Latin American Symposium on High Energy Physics (SILAFAE)

Measurements of the Ultra-High-Energy Cosmic Ray Spectrum with the Pierre Auger Observatory

Pierre Auger Observatory image courtesy Steven Saffi

Rita C. Anjos on behalf of the Pierre Auger Collaboration

Universidade Federal do Paraná - Setor Palotina - Brazil

SILAFAE 2024

04-08 November 2024, Mexico City

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PIERRE AUGER OBSERVATORY

PALOTINA UFPR 30 anos O FUTURO SE FORMA AQUI

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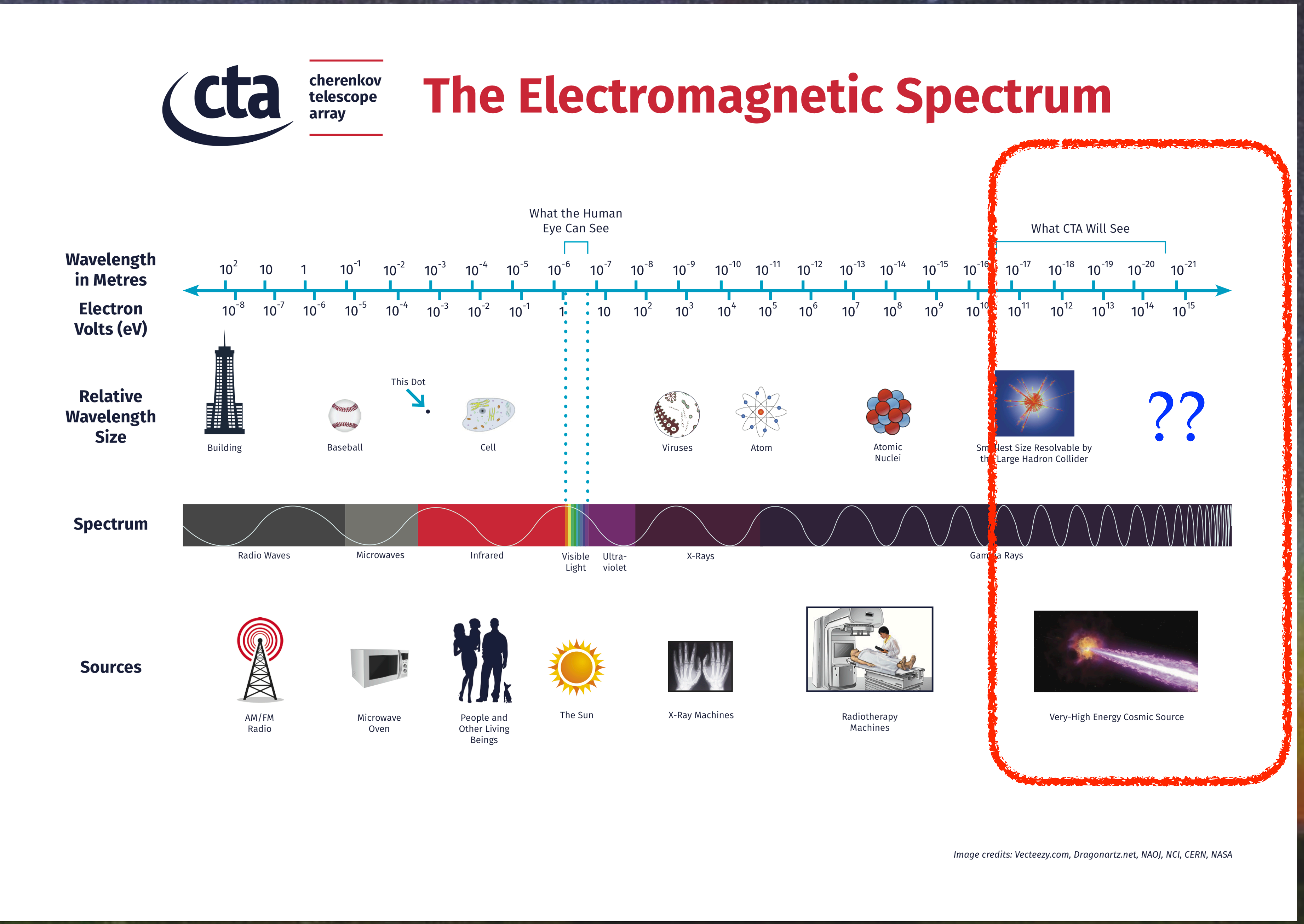

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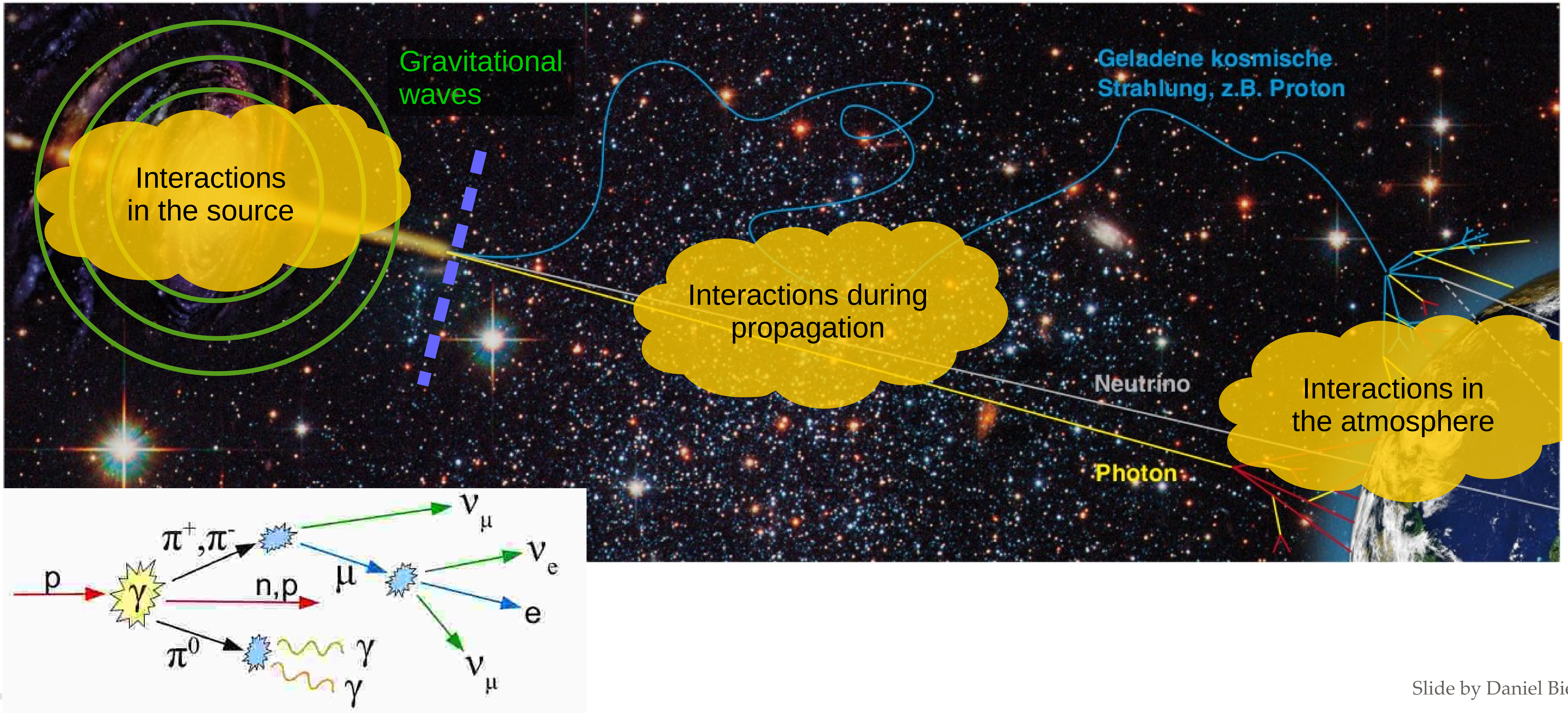
Overview

- Motivation and State-of-the-art
- Pierre Auger Observatory
- Energy spectrum
- Summary

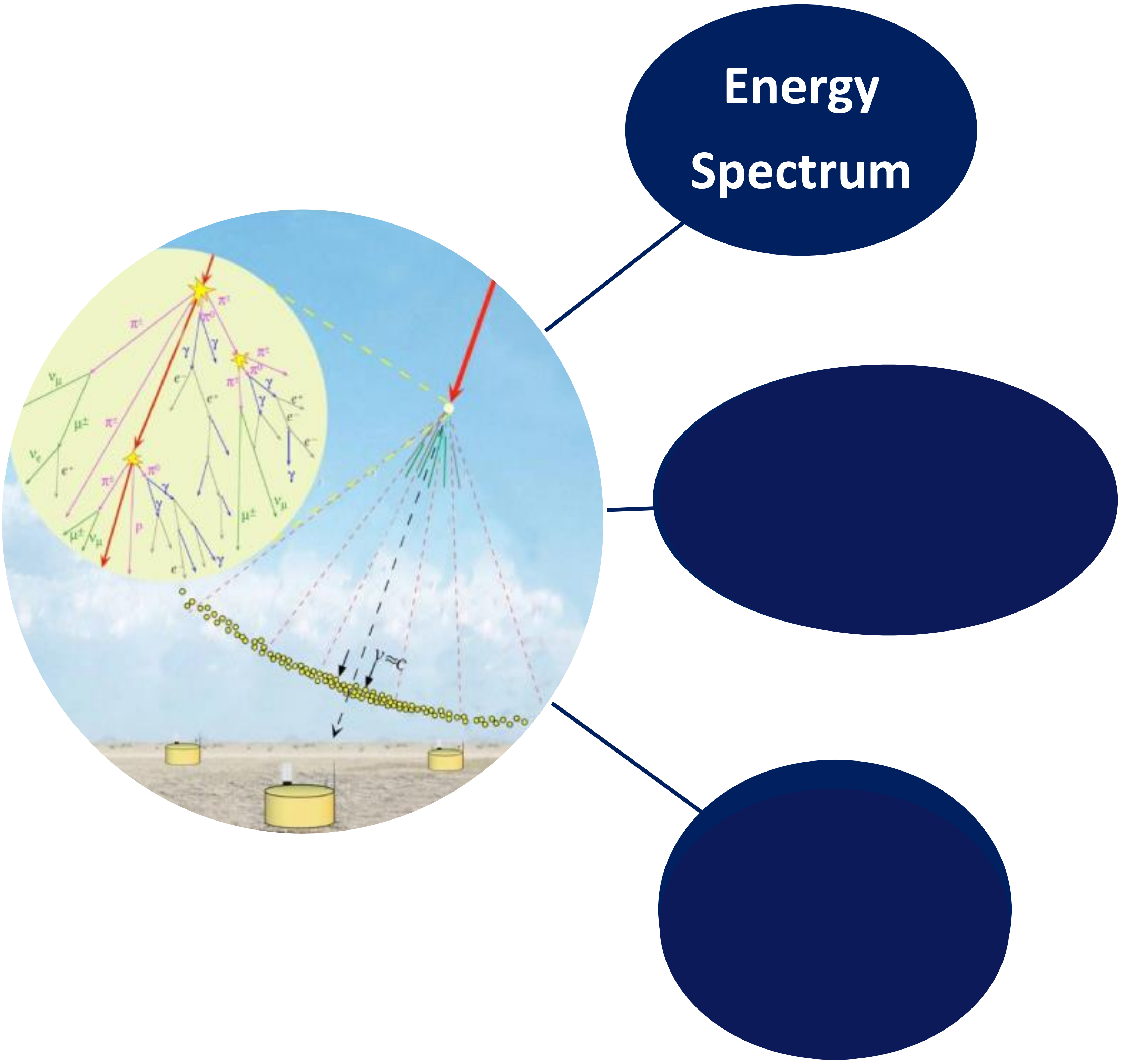
- Motivation and State-of-the-art

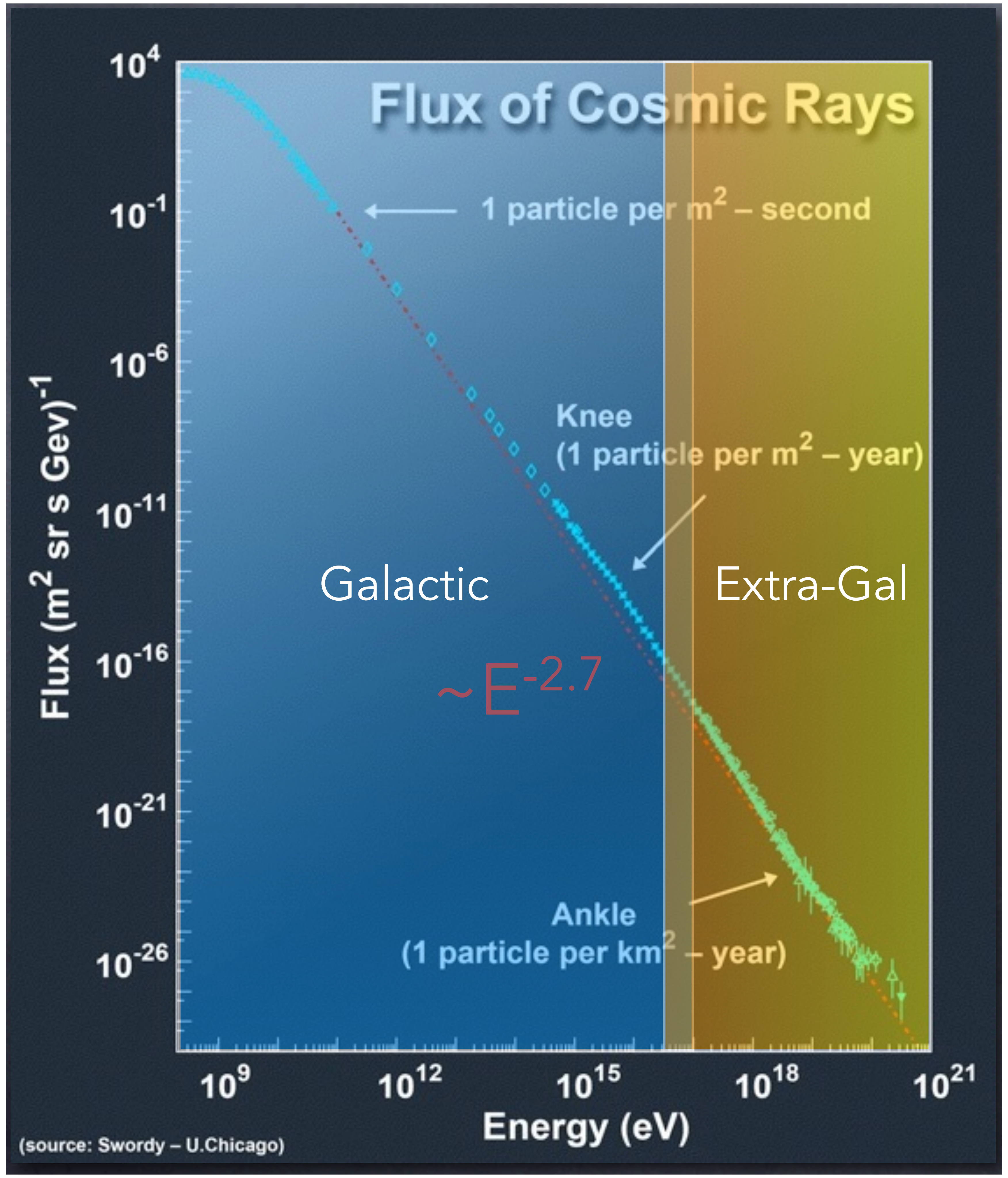


Slide by Daniel Biehl

• Motivation and State-of-the-art

What do we have?





$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim E^{-\alpha}$$

• Motivation and State-of-the-art

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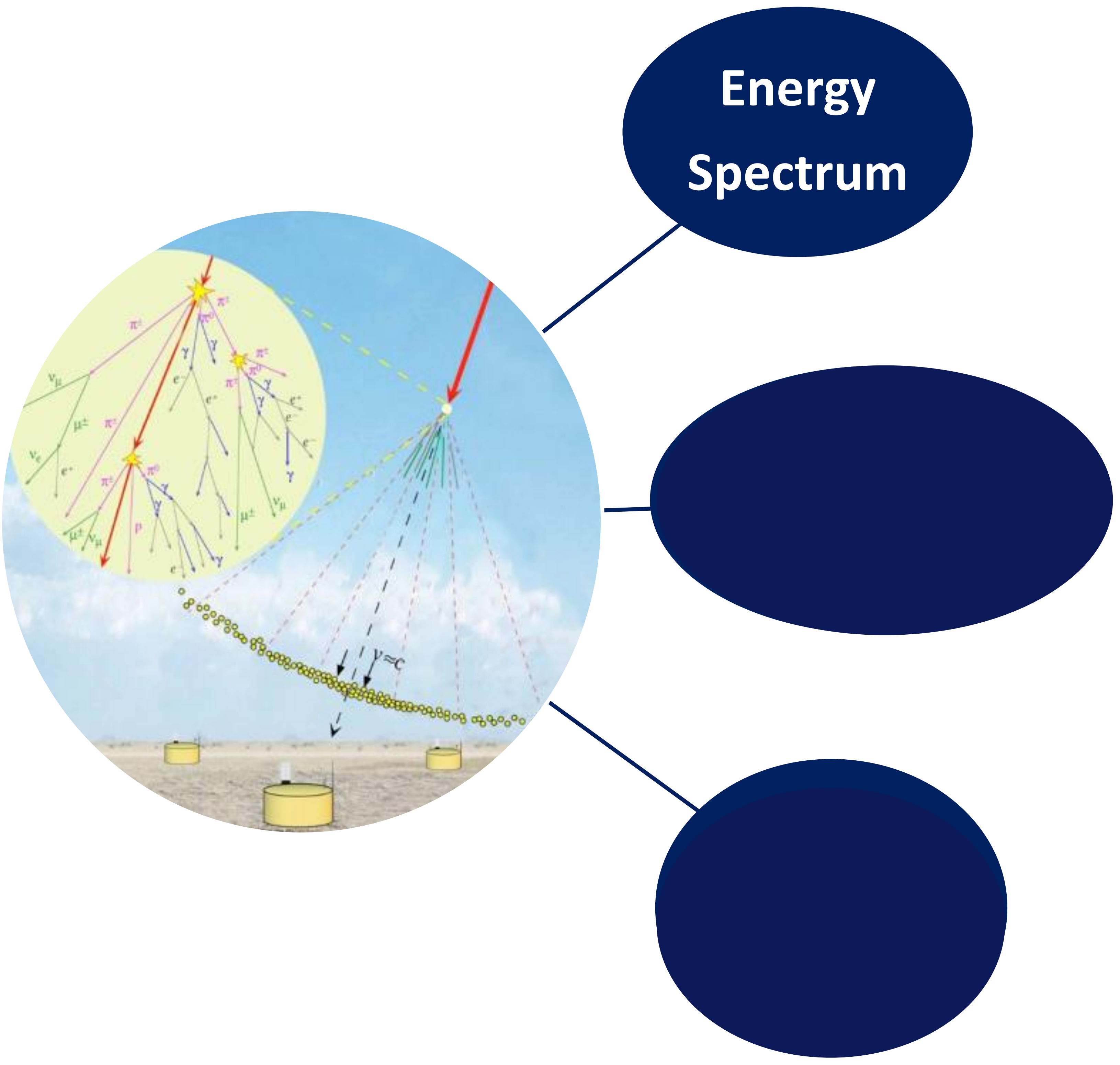
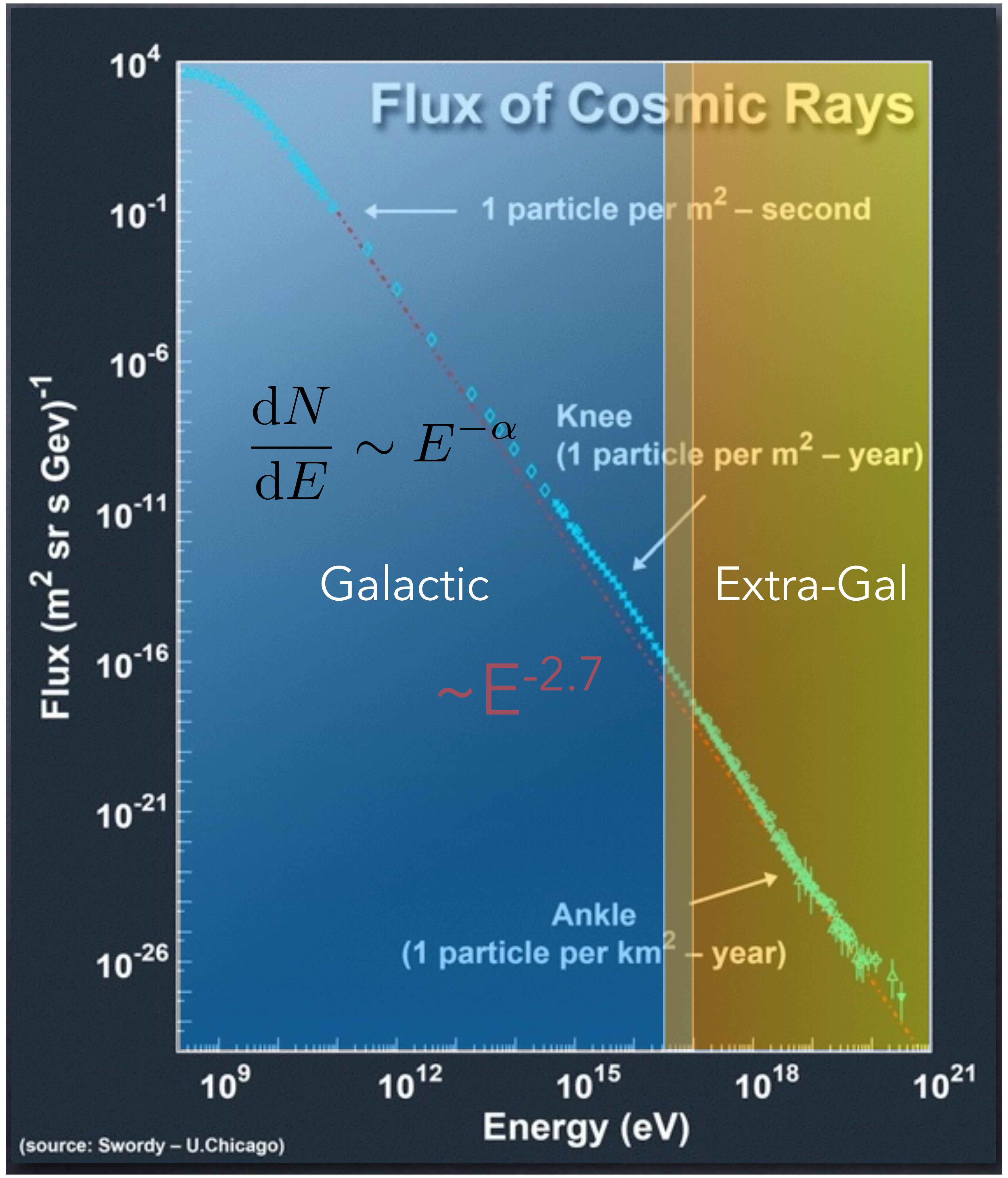


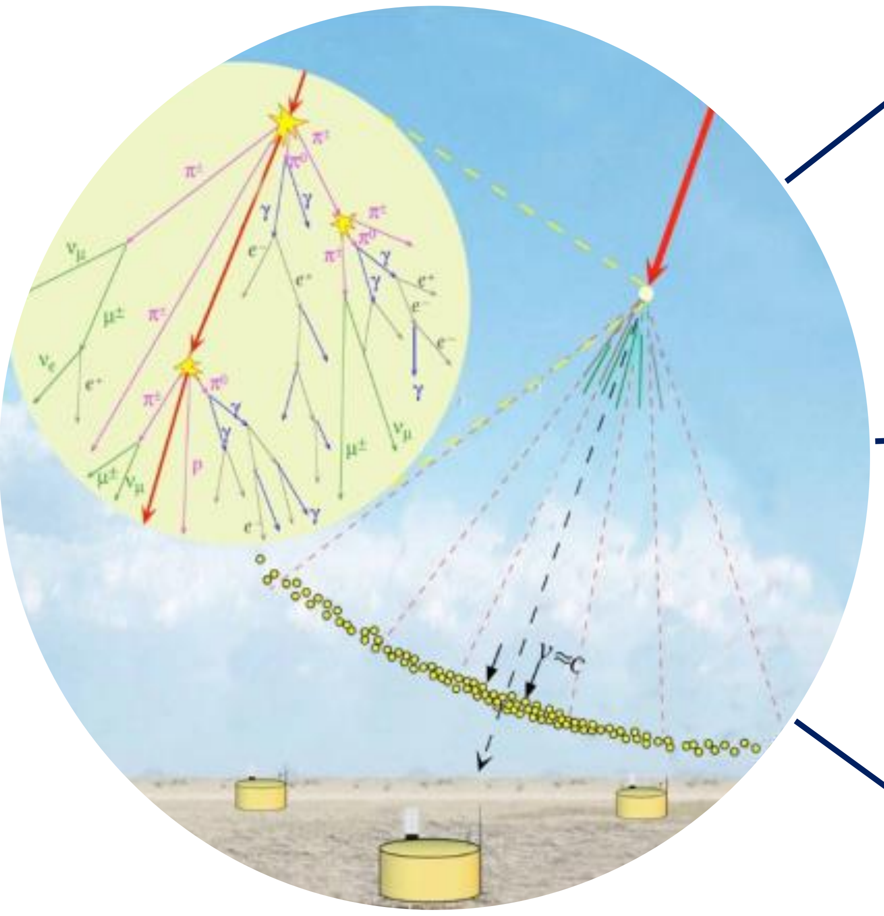


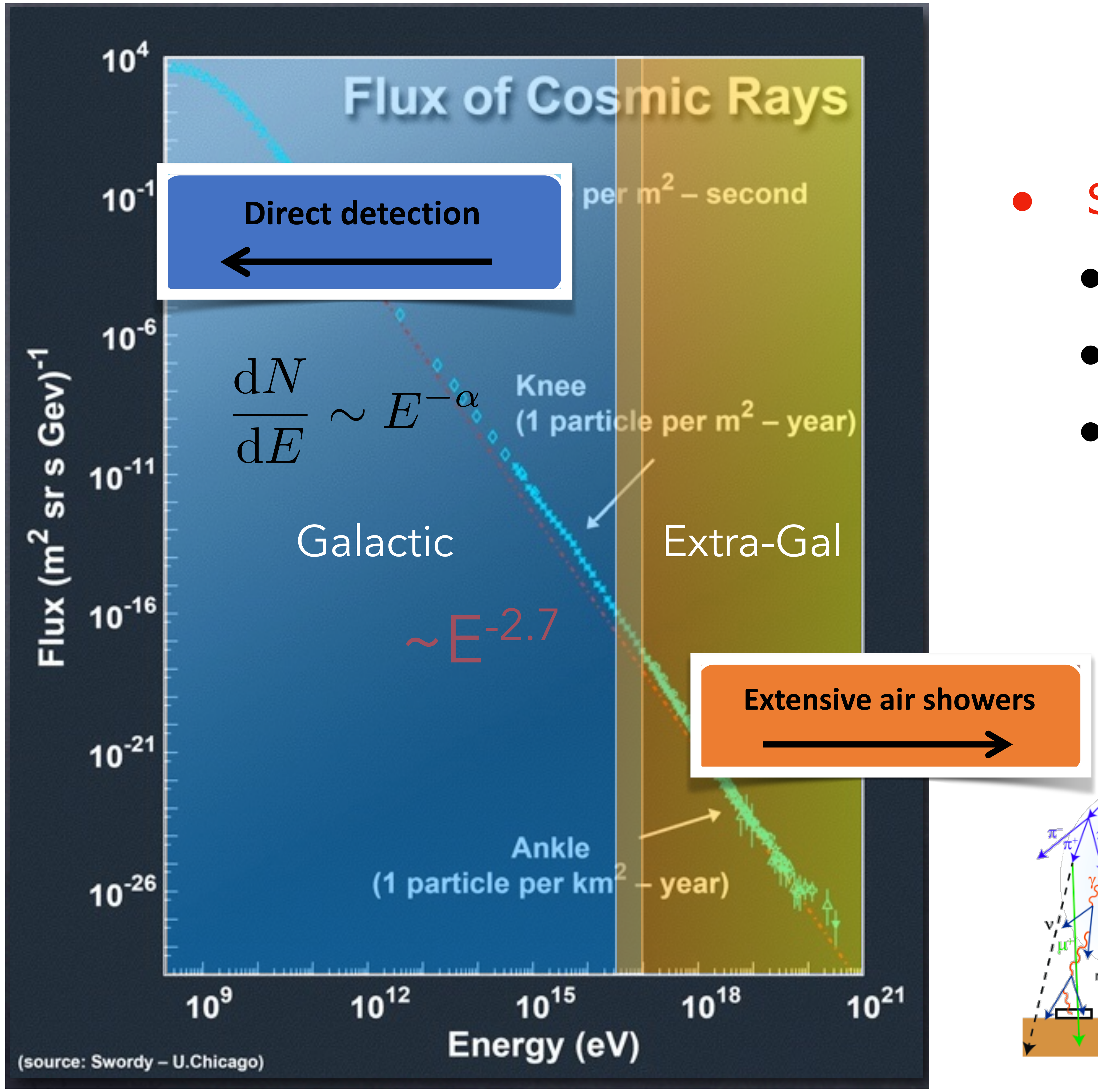
- Spectrum shape:
  - Different composition
  - Sources (Gal x Extragal)
  - Interaction with cosmic radiations

• Motivation and State-of-the-art

What do we have?

