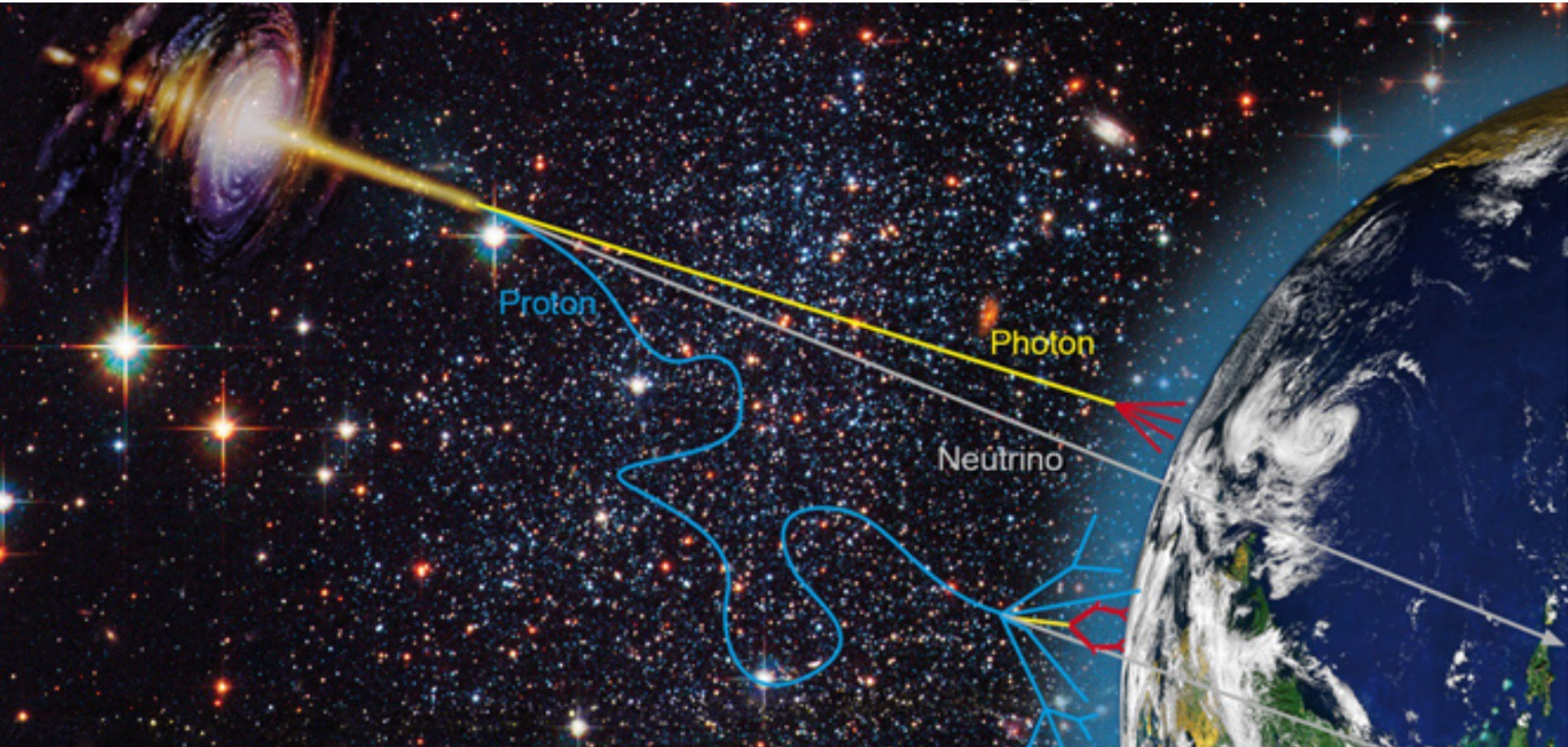


# Multi-messenger observations of Cosmic Rays

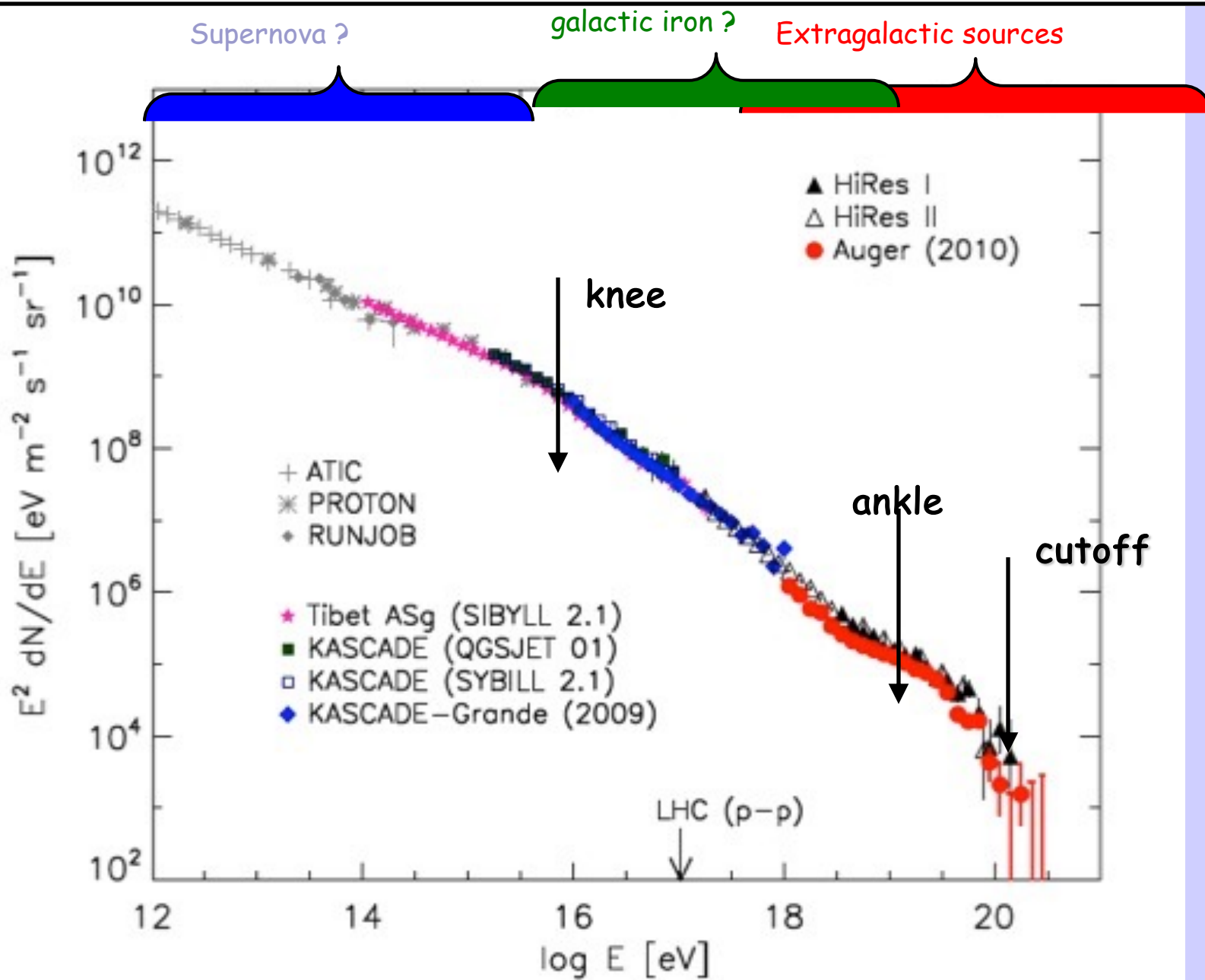


Dmitri Semikoz (APC)

# Plan

- Introduction: search of CR sources
- Ultra-high energy cosmic rays
- Cosmic rays at knee
- Galactic-extragalactic transition
- Conclusions

# *Introduction: search for CR sources*



# *Ultra-High-Energy Cosmic Rays*

# Telescope Array

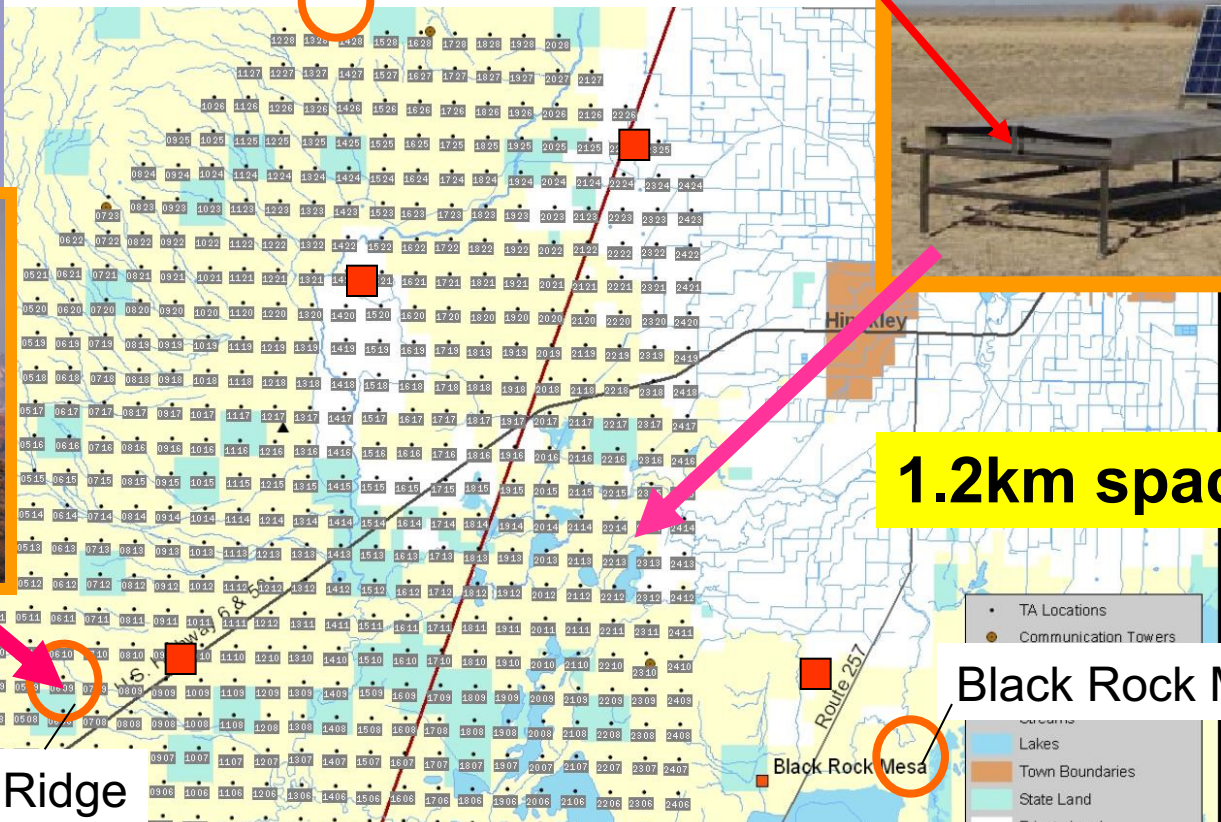
, APC, Sept 16 202

576 plastic scintillation  
Surface Detectors (SD)

