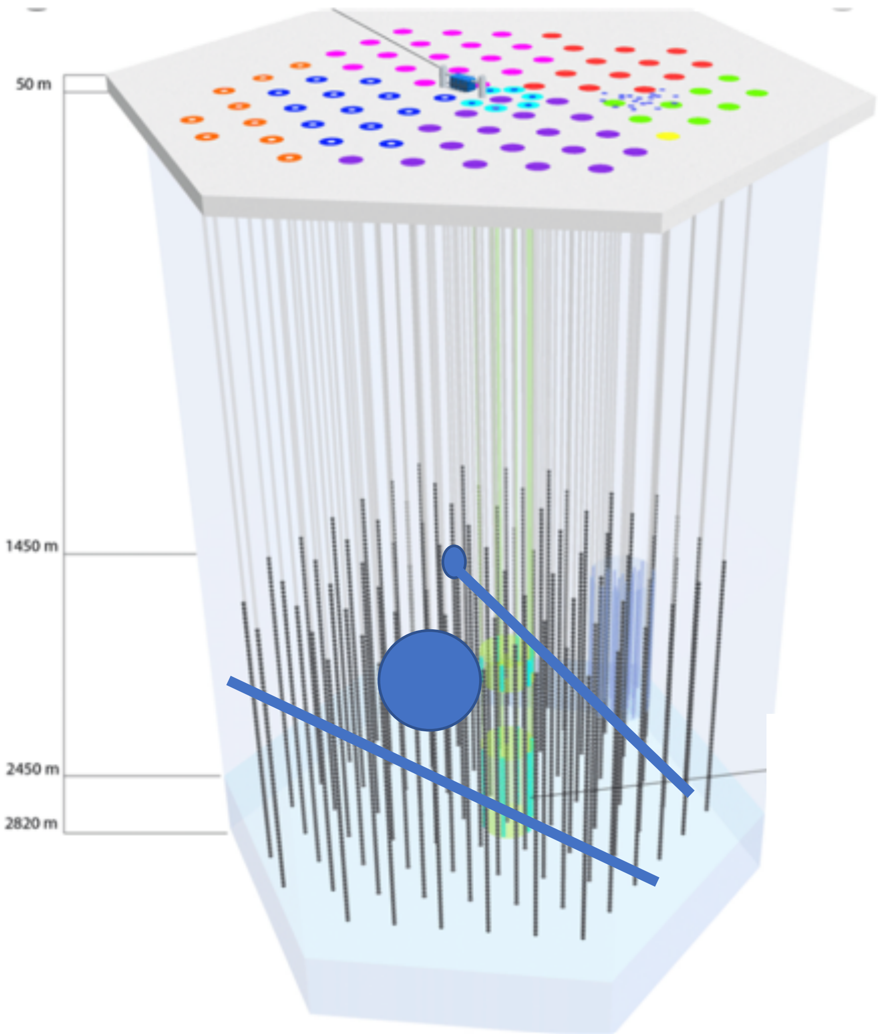
Km3NET (ARCA and ORCA) in Mediterranean Sea
under construction

High-energy neutrino telescopes feature large km^3 scale instrumented volumes which provide 10-100 m^2 effective area at 100 TeV, *much smaller than LHAASO*.

Astrophysical neutrino signal at 100 TeV is comparable to the residual background of atmospheric neutrinos and muons, *comparable to LHAASO at 100 TeV.*

Duty cycle close to 100%, comparable to LHAASO.

Astrophysical neutrino signal



7 years ago IceCube telescope has discovered astrophysical neutrino signal. The signal is measured using several techniques:

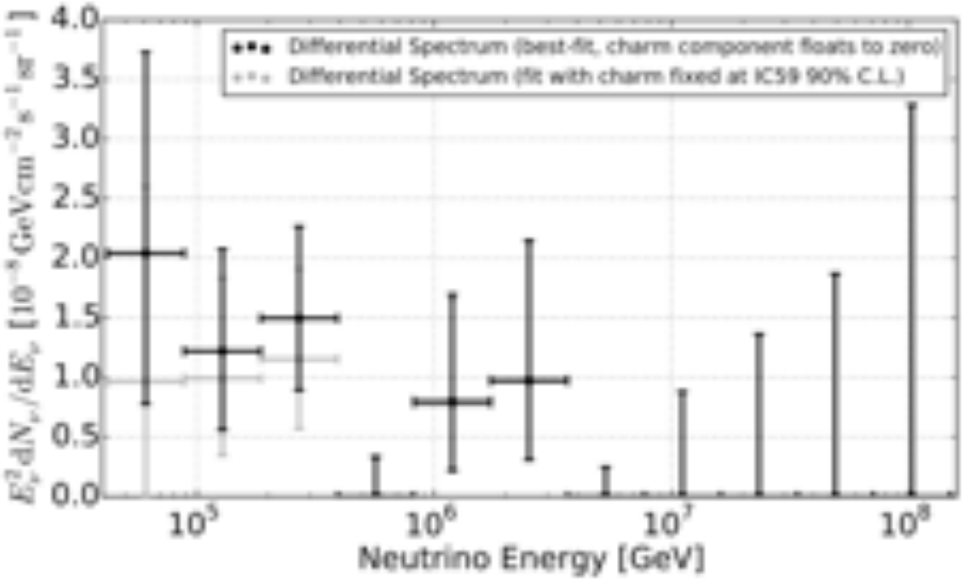
- ν_μ detectable through through-going muon tracks. This technique provides good angular resolution but poor energy resolution. Energy threshold above which the signal is detected in this channel is rather high $E > 200$ TeV.

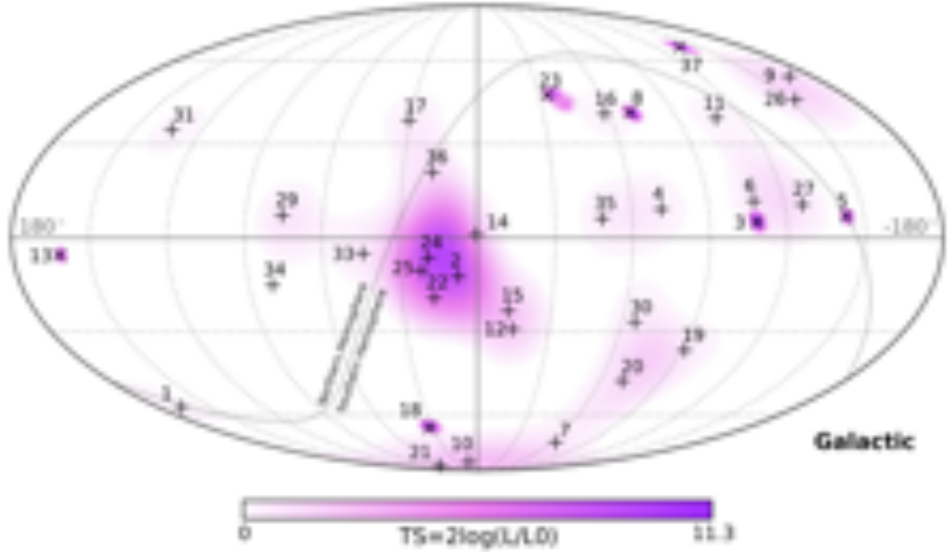
- Cascades contained in the detector, initiated by neutrinos or any flavour. This technique provides poor angular resolution but good energy resolution. The signal is detected above lower energy threshold $E \sim 10$ TeV.

- "High-Energy Starting Events" (HESE): both cascades and muon tracks starting inside the detector. This technique allows to veto the atmospheric background to observe the signal from Southern hemisphere where the background is high because of location of IceCube at the Southern Pole.

IceCube Collab. 2013+

Astrophysical neutrino signal





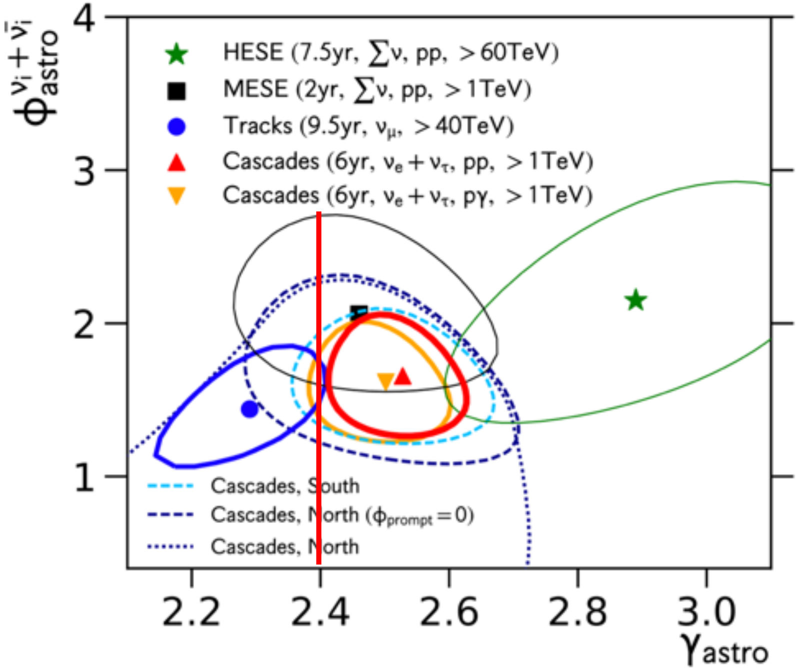
The astrophysical neutrino signal has initially been discovered in the HESE channel, dominated by the Southern sky.

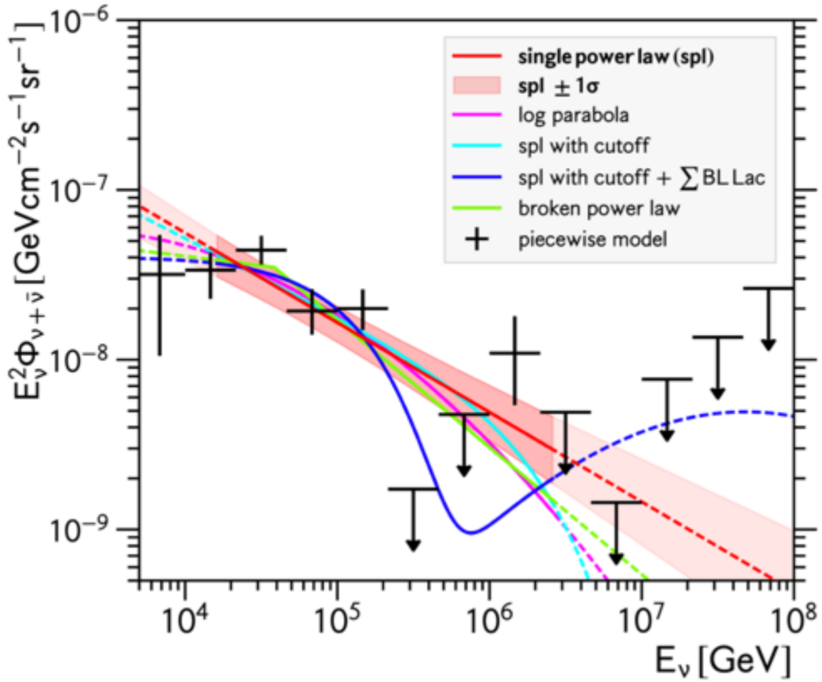
The signal distribution across the sky was found to be consistent with isotropic, signal consistent with powerlaw with relatively soft slope $\frac{dN_\nu}{dE} \propto E^{-\Gamma}, \Gamma \geq 2.5$.

Consistency with isotropy favours the extragalactic origin of the signal, the soft slope of the spectrum is, however, not consistent with the favoured extragalactic source model: interactions of high-energy protons with radiation fields in active galactic nuclei.

IceCube Collab., arXiv:1405.5303

Astrophysical neutrino signal… 7 years later





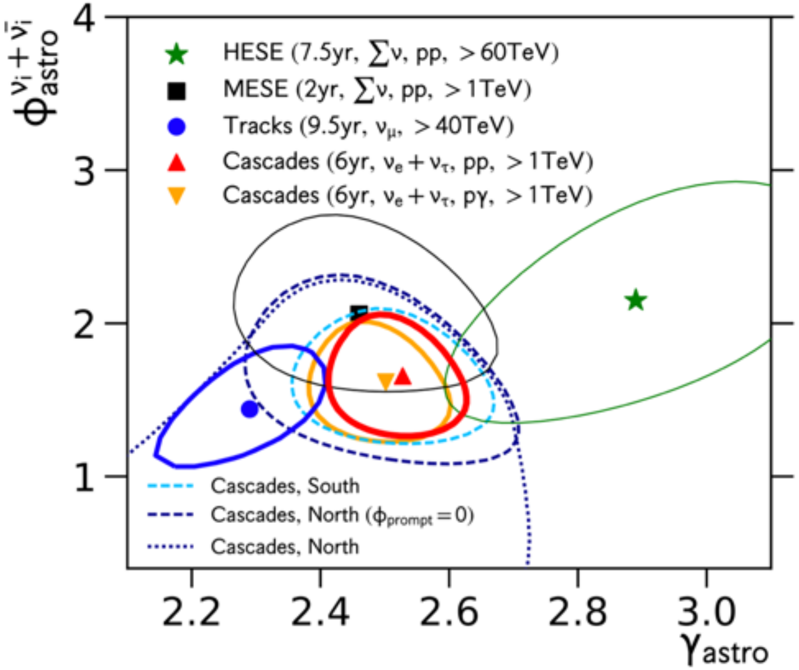
The signal is now detected also in muon neutrino channel, dominated by the Northern sky.

