Searching for the origin of Cosmic Rays

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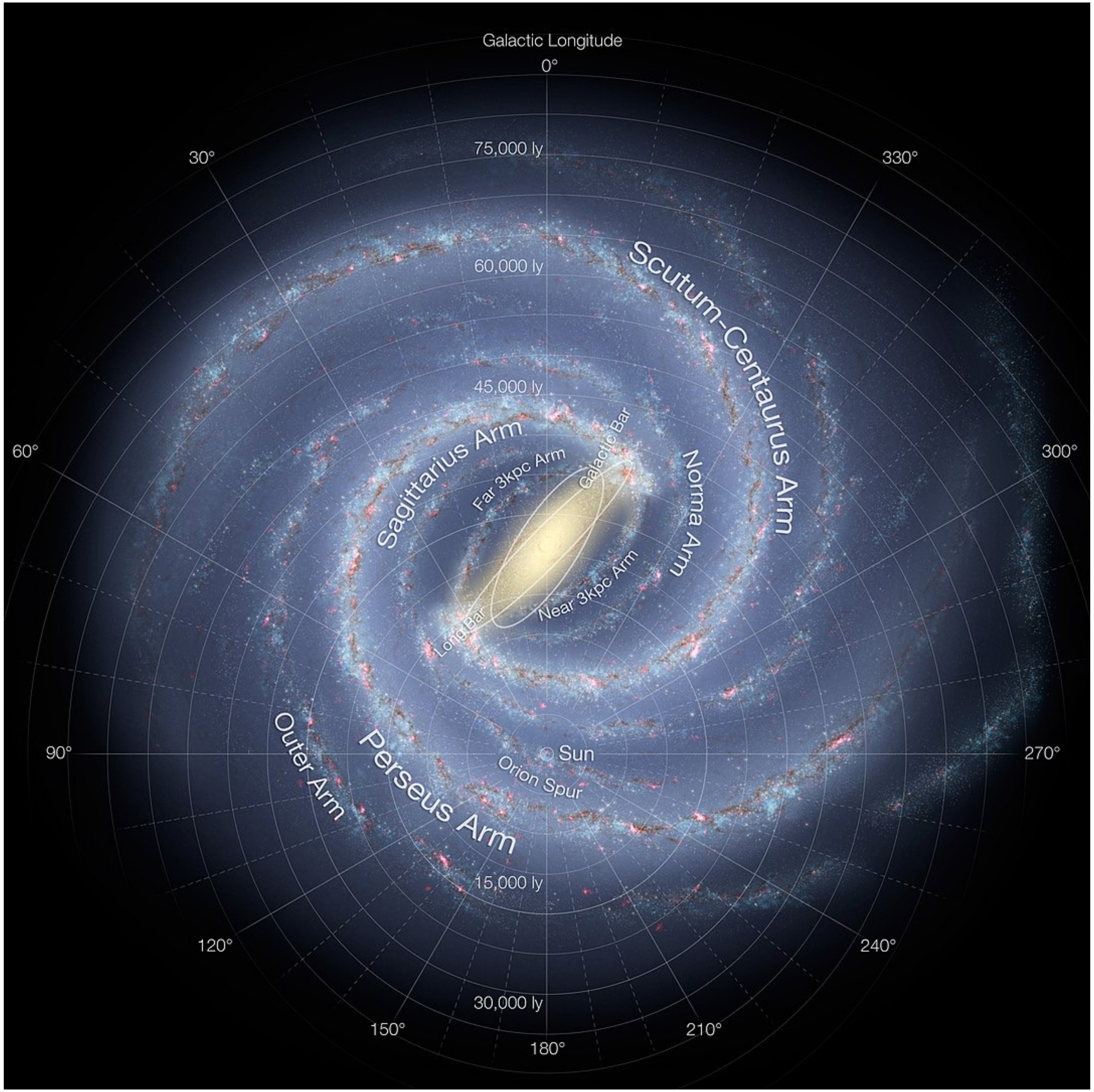
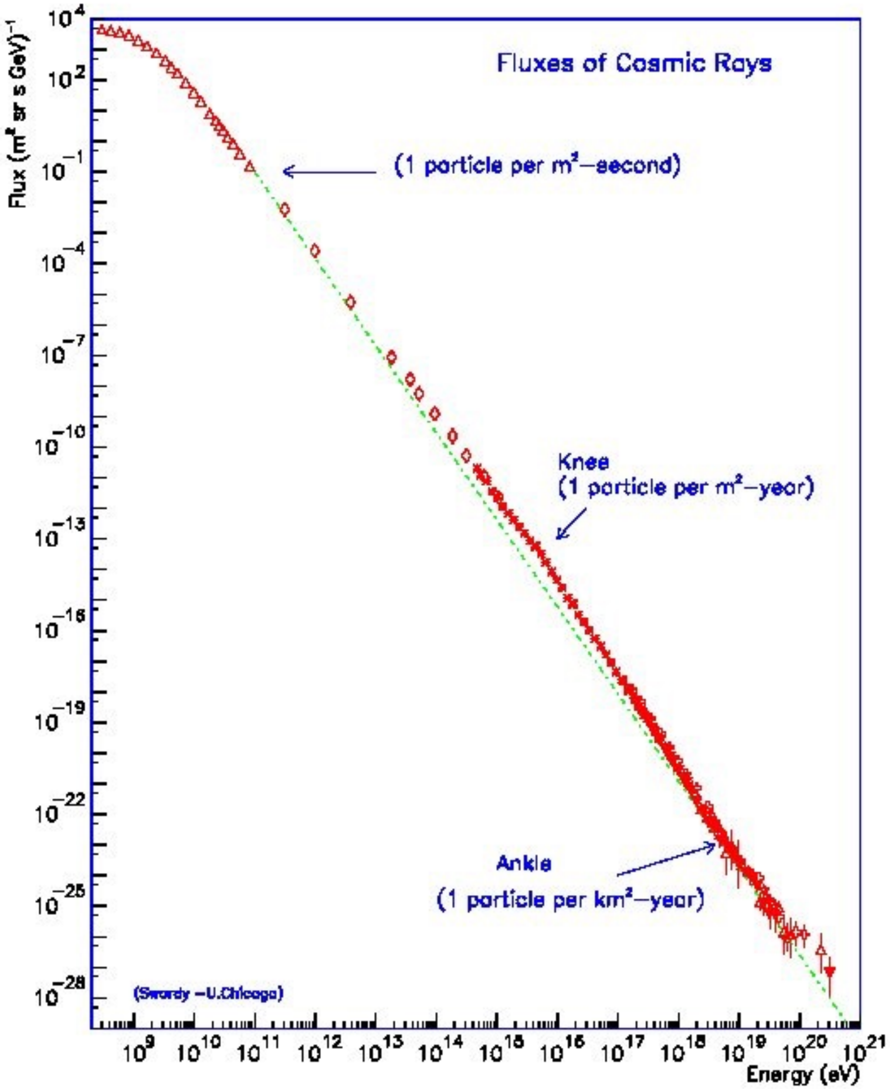
APC, Paris

Plan

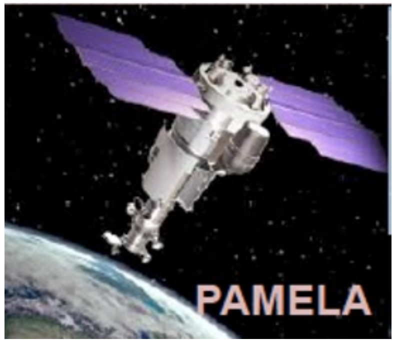
- Cosmic ray measurements at Earth
- Galactic Magnetic Field and cosmic ray propagation
- Search of extra-galactic sources with UHECR
- Gamma-ray and neutrino signatures of Galactic sources
- Conclusions

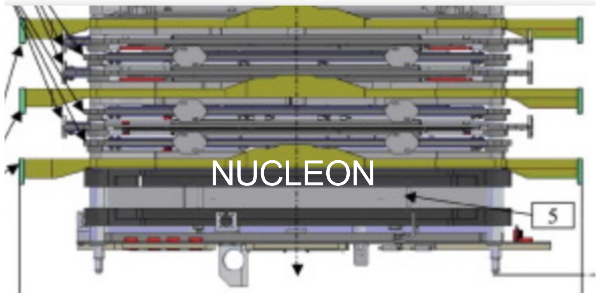
Cosmic ray measurements at Earth

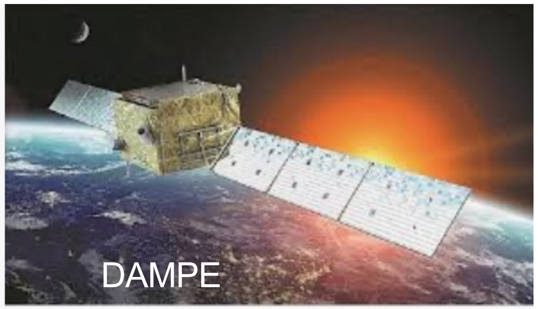

Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
180°
210°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

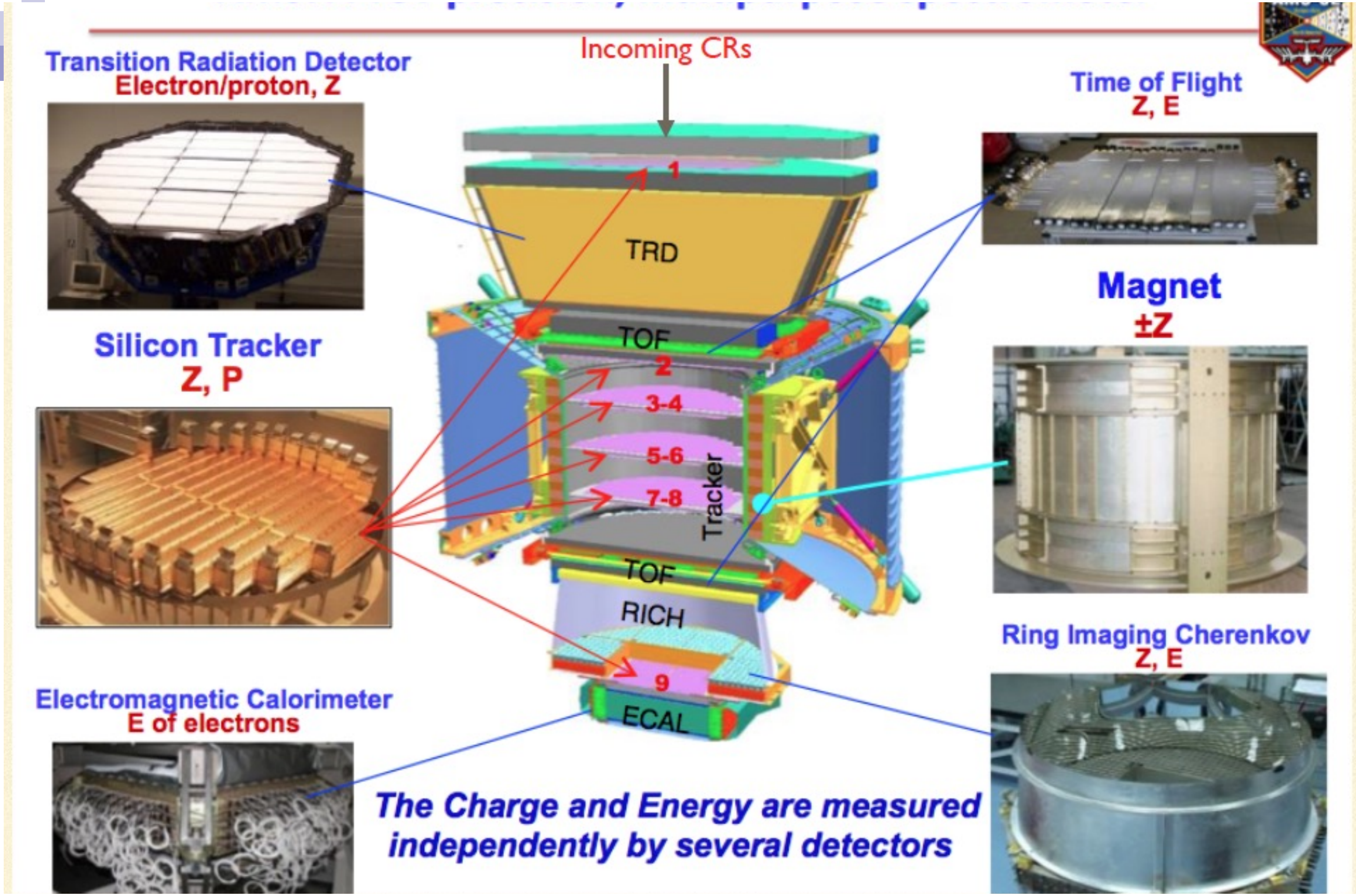

Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
(Swordy –U.Chicago)
Flux (m² sr s GeV)⁻¹
Energy (eV)

Direct Cosmic Ray measurements

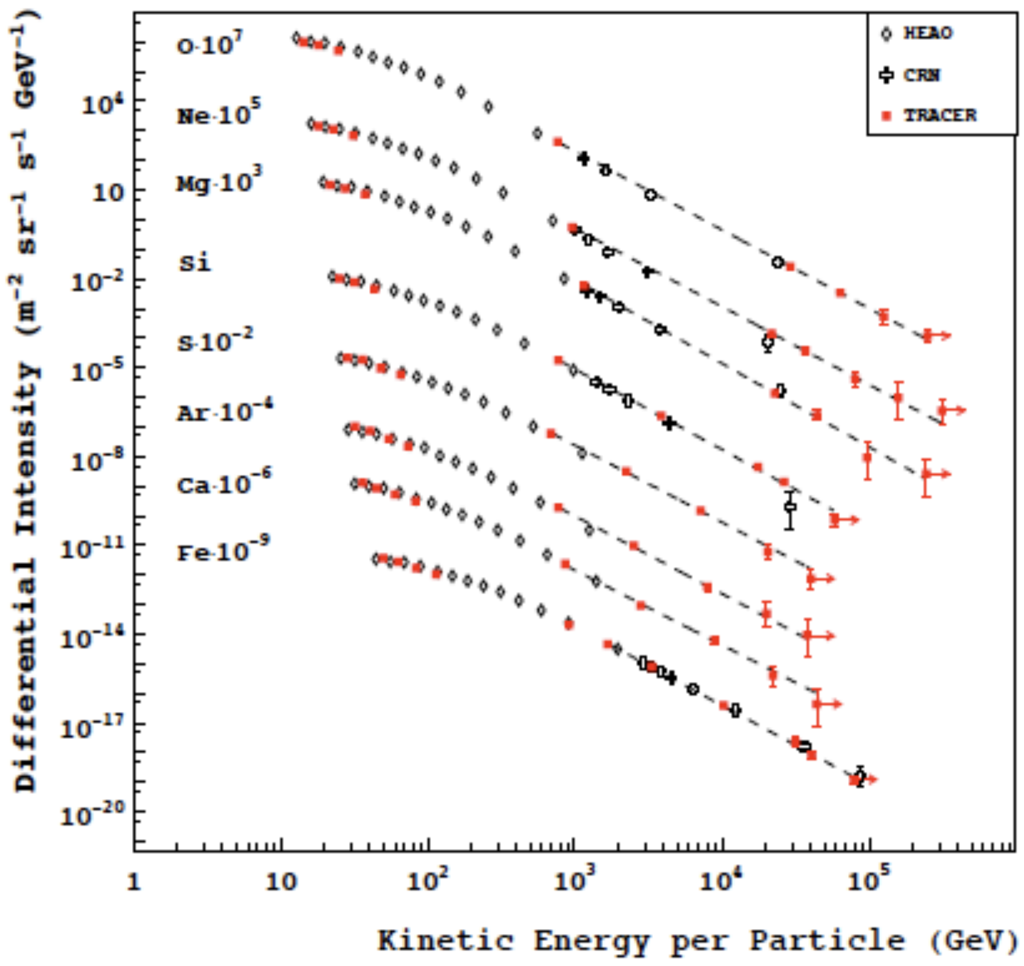




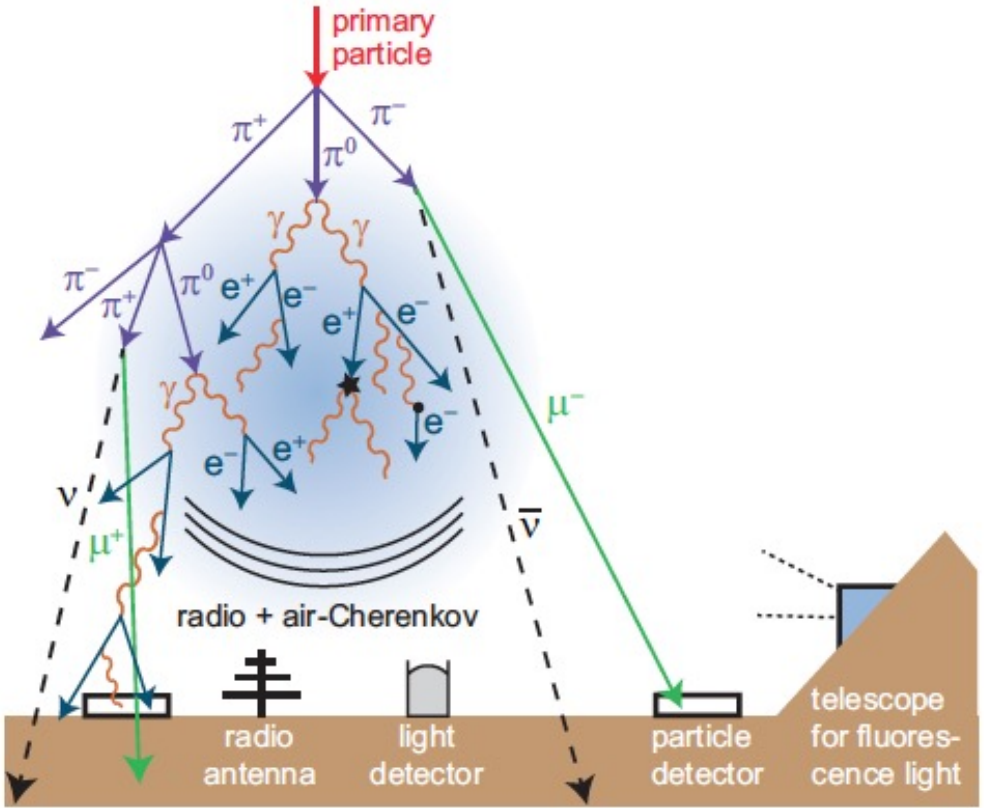


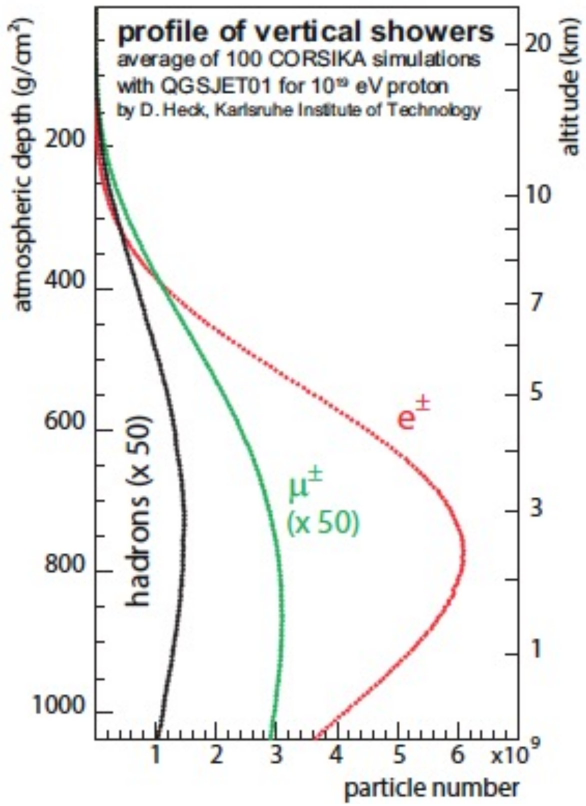

Incoming CRs
Transition Radiation Detector
Electron/proton, Z
Time of Flight
Z, E
TRD
TOF
1
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
Magnet
±Z
Silicon Tracker
Z, P
Ring Imaging Cherenkov
Z, E
Electromagnetic Calorimeter
E of electrons
The Charge and Energy are measured independently by several detectors

Spectra of individual nuclei

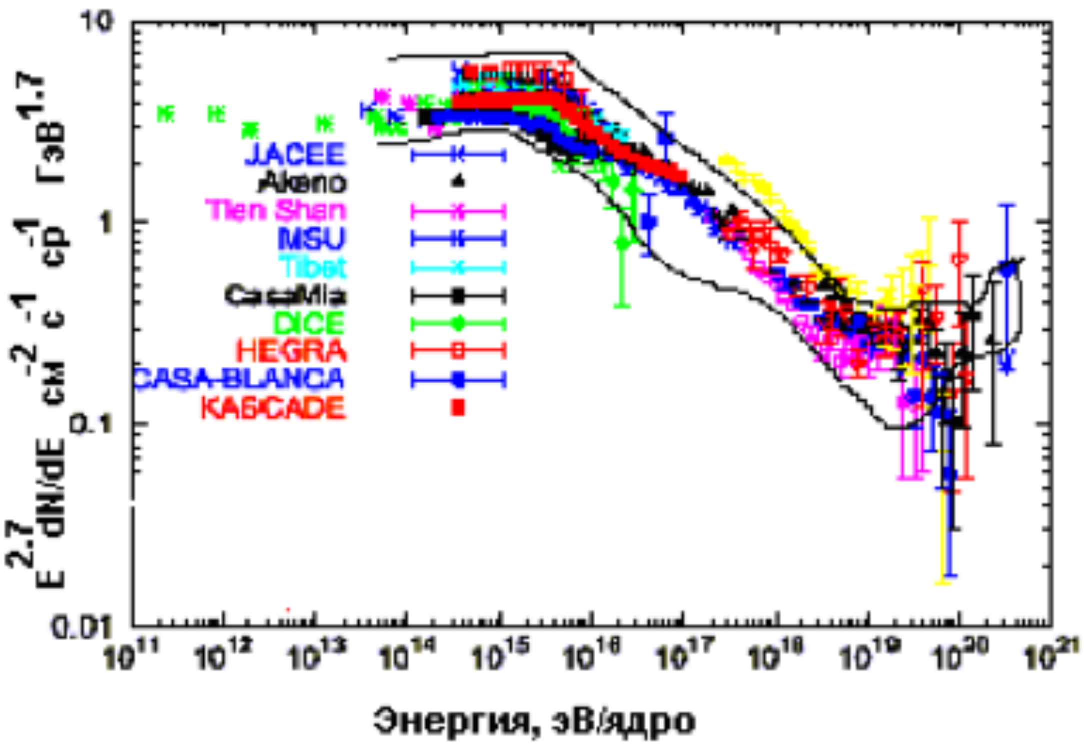


Detection techniques





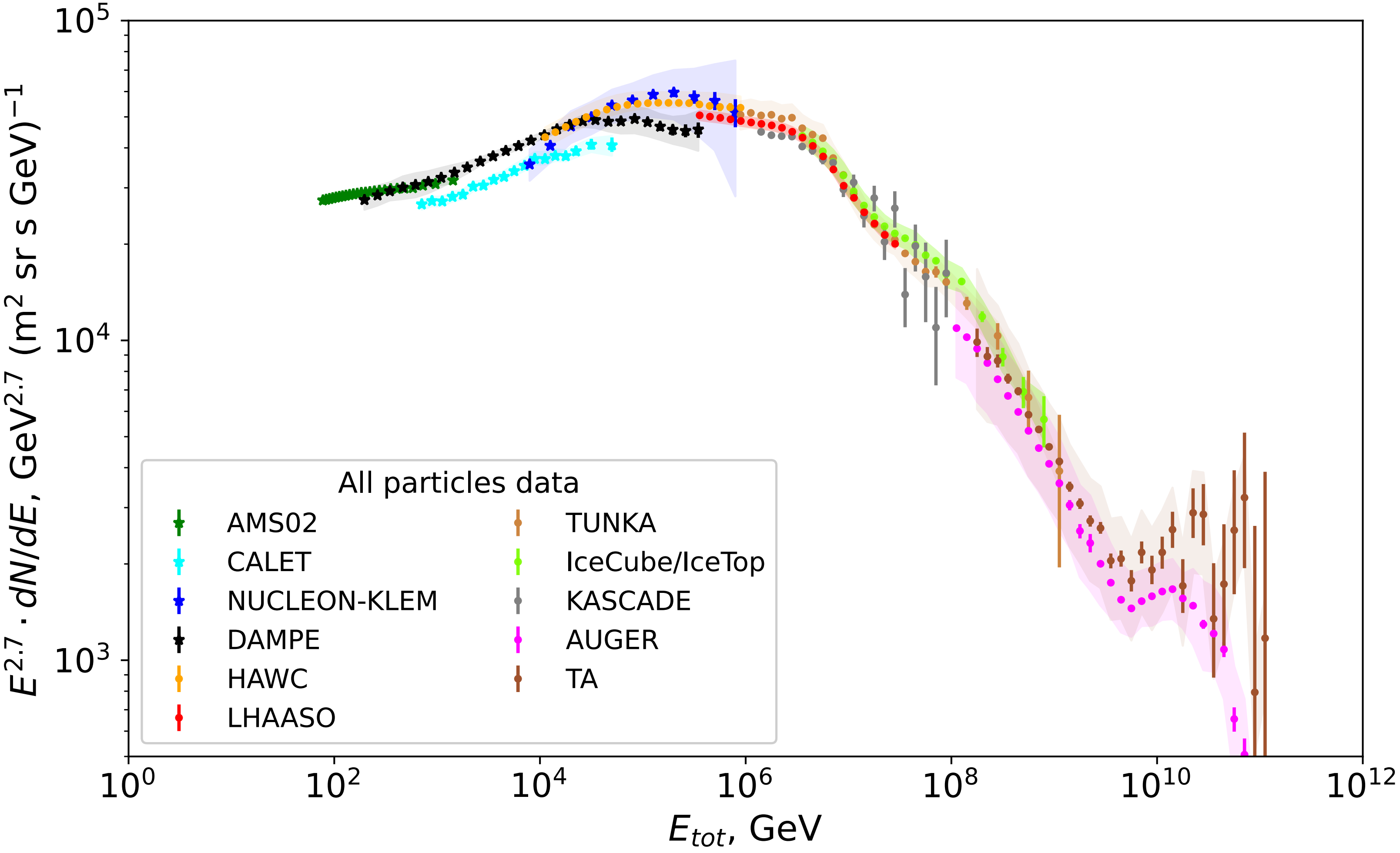
Knee in CR spectrum



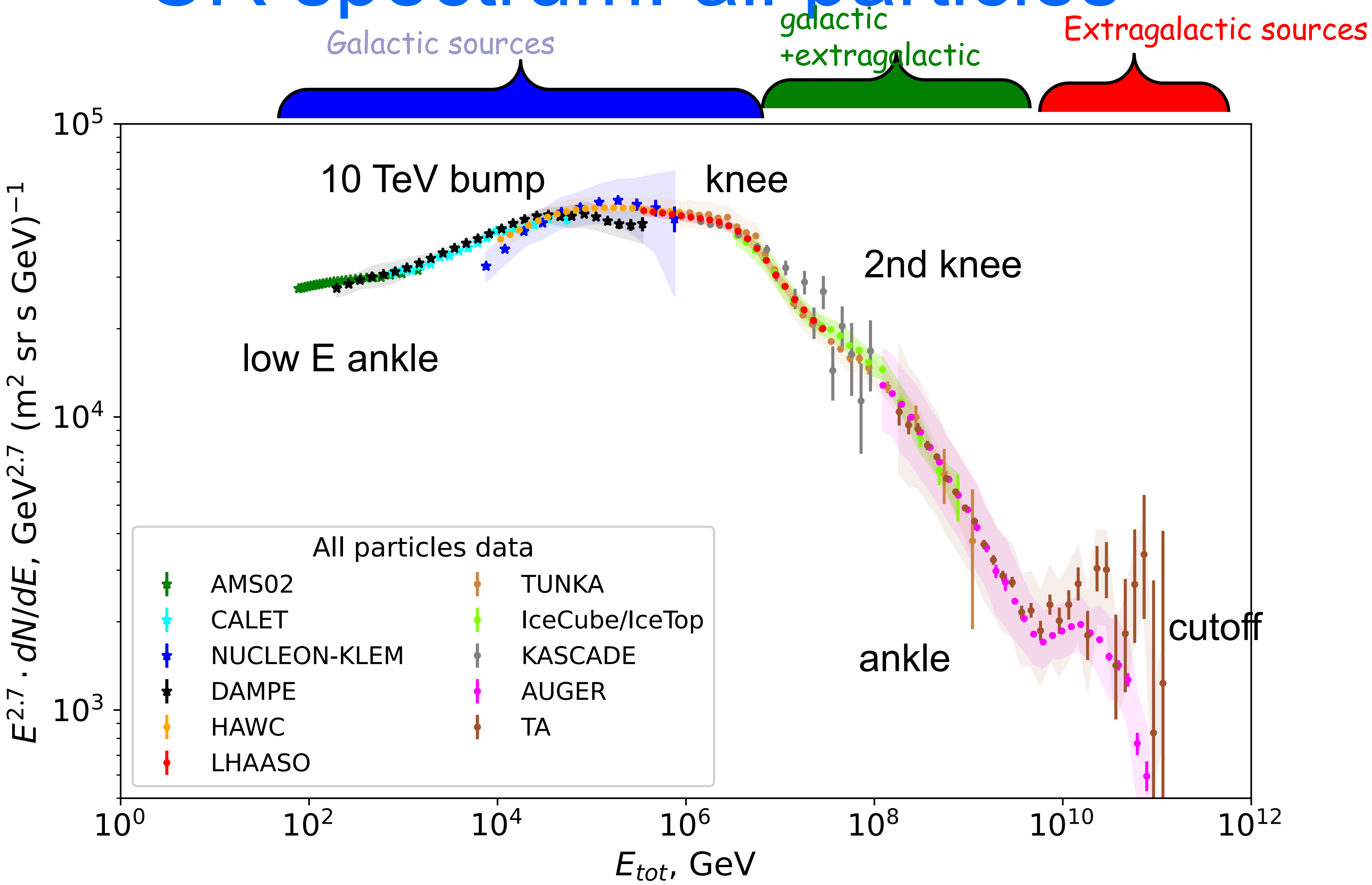
Knee was discovered by Kulikov and Khristiansen in data of MSU Experiment in 1958

