

Imaging and Modeling in Cosmic Ray Physics (Part 1)

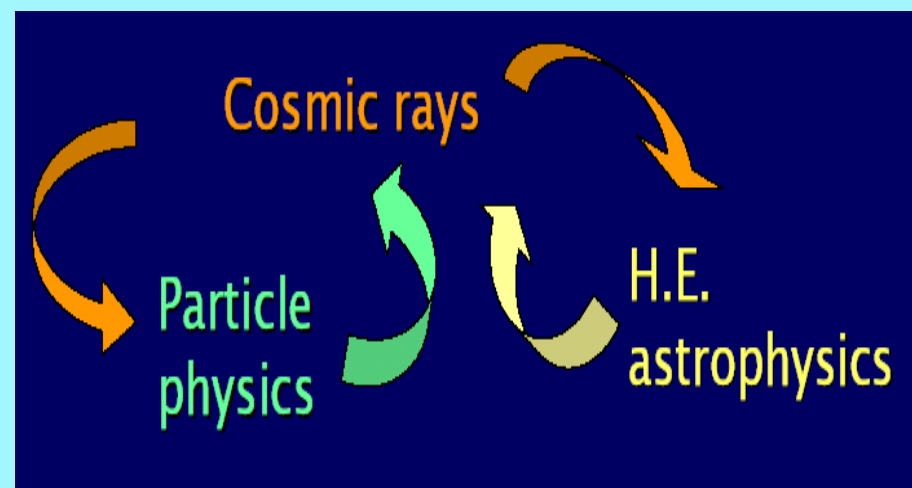
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<http://www.to.infn.it/~bertaina>



Victor Hess after his 1912 balloon flight, during which he discovered cosmic rays from space. © National Geographic.

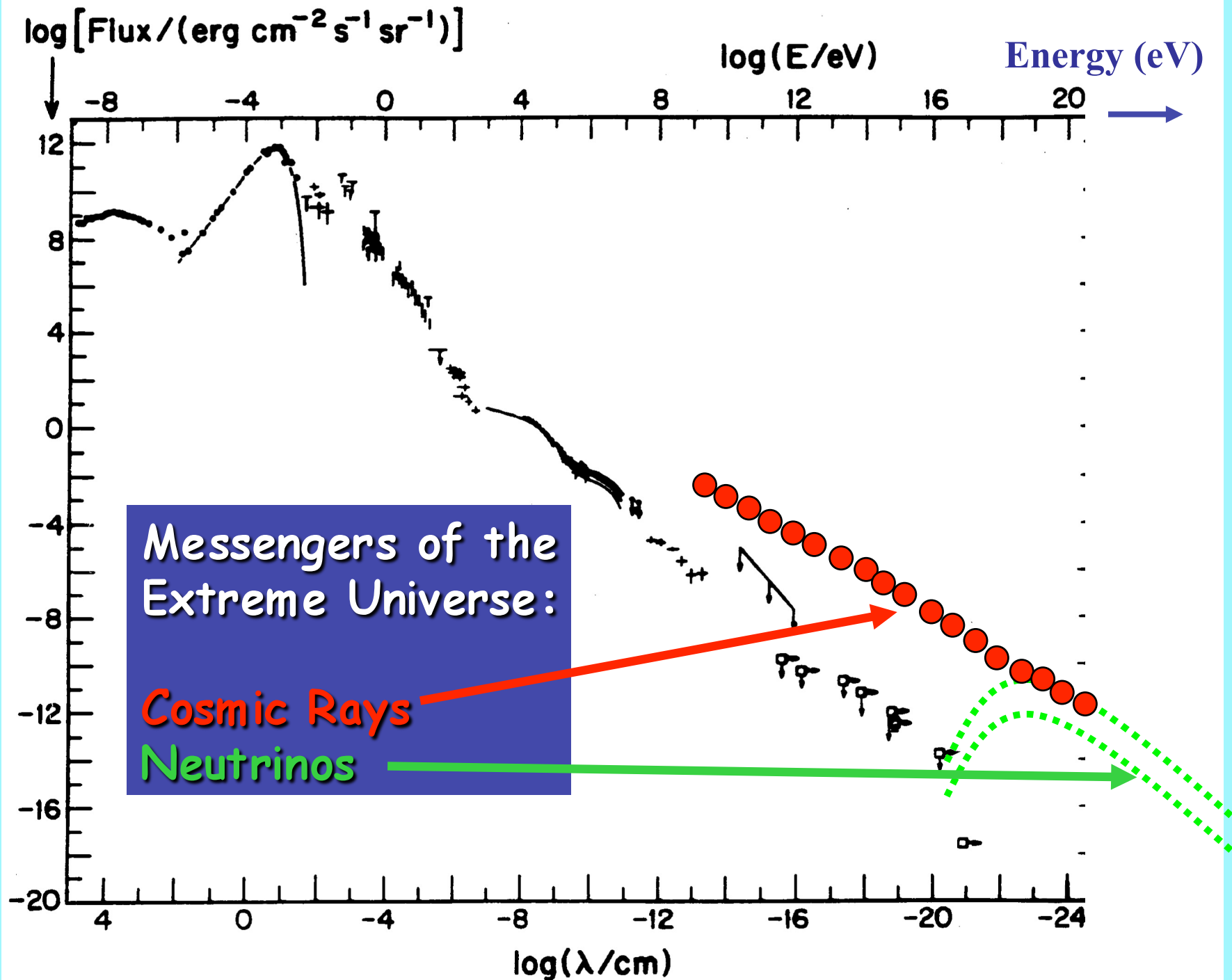


**Particle
Physics was
born with the
study of
cosmic rays**

Hess discovers cosmic rays	1912	
	1927	Cosmic rays measured in bubble chambers
Anderson discovers antimatter	1932	
	1937	Discovery of the muons
Auger discovers extensive air showers	1938	
	1946	First measurements of EAS
Fermi theory on cosmic rays	1949	
	1962	Discovery of the first event at $E = 10^{20}$ eV
Proposition of the GZK effect	1966	
	1991	Discovery of the first event at Fly's Eye
EECR events seen in Agasa	1994	
	1995	Start of the Auger project
Start of the EUSO project	1997	

Table 1. Discovery of elementary particles

Particle	Year	Discoverer (Nobel Prize)	Method
e^-	1897	Thomson (1906)	Discharges in gases
p	1919	Rutherford	Natural radioactivity
n	1932	Chadwik (1935)	Natural radioactivity
e^+	1933	Anderson (1936)	Cosmic Rays
$\mu^\pm$	1937	Neddermeyer, Anderson	Cosmic Rays
$\pi^\pm$	1947	Powell (1950) , Occhialini	Cosmic Rays
$K^\pm$	1949	Powell (1950)	Cosmic Rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic Rays
Λ^0	1951	Armenteros	Cosmic Rays
Δ	1932	Anderson	Cosmic Rays
Ξ^-	1932	Armenteros	Cosmic Rays
$\Sigma^\pm$	1953	Bonetti	Cosmic Rays
p^-	1955	Chamberlain, Segre' (1959)	Accelerators
anything else	1955 $\implies$ today	various groups	Accelerators
$m_\nu \neq 0$	2000	KAMIOKANDE	Cosmic rays



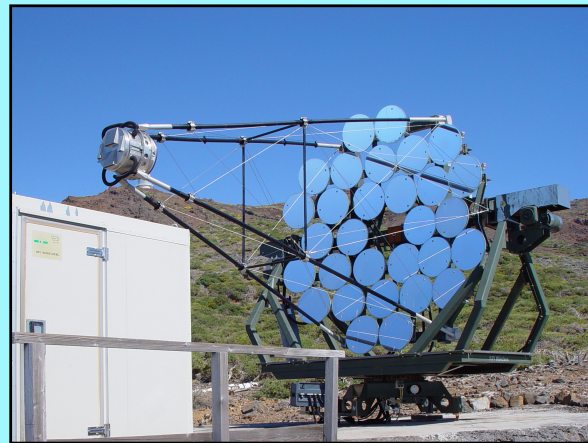
Progress in Cerenkov technique

Observation time necessary to detect the CRAB Nebula
TeV signal:



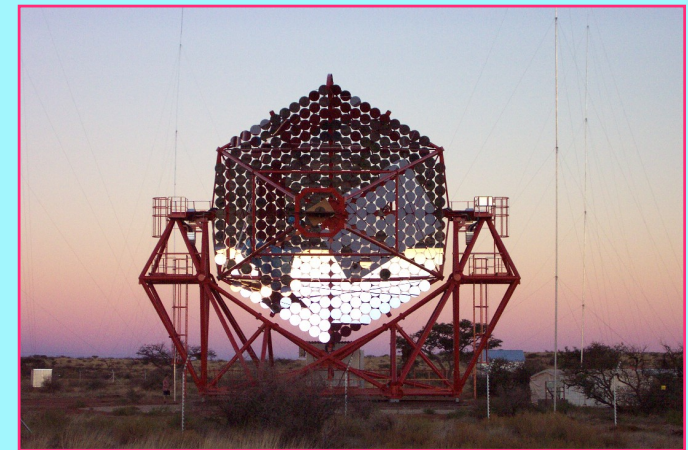
Whipple, 1989

50 h



HEGRA, 1997

15 m



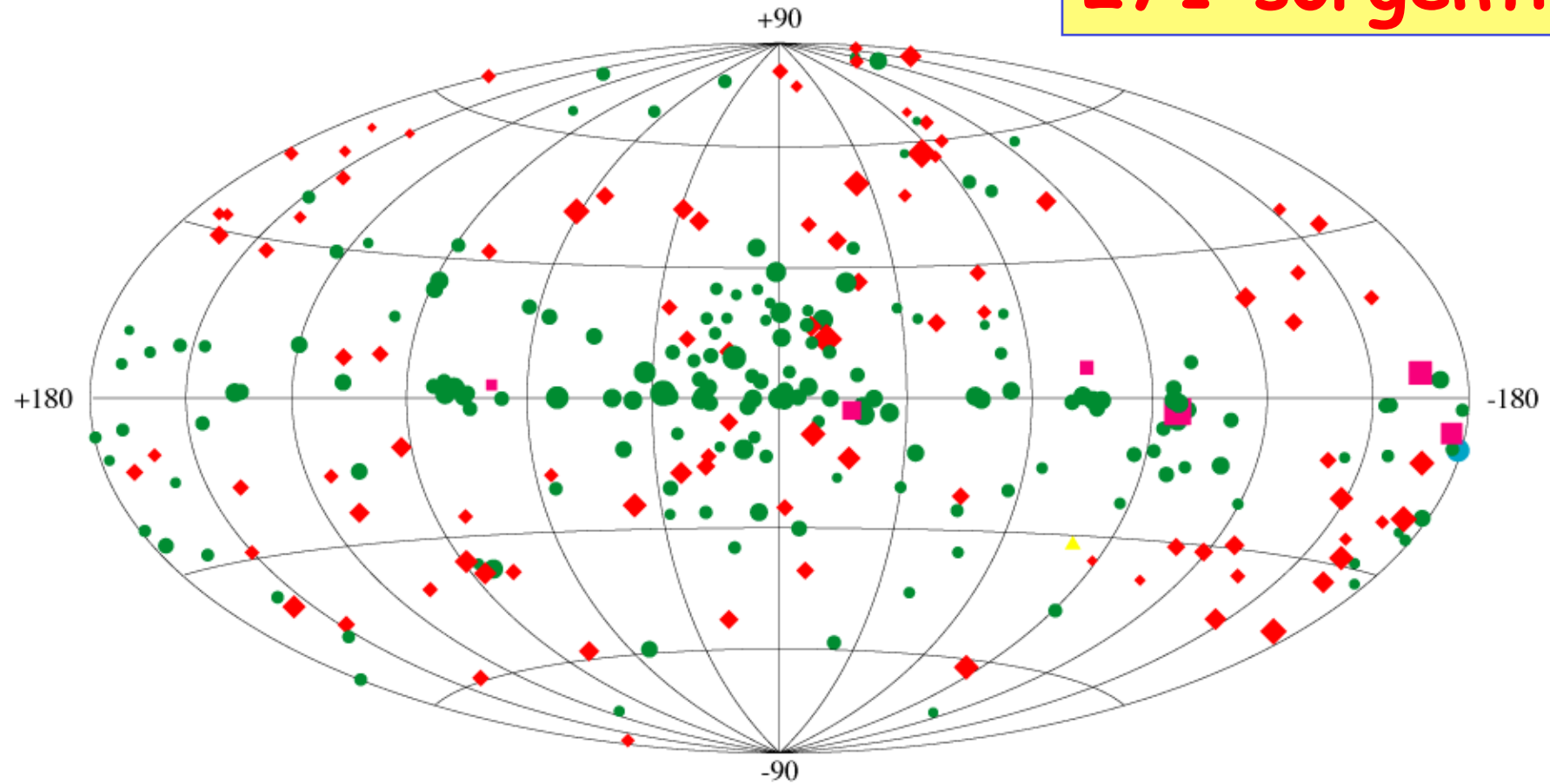
HESS, 2004

30 s !!!!

Third EGRET Catalog

$E > 100 \text{ MeV}$

271 sorgenti

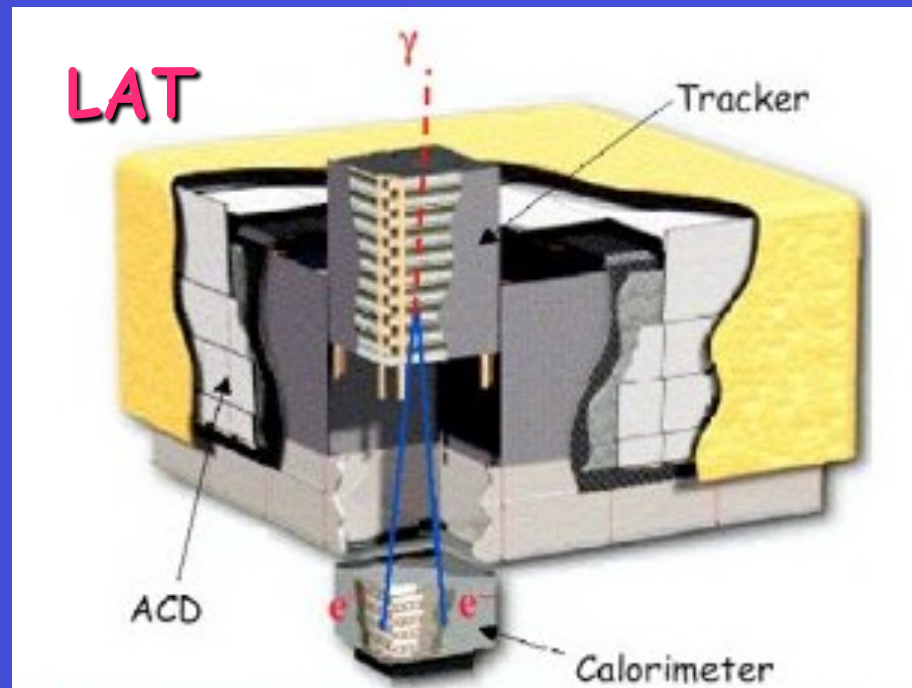


◆ Active Galactic Nuclei 94
● Unidentified EGRET Sources 170

■ Pulsars 6
▲ LMC
● Solar FLare

FERMI/GLAST

Gamma ray Large Area Space Telescope



50 times more sensitive than EGRET
at 100 MeV

Launch in Feb 2007

■ Large Area Telescope (LAT)

- 16 Tracker Modules (silicon-strip detector)
- Calorimeter
- Anti coincidence detector

$20 \text{ MeV} < E < 300 \text{ GeV}$

field of view $\approx 2.5 \text{ sr}$

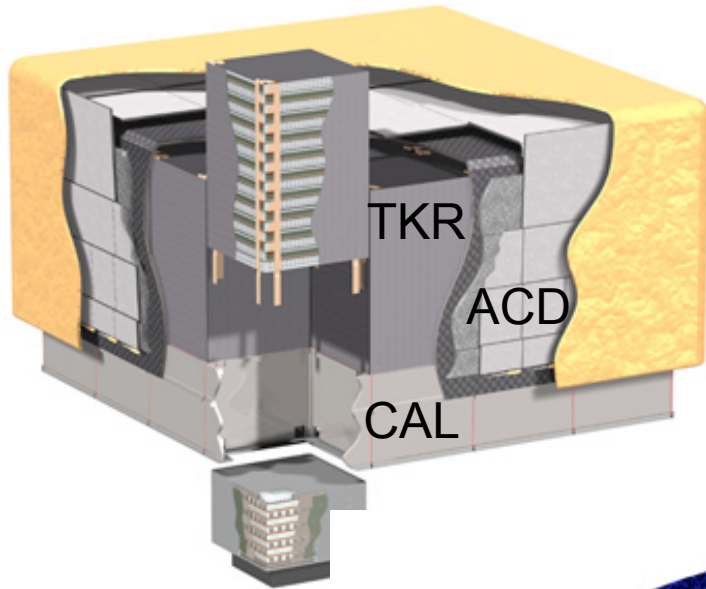
■ Burst Monitor

$10 \text{ KeV} < E < 25 \text{ MeV}$

field of view: 8 sr

Fermi Gamma-Ray Space Telescope

Pair production γ -ray telescope
detects photon energy and direction from
the whole sky between
 ~ 20 MeV and more than 300 GeV