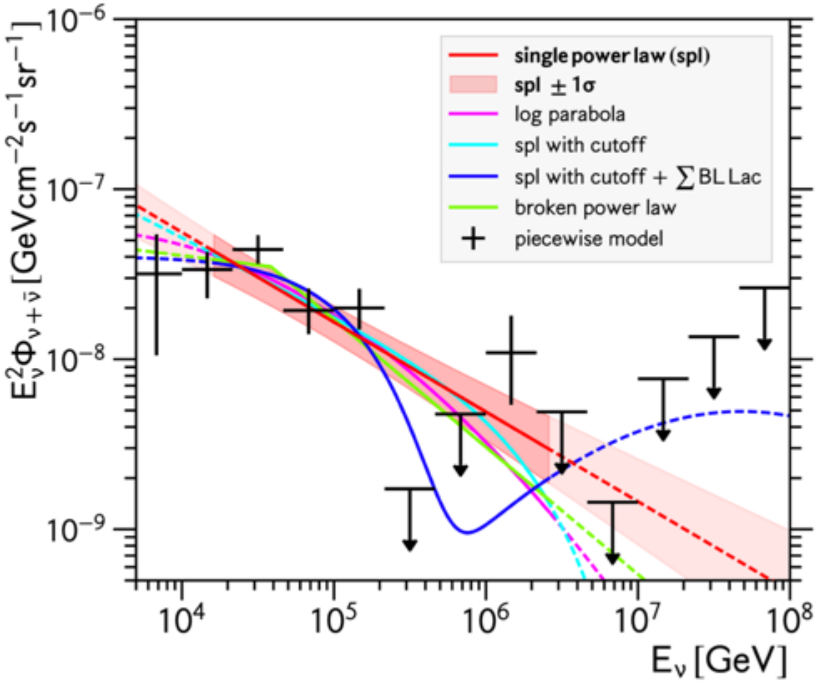
Measurements of the slope / normalization of the spectrum in different channels are marginally consistent with each other and with $\Gamma \simeq 2.4$ spectral slope.

HESE channel measurements tend to find softer spectrum, compared to muon track channel measurements.
Different techniques sense somewhat different energy ranges and sky regions. Tensions between different measurements might indicate either anisotropy of the signal or a break in the powerlaw spectrum.

IceCube Collab., arXiv:2001.09520

Astrophysical neutrino signal… 7 years later



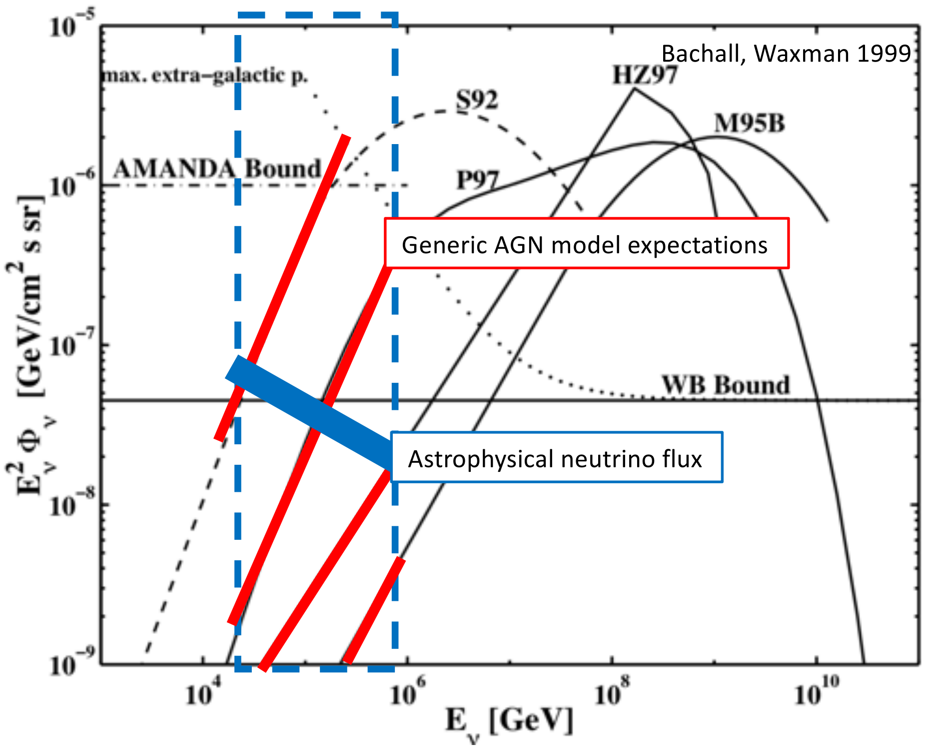


After a ~ 10 yr exposure, statistics of the measurements of the astrophysical neutrino signal in 10 TeV -10 PeV range will not anymore improve dramatically.

It might be difficult to find the origin of the astrophysical neutrino signal based on the properties of the signal itself. A multi-messenger approach involving electromagnetic counterpart of the signal is essential.

IceCube Collab., arXiv:2001.09520

Extragalactic neutrinos from p-gamma interactions AGN?



IceCube neutrino signal is consistent with being isotropic, which is consistent with extragalactic origin of the signal.

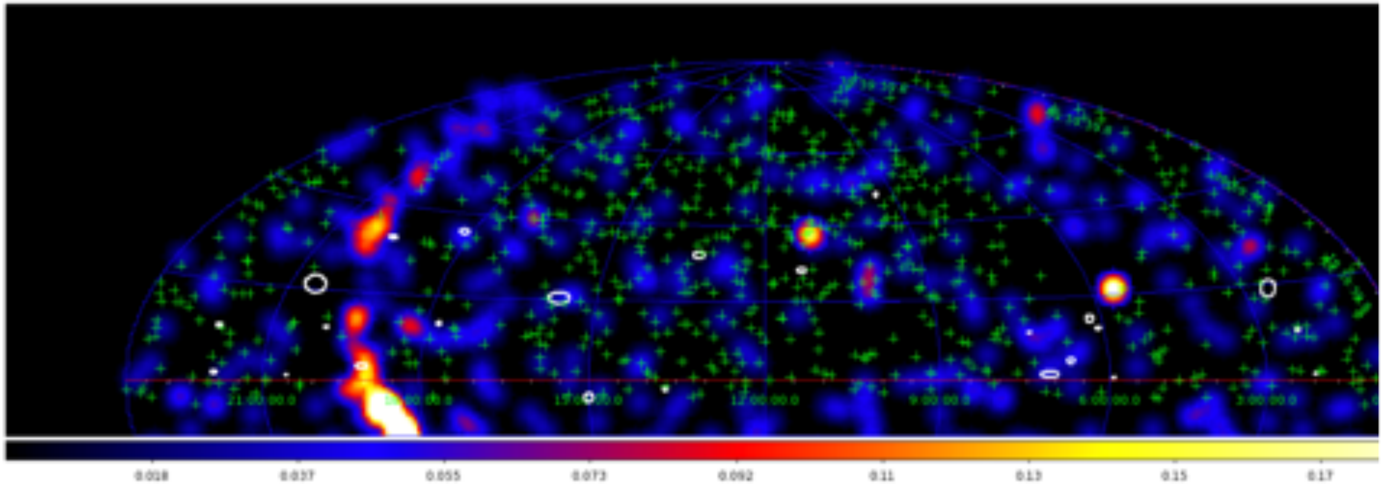
Active Galactic Nuclei are the most commonly discussed possible extragalactic neutrino source type. Typical AGN neutrino emission models predict hard neutrino spectra in the 100 TeV energy range. In these models, neutrinos are produced in proton-gamma interactions, which have a high energy threshold.

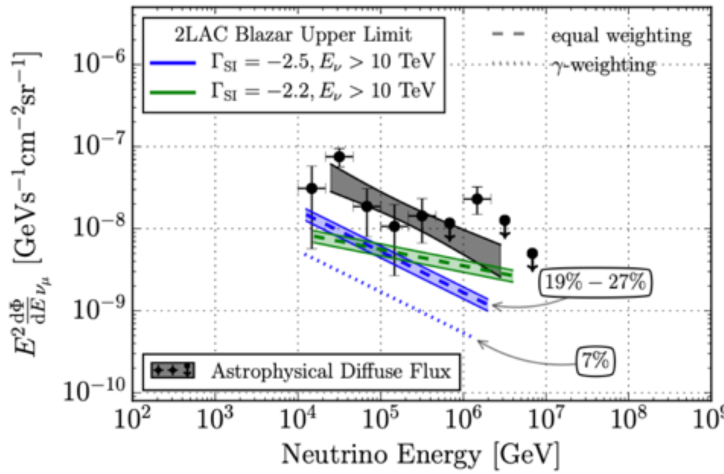
IceCube spectrum is much softer.....

Extragalactic neutrino sources do not have electromagnetic counterparts in the energy range of the astrophysical neutrino signal., because gamma-rays interact with low energy radiation fields and are absorbed on the way through the intergalactic medium.

Gamma-ray induced cascades might transfer emission power to lower energy range so that electromagnetic counterparts of extragalactic neutrino sources might be observable. Recent example of 3σ evidence for correlated neutrino and electromagnetic signal from a blazar TXS 0506+056 shows how such counterparts can be detected.

Extragalactic neutrinos from p-gamma interactions AGN?

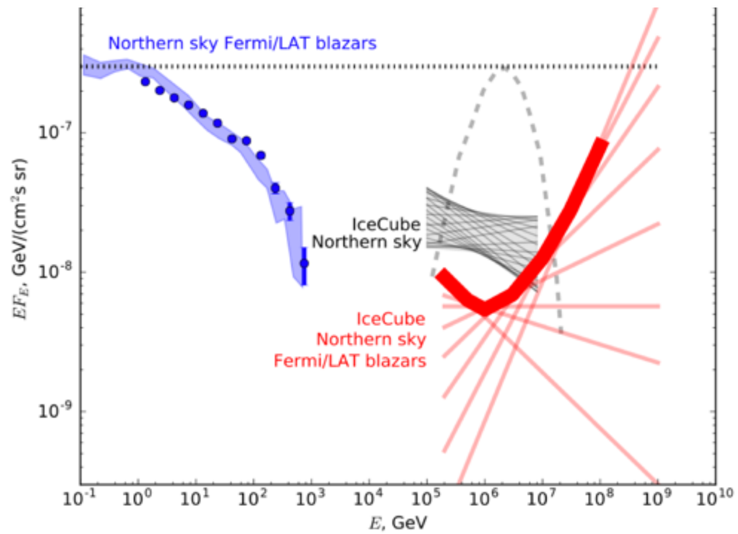




Gamma-ray induced cascades transfer power to gamma-rays in 0.1-100 GeV energy range. This power should be detectable with Fermi/LAT.

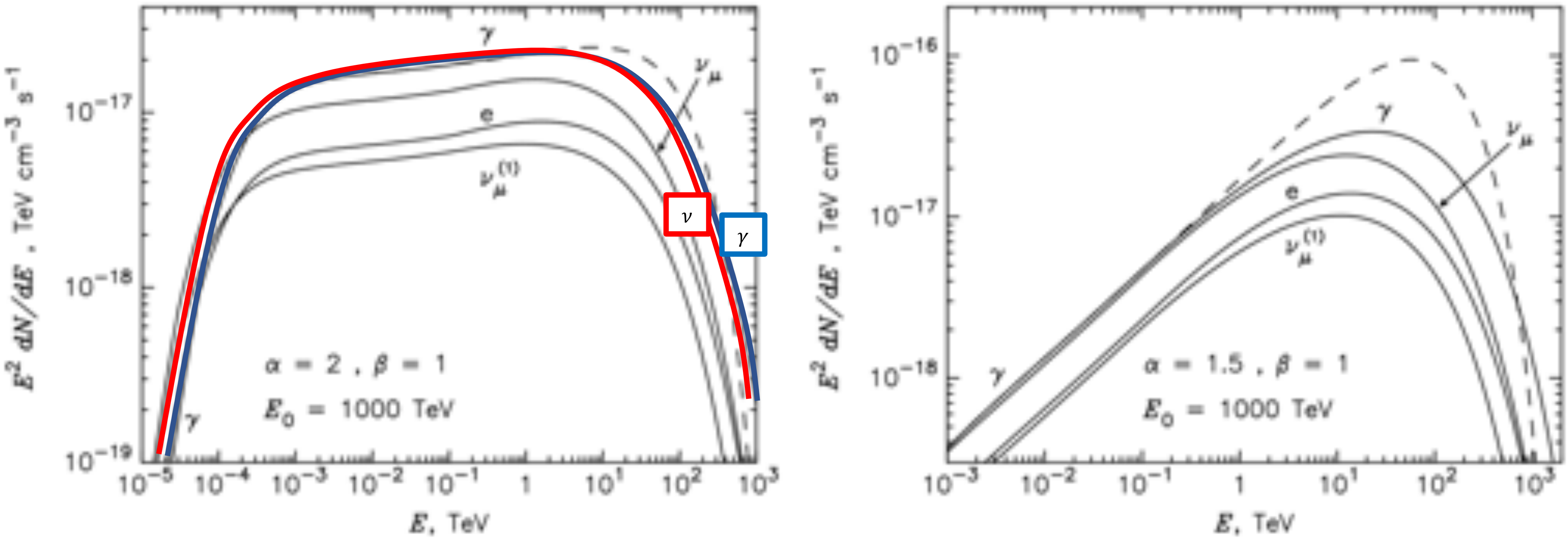
However, muon neutrino arrival directions do not correlate with positions of Fermi blazars. The bulk of neutrino signal is not produced by the same blazar population as the bulk of extragalactic gamma-ray signal.

