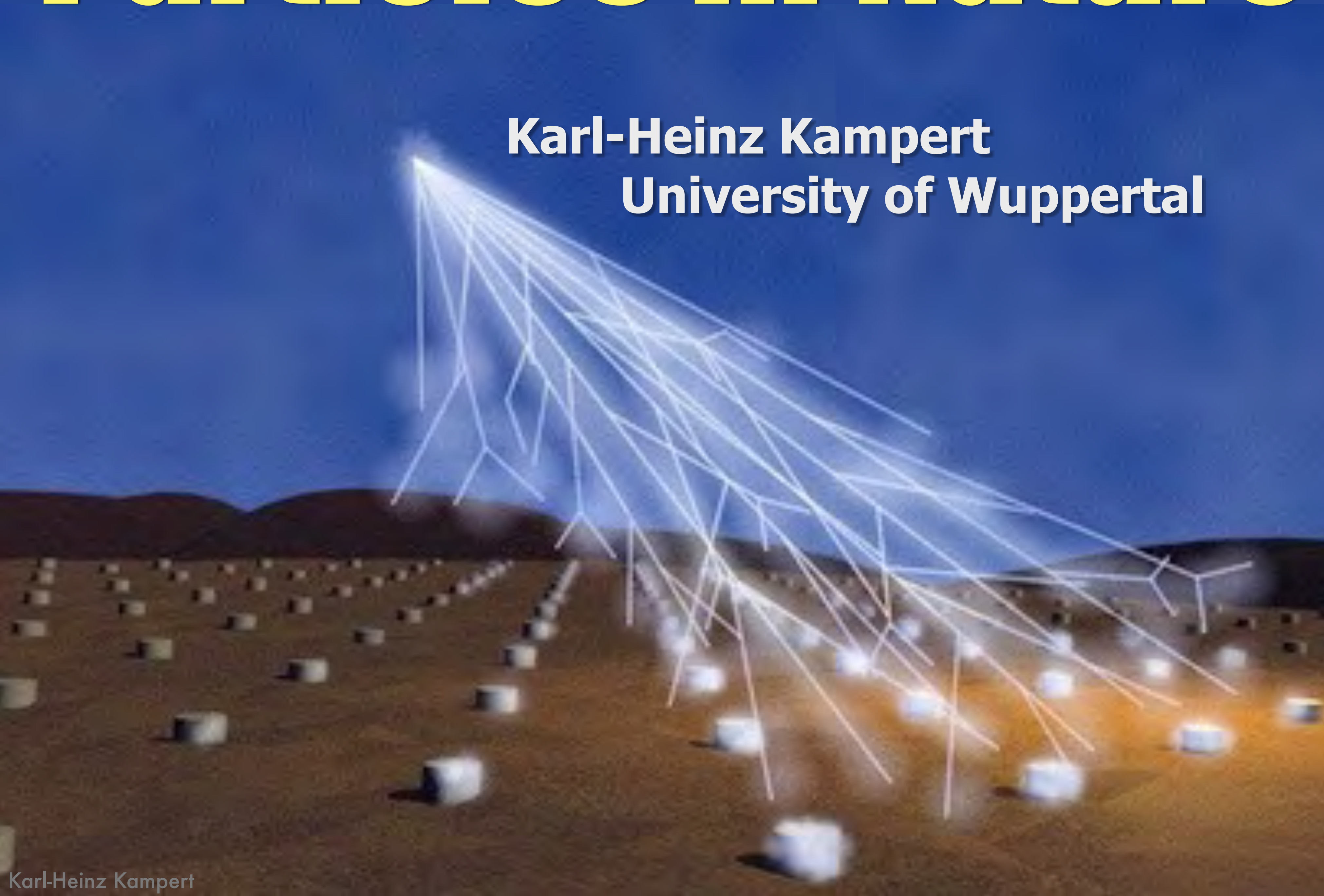
BERGISCHE UNIVERSITÄT WUPPERTAL

The Most Energetic Particles in Nature

Karl-Heinz Kampert
University of Wuppertal



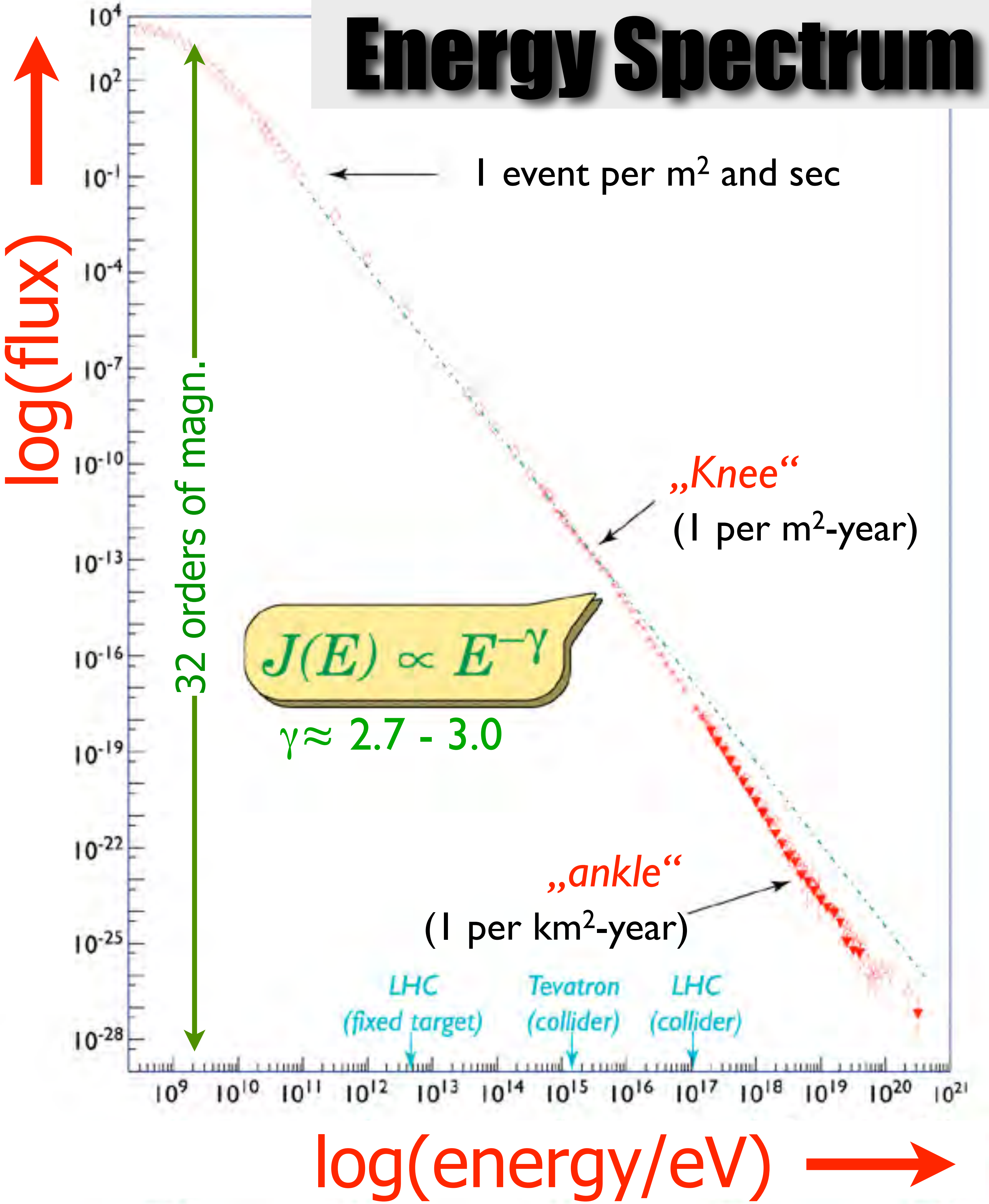
ASPERA

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

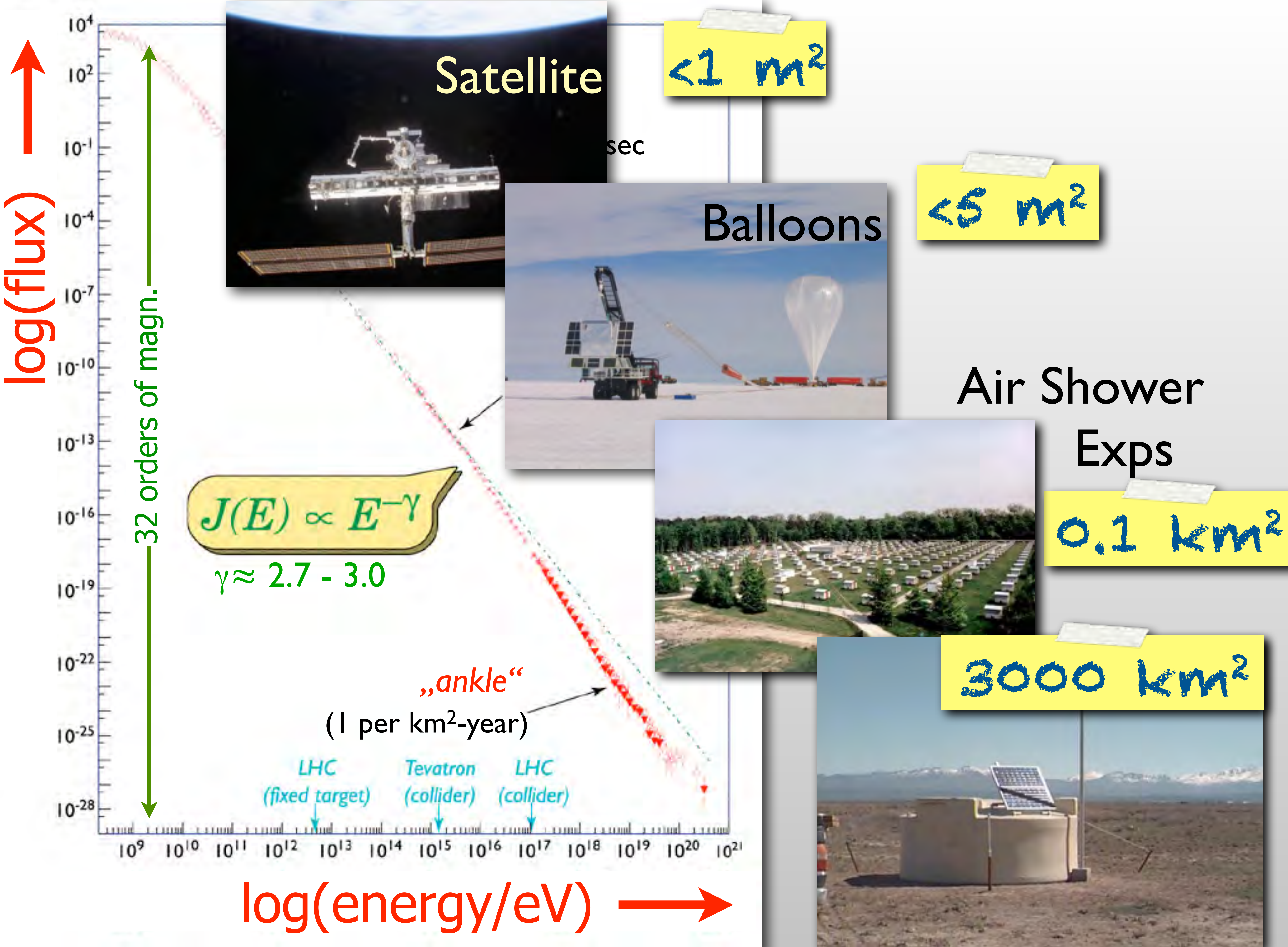
HELMHOLTZ GEMEINSCHAFT
Allianz für Astroteilchenphysik

Area $\propto$ Grant

Energy Spectrum of Cosmic Rays



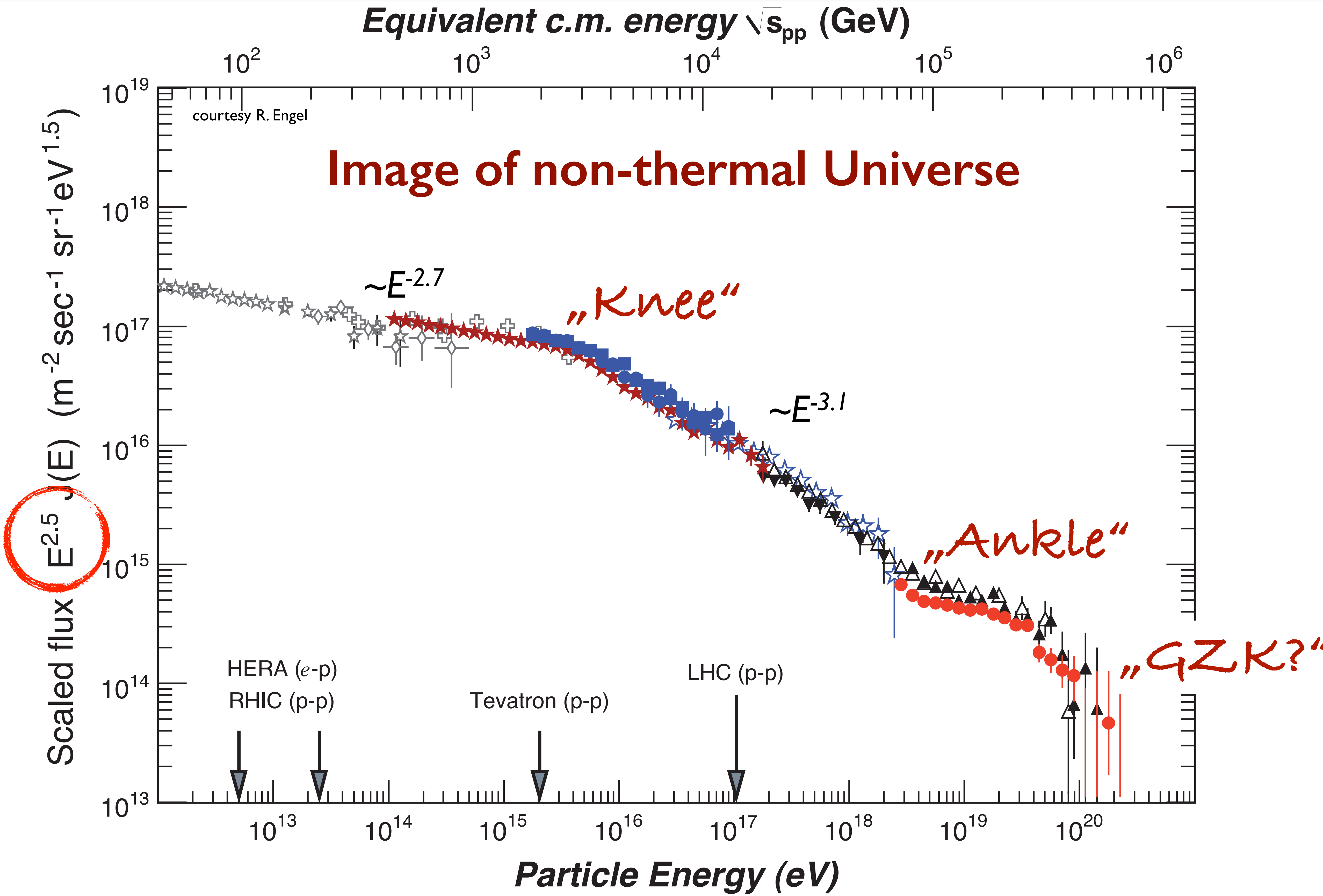
32 orders of magnitude:


Satellite
<1 m²
sec
Balloons
<5 m²
Air Shower Exps
0.1 km²
3000 km²
log(flux)
32 orders of magn.
J(E) ∝ E^−γ
γ≈ 2.7 - 3.0
„ankle“
(1 per km²-year)
LHC (fixed target)
Tevatron (collider)
LHC (collider)
10⁴ 10² 10⁻¹ 10⁻⁴ 10⁻⁷ 10⁻¹⁰ 10⁻¹³ 10⁻¹⁶ 10⁻¹⁹ 10⁻²² 10⁻²⁵ 10⁻²⁸
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹
log(energy/eV)

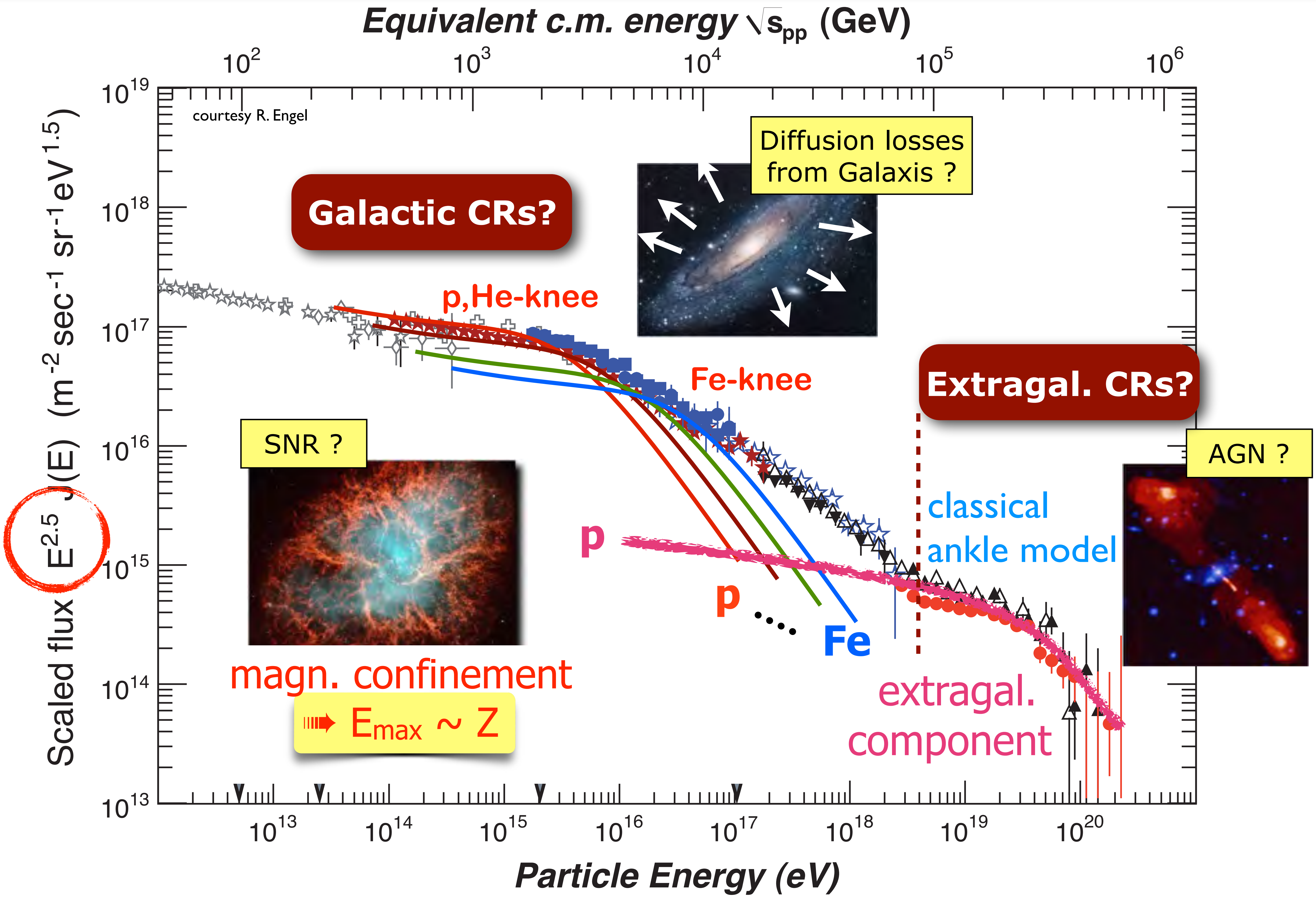
Key Questions about Ultra High-Energy Cosmic Rays

- **Where do they come from?**
- **What are they made of ?**
- **How do their accelerators work?**
- **Is there a maximum limit to their energy ?**
- **What can they tell us about fundamental and particle physics?**

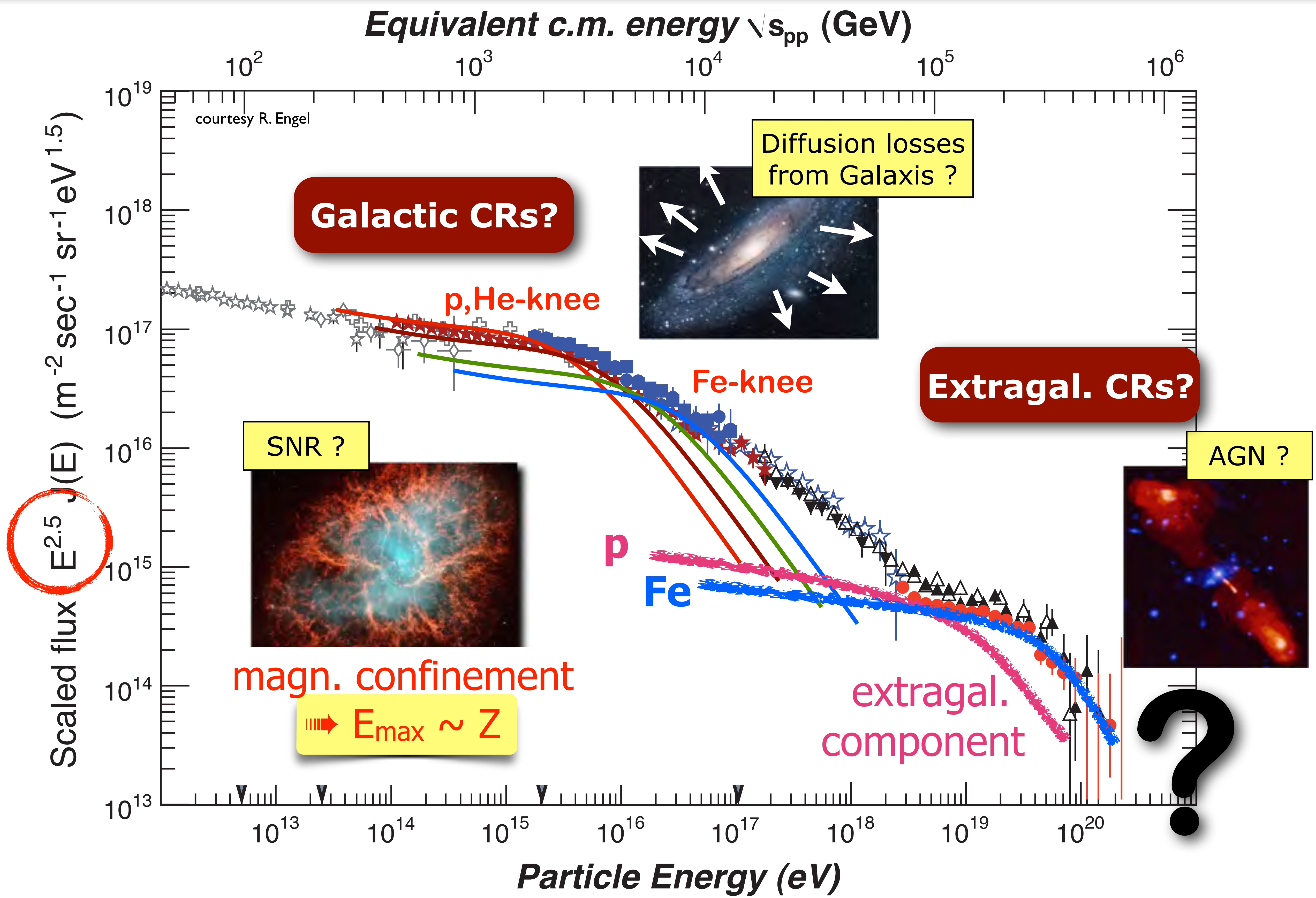
Features of CR spectrum



Features of CR spectrum

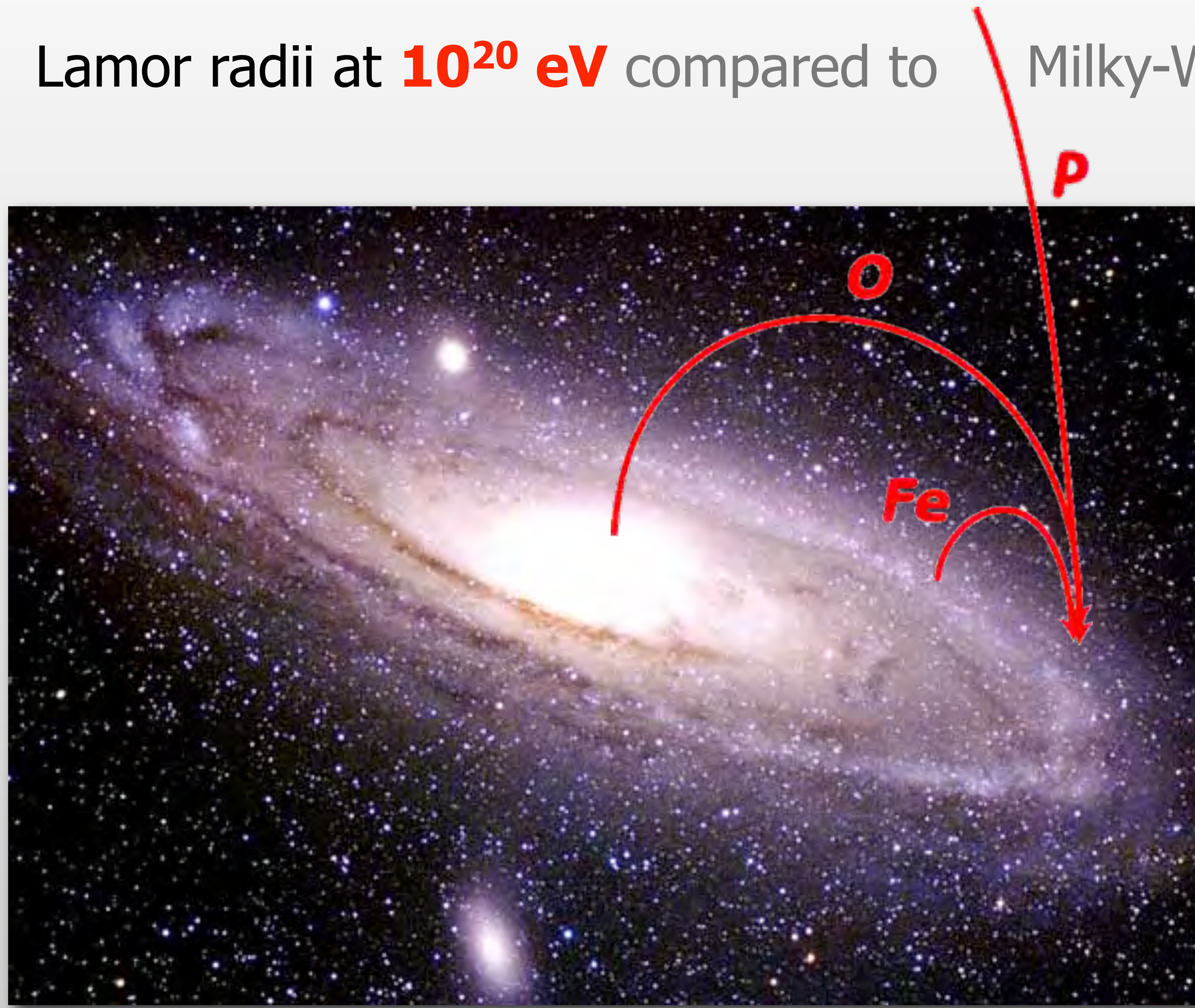


Features of CR spectrum



10^{20} eV CRs in our Galaxy ?