γ -ray astronomy

Steady
sources and
transients

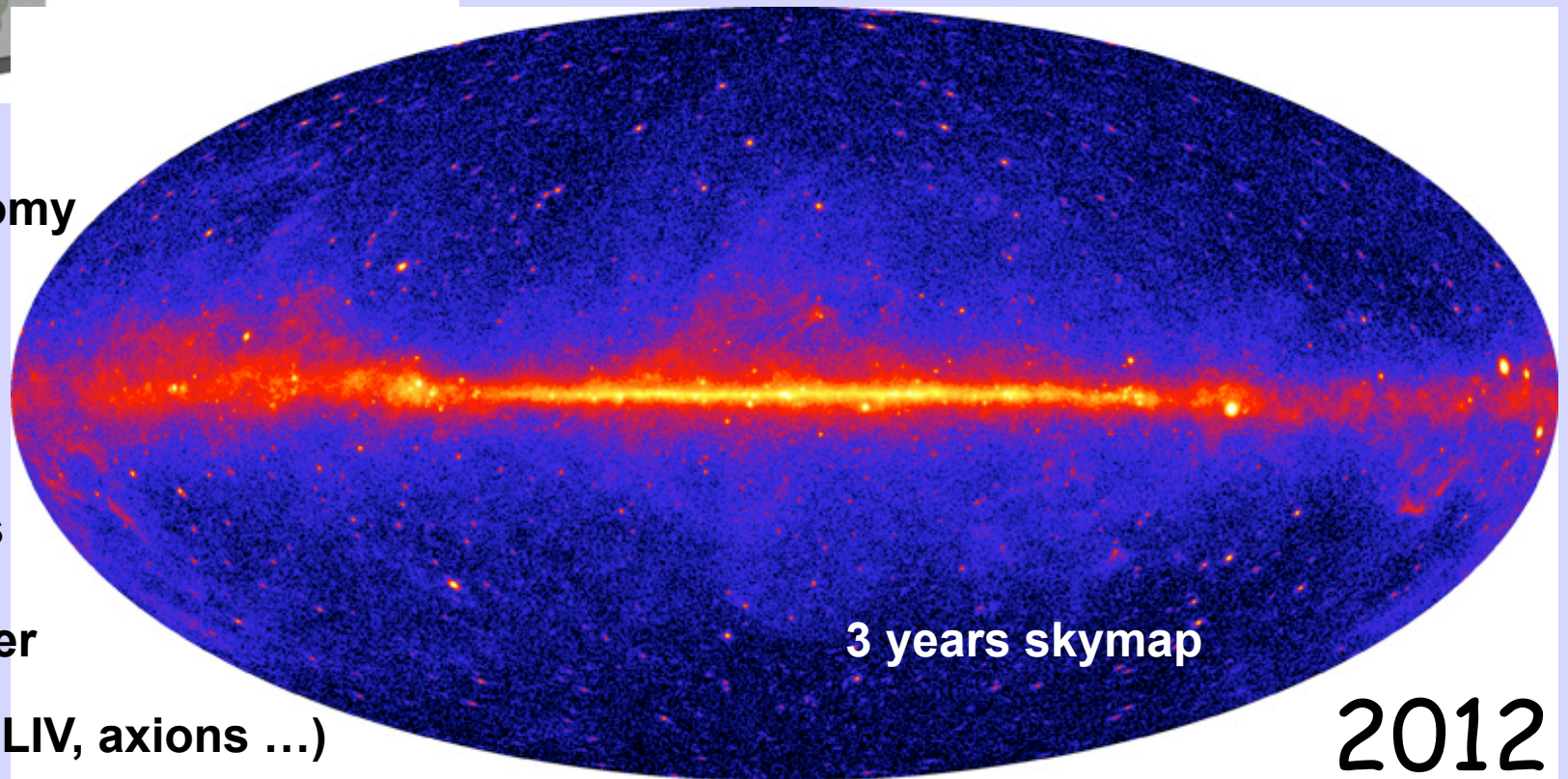
Cosmic rays

Dark Matter

New Physics (LIV, axions ...)

M. Bertina

Inter-galactic magnetic fields, opacity of the Universe



2012

New windows,...new discoveries

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi ...	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ -rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

Cosmic rays

Charged particles from the cosmos

- Protons, α -particles, heavier nuclei
- No significant anisotropy seen
(“well stirred” by Galactic magnetic field)
- Energies above 10^{10} eV are from our Galaxy
(note: TV or PC monitor uses 10^3 eV electron beam)
- Energies above 10^{18} eV are extra-galactic
- Intensity drops sharply with E (like $E^{-2.7}$):

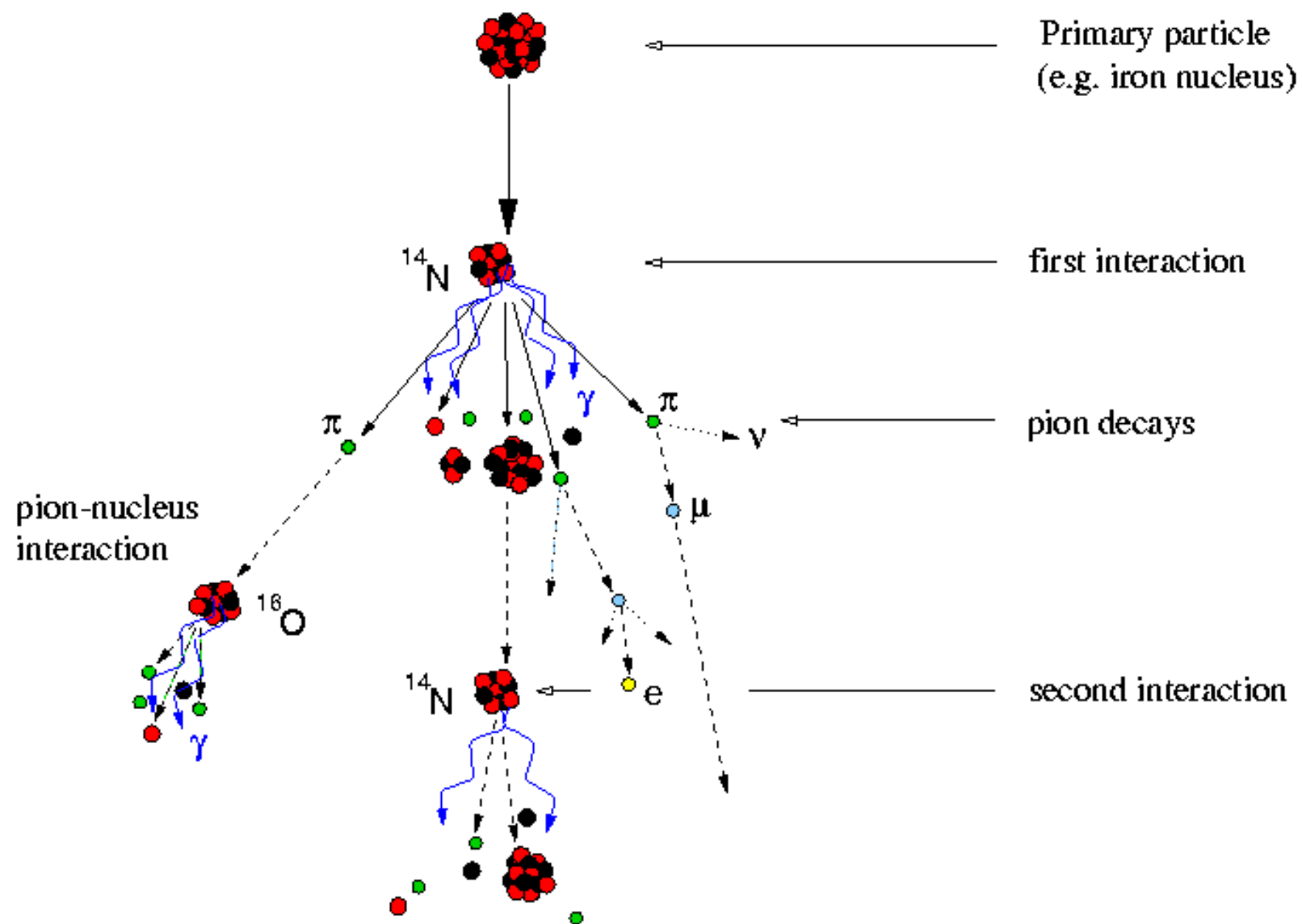
Energy	Rate of arrival
10^{10} eV	1000 per m^2 per sec
10^{12} eV	1 per m^2 per sec
10^{15} eV	1000 per m^2 per <u>year</u>
10^{19} eV	1 per <u>kilometer</u> ² per year

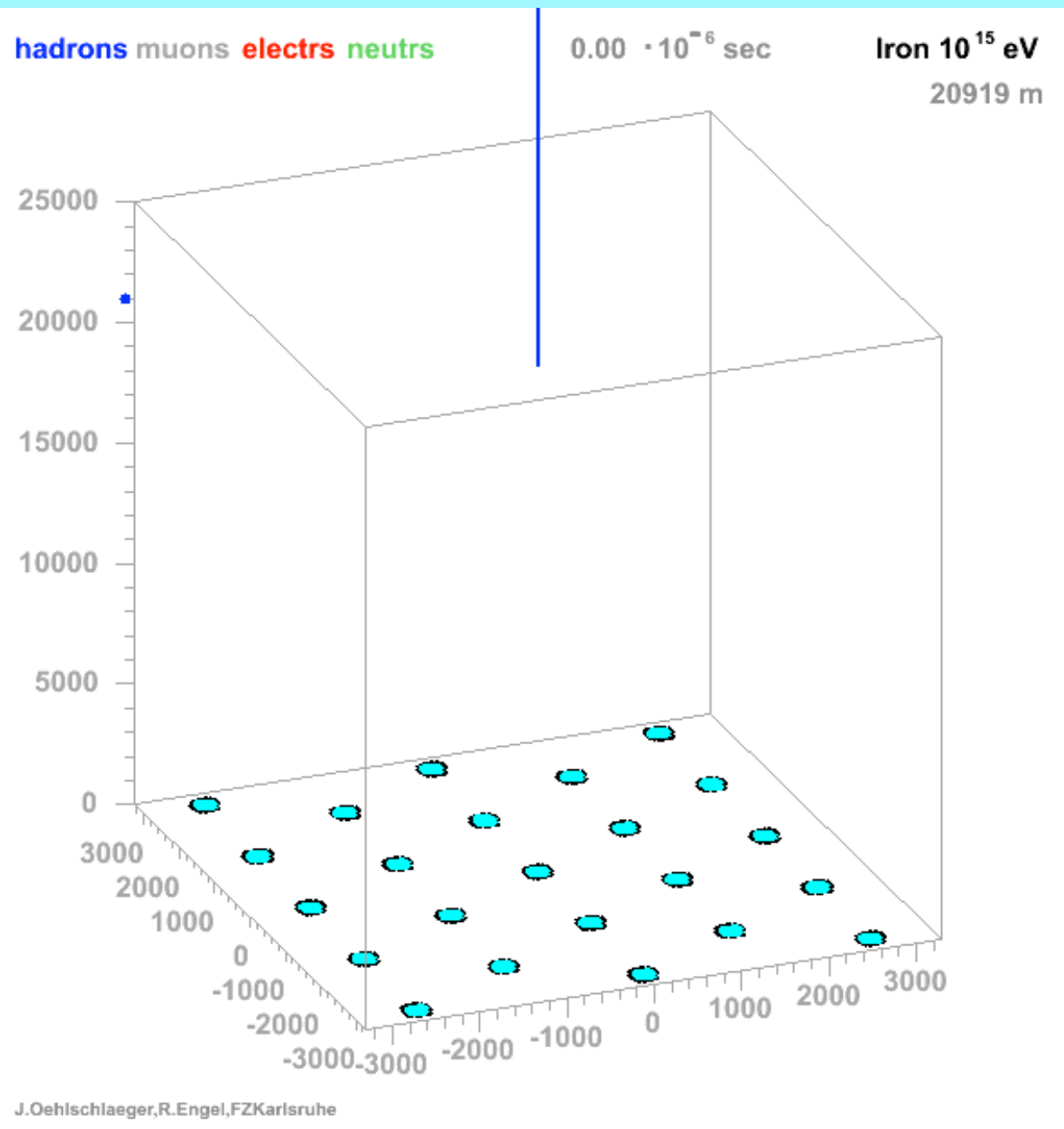
Highest energy seen is $\sim 10^{20}$ eV, about 50 joules
(energy of a 50 mph baseball in **one proton!**)

Many open questions:

- How/where are cosmic rays made?
- What process accelerates them to such enormous energies?
 - Supernova shocks?
 - Compact binary systems?
 - Active Galactic Nuclei?
- Why don't the highest energy cosmic rays point back to something interesting?
- Why are there kinks in the cosmic ray energy spectrum?
 - the knee at 10^{15} eV (1 PeV)
 - the ankle at 10^{19} eV (10 EeV)
 - the toe (?) at 10^{21} eV (1 XTeV)
- How can the highest energy cosmic rays ($>10^{20}$ eV) ever reach us?
 - **GZK cutoff** should stop them

