Ultra-High Energy Cosmic Rays: Results, and Prospects

Karl-Heinz Kampert, University Wuppertal

Area ∝ Grant

26th Texas Symposium on Relativistic Astrophysics, São Paulo, Brazil, 15.-20., 2012

Contents

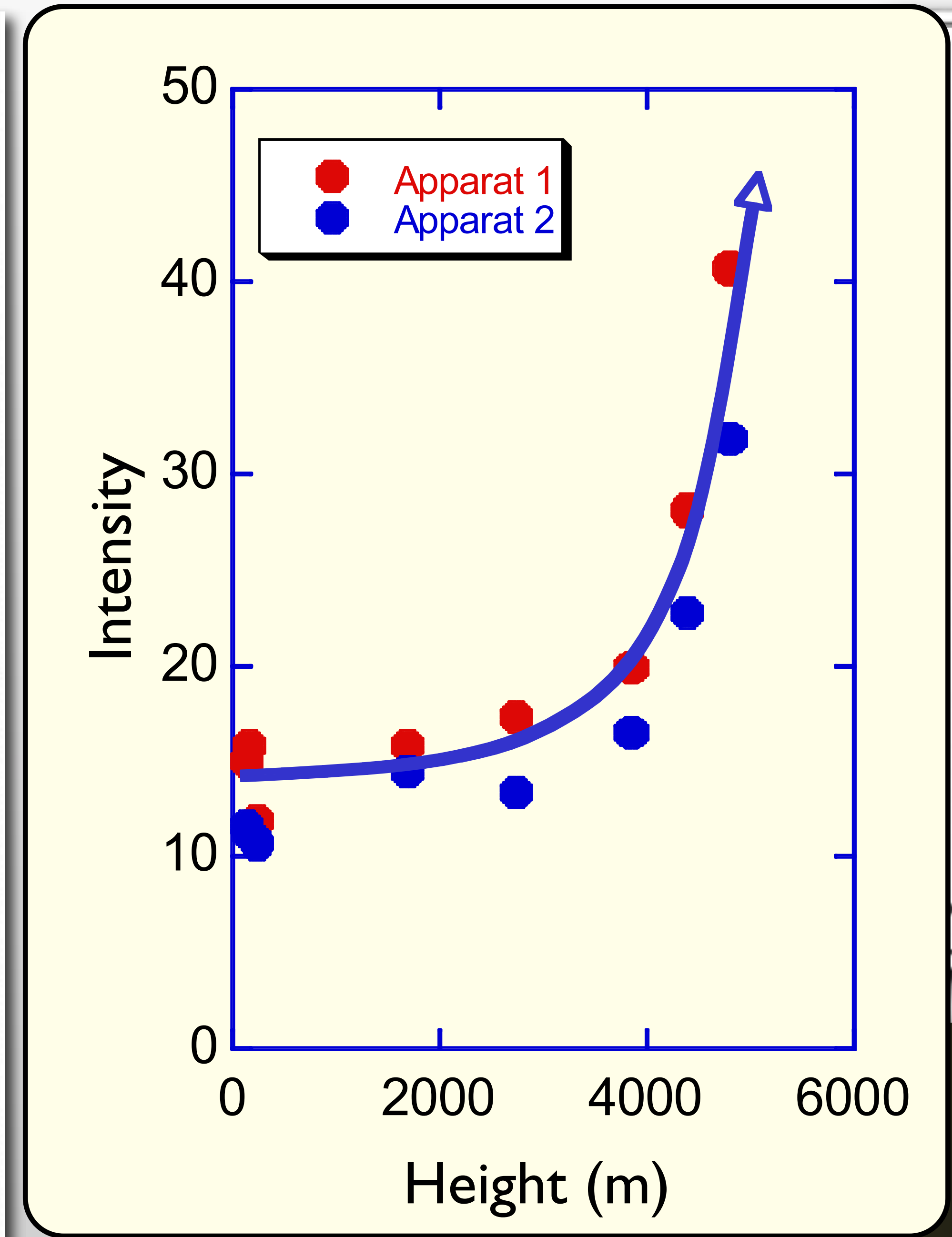
1. 100 years of CRs
– 50 years of 10^{20} eV physics
– 5 years of revolutionary development

2. Review of observational data:
do we see the long awaited GZK-effect
or the exhaustion of sources ?

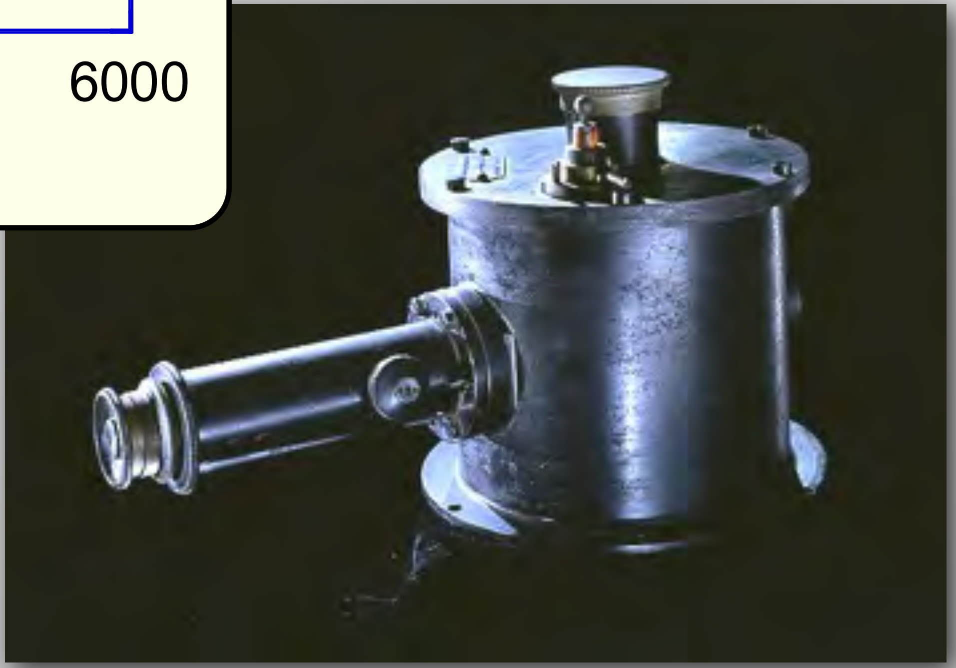
3. Recent developments in phenomenology /theory

4. Future plans

100 years ago: Discovery of Cosmic Radiadion



1936



1962, 50 Years ago: The First 10^{20} eV Event

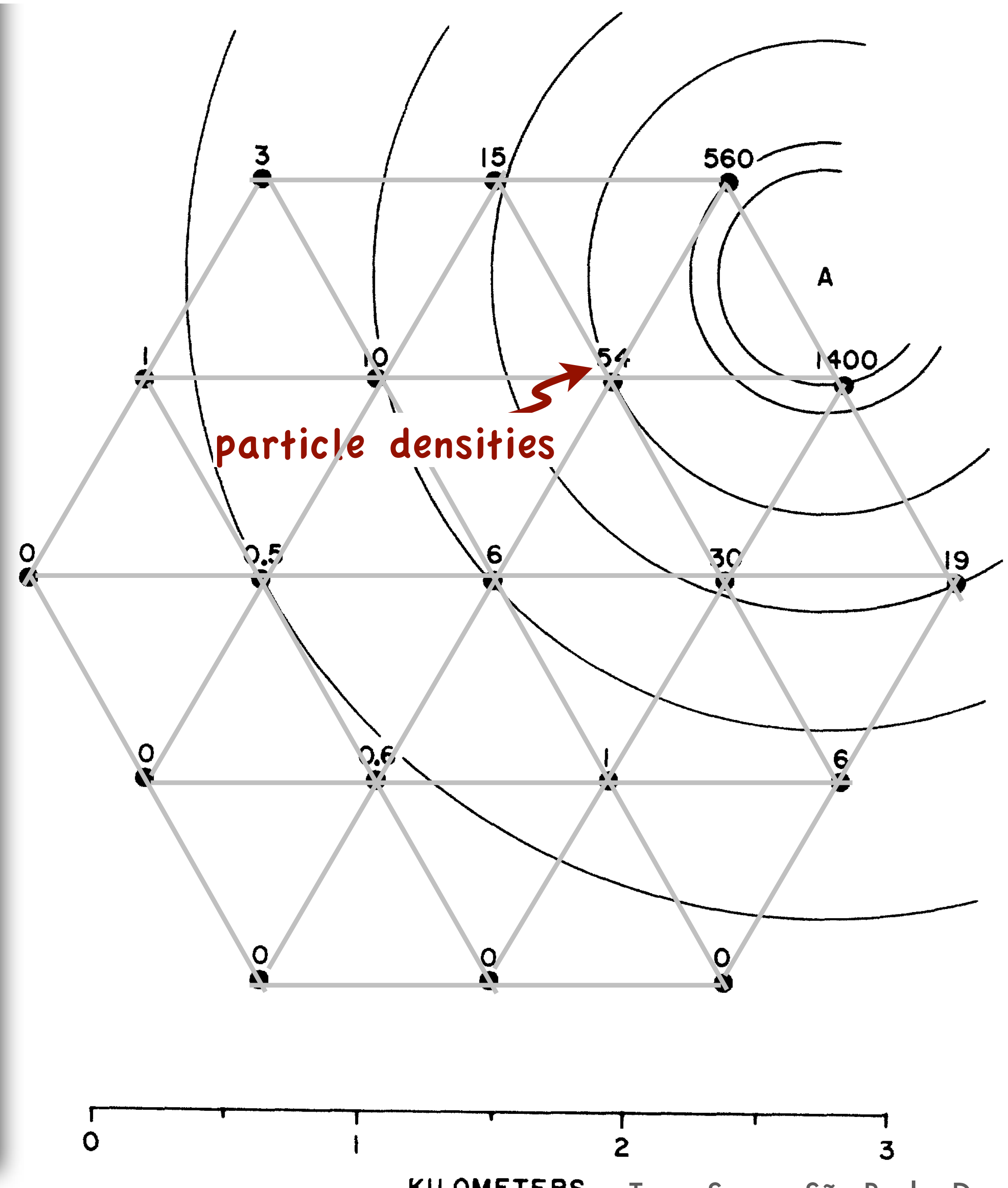
VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

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

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

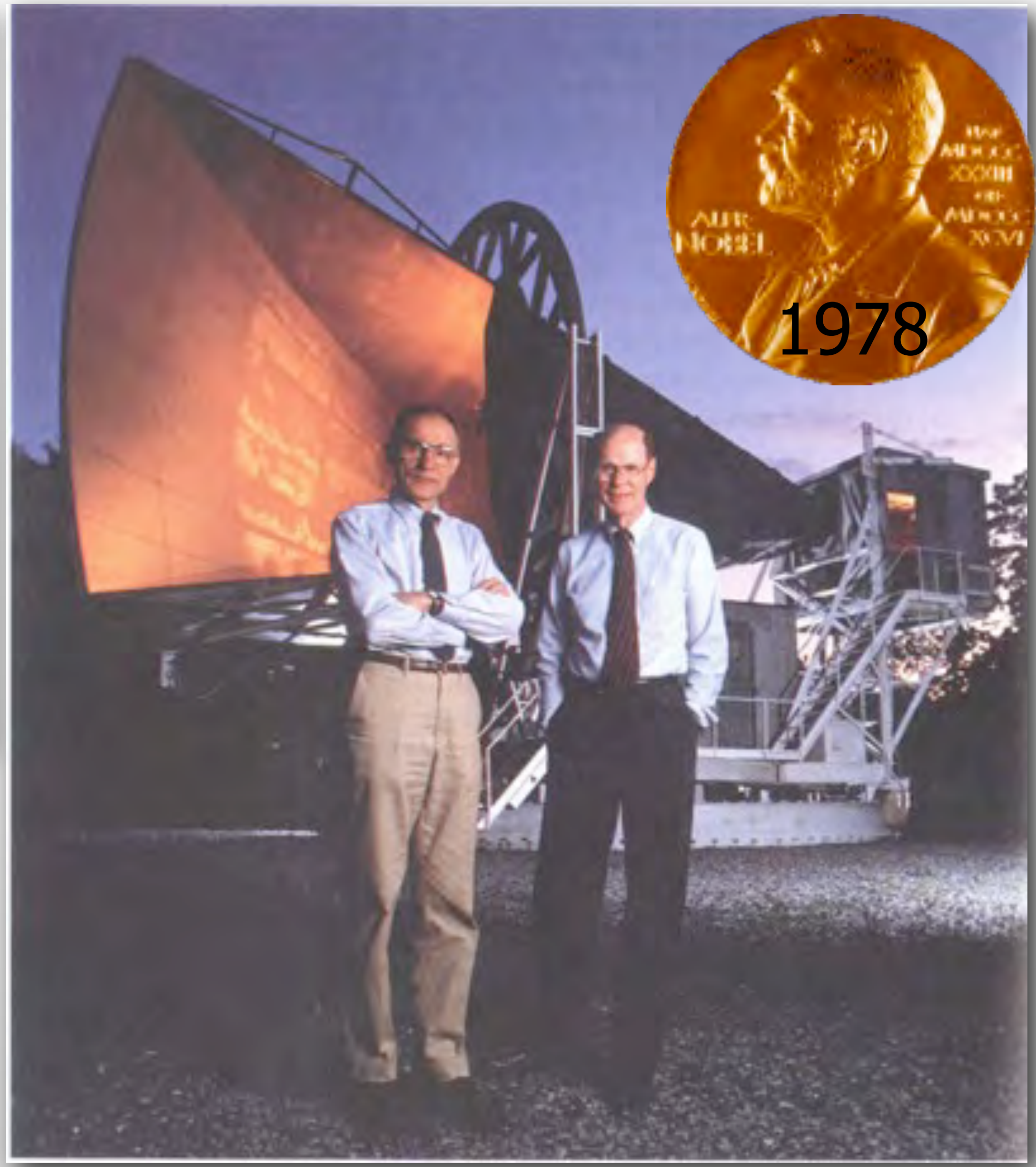
(Received 10 January 1963)

Volcano Ranch Air Shower Array, New Mexico

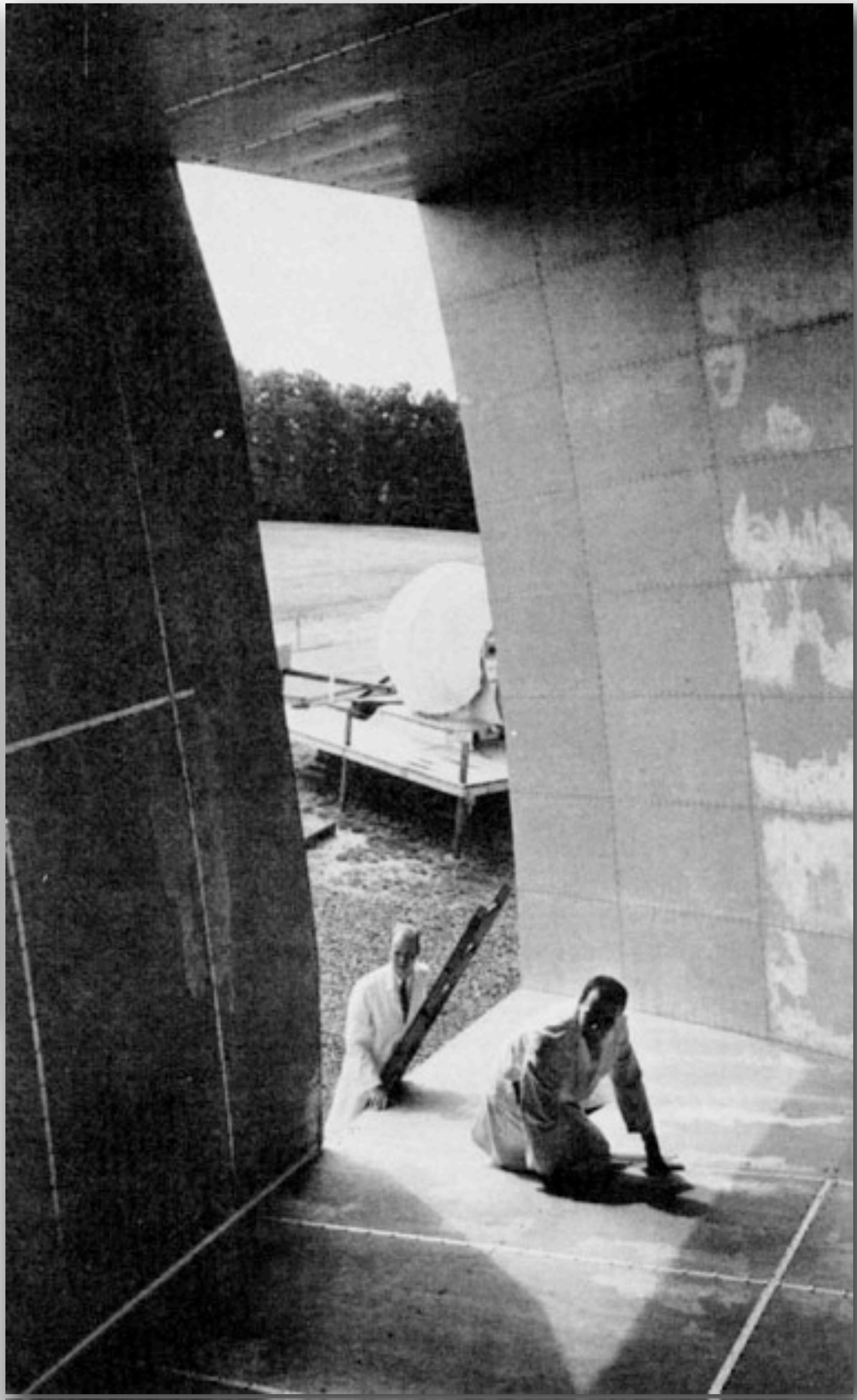


1965: Discovery of CMB

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

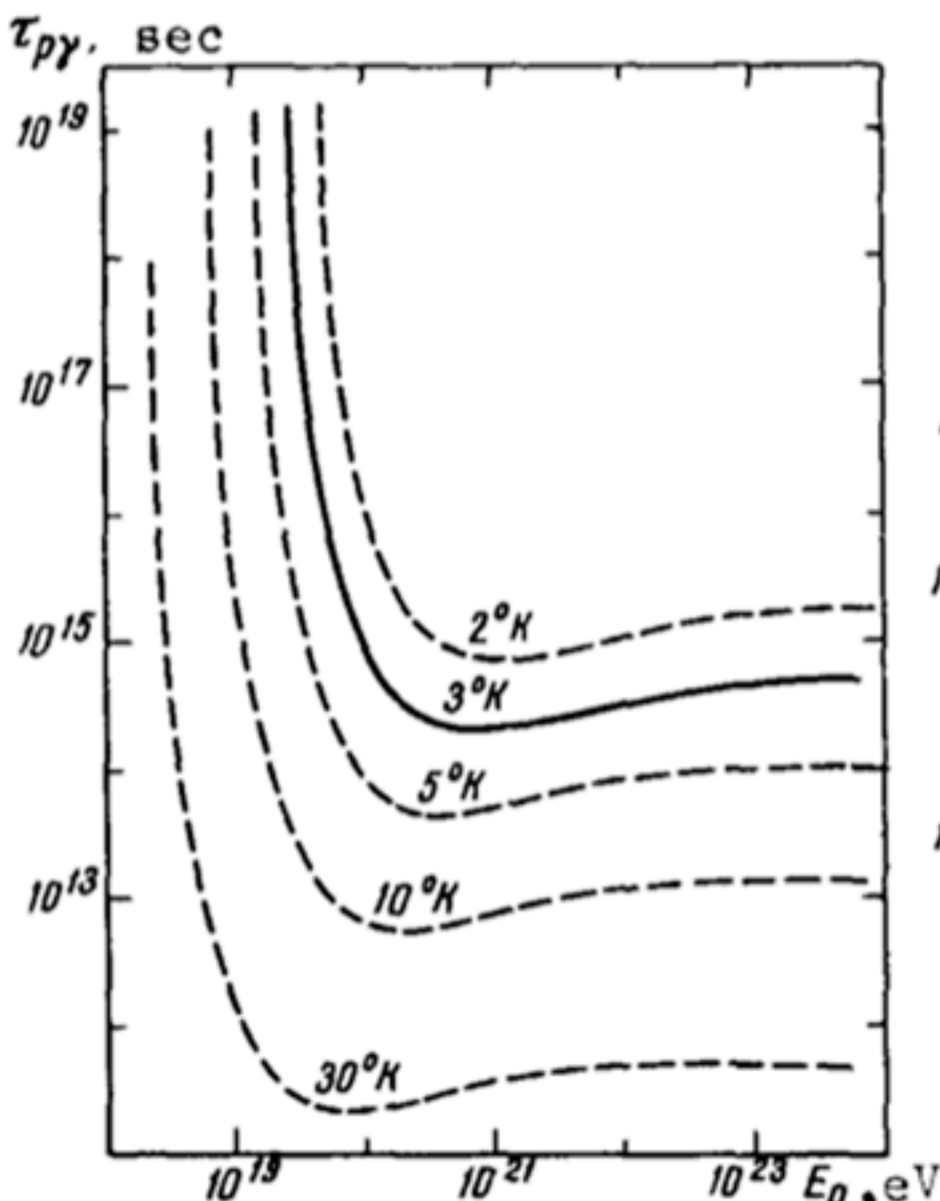
(Received 1 April 1966)

