Astrophysical cosmic rays lecture I Historical perspective

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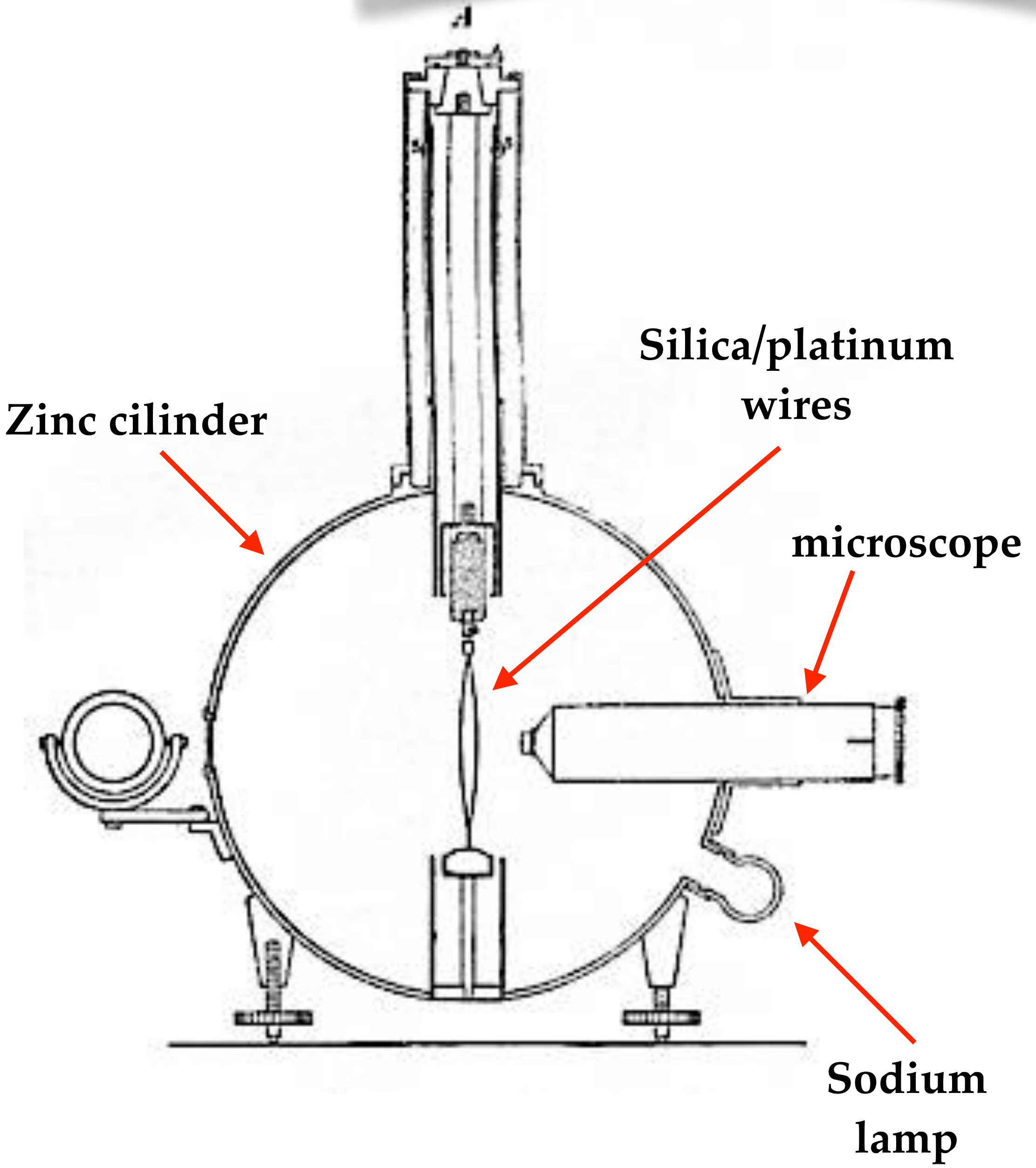
Ionizing radiation

- In 1909, **Theodor Wulf (1868-1946)**, a german jesuit priest, develops an electroscope using silica wires with a metallic layer (platinum) much more sensitive than the previous models based on gold foils.

- He makes good measurements at the top an basis of the Eiffel Tower ($\Delta h \sim 300$ m).



The birth of cosmic ray physics

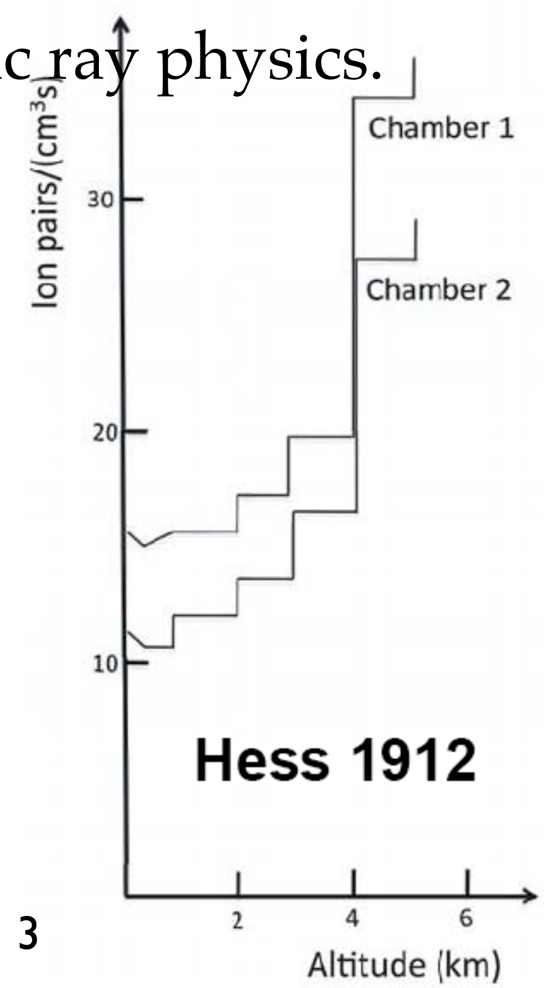
- In a balloon flight in 1912 (up to 5 km!), **Victor Hess** realizes that the intensity of ionizing radiation increases with altitude.

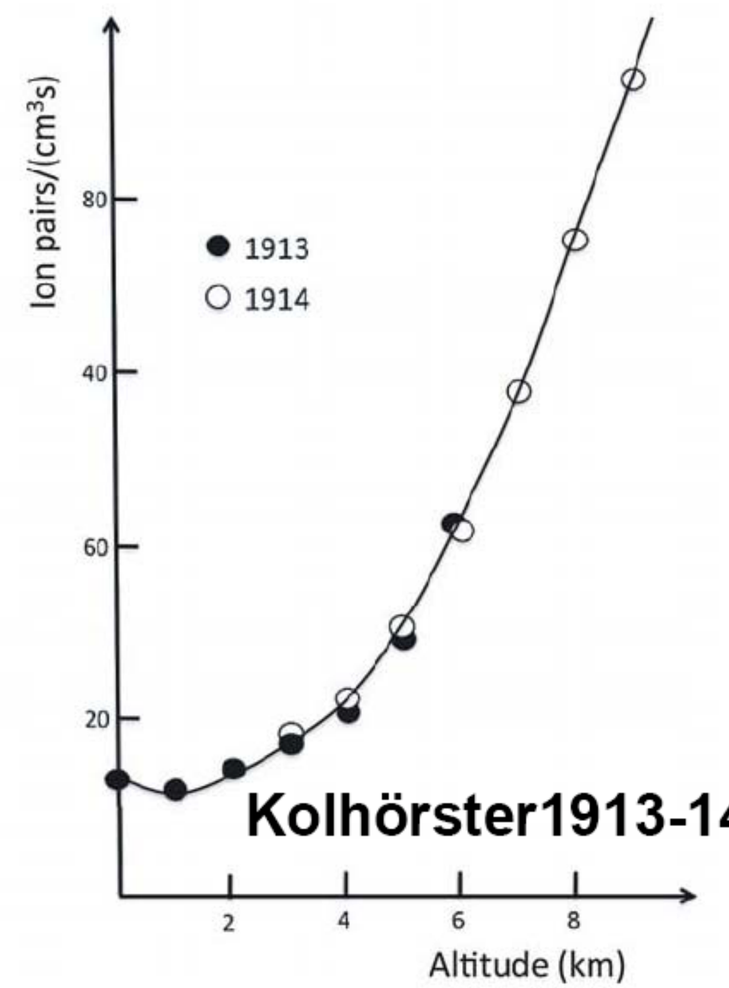
- The radiation could not be coming from the sun, since no significant change in intensity was observed during a solar eclipse.

- The event is considered the birth of cosmic ray physics.

Hess conclusion:

"The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."





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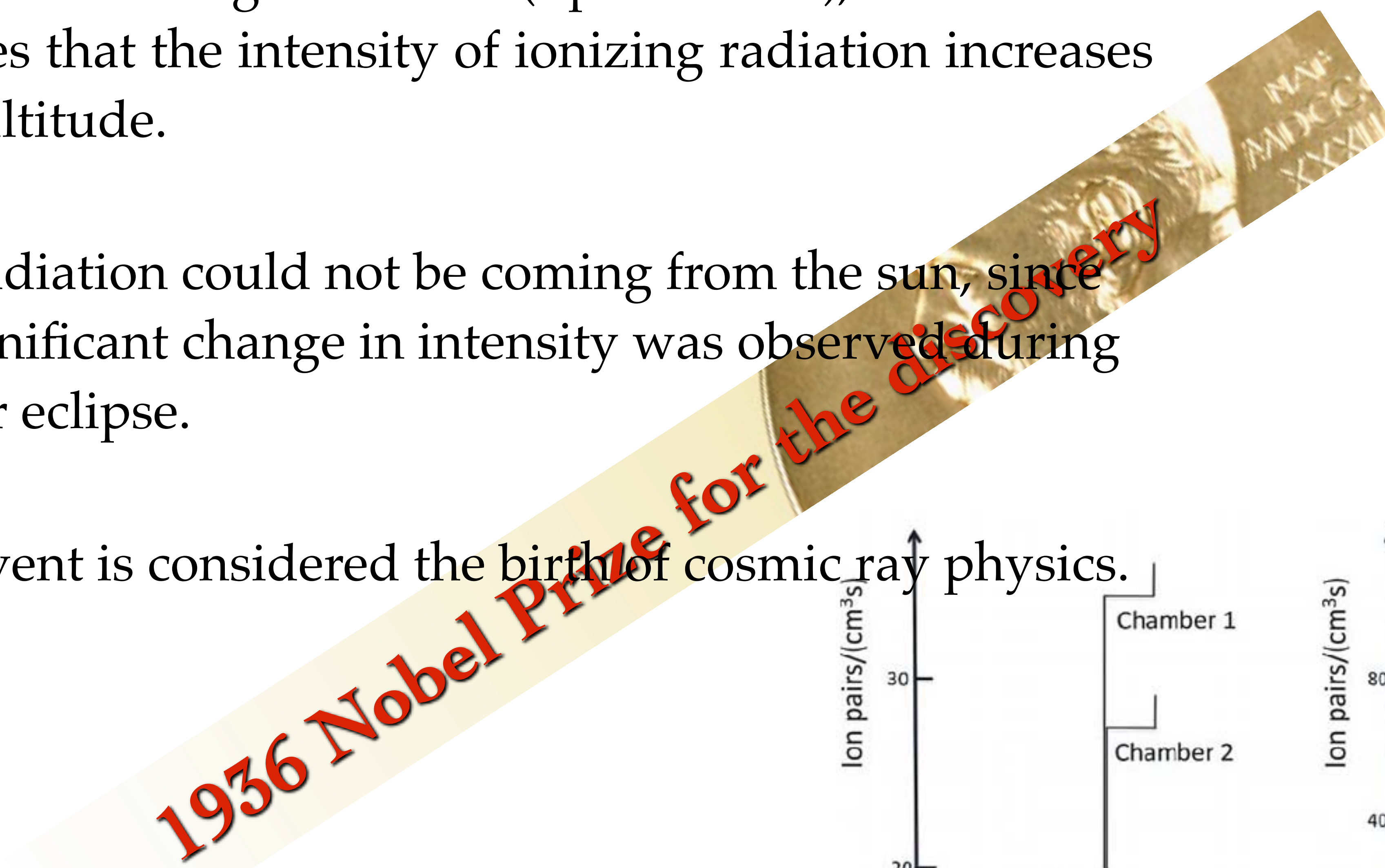

