Multi-messenger emission from Milky Way Galaxy

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Plan

- Introduction: Milky Way Galaxy: cosmic ray, gamma-ray and neutrino connection
- Multi-messenger models
- High energy diffuse gamma-rays in Galaxy with> 100 TeV with Tibet, HAWC and LHAASO
- Neutrino flux in IceCube, Baikal-GVD and ANTARES: galactic contribution from Ridge
- Gamma-ray and neutrino flux from Sygnus region
- Conclusions

Introduction: Cosmic rays

Electroscopes discharge spontaneously. Why?

- 1785: Coulomb found that electroscopes can spontaneously discharge by the action of the air and not by defective insulation

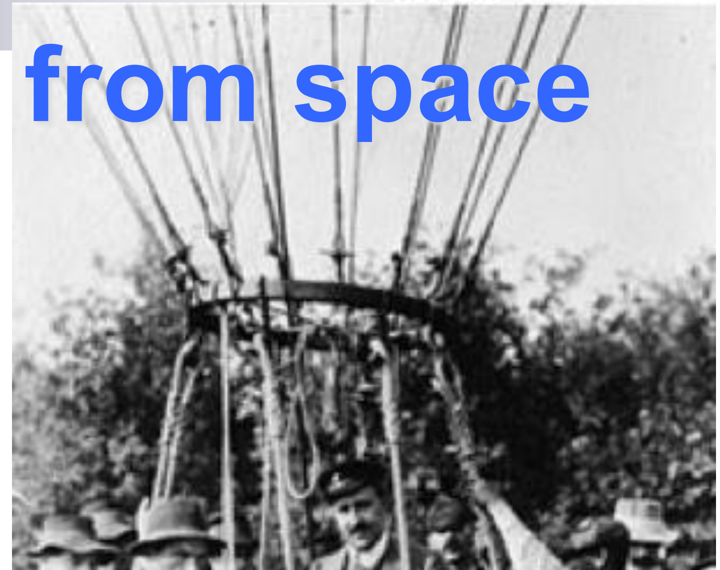
DARK CURRENT 1785-1912 (137 years)

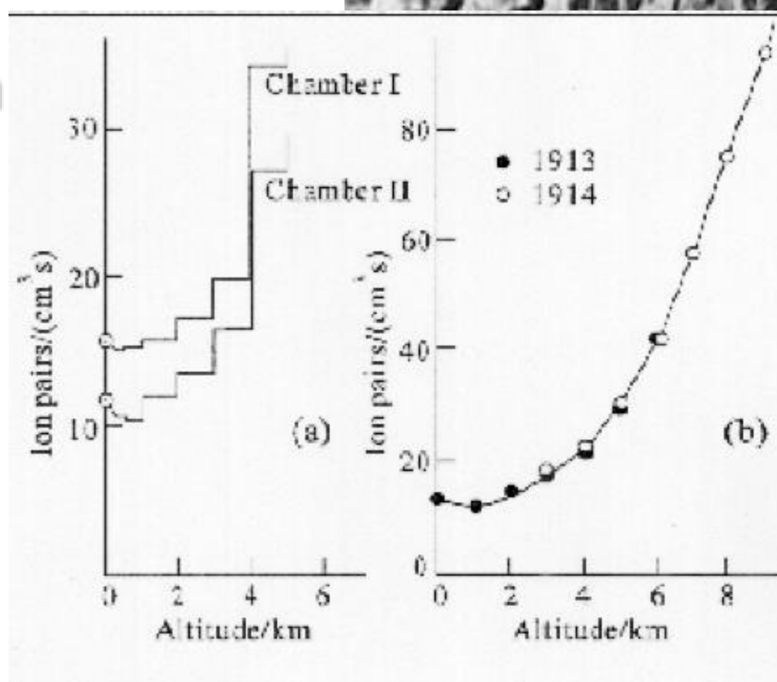
- observation by Coulomb, with better insulation technology
- 1879: Crookes measures that the speed of discharge of an electroscope decreased when pressure was reduced (conclusion: direct agent is the ionized air)

High-energy particles from space

Cosmic Rays (CR) are charged high-energy particles coming from outside the atmosphere.

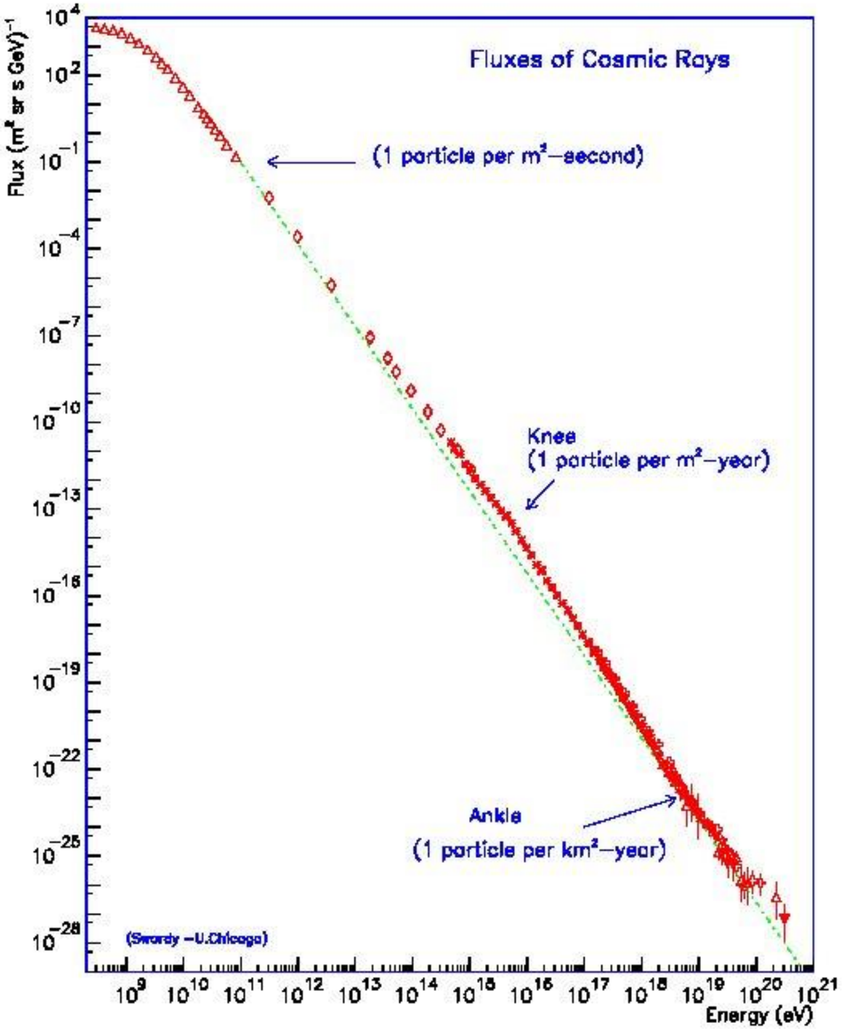
Discovered 113 yr ago by V.Hess in 1912, via detection of increase of the rate of discharge of an electrometer with increase of the altitude.

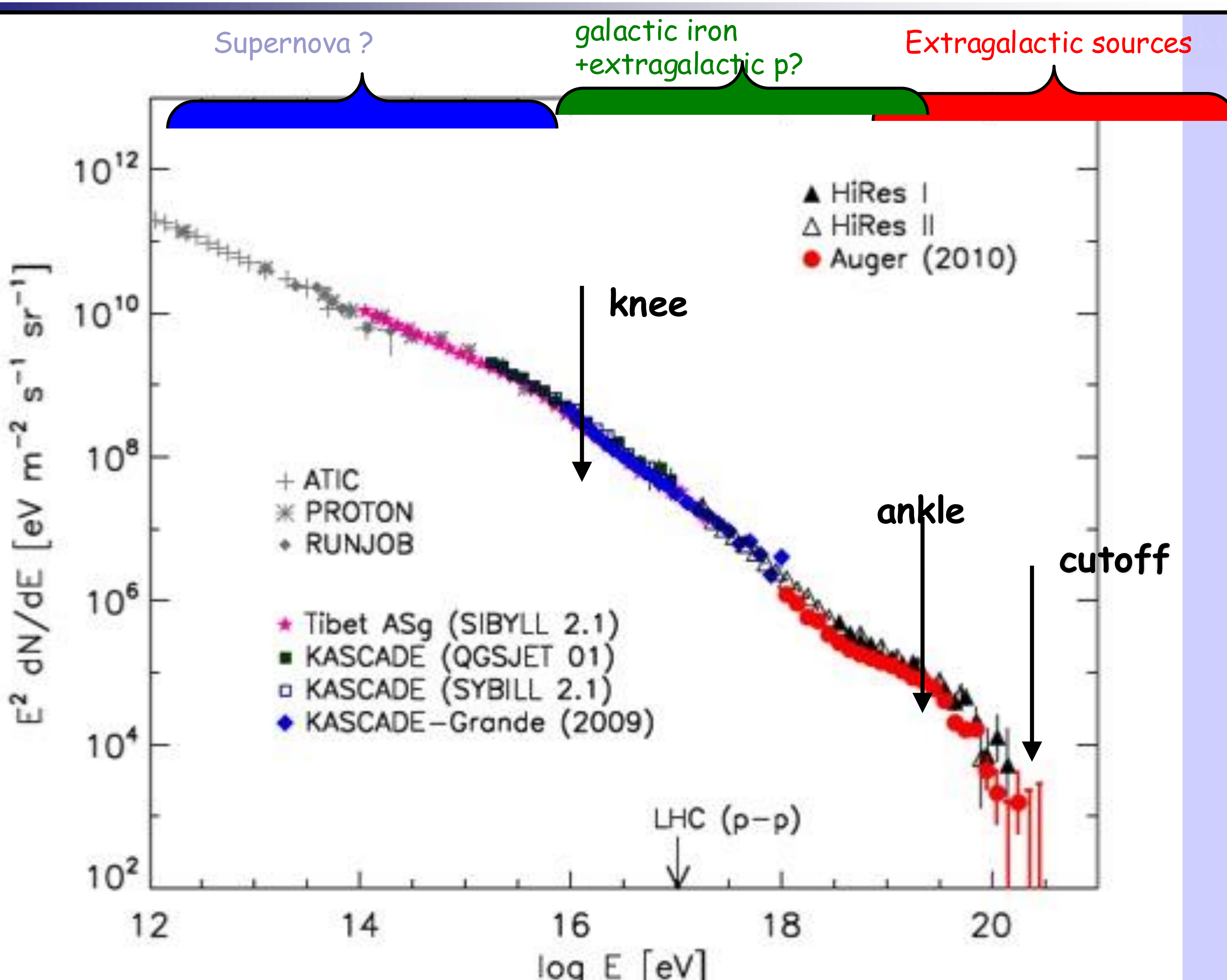




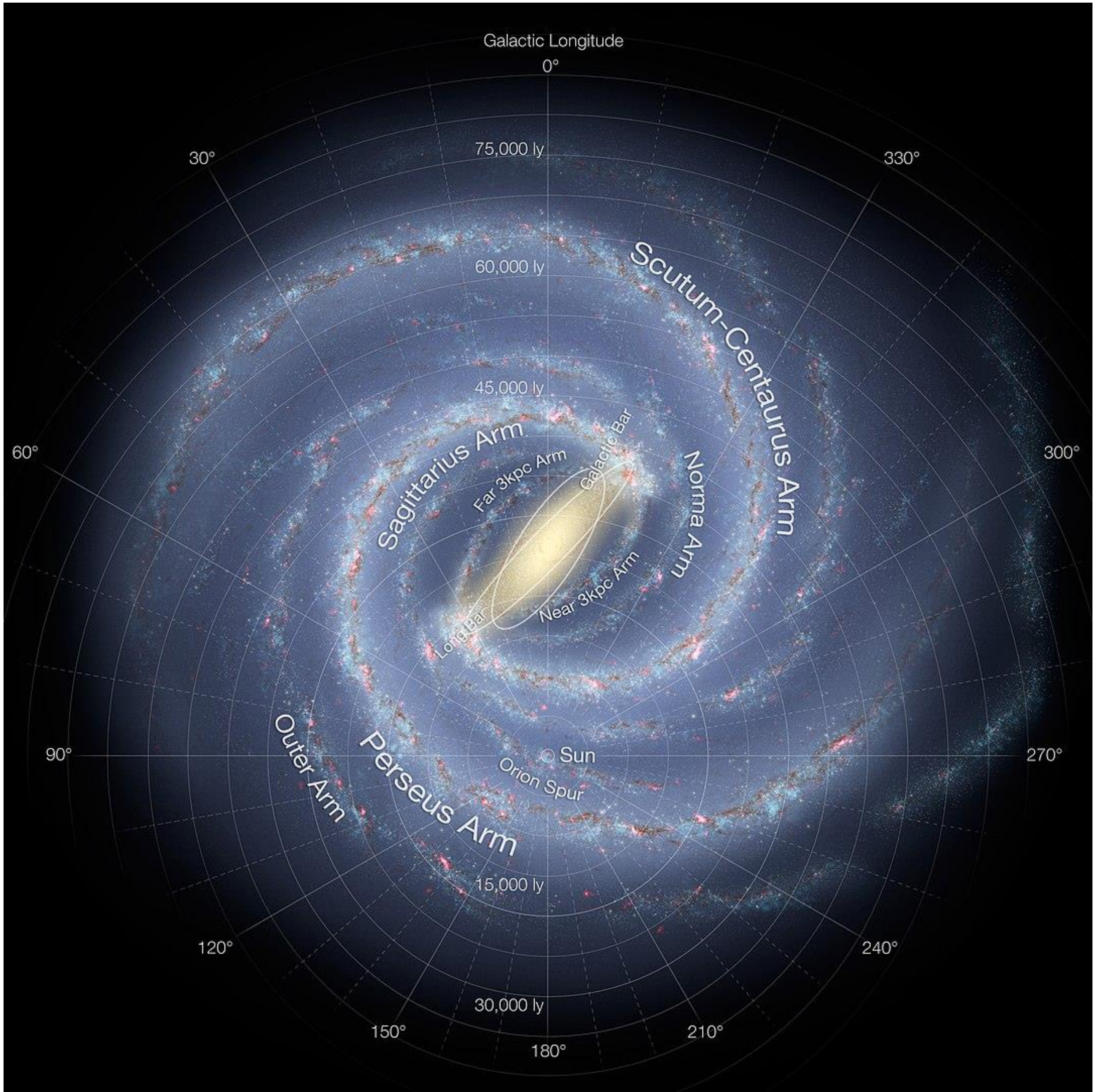
Cosmic rays: historical remarks

- *1938 Pierre Auger observed extensive air showers*
- *1954 First measurement of extensive air showers by Harvard College Observatory*
- *1958 Discovery of CR knee in Moscow University (*Kulikov and Khristiansen)

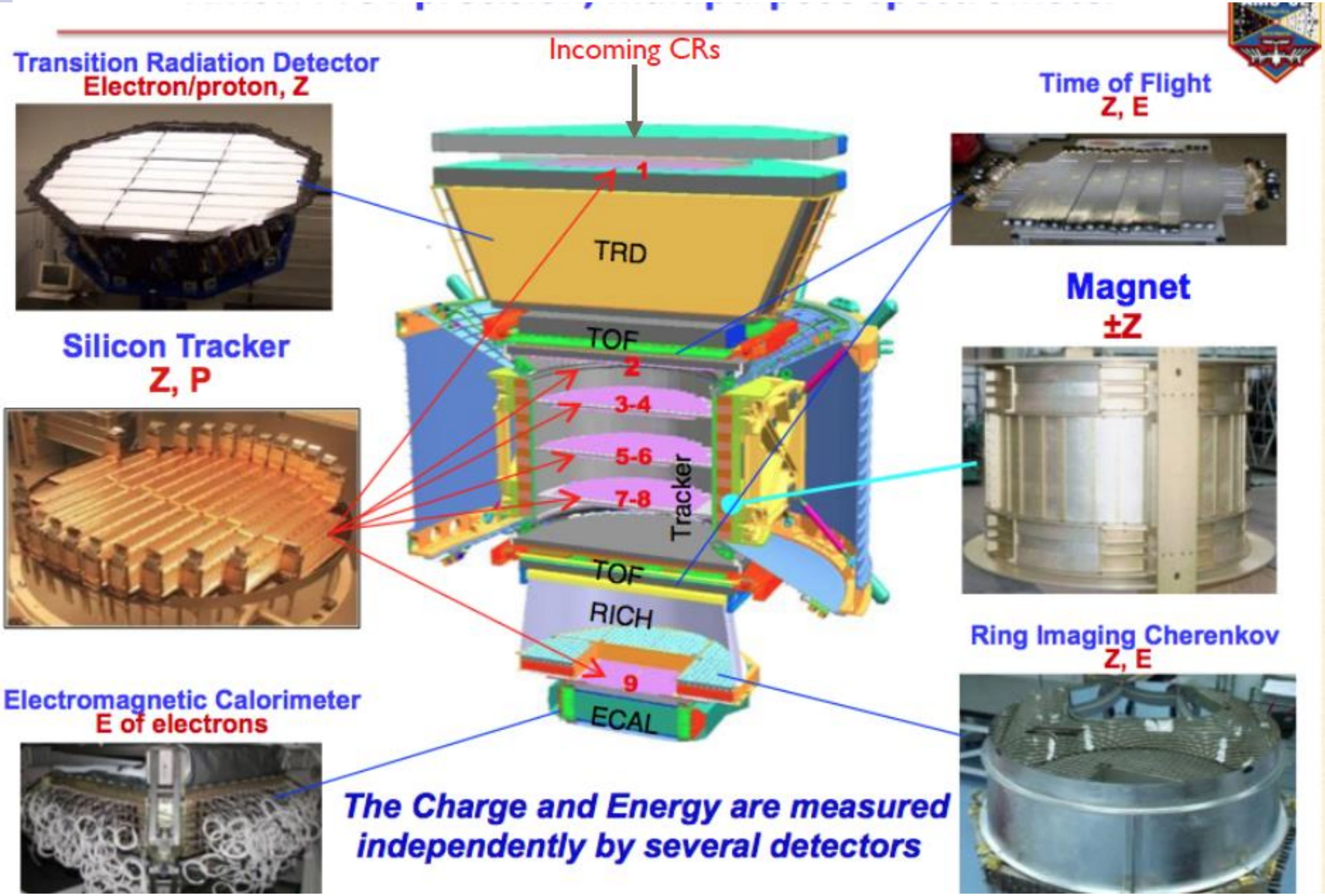

Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
(Swordy – U.Chicago)
Flux (m² sr s GeV)⁻¹
Energy (eV)



Supernova ?
galactic iron
+extragalactic p?
Extragalactic sources
knee
ankle
cutoff
HiRes I
HiRes II
Auger (2010)
ATIC
PROTON
RUNJOB
Tibet ASg (SIBYLL 2.1)
KASCADE (QGSJET 01)
KASCADE (SYBILL 2.1)
KASCADE-Grande (2009)
LHC (p-p)
E^2 dN/dE [eV m^{-2} s^{-1} sr^{-1}]
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
12
14
16
18
20
log E [eV]

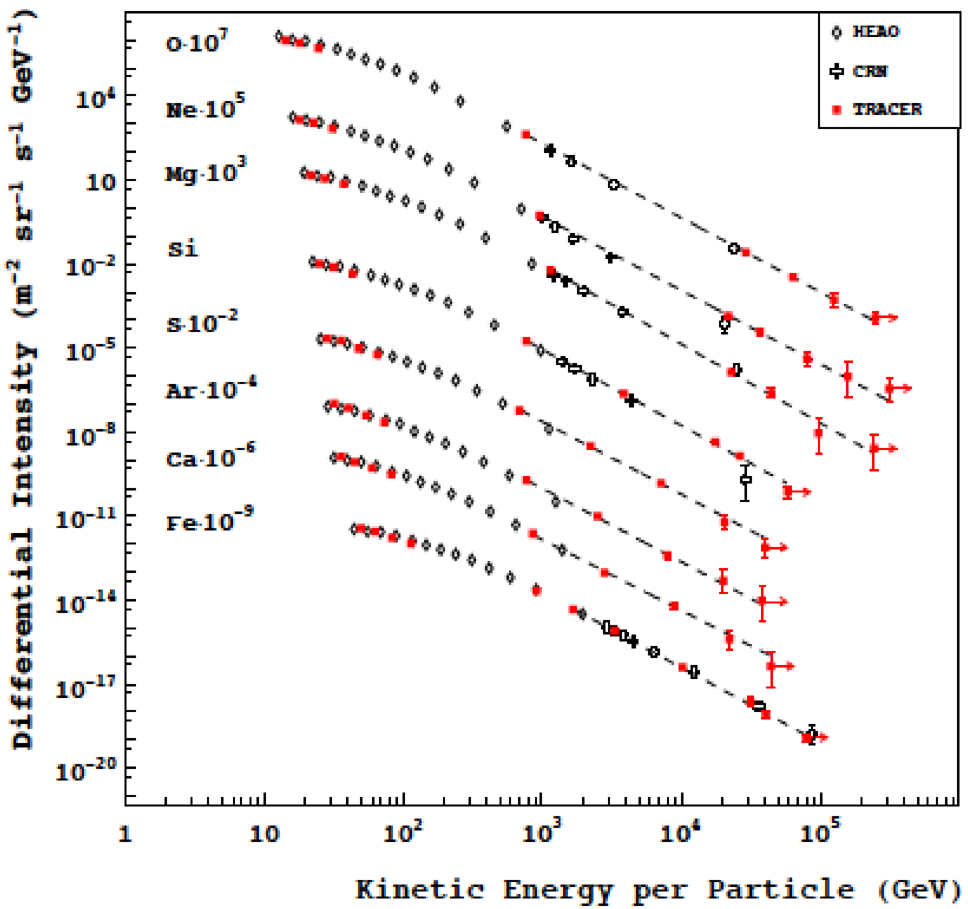

Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur


Space:
Short missions (days)/ Largerpayloads
CRN on Challenger
(3.5 days 1985)
VOYAGER
ACE
CRRES
HEAO
ULYSSES
IMPJ
AMS-01 on Discovery
(8 days, 1998)
Long missions (years)
Small payloads
Low energies..
IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
Fermi-LAT
PAMELA
AMS-02
Long missions
Large payloads

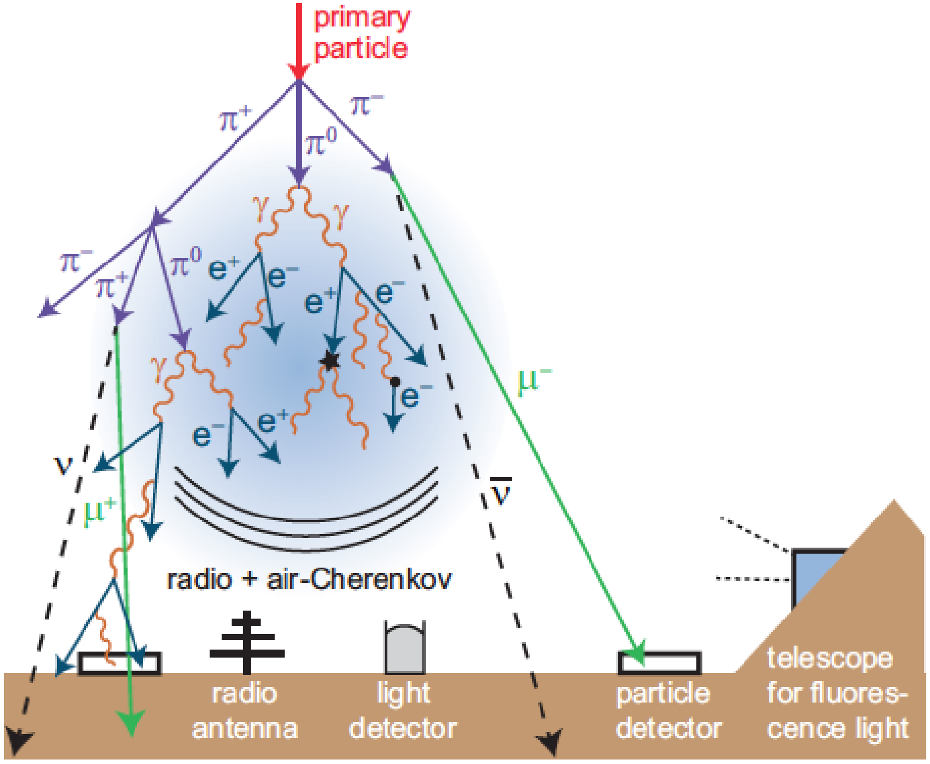


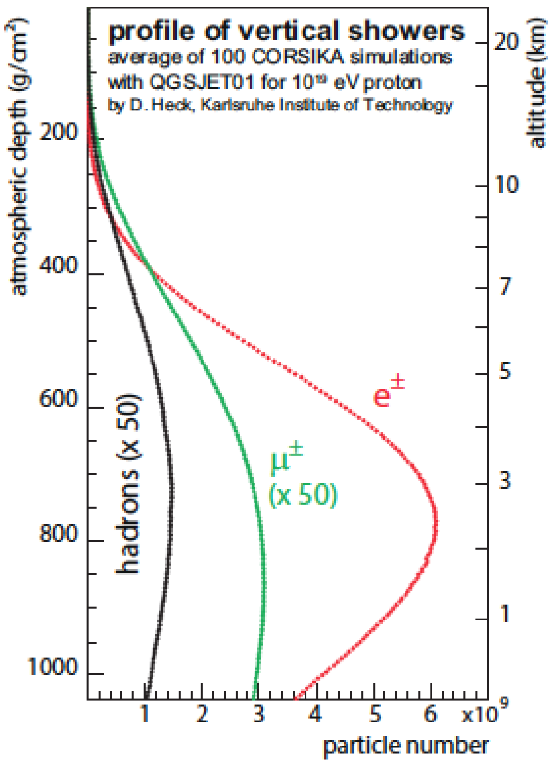
Incoming CRs
Transition Radiation Detector
Electron/proton, Z
Time of Flight
Z, E
TRD
1
Magnet
±Z
Silicon Tracker
Z, P
TOF
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
Ring Imaging Cherenkov
Z, E
Electromagnetic Calorimeter
E of electrons
The Charge and Energy are measured independently by several detectors

Spectra of individual nuclei

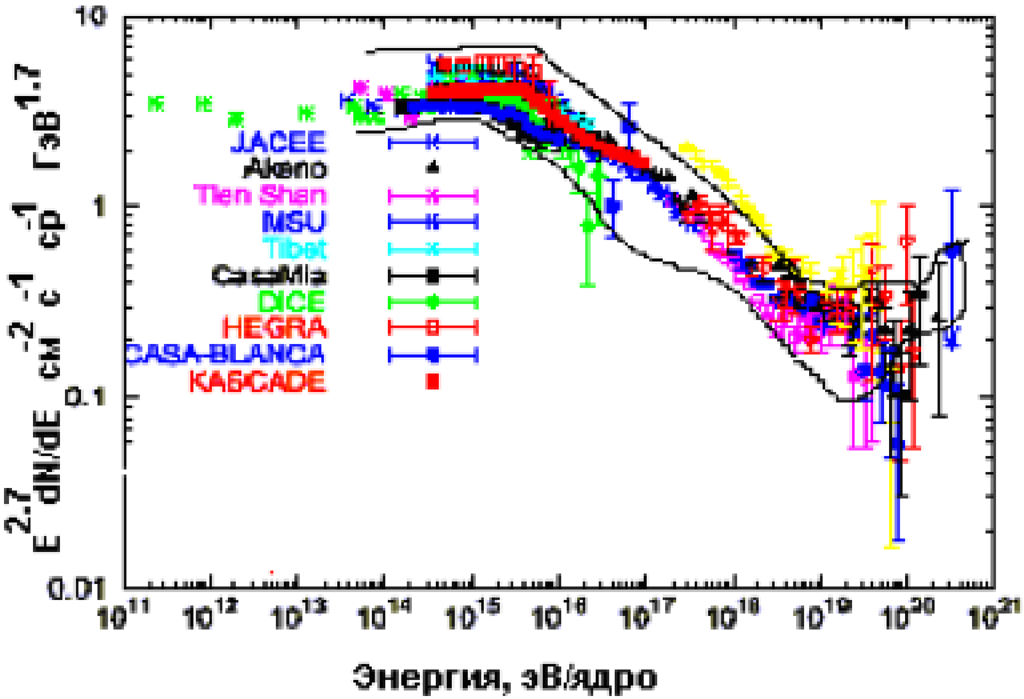


Detection techniques





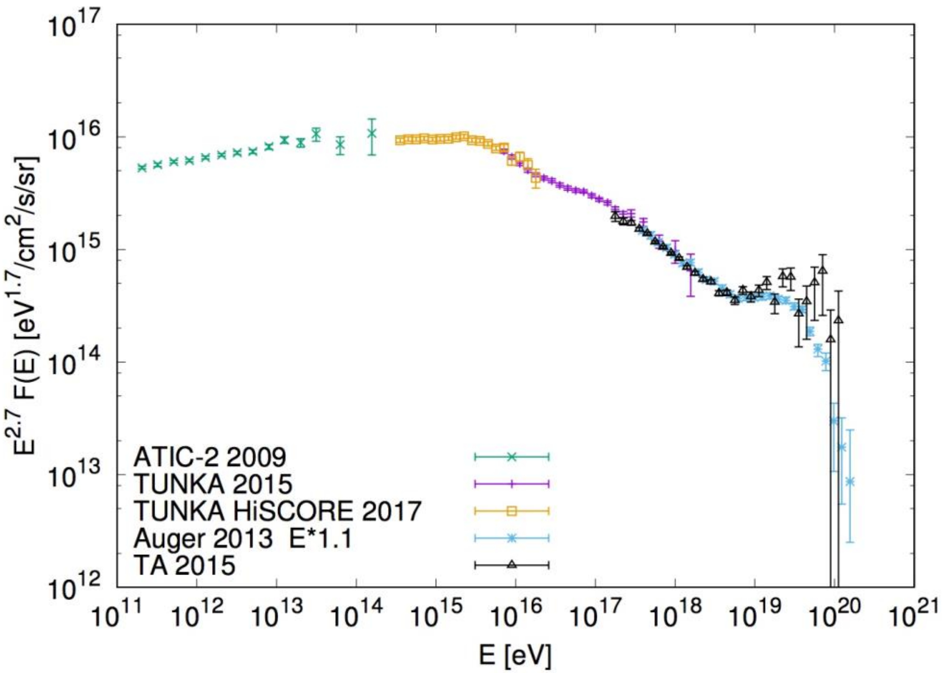
Knee in CR spectrum



Knee was discovered by Kulikov and Khristiansen in data of MSU Experiment in 1958

It was confirmed by all new independent eperiments

Features in CR spectrum



Ankle 300 GeV
Bump 10^{13} eV
Knee 4$10^{15}$ eV
Second knee 2 10^{17} eV
Ankle 3 10^{18} eV
Instep 4 10^{19} eV
Cutoff 6 10^{19} eV

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KASCADE experiment

40000 m^2 10^{15}-10^{17} eV

Measure electron and muon size at Karlsruhe, Germany (near sea level).
Energy spectra of 5 primary mass groups are obtained from two dimensional Ne-Nμ spectrum by unfolding method (P,He,CNO,Si,Fe).

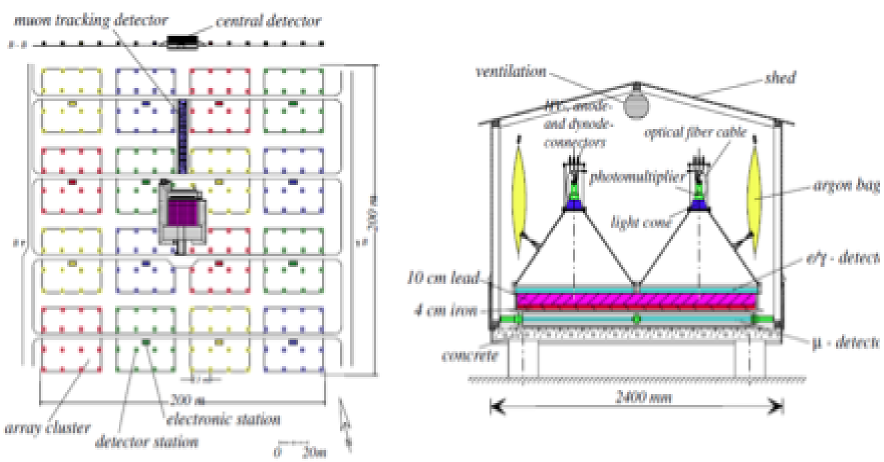


Fig. 1. Left: layout of the KASCADE air shower experiment; Right: sketch of a detector station with shielded and unshielded scintillation detectors.

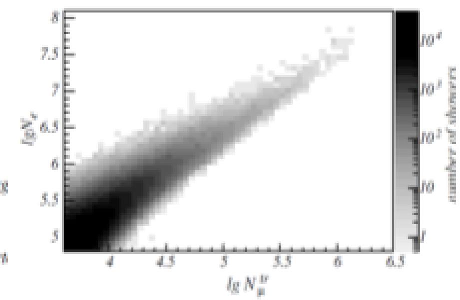
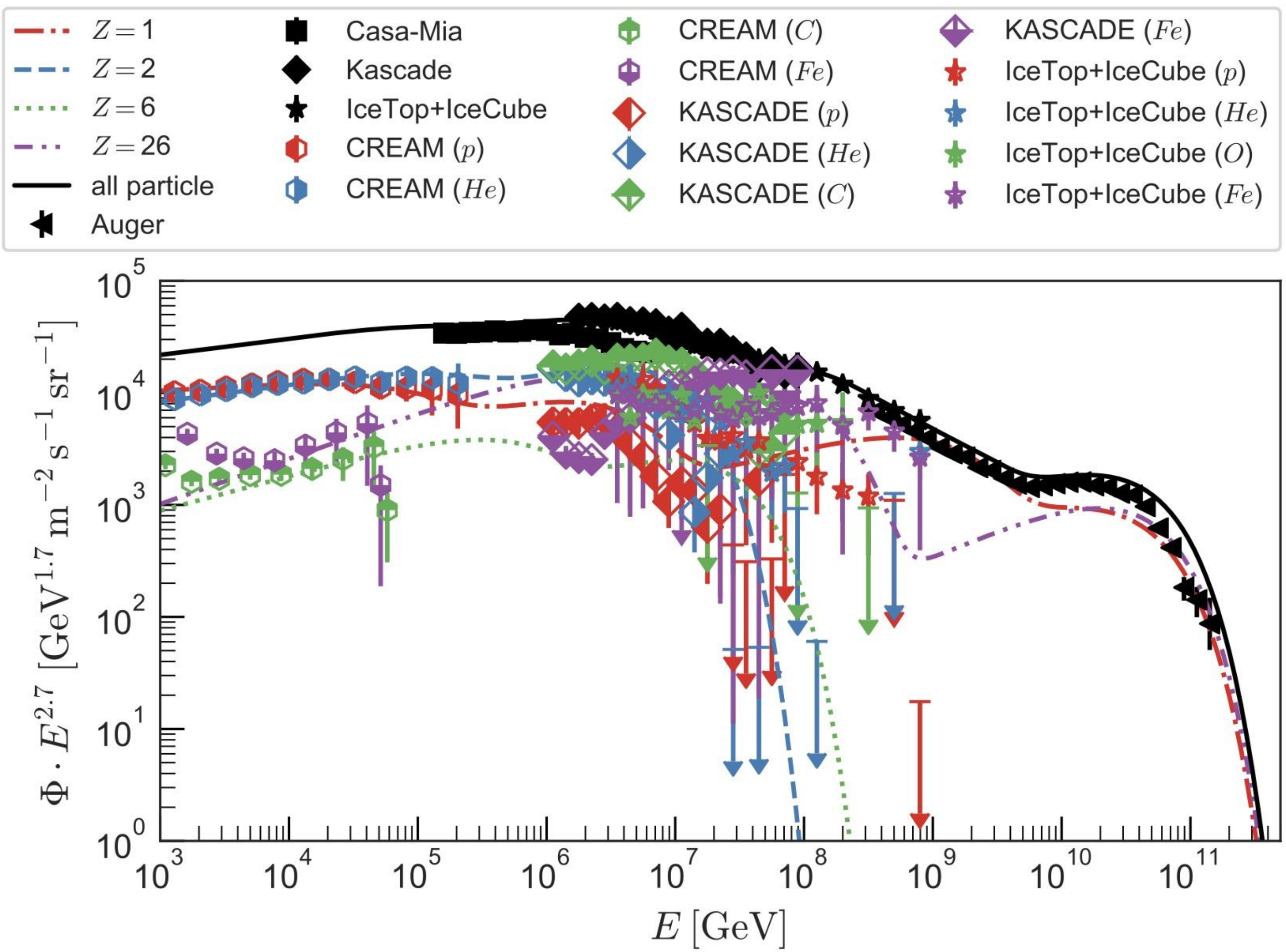


Fig. 2. Two-dimensional shower size spectrum used in th analysis. The range in lg N_e and lg N_μ^{tr} is chosen to avoi influences of inefficiencies.

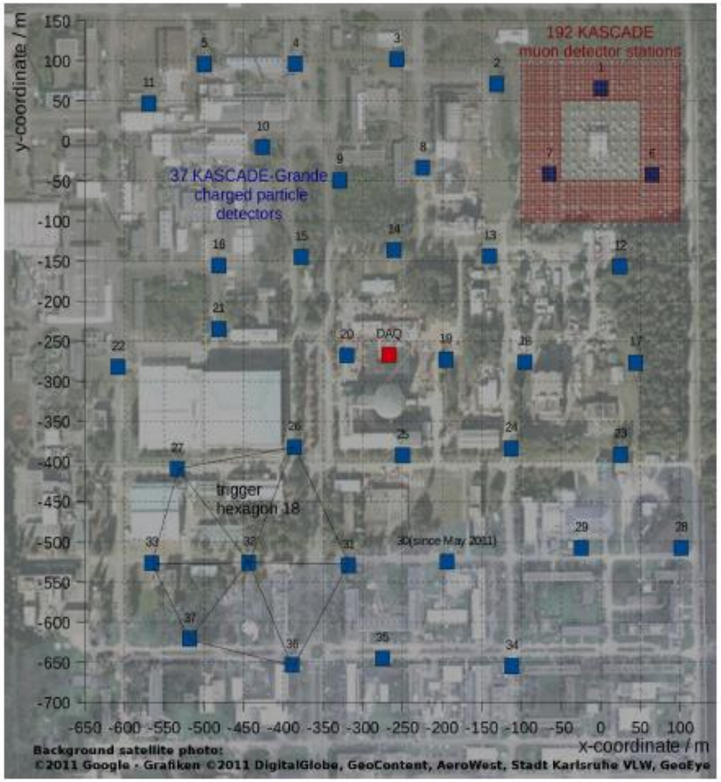
Operated before 2000

Knee-composition

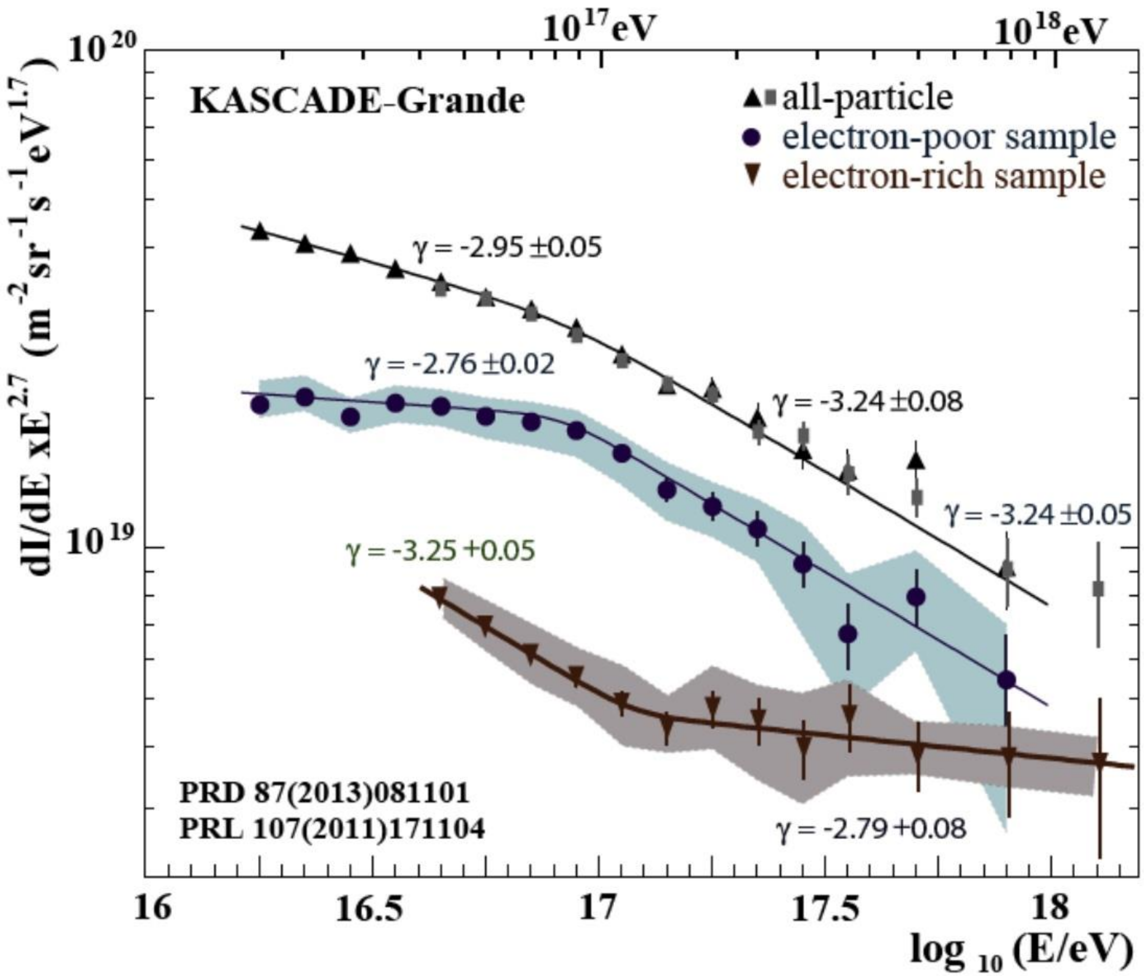


KASCADE-Grande

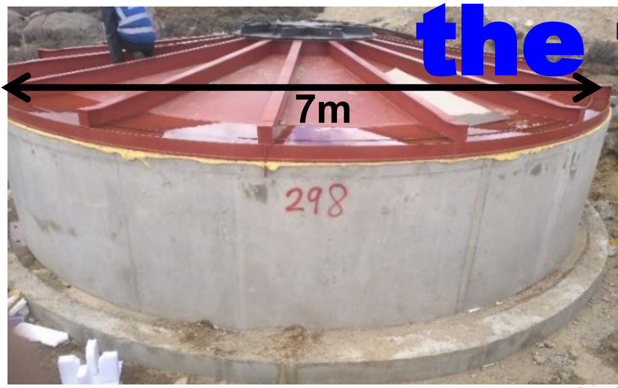
- KASCADE-Grande covered an area of about 1 km^2 and studied energy range 10^{16} eV-10^{18} eV
- Operated 2003- 2013.

