Diffuse gamma-ray and neutrino emission in multi-TeV energy range

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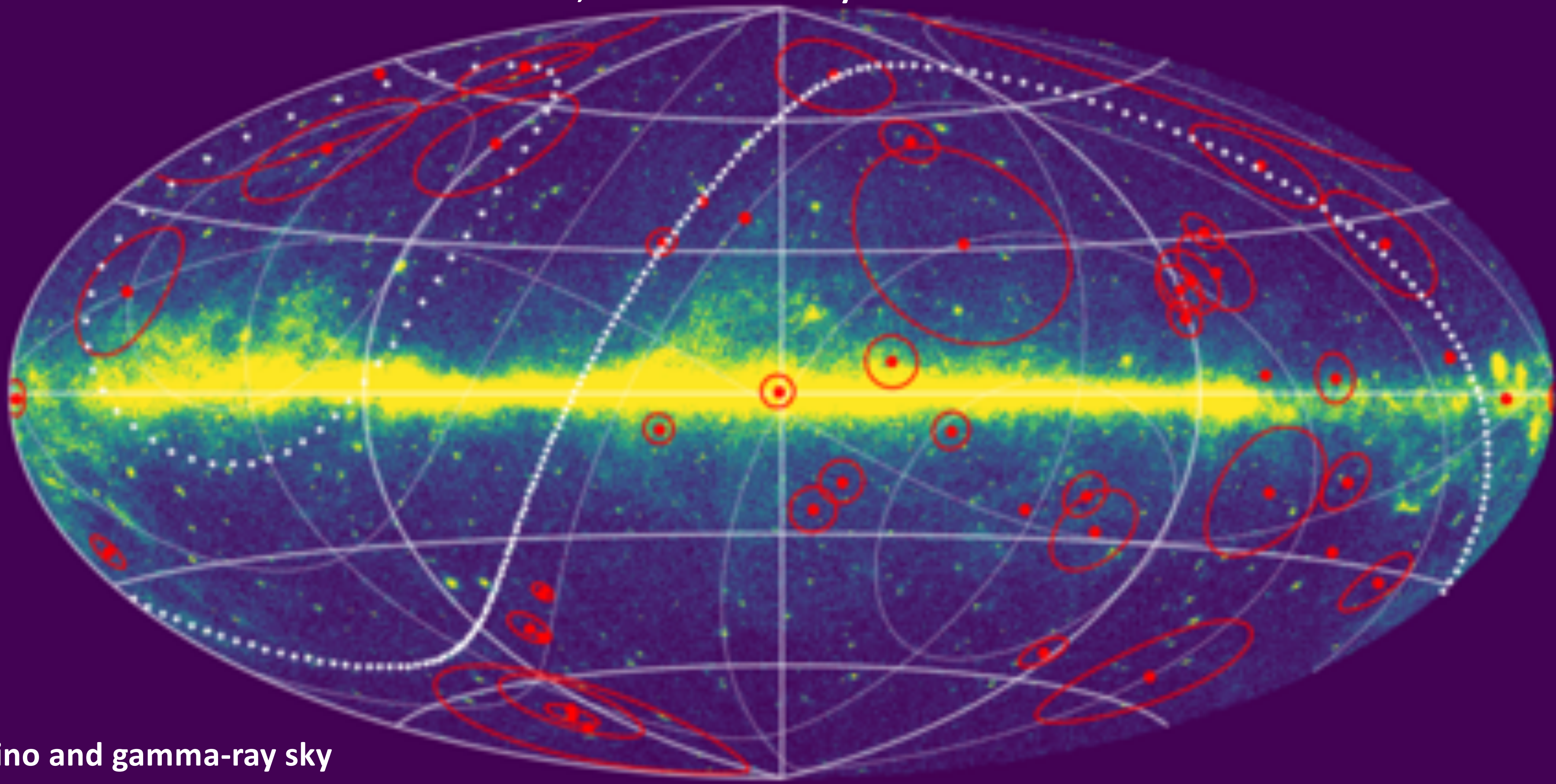
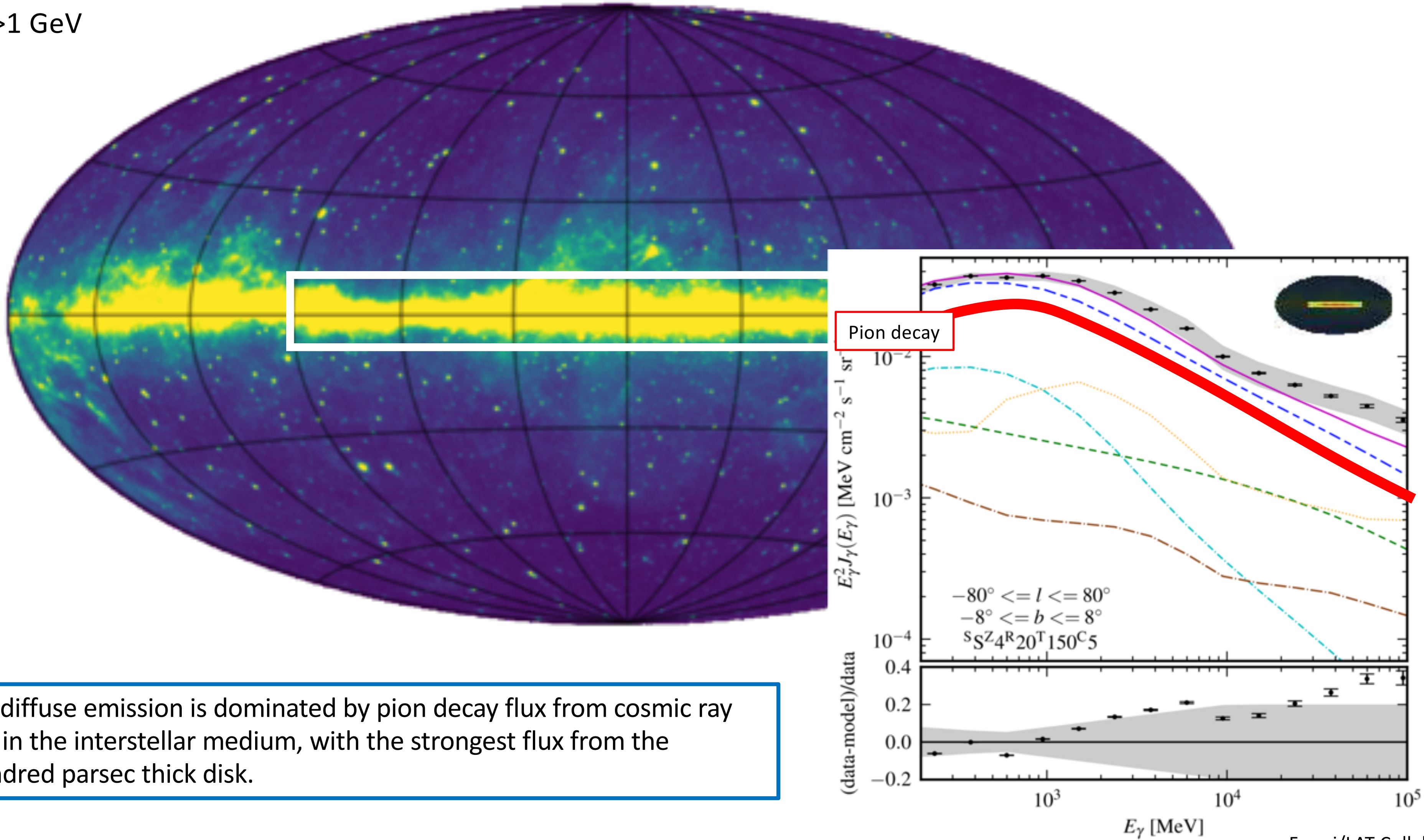


1) **Neutrino and gamma-ray sky**
2) **Gamma-ray diffuse Galactic emission at TeV with Fermi/LAT**
3) **Multi-TeV Galactic diffuse emission with Cherenkov telescopes and EAS arrays**

With D. Semikoz

Gamma-ray sky

Fermi/LAT E>1 GeV

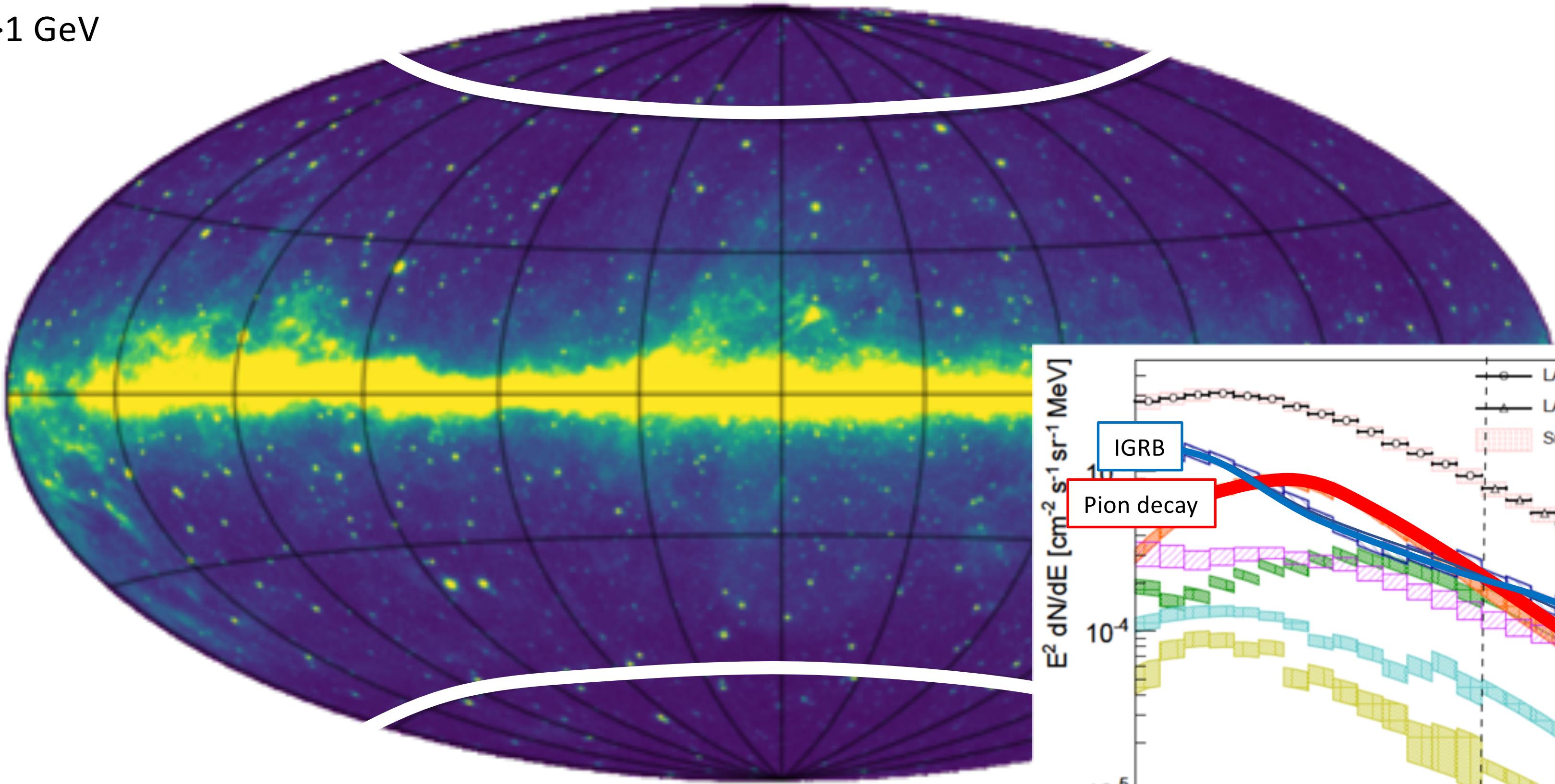


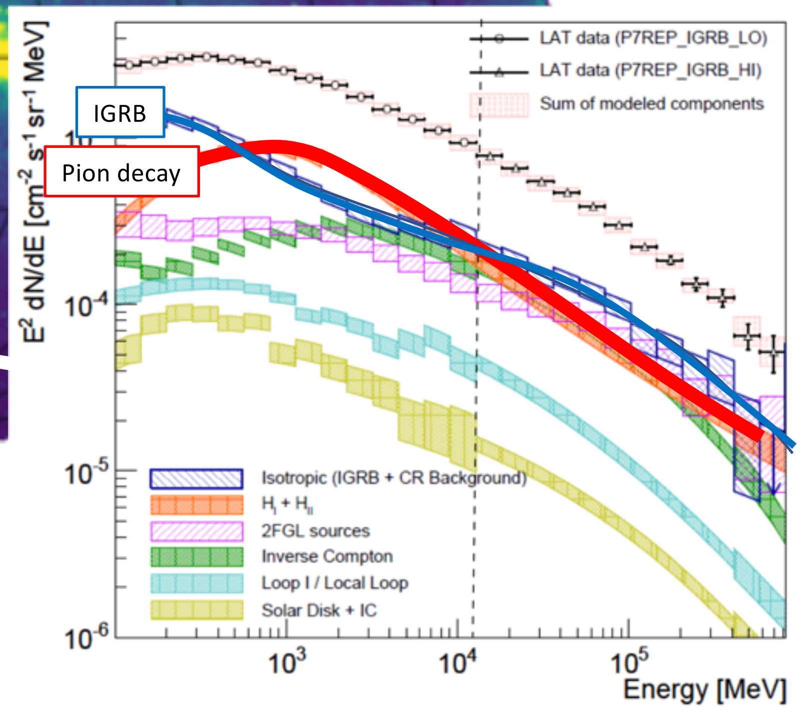
Fermi/LAT Collab. 2012

Gamma-ray diffuse emission is dominated by pion decay flux from cosmic ray interactions in the interstellar medium, with the strongest flux from the (several-hundred parsec thick disk.

Gamma-ray sky

Fermi/LAT E>1 GeV





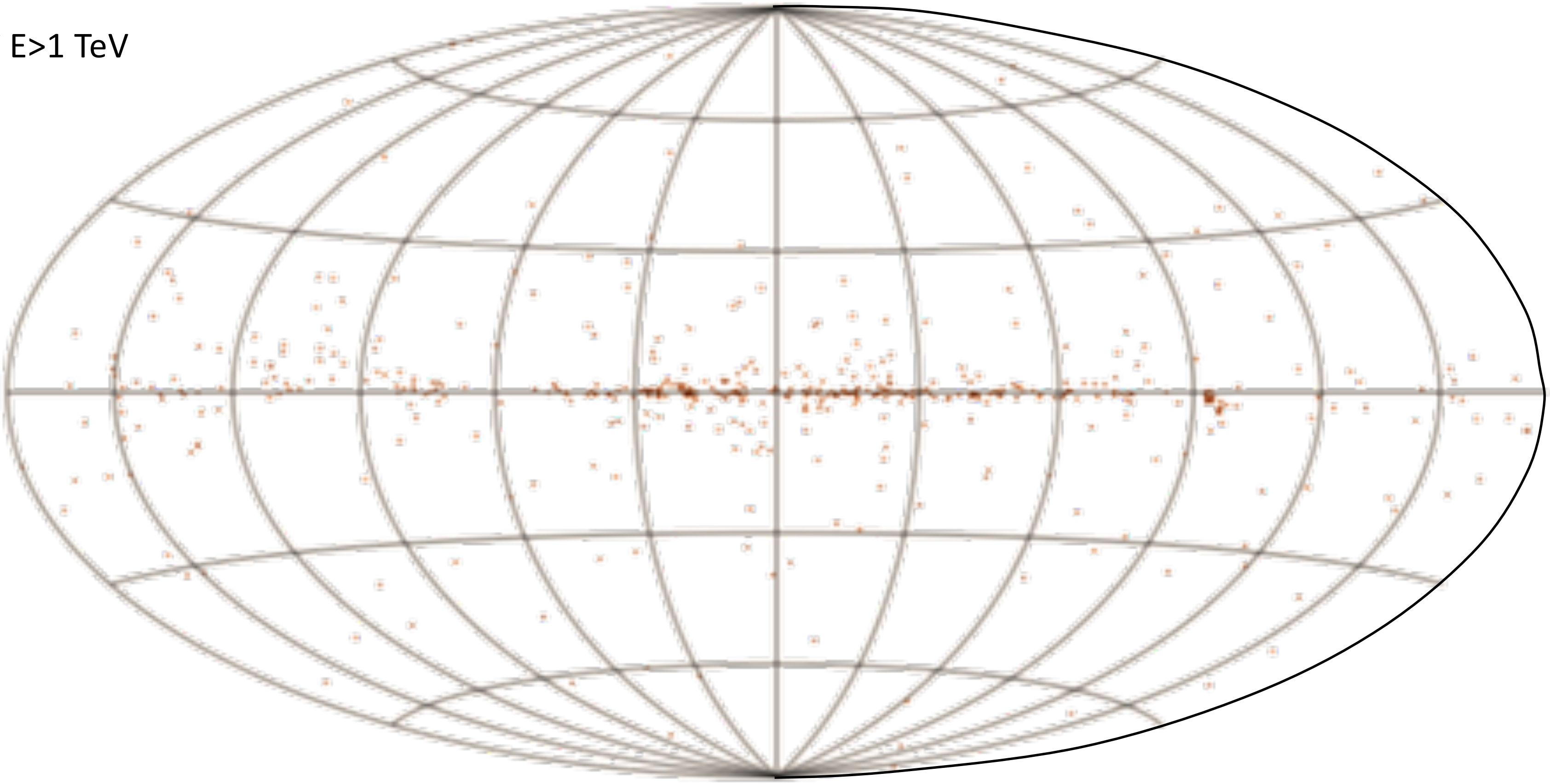
Fermi/LAT Collab. 2015

The weakest pion decay flux is from the Galactic pole regions (>60 degrees galactic latitude), where it is comparable to the isotropic diffuse background flux.

The isotropic flux at highest energies is dominated by (resolved and unresolved) blazars.