Atmospheric  
fluorescence  
telescope  
3 stations **FD**



5 communication towers  
Middle Drum  
3m<sup>2</sup> 1.2cm t  
two layers



1.2km spacing



Long Ridge

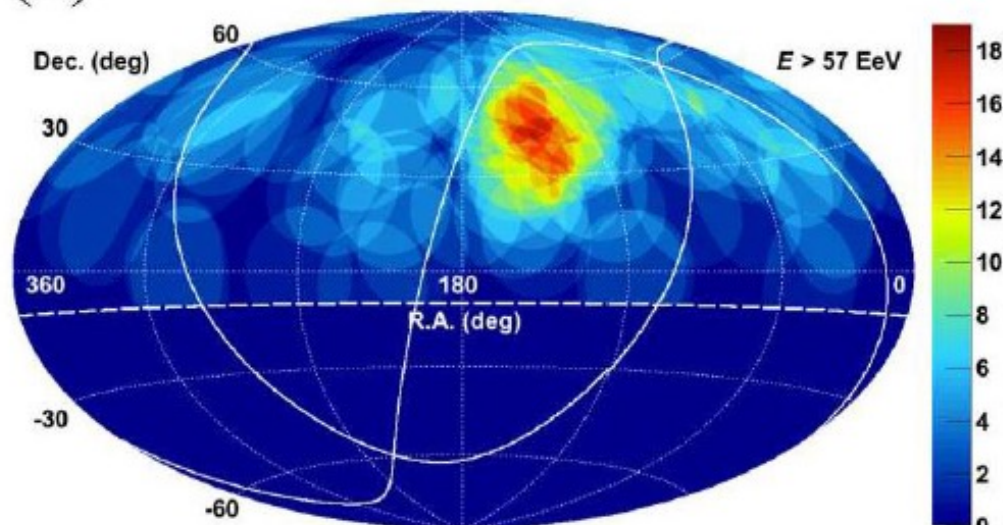


Black Rock Mesa

20km

Sensitivity of SD : ~9 x AGASA

(b)



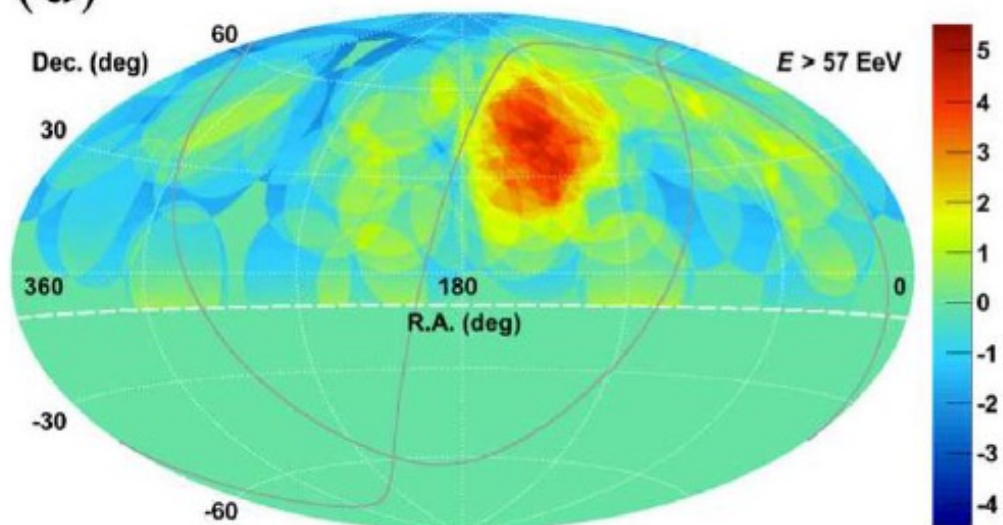
## Telescope Array

$10^6$  total events over 6 years

87 events  $> 57 \text{ EeV}$ ,  $< 60^\circ$

**Shown: events within  $20^\circ$  of each point**

(d)



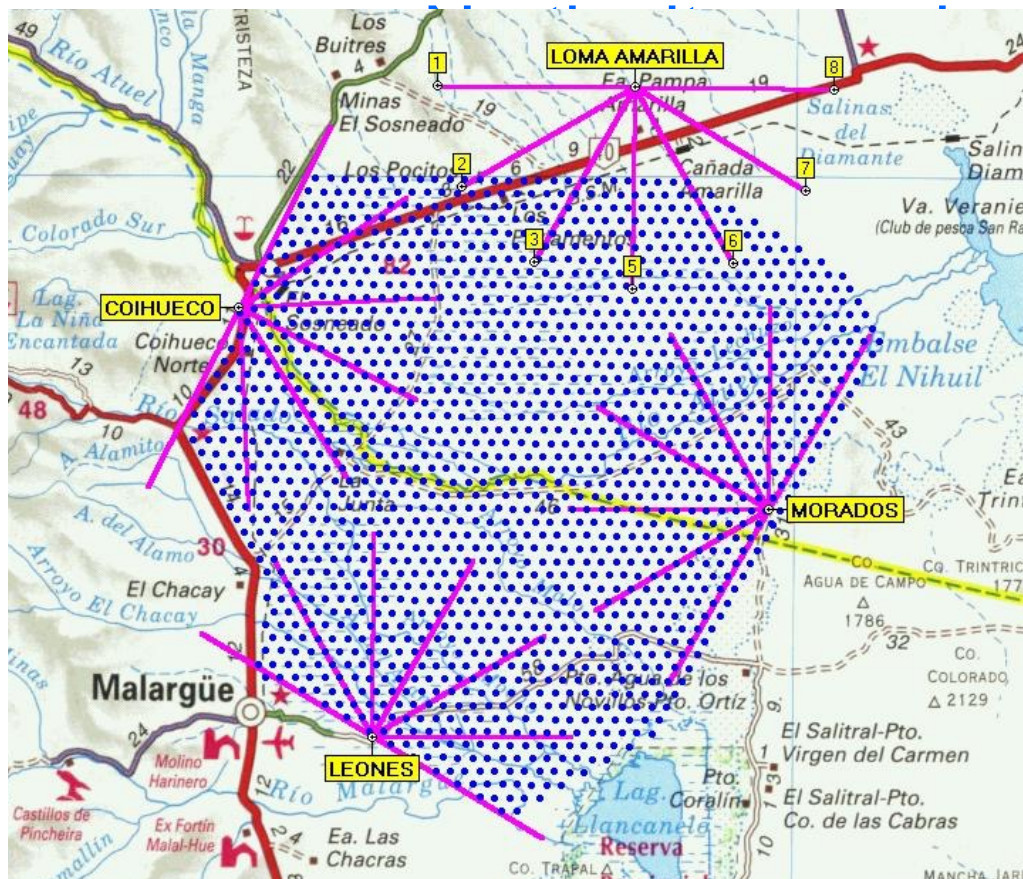
**Hot Spot** at

RA=  $148.4^\circ$  and dec=  $+44.5^\circ$   
(Mrk 421 is in the vicinity ...)

**$4.3 \sigma$**  significance compared to isotropic fluctuation

# Pierre Auger Observatory

## South site in Argentina almost finished

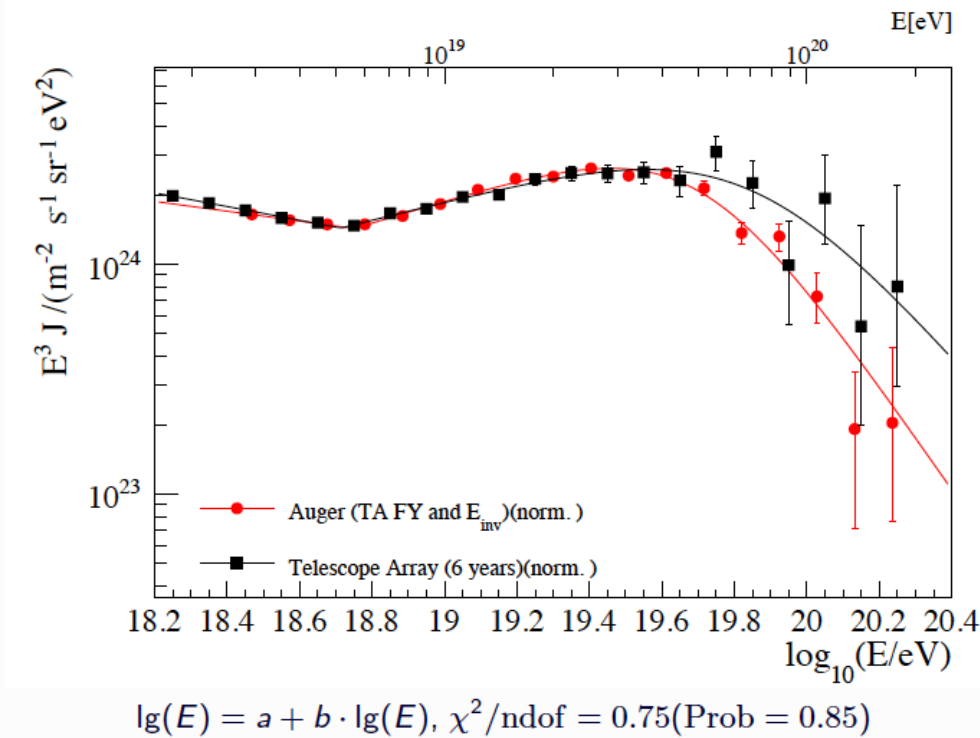


**Surface Array**  
*1600 detector stations*  
*1.5 Km spacing*  
*3000 Km<sup>2</sup> (30xAGASA)*

**Fluorescence Detectors**  
*4 Telescope enclosures*  
*6 Telescopes per enclosure*  
*24 Telescopes total*

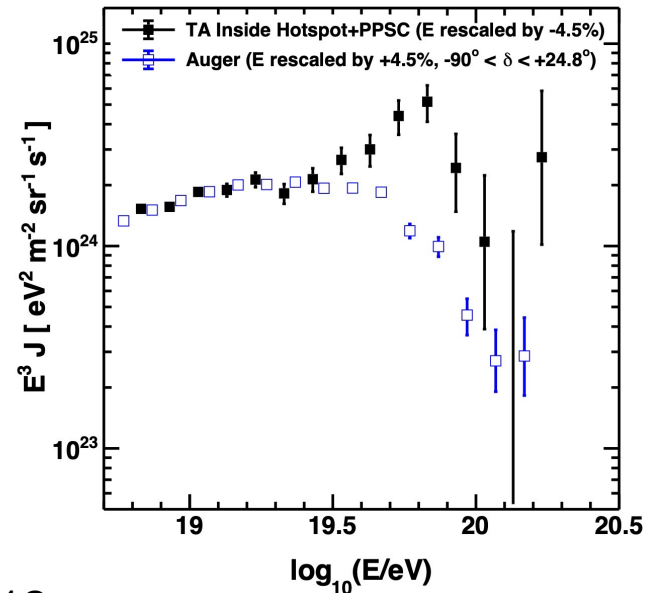
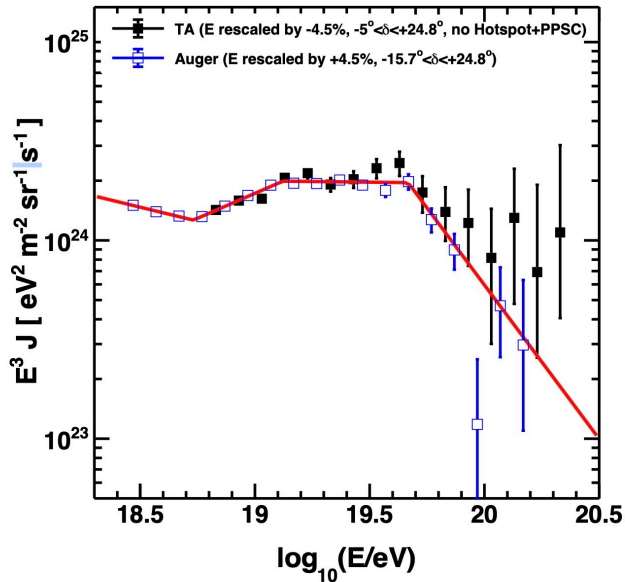
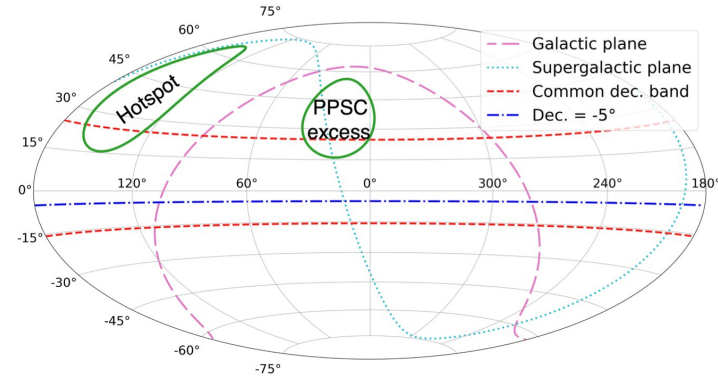