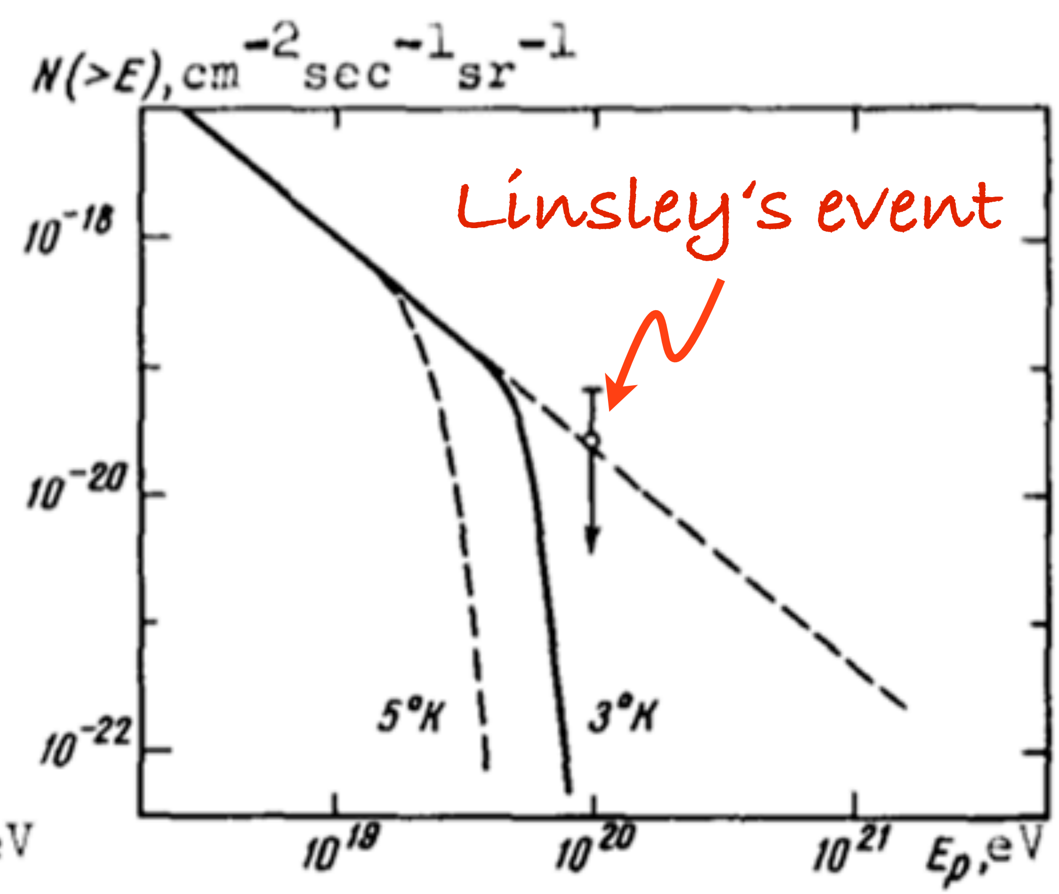
Greisen,
Zatsepin & Kuz'min

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





Problem 1: 10^{20} eV sources need to be nearby

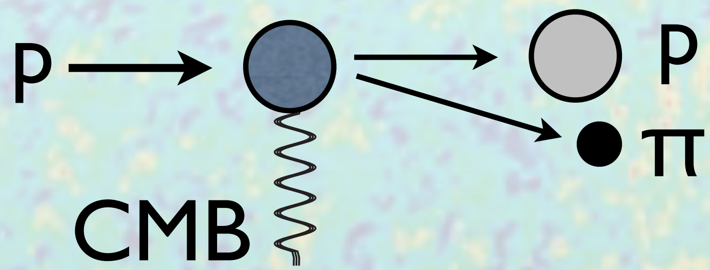


photo-pion production

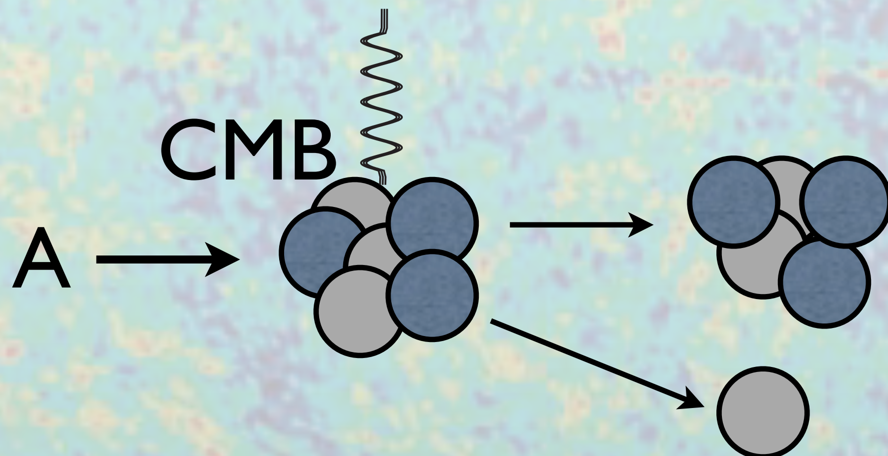


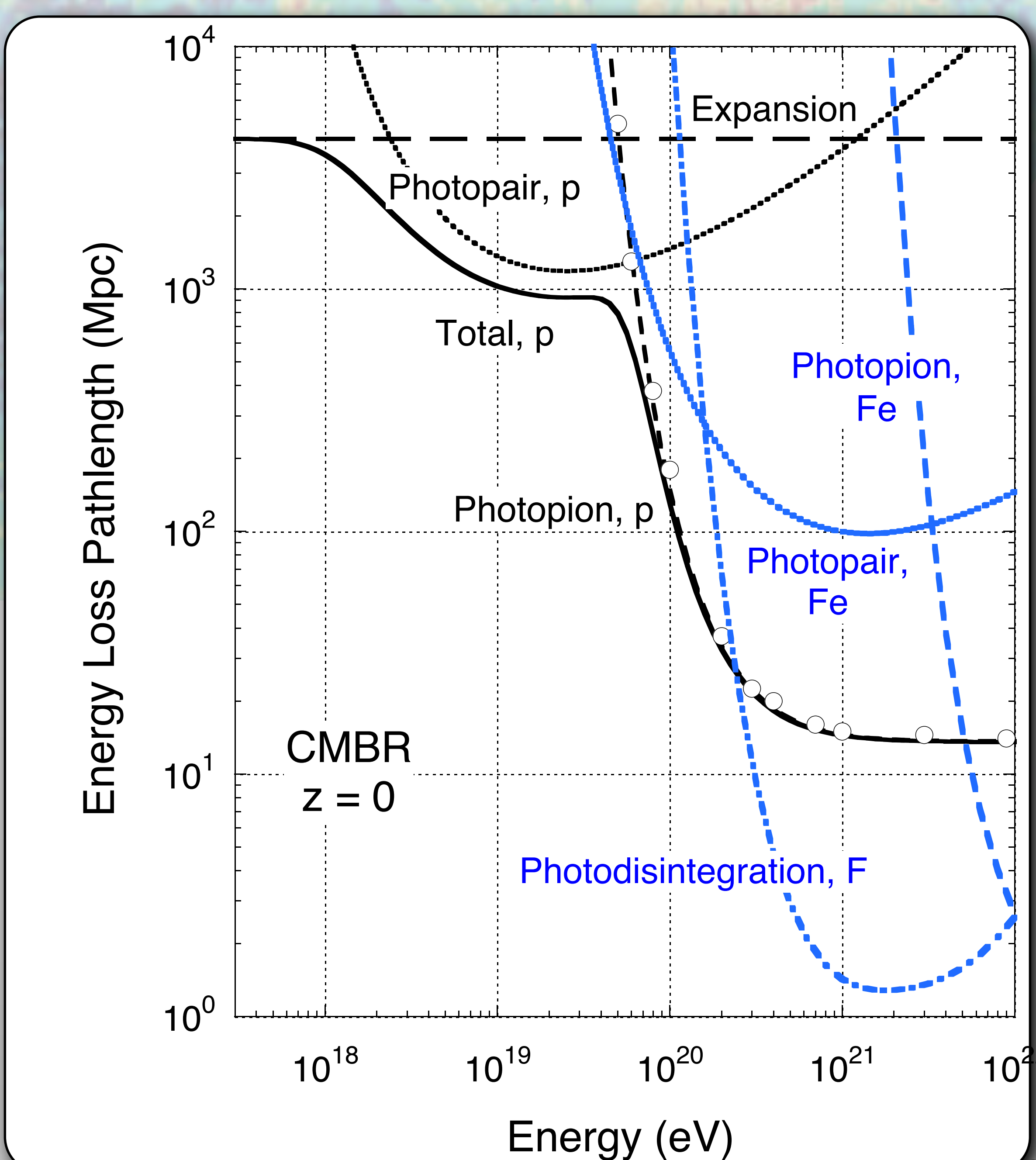
photo disintegration

Greisen-**Z**atsepin-**K**uz'min (1966)

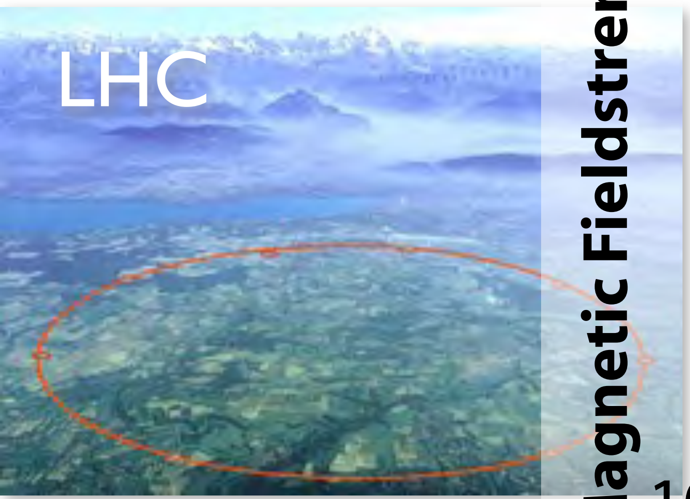
threshold: $E_p E_\gamma > (m_\Delta^2 - m_p^2)$

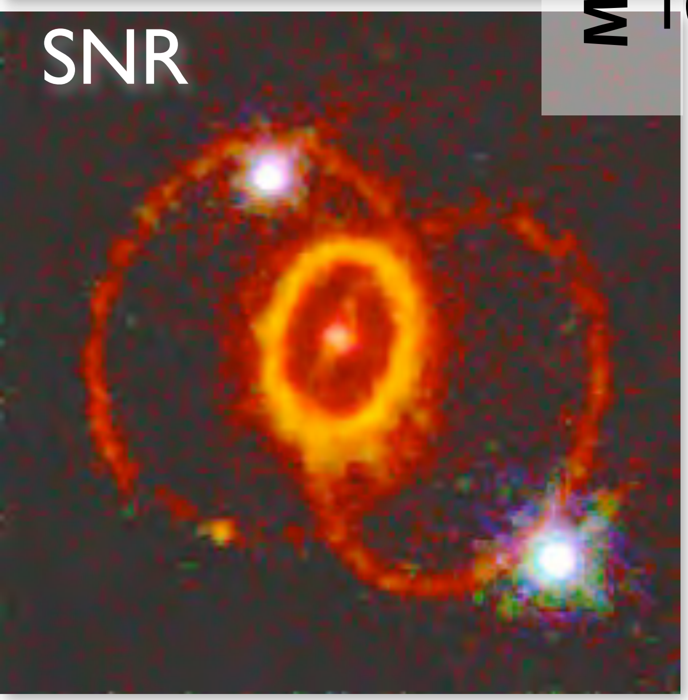
$\Rightarrow E_{GZK} \approx 6 \cdot 10^{19}$ eV

