Interpretation of the astrophysical neutrino signal

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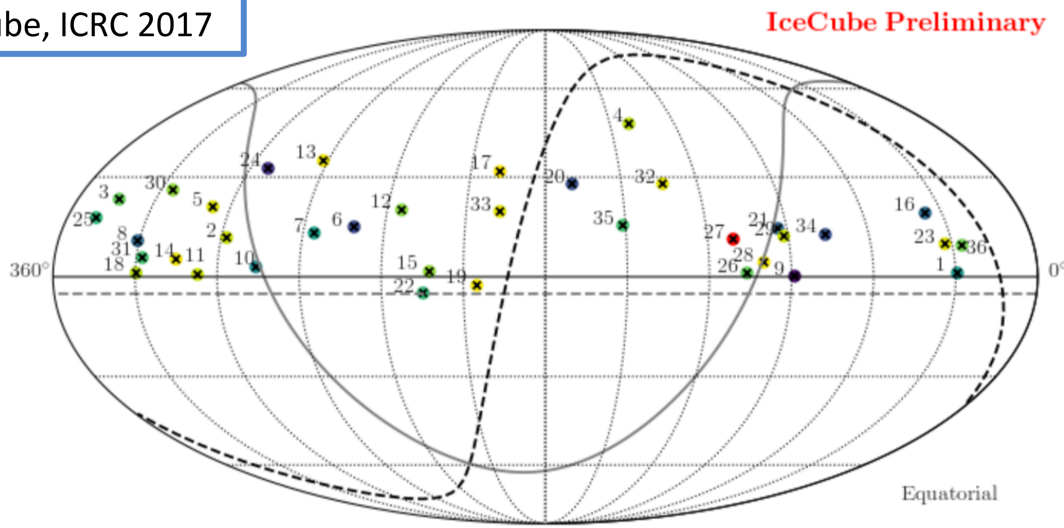
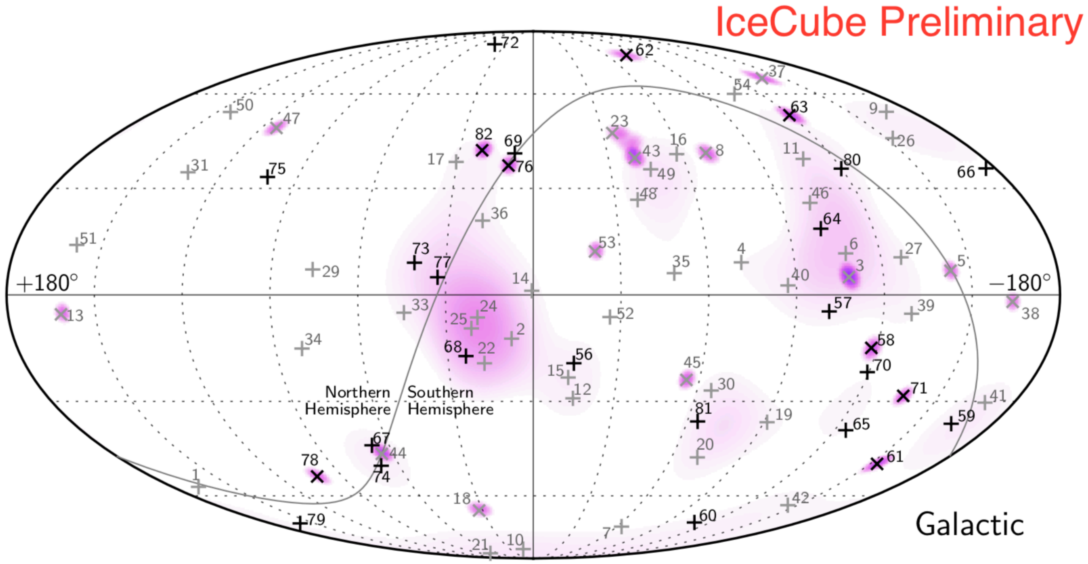
Astrophysical neutrino signal

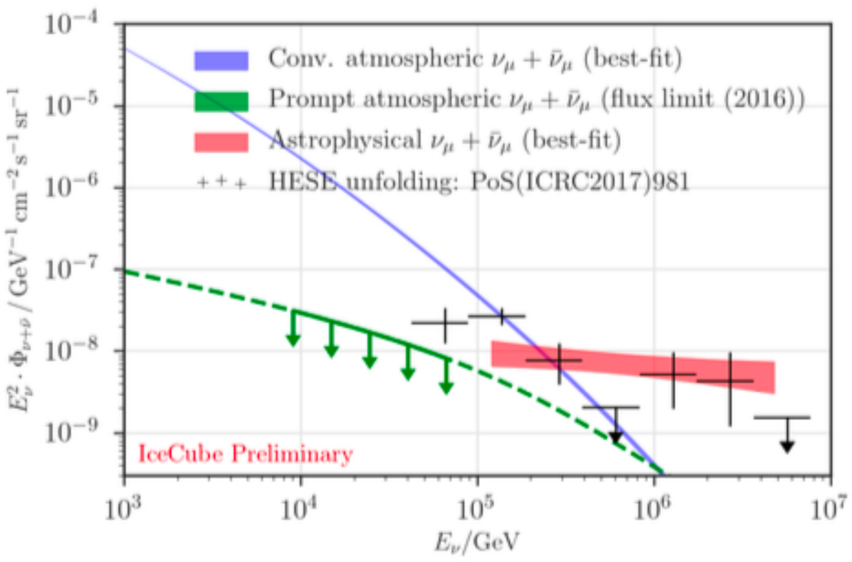
IceCube, ICRC 2017

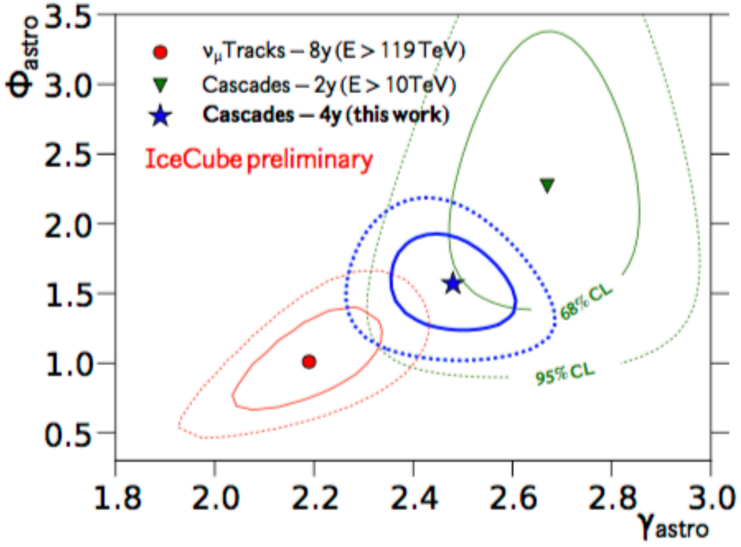


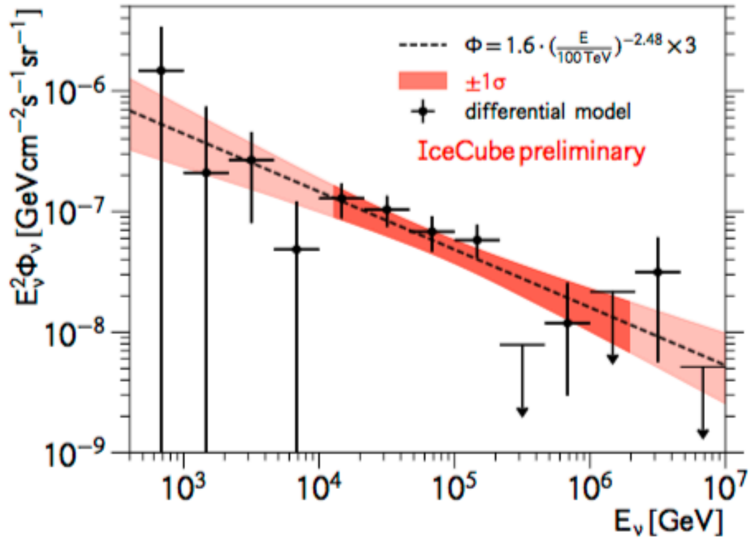


Muon neutrino sample

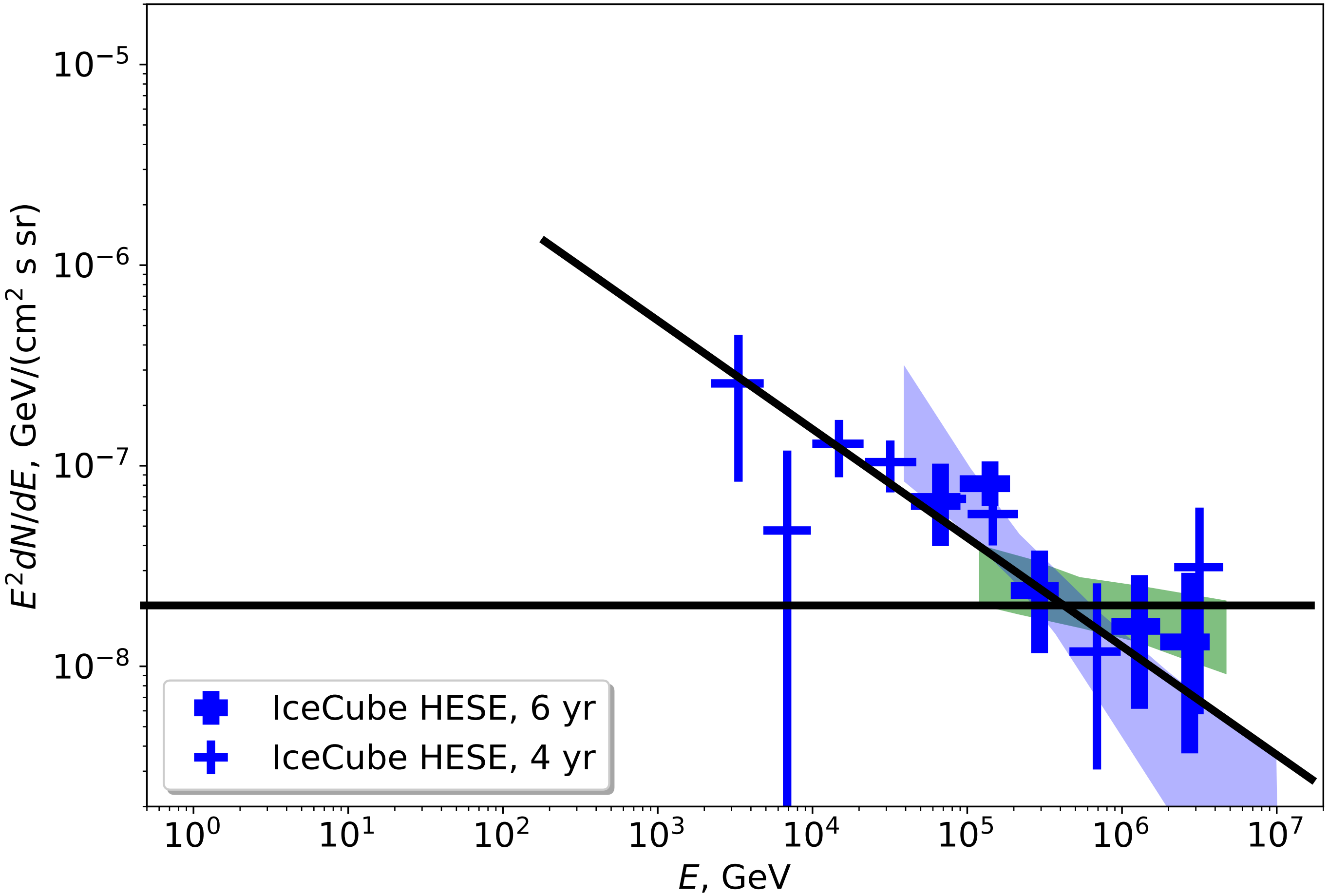
High Energy Starting Event neutrino sample







Astrophysical neutrino signal



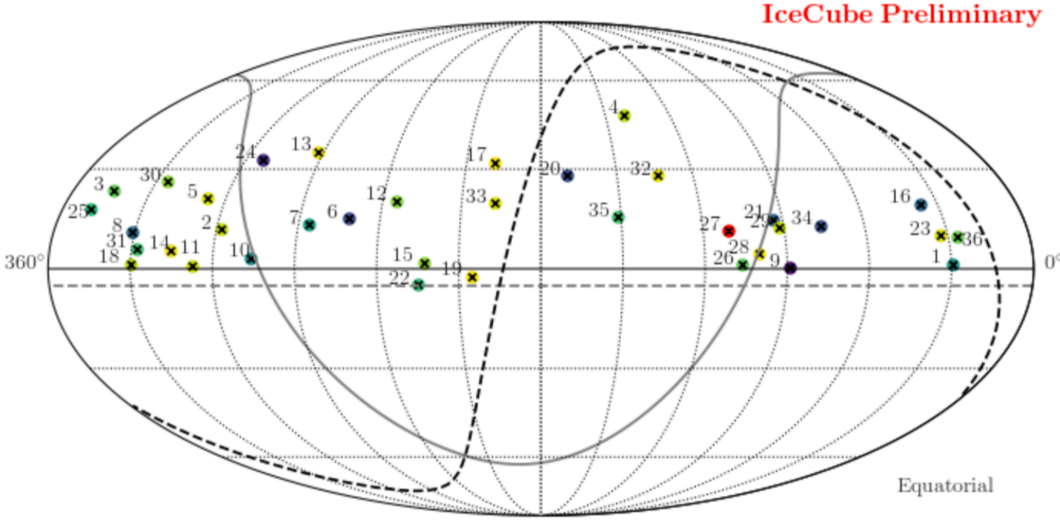
Extragalactic?

Galactic?

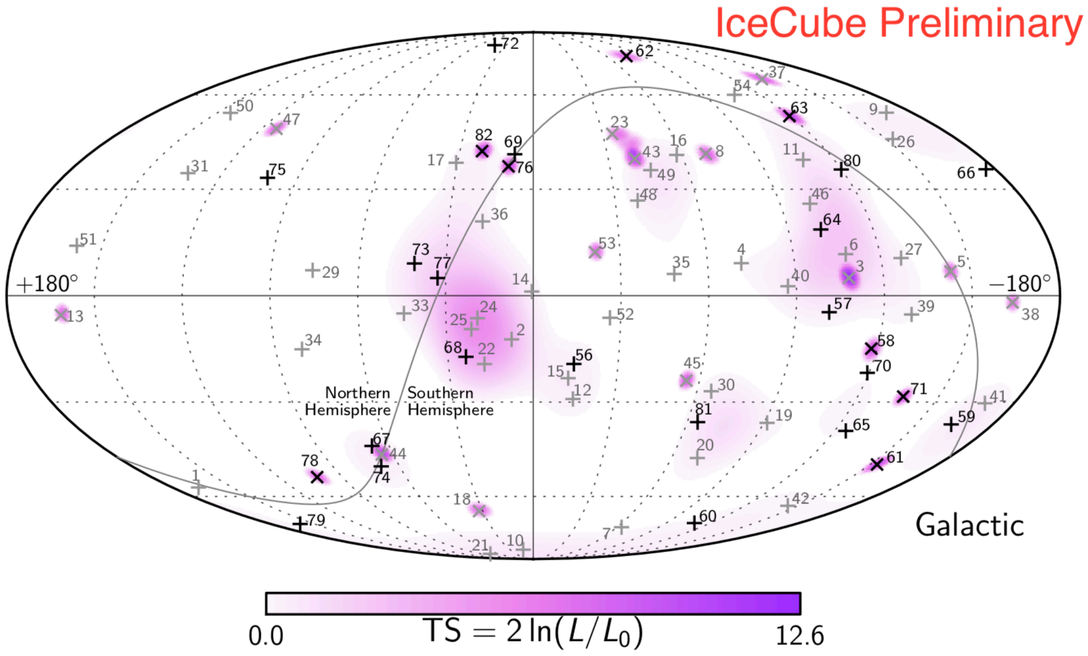
The astrophysical neutrino signal is distributed all over the sky (consistent with being isotropic)

Its spectral properties are marginally inconsistent with a single powerlaw. The spectrum might be hardening above several 100 TeV.

