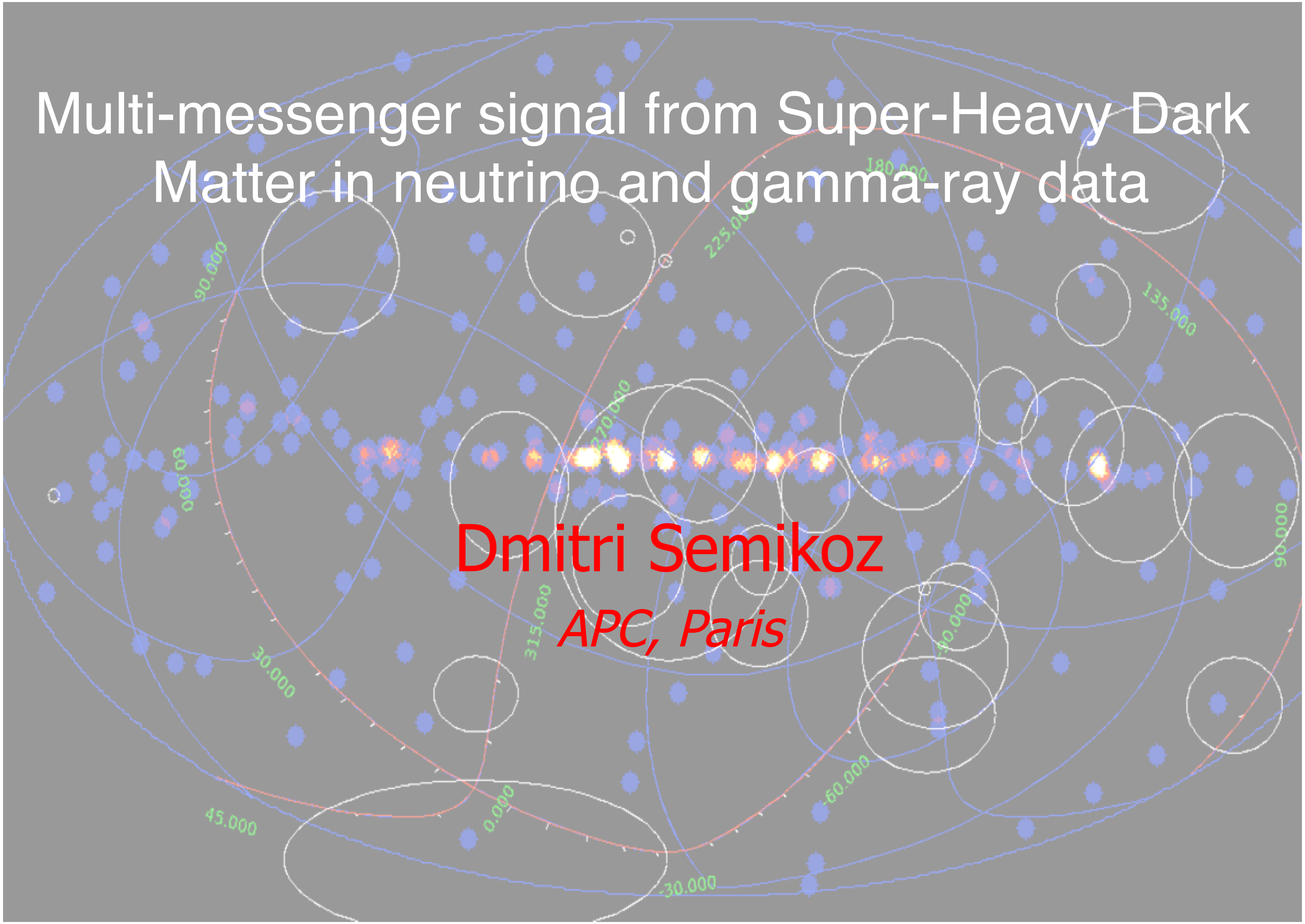
Multi-messenger signal from Super-Heavy Dark Matter in neutrino and gamma-ray data



Dmitri Semikoz

APC, Paris

Overview:

- *Introduction: astrophysical neutrinos in IceCube*
- *Gamma-ray anomaly at TeV: Neutrinos and gamma-rays from Galactic Halo/local CR source/Super-Heavy Dark Matter*
- *Diffuse gamma-ray background measurement by Cherenkov telescopes and LHAASO: 2 orders of magnitude progress in DM sensitivity*
- *Conclusions*

INTRODUCTION: astrophysical neutrinos

Pion production

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

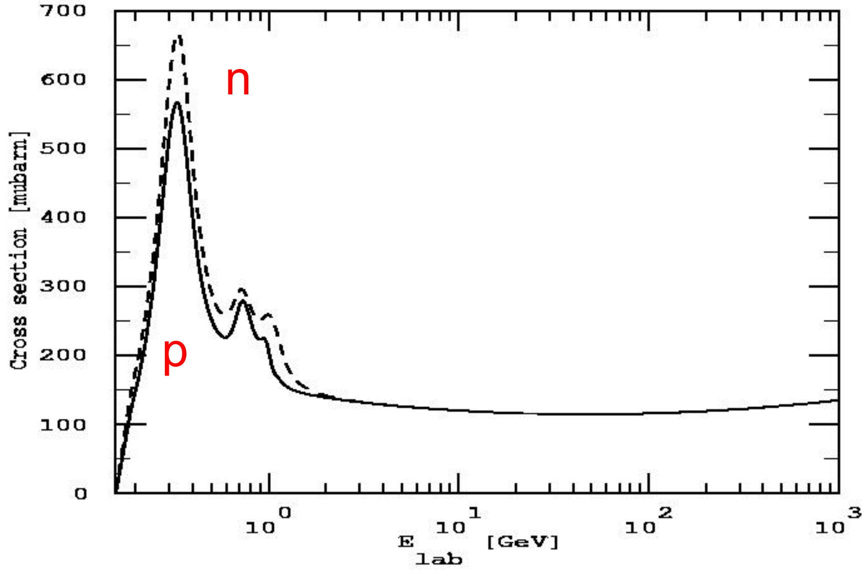
$$N + A_b \Rightarrow N' + \sum \pi^i$$

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

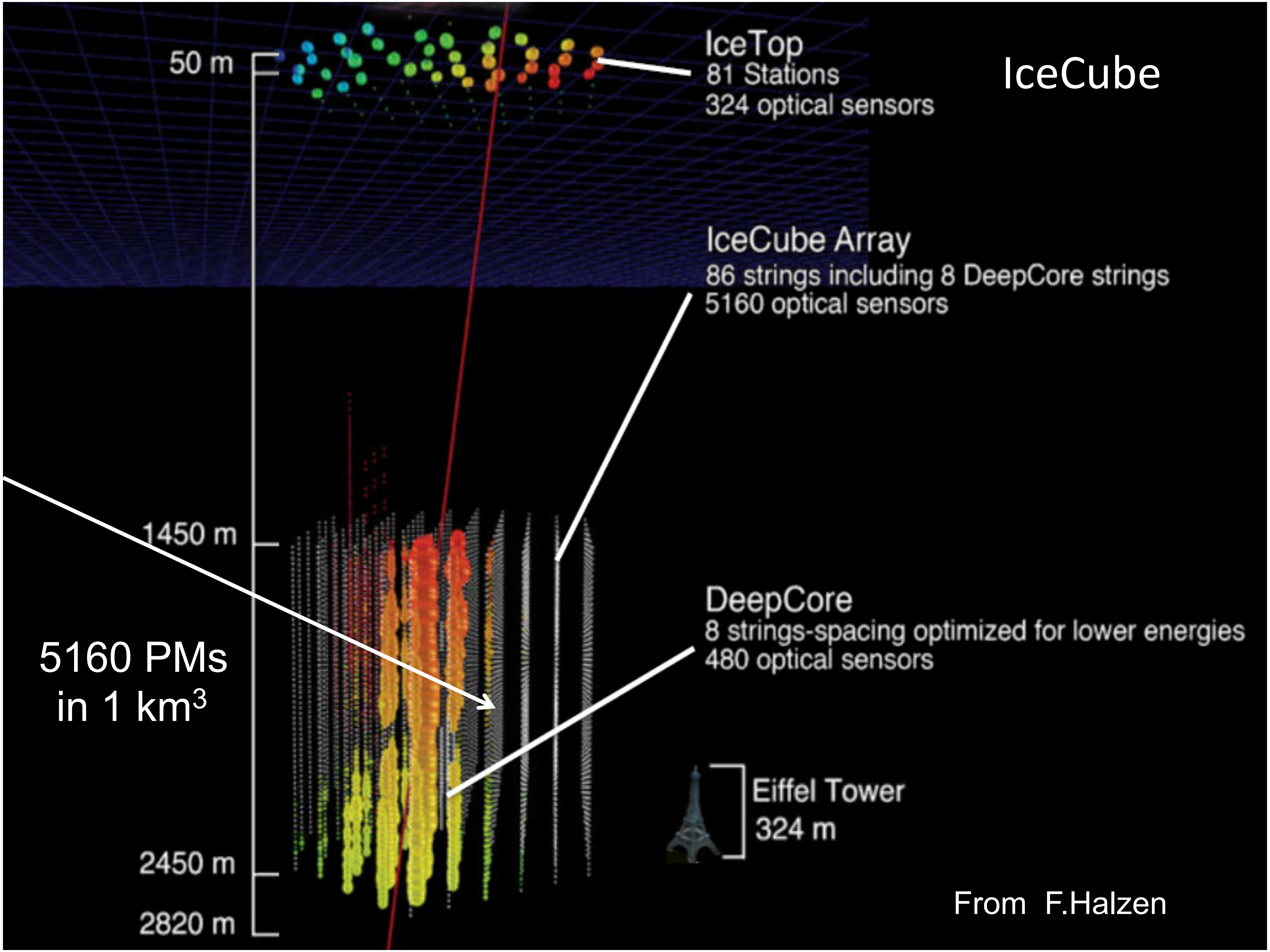
$$\pi^\pm \Rightarrow \mu^\pm + \nu_\mu$$

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

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

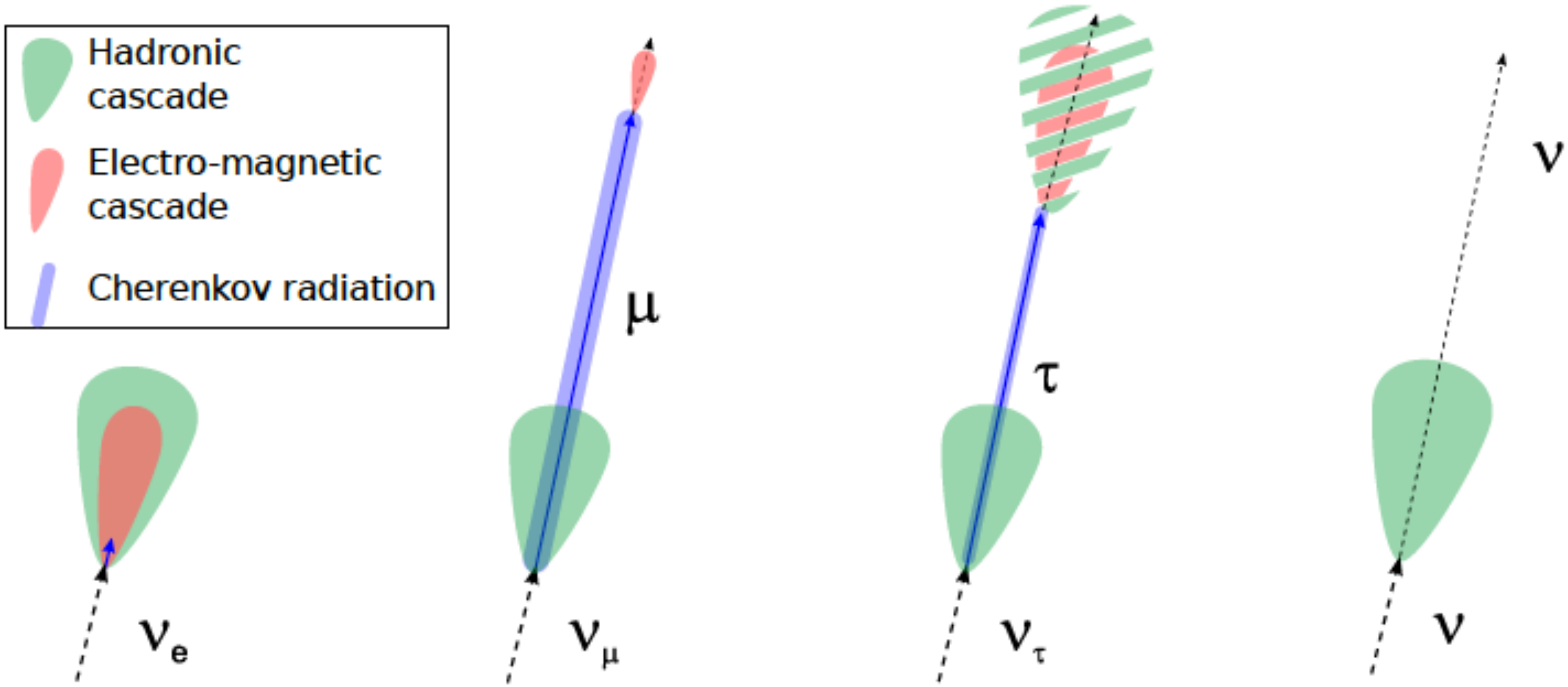


Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

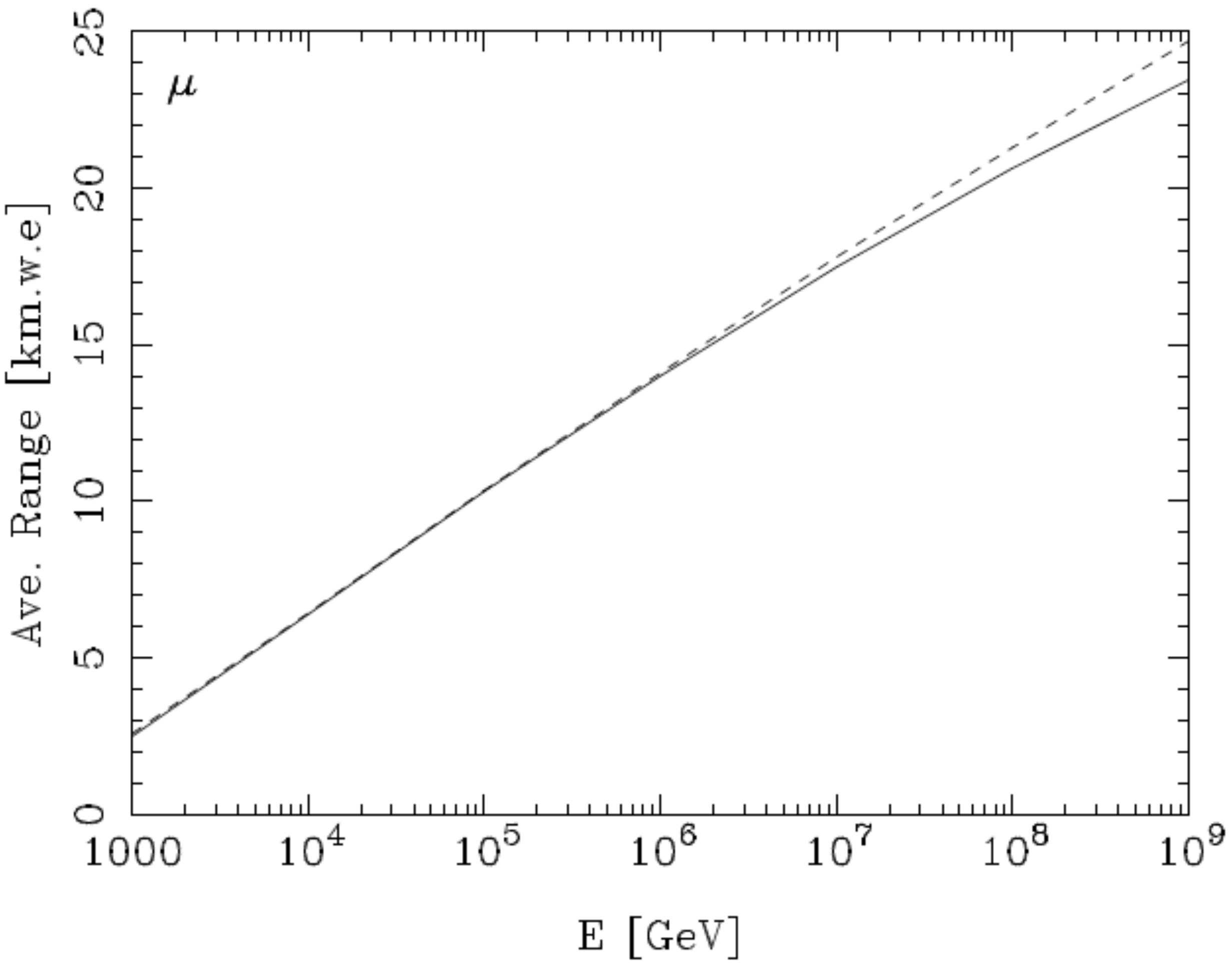


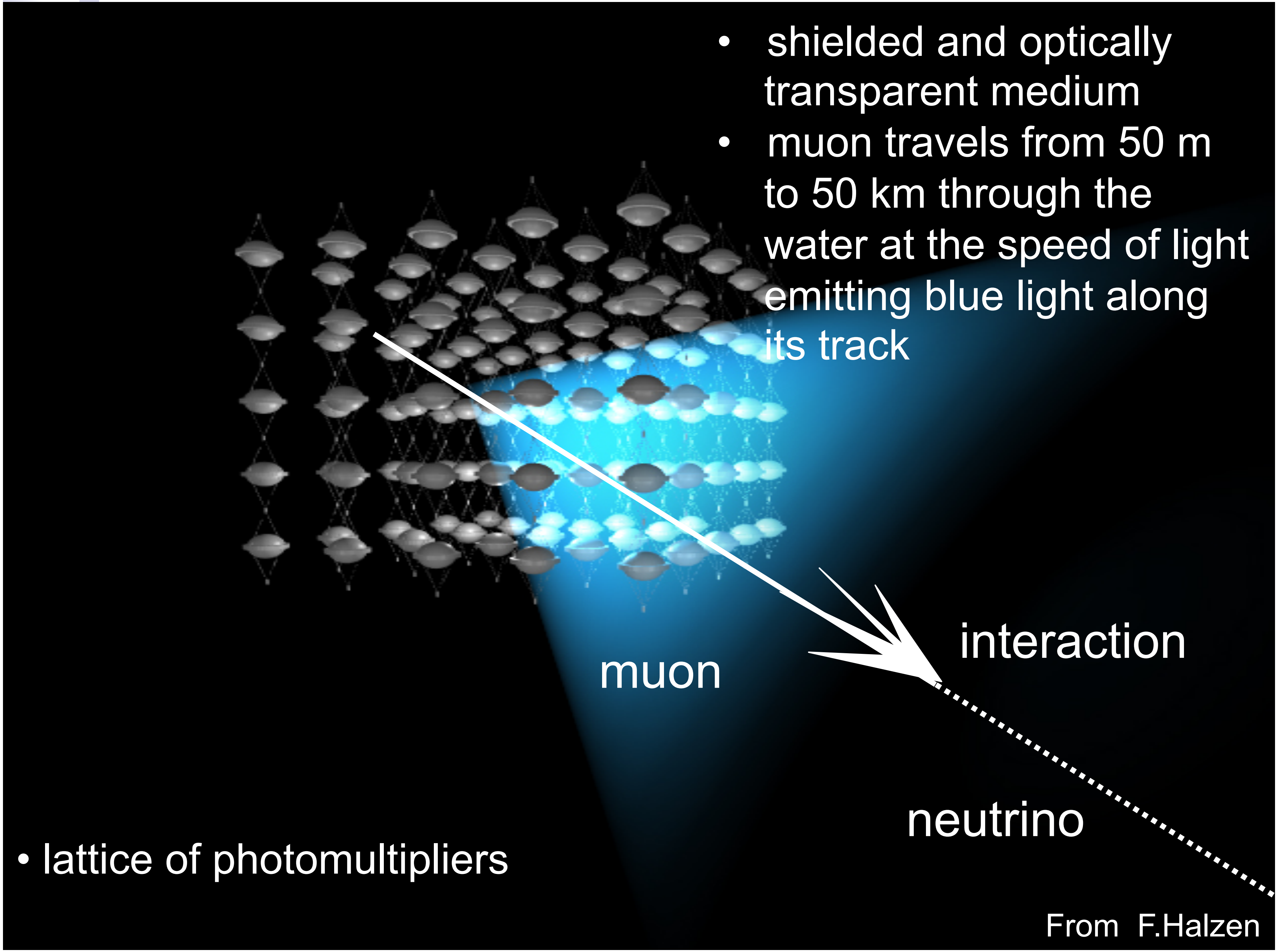
IceCube
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
5160 PMs
in 1 km3
From F.Halzen

Detection of neutrino interactions



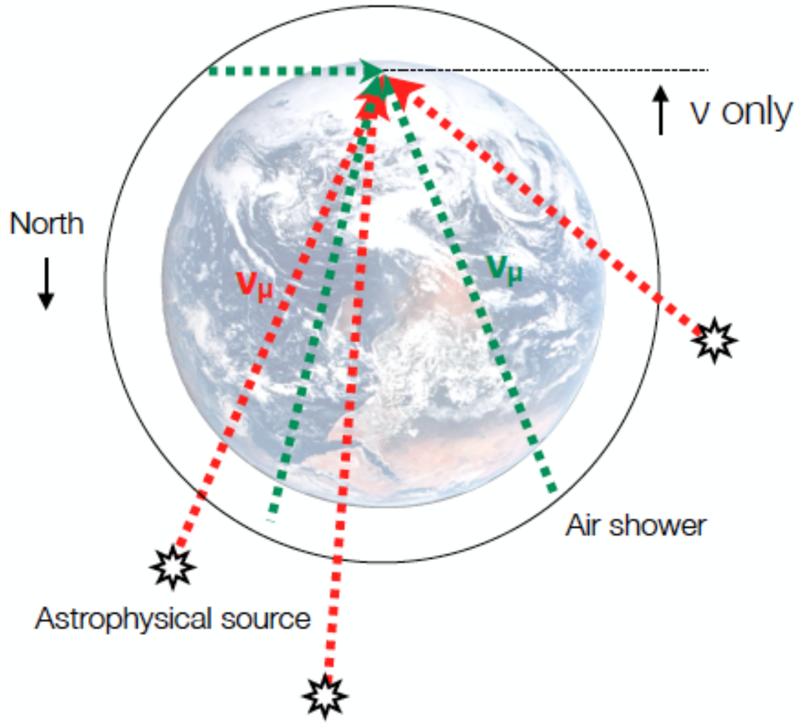
Muon losses

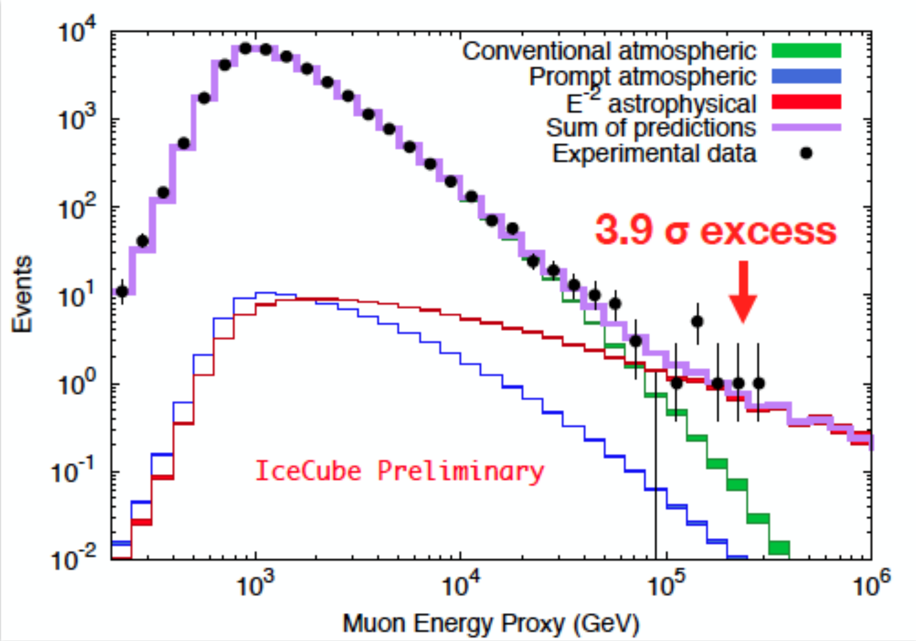



• shielded and optically transparent medium
• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
interaction
muon
neutrino
• lattice of photomultipliers
From F.Halzen

What about the northern sky and ν_μ?

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

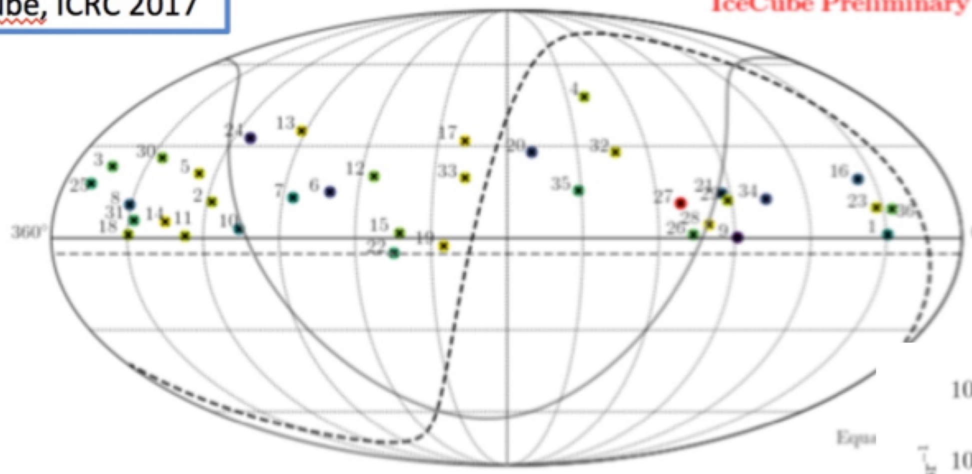




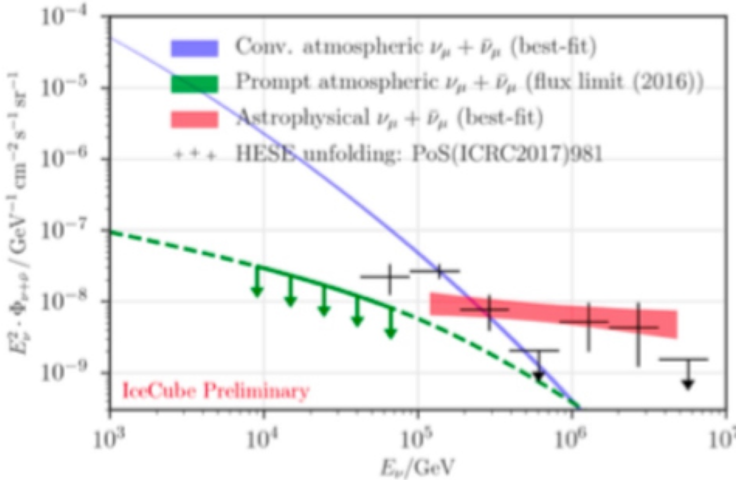
We look for the same excess in incoming muons from the northern sky
High-energy muons reach the detector from km away → large effective volume
Only sensitive to CC ν_μ → explicit handle on ν_μ flux

IceCube muon neutrinos above 200 TeV detected energy (average above 1 PeV)

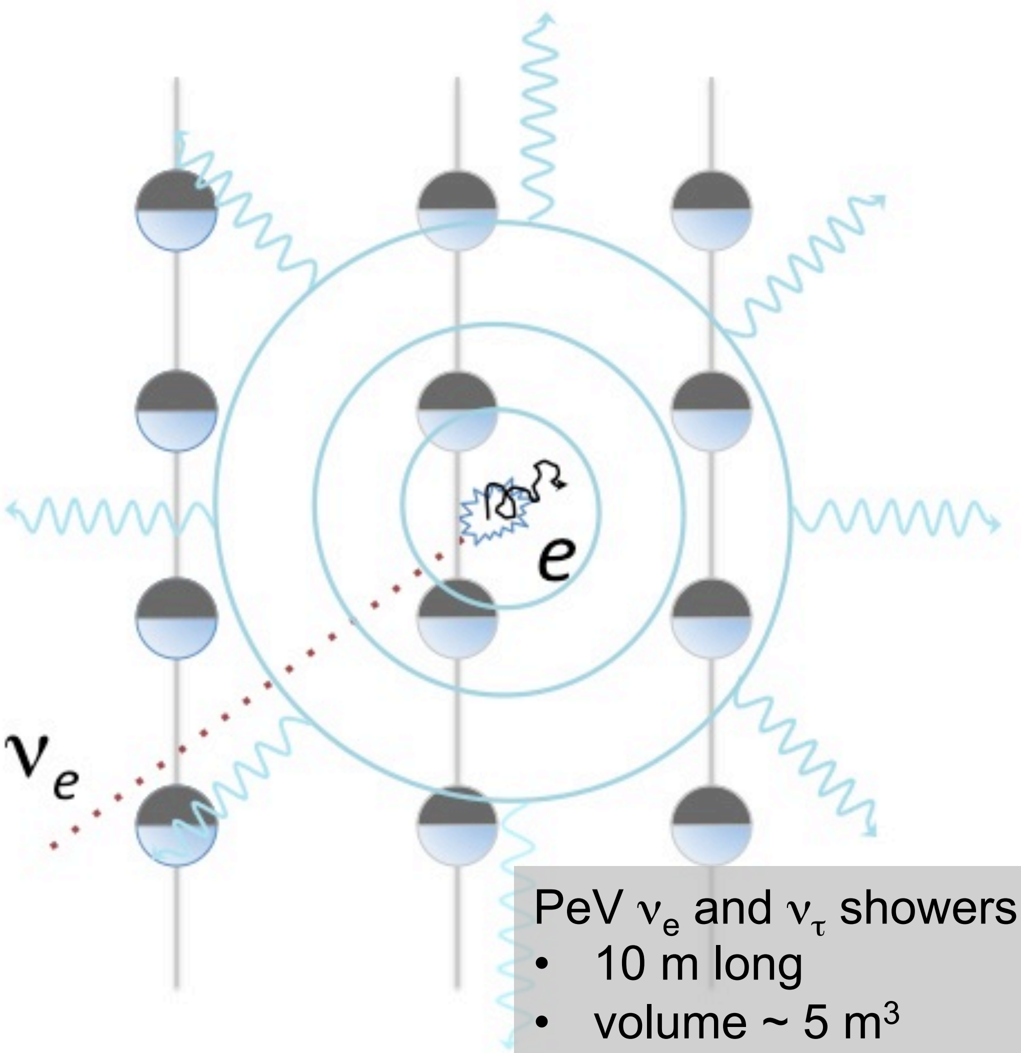
IceCube, ICRC 2017



Muon neutrino sample

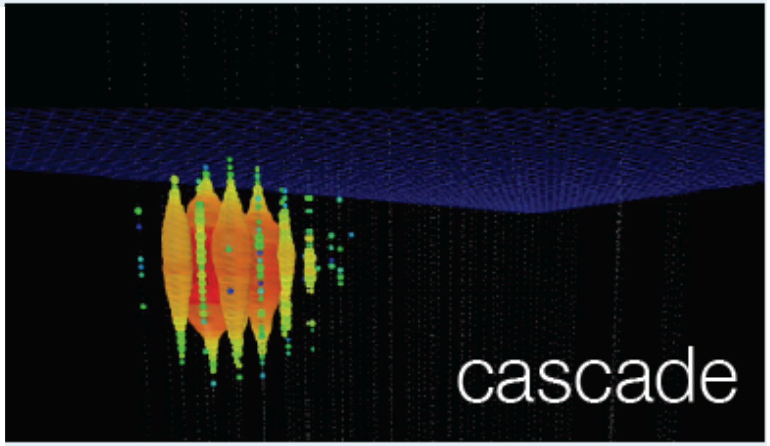


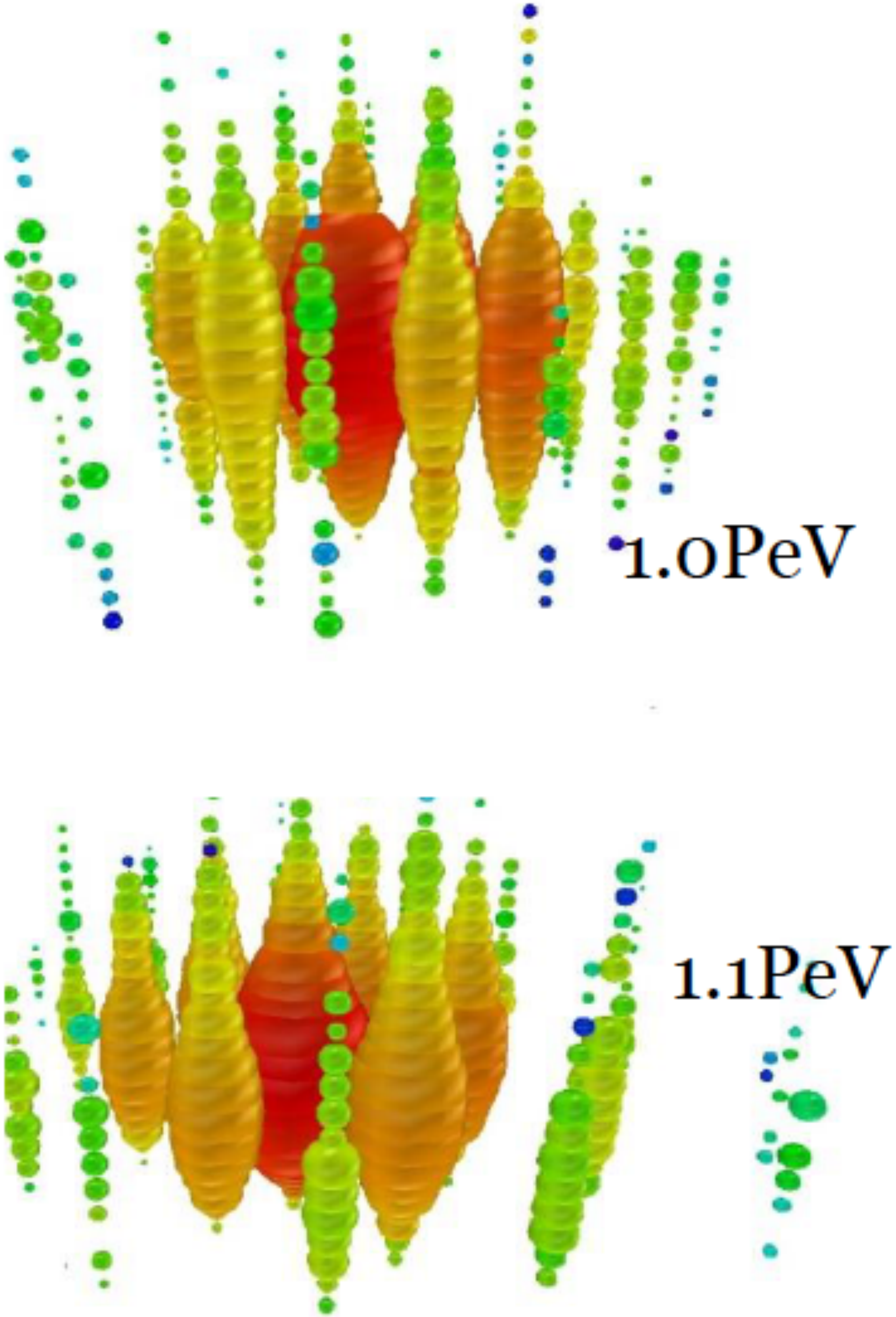
tracks and showers



PeV ν_e and ν_τ showers:

- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m





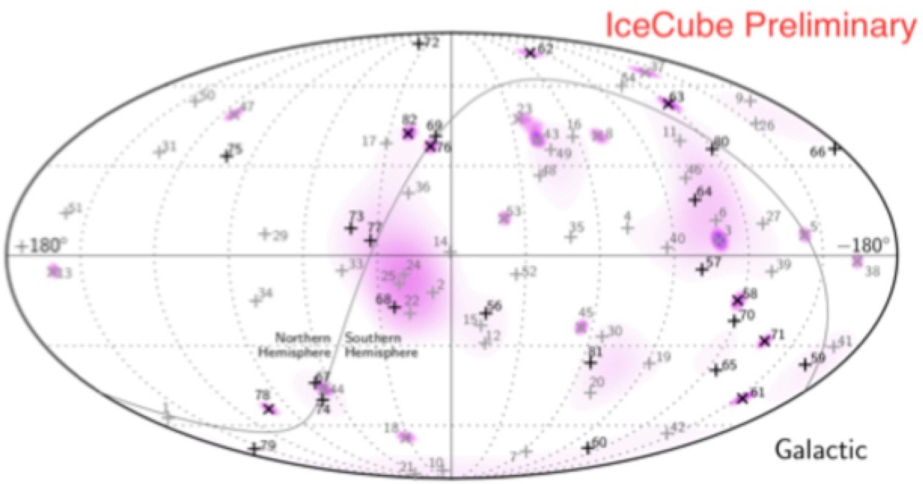
- energy

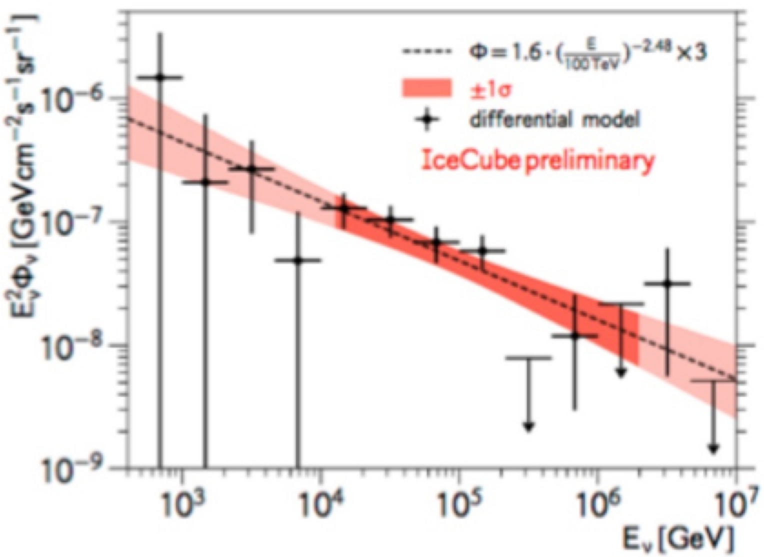
1,041 TeV
1,141 TeV
(15% resolution)

- not atmospheric: probability of no accompanying muon is 10^{-3} per event

→ flux at present level of diffuse limit

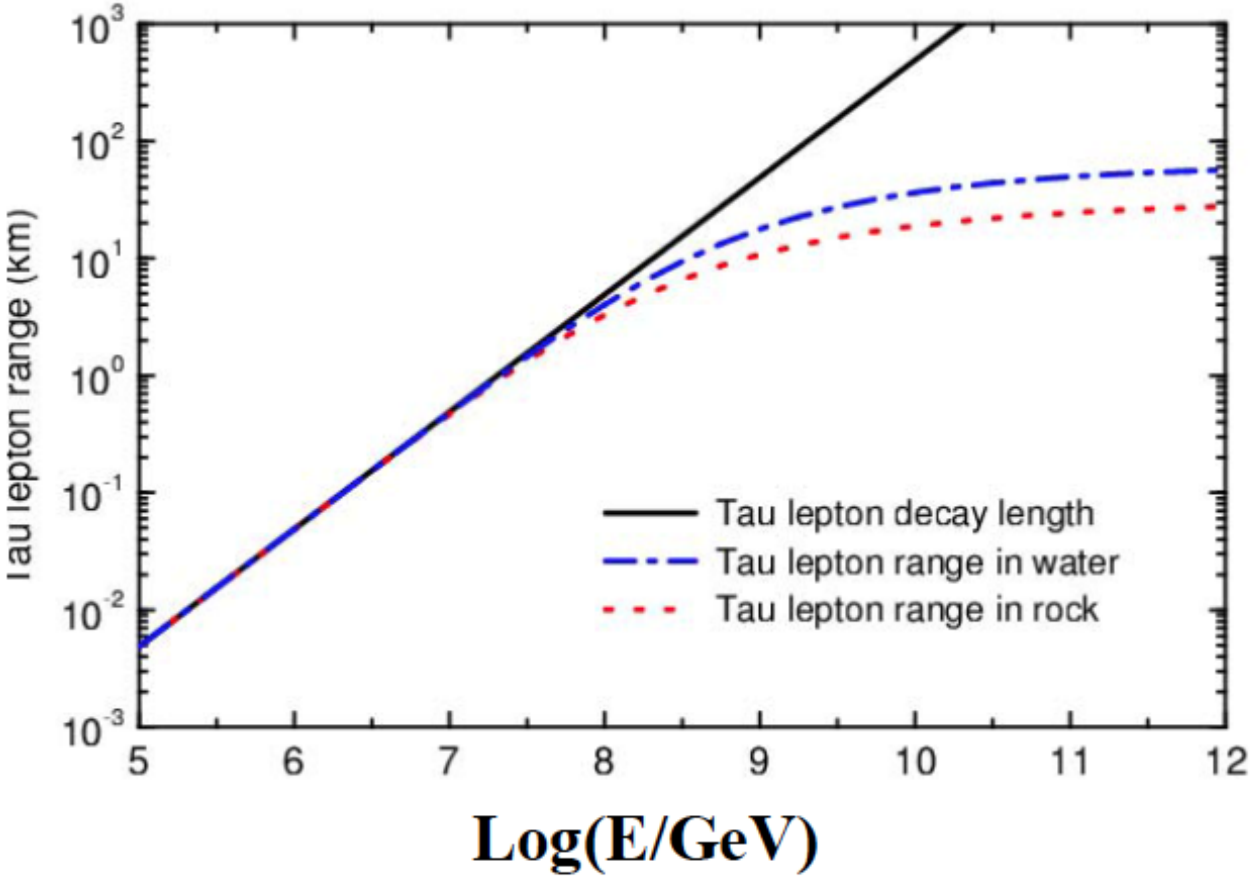
IceCube cascade neutrinos above 30 TeV arrival directions 15-30 degrees





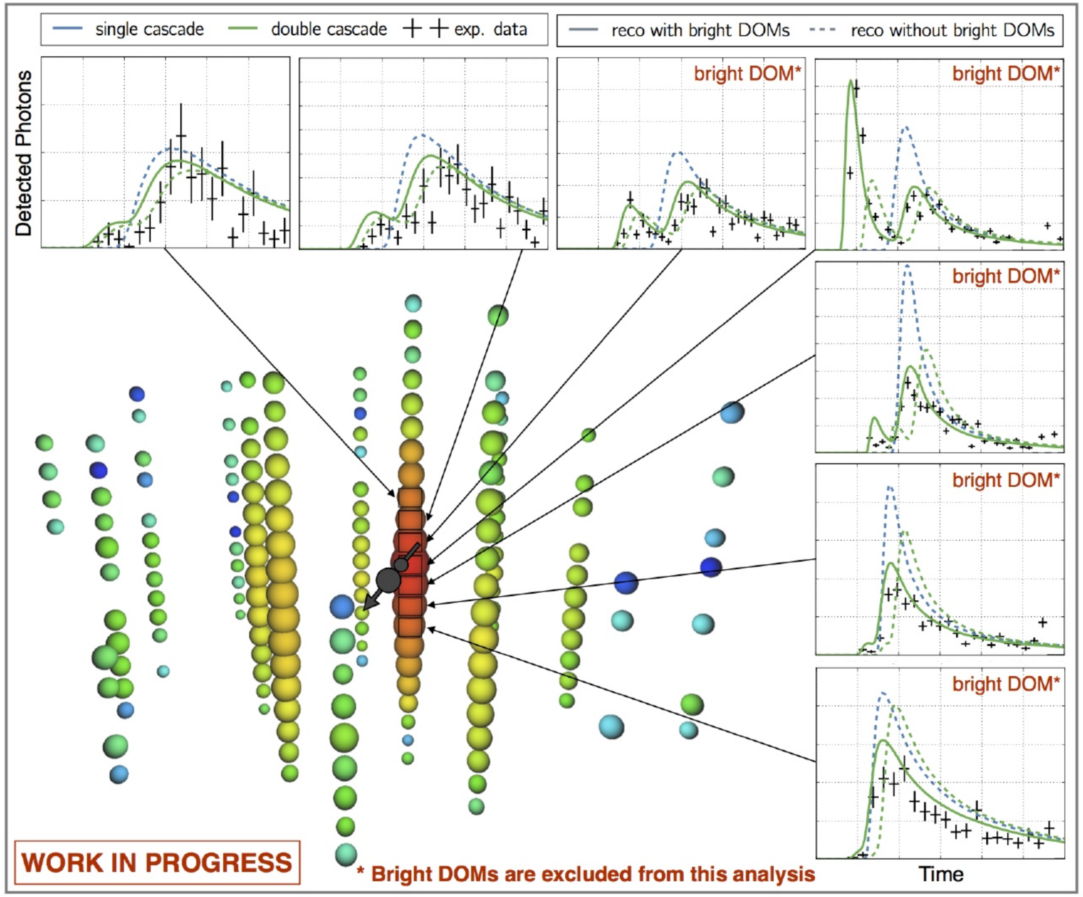
Tau energy losses

Iyer Dutta, Reno, Sarcevic, & Seckel, 01
Tseng, Yeh, Athar, Huang, Lee, & Lin, 03



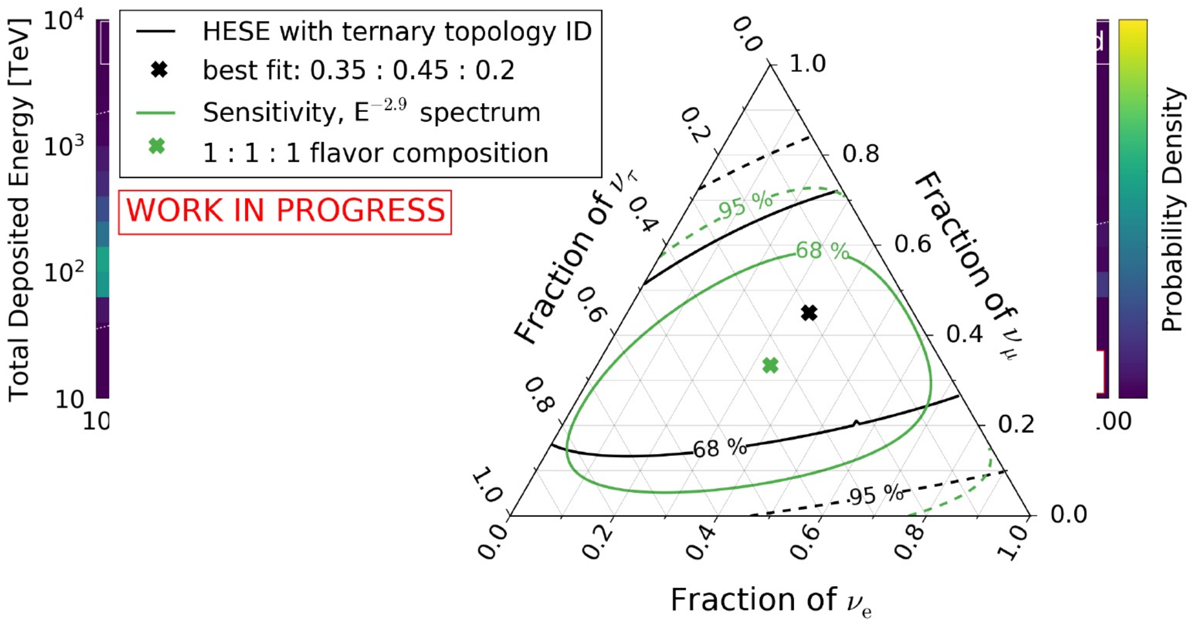
First tau events

a cosmic tau neutrino: livetime 17m



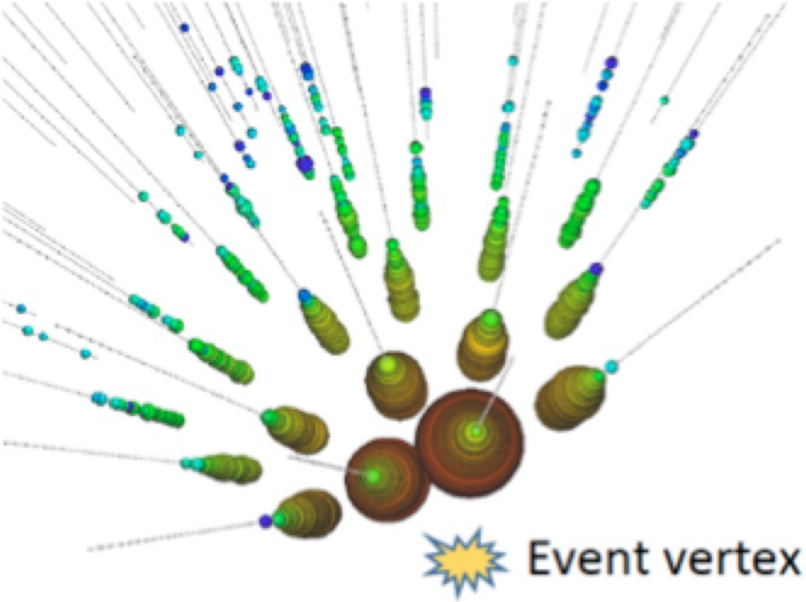
Flavor content consistent with 1:1:1

high-energy starting events – 7.5 yr

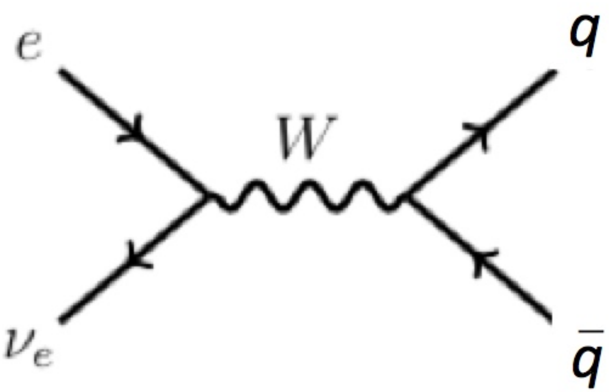


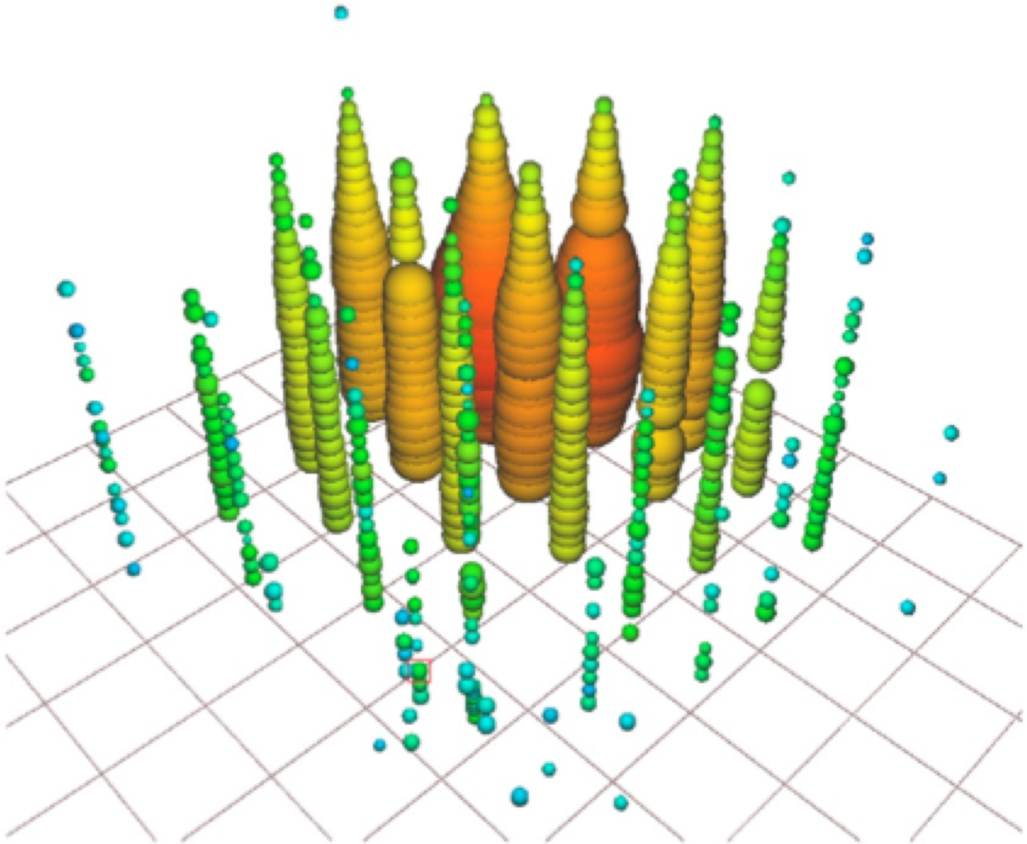
oscillations of PeV neutrinos over cosmic distances to 1:1:1

partially contained event with energy 6.3 PeV



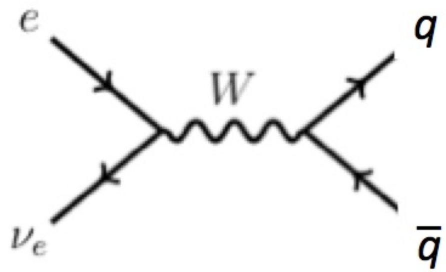
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

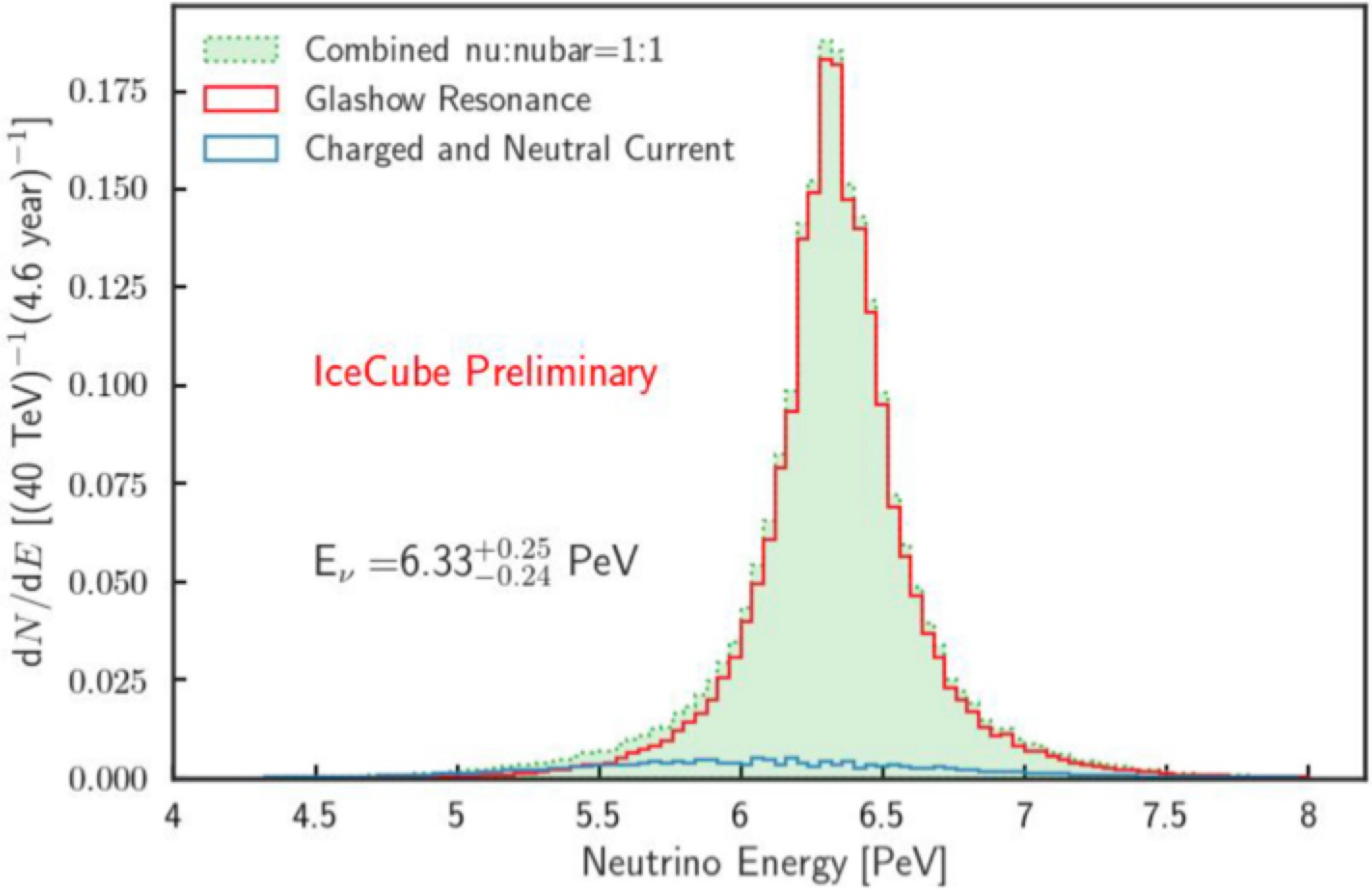




F.Halzen Neutrino 2020

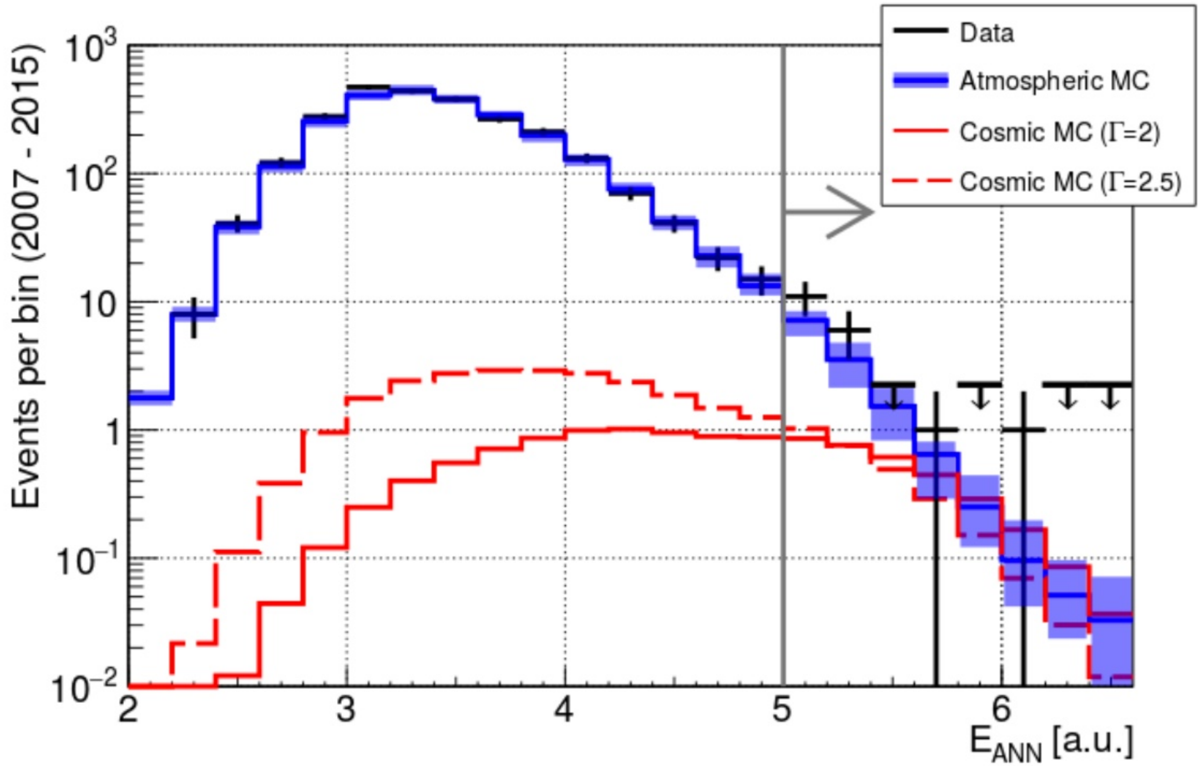
- energy measurement understood
- identification of anti-electron neutrinos





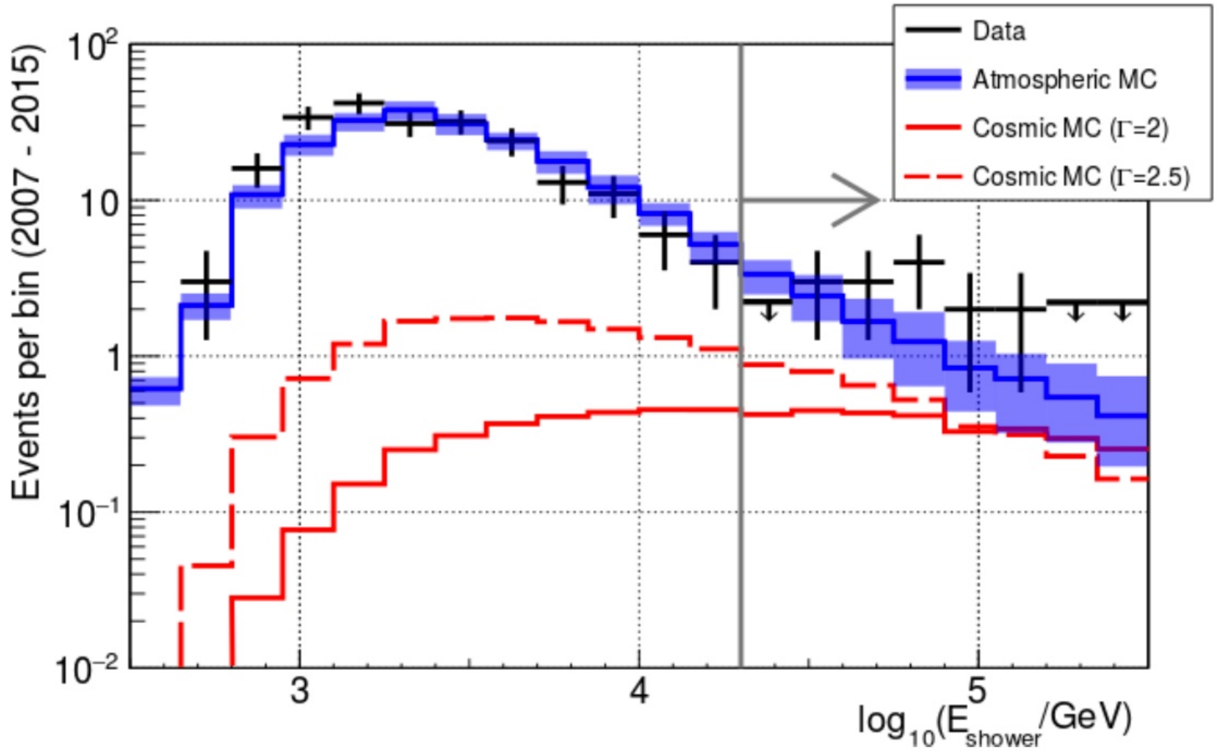
Other detectors

ANTARES 9 years tracks



Excess at 100 TeV 2 sigma 1 PeV 1 sigma
Albert et al, arXiv:1711.07212

ANTARES 9 years cascades 0.1 km^3 yr



MC will be redone E decrease, significance will be around 2-3 sigma
Events with cascade center on OM was removed
A. Albert et al, arXiv:1711.07212