Lamor radii at **10^{20} eV** compared to Milky-Way



$$E_{18} \leq Z \cdot B_{\mu G} \cdot R_{kpc}$$

Size × B-Field needs to be very large …

Conjecture:
Extragalactic origin

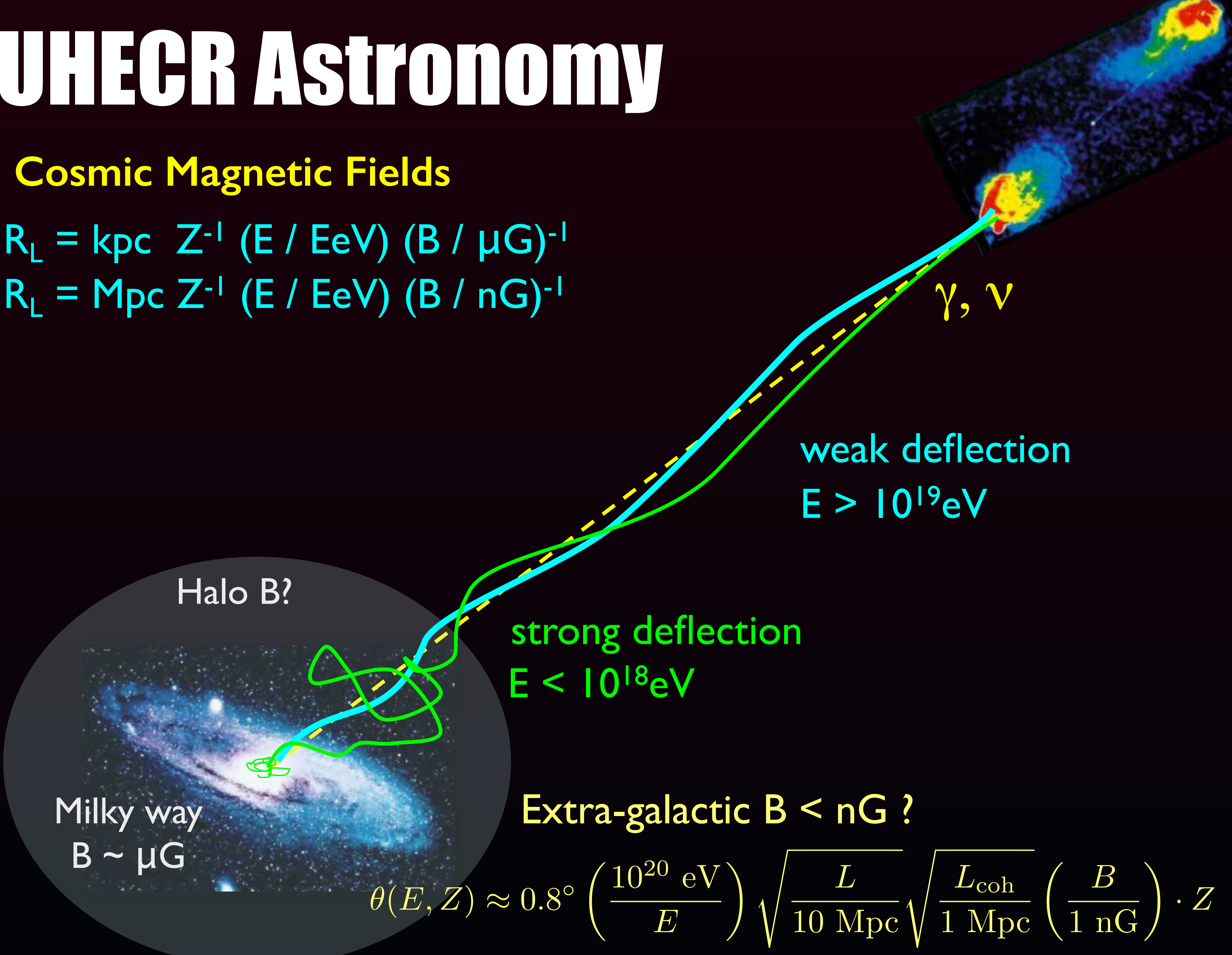
Interesting feature:
Can do astronomy with cosmic rays !

UHECR Astronomy

Cosmic Magnetic Fields

R_L = kpc Z^{-1} (E / EeV) (B / μG)$^{-1}$

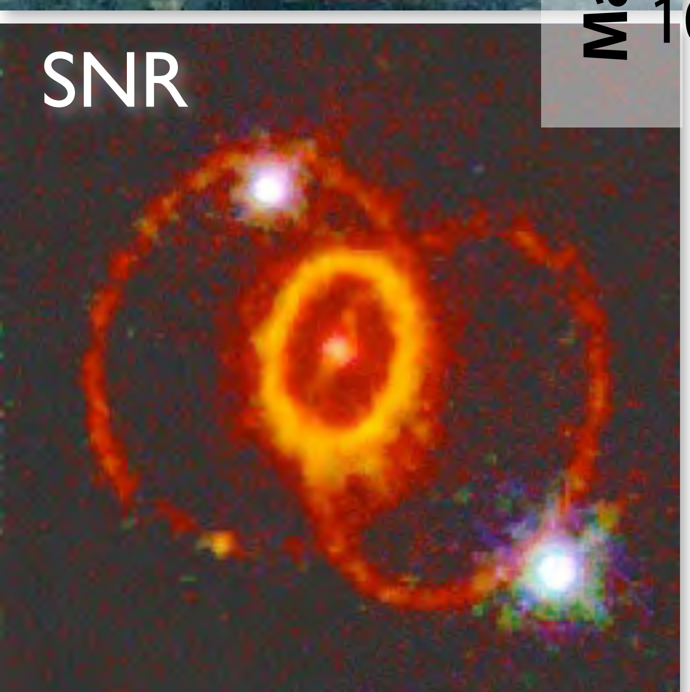
R_L = Mpc Z^{-1} (E / EeV) (B / nG)$^{-1}$

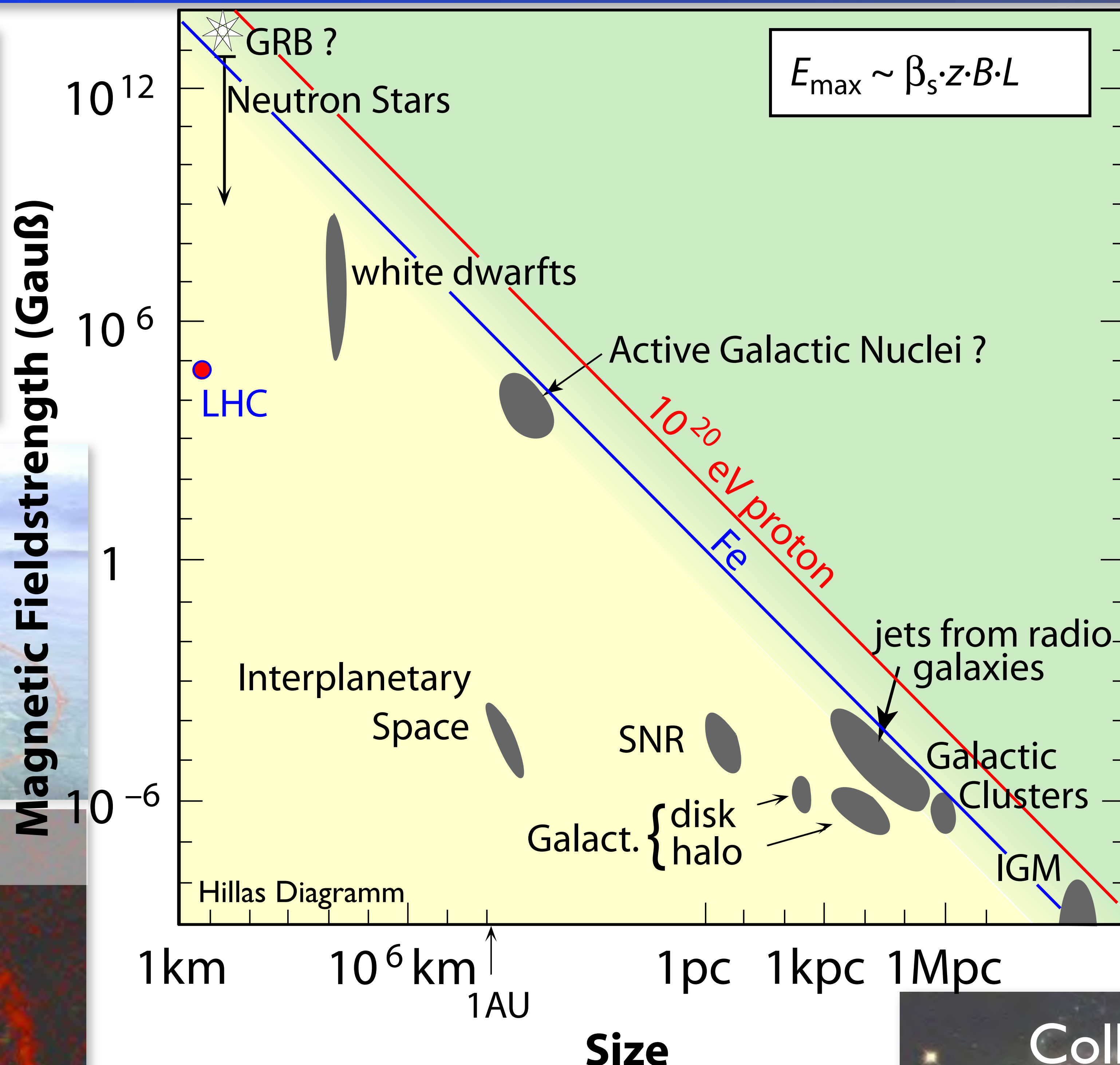


Extra-galactic B < nG ?

$$\theta(E,Z) \approx 0.8^\circ \left(\frac{10^{20}\ \mathrm{eV}}{E}\right)\sqrt{\frac{L}{10\ \mathrm{Mpc}}}\sqrt{\frac{L_{\mathrm{coh}}}{1\ \mathrm{Mpc}}}\left(\frac{B}{1\ \mathrm{nG}}\right)\cdot Z$$

Potential Sources of 10^{20} eV particles



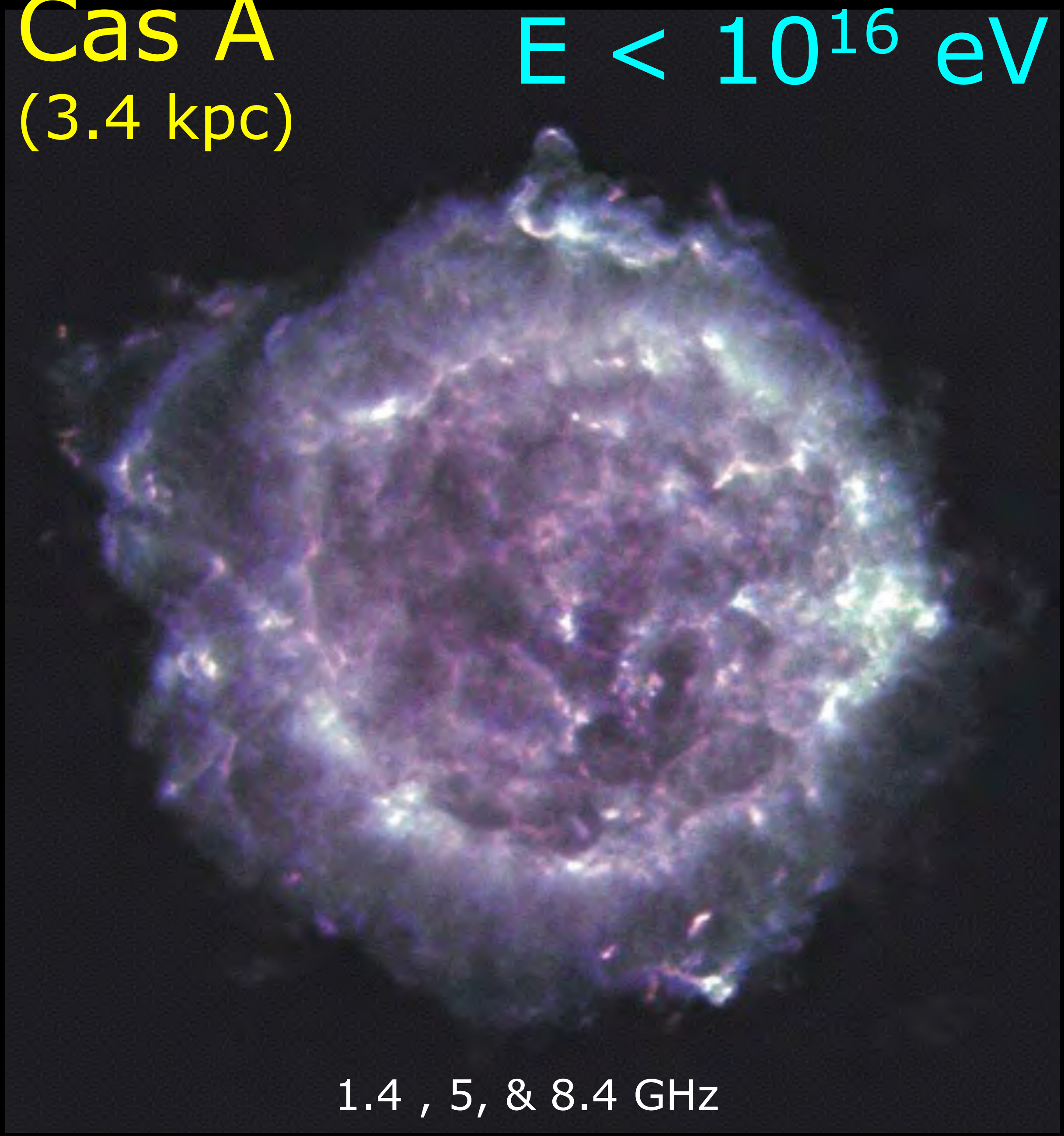


Realistic constraints more severe

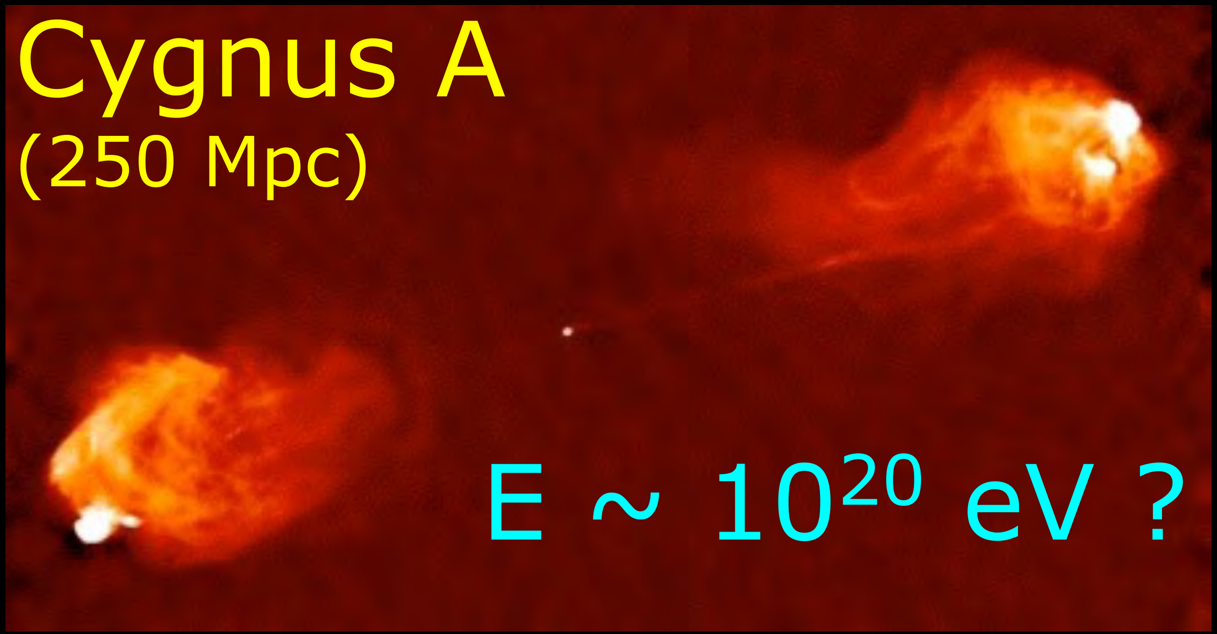
- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

Radio Images of Cosmic Accelerators

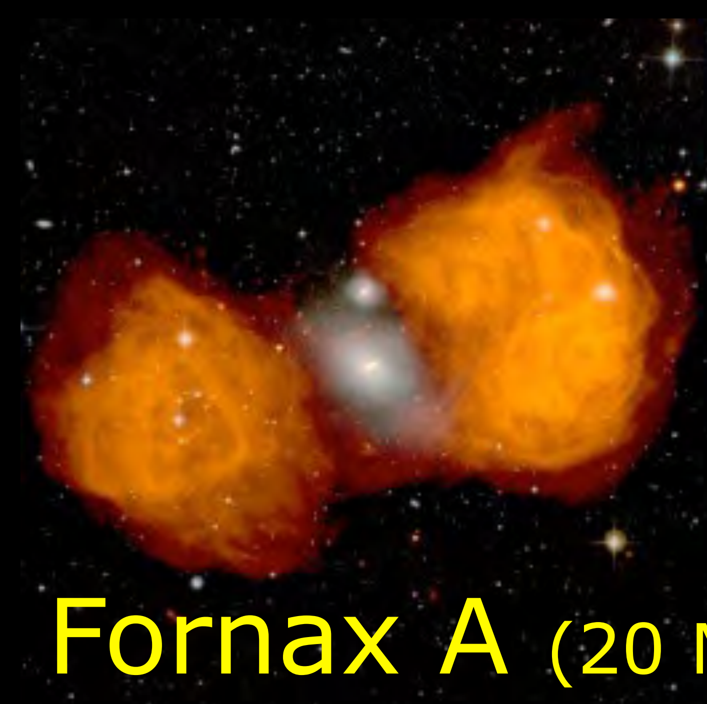
Supernova Remnants



Accreting Supermassive Black Holes

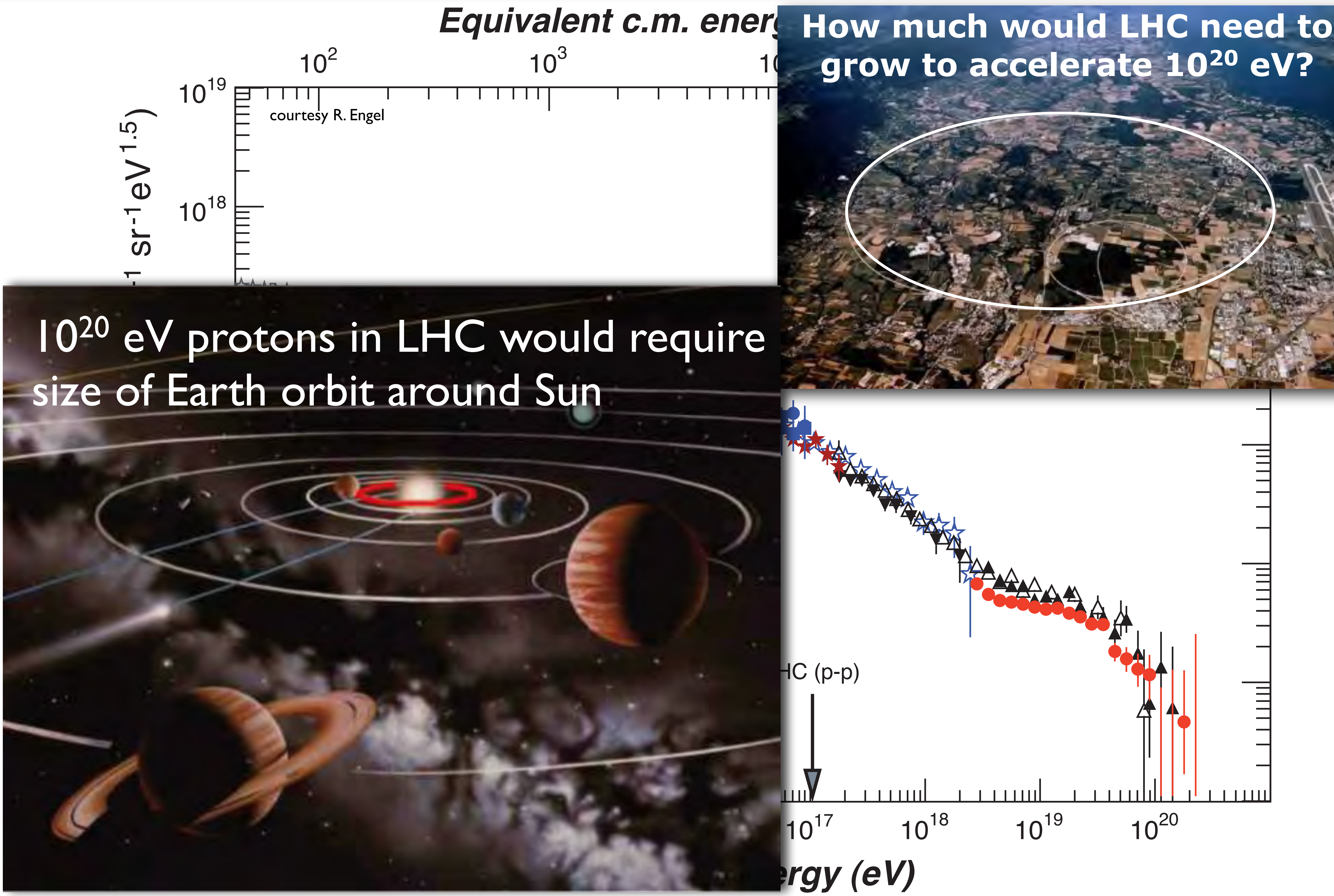


NRAO/AUI



Fornax A (20 Mpc)

The Cosmic Zevatron



1962: The First 10^{20} eV Event

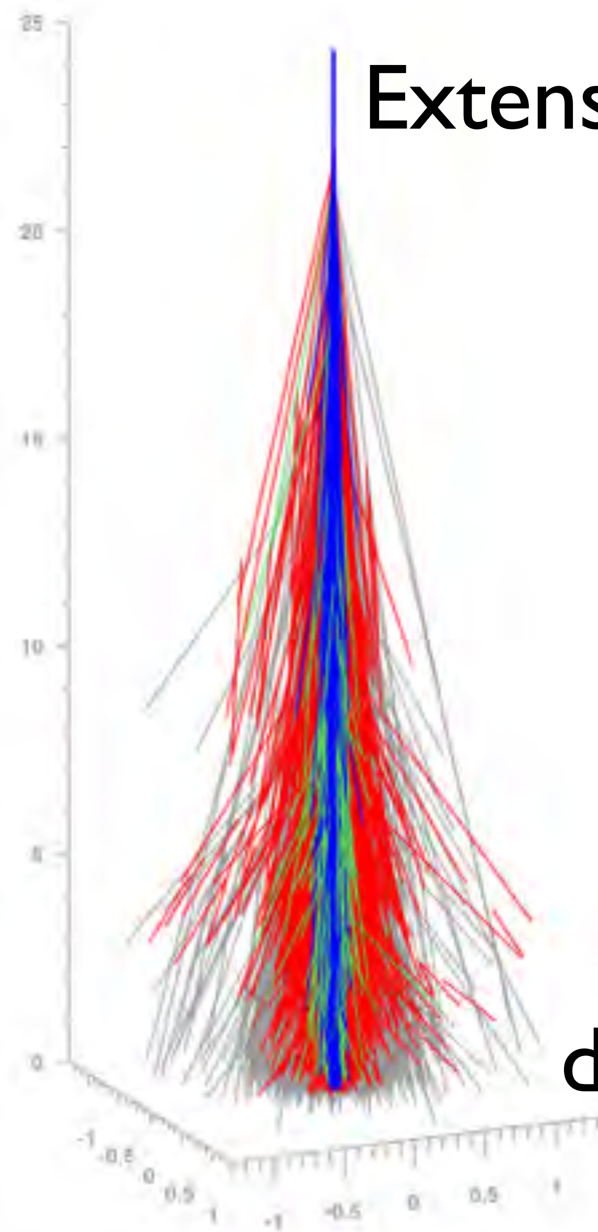
VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 10 January 1963)

Volcano Ranch Air Shower Array, New Mexico



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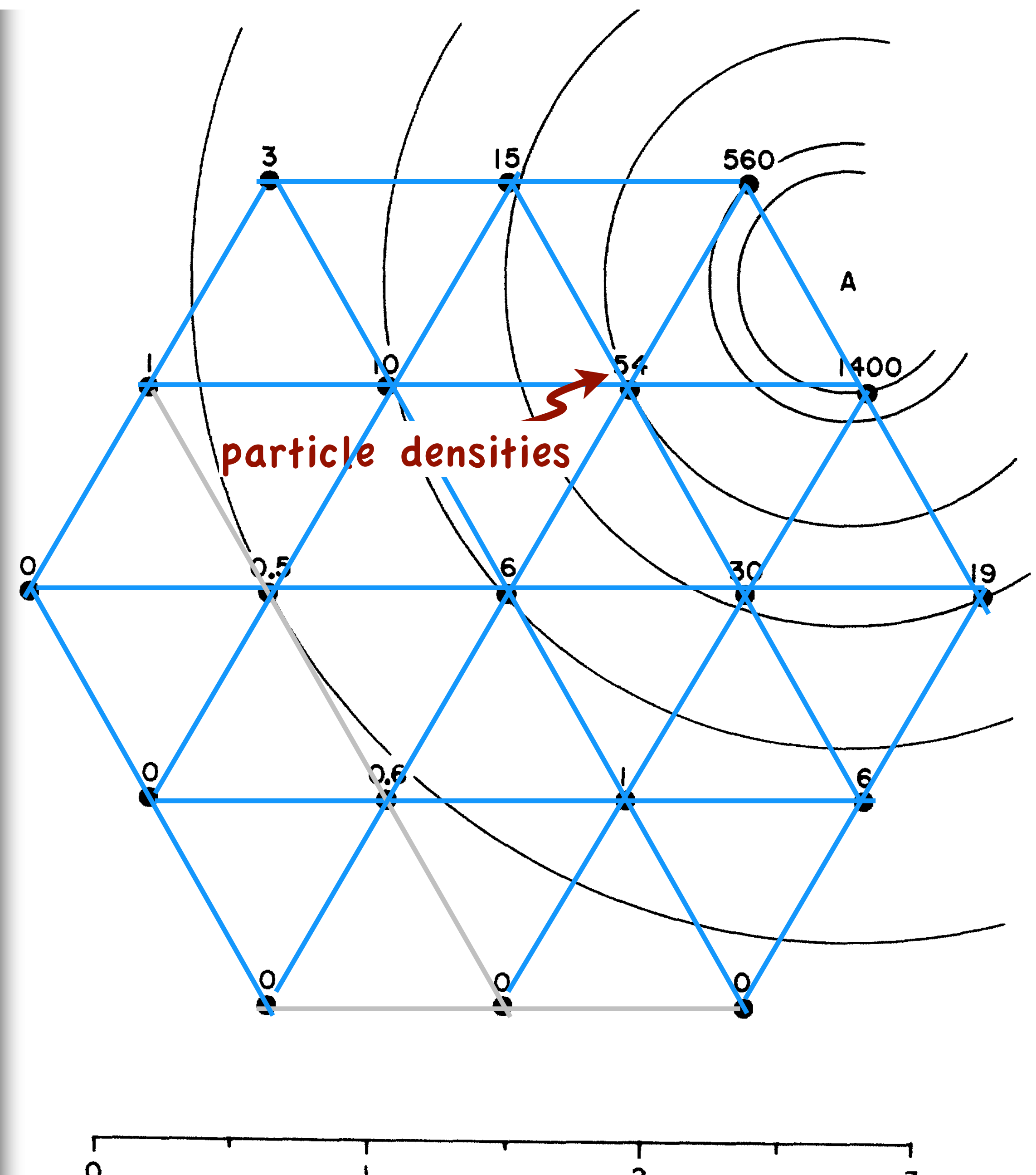
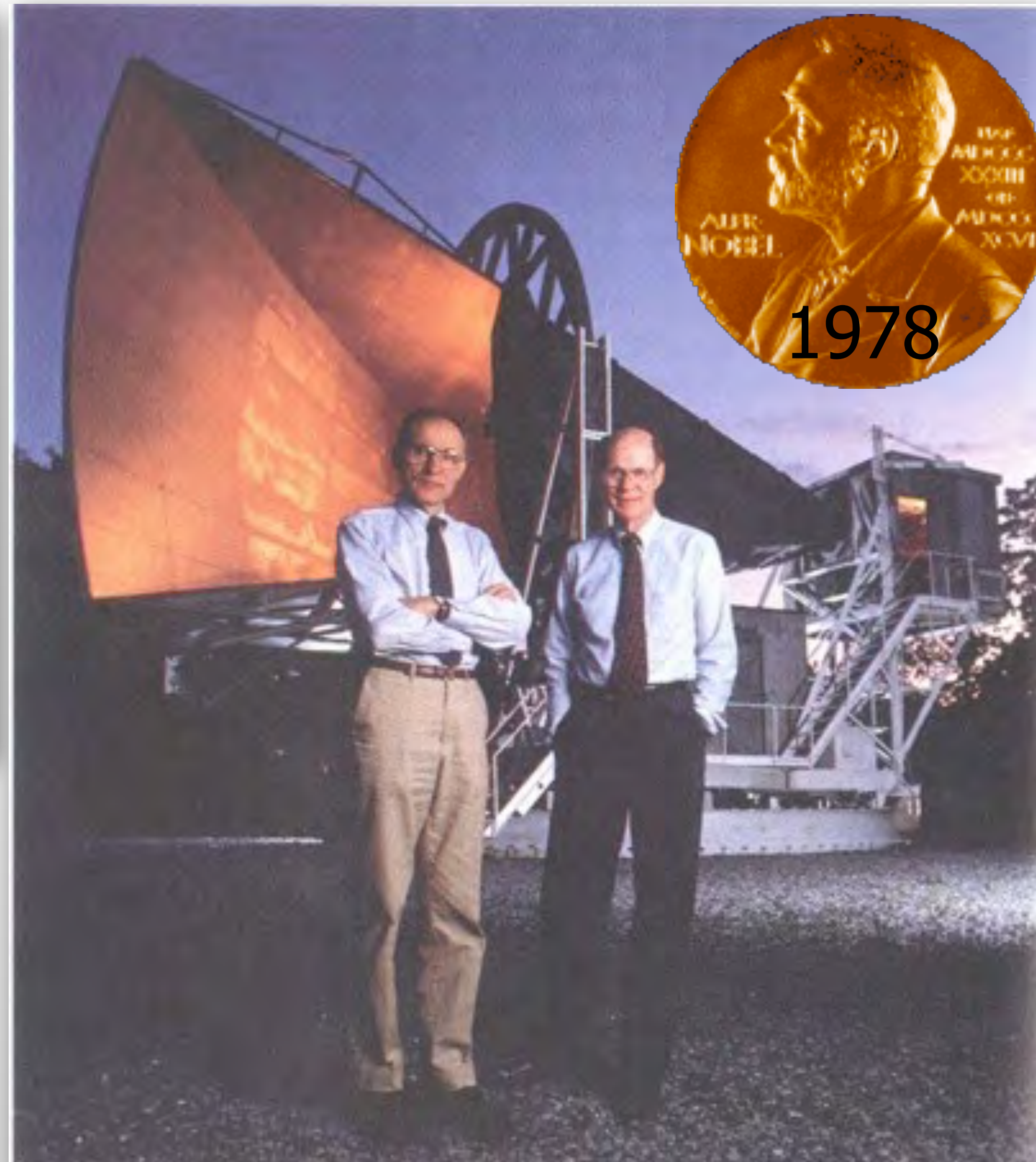


1965: Discovery of CMB

G. Gamow



Penzias & Wilson

Measurements @
4.08 GHz (7.35 cm)

1966: „End to the CR Spectrum ?"