It is still possible that sizeable part of the astrophysical neutrino flux is produced by blazars (AGN with jets aligned along the line of sight), but the populations of ”GeV gamma-ray loud” and “neutrino loud” blazars are different.



Neronov, Ptitsyna, Semikoz, arXiv:1611.06338
IceCube Collab. arXiv:1611.03874

Soft astrophysical neutrino spectrum from p-p interactions



Pion production in proton-proton interactions is characterized by energy threshold $E_{thr} \simeq 100$ MeV.

- Typical energy of neutrinos is $E_\nu \sim 0.03\, E_p$. Typical energy of gamma-rays $E_\gamma \sim 0.04\, E_p$
- Slope of neutrino spectrum $\Gamma_\nu \sim \Gamma_p - 0.1$; slope of gamma-ray spectrum $\Gamma_\gamma \sim \Gamma_\nu$.
- Normalization of neutrino flux $F_\nu \simeq 1.0 F_\gamma$ for $\Gamma_p \simeq 2.4$.

Really easy to work out models with soft neutrino emission spectra if neutrinos are produced in proton-proton interactions.

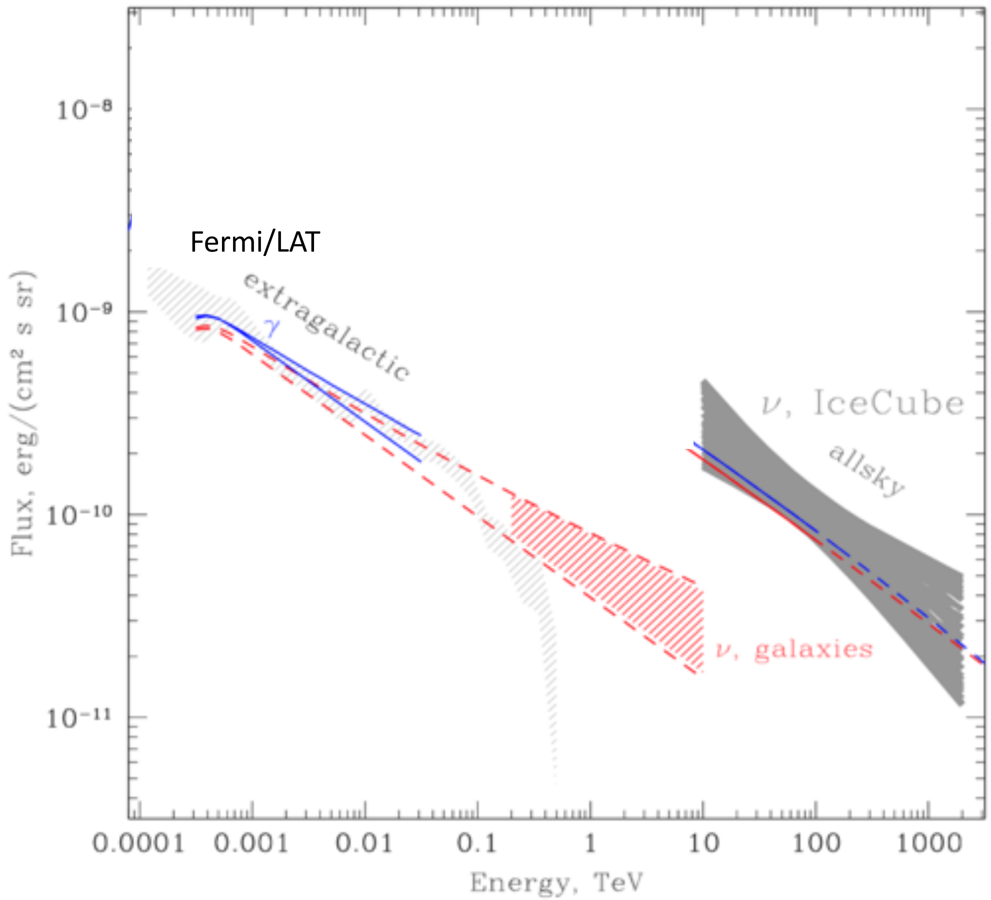
Kelner, Aharonian, Bugayov, astro-ph/0606058

Neutrinos from cosmic ray interactions in star-forming galaxies?

Cosmic ray – atomic nuclei interactions in star forming galaxies might produce soft extragalactic neutrino flux.

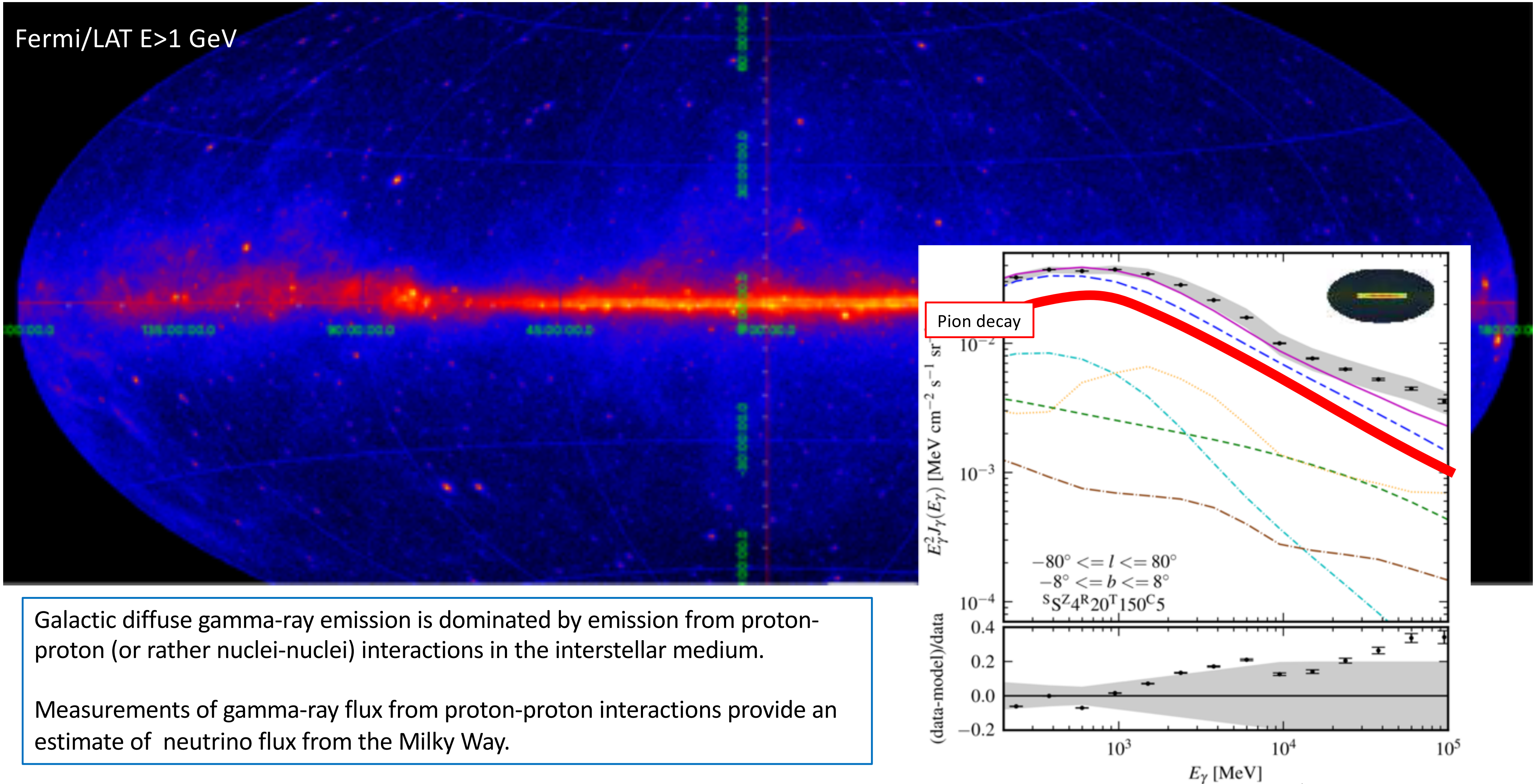
However, neutrino flux is expected to be comparable to the gamma-ray flux and have the same spectral properties. Gamma-ray flux from star-forming galaxies constitutes only a minor fraction of the extragalactic gamma-ray background.

Extragalactic neutrino signal from star forming galaxies produces only sub-dominant contribution to the neutrino flux.



Neronov, Semikoz, arXiv:1412.1690

Neutrinos from the Milky Way

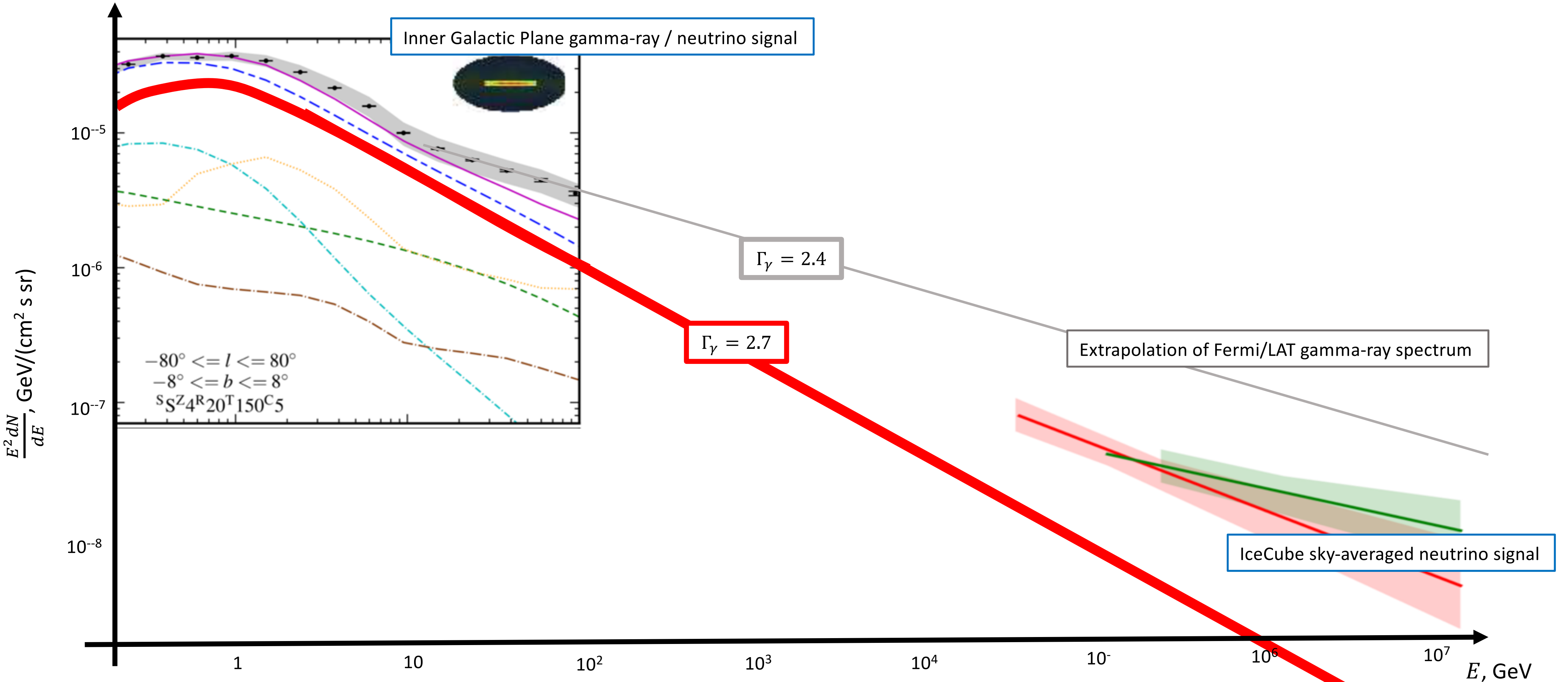


Fermi/LAT Collab. arXiv:1202.4039

Galactic diffuse gamma-ray emission is dominated by emission from proton-proton (or rather nuclei-nuclei) interactions in the interstellar medium.