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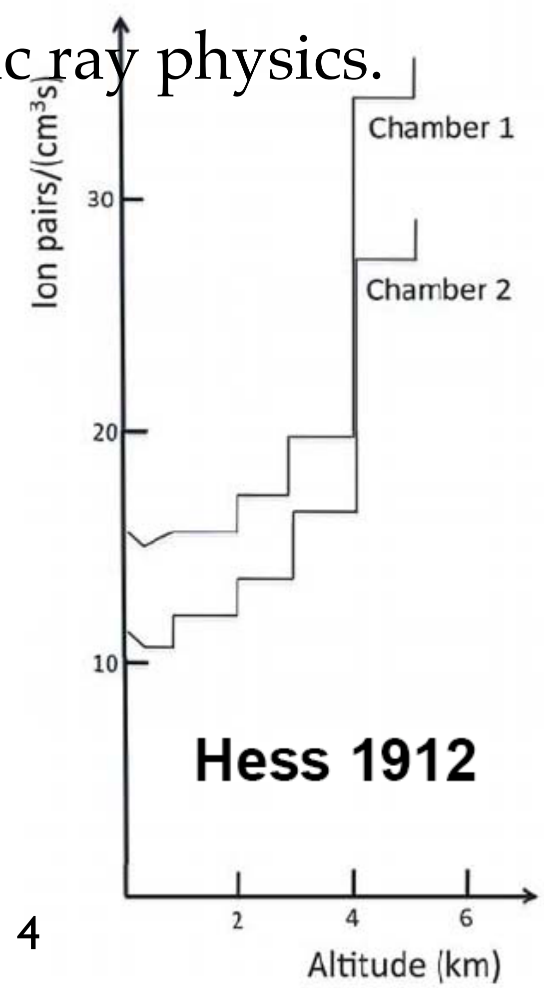
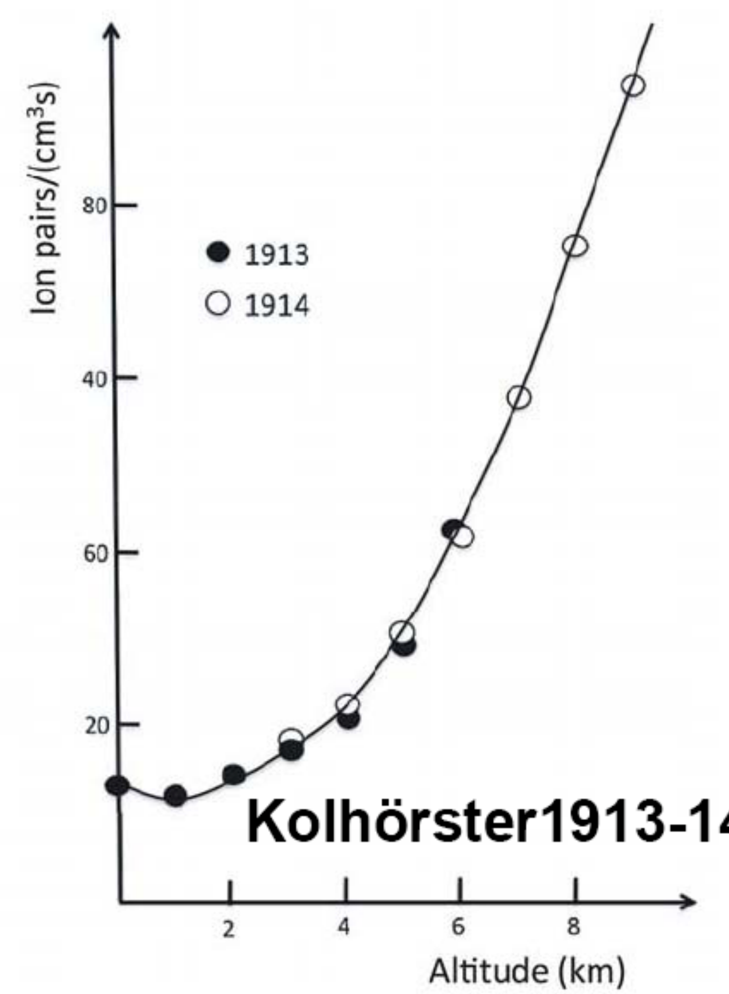
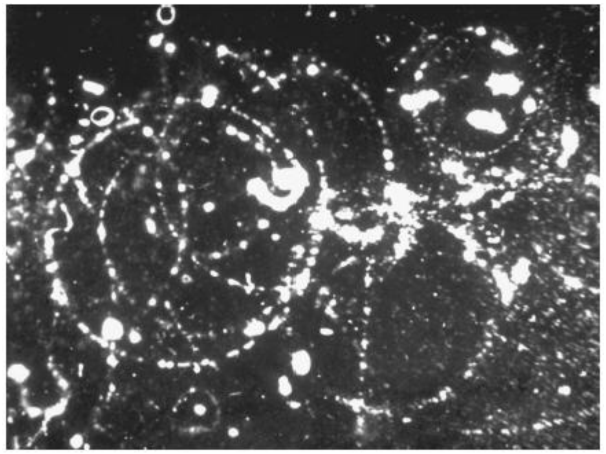


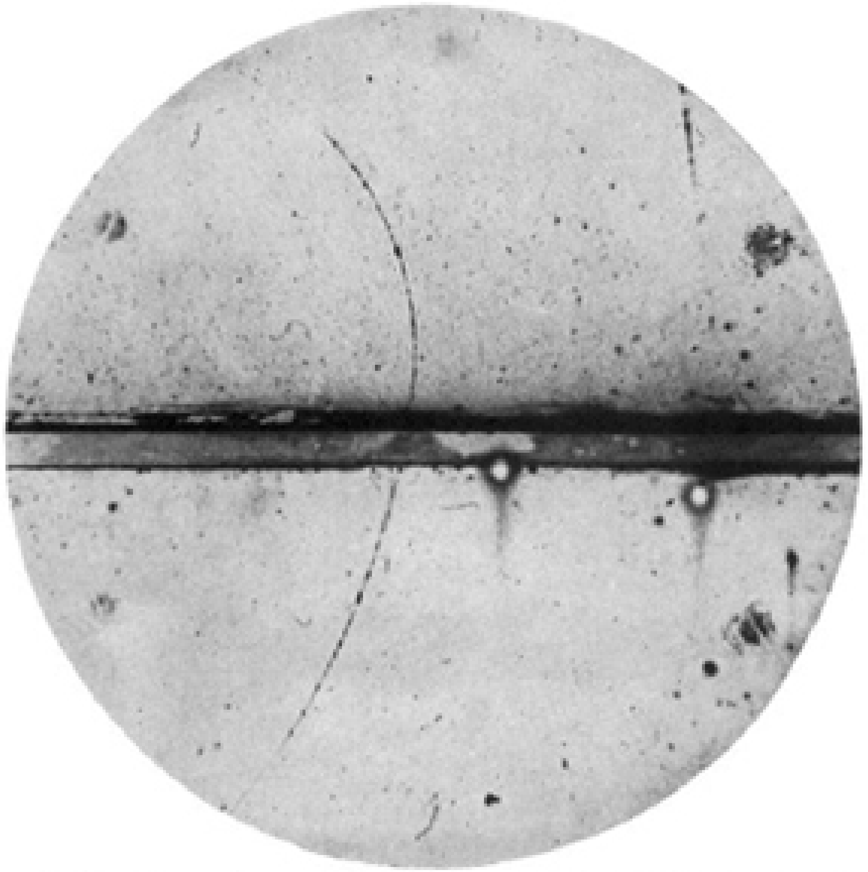


Cosmic rays and particle physics

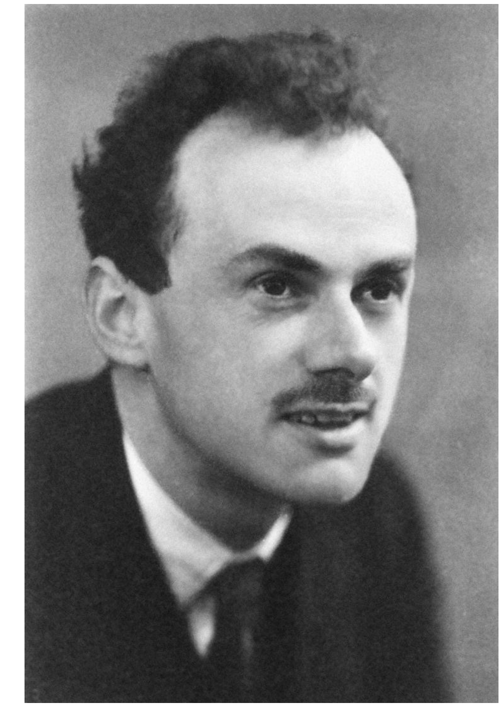
- 1927 - **Dmitry Skobelzyn** observes cosmic rays for the first time using a cloud chamber or Wilson chamber.



- 1932 - Also using a cloud chamber, **Carl Anderson** discovers the first form o antimatter, the **positron**, theoretically predicted by **Paul Dirac** in 1928.