KM3NeT in the Mediterranean

Environmental parameters

Mediterranean Sea – salt water

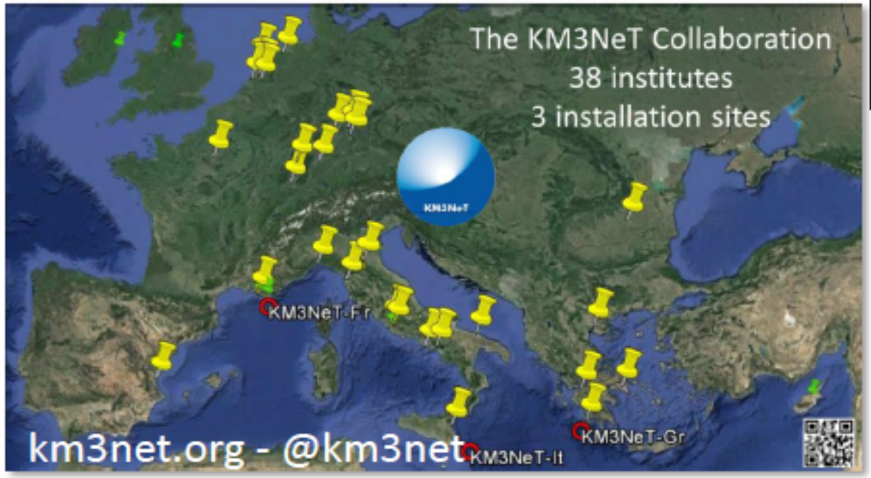
3 installation sites

distance to shore ~40-100 km

L_{abs} ~60-100 m

L_{scat} ~50-70m

depths ~2500-4500 m



Telescope design

~3.5-6 km^3 (depending on spacing)

6 shore-cables for 6 building blocks

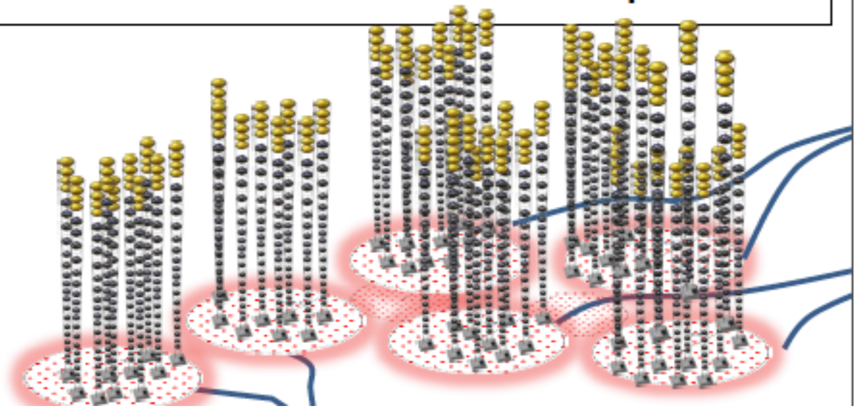
6 x 115 = 690 detection units

690 x 18 =12420 OMs

seabed data transmission infrastructure

installation requires ship + ROV

all-data-to-shore concept

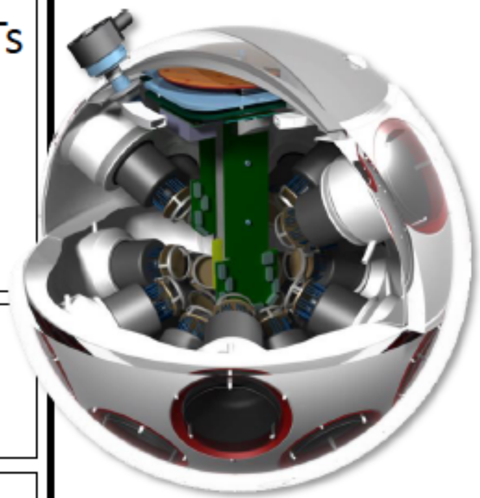


KM3NeT Optical Module

Segmented cathode area: 31 x 3” PMTs
Light concentrator ring
Cathode area: ~ 3 x 10-inch PMT
Custom low-power HV bases

LED & piezo inside
Compass and tiltmeter inside

PMT ToT measurements
FPGA readout, optical line terminator



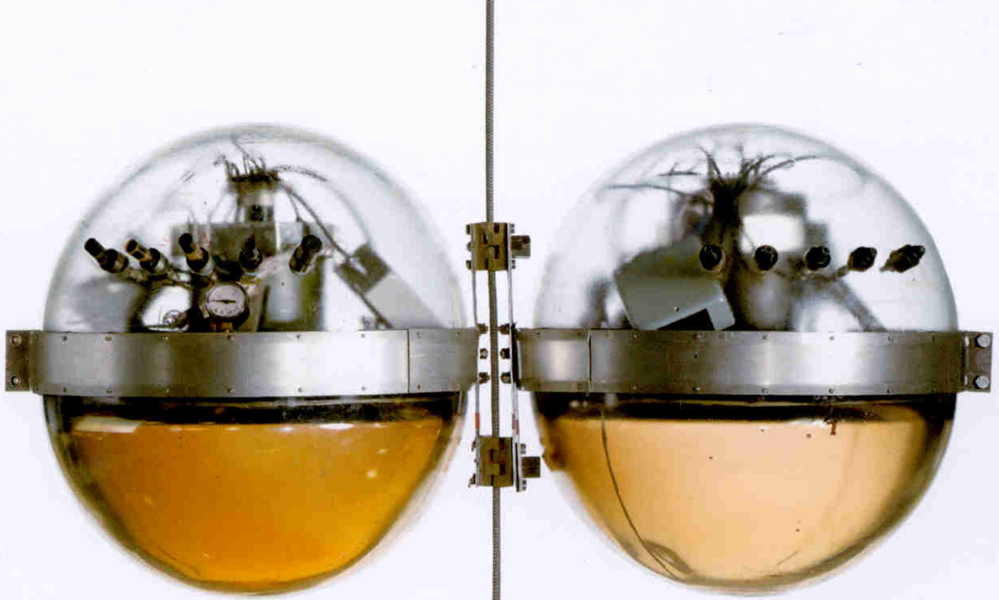
ETEL D792

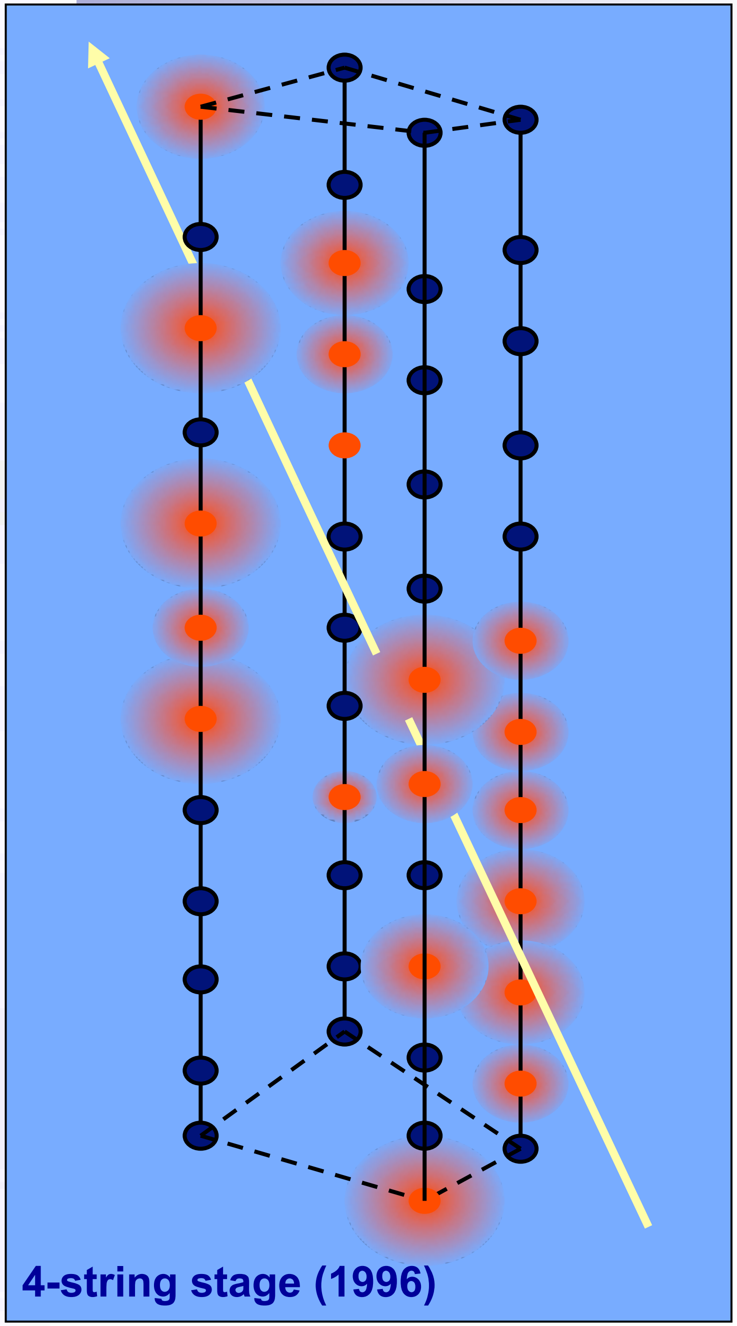
Hamamatsu R12199

HZC XP53B20

Lake Baikal

First underwater telescope
First atmospheric neutrinos at high energy





Baikal-GVD

Environmental parameters

Lake Baikal - fresh water

distance to shore ~6 km →

L_{abs} ~22-25 m

L_{scat} ~30-50m

depth ~1360 m

icefloor during winter →

Telescope design

~1.5 km3

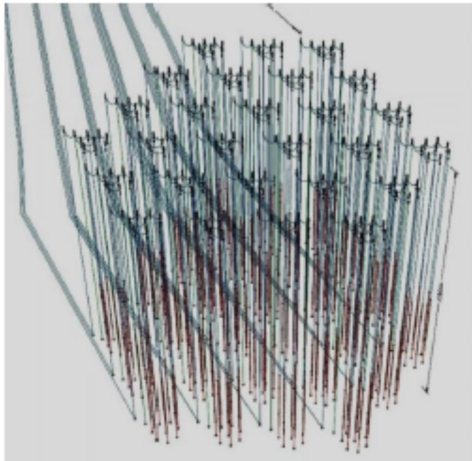
27 shore-cables for 27 clusters

27*8=216 strings

216*48=10368 OMs¶

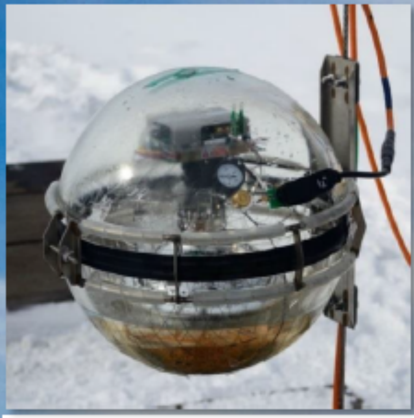
deployment from icefloor

shallow water DAQ infrastructure

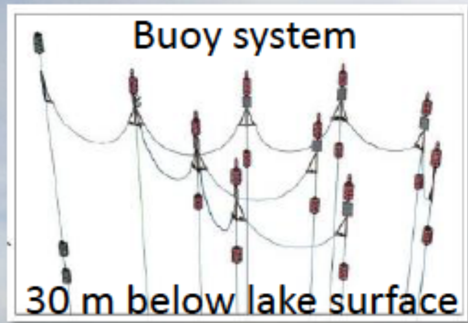


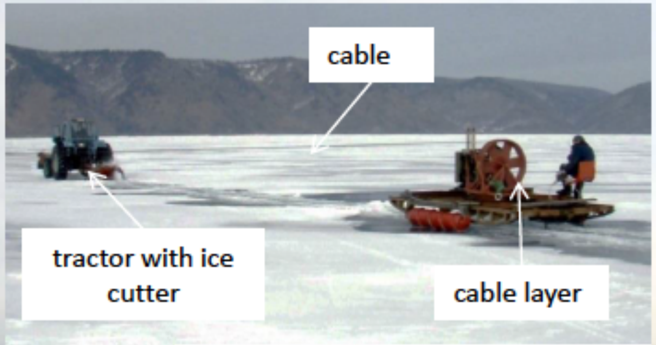
¶ OM – Optical Module

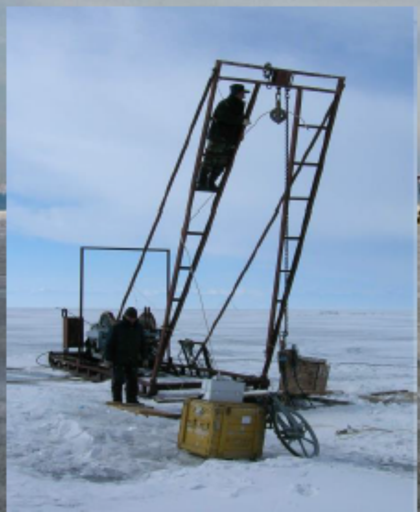
GVD technology

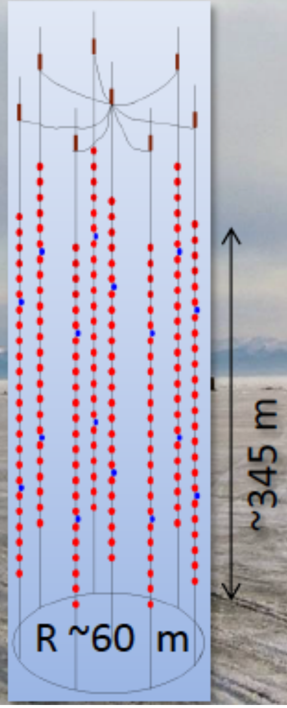


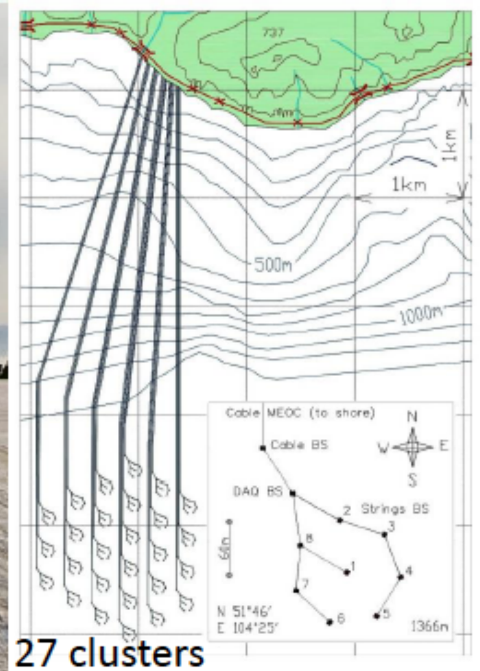
R7081HQE : D=10", ~0.35QE



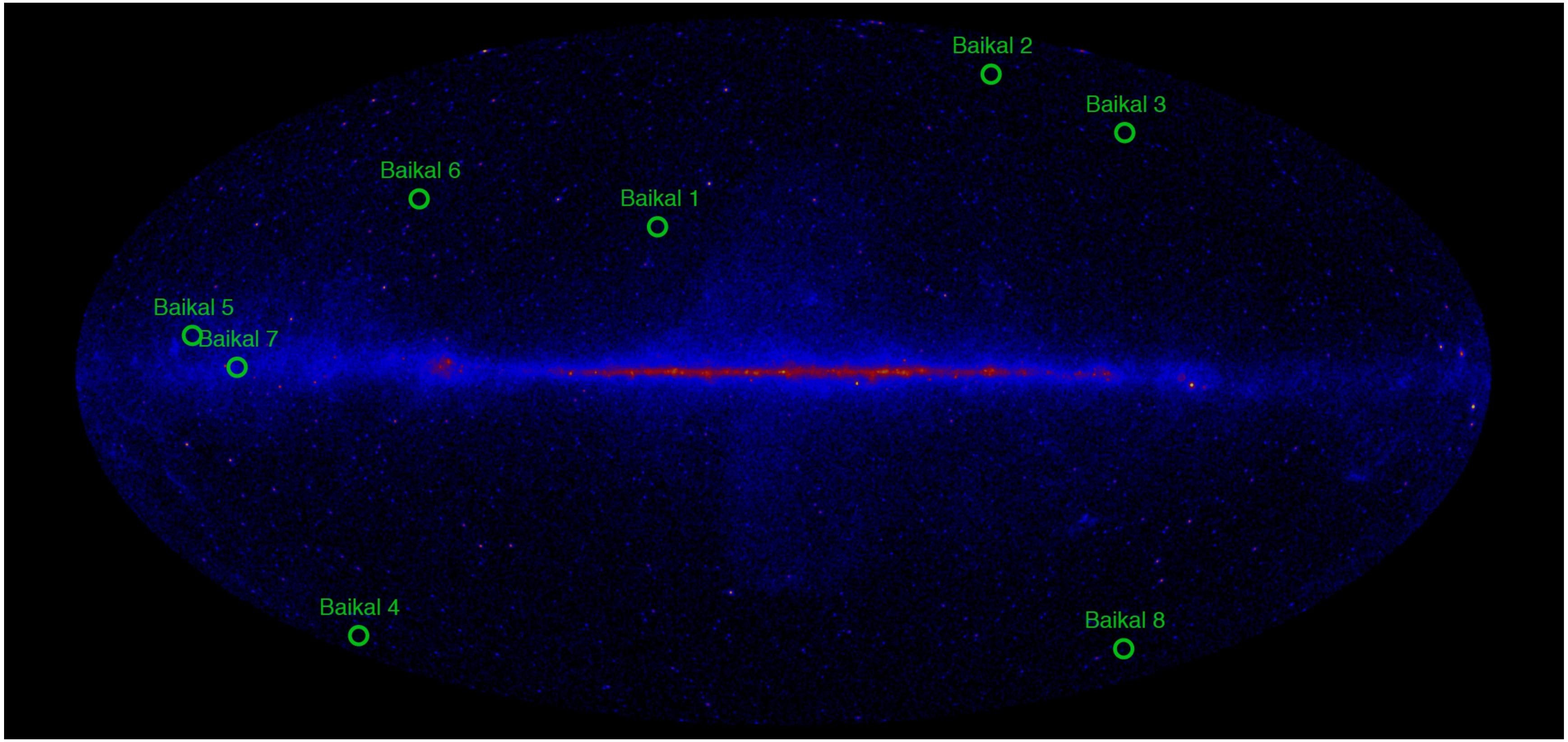






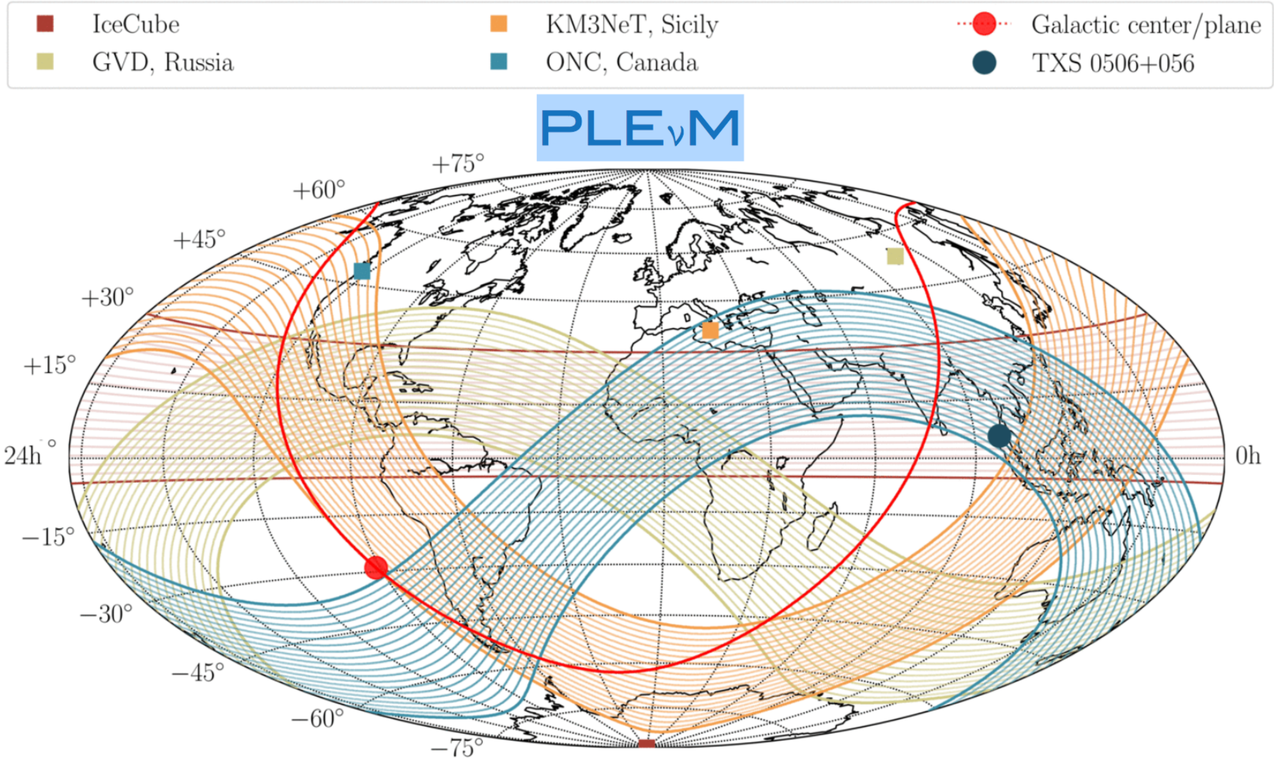


Baikal had 8 events (~4 background) E>100 TeV with 2015-2019 data



Sky coverage

THE FRONTIER: A PLANETARY NEUTRINO MONITORING SYSTEM

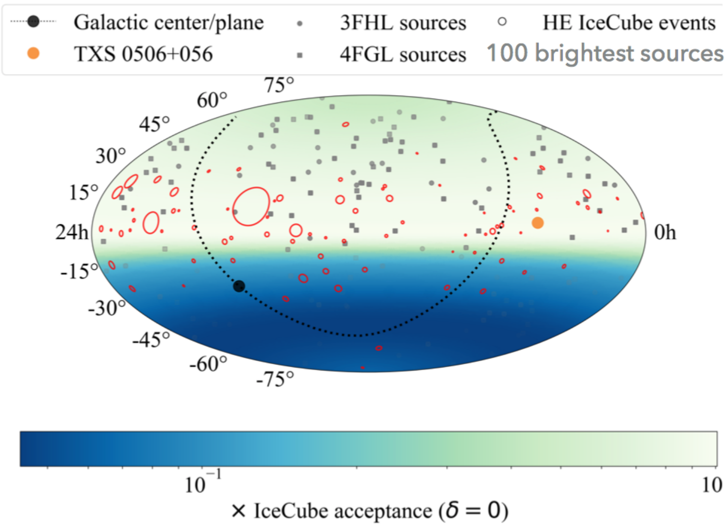


M. Huber (TUM)

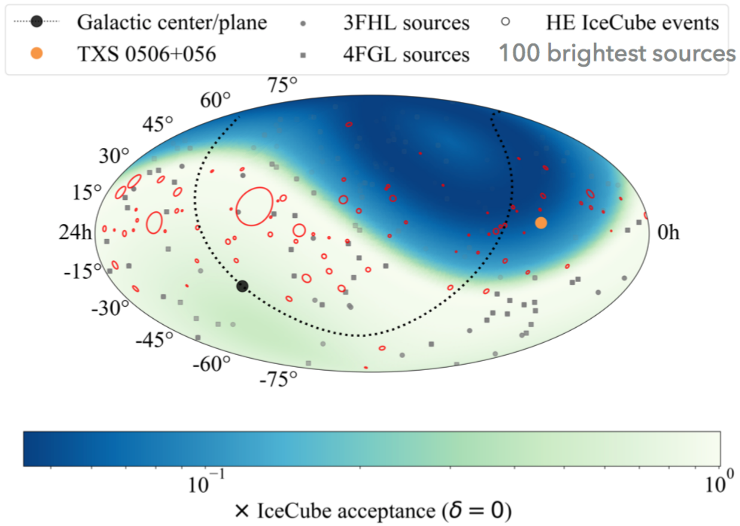
Sky coverage

ASSUME ONE ICECUBE @ BAIKAL, @ CAPO PASSERO, @ OCEAN NETWORK CANADA

PLEνM



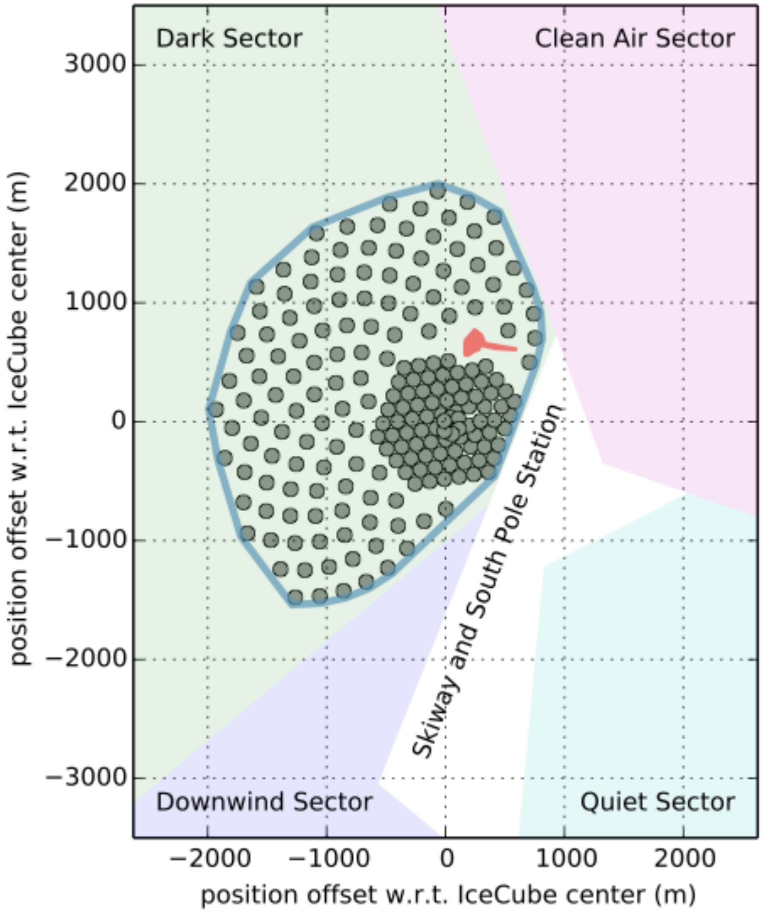
$$\text{IceCube acceptance} \equiv \int_0^\infty A_{\text{eff}}(\delta, E) \cdot E^{-\gamma} dE$$



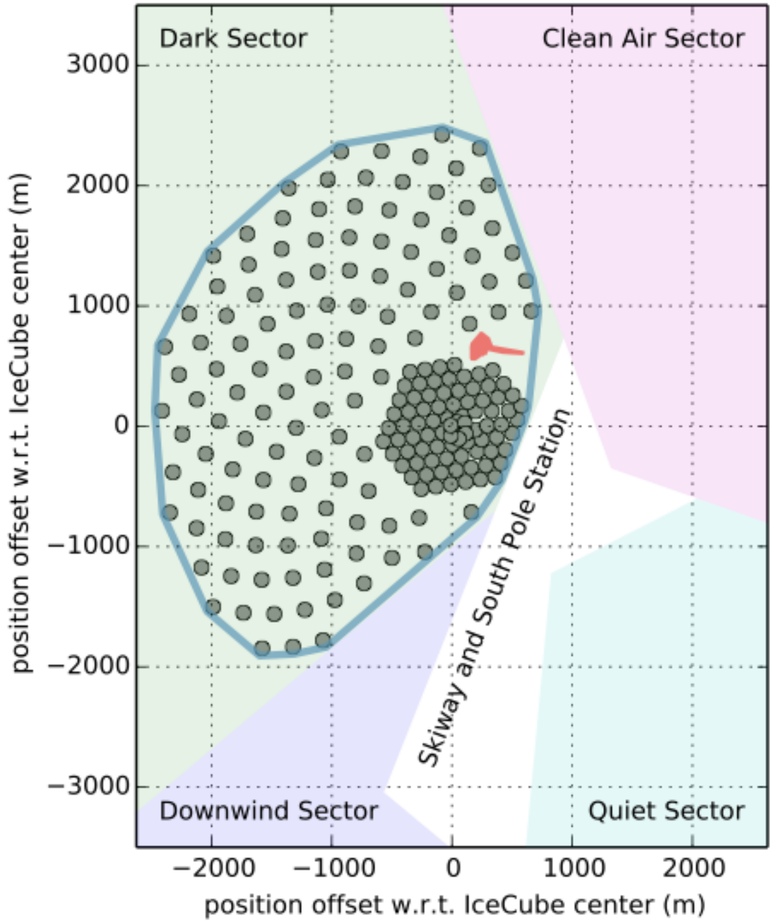
IceCube acceptance at the GVD location

on going study by M. Huber (TUM)

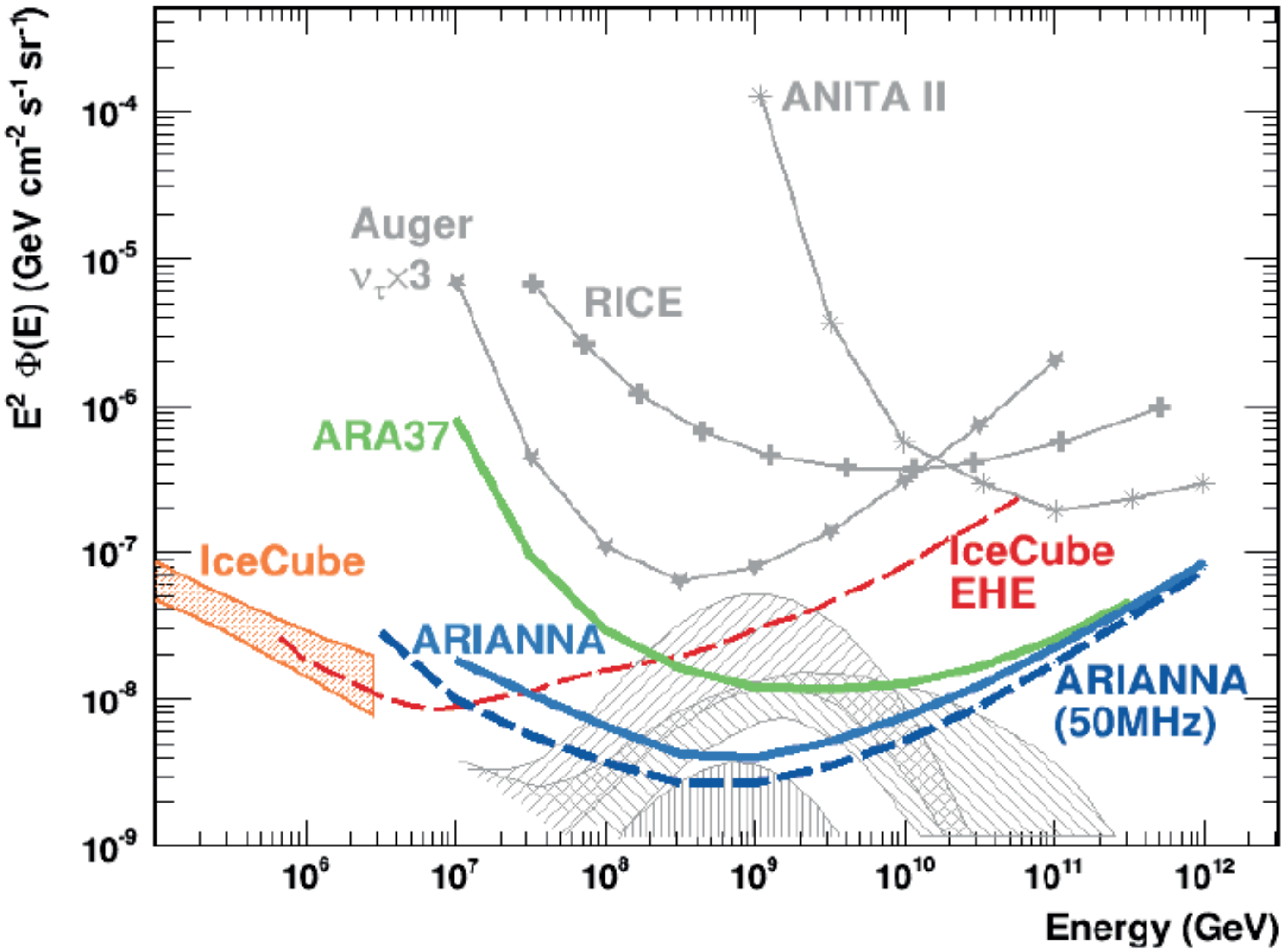
86 strings with 240-340 m spacing



(a) 240 m string spacing (“benchmark”)