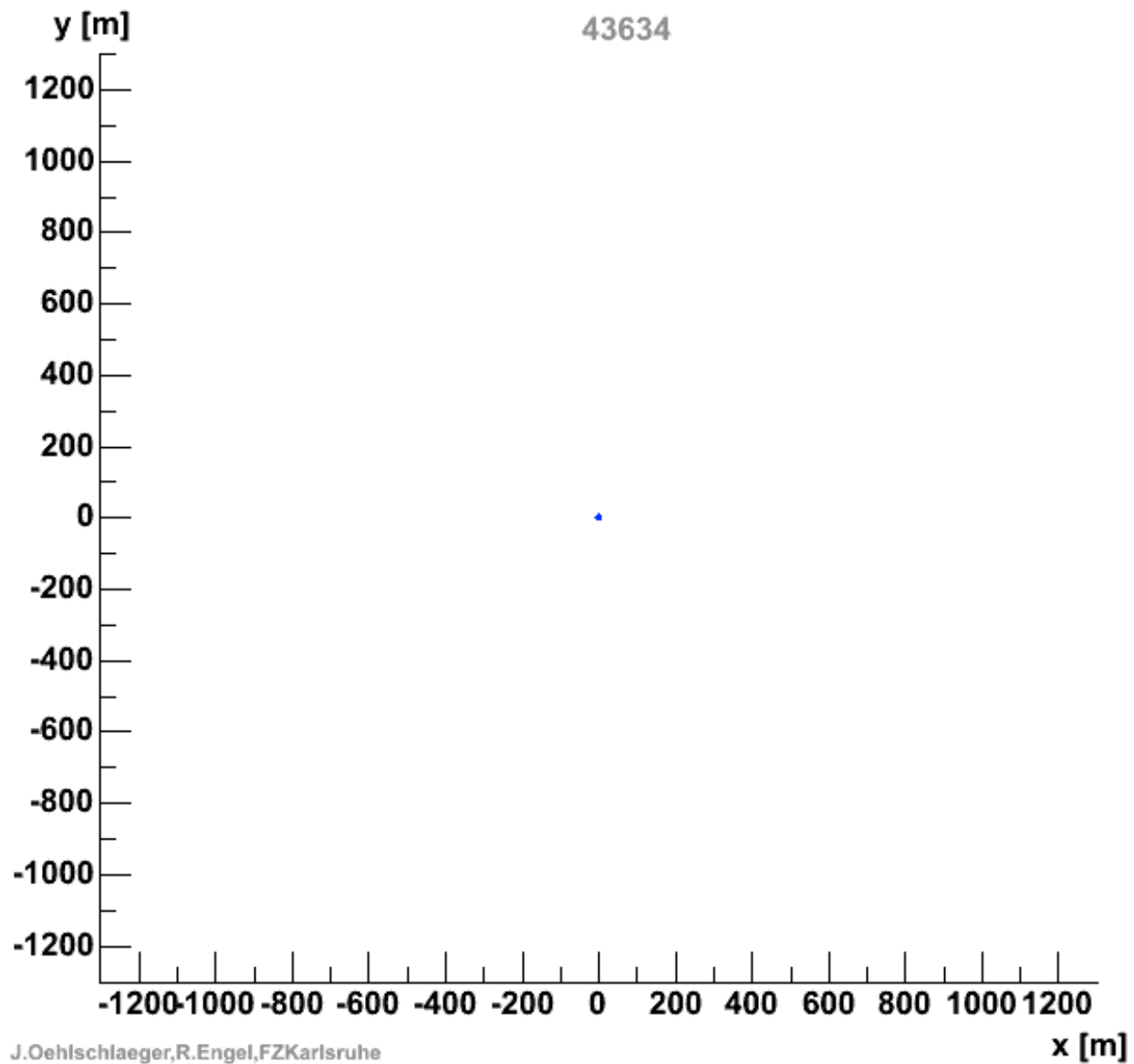
Development of cosmic-ray air showers





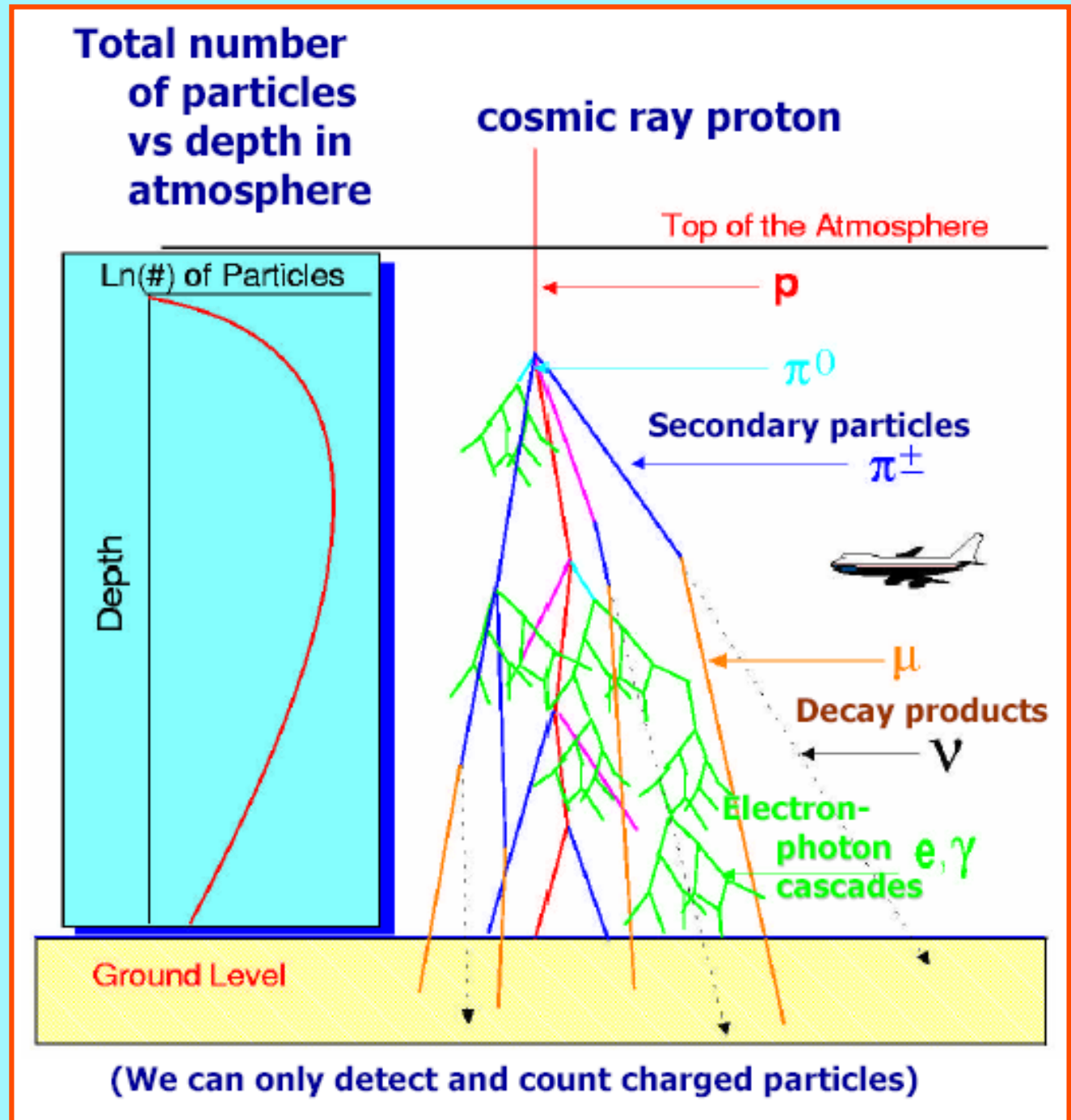
hadrons muons electrs neutrs

Iron 10^{14} eV

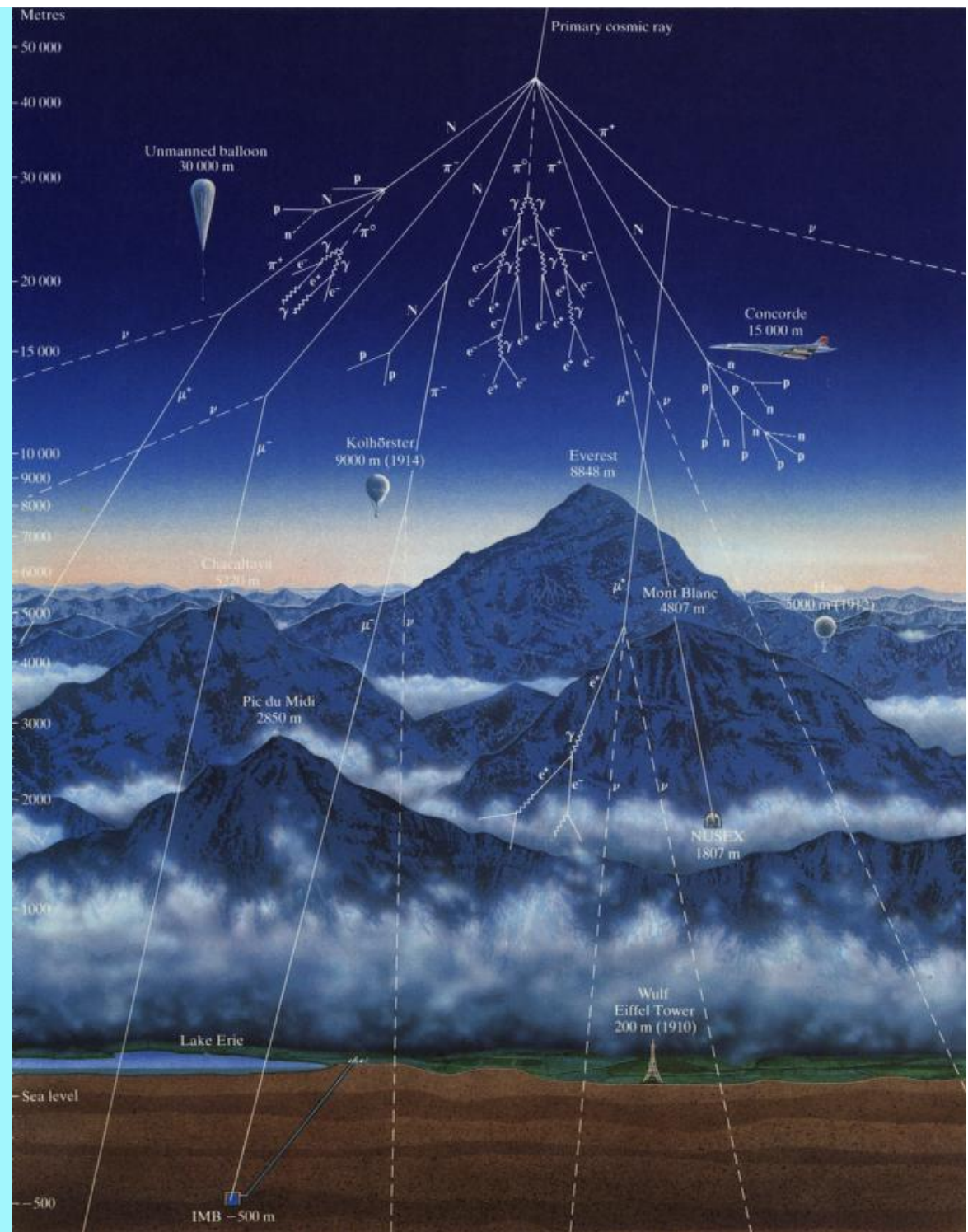


Cosmic Rays:

A connection
between
astrophysics,
Cosmology and
particle
physics



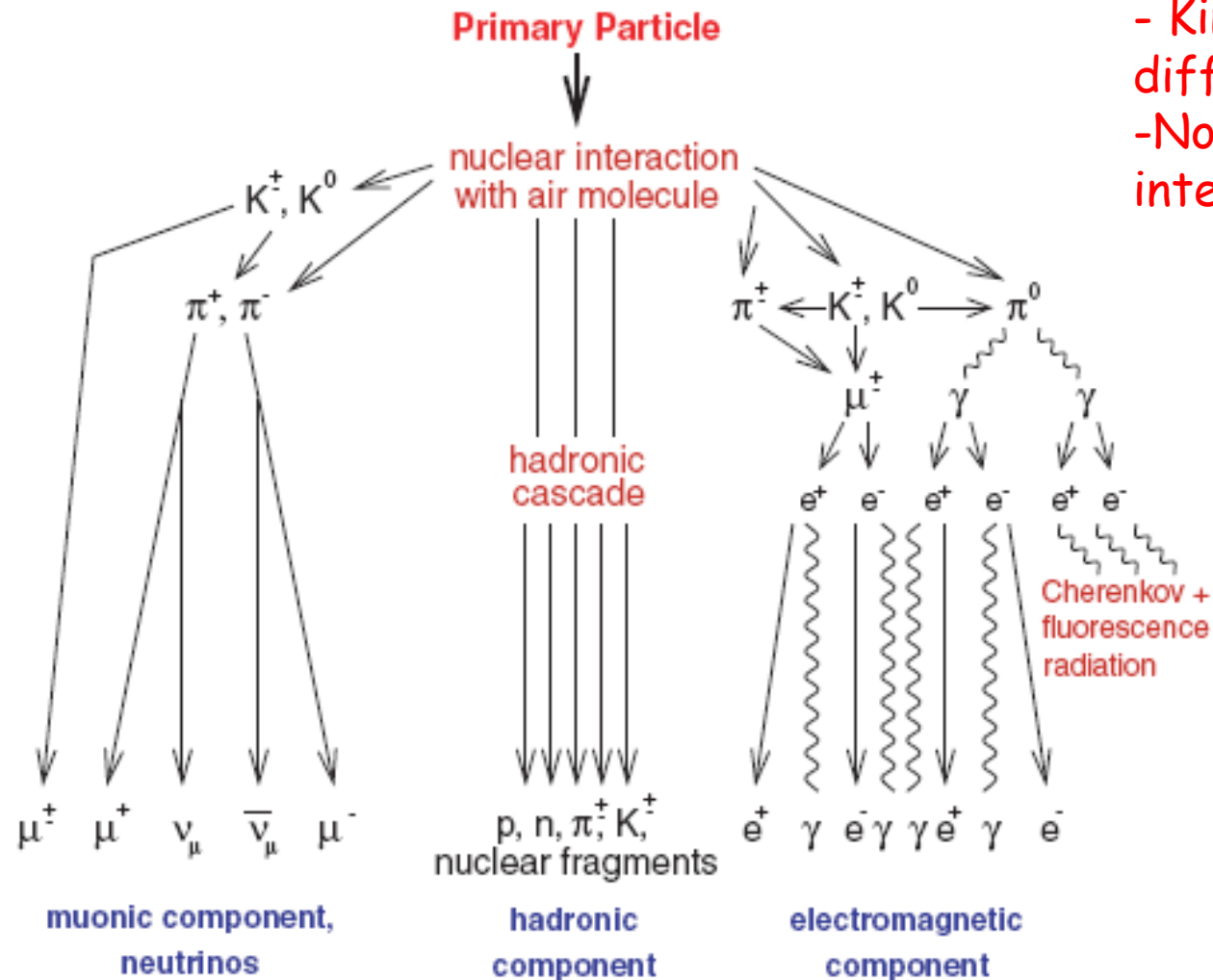
only μ and ν
can penetrate
deep under
the mountains



Deduce character of the original cosmic ray from shower observations on the ground:

- ◆ Number of particles in shower is related to energy of primary cosmic ray
- ◆ Average direction of shower particles is direction of primary cosmic ray
- ◆ Proportion of **muons** in the shower is related to type of cosmic ray (proton, nucleus or gamma ray)

- Primary interaction studied till $E \ll E_{RC}$
- Kinematic region very different from colliders
- No nucleus-nucleus interaction



$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \quad \text{B.R. } 99.988\%$$

$$\tau = 2.6 \times 10^{-8} \text{ s}$$

$$\pi^0 \rightarrow 2\gamma \quad \text{B.R. } 99.798\%$$

$$\tau = 8.4 \times 10^{-17} \text{ s}$$

Energy transfer in air showers

Energy of all hadrons

$$E_0$$

$$\frac{2}{3} E_0$$

$$\frac{2}{3} \left(\frac{2}{3} E_0 \right)$$

After n generations

$$E_{\text{had}} = \left(\frac{2}{3} \right)^n E_0$$

($n=5$, $E_{\text{had}} \sim 12\%$
 $n=6$, $E_{\text{had}} \sim 8\%$)

Energy of all em. particles

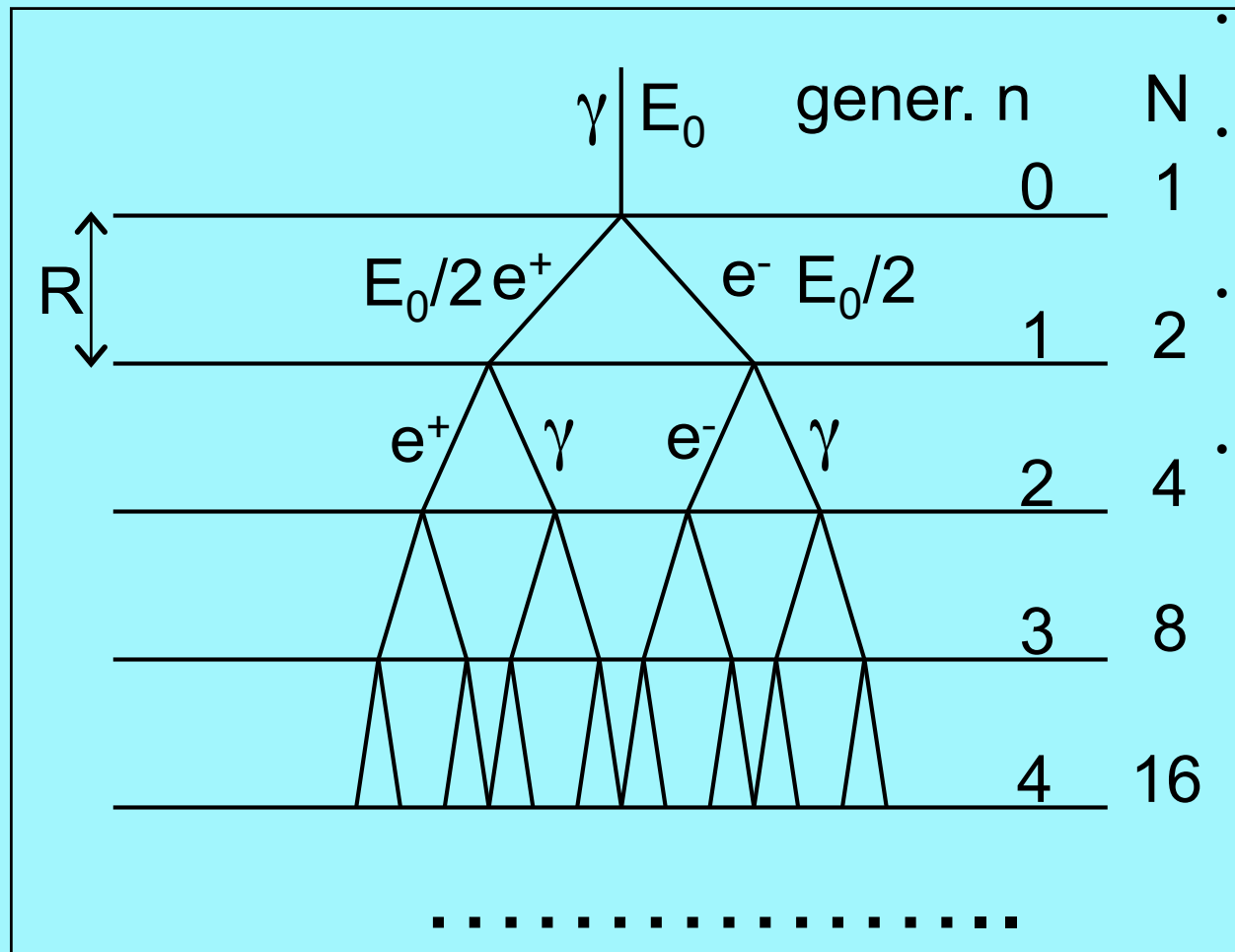
$$0$$

$$\frac{1}{3} E_0$$

$$\frac{1}{3} E_0 + \frac{1}{3} \left(\frac{2}{3} E_0 \right)$$

$$E_{\text{em}} = \left[1 - \left(\frac{2}{3} \right)^n \right] E_0$$

Heitler model



- In the n^{th} generation, 2^n particles ($e^\pm$ and γ) of energy $E_0 / 2^n$
- Shower maximum reached when E_c is reached, hence

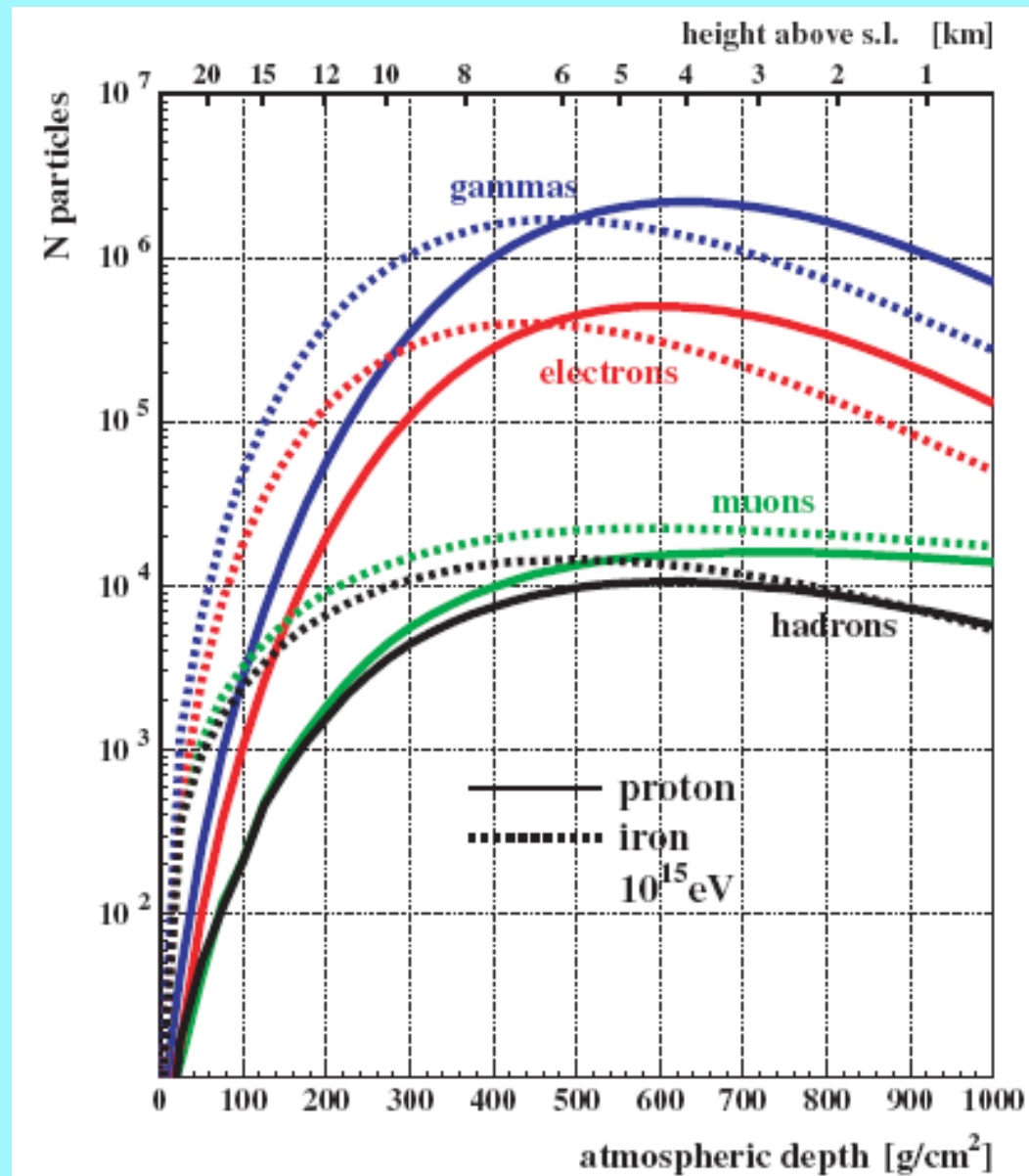
$$E_0 / 2^{n_{\text{max}}} = E_c$$
- Number of generations until shower maximum:

$$n_{\text{max}} = \ln(E_0 / E_c) / \ln(2)$$
- Atmospheric depth of shower maximum:

$$X_{\text{max}} \cong n_{\text{max}} \cdot R = X_0 \ln(E_0 / E_c)$$
 (depends logarithmically on E_0)