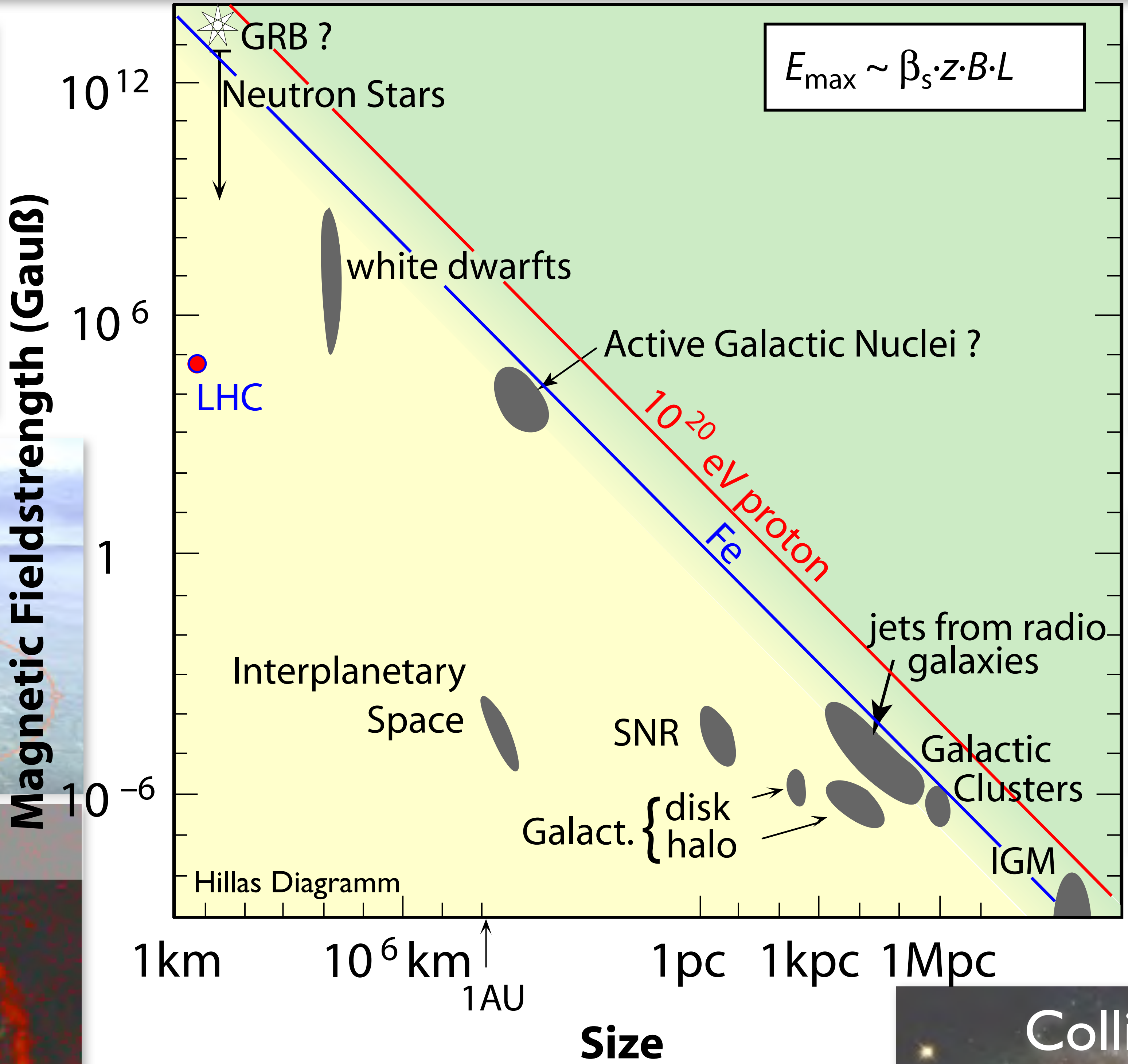
→ **GZK-Horizon ~ 60 Mpc**

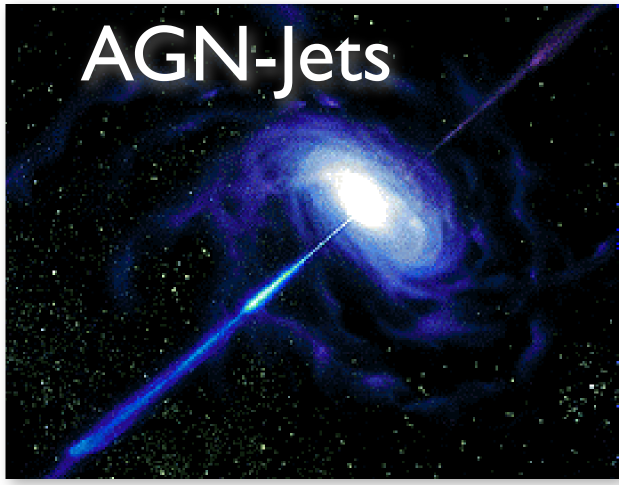


Problem 2: Sources of 10^{20} eV particles







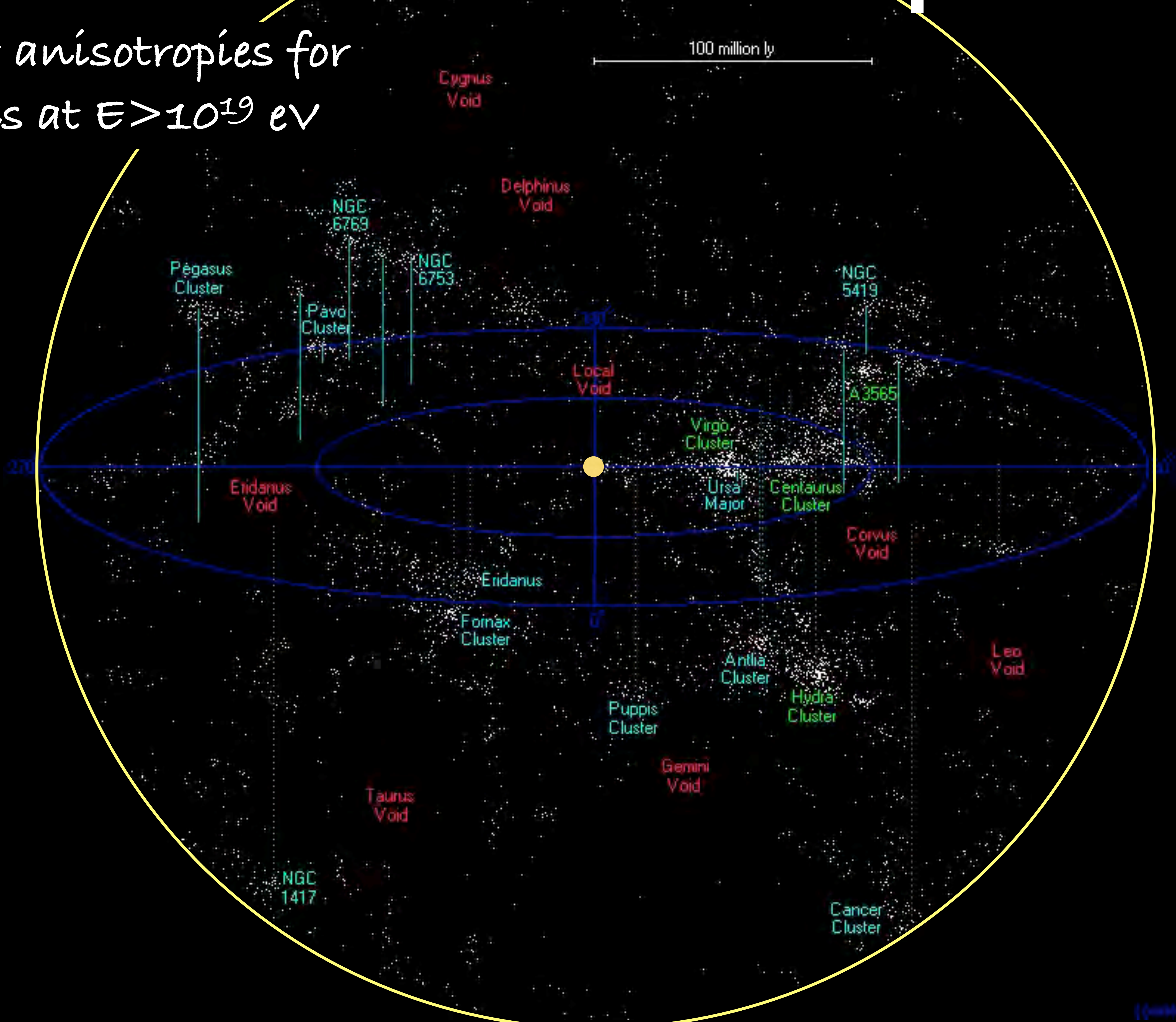


Realistic constraints more severe

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

Problem 3: Anisotropies

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

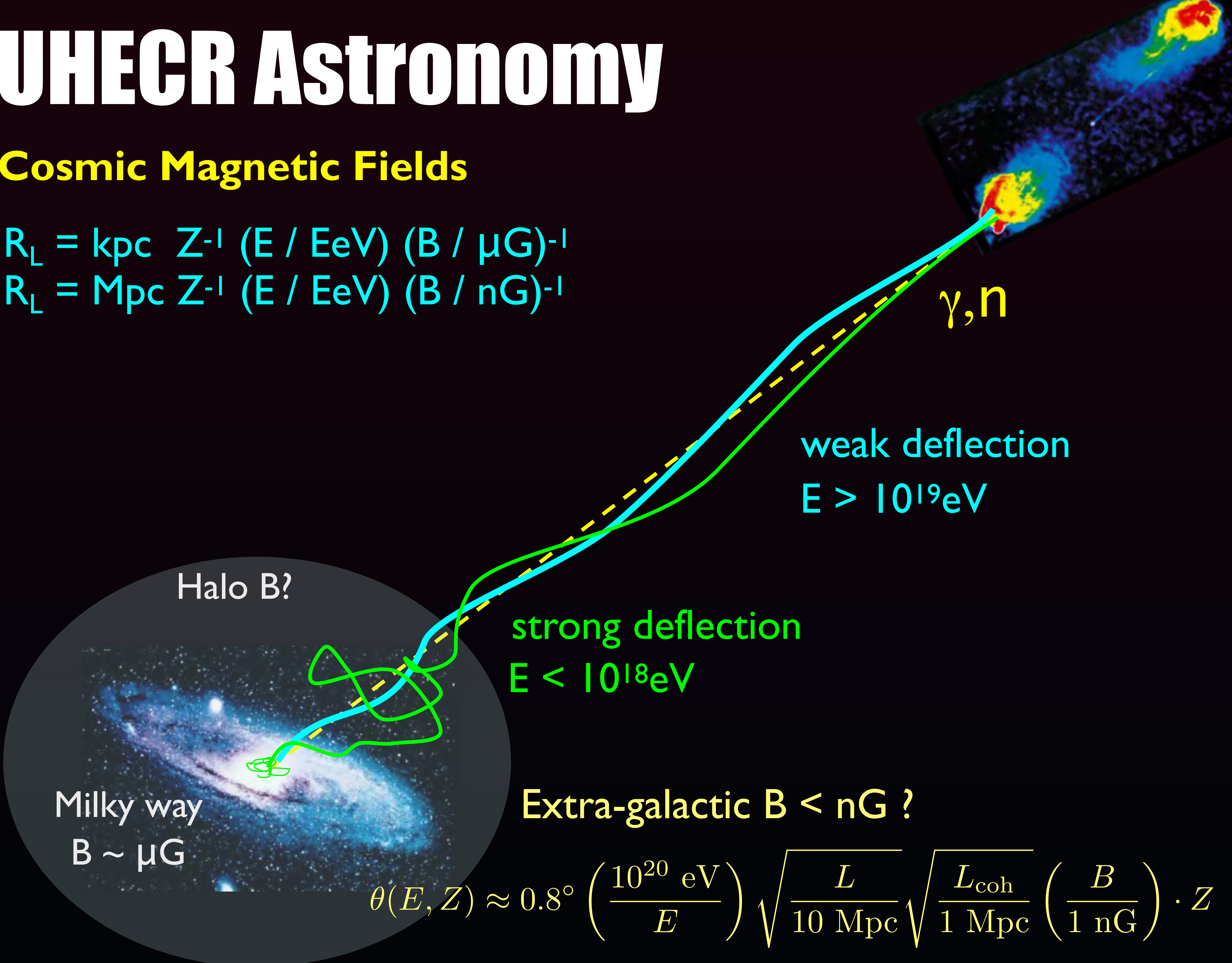


UHECR Astronomy

Cosmic Magnetic Fields

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

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



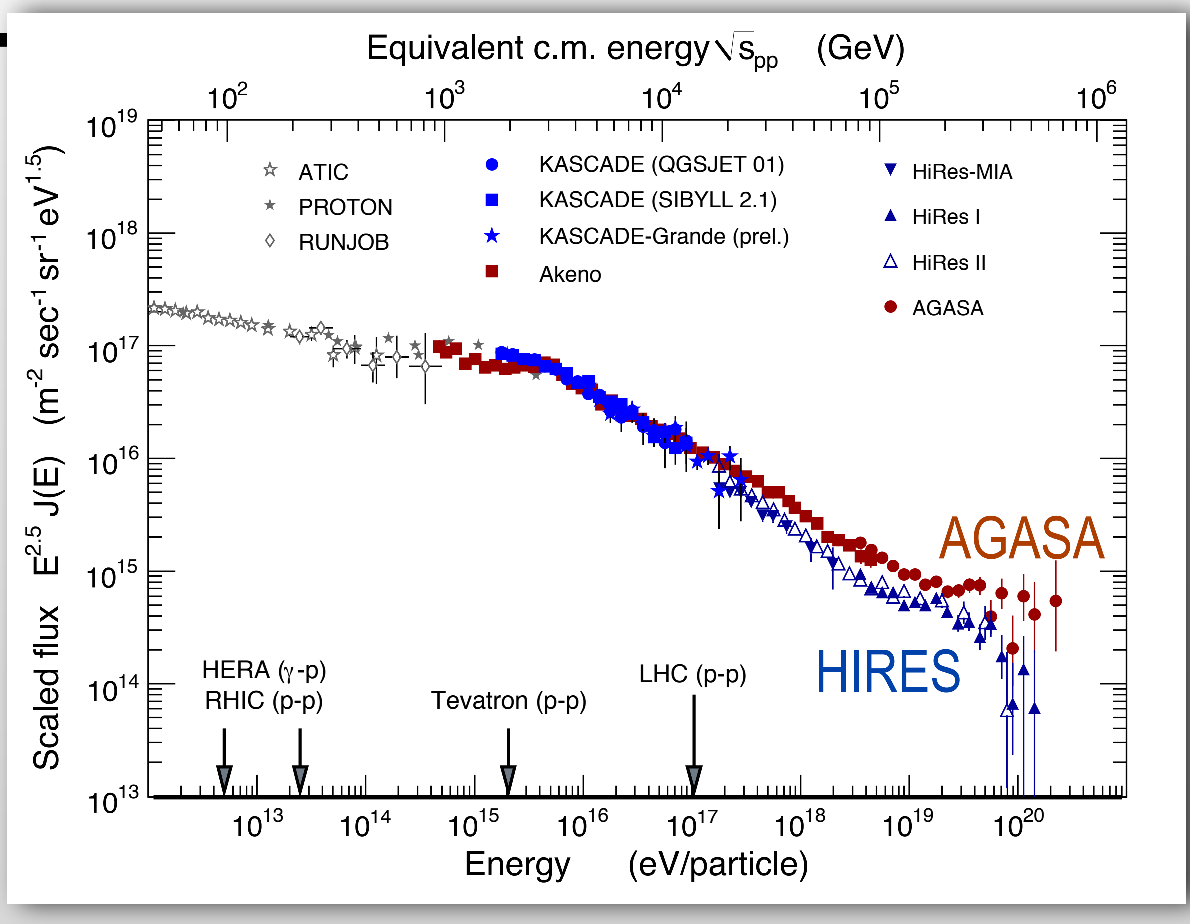
Extra-galactic B < nG ?

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

Situation ~5 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

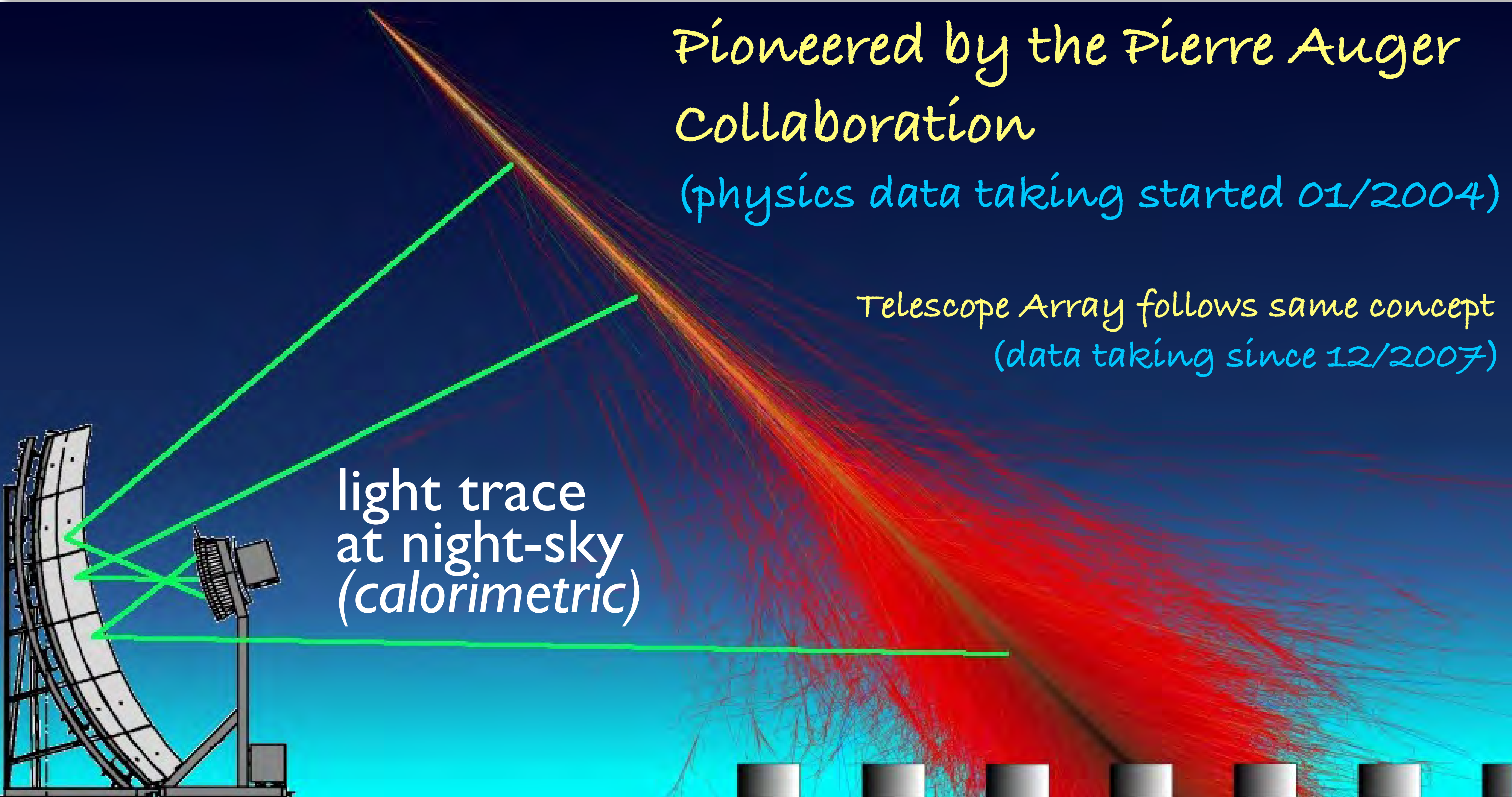


Apparent continuation of spectrum gave birth to exotic source and propagation scenarios

- 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



Fluorescence light

Particle-density and
-composition at ground

Also:
Detection of Radio- & Microwave-Signals

Pierre Auger Observatory

1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

160 radio antennas

…

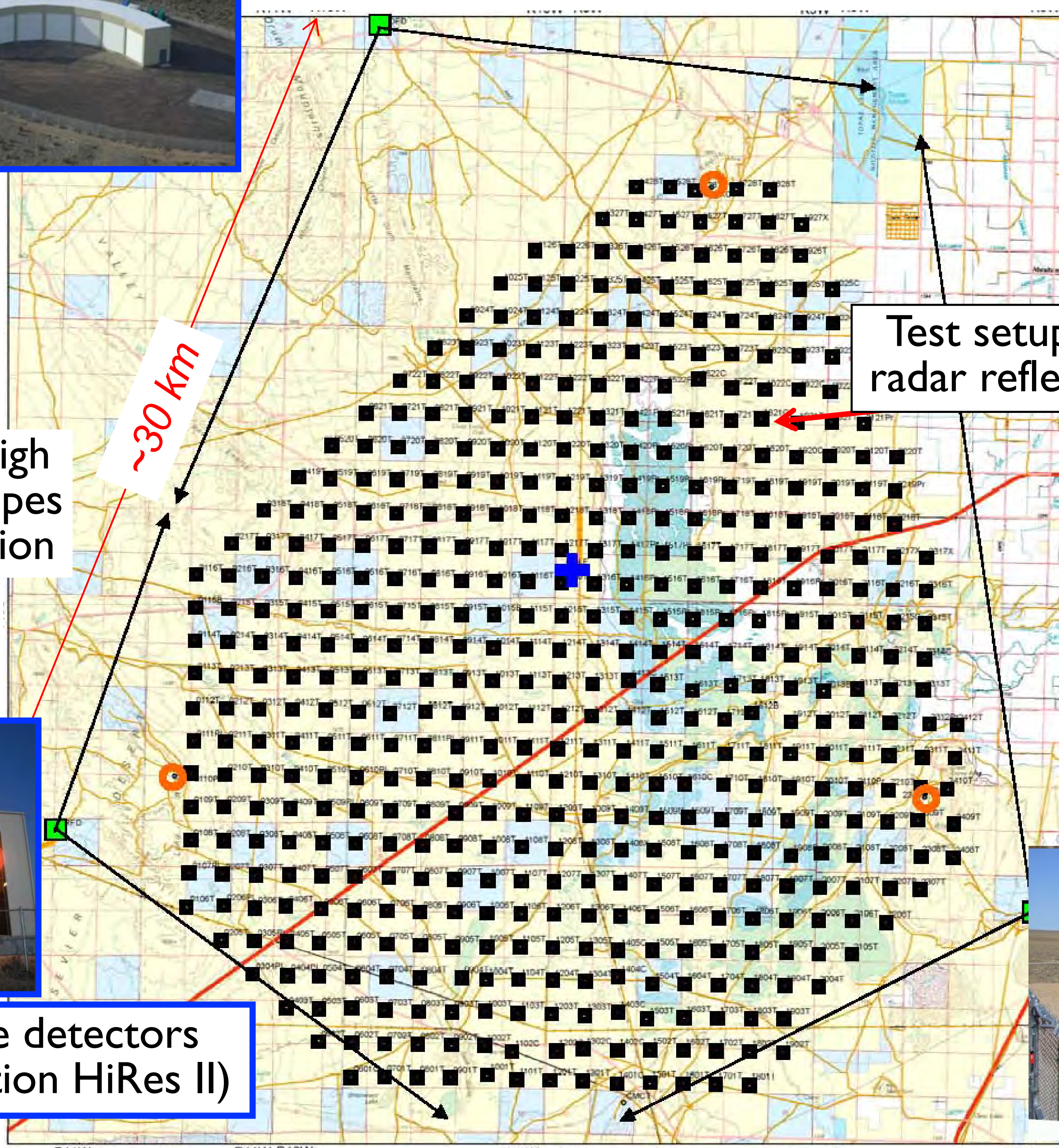
Southern hemisphere: Argentina

Telescope Array (TA)

Middle Drum: based on HiRes II

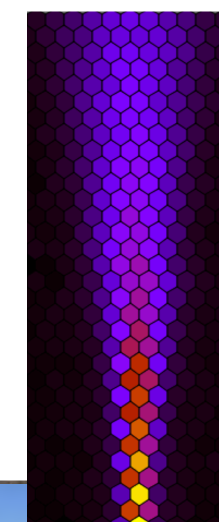
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

LIDAR
Laser facility

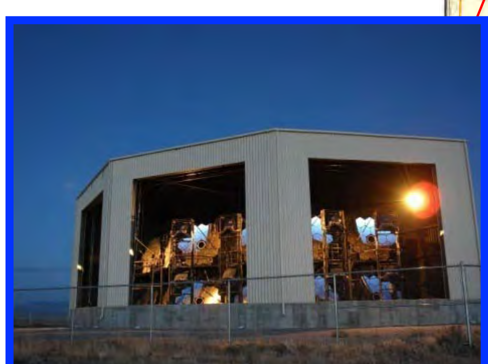


Test setup for
radar reflection

Infill array and high
elevation telescopes
under construction



Electron light source
(ELS): ~40 MeV

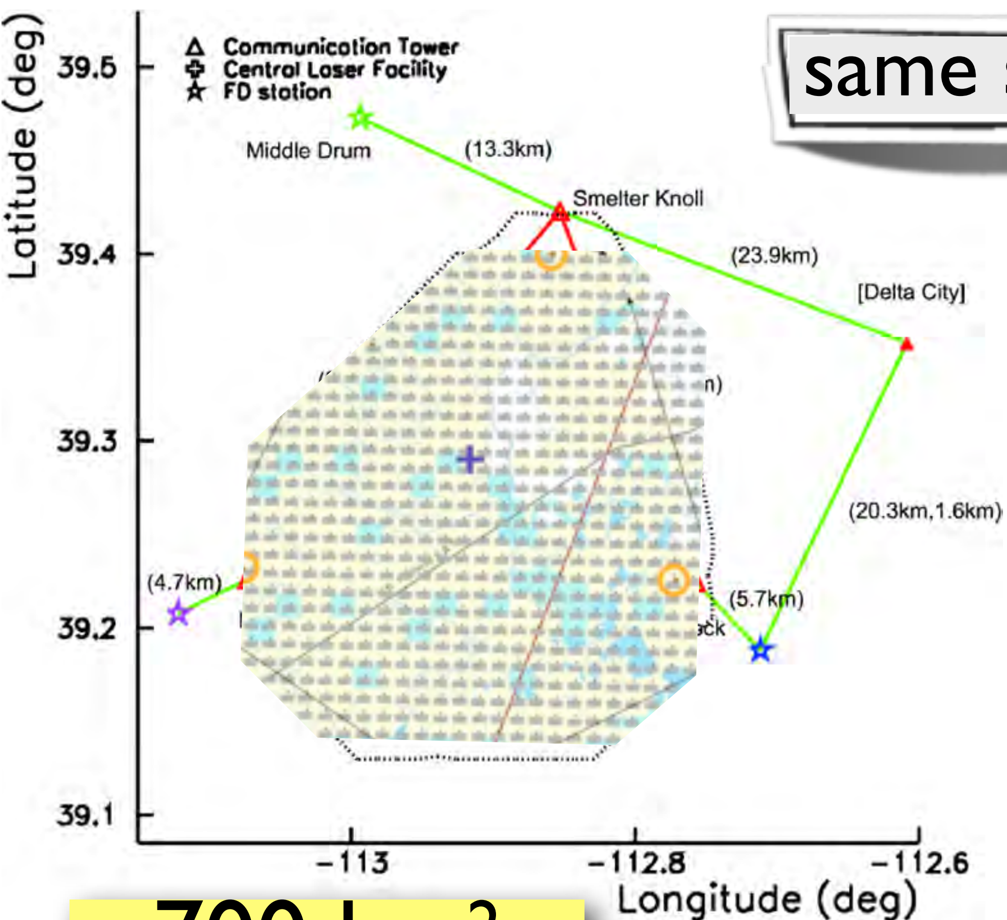


3 fluorescence detectors
(2 new, one station HiRes II)