VOLUME 16, NUMBER 17 PHYSICAL REVIEW LETTERS 25 APRIL 1966

END TO THE COSMIC-RAY SPECTRUM?

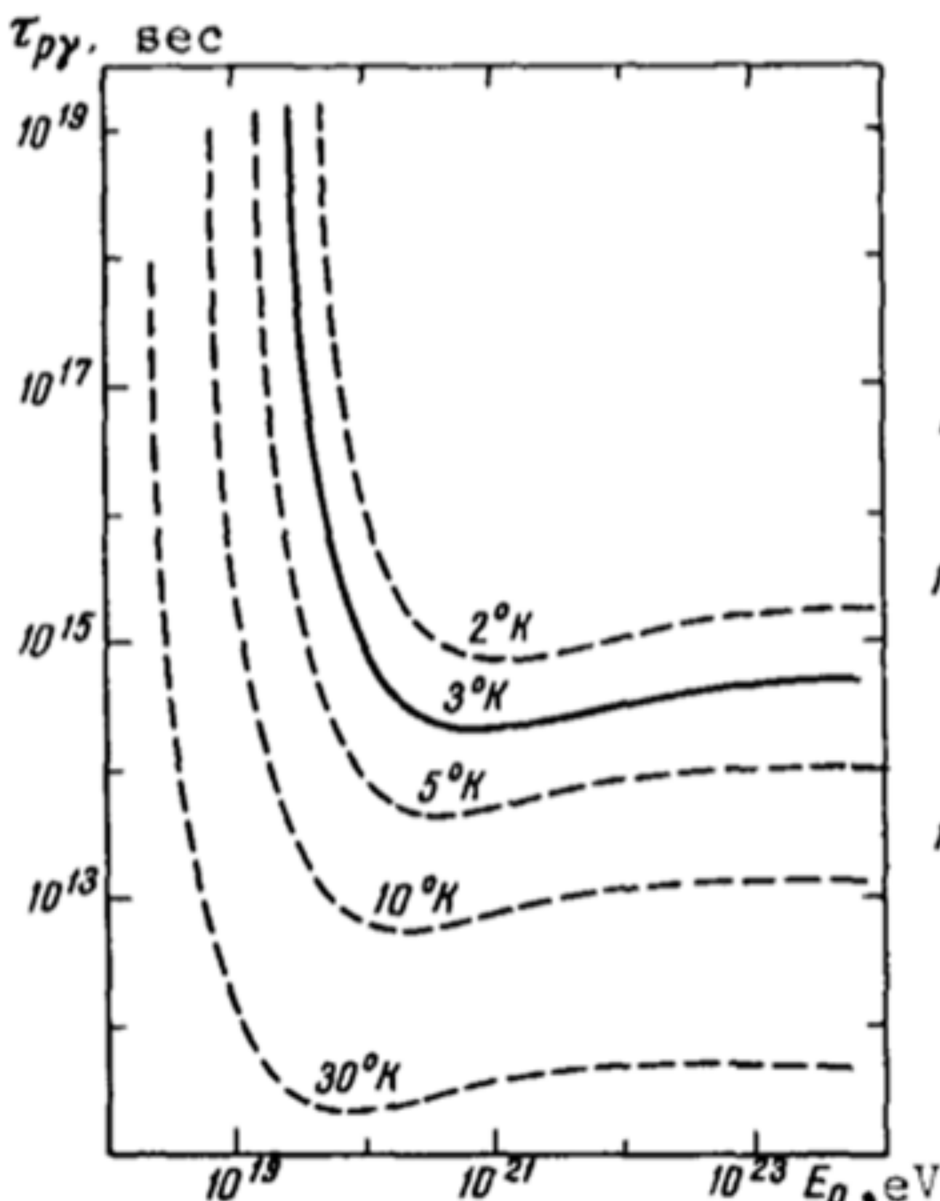
Kenneth Greisen

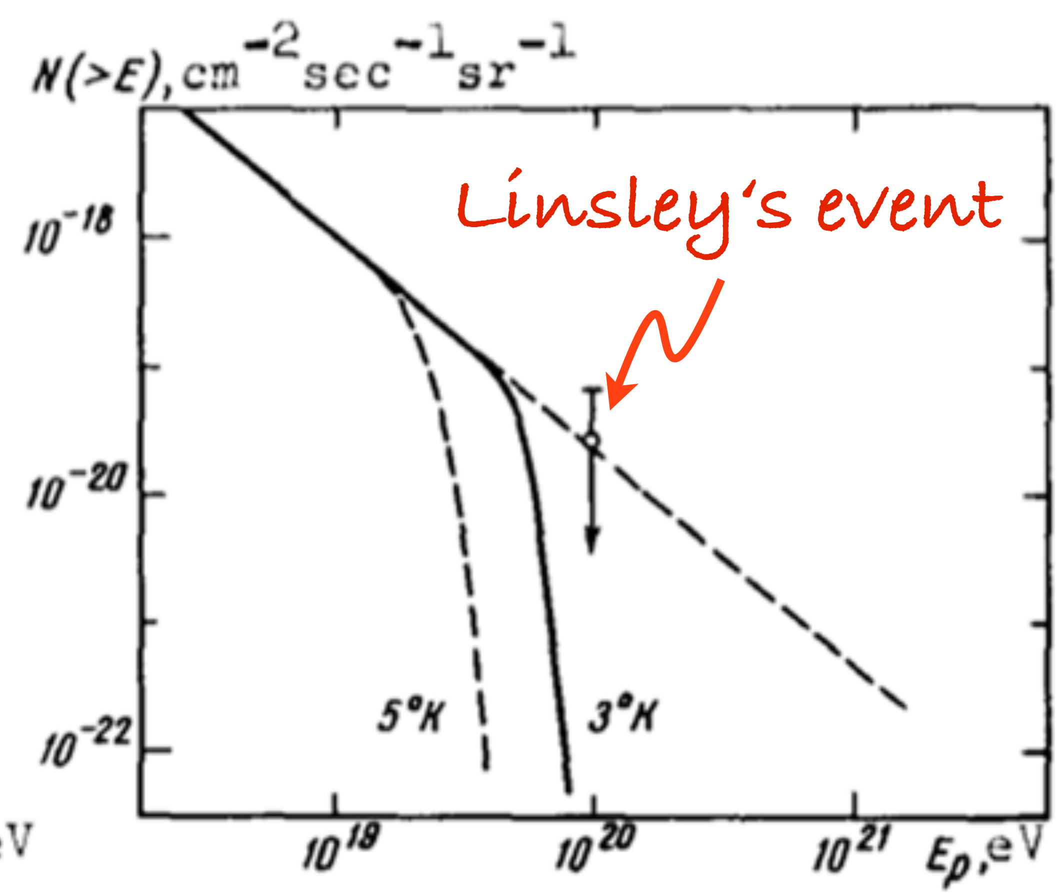
Cornell University, Ithaca, New York
(Received 1 April 1966)

Greisen,
Zatsepin & Kuz'min

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





GZK-effect: Rapid Energy Loss of p & nuclei in CMB

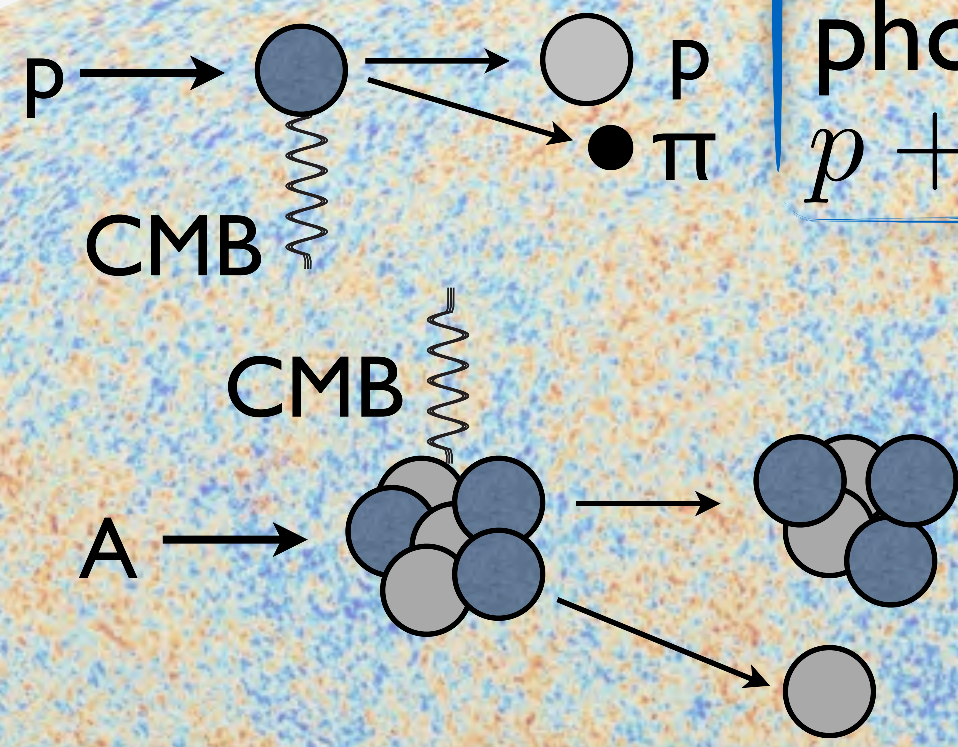
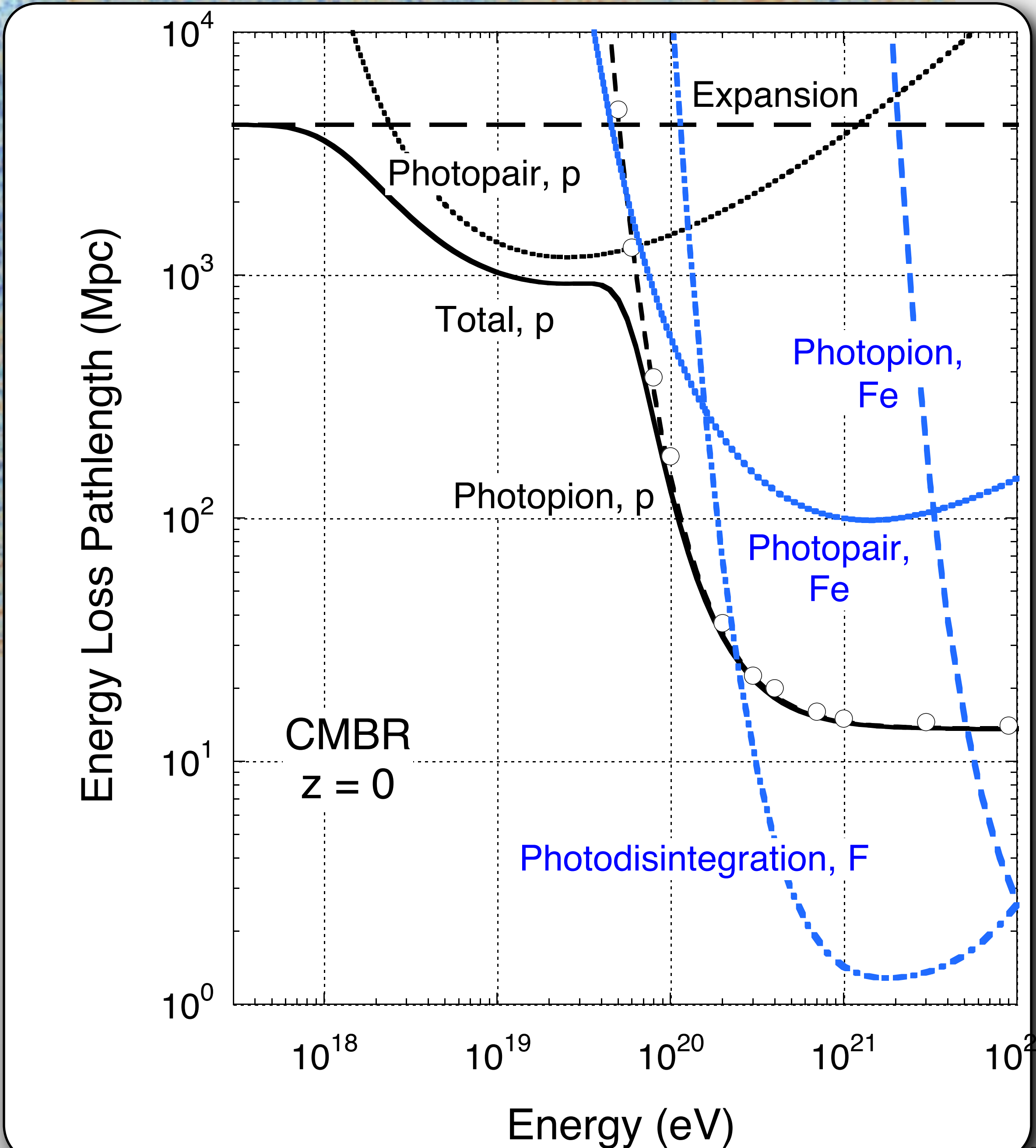


photo-pion production

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow p + \pi^0$$

photo disintegration

$$A + \gamma_{\mathrm{CMB}} \rightarrow (A-1) + n\ldots$$



Greisen-Zatsepin-Kuz'min (1966)

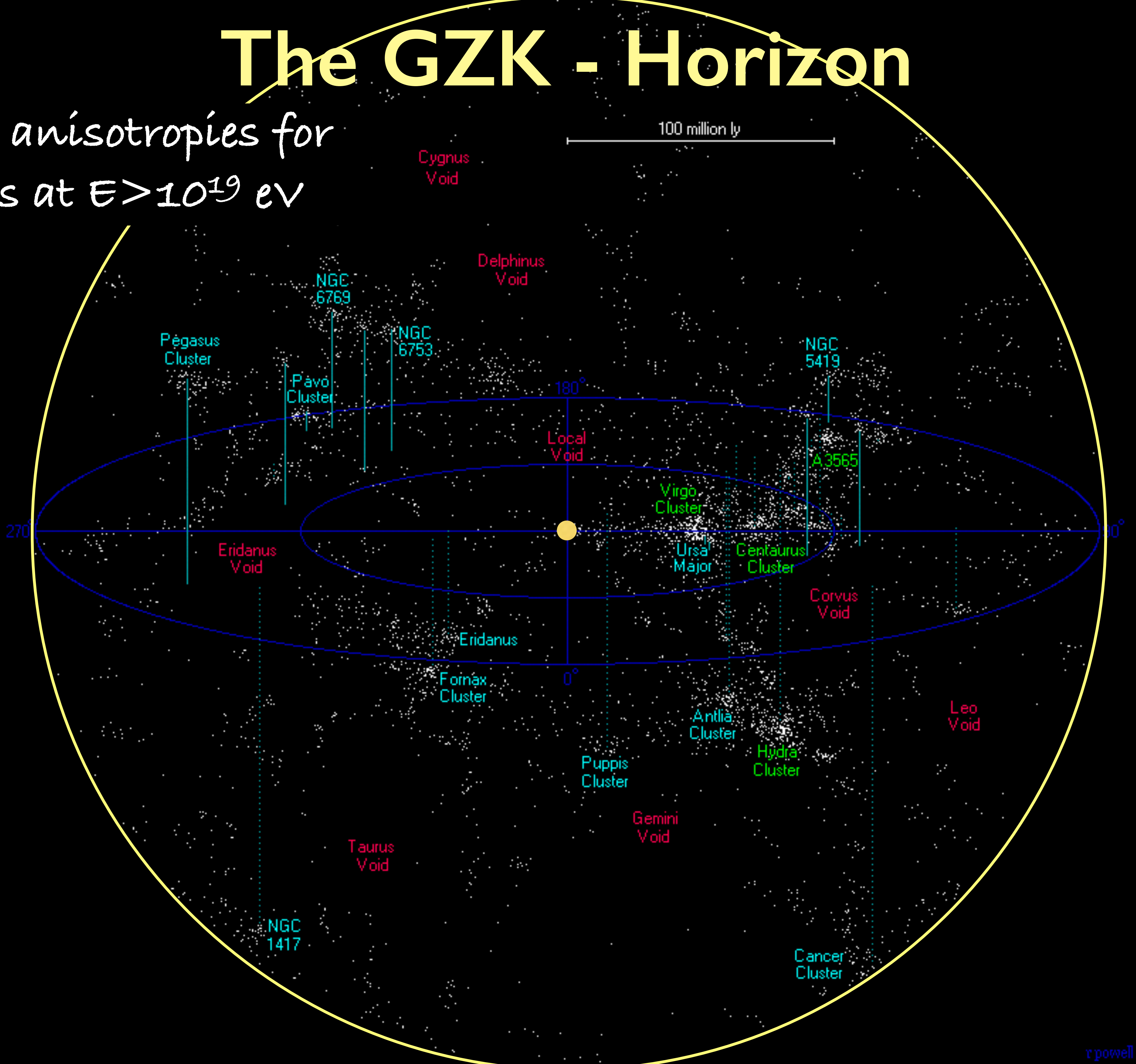
threshold: $E_p E_\gamma > (m_\Delta^2 - m_p^2)$

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

➙ **GZK-Horizon ~ 60 Mpc**

The GZK - Horizon

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



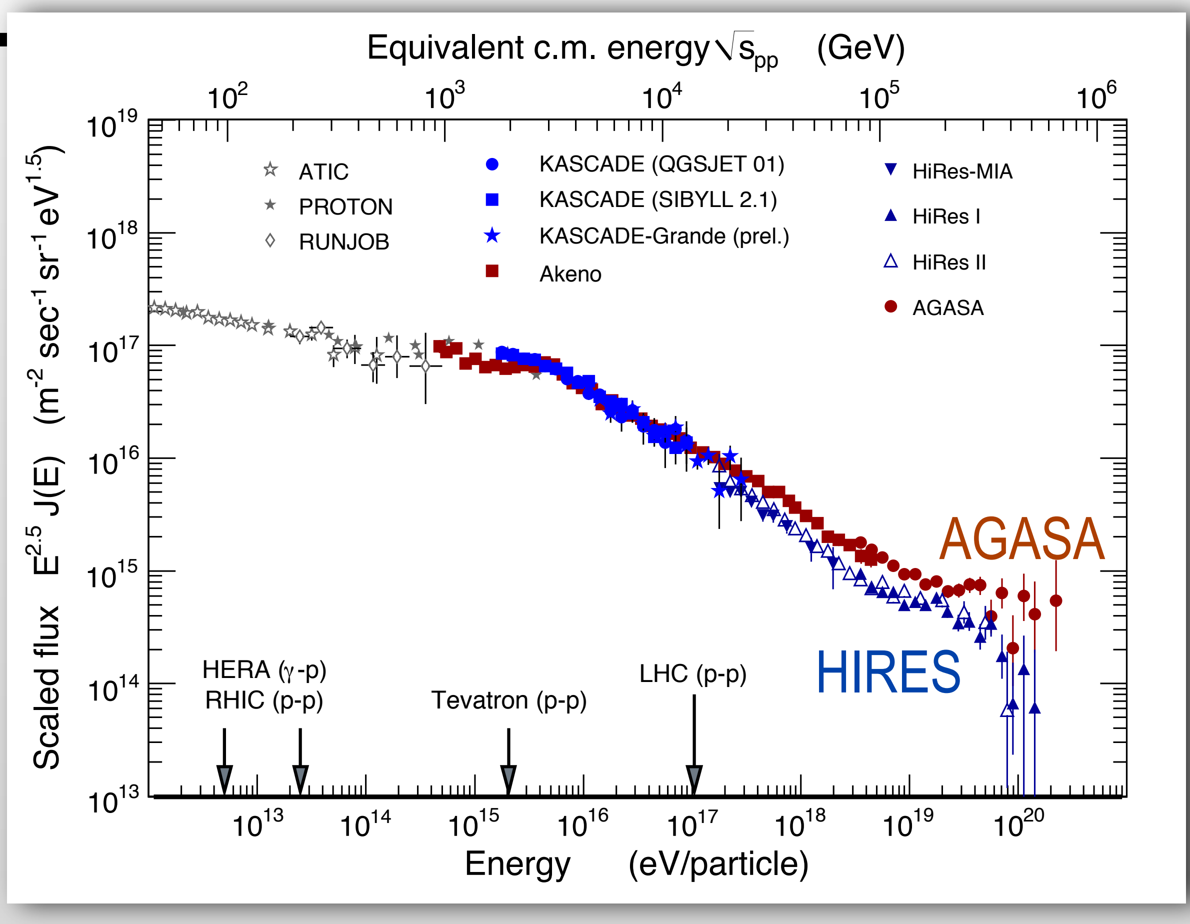
Situation ~8 years ago

Experiments: AGASA, HiRes, Haverah Park, Yakutsk, SUGAR

- does the GZK-suppression exist?
  - Flux data contradictory

    AGASA ➙ no suppression

    HiRes ➙ possibly a suppression
- Composition mostly protons
- Apparent isotropy



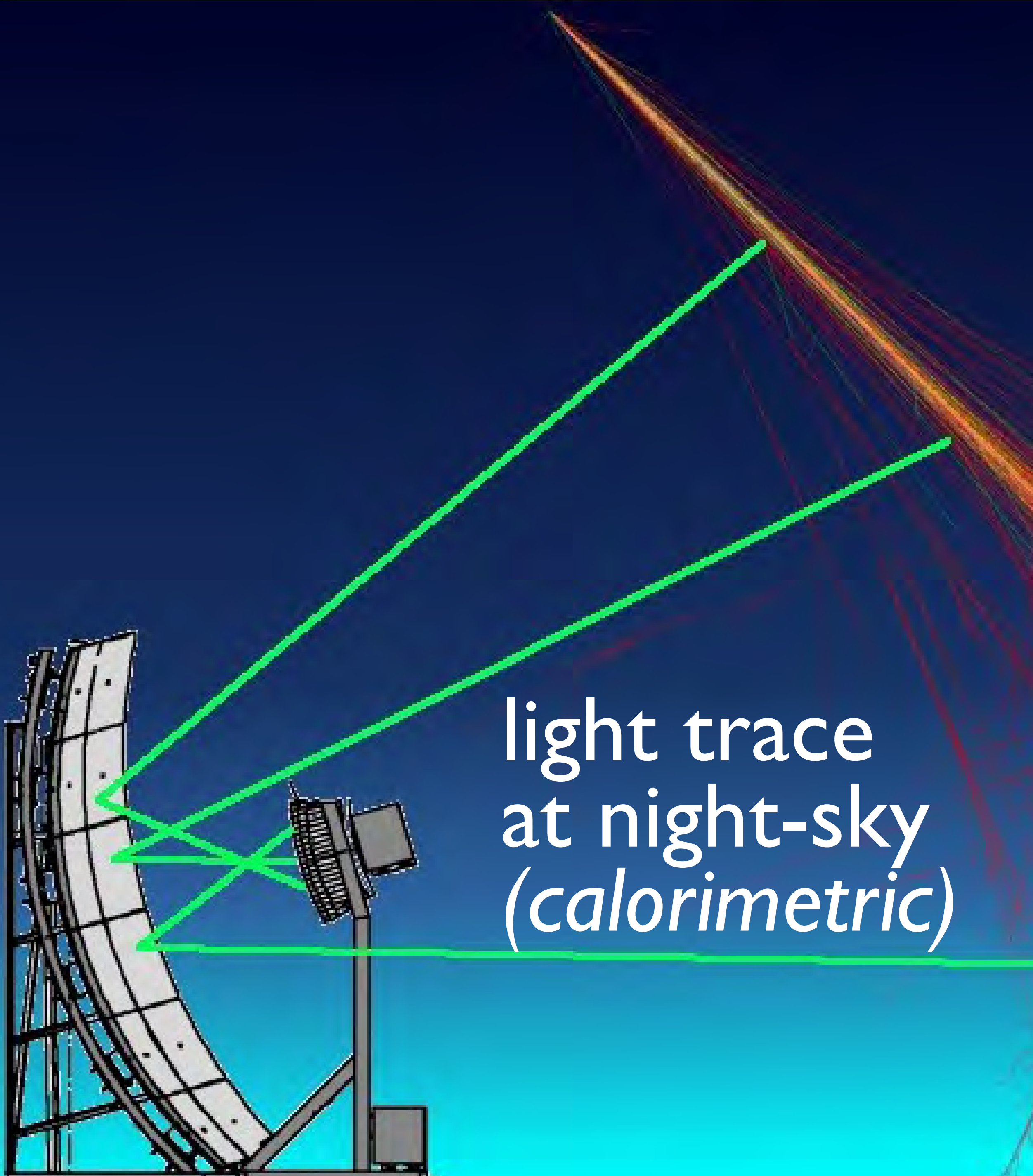
Apparent continuation of spectrum in AGASA gave birth to exotic source and propagation scenarios

- Top Down Models
  - Topological Defects, Super-Heavy Dark Matter Particles, WIMPzillas, Cryptons, ...
- Z-Burst Model ➙ massive neutrinos

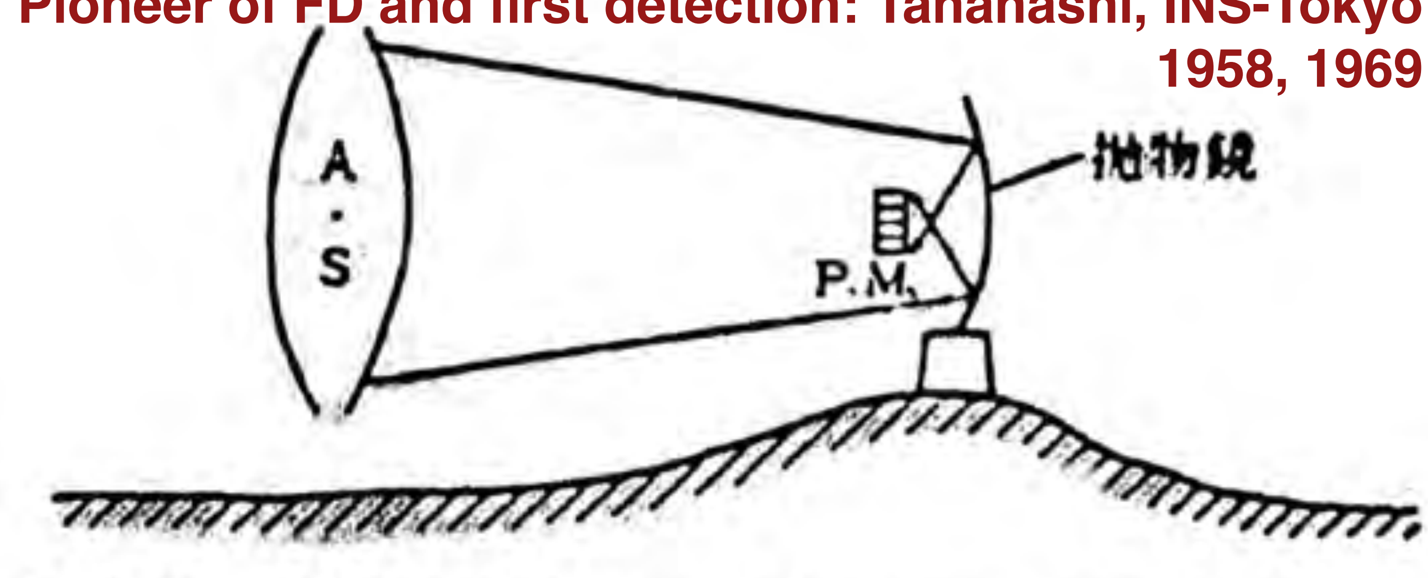
➙ expect EHE γ's and ν's

A New Generation: Hybrid Observation of EAS

Concept pioneered by the
Pierre Auger Collaboration
(Fully operational since 06/2008)
(Concept employed also by
Telescope Array (TA))