(b) 300 m string spacing

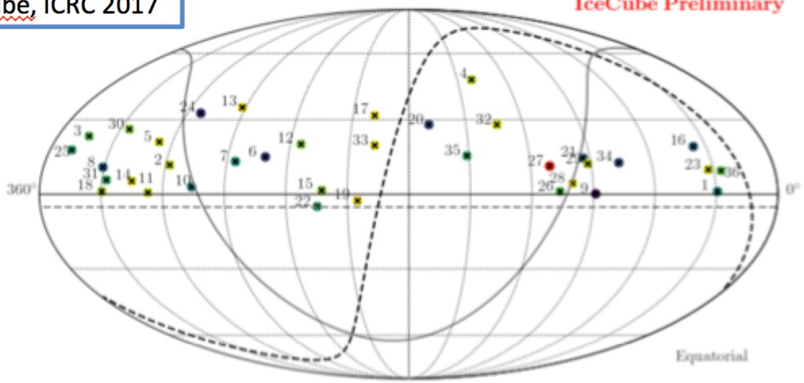

ANITA II
Auger
$\nu_\tau \times 3$
RICE
ARA37
IceCube
IceCube
EHE
ARIANNA
ARIANNA
(50MHz)
$E^2\ \Phi(E)$ (GeV cm^{-2} s^{-1} sr^{-1})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
Energy (GeV)

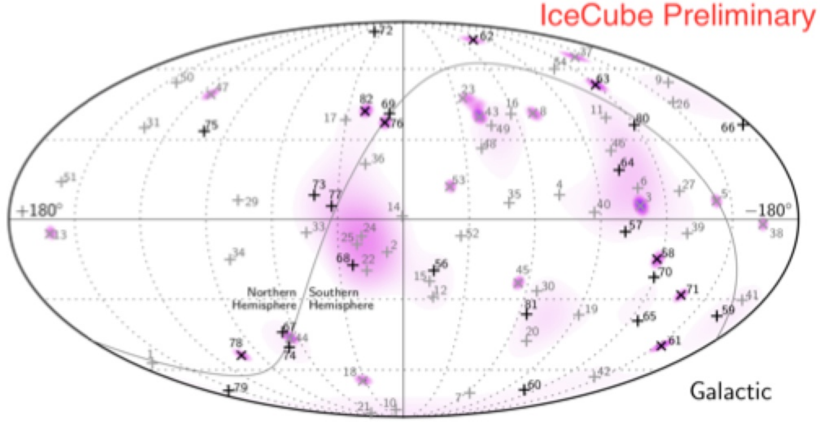
Present situation

IceCube ICRC 2017

Astrophysical neutrino signal

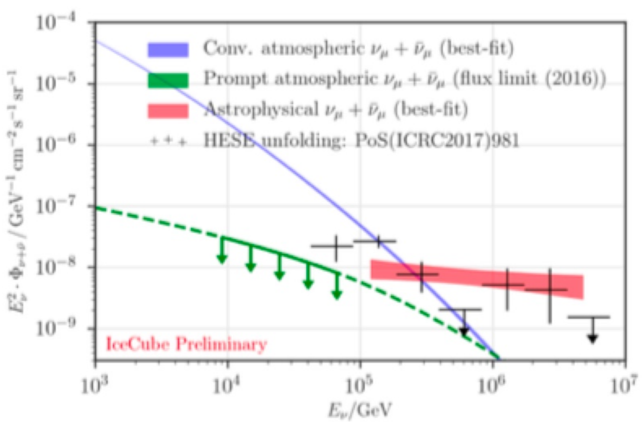
IceCube, ICRC 2017

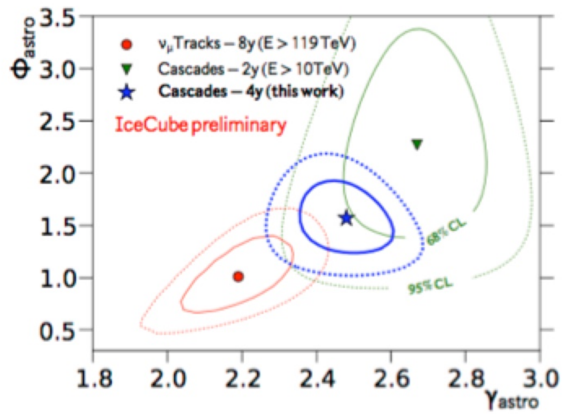


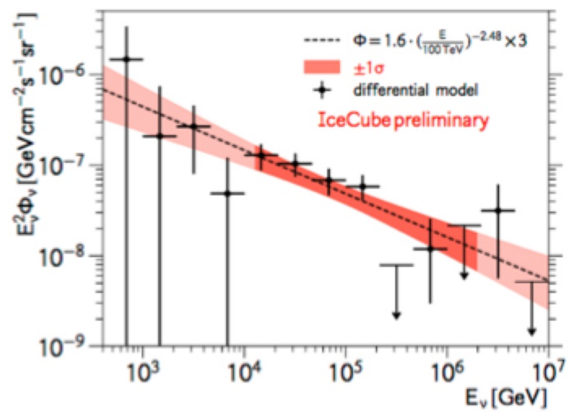


Muon neutrino sample

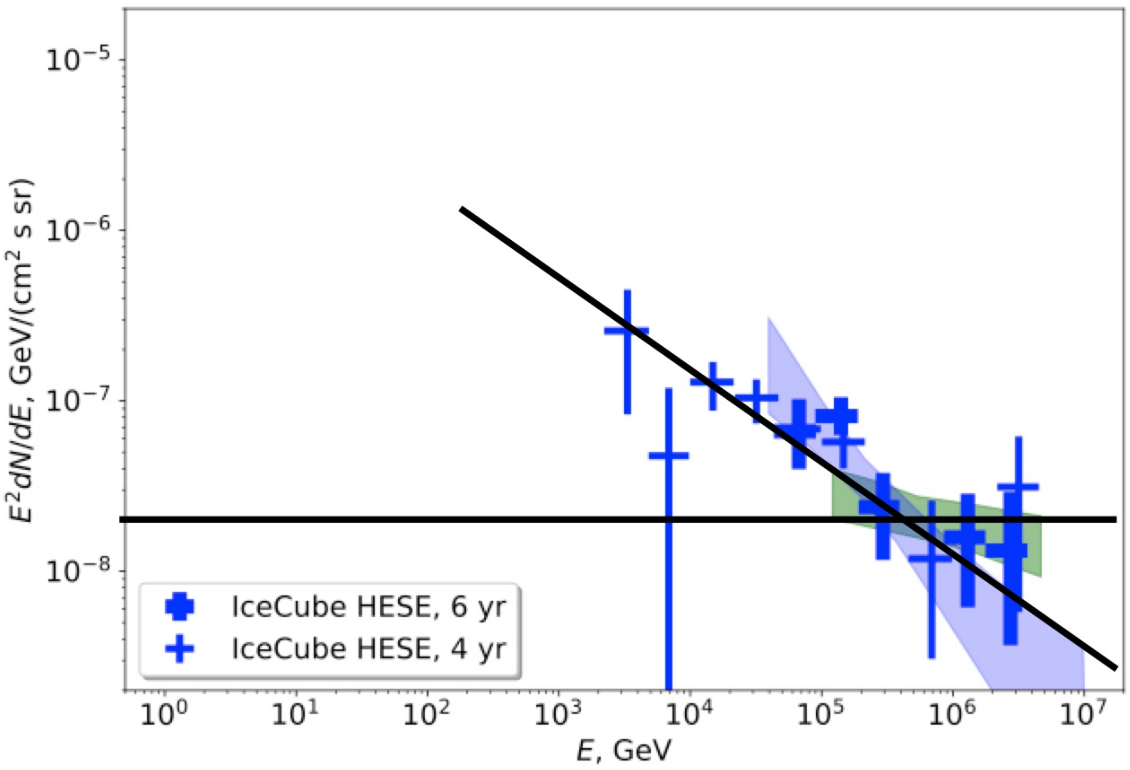
High Energy Starting Event neutrino sample







IceCube data



Diffuse gamma-ray background

Pion production

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

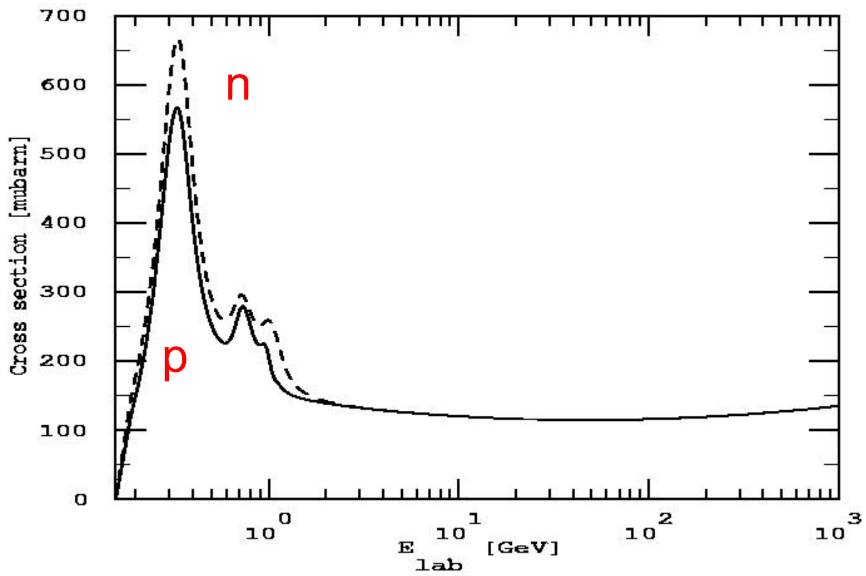
$$N + A_b \Rightarrow N^{'} + \sum \pi^{i}$$

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

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

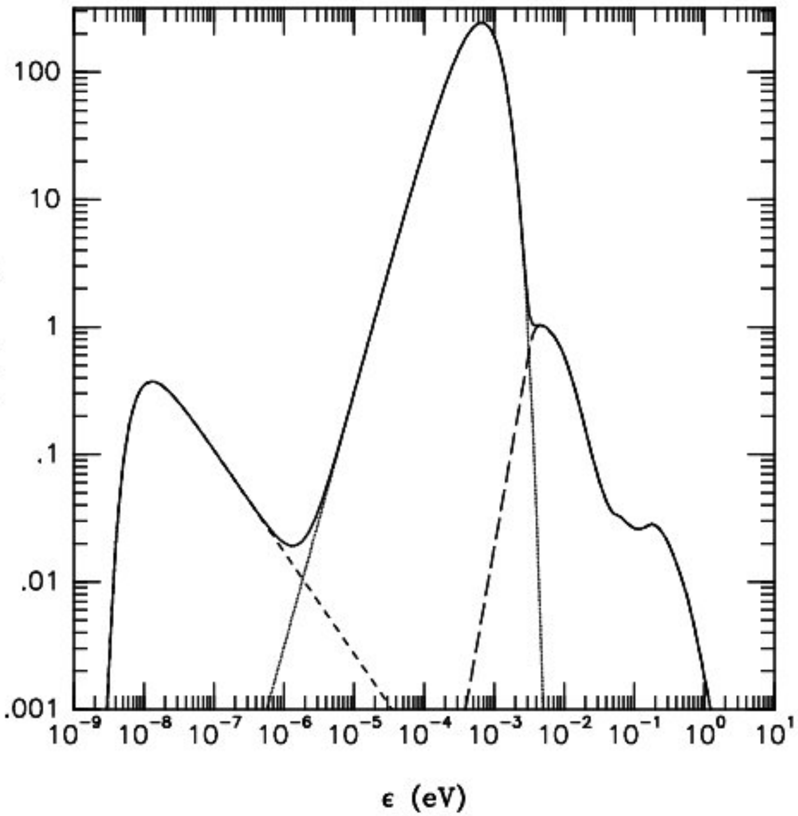
$$\mu^{\pm} \Rightarrow e^{\pm} + \overline{\nu}_e + \nu_{\mu}$$

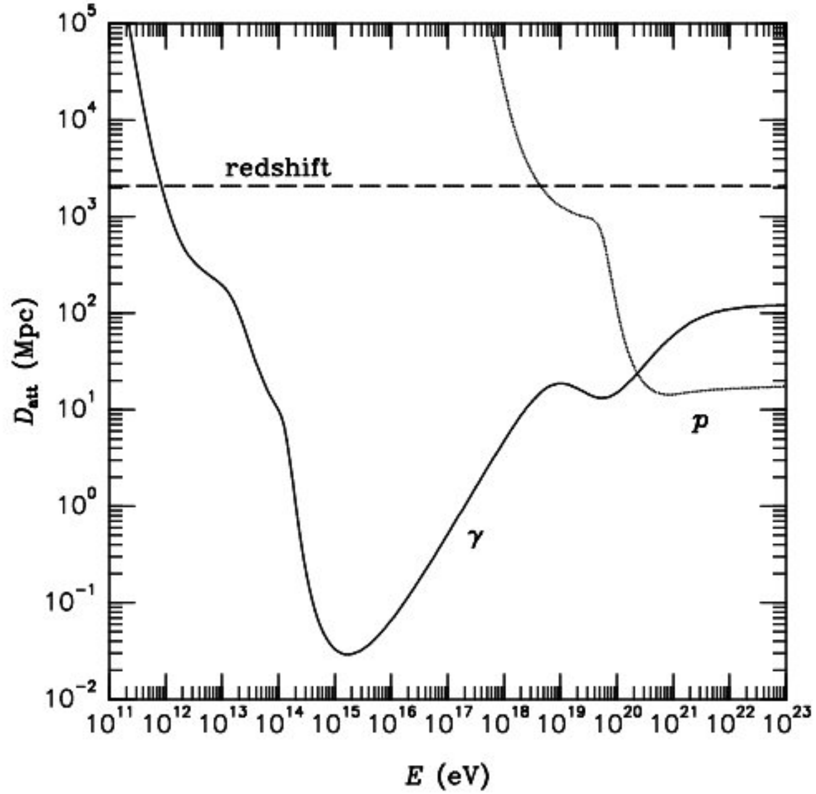
$$n \Rightarrow p + e^{-} + \overline{\nu}_e$$



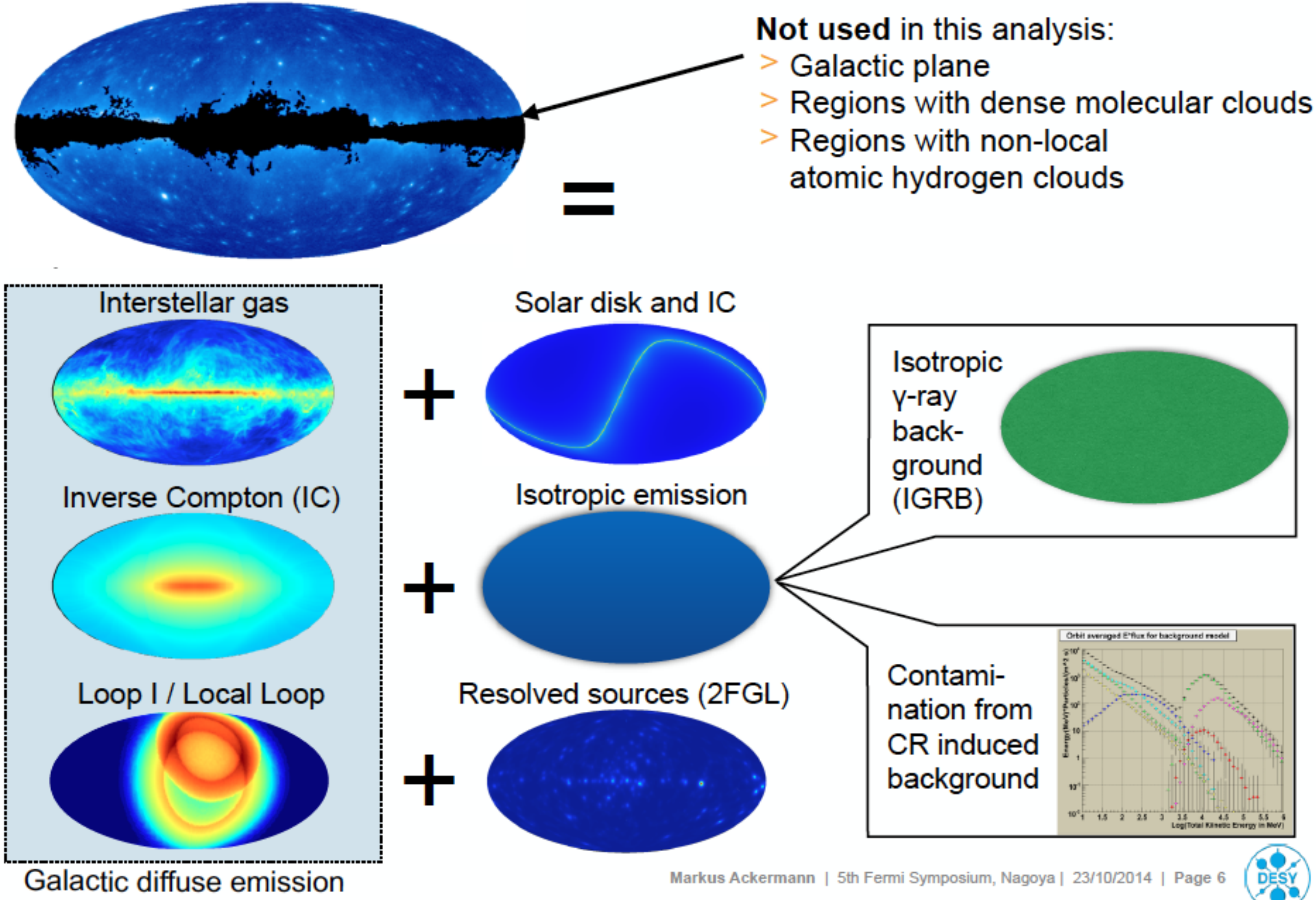
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_{\gamma}^{tot} \sim E_{\nu}^{tot}$

Diffuse backgrounds

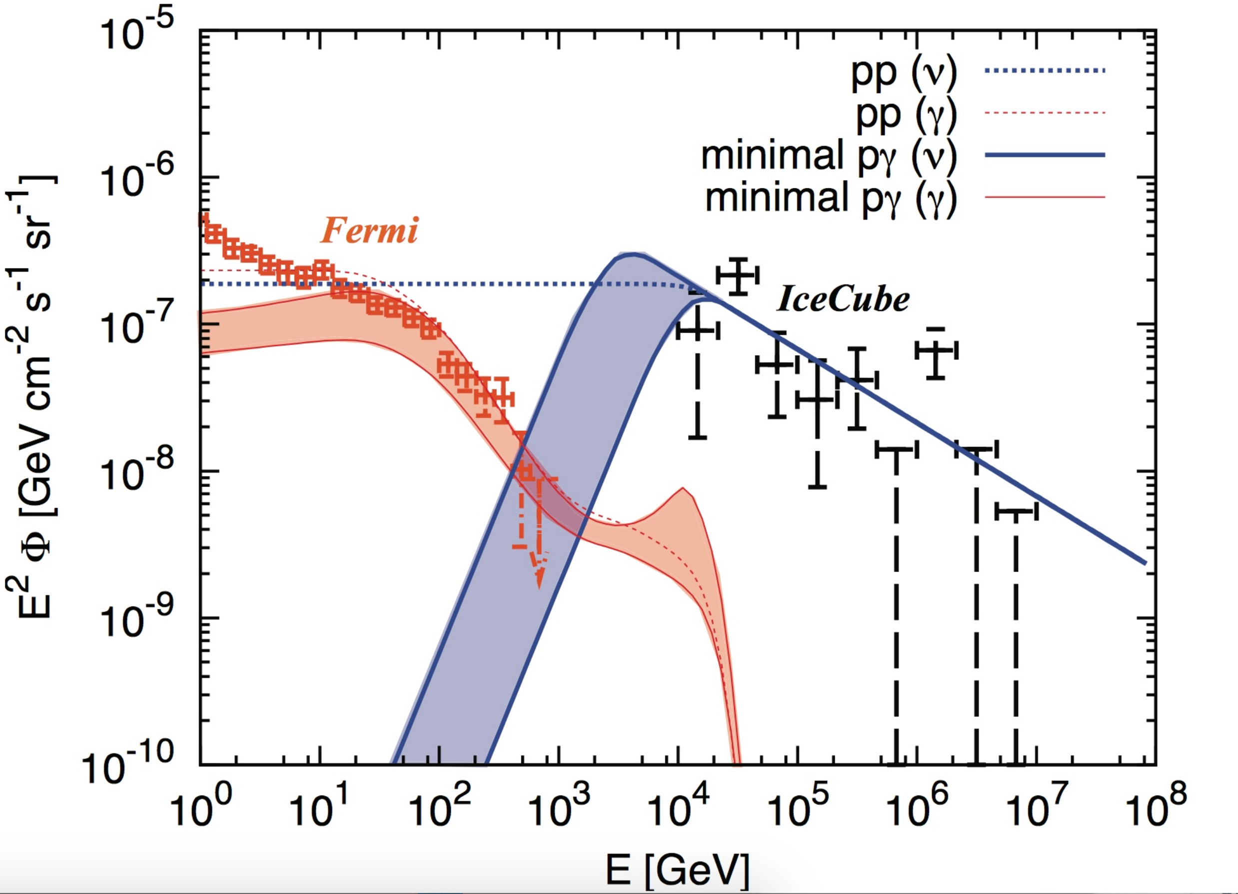




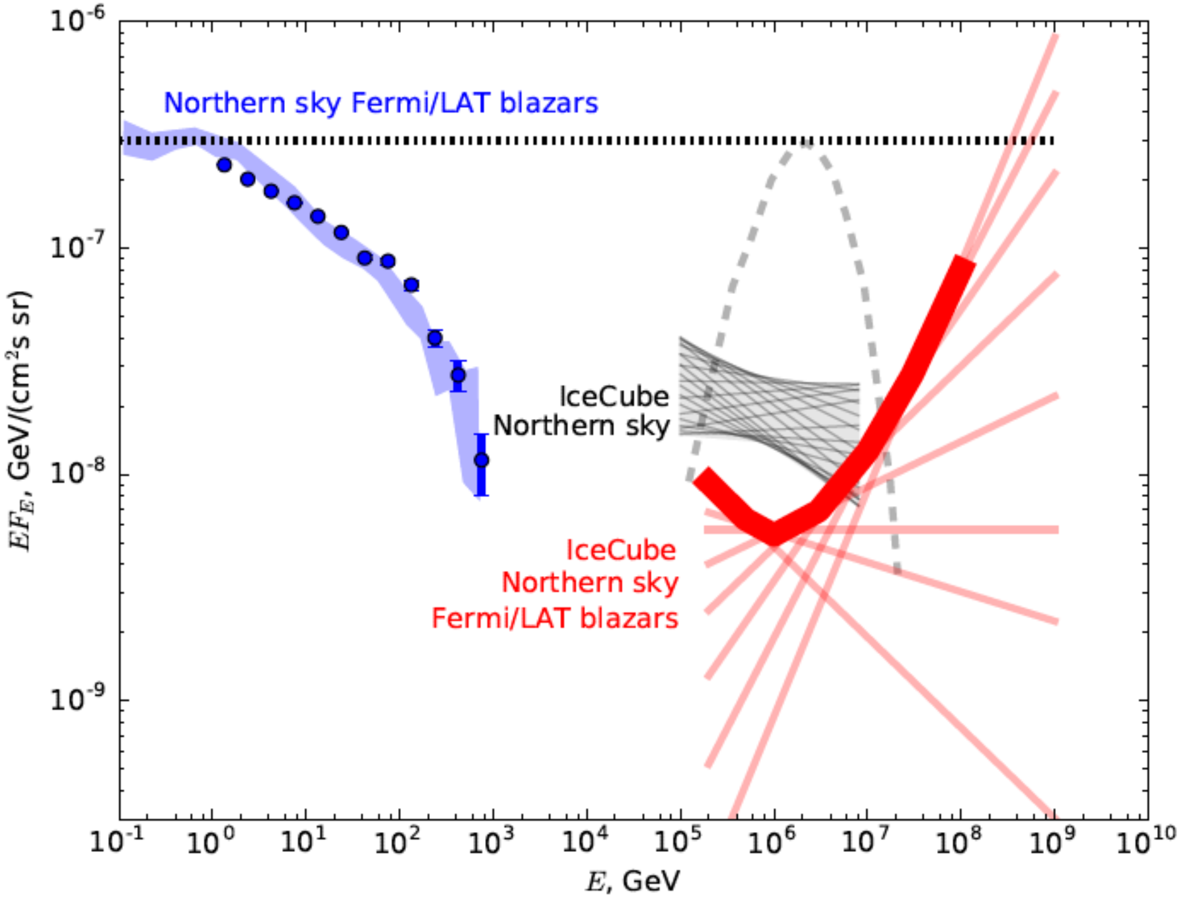
Derivation of the isotropic gamma-ray background



Self-consistent extragalactic sources

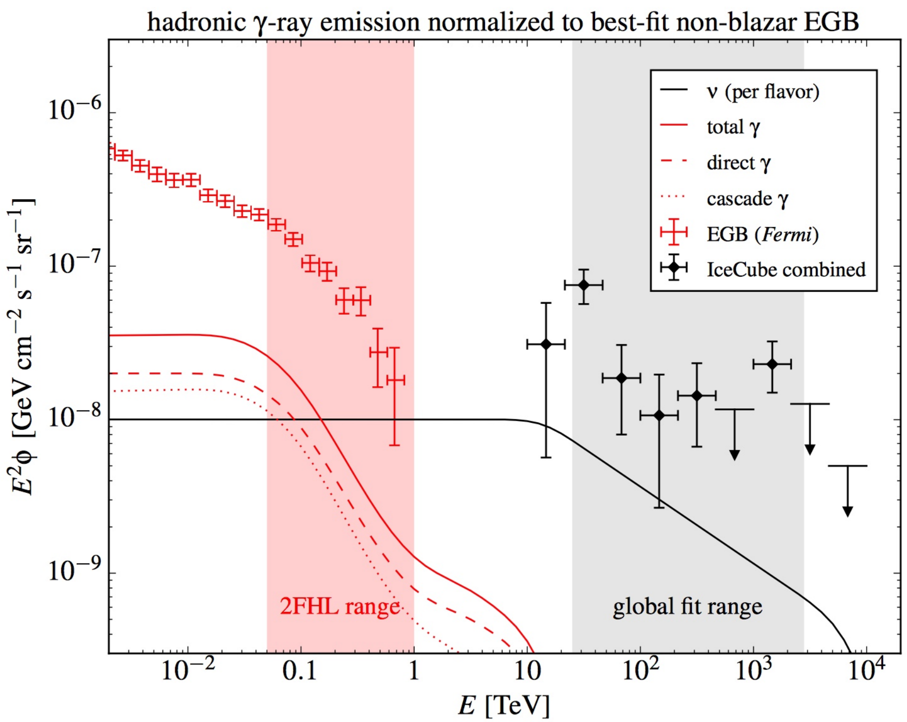


Neutrinos not from Fermi blazars



IceCube arXiv:1611.03874

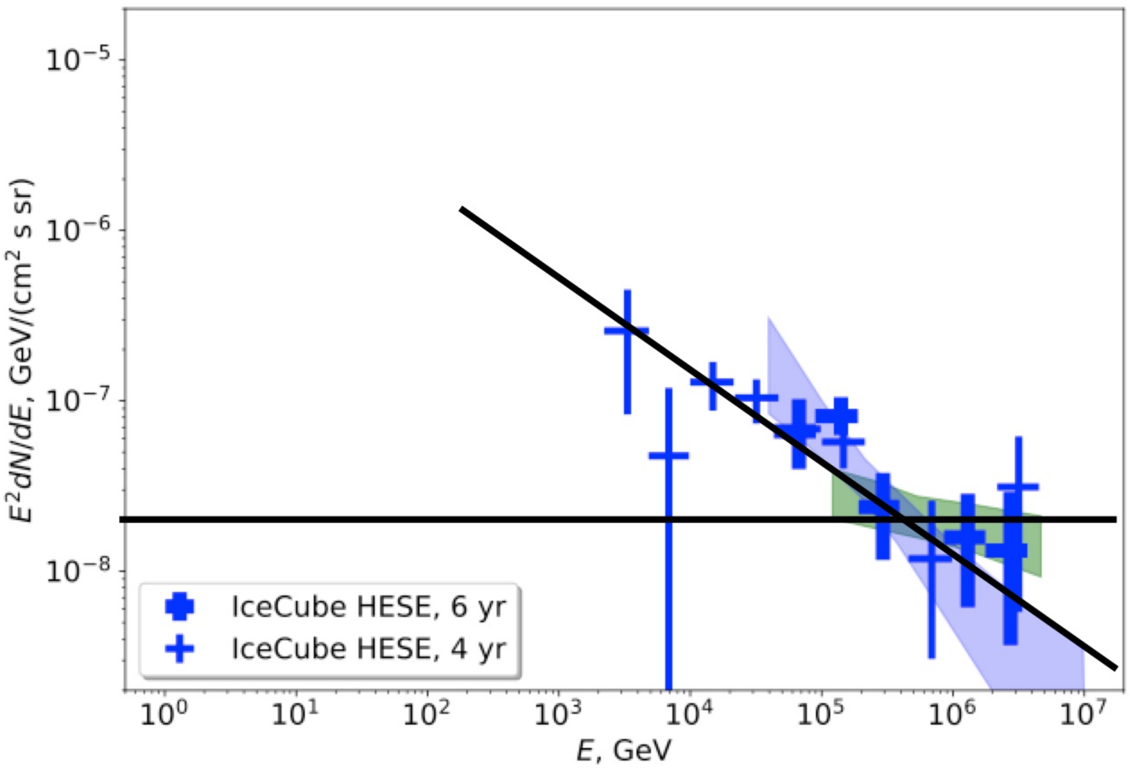
Self-consistent extragalactic sources: no blazars



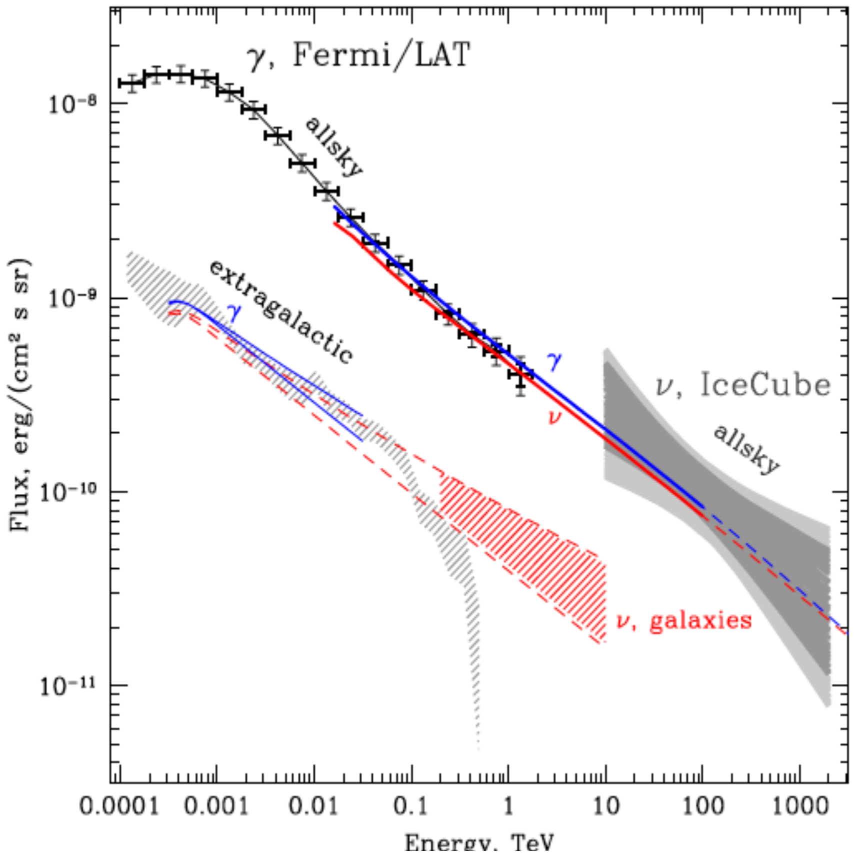
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

