

Cosmic rays at the knee

Results and implications



«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

INTERNATIONAL SCHOOL OF COSMIC-RAY ASTROPHYSICS

«MAURICE M. SHAPIRO»

24th Course: "Particles and the Cosmos – Bridging the infinitesimal and the infinite"
29 July – 6 August 2026

PRESIDENT AND DIRECTOR OF THE CENTRE: PROFESSOR A. ZICHICHI

DIRECTORS OF THE COURSE: PROFESSORS J.R. HÖRANDEL, R. SPARVOLI, T. STANEV



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energy density

$$\rho_E = \frac{4\pi}{c} \int \frac{E}{\beta} \frac{dN}{dE} dE \approx 1 \frac{\text{eV}}{\text{cm}^3}$$

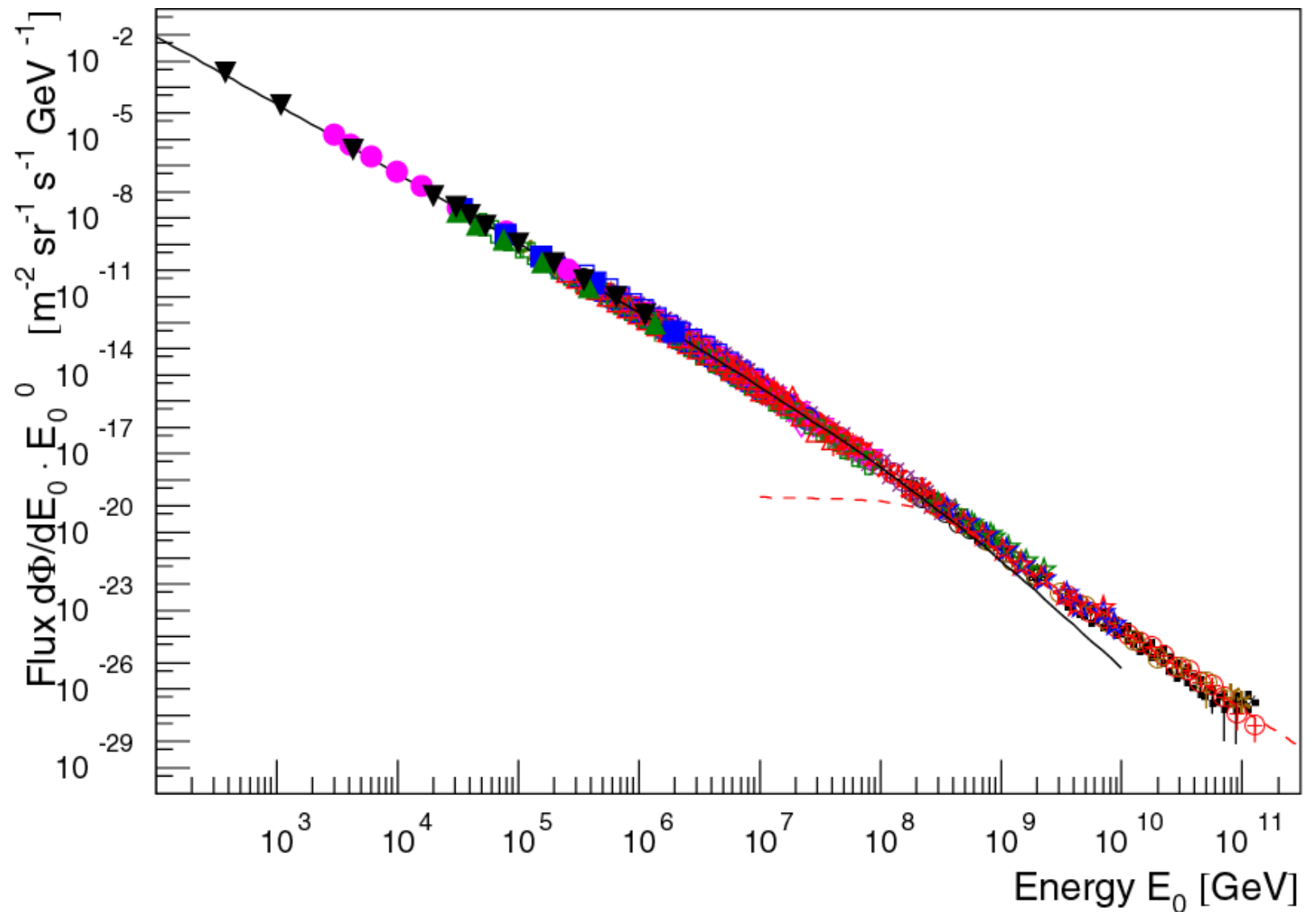
for comparison:

$$\rho_B = \frac{B^2}{2\mu_0} \approx 0.25 \text{ eV/cm}^3$$

$$\rho_{SL} \approx 0.3 \text{ eV/cm}^3$$

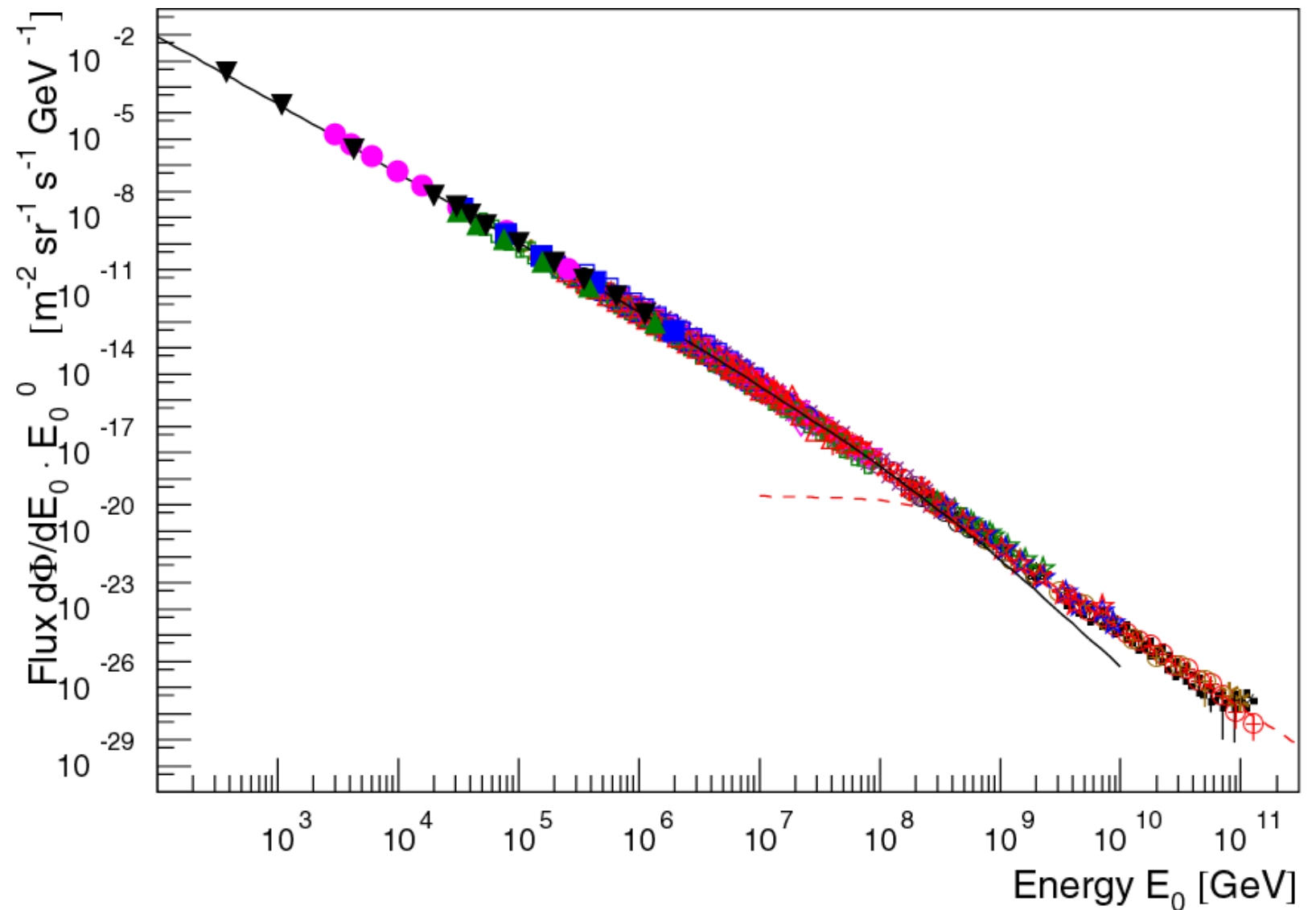
$$\rho_{IR} \approx 0.4 \text{ eV/cm}^3$$

$$\rho_{3K} \approx 0.25 \text{ eV/cm}^3$$



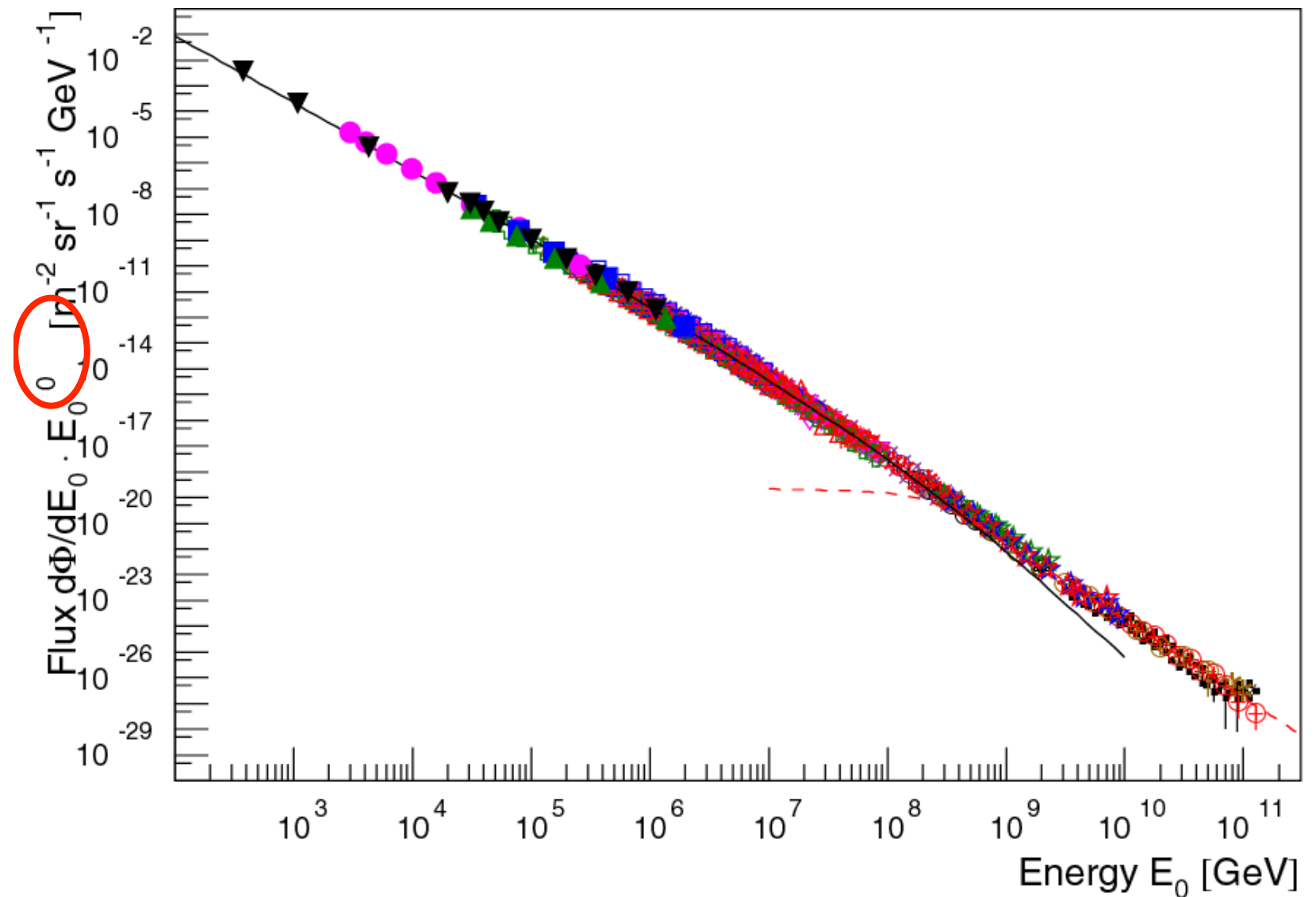
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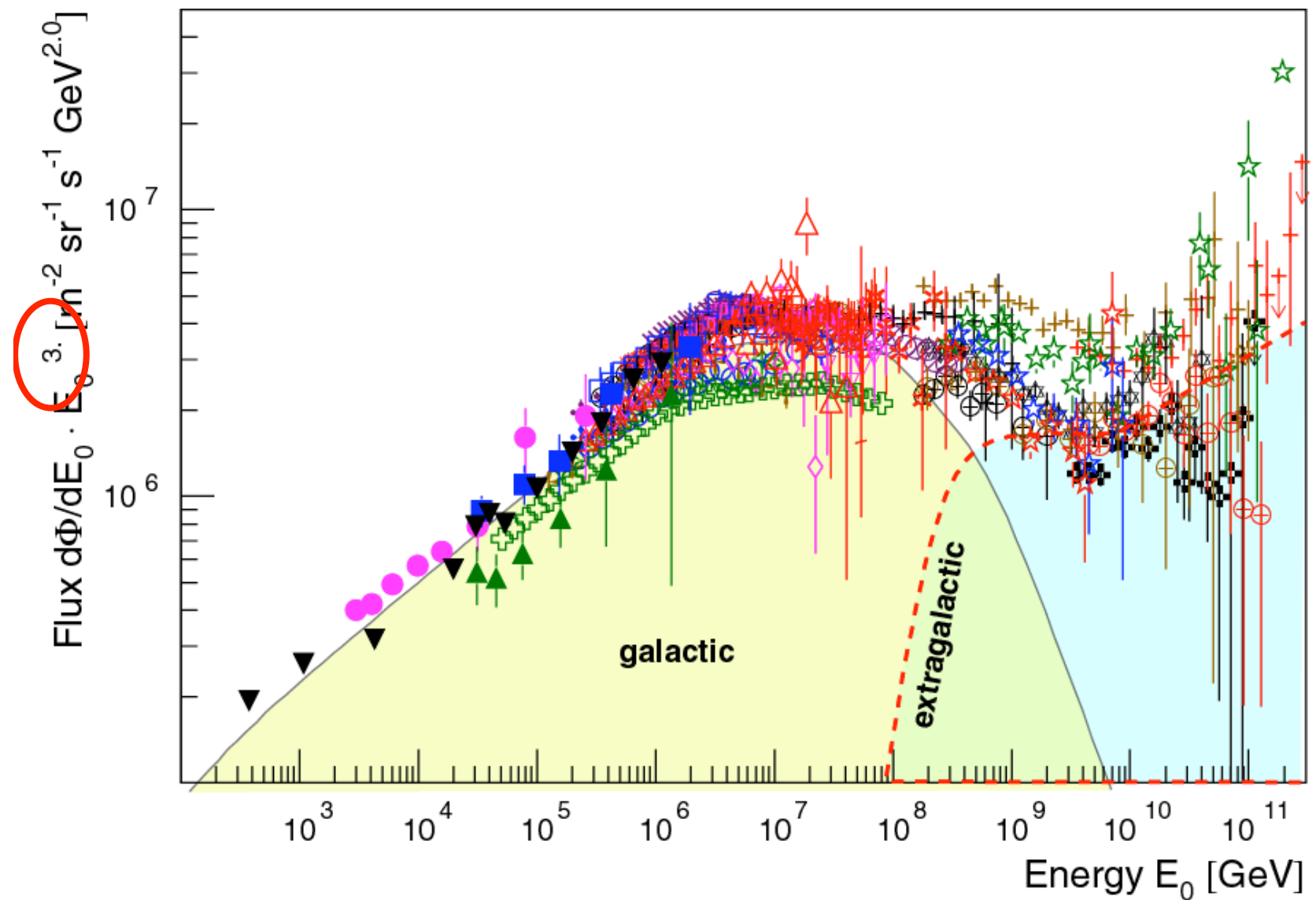
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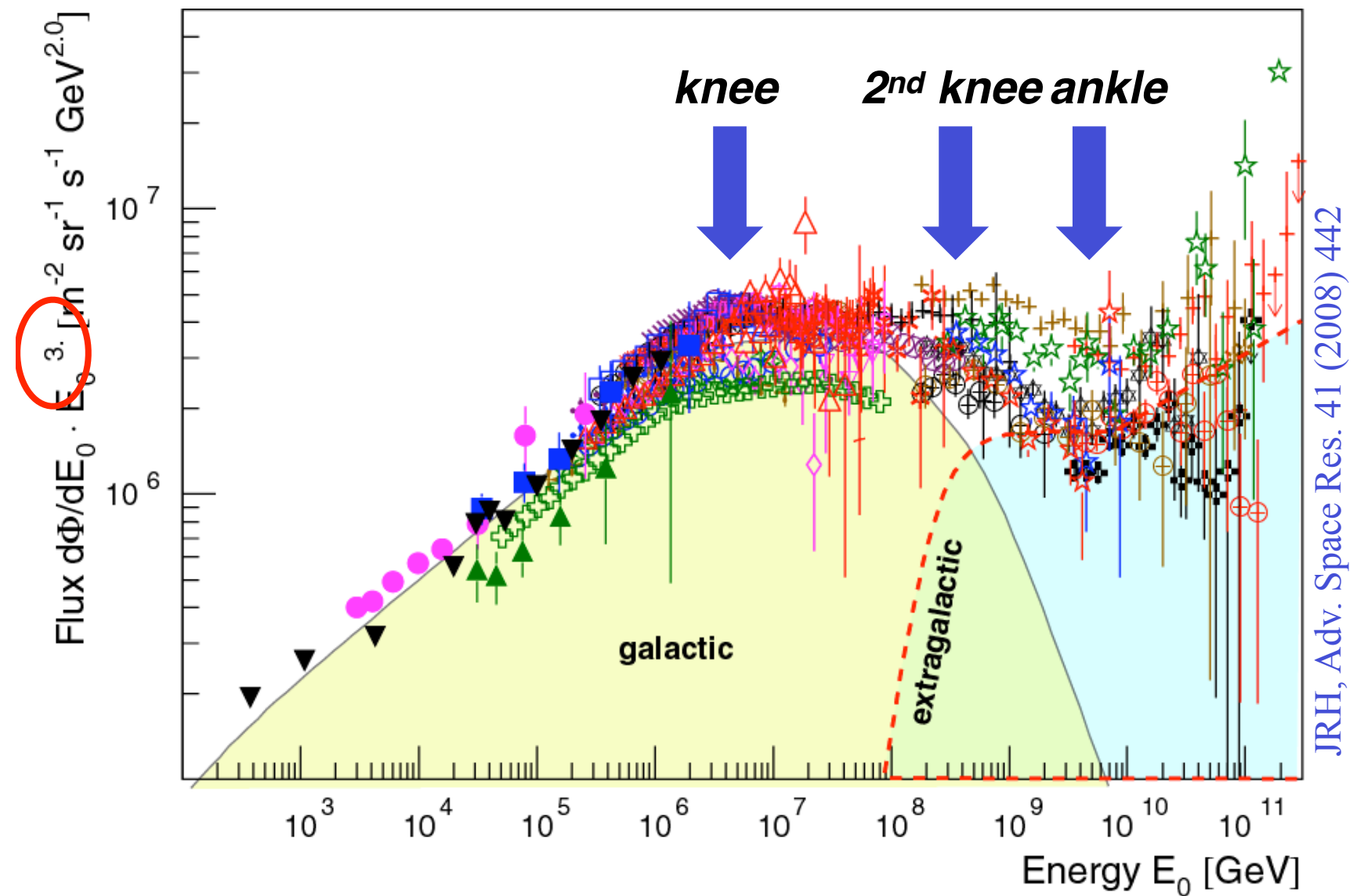
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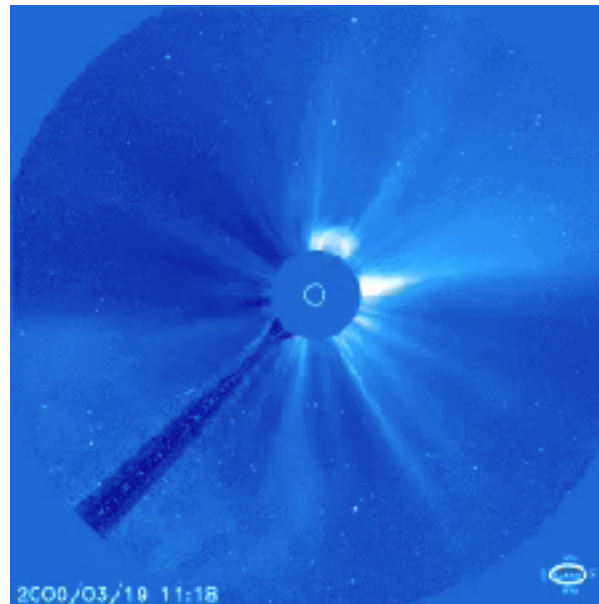
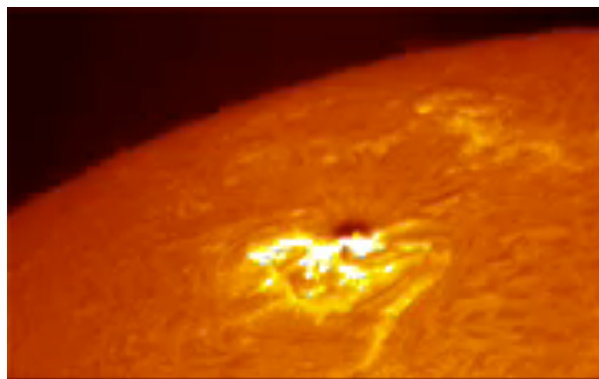


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Cosmic rays at the knee

Results and implications

Solar flares

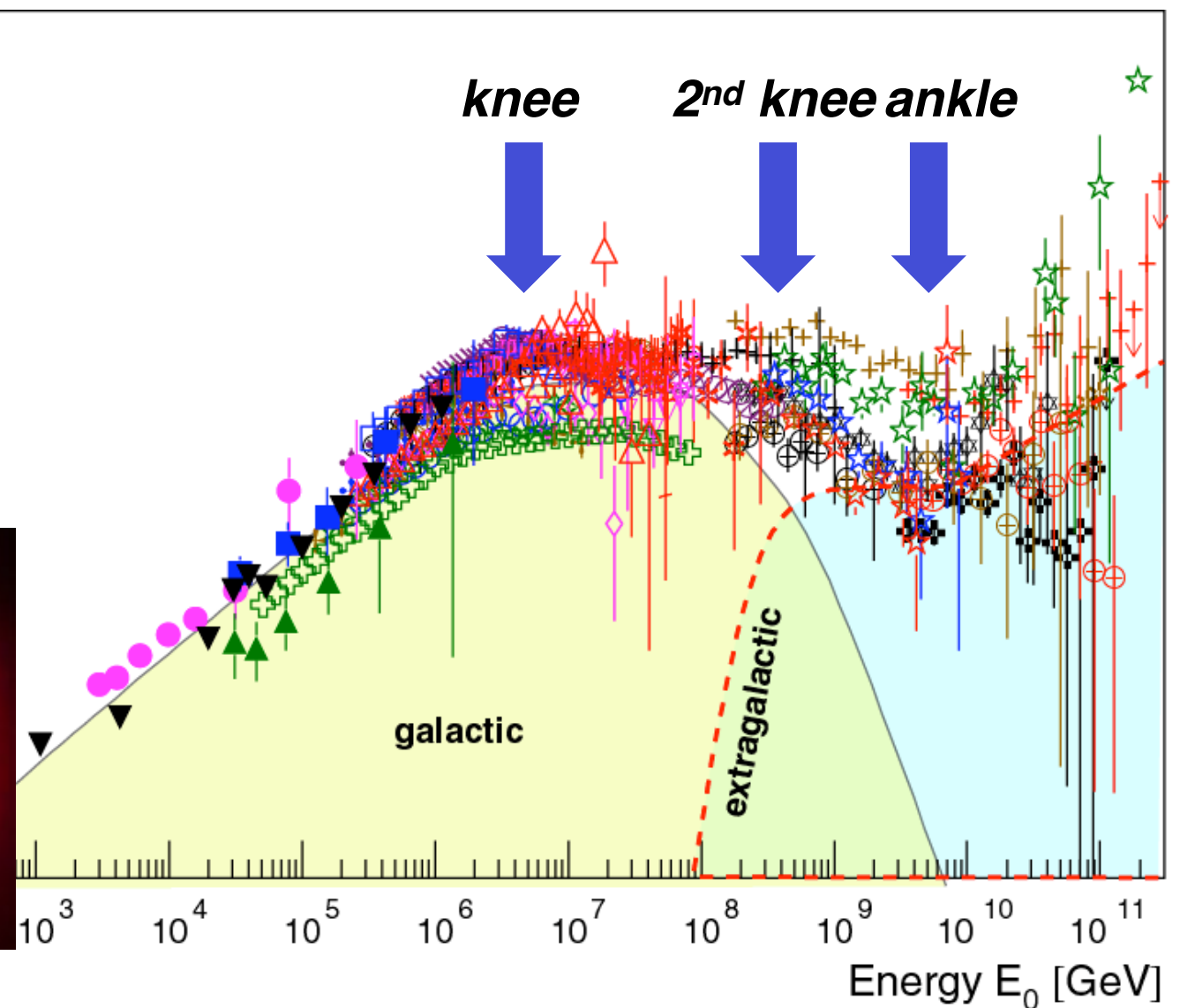


solar particles



$E_0 \cdot E_0^3 \cdot [\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{GeV}^{2.0}]$

10^7

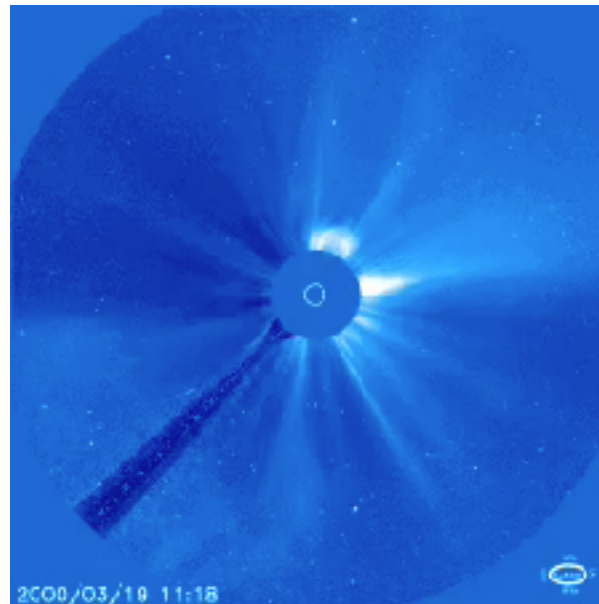
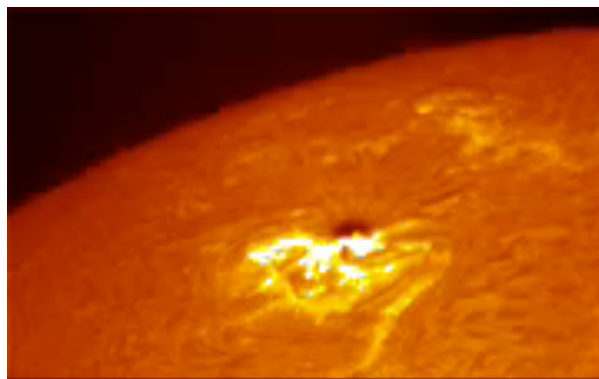


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Cosmic rays at the knee

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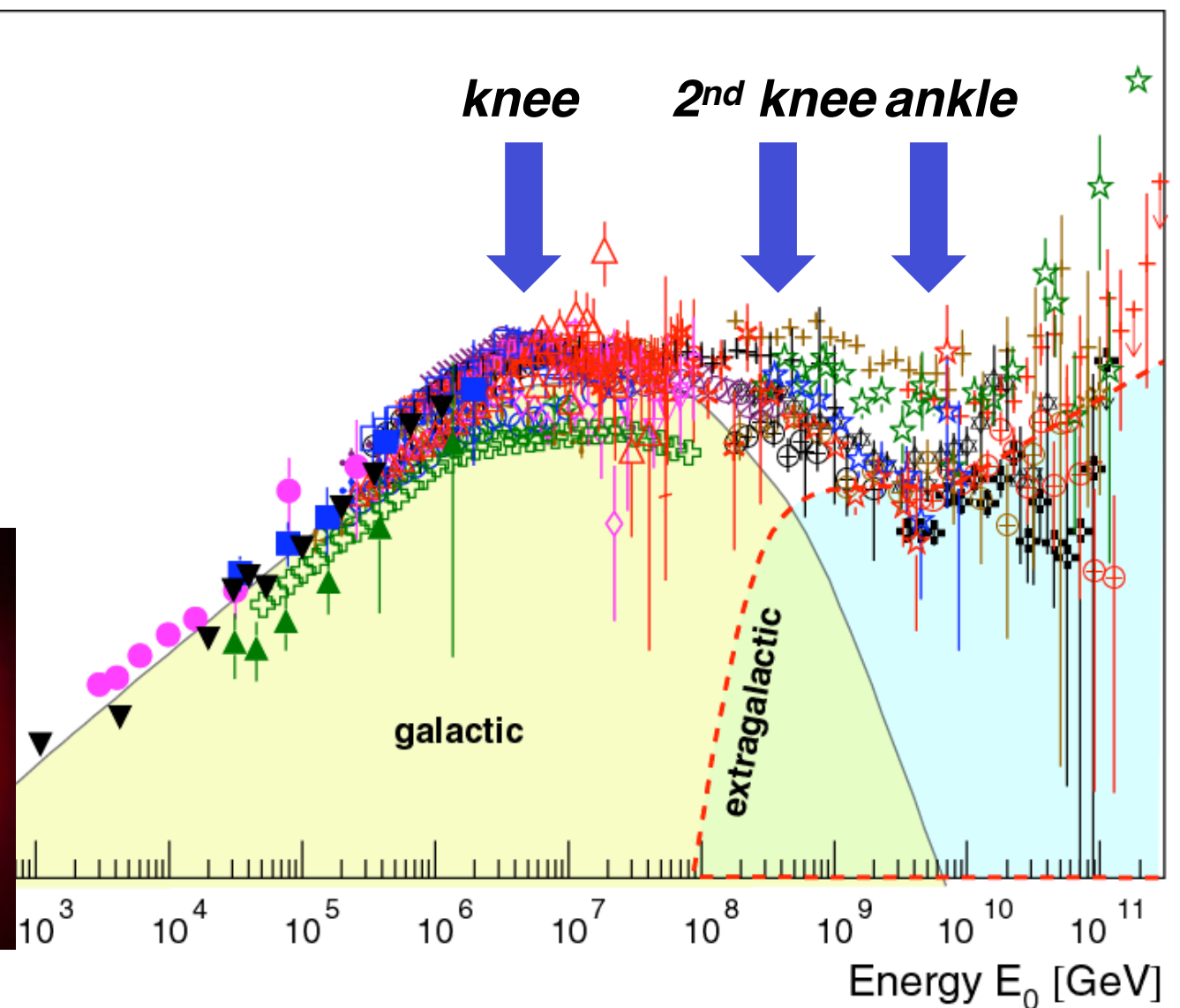
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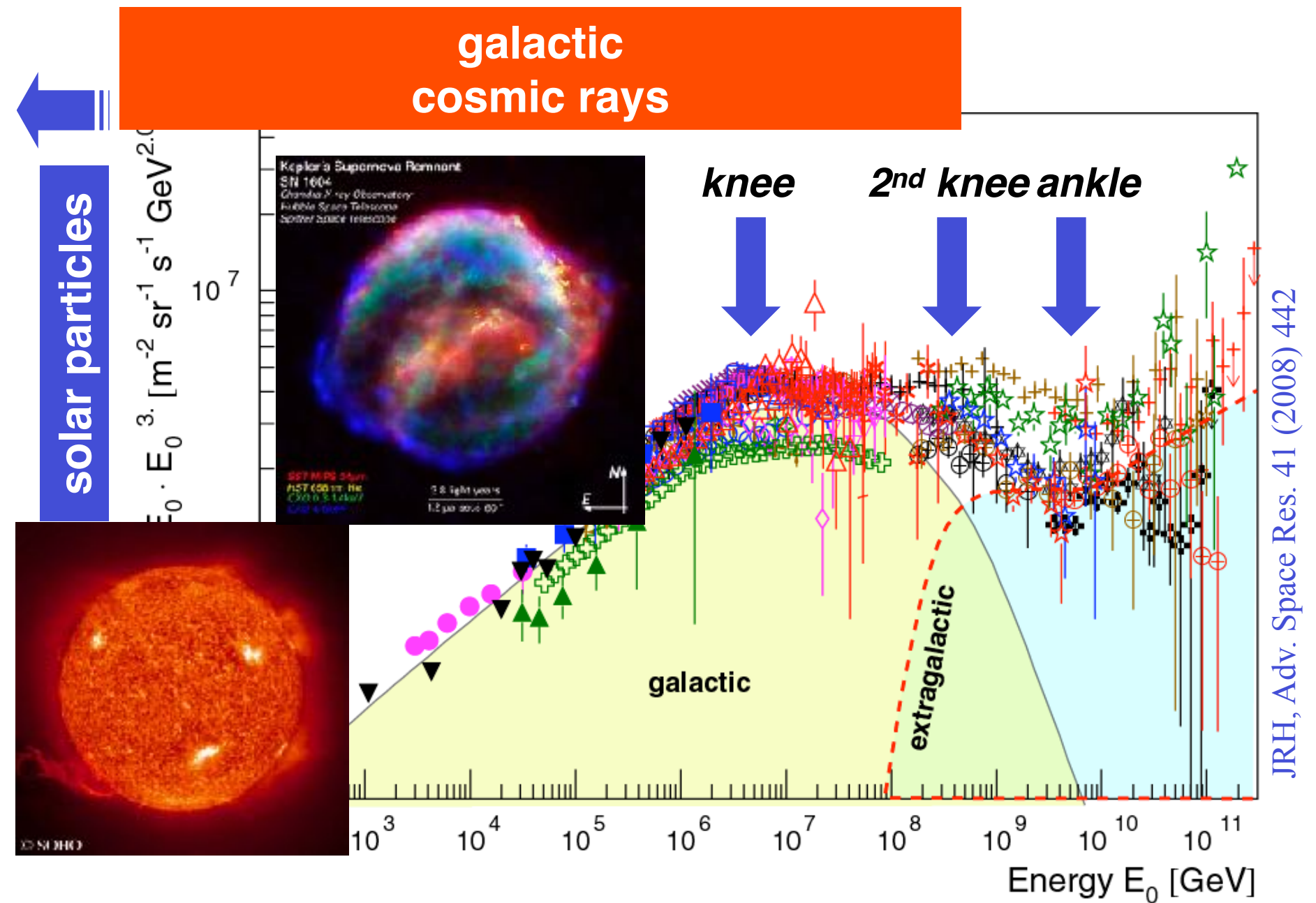
$E_0 \cdot E_0^3 \cdot [\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{GeV}^{2.0}]$



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Cosmic rays at the knee

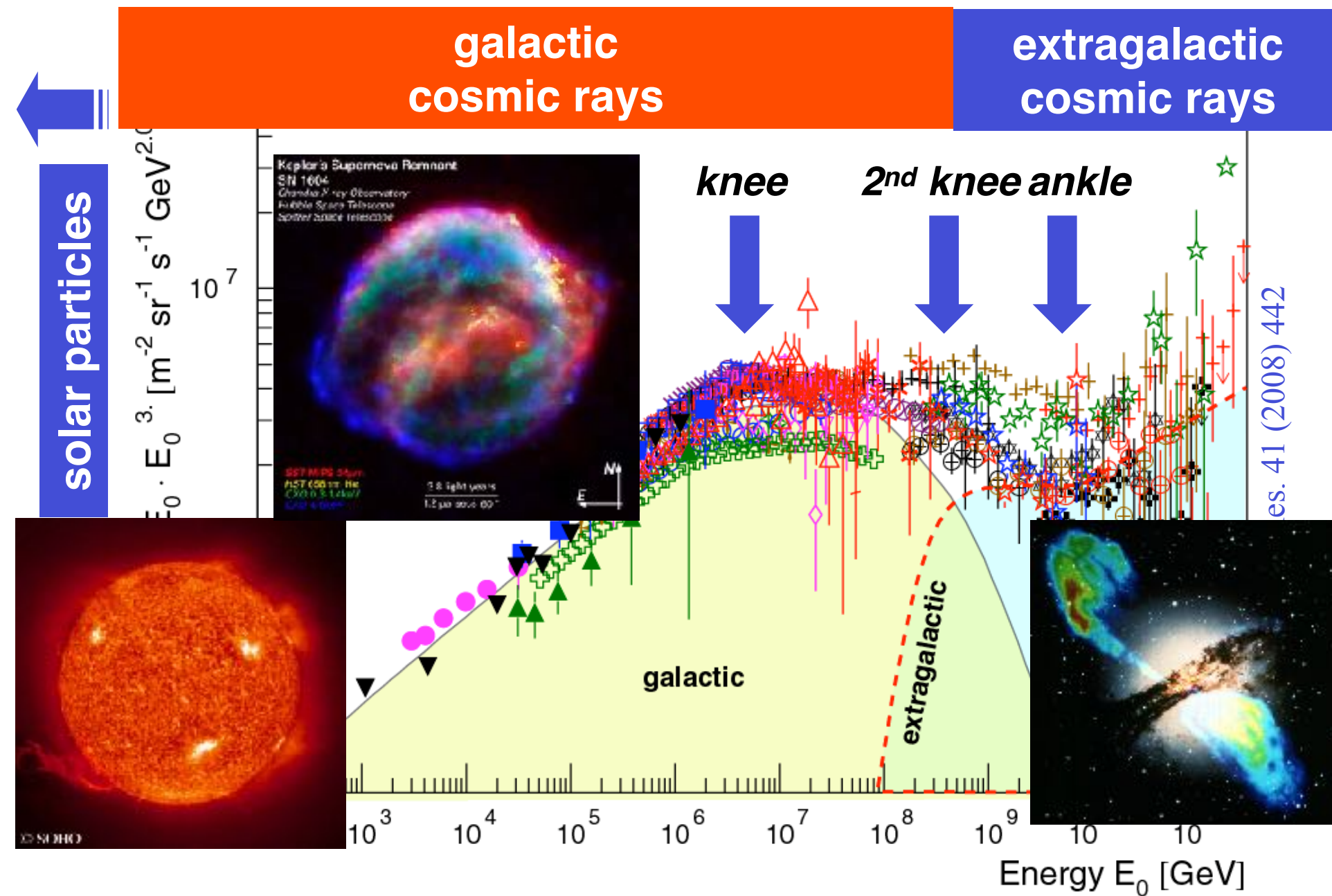
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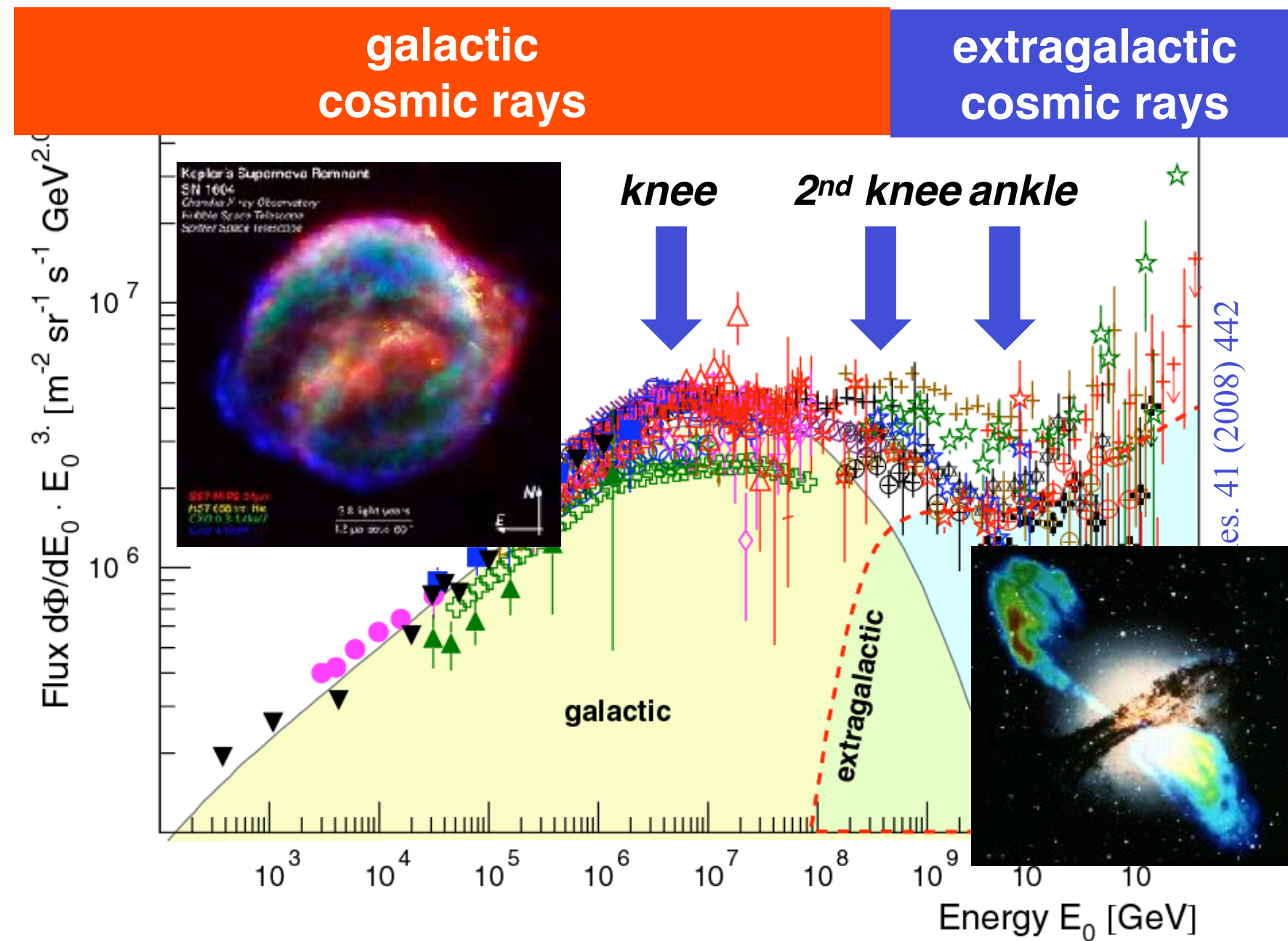
Cosmic rays at the knee

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Cosmic rays at the knee

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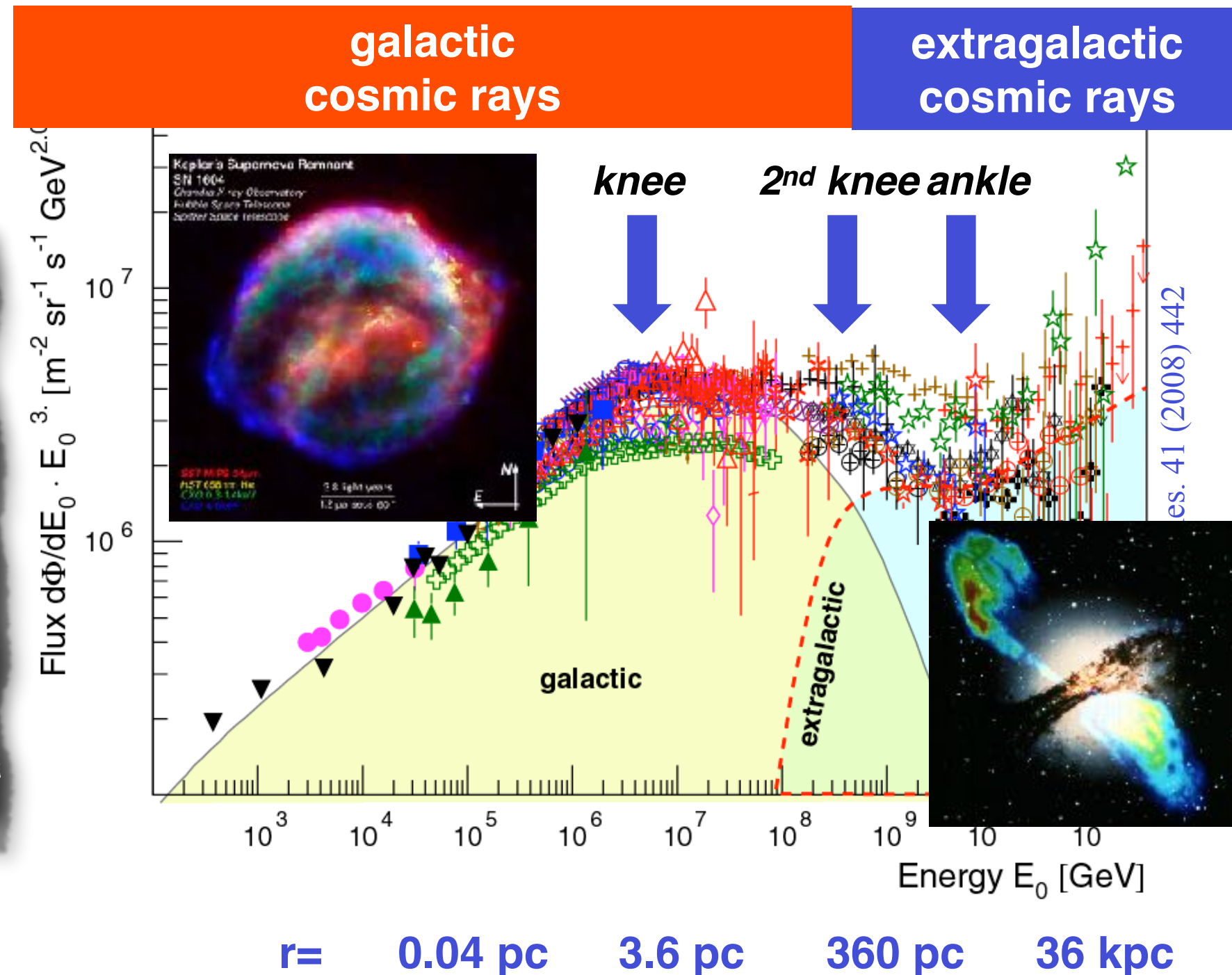


Cosmic rays at the knee

Results and implications

Radius of particle
in magnetic field

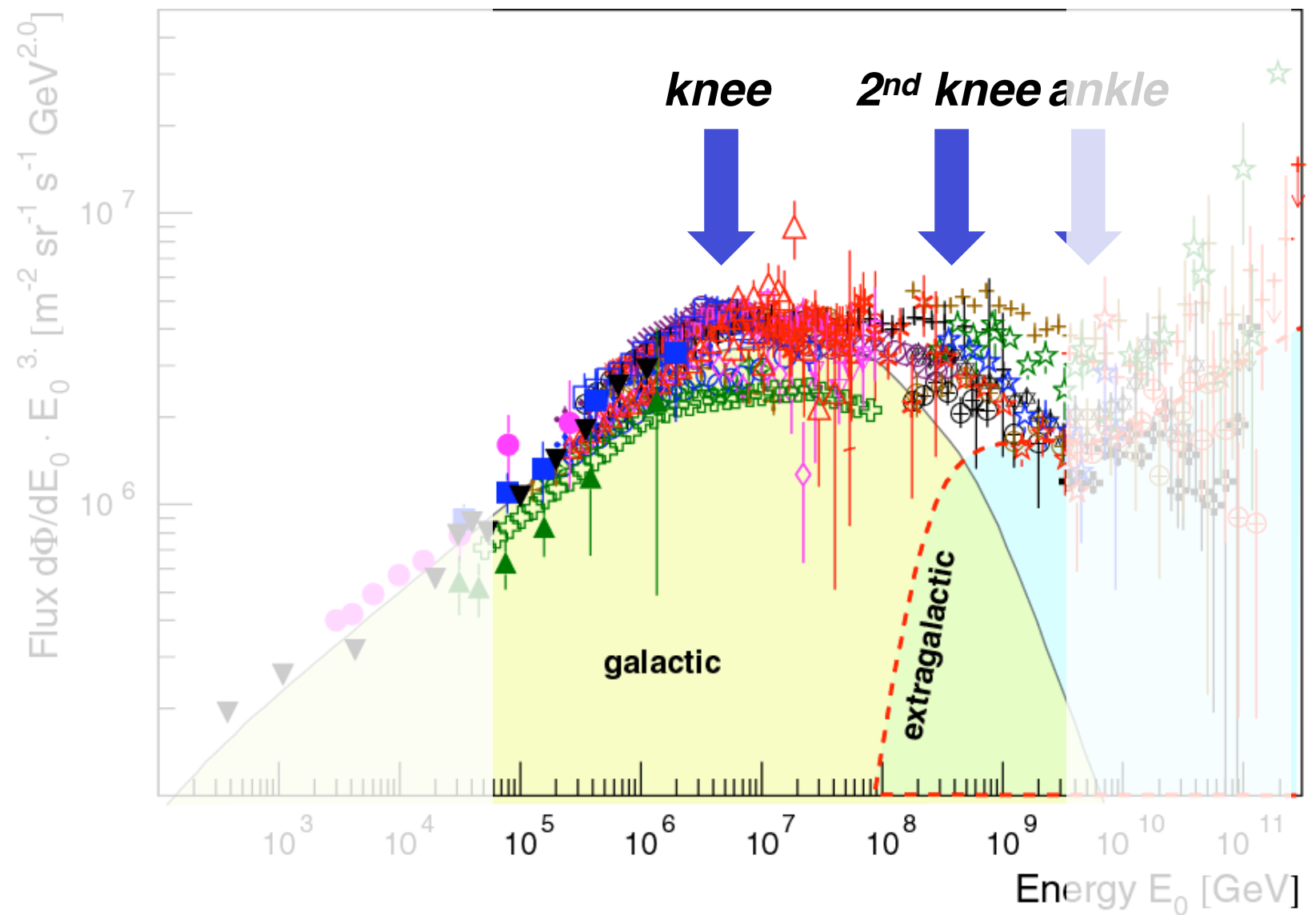
$$r = \frac{p}{ZeB} \quad r[\text{pc}] = 1.08 \cdot \frac{E [\text{PeV}]}{B [\mu\text{G}]}$$