# Auger/TA Energy Spectrum

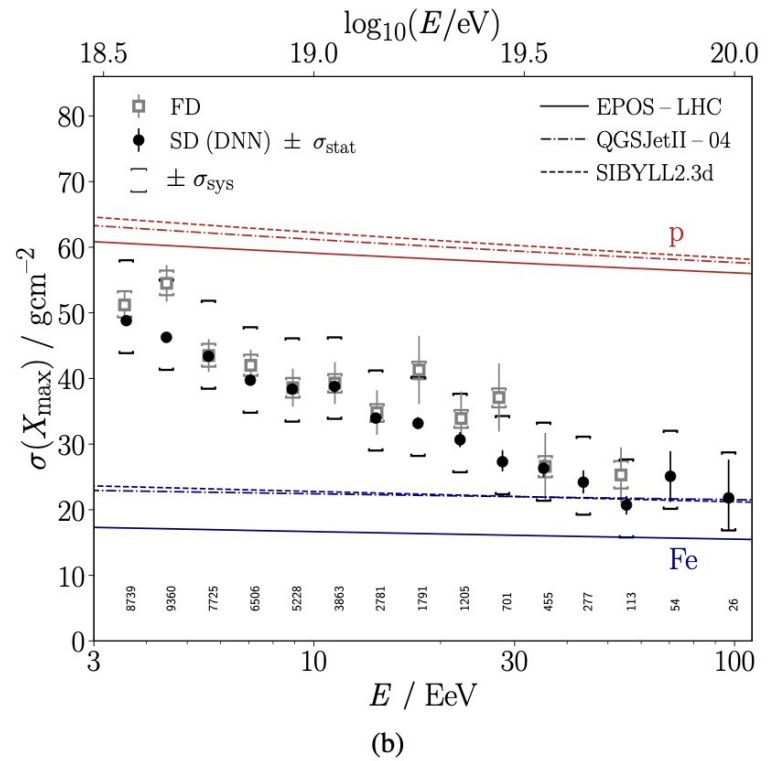
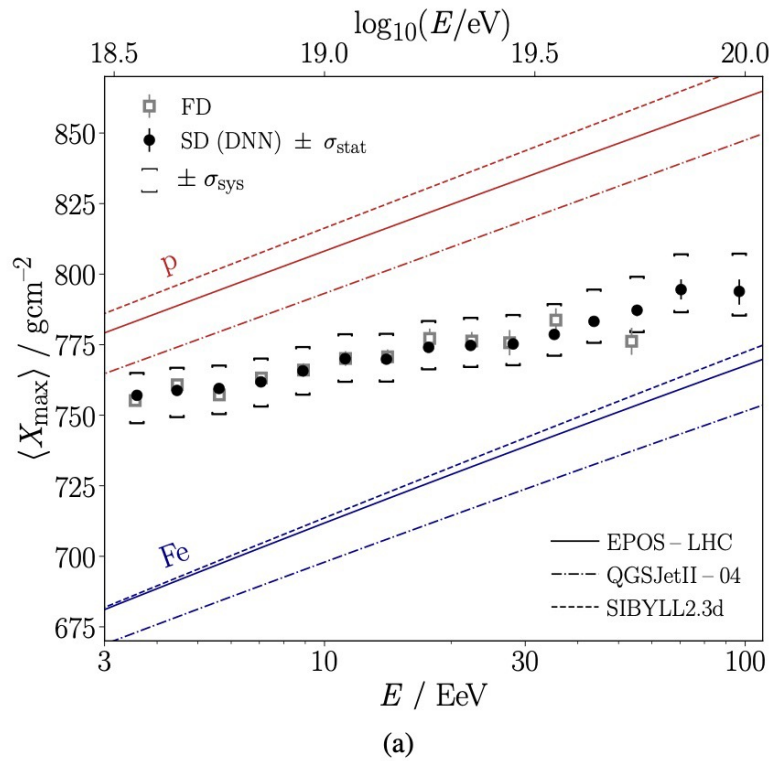


UHECR 2014

# Auger/TA Energy Spectrum

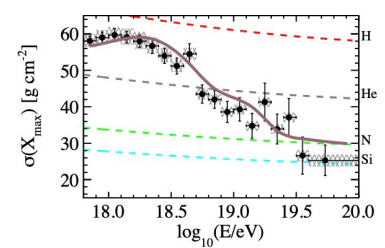
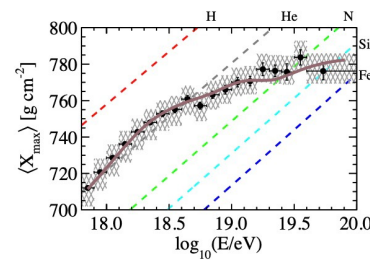
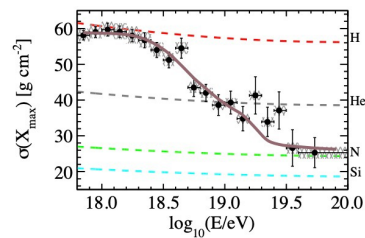
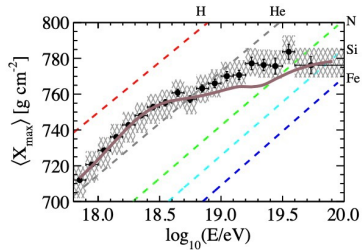
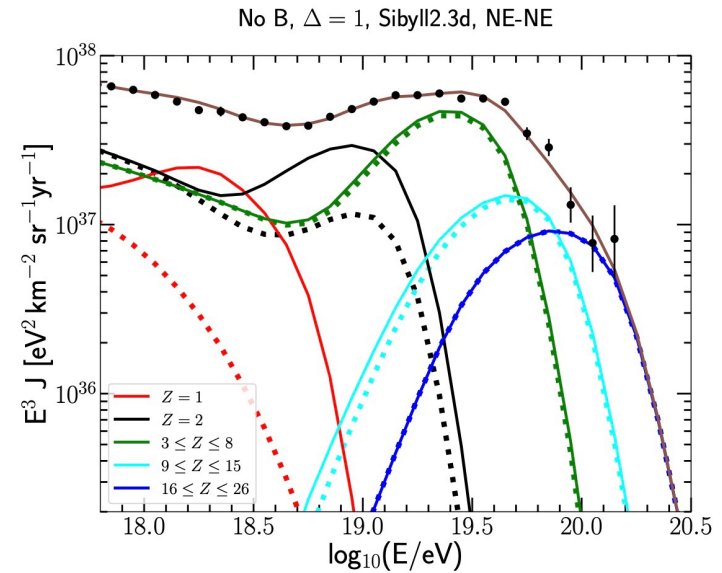
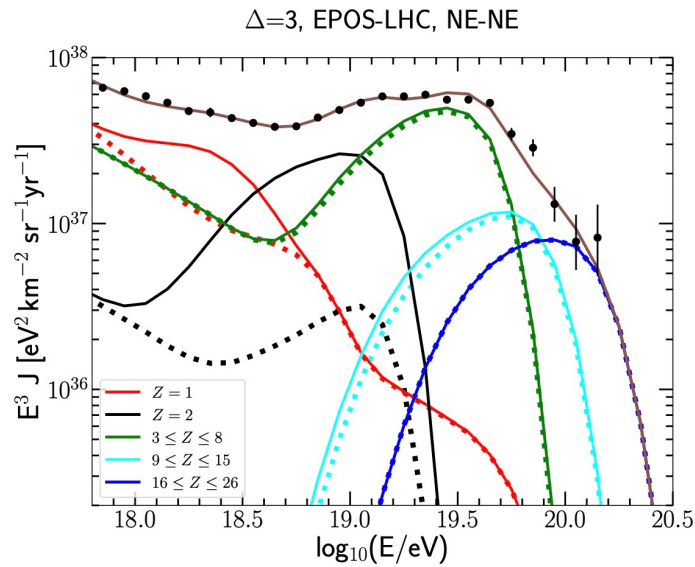


# Auger composition



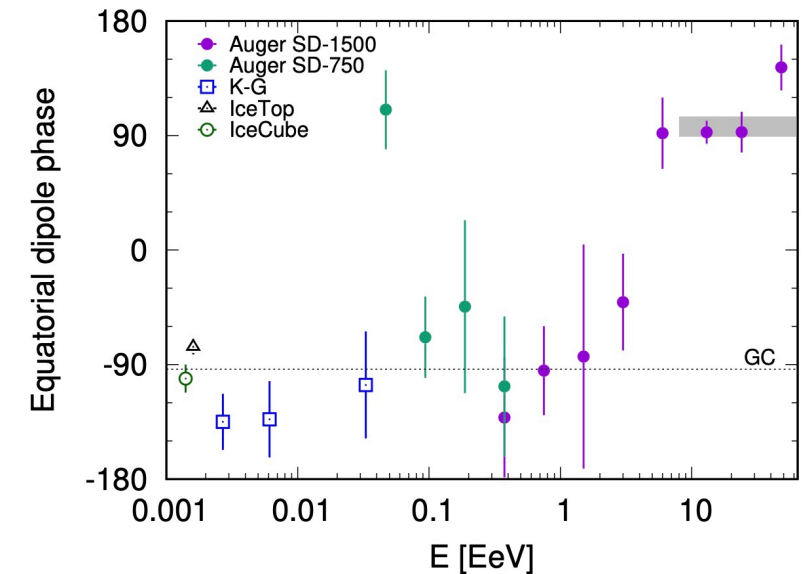
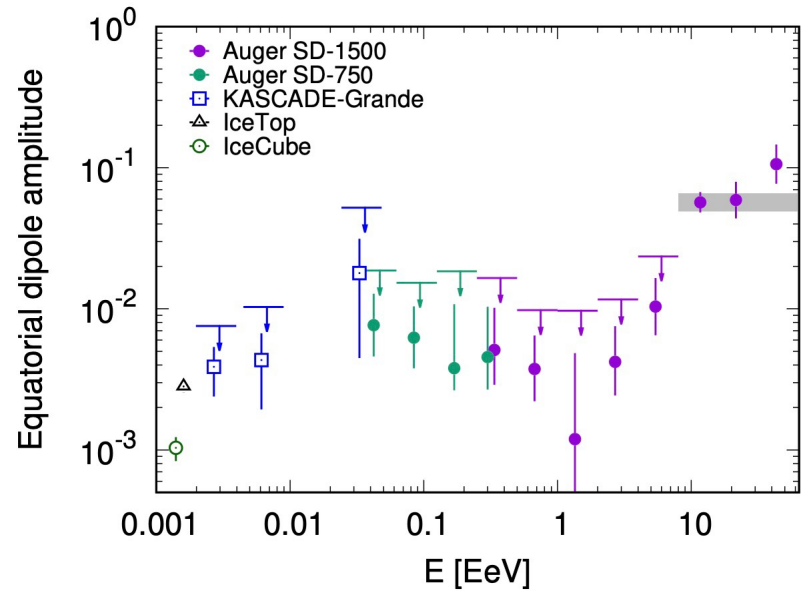
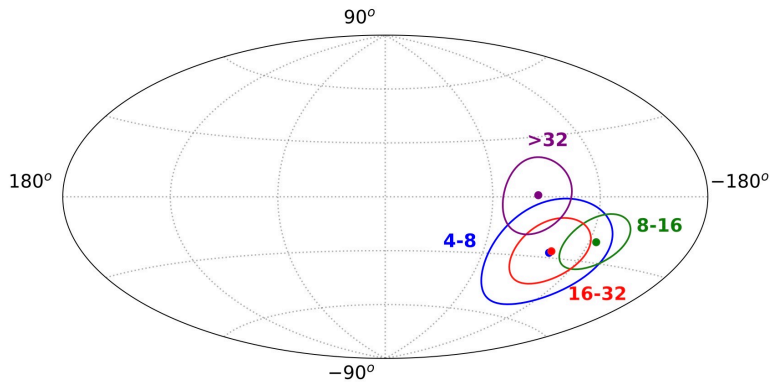
Auger 2406.06315

