Menu...

LECTURE 2

1) The Big Picture: A quick overview

2) Astrophysics and Detection of E<10^{14} eV Galactic CRs (very brief)

3) Detection of E>10^{14} eV: Basic air shower phenomenology

4) **Basic concepts and technologies of EAS experiments** (very brief & qualitatively)

5)

6)

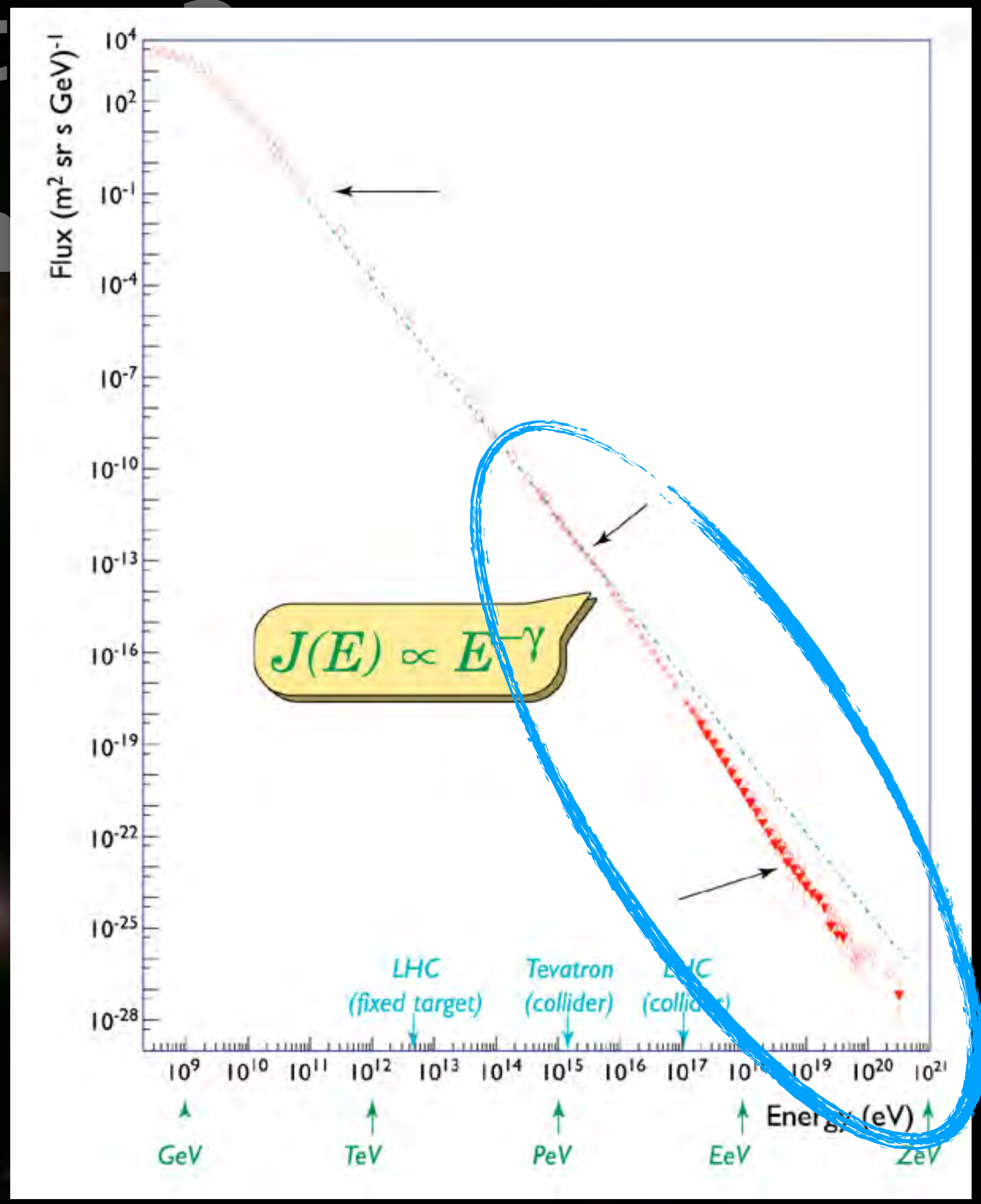
7)

8)

9)

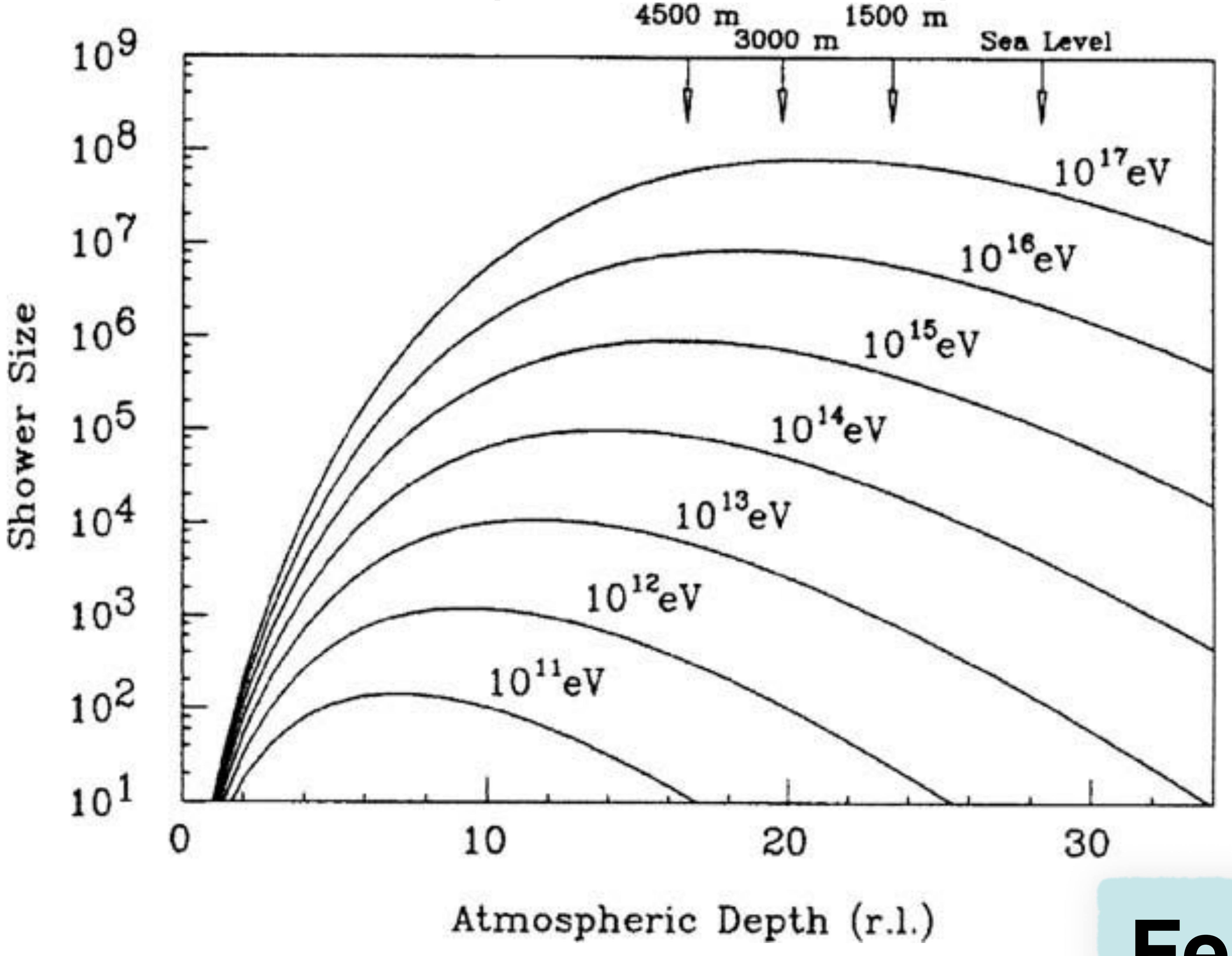
10)

- Observing EAS
  - particle component
  - optical component
  - radio component
  - microwave component

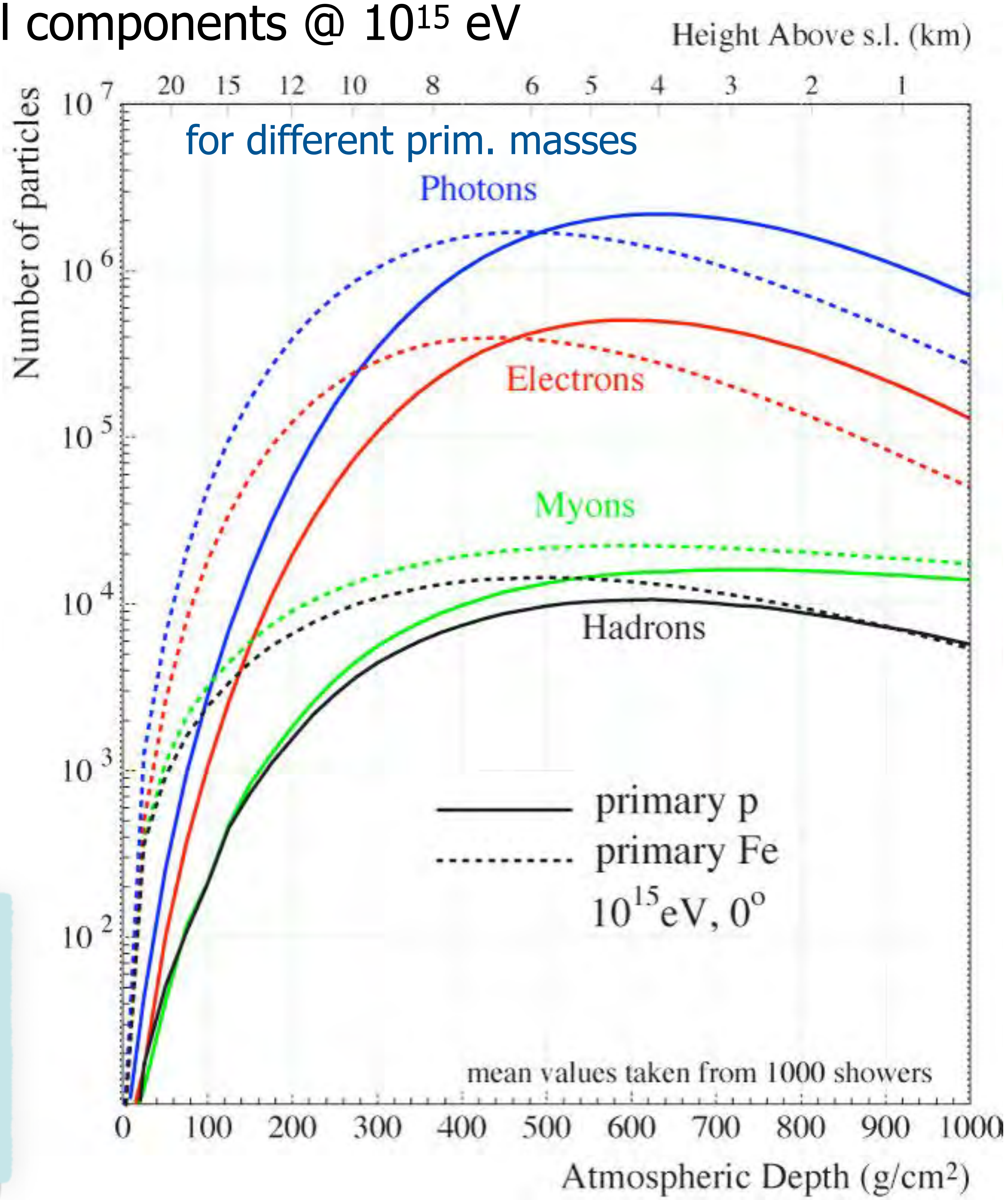


Recap: Particles Component of EAS

all shower particles added up



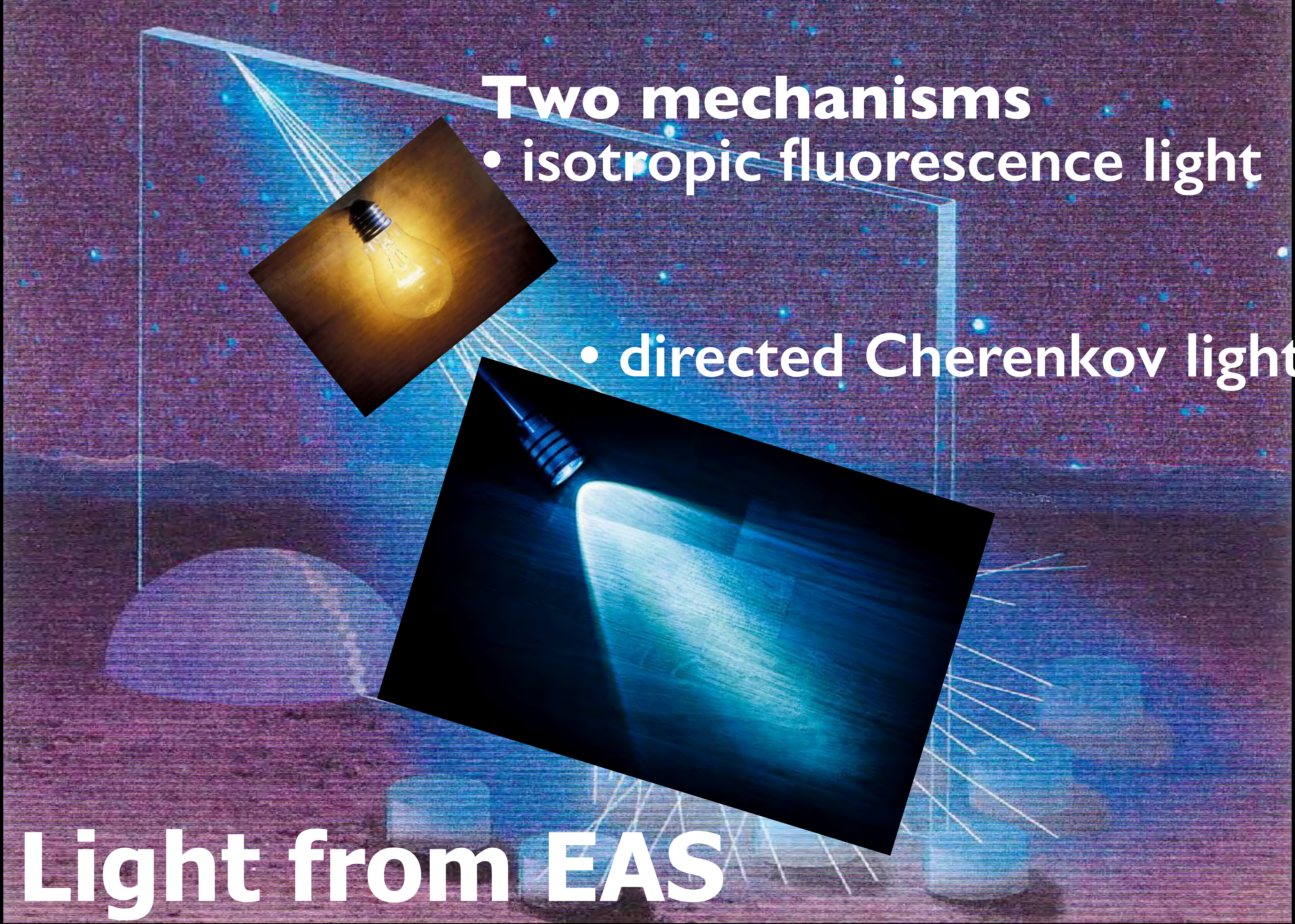
Individual components @ 10^{15} eV



for different prim. masses

Fe-shower:
few more μ's
fewer e's

Light from EAS

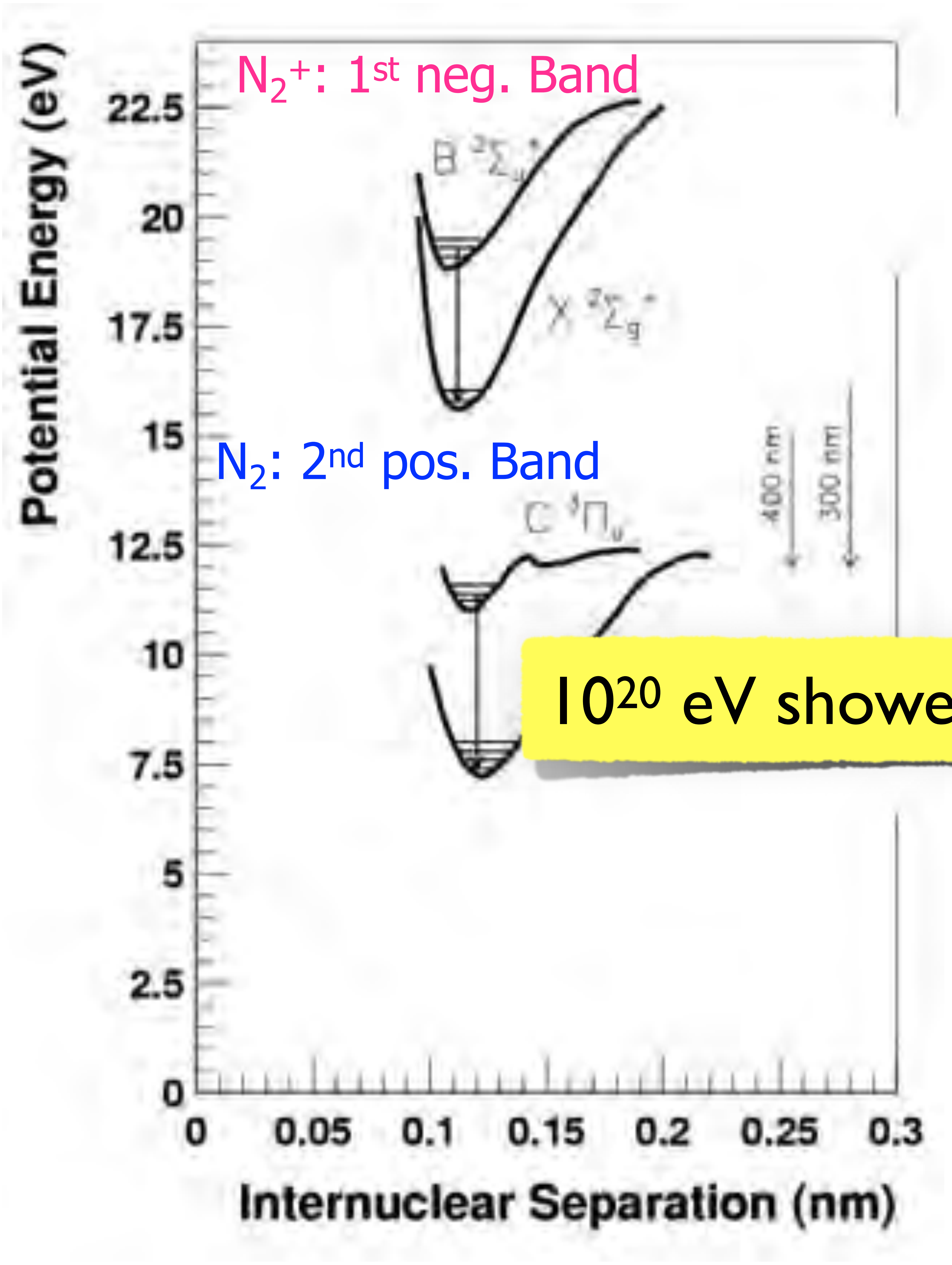


Two mechanisms

- isotropic fluorescence light
- directed Cherenkov light

Fluorescence Light in Air

Molecular excitations

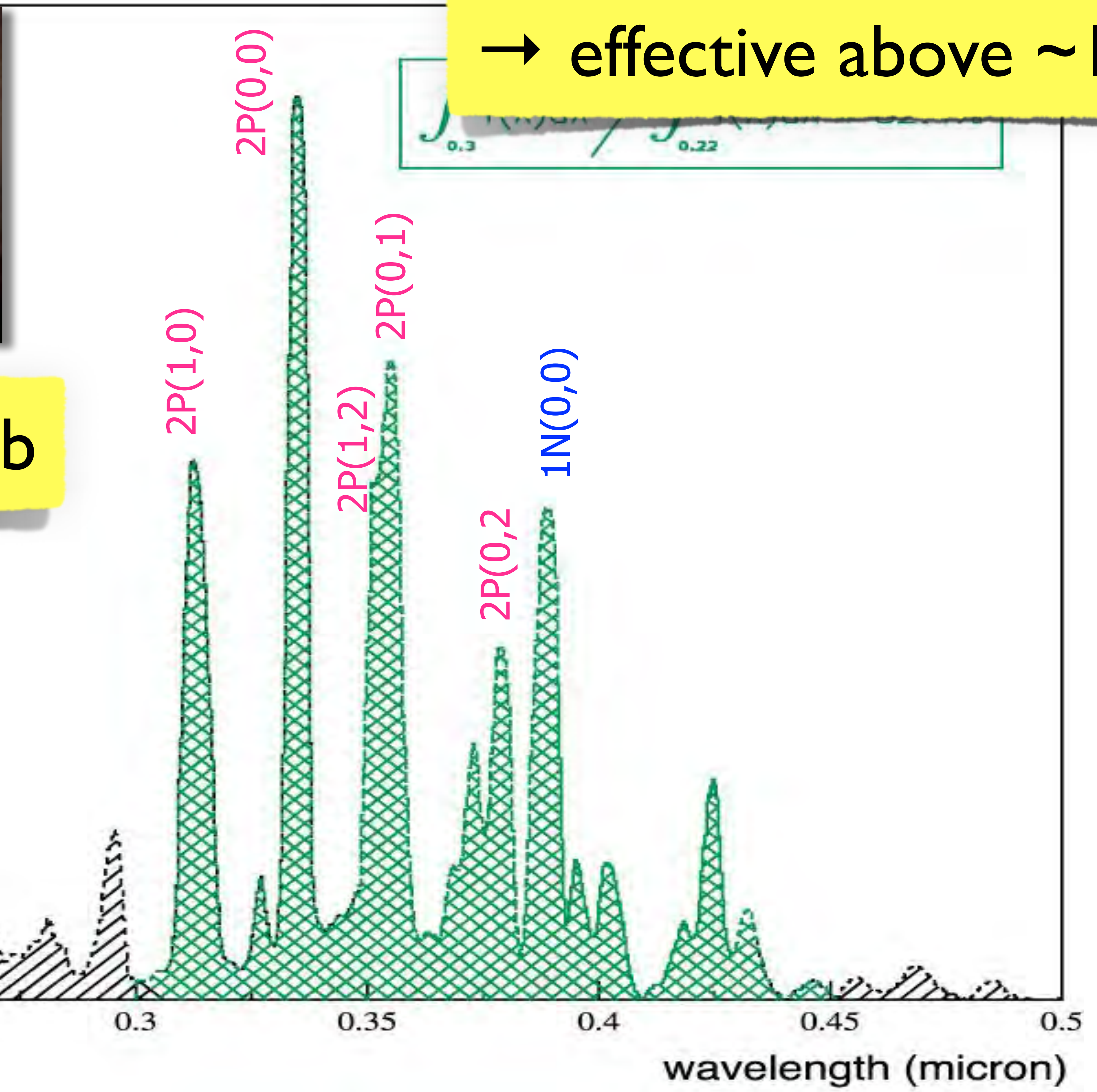


~4 photons/m/electron

~5.6 photons/MeV (~0.5 % of dE/dx)

10^{20} eV shower ≈ 60 W light bulb

→ effective above ~10^{17} eV



Sky and TELESCOPE

1st Fly's Eye

his Issue:

gh-Energy Cosmic Rays

e IAU at Prague

erican Astronomers
Report

nar Orbiter 5 Takes
Unusual Pictures

onvention at
Long Beach

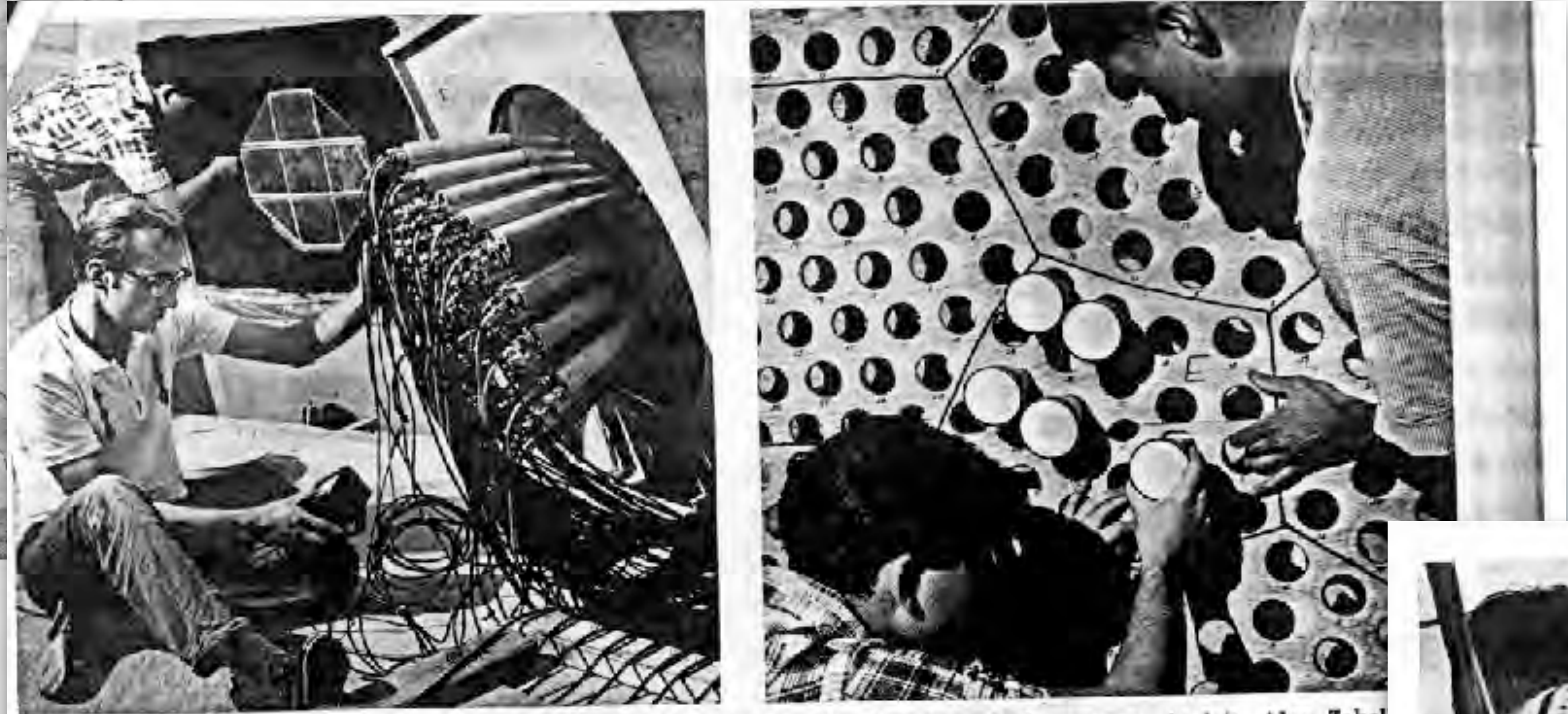
Russell W. Porter
Exhibit

aboratory Exercises
in Astronomy—
Variable Stars
in M15

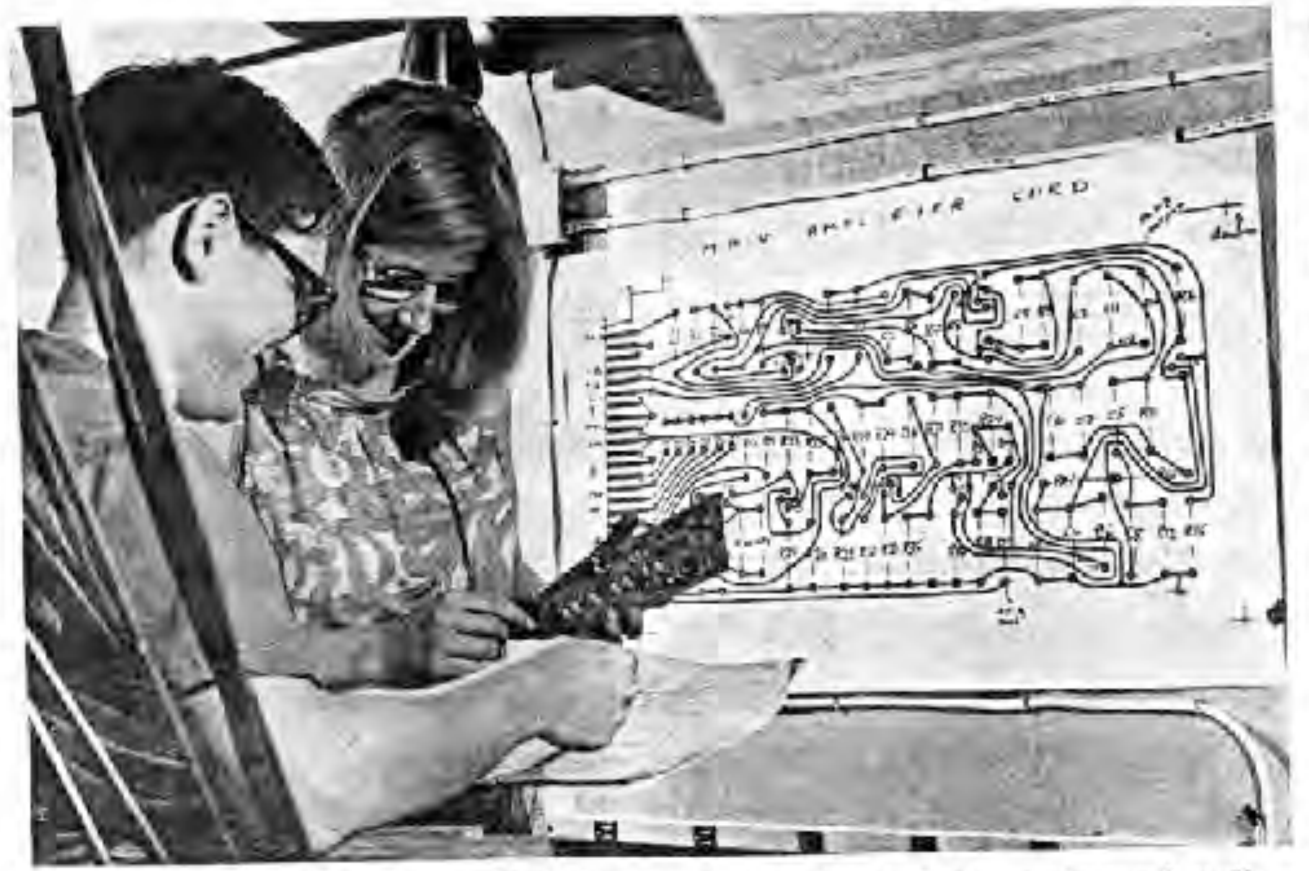
★

Vol. 34, No. 4

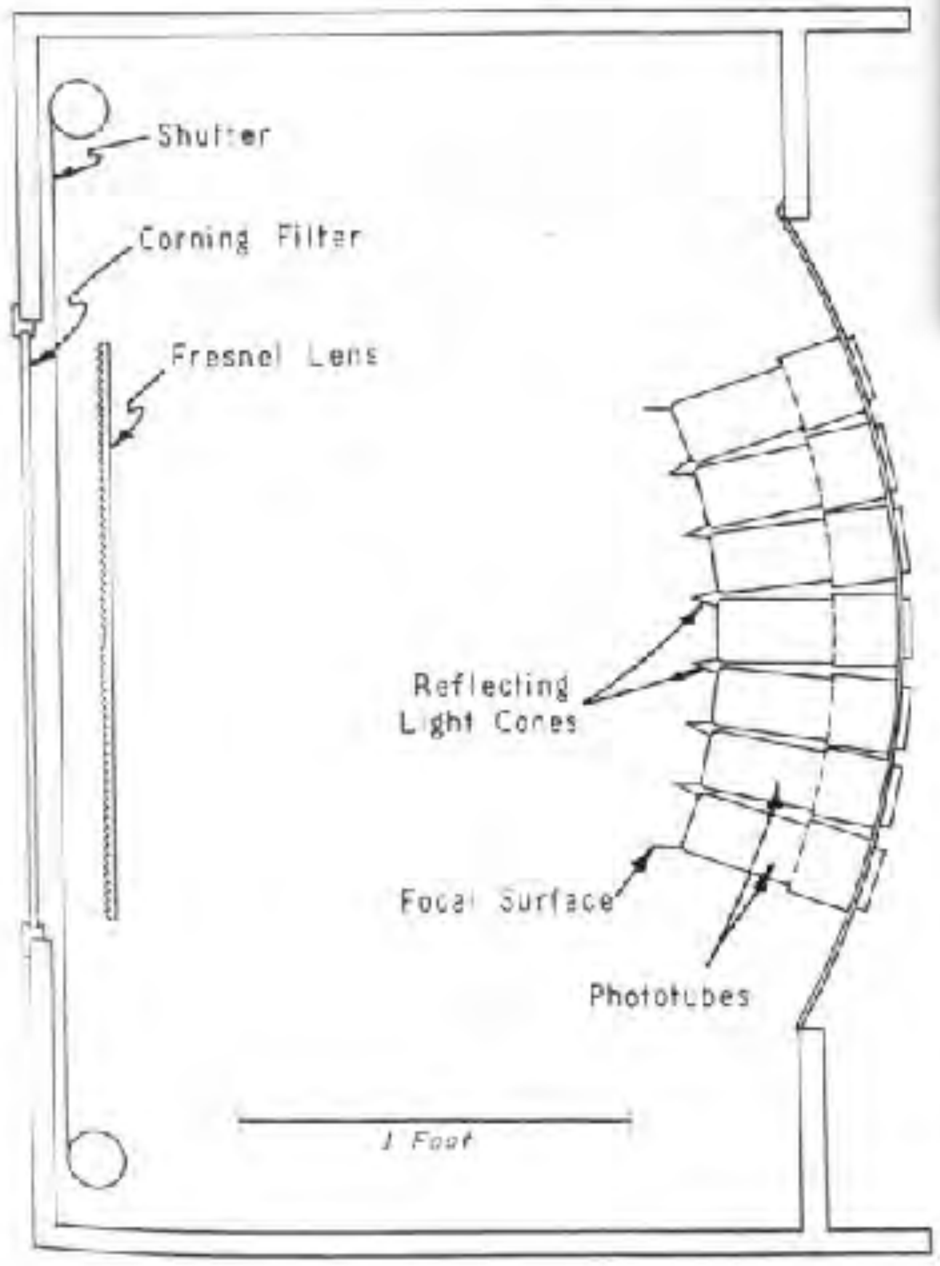
OCTOBER, 1967

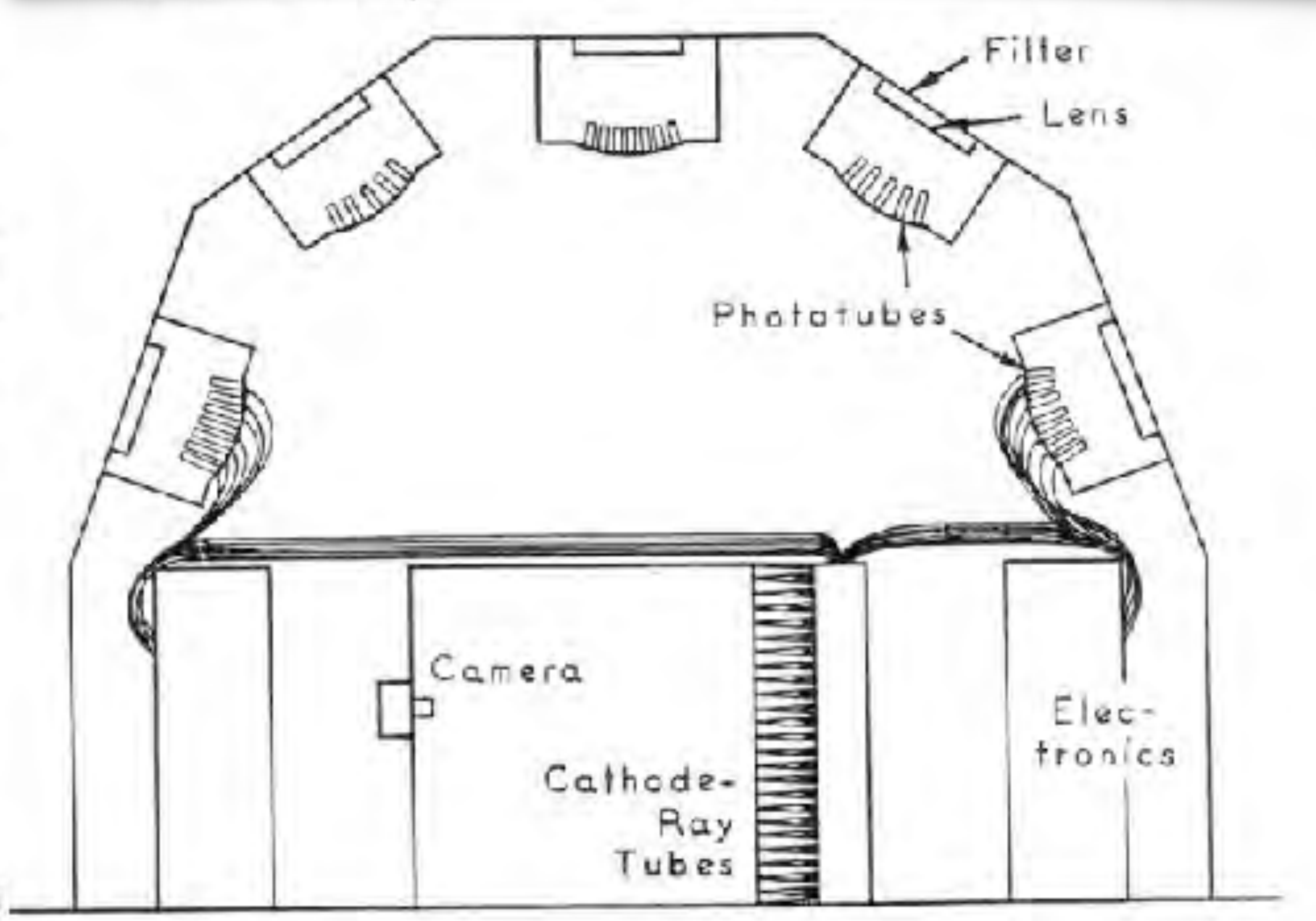


Graduate students at work in the "Cosmic House," their nickname for the unusual observatory. At left, Alan Zabel Brooklyn, New York, mounts a filter over an observing aperture, while Fred Ruckdeschel, Whitestone, New York, ch out a bank of phototube preamplifier bases. At right, Mr. Zabell and Roscoe E. Marrs, Schenectady, New York, m cathode-ray tubes in the camera-room display.