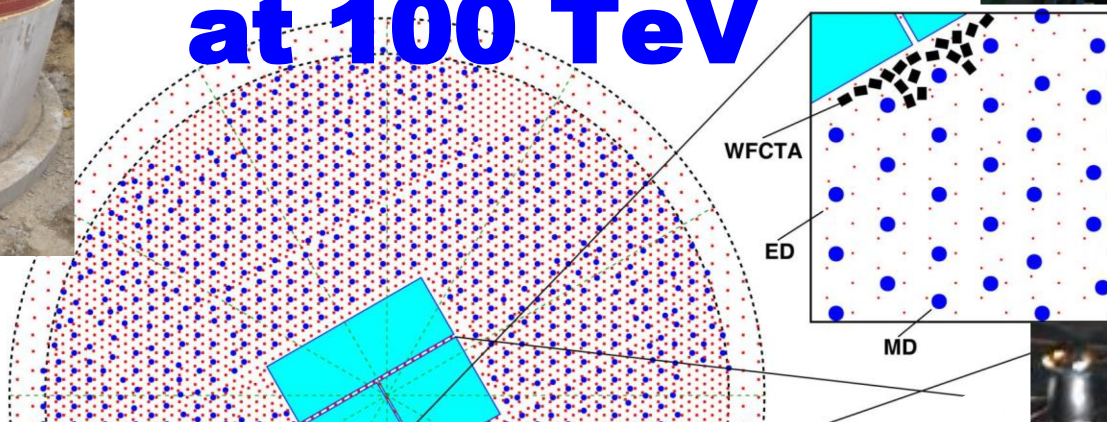


KASCADE-Grande

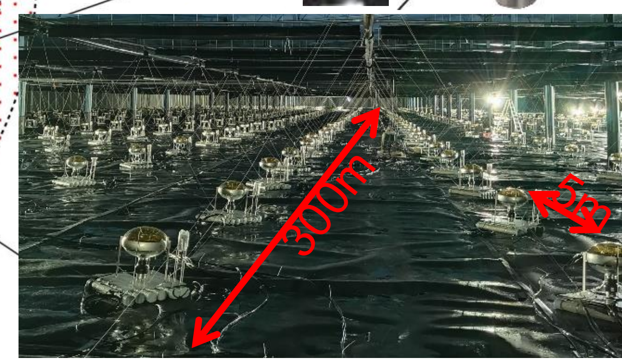


LHAASO Layout: 3 types of detectors for the first time in history at 100 TeV



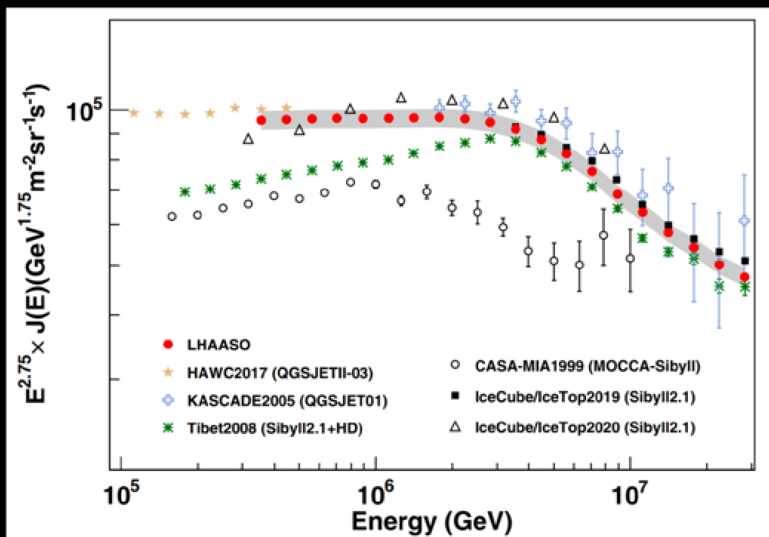


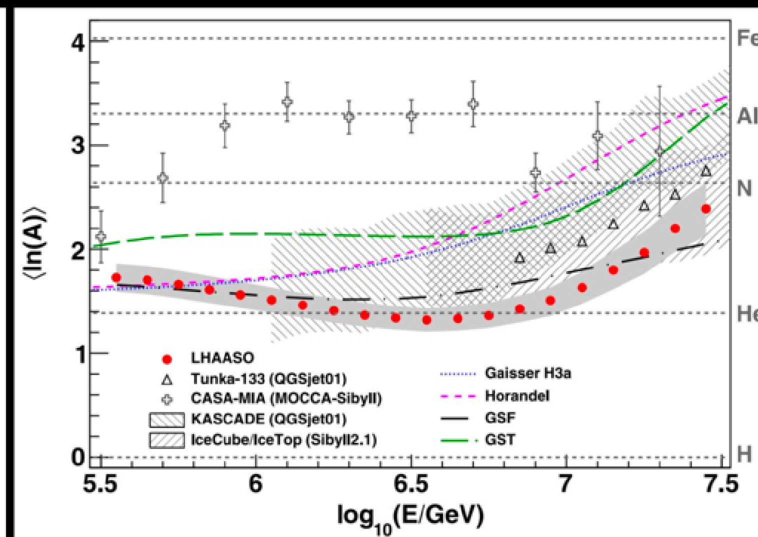
1.2 m



Construction finished on July 2021,
CR results 2024

All-particle energy spectrum & <lnA>





	Flux $J(E)$	$\langle \ln(A) \rangle$
Air preesure	$\pm 3\%$	$\pm 4\%$
Composition models	$\pm 1.5\%$	$\pm 3\%$
Interaction models	$\pm 2.5\%$	$\pm 6\%$

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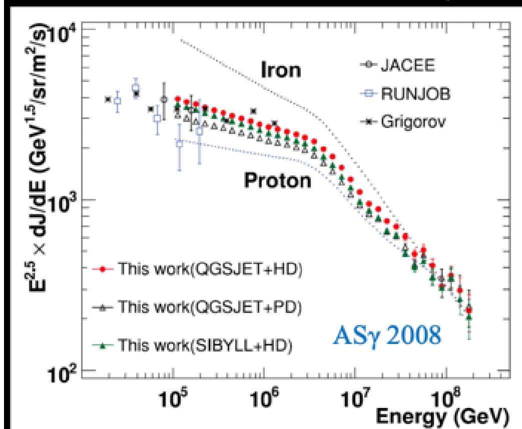
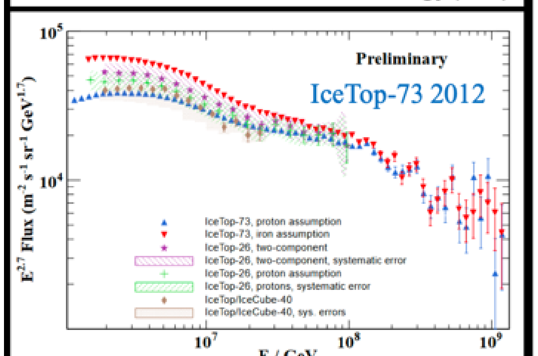
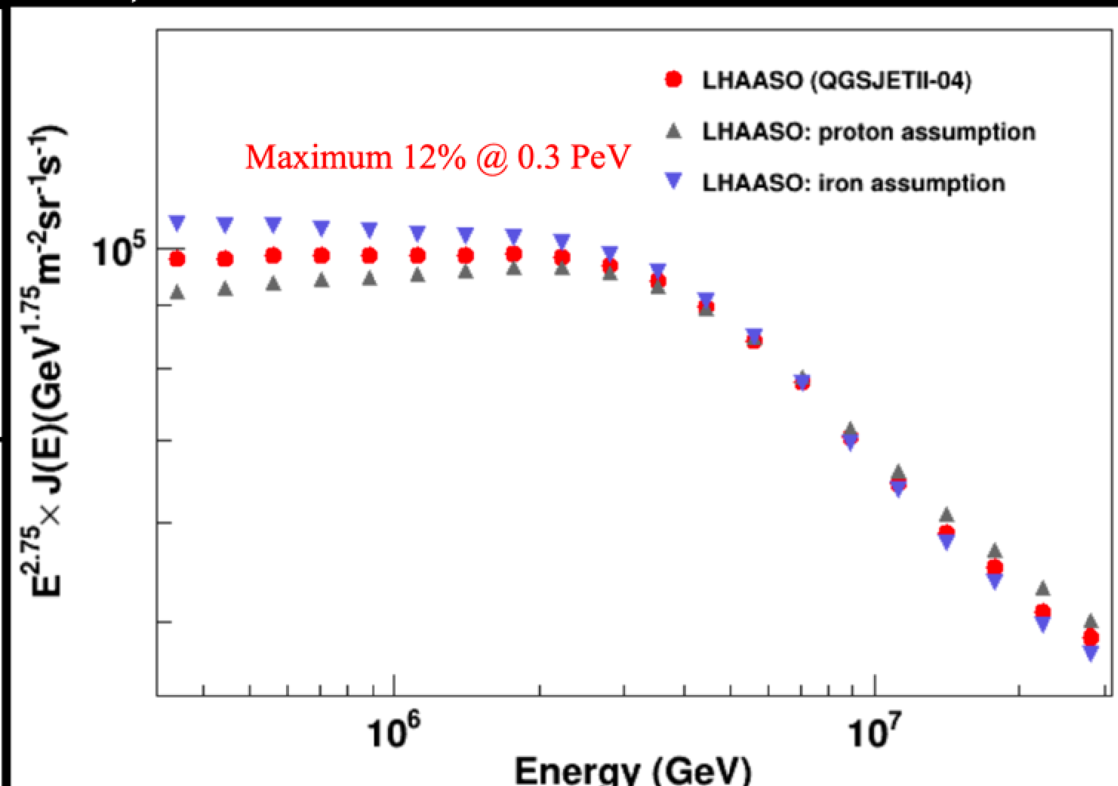
•*LHAASO collab.,* Zh.Cao et al, [2403.10010](2403.10010)
, *Phys.Rev.Lett.* 132 (2024) 13, 131002

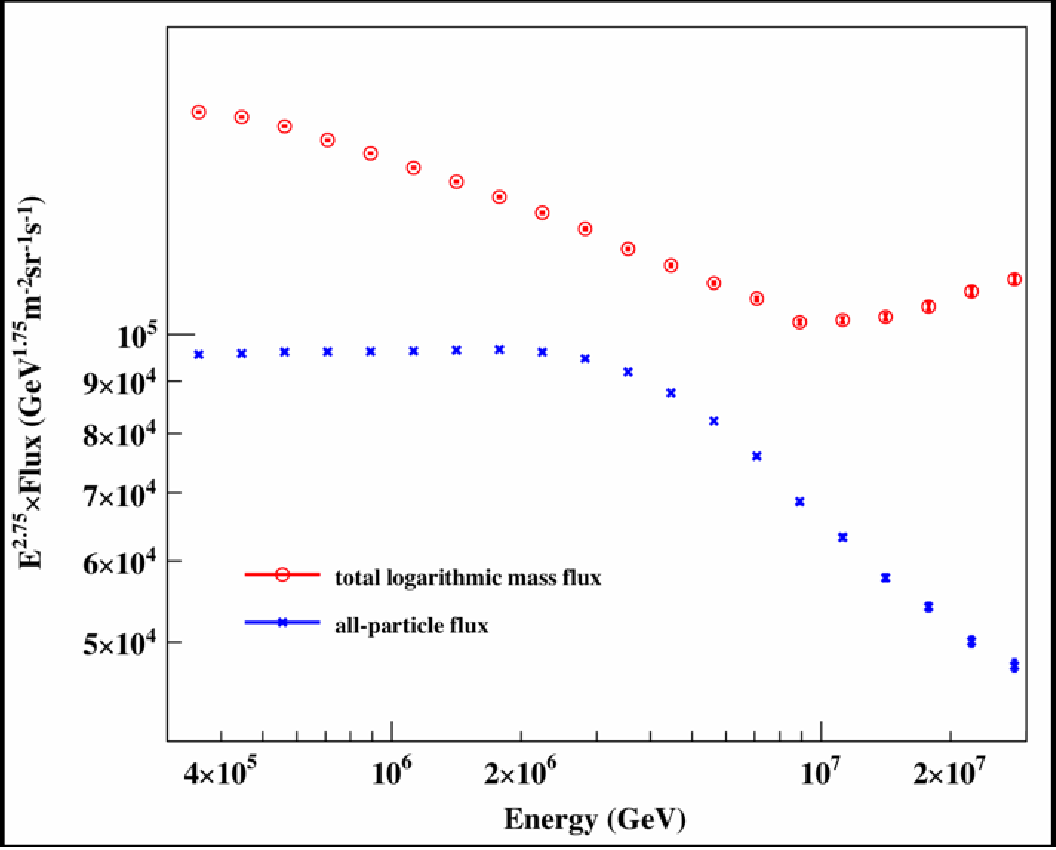
From 350%(150%) to 12%



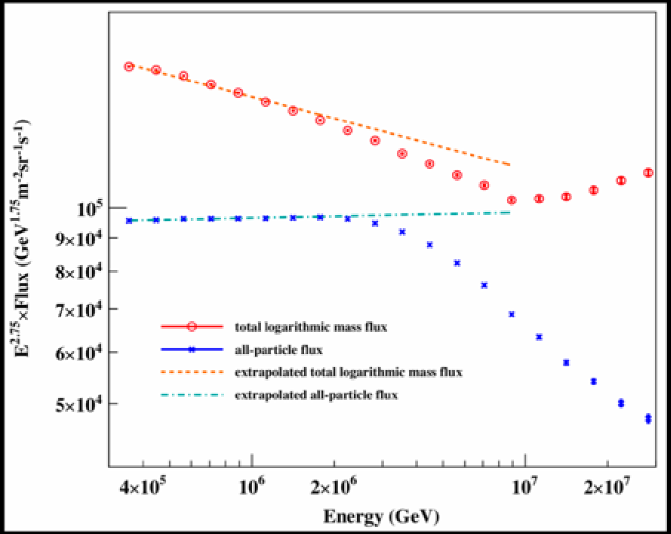




The all-particle and TLM spectra by KM2A



Does proton spectrum break at the knee?



- Parameters from LHAASO paper
  - All-particle flux $F' = F_0\left(\frac{E}{1\ PeV}\right)^{\gamma_F}$
  - <lnA> $m' = m_0\left(\frac{E}{1\ PeV}\right)^{\gamma_m}$
  - ➢TLM
- Loss $M' = F' \times m' = F_0 \times M_0\left(\frac{E}{1\ PeV}\right)^{\gamma_F+\gamma_m}$
  - All-particle flux $\Delta F = F' - F$
  - TLM $\Delta M = M' - M$
  - <lnA> of ΔF

$$m_{\Delta F} = \frac{\Delta M}{\Delta F} = q_p \times m_p + (1-q_p)\times m_{\geq He} = (1-q_p)\times m_{\geq He}$$

- TLM anticipation

$$M'' = M' - \Delta F \times m_{\Delta F}$$

- H_0: no, q_p=0 → best-fit $m_{\Delta F} = \ln 4$
- H_1: yes, q_p>0 → best-fit $m_{\Delta F} = 0.66 \pm 0.02$
- Significance of rejecting H_0: 36.8σ

→Proton spectrum breaks at the knee!

Only proton spectrum breaks at the knee?

- H_0: yes, q_p=1
- H_1: no, q_p<1
- Significance of rejecting H_0
  - Paper: 41.8σ
  - 1-10 PeV: 6.3σ

$$m_{\Delta F} = \frac{\Delta M}{\Delta F} = (1 - q_p) \times m_{\geq He}$$

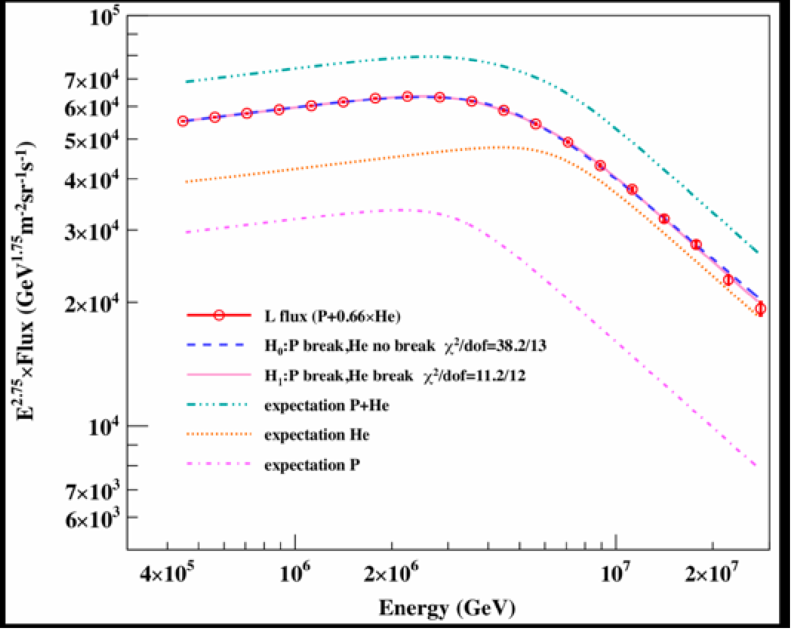
- proton proportion
  - Paper: $52.7\% \pm 1.2\% \leq q_p \leq 83.7\% \pm 0.04\%$
  - 1-10 PeV: $72.6\% \pm 4.5\% \leq q_p \leq 90.6\% \pm 1.5\%$

→Proton dominates the knee but it's not the only one whose spectrum breaks!

Features of the proton knee

- $E_p = 3.2 \pm 0.2$ PeV
- Spectral index before the cutoff: -2.6559 ± 0.0009
- Change of spectral index: -0.79 ± 0.03
- Sharpness： 5.1 ± 0.5
- $f_p = 0.43 \pm 0.06$

- Light: $2.35 \pm 0.06 \times 10^{-12}$ /GeV/m²/sr/s
- (all: 3×10^{-12} /GeV/m²/sr/s)



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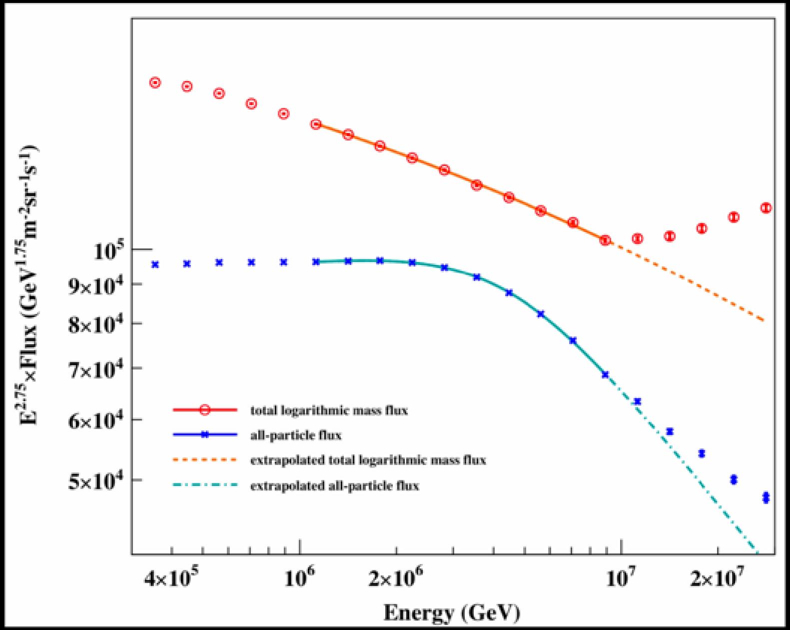
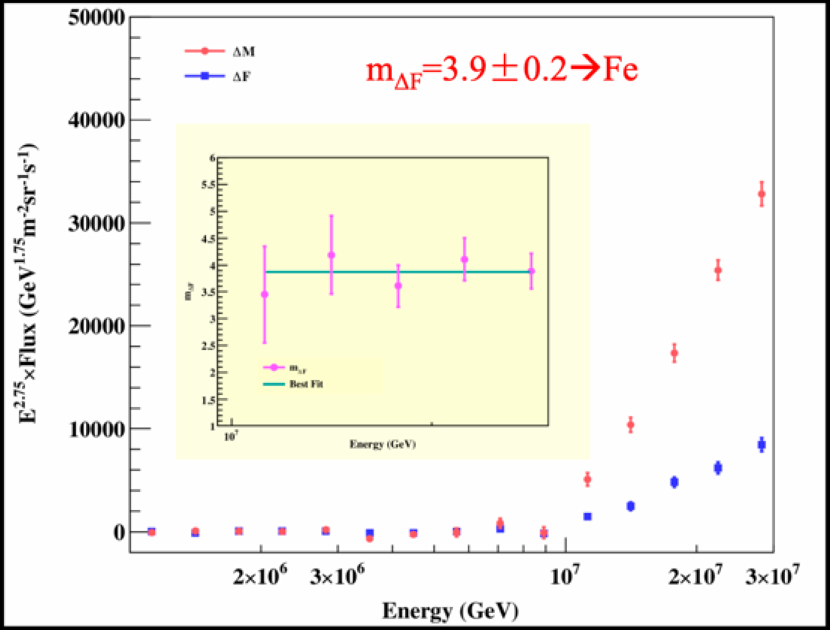
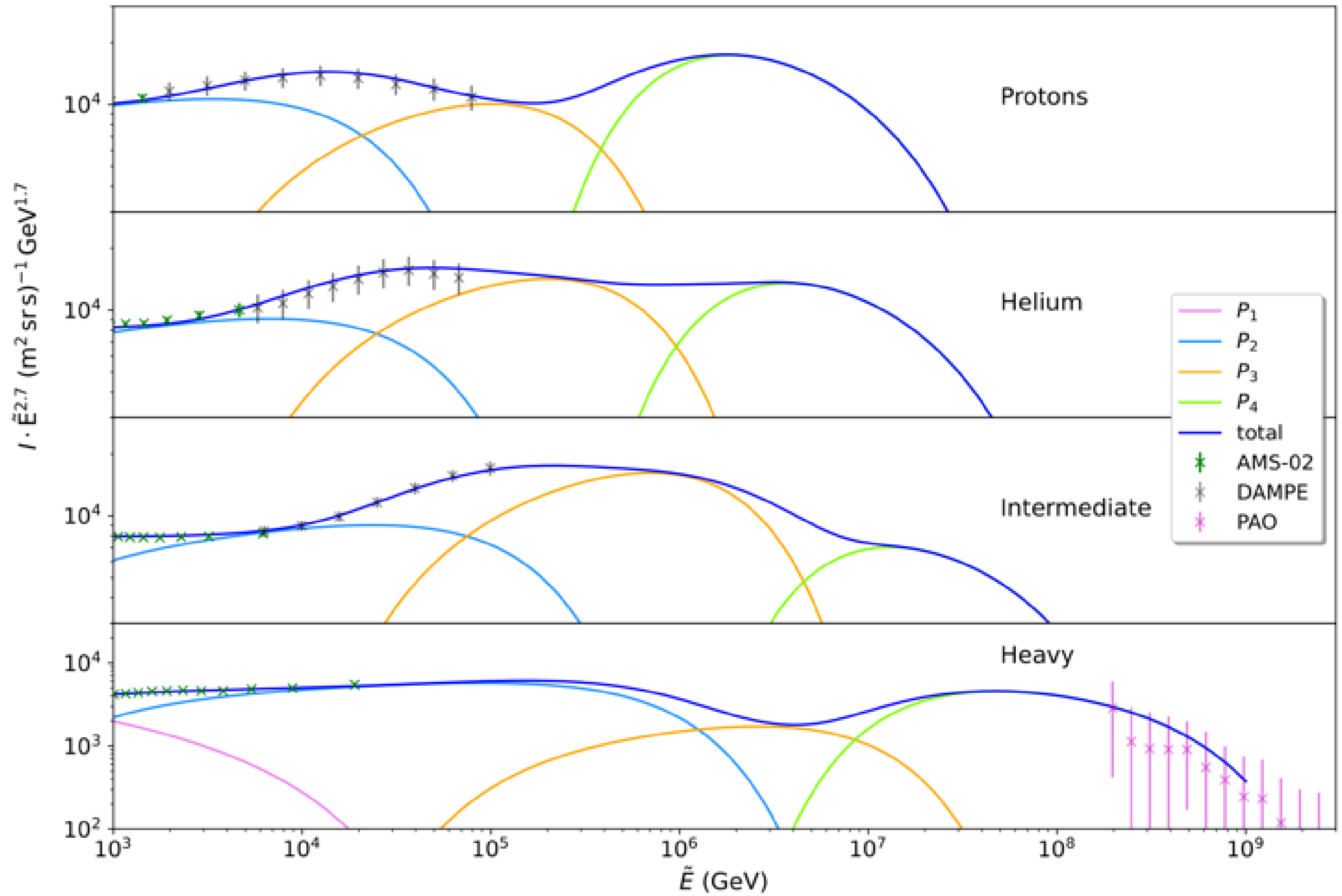
Discovery of an ankle-like structure due to Fe

- Break energy: 9.7±0.2 PeV

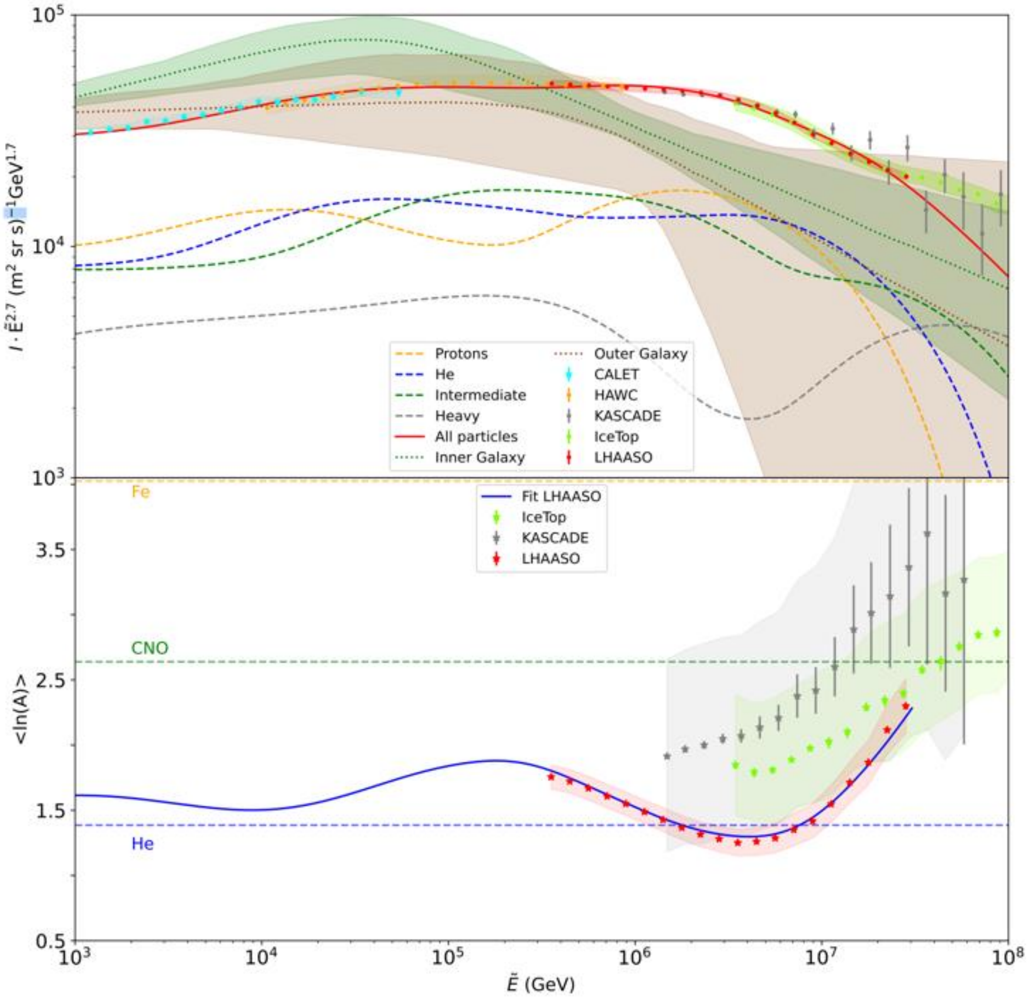






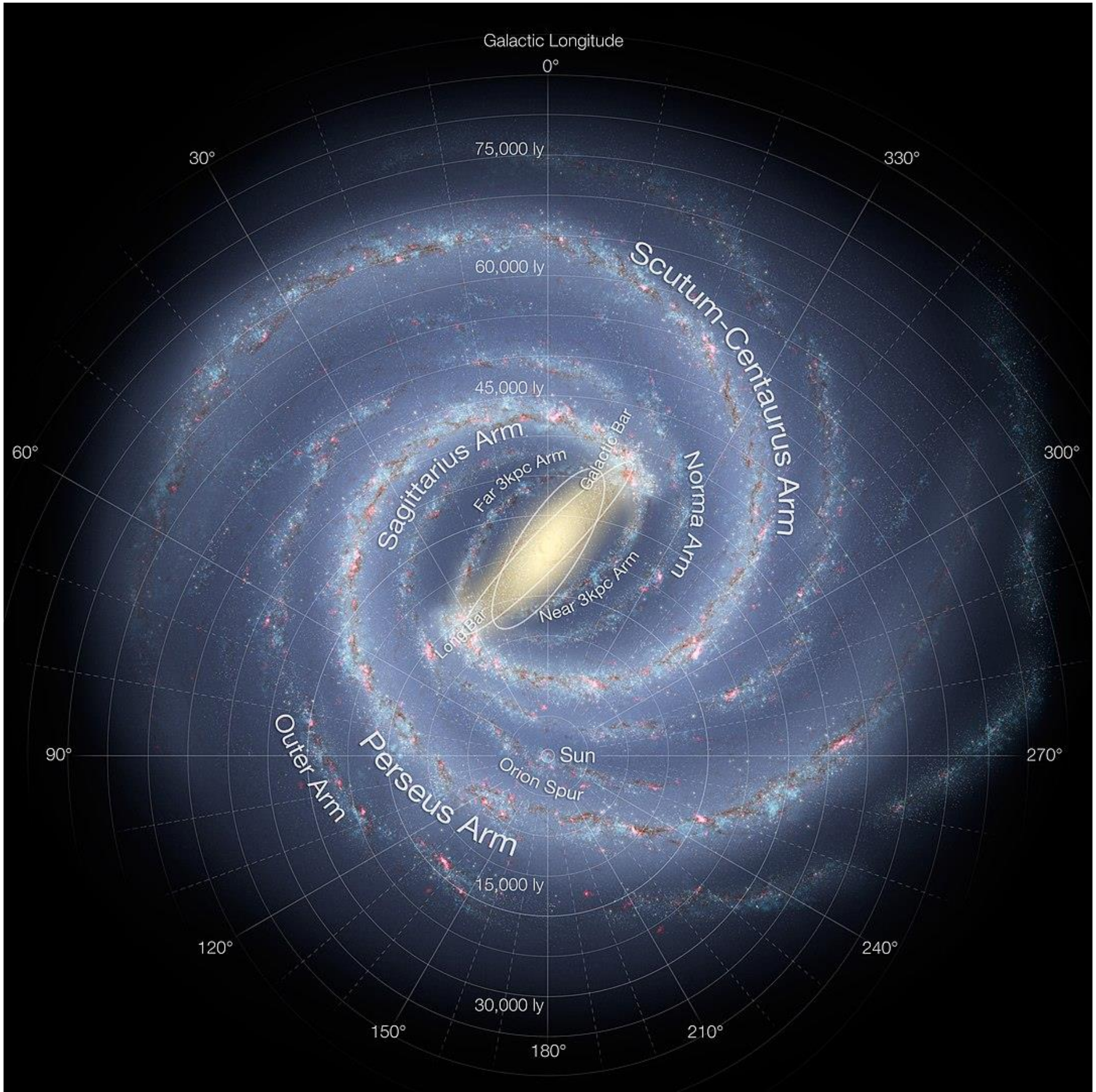
C. Prevotat et al, [2407.11911](2407.11911)

Knee in Galaxy vs local Cosmic Rays

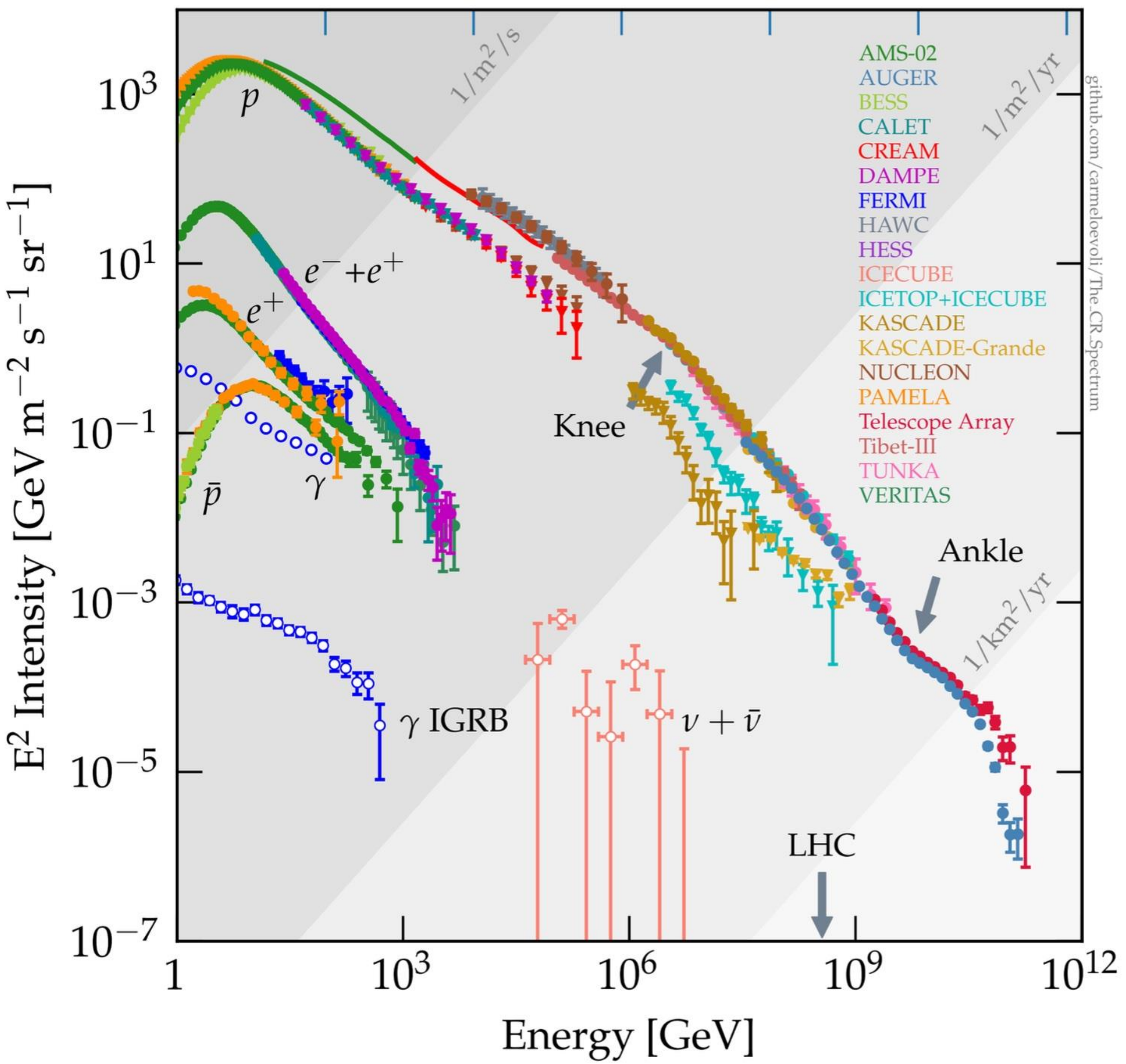


C. Prevotat et al, 2407.11911

Gamma-rays from Milky Way Galaxy and connection to cosmic rays


Galactic Longitude
0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
60°
300°
90°
270°
Sun
Orion Spur
Outer Arm
Perseus Arm
15,000 ly
30,000 ly
120°
240°
150°
210°
180°

Cosmic ray energy spectrum



From C.Evoli

Pion production

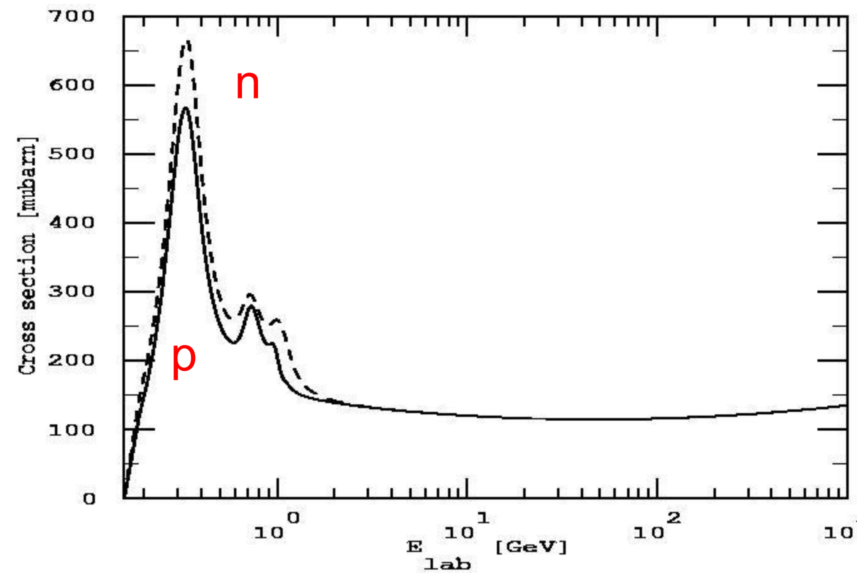
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

$$N + A_b \square \; N' + \square \, \pi^i$$

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

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

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



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

Conclusion: CR, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones (model dependent) :

$$E_\gamma^{tot} \sim E_\nu^{tot}$$

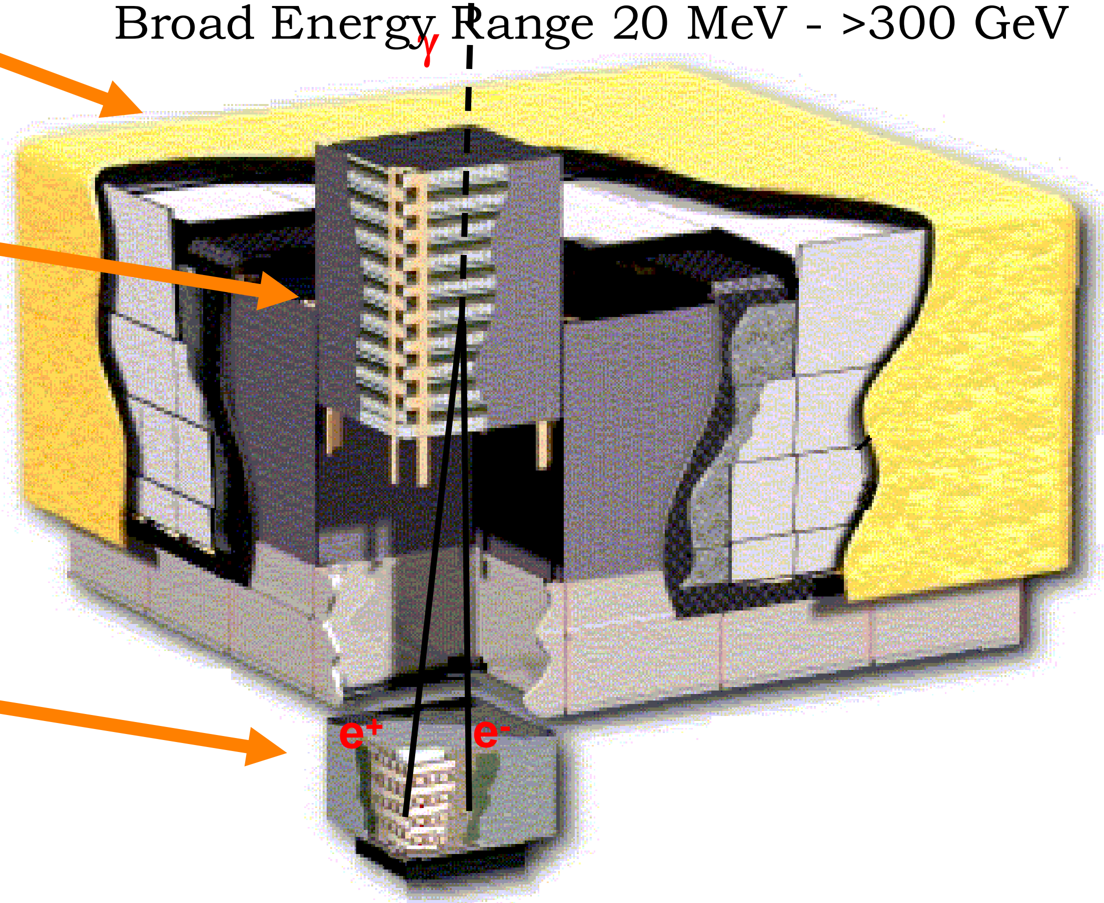
Fermi Large Area Telescope (LAT)

Large Field of View >2.4 sr
Broad Energy Range 20 MeV - >300 GeV

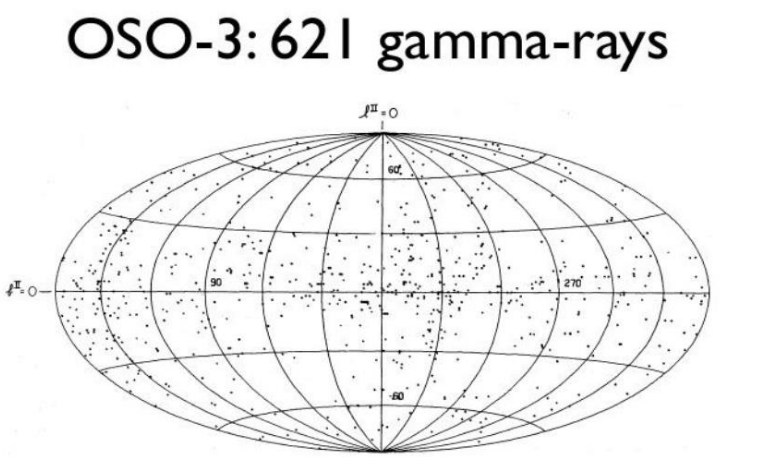
ACD
scintillator
89 tiles

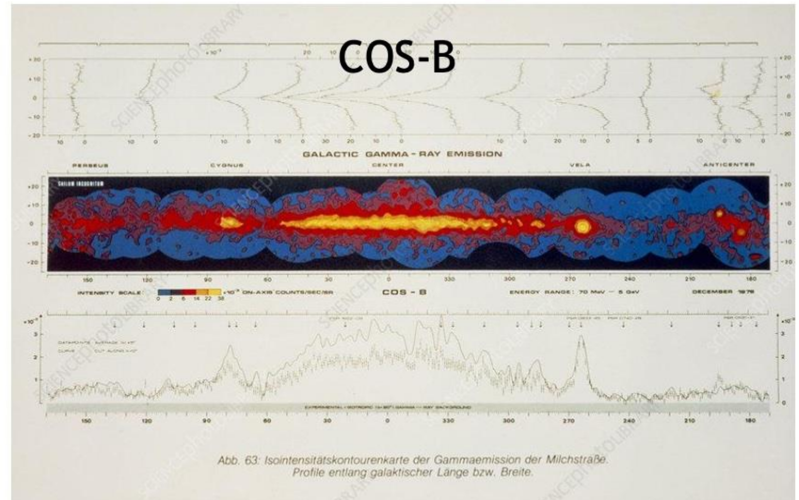
Tracker
Si strip detectors
Tungsten foil
converters
pitch = 228 um
8.8×10^5 channels
18 planes

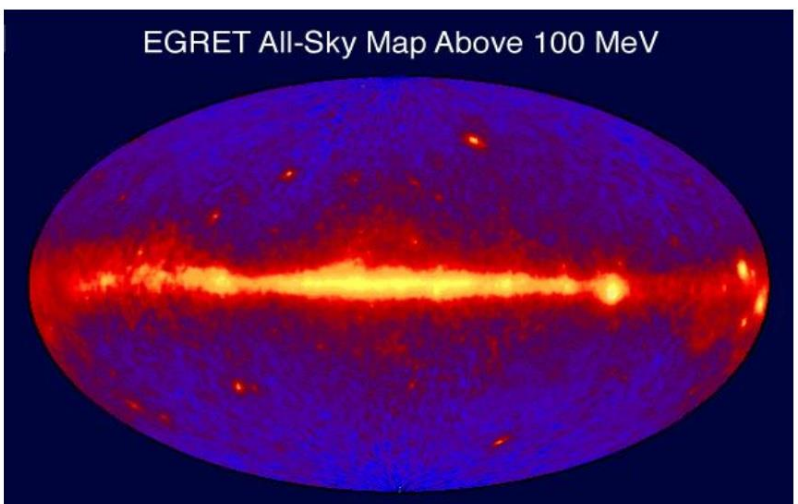
Calorimeter
CsI crystals
hodoscopic array
6.1×10^3 channels
8 layers

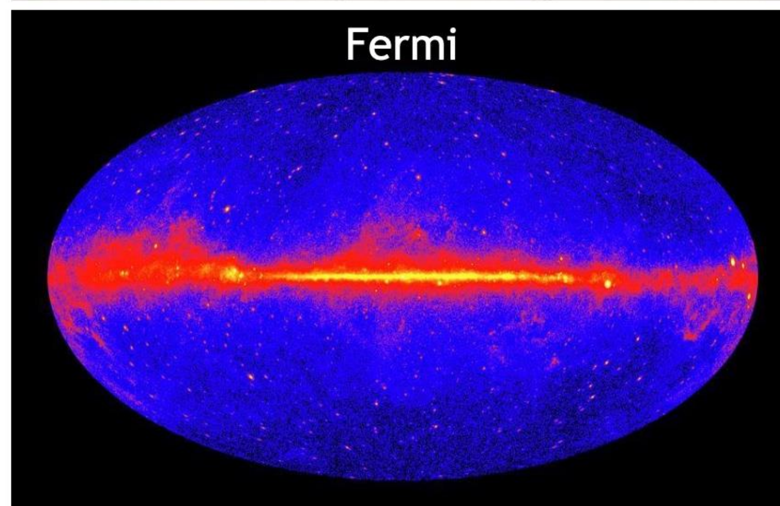


Diffuse γ-ray observations from space



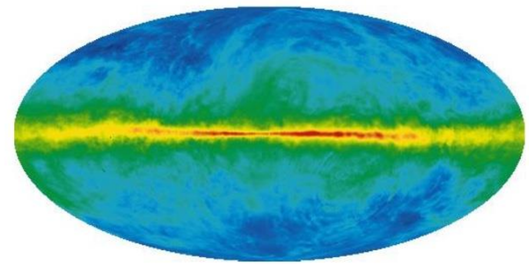




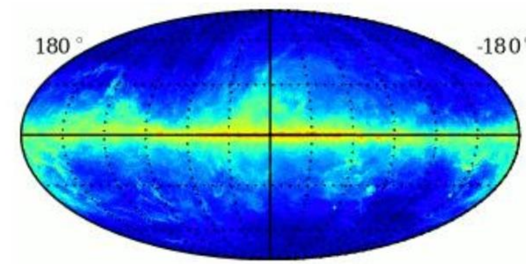


Origins of Galactic diffuse γ rays

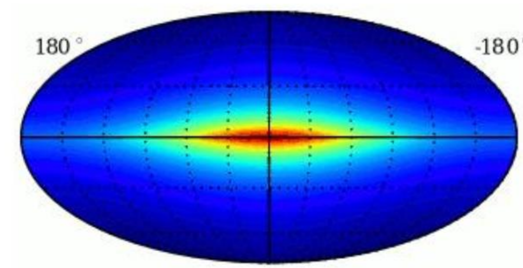
p,α + ISM → π^0 → 2γ



e + ISM → γ (bremsstrahlung)



e + ISRF → γ (inverse Compton)



Diffuse gamma-ray and neutrino fluxes

$$\Xi^{A,A'}(E,l,b) = \int_0^\infty \mathrm{d}s\, n_{\mathrm{gas}}^{A'}(\boldsymbol{x}) I_{\mathrm{CR}}^{A}(E,\boldsymbol{x})$$

$$I_\nu(E,l,b) = \sum_{A,A'} \int_E^\infty \mathrm{d}E'\, \Xi^{A,A'}(E',l,b) \frac{\mathrm{d}\sigma^{AA'\to\nu}(E',E)}{\mathrm{d}E}$$

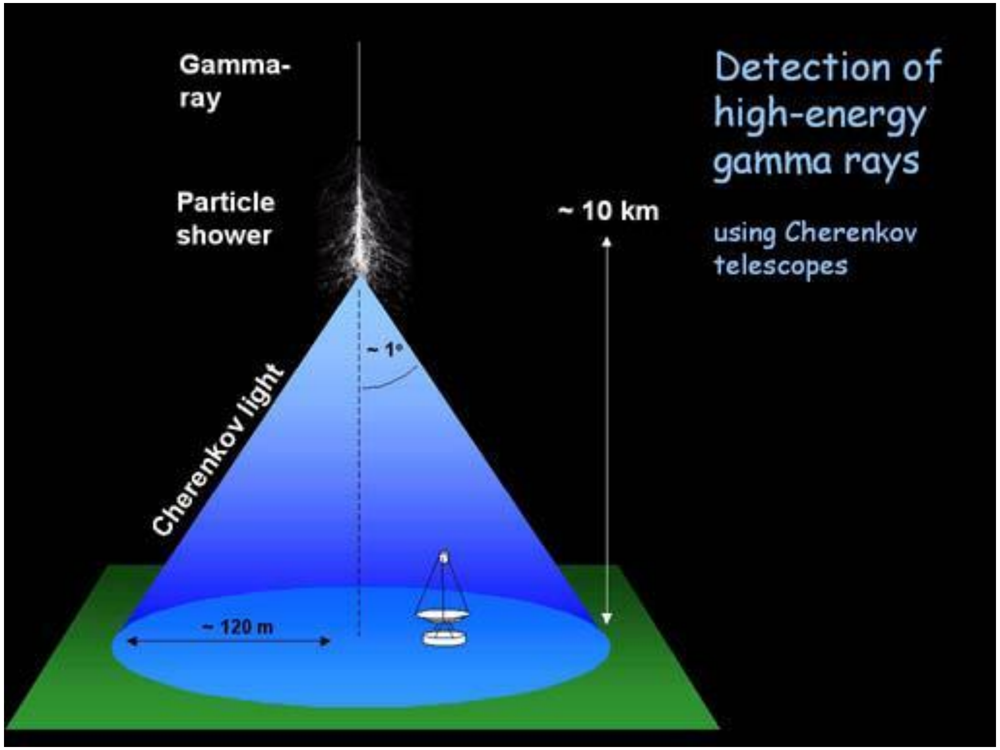
Cherenkov telescopes

Very high energies, above 50 GeV

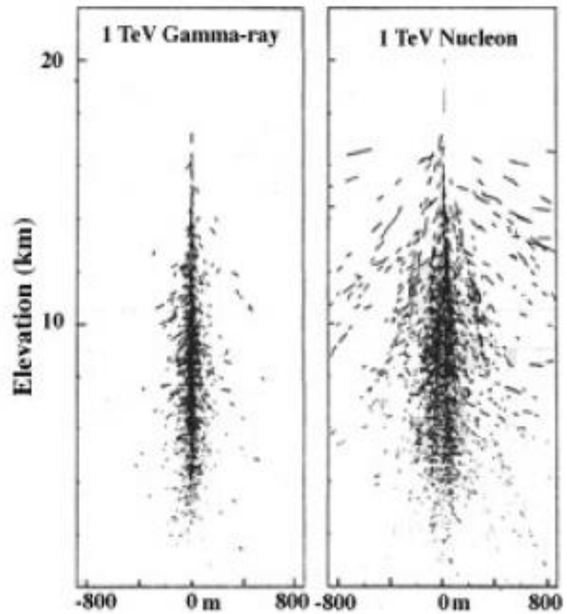
Crab nebula: flux(E > 1 TeV) = 2 x 10^{-11} cm^{-2} s^{-1}
Large effective detection areas (>30 000 m^2) needed