# Auger composition



Auger 2404.03533

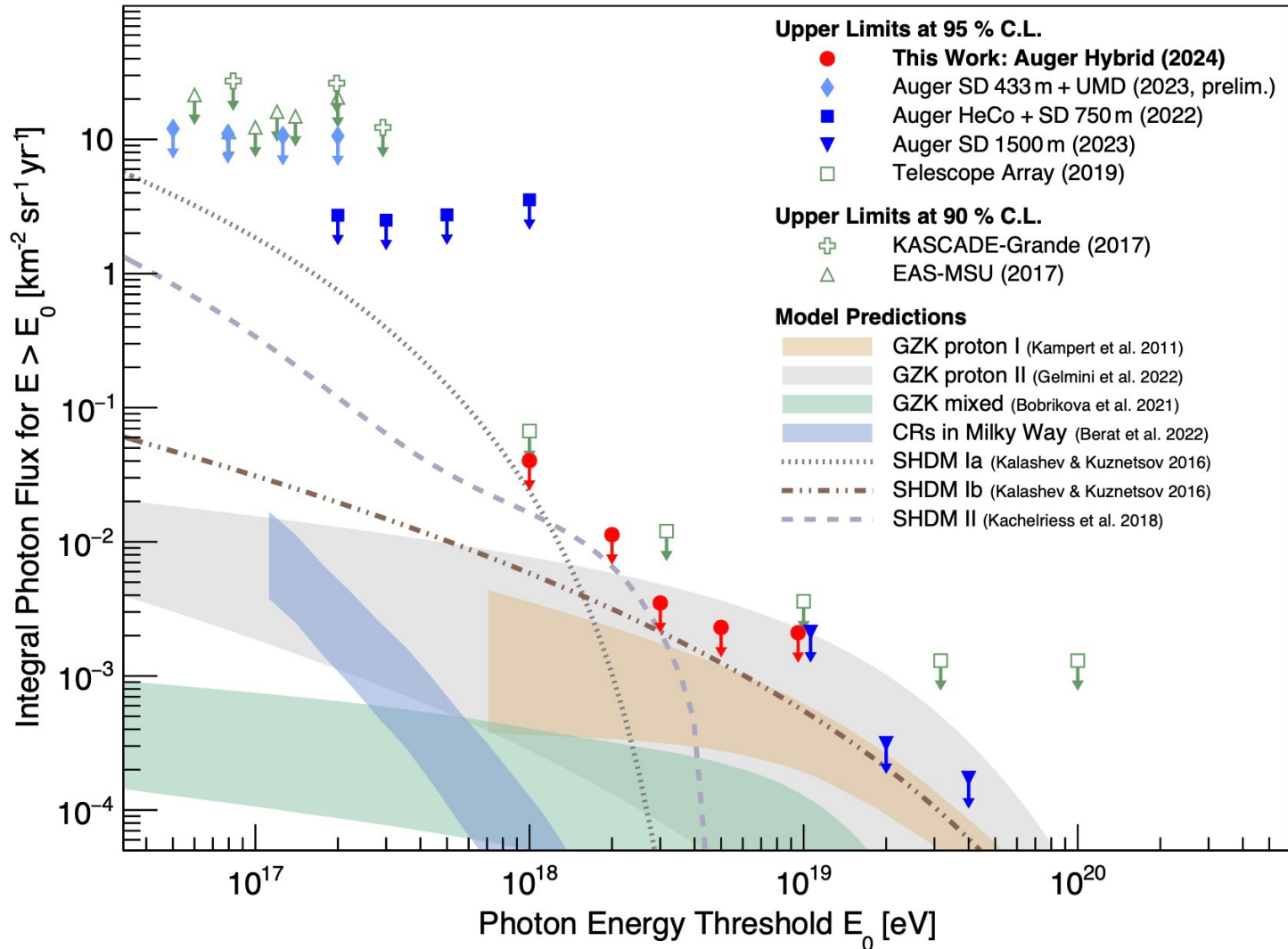
# Auger dipole



8-16 EeV 5.7 sigma in 20 years

Auger 2404.03533

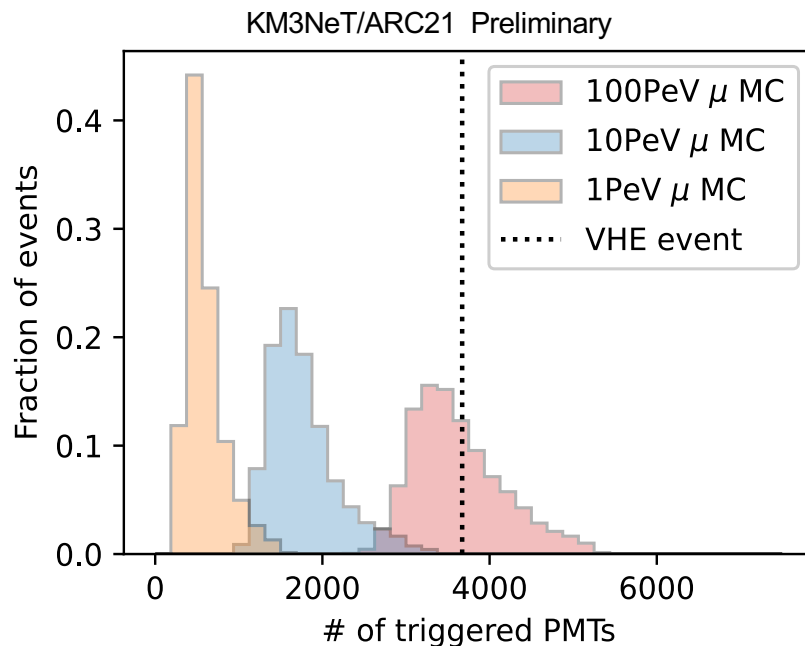
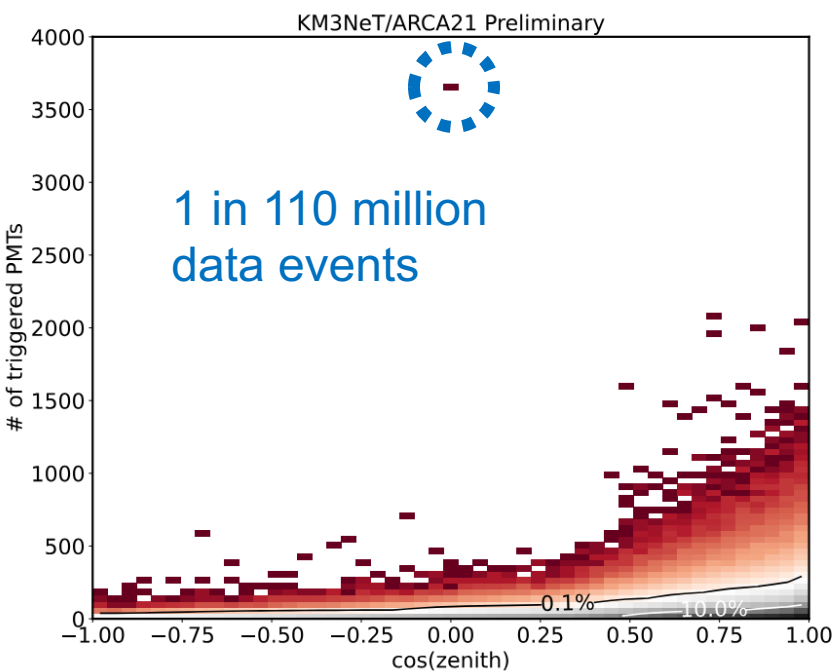
# UHE photons