Peter B. Landecker of New York City and Mrs. Cassel, both postdoctoral staff members at Cornell University, examine a main amplifier card that carries the amplification and logic circuits, as diagramed at the right.



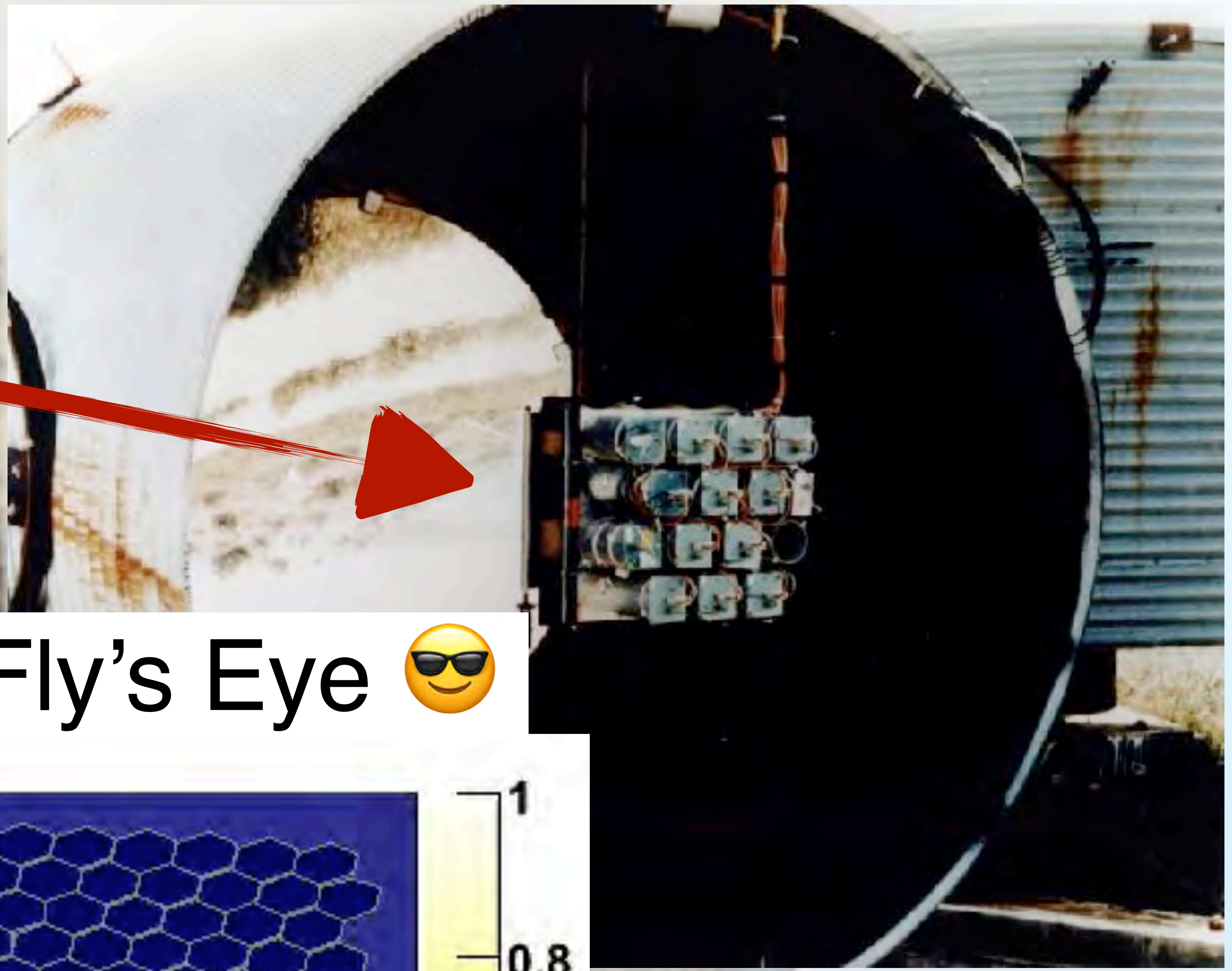


The unsuccessful pioneers...

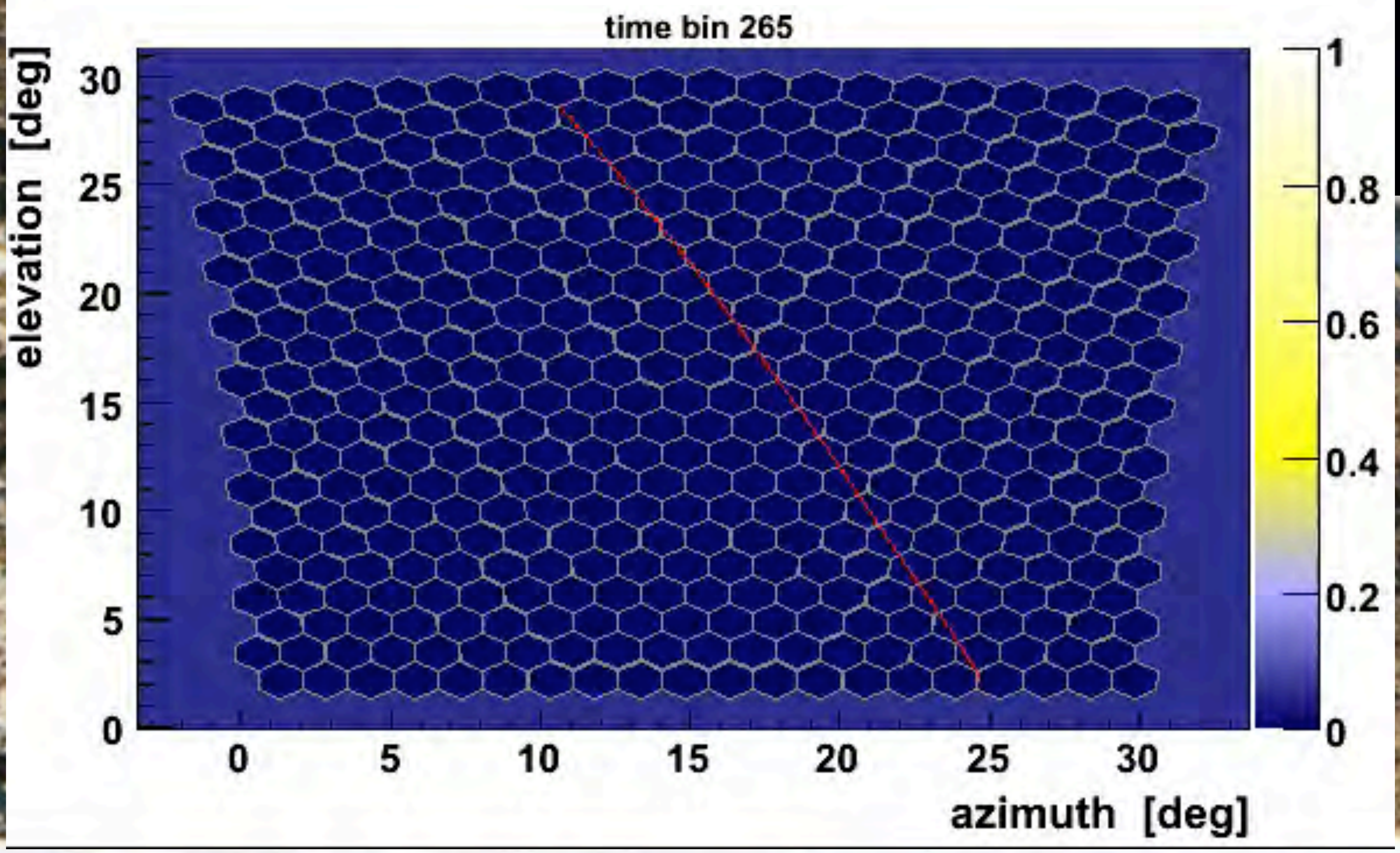
1967: K. Greisen with a group of students

2nd Fly’s Eye (Utah) ~1980-1995

2nd Fly's Eye (Utah) ~1980-1995

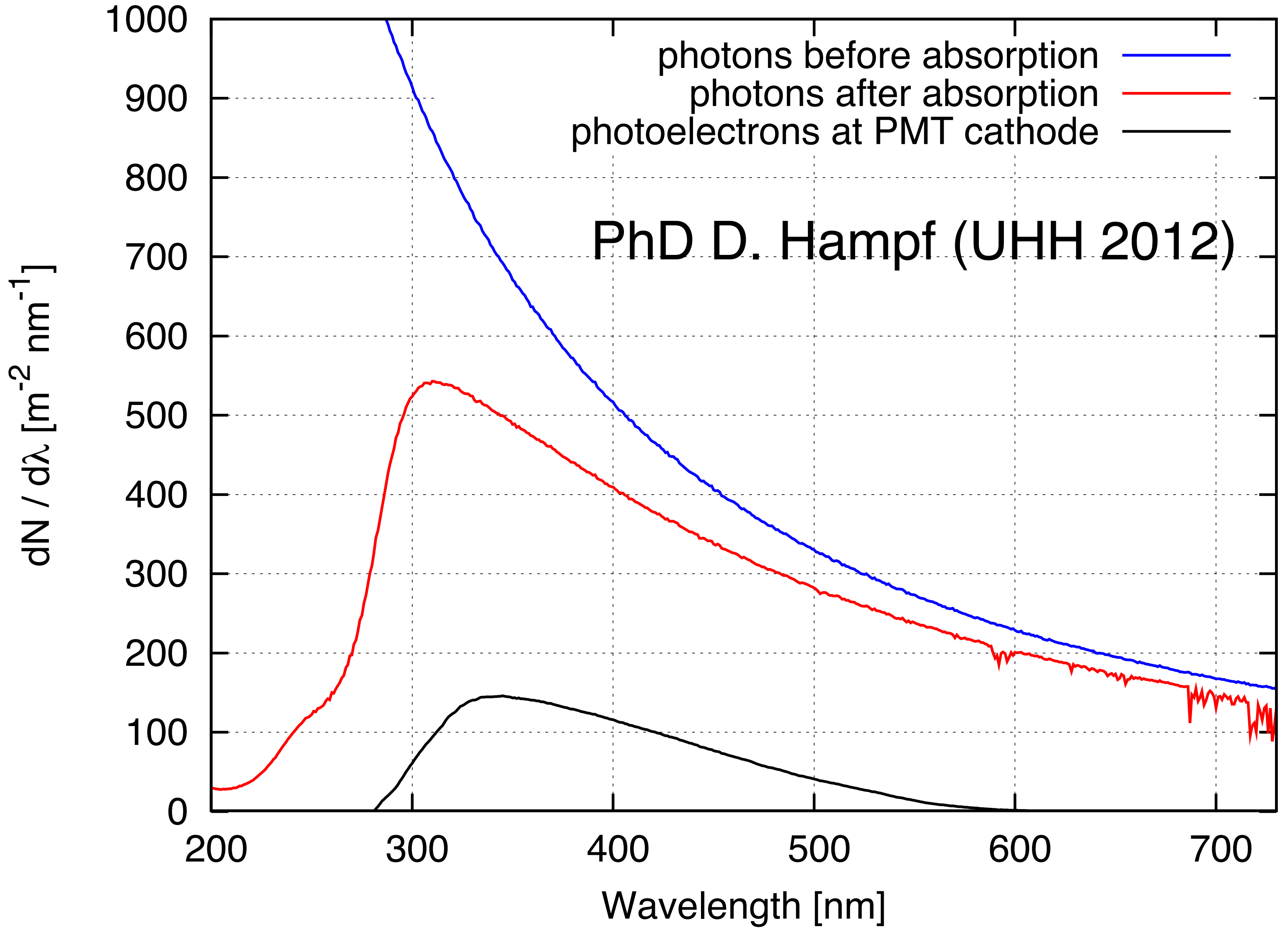


Auger 2007: The best Fly's Eye 😎



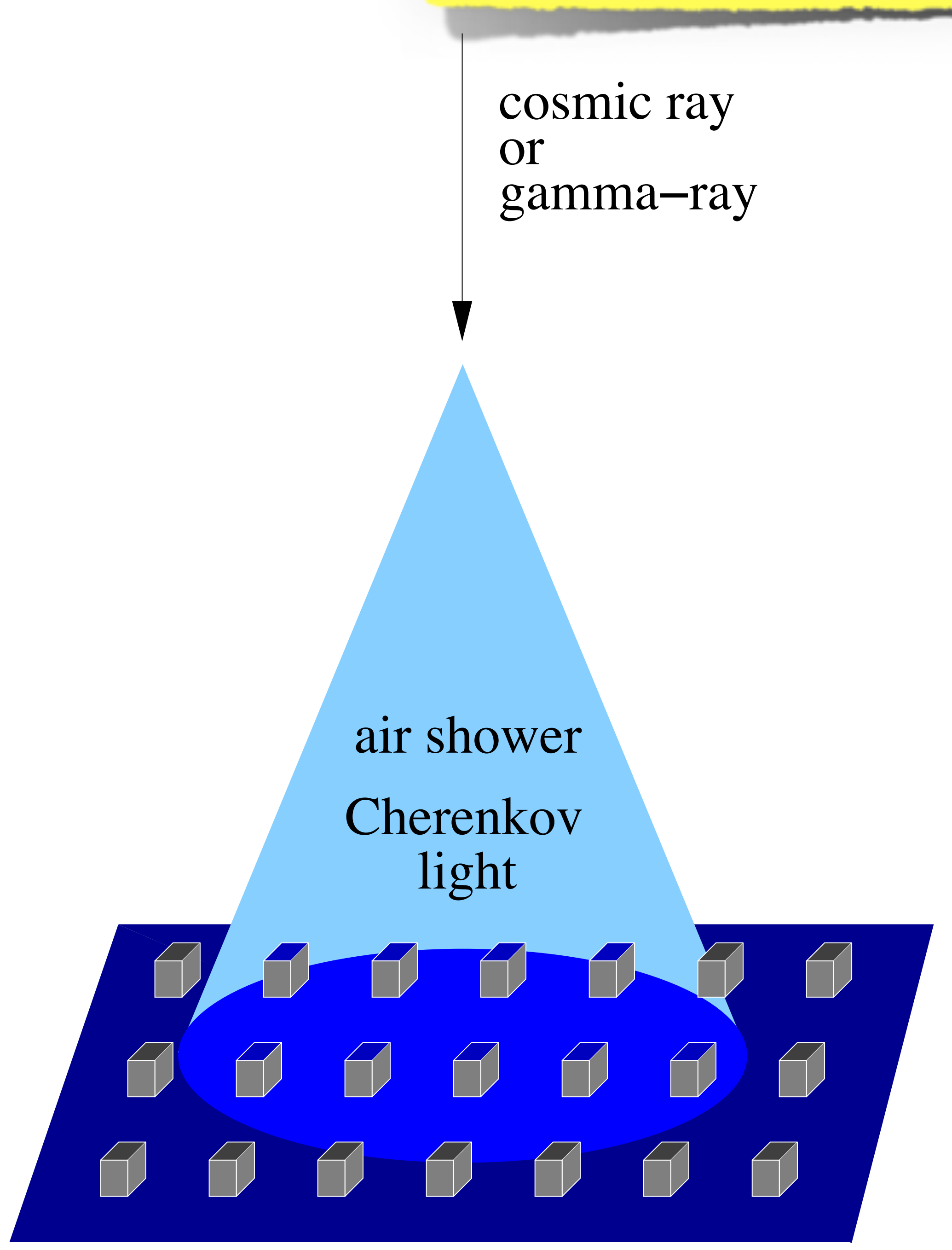
Cherenkov Light in EAS Experiments

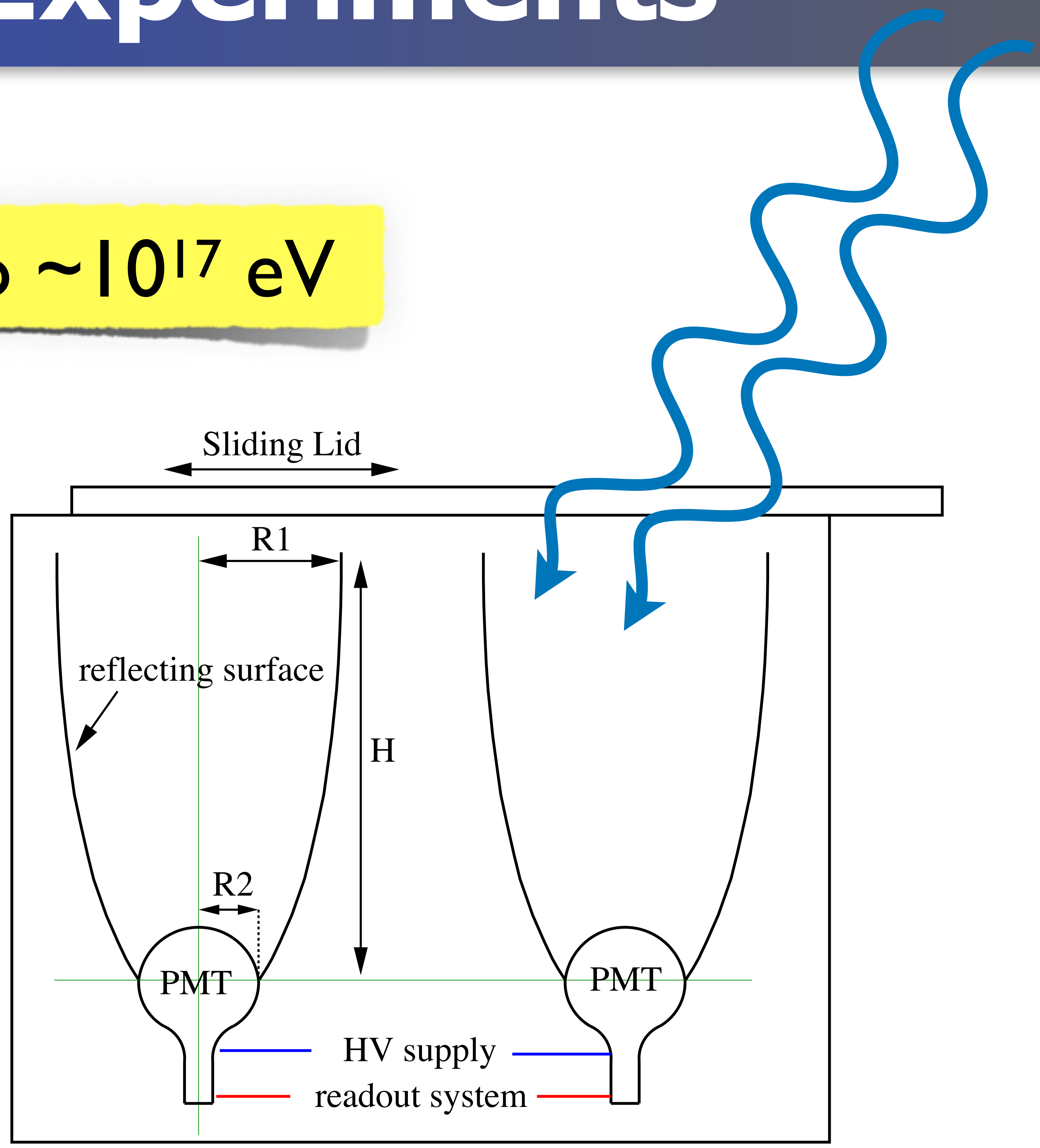
Much higher intensity as compared to fluorescence,
but only ~1° cone of EAS direction → only suited up to ~10^{17} eV



PhD D. Hampf (UHH 2012)

like fluorescence: ~300-500 nm

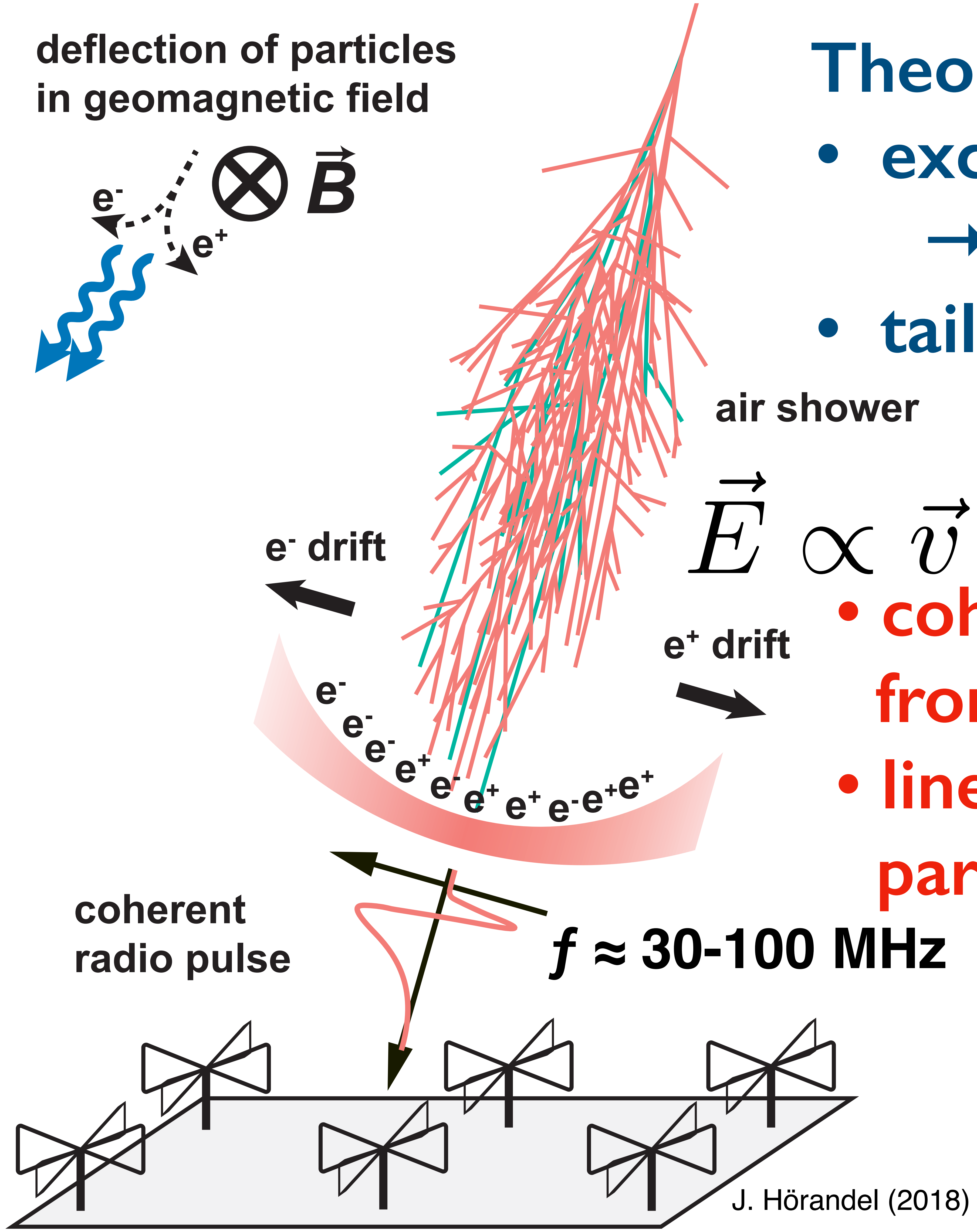




Pioneered by AEROBIC in HEGRA
Now: HiSCORE @ Tunka Valley

Most recent: Radio Emission in EAS

Mainly charge separation in geomagnetic field (~90%)



J. Hörandel (2018)

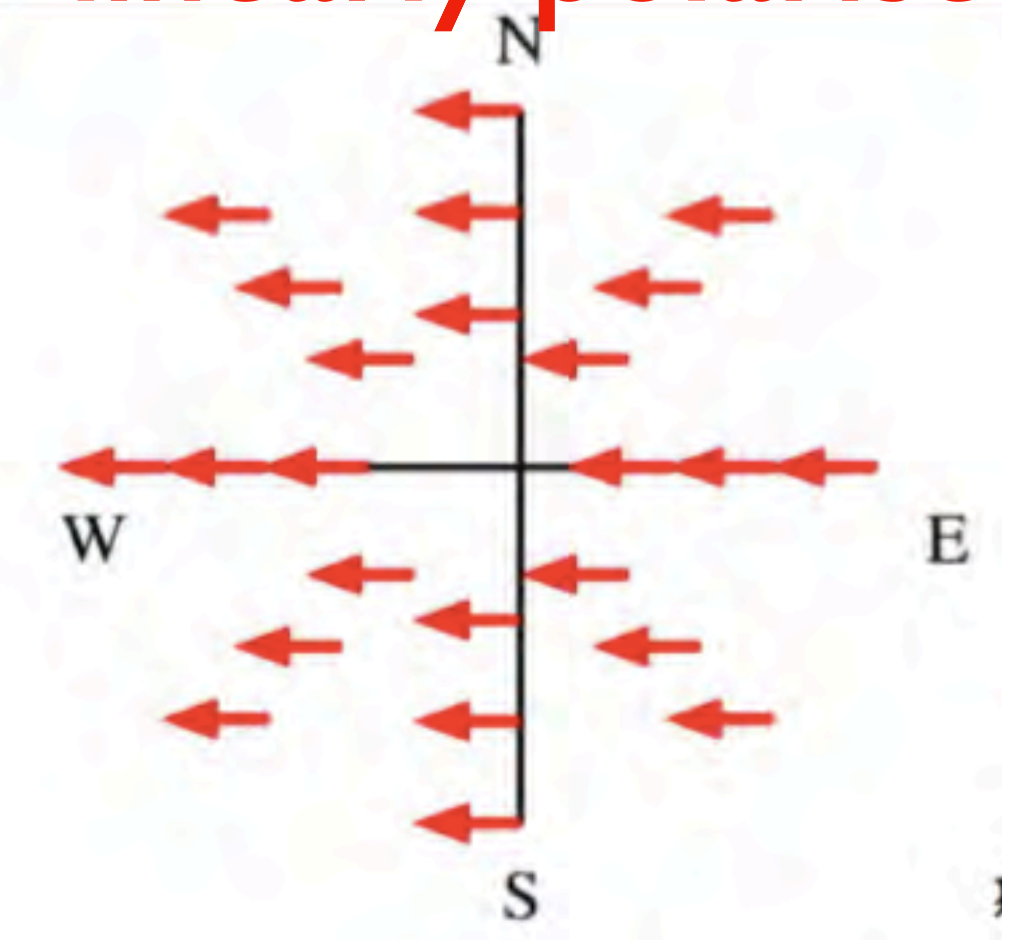
Theory predicts additional mechanisms:

- excess of electrons in shower front
  - → charge excess (Askaryan), ~10%
- tail of Cherenkov effects

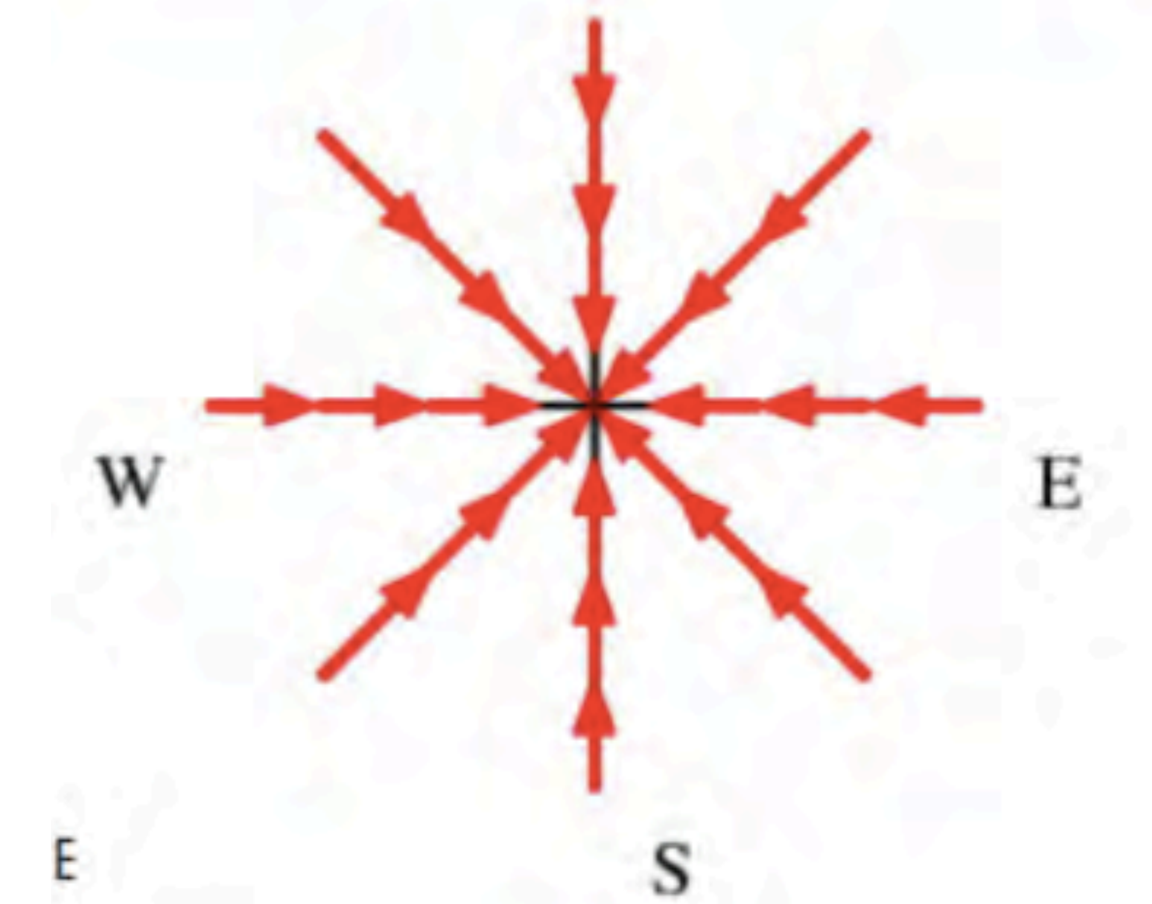
$$\vec{E} \propto \vec{v} \times \vec{B}$$

- coherent emission from shower front
- linear polarisation parallel to v x B

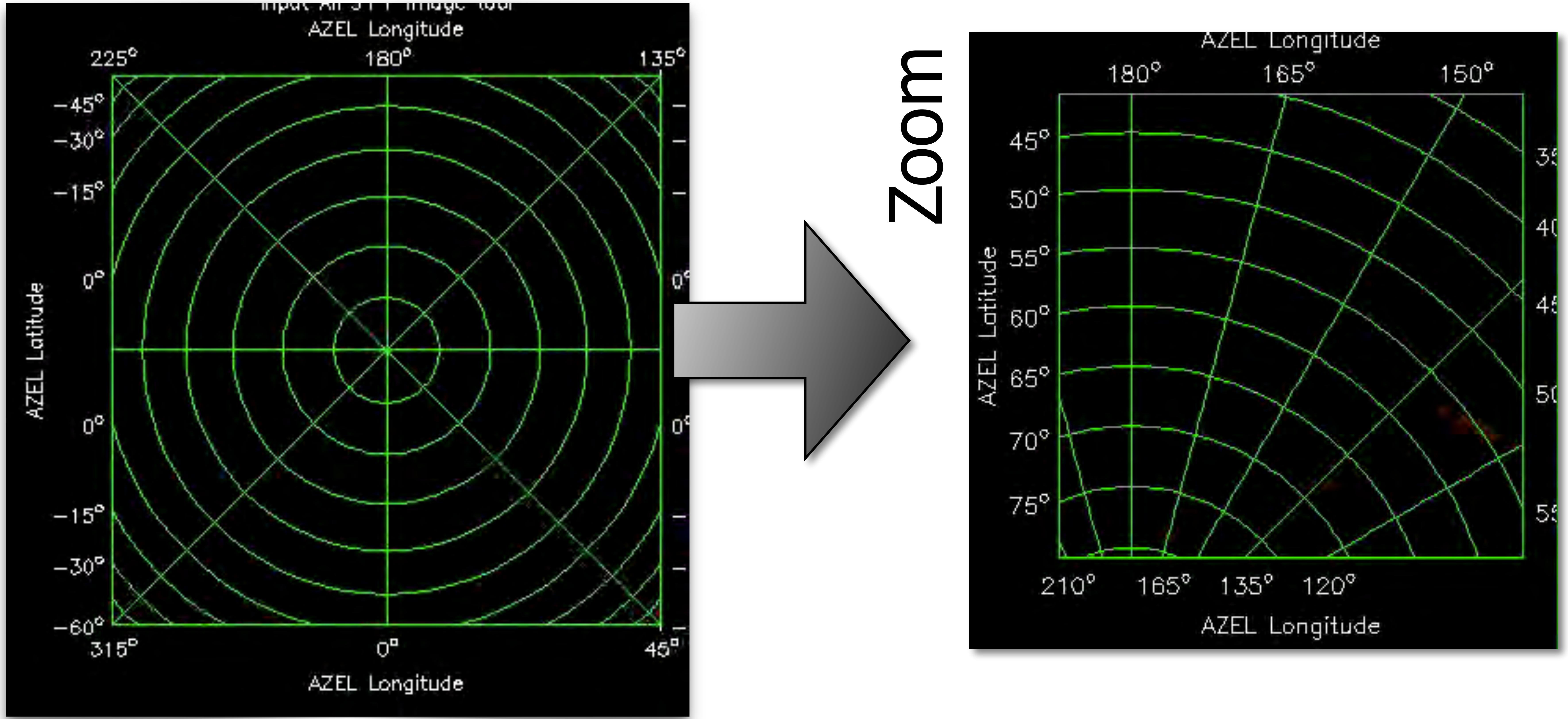
geomagnetic:
linearly polarised



Askaryan:
radially polarised



LOPES Experiment: proof of principle



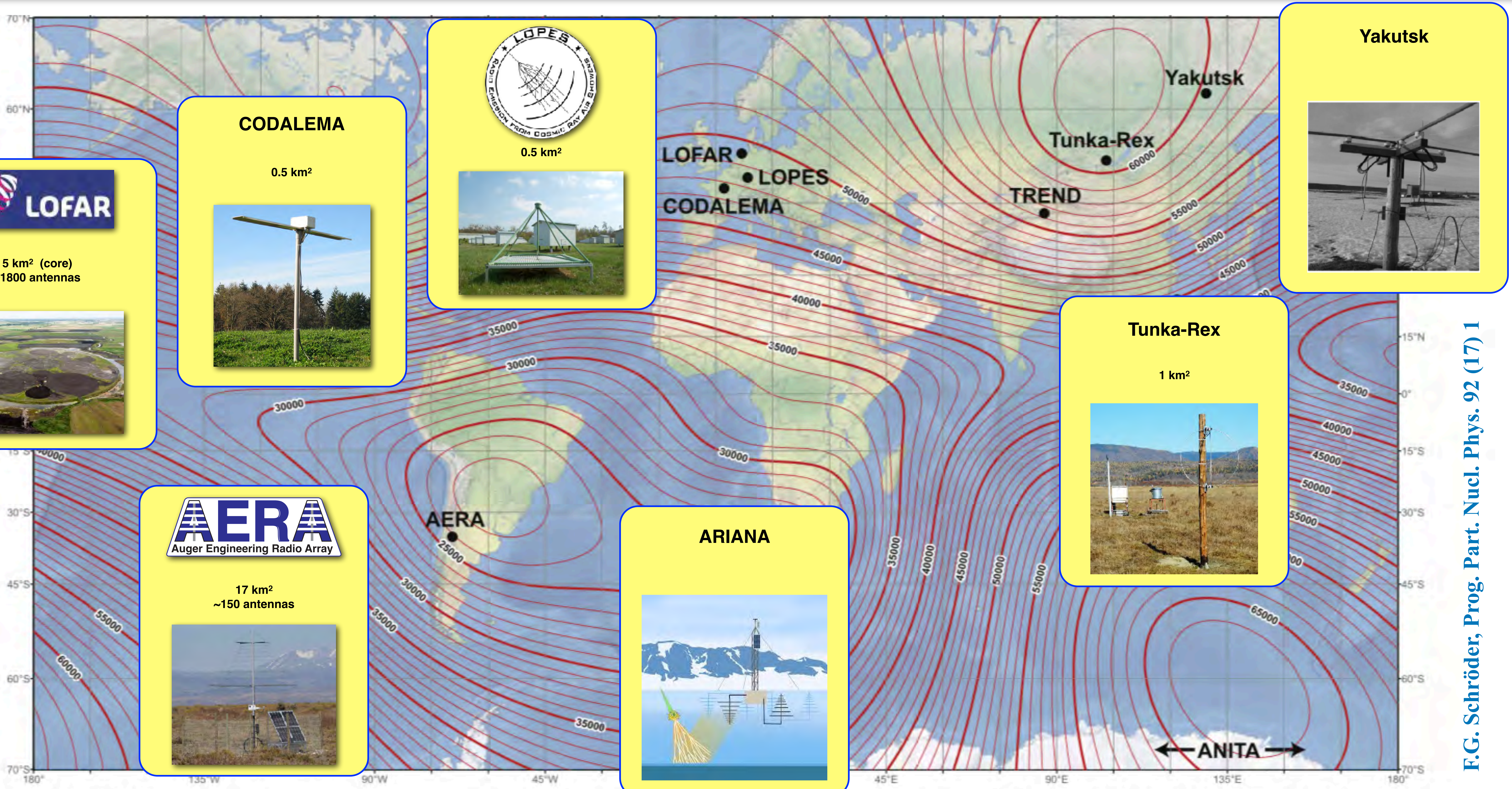
A 10^{17} eV airshower produces a 1 GJy radio flare in 25 ns (40 MHz bandwidth)!