Dirac and the positron



Studying a relativistic wave equation for the electron that was linear in the momentum and energy:

$$i\hbar\beta\frac{\partial\psi}{\partial t} = -i\hbar c\beta\,\boldsymbol{\alpha}\cdot\boldsymbol{\nabla}\psi + mc^2\psi$$

Dirac realizes that the free-particle solutions of this equation:

$$\psi(x^\mu) = u(\mathbf{p})e^{ik_\mu x^\mu}$$

appeared with multiplicity 4:

$$u_A^{(1)} = N\begin{pmatrix} 1 \\ 0 \\ \frac{cp_z}{E+mc^2} \\ \frac{c(p_x+ip_y)}{E+mc^2} \end{pmatrix} \qquad u_A^{(2)} = N\begin{pmatrix} 0 \\ 1 \\ \frac{c(p_x-ip_y)}{E+mc^2} \\ \frac{-cp_z}{E+mc^2} \end{pmatrix}$$

Energy E>0 (elétron)

$$E = \pm\sqrt{m^2c^4 + \mathbf{p}^2c^2}$$

$$u_A^{(3)} = N\begin{pmatrix} \frac{-cp_z}{E-mc^2} \\ \frac{c(p_x+ip_y)}{E-mc^2} \\ 1 \\ 0 \end{pmatrix} \qquad u_A^{(4)} = N\begin{pmatrix} \frac{c(p_x-ip_y)}{E-mc^2} \\ \frac{-cp_z}{E-mc^2} \\ 0 \\ 1 \end{pmatrix}$$

Energy E<0 (pósitron)

spin 1/2 (s_z=1/2) **spin 1/2 (s_z=-1/2)**

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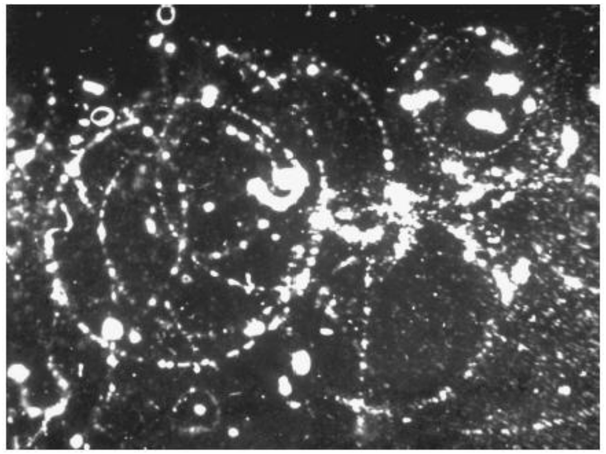

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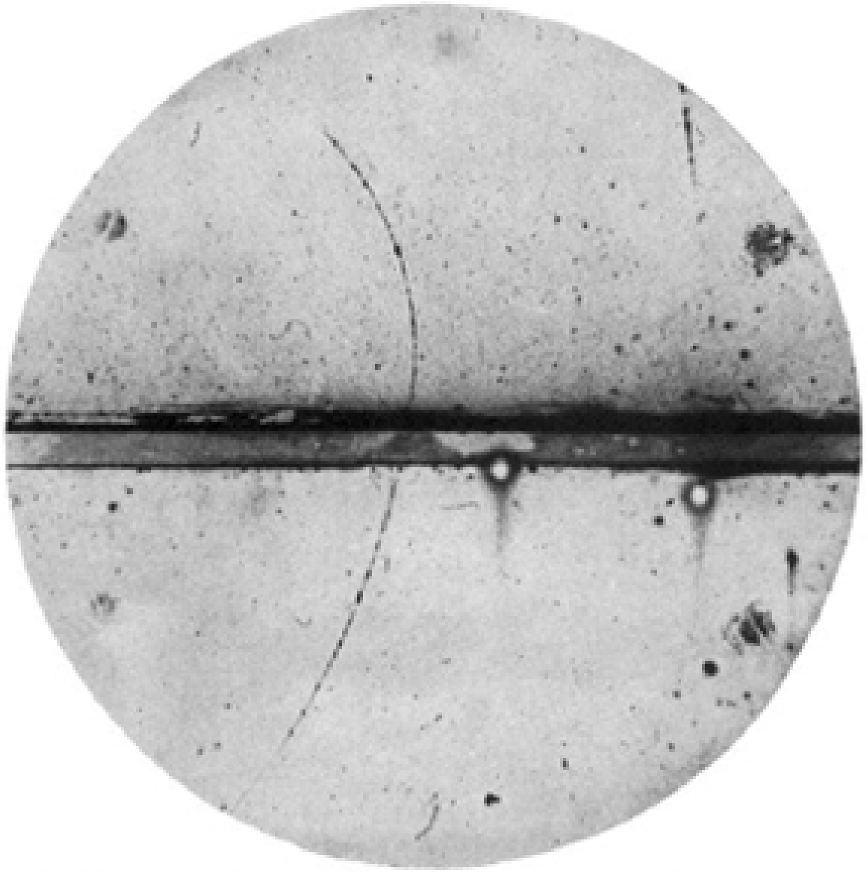
- 1937 - **Seth Neddermeyer e Carl Anderson** discover the muon in the cosmic radiation.



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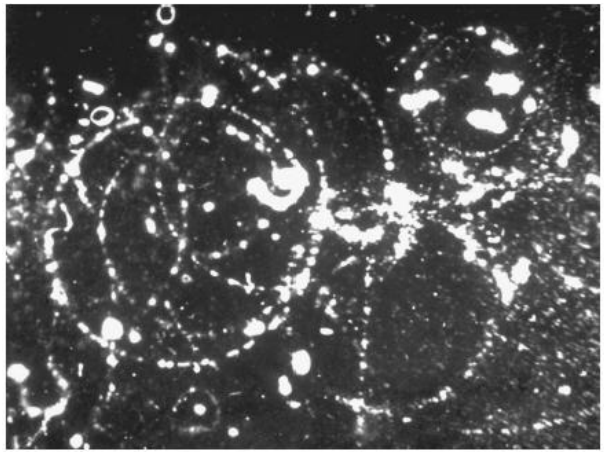
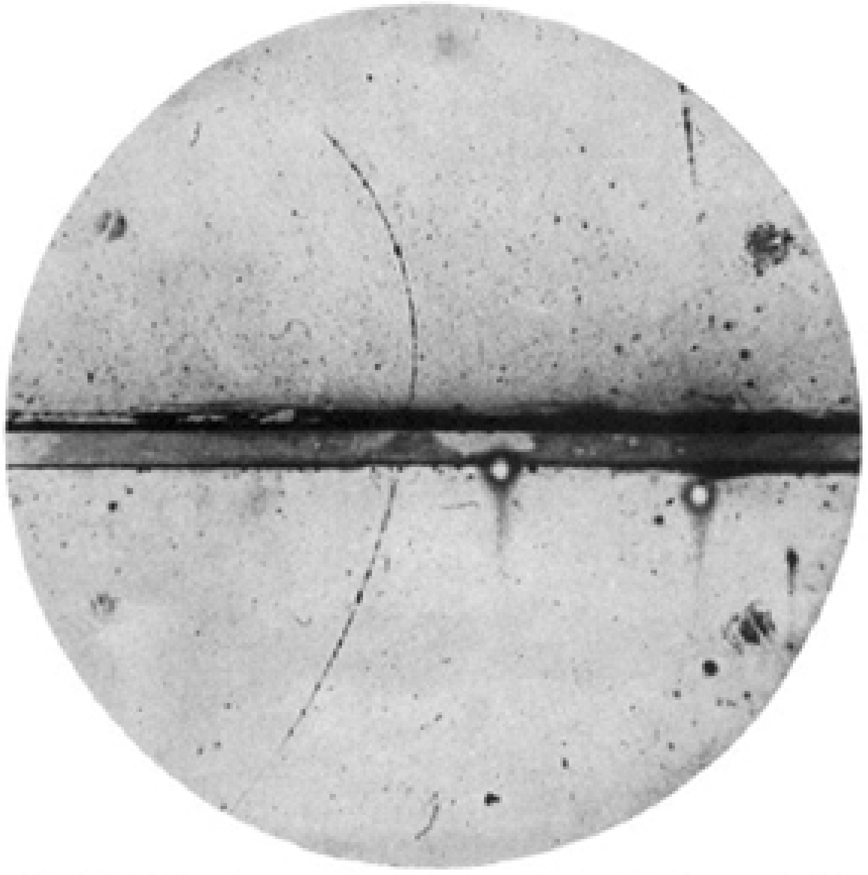


Prêmio Nobel em 1936 a Carl Anderson



Extensive Air Showers

- In 1938 **Pierre Auger** detects for the first time an extensive air shower (EAS).
- Geiger counters at ground level would trigger almost simultaneously when ionizing particles hit them.

Auger's conclusion

He had observed particle showers with energy around 10^{15} eV, 10 million times larger than any particle measured at Earth before!

P. Auger; et al. (1939). "Extensive Cosmic-Ray Showers". Rev. Mod. Phys. 11 (3–4): 288–291

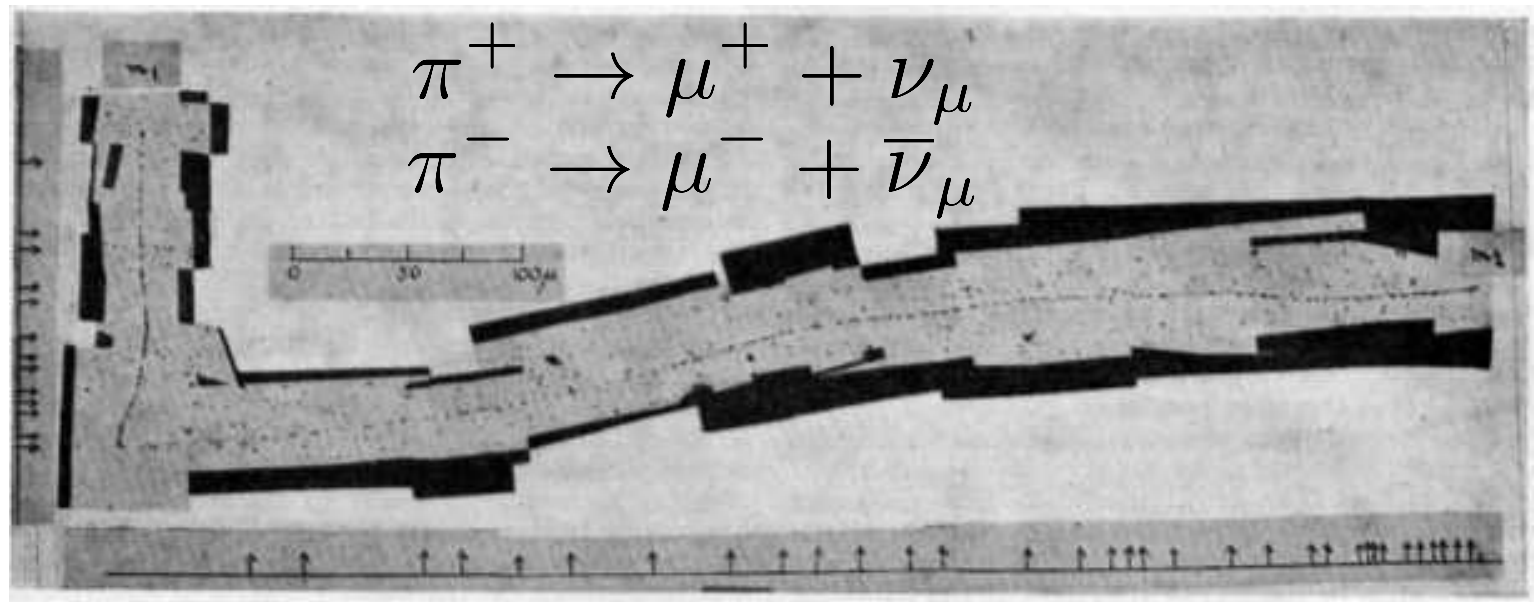
Wataghin and the penetrating showers

In 1934, **Gleb Wataghin** arrives at the recently created USP and starts to study the properties of penetrating atmospheric showers through measurements in several places in Brazil.

