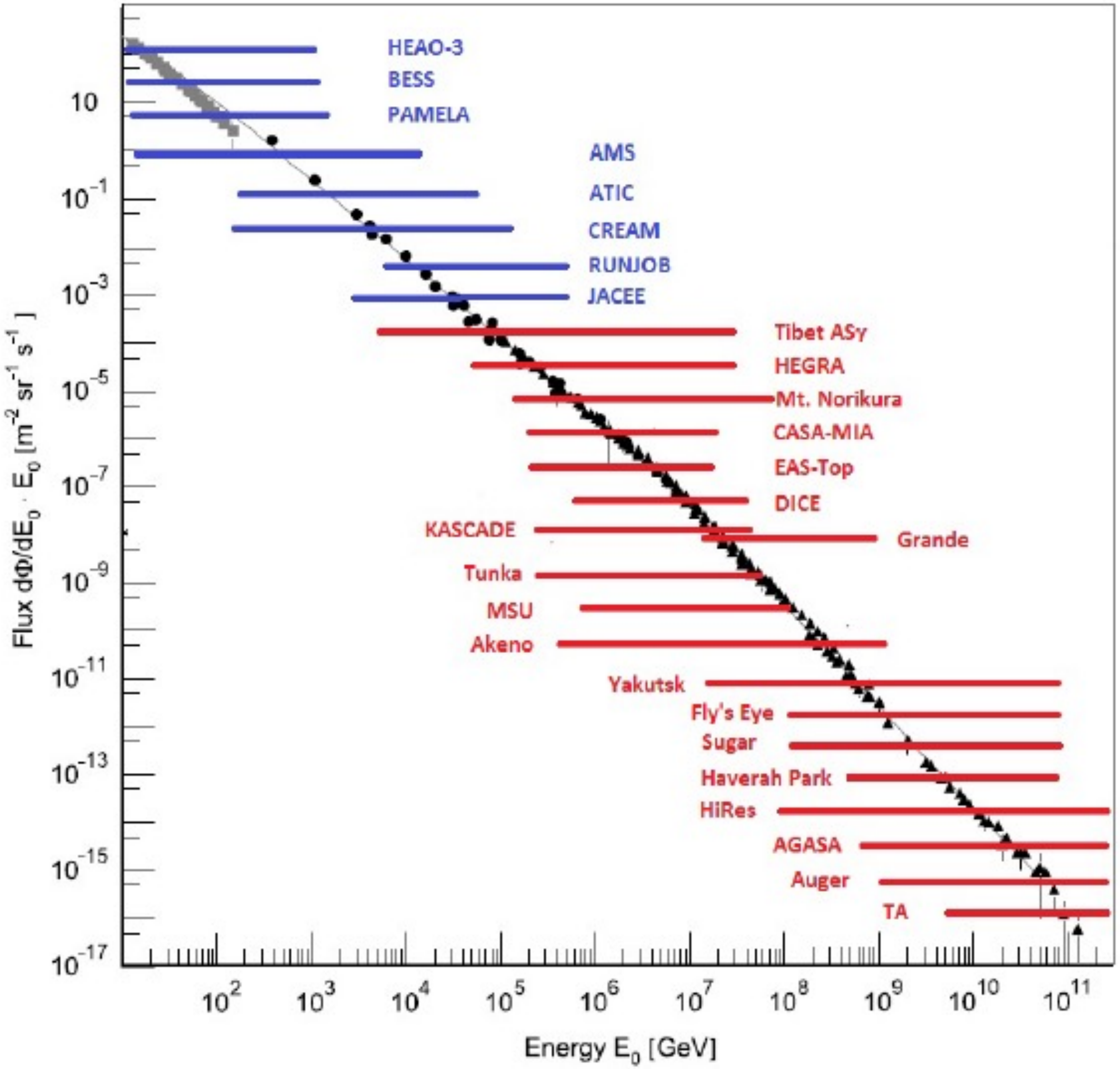
Astrofisica Nucleare e Subnucleare

UHECR

Slides from M.Spurio

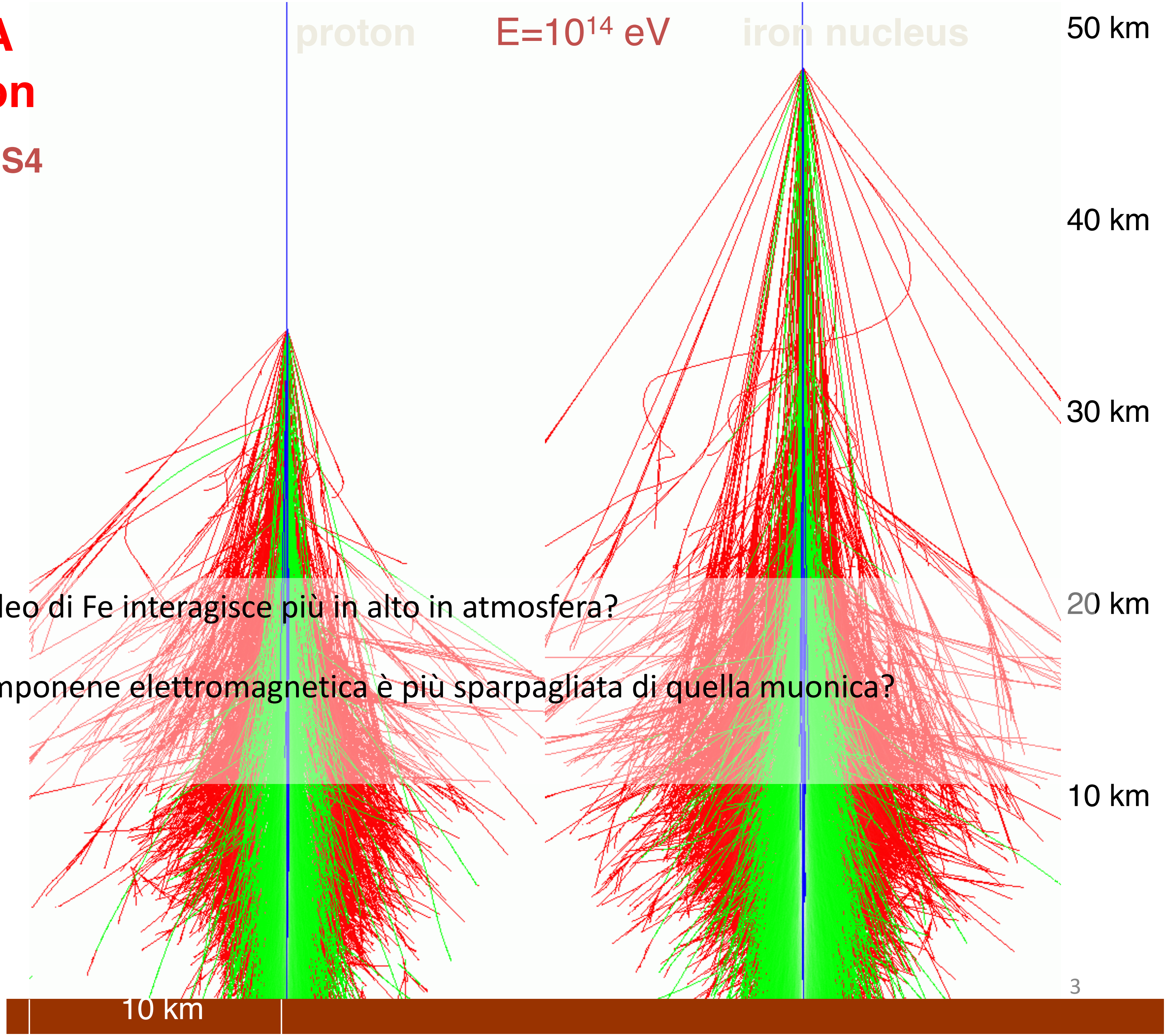
Metodi di misura dei raggi cosmici

Misure dirette
$E<10^{14}$ eV
Misure indirette,
$E>10^{14}$ eV



CORSIKA Simulation

QGSJET/EGS4

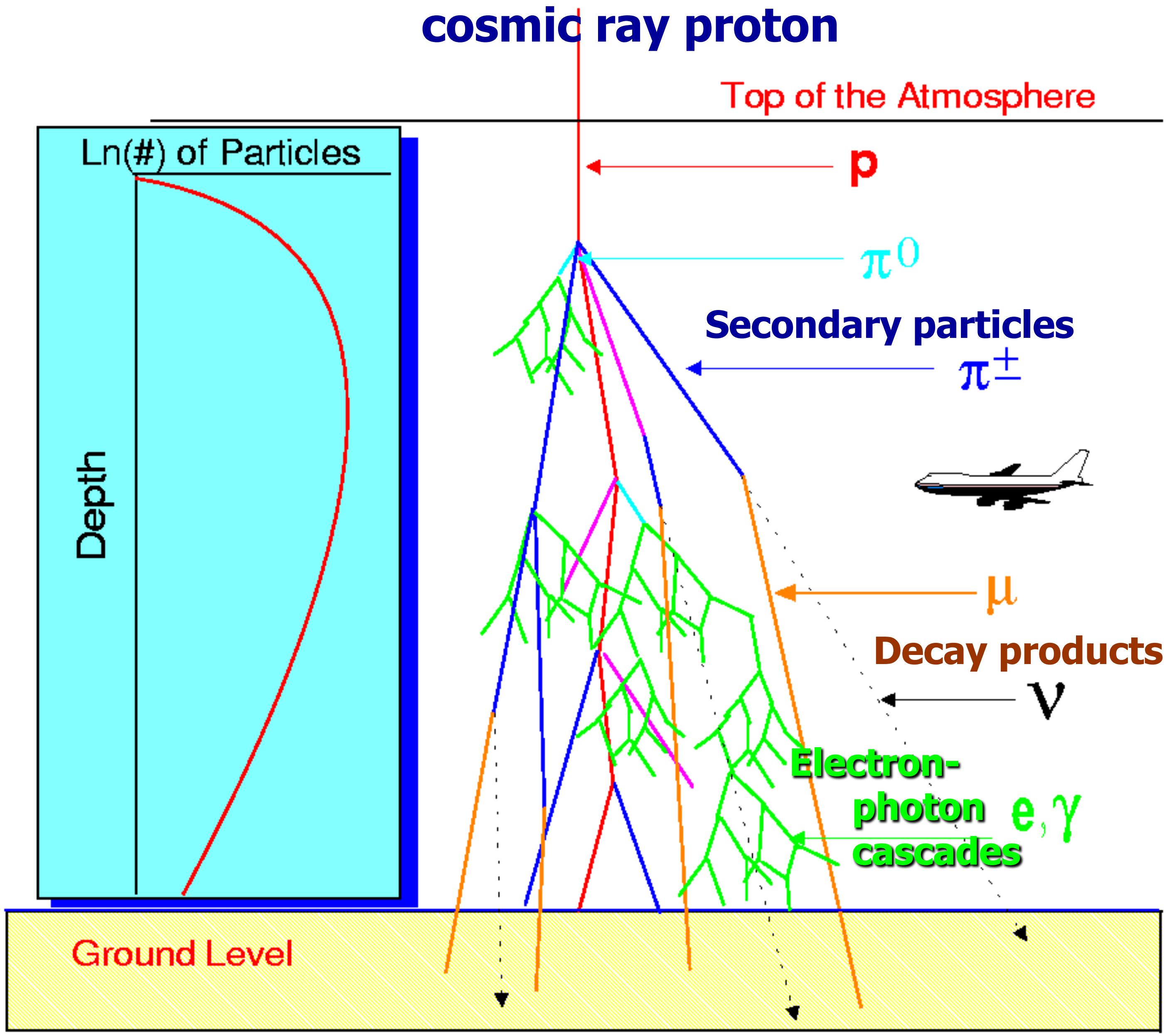


Perchè il nucleo di Fe interagisce più in alto in atmosfera?

Perchè la componene elettromagnetica è più sparpagliata di quella muonica?

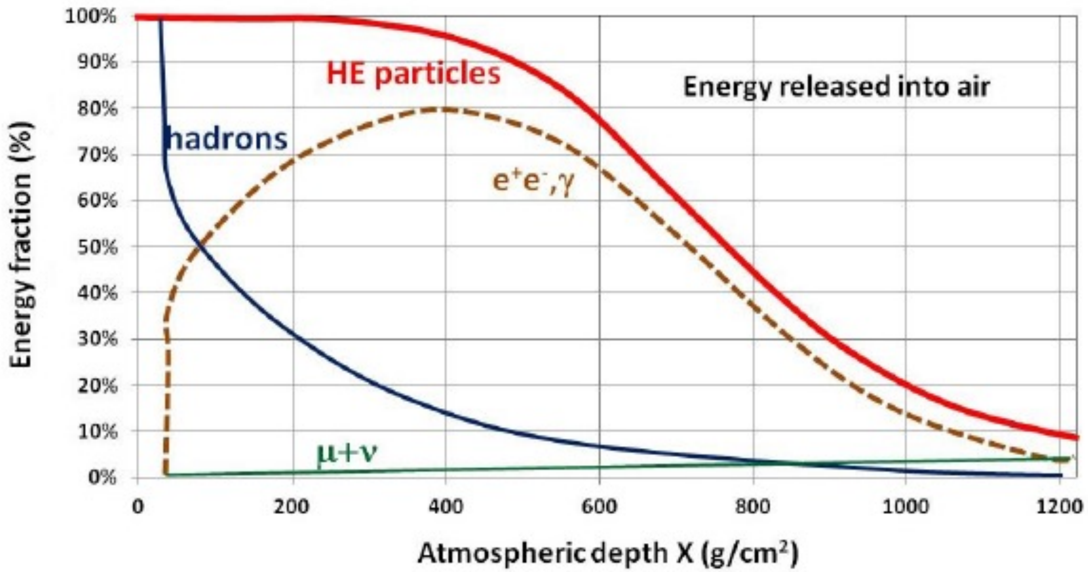
e/γ
μ
h

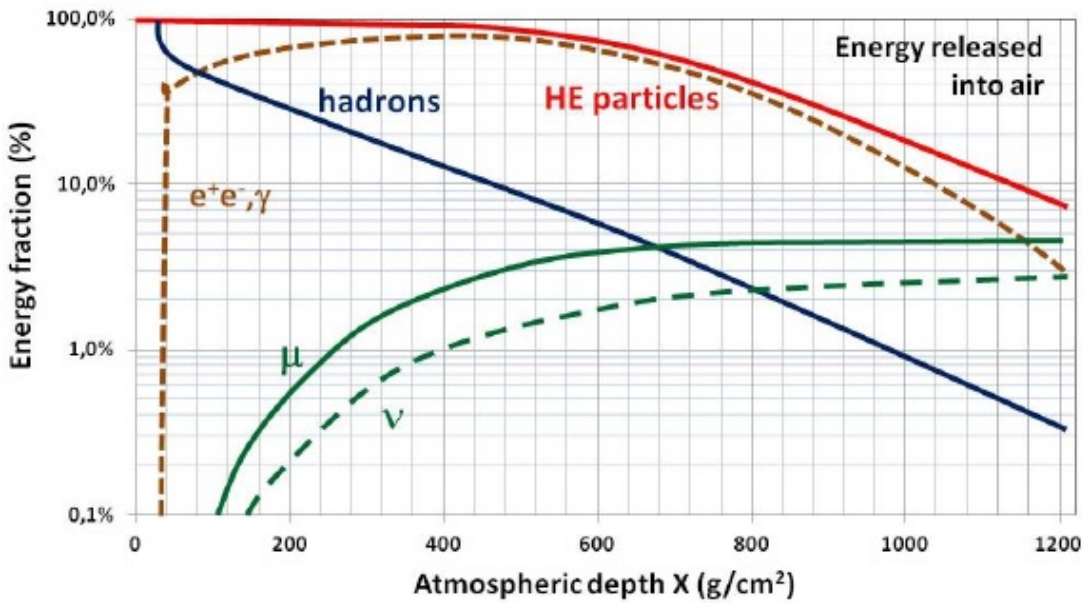
Le componenti dello sciame



Caratteristiche generali dello sciame

- Gli adroni vengono esponenzialmente attenuati
- Lo sciame EM si sviluppa esponenzialmente sino ad un massimo, la cui profondità aumenta con E_o (E primario)
- Sulla superficie terrestre (ed underground), prevalentemente muoni





Domanda: *che differenza c'è tra le 2 figure?*

Caratteristiche generali dello sciame

- Un altro modo di vedere le cose:

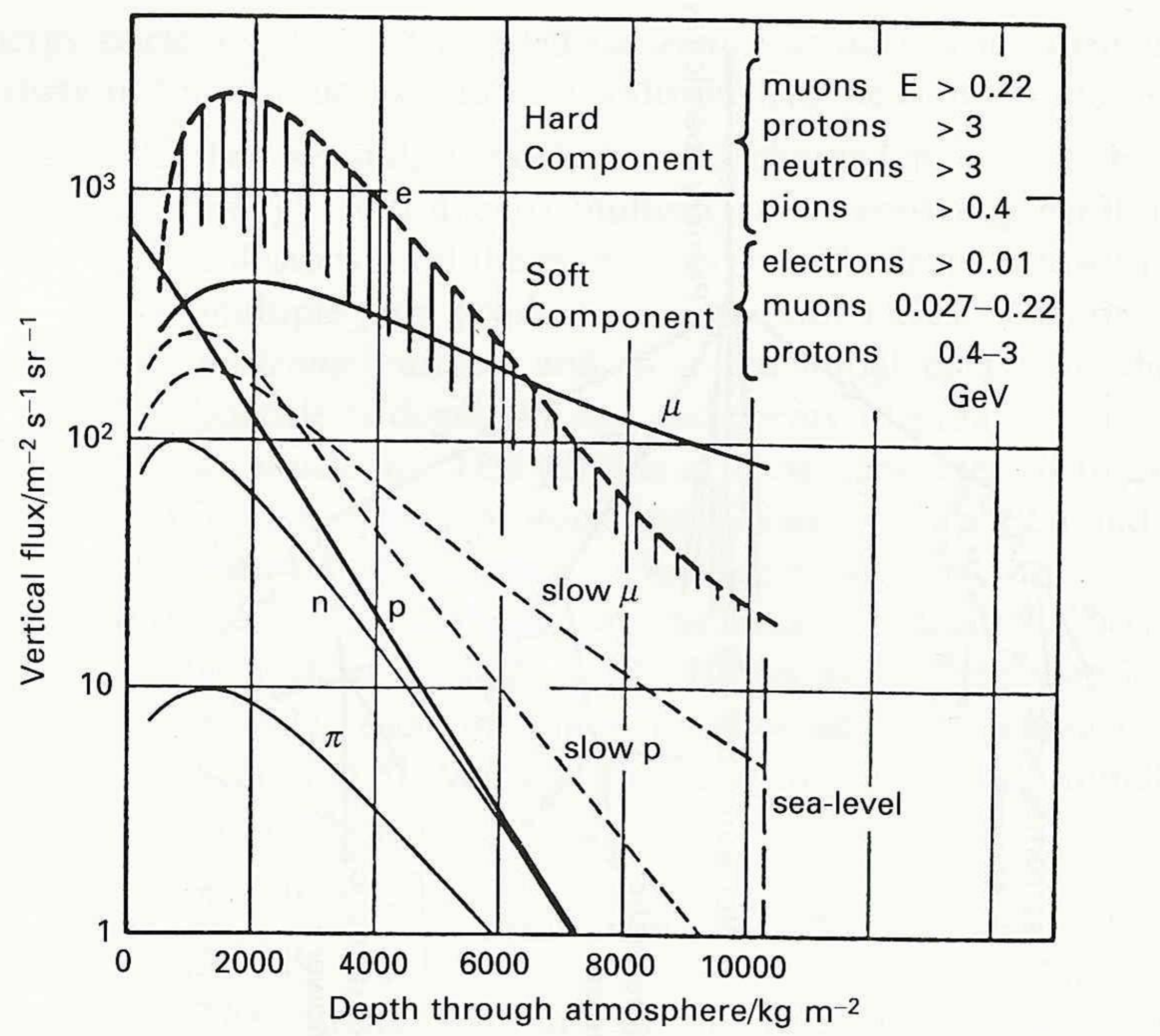


Figure 5.12. The vertical fluxes of different components of cosmic rays in atmosphere. (From A. M. Hillas (1972). *Cosmic rays*, page 50, Oxford: Pe

Come rivelare I RC di alta energia?

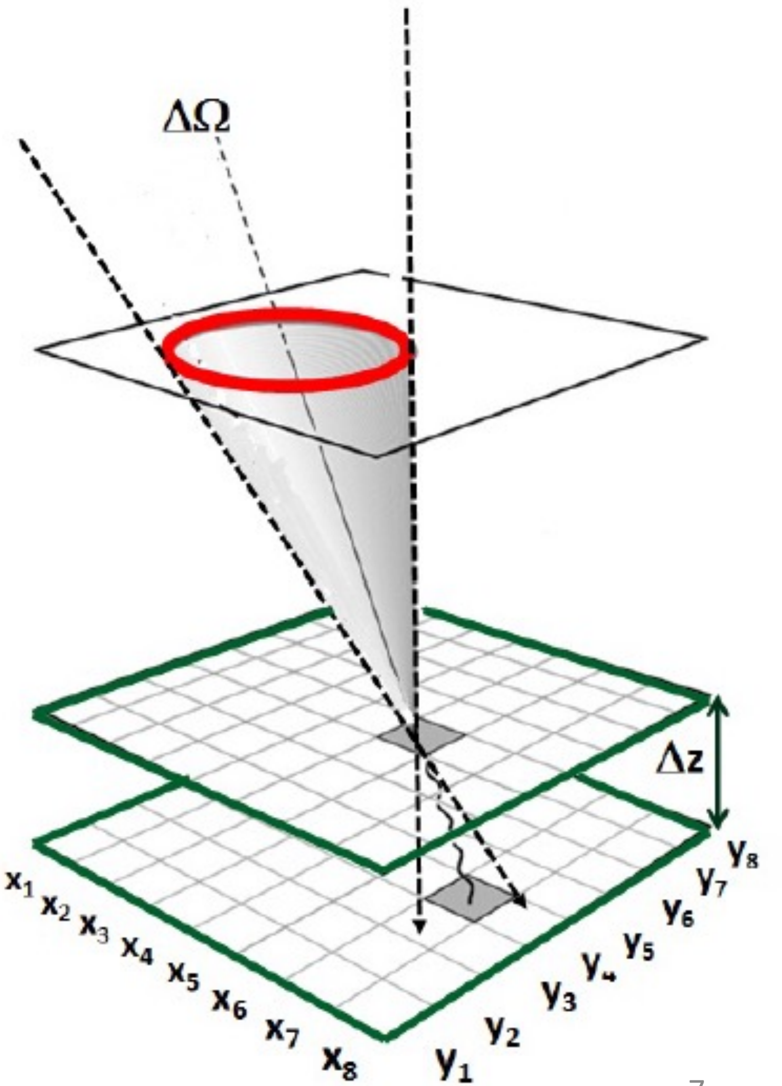
Per rivelare I raggi cosmici di energia elevata, occorre:

Una grande area di raccolta, *S*

Una grande accettanza in angolo solido

Un grande tempo di esposizione T

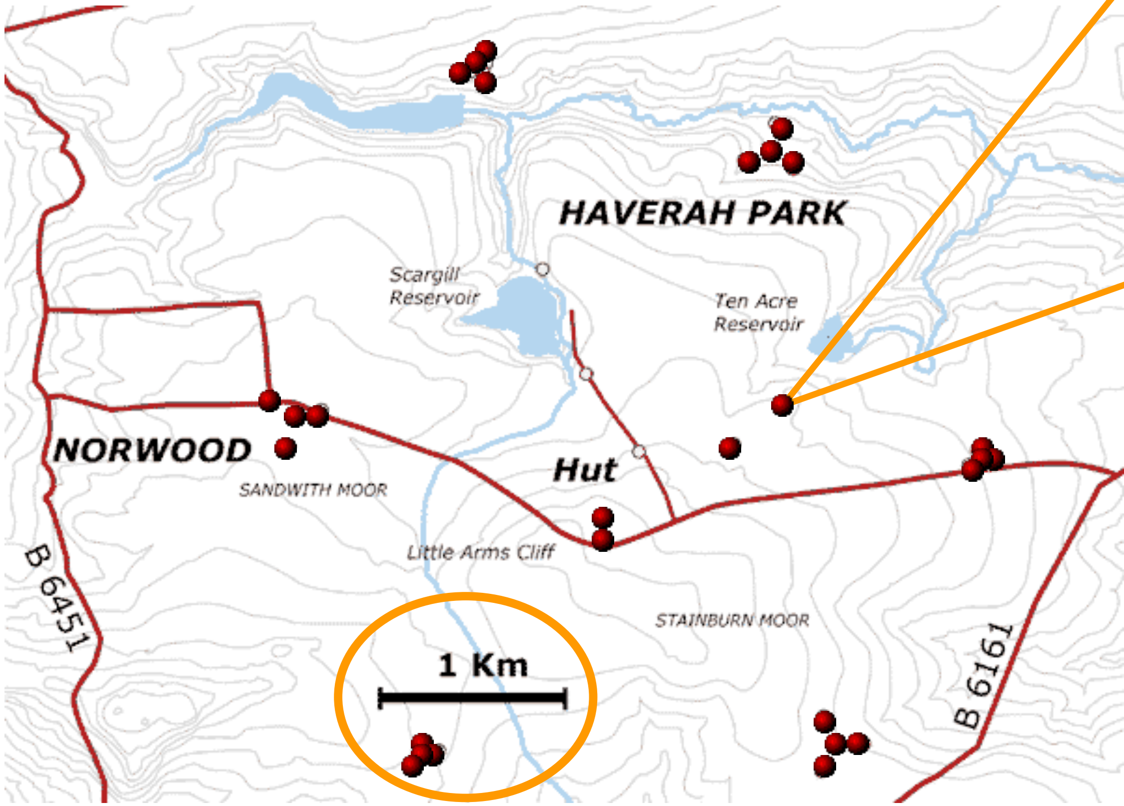
L'esposizione A·$\Delta\Omega$ · T = cm^2-sr-s determina il numero di eventi rivelabili.

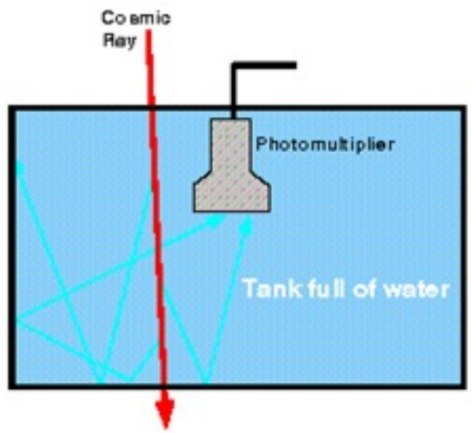


Il flusso di primari con energia $E_o>10^{19}$ eV è circa:
0.5 particelle per km^2-sr-*year*

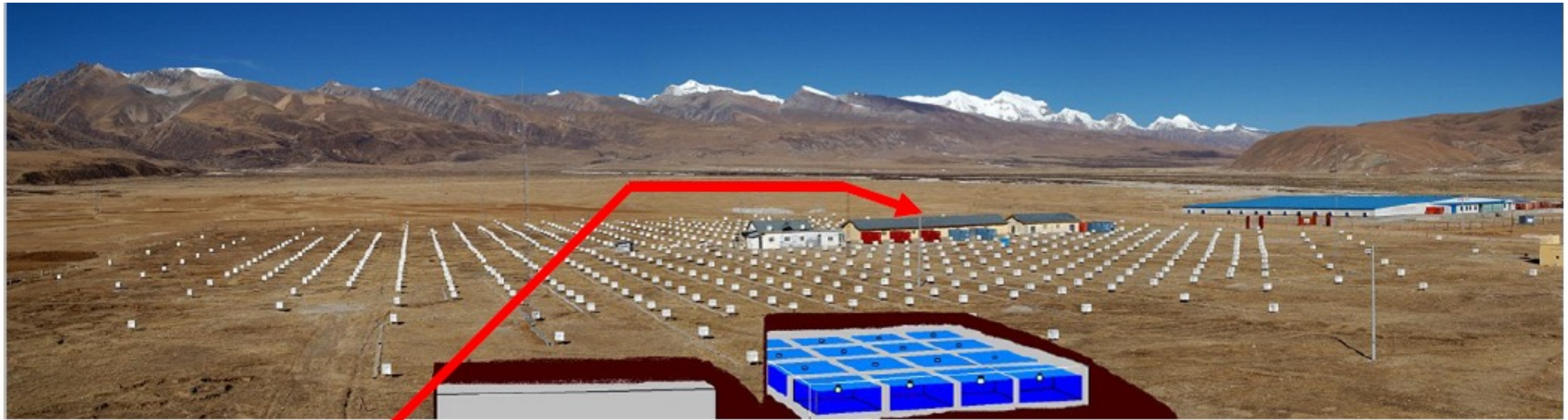
Rivelatori di Sciami

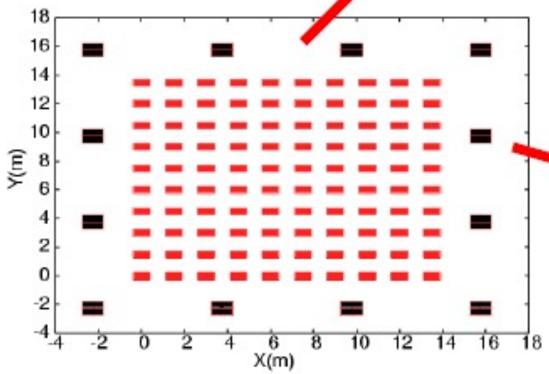
- Apparati sperimentali (Extensive Air Shower Arrays, EAS) che misurano sciami estesi sono in genere situati in alta quota.
- Misurano lo sciame "campionandolo" su una vasta superficie

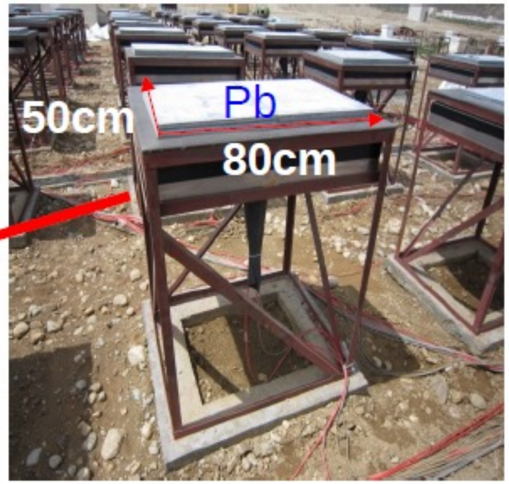




Tibet





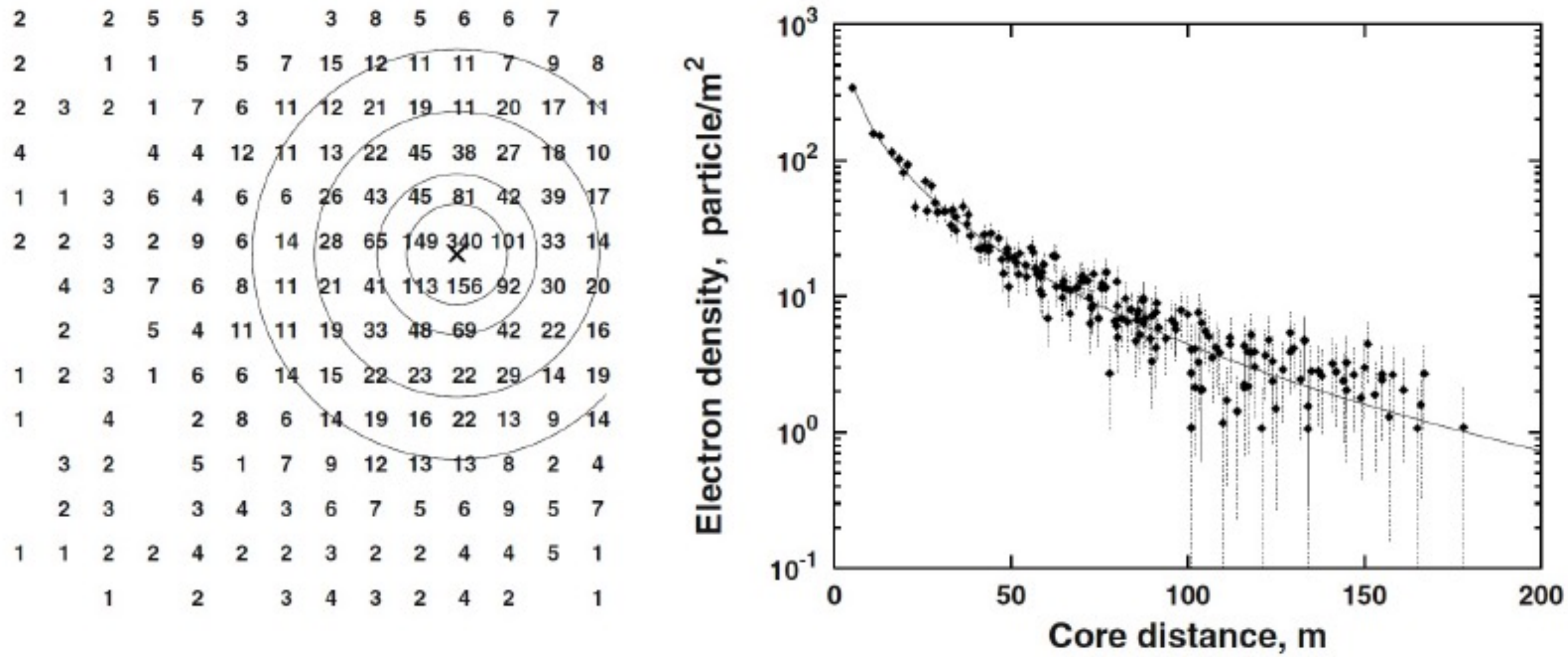


J. Huang (ICRC2011, Beijing, China)

- Il rivelatore di sciami **KASKADE (Karlsruhe) in Germania**
- Ciascuna casetta contiene un rivelatore
- Distanza media: 13 m. L'edificio centrale contiene l'elettronica necessaria per l'esperimento
- Ottimizzato per lo studio dei RC nella regione del ginocchio. Non deve essere un array di grandissime dimensioni.

e/μ

A toy model (Array energy range)



Left: A simulated event on an ideal detector with 196 counters on a 15 m grid (geometry similar to KASCADE array). Area A= 10^8 cm^2.