The brightest radio source, the sun, has 1MJy.

Codalema (Nantes) succeeded almost in parallel

Falcke, KHK, et al., Nature 435 (2005) 313

Radio Detection of EAS around the world



LOFAR

5 km² (core)
~1800 antennas

CODALEMA

0.5 km²

LOPES

0.5 km²

Yakutsk

Tunka-Rex

1 km²

AERA

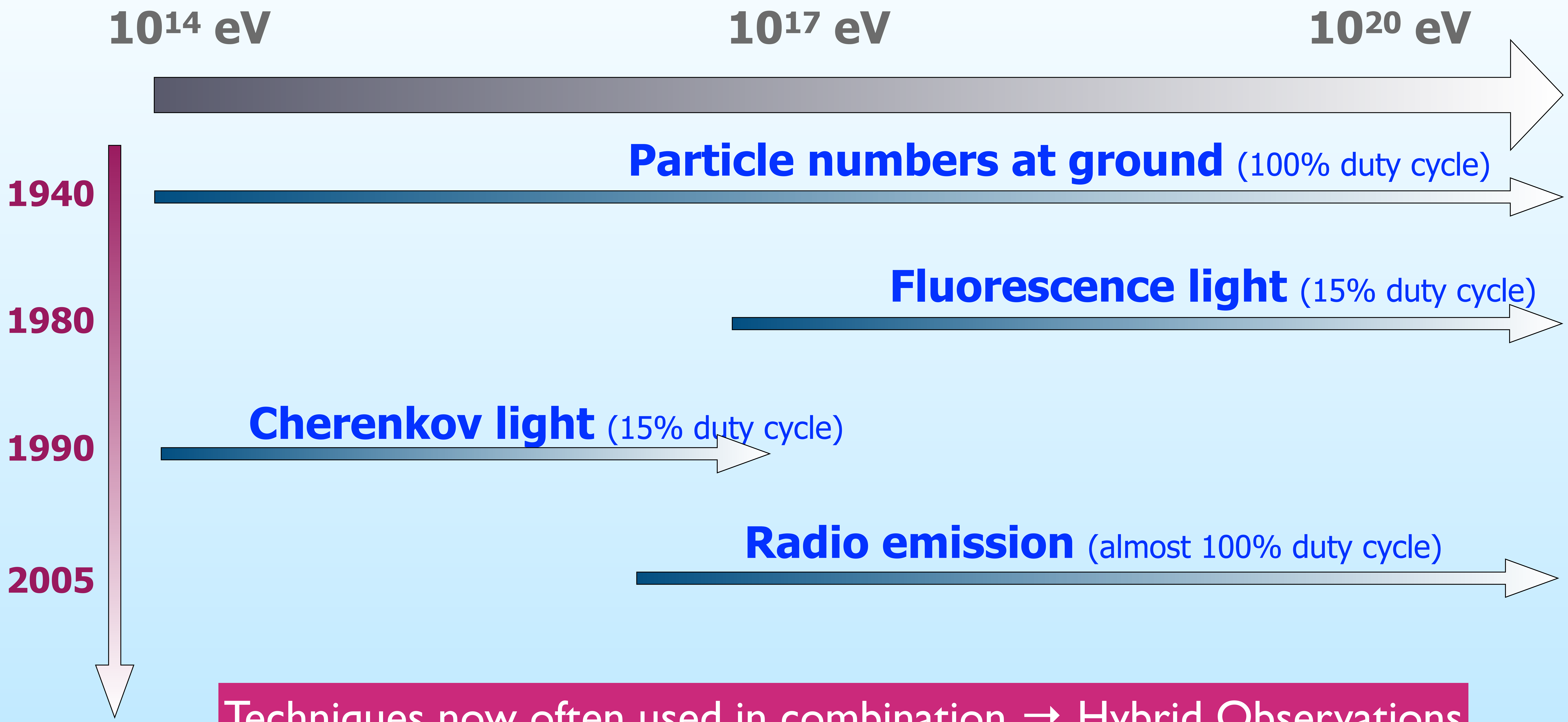
Auger Engineering Radio Array

17 km²
~150 antennas

ARIANA

F.G. Schröder, Prog. Part. Nucl. Phys. 92 (17) 1

Application Ranges of EAS Observables



10^{14} eV

10^{17} eV

10^{20} eV

1940

Particle numbers at ground (100% duty cycle)

1980

Fluorescence light (15% duty cycle)

1990

Cherenkov light (15% duty cycle)

2005

Radio emission (almost 100% duty cycle)

Techniques now often used in combination → Hybrid Observations

Menu…

3) Detection of E>10^{14} eV: Basic air shower phenomenology

4) Basic concepts and technologies of EAS experiments

5) The light and heavy knee: E_{max} of galactic accelerators?

6) T … accelerators?

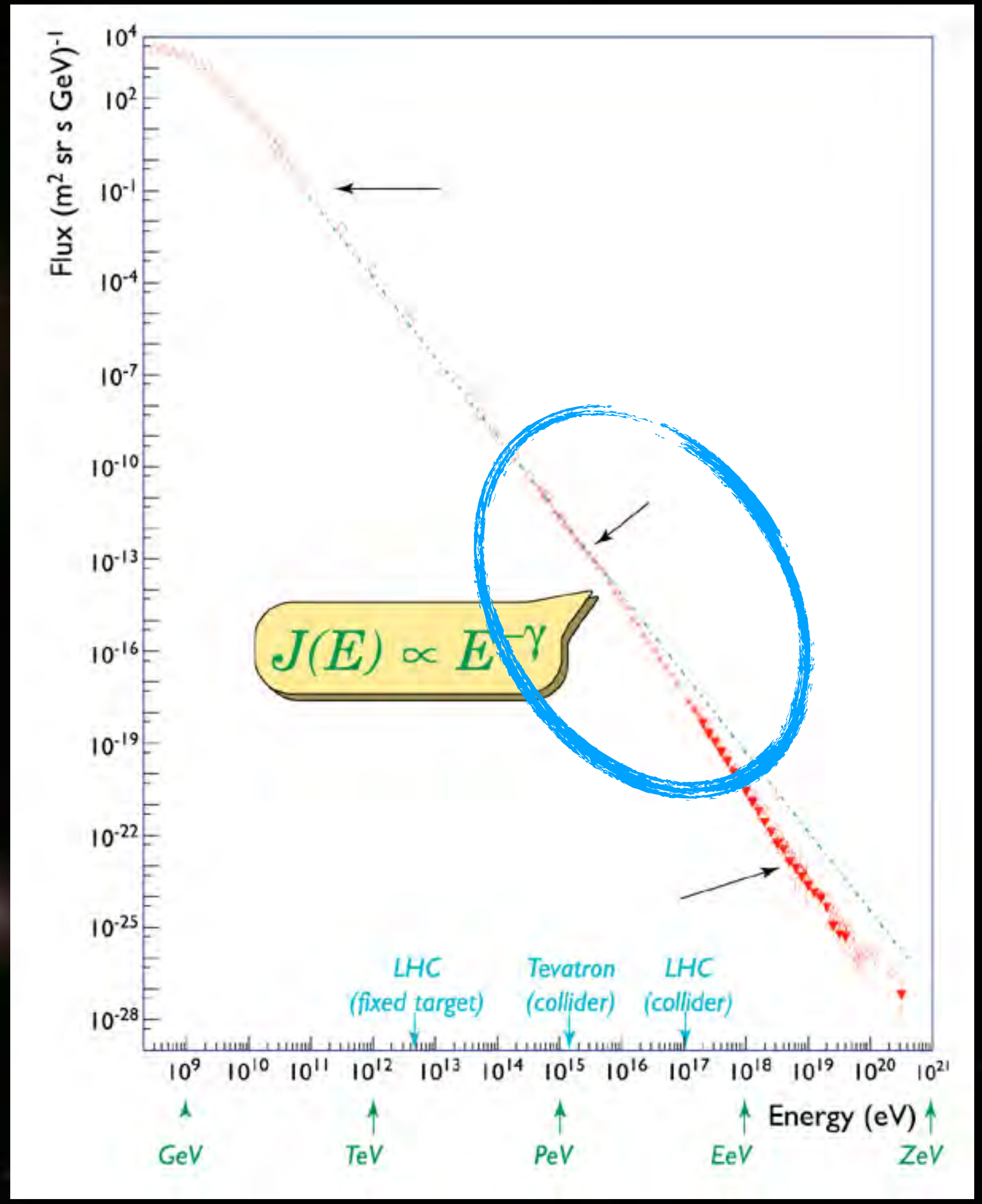
7) A

8) M

9) R

10)

- Experiments in the energy range of the knee
- The Knee and the „heavy knee“
- Interpretation:
  - maximum energy of galactic sources ?
  - diffusion losses from galaxy ?



Major EAS experiments around the knee from recent past to present

IceCube/IceTop

Argo-YJB

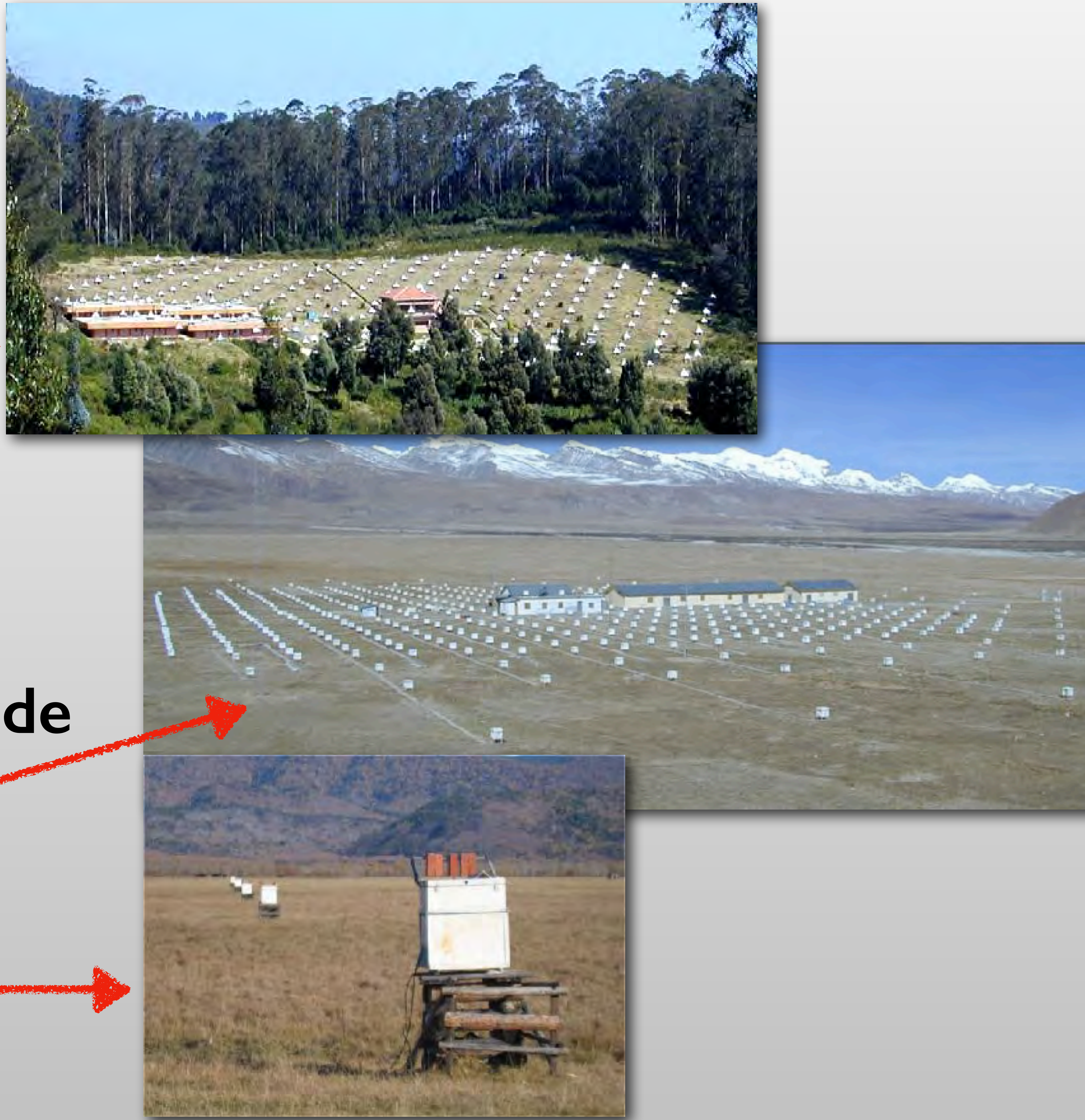
GRAPES

KASCADE

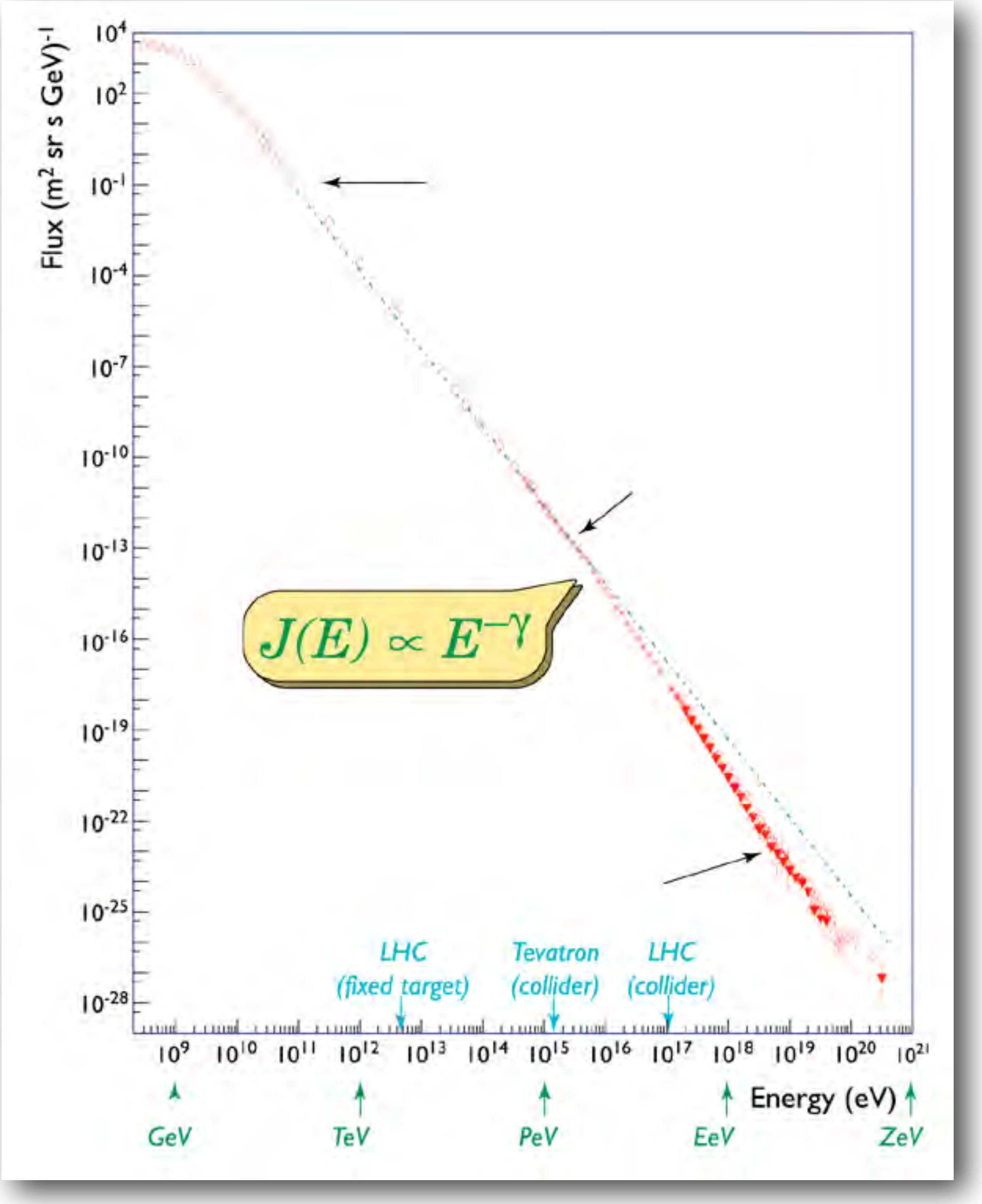
KASCADE-Grande

Tibet Asγ

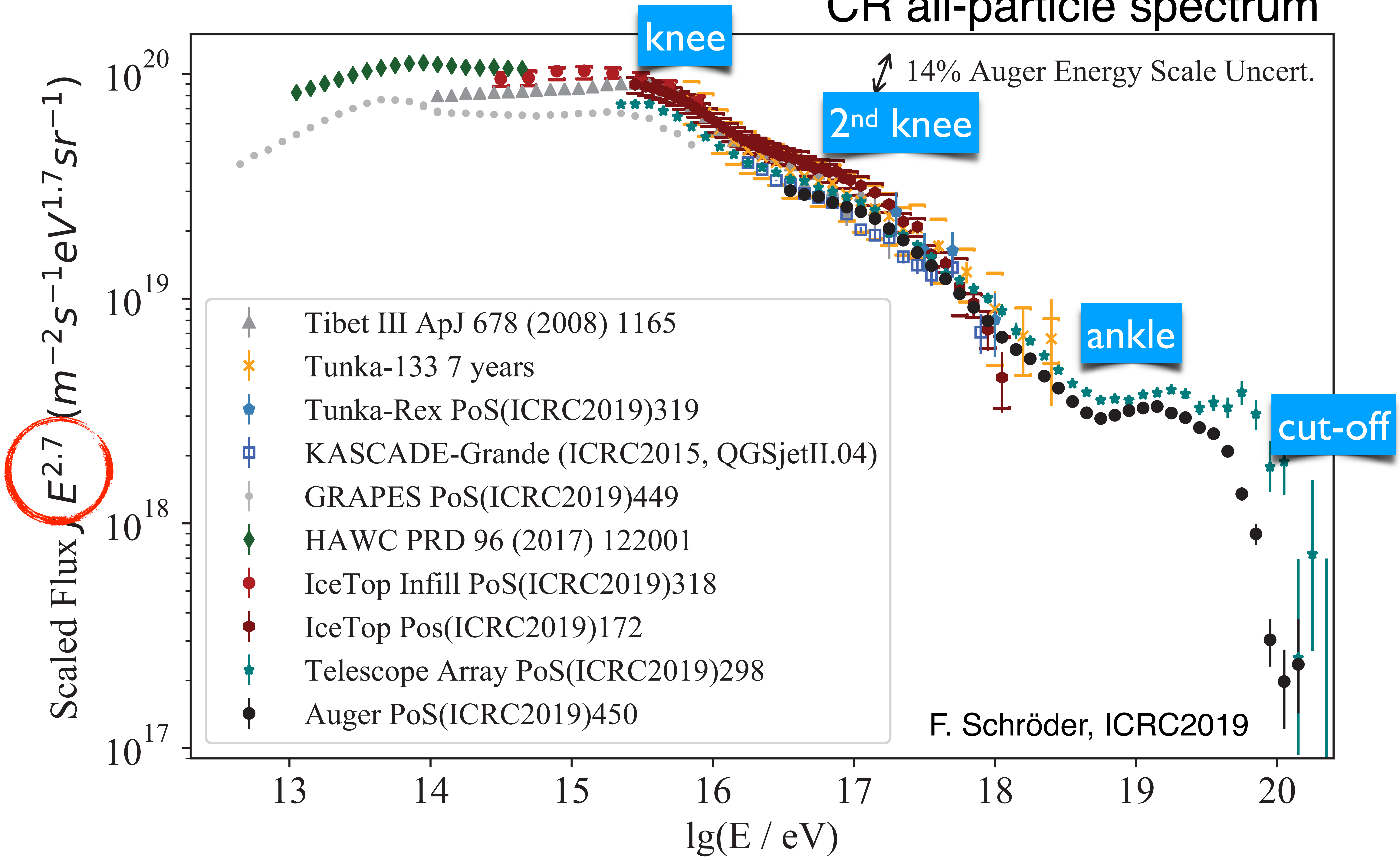
Tunka/HiScore



Features of the CR spectrum

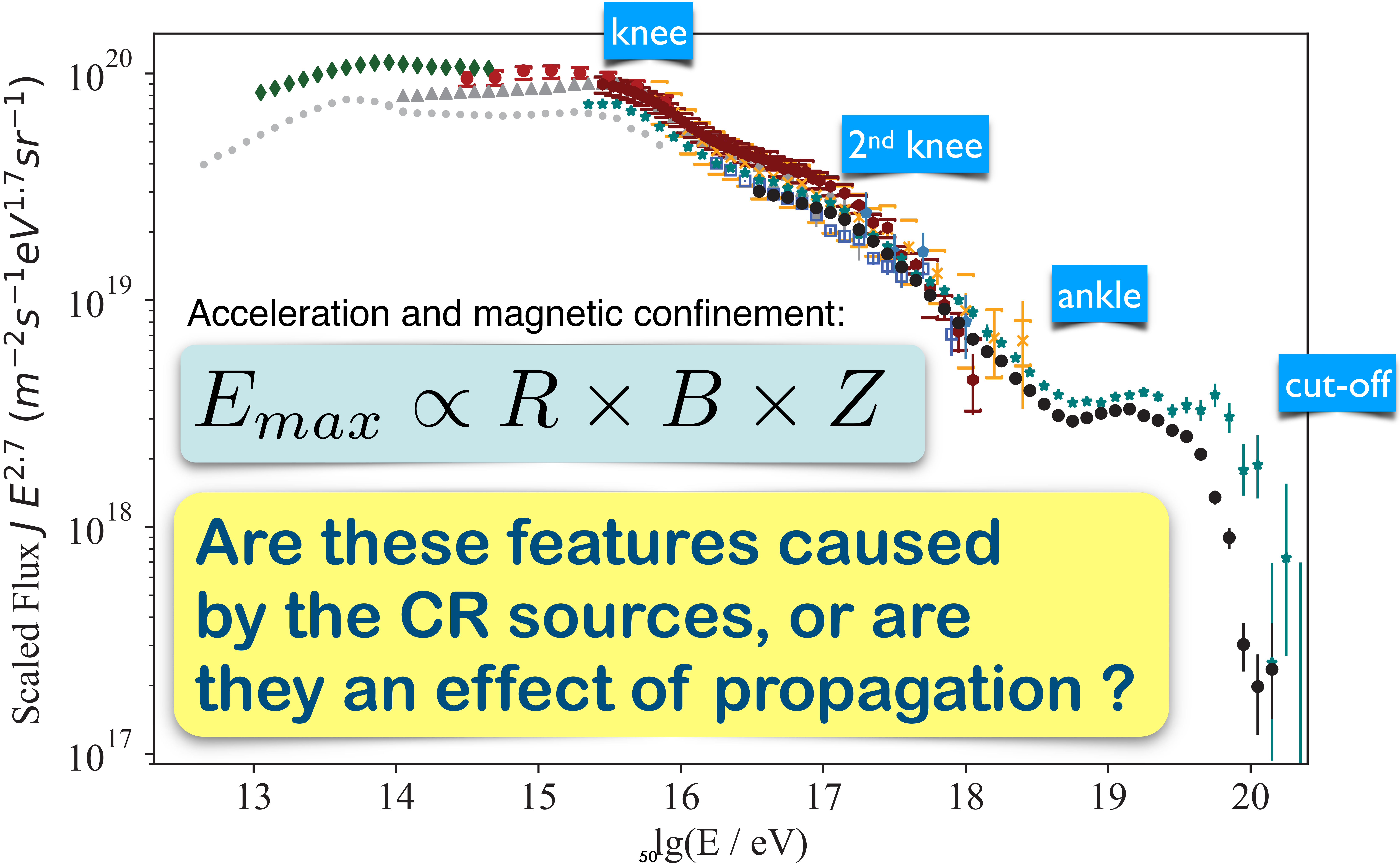


CR all-particle spectrum



F. Schröder, ICRC2019

Features of the CR spectrum



Acceleration and magnetic confinement:

$$E_{max} \propto R \times B \times Z$$

Are these features caused by the CR sources, or are they an effect of propagation ?

Putative

Cosmic Particle Accelerators

Supernova Remnants

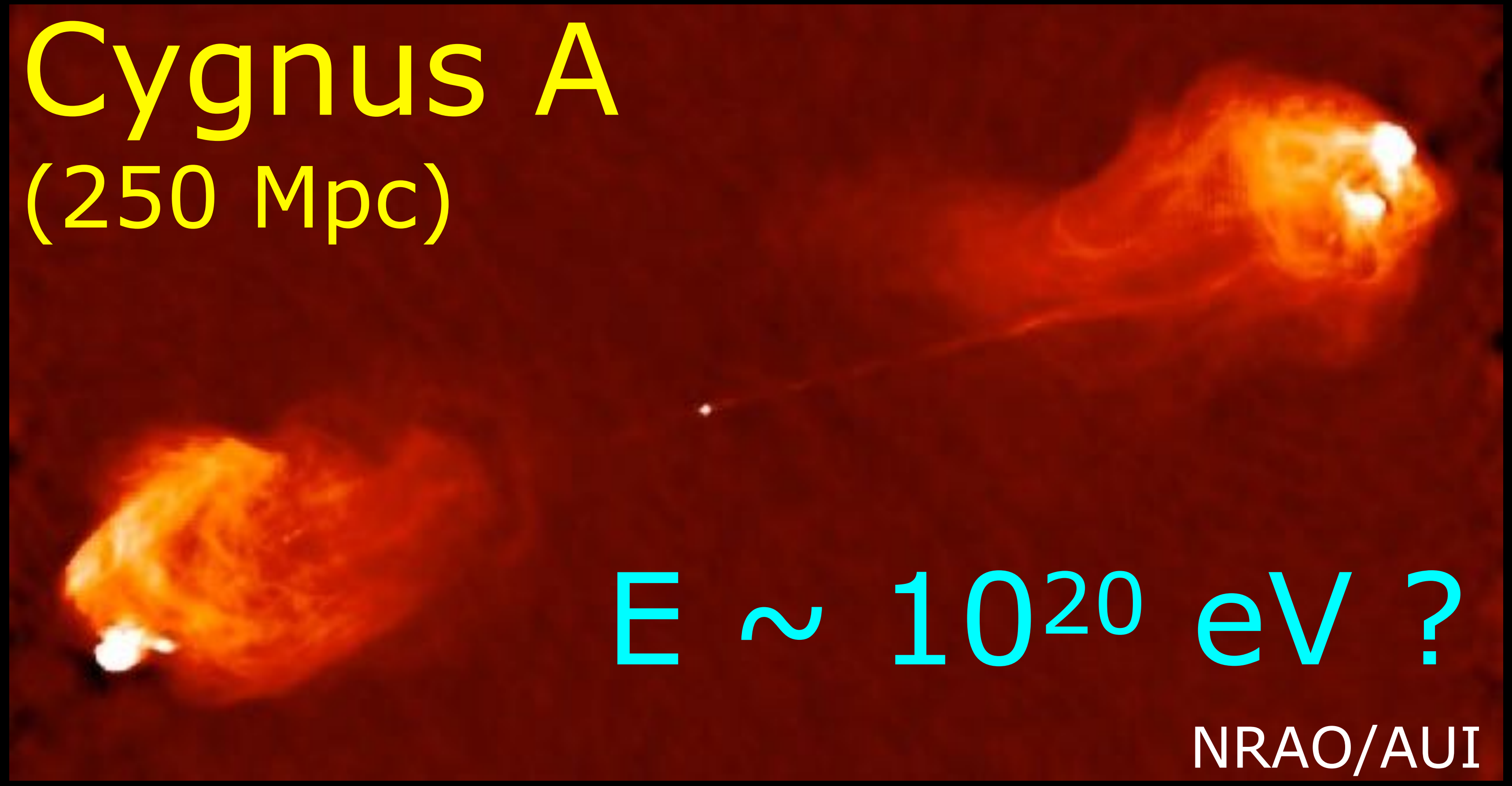
SNR509
(50 kpc)

$E < 10^{16}$ eV

X-ray (Chandra) + optical (Hubble)

particle acceleration at shock waves

AGN and their Jets/Lobes



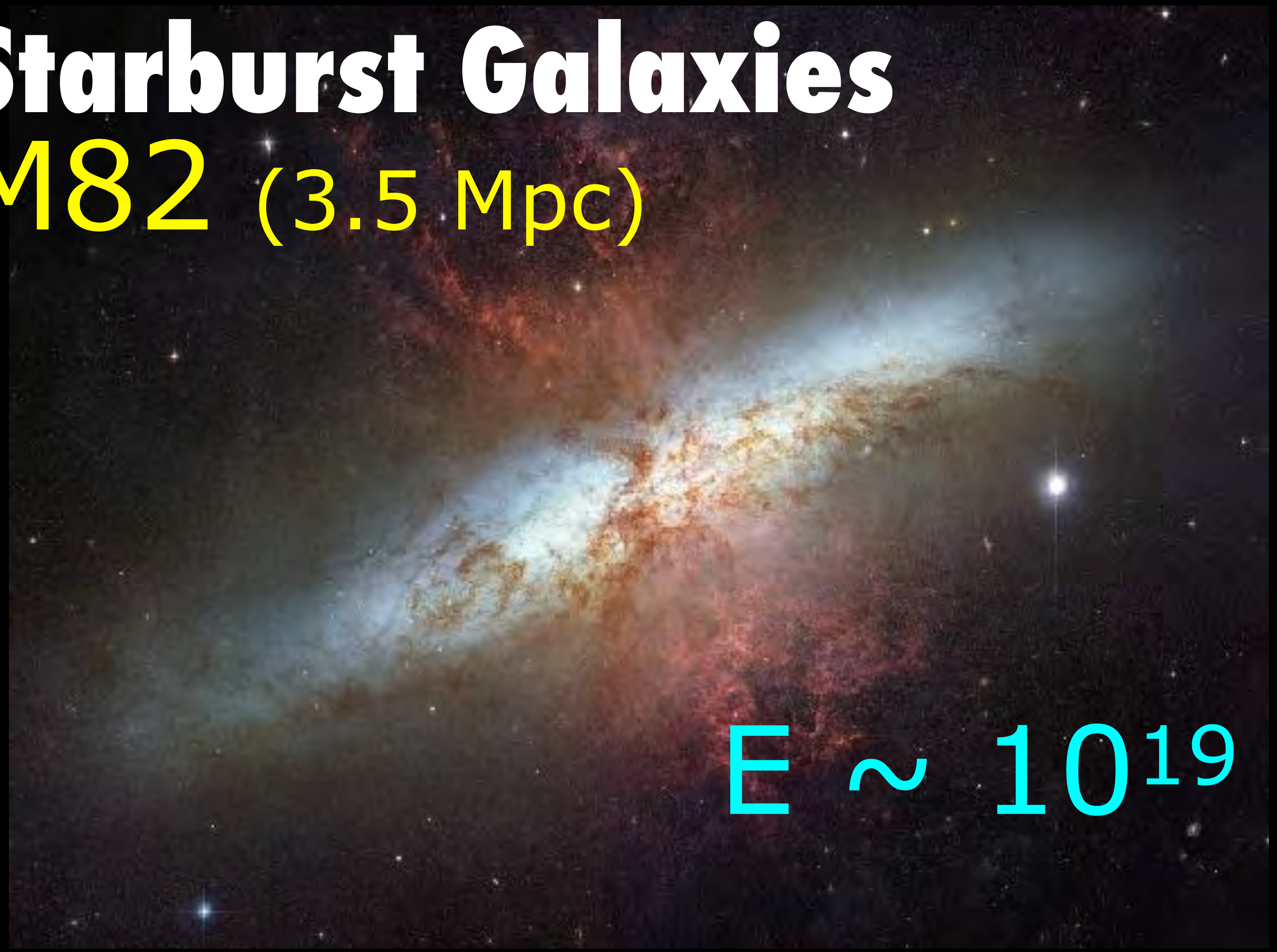
Cygnus A
(250 Mpc)

$E \sim 10^{20}$ eV ?