Lattes, Yukawa and the pions

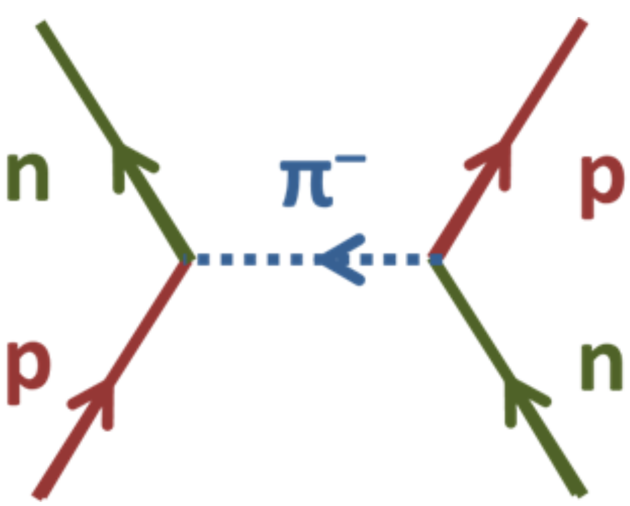
César Lattes, Occhialini e Powell discover the pion (1947) in nuclear emulsions exposed to the ionizing radiation in Chacaltaya, Bolivia (at 5500 m a.s.l.).

C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini, C.F. Powell, Processes involving charged mesons, Nature 159 (4047), 694-697.

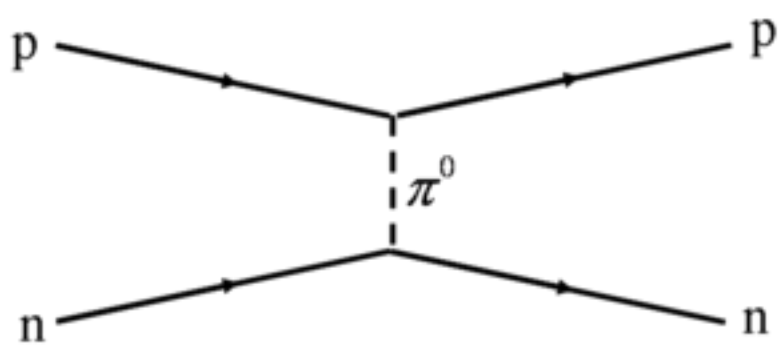


$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

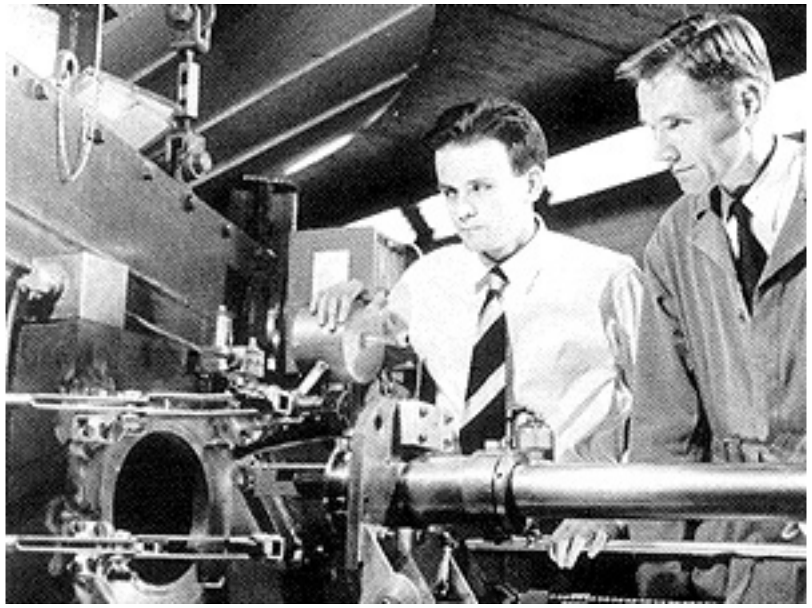
Similar to the positron, the pion has been theoretically predicted before (in 1935) by the Japanese physicist Hideki Yukawa in his effective theory of nuclear interactions.



$$V_Y(r) = -g^2 \frac{e^{-mr}}{r}$$



The pions are soon produced artificially in 1948 by **Eugene Gardner and Lattes** in a cyclotron at the University of California.



1950-60 Groups led by **Bruno Rossi** in US and **Georgi Zatsepin** in the Soviet Union build experiments to study EAS. These are first giant arrays of surface detectors to be built.

The most energetic particles

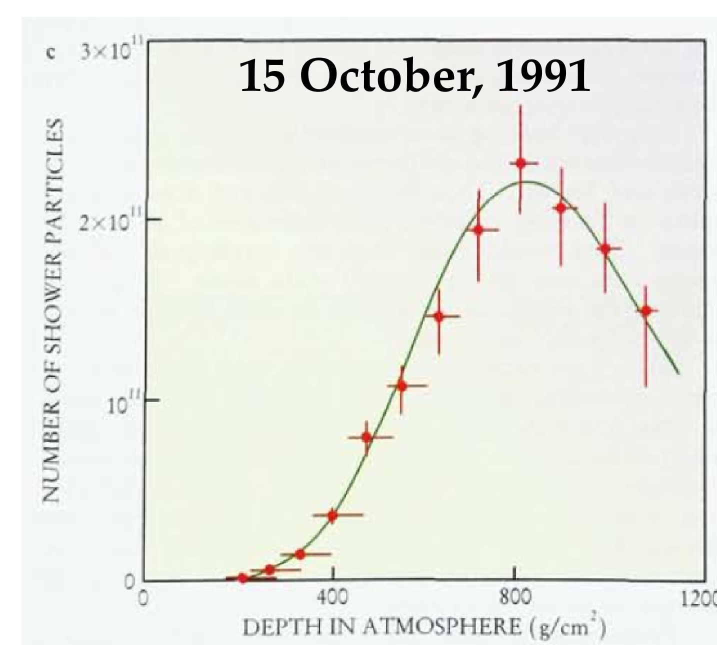
In 1962, groups led by **John Linsley** and collaborators detect the first cosmic ray with energy around 10^{20} eV (~16 Joules) using an array of surface detectors in New Mexico, USA.

This was a chock to astrophysicists: a subatomic particle with kinetic energy of a tennis ball (~100 g) at about 65 km/h !!!

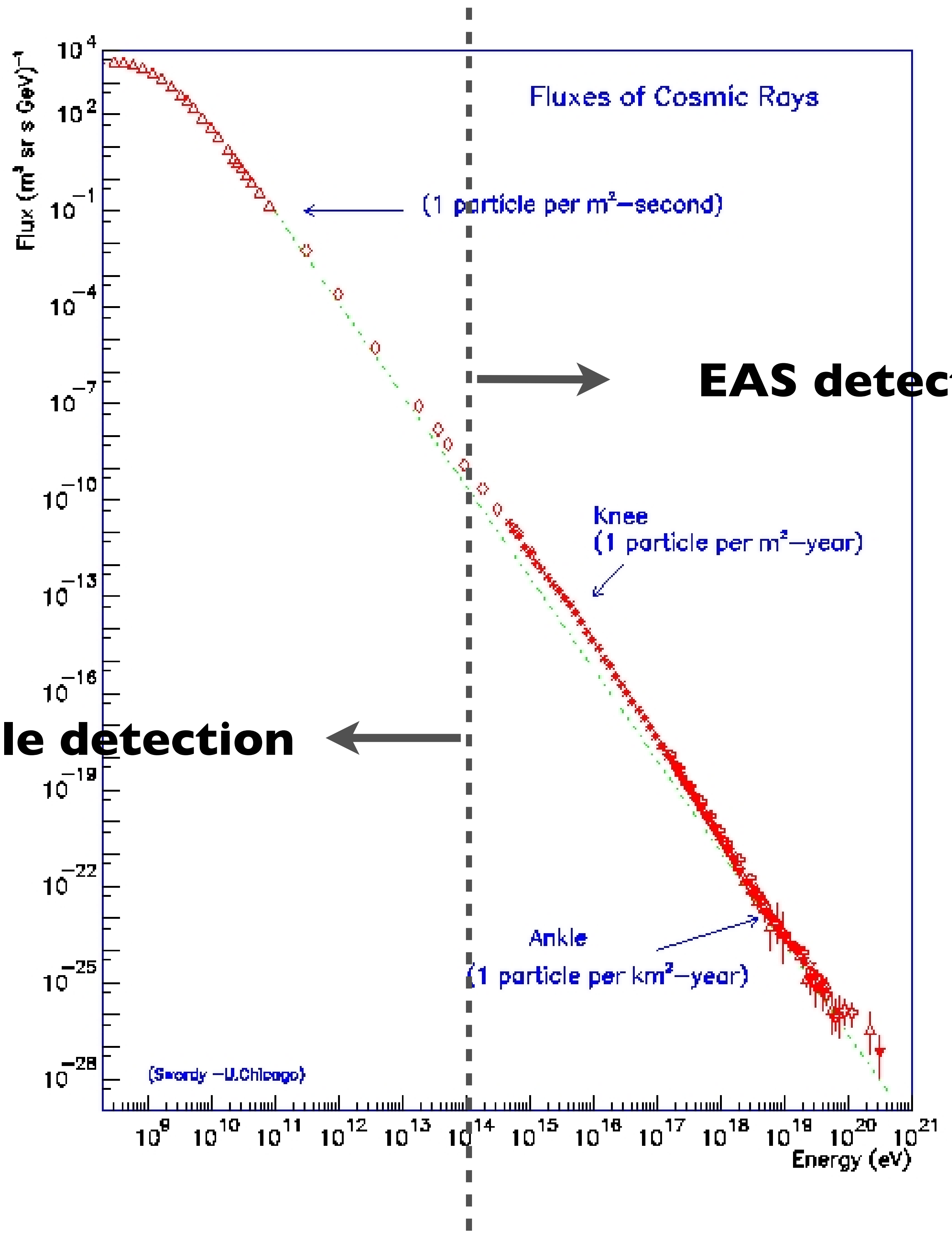
In the 1990's, the Fly's Eye experiment in Utah, USA, uses for the first time the atmospheric fluorescence technique to detect ultra-energetic cosmic rays.

The world record

Energy: 3×10^{20} eV (48 J)