Cosmic rays at the knee

galactic
cosmic rays

extragalactic
cosmic rays

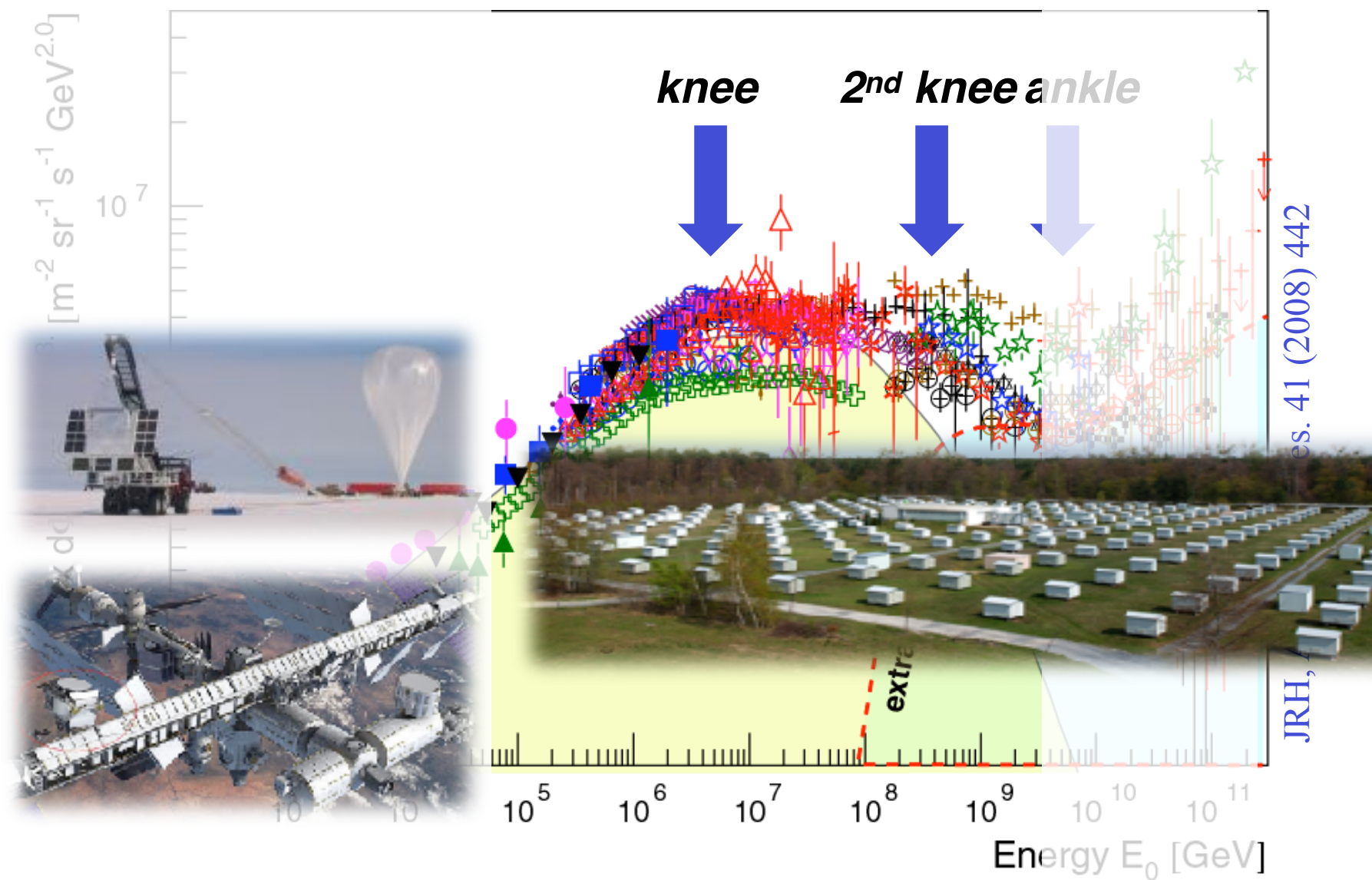


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Cosmic rays at the knee

galactic
cosmic rays

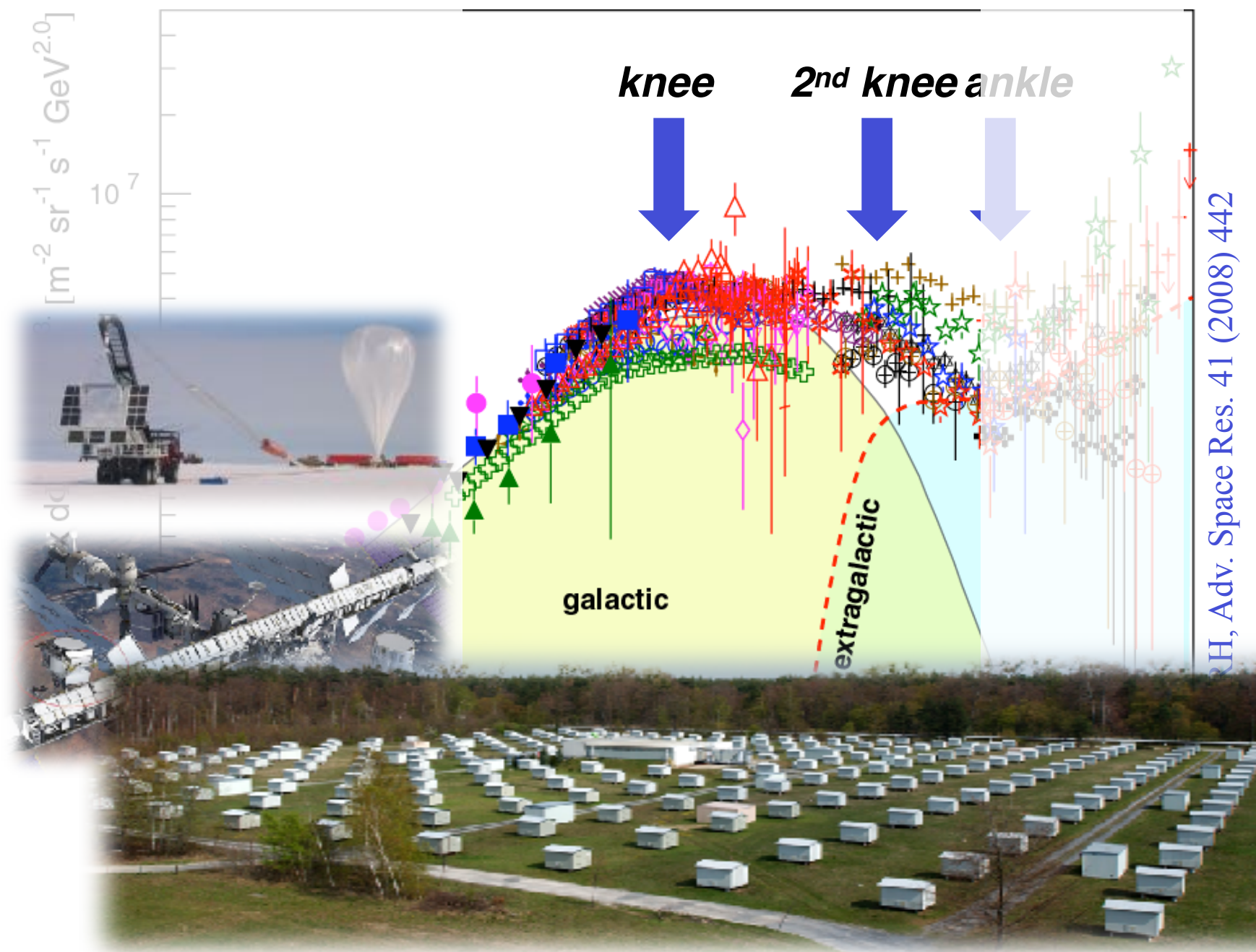
extragalactic
cosmic rays



Cosmic rays at the knee

galactic
cosmic rays

extragalactic
cosmic rays



Extensive Air Showers

electromagnetic hadronic muonic
shower component

~ 98%

< 1%

~2%



Extensive Air Showers



electromagnetic **hadronic** **muonic**
shower component

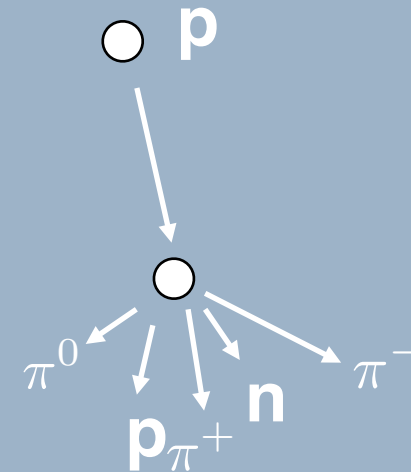
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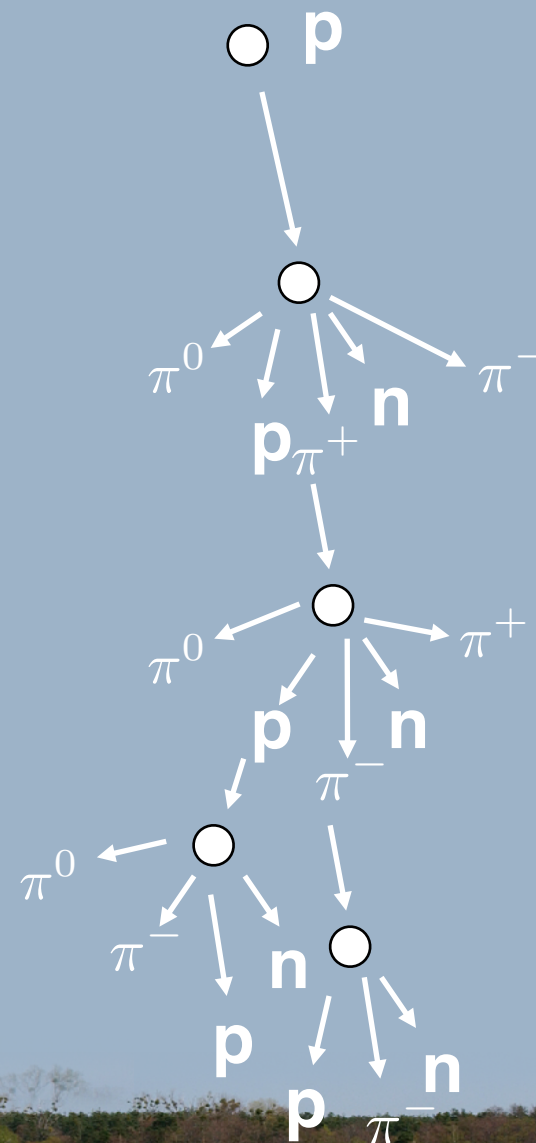
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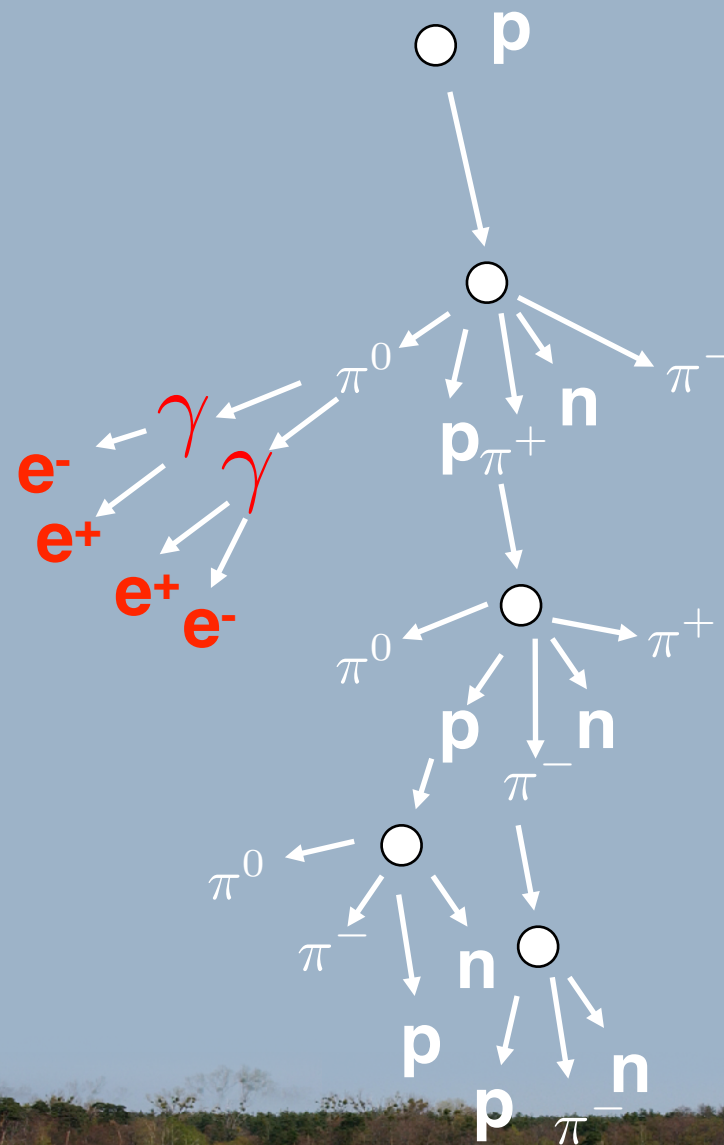
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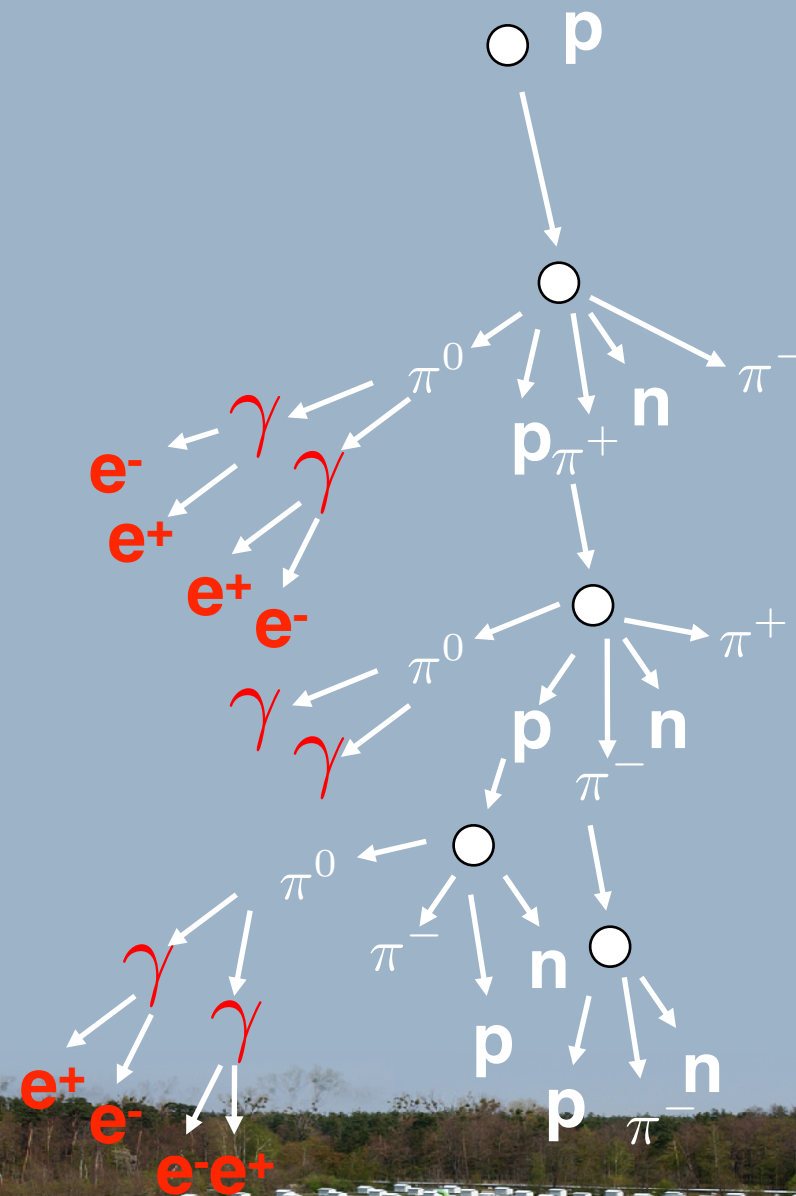
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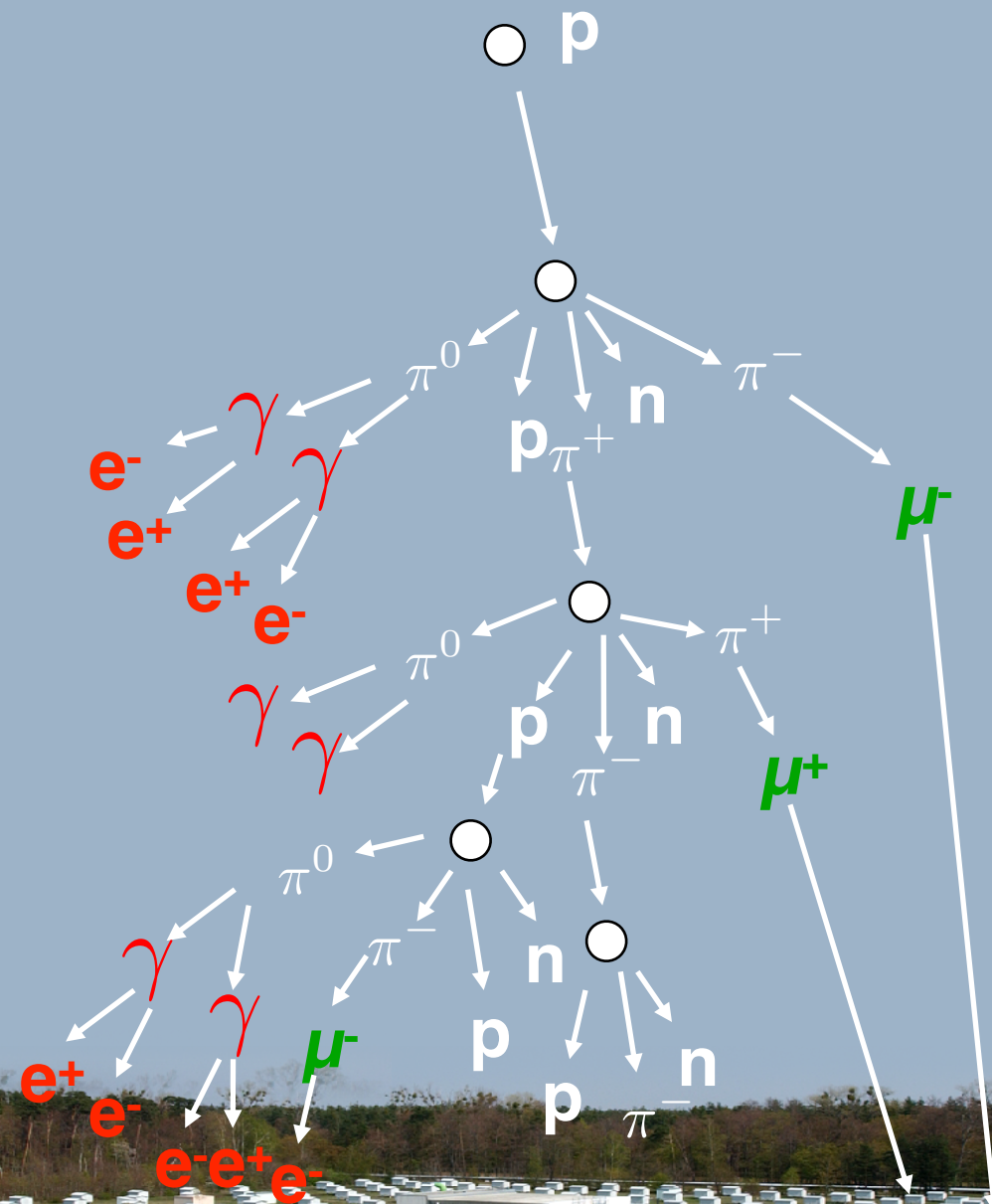
Extensive Air Showers

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A Matthews Heitler Model – mass resolution in EAS measurements

depth of shower maximum

$$X_{\max}^A = X_{\max}^p - X_0 \ln A$$

radiation length $X_0=36.7$ g/cm²

electron-muon ratio

$$\lg(N_e/N_\mu) = C - 0.065 \ln A.$$

A Matthews Heitler Model – mass resolution in EAS measurements

depth of shower maximum

$$X_{\max}^A = X_{\max}^p - X_0 \ln A$$

radiation length $X_0=36.7$ g/cm²

typical uncertainty

$$\Delta X_{\max} \approx 20 \text{ g/cm}^2$$

electron-muon ratio

$$\lg(N_e/N_\mu) = C - 0.065 \ln A.$$

$$\Delta \frac{N_e}{N_\mu} \approx 16\% - 20\%$$

A Matthews Heitler Model – mass resolution in EAS measurements

depth of shower maximum

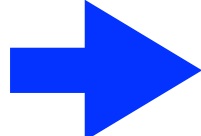
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typical uncertainty

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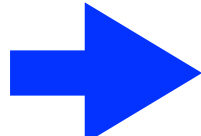
expected mass resolution


$$\Delta \ln A \approx 0.8 - 1$$

electron-muon ratio

$$\lg(N_e/N_\mu) = C - 0.065 \ln A.$$

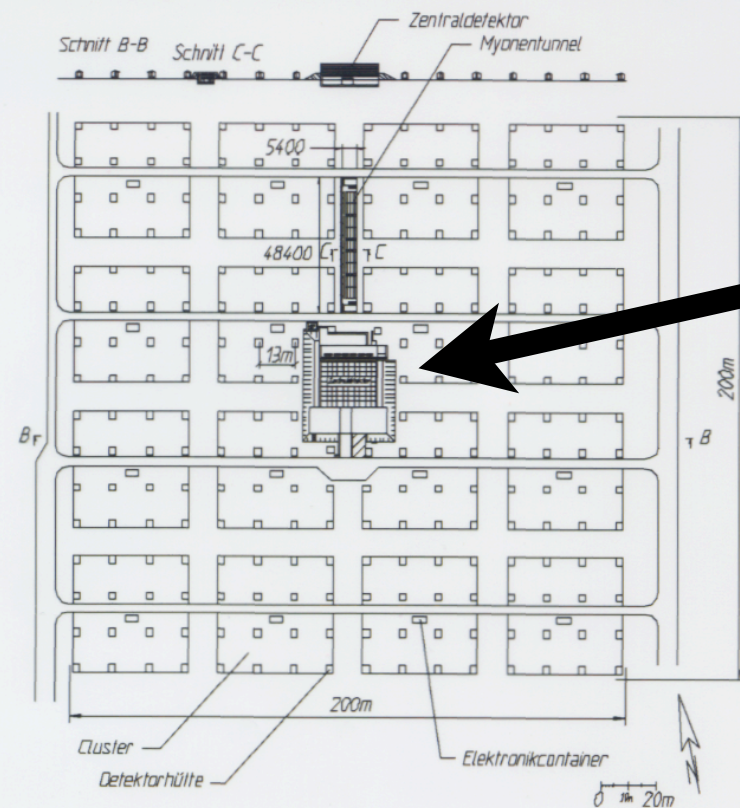
$$\Delta \frac{N_e}{N_\mu} \approx 16\% - 20\%$$



4 to 5 mass groups
p, He, CNO, (Si), Fe

The KASCADE Array

200 m



Array

200 m

252 stations with

□ e/γ detectors: 4 cm liquid scintillator ($\approx 3.1 \text{ m}^2$)

□ muon detectors: 3 cm plastic scintillator ($\approx 3.2 \text{ m}^2$)

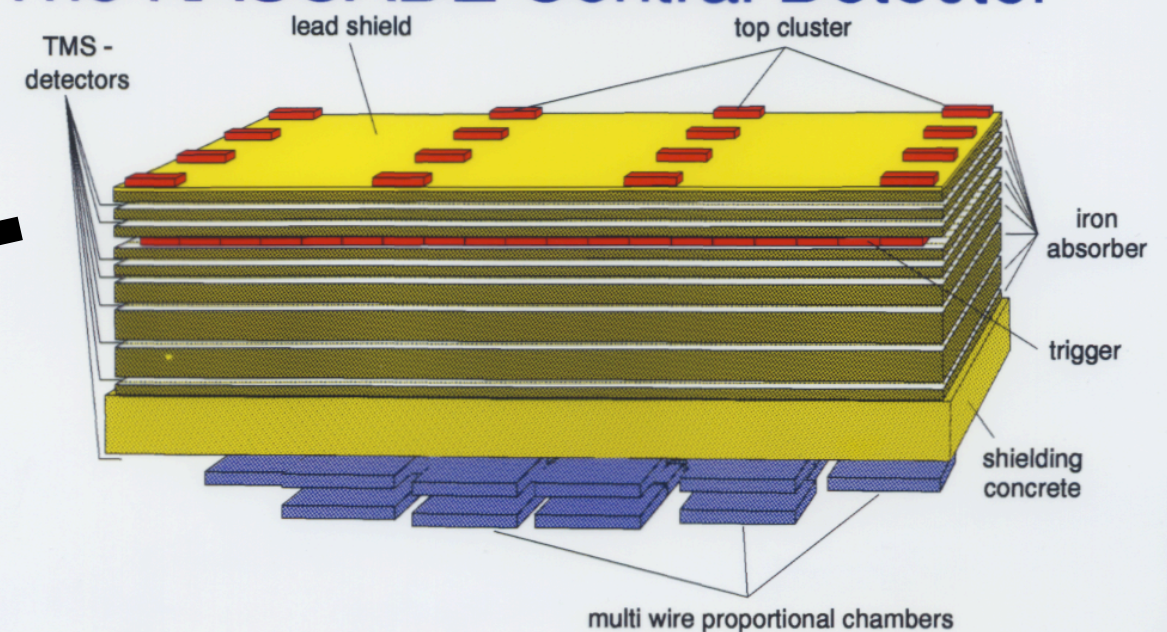
shield 10 cm Pb + 4 cm Fe $\rightarrow 20 X_0$

⇒ $E_\mu > 300 \text{ MeV}$

→ measurement of particle densities and arrival times

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The KASCADE Central Detector



4 different detector systems:

□ Top array $32 \times 0.45 \text{ m}^2$ scintillation counters (14 m^2)

□ Trigger layer $456 \times 0.45 \text{ m}^2$ scintillation counters (206 m^2)

□ 32 Multiwire proportional chambers ($2 \times 150 \text{ m}^2$) $E_\mu > 2 \text{ GeV}$

□ Iron sampling calorimeter ($16 \times 20 \text{ m}^2$)

8 active layers $\rightarrow 10\,000$ liquid ionisation chambers

40 000 electronic channels

separation of individual hadrons by a fine segmentation

depth $\approx 11 \lambda_i \rightarrow$ hadrons up to 10 TeV 95% contained

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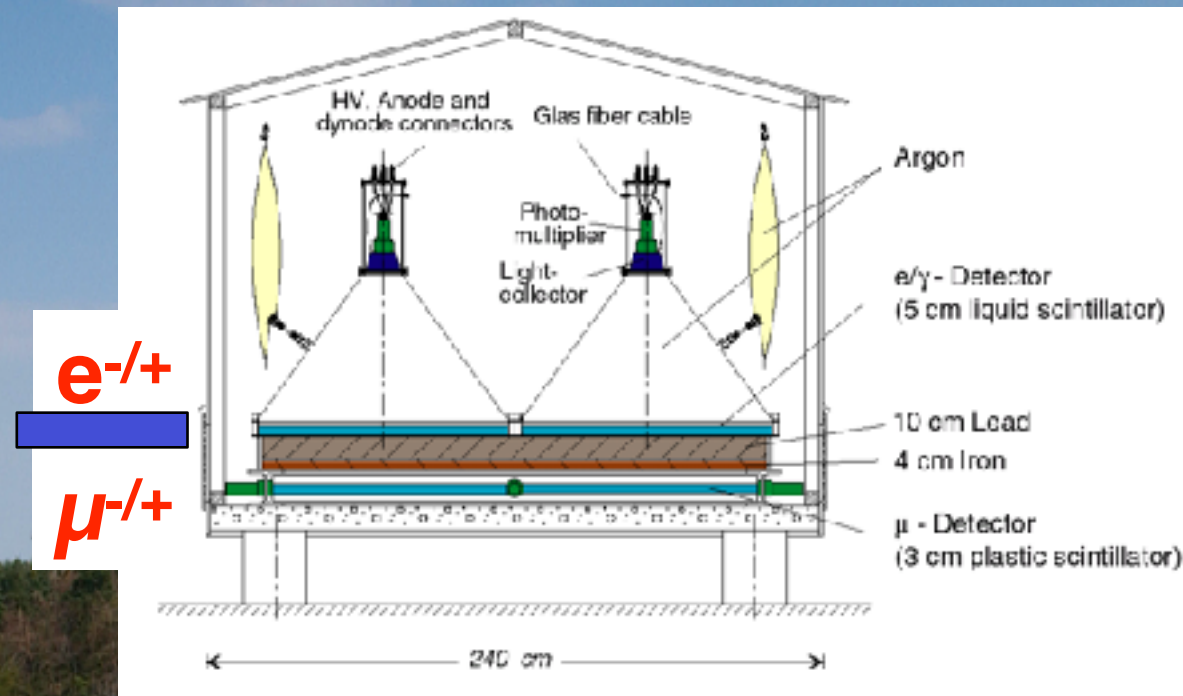
KArlsruhe Shower Core and Array DEtector

**Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components**



KArlsruhe Shower Core and Array DEtector

Simultaneous measurement of
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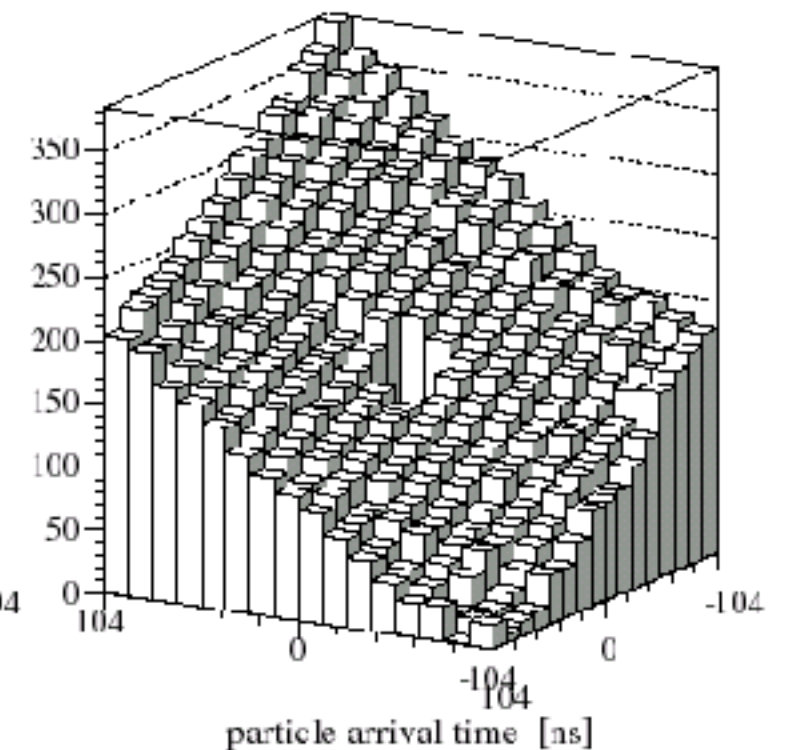
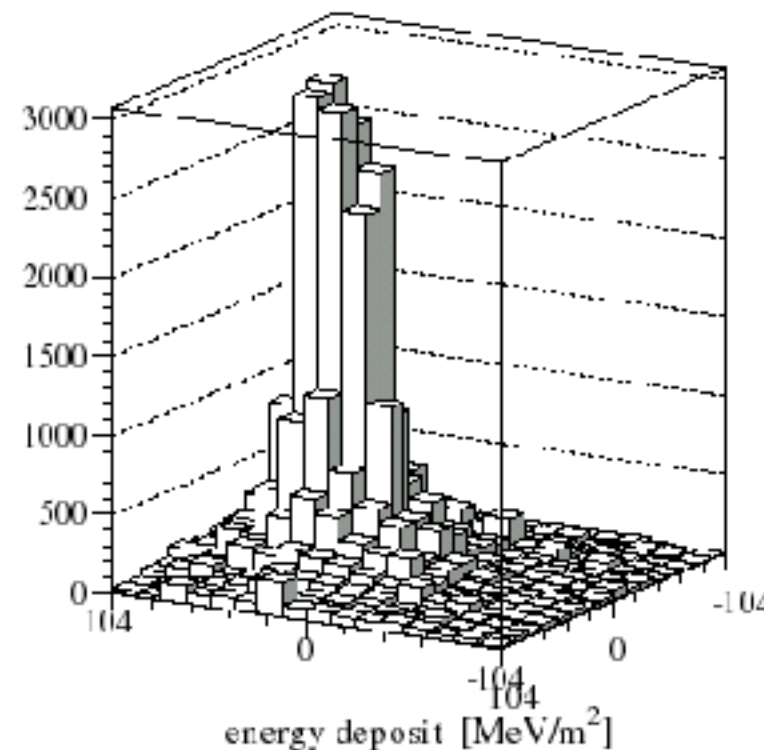
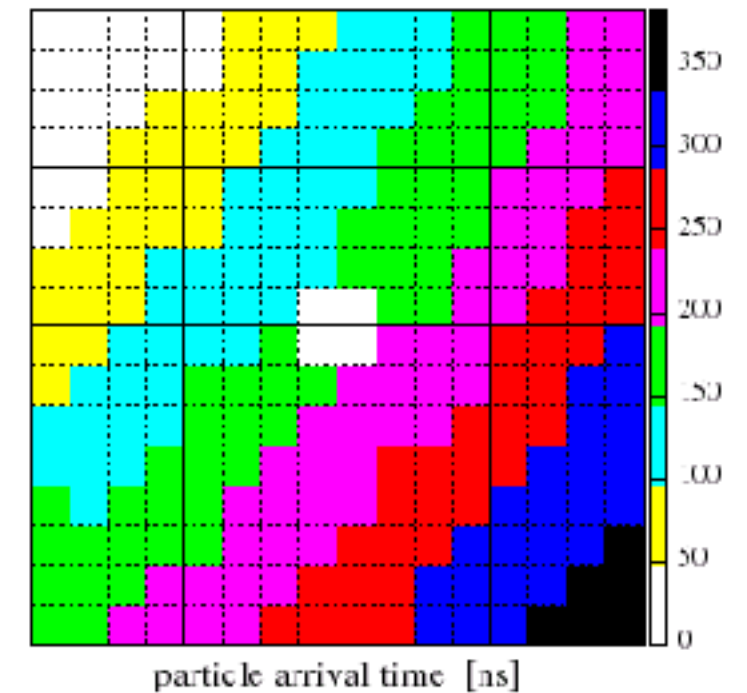
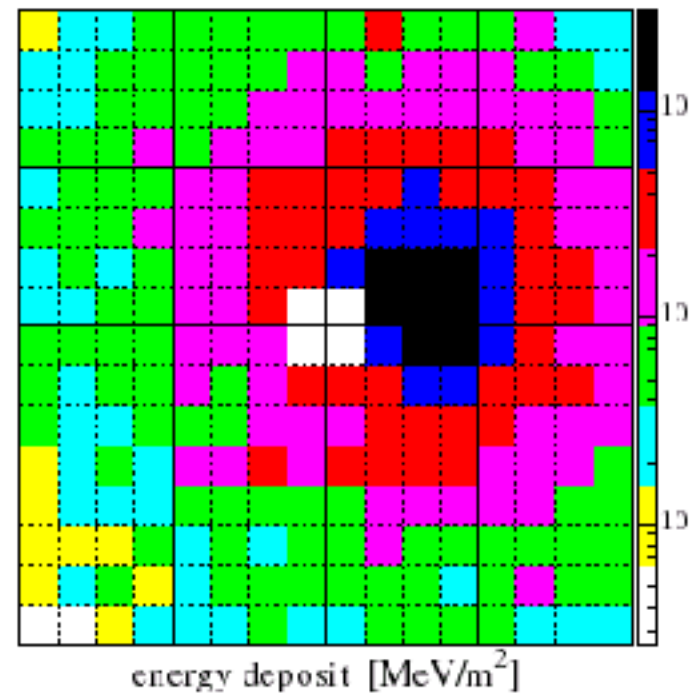


Event reconstruction in the scintillator array

electromagnetic component

shower core	$\Delta r = 2.5 - 5.5 \text{ m}$
shower direction	$\Delta\alpha = 0.5^\circ - 1.2^\circ$
shower size	$\Delta N_e/N_e = 6 - 12 \%$

e/ γ -Detectors, Run 1, Event 71089, 96-03-05 22:07:48.956078



KASCADE GRANDE Array

37 detector stations

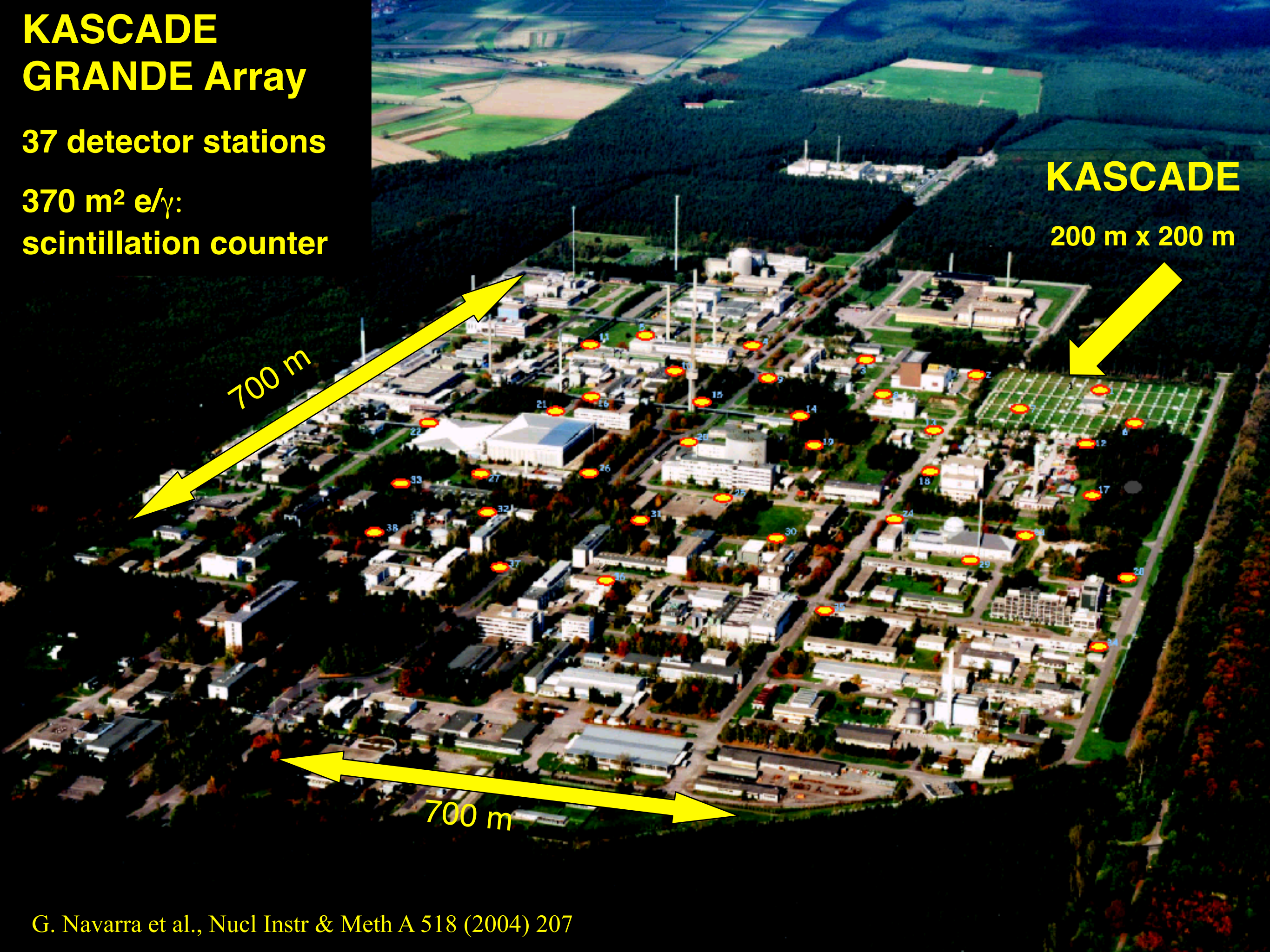
370 m² e/ γ :
scintillation counter

KASCADE

200 m x 200 m

700 m

700 m



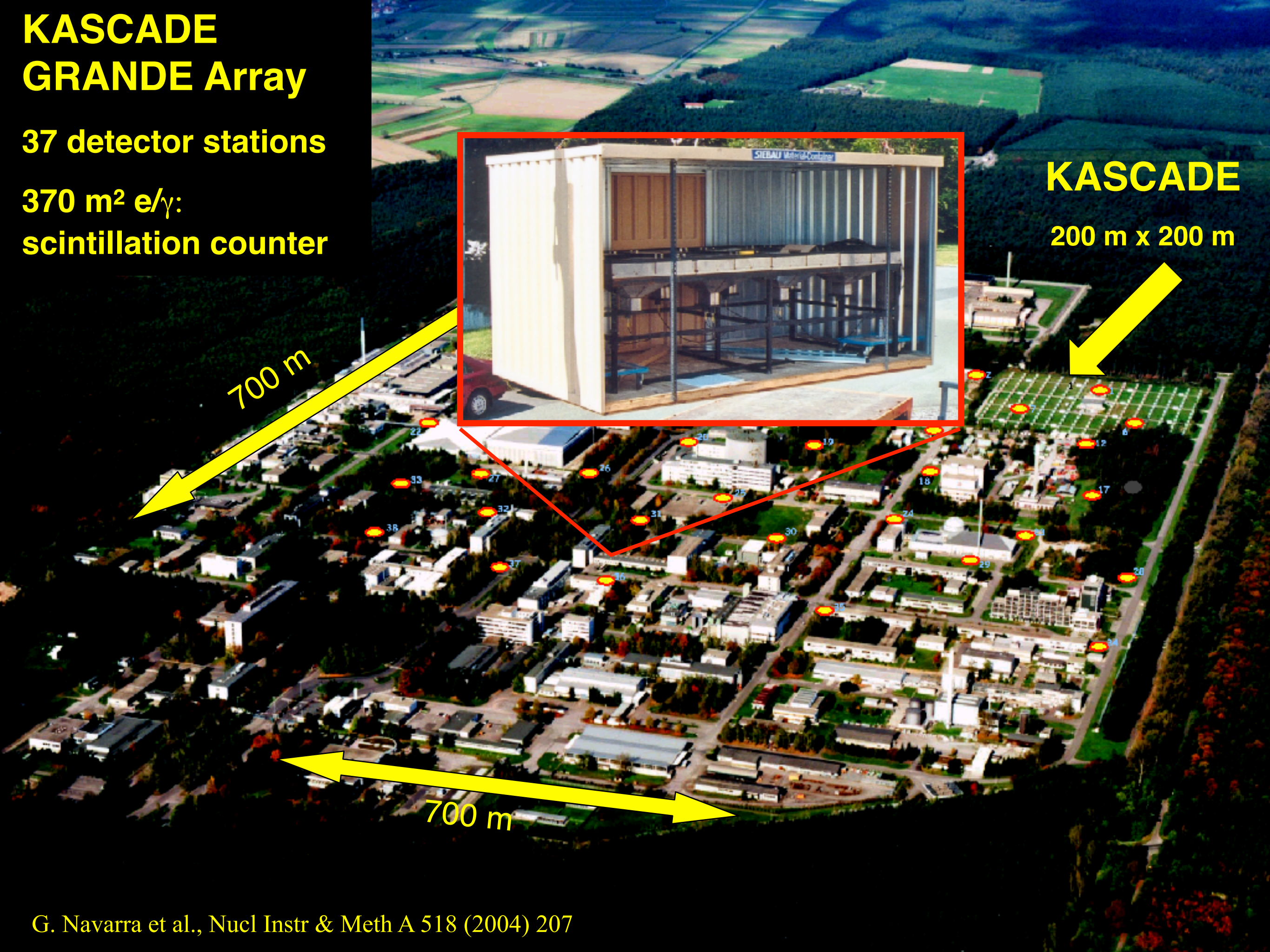
KASCADE GRANDE Array

37 detector stations

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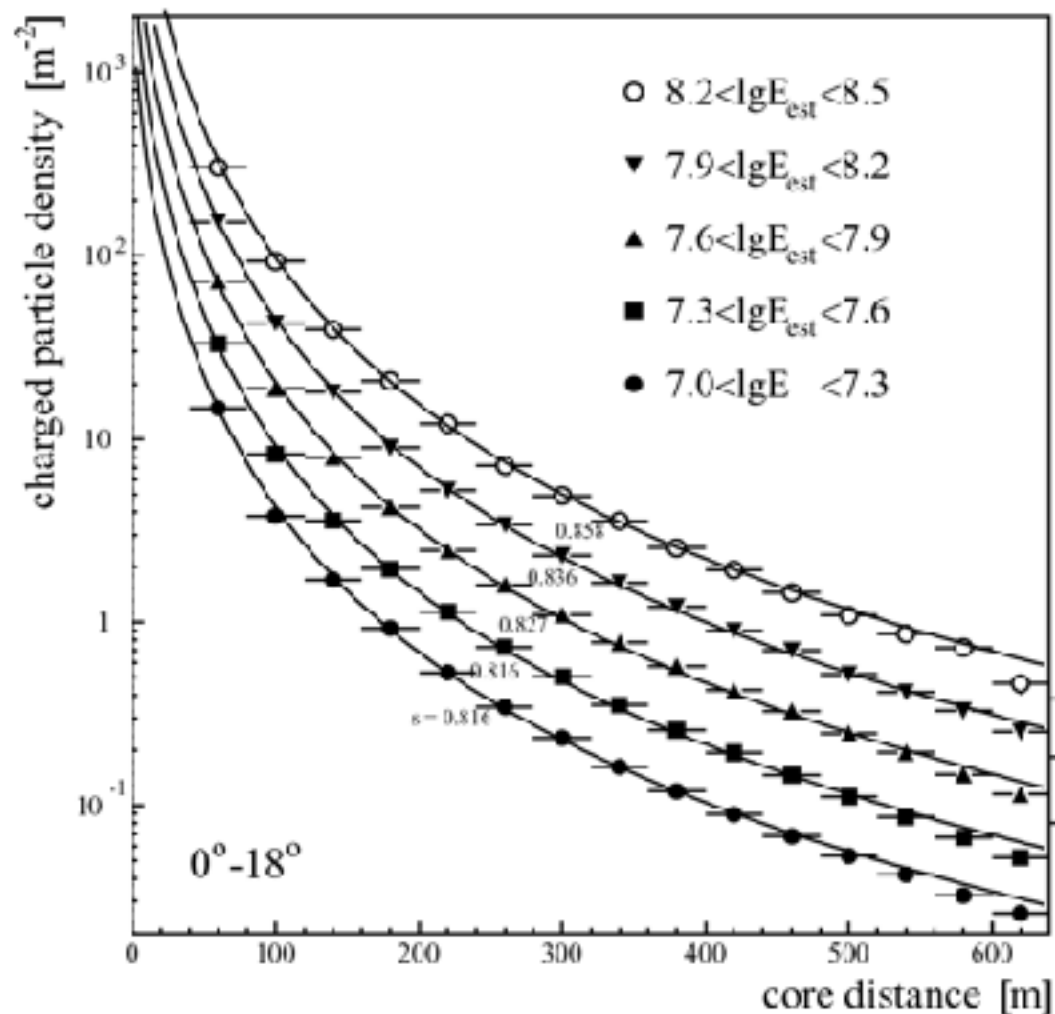
KASCADE

200 m x 200 m

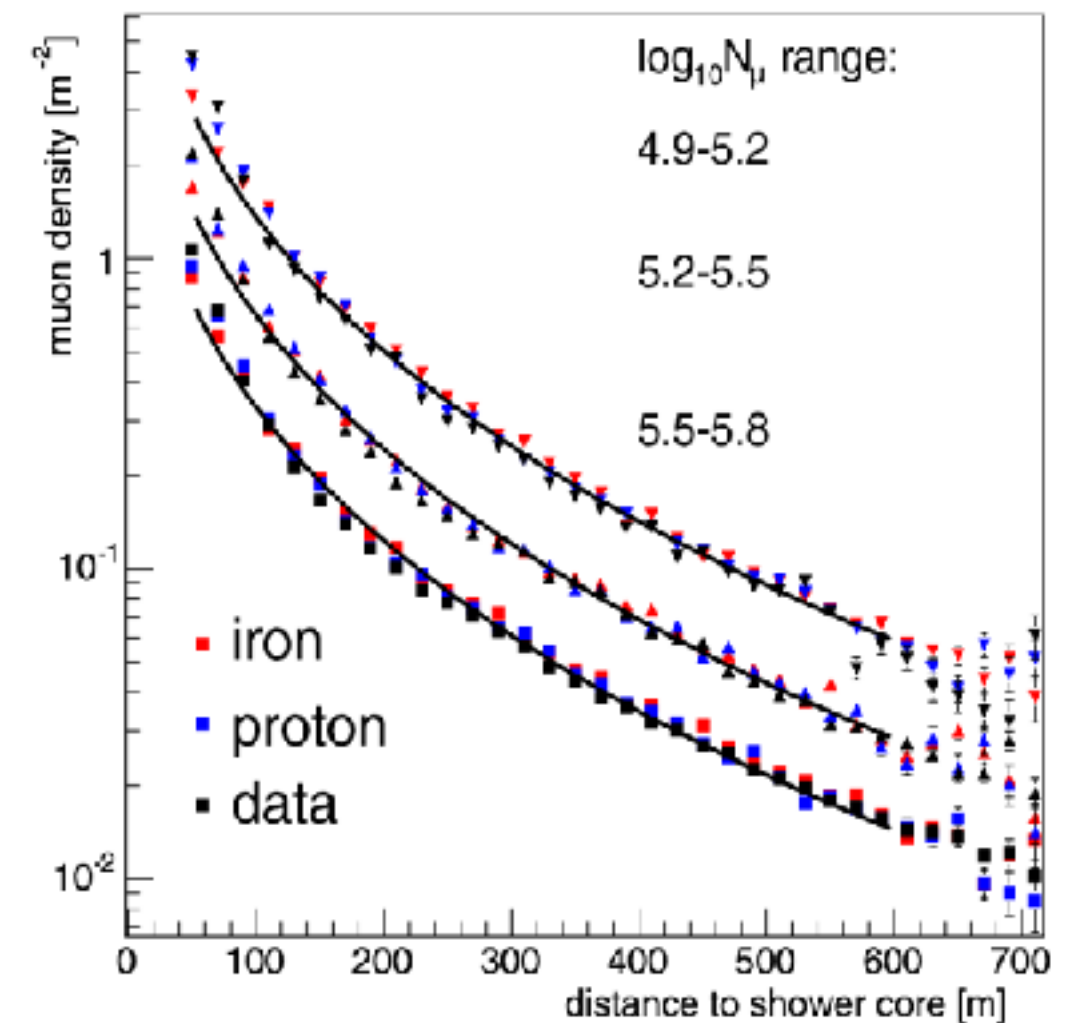


KASCADE-Grande – Lateral distributions

Electromagnetic component



Muons



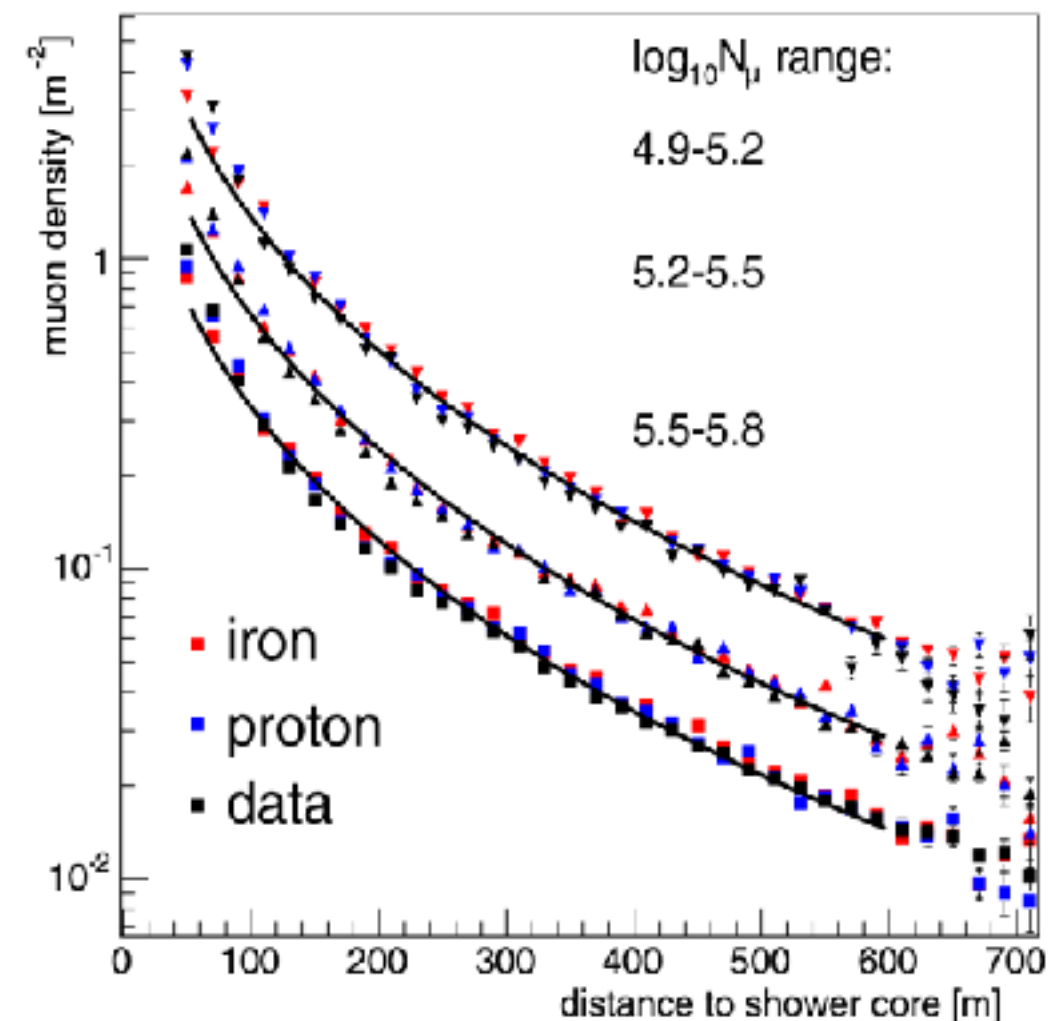
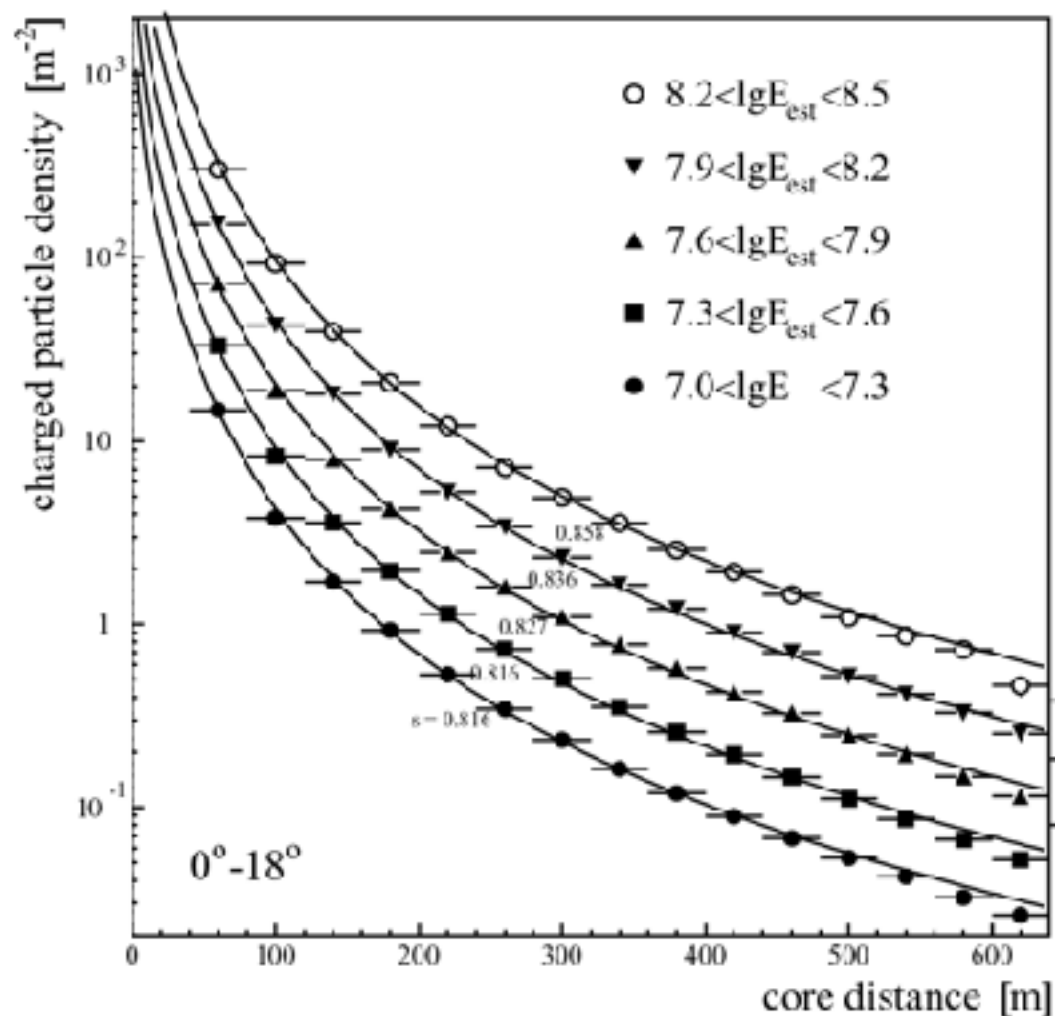
KASCADE-Grande – Lateral distributions