NRAO/AUI

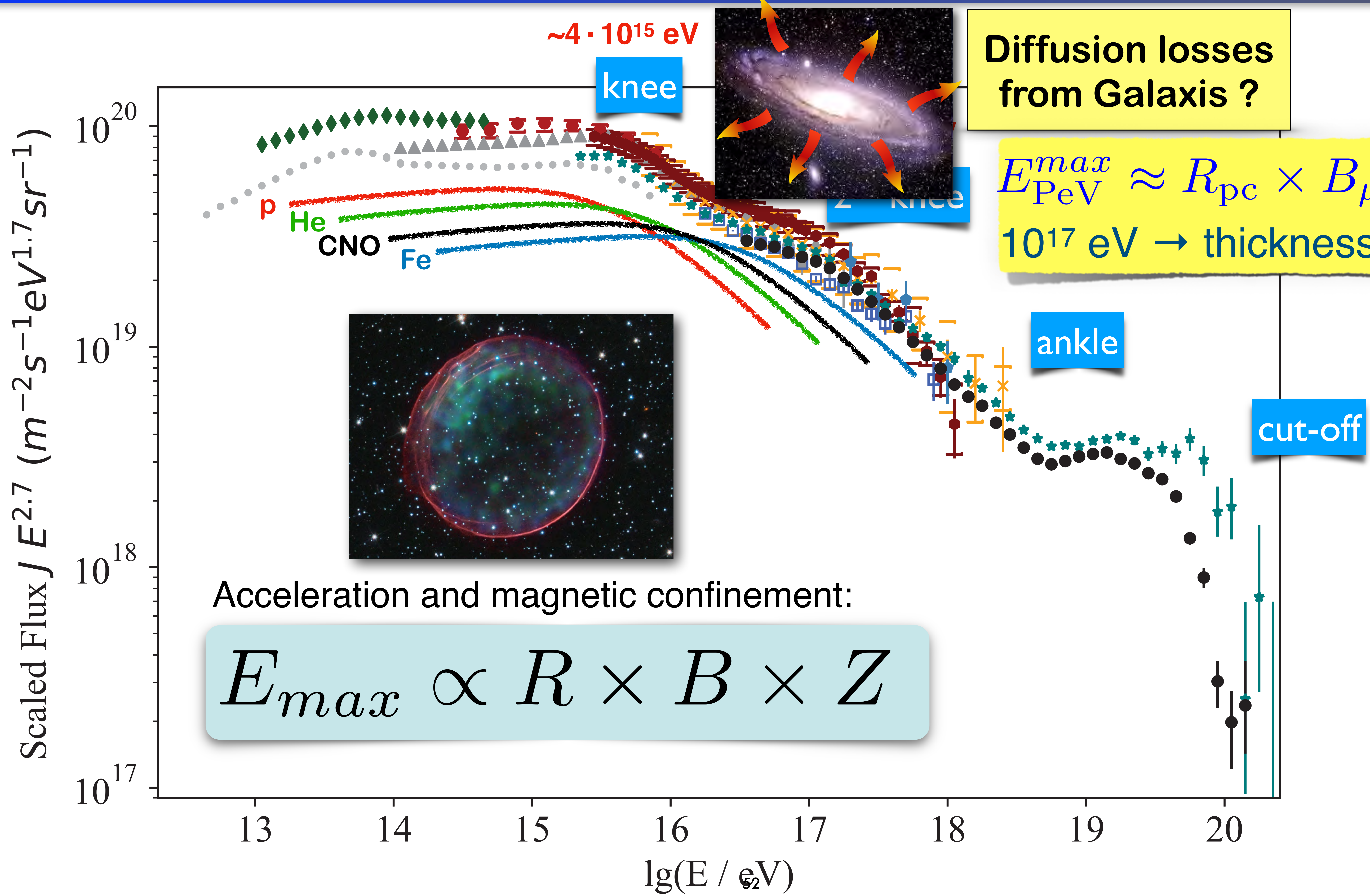
Starburst Galaxies

M82 (3.5 Mpc)



$E \sim 10^{19}$ eV ?

Features of the CR spectrum



Diffusion losses from Galaxis ?

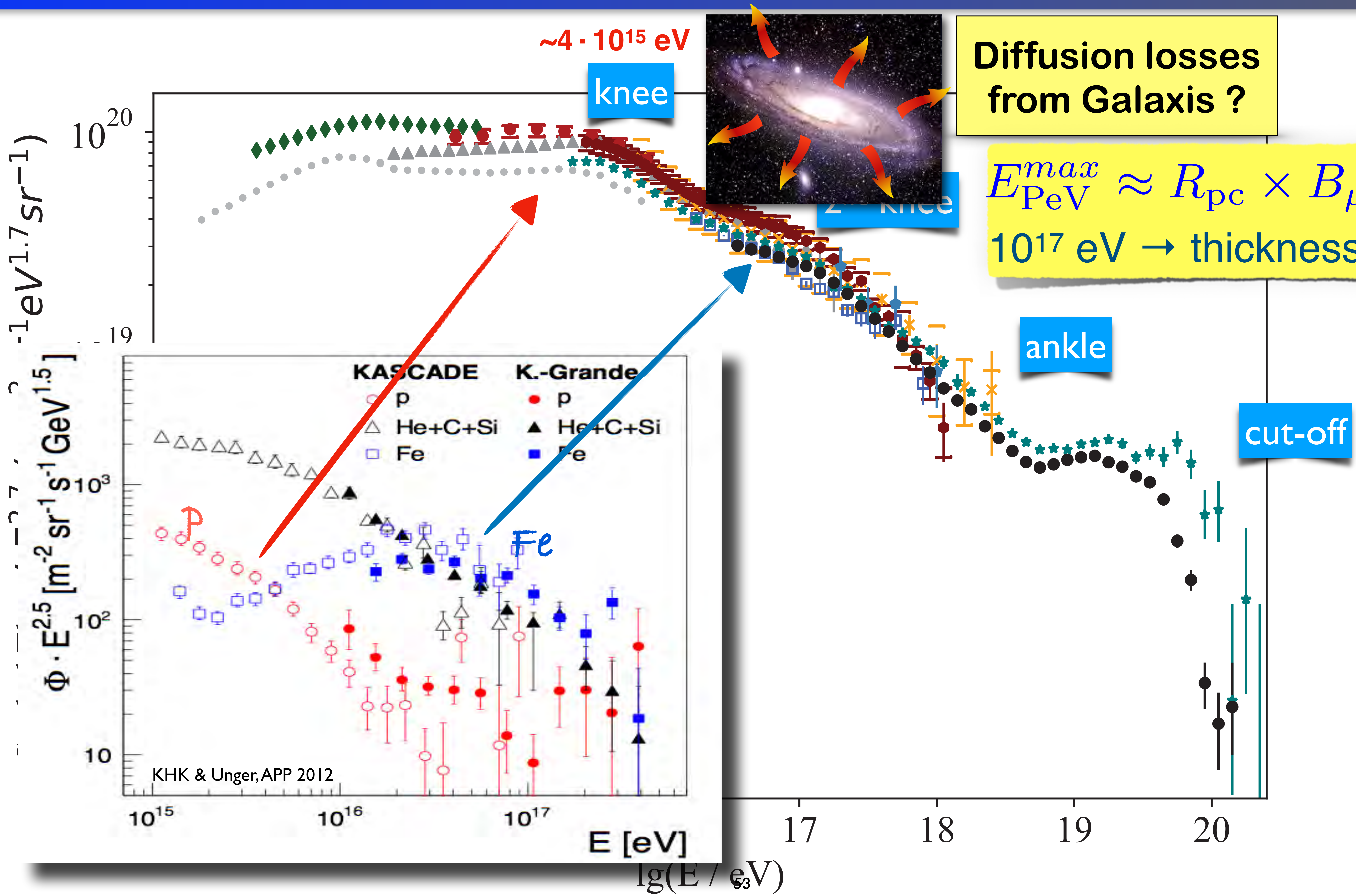
$$E^{max}_{\mathrm{PeV}} \approx R_{\mathrm{pc}} \times B_{\mu\mathrm{G}} \times Z$$

10^{17} eV → thickness gal. disk

Acceleration and magnetic confinement:

$$E_{max} \propto R \times B \times Z$$

Features of the CR spectrum

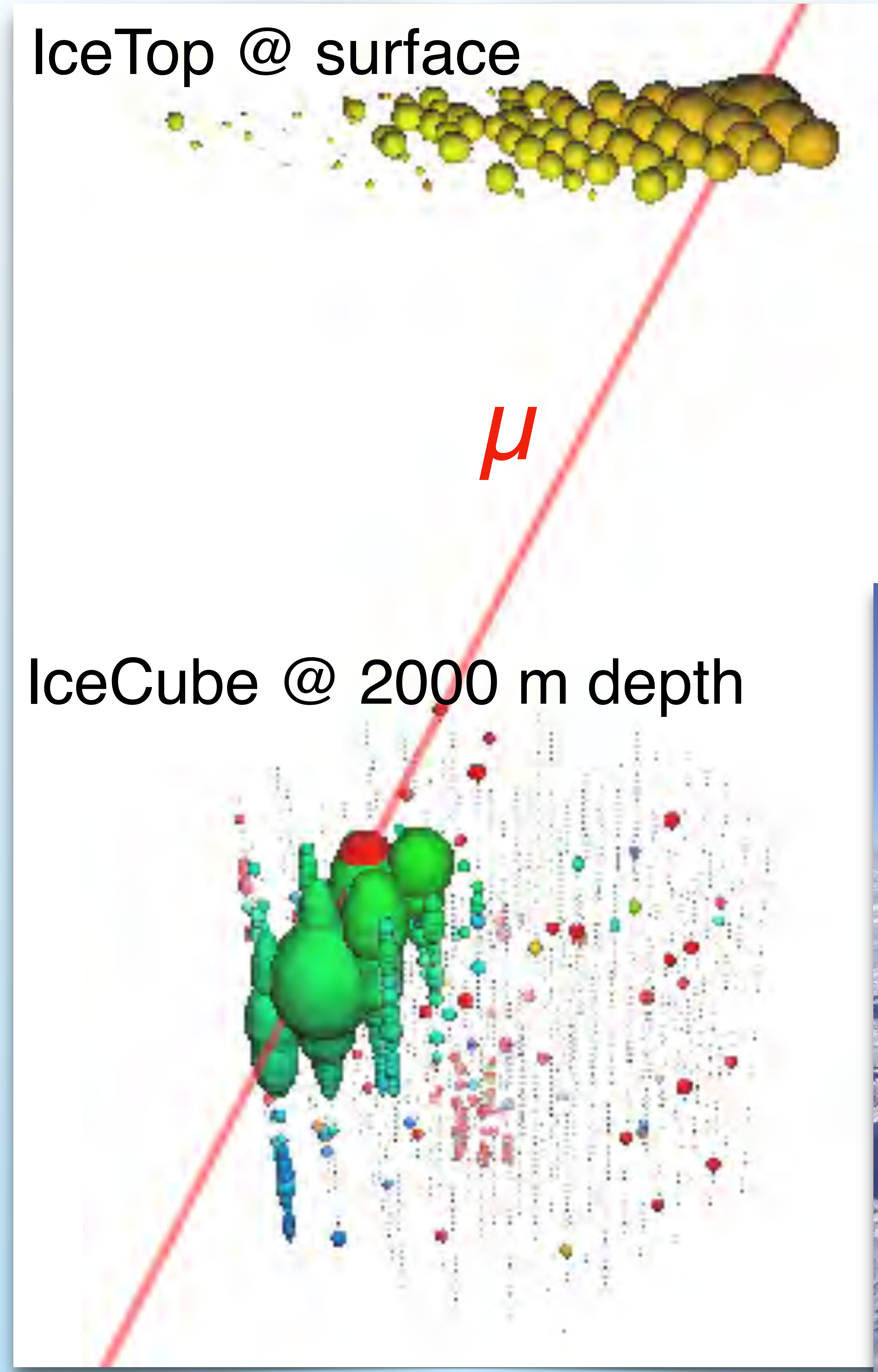


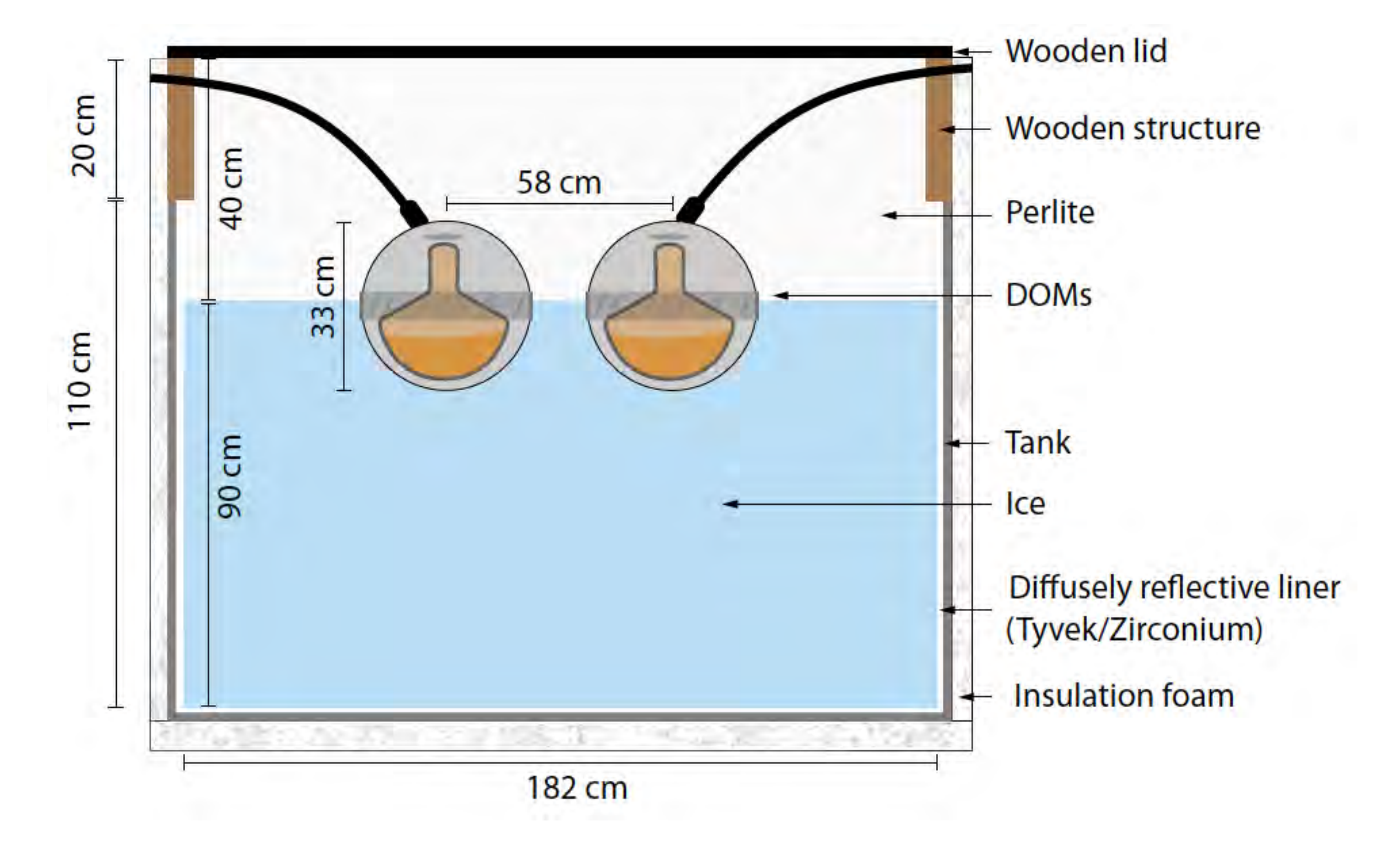
Diffusion losses from Galaxis ?

$$E_{\mathrm{PeV}}^{max} \approx R_{\mathrm{pc}} \times B_{\mu\mathrm{G}} \times Z$$

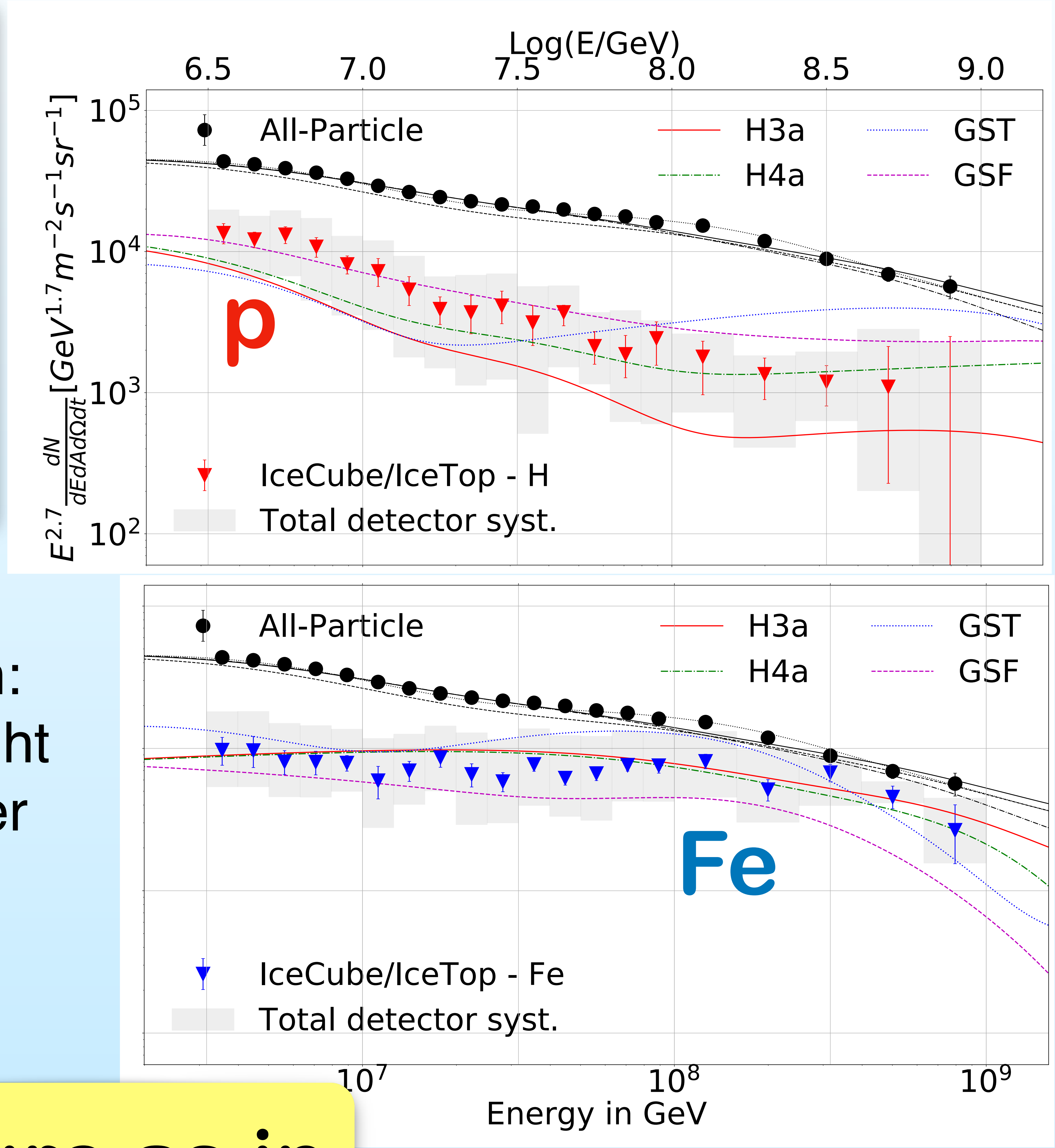
10^{17} eV → thickness gal. disk

IceTop at South Pole





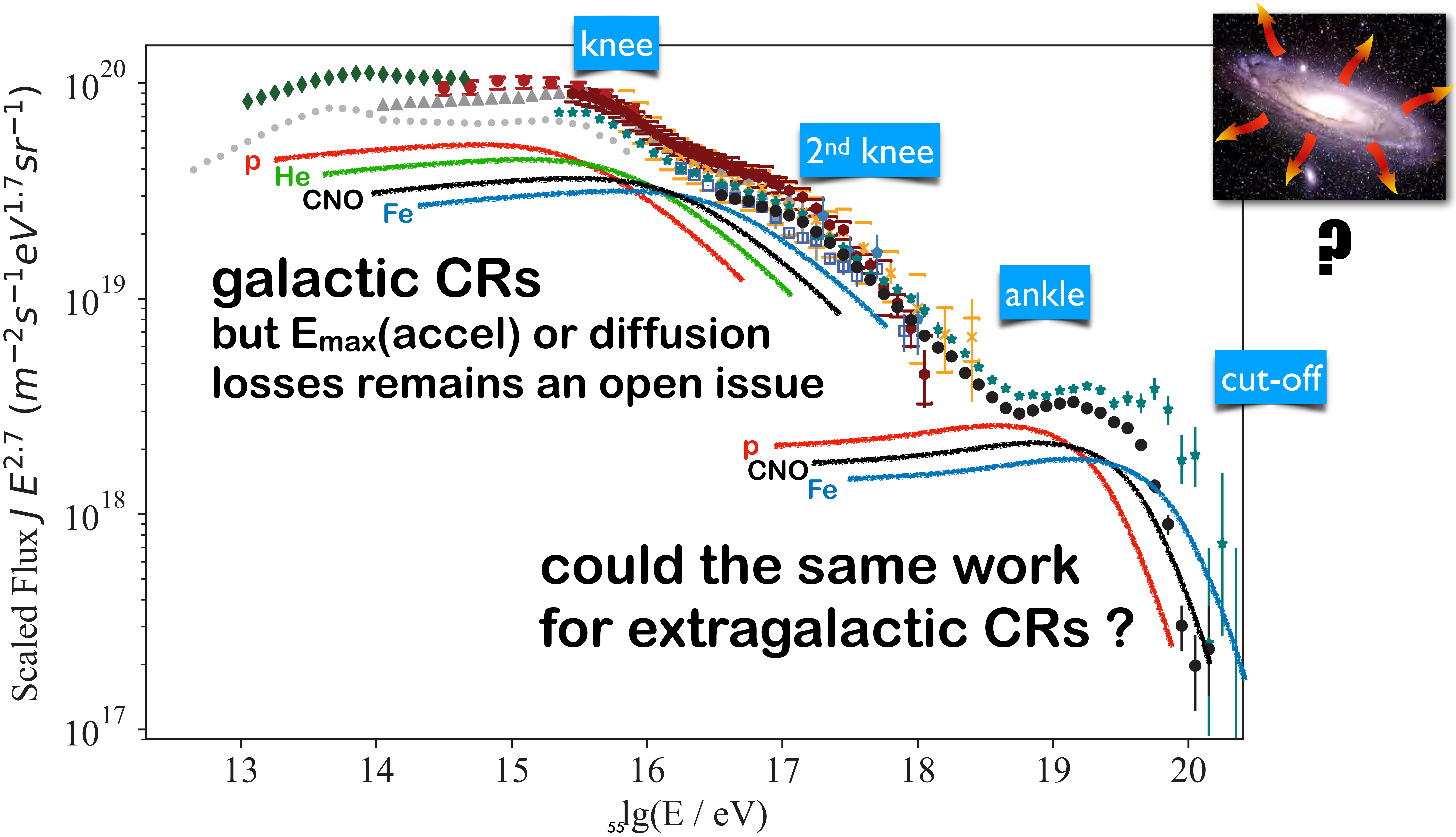
IceTop station:
Cherenkov light
in frozen water



D. Soldin @ ICRC2019

Same feature as in KASCADE-Grande

Features of the CR spectrum

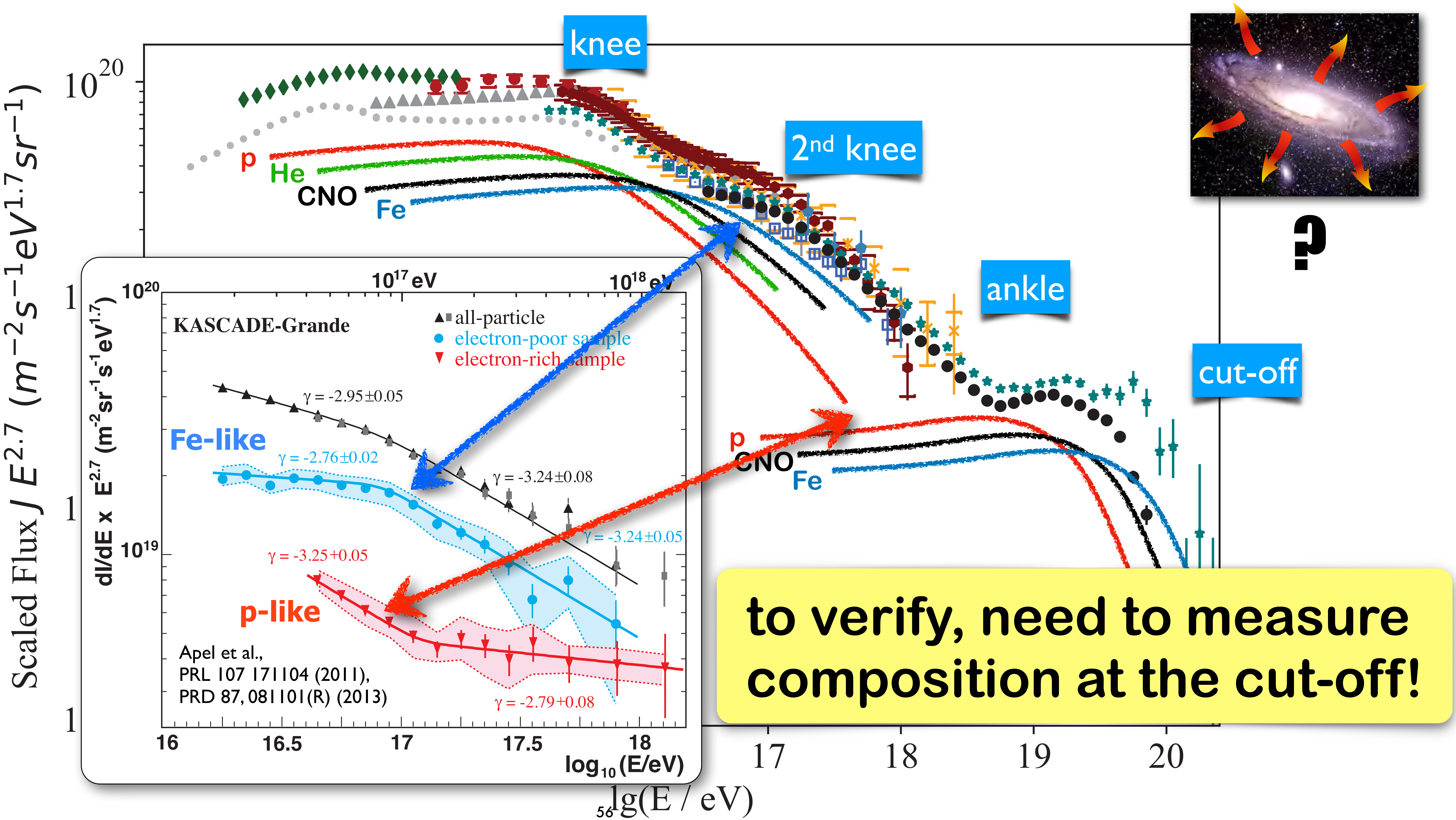


galactic CRs

but E_{max}(accel) or diffusion losses remains an open issue

could the same work for extragalactic CRs ?

Features of the CR spectrum



Apel et al.,
PRL 107 171104 (2011),
PRD 87, 081101(R) (2013)

to verify, need to measure composition at the cut-off!

Menu…

3) Detection of E>10^{14} eV: Basic air shower phenomenology

4) Basic concepts and technologies of EAS experiments

5) The light and heavy knee: E_{max} of galactic accelerators?

6) The end of the CR-spectrum: E_{max} of extragalactic accelerators?

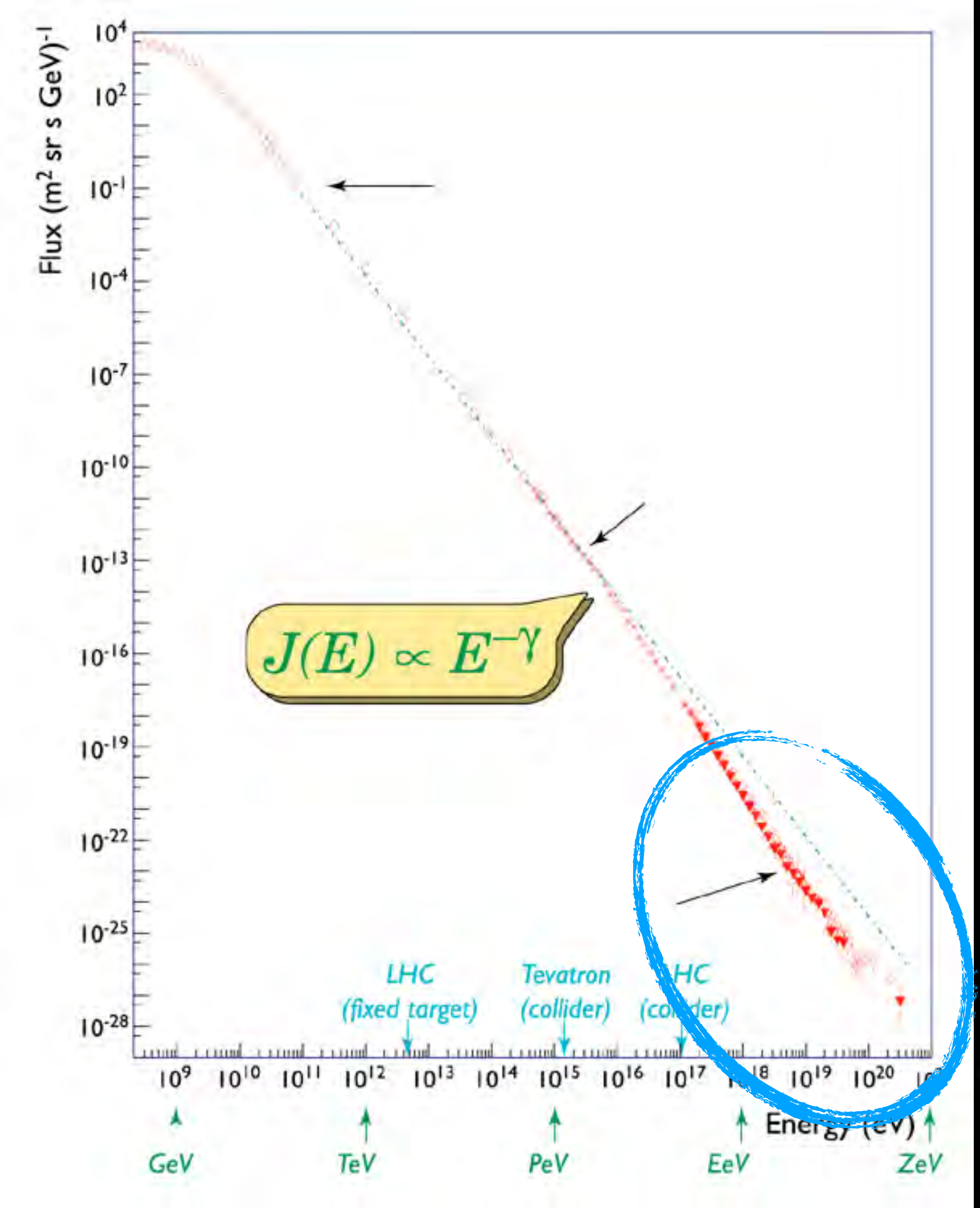
- Pierre Auger Observatory
- Telescope Array
- E-spectrum
- Propagation of UHECR
- Composition
- open issues & debates

7)

8)

9)

10)



Hybrid Detection of EAS

extremely high
energy nuclear
collisions

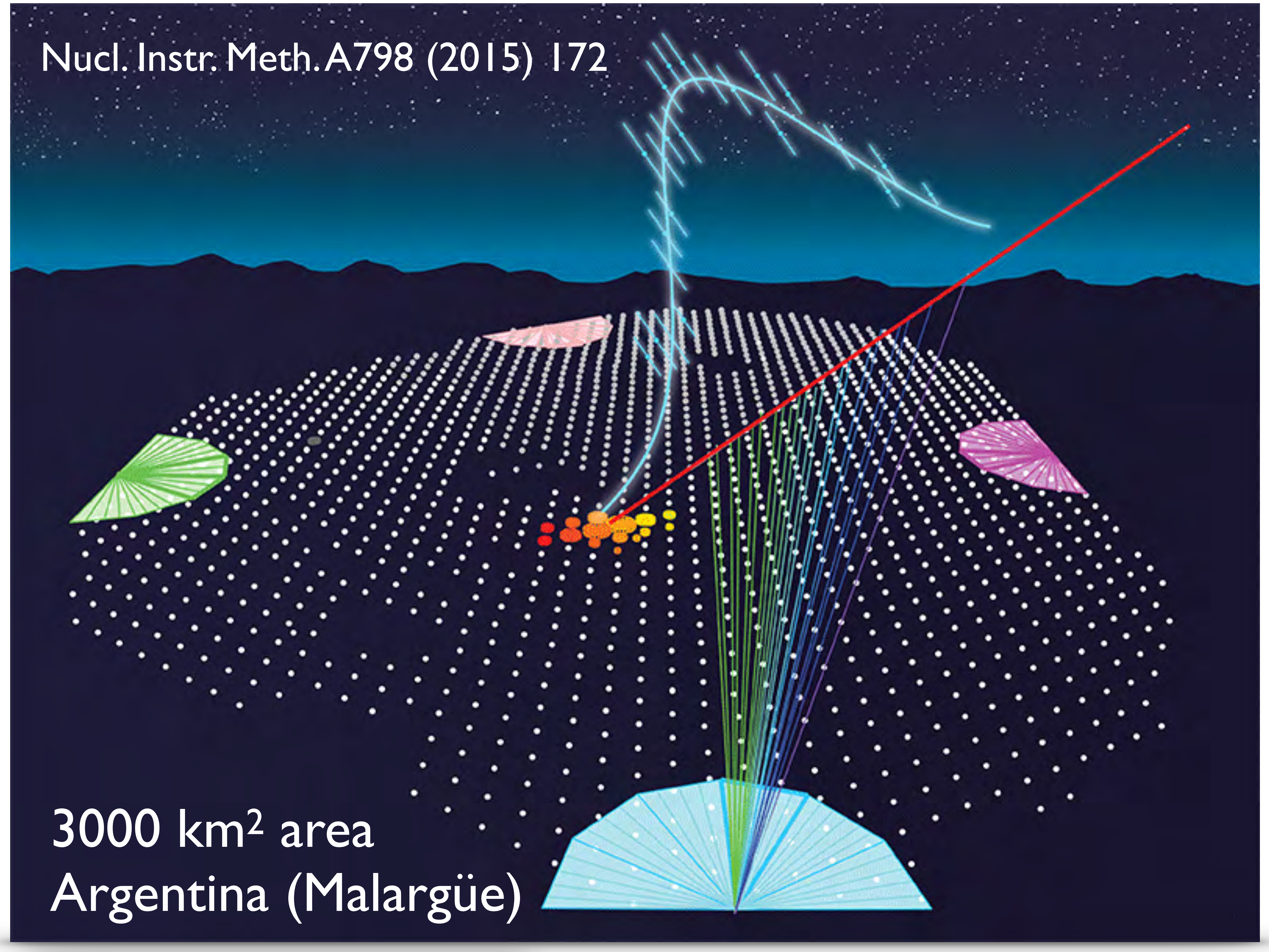
Primary particles initiate
an extensive air shower

light trace
at night-sky
(calorimetric)

Fluorescence Light

Particle Footprint at Ground

Hybrid Detection of UHECR: Pierre Auger Observatory



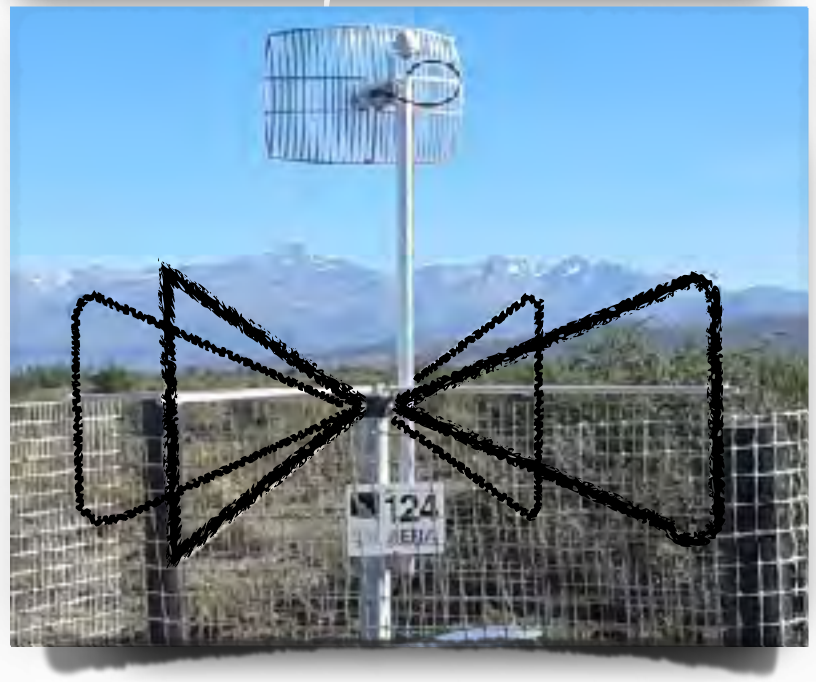
Nucl. Instr. Meth. A798 (2015) 172

3000 km^2 area
Argentina (Malargüe)