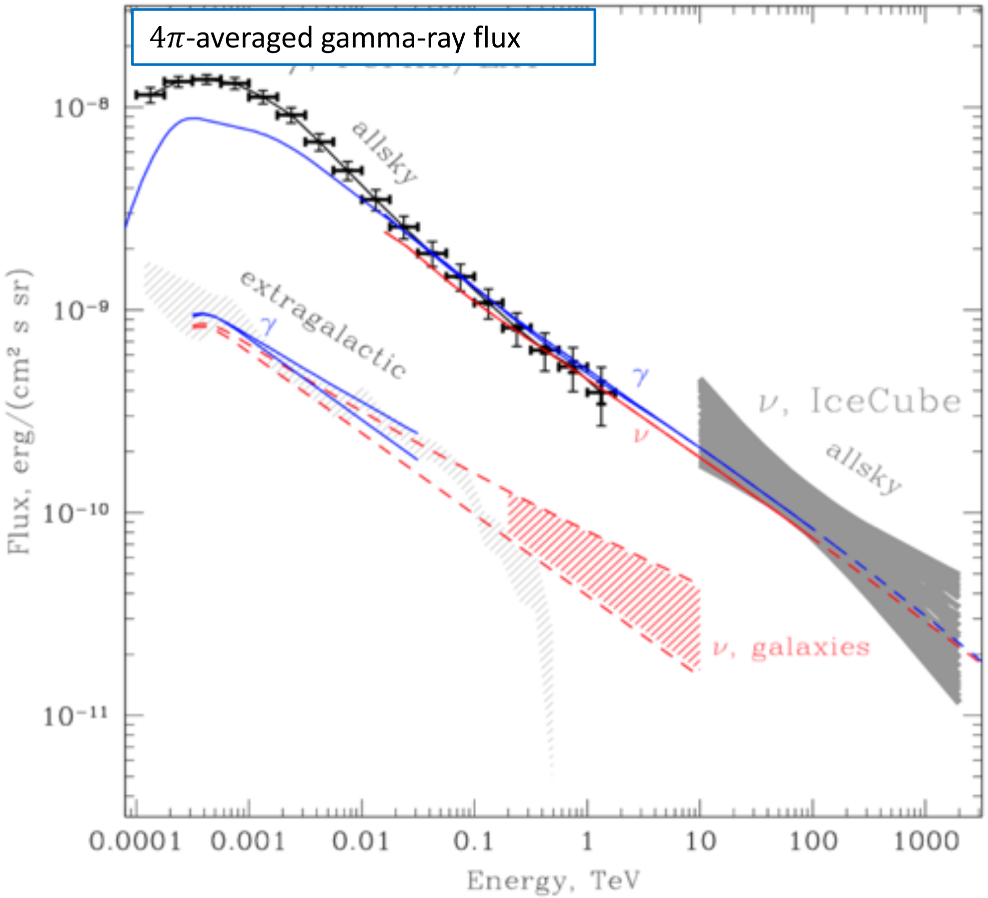
Measurements of gamma-ray flux from proton-proton interactions provide an estimate of neutrino flux from the Milky Way.

Connecting GeV-TeV band measurements with IceCube measurements above 30 TeV



The spectrum of cosmic rays residing in the interstellar medium is a powerlaw. If the slope of the average cosmic ray spectrum all over the Milky Way would be known, a robust estimate of the neutrino flux above 30 TeV would be possible directly from gamma-ray measurements in the GeV-TeV band.

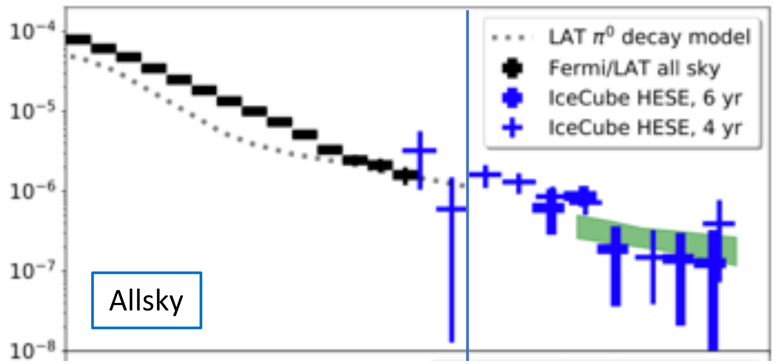
Connecting GeV-TeV band measurements with IceCube measurements above 30 TeV

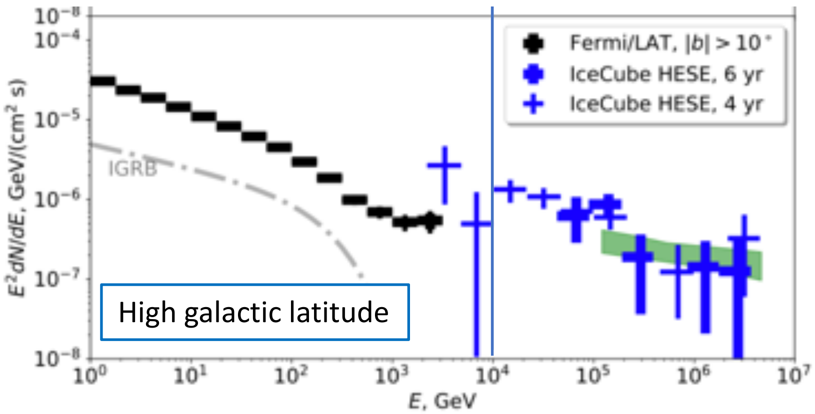


All-sky gamma-ray flux (dominated by diffuse emission from the Milky Way) is consistent with the IceCube neutrino flux.

Neronov, Semikoz, arXiv:1412.1690
Neronov, Kachelriess, Semikoz, 1802.09983

Connecting GeV-TeV band measurements with IceCube measurements above 30 TeV



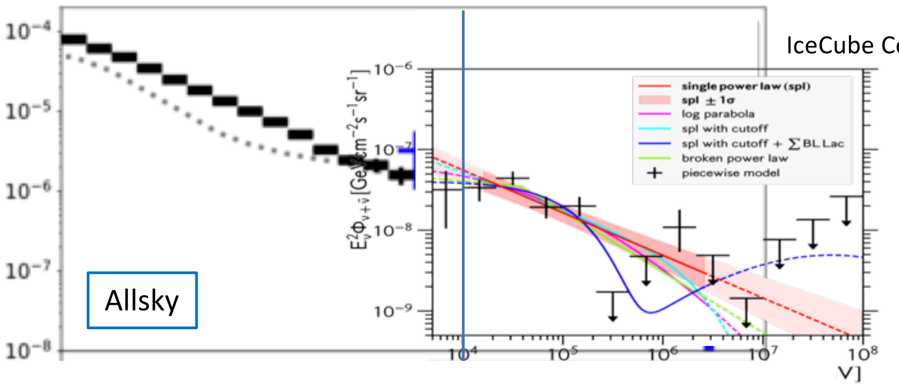


All-sky gamma-ray flux (dominated by diffuse emission from the Milky Way) is consistent with the IceCube neutrino flux.

Assuming that neutrino flux is nearly isotropic, neutrino flux level at high Galactic latitudes exceeds the powerlaw extrapolation of the gamma-ray flux (see the talk of D.Semikoz).

Neronov, Semikoz, arXiv:1412.1690
Neronov, Kachelriess, Semikoz, 1802.09983

Connecting GeV-TeV band measurements with IceCube measurements above 30 TeV



IceCube Collab., arXiv:2001.09520

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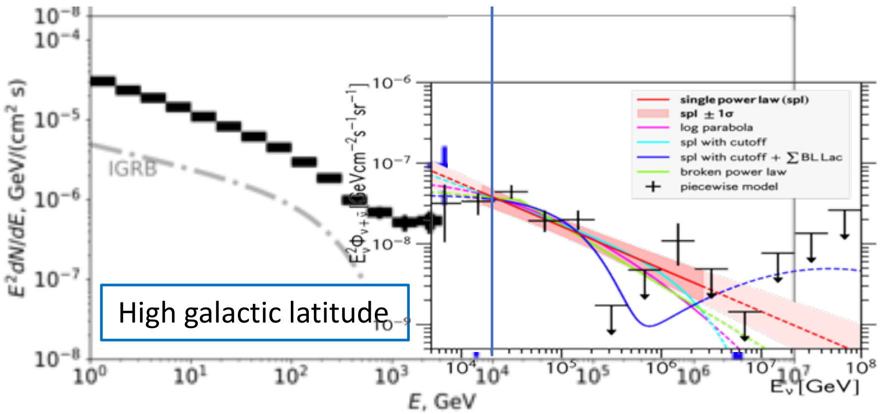
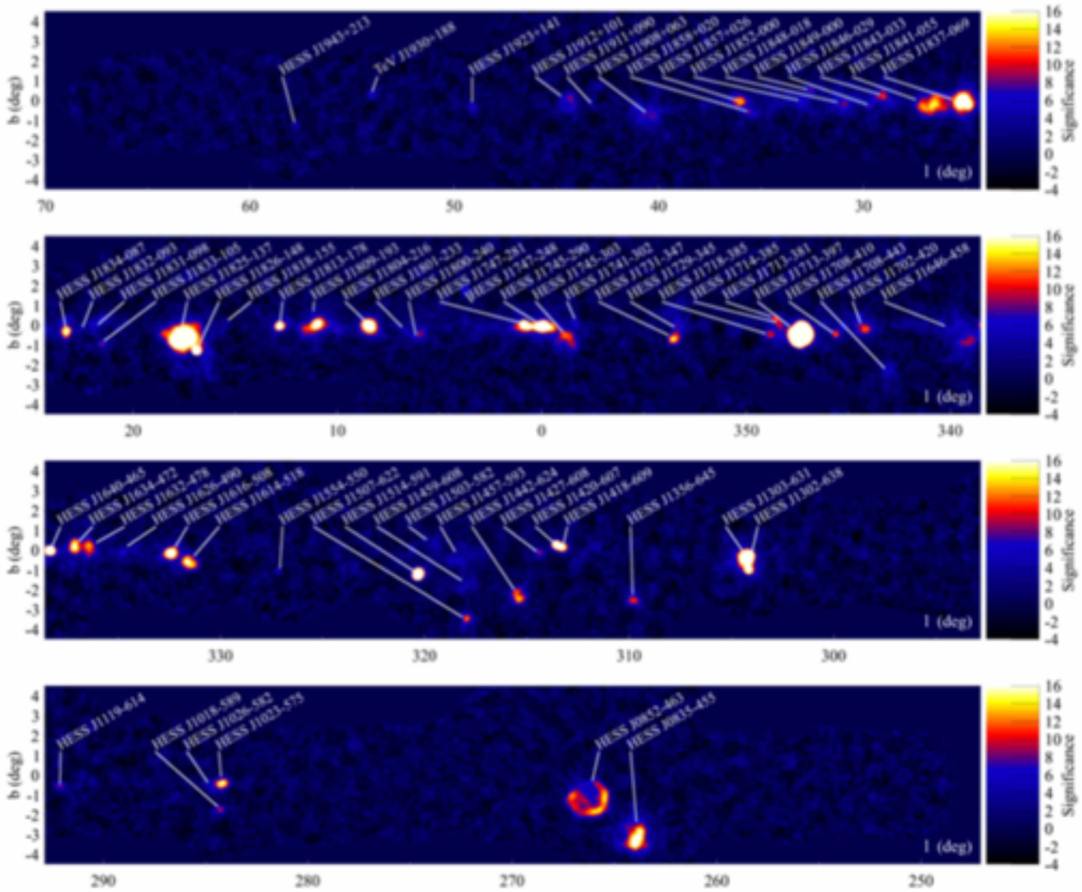


Galactic neutrino and gamma-ray fluxes in the (multi)TeV band consist of:

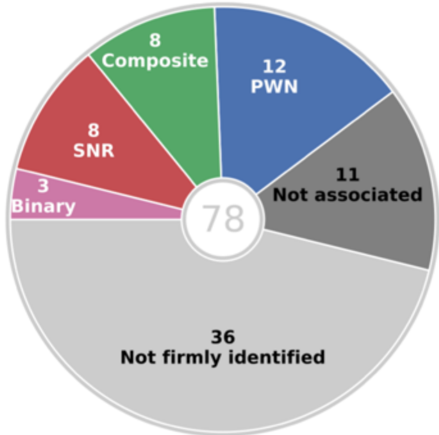
- Isolated sources
- Diffuse emission from cosmic ray interactions in the interstellar medium

Neronov, Semikoz, arXiv:1412.1690
Neronov, Kachelriess, Semikoz, 1802.09983

Neutrinos from isolated multi-TeV gamma-ray sources



HESS Galactic Plane survey

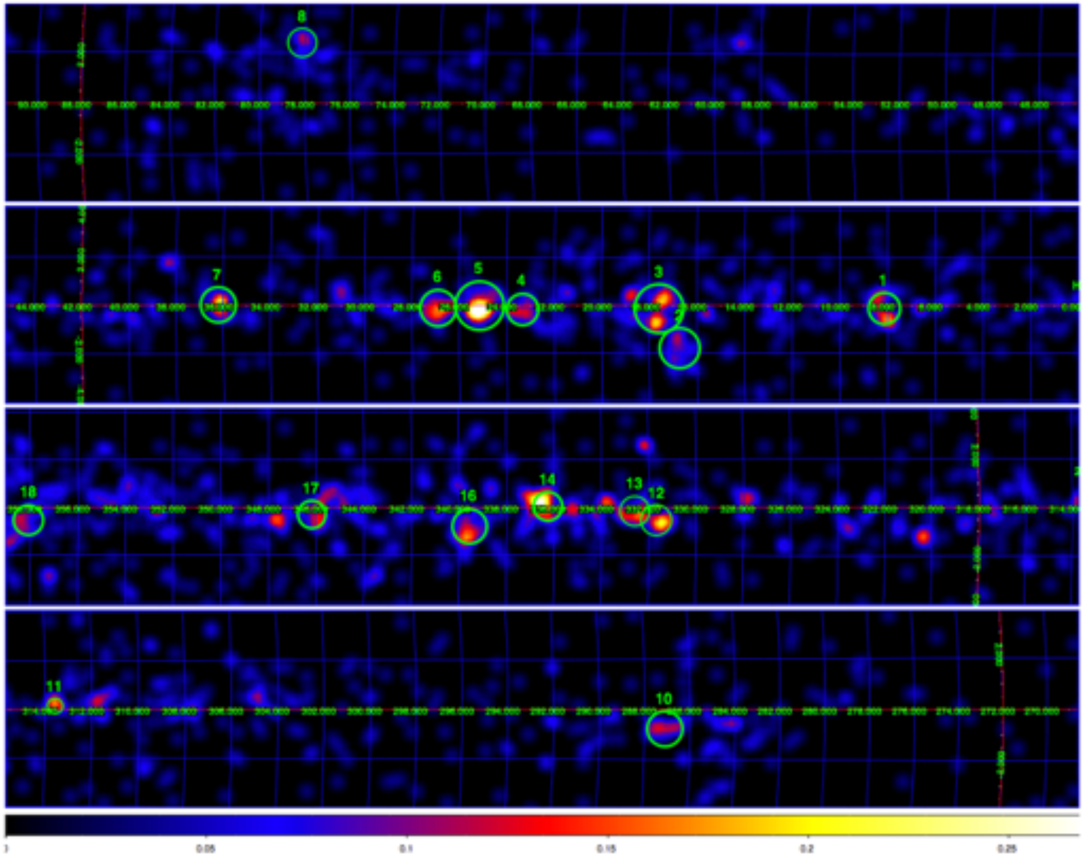


Gamma-ray flux / spectrum measurements for individual Galactic sources could be used for robust estimates of neutrino flux for large part of multi-TeV source populations