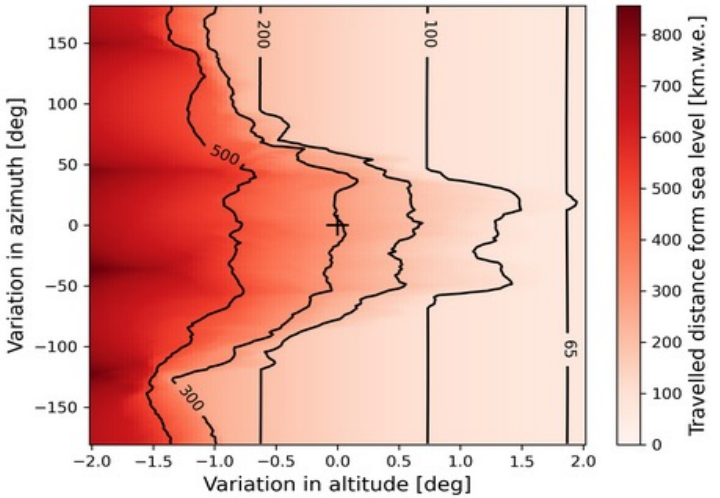
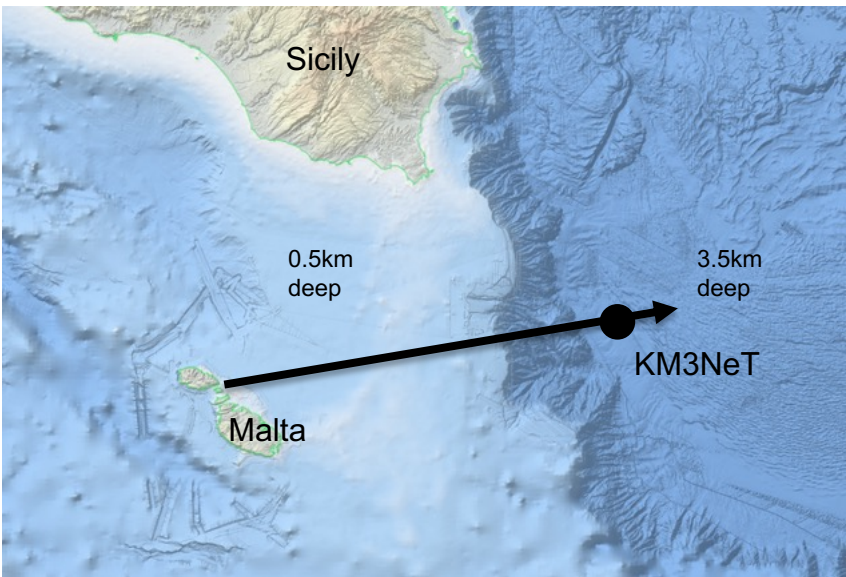
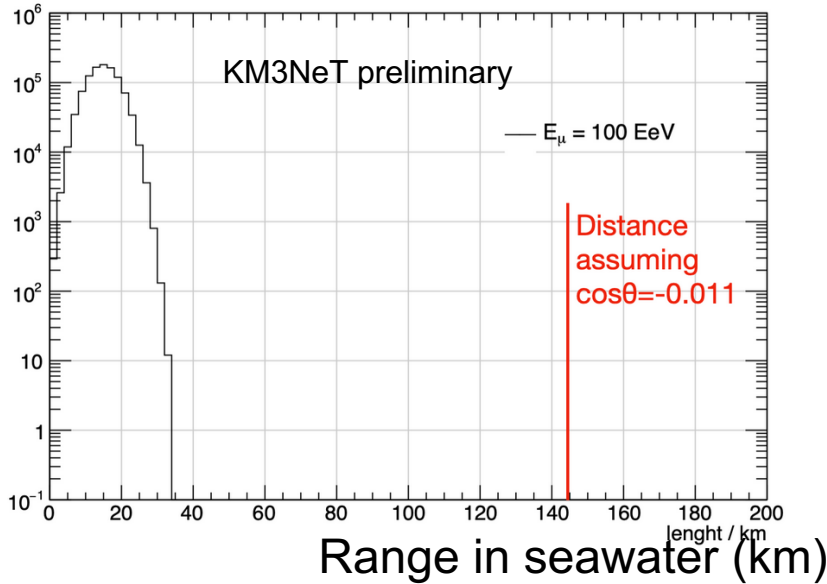
# 100 PeV neutrino by KM3Net

- Significant event observed with huge amount of light
- Horizontal event ( $1^\circ$  above horizon)
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV





# Not an atmospheric muon

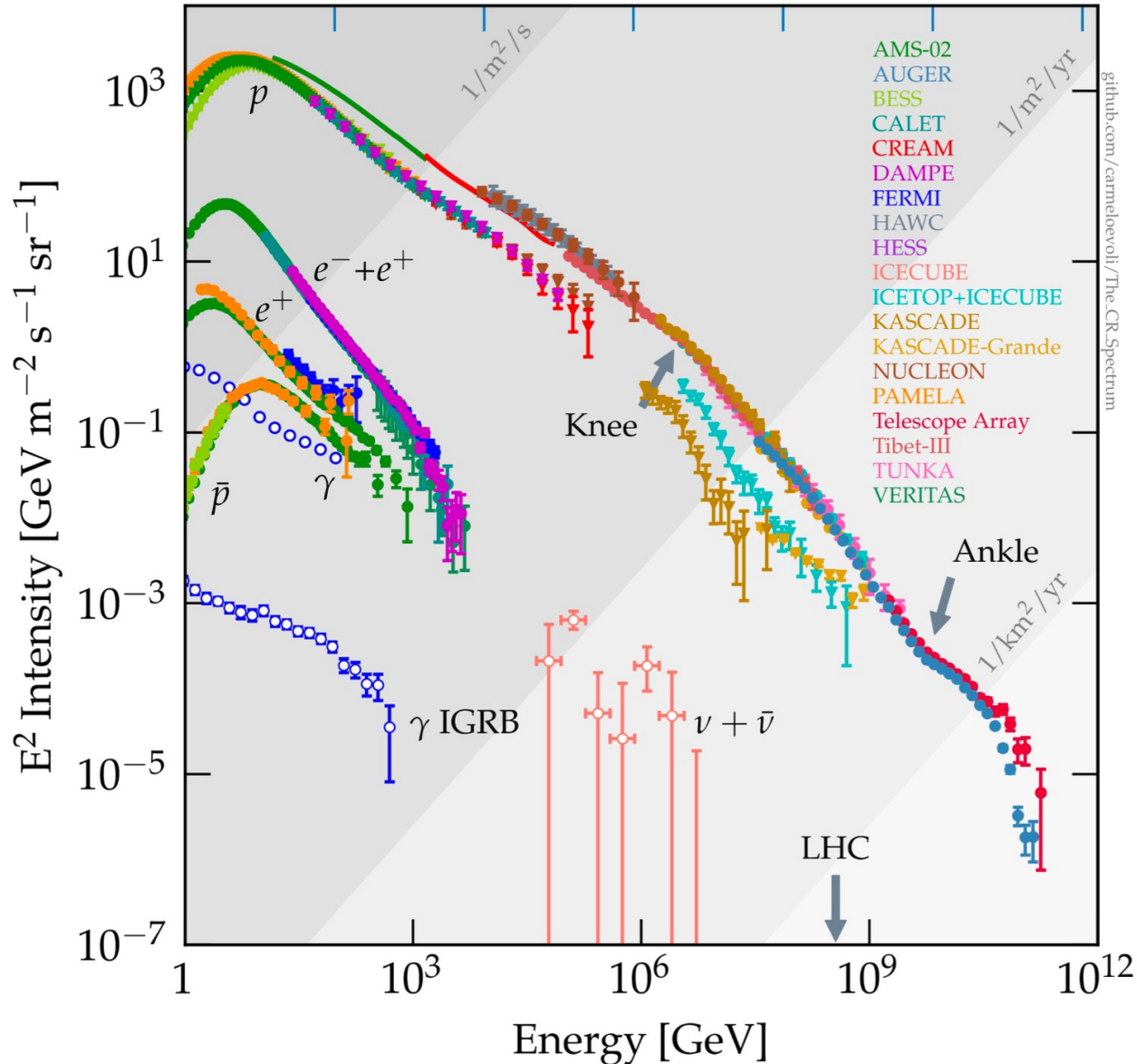


Passes through continental shelf/Malta  
actual amount of matter is even larger...



# *Cosmic Rays at knee*

# Cosmic ray energy spectrum





**The ultimate goal is to identify origins of CRs**

# **Large High Altitude Air Shower Observatory**

LHAASO

## **Scientific Goals**

**$\gamma$ -ray astronomy**

**Survey for sources (above 500 GeV)**

**PeVatrons (above 100 TeV)**

**All kind of sources: SNR, PWN, MYC,**

**binary, pulsar**

**AGN, GRB etc.**

## **Cosmic Ray Physics**

**The knees**

**Compositions : individual species H, He and**

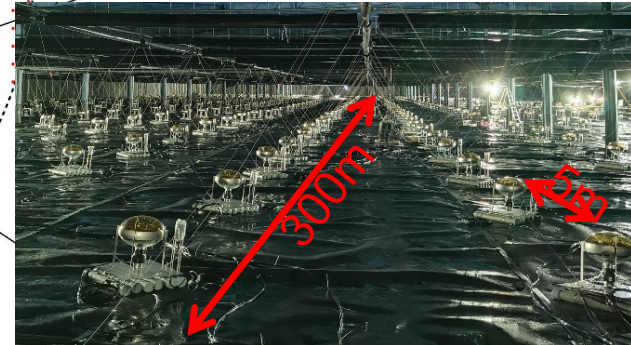
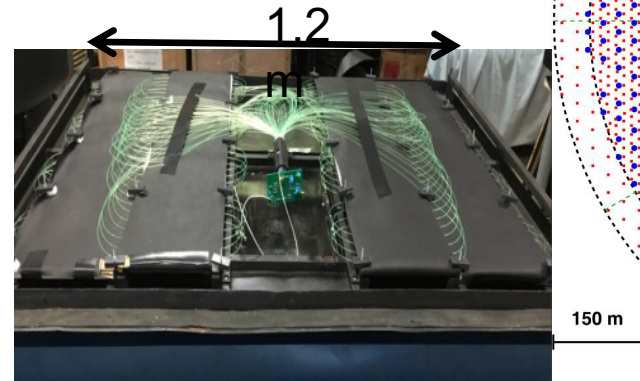
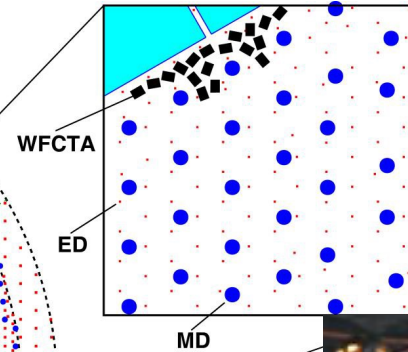
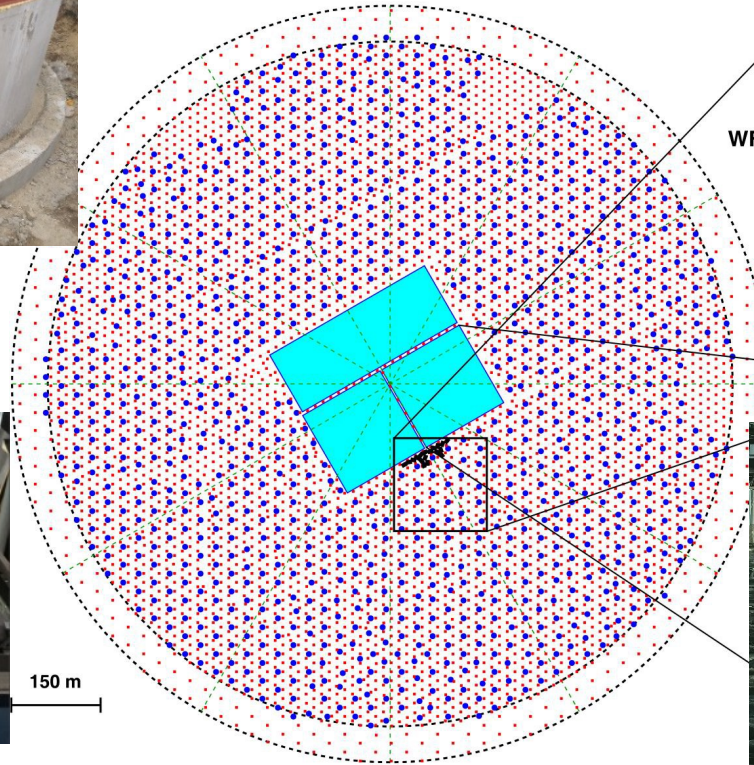
**Fe**