Each 1 m^2 counter contains the number of measured particles.

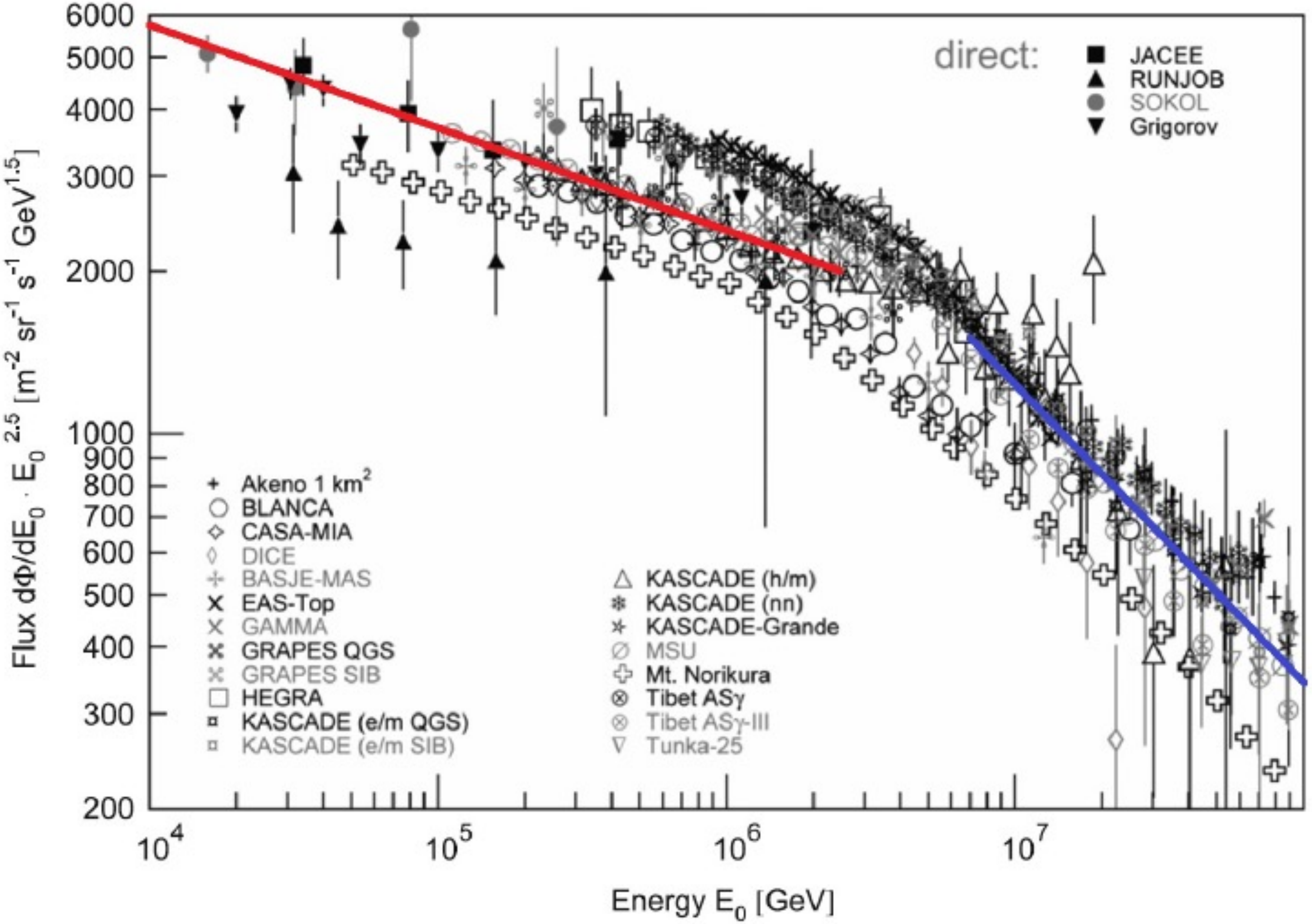
Energy E*= 4 × 10^{15} eV ; Shower size: **Ne=8 × 10^5** particles

Right: The density distribution for the shower shown on the left side. The line shows the average particle lateral distribution

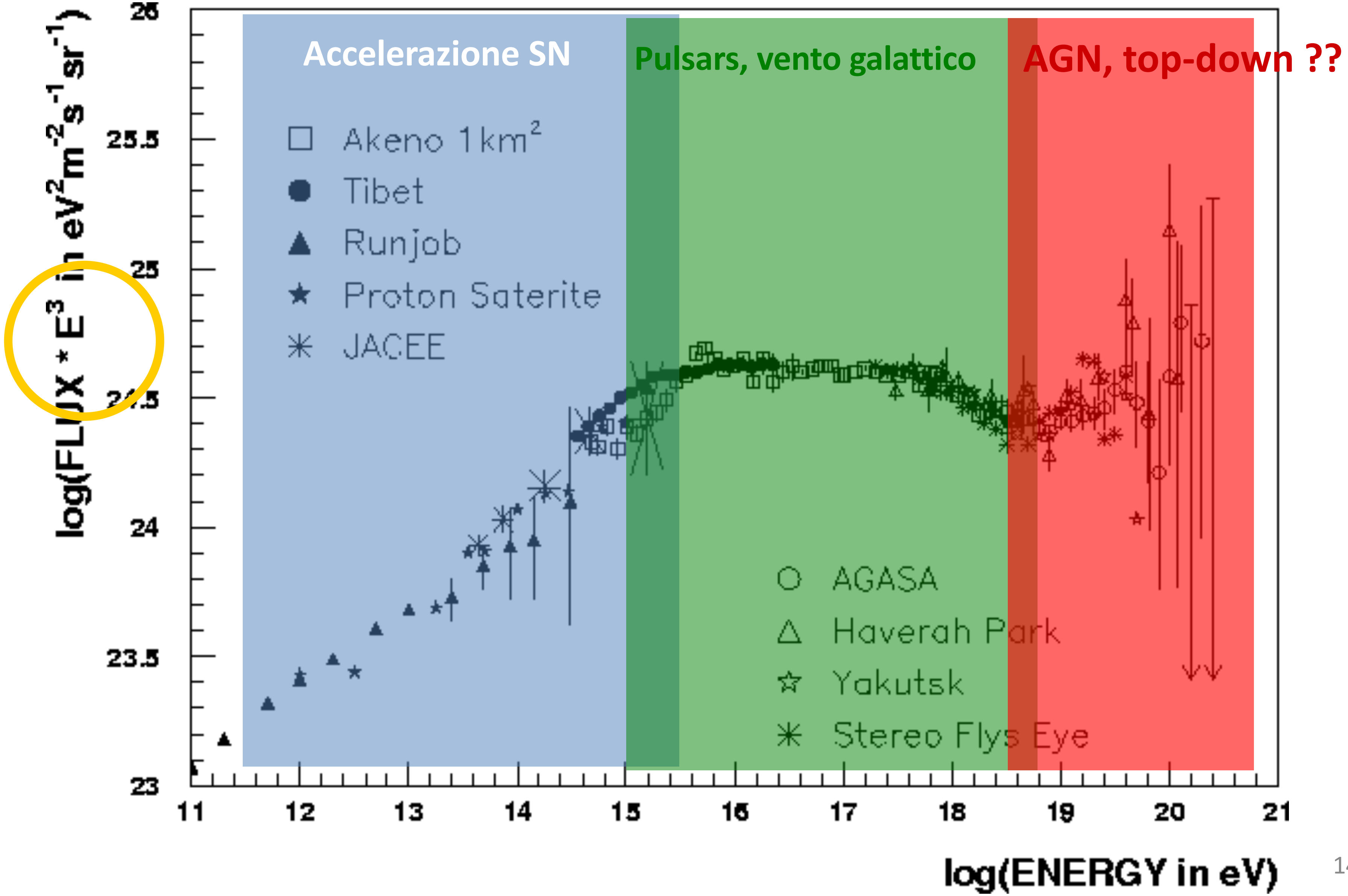
Caratteristiche generali dei rivelatori di sciami

- La distanza media tra i contatori determina la *energia minima* dello sciame rivelabile.
- Il numero dei contatori, la *precisione* della misura
- L'area totale coperta, determina la *massima energia* misurabile.
- Ciascun contatore (*casetta*) misura in modo proporzionale la perdita di energia delle particelle che lo attraversa; da qui, si risale al numero di particelle incidenti
- Dalle misure della densità di particelle in ciascuna casetta dell'array, si risale alla distribuzione laterale *D(r)*.
- Dalla misura di *D(r)* si risale all'energia del primario, *e dalla frequenza del numero di conteggi* si risale al flusso.
- La direzione dello sciame può essere determinata dalla *misura dei tempi di ritardo temporale* nell'arrivo dello sciame su diverse casette (le particelle dello sciame sono $\perp$ al suo asse)

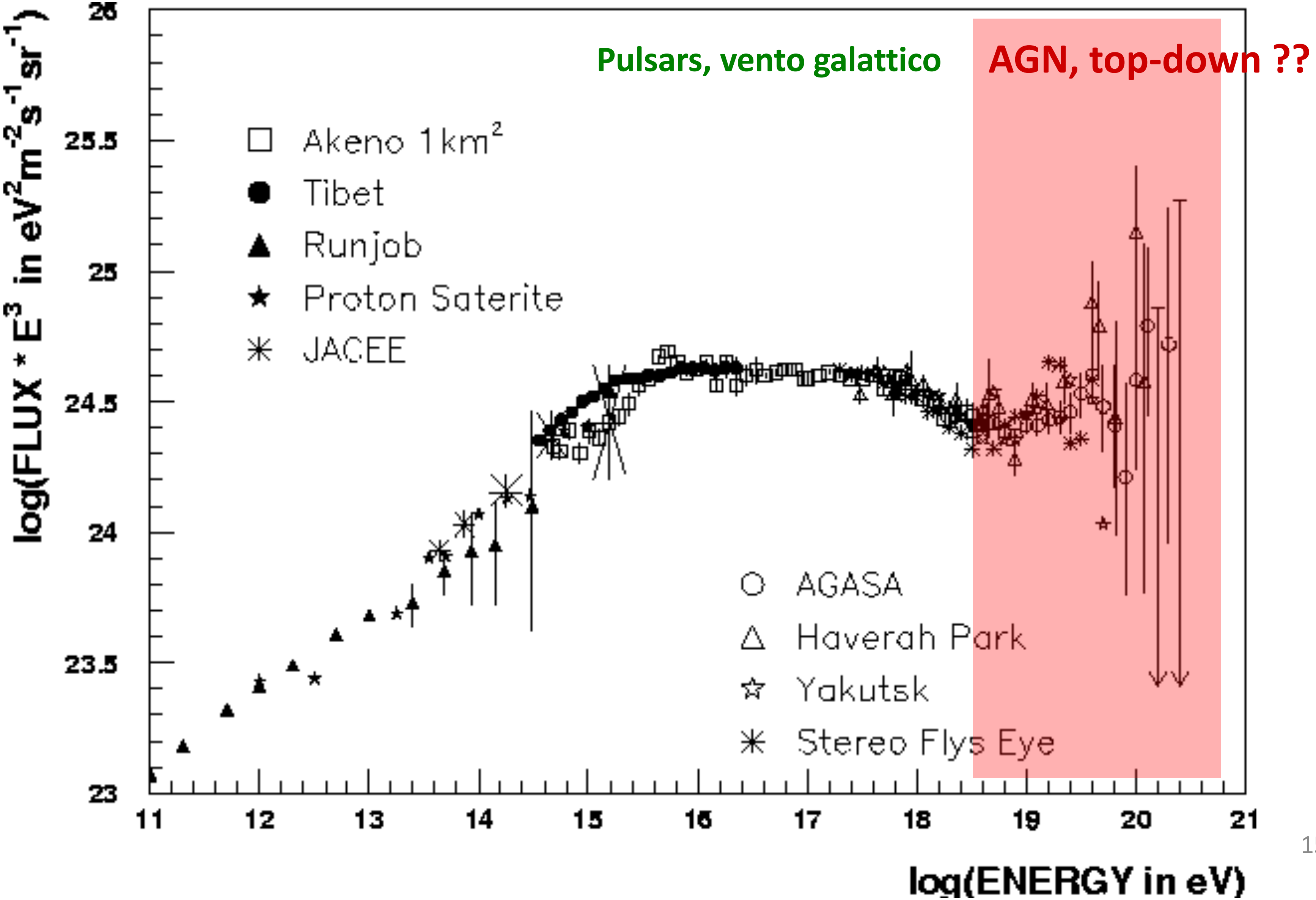
I dati sperimentali



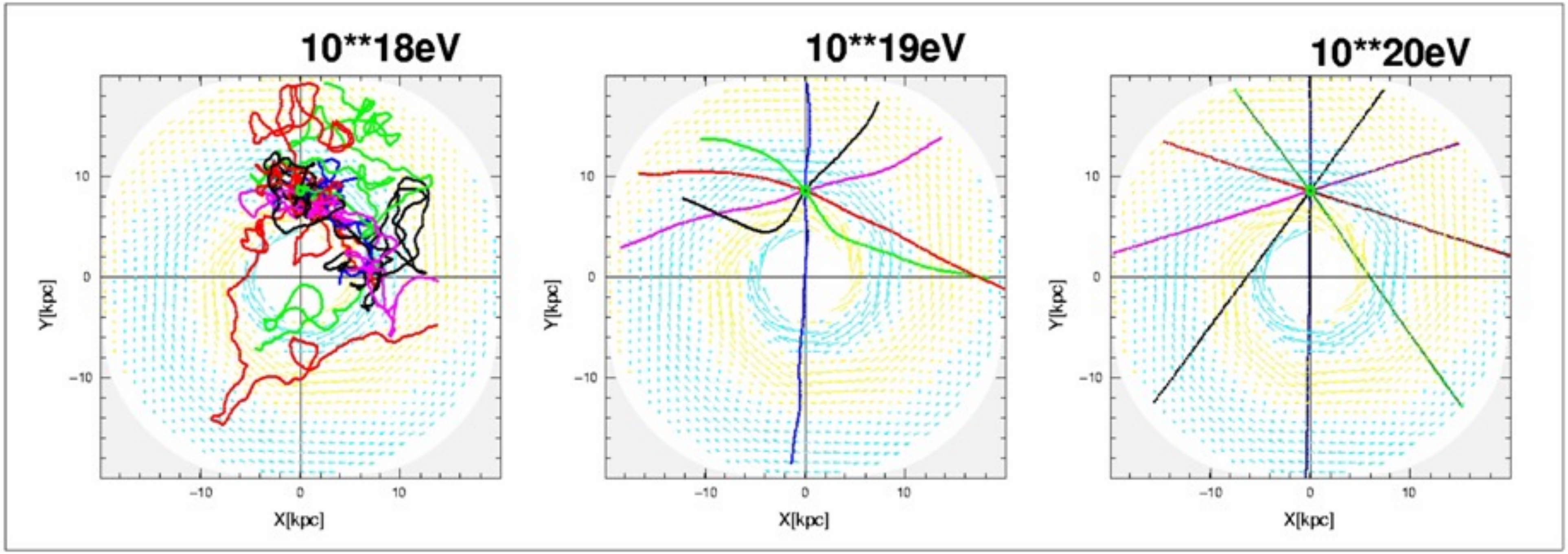
Dati e sorgenti ipotizzate



I RC di Energia Estrema >10^{18} Ev (Extragalattici?)



Confinamento (richiamo)



$$r(kpc) \cong \frac{E(EeV)}{ZB(\mu G)}$$

~ 10^{18} eV: RC ben confinati nella galassia

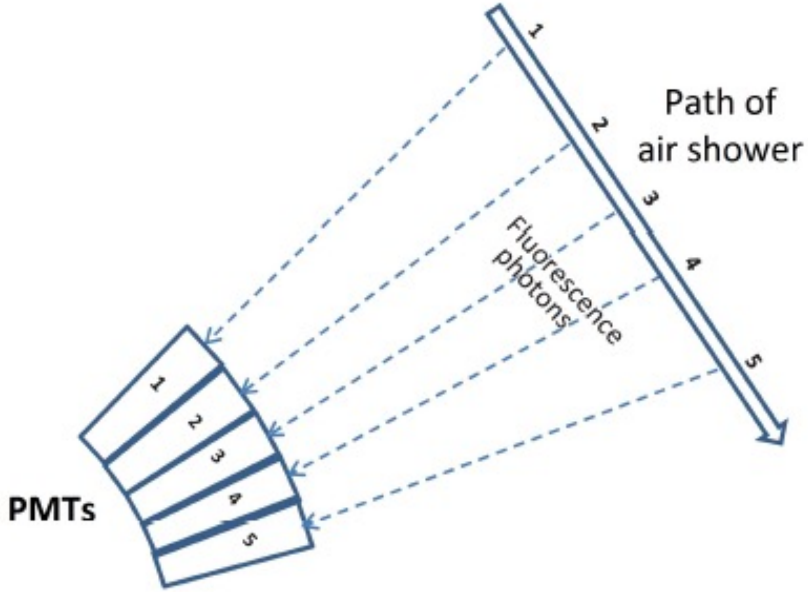
≳ 10^{19} eV: sorgenti extragalattiche

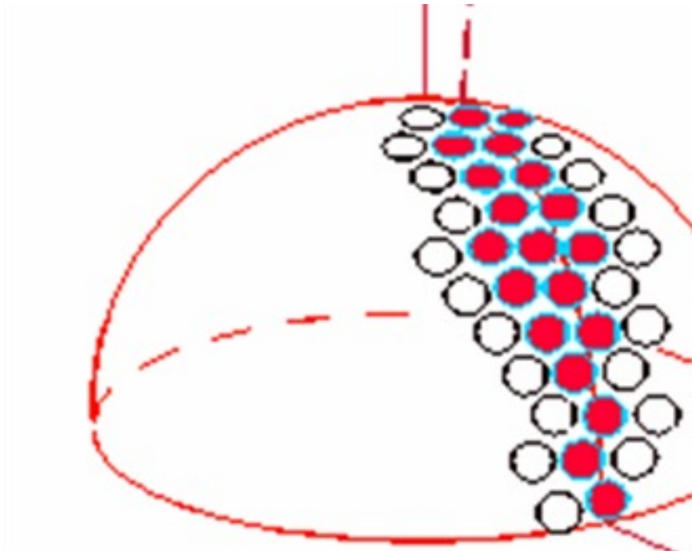
~ 10^{20} eV la deviazione nella galassia è inferiore ad 1°

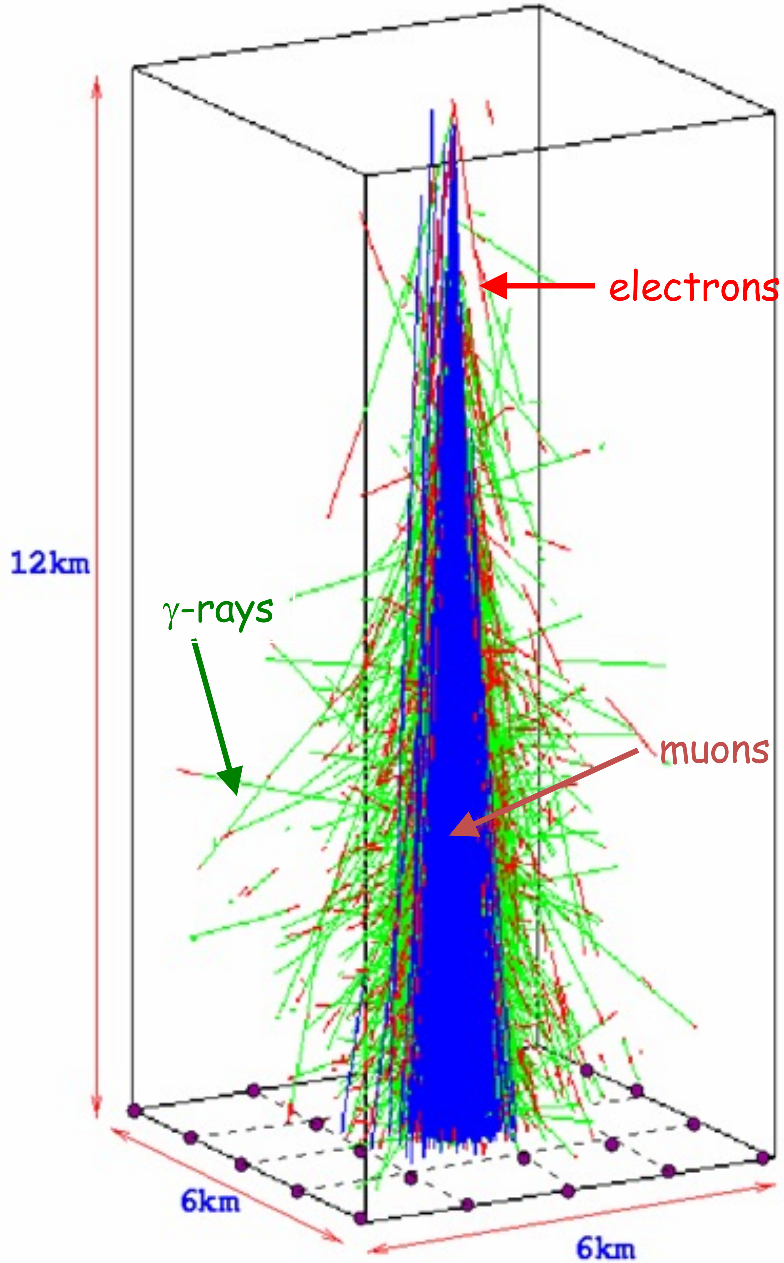
Altri metodi di Rivelazione

- Le particelle cariche dello sciame EM che giungono al suolo possono essere rivelate da **rivelatori di sciami estesi**
- Gli sciami di particelle producono anche **luce nell'atmosfera per effetto Cerenkov** (gli elettroni con E>20÷30 MeV).
- La luce Cerenkov può venire rivelata (**telescopi Cerenkov**) nelle notti senza luna da appositi rivelatori al suolo.
- Gli sciami EM inducono anche **l'eccitazione dell'azoto atmosferico**, che riemette irraggiando luce. Questa fluorescenza può essere rivelata al suolo (**Rivelatori fluorescenza**).
- La componente di muoni può essere rivelata da rivelatori "**underground**".

Rivelatori di sciami di alta energia

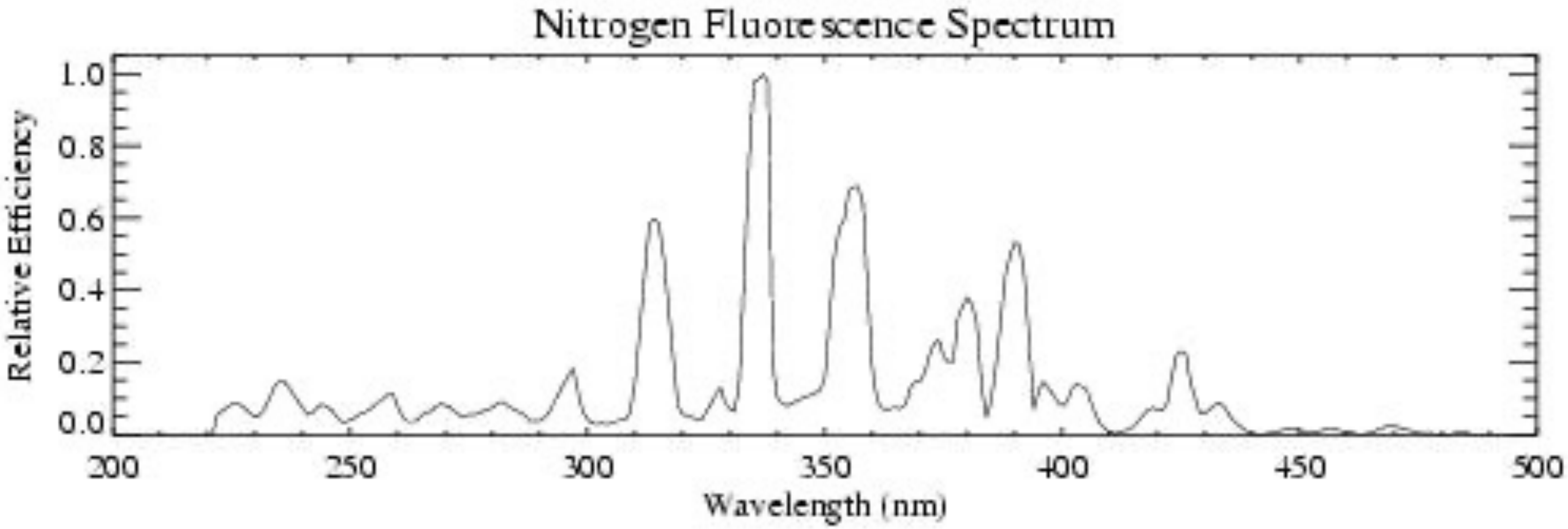






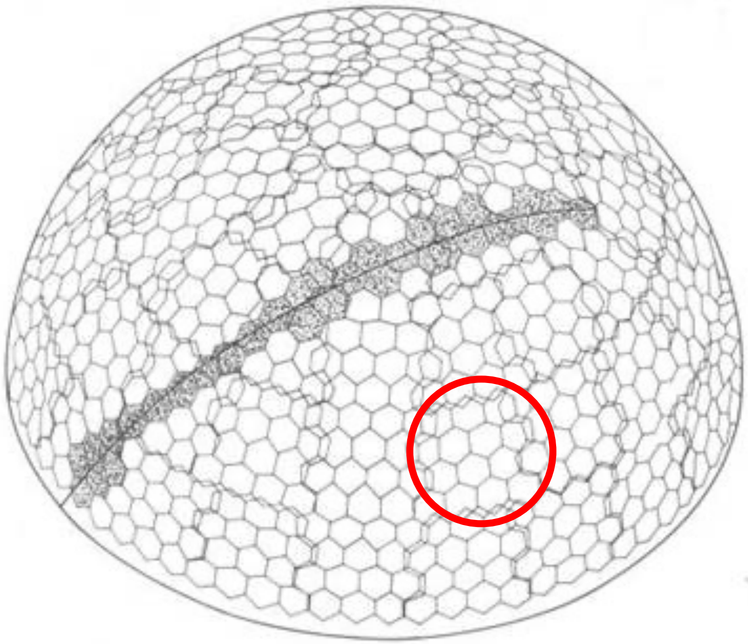
Il rivelatore Fly's Eye (USA)

Utah, 160 km da Slat Lake City
Specchi con fotomoltiplicatori rivelano la fluorescenza (visibile e UV) di N_2 indotta dalla cascata
Si può quindi studiare lo sviluppo dello sciame e risalire alla energia del primario

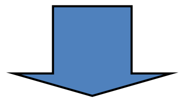


Il rivelatore Fly's Eye - 2

- 67 specchi con PM osservano la volta celeste
- È possibile ricostruire il profilo della cascata