- 1400 m altitude
- 35° S, 69° W

- 27 Telescopes to measure light trace of EAS in atmosphere
- integrated light intensity → CR energy
- 13% duty cycle

- 1660 Water Cherenkov detectors on 1.5 km grid to measure footprint of particles at ground
- 100% duty cycle
- cross calibrated with FD-telescopes with hybrid events

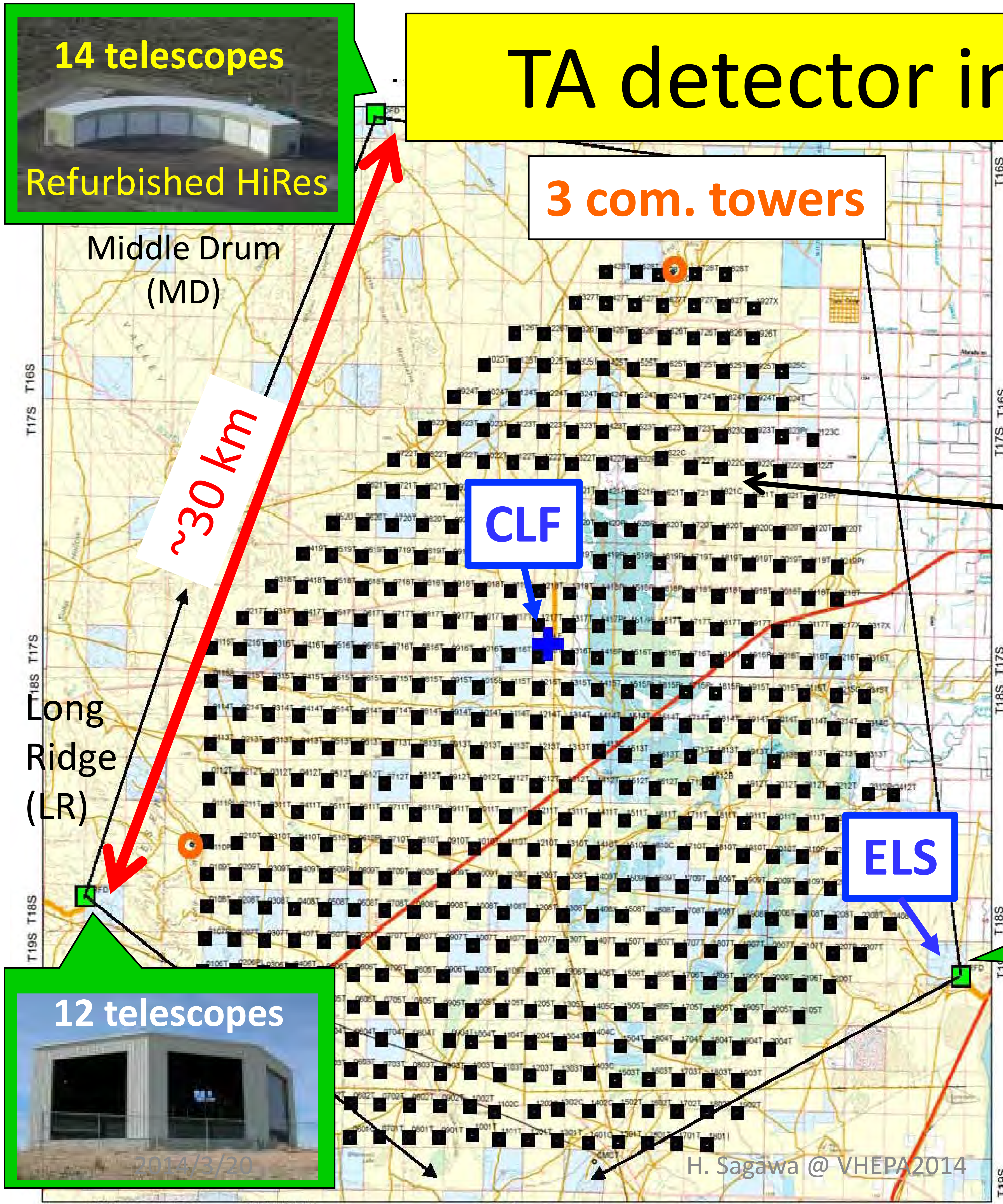


- 153 radio antennas for em-radiated energy
- 18 km^2 area
- 100% duty cycle

Central campus with visitors center

TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

~700 km^2

Fluorescence Detector(FD)

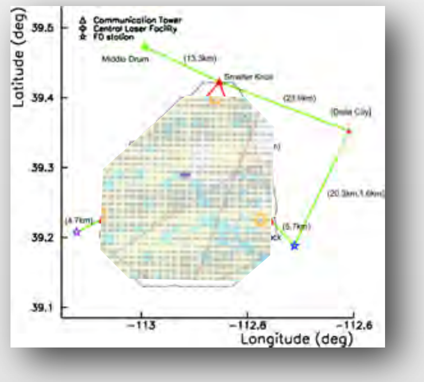
3 stations

38 telescopes

FD and SD: fully operational since 2008/May

Auger and TA

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

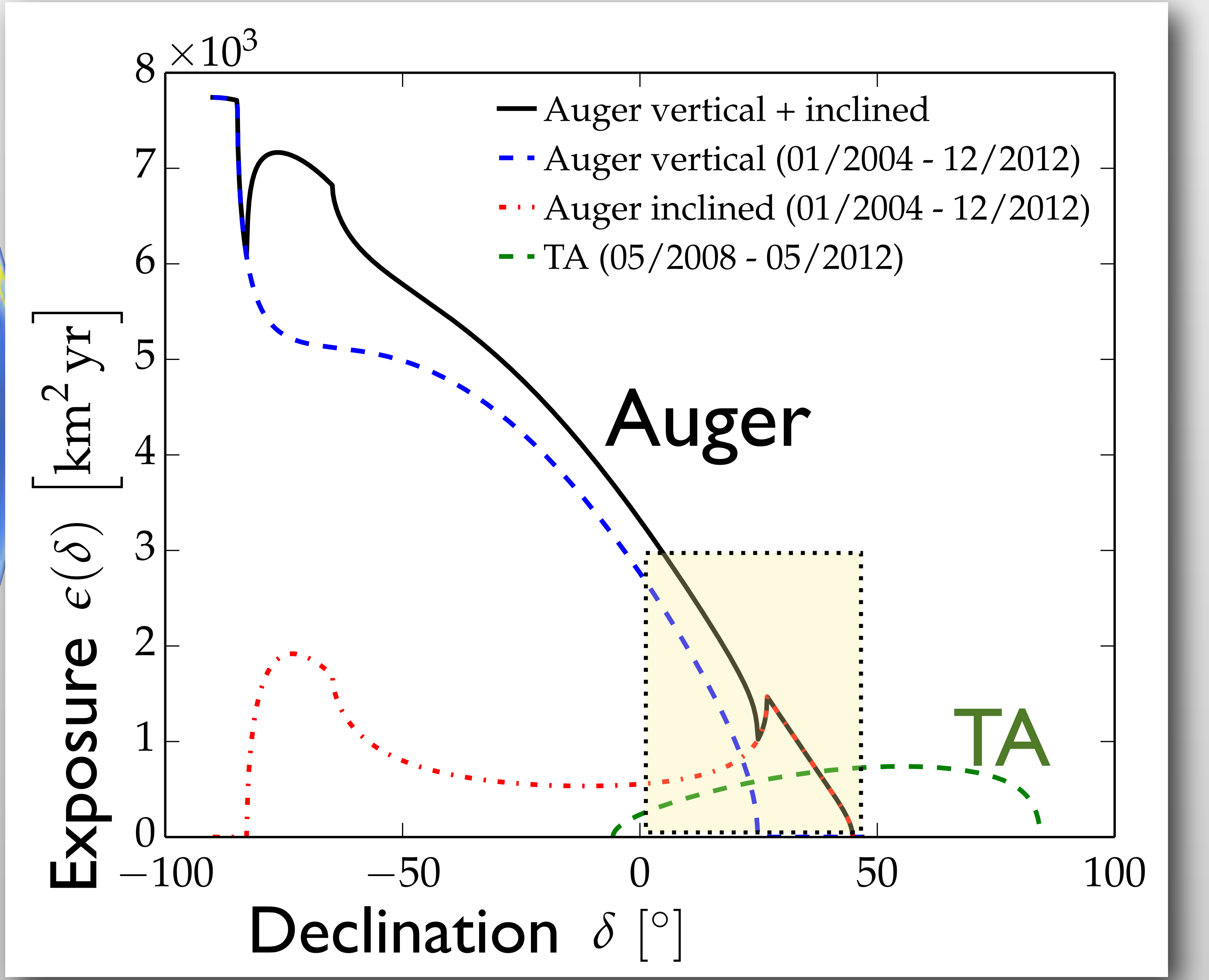


same scale

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

Auger and TA can see the same sky

Auger: started 01/2004
TA: started 05/2008

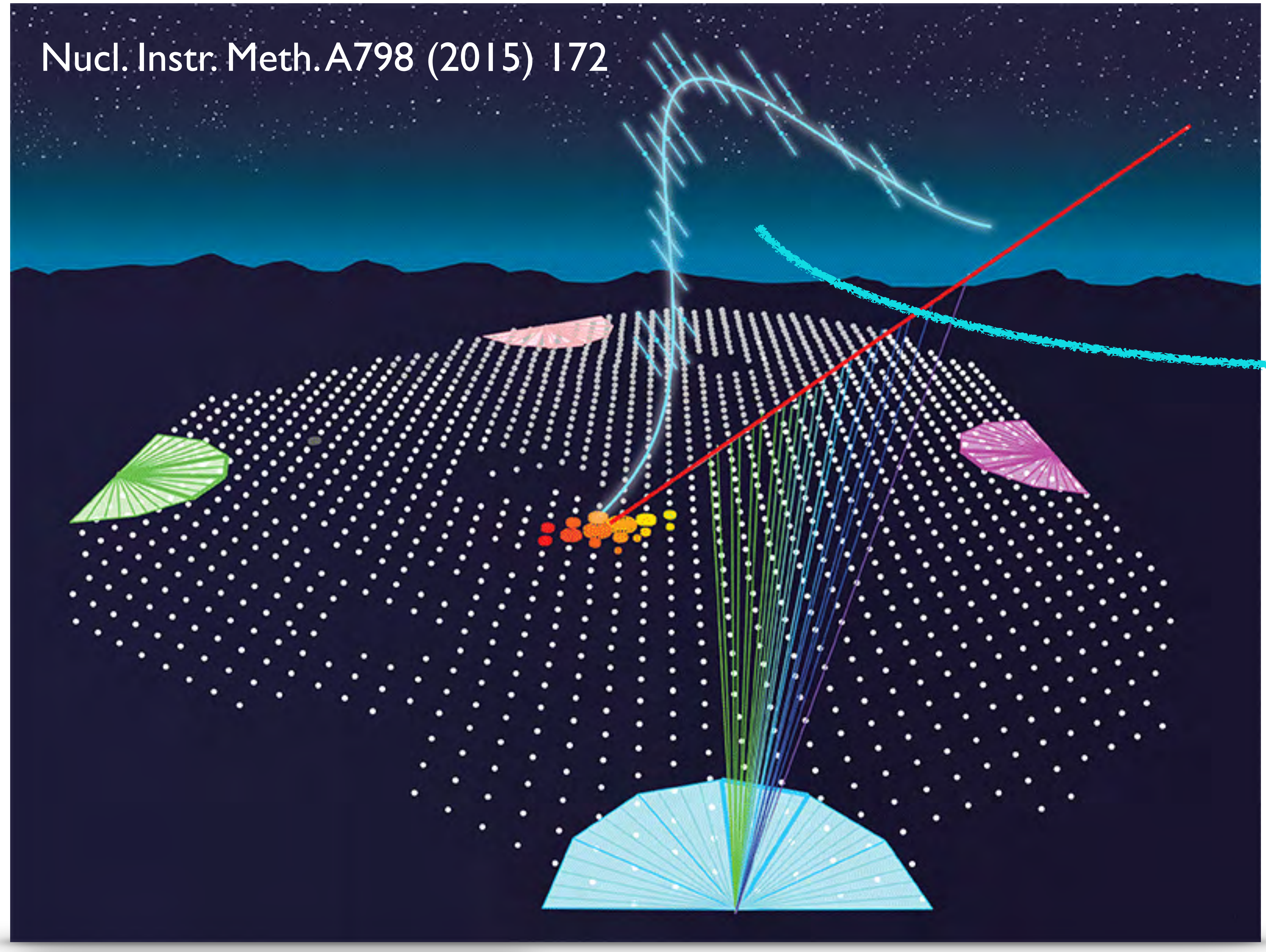


Auger exposure ~8 times that of TA

A quadruple event

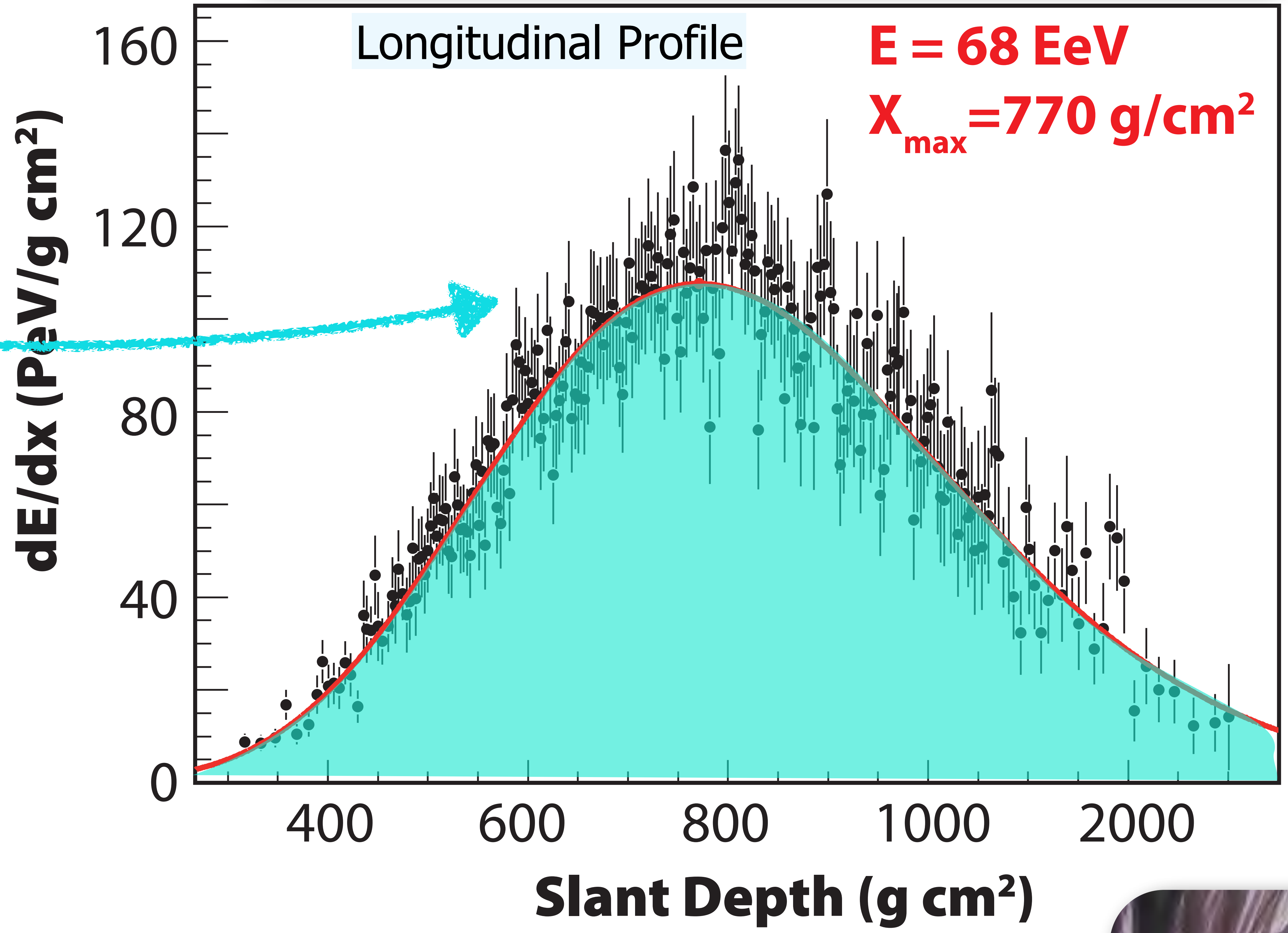
4 Telescopes + 20 km2 Footprint

Calibrating the Primary Energy



Nucl. Instr. Meth. A798 (2015) 172

absolute E-scale from light intensity

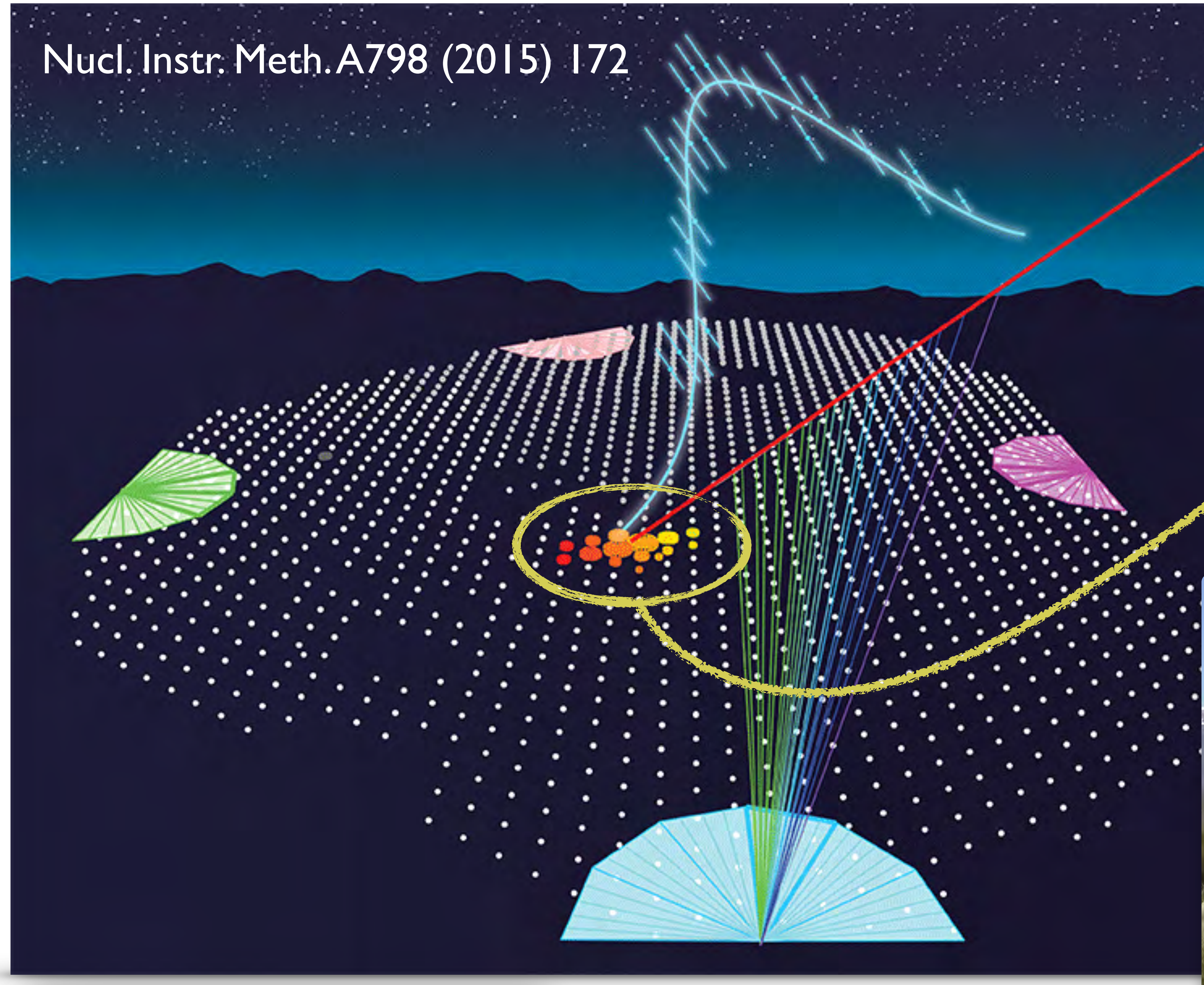


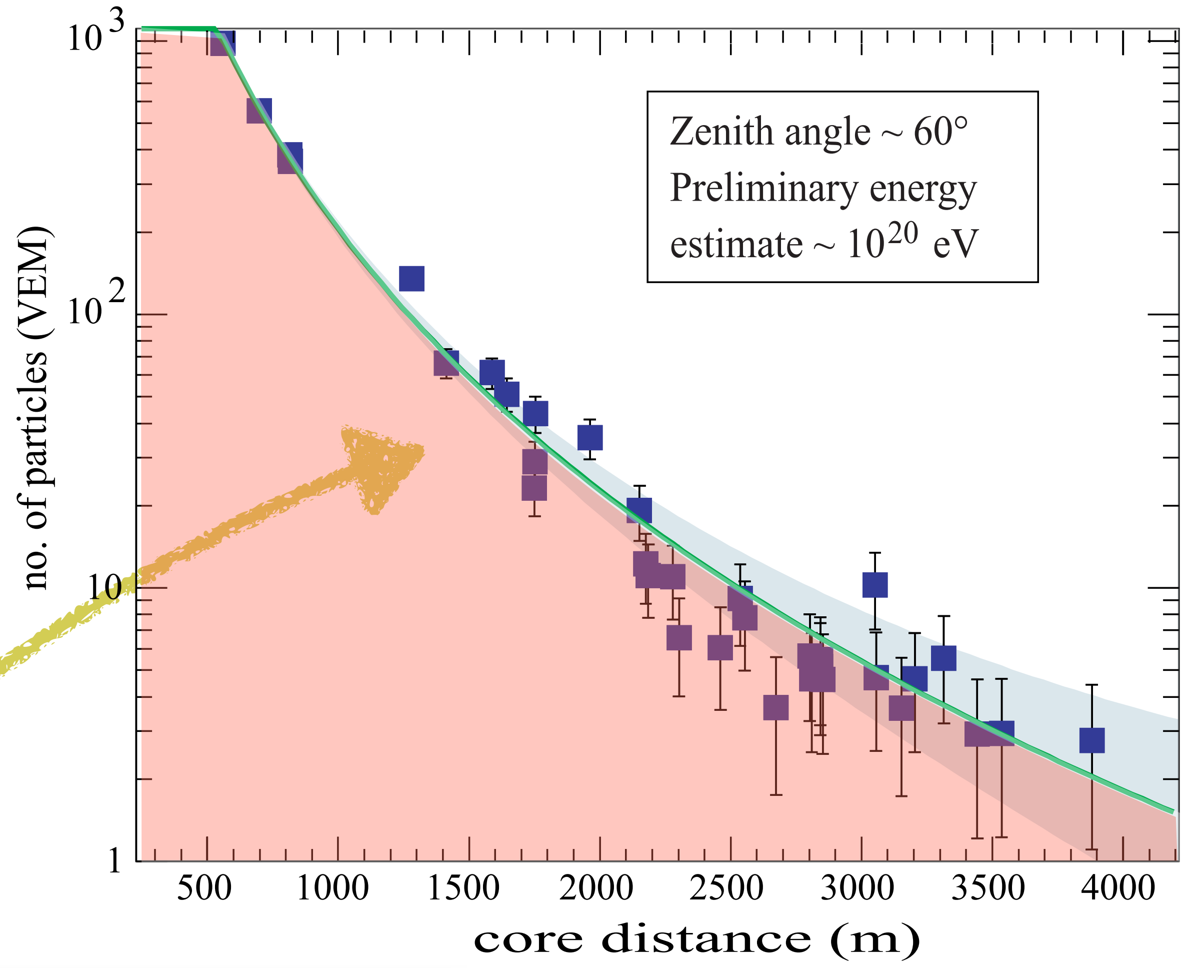
$$E_{cr} = \int \varepsilon_\gamma \frac{dN_\gamma}{dx} dx = \int \frac{dE}{dx} dx$$

fluorescence yield

Central campus with visitors center

Calibrating the Primary Energy

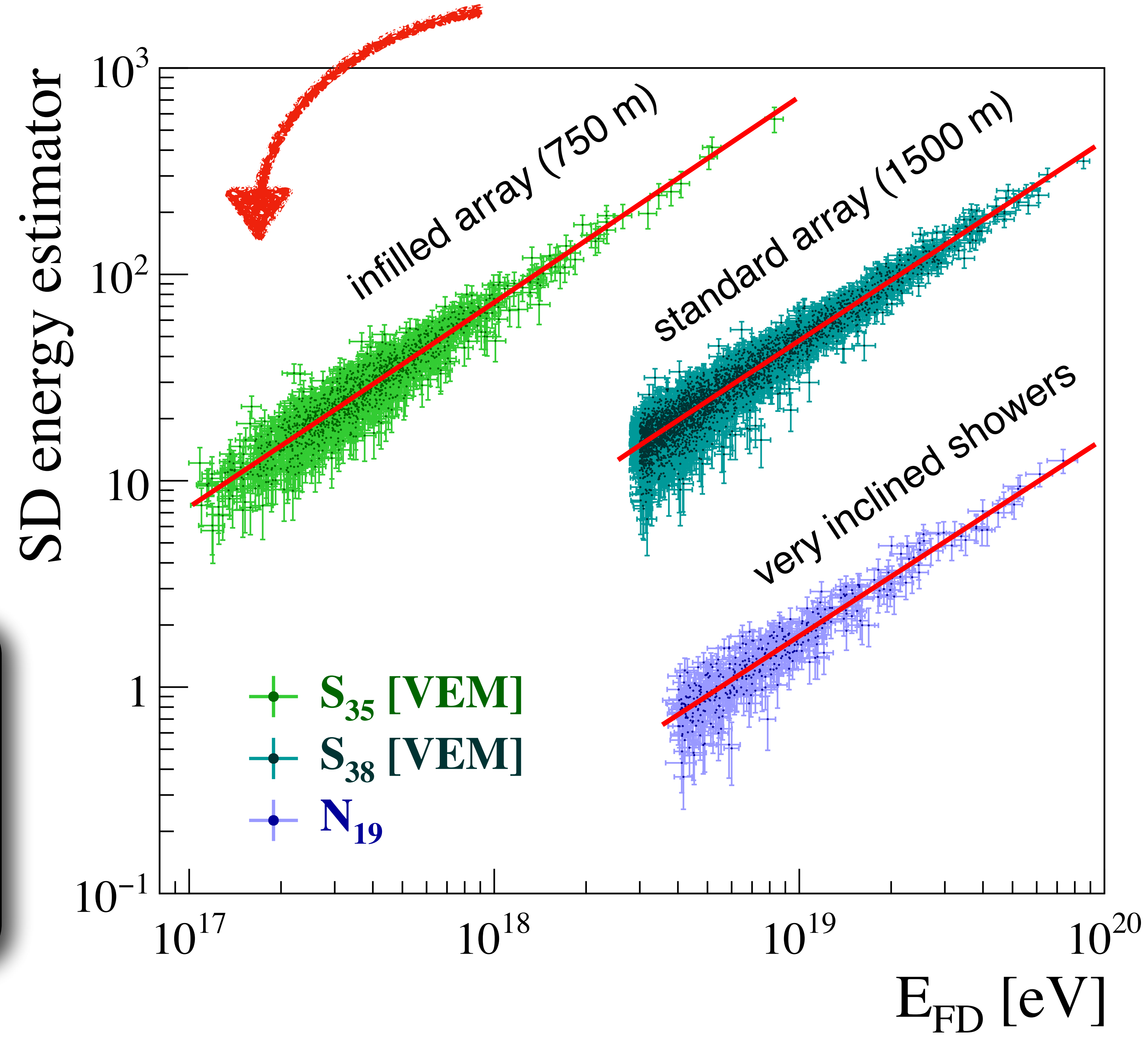

Nucl. Instr. Meth. A798 (2015) 172



Fit of particle density as a fct of distance from shower core → ρ(r)

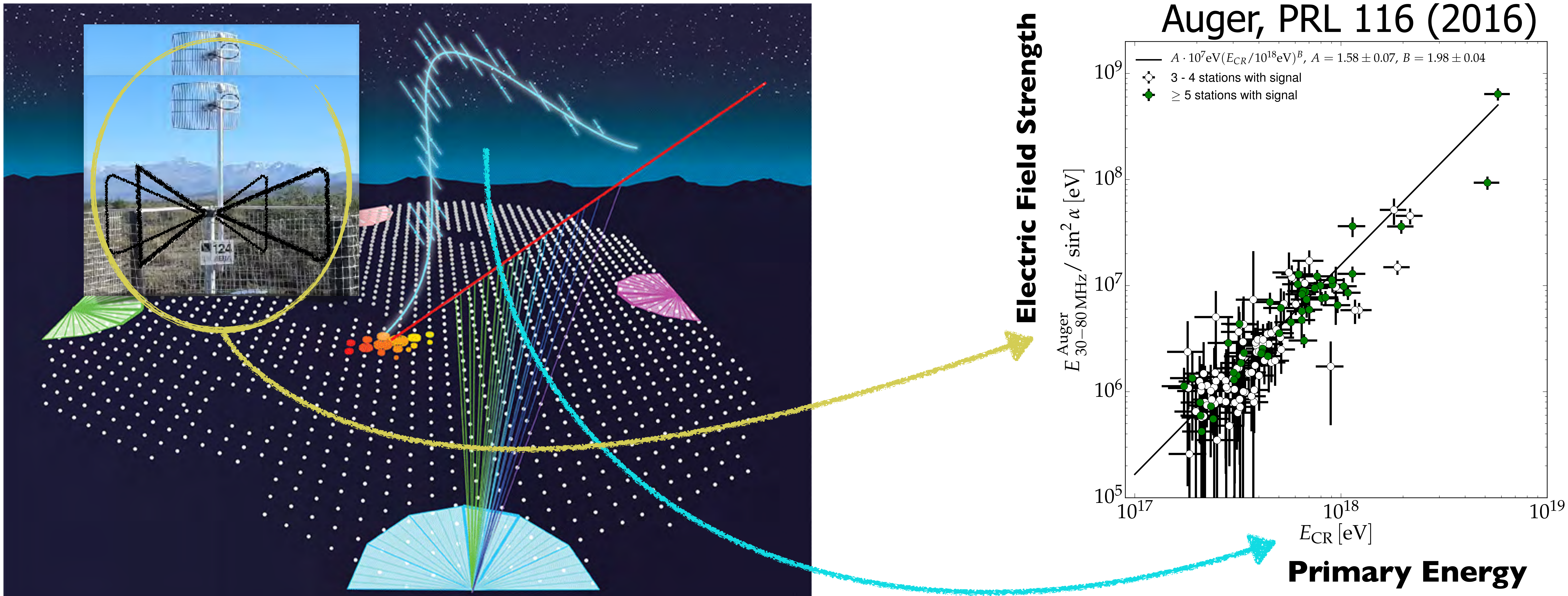
$$S_{tot} = \int 2\pi r \rho(r) dr$$

Normalise S_{tot} to specific zenith angle → S_{38}, etc



Note, this way the surface detector array is calibrated by the fluorescence telescopes, based on lab measurements!