Energy Spectrum





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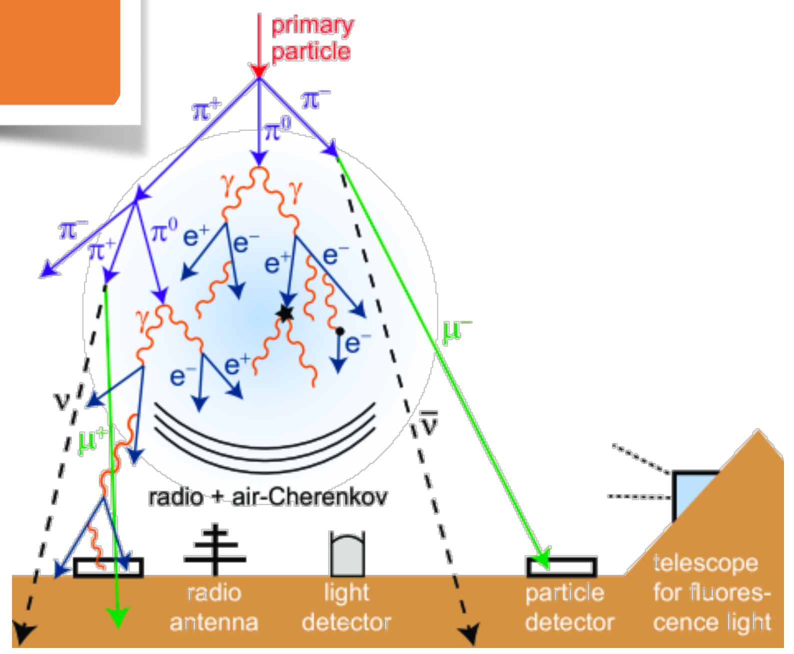

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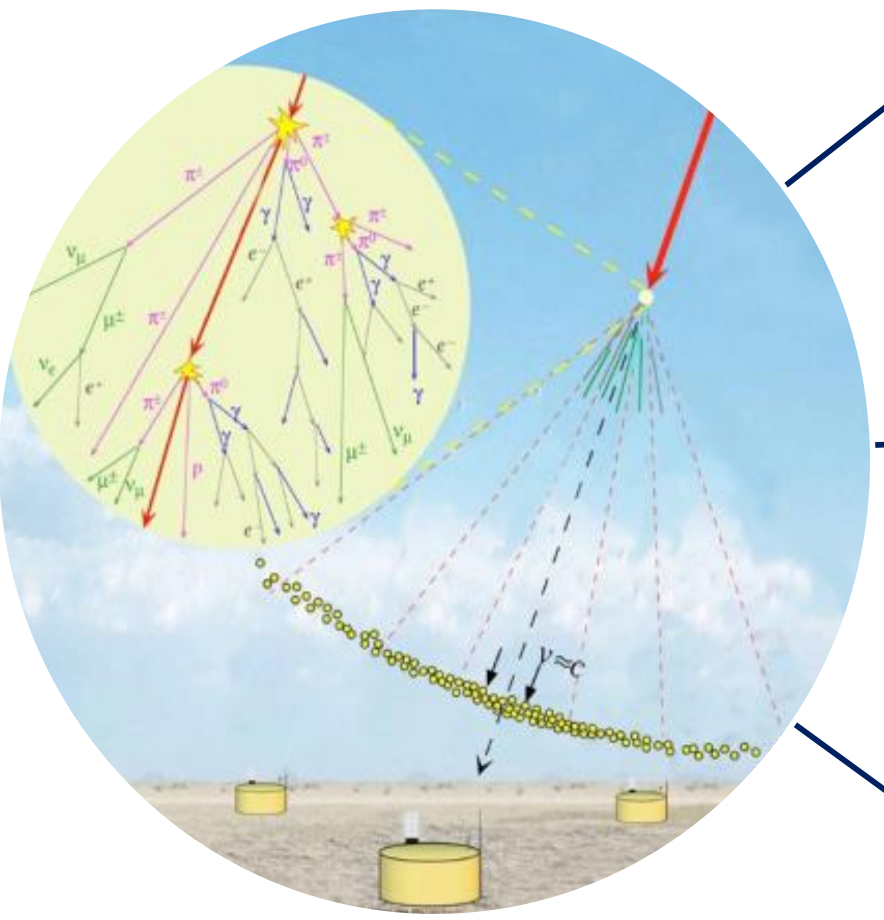
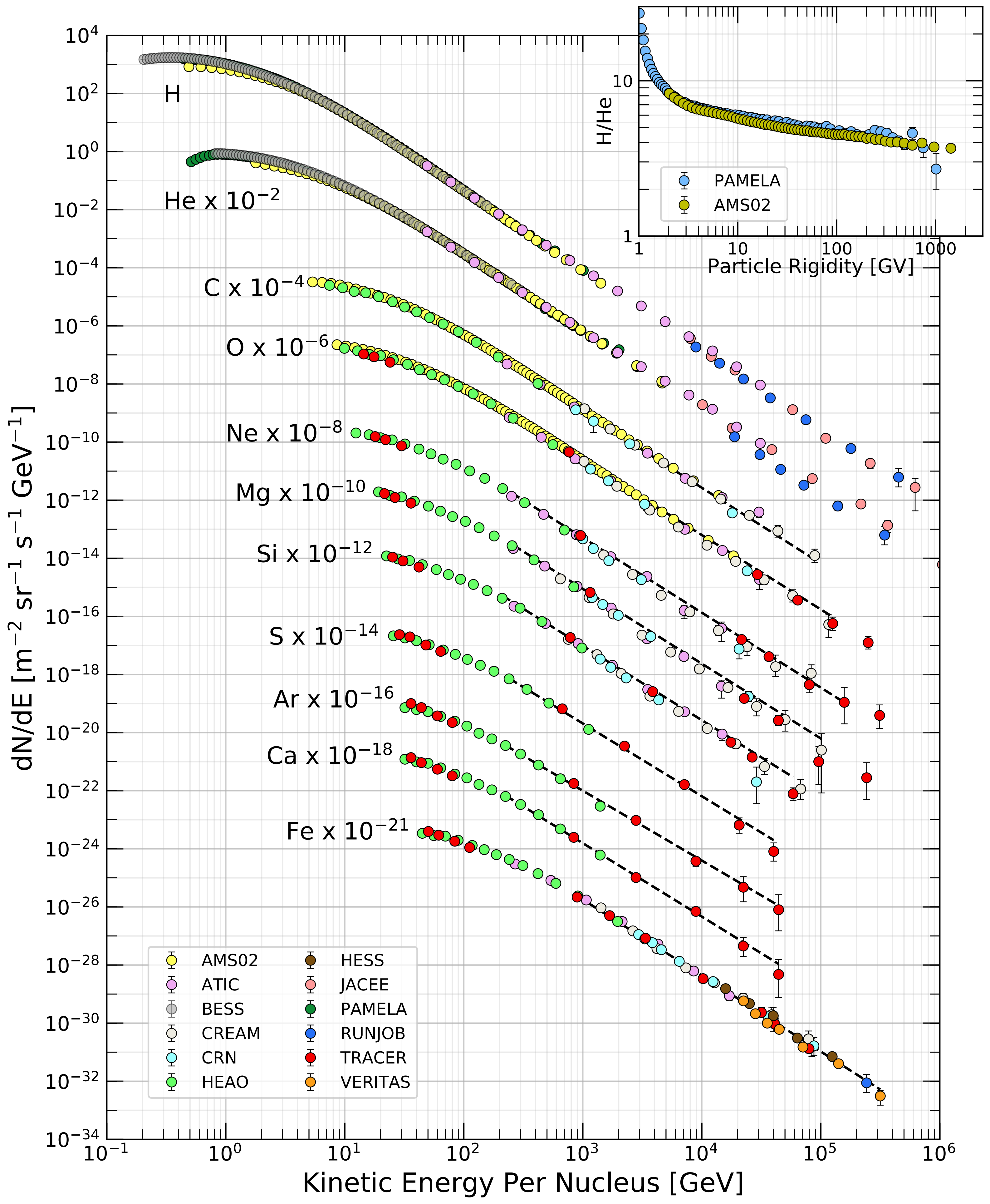


Energy Spectrum

Chemical Composition



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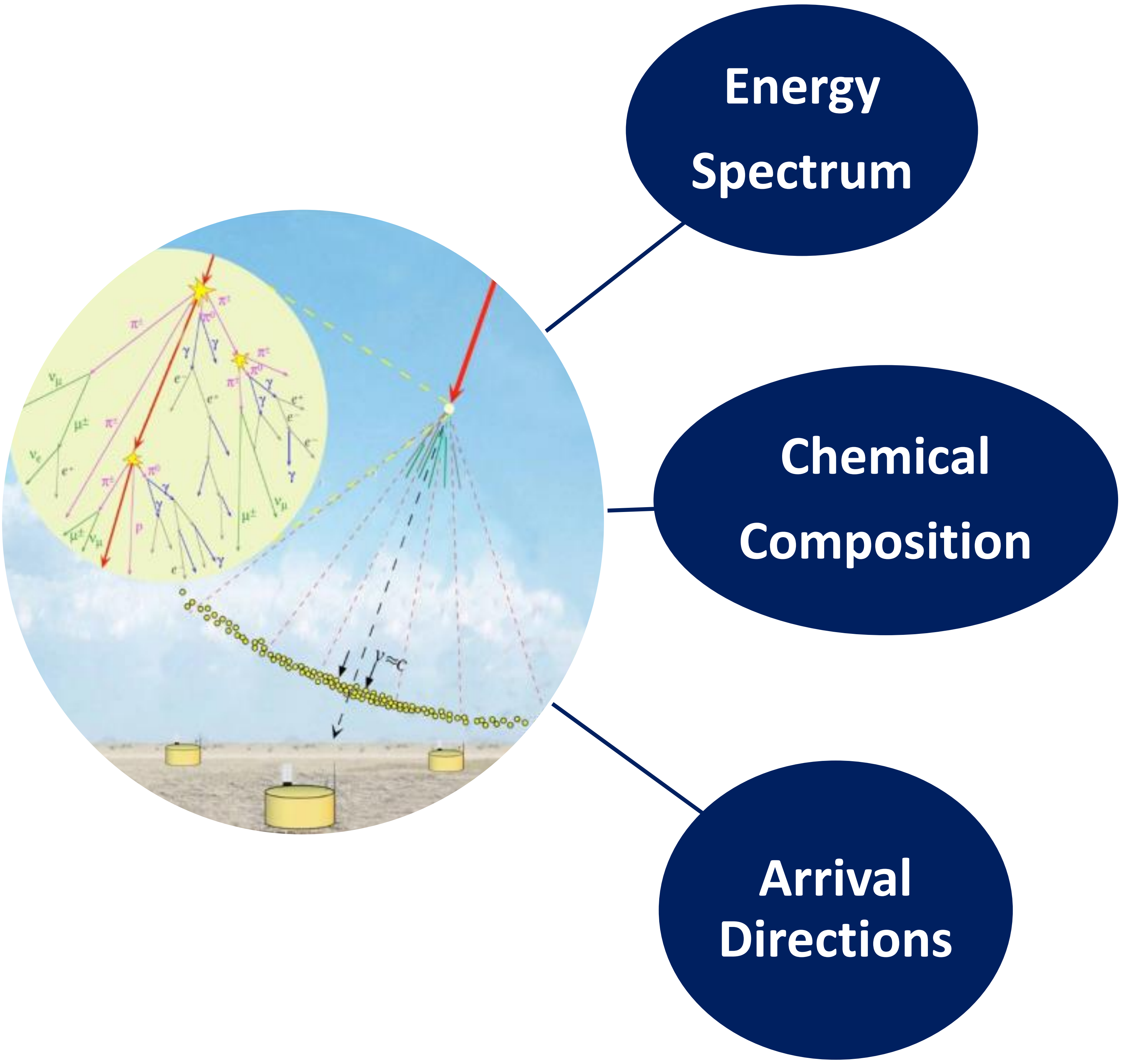
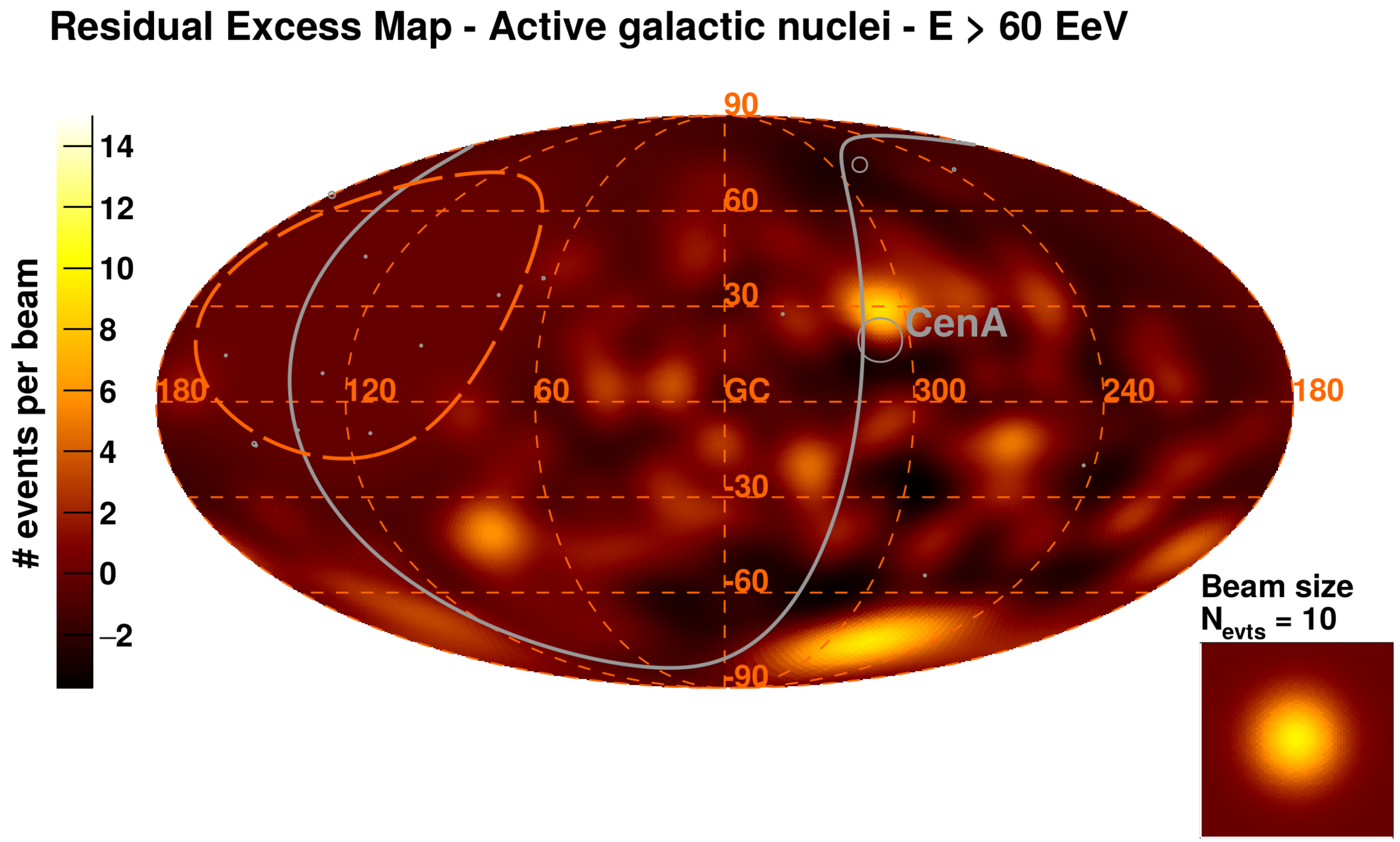
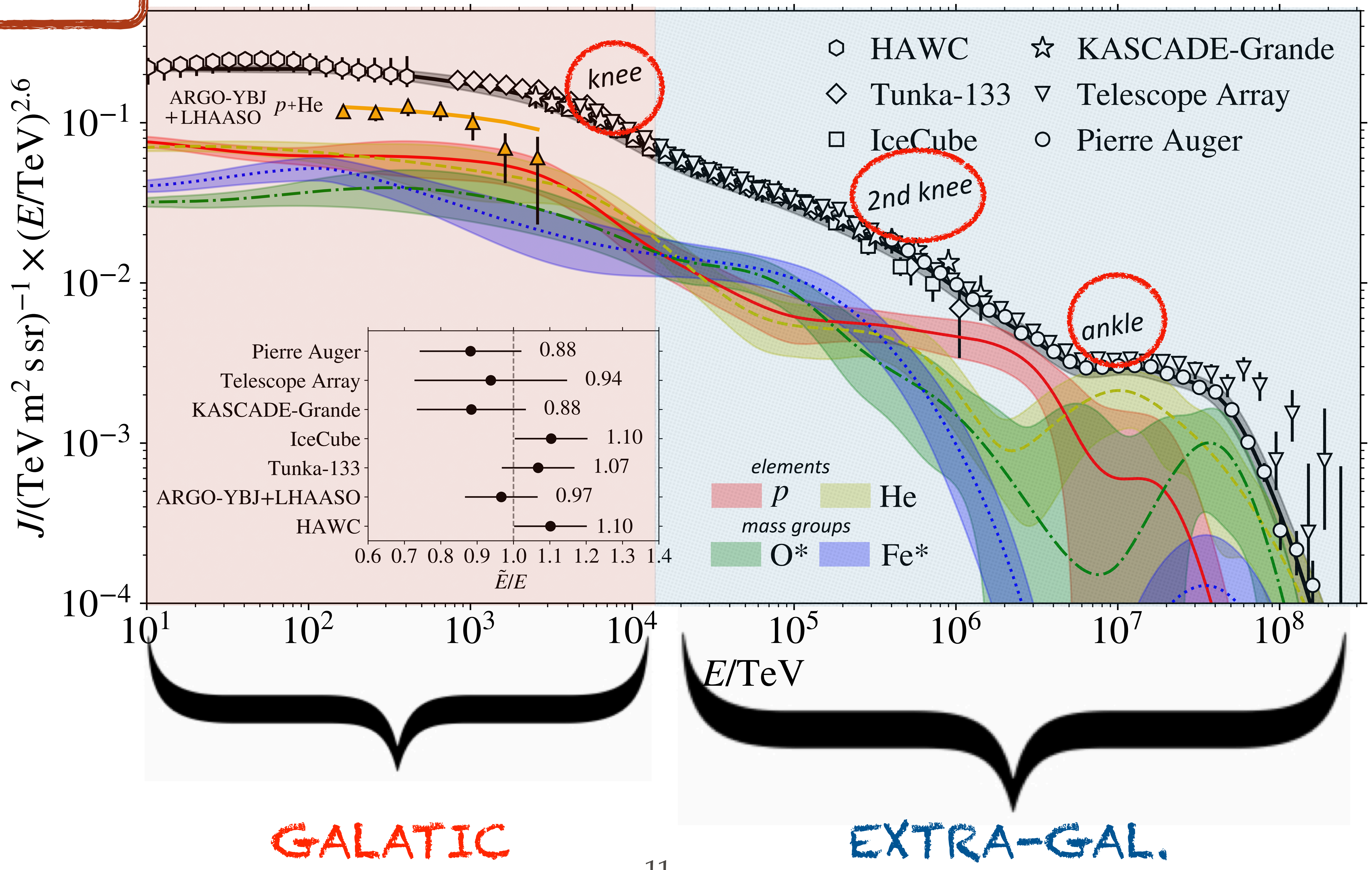




- Motivation and State-of-the-art

What do we know ?



arXiv:1903.07713v1, arXiv:1301.6824
PAOl. Science 2017;357:1266-1270
Anjos et al 2018
Björn Eichmann, UHECR2018, Paris

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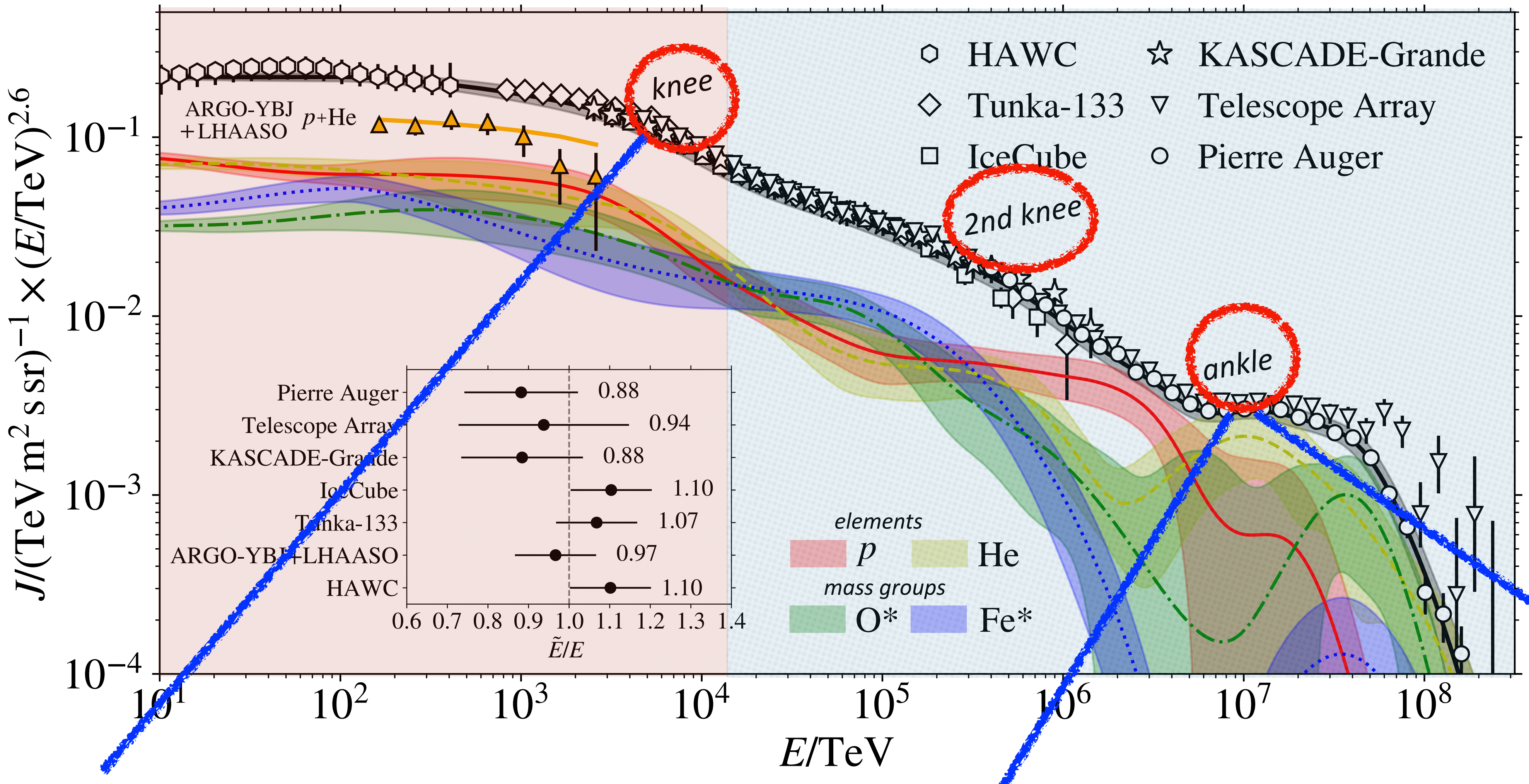