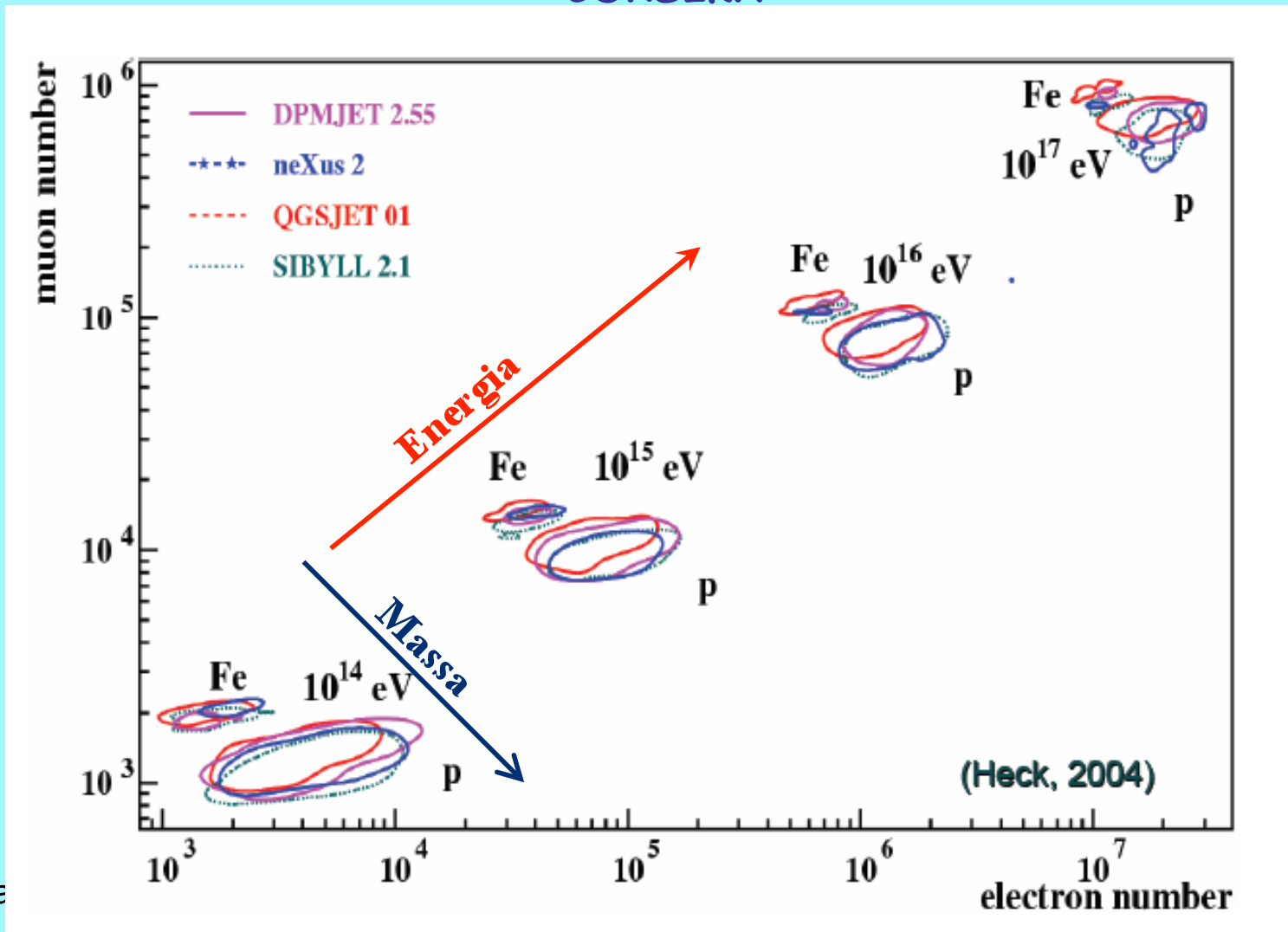
$R \sim 40 \text{ g cm}^{-2}$, 2000 m a.s.l. $\sim 800 \text{ g cm}^{-2}$, sea level $\sim 1000 \text{ g cm}^{-2}$

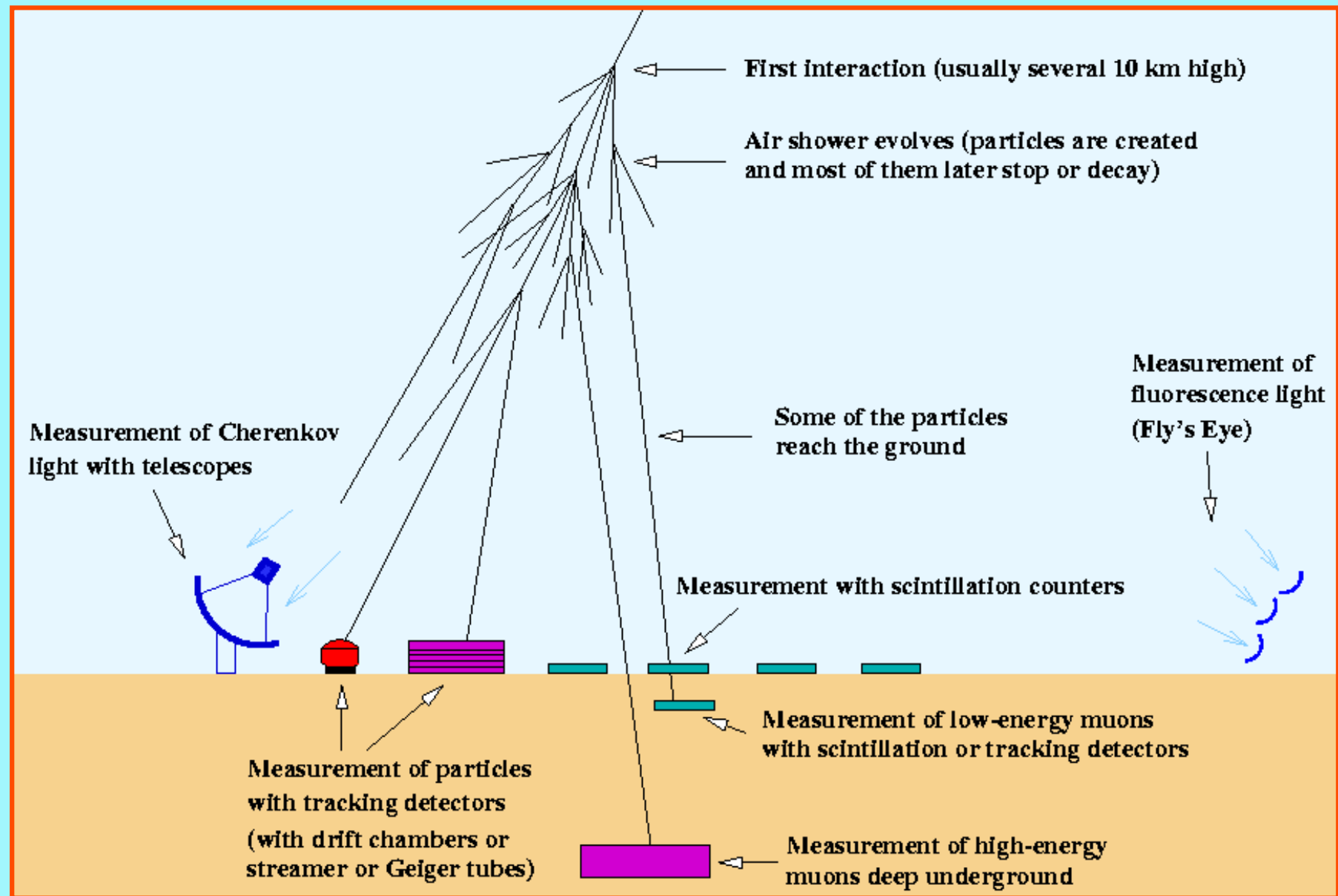
Development in atmosphere of EAS produced by protons or Fe nuclei at $E=10^{15}$ eV

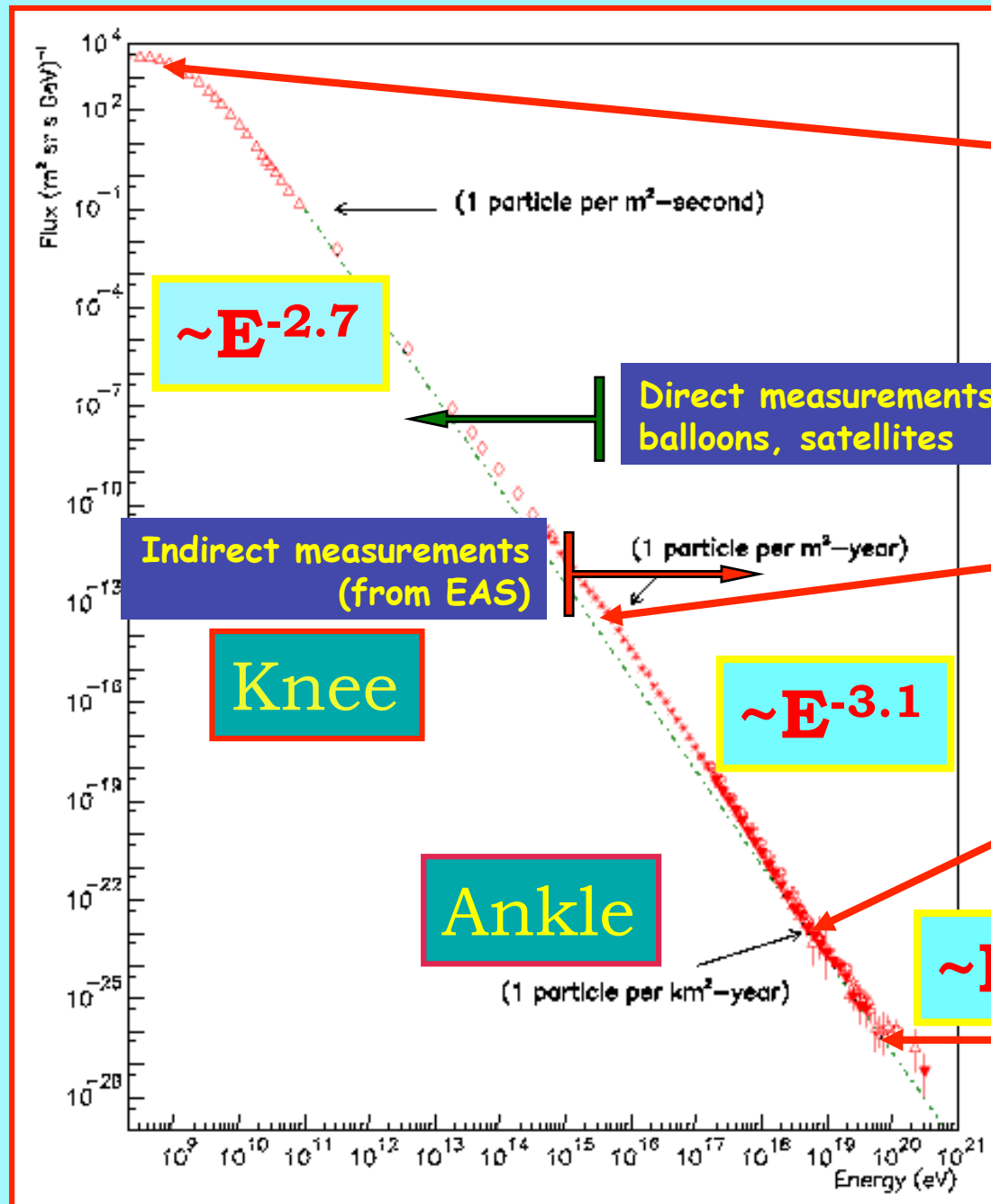


Relation between number of μ and number of electrons at sea level
It is important to observe the level of fluctuations in the EAS development
Different colors represent different hadronic interaction models

CORSIKA







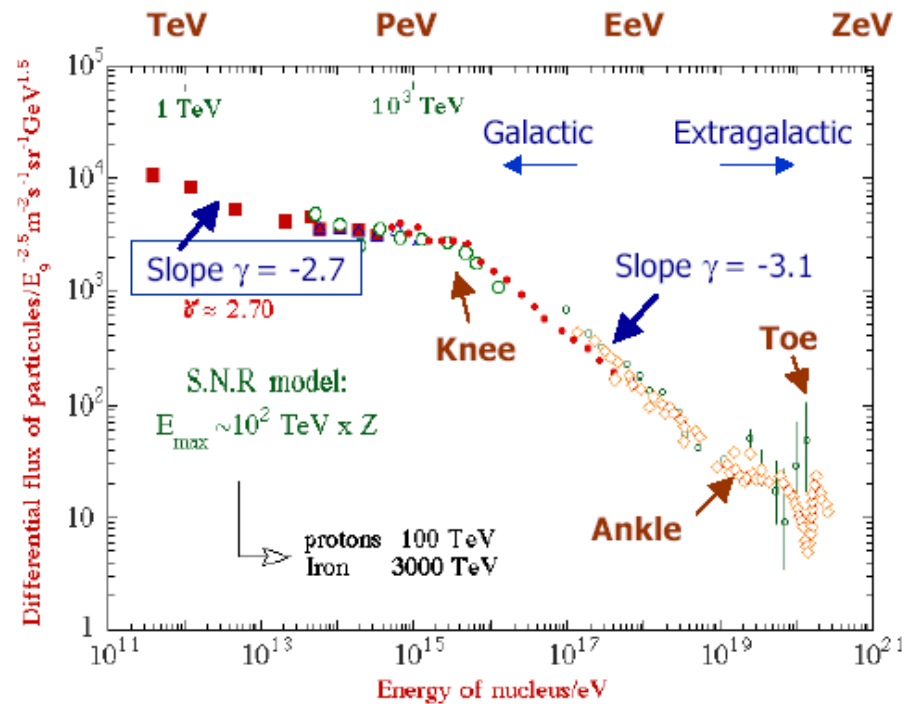
$\sim 10^2 / \text{m}^2 / \text{second}$

$\sim 1 / \text{m}^2 / \text{year}$

$\sim 1 / \text{km}^2 / \text{year}$

$\sim 1 / \text{km}^2 / \text{millen.}$

The Cosmic Ray Spectrum



All-charged-particle spectrum plotted to make it easier to see slope changes (flux is scaled by $E^{2.5}$)

PS: Need to know prefixes for really big powers of 10!

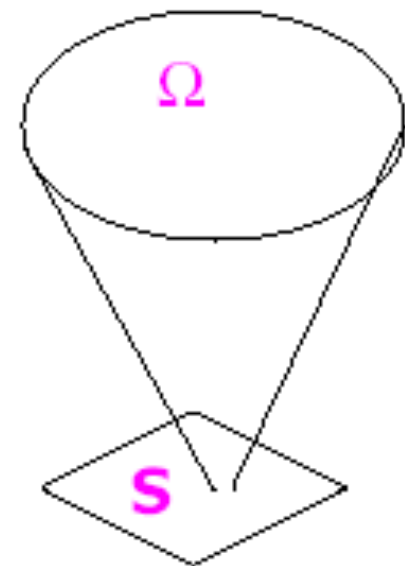
- TeV = Tera-electron-volt (10^{12} eV)
- PeV = Peta-electron-volt (10^{15} eV)
- EeV = Exa-electron-volt (10^{18} eV)
- ZeV = Zetta-electron-volt (10^{21} eV)

Exposure $S\Omega T = \text{m}^2\text{-steradian-days}$

Rate of arrival at highest energies:
about 1 particle per $2 \text{ km}^2\text{-sr-year}$
for energy $> 10^{19} \text{ eV}$

To detect high energy cosmic rays, we need lots of exposure:

- Large collecting area S
- Large solid-angle acceptance Ω
- Large collecting time T



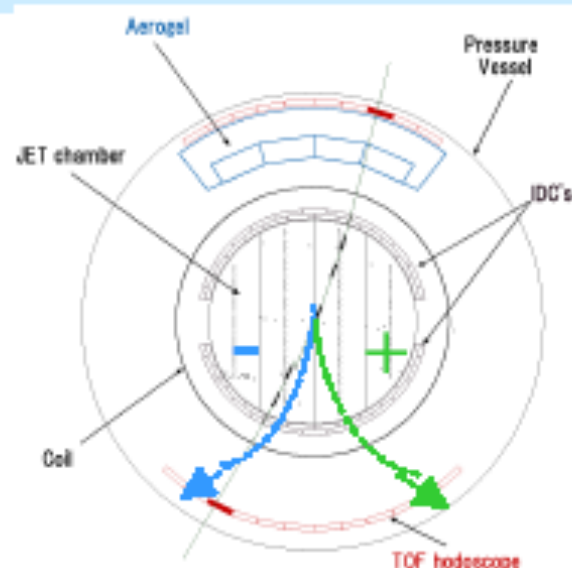
Typical direct observations

Experiment	Observables	Energy
JACEE(1979-1995)	p, He, ..., Fe;	TeV – 1 PeV
RUNJOB(1995-1999)	p, He, ..., Fe; ultra-heavy ($Z \geq 30$);	TeV – 1 PeV 1-10 GeV/n
ATIC(2001-2002)	p, He, ..., Fe;	10 GeV-100 TeV
BESS(1993, -)	p, He; anti-p, anti-He, $e^\pm$;	1-500 GeV .1-10 GeV
AMS(1999,...)	p, He, C, ..., Fe(?); anti-p, anti-He, anti-C, $e^\pm$;	1 GeV-1 TeV .1-10 GeV