All particle spectrum change power law from 2.7 to 3.1 at E=4 PeV

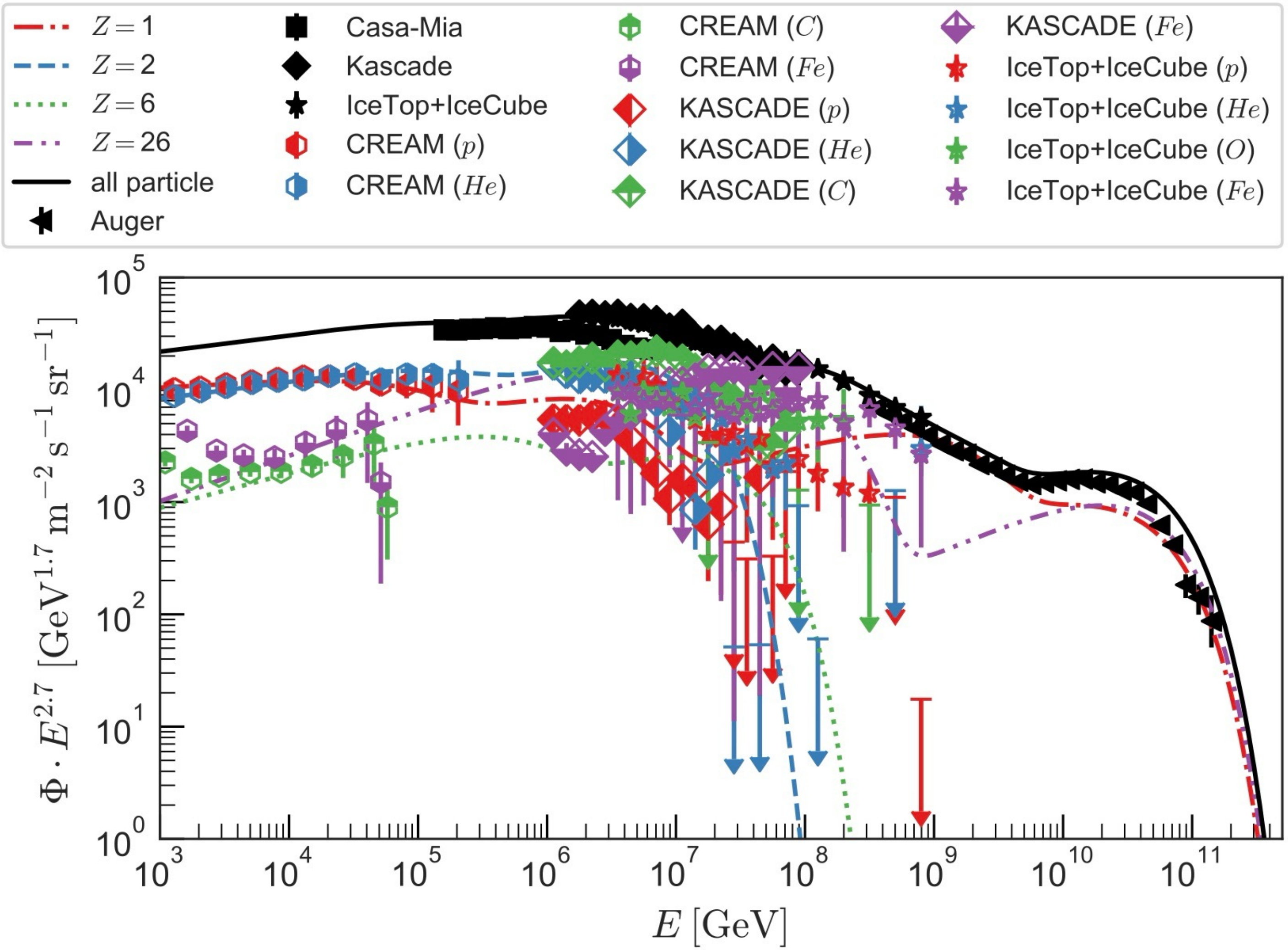
CR spectrum: all particles



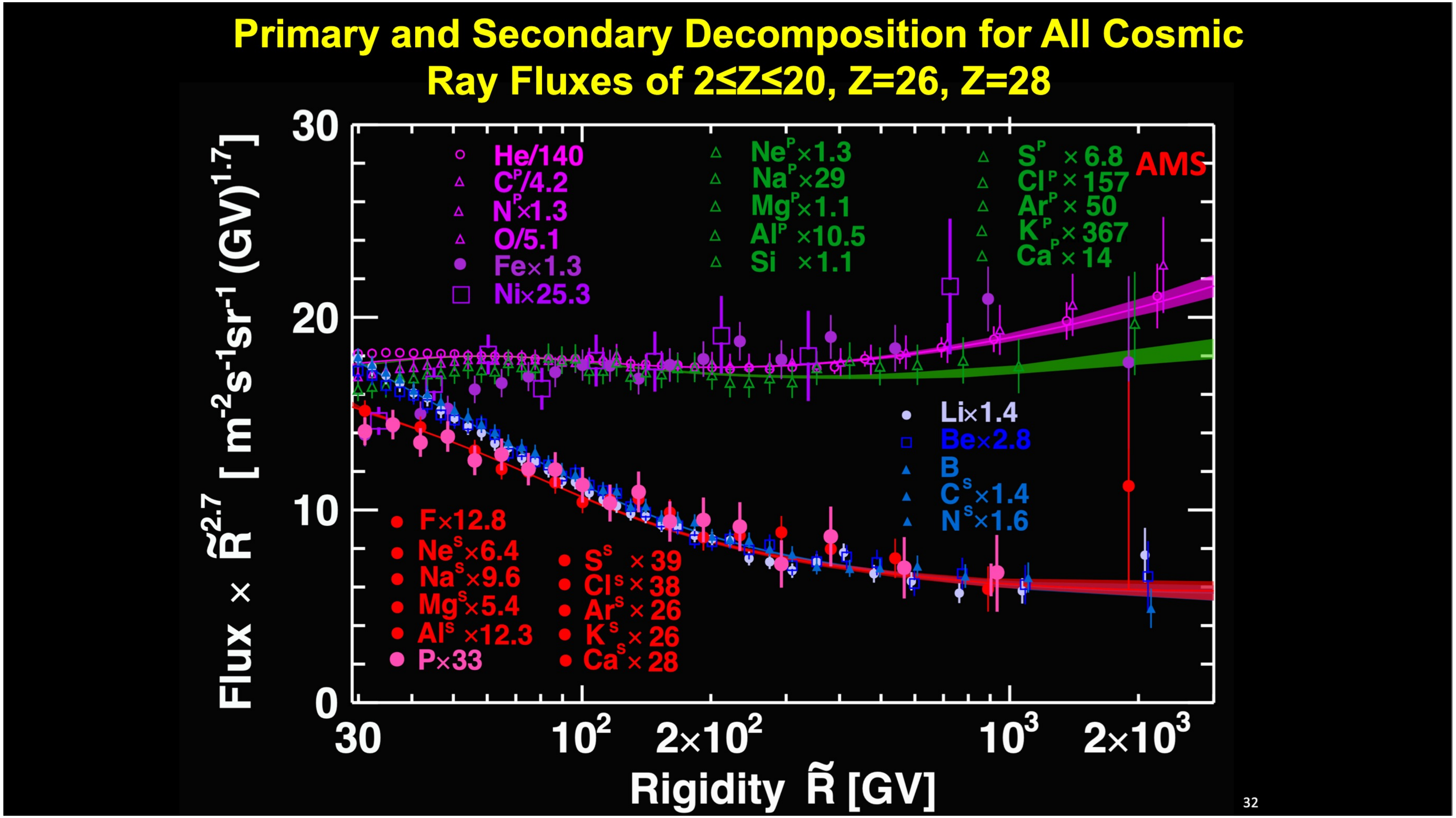
CR spectrum: all particles



CR-composition

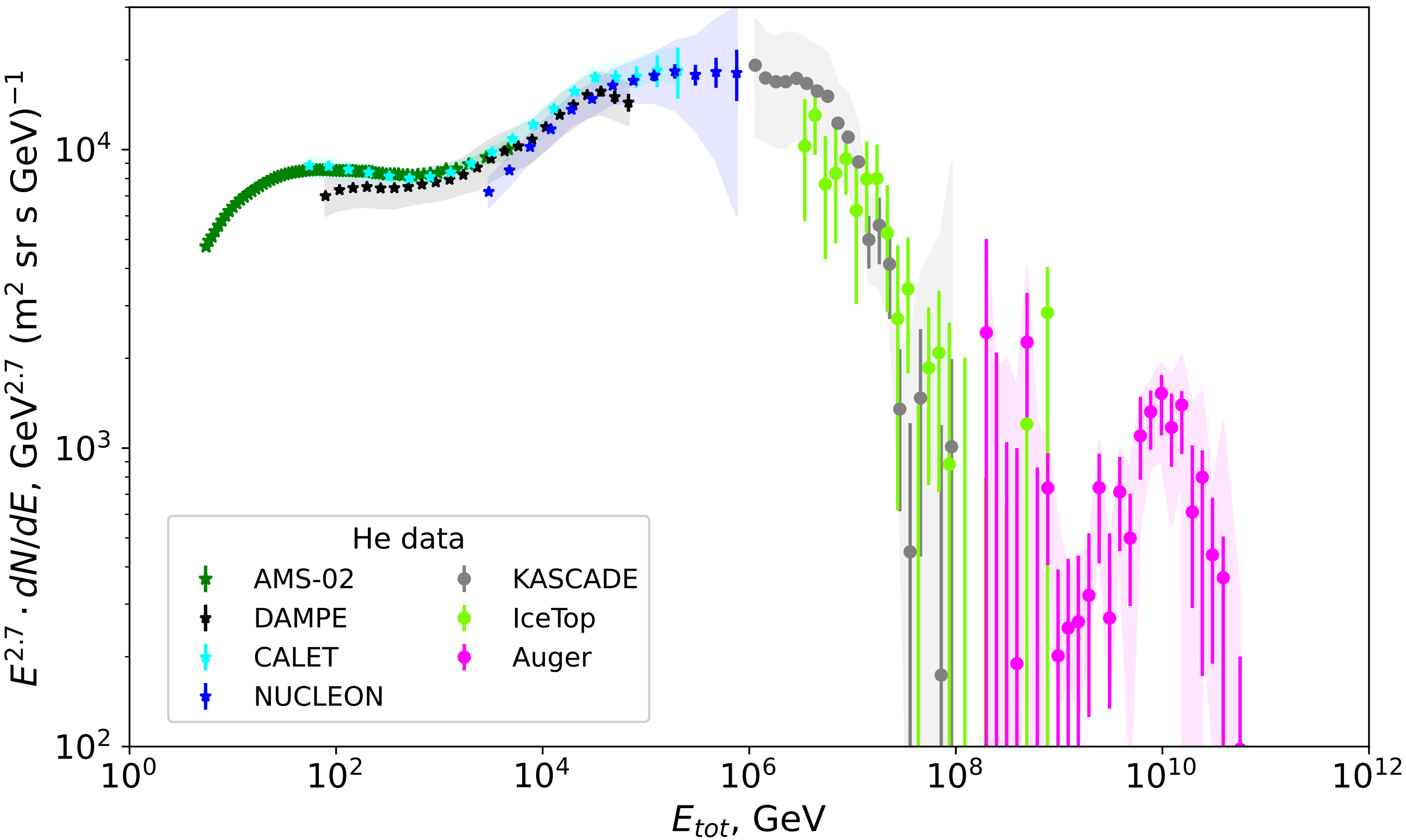


AMS-02 spectra



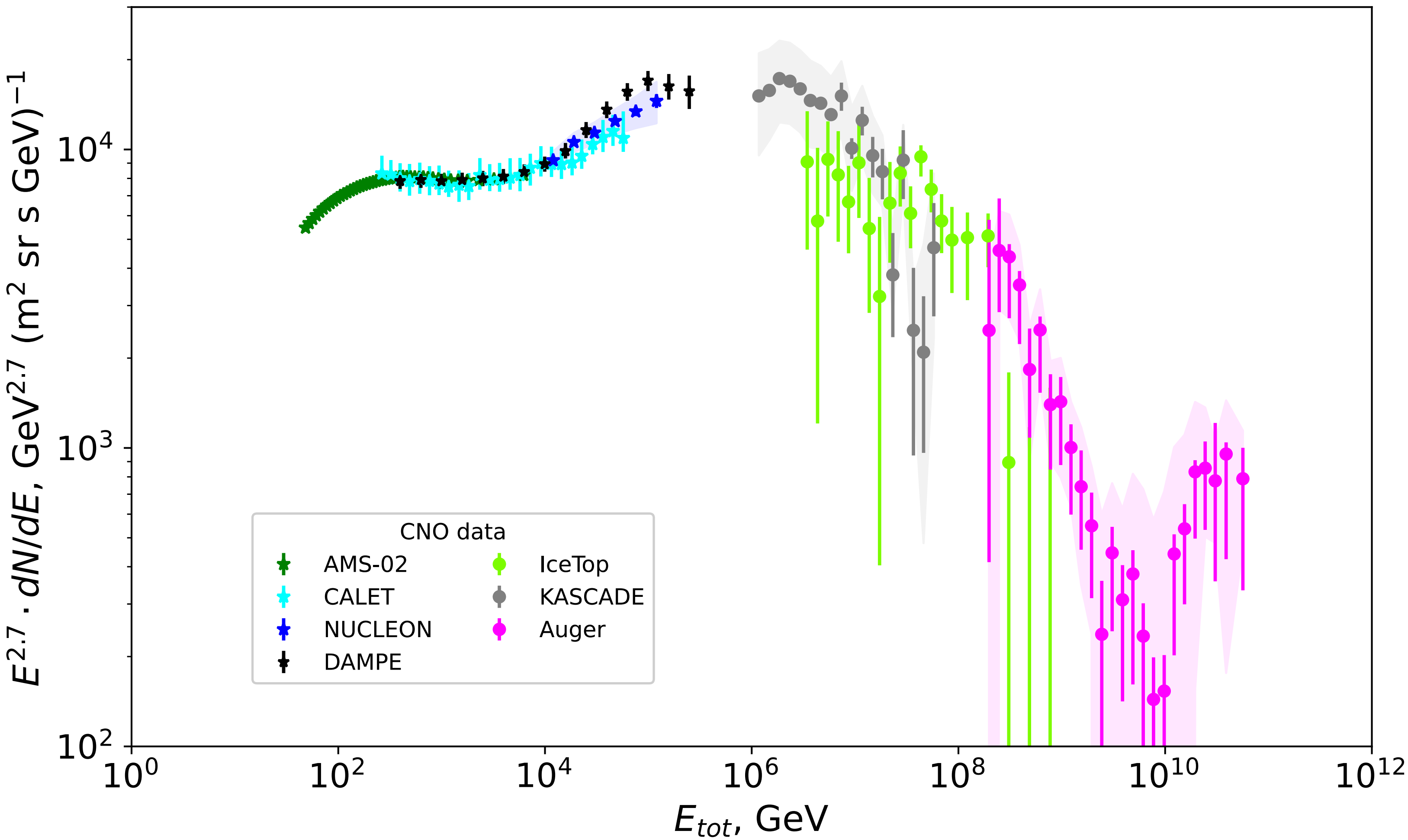
From V.Choutko, TAUP 2025

He spectrum

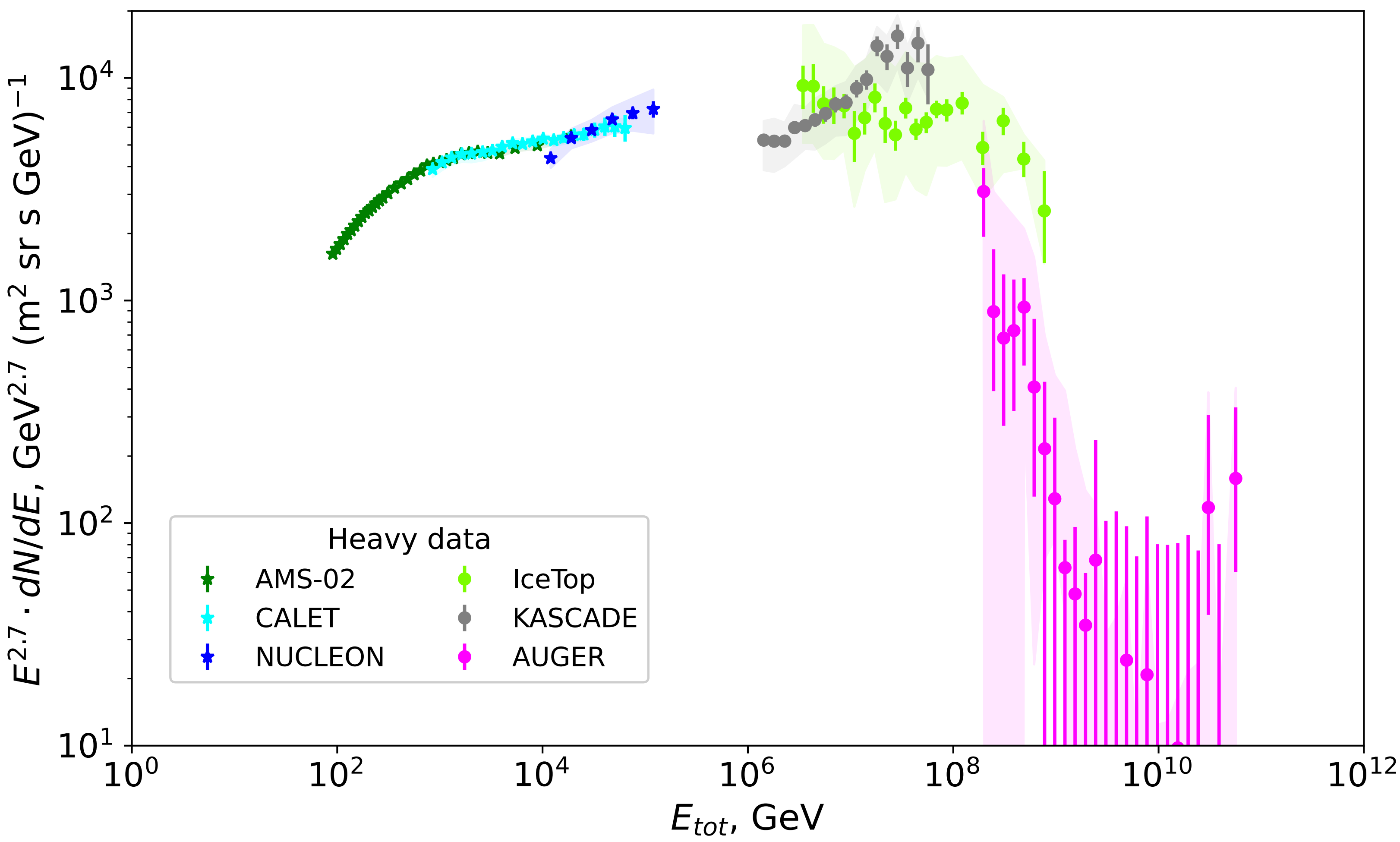


$E^{2.7} \cdot dN/dE$, $GeV^{2.7}$ $(m^2 \text{ sr s GeV})^{-1}$
10^2
10^3
10^4
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
E_{tot}, GeV
He data
AMS-02
DAMPE
CALET
NUCLEON
KASCADE
IceTop
Auger

CNO spectrum

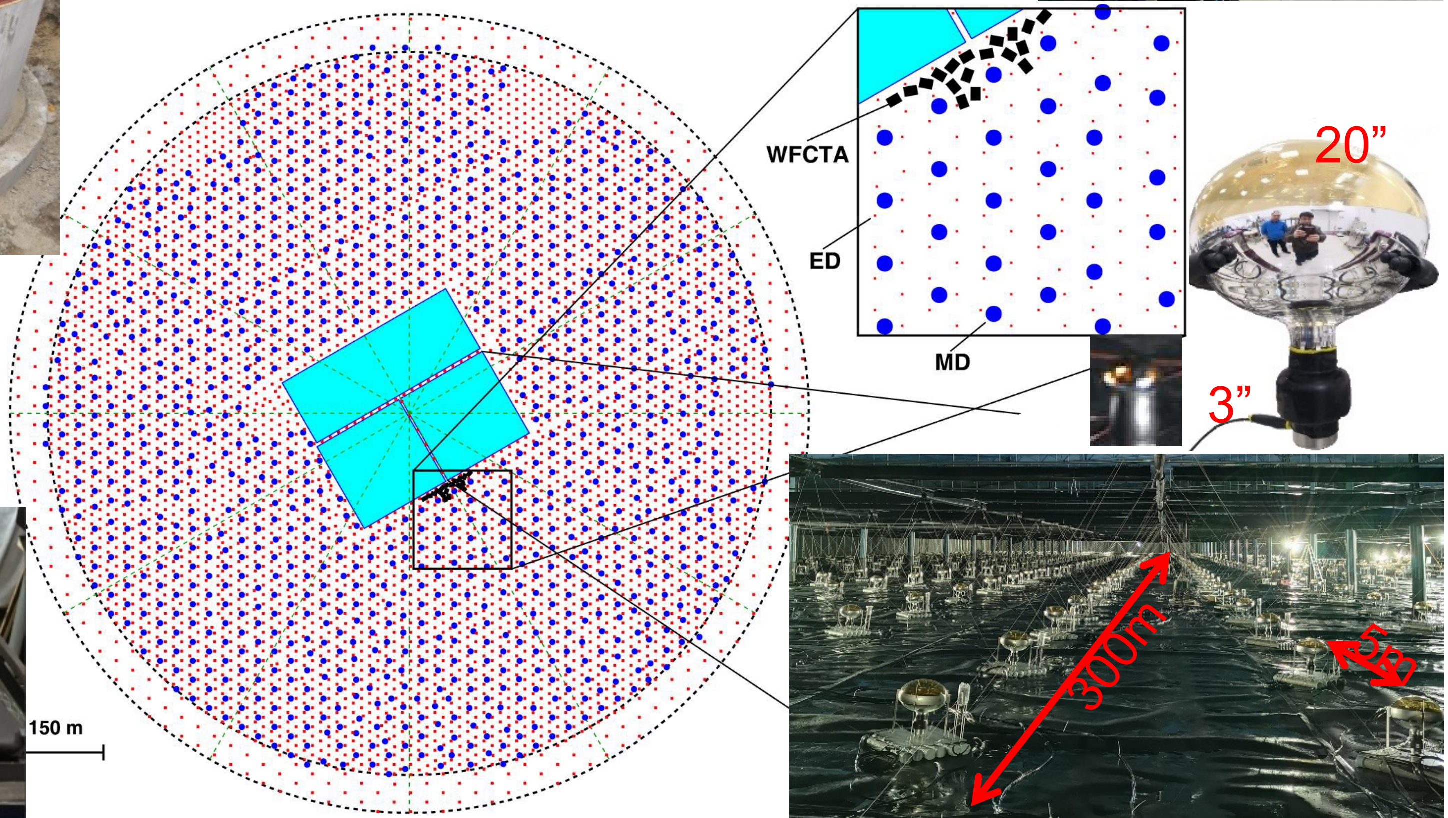


Fe spectrum



$E^{2.7} \cdot dN/dE$, GeV$^{2.7}$ (m^2 sr s GeV)$^{-1}$
10^4
10^3
10^2
10^1
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
E_{tot}, GeV
Heavy data
AMS-02
CALET
NUCLEON
IceTop
KASCADE
AUGER

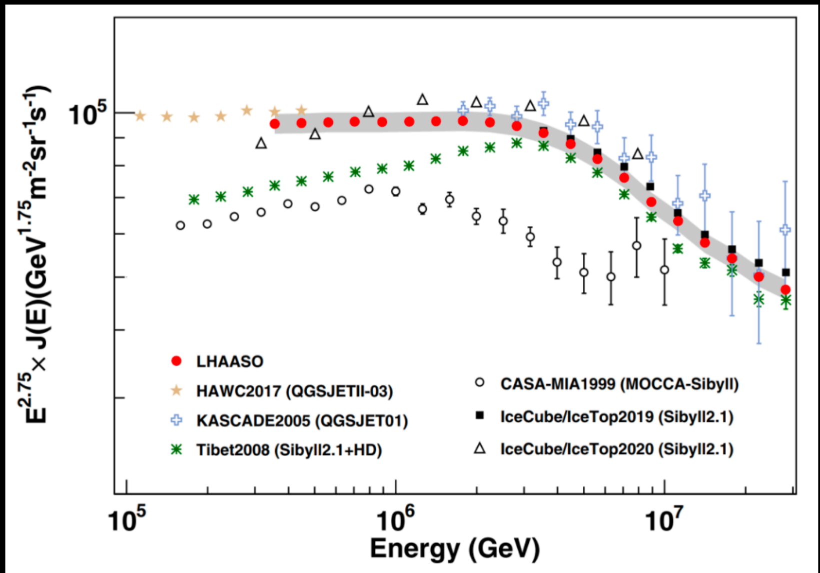
LHAASO: 3 types of detectors from 100 TeV

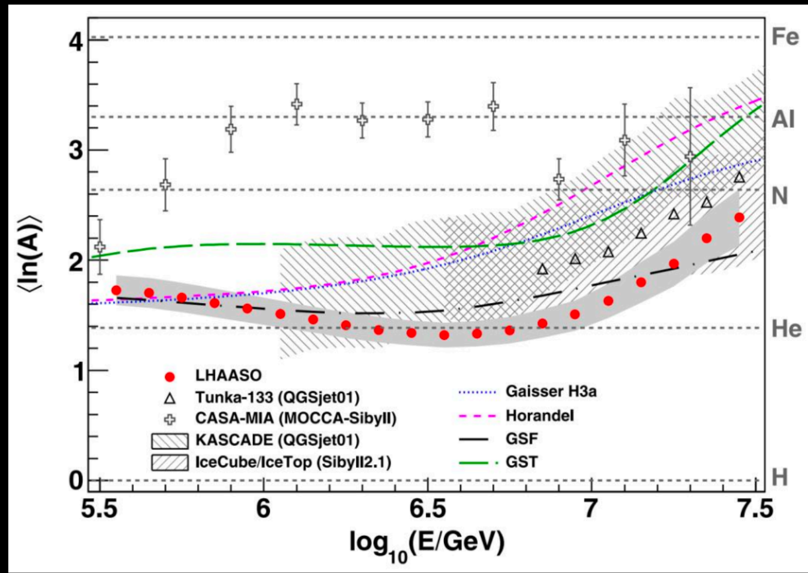


1.2 m

Construction finished on July 2021,
Gamma-ray results from 2019, CR results from 2024

All-particle energy spectrum & <lnA>



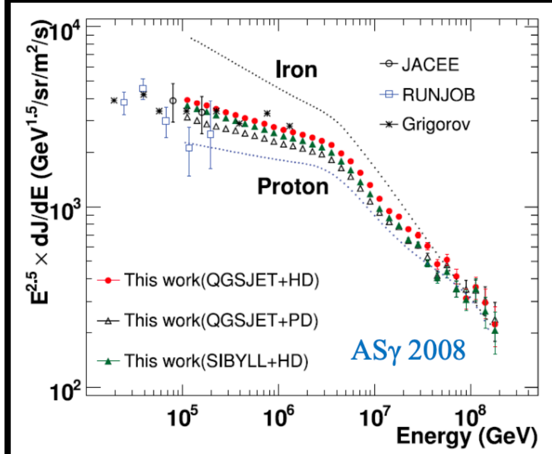


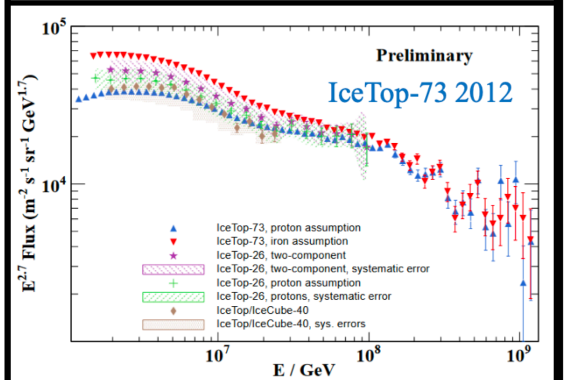
	Flux $J(E)$	$\langle\ln(A)\rangle$
Air preesure	$\pm3\%$	$\pm4\%$
Composition models	$\pm1.5\%$	$\pm3\%$
Interaction models	$\pm2.5\%$	$\pm6\%$