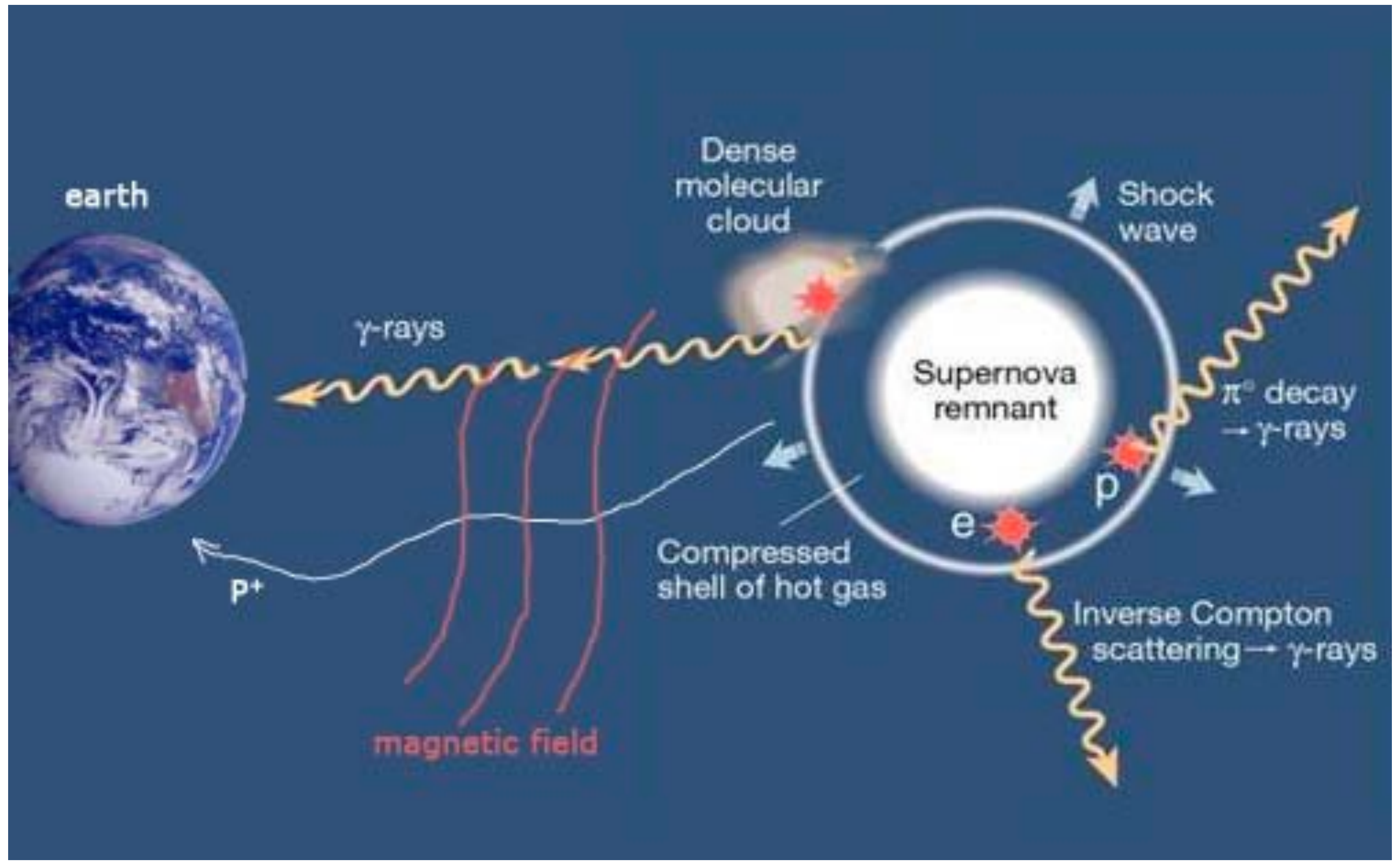

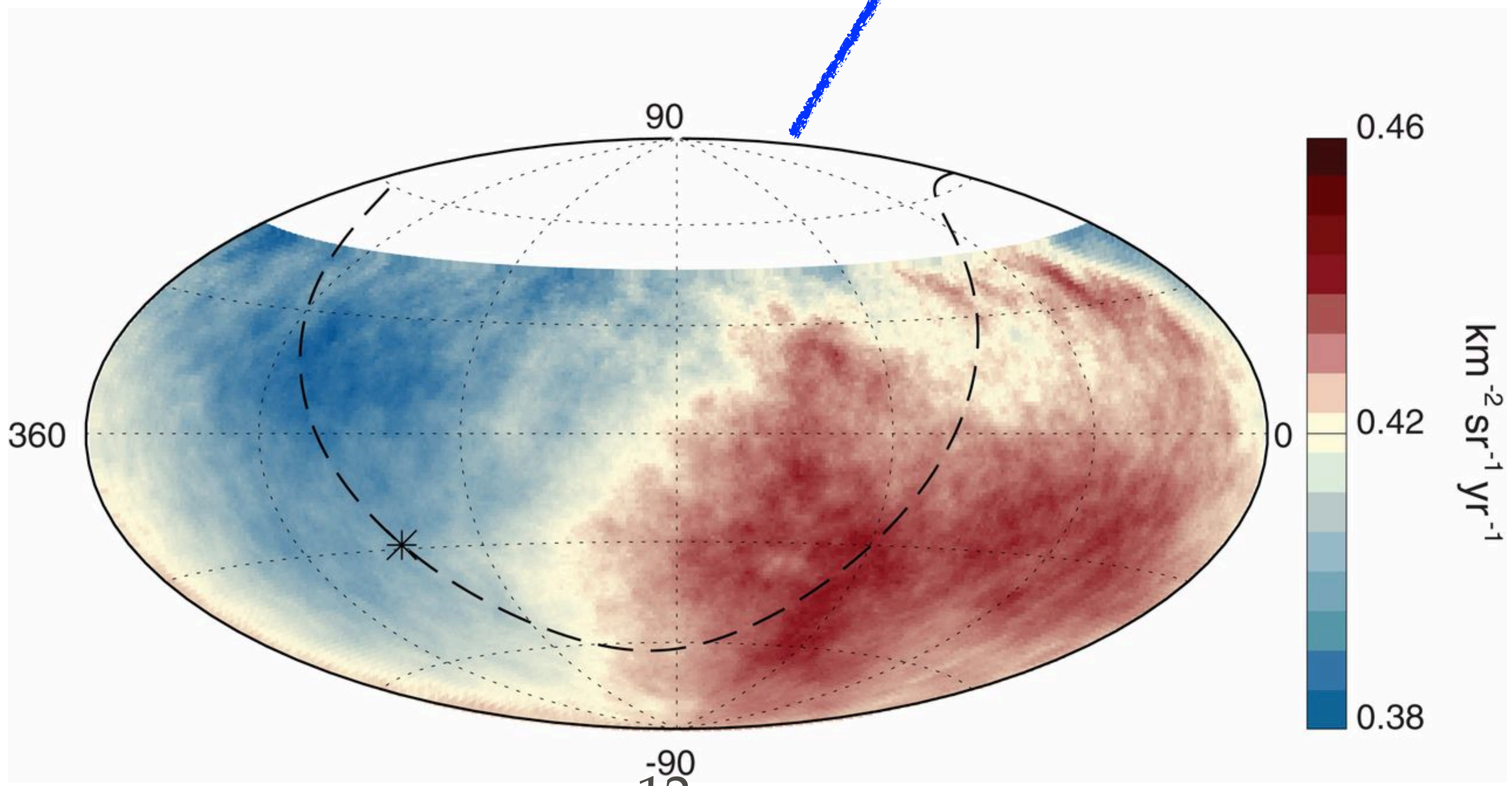

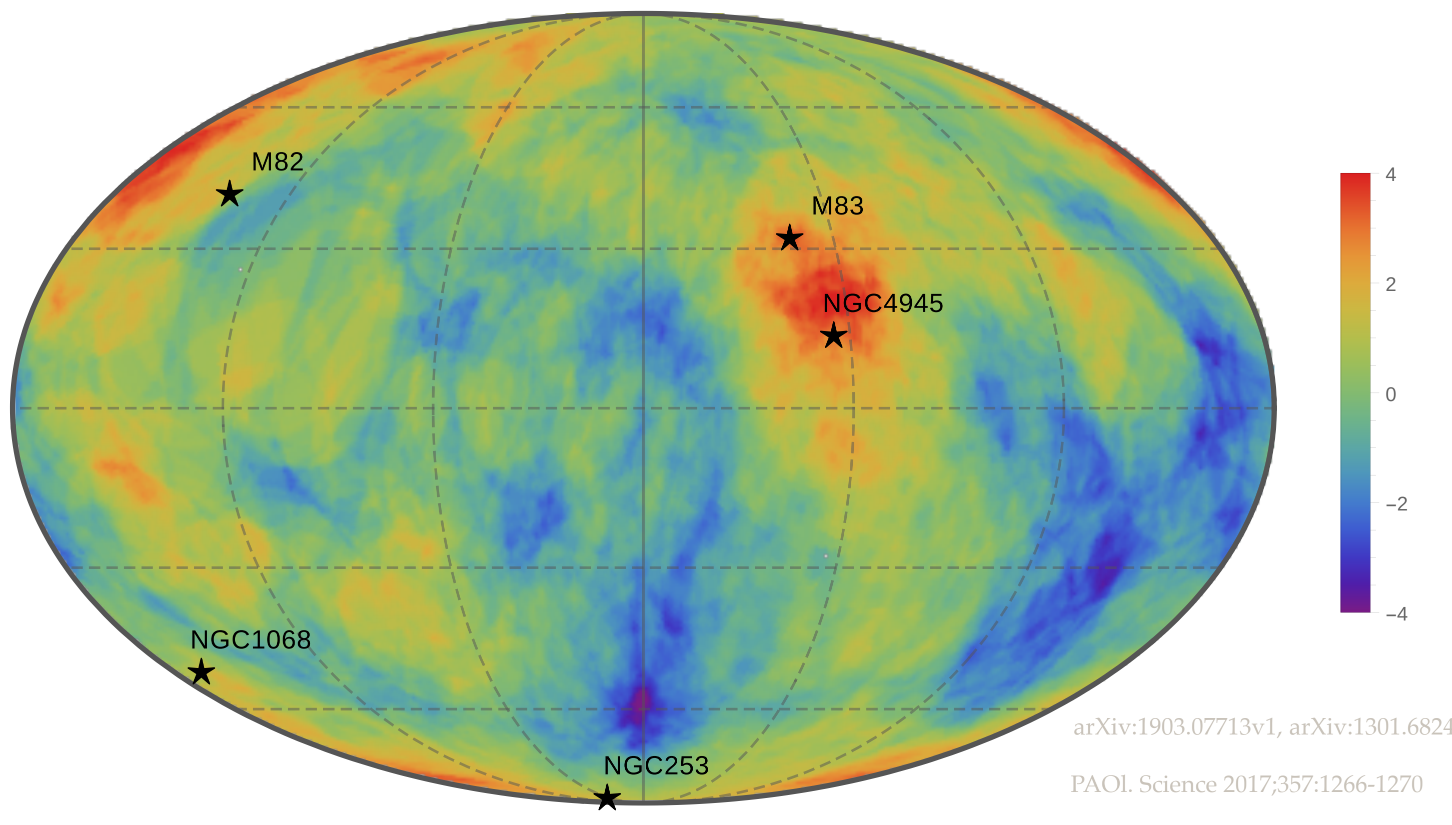

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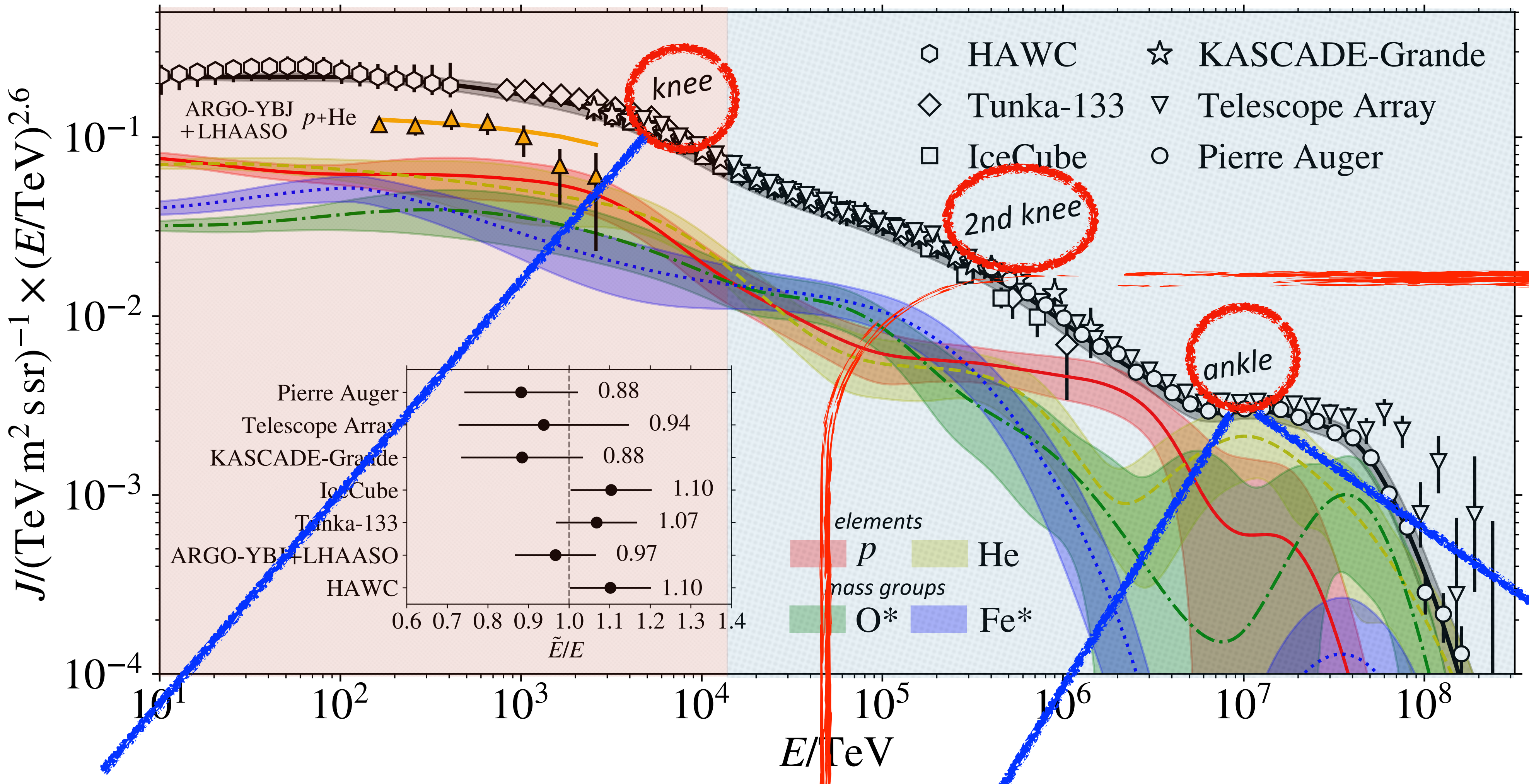

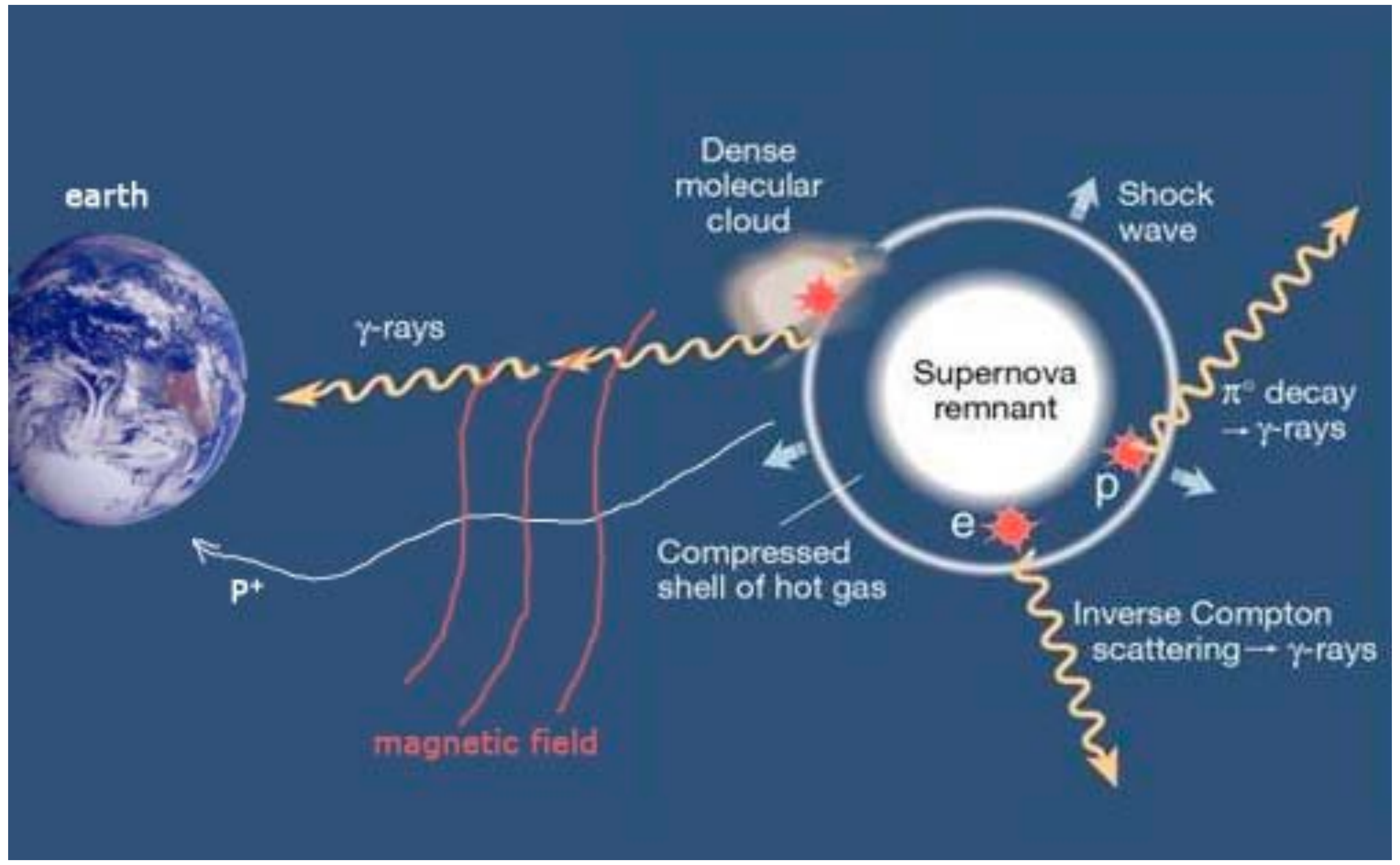

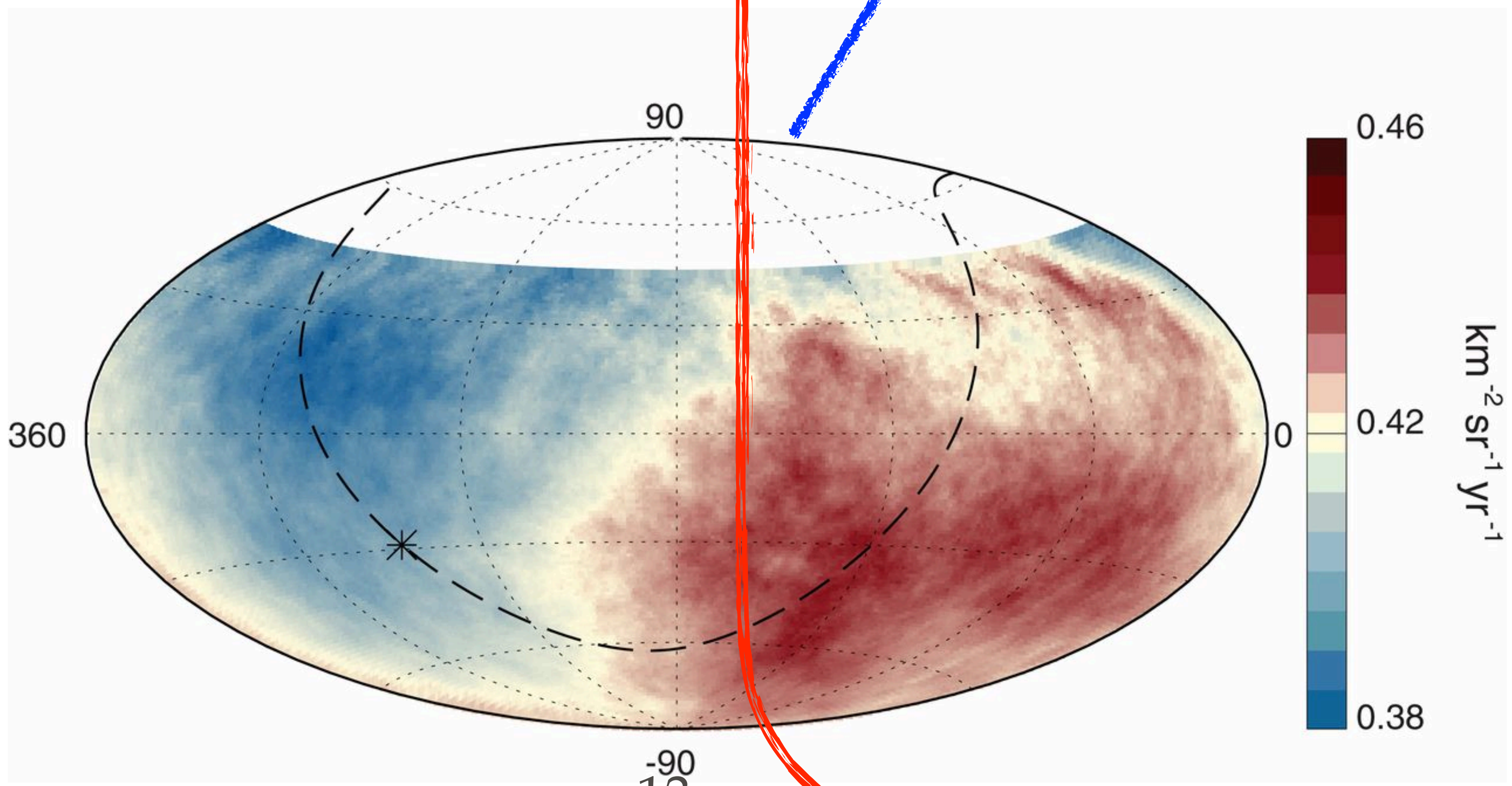

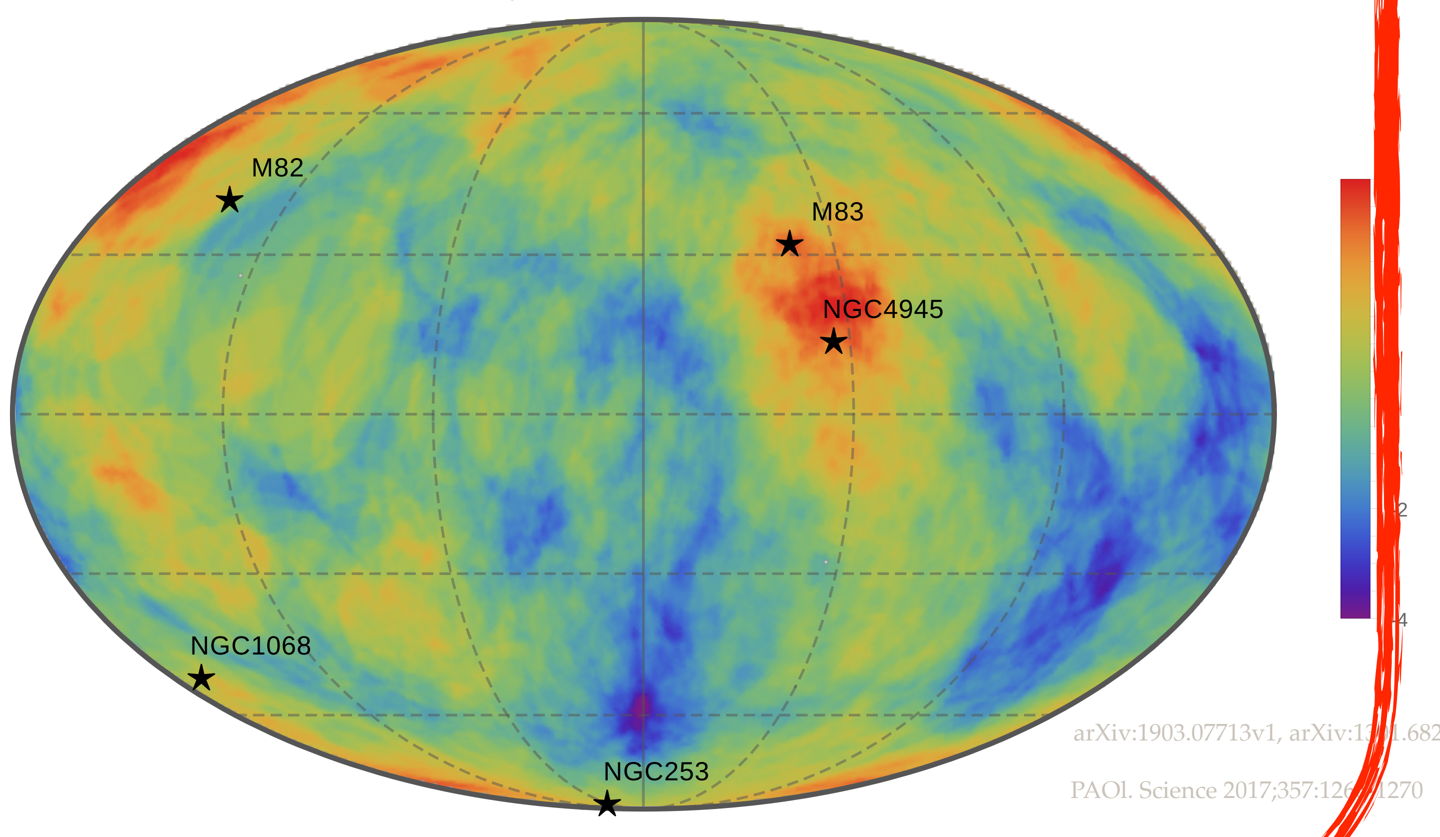

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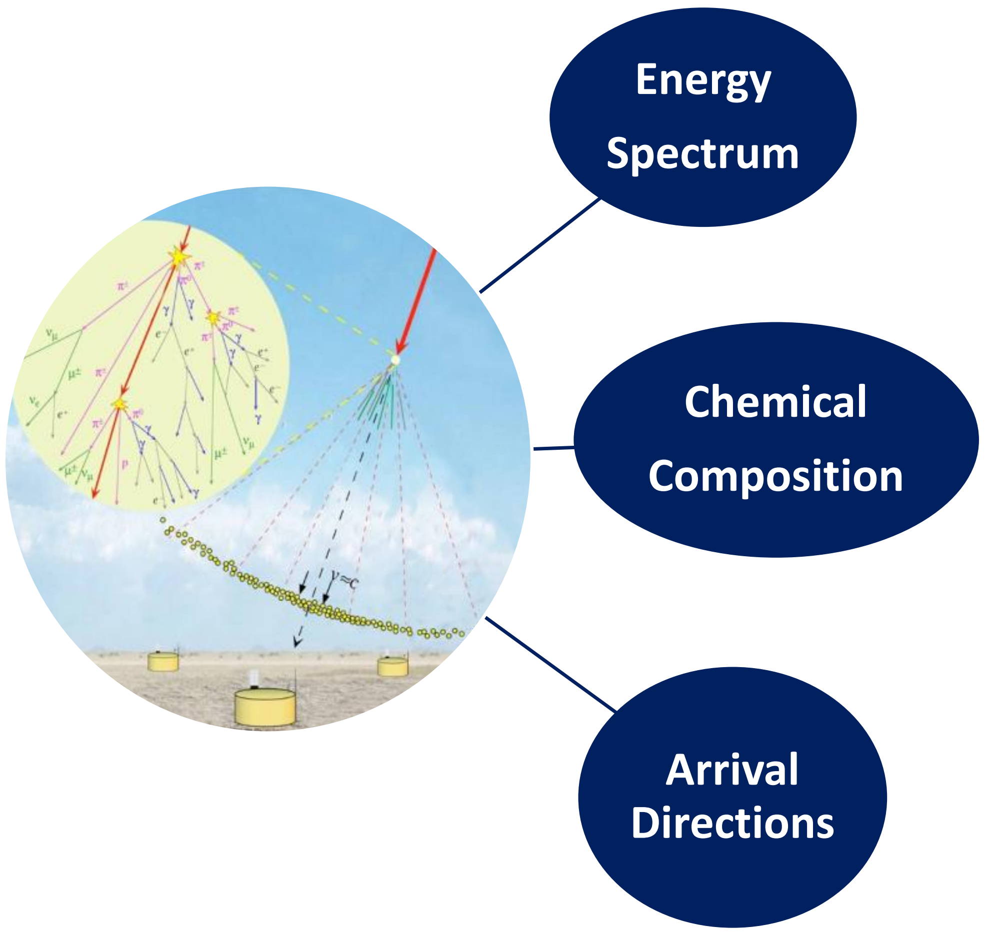

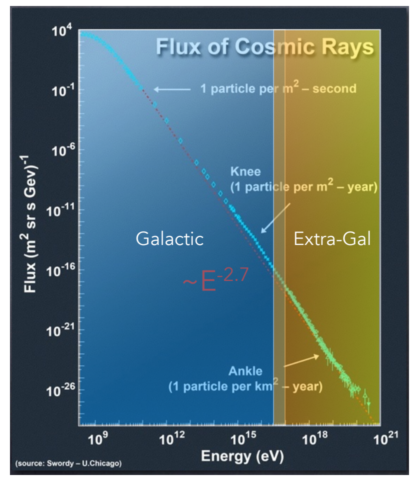

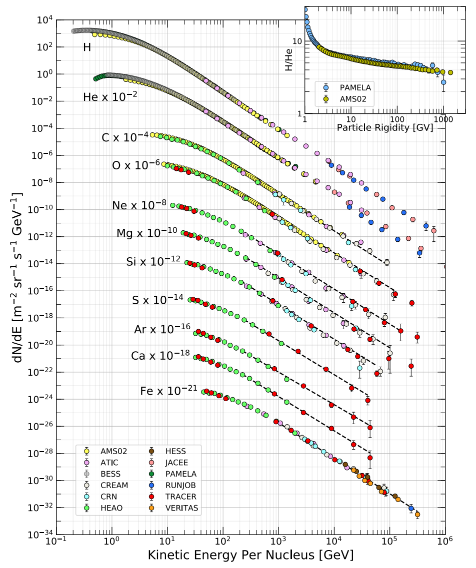

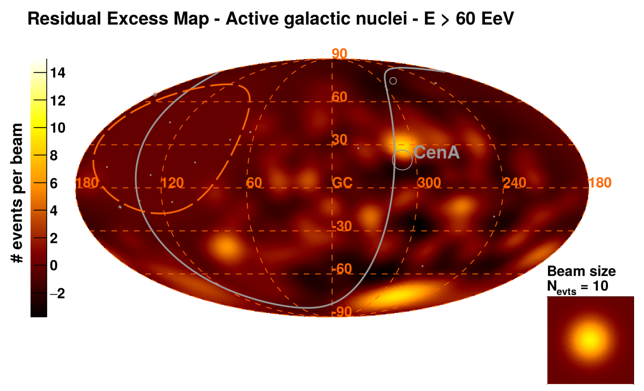

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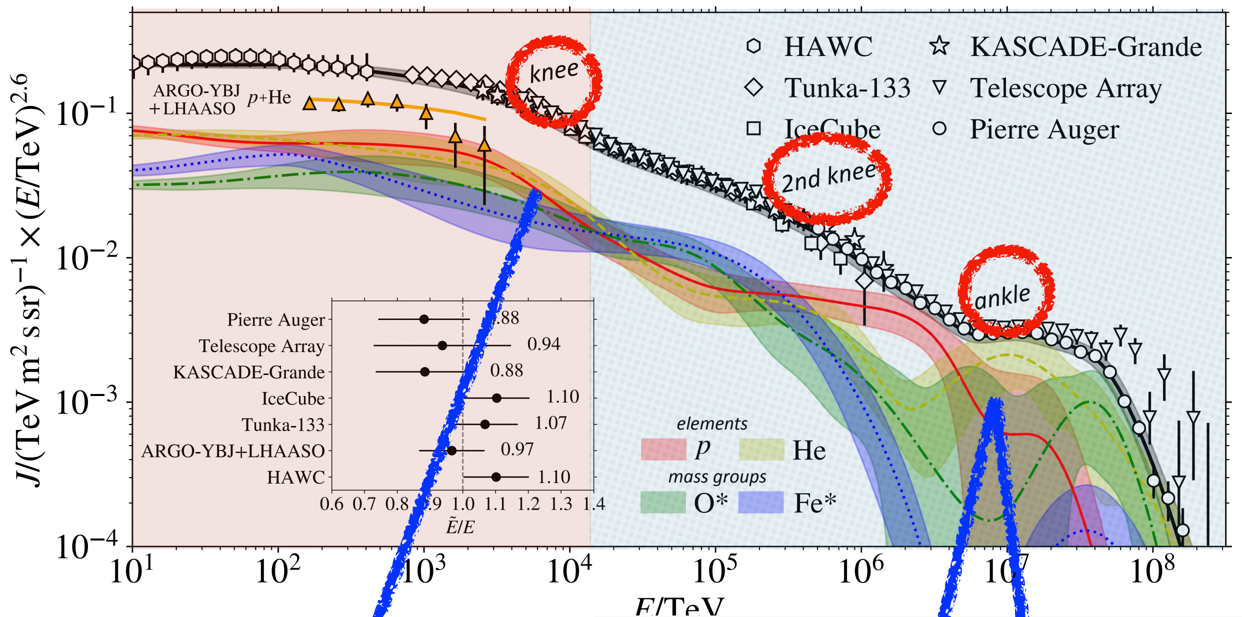

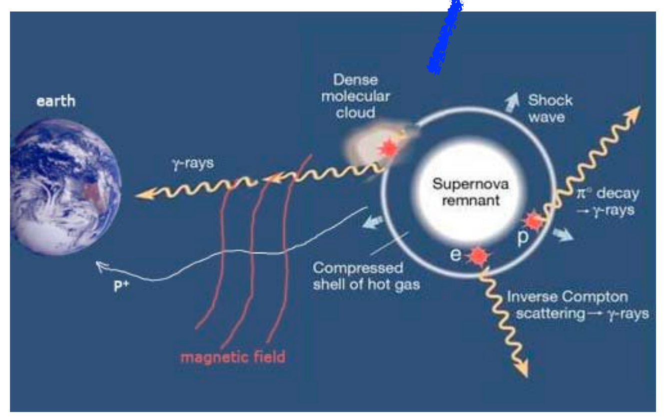

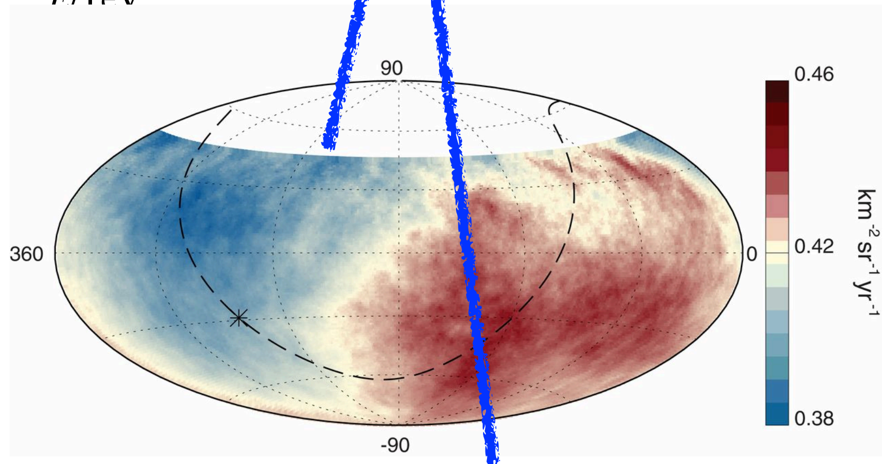

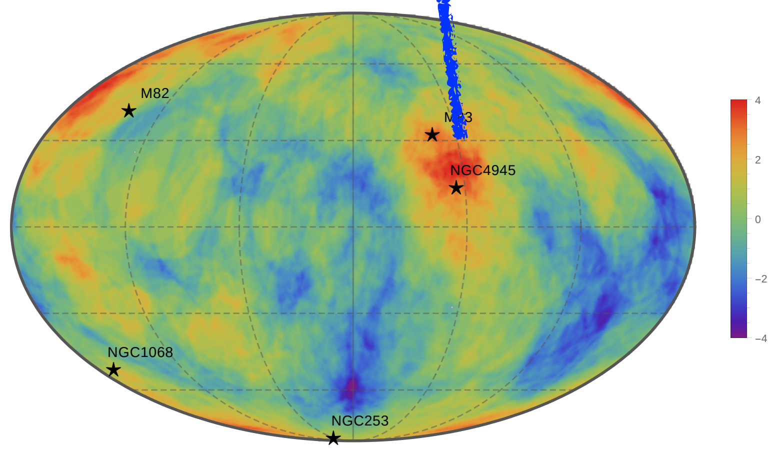

What do we want to answer?

- Some big questions and goals …

1. What other sources might there be in the Galaxy?
2. How do we describe the transition to the extra-galactic component?
3. What are extra-galactic sources?
4. How do particles are accelerated?