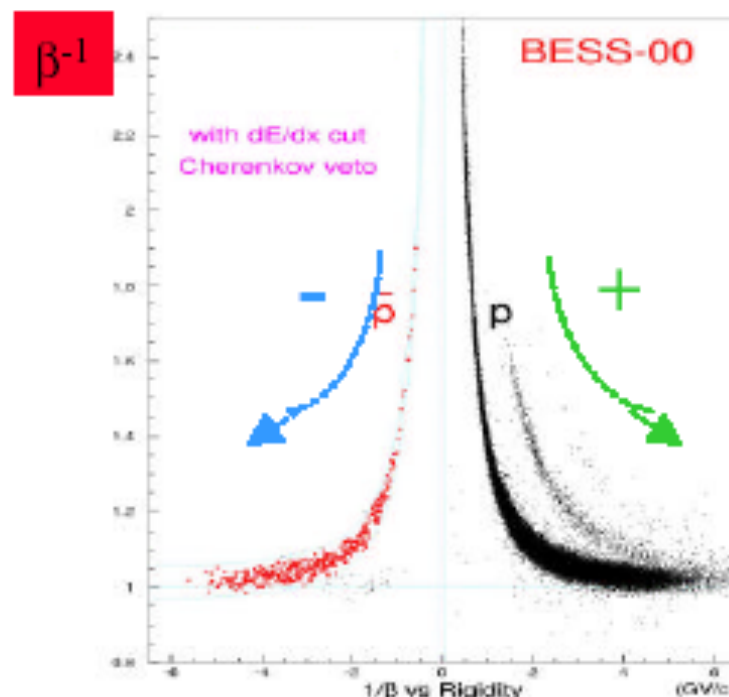
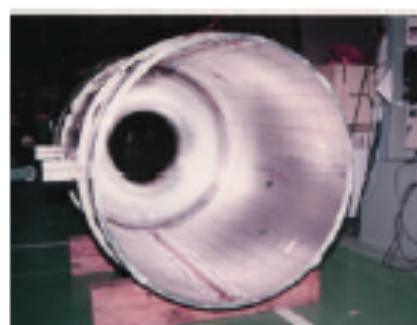
Measurement Technique

Particle identification by mass and charge

Charge-sign from deflection direction



Warm bore solenoid
 $B \sim 1$ Tesla $\pm 3\%$
Drift chambers
 $dx \sim 150$ microns

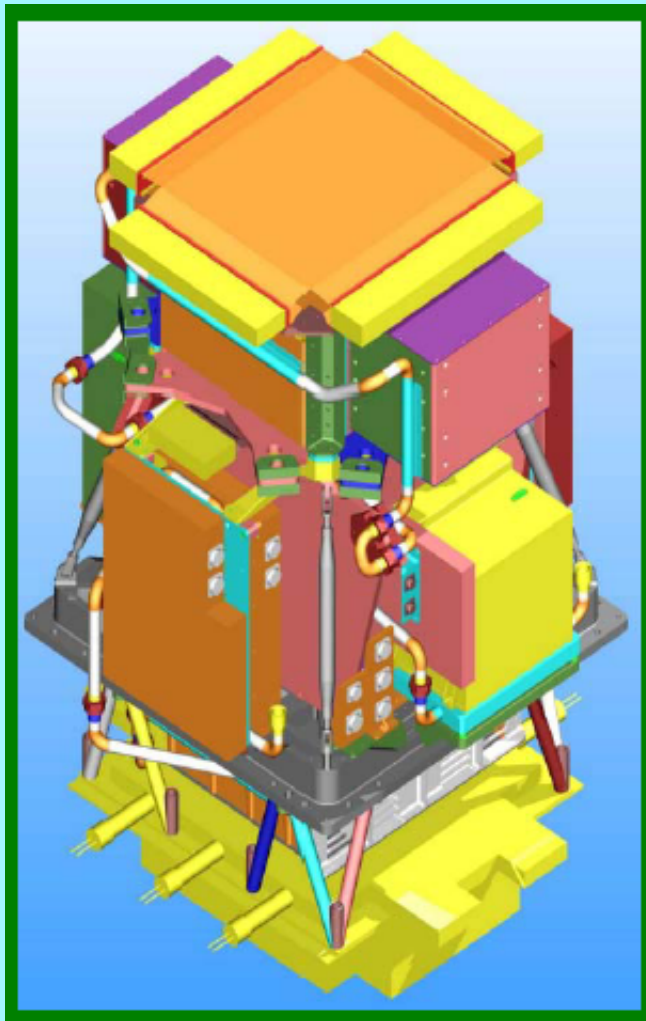


Rigidity
($R = pA/Ze$)

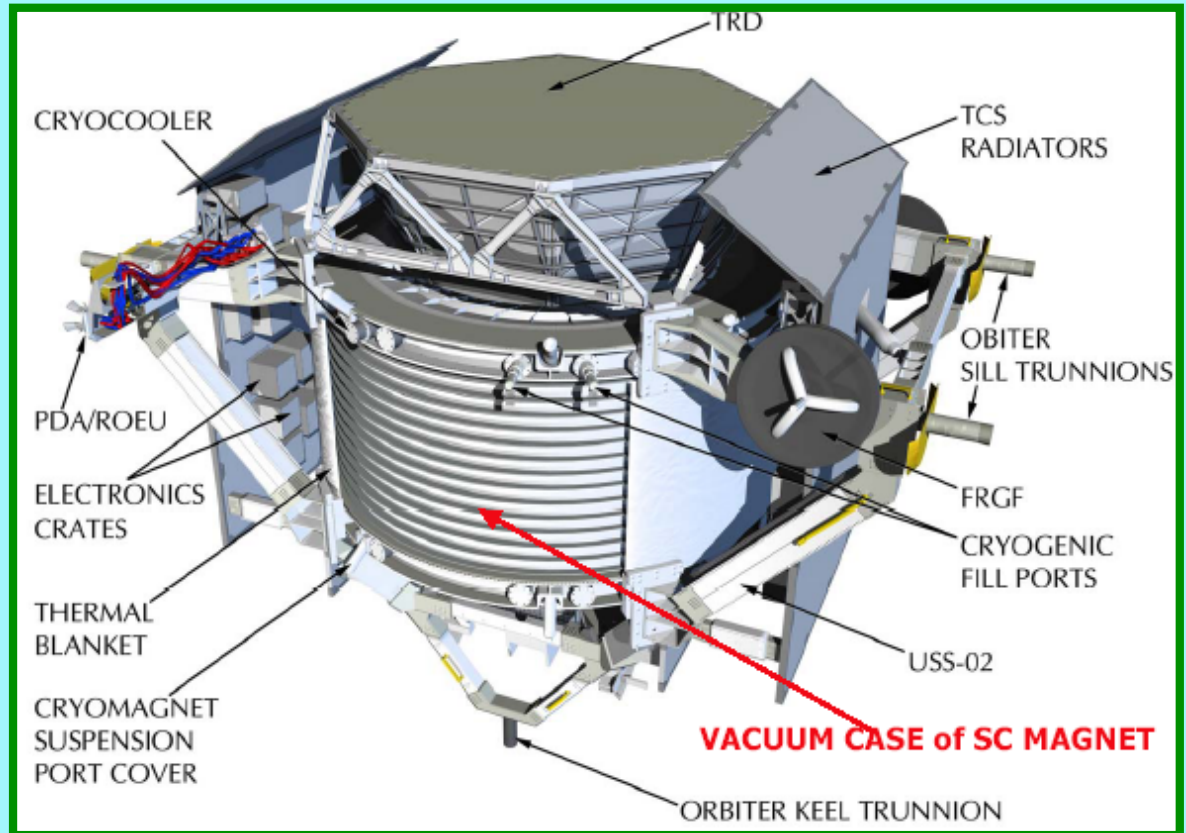
$$m = \frac{RZe}{\gamma\beta c}$$

- Superconducting magnetic-rigidity spectrometer ($B \sim 1$ Tesla)
 - measures momentum per unit charge or rigidity (pA/Ze)
- Precision time-of-flight system: measures velocity and charge
- Silica-aerogel Cherenkov detector: background rejection

Pamela e AMS



- $\bar{p}$: 80 MeV $\div$ 190 GeV
- e^+ : 50 MeV $\div$ 270 GeV
- $\bar{\text{He}}/\text{He}$: some unity 10^{-7}
- nuclei spectra (H to O)
- 100 MeV/n $\div$ 200 GeV/n



AMS will search for extraterrestrial p^+ , e^- , γ ; antimatter nuclei (anti-He, C, 10^{-9}); light isotopes;



May 16, 2011, 08:56 AM

Total weight: 2008 t
AMS weight: 7.5 t

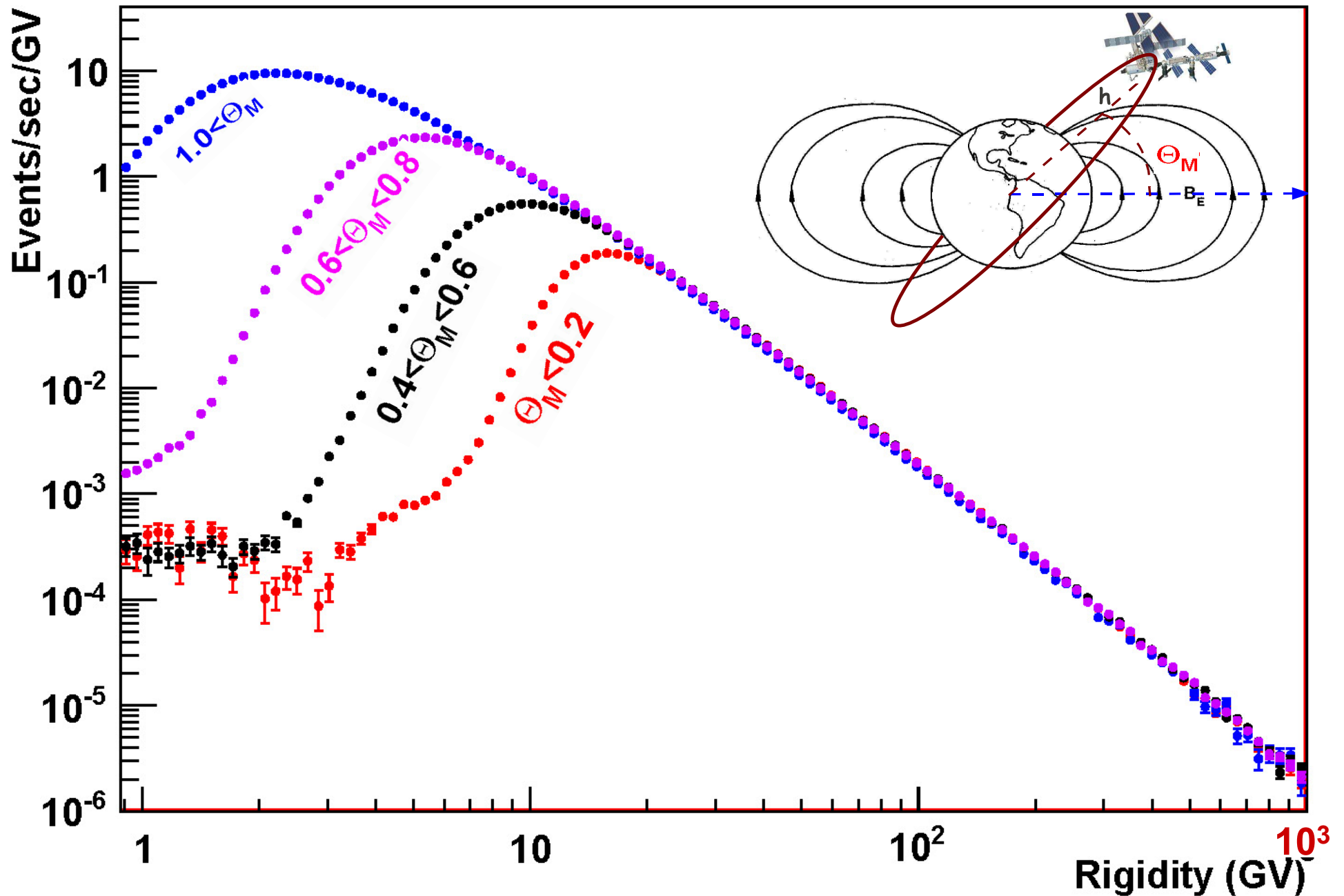


May 16, 2011, 08:56 AM

Total weight: 2008 t
AMS weight: 7.5 t



AMS data on ISS: He rate



RUNJOB experiments



recovery



dismounting
early August



launching
mid. July

construction
early May
(ISAS, ICRR)

RUNJOB detector

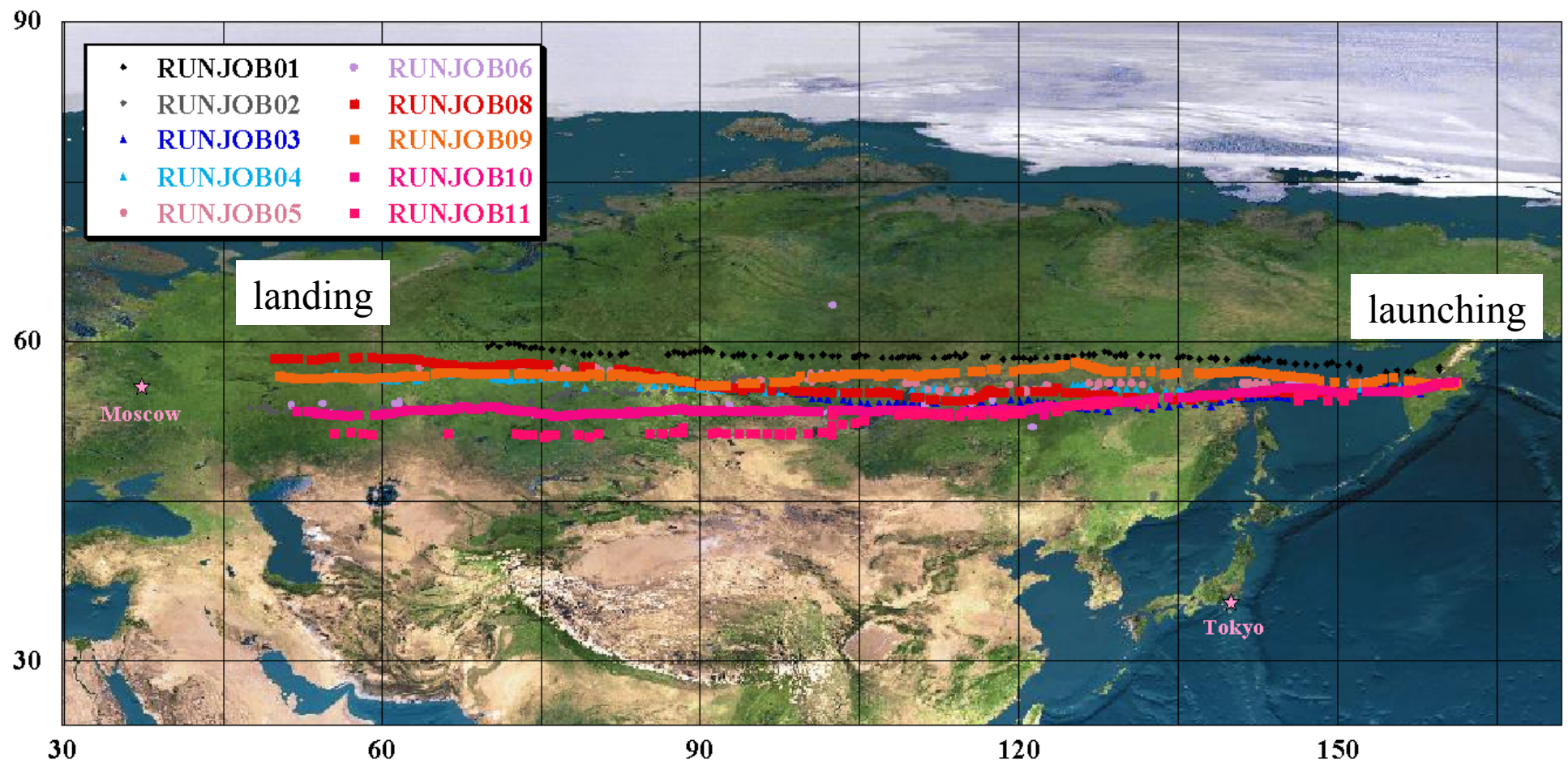
target (~ 10 cm)

spacer (~ 20 cm)

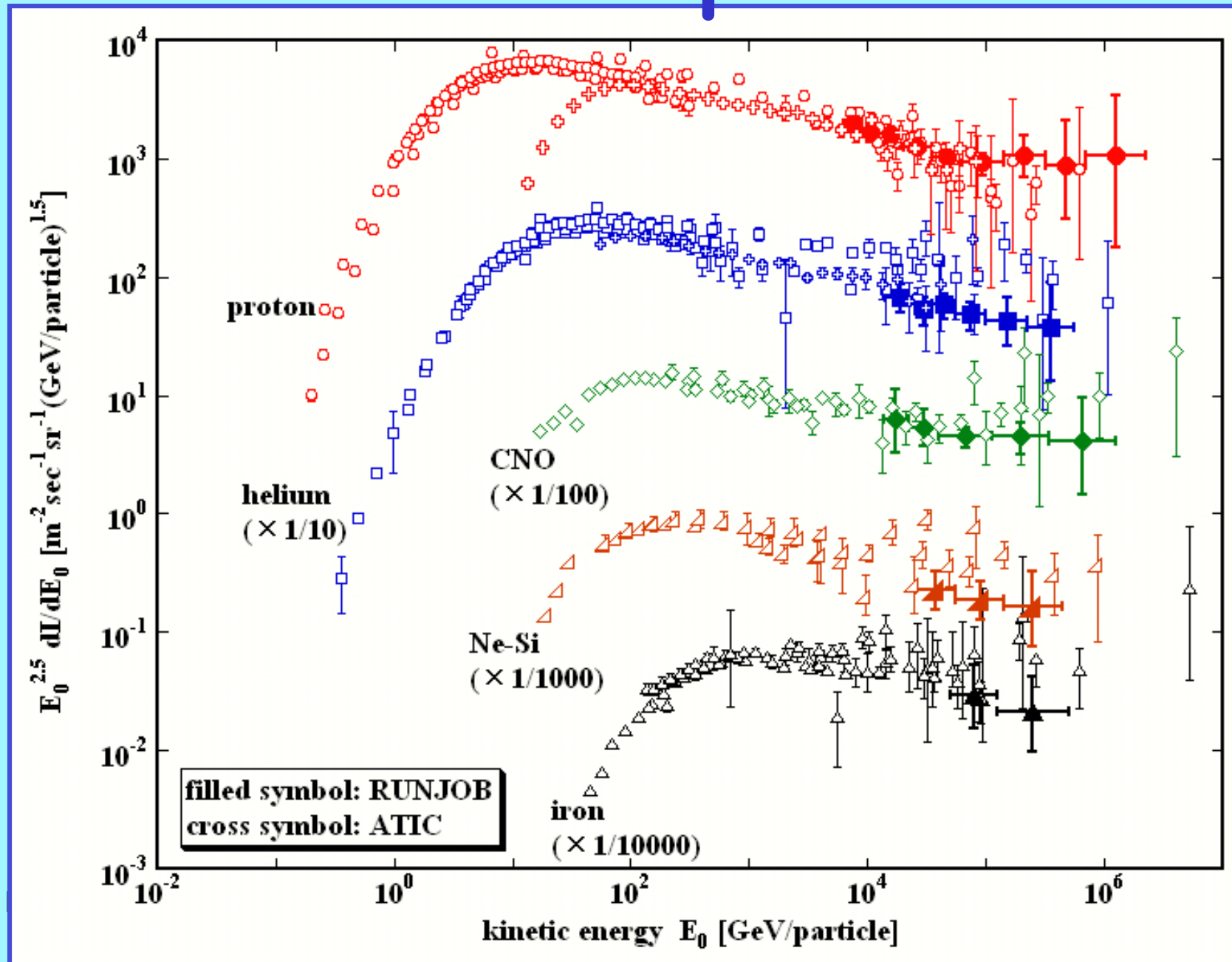
thin EC (~ 5 c.u.)