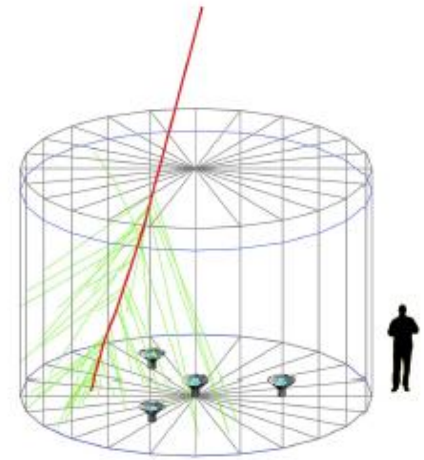
-> Back to the ground

Use the atmosphere as a huge calorimeter and detect γ-ray-induced atmospheric showers through Cherenkov light



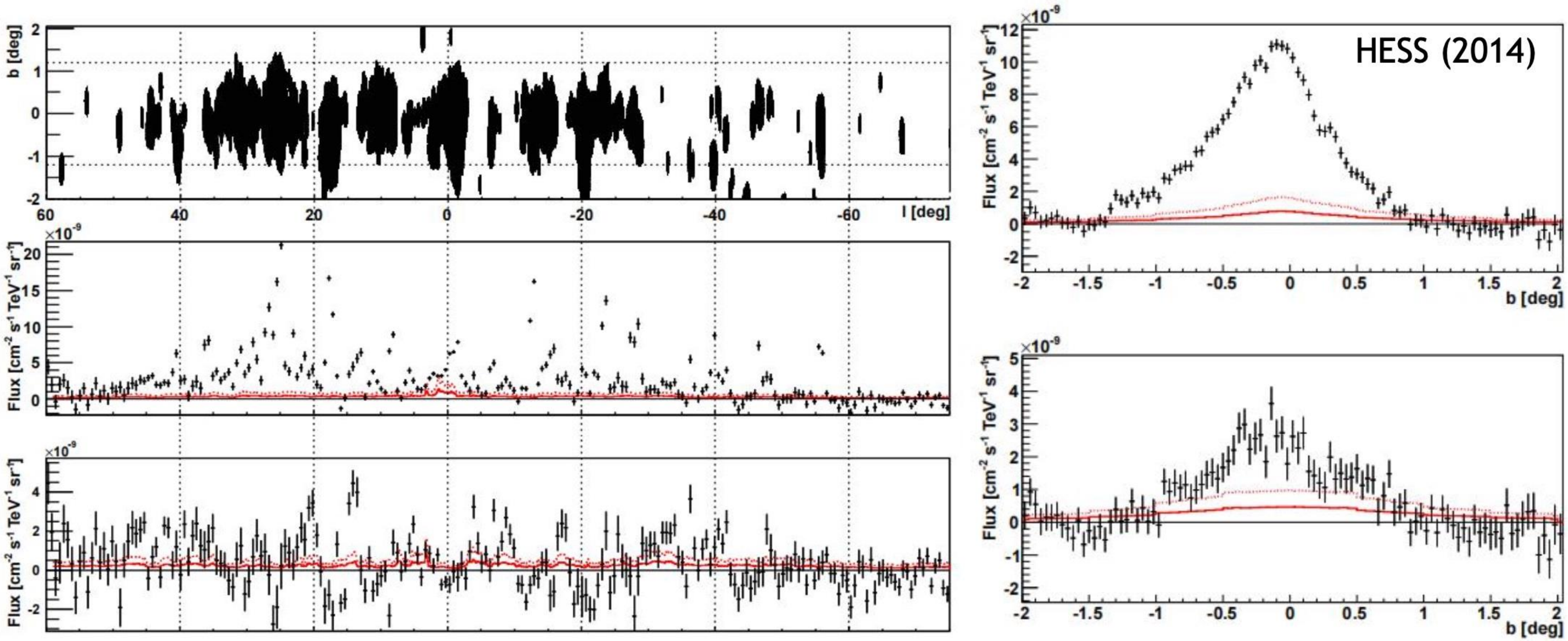
Detection Technique of the EAS Arrays





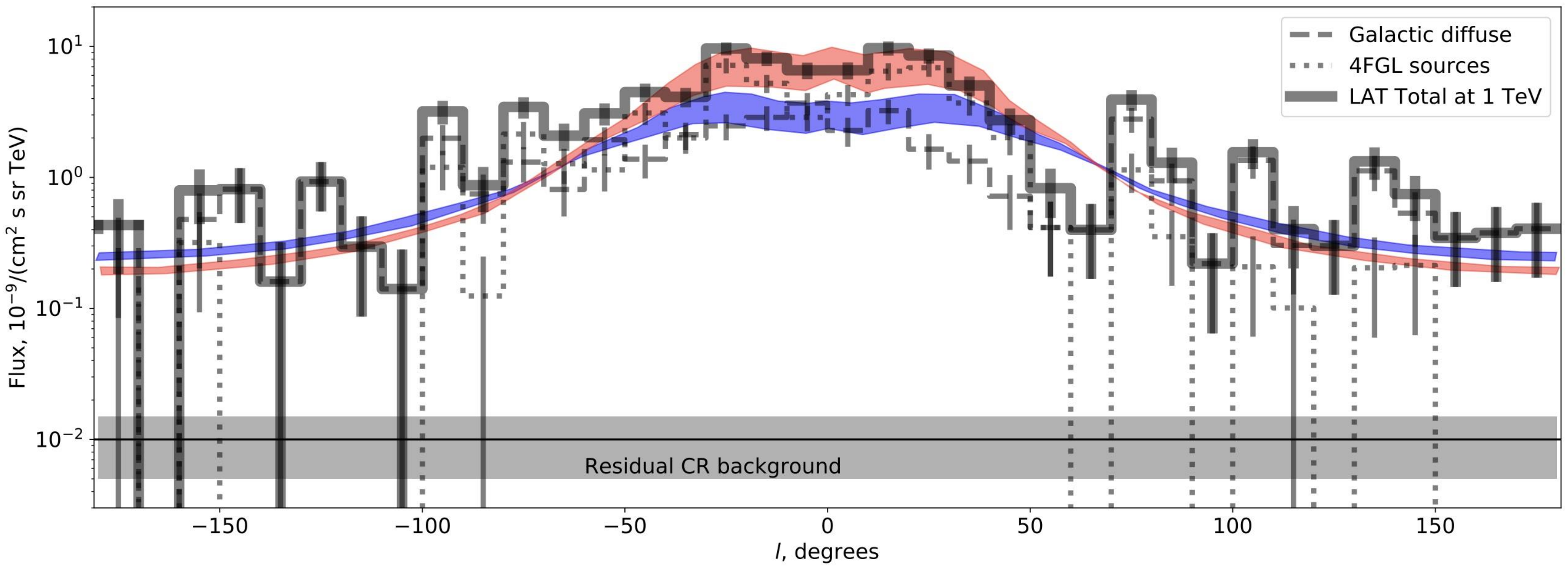
- The particle detectors can be tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- Gamma/hadron can be discriminated based on the event footprint on the detector. Although is one of the challenges of this kind of detectors.

VHE diffuse emission by HESS



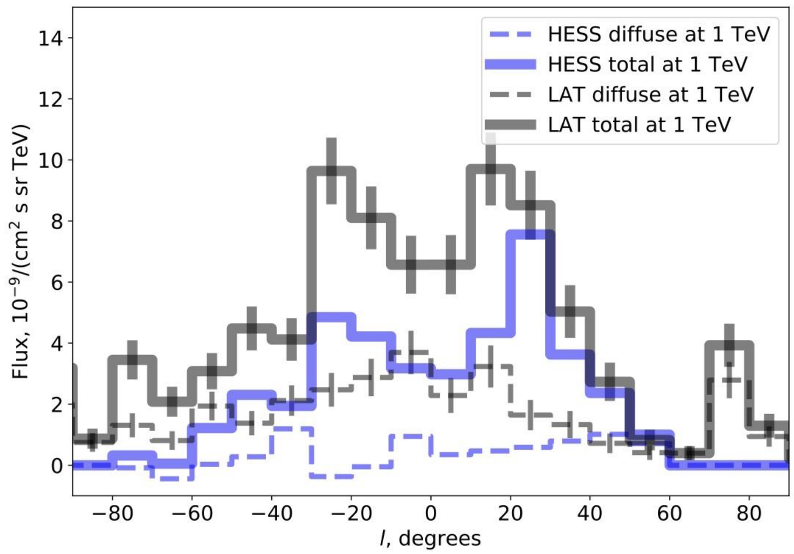
ray flux measurements were made over an extensive grid of celestial locations. Longitudinal and latitudinal profiles of the observed γ-ray fluxes show characteristic excess emission not attributable to known γ-ray sources. For the first time large-scale γ-ray emission along the

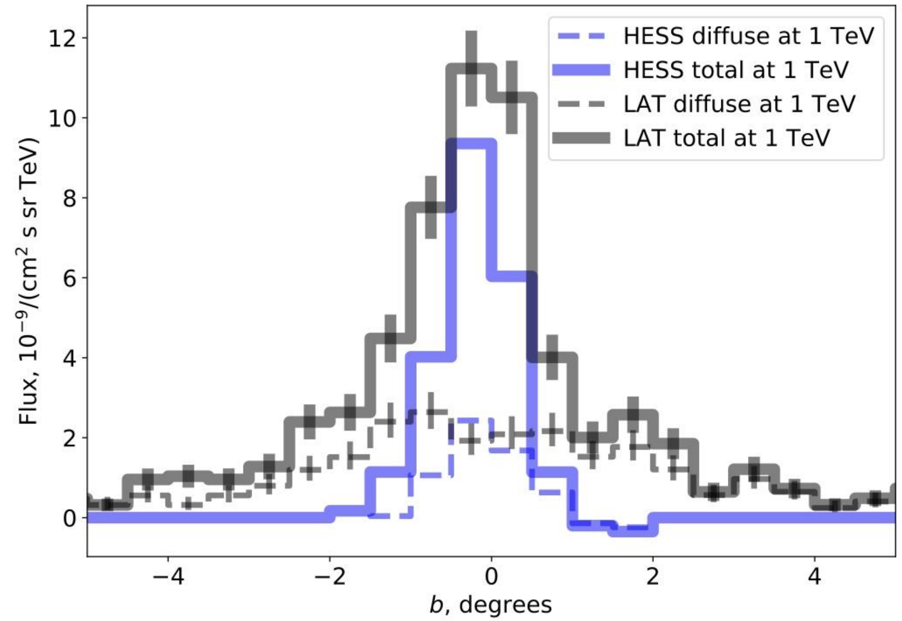
Fermi LAT galactic plane 1TeV



A,.Neronov and D.S., Astron.Astrophys. 633 (2020) A94, arXiv:1907.06061

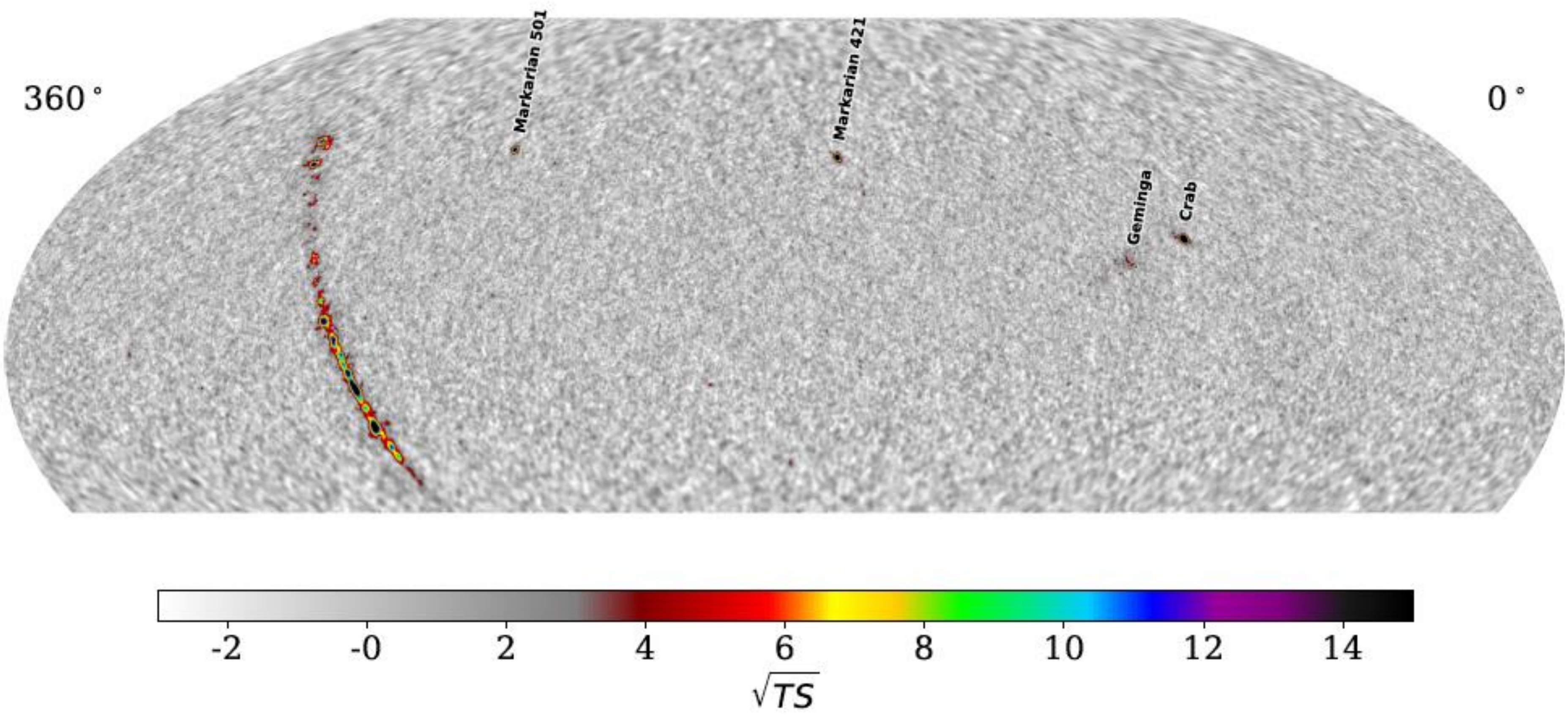
HESS vs Fermi LAT galactic plane 1TeV





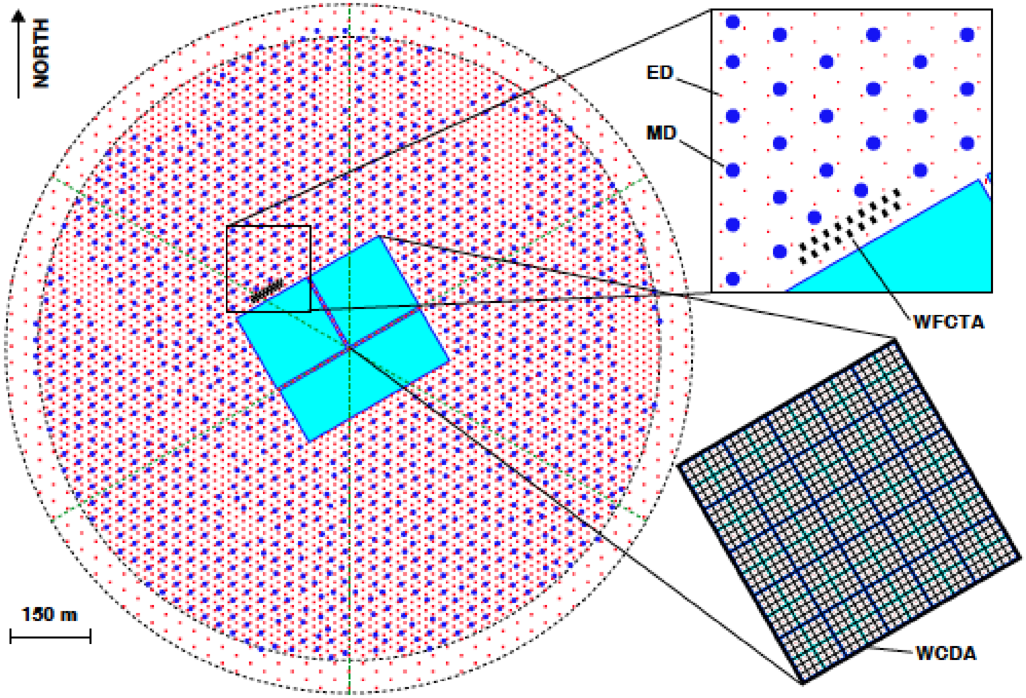
A,.Neronov and D.Semikoz, Astron.Astrophys. 633 (2020) A94, arXiv:1907.06061

HAWC sky map 10 TeV



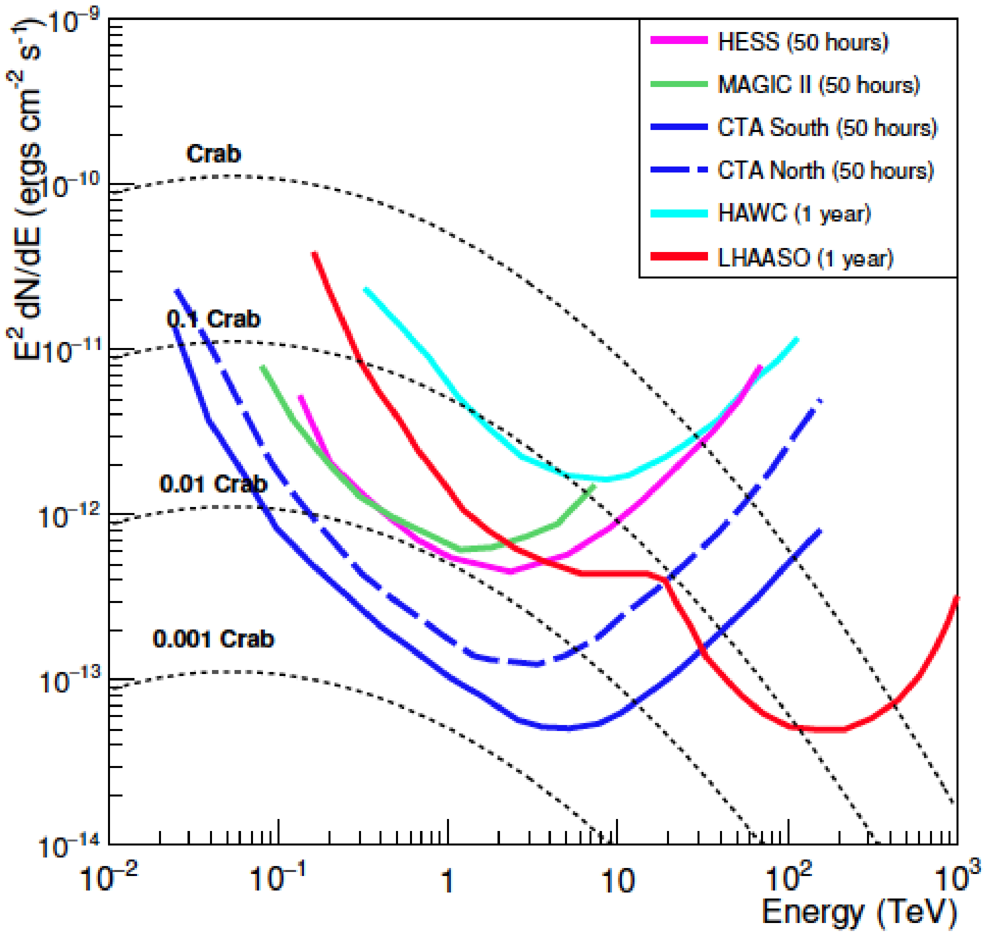
The LHAASO experiment

- 1 km^2 array, including 4941 scintillator detectors 1 m^2 each, with 15 m spacing.
- An overlapping 1 km^2 array of 1146, underground water Cherenkov tanks 36 m^2 each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m^2).



- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m^2.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.

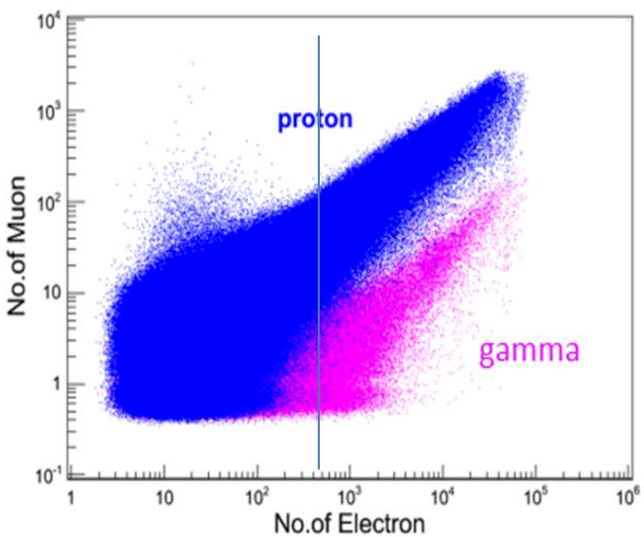
Sensitivity future detectors

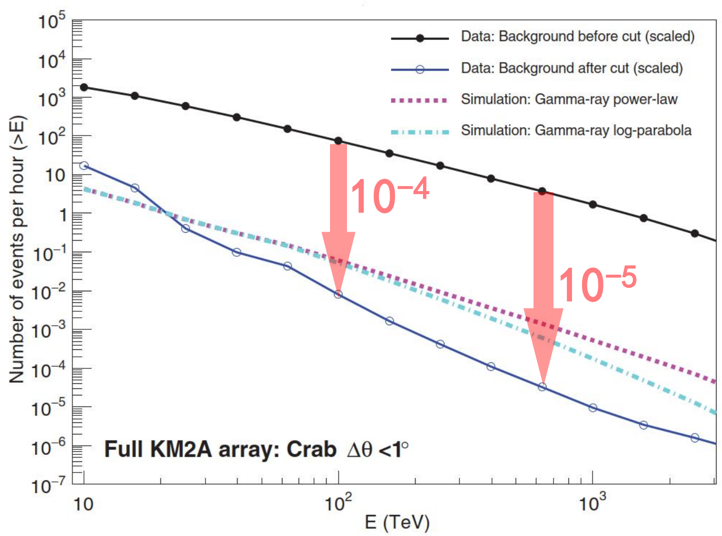


CR background Rejection in KM2A

- Counting number of measured muons in a shower
- Cutting on ratio N_μ/N_e<**1/230**
- BG-free (N_γ>10N_{CR}) Photon Counting

for showers with E>100 TeV from the Crab

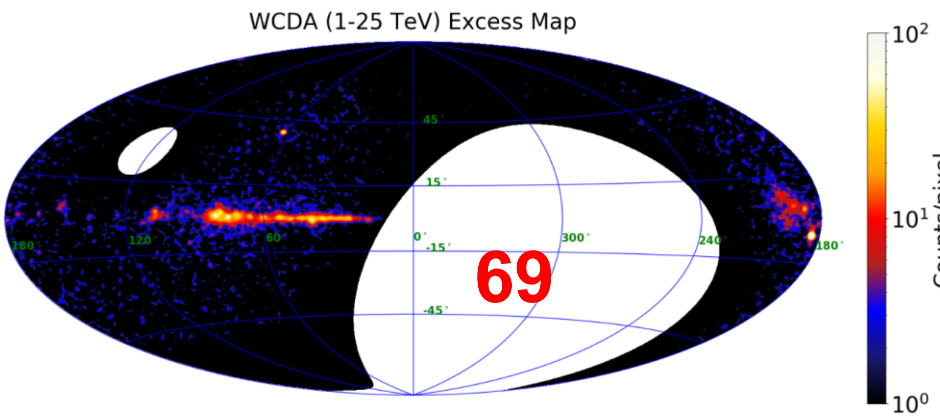


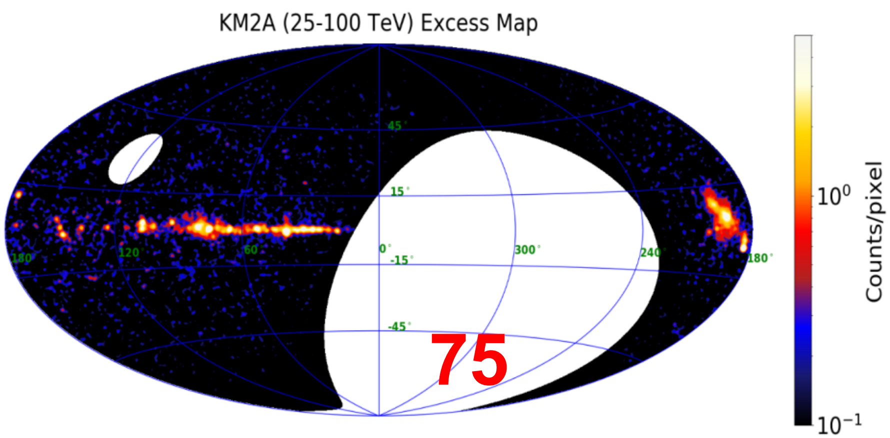


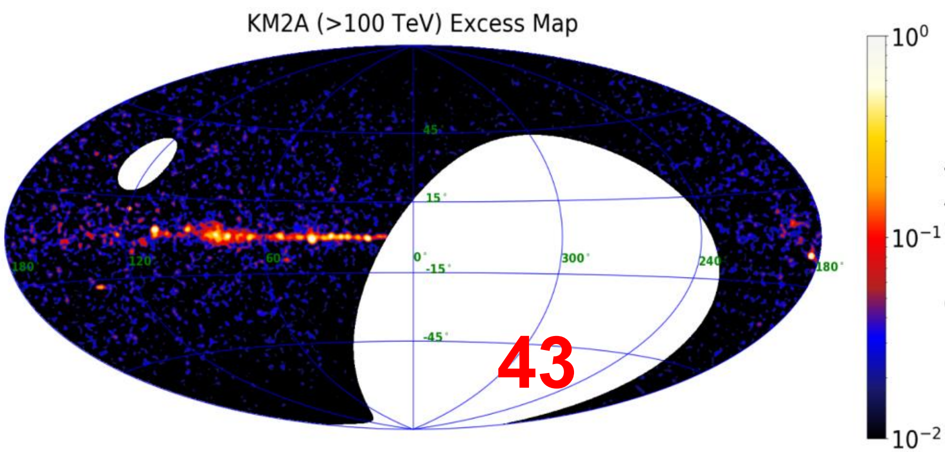
LHAASO Coll., ***Science***, 373, 425 (2021)

1 LHAASO catalog

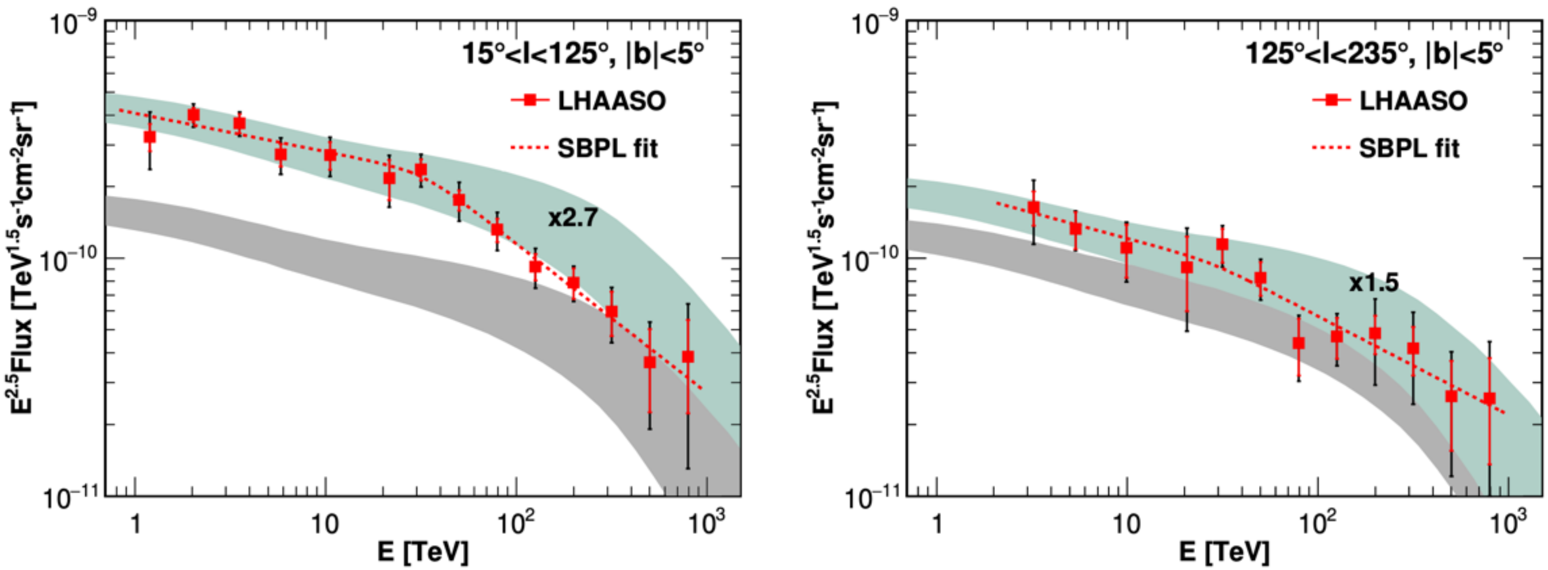
- **90 in 1st LHAASO sources.**
- **32 new discoveries**
- **43 UHE**







LHAASO diffuse



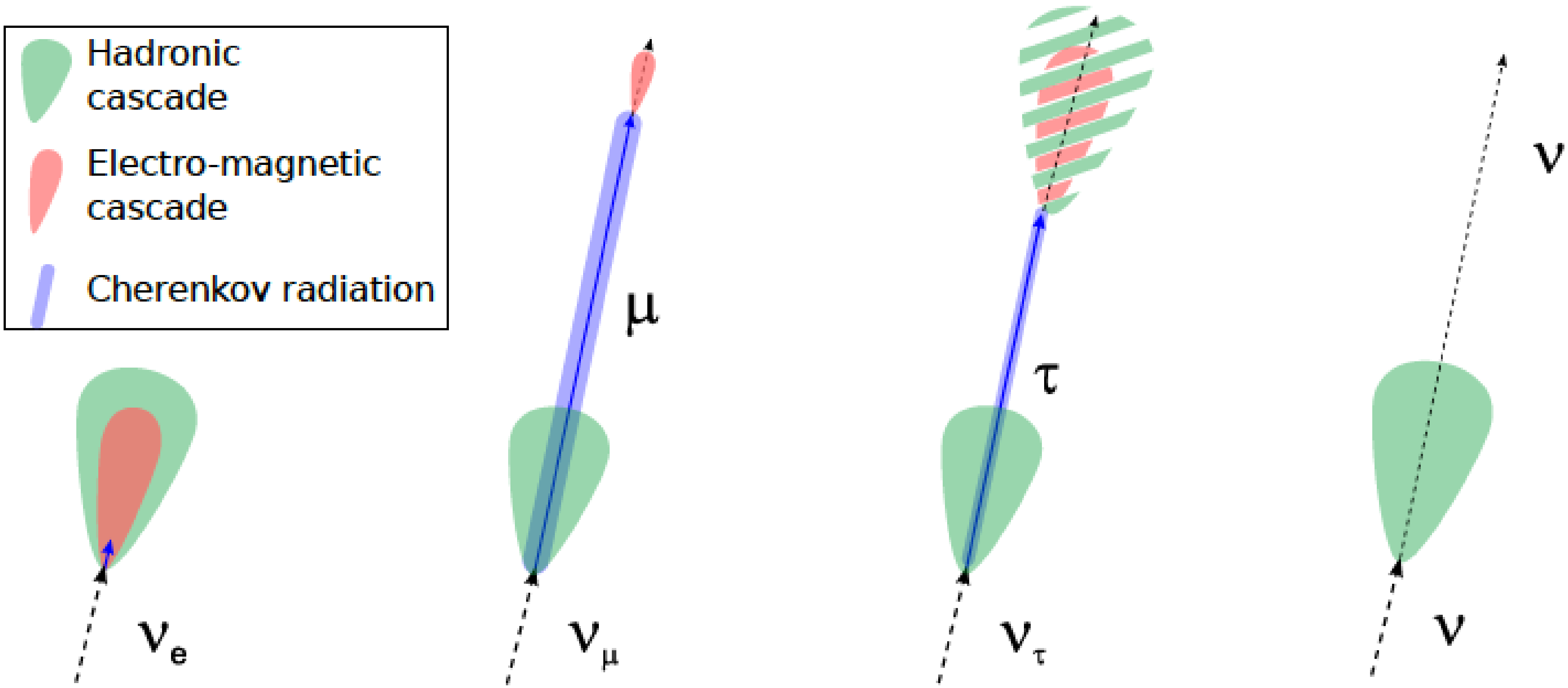
$$\Xi^{A,A'}(E,l,b) = \int_0^\infty \mathrm{d}s\, n_{\rm gas}^{A'}(\boldsymbol{x}) I_{\rm CR}^{A}(E,\boldsymbol{x})$$

$$I_\nu(E,l,b) = \sum_{A,A'} \int_E^\infty \mathrm{d}E'\, \Xi^{A,A'}(E',l,b) \frac{\mathrm{d}\sigma^{AA'\to\nu}(E',E)}{\mathrm{d}E}$$

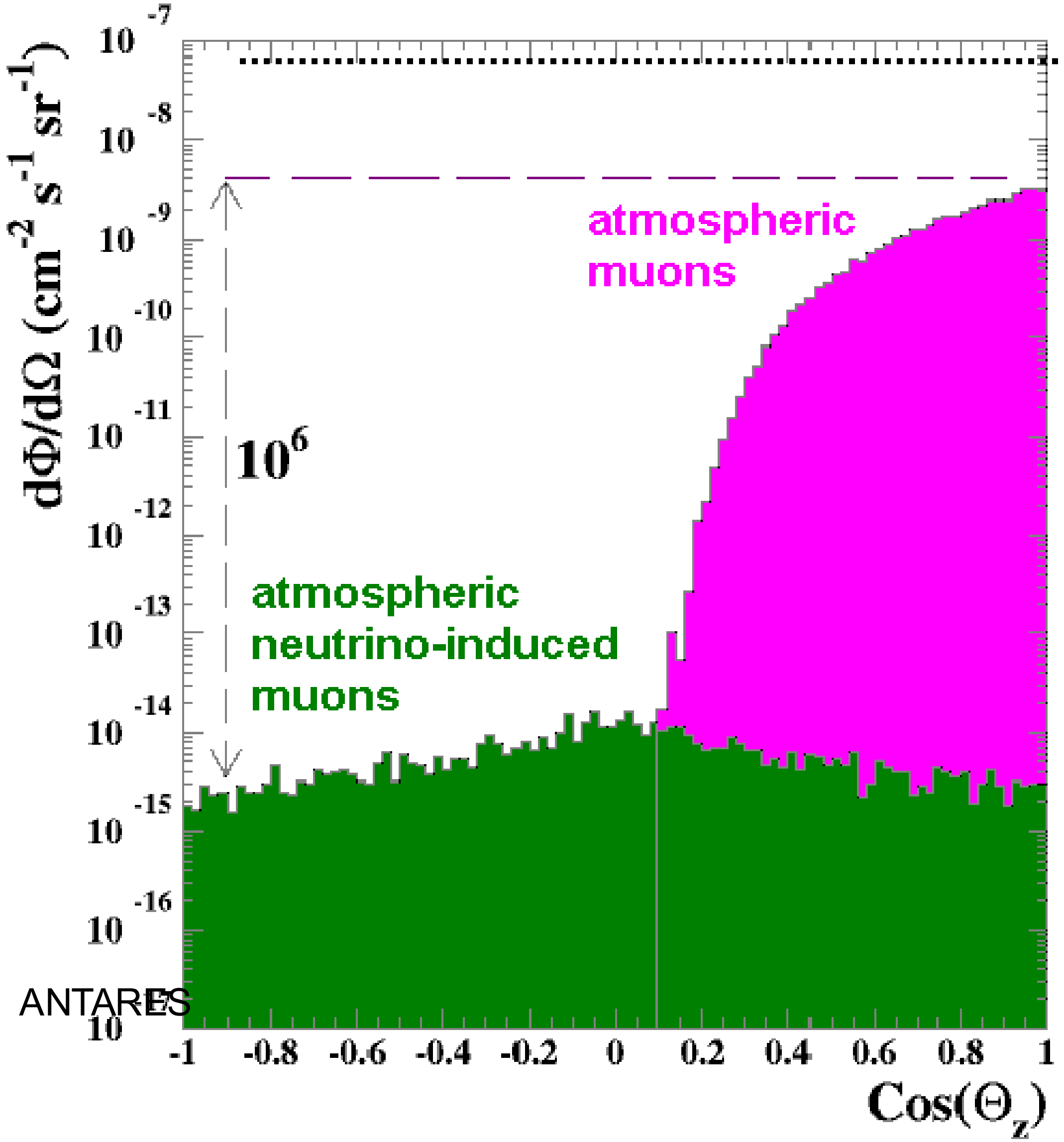
LHAASO collaboration, arXiv: 2305.05372, 2411.01621

Neutrino measurements and connection to cosmic rays

Detection of neutrino interactions



Backgrounds: atmospheric muons and neutrinos



Atmospheric neutrinos:

- upward tracks are good neutrino candidates;
- event direction and energy criteria can be used to discriminate background from astrophysical signals.

Atmospheric muons:

- downgoing events background is due to mis-reconstructed (fake) tracks;
- improve analysis filters for atmospheric muon background rejection.

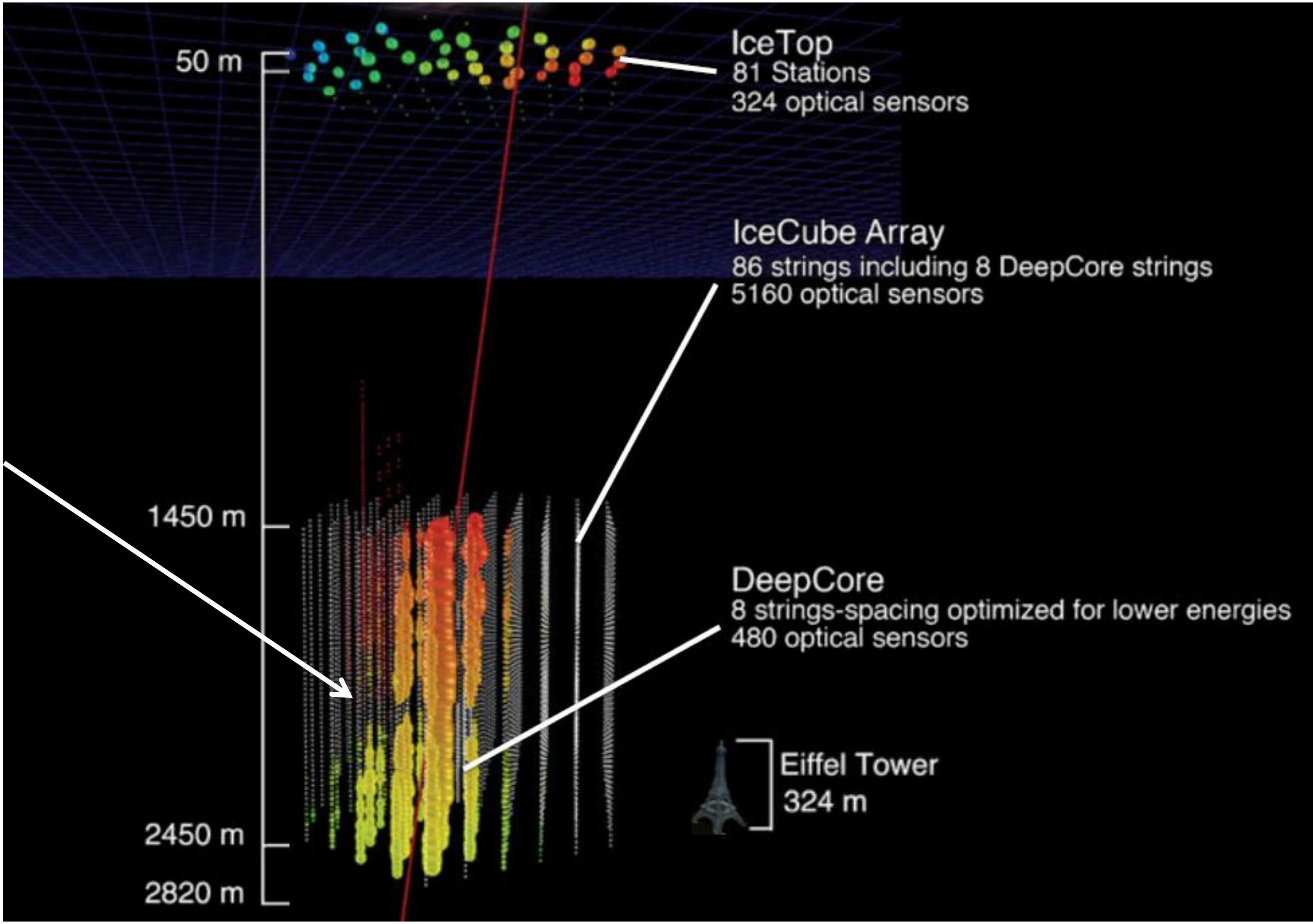
… you looked at 10msec of data !

muons detected per year:

• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	~ 10

* 3000 per second

** 1 every 6 minutes


50 m
1450 m
2450 m
2820 m
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

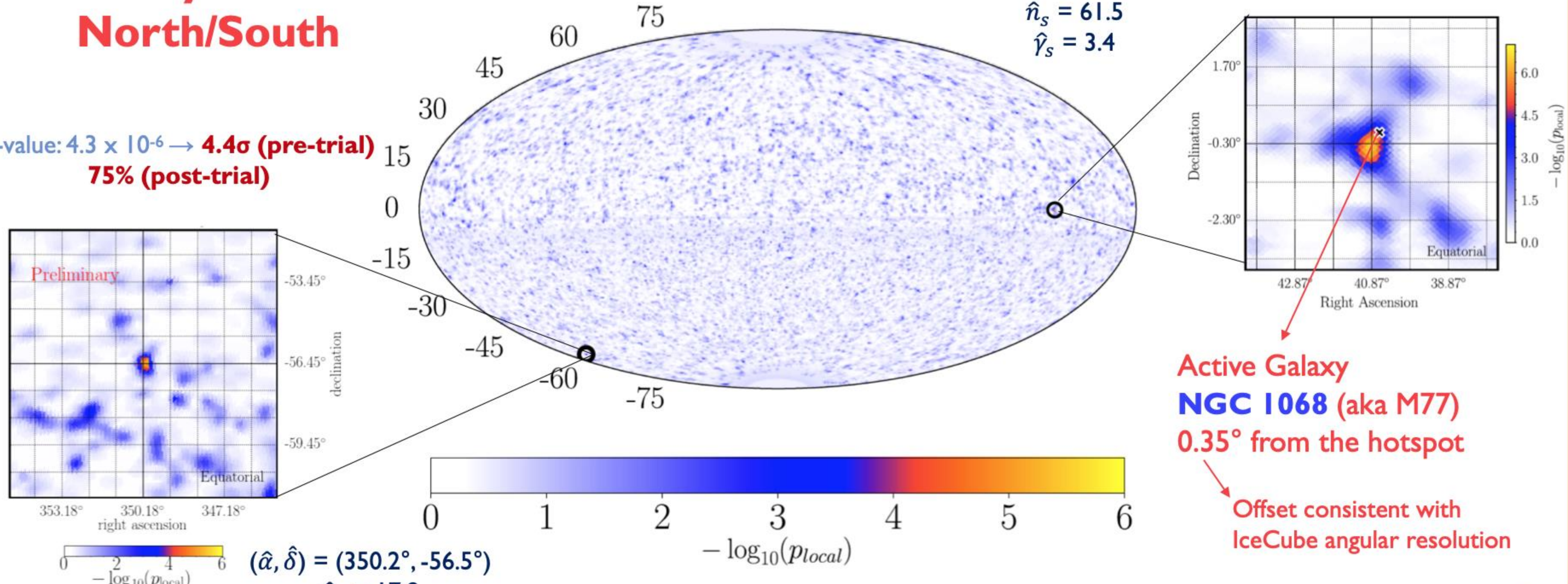
IceCube 10-year: point-source with tracks

All-sky search North/South

p-value: 4.3 x 10^{-6} → **4.4σ (pre-trial)**
75% (post-trial)

$(\hat{\alpha}, \hat{\delta})$ = (40.9°, -0.3°)
$\hat{n}_s$ = 61.5
$\hat{\gamma}_s$ = 3.4

p-value: 3.5 x 10^{-7} → **5.0σ (pre-trial)**
9.9 x 10^{-2} → **1.3σ (post-trial)**