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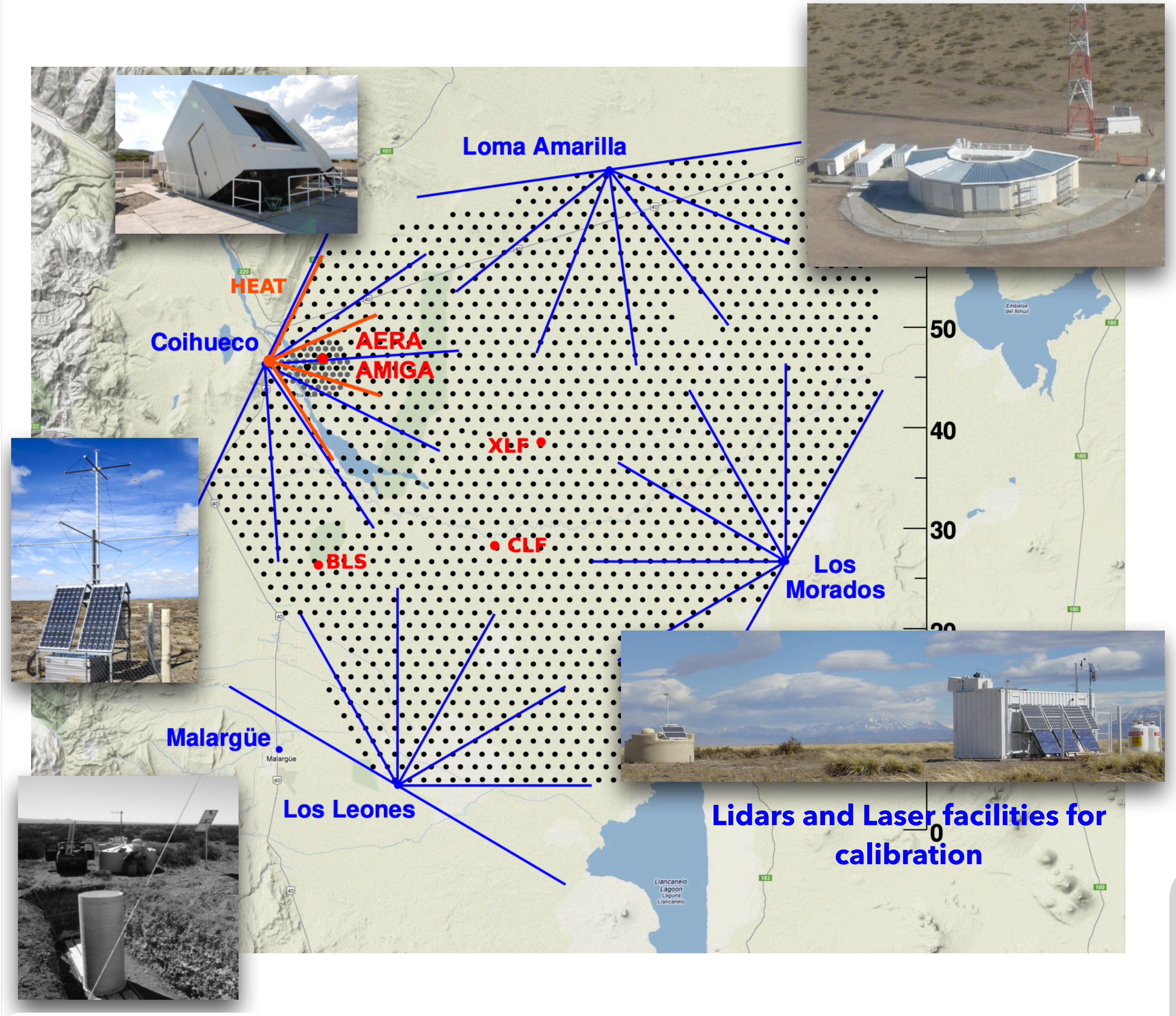
• Pierre Auger Observatory

The **Pierre Auger Observatory** at a glance



Southern hemisphere:
Malargue, Province Mendoza, Argentina

Surface detector (SD)

- 1600 stations in 1.5 km grid, 3000 km^2 E > $10^{18.5}$ eV
- 61 stations in 750 m grid, 23.5 km^2, E > $10^{17.5}$ eV
- 19 stations in 433 m grid, E > 6 10^{16} eV

Fluorescence detector (FD)

- 24 telescopes in 4 sites, FoV: 0-30^o, E>10^{18} eV
- HEAT (3 telescopes), FoV: 30 - 60^o, E>10^{17} eV

Auger Engineering Radio Array (AERA)

- 153 antennas in 17 km^2 array, E> 4 10^{18}eV

Underground muon detector

- 19(61) stations in 433(750)m array $10^{16.5}$<E< 10^{19} eV

Auger Phase I data taking from 2004 on (from 2008 with the full array) to 2023
Auger Phase II data taking from 2024 to 2035

Figure by S. Mayotte

Slide by F. Salamida

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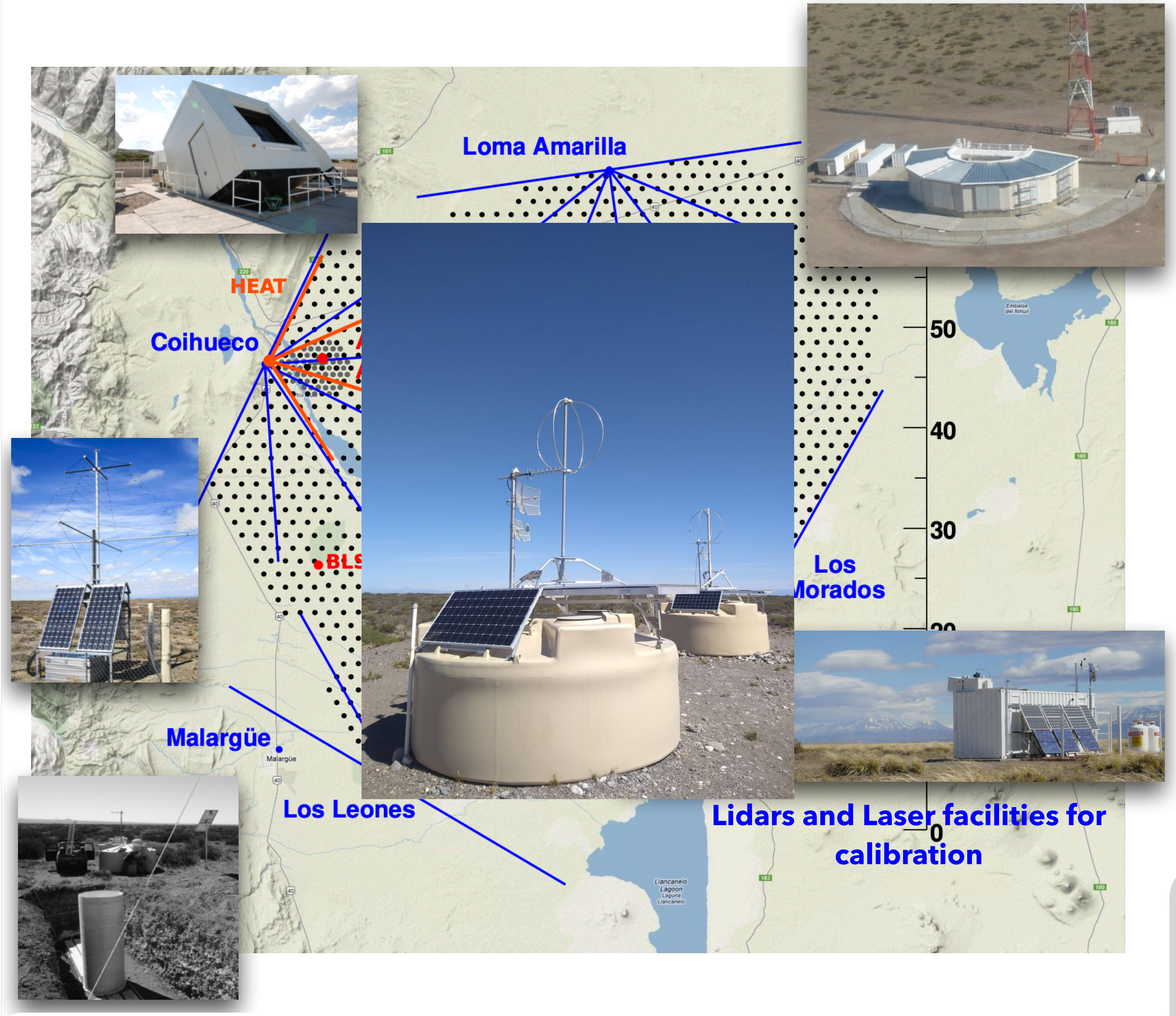

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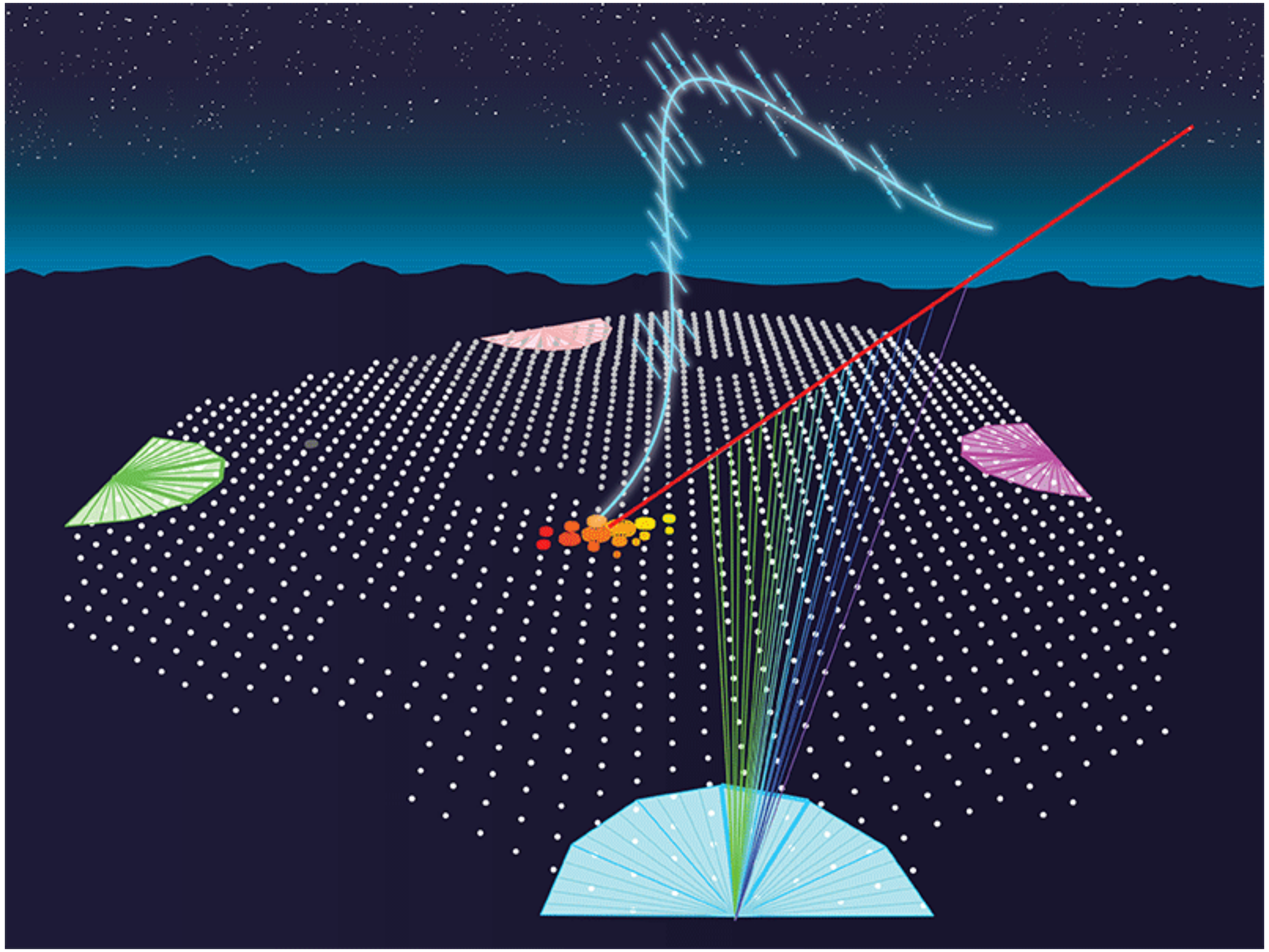

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.192001

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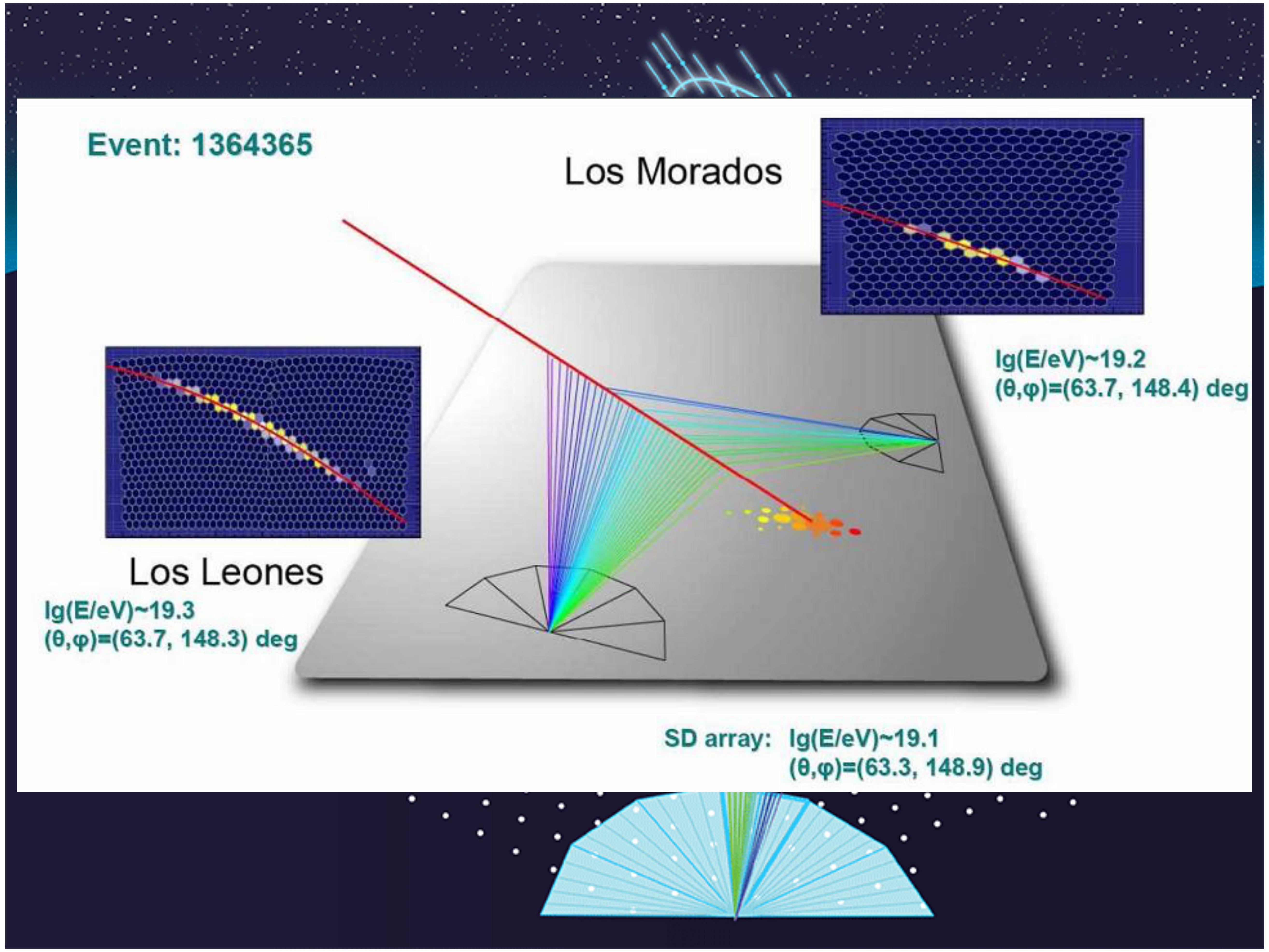
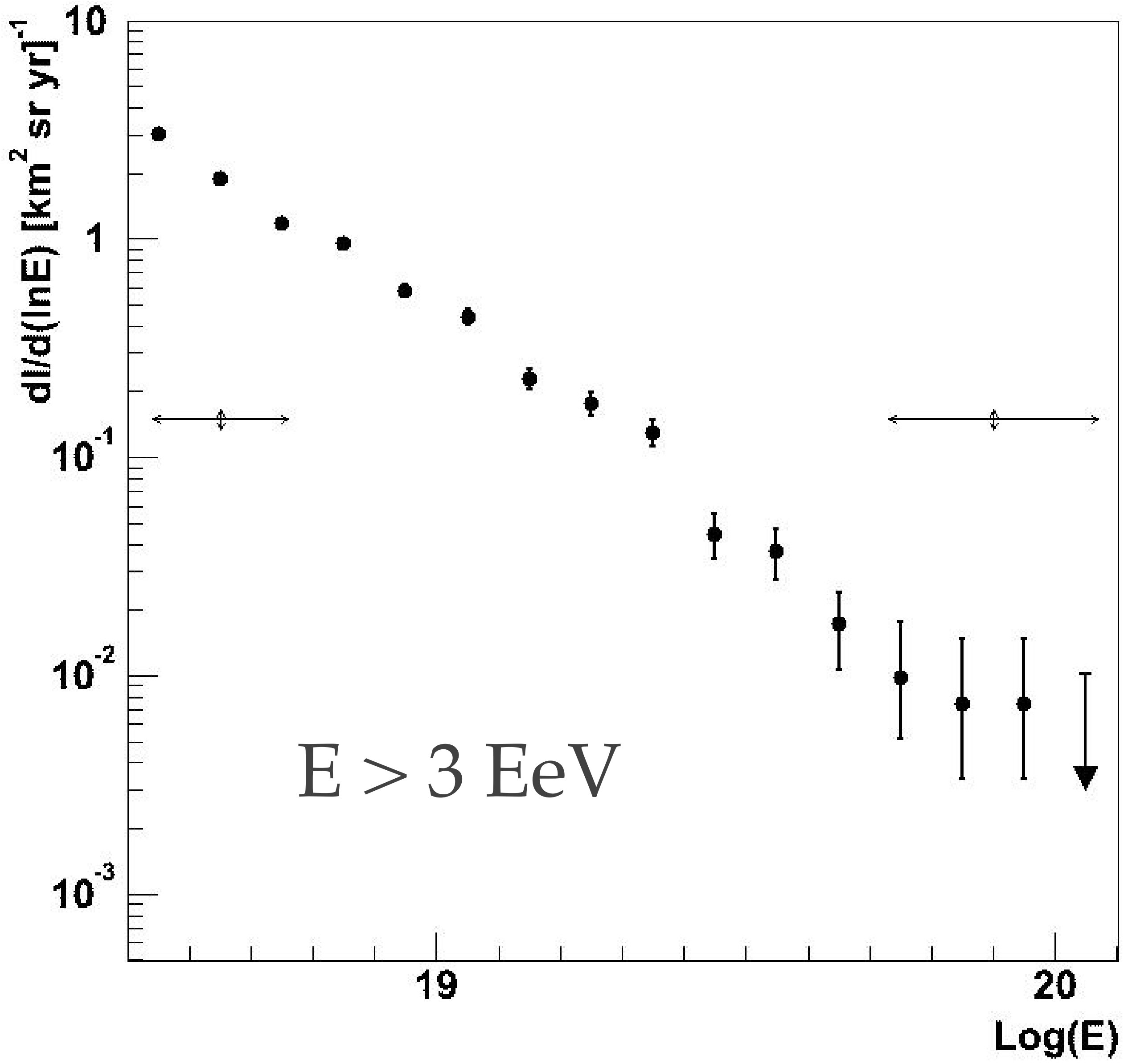
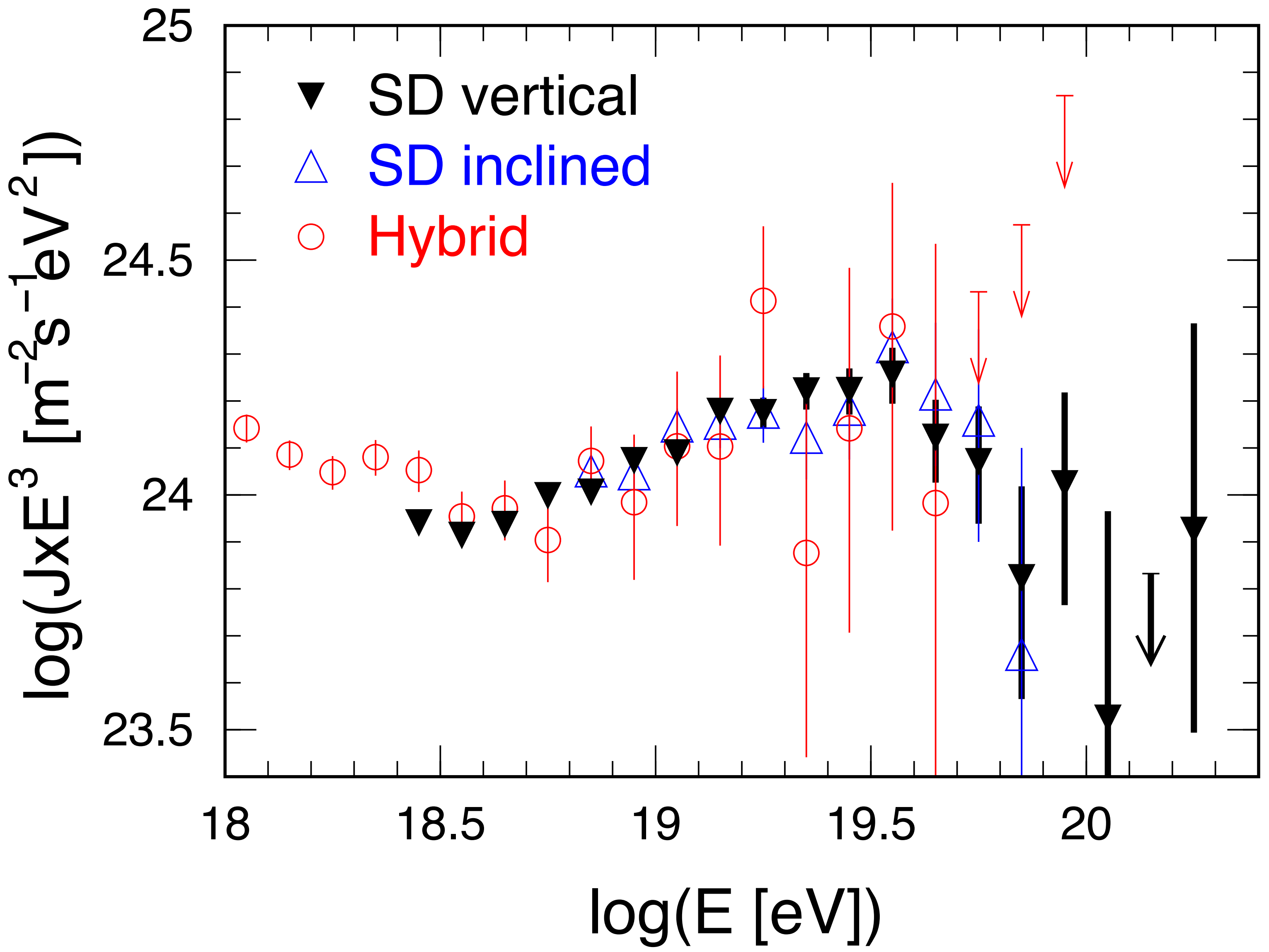
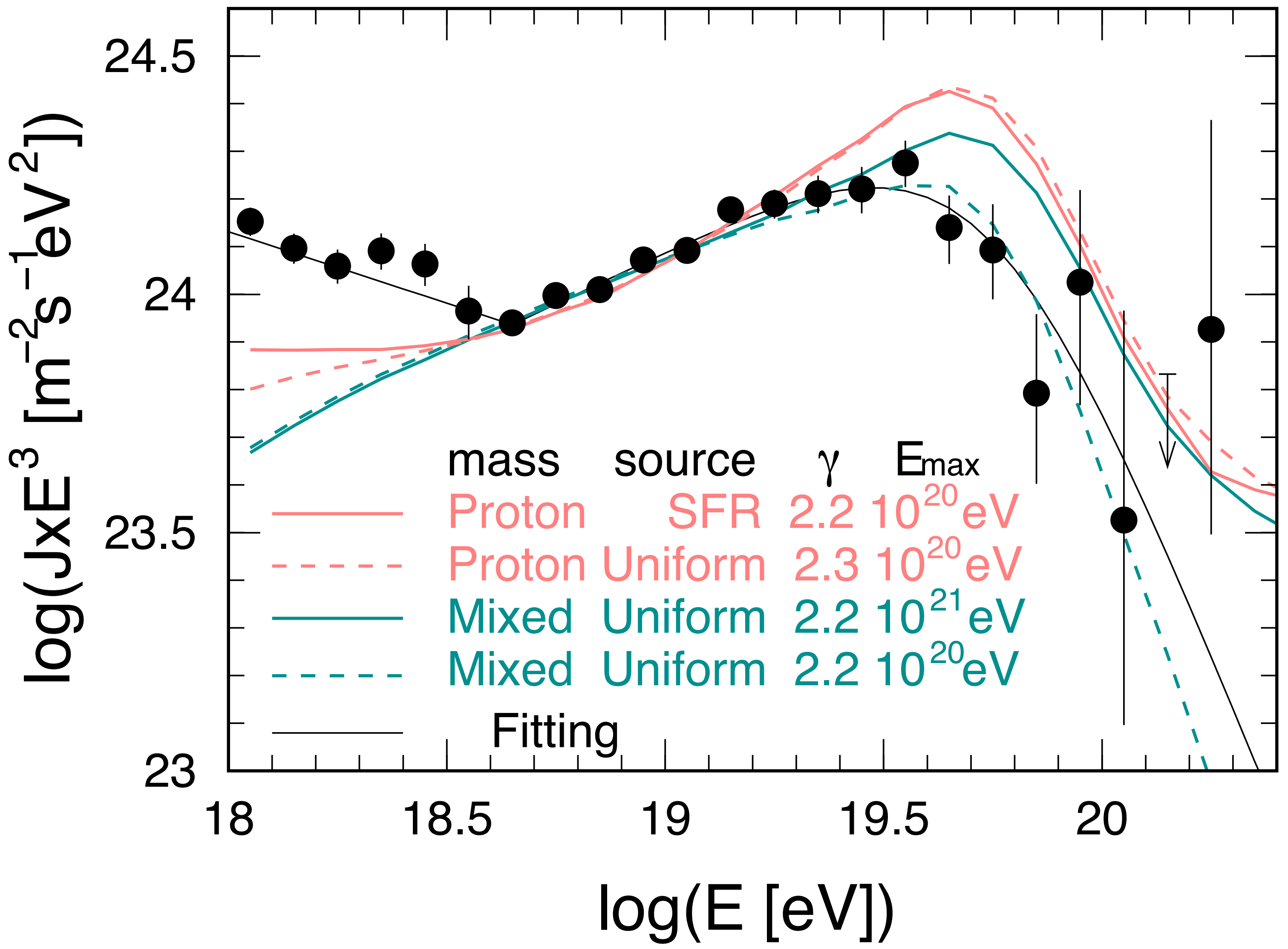


• Energy spectrum







- First estimate of the primary cosmic ray energy spectrum
- Data from SD and FD

ICRC 2005

- Fitted the combined spectrum following a simple power law + smooth function

$$J(E; E < E_{ankle}) \propto E^{-\gamma_1}$$
$$J(E; E > E_{ankle}) \propto E^{-\gamma_2} \frac{1}{1 + \exp\left(\frac{\lg E - \lg E_c}{W_c}\right)}$$

ICRC 2007

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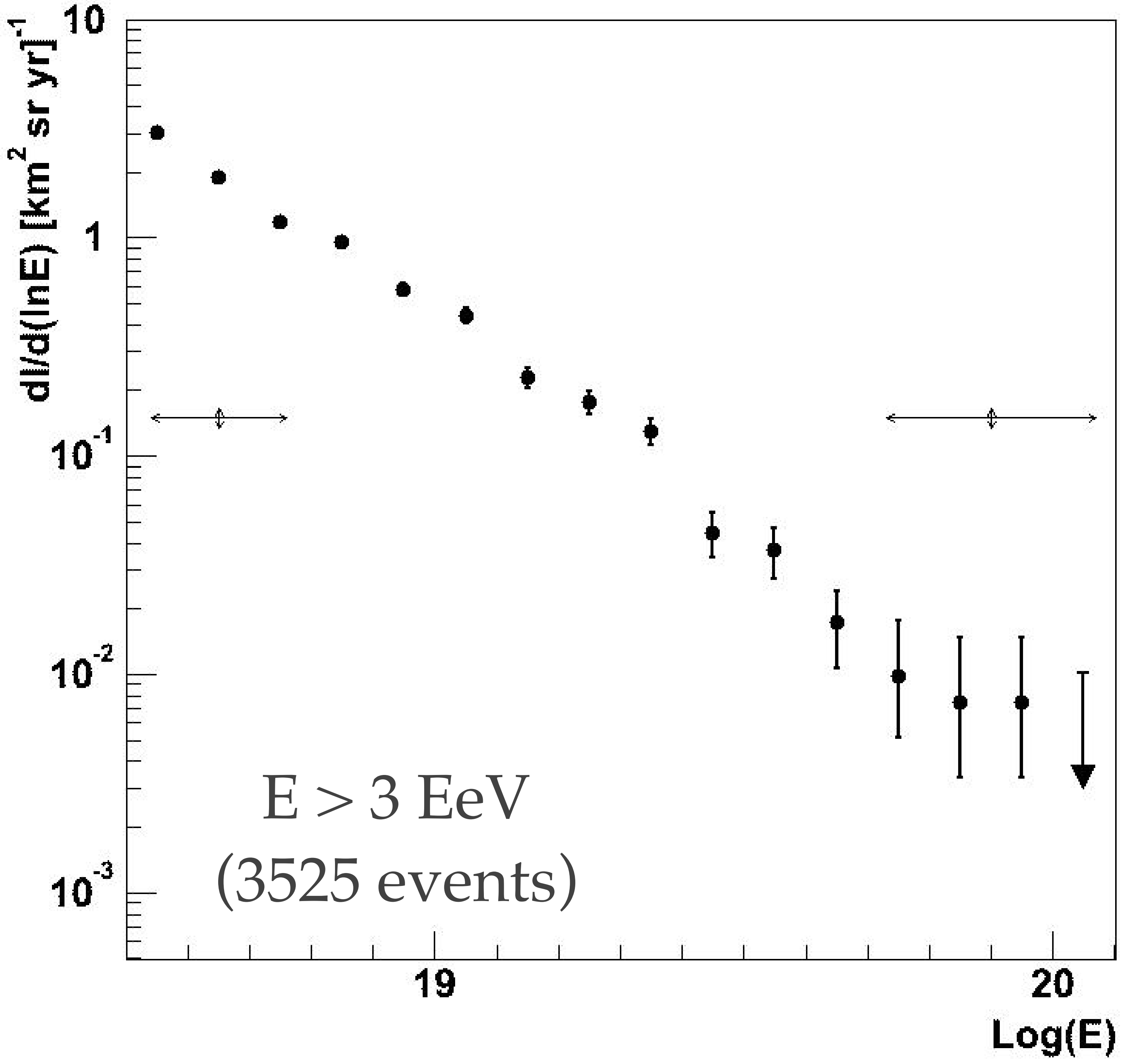