Gamma-ray sky

Fermi/LAT E>1 TeV

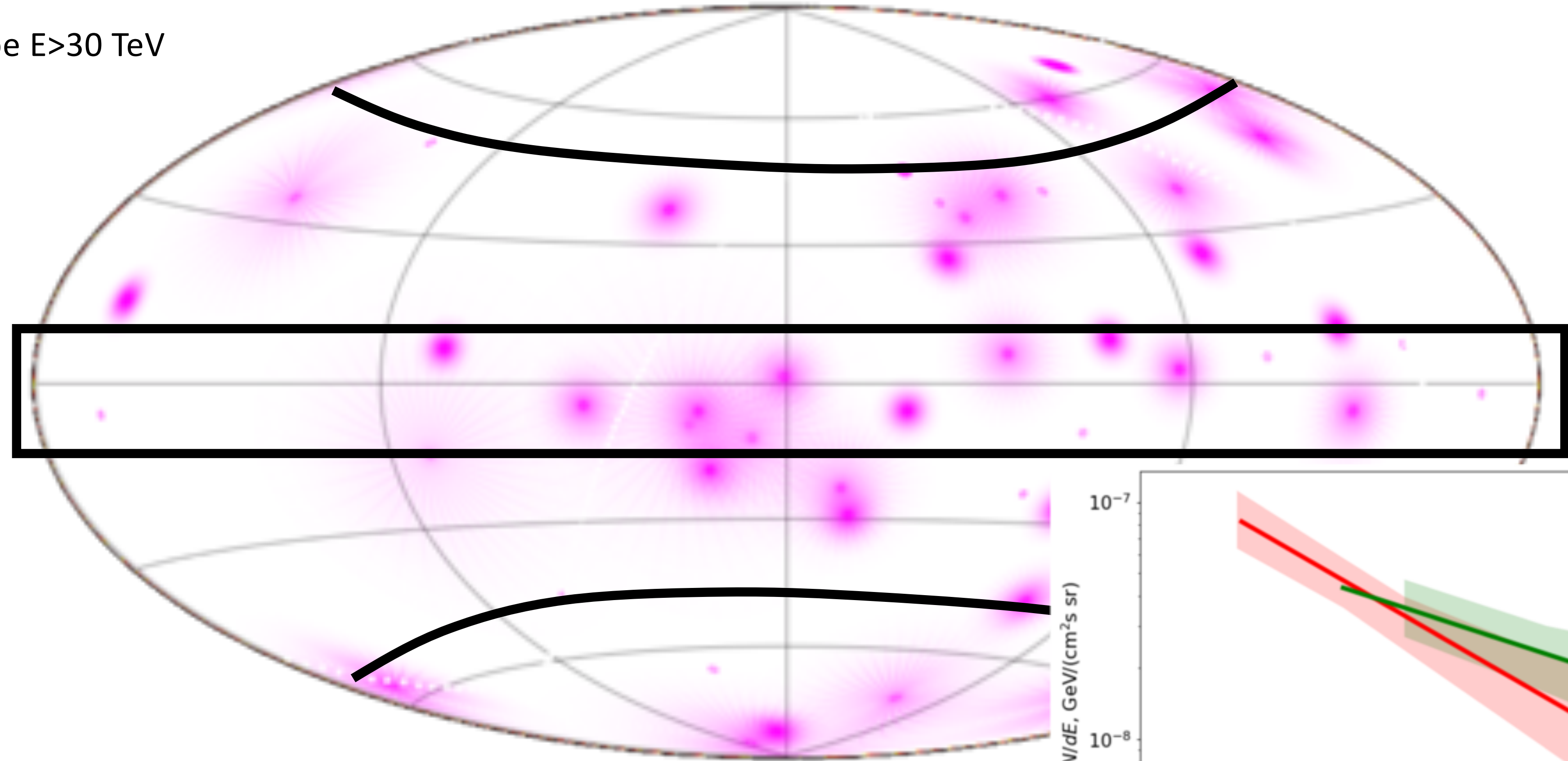


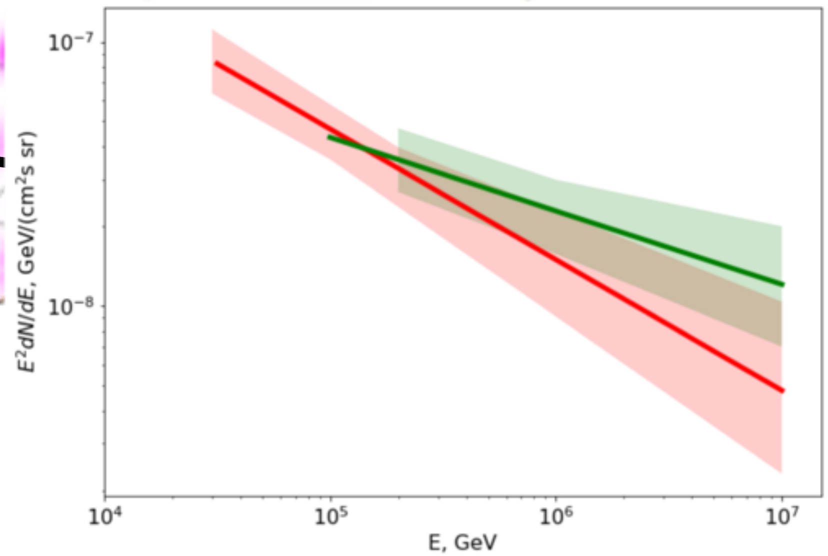
Fermi-LAT is running out of statistics above 1 TeV (about 500 photons in the TeV image above).

Ground-based telescopes (HESS, MAGIC, VERITAS, HAWC, LHAASO) suffer from high charged cosmic ray background contamination at 10 TeV, precluding the measurement of diffuse flux.

Neutrino sky

IceCube E>30 TeV





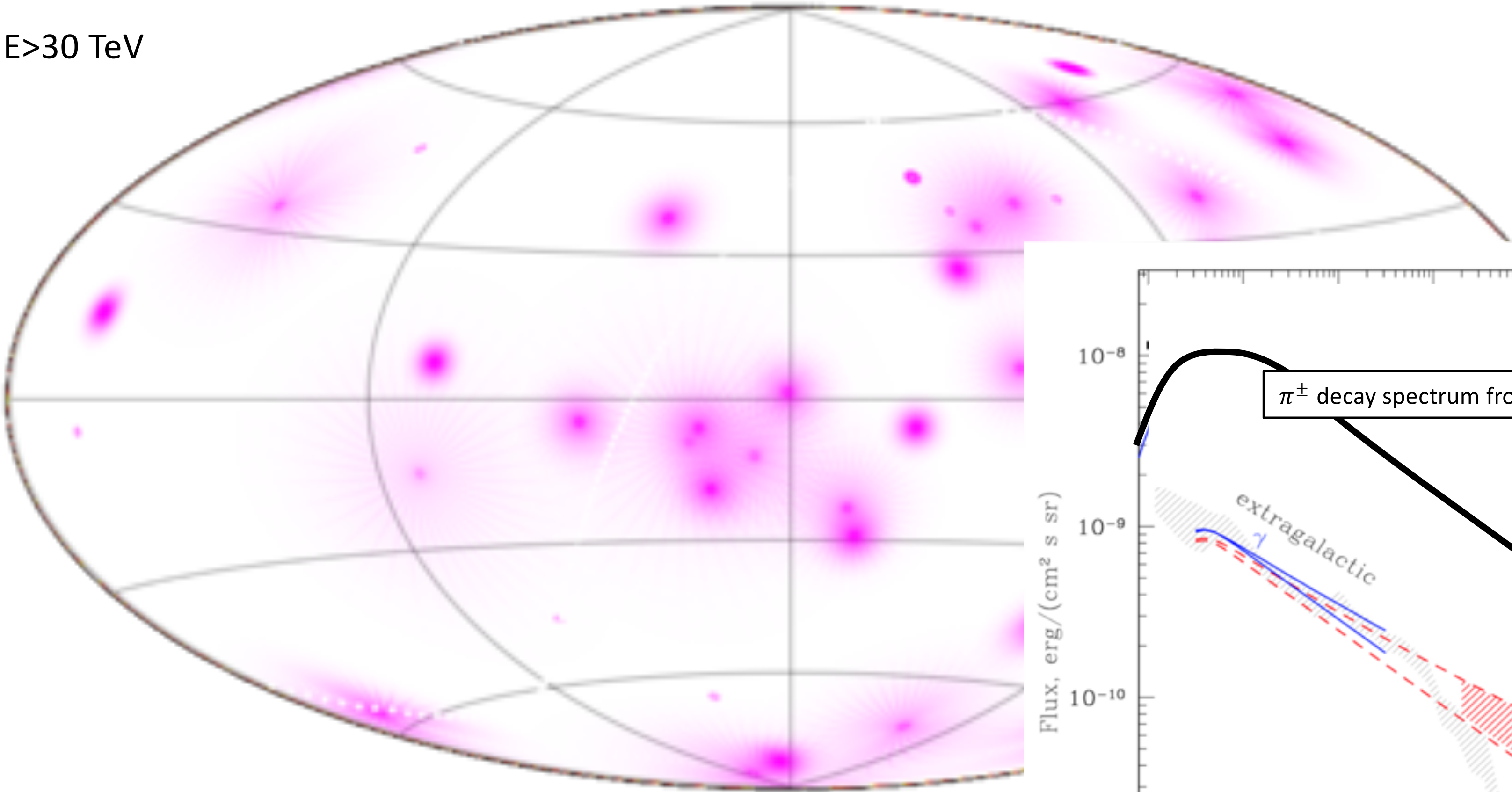
IceCube Collab. 2015

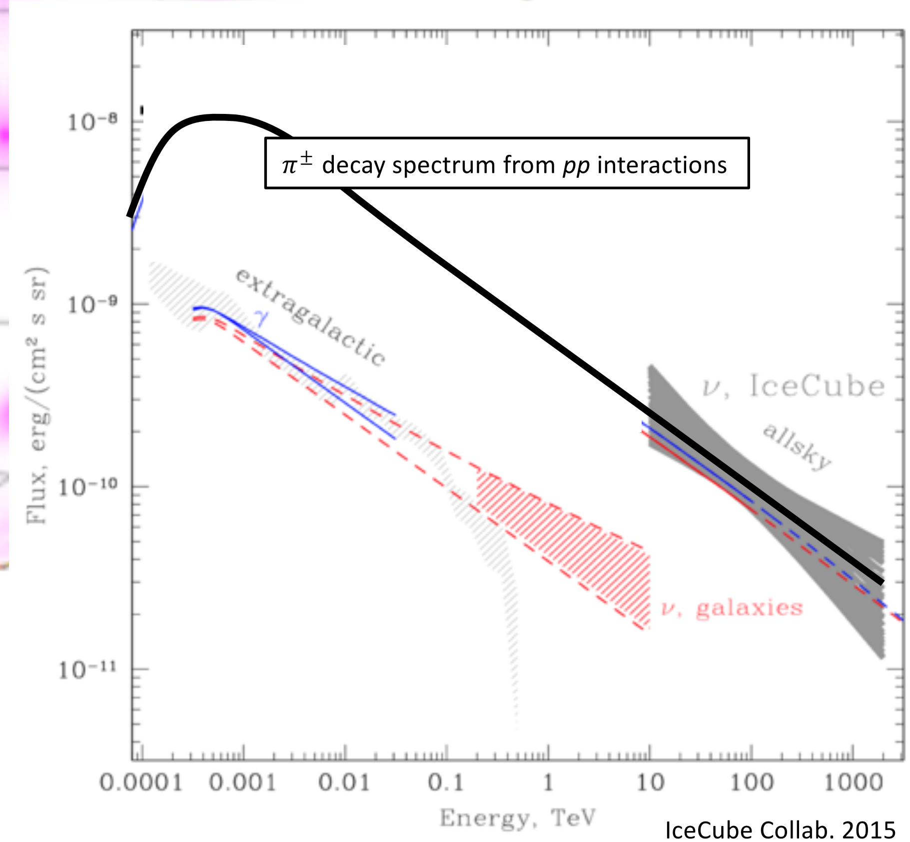
Contrary to diffuse gamma-ray flux, the nature of neutrino flux above 30 TeV is uncertain:

– diffuse or dominated by resolvable sources
– from the Galaxy or extragalactic sources

Neutrino sky

IceCube E>30 TeV



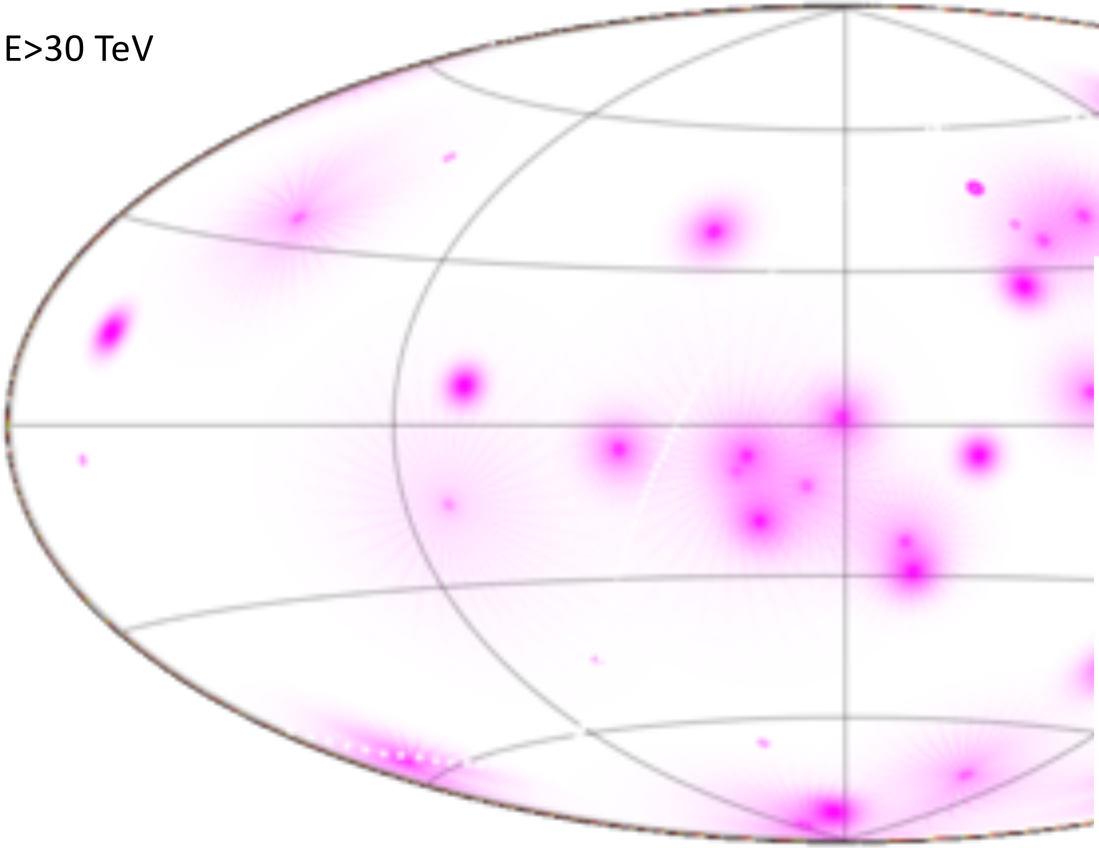


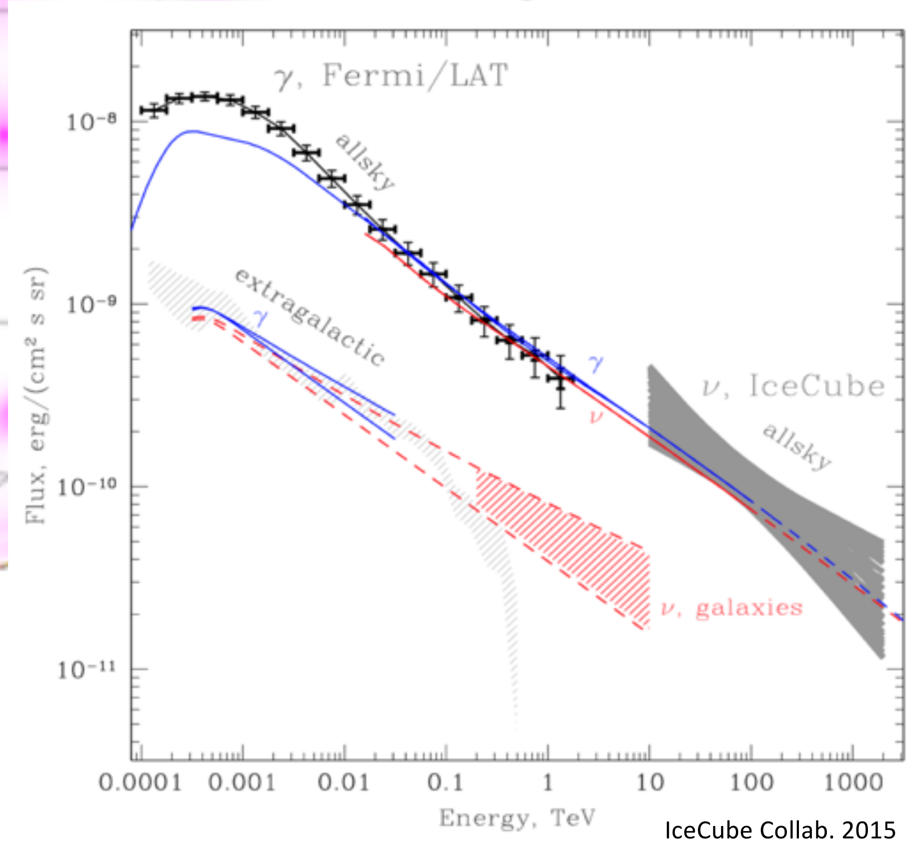
IceCube Collab. 2015
AN, Semikoz 2015

Powerlaw extrapolation (or $\pi^{\pm}$ decay spectrum from *pp*) of HESE / cascade spectrum largely overshoots the extragalactic γ-ray flux.