Electromagnetic component

Muons

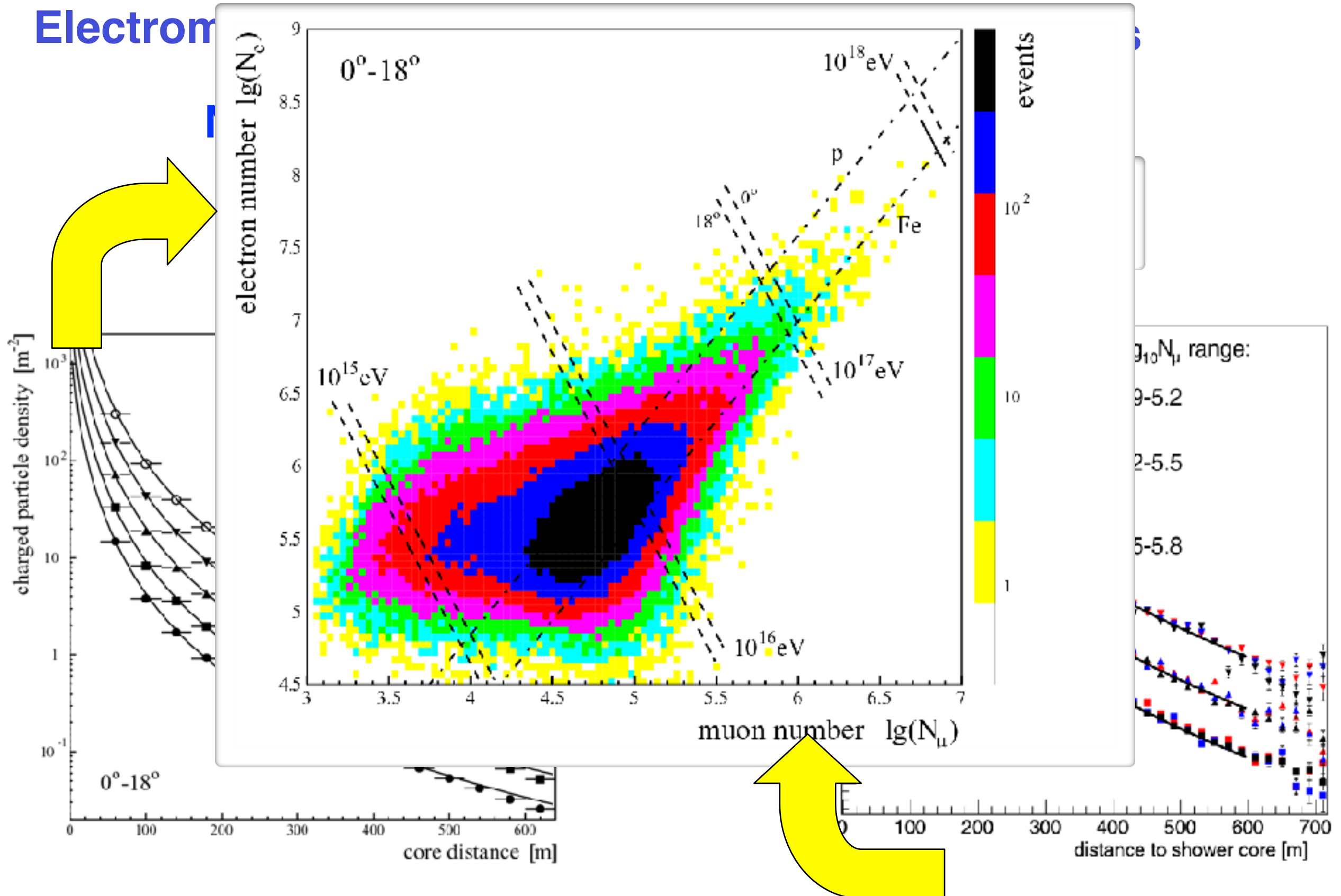
NKG function

$$\rho(r, s, N_e) = \frac{N_e}{r_M^2} \frac{\Gamma(4.5 - s)}{2\pi\Gamma(s)\Gamma(4.5 - 2s)} \left(\frac{r}{r_M}\right)^{s-2} \left(1 + \frac{r}{r_M}\right)^{s-4.5}$$



KASCADE-Grande – Lateral distributions

Electromagnetic

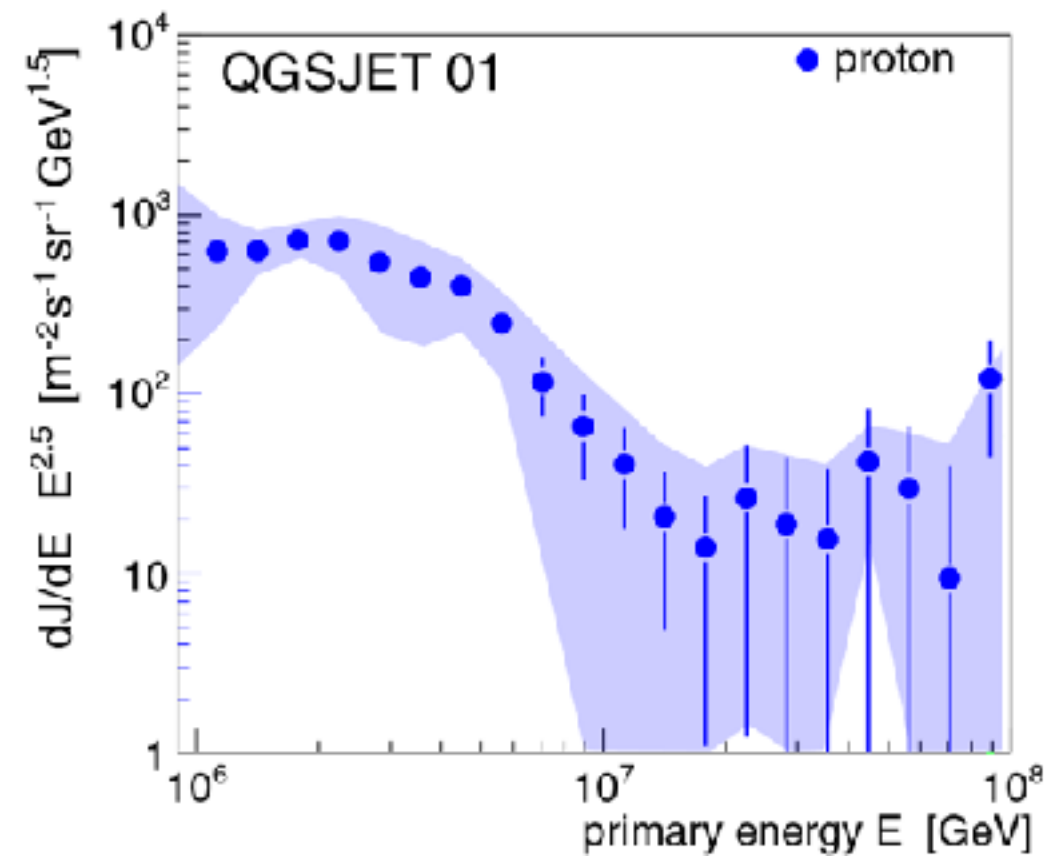


J. v. Buren et al., Proc. 29th ICRC, Pune 6 (2005) 301

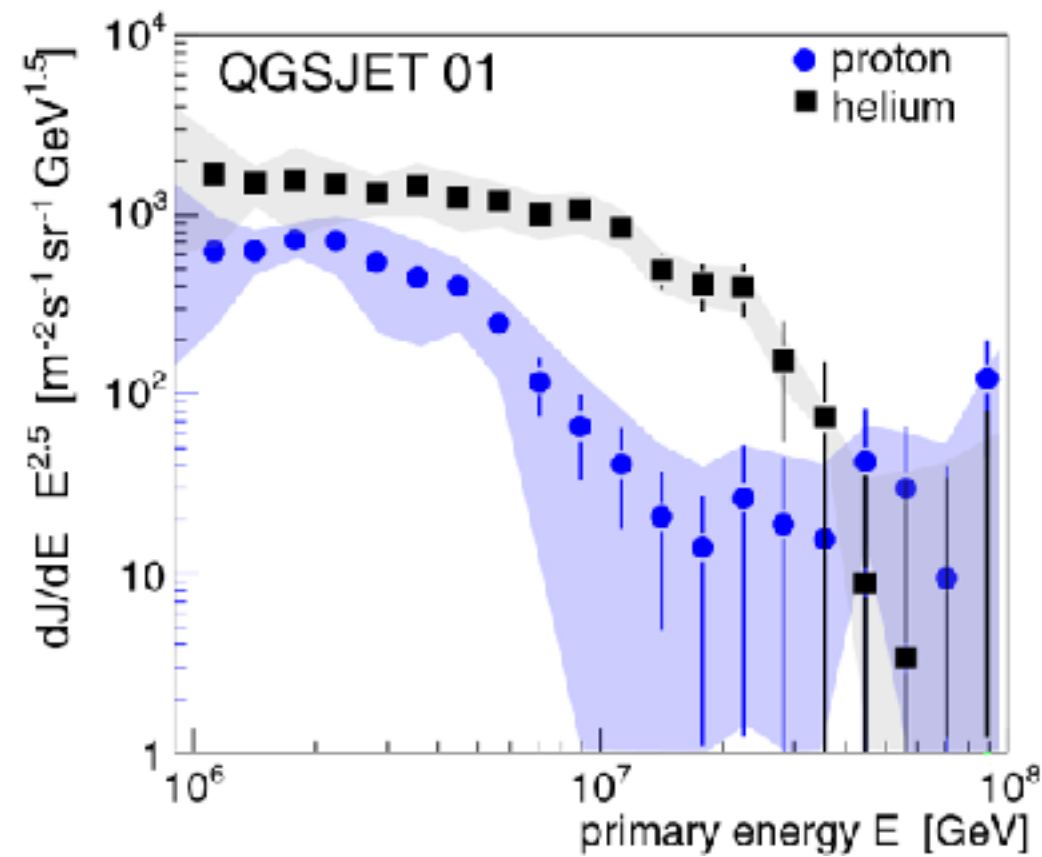
R. Glasstetter et al., Proc. 29th ICRC, Pune 6 (2005) 293

Jörg R. Hörandel, ISCR A Erice 2026 13

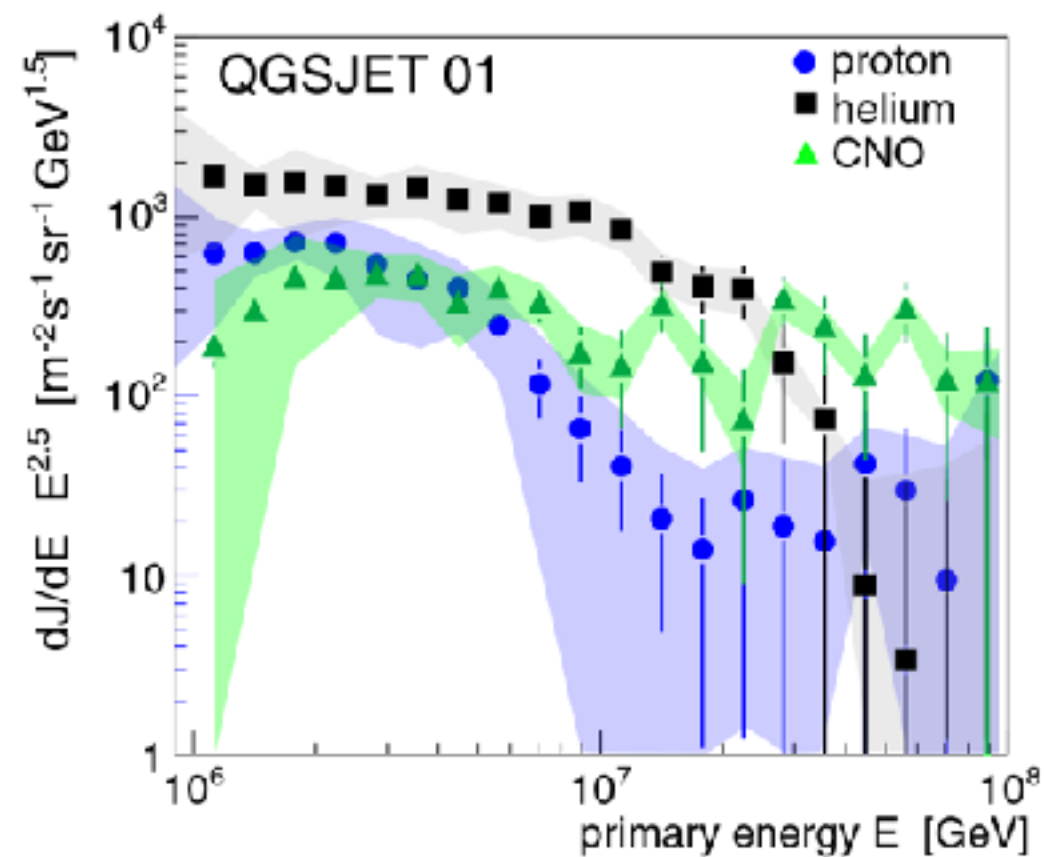
KASCADE: Energy spectra for elemental groups



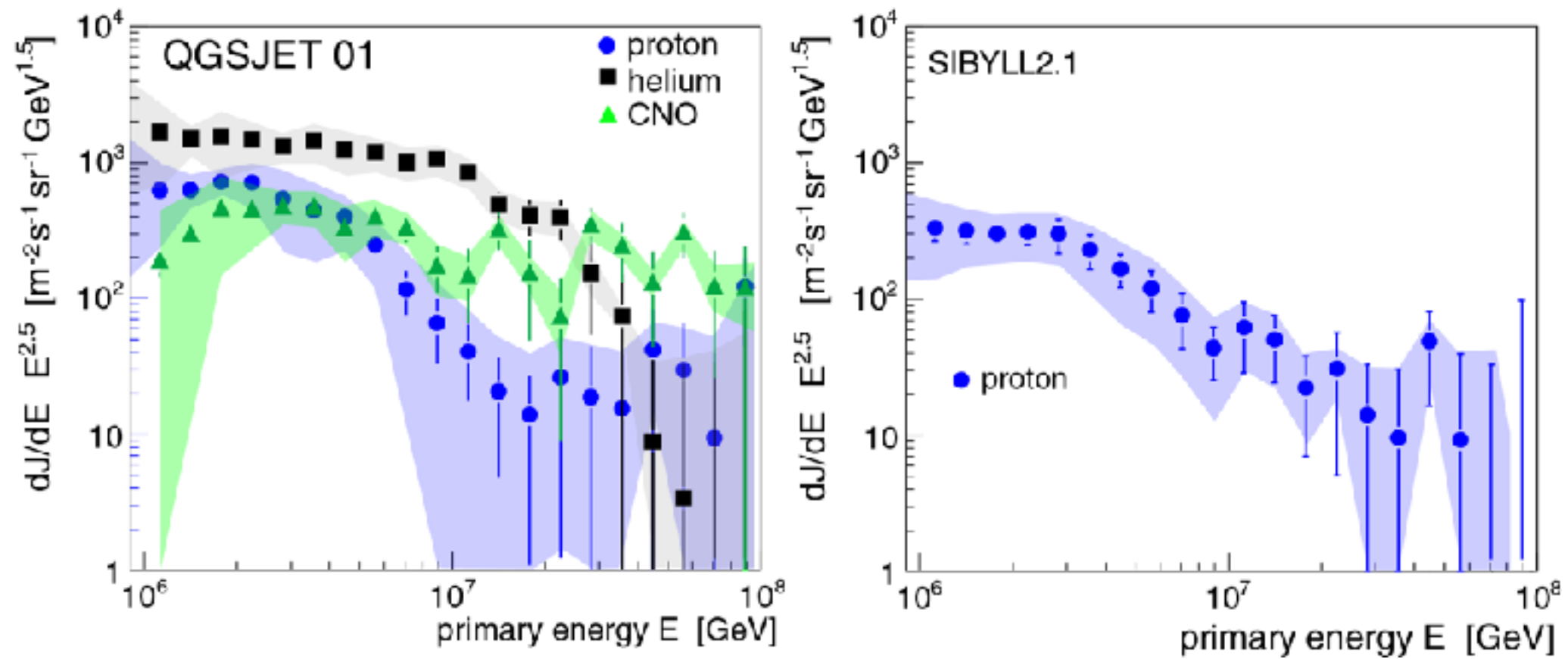
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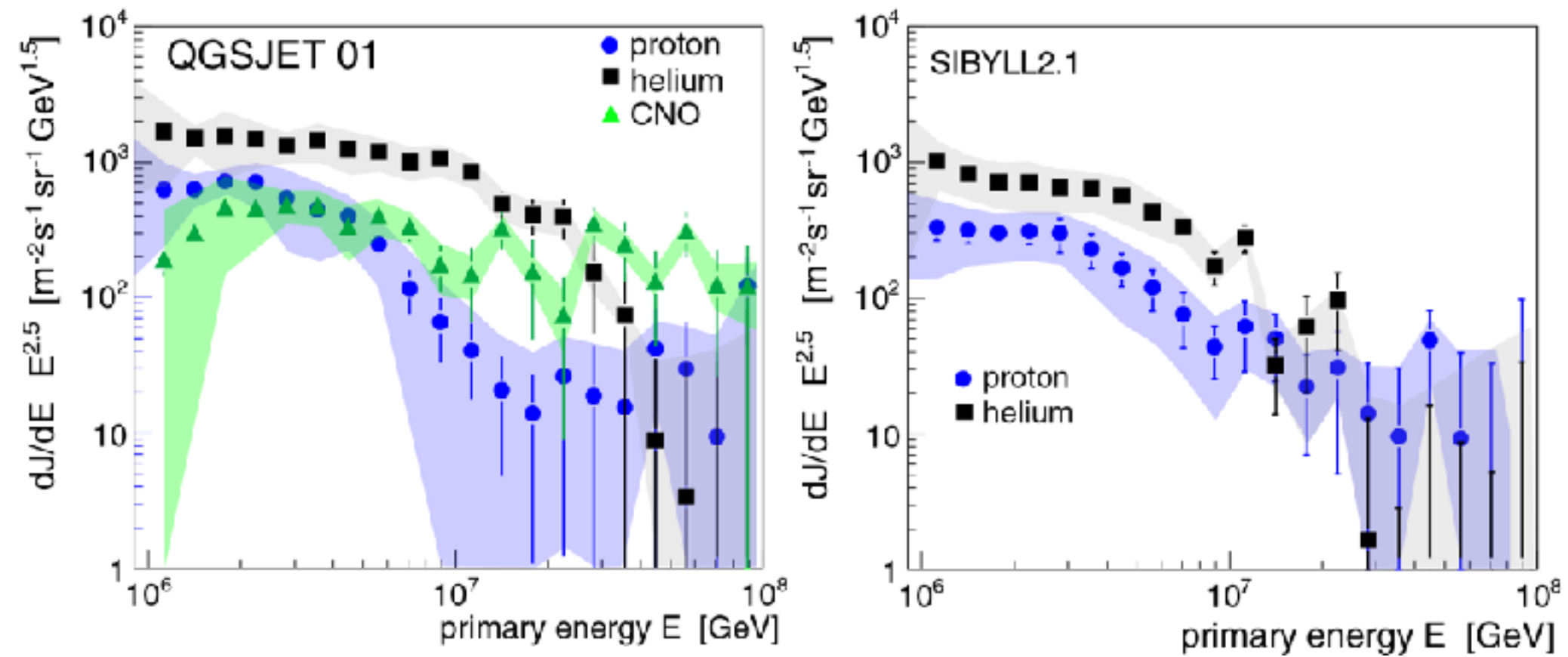
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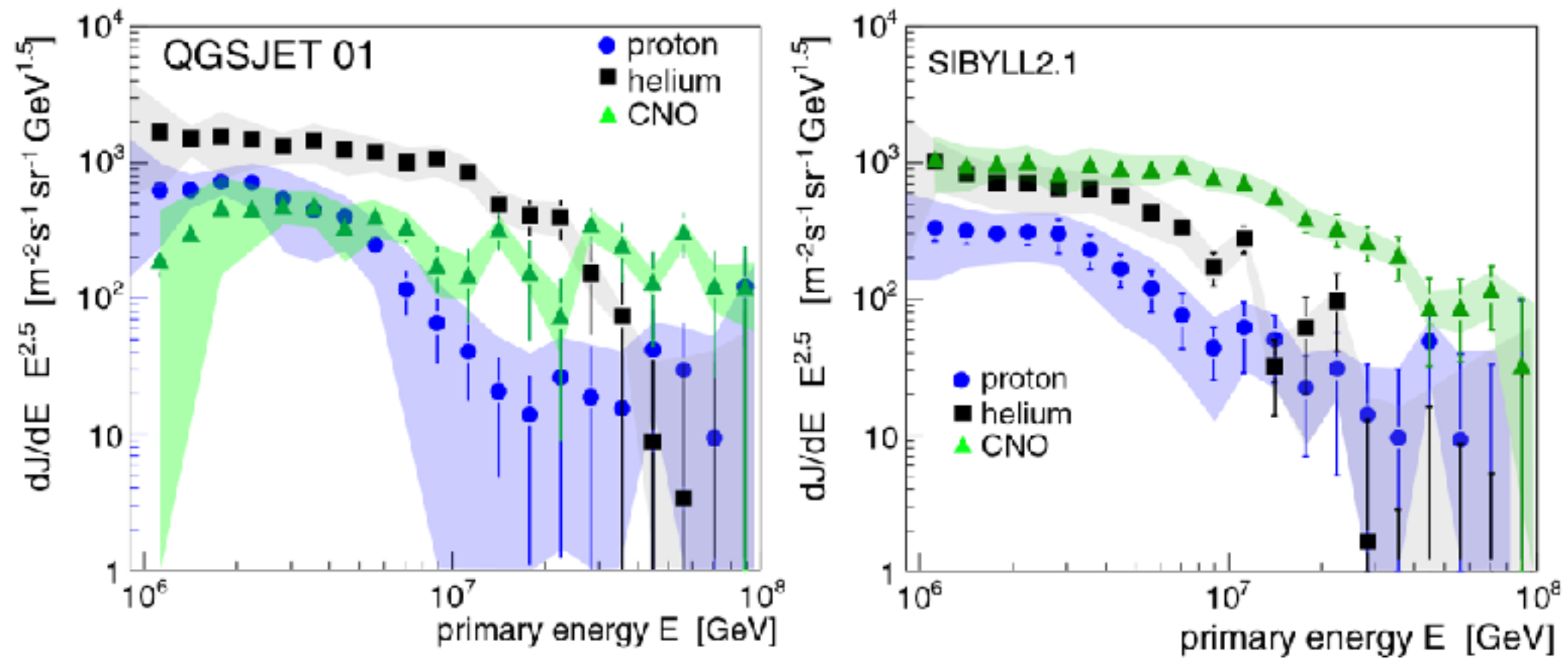
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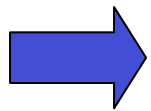
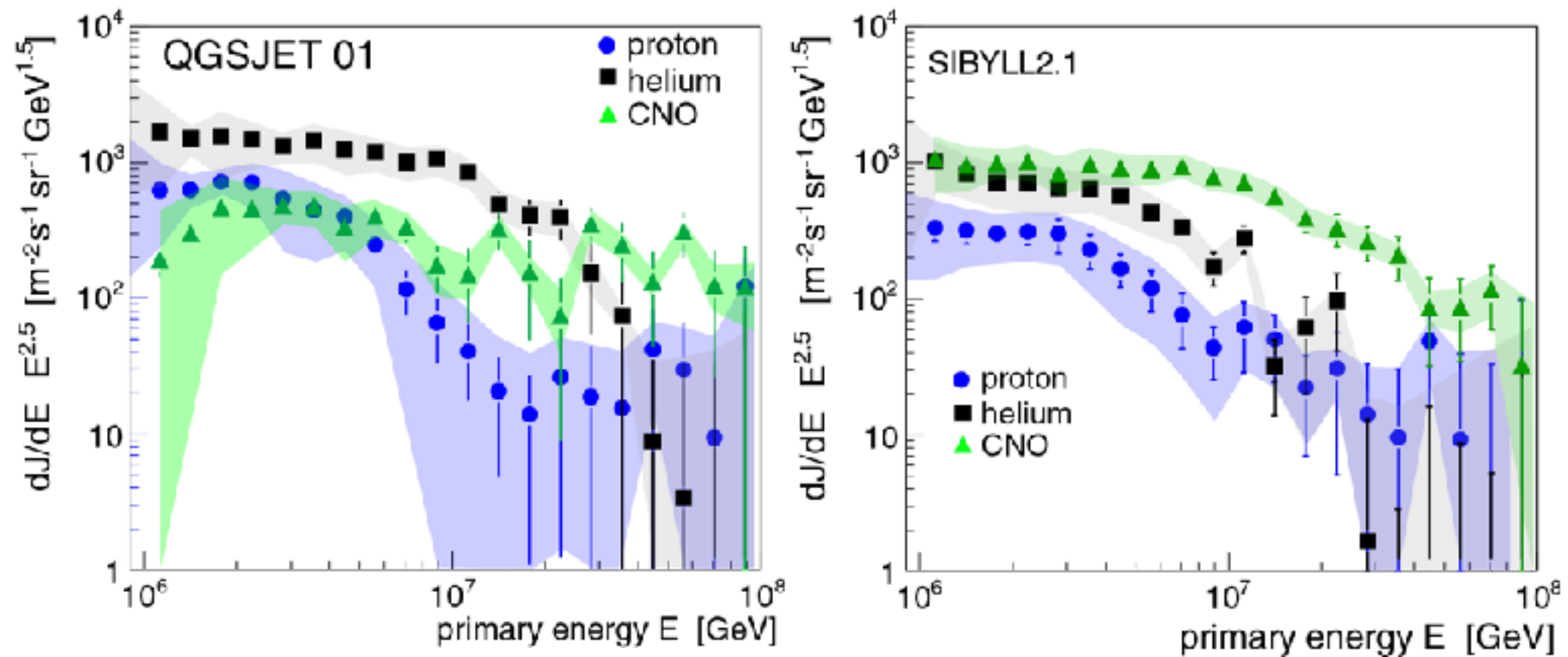
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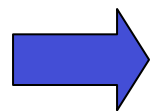
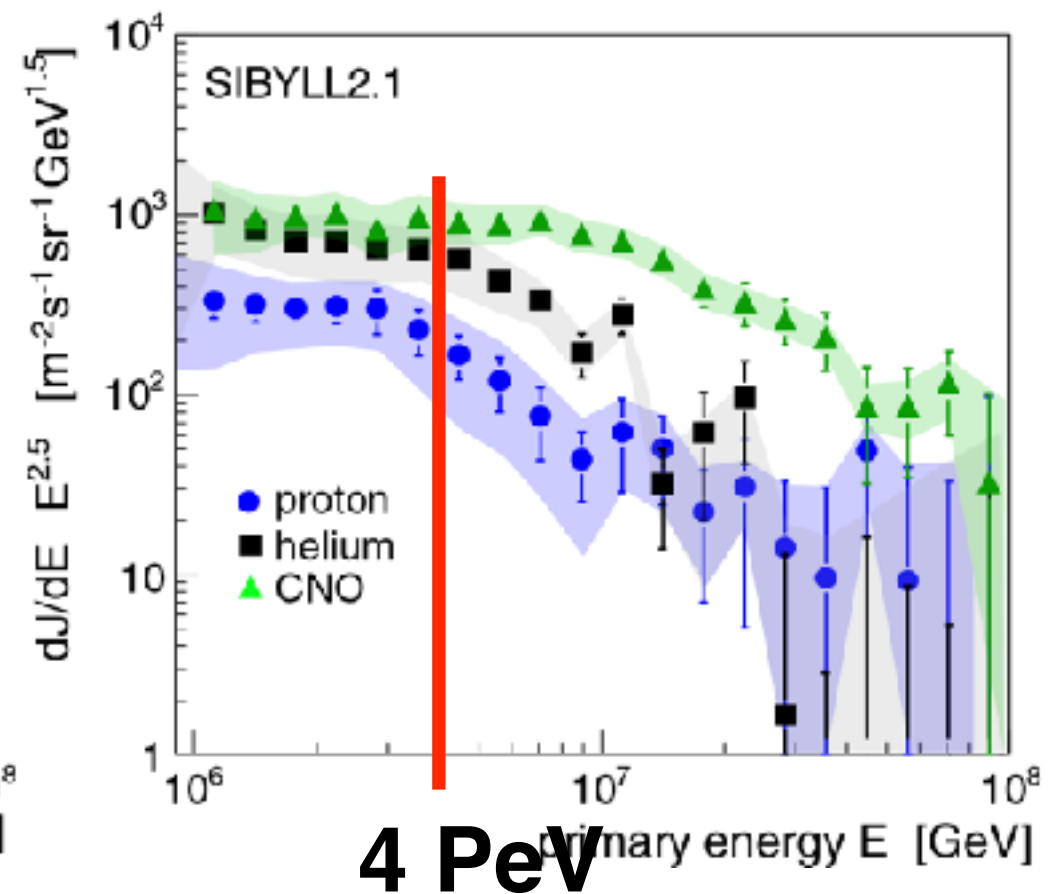
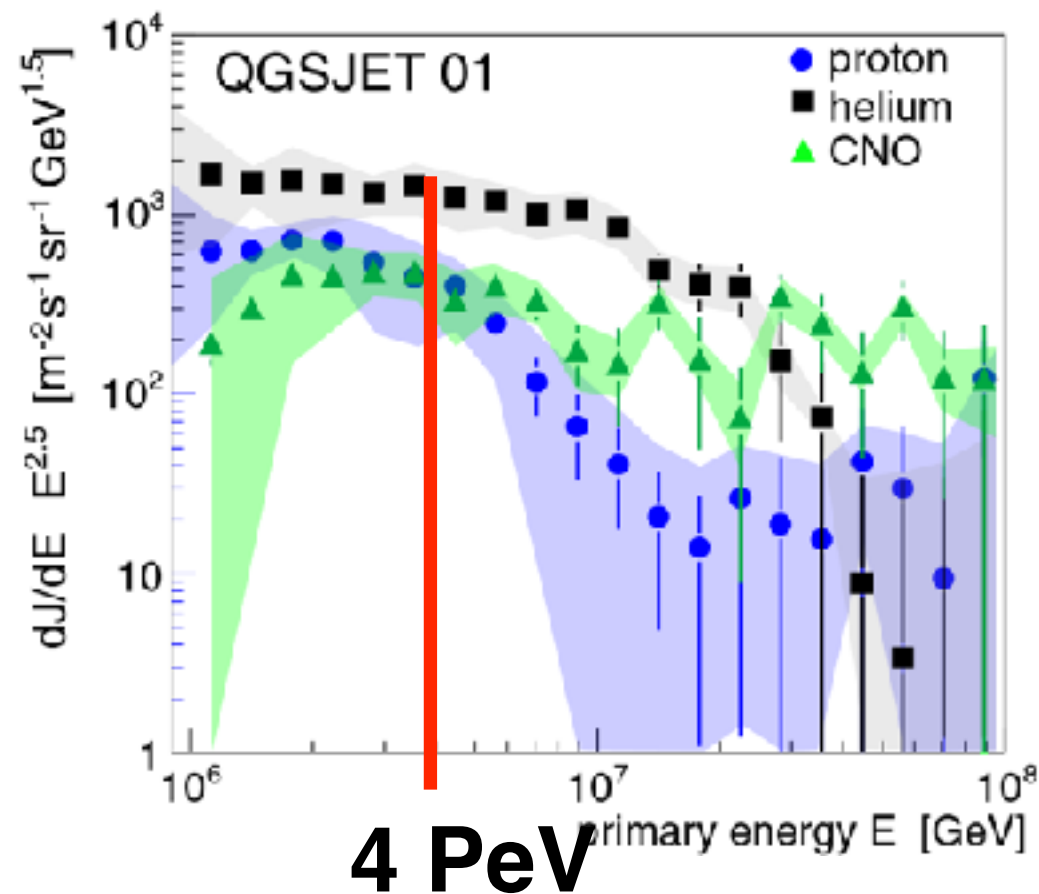
KASCADE: Energy spectra for elemental groups



Knee caused by cut-off for light elements

**Astrophysical interpretation
limited by description of
interactions in the atmosphere**

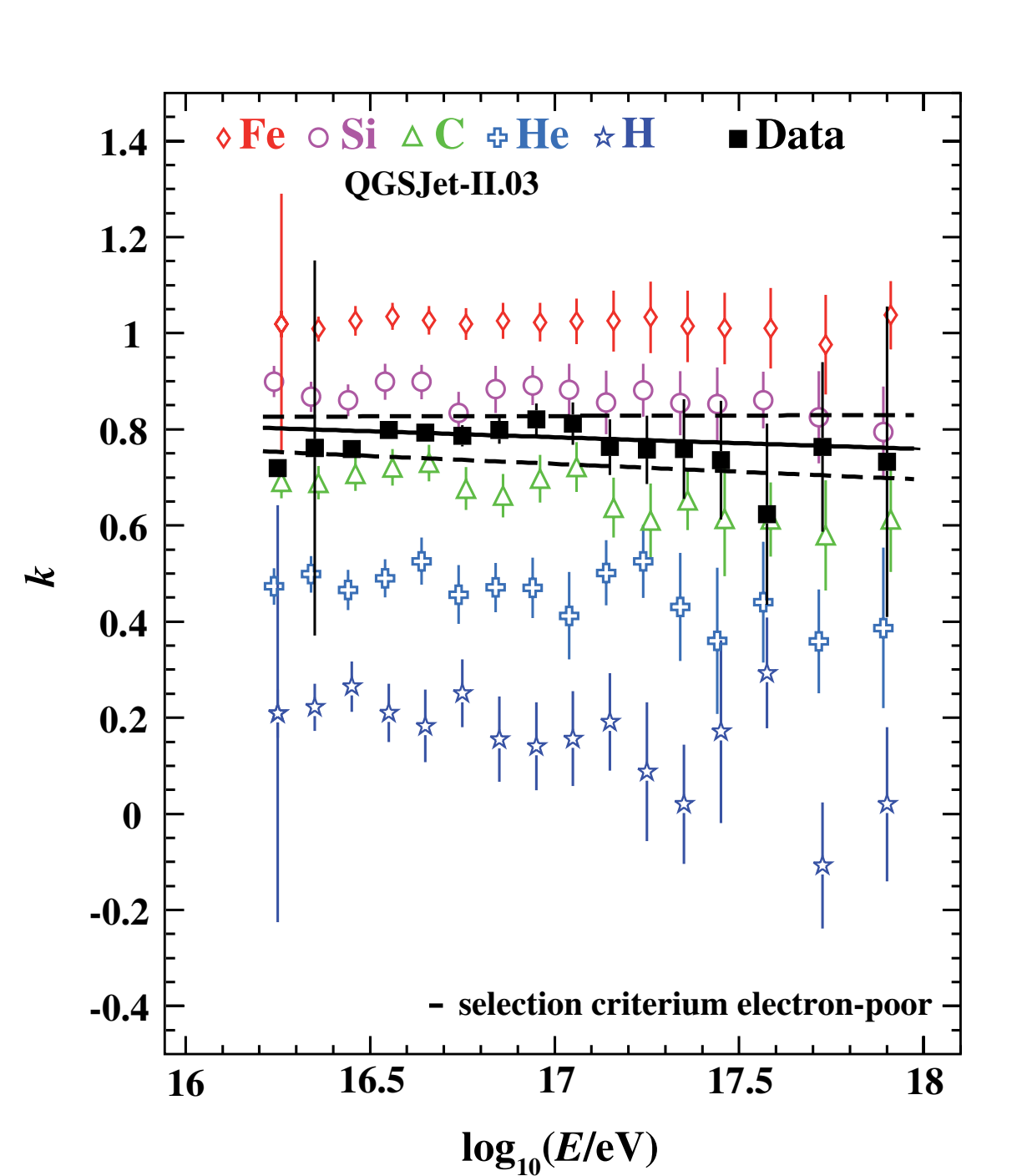
KASCADE: Energy spectra for elemental groups



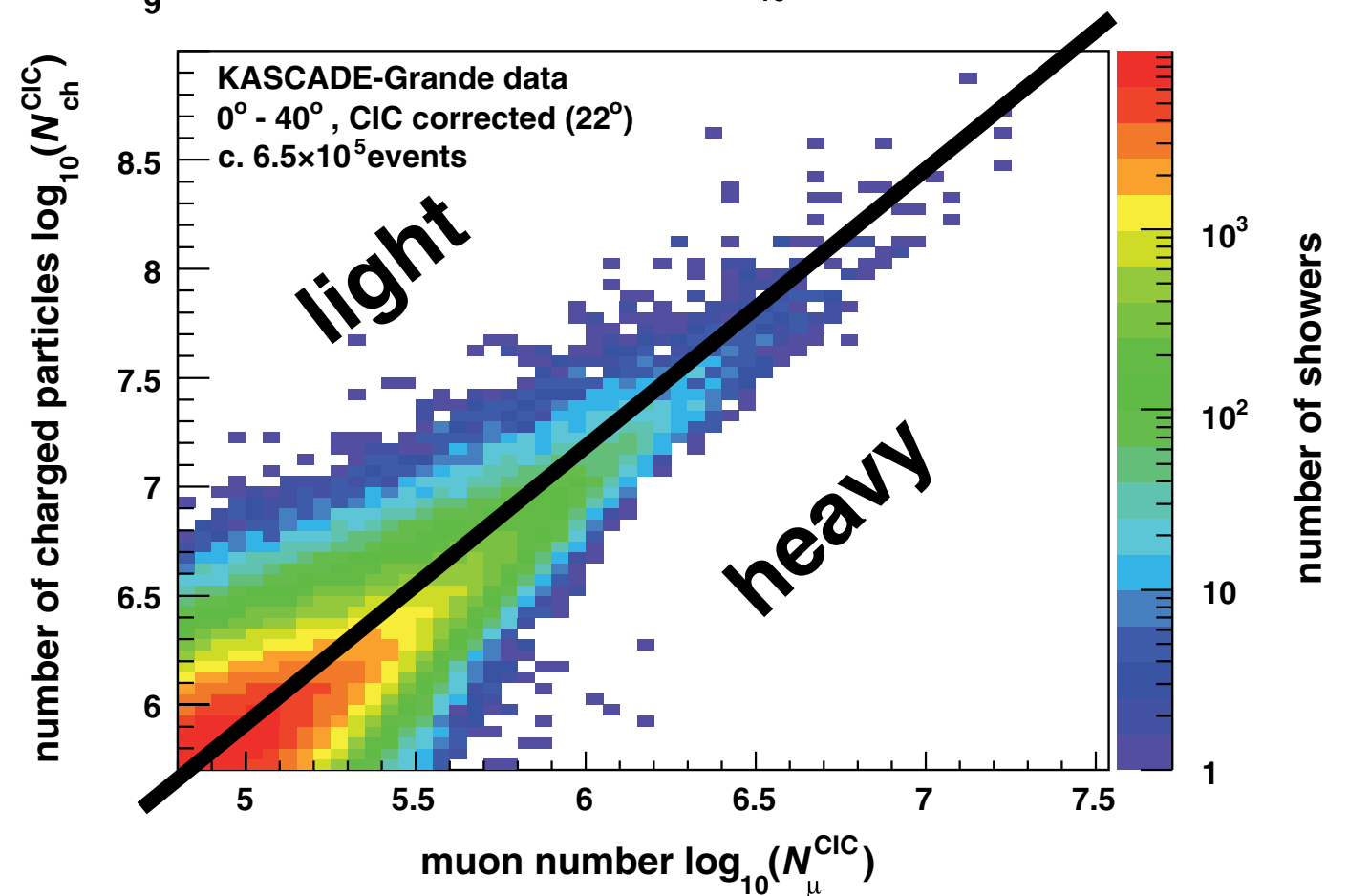
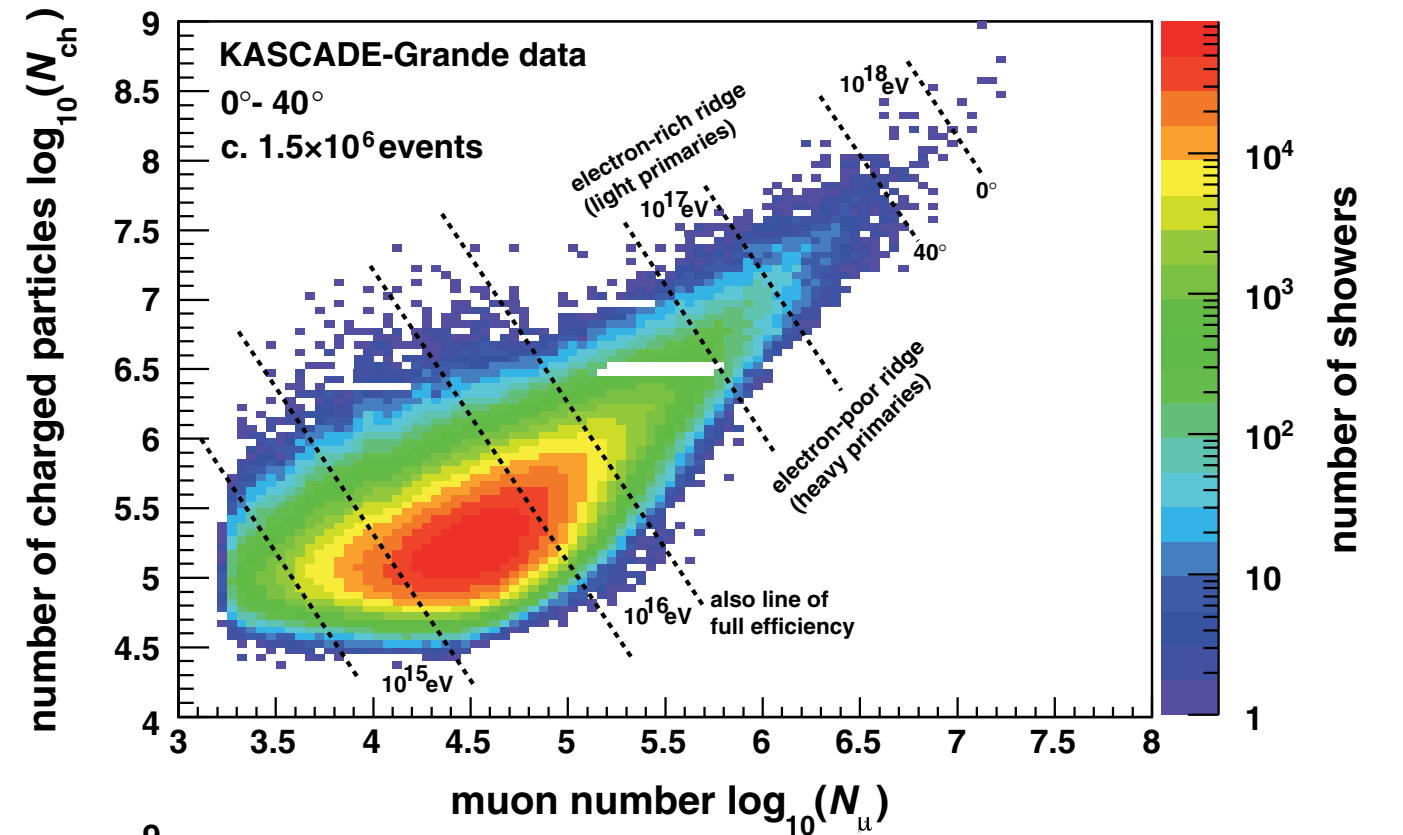
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**Astrophysical interpretation
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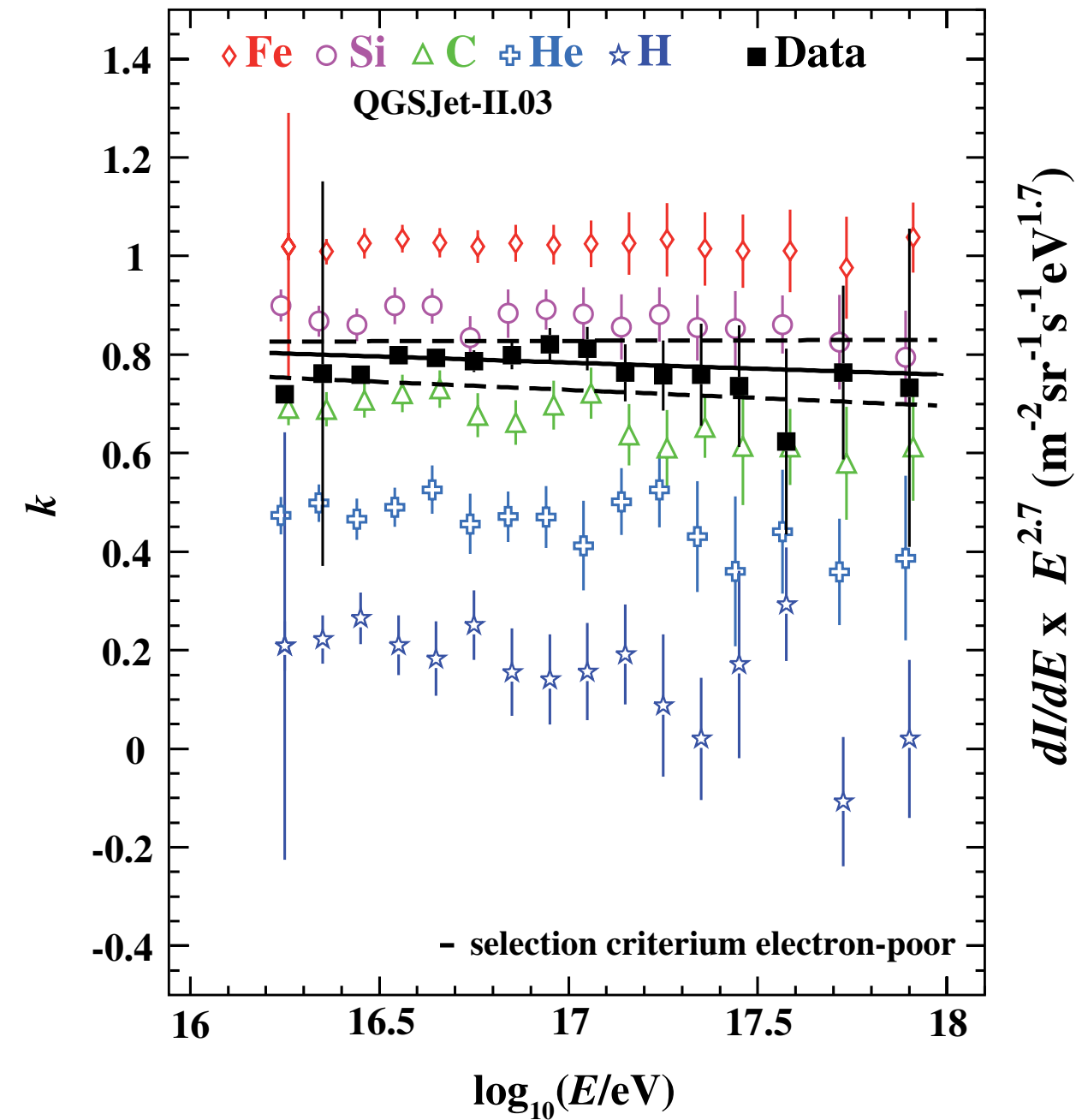
KASCADE-Grande



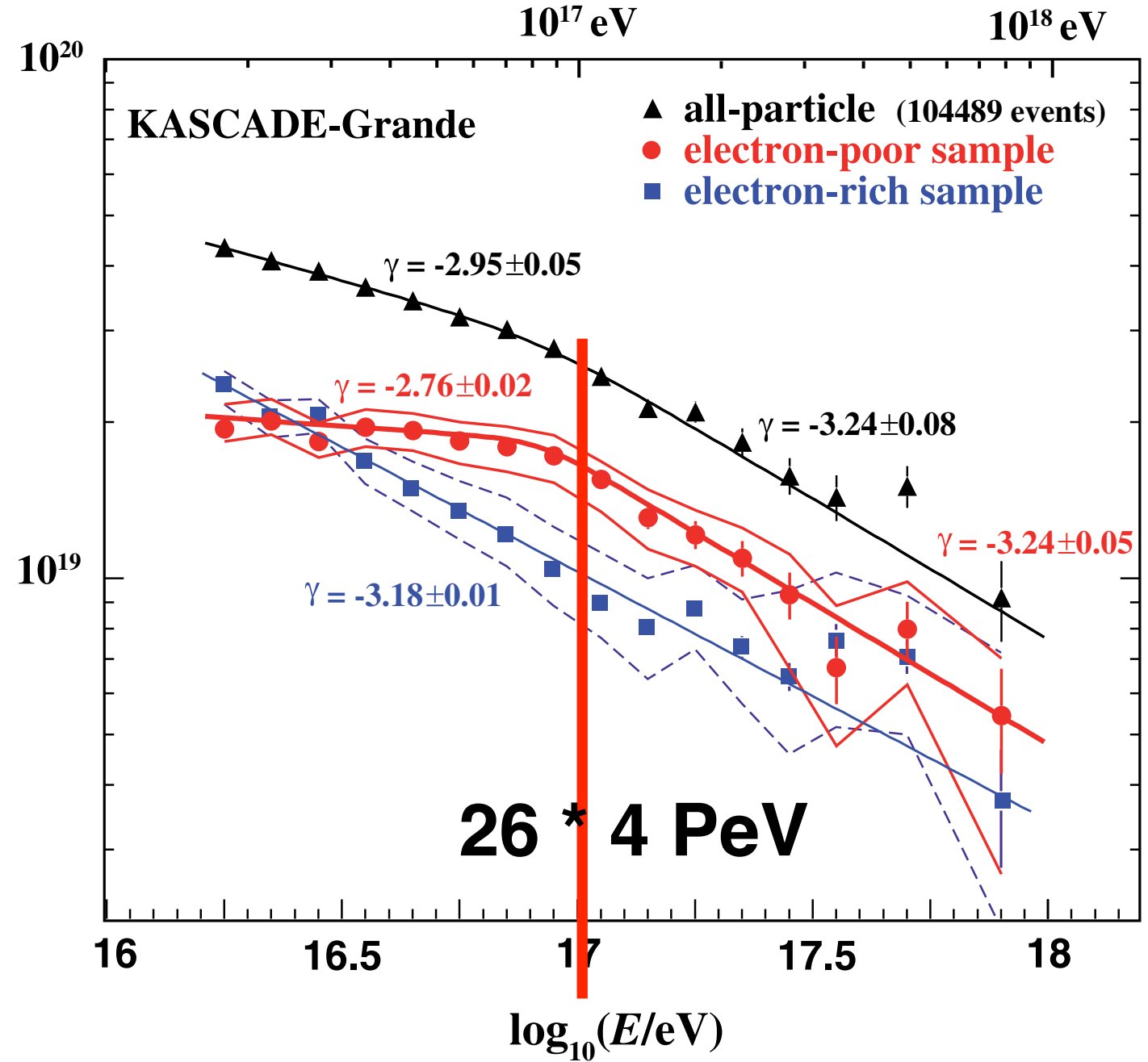
$$k = \frac{\log_{10}(N_{\text{ch}}/N_{\mu}) - \log_{10}(N_{\text{ch}}/N_{\mu})_{\text{H}}}{\log_{10}(N_{\text{ch}}/N_{\mu})_{\text{Fe}} - \log_{10}(N_{\text{ch}}/N_{\mu})_{\text{H}}},$$