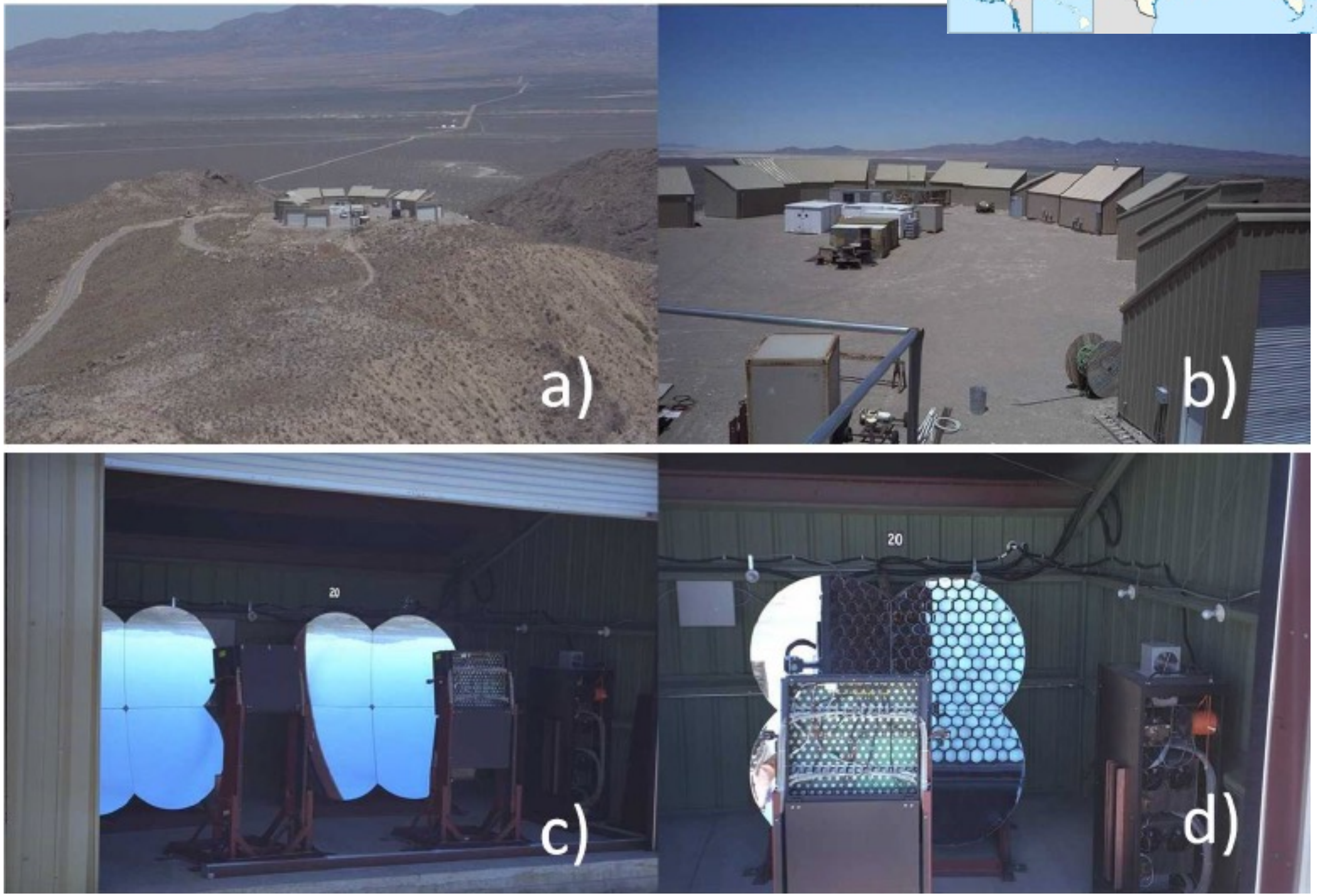


Si misura così energia (sviluppo shower) e direzione del primario



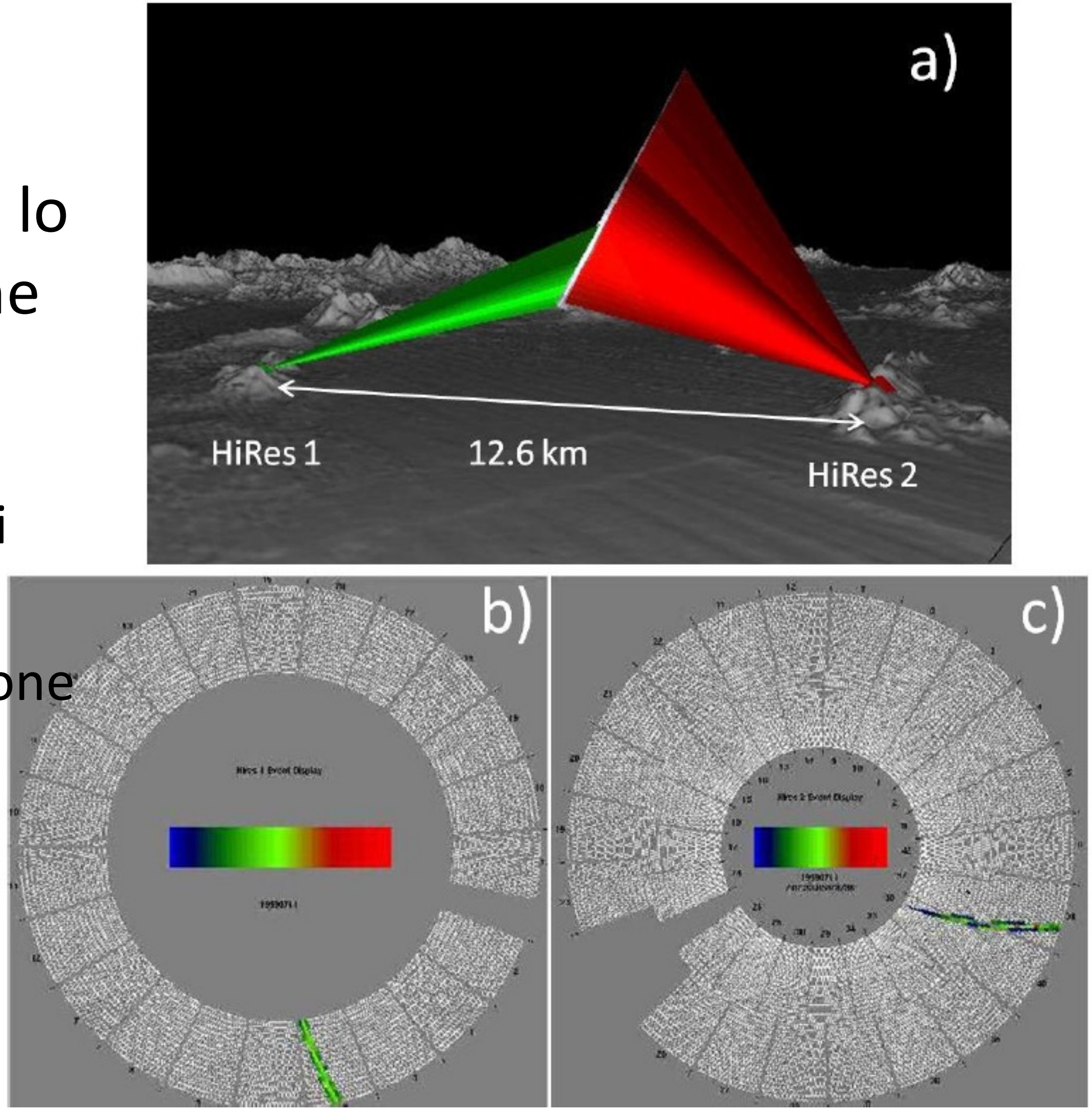
FE2: visione stereoscopica

HiRes (Utah)



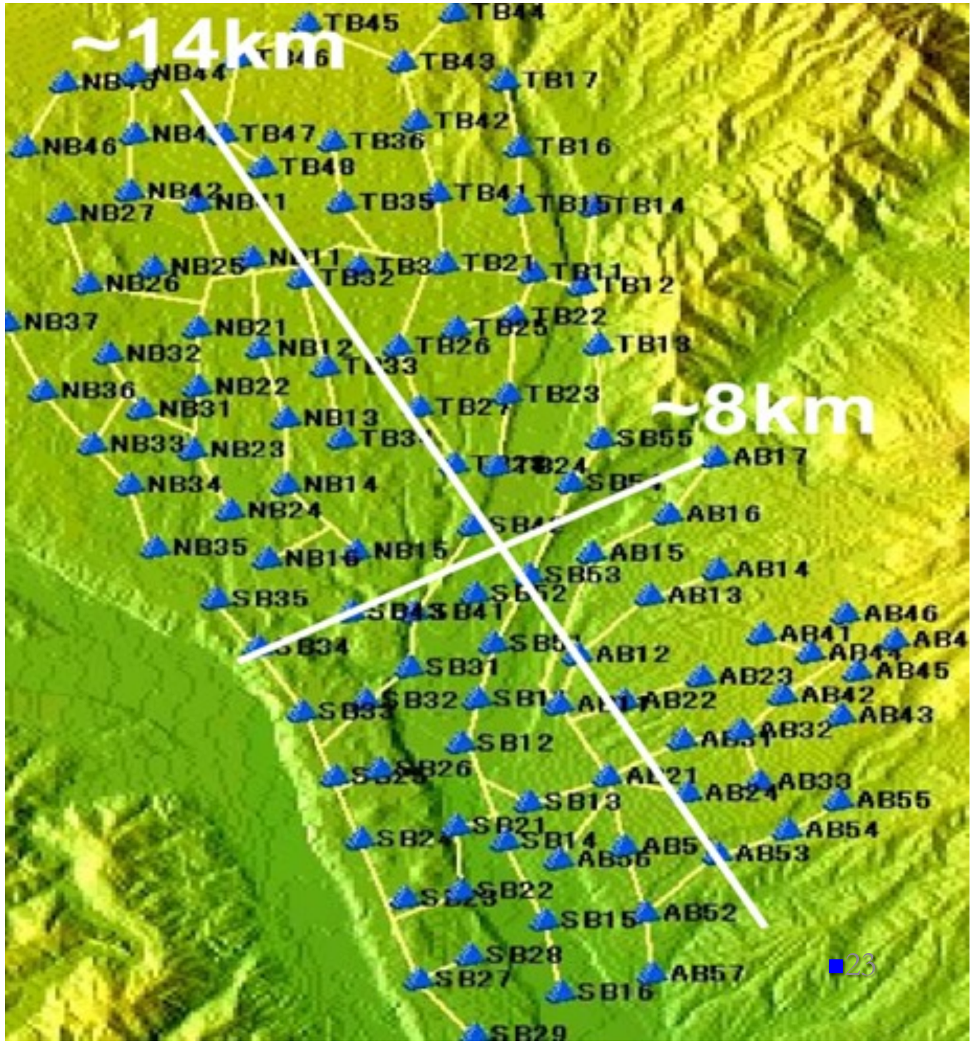
Fly's eye→HiRes

- *Stereo* Hires: due insiemi di rivelatori per ricostruire in 3D lo sviluppo dello sciame
  - Migliore risoluzione angolare, studio correlazioni a piccoli angoli
  - Migliore comprensione della composizione chimica dei primari



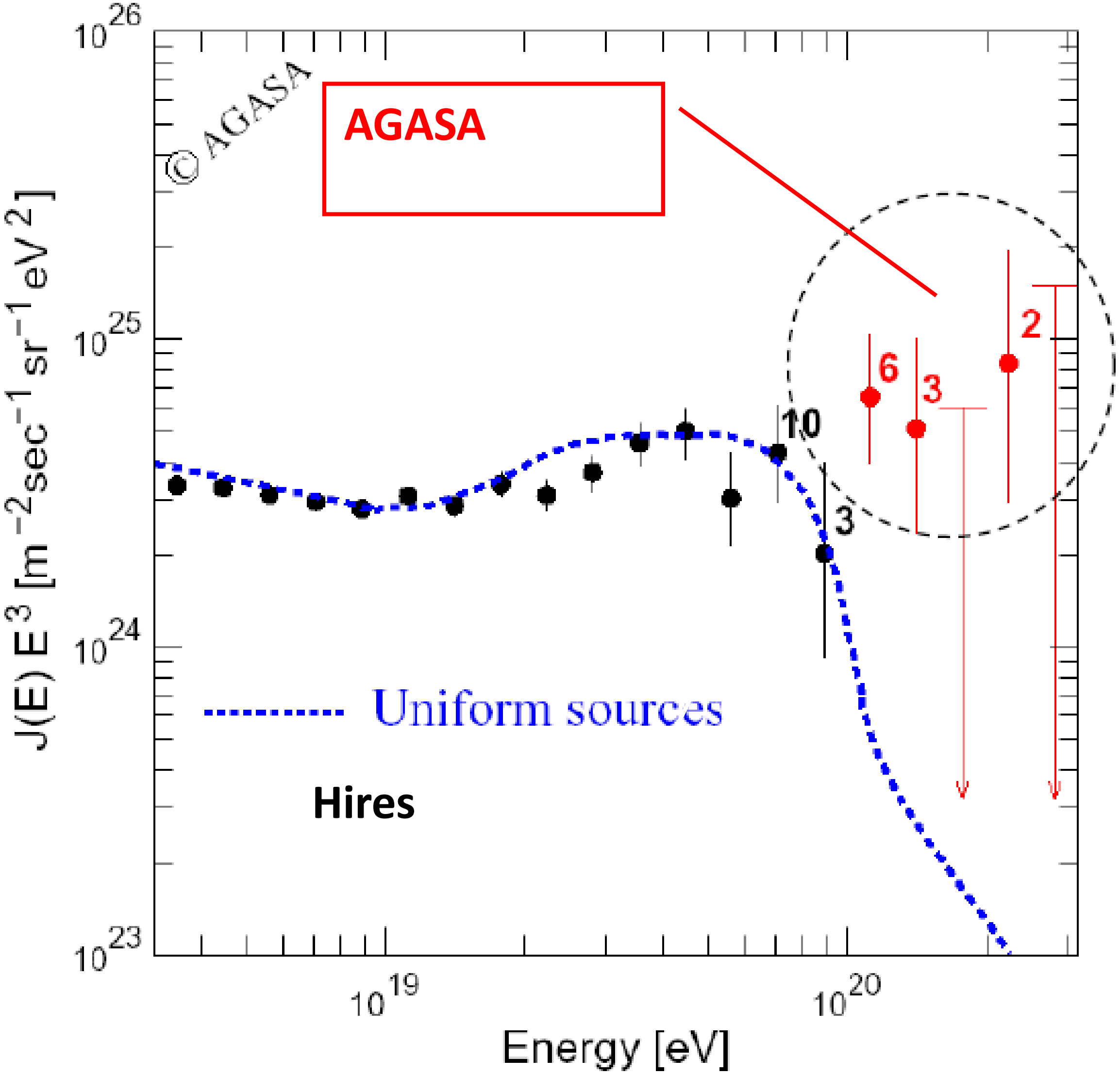
Agasa (Giappone)

- 100 km^2, 111 rivelatori a scintillazione, 27 per muoni, separazione ~1 km – $5 \cdot 10^{16}$ $m^2 s$ sr per $E > 10^{19}$ eV, $\theta < 45^\circ$



Risultati sperimentali per E>10^{19} eV prima del 2007

- Linea BLU: spettro atteso per distribuzione uniforme di sorgenti e cut-off di GZK.
- AGASA: osservati 11 eventi con E> 10^{20} eV
- Eventi attesi: 1.9 eventi, assumendo cutoff GZK

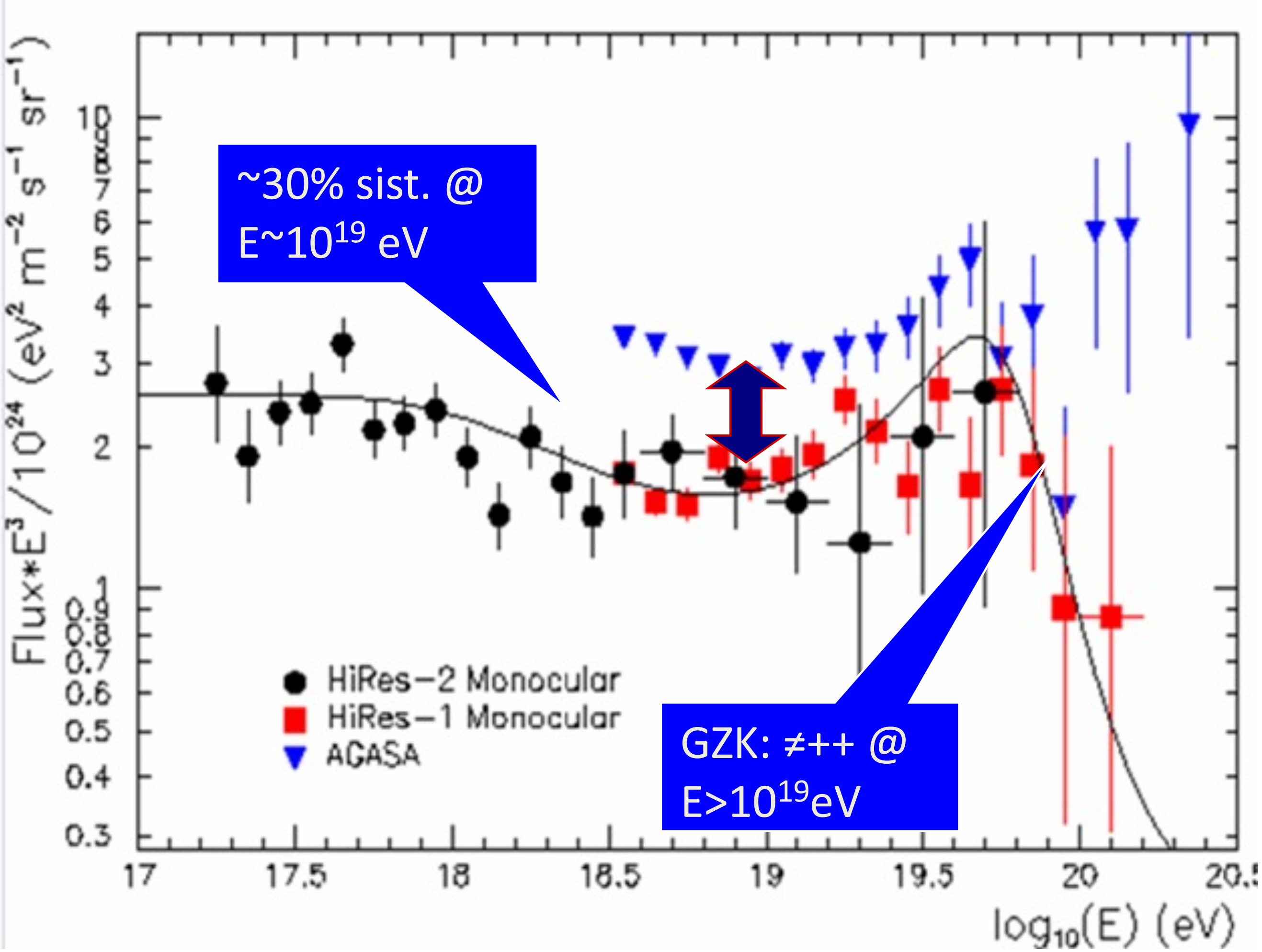


“Conflitto” AGASA-HiRes

Confronto tra dati Agasa-Hires: differenza *sistematica* del 20-30% per E < 10^{20} eV

Pur correggendo per questa differenza, a E > 10^{20} eV,i risultati differiscono per ~2 σ

PROBLEMA: Poca statistica!



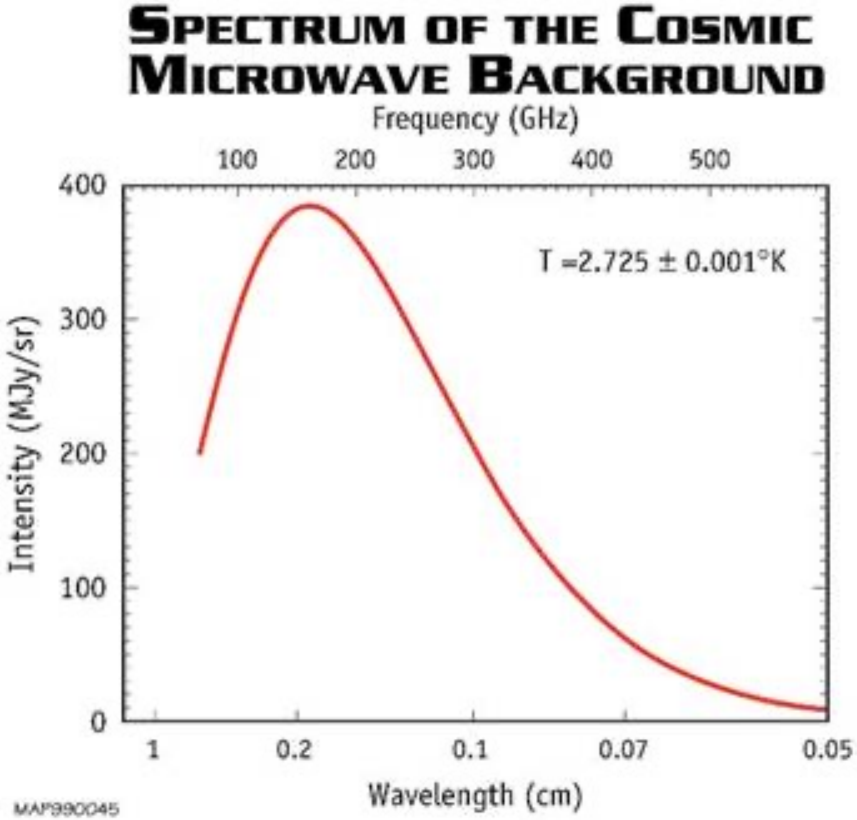
Quale è la natura e la ragione del “conflitto” tra i due esperimenti?

Volume di confinamento dei RC : il cutoff di Greisen-Zatsepin-Kuzmin

- L' universo è permeato dalla Radiazione Cosmica di Fondo a 3° K (CMBR). Frequenza media 280 GHz
- CMBR: fotoni di energia

$$E_{cmb} = h\overline{\nu} \simeq 1.2 \times 10^{-3}\ \mathrm{eV}\ .$$

- La densità dei fotoni di fondo è ~400/cm^3
- Il fondo di radiazione pone un limite sulla distanza massima da cui i RC possono provenire.



$G_{reisen}Z_{atsepin}K_{uzmin}$ cutoff
Soglia per reazioni di fotoproduzione

- **Fotoproduzione**: Protoni di alta energia possono interagire con fotoni, producendo un pione:

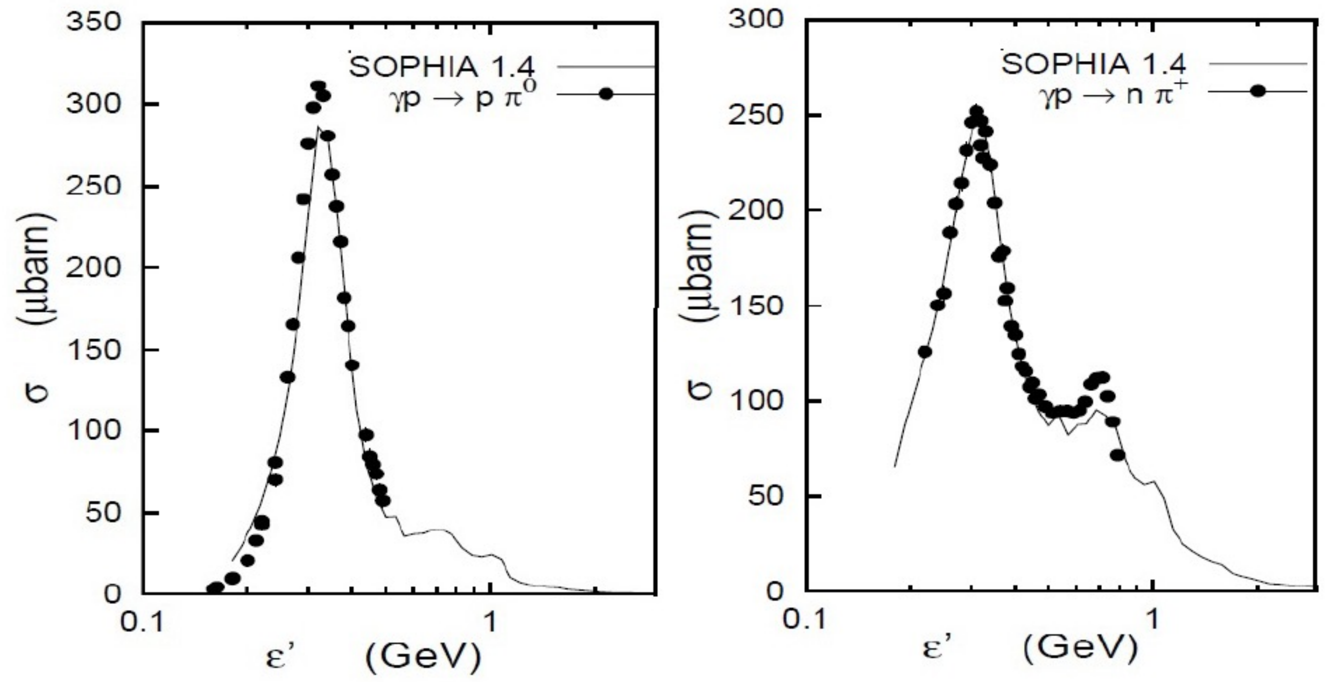
$$p^+\gamma_{cmb} \rightarrow \Delta^+ \rightarrow \pi^+ n$$
$$\rightarrow \pi^0 p$$

- È necessario essere sopra la soglia di fotoproduzione nel sistema del CM: $E_0^{FP} \approx 300$ MeV
- Il processo ha una sezione d'urto in risonanza

$\sigma_0^P \approx 250$ μb

- la densità numerica della CMBR è n_g=400 cm^{-3}, da cui si ricava il cammino libero medio del p

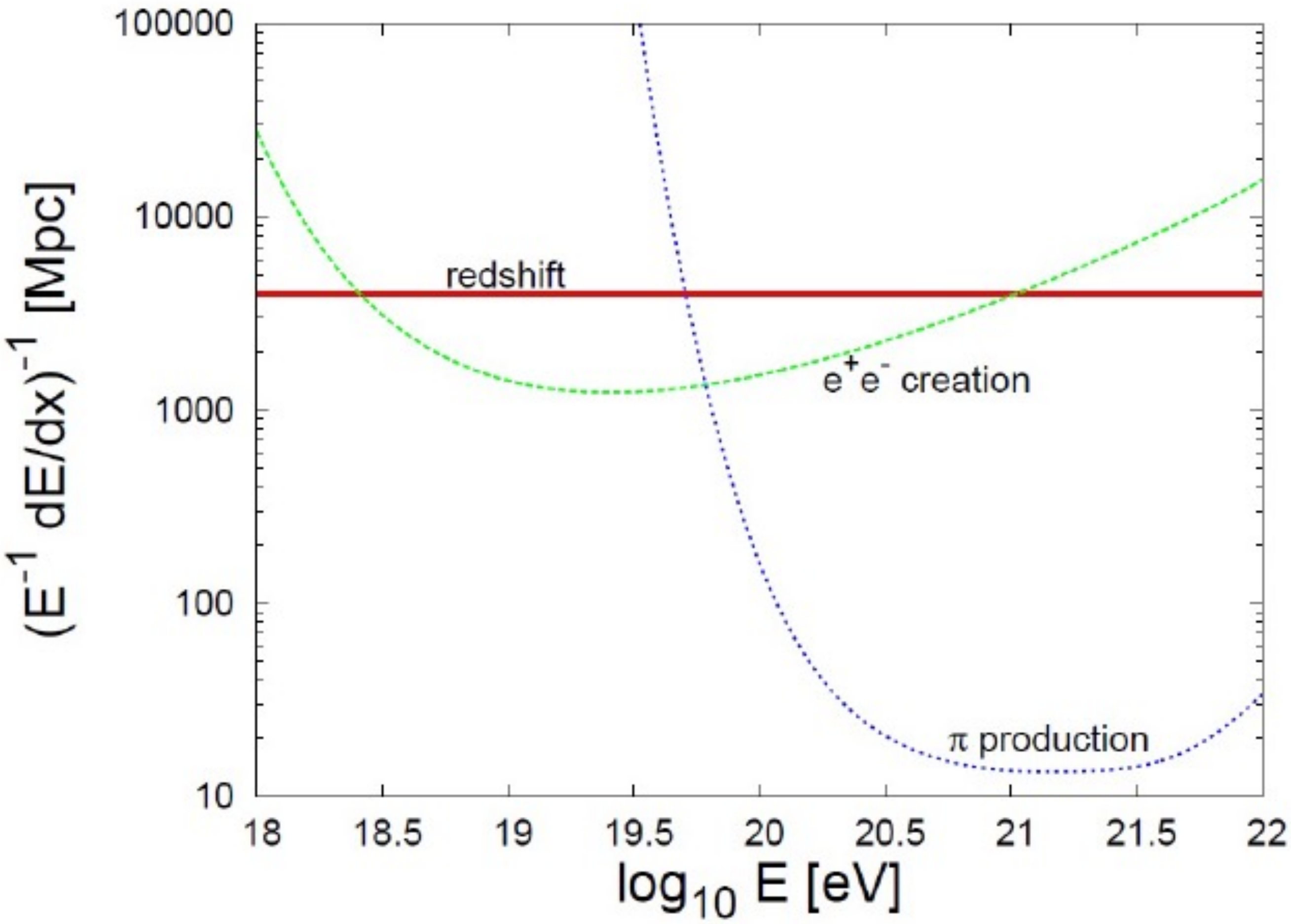
Sezione d'urto per la Δ



In ogni processo, il p perde circa 1/10 della sua energia

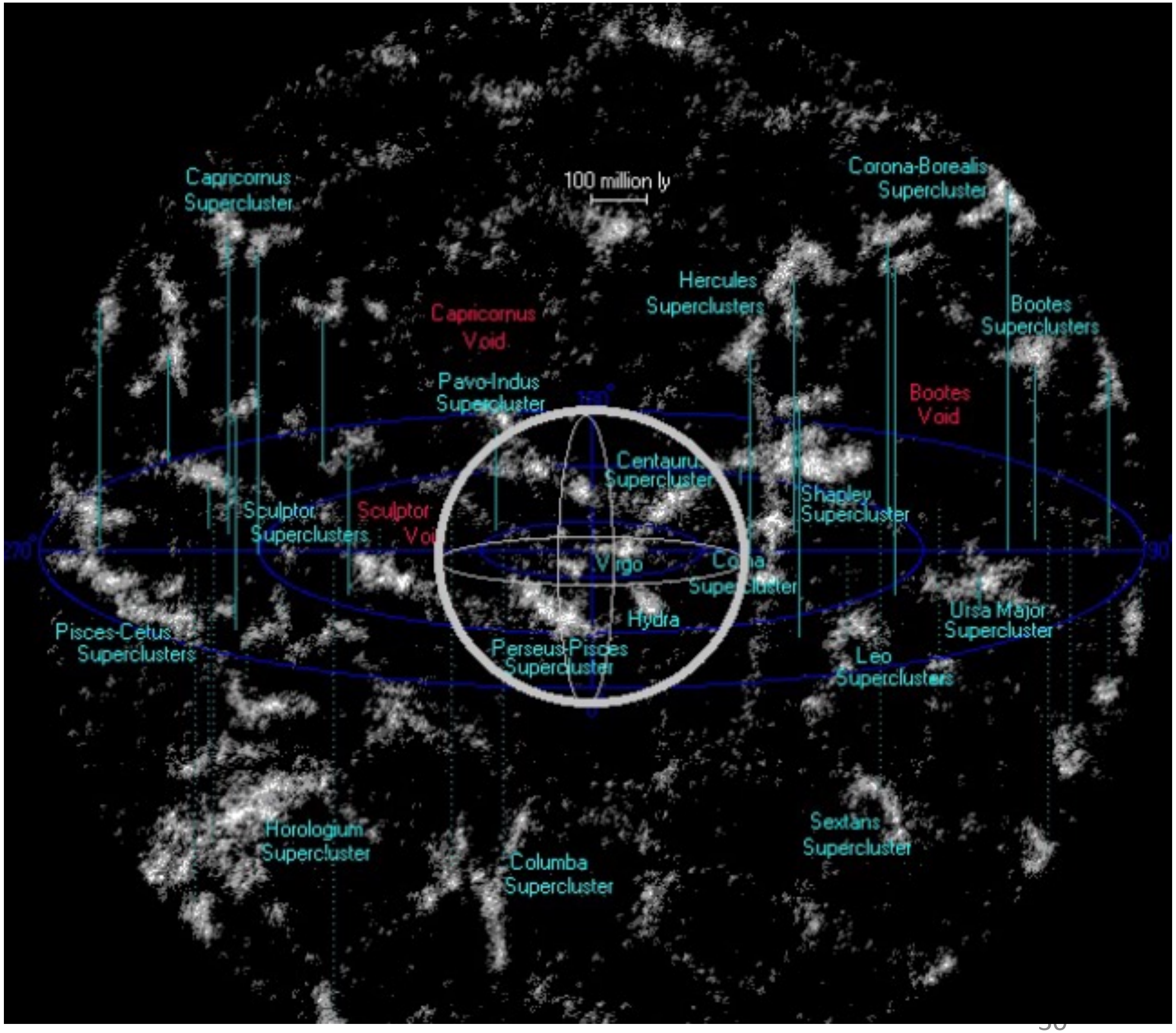
Si può dunque stimare che i p NON possano giungere da distanze superiori a 10×3 Mpc = 30 Mp

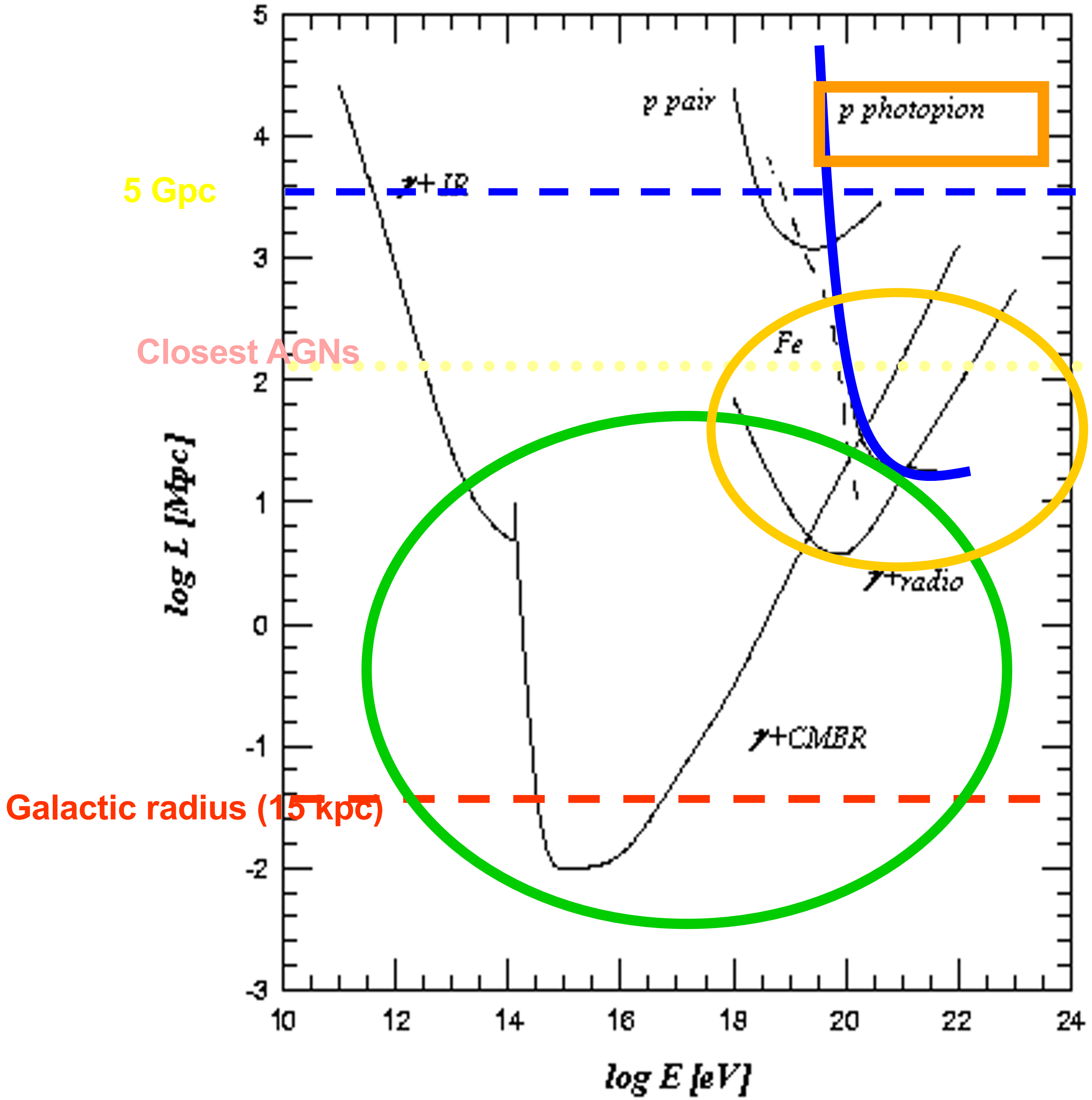
Figura: Risultato di calcoli dettagliati.