Pioneer of FD and first detection: Tanahashi, INS-Tokyo 1958, 1969



第3図 1958年乗鞍シンポジウムで話されたシャワー・カーブ測定の提案

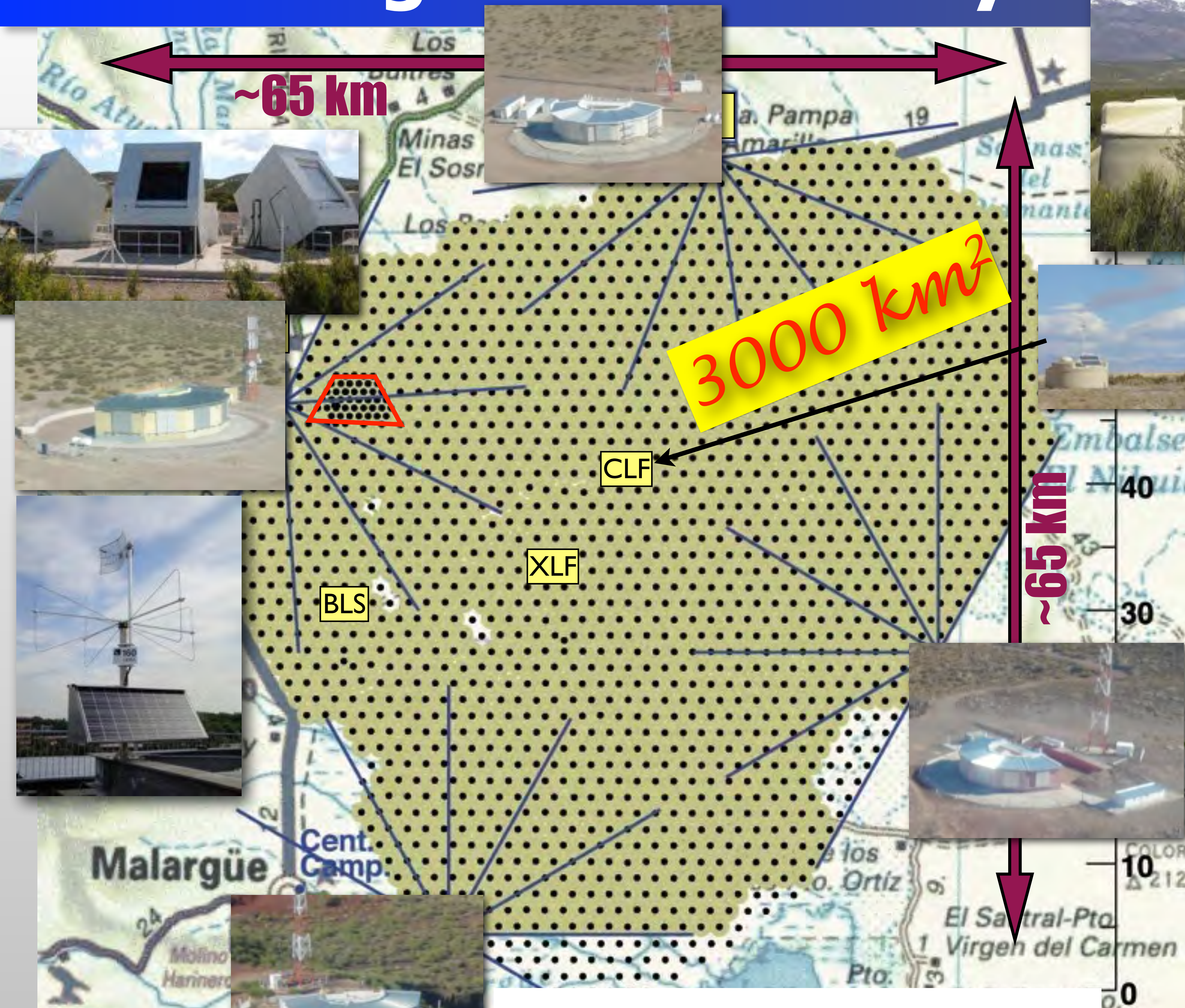
Kampert & Watson, EPJ H37 (2012) 359

Fluorescence light

Particle-density and -composition at ground

Also:
Detection of Radio- & Microwave-Signals

Pierre Auger Observatory

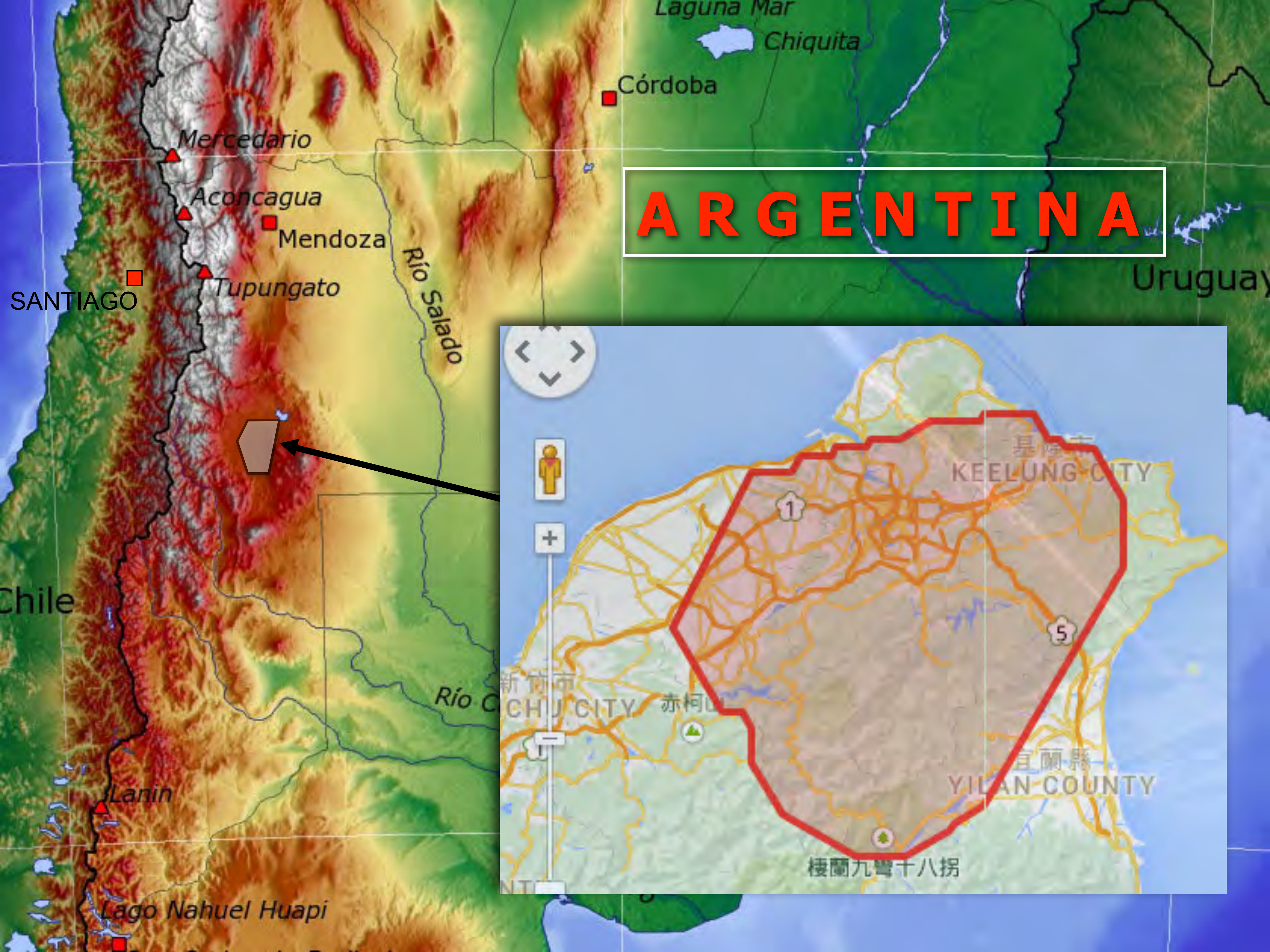


Province Mendoza, Argentina

1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

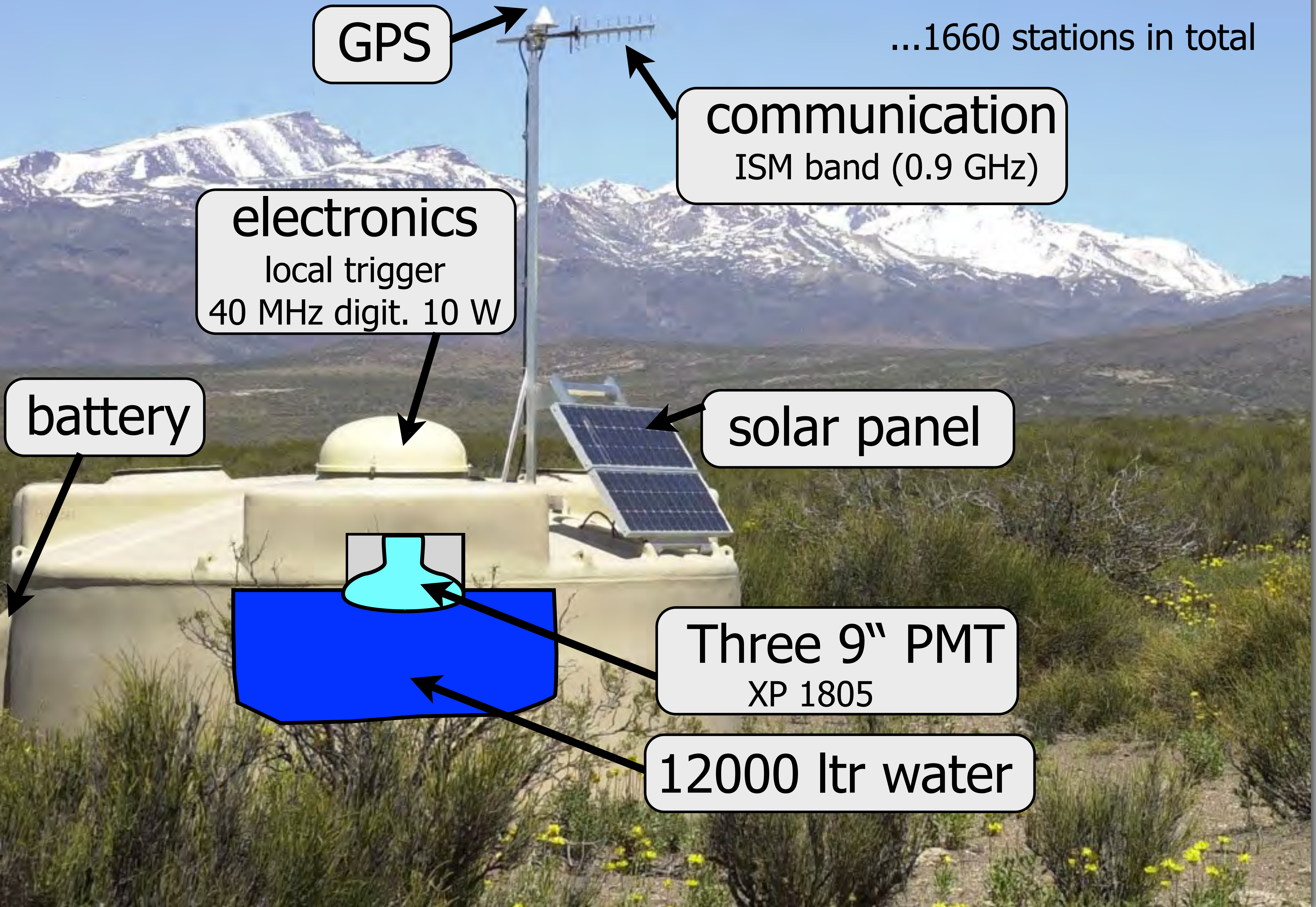
160 radio antennas


ARGENTINA
Laguna Mar Chiquita
Córdoba
Mercedario
Aconcagua
Mendoza
Río Salado
Tupungato
SANTIAGO
Uruguay
Chile
Lanin
Lago Nahuel Huapi
基隆市
KEELUNG CITY
宜蘭縣
YILAN COUNTY
棲蘭九彎十八拐

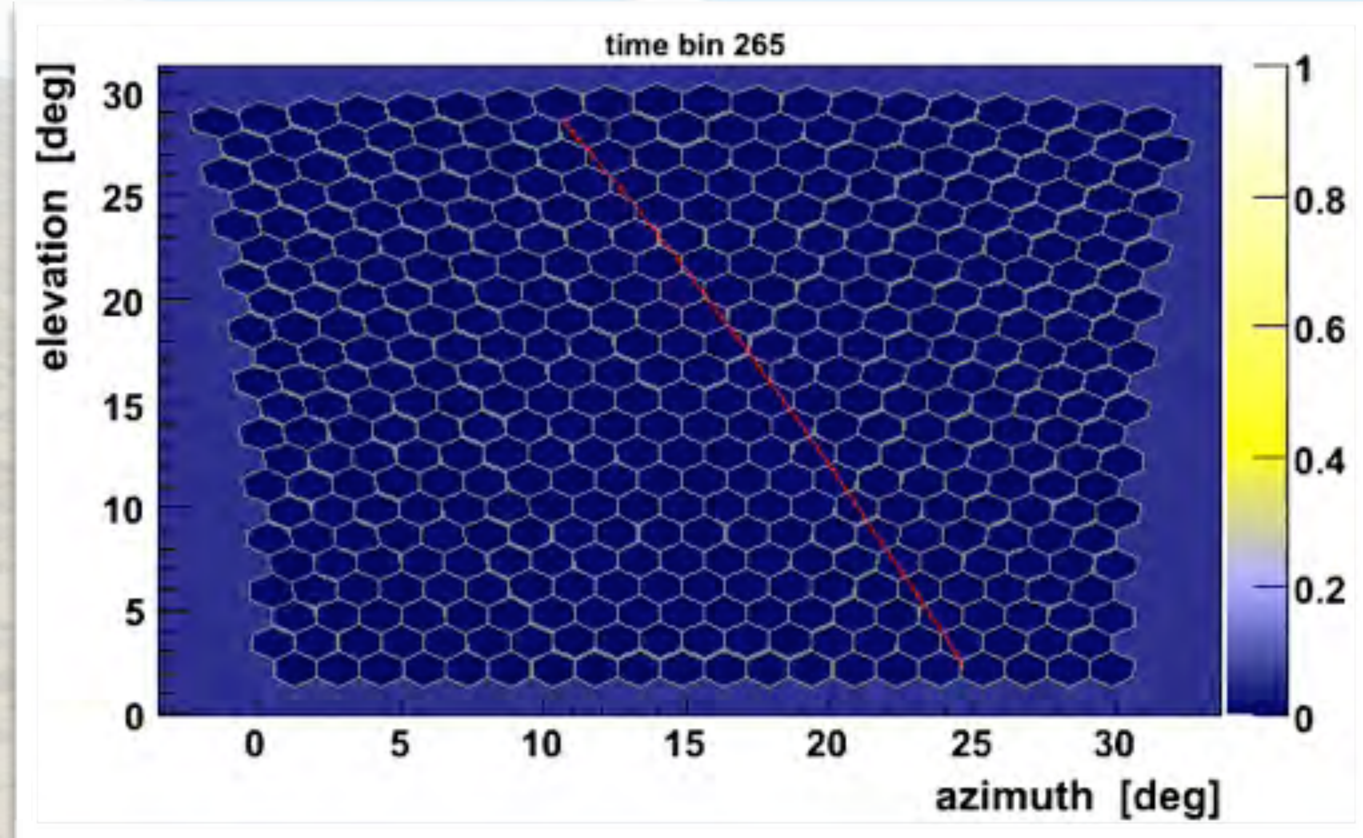
Water Cherenkov Station

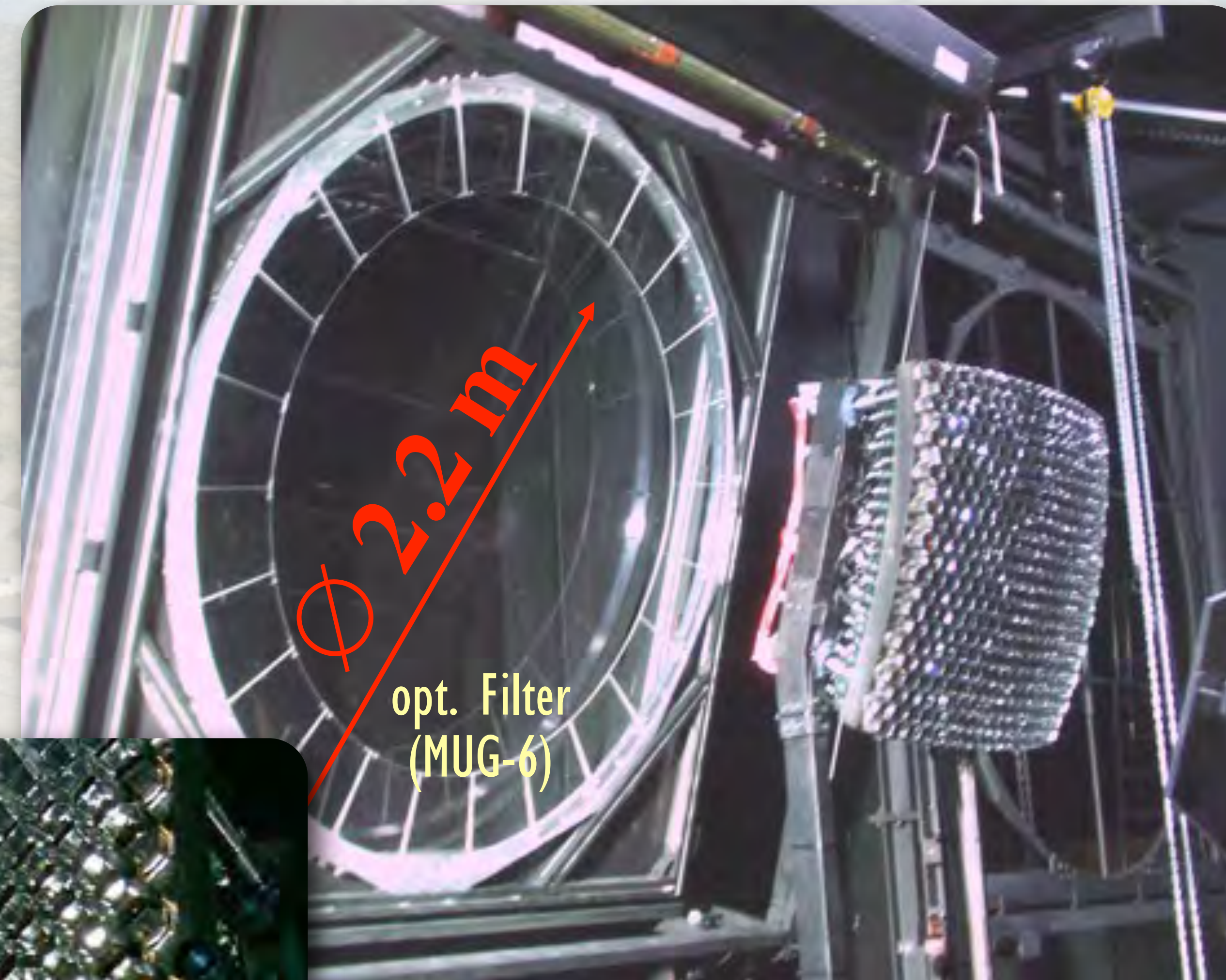
...1660 stations in total

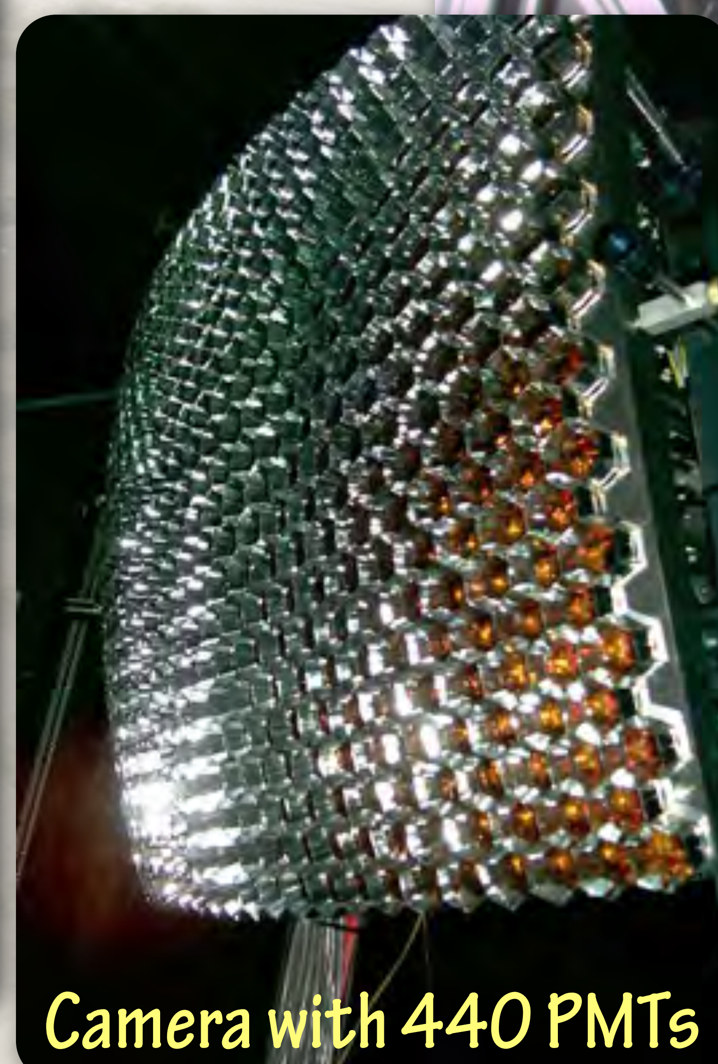
Water Cherenkov Station

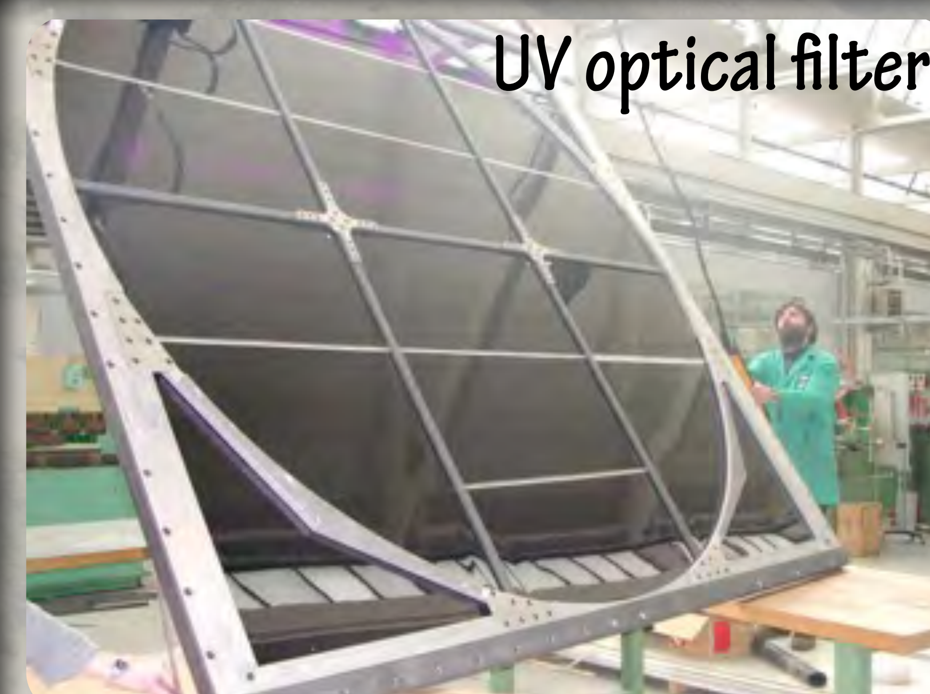


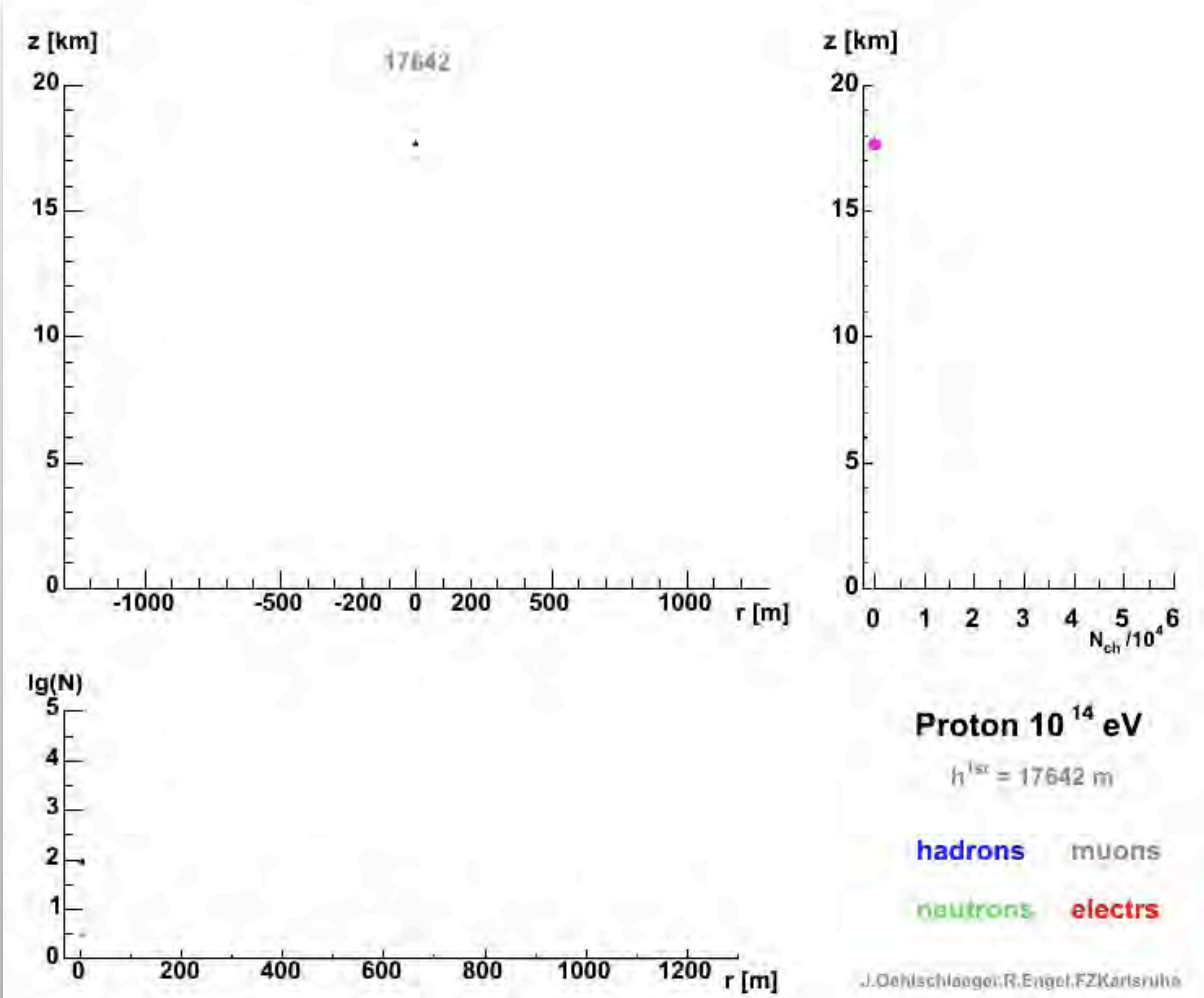

Google maps
Image © 2006 DigitalGlobe


time bin 265
elevation [deg]
azimuth [deg]
0
5
10
15
20
25
30
0
0.2
0.4
0.6
0.8
1


ϕ 2.2 m
opt. Filter
(MUG-6)