Neutrino sky

IceCube E>30 TeV



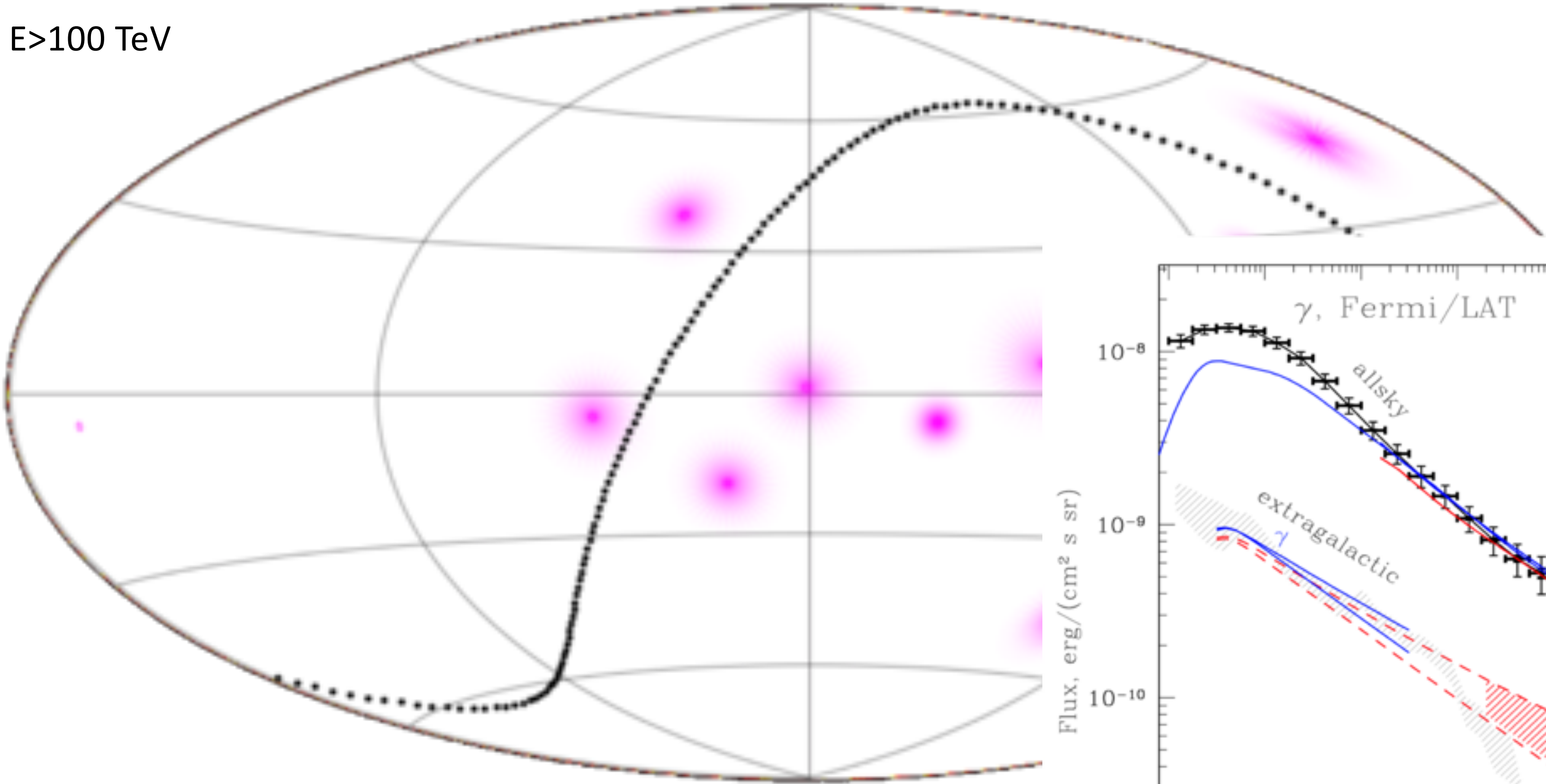


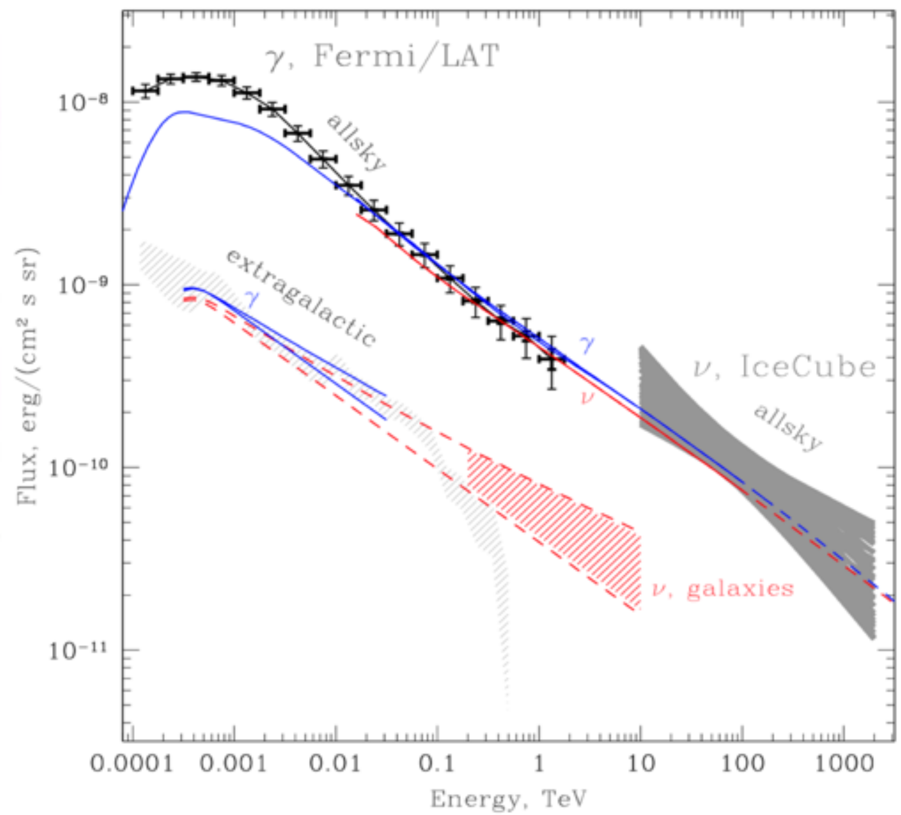
Powerlaw extrapolation (or $\pi^{\pm}$ decay spectrum from *pp*) of HESE / cascade spectrum is consistent with overall diffuse γ-ray flux (dominated by Galactic diffuse emission).

IceCube Collab. 2015
AN, Semikoz 2015

Neutrino sky

IceCube E>100 TeV



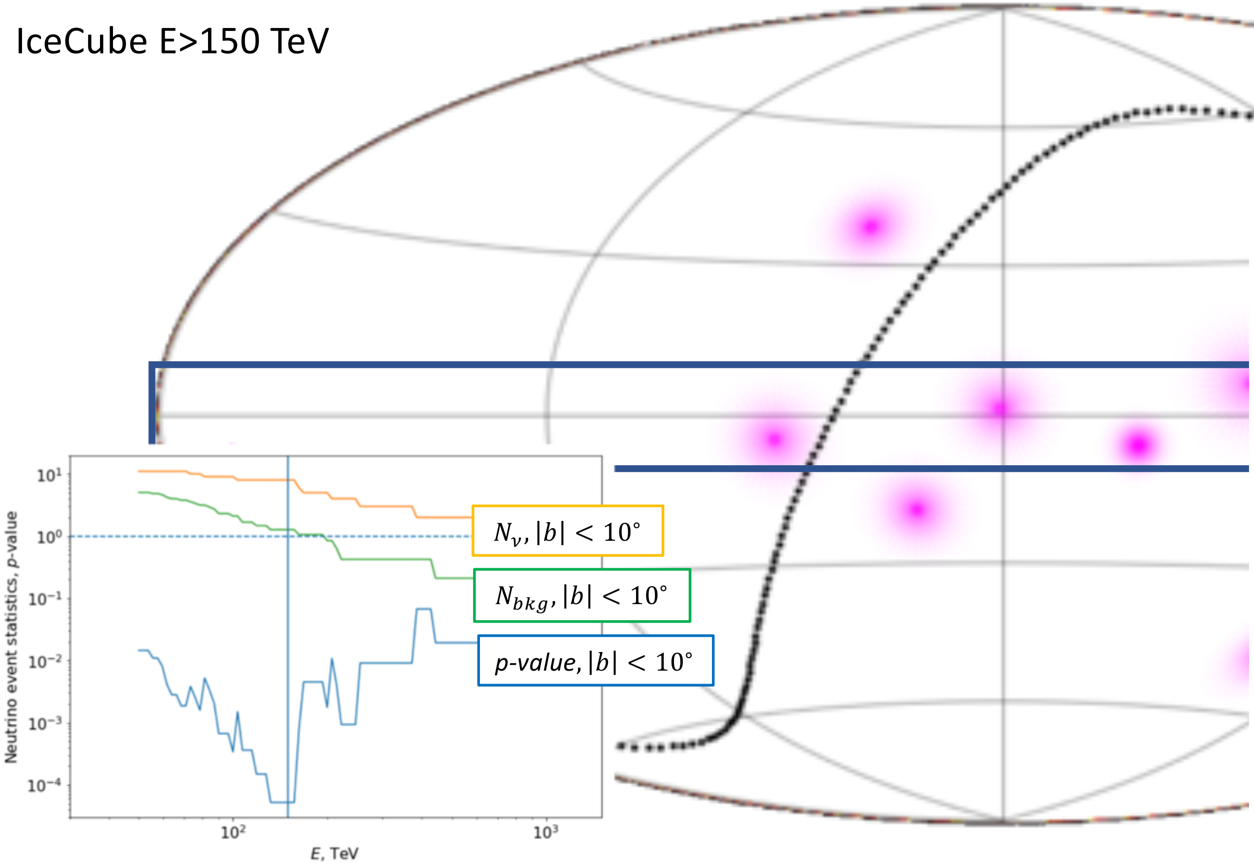


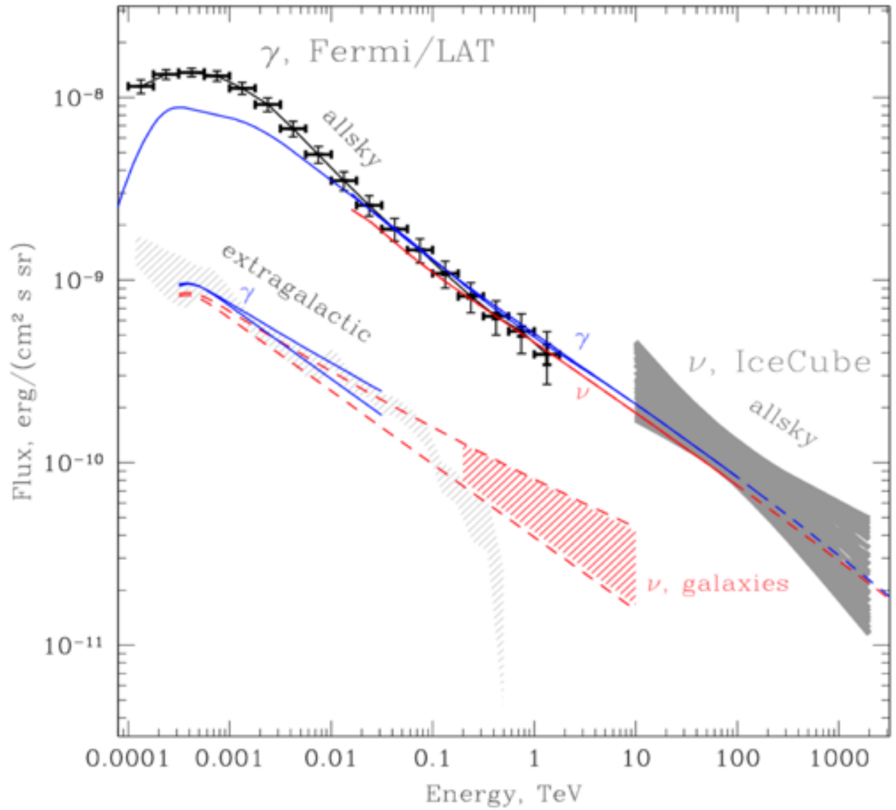
Half of HESE event flux above 30 TeV is from atmospheric background. Going to higher energy allows to reveal possible sky morphology of the signal (presence of non-isotropic component (?).

AN, Semikoz 2015, 2016, 2019

Neutrino sky

IceCube E>150 TeV





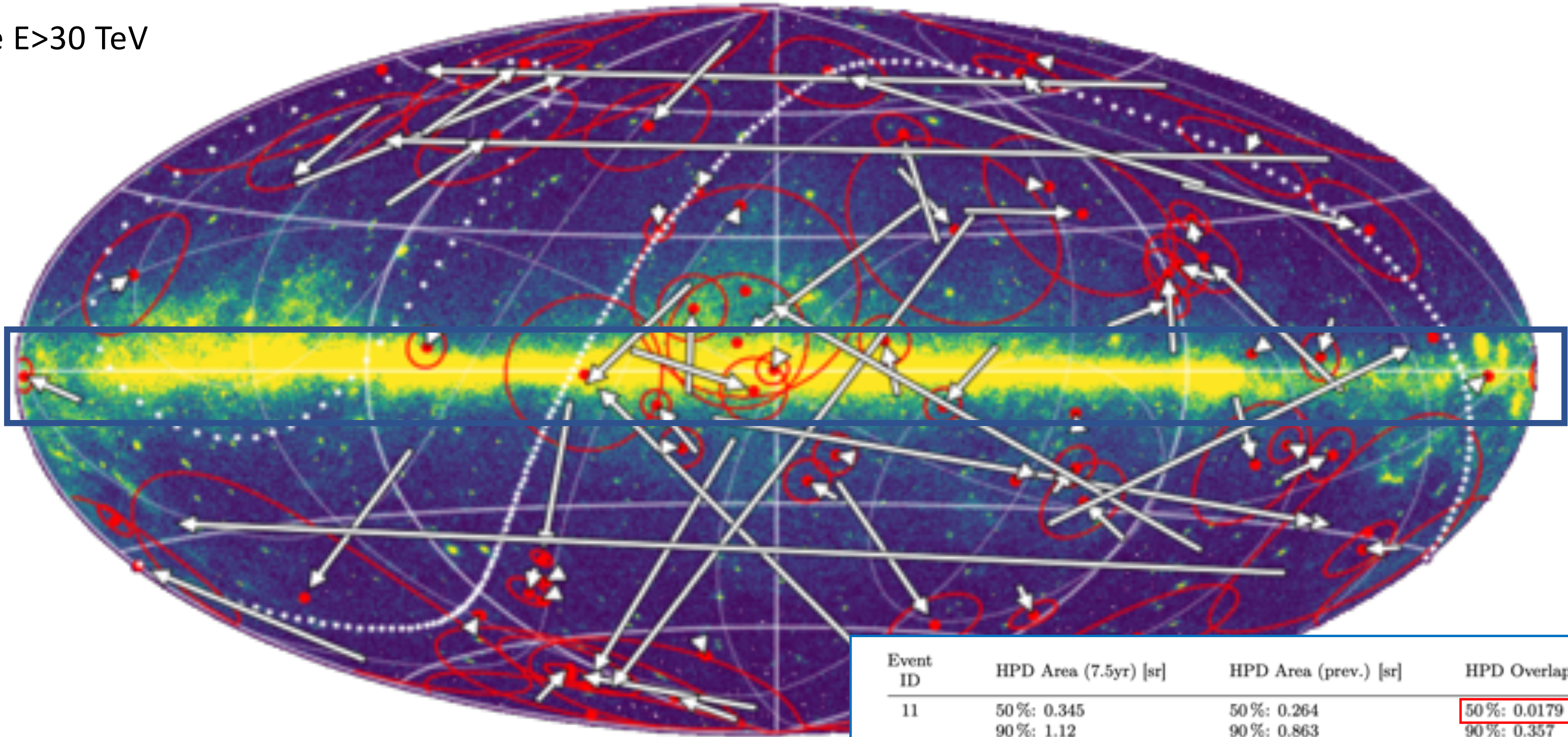
Excess of events toward Galactic Plane is generically expected if the signal has contribution from Galactic diffuse emission from cosmic ray interactions.

Only HESE event sample is publicly available. A $\sim 3\sigma$ (post-trial) excess of low Galactic latitude signal statistics has been present in initial 4-year HESE sample.

AN, Semikoz 2015, 2016, 2019

Neutrino sky

IceCube E>30 TeV
revised



Event ID	HPD Area (7.5yr) [sr]	HPD Area (prev.) [sr]	HPD Overlap Area [sr]
11	50%: 0.345	50%: 0.264	50%: 0.0179
	90%: 1.12	90%: 0.863	90%: 0.357
12	50%: 0.0881	50%: 0.0920	50%: 0.0429
	90%: 0.296	90%: 0.304	90%: 0.219
13	50%: 0.0269	50%: 1.36×10^{-3}	50%: 0.00
	90%: 0.0893	90%: 4.51×10^{-3}	90%: 0.00
14	50%: 0.0445	50%: 0.167	50%: 0.0445
	90%: 0.148	90%: 0.547	90%: 0.148
15	50%: 0.219	50%: 0.367	50%: 0.0242
	90%: 0.536	90%: 1.19	90%: 0.290
16	50%: 0.787	50%: 0.358	50%: 0.109

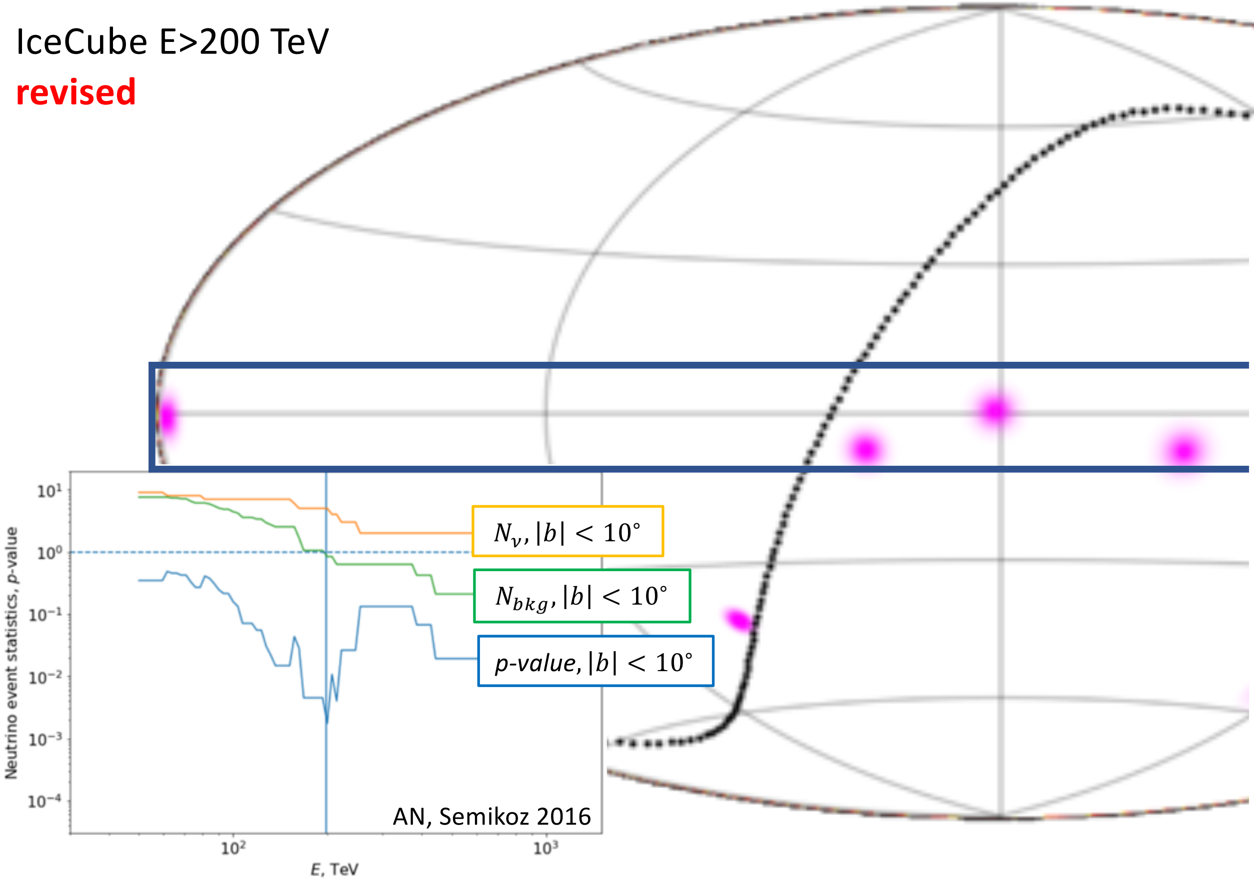
....

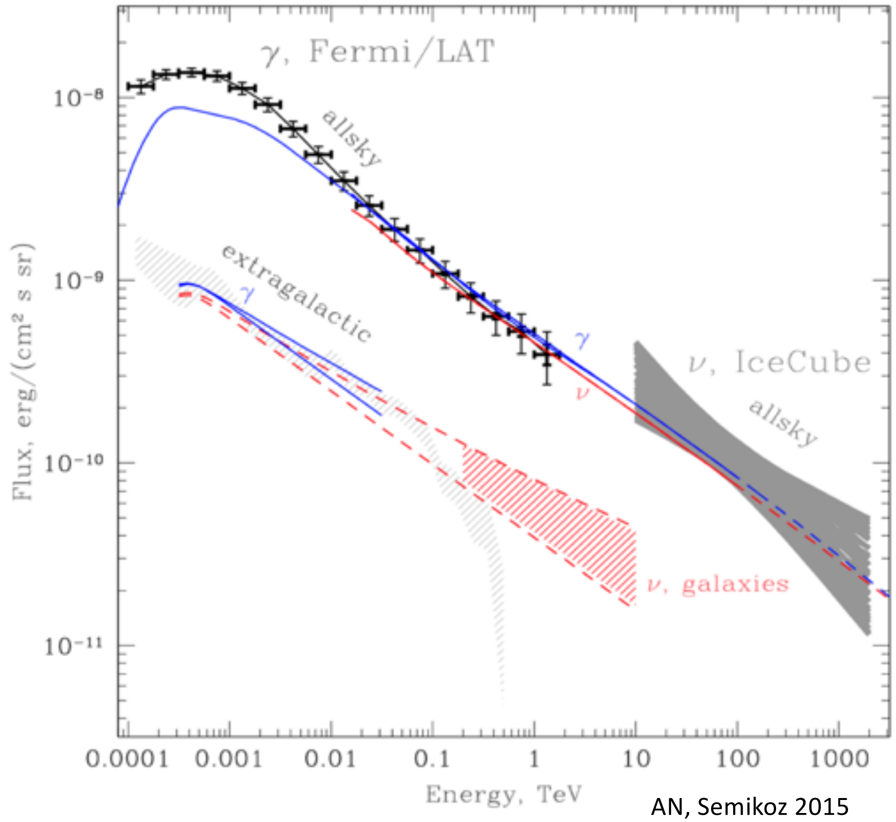
Re-analysis of ice properties has led to significant revision of IceCube HESE events. Positions shift by more than median error (which was already ~15°.
Sizes of error regions also have increased.