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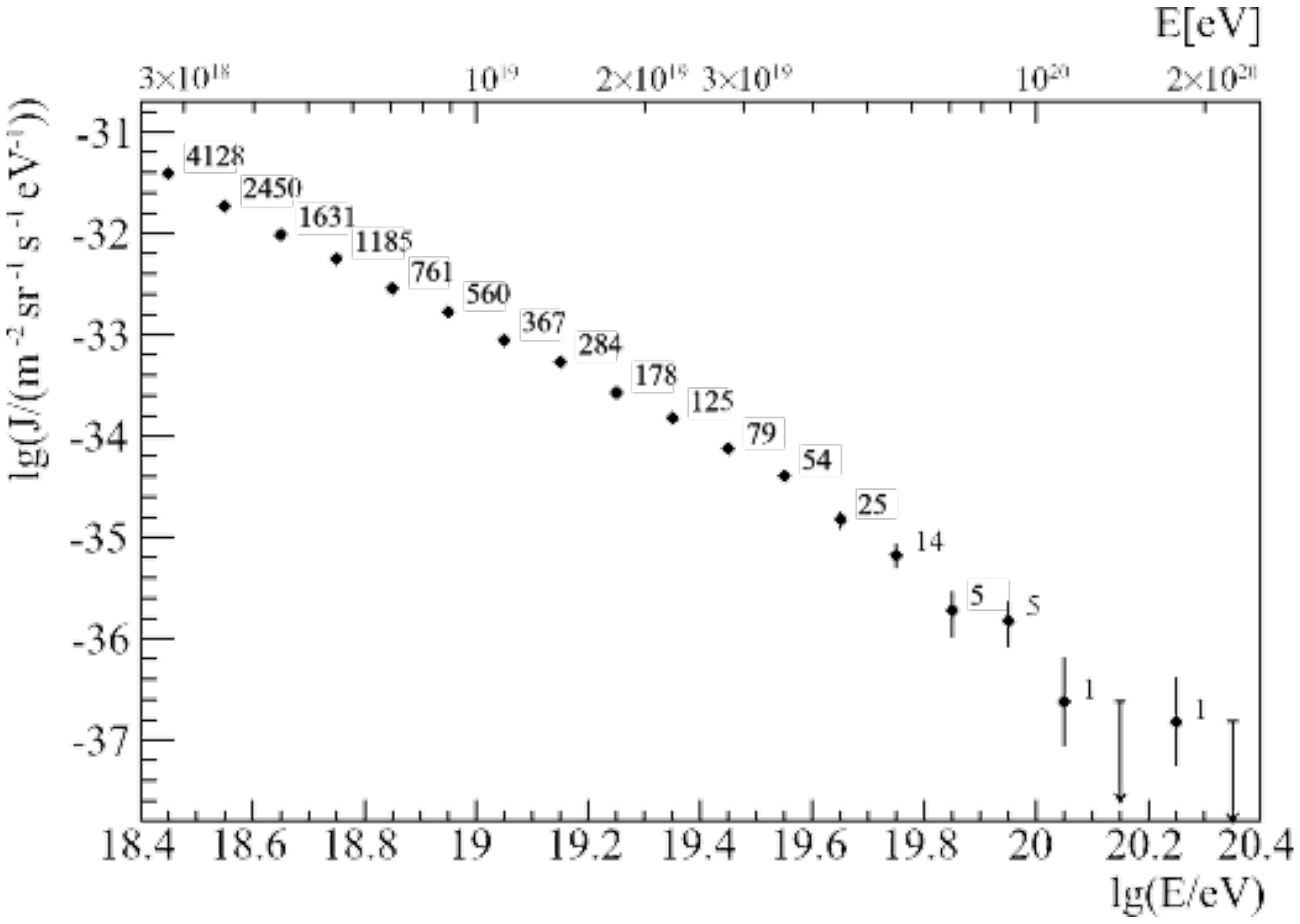

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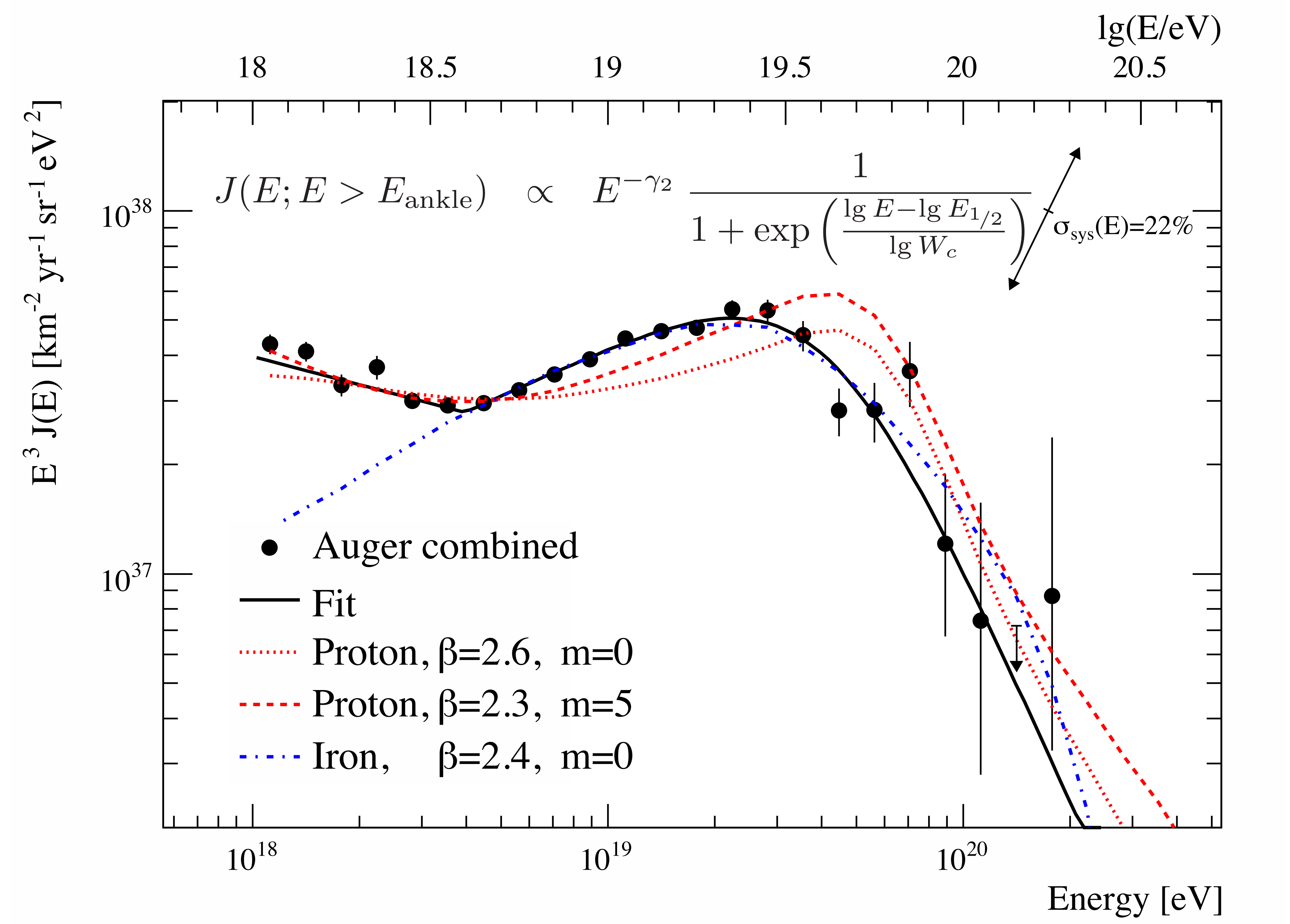

- Cosmological evolution of the source luminosity
- Only proton or iron composition at the source

parameter	broken power laws	power laws + smooth function
$\gamma_1(E < E_{\rm ankle})$	3.26 ± 0.04	3.26 ± 0.04
$\lg(E_{\rm ankle}/{\rm eV})$	18.61 ± 0.01	18.60 ± 0.01
$\gamma_2(E > E_{\rm ankle})$	2.59 ± 0.02	2.55 ± 0.04
$\lg(E_{\rm break}/{\rm eV})$	19.46 ± 0.03	
$\gamma_3(E > E_{\rm break})$	4.3 ± 0.2	
$\lg(E_{1/2}/{\rm eV})$		19.61 ± 0.03
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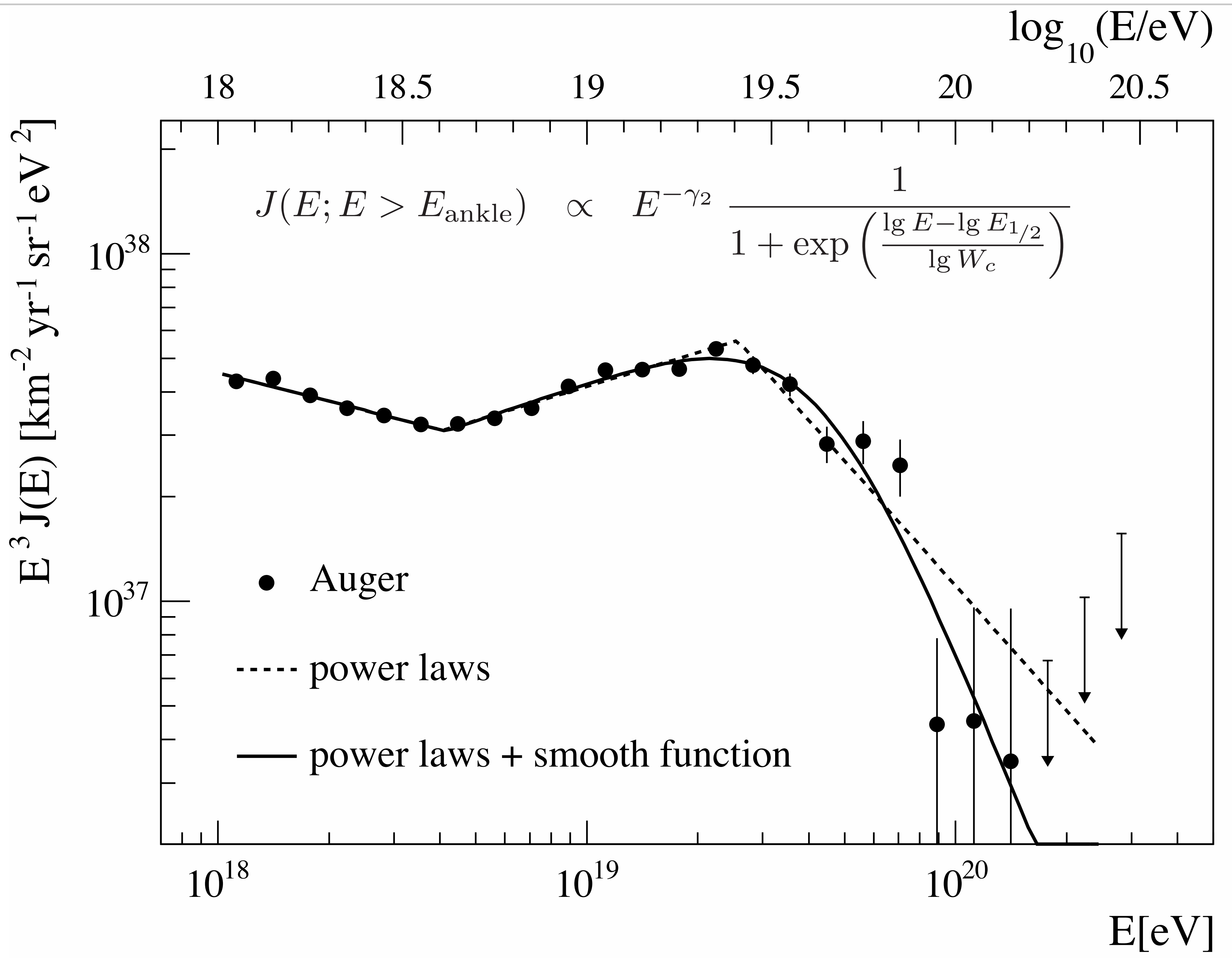
ICRC 2009



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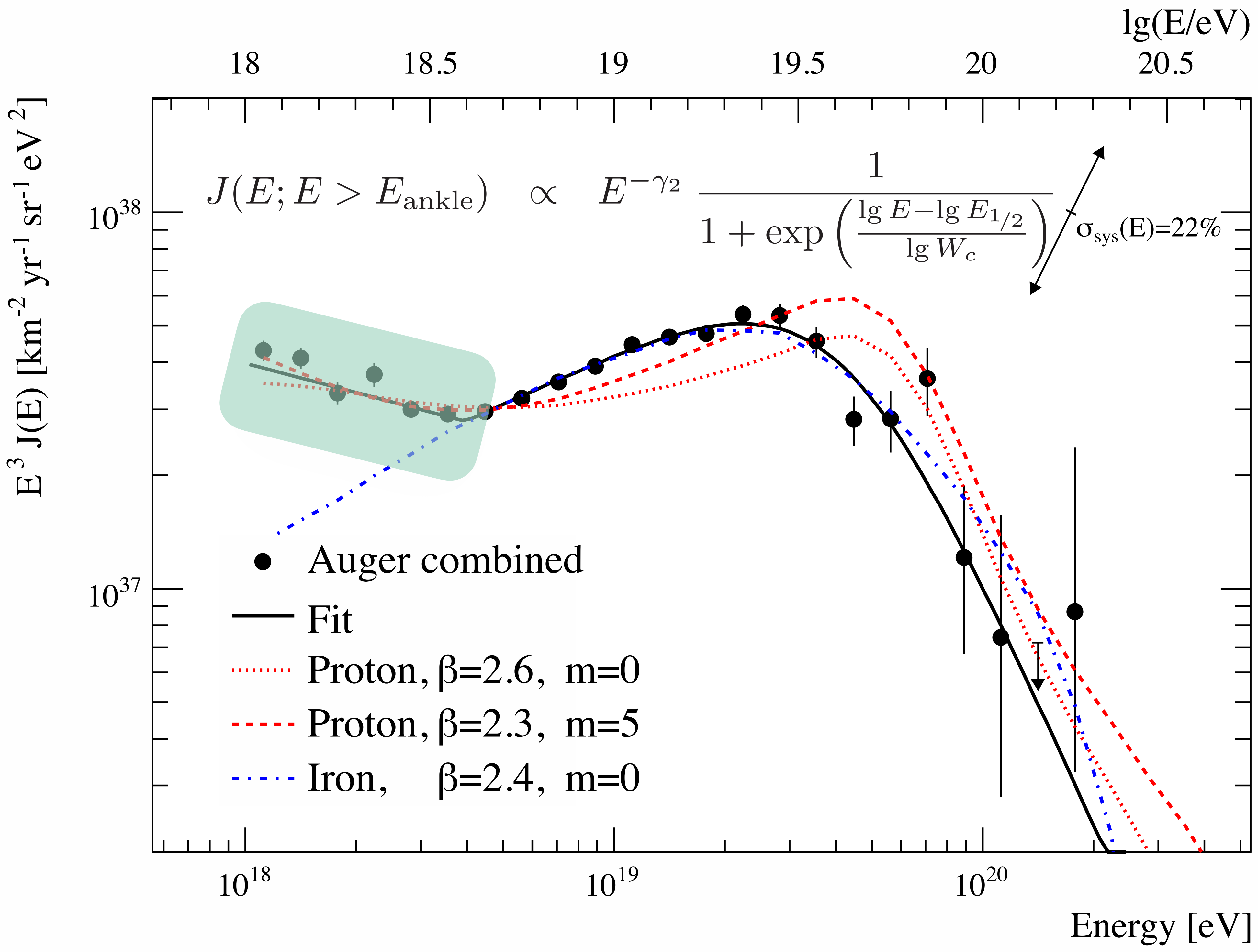
$\gamma_3(E > E_{\rm break})$	4.2 ± 0.1	
$\lg(E_{1/2}/{\rm eV})$		19.63 ± 0.02
$\lg(W_c/{\rm eV})$		0.15 ± 0.02
$\chi^2/{\rm ndof}$	$37.8/16 = 2.7$	$33.7/16 = 2.3$

ICRC 2011

- Energy spectrum



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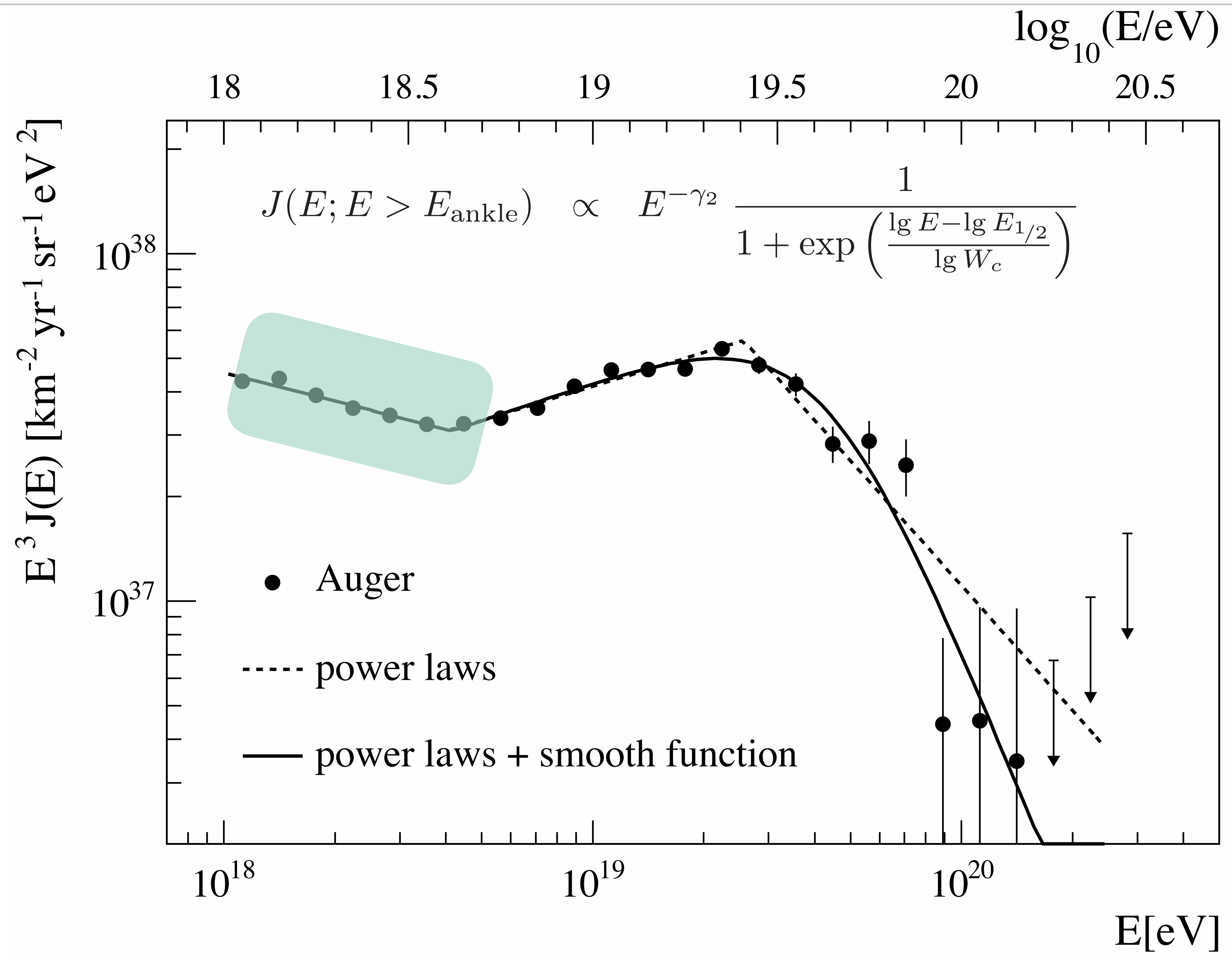

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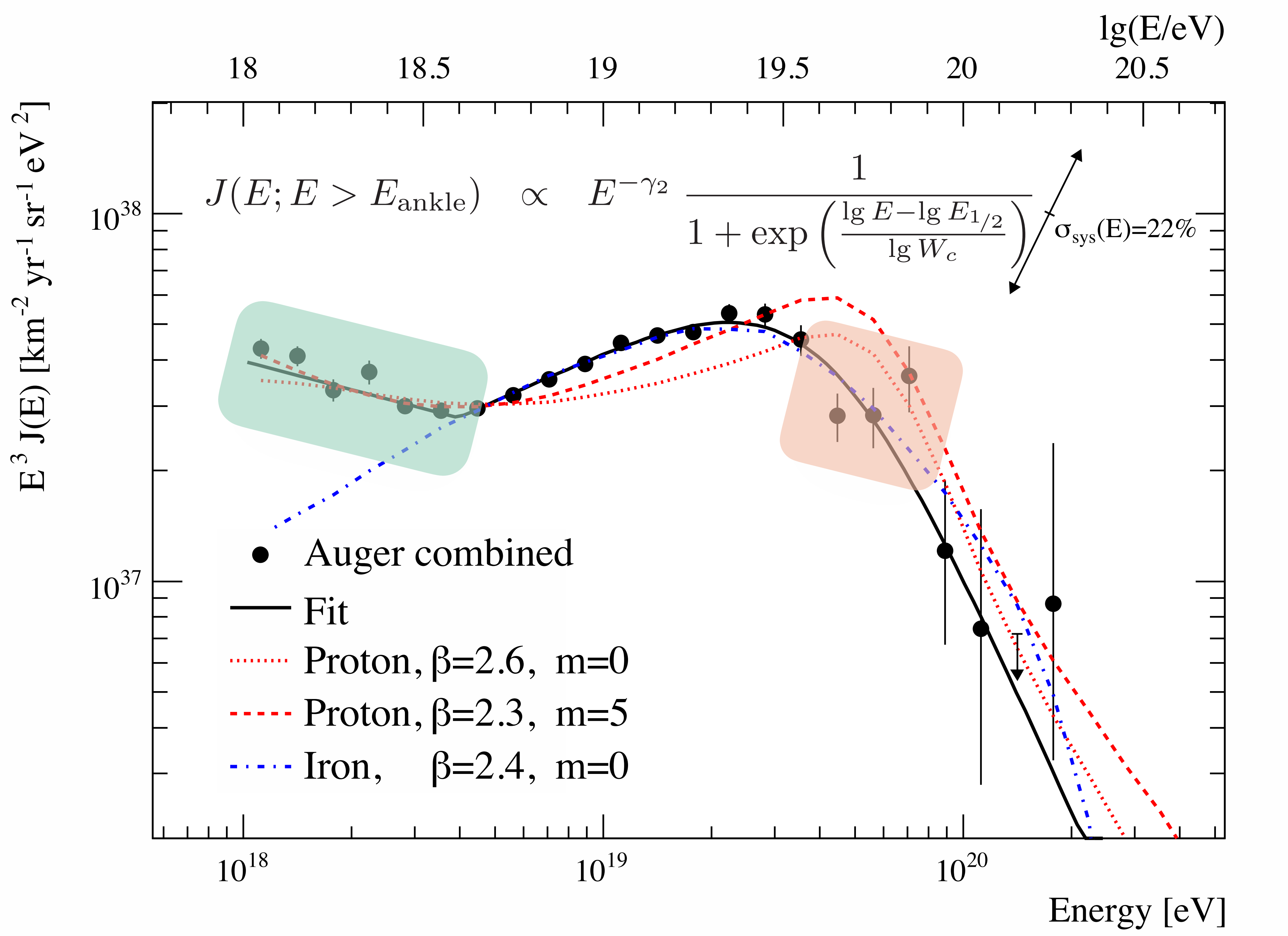

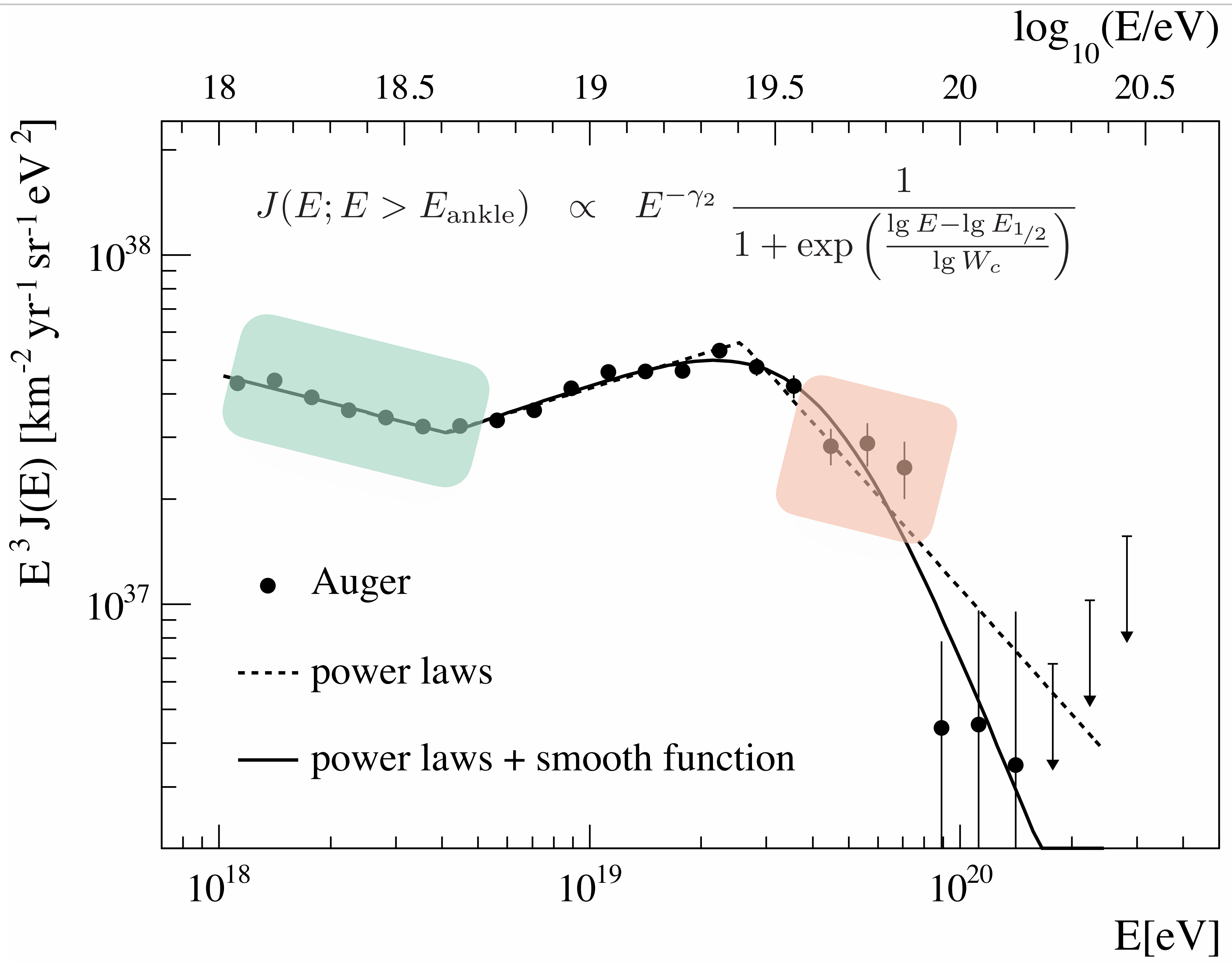

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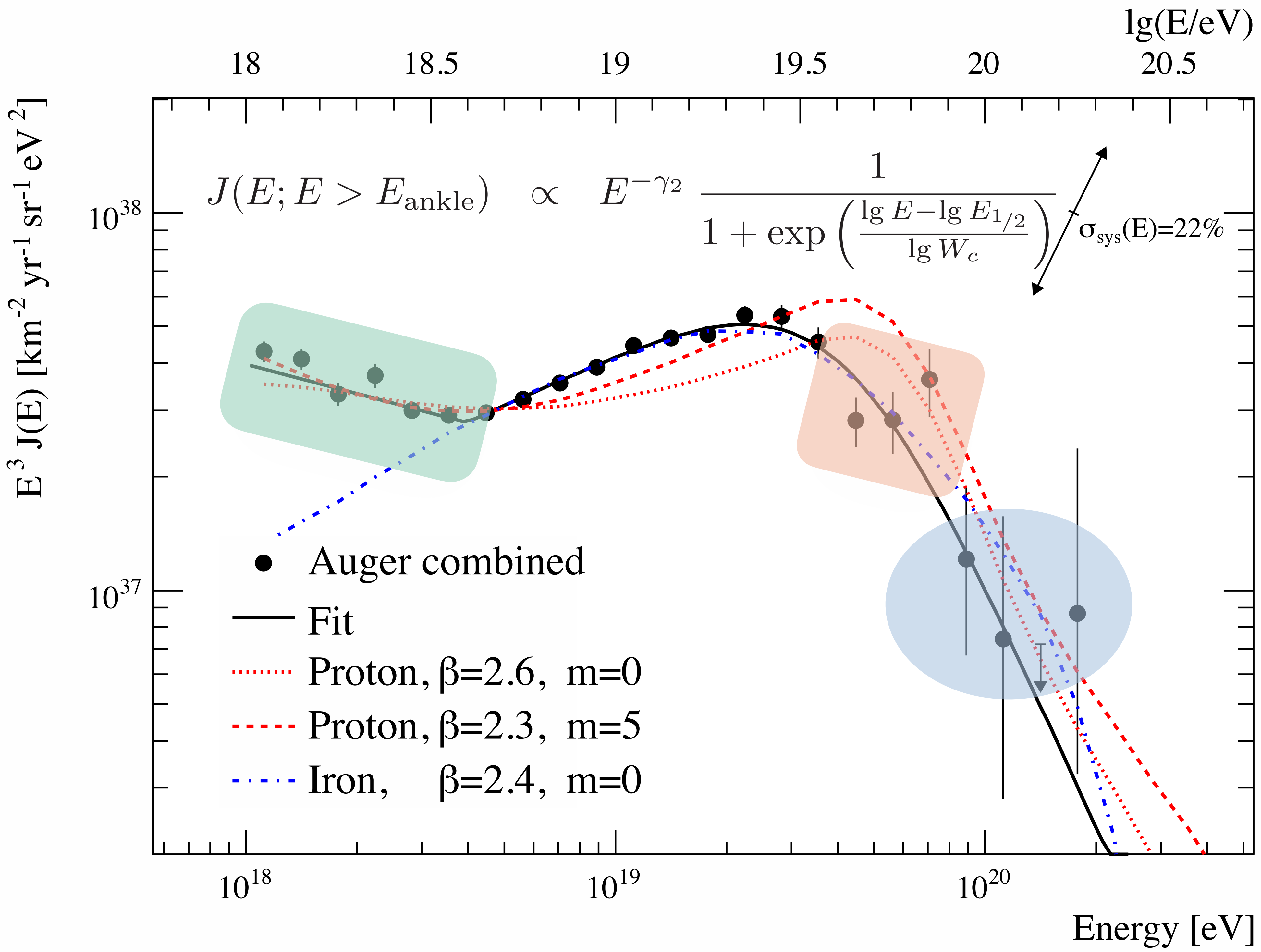
ICRC 2011