Astrophysical neutrino sources

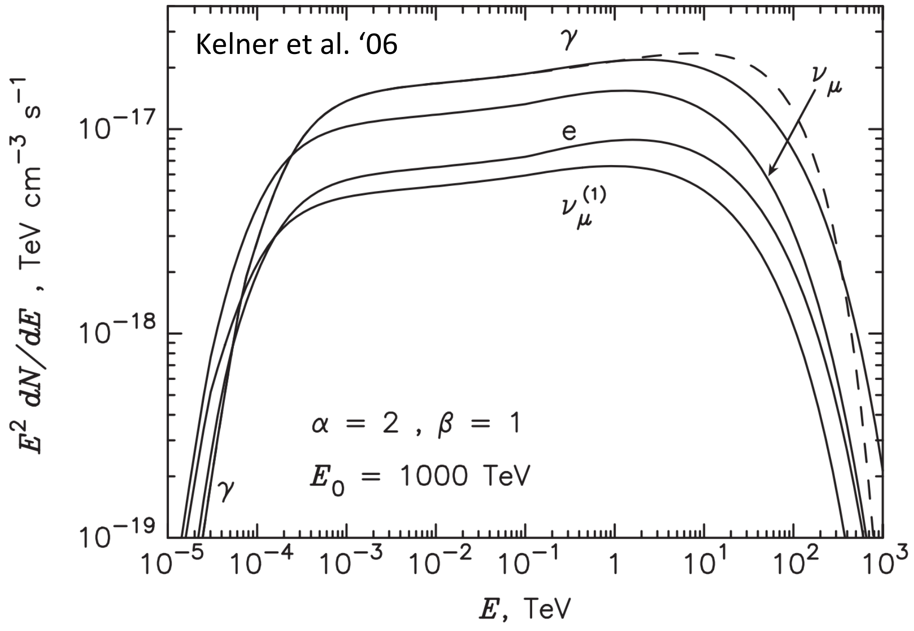


Statistics of both muon neutrino sample is not sufficient for the search of isolated astronomical sources as event clusters within point spread function.



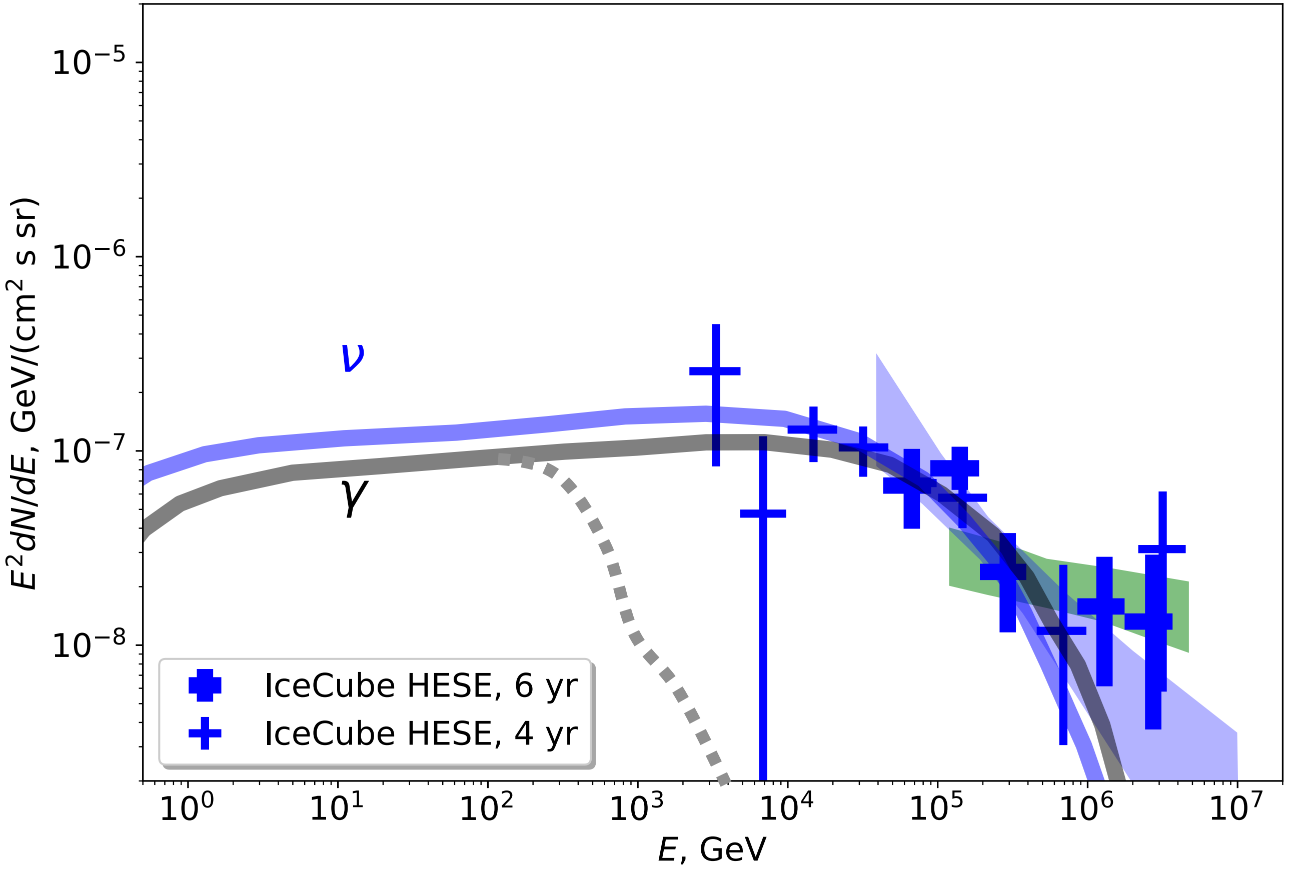
Angular resolution and statistics of HESE neutrino sample is not sufficient for the search of isolated astronomical sources as event clusters within point spread function.

Multi-messenger signal from neutrino sources



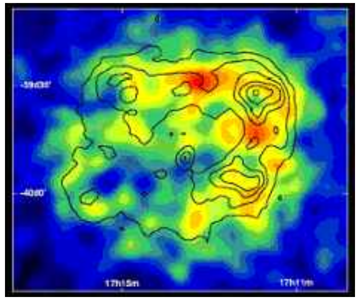
Neutrino sources could be identified based on their "multi-messenger" gamma-ray counterparts.

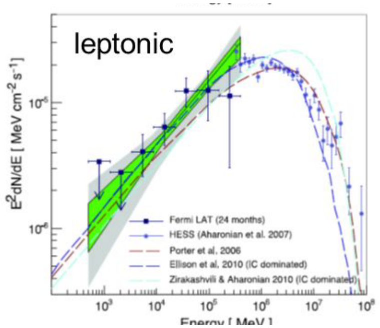
Gamma-ray flux from extragalactic sources is suppressed in the TeV-PeV range due to the pair production on Extragalactic Backgorund Light (EBL).

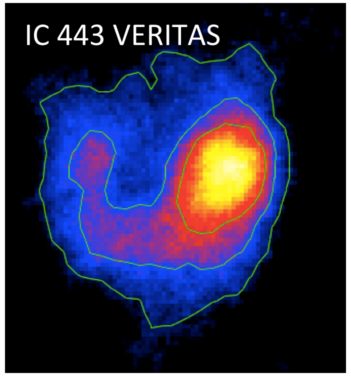


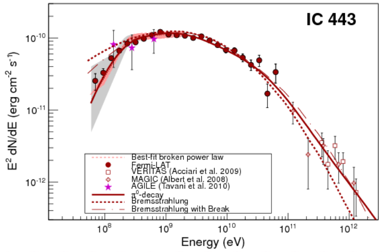
Galactic vs. extragalactic origin of the neutrino signal could be established based on the presence / absence of the gamma-ray counterpart.

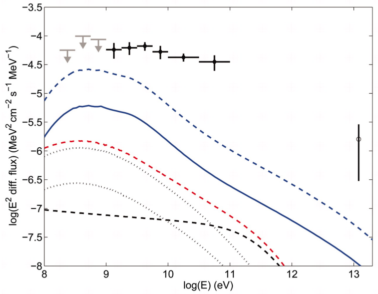
Galactic neutrino source candidates

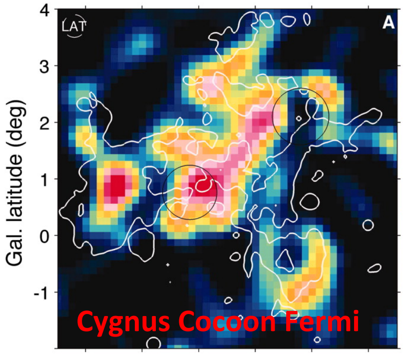


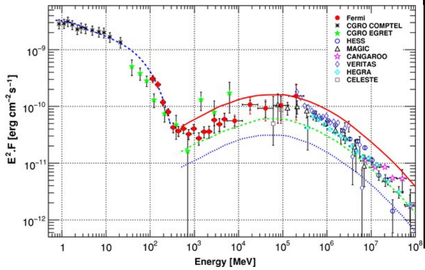


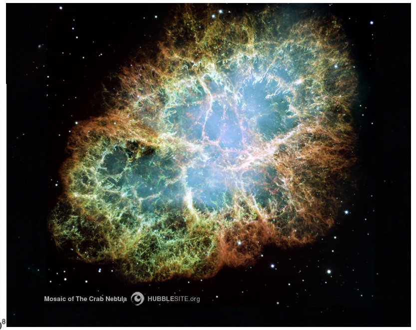












Individual supernova remnants, pulsar wind nebulae and star forming regions are all visible in gamma-ray telescopes.

Gamma-ray emission might be produced either as inverse Compton emission from high-energy electrons (no neutrino counterpart) or via pion decays (with neutrino counterpart).

Supernova explosions are expected to result in injection of 10^{50} **erg** per event into cosmic rays, with the spectrum close to $dN/dE \sim E^{-2}$

Cosmic rays release energy into neutrino and gamma-rays on time scale $t_{pp} \sim 10^8\ (n_{ISM}/0.5\ \mathrm{cm}^{-3})$ yr. This results in luminosity

$$L \sim 10^{50}\ \mathrm{erg}\ /\ 10^8\ \mathrm{yr} \sim 3\times10^{34}\ (n_{ISM}/0.5\ \mathrm{cm}^{-3})\ \mathrm{erg/s}$$

per source.

A source at the distance 1.5 kpc would produce flux

$$F \sim 10^{-10}\ (n_{ISM}/0.5\ \mathrm{cm}^{-3})\ (d/1.5\ \mathrm{kpc})^{-2}\ \mathrm{erg/(cm^2\ s)}$$

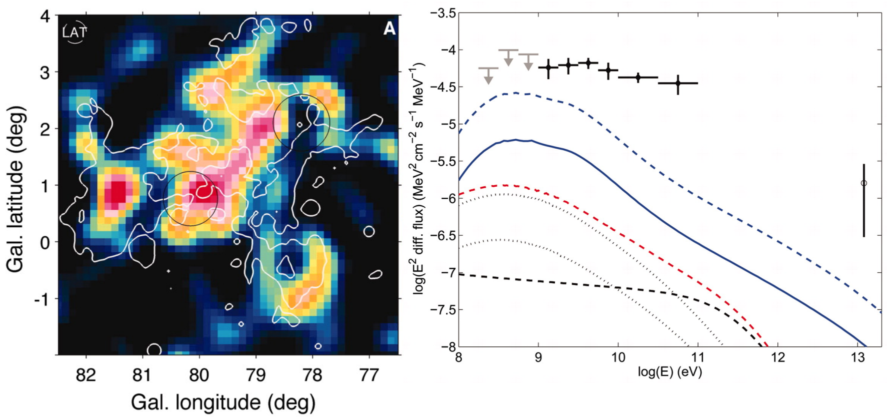
The signal is divided between gamma-rays and neutrinos and spread over several decades in energy, so that the flux per decade is

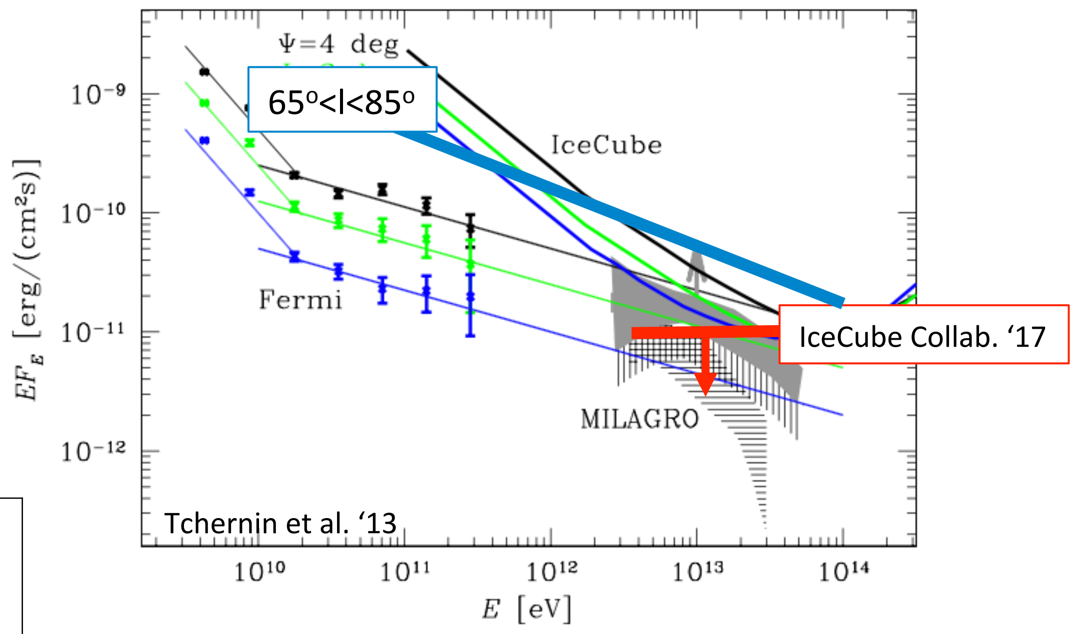
$$F \sim 10^{-11}\ (n_{ISM}/0.5\ \mathrm{cm}^{-3})\ (d/1.5\ \mathrm{kpc})^{-2}\ \mathrm{erg/(cm^2\ s)}$$

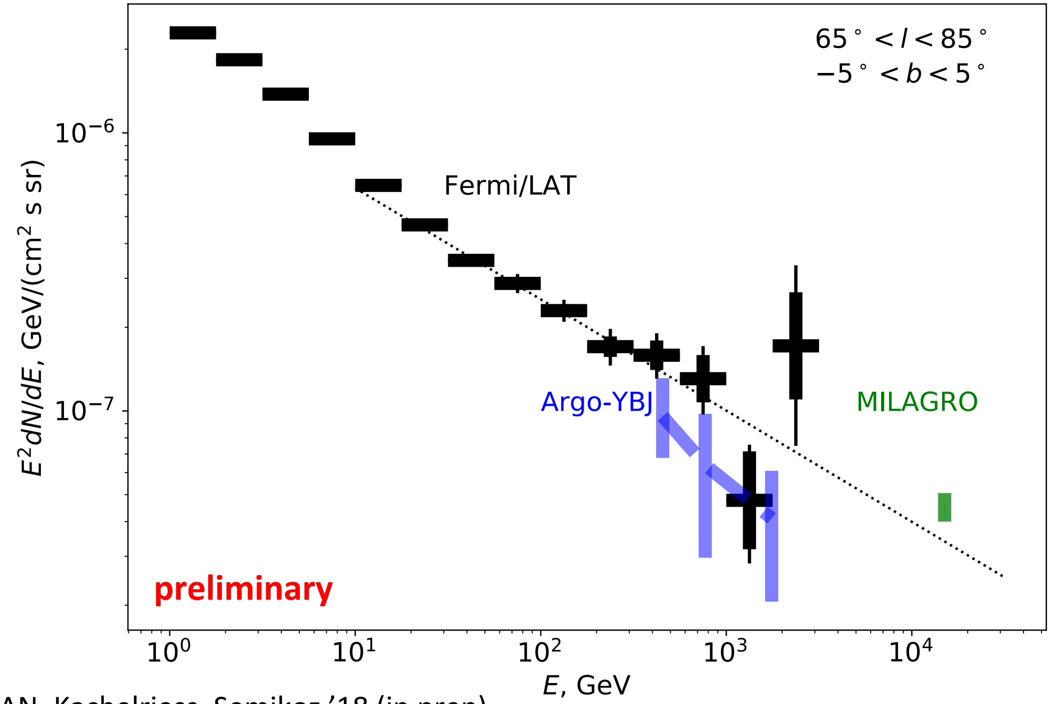
$$\sim 10^{-8} (n_{ISM}/0.5\ \mathrm{cm}^{-3})\ (d/1.5\ \mathrm{kpc})^{-2}\ \mathrm{GeV/(cm^2\ s)}$$