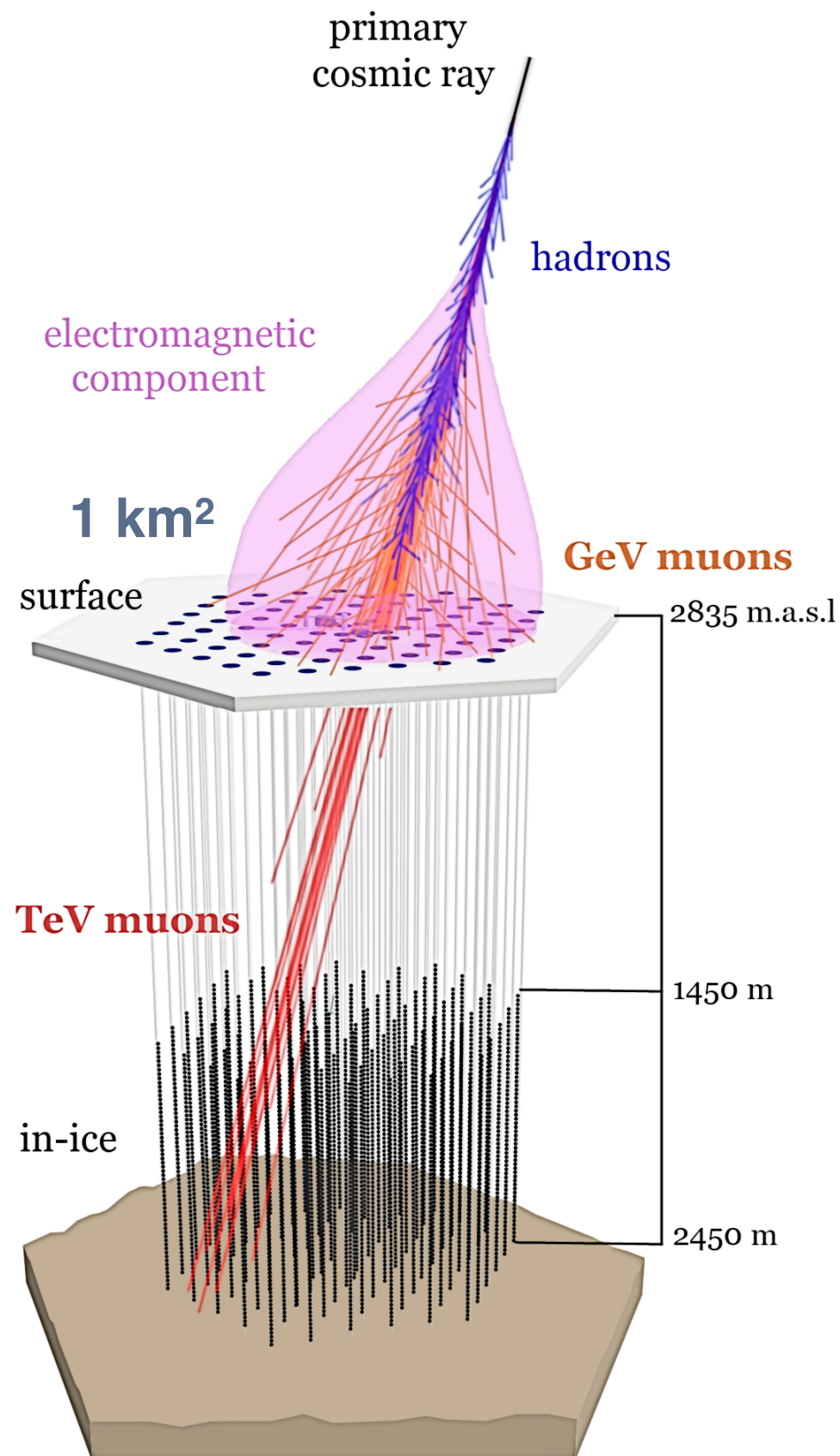
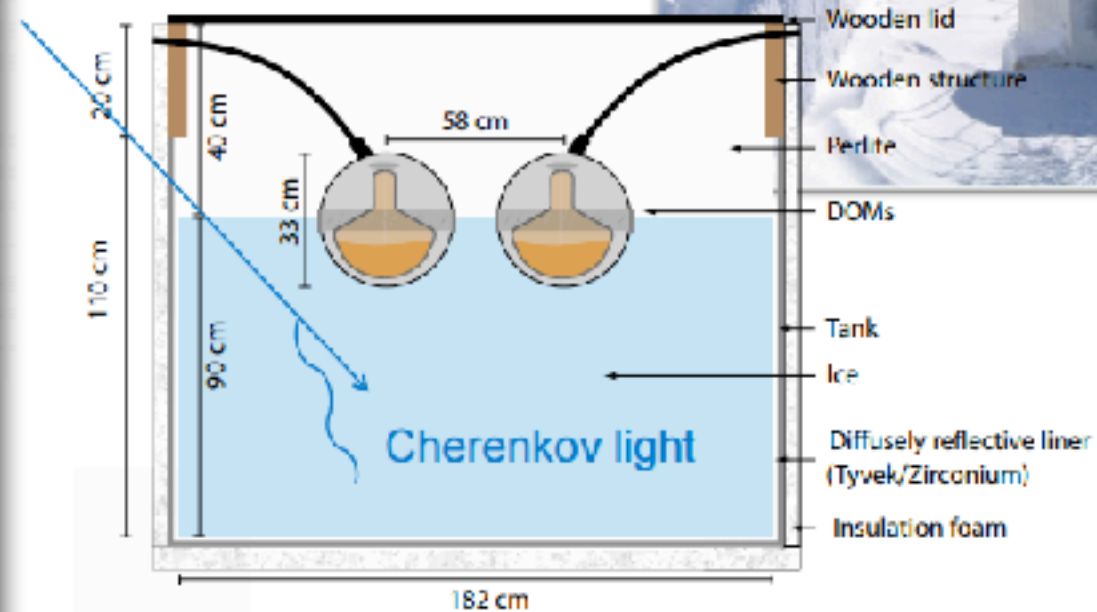
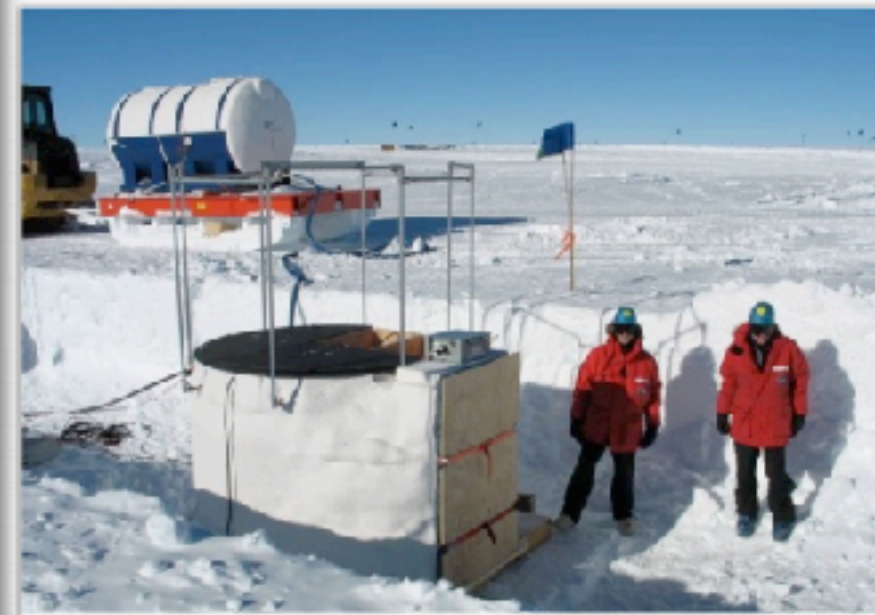
KASCADE-Grande



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Ice Cube - Ice Top



*see also
Halzen*

Cosmic ray spectrum and composition from PeV to EeV using 3 years of data from IceTop and IceCube

Ice Cube - Ice Top

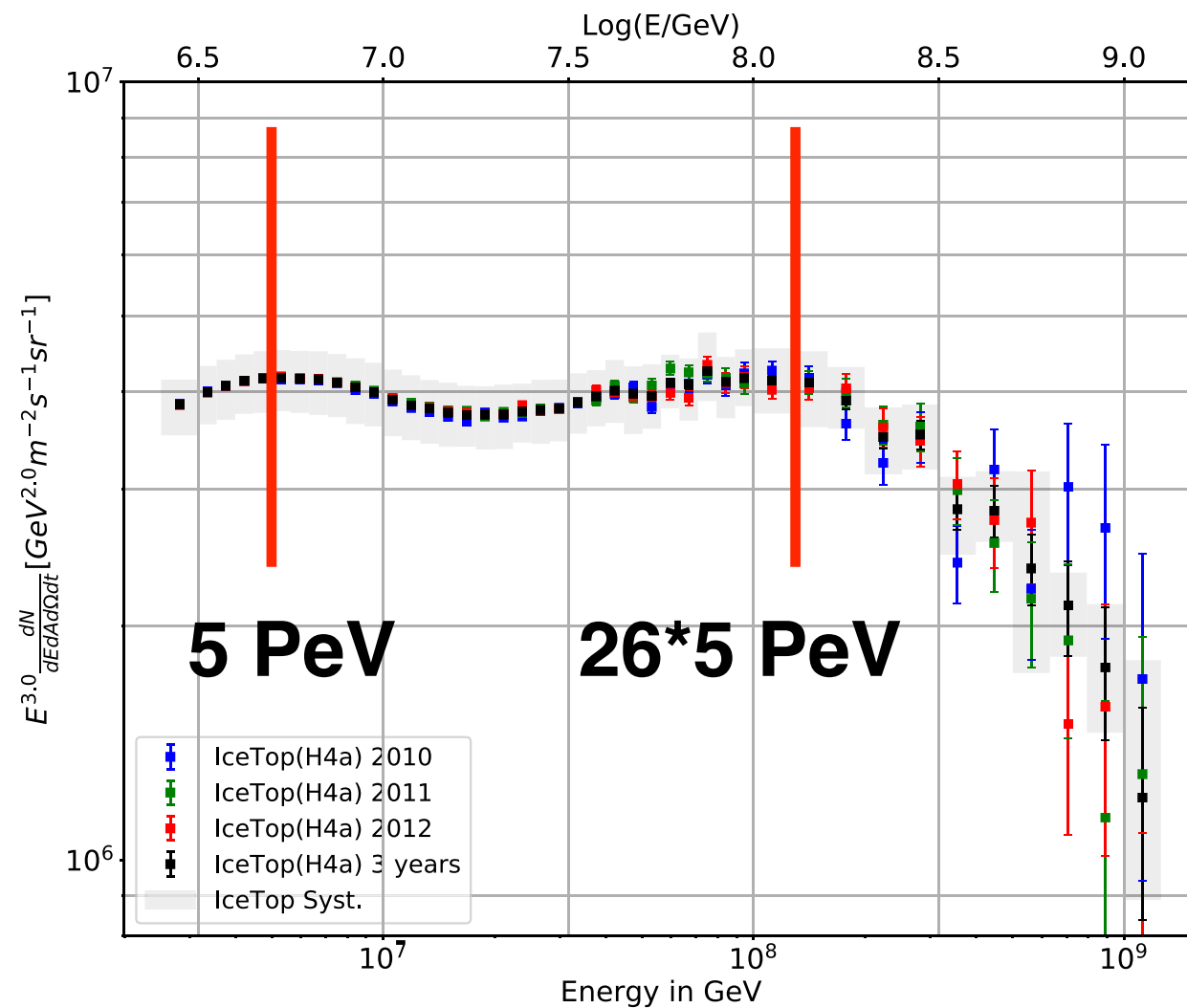


FIG. 9. All-particle energy spectrum from the IceTop-alone analysis from each of the 3 years and the 3 years together.

Ice Top only

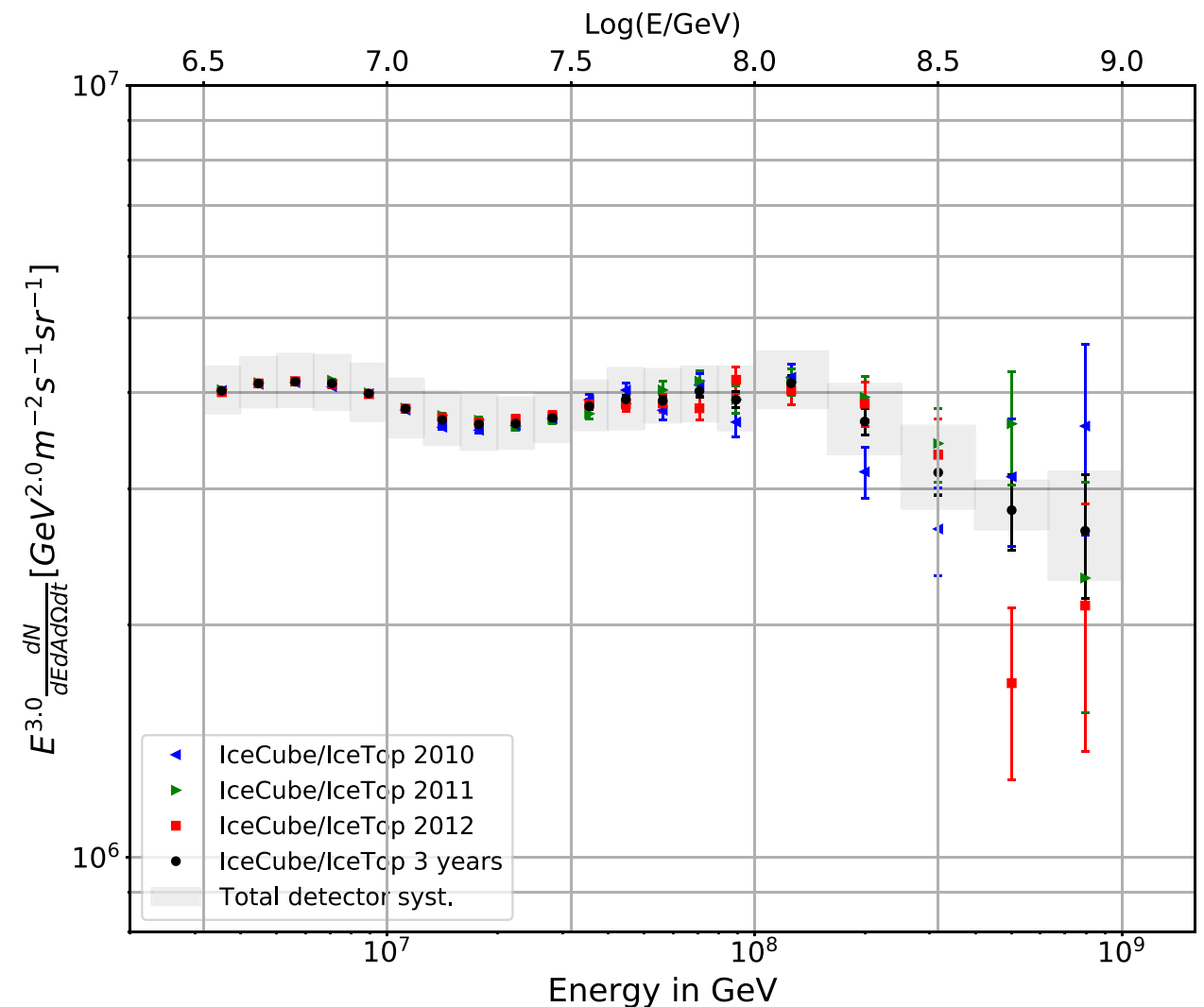
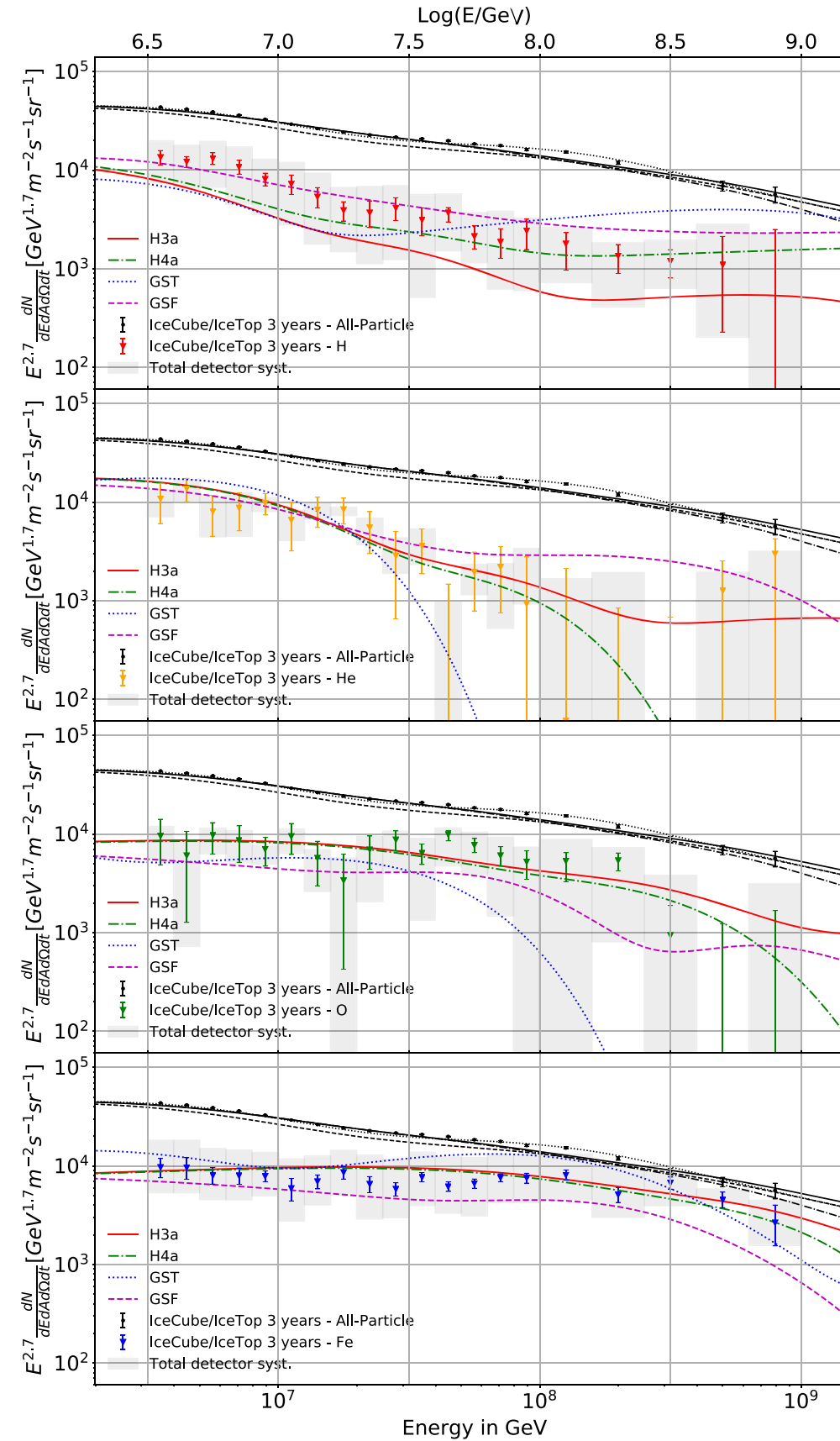
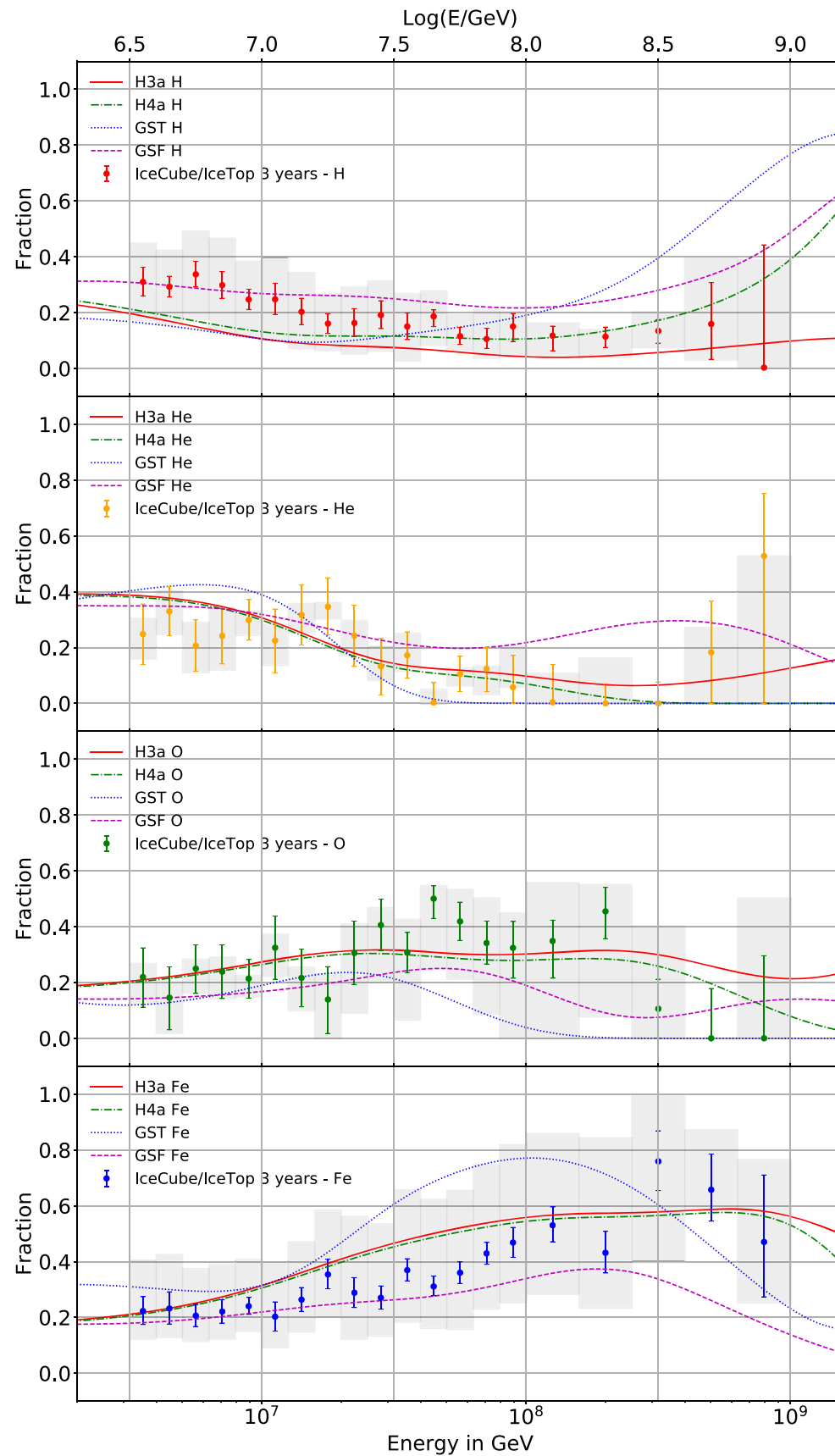


FIG. 12. All-particle energy spectrum from the coincident analysis from each of the 3 years analyzed individually compared to the combined result. The gray band represents the total detector uncertainty from both the IceTop and InIce arrays, as discussed in Sec. IV B.

combined

Cosmic ray spectrum and composition from PeV to EeV using 3 years of data from IceTop and IceCube

Ice Cube - Ice Top



p

He

CNO

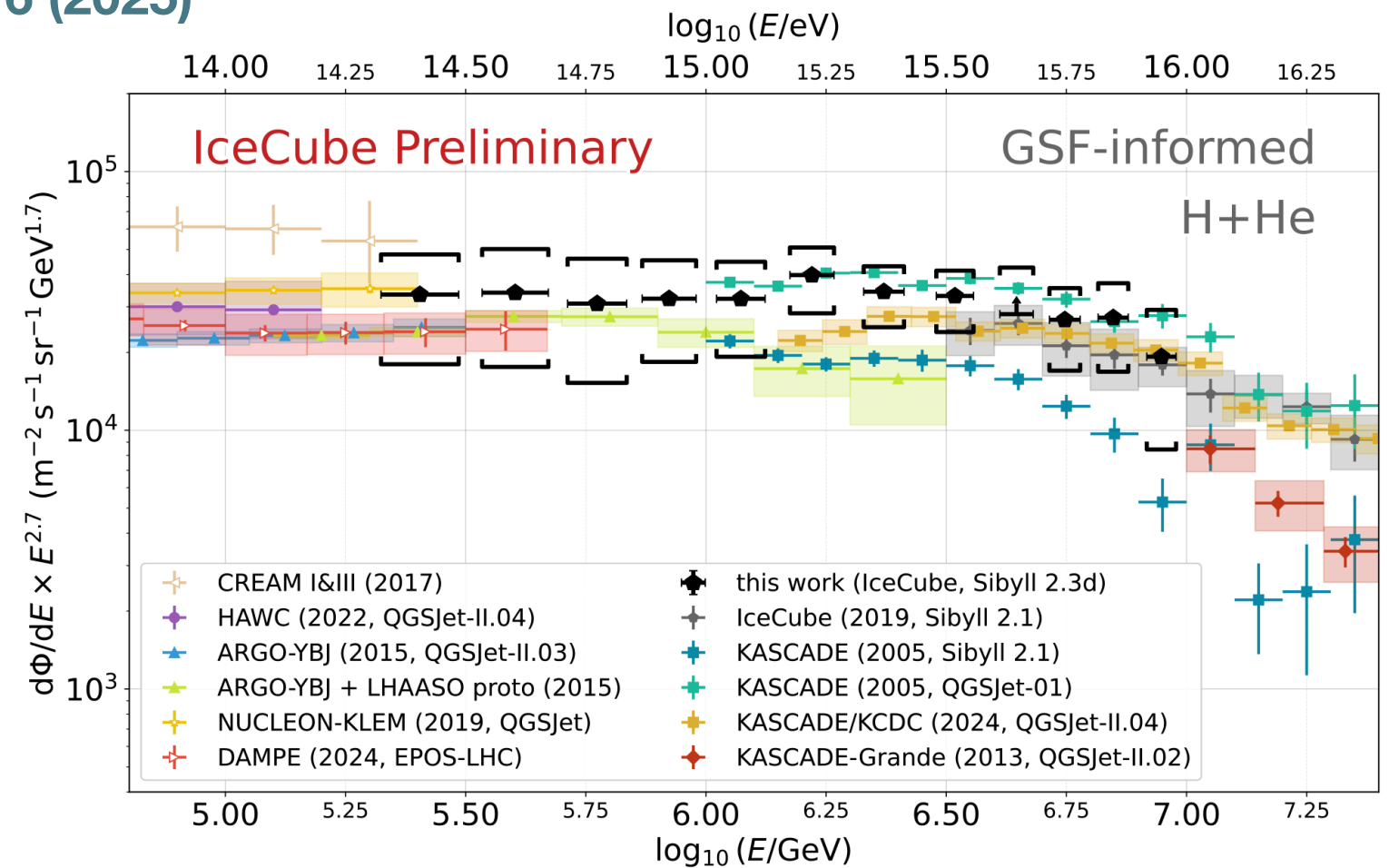
Fe

Outlook: Flux of Light Nuclei

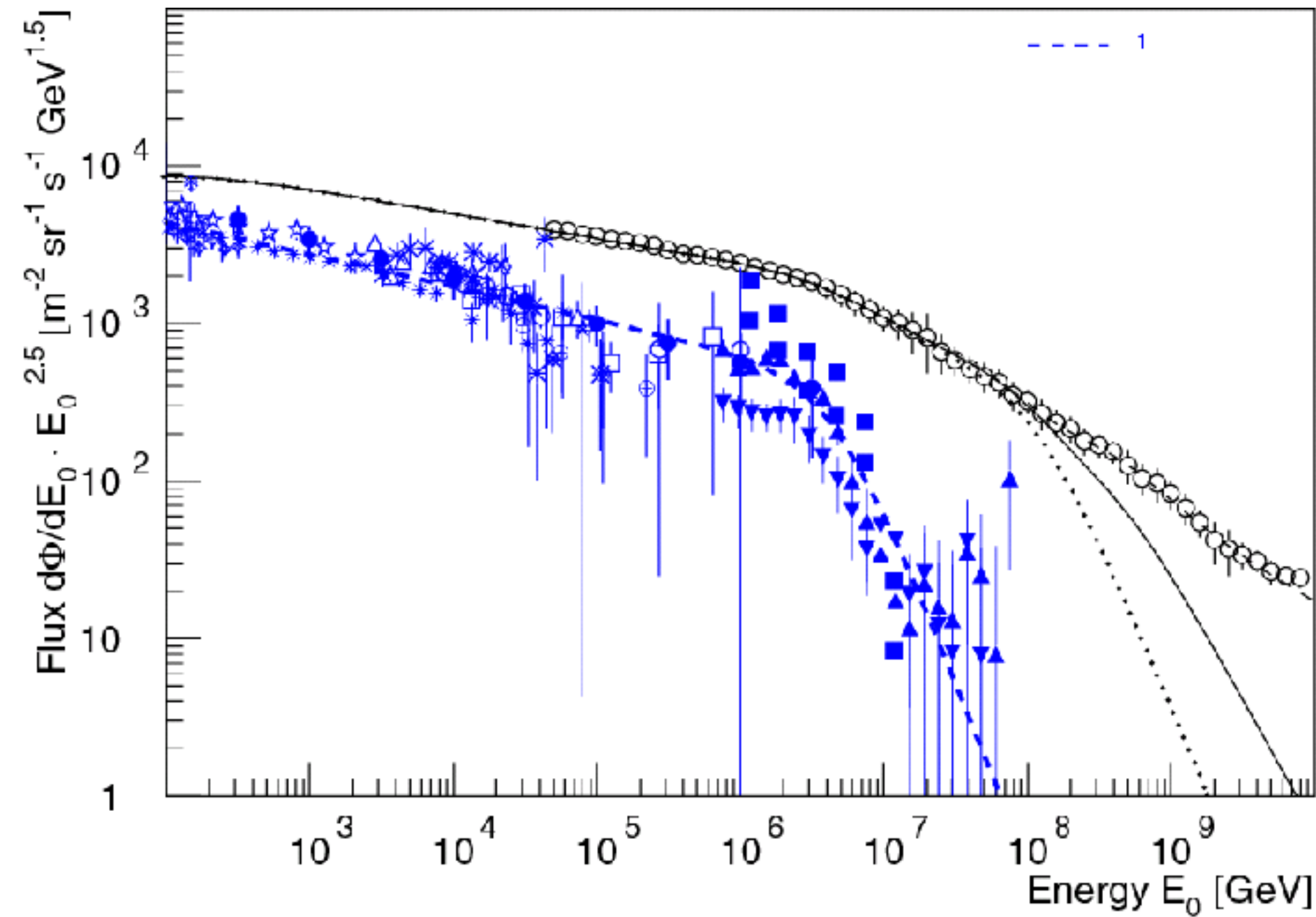


The IceCube Coll., PoS-ICRC2025-376 (2025)

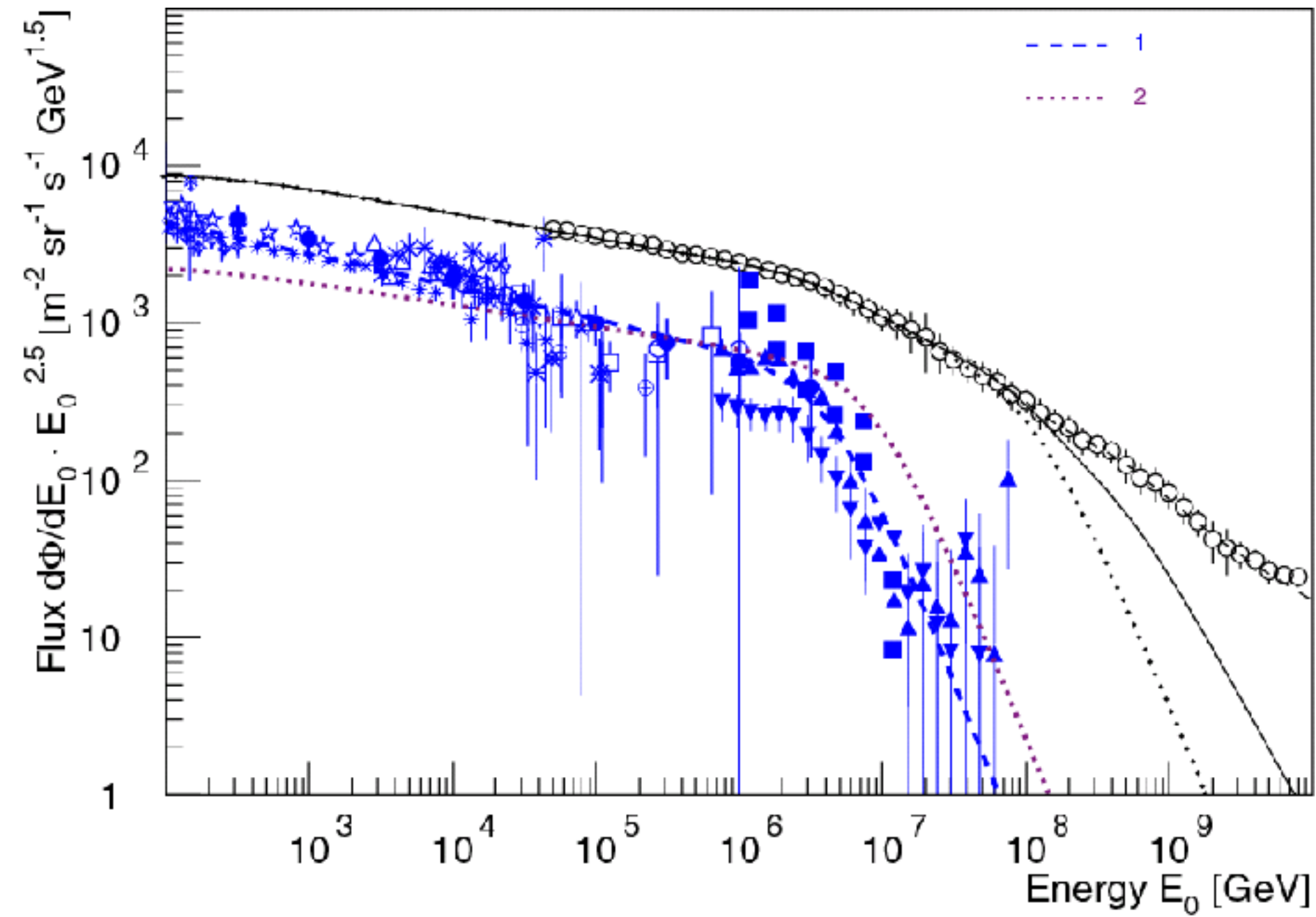
- Proton and Helium flux from 200 TeV to 10 PeV (1 year of data)
- Neural network assigns a "lightness" score
- Uncertainties assume a GSF composition
- Bridging gap between direct and indirect detection



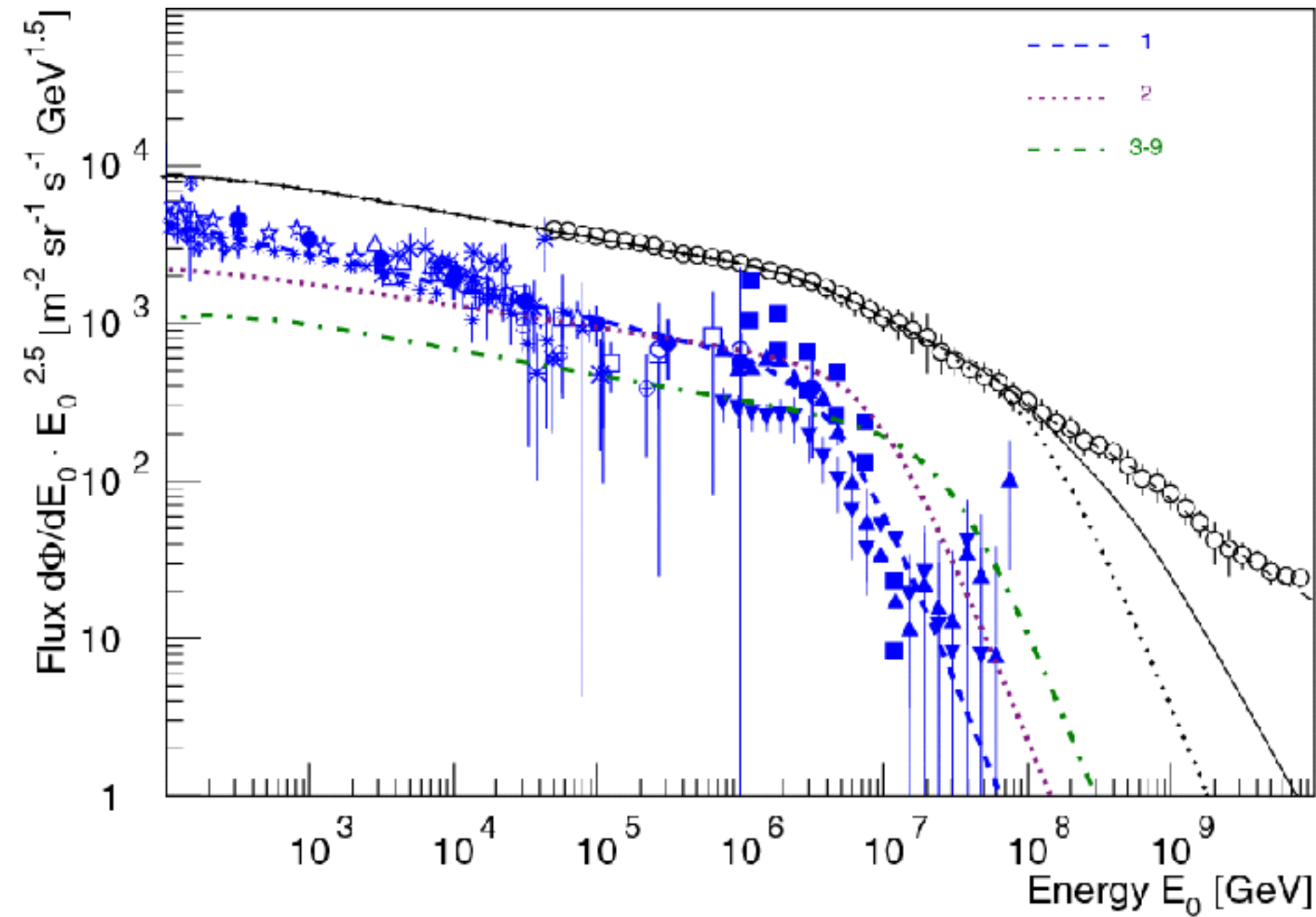
Cosmic-ray energy spectrum



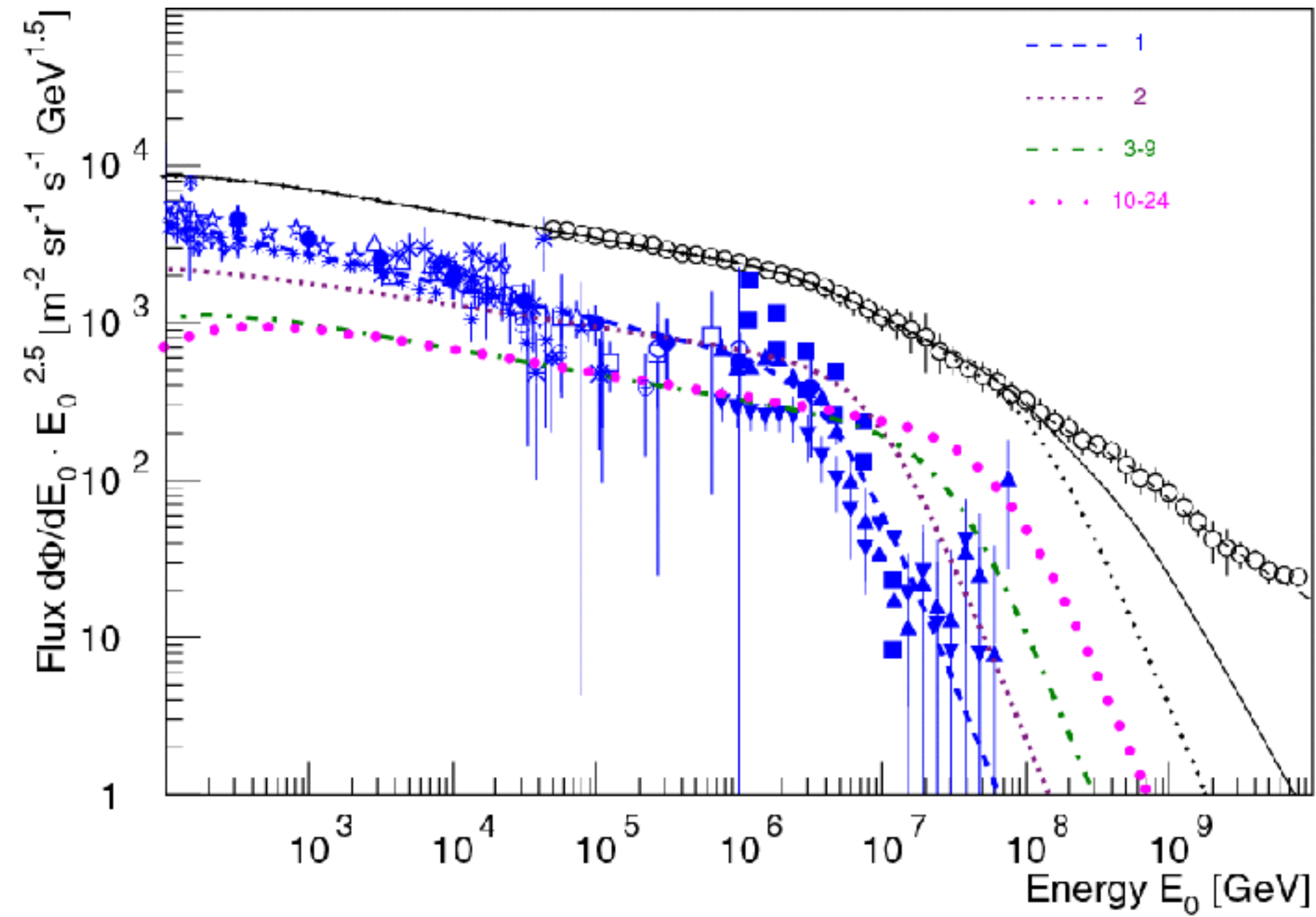
Cosmic-ray energy spectrum



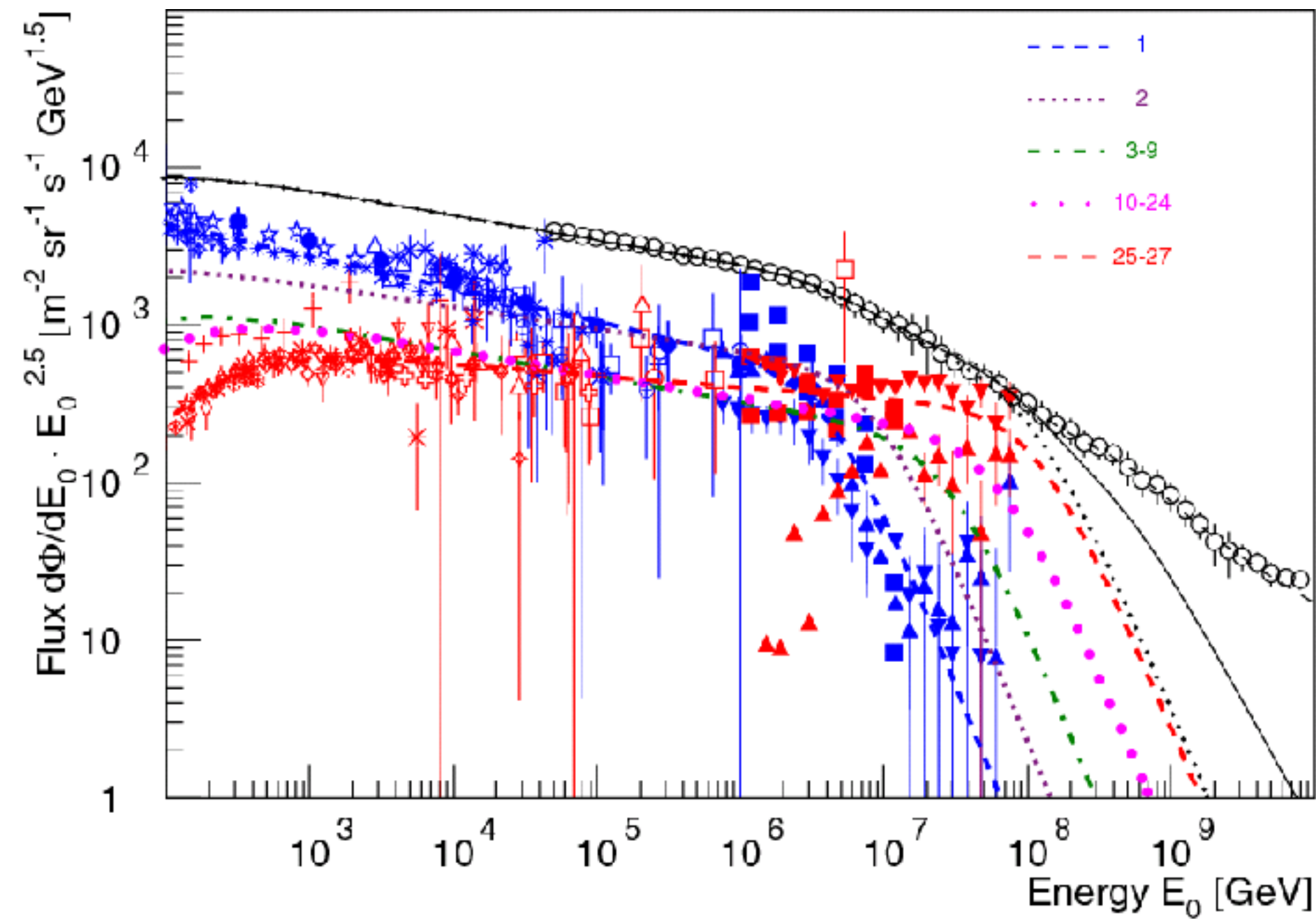
Cosmic-ray energy spectrum



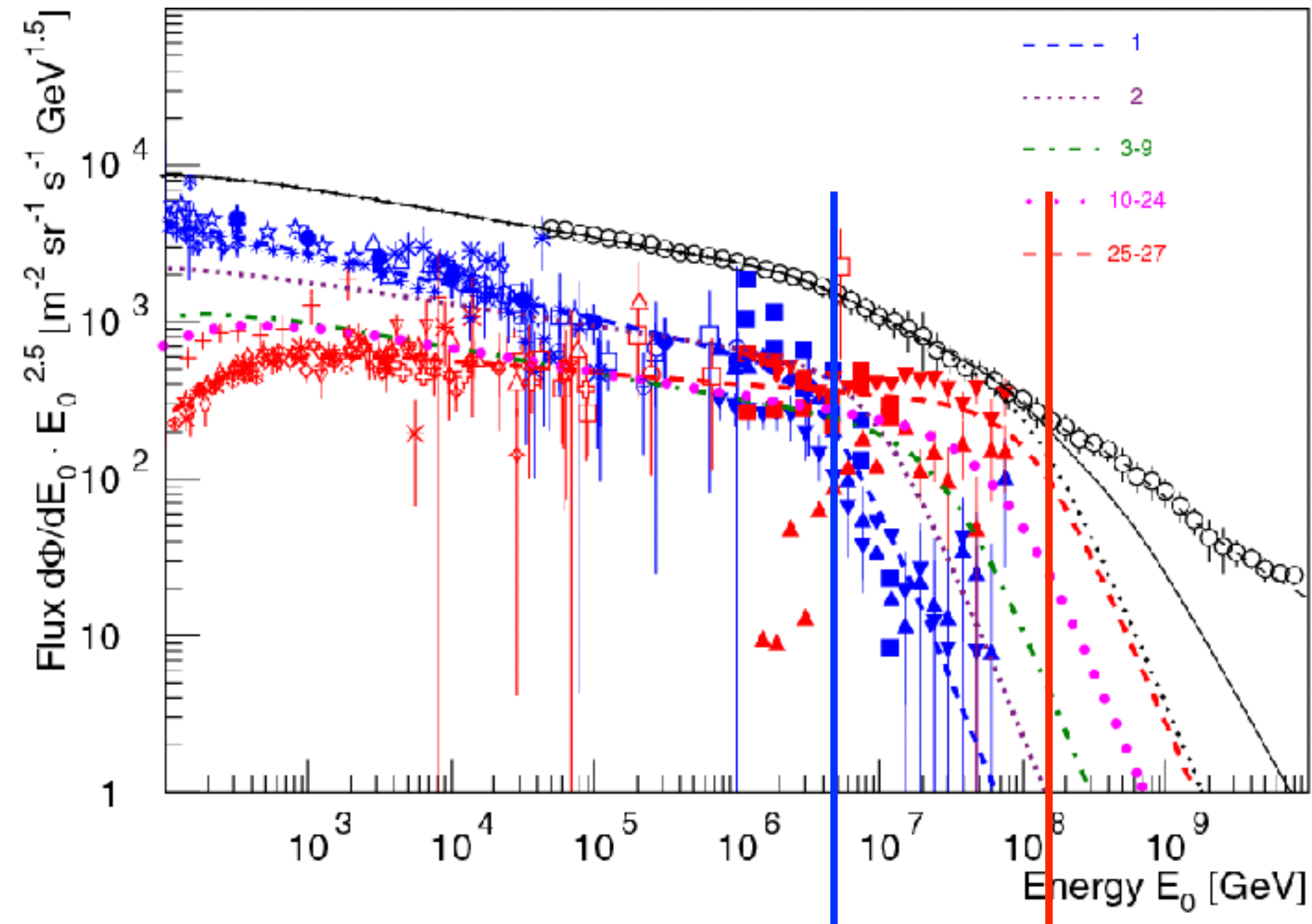
Cosmic-ray energy spectrum



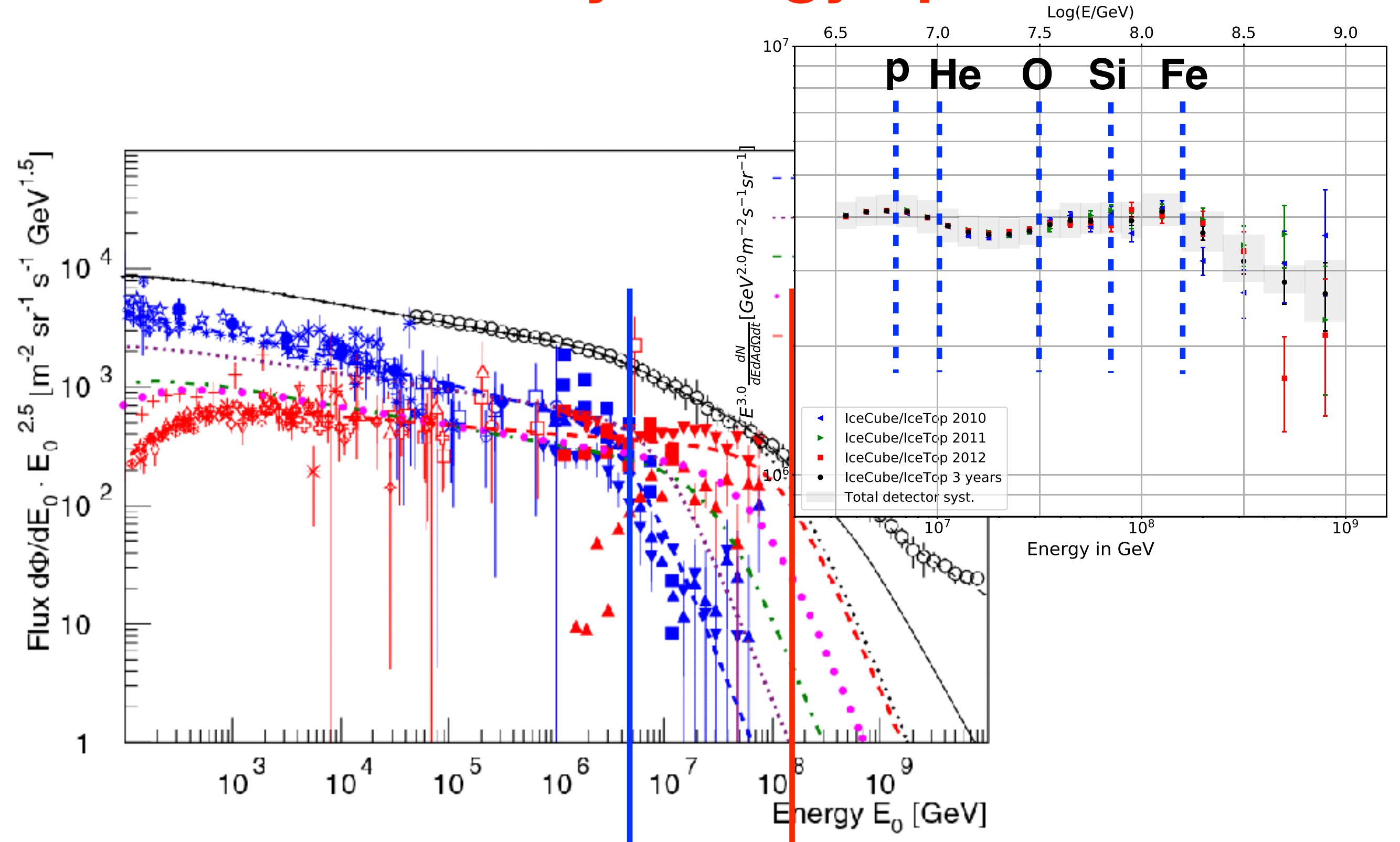
Cosmic-ray energy spectrum



Cosmic-ray energy spectrum



Cosmic-ray energy spectrum



general considerations about accelerators

trajectory of particle in B field

centripetal force = Lorentz force

$$m \frac{v^2}{r} = q \cdot v \cdot B \qquad m \cdot v = p \quad \textbf{momentum}$$