IceCube Collab. 2020

Neutrino sky

IceCube E>200 TeV
revised





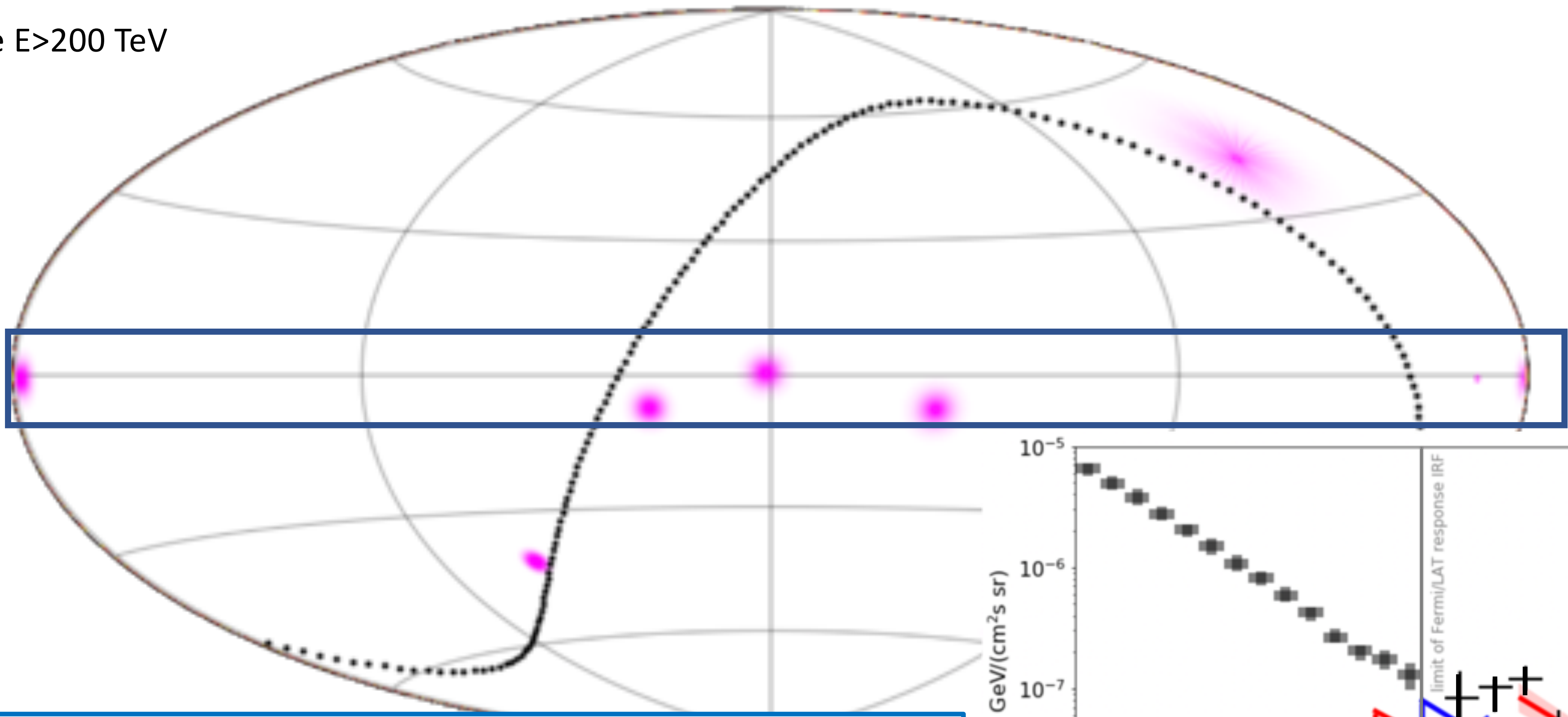
AN, Semikoz 2015
AN, Semikoz 2019

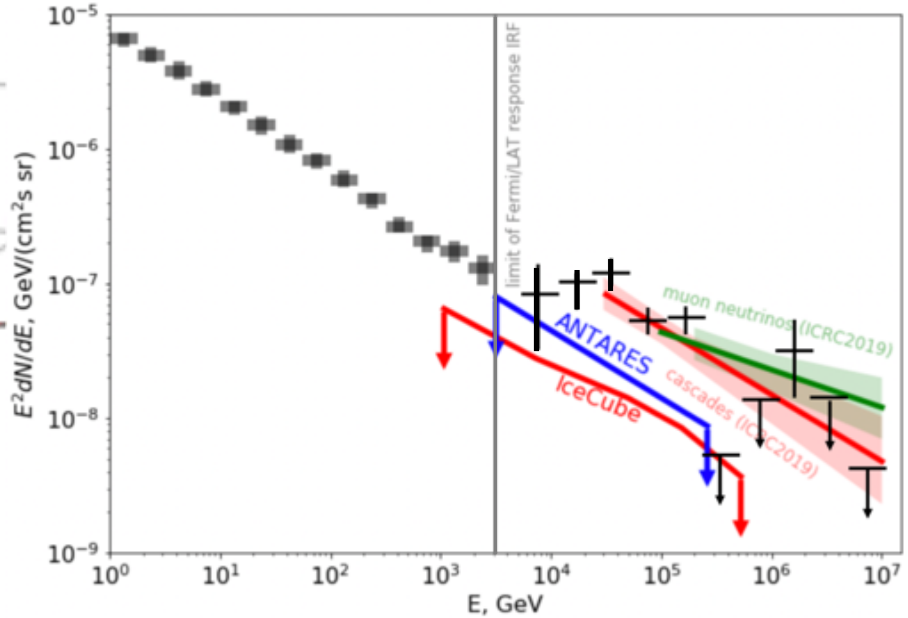
Revised HESE event sample does not show an excess event count toward low Galactic latitudes (p-value down from 5e-5 to 2e-3 pre-trial).

Does this constrain the Galactic diffuse emission from cosmic ray interactions in the interstellar medium?

Neutrino sky

IceCube E>200 TeV
revised





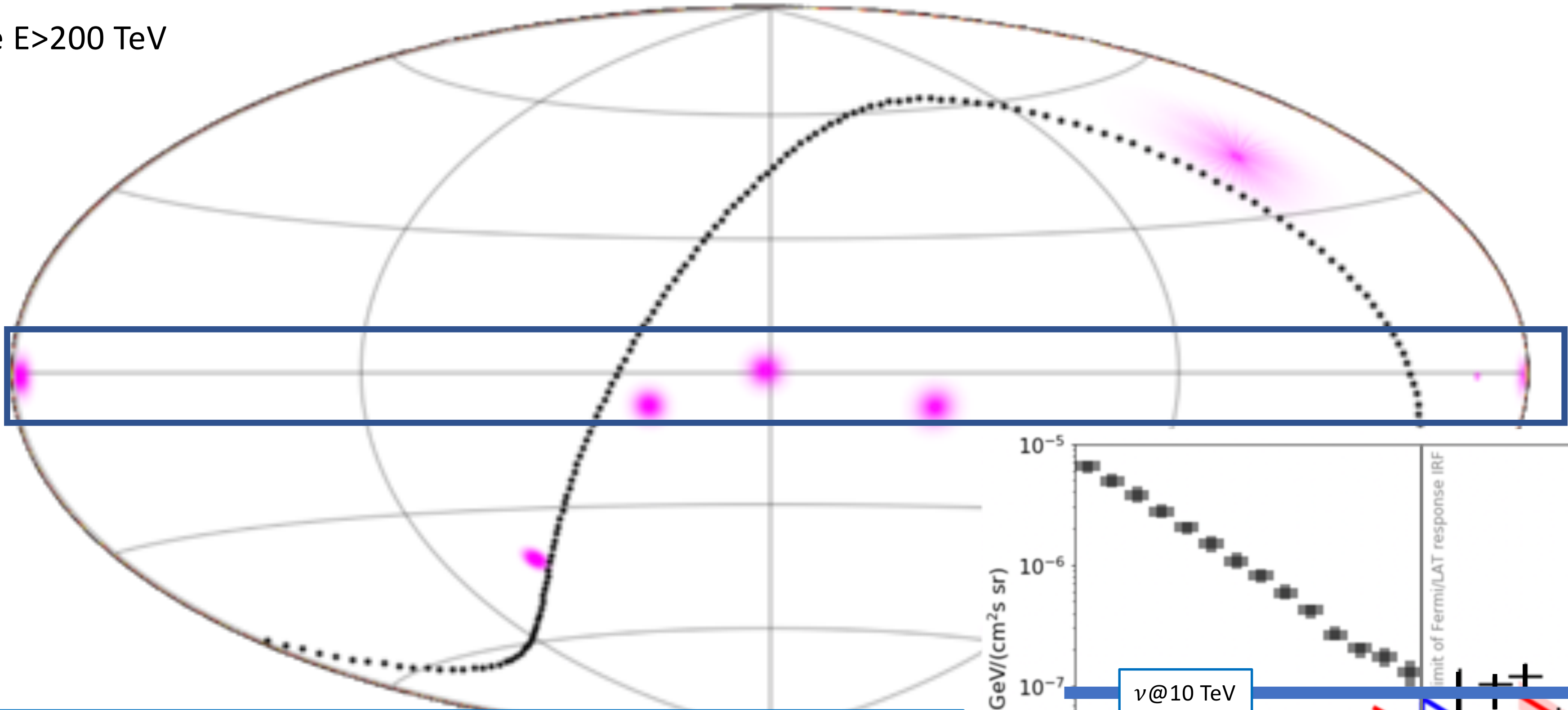
IceCube Collab. '17, '18 ANTARES Collab. 17, '18

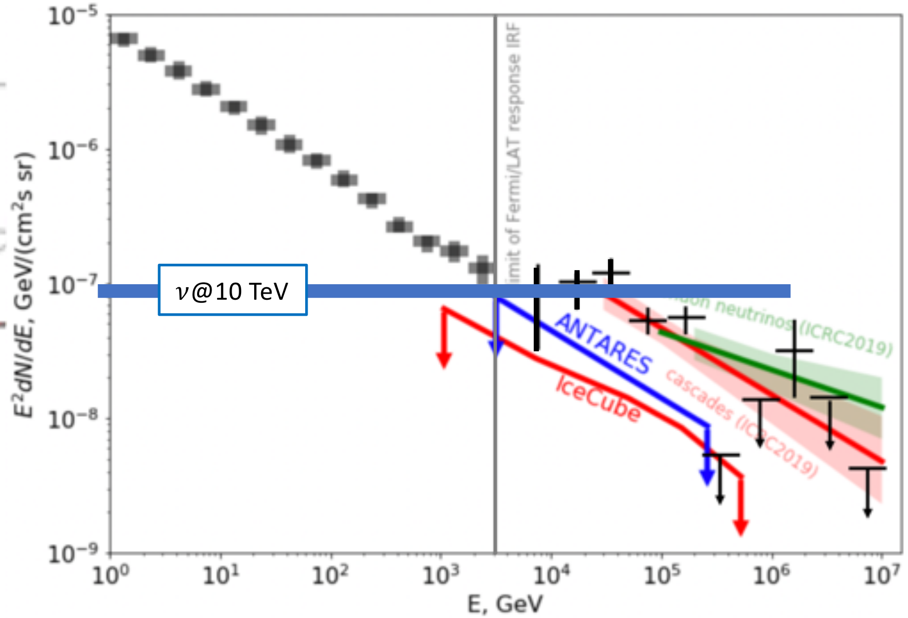
IceCube and ANTARES have attempted to constrain the flux of "Galactic component" by fitting a template for $\pi^{\pm}$decay emission inspired by Fermi diffuse emission data.

It is not evident that we know well the expected template of diffuse flux produced by 1-100 PeV cosmic rays. Better possibility is to constrain the diffuse emission pattern using the neutrino data.

Neutrino sky

IceCube E>200 TeV
revised





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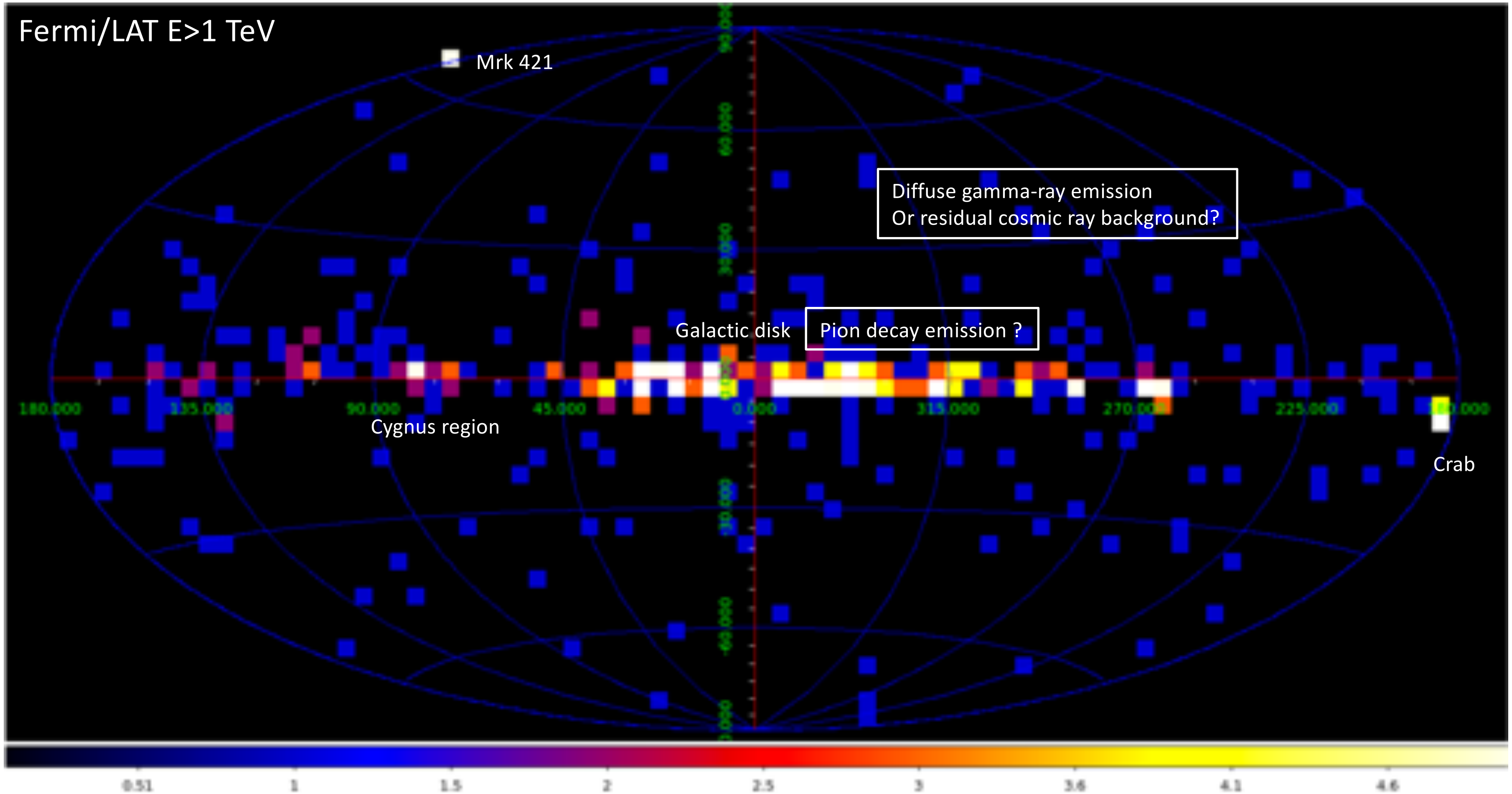
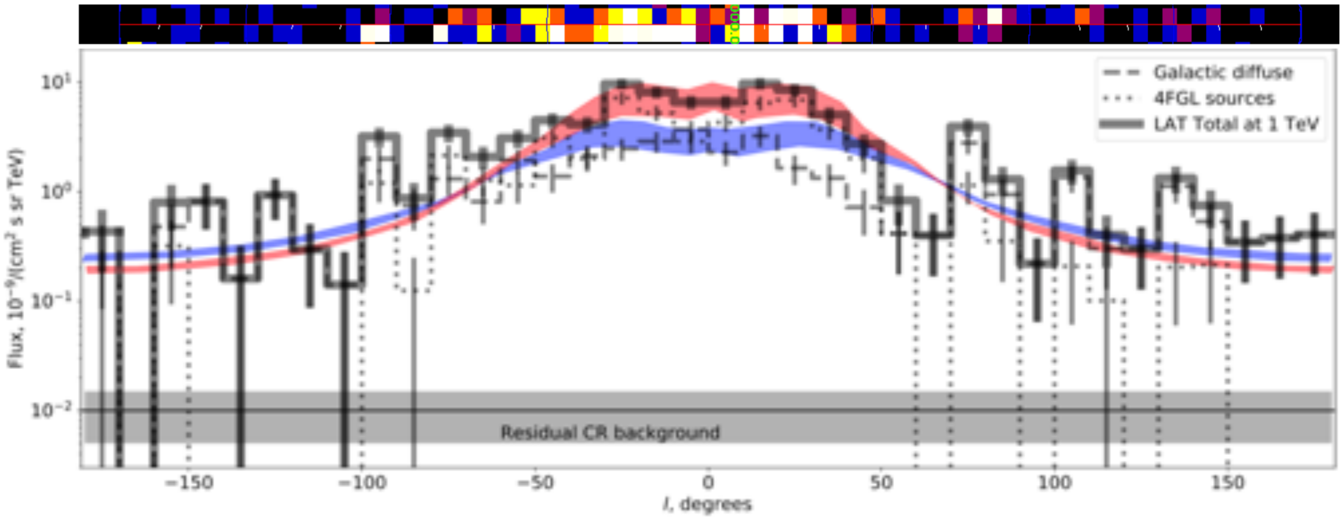
It is not evident that we know well the expected template of diffuse flux produced by 1-100 PeV cosmic rays. Better possibility is to constrain the diffuse emission pattern using gamma-ray and neutrino data.