Northern hemisphere: Utah, USA

The UHECR Hybrid Generation

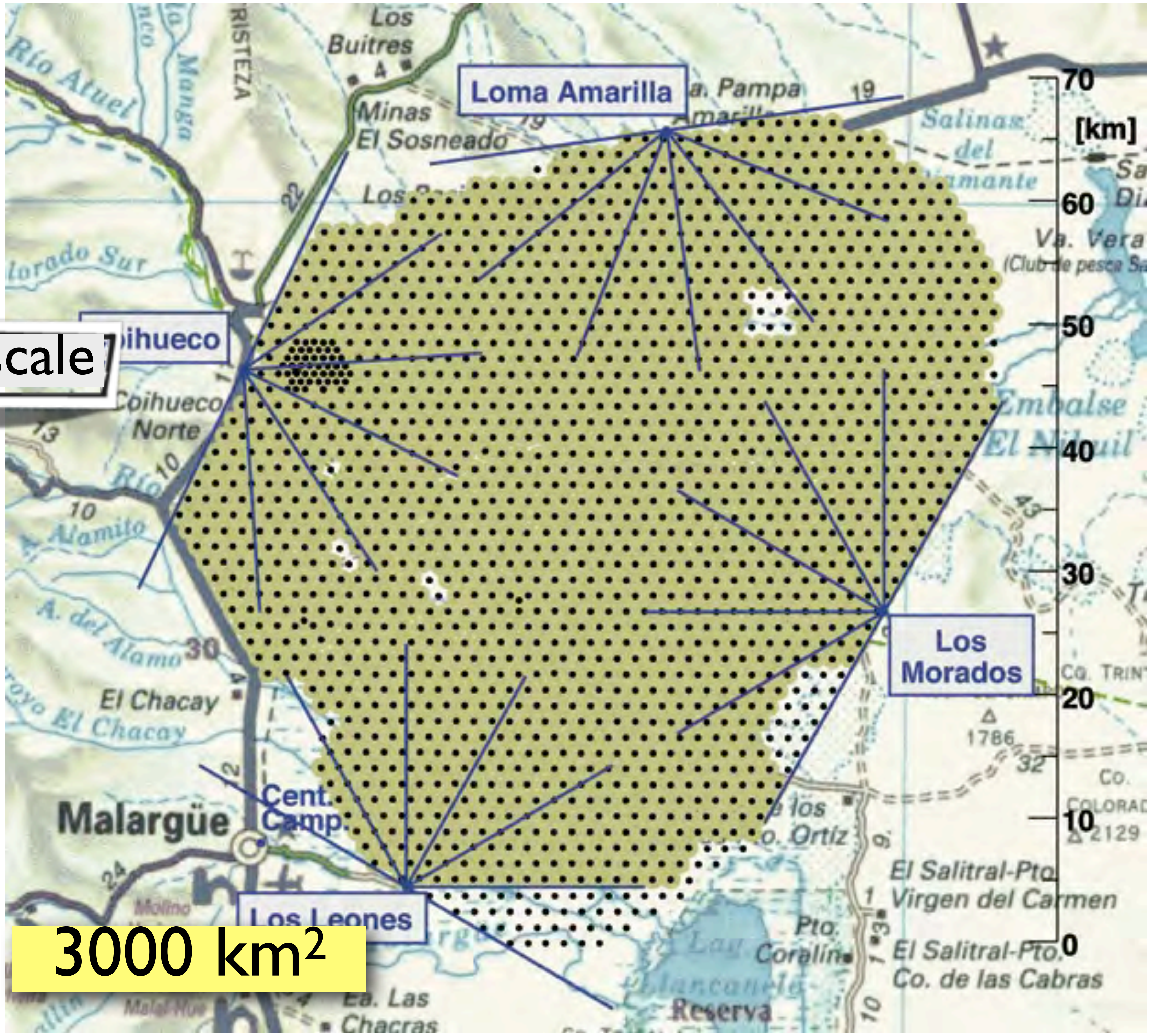
Telescope Array



700 km²

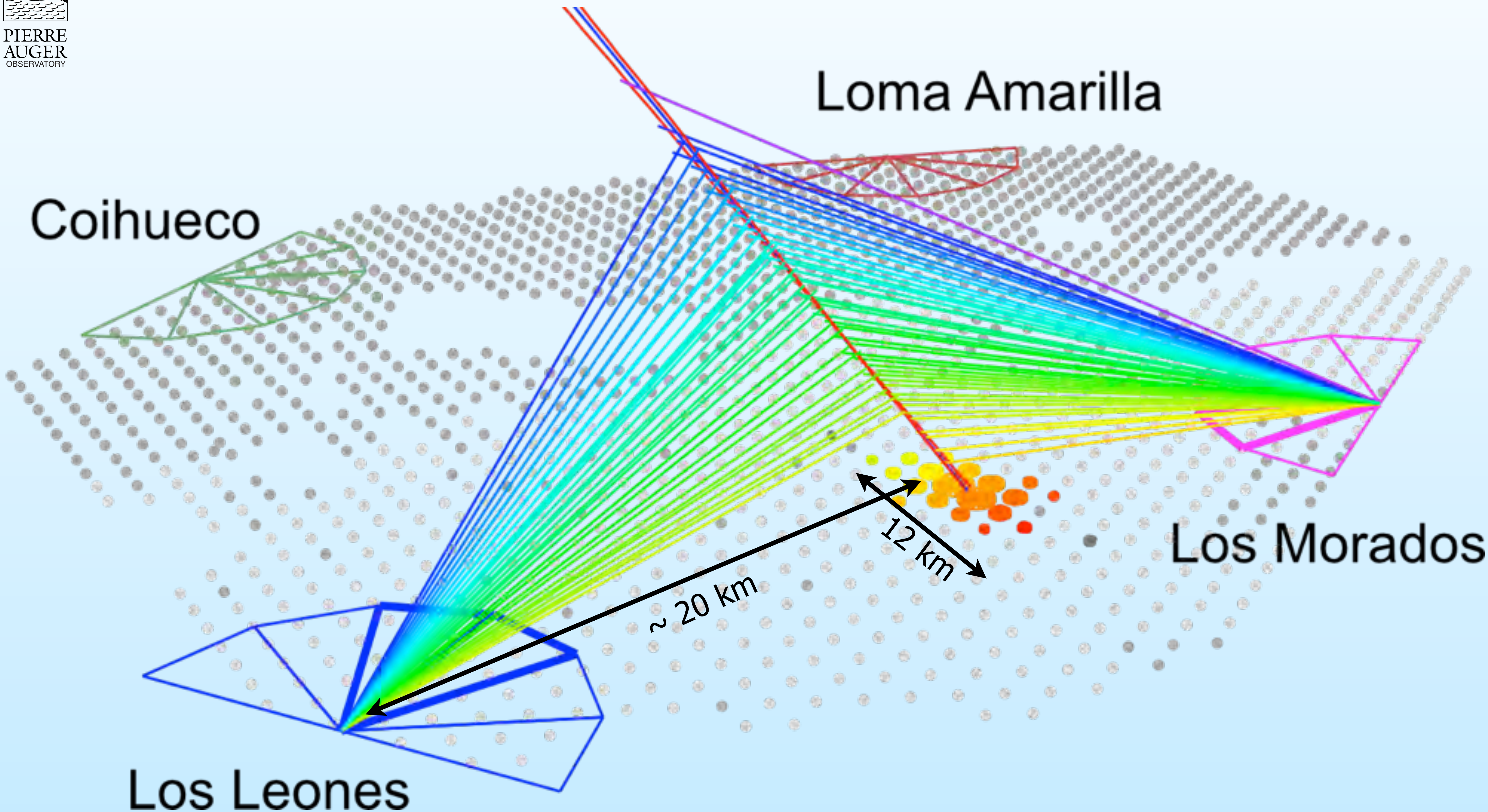
same scale

Pierre Auger Observatory

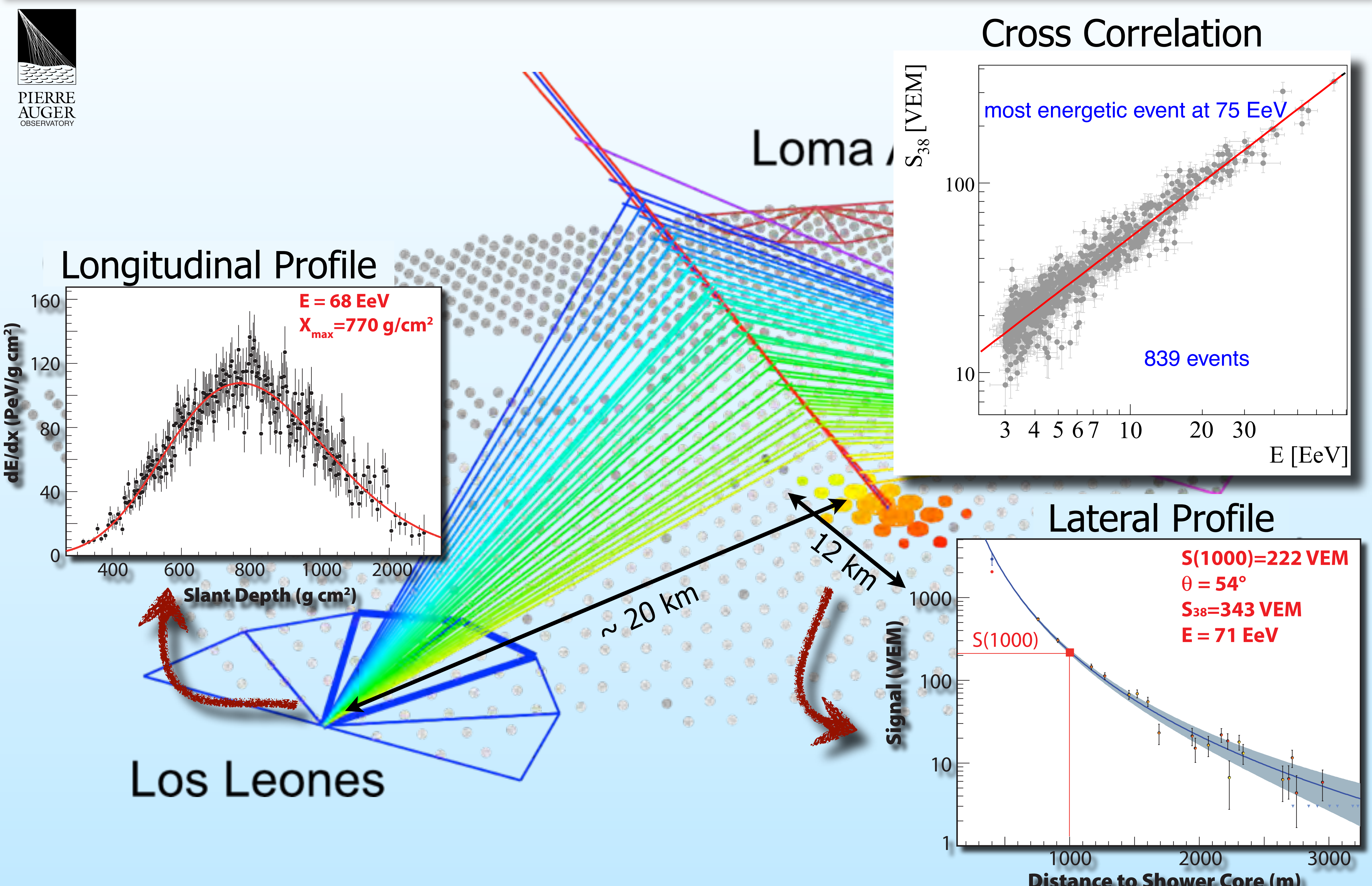


3000 km²

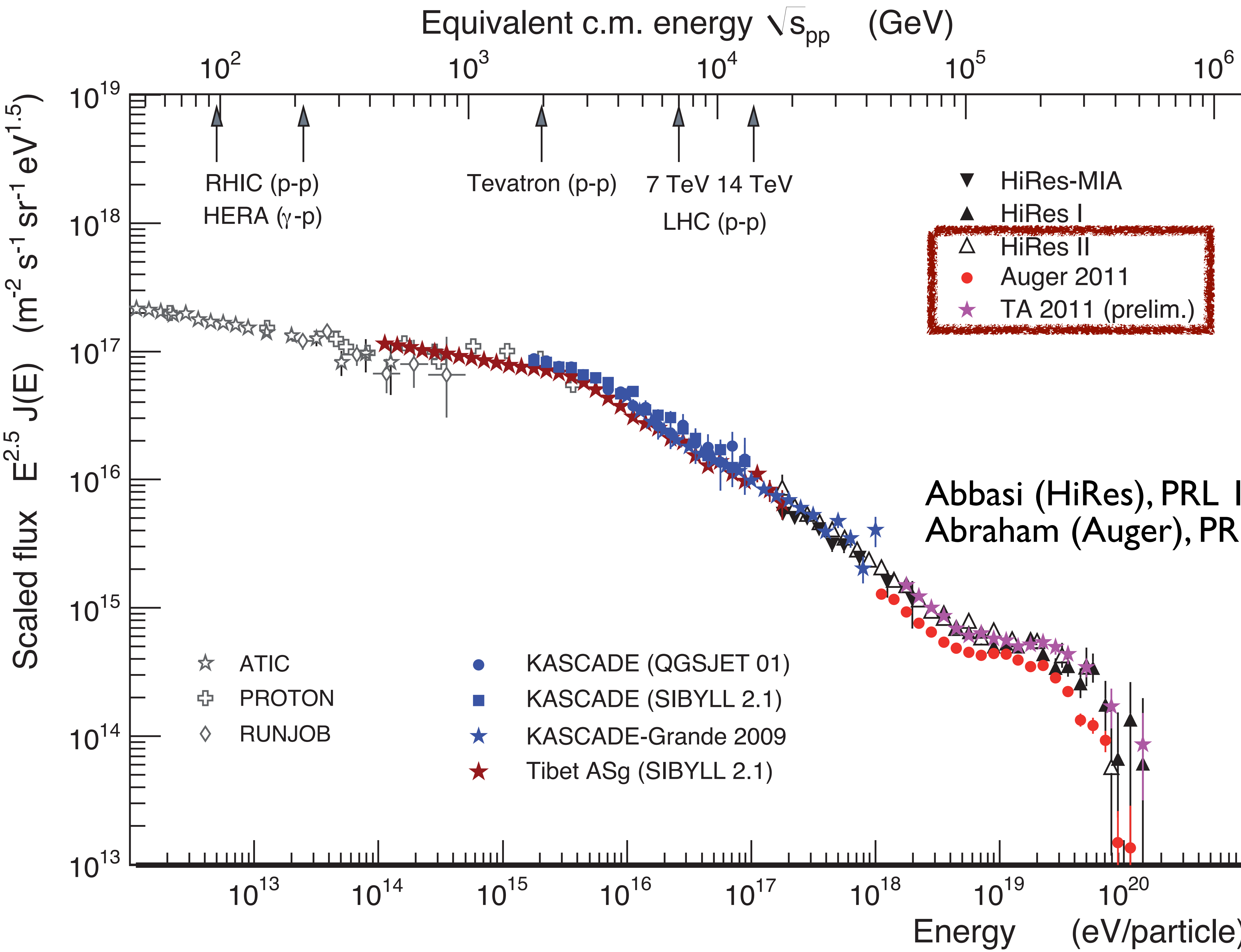
Event Example in Auger Observatory



Event Example in Auger Observatory

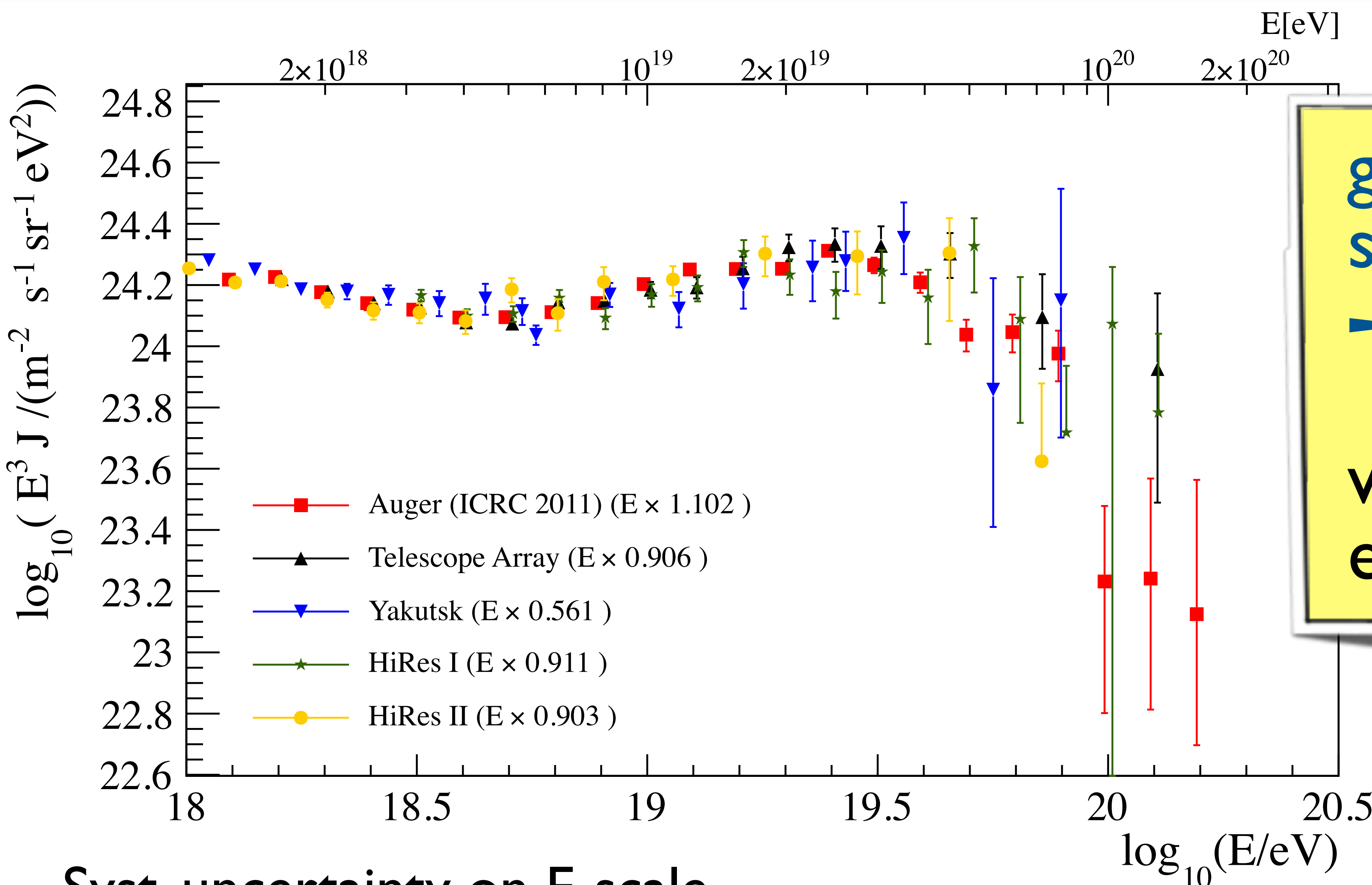


2008: Unambigiuous Detection of Flux Suppression



Abbasi (HiRes), PRL 100 (2008)
Abraham (Auger), PRL 101(2008)

Comparison of Experiments



global shifts to energy scale by ±10%
→ perfect agreement

(except for Yakutsk)

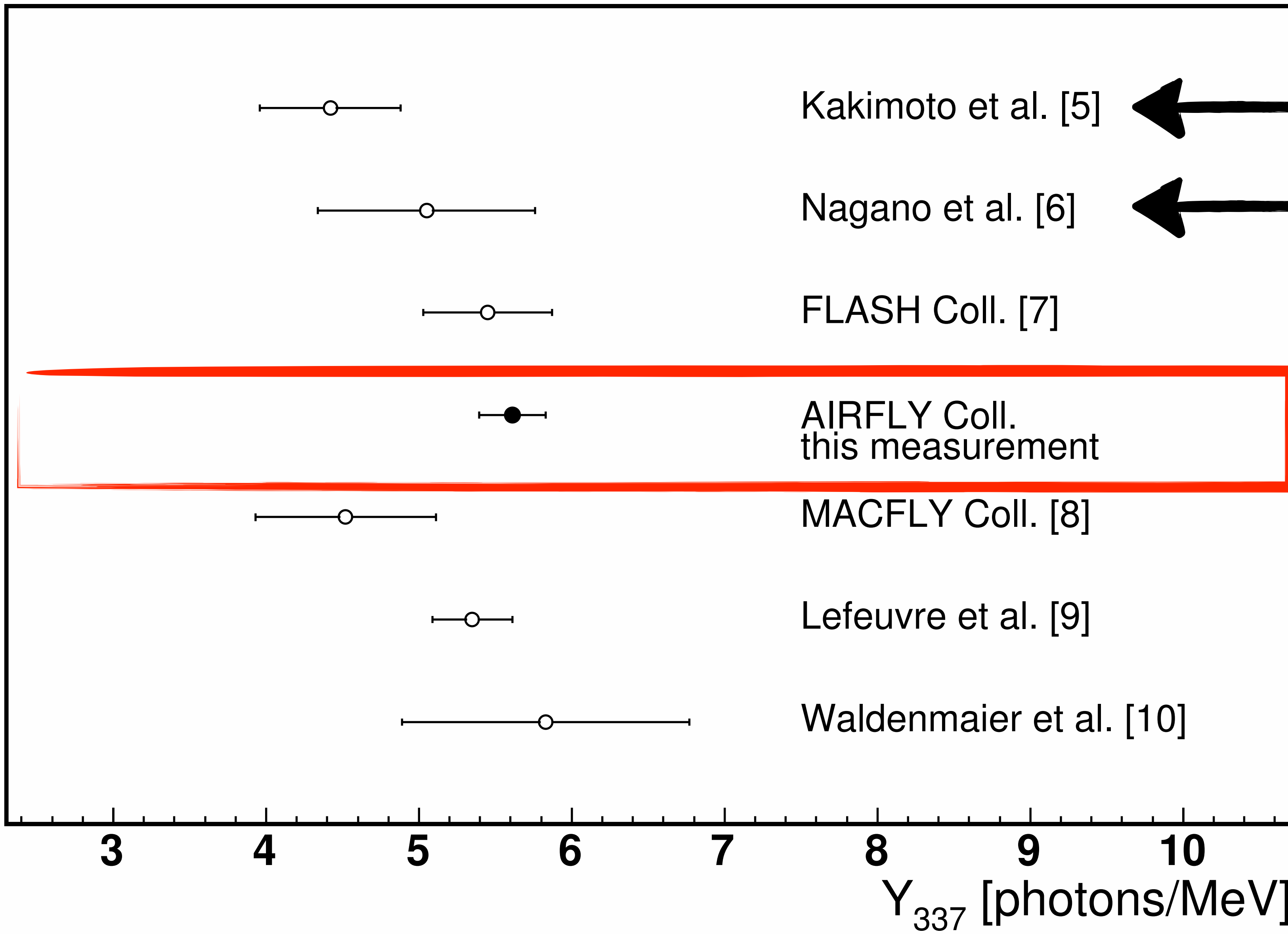
well allowed for by error budgets

Syst. uncertainty on E-scale

	HiRes	Auger	TA
Photometric calibration	10%	9.5%	10%
Fluorescence Yield	6%	14%	11%
Atmosphere	5%	8%	11%
Reconstruction	15%	10%	10%
Invisible Energy	5%	4%	incl. above
TOTAL	**17%**	**22%**	**21%**

Auger-TA-HiRes-Yakutsk Working group @ UHECR2012 to appear in EPJ (web of conf)

New Measurement of Fluorescence Yield



used by TA and HiRes

used by Auger

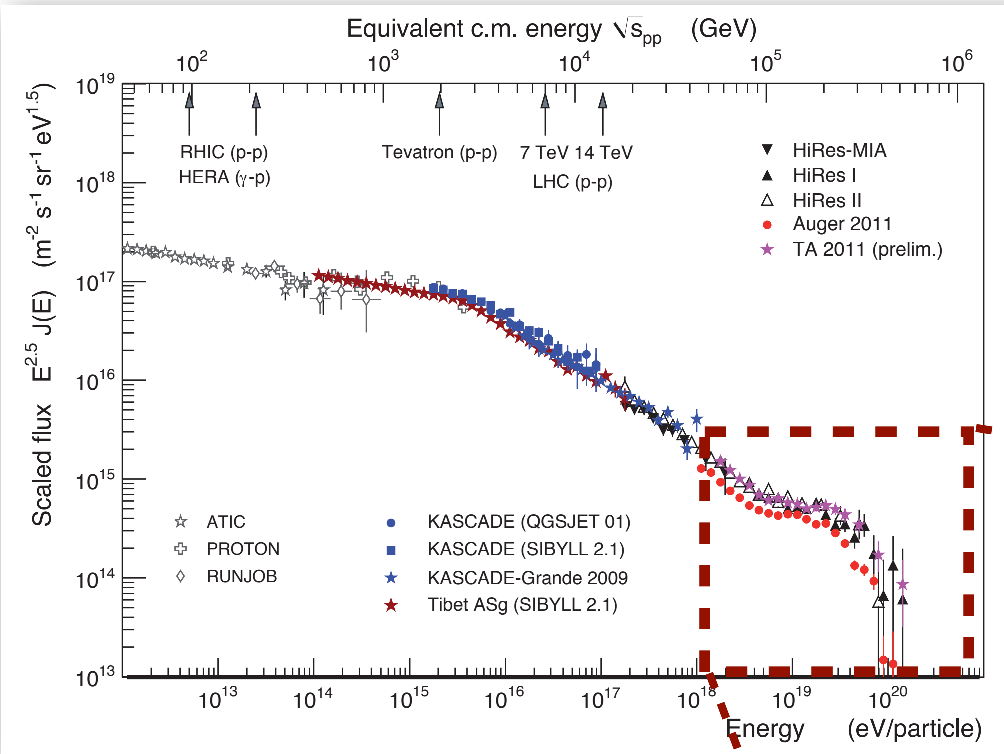
AirFly 2012 final

(Ave et al., arXiv:1210.6734)

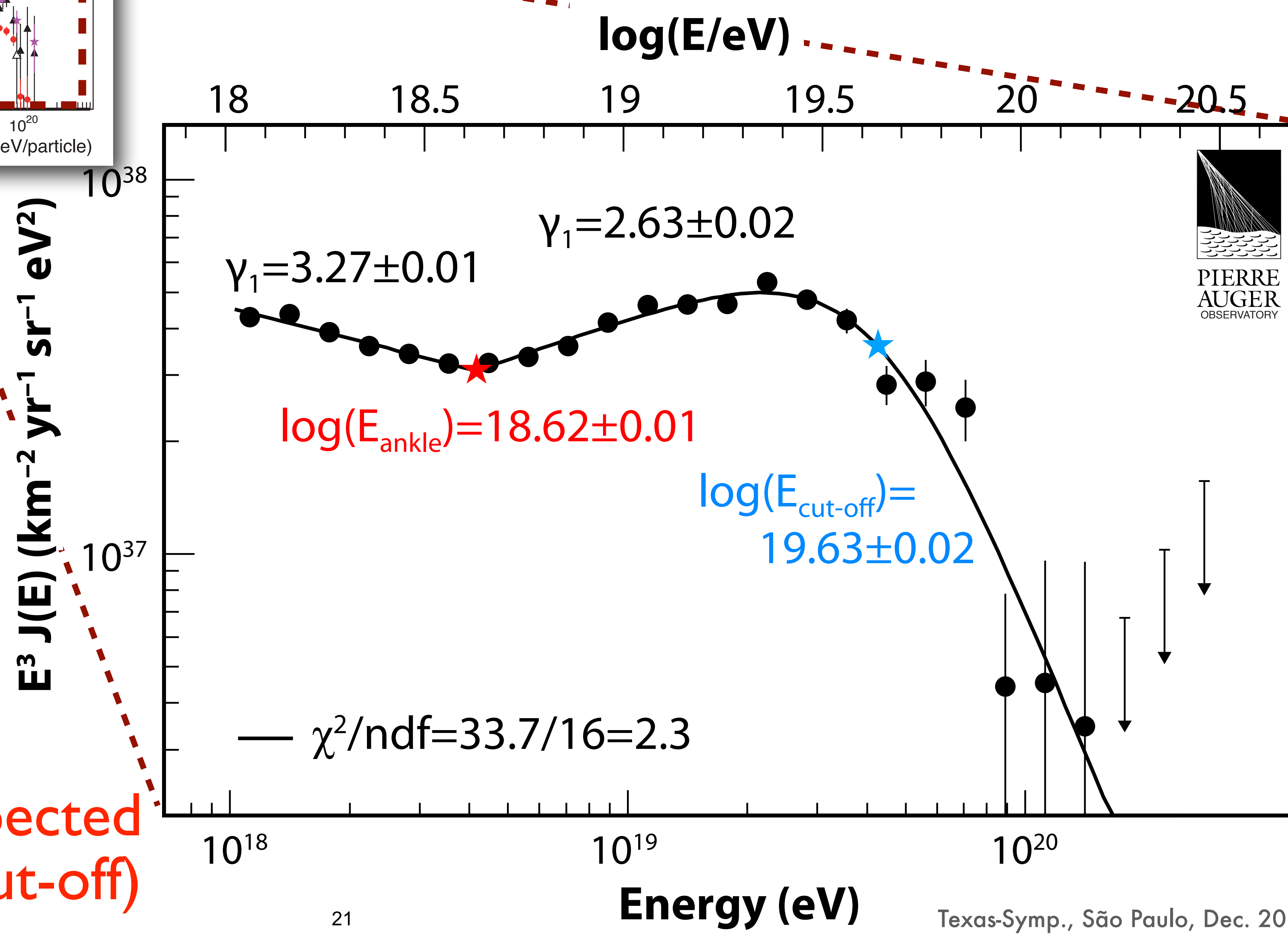
$Y_{337} = 5.61 \pm 0.06_{stat} \pm 0.21_{syst}$ (now with only 4% uncertainty!)