Galactic neutrino source candidates

Fermi LAT Colab. '11





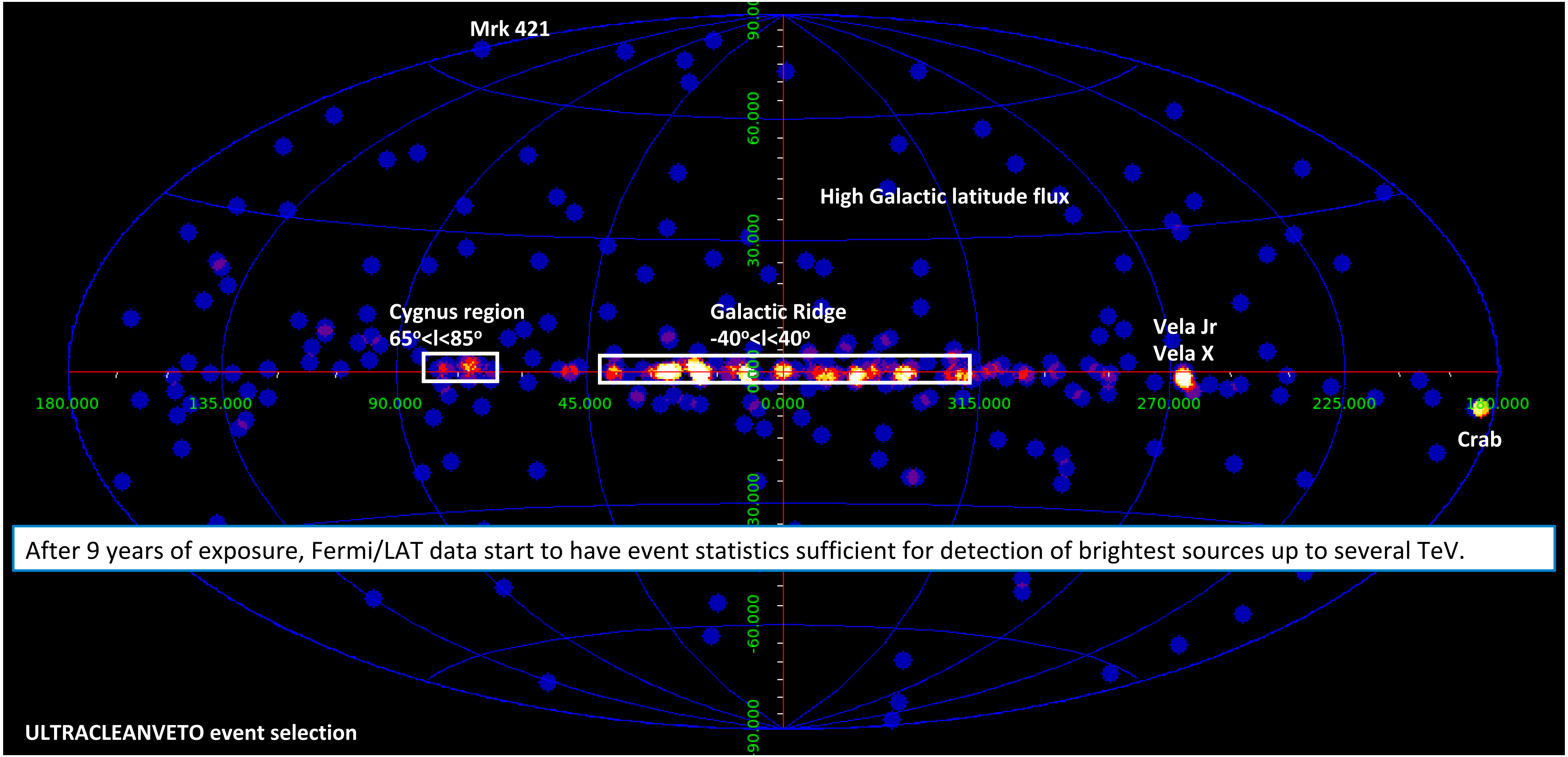


AN, Kachelriess, Semikoz '18 (in prep)

IceCube sensitivity is marginally sufficient for detection of neutrino counterpart of gamma-ray signal from cosmic ray interactions in brightest nearby sources, like Cygnus X region.

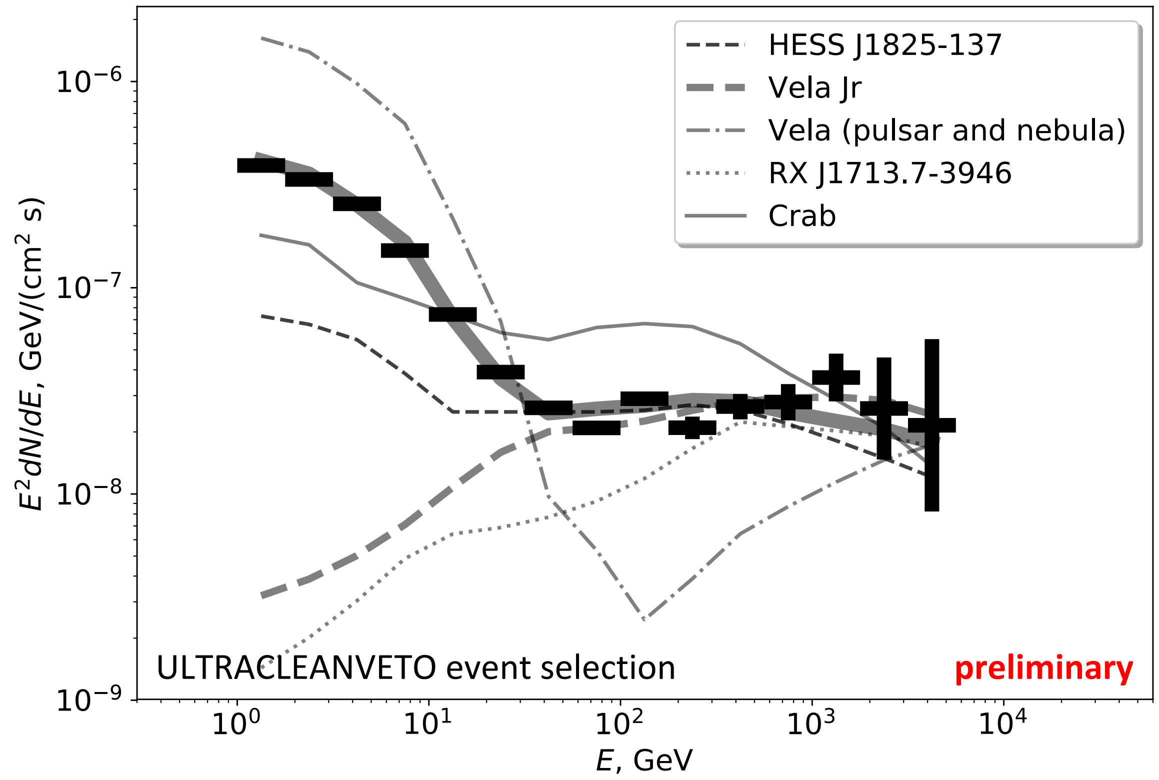
The *would-be* gamma-ray counterpart of neutrino signal could now be also detected in the multi-TeV band with Fermi LAT telescope.

Fermi/LAT multi-TeV sky



After 9 years of exposure, Fermi/LAT data start to have event statistics sufficient for detection of brightest sources up to several TeV.

Fermi/LAT multi-TeV sky



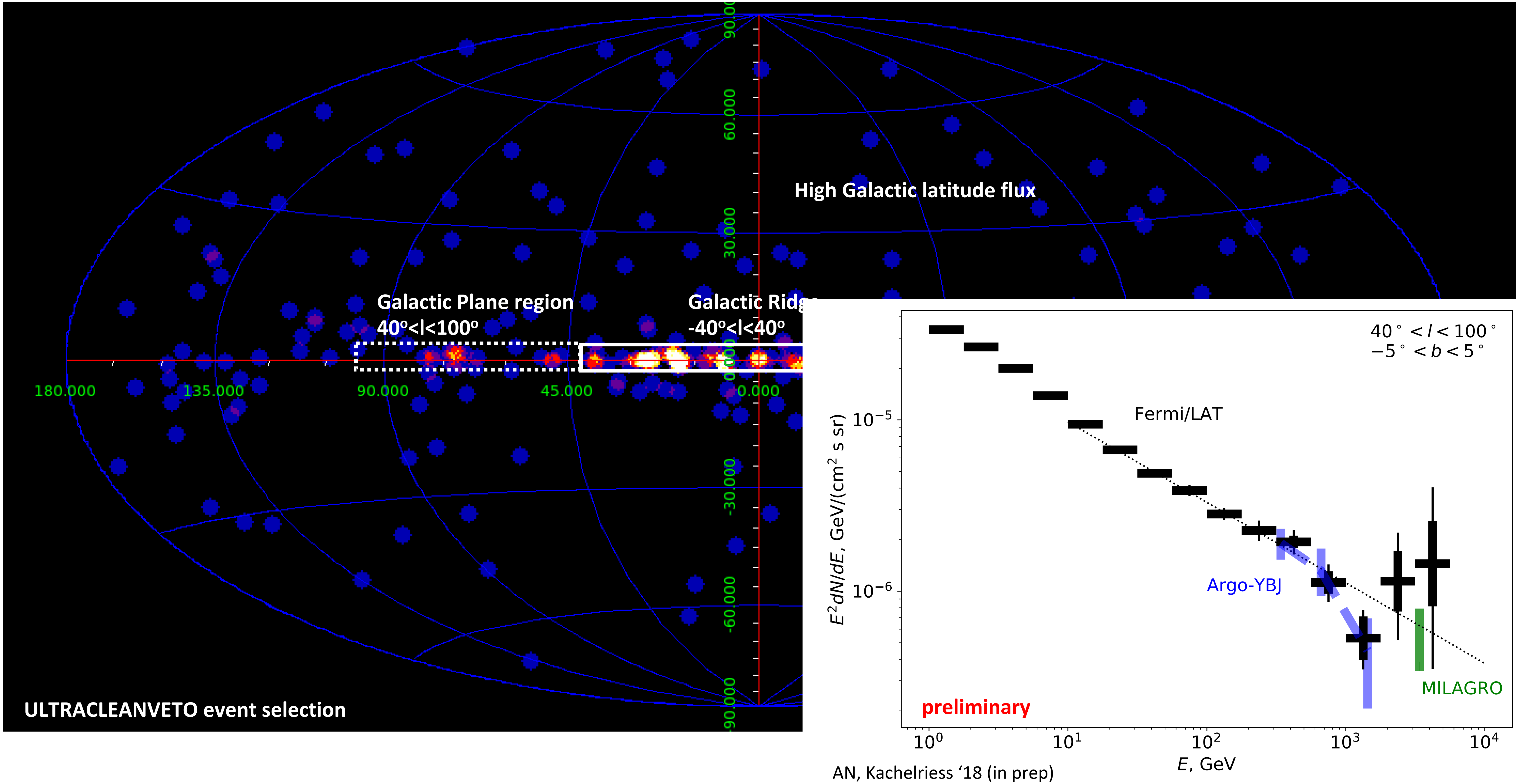
After 9 years of exposure, Fermi/LAT data start to have event statistics sufficient for detection of brightest sources up to several TeV.

Fermi /LAT calibration is not assured above 1 TeV (https://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html). Those need to be derived / verified.

This could be done via cross-calibration with the ground-based gamma-ray telescopes (HESS, MAGIC, VERITAS) and air shower arrays (MILAGRO, HAWC, ARGO-YBJ)

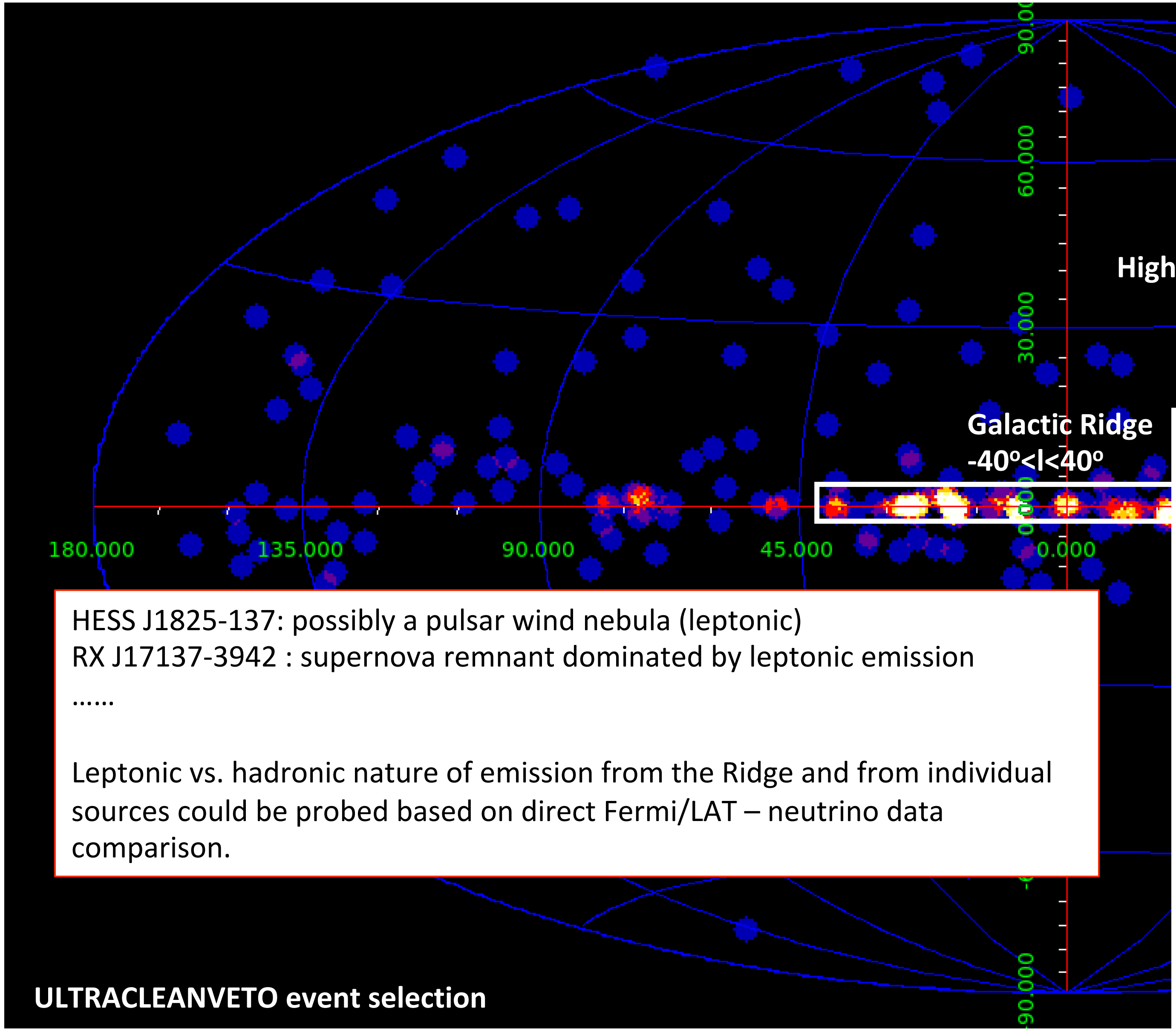
AN, Kachelriess, Semikoz ’18 (in prep)