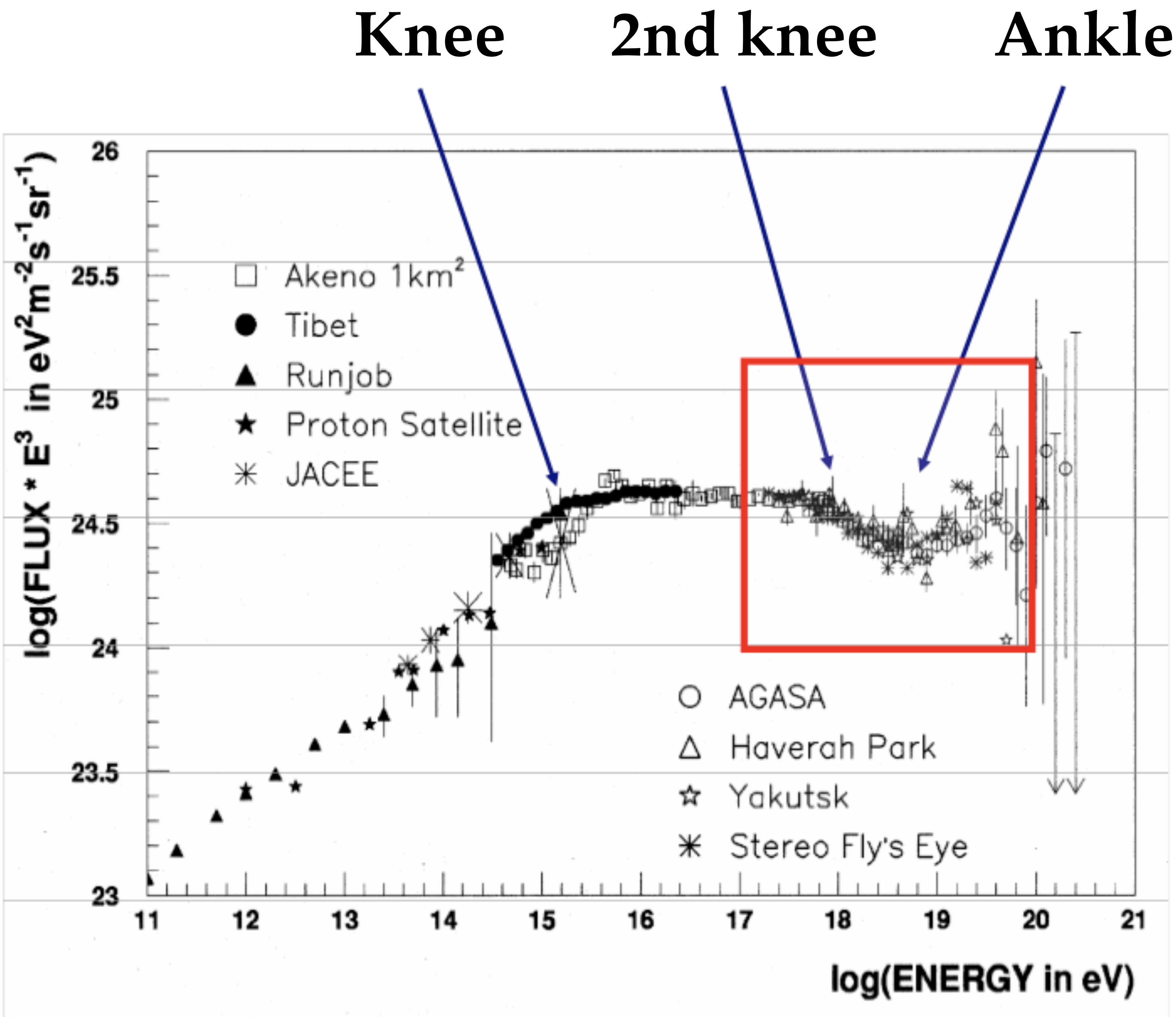
Energy spectrum



EAS detection

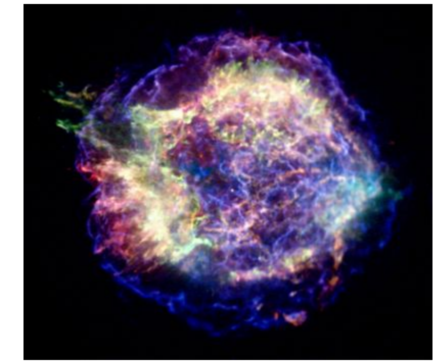
Primary particle detection

Anatomy of the spectrum



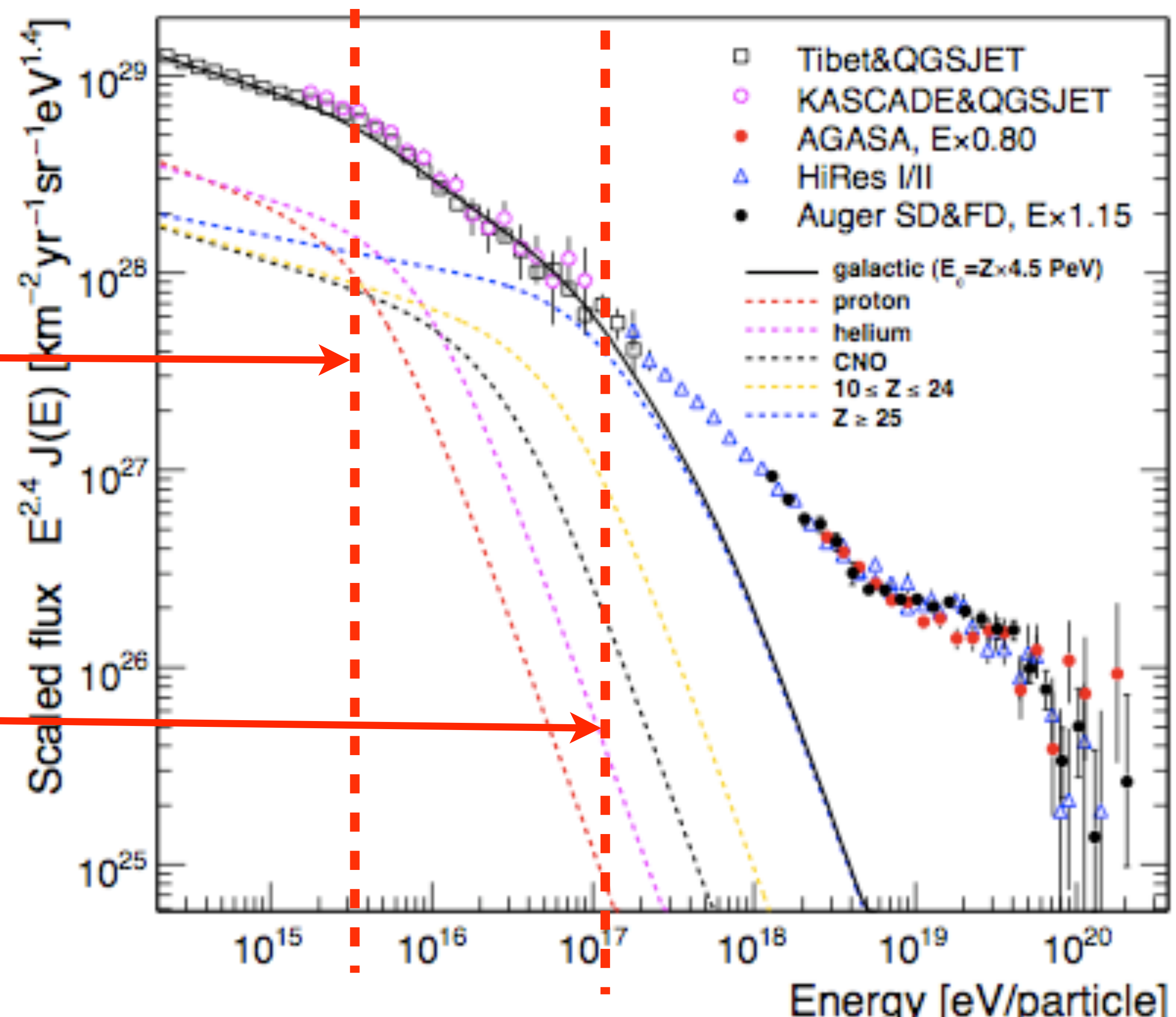
A "Standard Model" for the knee?

- Hypothesis: Supernova explosions in the galaxy are able to produce protons up to 10^{15} eV.
- Competition between maximum energy and escape probability in the galaxy.



1st knee would be formed when light nuclei (p,He,Li) start escaping from the galaxy.

2nd knee would be formed when heavier elements (CNO, Fe) start to escape.



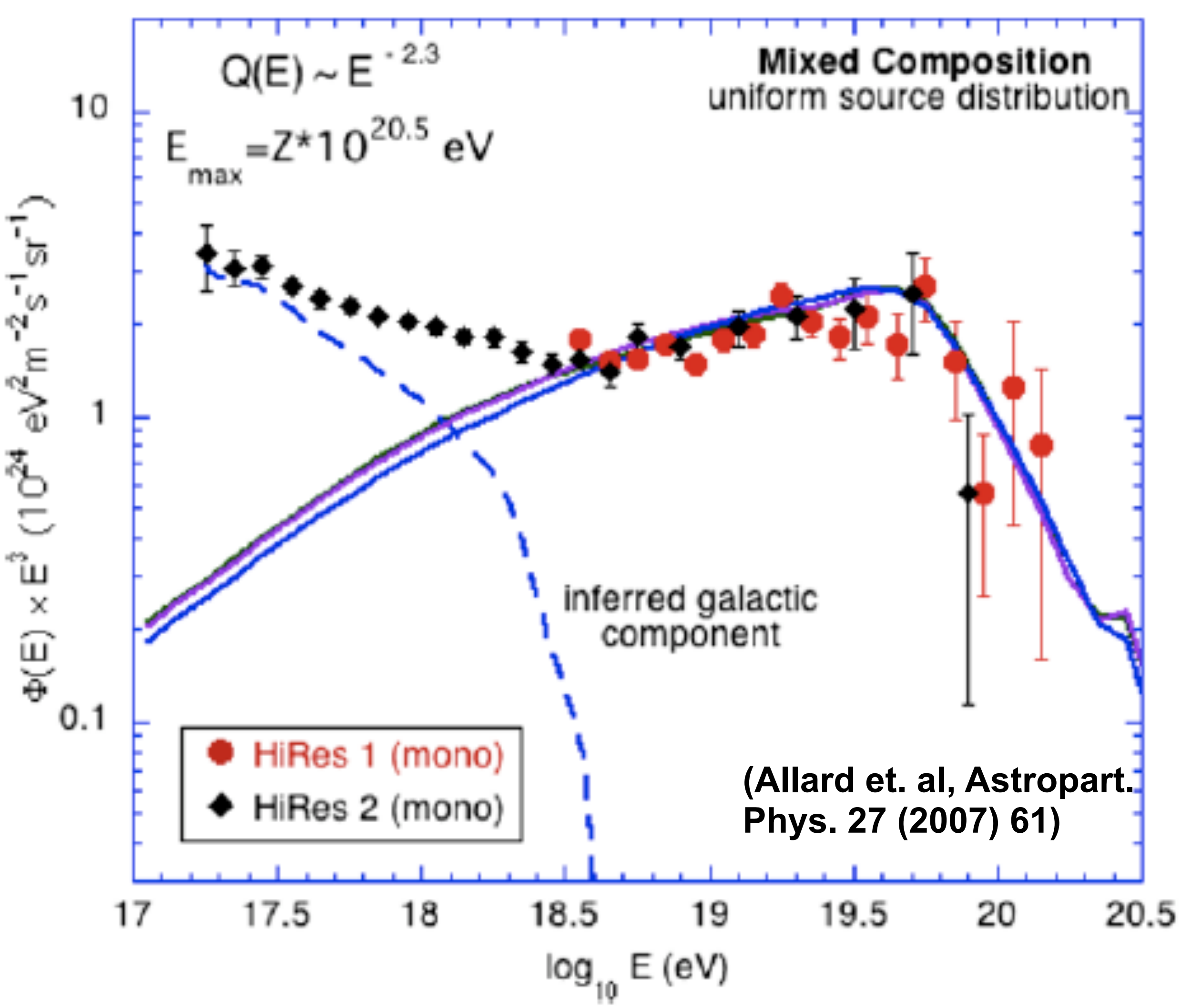
(J. R. Hörandel, Astropart. Phys. 19 (2003) 193)