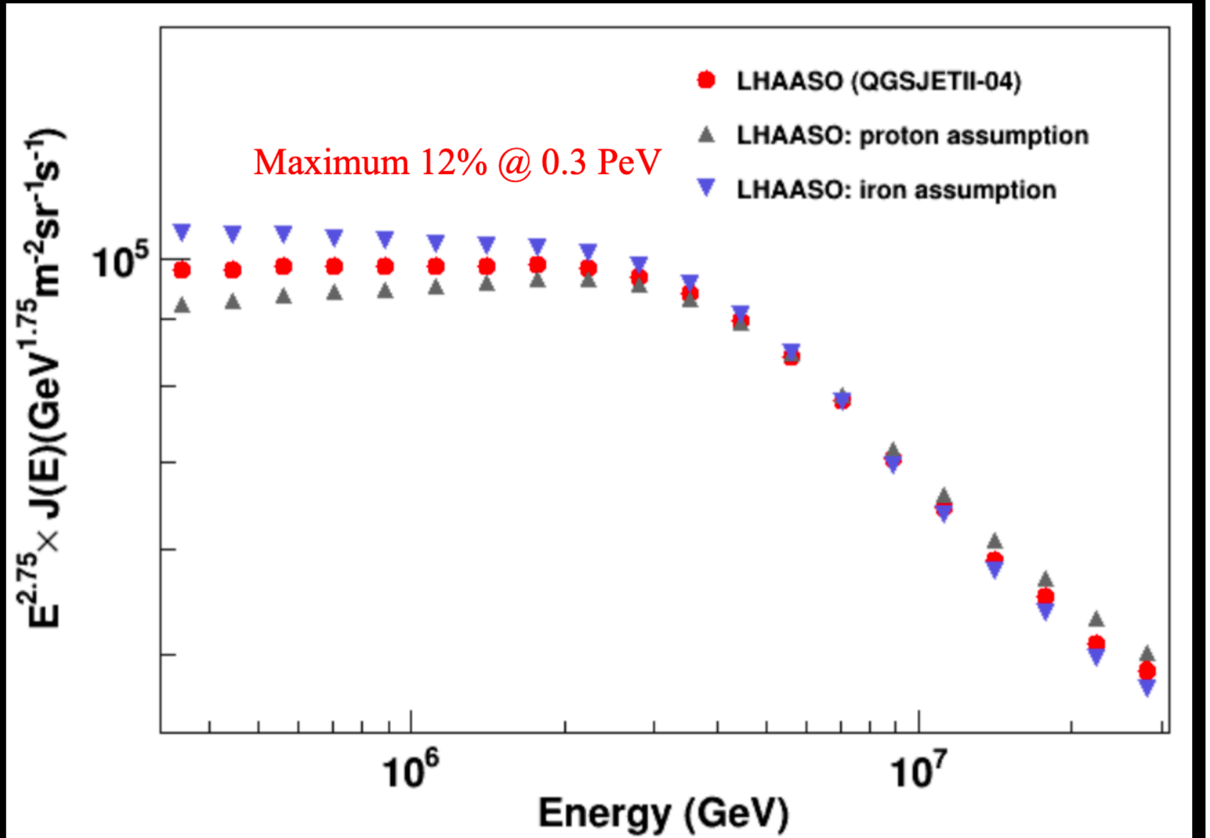
hhh@ihep.ac.cn

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

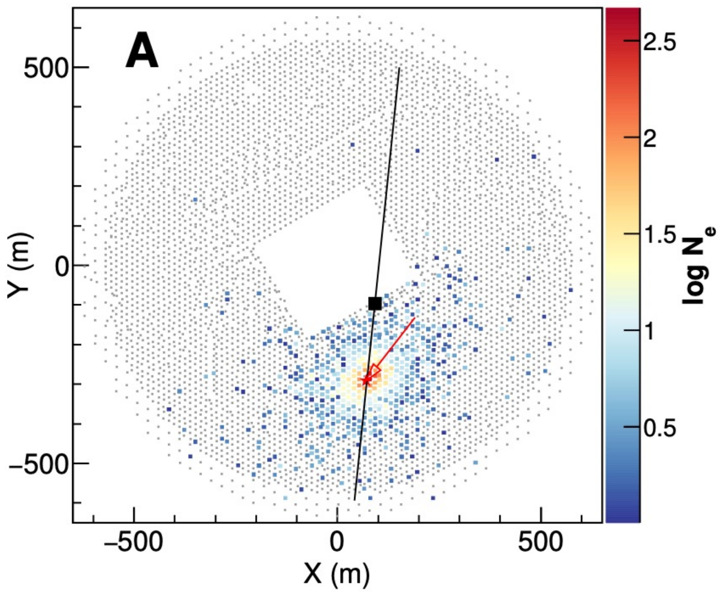
From 350%(150%) to 12%

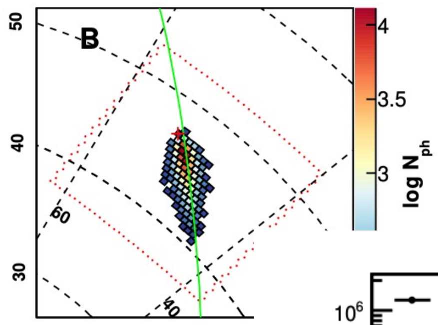


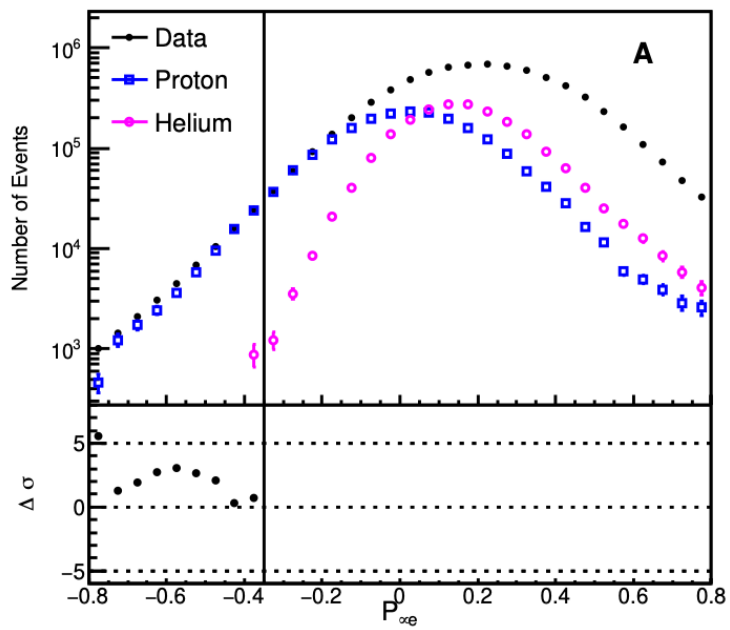




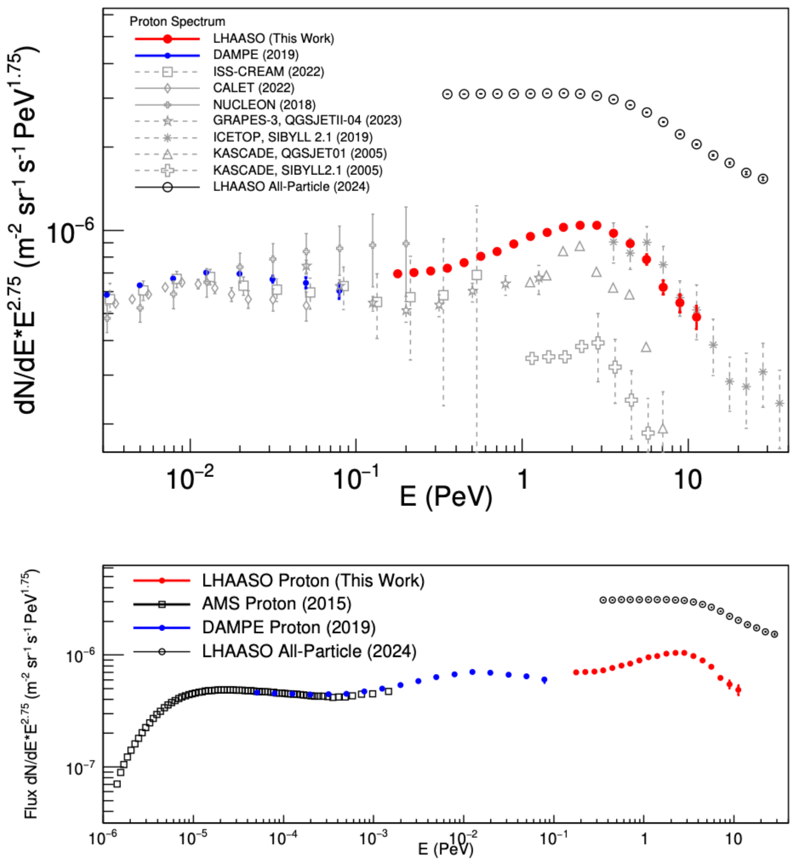
LHAASO Proton measurement





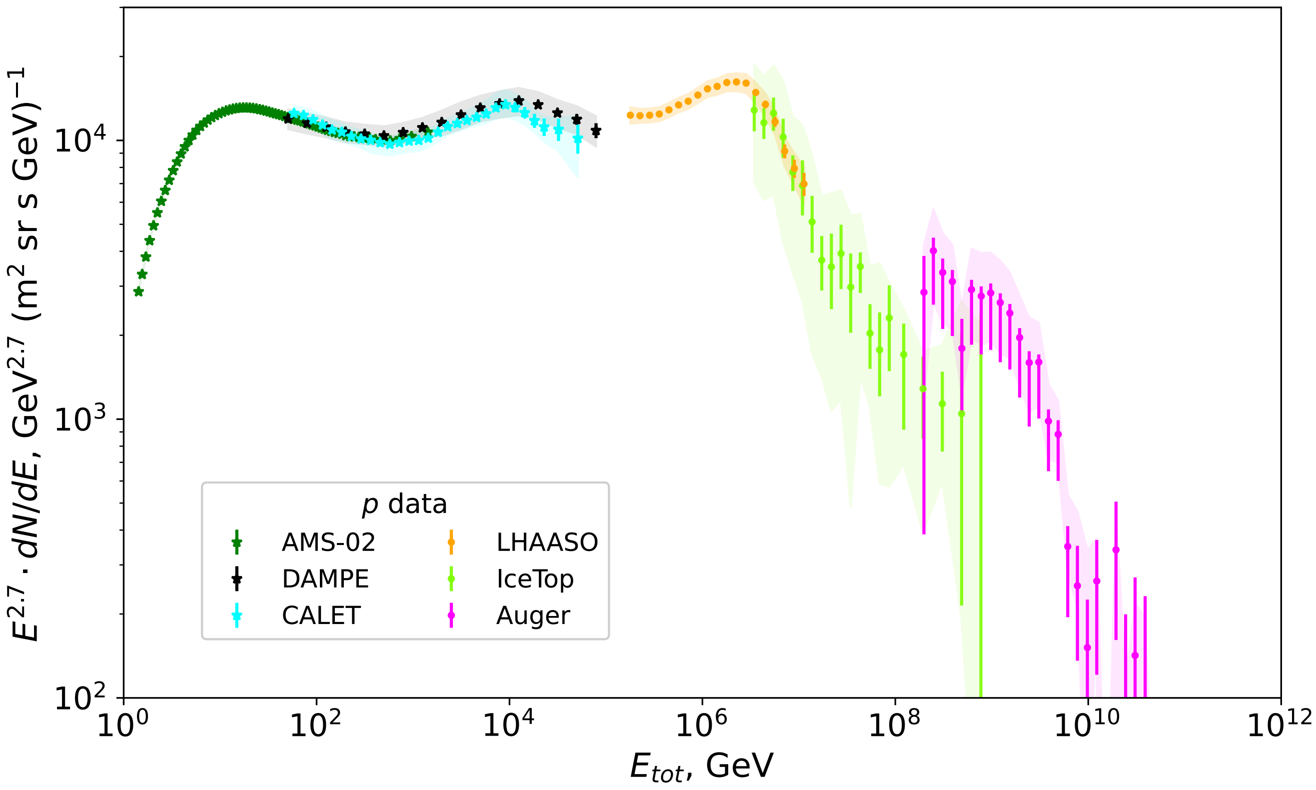


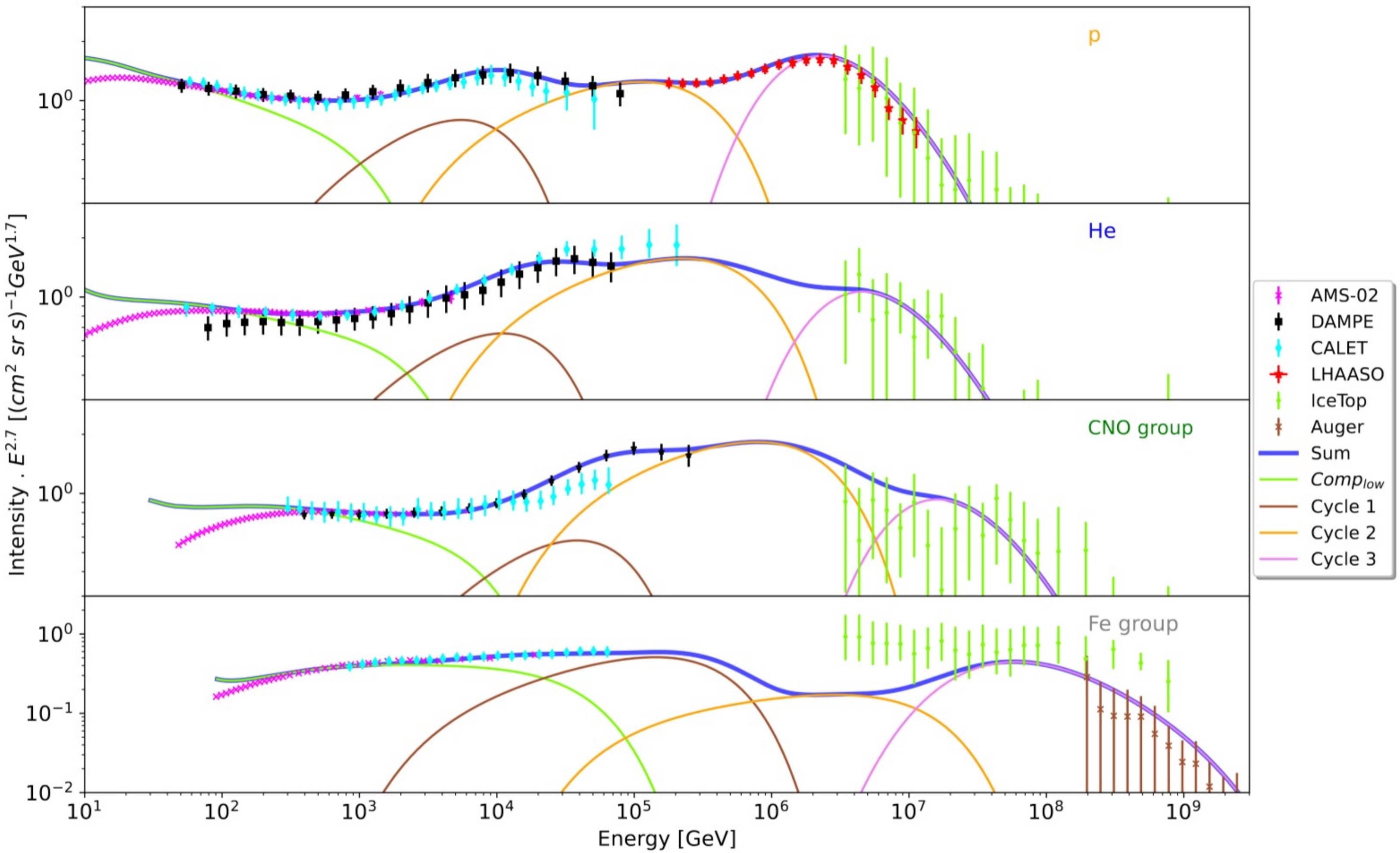
Proton spectrum



LHAASO collaboration, 2505.14447

Proton spectrum





C. Prevotat et al, 2407.11911, 2507.10823

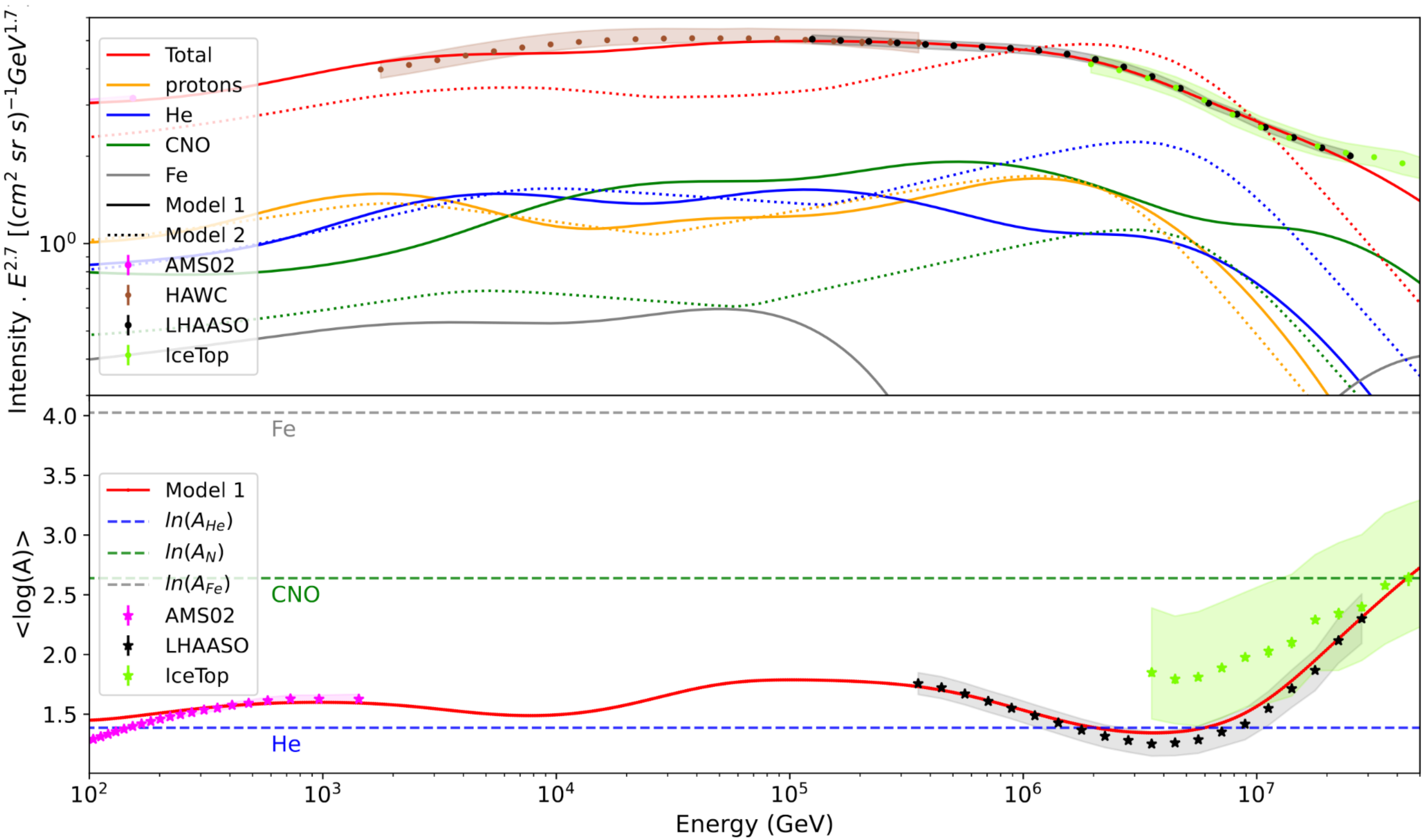
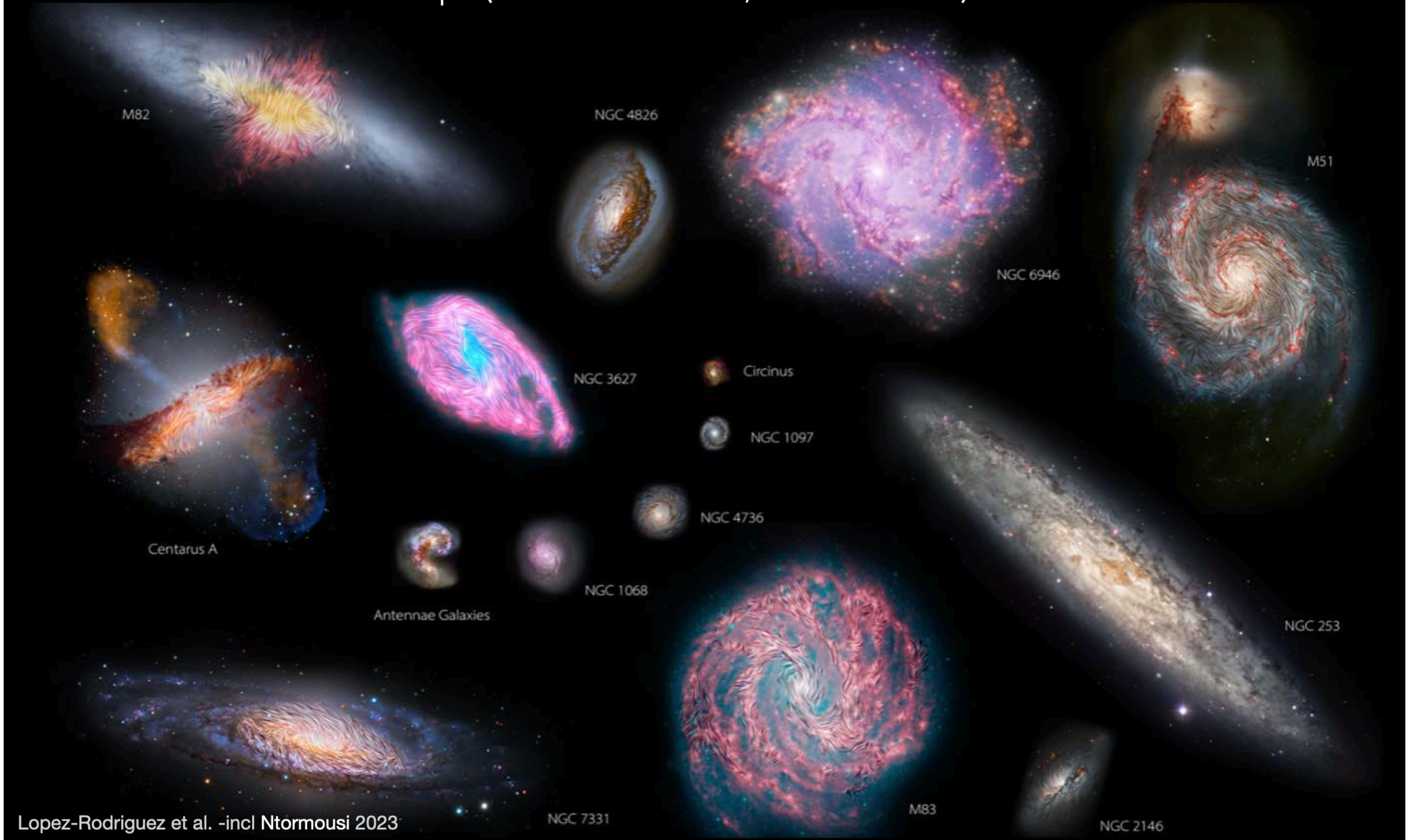


FIG. 2: Result of the fit for the all-particles spectrum, and mean logarithmic mass of the CR spectrum.

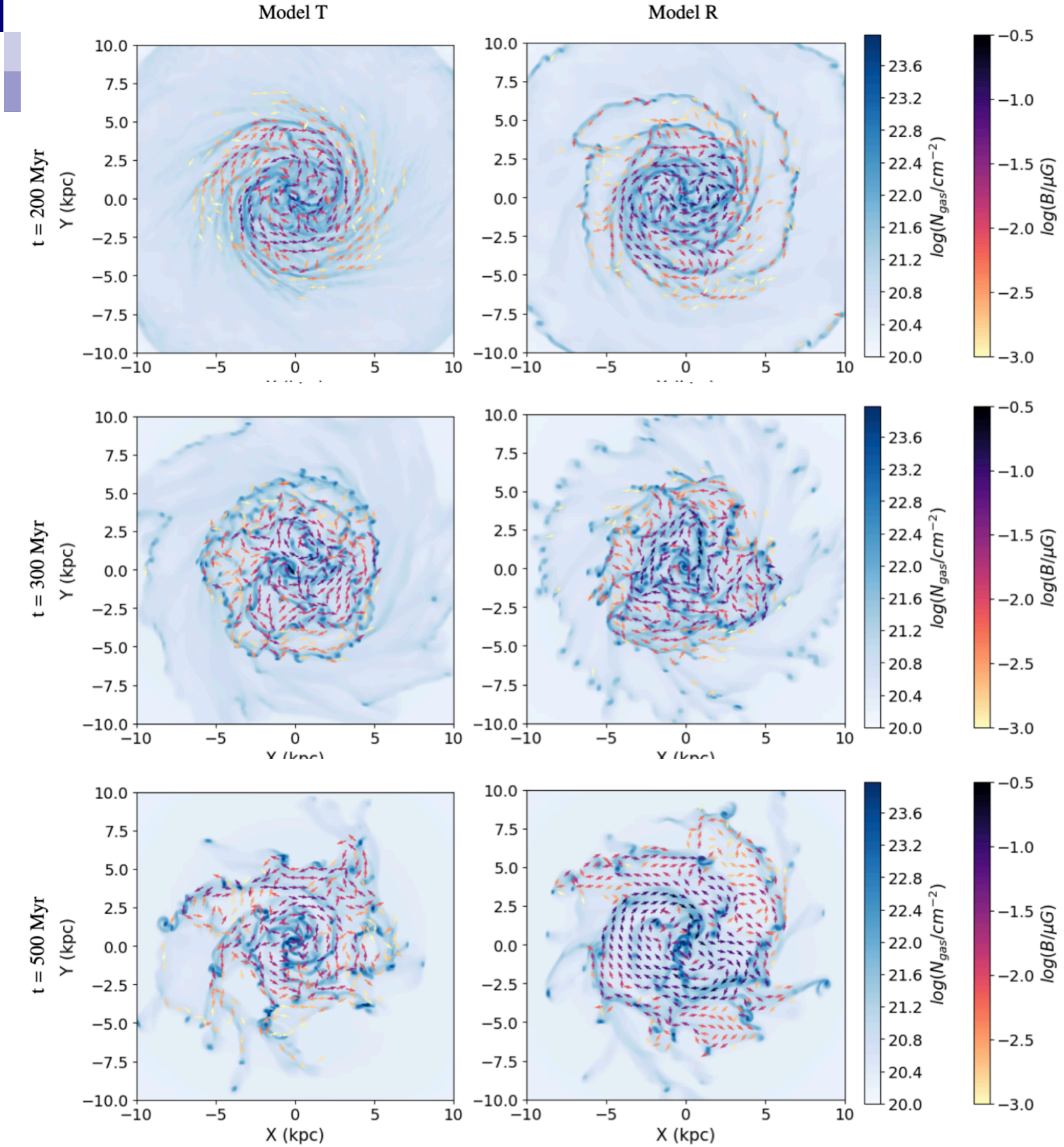
C. Prevotat et al, 2407.11911, 2507.10823

Cosmic ray propagation in Milky Way and Galactic Magnetic Field

Present-day spirals host large-scale coherent magnetic fields with a typical strength of a few μG (Fletcher et al. 2016,Beck et al. 2019)



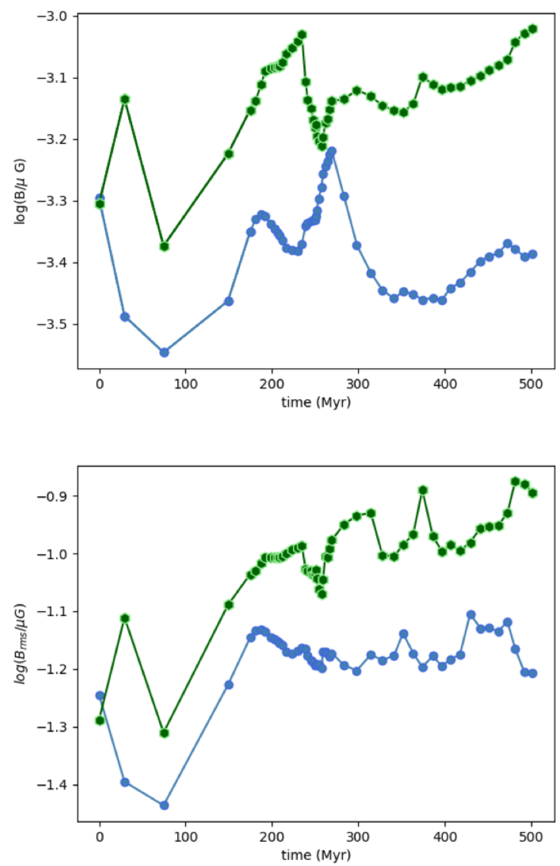
The first estimates for redshifts z>1 yield fields of the order of μG already at these epochs! (Bernet et al. 2008, Mao et al. 2017,Geach et al. 2023,Chen et al.2024)



Subtle differences in the model evolution:

Model R is slightly larger in the radial direction

Model R's magnetic field is stronger over a wider radial range



A. Konstantinou, E. Ntormousi, K. Tassis & A. Pallottini A&A 2024

Anti-symmetric RM sky: halo B fields = A0 dynamo

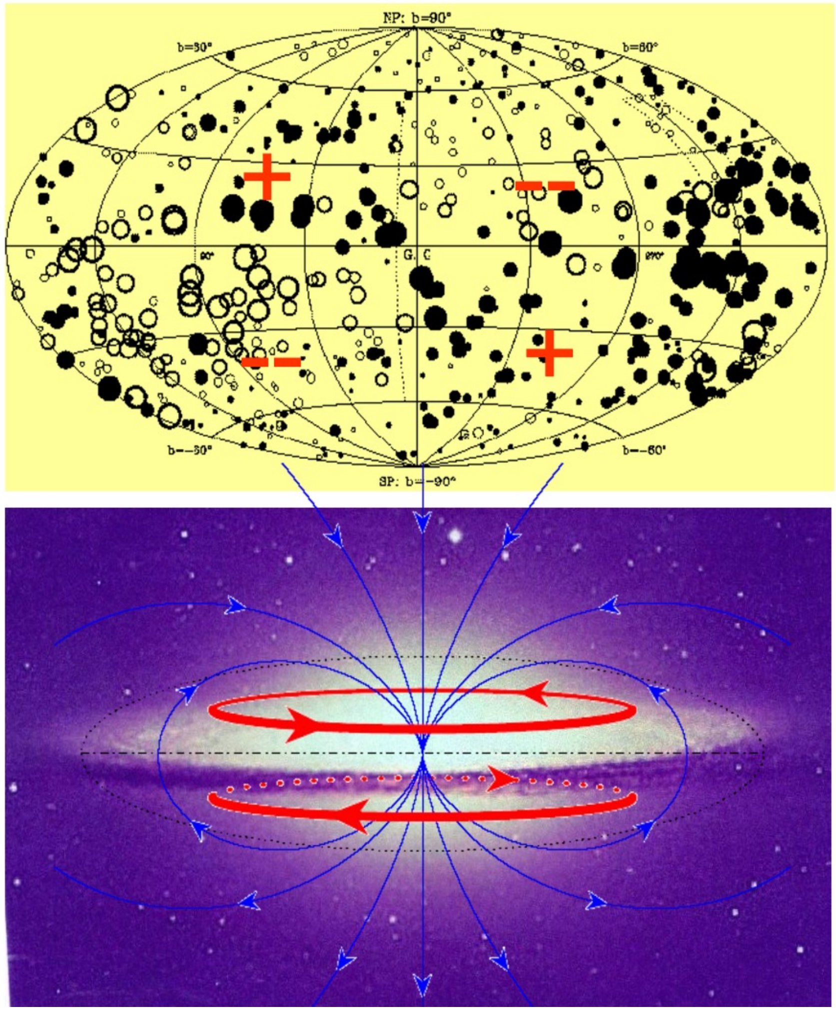
(Han et al. 1997, A&A322, 98)

Evidence for global scale B

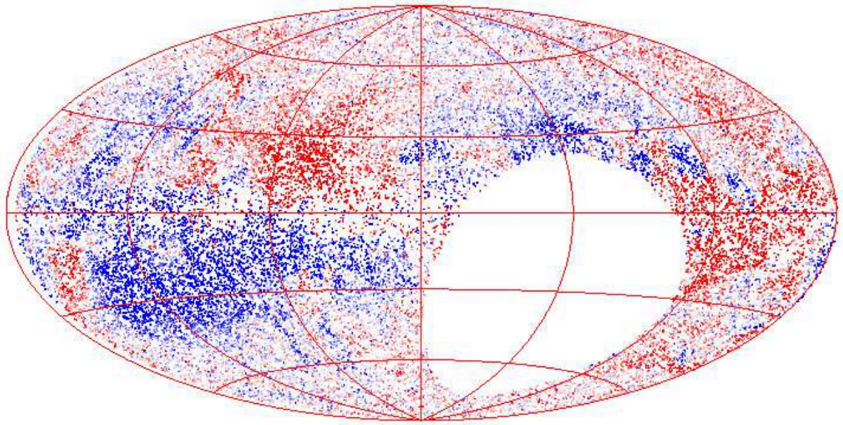
- High anti-symmetry to the Galactic coordinates
- Only in inner Galaxy
- nearby pulsars show it at higher latitudes

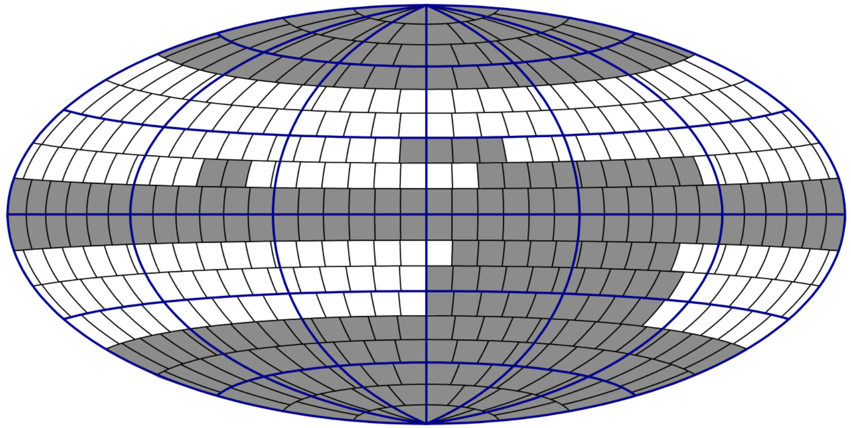
Implications

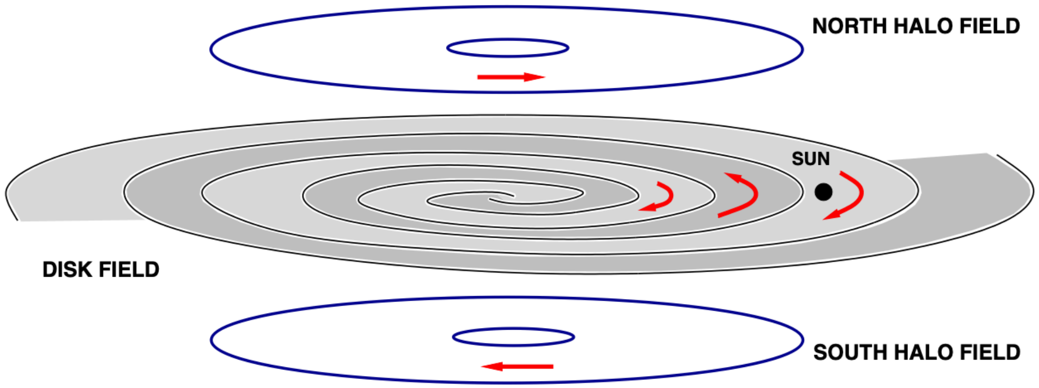
- Consistent with B-field configuration of A0 dynamo
- The first dynamo mode identified on galactic scales