Camera with 440 PMTs


UV optical filter

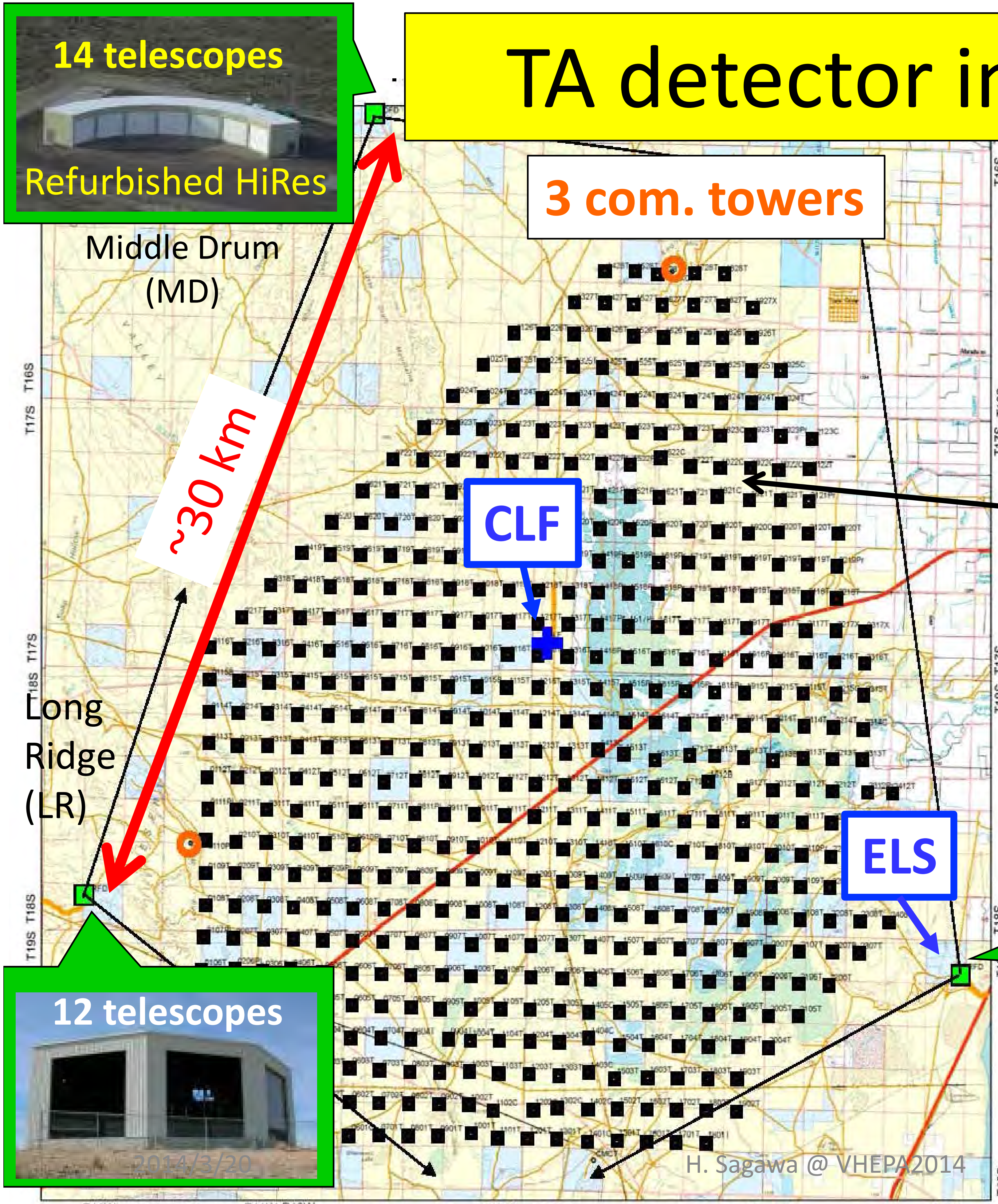

17642
z [km]
20
15
10
5
0
-1000
-500
-200
0
200
500
1000
r [m]
z [km]
0
1
2
3
4
5
6
$N_{ch}/10^4$
lg(N)
0
200
400
600
800
1000
1200
r [m]
Proton 10^{14} eV
h^{1st} = 17642 m
hadrons
muons
neutrons
electrs
J.Oehlschlaeger,R.Engel,FZKarlsruhe

Central Campus

Visitors are welcome (almost 100 000 visitors already)

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 km²

Fluorescence Detector(FD)

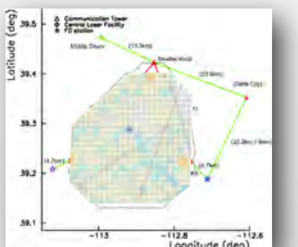
3 stations

38 telescopes

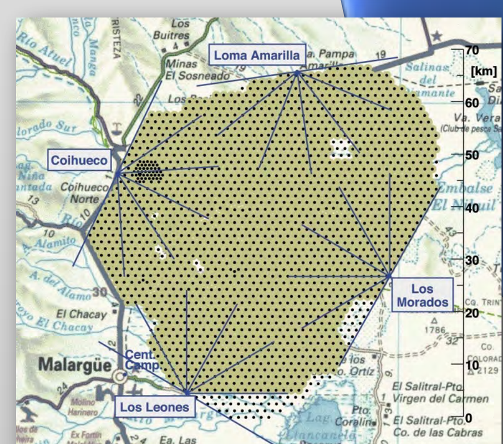
FD and SD: fully operational since 2008/May

Auger and TA

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes



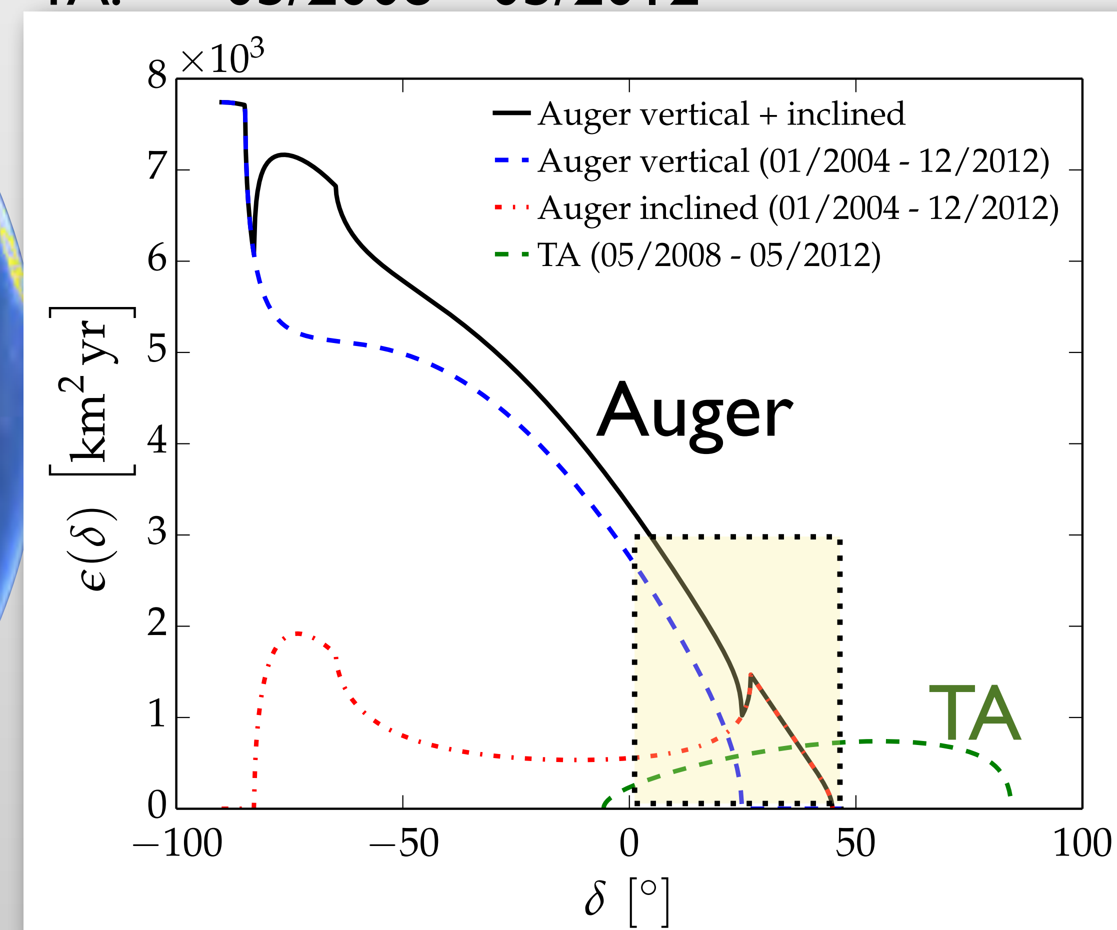
same
scale



Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

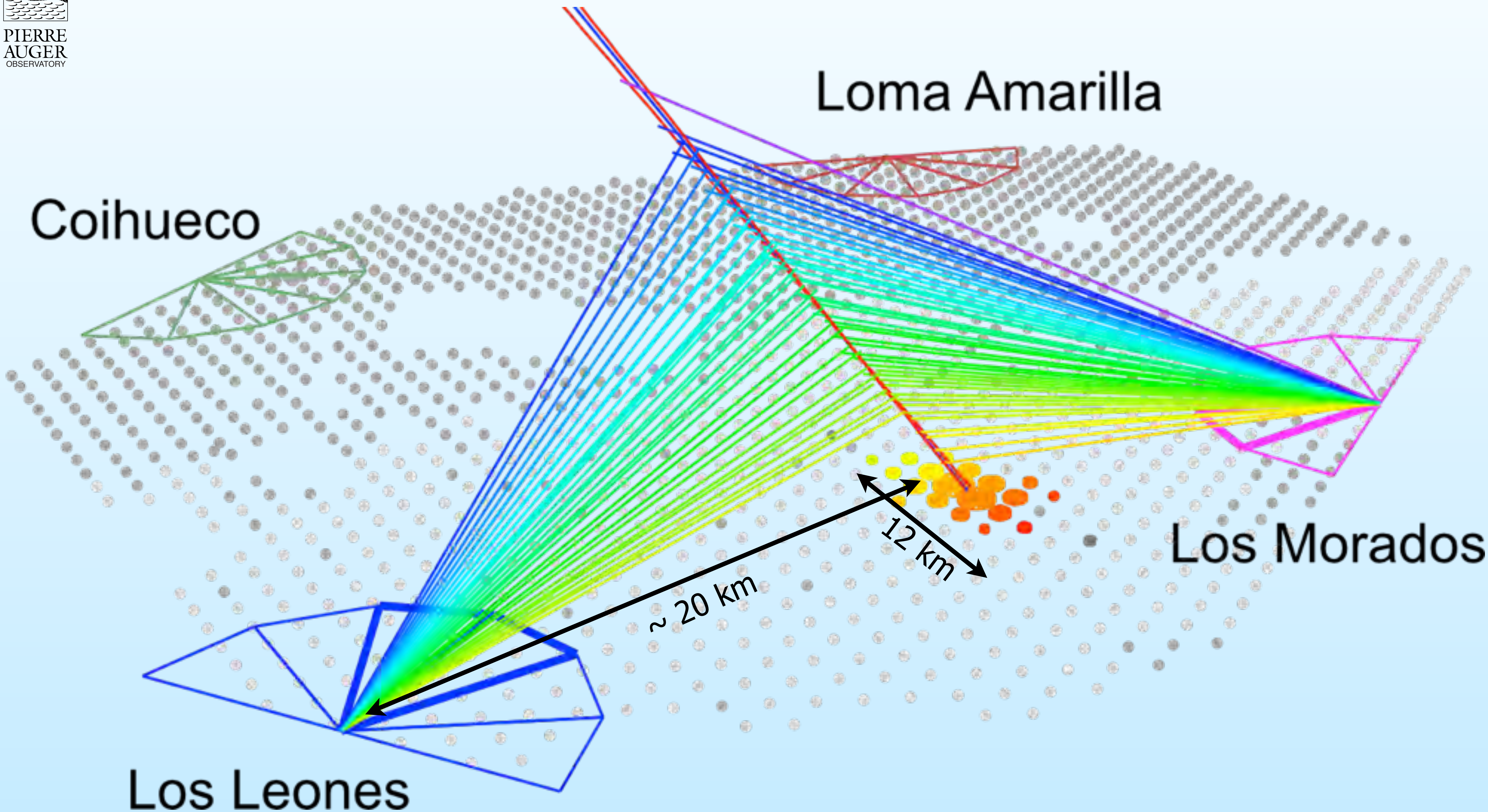
Auger and TA can see the same sky

Auger: 01/2004 - 12/2012
TA: 05/2008 - 05/2012



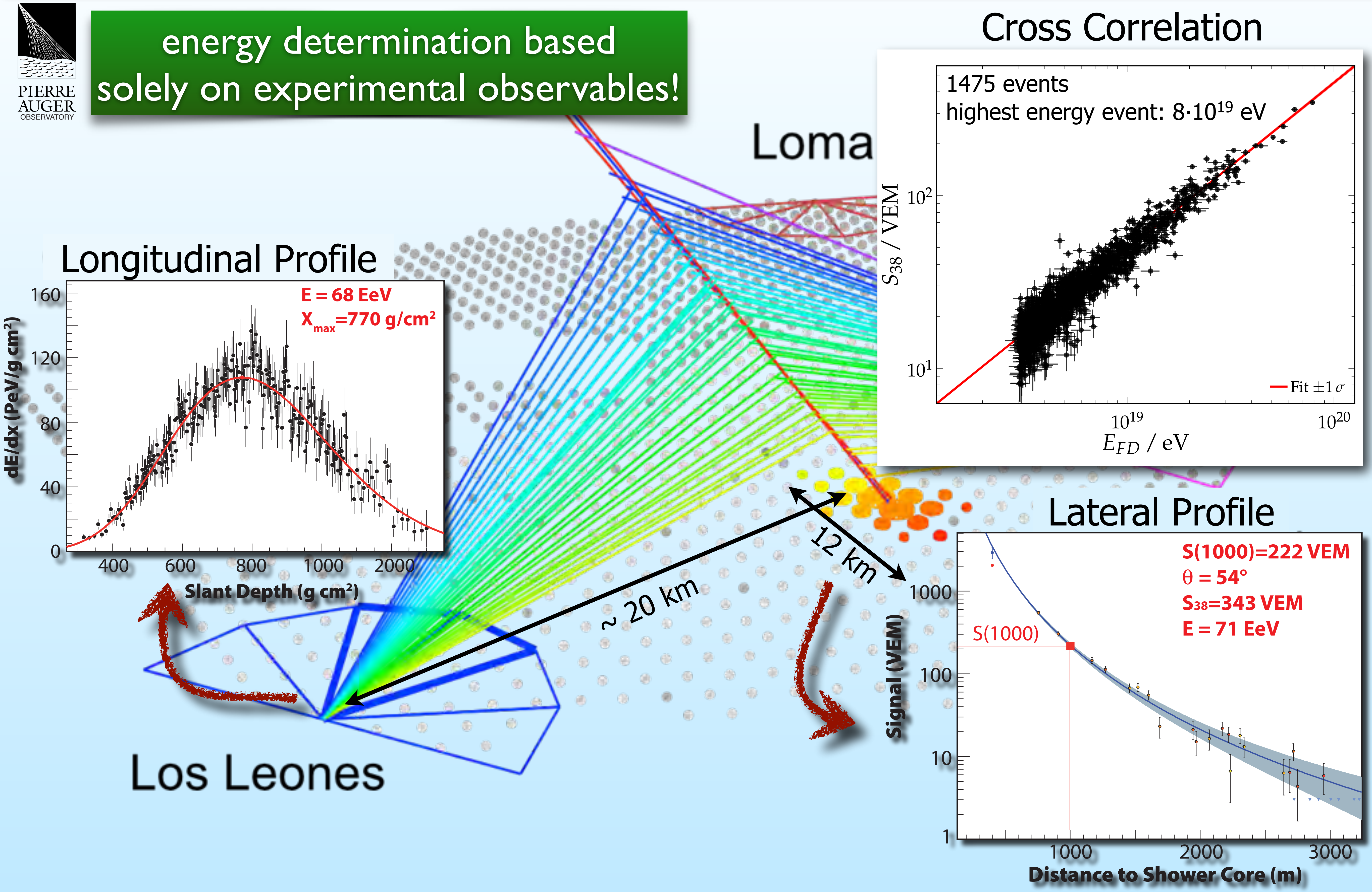
Auger exposure ~10 times that of TA

Event Example in Auger Observatory



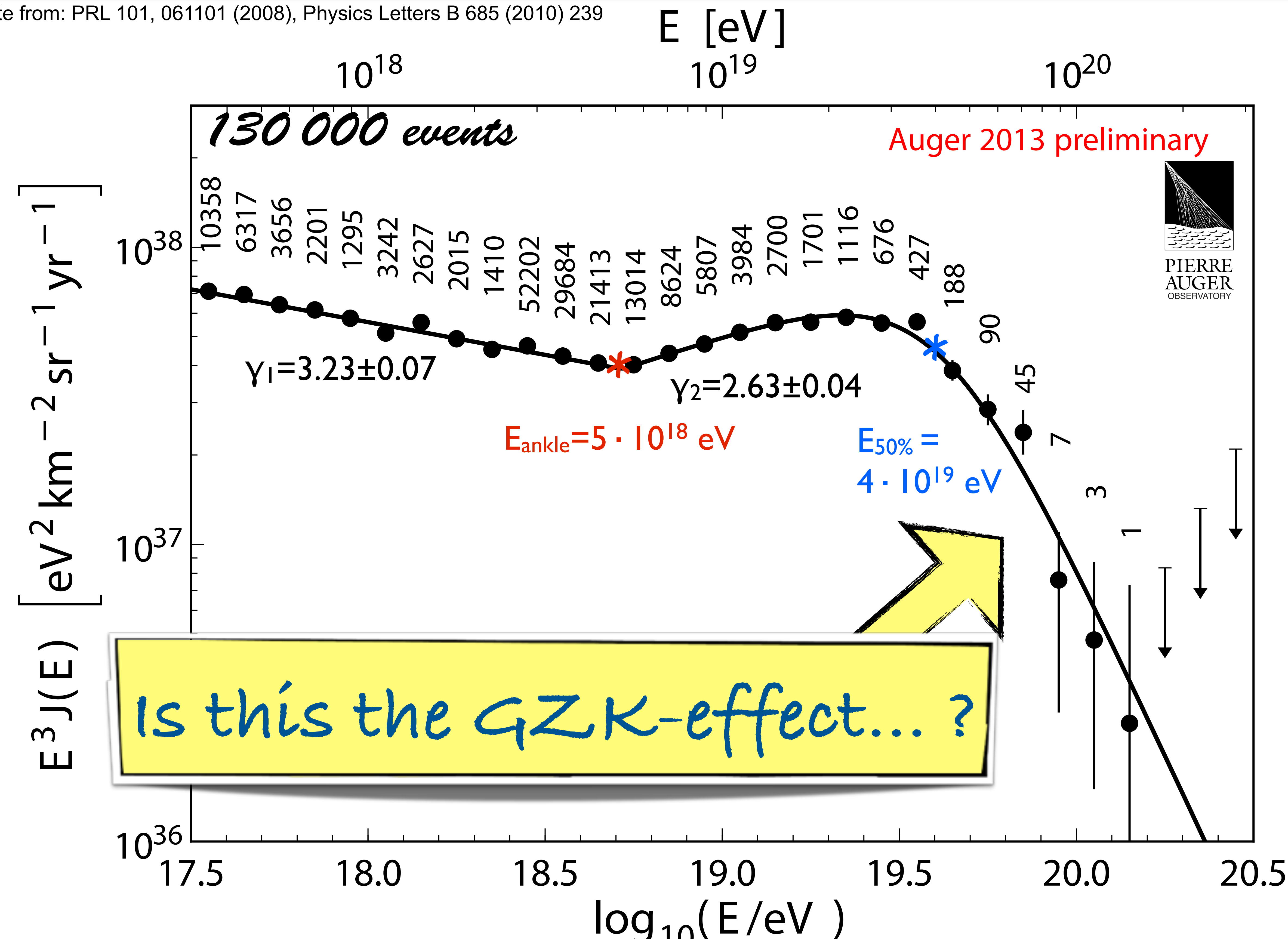
Event Example in Auger Observatory

energy determination based solely on experimental observables!

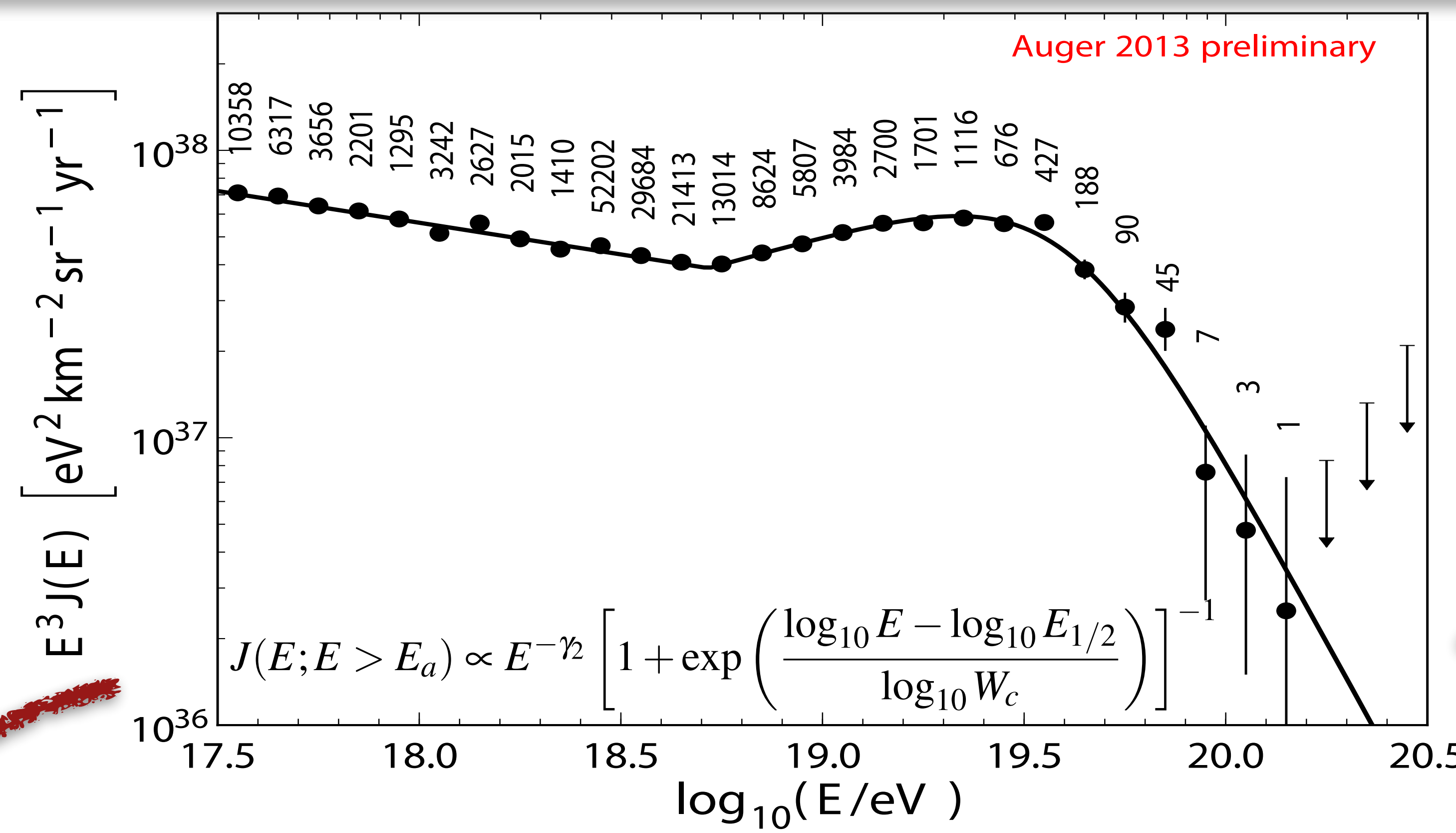


Auger Combined E-Spectrum (0°-80°)

Update from: PRL 101, 061101 (2008), Physics Letters B 685 (2010) 239

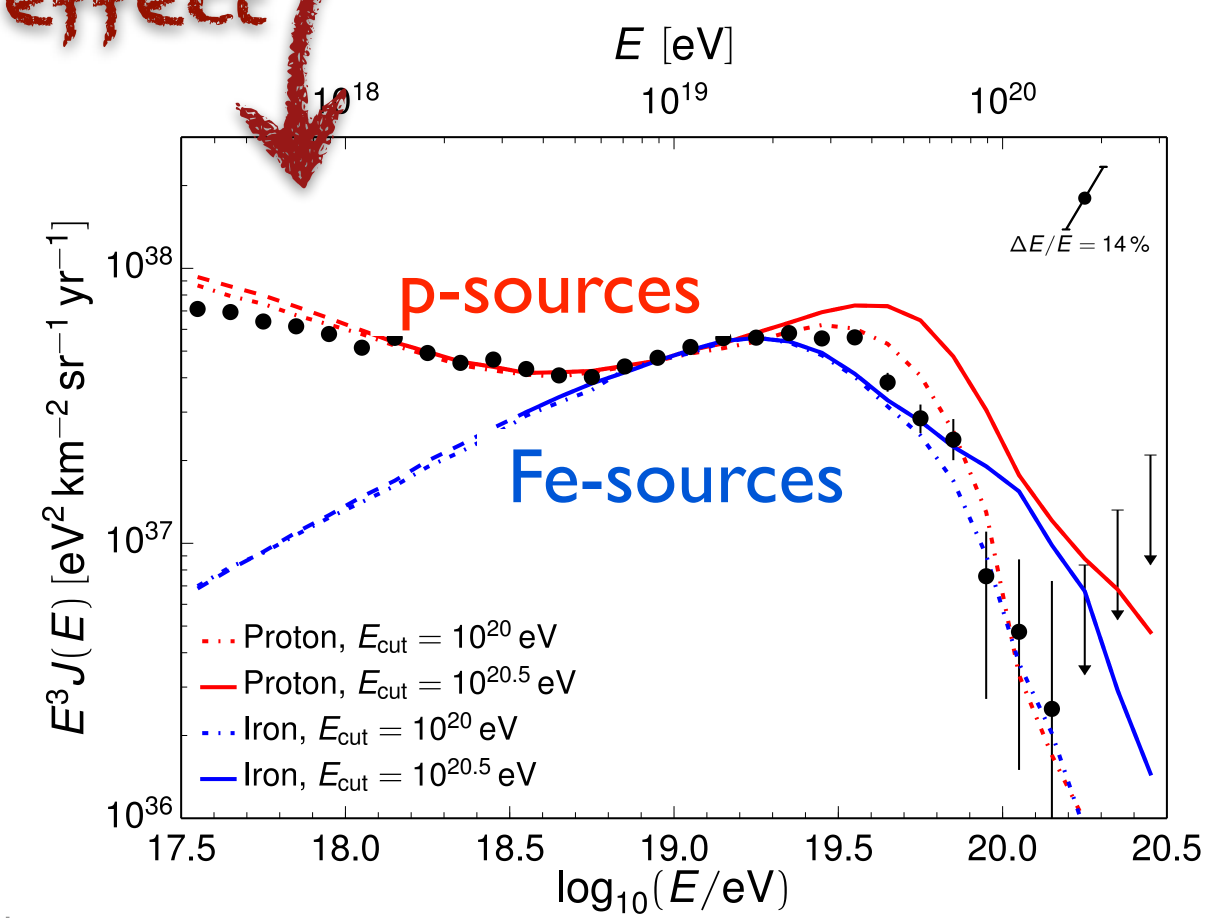


GZK-Effect or Exhausted Sources?