Cross-calibration of Fermi/LAT with air shower arrays



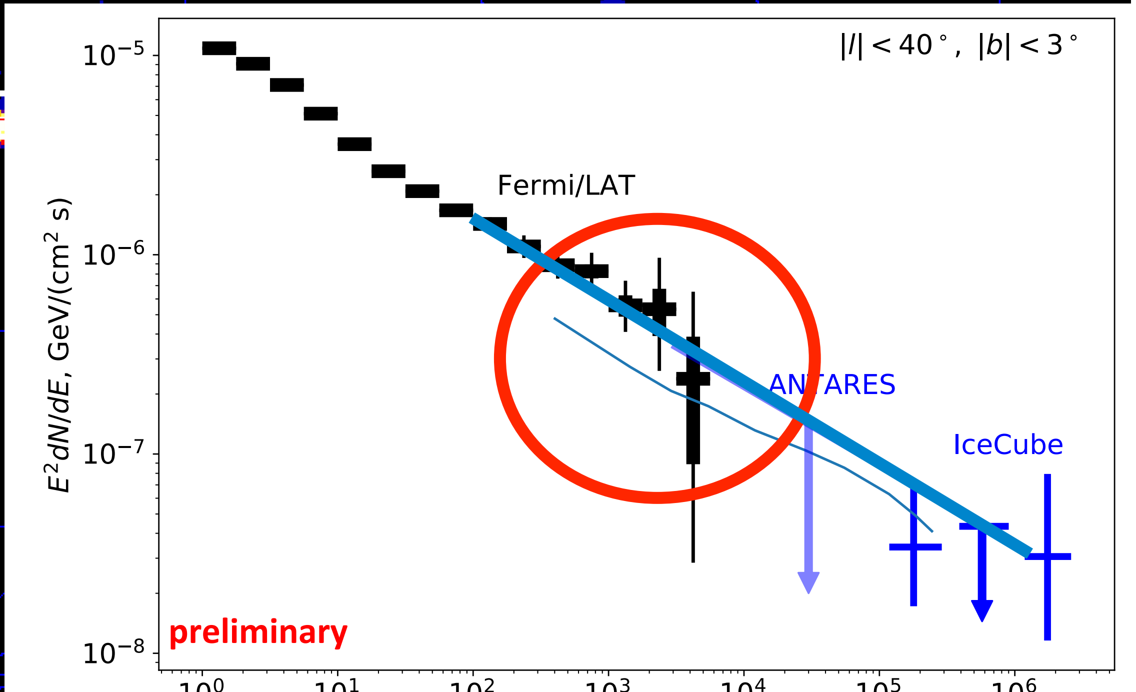
AN, Kachelriess '18 (in prep)

Multi-messenger spectrum of the Galactic Ridge



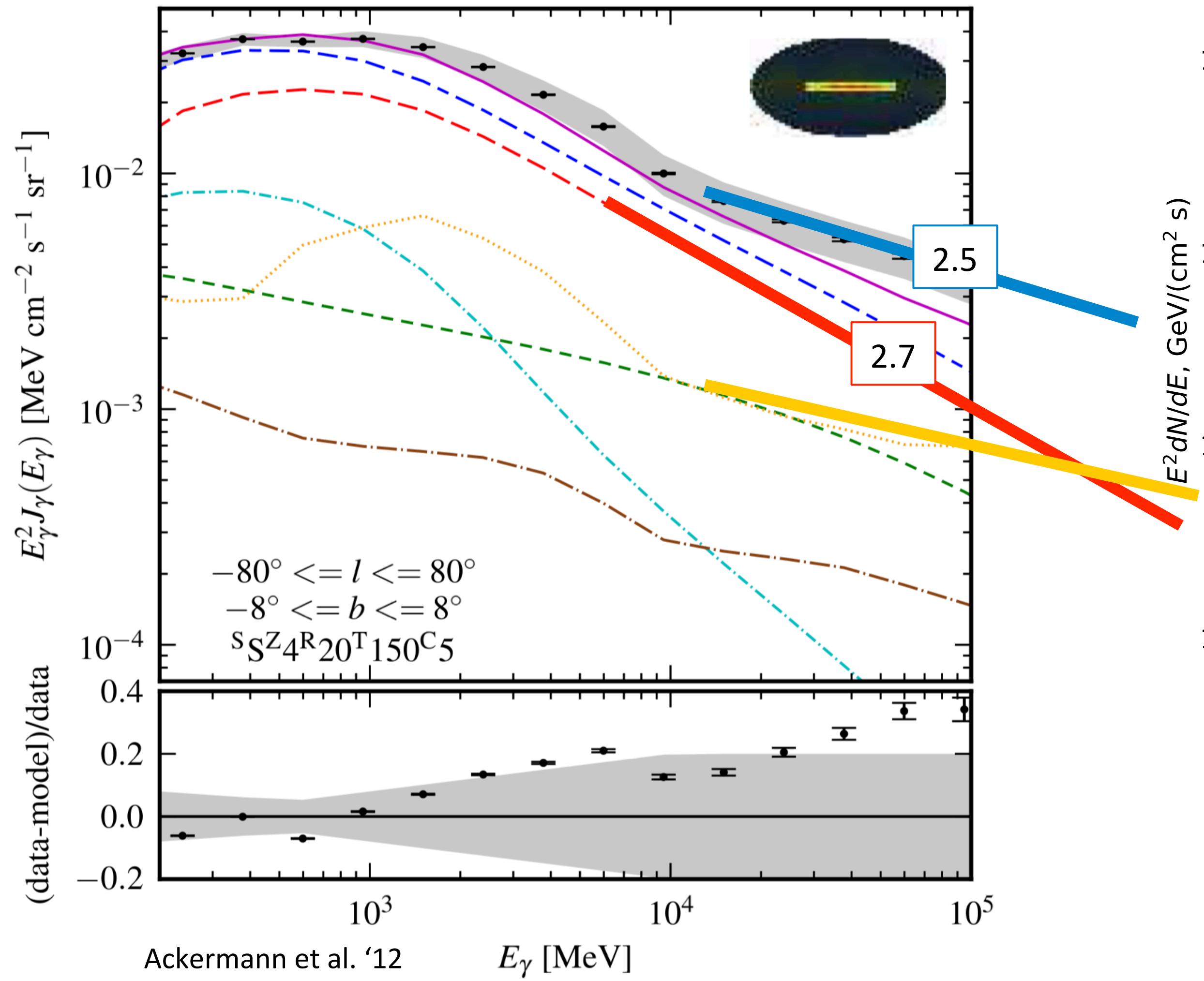
HESS J1825-137: possibly a pulsar wind nebula (leptonic)
RX J17137-3942 : supernova remnant dominated by leptonic emission
……

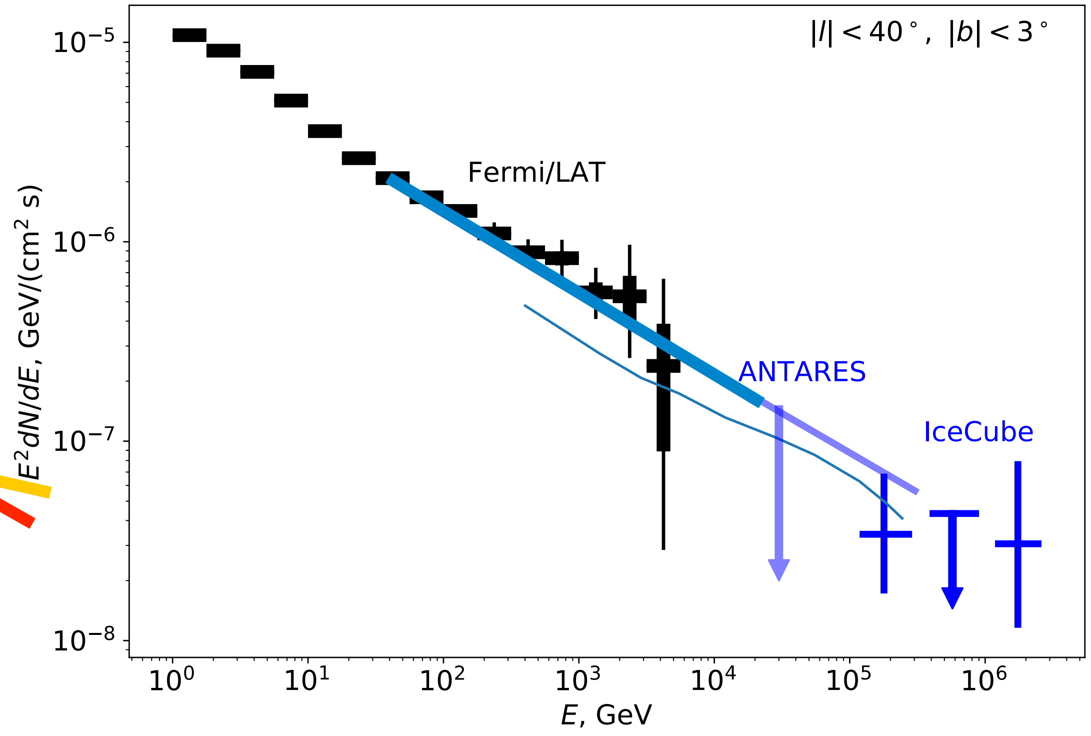
Leptonic vs. hadronic nature of emission from the Ridge and from individual sources could be probed based on direct Fermi/LAT – neutrino data comparison.



AN, Semikoz, Tchernin '14, Adrian-Martinez et al. '16
AN, Semikoz, Kachelriess '18 (in prep)

Multi-messenger spectrum of the Galactic Ridge / inner Galactic Plane

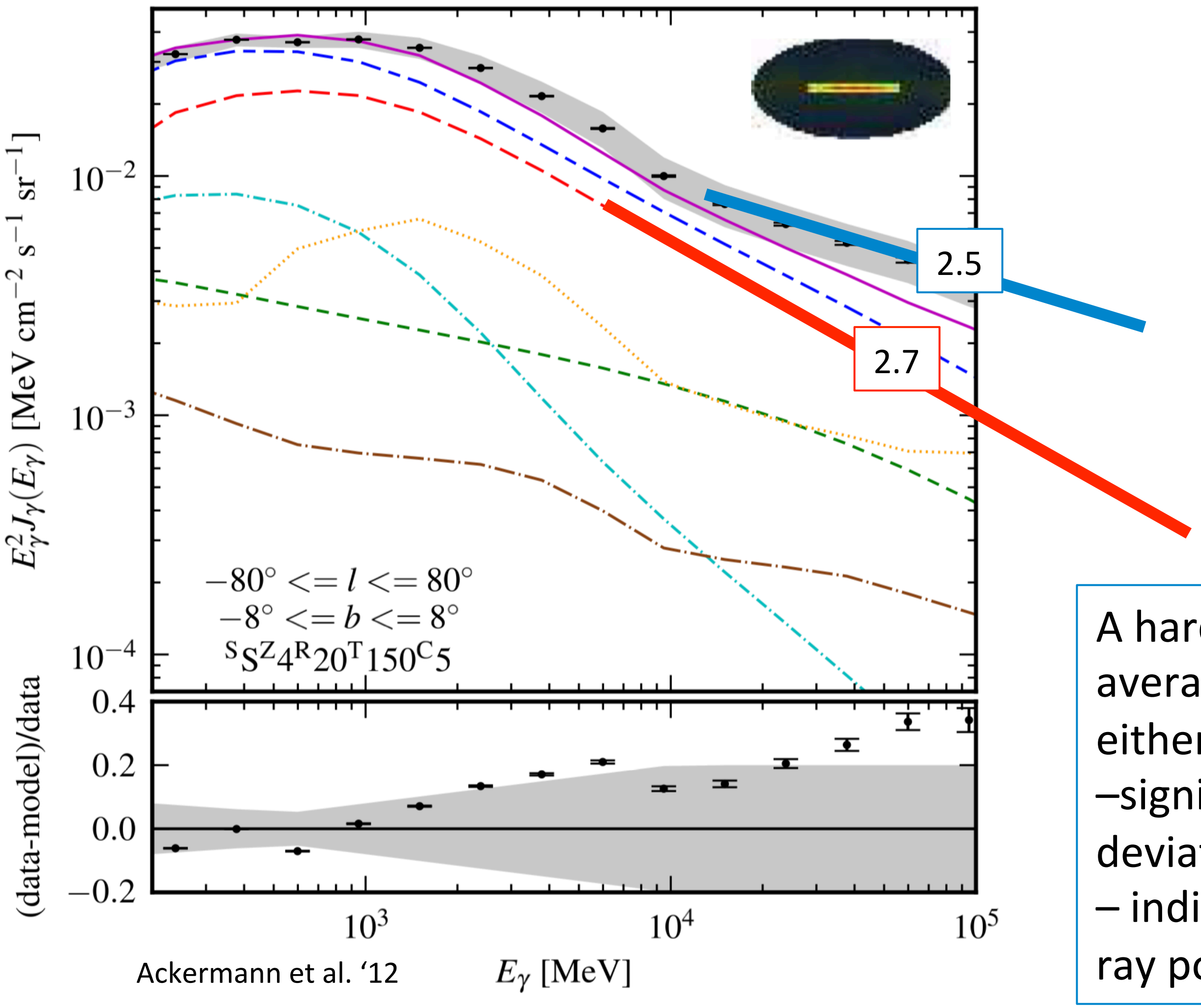




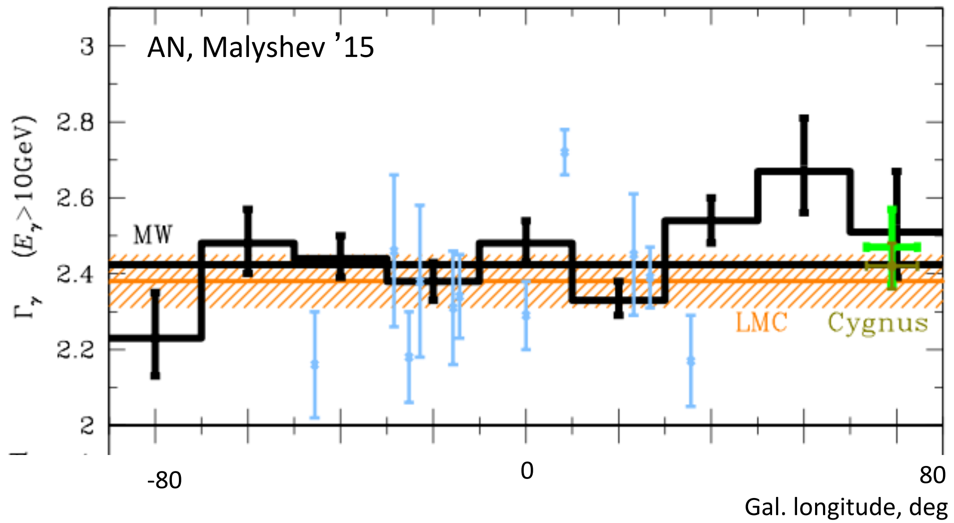
AN, Malyshev '15
Gaggero et al. '15
Fermi LAT Collab. '16
Yang, Aharonian '16

A hypothesis to be verified with multi-messenger signal from the Galactic Ridge is harder spectrum of cosmic rays vs. large presence of a population of resolved leptonic sources (pulsar wind nebulae?) or hadronic sources (supernova remnants?).