$$\frac{p}{r} = Z \cdot e \cdot B$$

$$r_L = \frac{p}{z \cdot e \cdot B} \quad \textbf{Larmor radius}$$

L dimension of accelerator

$$L > 2 r_L$$

closer look (Hillas 1984): $L > \frac{2r_L}{\beta}$

velocity of scattering centers $\beta = \frac{v}{c}$



$$L > \frac{2 \cdot p}{z \cdot e \cdot B \cdot \beta}$$

$$B \cdot L > \frac{2 \cdot p}{z \cdot e \cdot \beta}$$

Hillas criterion

in astrophysical units

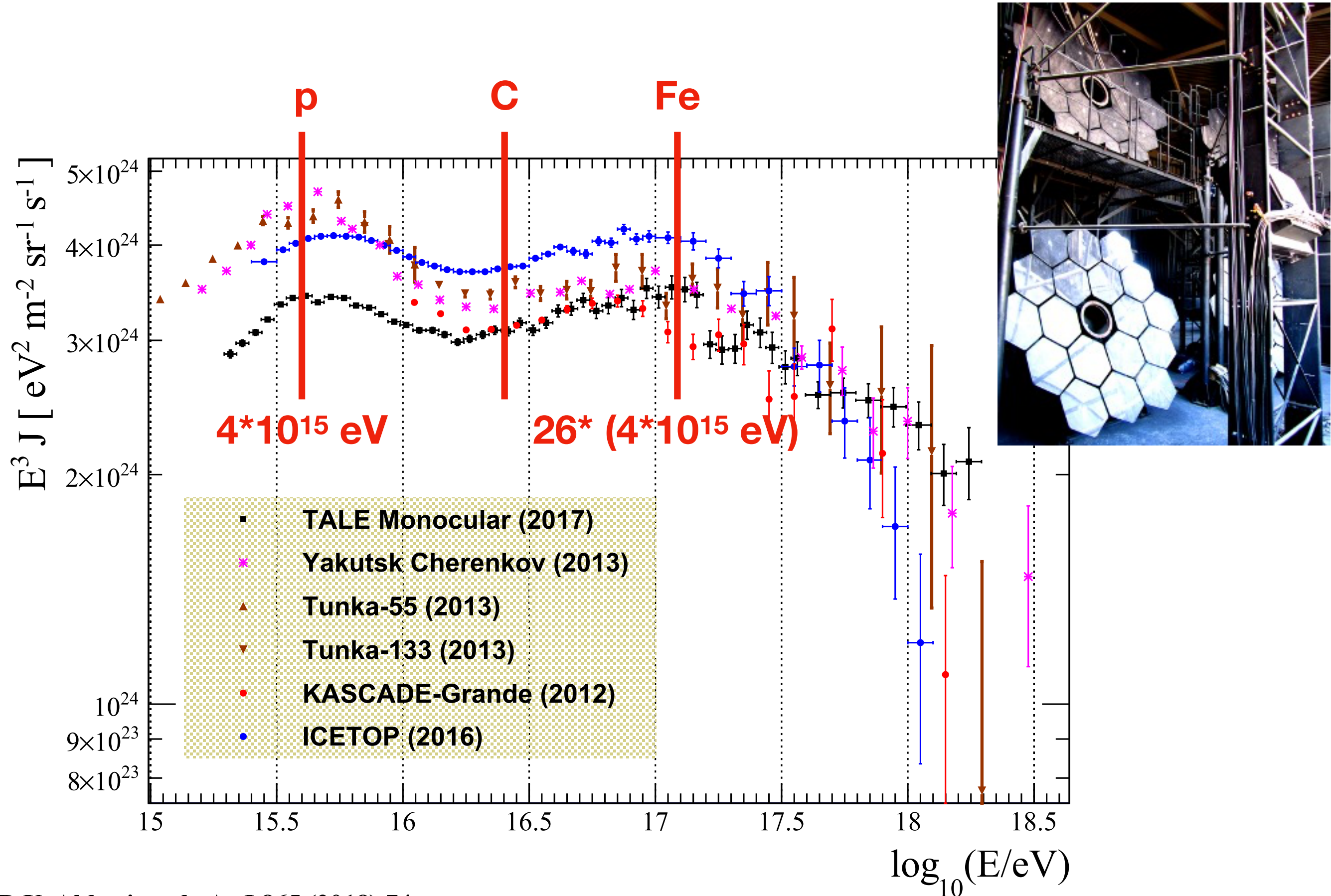
$$r_L = 1.08 \text{ pc} \frac{E_{15}}{Z \cdot B_{\mu G}}$$

$$B_{\mu G} \cdot L_{pc} > \frac{2 \cdot E_{15}}{Z \cdot \beta}$$

**necessary condition
not sufficient**

$$E_{15} < Z \cdot B_{\mu G} \cdot L_{pc} \cdot \frac{\beta}{2}$$

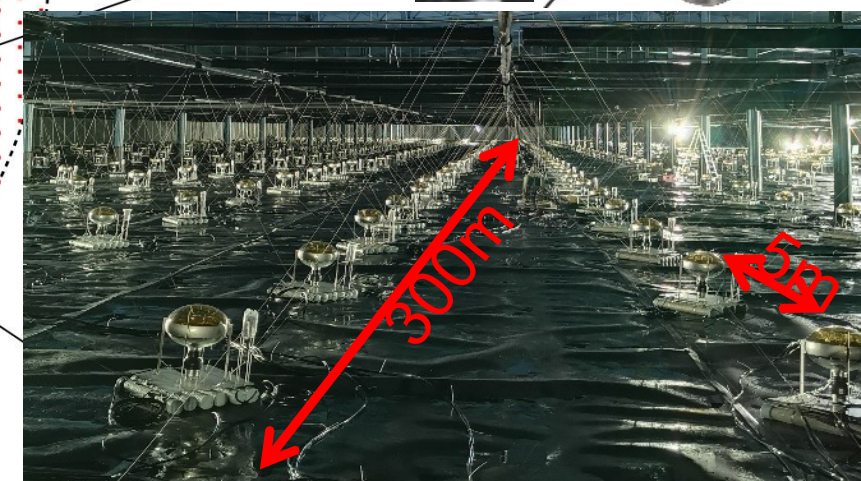
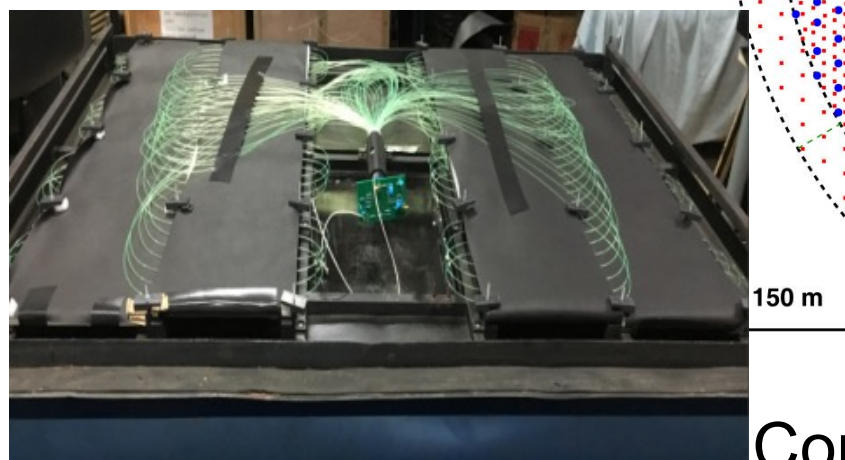
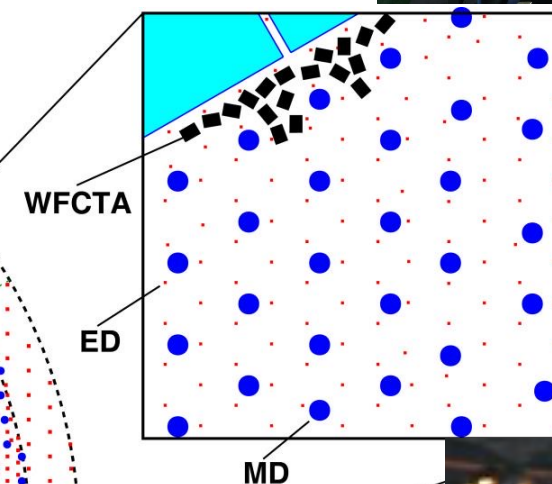
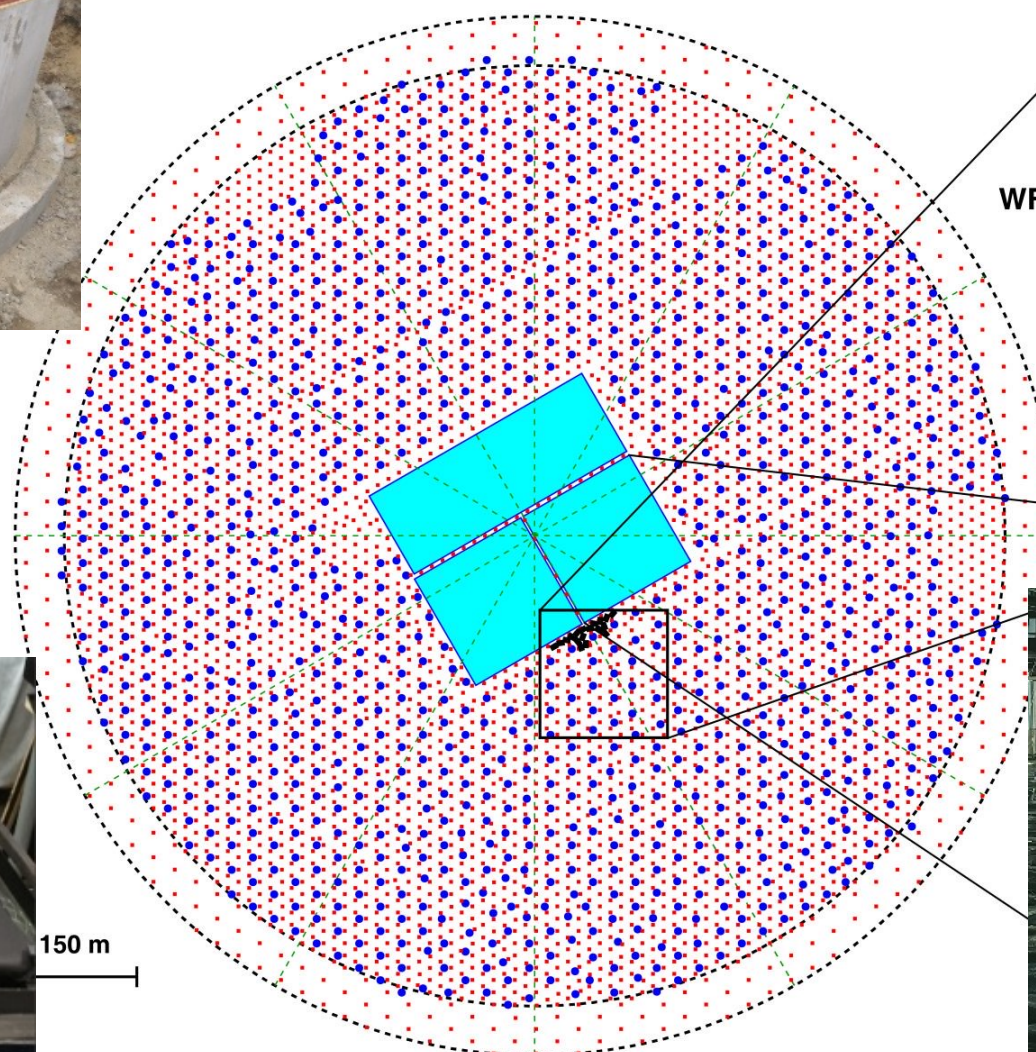
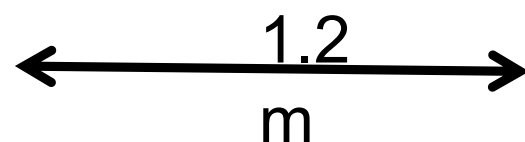
TALE (TA low-energy extension)





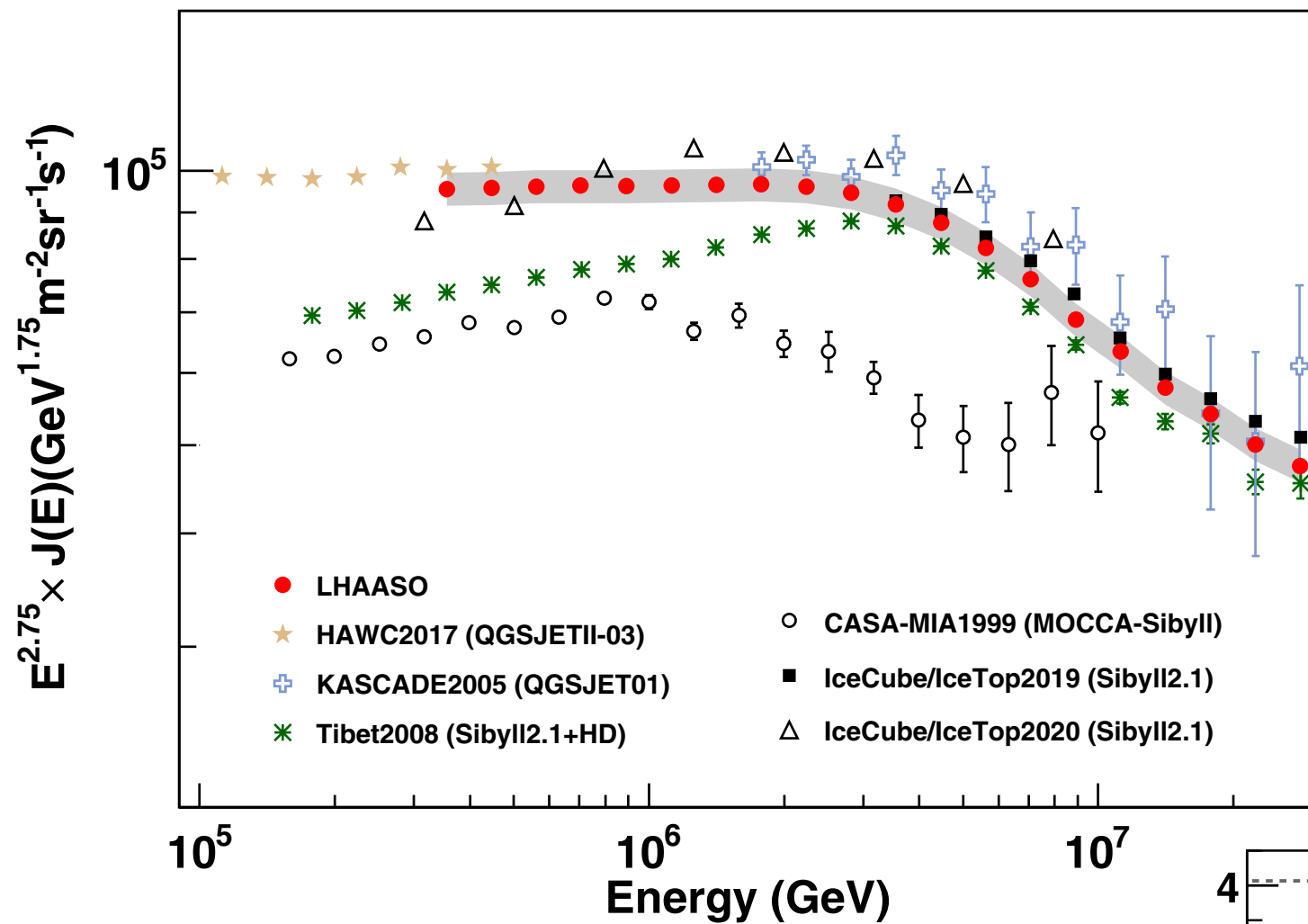
LHAASO

LHAASO: 3 types of detectors from 100 TeV



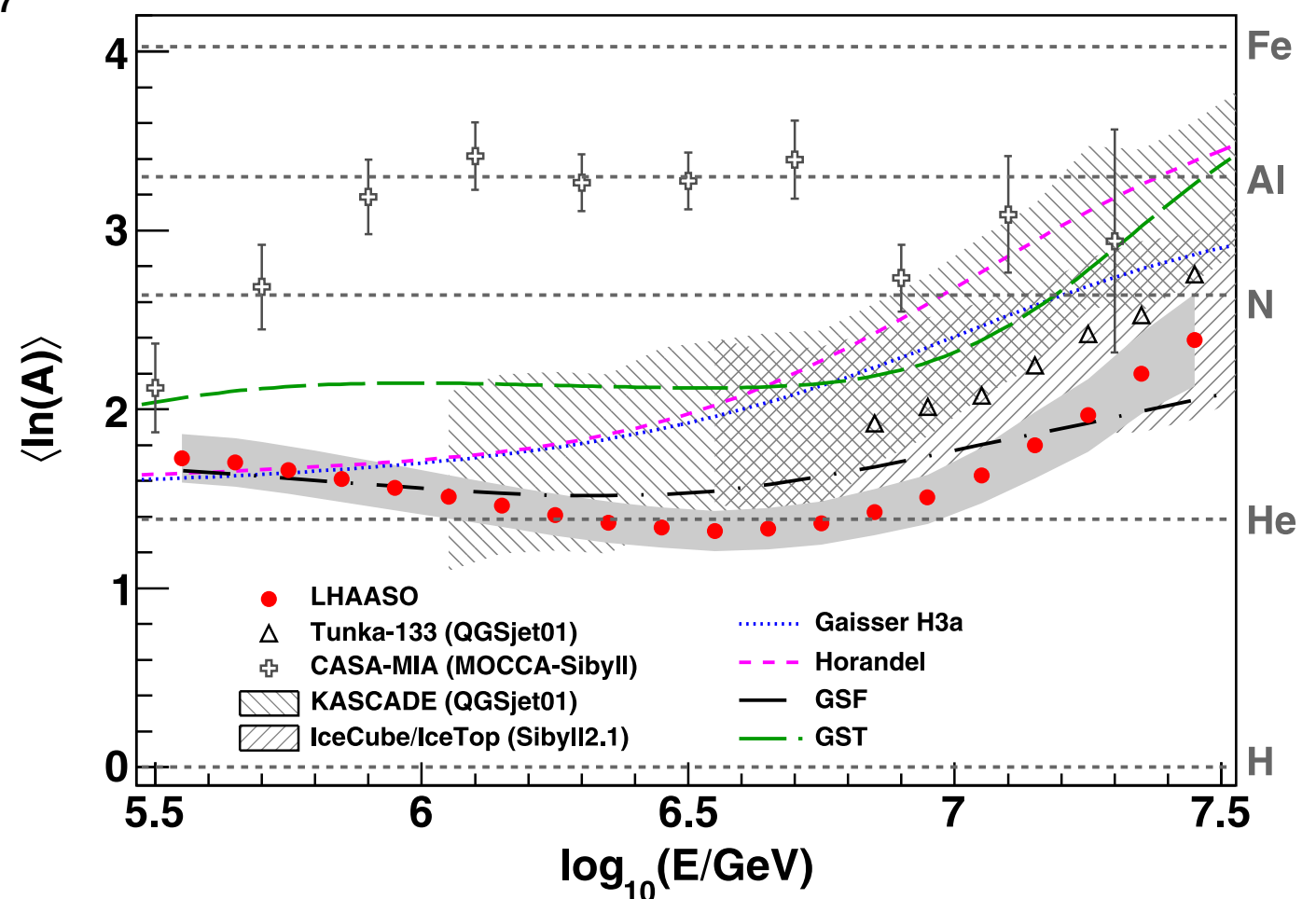
Construction finished on July 2021,
Gamma-ray results from 2019, CR results from 2024