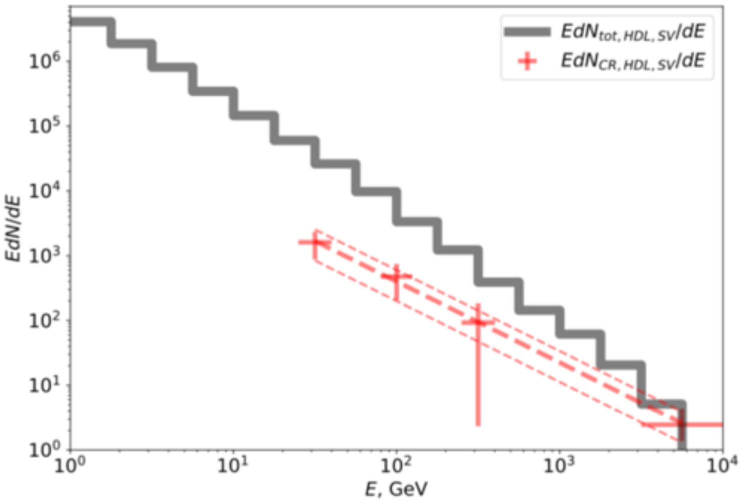
Diffuse gamma-ray emission in multi-TeV band

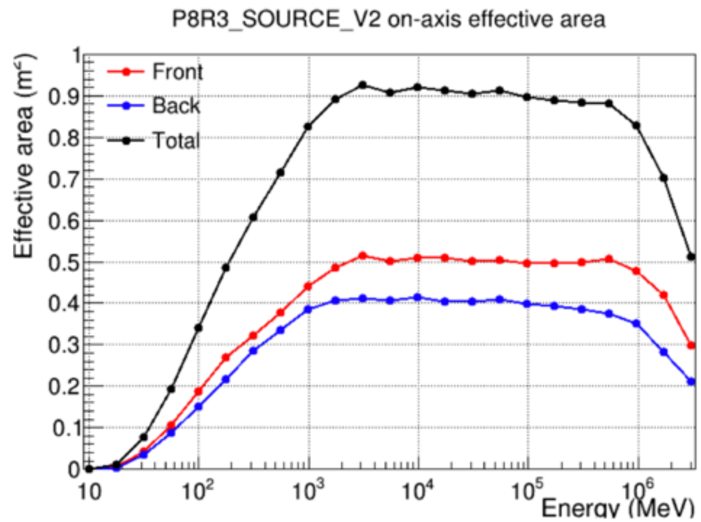


AN, Semikoz '19

Diffuse multi-TeV emission from Galactic Plane



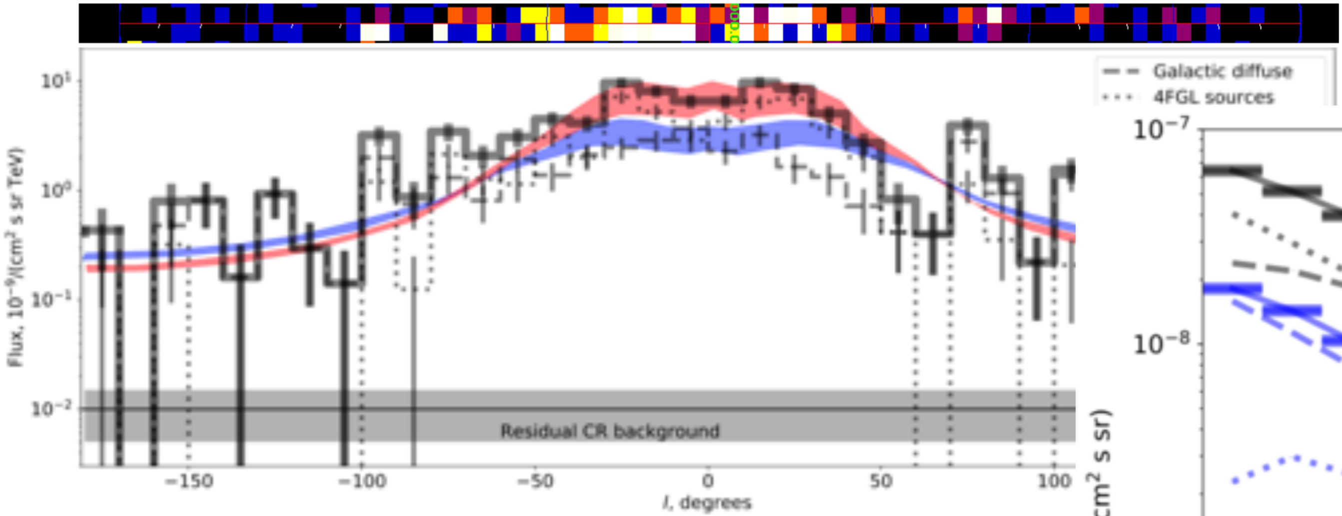


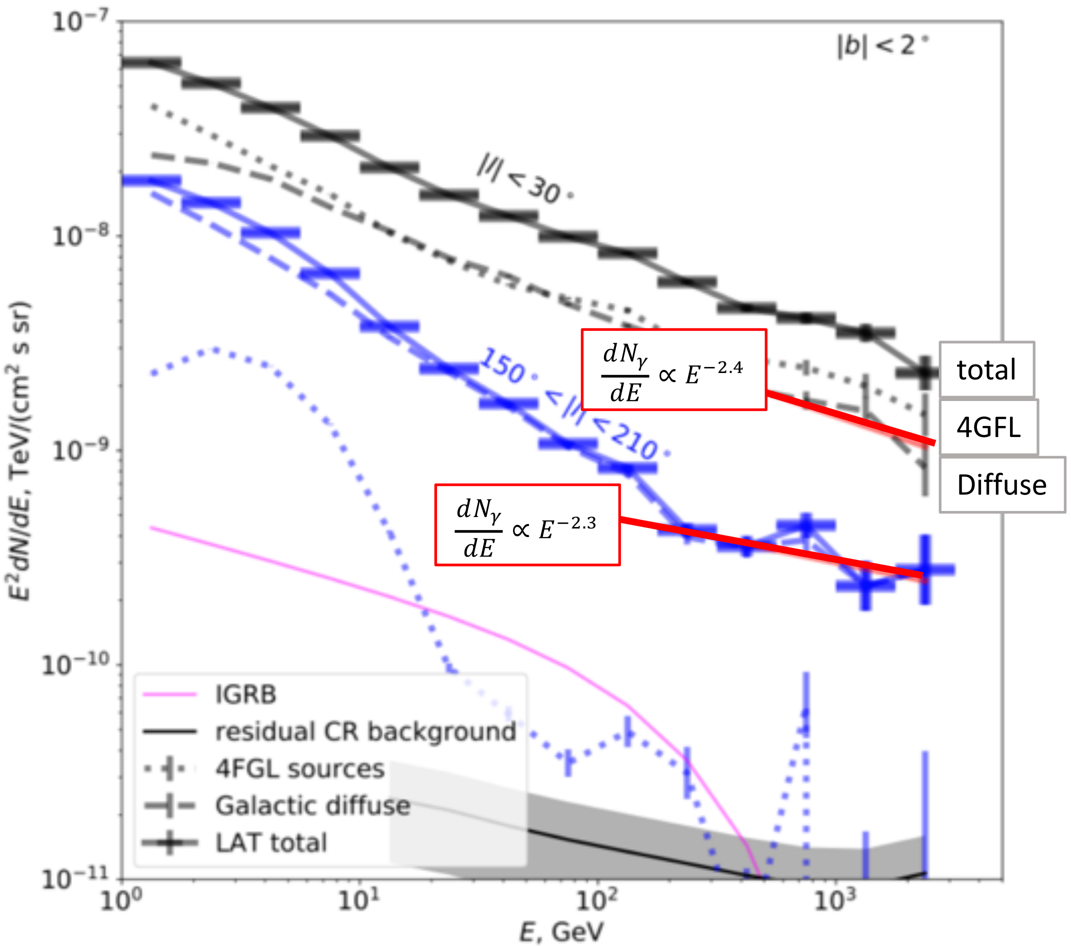


In spite of small (and decreasing) effective area in multi-TeV range, Fermi/LAT is well suited for the measurement of diffuse Galactic flux in this band, because of very good charged cosmic ray background rejection.

Bruel et al. '18
AN, Semikoz '19

Diffuse multi-TeV emission from Galactic Plane



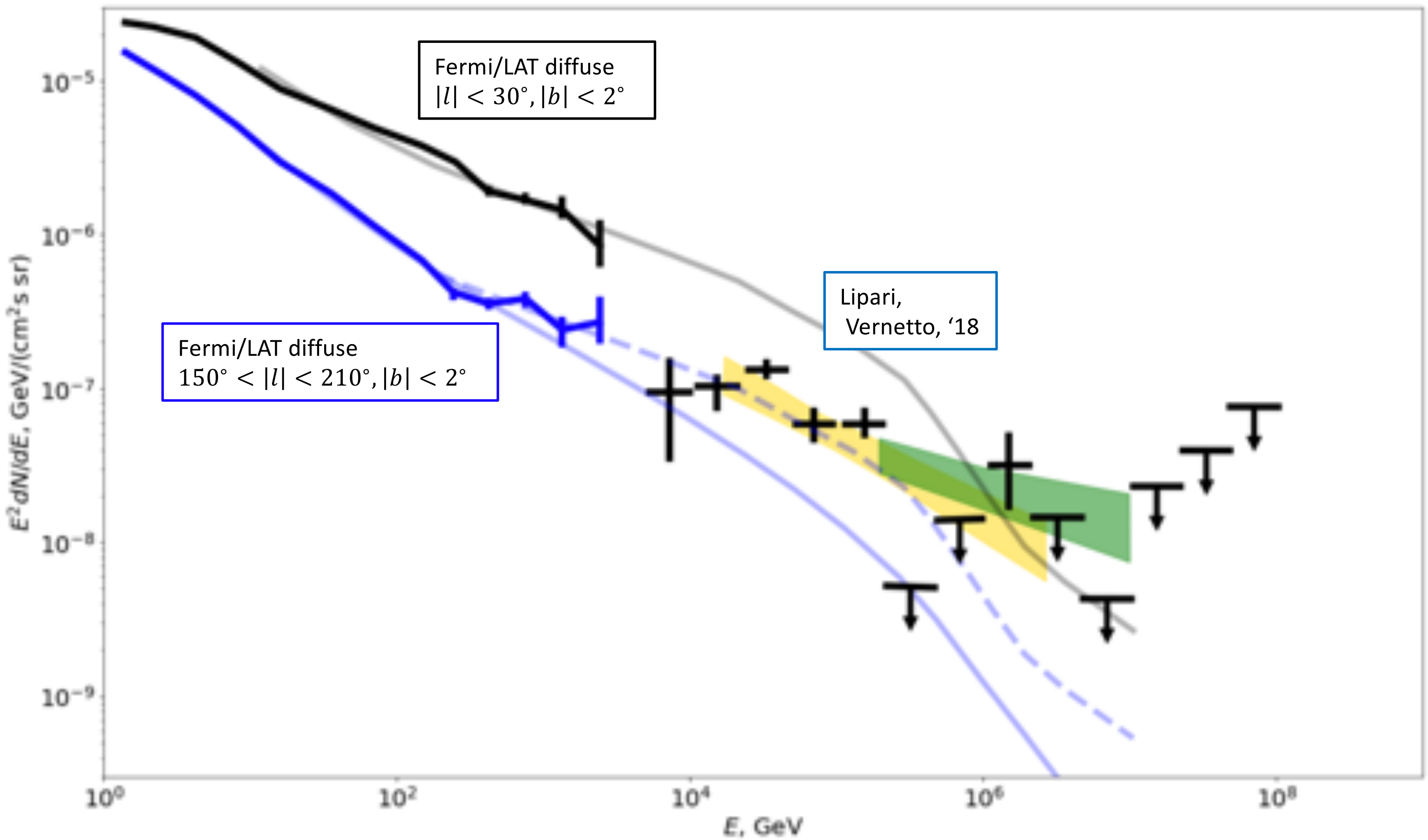


The Galactic Plane flux from $|b| < 2°$ (diffuse emission, circles around 4FGL sources excluded) has the slope $\Gamma \simeq 2.4$.

If the diffuse emission is from cosmic ray interactions, the slope of the parent 10-100 TeV cosmic ray spectrum is much harder than locally measured cosmic ray spectrum in the same energy range.

AN, Semikoz '19

Diffuse multi-TeV emission from Galactic Plane

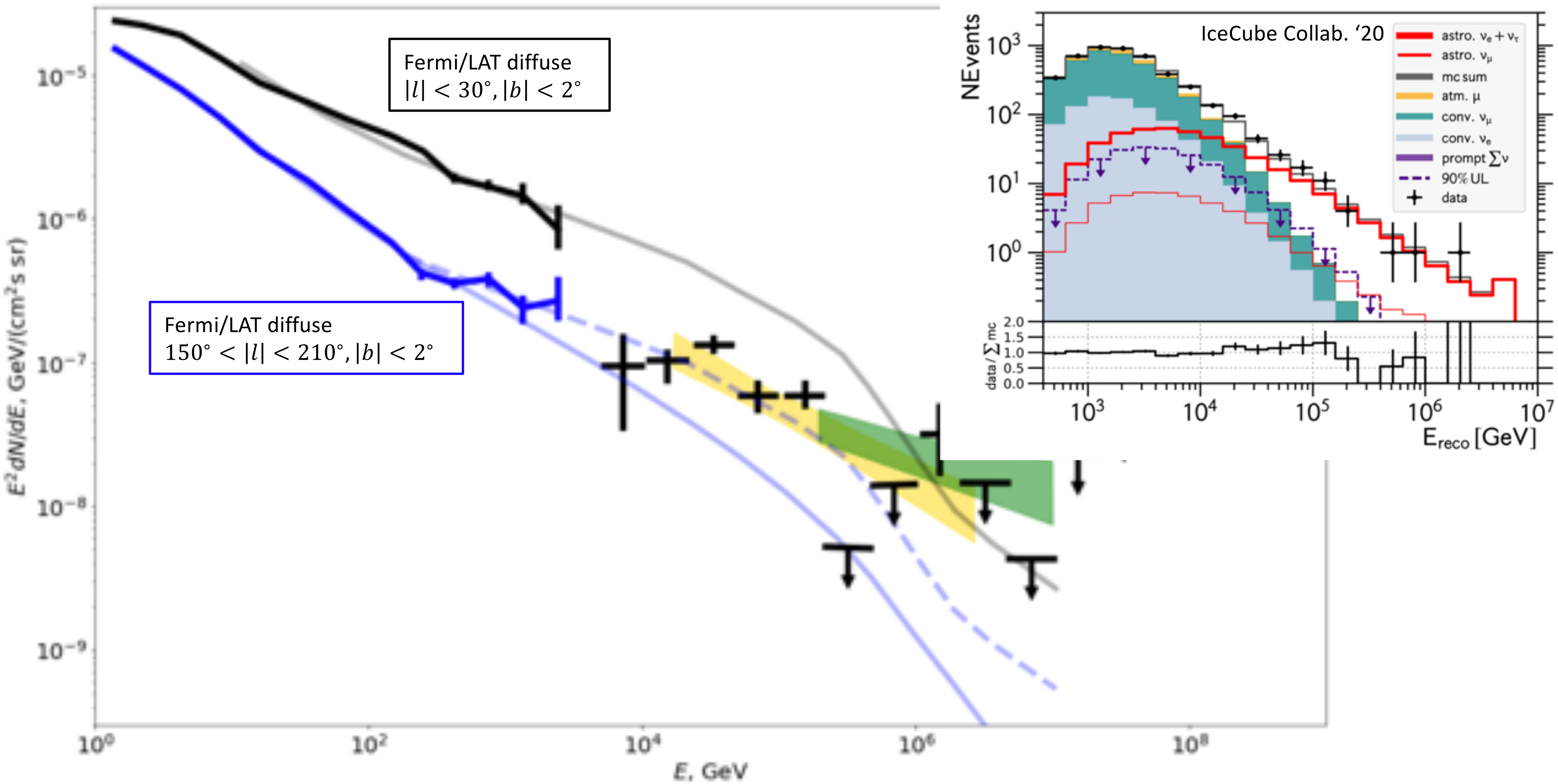


The flux from the Galactic Plane ($|b| < 2°$) is typically higher than the IceCube flux level.

Does this suggest a sharp cut-off in at 10 TeV e.g. in the diffuse emission spectrum of inner Galactic Plane?

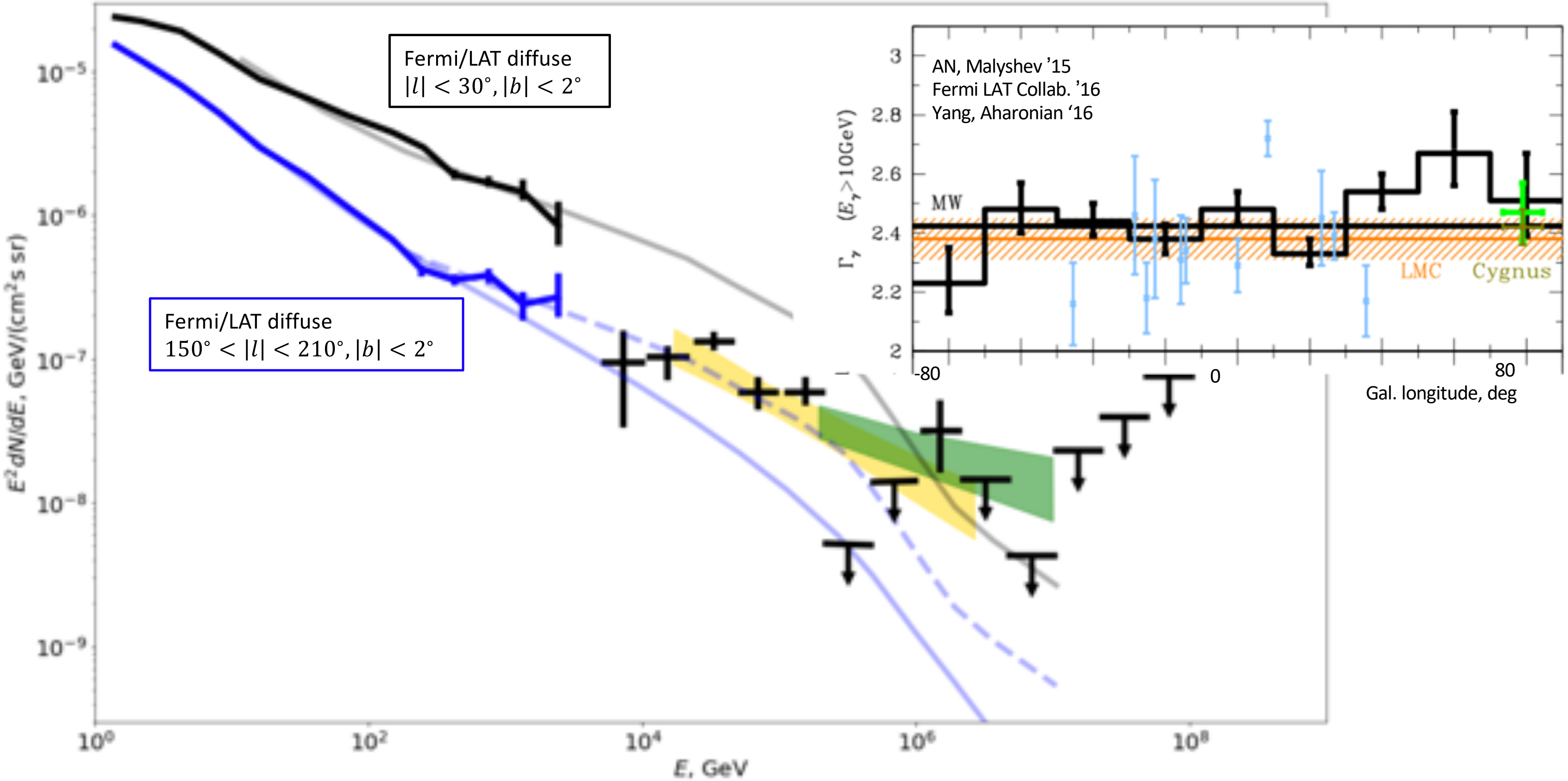
AN, Semikoz '19

Diffuse multi-TeV emission from Galactic Plane



IceCube observes $O(100)$ events from the full sky (4π sr) in cascade event selection: 8 events per sr.
The Galactic Ridge occupies 0.07 sr, with 0.5 isotropic flux events expected.
Gamma-ray flux extrapolation suggest flux 5 times higher than sky-average IceCube flux at 10 TeV, i.e $\sim$ 2.5 event statistics in the Ridge, compatible with observed neutrino statistics.