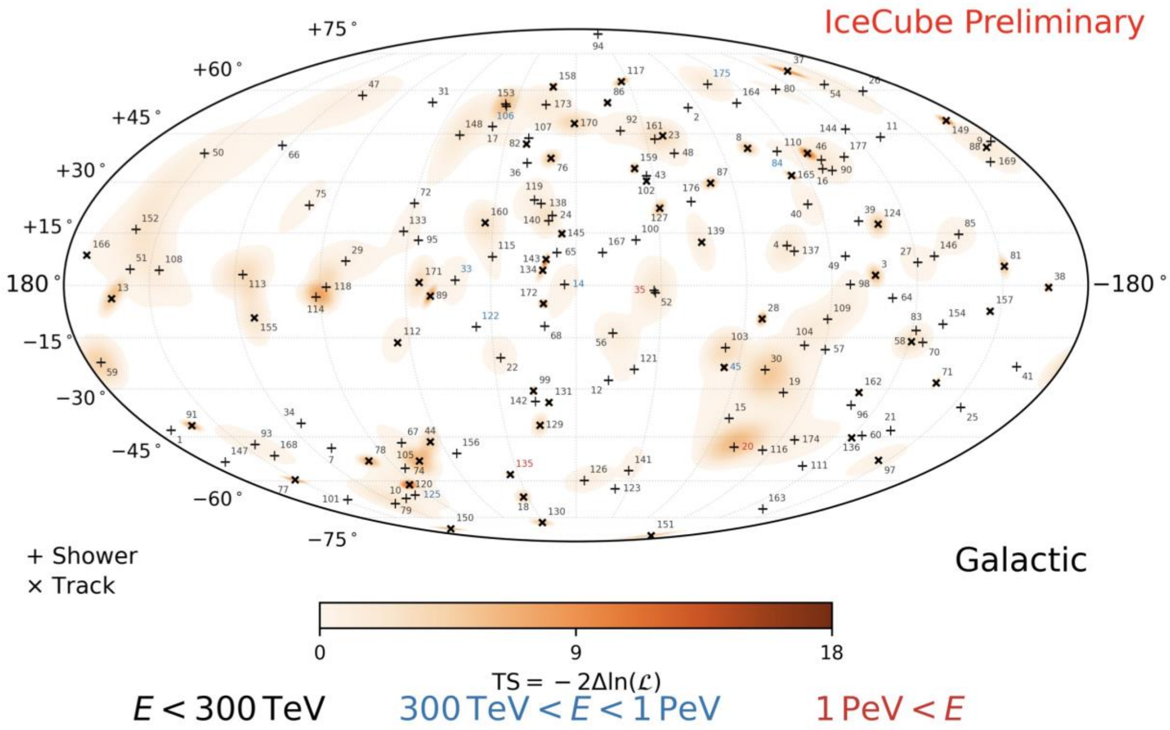


$(\hat{\alpha}, \hat{\delta})$ = (350.2°, -56.5°)
$\hat{n}_s$ = 17.8
$\hat{\gamma}_s$ = 3.3

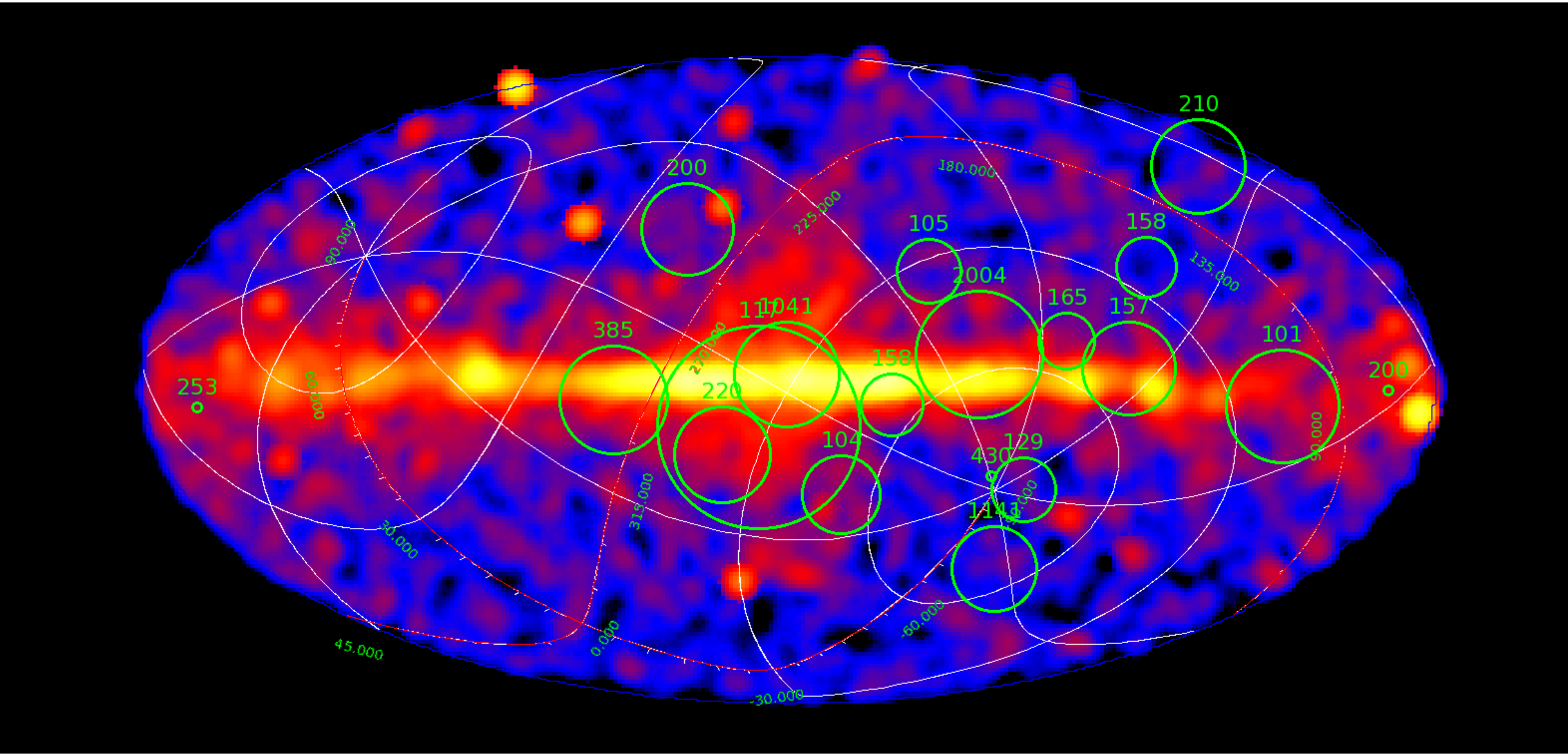
Active Galaxy
NGC 1068 (aka M77)
0.35° from the hotspot

Offset consistent with IceCube angular resolution

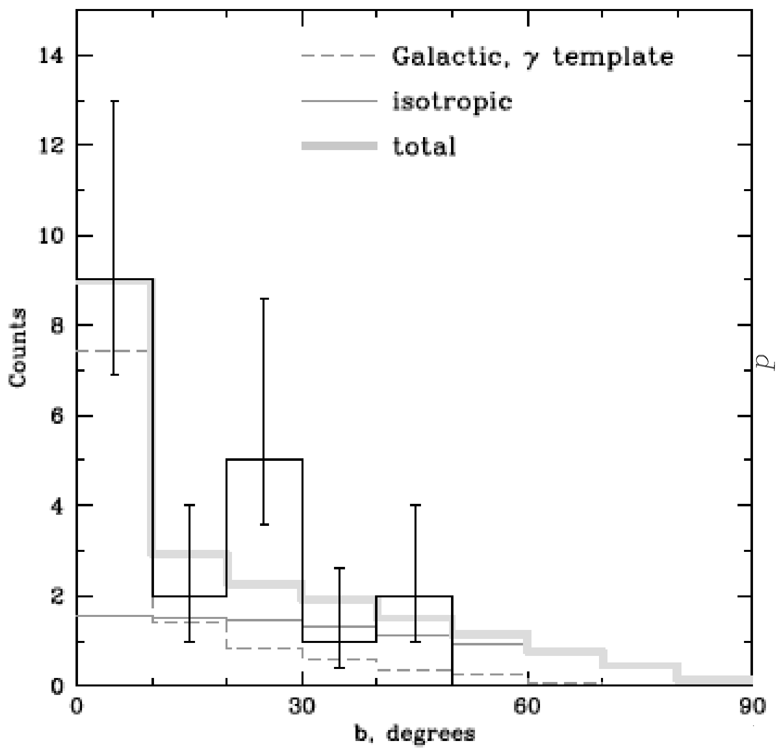
IceCube HESE data ICRC 2023

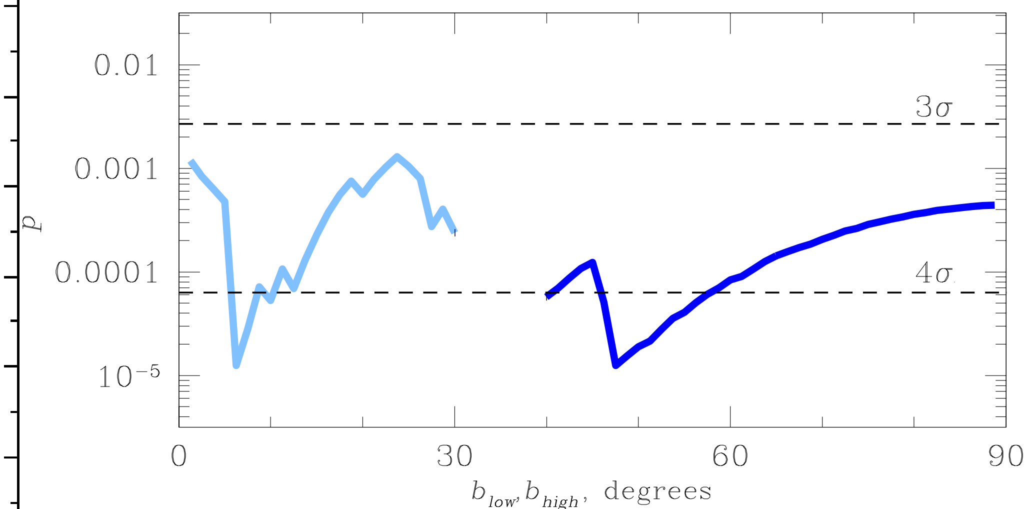


IceCube neutrino sky map 4 years E> 100 TeV and Fermi E>100 GeV 5 degree smoothed



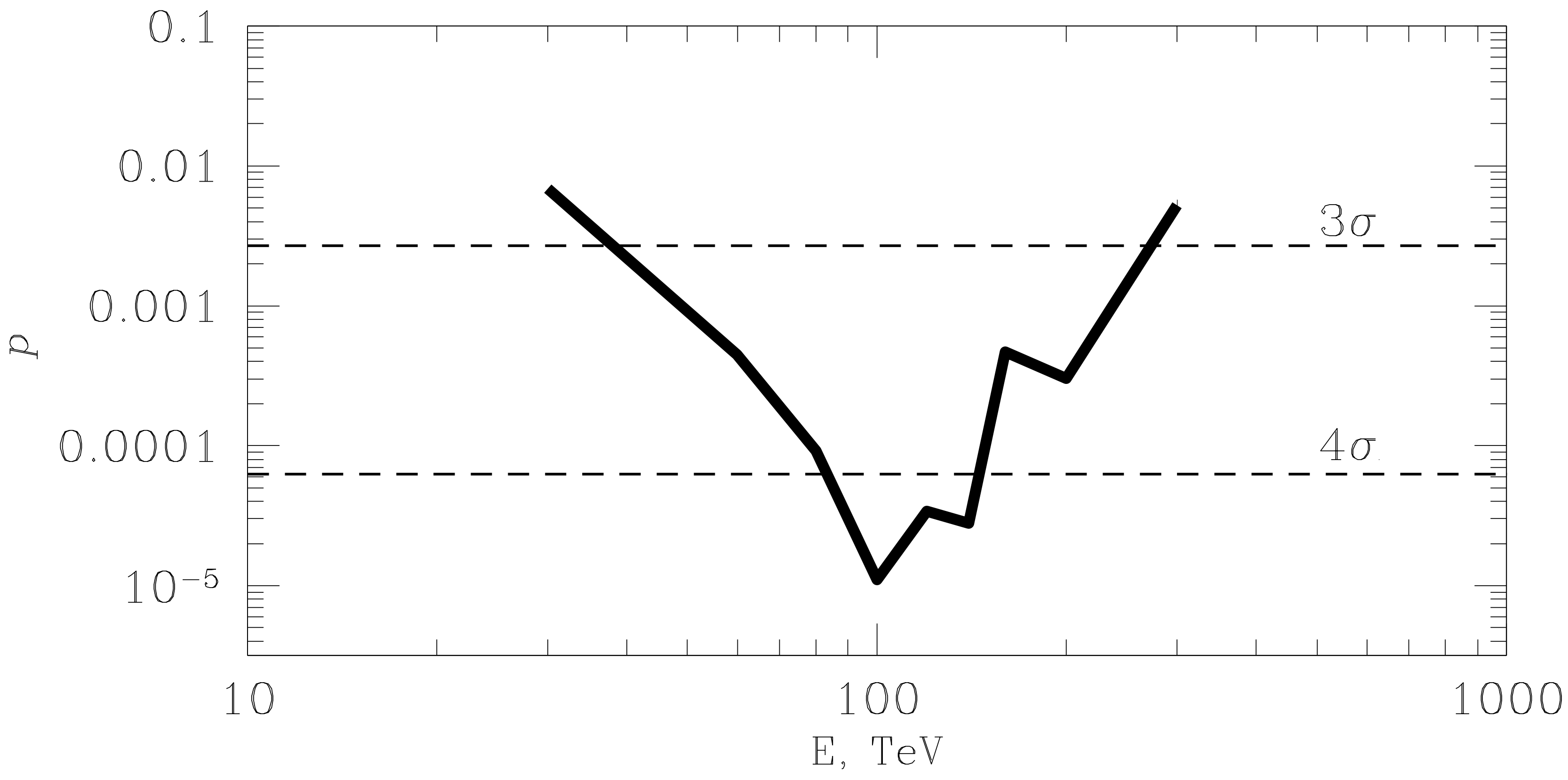
Evidence of Galactic component in 4 year IceCube data E>100 TeV





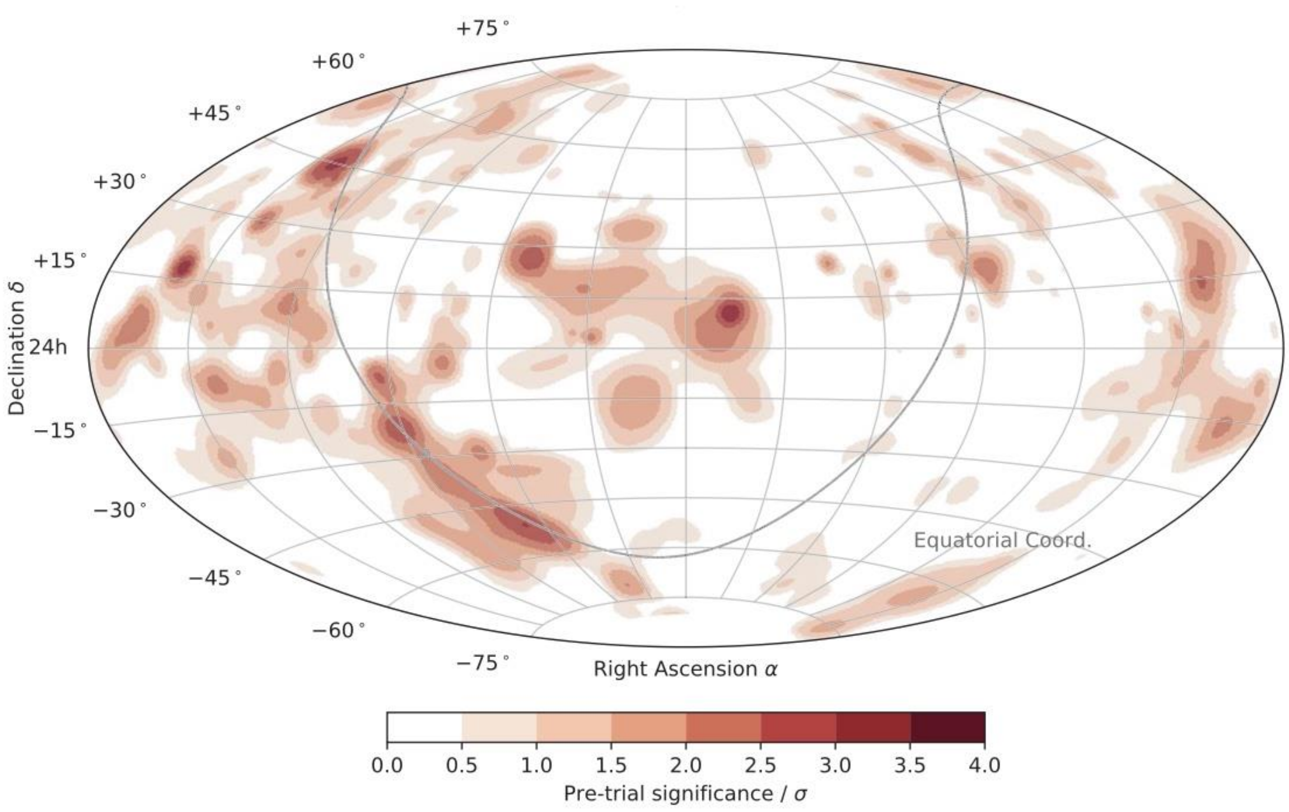
A. Neronov & D.S. arXiv: 1509.03522

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



A. Neronov & D.S. arXiv: 1509.03522

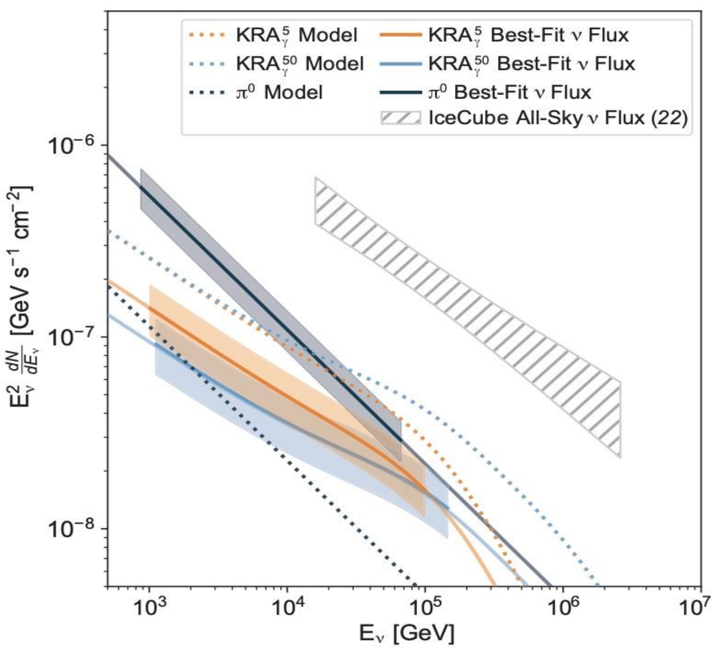
IceCube cascades



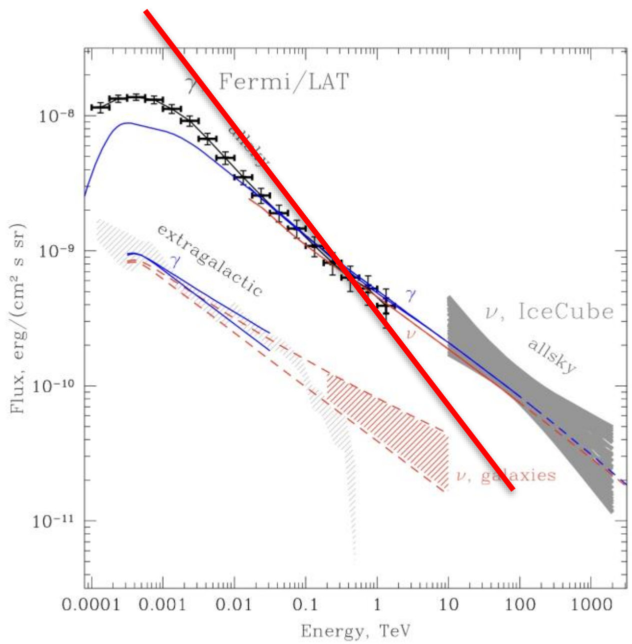
IceCube collaboration, Science **380**, 1338 (2023)

IceCube flux all sky

Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	0.16×MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}$×MF
KRA_γ^{50}	0.11×MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}$×MF

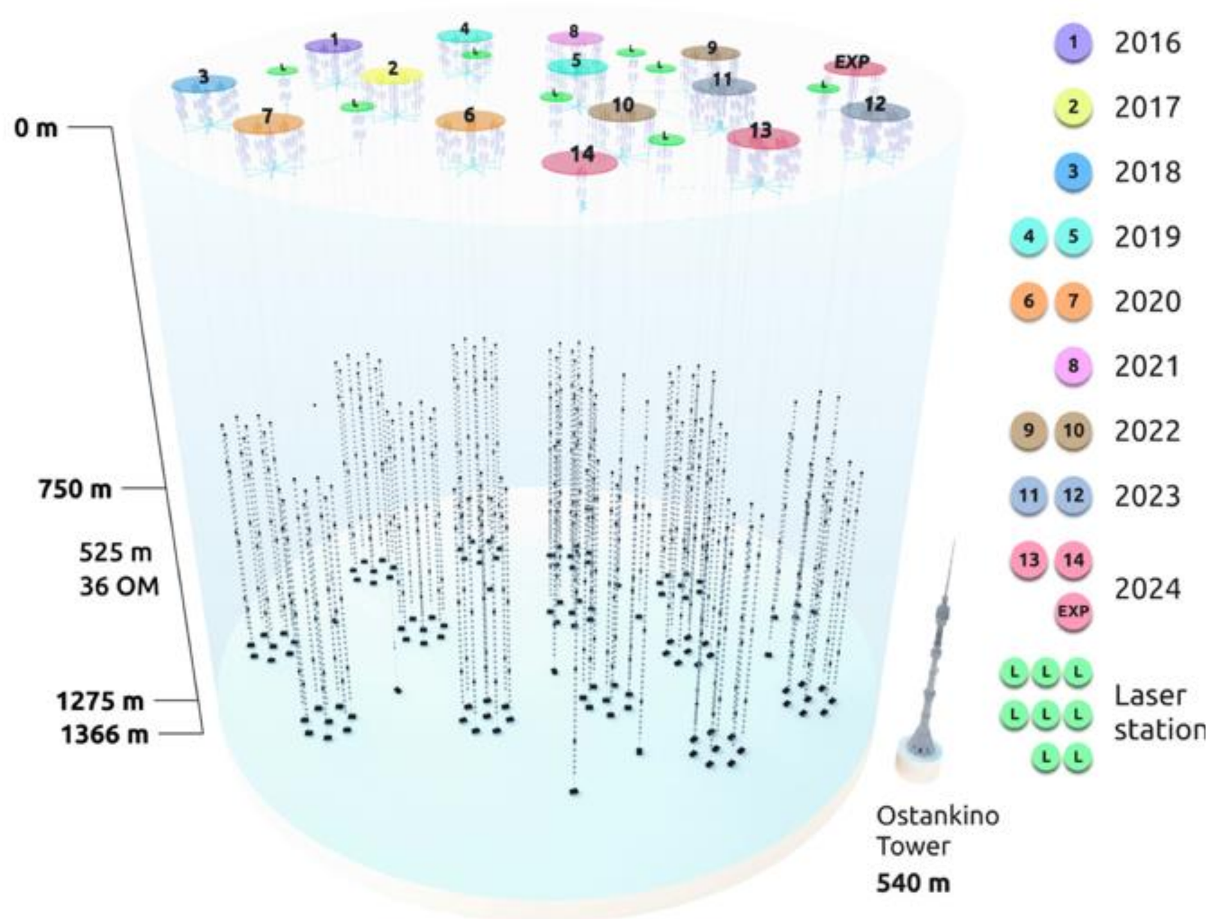


IceCube collaboration, Science **380**, 1338 (2023)

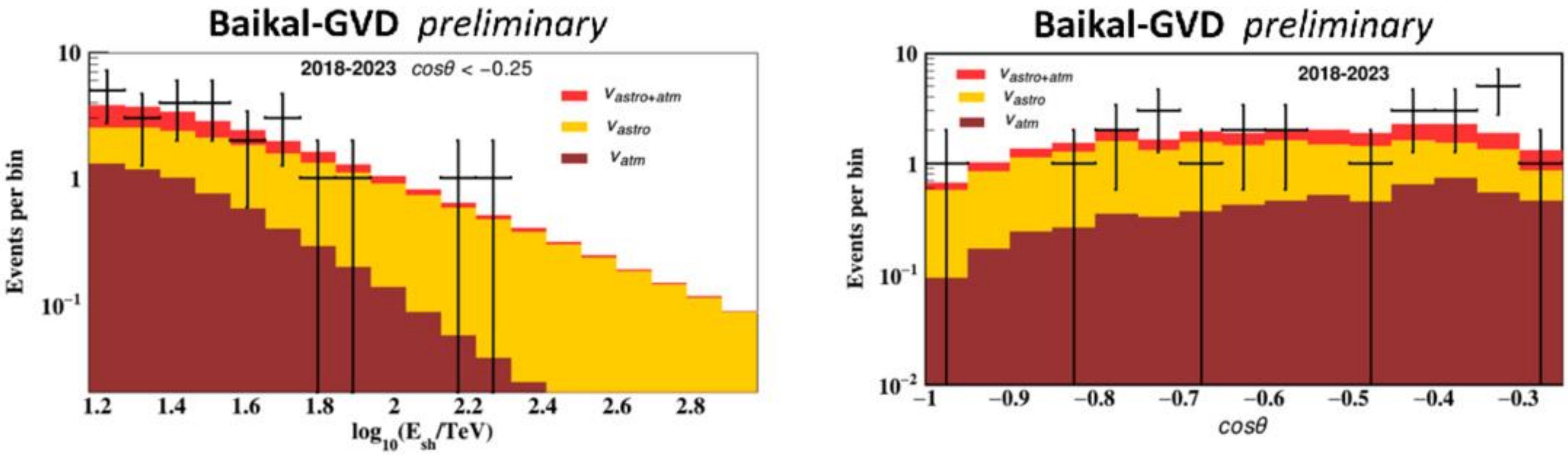


A.Neronov and D.S. 1412.1690

Status BAIKAL



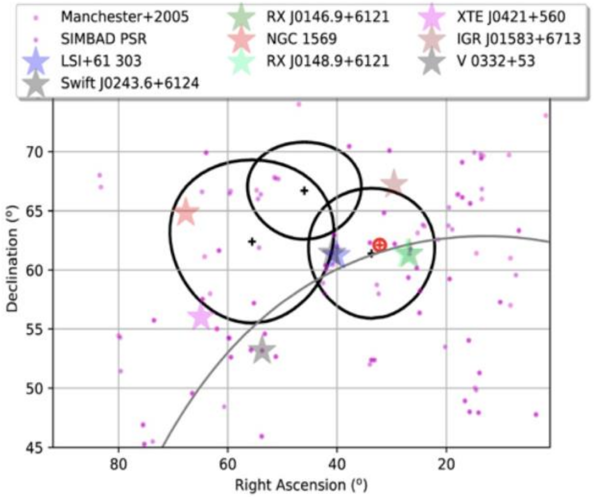
Confirmation of astrophysical neutrino flux



Baikal collaboration, RICAP-2024 conference

5.5 sigma confirmation of diffused flux

Event triplet near Galactic plane



Three events (GVD190216CA, GVD190604CA and GVD210716CA) close to the Galactic plane (grey line) and their corresponding 90% errors (black).

The red plus and circle – IC hotspot and 0.5° uncertainty at 90% level (Aartsen & et al. ApJ, 835,151 (2017))

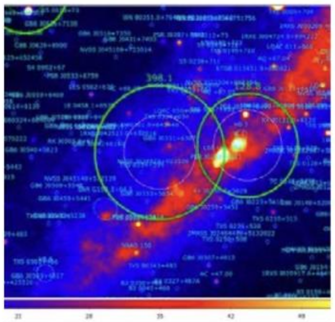
Stars - Several close high-mass X-ray binaries.

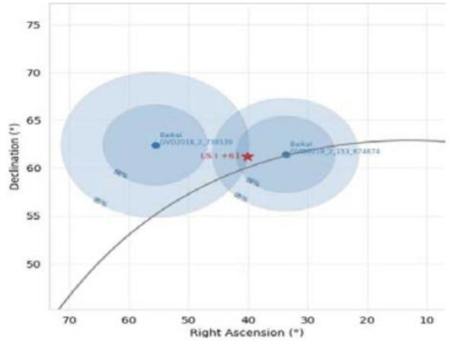
Dots - Galactic pulsars (Manchester et al. 2005, SIMBAD Astronomical Database)

★ LSI +61° 303 γ-ray active binary system

★ Swift J0243.6+6124 s the only discovered pulsating ultraluminous X-ray source (PULX) in the Galaxy.

LSI +61 303 and the two Baikal-GVD events





LSI +61 303 – γ-ray microquasar 3.1° from GVD190604CA and 7.4° from GVD190216CA (both are down-going events). Using the PSFs of all 16 HE-events, the chance probability to observe such a doublet near LSI +61 303 was estimated as 0.0187 (2.35σ) [not corrected for the "look elsewhere effect"]

Cascades E>200 TeV Baikal and IceCube

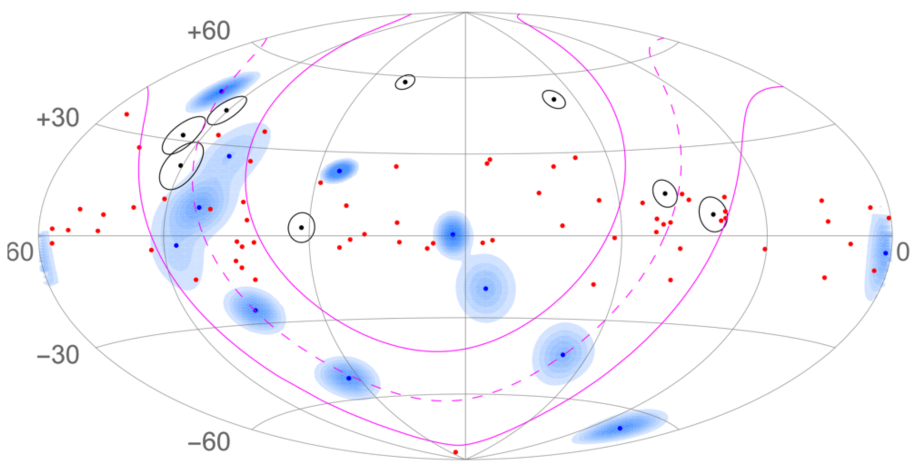


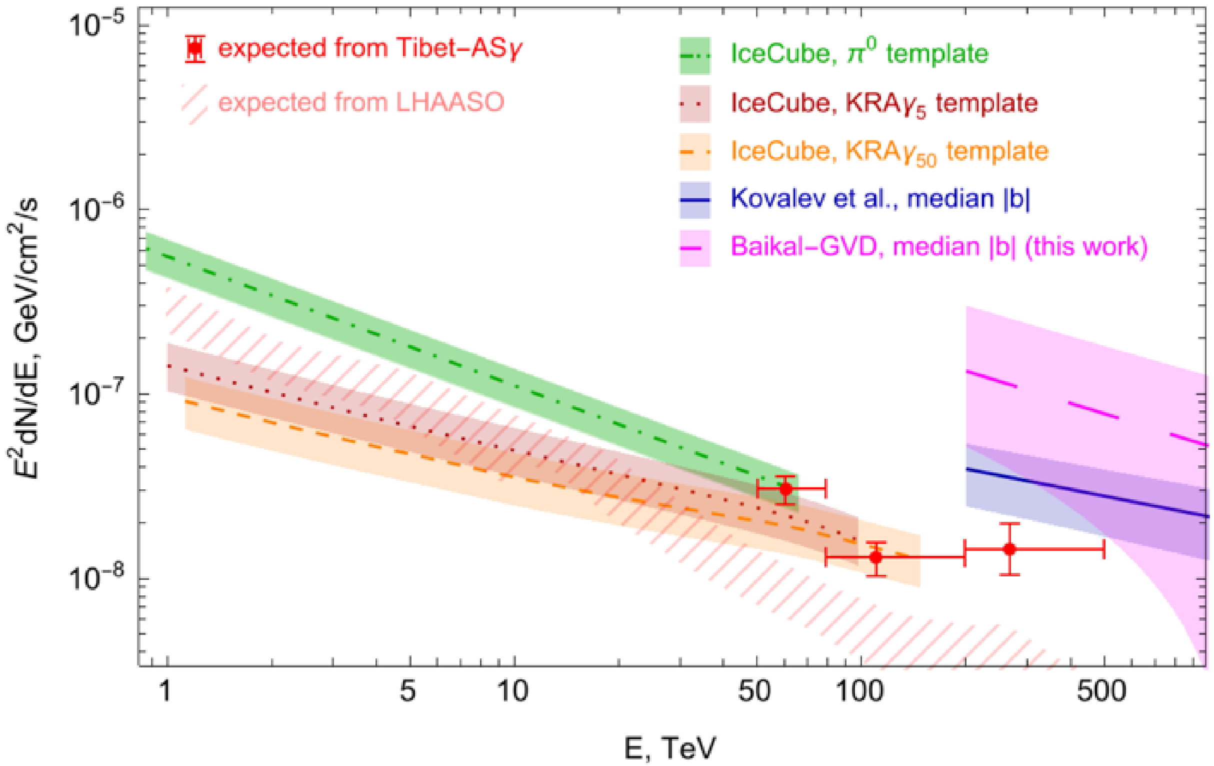
Table 2
Results (This Work) of the Search for the Galactic Component of the Neutrino Flux above 200 TeV (see the Text for Details)

Sample	$\|b\|_{med}$ Observed (deg)	$\langle\|b\|_{med}\rangle$ Expected (deg)	p
Baikal-GVD cascades	10.4	31.4	1.4×10^{-2} (2.5σ)
IceCube cascades	12.4	31.9	8.7×10^{-3} (2.6σ)
Combined	12.4	31.5	1.7×10^{-3} (3.1σ)
IceCube tracks	24.7	36.0	1.8×10^{-3} (3.1σ)
All combined	23.4	35.0	3.4×10^{-4} (3.6σ)

Baikal collaboration,

2411.05608

Diffuse gamma-ray and neutrino flux



Baikal collaboration, 2411.05608

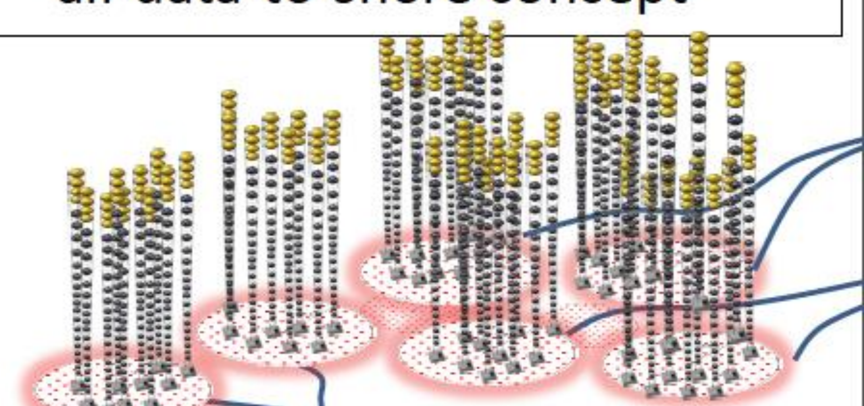
KM3NeT in the Mediterranean

Environmental parameters

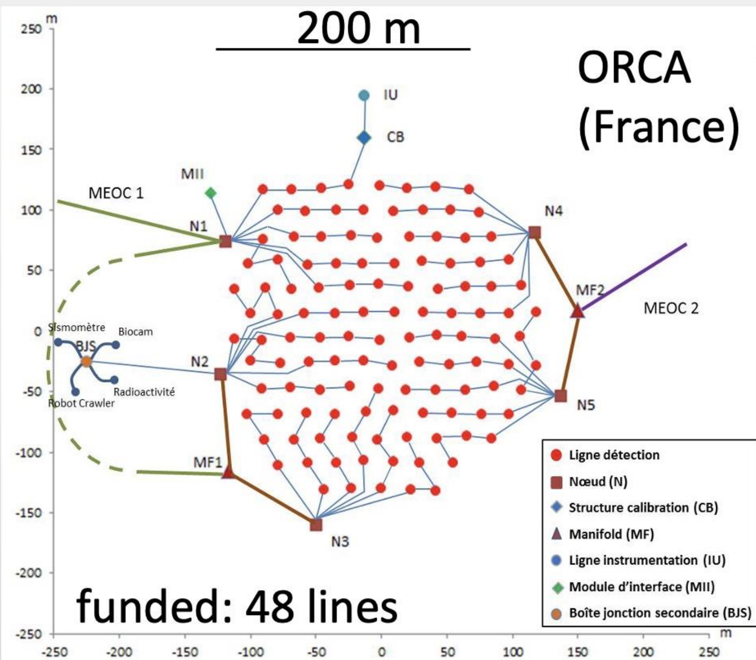
Mediterranean Sea – salt water
3 installation sites
distance to shore ~40-100 km
L_{abs} ~60-100 m
L_{scat} ~50-70m
depths ~2500-4500 m

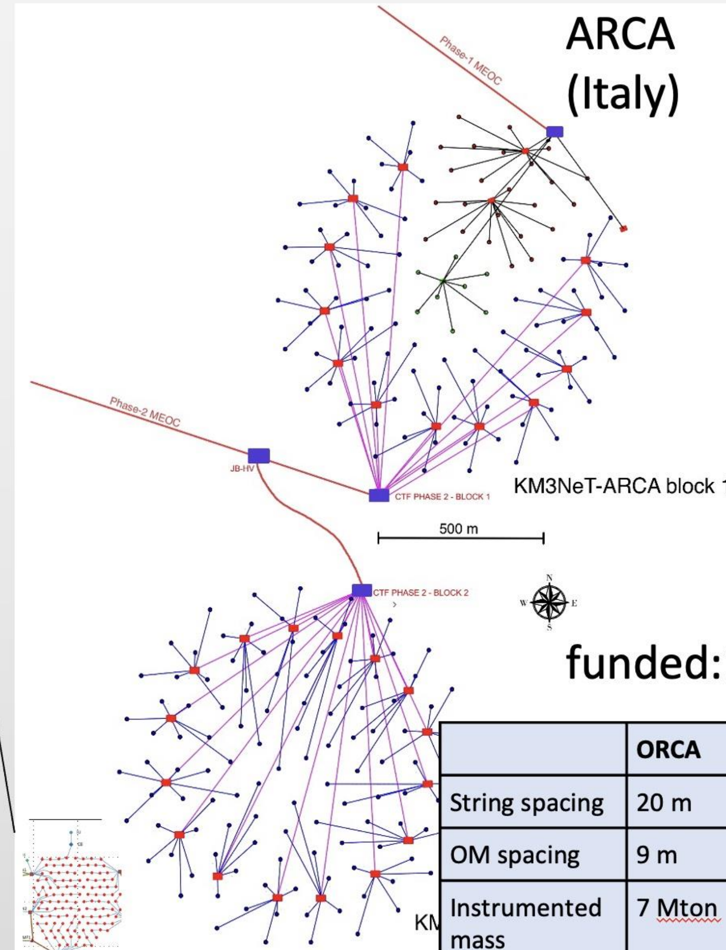
Telescope design

~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



Building blocks



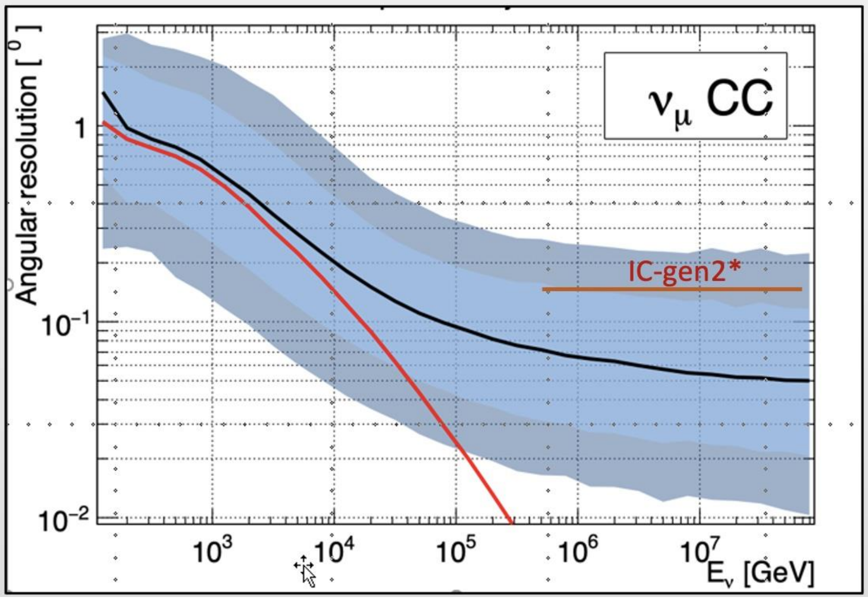


funded:130 lines

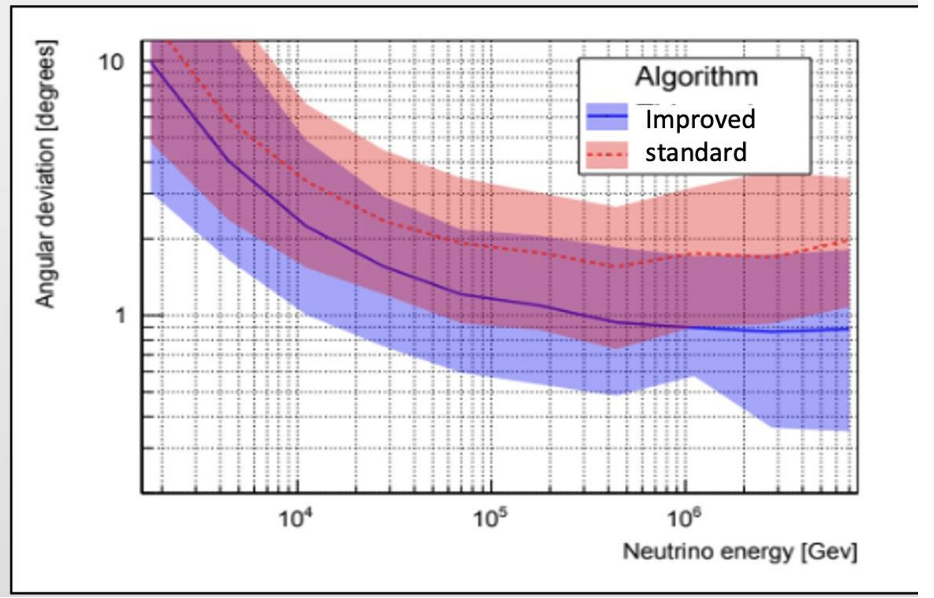
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Instrumented mass	7 Mton	500*2 Mton

KM3NeT Resolutions

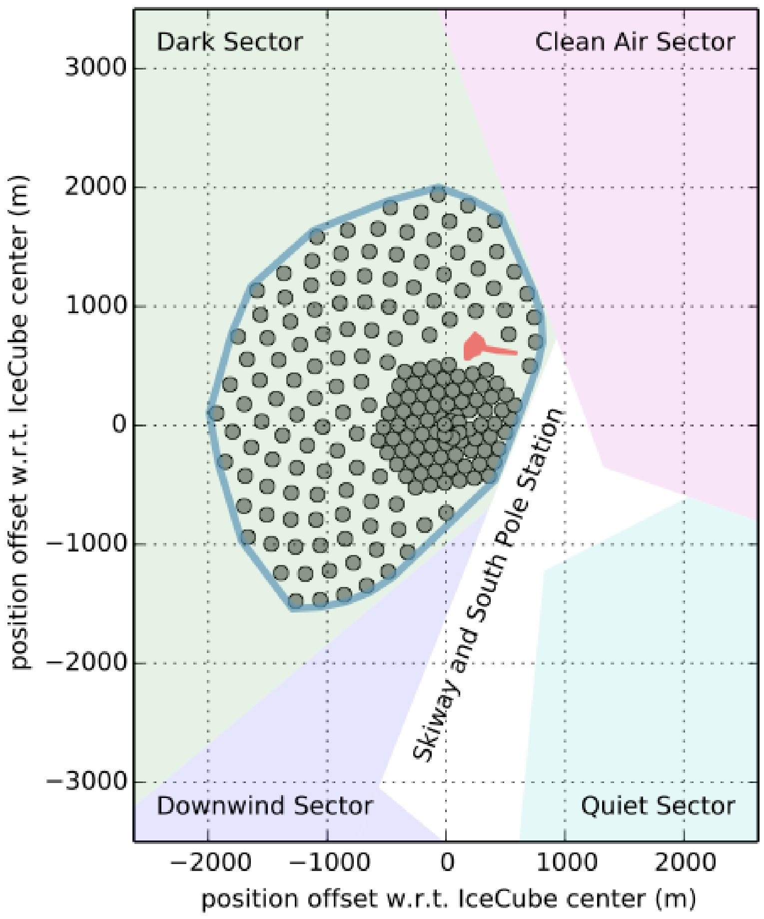
Tracks



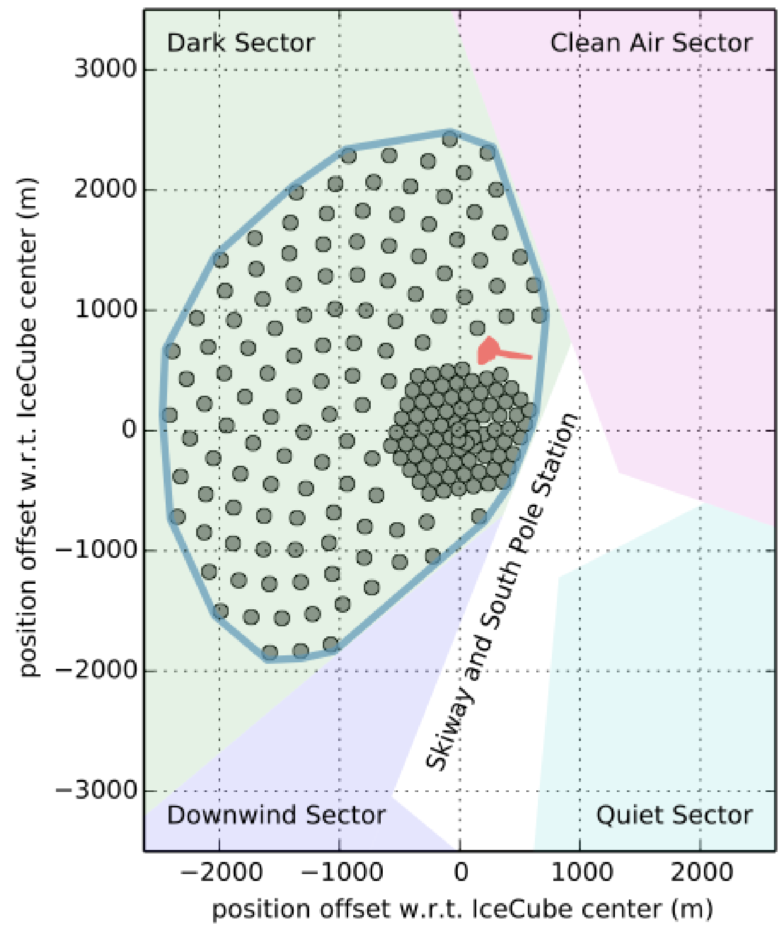
Cascades



86 strings with 240-340 m spacing

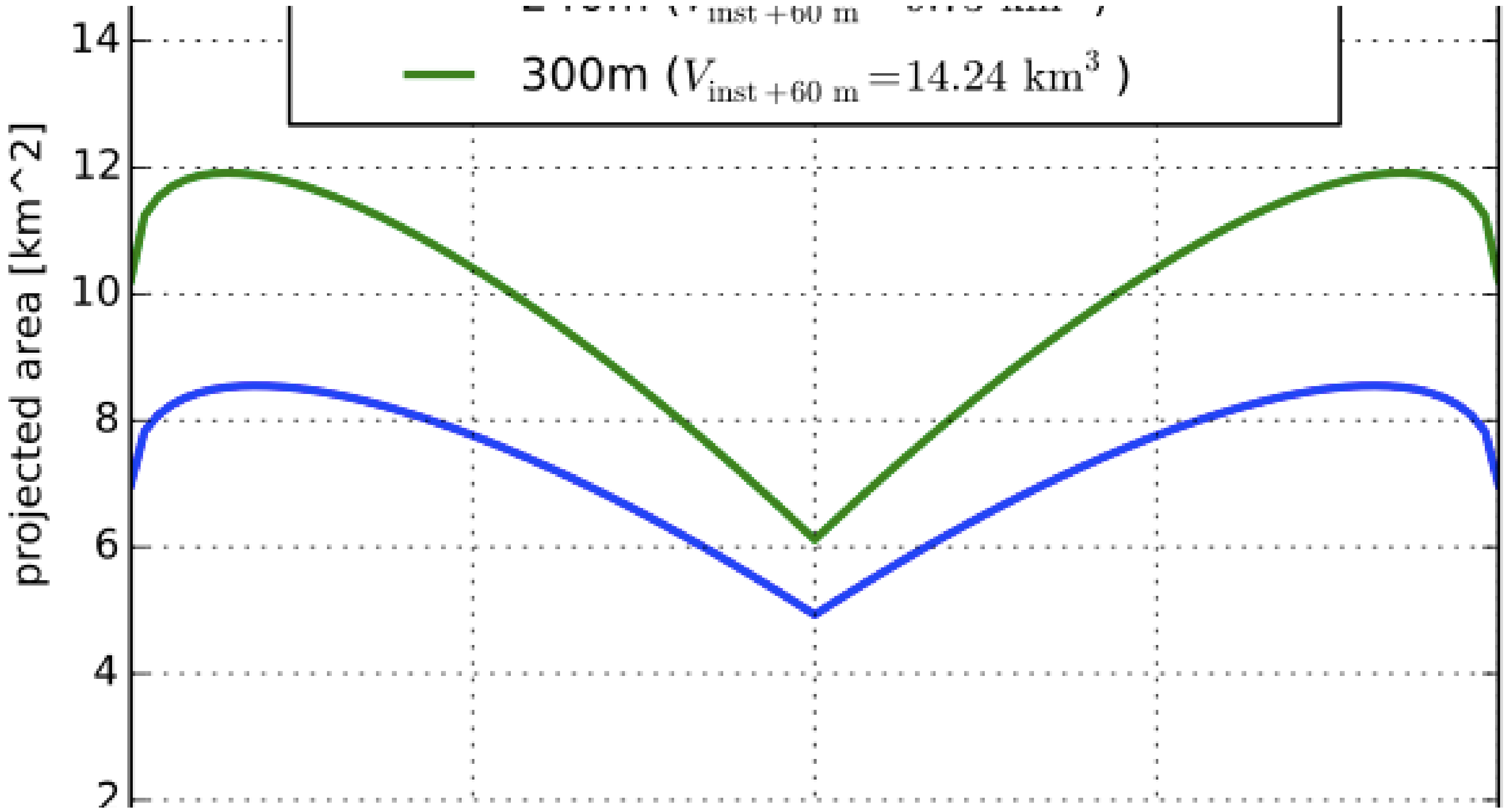


(a) 240 m string spacing (“benchmark”)