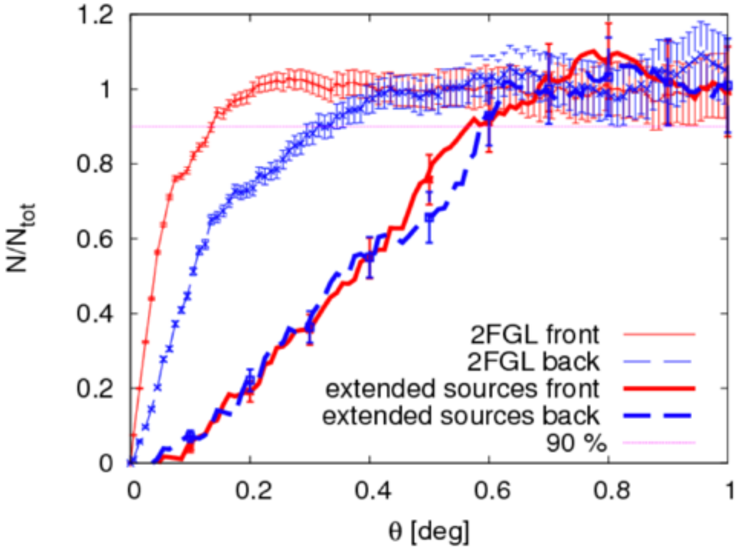
- Cosmic ray interactions with medium inside sources and in the interstellar medium around the sources can be used to study both particle acceleration mechanisms and escape of cosmic rays through the interstellar medium
- Sources are typically transparent to gamma-rays, contrary to extragalactic sources, neutrino sources in Milky Way generically have gamma-ray counterpart in the energy band of neutrino signal.

Aharonian et al., 2005
HESS Collab., 2018

Neutrinos from isolated multi-TeV gamma-ray sources



Fermi/LAT E>100 GeV

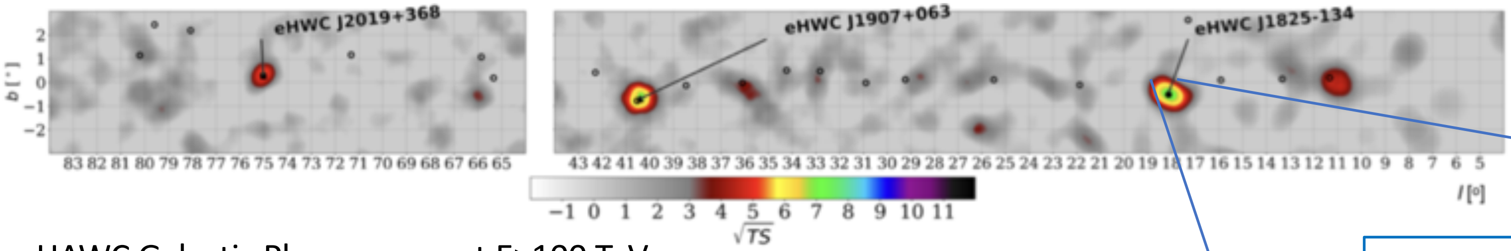


Brightest Very-High-Energy gamma-ray sources in the Galactic Plane are extended.

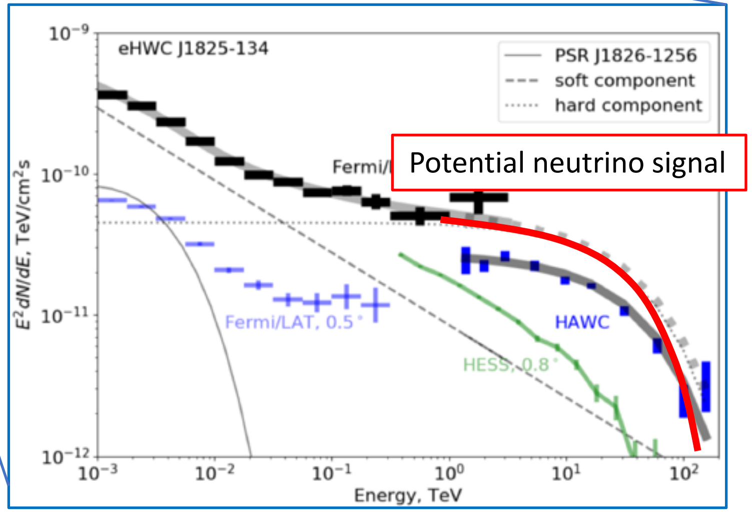
Source extensions trace escape of cosmic rays into interstellar medium. There is no strict boundary between “isolated source” and “diffuse emission” components of the gamma-ray (and neutrino) flux.

Neronov, Semikoz, 1201.1660

Example: possible neutrino signal from eHWC J1825-134 region



HAWC Galactic Plane survey at E>100 TeV



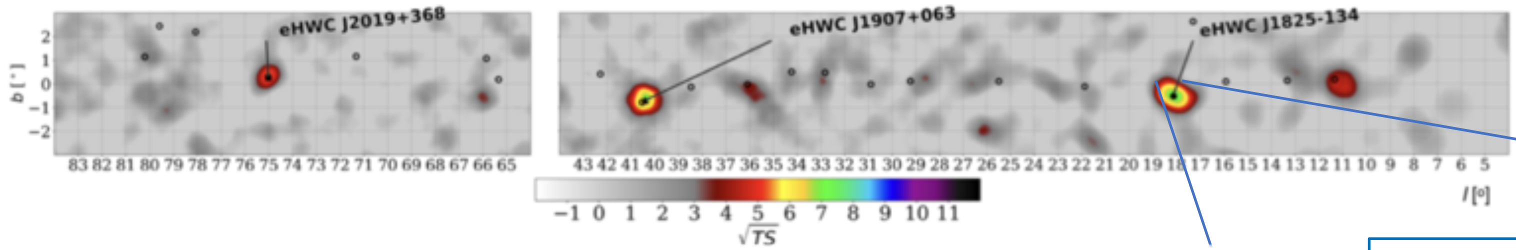
HAWC telescope has reported detections of gamma-ray sources at 100 TeV, i.e. in the energy range overlapping with that of IceCube and Km3NET.

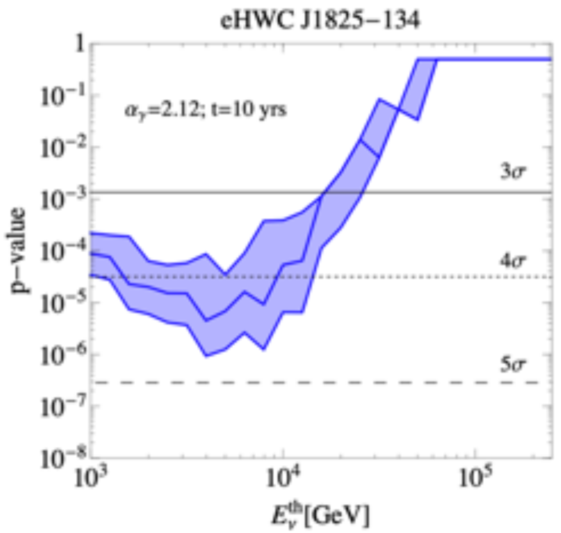
100 TeV gamma-ray emission is most probably of ”hadronic” origin (i.e. accompanied by neutrinos) because the Inverse Compton (on interstellar radiation field) emission is suppressed in the Klein-Nishina regime.

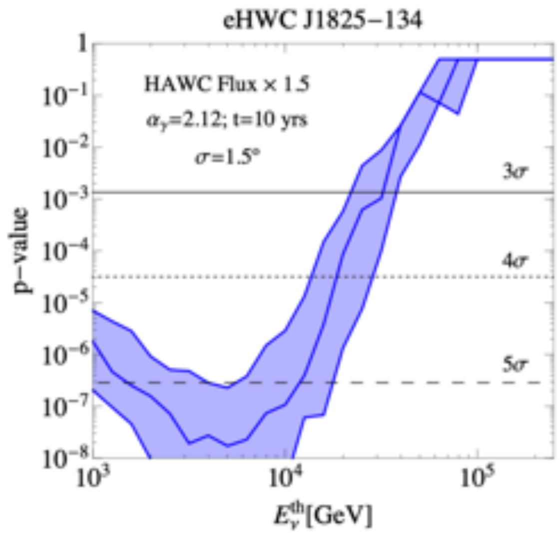
eHWC J1825-134 is the brightest 100 TeV source in HAWC survey.

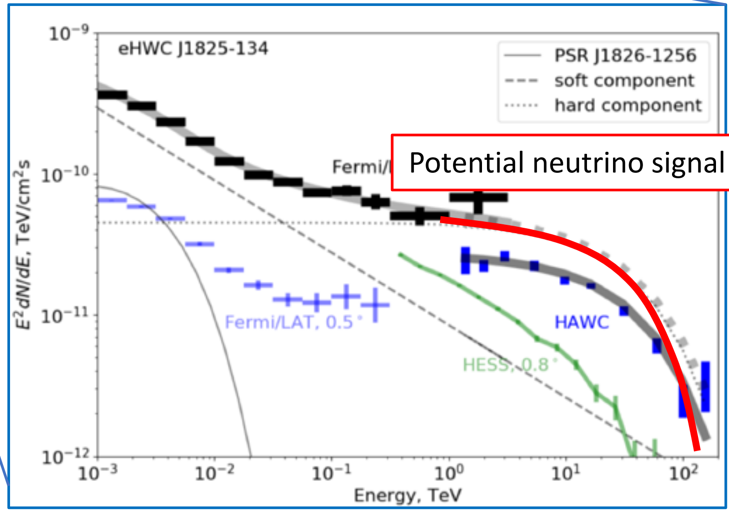
HAWC Collab. arXiv:1909.08609
Niro, Neronov, Fusco, Gabici, Semikoz, arXiv:1910.09065

Example: possible neutrino signal from eHWC J1825-134 region









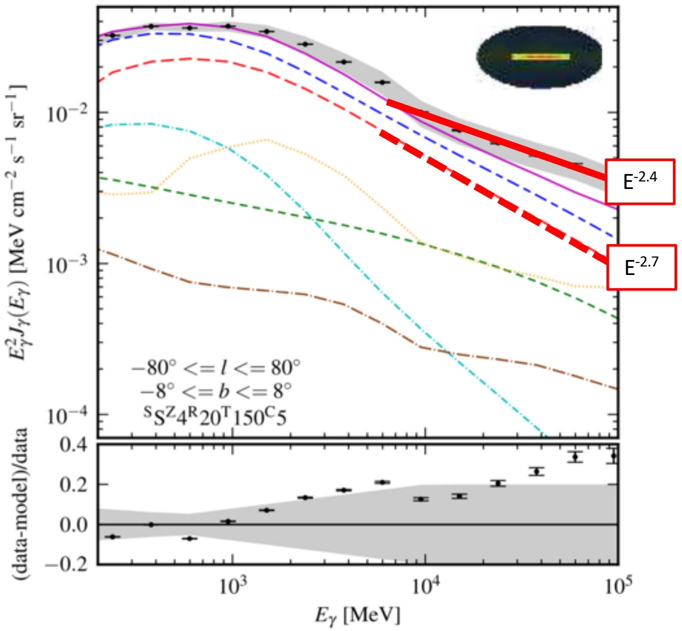
Example modelling and Km3NET signal estimate for the brightest 100 TeV source on the Northern sky. Detection of individual sources is challenging. Discovery threshold could possibly be reached after ~10 year exposure.