This will almost eliminate the difference between Auger and TA/HiRes!

Flux Suppression in Detail



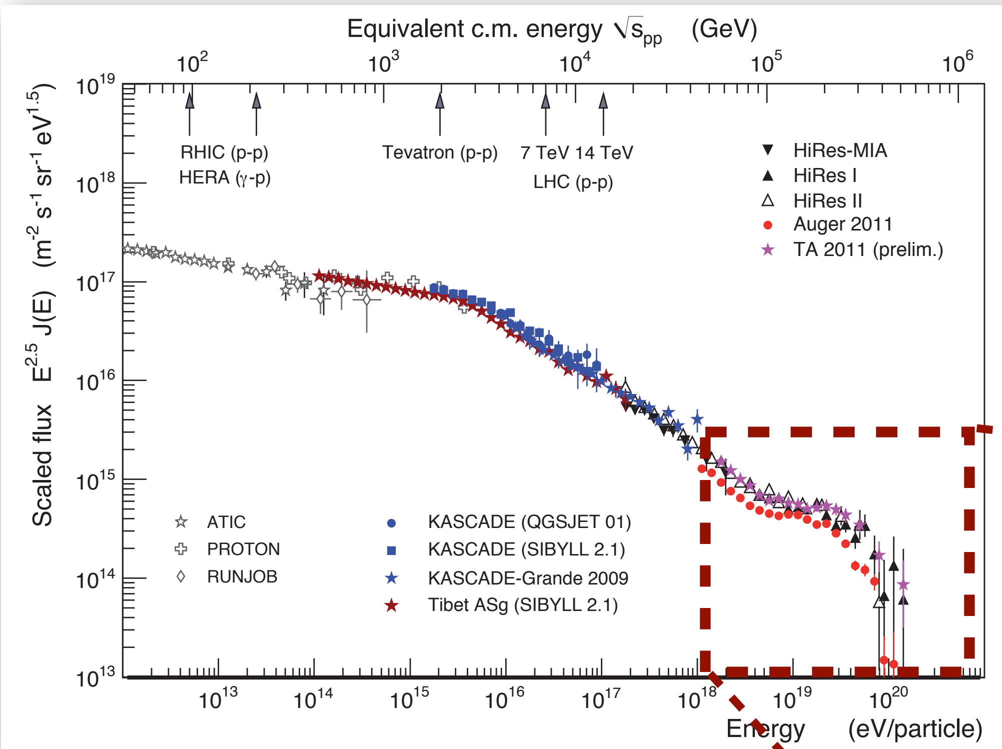
Is this the GZK-effect... ?



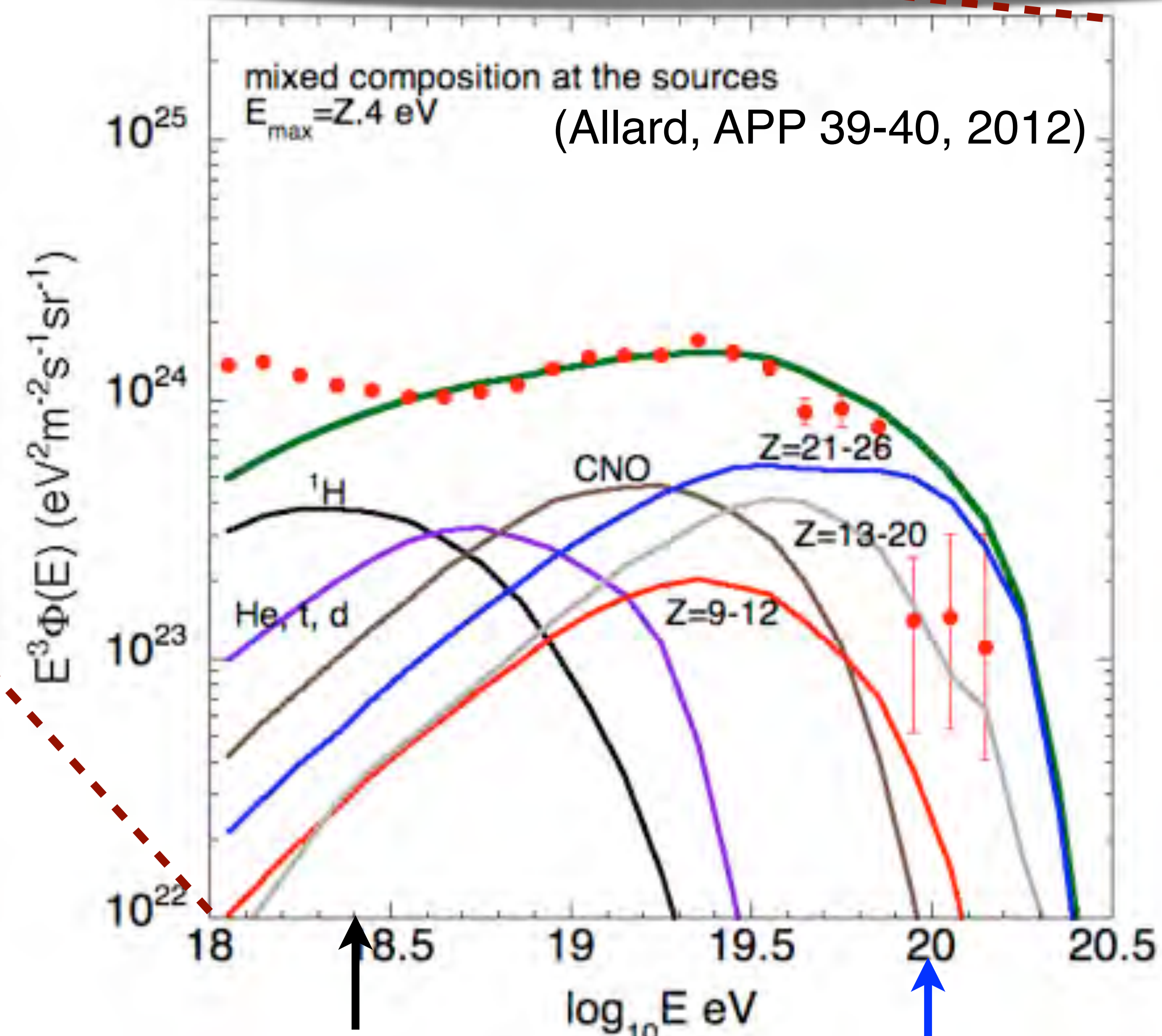
also: absence of HE

ν's and γ's (would be expected if spectrum showed no cut-off)

Flux Suppression in Detail



... or the limiting energy of sources ?



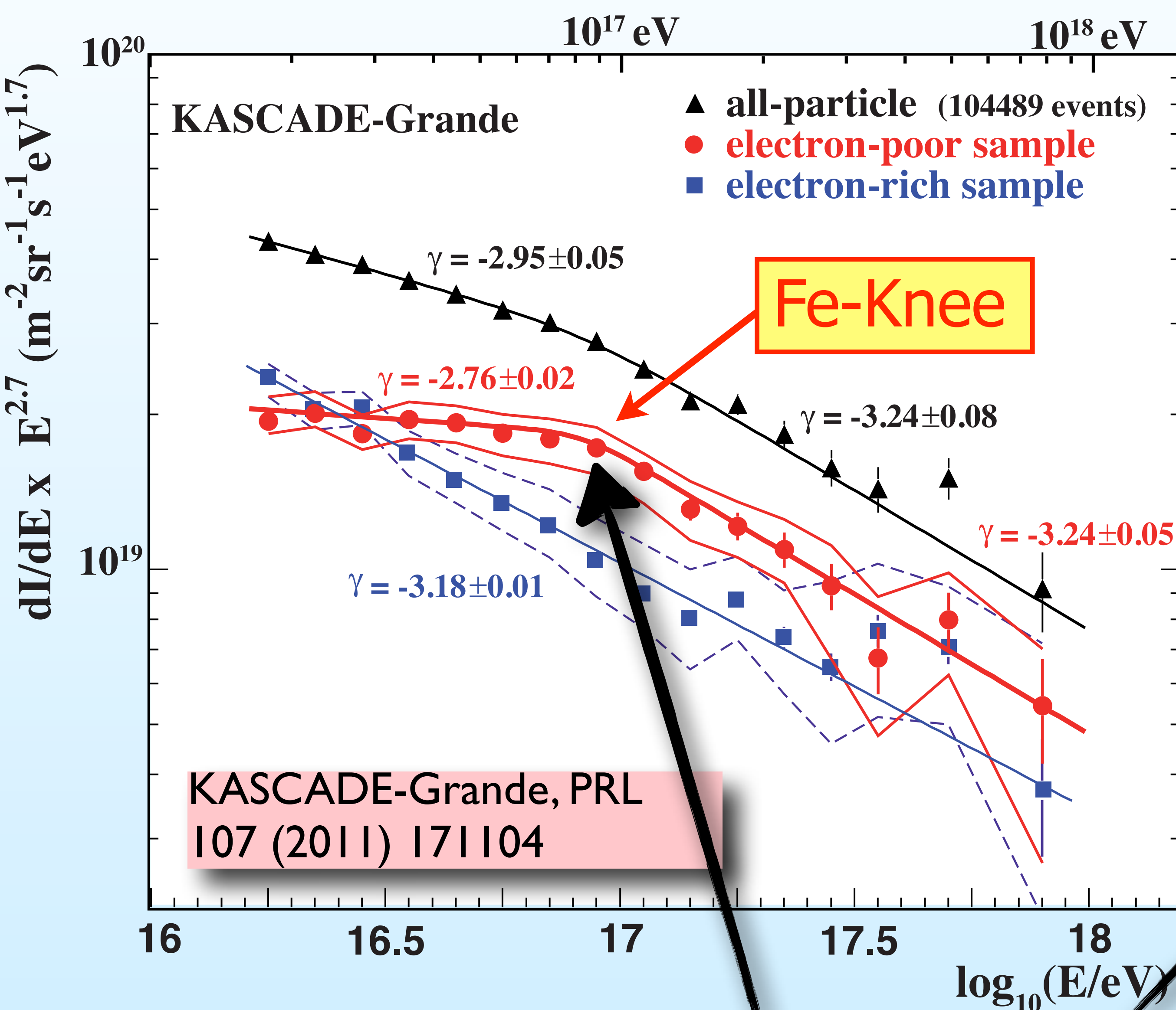
Expect to see heavier composition at high energy !

However, astrophysically very exotic result !! ($dN/dE_{source} \sim E^{-1.6}$)

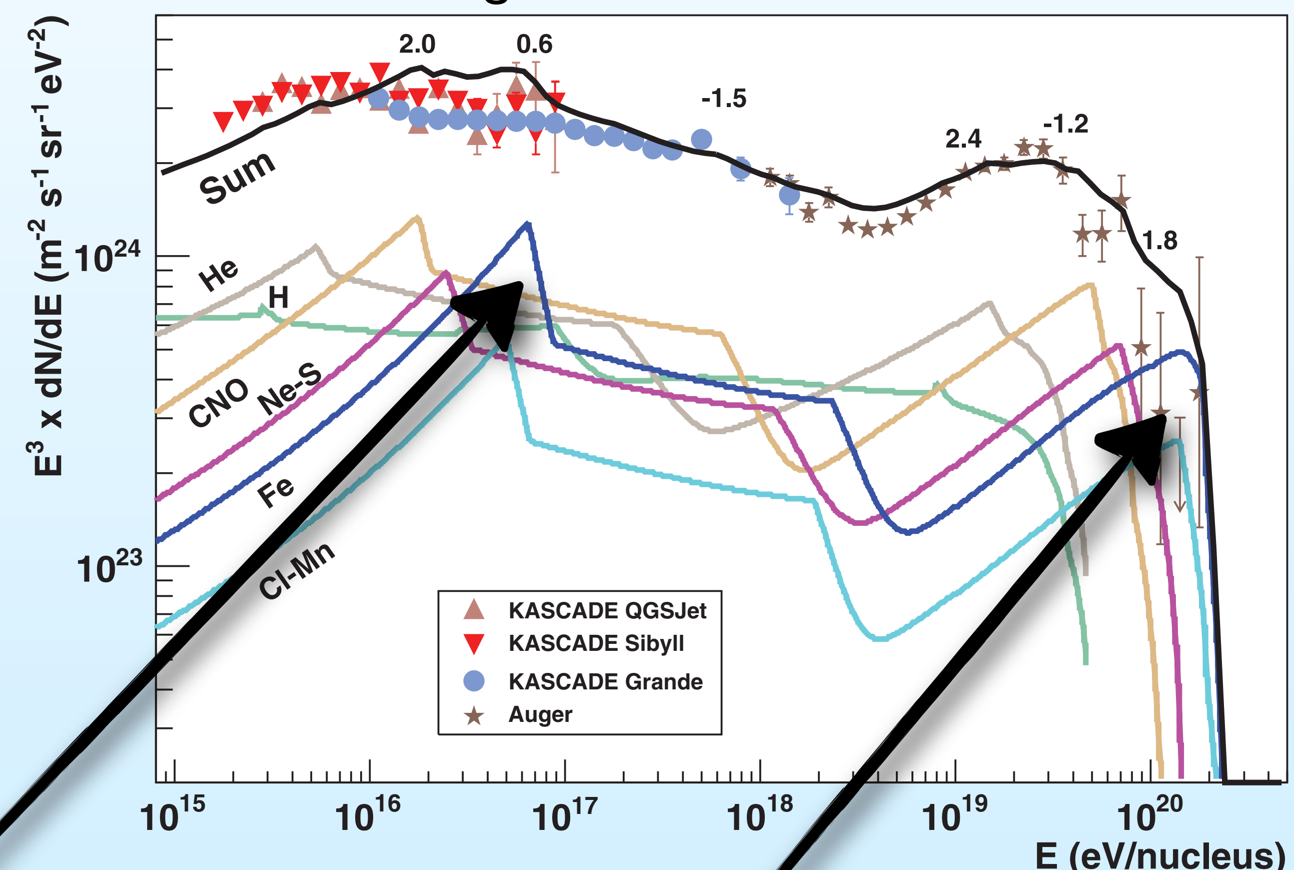
Protons $E_{max,p} = 10^{18.4}$ eV

Iron $E_{max,\,Fe} = 26\ E_{max,p} = 10^{20}$ eV

Rigidity Effect established at „Knee“



Biermann & de Souza, ApJ 746 (2012)
Cen A as extragalactic source above the knee

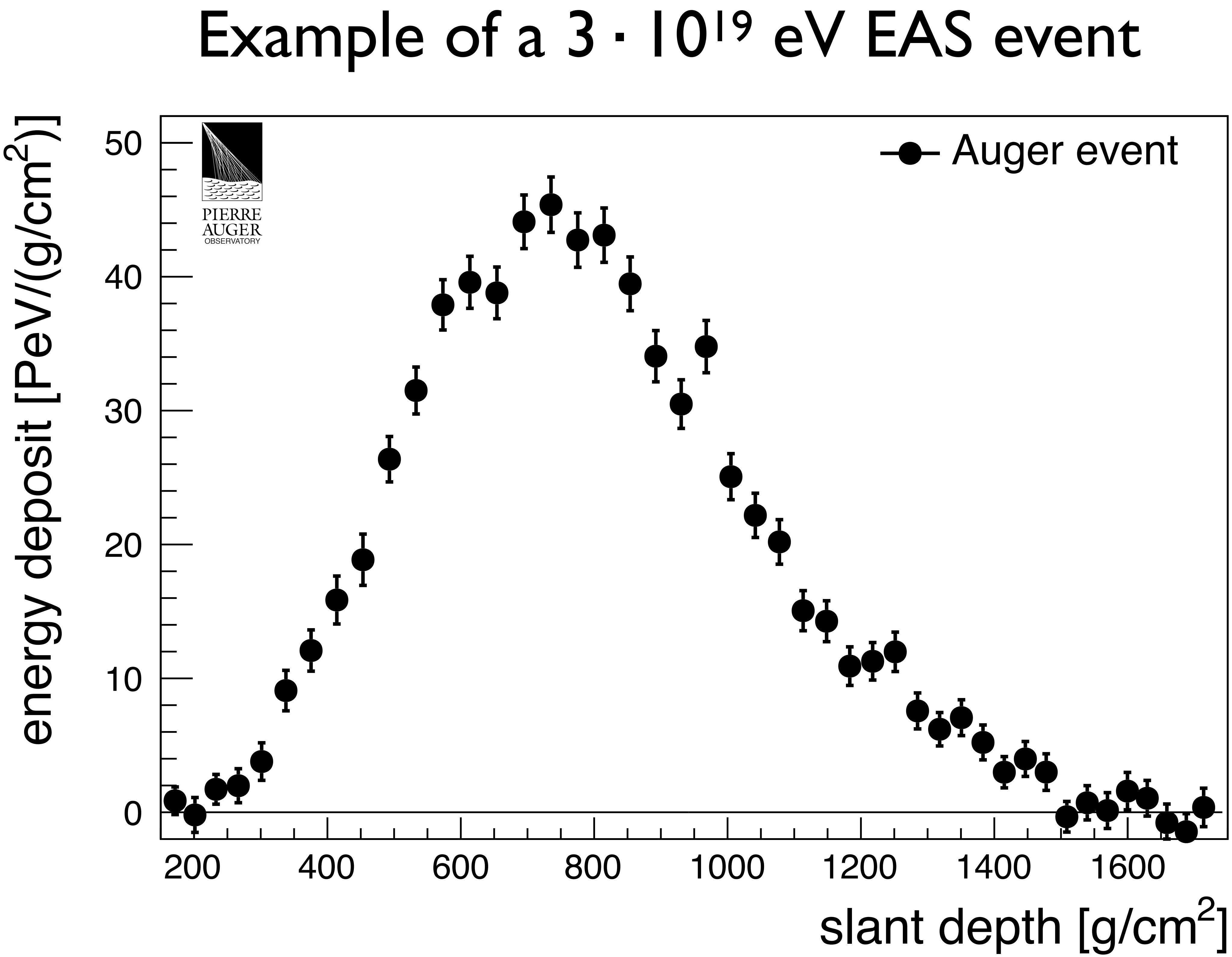


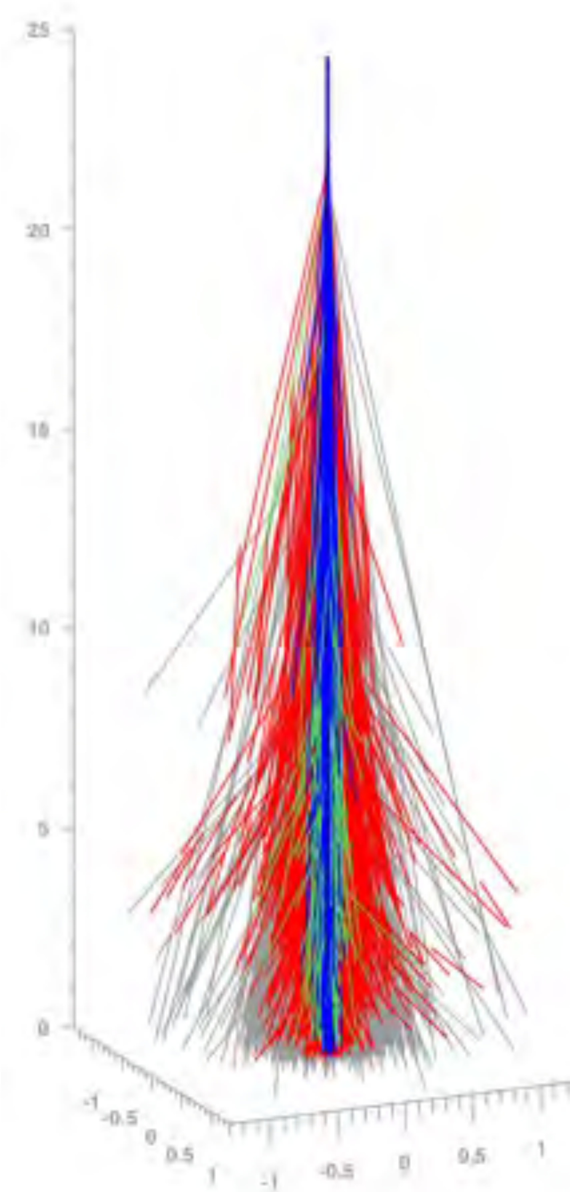
Limiting energy of galactic sources

Limiting energy of extragalactic sources?