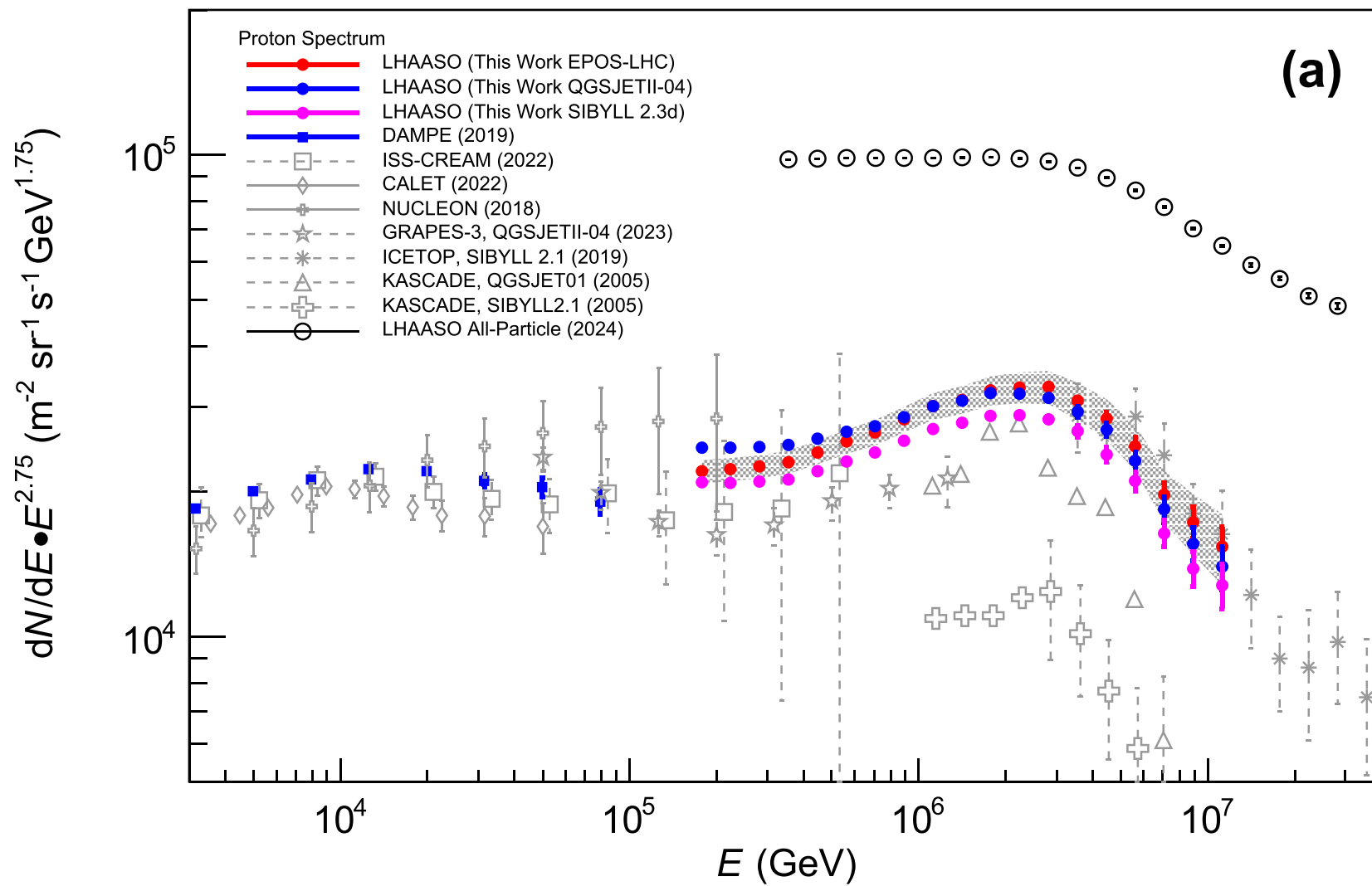
*see also
GaO*



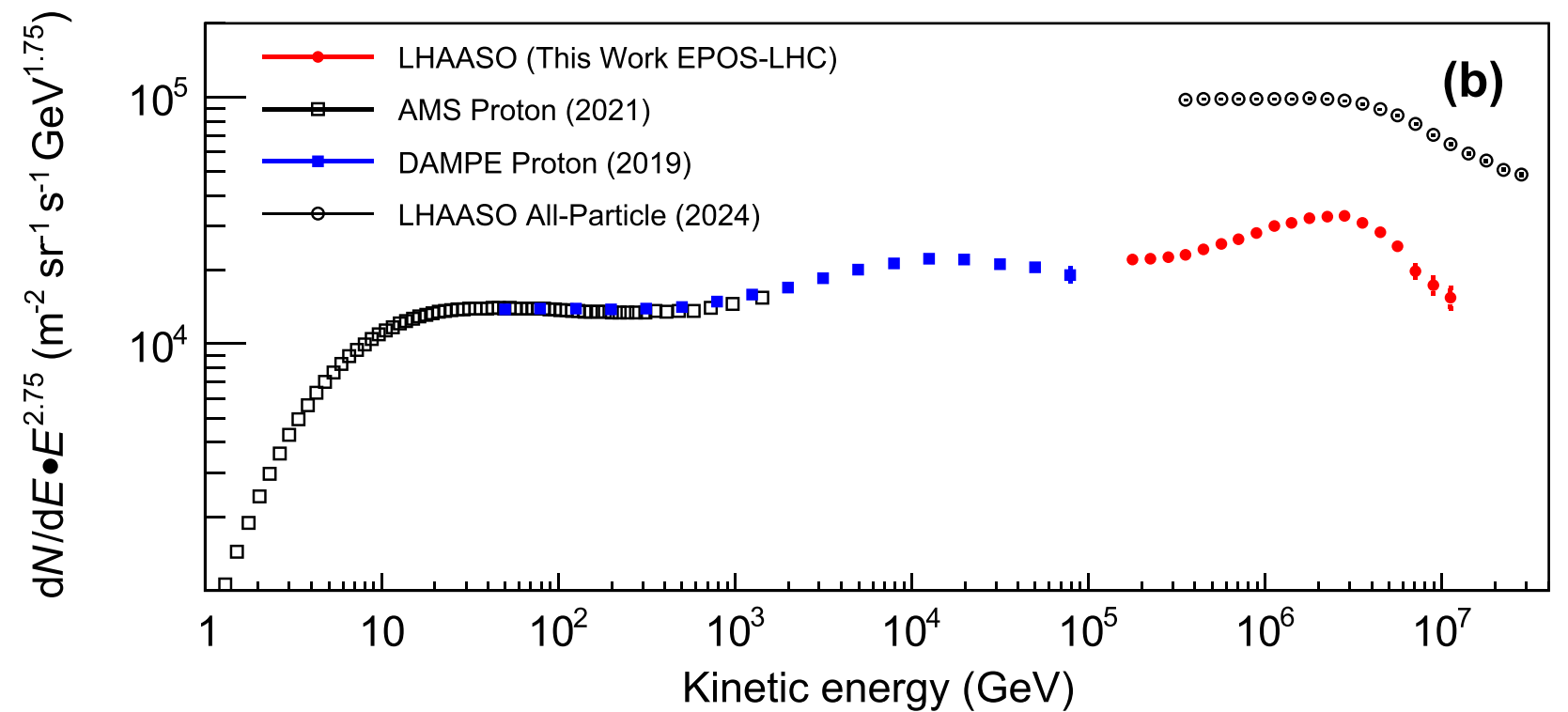
all-particle energy spectrum

mean logarithmic mass

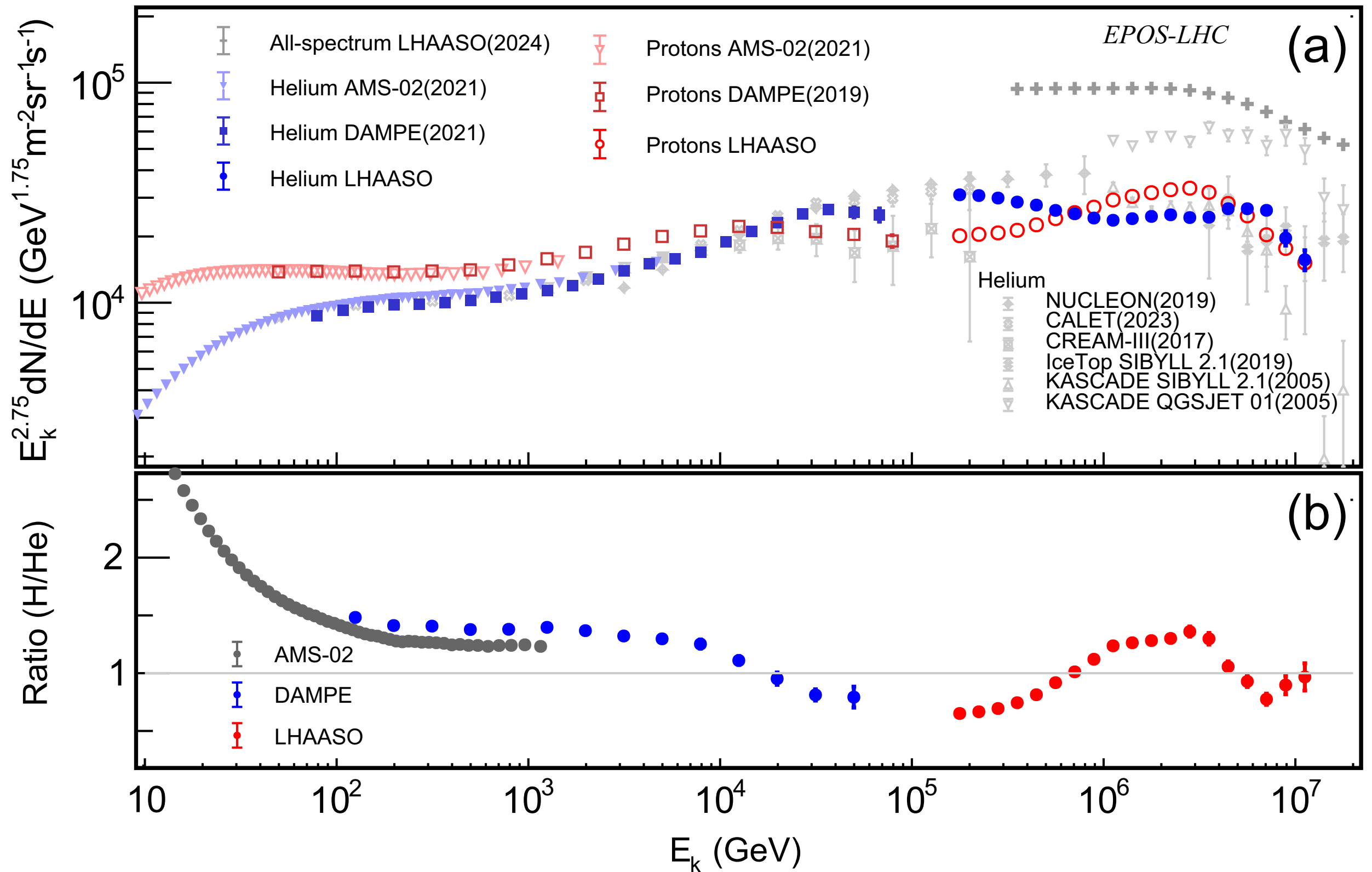




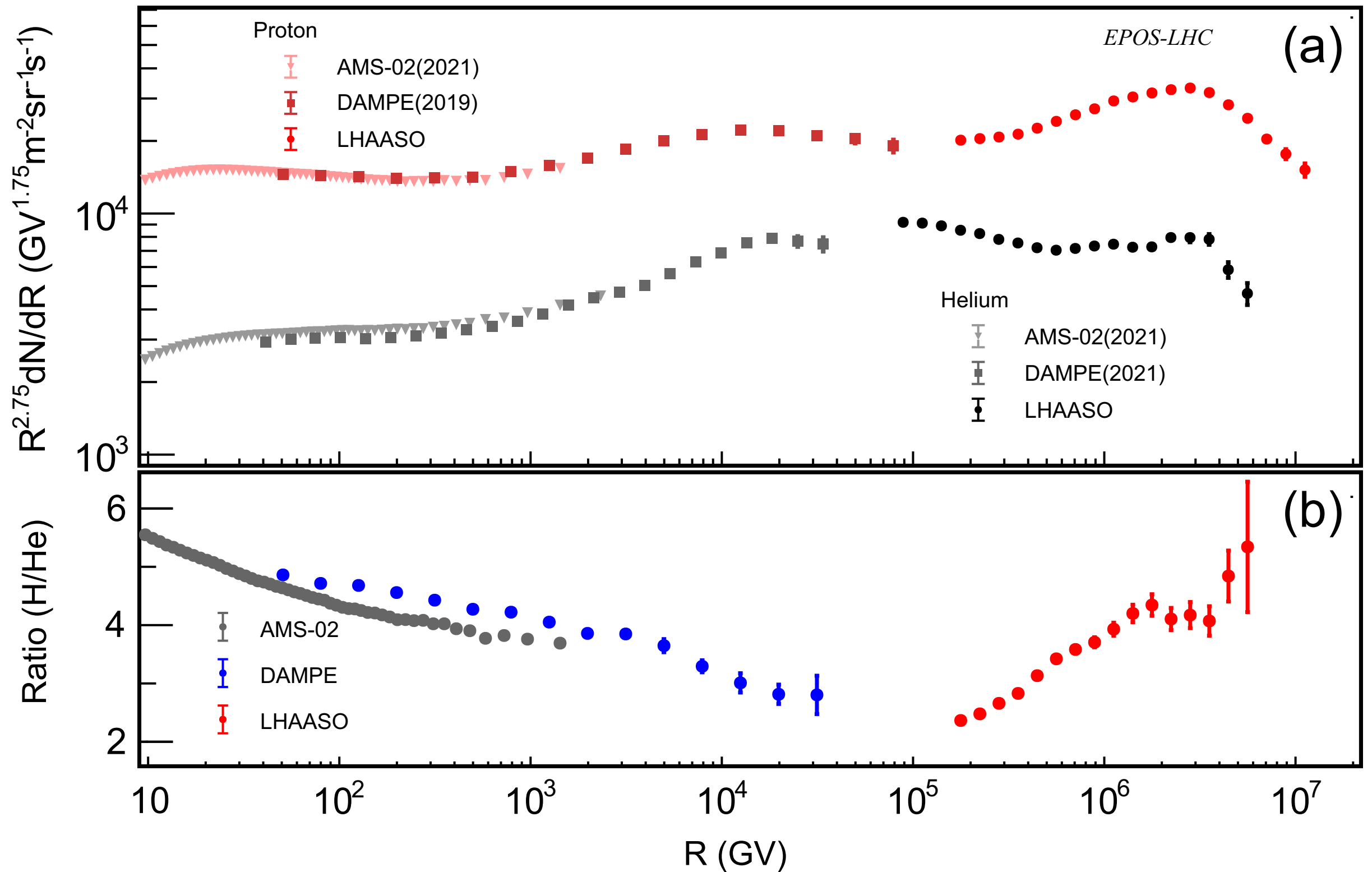
**proton energy
spectrum**



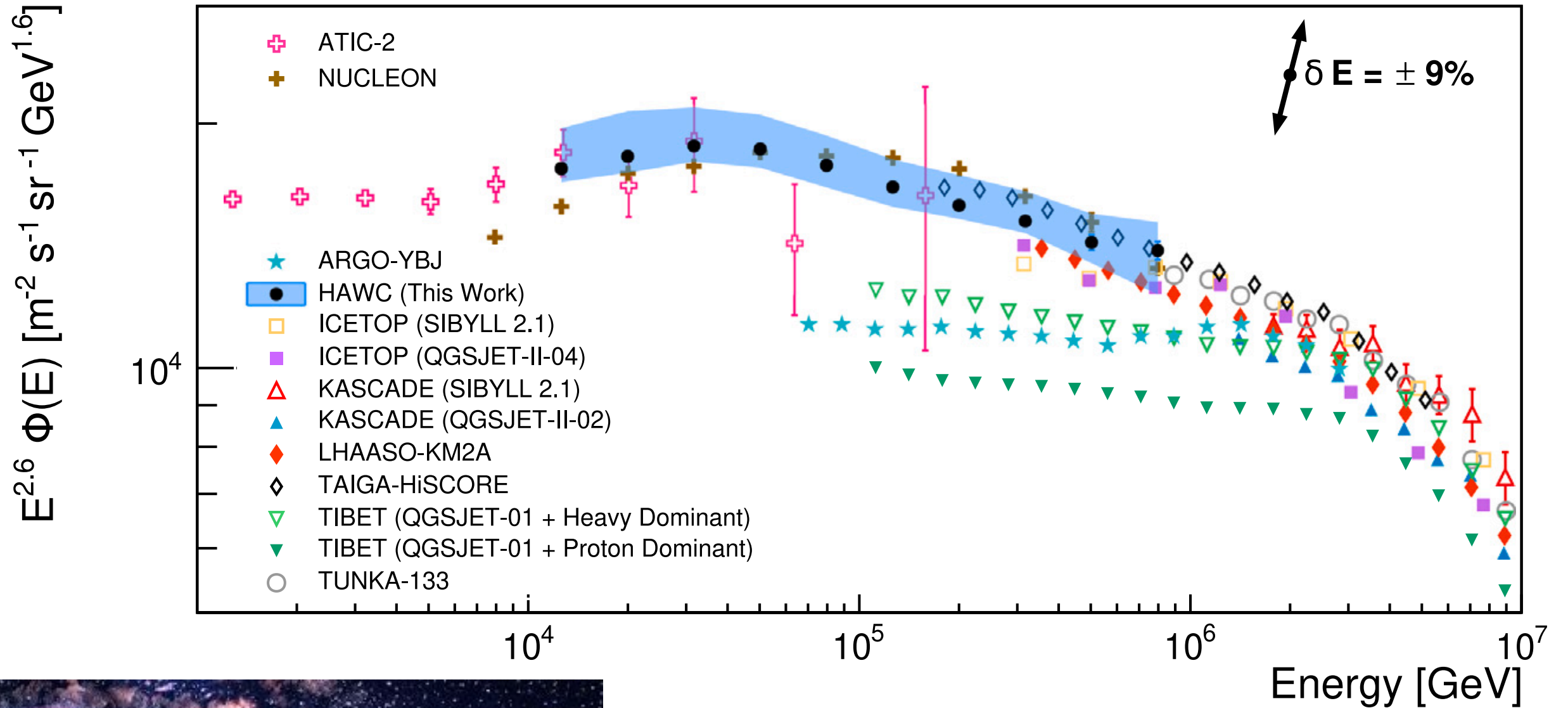
He energy spectrum - LHAASO



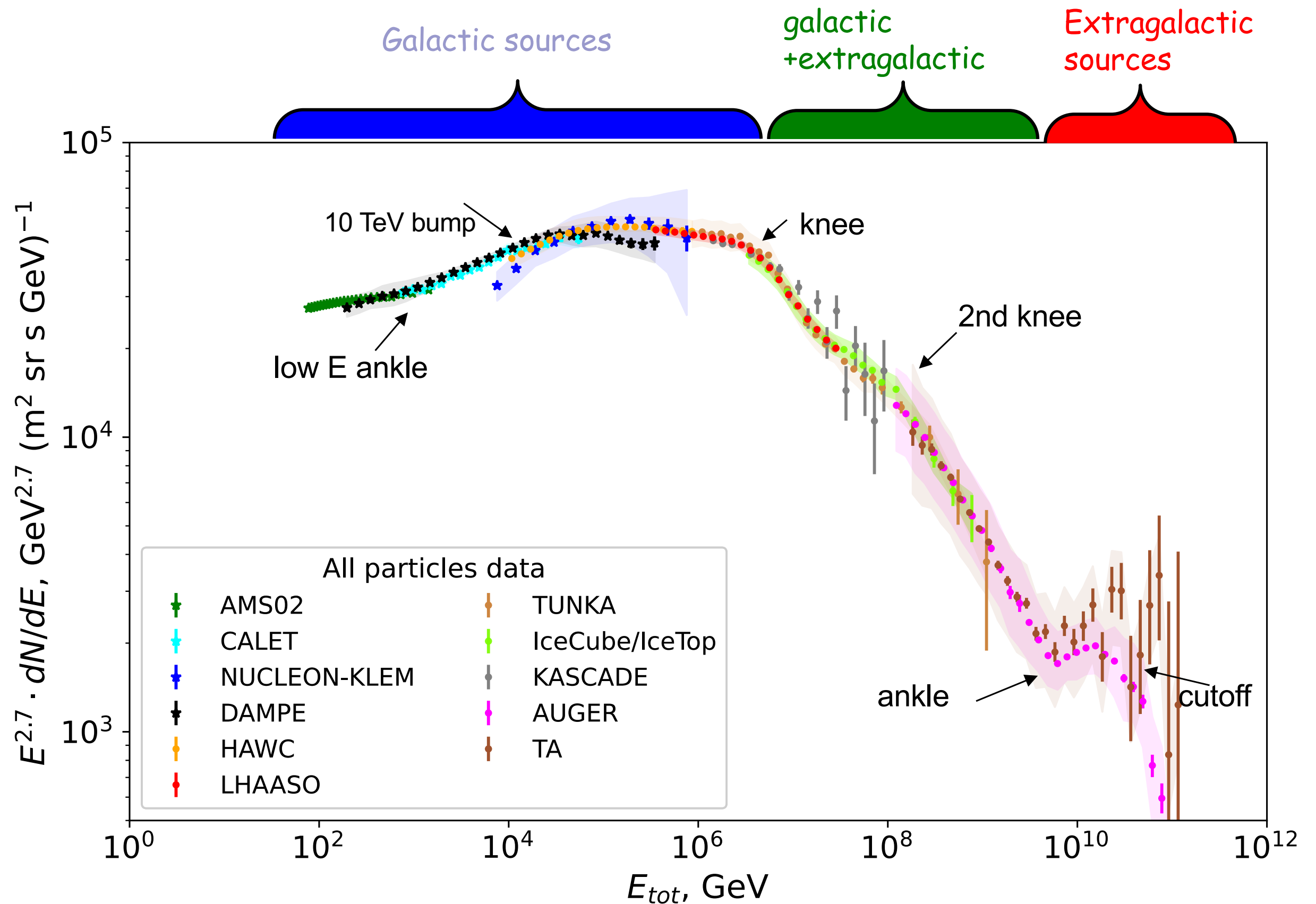
rigidity - LHAASO



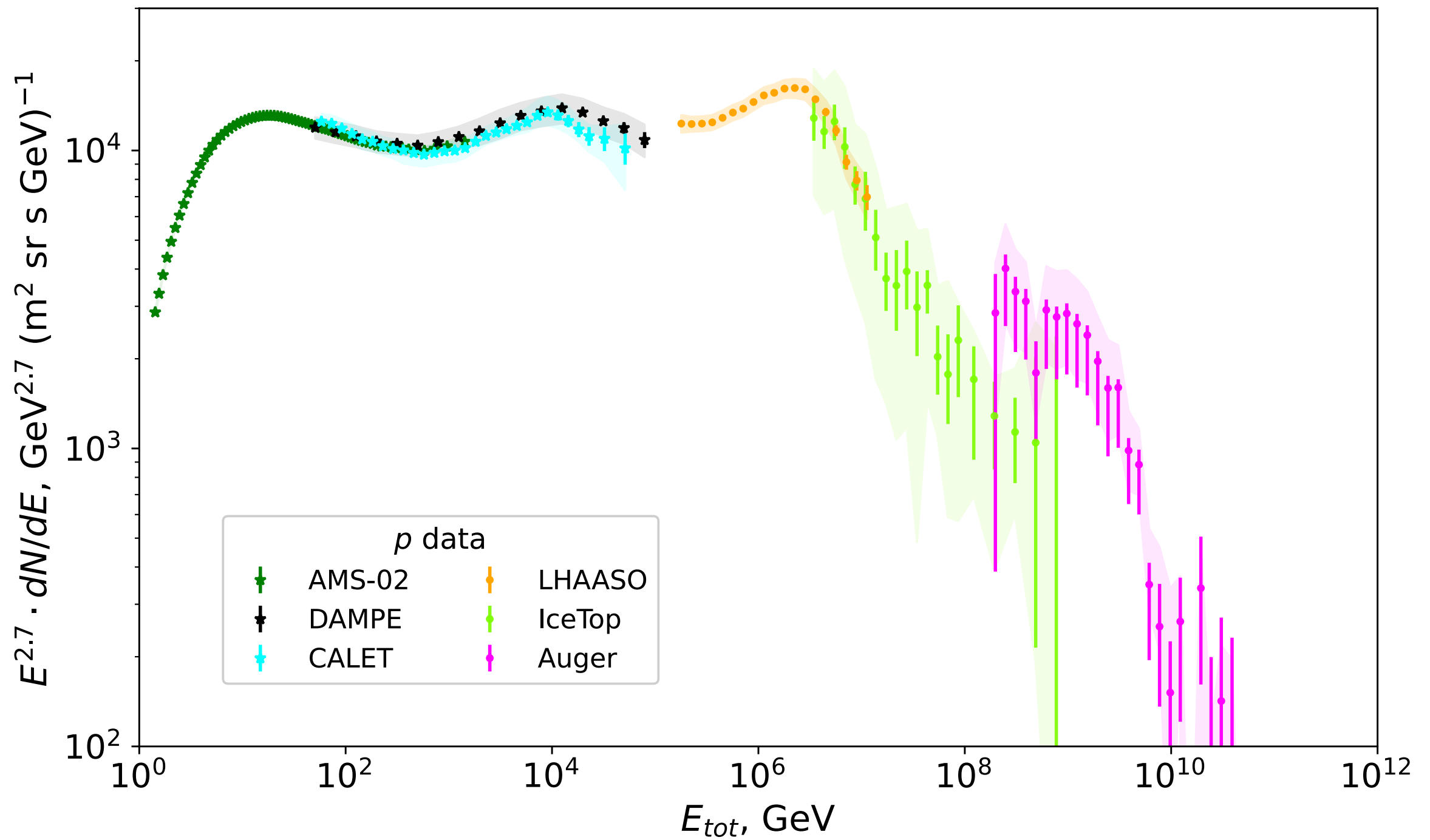
HAWC all particle energy spectrum



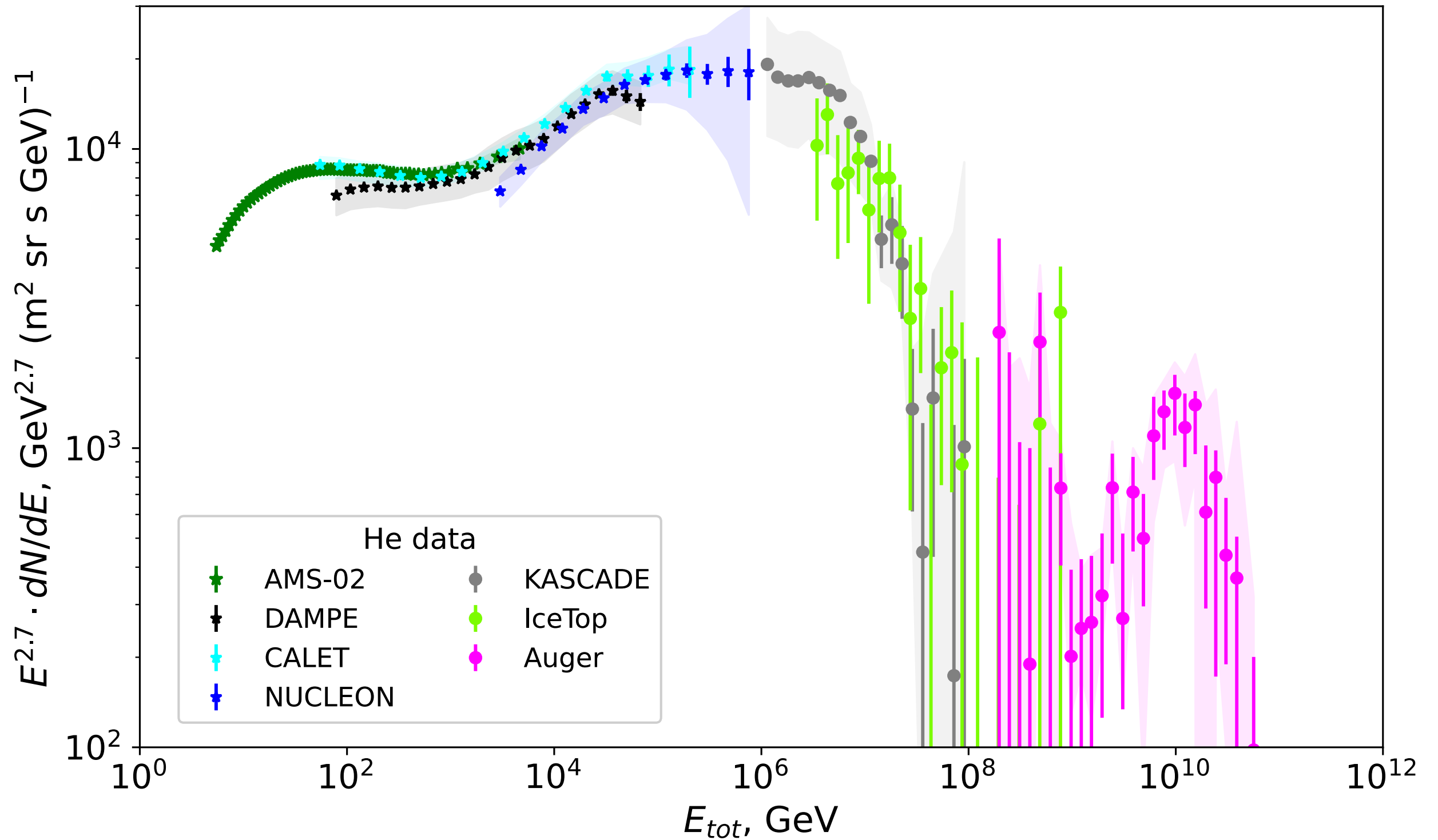
all-particle energy spectrum



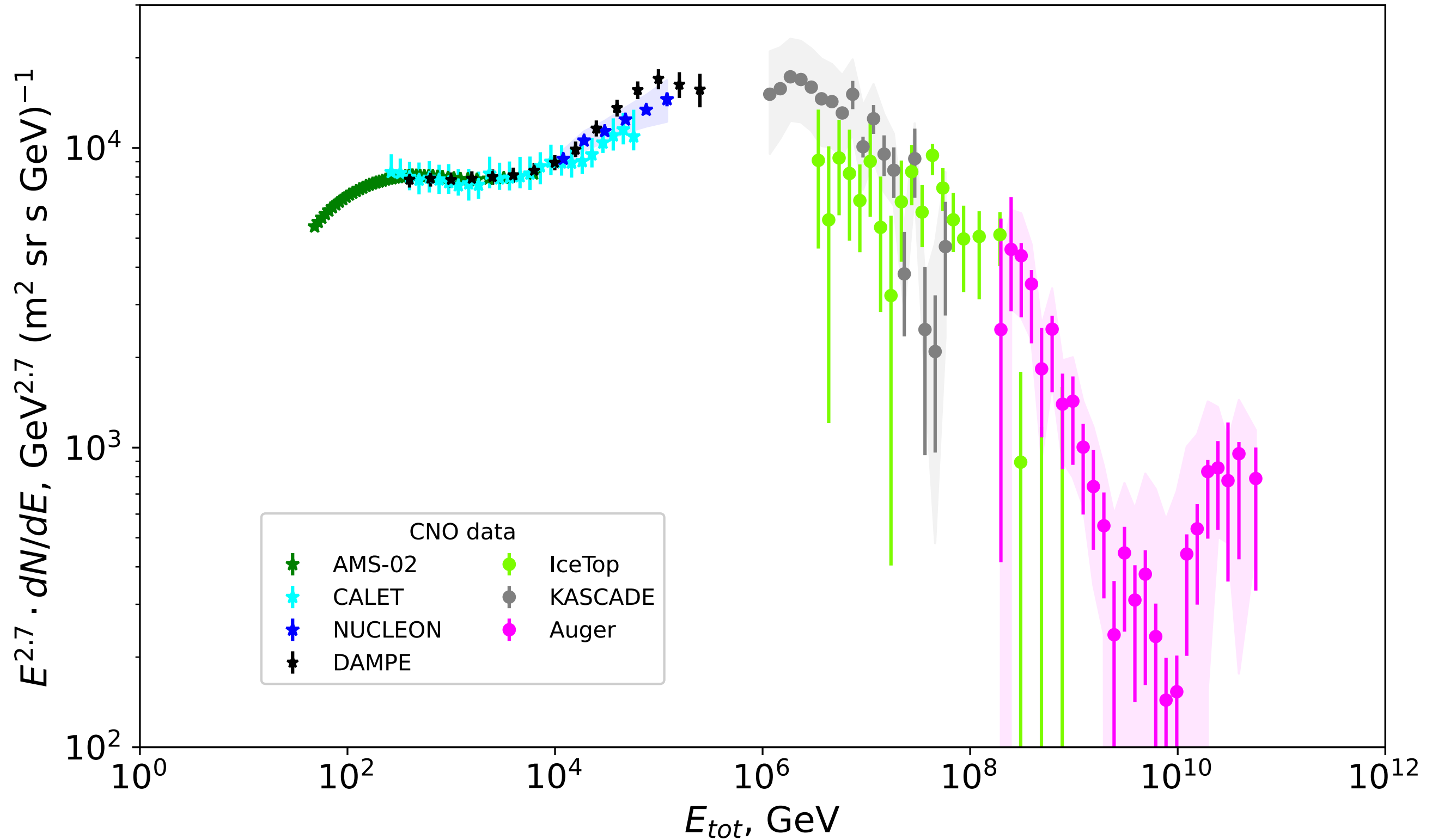
Proton Spectrum



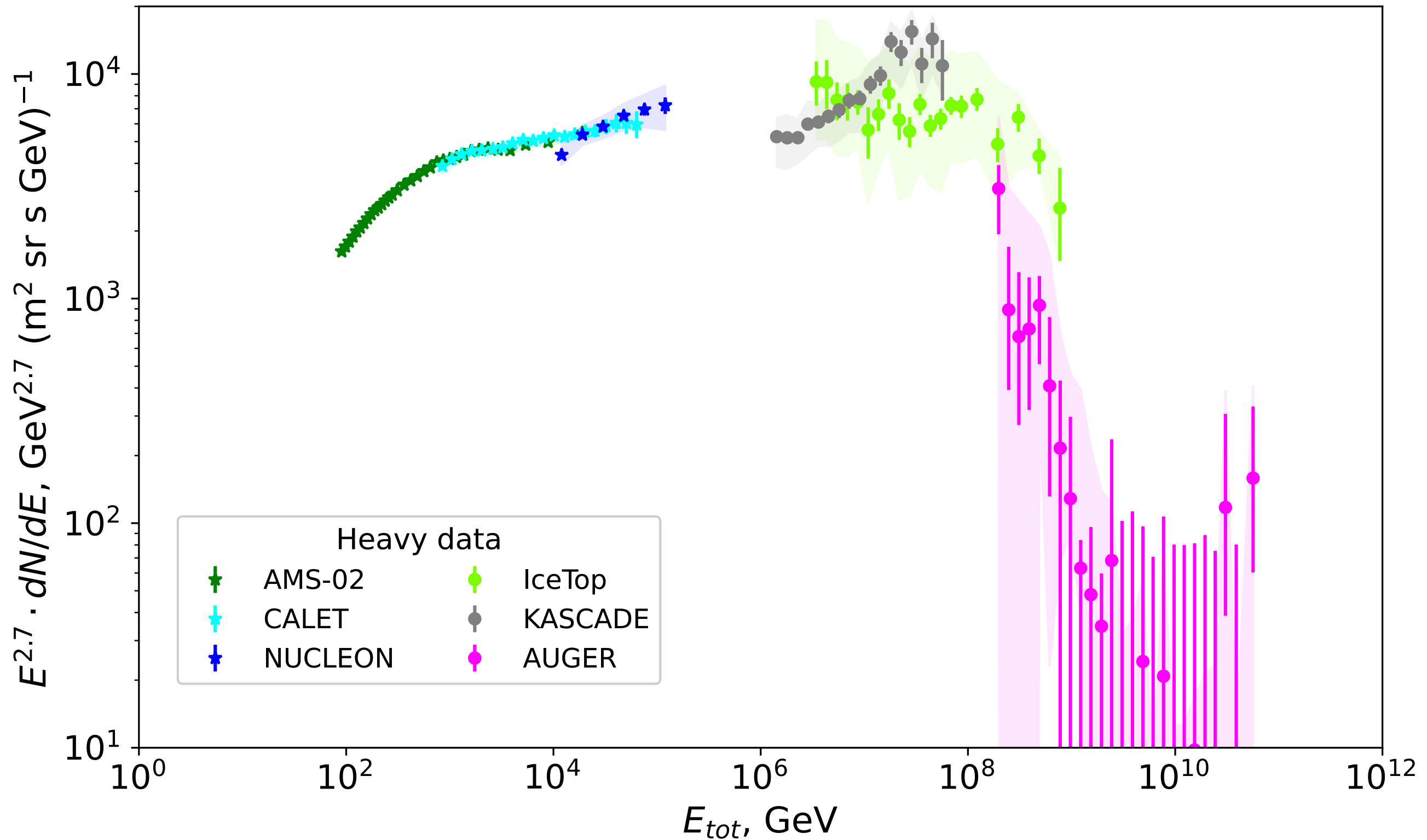
Helium Spectrum



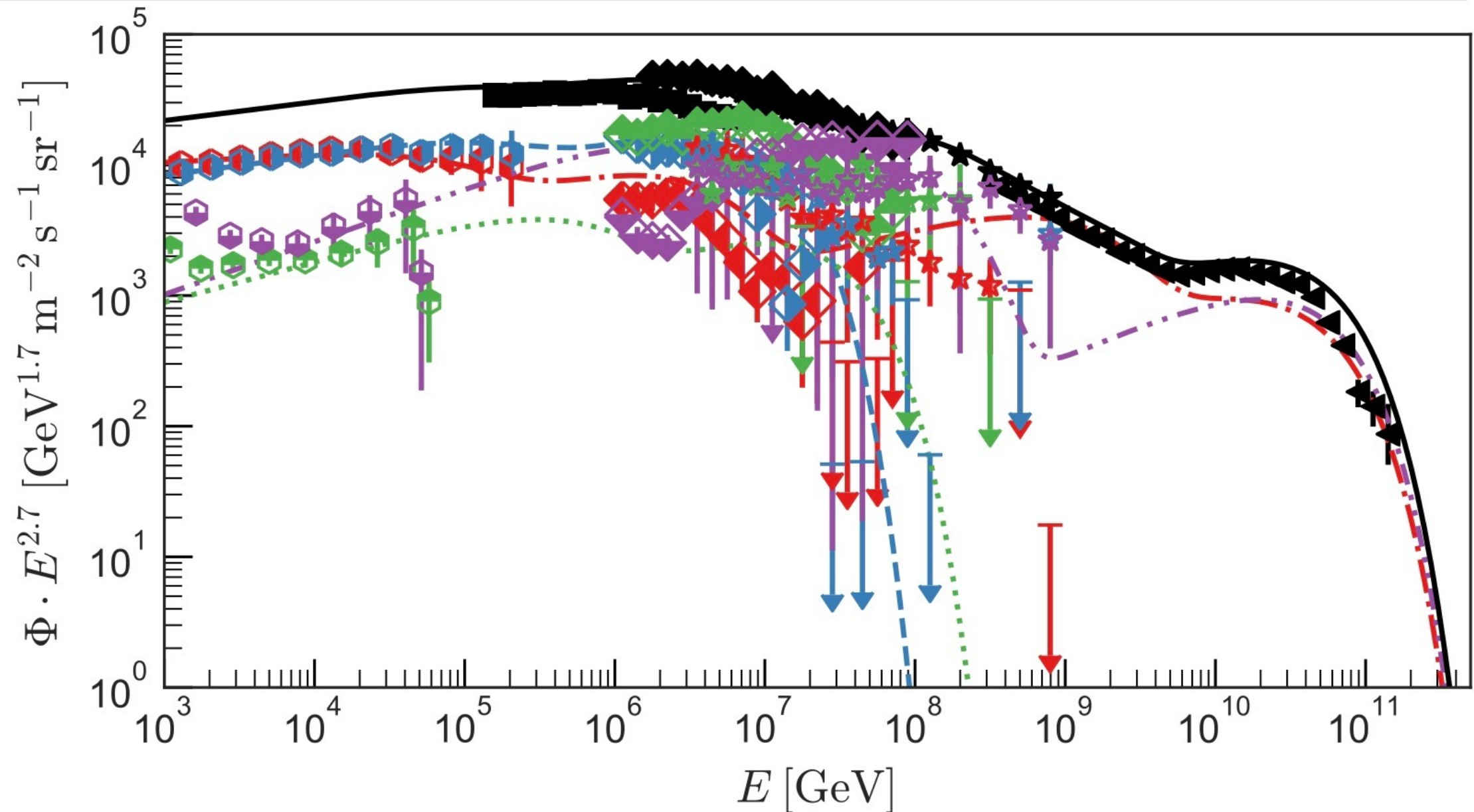
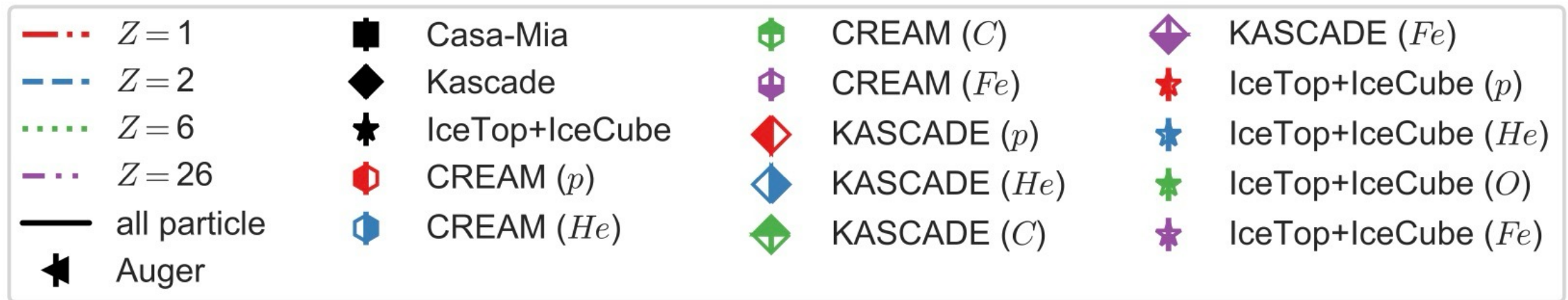
CNO Spectrum



Iron Spectrum

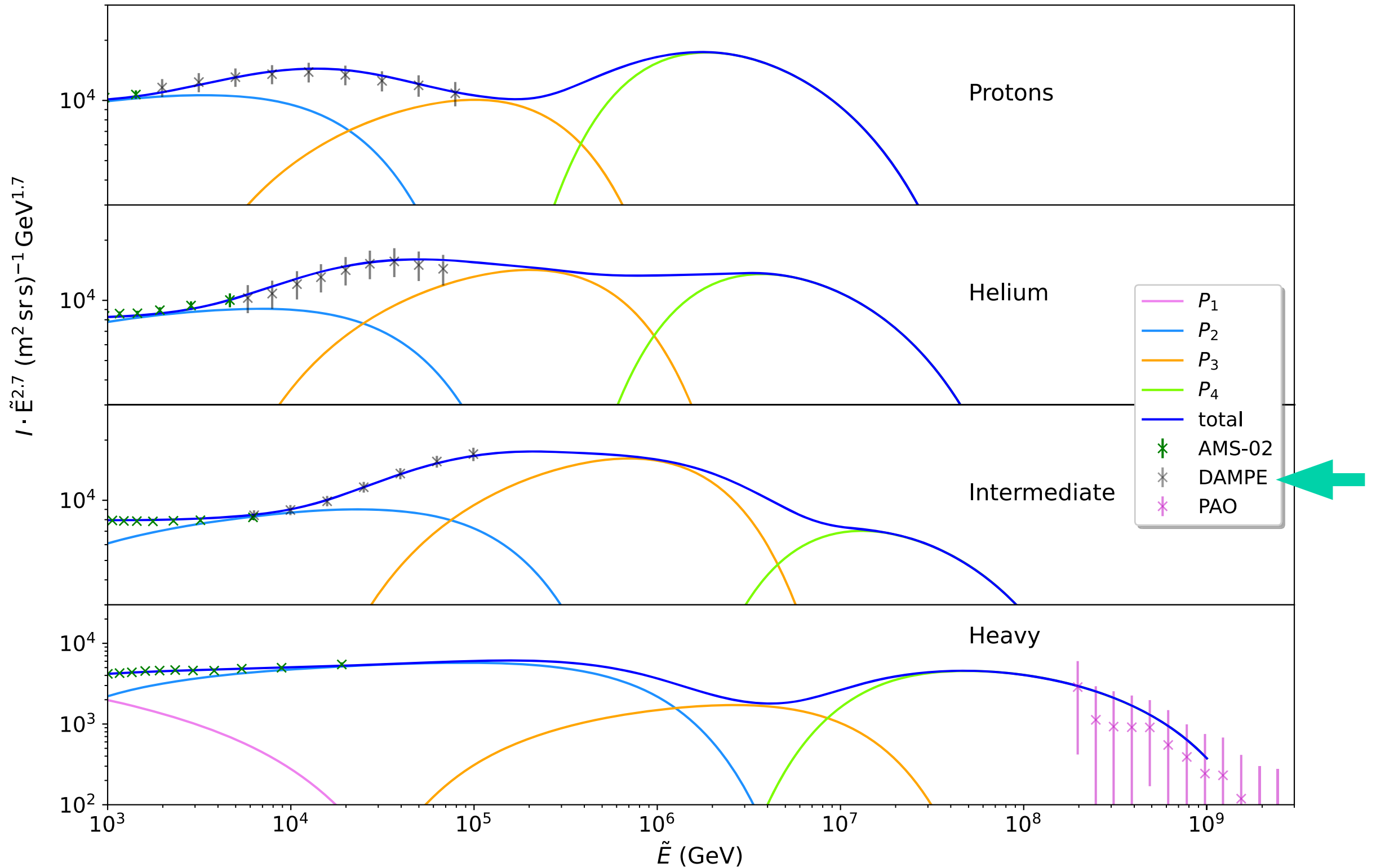


Cosmic-ray Composition



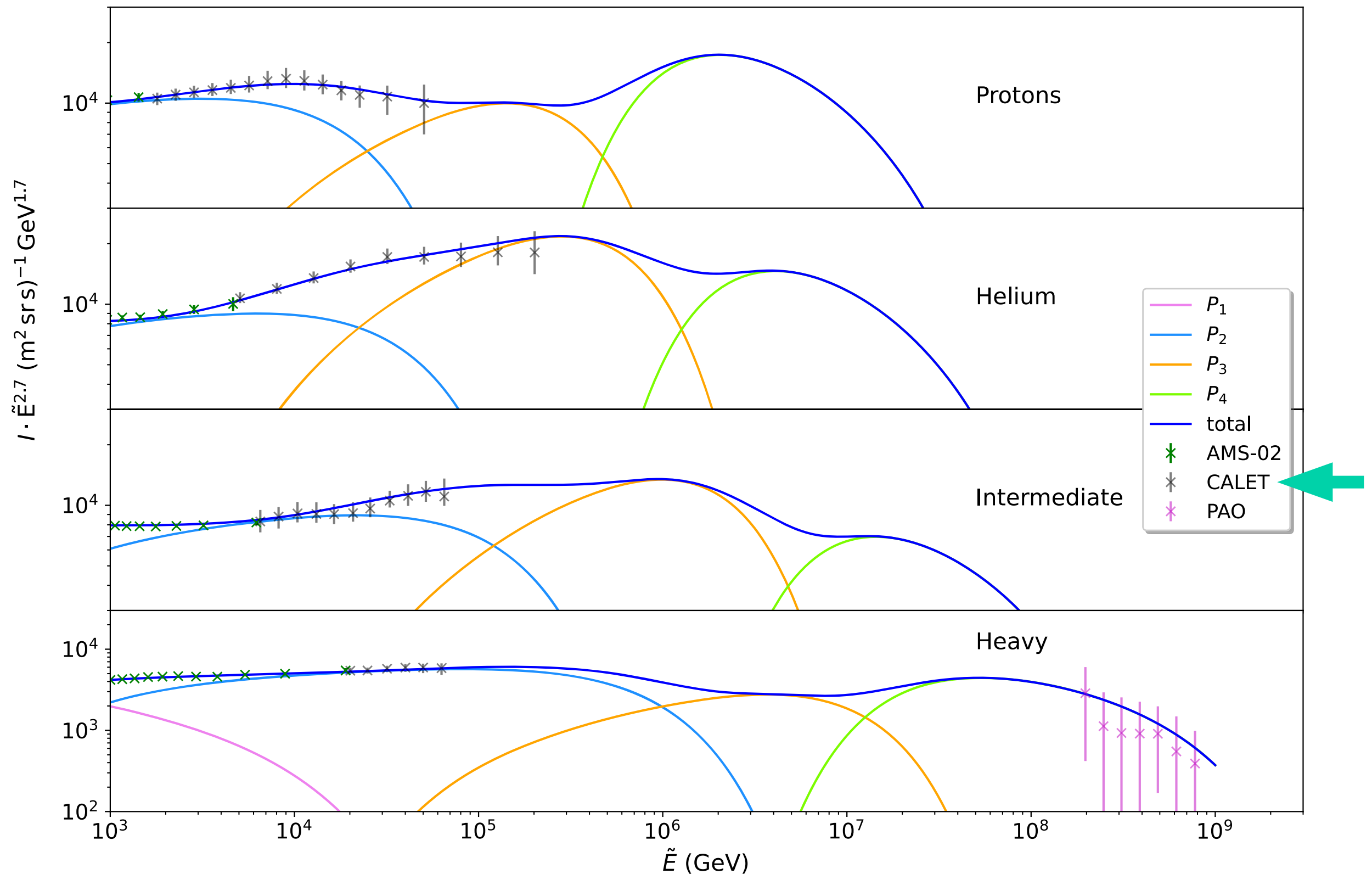
Energy dependence of the knee in the cosmic-ray spectrum across the Milky Way

C. Prévotat,¹ M. Kachelrieß,² S. Koldobskiy³, A. Neronov,^{1,4} and D. Semikoz¹

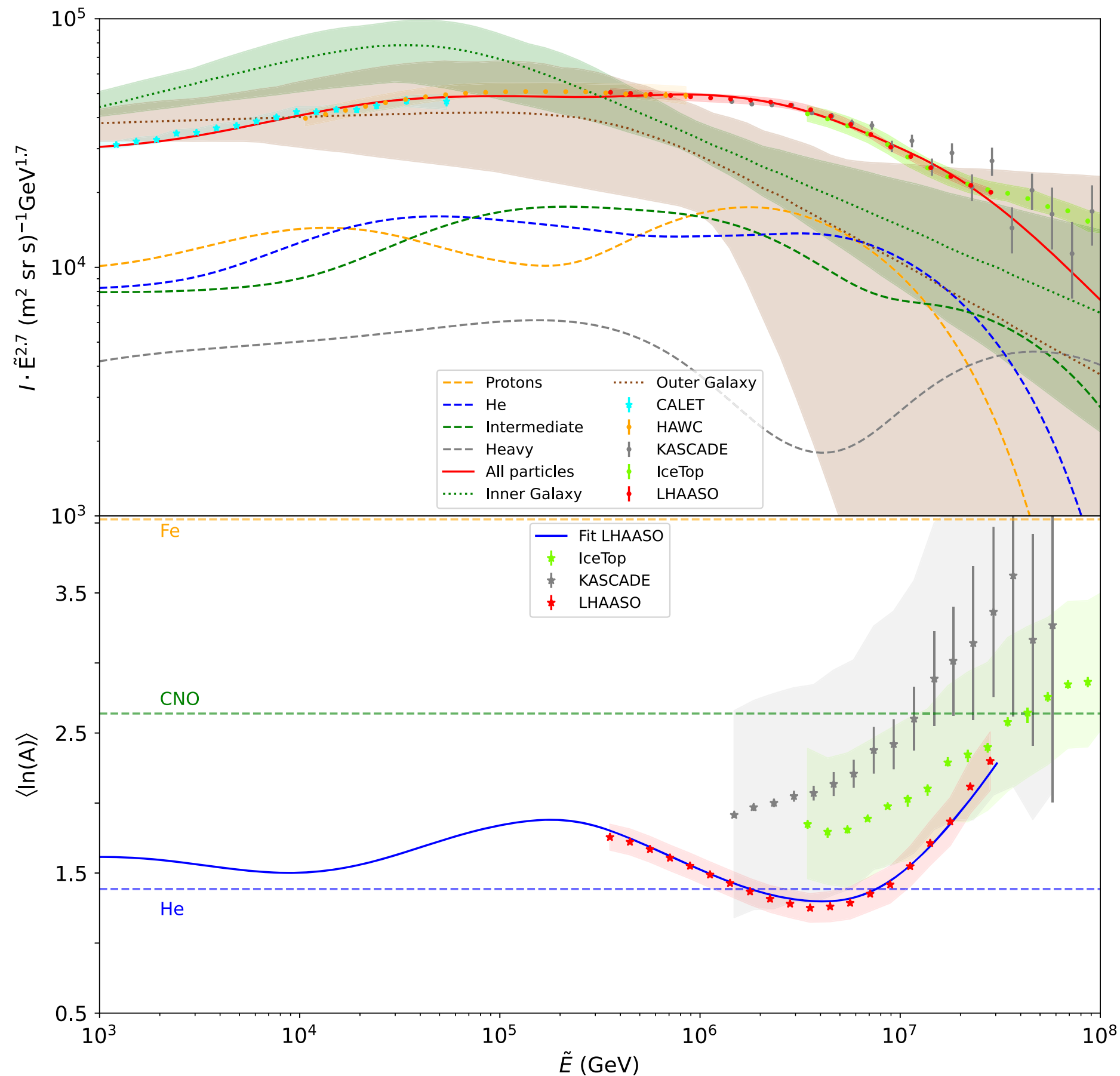


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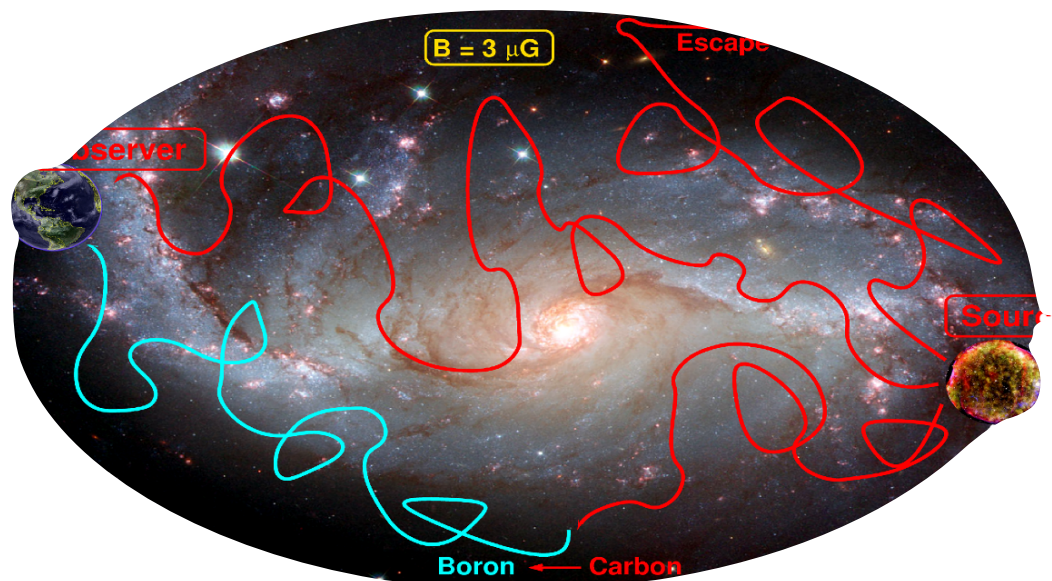
all-particle energy spectrum & mean mass



Transport equation for cosmic rays in the Galaxy

*see also
Mertsch*

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j\tau_{ij}}$$

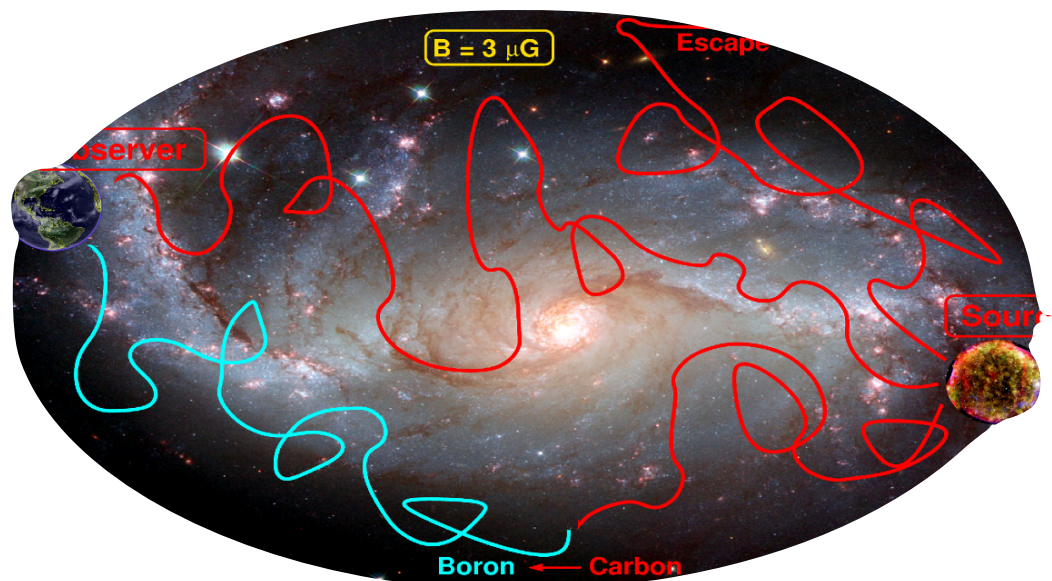


Transport equation for cosmic rays in the Galaxy

diffusion

*see also
Mertsch*

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n \nu \sigma_i N_i - \frac{N_i}{\gamma \tau_i} + Q_i + \sum_{j>i} n \nu \sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$



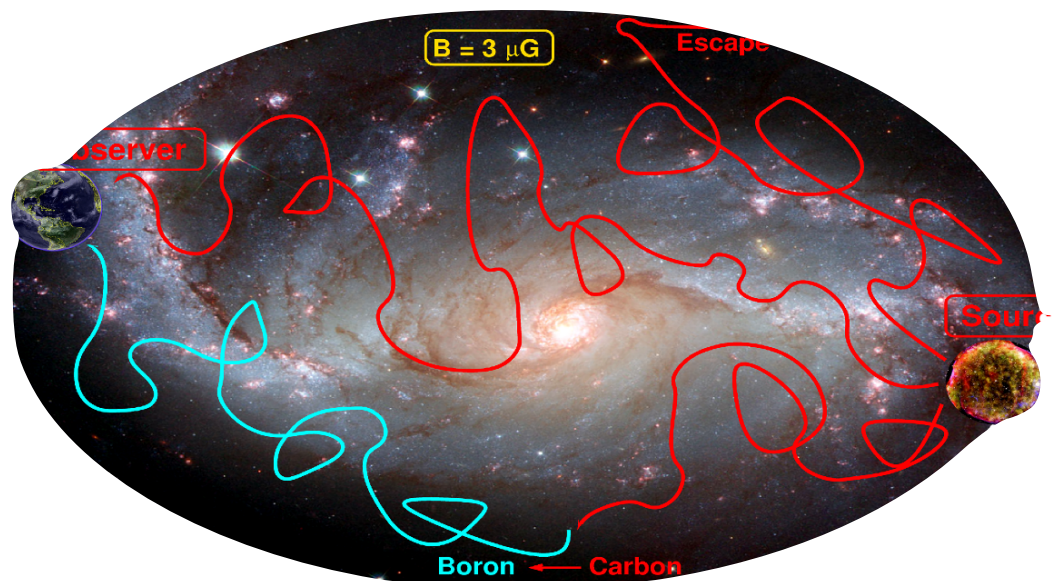
Transport equation for cosmic rays in the Galaxy

*see also
Mertsch*

diffusion

energy loss (Bethe Bloch)

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j\tau_{ij}}$$



Transport equation for cosmic rays in the Galaxy

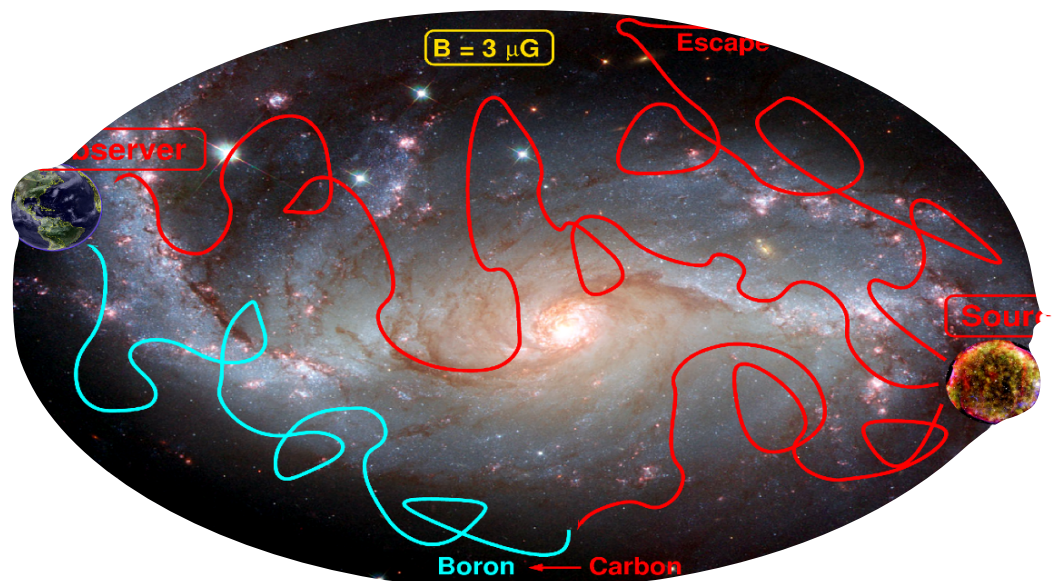
*see also
Mertsch*

diffusion

energy loss (Bethe Bloch)

loss through interactions
with ISM (spallation)

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j\tau_{ij}}$$



Transport equation for cosmic rays in the Galaxy

*see also
Mertsch*

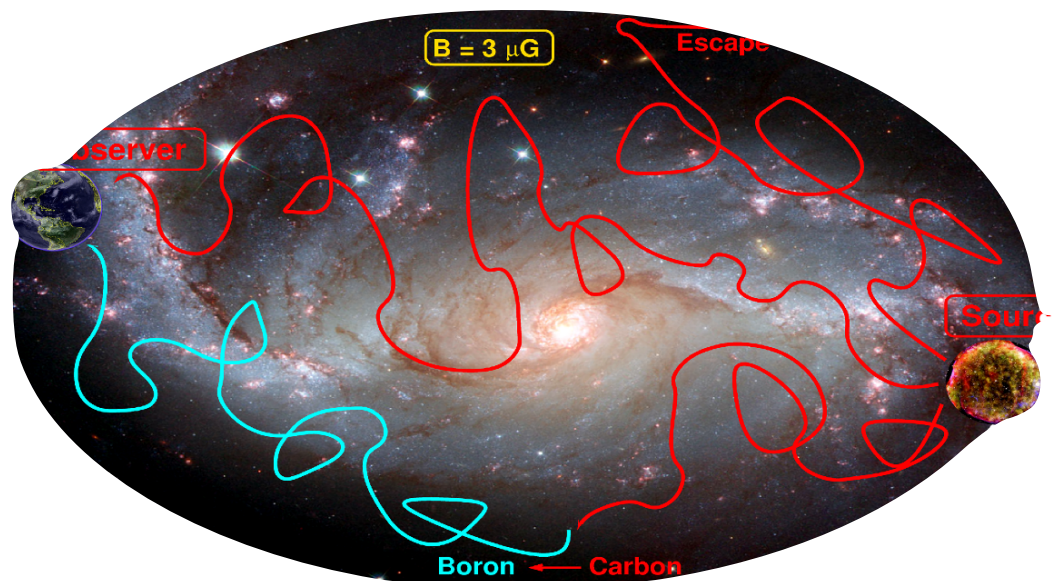
diffusion

energy loss (Bethe Bloch)

loss through interactions
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loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j\tau_{ij}}$$



Transport equation for cosmic rays in the Galaxy

*see also
Mertsch*

diffusion

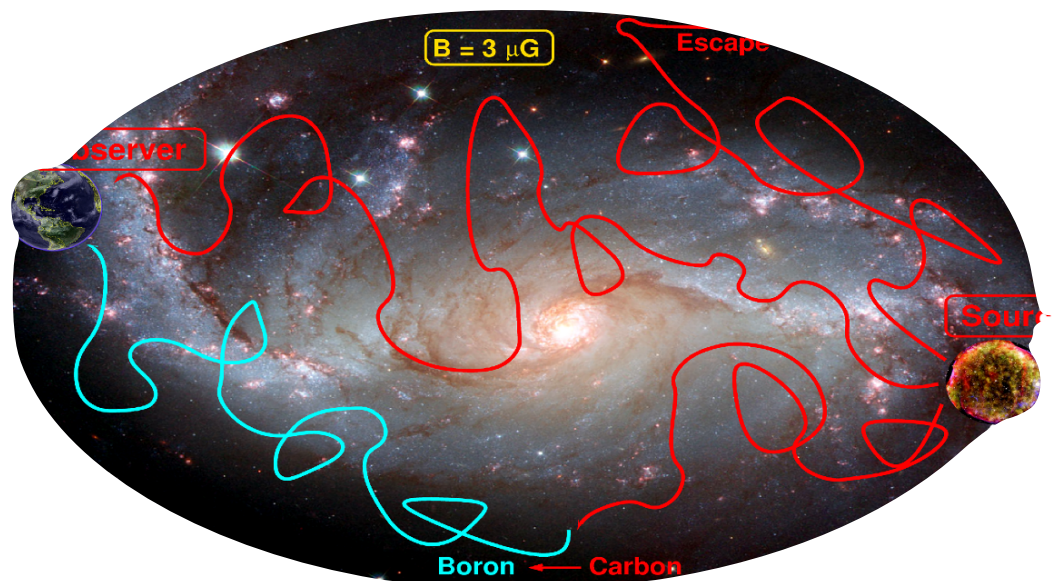
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source term



Transport equation for cosmic rays in the Galaxy

*see also
Mertsch*

diffusion

energy loss (Bethe Bloch)

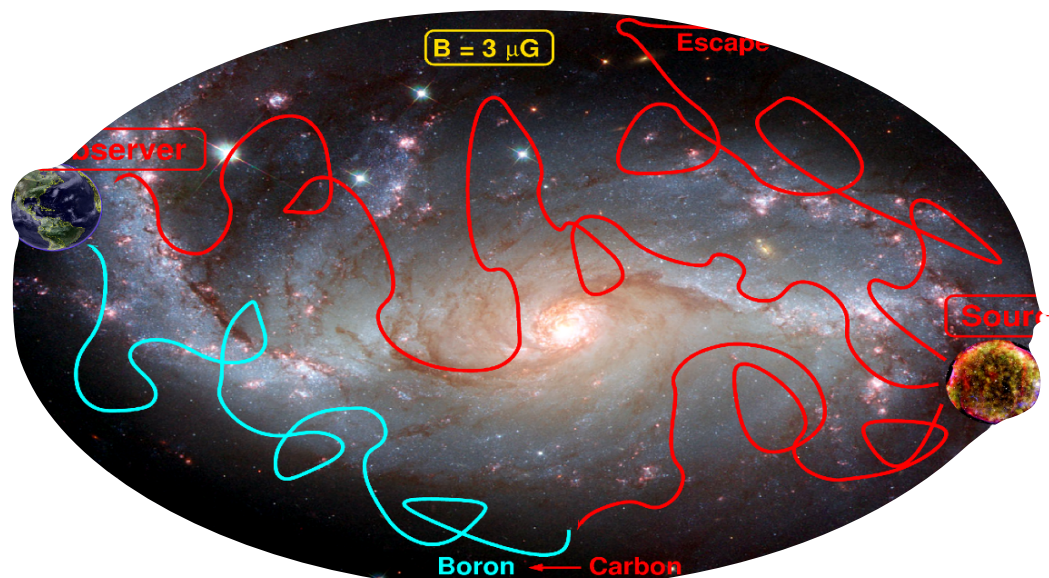
loss through interactions
with ISM (spallation)

loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j\tau_{ij}}$$

source term

production through spallation
of heavy nuclei



Transport equation for cosmic rays in the Galaxy

*see also
Mertsch*

diffusion

energy loss (Bethe Bloch)

loss through interactions
with ISM (spallation)

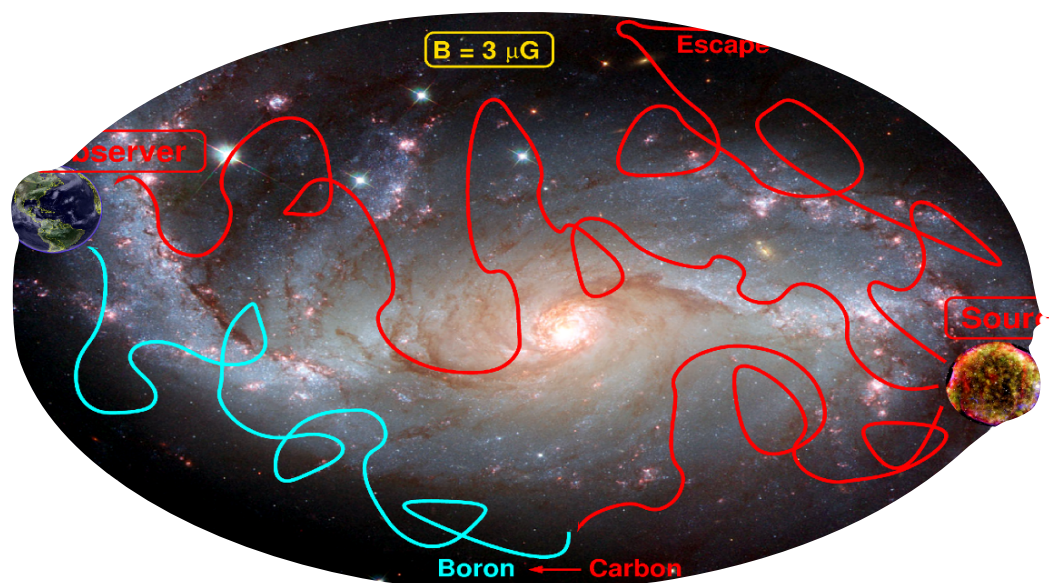
loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j\tau_{ij}}$$

source term

production through spallation
of heavy nuclei

production through decay
of heavy nuclei

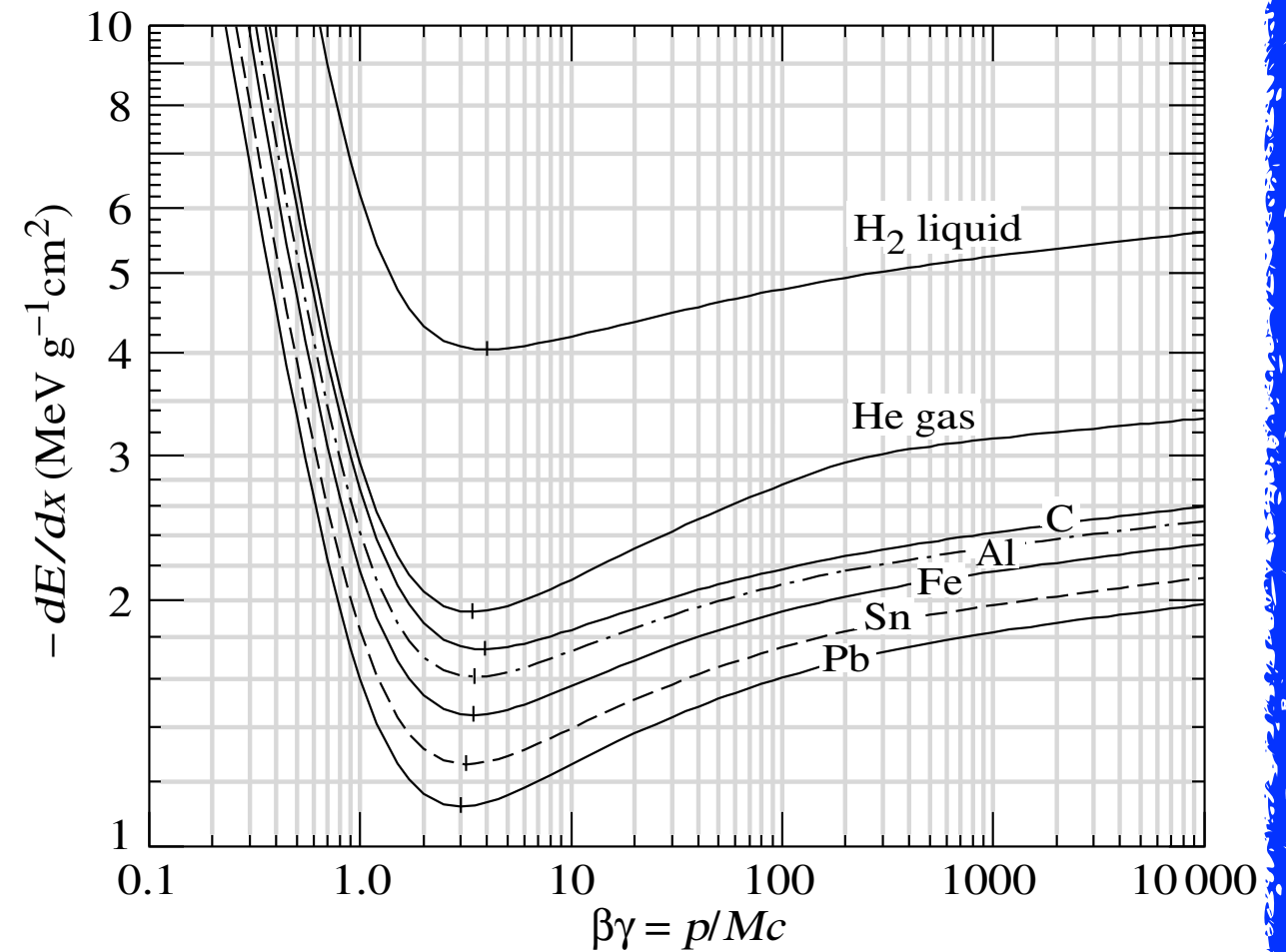


Transport equation for Galactic Cosmic Rays

diffusion

energy loss (Bethe Bloch)

loss through with

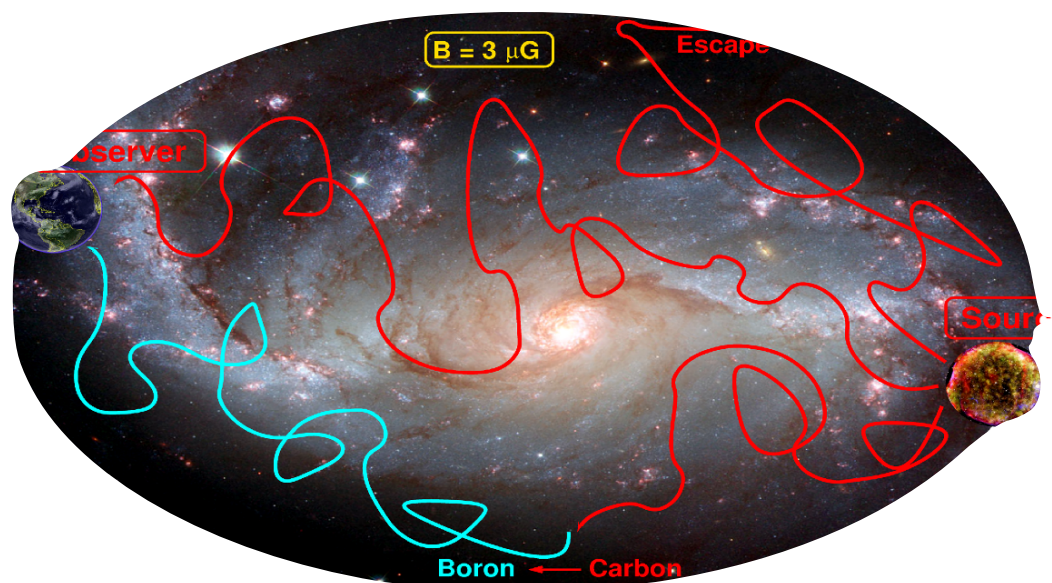


$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E} (E N_i) - n \nu \sigma_i N_i - \frac{N_i}{\gamma \tau_i} + Q_i + \sum_{j>i} n \nu \sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

source term

production through spallation of heavy nuclei

production through decay of heavy nuclei



Transport equation for cosmic rays in the Galaxy

diffusion

energy loss (Bethe Bloch)

loss through interactions
with ISM (spallation)