Rotation measure





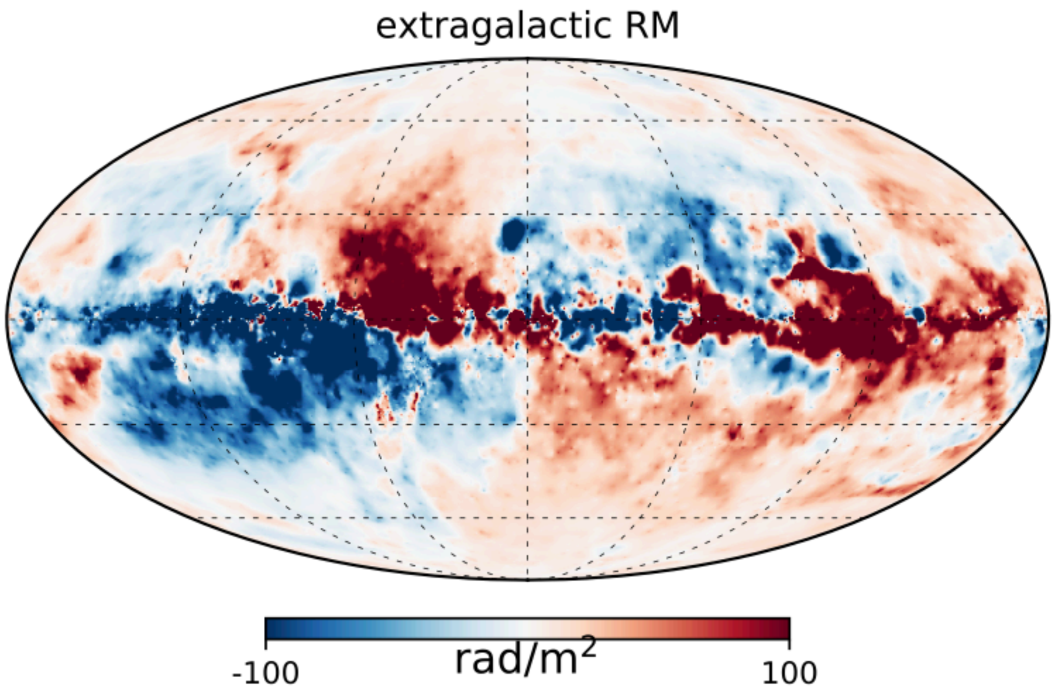


$$\mathrm{RM} \approx 0.812 \int_0^l \left[\frac{n_e(s)}{\mathrm{cm}^{-3}}\right]\left[\frac{B_\parallel(s)}{10^{-6}\,\mathrm{G}}\right]\left[\frac{\mathrm{d}s}{\mathrm{pc}}\right] \mathrm{rad/m^2}.$$

Pshirkov,Tinyakov, Kronberg and Newton-McGee

model 2011

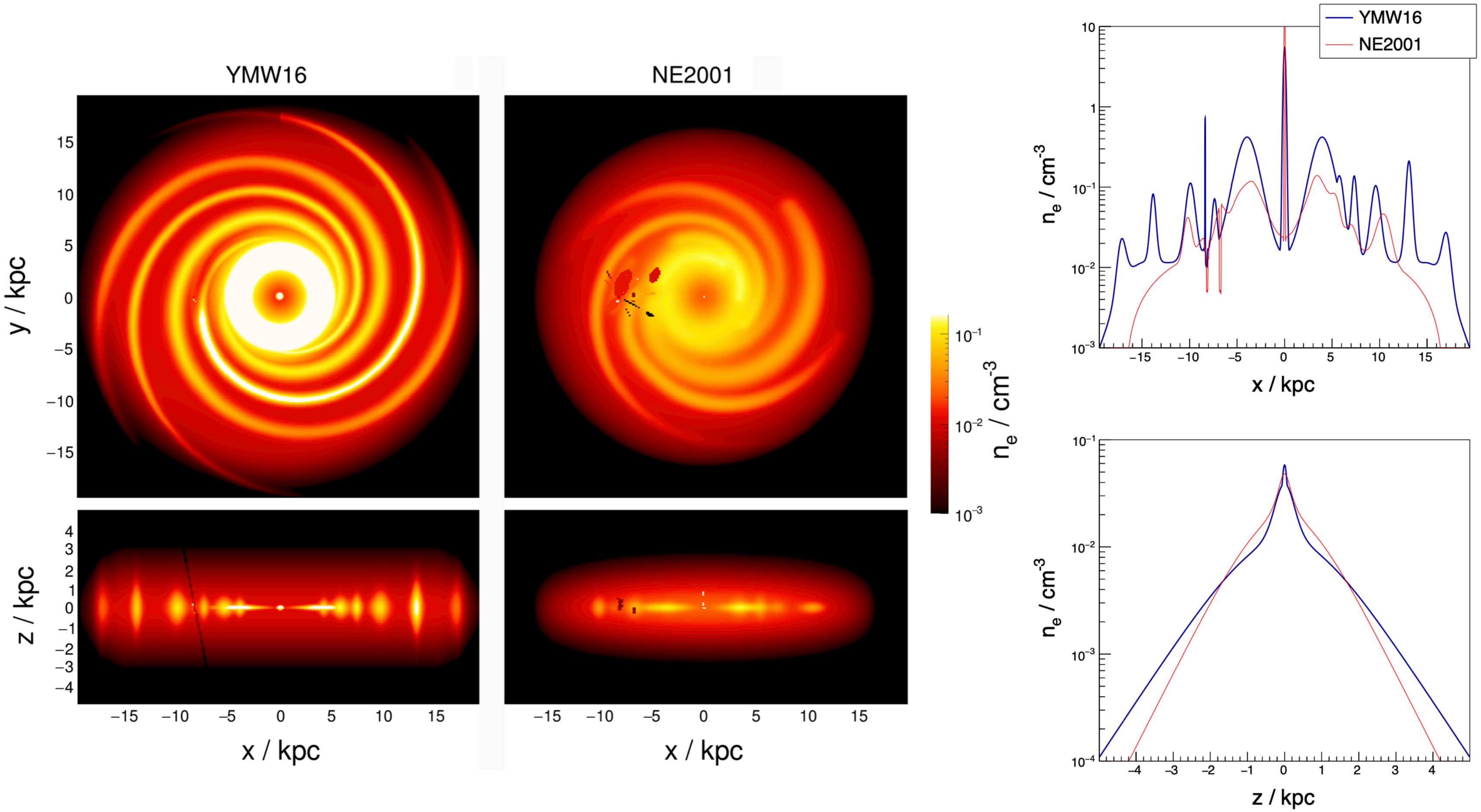
ROTATION MEASURE



60000 extragalactic objects

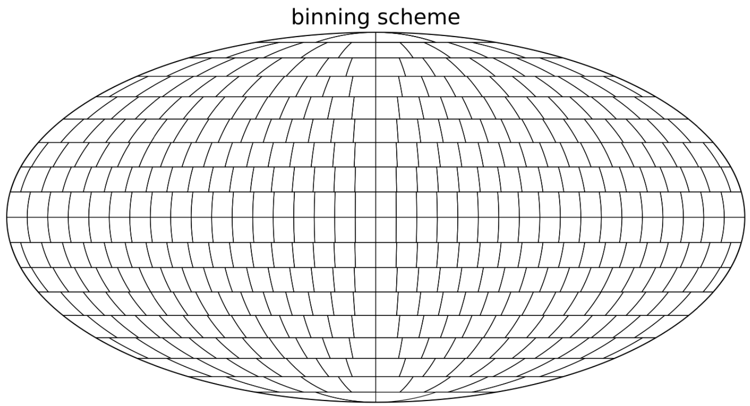
$$\mathrm{RM} \approx 0.812 \int_0^l \left[\frac{n_e(s)}{\mathrm{cm}^{-3}}\right]\left[\frac{B_{\|}(s)}{10^{-6}\,\mathrm{G}}\right]\left[\frac{\mathrm{d}s}{\mathrm{pc}}\right] \ \mathrm{rad/m^2}.$$

Thermal electrons model

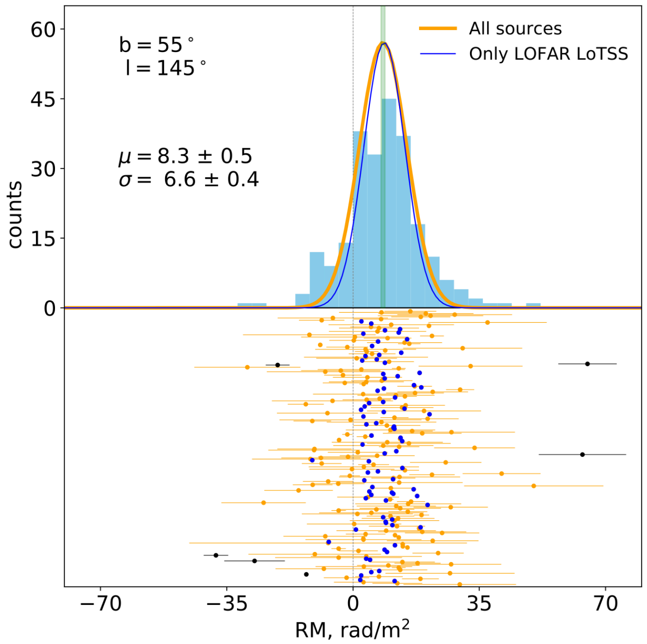


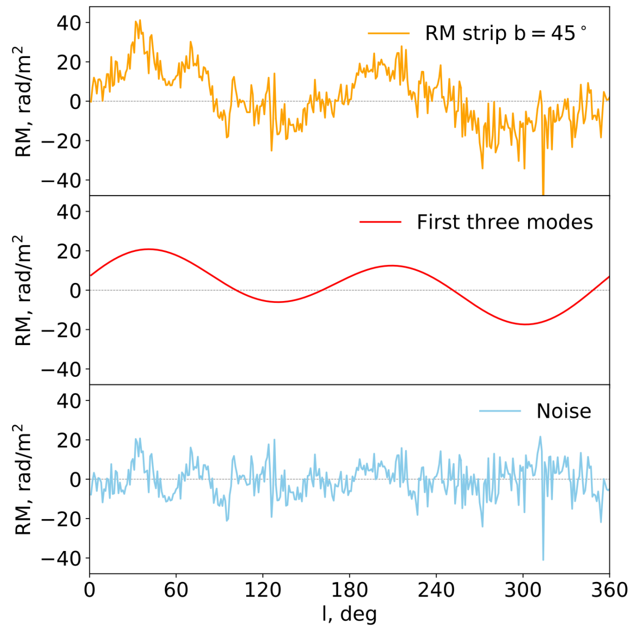
From M.Unger and G.Farrar 2311.12120

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

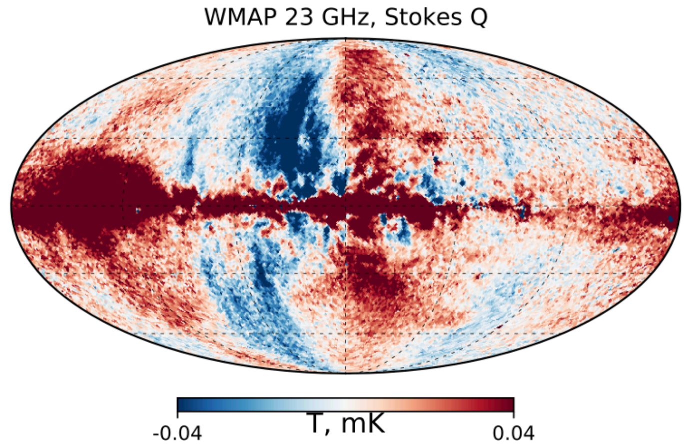


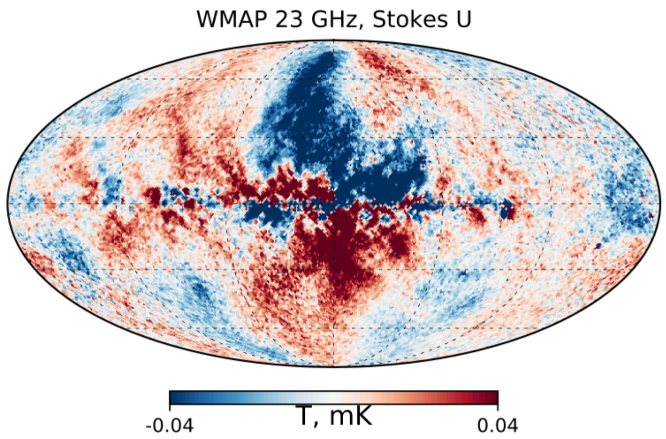


A.Korochkin, D.S. and P.Tinyakov, 2407.02148

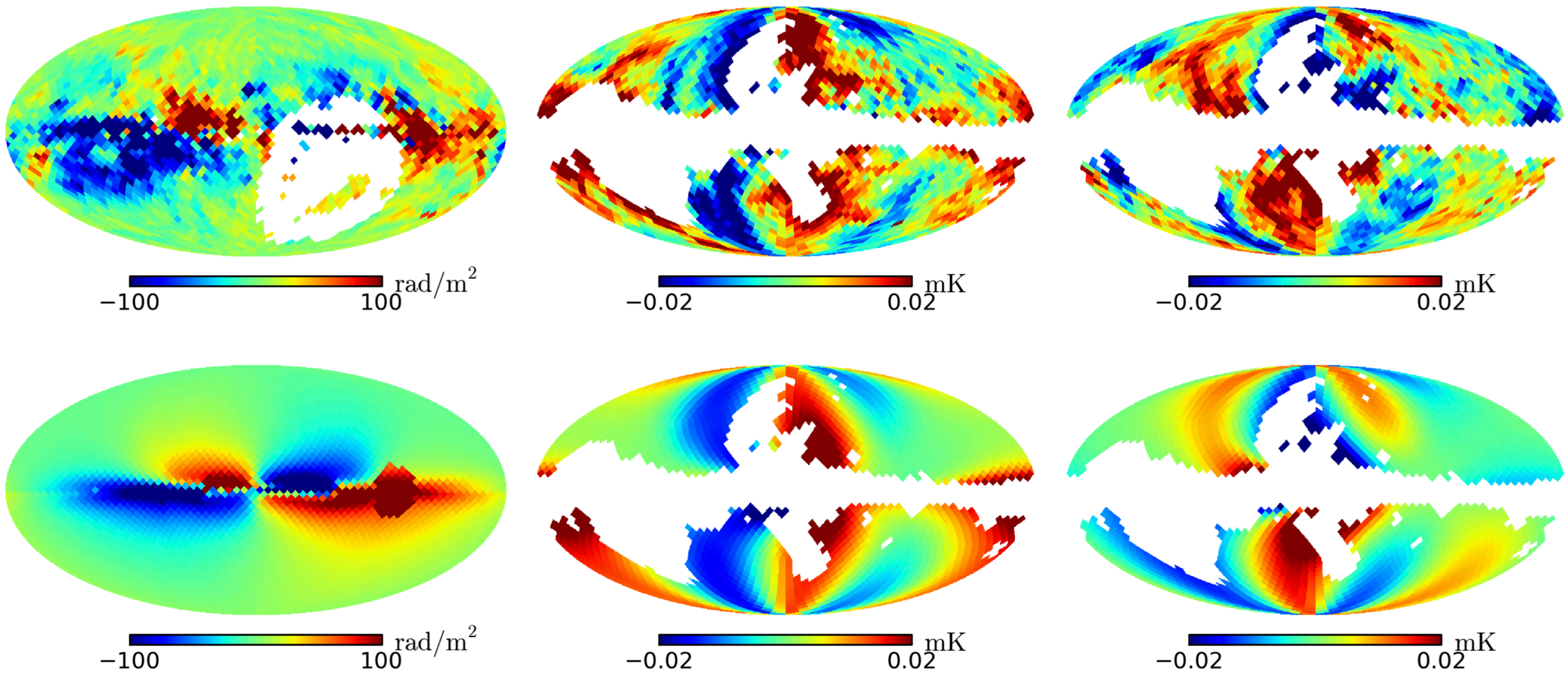
Synchrotron radiation

$$\nu_c \approx 1.6 \left[\frac{B_\perp}{10^{-6}\,\mathrm{G}}\right]\left[\frac{E}{10\,\mathrm{GeV}}\right]^2 \ \mathrm{GHz}.$$



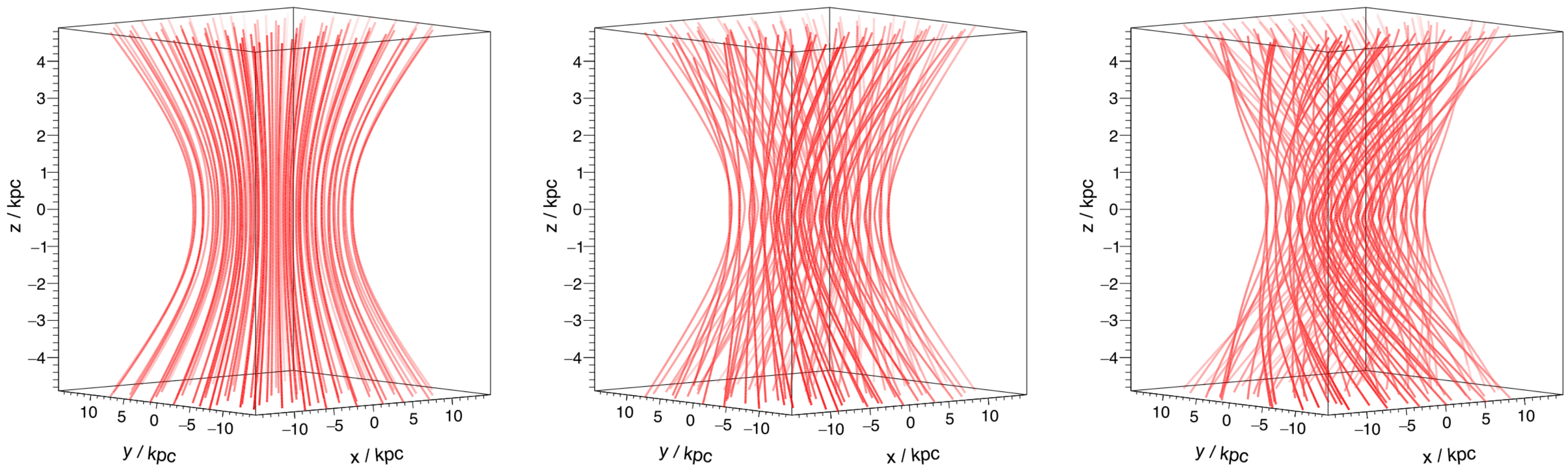


Jansson-Farrar 2012 model



X-shape field, torroidal halo field, disc with spiral arms

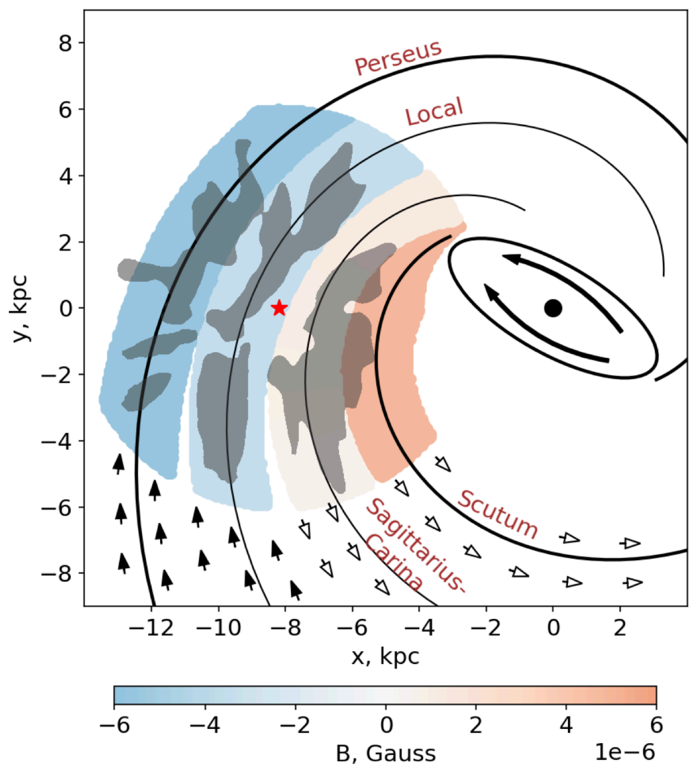
Dynamical halo model

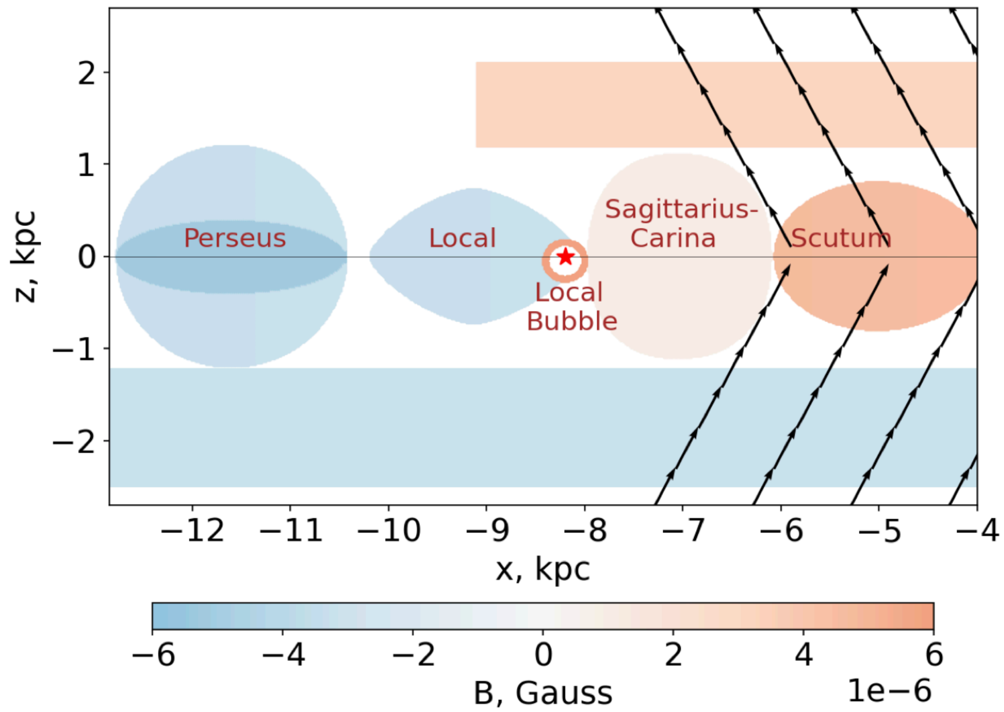


a: $t = 0$ Myr b: $t = 25$ Myr c: $t = 50$ Myr

M.Unger and G.Farrar 2311.12120

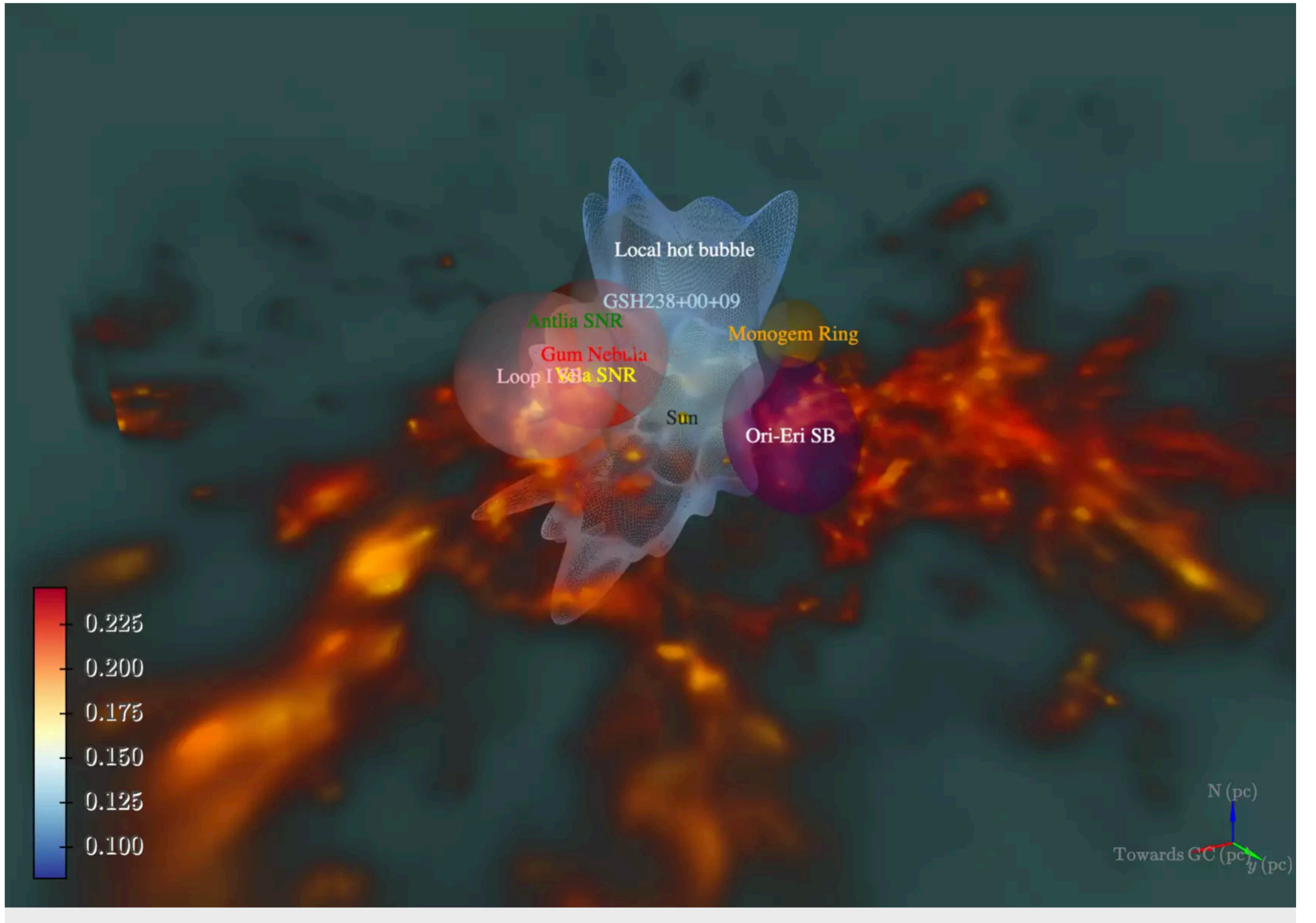
GMF models:Local Bubble





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

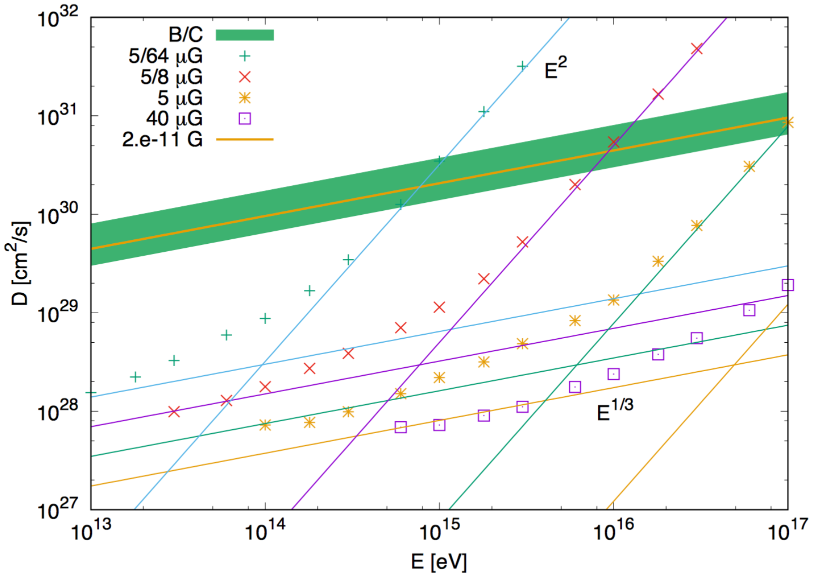
Local Bubble

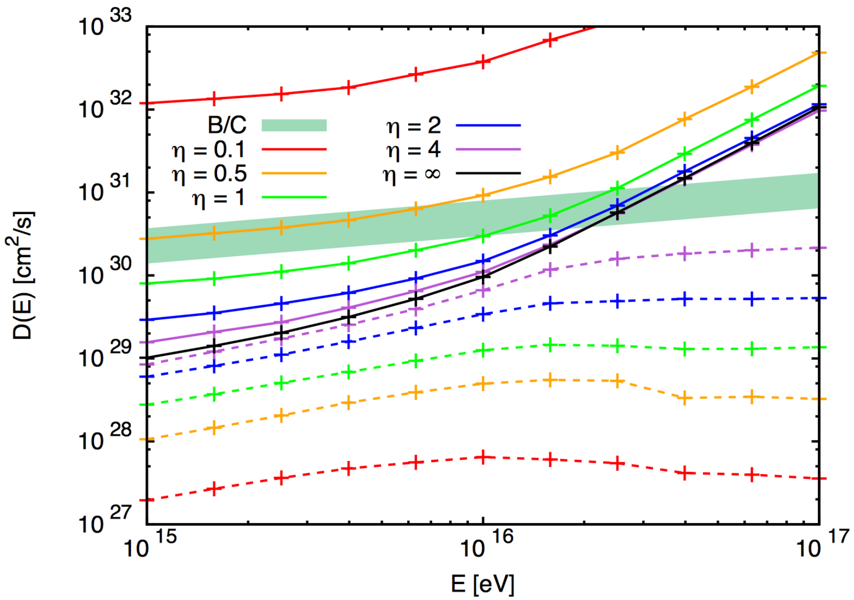


3D model of the solar neighbourhood. The colour bar represents the temperature of the LHB as coloured on the LHB surface. The direction of the Galactic Centre (GC) and Galactic North (N) is shown in the bottom right. The link to the interactive version can be found at the bottom of the page.