Low energy excess

IceCube data

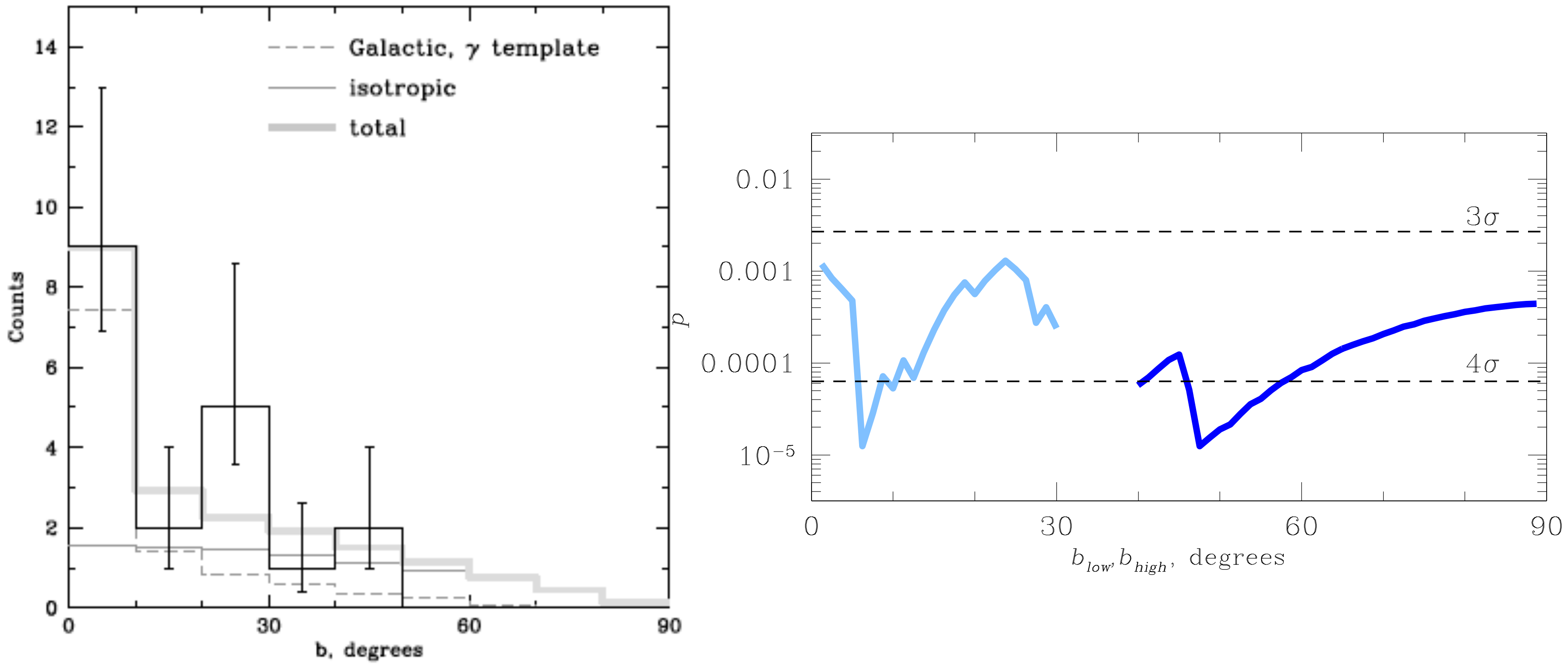


IceCube + Fermi LAT all sky: protons 1/E^2.5



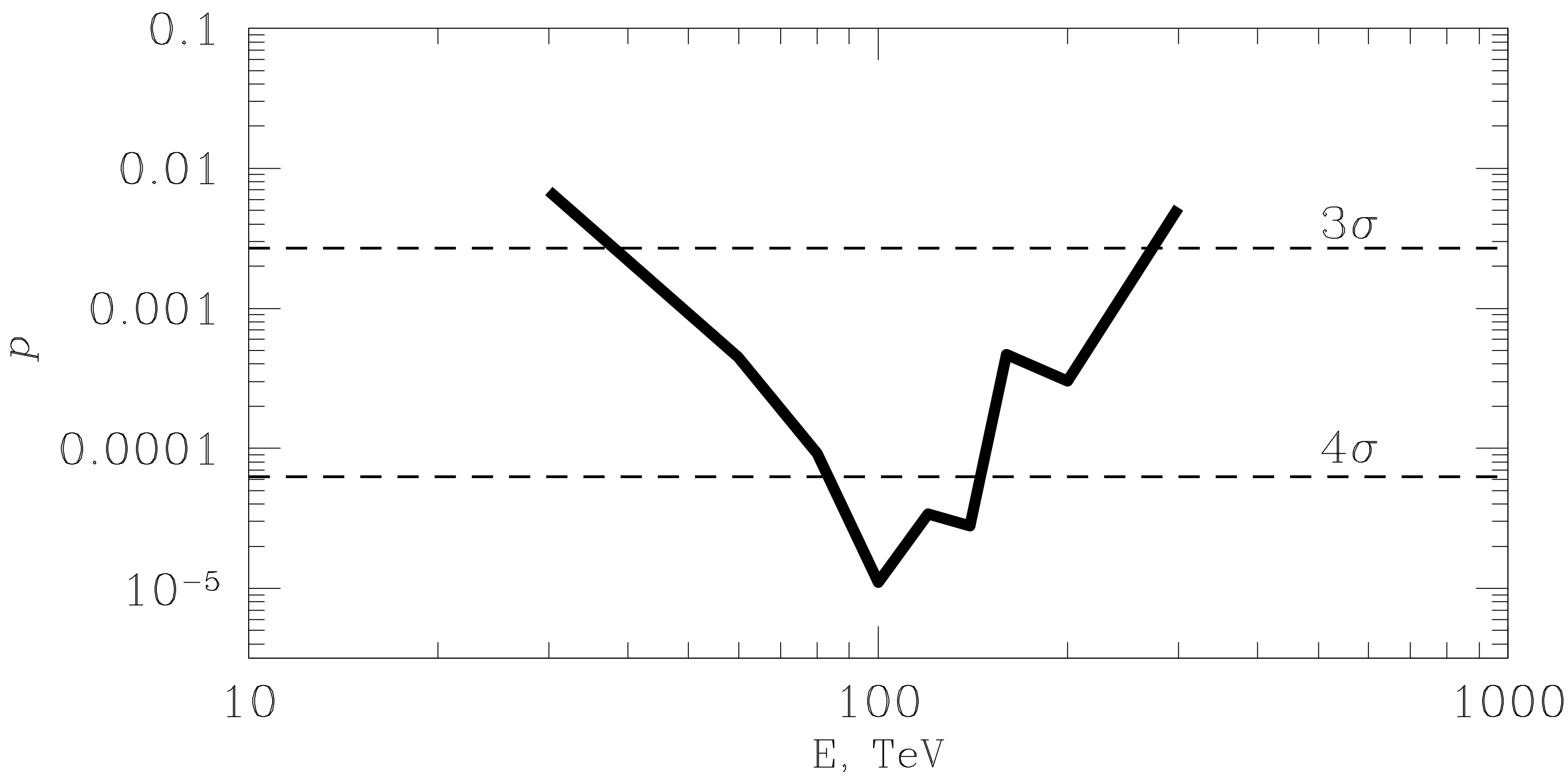
A.Neronov, D.S. arXiv:1412.1690

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



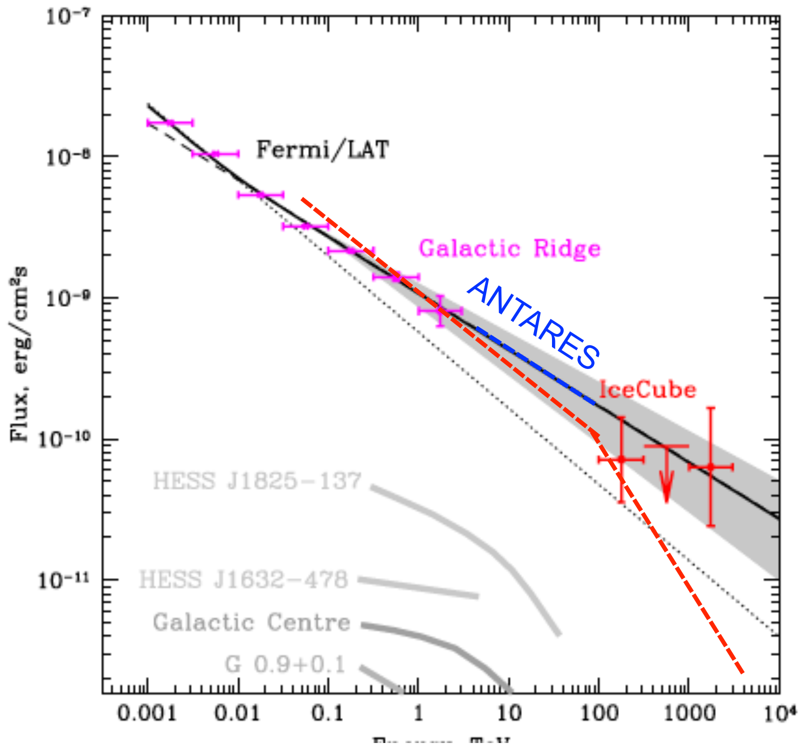
A. Neronov & D.S. arXiv: 1509.03522

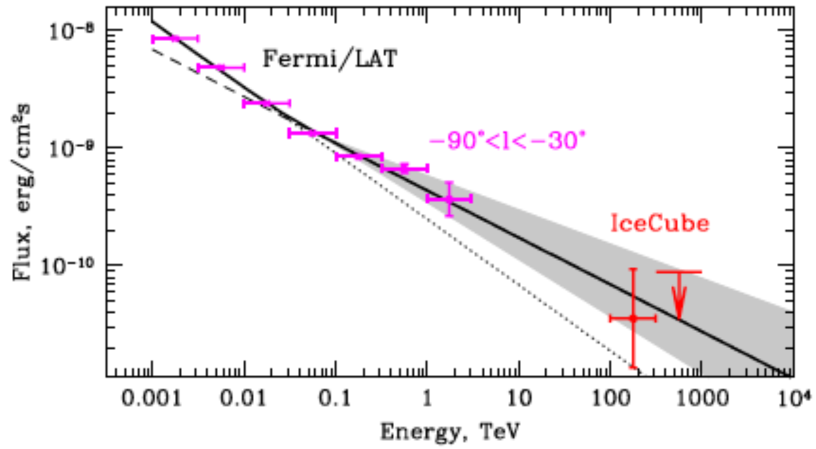
Post-trial probability is $1.7*10^{-3}$



A. Neronov & D.S. arXiv: 1509.03522

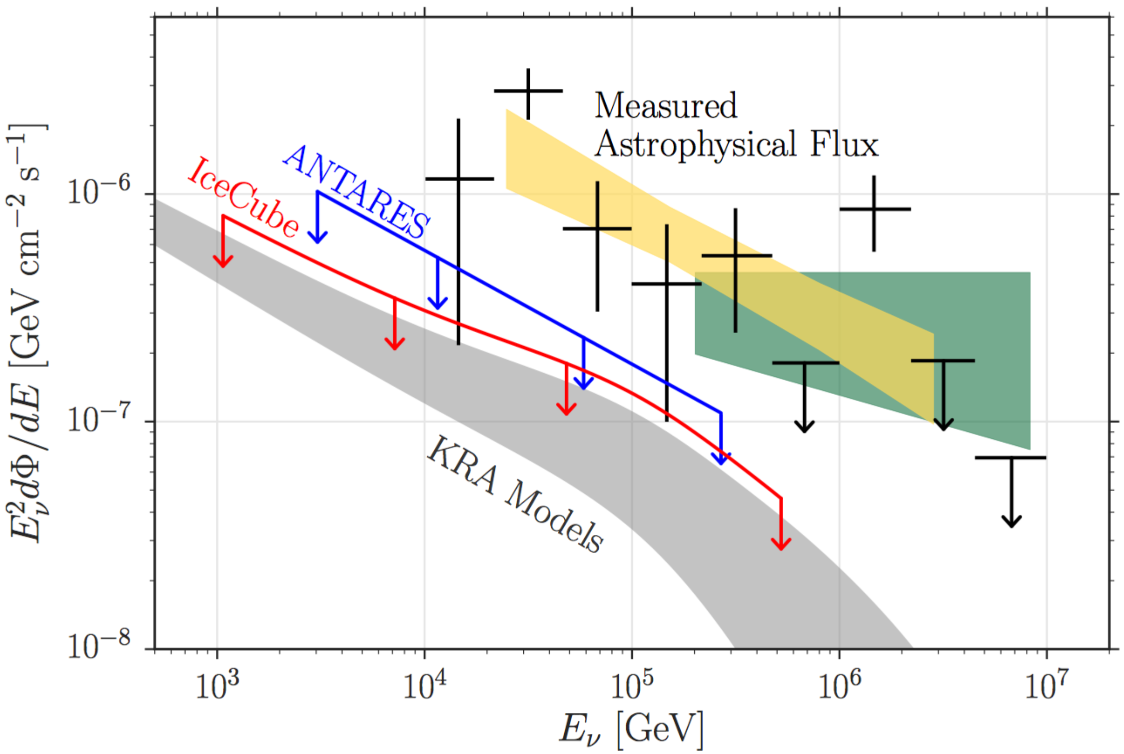
Real multimessenger fluxes, alpha=2.5





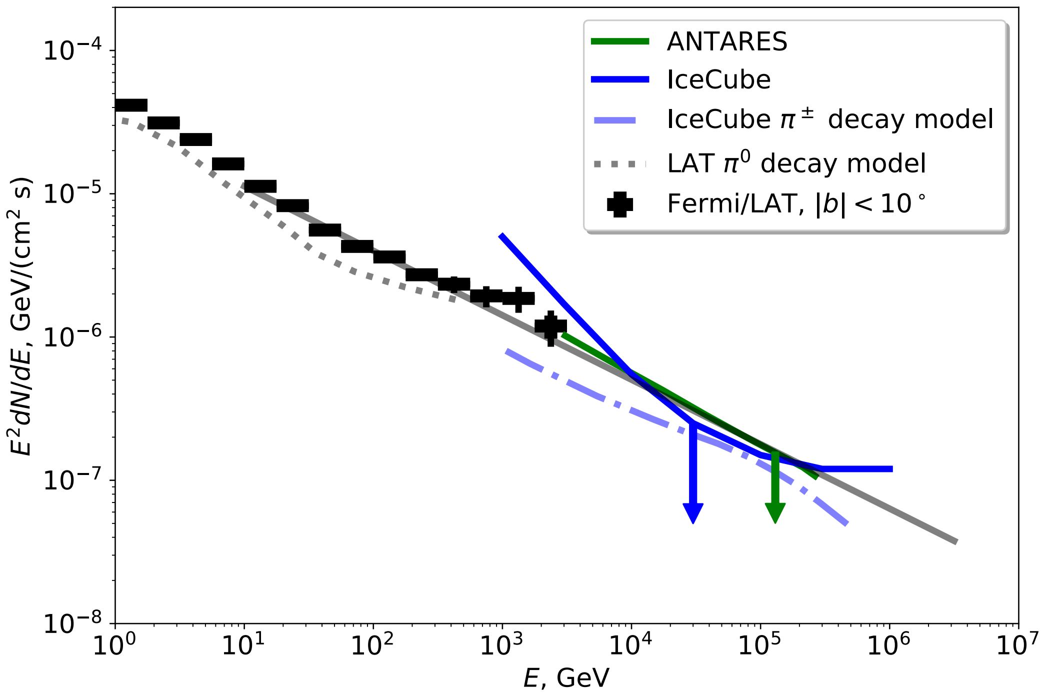
V.Berezinsky & A.Smirnov 1975

IceCube and ANTARES galalactic plane



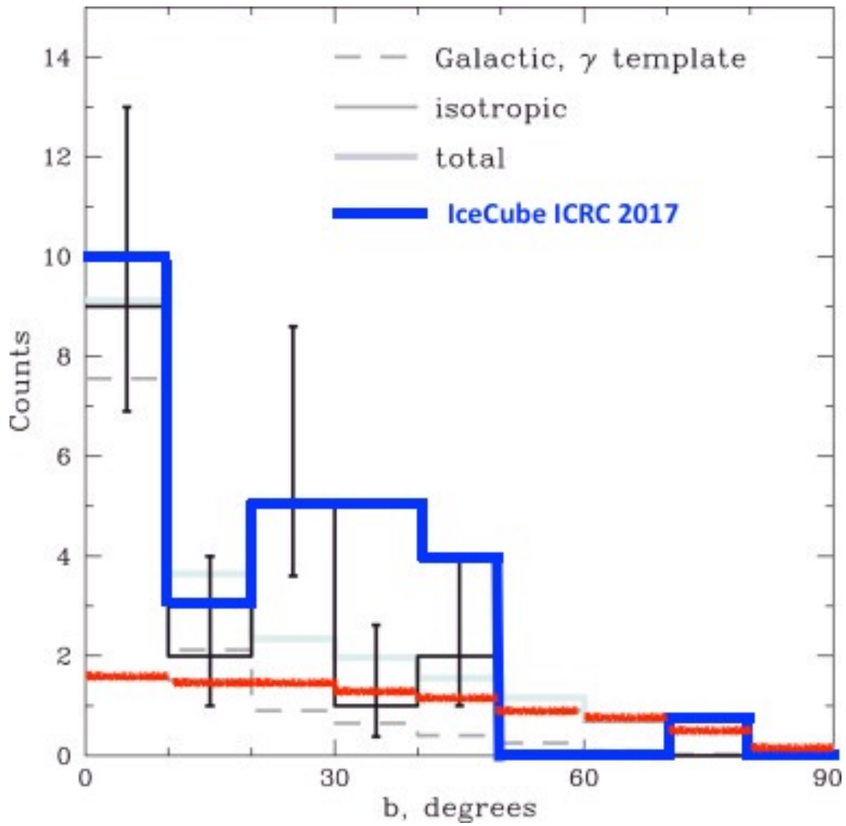
ICRC 2017

IceCube + Fermi LAT Galactic plane



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

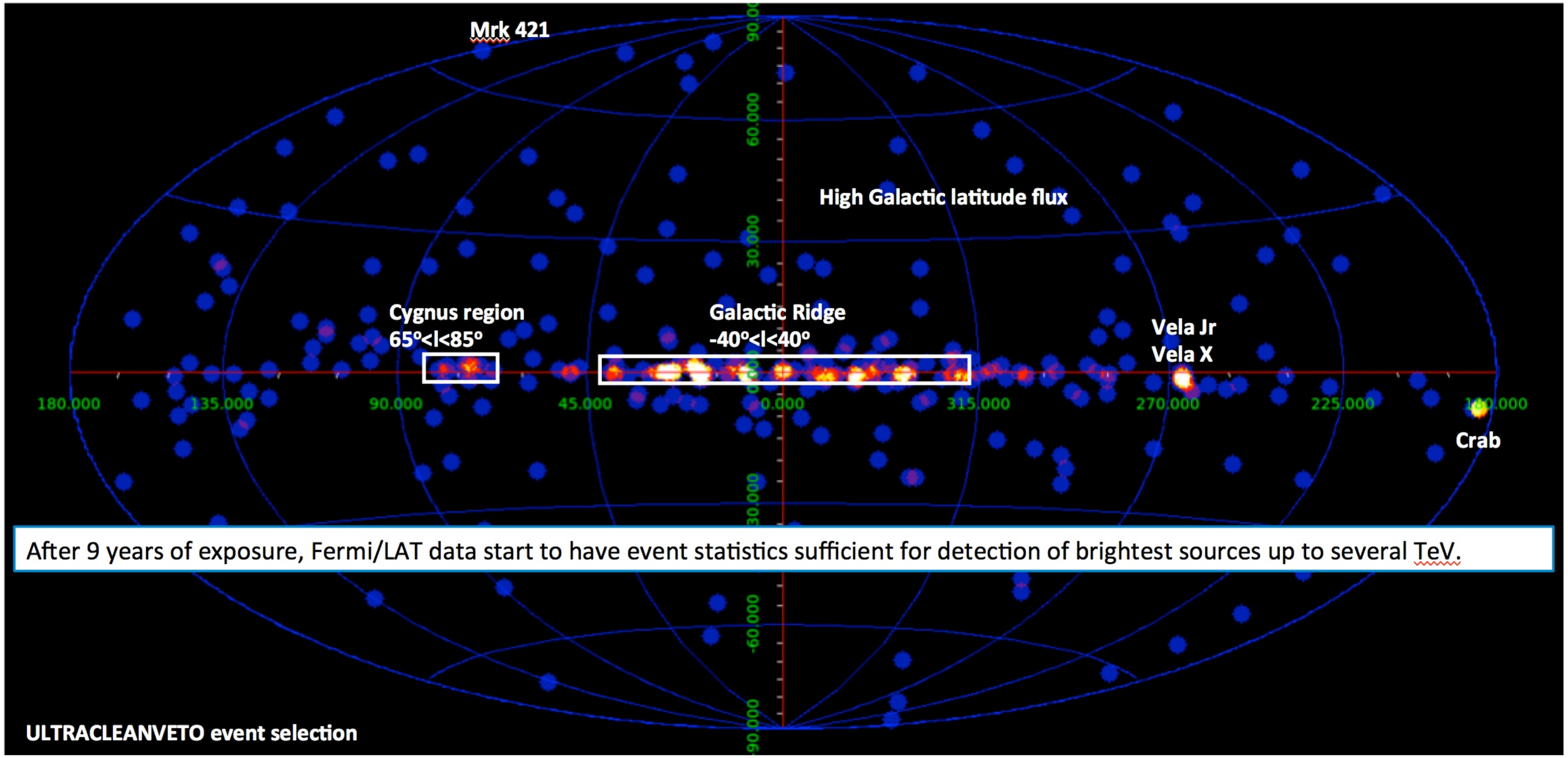
Anisotropy at E>100 TeV



A. Neronov, M.Kachelriess and D.S. 2018

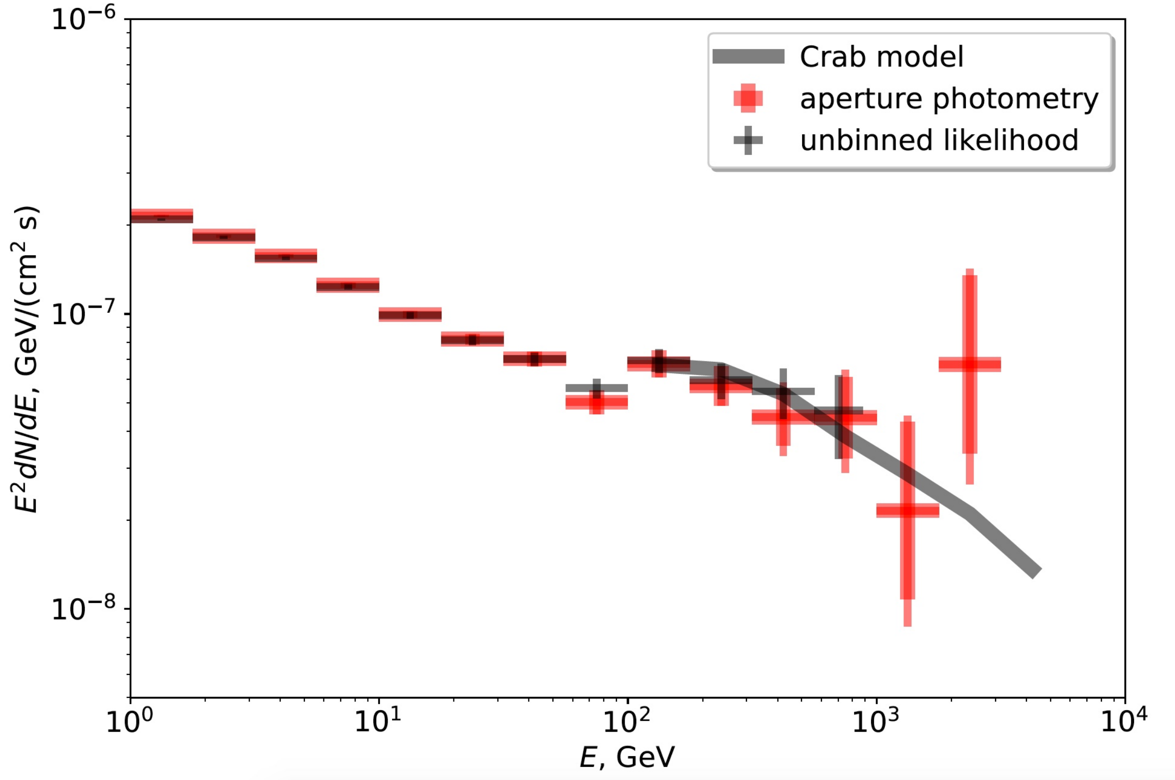
Gamma-ray anomaly at TeV

Fermi sky map E> 1 TeV



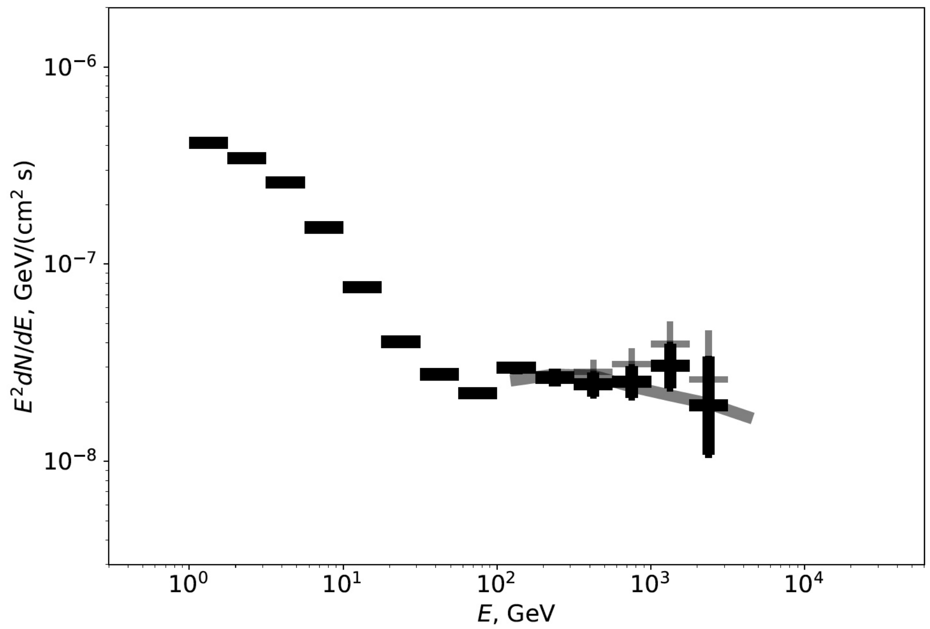
After 9 years of exposure, Fermi/LAT data start to have event statistics sufficient for detection of brightest sources up to several TeV.

Crab pulsar



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

Fermi/LAT multi-TeV sky



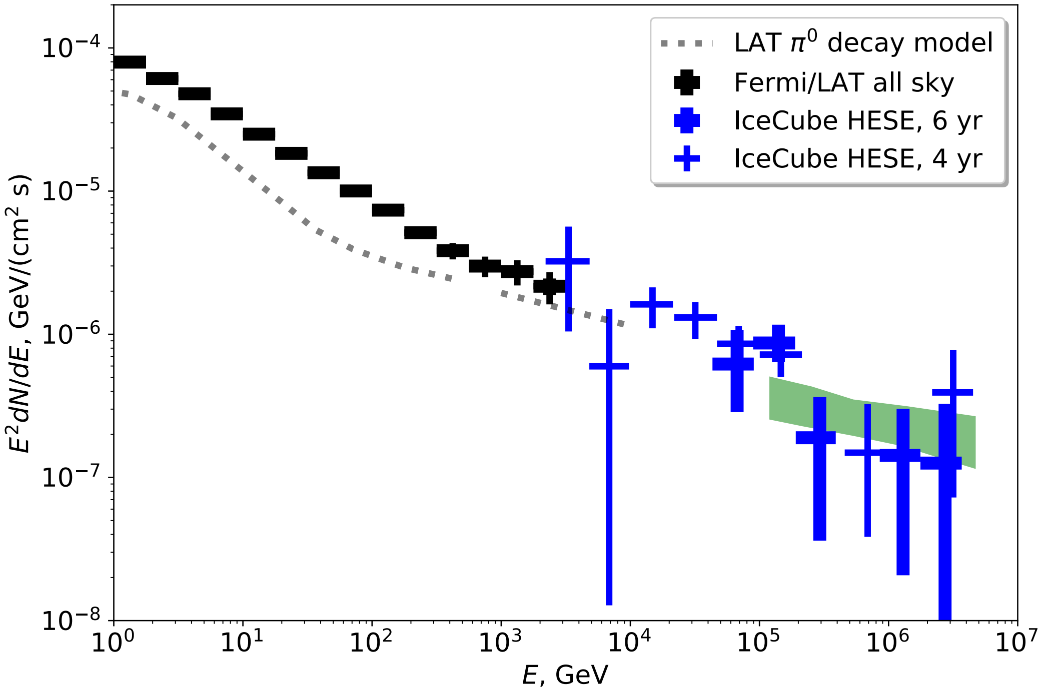
After 9 years of exposure, Fermi/LAT data start to have event statistics sufficient for detection of brightest sources up to several TeV.

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).