**Anisotropy: (1 TeV to 10 PeV)**

**New Physics Front: DM, LIV, etc.**

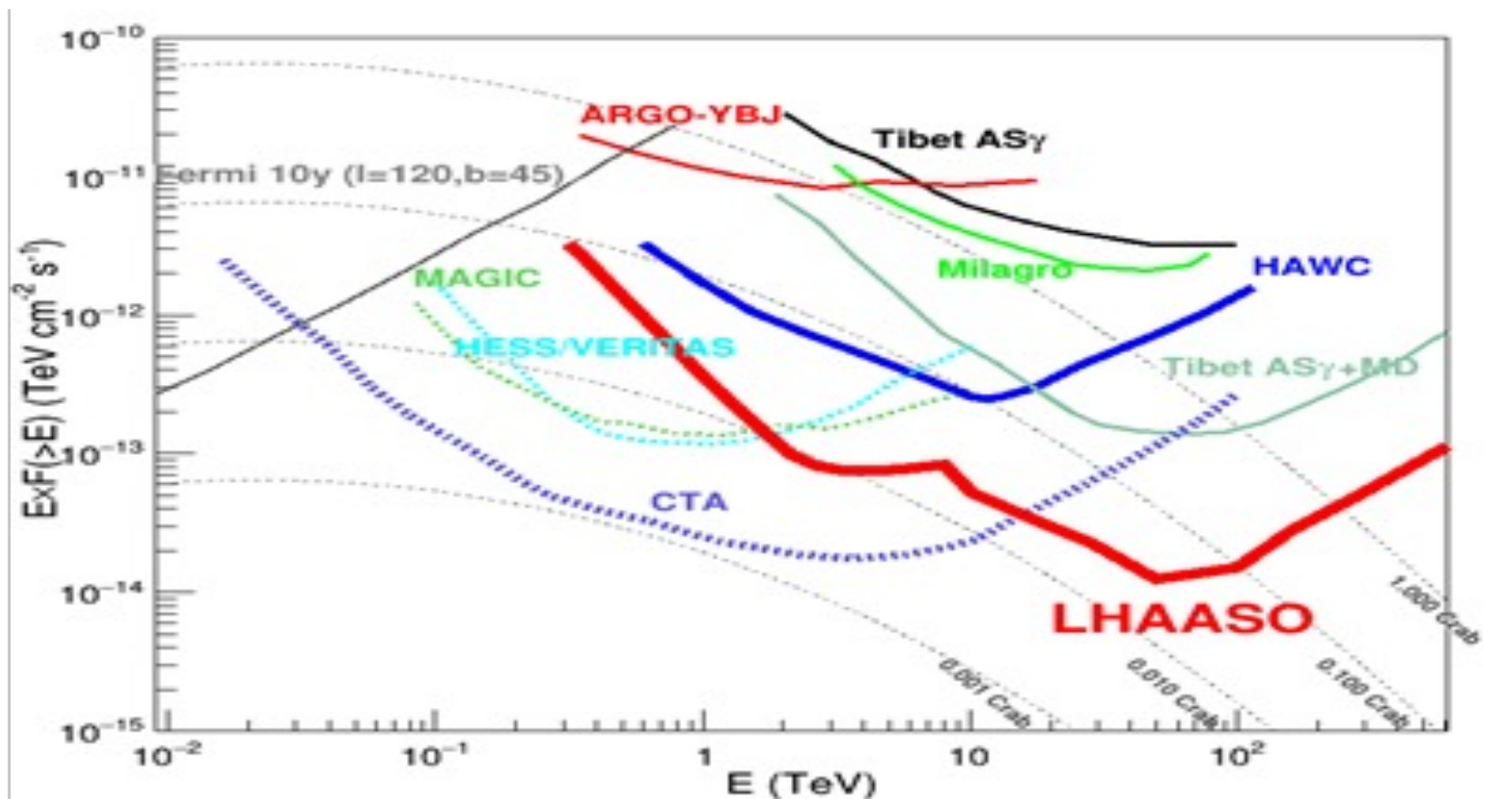


# LHAASO Layout

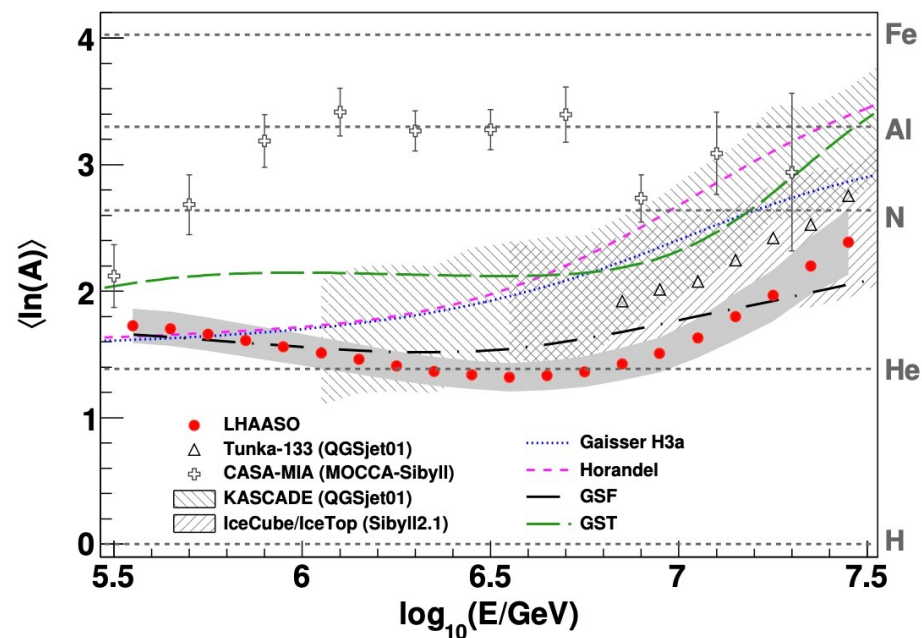
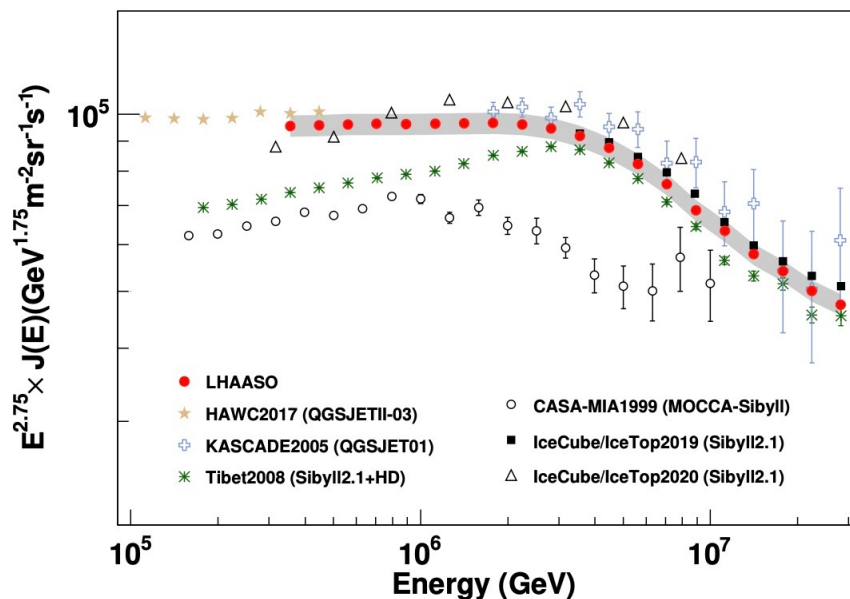


# LHAASO sensitivity

With large FOV and high sensitivity, LHAASO is an ideal detector for sky survey to search VHE and UHE sources!



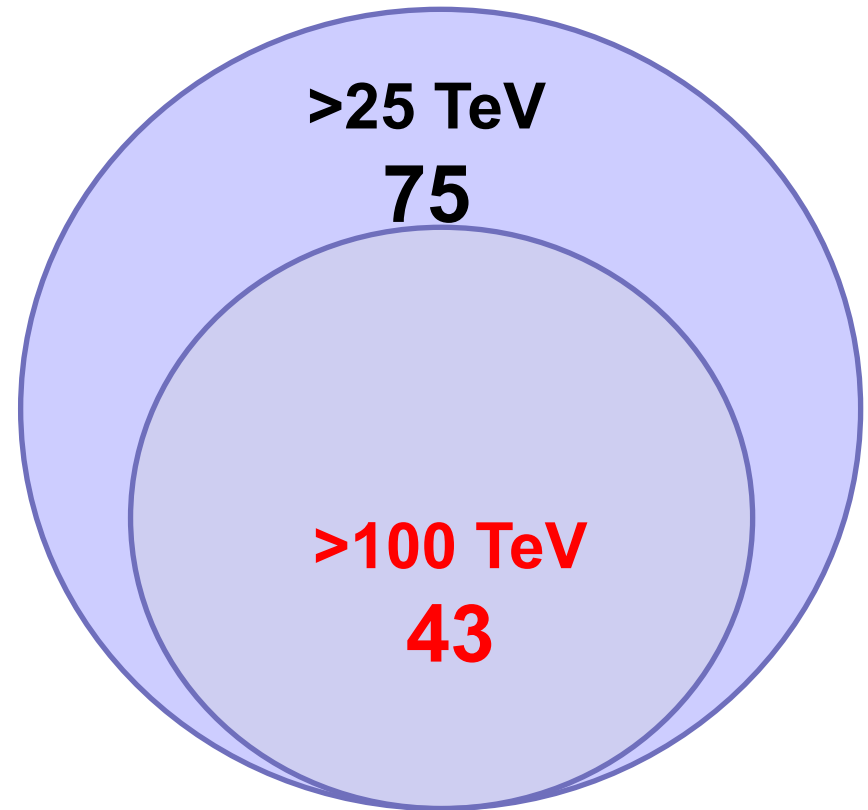
# CR spectrum and mass composition



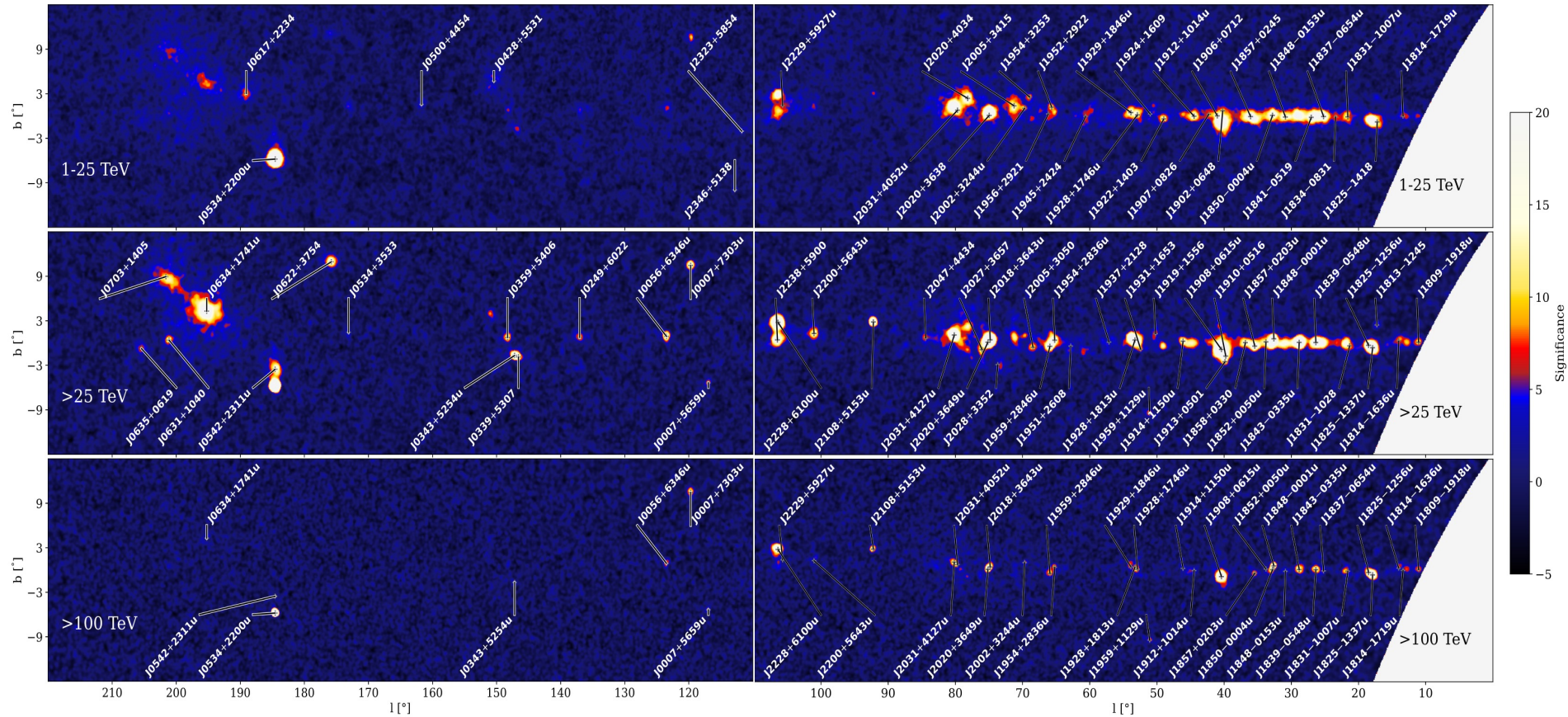
• *LHAASO collab.*, Zh.Cao et al, [2403.10010](https://arxiv.org/abs/2403.10010)  
 , *Phys.Rev.Lett.* 132 (2024) 13, 131002