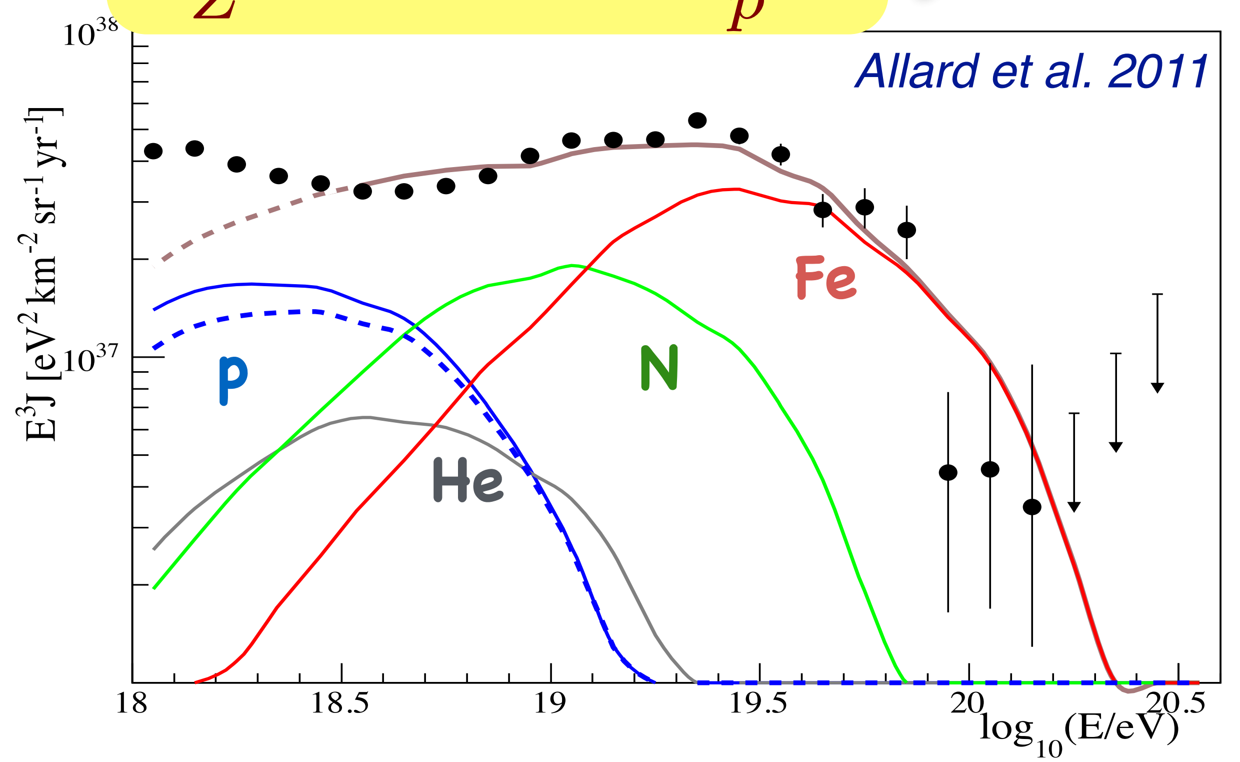


GZK-effect

exhausted sources



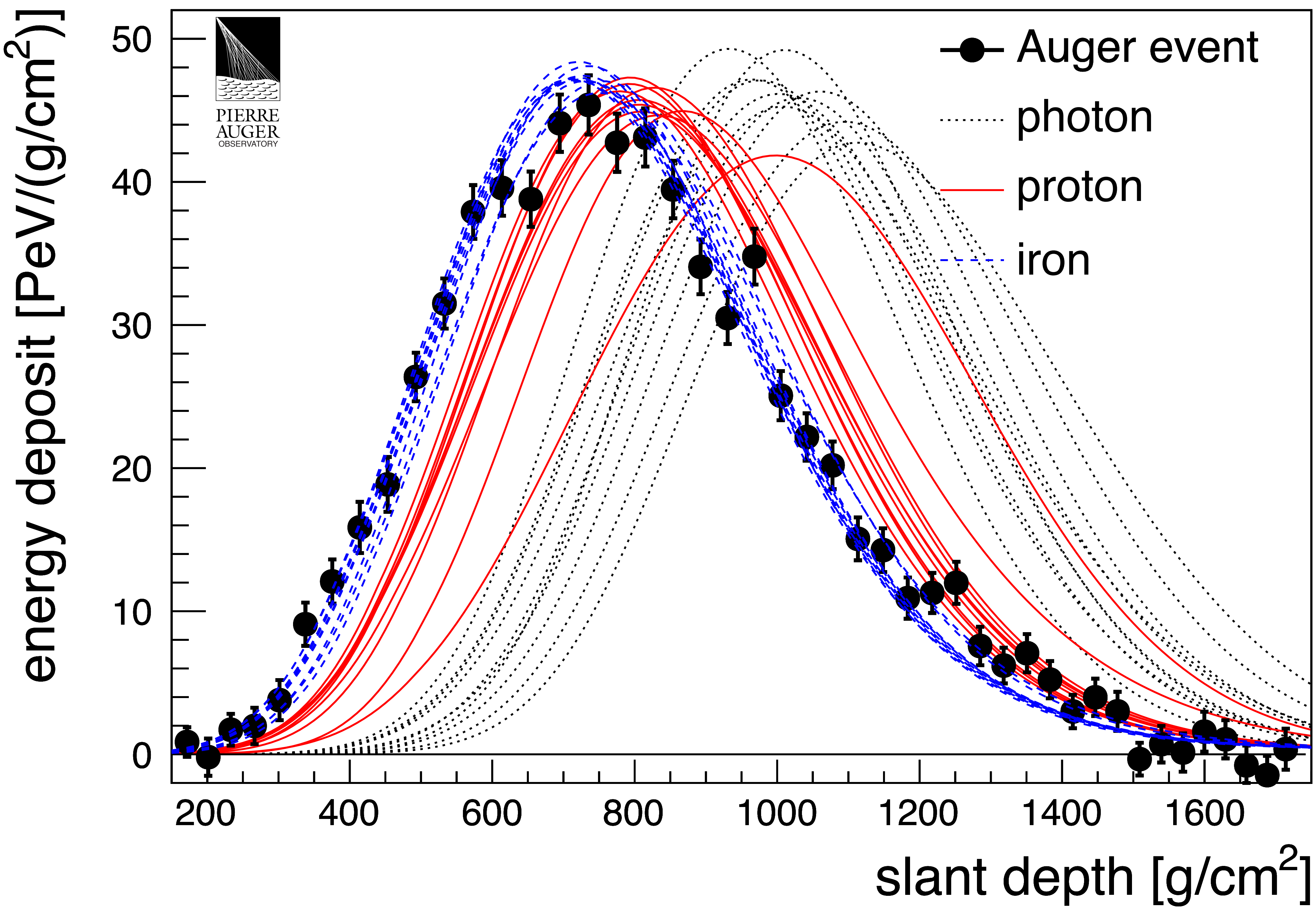
$$E_Z^{\max} \propto Z \times E_p^{\max}$$

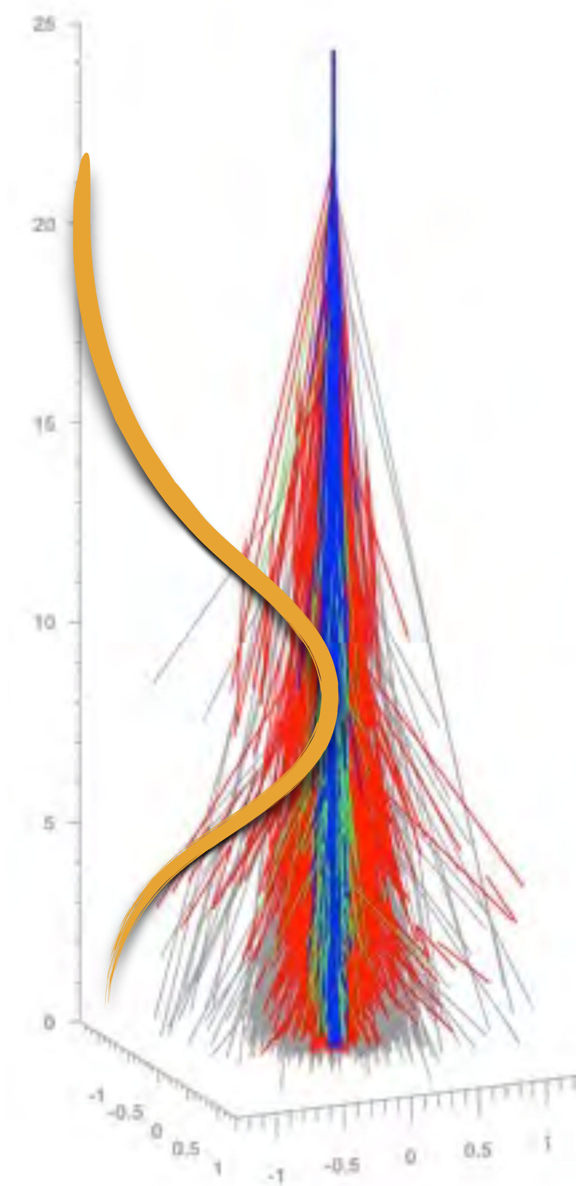


Longitudinal Shower Development → Primary Mass

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

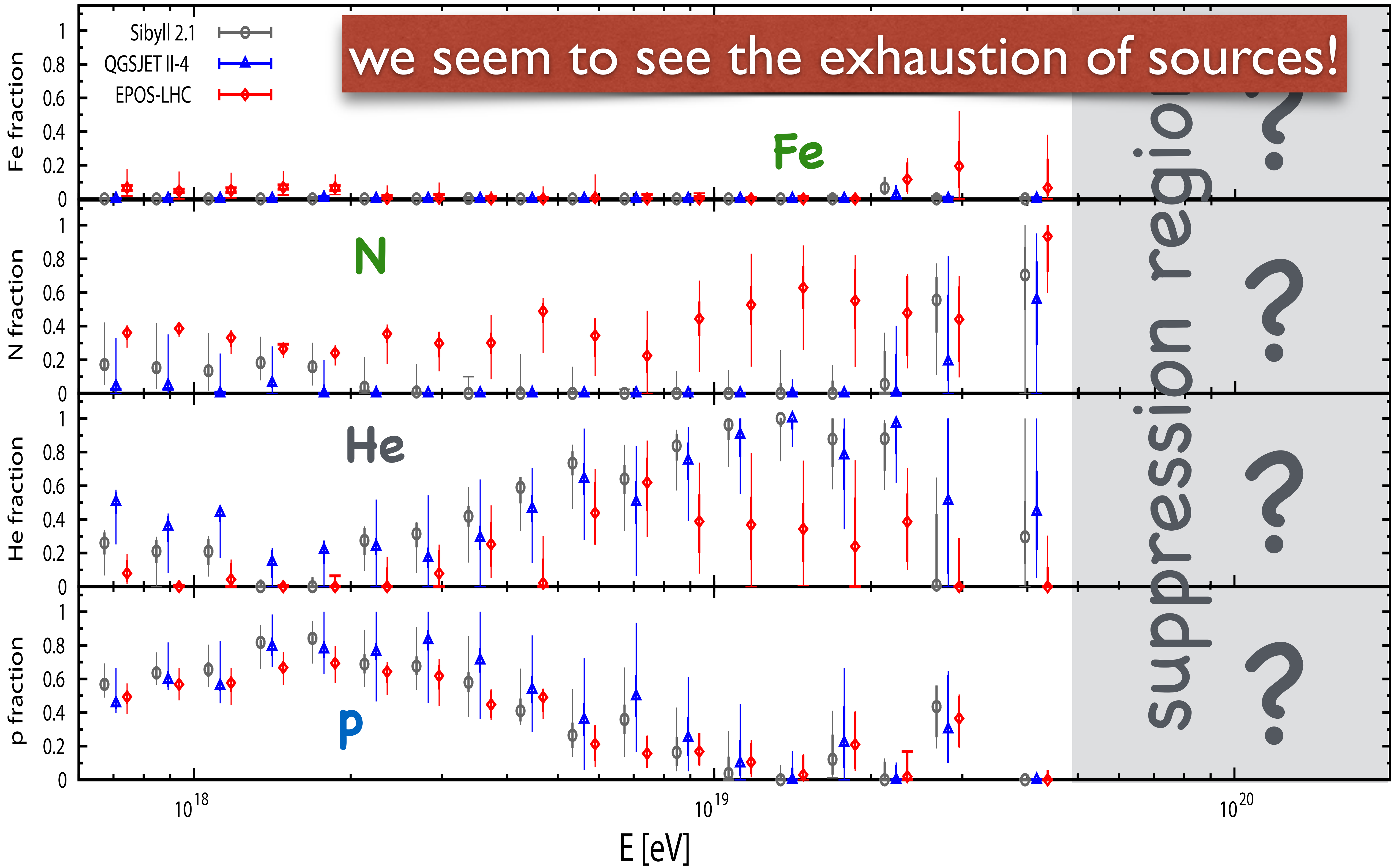
Example of a $3 \cdot 10^{19}$ eV EAS event in FD





Decomposition of X_{max}-Distributions

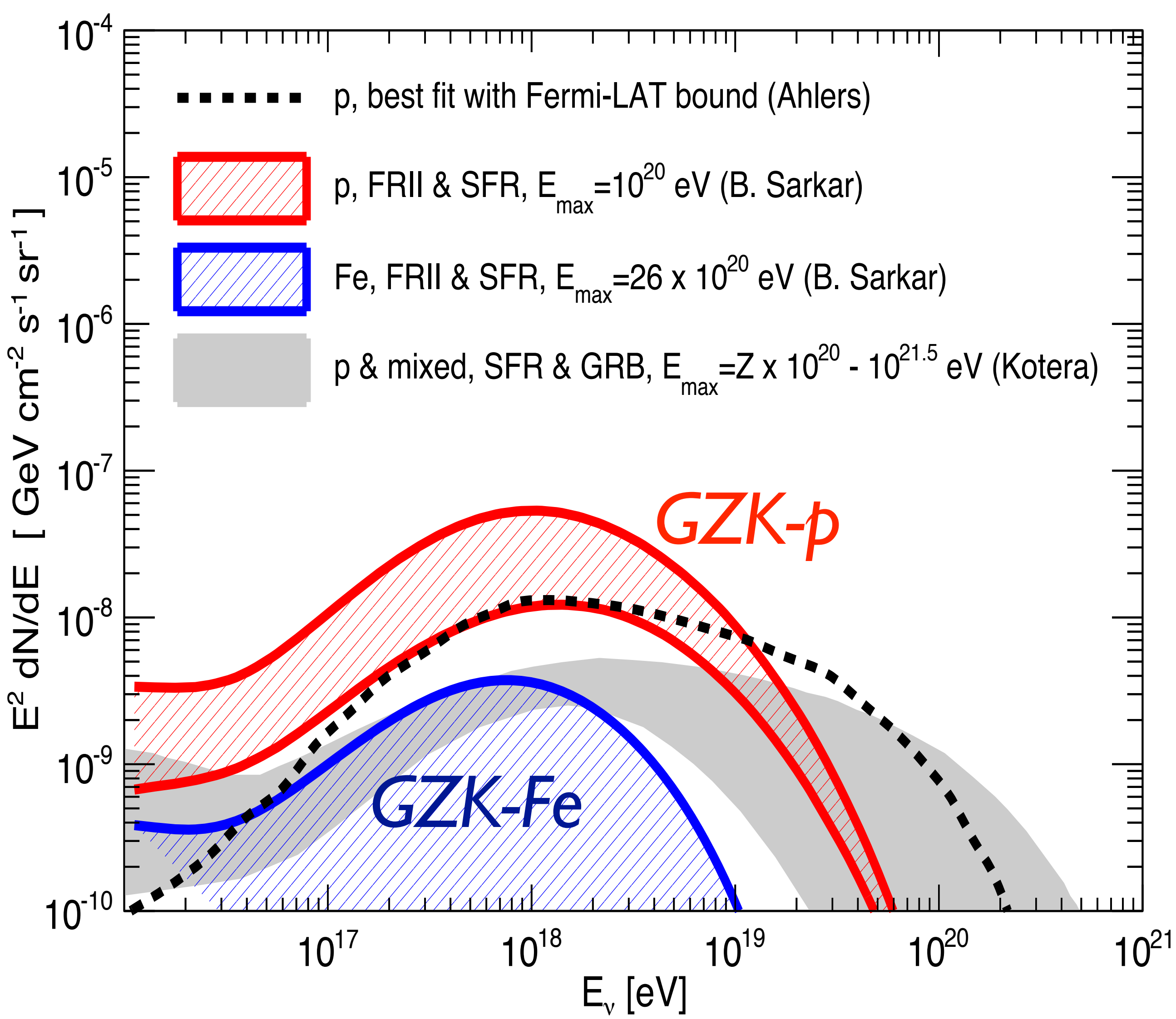
Auger collaboration, Phys. Rev. D 90, 122006 (2014)

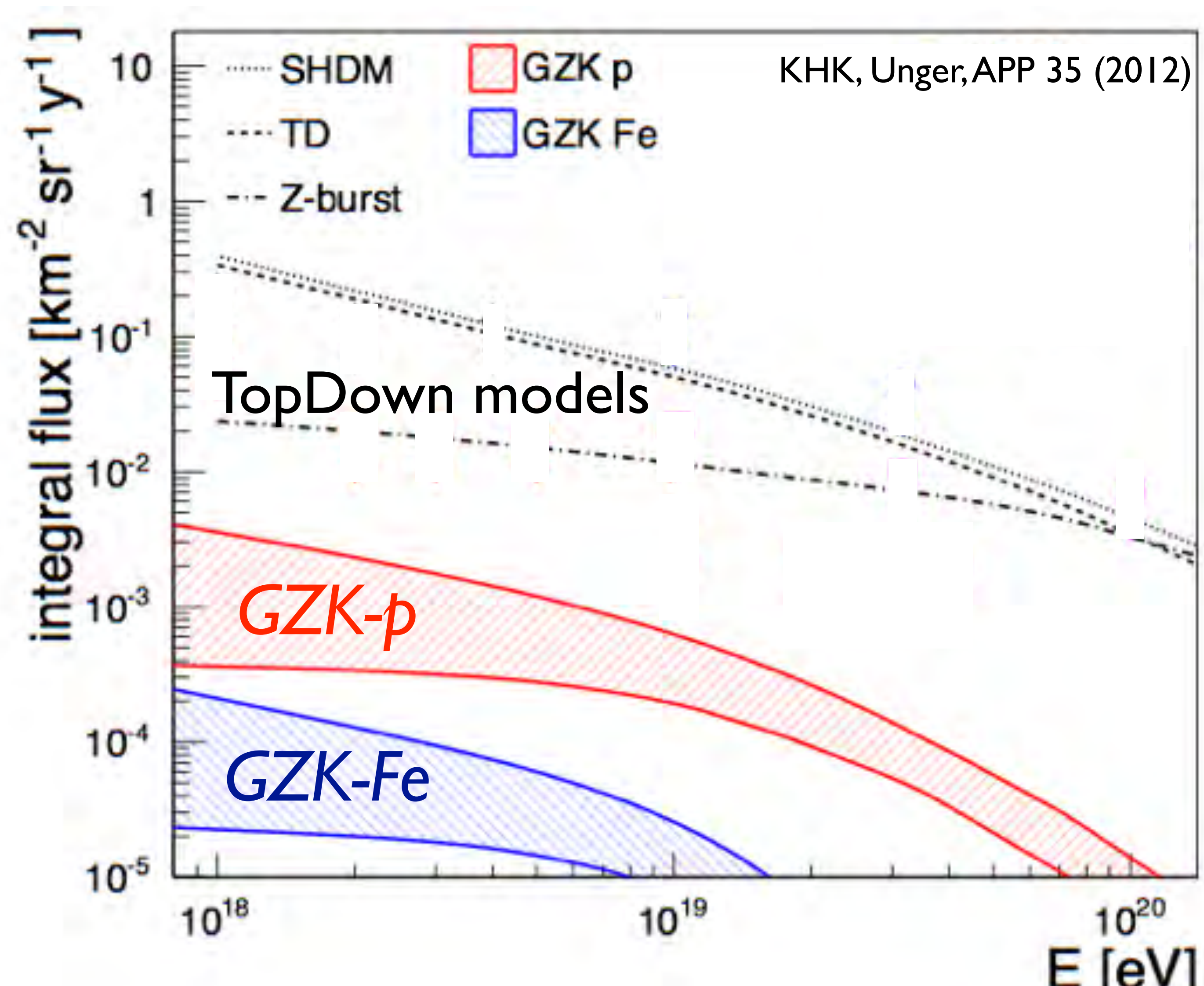


Cosmogenic Neutrinos and Photons
– a guaranteed signal in presence of GZK –

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow$$

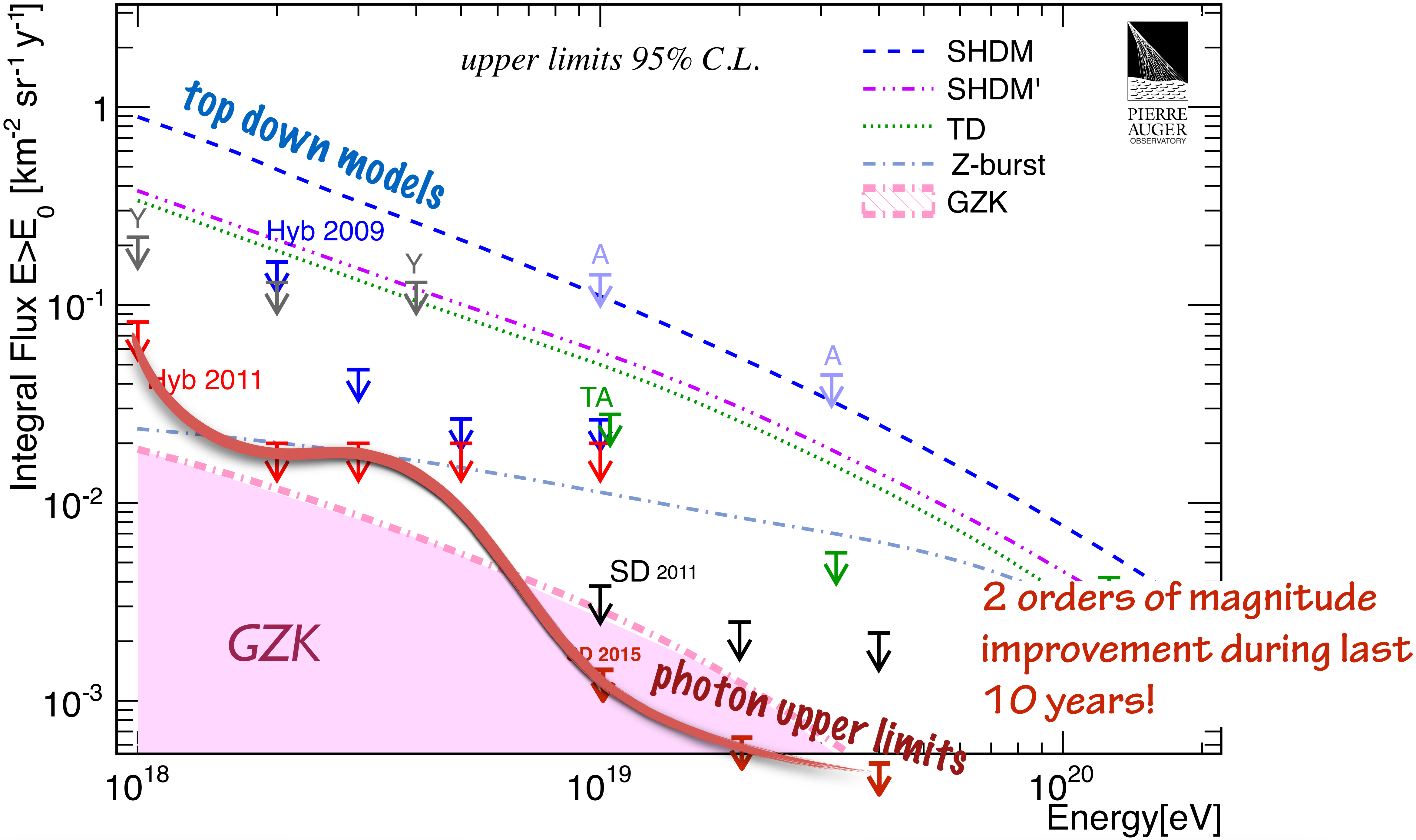
$$\rightarrow n + \pi^{+} \boxed{\rightarrow \nu_{\mathrm{EeV}}} \qquad \rightarrow p + \pi^{0} \boxed{\rightarrow \gamma_{\mathrm{EeV}}}$$





Absence of Photons ⇒ TopDown ruled out

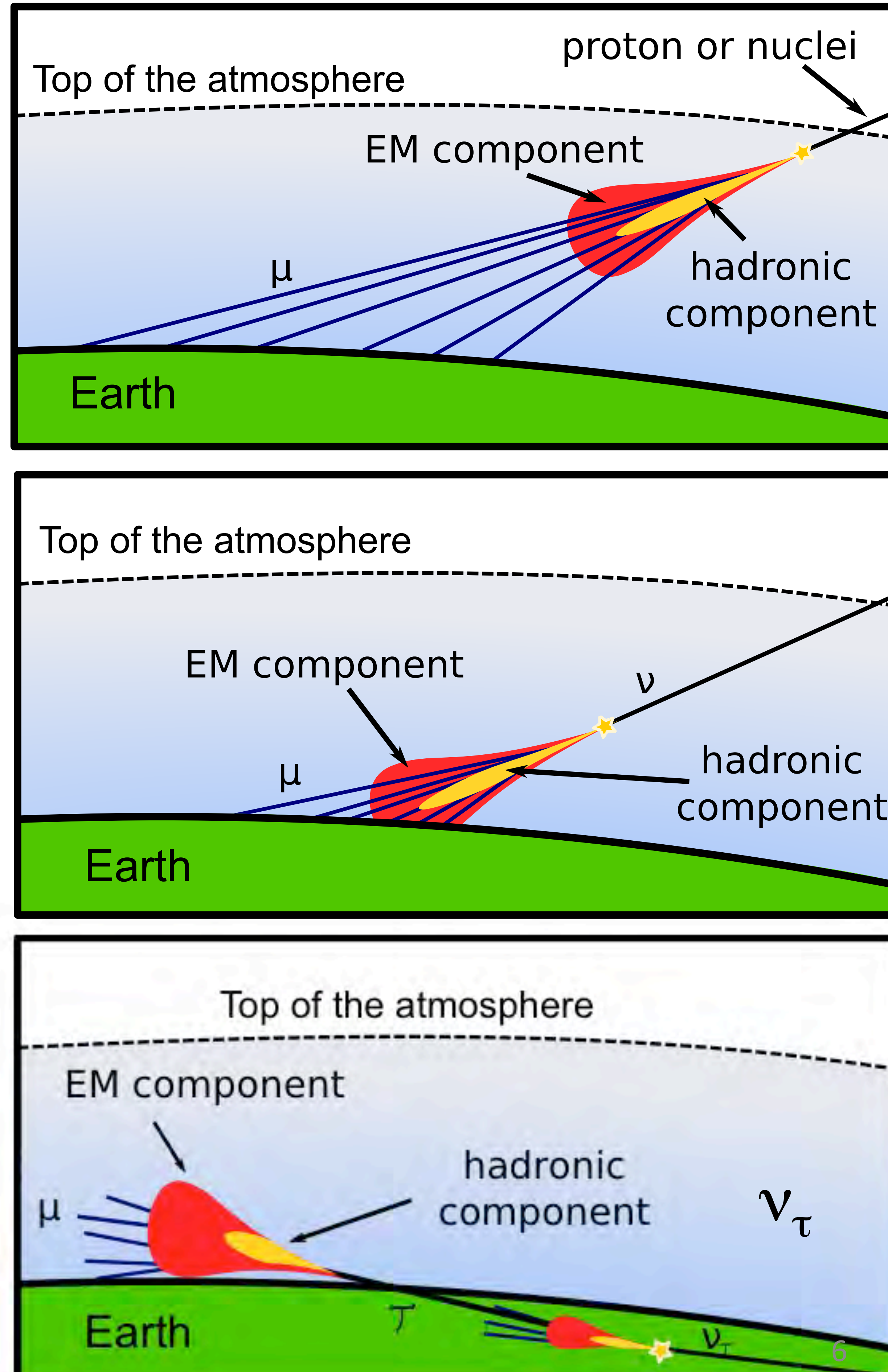
Update from: Astropart. Phys. 31 (2009) 399; ICRC2015



Photon upper limits rule out Top-Down Models and start to constrain GZK-expectatinons