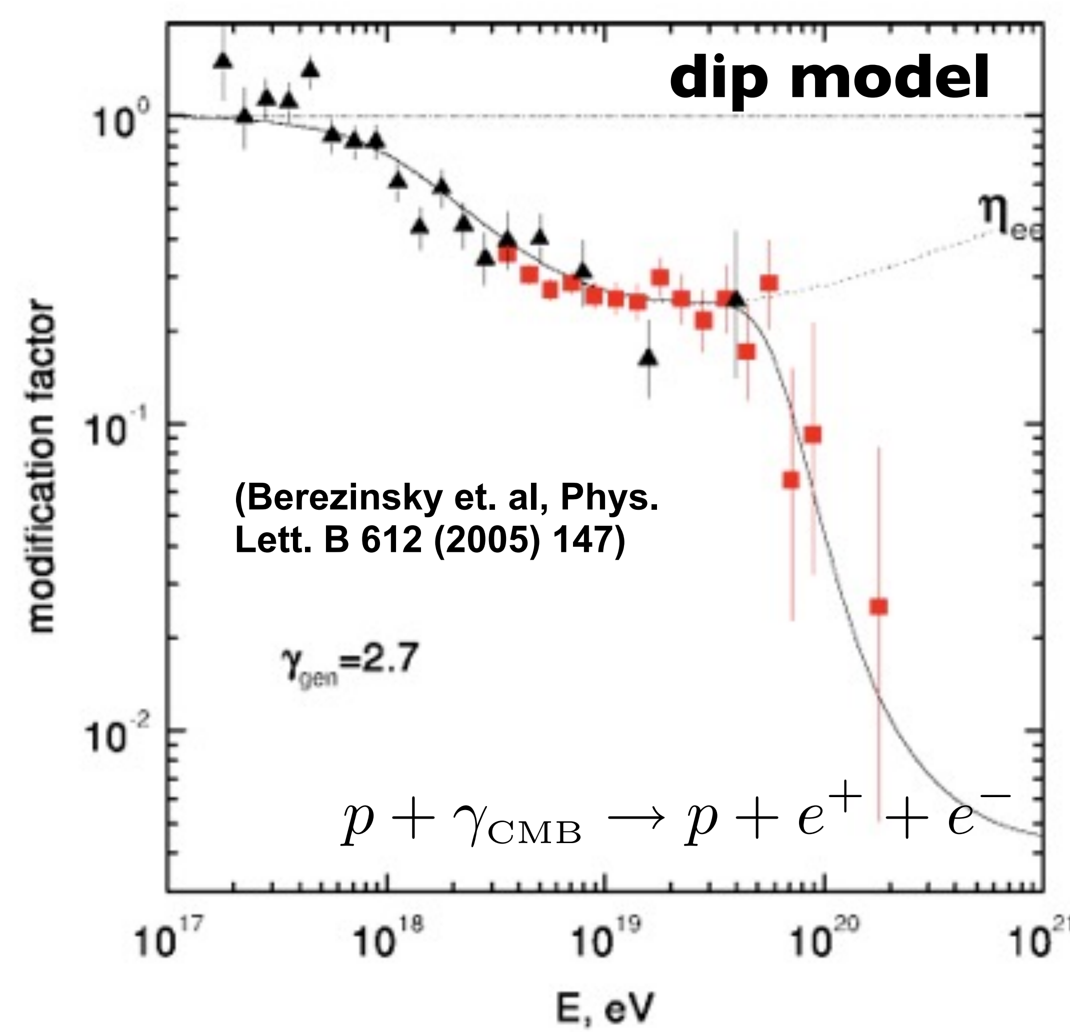
The ankle and the gal-xgal transition

Two competing models:

- ➤ Ankle would be due to the Galactic-Extragalactic transition around 10^{18} eV
- ➤ Mixed chemical composition due to CMB-induced nuclear photo-disintegration

- ➤ Ankle is due to e+/e- pair production from an pure proton extragalactic beam.
- ➤ Gal-Xgal transition around 10^{17} eV
- ➤ Fine tuned modelo, since it is very sensitive to small contaminations from heavier elements.





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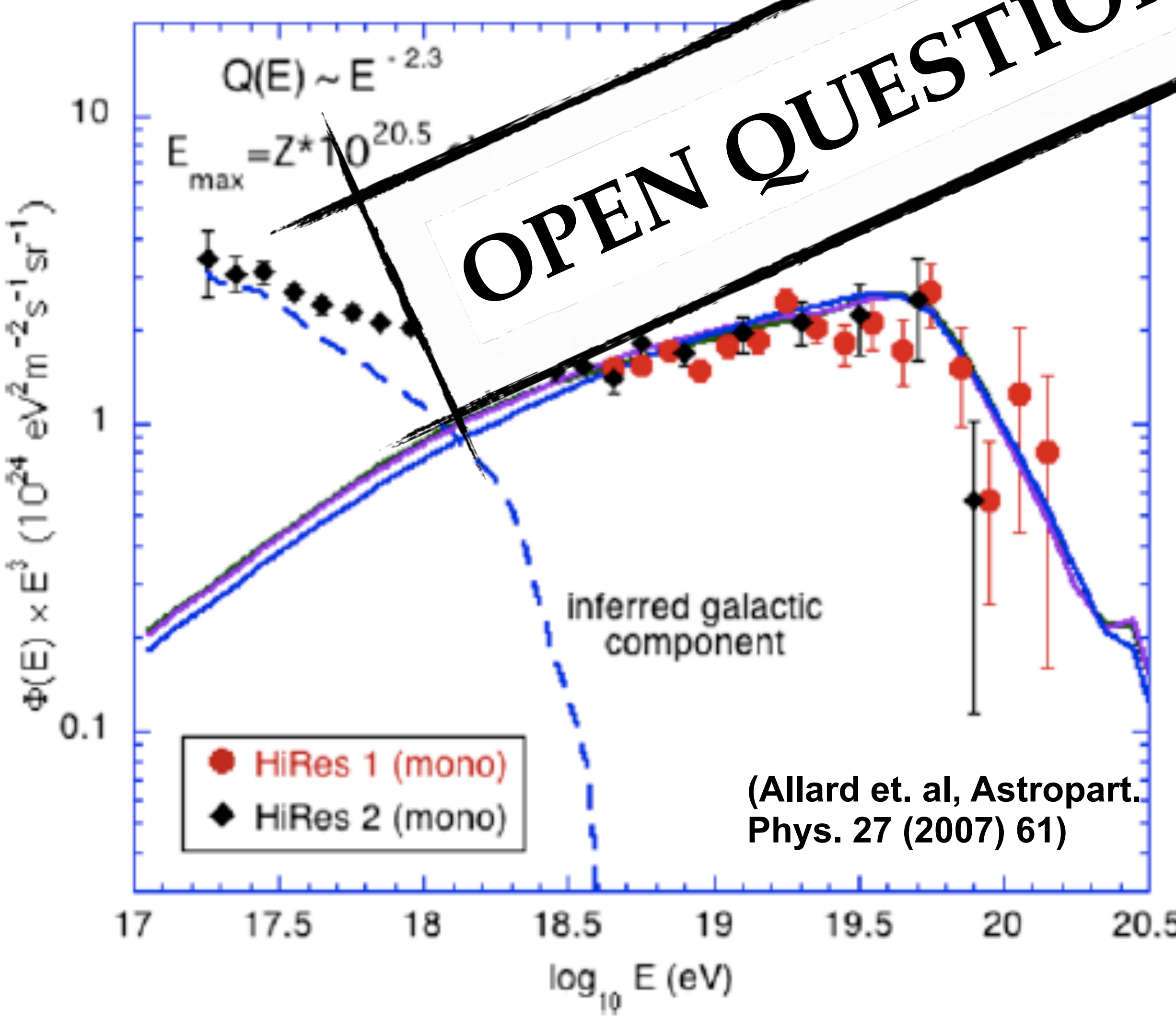
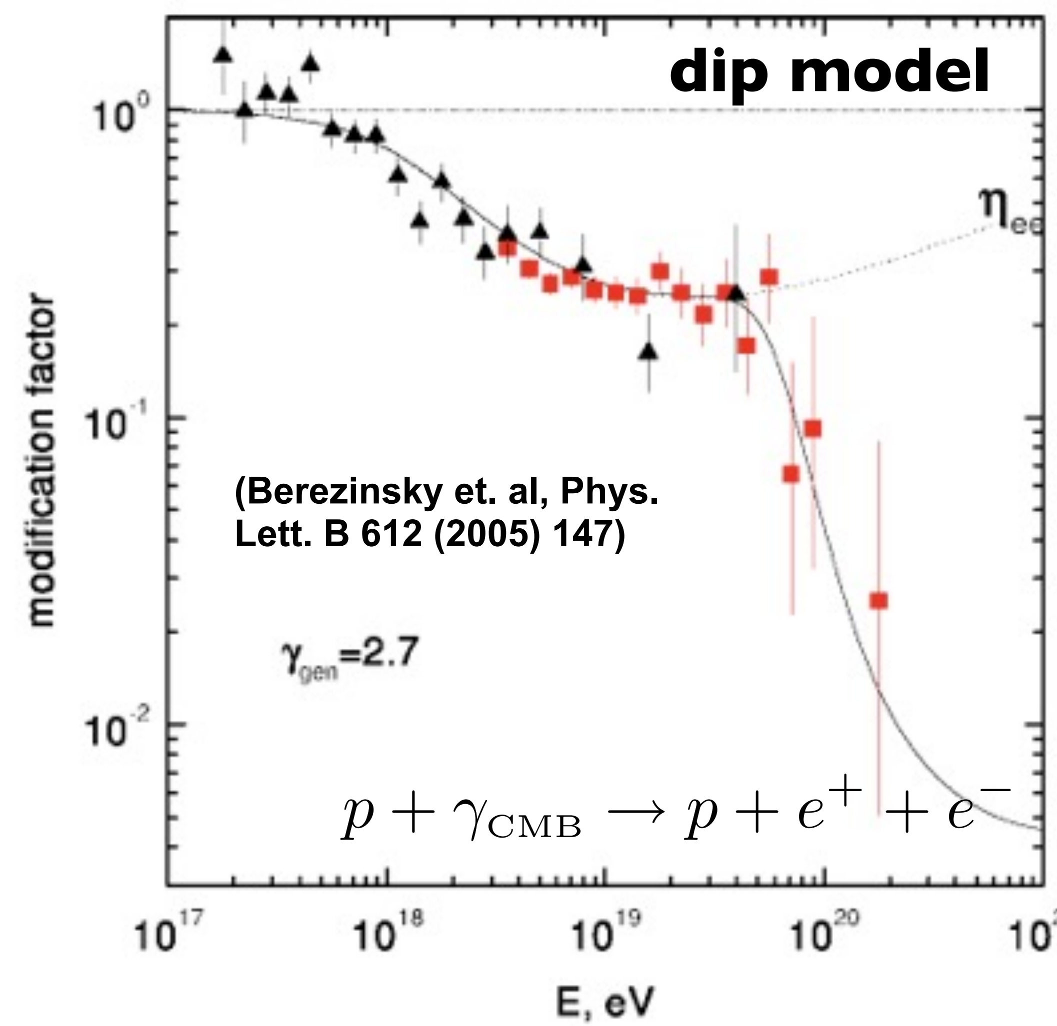
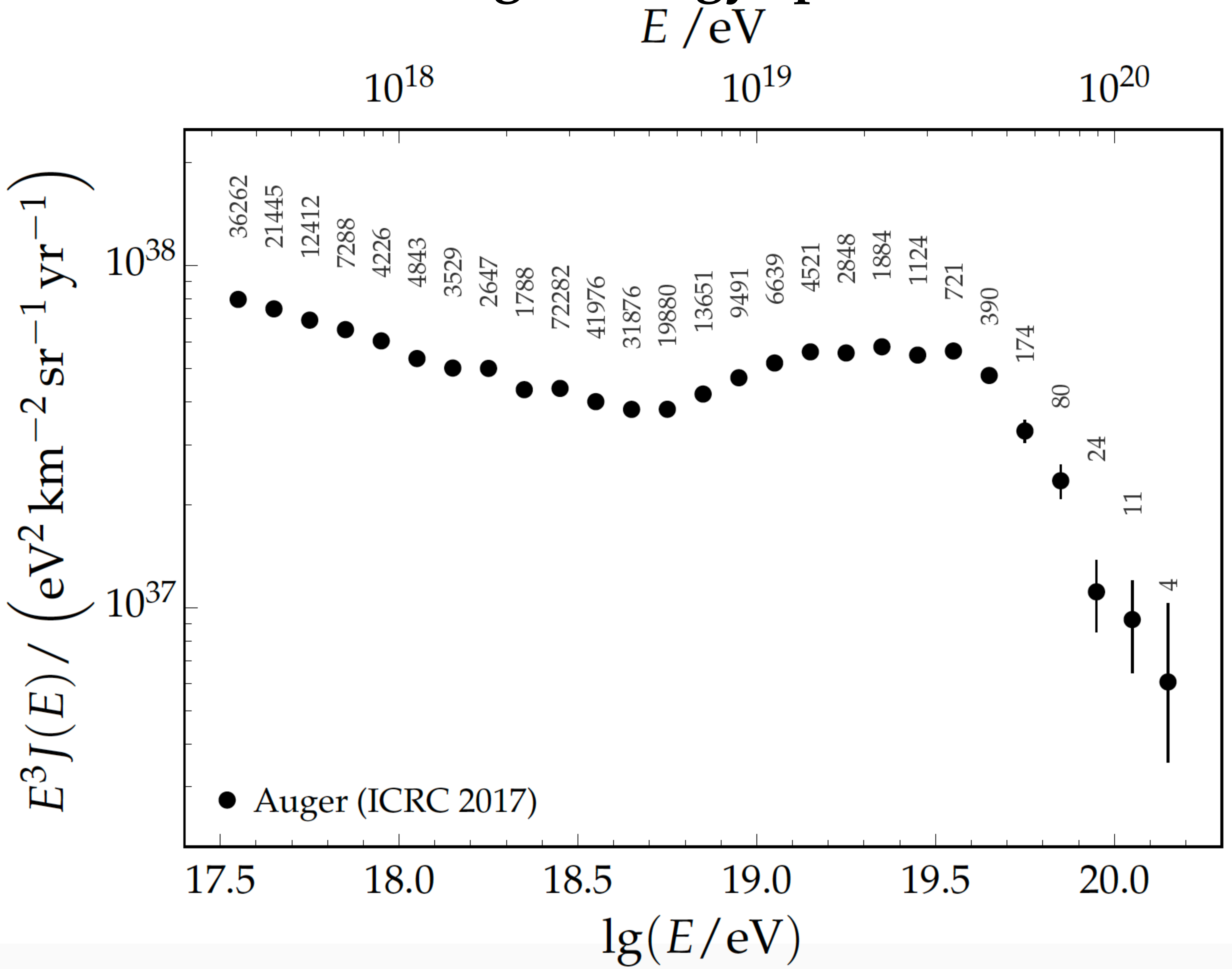
- ➤ Gal-X round 10^{17} eV
- elo, since it is very sensitive contaminations from heavier elements.