Average cosmic ray spectrum in the Galaxy



Ackermann et al. '12

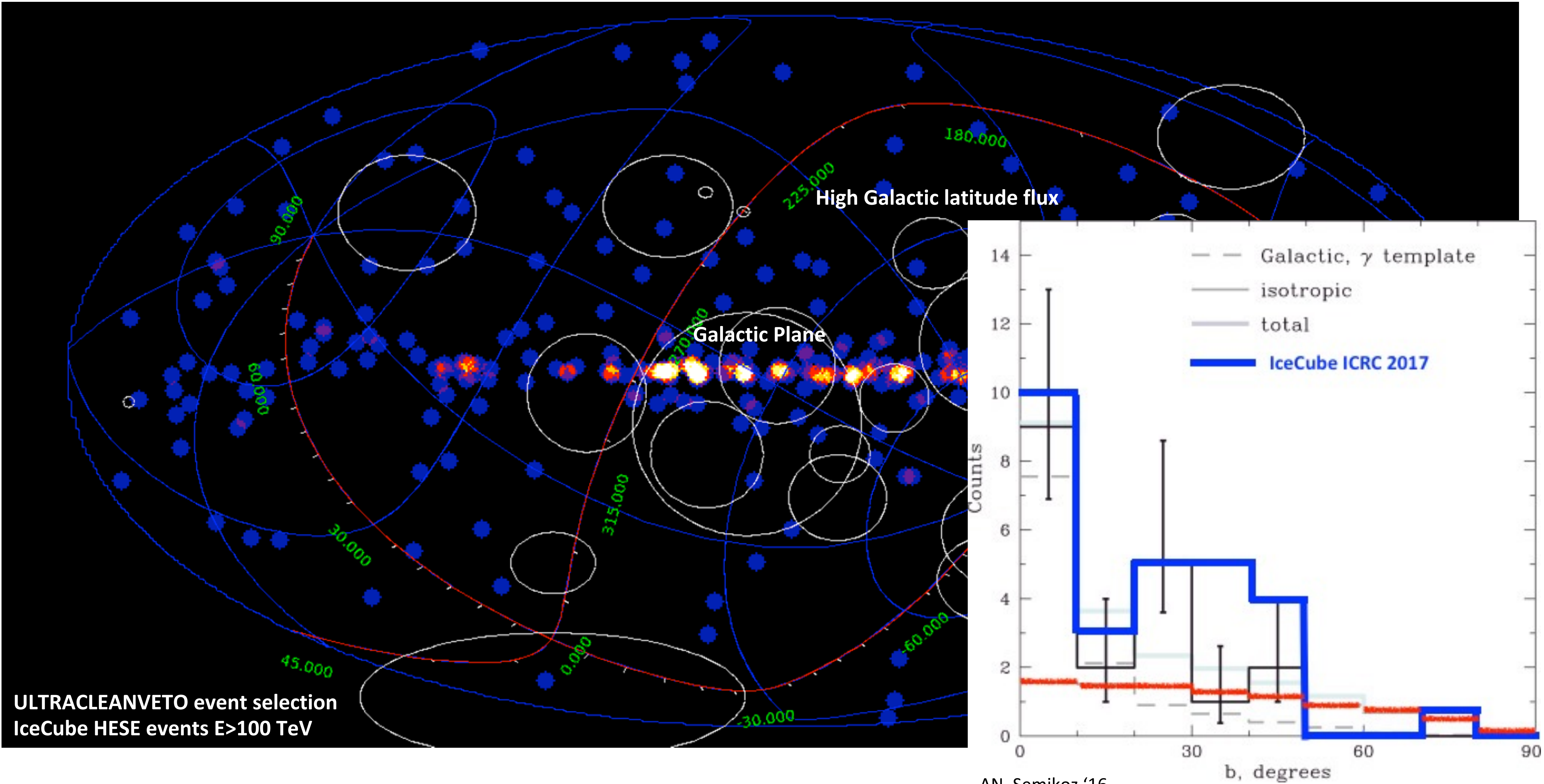


A harder (compared to the locally measured) average Galactic cosmic ray spectrum could be either
–signify that the locally measured spectrum deviates from the average Galactic spectrum or
– indicate a change of the properties of cosmic ray population from inner to outer Galaxy.

AN, Malyshev '15
Gaggero et al. '15
Fermi LAT Collab. '16
Yang, Aharonian '16

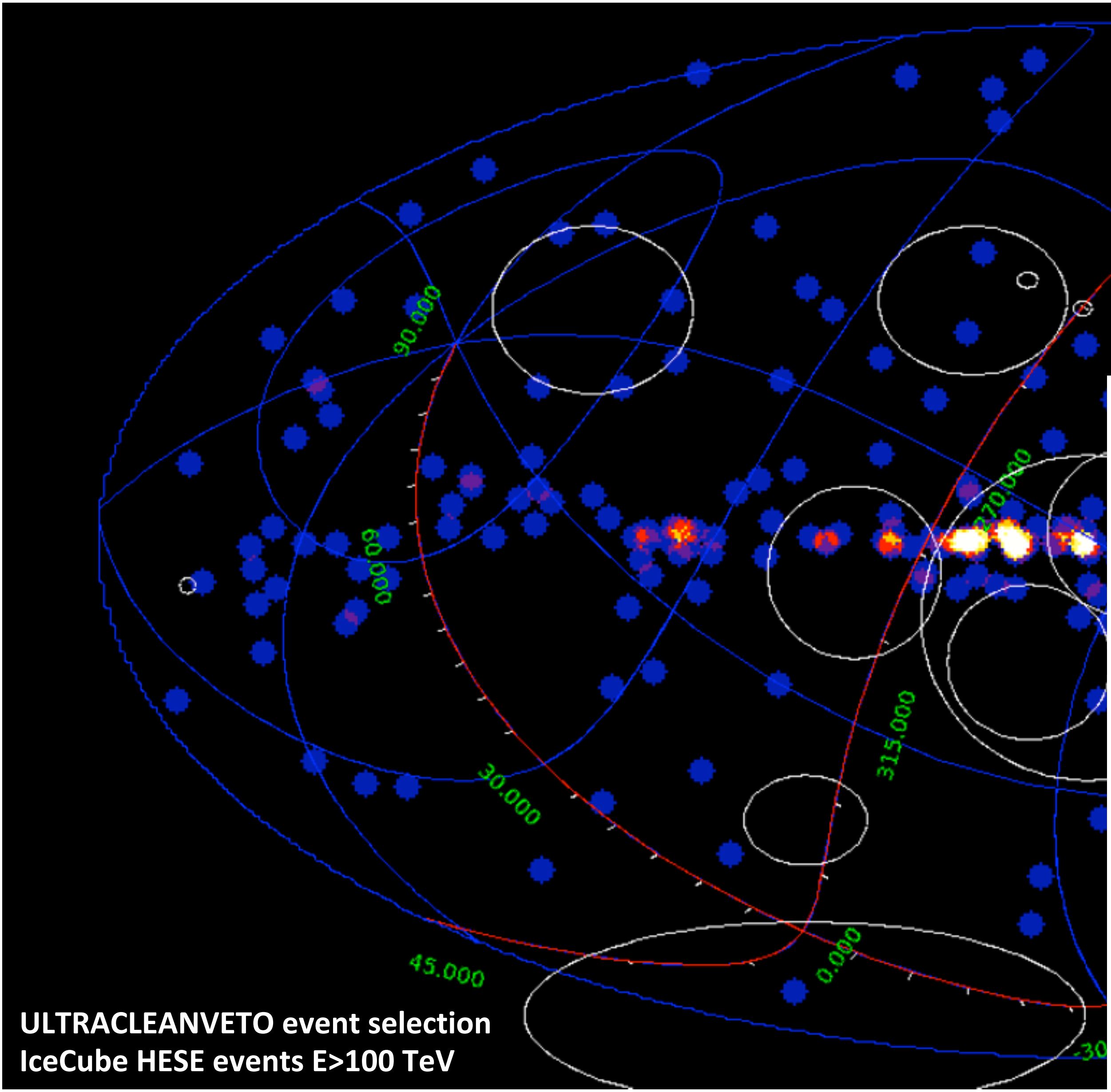
A hypothesis to be verified with multi-messenger signal from the Galactic Ridge is harder spectrum of cosmic rays vs. large presence of a population of leptonic sources (pulsar wind nebulae?).

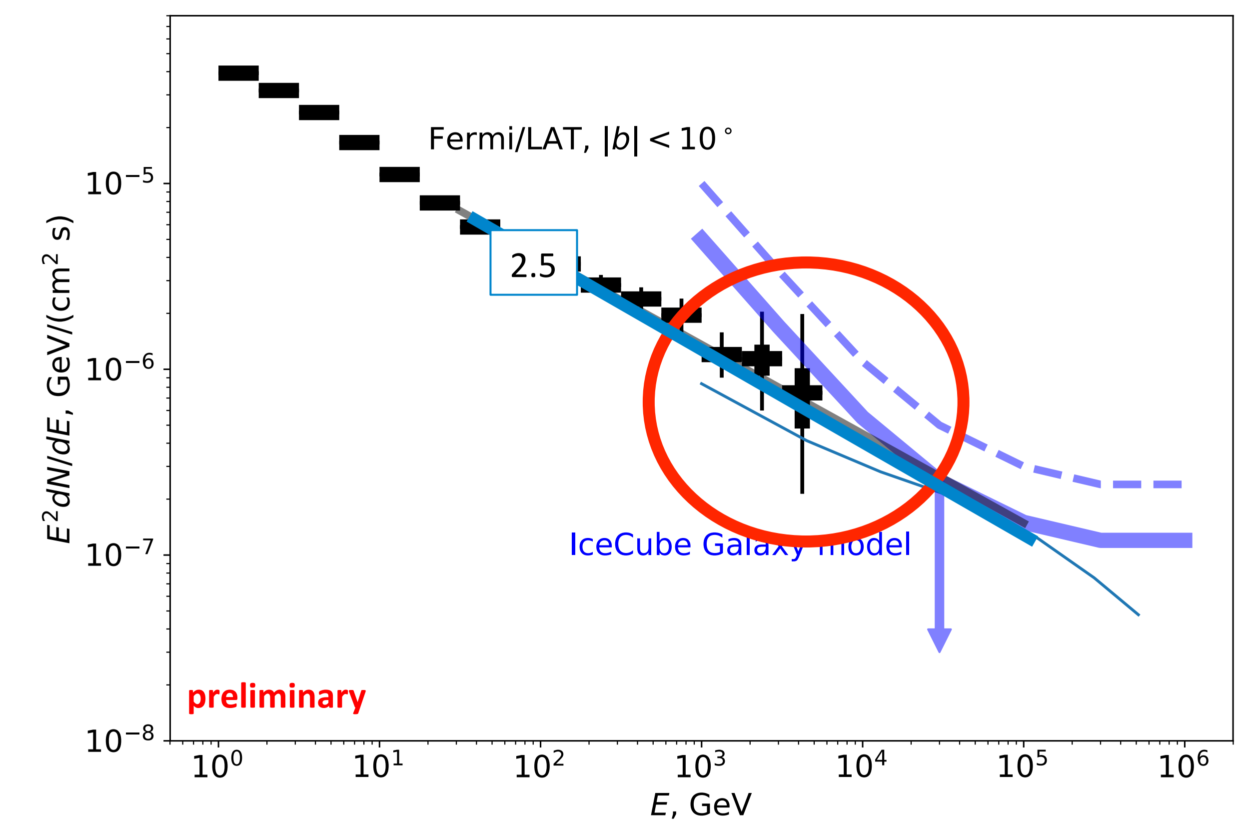
Multi-messenger spectrum of the Galactic Plane



AN, Semikoz '16

Multi-messenger spectrum of the Galactic Plane

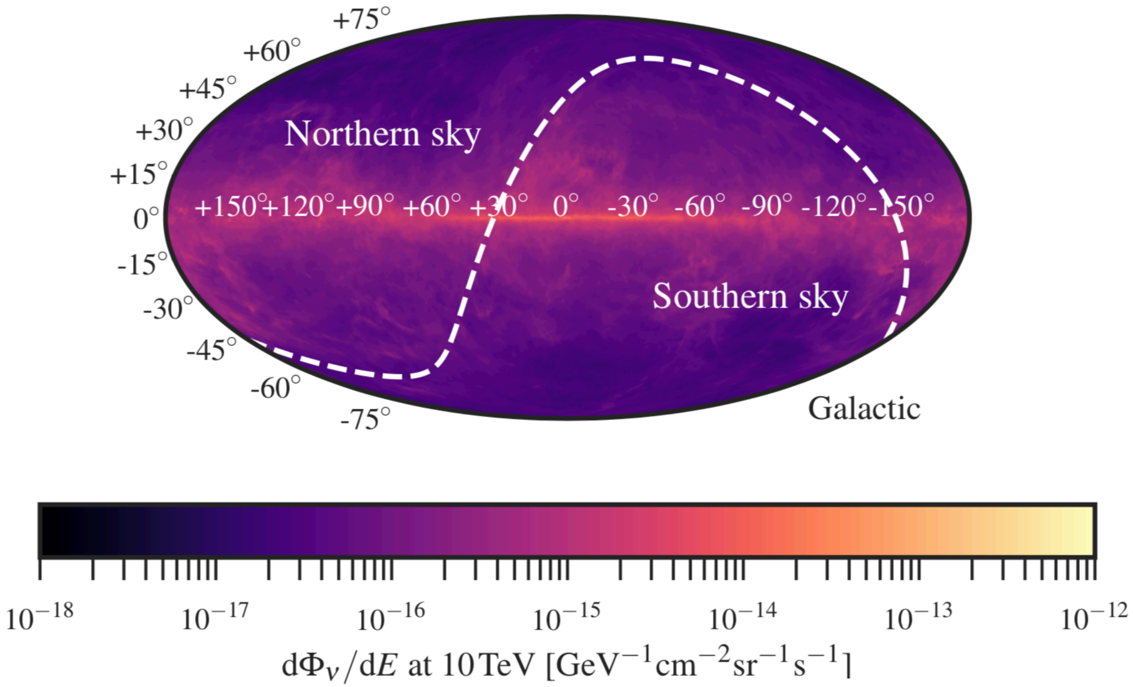


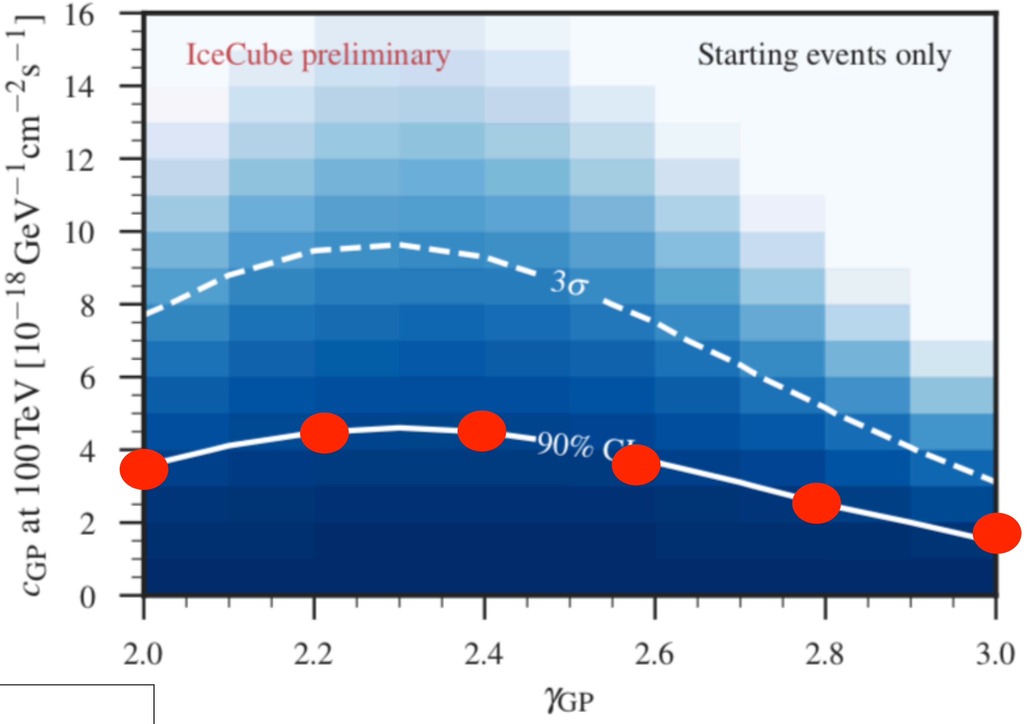


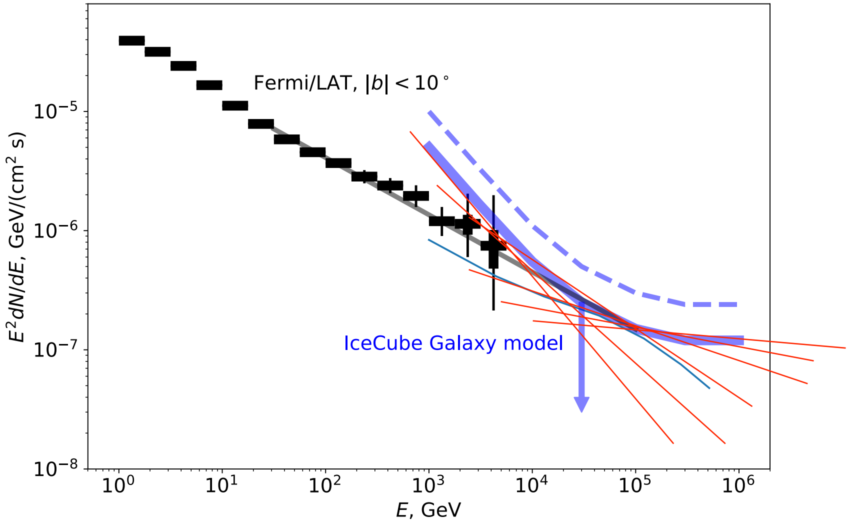
IceCube Collab. ICRC2017, AN, Kachelriess, Semikoz '18 (in prep)