Orizzonte dell'Universo per p

- The neighboring superclusters of galaxies (<300 Mpc)
- There are about 100 superclusters and about 3 10^6 large galaxies.
- The central sphere corresponds to 100 Mpc (GZK limit)





L'Universo NON è trasparente ai protoni di altissima energia

L'Universo NON è trasparente ai fotoni di alta energia

Ricerca delle sorgenti

- Nella reazione di fotoproduzione (responsabile del cutoff di GZK) sono prodotti $\pi^{\pm}$, π^0 che decadono:

$$\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow \nu_\mu \nu_\mu \nu_e e^+$$

$$\pi_0 \rightarrow \gamma\gamma$$

- Neutrini e fotoni di altissima energia possono quindi essere studiati per confermare il meccanismo GZK, e per localizzare le sorgenti di RC a $E > 10^{19}$ eV

Il RC di più alta energia osservato: $\gtrsim 3.2 \cdot 10^{20}$ eV **(?)**

Se le sorgenti **non possono** essere troppo lontane (<30 Mpc), possiamo cercare di localizzarle tramite:

→ Studi di anisotropia con esperimenti di RC

→ Confronto con altre misure astronomiche

→ Rivelazione gamma e neutrini di fotoproduzione

L'esperimento Auger

L'esperimento AUGER è finalizzato a risolvere il problema della bassa statistica di eventi per energie sopra il cutoff GZK, utilizzando ENTRAMBE le tecniche sperimentali di AGASA (EAS) e HiRes (Fluorescenza)

Due rivelatori simili sono proposti: uno nell'emisfero Australe (Argentina). Quello nel Nord non è stato finanziato

Per avere statistica sufficiente, i rivelatori sono distribuiti su un'area pari a 3000 km2

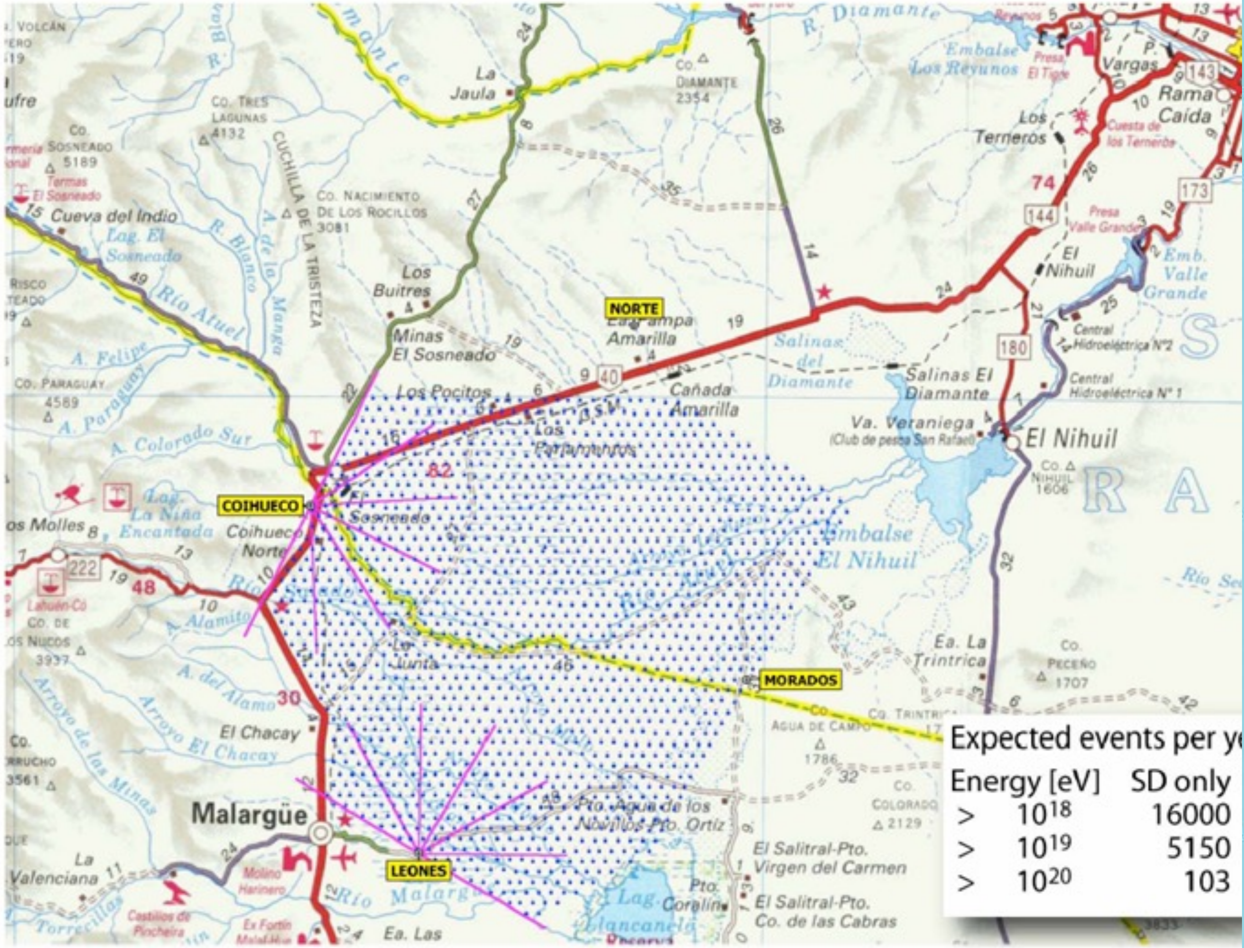
Le differenti tecniche sperimentali permettono una buona risoluzione angolare, sensibilità alla specie del RC che origina la cascata (p o nuclei pesanti), e la possibilità di effettuare calibrazioni energetiche incrociate

AUGER: Un rivelatore ibrido

Rivelatore di sciami: 1600 taniche cilindriche (ciascuna di 10 m^2 ed alte 1.5 m) riempite di acqua, per rivelare gli sciami al suolo tramite la luce Cerenkov emessa dagli elettroni nell'acqua

- Il rivelatore di sciami misura la distribuzione laterale e temporale dello sciame
- Distanza tra taniche: 1.5 km
- Area di forma esagonale, di 60×60 km^2
- Rivelatori di fluorescenza: 6 telescopi con ciascuno 4 "occhi" per determinare il profilo longitudinale dello sciame e l'altezza del suo massimo.

AUGER



Expected events per ye

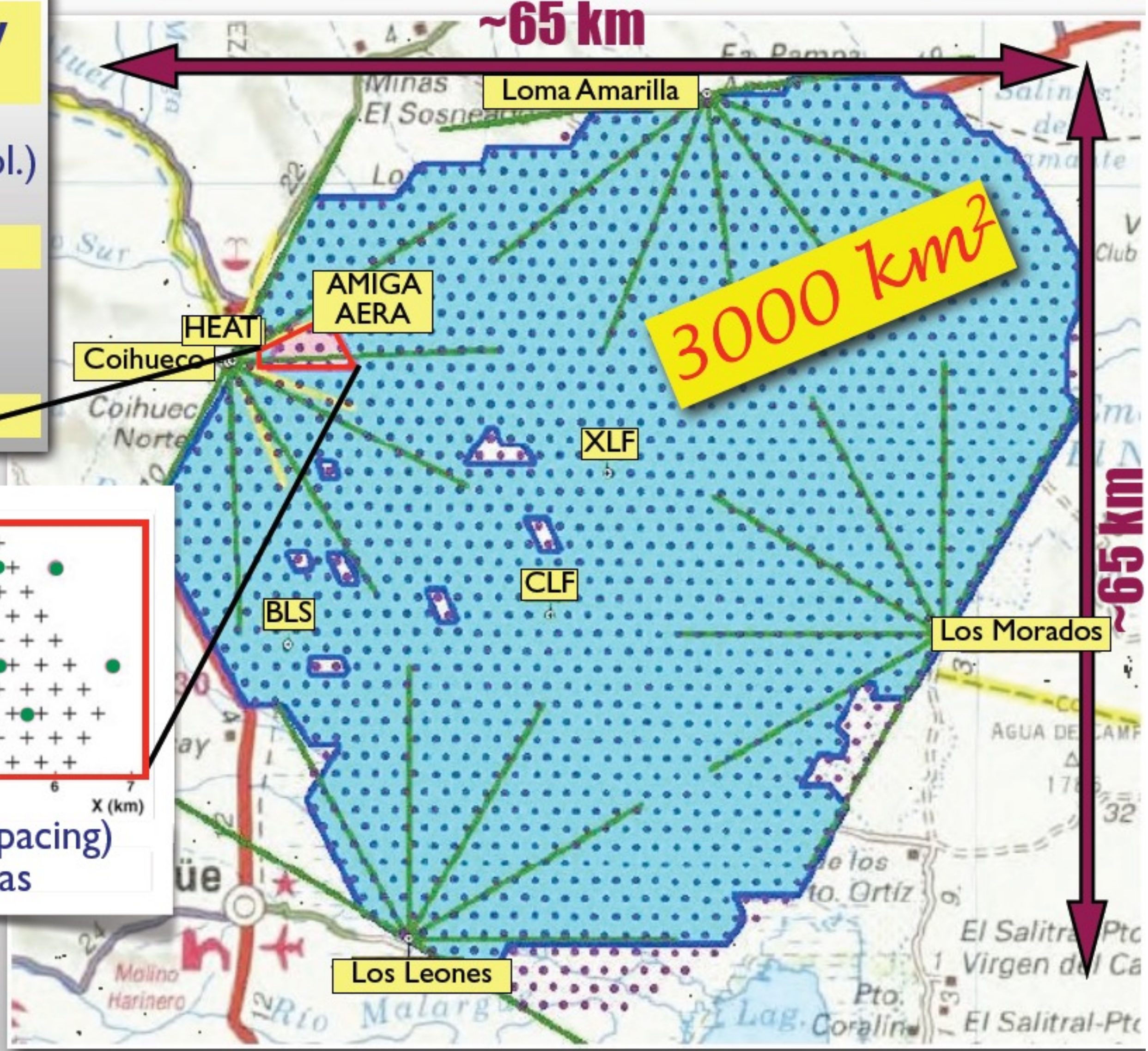
Energy [eV]		SD only
>	10^{18}	16000
>	10^{19}	5150
>	10^{20}	103

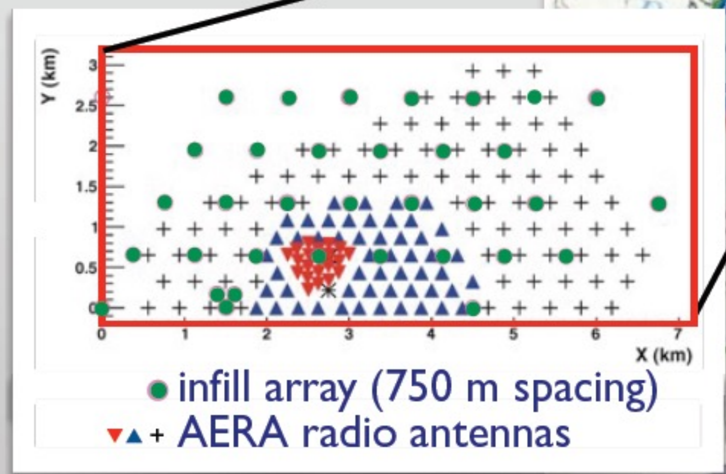
Pierre Auger Observatory in Argentina

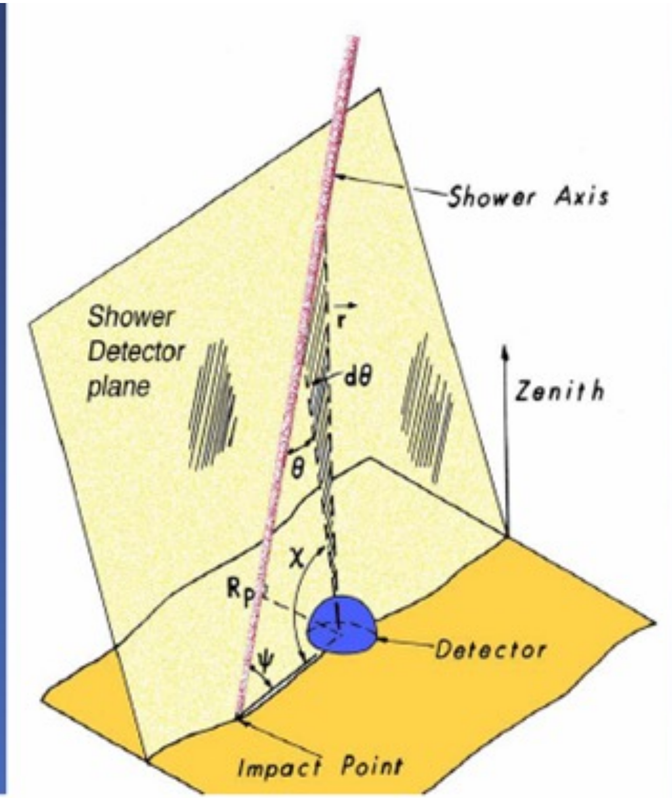
1660 Water-Cherenkov tanks
1.5 km standard grid
0.75 km infill-grid (53/61 depl.)

27 telescopes
in 4+1 buildings at the periphery

3000 km² area

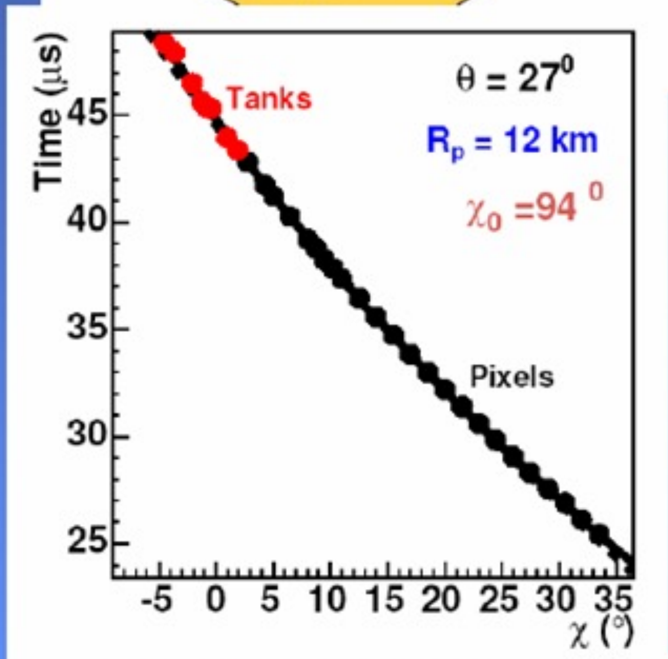


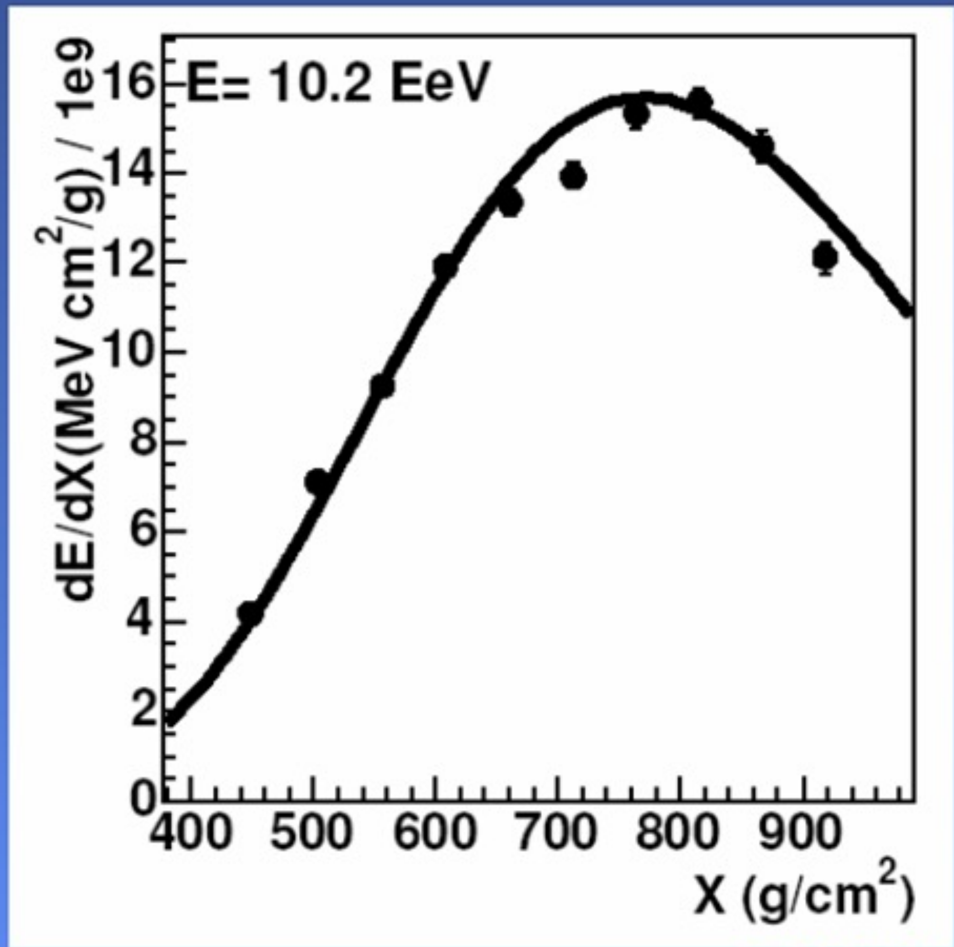


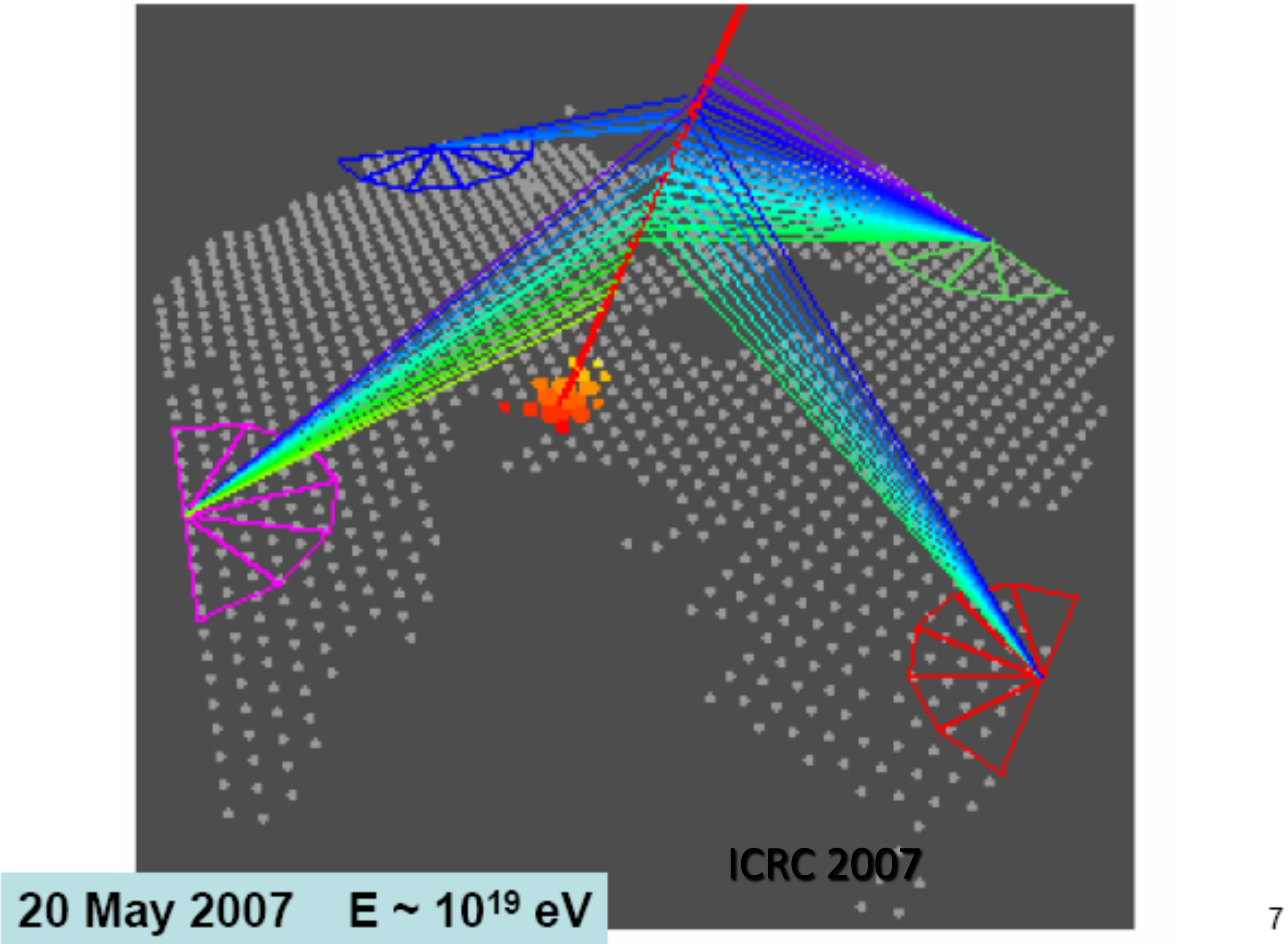


Hybrid Event (FD view)

A hybrid event – 1021302
Zenith angle ~ 30º, Energy ~ 10 EeV



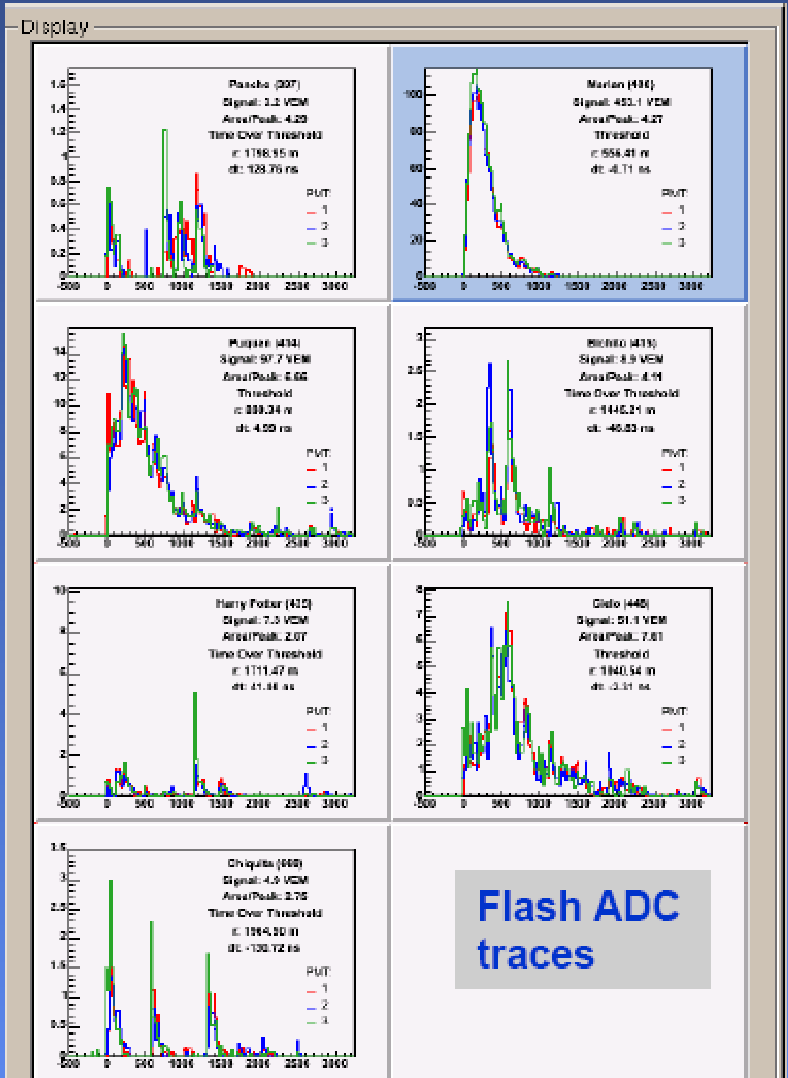


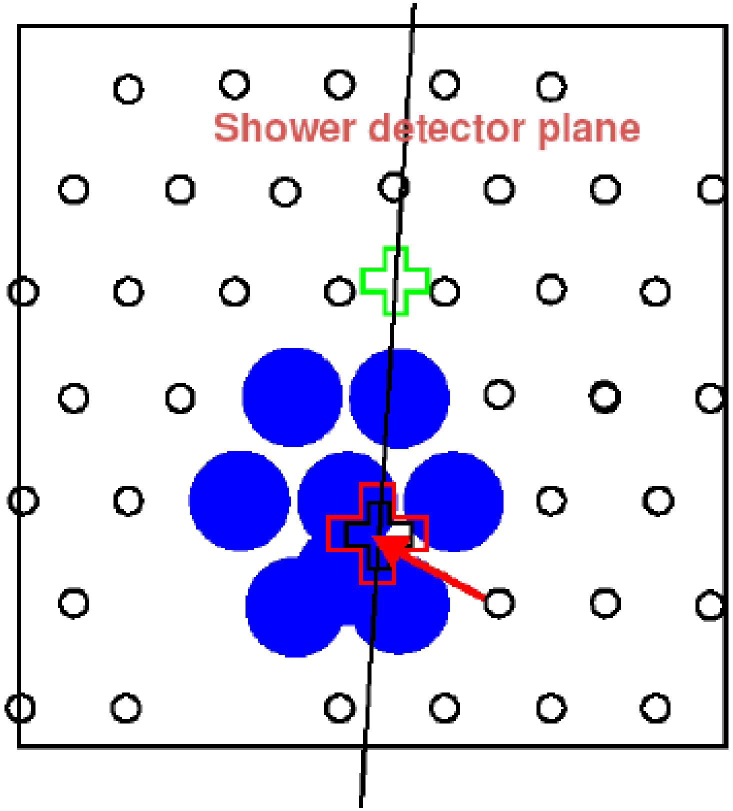


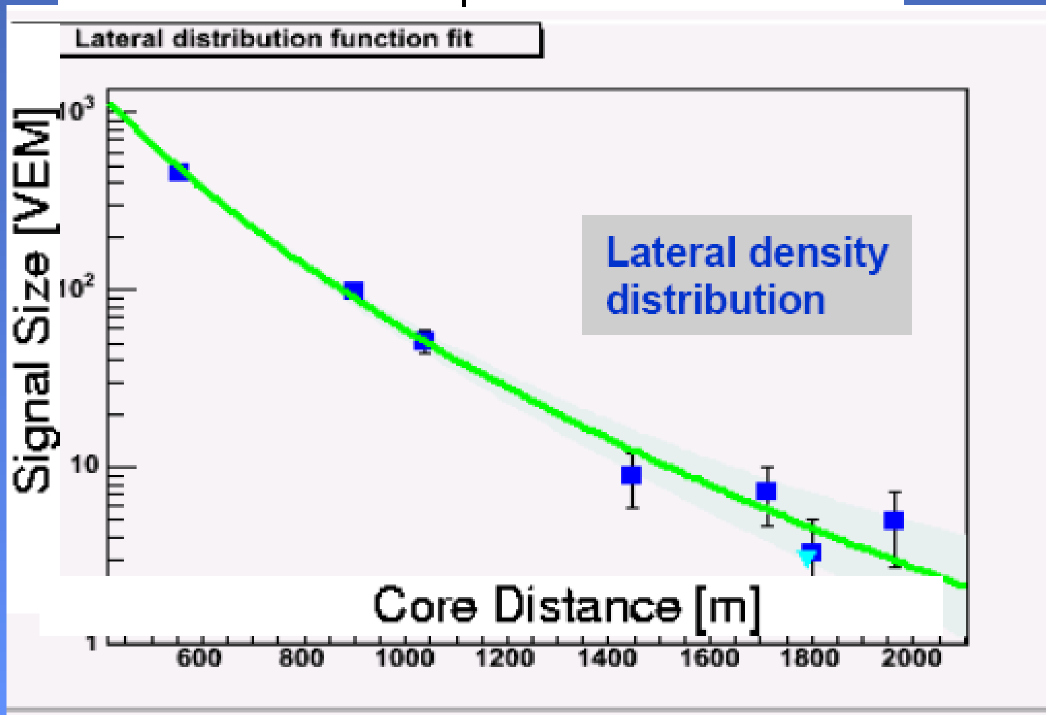
http://www.auger.org/

Hybrid Event (SD view)