diffuser (~ 4 cm)

Balloon Trajectory



individual spectra



The Primary Cosmic Ray Flux

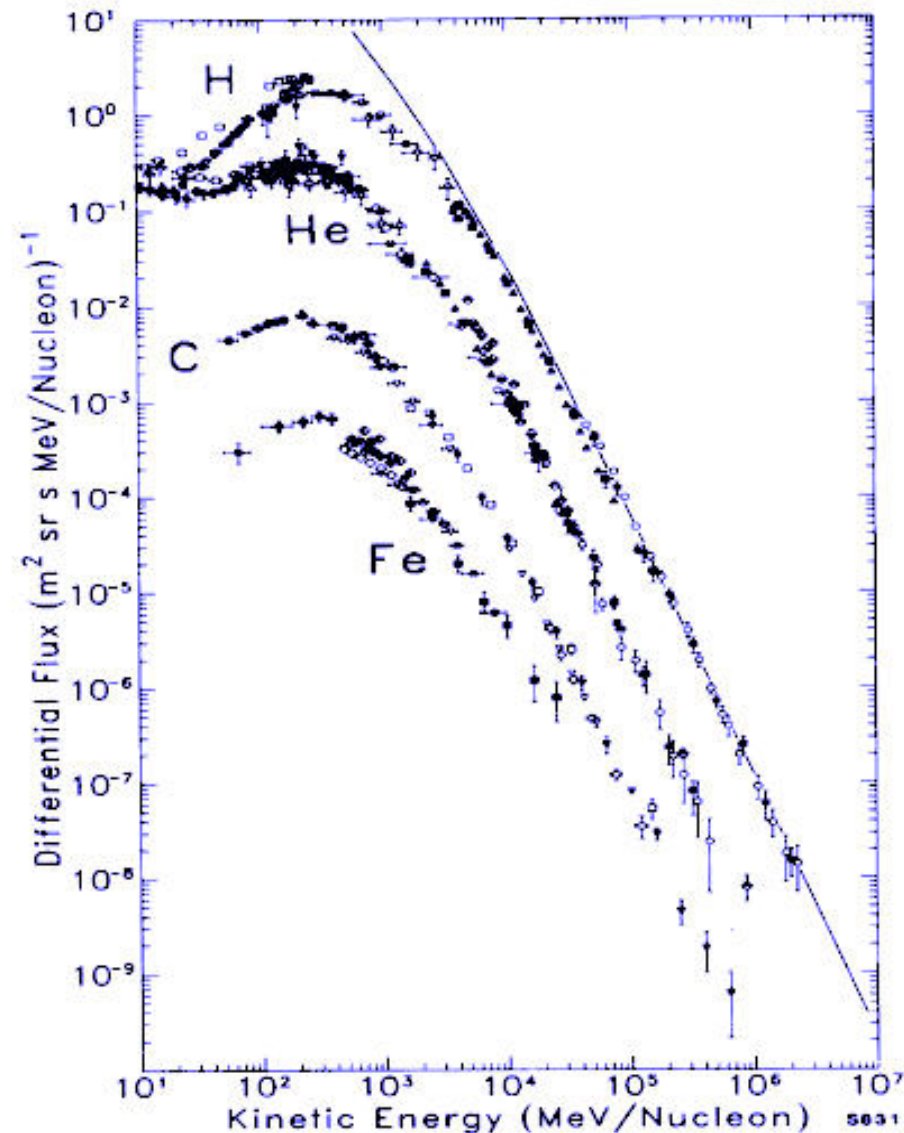
DIRECT MEASUREMENT

Interstellar fluxes

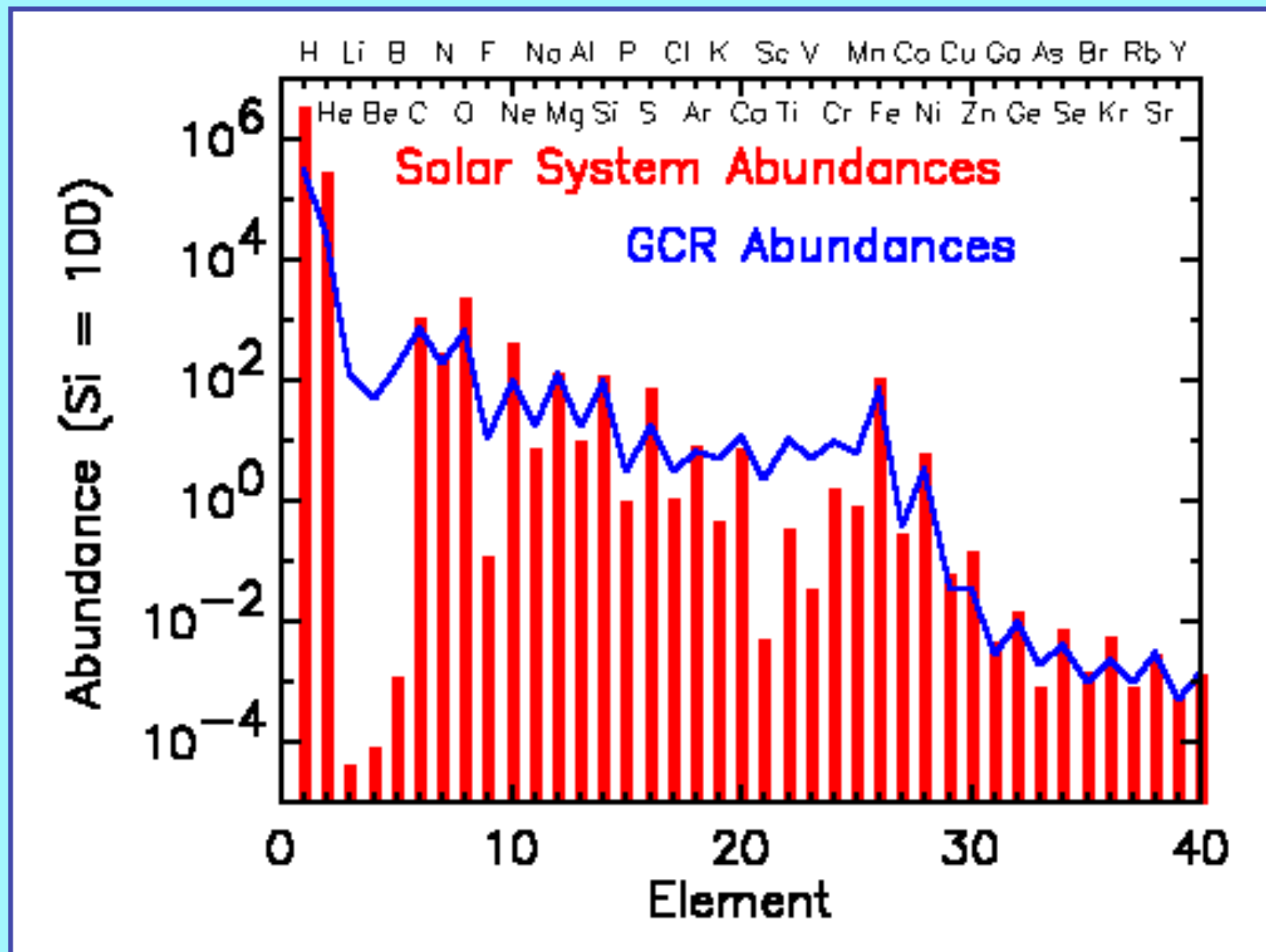
Solar modulation

Geomagnetic effects

M. Bertaina

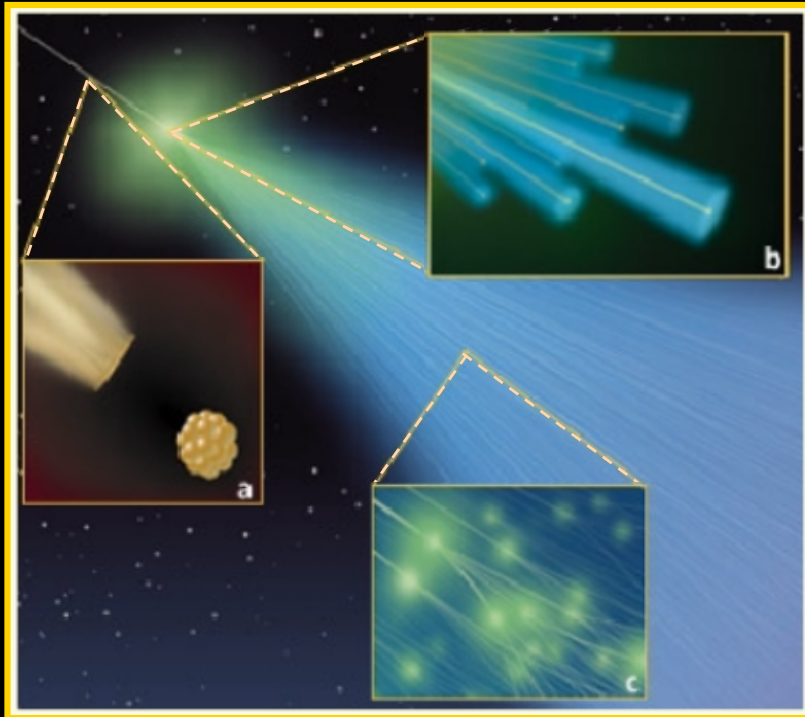


C



... and Extensive Air Shower (EAS) ?

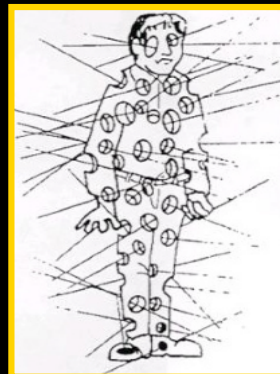
When it crosses the atmosphere



- The **cosmic ray (primary particle)** collides with the nuclei of air and creates a
- cascade of **secondary particles** of lower energy that, on their turn
- make further collisions that produce a **shower** of **billions or more** particles that reach the ground in an area whose **extension** can be of several square kilometers.

More than hundreds of **secondary particles** cross our body every seconds !
... and the exposure grows with altitude

(cosmic rays are of great importance in biology; contributing, along time, to genetic mutations, have played a role and continue to play an important role on the evolution of life on the Earth)



The EAS contains everything:

- nucleons, nuclei,
- hard gamma,
- mesons ($\pi^\pm, \pi^0, K^\pm, \dots$),
- charged leptons ($e^\pm, \mu^\pm, \tau^\pm$),
- neutrinos (ν_e, ν_μ, ν_τ).
- ...

INDIRECT MEASUREMENT

Indirect techniques measure the secondary products of the interaction of cosmic rays in atmosphere.

EAS EXTENSIVE AIR SHOWER

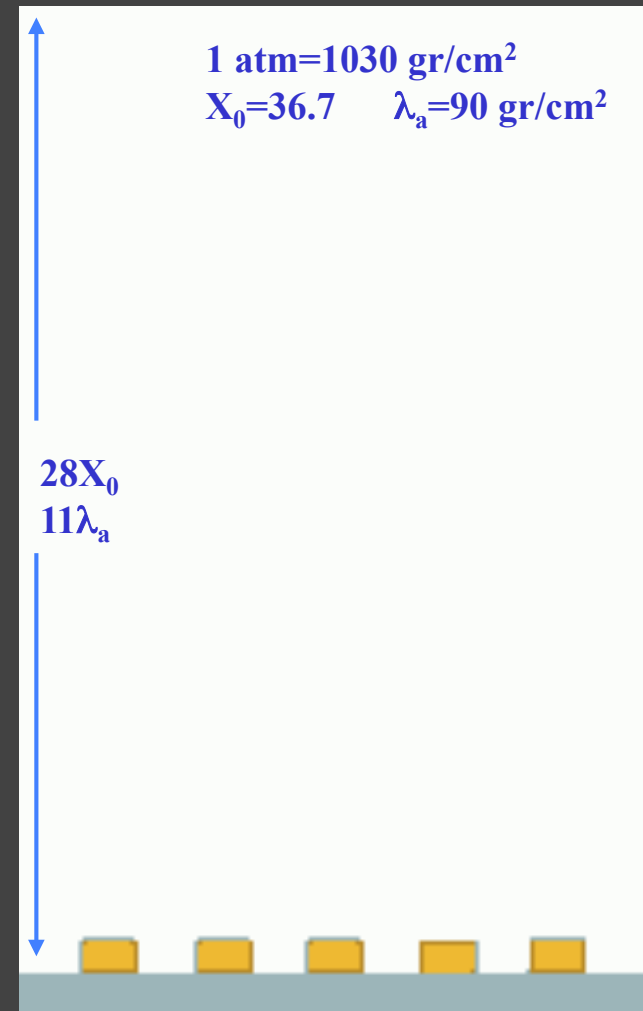
In the interaction the identity of primary is lost.

Only in a statistical way, with multi-parametric analysis it is possible to separate groups of elements (p+He, CNO, Fe)

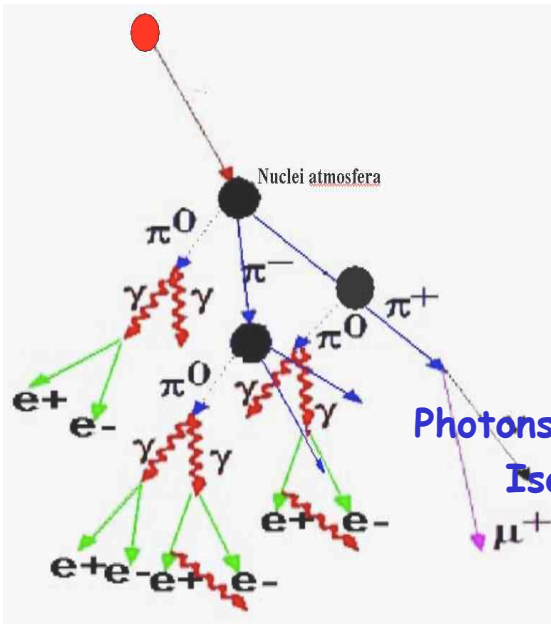
Fundamental is the necessity to use simulations extrapolating at high energies the results obtained at accelerators

M. Bertaina

Cosmic Rays



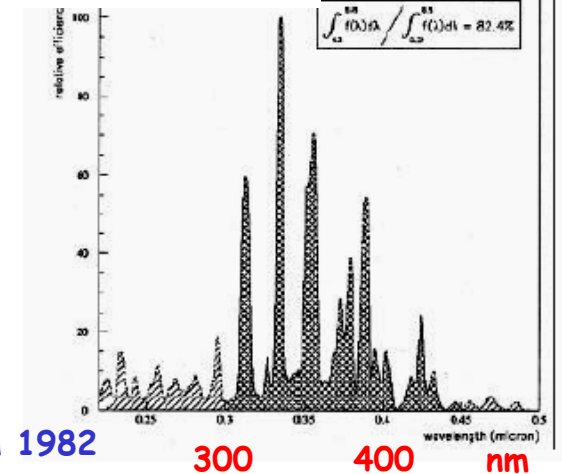
Primary Cosmic Ray



Photons of UV Fluorescence
Isotropic Emission

Emission of fluorescence Nitrogen

$\lambda_{\text{abs}} \sim 15 \text{ Km}$
 $4 \div 5 \text{ y/m.}$
 $N_e > 10^8 \text{ e}$
 $E \sim 10^{18} \text{ eV}$