Multi-messenger spectrum of the Galactic Plane

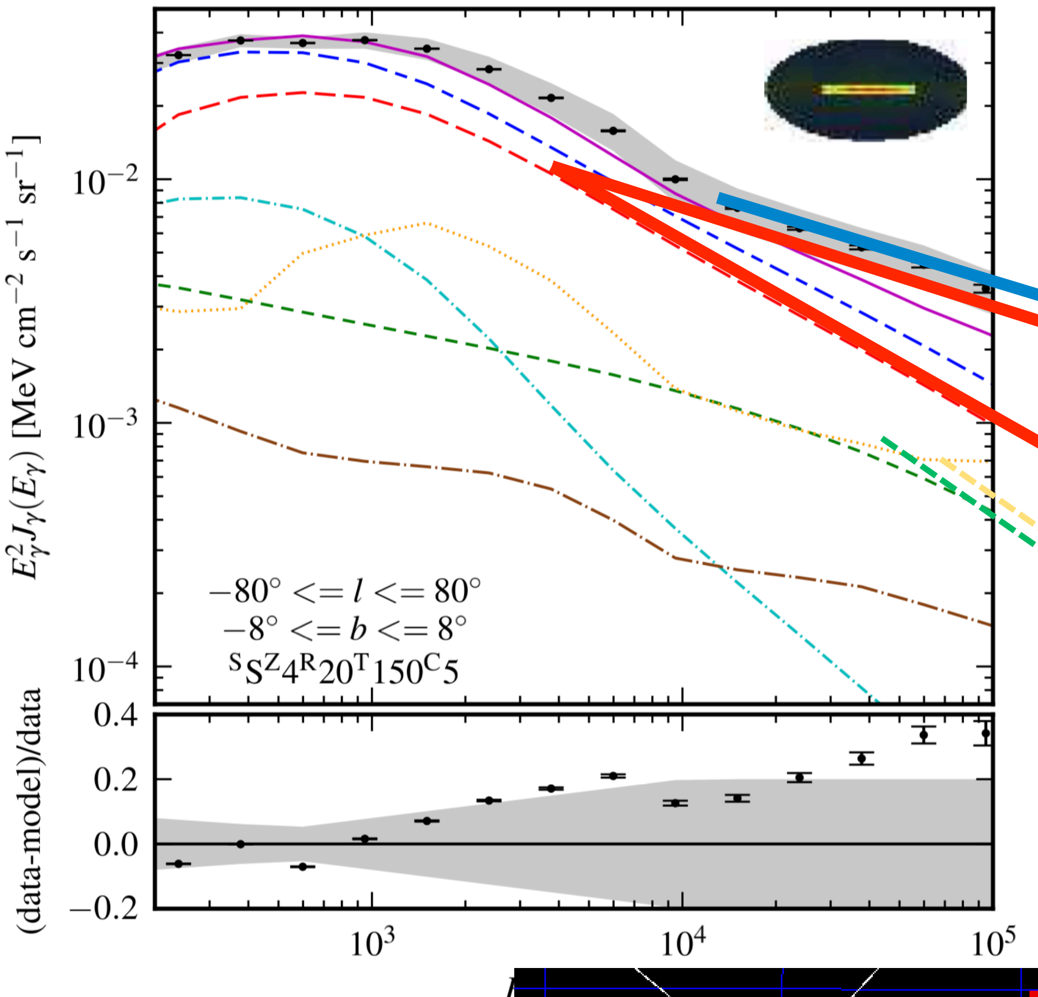
IceCube, ICRC2017







Multi-messenger spectrum of the Galactic Plane



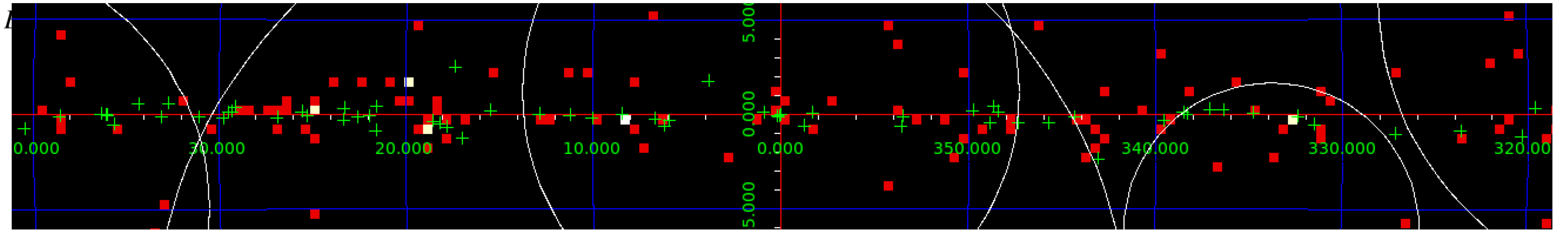
Fermi/LAT multi-TeV emission from the Galactic Plane could hardly be dominated by diffuse emission process which does not generate neutrinos.

It also does not come from known isolated sources

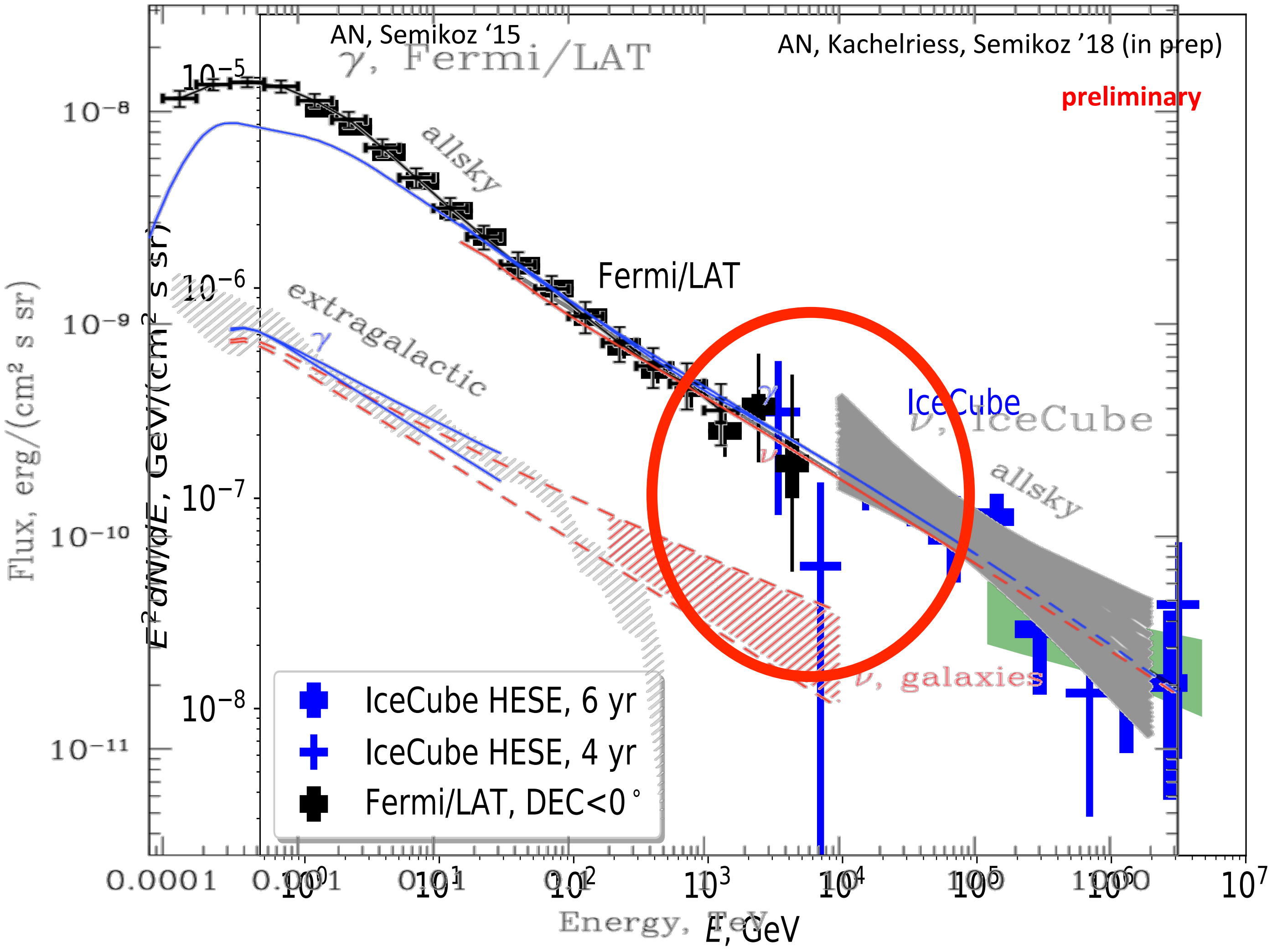
π^0 decays

Inverse Compton

Catalog sources

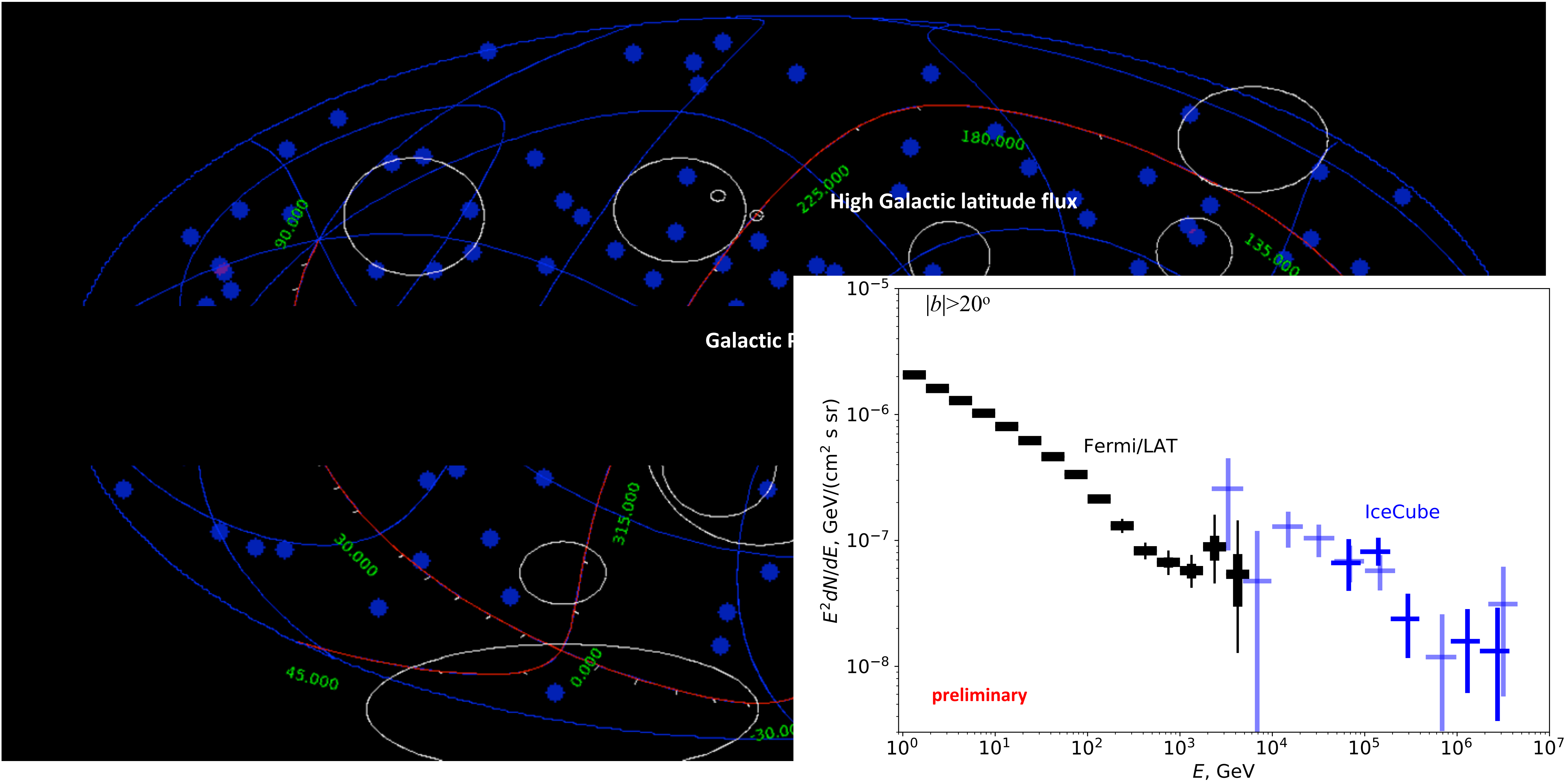


Multi-messenger signal from multi-TeV sky



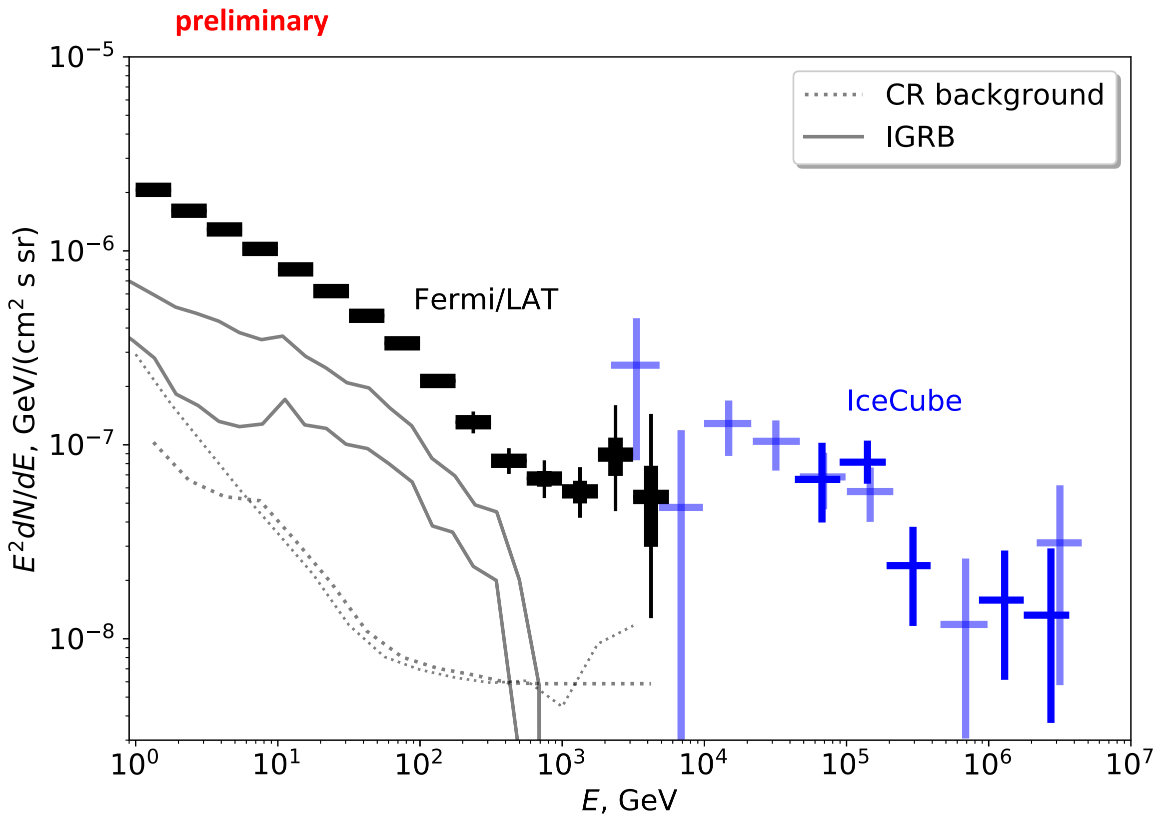
Consistency of the gamma-ray and neutrino spectra suggest the presence of gamma-ray counterpart of the neutrino signal and, therefore, Galactic origin of (a part of) neutrino flux.