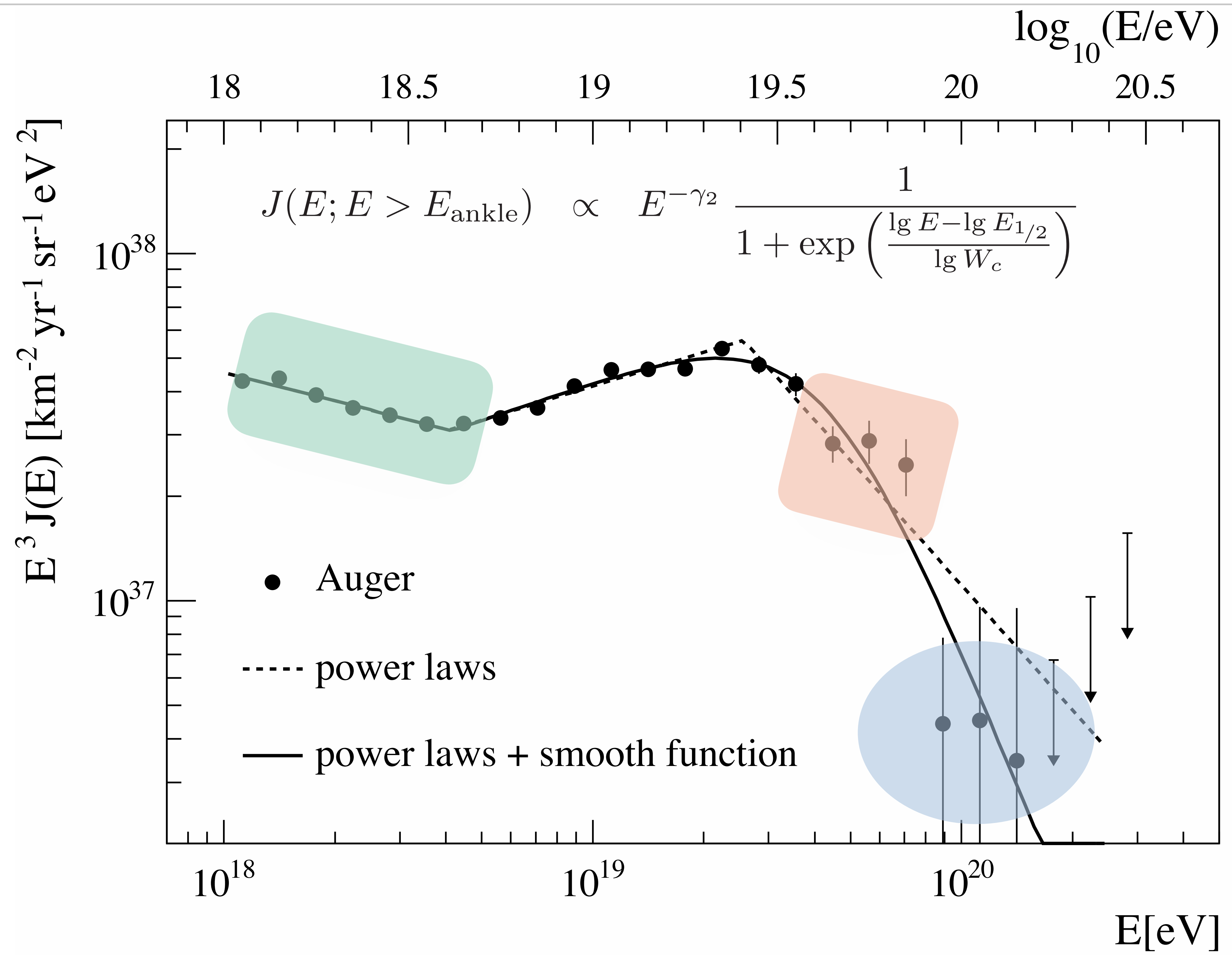
• Energy spectrum



- Cosmological evolution of the source luminosity
- Only proton or iron composition at the source

parameter	broken power laws	power laws + smooth function
$\gamma_1(E < E_{\rm ankle})$	3.26 ± 0.04	3.26 ± 0.04
$\lg(E_{\rm ankle}/\rm eV)$	18.61 ± 0.01	18.60 ± 0.01
$\gamma_2(E > E_{\rm ankle})$	2.59 ± 0.02	2.55 ± 0.04
$\lg(E_{\rm break}/\rm eV)$	19.46 ± 0.03	
$\gamma_3(E > E_{\rm break})$	4.3 ± 0.2	
$\lg(E_{1/2}/\rm eV)$		19.61 ± 0.03
$\lg(W_c/\rm eV)$		0.16 ± 0.03

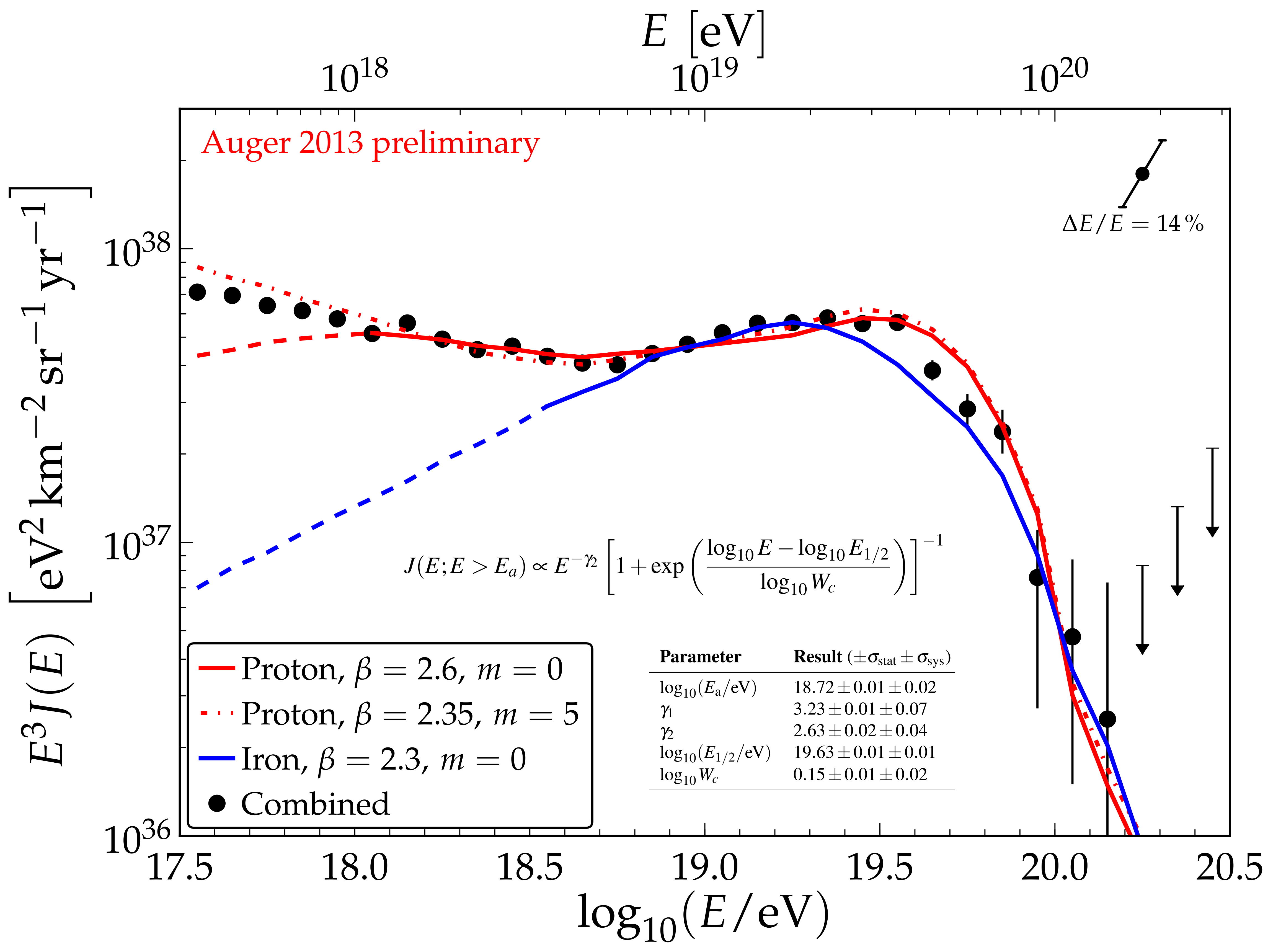
ICRC 2009



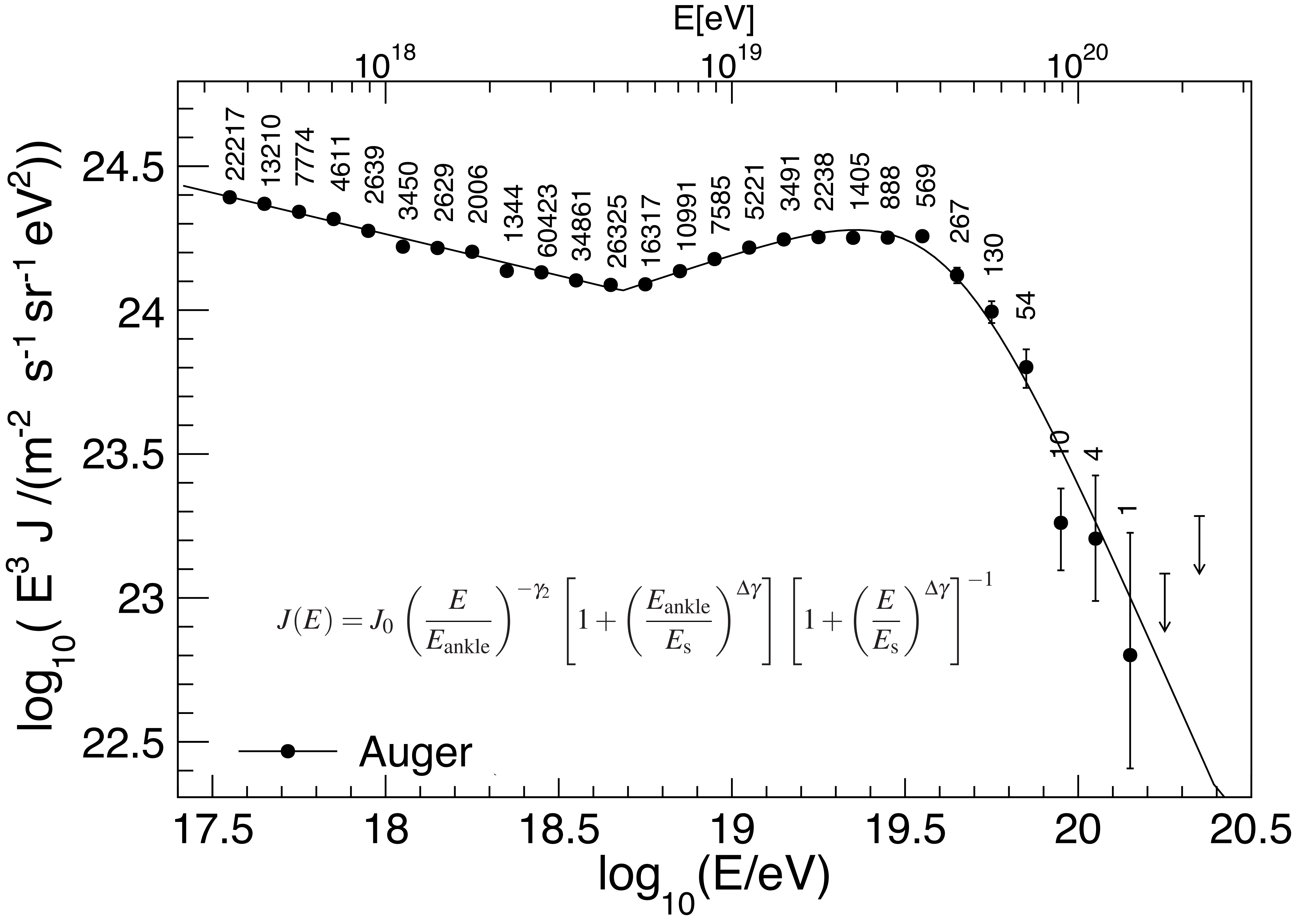
parameter	broken power laws	power laws + smooth function
$\gamma_1(E < E_{\rm ankle})$	3.27 ± 0.02	3.27 ± 0.01
$\lg(E_{\rm ankle}/\rm eV)$	18.61 ± 0.01	18.62 ± 0.01
$\gamma_2(E > E_{\rm ankle})$	2.68 ± 0.01	2.63 ± 0.02
$\lg(E_{\rm break}/\rm eV)$	19.41 ± 0.02	
$\gamma_3(E > E_{\rm break})$	4.2 ± 0.1	
$\lg(E_{1/2}/\rm eV)$		19.63 ± 0.02
$\lg(W_c/\rm eV)$		0.15 ± 0.02
$\chi^2/\rm ndof$	$37.8/16 = 2.7$	$33.7/16 = 2.3$