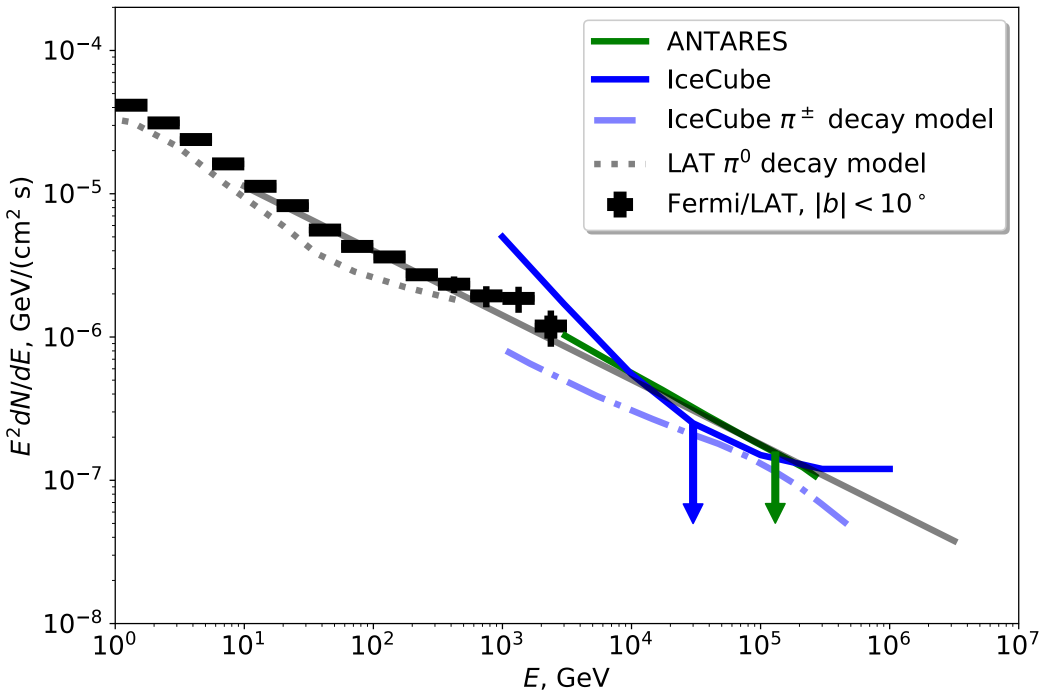
A.Neronov, M.Kachelriess, D.S. '18

IceCube + Fermi LAT all sky



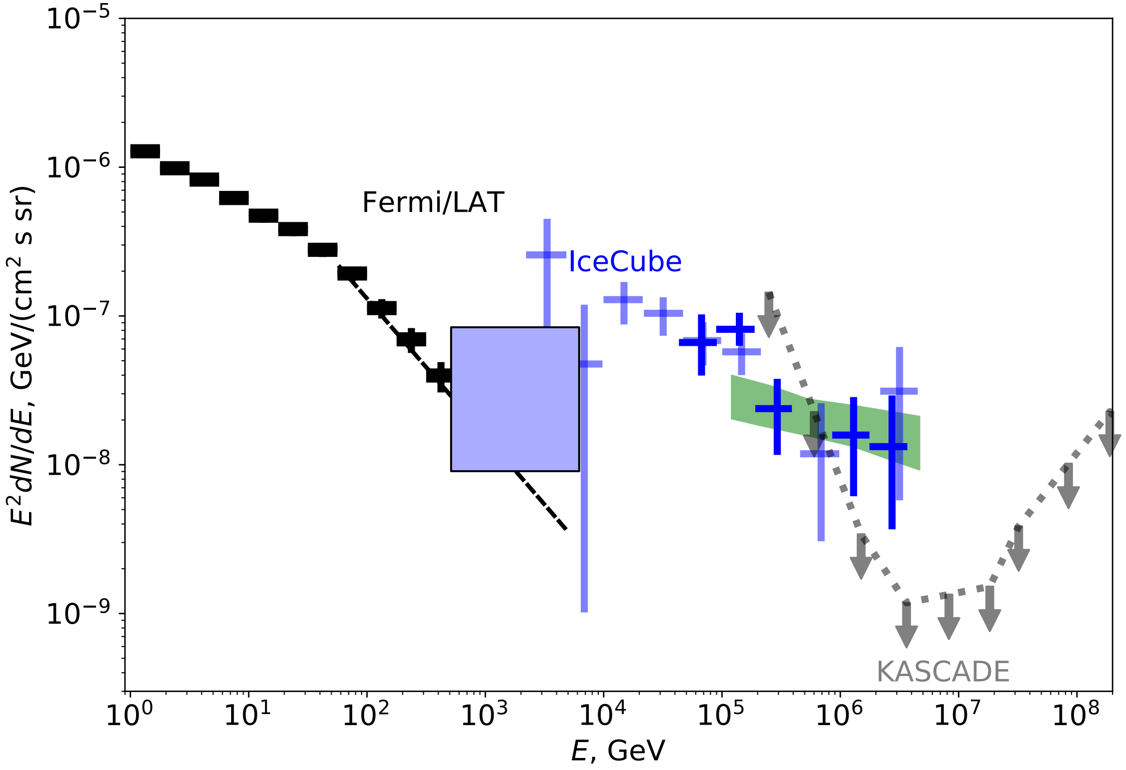
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

IceCube + Fermi LAT Galactic plane



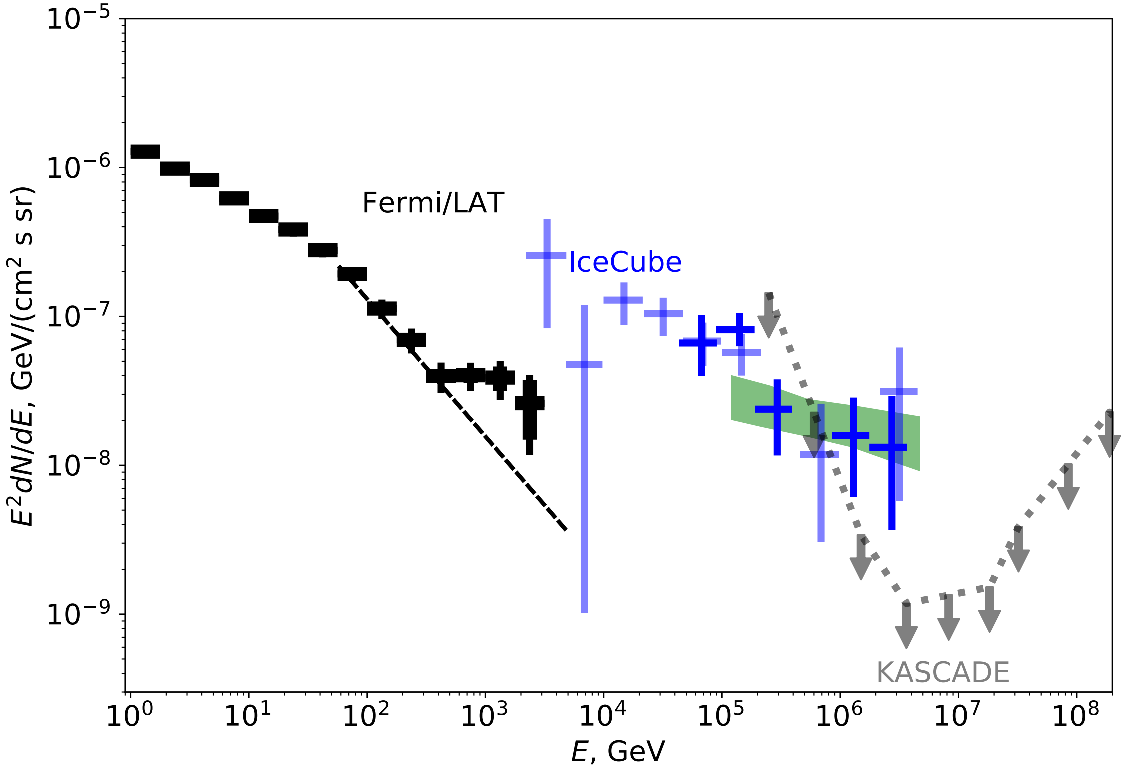
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

IceCube + Fermi LAT high galactic latitude ÌbÌ>20 deg



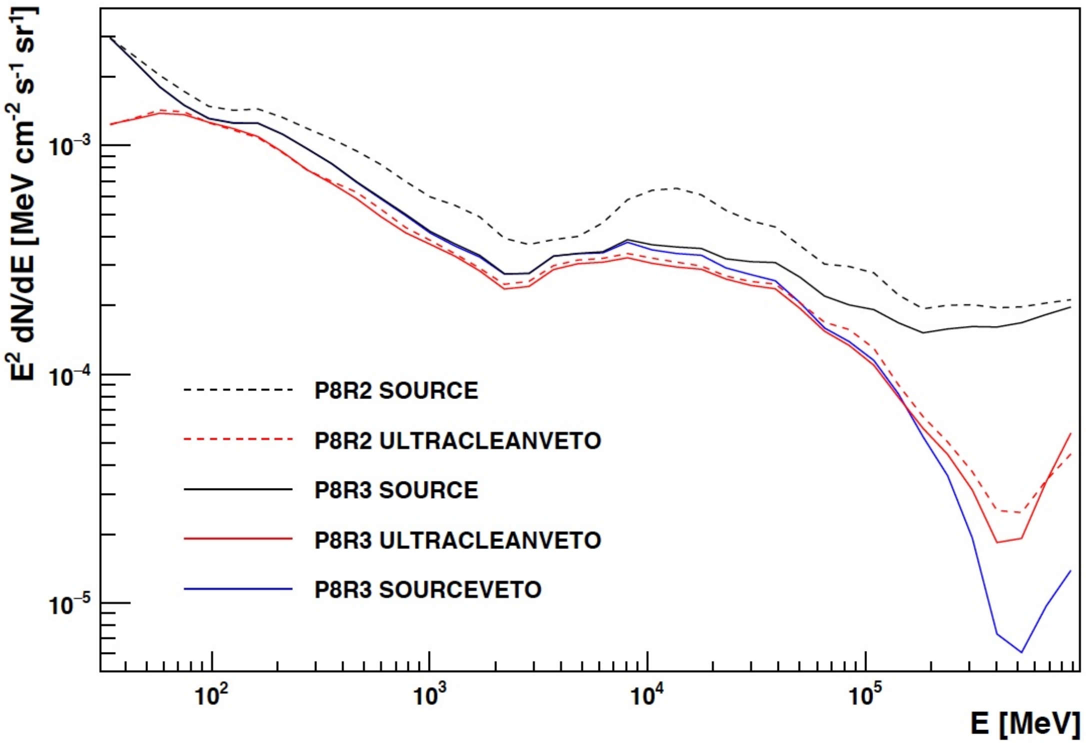
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

IceCube + Fermi LAT high galactic latitude ÌbÌ>20 deg



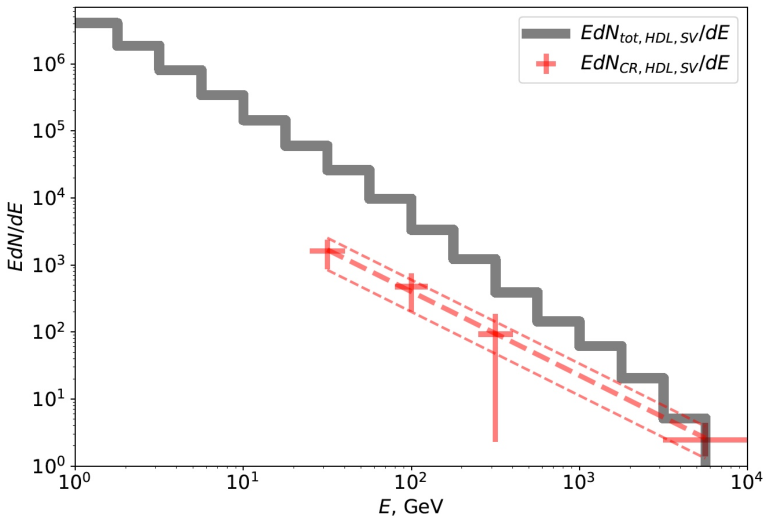
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

Fermi new pass SOURCEVETO

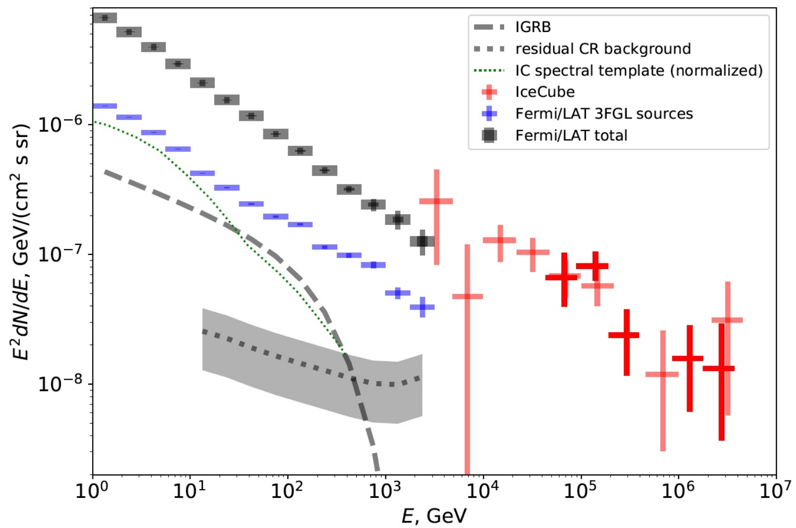


Fermi collaboration, Dec 2018

Fermi TeV: new pass SOURCEVETO works up to 3 TeV



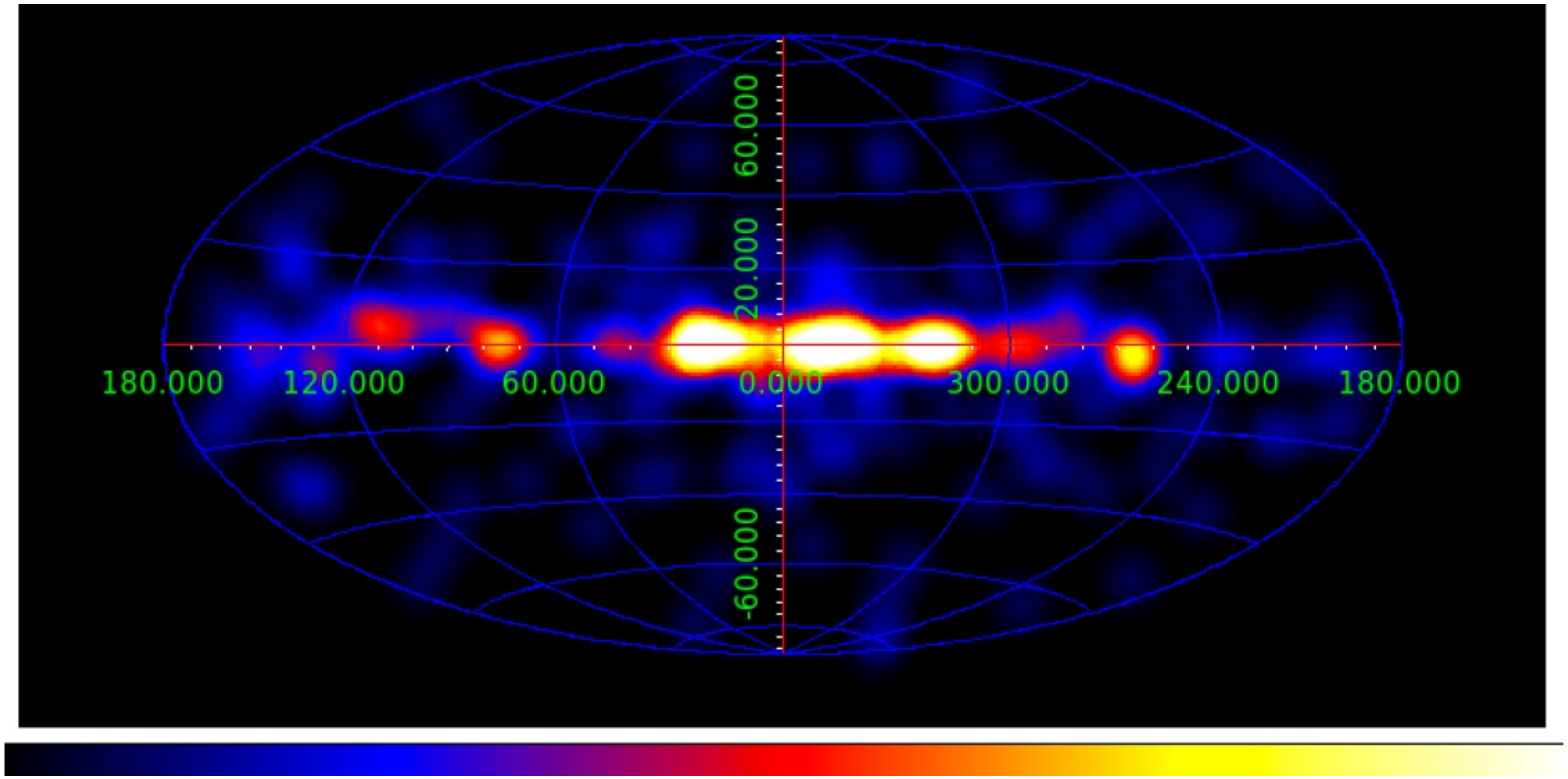
Cosmic ray background



All sky signal

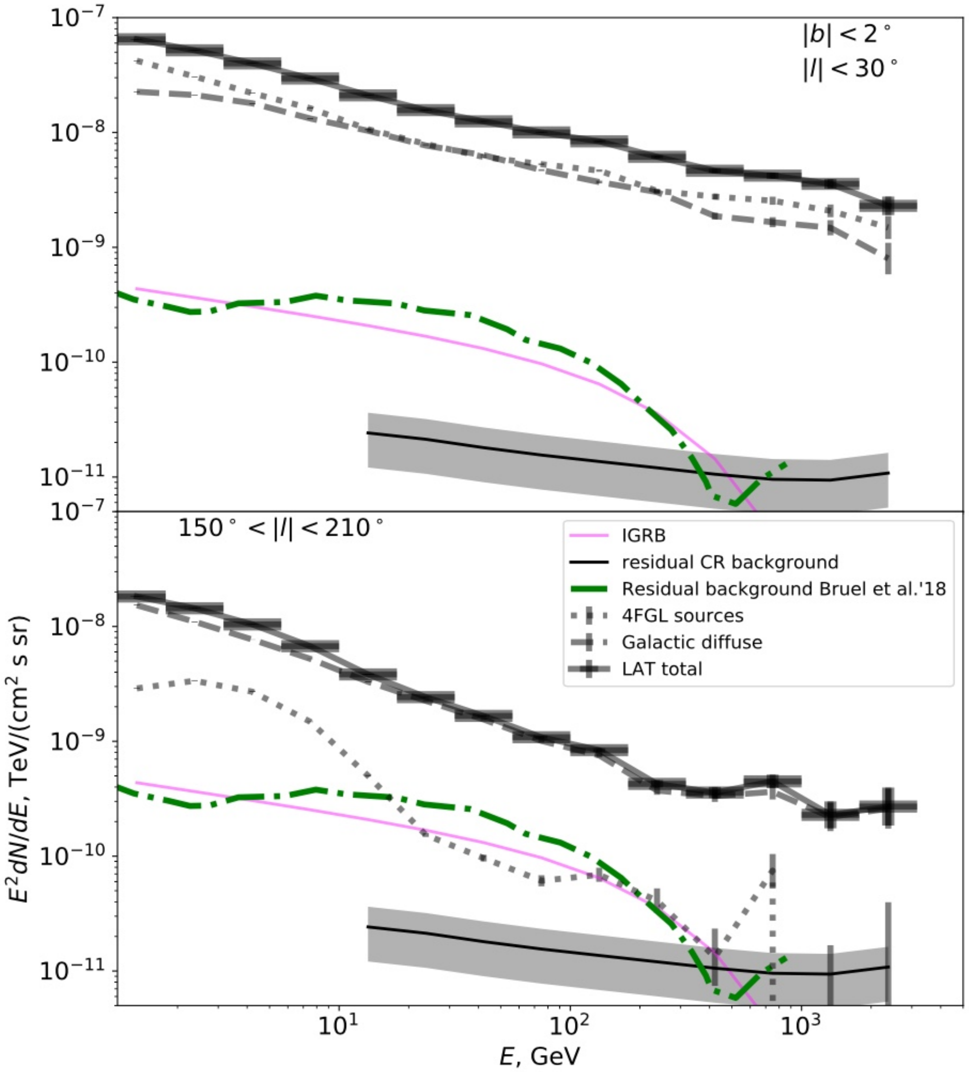
A.Neronov and D.S. , 1907.06061

Sky map E> 1TeV Fermi



A.Neronov and D.S. , 1907.06061

Galactic Plane, spectrum

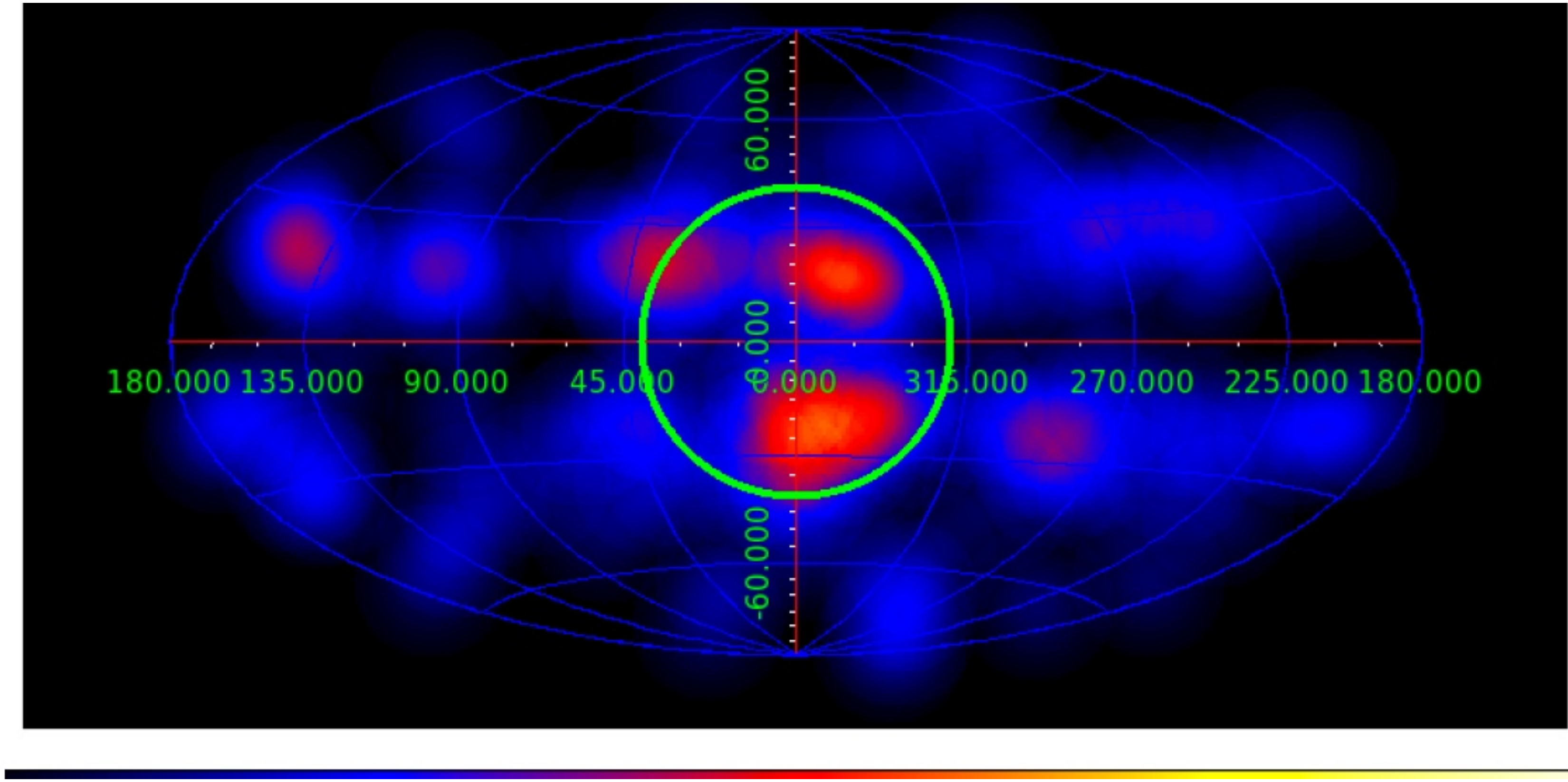


Inner galaxy 2.4

Outer Galaxy
2.7 break 200 GeV and 2.2

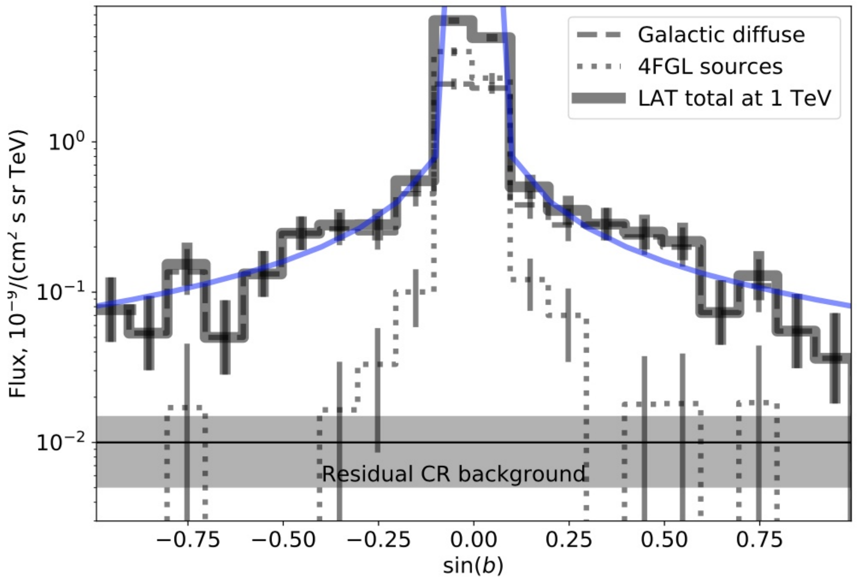
A.Neronov and D.S. ,
1907.06061

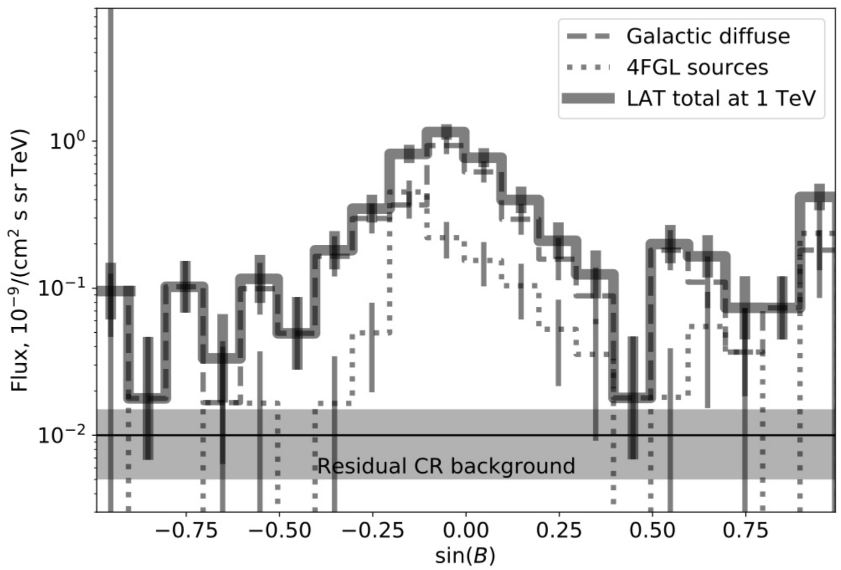
Sky map E> 1TeV no galactic plane |b|> 10 deg



A.Neronov and D.S. , 1907.06061

High |b|

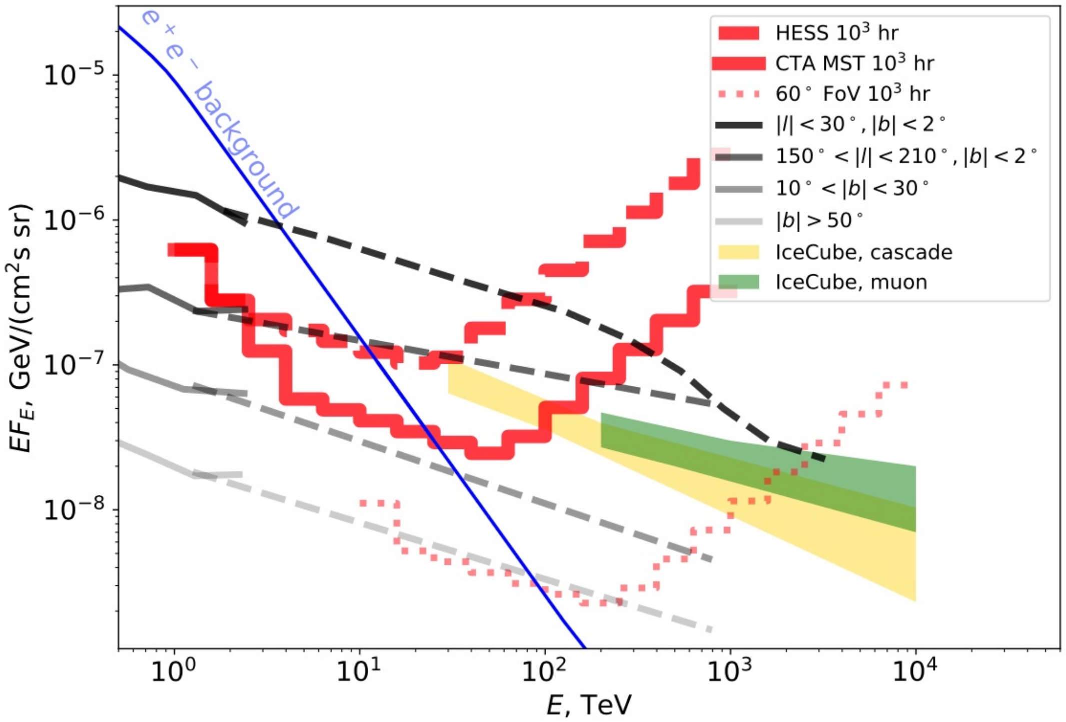




A.Neronov and D.S. ,
1907.06061

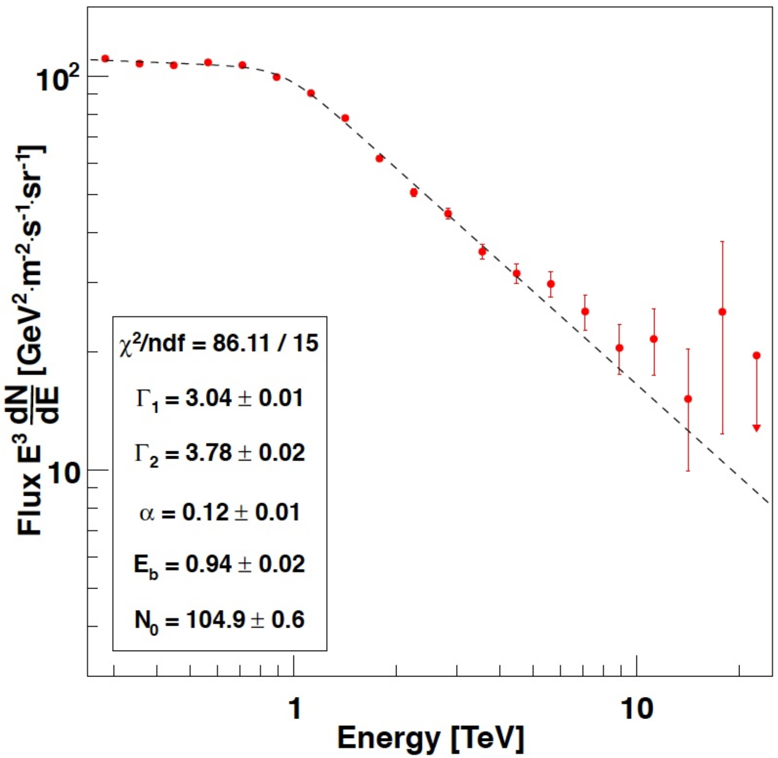
Gamma-ray sky at 10-100 TeV with Cherenkov telescopes

Galactic diffuse flux at 10-100 TeV energies with Cherenkov



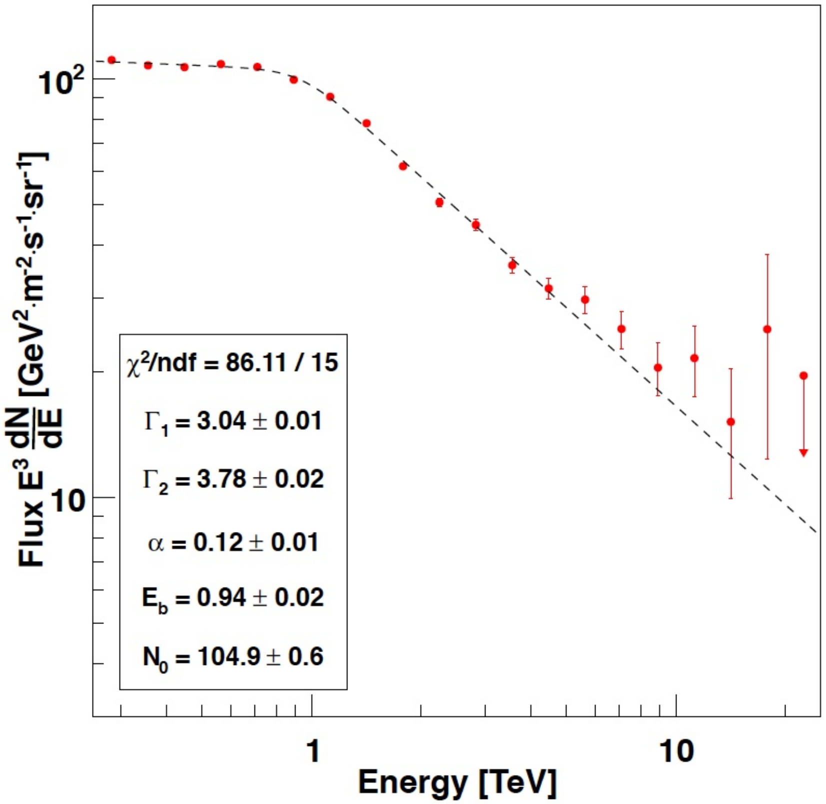
A.Neronov and D.S. , astro-ph/2001.00922