Fly's Eye Utah 1982

Observables

$N_e \sim E_0$

N_μ

X_{MAX}

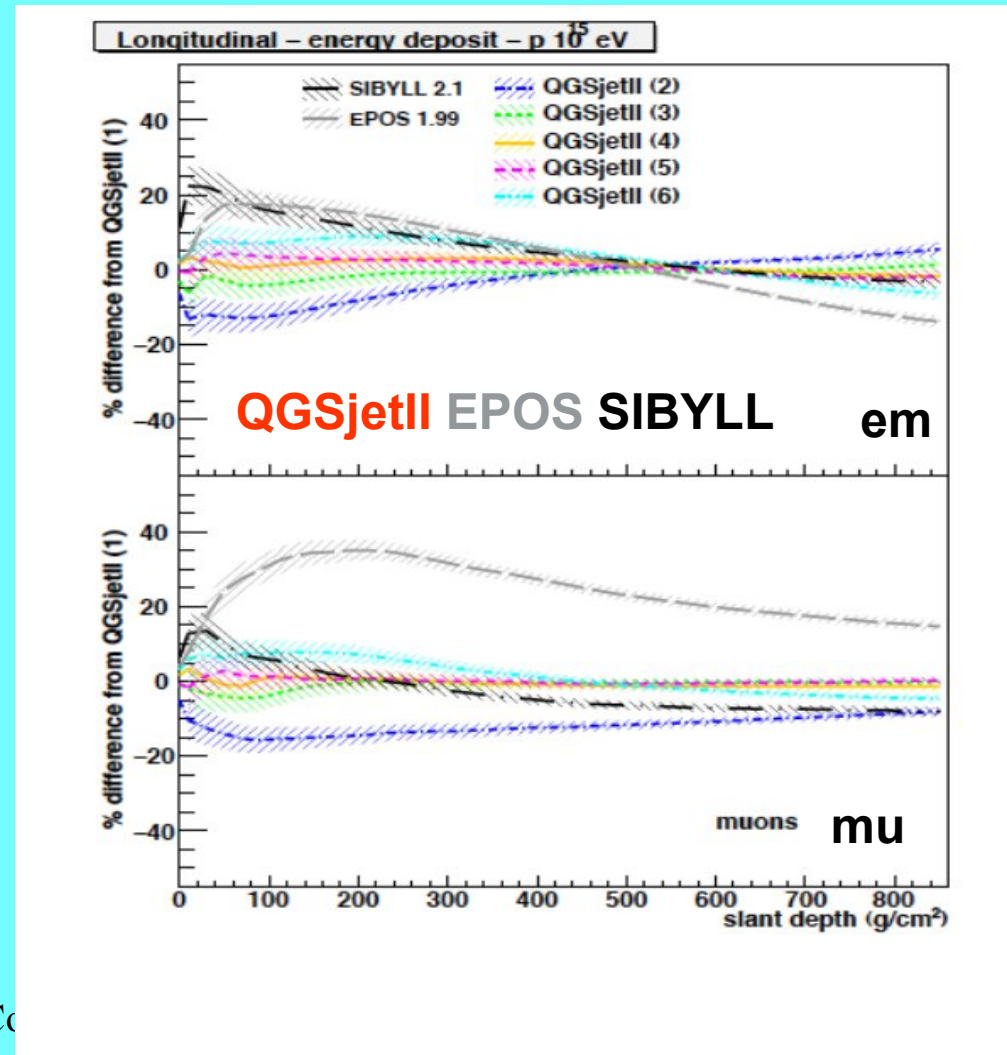
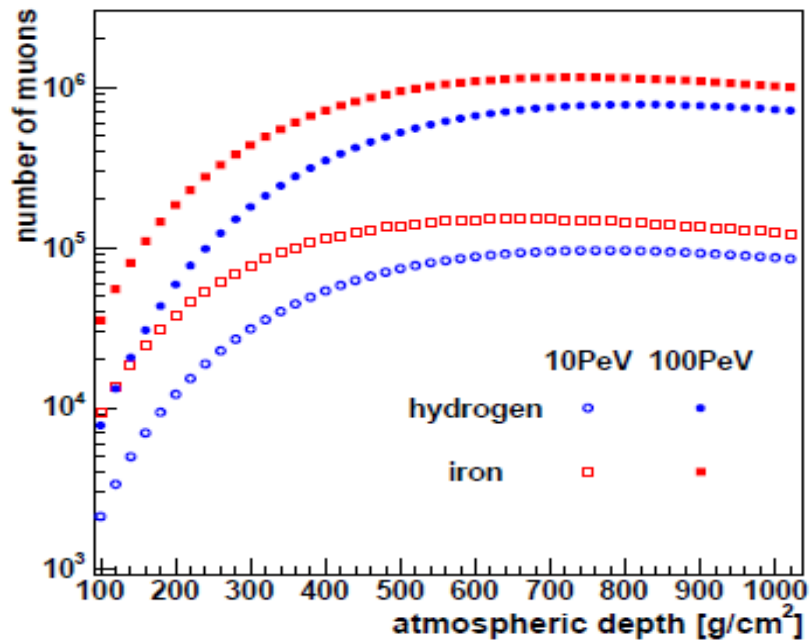
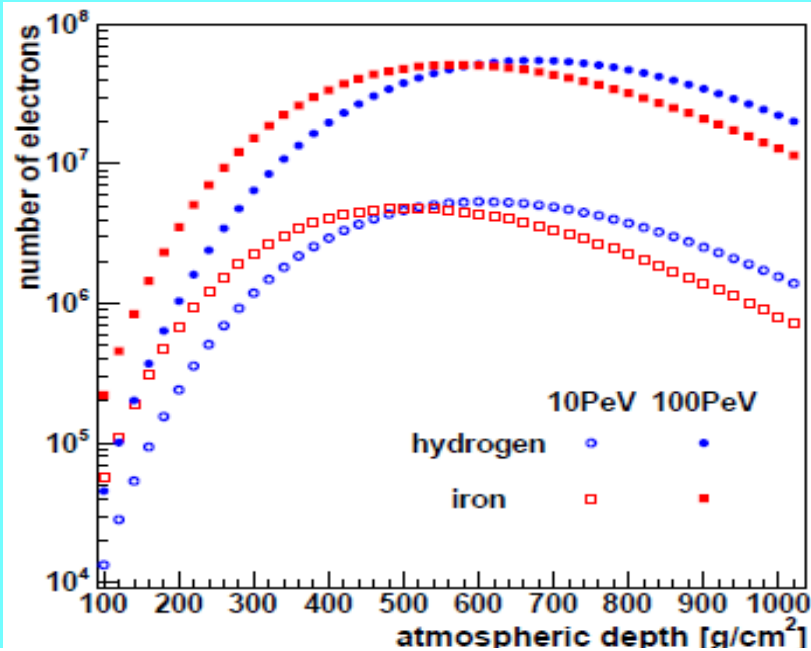
directions

Apparato sciame
al suolo

Electromagnetic shower
 $e^+, e^-, \mu^+, \mu^-, \gamma$

Cherenkov
Radiation

Longitudinal distribution of EAS & model dependence



Towards the Knee...

Measurement of elemental fluxes vs. E

Relevant for:

Astrophysics

Acceleration and confinement of c.r.

Particle Physics

fluxes of secondaries in atmosphere

Benchmarks for shower/interaction models

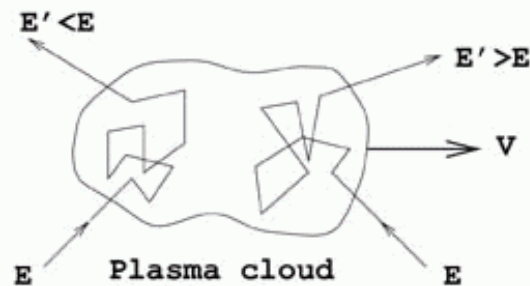
input for atmospheric neutrino analysis

(oscillation physics)

Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

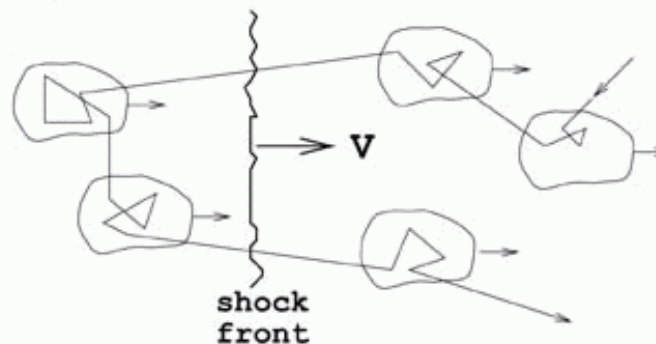
2nd order :
randomly distributed magnetic mirrors



$$\frac{\Delta E}{E} \sim \beta^2 \quad \beta = \frac{V}{c} \lesssim 10^{-4}$$

[Slow and inefficient]

1st order :
acceleration in strong shock waves
(supernova ejecta, RG hot spots...)



$$\frac{\Delta E}{E} \sim \beta \quad \beta = \frac{V}{c} \lesssim 10^{-1}$$

1

What is the origin of the knee?

1a

The energetic limit of the acceleration mechanism of galactic c.r.?

$$E_{\max} \sim Z \cdot 10^{15} \text{ eV}$$

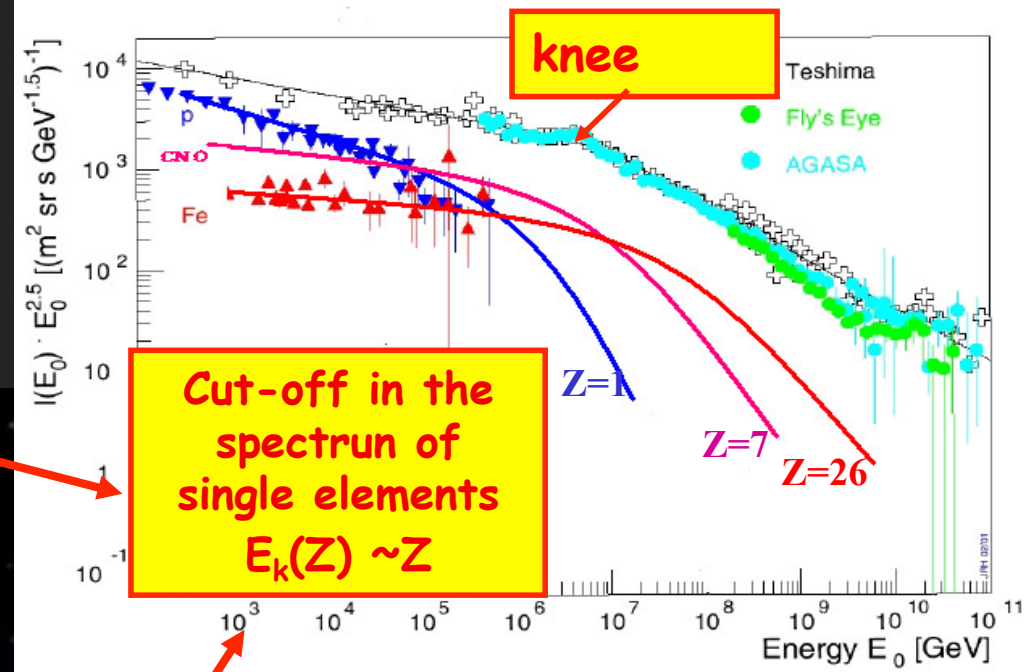
Acceleration in Supernova Remnant

$B \sim 3 \mu\text{G}$

1b

It is due to the limit due to the increase of probability to escape probability of galactic confinement?

$$P_{\text{fuga}} \sim \text{rigidita}' \sim 1/Z$$

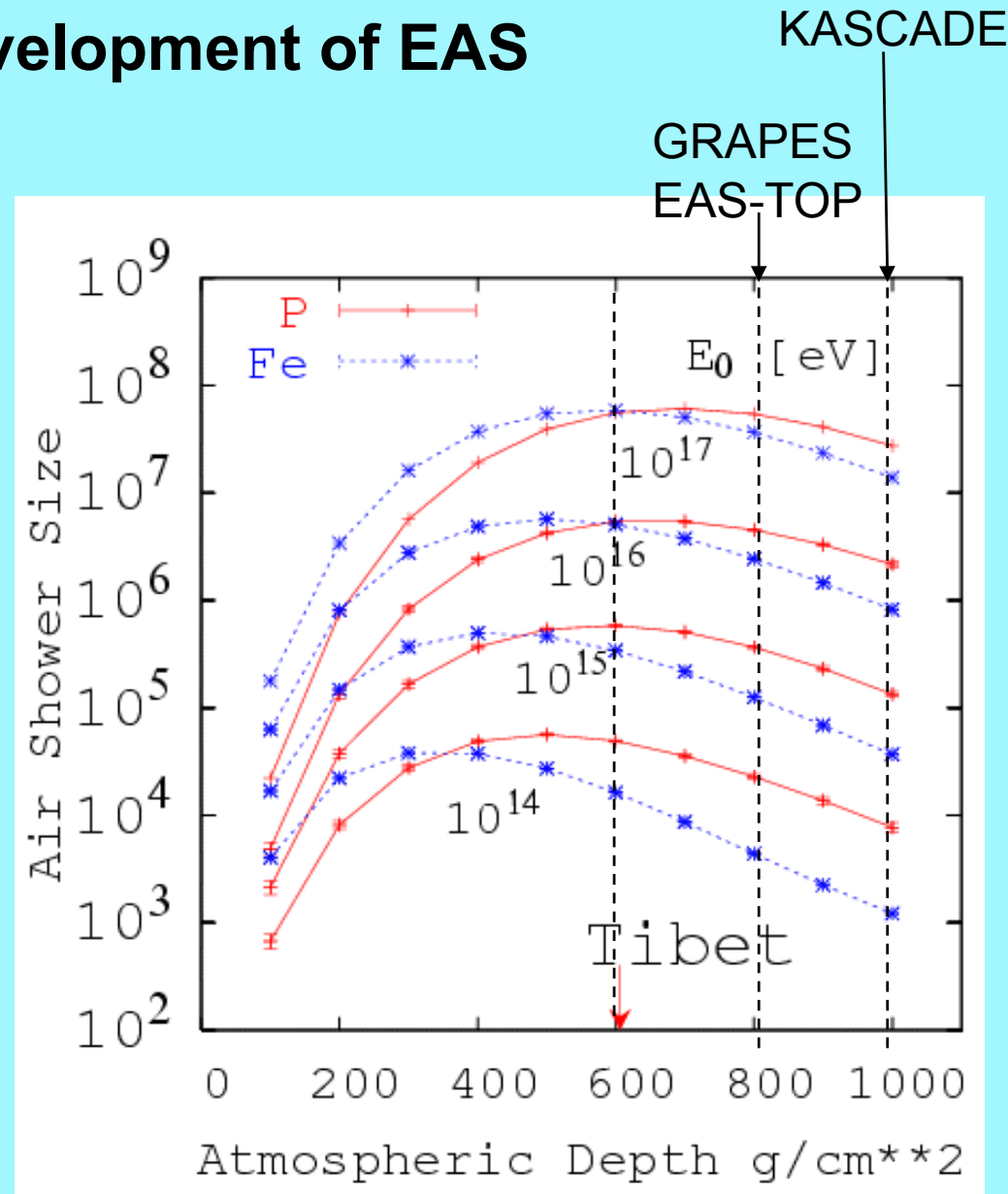


Longitudinal development of EAS

In the knee region:

At high mountain the shower is at maximum
less fluctuations

Sea level is better
for composition studies
because **H – Fe**
separation is easier



M. Shibata, CRHEU 2007.3.8.

Cosmic Rays

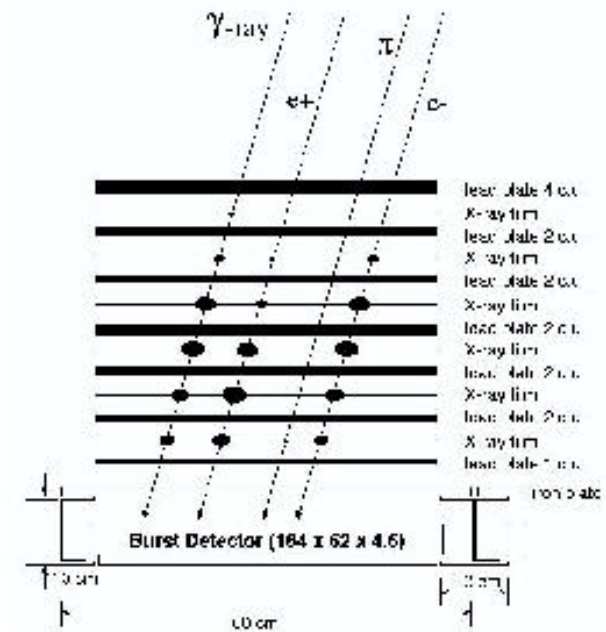
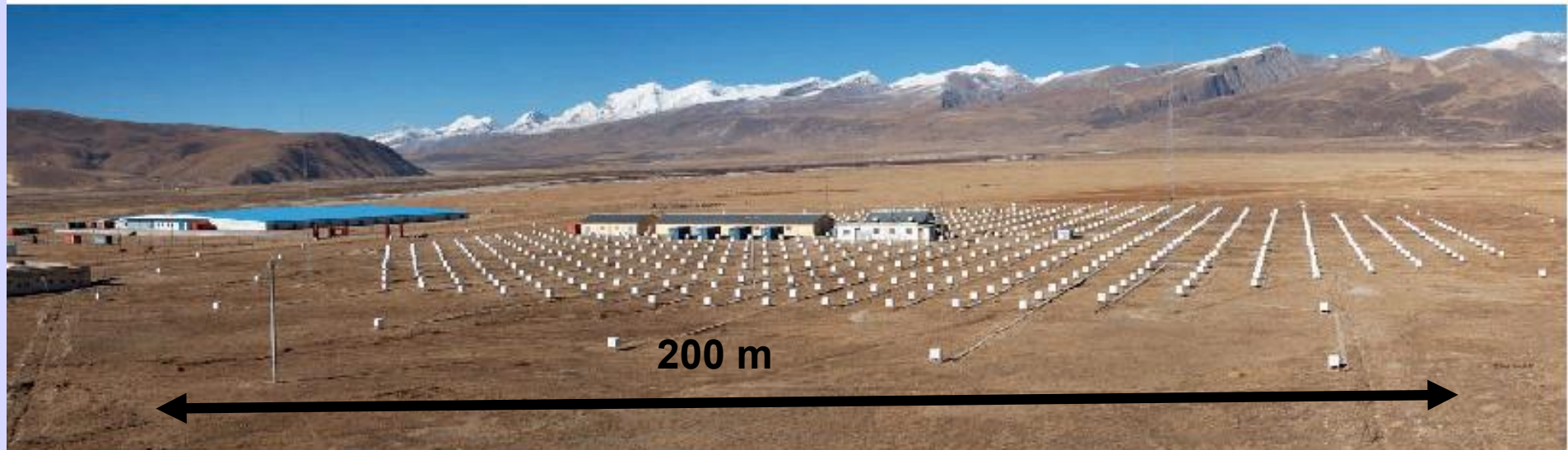
BASJE - MAS

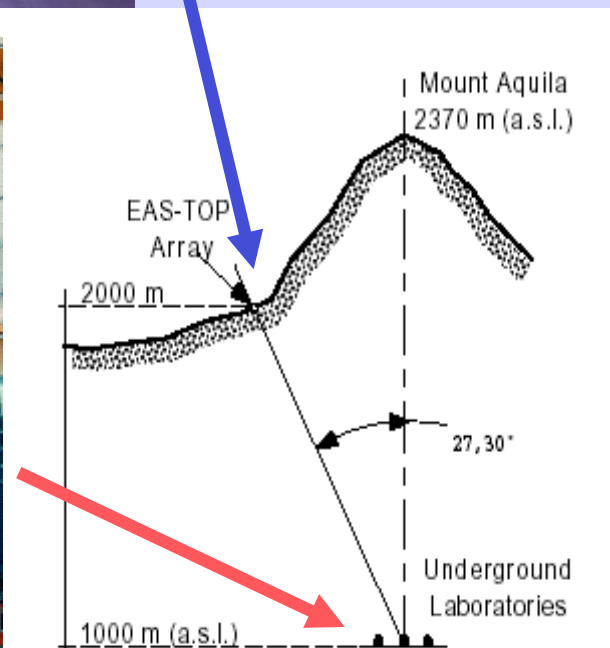


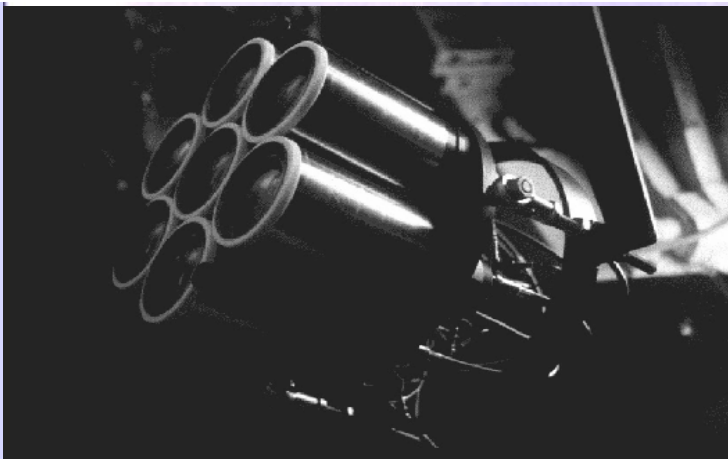
$E_{th} \sim 6 \text{ TeV}$
Chacaltaya, 5200 m a.s.l.