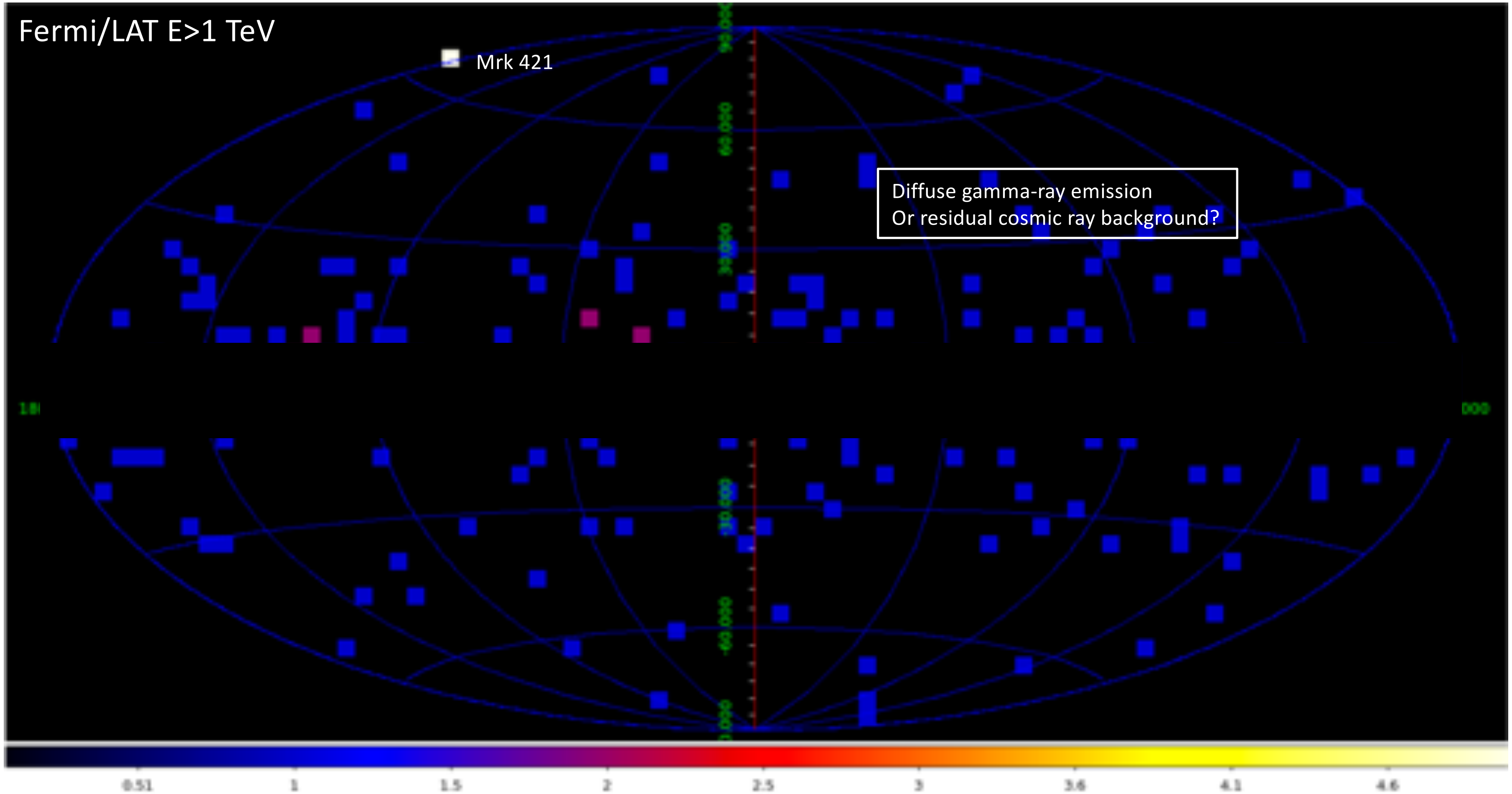
Diffuse multi-TeV emission from Galactic Plane



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 $\Gamma \simeq 2.7$. Detection of Galactic Plane signal with neutrino telescopes will confirm / disprove the hypothesis of spatial variations of cosmic ray spectrum.

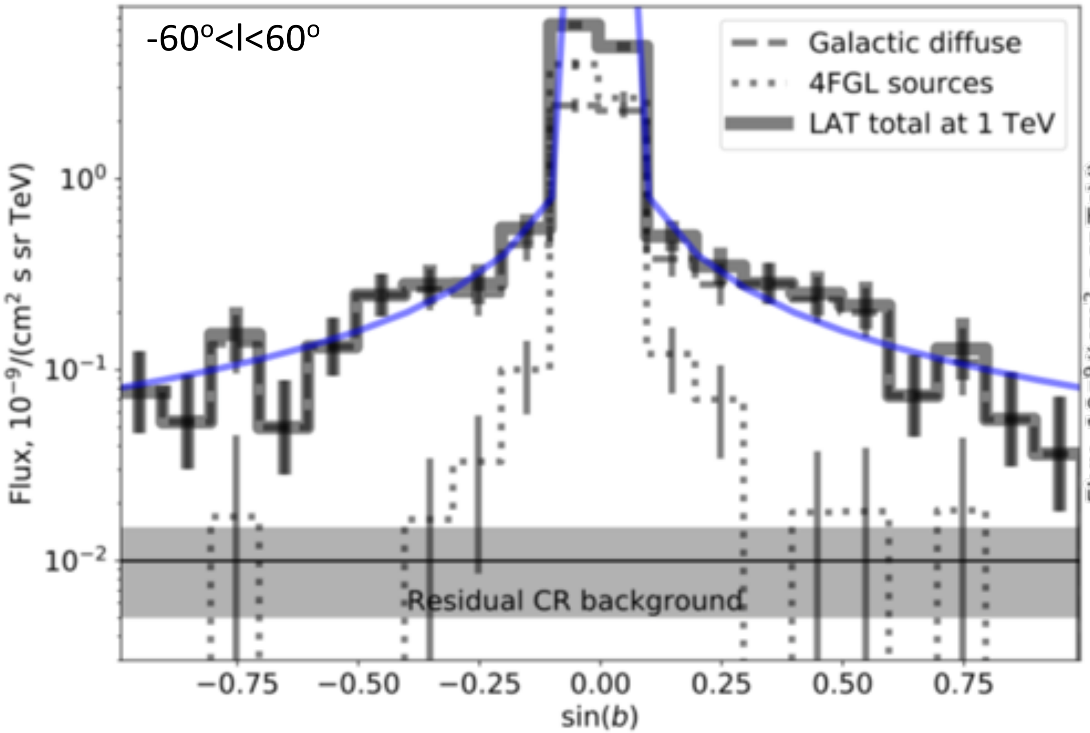
AN, Semikoz '19

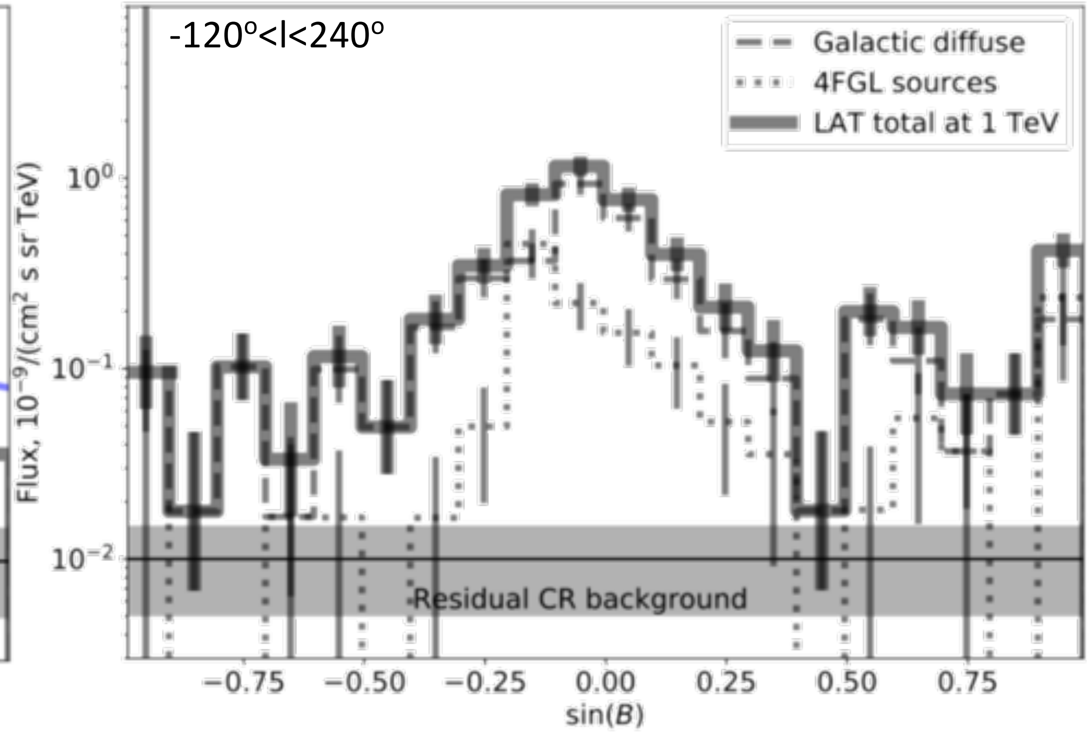
Diffuse multi-TeV emission from high Galactic latitude



AN, Semikoz '19

Diffuse multi-TeV emission from high Galactic latitude

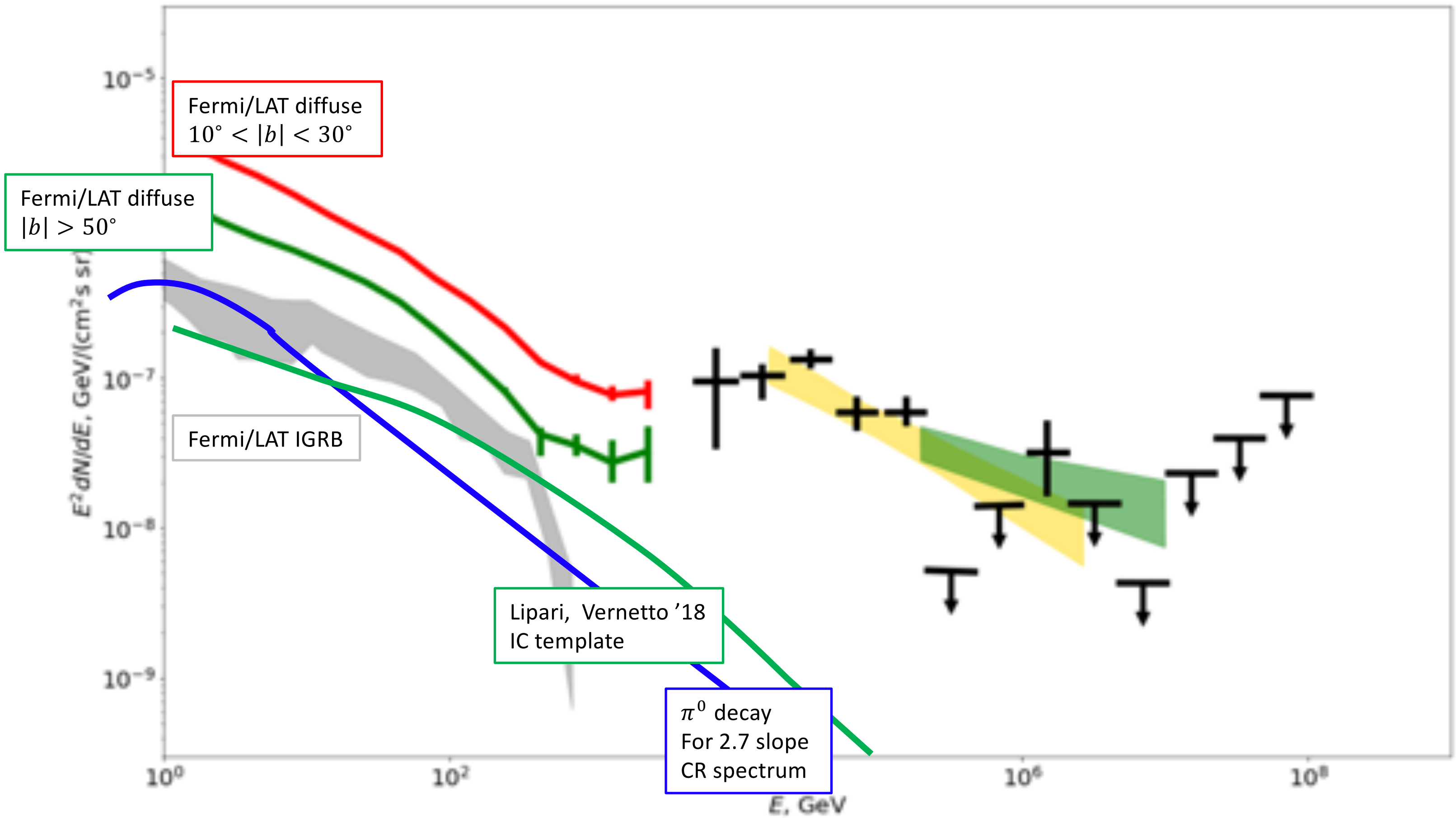




Residual cosmic ray background is also lower than the observed flux at high Galactic latitude. This means that large part of the high-latitude counts with E>1TeV in Fermi/LAT are photons.

AN, Semikoz, '19

Diffuse multi-TeV emission from high Galactic latitude

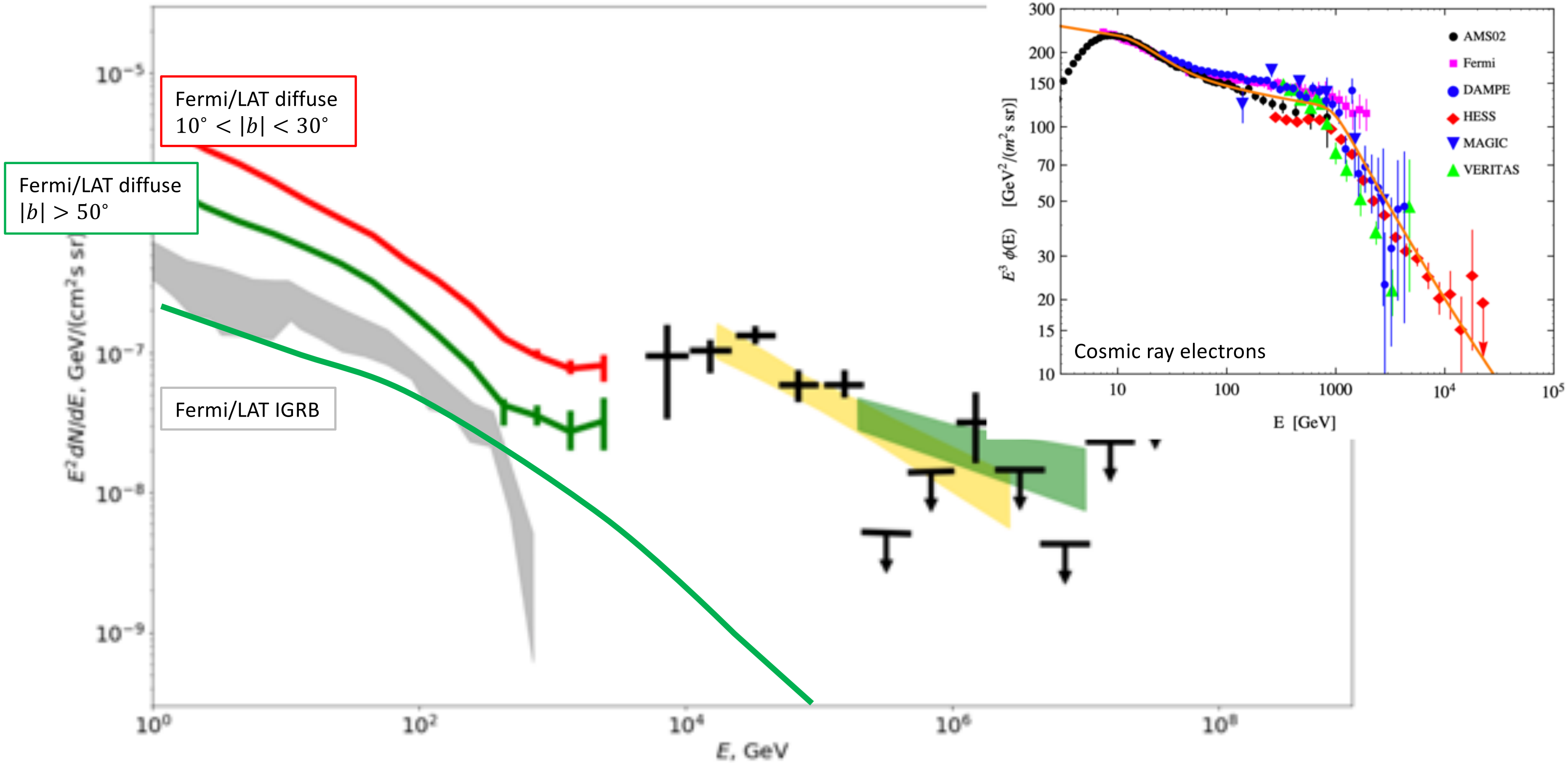


Multi-TeV flux at mid-latitudes is comparable to IceCube flux at 10 TeV.

The TeV flux might have large inverse Compton component from electrons in local interstellar medium (and thus, no neutrino counterpart).

Fermi LAT Collab. '12, '15, Lipari Vernetto '18, AN, Semikoz '19

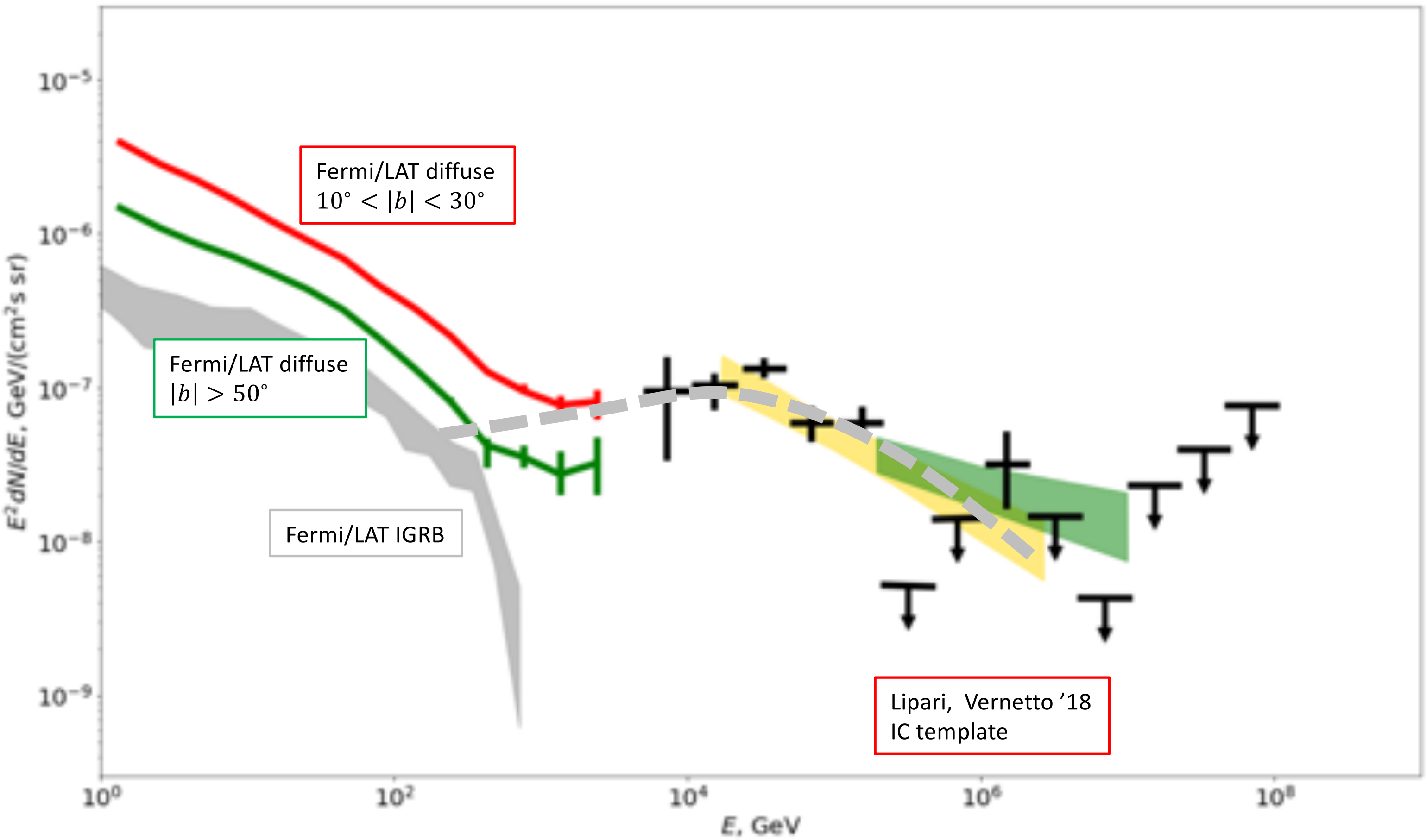
Diffuse multi-TeV emission from high Galactic latitude



The IC flux is gradually suppressed due to Thomson – Klein-Nishina transition and softening of electron spectrum.