OPEN QUESTION IN THE AREA !





Pierre Auger energy spectrum



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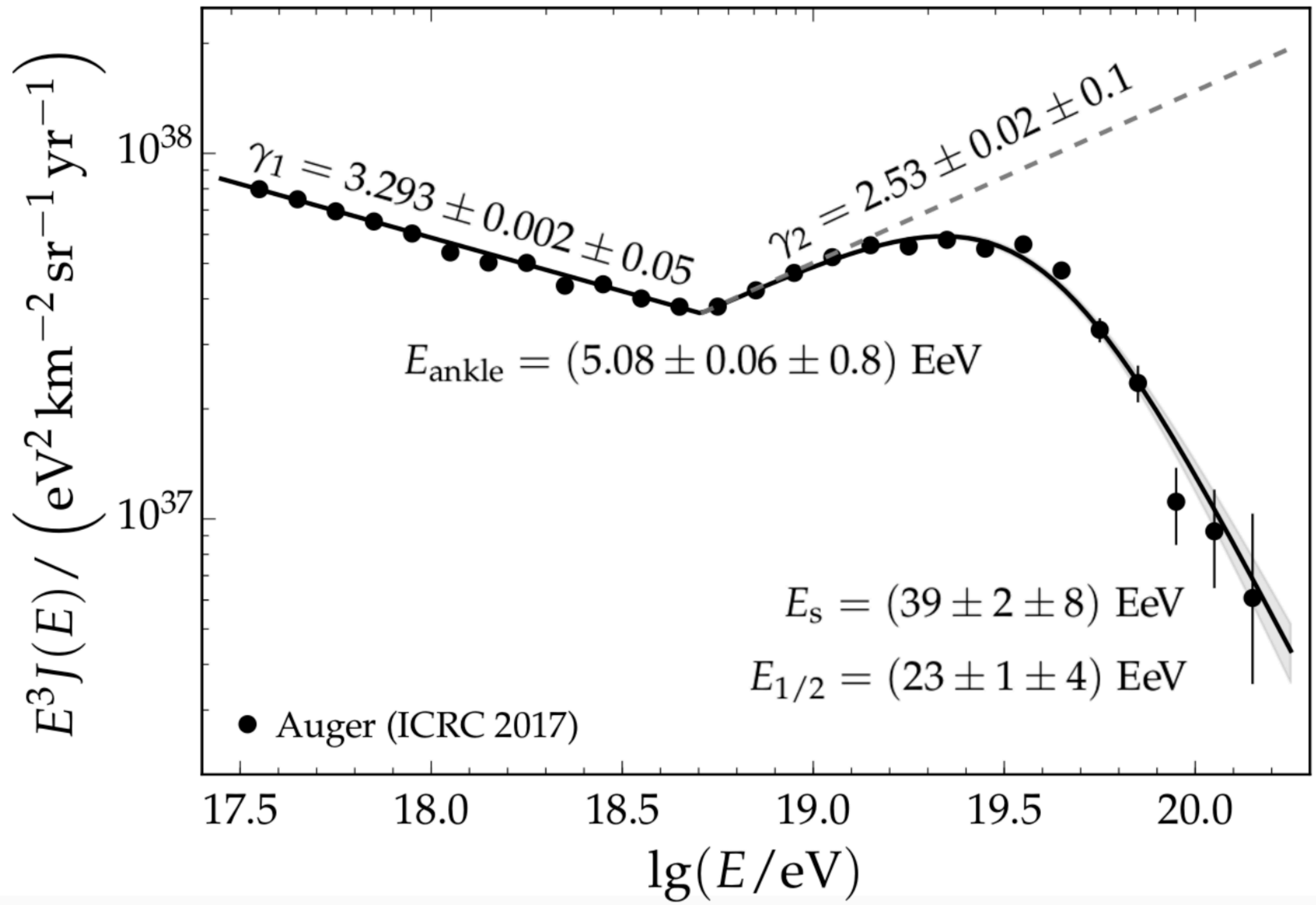
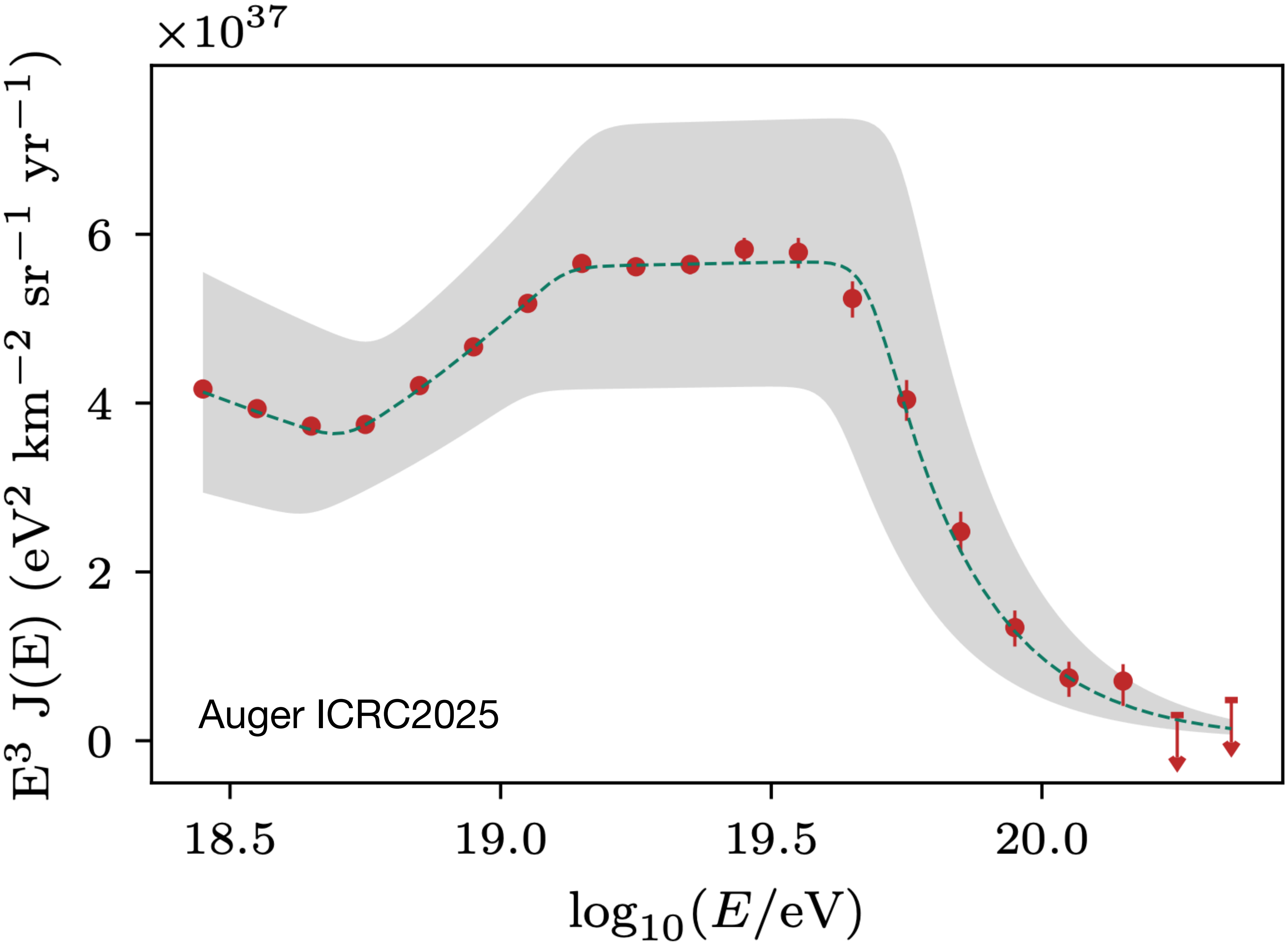
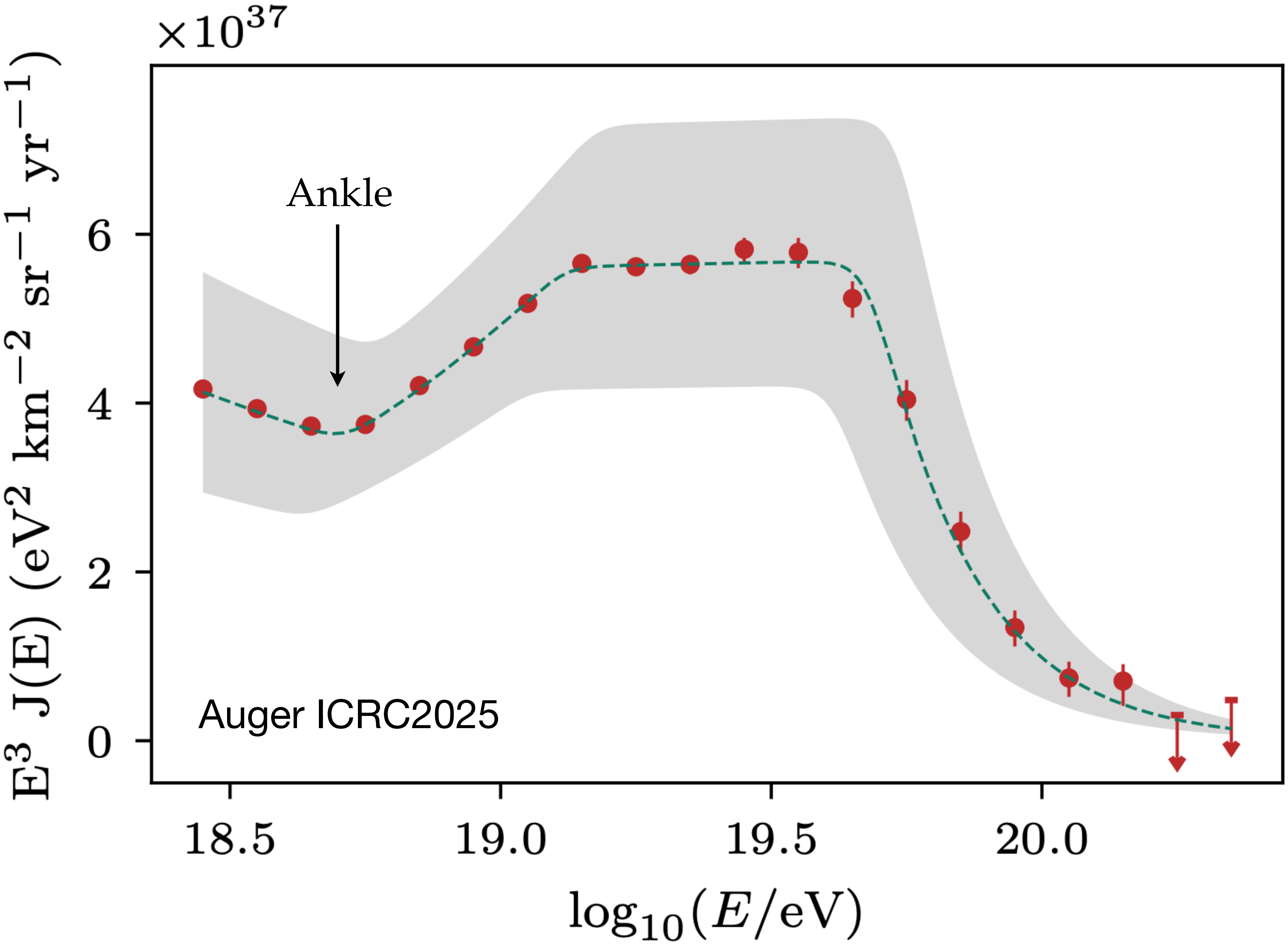