Search for EeV Neutrinos in inclined showers

- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components

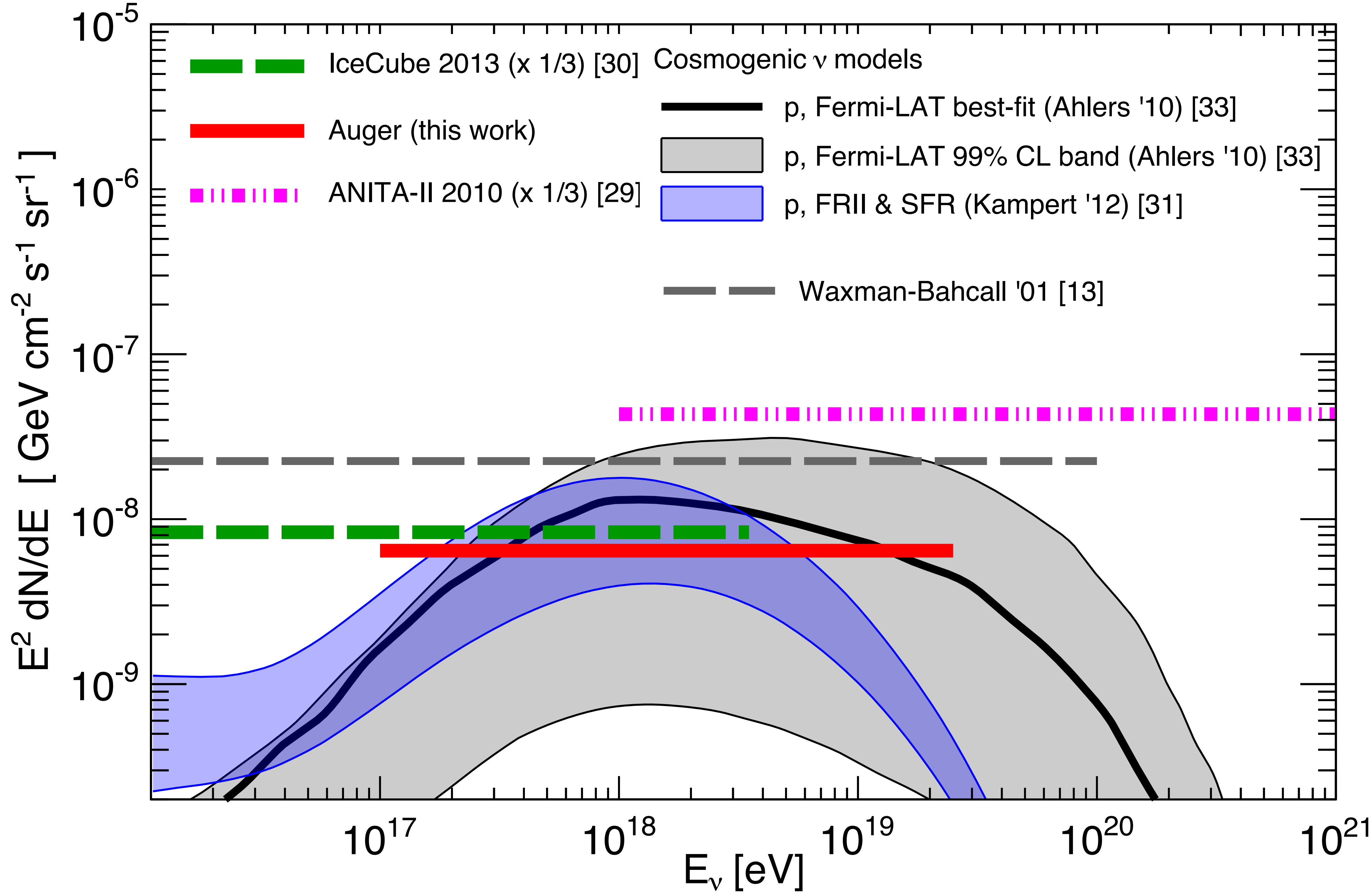


Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

Upper Limits on Neutrinos

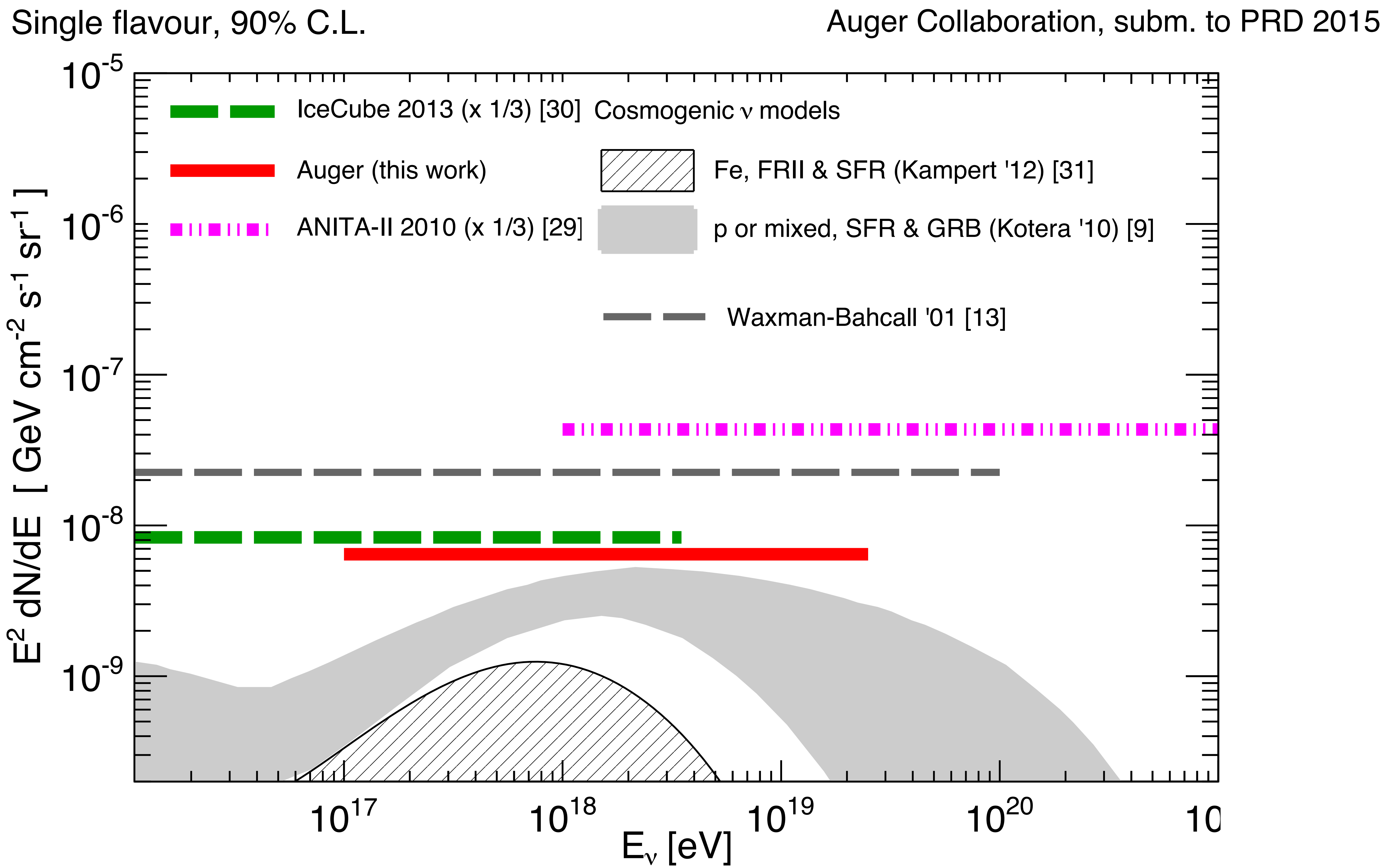
Single flavour, 90% C.L.

Auger Collaboration, subm. to PRD 2015



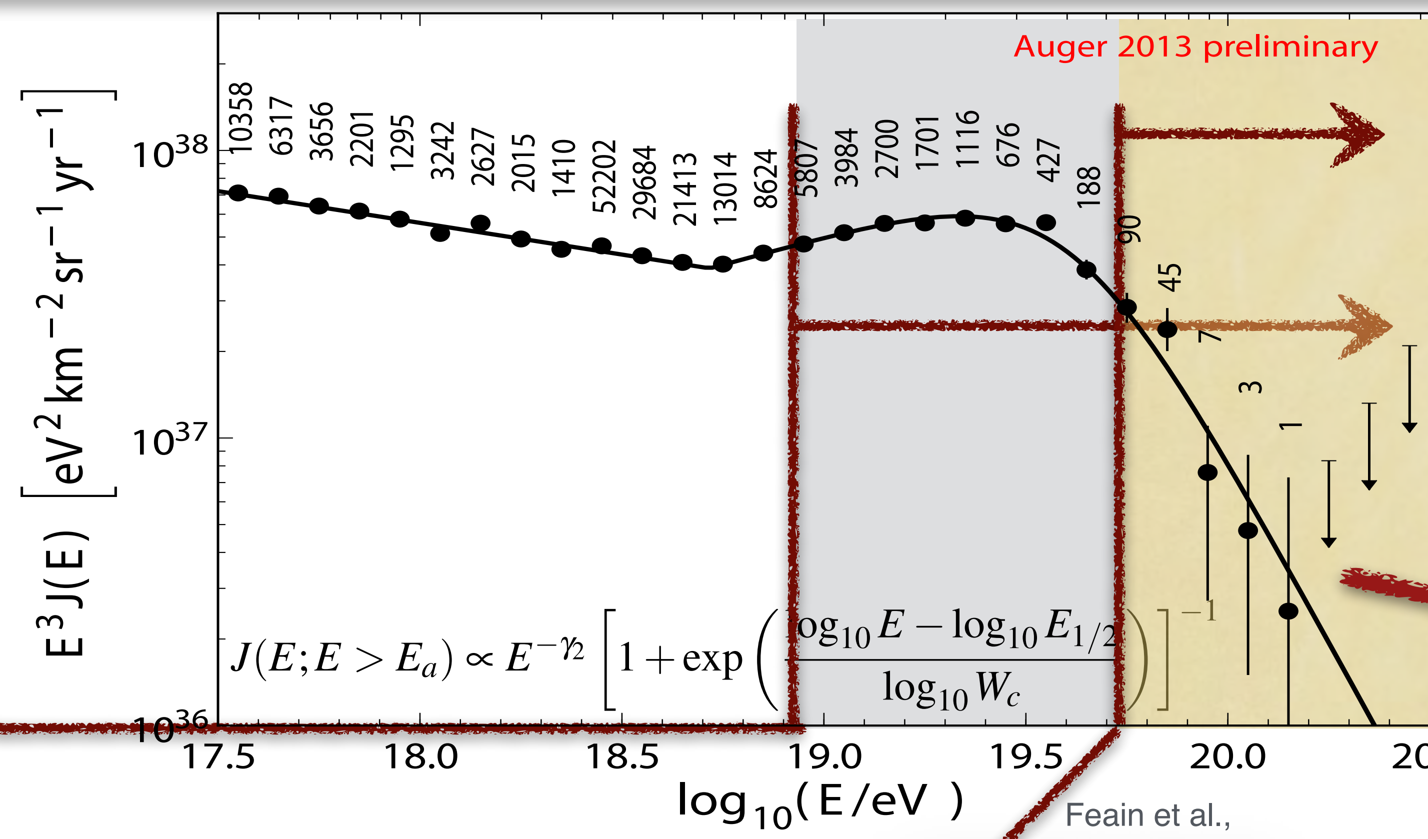
Neutrino upper limits start to constrain cosmogenic neutrino fluxes of p-sources

Upper Limits on Neutrinos



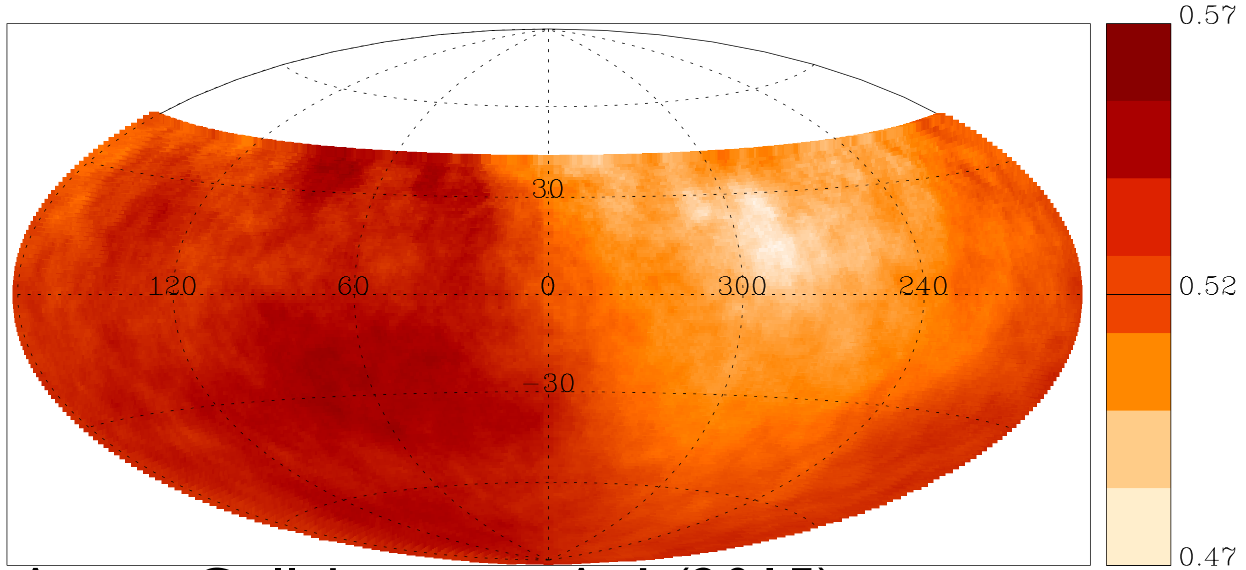
Neutrino upper limits start still above cosmogenic neutrino fluxes for Fe-sources

UHECR Sky surprisingly isotropic



dipole like anisotropy

E>8 EeV



Auger Collaboration ApJ (2015) in press

Amplitude: (4.4±1.0)%; p=6.4 · 10^{-5}

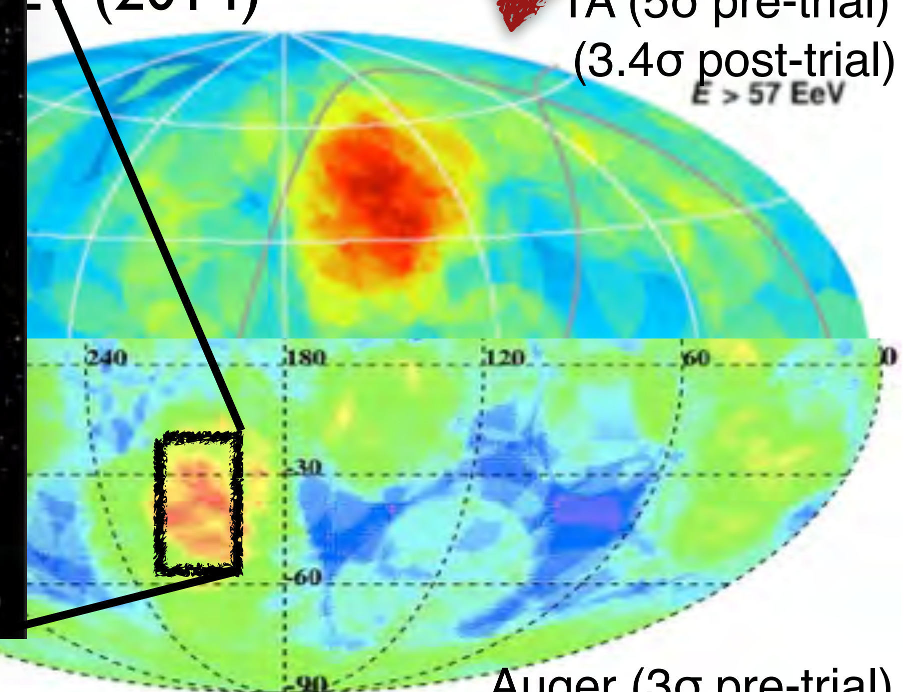
Feain et al., ApJ 740 (2011) 17

E>57 EeV

(2014)

TA (5σ pre-trial)

(3.4σ post-trial)

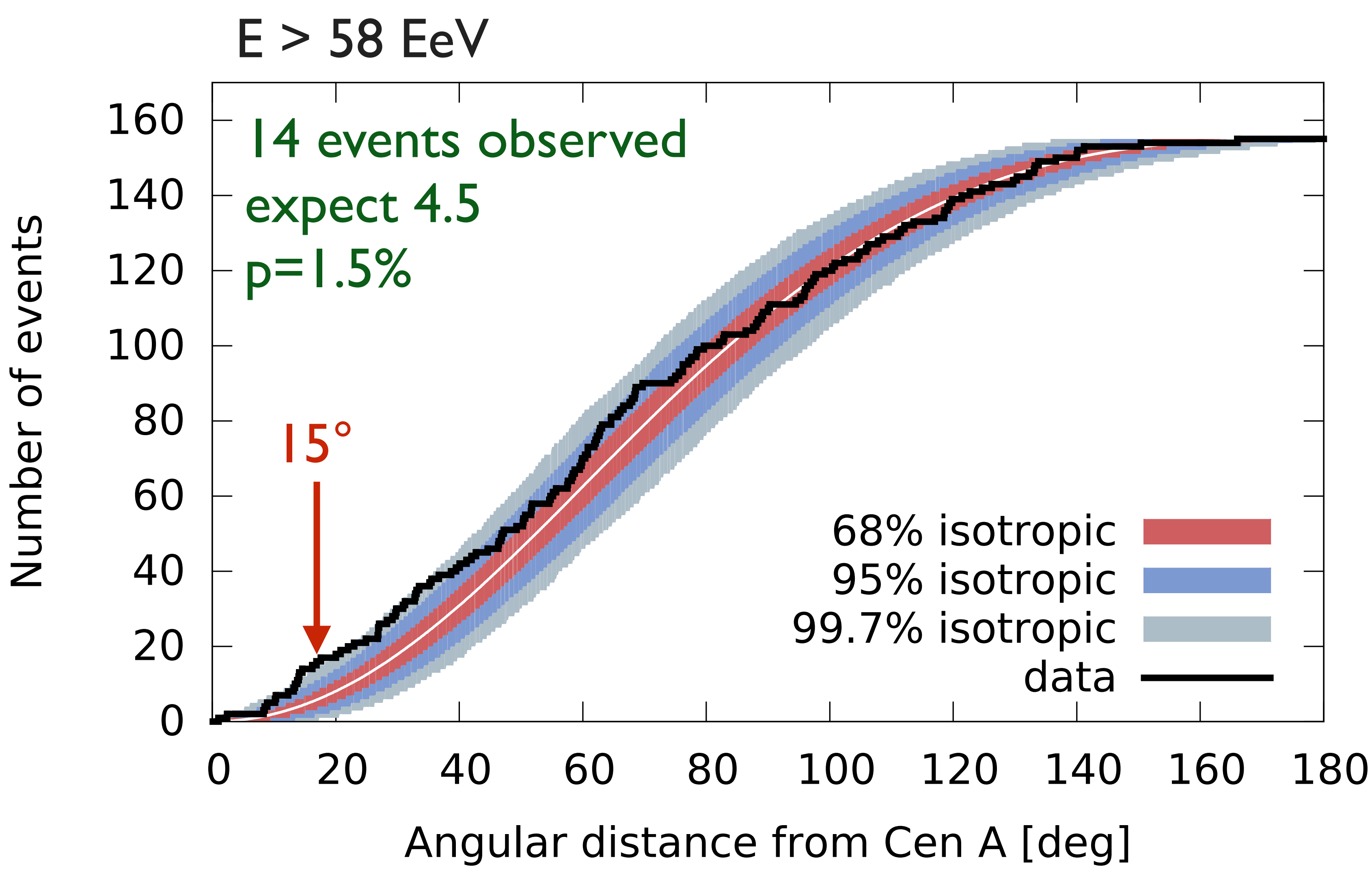


Auger (3σ pre-trial)

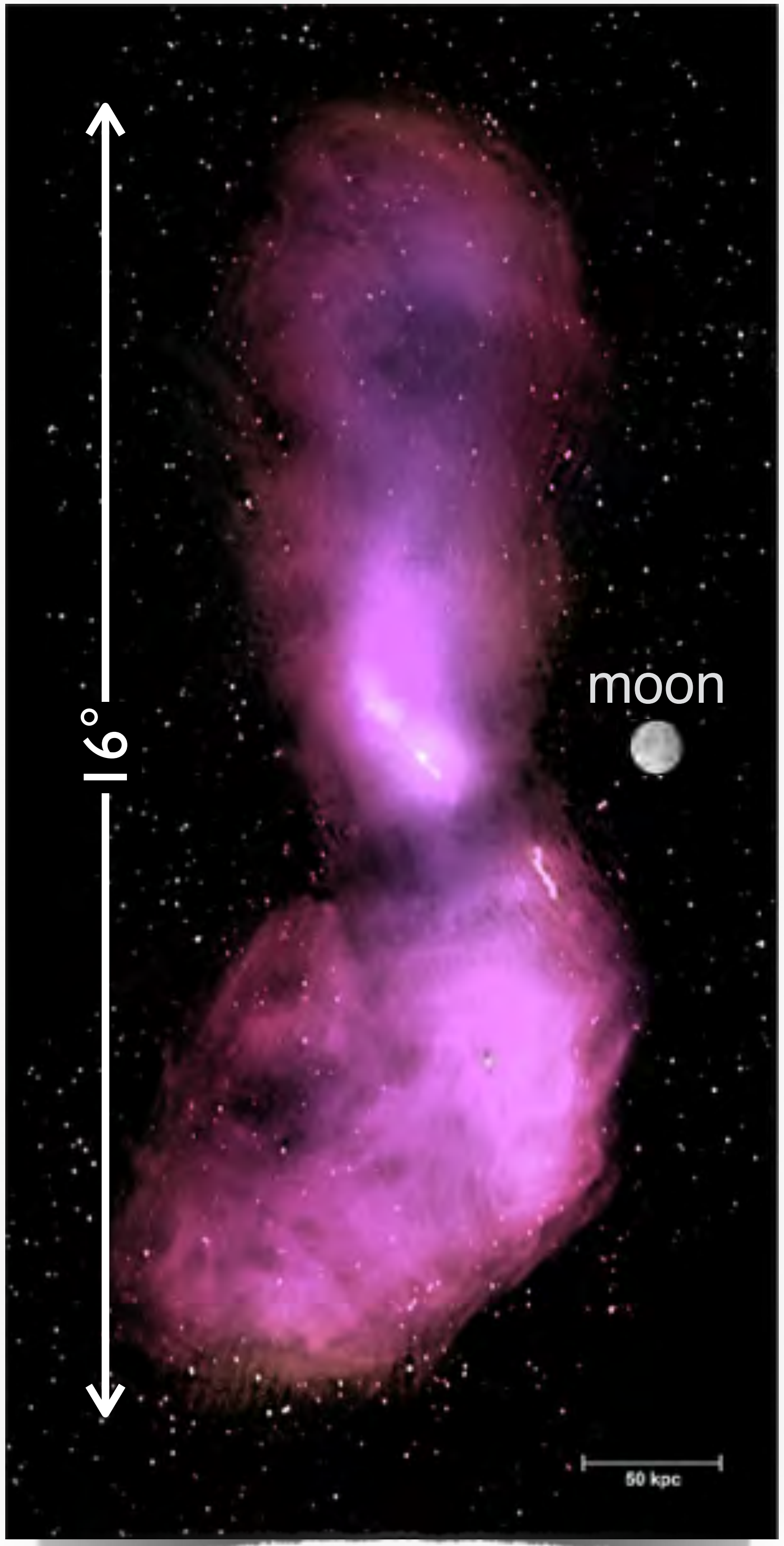
Auger: APP 34(2010) 314

Weak excess of events around Cen A

giant lobes ~ 280 kpc
physical age ~ 560 Myr
distance ~ 3.8 Mpc



Auger 1411.6111; ApJ (2015) in press

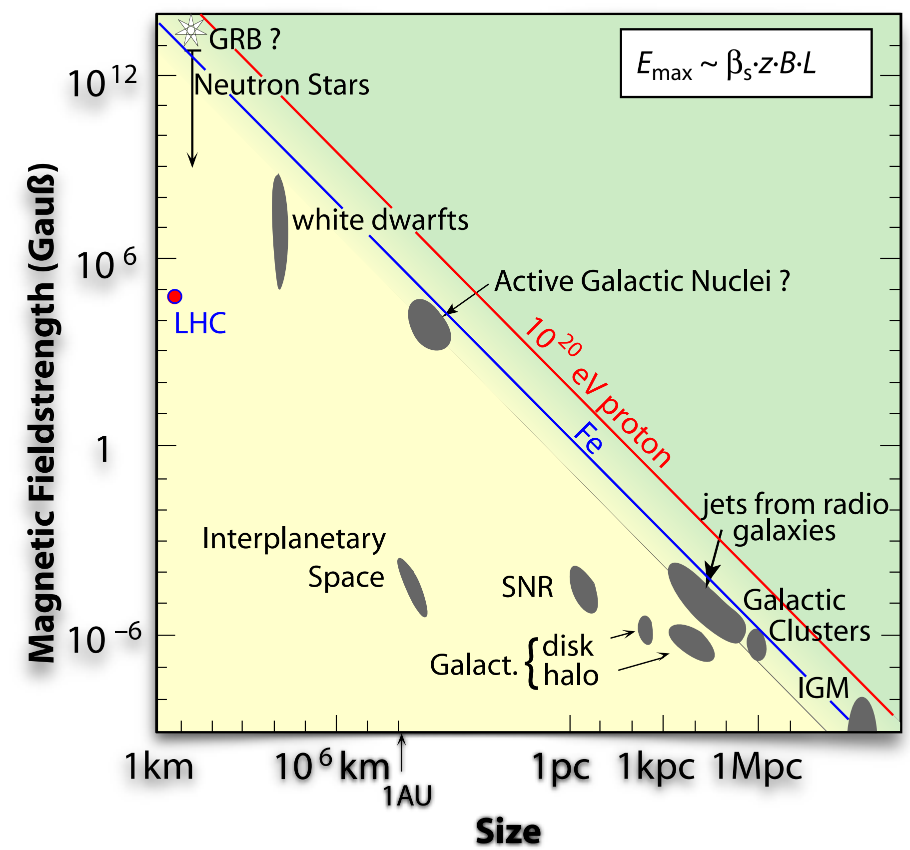


Feain et al., ApJ 740 (2011) 17

Résumé

Data from the Auger Observatory indicate that the flux suppression is mostly due to seeing the exhaustion of the sources:

1) change towards a heavier composition
2) constraints on GZK photons and neutrinos
3) highly isotropic sky



Logical next step:
Measure composition event-by-event into the flux suppression region
➡ composition becoming increasingly heavier?
➡ enable composition enhanced anisotropy studies
➡ do particle physics at $\sqrt{s} \approx 100$ TeV