Electron + positron measurements by HESS 2004- March 2010



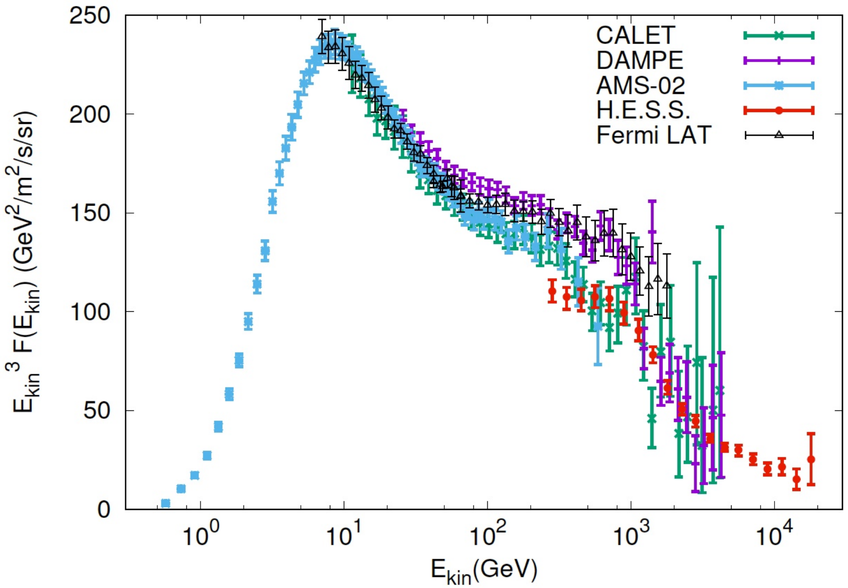
HESS collab. 2017

Electron+ positron+ diffuse gamma measurements by HESS 2004- March 2010

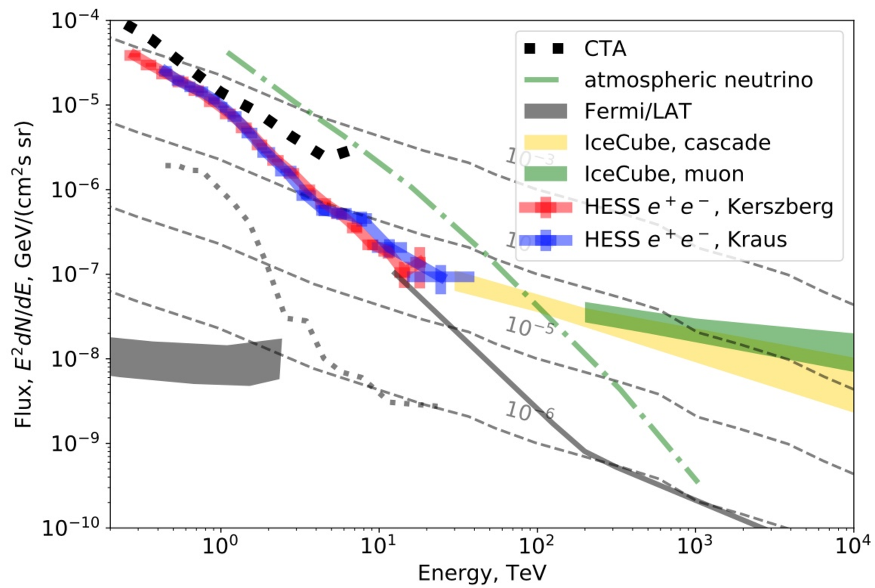


HESS collab. 2017

Electron+ positron+ diffuse gamma measurements by HESS 2004- March 2010

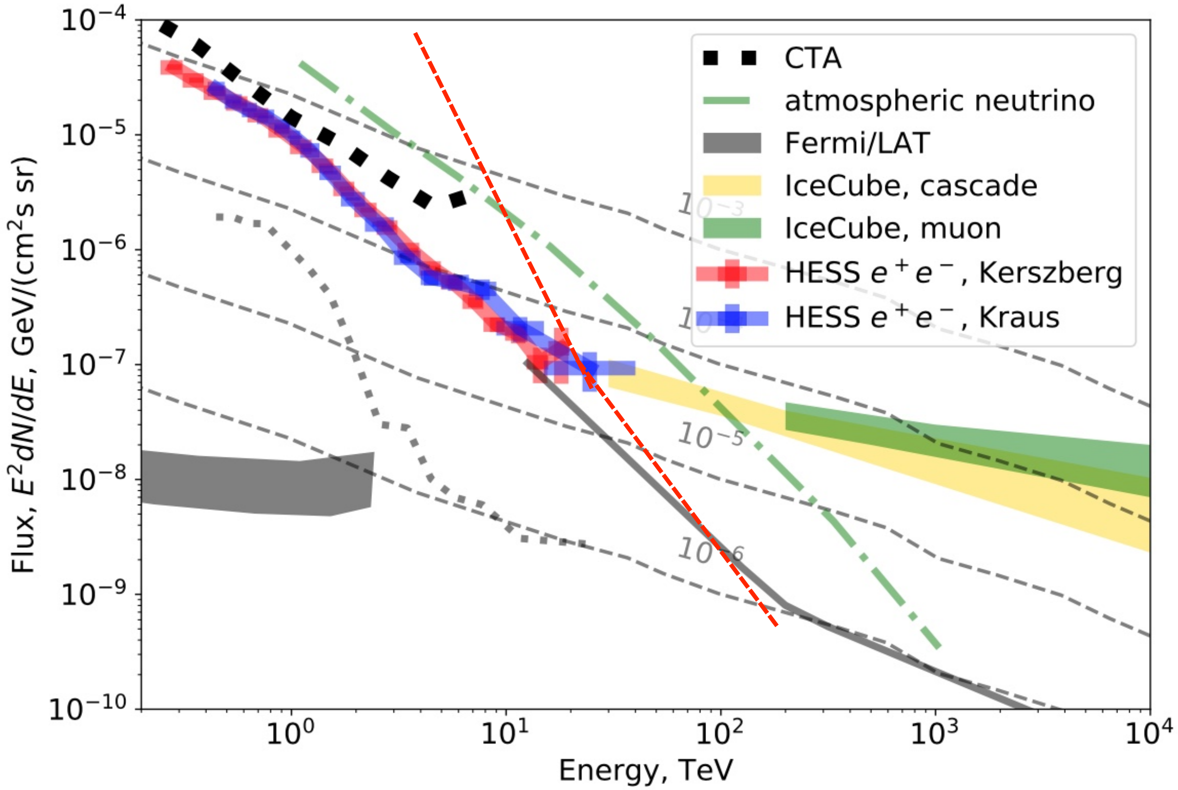


M.Kachelriess and D.S., Cosmic ray models, review astro-ph/1904.08160



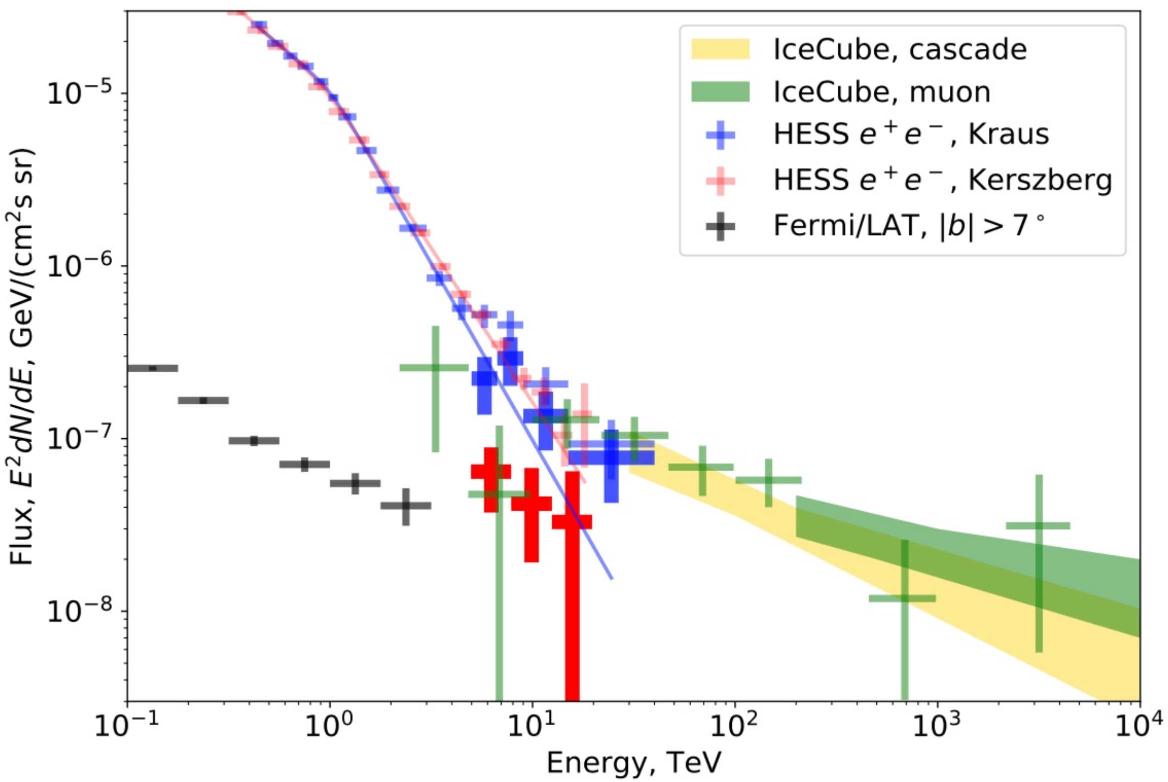
A.Neronov and D.S. , astro-ph/2001.00922

LHAASO sensitivity from 1905.02773



A.Neronov and D.S. , astro-ph/2001.00922

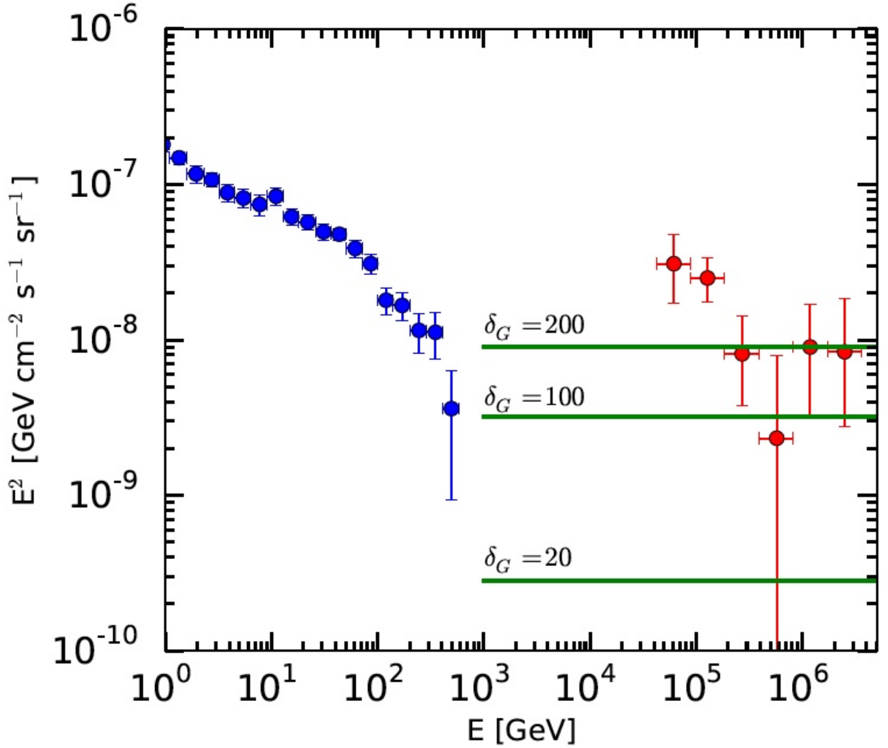
New component in HESS data



A.Neronov and D.S. , astro-ph/2001.00922

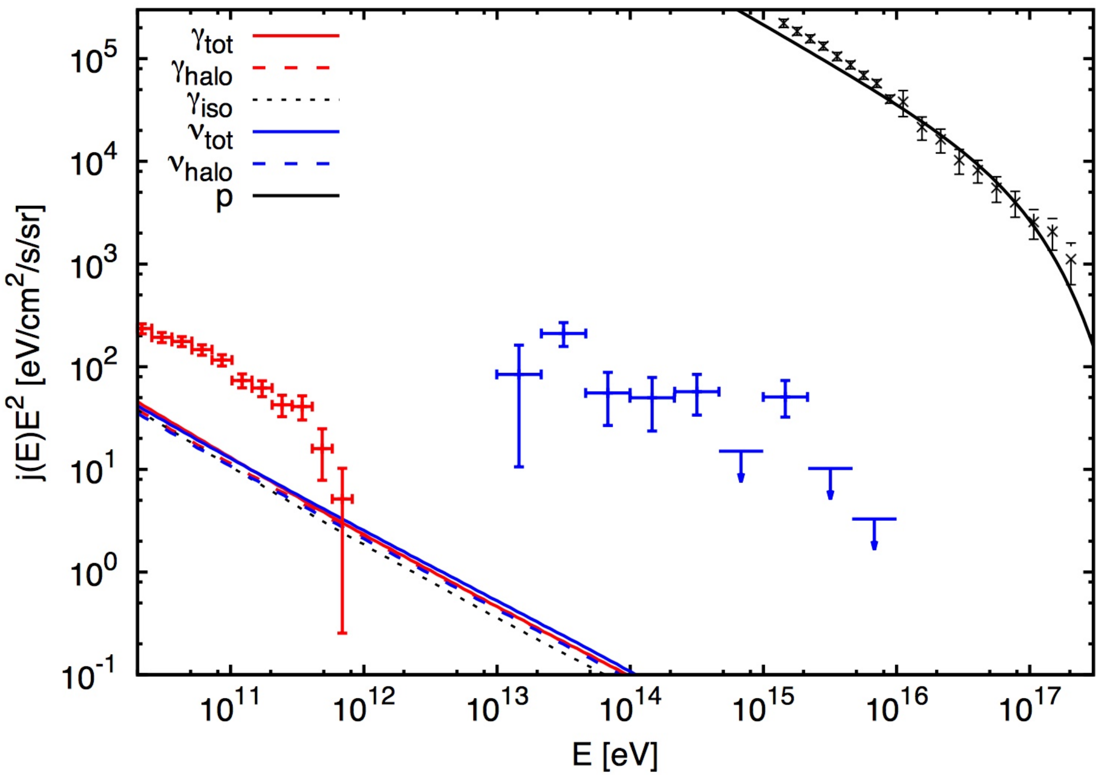
Galactic CR interaction in galactic halo

Neutrinos from cosmic ray interactions in Galactic Halo



A.Taylor, S.Gabici and F.Aharonian, 1403.3206
P.Blasi and E.Amato , 1901. 03609

Neutrinos from cosmic ray interactions in Galactic Halo



O.Kalashev and S.Troitsky, 1608.07421

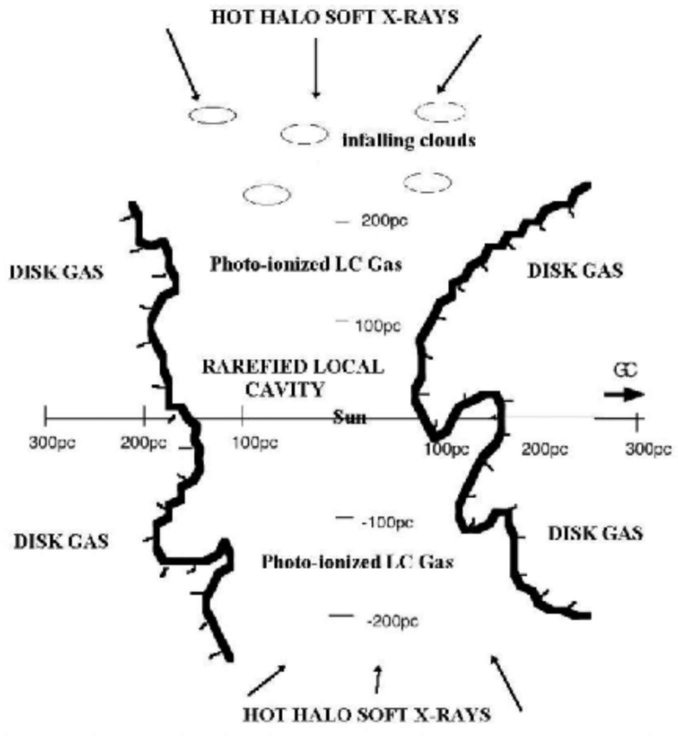
Galactic CR interaction with Local bubble

Model of propagation (Motivations for Local MF)

The immediate Galactic vicinity of the Sun is dominated by a low density ionized structure, commonly referred to as the "Local Bubble". It is bounded by relatively higher density material as traced by Sodium and Calcium absorption line measurements, as well as extinction data (Lallement et al. 2003; Welsh et al. 2010; Lallement et al. 2014). Such measurements show a roughly cylindrical structure with a typical radius of about 100-175 pc, with missing ends towards the north and south Galactic poles. This structure is generally interpreted as being due to strong stellar winds and supernovae evacuating the space, with "blow-outs" in the directions out of the Galactic plane (Lallement et al. 2003).

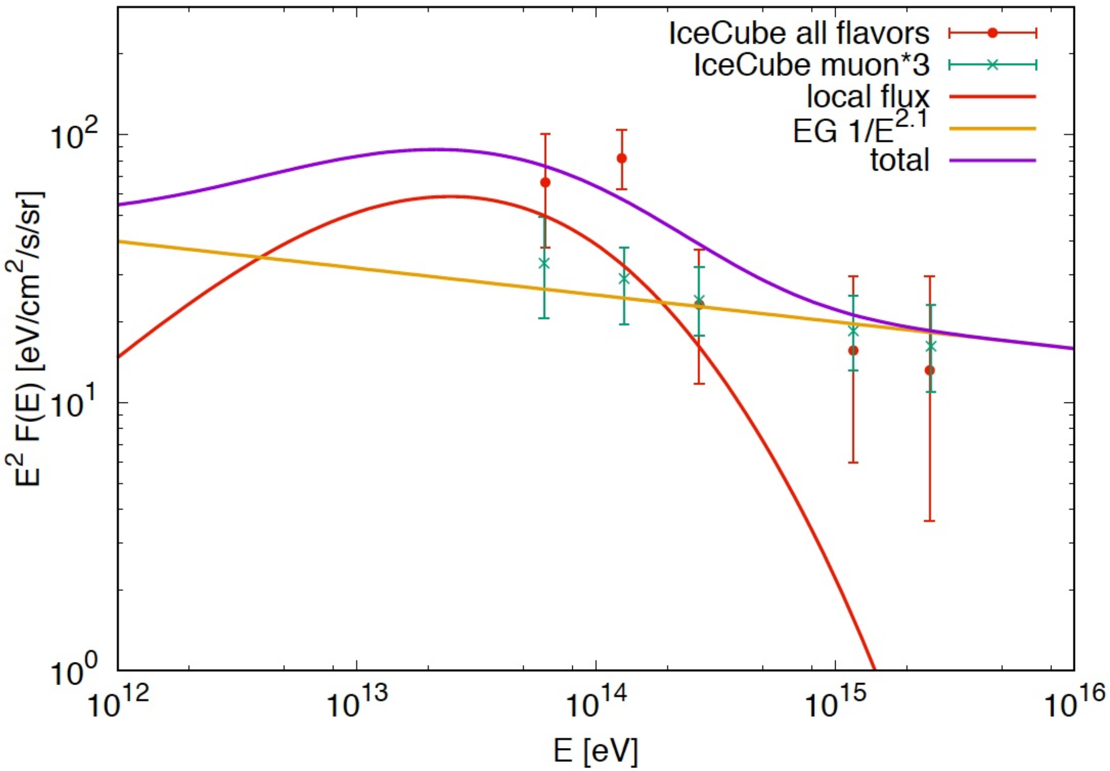
analysis from Lehner et al. (2003) to estimate the gas pressure, density and turbulence, they derived a magnetic field strength of $B_\perp = 8^{+5}_{-3}\mu G$, equivalent to a magnetic pressure of $P_B/k \approx 18,000$ K cm^{-3}, consistent with the results from the X-ray and the EUV observations.

Ilija Medan & Anderson 2019
arXiv 1901.07692



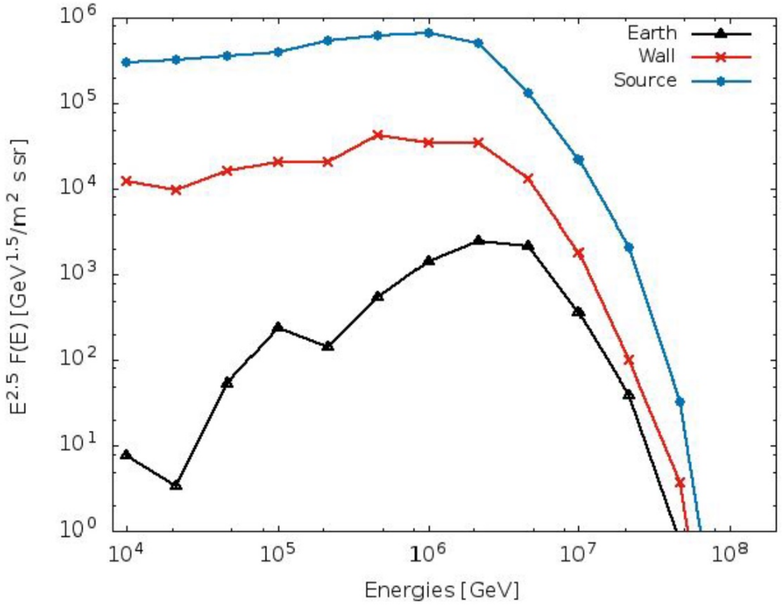
Welsh & Shelton 2009 arXiv 0906.2827

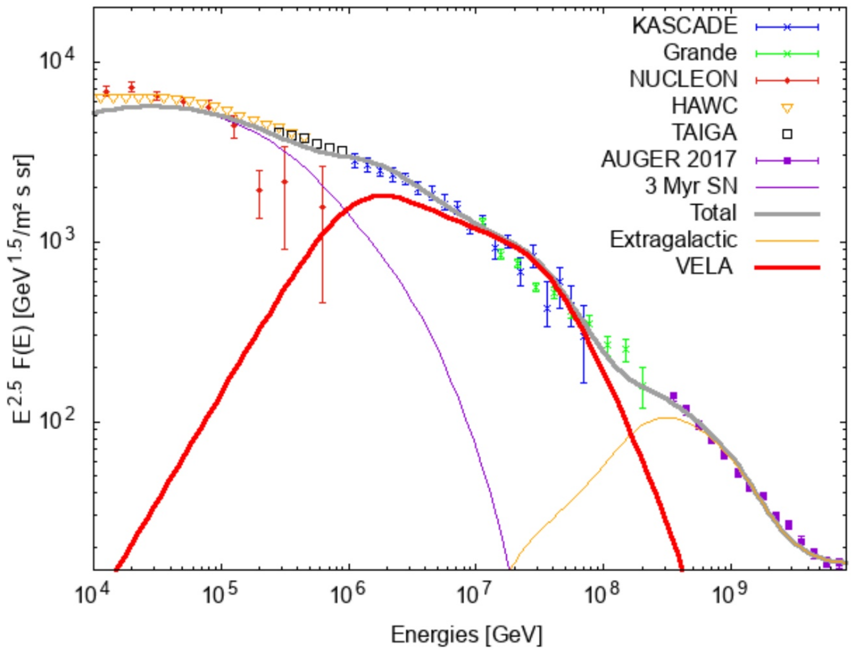
Local bubble neutrino flux



K.Andersen, M.Kachelriess and D.Semikoz, arXiv:1712.03153

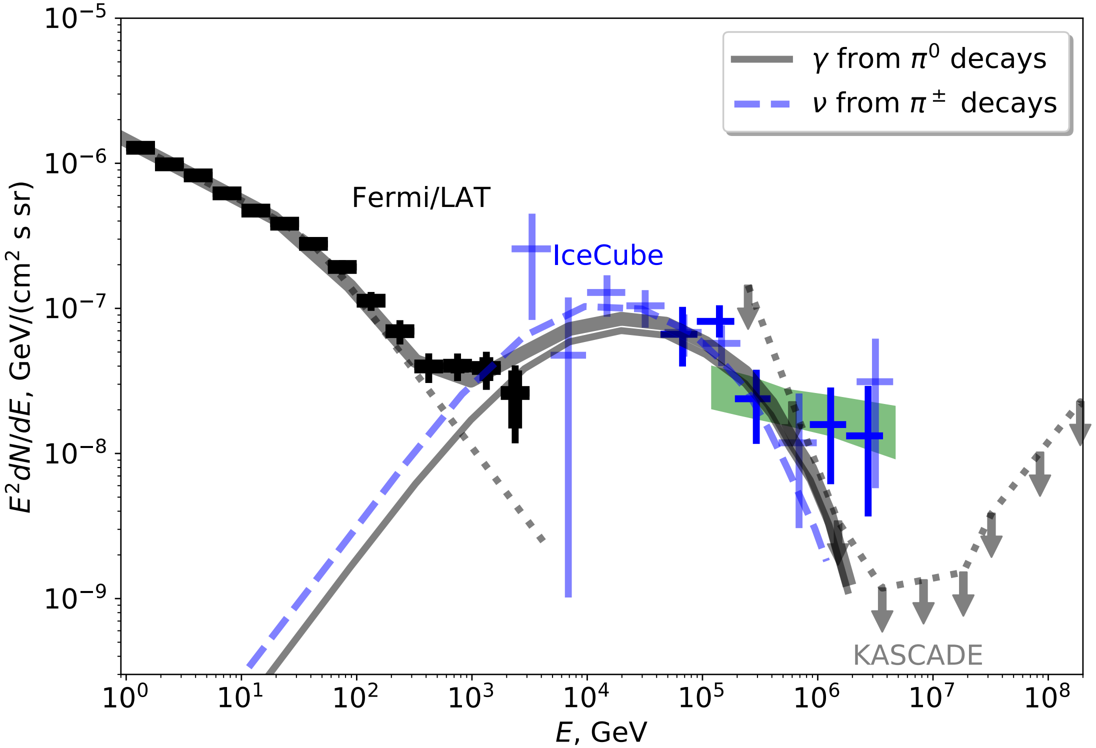
Spectrum in presence of Local bubble





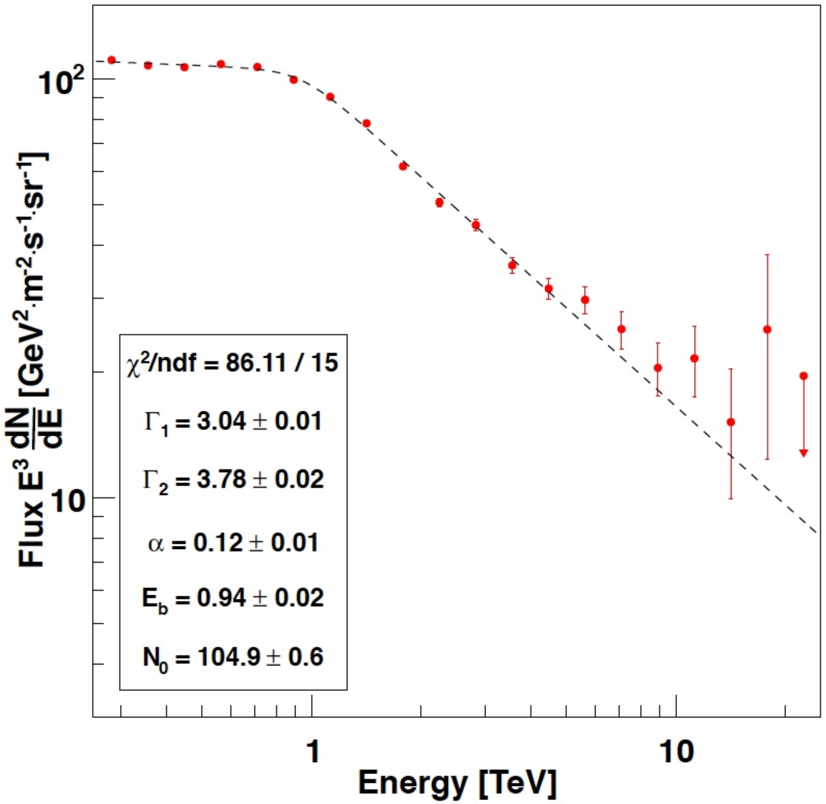
M.Bouyahiaoui, M.Kachelriess and D.S., arXiv:1812.03522

IceCube + Fermi LAT : local source



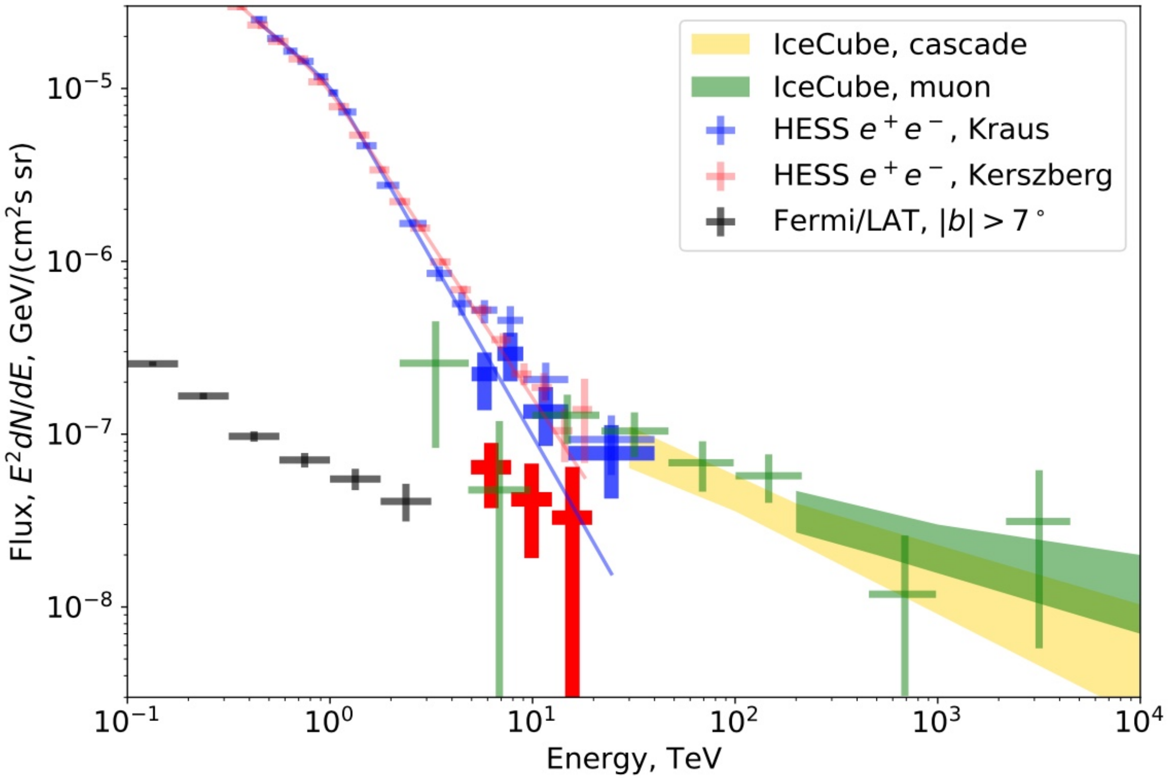
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