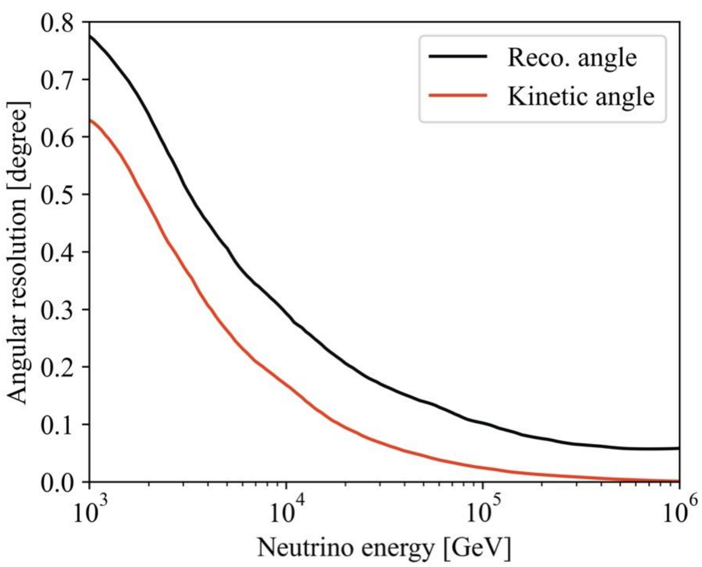
(b) 300 m string spacing

Effective volume



IceCube Collaboration, **arXiv:1412.5106**

TRIDENT project 30 km3



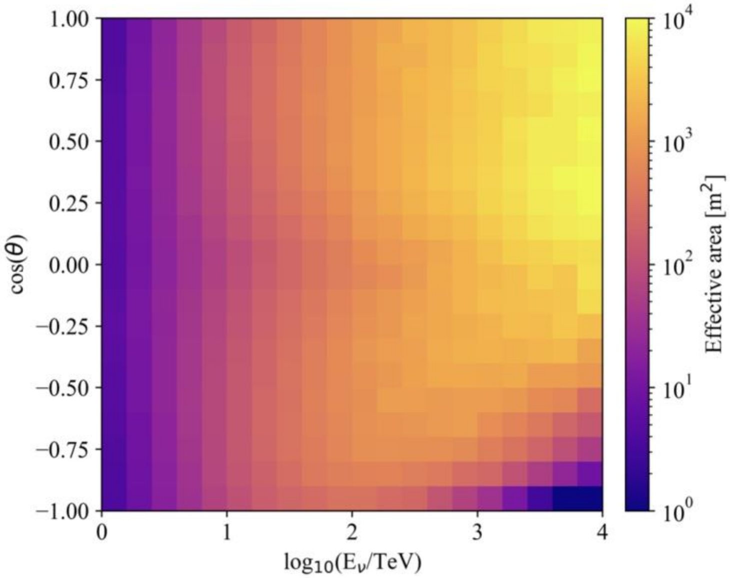
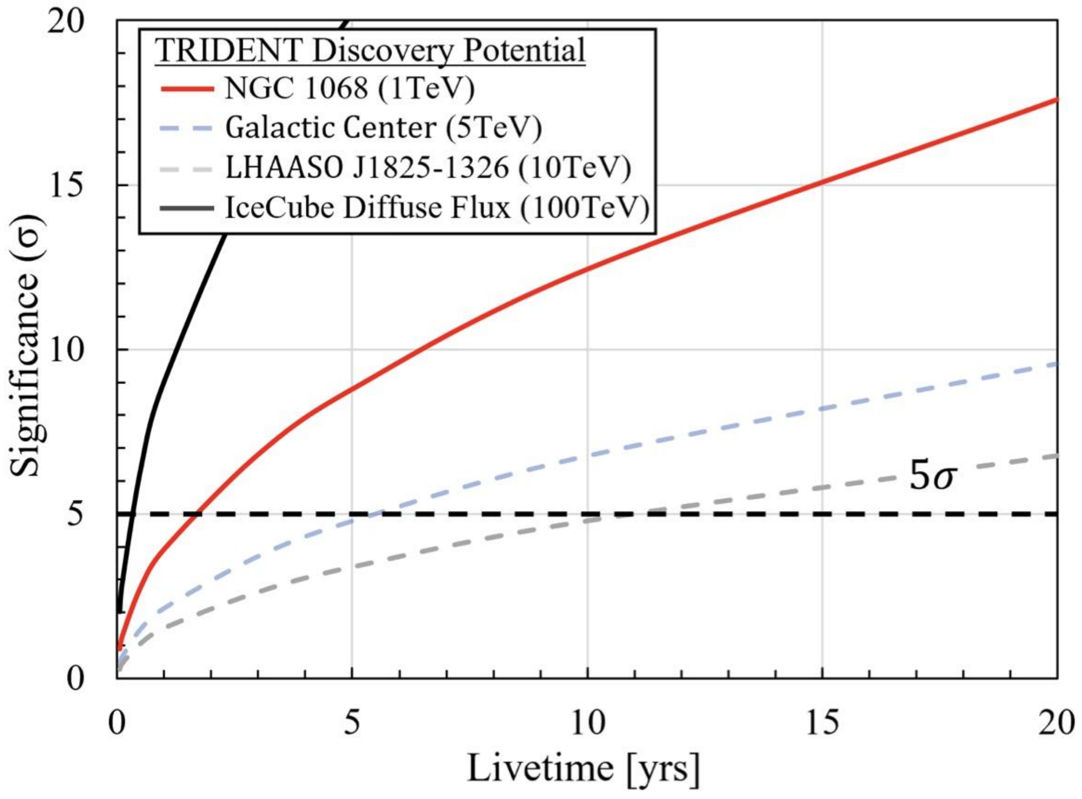


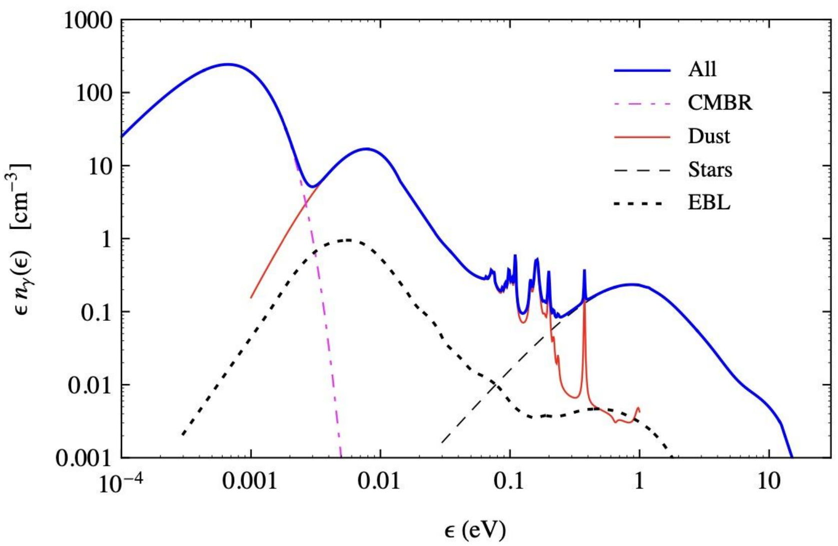
Figure 15: Effective areas at event reconstruction level for ν_μ track events as a function of primary neutrino energy and zenith angle in TRIDENT. At an energy of $\sim$ 100 TeV, the effective area for up-going events is expected to reach 7×10^2 m^2. Only events with anglular error less than 6 degree are selected to evaluate the effective area.

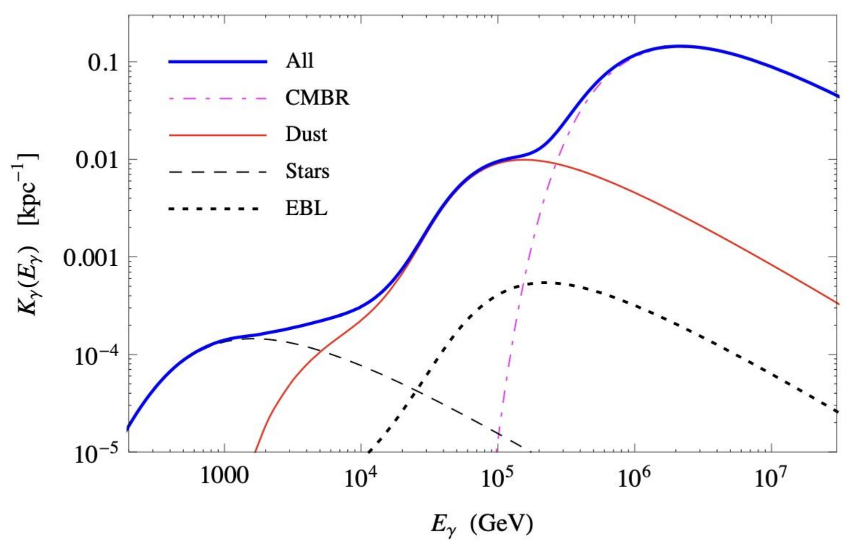
TRIDENT project 30 km3



Lipari-Vernetto model

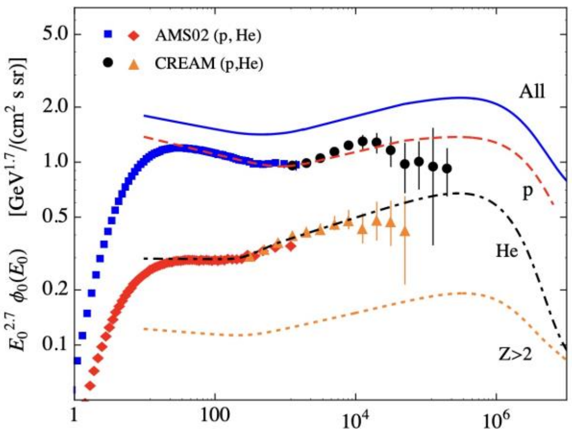
Gamma-ray absorption in Galaxy

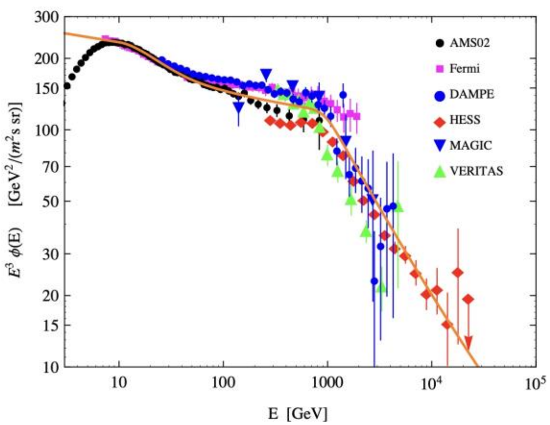


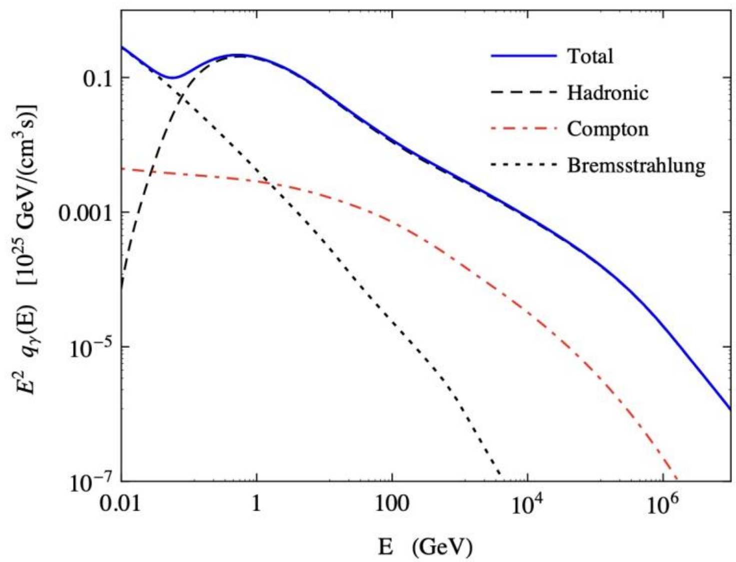


Lipari & Vernetto (2018)

Cosmic ray interaction

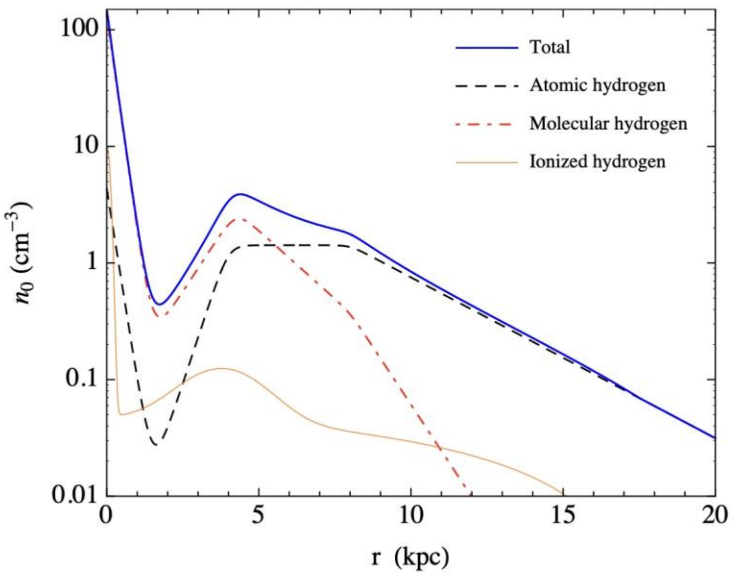


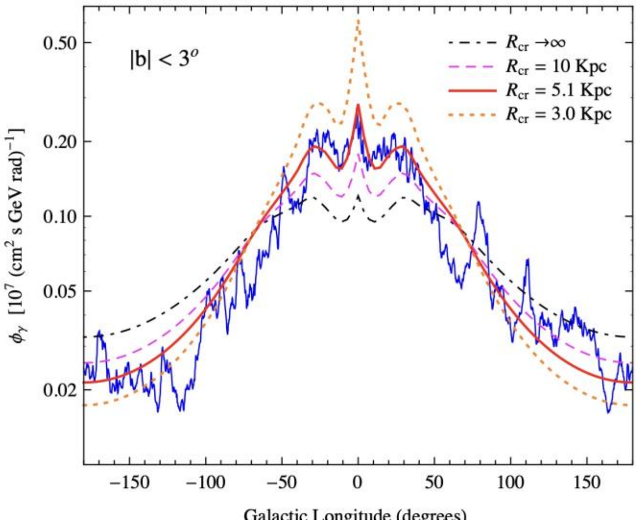




Lipari & Vernetto (2018)

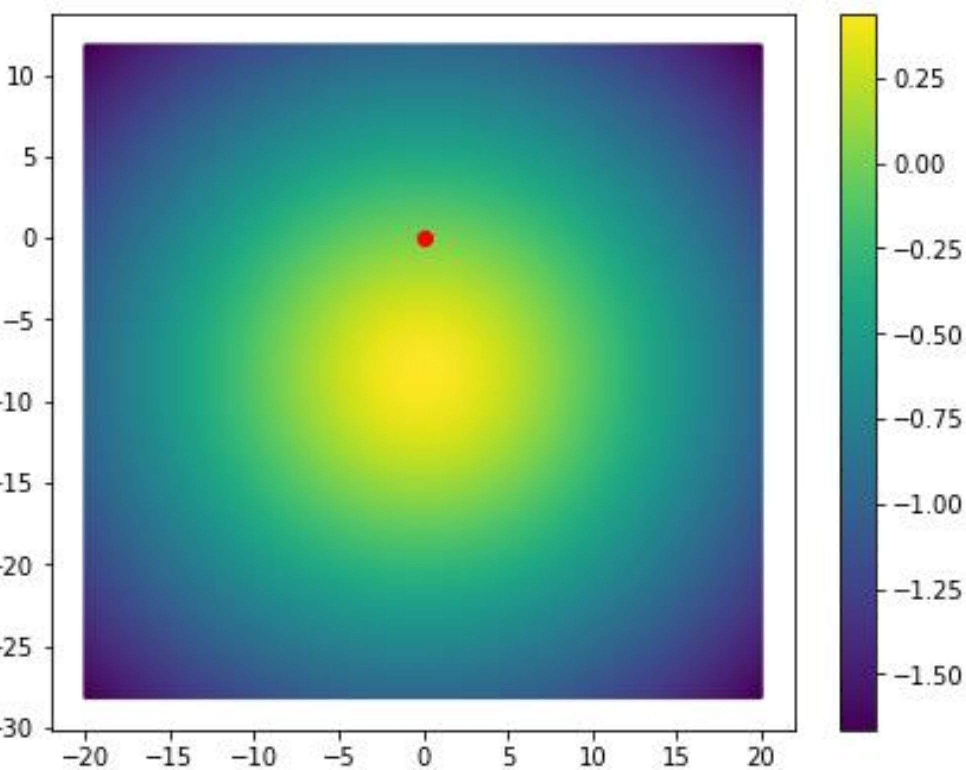
Gas density and fit of 10 GeV data

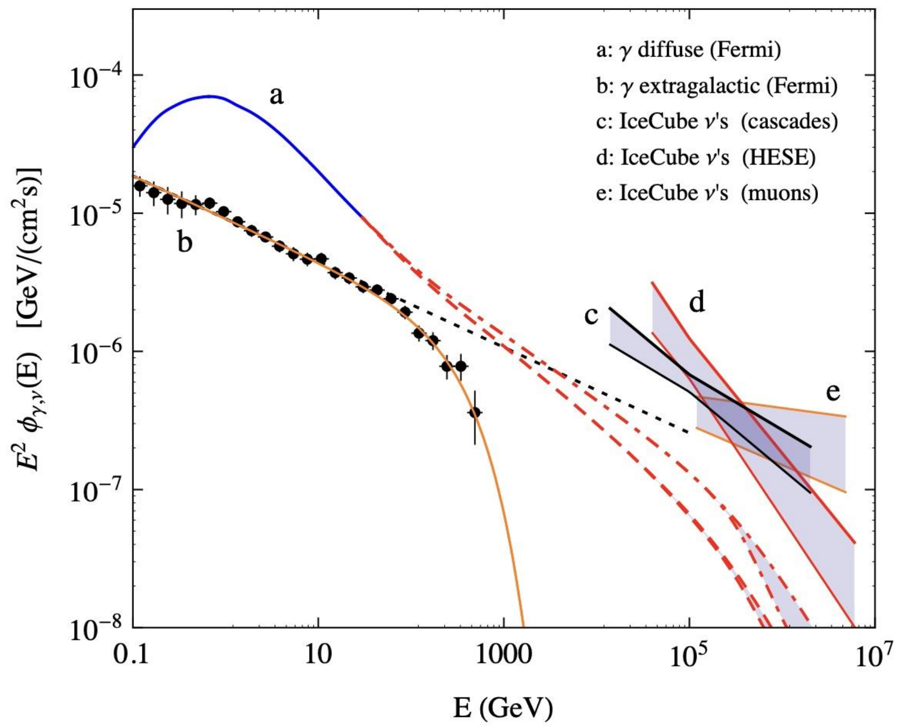




Lipari & Vernetto (2018)

Gamma-ray spectrum predictions

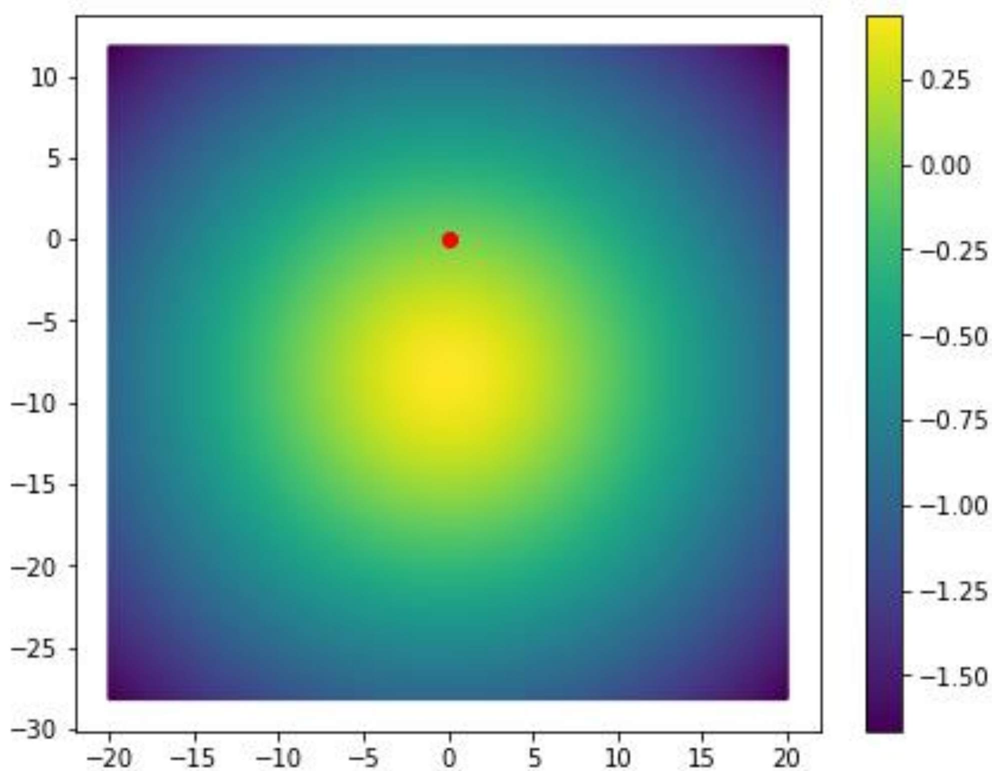


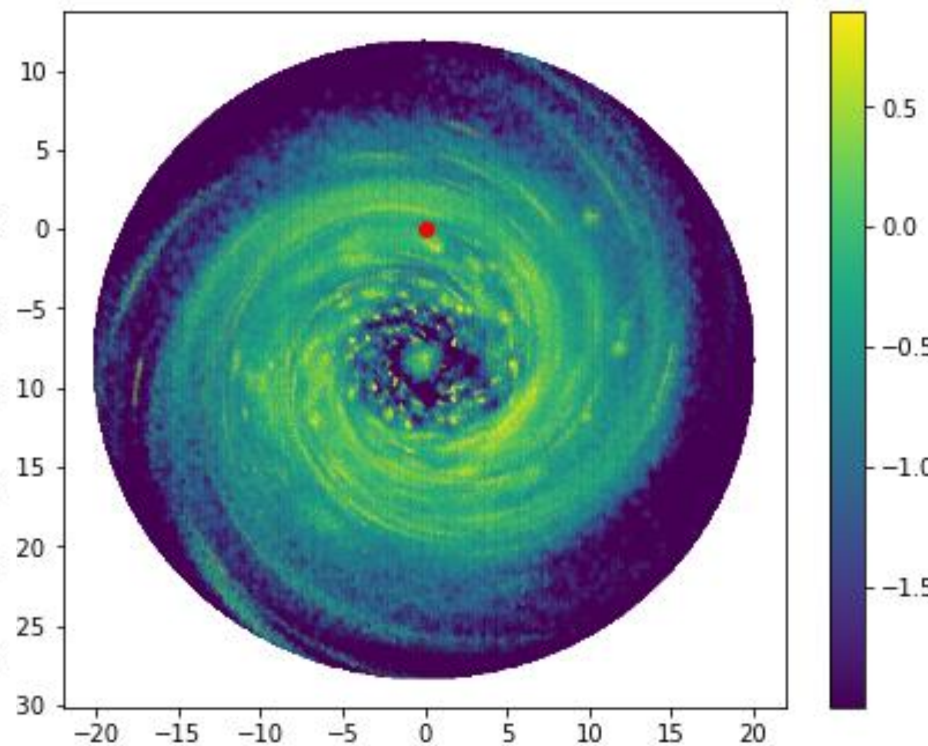


Lipari & Vernetto (2018)

New multi-messenger model of Milky Way at PeV

1 PeV CR density in the Gal. plane

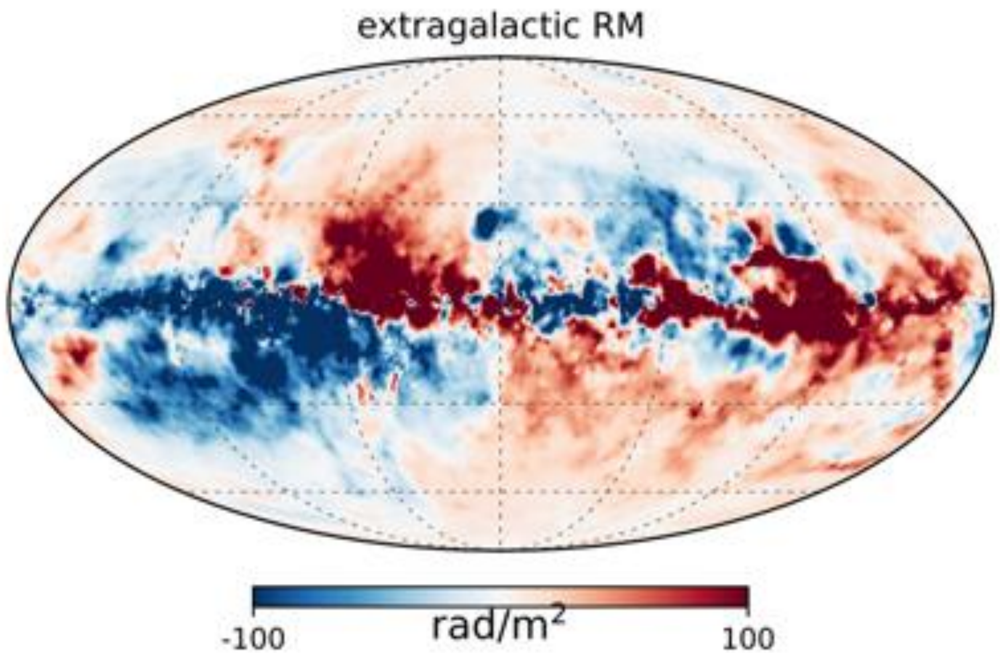




P.Lipari & S.Vernetto (2018)

G.Giacinti & D.S., 2305.10251

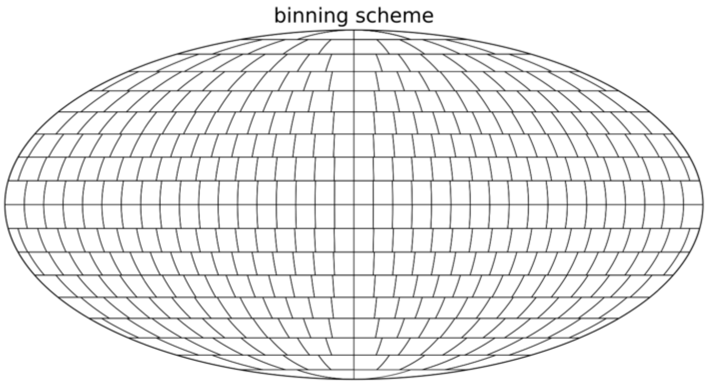
ROTATION MEASURE



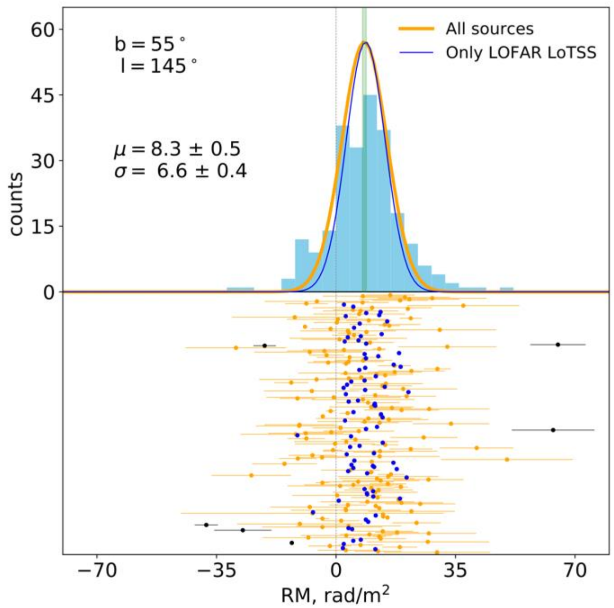
60000 extragalactic objects

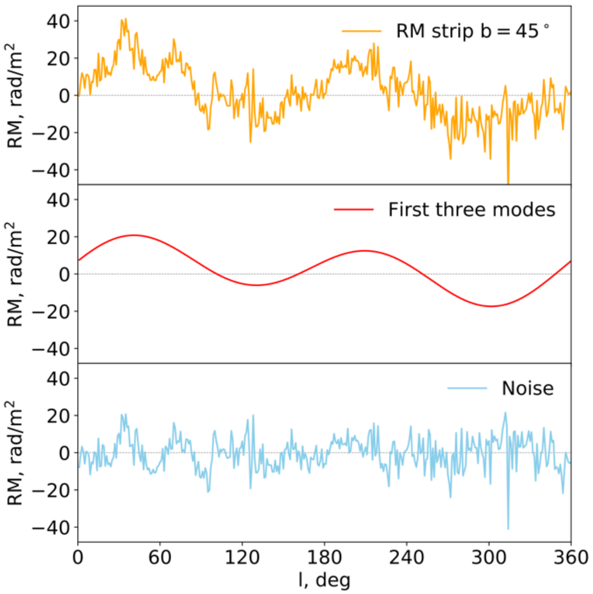
$$\mathrm{RM} \approx 0.812 \int_0^l \left[\frac{n_e(s)}{\mathrm{cm}^{-3}}\right]\left[\frac{B_\parallel(s)}{10^{-6}\,\mathrm{G}}\right]\left[\frac{\mathrm{d}s}{\mathrm{pc}}\right] \;\mathrm{rad/m^2}.$$

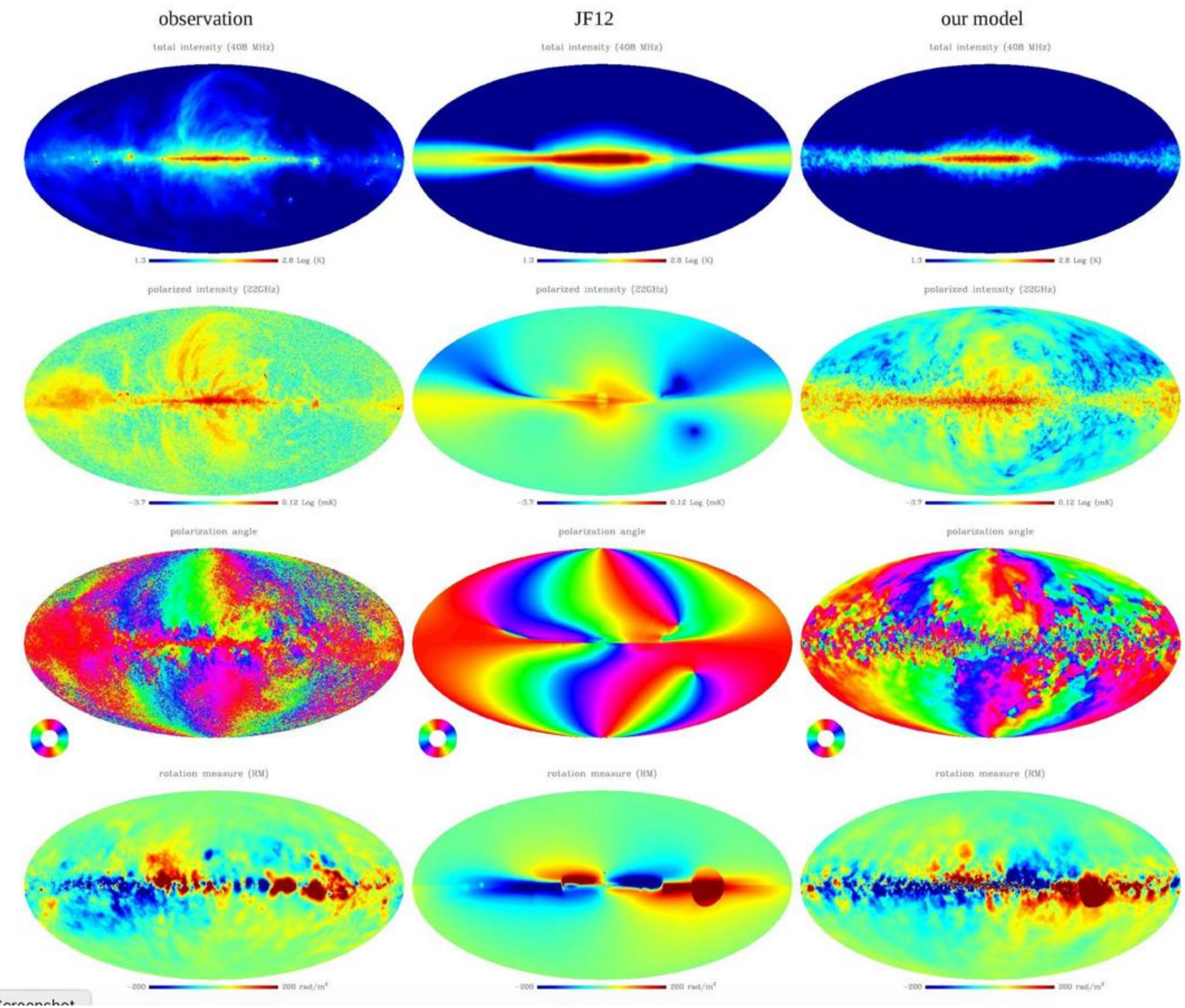
Model RM



	χ^2	χ^2/ndf	ndf	χ^2_{var}	χ^2_{var}/ndf
RM	544	**1.92**	283	145	0.51
Q	385	**1.11**	348	238	0.68
U	482	**1.38**	348	251	0.72
total	1411	**1.36**	1037	634	0.61

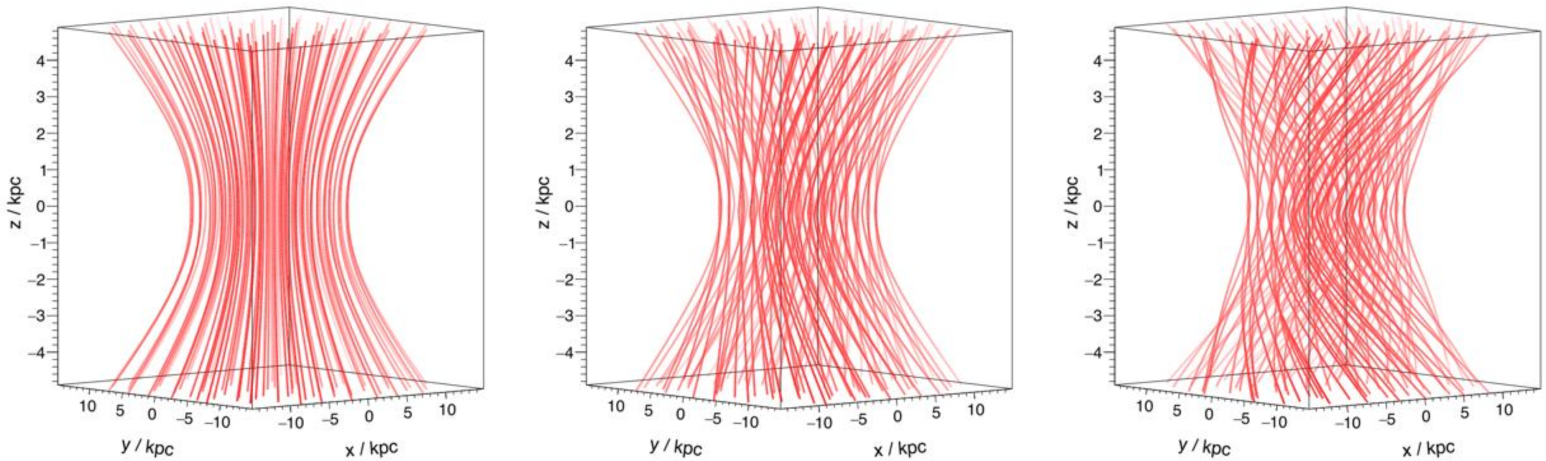






Beck et al, 1409.5120

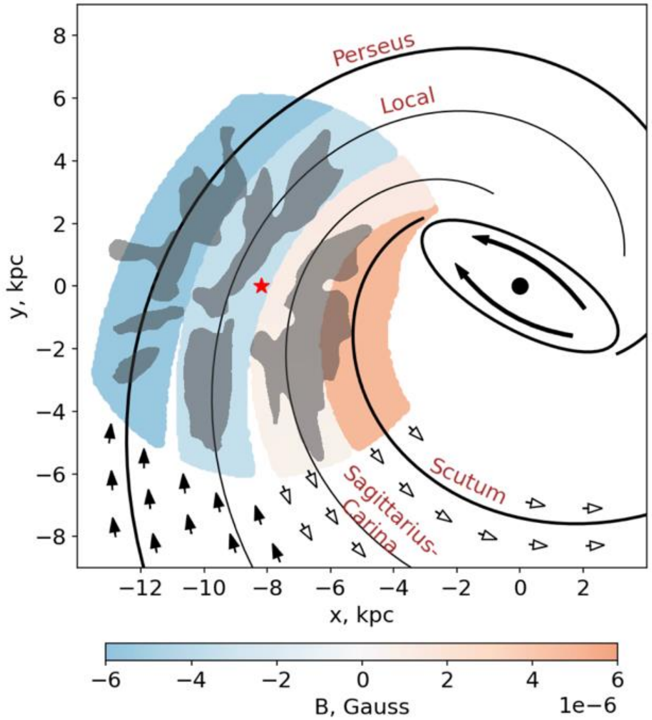
Dynamical halo model

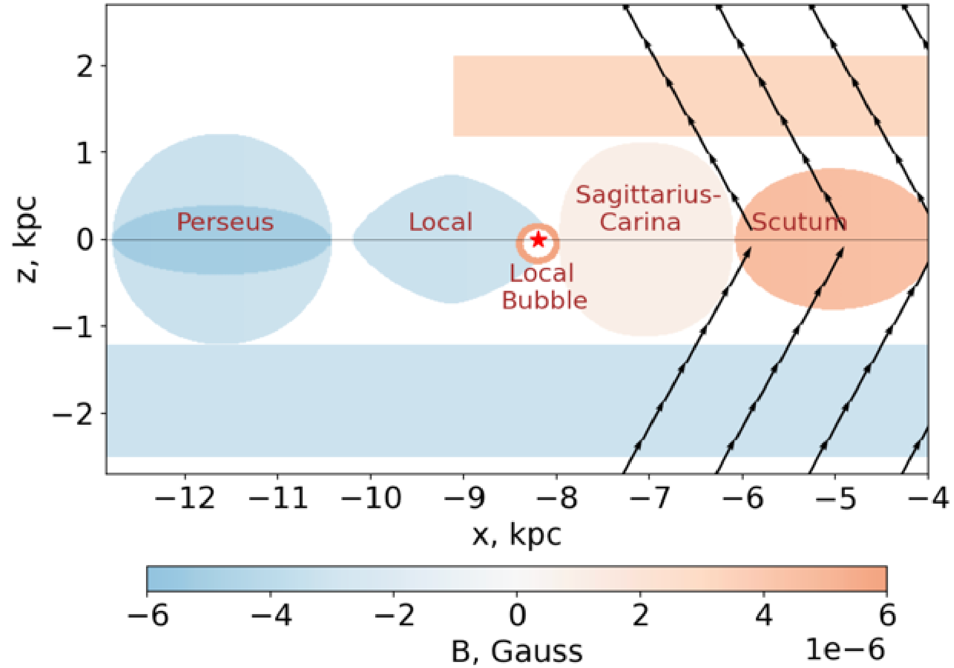


a: $t = 0$ Myr b: $t = 25$ Myr c: $t = 50$ Myr

M.Under and G.Farrar 2311.12120

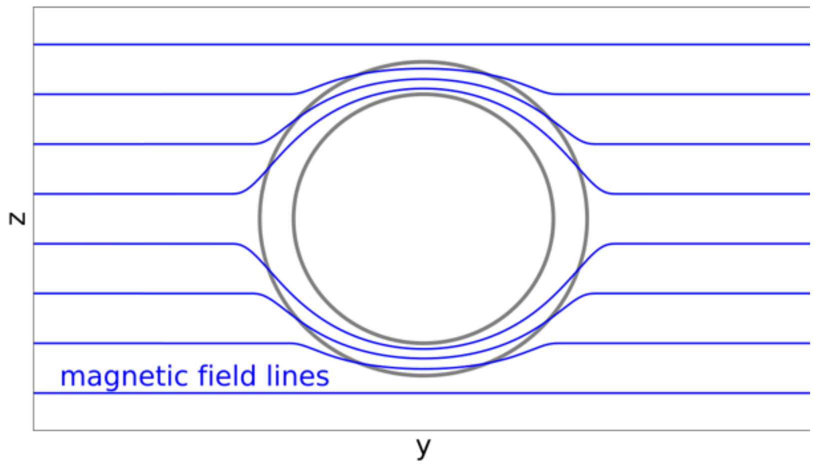
New model 2024

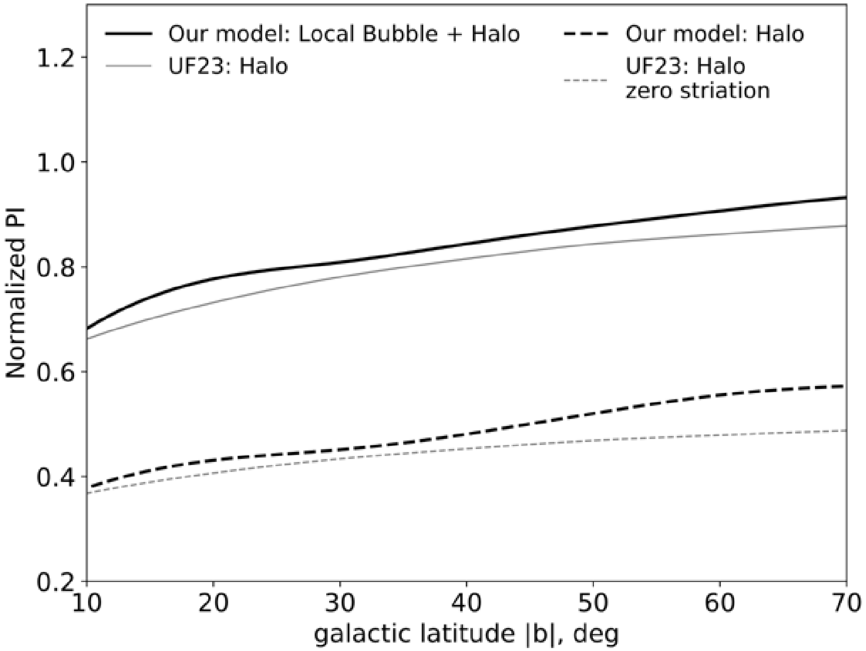




A.Korochkin, D.S. and P.Tinyakov, 2407.02148

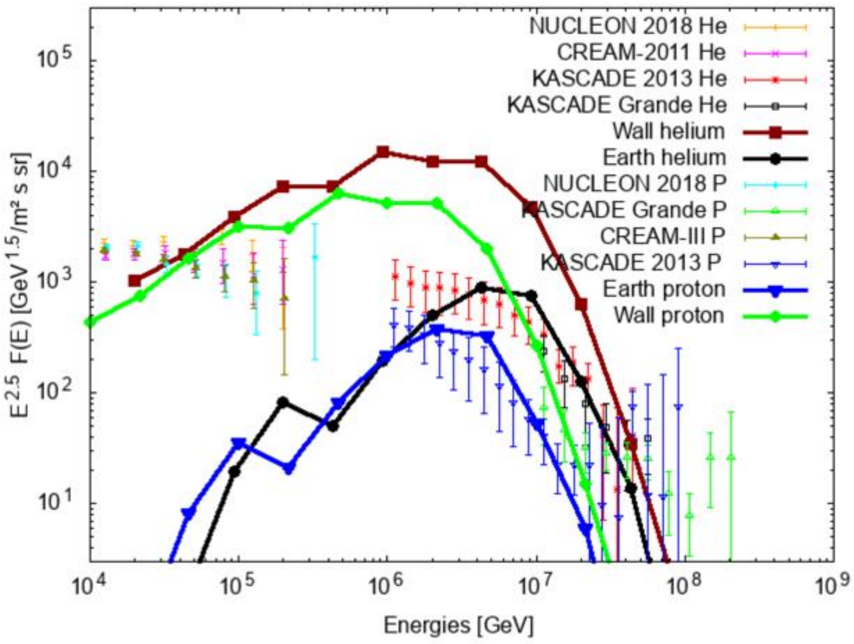
Local Bubble solved discrepansy between RM and synchrotron