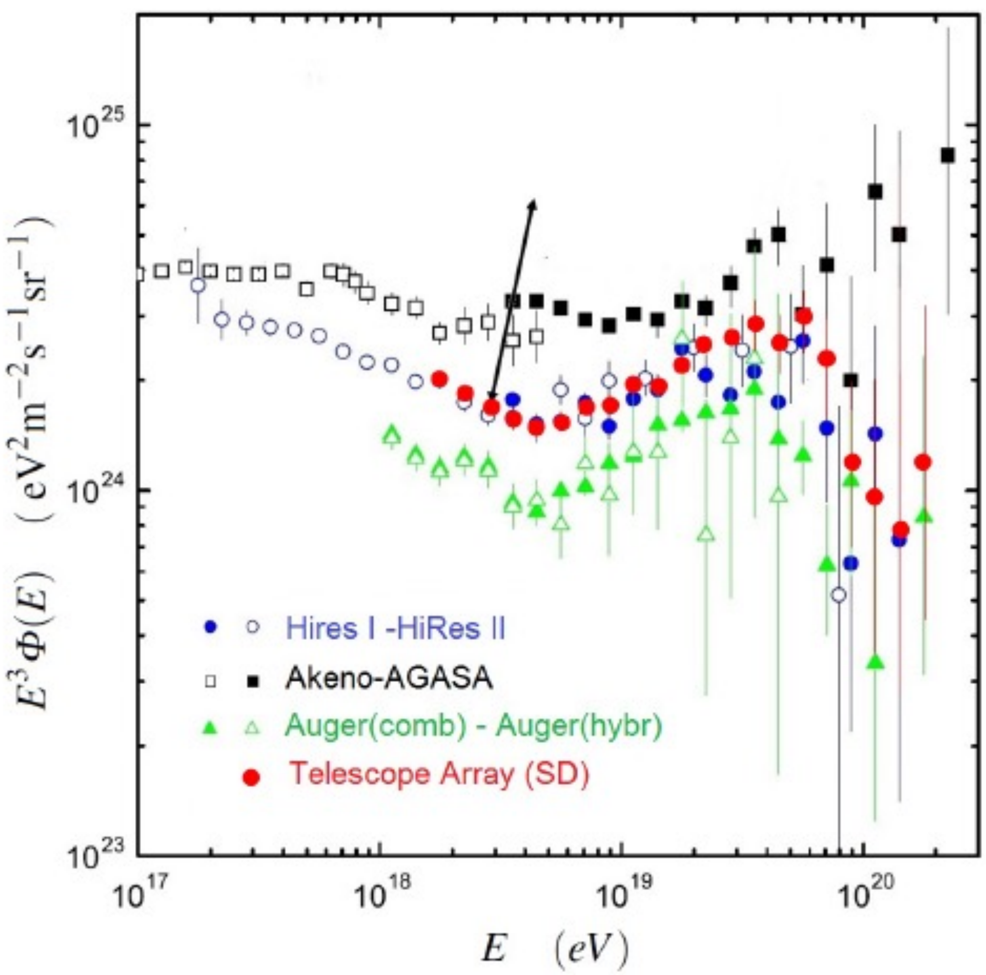
A hybrid event – 1021302
Zenith angle ~ 30º, Energy ~ 10 EeV







Comparison of Energy Spectra between the largest experiments

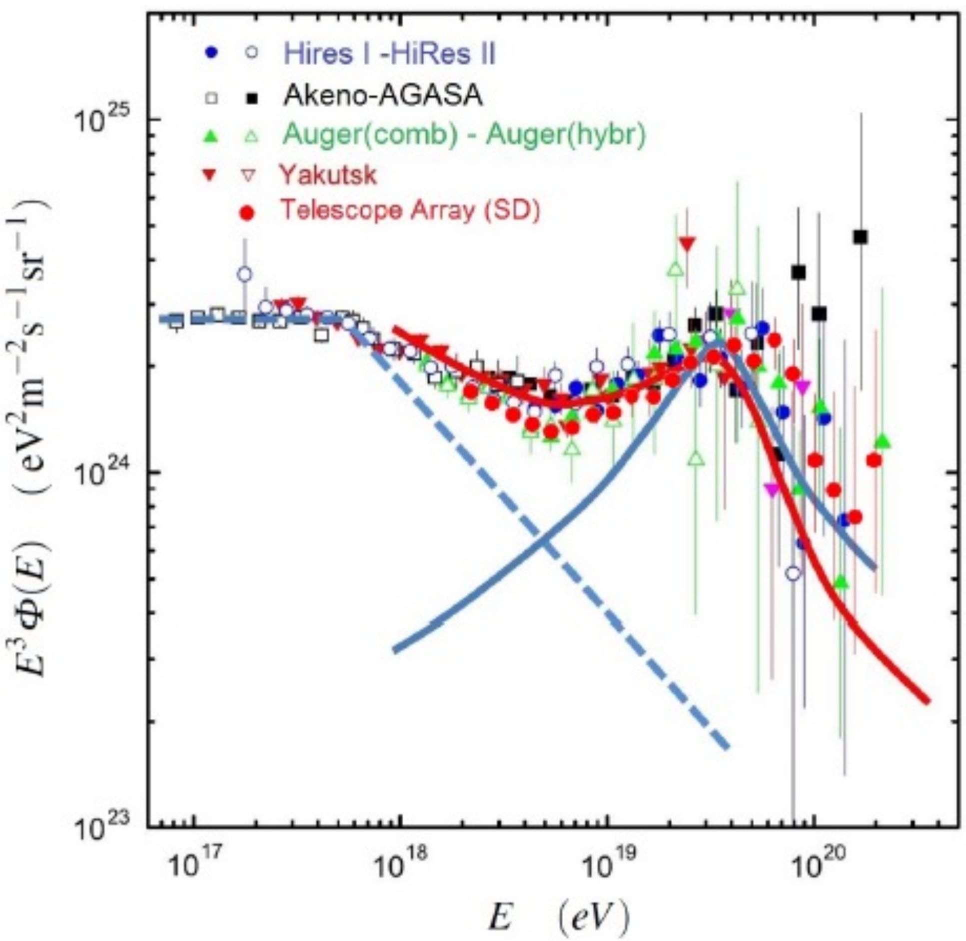


Flux of UHECRs multiplied by E^3 as measured by Akeno-AGASA, HiRes, Telescope Array and PAO.

The values as published by the Collaborations using the nominal calibration of the detectors are reported.

The end of the arrow on the first point of AGASA indicates the position of the point with a 25% shift in the energy scale

Possible source models



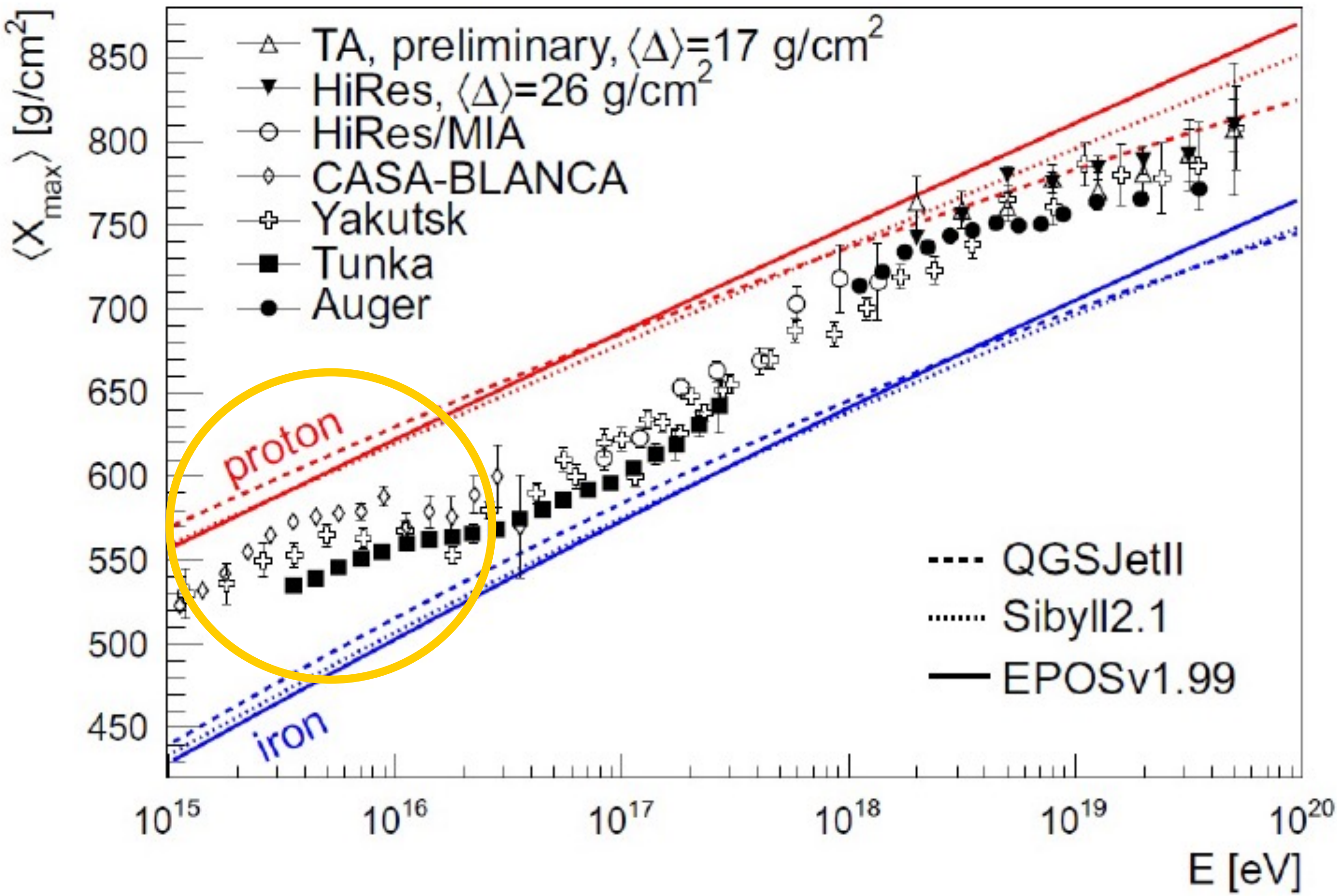
- The same data, after rescaling the energy of the experiments to obtain a common position of the "dip" at 5x10^{18} eV.
- The nominal energy scales multiplied by 1.2 (Auger), 1.0 (HiRes), 0.75 (AGASA), 0.95 (TA) and 0.625 (Yakutsk)

Predictions

- Red line: dip model due to extragalactic protons.
- Blue line: superposition model. A galactic (dashed line) + extra-galactic component (full line)

Composizione chimica dei RC nella regione degli EAS

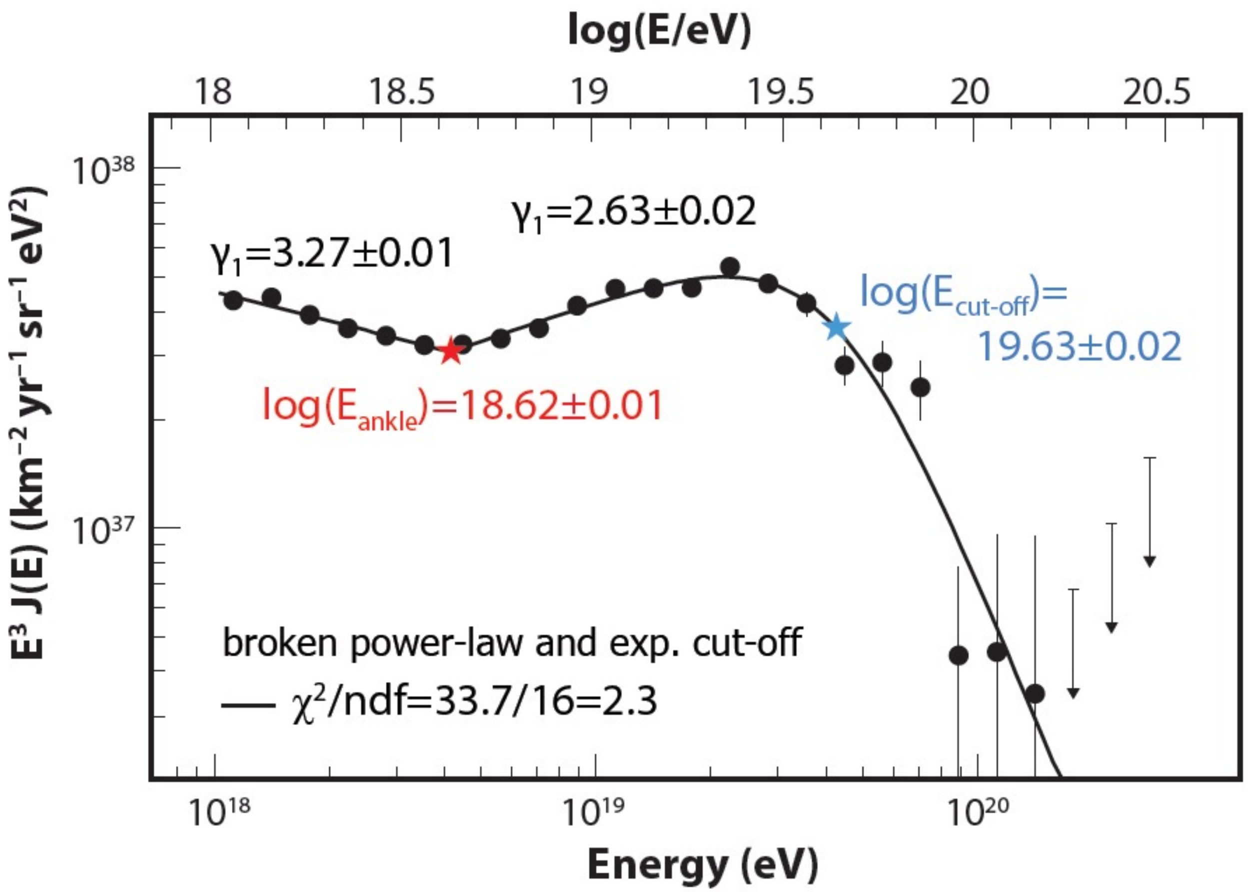
- Il modello del ***leaky box*** prevede un arricchimento di elementi pesanti nei RC sino al ginocchio.
- Gli EAS possono misurare <A> con difficoltà.
- Le misure possono essere poi confrontate con *modelli estremi* (solo p o Fe) via MC



AUGER Energy spectrum

SD+Hybrid Combined Spectrum

#893: Salamida
#724: Dembinsky



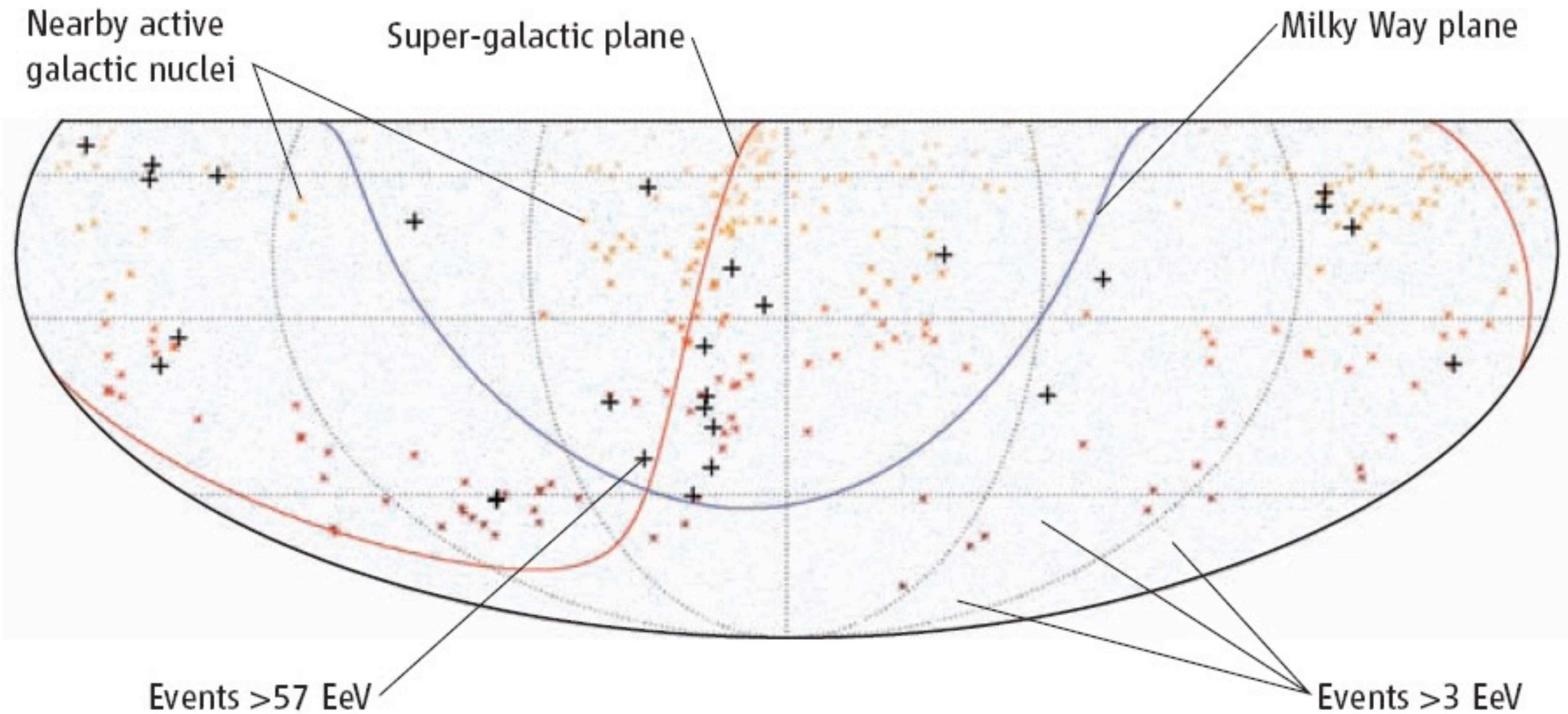
Exposure = 20905 km² sr yr (60% increase over PLB 685 (2010) 239)

Inclined showers add another 5300 km² sr yr (→ #724)

Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects

www.sciencemag.org on November 9, 2007

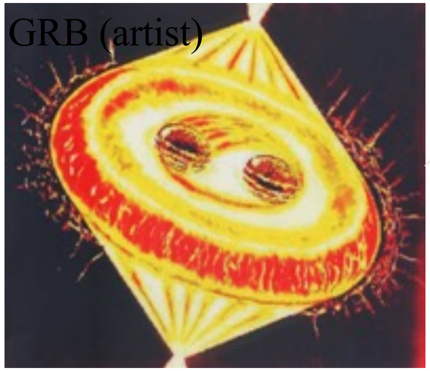
The Pierre Auger Collaboration*

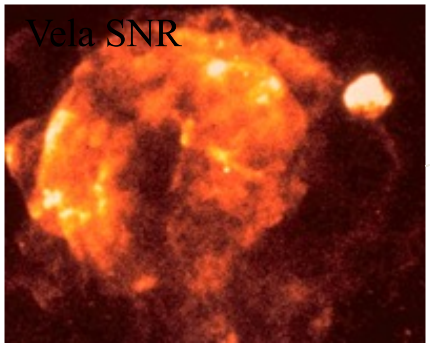


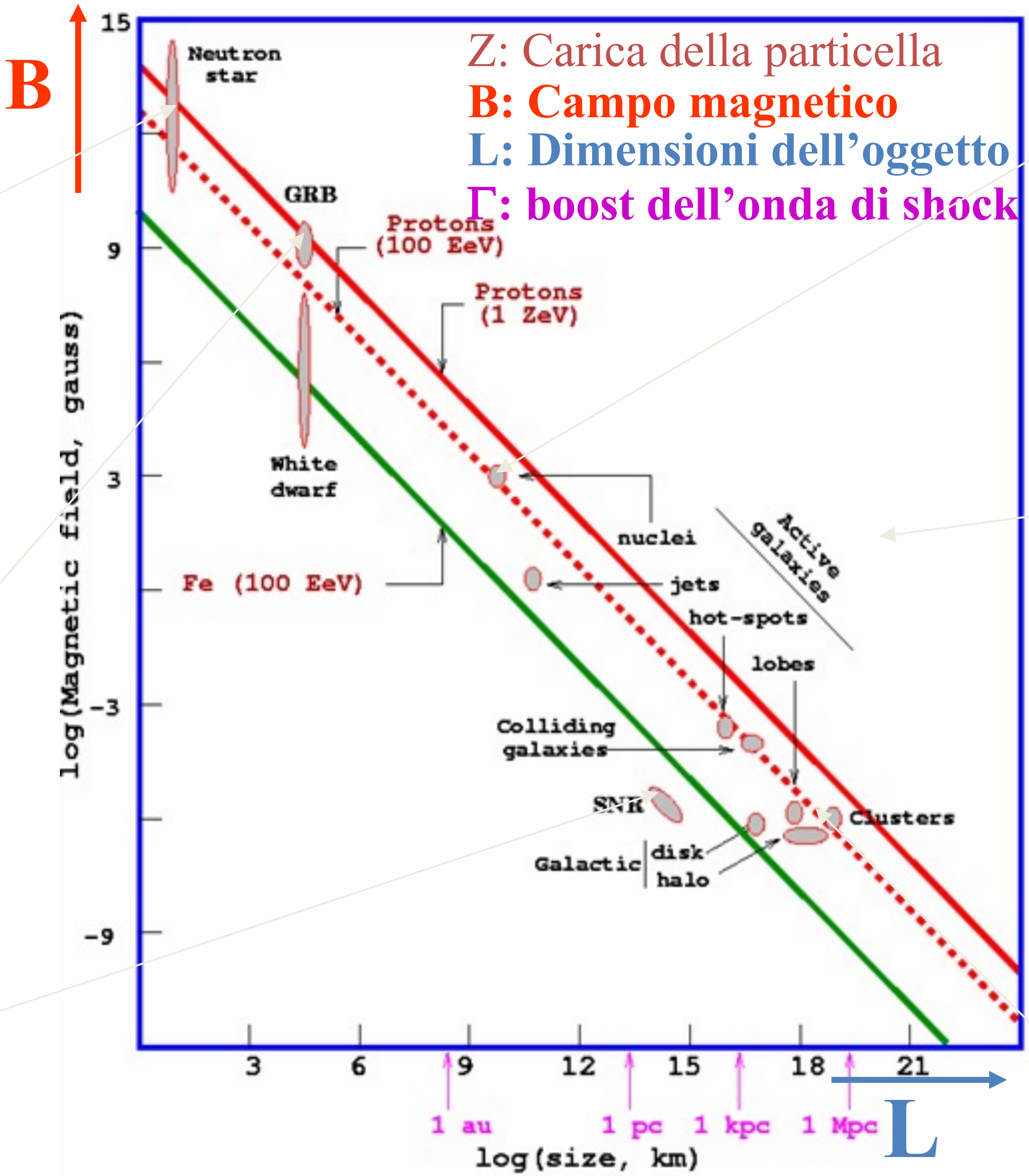
Sky map (2) showing cosmic rays detected by the Pierre Auger Observatory. Low-energy cosmic rays appear to originate from evenly distributed sources (blue dots), but the origins of the highest-energy events (crosses) correlate with the distribution of local matter as represented by nearby active galactic nuclei (red stars). Thus, active galactic nuclei are a likely source of these rare high-energy cosmic rays.

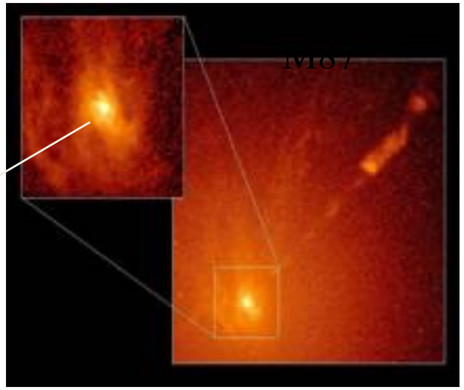
BREAKING NEWS 2009: AUGER trova una correlazione molto meno accentuata tra provenienza dei UHERC AGN

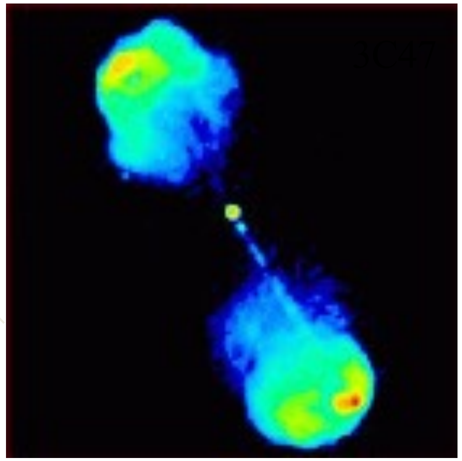
Possibili macchine acceleratrici

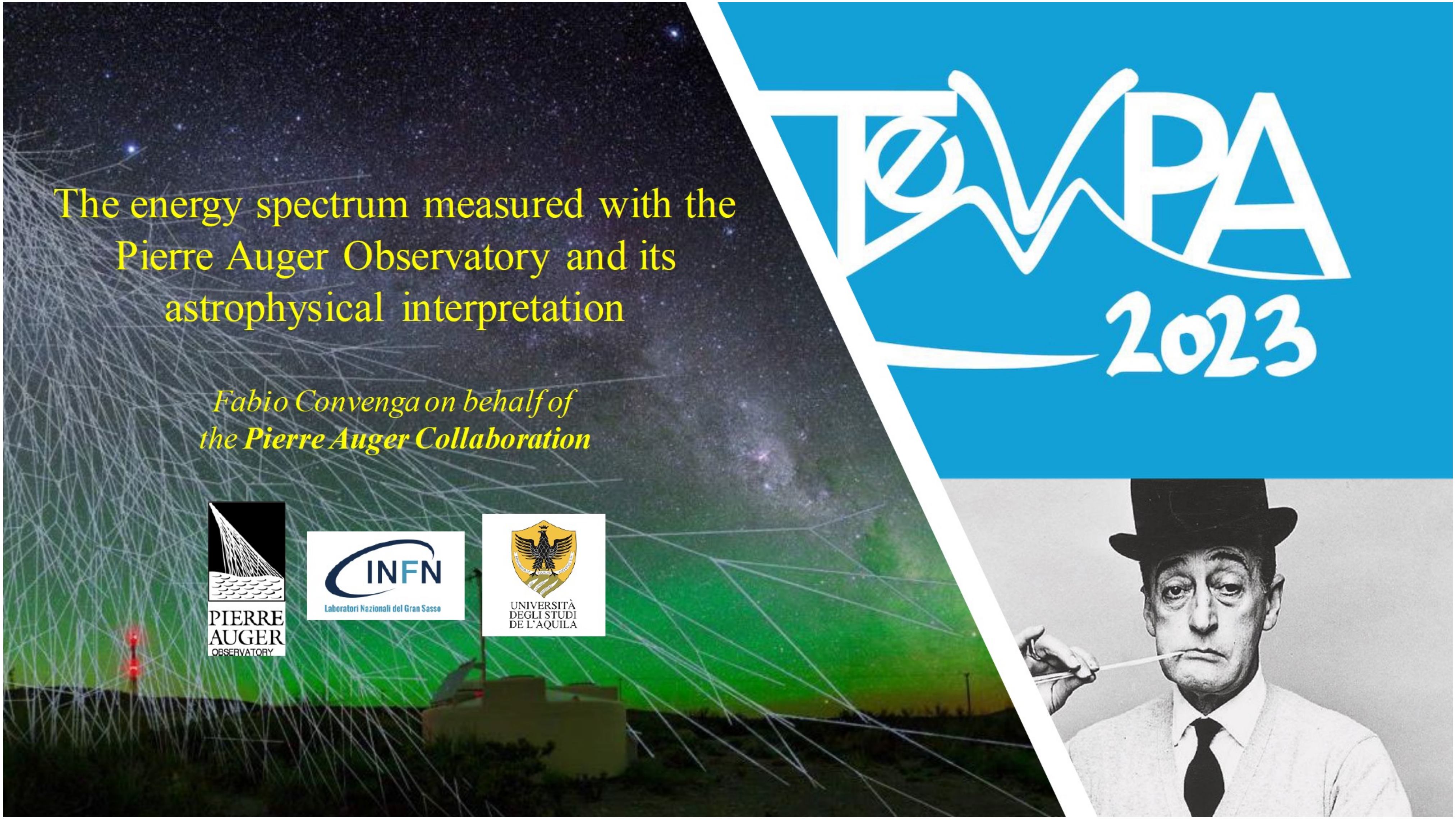






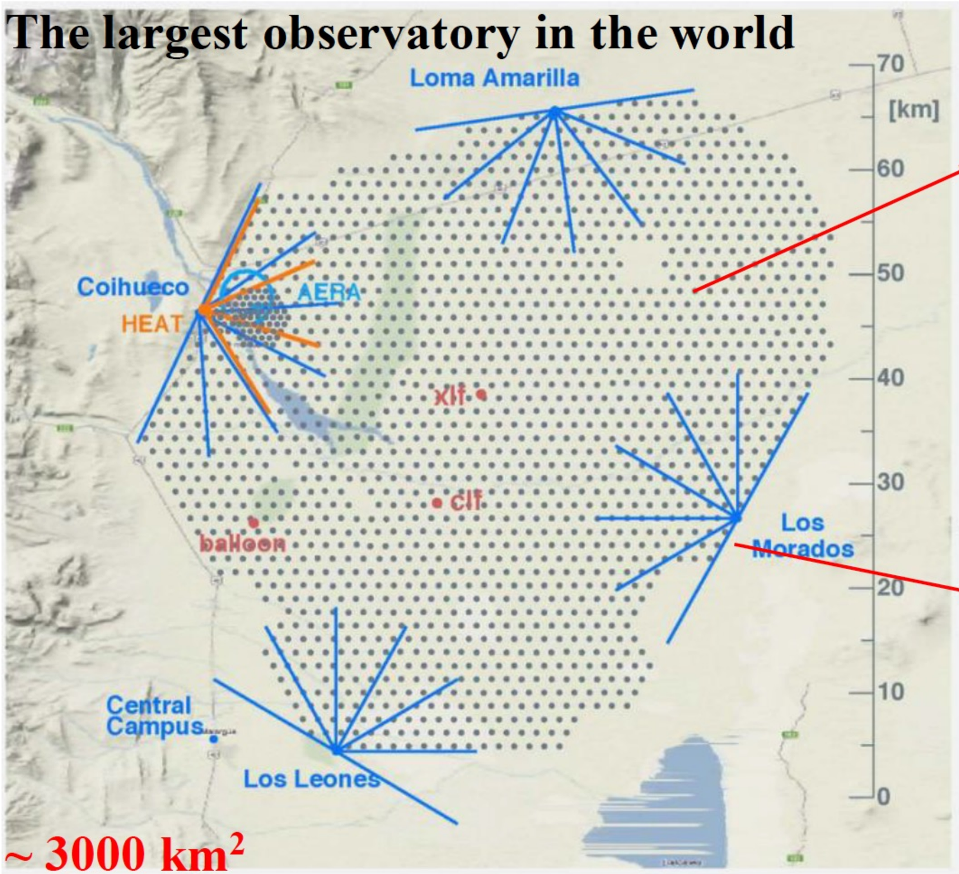





The energy spectrum measured with the Pierre Auger Observatory and its astrophysical interpretation
Fabio Convenga on behalf of the Pierre Auger Collaboration
PIERRE AUGER OBSERVATORY
INFN
Laboratori Nazionali del Gran Sasso
UNIVERSITÀ DEGLI STUDI DE L'AQUILA
TeVPA 2023