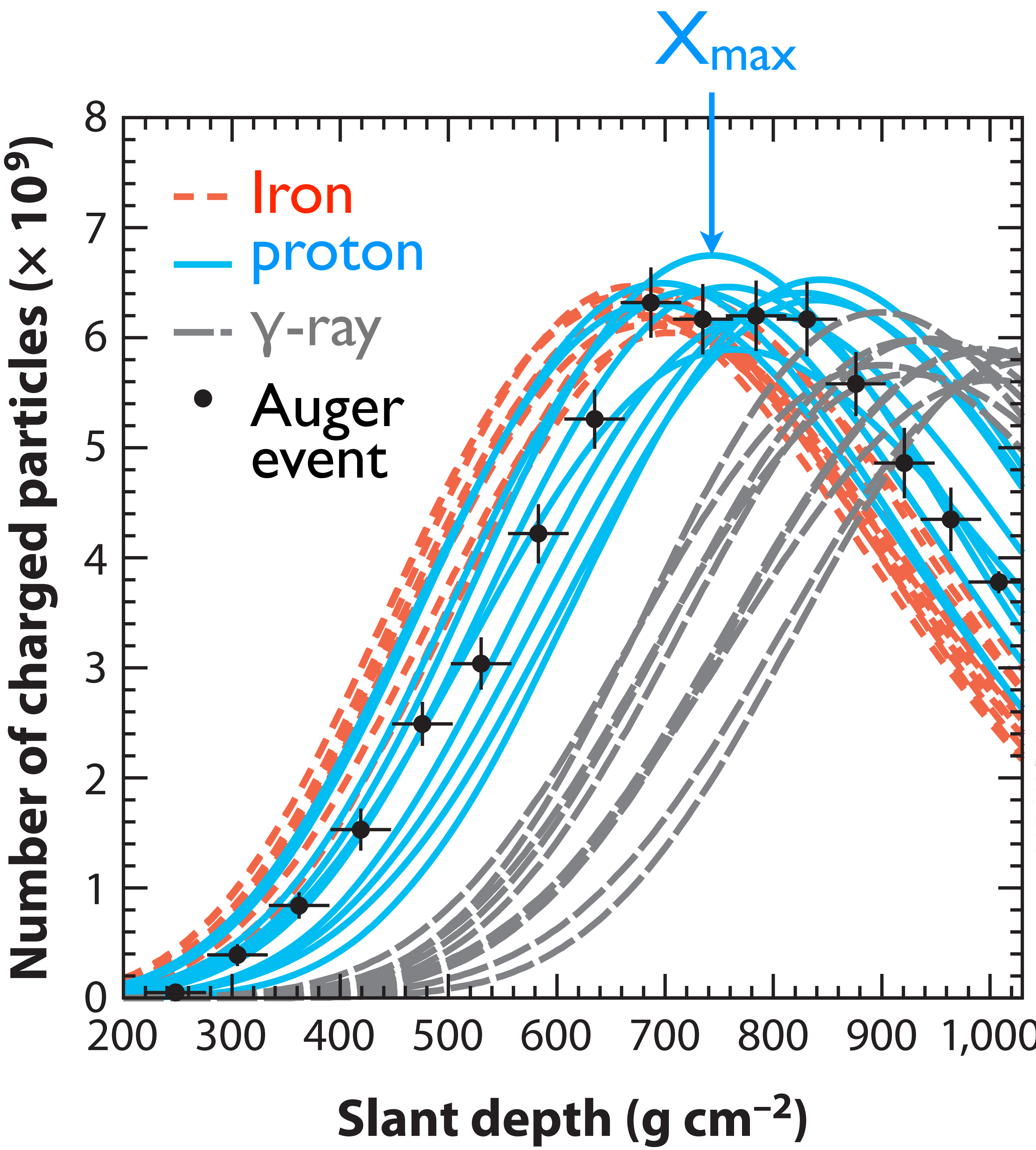
Longitudinal Shower Development → Primary Mass

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





Longitudinal Shower Development → Primary Mass



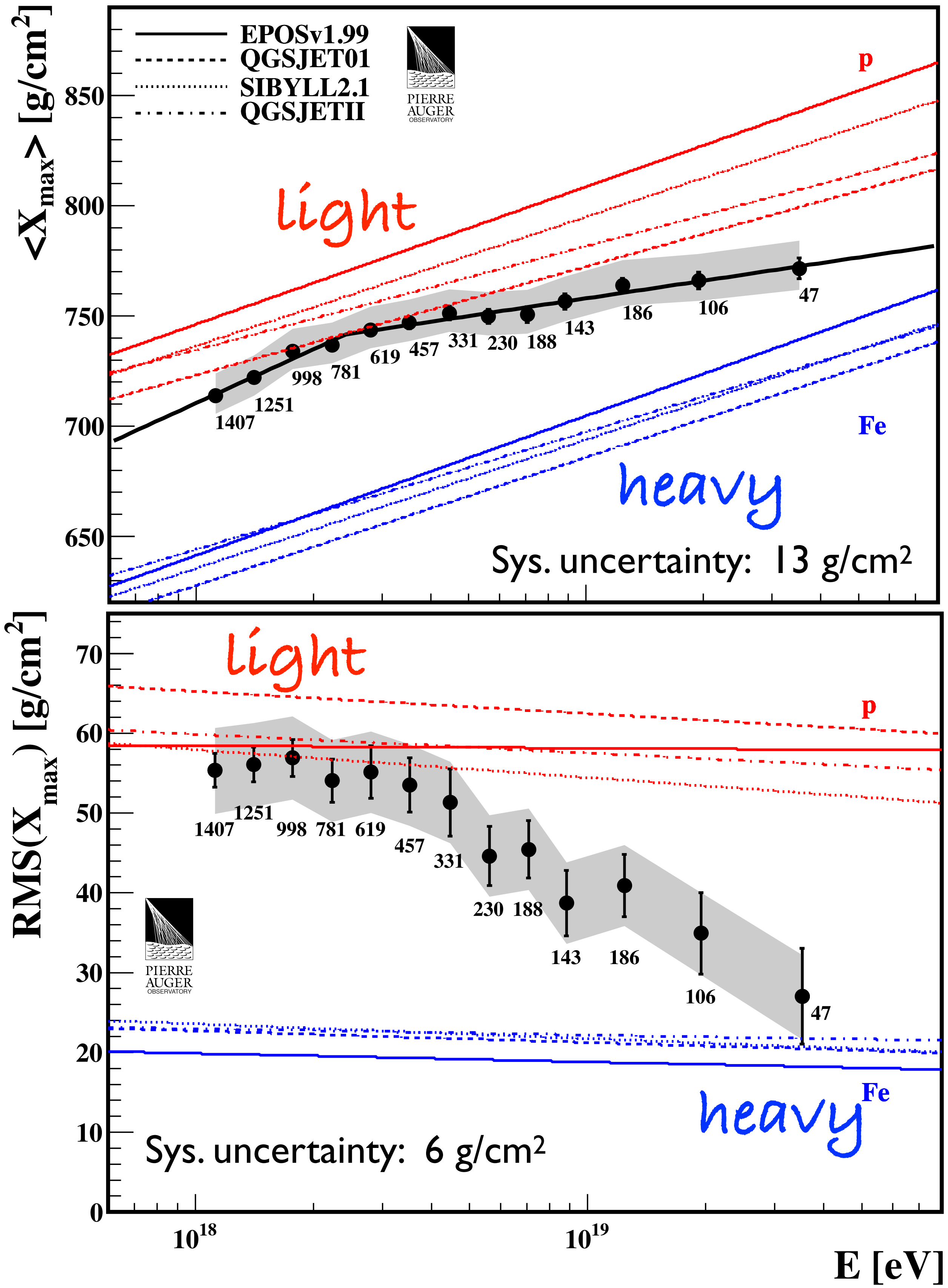
Position of X_{max} can be measured using fluorescence telescopes;

⟨Xmax⟩ and RMS(Xmax) → primary mass

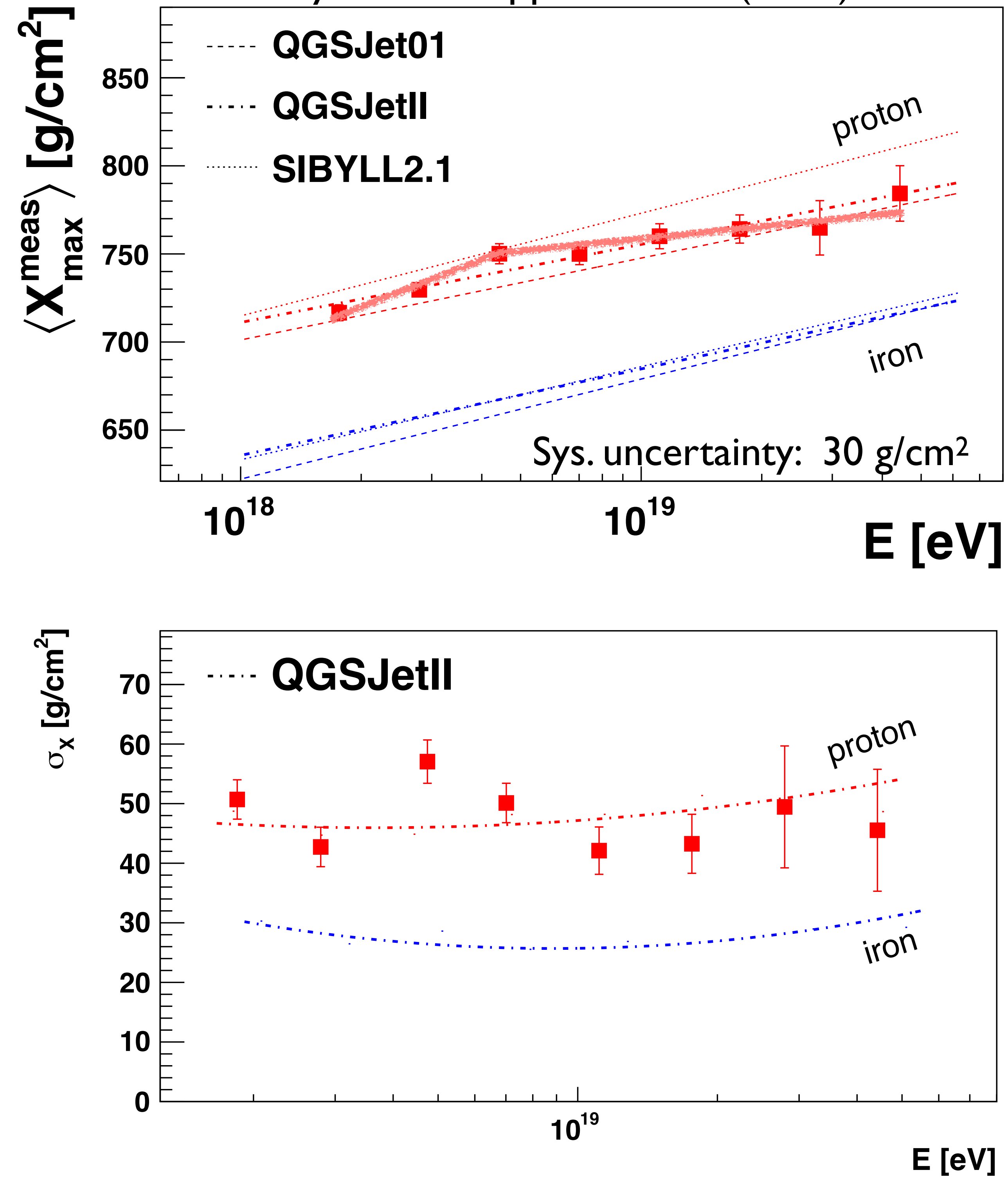
PIERRE AUGER OBSERVATORY

Much debated: Auger vs HiRes

Auger Collab. PRL 104, 2010, updated: Facal, ICRC 2011



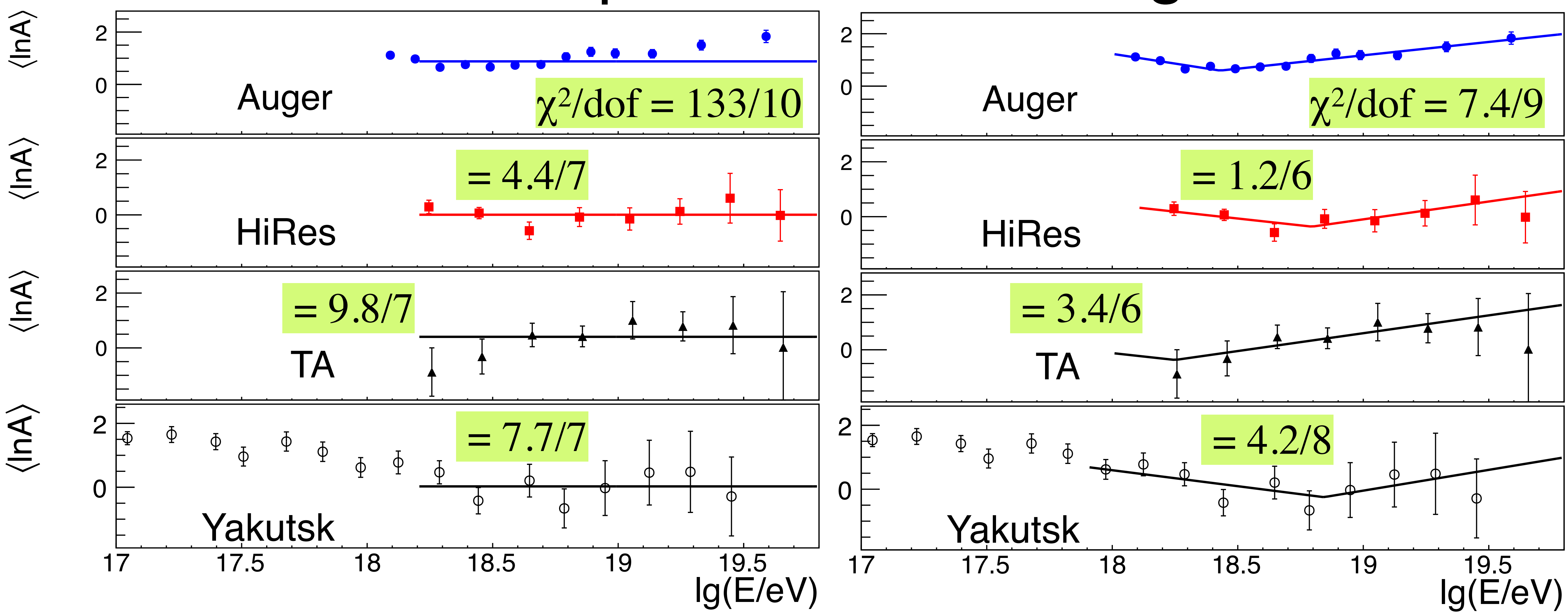
HiRes Collab.,
Nucl. Phys. Proc. Suppl. 212-213 (2011) 74



⟨ lnA ⟩ as a fct of Energy

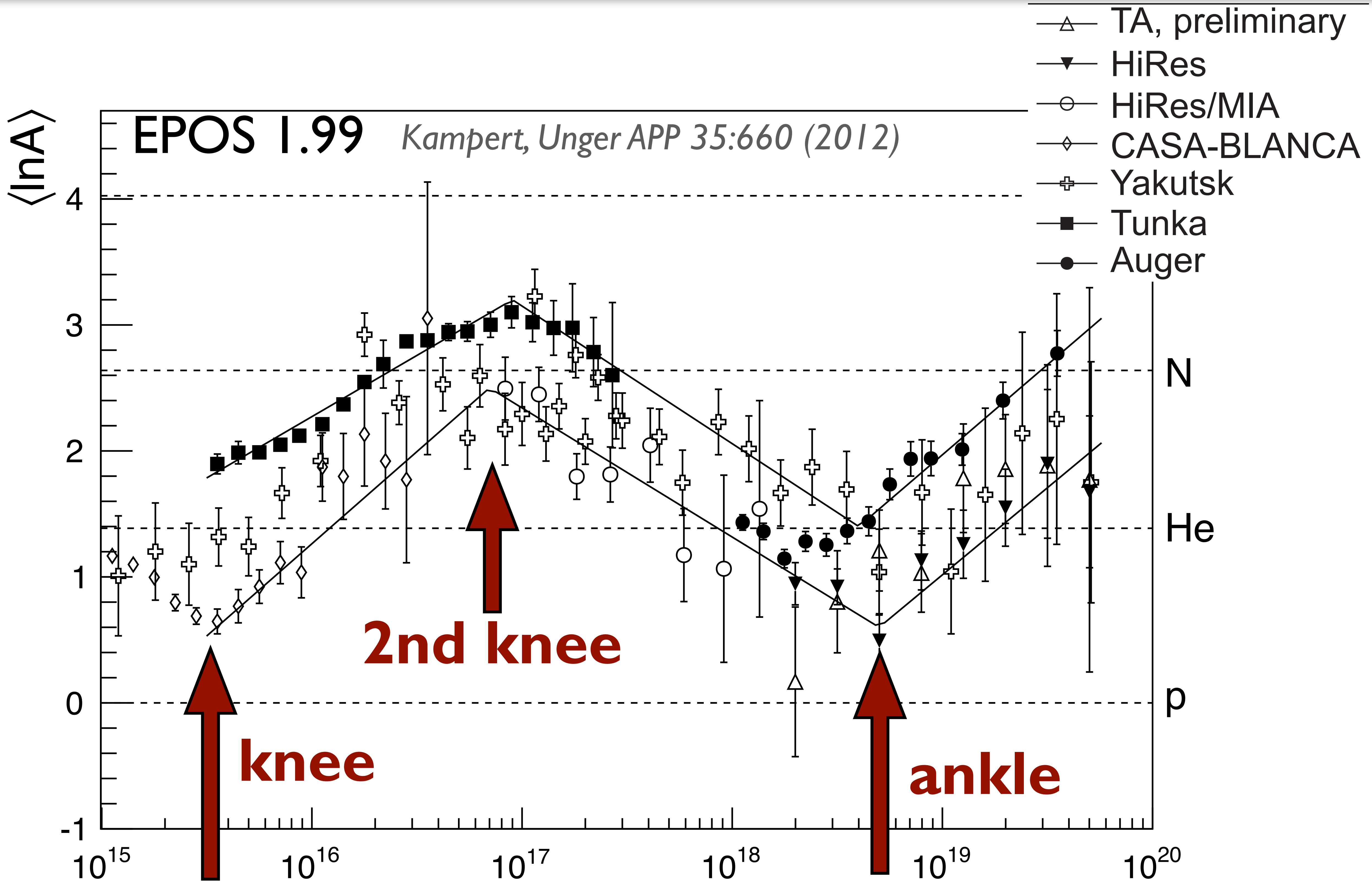
Auger-TA-HiRes-Yakutsk
Working group @ UHECR2012
to appear in EPJ (web of conf)

fit to constant compos. | allowing a break



1. All experiments prefer an increasing mass
2. Due to statistics, all but Auger are consistent with a constant composition
3. Absolute scale differs, needs further study

A more global view on composition



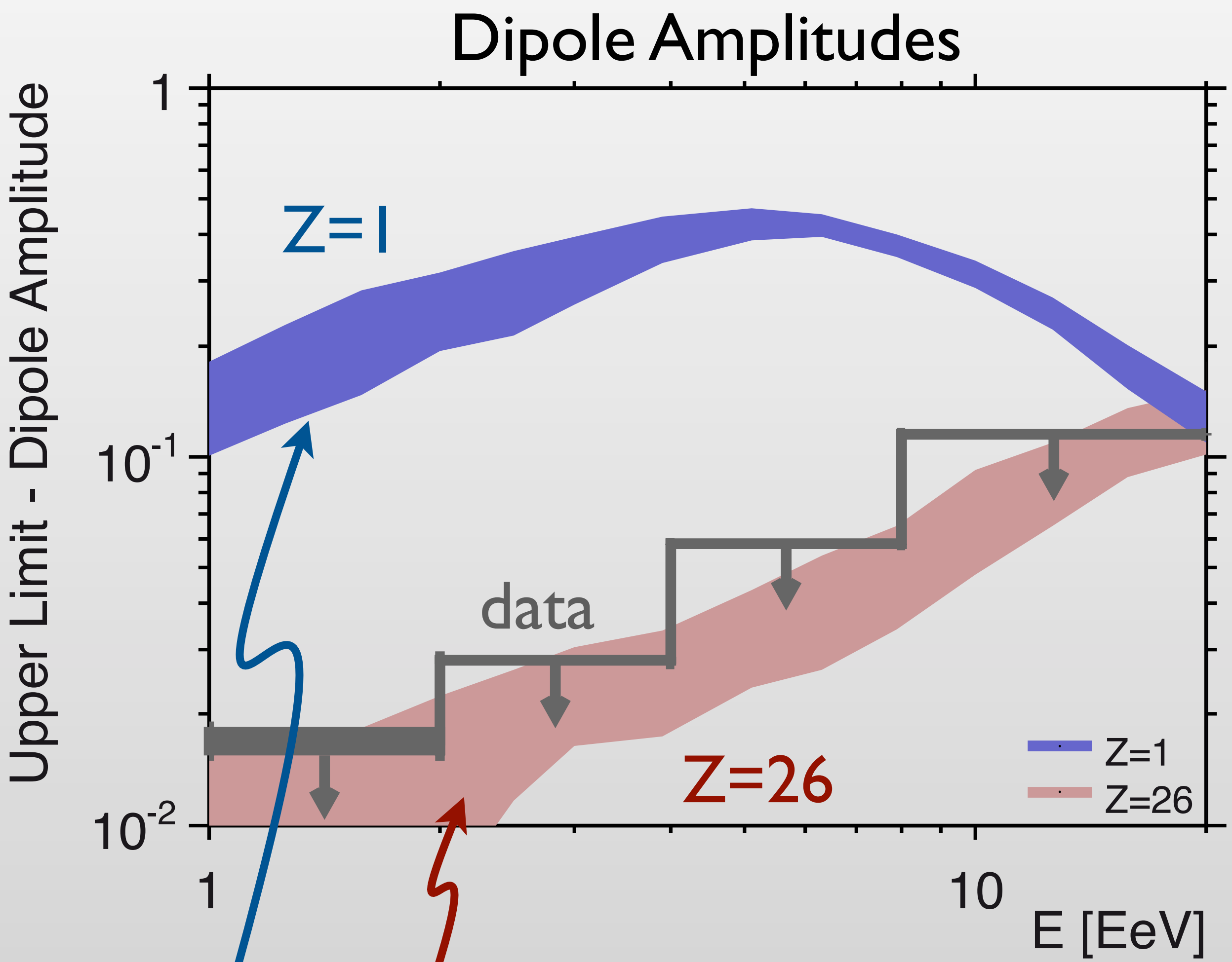
$E_p^{max,g} \sim 3\cdot 10^{15}$ eV

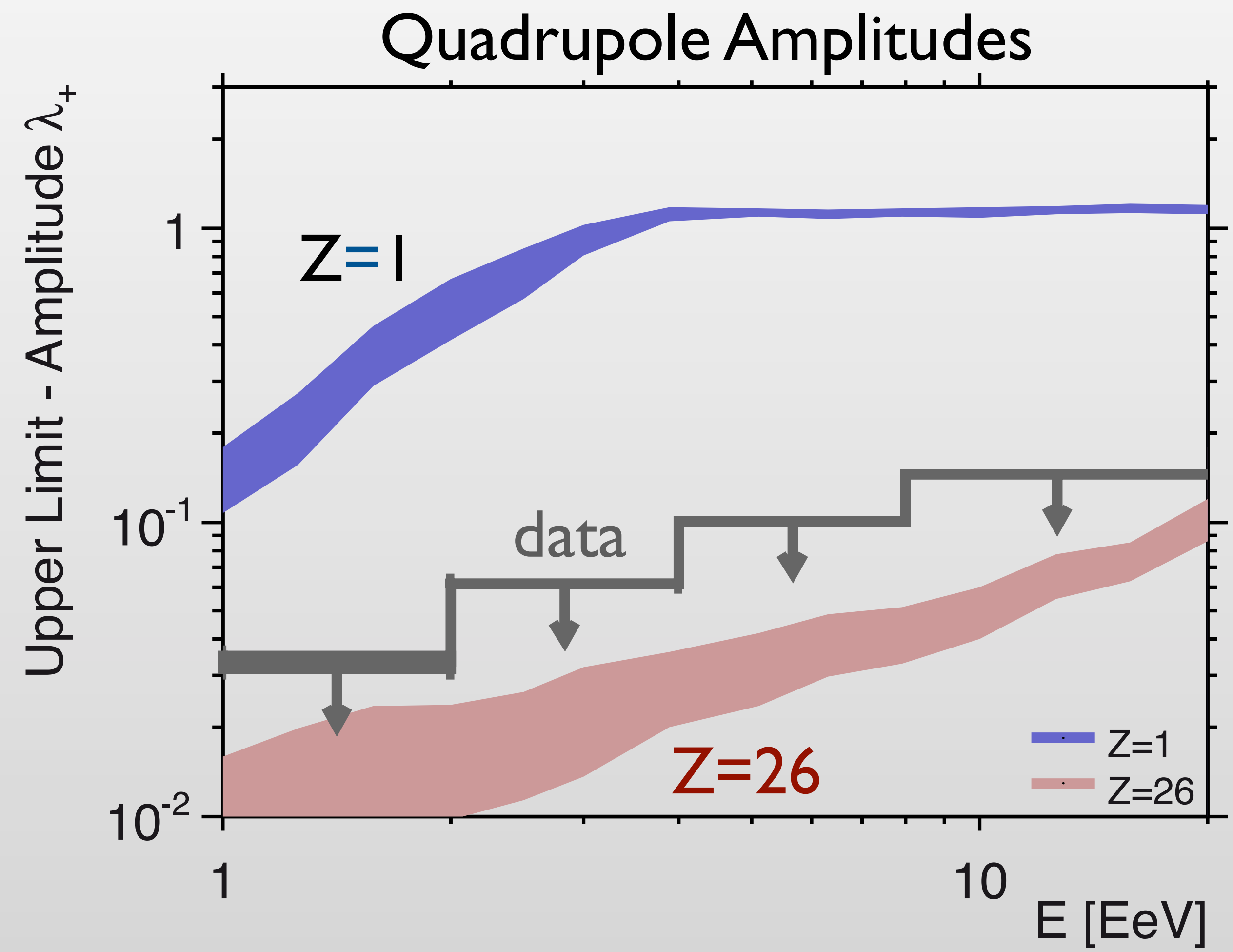
$E_p^{max,EG} \sim 4\cdot 10^{18}$ eV ?