AN, Semikoz ‘19

Diffuse multi-TeV emission from high Galactic latitude

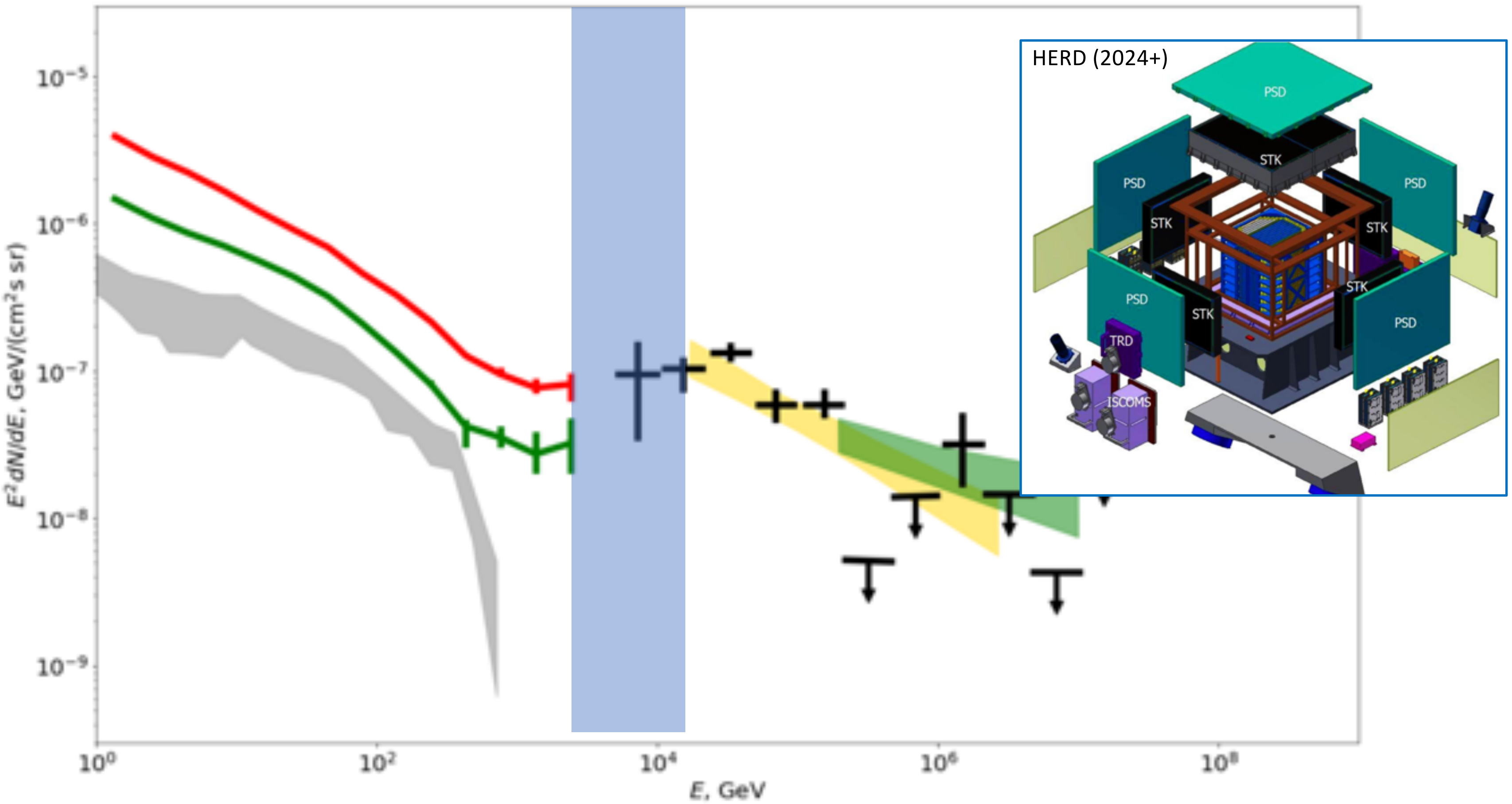


It is possible that gamma-ray counterpart of neutrino flux is still present in the spectrum (e.g. local source component?)

N.B. Contamination of Fermi/LAT TeV flux measurements by residual charged cosmic ray background and energy / effective area to be scrutinized)

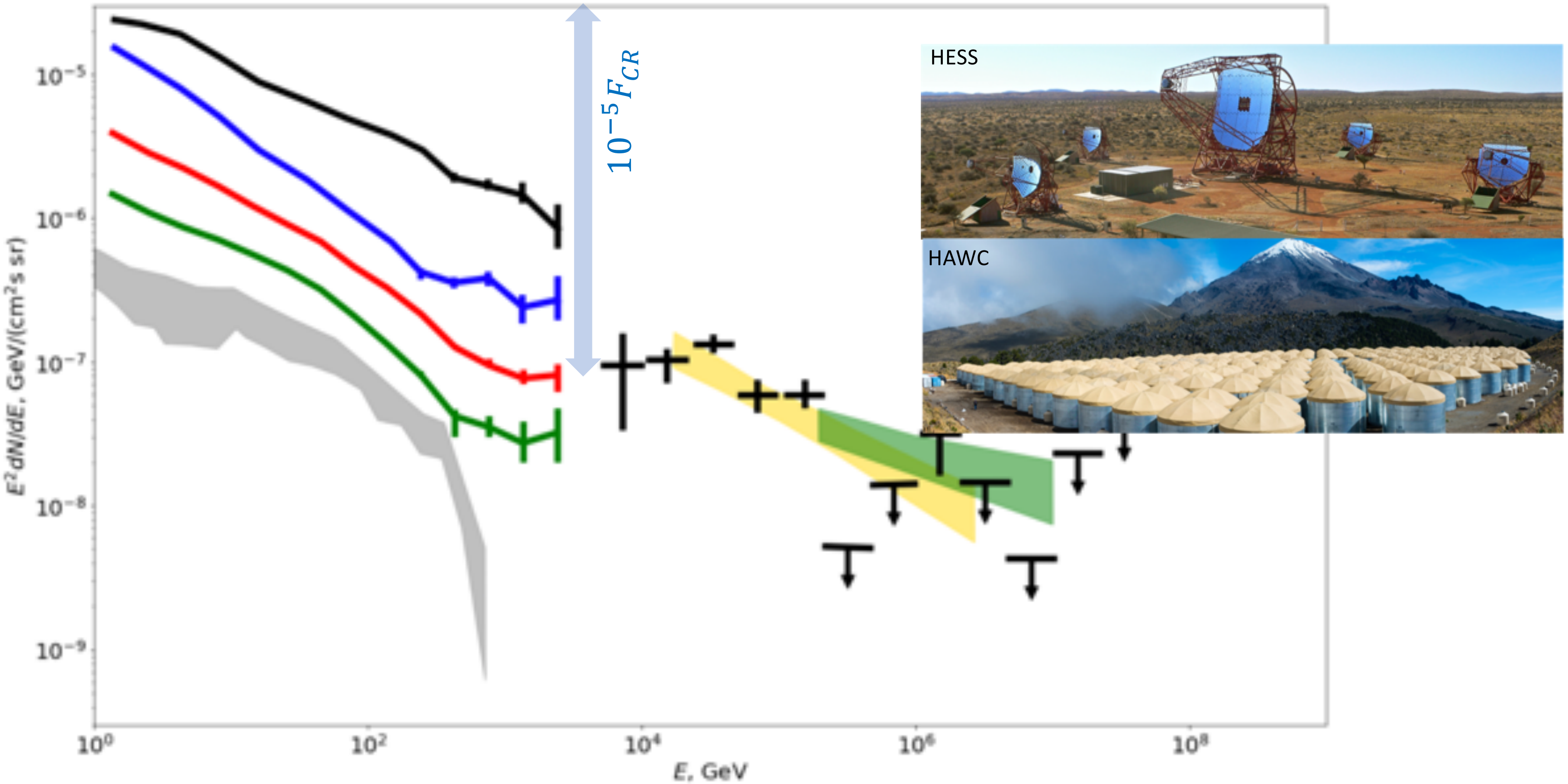
AN, Kachelriess, Neronov, '18; AN, Semikoz '19

Diffuse gamma-ray flux measurements in 10-100 TeV band?



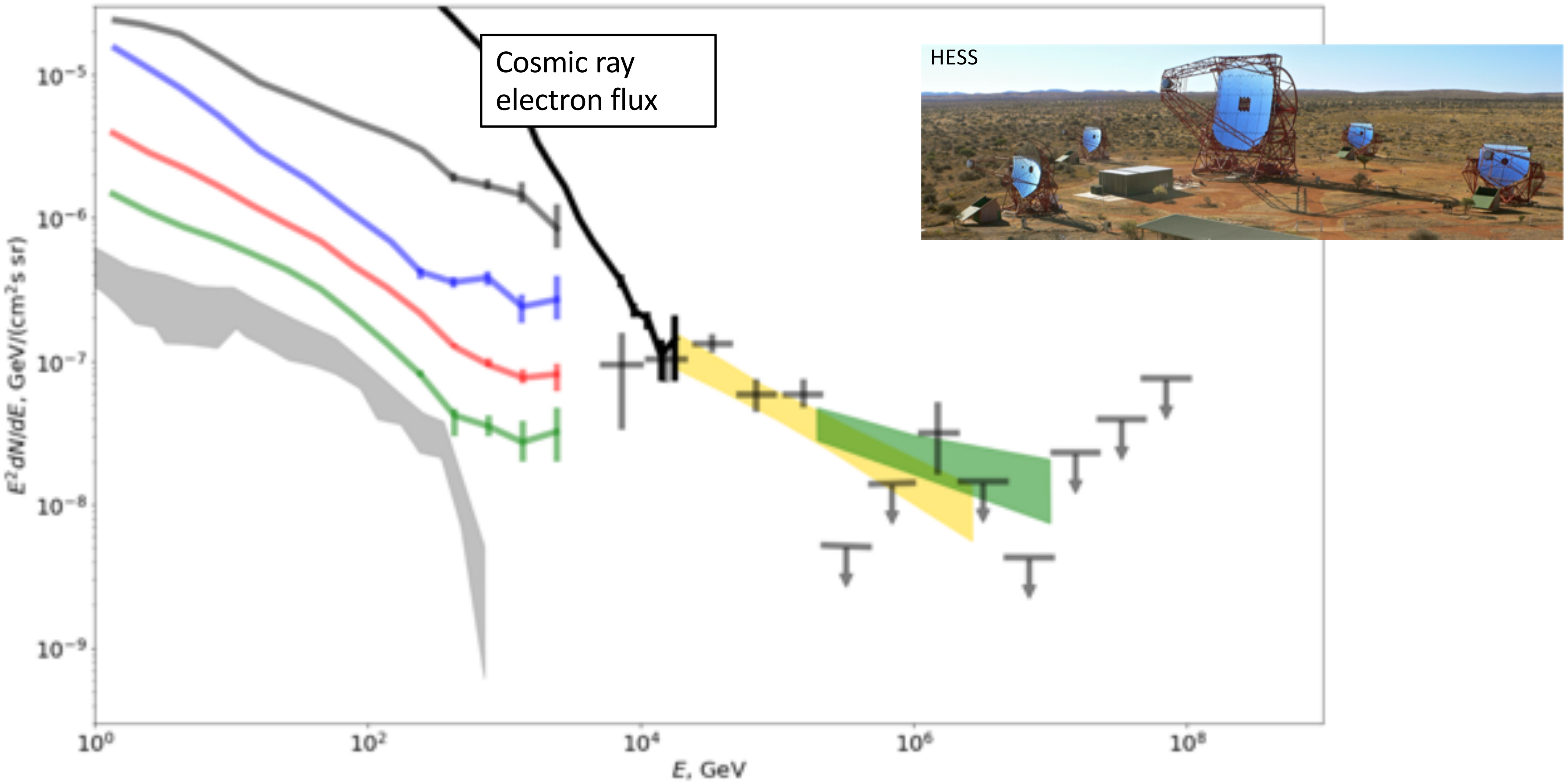
Fermi/LAT measurements can potentially be extended to 10 TeV where ~ 50 events have been detected in 10+ years of Fermi/LAT exposure (calibrations derived from MC are now available only to 3 TeV). Next generation space-based telescope HERD will have deeper calorimeter (better energy resolution), but will have aperture comparable to Fermi/LAT ($\sim 2.5\ \mathrm{m}^2\ \mathrm{sr}$) and will also run out of statistics above 10 TeV.

Diffuse gamma-ray flux measurements in 10-100 TeV band?



Ground-based gamma-ray telescopes suffer from high residual cosmic ray background and can not detect diffuse gamma-ray emission from large sky regions.

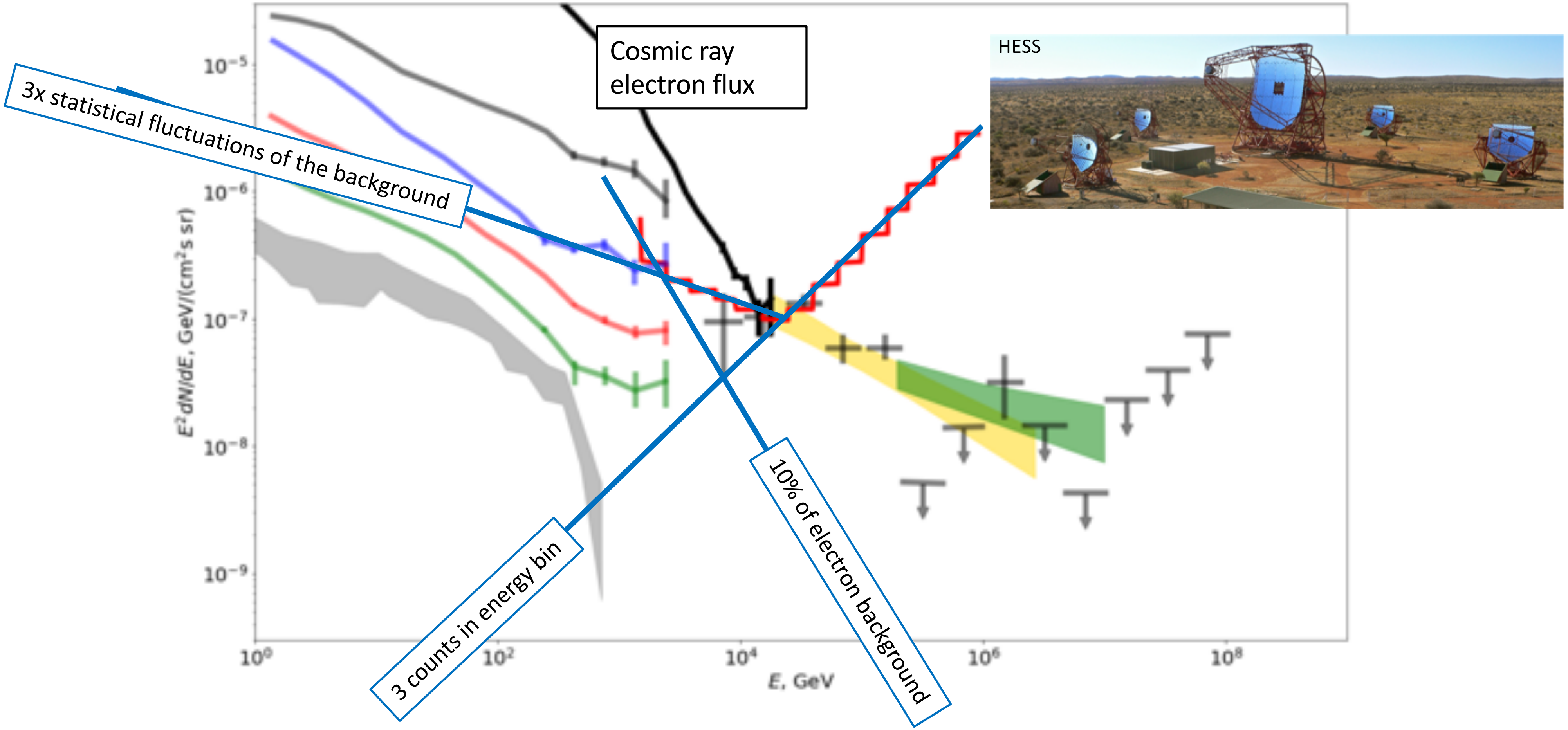
Diffuse gamma-ray flux measurements in 10-100 TeV band?



An irreducible background for ground-based telescopes is that of cosmic ray electrons. Cosmic ray electron flux decreases below the sky-averaged astrophysical neutrino flux at about 20 TeV. Above this energy diffuse emission from large regions of the sky should be detectable, if background rejection similar to that achieved by HESS for electron flux measurement is implemented.