THE PIERRE AUGER OBSERVATORY

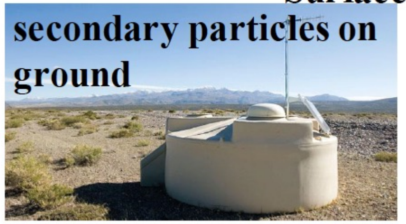
The largest observatory in the world



~ 3000 km^2

Extensive Air Showers (EAS) detection

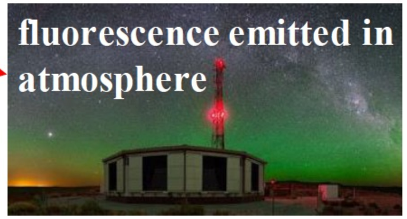
Surface Detector (SD)



- Cherenkov detectors
- 1600 station
- different spacing

SD1500	**SD750**	**SD433**
3000 km^2	23.5 km^2	1.9 km^2
1500 m grid	750 m grid	433 m grid
$E_{th} > 10^{18.4}$ eV	$E_{th} > 10^{17}$ eV	$E_{th} > 10^{16.8}$ eV

Fluorescence Detector (FD)



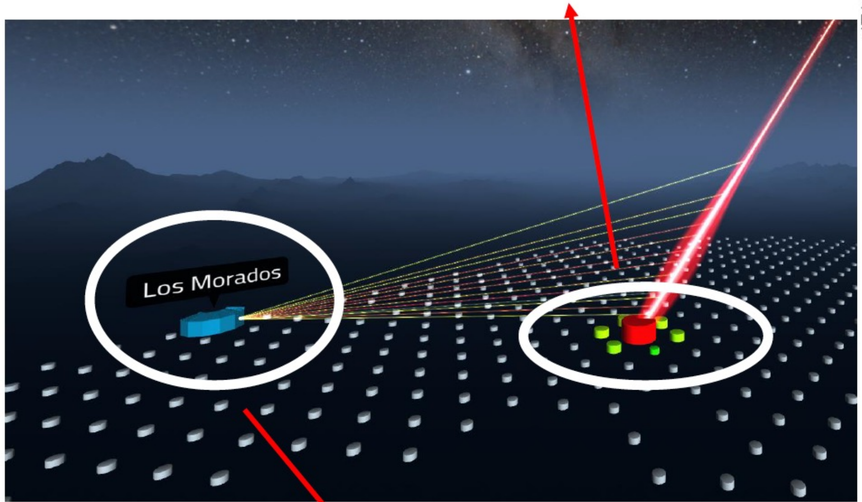
4 sites overlooking SD1500	*1 site overlooking SD750 – SD433*
24 telescopes Elevation 0-30° E>10^{18} eV	3 telescopes Elevation 30°-60° E> $10^{15.8}$ eV

Atmospheric monitoring
XLF, CLF
Lidars, cloud camera

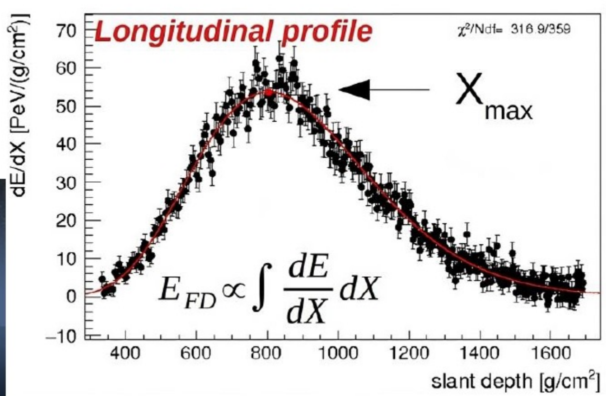
AugerPrime will add new detectors, station will become multi-hybrid instrument. (**I. Allekotte, TevPa2023**)

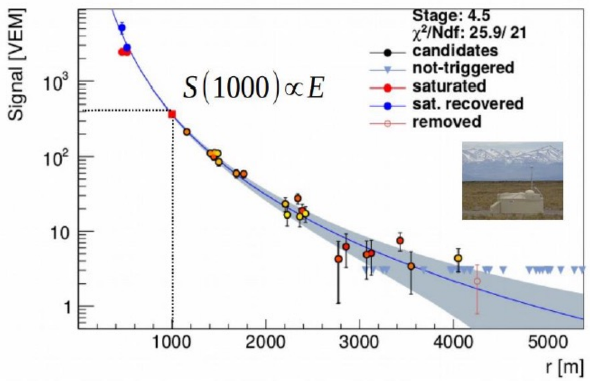
THE HYBRID DETECTION

Duty Cycle ~ 100%

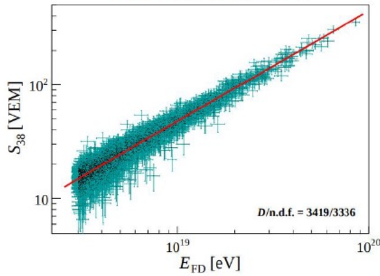


Duty Cycle ~ 13%





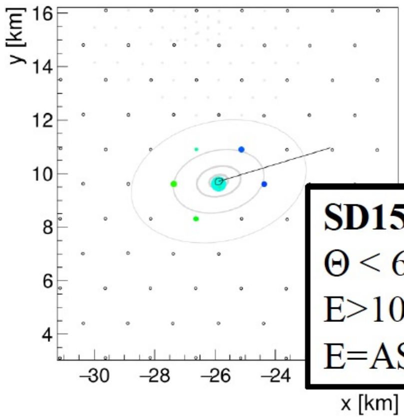
Hybrid energy calibration



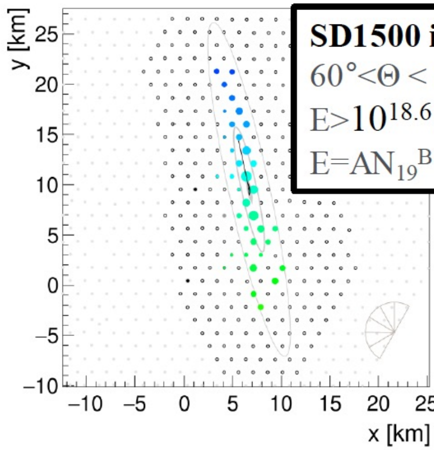
- Energy scale systematic uncertainty 14%
- Energy spectrum free of assumptions about hadronic physics

Energy resolution
20% $E \cong 3 \cdot 10^{18}$ eV
7% $E > 2 \cdot 10^{19}$ eV

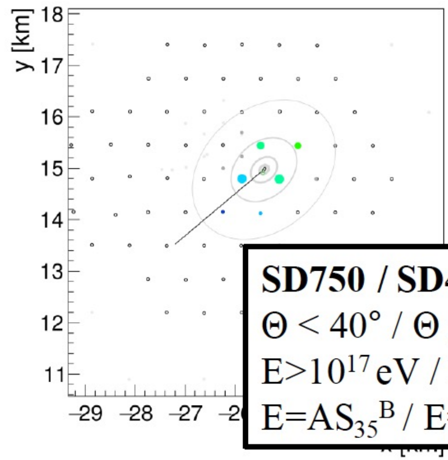
DIFFERENT SPECTRUM MEASUREMENTS



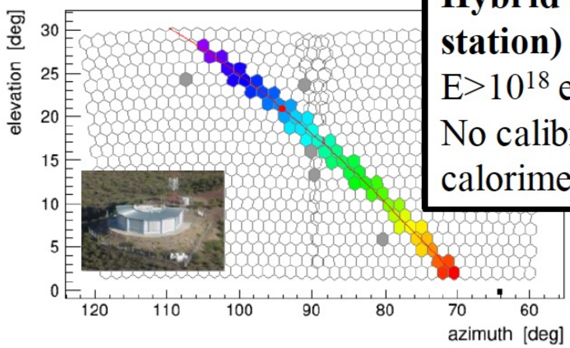
SD1500 vertical
Θ < 60°
E>$10^{18.4}$ eV
E=AS_{38}^{B}



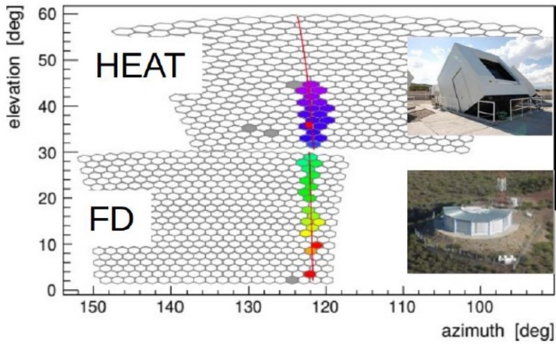
SD1500 inclined
60°<Θ < 80°
E>$10^{18.6}$ eV
E=AN_{19}^{B}



SD750 / SD433
Θ < 40° / Θ ≤ 45°
E>10^{17} eV / E>$10^{16.8}$ eV
E=AS_{35}^{B} / E=AS_{30}^{B}



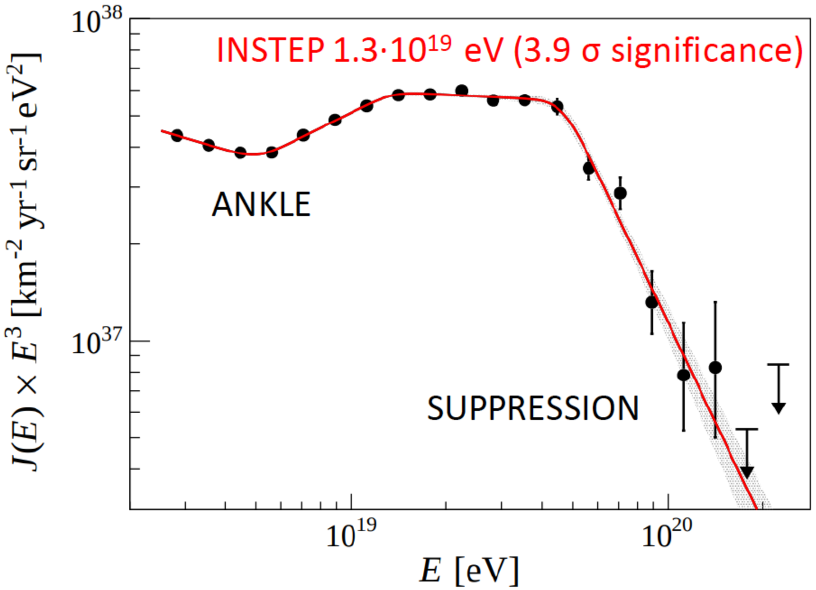
Hybrid (FD+1 SD station)
E>10^{18} eV
No calibration, calorimetric estimate

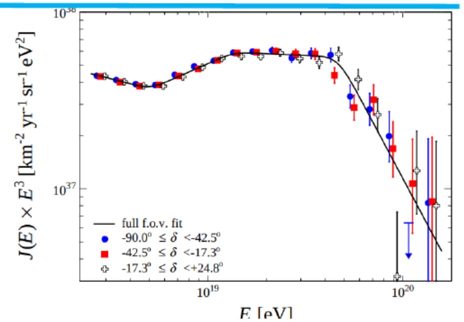


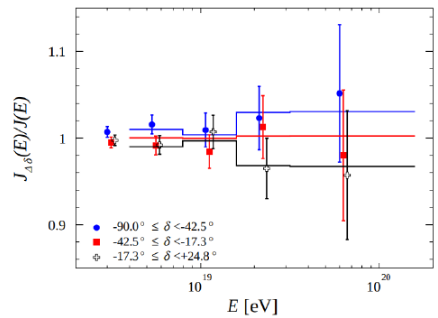
Cherenkov
E>$10^{15.8}$ eV
No calibration, calorimetric estimate

SD1500 VERTICAL SPECTRUM (Θ < 60°)

- High statistics of events reconstructed by SD1500
- From SD only energy estimator S(1000)
- **Correction of the attenuation** in atmosphere from S(1000) to S_{38}
- Calibrate the energy estimator with hybrid events (SD+FD reconstructions)
- Full efficiency above $10^{18.4}$ eV
- **Unfolding with resolution and bias from FD data**







Highest statistics for the spectrum achieved so far

New features: **instep**

No (strong) declination dependence observed, Mild southern excess from dipole anisotropy

Removal of most model dependencies

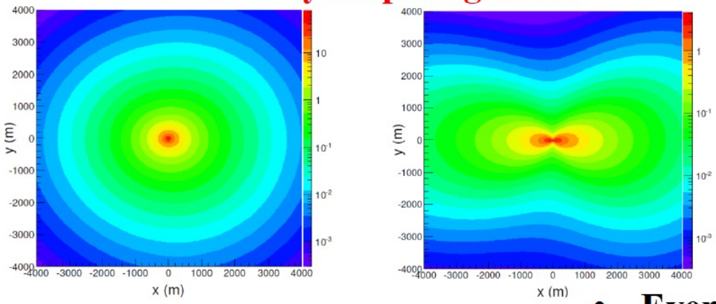
Suppression confirmed $4.6 \cdot 10^{19}$ eV

Ankle confirmed

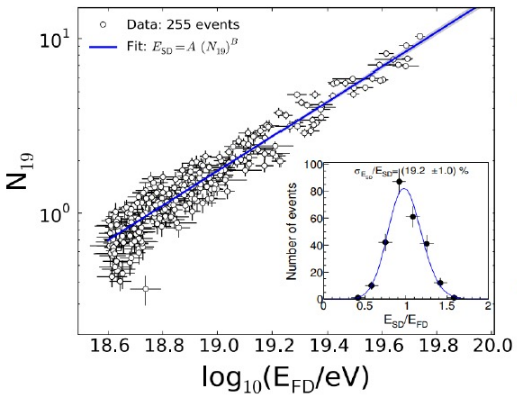
Reference:
[Phys. Rev. D 102, 062005 (2020)]

SD1500 INCLINED SPECTRUM (60°<Θ < 80°)

Muon density map on ground

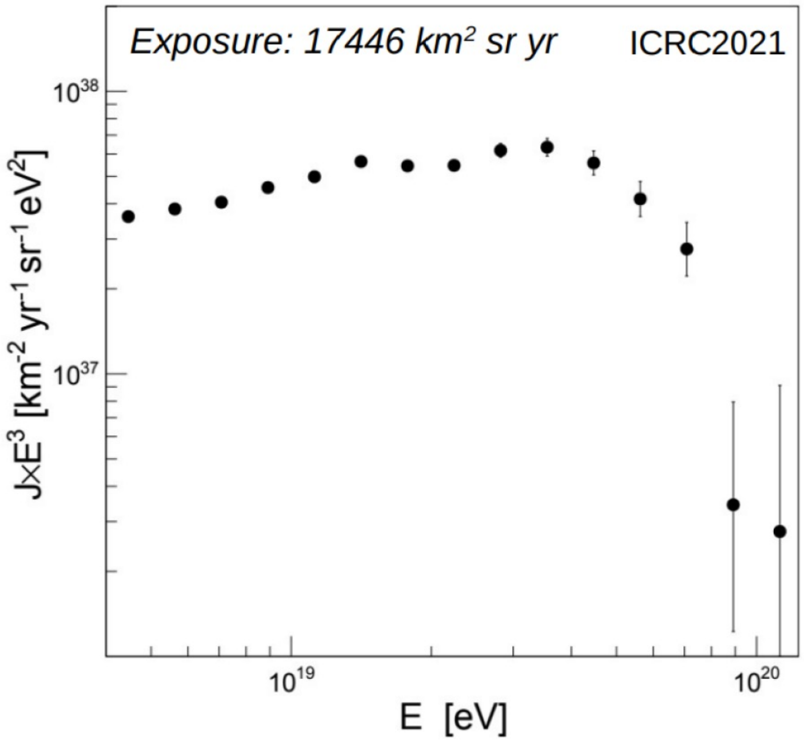


Calibration with Hybrid events



N_{19} measure of the shower size: relative normalization with respect to a MC ground muon distribution

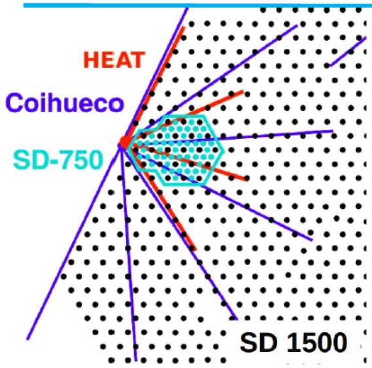
- **Events dominated by muonic component** (EM component is attenuated)
- Shape of the muon distribution is approximately universal for a given shower direction
- only the overall normalisation of the muon distribution depends on the shower energy and primary mass
- Fully efficient for E>$10^{18.6}$ eV



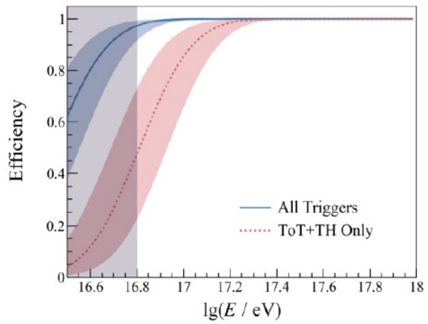
$$\rho_\mu(\vec{r}) = N_{19}\ \rho_{\mu,19}(\vec{r};\theta,\phi)$$

Reference:
JCAP 08 (2015) 049

SD750 – SD433 SPECTRA

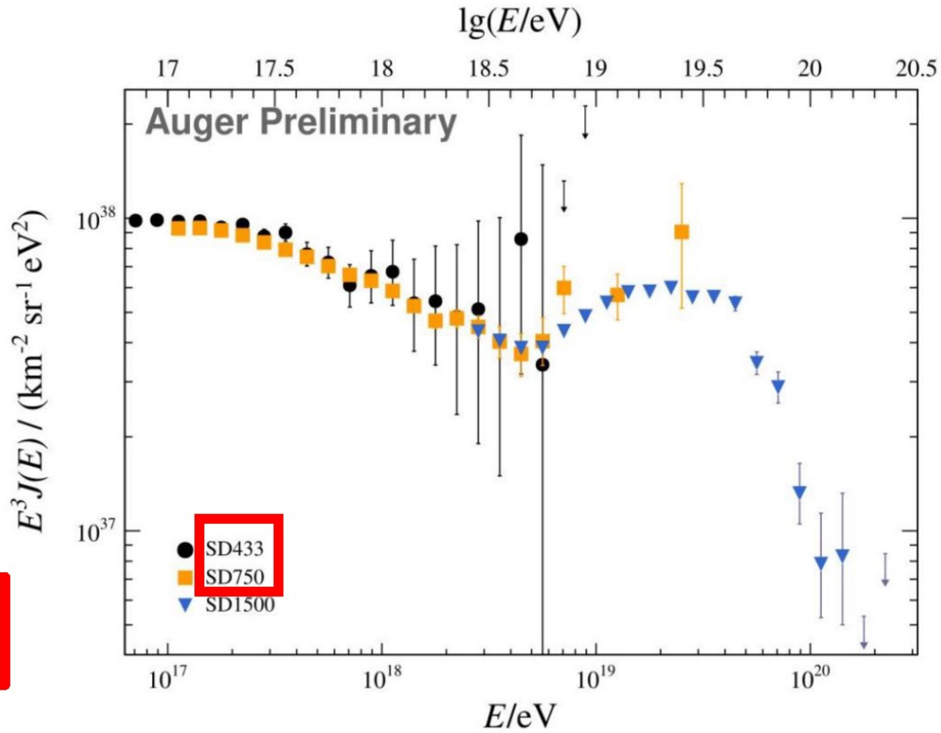


- Low energy triggers used



SD750	SD433
Calibration with high elevation FD	Calibration with events reconstructed with SD750 and SD433
Fully efficient 10^{17} eV	Fully efficient $10^{16.8}$ eV
Energy estimator S(450) -> S_{35}	Energy estimator S(300) -> S_{30}

Combination fundamental to study the galactic to extragalactic transition



Reference:
Eur. Phys. J. C (2021) 81:966

Reference:
POS(ICRC2023)398

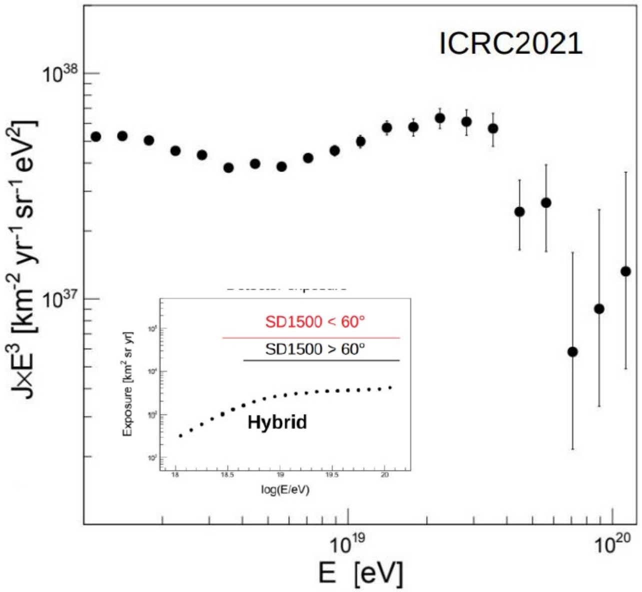
HYBRID – CHERENKOV SPECTRA

- Spectrum using the **FD + 1 SD station**
- Single SD station triggered to **constrain geometry of the shower**
- E>10^{18} eV

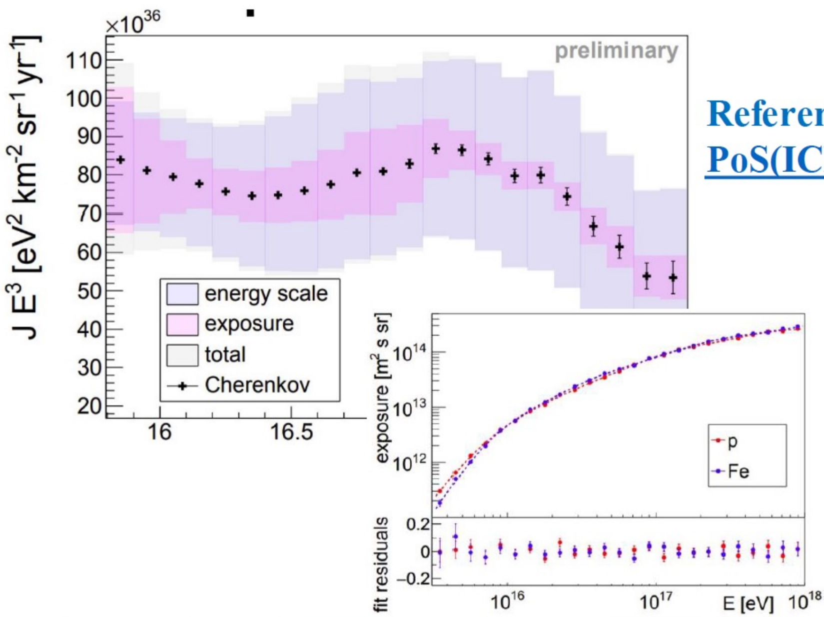
No SD counterpart: monocular mode only

Lower the energy threshold to $10^{15.8}$ eV

Geometry determined with a constraint on the shower profile

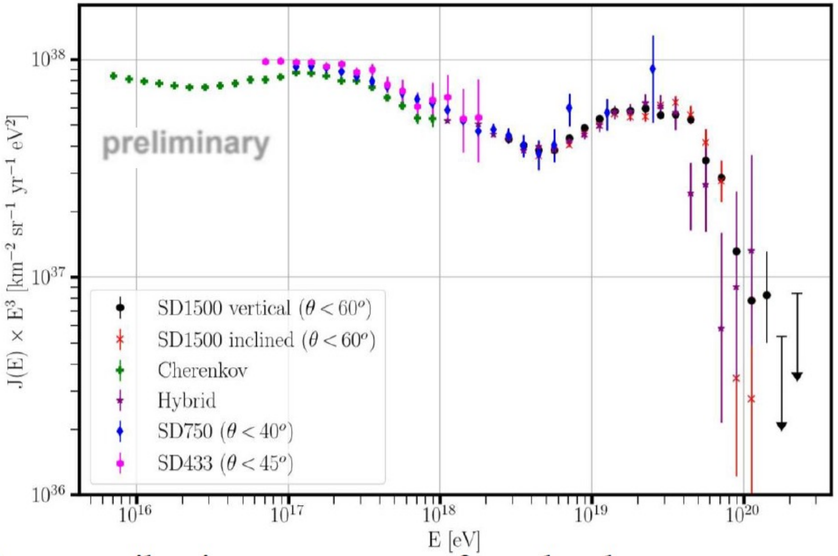


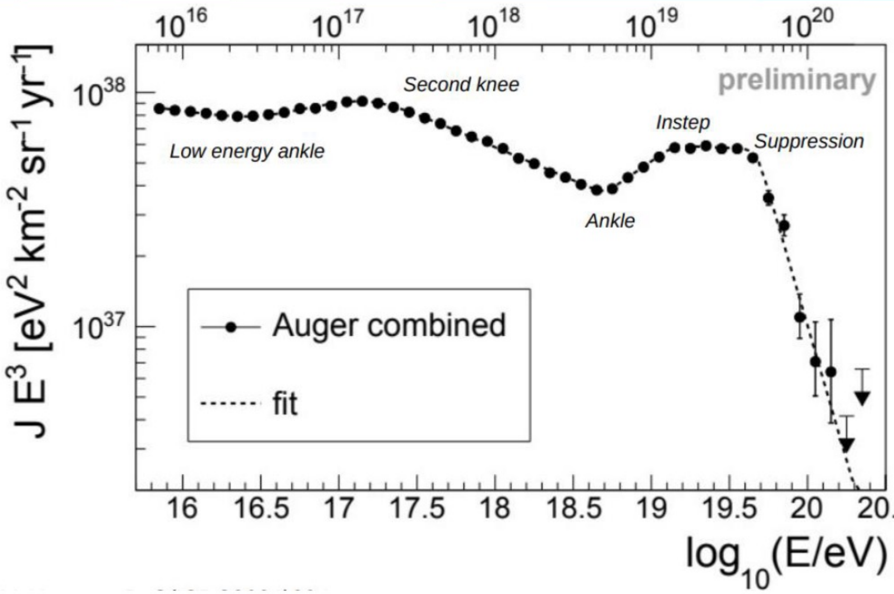
Reference: [EPJ Plus (2012) 127: 87]



Reference: [PoS(ICRC2021)324]

COMBINED SPECTRUM





The contributing spectra are found to be in agreement within their uncorrelated systematic uncertainties

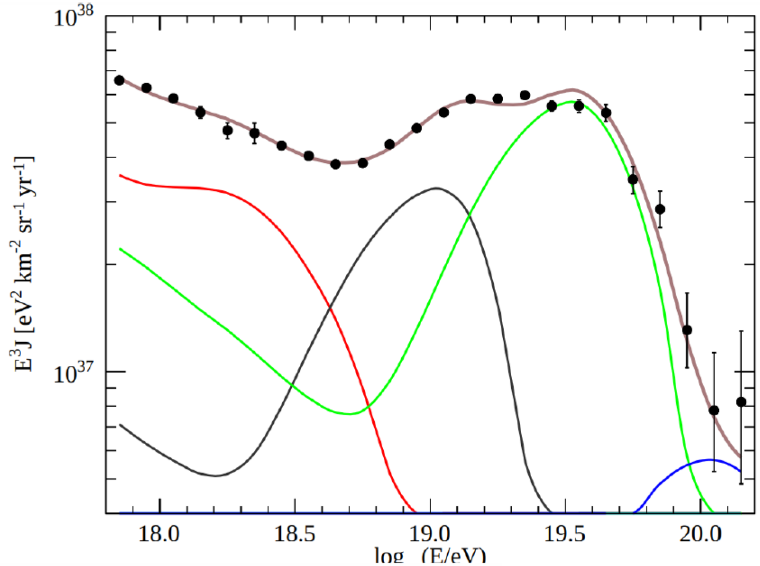
Overall fit of all the spectra accounting for systematics on exposure and energy

Reference: [**PoS(ICRC2021)324**]

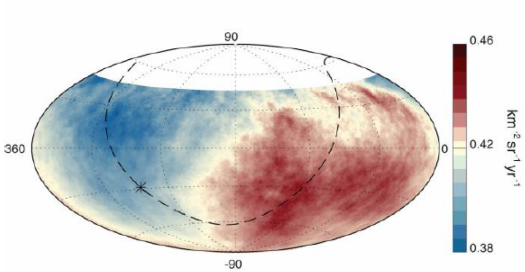
$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}\ \mathrm{km^{-2}sr^{-1}yr^{-1}eV^{-1}}$

		$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
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	$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

INTERPRETATION



- Above the **ankle**: mixed composition with a hard spectrum and a low rigidity cutoff
- Below the **ankle**: component with very soft spectrum and a mix of protons and intermediate-mass nuclei
- **Instep**: interplay between He and CNO components
- GZK* only scenario disfavored (**Phys. Rev. Lett. 16, 748 (1966)**)
- **Suppression**: combination of maximum accelerator energy + propagation effects



Extragalactic origin above 8 EeV: proven with arrival direction distribution (**E. Martins, TeVPa2023**)

AugerPrime will allow the measurement of the mass composition beyond the present limit, testing the presence of a possible sub-dominant light contribution at the highest energies .

Reference:
[Phys. Rev. Lett. 125, 121106 (2020)]

Recent UHECR results and their interpretation

Denise Boncioli

Università degli Studi dell'Aquila, Dipartimento di Scienze Fisiche e Chimiche
INFN-LNGS

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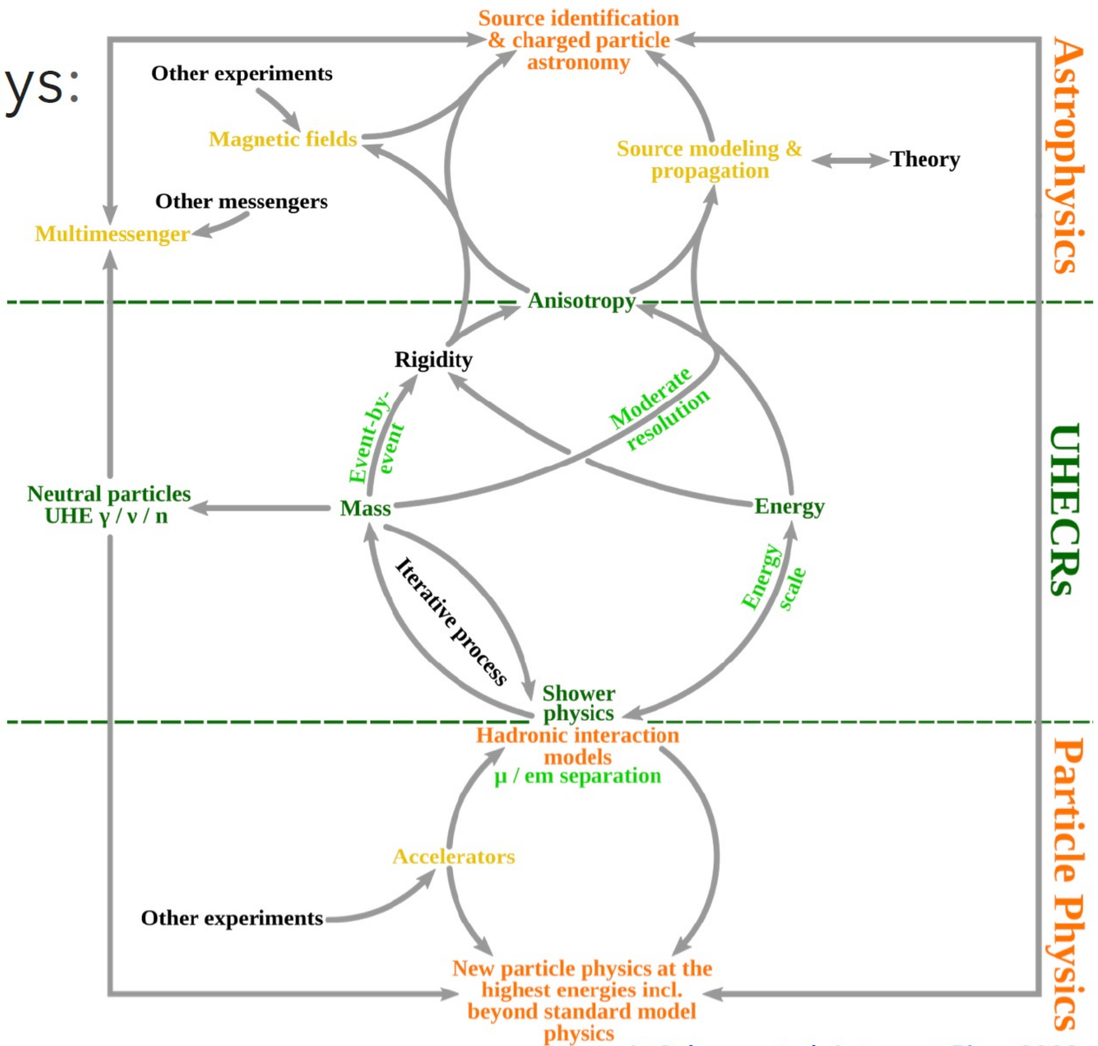
TeVPA Conference,
Napoli, September 11-15, 2023

Ultra-High-Energy Cosmic Rays:

a field of… connections!