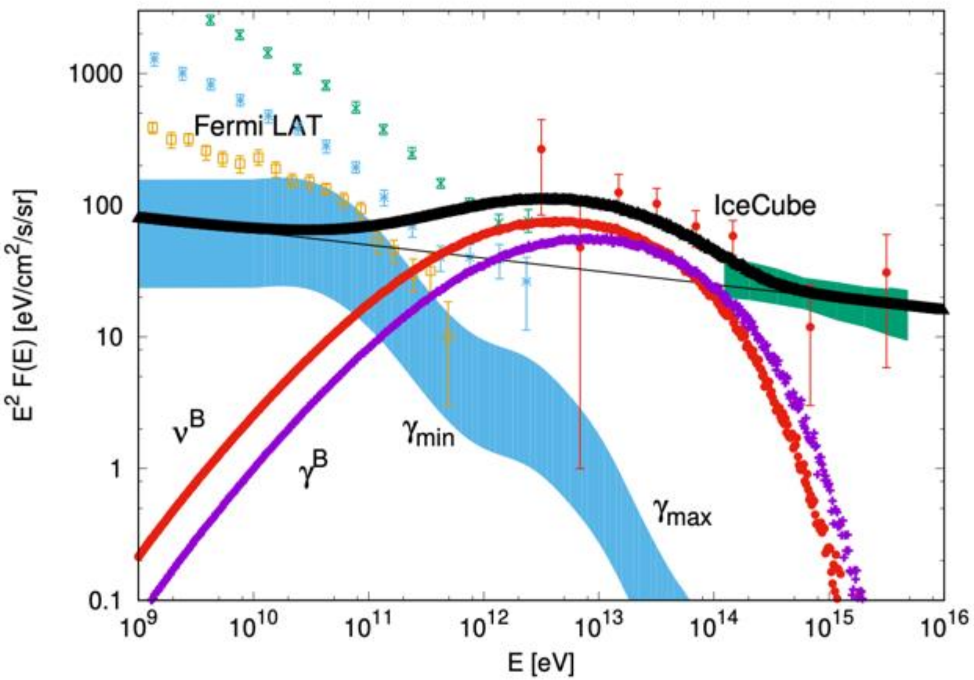




A.Korochkin, D.S. and P.Tinyakov, 2407.02148

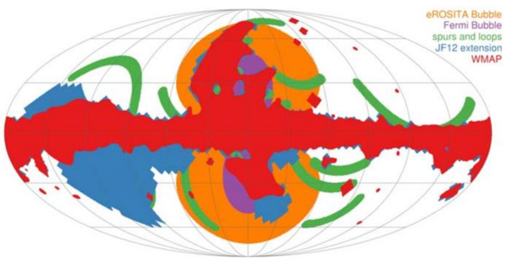
IceCube + Fermi LAT : Local Bubble



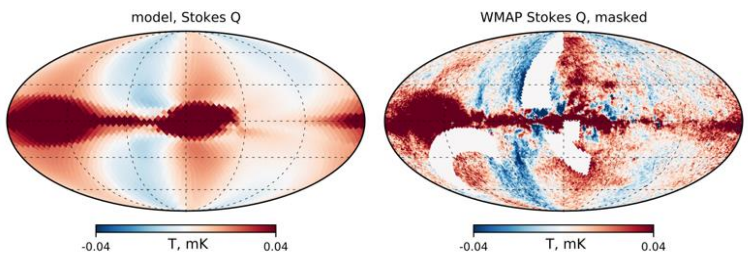


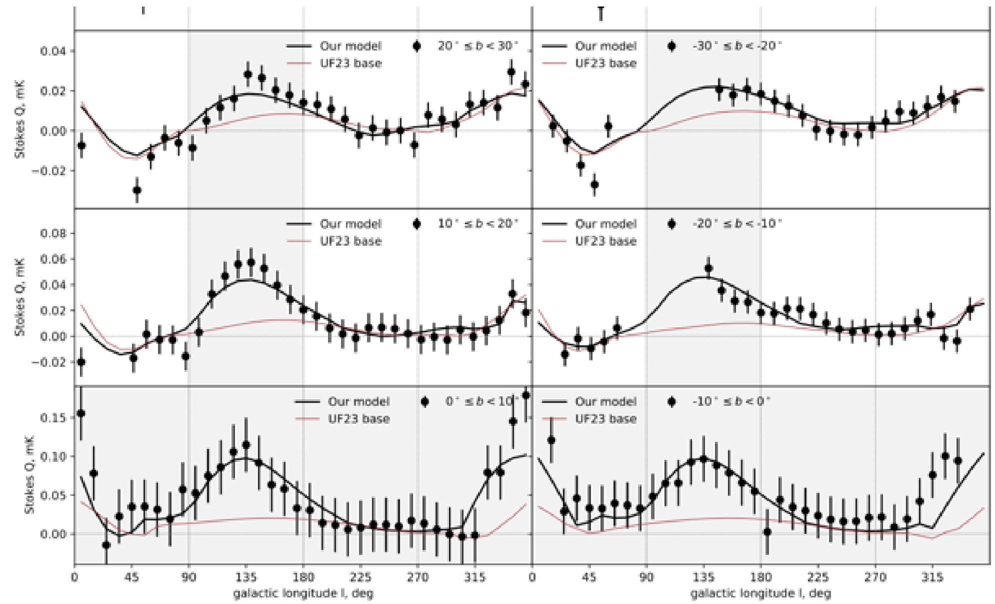
•M. Bouyahiaoui, M. Kachelriess, D.V. Semikoz , arXiv: 20001.00768

FAN REGION



UF 2023





For the first time self-consistent in this region: electrons are in same GMF model of arms with DRAGON code

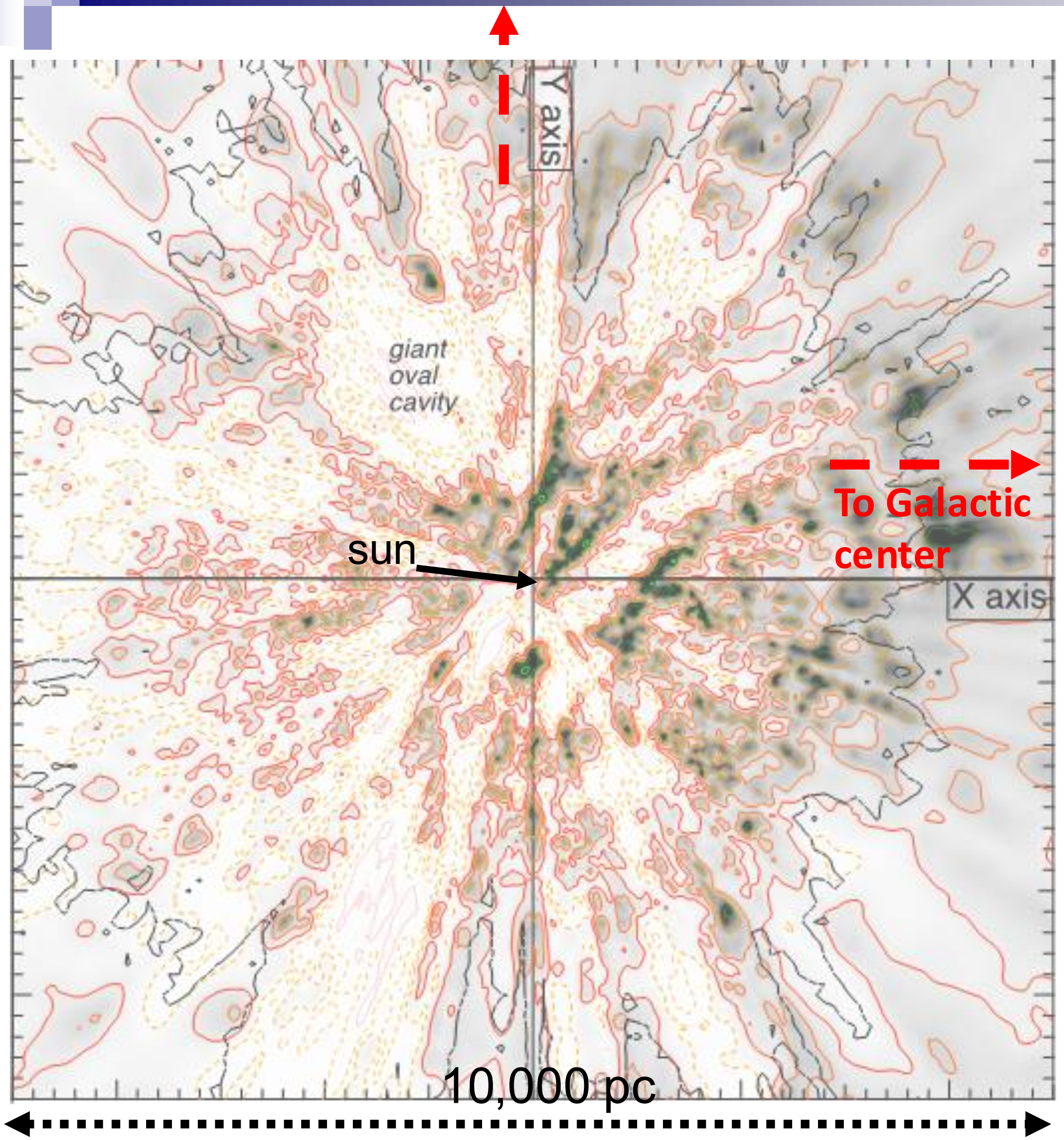
A.Korochkin, D.S. and P.Tinyakov, 2407.02148

Diffuse gamma-ray and neutrino fluxes

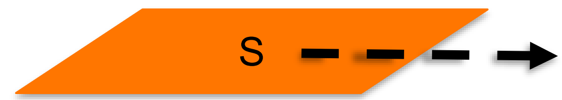
$$\Xi^{A,A'}(E,l,b) = \int_0^\infty \mathrm{d}s\, n_{\mathrm{gas}}^{A'}(\boldsymbol{x}) I_{\mathrm{CR}}^{A}(E,\boldsymbol{x})$$

$$I_\nu(E,l,b) = \sum_{A,A'} \int_E^\infty \mathrm{d}E'\, \Xi^{A,A'}(E',l,b) \frac{\mathrm{d}\sigma^{AA'\to\nu}(E',E)}{\mathrm{d}E}$$

In case of PeV energy and Milky Way galaxy
both gas and CR as space-dependent



Galactic Plane = Plane of the image



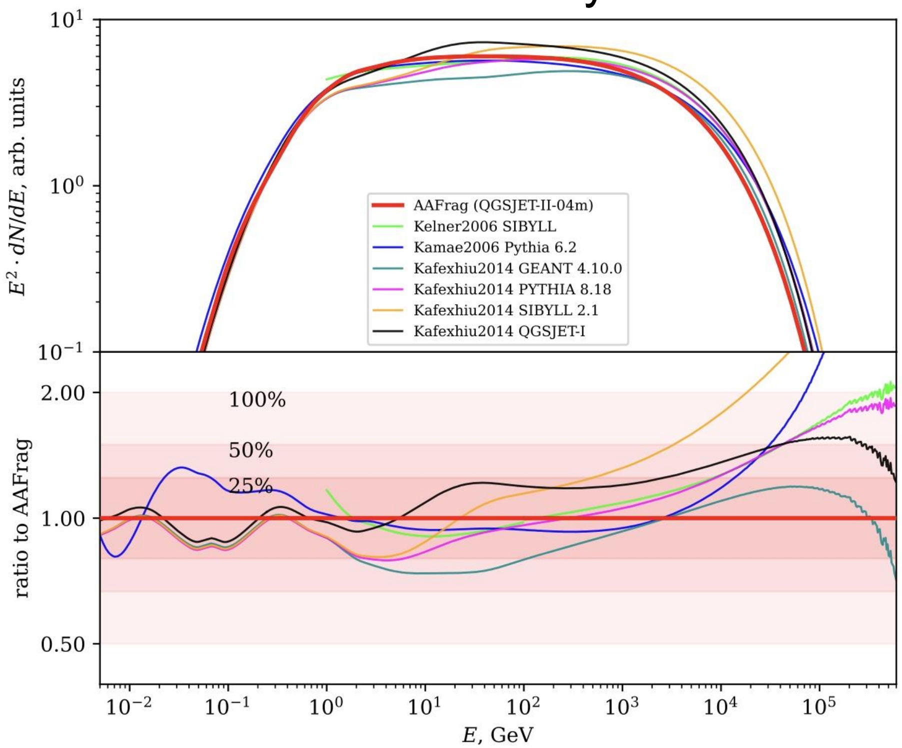
Black: dense dust clouds

Represented quantity:
extinction per parsec (in mag)

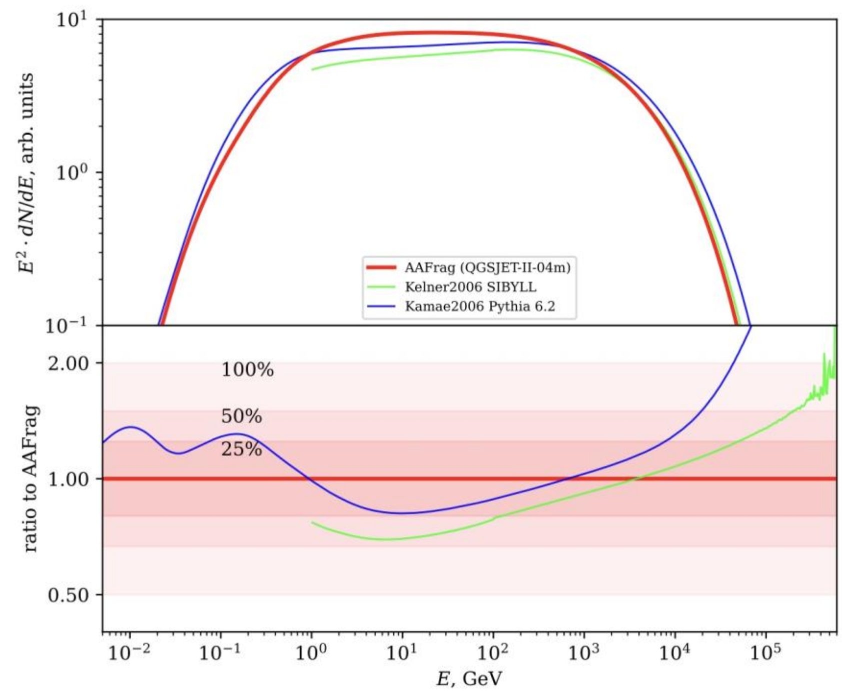
From **R. Lallement**

Secondary gamma-rays and neutrinos from AAfrag QGSJetII-4m

Gamma-rays

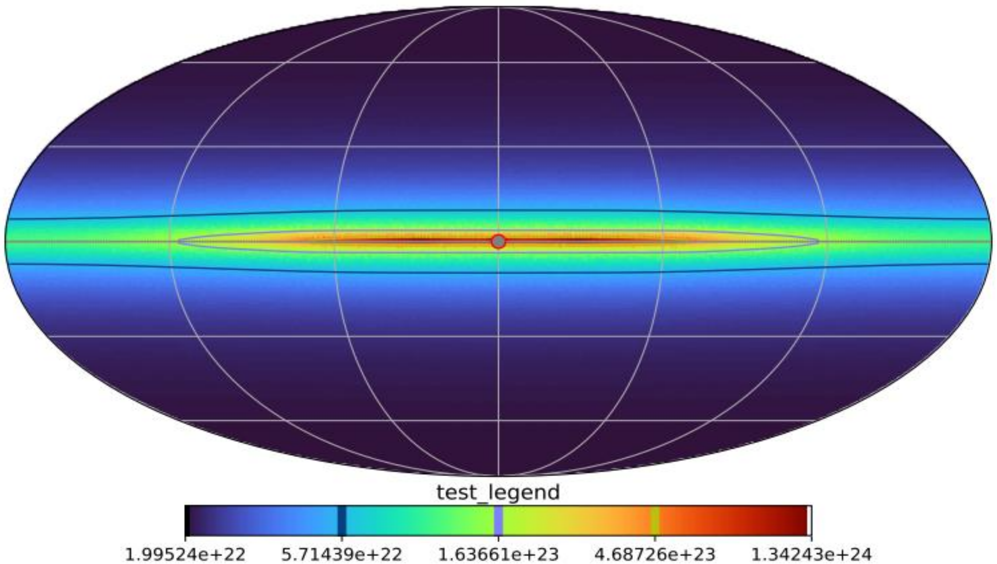


neutrinos



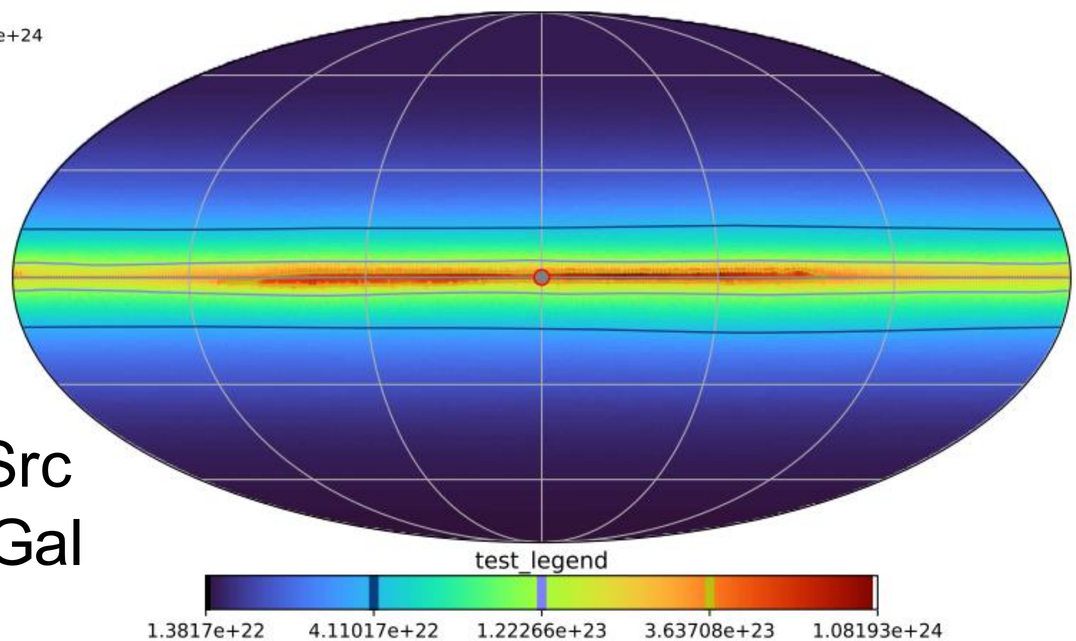
S.Koldobskiy et al, *Phys.Rev.D* 104 (2021) 12, 123027, arXiv 2110.00496

Diffuse 100 TeV γ-ray emission



Lipari & Vernetto (2018)

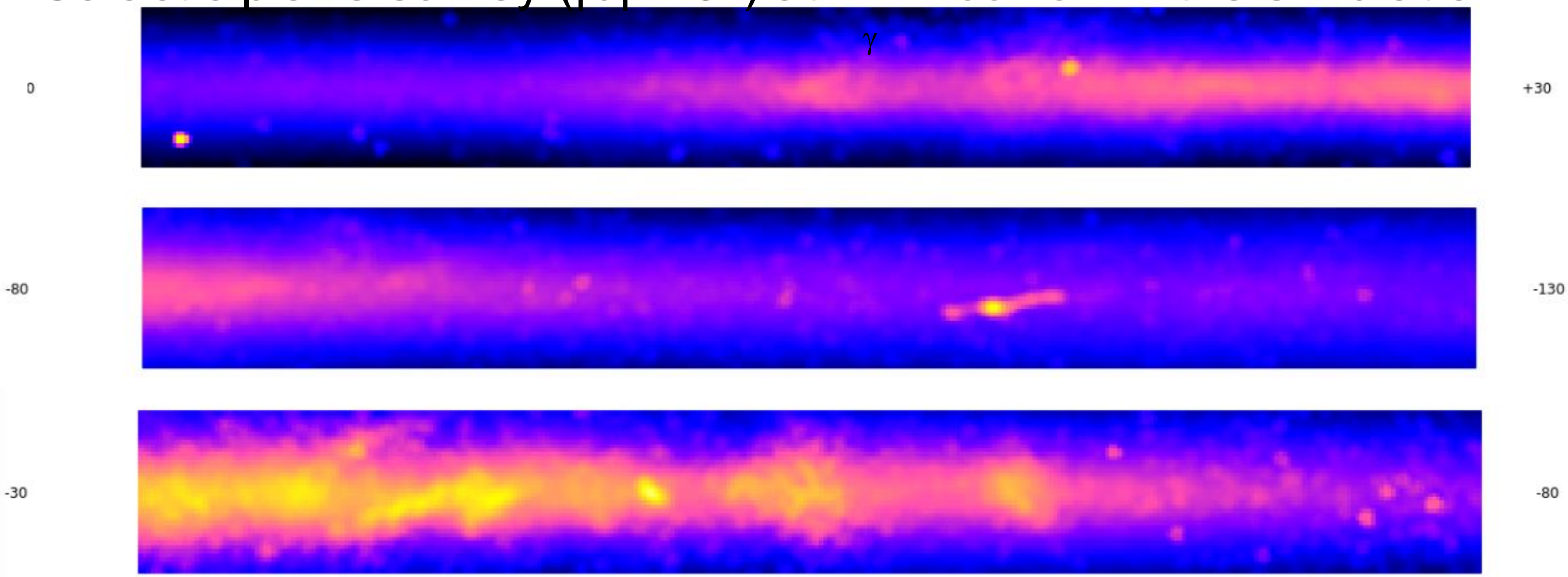
Giacinti,Kachelriess, Koldobskiy, Neronov D.S., In prep. (2025)



→ More patchy + Extended Src
→ Less contrast inner/outer Gal
→ Broader in some places.

Zoom on our simulated Gal. plane

Galactic plane survey ($|b| < 3^o$) at E_γ = 100 TeV in the simulation:

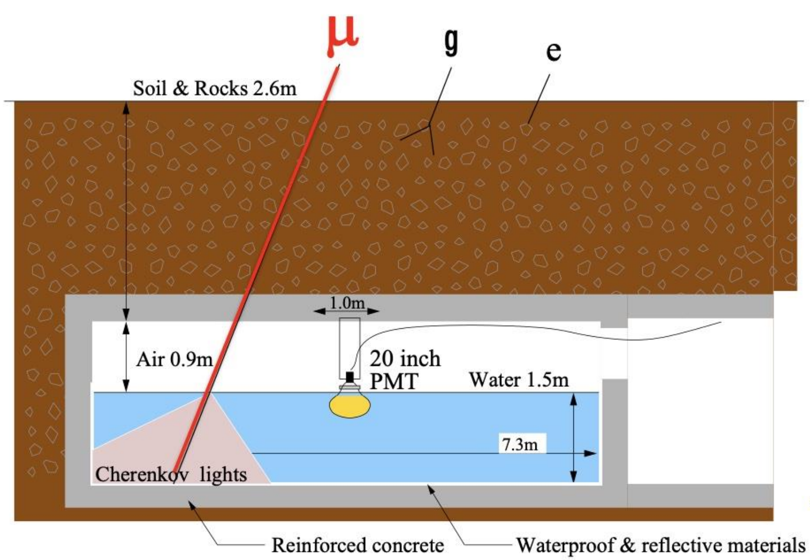


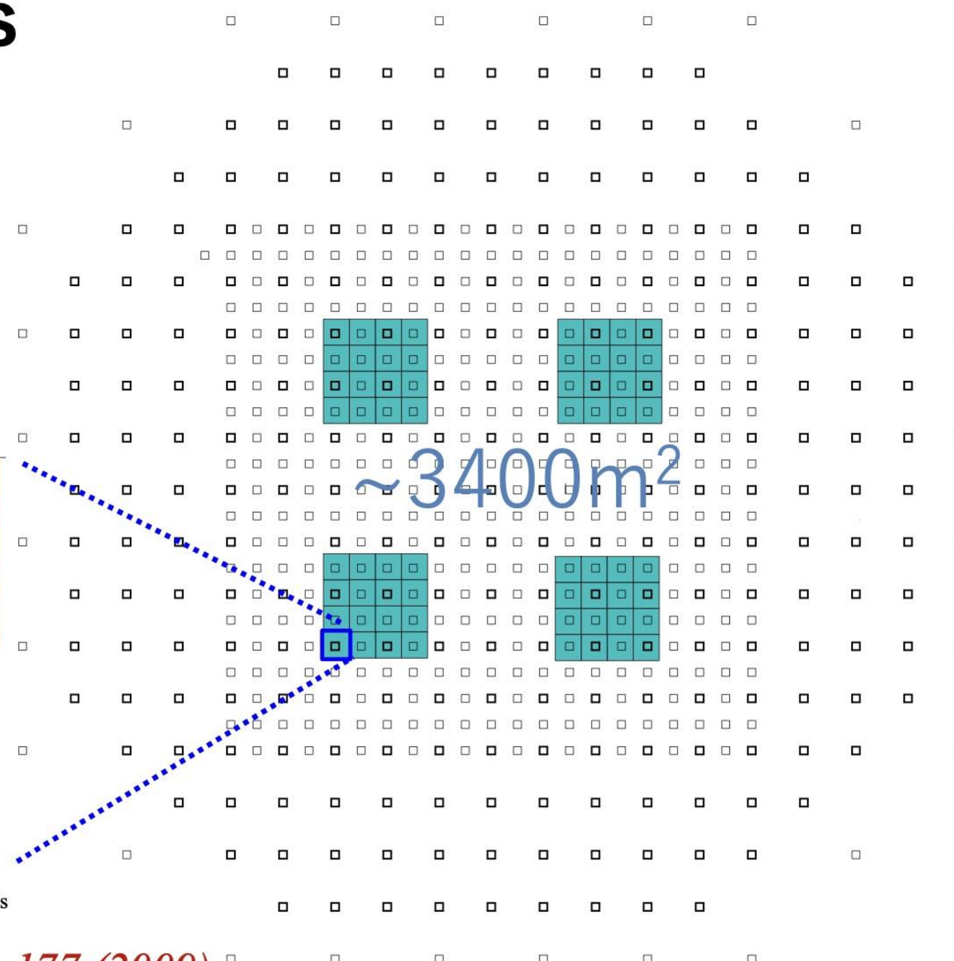
G.Giacinti, M.Kachelriess, S.Koldobskiy, A.Neronov, D.S., In prep.

Diffuse gamma-rays with E>100 TeV Tibet ASgamma and LHAASO

Underground Water Cherenkov Muon detectors

- ✓ 2.4m underground (~515g/cm² ~9X_0)
- ✓ 4 pools, 16 units / pool
- ✓ 7.35m × 7.35m × 1.5m deep (water)
- ✓ 20" Φ PMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets



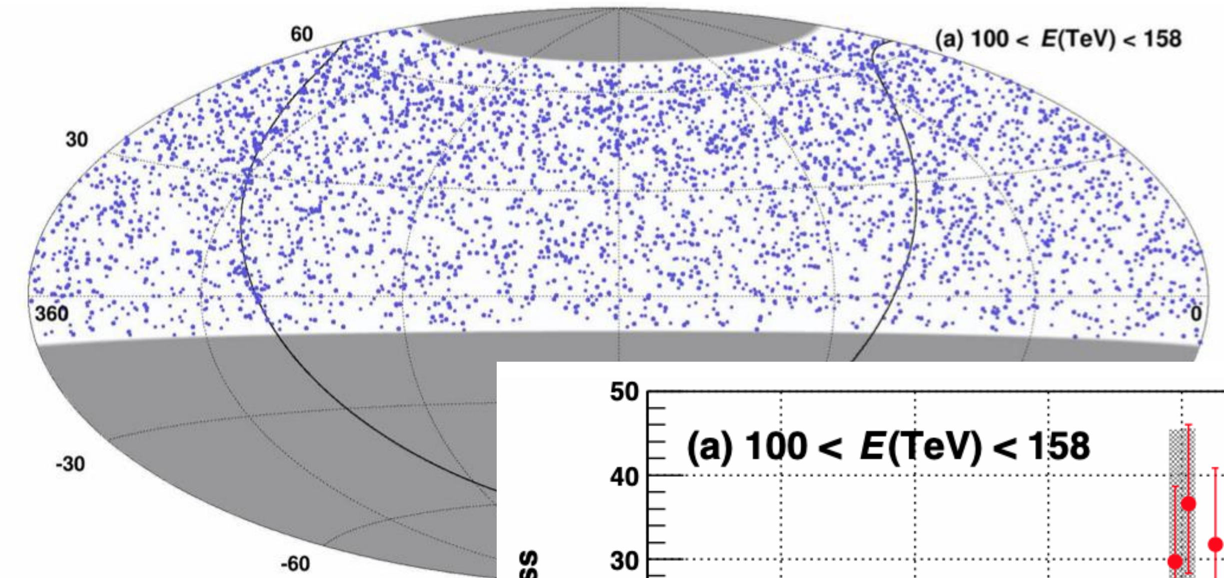


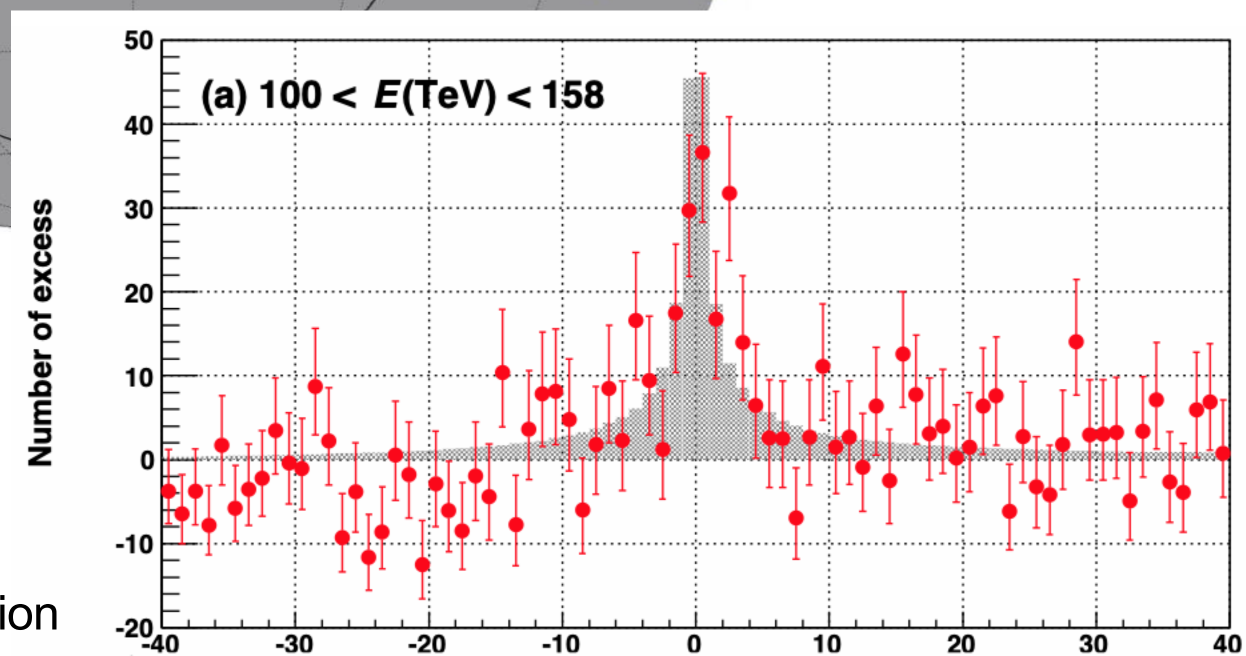
Basic idea: T. K. Sako+, Astropart. Phys. 32, 177 (2009)

Measurement of # of μ in AS → γ／CR discrimination

DATA: February, 2014 - May, 2017 Live time: 719 days

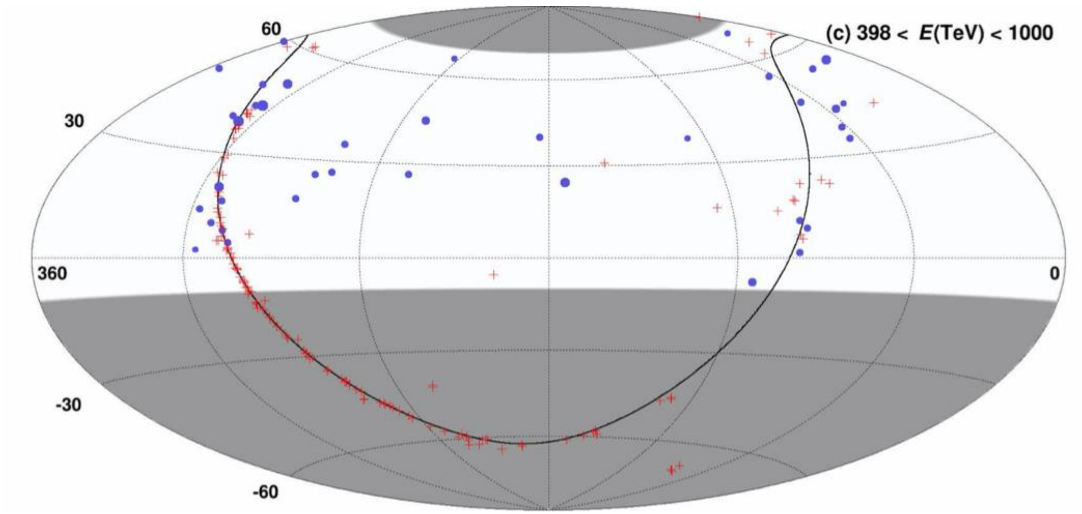
Tibet AS-g gamma-ray sky

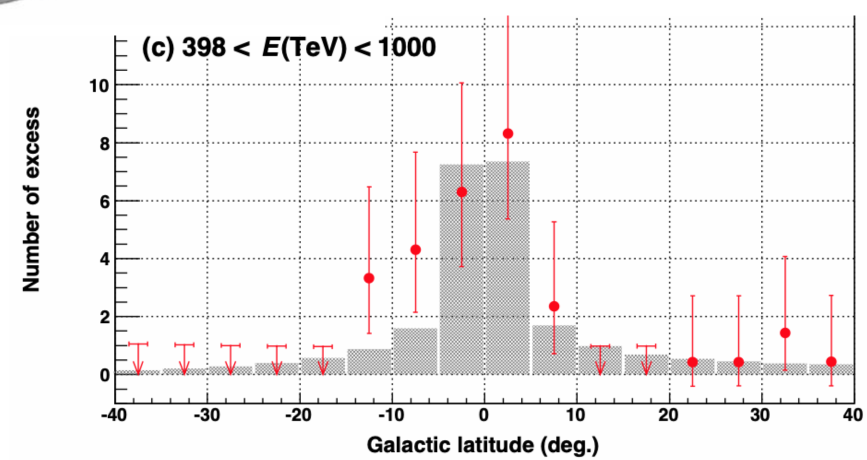




Tibet Asgamma collaboration
arXiv:2104.05181

Tibet AS gamma sky 400 TeV



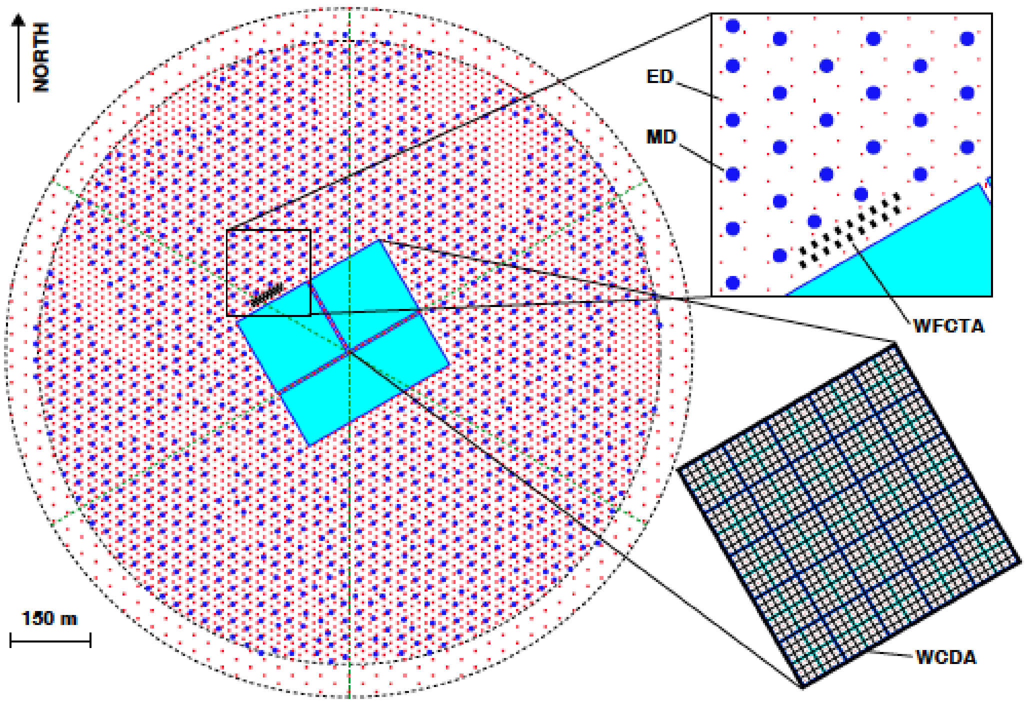


Hadron regection factor 1/10^6

Tibet Asgamma collaboration arXiv:2104.05181

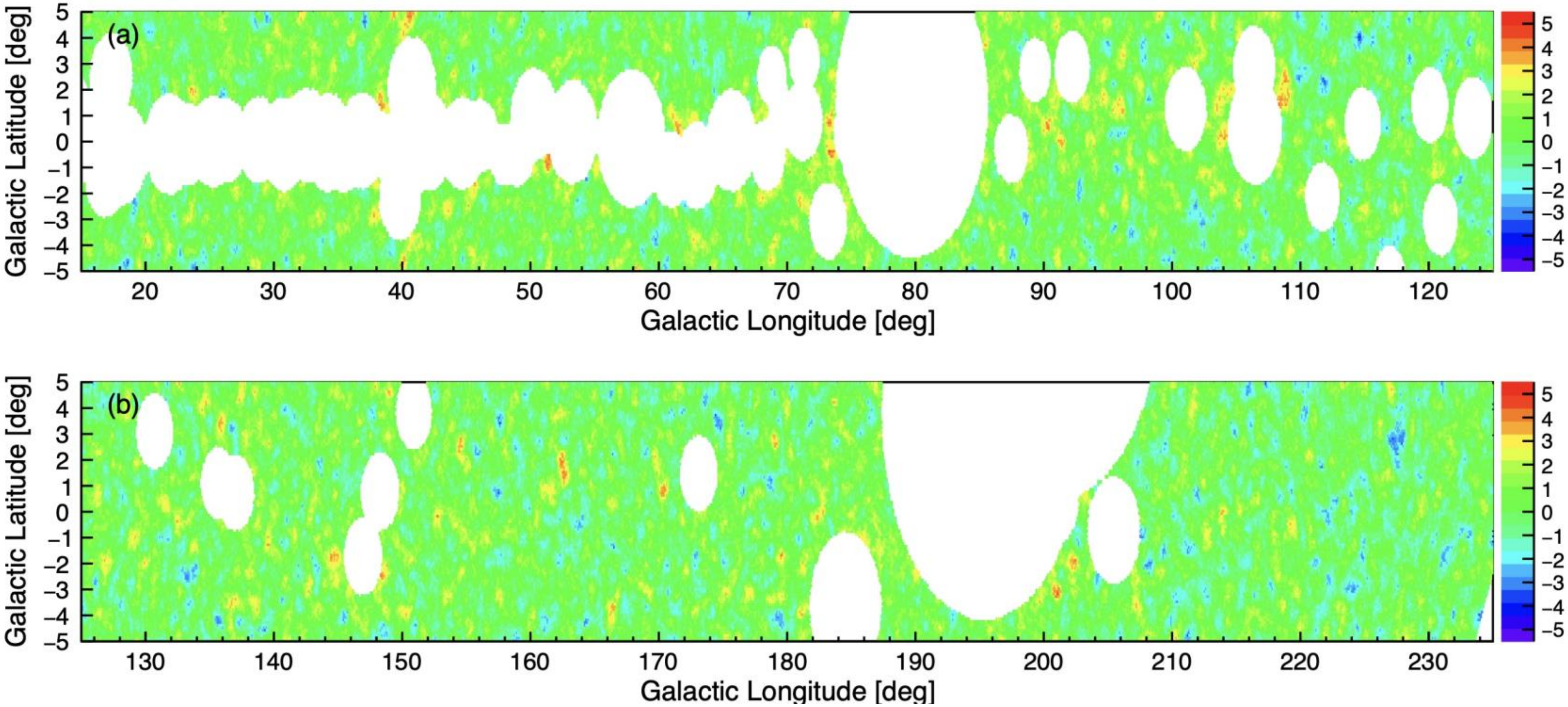
The LHAASO experiment

- 1 km^2 array, including 4941 scintillator detectors 1 m^2 each, with 15 m spacing.
- An overlapping 1 km^2 array of 1146, underground water Cherenkov tanks 36 m^2 each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m^2).



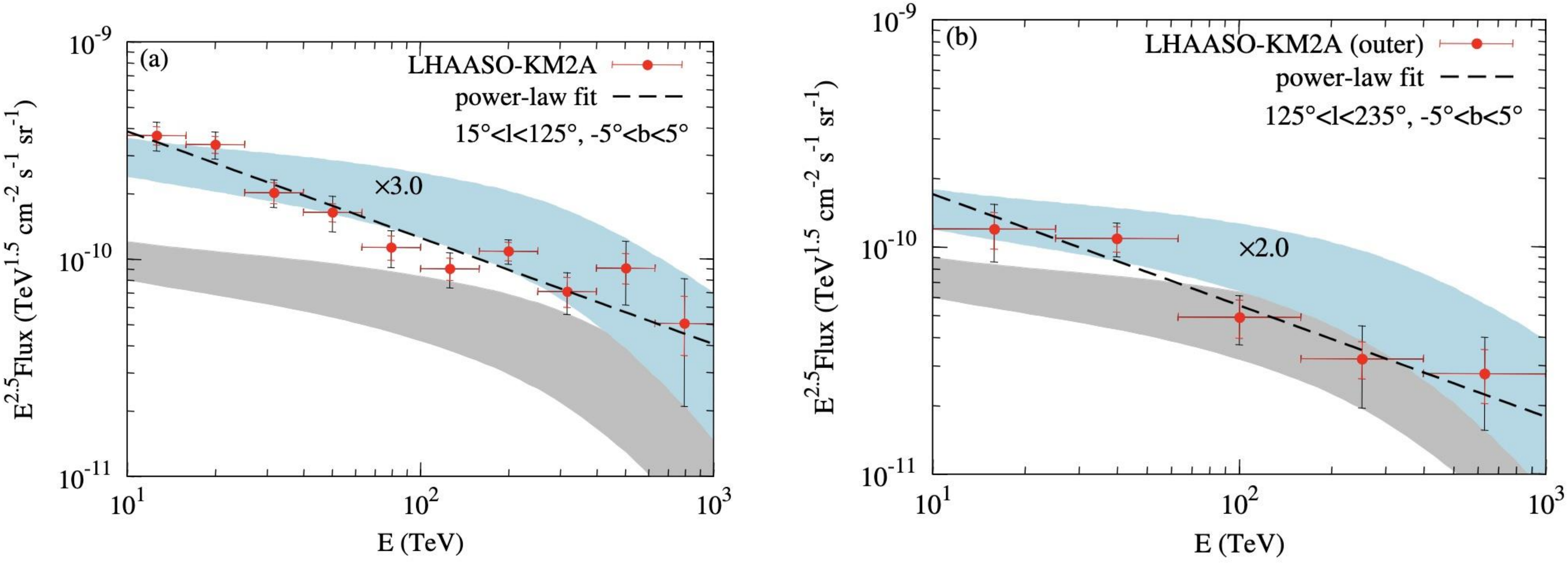
- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m^2.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.