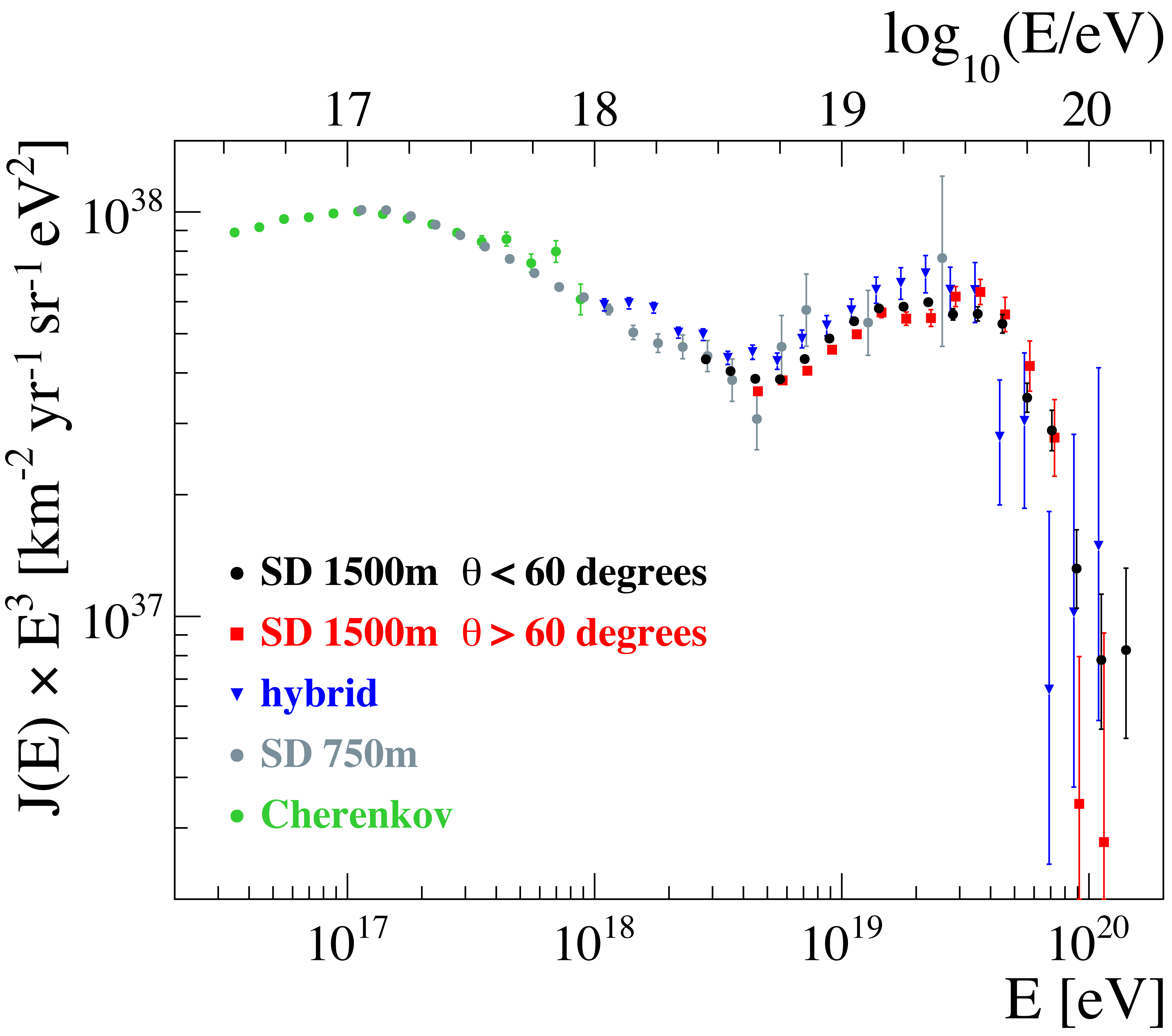
Calibrating the Primary Energy

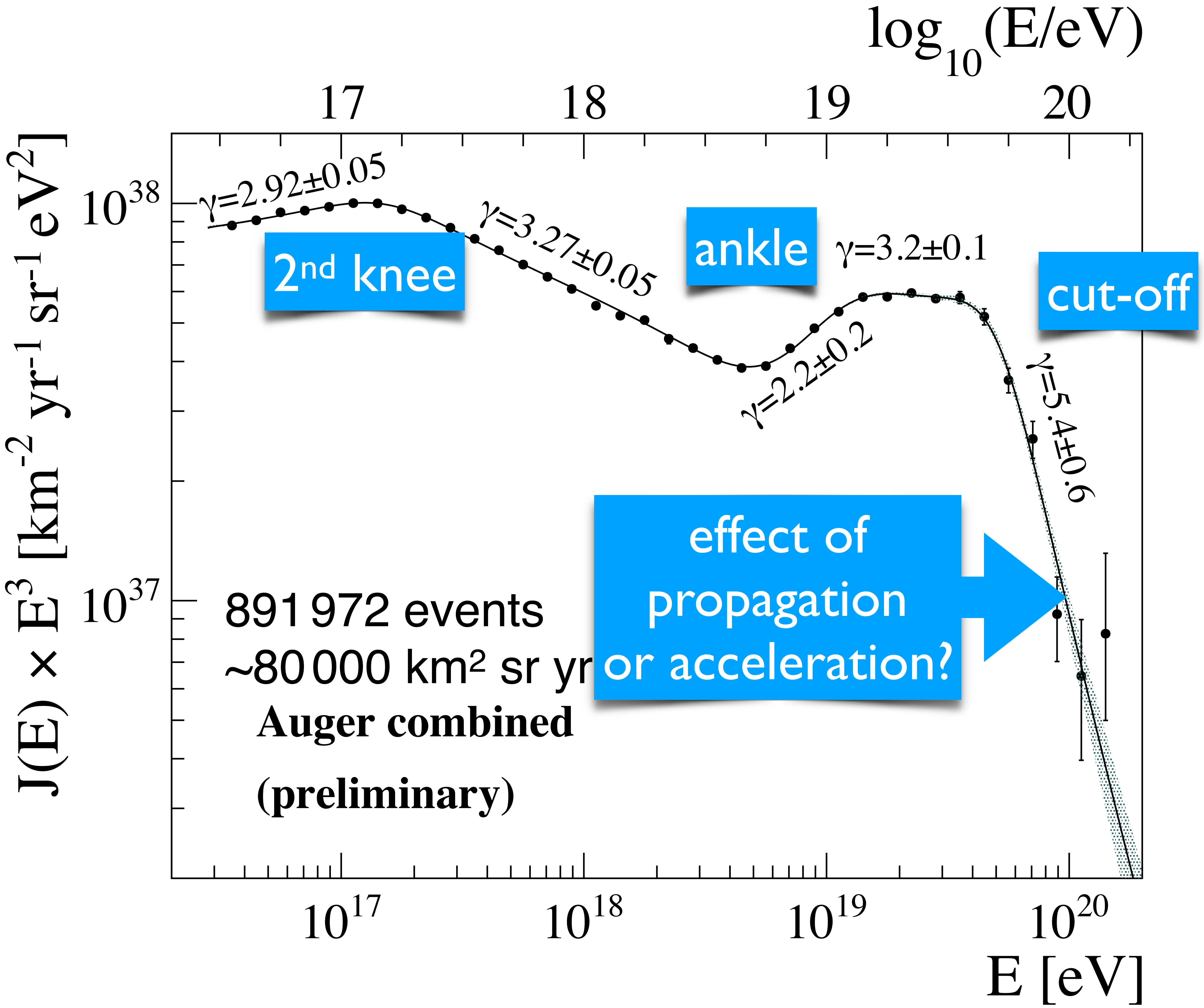


Auger, PRL 116 (2016)

Absolute calibration of radio signal:
18 MeV energy radiated in radio signal @ 1 EeV

Auger UHECR Energy Spectrum





2nd knee

ankle

cut-off

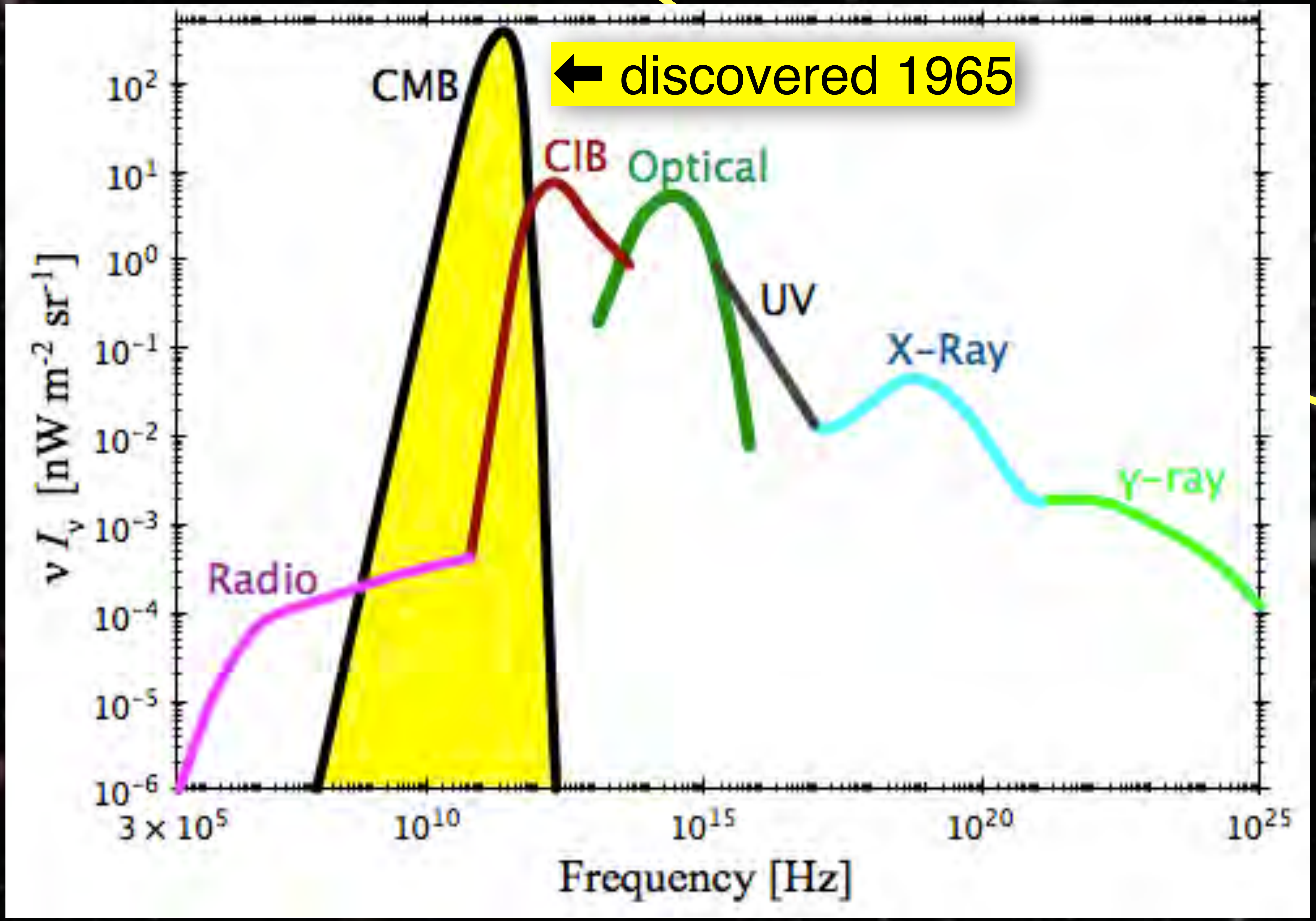
effect of propagation or acceleration?

Castellina @ ICRC2019

(

Interlude:

Intergalactic Propagation



Diffuse Extragalactic Background Radiation

CMB: 412 photons/cm^3

for comparison: ρ_H < 1 proton/m^3

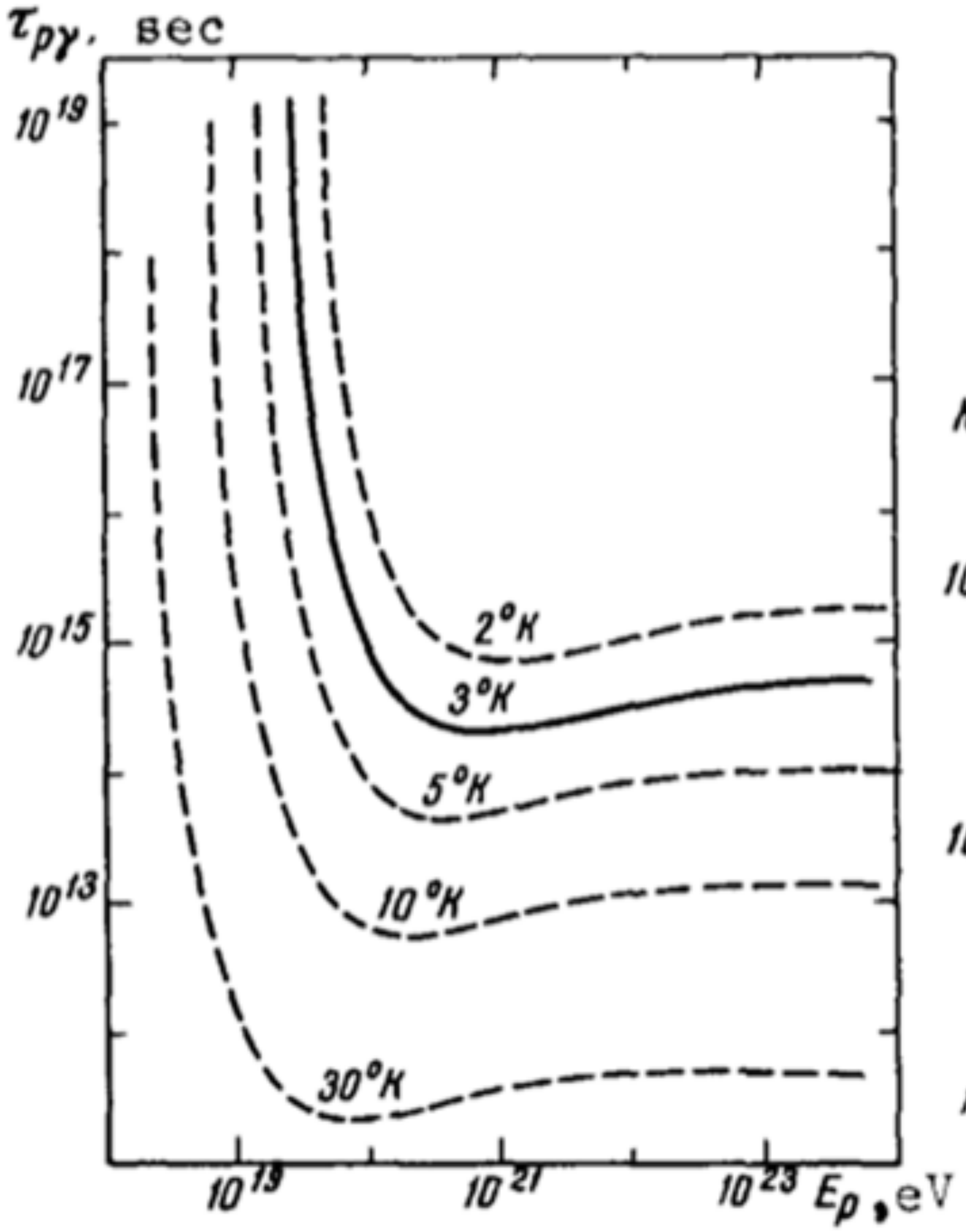
1966: „End to the CR Spectrum ?"

Greisen,
Zatsepin & Kuz'min

VOLUME 16, NUMBER 17 PHYSICAL REVIEW LETTERS 25 APRIL 1966

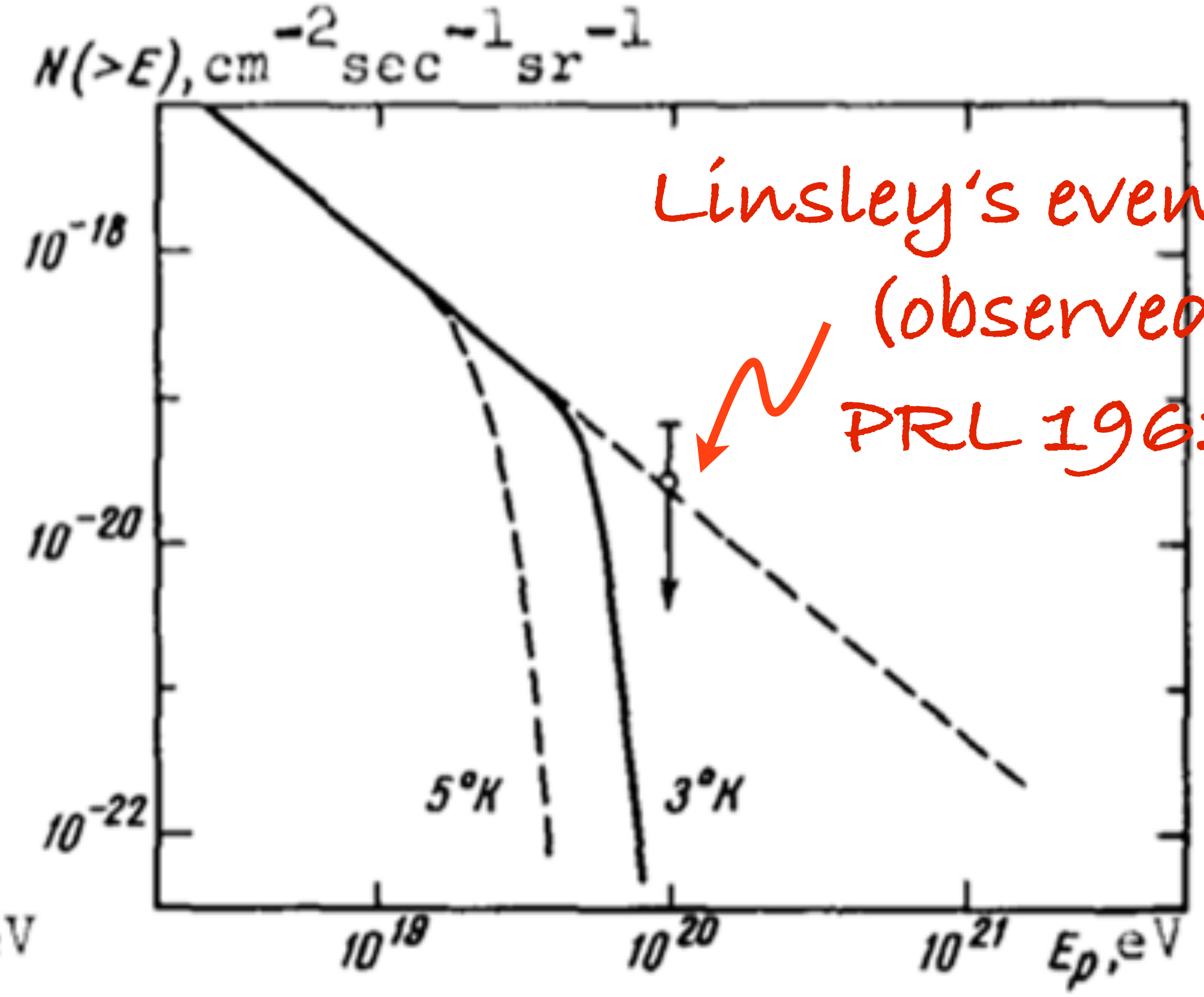
END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen
Cornell University, Ithaca, New York
(Received 1 April 1966)



UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

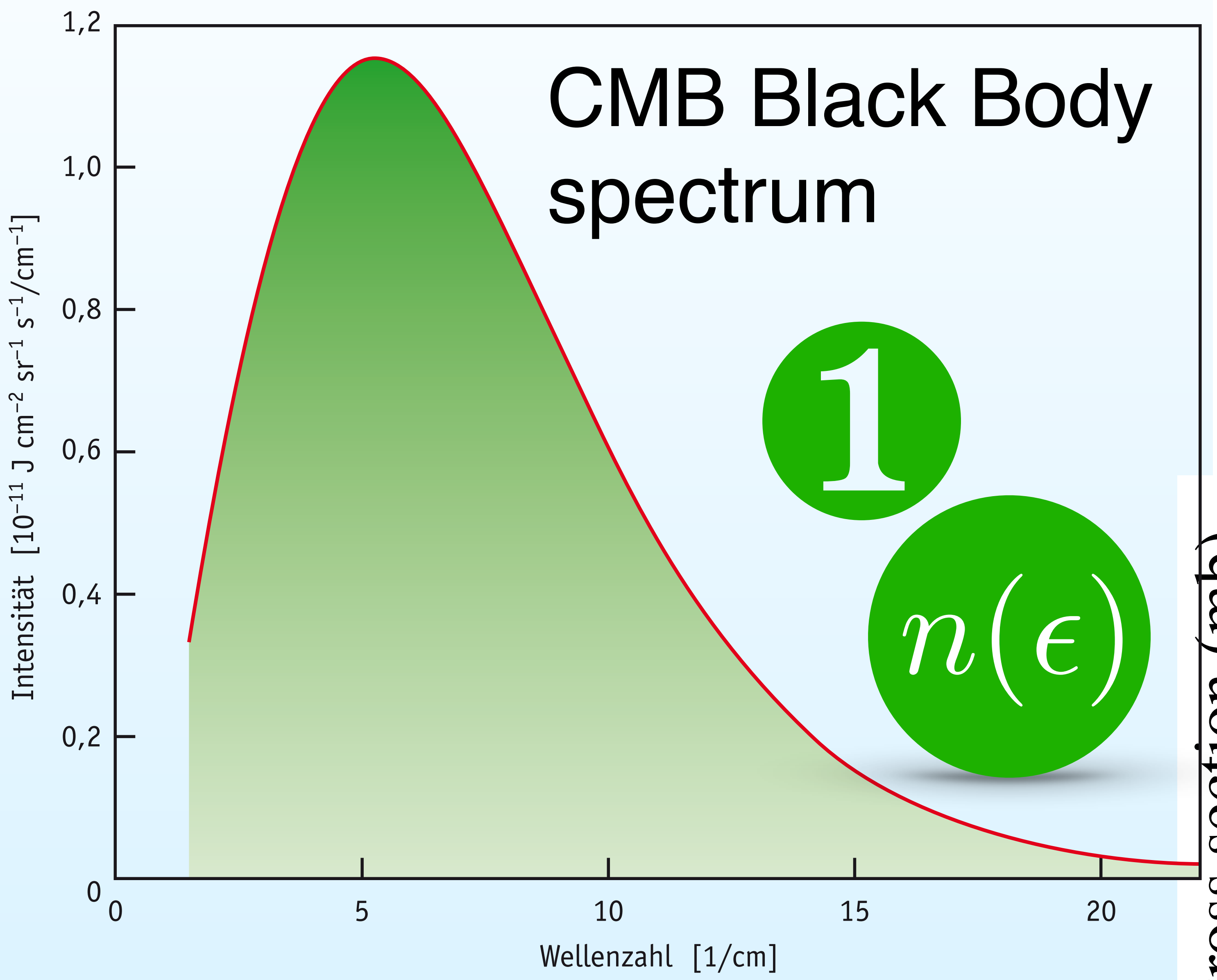
G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966



Linsley's event
(observed 1962
PRL 1963)

John Linsley @ Volcano Ranch

GZK effect for CR protons: The Two Ingredients

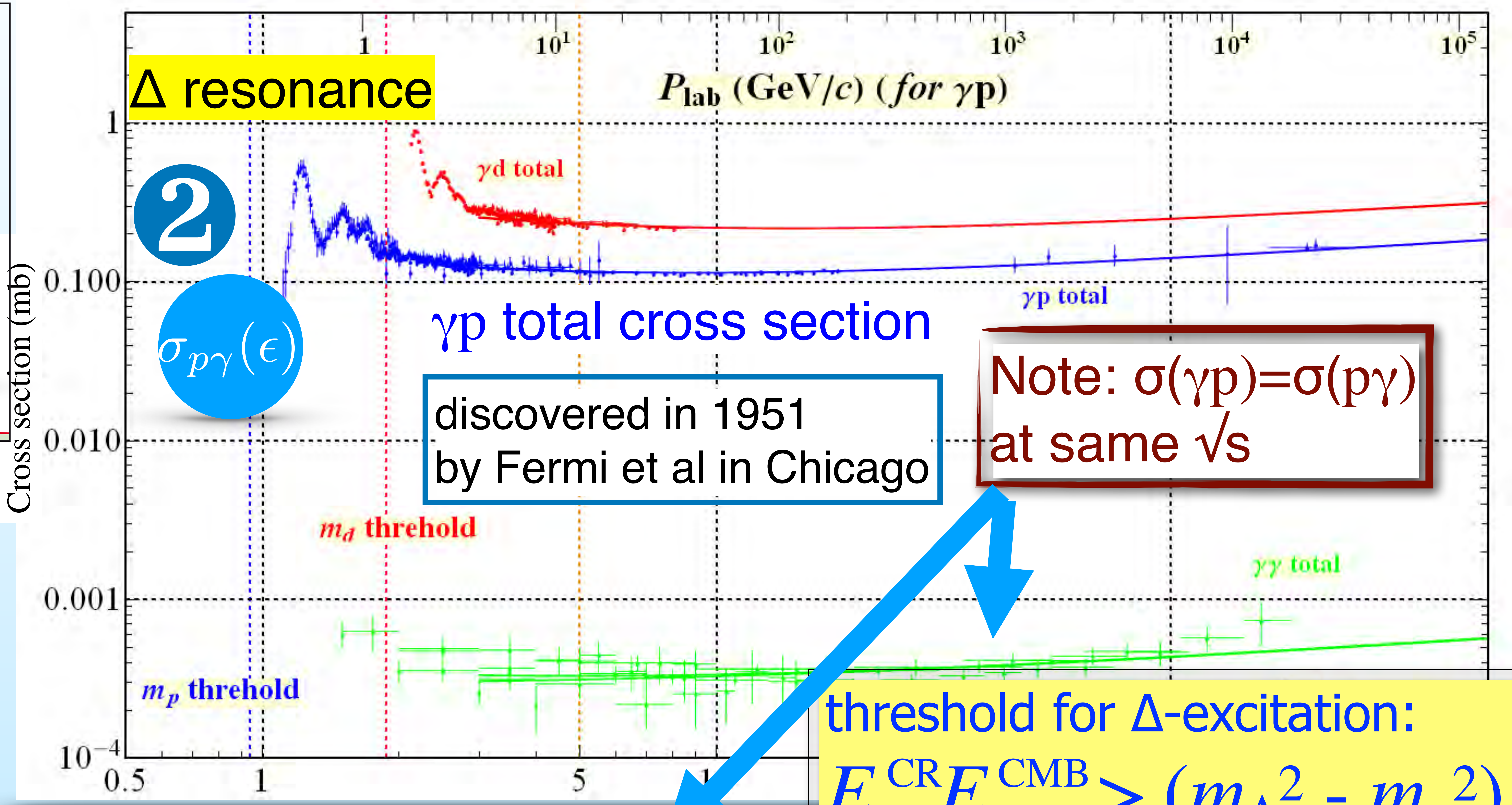


CMB Black Body spectrum

1

$n(\epsilon)$

discovered in 1965
by Penzias & Wilson



Δ resonance

2

$\sigma_{p\gamma}(\epsilon)$

γp total cross section

discovered in 1951
by Fermi et al in Chicago

Note: σ(γp)=σ(pγ)
at same √s

threshold for Δ-excitation:

$E_p^{\mathrm{CR}} E_\gamma^{\mathrm{CMB}} > (m_\Delta^2 - m_p^2)$

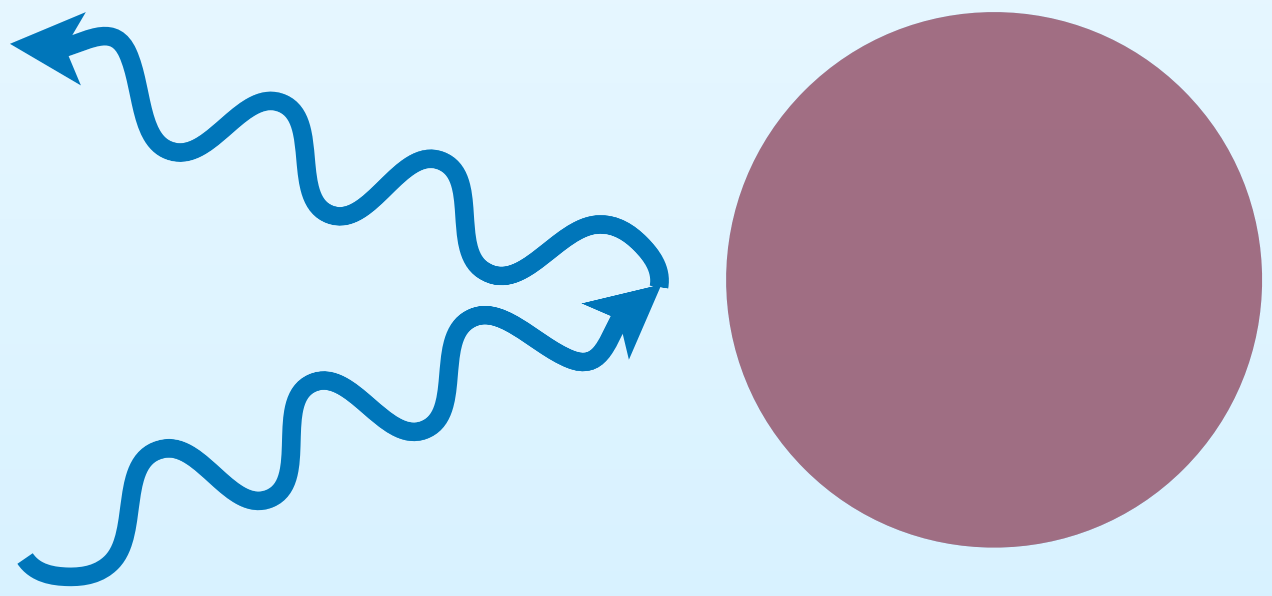
$\Rightarrow E_{\mathrm{GZK}} \approx 6 \cdot 10^{19}$ eV

$$\lambda_{eff} = \left(\int n(\epsilon) \cdot \sigma_{\gamma p}(\epsilon) d\epsilon \right)^{-1} \approx 8 \ \mathrm{Mpc}$$

GZK effect for CR Nuclei

Note: This case was treated in the same two papers!

interaction with CMB photon may induce a collective oscillation of neutrons against protons

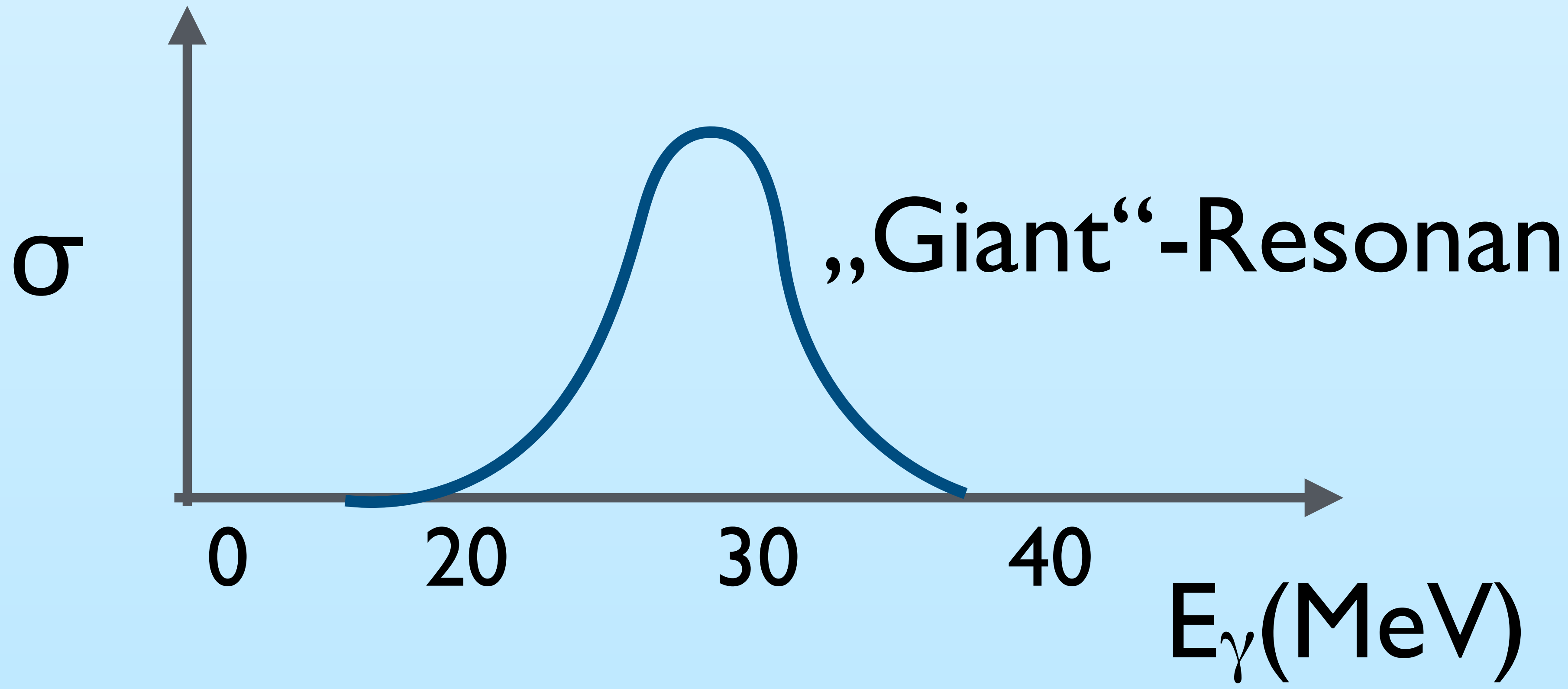


neutrons and protons
in an atomic nucleus

Often, single or multiple nucleons are lost in this process
→ **photodisintegration**

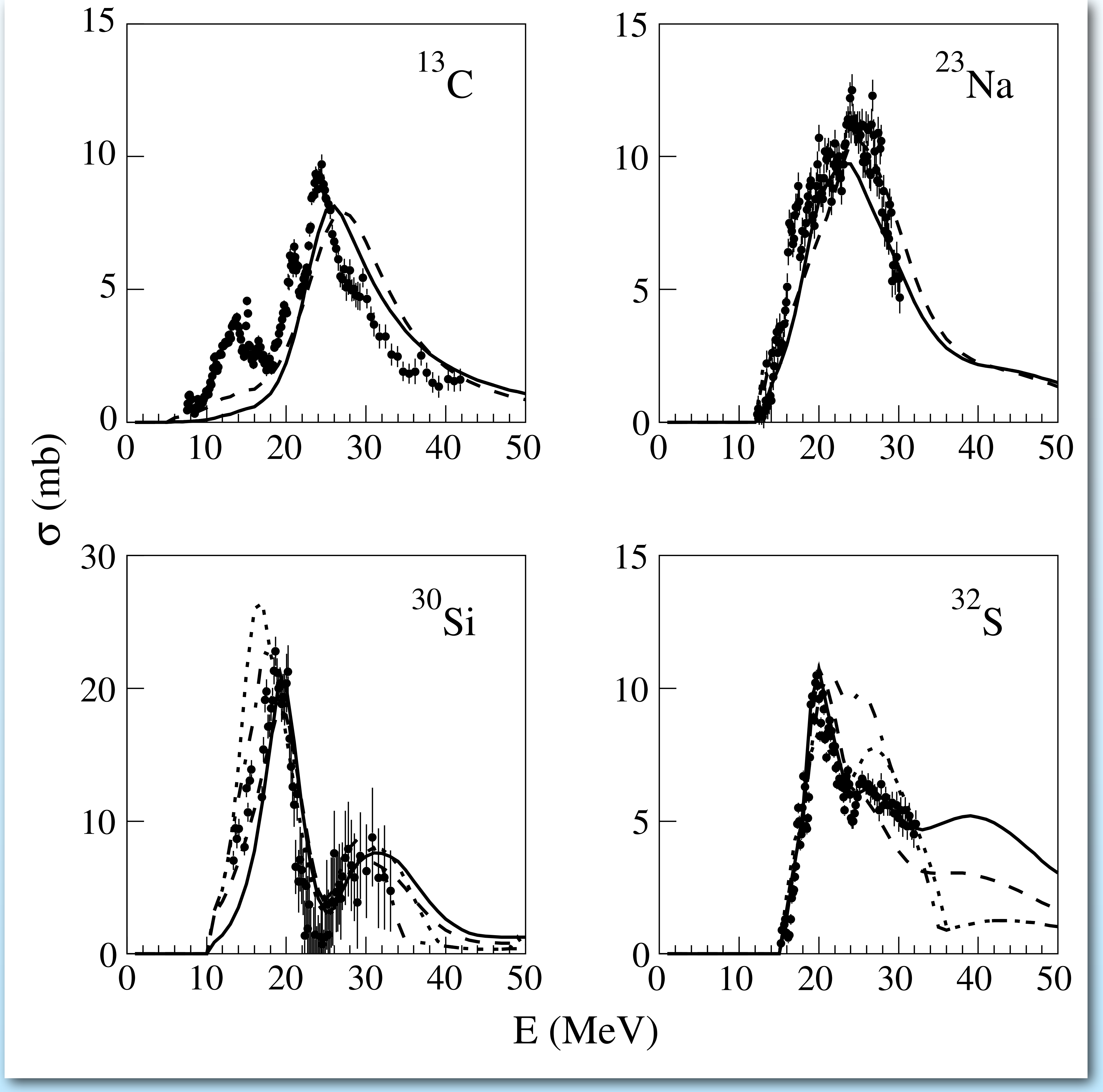
$$
\begin{aligned}
(Z,N) + \gamma &\rightarrow (Z,N-1) + n \\
&\rightarrow (Z-1,N) + p \\
&\rightarrow (Z,N-2) + 2n \\
&\rightarrow \ldots
\end{aligned}
$$