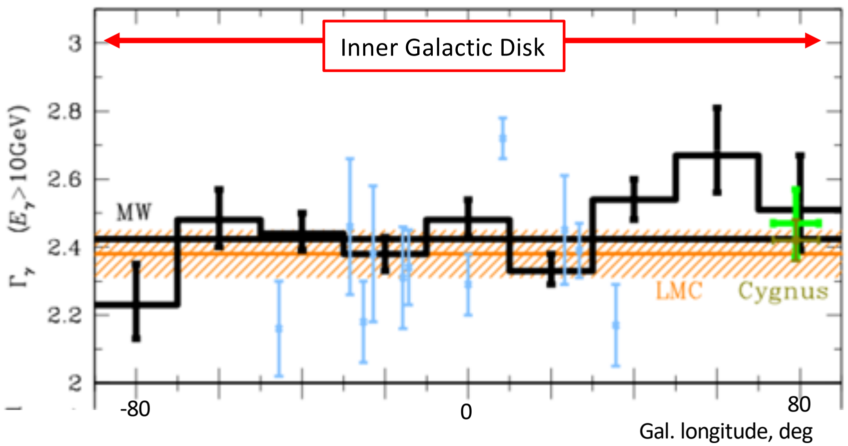
LHAASO can / should be used to facilitate neutrino source detections, providing spatial and spectral templates for neutrino analysis in the 100 TeV energy range, where neutrino telescopes are most sensitive. LHAASO has higher sensitivity in this energy range, because of the larger collection area and comparable background rejection capability. i

HAWC Collab. arXiv:1909.08609
Niro, Neronov, Fusco, Gabici, Semikoz, arXiv:1910.09065

Diffuse neutrino flux

Fermi LAT Collab. '12

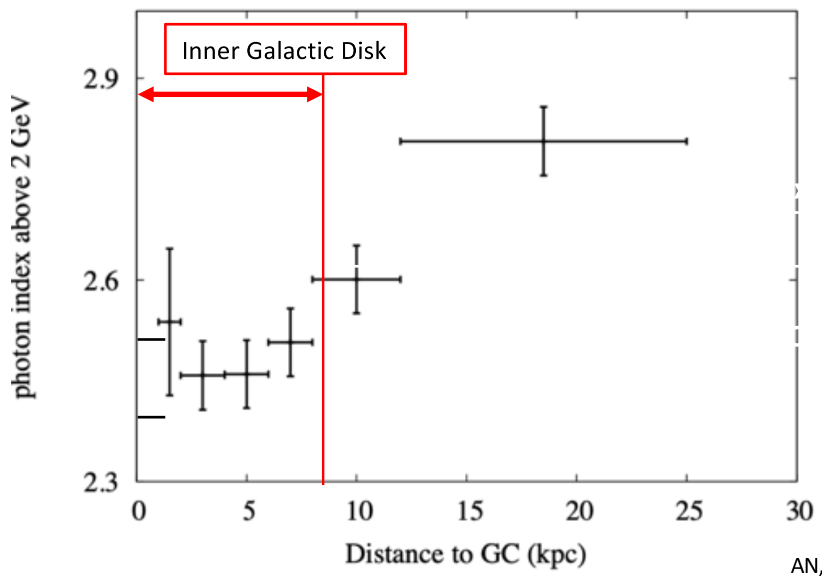




Fermi/LAT gamma-ray data suggest that average cosmic ray spectrum in the Galactic Disk is different from the locally measured one. Average spectrum of cosmic rays residing in the inner Galactic Disk (within the distance of the Sun) has the slope $\frac{dN}{dE} \propto E^{-\Gamma}$, $\Gamma = 2.4$, rather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

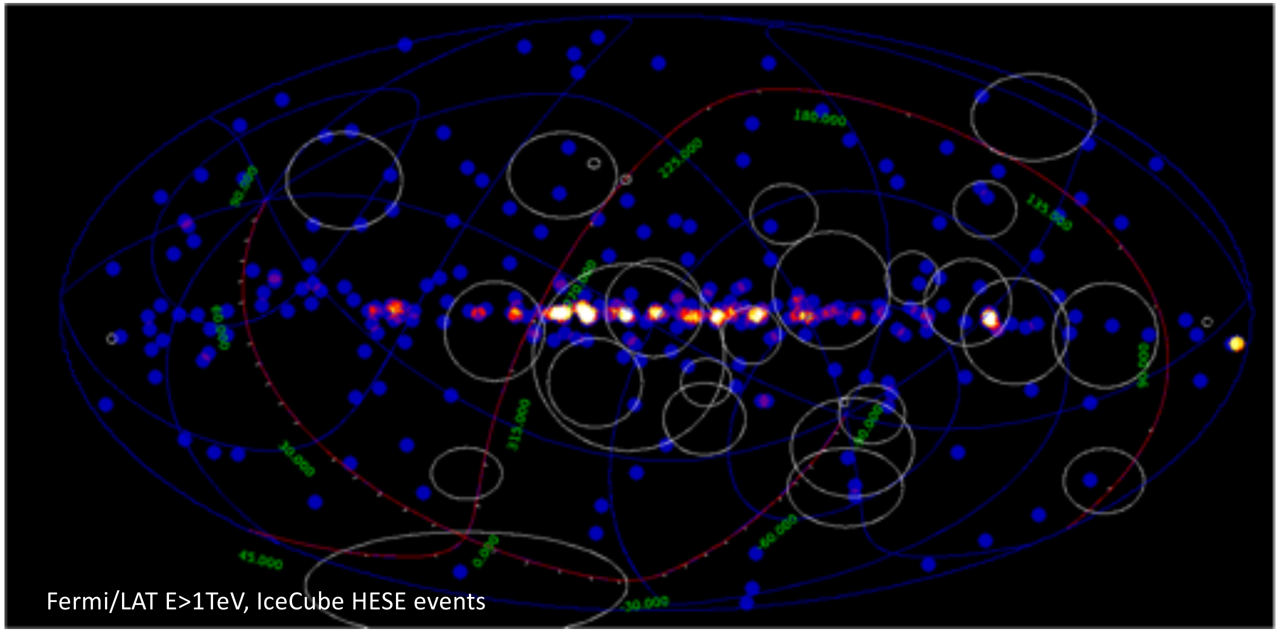
Similar slope is found for cosmic rays residing in the Large Magellanic Cloud.

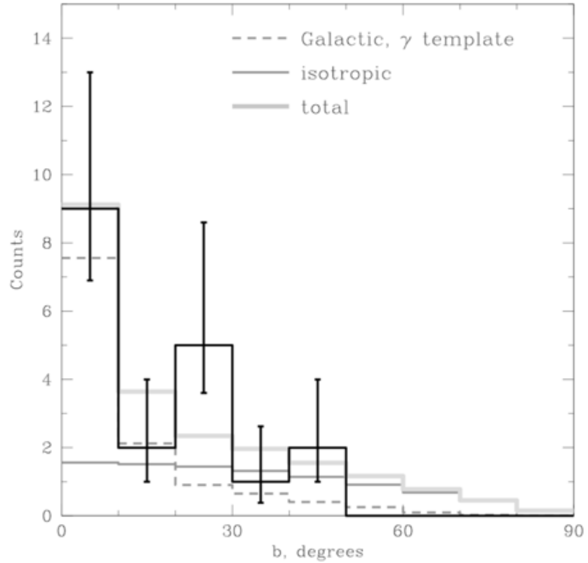
This slope is consistent with that of the astrophysical neutrino spectrum.

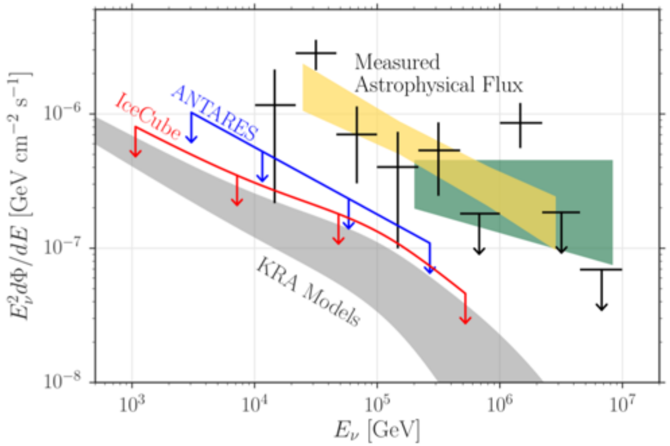


AN, Malyshev, arXiv: 1505.07601
Fermi LAT Collab. arXiv: 1602.07246
Yang, Aharonian, Evoli, 1602.04710

Diffuse Galactic neutrino flux (?)





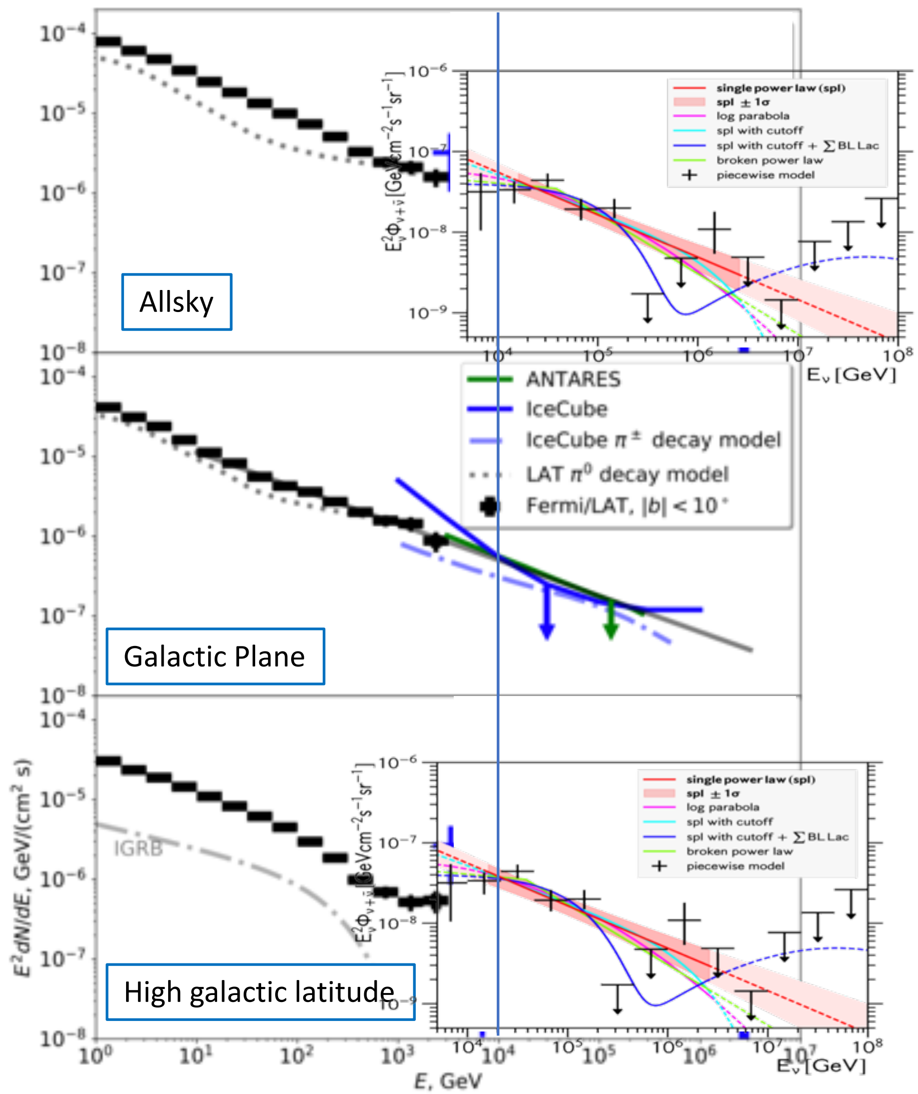


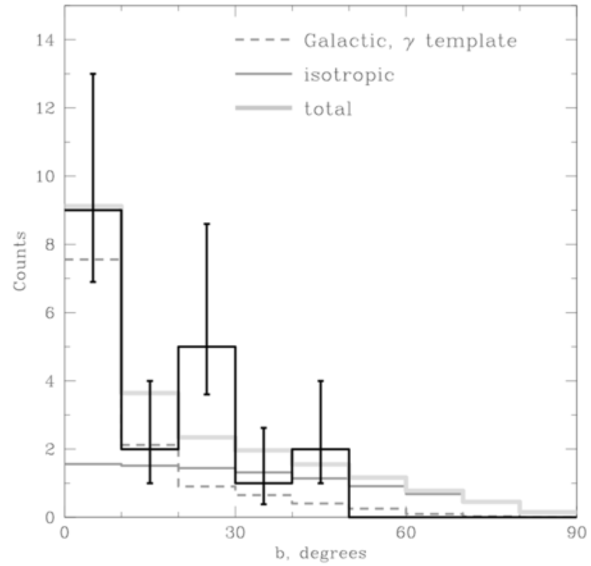
Mild evidence for anisotropy of neutrino signal: (at 3σ significance post-trial in 5 year HESE event set).

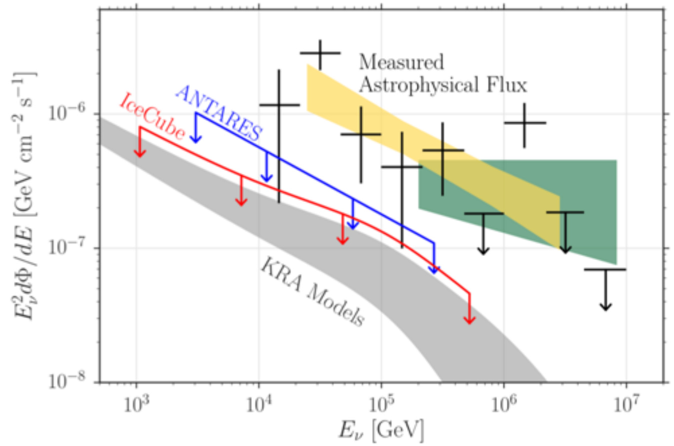
Fit of KRAγ model of Galactic pion decay emission from the Galactic Plane (a specific spectral-imaging template of diffuse emission) to IceCube data shows an excess at 2.3σ level in IceCube cascade event analysis of 2019).

IceCube Collab. 2017, 2018, 2019 ANTARES Collab. 2017, 2018
IceCube Collab. arXiv:1907.06714.
Neronov, Semikoz, arXiv:1509.03522, arXiv:1603.06733

Diffuse Galactic gamma-ray and neutrino flux (?)