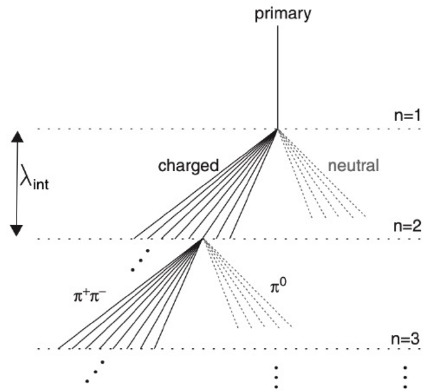
- The observables:
  - Energy, mass, arrival direction
- The messengers:
  - Cosmic Rays, Neutrinos, Photons, …
- Physics:
  - Astrophysics, Particle Physics, Physics beyond the Standard Model…



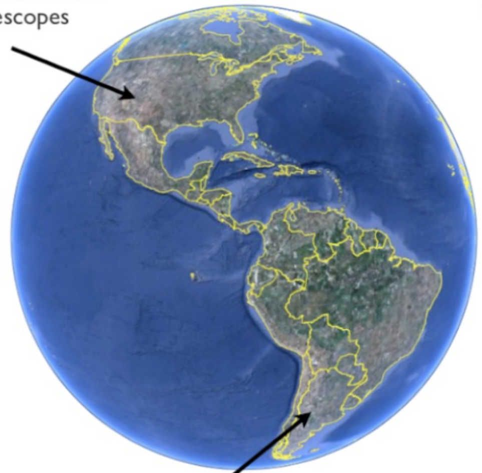
A. Coleman et al. Astropart. Phys. 2023

2

THE ERA OF **GIANT OBSERVATORIES**

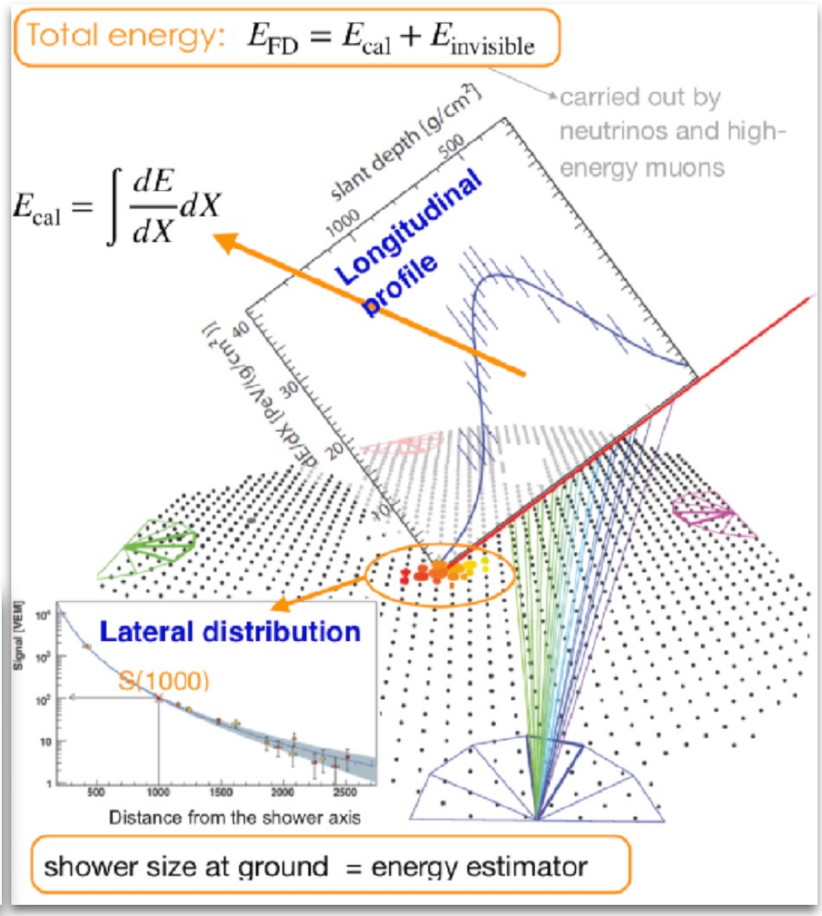


Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes



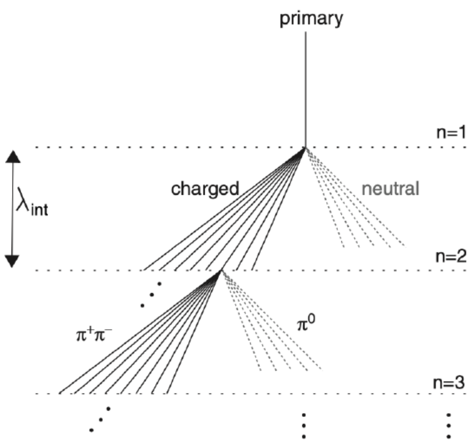
Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

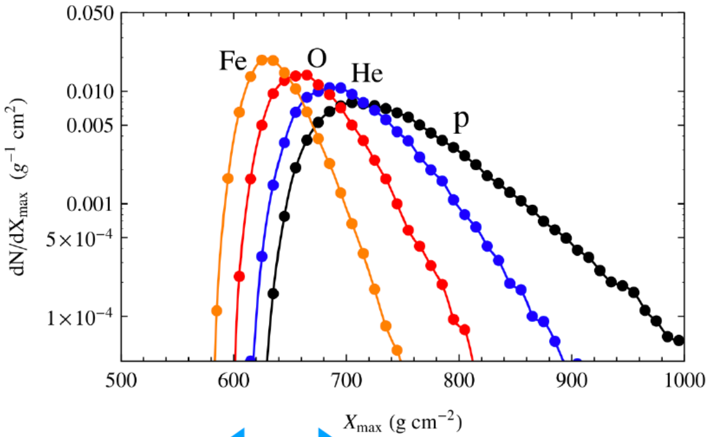
3



BELIEVES FROM THE PAST AND CURRENT EVIDENCES

ONE EXAMPLE: THE **UHECR MASS COMPOSITION**





$$X_{\max} \propto \ln(E_0/E_c)$$

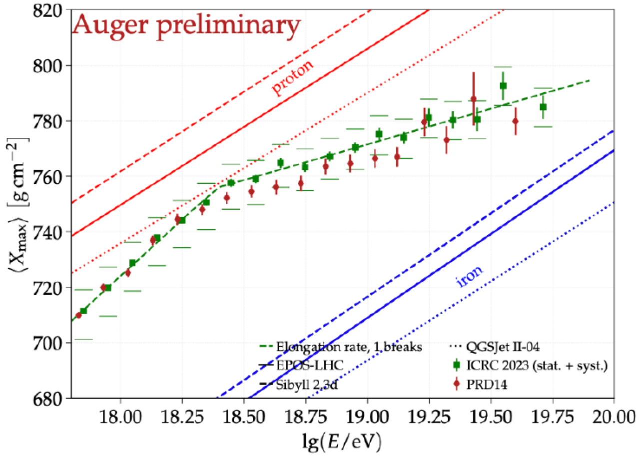
$$^{A}X, E_0 \leftrightarrow A \times n, E_0/A$$

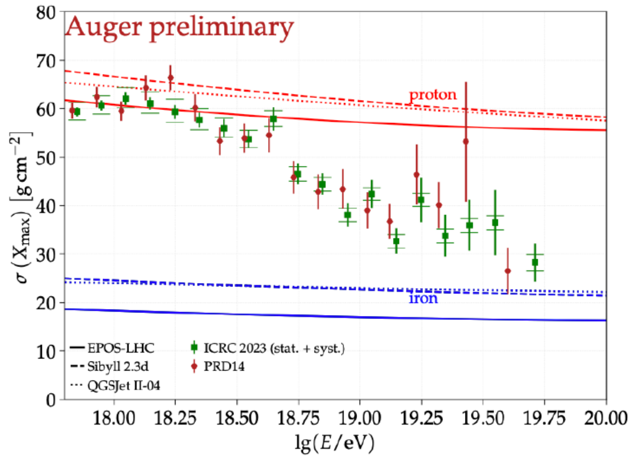
$$X^{A}_{\max} \propto X_{\max}(E_0/A)$$

Evidences:

- First momentum: elongation rate is not constant
- Second momentum: fluctuations decrease

The Pierre Auger Collab. ICRC23





- See A. Watson EPJ Web Conf. 2023 for a historical overview about composition measurements

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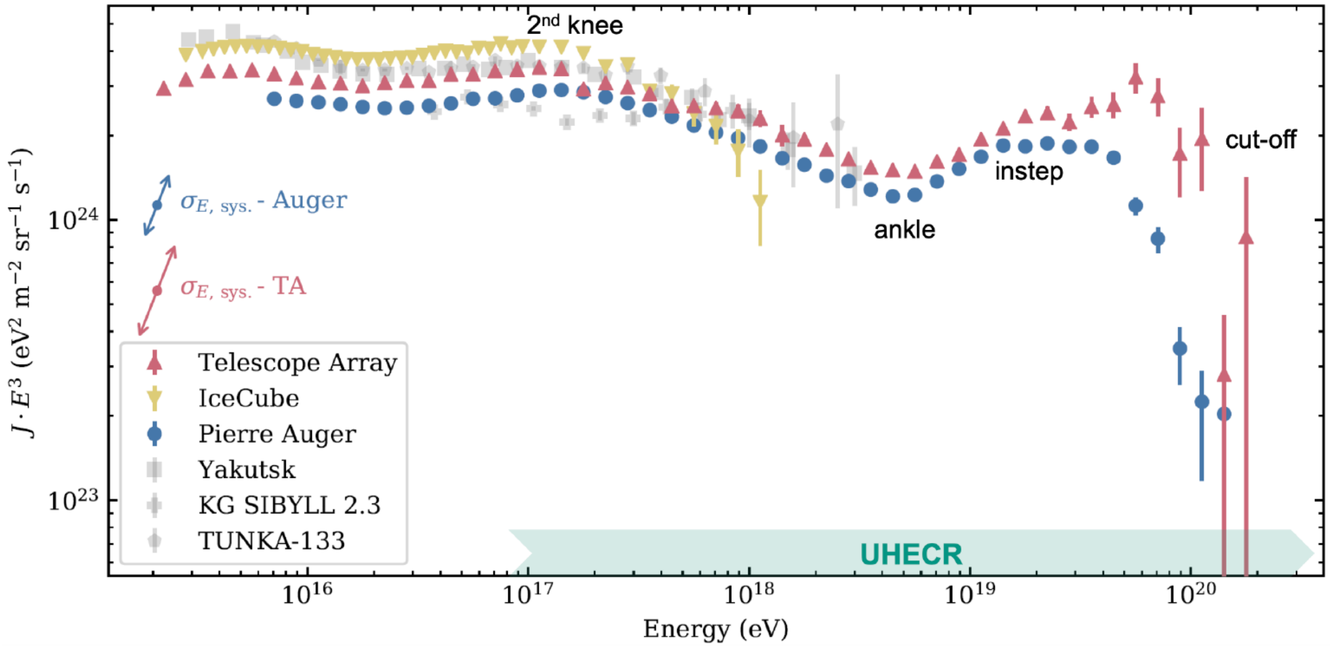
THE UHECR ENERGY SPECTRUM

Talks by **K. Fujisue** and **F. Convenga**:
Wed, CCR session



Origin of inflection points: imprints of:

- Extragalactic propagation?
- Power of sources?
- Distribution of sources?
- Transition from Galactic to extragalactic contribution?

A. Coleman et al. Astropart. Phys. 2023

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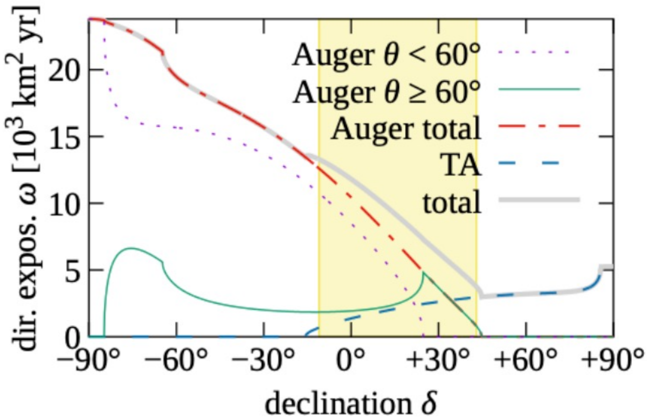
THE UHECR ARRIVAL DIRECTIONS

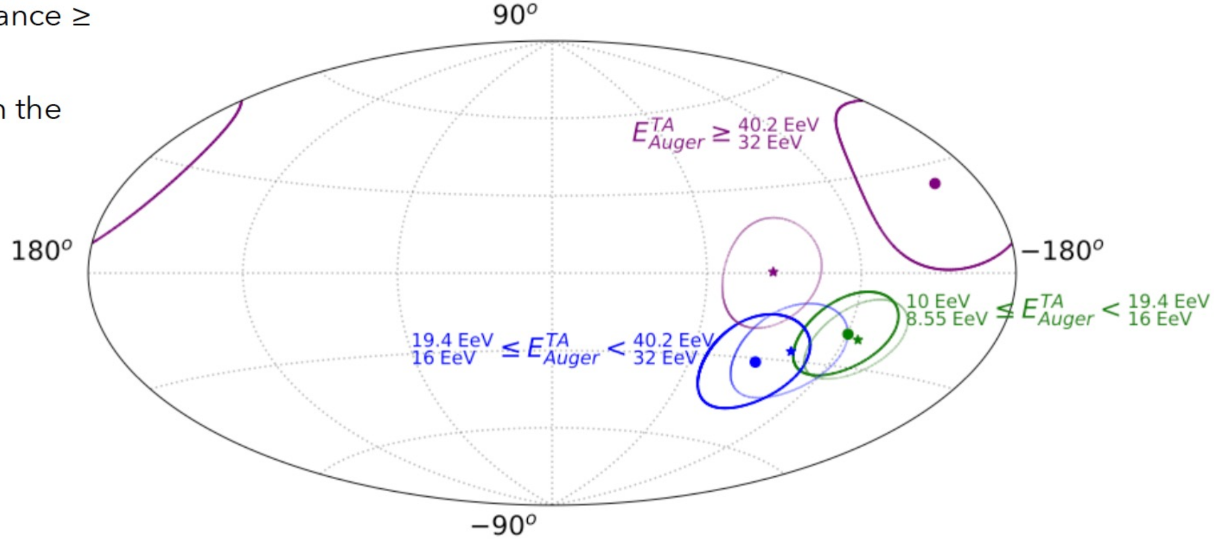
Telescope Array and Pierre Auger Collab. Joint WG on Arrival Directions, ICRC23

Talks by **K. Fujisue** and **E. Martins**, Wed, CCR session

- Full sky coverage thanks to Auger + TA
- Anisotropy detected with statistical significance ≥ 5 sigma: **modulation in right ascension**
  - Dipole pointing 114 degrees away from the Galactic center

-> extragalactic origin of UHECRs



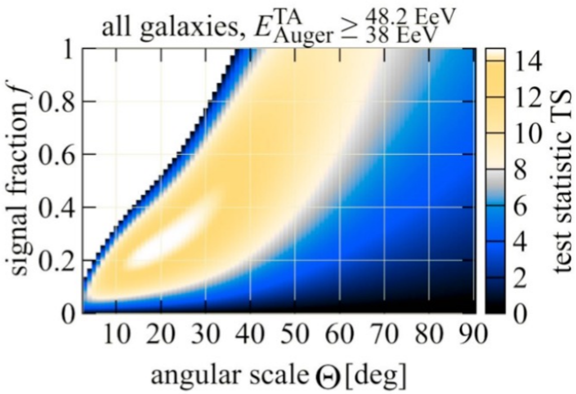


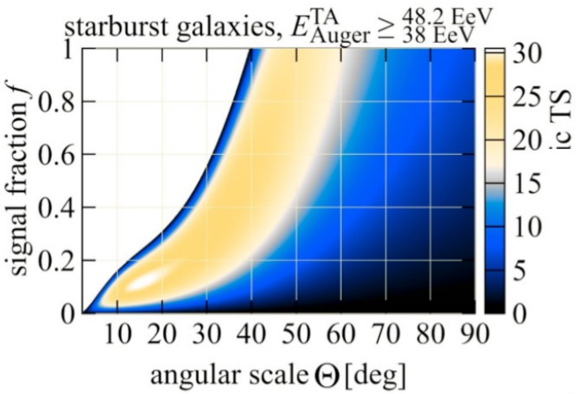
THE UHECR ARRIVAL DIRECTIONS

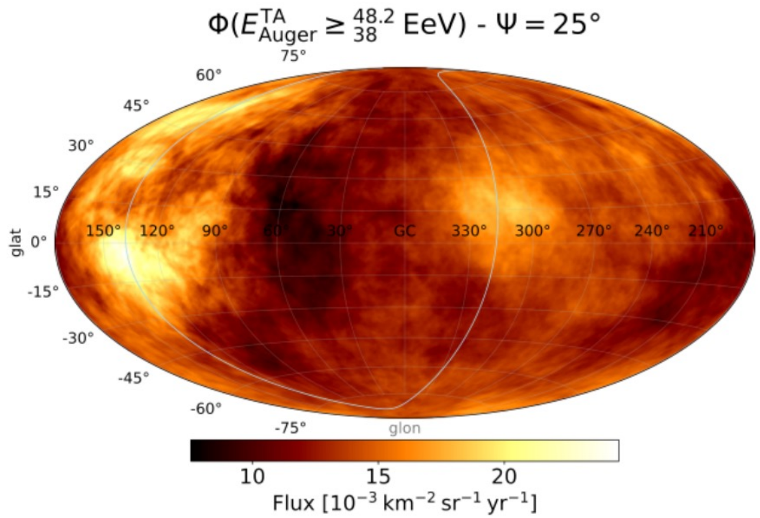
Telescope Array and Pierre Auger Collab. Joint WG on Arrival Directions, ICRC23

Talks by **K. Fujisue** and **E. Martins**, Wed, CCR session

- Catalogs are used to compare the arrival directions with positions of source classes
  - The contribution of each object is weighted based on its relative flux in the band chosen for each catalog
  - Parameters: angular width and relative weight



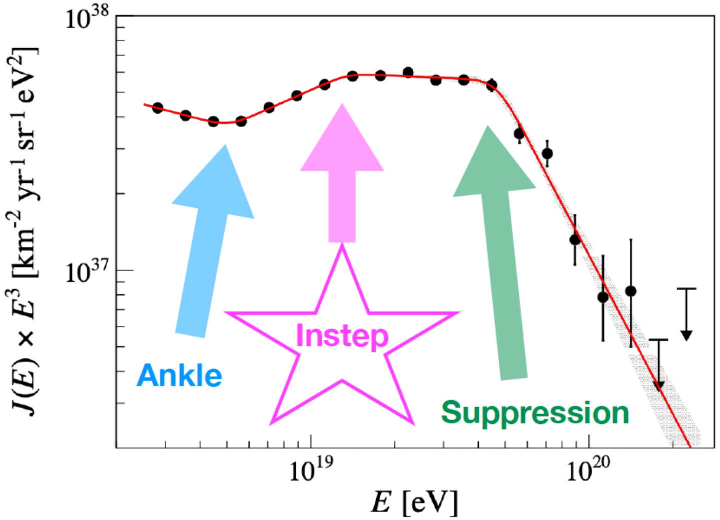




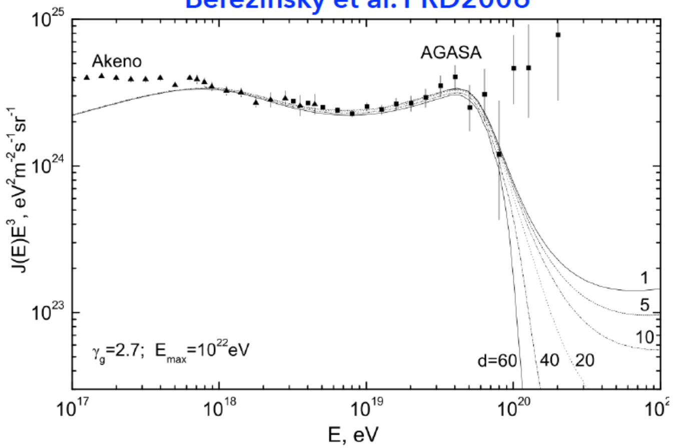
- **Significance of Starburst catalog: 4.6 sigma**
- Spots in the southern hemisphere (Centaurus region) and in the northern hemisphere (two spots: Perseus-Pisces region and Ursa Major region)

ASTROPHYSICAL INTERPRETATION(S)

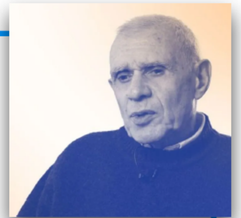
The Pierre Auger Collab. PRD2020

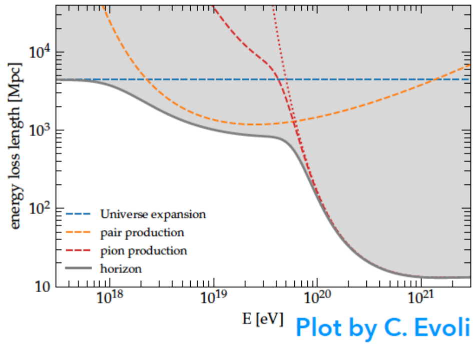


Berezinsky et al. PRD2006



V. Berezinsky,
1934-2023





Plot by C. Evoli

- Identical sources, uniformly distributed
- Pure protons at emission, power law-spectrum

"**Dip model**" interpretation is challenged due to

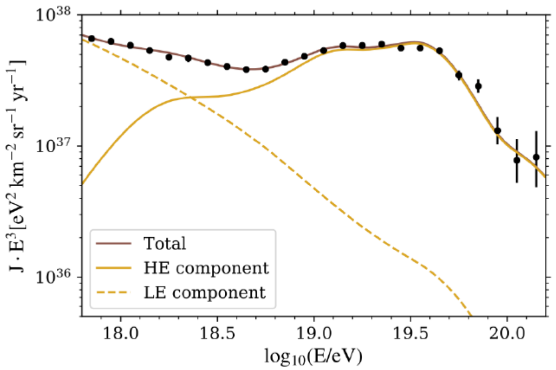
- Evidence for heavier mass composition
- Sharpness of the ankle feature
- Instep not explained

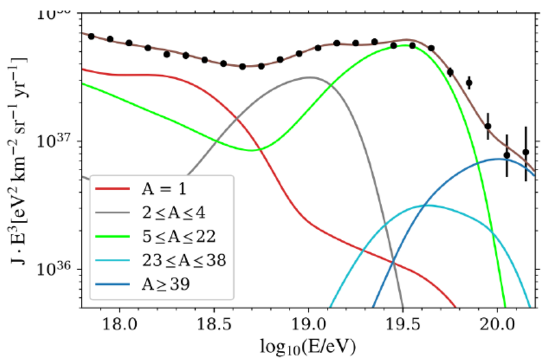
→

- Extended range of nuclear species to be considered at the source
- Consider more than one source population?

ASTROPHYSICAL INTERPRETATION(S)

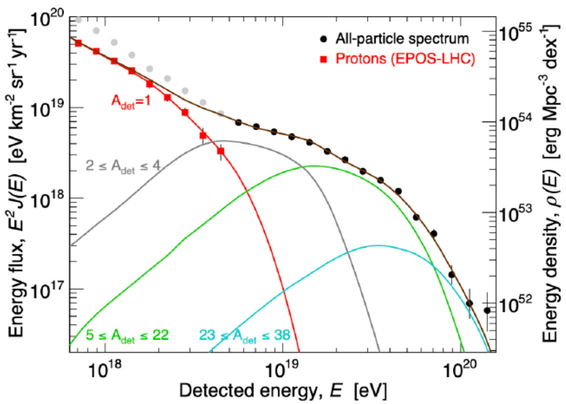
Different populations of sources contributing at LE and HE





Aloisio et al, JCAP 2014; Mollerach & Roulet PRD 2020; **The Pierre Auger Collab. JCAP 2023**

One population of sources, softer spectrum of protons due to in-source interactions



Contribution from <u>heavier particles</u> <u>below the ankle</u> needed to account for

- mixed composition
- missing flux

Luce et al, ApJ 2022

Basic scenario:

- identical sources
- power-law spectra at escape, with rigidity dependence

Extragalactic propagation taken into account; results presented in this talk are obtained with:

- SimProp, Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2017
- CRPropa, R. Alves Batista et al JCAP2022

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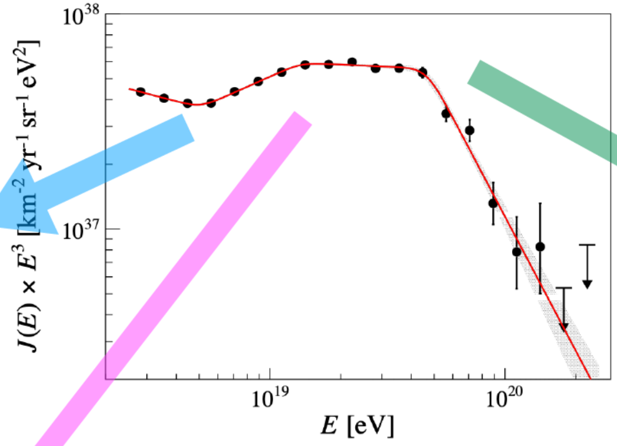
WHAT IS THE ORIGIN OF THE SPECTRUM (AND COMPOSITION) FEATURES ?

The Pierre Auger Collab. JCAP 2023



Ankle: interplay between (soft) LE and (hard) HE components

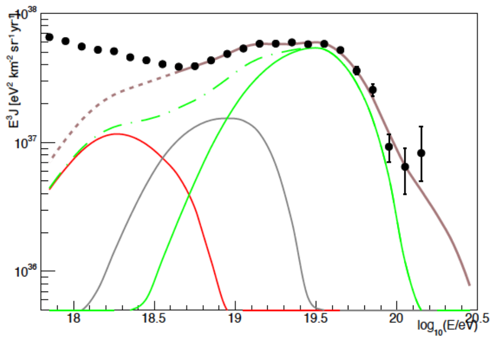
- Different populations of UHECR sources
- In-source interactions

- Independently of the scenario, decreasing fluctuations of Xmax can be found corresponding to **limited mixing of spectra of different nuclear species at HE**, meaning
  - HE: hard spectra + low rigidity cutoff
  - LE: soft spectra + rigidity less constrainable

In terms of interpretation the **suppression**,

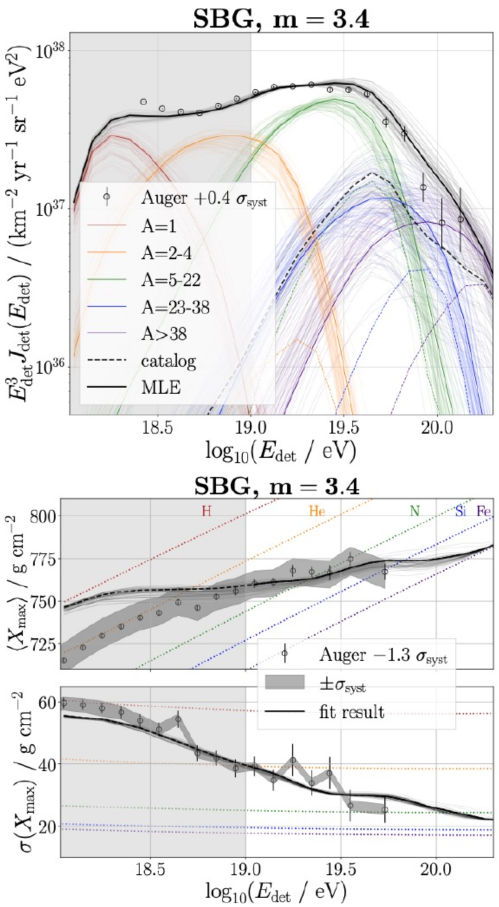
- Propagation effect
- Indication of source power

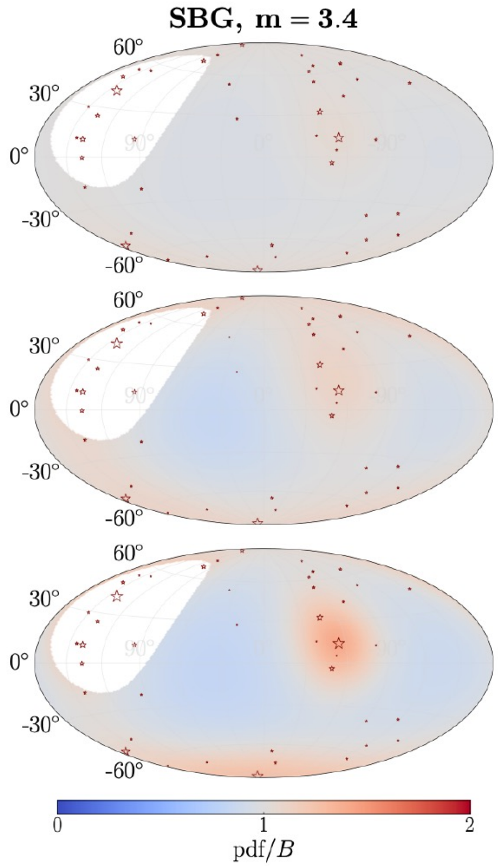
Instep: interplay between the flux contributions of the He and CNO components injected at the source with their distinct cut-off energies, shaped by photodisintegration during the propagation



REFINING THE BASIC PICTURE

Investigating the source distribution





- Signal fraction and uncertainty in arrival direction included in the analysis
- Best improvement with respect to spectrum + composition fit found for **starburst sources**
- gamma-AGN sources disfavoured

Talk by **E. Martins**, Wed, CCR session

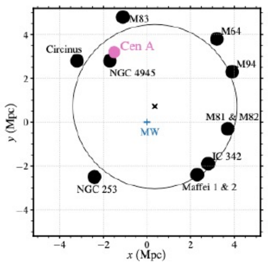
The Pierre Auger Collab. arXiv:2305:16693v1

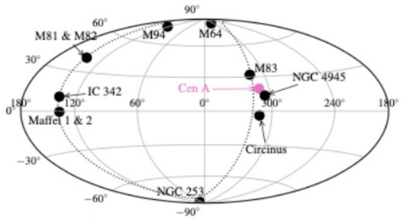
REFINING THE BASIC PICTURE

Investigating the source distribution

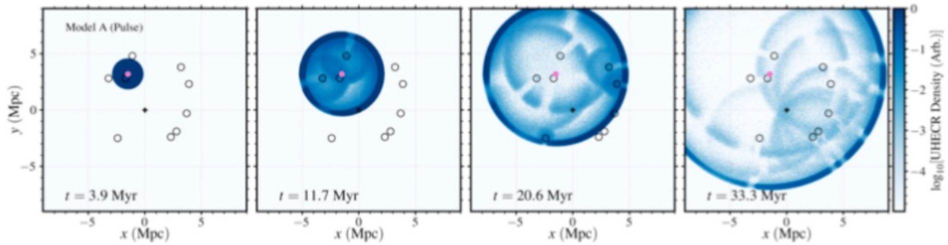
- Correlation with SBGs established
  - Can the correlation of UHECR with local structure be ascribed to the deflection of UHECRs, initially released by Cen A, on nearby galaxy systems?