# UHE gamma-ray sources

- The position and extension achieved by KM2A at  $>25$  TeV are used.
- Sources with significance  $>4\sigma$  at  $>100$  TeV are labeled as UHE sources
- LHAASO: 4  $\rightarrow$  43

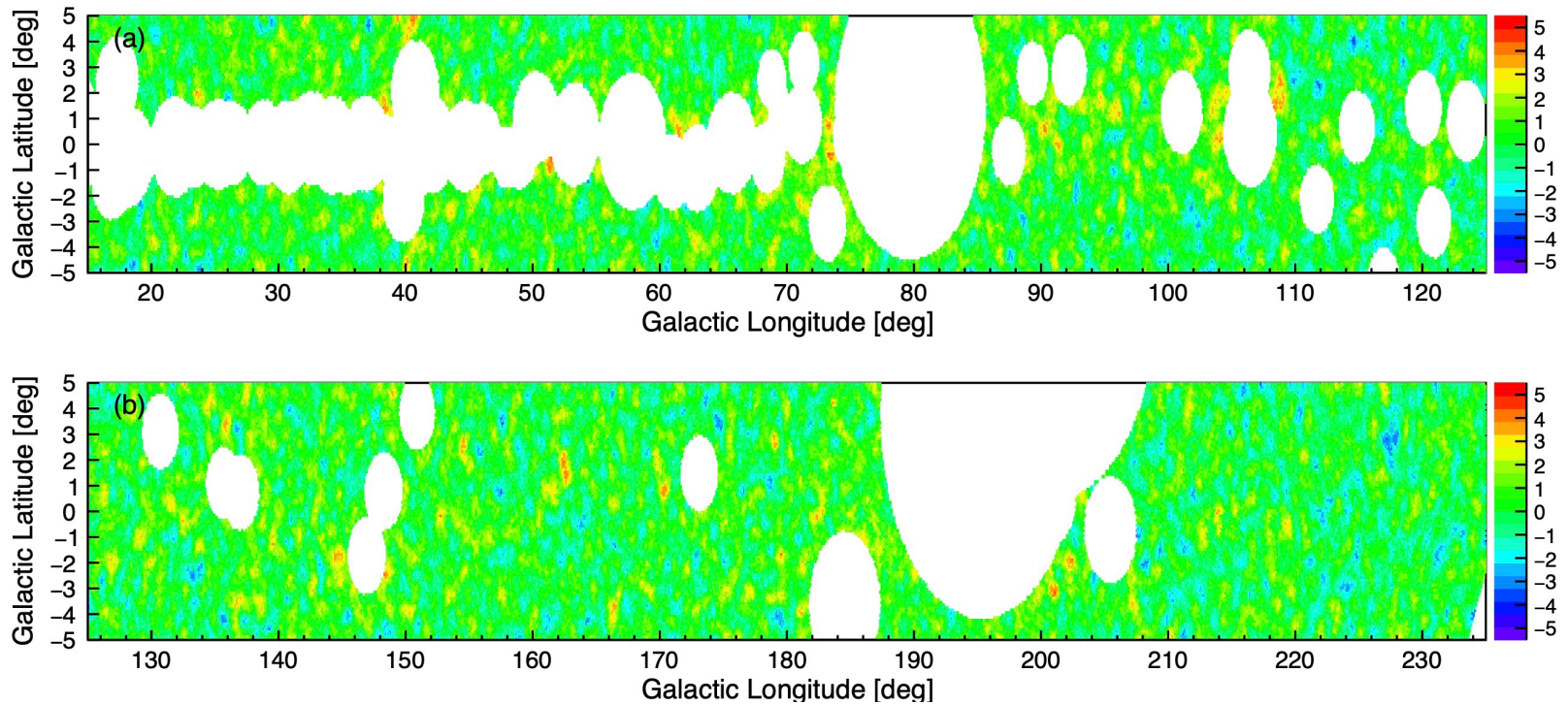


# 82 sources with the Galactic latitude $|b| < 12^\circ$

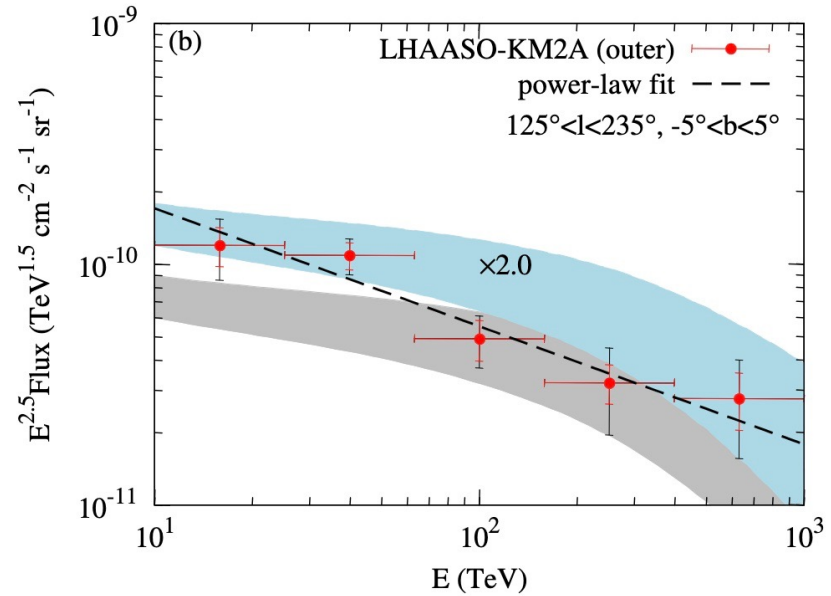
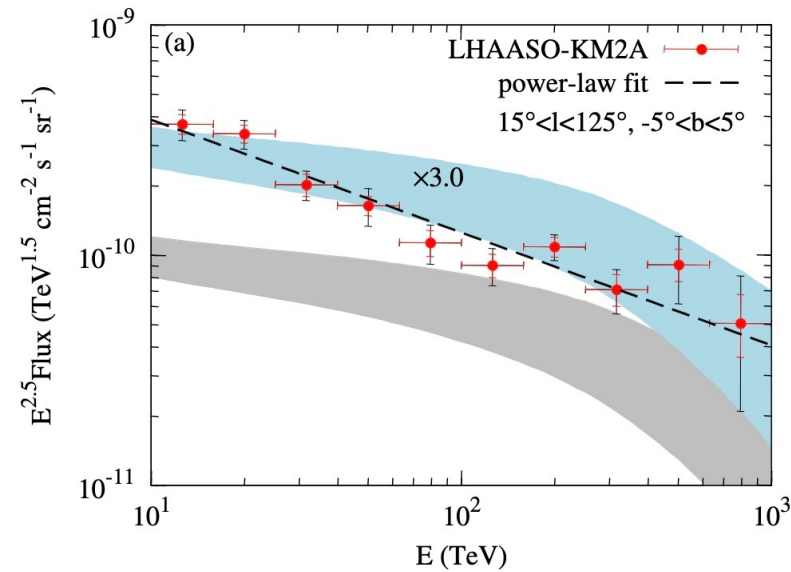




# Mask LHAASO



# LHAASO diffuse



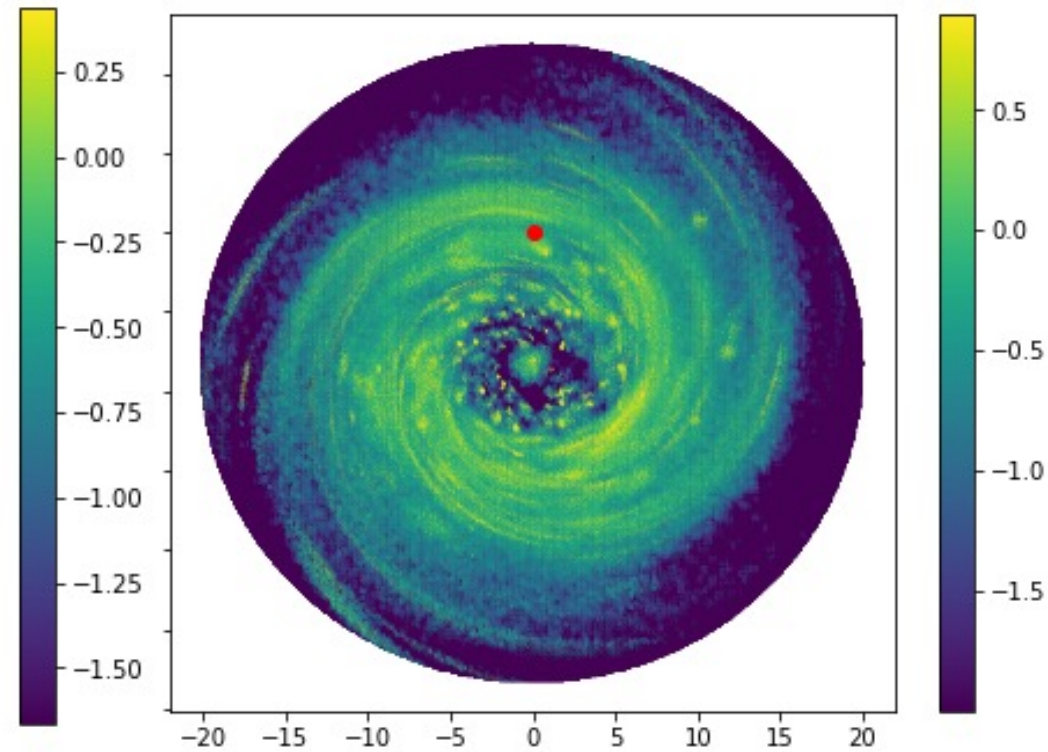
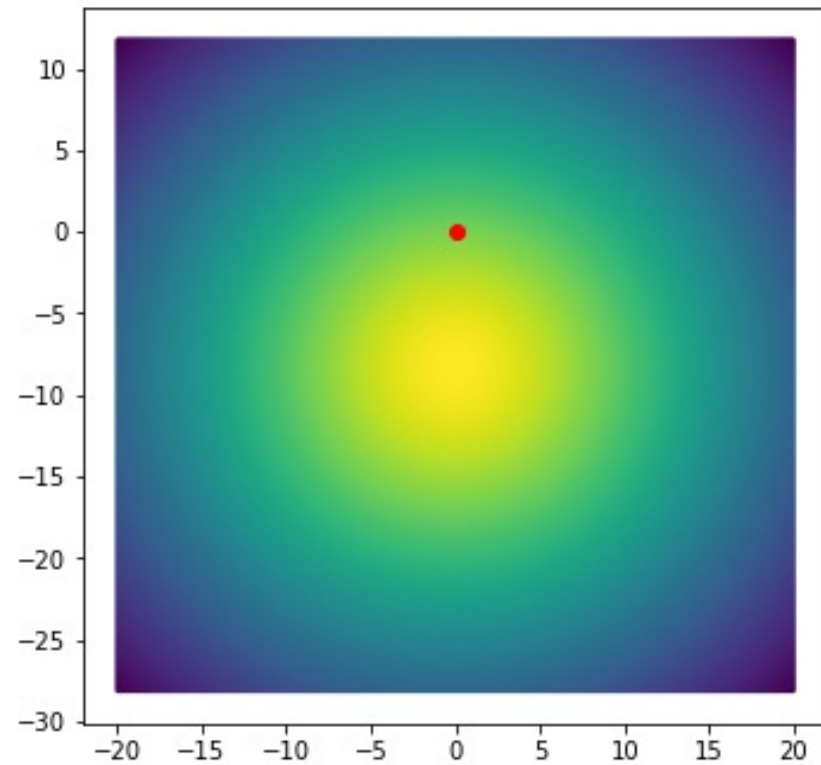
$$\Xi^{A,A'}(E, l, b) = \int_0^\infty ds n_{\text{gas}}^{A'}(\mathbf{x}) I_{\text{CR}}^A(E, \mathbf{x})$$