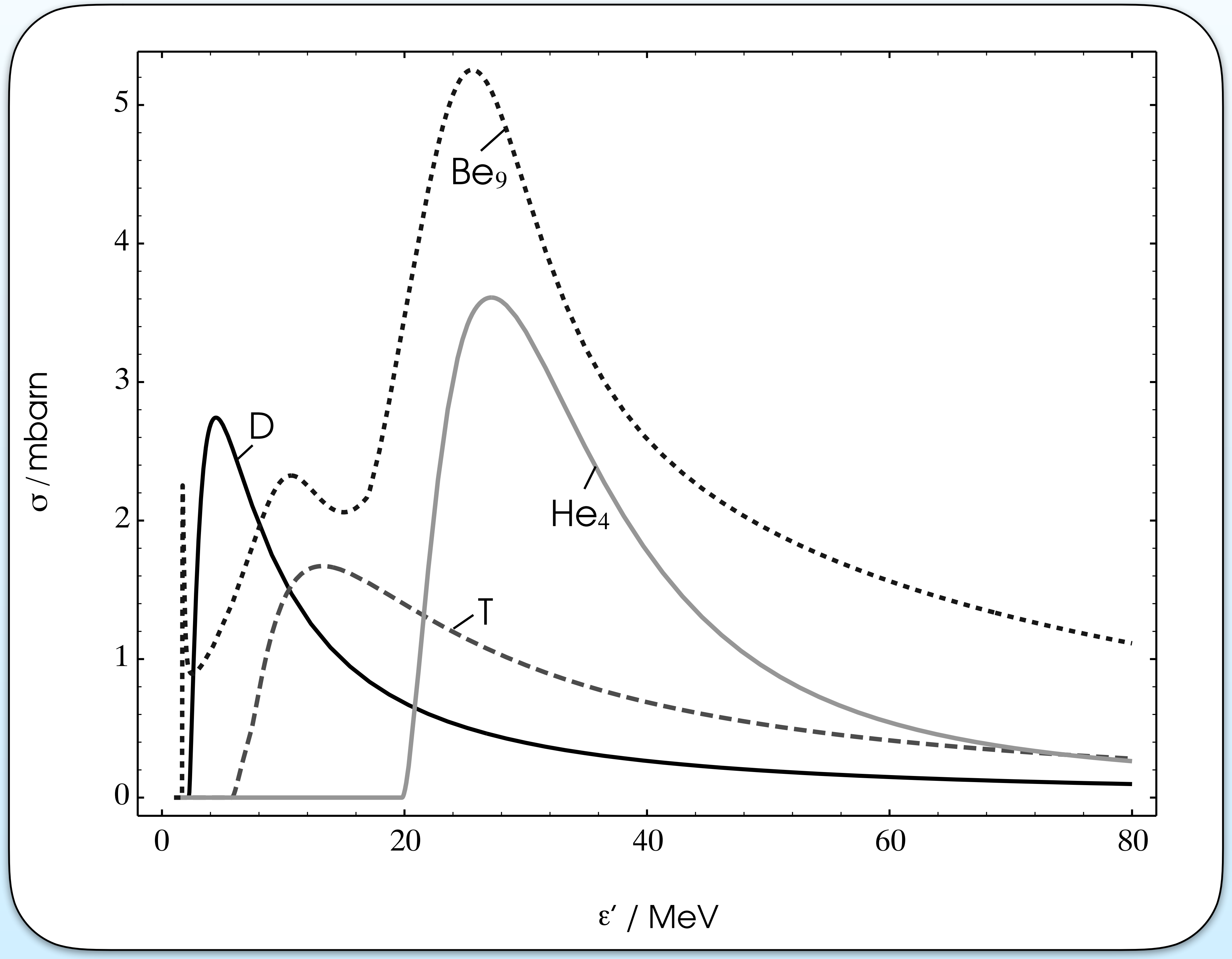
discovered 1947



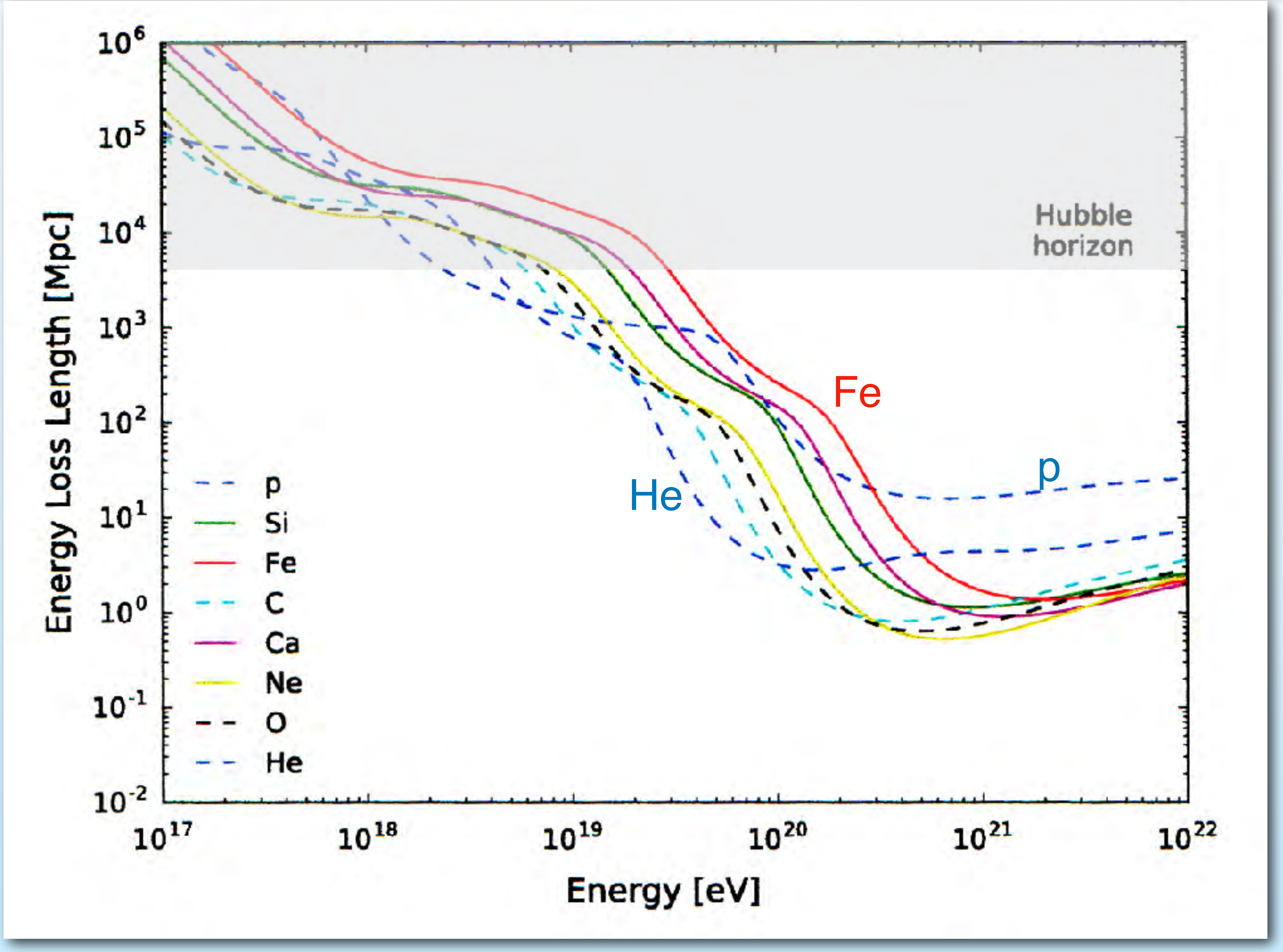
→ nuclei don’t survive propagation if energy is above Giant Resonance threshold

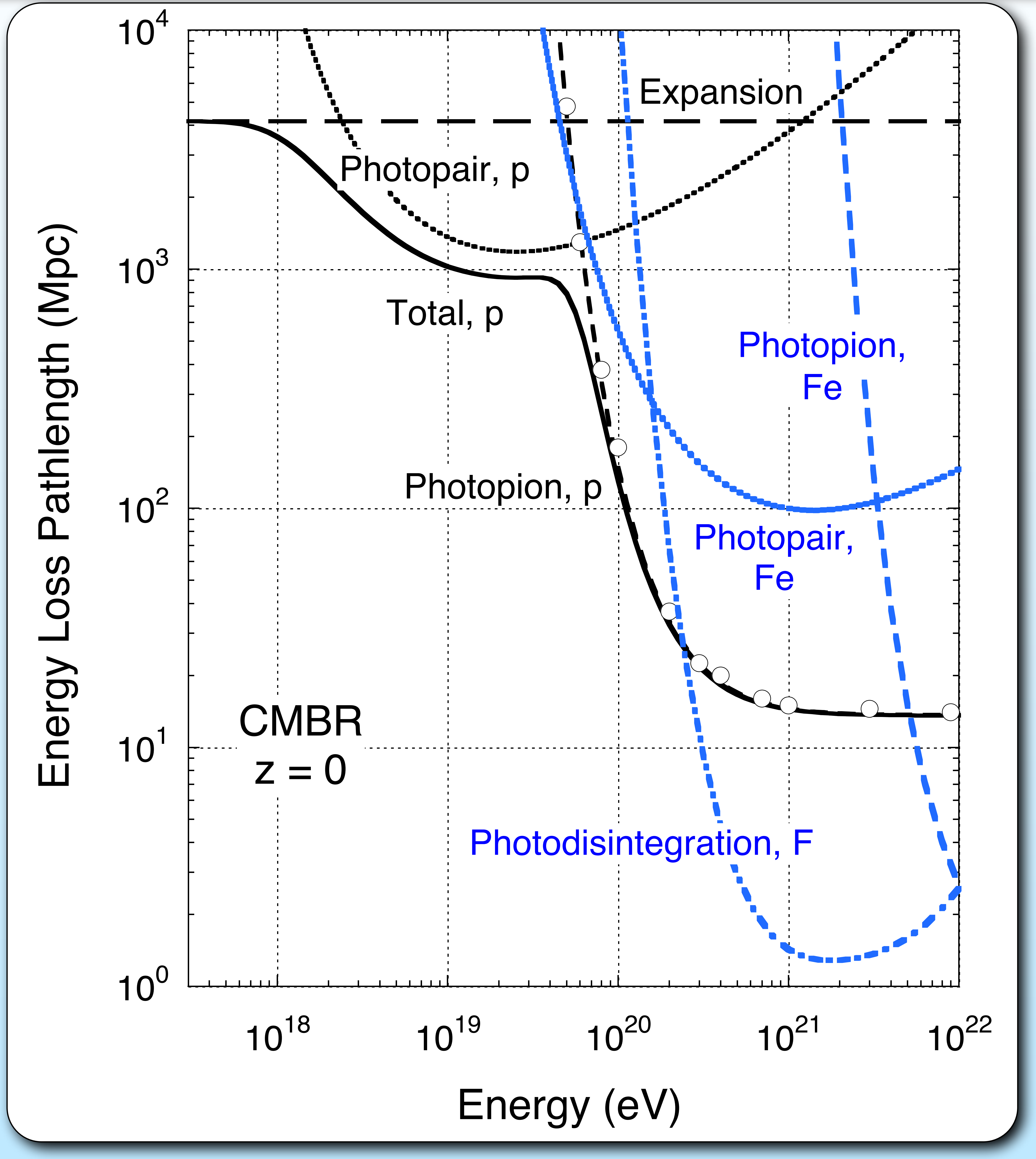
Examples of Giant-Dipole Cross sections





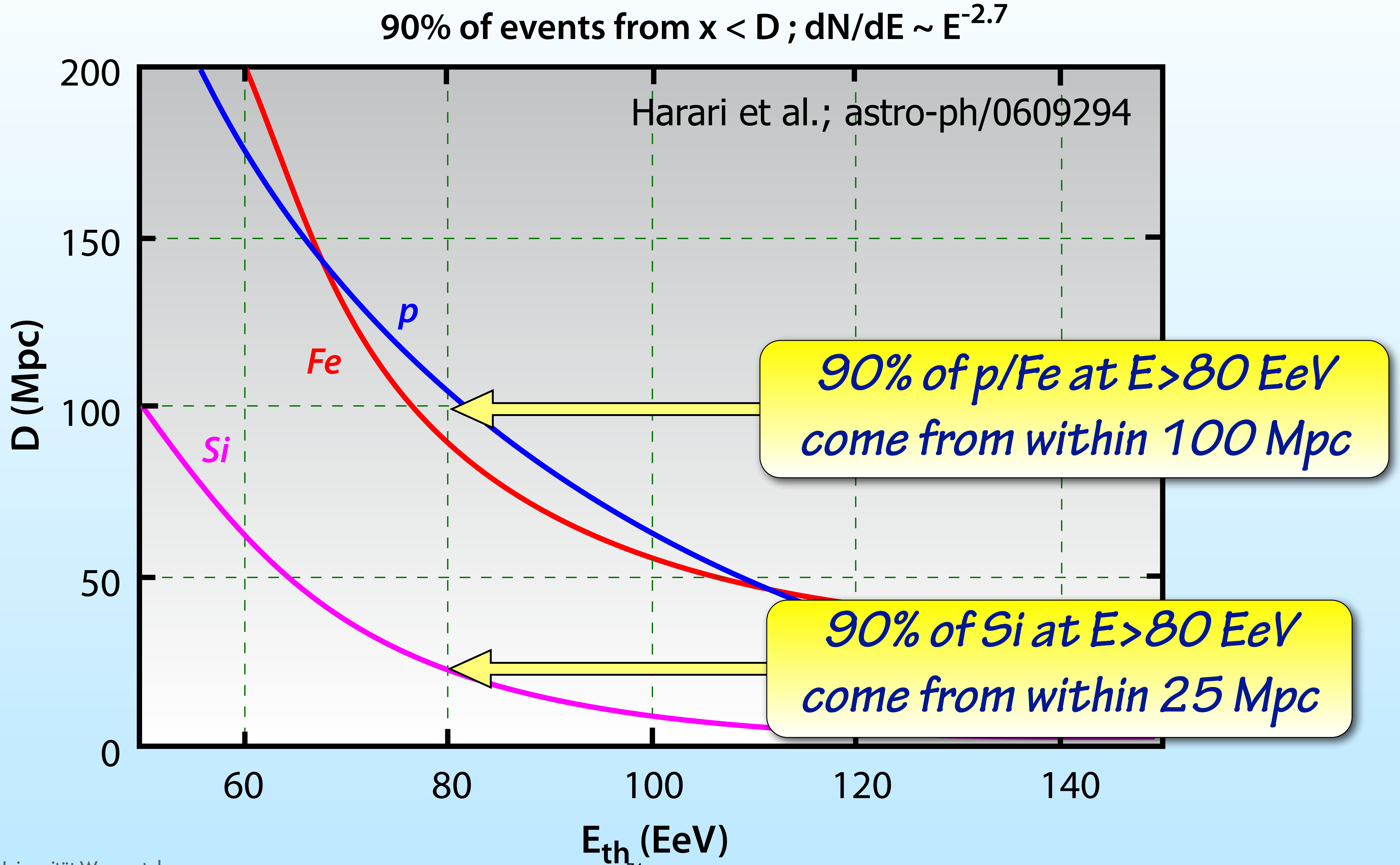
Energy Loss Length for Nuclei





It's a coincidence of nature that the threshold energies for photo-pion production and photodisintegration are about the same

GZK Horizon

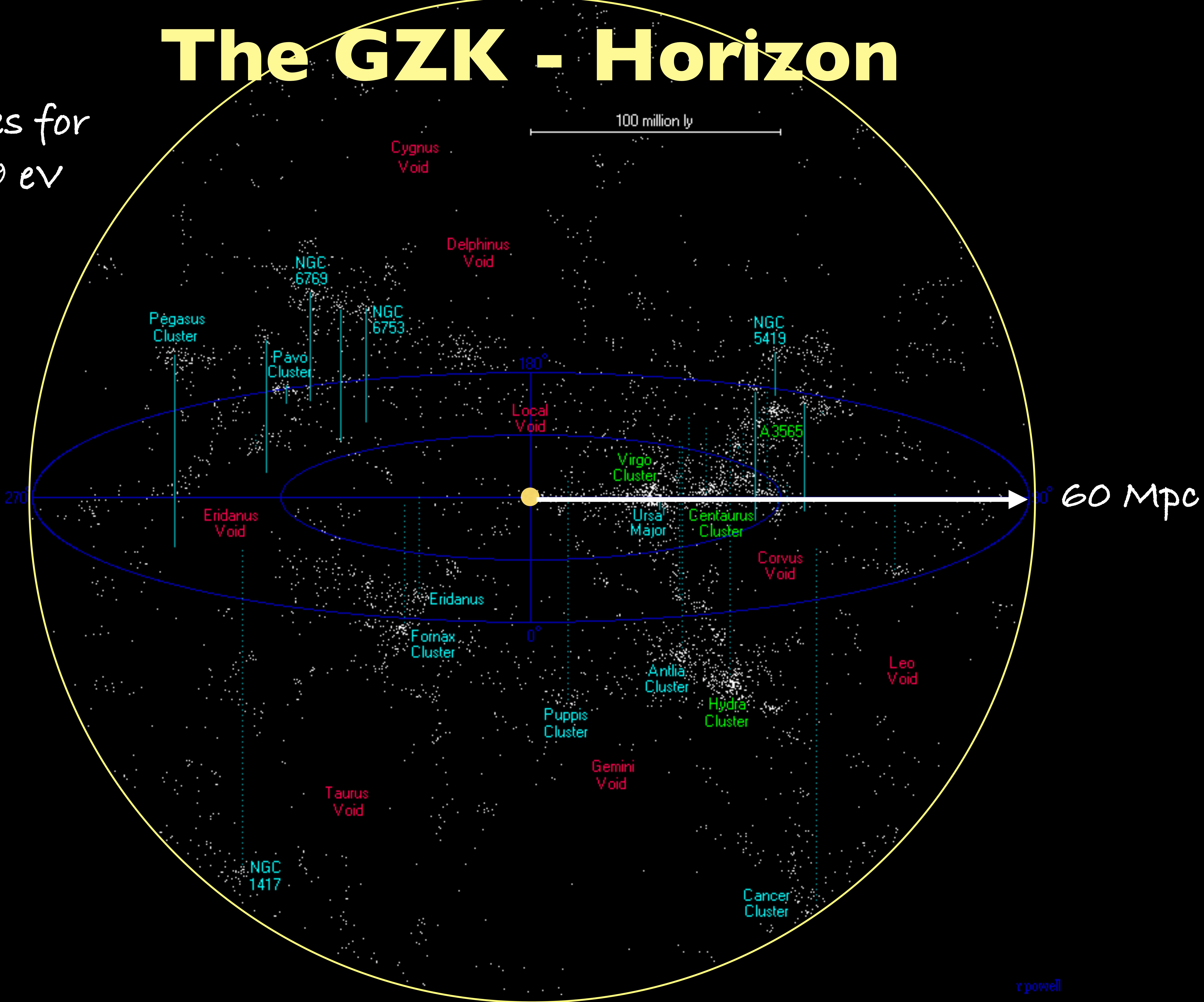


90% of p/Fe at E>80 EeV come from within 100 Mpc

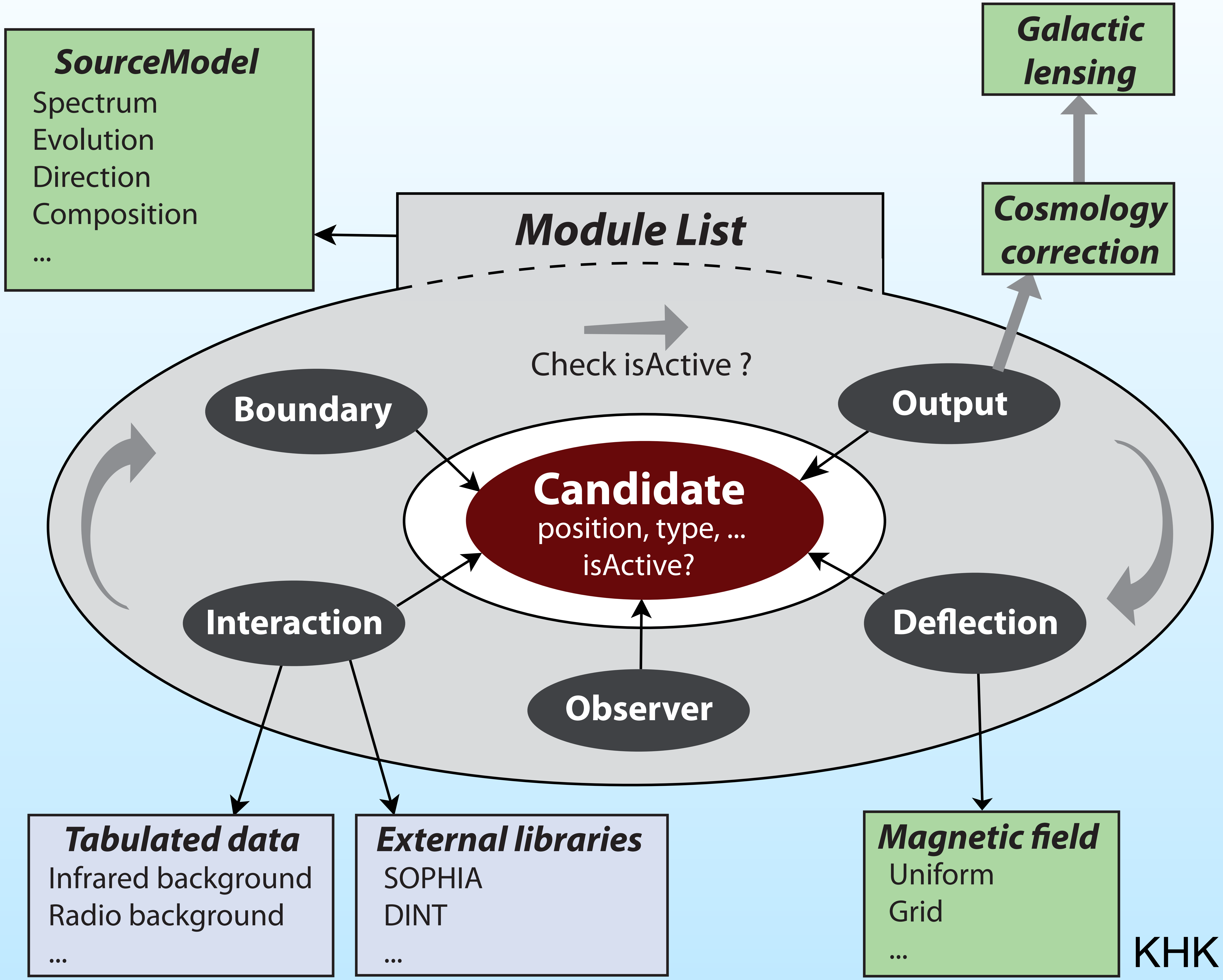
90% of Si at E>80 EeV come from within 25 Mpc

The GZK - Horizon

Expect anisotropies for protons at E>10^{19} eV



CRPropa: Open Source Public Code

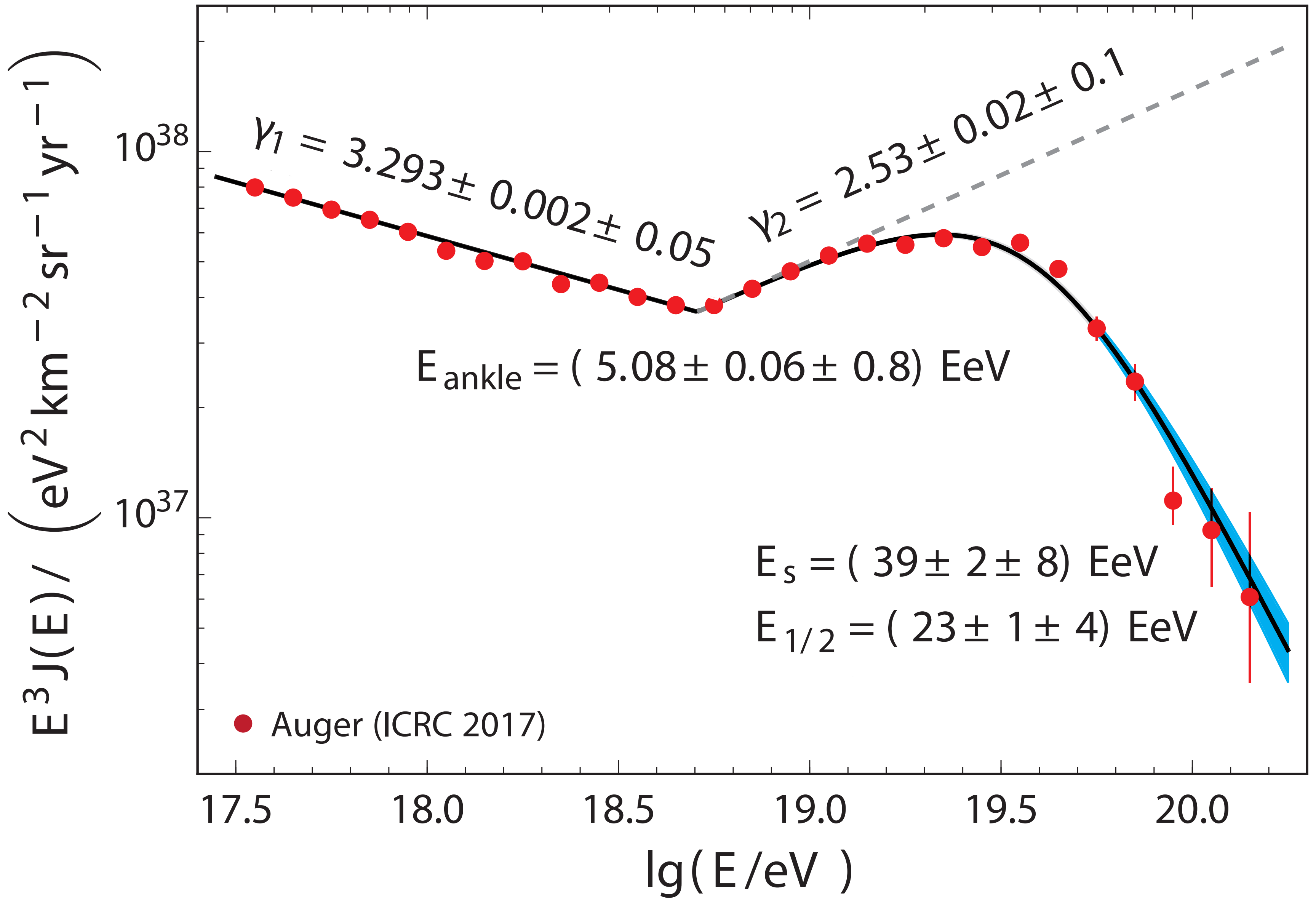


Propagates CR particles from source to observer and accounts for all type of interactions in photon fields as well as in magnetic fields.

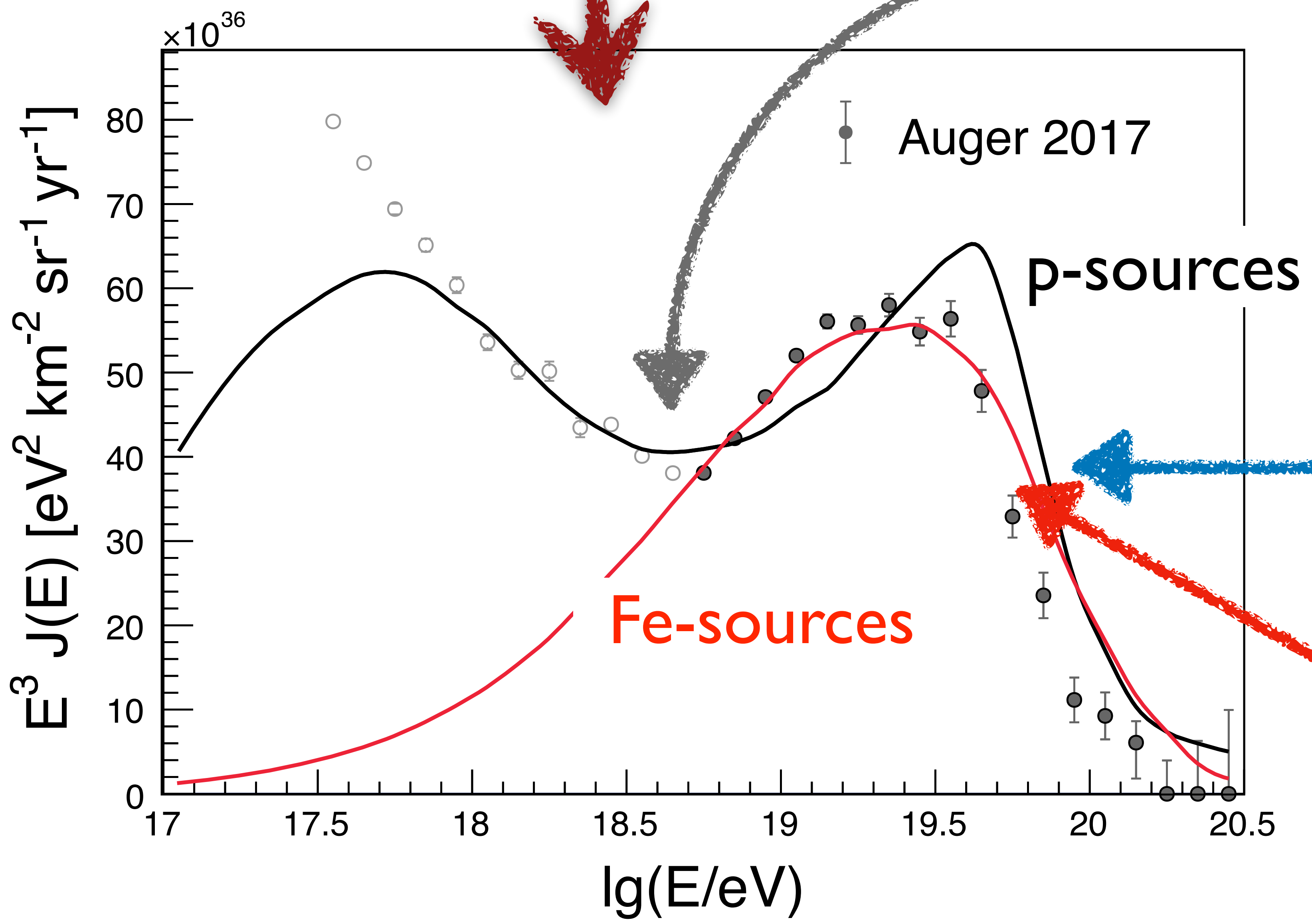
KHK et al, Astropart. Phys. 42 (2013) 41
R.A. Batista, KHK et al, JCAP 05 (2016) 038

)

GZK-effect, i.e. propagation effect ?



GZK-effect



Why is there a „dip“ for propagated protons ?

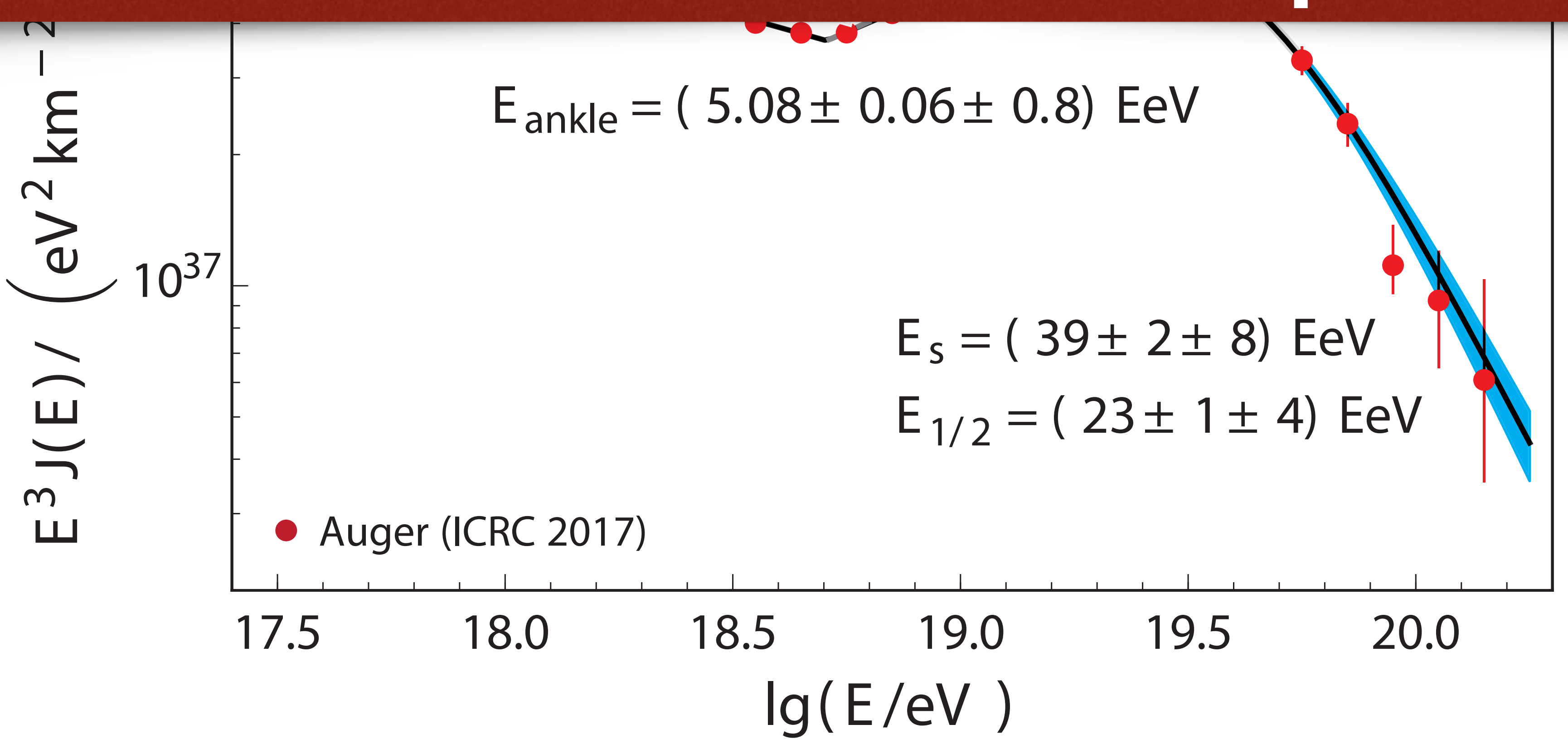
$p\gamma \rightarrow e^+e^- + p$ first pointed out by V. Berezinsky

$p\gamma \rightarrow \Delta \rightarrow p+\pi$

$Fe+\gamma \rightarrow$ „Cr“ $+ p + n$

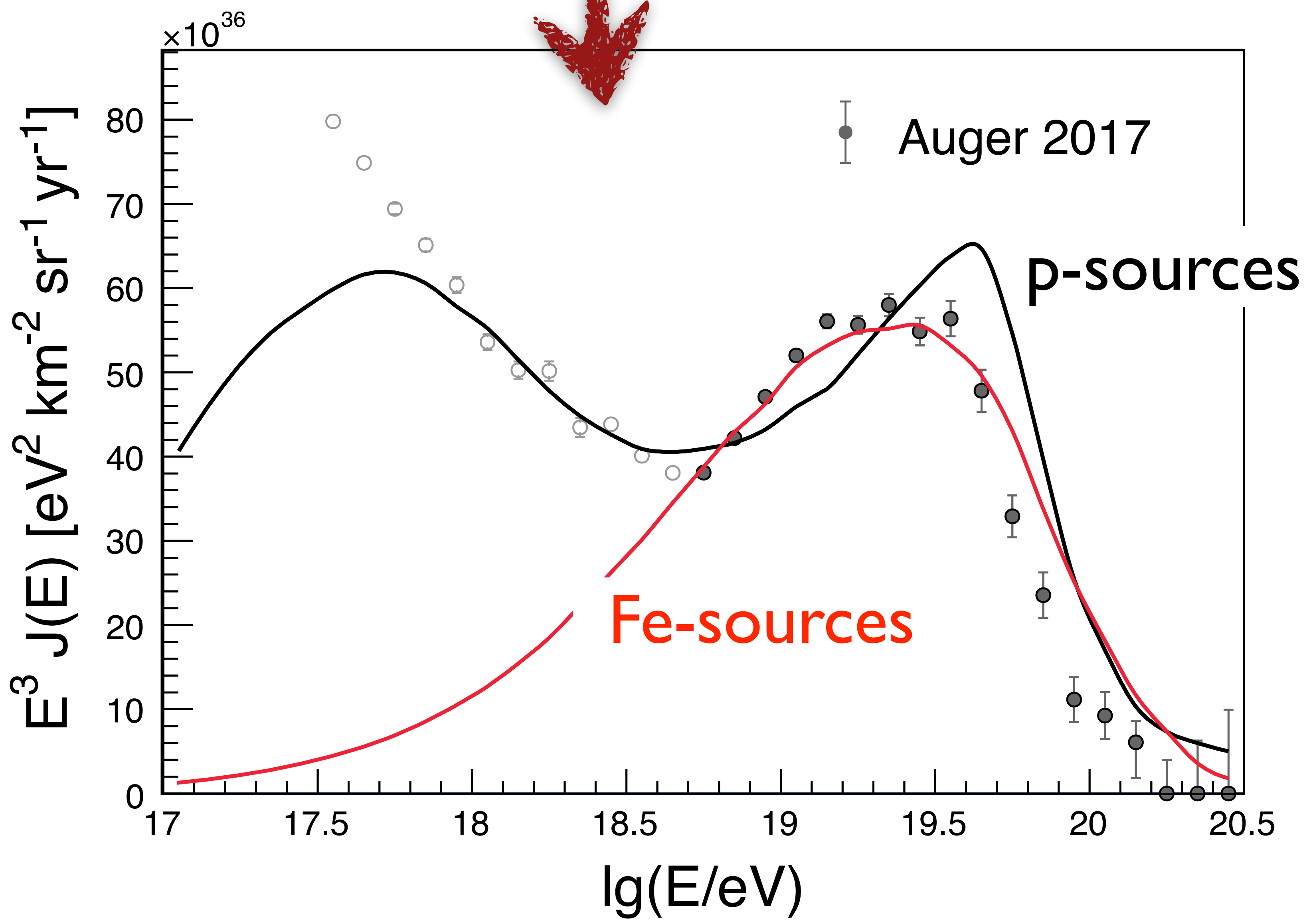
GZK-effect or Sources running at their RxB limits?