$$J_{\mathrm{unf}}(E) = \begin{cases} J_0\left(\frac{E}{E_{\mathrm{ankle}}}\right)^{-\gamma_1} & E < E_{\mathrm{ankle}} \\ J_0\left(\frac{E}{E_{\mathrm{ankle}}}\right)^{-\gamma_2} \left[1 + \left(\frac{E_{\mathrm{ankle}}}{E_{\mathrm{s}}}\right)^{\Delta\gamma}\right] \left[1 + \left(\frac{E}{E_{\mathrm{s}}}\right)^{\Delta\gamma}\right]^{-1} & E > E_{\mathrm{ankle}} \end{cases}$$



Pierre Auger Collaboration arXiv:2507.08573



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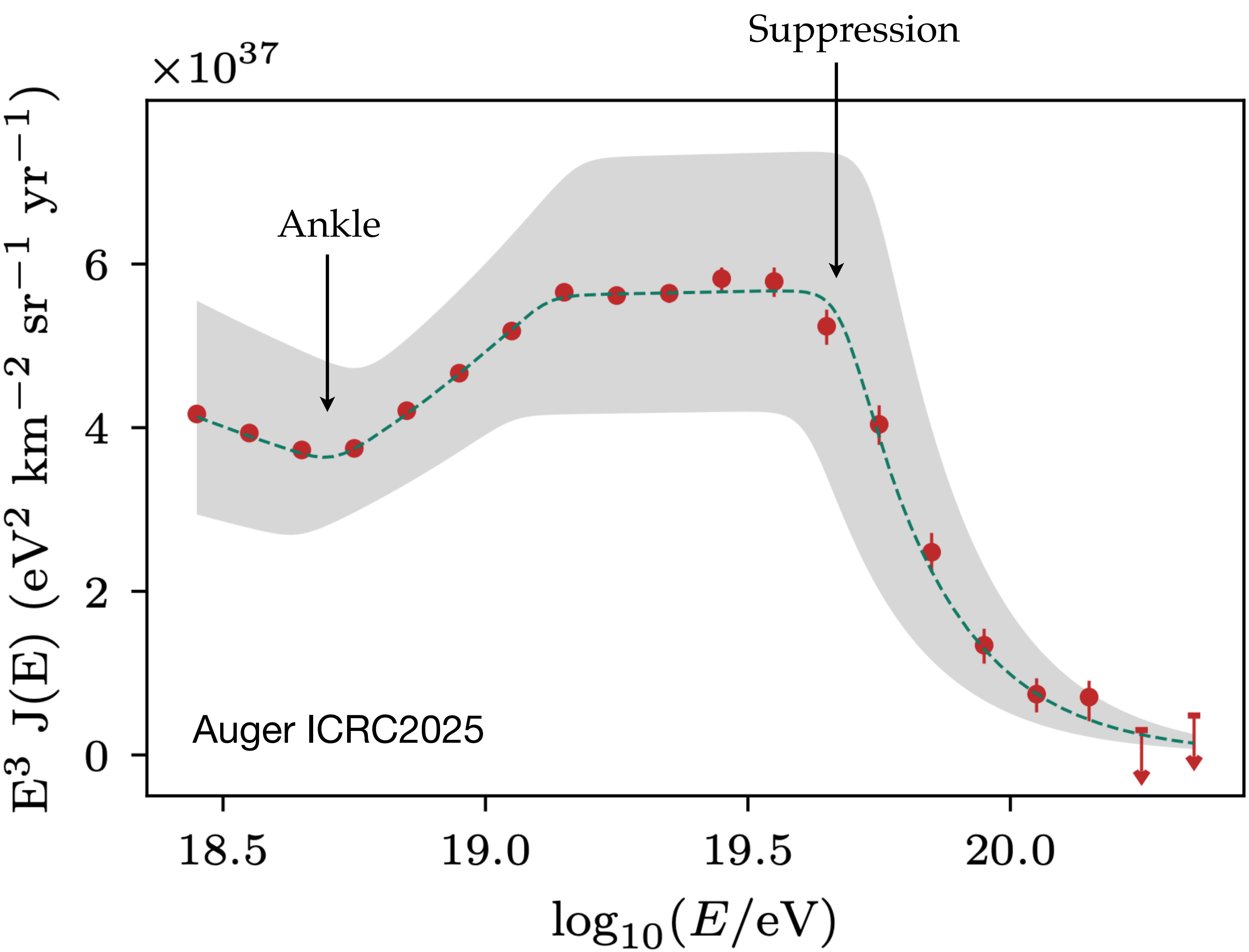

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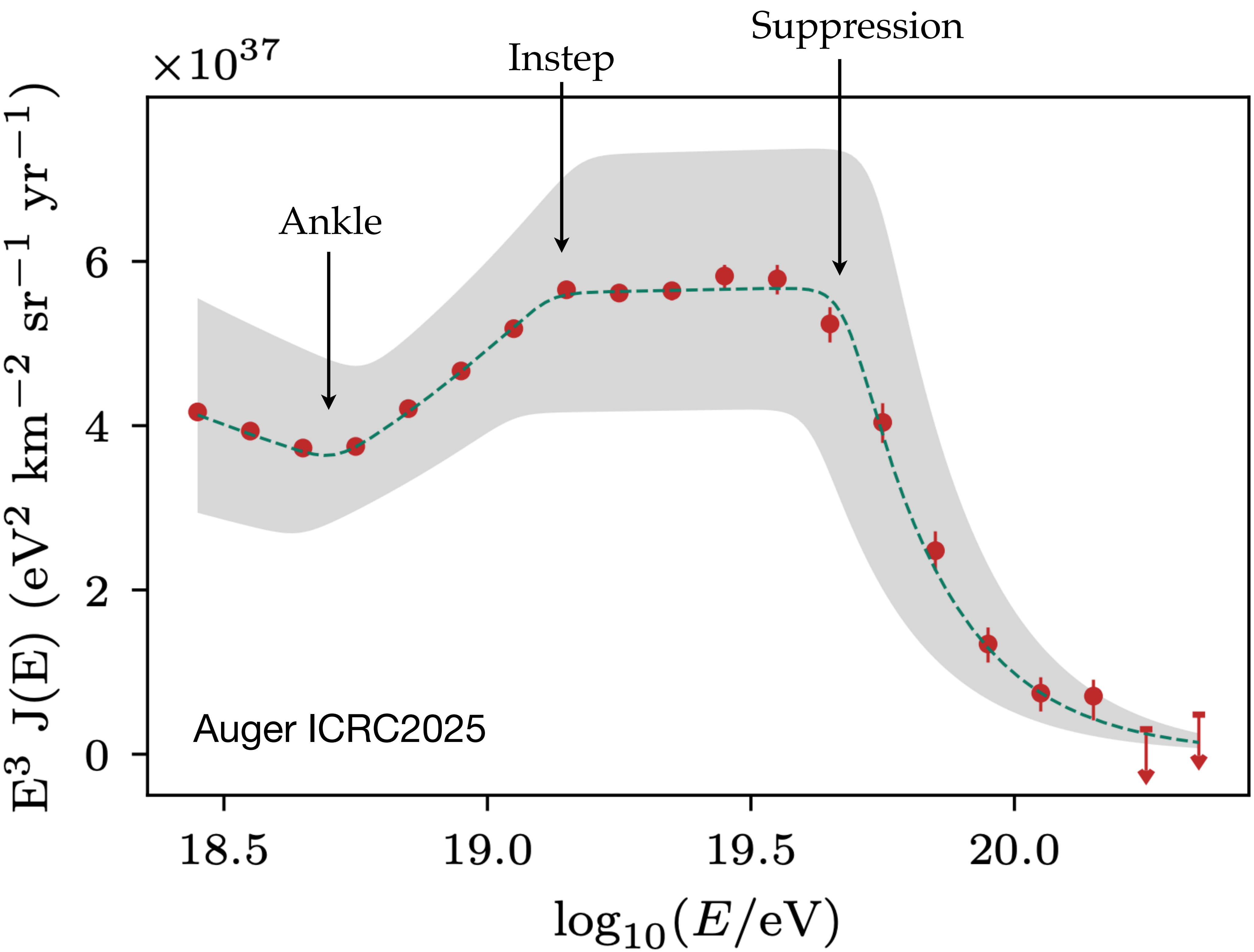

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