Electron+ positron+ diffuse gamma measurements by HESS 2004- March 2010



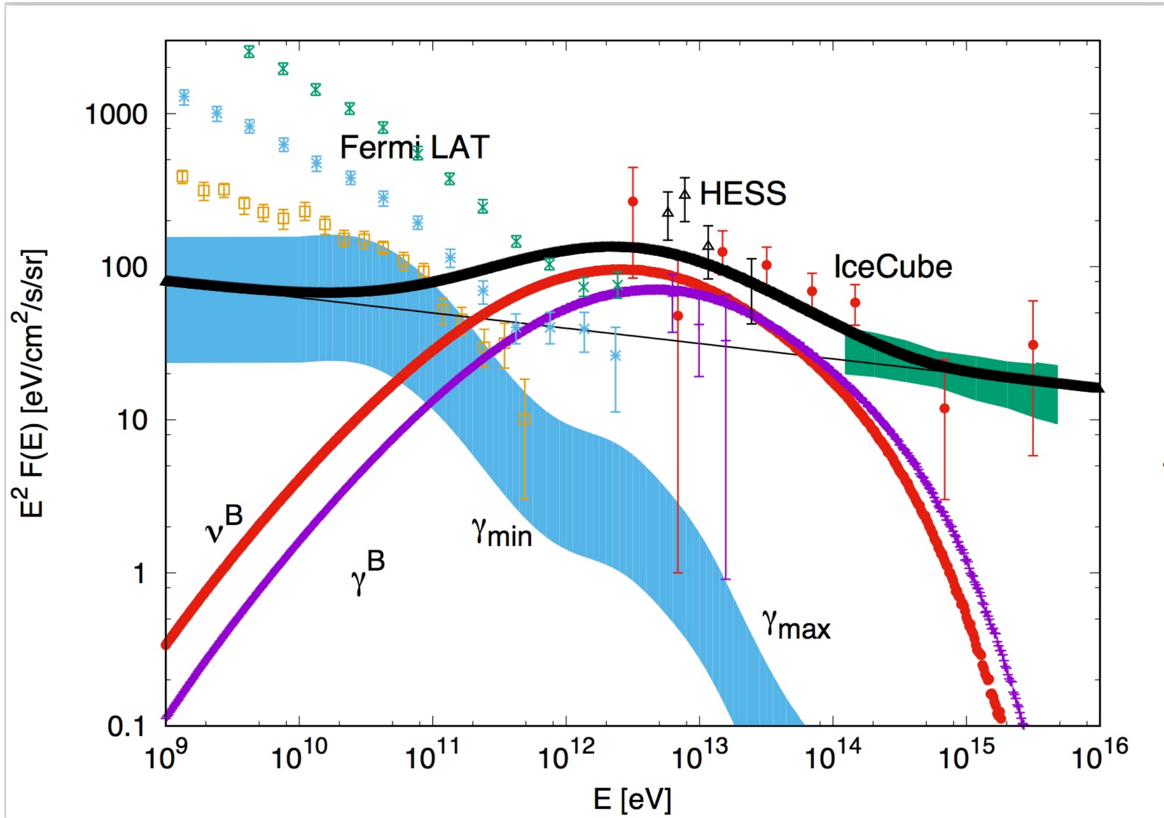
HESS collab. 2017

New component in HESS data



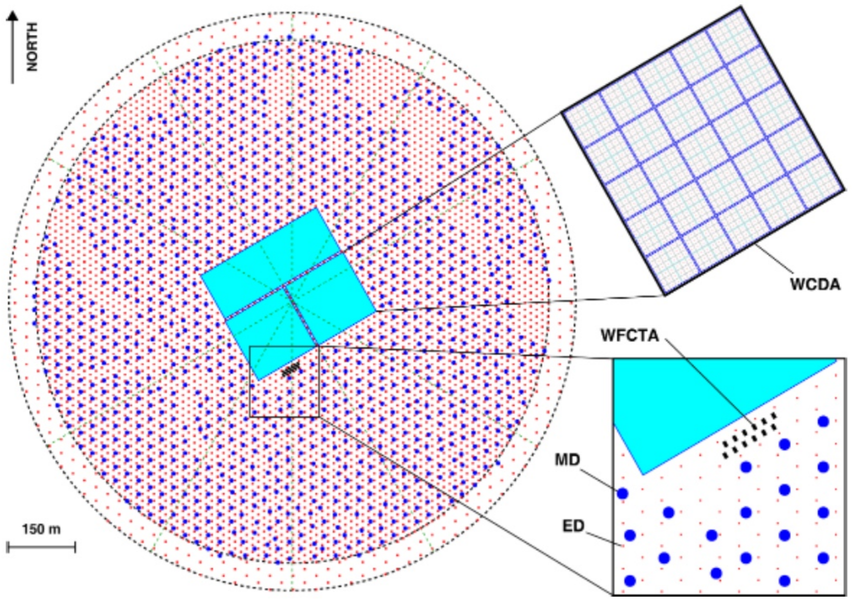
A.Neronov and D.S. , astro-ph/2001.00922

IceCube + Fermi LAT+HESS : local source



M.Bouyahiaoui, M.Kachelriess and D.S. , arXiv:2001.00768

LHAASO detectors

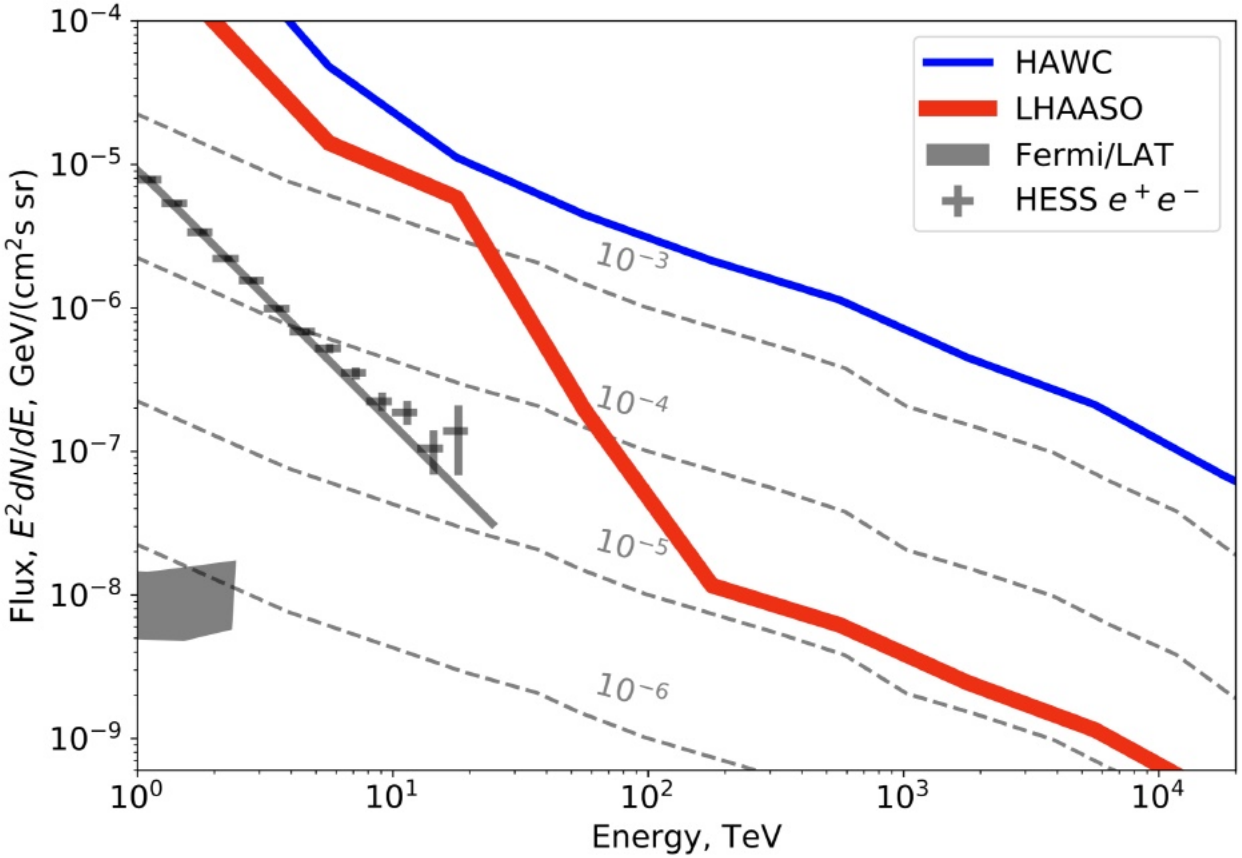


1.3 km^2

- 5195 EDs
  - 1 m^2 each
  - 15 m spacing
- 1171 MDs
  - 36 m^2 each
  - 30 m spacing
- 3120 WCDs
  - 25 m^2 each
- 12 WFCTs

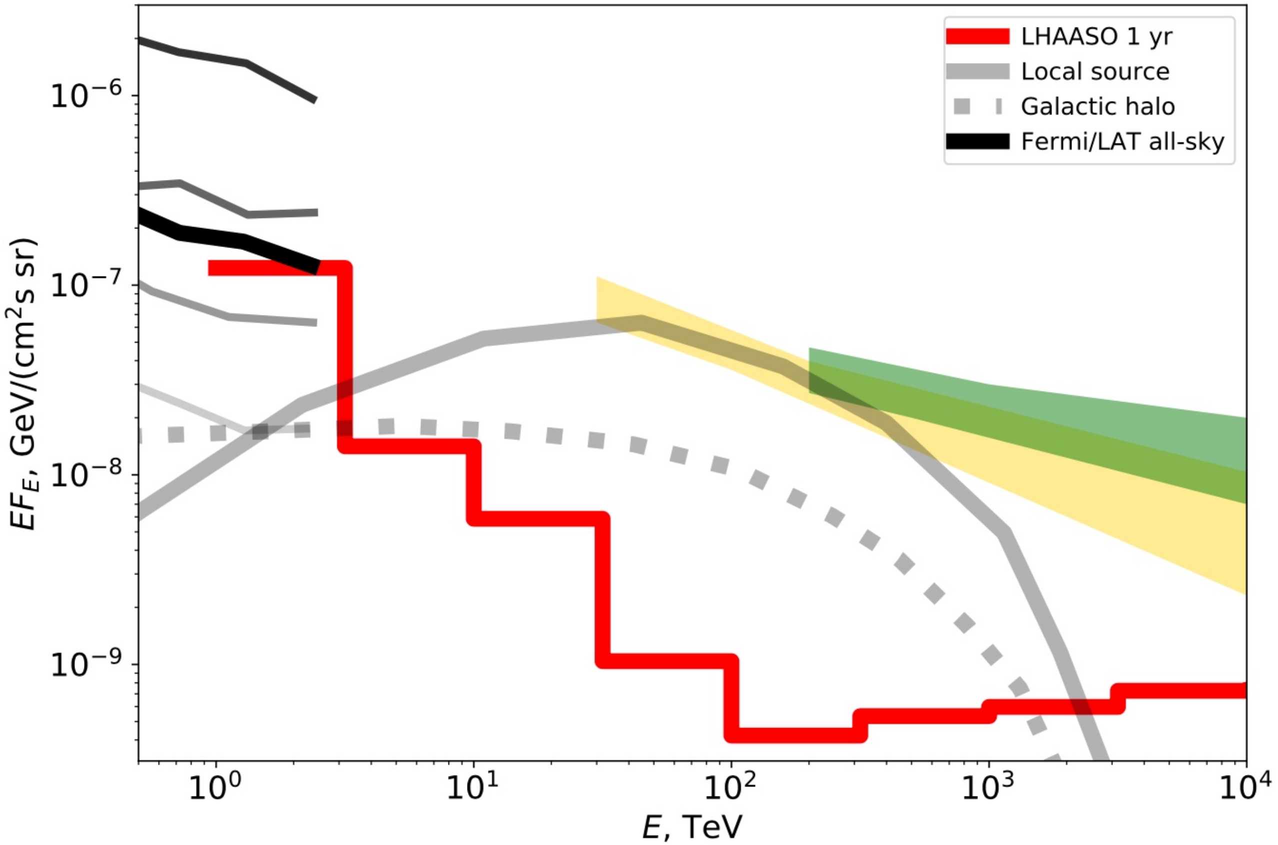
KM2A:
UHE γ-rays
20 TeV-1 PeV

LHAASO sensitivity DM



A.Neronov and D.S. , astro-ph/2001.11881

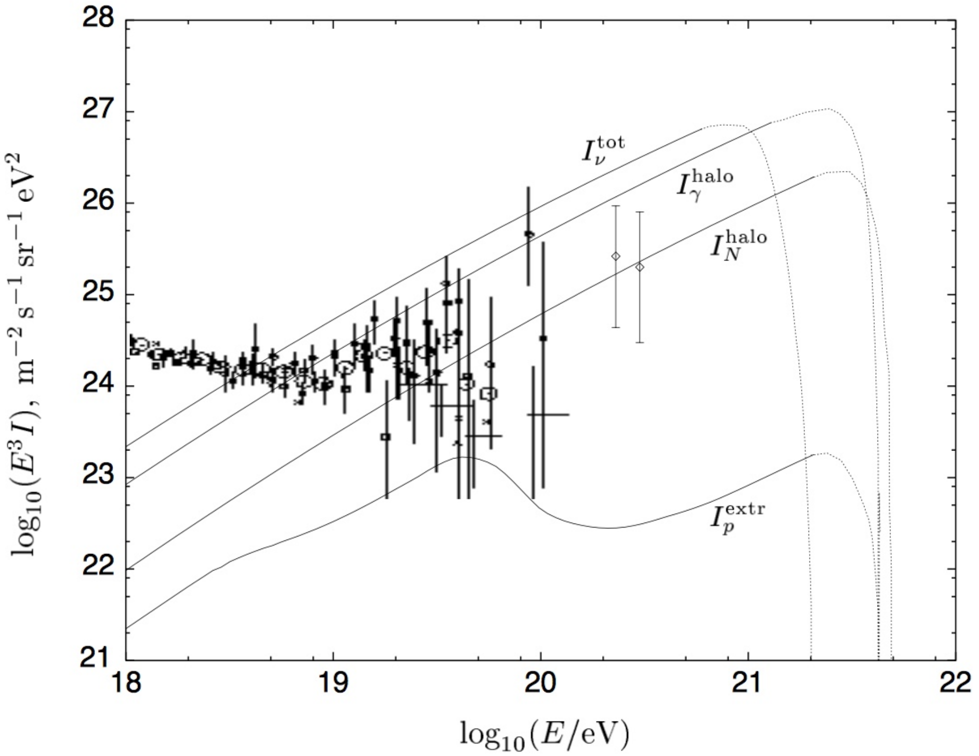
LHAASO sensitivity Local SuperBubble and Galactic Halo



A.Neronov and D.S. , astro-ph/2001.11881

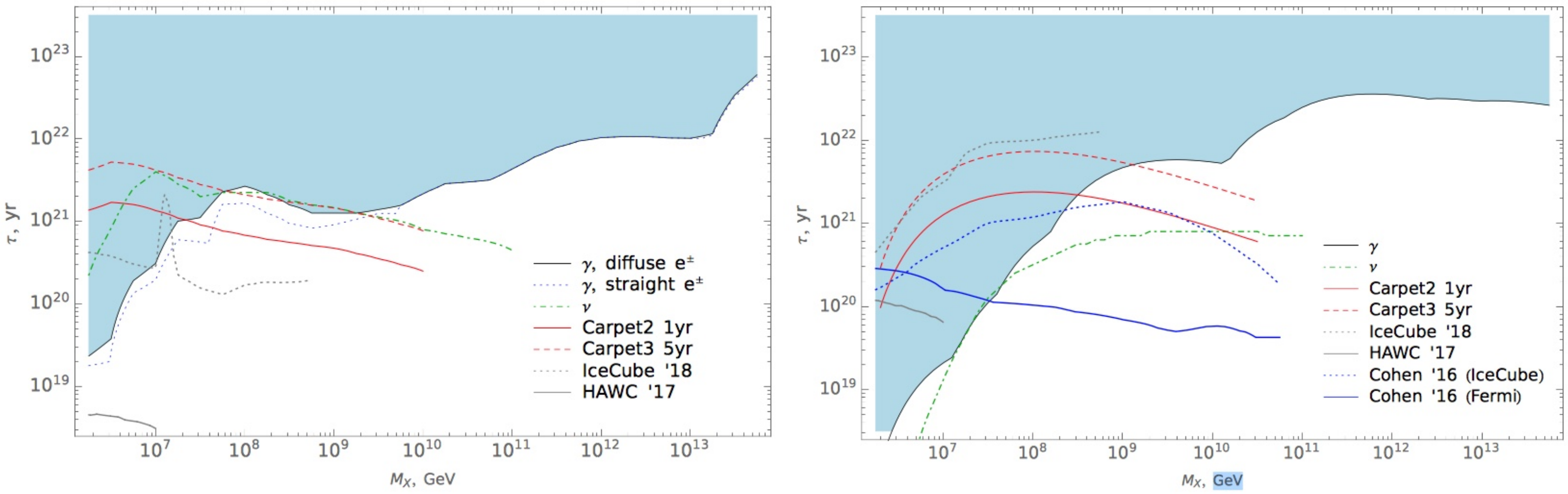
Super-Heavy Dark Matter

For SHDM galactic flux dominates in neutrinos and gamma-rays



V.Berezinsky, M.Kachelriess and A.Vilenkin, 1997

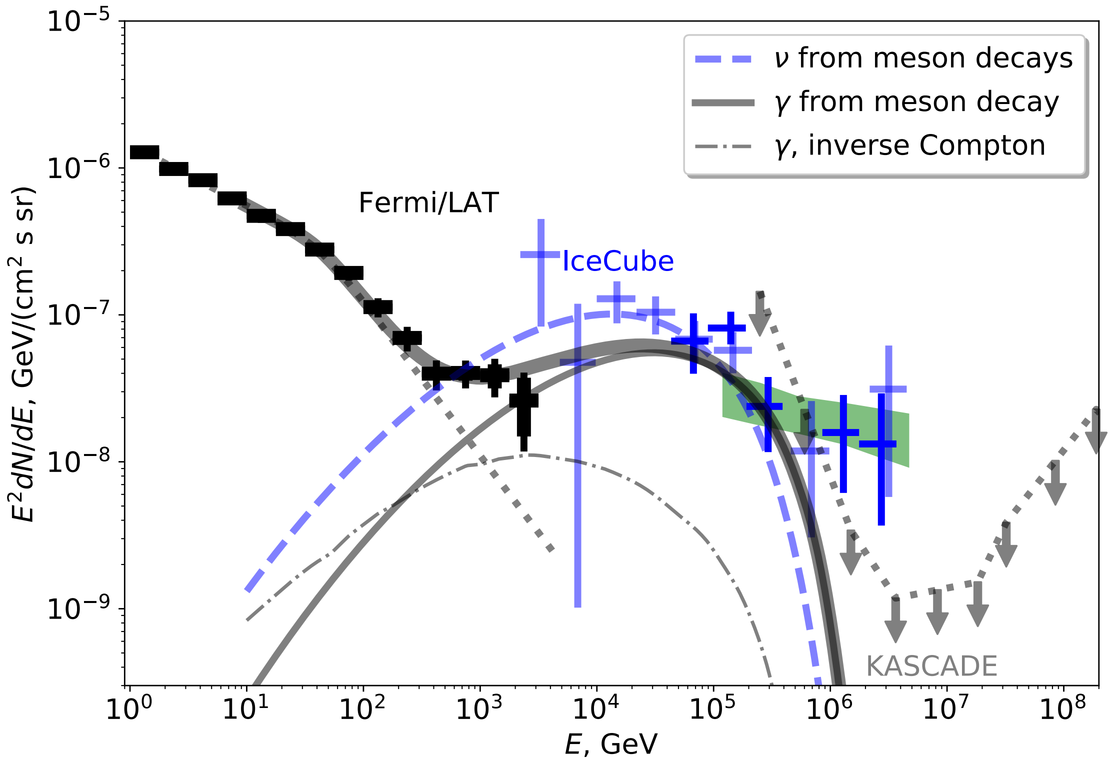
Modern constraints on SHDM



(a) $X \to \nu\bar{\nu}$ (b) $X \to q\bar{q}$

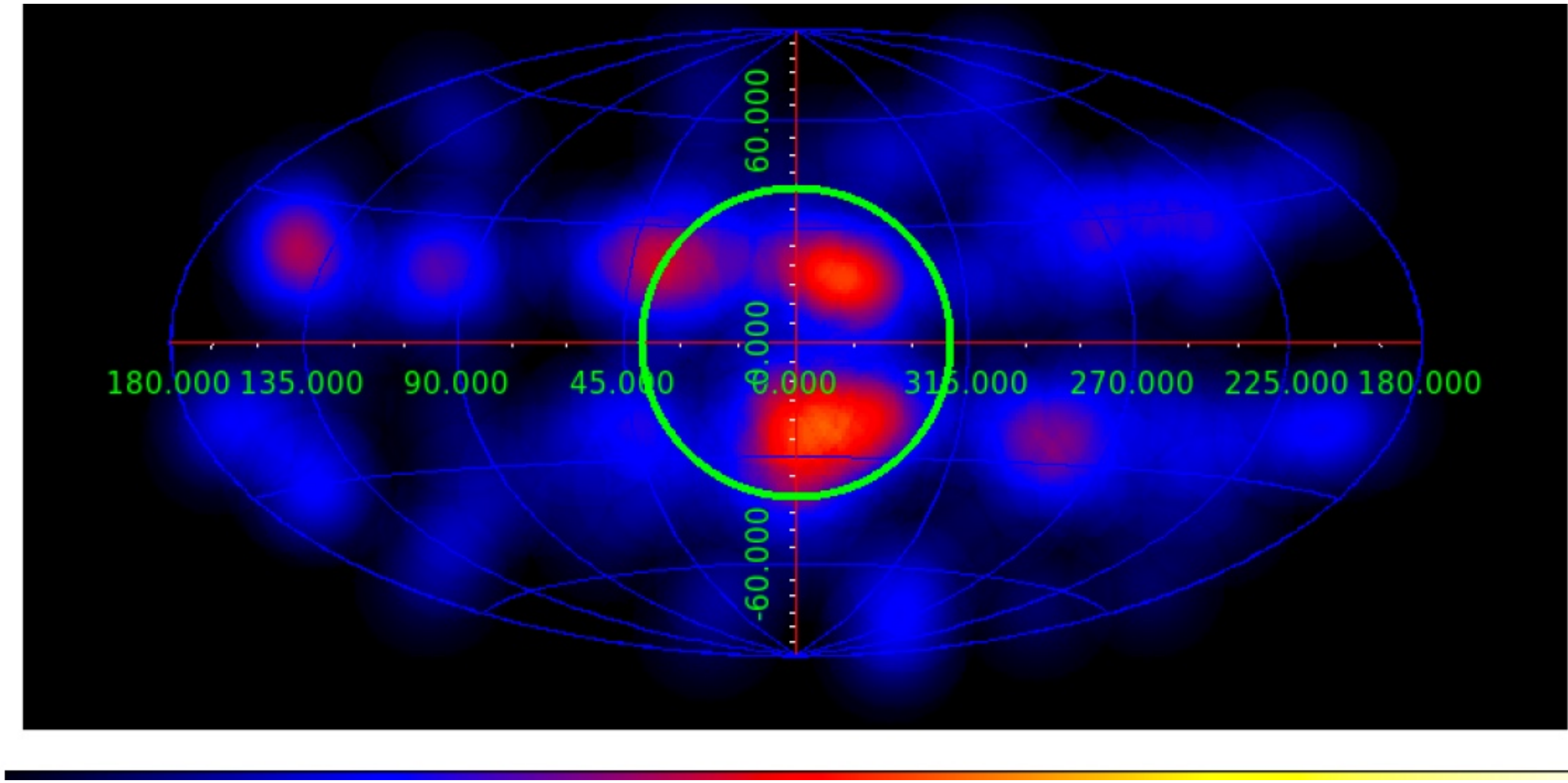
M. Kachelriess, O. E. Kalashev and M. Yu. Kuznetsov, 1805.04500

IceCube + Fermi LAT Dark Matter m=5 PeV



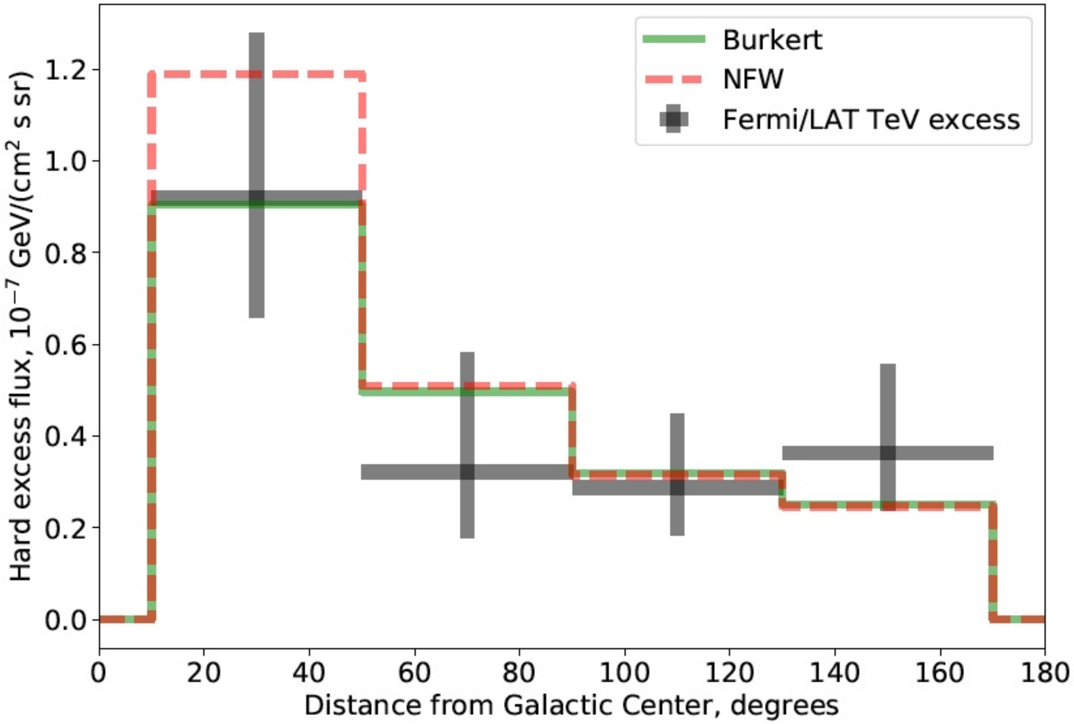
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

Sky map E> 1TeV no galactic plane |b|> 10 deg



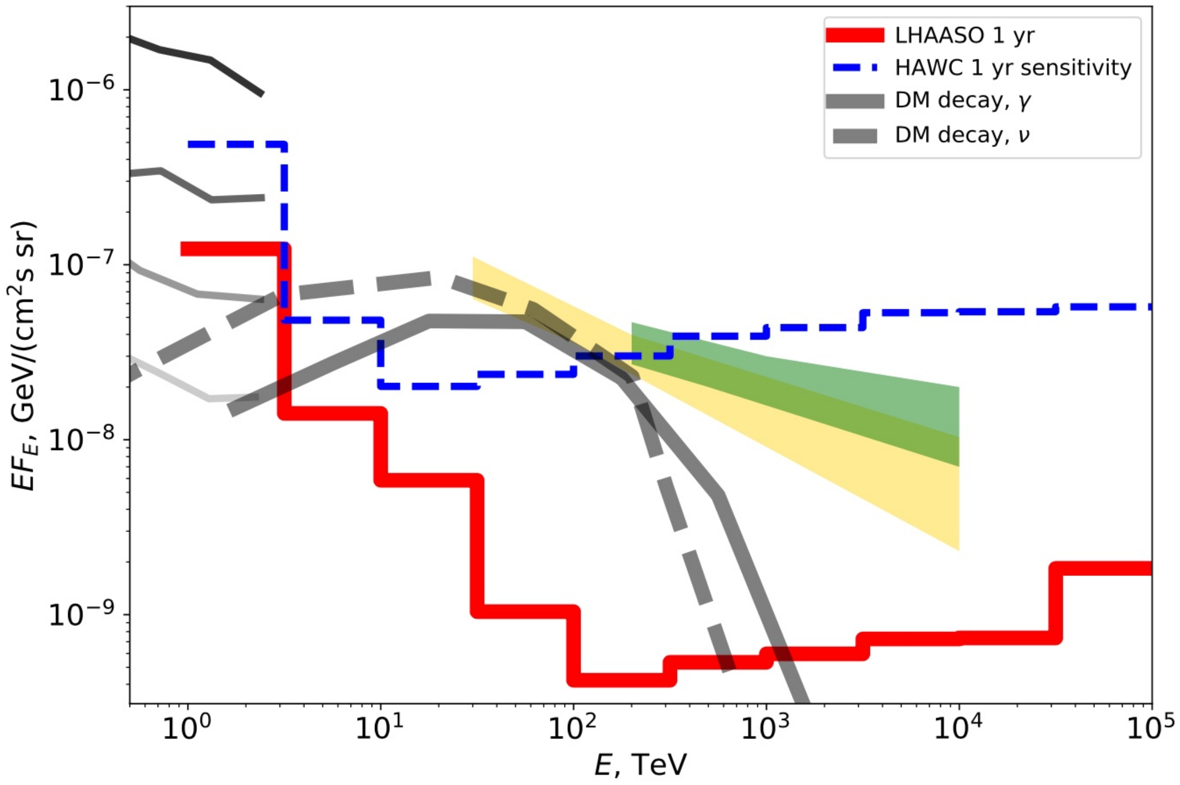
A.Neronov and D.S.

Flux SHDM



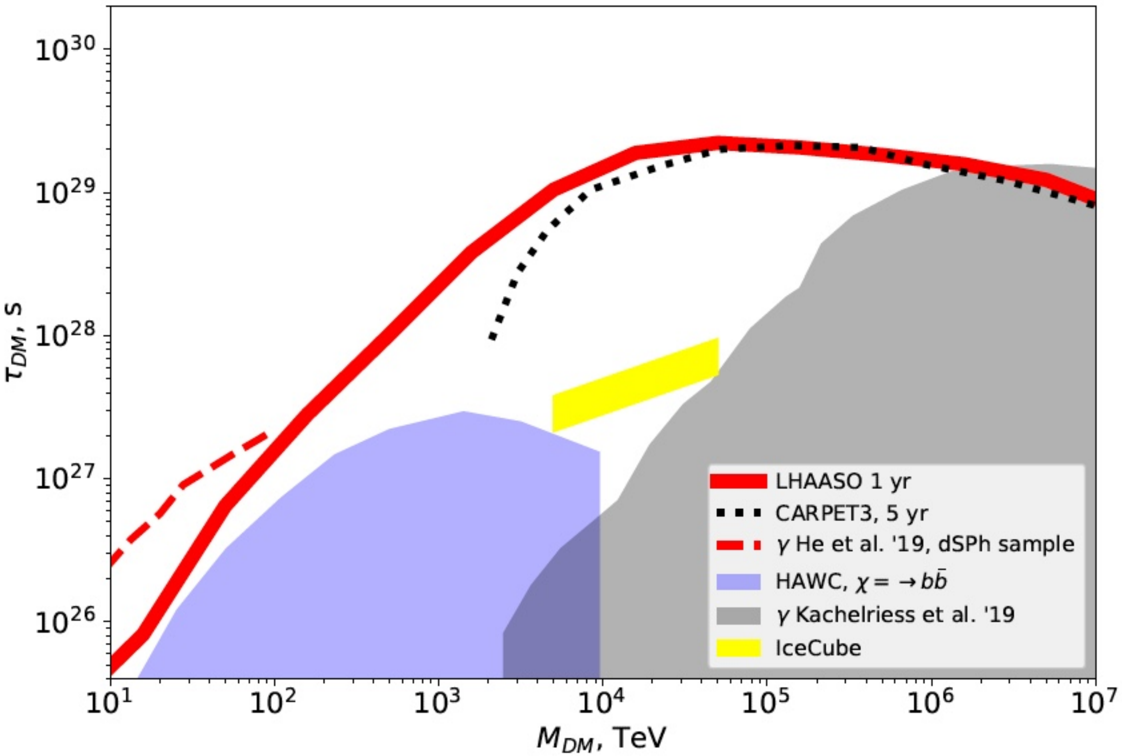
A.Neronov and D.S.

LHAASO sensitivity DM



A.Neronov and D.S. , astro-ph/2001.11881

LHAASO sensitivity DM



A.Addasi et al, LHAASO science book

SUMMARY

- *Extragalactic sources can not explain too high astrophysical neutrino flux at E< 100 TeV*
- *Fermi flux outside of galactic plane has new Galactic component in TeV energy range*
- *Significant part of neutrinos with E< 100 TeV come from Galaxy.*
- *Astrophysical models: Galactic halo and Local Bubble interaction of CR from local source (Vela)*
- *Alternatively: Dark Matter with 5 PeV mass*