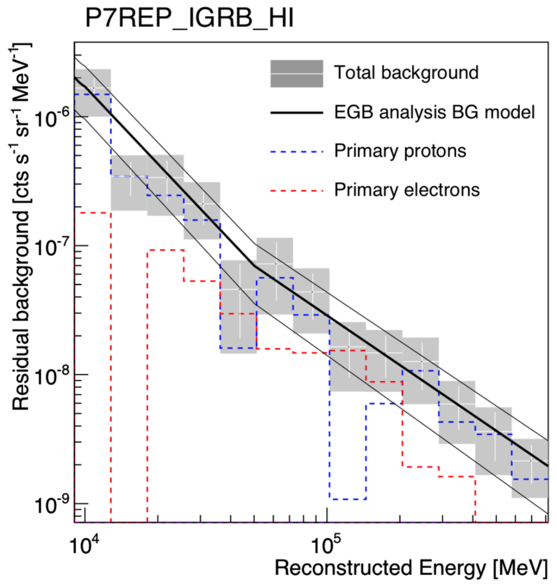
Multi-messenger signal from high Galactic latitude multi-TeV sky

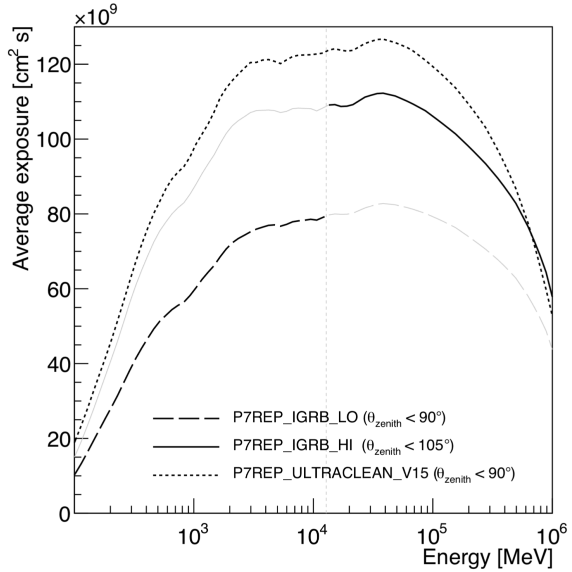


AN, Kachelriess, Semikoz '18 (in prep)

Multi-messenger signal from high Galactic latitude multi-TeV sky

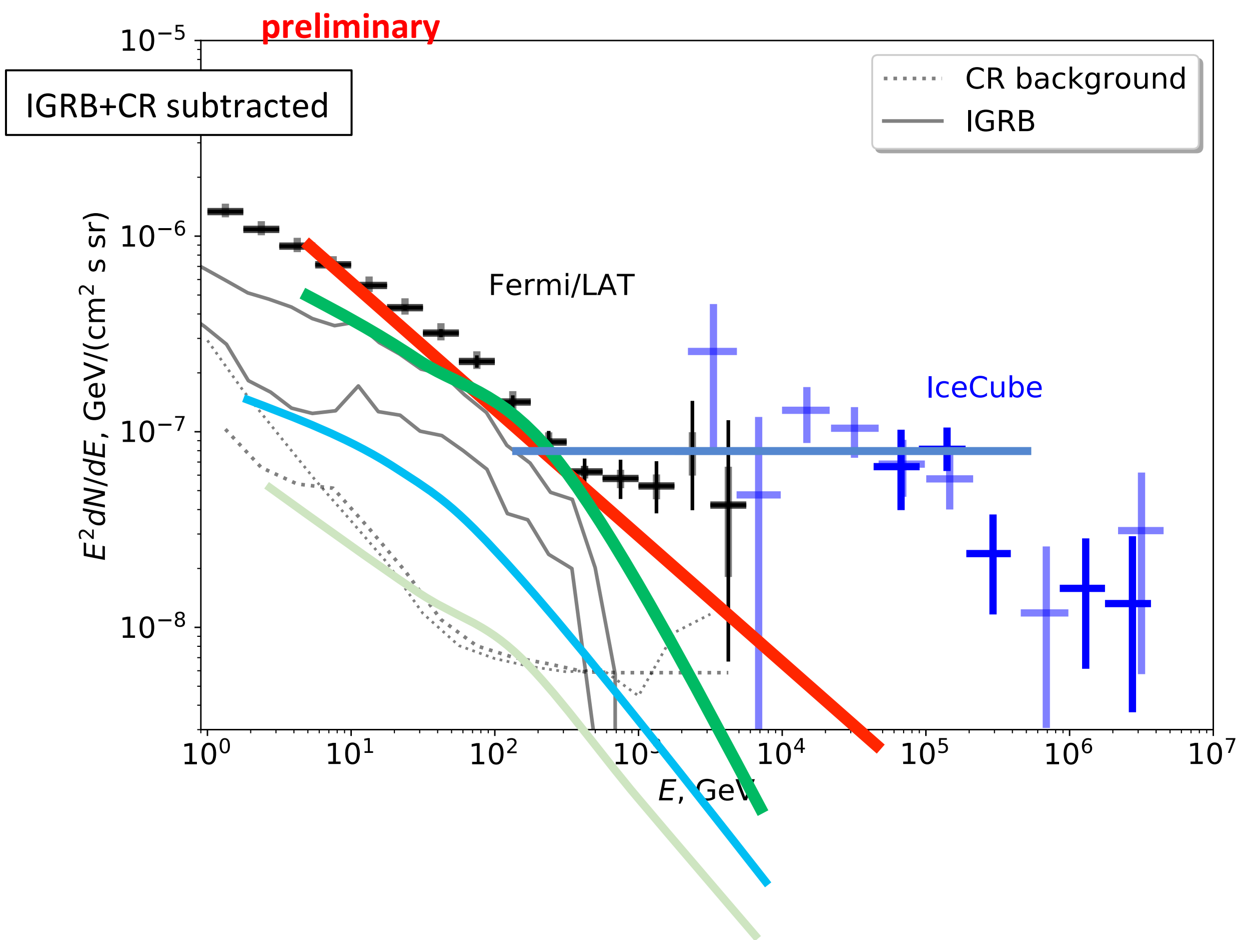


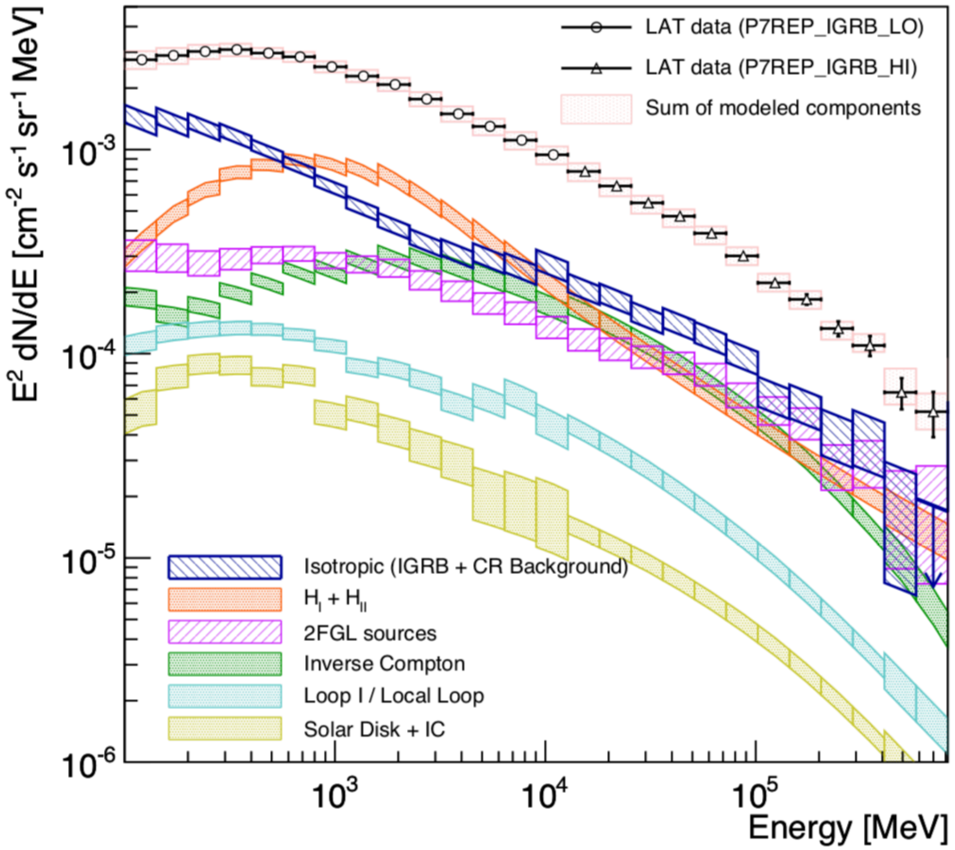




- Assuming residual cosmic ray background model from Fermi Collab. '14 publication (broken powerlaw in cts/s/sr)
- Assuming calibration of the effective area on known TeV sources.

Multi-messenger signal from high Galactic latitude multi-TeV sky

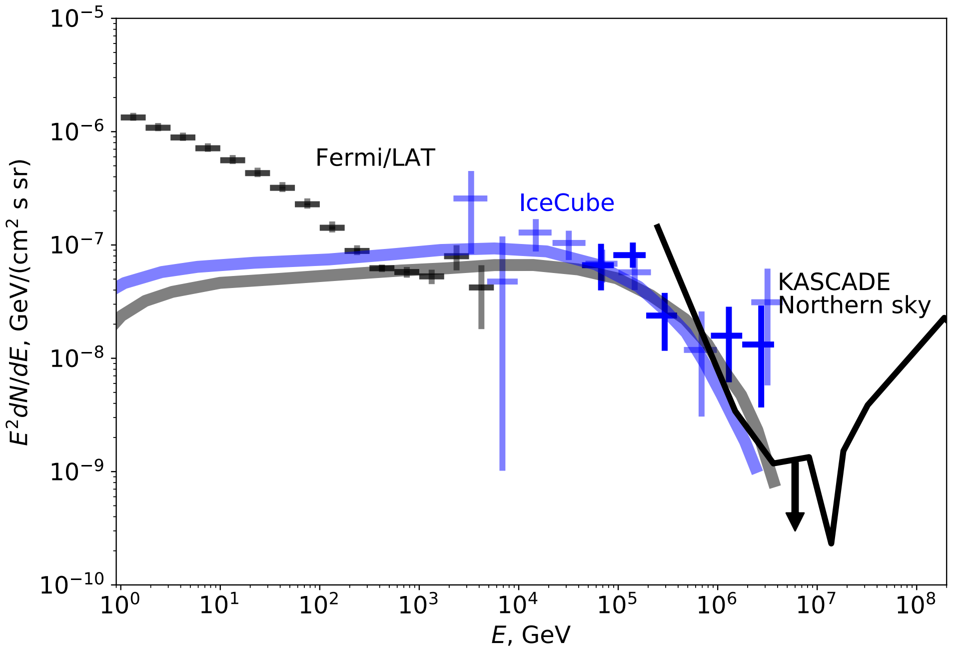




Known Galactic flux components have steep spectrum in the TeV range.

New flux component with hard spectrum appears to match the neutrino flux component in the multi-TeV range.

Multi-messenger signal from high Galactic latitude multi-TeV sky

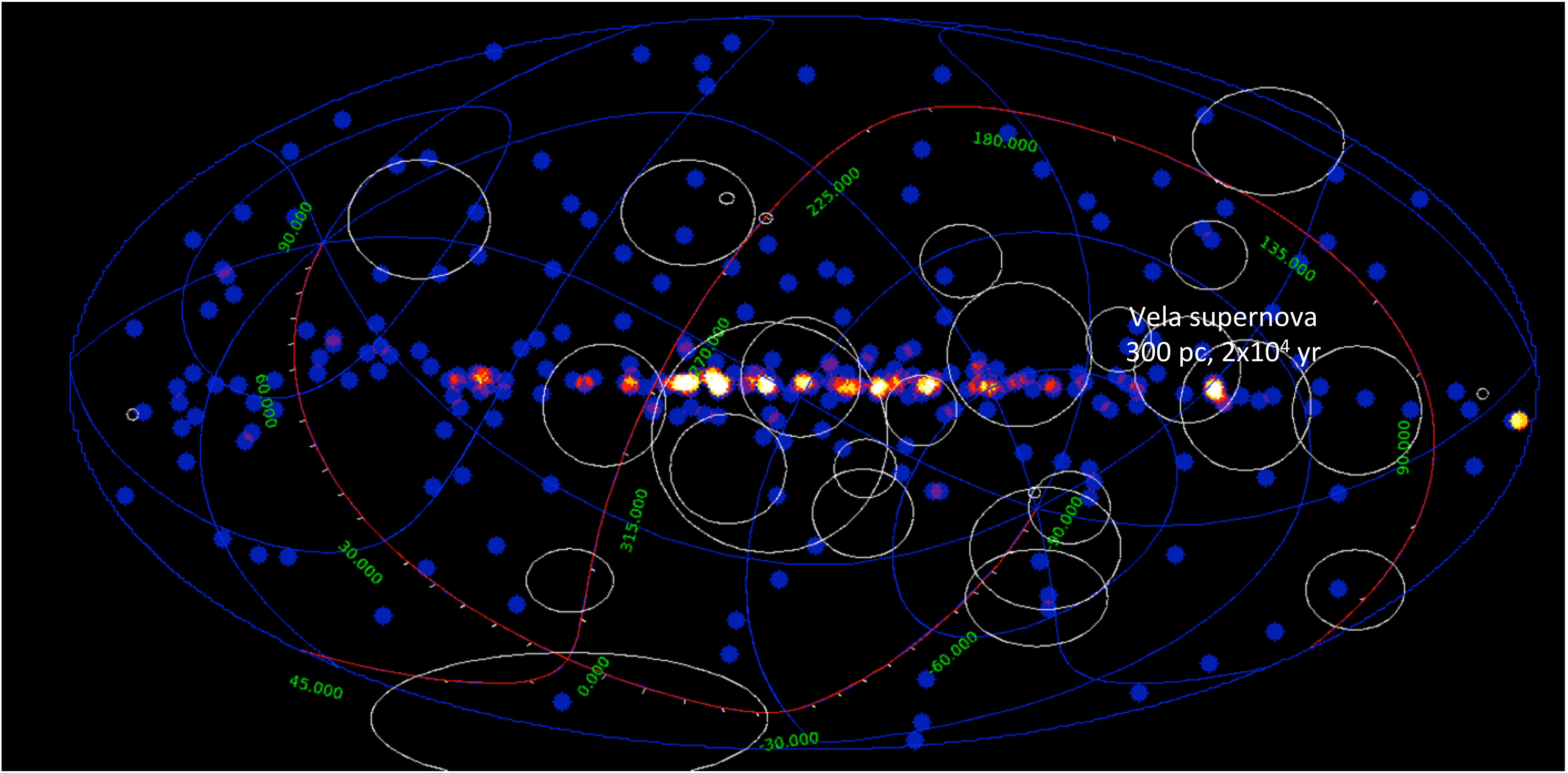


Cosmic rays with total energy **10^{50} erg** which have escaped nearby recent (within the escape time of PeV particles) source loose energy into neutrino and gamma-rays on time scale $t_{pp}\sim10^8\ (n_{ISM}/0.5\ \mathrm{cm^{-3}})$ yr.