ICRC 2011

- Energy spectrum

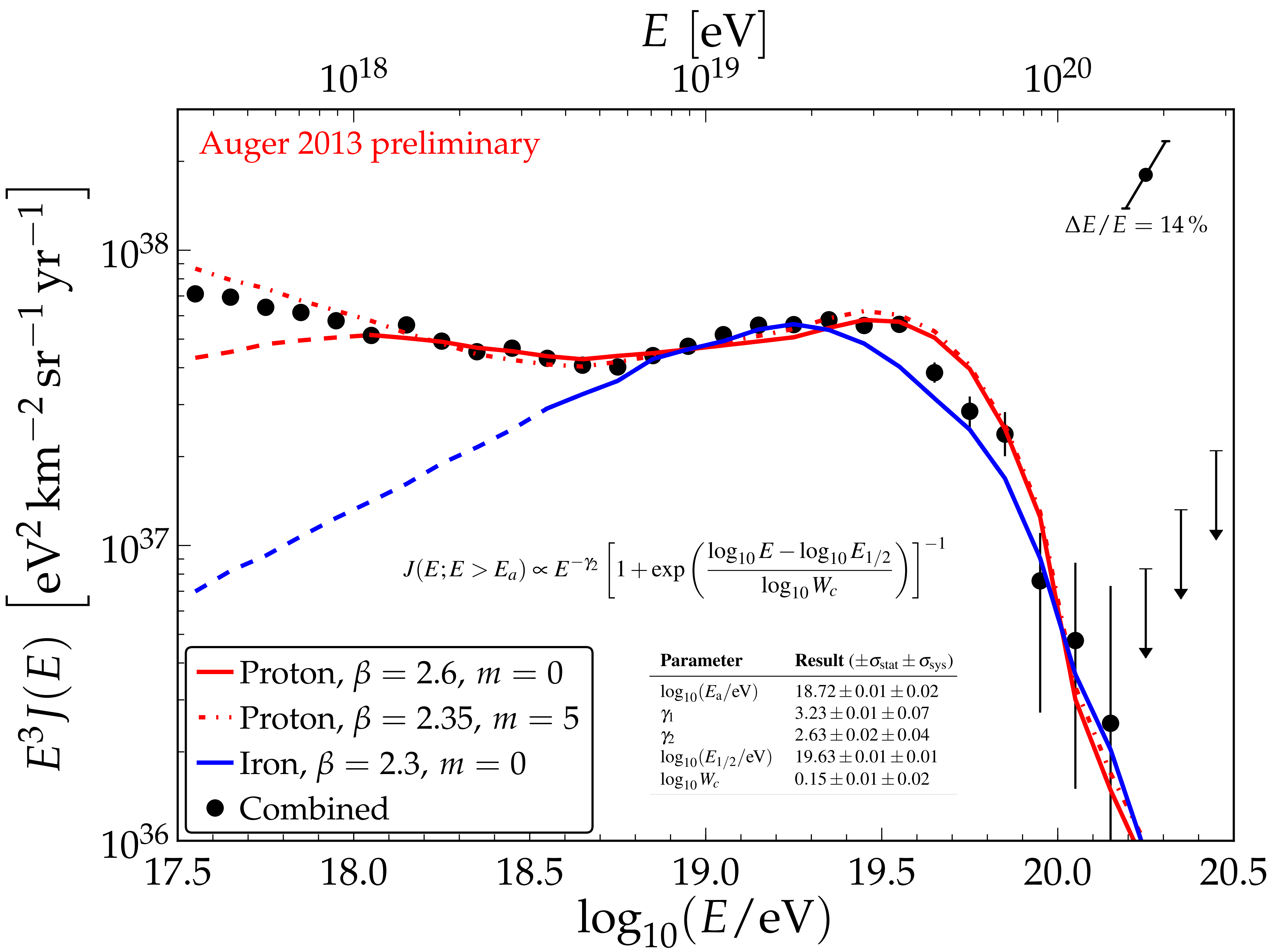


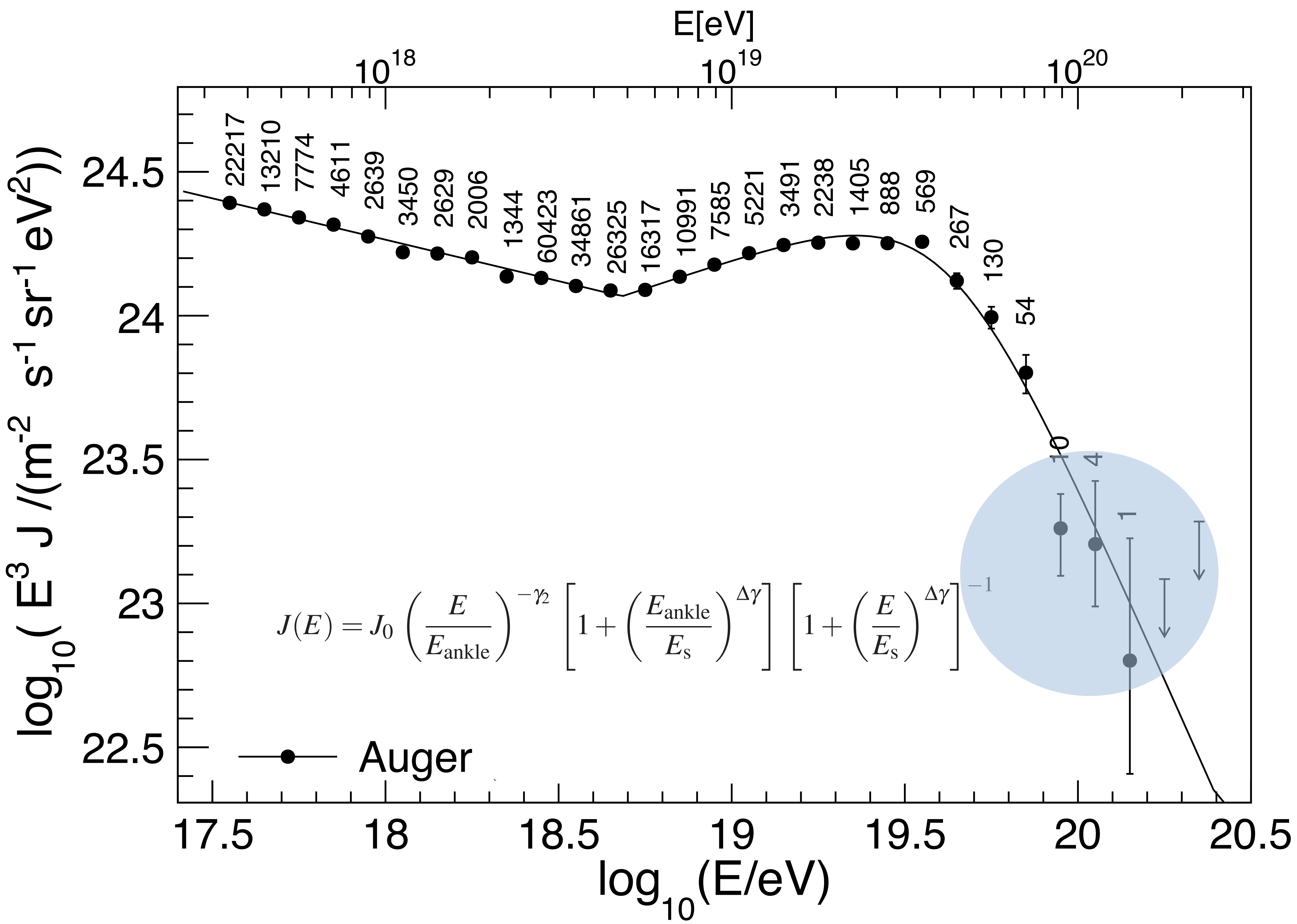
ICRC 2013



ICRC 2015

- Energy spectrum

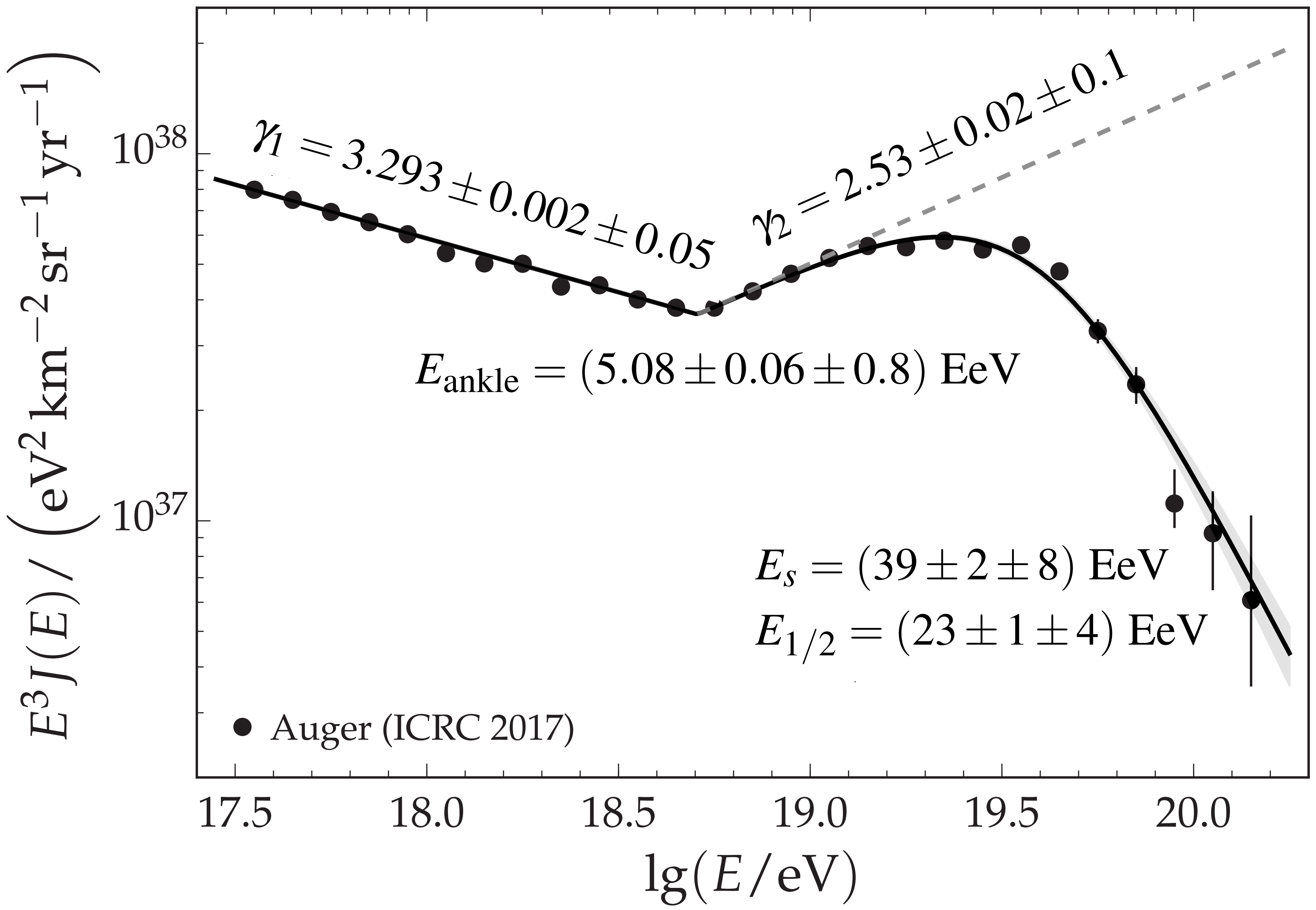




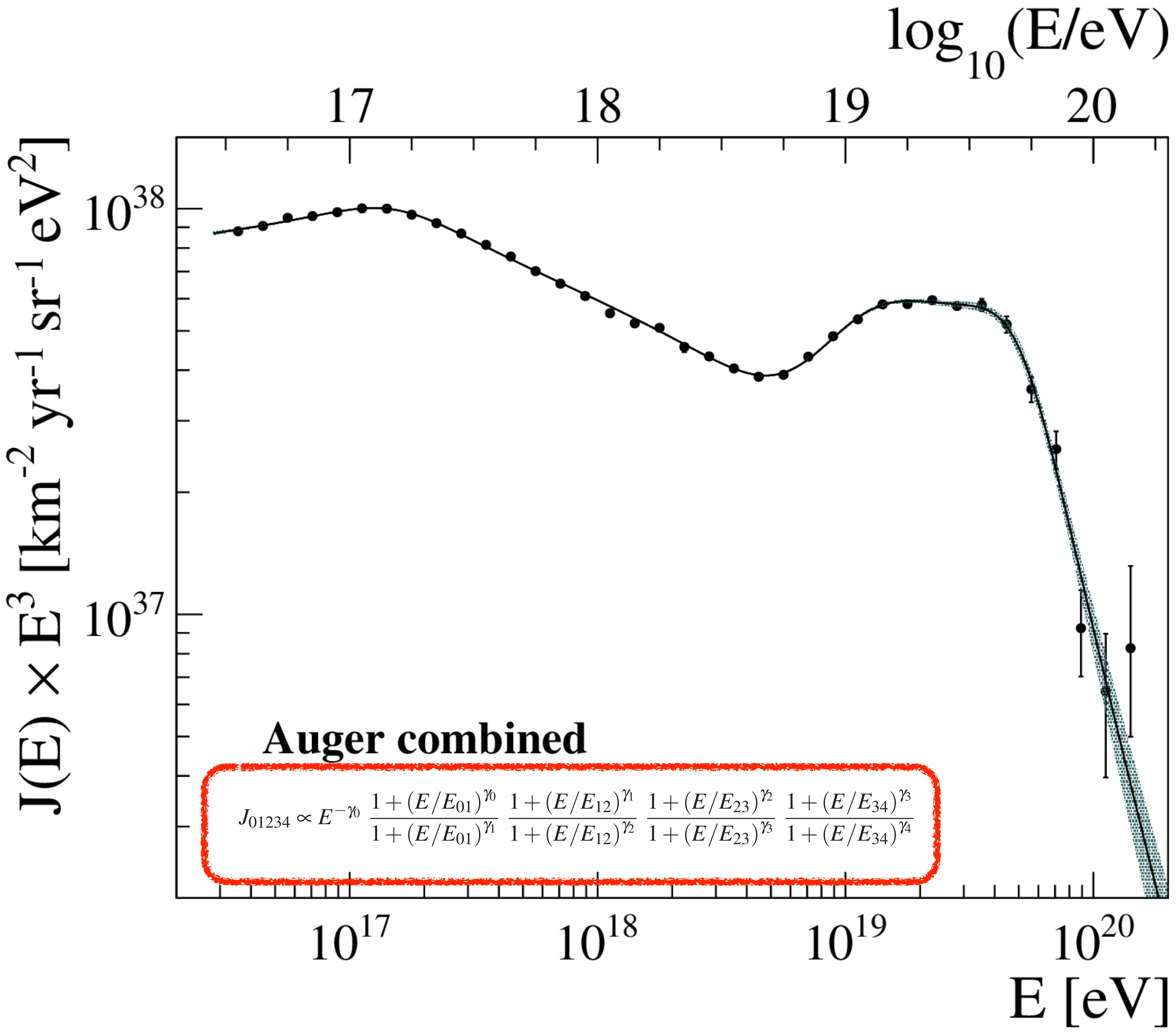
ICRC 2013

ICRC 2015

- Energy spectrum

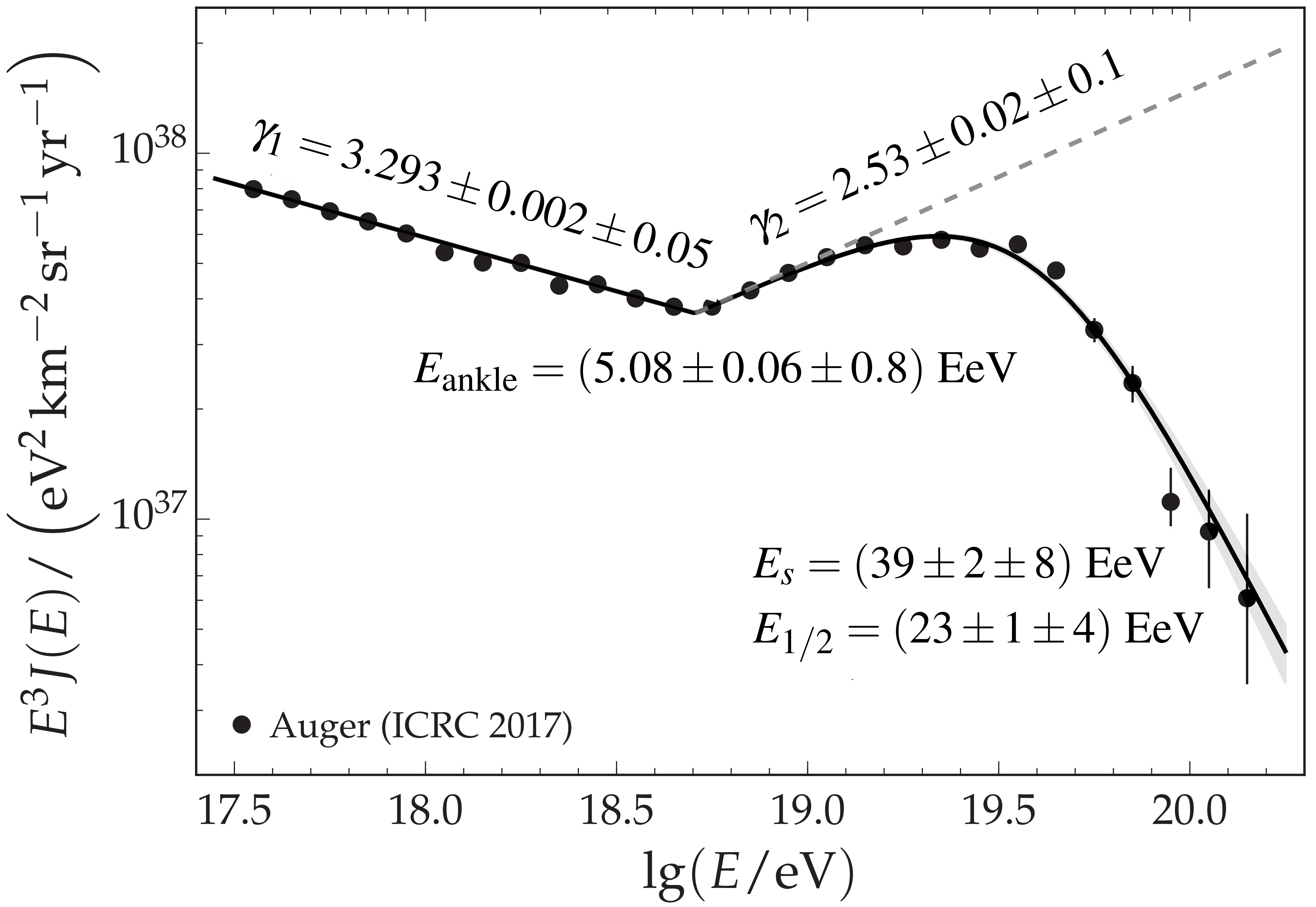


ICRC 2017

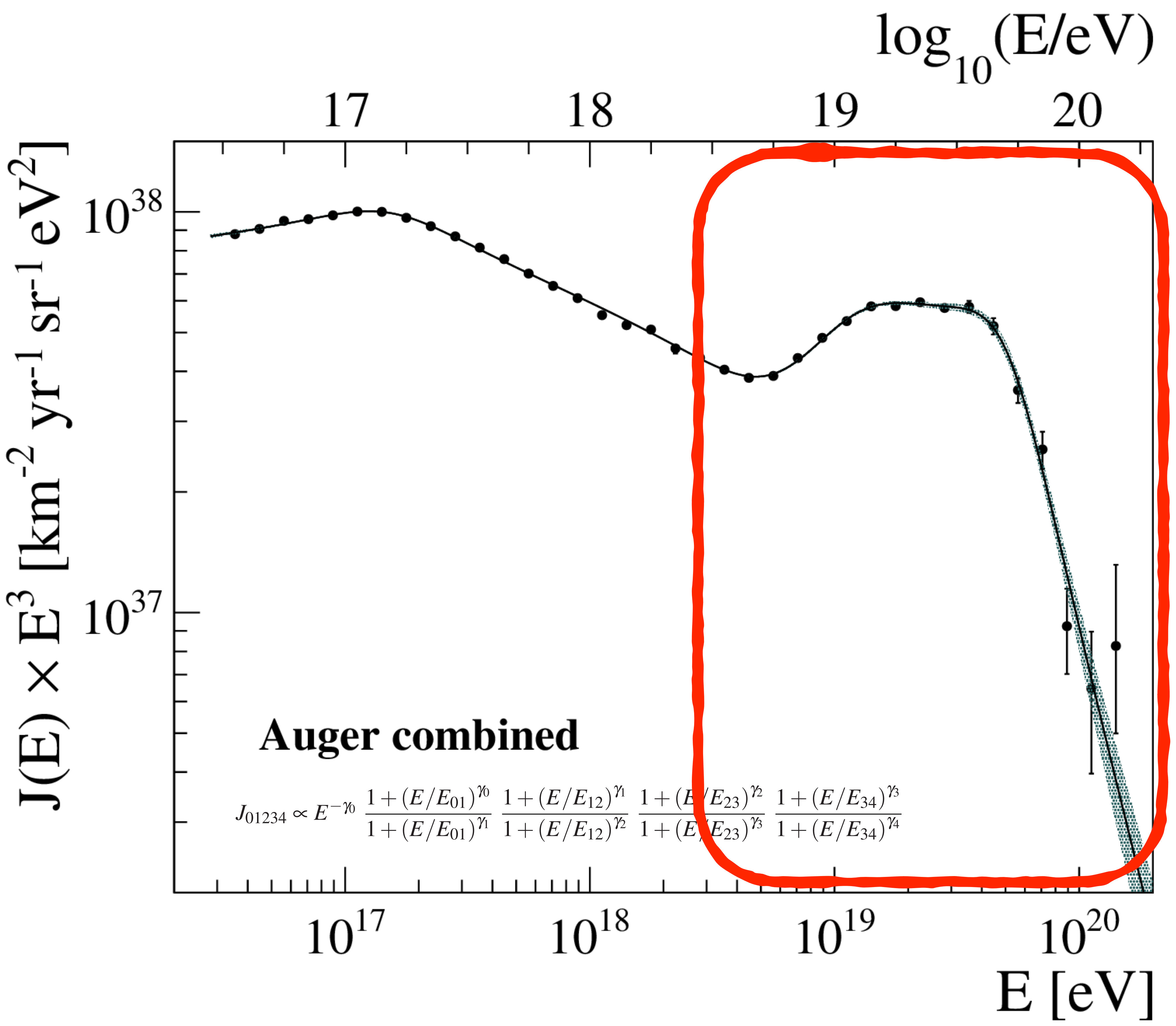


ICRC 2019

- Energy spectrum

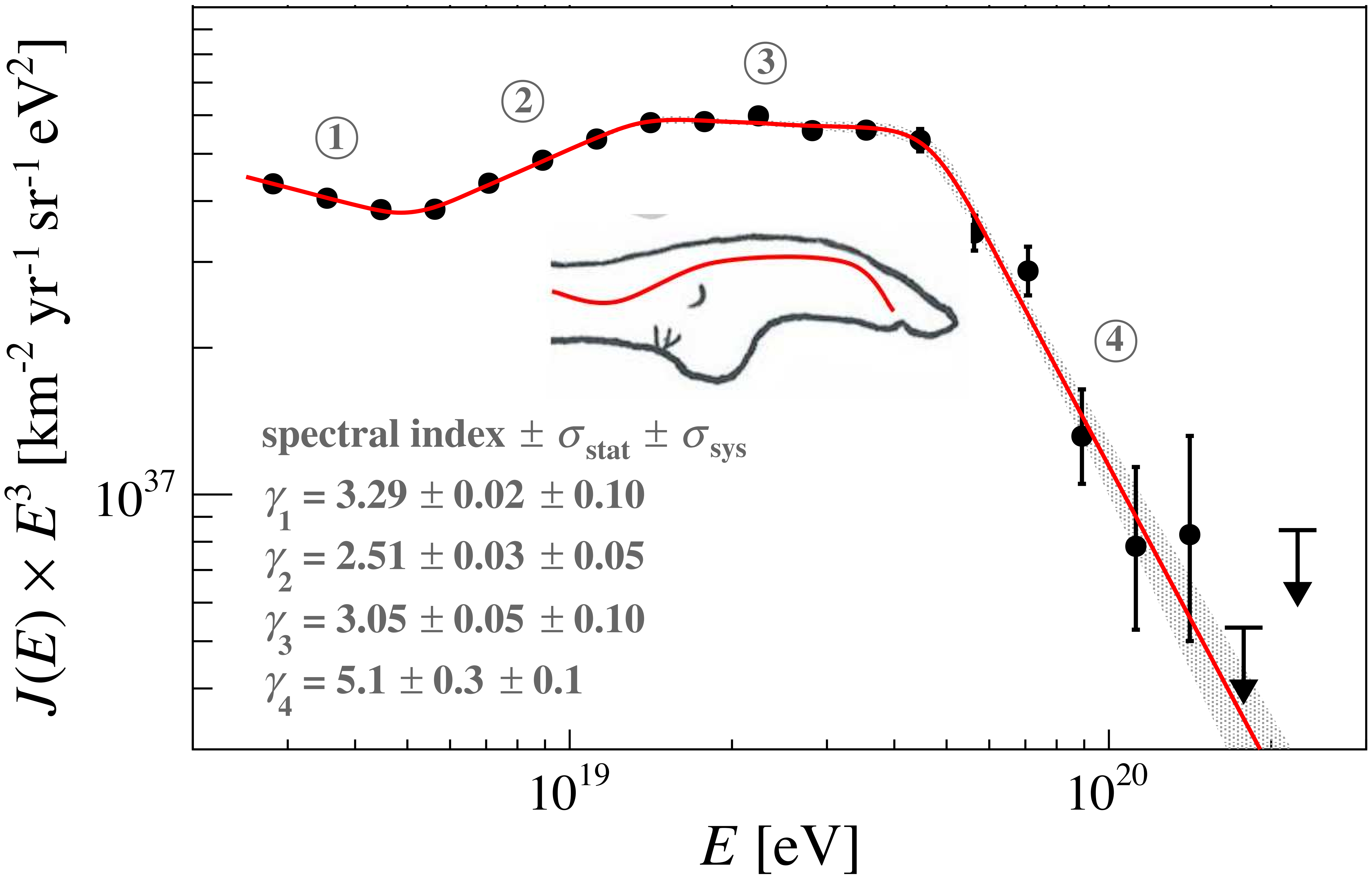


ICRC 2017



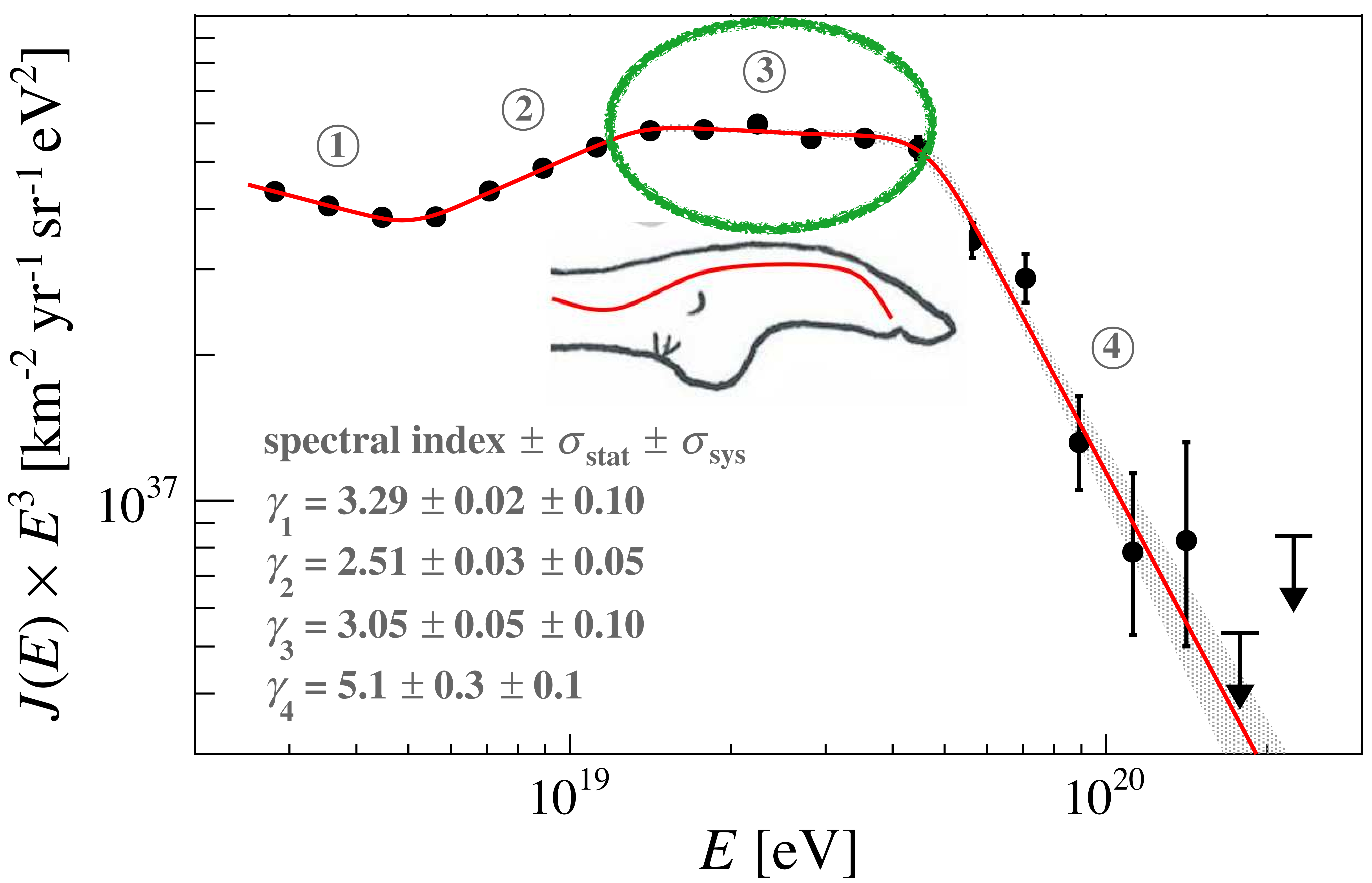
ICRC 2019

- Energy spectrum



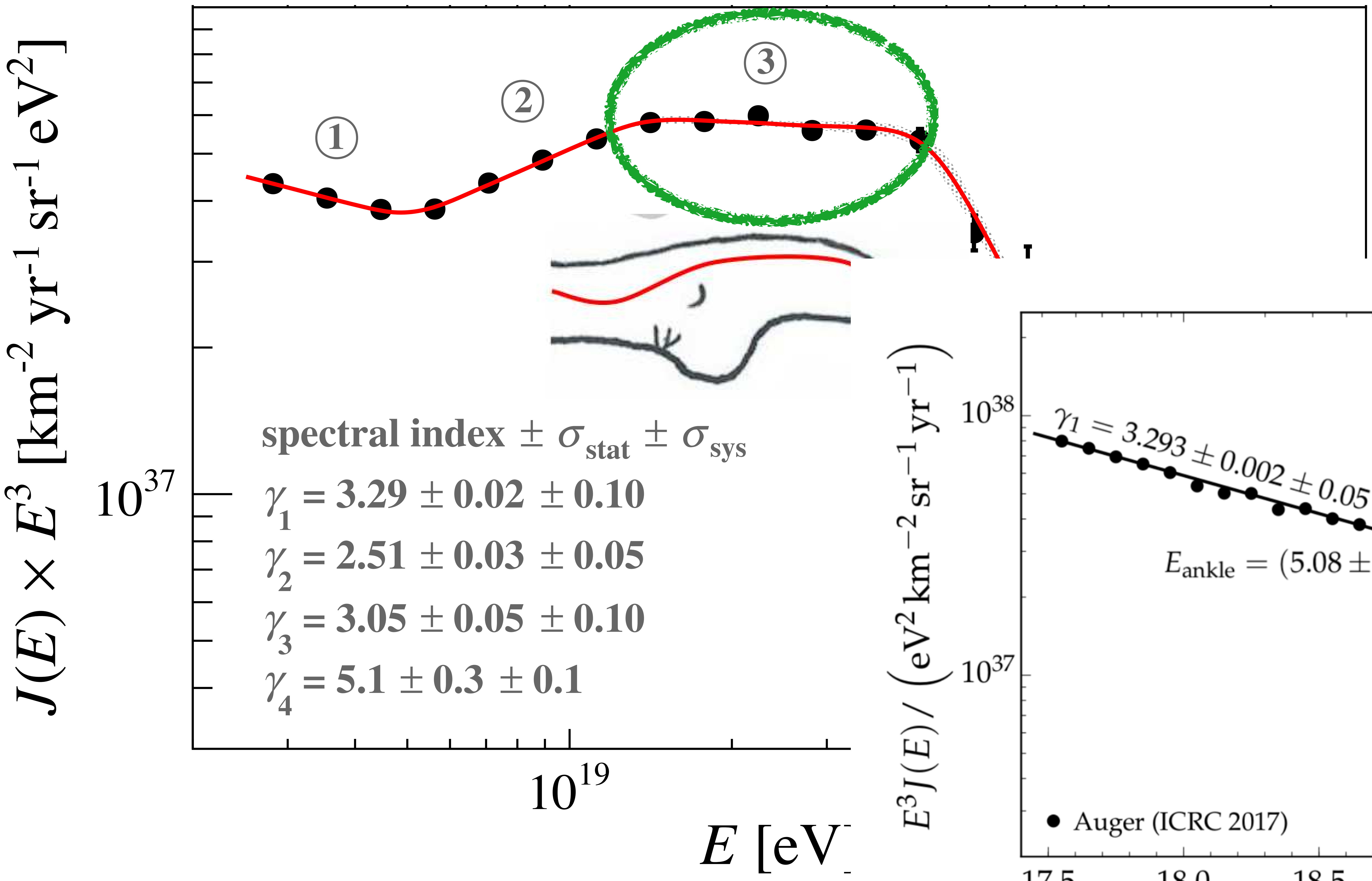
Aab et al. PRL 2020

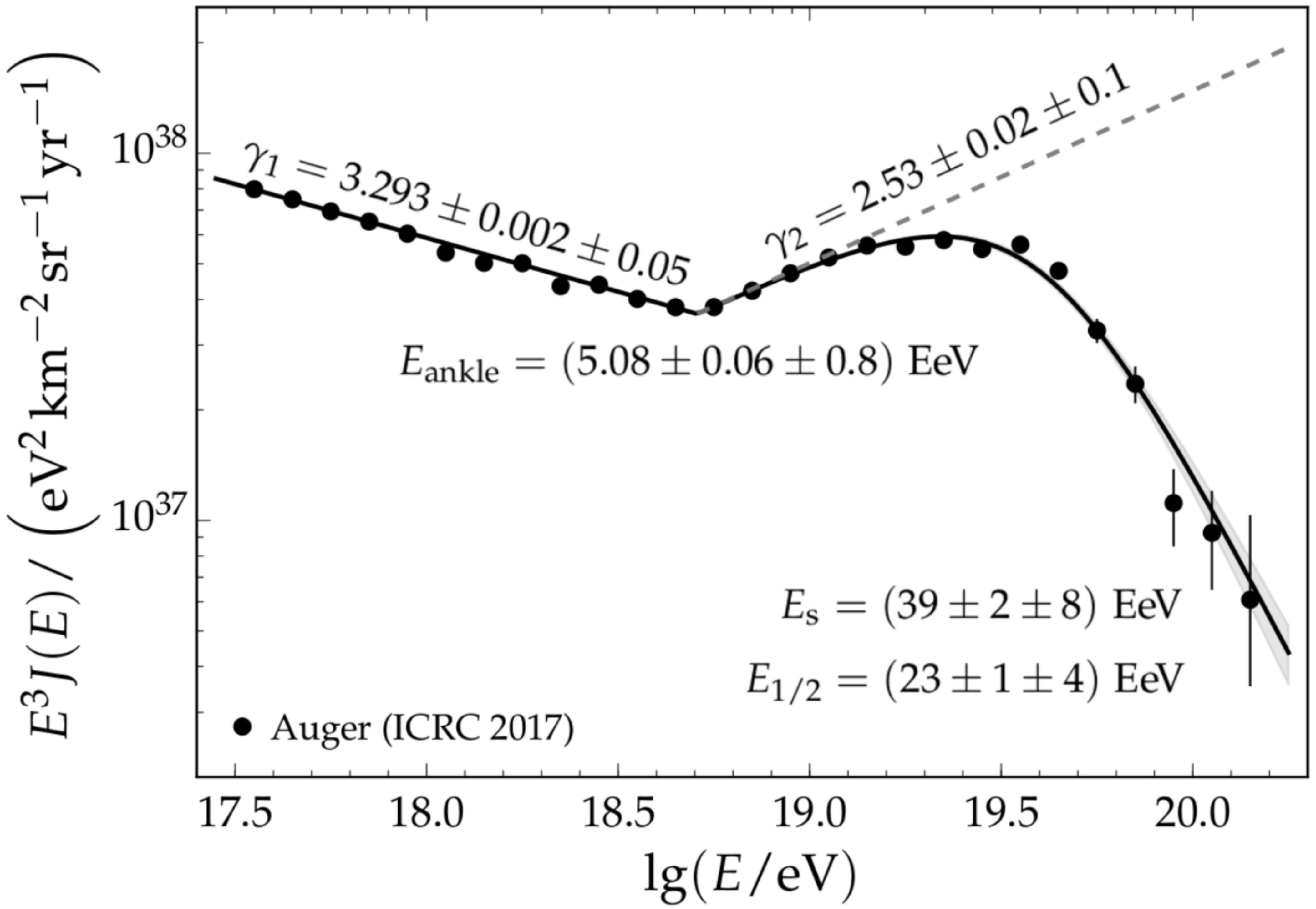
- Energy spectrum



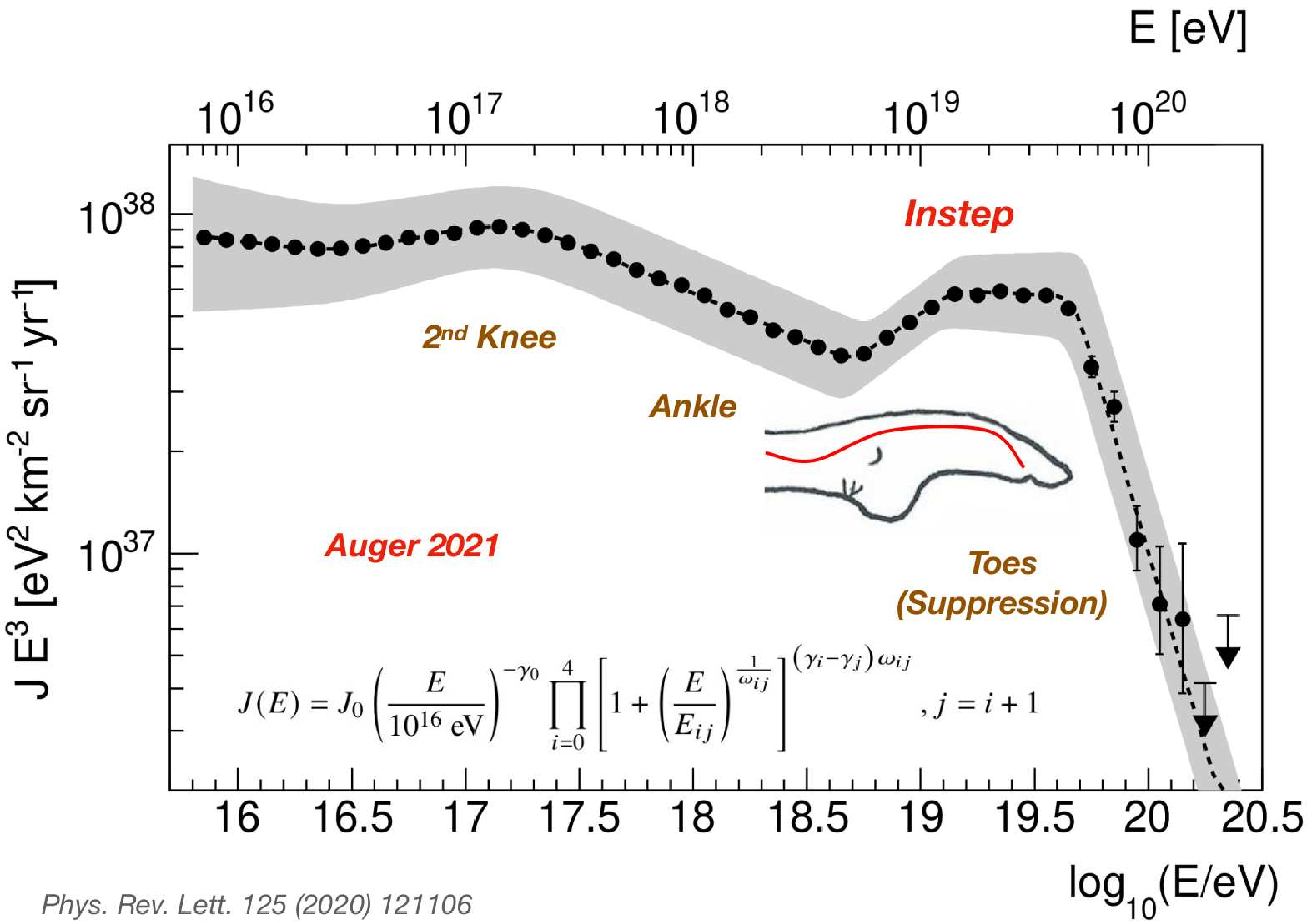
Aab et al. PRL 2020

- Energy spectrum





- Energy spectrum



Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
Eur. Phys. J. C81 (2021) 966

		$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
low energy ankle	$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV	$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
2nd knee	$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV	$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
ankle	$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV	$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$
instep	$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV	$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$
suppression	$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV	$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

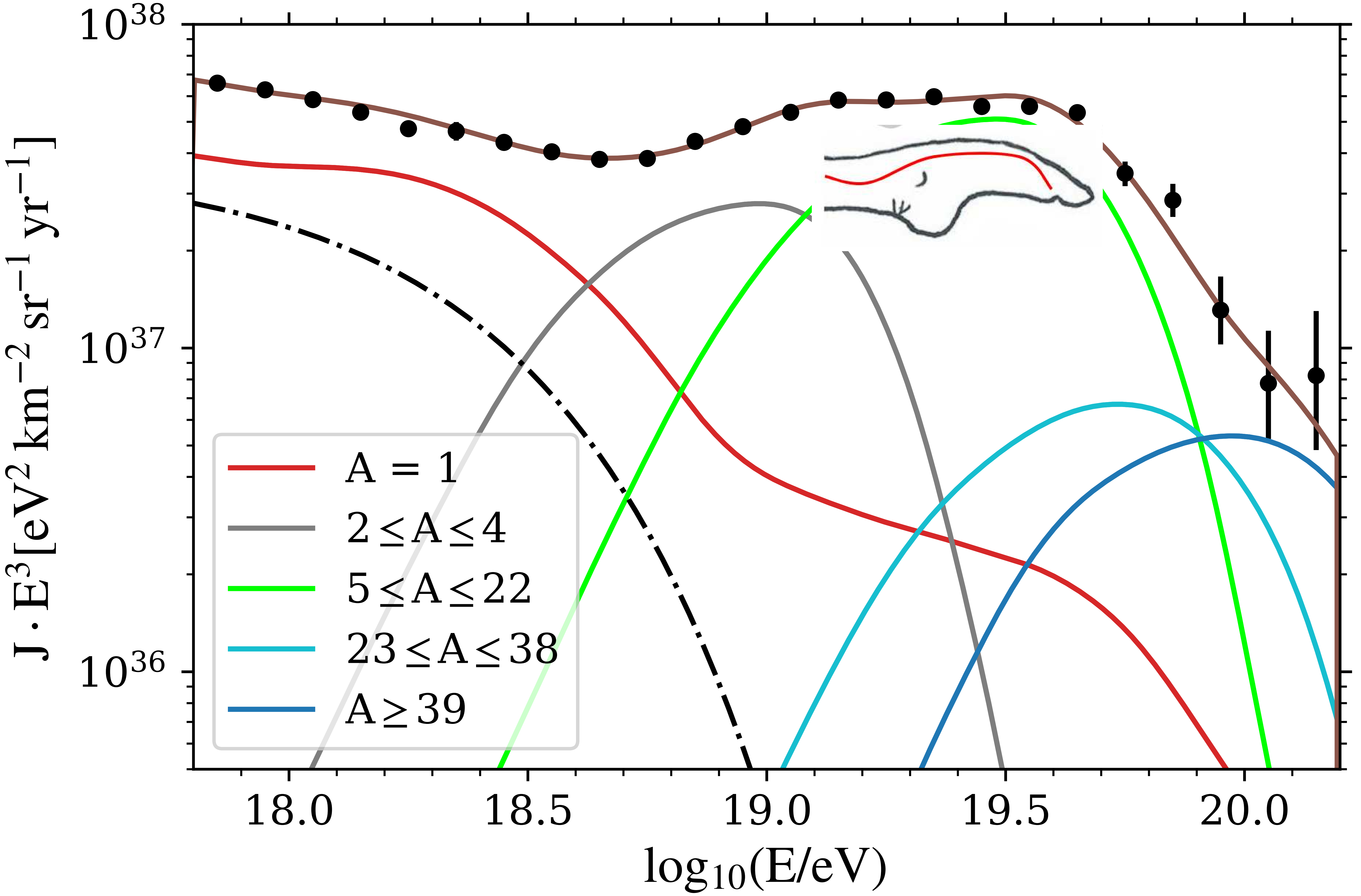
Suppression at ~ 5 × 10^{19} eV → Energy losses
Instep at ~ 10^{19} eV → Light to intermediate nuclei
Ankle at ~ 5 × 10^{18} eV → Hardening of the spectrum
2nd knee at ~ 2 × 10^{17} eV – End of GCR?
Hint for low energy ankle at ~ 10^{17} eV