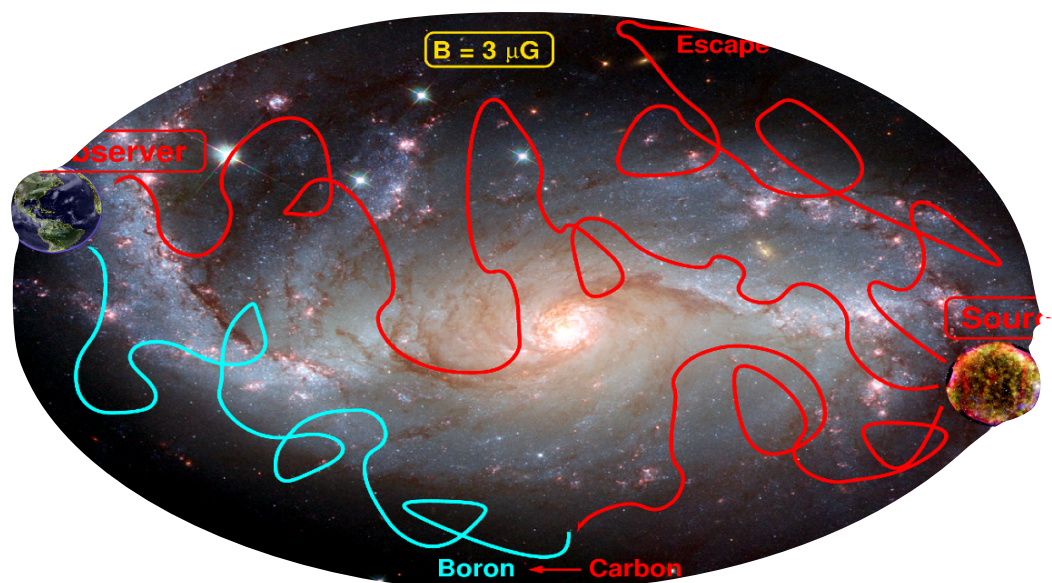
loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E} (E N_i) - n \nu \sigma_i N_i - \frac{N_i}{\gamma \tau_i} + Q_i + \sum_{j>i} n \nu \sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

source term

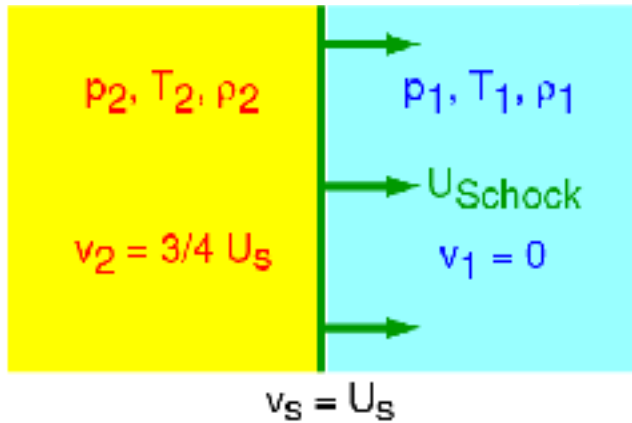
production through spallation
of heavy nuclei

production through decay
of heavy nuclei

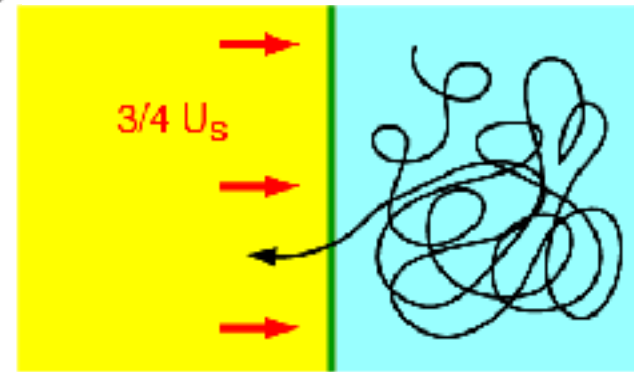


1st order Fermi acceleration at strong shock

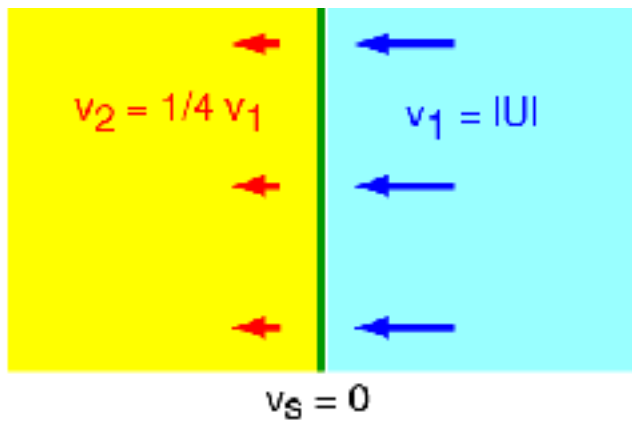
a) rest system of unshocked ISM



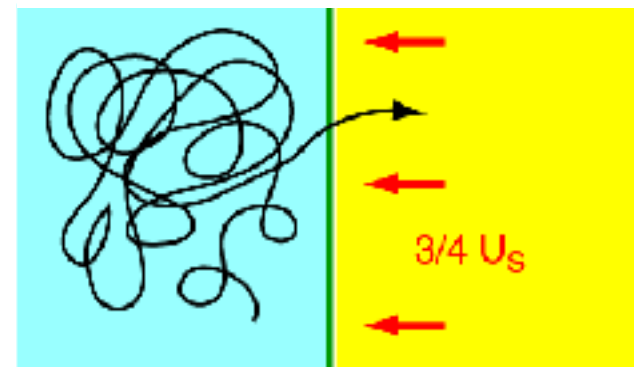
b) rest system of unshocked ISM



c) rest system of shock front

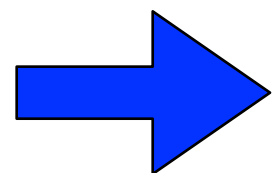


d) rest system of shocked ISM



energy gain

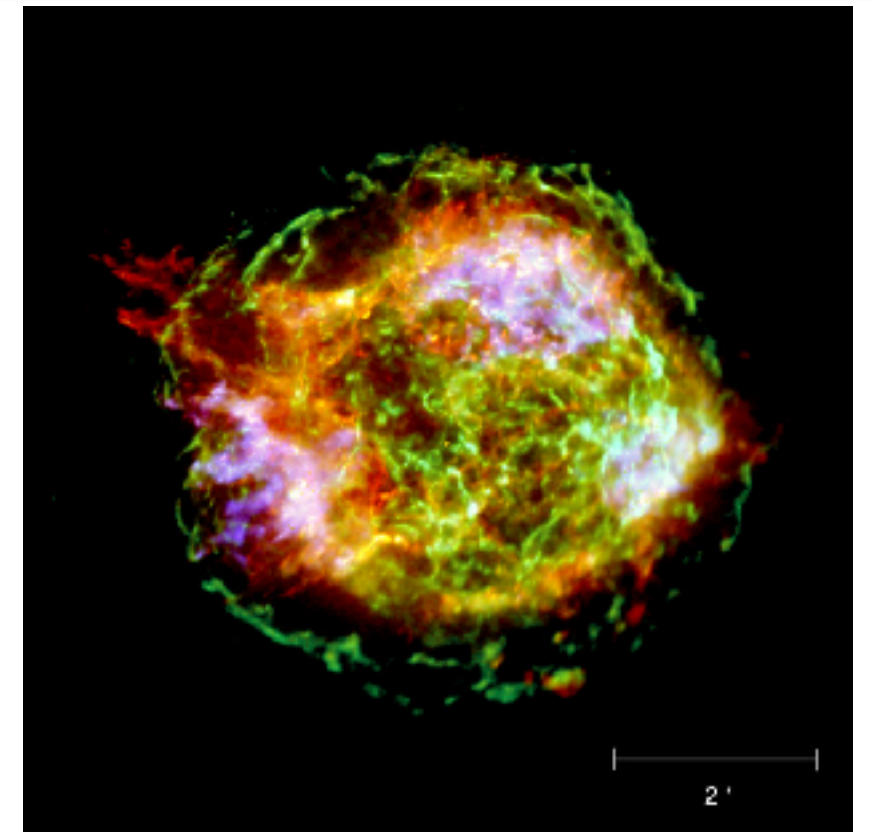
$$\frac{\Delta E}{E} \propto \frac{U_s}{c}$$



$$N(E) dE \propto E^{-2} dE$$

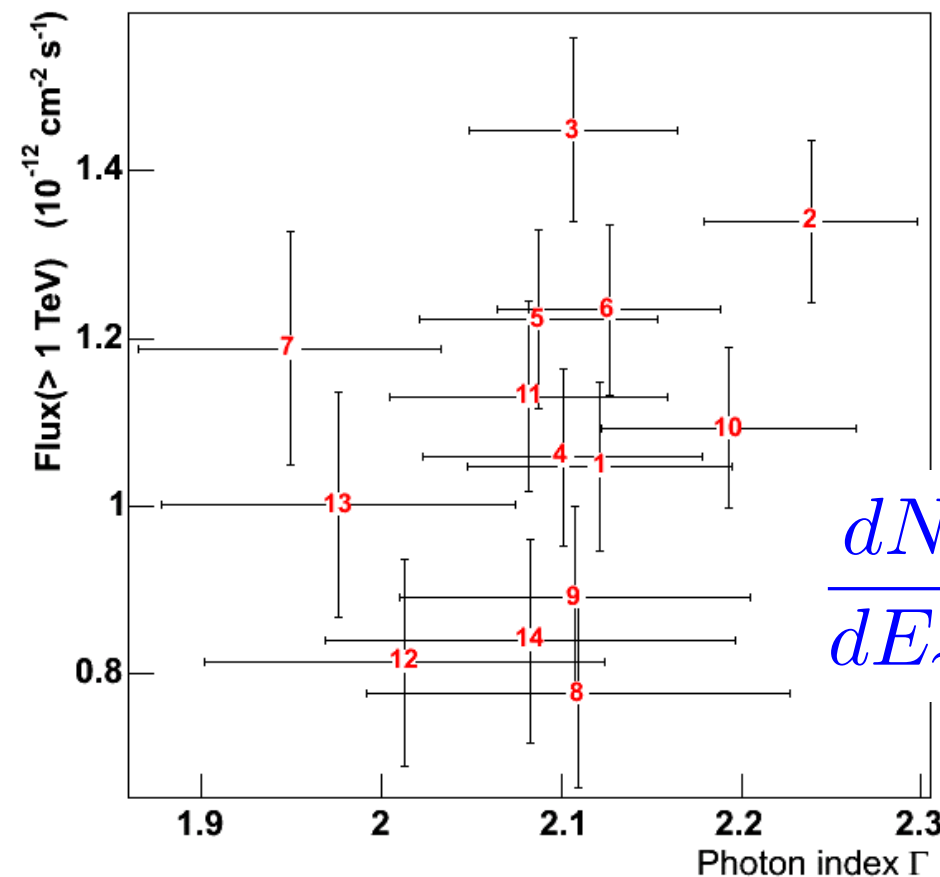
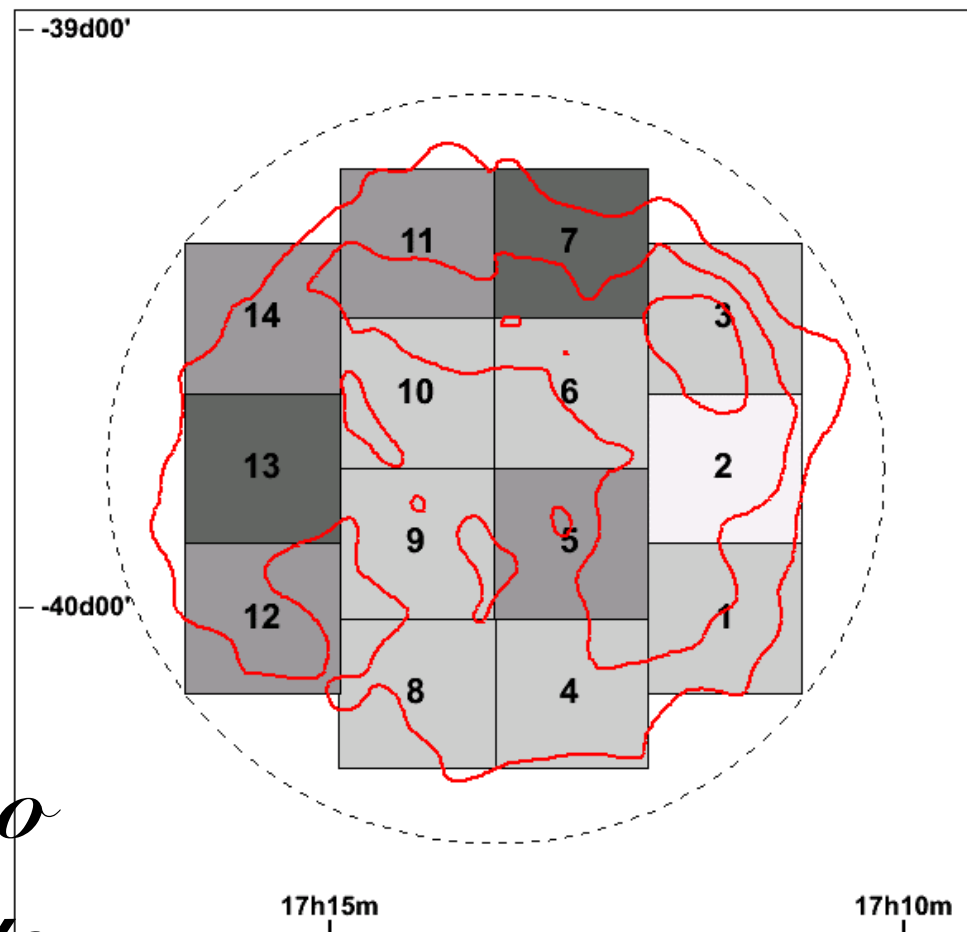
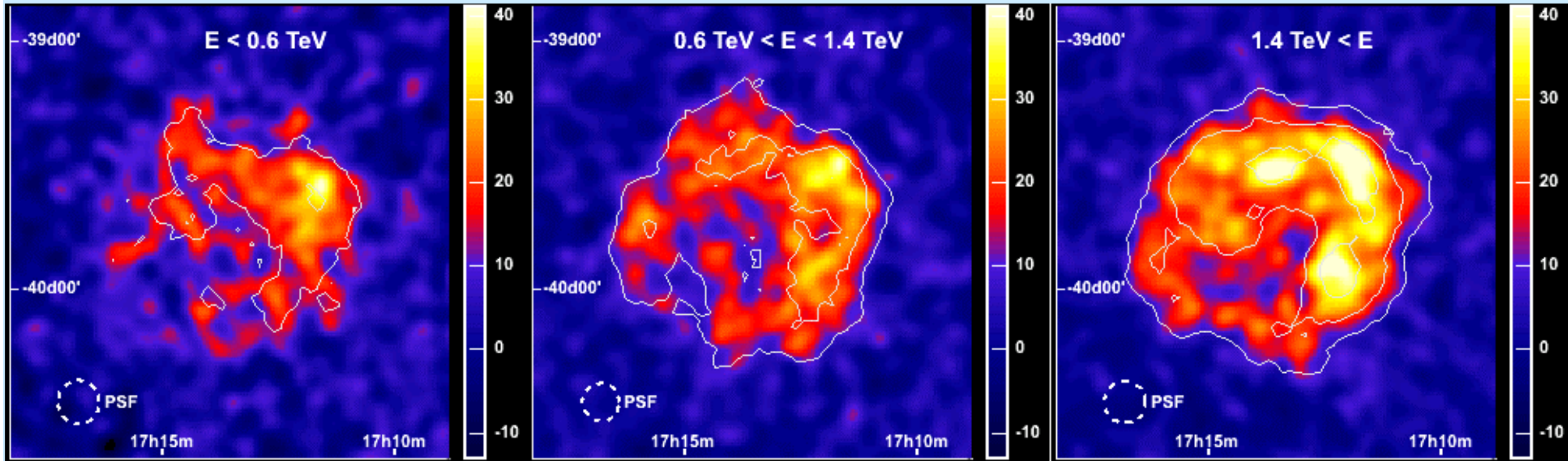
power law with spectral index
-2.0 ... -2.1

Bell, Blanford, Ostriker (1978)



Supernova remnant (SNR)
Cassiopeia A

H.E.S.S. supernova remnant RXJ 1713



$$\frac{dN}{dE_{\gamma}} \propto E_{\gamma}^{-\Gamma}$$

see also
Egberts

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources

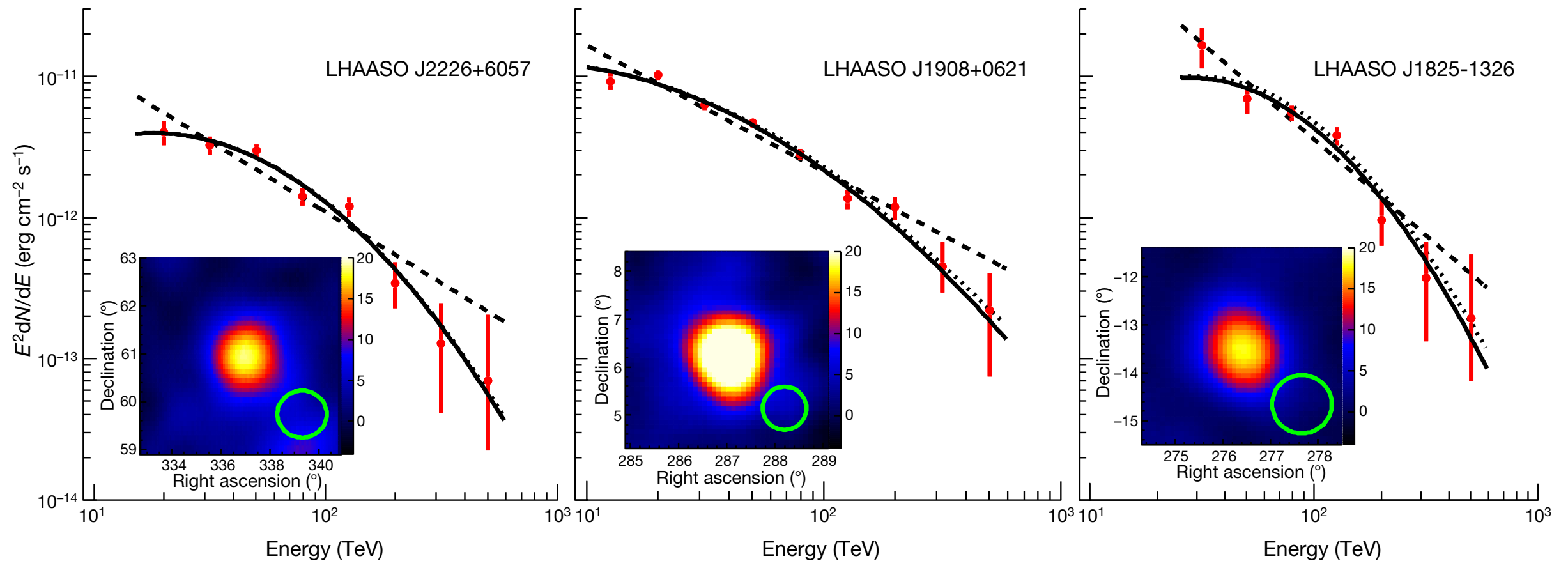


Fig. 1 | Spectral energy distributions and significance maps. a–c, Data are shown for LHAASO J2226+6057 (**a**), LHAASO J1908+0621 (**b**), and LHAASO J1825-1326 (**c**). Spectral fits with a log-parabola function (solid lines) in the form of $[E/(10 \text{ TeV})]^{-a-b \log[E/(10 \text{ TeV})]}$ are compared with the power-law fits $E^{-\Gamma}$ for: $a=1.56$, $b=0.88$ and $\Gamma=3.01$ (**a**); $a=2.27$, $b=0.46$ and $\Gamma=2.89$ (**b**); and $a=0.92$, $b=1.19$ and $\Gamma=3.36$ (**c**). The dotted curves correspond to the log-parabola fits corrected for the interstellar γ - γ absorption (see Methods for the radiation fields and Extended Data Fig. 6 for the opacity curves). The comparison of the power-law (PL) model and the log-parabola (LOG) model with the Akaike Information Criterion²⁰ (AIC) gives: $\text{AIC}_{\text{LOG}}=12.3$ and $\text{AIC}_{\text{PL}}=24.4$ for LHAASO J2226+6057; $\text{AIC}_{\text{LOG}}=15.1$ and $\text{AIC}_{\text{PL}}=30.1$ for LHAASO J1908+0621; and

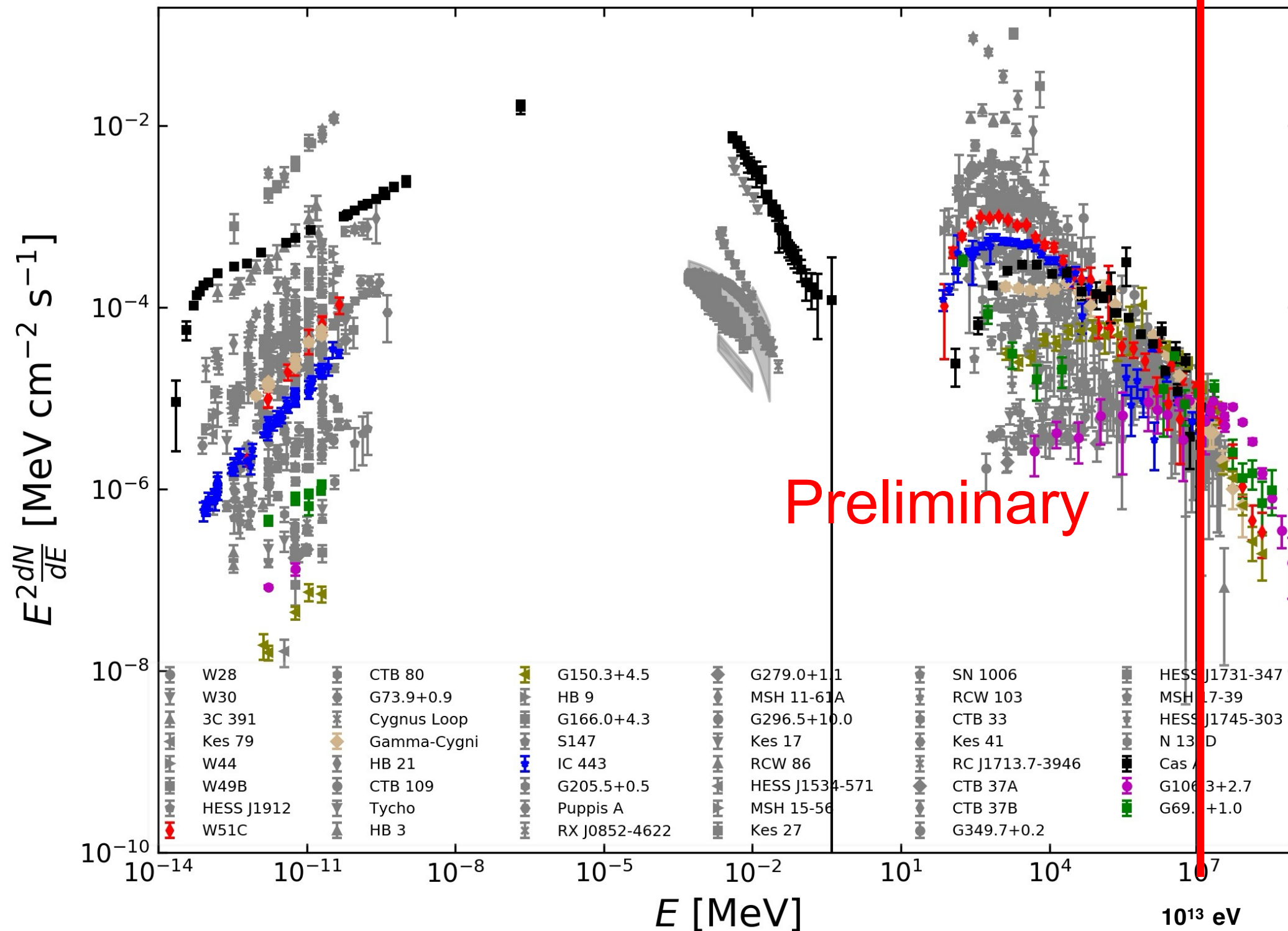
$\text{AIC}_{\text{LOG}}=11.6$ and $\text{AIC}_{\text{PL}}=14.8$ for LHAASO J1825-1326. The insets show the significance maps of the three sources, obtained for γ -rays above 25 TeV. The colour bars show the square root of test statistics (TS), which is equivalent to the significance. The significance ($\sqrt{\text{TS}}$) maps are smoothed with the Gaussian-type point spread function (PSF) of each source. The size of PSFs (68% contamination regions) are shown at the bottom right of each map. We note that the PSFs of the three sources are slightly different owing to different inclination angles. Namely, the 68% contamination angles are 0.49° for LHAASO J2226+6057, 0.45° for LHAASO J1908+0621 and 0.62° for LHAASO J1825-1326. Error bars represent one standard deviation.

see also Gao

$\text{CR} + \text{ISM} \rightarrow \pi^0 \rightarrow \gamma$
also ambiguities due to e/m channels

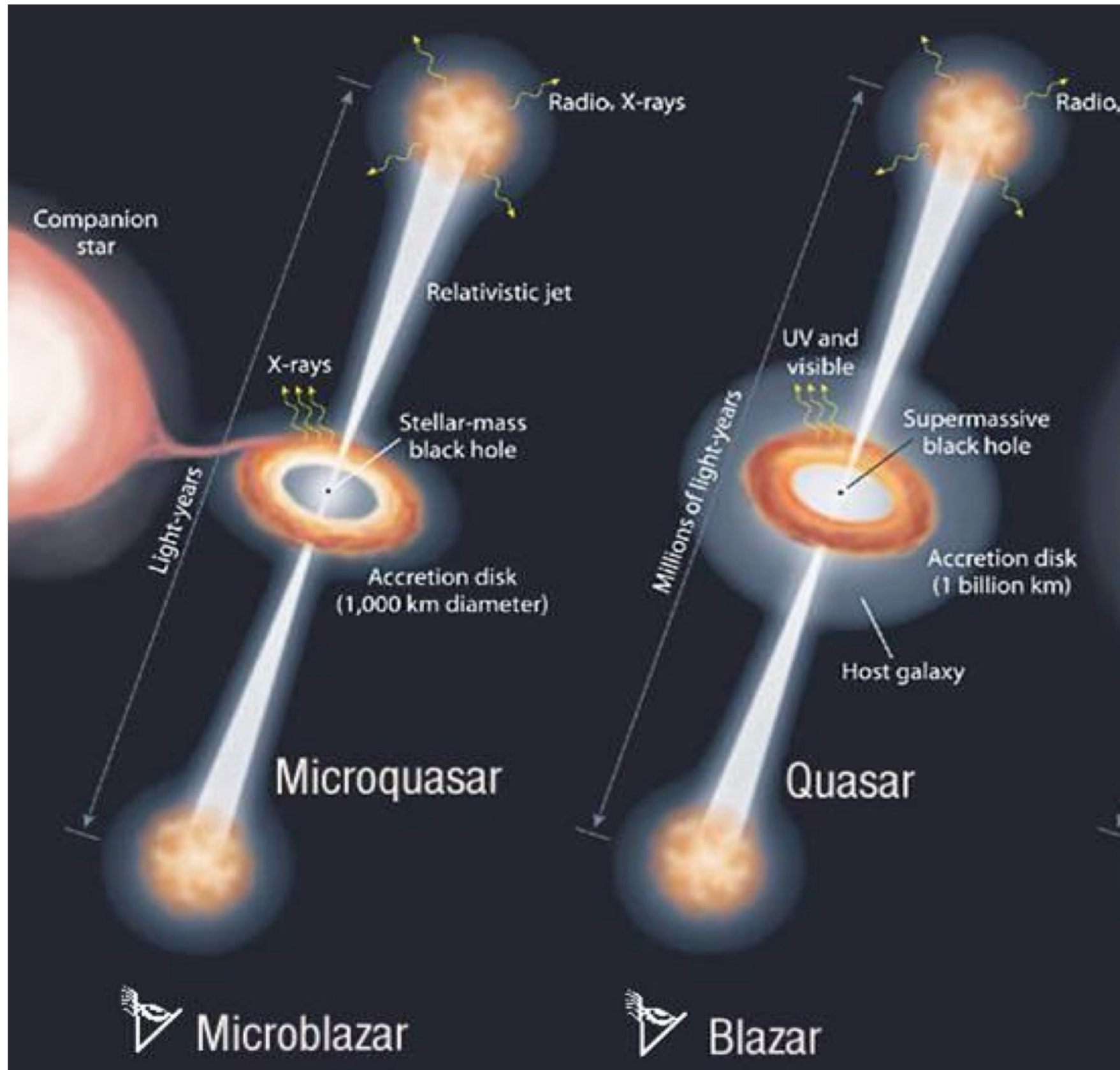
SNR detected by LHAASO

Cas A; IC 443; W51C; Gamma-Cygni; G106.3+2.7; G69.7+1.0; G150.3+4.5



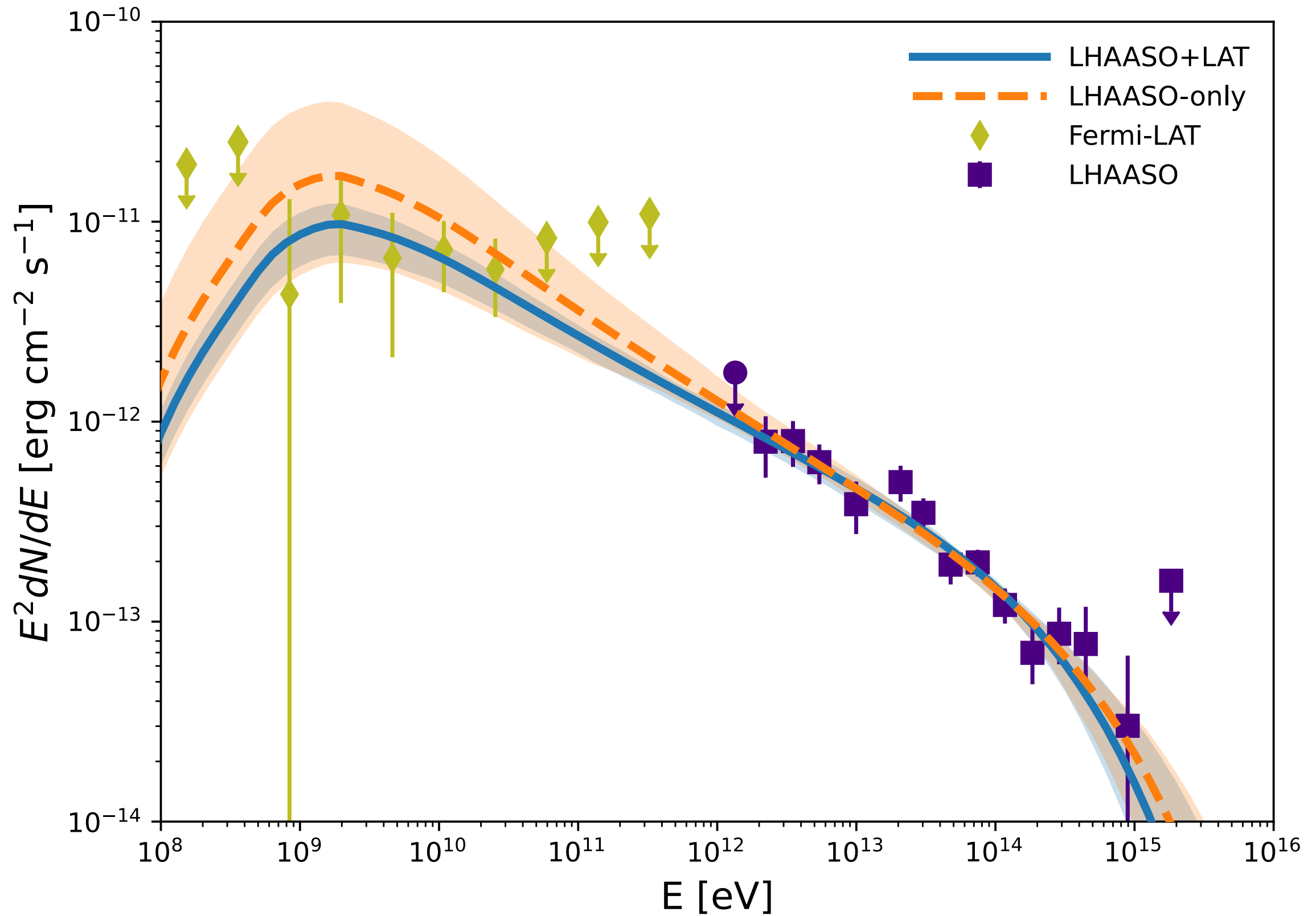
10TeV

Microquasar and Quasar

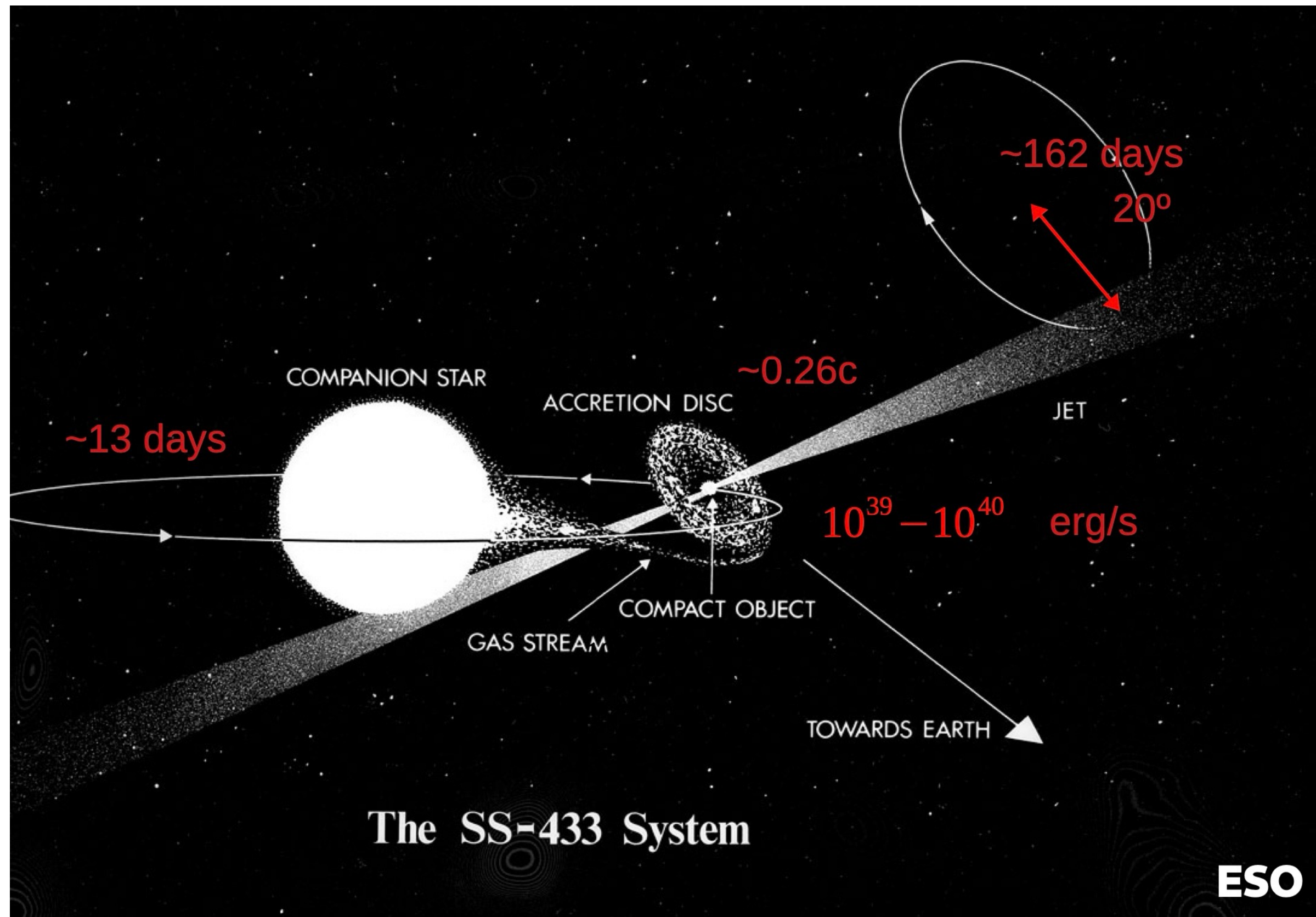


From F.Mirabel,
1206.1041

LHAASO GRS 1915+105

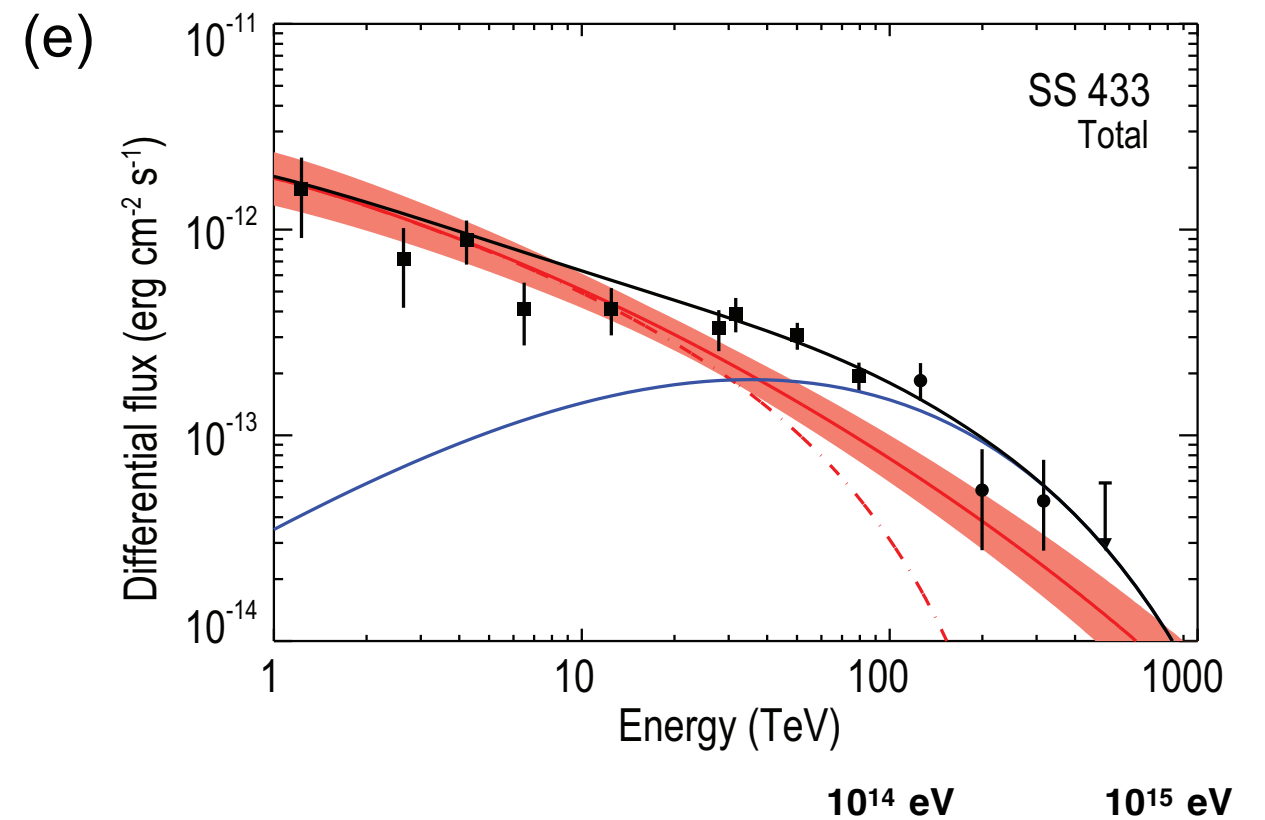
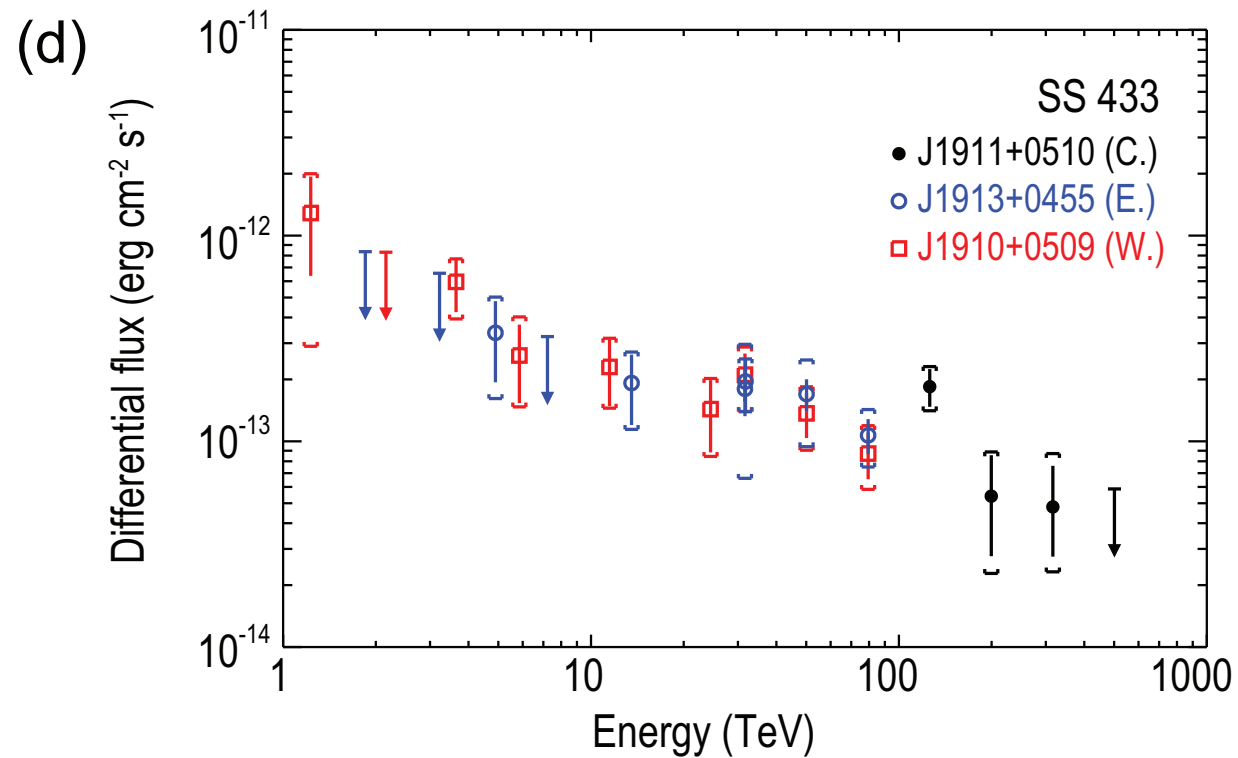
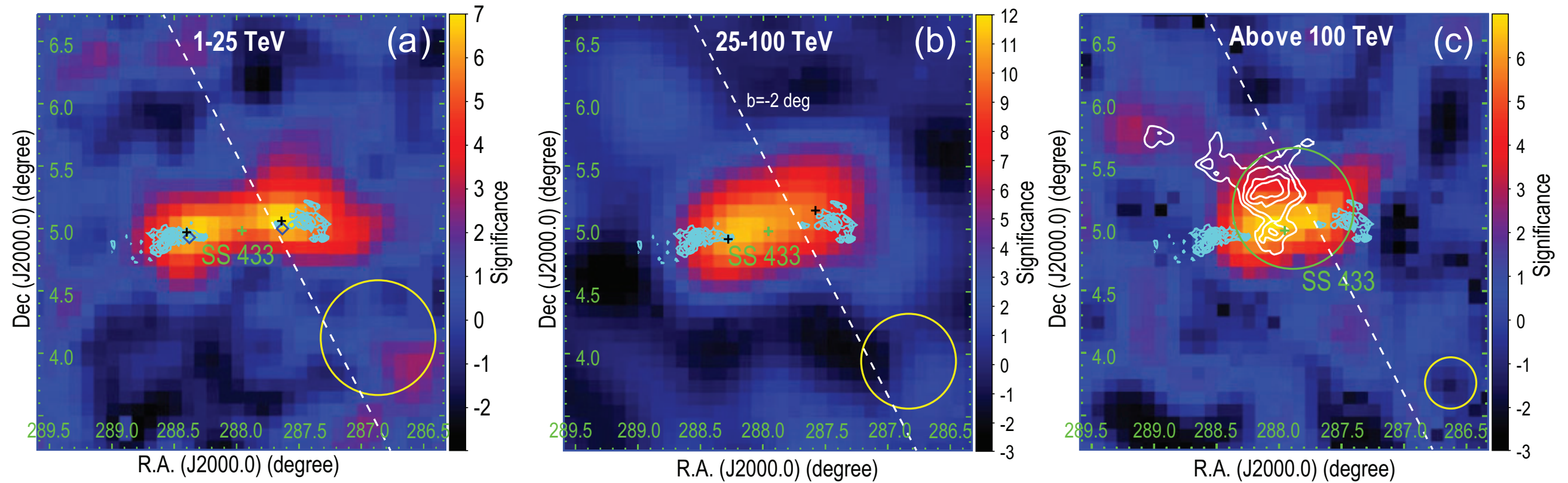


SS-433 central engine

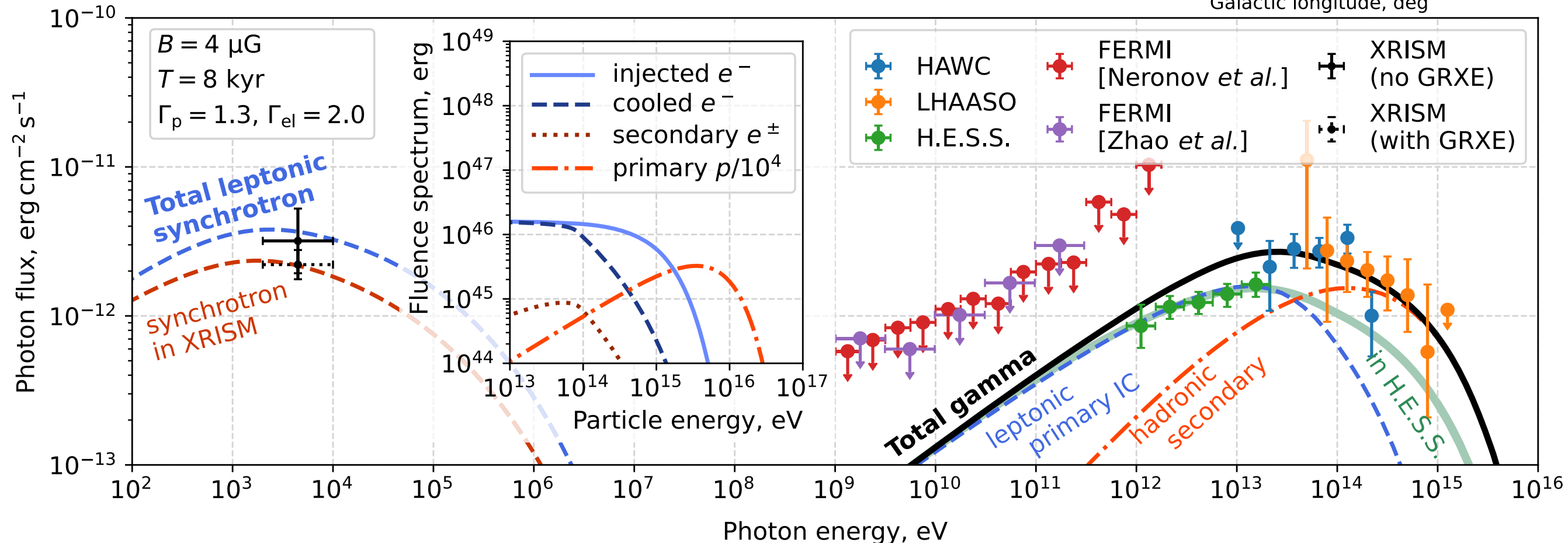
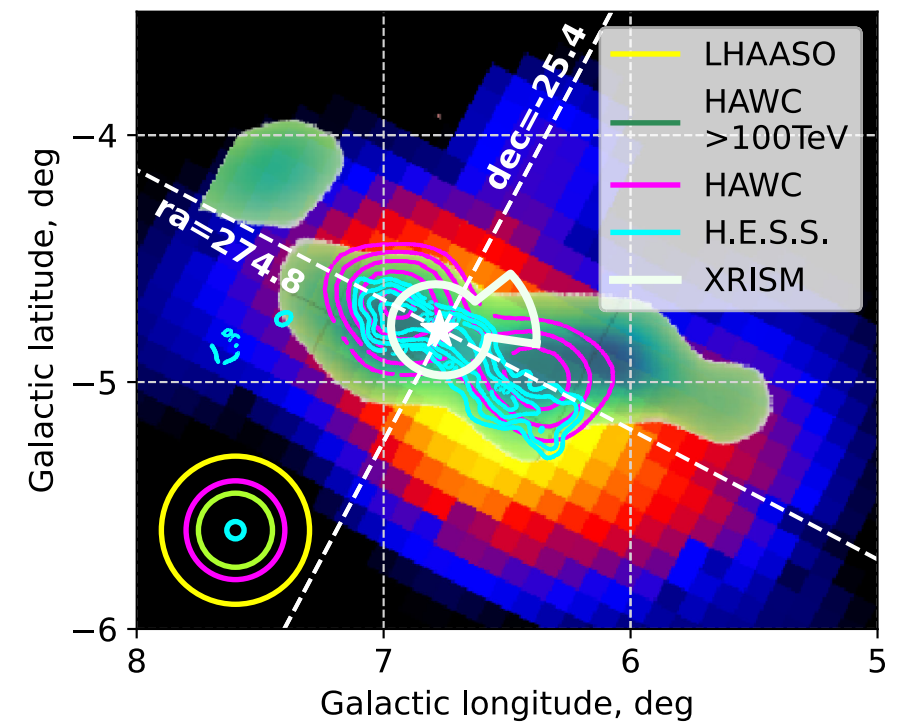
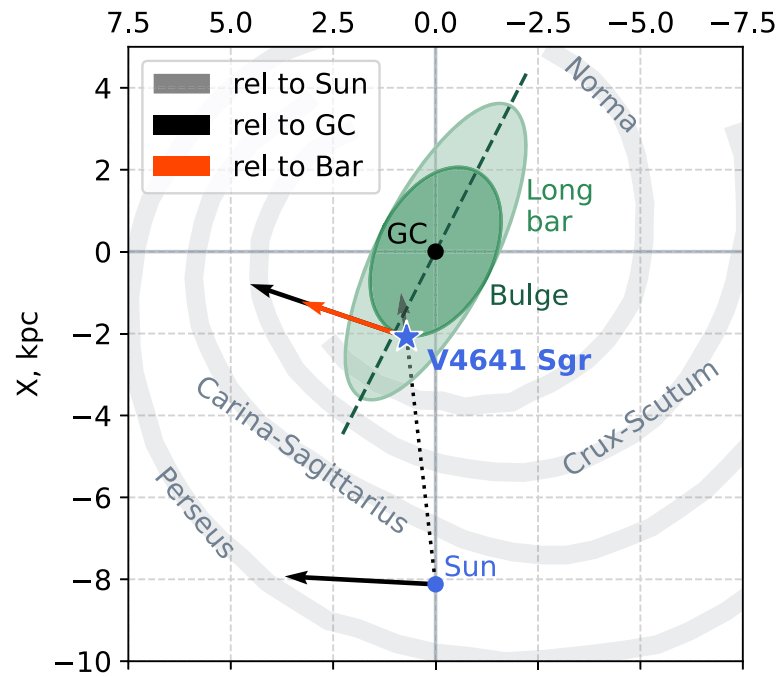


At distance 5.5 kpc towards central Galaxy $l=39.7$ $b=-2.2$

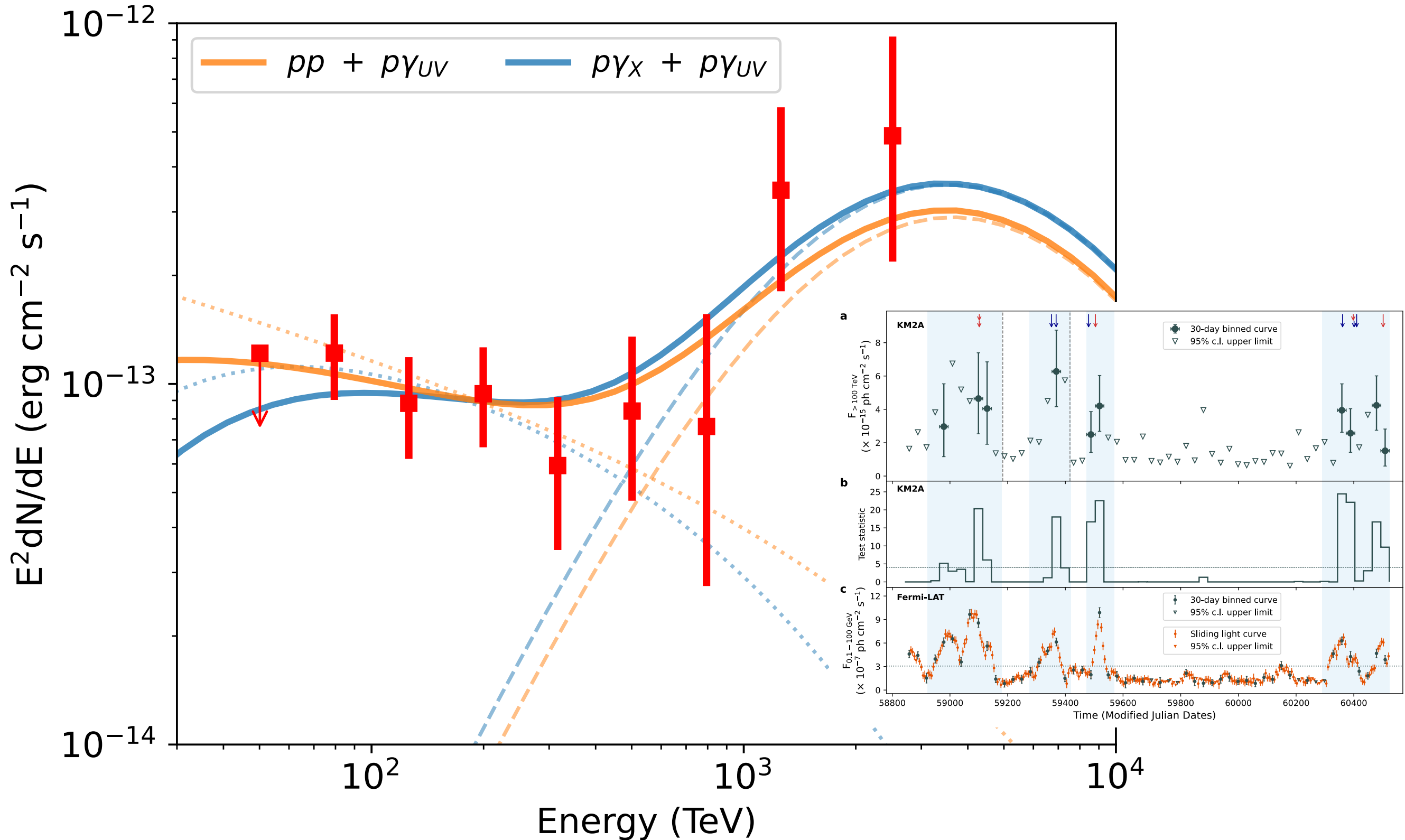
LHAASO - SS-433



Leptonic and hadronic models of the high-energy nebula around V4641 Sgr



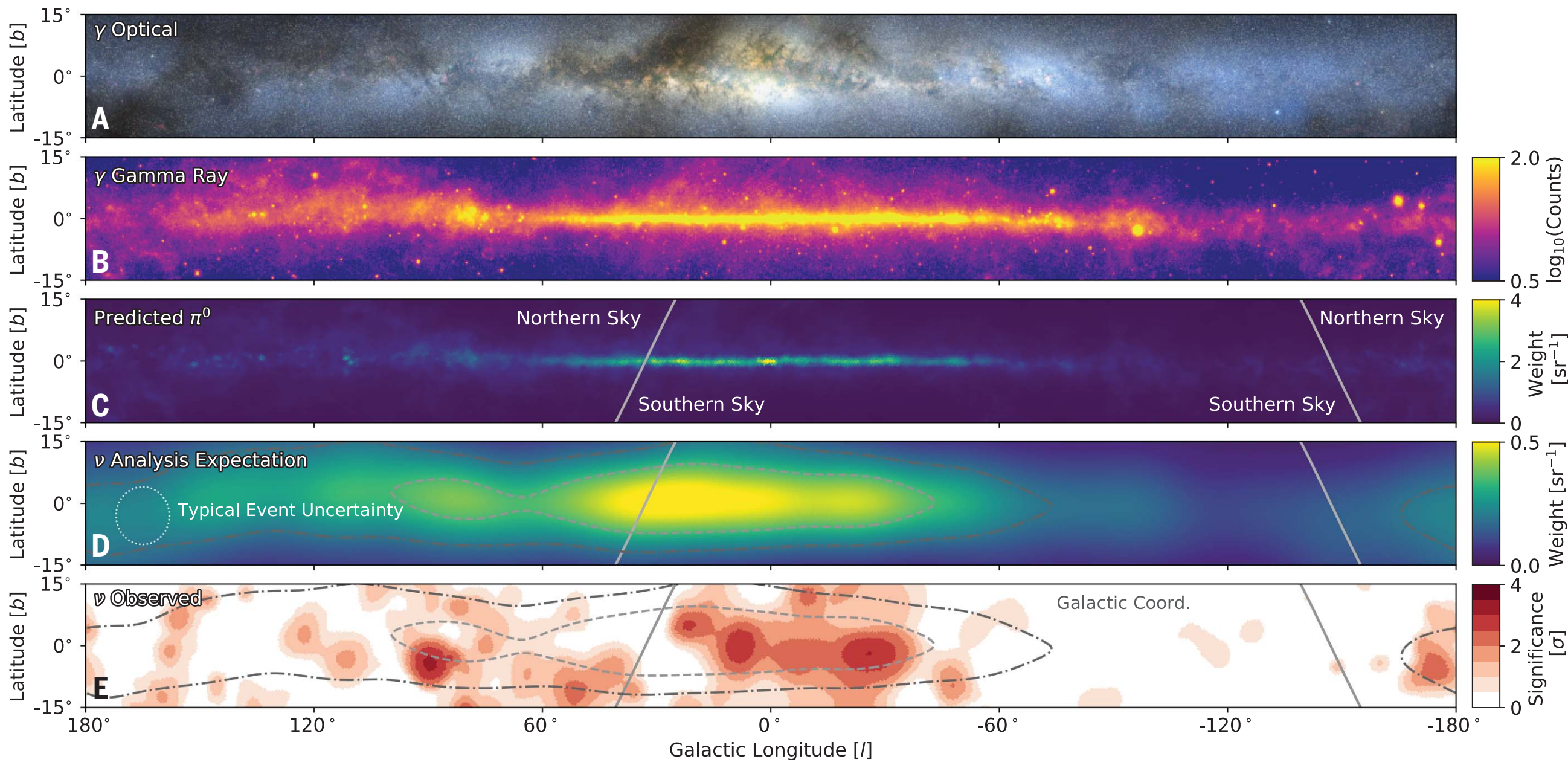
Highest-energy photon detected from any source in the sky $E=3.7$ PeV