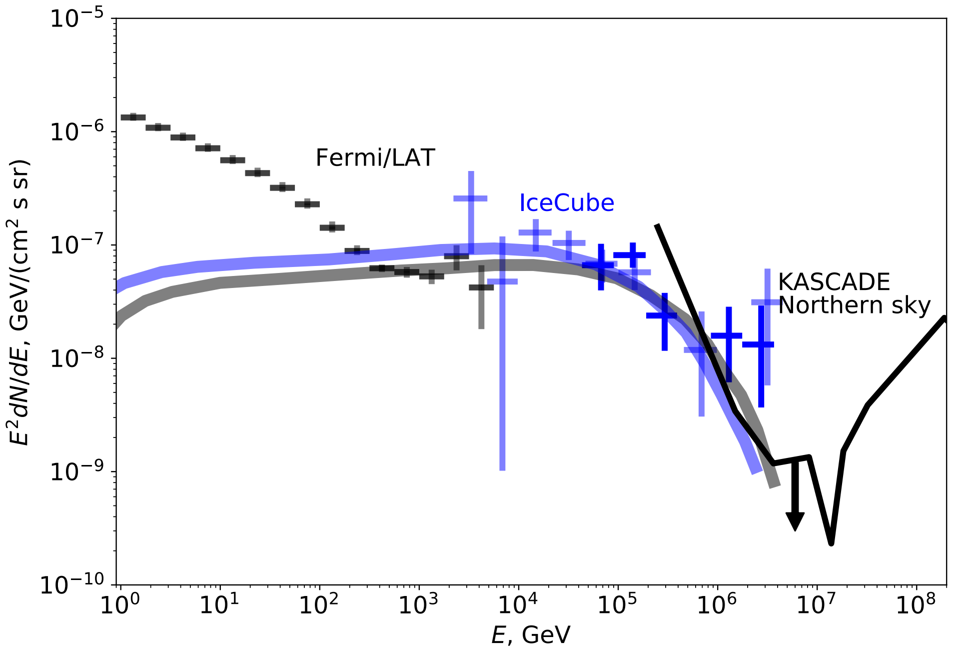
This might result in very extended emission with a flux

$$F\sim10^{-10}\ (n_{ISM}/0.5\ \mathrm{cm^{-3}})\ (d/0.5\ \mathrm{kpc})^{-2}\ \mathrm{erg/(cm^2\ s)}$$
$$\sim10^{-7}\mathrm{GeV/(cm^2\ s)}$$

Multi-messenger signal from high Galactic latitude multi-TeV sky



Multi-messenger signal from high Galactic latitude multi-TeV sky



Cosmic rays with total energy **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 $t_{pp} \sim 10^8 \, (n_{ISM}/0.5 \text{ cm}^{-3})$ yr.

This might result in very extended emission with a flux

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

Cosmic rays with total energy of **10^{58} erg** residing in 100 kpc scale halo loose energy on the time scale $t_{pp} \sim 10^{11} \, (n_{ISM}/10^{-3} \text{ cm}^{-3})$ yr and produce luminosity

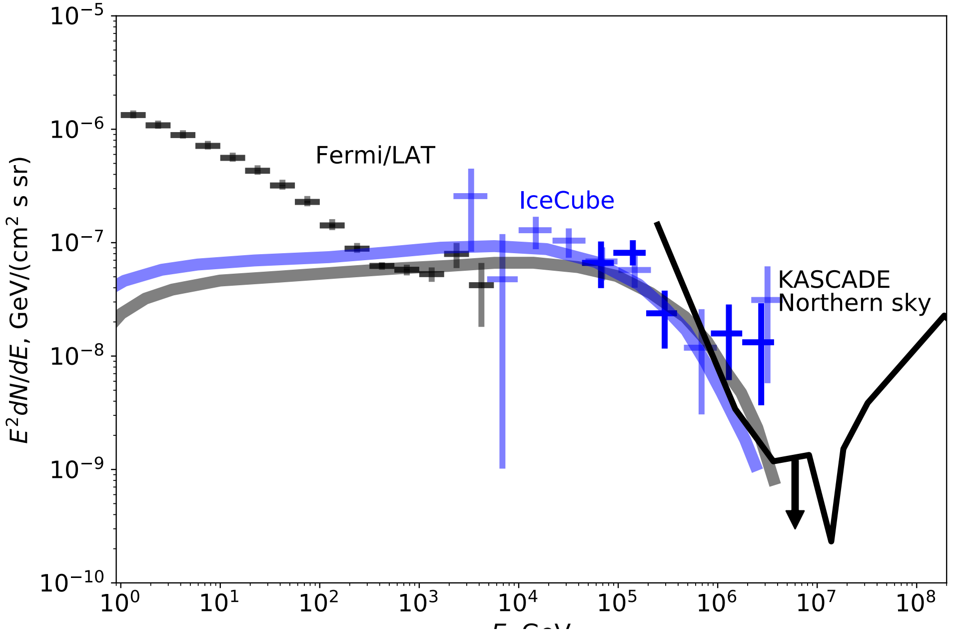
$$L \sim 10^{58} \text{ erg} / 10^{11} \text{ yr} \sim 3\text{x}10^{39} \, (n_{ISM}/10^{-3} \text{ cm}^{-3}) \text{ erg/s}$$

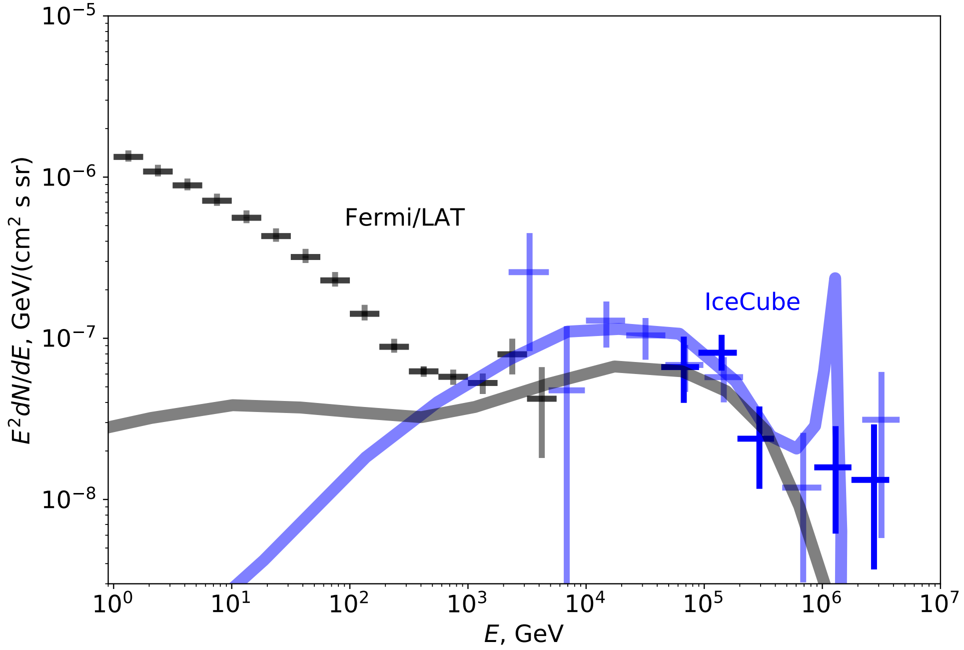
Thus providing a flux per neutrinos / gamma-rays per energy decade

$$F \sim 10^{-10} \, (n_{ISM}/10^{-3} \text{ cm}^{-3}) \, (d/100 \text{ kpc})^{-2} \text{ erg/(cm}^2 \text{ s)}$$
$$\sim 10^{-7} \text{ GeV/(cm}^2 \text{ s)}$$

Taylor, Gabici, Aharonian '14

Multi-messenger signal from high Galactic latitude multi-TeV sky





Cosmic rays with total energy **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 $t_{pp} \sim 10^8\ (n_{ISM}/0.5\ \text{cm}^{-3})$ yr.

This might result in very extended emission with a flux

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

Cosmic rays with total energy of **10^{58} erg** residing in 100 kpc scale halo loose energy on the time scale $t_{pp} \sim 10^{11}\ (n_{ISM}/10^{-3}\ \text{cm}^{-3})$ yr and produce luminosity

$$L \sim 10^{58}\ \text{erg} / 10^{11}\ \text{yr} \sim 3\text{x}10^{39}\ (n_{ISM}/10^{-3}\ \text{cm}^{-3})\ \text{erg/s}$$

Thus providing a flux per neutrinos / gamma-rays per energy decade

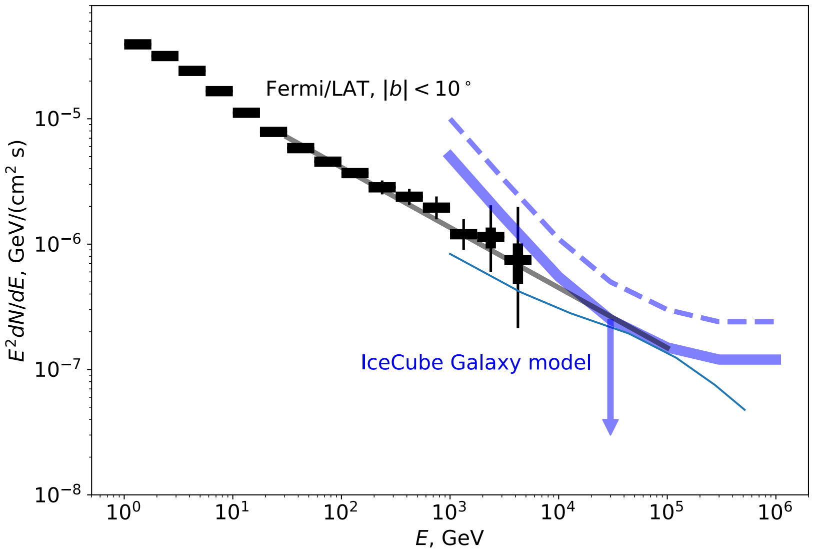
$$F \sim 10^{-10}\ (n_{ISM}/10^{-3}\ \text{cm}^{-3})\ (d/100\ \text{kpc})^{-2}\ \text{erg/(cm}^2\ \text{s)}$$
$$\sim 10^{-7}\ \text{GeV/(cm}^2\ \text{s)}$$

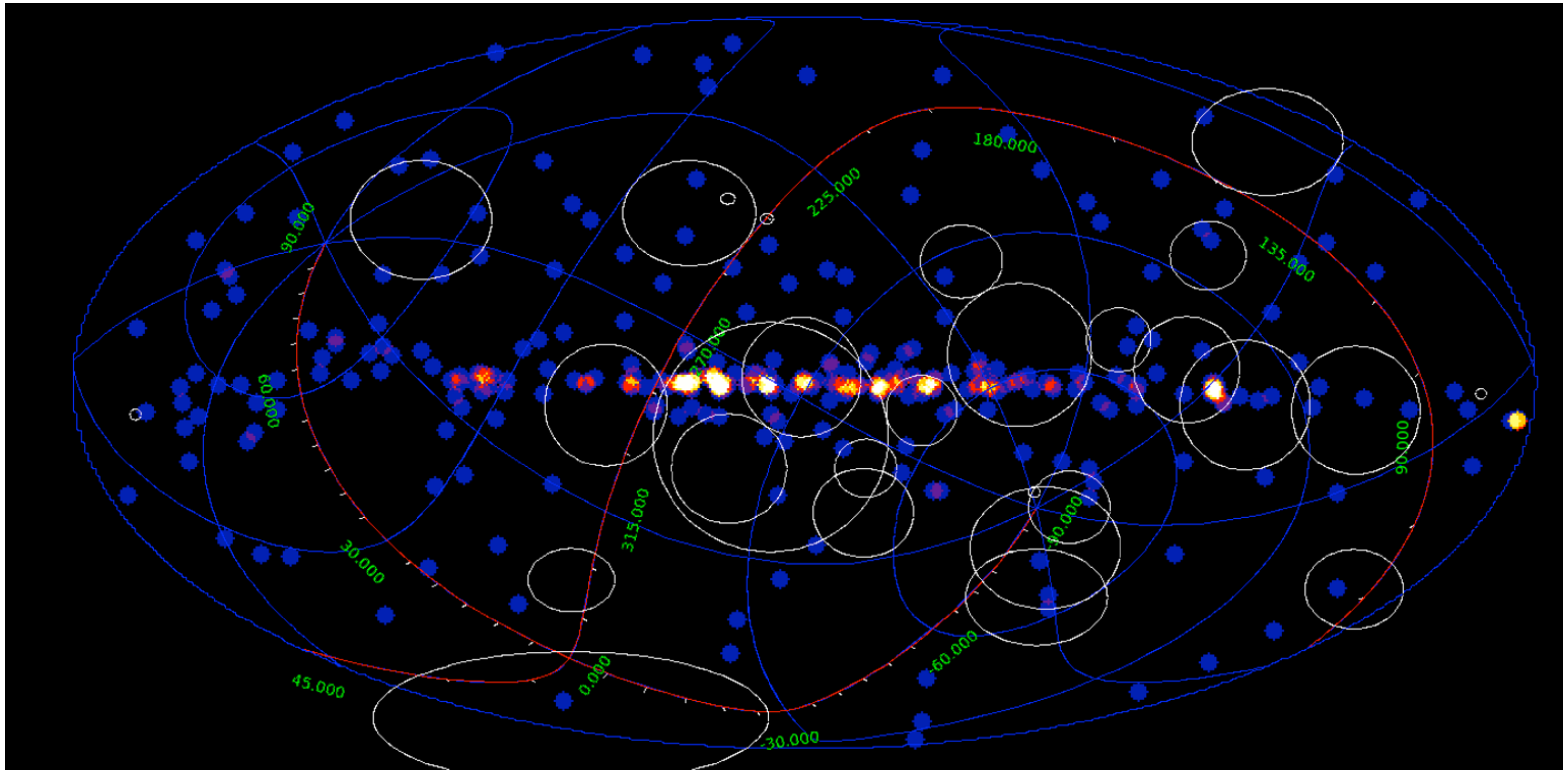
Taylor, Gabici, Aharonian '14

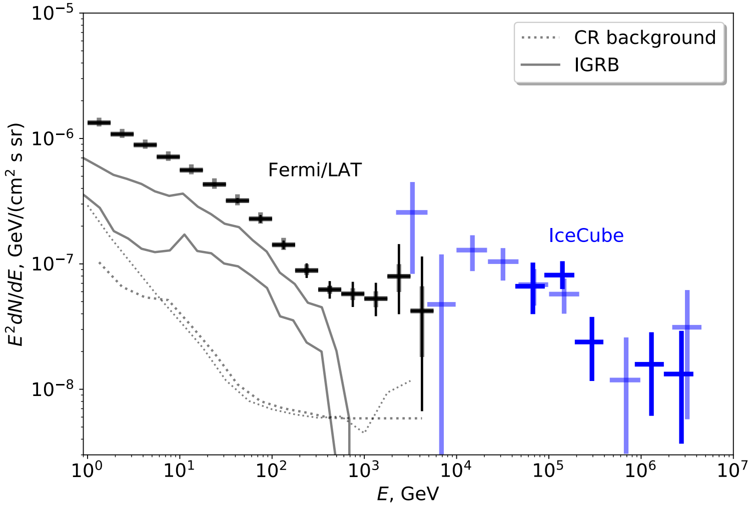
Decays of heavy dark matter particles with lifetime $\sim 10^{28}$ s into pions or directly into neutrinos and gamma-rays could provide the required multi-messenger flux at high Galactic latitude.

Murase et al. '15
Feldstein et al. '13
Berezinsky et al. '95

Summary







Astrophyisical neutrino flux has gamma-ray ”multi-messenger” counterpart in the multi-TeV band.

This indicates Galactic origin of at least a part of the neutrino flux (harder spectrum multi-PeV component could be extragalactic).

High Galactic latitude multi-messenger signal could originate from small or large scale cosmic ray halo or from dark matter decays.