(Auger) Data suggest that we may see the exhaustion of sources

Large Scale Anisotropies

Auger Collaboration: ApJL, 762, L13 (2012), ApJS 203,34 (2012)





expectations from stationary galactic sources distributed in the disk

light CR component cannot originate from stationary sources in the galactic disk

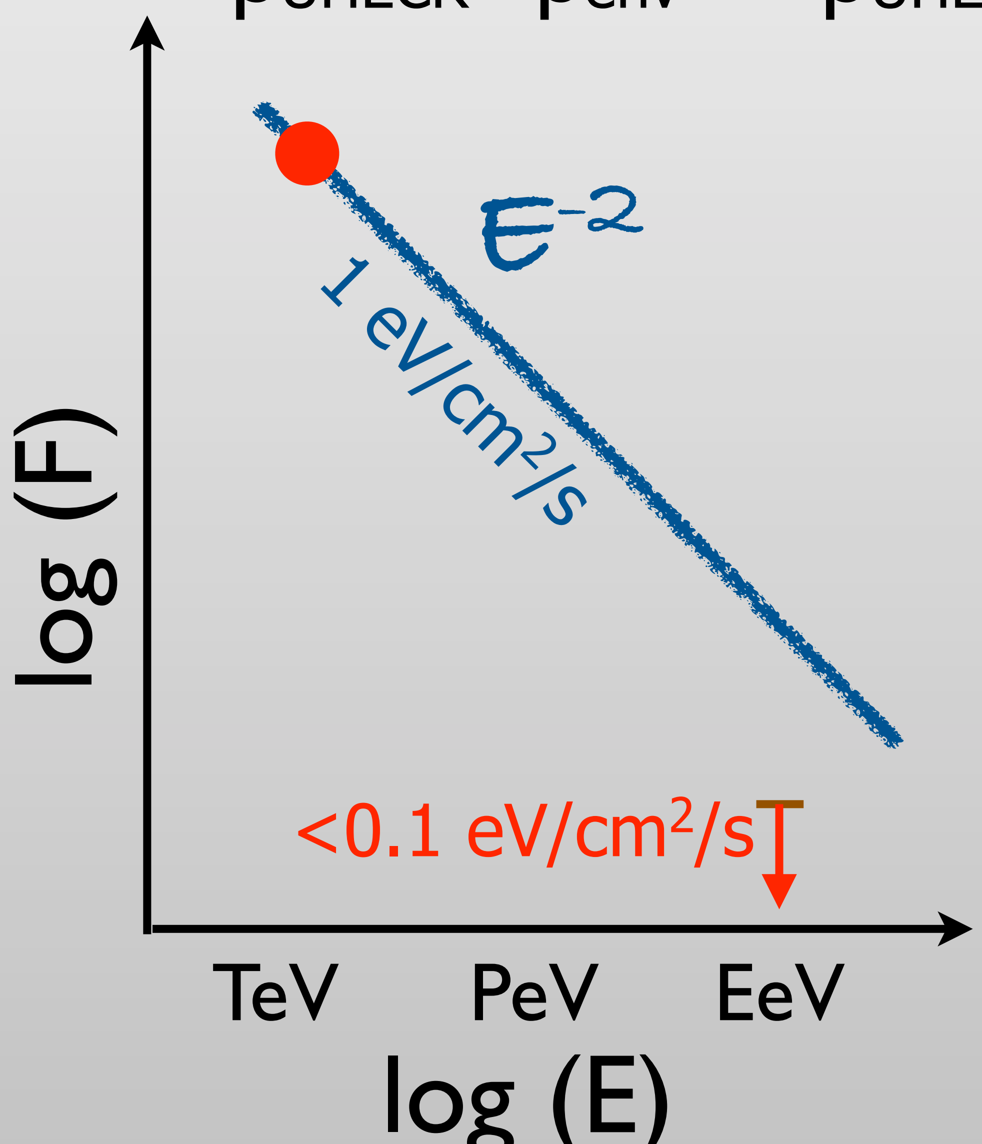
Neutron Astronomy

d_{decay} = 9.2 kpc × E (EeV)

→ above 2 EeV see most of galactic disk

produced more efficiently than γ's from π^0:

- $p_{UHECR} + p_{env} \rightarrow n_{UHECR} + p_{env} + \pi^+$ (n takes most of energy)
- $p_{UHECR} + p_{env} \rightarrow p_{UHECR} + p_{env} + \pi^0$ (π^0 takes small energy only)



→ galactic TeV sources should plausibly produce neutrons

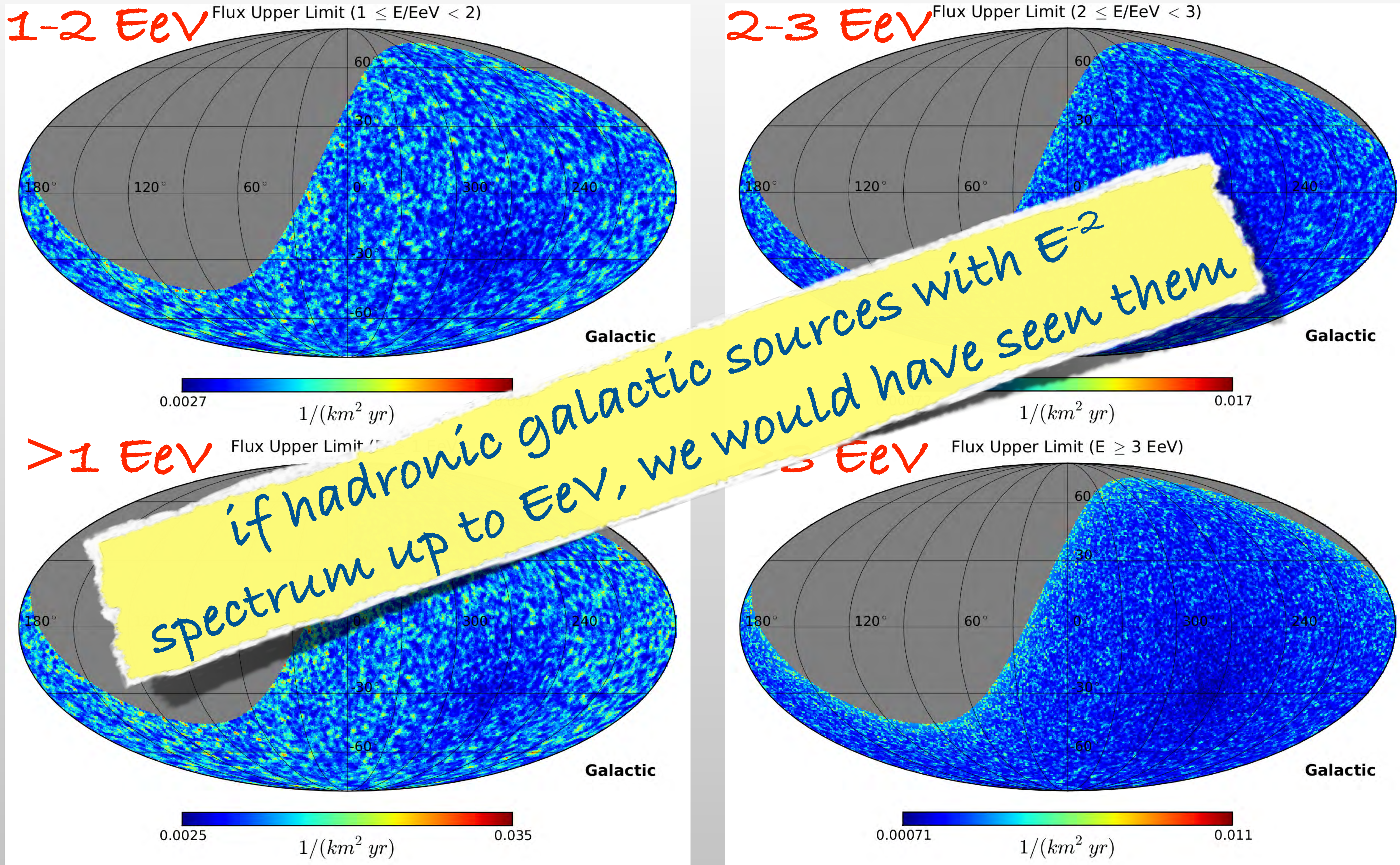
energy flux of some γ sources exceeds 1 eV/cm²/s at Earth

→ assuming E^{-2} spectrum expect also 1 eV/cm²/s @ EeV energy

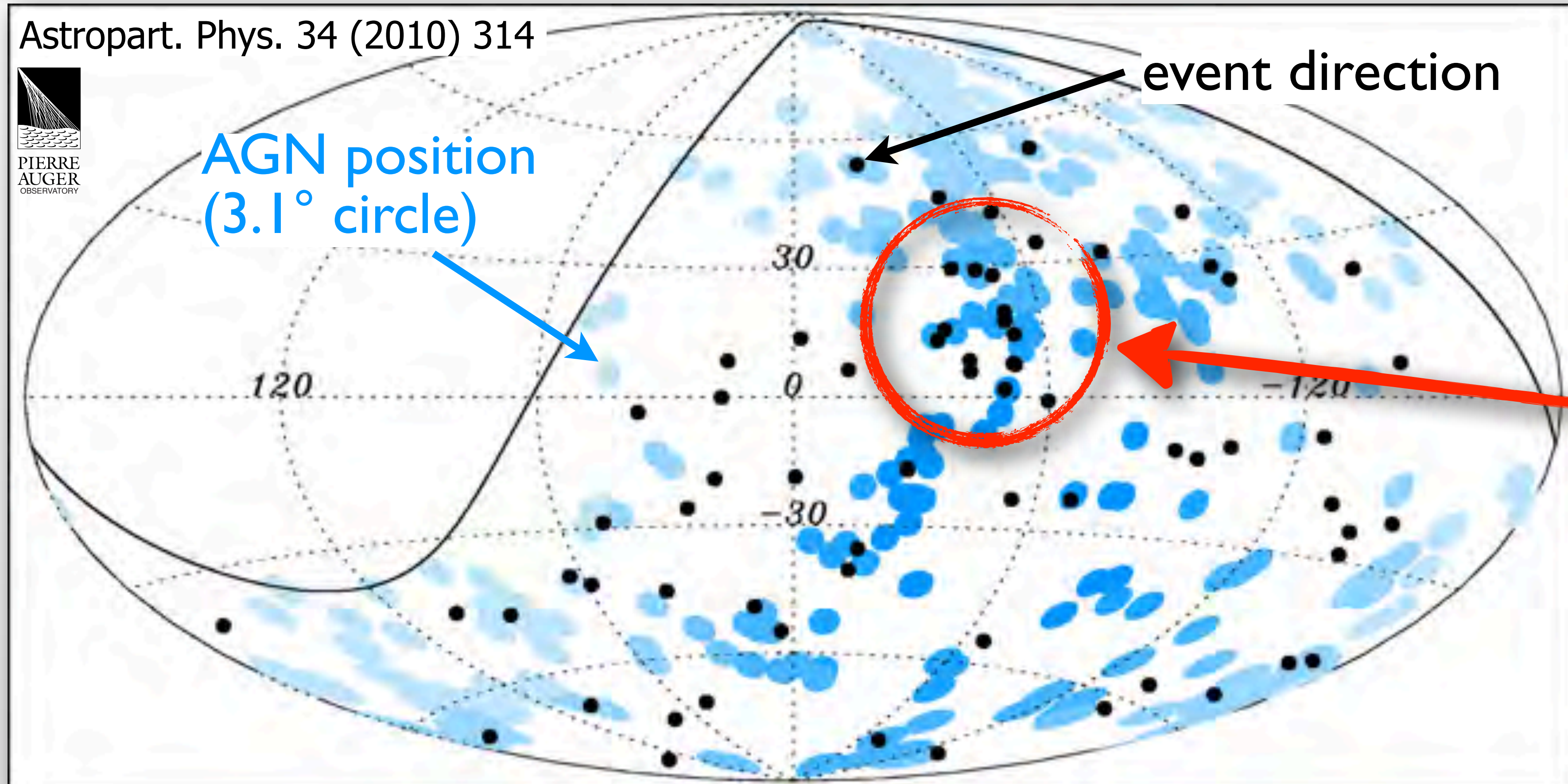
upper limits of neutrons further down by more than a factor of 10!

Neutrons Upper Limit Sky-Maps

Auger Collaboration, ApJ, 760, 148 (2012)



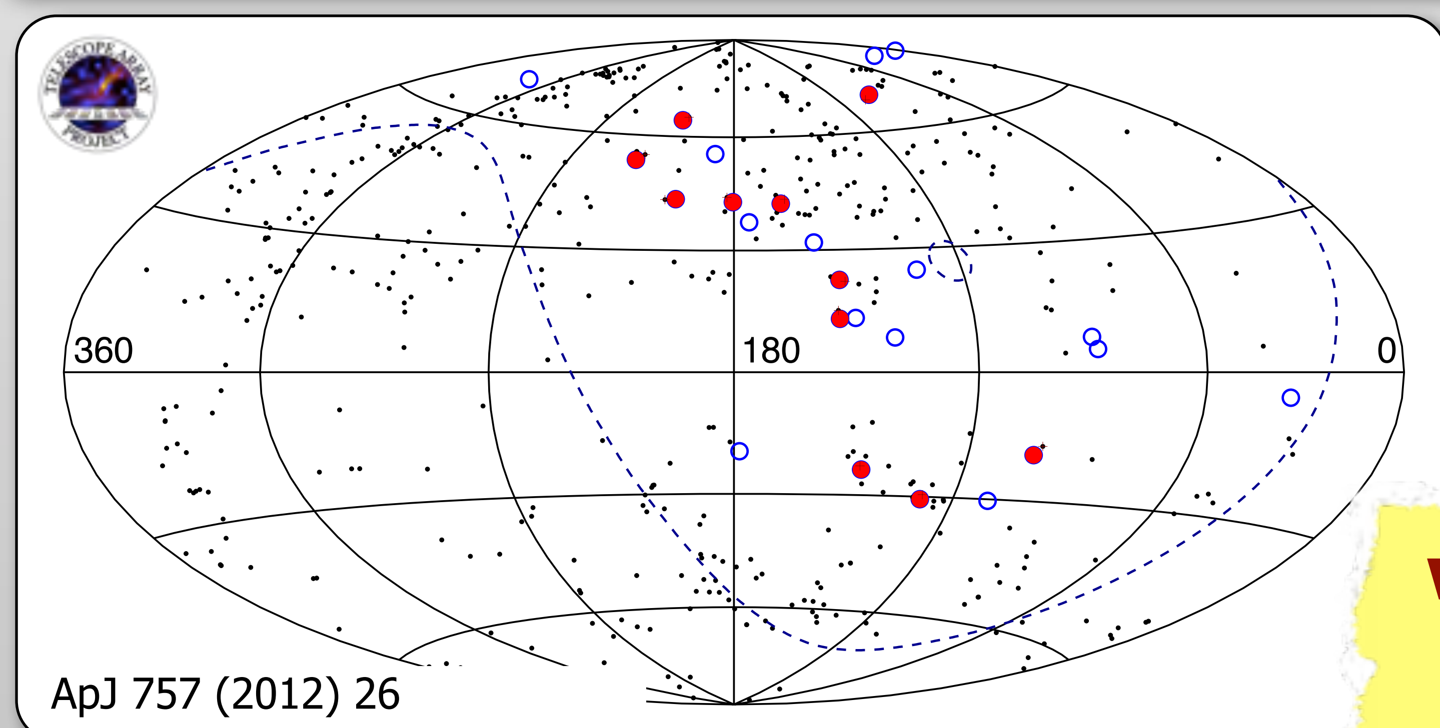
UHECR Astronomy: Correlation with AGN



Centaurus A

Auger Observatory:
28/84 = 33%
with iso-bkg = 21%
➙ <1 % chance probability

Combined chance probability < 10^{-3}

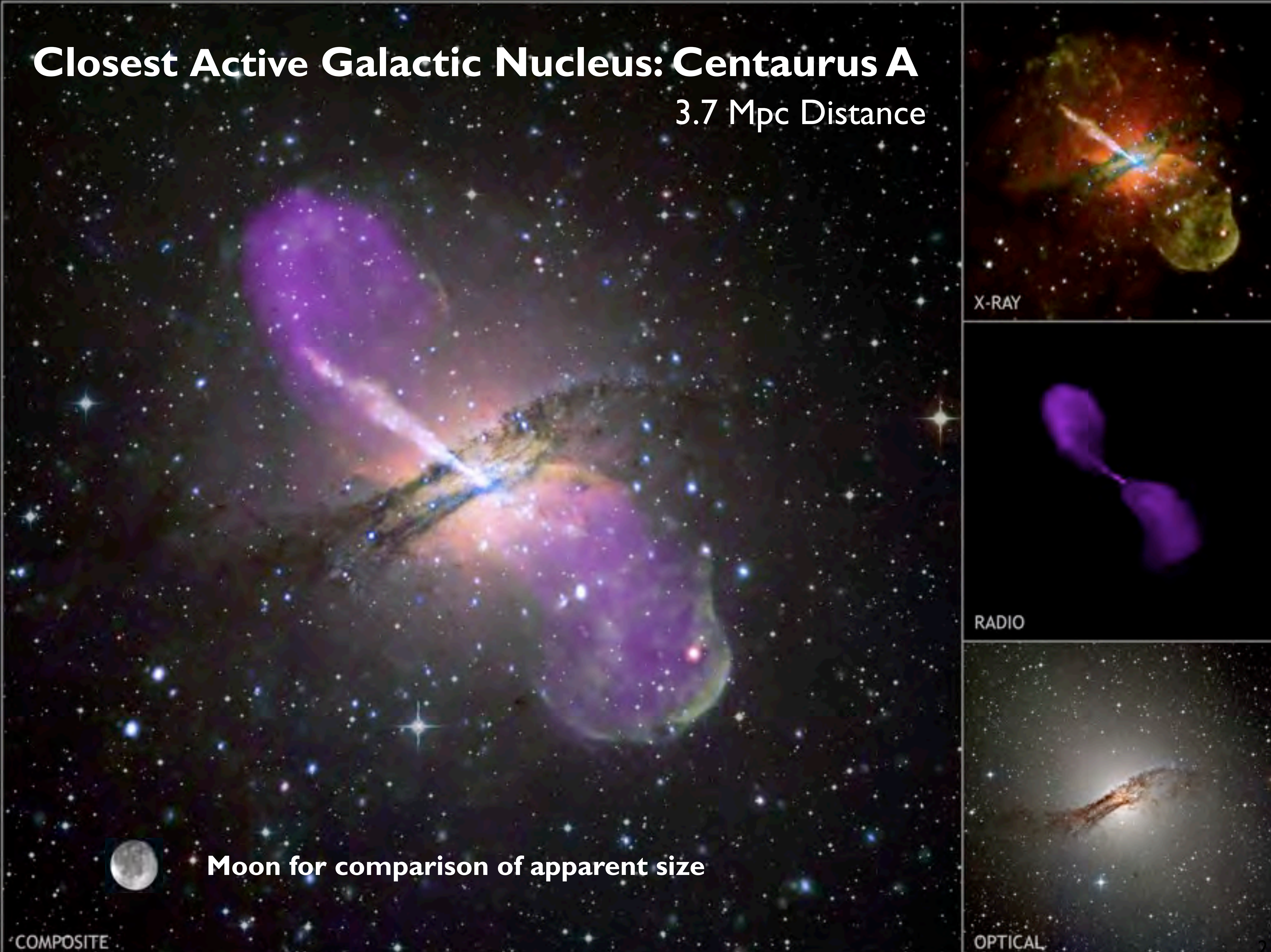


Telescope Array:
11/25 = 44%
with iso-bkg = 24%
➙ 2% chance probability
➙ agree with Auger

when correcting for accidentals, ~ 15 % of events with E > 56 EeV point to nearby AGN

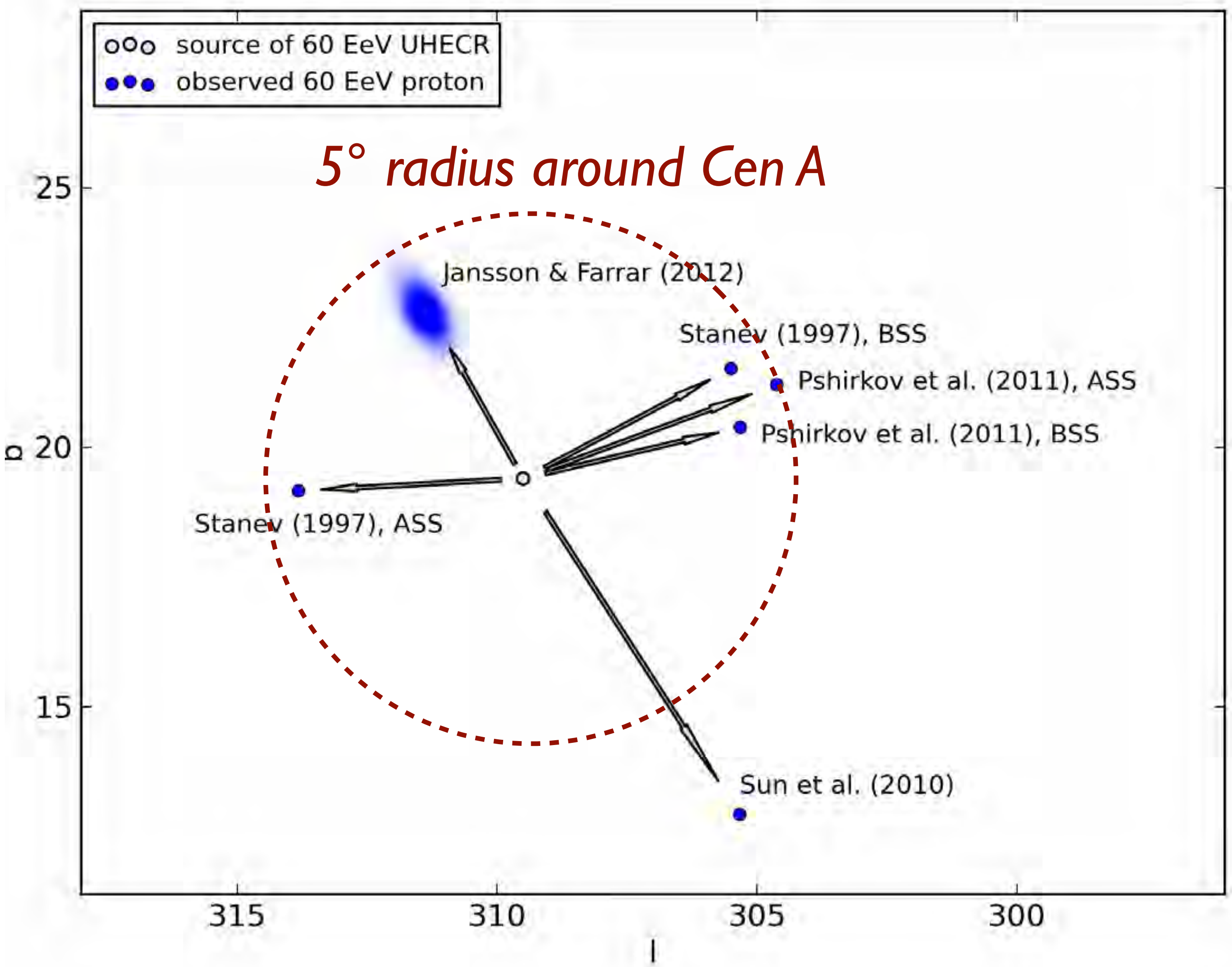
Closest Active Galactic Nucleus: Centaurus A

3.7 Mpc Distance



Moon for comparison of apparent size

Cen A a dominant UHECR Source ?