Bell & Matthews MNRAS 2022;
Taylor et al MNRAS 2023

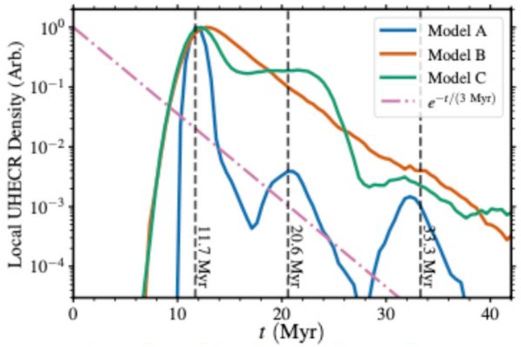




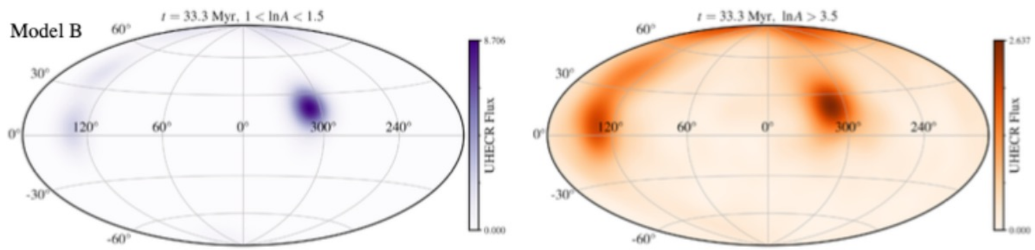
Council of Giants



After the release from CenA, particles are scattered by magnetic fields around galactic structures



Local particle density depends on release models



- UHECR nuclei provide a signature of the propagation scenario

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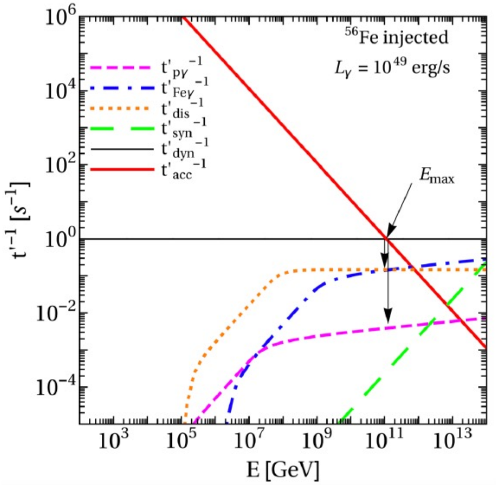
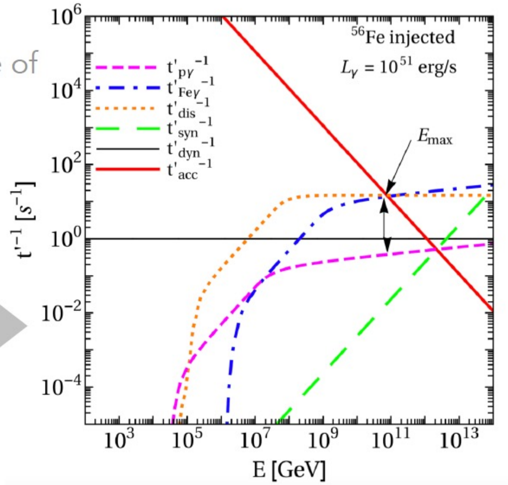
REFINING THE BASIC PICTURE



Increase of photon density

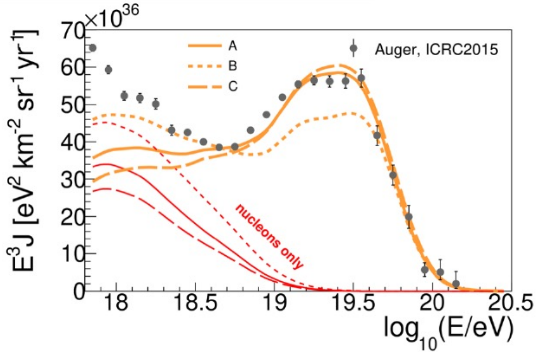


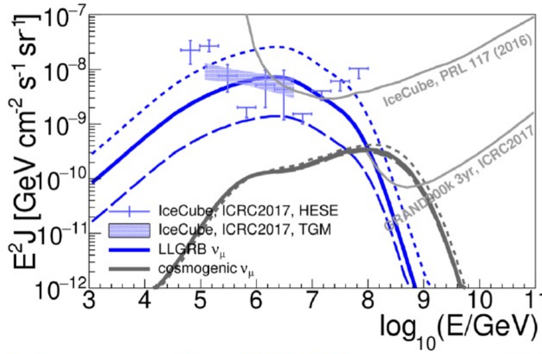
- Flux at escape (spectral index, mass composition, maximum energy) from source environment depends on source details (interaction efficiency, diffusion…)
  - Example from GRBs and LL-GRBs; other cases explored for TDEs, blazars, SBG nuclei…
  - **Basic conclusion: large photon density -> efficient interactions -> large amount of protons at escape & neutrinos**

- UHECR-astrophysical neutrino connection: energies below the ankle

Unger et al PRD 2015; Biehl, **DB** et al Astron. Astrophys. 2018; **DB** et al ApJ 2019; Muzio et al PRD 2019; Condorelli, **DB**, Peretti & Petrera PRD 2023

See other talks about in-source interactions and multimessenger connections: **E. Peretti** (this session); **X. Rodrigues** and **A. Reimer** (CCR session, today); **S. Hussain** (GRA session, Thu); **R. Matsui** (GWMM session, Thu)





- Other info from UHECR-cosmogenic neutrino connection: UHECR source evolution

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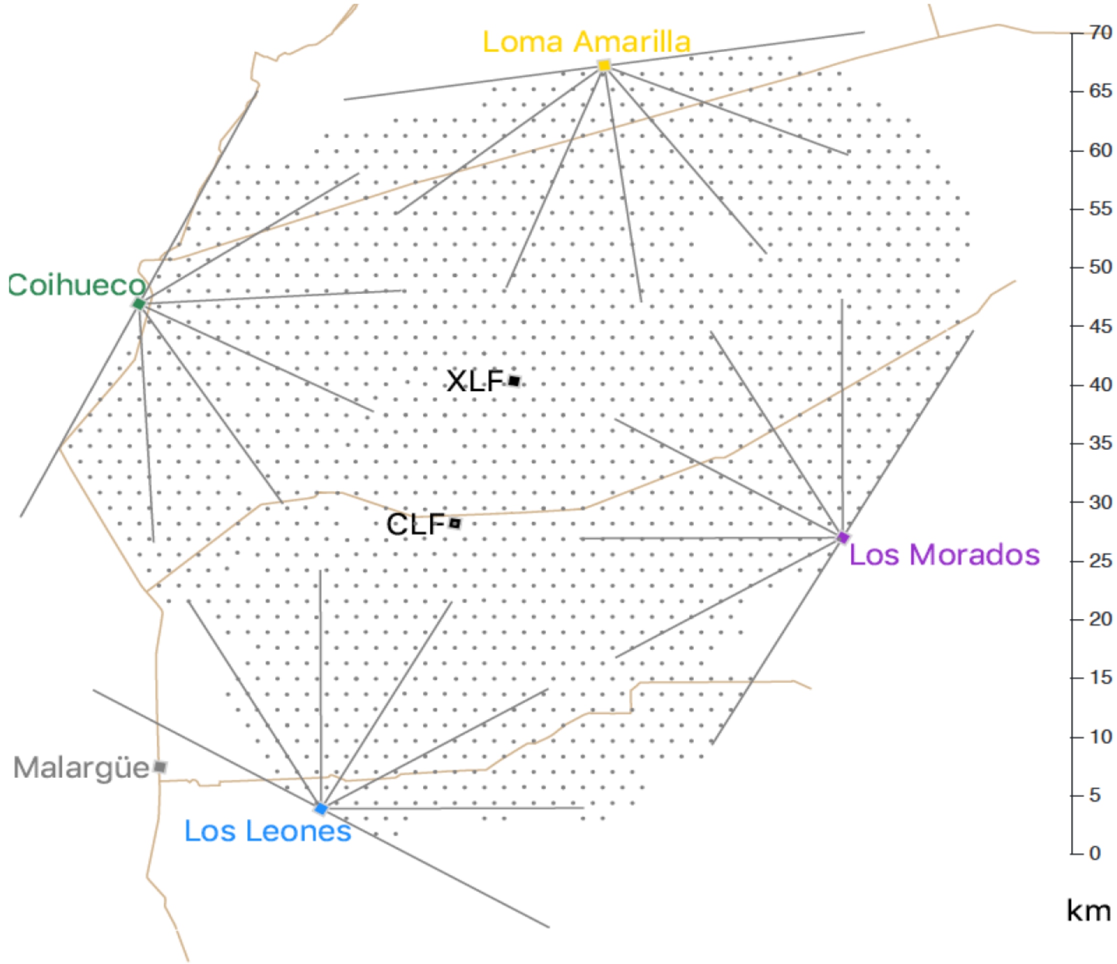
AugerPrime:
the Upgrade of the Pierre Auger Observatory
Ingo Allekotte
for the Pierre Auger Collaboration
Pierre Auger Observatory
CNEA – Instituto Balseiro – Bariloche, Argentina
ingo@cab.cnea.gov.ar
PIERRE AUGER OBSERVATORY
CNEA

The Pierre Auger Observatory, Phase I

- See previous presentations by:
  Fabio Convenga
  Emily Martins
- Hybrid: FD + SD
- 1660 Water Cherenkov Detectors:
  1500 m spacing, 3000 km^2, E > $10^{18.5}$ eV
  750 m spacing, 23.5 km^2, E > $10^{17.5}$ eV
  433 m spacing, 1.9 km^2, E > 63 PeV
- 24 Fluorescence Telescopes
  30° x 30° FoV
  + 3 “HEAT” FD high elevation FoV
- Atmospheric monitoring



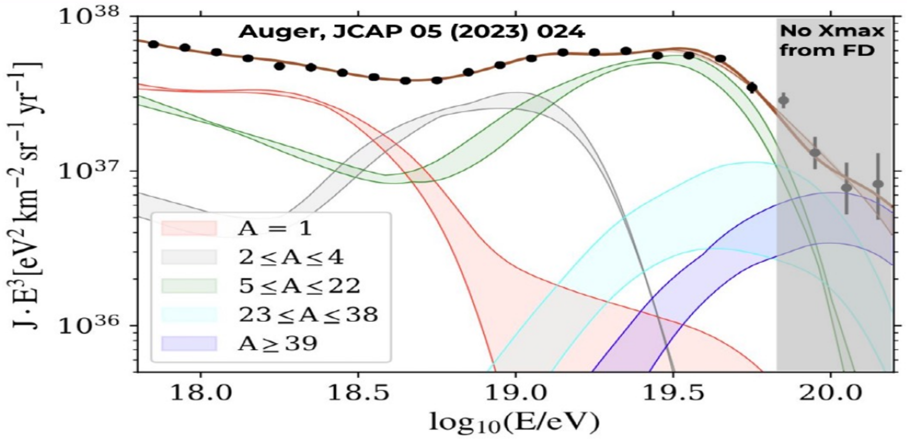
AugerPrime: goals of the Upgrade

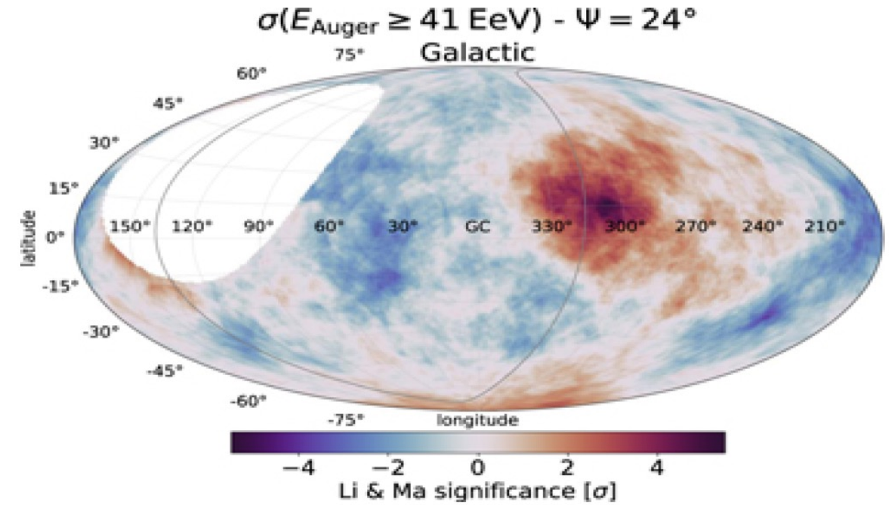
AugerPrime wants to address:

- Nature and origin of UHECRs
- Origin of the flux suppression at highest energies
- Search for UHE neutrinos and photons
- Hadronic interactions at high energies
- “Muon deficit” in simulations

- Increase composition sensitivity (event by event)
- Composition at the highest energies
- Composition-related anisotropies
- Search for fraction of light components
- Continue increasing statistics

- Assess potentiality of future instruments



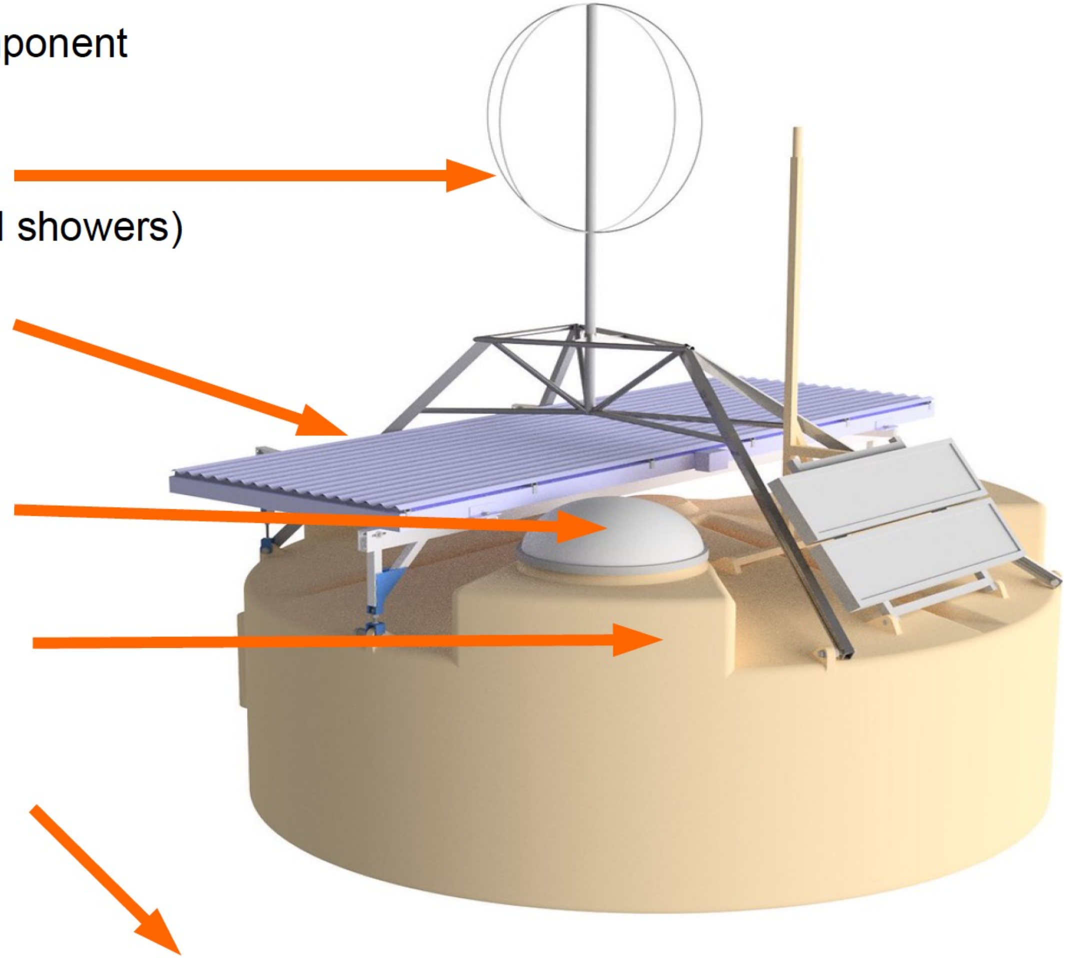


Auger 2022 ApJ 935-170

AugerPrime: the Upgrade

Different sensitivity to MUONS and EM component

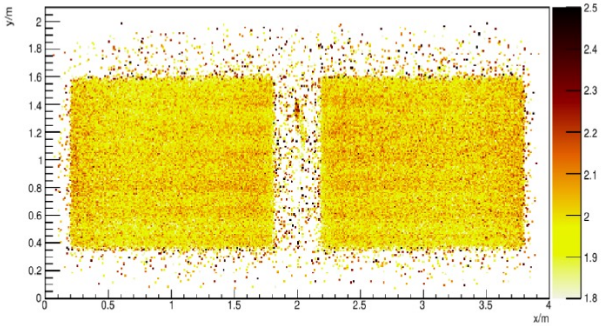
- RD:
  Radio Detectors (sensitive to EM, horizontal showers)
- SSD:
  Scintillation Surface Detectors
  (more sensitive to EM, vertical showers)
- UUB:
  New SD electronics
- SPMT:
  Small PMTs (increased dynamic range)
- UMD:
  Underground Muon Detectors
  (direct measurement of μ at lower E)

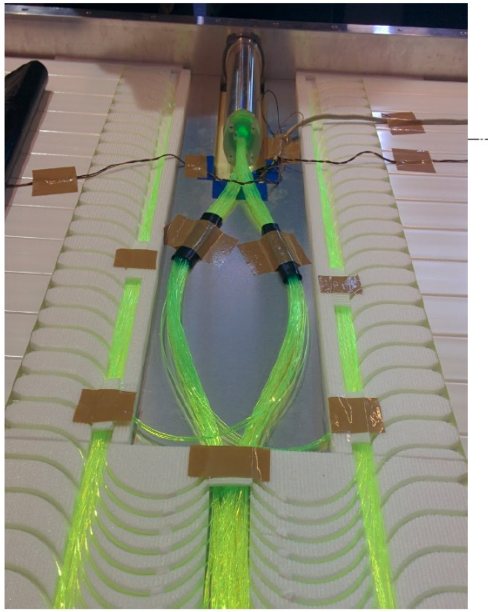


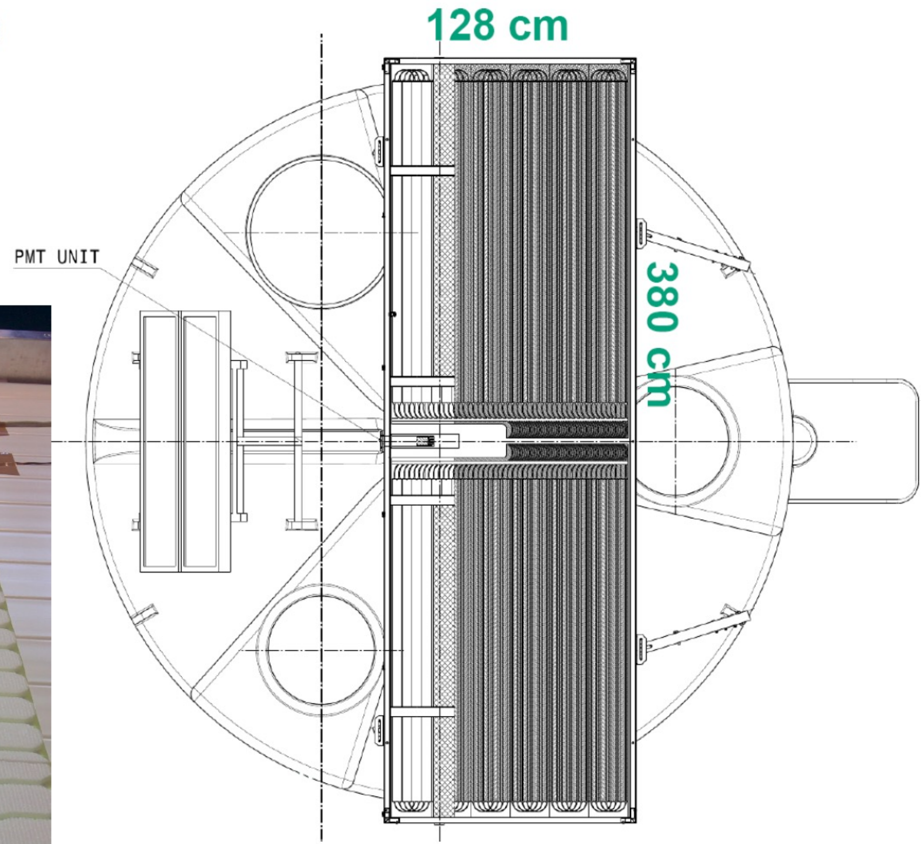
The Scintillation Surface Detector

- Plastic scintillator (extruded polystyrene w. 1% PPO + 0.03% POPOP)
- 2 panels x 24 scintillator bars
- 3.8 m^2 detector area
- 1 mm WLS fiber
- 1.5” PMT Hamamatsu R9420
- Al mechanical structure / support
- Corrugated Al sunroof

- Uniformity (muon hodoscope)
- Resistance to weather conditions

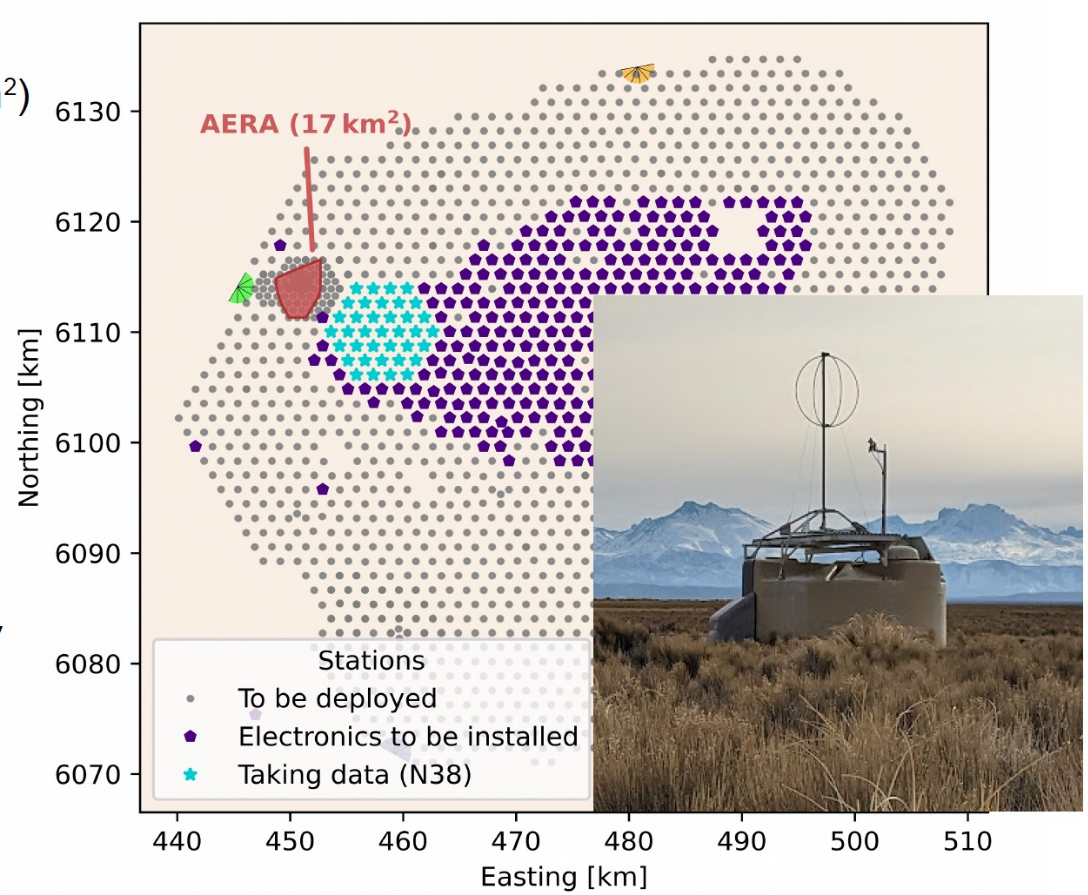






The Radio Detector

- Experience from AERA (150 antennas, 17 km²)
- Loop antenna (SALLA)
  (short aperiodic loaded loop antenna)
- 30 – 80 MHz
- 2 polarizations
- Good EM component determination for inclined showers
- Expectation: >3000 showers above 10 EeV in 10 years



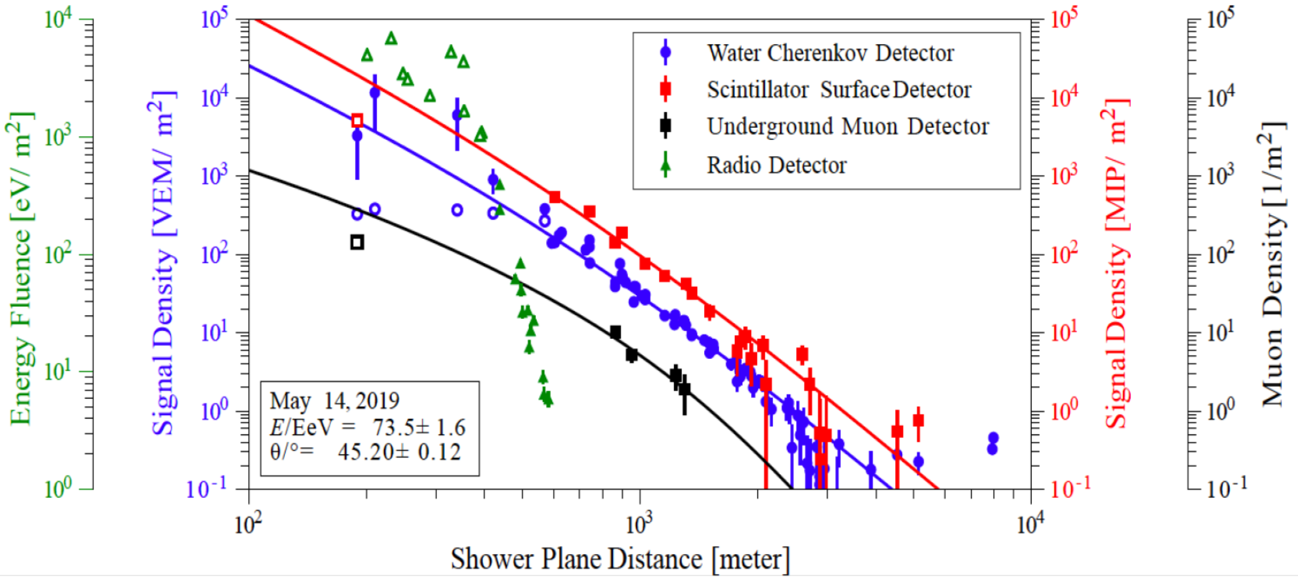
J. Pawlowsky PoS (ICRC2023) 344 – updated

The Underground Muon Detector

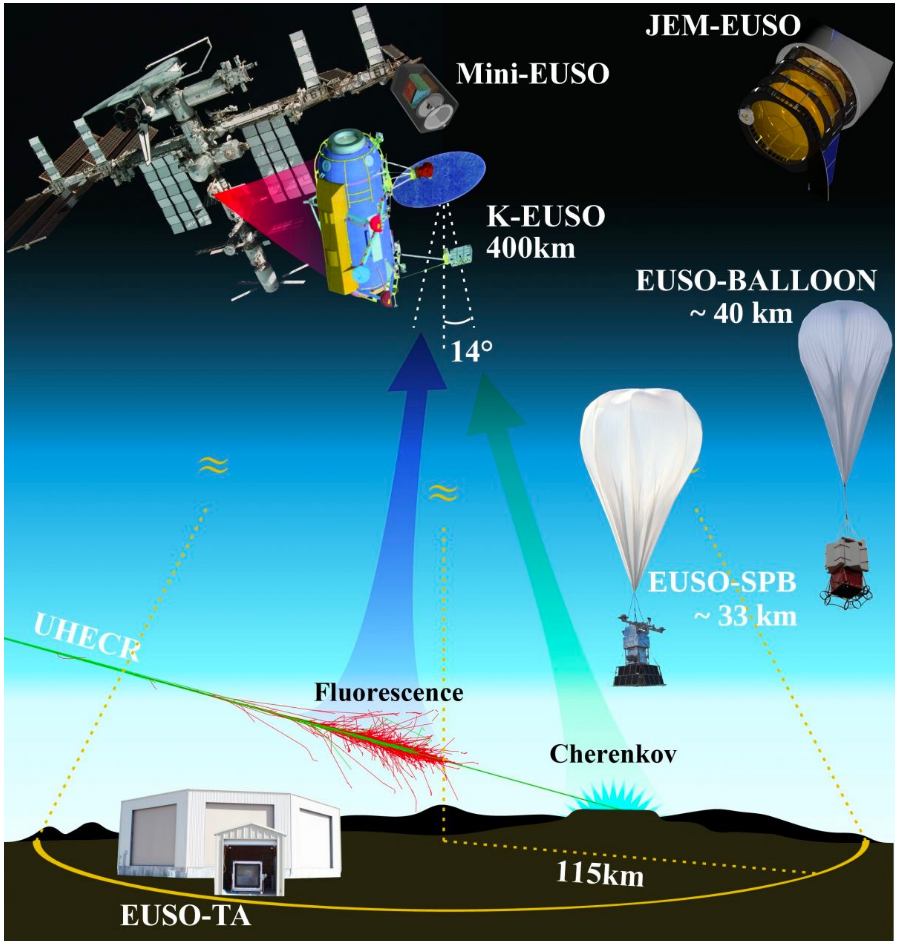
- Direct muon counting
- 2.3 m underground (540 g/cm^2)
- 3 modules x 10 m^2 per position
- 23 km^2
- Plastic scintillator + WLS fiber
- 64-SiPM array detectors
- Counter / Integrator mode

Conclusions and Outlook

- Construction nearly completed
- Data taking not interrupted during construction
- Commissioning underway
- Progress in understanding noise levels, triggers, failure modes
- Multi-hybrid detection (WCD + SSD + RD + UMD + FD)
- Expect 10 years of data taking
- Cosmo-geo studies ongoing
- Open access data
- Auger is an ideal platform for testing of instruments



EUSO



https://www.jemeuso.org/