[less]

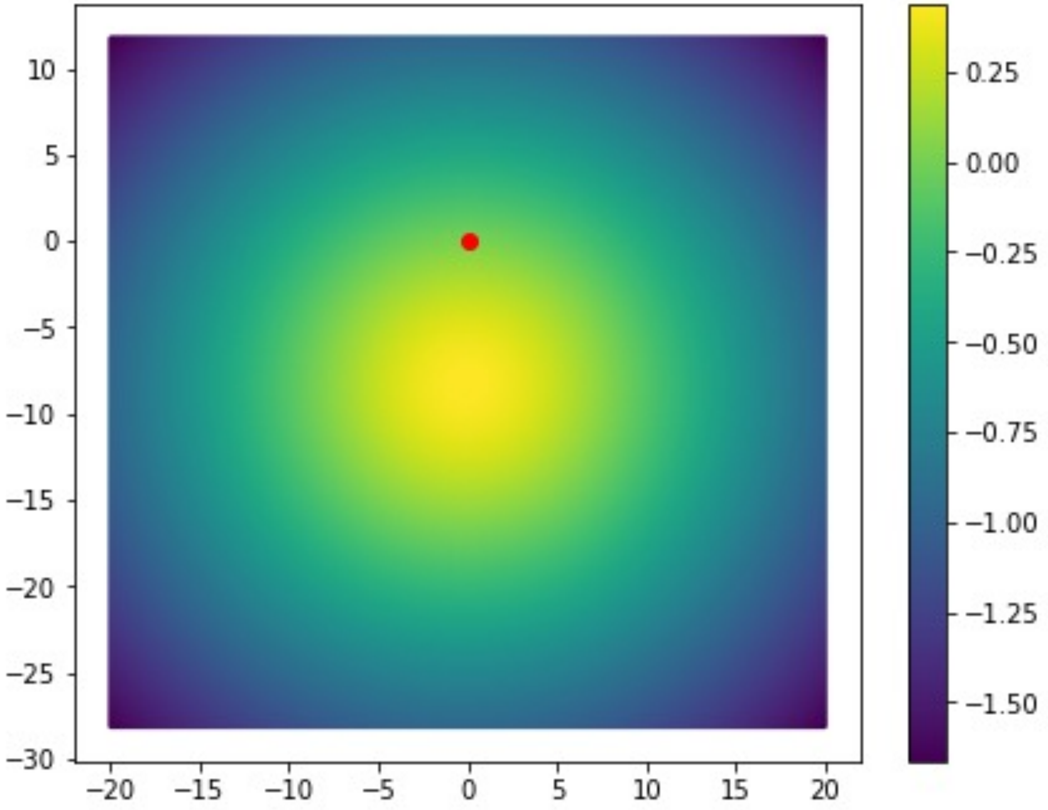
Escape of CR and magnetic field



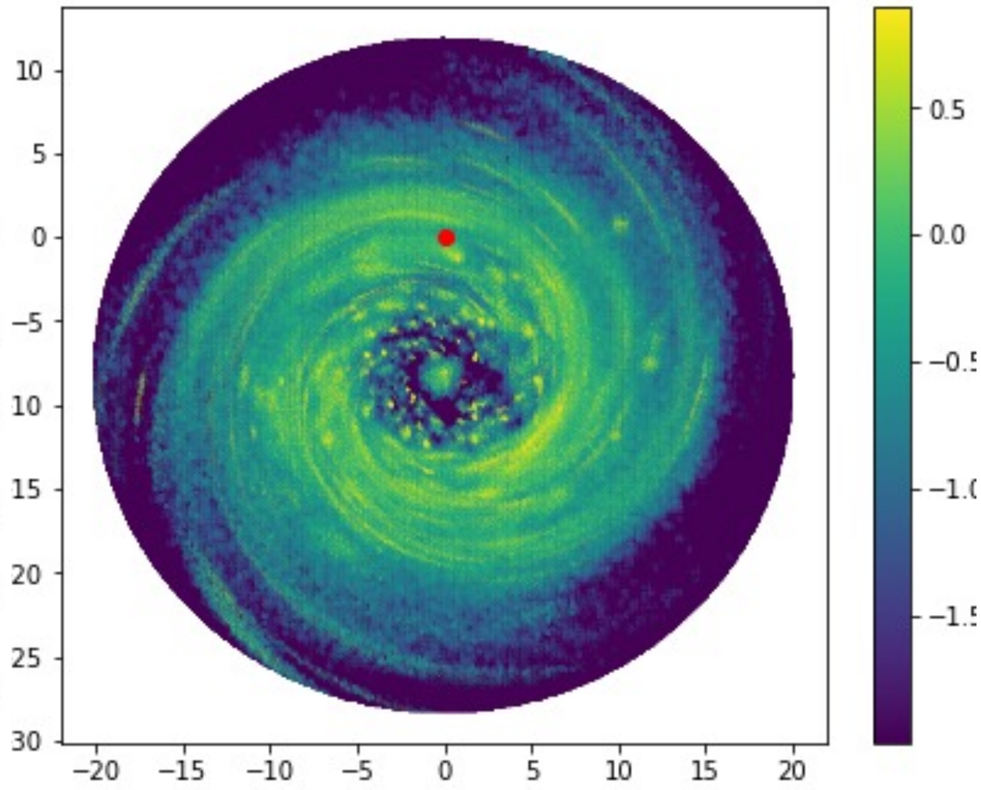


Giacinti et al, 1710.08205

1 PeV CR density in the Gal. plane



P.Lipari & S.Vernetto (2018)



G.Giacinti & D.S., 2305.10251

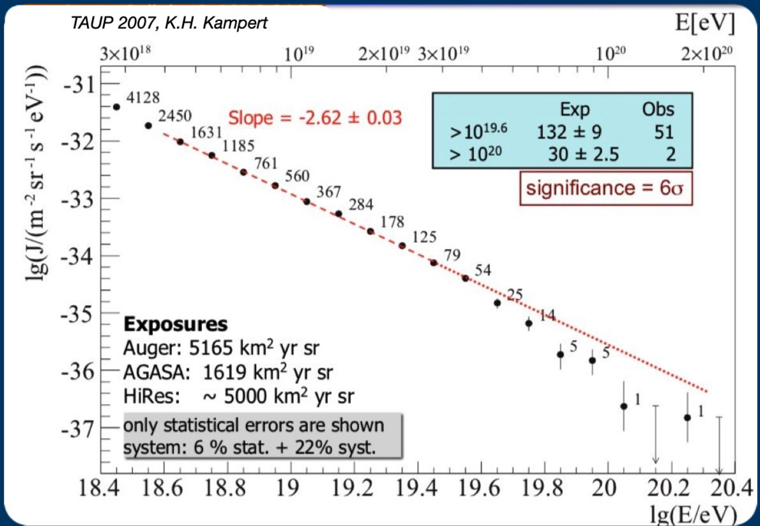
Search for the Sources of Ultra-High Energy Cosmic Rays

Spectrum Auger

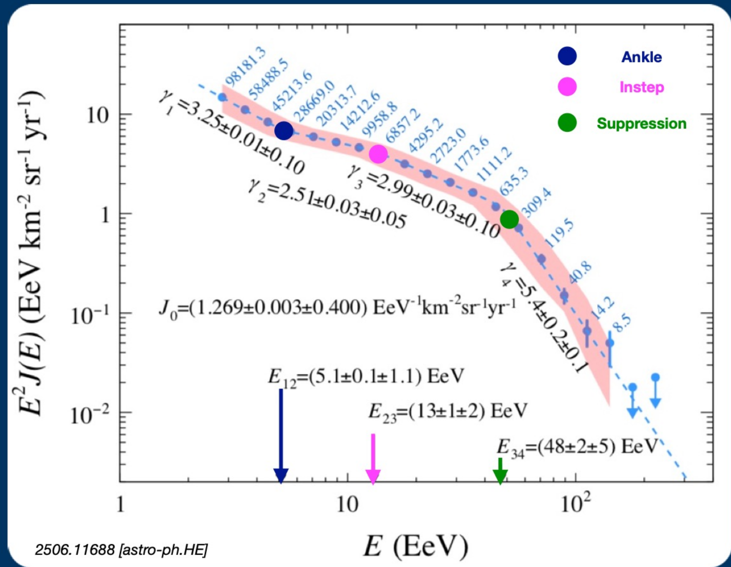
Energy spectrum, from ≈ 5000 km² sr y to ≈100000 km² sr y

A 20x exposure allows the discovery of a new feature in the energy spectrum…

2007



2025

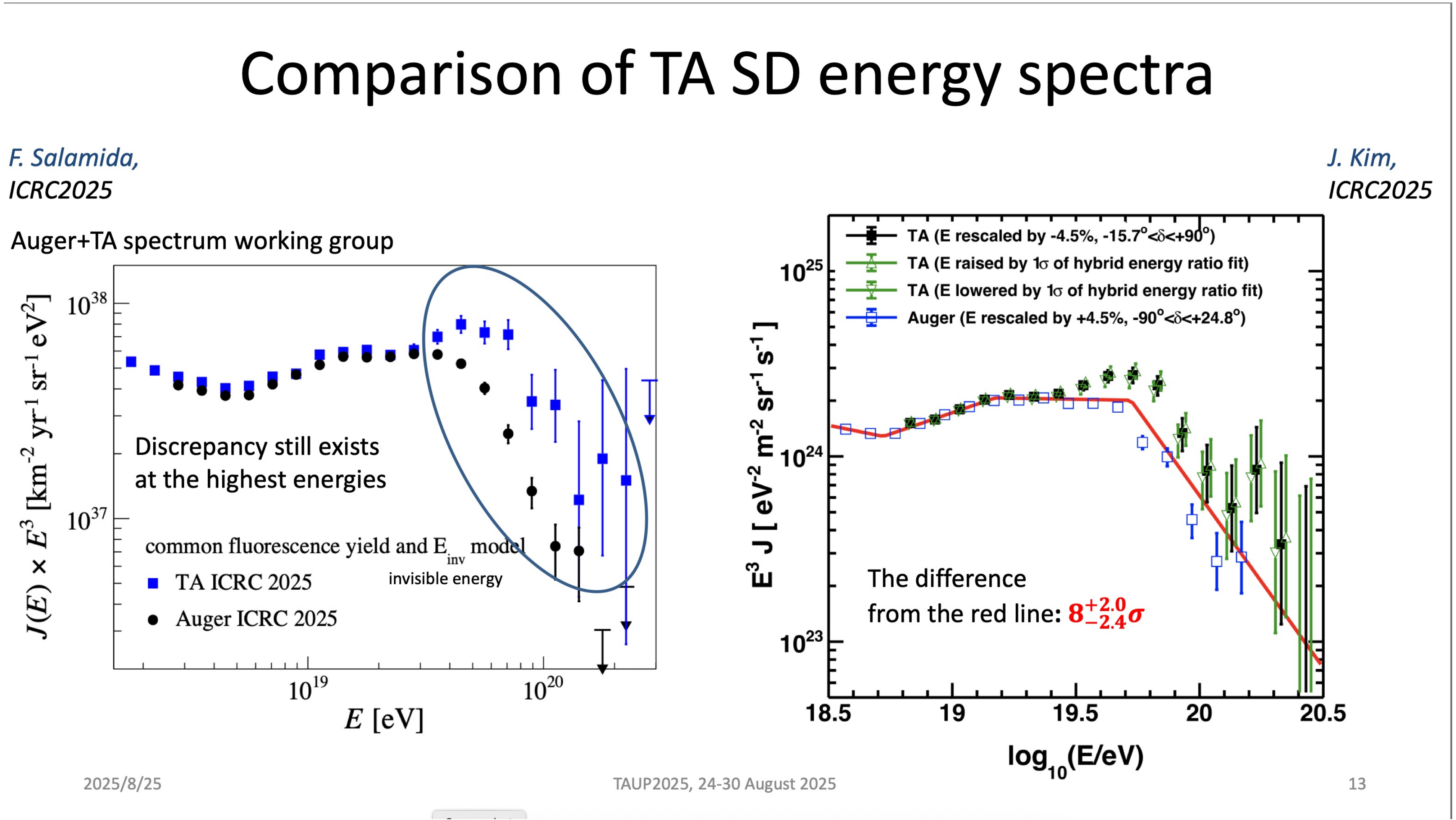


SD-1500: Full efficiency at 3x10¹⁸ eV
≈ **5000** km² sr y (AGASAx3)
≈ **12000** events (0-60°)
Observation of a suppression at ≈ 5 x 10¹⁹ eV (6 σ)

SD: Full efficiency at 3x10¹⁸ eV
≈ **105000** km² sr y [20x]
≈ **310000** events (0-80°) [25x]
Discovery of a new feature (instep, 5.5 σ)

From P.Gia talk TAUP 2025

Spectrum Auger/TA

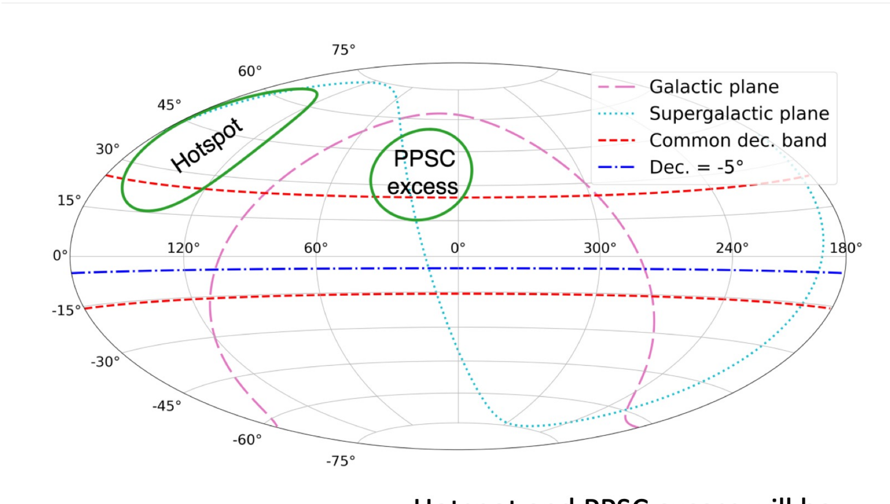


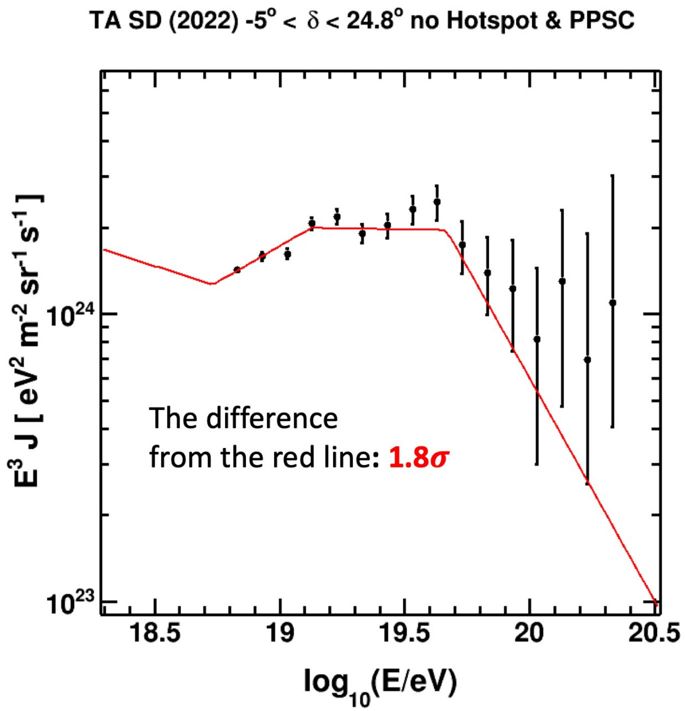
From E.Kido talk TAUP 2025

Spectrum Auger/TA

Energy spectrum in -5° < δ < 24.8° + excess region cuts

J. Kim, ICRC2025

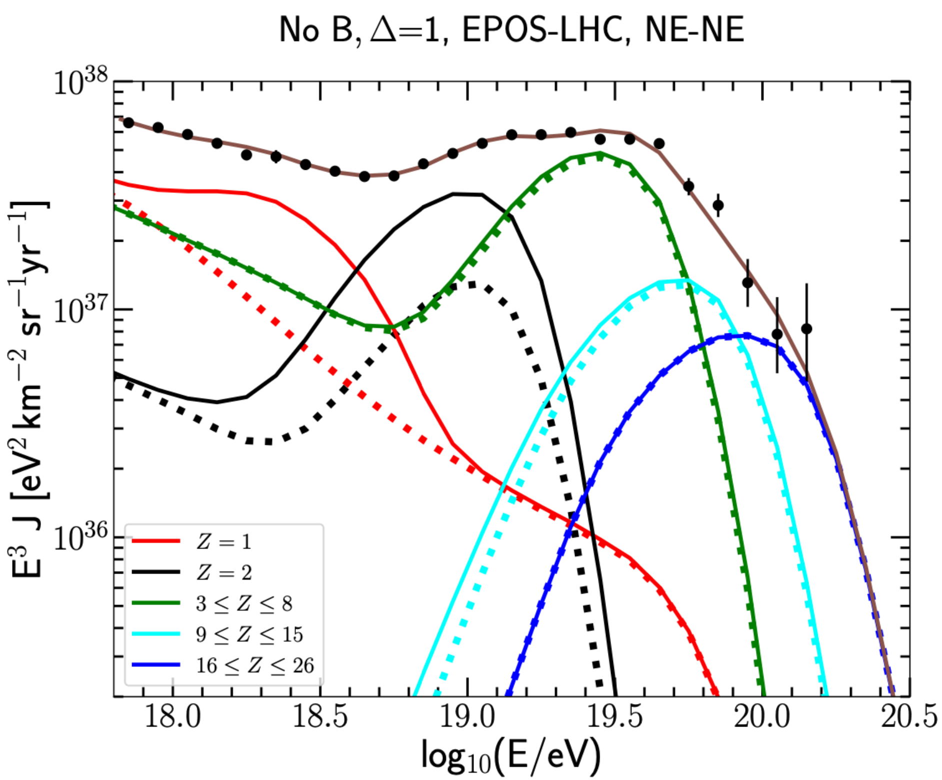


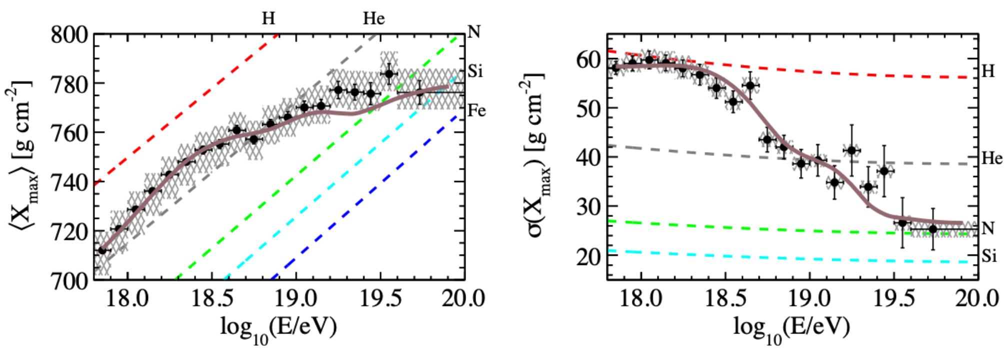


Hotspot and PPSC excess will be shown in the later slide.

From E.Kido talk TAUP 2025

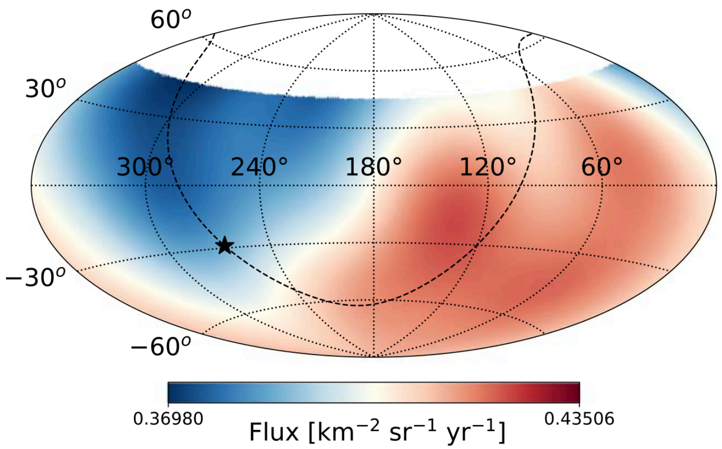
Auger spectrum and composition

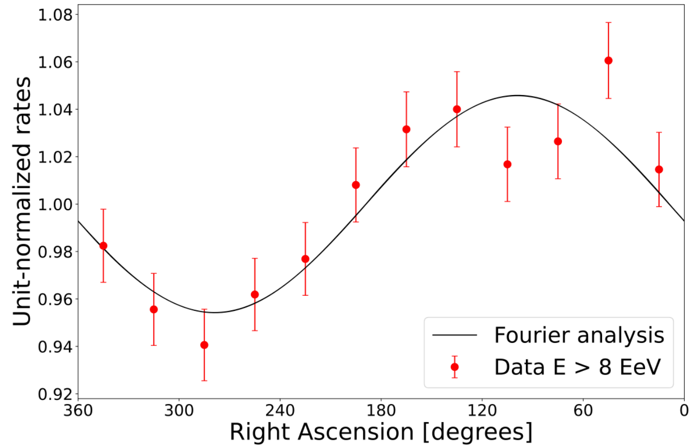


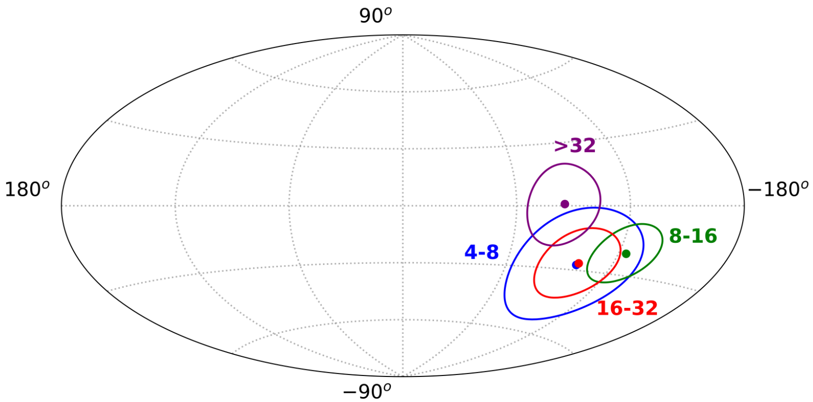


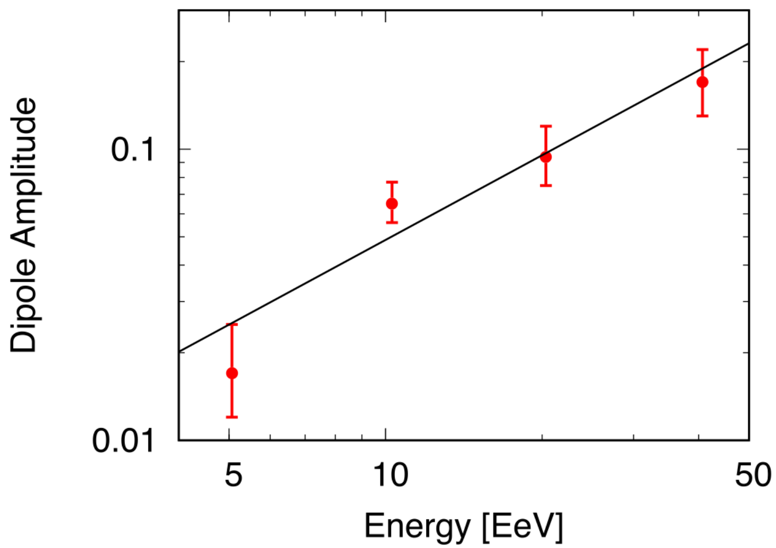
Pierre Auger Collaboration,
2404.03533

Auger dipole 6 sigma



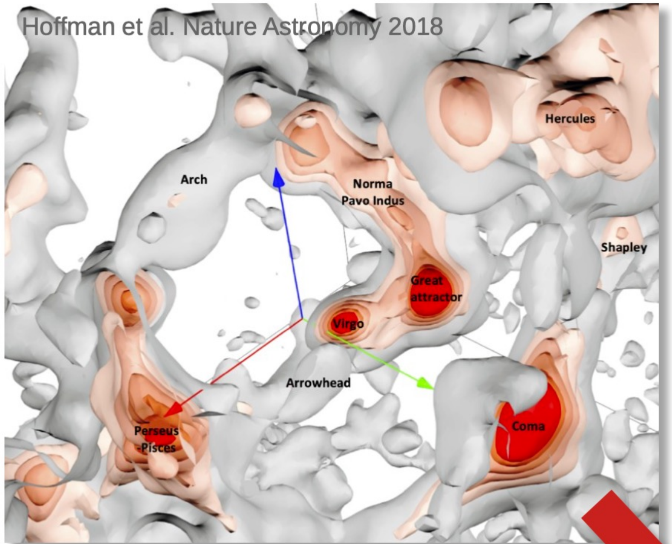






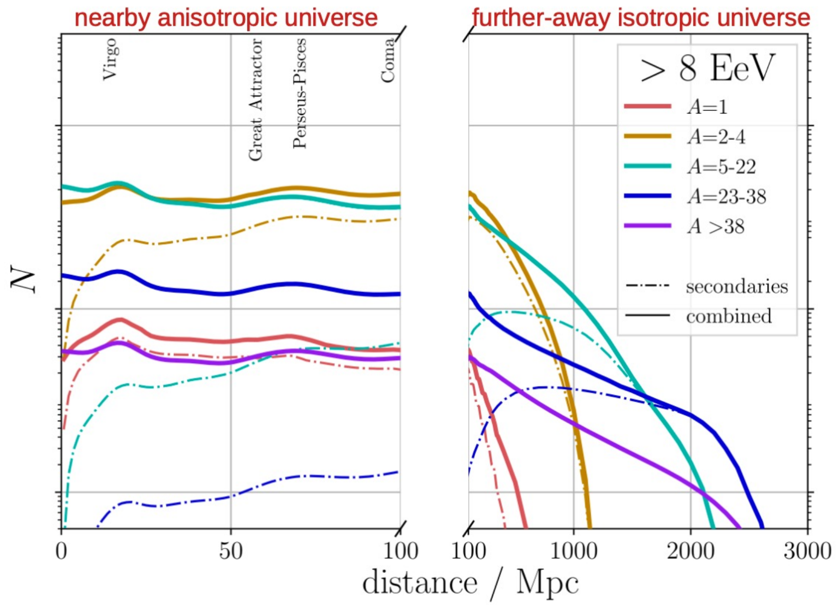
Pierre Auger Collaboration, 2408.05292

UHECR Flux from the large-scale structure > 8 EeV

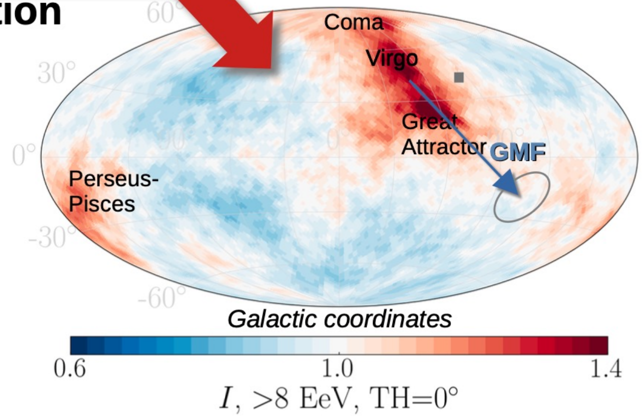


use as source distribution

combined fit to spectrum and composition data



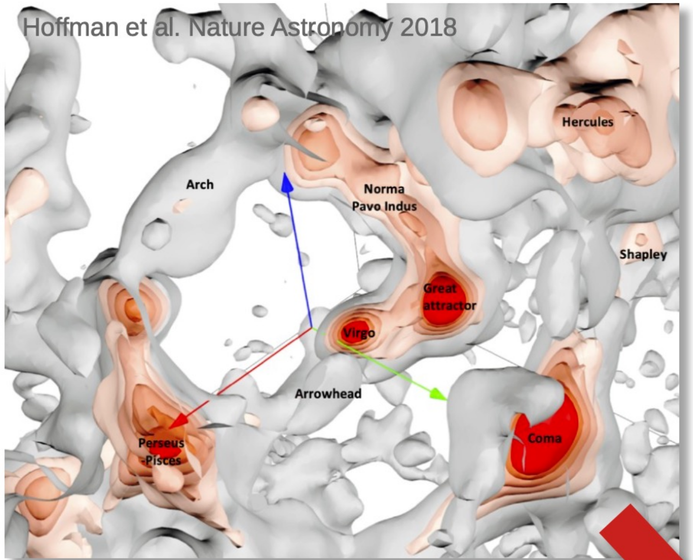
predicted flux at edge of Galaxy:



In the LSS + combined fit model, the dipole at ~8 EeV is generated by **primary Helium & CNO** from Virgo, Great Attractor & Coma

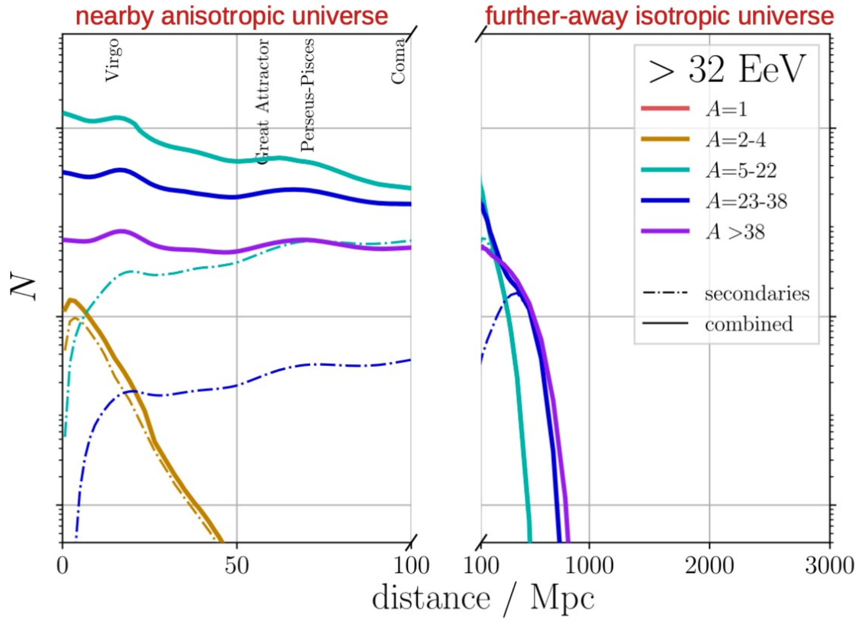
Bister & Farrar
ApJ 966 71 (2024)

UHECR Flux from the large-scale structure >32 EeV

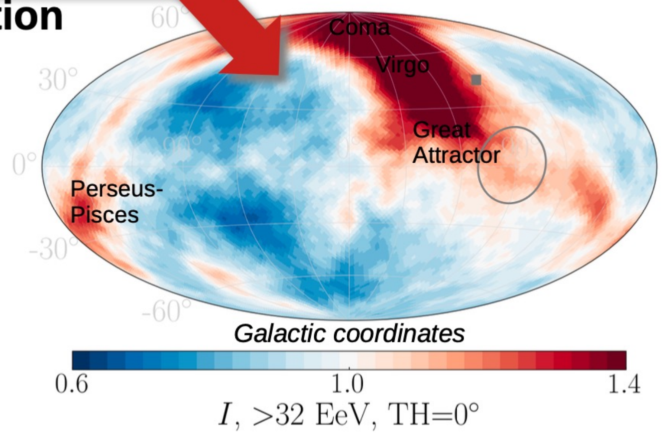


use as source distribution

combined fit to spectrum and composition data



predicted flux at edge of Galaxy:

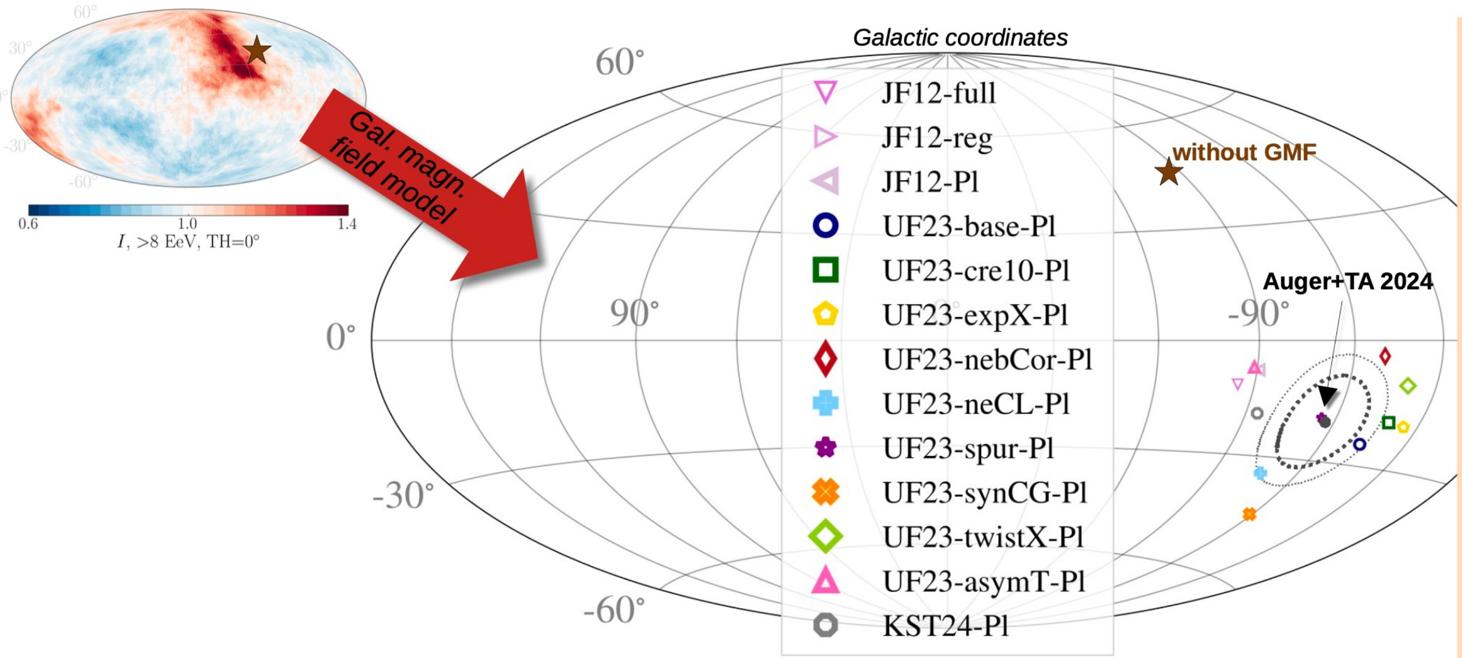


flux **>32 EeV** mostly **primary CNO** from within ~200 Mpc

→ dipole amplitude rises due to shrinking propagation length

Bister & Farrar
ApJ 966 71 (2024)

Dipole direction > 8 EeV



for JF12: difference to predictions based on 2MRS galaxy catalog ~10° ✓
Auger ApJ 976 48 (2024),
Allard et al. A&A A292 (2024)

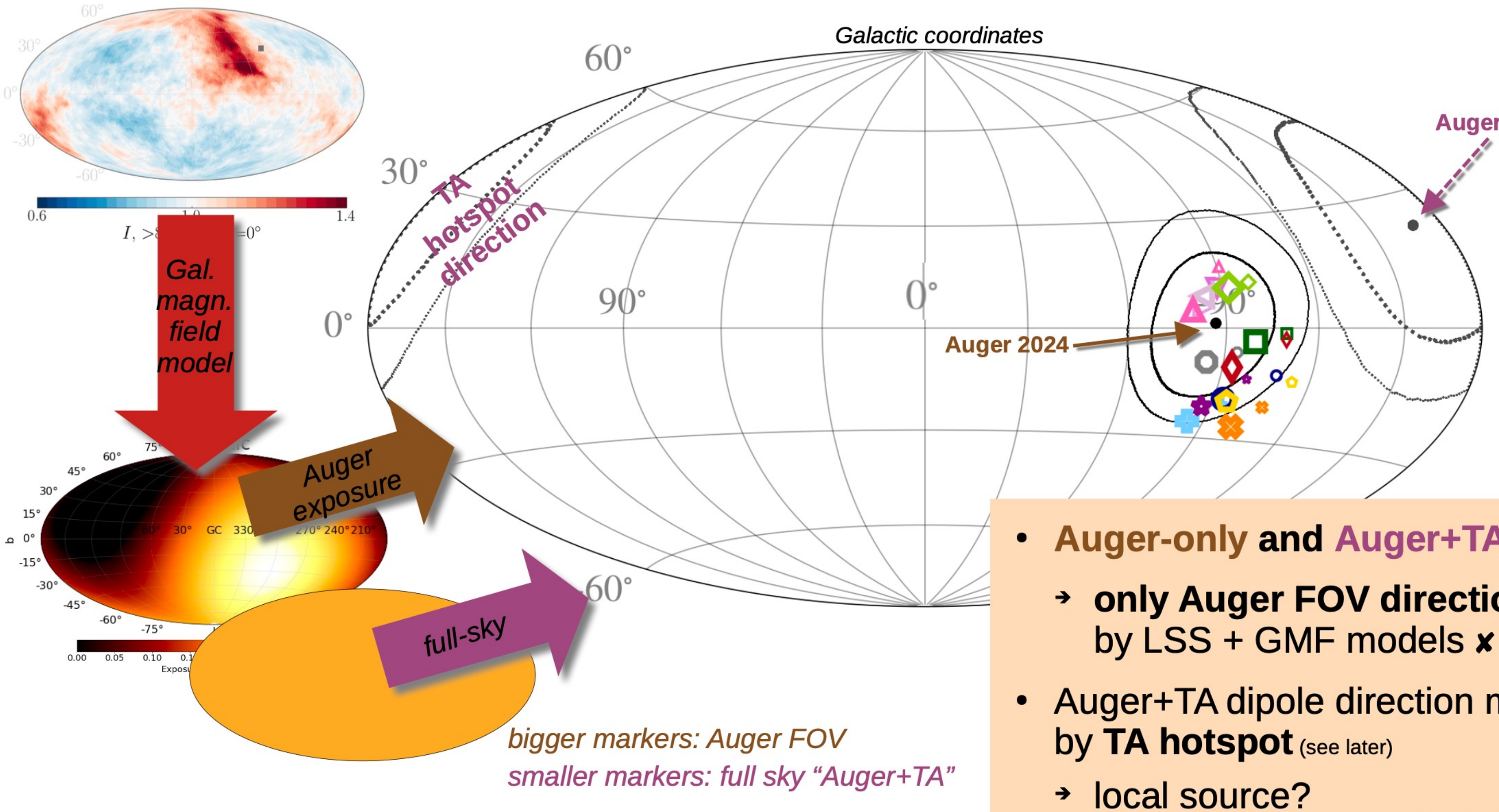
all models predict dipole direction close to measured one ✓

uncertainty estimate of GMF model ✓

Note: cannot get predicted dipole direction to match measurements with **proton-only composition ✘**
Ding, Globus, Farrar ApJL 913 (2021)

Bister, Farrar, Unger ApJL 975 L21 (2024)
+ KST24 model from Korochkin et al. A&A 693 (2025)
+ UF23-asymT model from Unger & Farrar UHECR (2024)

Dipole direction <u>> 32 EeV</u>



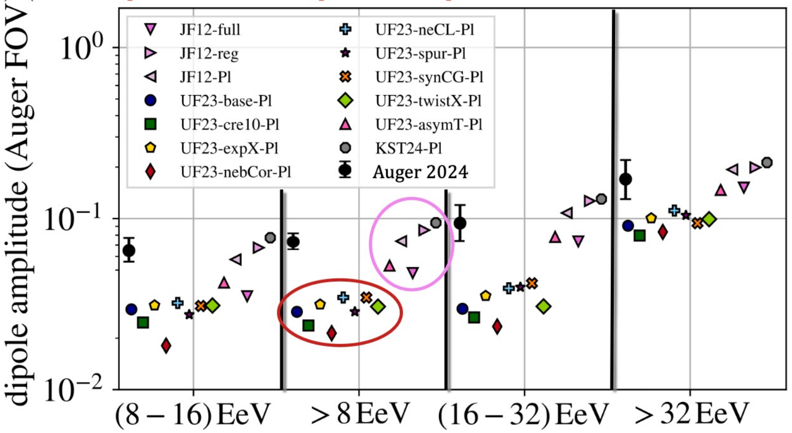
- **Auger-only and Auger+TA differ by 81°**
  - **only Auger FOV direction reproduced** by LSS + GMF models ✘
- Auger+TA dipole direction mainly influenced by **TA hotspot** (see later)
  - local source?
    → e.g. M82, see also H. He et al PRD 93 (2016)

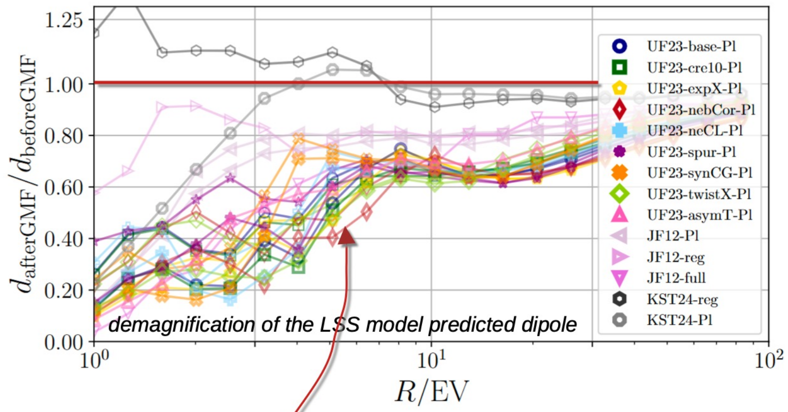
Bister, Farrar, Unger ApJL 975 L21 (2024)
+ KST24 model from Korochkin et al. A&A 693 (2025)
+ UF23-asymT model from Unger & Farrar UHECR (2024)

continuous model (infinite source density)

Dipole amplitude ↔ (de-)magnification

predicted dipole amplitudes:

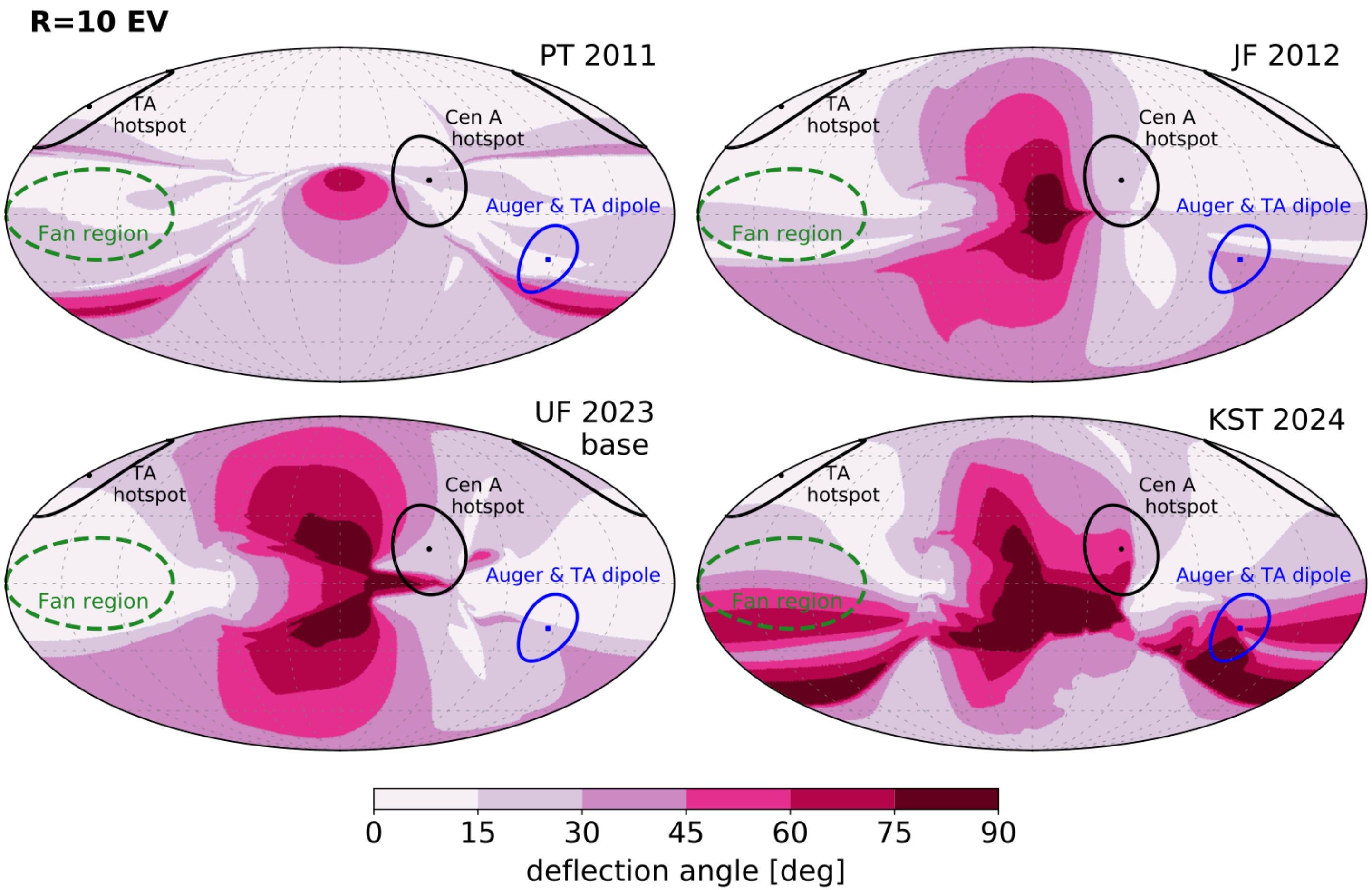




due to (de-)magnification differences!

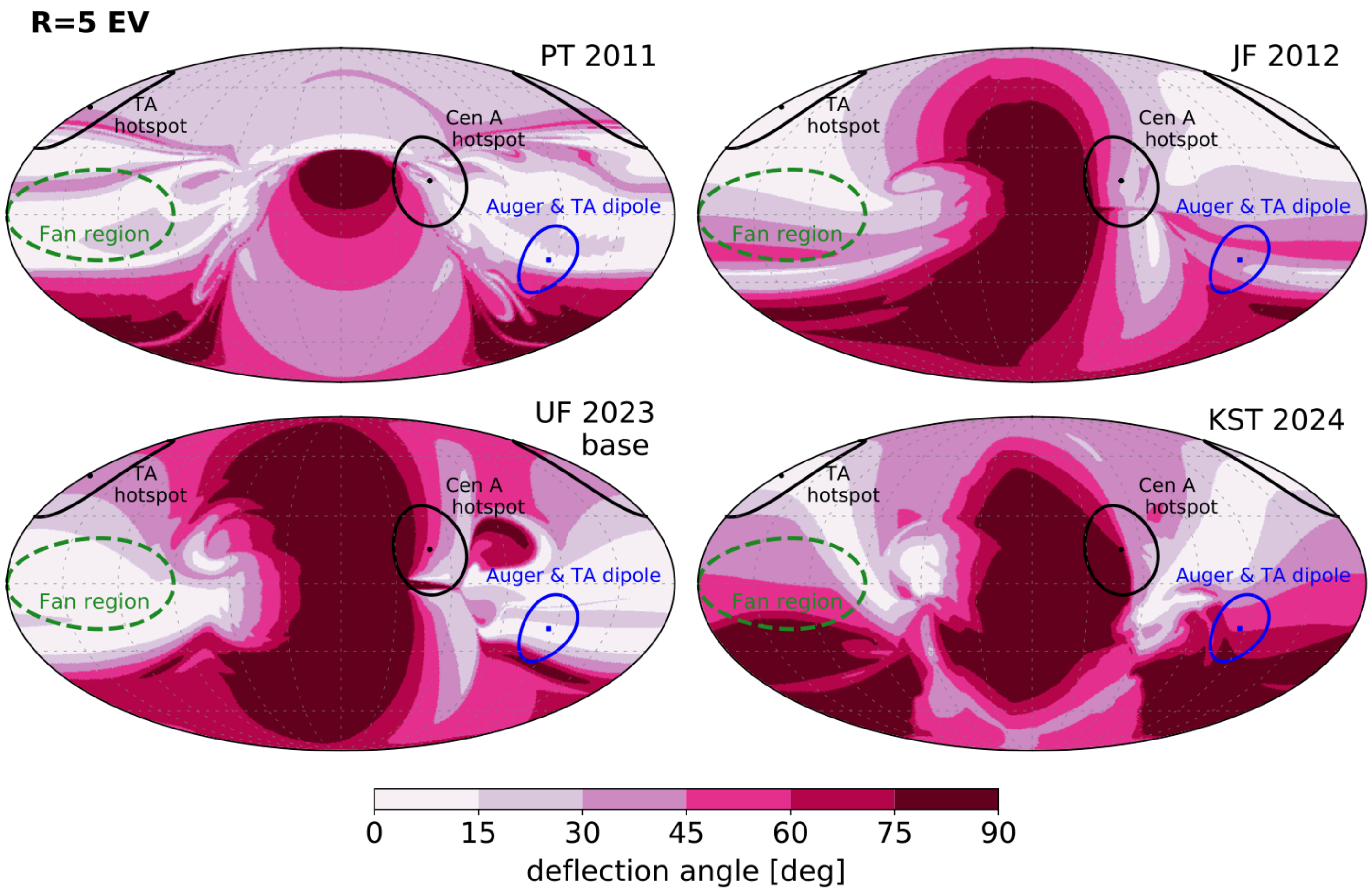
UF23 models predict significantly smaller dipole amplitude than JF12 / KST24 / UF23-asymT

UHECR R=10 EV



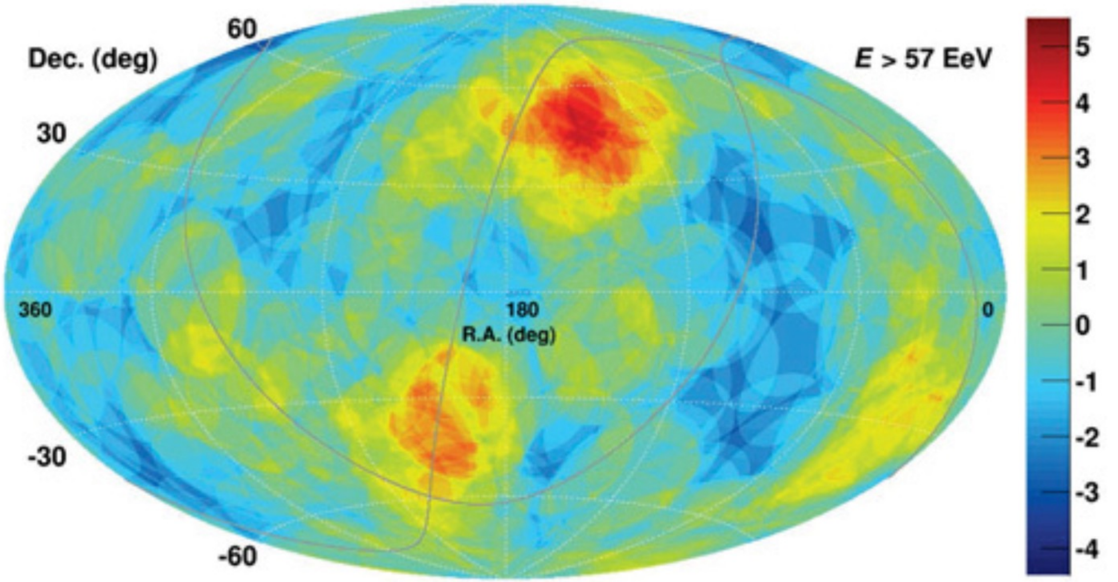
A. Korochkin, D.S. and P.Tinyakov 2501.16158

UHECR R=5 EV



A. Korochkin, D.S. and P.Tinyakov 2501.16158

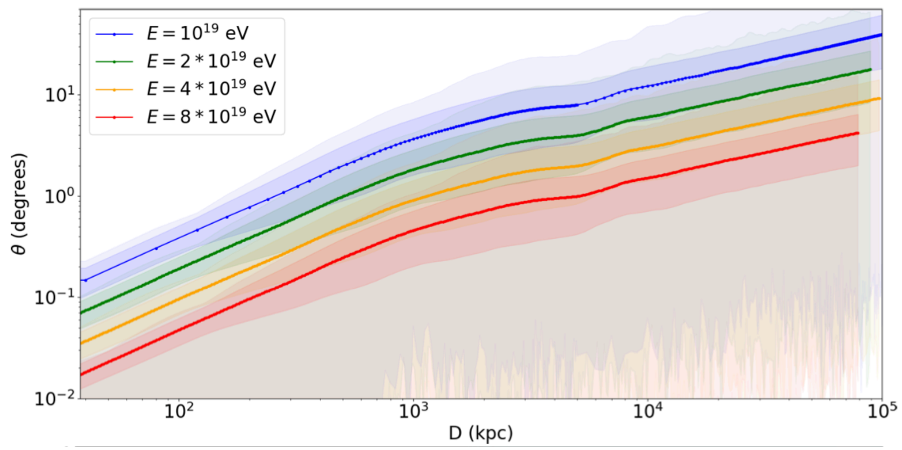
Auger-TA sky map E>57 EeV

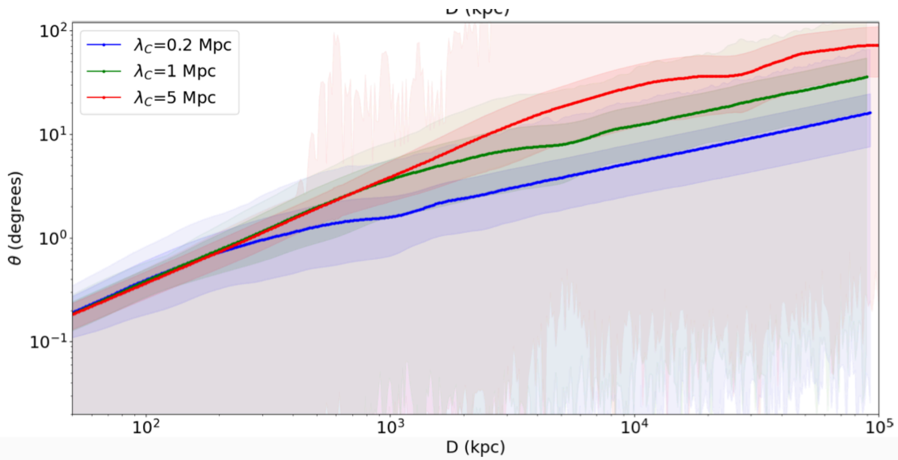


Full sky map combining the Telescope Array and Pierre Auger data events with E > 5.7×10 19 eV. The events have oversampling with a 20 @BULLET radius circle. The Telescope Array data set includes 109 events, representing the first 7 years of data collection. The Auger data set includes 157 events, representing 10 years of data. No correction was made for the energy scale difference between the Telescope Array and Pierre Auger data sets.

Auger & TA collaboration

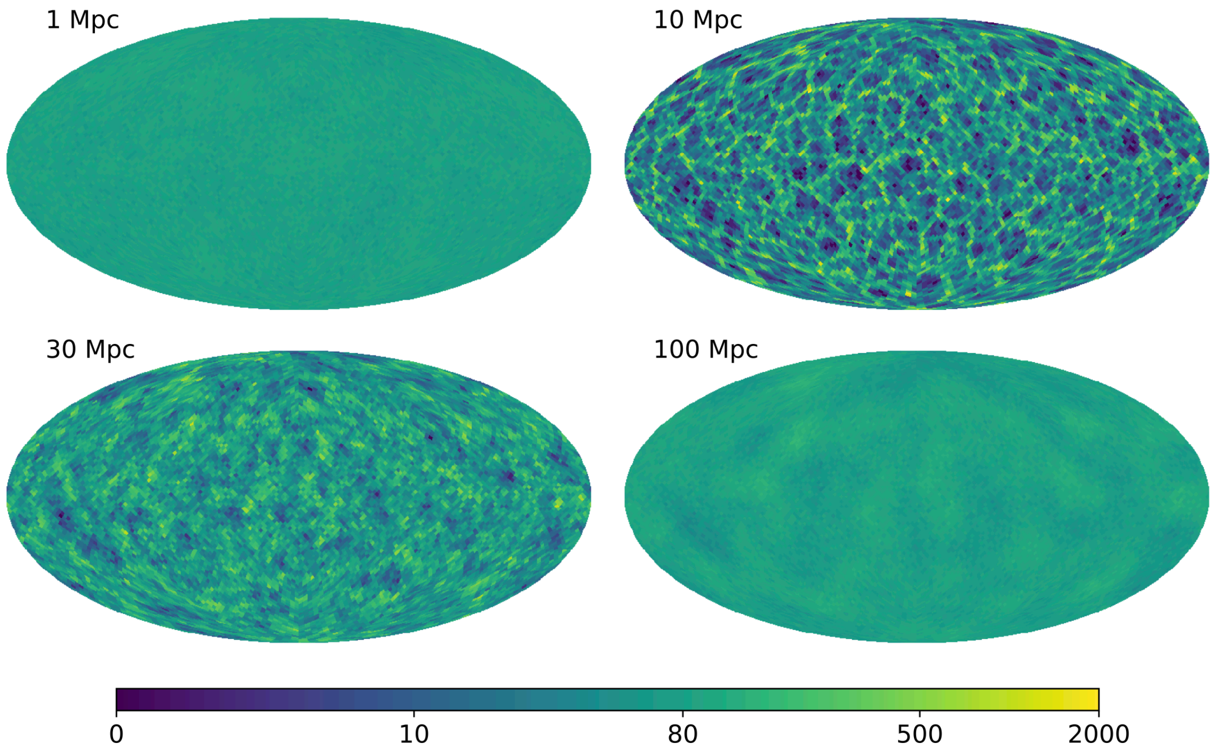
UHECR propagation in IGMF





$$\theta \sim 4^\circ \, Z \frac{B}{\text{nG}} \frac{10 \text{ EeV}}{E} \sqrt{\frac{D}{\text{Mpc}}} \sqrt{\frac{\lambda_C}{\text{Mpc}}}$$

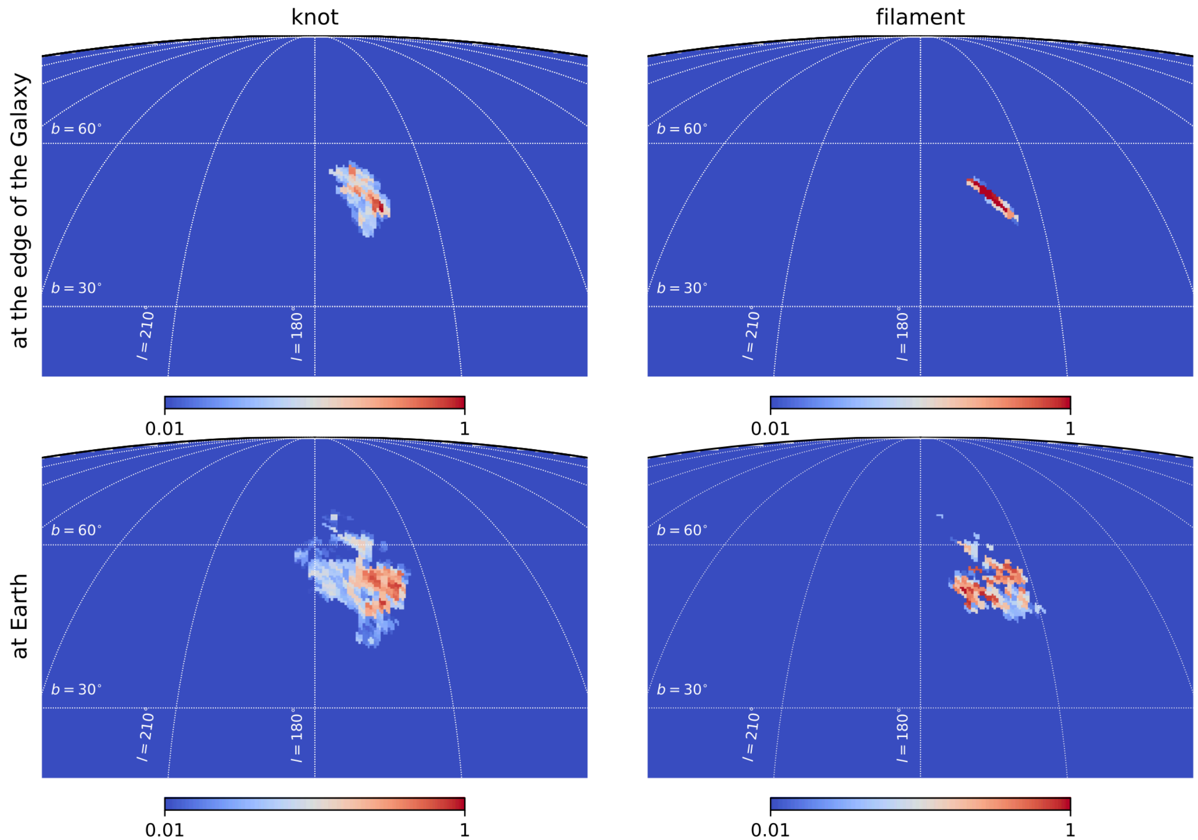
UHECR propagation in IGMF: caustics



Lambda=0.3 Mpc R=10 EV

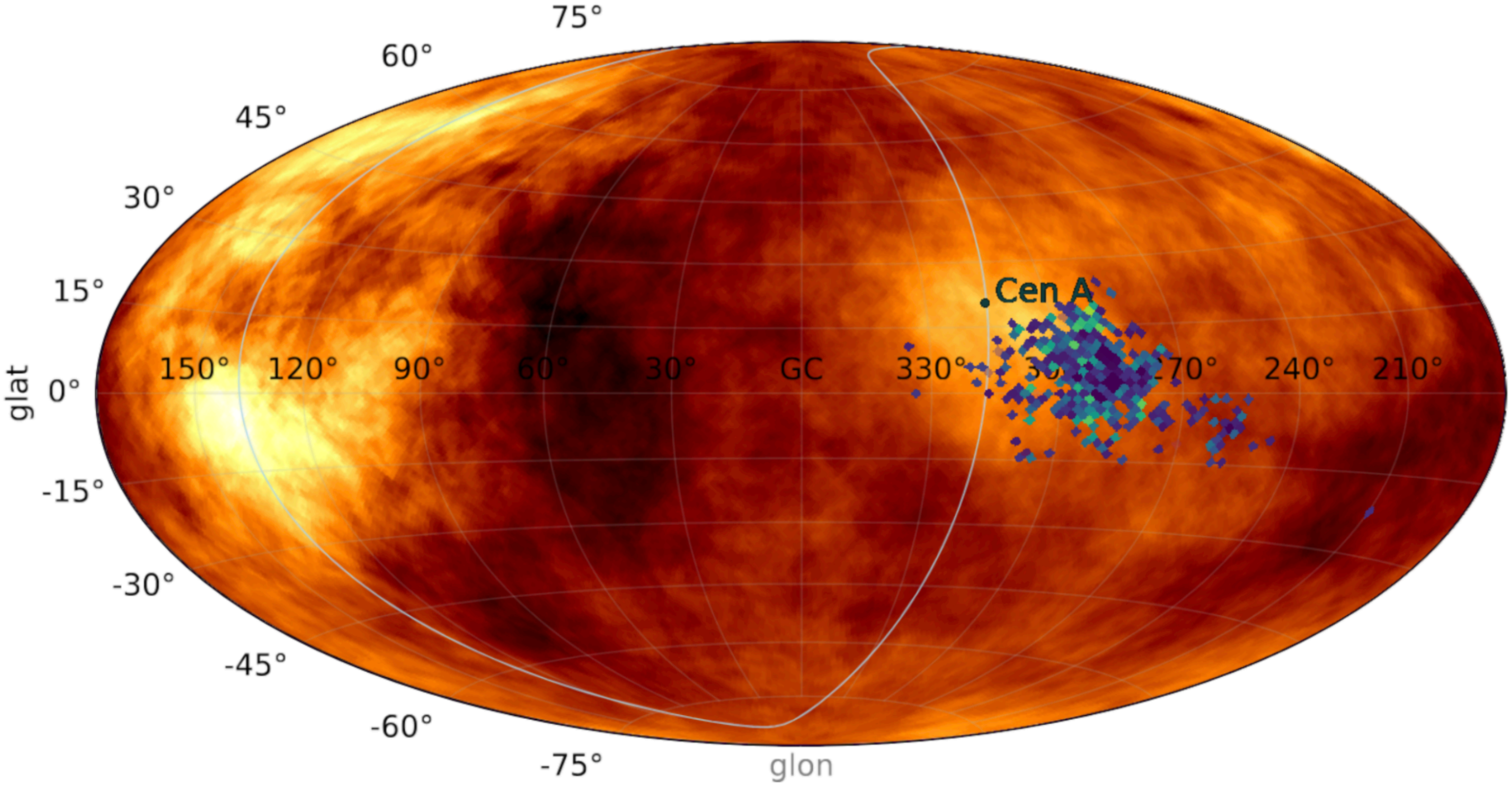
A.Dolgikh, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, 2212.01494