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

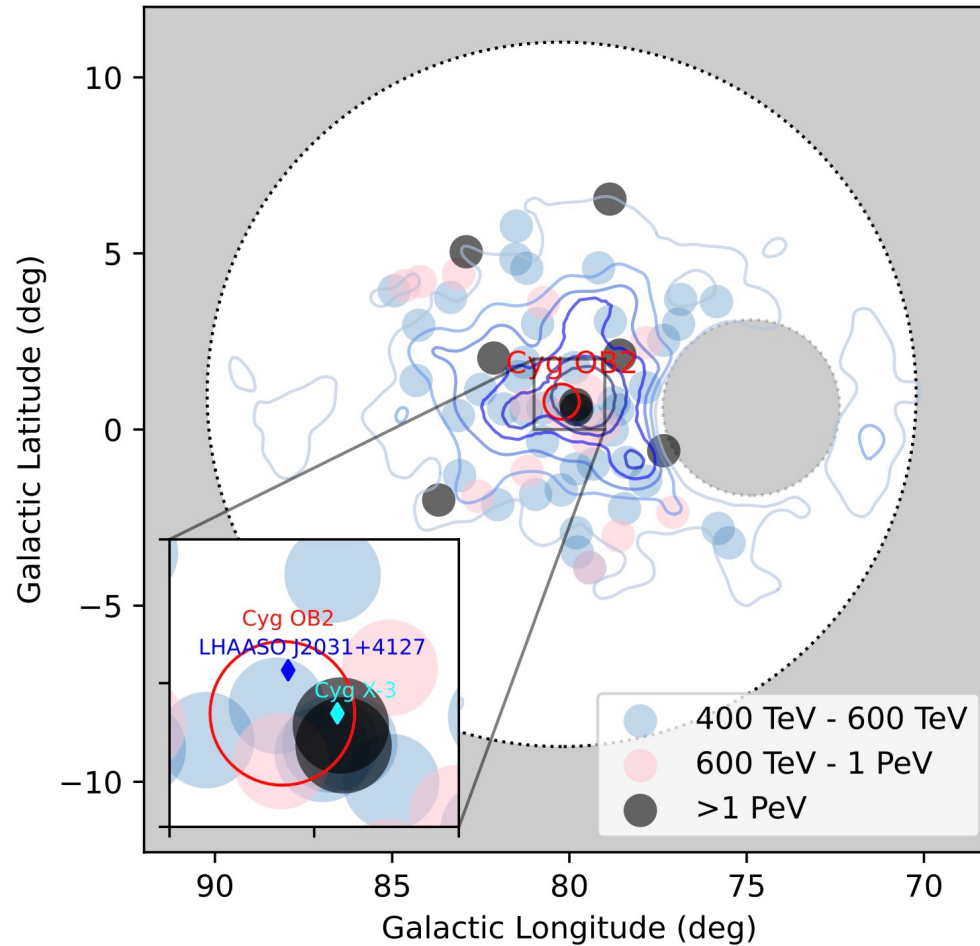
# 1 PeV CR density in the Gal. plane

Lipari & Vernetto (2018)

G.Giacinti & D.S., 2305.10251

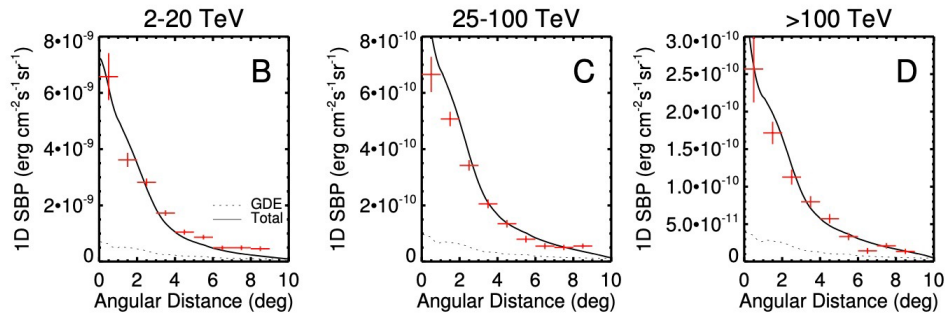
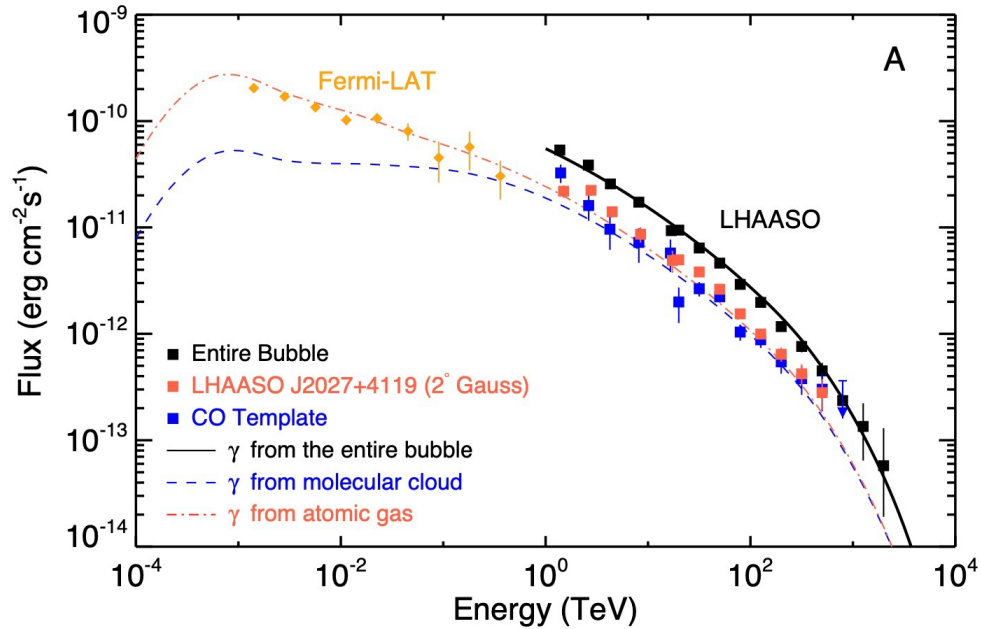


## Cygnus region



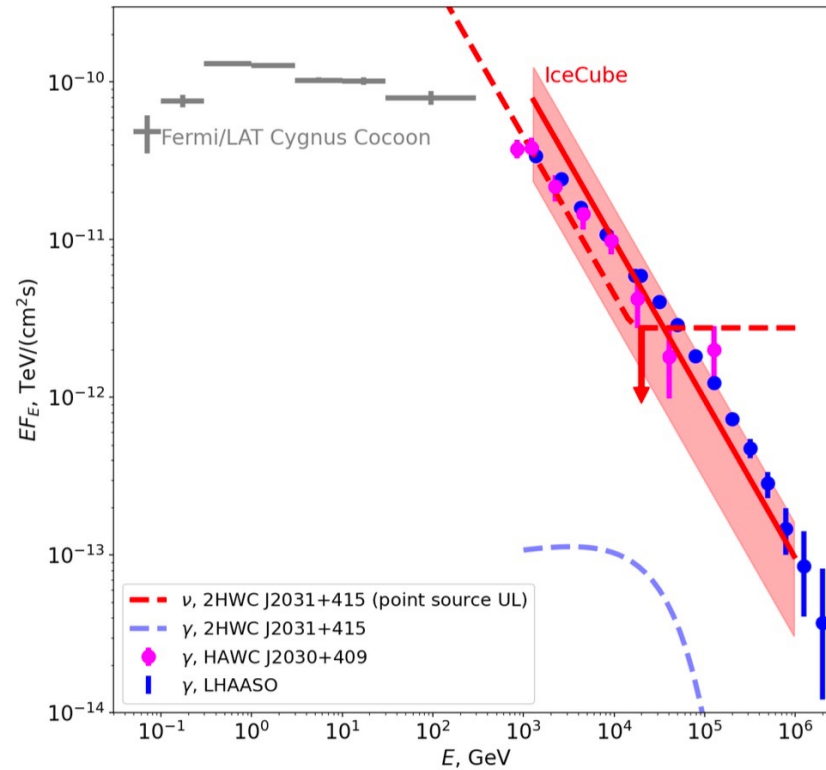
• *LHAASO collab.*, Zh.Cao et al, [2310.10100](https://arxiv.org/abs/2310.10100), *Sci.Bull.* 69 (2024) 4, 449

# Cygnus region



•LHAASO collab., Zh.Cao et al, [2310.10100](https://arxiv.org/abs/2310.10100) , *Sci.Bull.* 69 (2024) 4, 449

# Neutrinos from Cygnus region



# Summary

- UHECR: spectrum has several breaks, composition is mixed, dipole at 8-16 and 16-32 is measured. KM3Net neutrino event 0.1 EeV is promising!
- First LHAASO results on logA of cosmic rays are very good. We expect a lot of good quality CR data in near future
- LHAASO presented first catalog of 90 sources. Number of UHE gamma-ray sources above 100 TeV increased from 4 to 43 by LHAASO observations
- Diffuse emission from Galaxy: new models required
- Cygnus region: hadronic Pevatron source in central part.