Observation of high-energy neutrinos from the Galactic plane

*see also
Halzen*

IceCube Collaboration*†



$$\text{CR} + \text{ISM} \rightarrow \pi^{\pm} \rightarrow \nu$$

Transport equation for cosmic rays in the Galaxy

diffusion

energy loss (Bethe Bloch)

loss through interactions
with ISM (spallation)

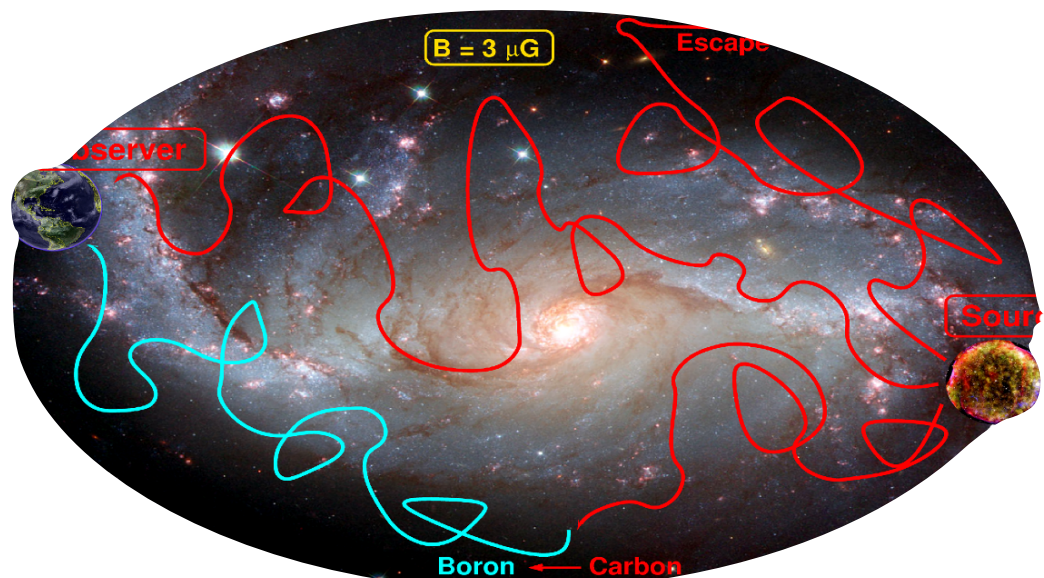
loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E} (E N_i) - n \nu \sigma_i N_i - \frac{N_i}{\gamma \tau_i} + Q_i + \sum_{j>i} n \nu \sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

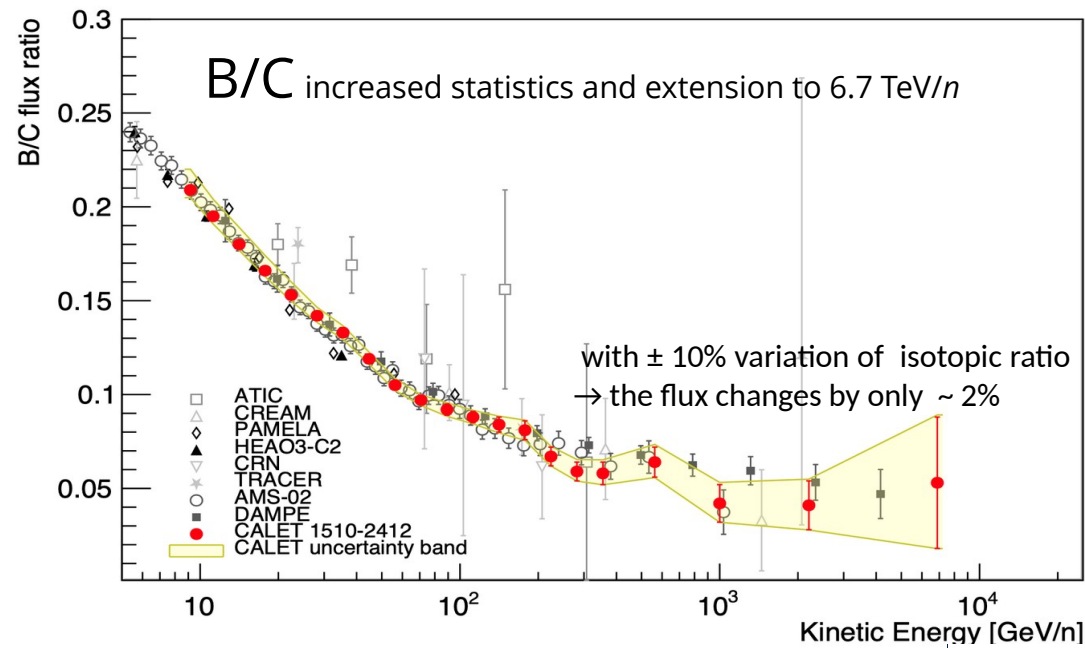
source term

production through spallation
of heavy nuclei

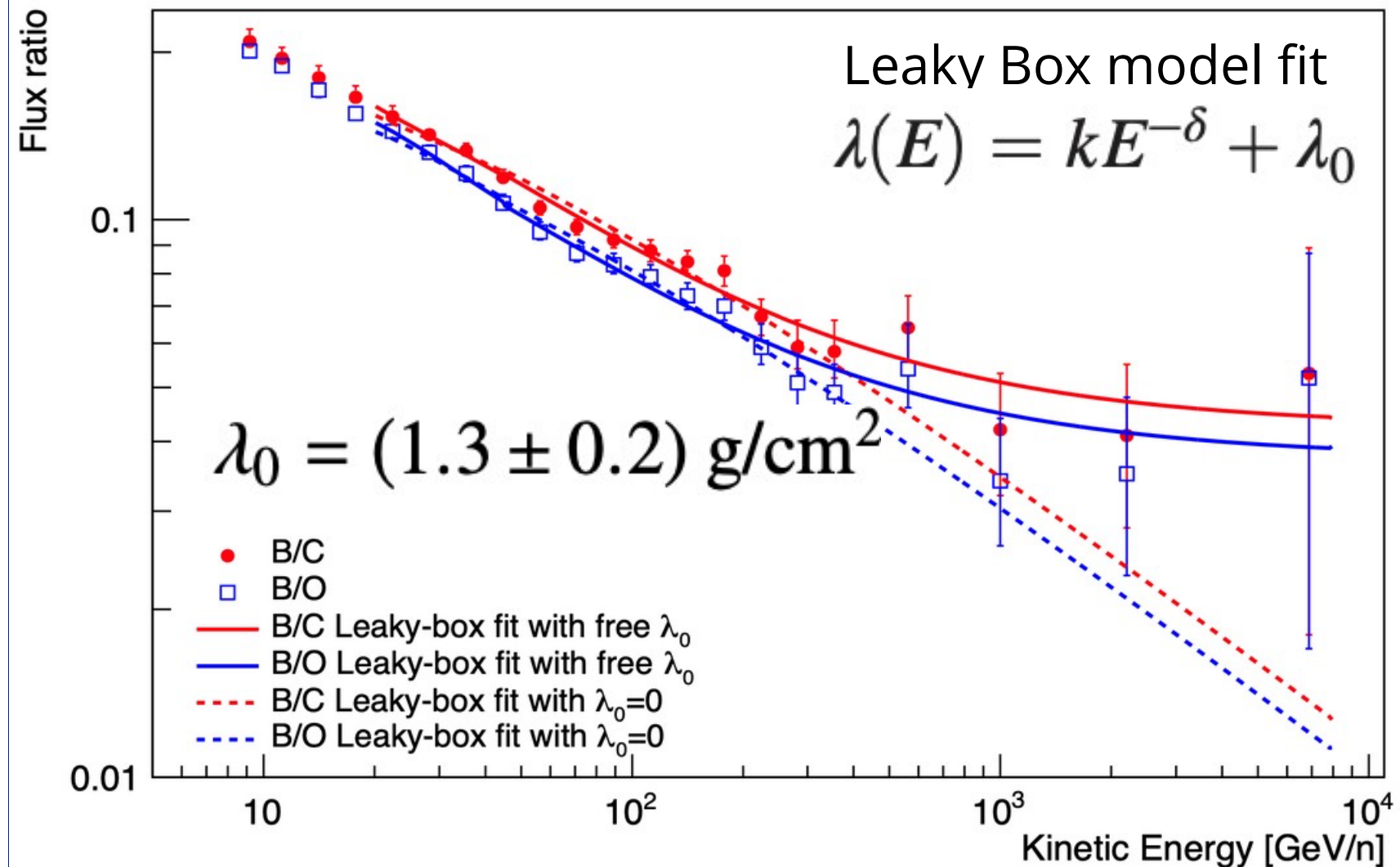
production through decay
of heavy nuclei



Pathlength of cosmic rays in Galaxy



CALET



Pathlength vs. interaction length

pathlength in Galaxy

$$\lambda_{esc} = 5 - 10 \text{ g/cm}^2$$

interaction length

nuclear radius

$$r = r_0 A^{1/3} \quad r_0 = 1.3 \cdot 10^{-13} \text{ cm}$$

cross section

$$\sigma_{p-A} = \pi (r_p + r_0 A^{1/3})^2$$

ISM: protons

$$n = 1/\text{cm}^3 \quad \rho = 1.67 \cdot 10^{-24} \text{ g/cm}^3$$

interaction length

$$\lambda_{p-A} = \frac{\rho}{\sigma_{p-A} \cdot n}$$

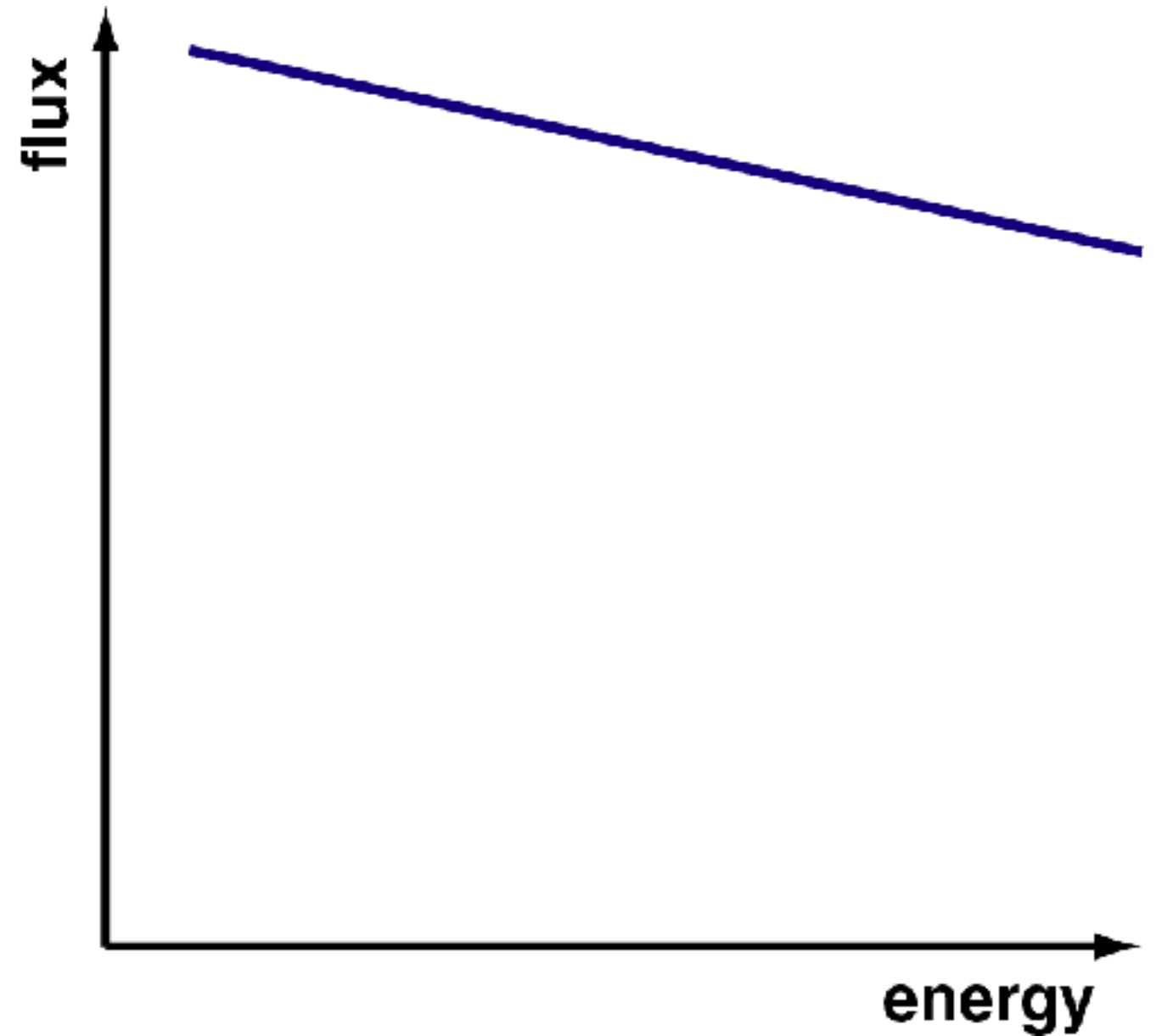
$$\lambda_{p-p} = 21 \text{ g/cm}^2 > \lambda_{esc}$$

$$\lambda_{p-Fe} = 1.6 \text{ g/cm}^2 < \lambda_{esc}$$

Shape of energy spectrum

$$\frac{dN}{dE} \propto E_0^\gamma$$

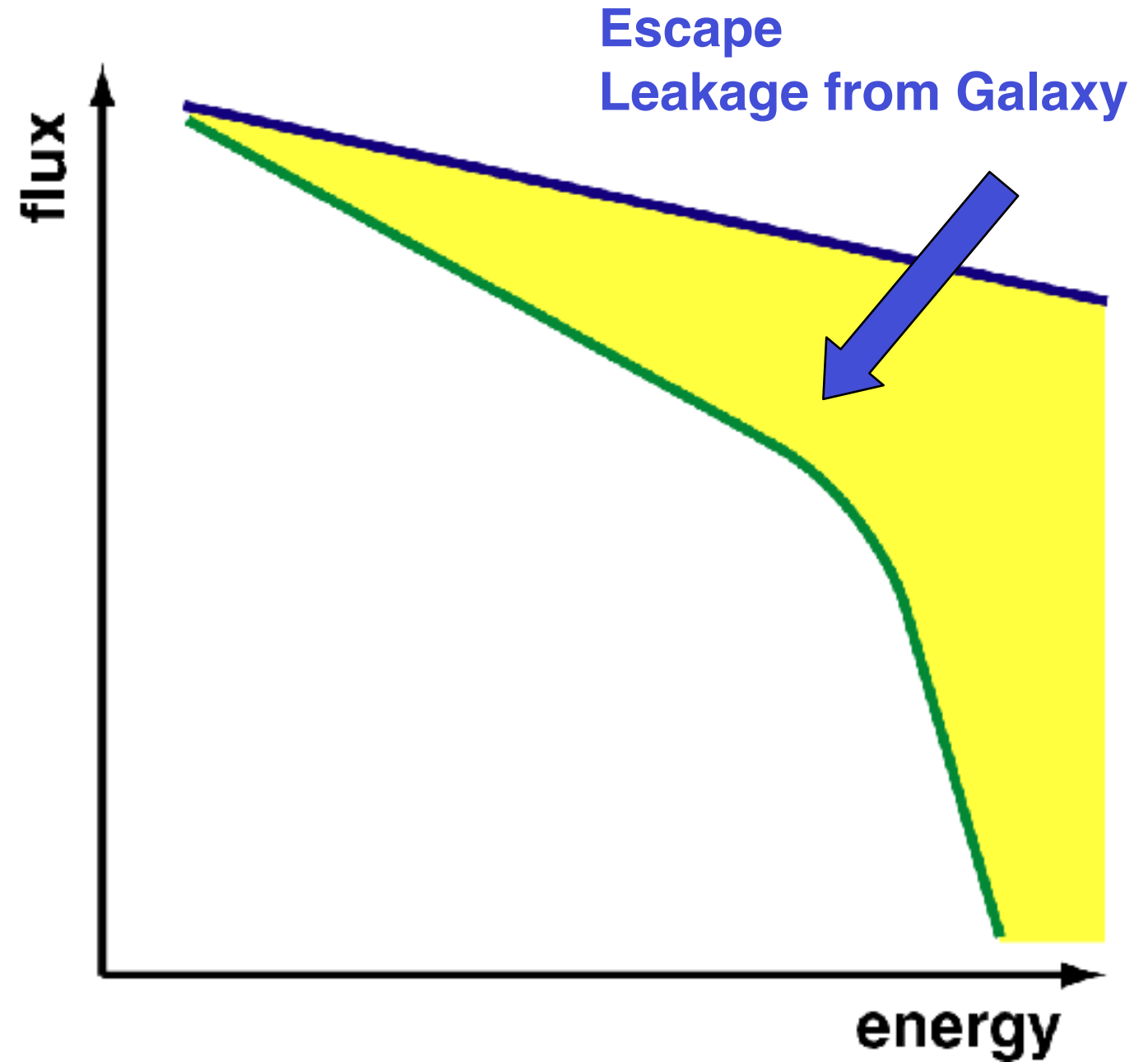
at source $\gamma \sim -2.1$



Shape of energy spectrum

$$\frac{dN}{dE} \propto E_0^\gamma$$

at source $\gamma \sim -2.1$

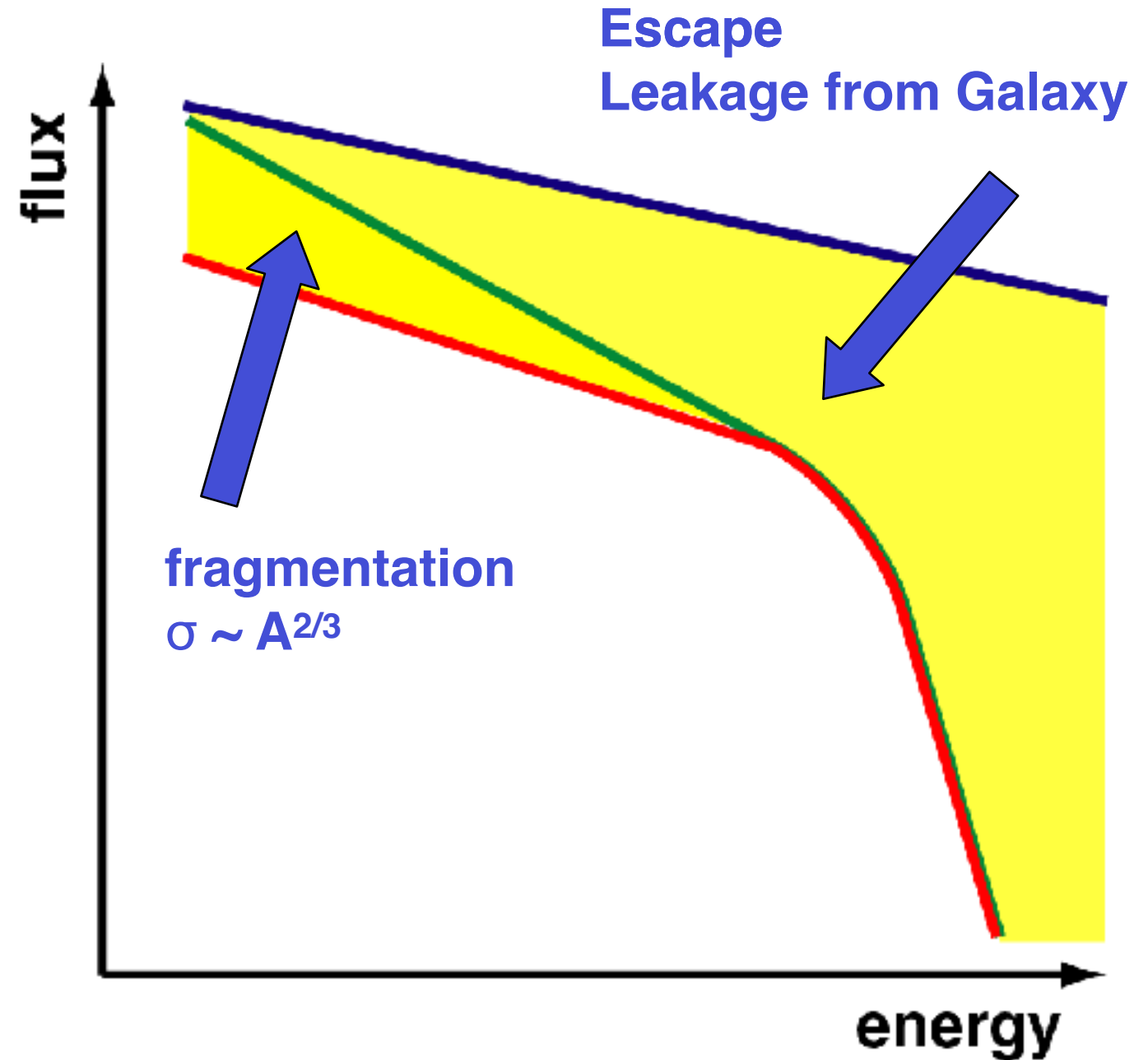


Shape of energy spectrum

$$\frac{dN}{dE} \propto E_0^\gamma$$

at source $\gamma \sim -2.1$

at Earth $\gamma \sim -2.6$ to -2.7



Shape of energy spectrum

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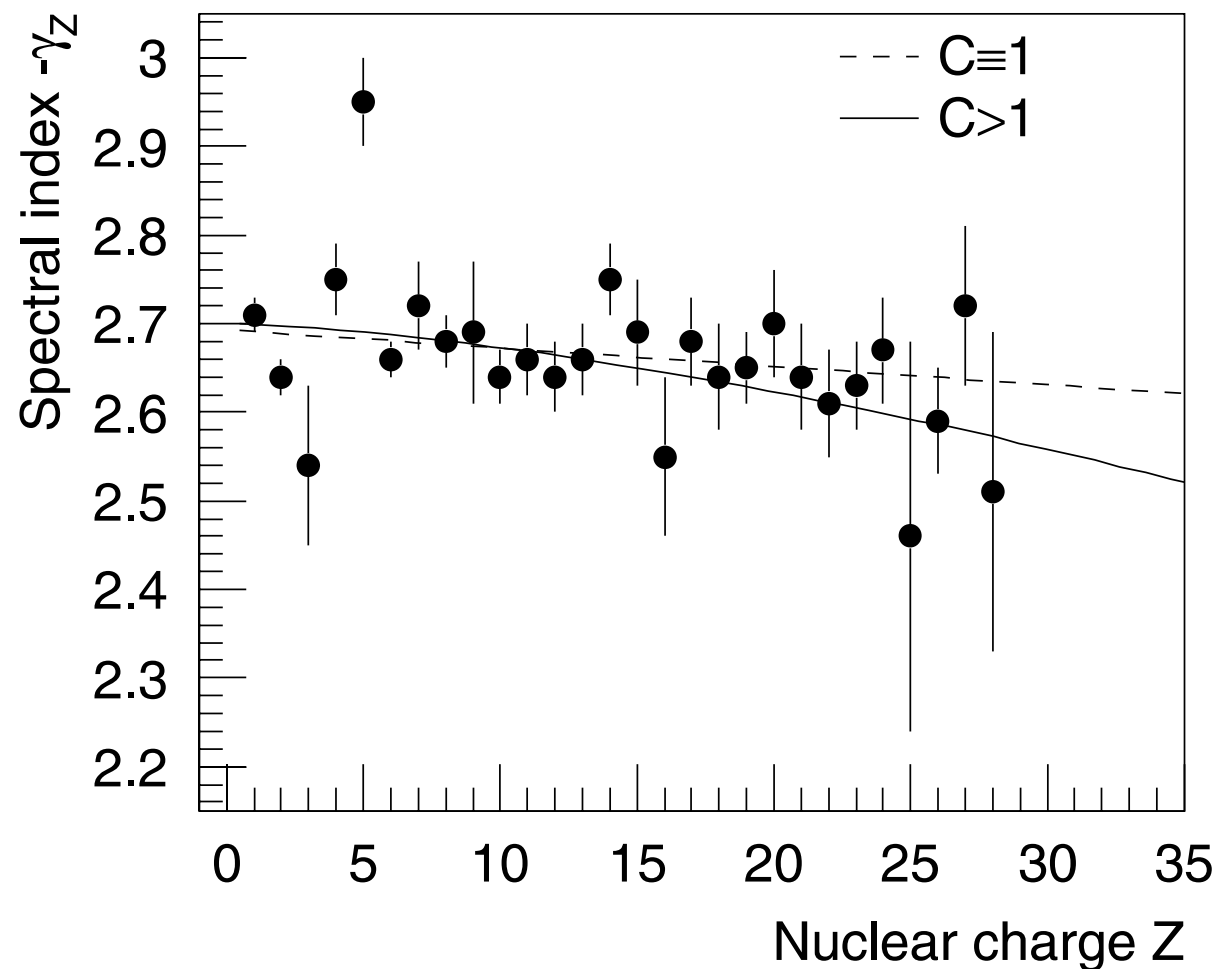
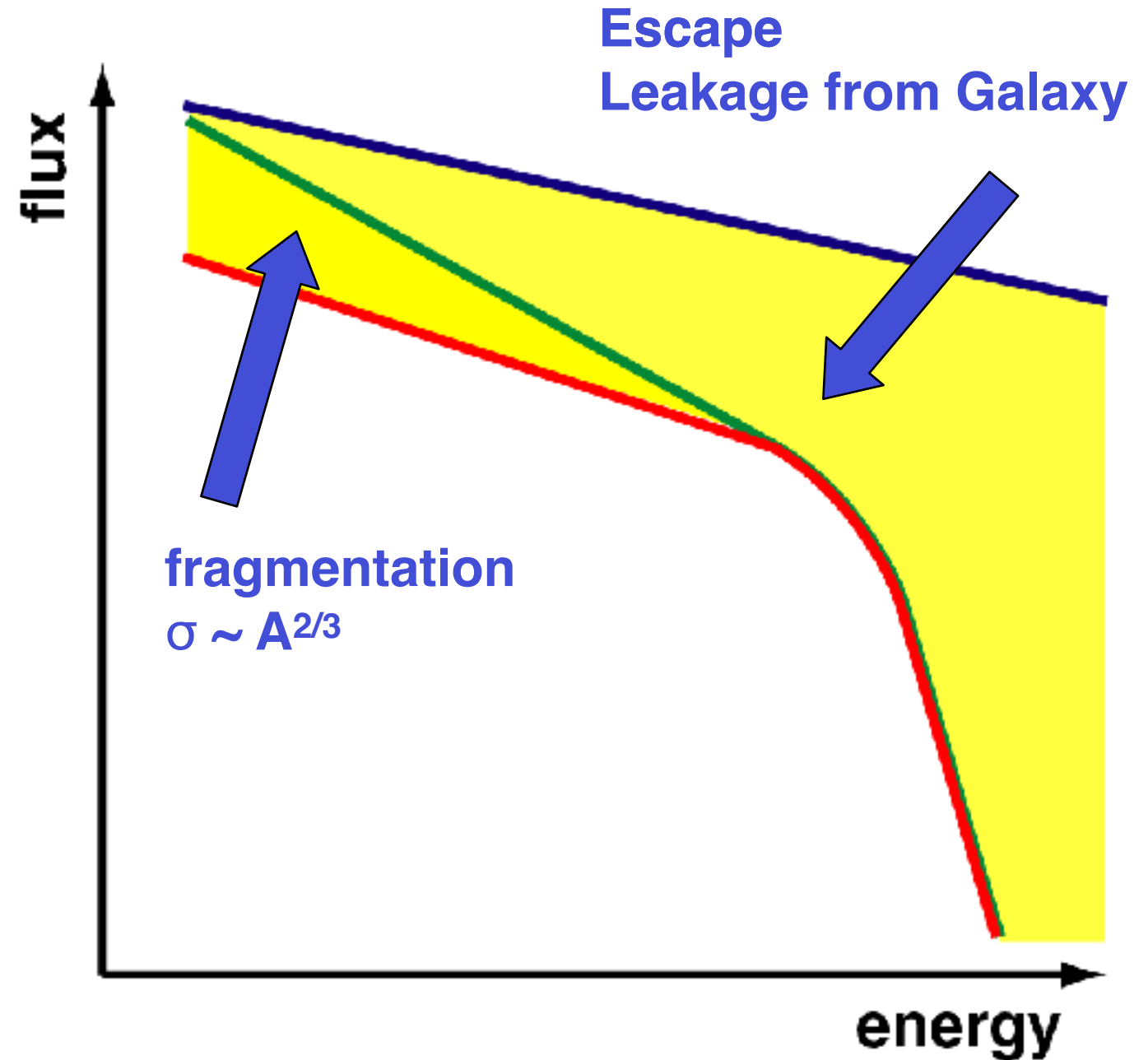


Fig. 5. Spectral index γ_Z versus nuclear charge Z (see Table 1). The solid line represents a three parameter fit according to Eq. (6), the dashed graph a linear fit.



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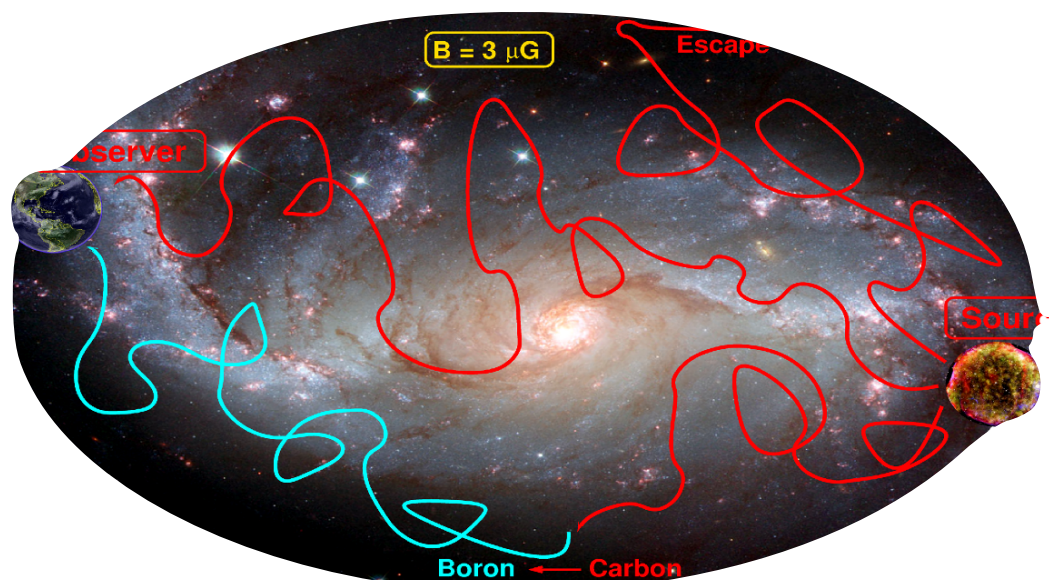
loss through radioactive decay

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source term

production through spallation
of heavy nuclei

production through decay
of heavy nuclei



Propagation of super-high-energy cosmic rays in the Galaxy

Jörg R. Hörandel ^{a,*}, Nikolai N. Kalmykov ^b, Aleksei V. Timokhin ^c

The steady-state diffusion equation for the cosmic-ray density $N(r)$ is (neglecting nuclear interactions and energy losses)

$$-\nabla_i D_{ij}(r) \nabla_j N(r) = Q(r). \quad (1)$$

$Q(r)$ is the cosmic-ray source term and $D_{ij}(r)$ the diffusion tensor.

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Under the assumption of azimuthal symmetry and taking into account the predominance of the toroidal component of the magnetic field, Eq. (1) is presented in cylindrical coordinates as

$$\left[-\frac{1}{r} \frac{\partial}{\partial r} r D_{\perp} \frac{\partial}{\partial r} - \frac{\partial}{\partial z} D_{\perp} \frac{\partial}{\partial z} - \frac{\partial}{\partial z} D_A \frac{\partial}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} r D_A \frac{\partial}{\partial z} \right] N(r, z) = Q(r, z), \quad (2)$$

where $N(r, z)$ is the cosmic-ray density averaged over the large-scale fluctuations with a characteristic scale $L \sim 100$ pc [3]. $D_{\perp} \propto E^m$ is the diffusion coefficient, where m is much less than one ($m \approx 0.2$), and $D_A \propto E$ the Hall diffusion coefficient. The influence of Hall diffusion becomes predominant at high energies ($>10^{15}$ eV). The sharp

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The magnetic field of the Galaxy consists of a large-scale regular and a chaotic, irregular component $\vec{B} = \vec{B}_{\text{reg}} + \vec{B}_{\text{irr}}$. A purely azimuthal magnetic field was assumed for the regular field

$$B_z = 0, \quad B_r = 0, \quad B_{\phi} = 1 \mu\text{G} \exp \left(-\frac{z^2}{z_0^2} - \frac{r^2}{r_0^2} \right),$$

where $z_0 = 5$ kpc and $r_0 = 10$ kpc are constants [3].

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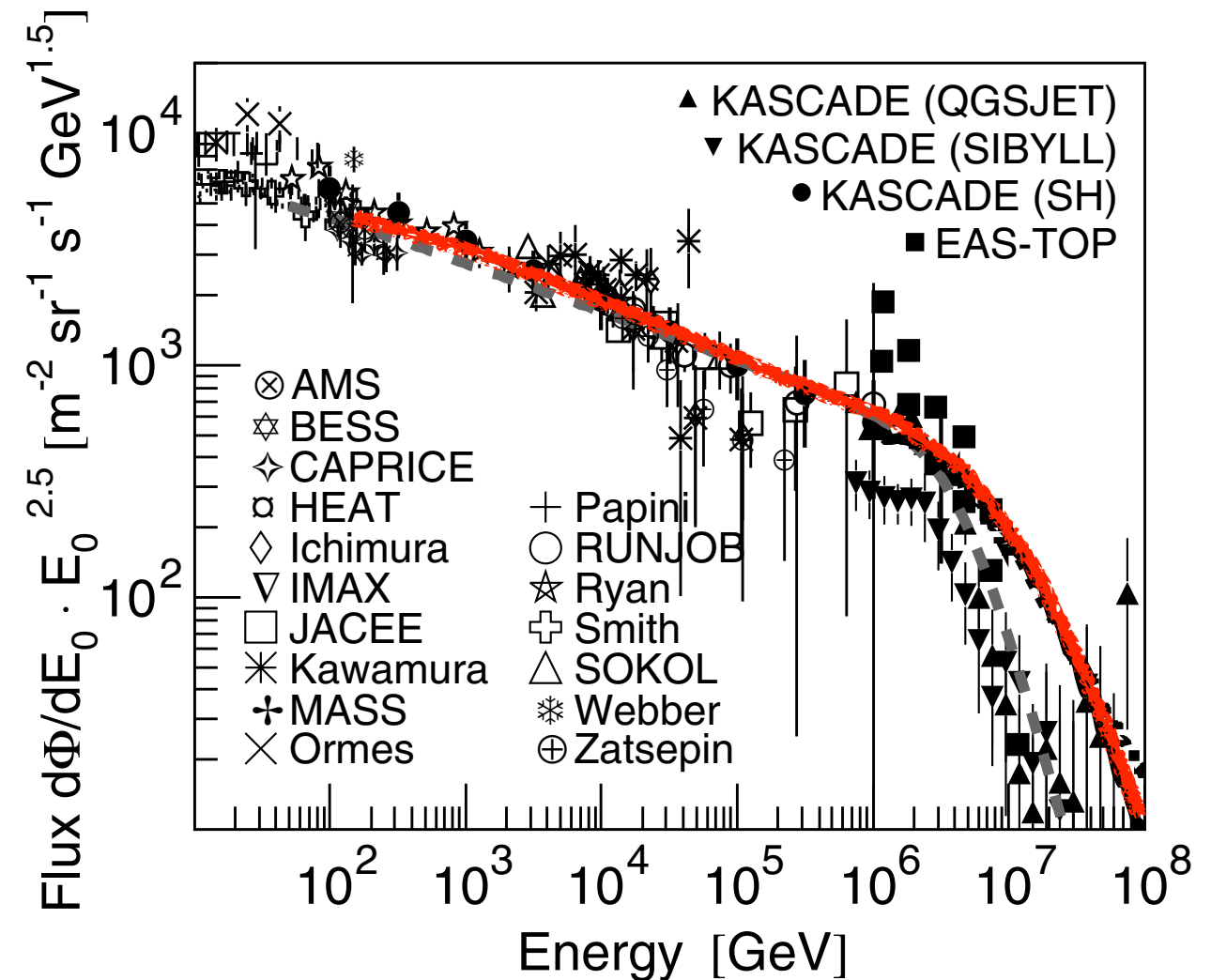


Fig. 7. Proton flux as obtained from various measurements, for references see [28], compared to the spectra shown in Fig. 6 (black lines) and the *polygono* model [26] (grey, dashed line).

Transition to extragalactic CR component

J. Blümer et al. / Progress in Particle and Nuclear Physics 63 (2009) 293–338

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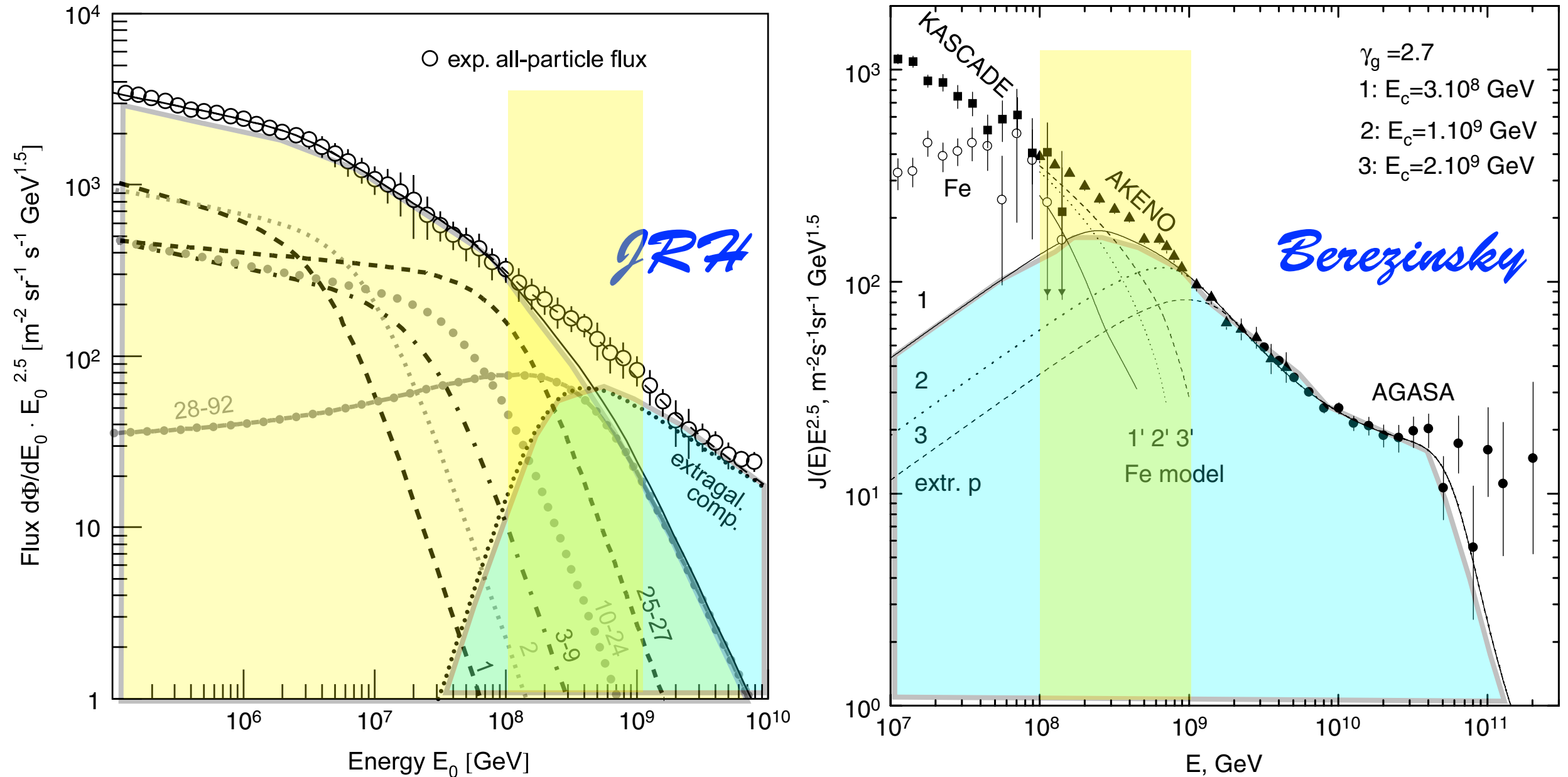
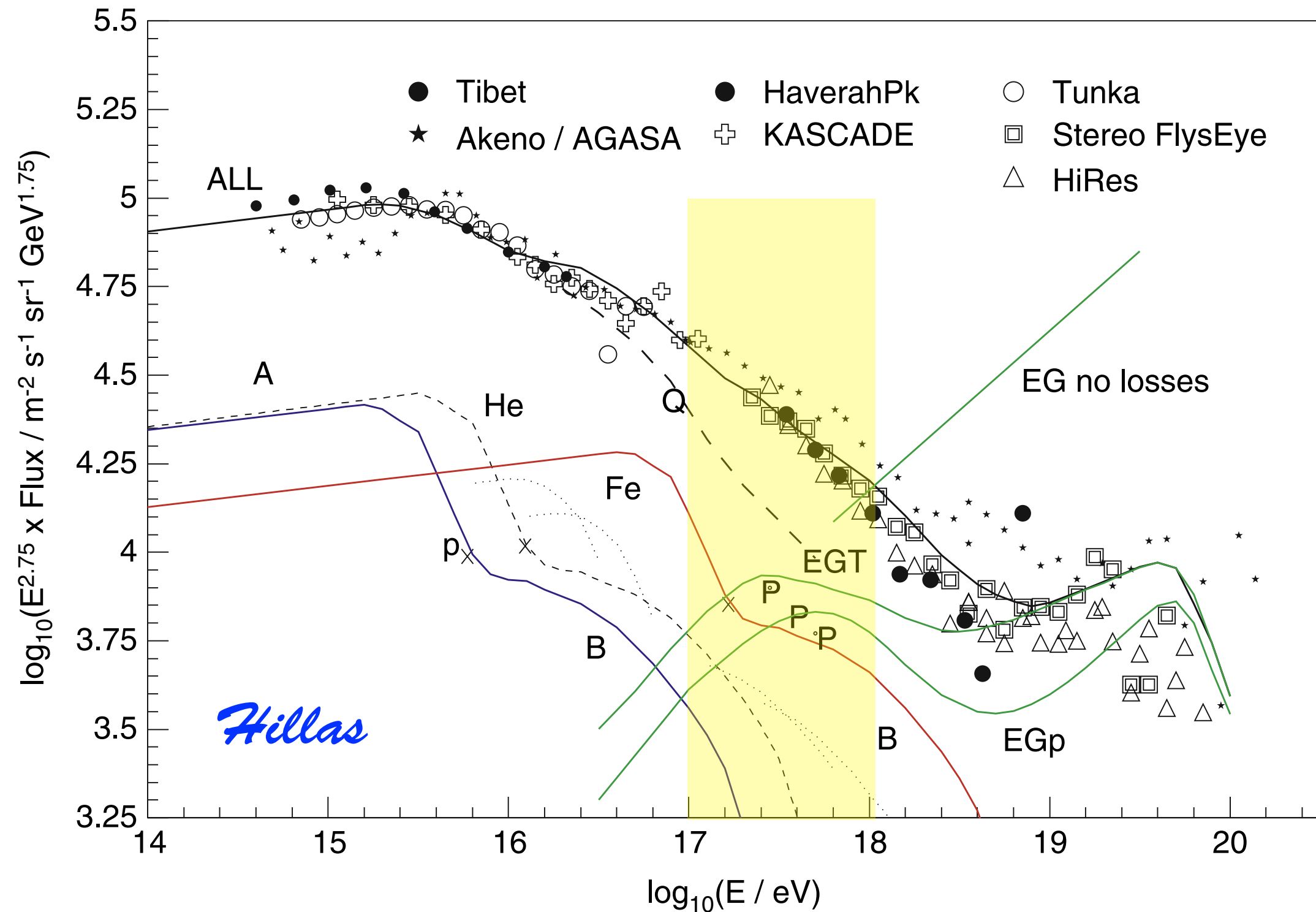


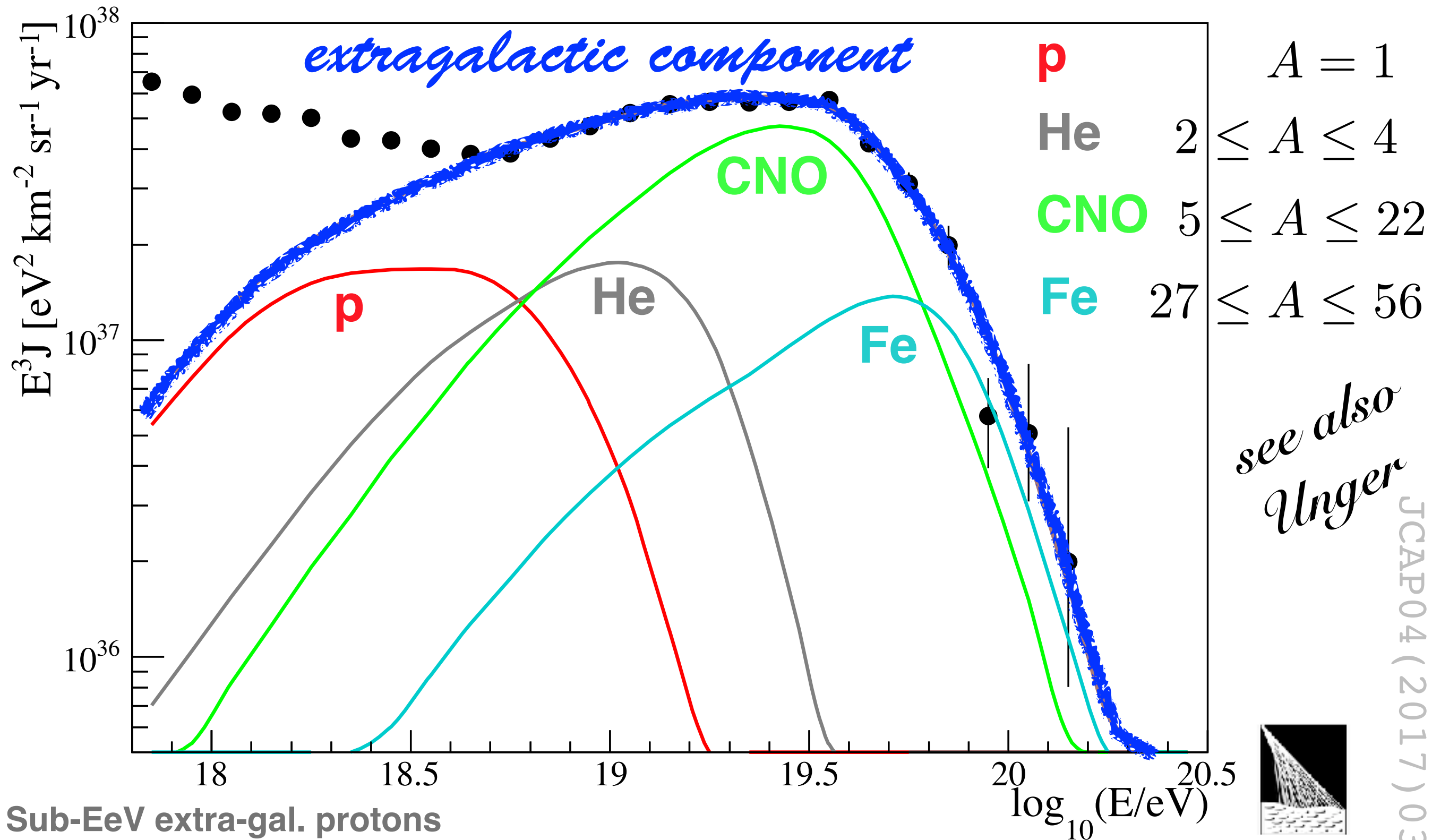
Fig. 26. *Left panel:* Cosmic-ray energy spectra according to the poly-gonato model [2]. The spectra for groups of elements are labeled by their respective nuclear charge numbers. The sum of all elements yields the galactic all-particle spectrum (—) which is compared to the average measured flux. In addition, a hypothetical extragalactic component is shown to account for the observed all-particle flux (---). *Right panel:* Transition from galactic to extragalactic cosmic rays according to Berezhinsky et al. [451]. Calculated spectra of extragalactic protons (curves 1, 2, 3) and of galactic iron nuclei (curves 1', 2', 3') are compared with the all-particle spectrum from the Akeno and AGASA experiments. KASCADE data are shown as filled squares for the all-particle flux and as open circles for the flux of iron nuclei.

Transition to extragalactic CR component



„classical“ supernovae + additional component

Combined fit of spectrum and
composition data as measured by the
Pierre Auger Observatory



*see also
Unger*

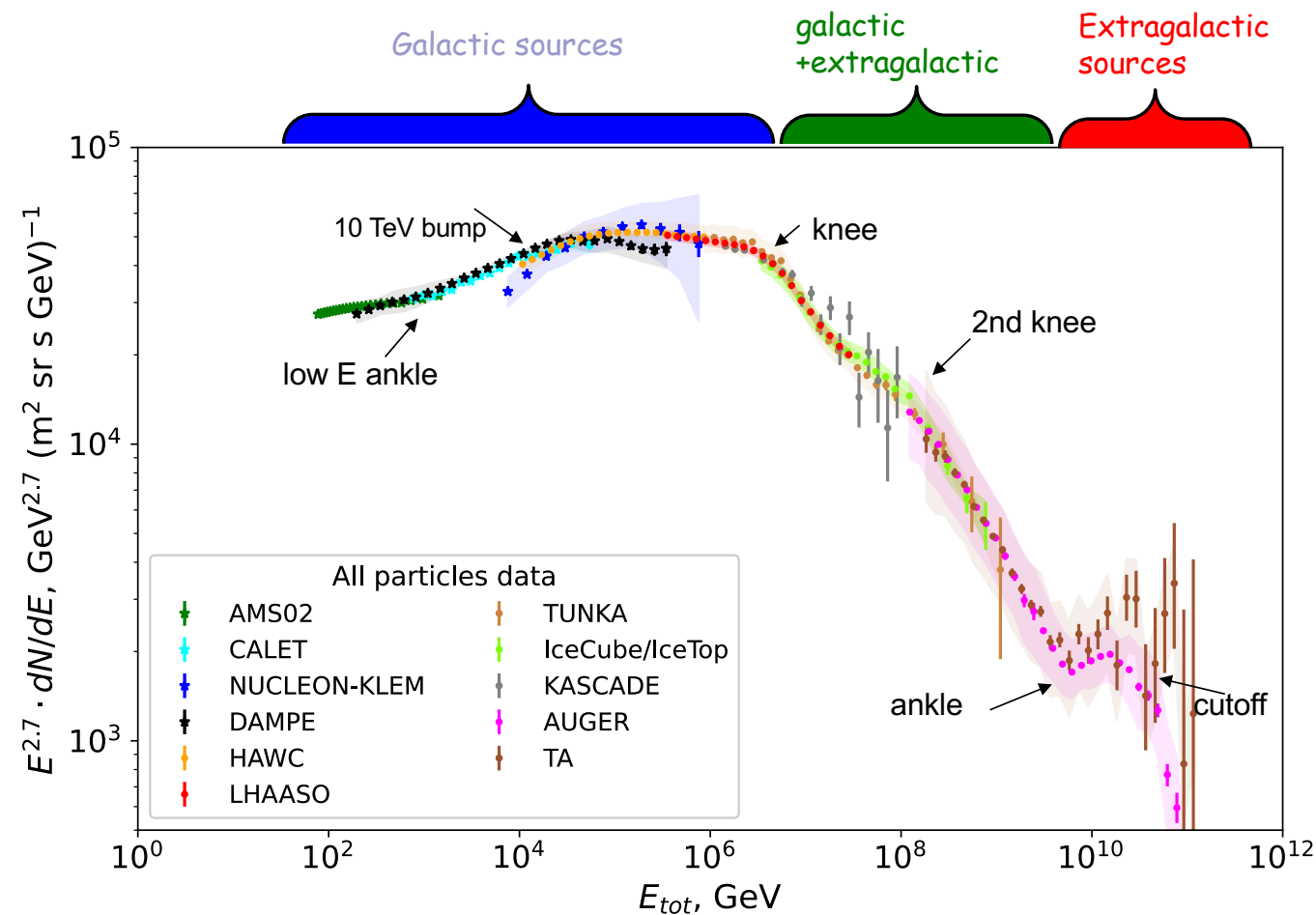


JCAP04(2017)038

Sub-EeV extra-gal. protons
from interactions of heavier
nuclei

Cosmic rays at the knee

Results and implications



- enormous progress in last years
- precision measurements (direct & indirect)
- more details evolve in spectra (individual nuclei + all-particle)
- potential sources (gamma rays)

- no final conclusion yet
- complex picture seems to evolve with different source populations