UHECR source in TA hot spot



A.Dolgikh, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, 2312.06391

Cen A flux is shifted in JF12 GMF model



K.Dolgih, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, to appear arXiv:2505…

M83 is of for JF12 GMF model

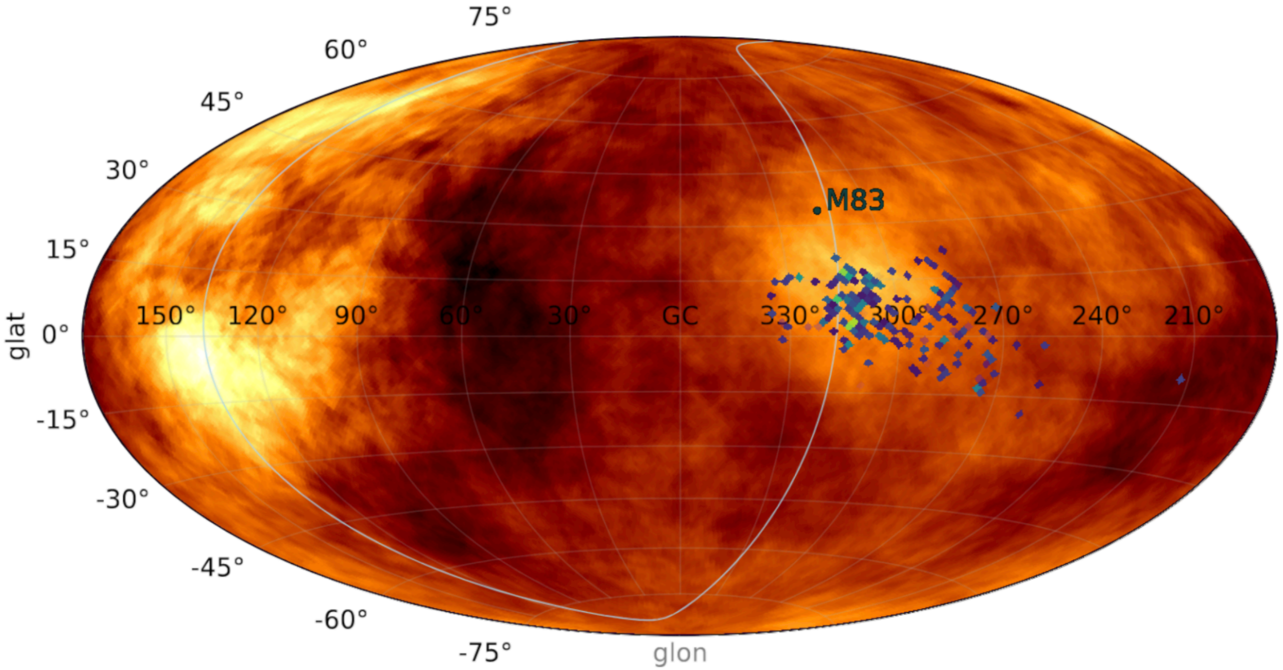
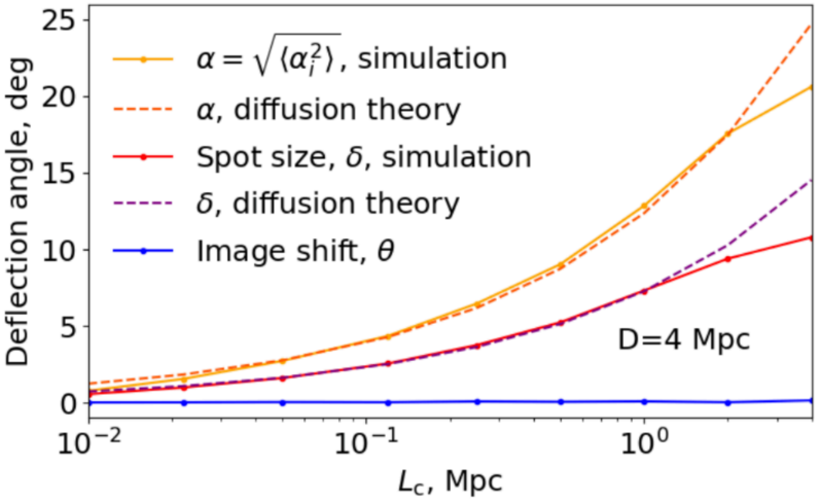
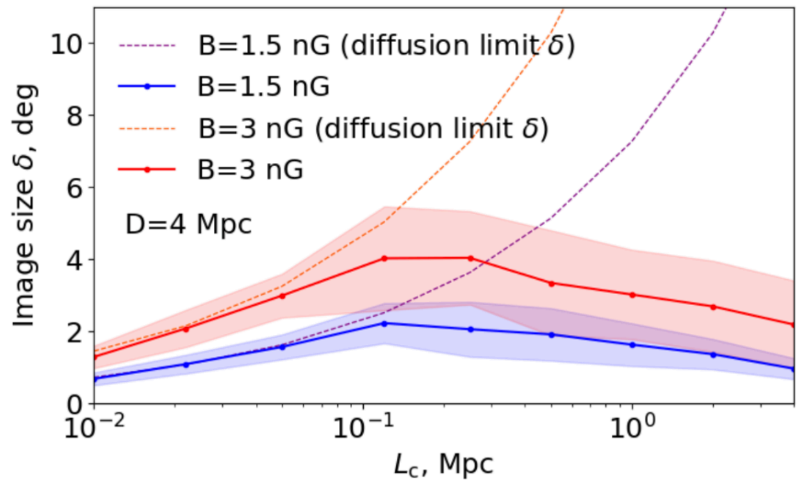


FIG. 3. Arrival directions of the carbon nuclei with $E = 60$ EeV from M 83 for the same magnetic fields and as Fig. 2.

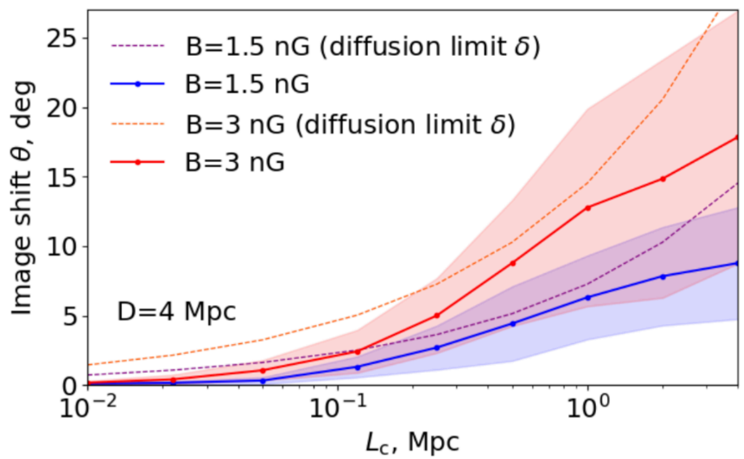
K.Dolgih, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, to appear arXiv: 2505.14344

Diffusion in angle



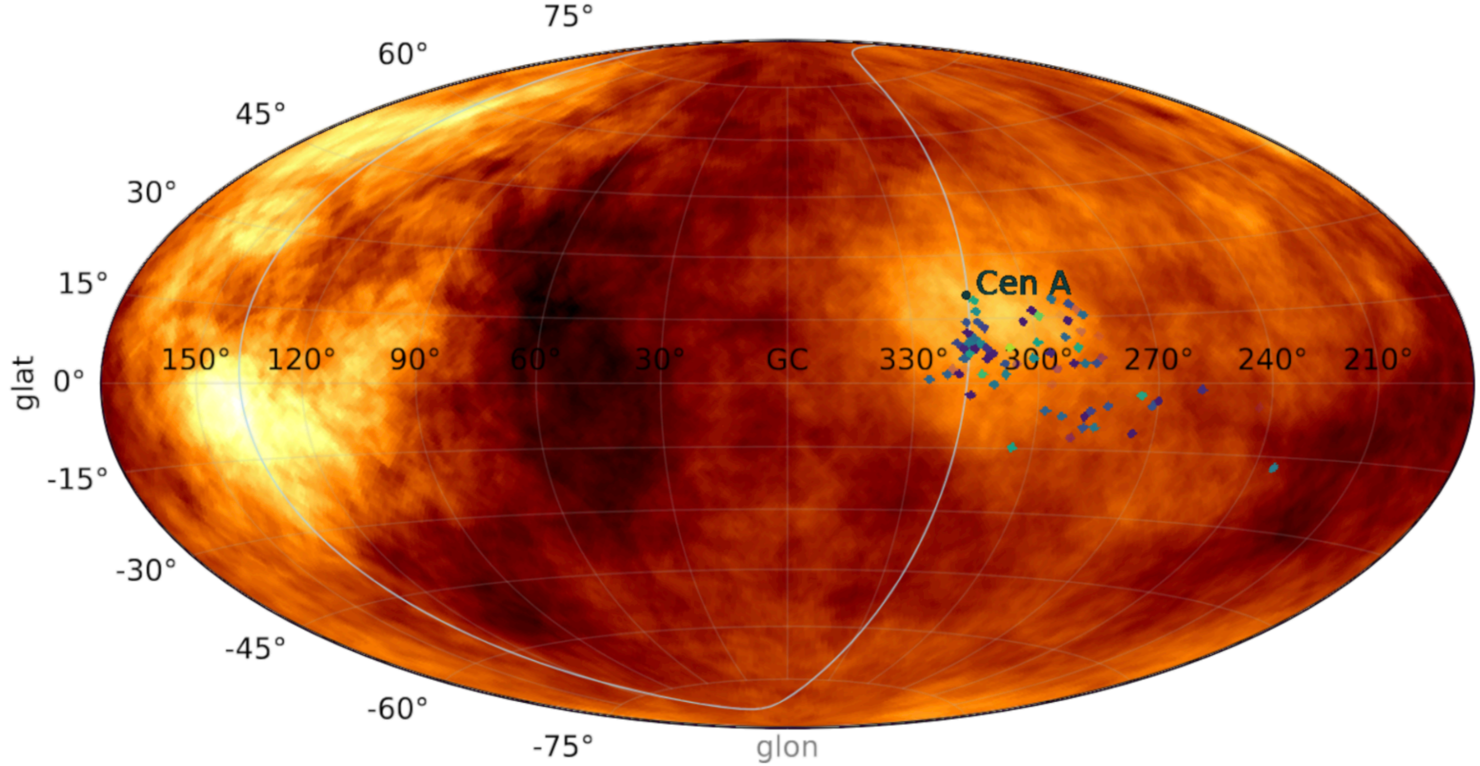


$$\begin{cases} \alpha = 3.74^\circ \cdot Z \left[\frac{B}{1\,\mathrm{nG}}\right] \left[\frac{E}{10^{19}\,\mathrm{eV}}\right]^{-1} \left[\frac{D}{10\,\mathrm{Mpc}}\right]^{\frac{1}{2}} \left[\frac{L_{\max}}{500\,\mathrm{kpc}}\right]^{\frac{1}{2}} \\ \delta = \alpha/\sqrt{3} \\ \theta = 0. \end{cases}$$



K.Dolgih, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, to appear arXiv:2505.14344

Cen A back to place due to IGMF

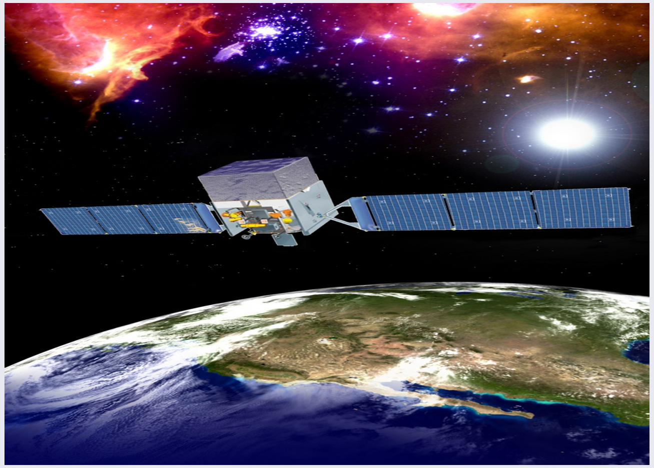


K.Dolgih, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, to appear arXiv: 2505.14344

Gamma-rays and neutrinos from Milky Way Galaxy

Gamma-ray detectors

Space-based
EGRET, AGILE,
Fermi



HE: >0.1 GeV
Large FOV
80% duty cycle
0.1° ~ 5°
resolution
1 m^2 area

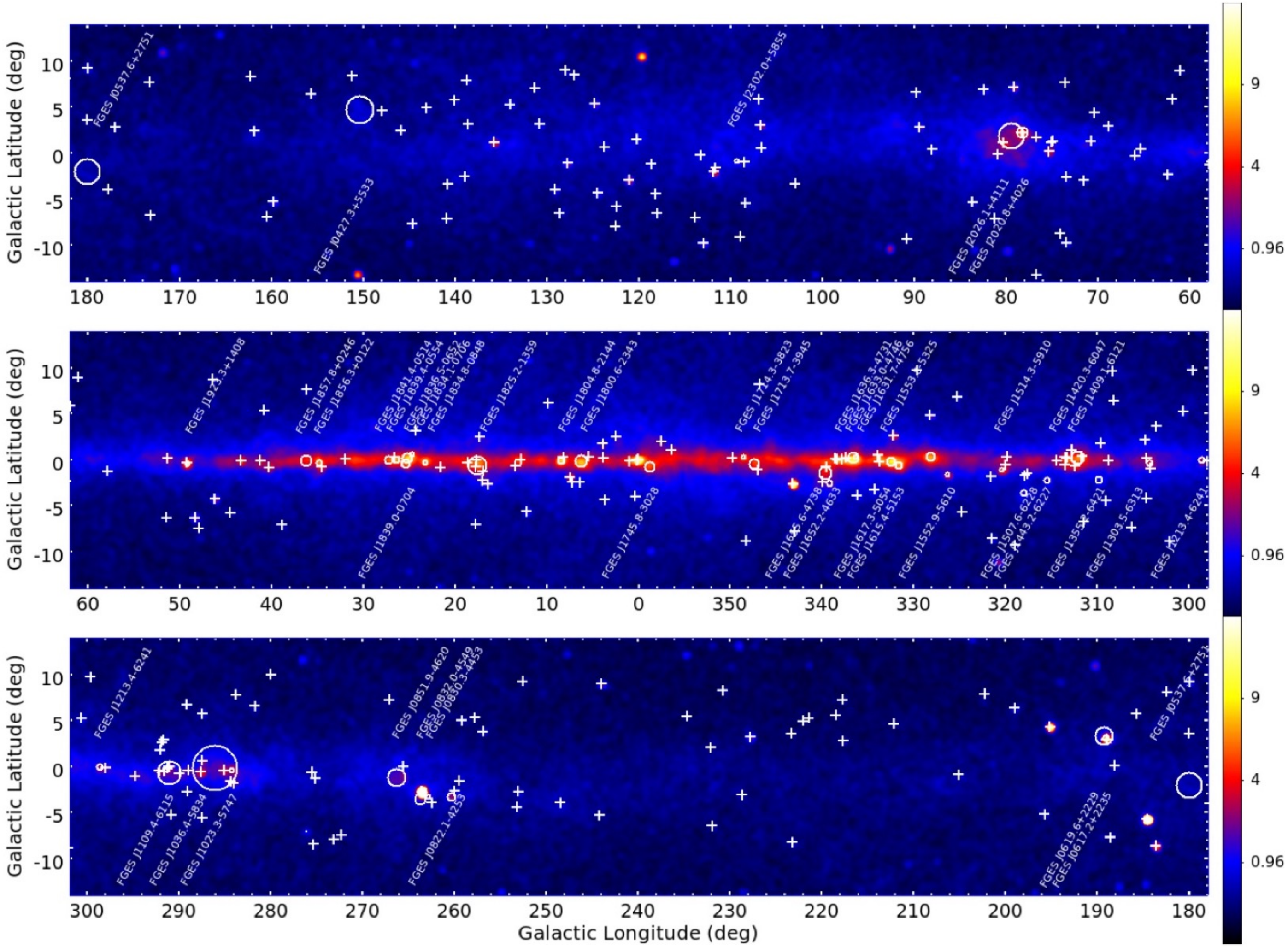
IACTs:
H.E.S.S., MAGIC, VERITAS,
CTA

VHE:>0.1 TeV
3°~5° FOV
15% duty cycle
0.06°~ 0.17°
resolution
10^5 m^2 area

EAS arrays:
Milagro, ARGO-YBJ
Tibet Asγ, HAWC,
LHAASO, SWGO

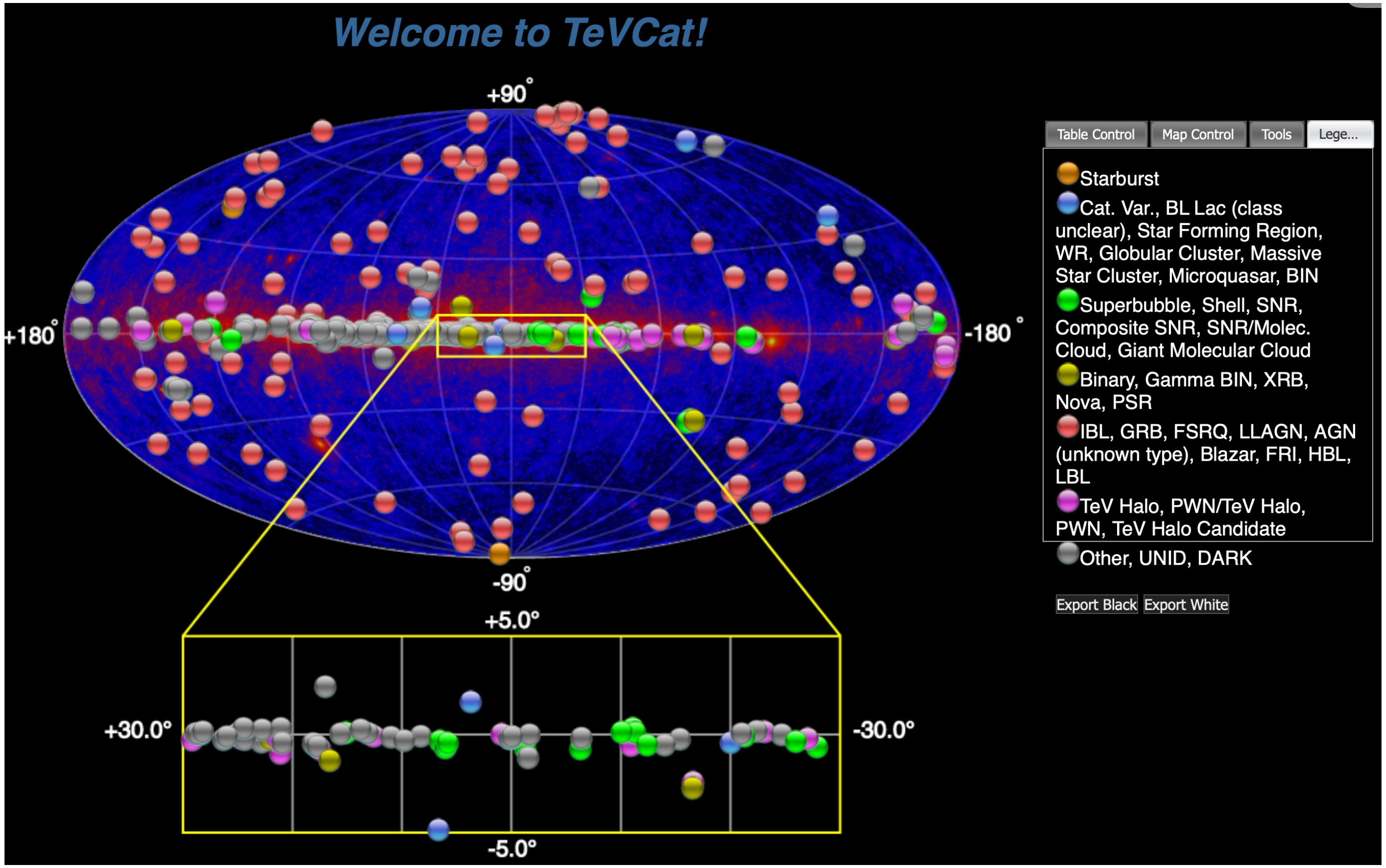
VHE: >0.1 TeV
UHE: >0.1 PeV
Large FOV
100% duty cycle
0.1° ~ 1° resolution
10^{3-6} m^2 area

Fermi LAT 600 identified Galactic sources



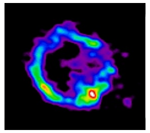
Fermi LAT 1702.00476

Cherenkov telescopes+ HAWC/LHAASO



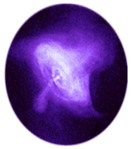
Around 200 sources in the Galactic plane at TeV energies

Galactic sources

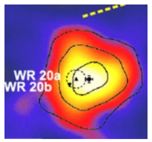


Supernova Remnants

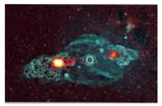
Talk by Songzhan Chen



Pulsar wind nebulas



Star clusters



Microquasars

Pion production

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

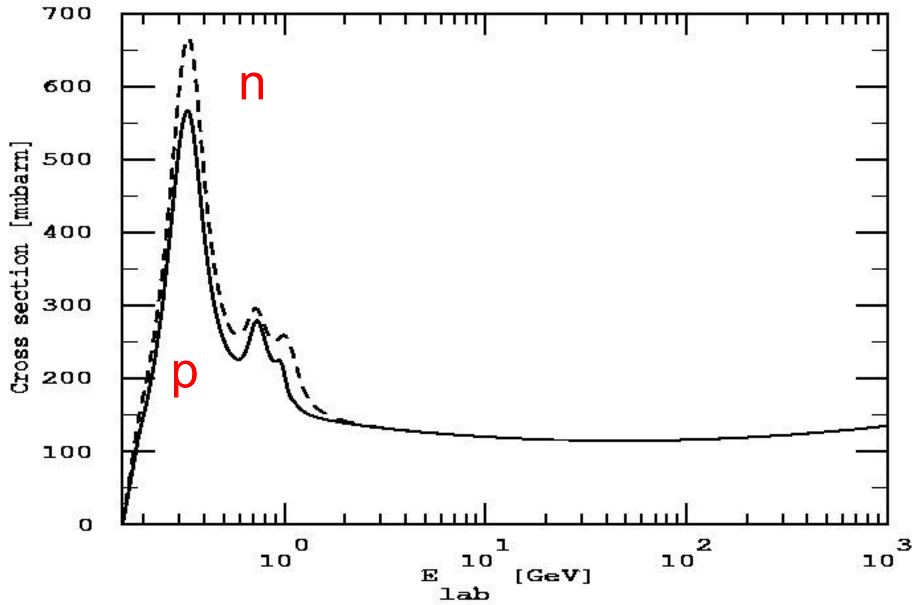
$$N + A_b \Rightarrow N' + \sum \pi^i$$

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

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

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

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



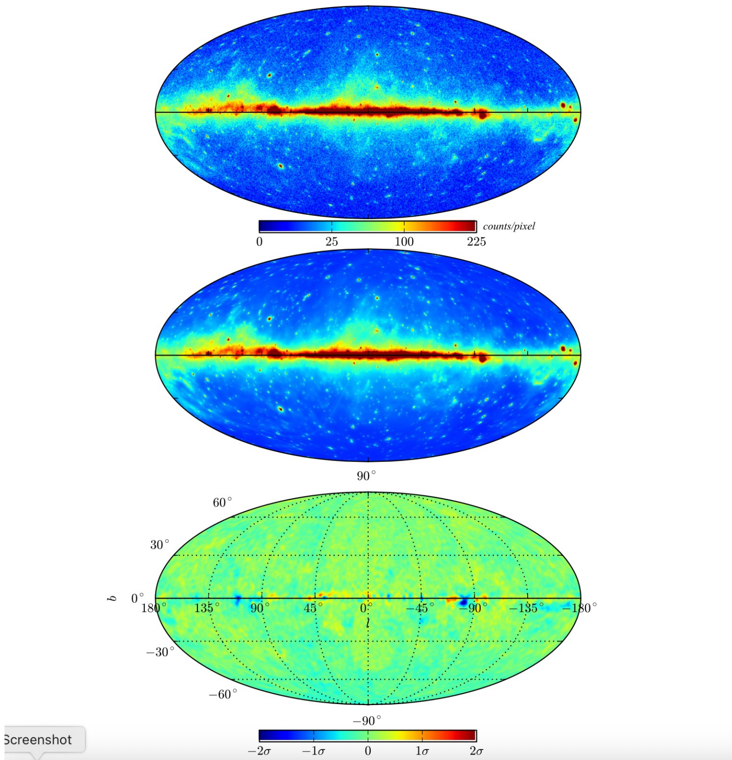
Conclusion: CR, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones (model dependent) : $E_\gamma^{tot} \sim E_\nu^{tot}$