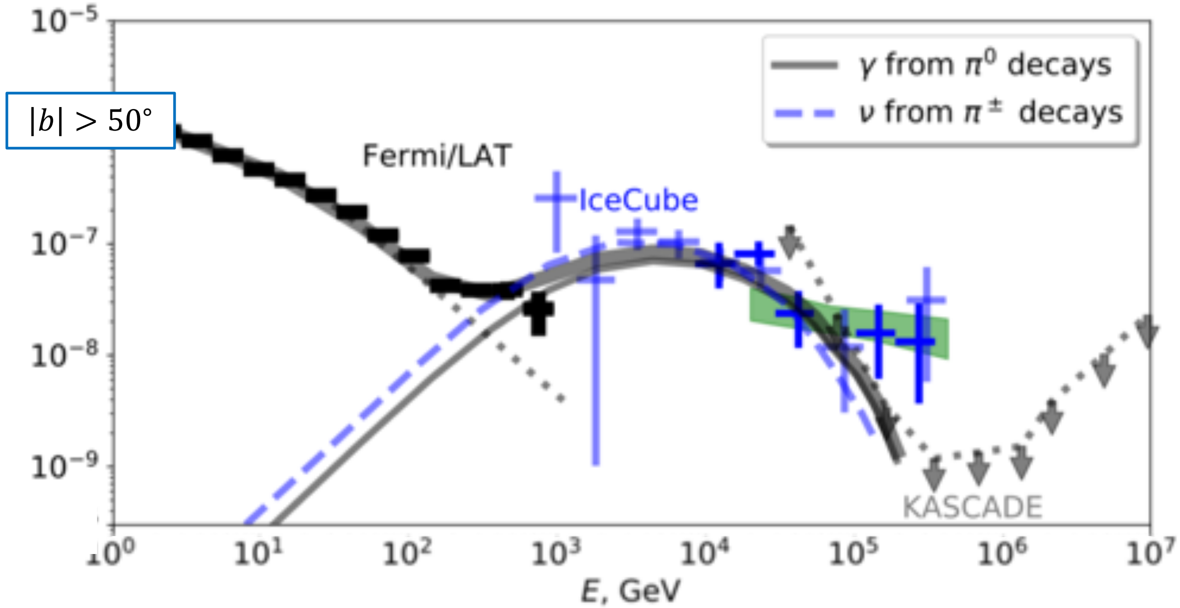






IceCube Collab. 2017, 2018, 2019 ANTARES Collab. 2017, 2018
Neronov, Semikoz, arXiv:1509.03522

Possible influence of individual nearby recent sources



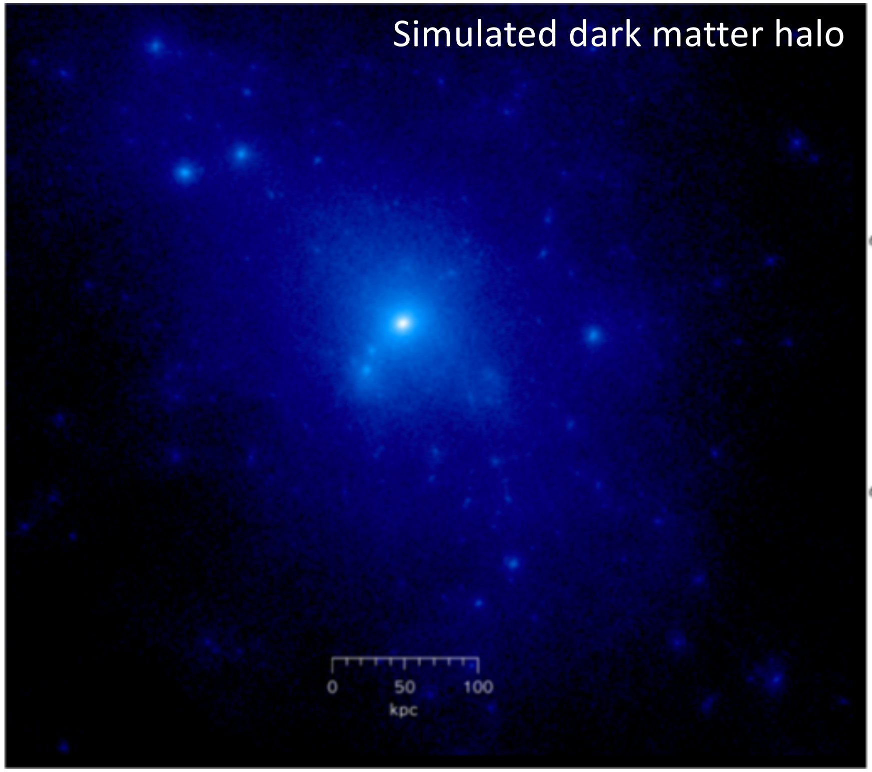
Diffuse emission from cosmic rays injected by nearby source.

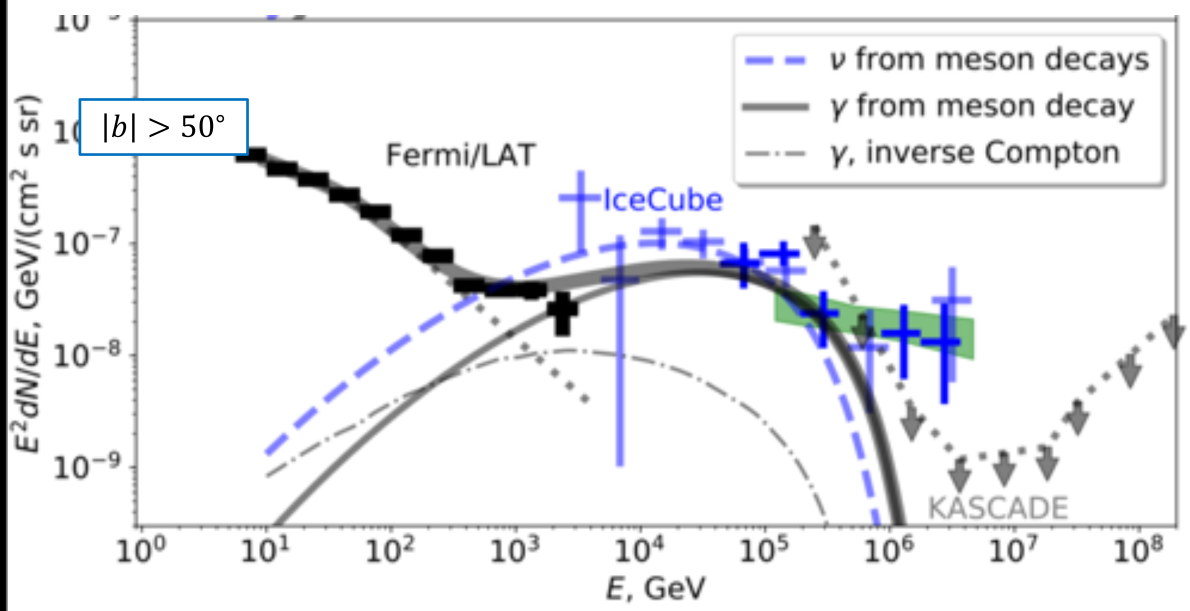
Cosmic rays with total energy $\mathbf{10^{50}}$ **erg** which have escaped nearby recent (within the escape time of PeV particles) source loose energy into neutrino and gamma-rays on time scale $t_{pp}\sim 10^8\ (n_{ISM}/0.5\ \mathrm{cm}^{-3})$ yr.
This might result in very extended emission with a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

Dark matter decay flux?

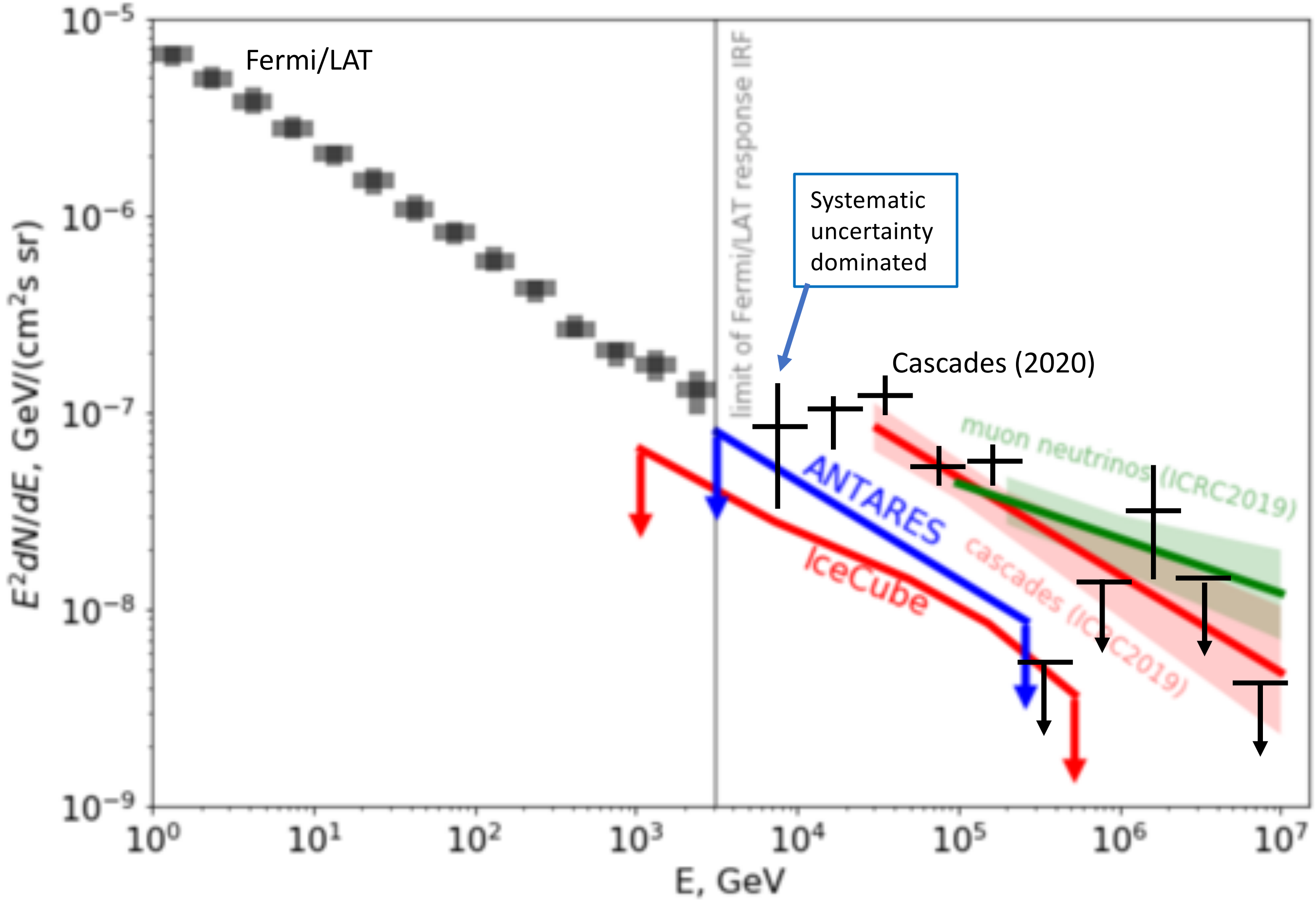




Diffuse emission from decays of heavy dark matter particles with lifetime $\sim 10^{28}$ s into pions or directly into neutrinos and gamma-rays could provide the required multi-messenger flux at high Galactic latitude.

Neronov, Semikoz, Kachelriess 2018

How to close the gap between neutrino and gamma-ray measurements?