Mask LHAASO



LHAASO collaboration arXiv: 2305.05372

LHAASO diffuse gamma-ray background



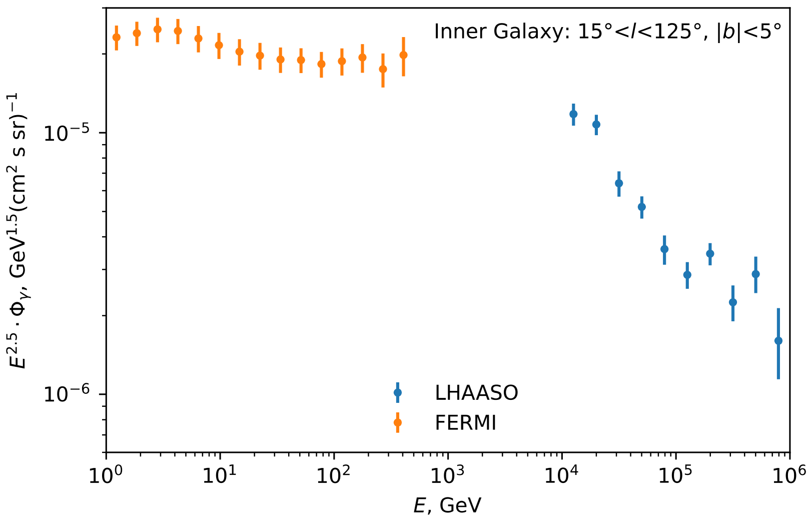
$$\Xi^{A,A'}(E,l,b) = \int_0^\infty \mathrm{d}s\, n_{\mathrm{gas}}^{A'}(\boldsymbol{x}) I_{\mathrm{CR}}^{A}(E,\boldsymbol{x})$$

$$I_\nu(E,l,b) = \sum_{A,A'} \int_E^\infty \mathrm{d}E'\, \Xi^{A,A'}(E',l,b) \frac{\mathrm{d}\sigma^{AA'\to\nu}(E',E)}{\mathrm{d}E}$$

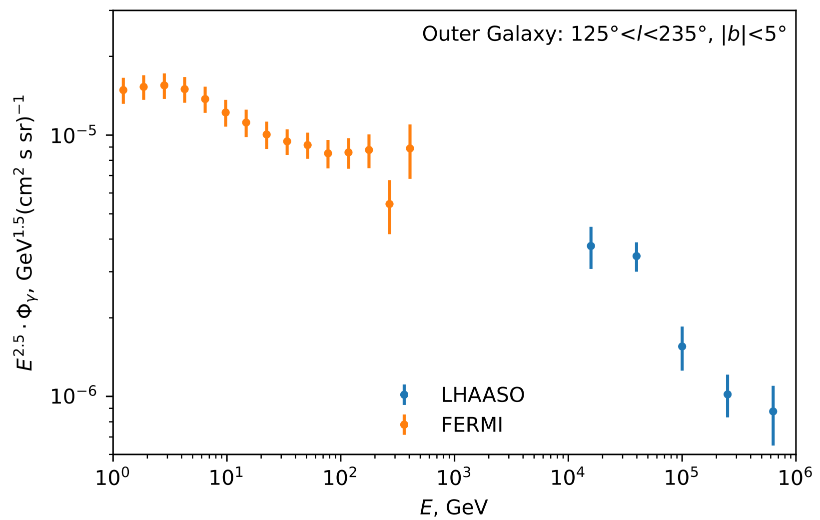
LHAASO collaboration, arXiv: 2305.05372

Gamma-ray flux in inner and outer Galaxy

Knee in cosmic rays 10 TeV gamma



Inclear details of spectrum

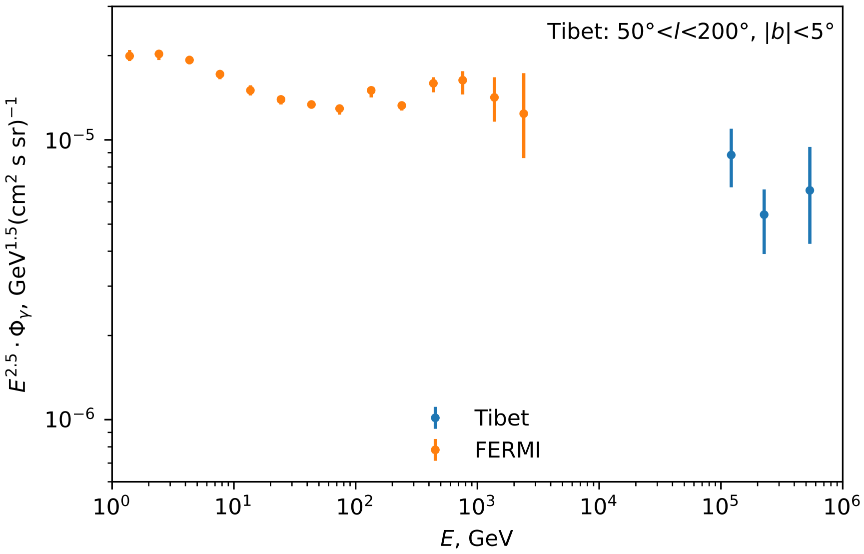


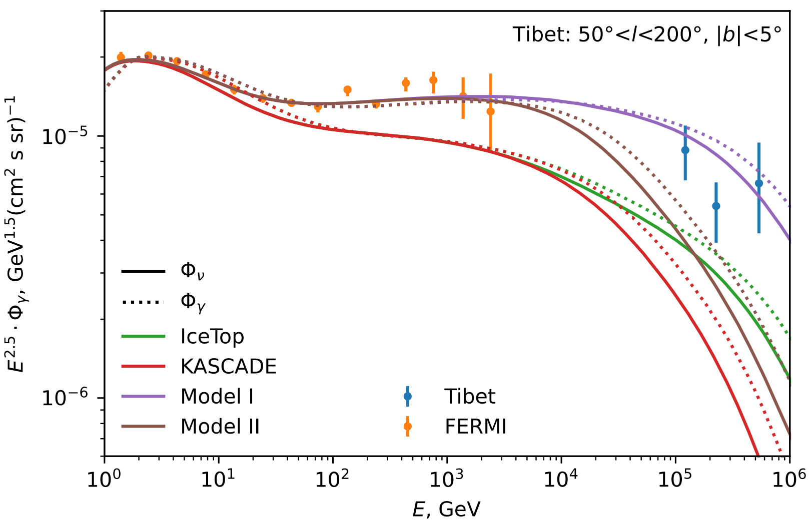
LHAASO data from LHAASO collaboration, 2305.05372

Fermi from R. Zhang et al, 2305.06948

Gamma-ray flux in LHAASO is same 1/E^3, but combination with Fermi looks different.

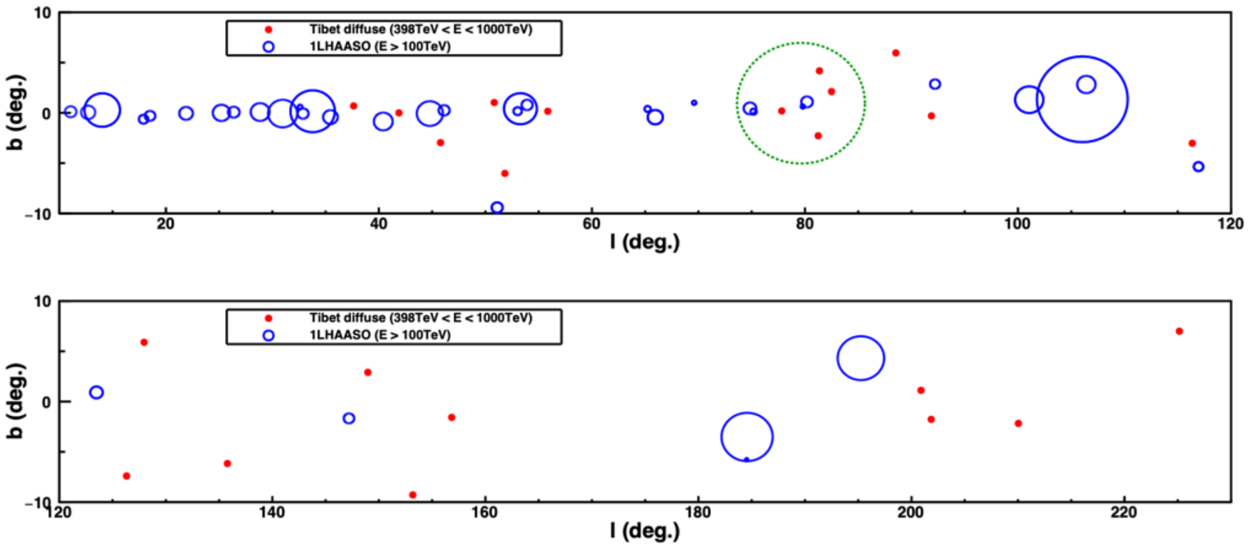
Models in outer Galaxy 50-200 degrees without mask (diffuse plus extended sources



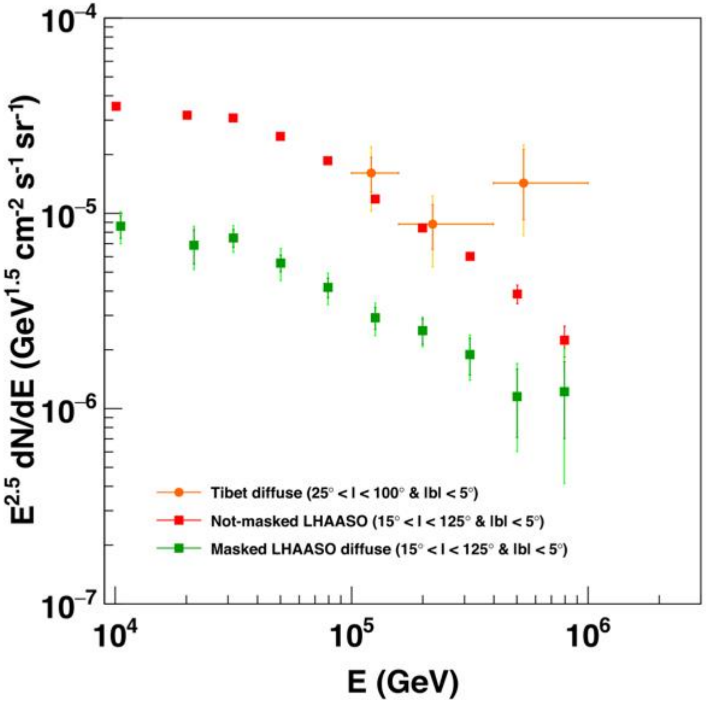


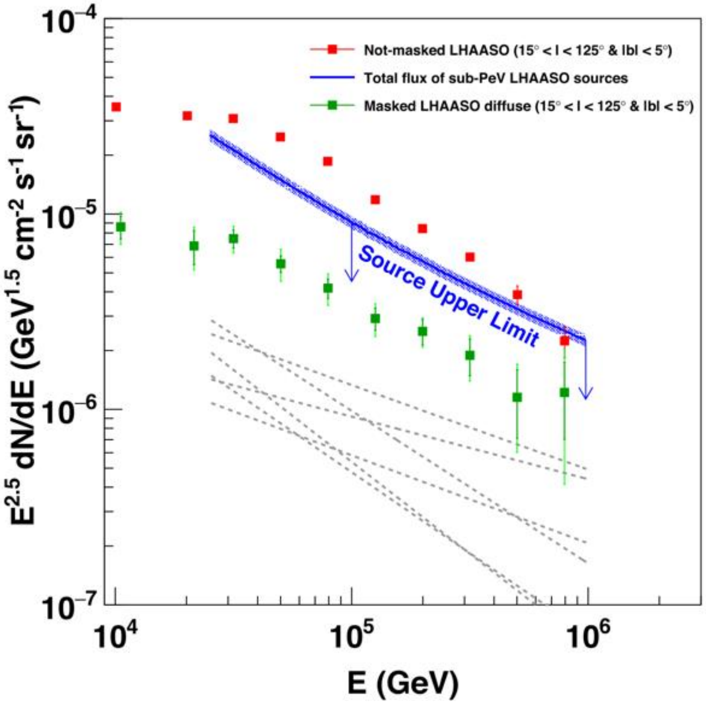
From comparison Tibet and LHAASO: 2/3 of Tibet flux from extended sources.

Tibet diffuse and LHAASO



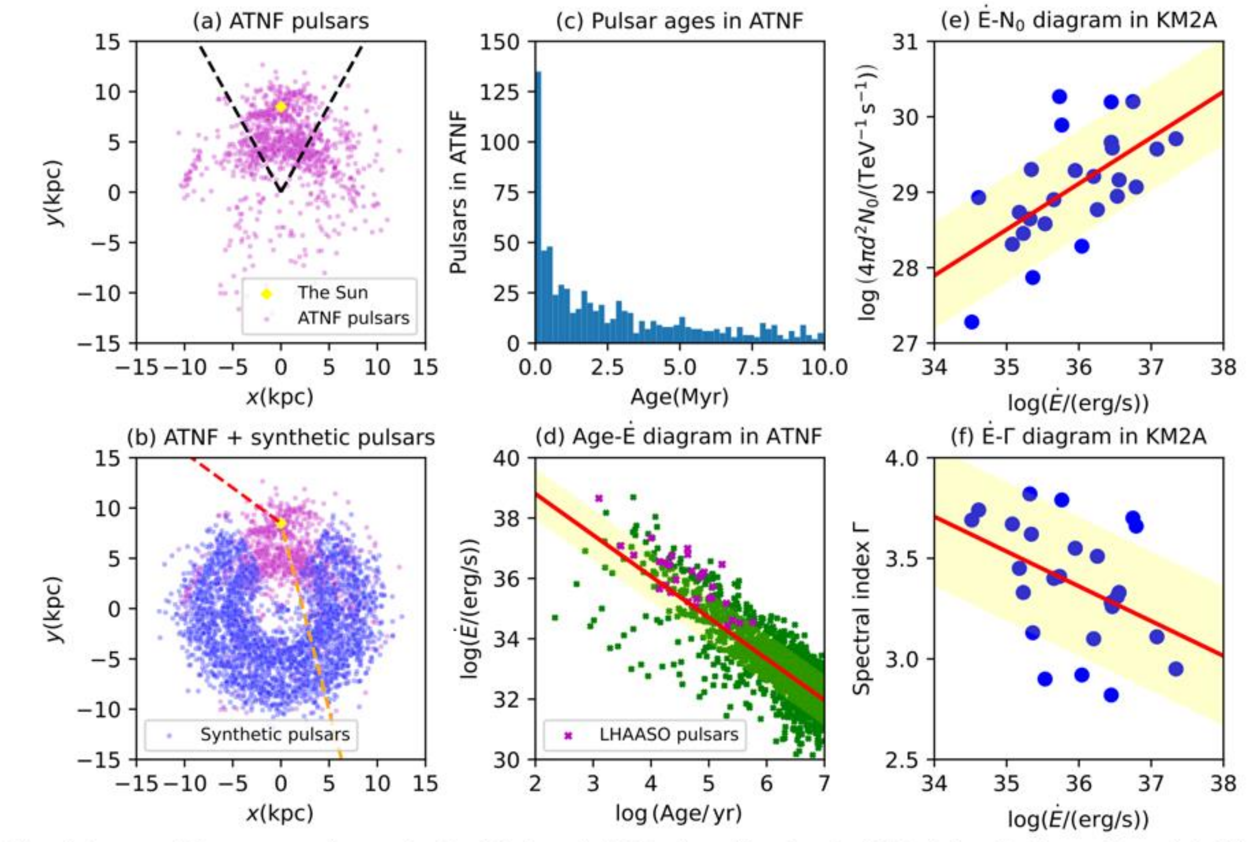
Total flux OK





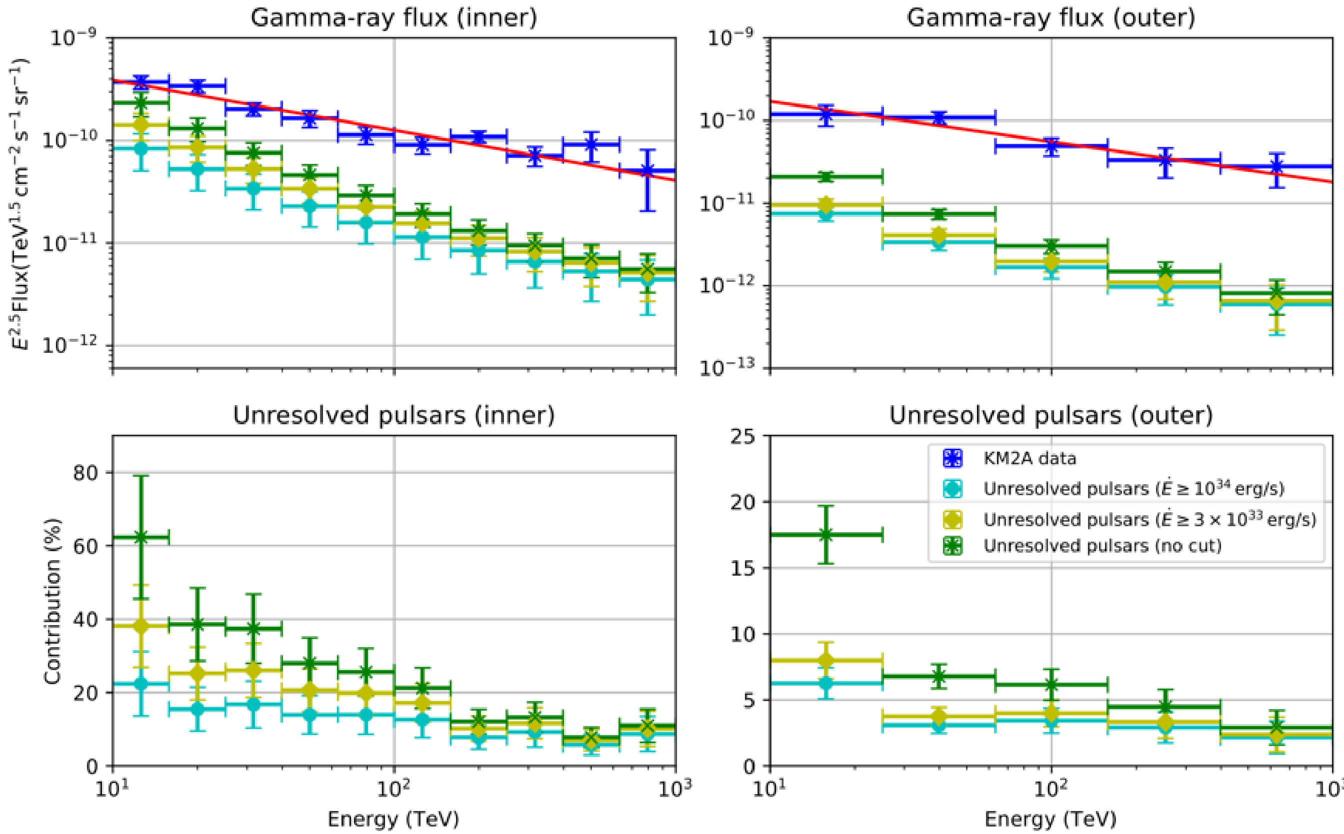
S.Kato et al, 2504.01799

Unresolved leptonic sources

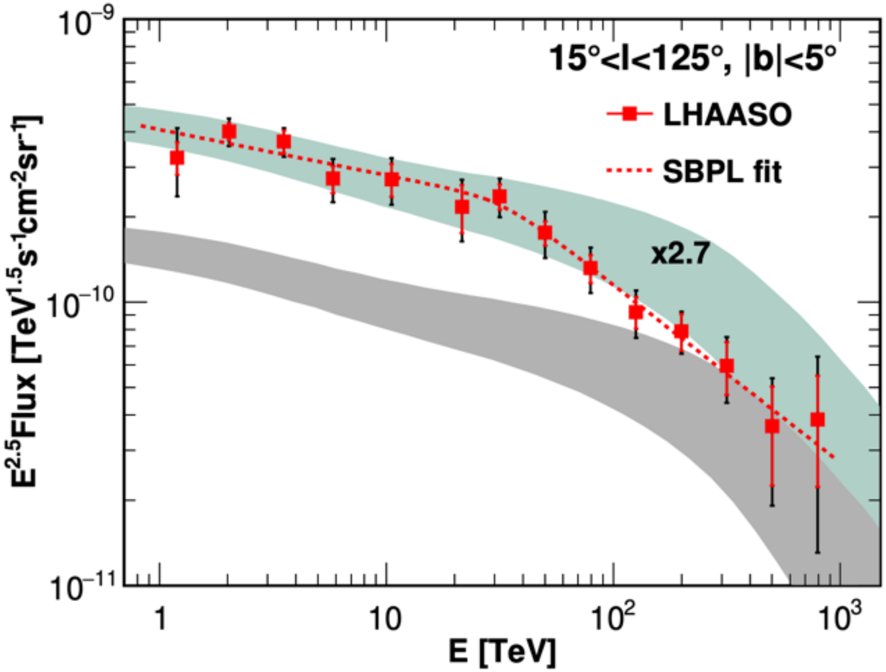


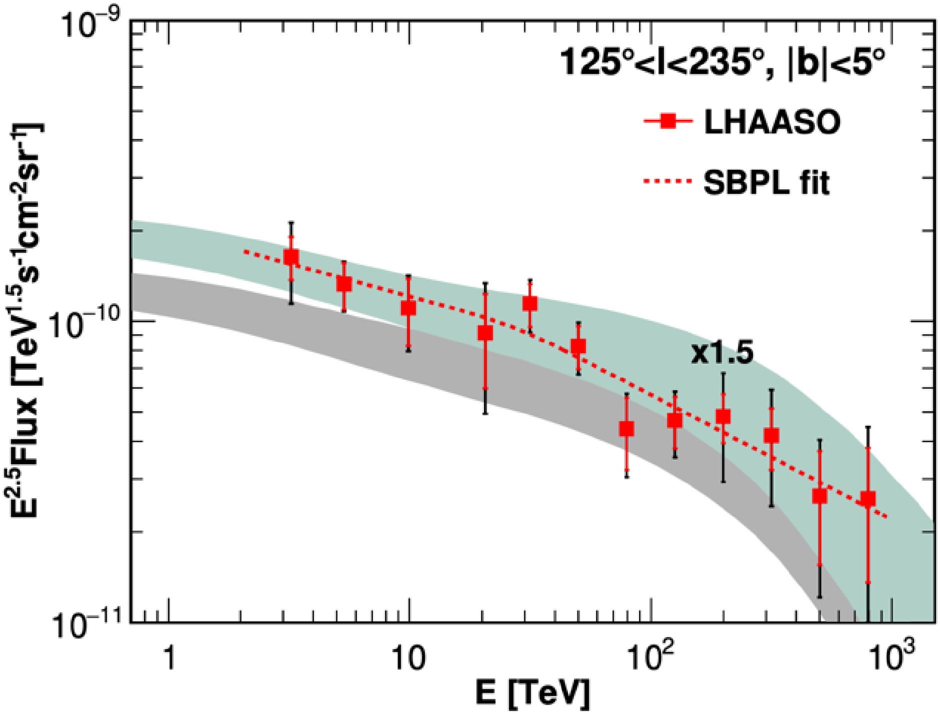
S.Kaci, G.Giacinti and D.S., 2407.20186

Unresolved leptonic sources

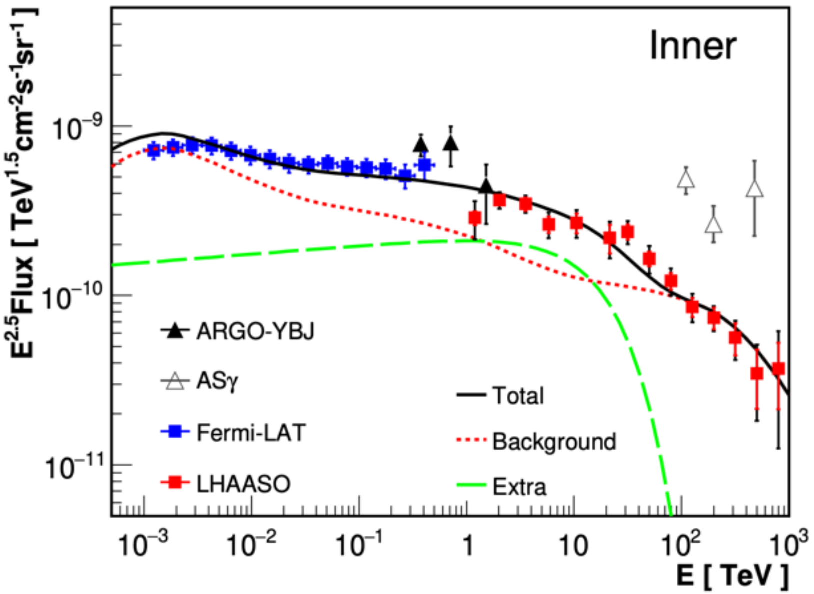


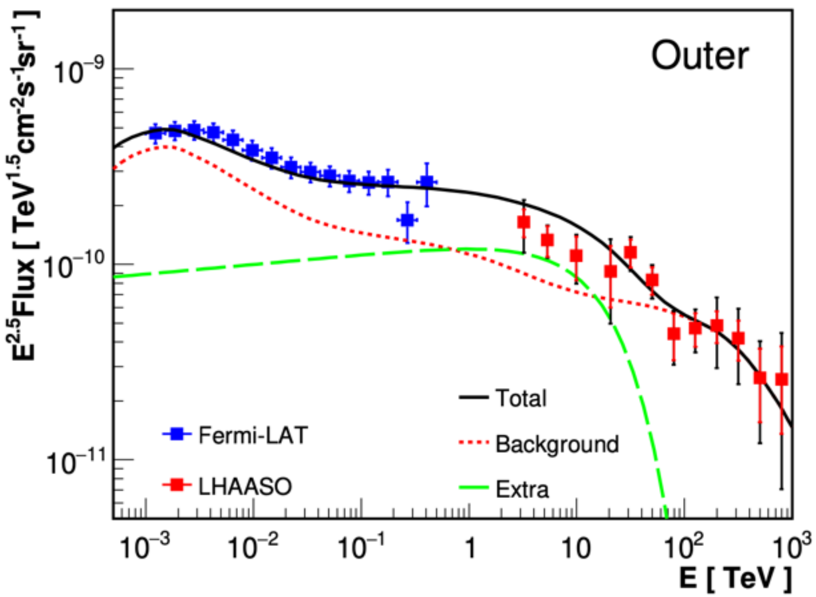
S.Kaci, G.Giacinti and D.S., 2407.20186





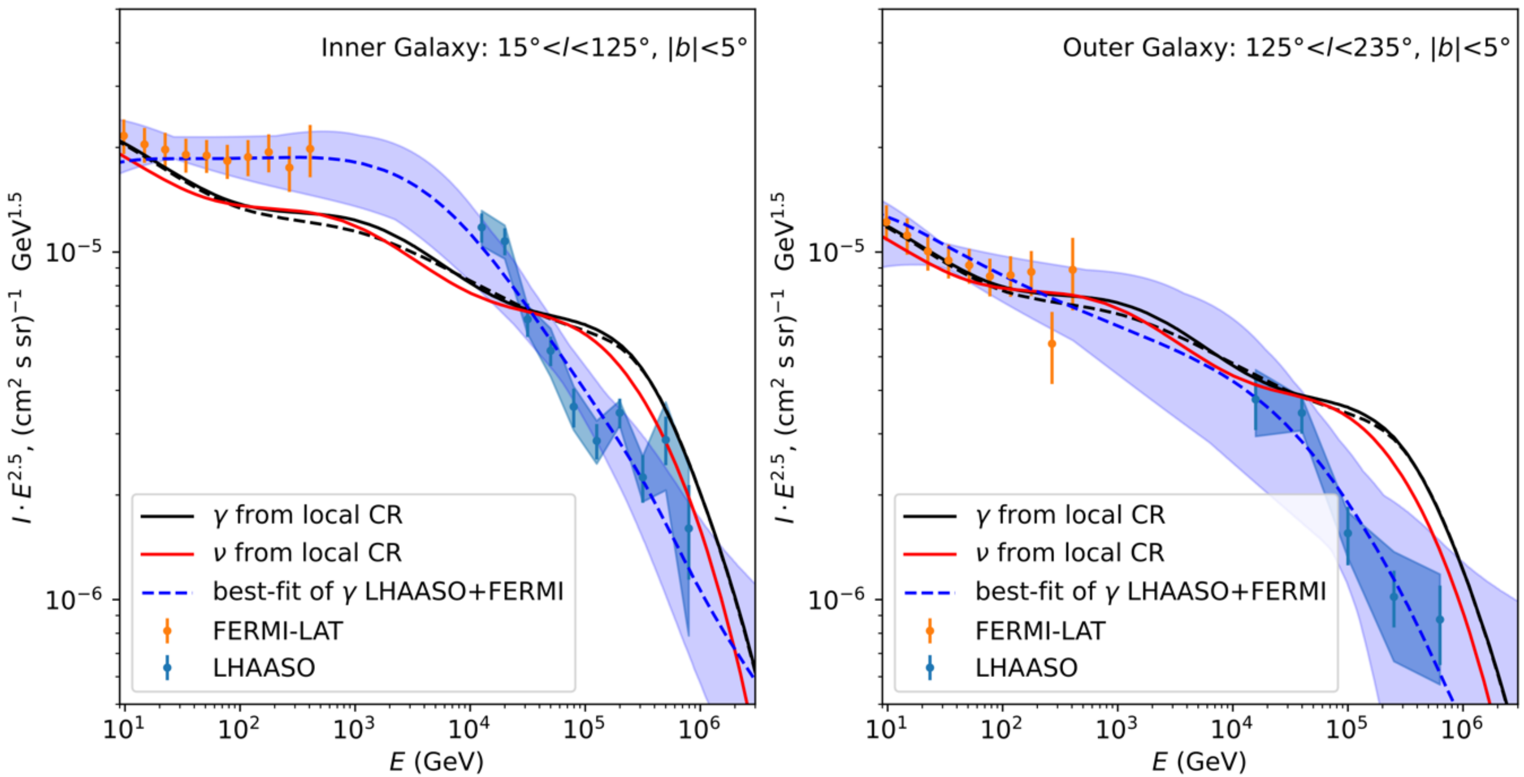
LHAASO Collaboration 2411.16021





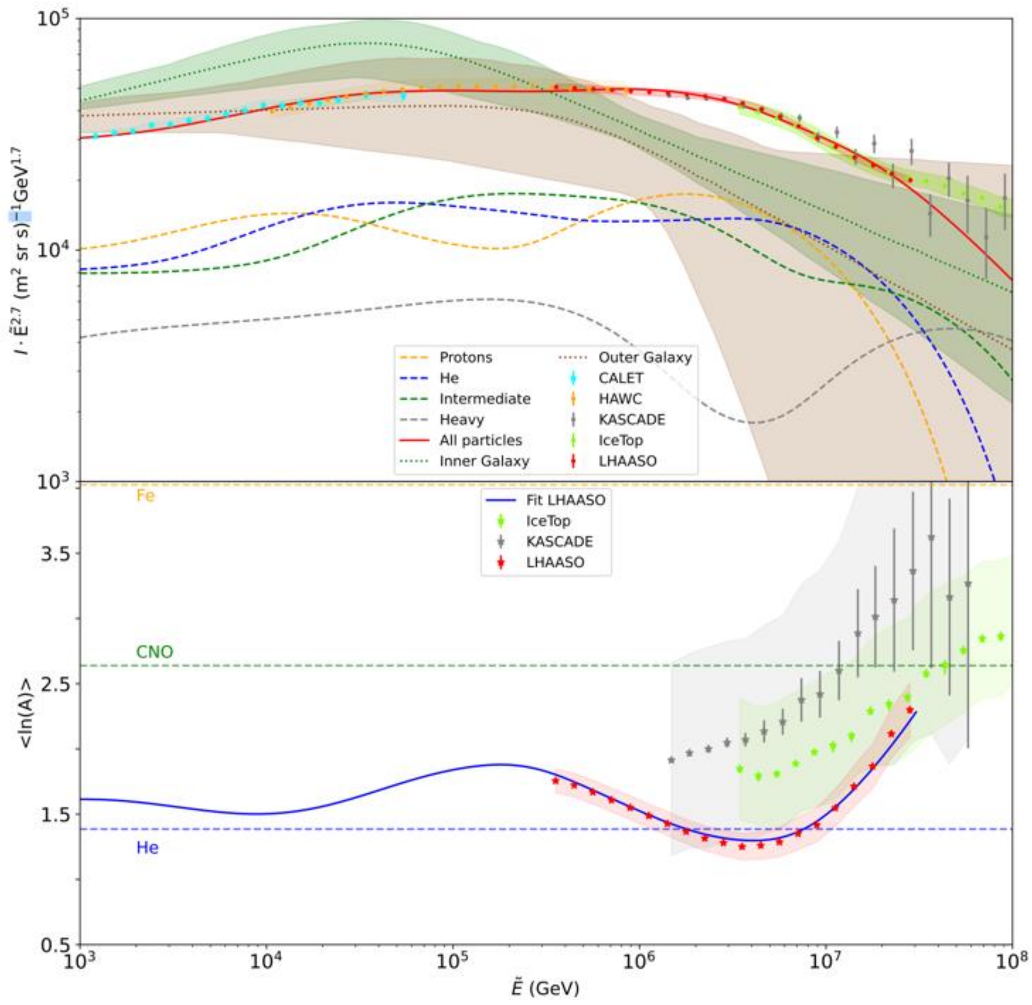
LHAASO Collaboration 2411.16021

Lower knee in Galaxy



C. Prevotat et al, 2407.11911

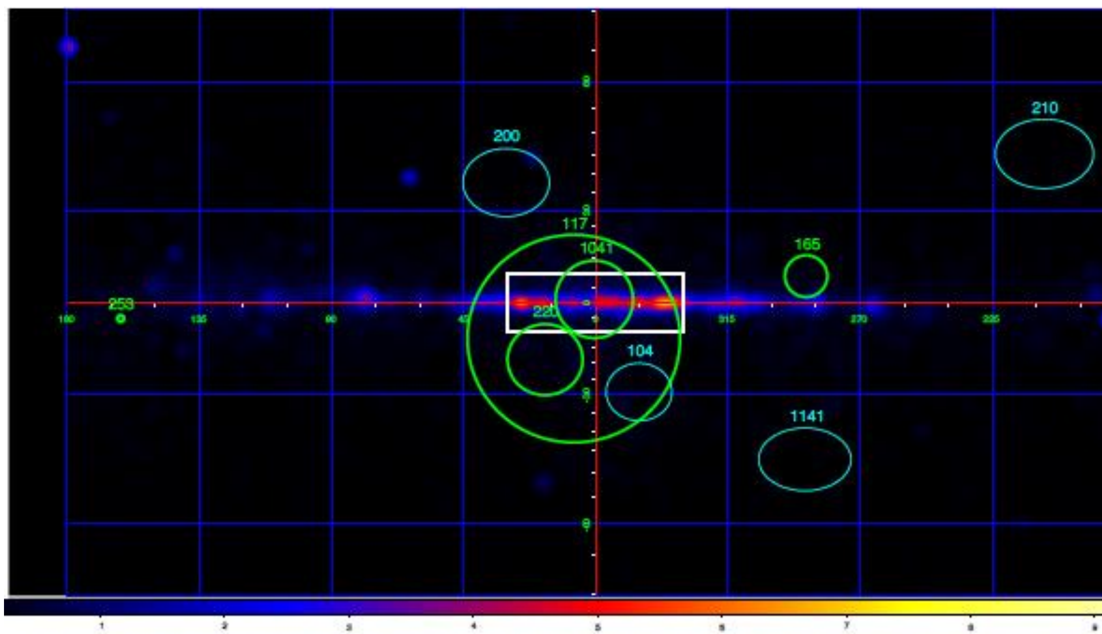
Low energy knee in Galaxy

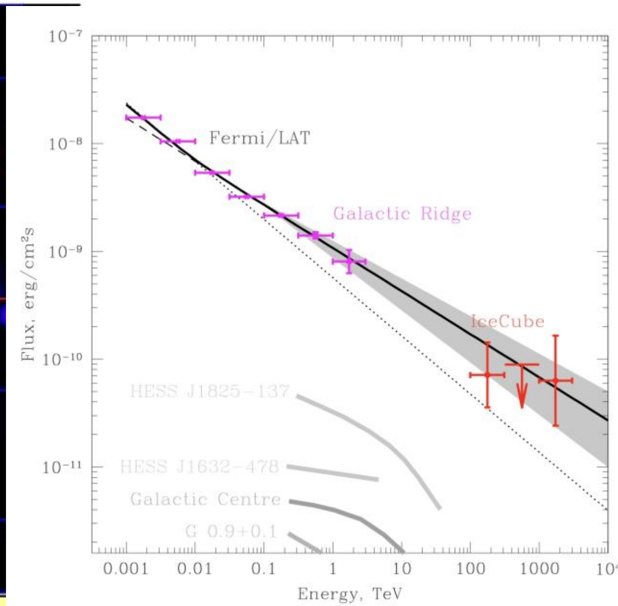


C. Prevotat et al, 2407.11911

Galactic Ridge neutrino flux in IceCube and ANTARES

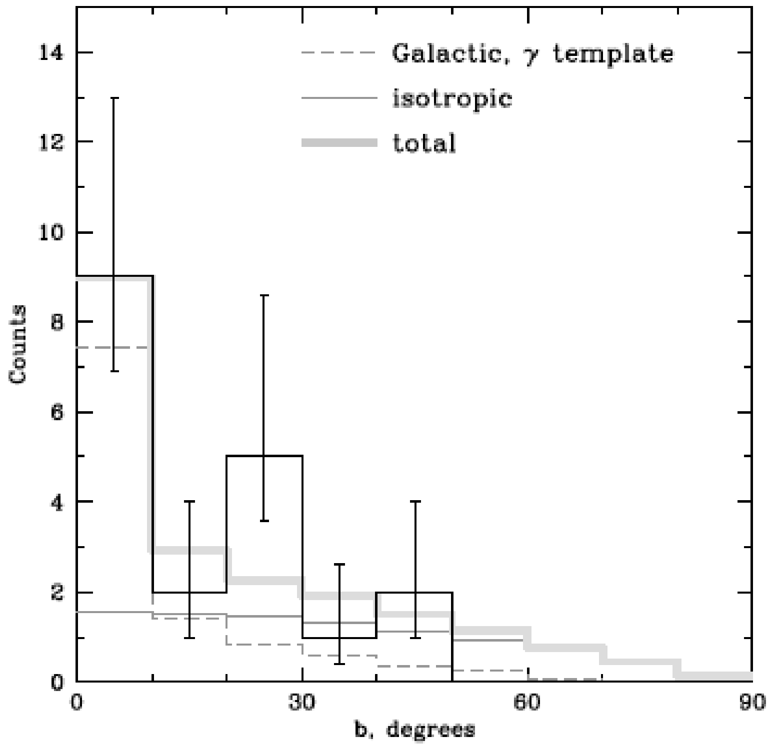
First 3 years: half of ICECUBE events E>100 TeV are consistent with Galactic plane. Are they correlate with gamma-rays?

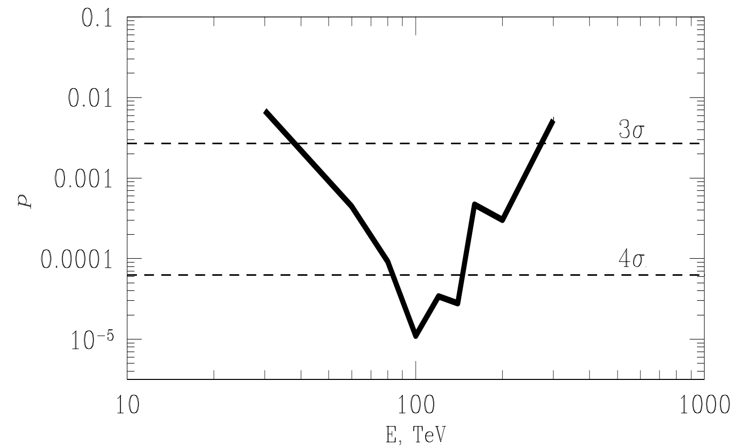




A.Neronov, D.S. and C.Tchernin, Phys.Rev.D 89 (2014) 10, 103002 arXiv:1307.2158

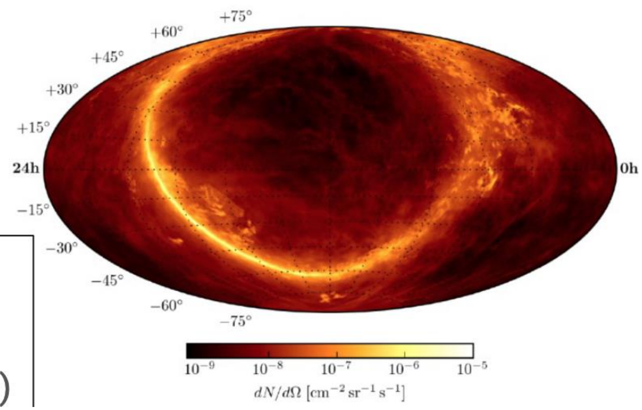
Evidence of Galactic component in 4 year IceCube data E>100 TeV



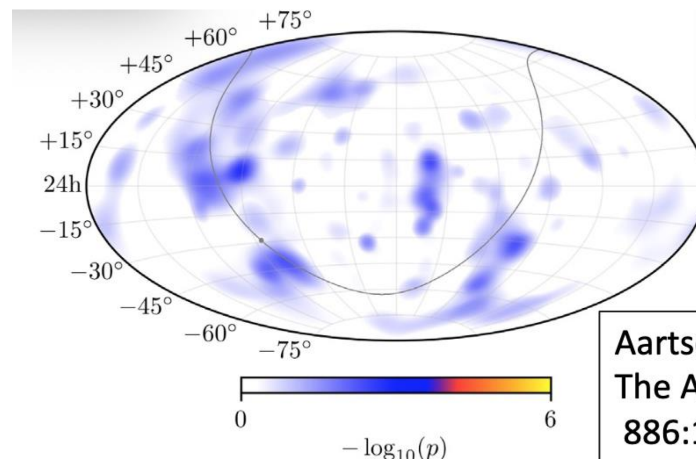


A. Neronov & D.S. arXiv: 1509.03522

IceCube galactic plane



Kheirandish
Astrophysics
and Space
Science 365(6)

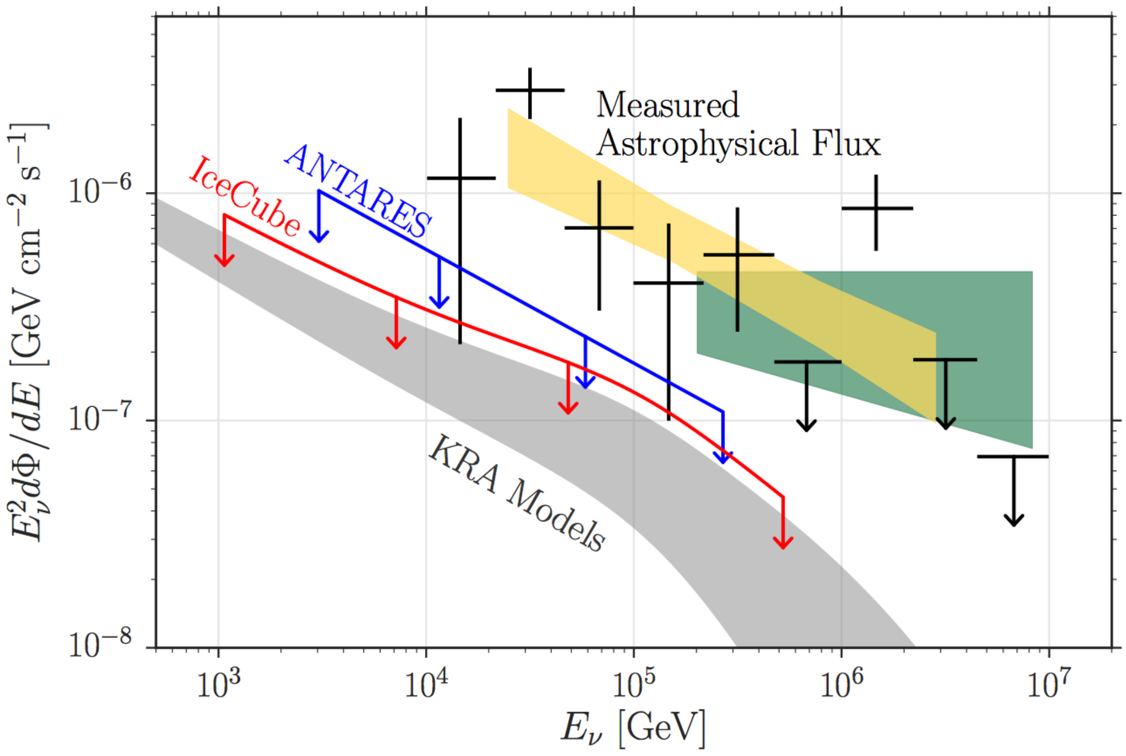


analysi
0.85 *

Aartsen et al.,
The Astrophys
886:12, 2019

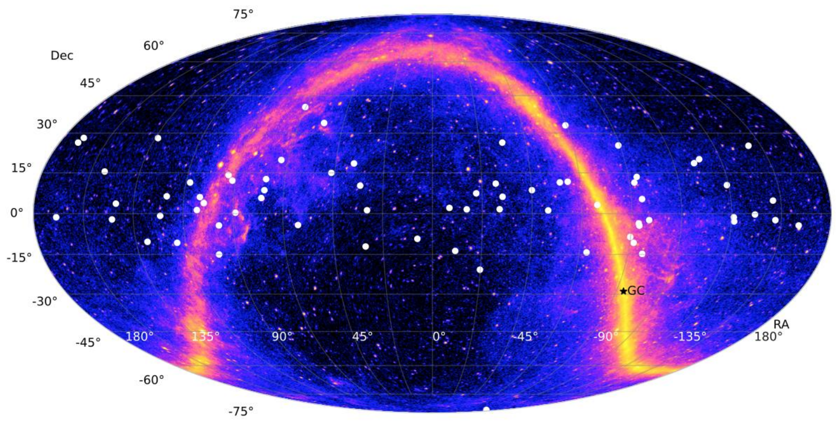
Fermi LAT and IceCube data

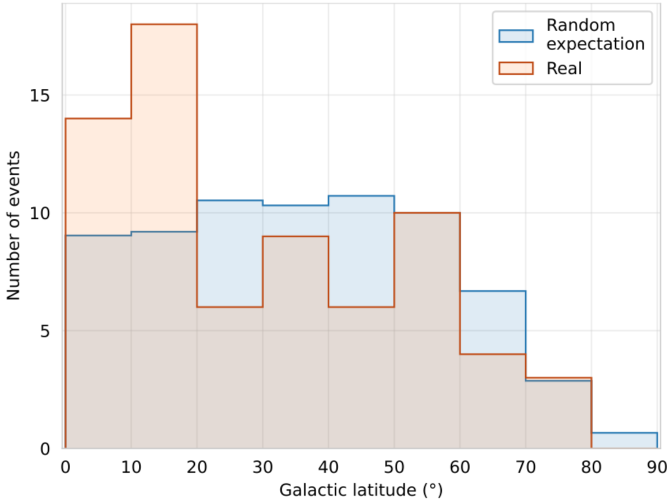
IceCube and ANTARES galalactic plane models limits