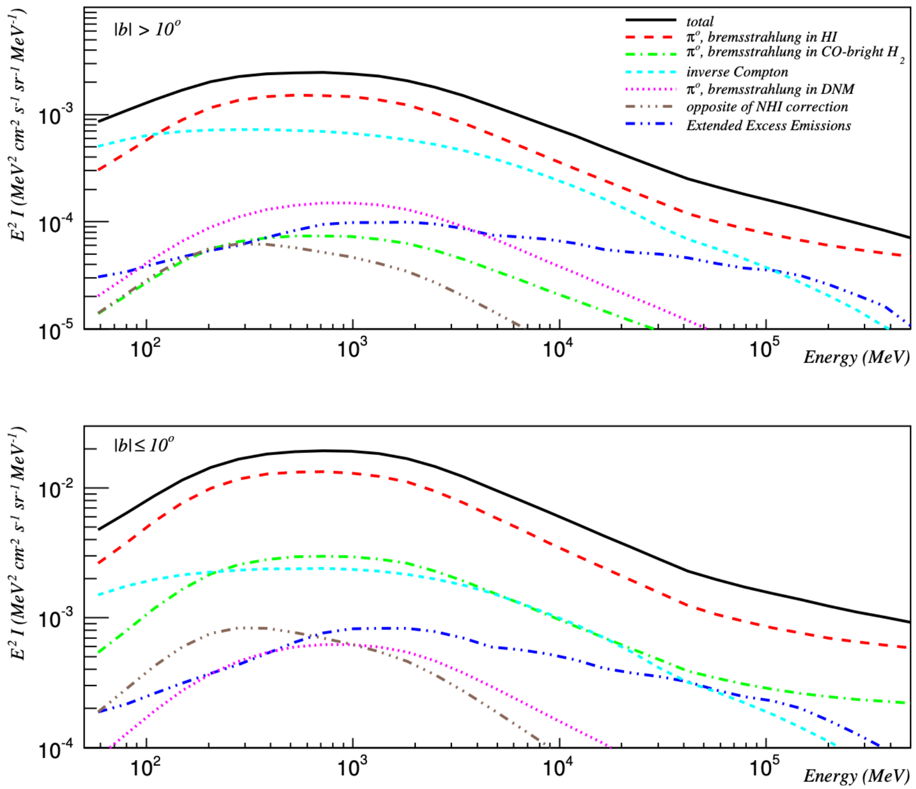
Diffuse gamma-ray and neutrino fluxes

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

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

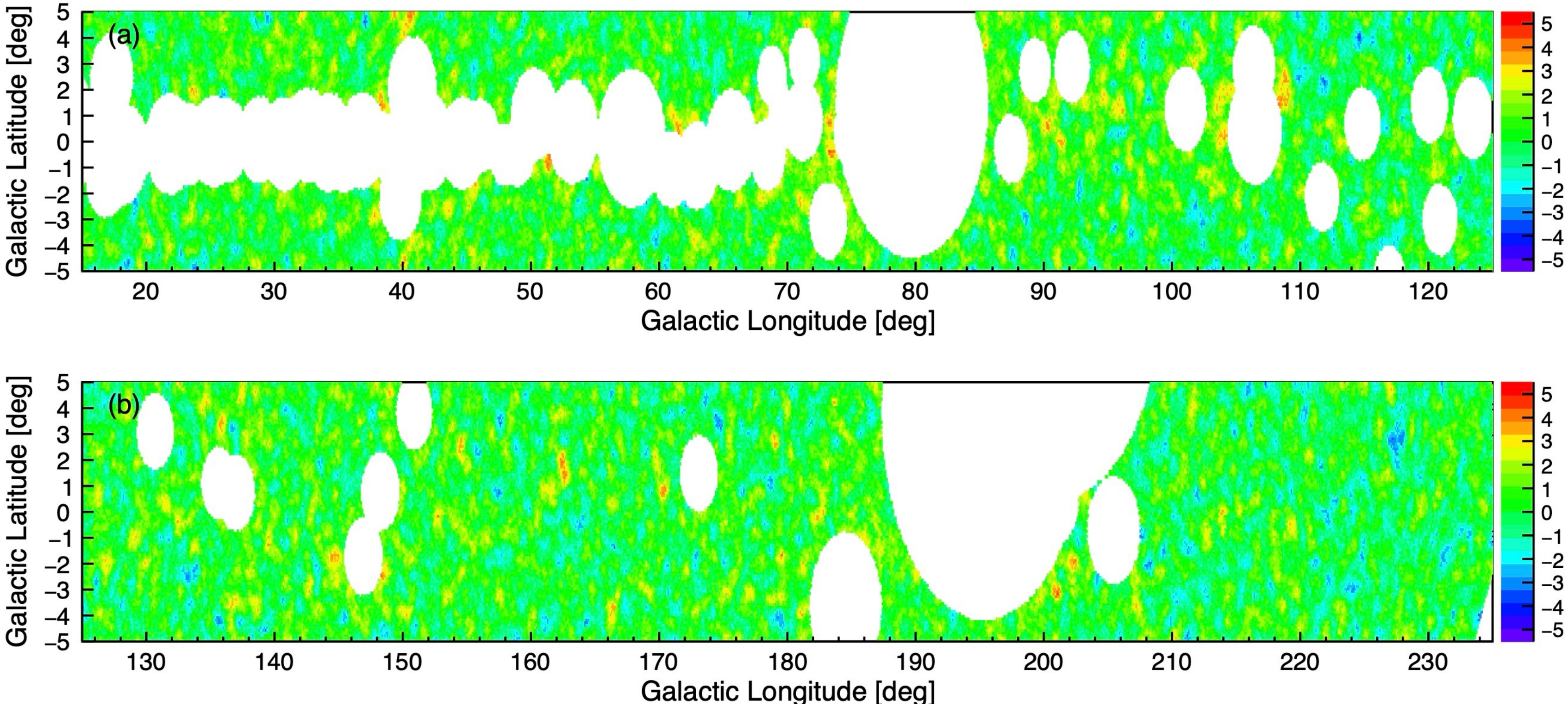
Gamma-ray flux





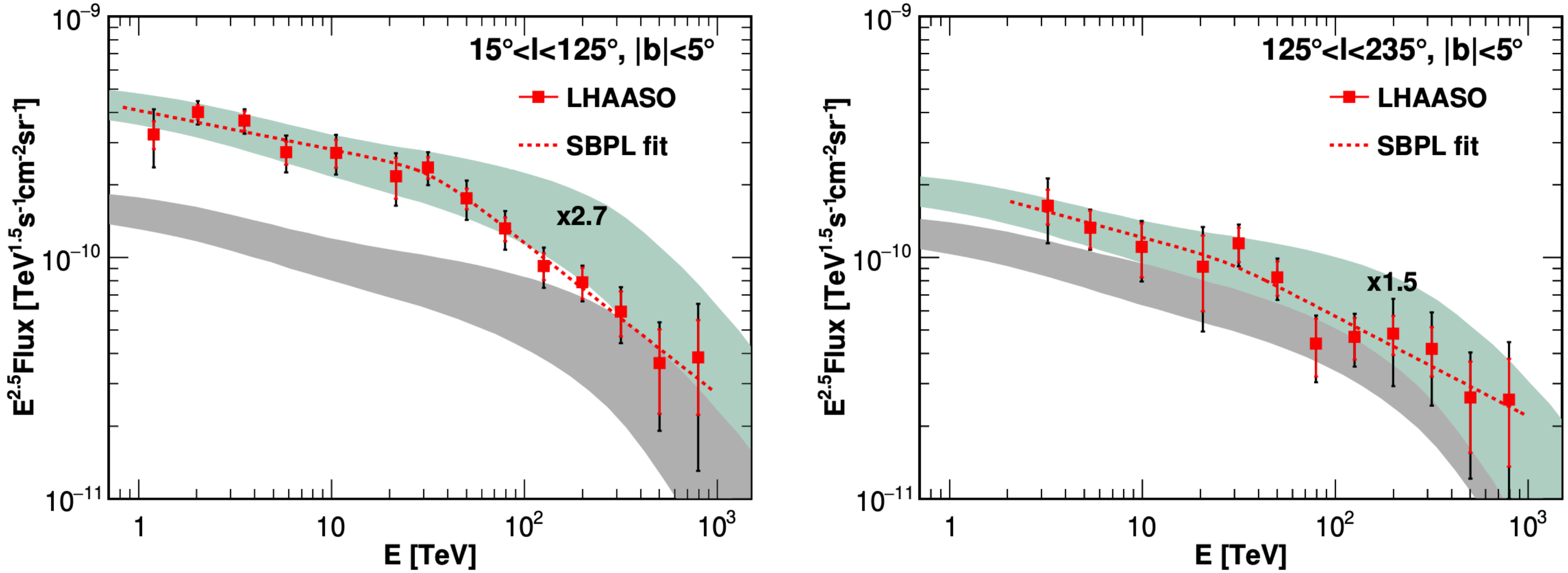
Fermi collaboration, 1602.07246

Mask LHAASO



LHAASO collaboration arXiv: 2305.05372

LHAASO diffuse



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

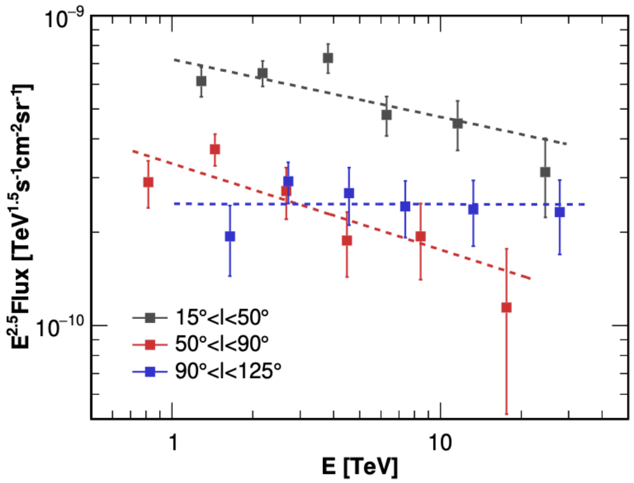
$$I_\nu(E,l,b) = \sum_{A,A'} \int_E^\infty \mathrm{d}E'\, \Xi^{A,A'}(E',l,b) \frac{\mathrm{d}\sigma^{AA'\to\nu}(E',E)}{\mathrm{d}E}$$

LHAASO collaboration, arXiv: 2305.05372, 2411.01621

Variation of diffuse flux over Galaxy

Table 2
Spectrum of the GDE in Various Subregions of the ROI

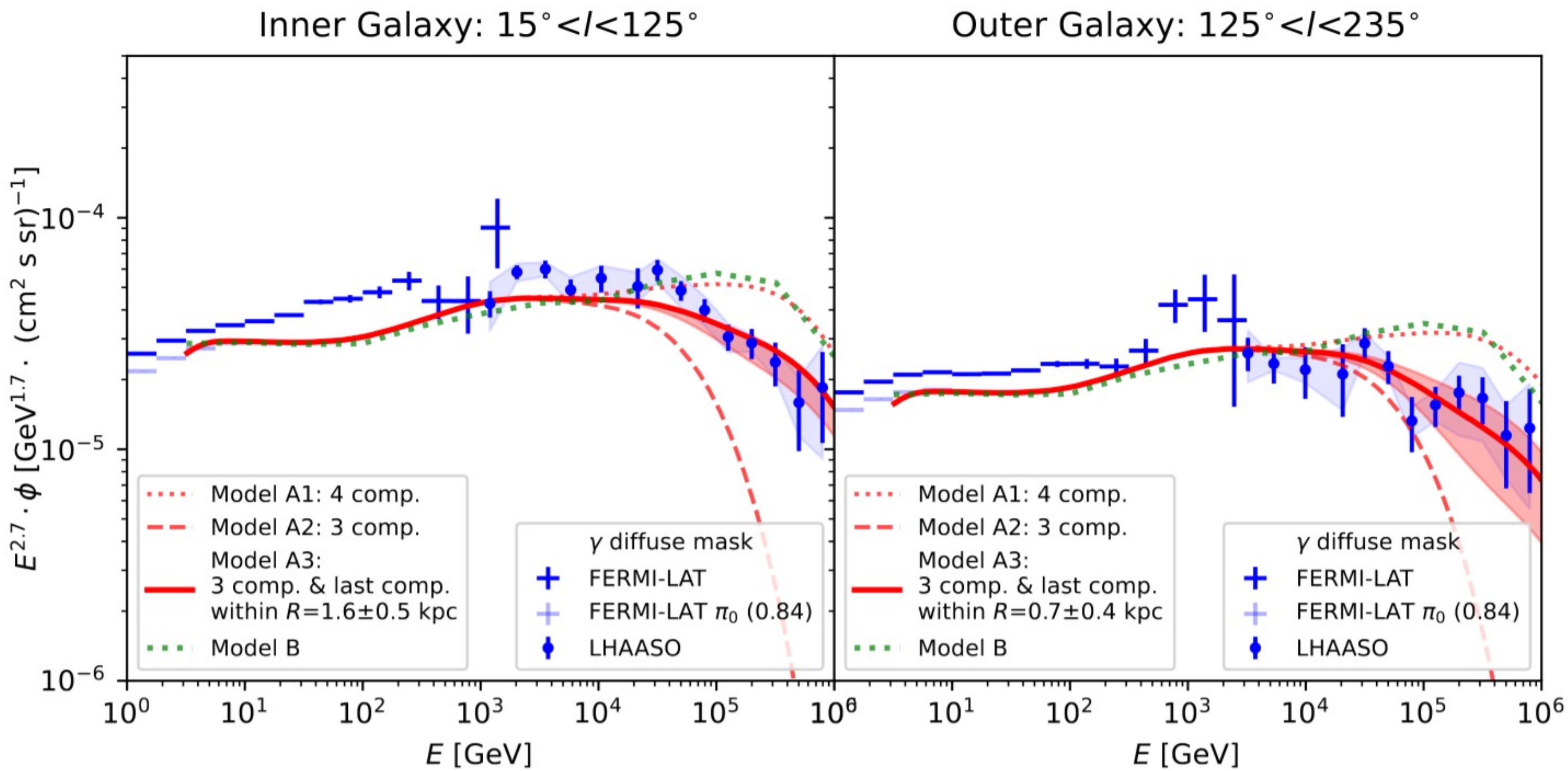
l_{min} (deg)	l_{max} (deg)	$\lvert b \rvert <$ (deg)	$F_7 \times 10^{-12}$ ($TeV^{-1}\ s^{-1}\ cm^{-2}\ sr^{-1}$)	Index
43	73	2	$8.89 \pm 0.37^{-0.70}_{+0.48}$	$-2.61 \pm 0.03^{-0.04}_{+0.02}$
43	73	4	$5.45 \pm 0.25^{-0.44}_{+0.38}$	$-2.60 \pm 0.03^{-0.04}_{+0.01}$
43	56	2	9.9 ± 0.6	-2.70 ± 0.04
43	56	4	5.8 ± 0.4	-2.69 ± 0.05
56	64	2	8.9 ± 0.7	-2.58 ± 0.06
56	64	4	5.2 ± 0.5	-2.60 ± 0.07
64	73	2	7.8 ± 0.7	-2.48 ± 0.07
64	73	4	5.5 ± 0.45	-2.51 ± 0.06



HAWC collaboration,
2310.09117

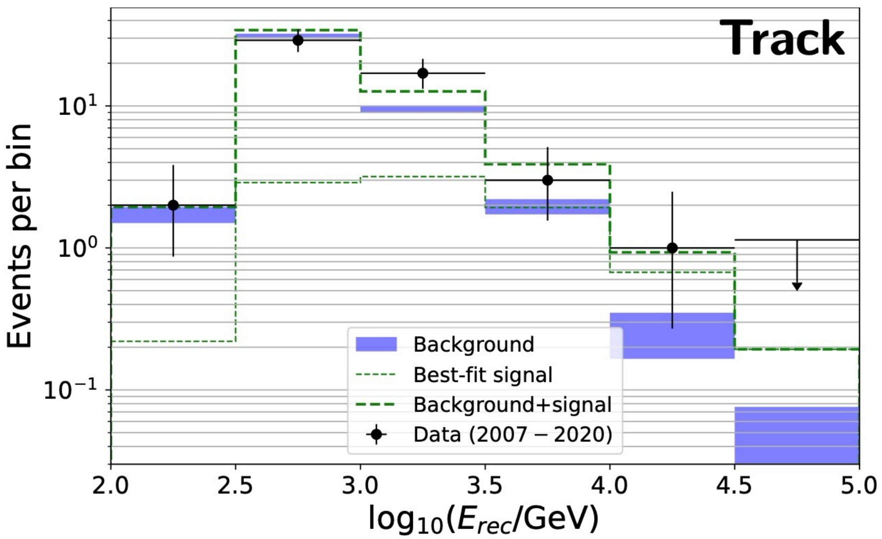
LHAASO collaboration,
arXiv: 2411.01621

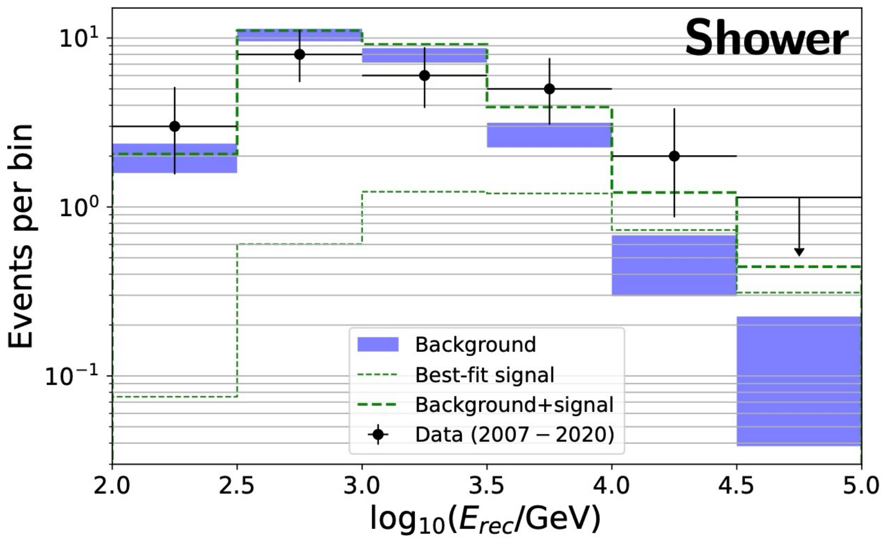
Lower knee in Galaxy



C. Prevotat et al, 2407.11911, 2507.10823

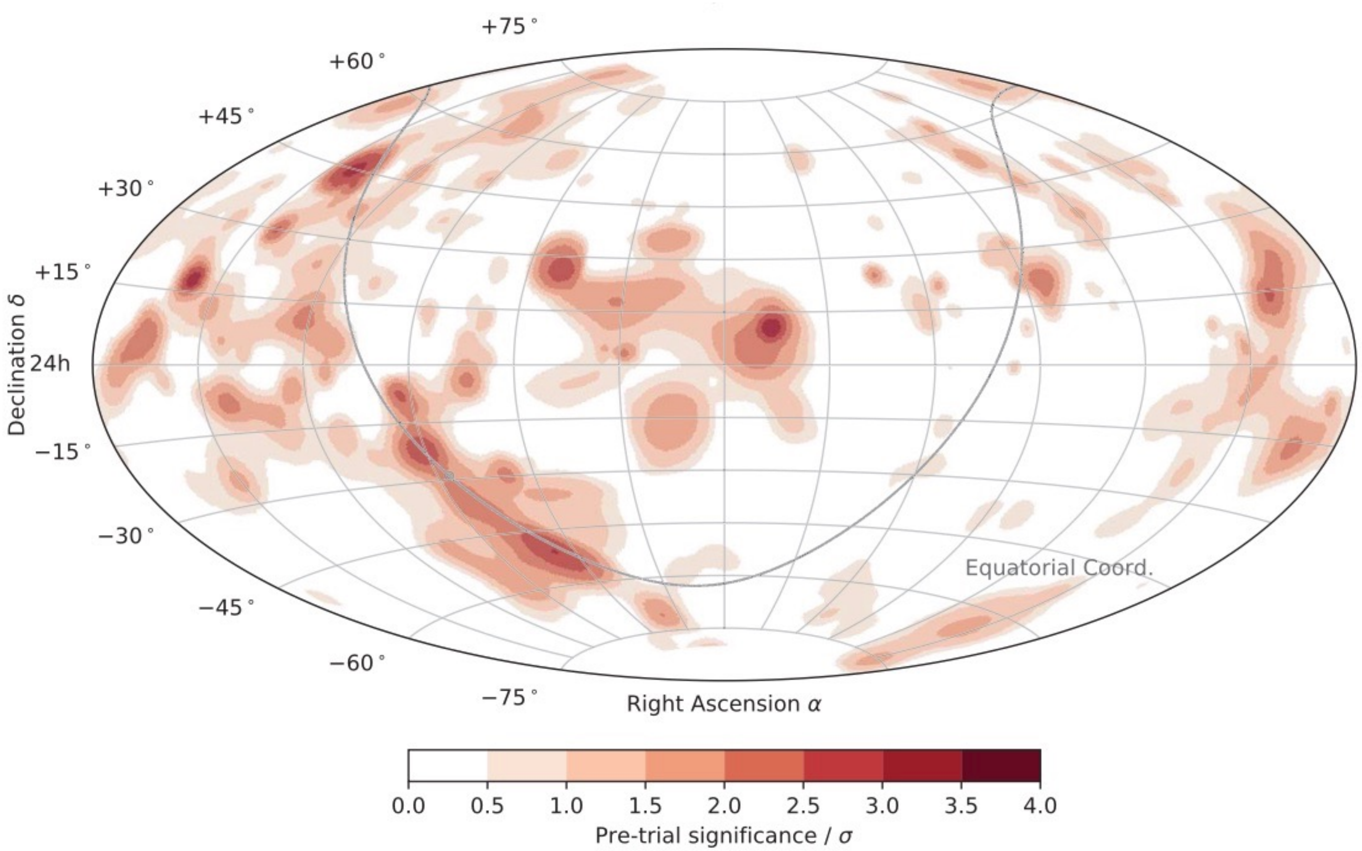
Neutrinos from Galactic plane: ANTARES 2022: 2 sigma excess





A.Albert et al, arXiv:2212.11876

IceCube cascades: 4 sigma



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

Cascades E>200 TeV Baikal and IceCube

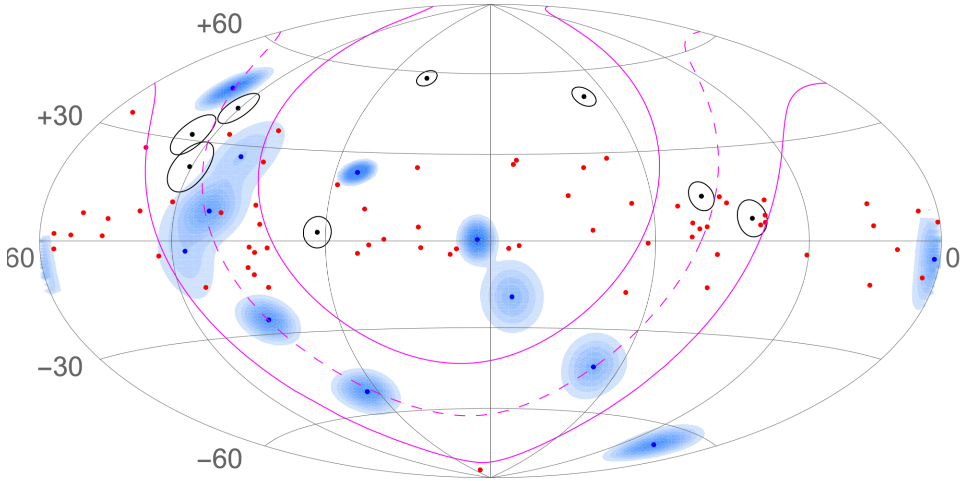


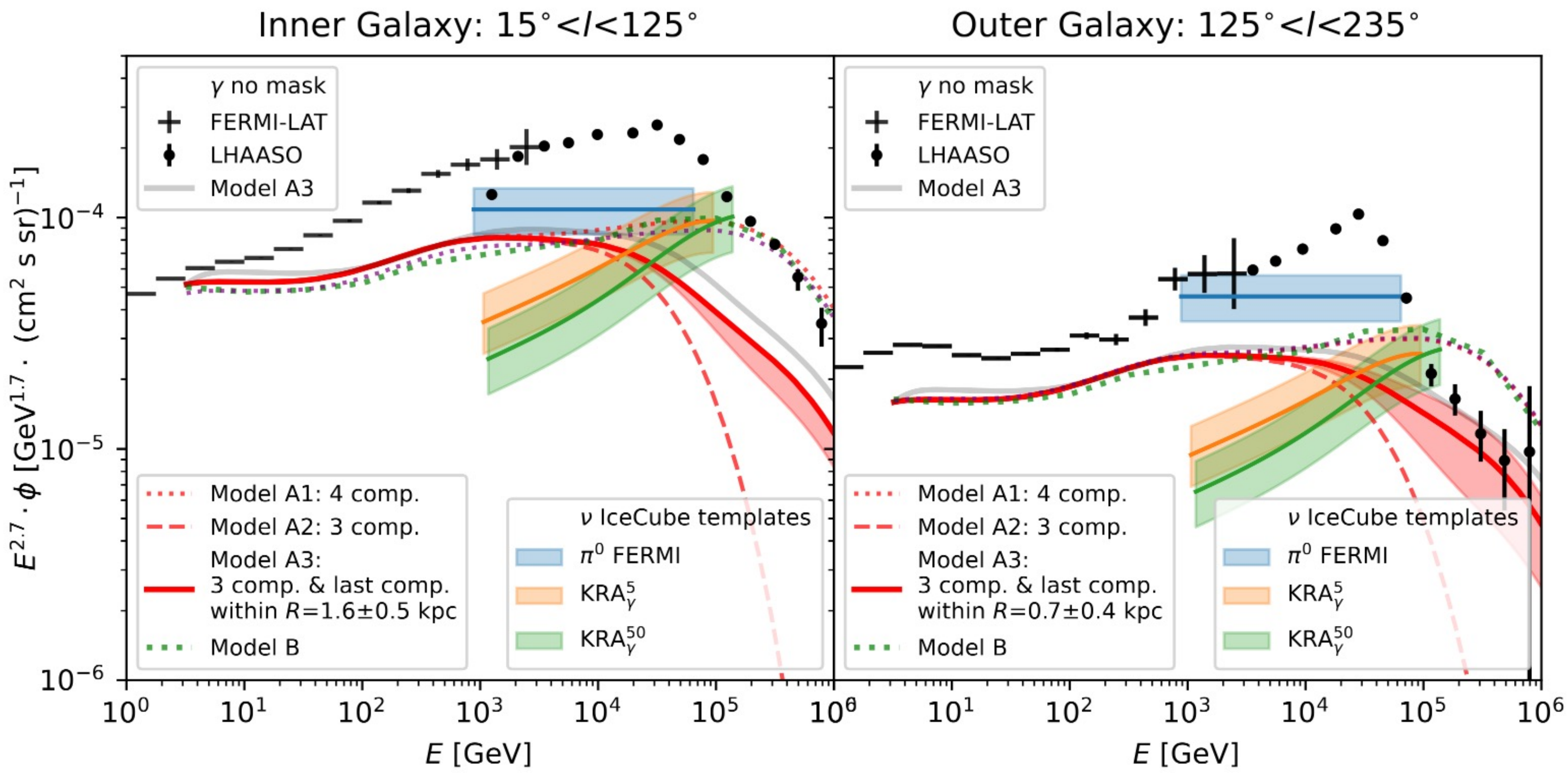
Table 2
Results (This Work) of the Search for the Galactic Component of the Neutrino Flux above 200 TeV (see the Text for Details)

Sample	$\lvert b\rvert_{\rm med}$ Observed (deg)	$\langle\lvert b\rvert_{\rm med}\rangle$ 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,

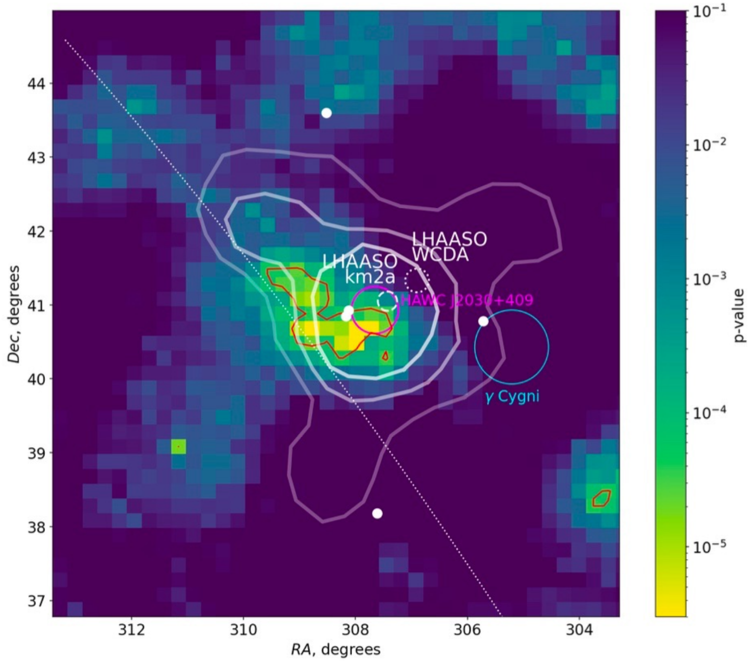
2411.05608

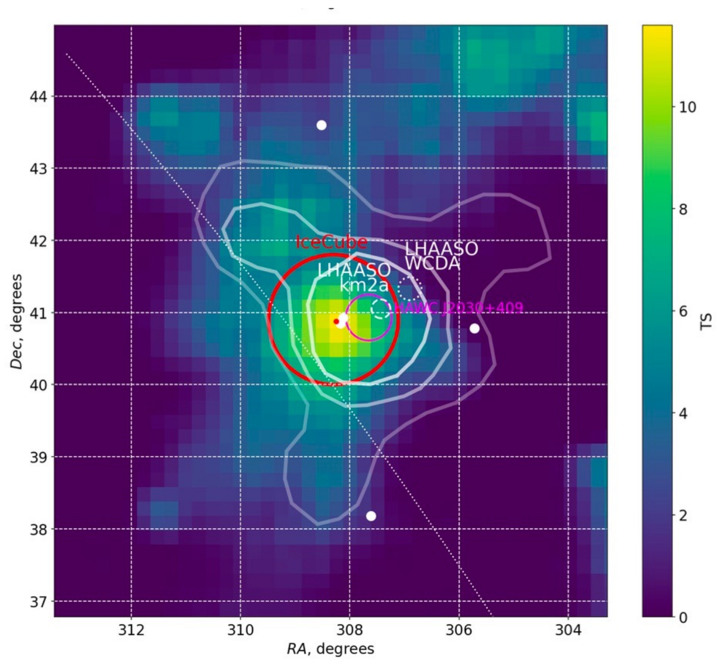
Diffuse neutrino background Galactic plane



C. Prevotat et al, 2507.10823

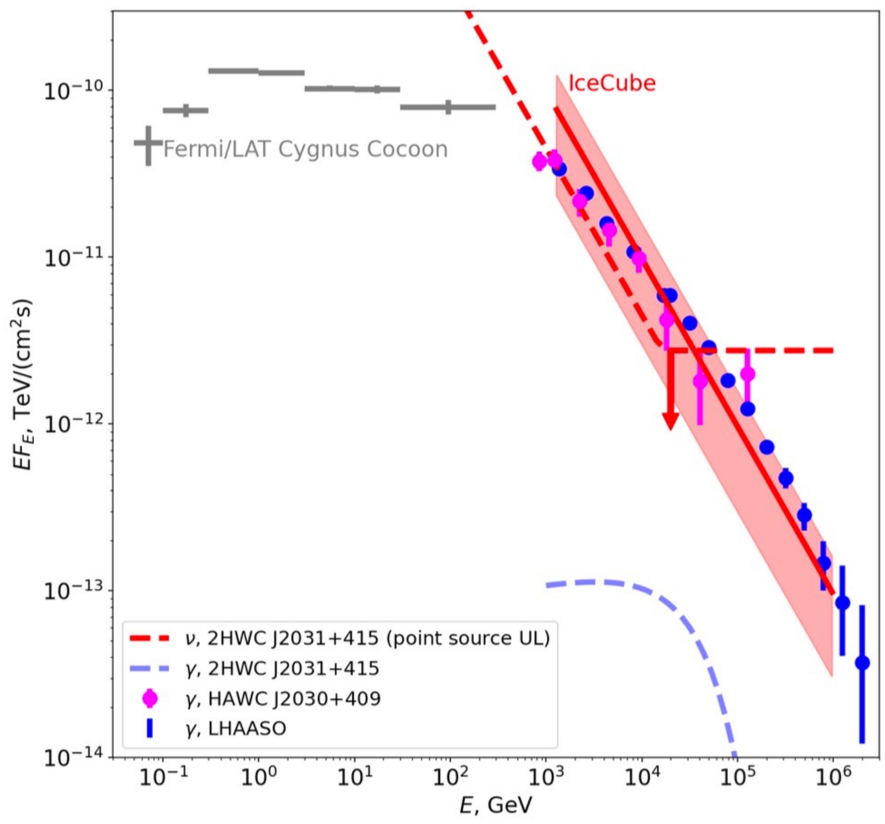
Neutrinos from Cygnus region





A.Neronov et al, arXiv:2311.13711

Neutrinos from Cygnus region



A.Neronov et al, arXiv:2311.13711

Summary

- Cosmic ray flux of individual nuclei measured by satellite experiments from space. AMS02, DAMPE and CALET see several breaks in spectrum, which have to be explained.

- LHAASO for the first time measured proton spectrum at knee from the ground. Composition established at knee with high precision measurements of logA and total flux.

- As next step we will need good 10 PeV – 1 EeV measurements of mass composition

- Breaks in CR proton spectrum from GeV to PeV energies can be propagation features or due to contributions of the different populations of sources. Break at 300 GeV is due to propagation according to AMS-02

- We start to understand general structure of magnetic field in Milky Way. Local Bubble is important for CR.

Summary

- UHECR dipole can be explained by sources in LSS and GMF.
- UHECR anysotropies at highest energies are from nearby sources, but detailed knowledge of IGMF and GMF does not allow to establish them for the moment
- We can study cosmic ray flux in different places in Galaxy with help of gamma-ray and neutrino observations.
- Diffuse gamma-ray emission from Milky Way was measured by Fermi LAT at energies between 1 GeV and 1 TeV and by LHAASO 1 TeV – 1 PeV. We need SWGO to measure Southern sky
- First signal from neutrinos from the Galaxy in cascades by IceCube. Some hints from ANTARES and Baikal GVD, waiting for KM3NET first results.
- We do not know which part of neutrino signal is from isolated sources. First source in Cygnus region. We need next generation neutrino telescopes to divide signal between sources and diffuse neutrino background from Galaxy: IceCube-gen2, TRIDENT, HUNT