ICRC 2021

Figure by D. Nitz and V. Varma

• Energy spectrum

Galactic the extragalactic contributions to the energy spectrum

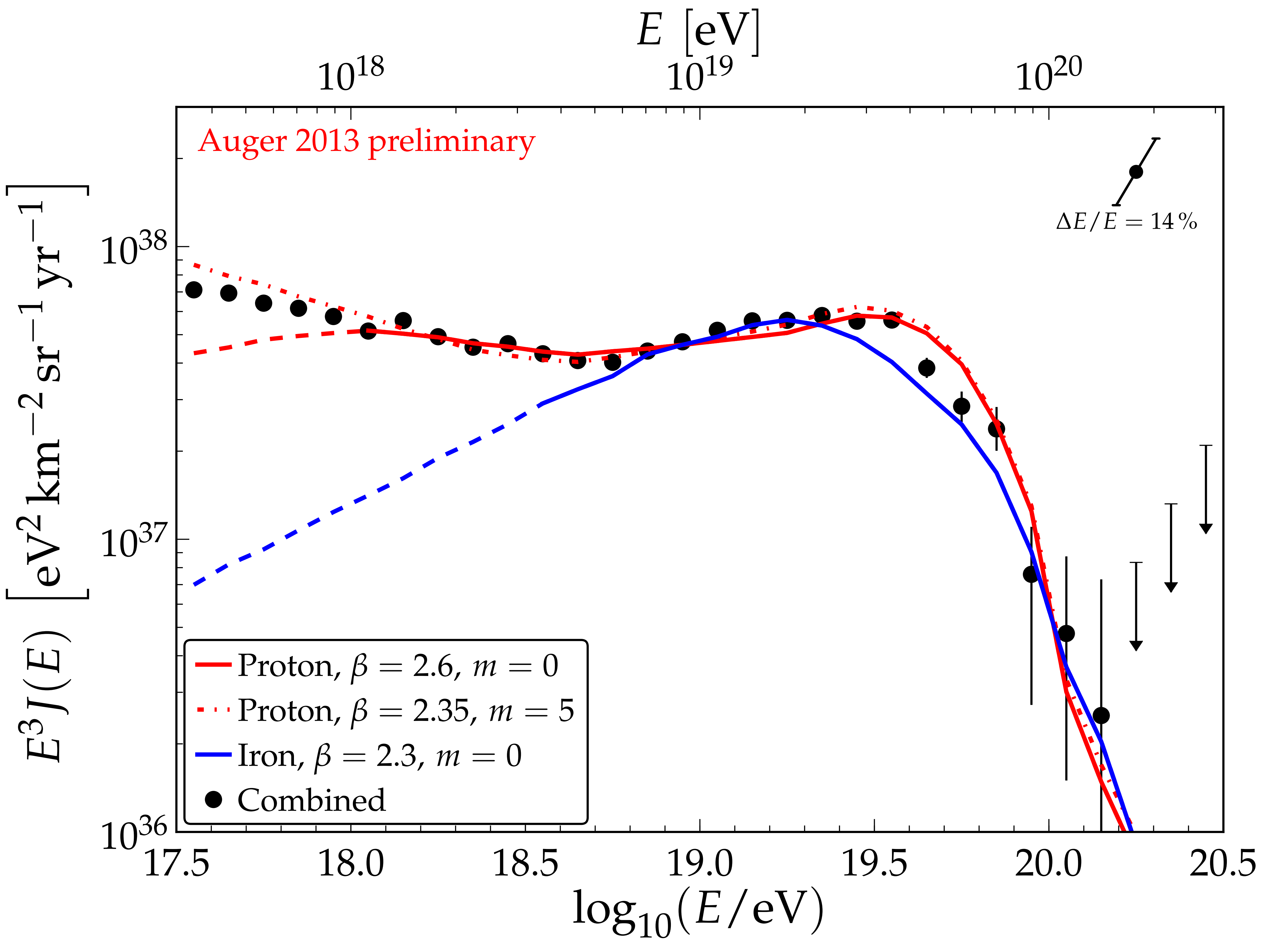


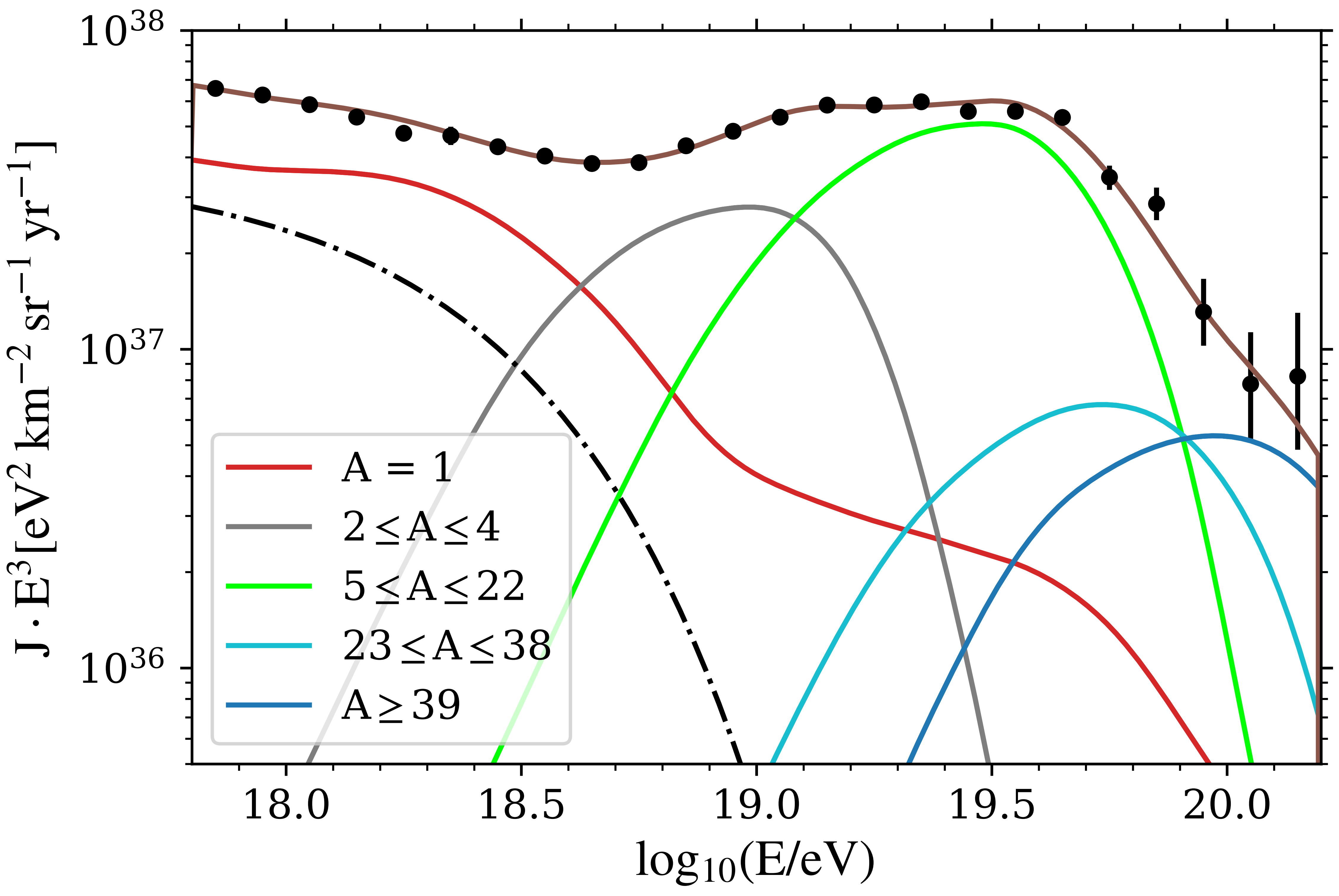
I_{H} (%)	100 (fixed)	0.0 ± 0.0
I_{He} (%)	—	24.5 ± 3.0
I_{N} (%)	—	68.1 ± 5.0
I_{Si} (%)	—	4.9 ± 3.9
I_{Fe} (%)	—	2.5 ± 0.2

JCAP05(2023)24

• Energy spectrum

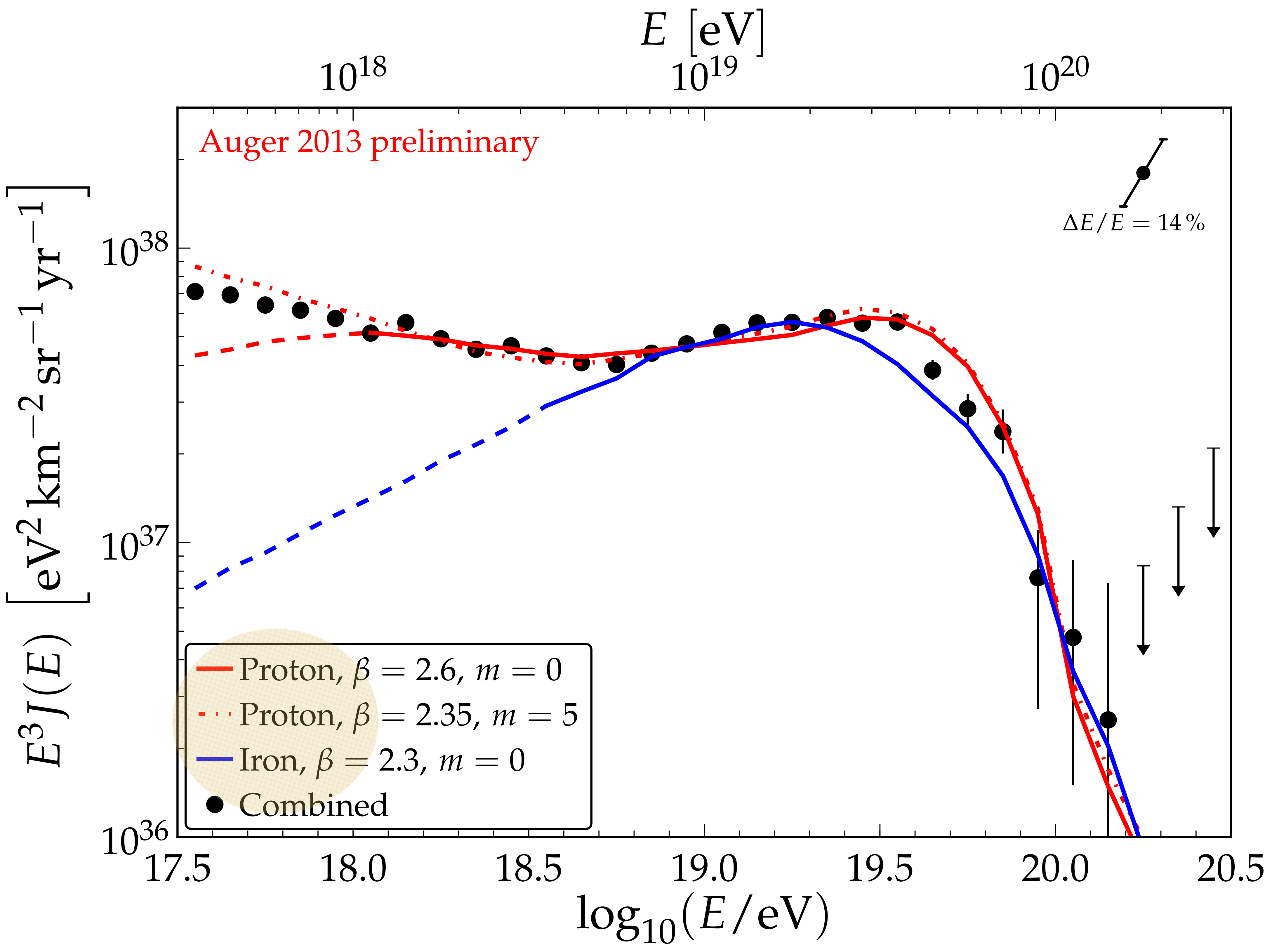
Increase in data -> Change in composition

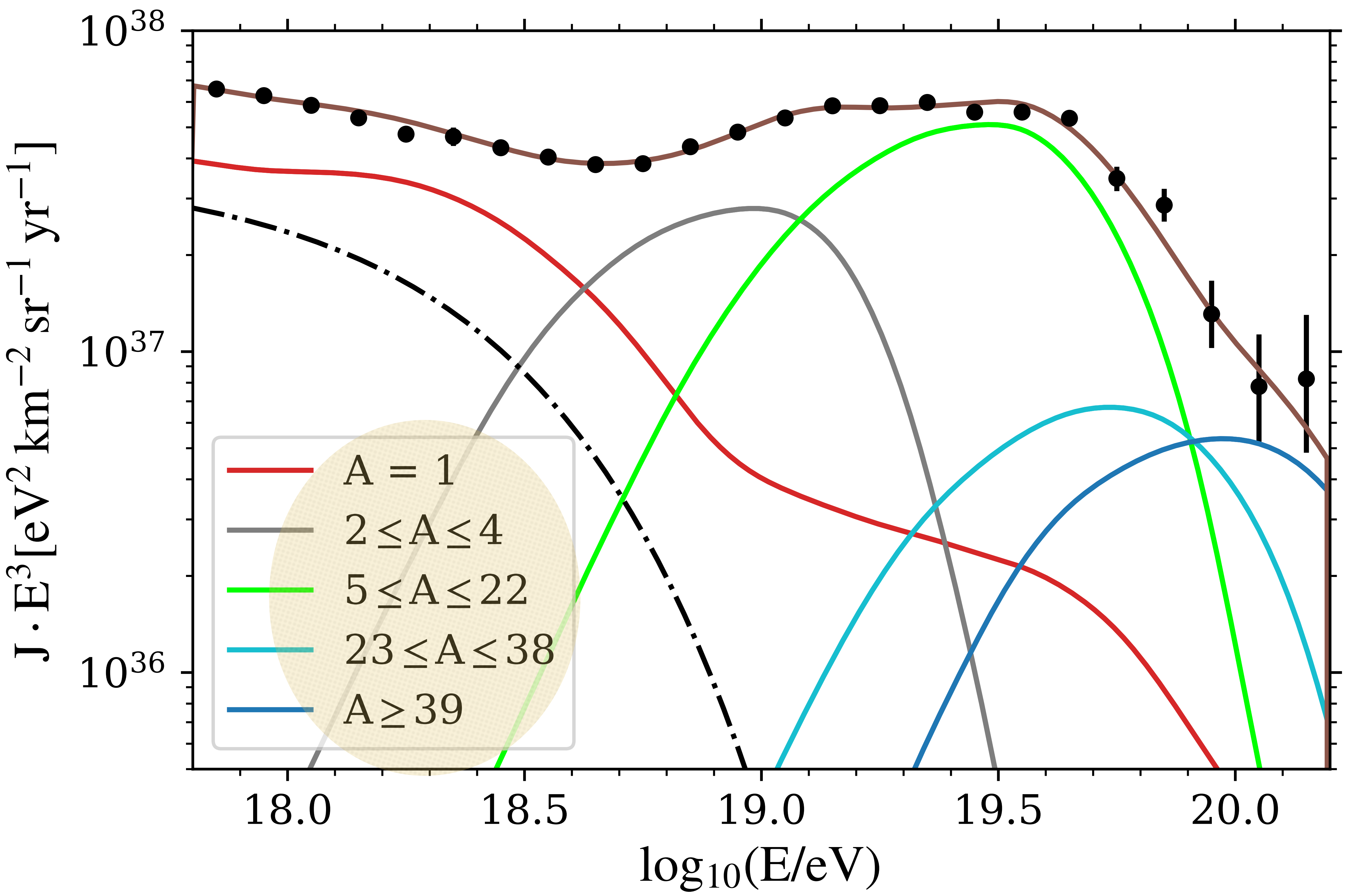




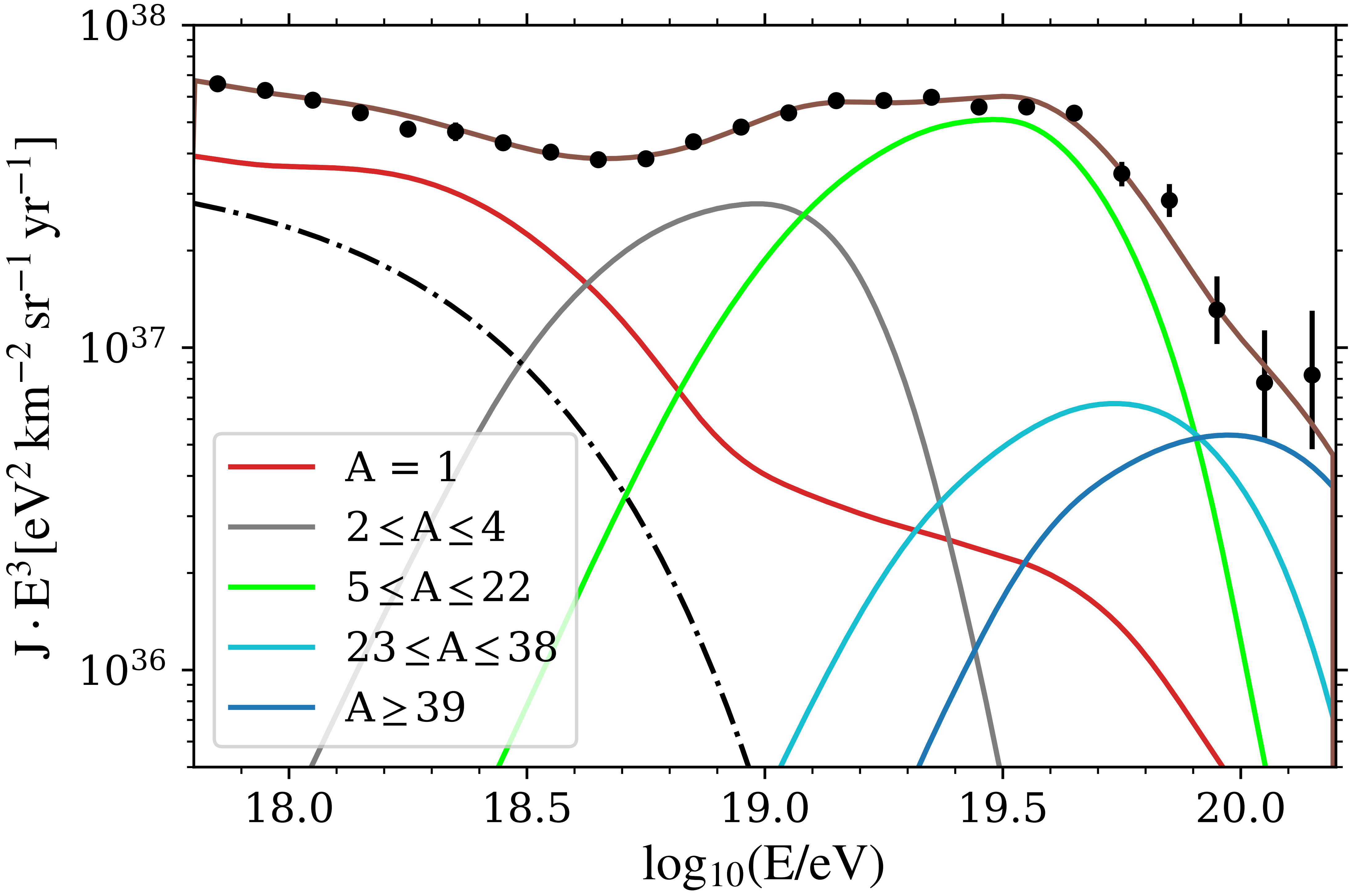
• Energy spectrum

Increase in data -> Change in composition

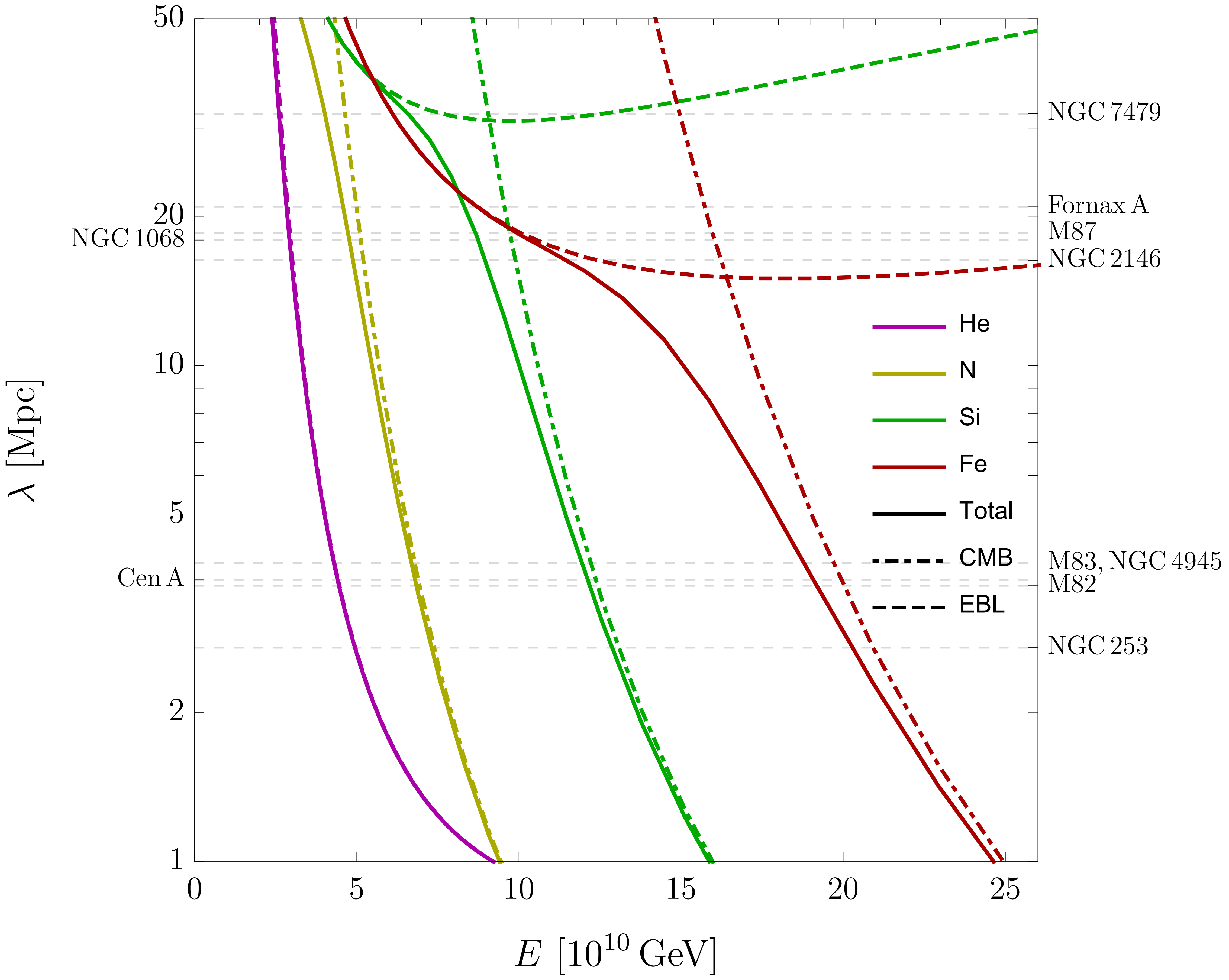




• Energy spectrum

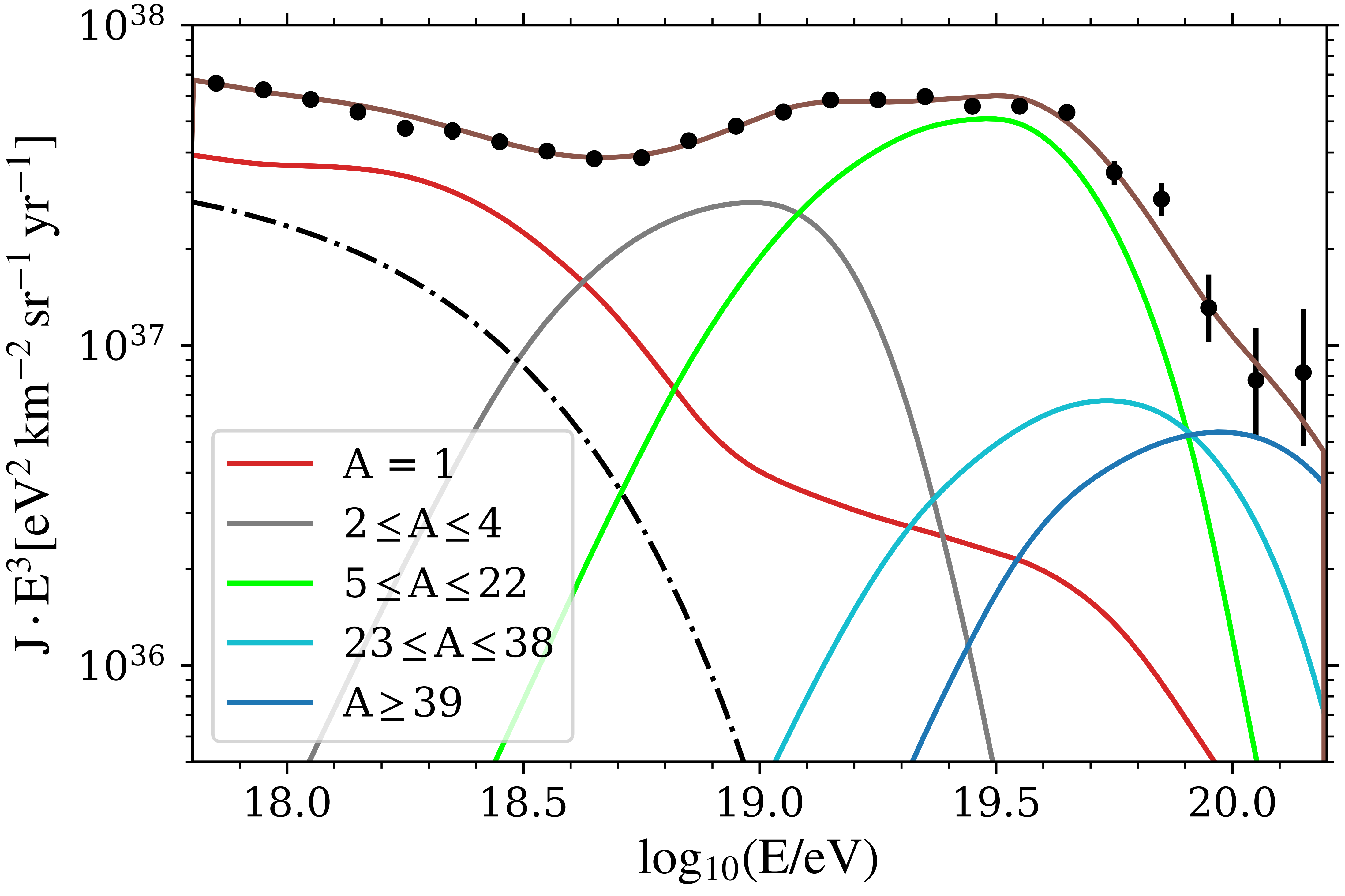


JCAP05(2023)24

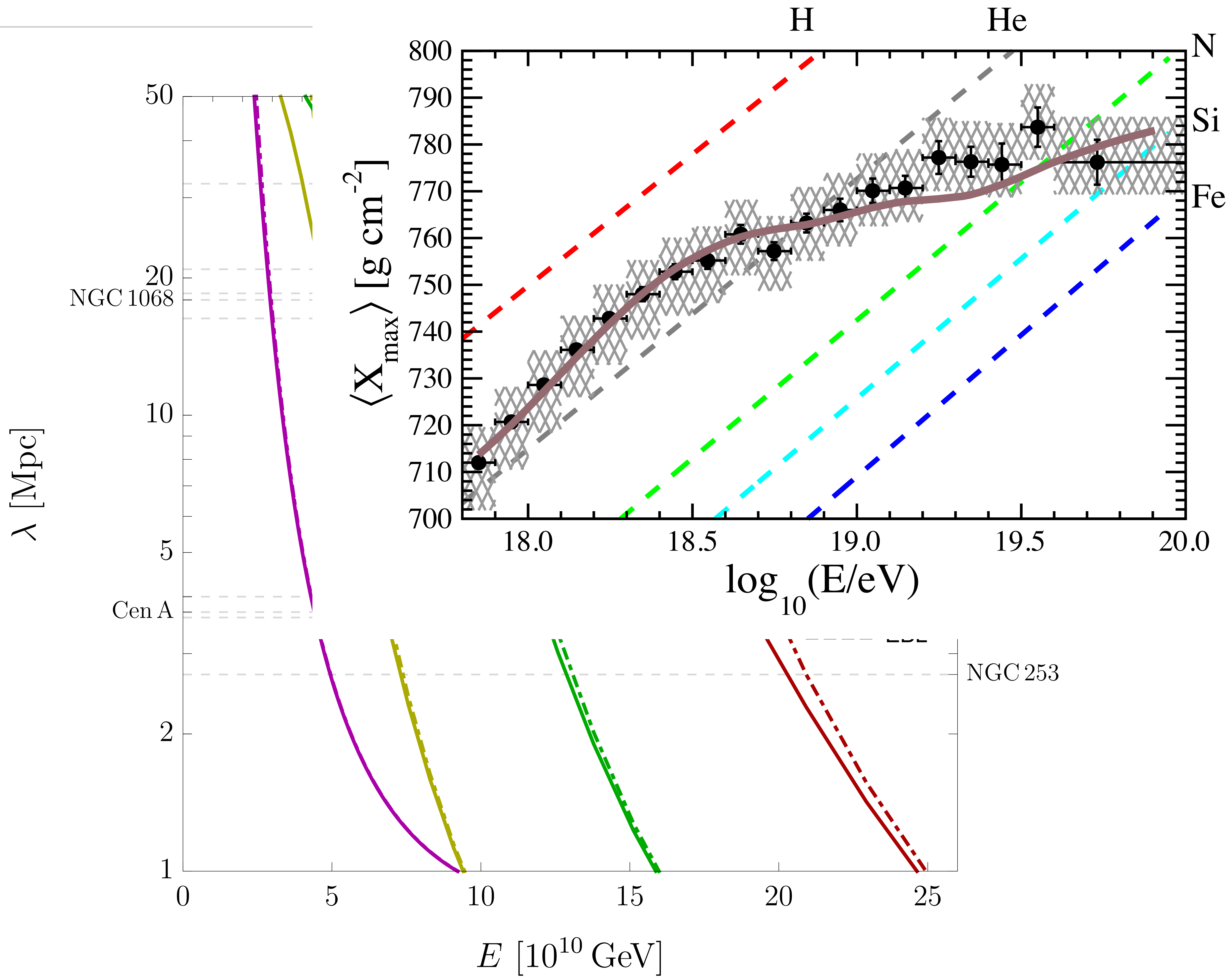


PRD(2018)123018

• Energy spectrum



JCAP05(2023)24



PRD(2018)123018
JCAP05(2023)024

• Summary

- **Heavy nuclei** are more common at higher energies before the suppression.
- Improvement of **acceleration mechanisms and propagation processes** energy spectrum.
- The improved precision of **Auger Phase II** might reveal details in future analyses with increased composition sensitivity.

• Summary

- **Heavy nuclei** are more common at higher energies before the suppression.
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Thank you