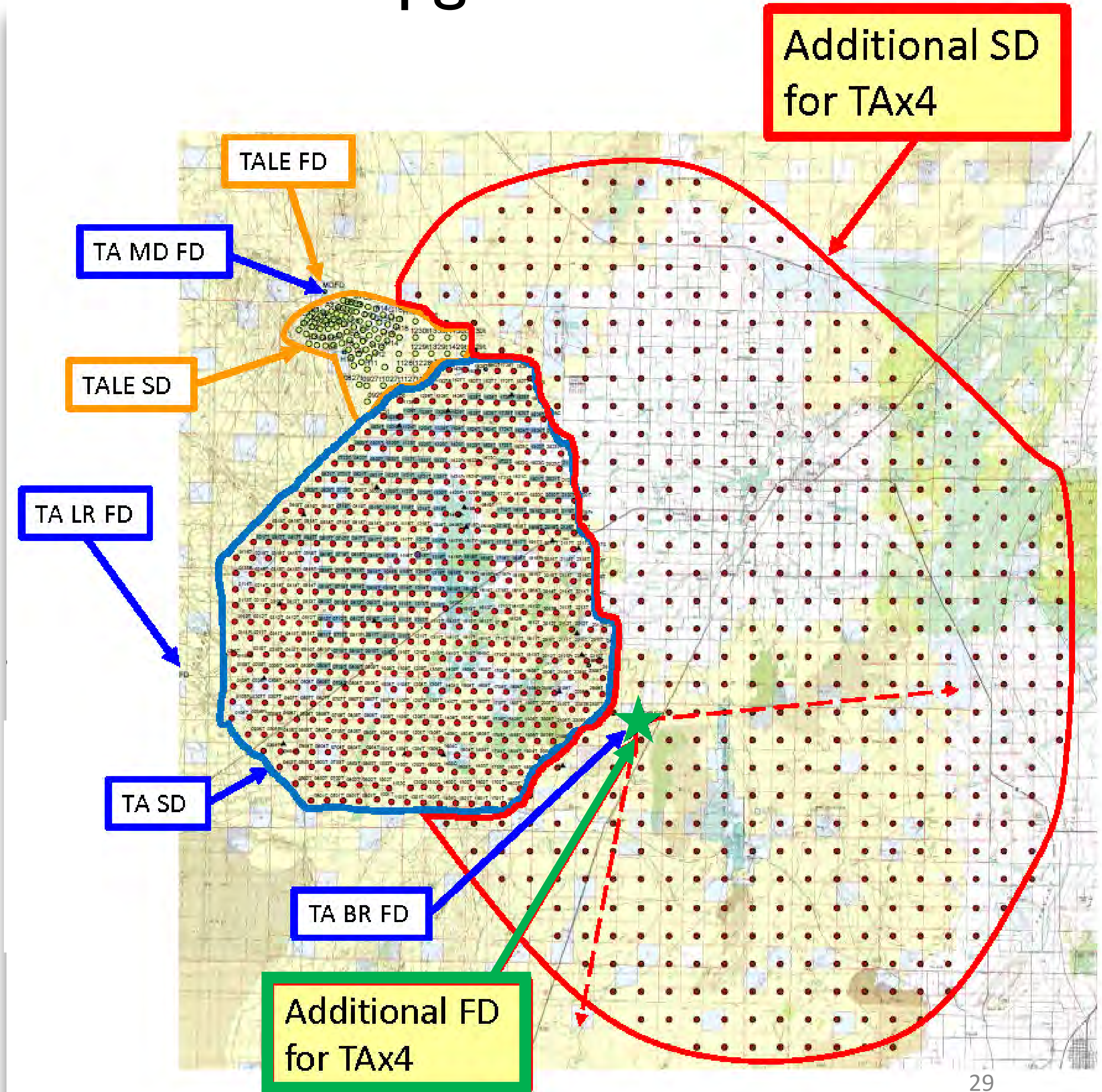
UHECR: Near Future

Auger upgrade: mass composition with ground array

origin of the flux suppression

hadronic interactions beyond LHC

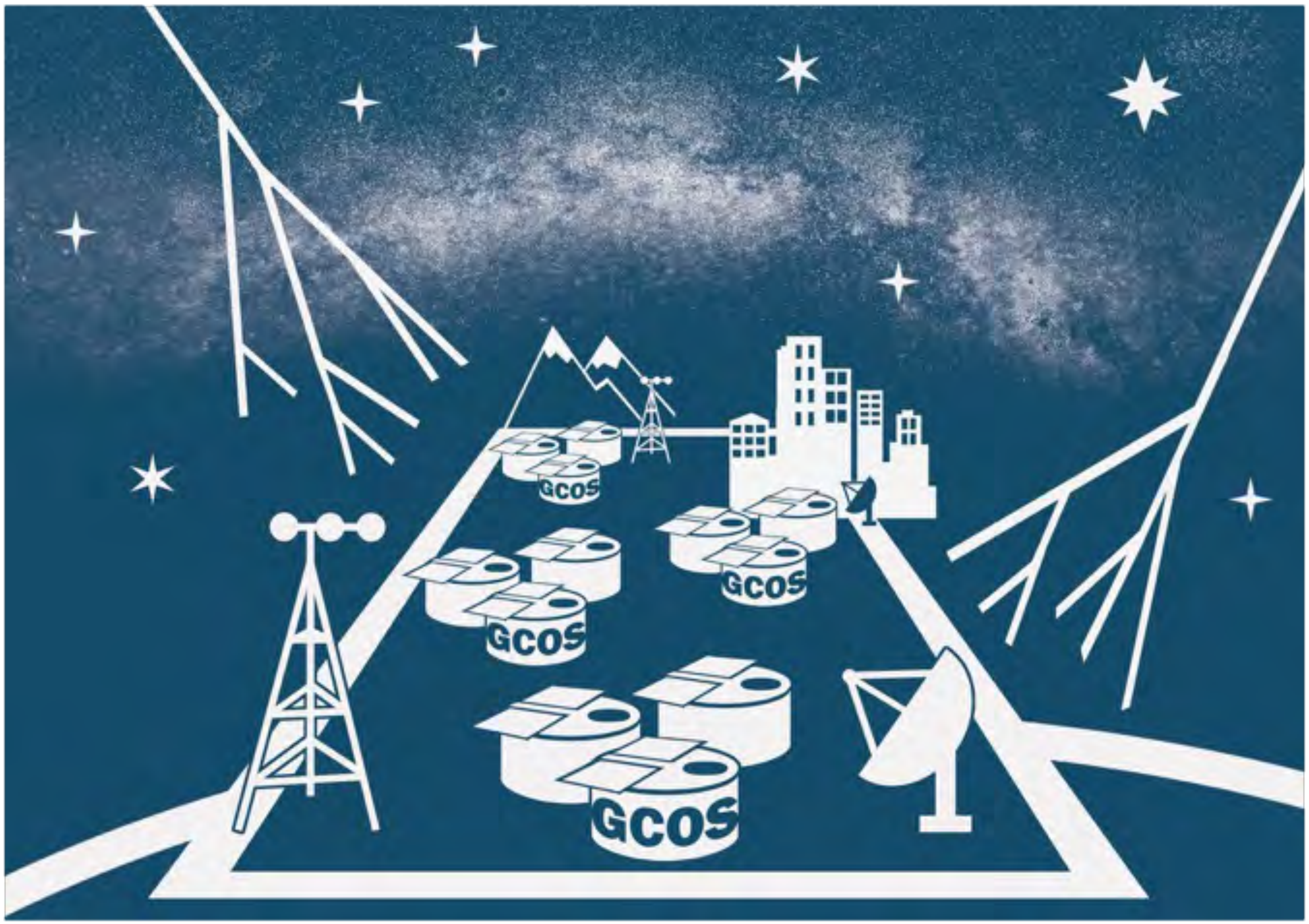
TA upgrade: area * 4



more rapid increase of statistics

UHECR: Long Term Plan

Global Cosmic Ray Observatory (GCOS)
few sites in N+S, 90 000 km^2



感谢您的关注!

Bounds on LIV and Smoothness of Class. Space-Time

Klinkhamer/Risse; PRD77 (2008) 016002; 117901; Klinkhamer, AIP Conf.Proc.977:181-201,2008

Observation of 10^{20} eV events
proofs absence of Vacuum Cherenkov-Radiation
→ Provides limits on smoothness of space & LIV-effects

- Conservative limit on any small-scale structure of space:

  LEP/LHC: $\ell \leq 10^{-19}$ m $\approx \hbar c/(1$ TeV$)$.

- Use published 27 Auger events + 1 AGASA + 1 Fly's-Eye

  ↪ single scale classical space-time foam at

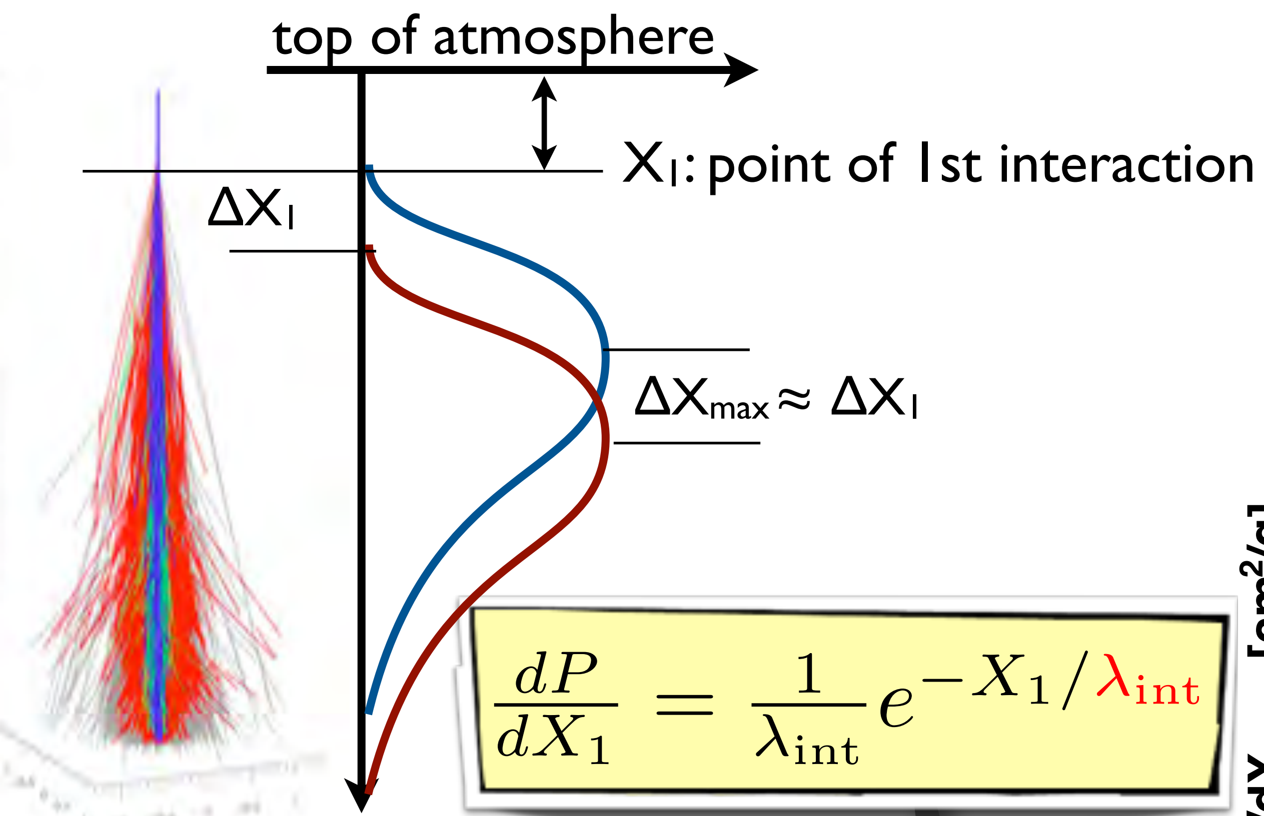
  UHECRs: $b \leq 10^{-26}$ m $\approx \hbar c/(2 \cdot 10^{10}$ GeV$)$

  by far best (3 to 8 orders of magn.!) existing bounds of Standard Model Extension parameters of nonbirefringent modified Maxwell theory

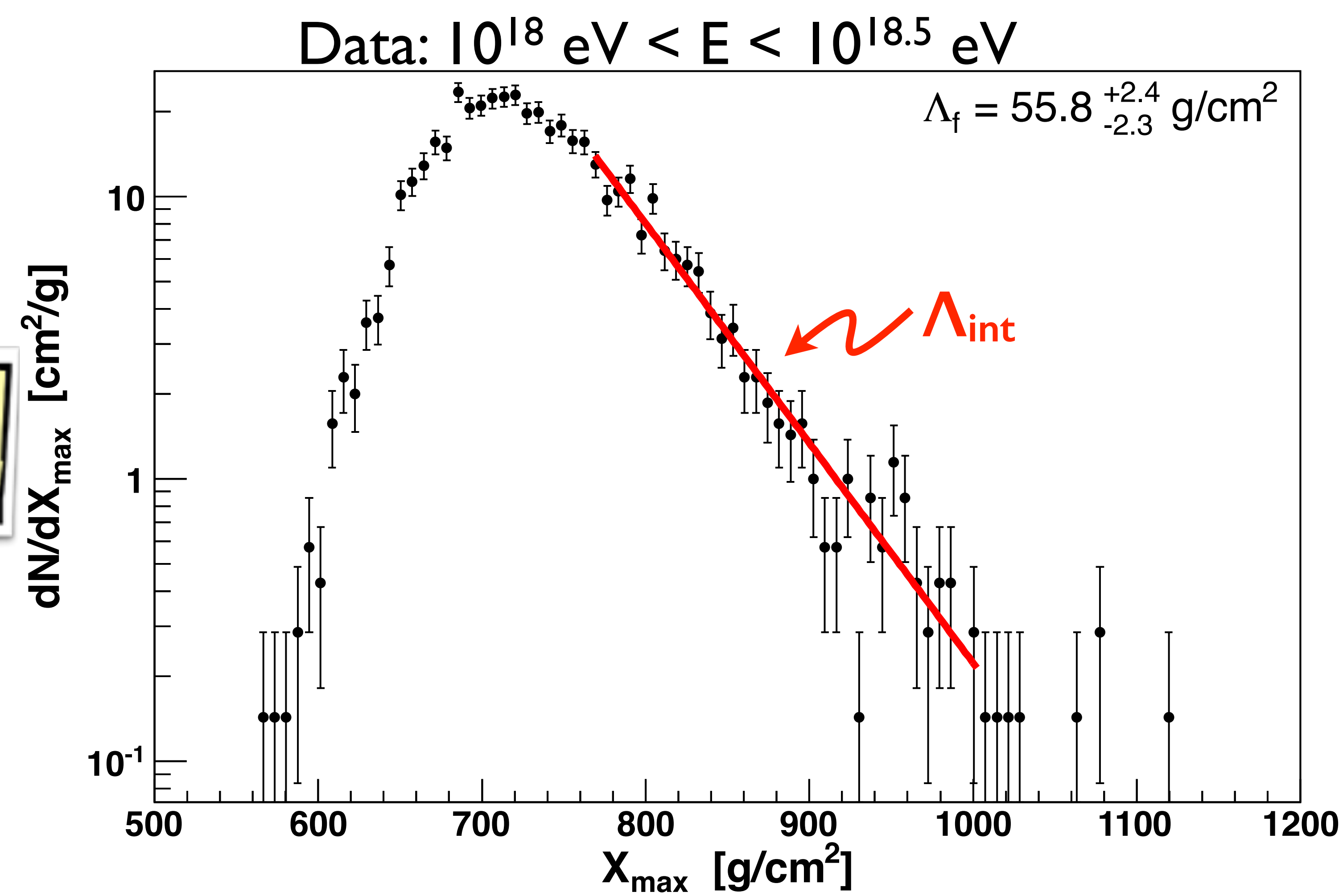
  Results complemented by TeV γ-rays

- **Conjecture:** fundamental length scale of quantum space time may be different from Planck length and may be linked to cosmological constant

p-Air Cross-Section from X_{max} distribution



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$



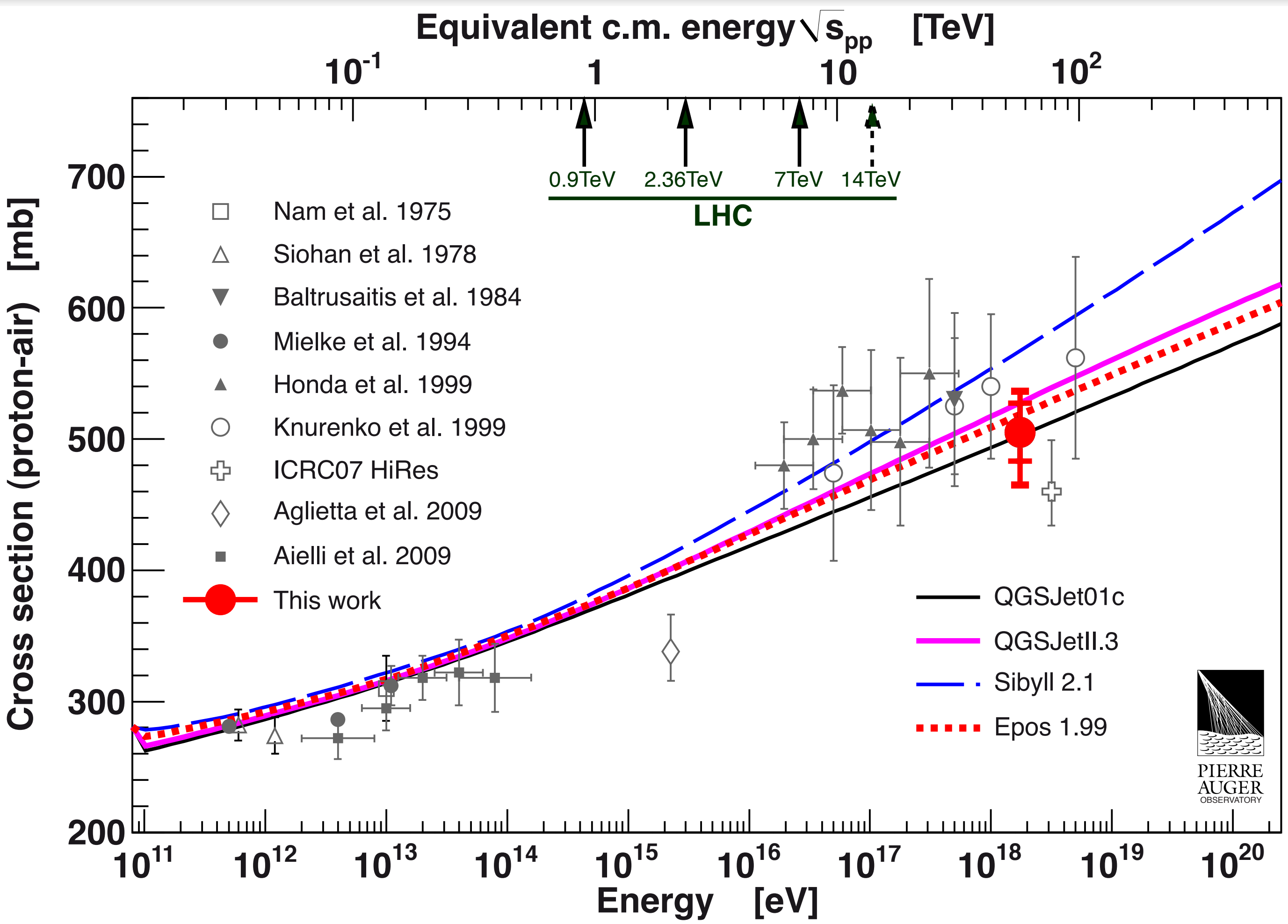
Difficulties:

- mass composition can alter Λ
- fluctuations in X_{max}
- experimental resolution ~ 20 g/cm^2

$$\sigma_{p-Air} = \frac{\langle m_{Air} \rangle}{\lambda_{int}}$$

In practice: $\sigma_{p\text{-}Air}$ by tuning models to describe Λ seen in data

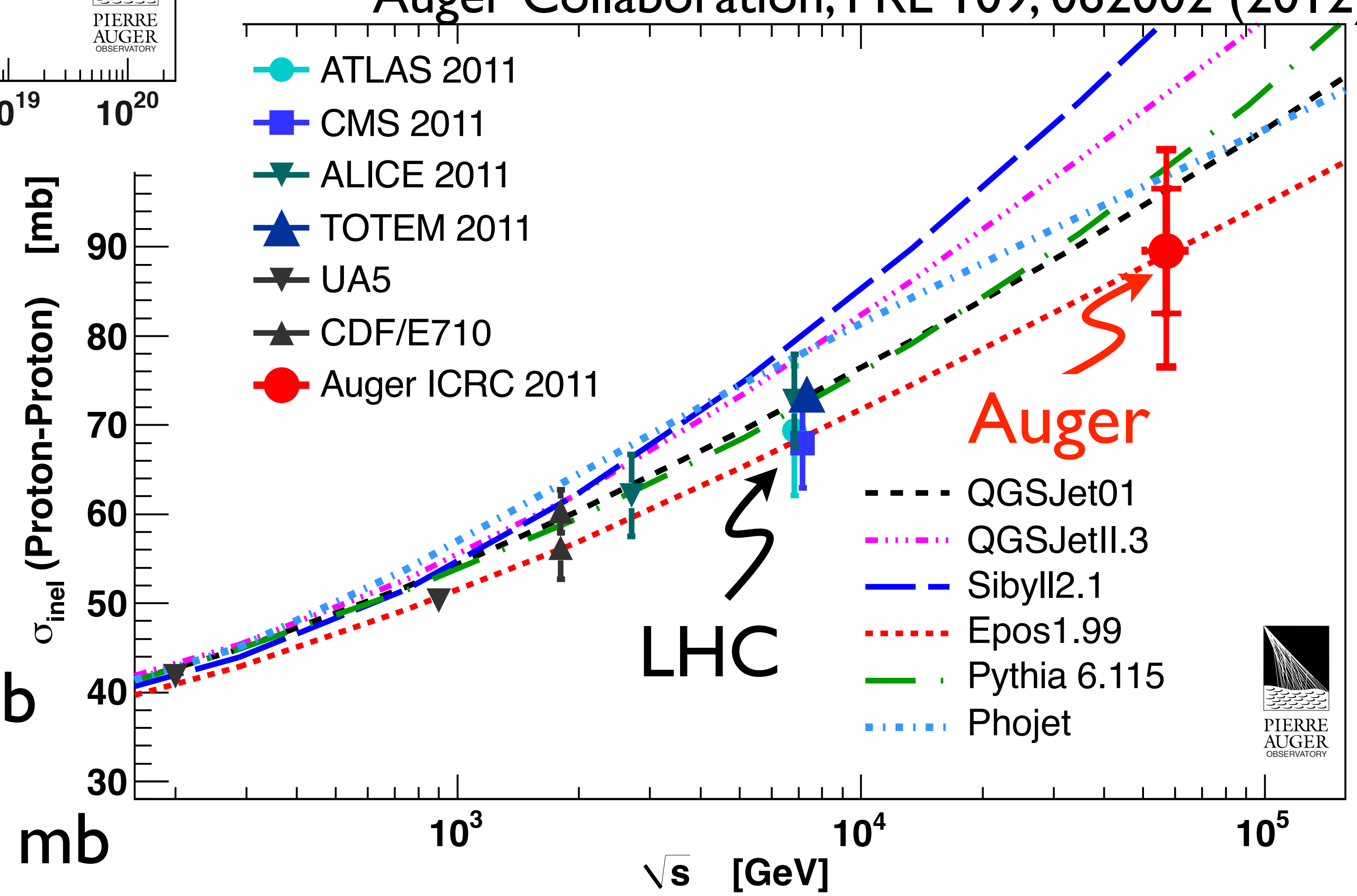
p-Air and pp Cross section @ √s=57 TeV



Conversion from p-air to p-p cross section by Glauber-approach

$$\sigma^{prod}_{p\text{-}Air} = (505 \pm 22_{stat}\,(^{+26}_{-34})_{sys}\,)\ \mathrm{mb}$$

Auger Collaboration, PRL 109, 062002 (2012)

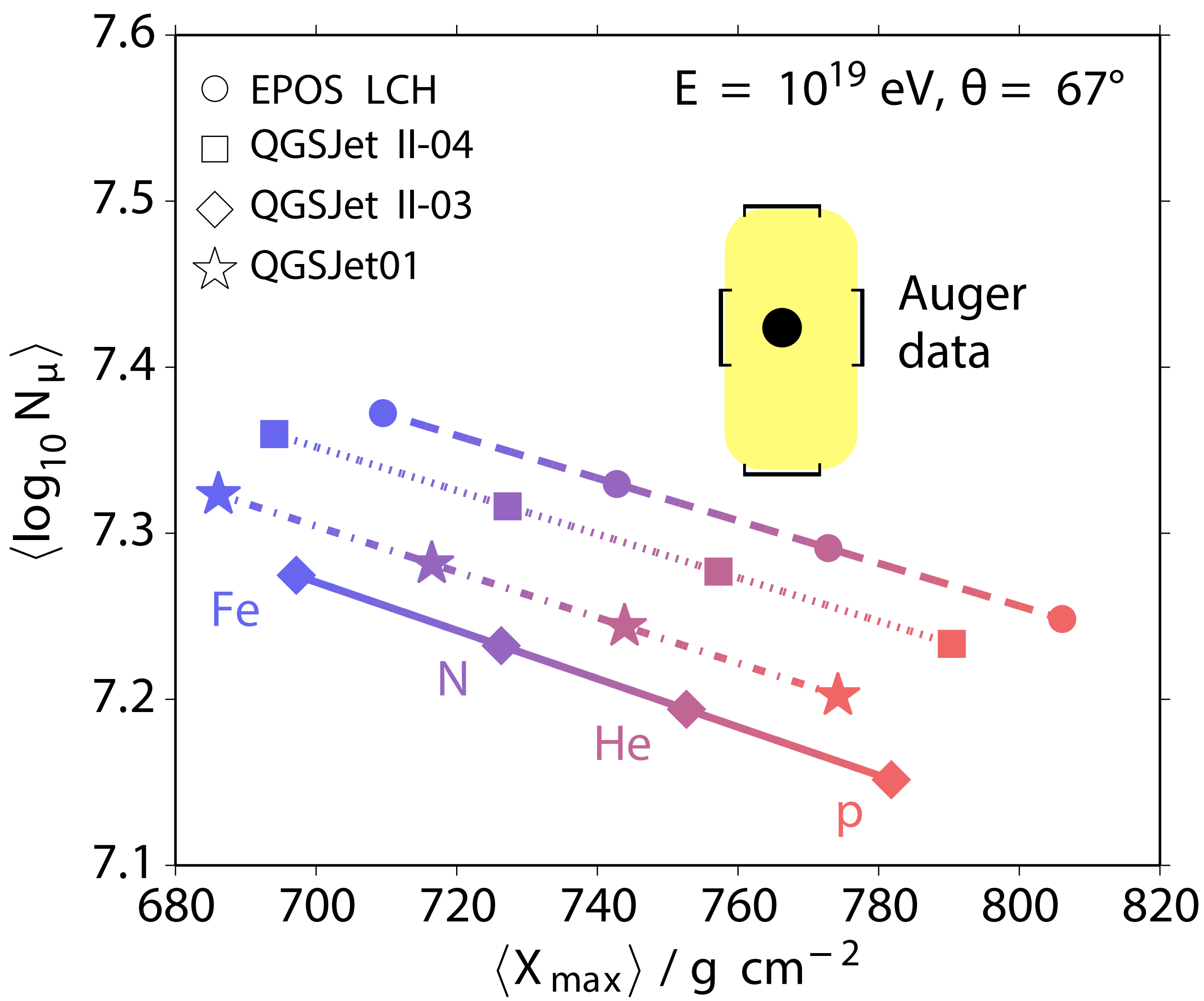


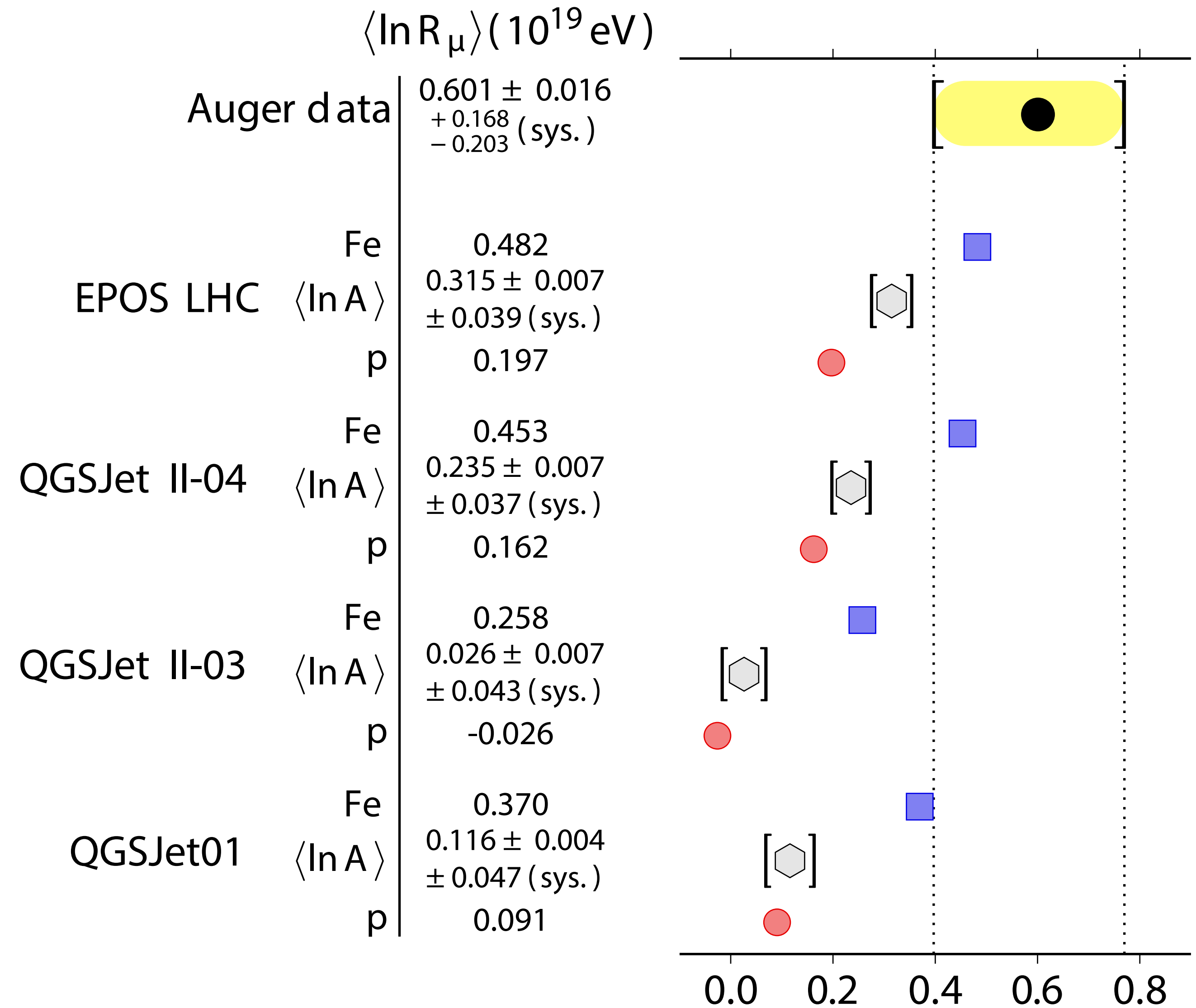
$$\sigma^{inel}_{pp} = [92 \pm 7_{stat}\,(^{+9}_{-11})_{sys} \pm 7.0_{Glauber}]\ \mathrm{mb}$$

$$\sigma^{tot}_{pp} = [133 \pm 13_{stat}\,(^{+17}_{-20})_{sys} \pm 16_{Glauber}]\ \mathrm{mb}$$

Interaction Models lack Muons in EAS

Auger Collaboration, Phys. Rev. D 91, 032003 (2015); editors suggestion





μ-deficit points to deficiencies of hadronic interaction models
LHC forward physics program highly relevant
joint efforts by people from both communities