HESS Collab, '17 Neronov, Semikoz, '20

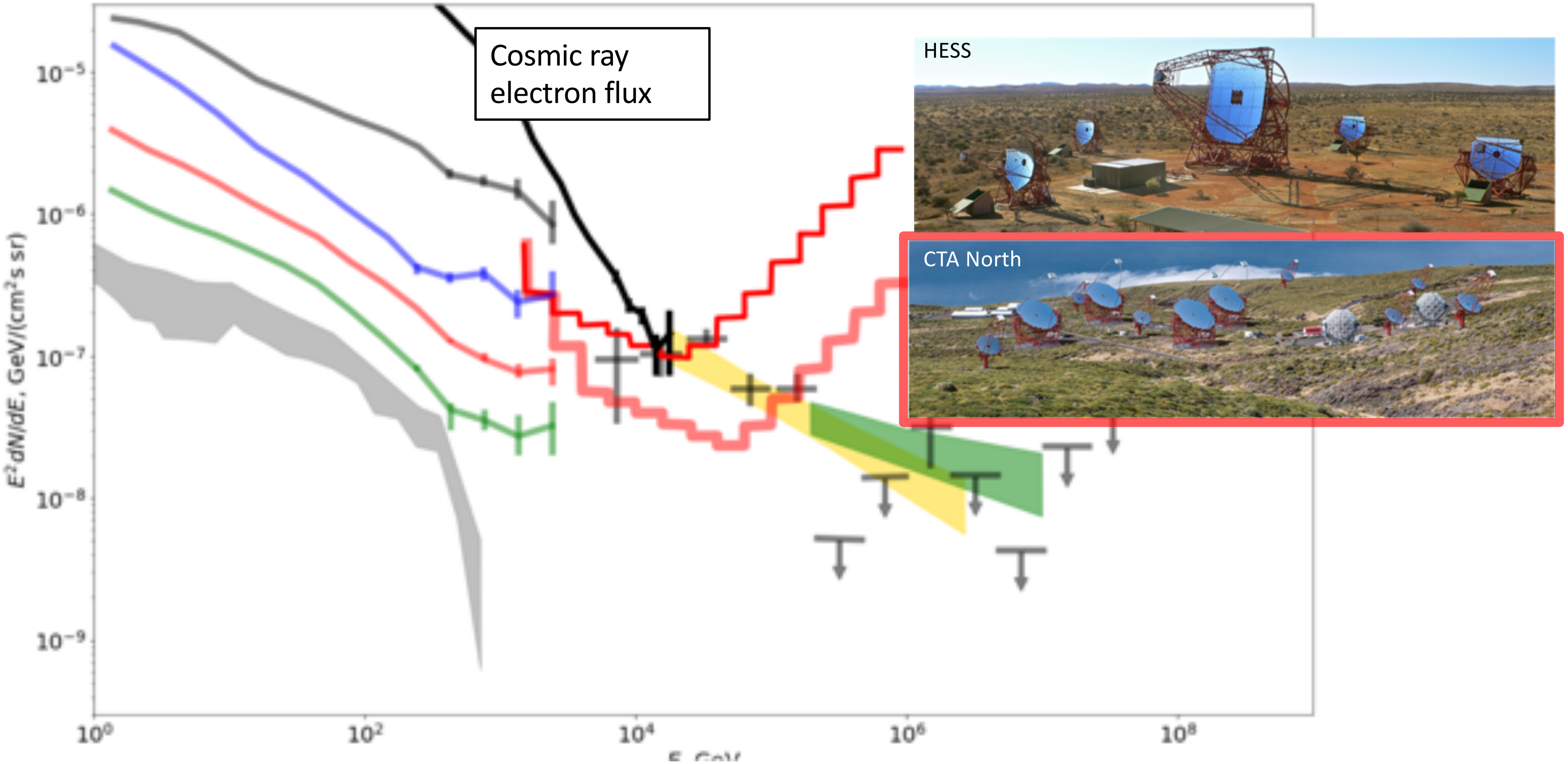
Diffuse gamma-ray flux measurements in 10-100 TeV band?



HESS can possibly detect the large-scale diffuse gamma-ray background all across the Galactic Plane (inner and outer Galaxy, in the "minimal possible background" analysis used for electron flux measurements.
Such measurement method would be complementary to that used in HESS 2014 result on the diffuse emission.

Neronov, Semikoz, '20

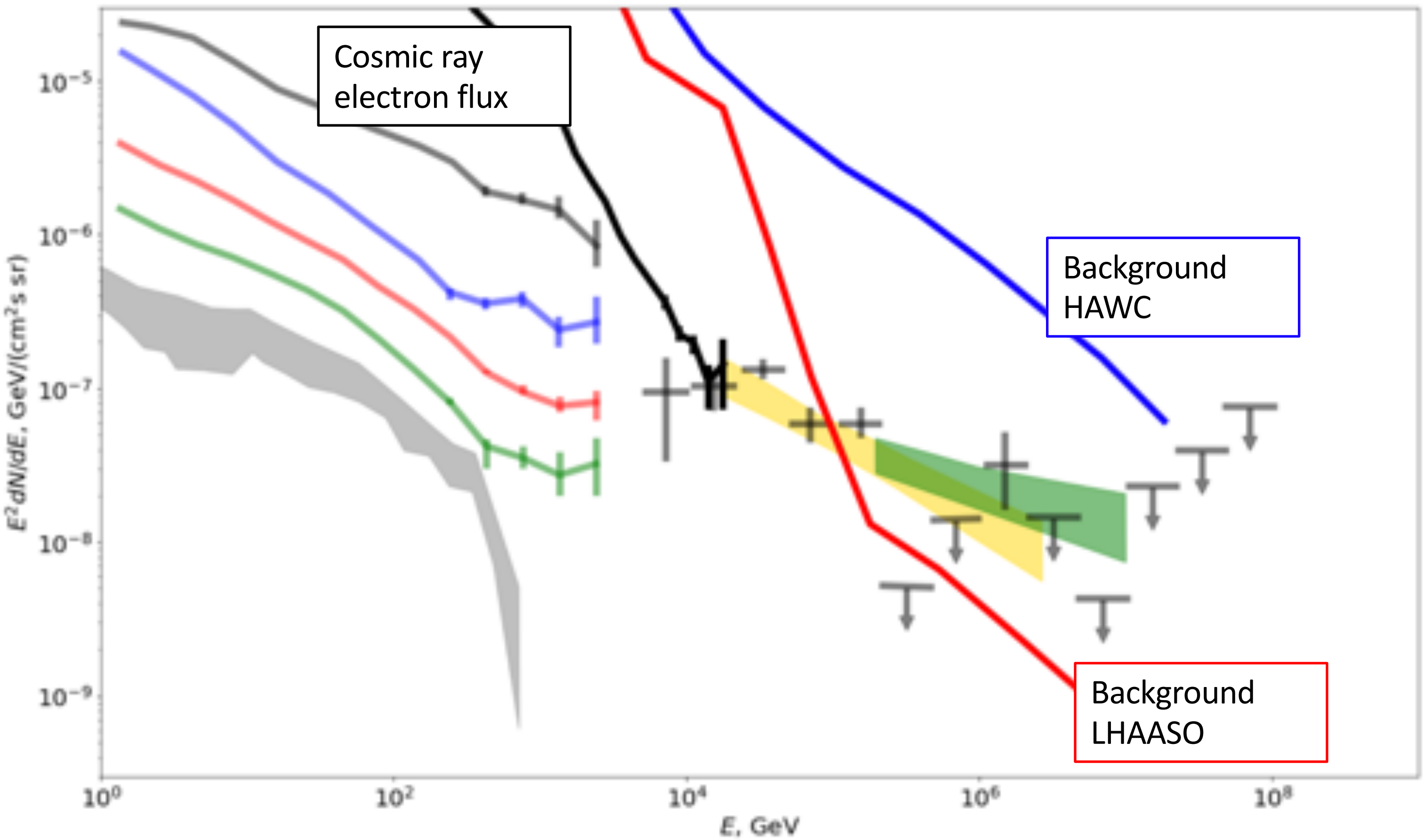
Diffuse gamma-ray flux measurements in 10-100 TeV band?



Same approach with CTA / MST can provide better sensitivity, due to larger collection area and larger FoV (if the 150 m core distance cut is imposed, similar to the HESS electron analysis, CTA / MST collection area is just 2.6 times larger than that of HESS).

Neronov, Semikoz, '20

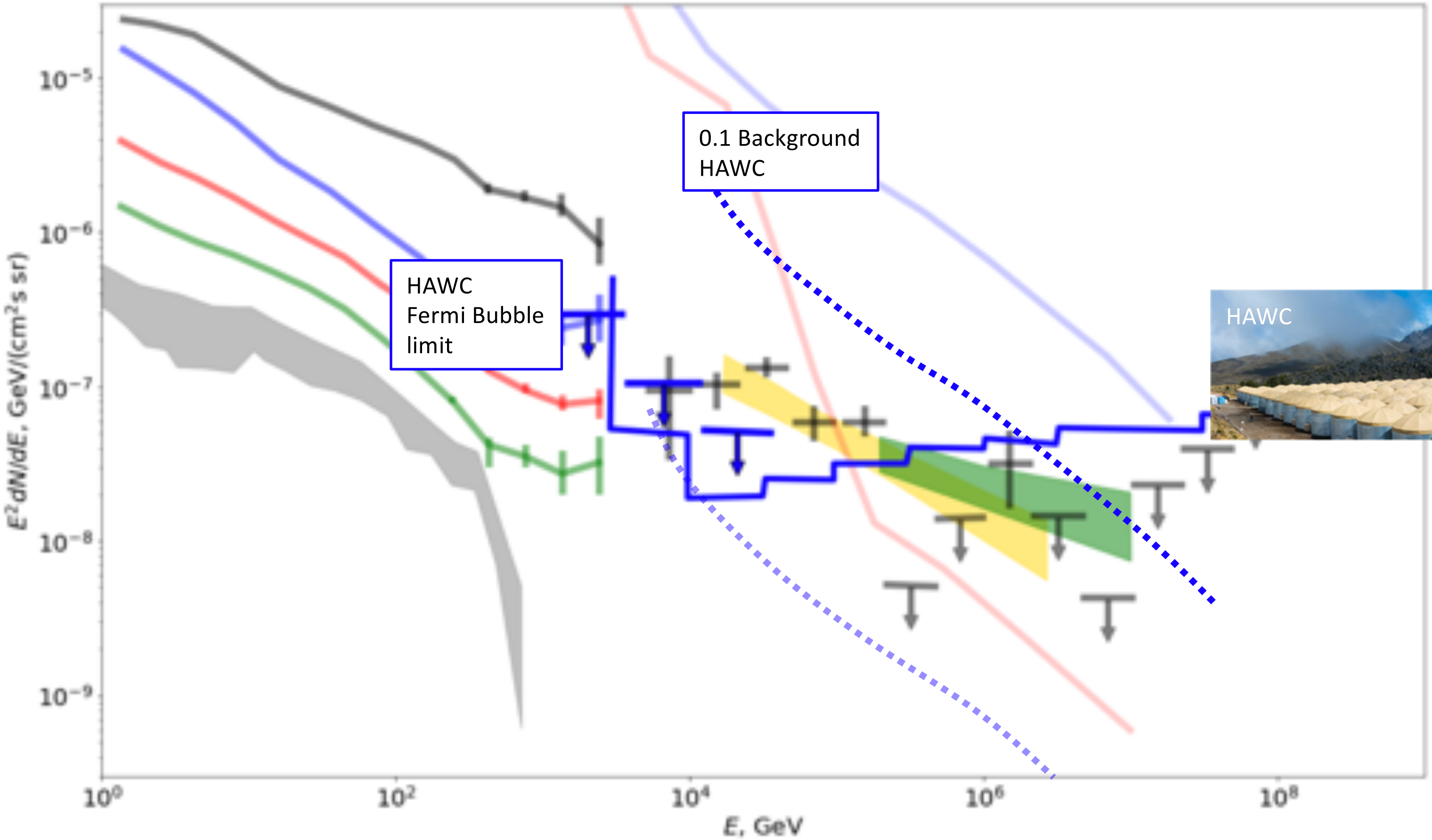
Diffuse gamma-ray flux measurements in 10-100 TeV band?



Air Shower arrays are worse in rejecting the charged cosmic ray background in 10-100 TeV band, but LHAASO will provide a crucial improvement of background suppression above 100 TeV. At the same time, the EAS arrays have demonstrated detection of anisotropies of cosmic ray flux at 10^{-3} level. One can adapt an assumption that gamma-ray flux at the level of 10^{-3} of residual background can be detected.

Neronov, Semikoz, '20

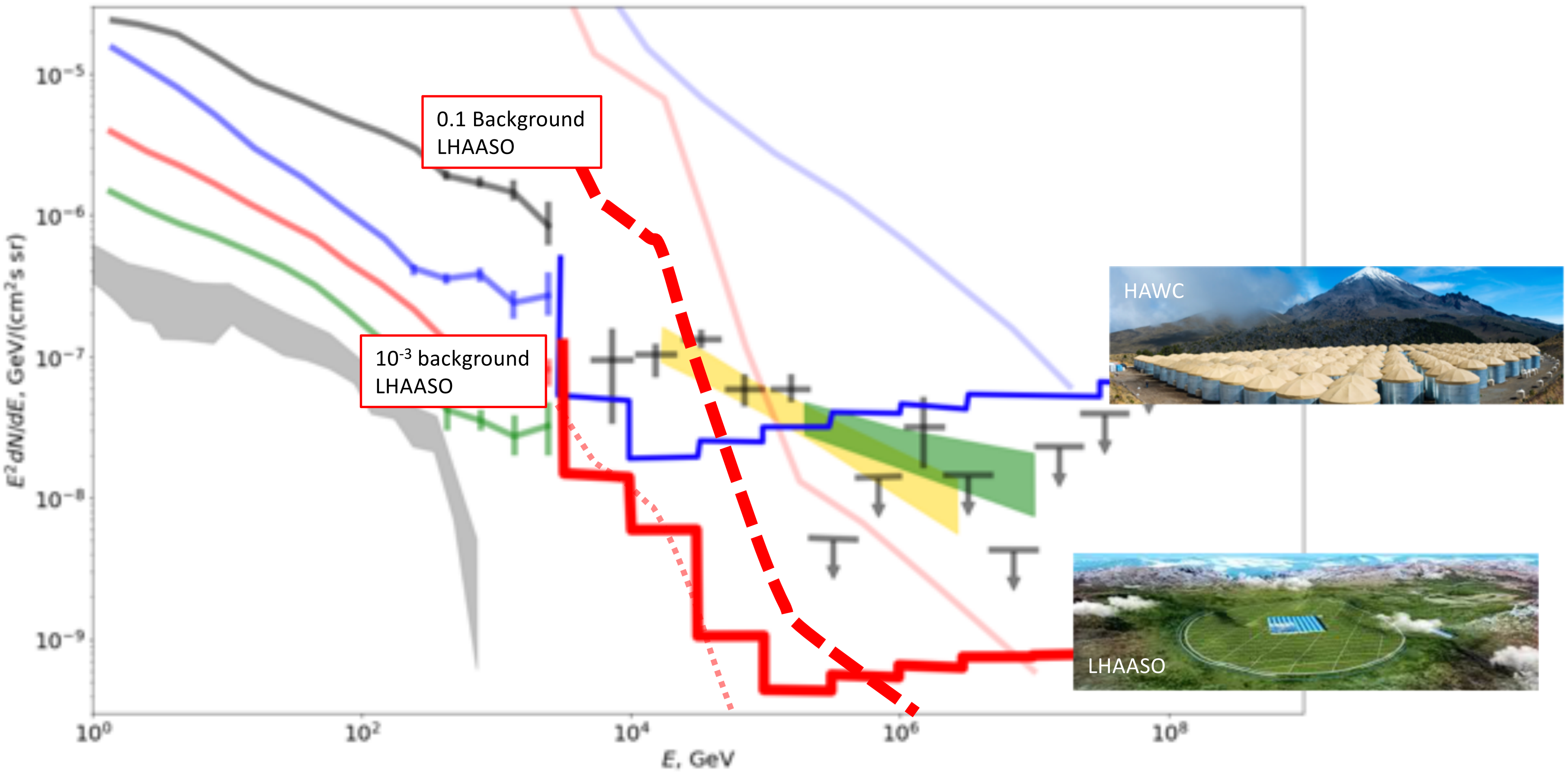
Diffuse gamma-ray flux measurements in 10-100 TeV band?



HAWC will be able to detect diffuse background from all along the Galactic Plane provided that it is indeed able to find anisotropies of residual charged particle background down to 10^{-3} level. This type of analysis has already been reported by HAWC in the paper on upper limit on gamma-ray flux from Northern Fermi Bubble.

HAWC Collab. '17, Neronov, Semikoz, '20

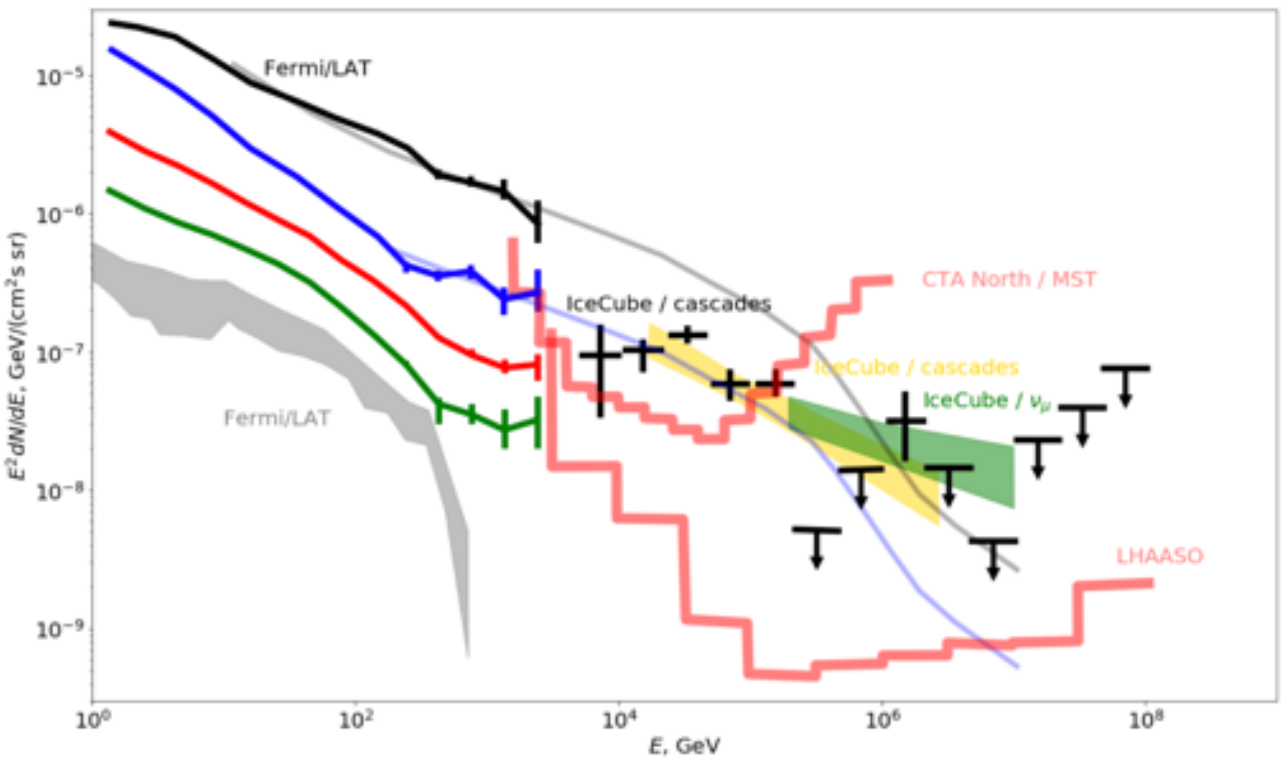
Diffuse gamma-ray flux measurements in 10-100 TeV band?



LHAASO uses similar detection technique, but with larger effective area and better background rejection above 100 TeV. This should allow full exploration of diffuse gamma-ray emission over the entire sky in a broad energy range 10 TeV – PeV.

HAWC Collab. '17, Neronov, Semikoz, '20

Summary



Fermi/LAT provides detailed measurements of Galactic diffuse γ-ray emission in multi-TeV band.

Pion decay flux from the Galactic Plane is above the astrophysical neutrino flux. Neutrino telescopes have to find neutrino counterpart of the Galactic Plane signal.

Ground-based gamma-ray telescopes can measure diffuse Galactic flux in the energy range above 10 TeV. They can / have to find the gamma-ray counterpart of the Galactic part of the astrophysical neutrino signal.

Combination of gamma-ray and neutrino measurements of diffuse emission in TeV-PeV band will clarify the properties of the average Galactic cosmic ray spectrum, its variations across the Galaxy, universal or local nature of the knee of CR spectrum.