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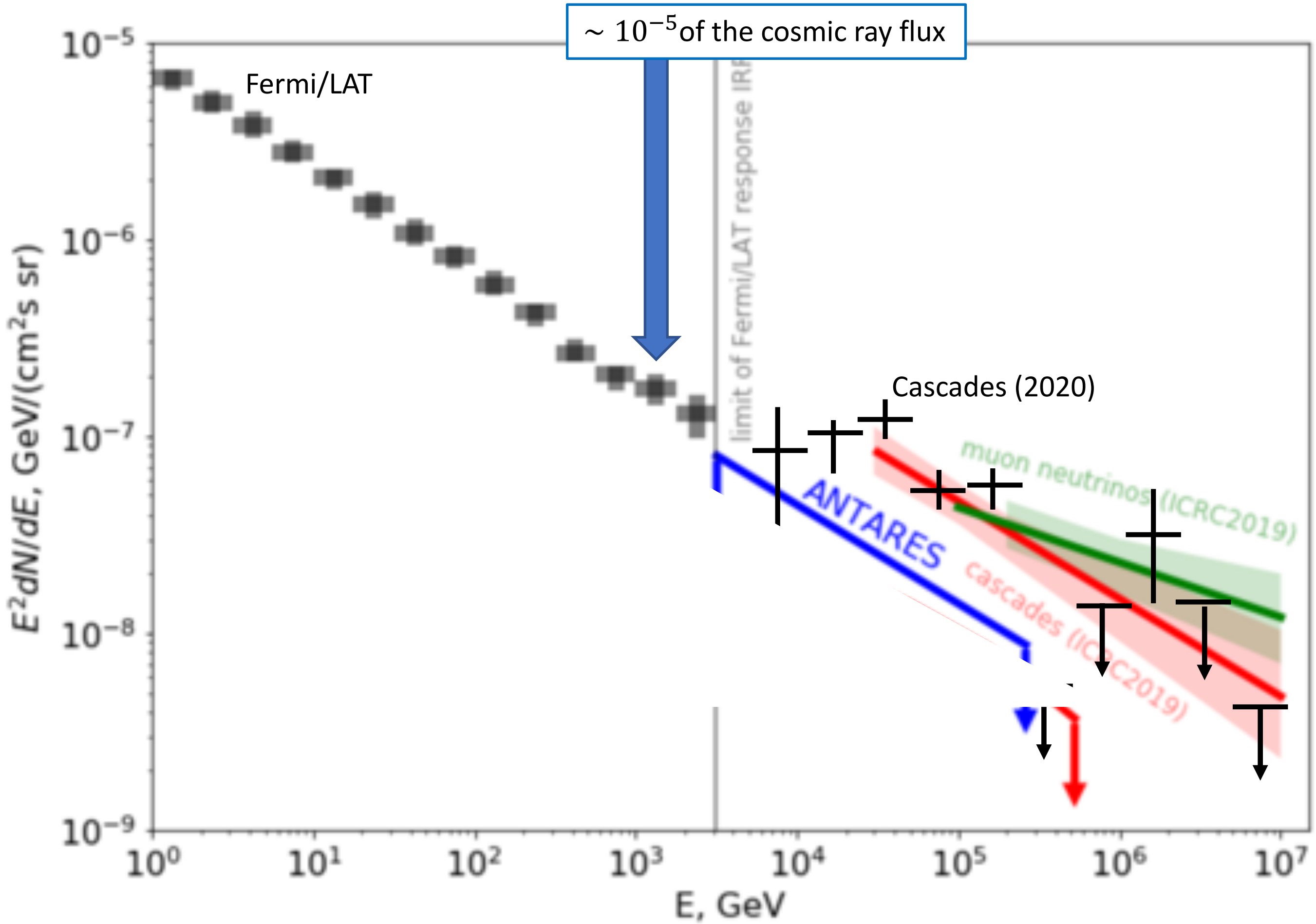

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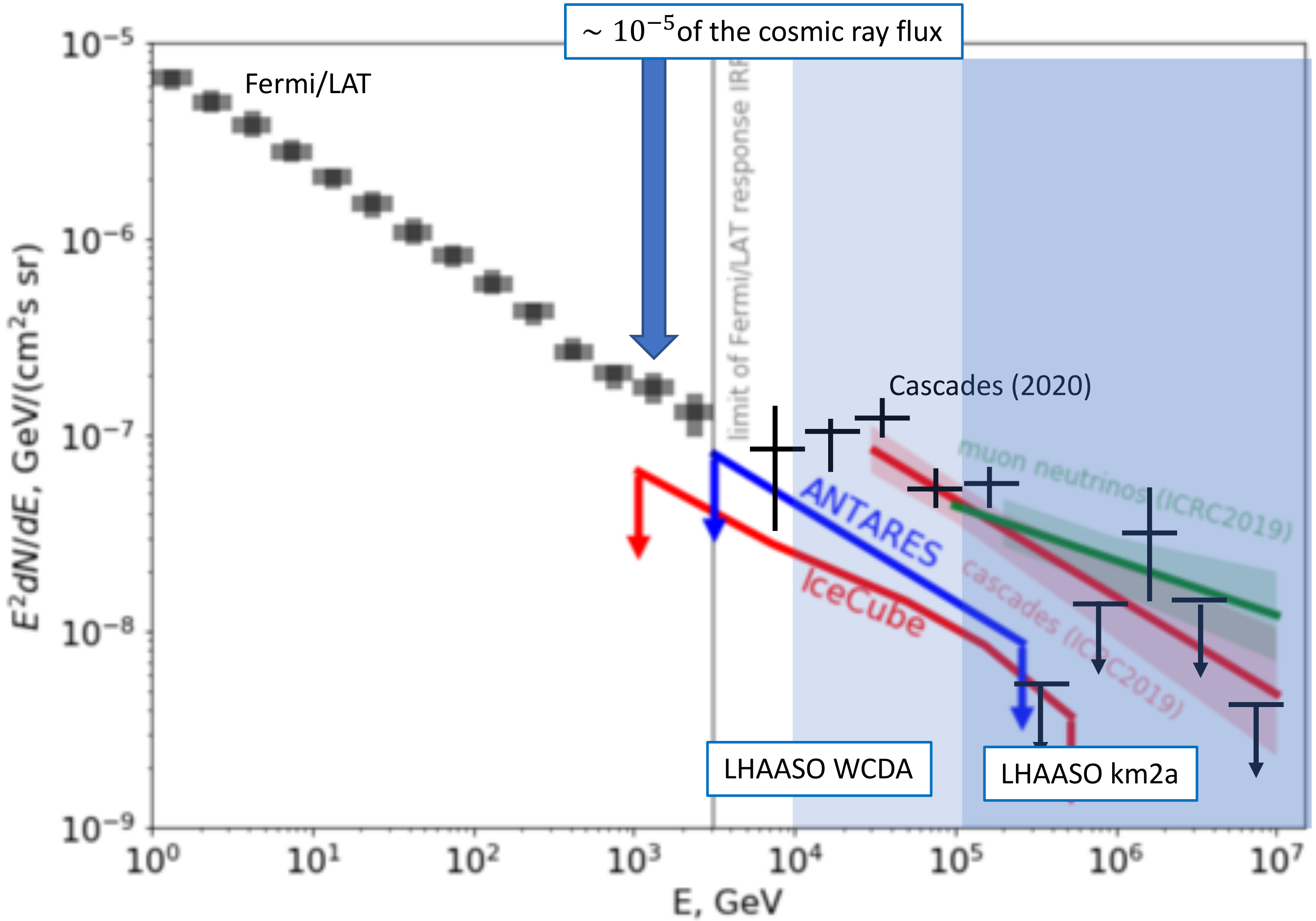

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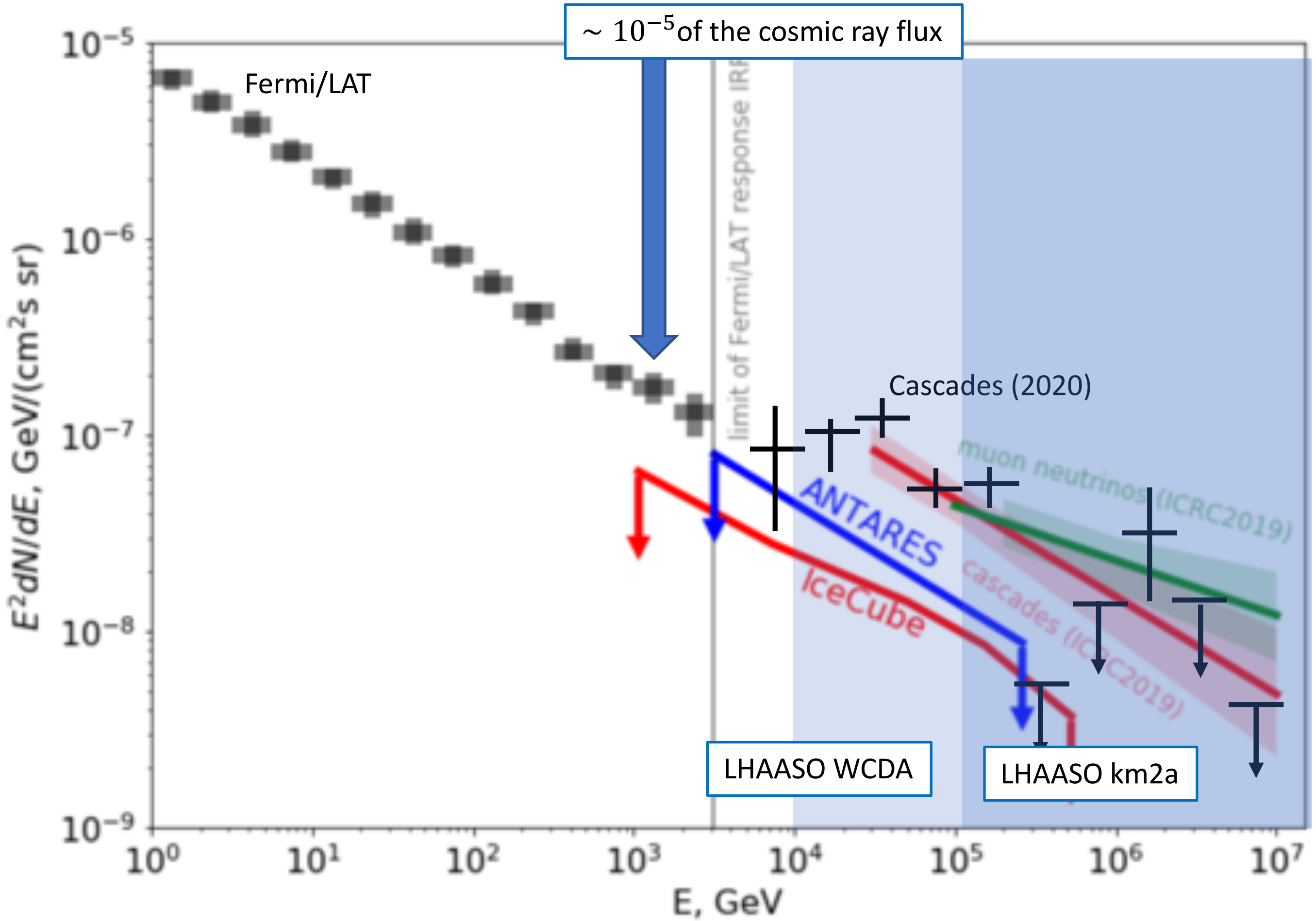

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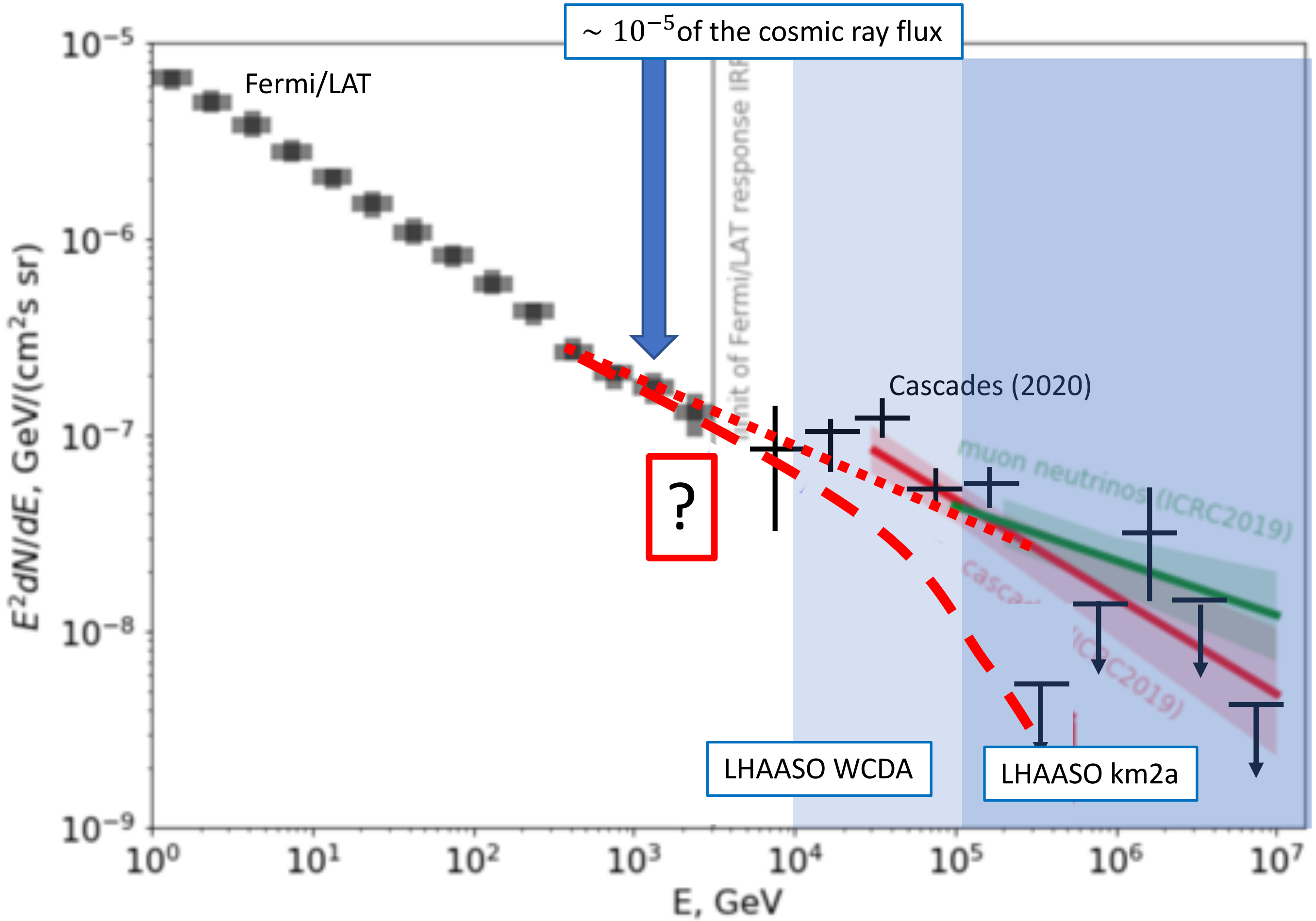

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