Energy spectrum alone cannot tell origin of the cut-off, need mass composition in addition

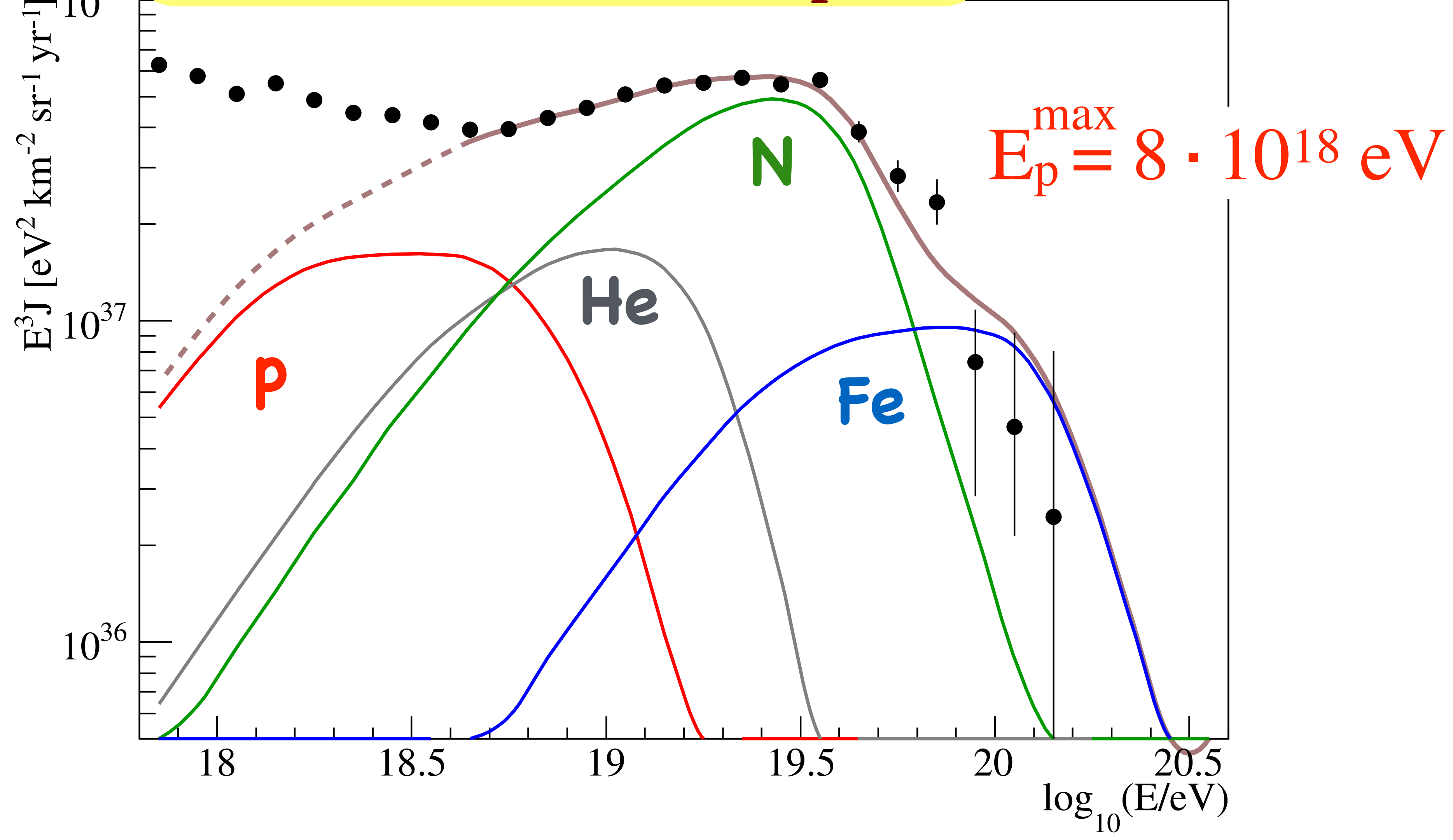


GZK-effect

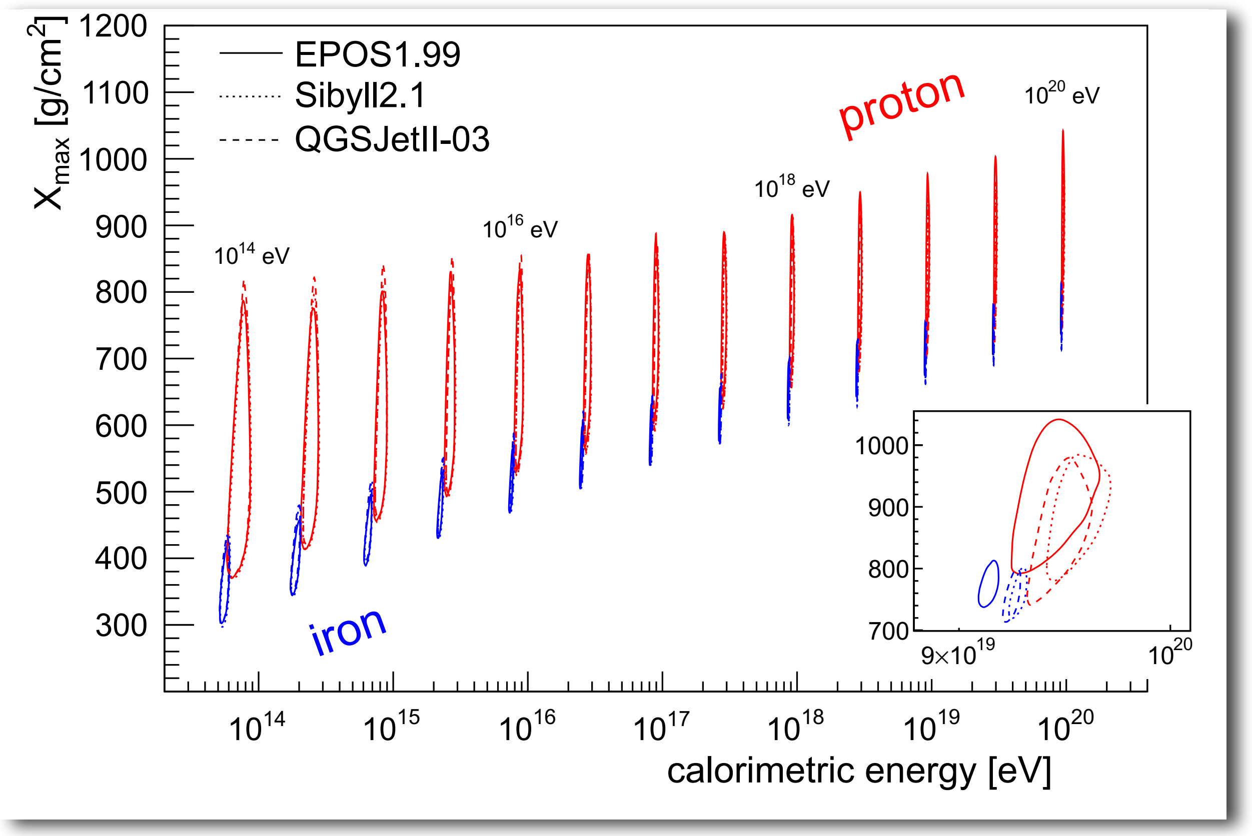
Emax of sources



$$E_Z^{\max} \propto Z \times E_p^{\max}$$



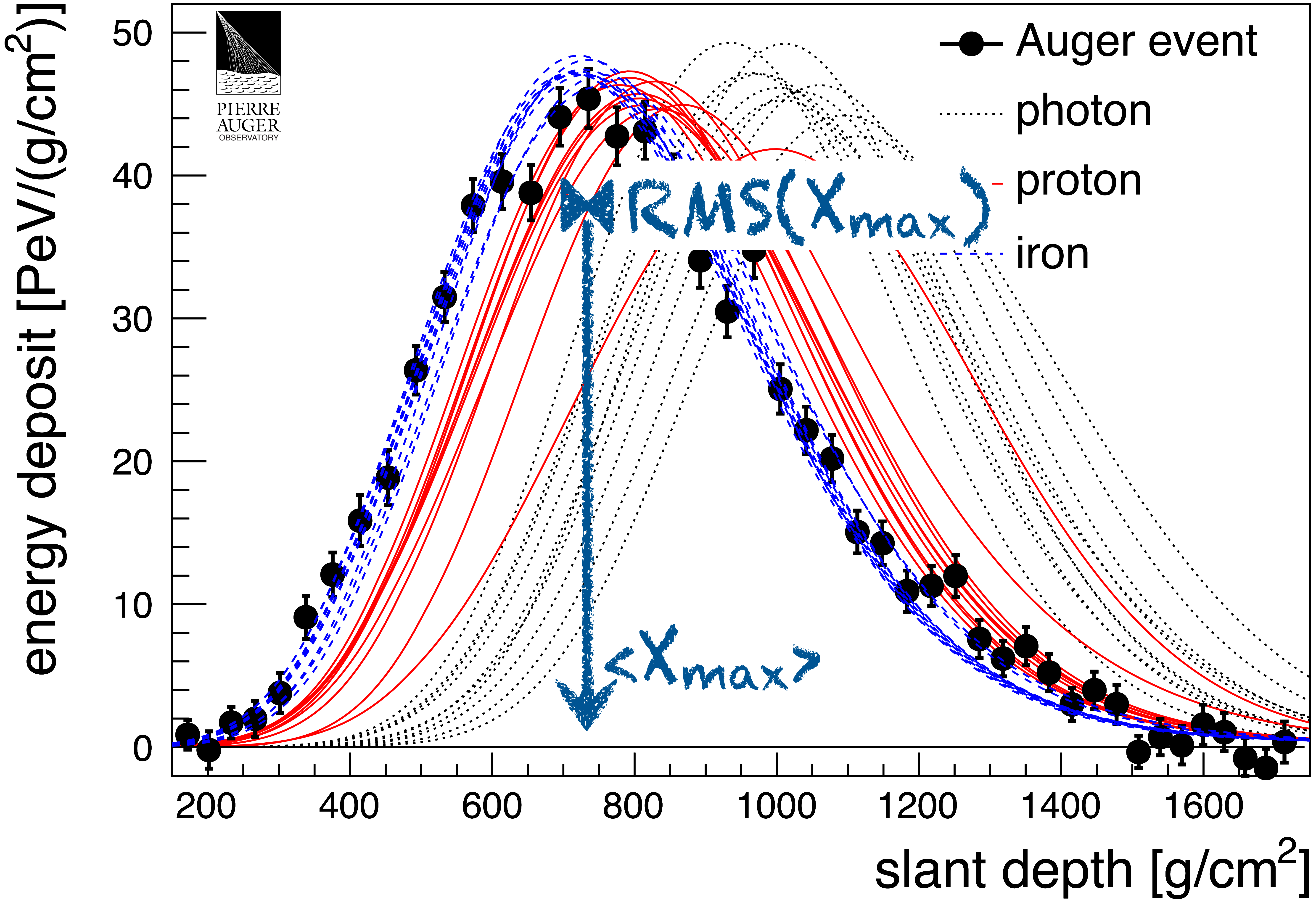
Longitudinal Shower Development → Primary Mass

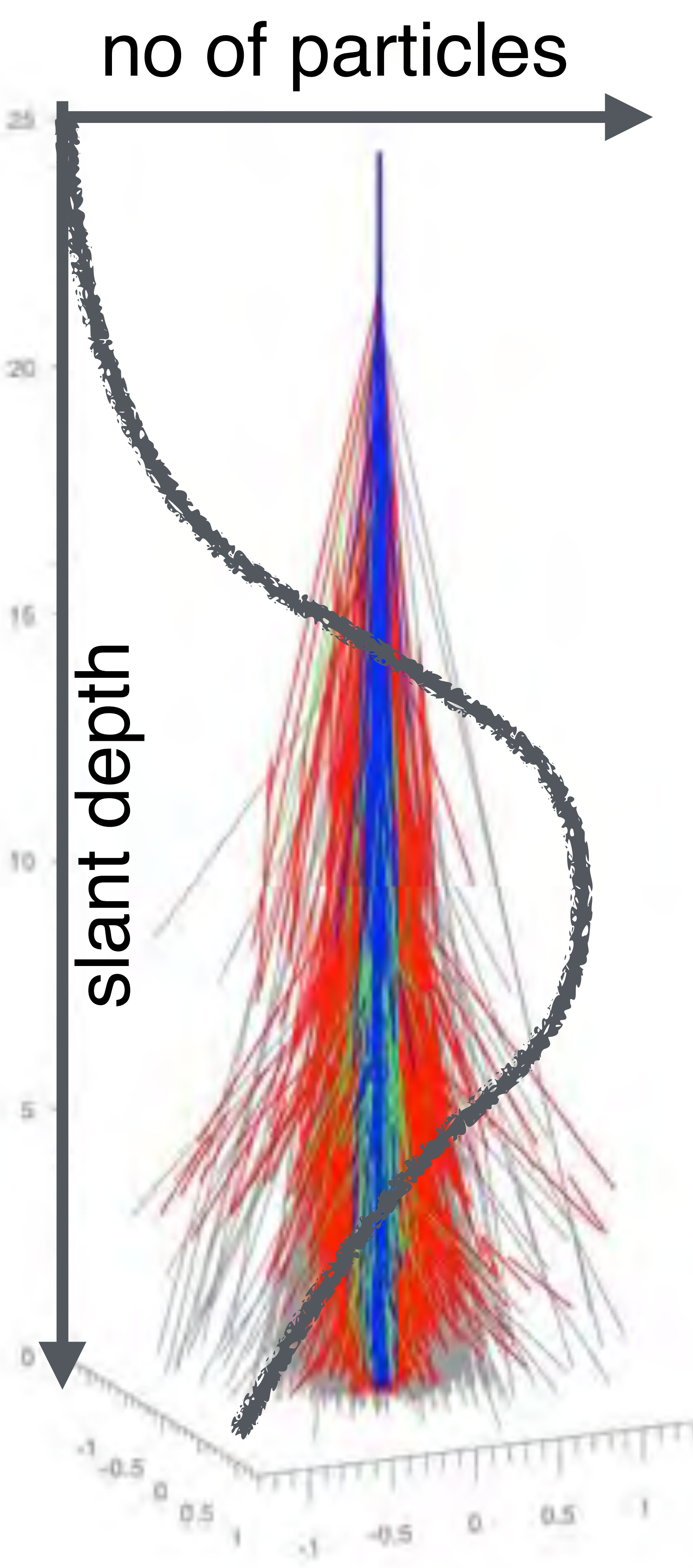


from slide 32

KHK, Unger, APP 35 (2012)
EPOS 1.99 Simulations

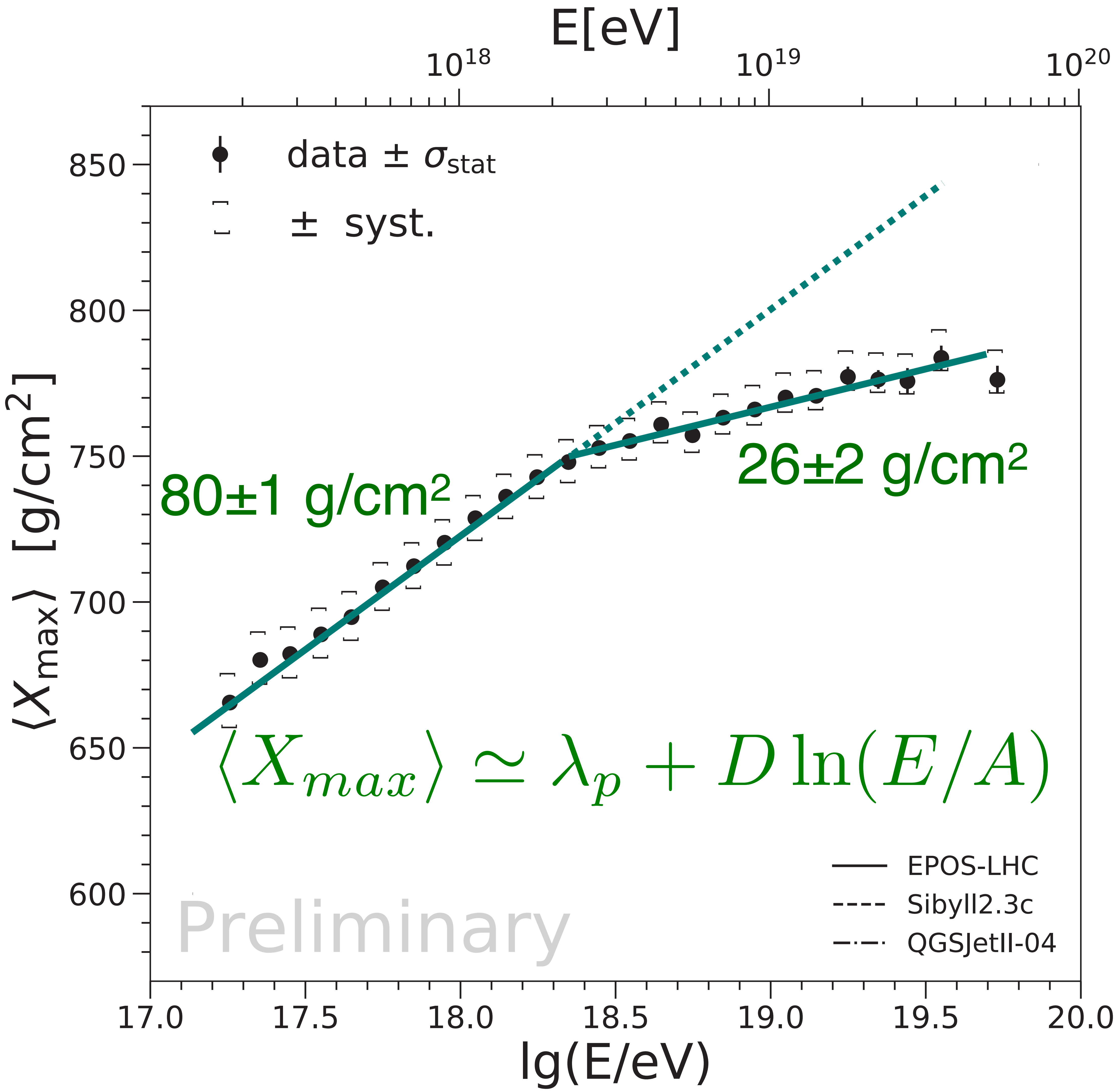
Example of a $3 \cdot 10^{19}$ eV EAS event in FD

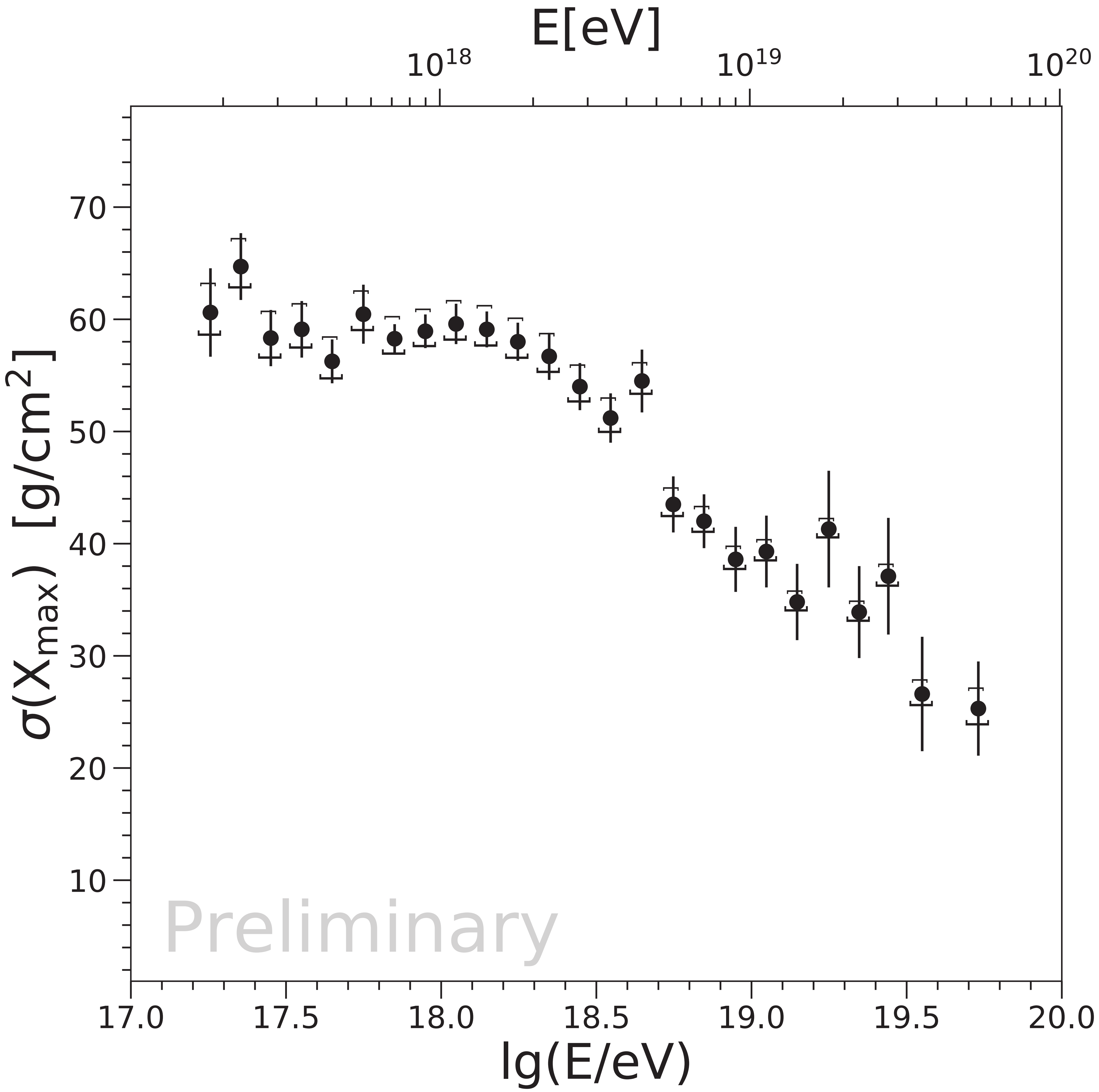




<X_{max}> and RMS(X_{max})

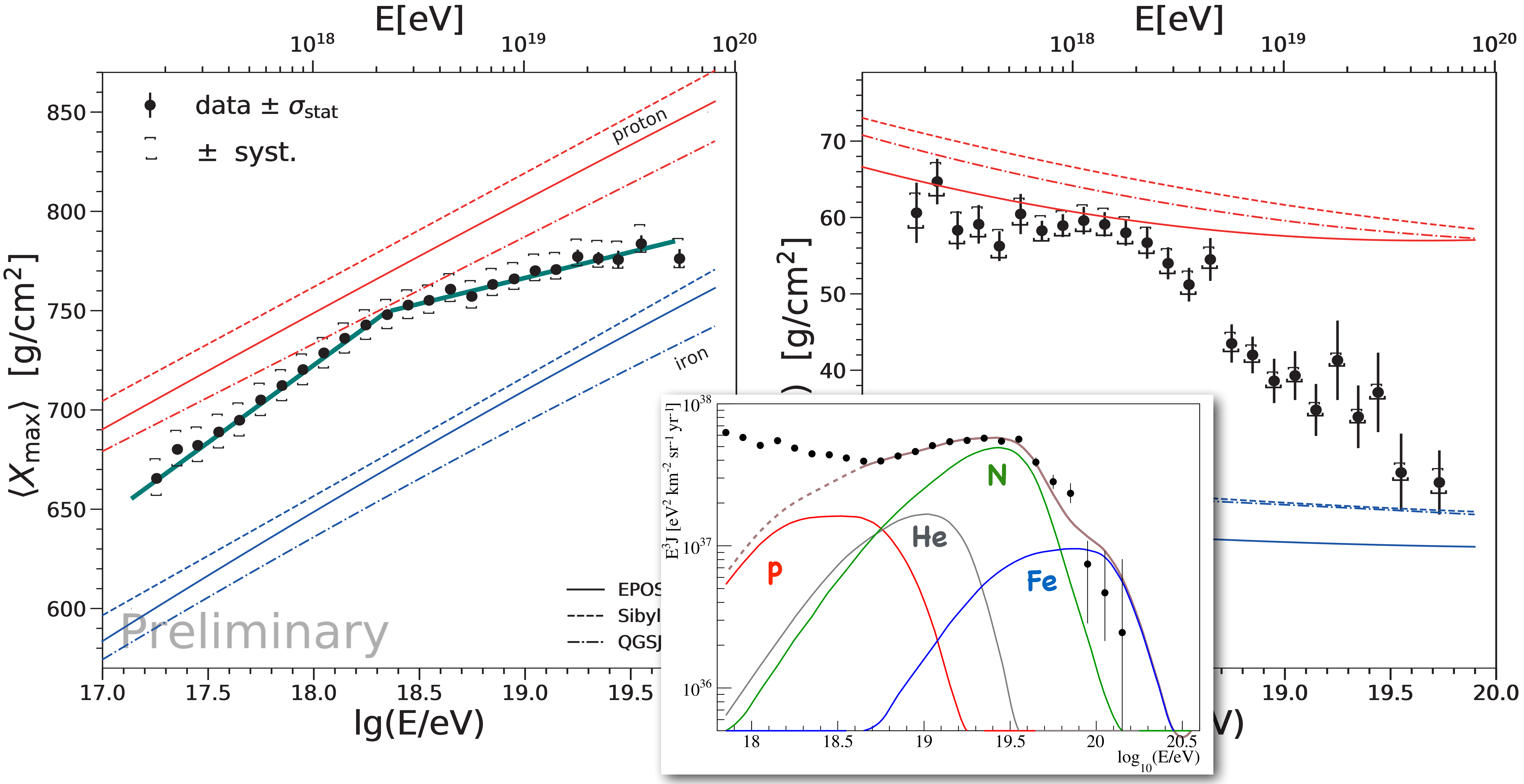
Auger @ ICRC2019: arXiv:1909.09073



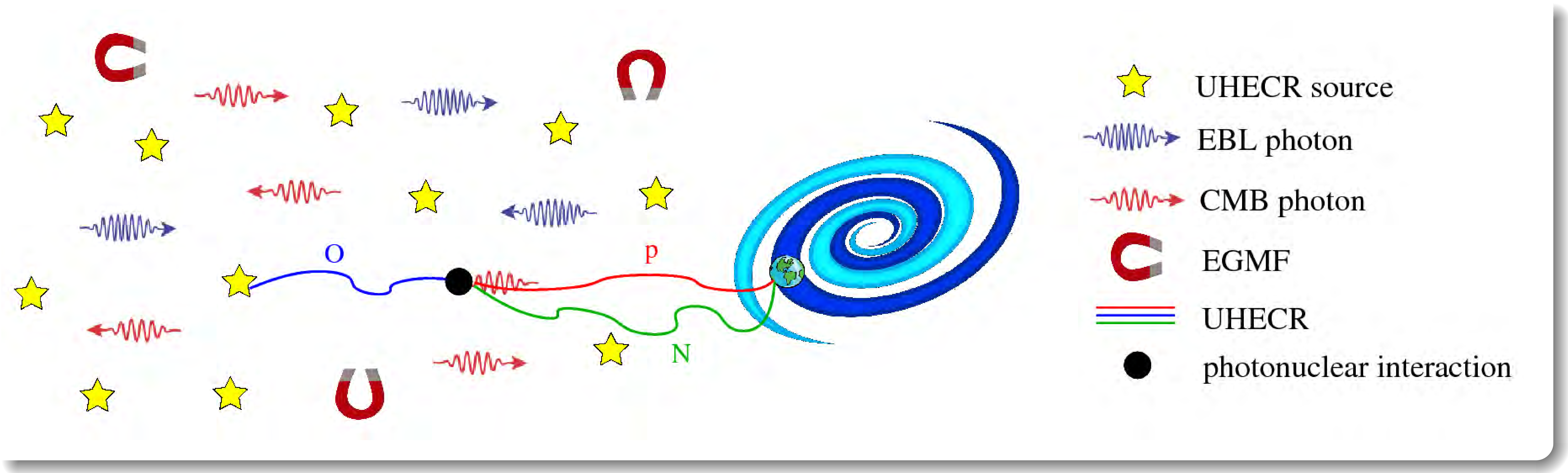


<X$_{max}$> and RMS(X$_{max}$)

Auger @ ICRC2019: arXiv:1909.09073



Combined Fit of E-spec, X_{max}, $\sigma(X_{max})$



minimal astrophysical model

Pierre Auger Coll., JCAP 1704 (2017) no.04, 038

- $E_{\text{max}} = R_{\text{cut}}\, Z$
- power law injection $E^{-\gamma}$
- five mass groups: p, He, N, Si
- source evolution $(1 + z)^m$
- 1D propagation with CRPropa3
- Gilmore+12 EBL photon field

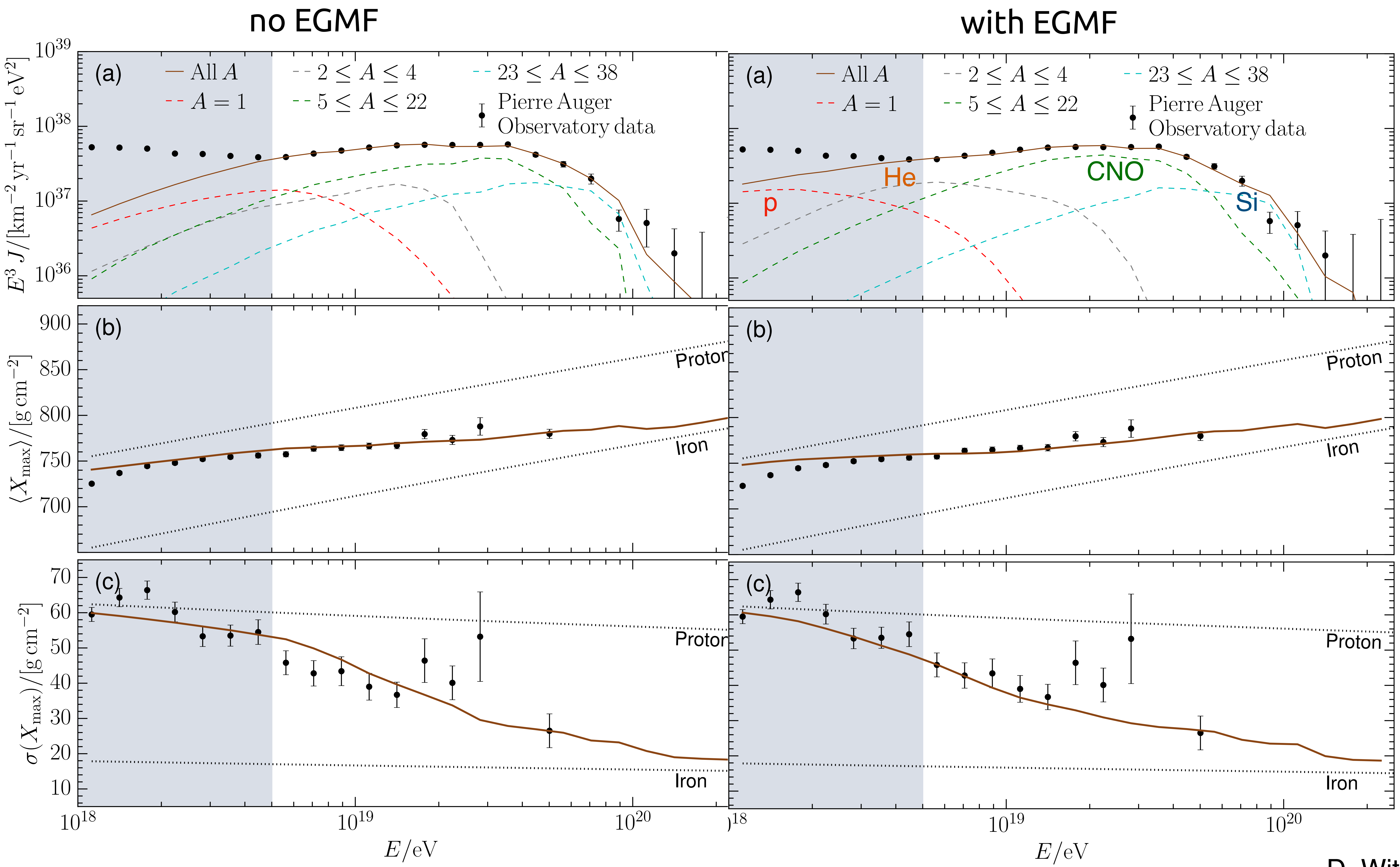
extended model

D. Wittkowski for the Pierre Auger Coll., ICRC15

- local large scale structure (Dolag+12)
- extragalactic magnetic field (Sigl+03)
- 4D propagation with CRPropa3

slide adapted from M. Unger

Combined Fit of E-spec, X_{max}, $\sigma(X_{max})$


no EGMF

with EGMF

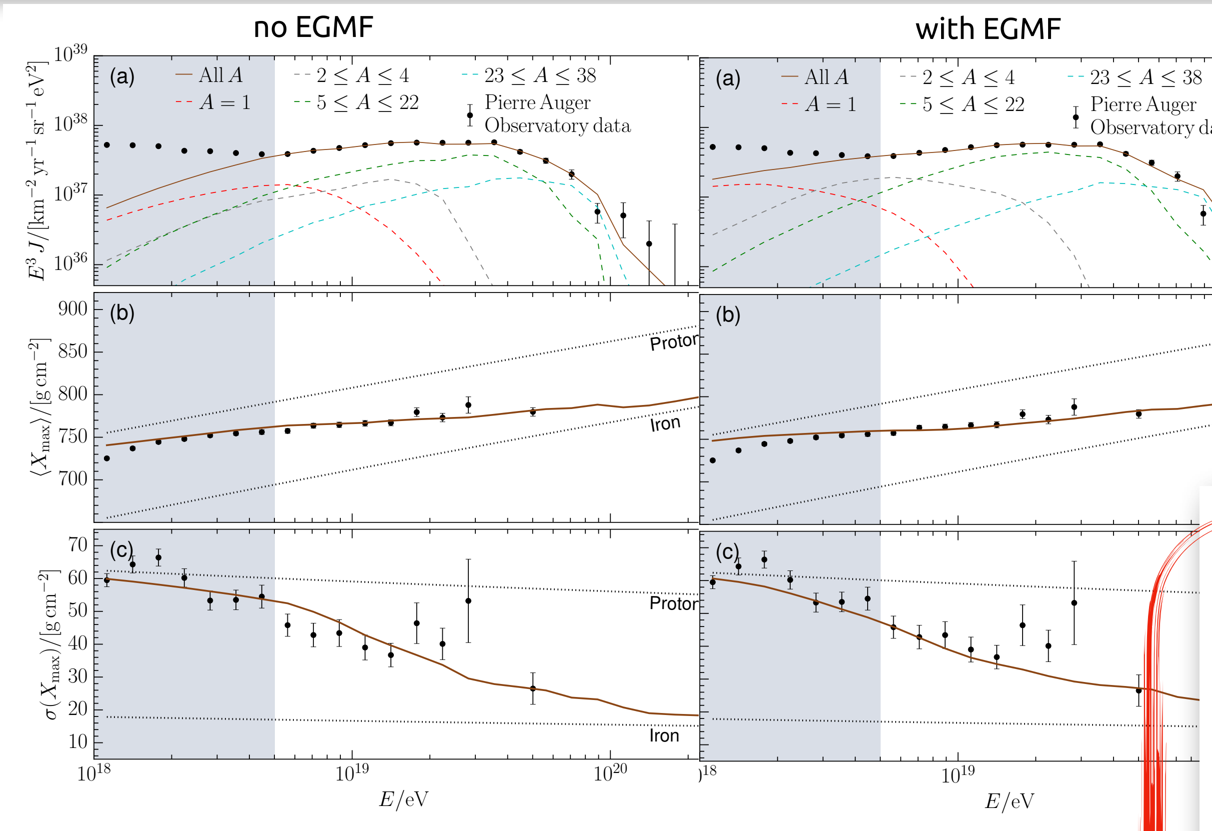
E-spec

$<X_{max}>$

$\sigma(X_{max})$

D. Wittkowski, ICRC2017

Combined Fit of E-spec, X_{max}, $\sigma(X_{max})$



Source properties	4D with EGMF	4D no EGMF	1D no EGMF
γ	1.61	0.61	0.87
$\log_{10}(R_{\mathrm{cut}}/\mathrm{eV})$	18.88	18.48	18.62

Lessons learned:

1) maximum source rigidity describes data very well
2) EGMF has significant effect
3) source rigidity found to be < 10^{19} V
4) need very hard source spectra

D. Wittkowski, ICRC2017