G. Farrar et al., JCAP 2012
Galactic magnetic field model of Jansson-Farrar-2012
→ 60 EeV protons off by ~ 3°

R.-Y. Liu, et al, ApJ 755, 139 (2012),
Hardcastle, et al., ...
Particles with Z<10 may remain within opening of 20°

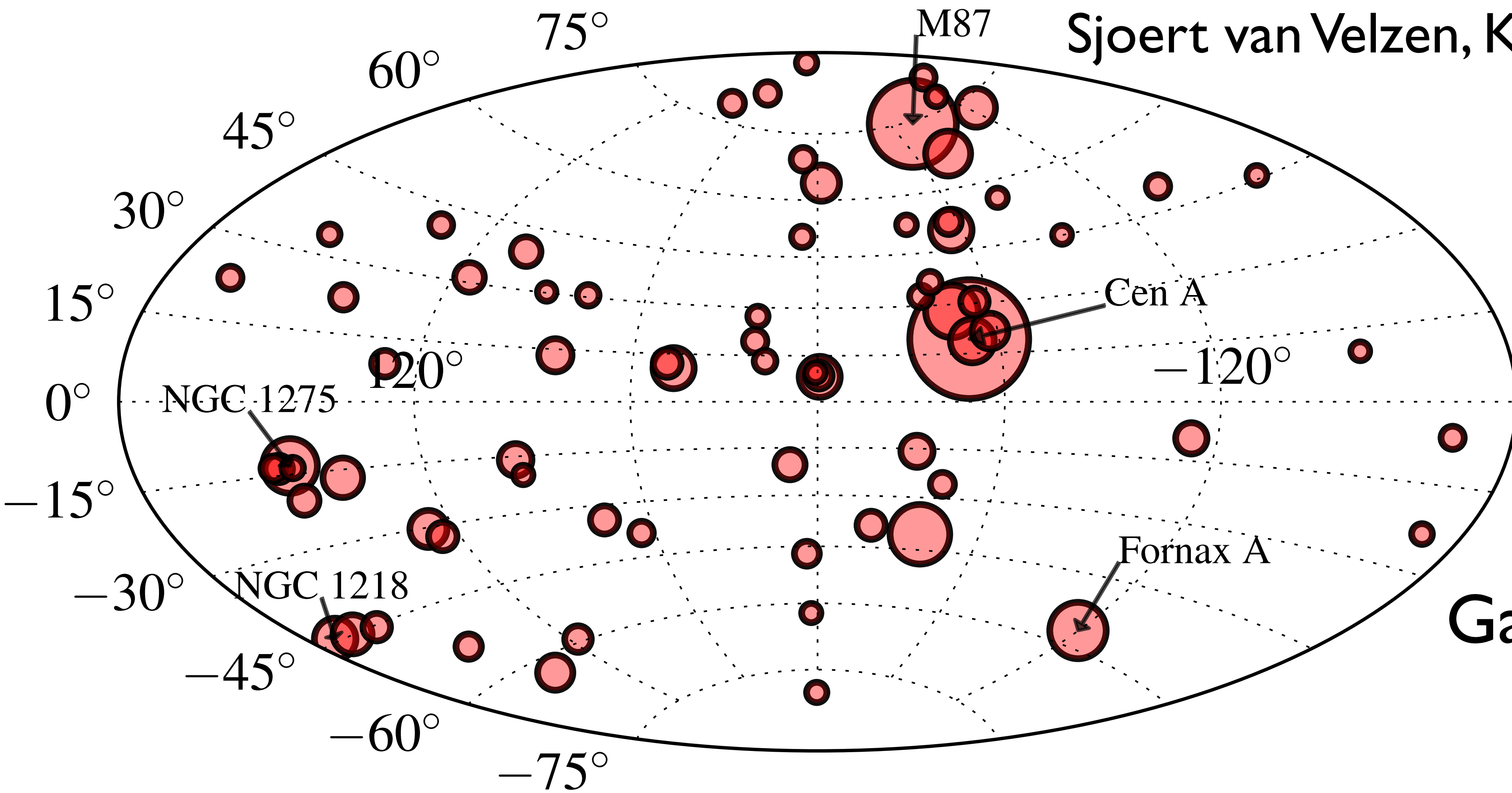
H. B. Kim, arXiv:1206.3839, ...:
Further support for source in direction of Cen A

H. Yüksel et al, ApJ 758, 16 (2012):
If UHECRs were protons → EGMF would be > 20 nG

N. Fraija et al, ApJ 753, 40 (2012) & S. Sahu et al. PRD 85, 043012 (2012):
Assuming pp-interactions at source → MeV-TeV γ's agree with Auger flux

Volume limited all-sky catalog of RG

Sjoert van Velzen, KHK, et al., ApJ 544 (2012)



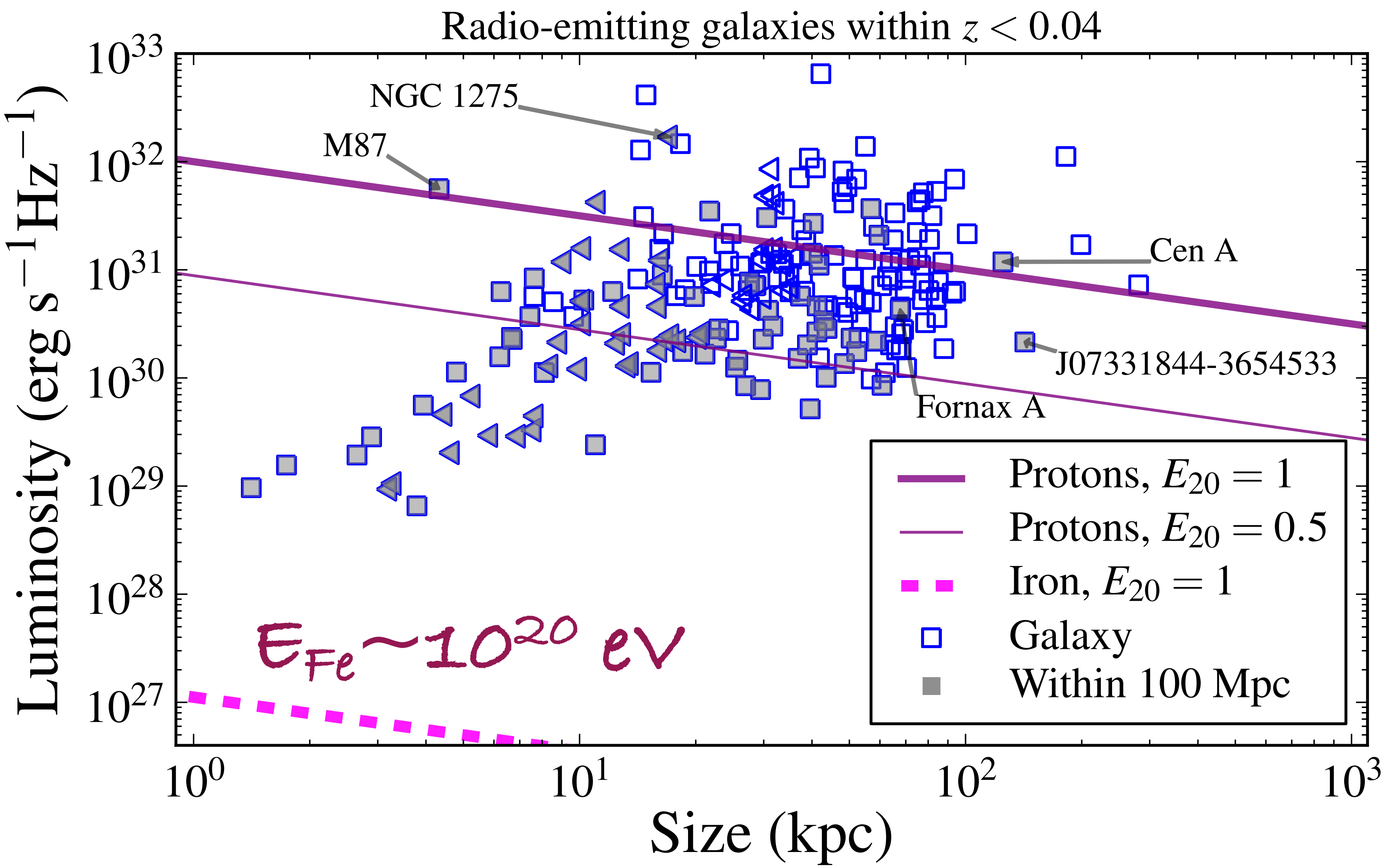
constructed from NVSS and SUMSS radio surveys + 2MASS Redshift Survey (2MRS)

Galactic coordinates

- $z < 0.03$
- $K > 11.75$ & ($F_{1400} > 213$ mJy or $F_{843} > 289$ mJy)
- total of 575 sources
- area of circles ~ radio flux of the source

Hillas Diagram of Radio Galaxies

Sjoert van Velzen et al. (work in progress)



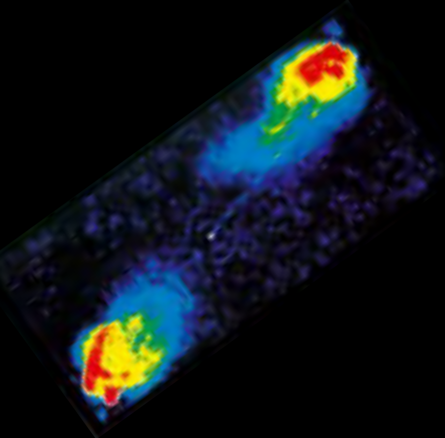
$E_p \sim 10^{20}$ eV

$\sim 5 \cdot 10^{19}$ eV

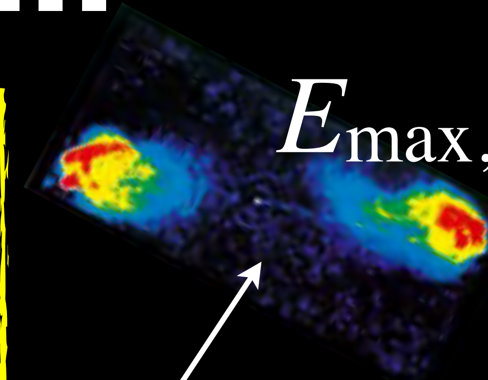
Magnetic field inferred from radio luminosity and size

$$B = \left(\frac{L_\nu/\epsilon}{10^{31}\,\mathrm{erg\,s^{-1}Hz^{-1}}}\right)^{2/7}\left(\frac{R}{100\,\mathrm{kpc}}\right)^{-6/7}\left(\frac{\nu}{\mathrm{GHz}}\right)^{1/7}\mu\mathrm{G}$$

A quite natural scenario...

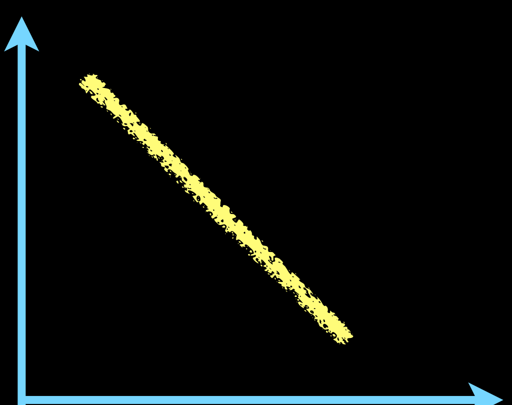


The most nearby source most likely will have a low E_{max}



$E_{\max,2}$

$$\frac{dN}{dE_{\max}} \propto E^{\zeta}$$

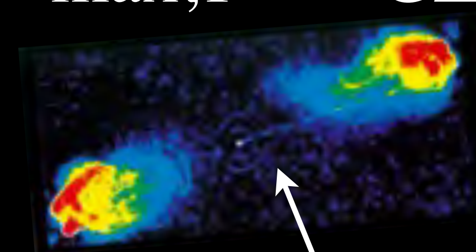


$\lg(E_{\max})$

$R_2 \gtrsim D_{GZK}$

for $\varrho_S \lesssim 10^{-5}$ Mpc^{-3}

$E_{\max,1} < E_{GZK}$



$$F_{cr} \propto \frac{1}{R^2}$$

$R_1 < D_{GZK}$

We may see a nearby low-E_{max} source on a background of protons from distant sources

How to Uncover the Origin of the Flux Suppression ?

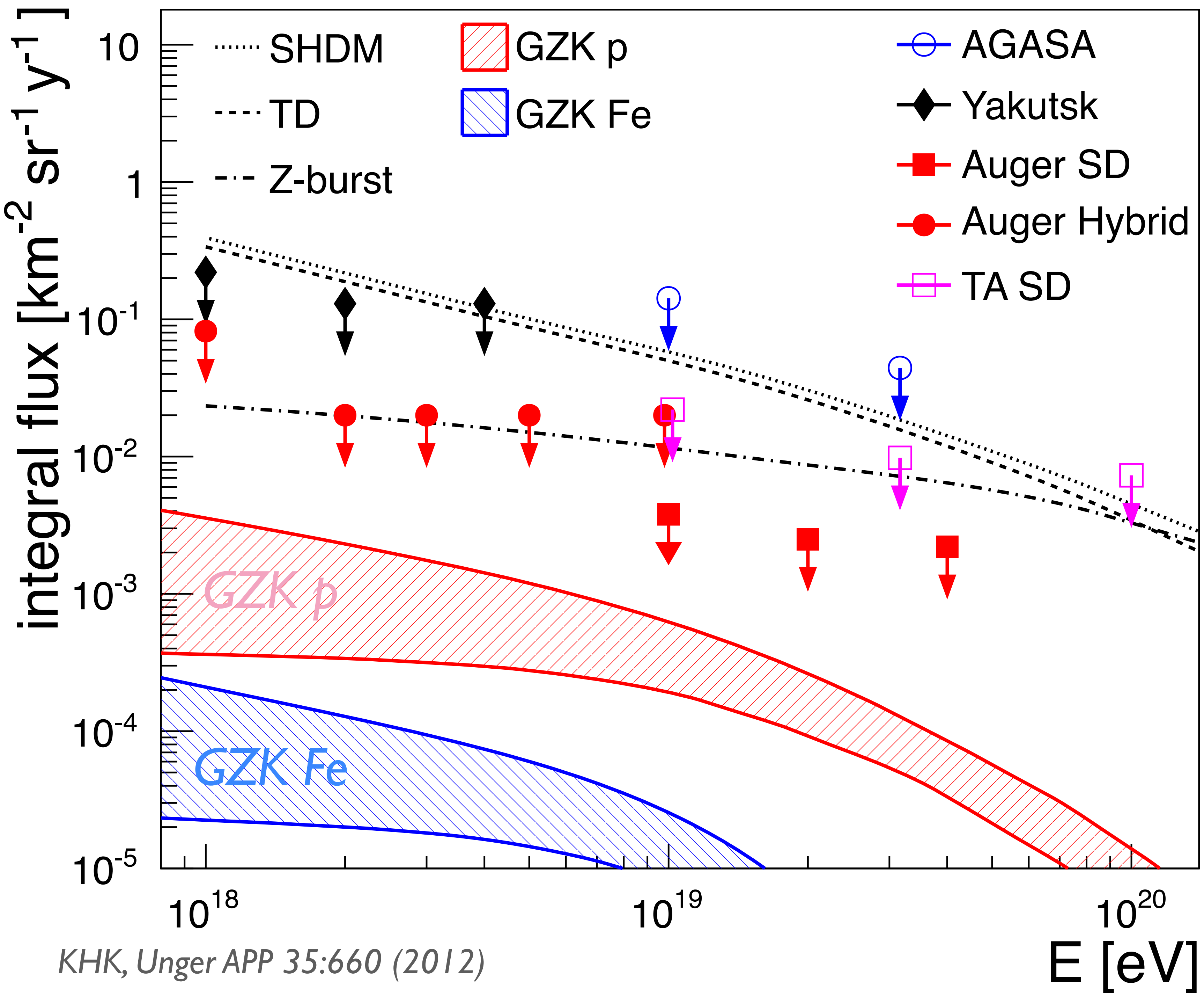
Composition on event-by-event basis up to the highest energies

Expect a different sky and E-spectrum for light vs heavy primaries:

- p-like primaries (~15% of flux?):
  - ➙ point back to sources, strong AGN correlation
  - ➙ GZK-like E-spectrum
- intermediate-heavy primaries
  - ➙ much more isotropic, no AGN correlation

GZK-Photons and Neutrinos

Present Upper limits on photon fluxes



KHK, Unger APP 35:660 (2012)

γ-showers penetrate deeper into atmosphere and contain almost no μ's

Presence of GZK-effect could independently be verified by EHE photons and neutrinos

Next Steps...
where to we need to go ?

UHECR Mission I: Ground Based

- **Understand Nature of End of Cosmic Ray Spectrum**
- **Particle Physics at E_{cm} ~ 100 E_{LHC}**

Pierre Auger Observatory:

- Upgrades to improve
  a) shower-based primary mass measurement at highest energies
  b) particle physics capabilities (true high energy frontier!)

Telescope Array

- Upgrades to improve statistics with surface array

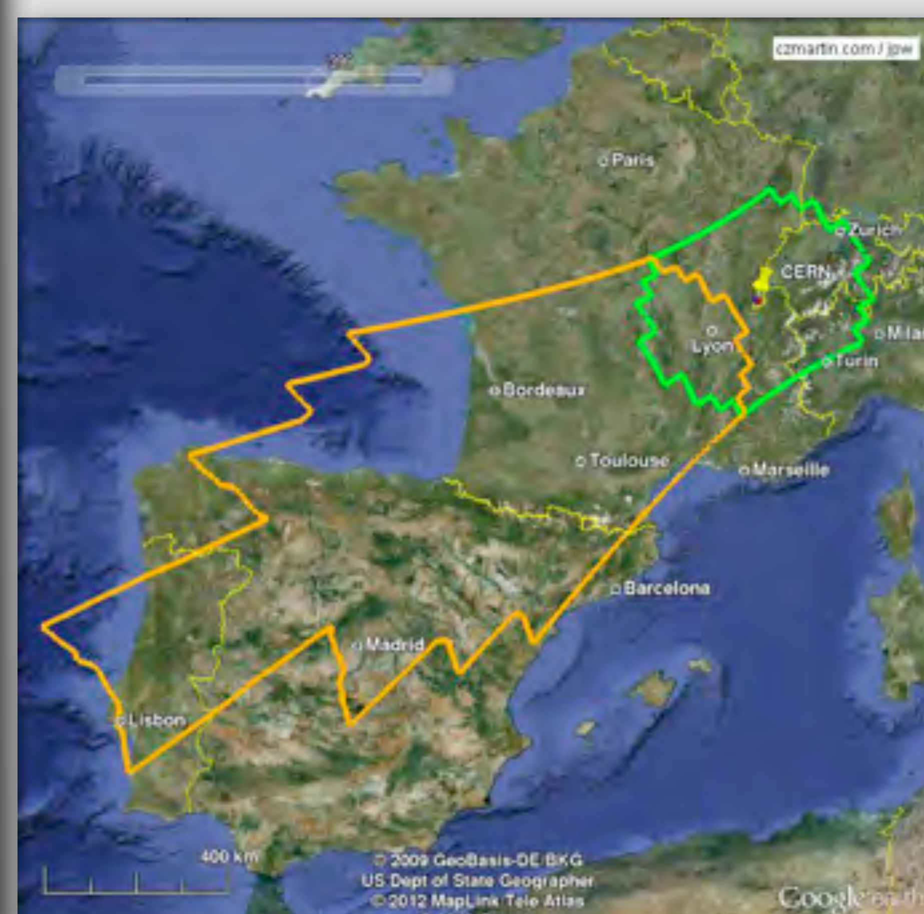
World-Wide Consortium: NGGO → Study UHECR Sources

- Prepare for a Next Generation Ground-based Observatory (NGGO) with much larger aperture and with particle physics capabilities (to be operated in 2022 ff)

UHECR Mission II: Space Based

- **UHECR Astronomy and Source Hunting**

- Effective aperture 5-10 times larger than Auger
  (but little particle physics capabilities)
- full-sky by construction
- hope for launch 2017/18



Thanks for your Attention !

Sorry, Prof. Hess,

we are almost there but still need a bit more time