ICRC 2017

IceCube muon neutrinos from Galaxy at 20 degree scale



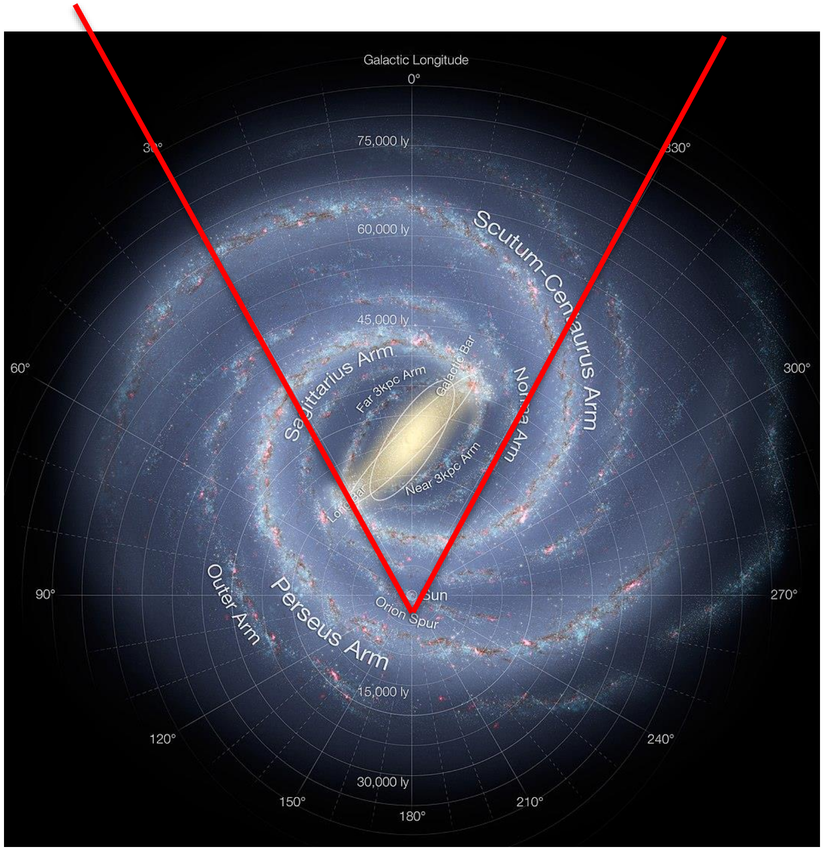


4.3 sigma excess in 20 degrees from galactic plane

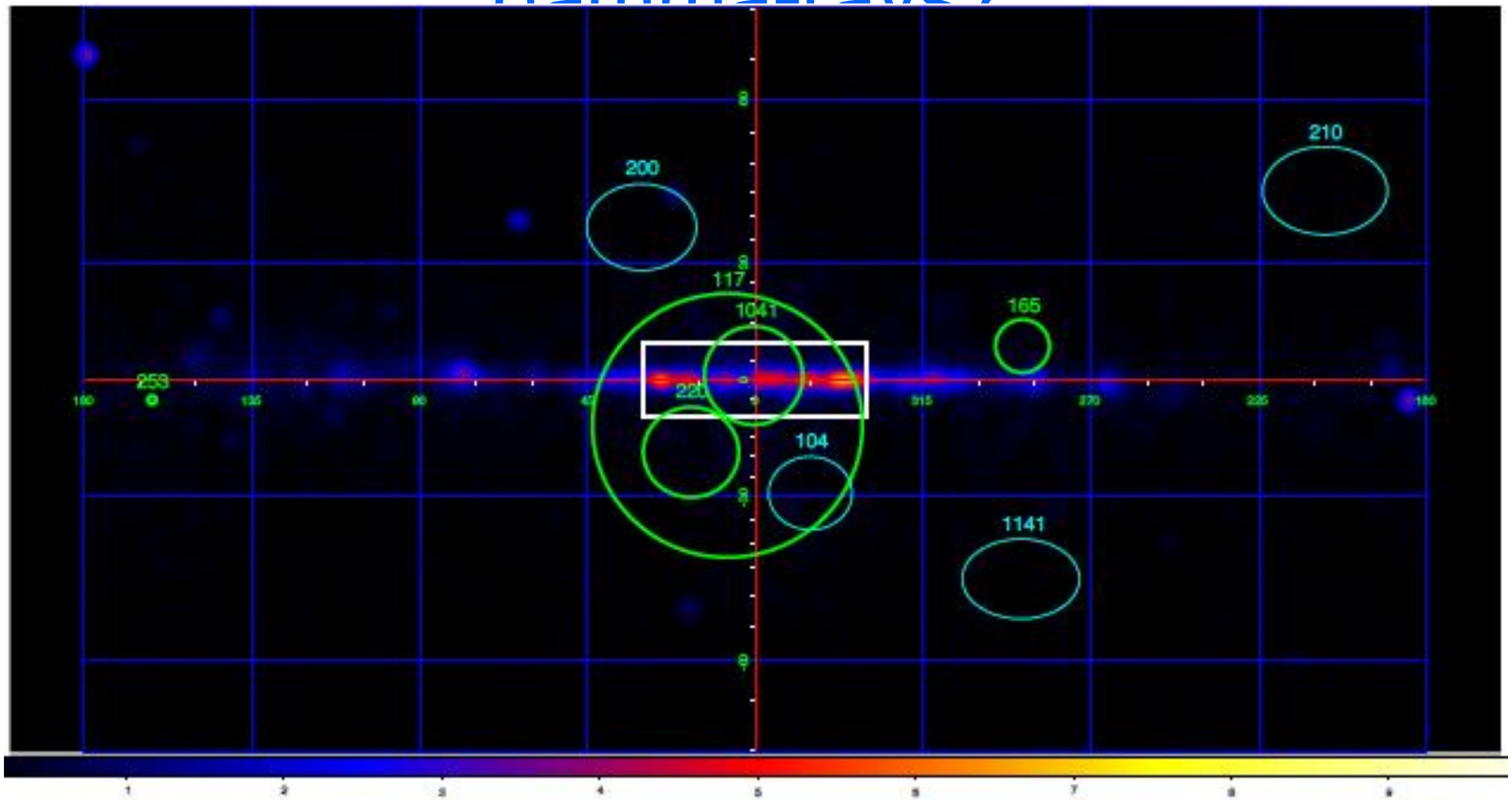
70 events: 23 33% atmospheric background
13 18.5% astro-anisotropic: galactic
34 48.5% astro-isotorpic: extragalactic

Yu.Kovalev, A.Plavin and S.Troitsky , 2208.08423

Milky Way Galaxy: Ridge

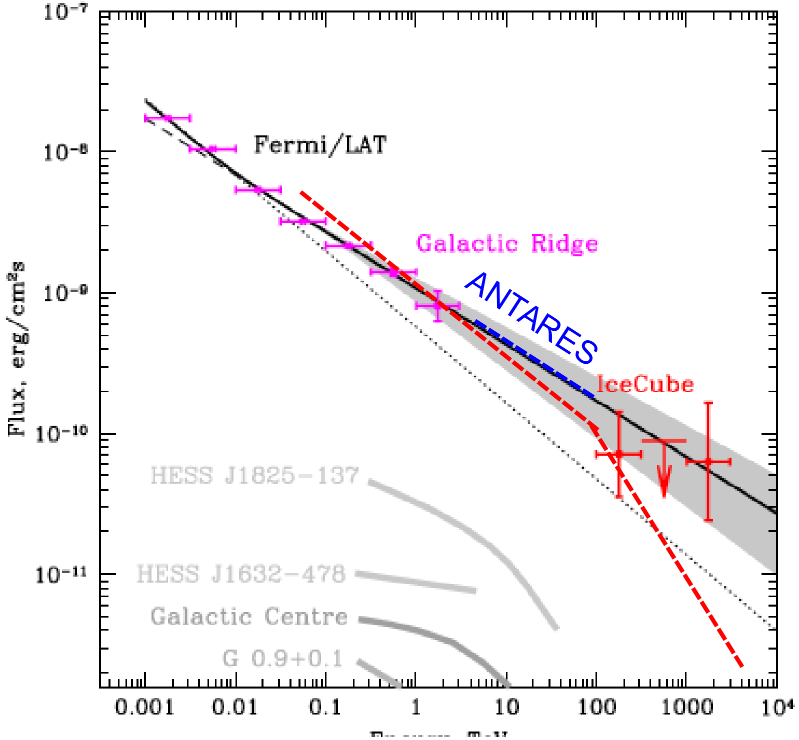


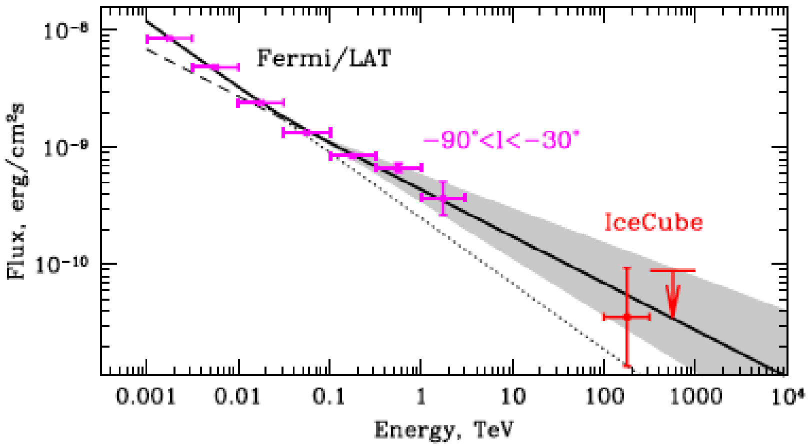
Half of ICECUBE events E>100 TeV are in Galactic plane. Are they correlate with gamma-rays?



A.Neronov, D.S. and C.Tchernin, arXiv:1307.2158

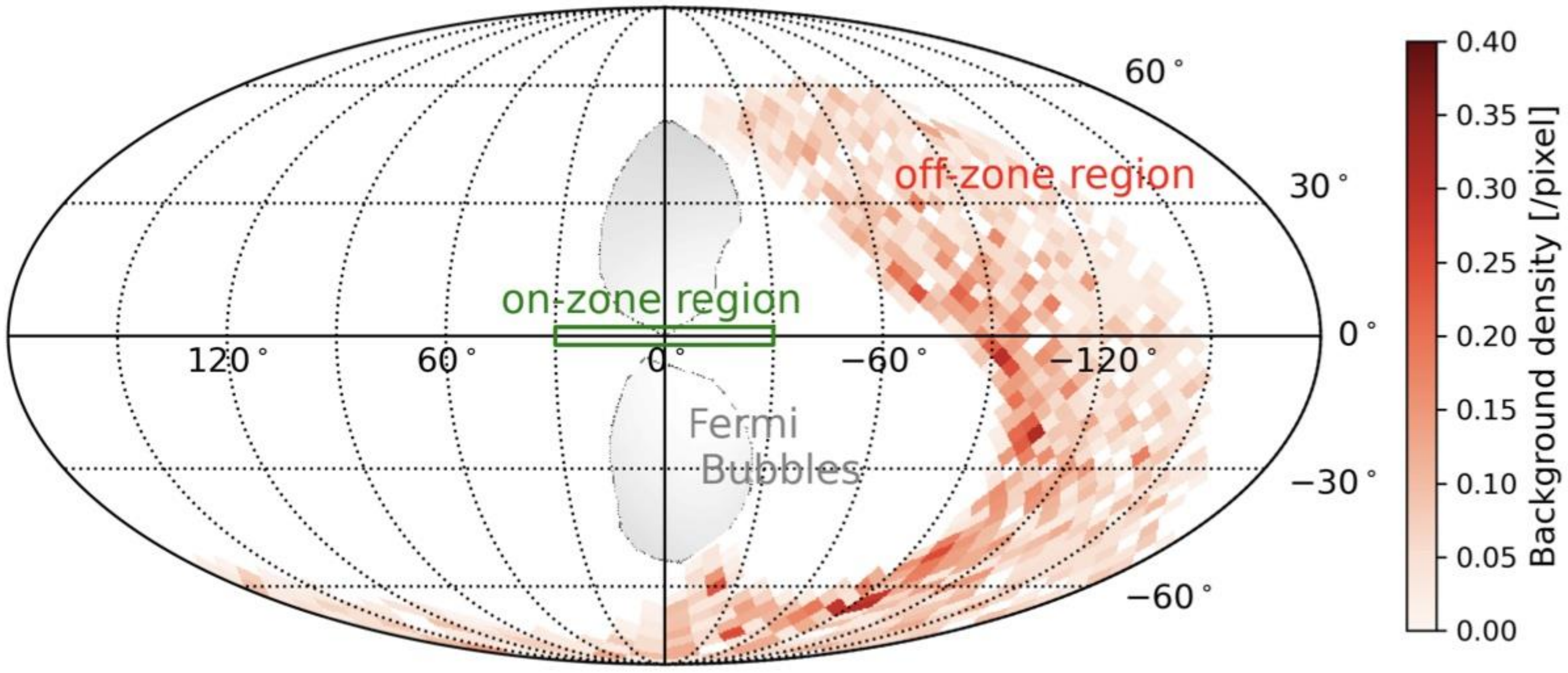
Real multimessenger fluxes, alpha=2.5





V.Berezinsky & A.Smirnov 1975

ANTARES 2022



A.Albert et al, arXiv:2212.11876

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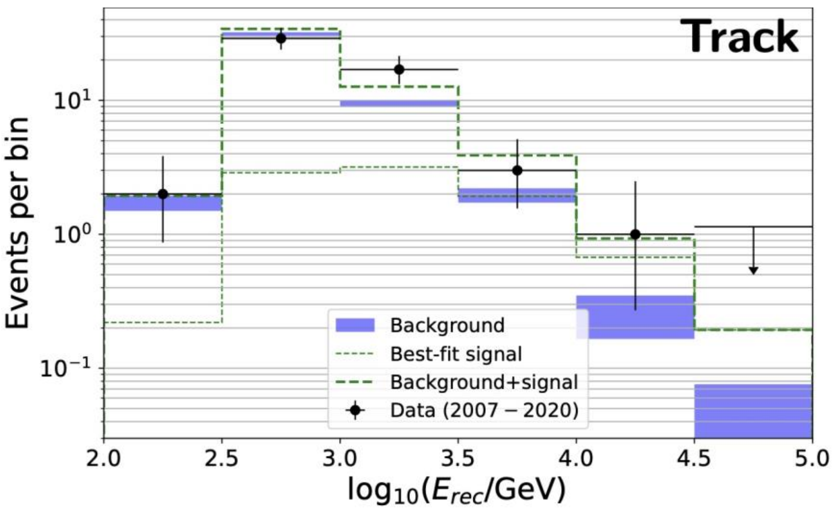

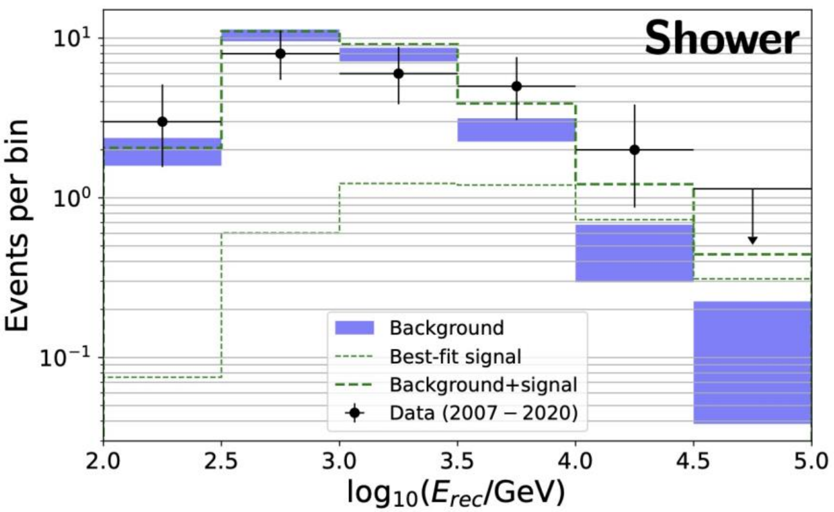

A.Albert et al, arXiv:2212.11876

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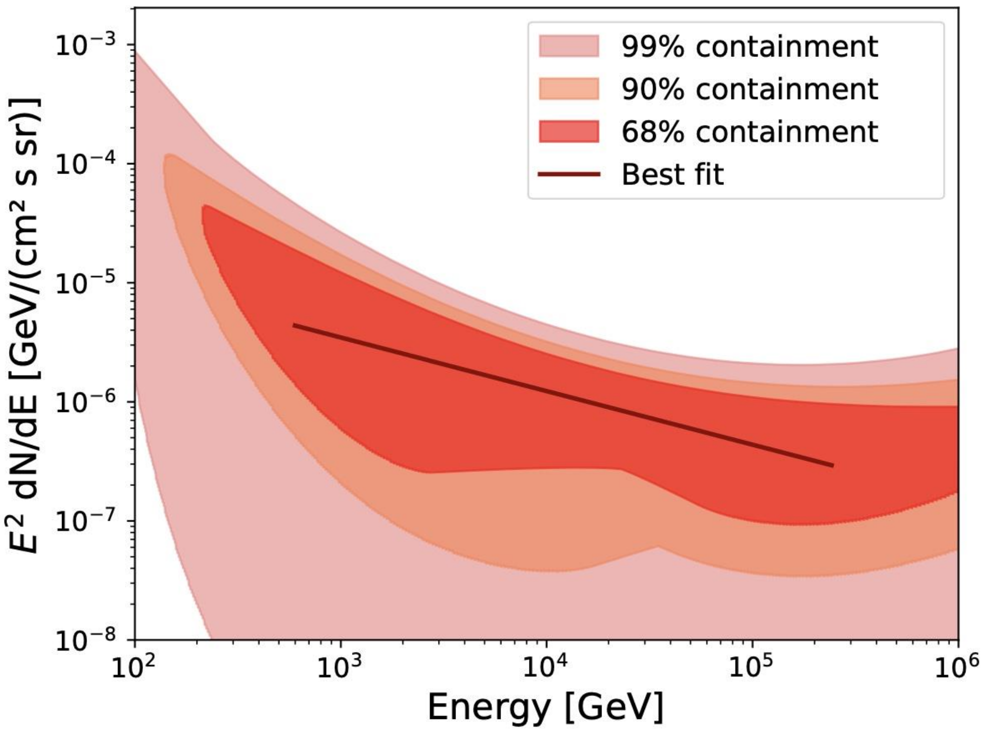
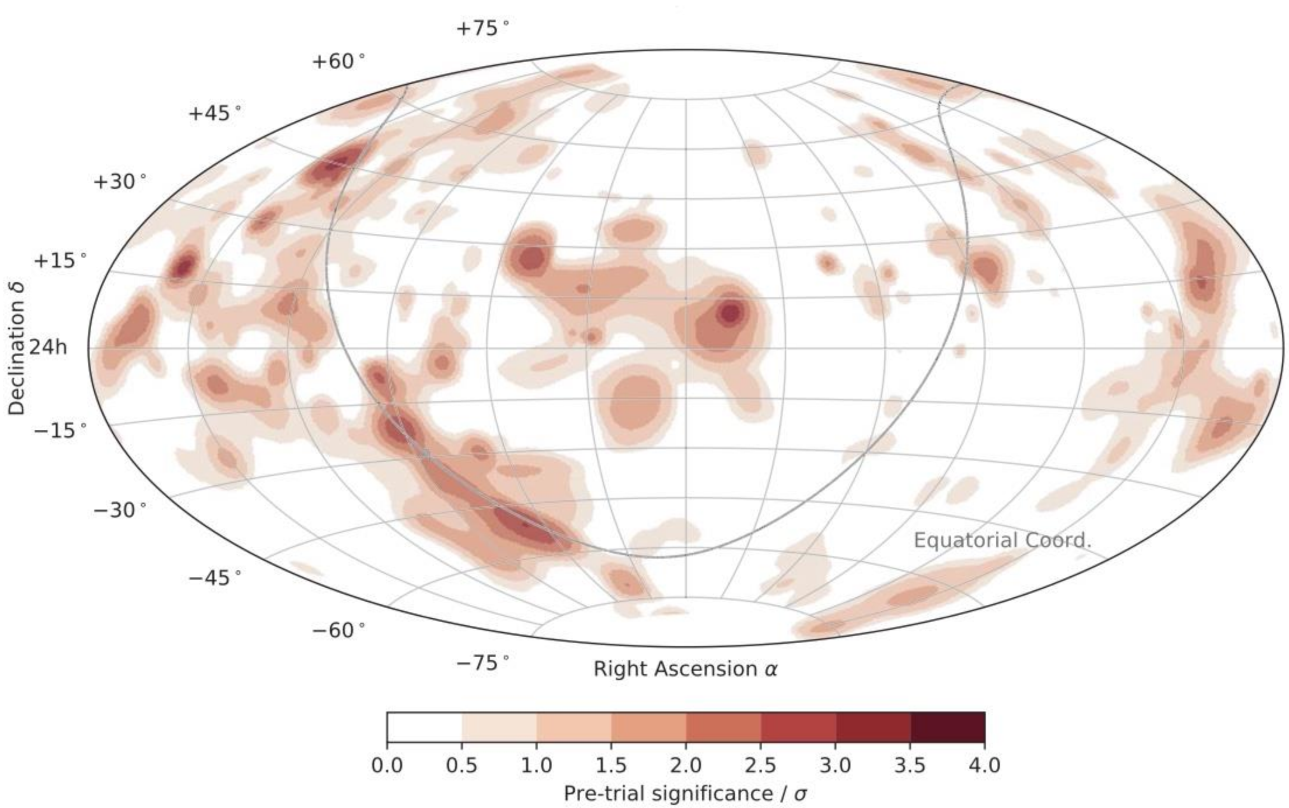


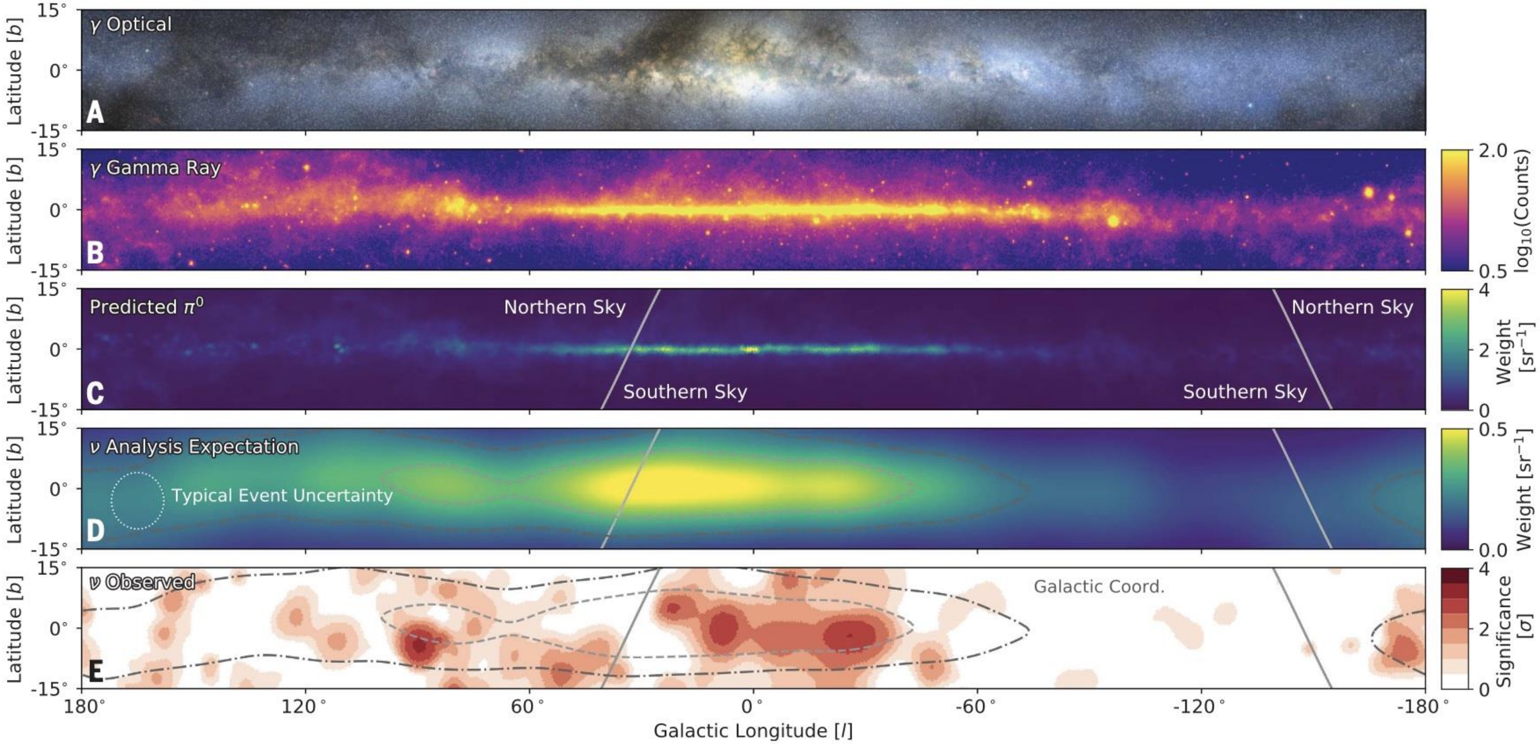
A.Albert et al, arXiv:2212.11876

IceCube cascades



IceCube collaboration, Science **380**, 1338 (2023)

IceCube 10 years km3 cascades galactic plane

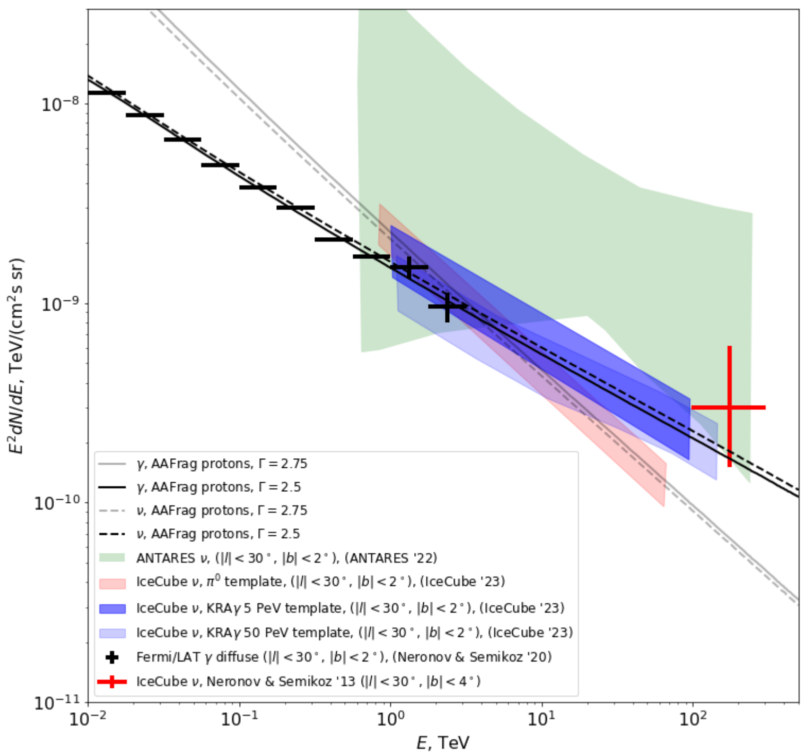


IceCube collaboration, Science **380**, 1338 (2023)

IceCube and ANTARES ridge

Flux with Gamma=2.5 in Galactic Ridge

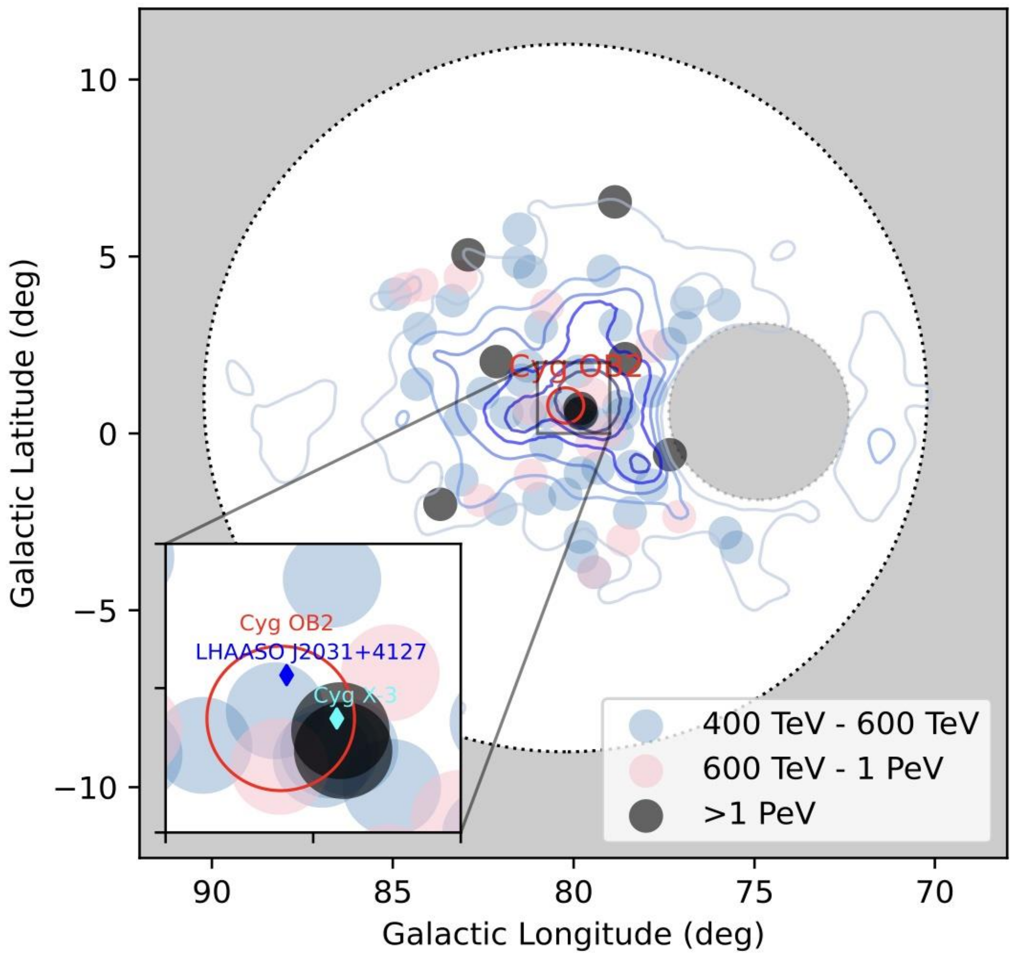
Galactic Ridge



A.Neronov et al, arXiv:2307.07978 [astro-ph.HE],

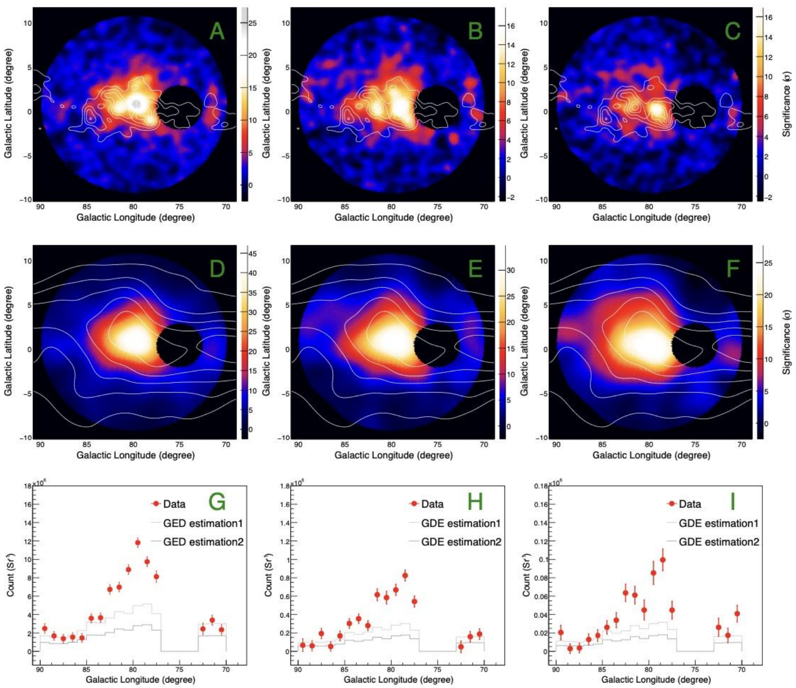
Cygnus region flux in IceCube and LHAASO

Gamma-rays from Cygnus region

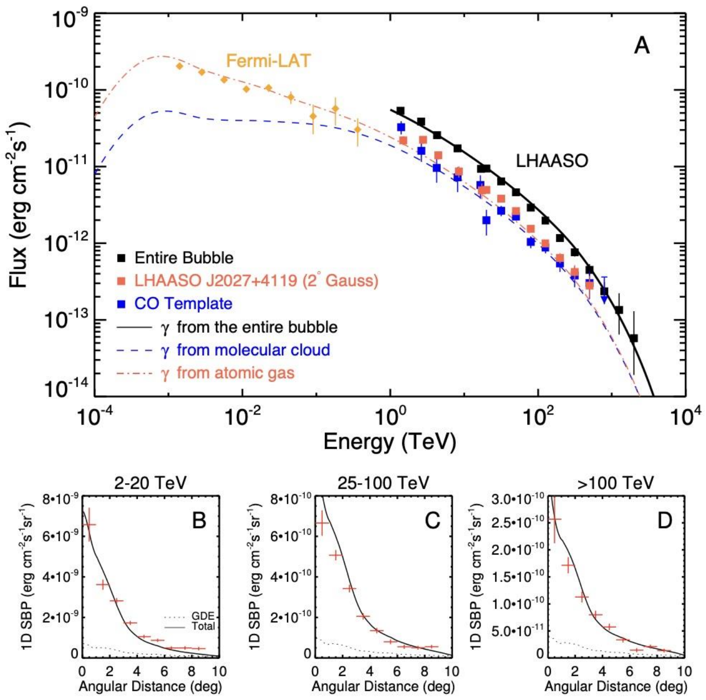


Z.Cao et al.[LHAASO] [arXiv:2310.10100].

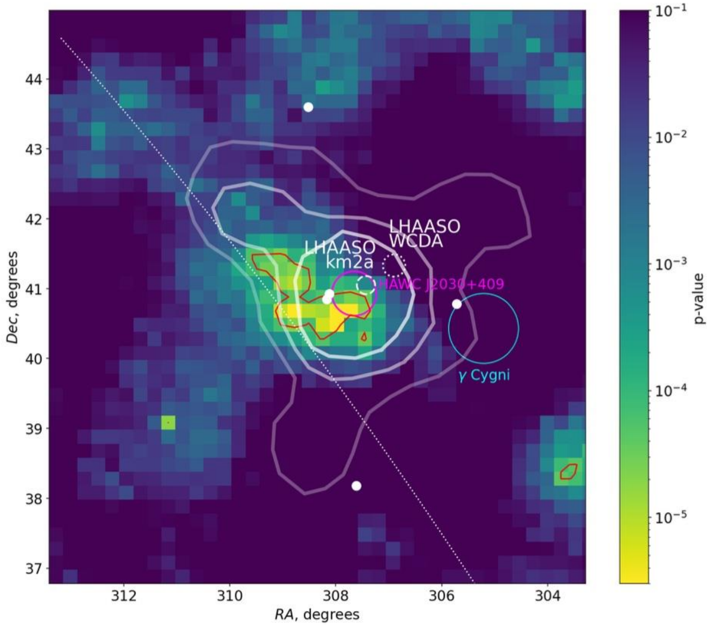
Gamma-rays from Cygnus region

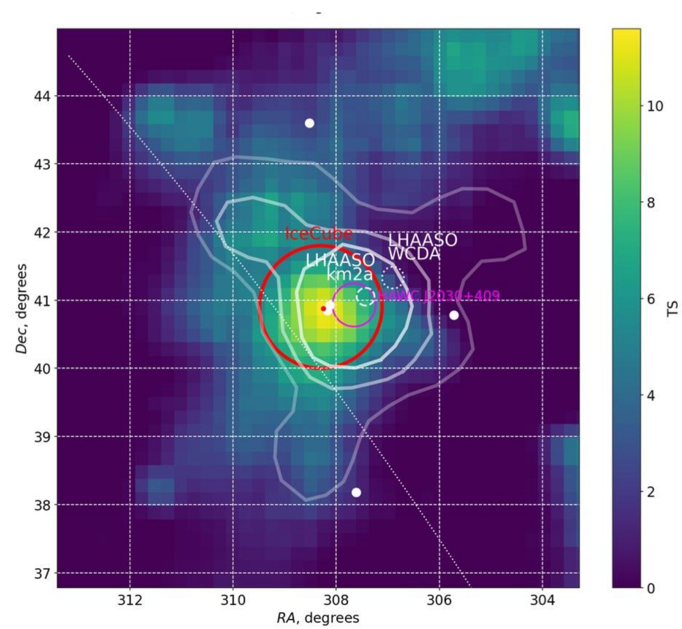


Gamma-rays from Cygnus region



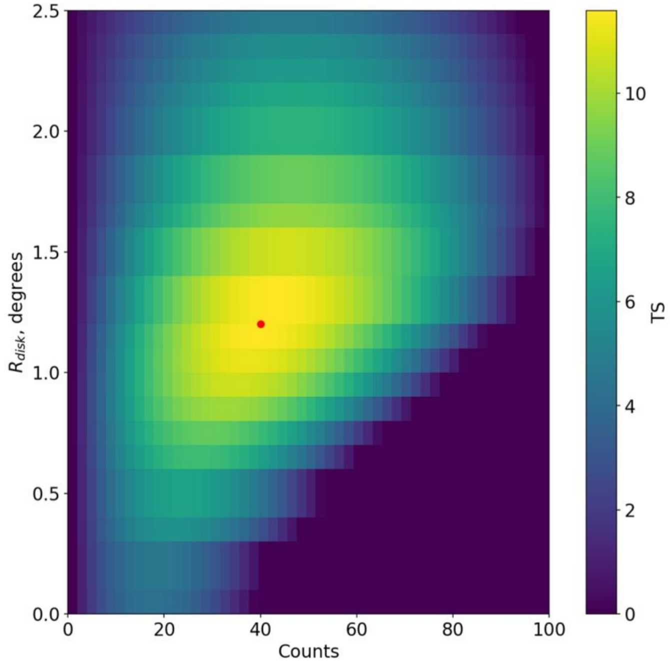
Neutrinos from Cygnus region





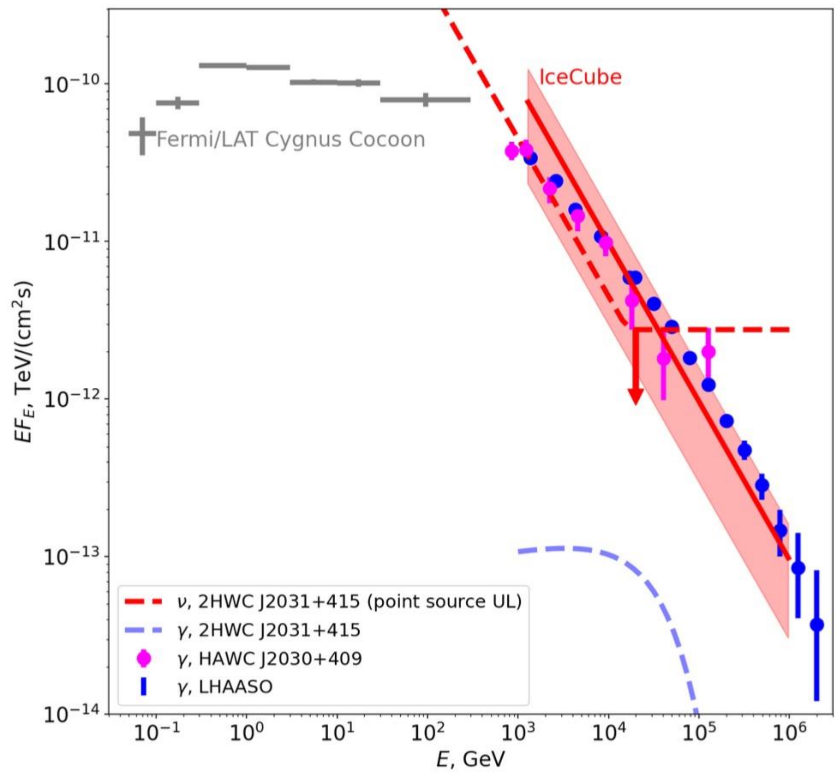
A.Neronov, D.S. and D.Savchenko, arXiv:2311.13711

Neutrinos from Cygnus region



A.Neronov, D.S. and D.Savchenko, arXiv:2311.13711

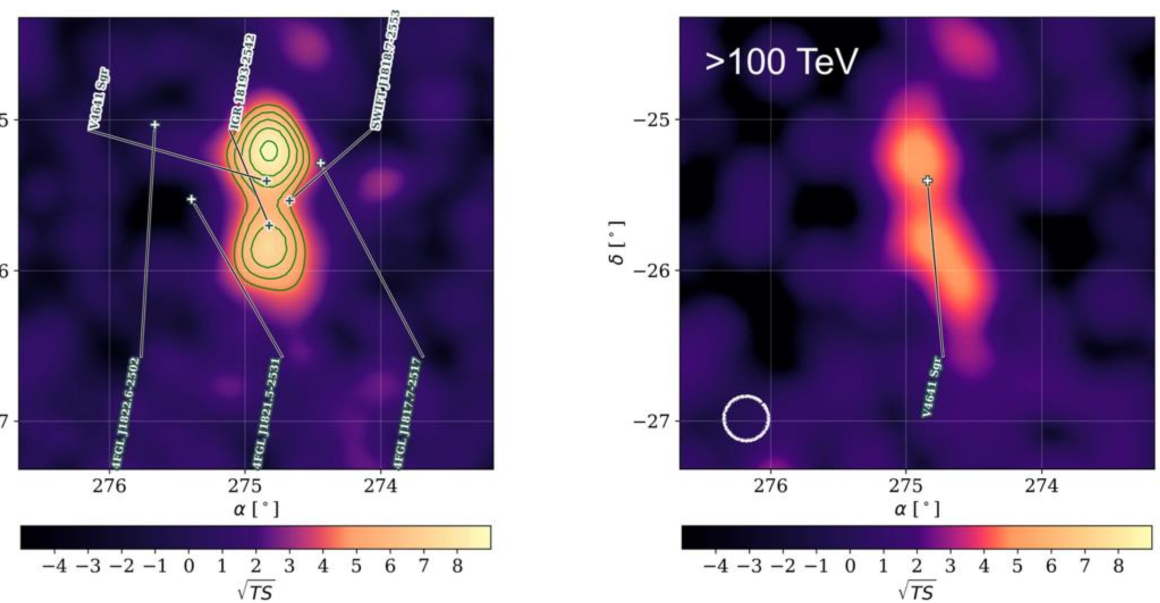
Neutrinos from Cygnus region



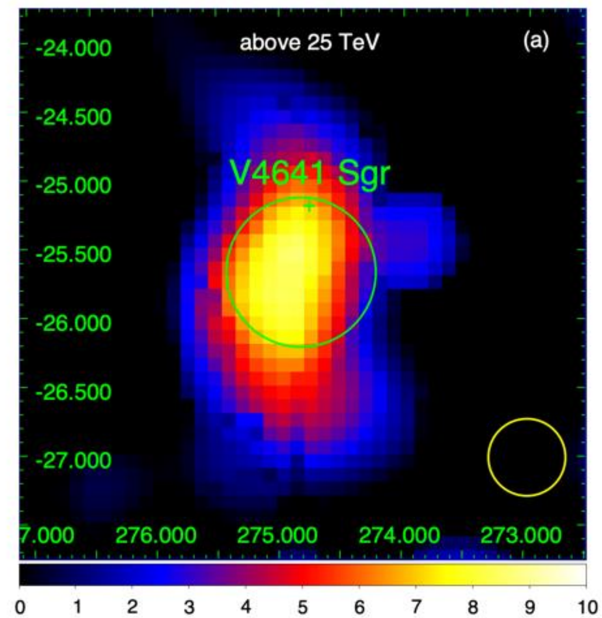
A.Neronov, D.S. and D.Savchenko, arXiv:2311.13711

Gamma-ray and neutrinos from V4146

Gamma-rays from V4146

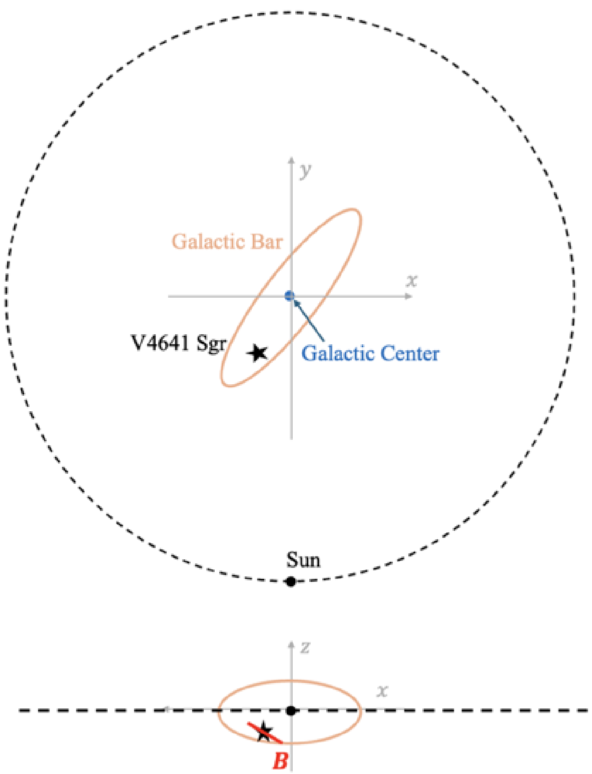


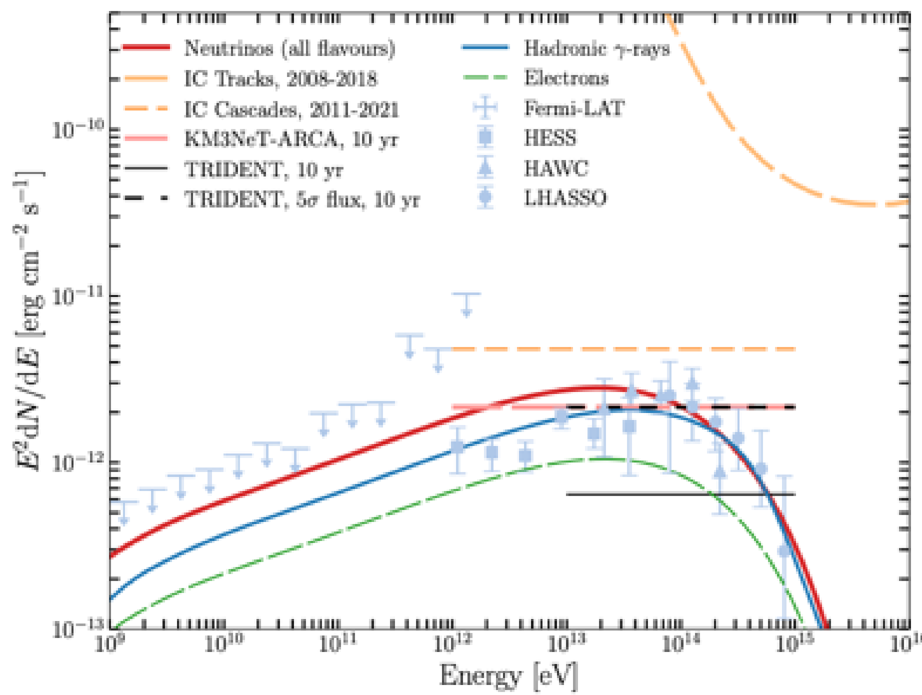
HAWC coll., arXiv:2410.16117



LHAASO coll., arXiv: 2410.08988

Neutrinos from V4146





A.Neronov, F.Oikonomou and D.S., arXiv:2410.17608

Summary

- We can study cosmic ray flux in different places in Galaxy with help of gamma-ray and neutrino observations.
- We are developing new model of cosmic ray propagation at knee, which include anisotropic CR propagation, 3d gas density, new interaction code AAfrag. This 3d anisotropic model of Milky Way can be tested in near future data of LHAASO in gamma-rays and by KM3 and Baikal-GVD neutrino telescopes in neutrinos
- Tibet ASgamma detected first diffuse gamma-ray signal E>100 TeV, which was studied in great details by LHAASO. First study of diffuse background by LHAASO combined with Fermi, confirms that CR spectrum varies in different parts of Galaxy
- IceCube cascade channel signal from galactic plane is dominated by Galactic Ridge. Combined with Fermi, this signal is consistent with earlier HESE IceCube data and with ANTARES hint of signal from Ridge. Multi-messenger data from Galactic Ridge consistent with cosmic ray flux with power law index Gamma=2.5 in this region, confirming variation of cosmic ray spectrum in Galaxy. km3 and Baikal will measure Galactic Ridge with high significance in muon channel.
- Sygnus region is brightest region of Galaxy in multi-TeV domain in North sky. Pevatron source was seen by LHAASO and IceCube at TeV energies.
- V4146 will be seen in future in neutrinos by 10+ km3 detectors