TIBET

TIBET, 4250 m s.l.m.







2 wide angle detectors per telescope
 (MIRROR: $A = 0.5 \text{ m}^2$, f.l. = 40 cm , f.o.v. = 0.16 sr)
equipped with 7 photomultipliers
 (d = 6.8 cm , f.o.v. = 0.023 sr)



Trigger threshold: $N_{\text{phe,th}} = 120 \text{ phe / mirror}$ ($E_{\text{thr}} \approx 40 \text{ TeV}$ at $r = 130 \text{ m}$)

Trigger rate: 7 Hz/telescope

Cherenkov event: coincidence in $\Delta T \in [30 \text{ ns}, 1 \mu\text{s}]$ between any 2 corresponding PMs.

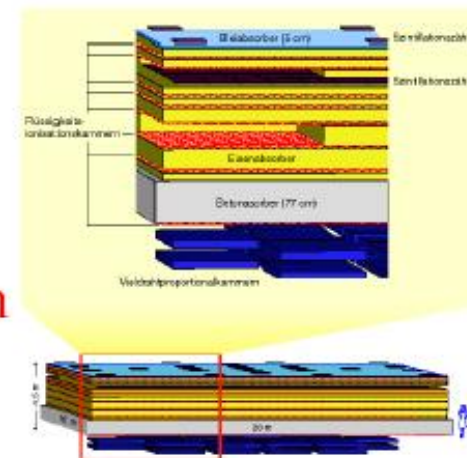
KASCADE

- energy range 100 TeV – 80 PeV
- up to 2003: $4 \cdot 10^7$ EAS triggers
- large number of observables:
 - electrons
 - muons (@ 4 threshold energies)
 - hadrons



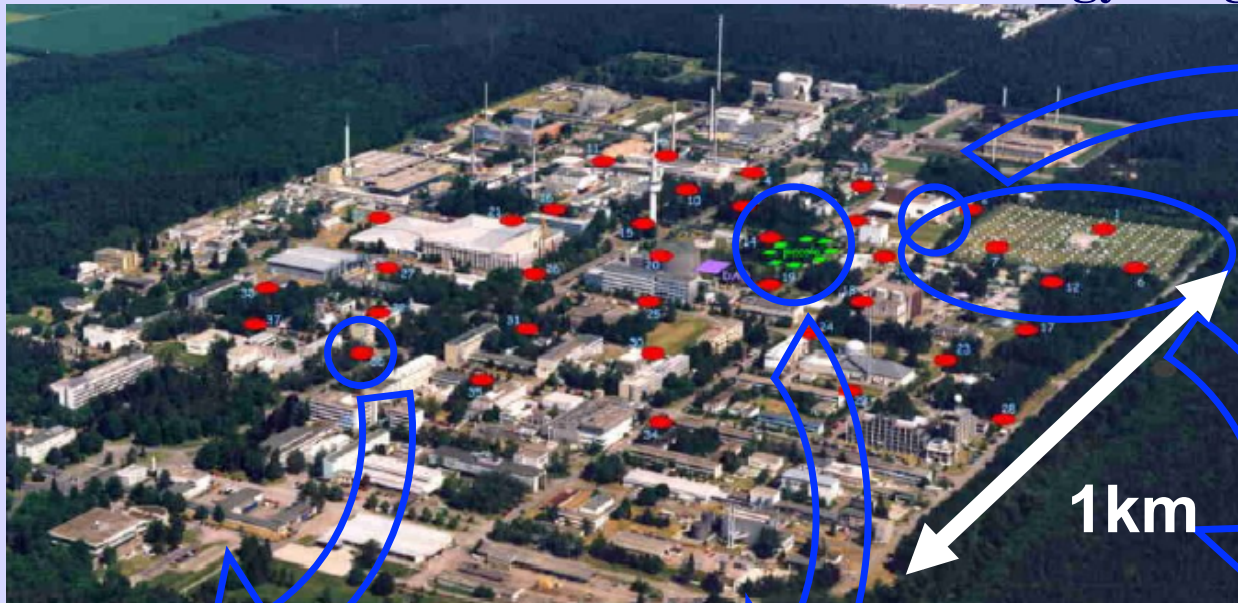
e/μ

Hadron

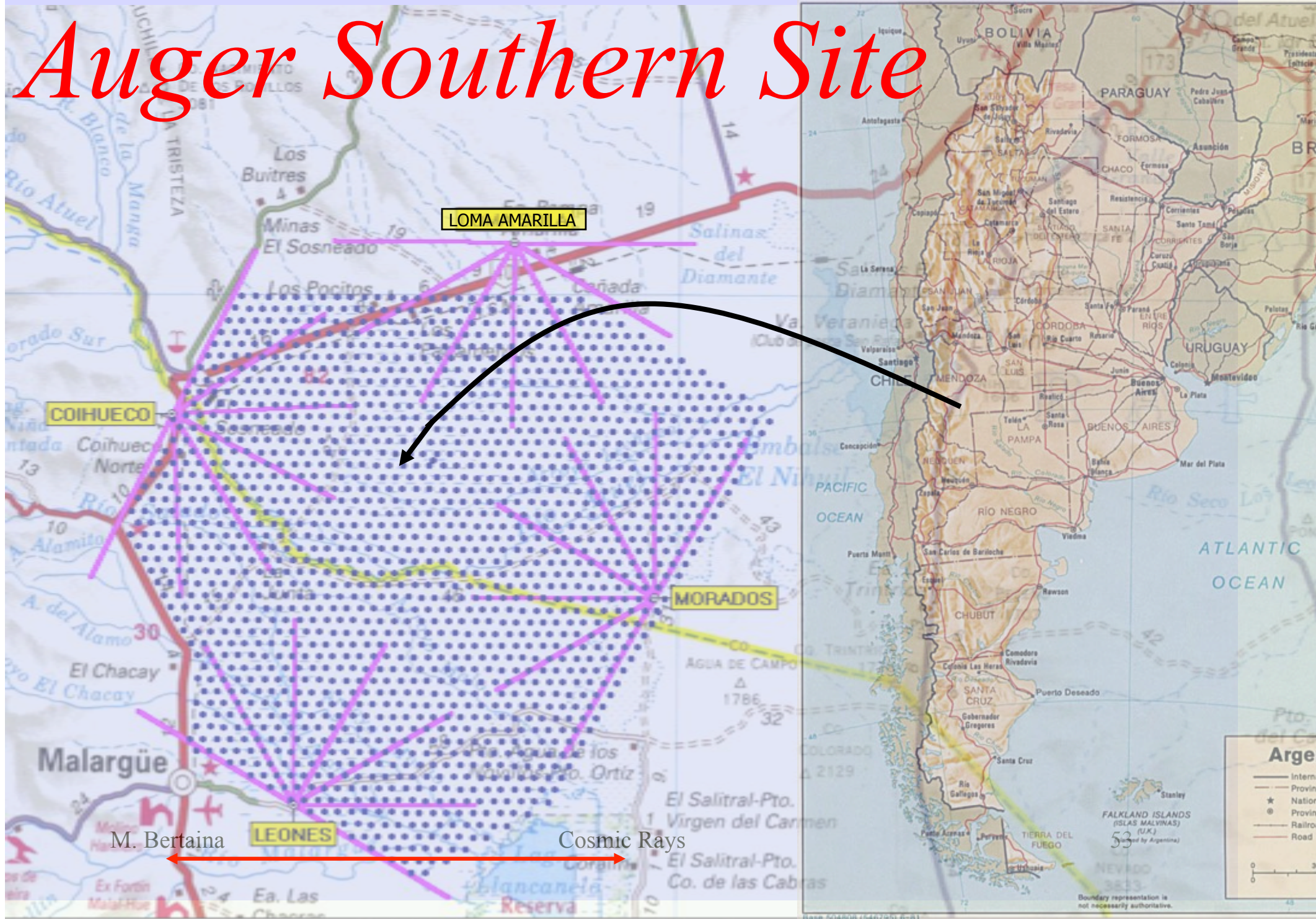


KASCADE-Grande = **K**arlsruhe **S**hower **C**ore and **A**rray **D**etector + **G**rande and **L**OPES

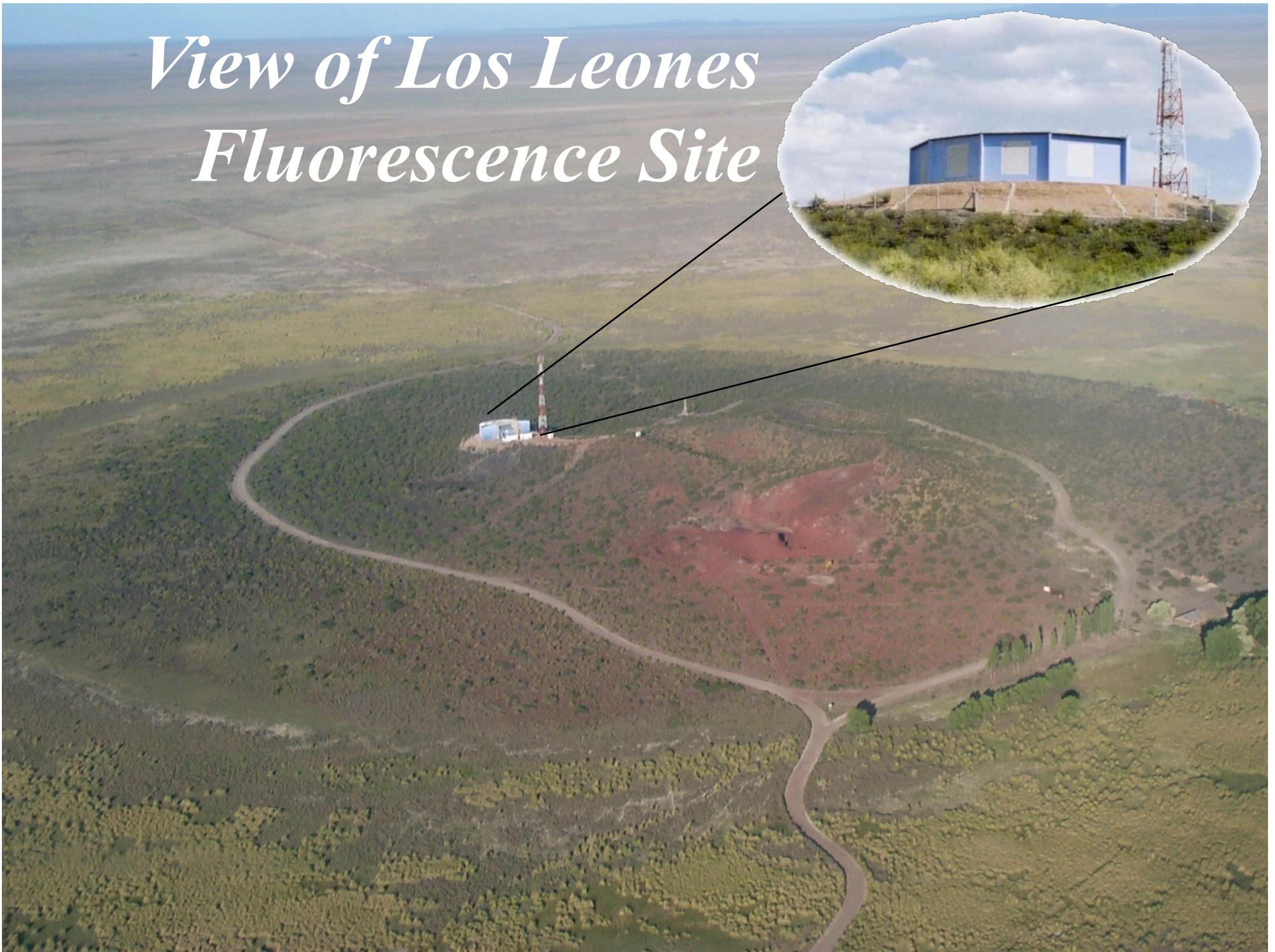
Measurements of air showers in the energy range $E_0 = 100 \text{ TeV} - 1 \text{ EeV}$



Auger Southern Site



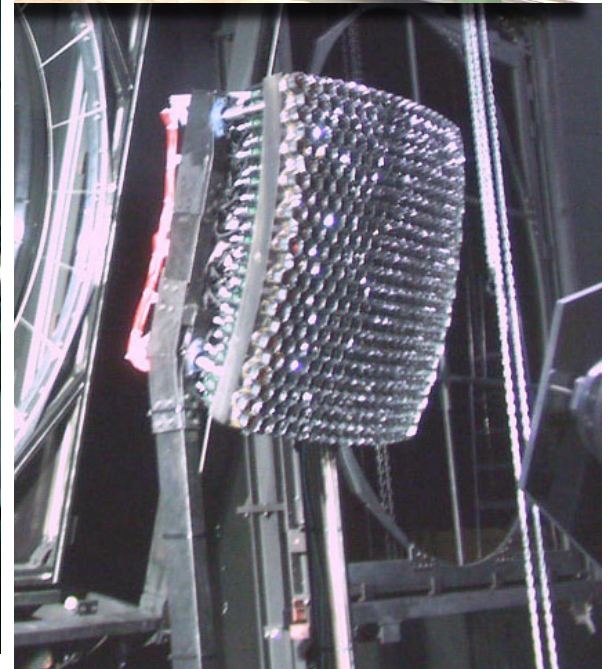
View of Los Leones Fluorescence Site



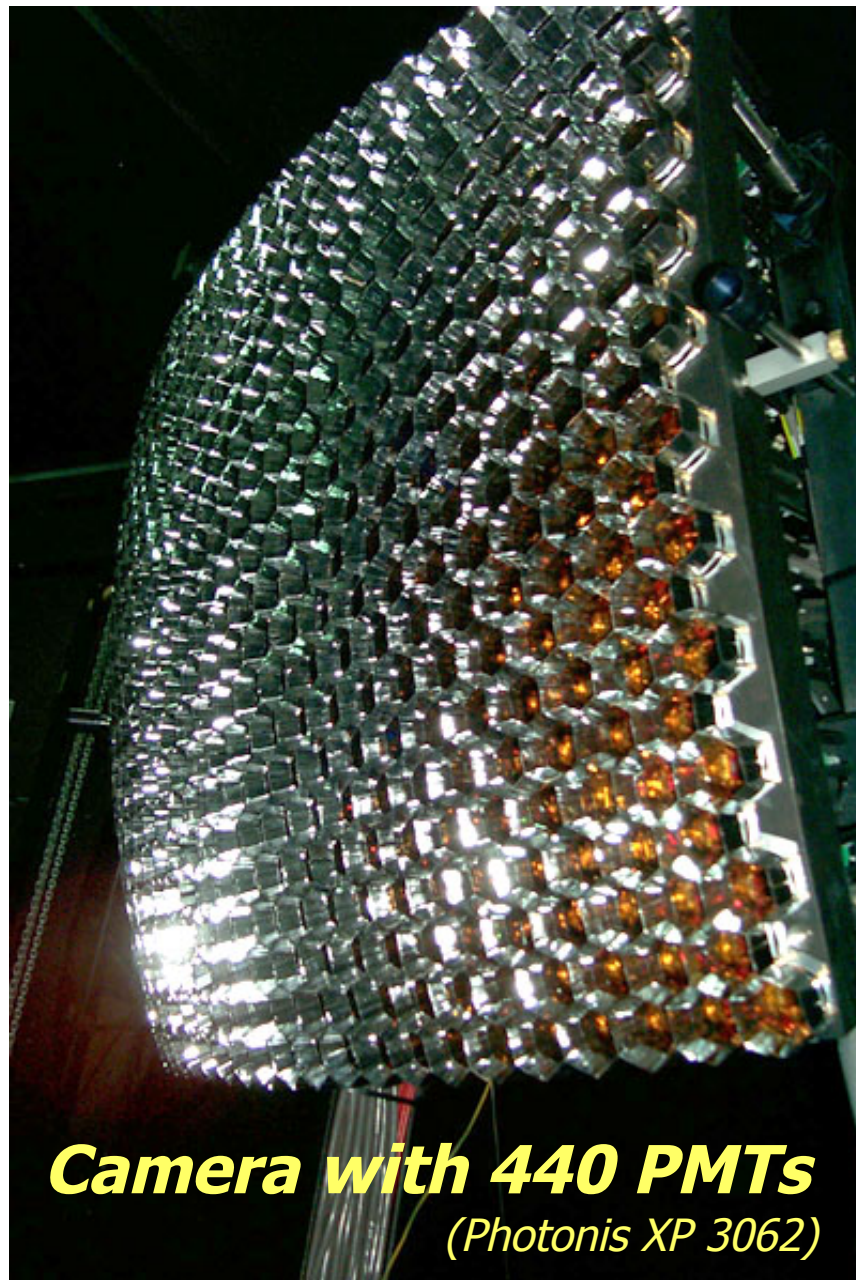
***Schmidt Telescope
using 11 m² mirrors***



UV optical filter



***Camera with 440 PMTs
(Photonis XP 3062)***



Water Cherenkov Tank in the Pampa

Communication
antenna

GPS
antenna

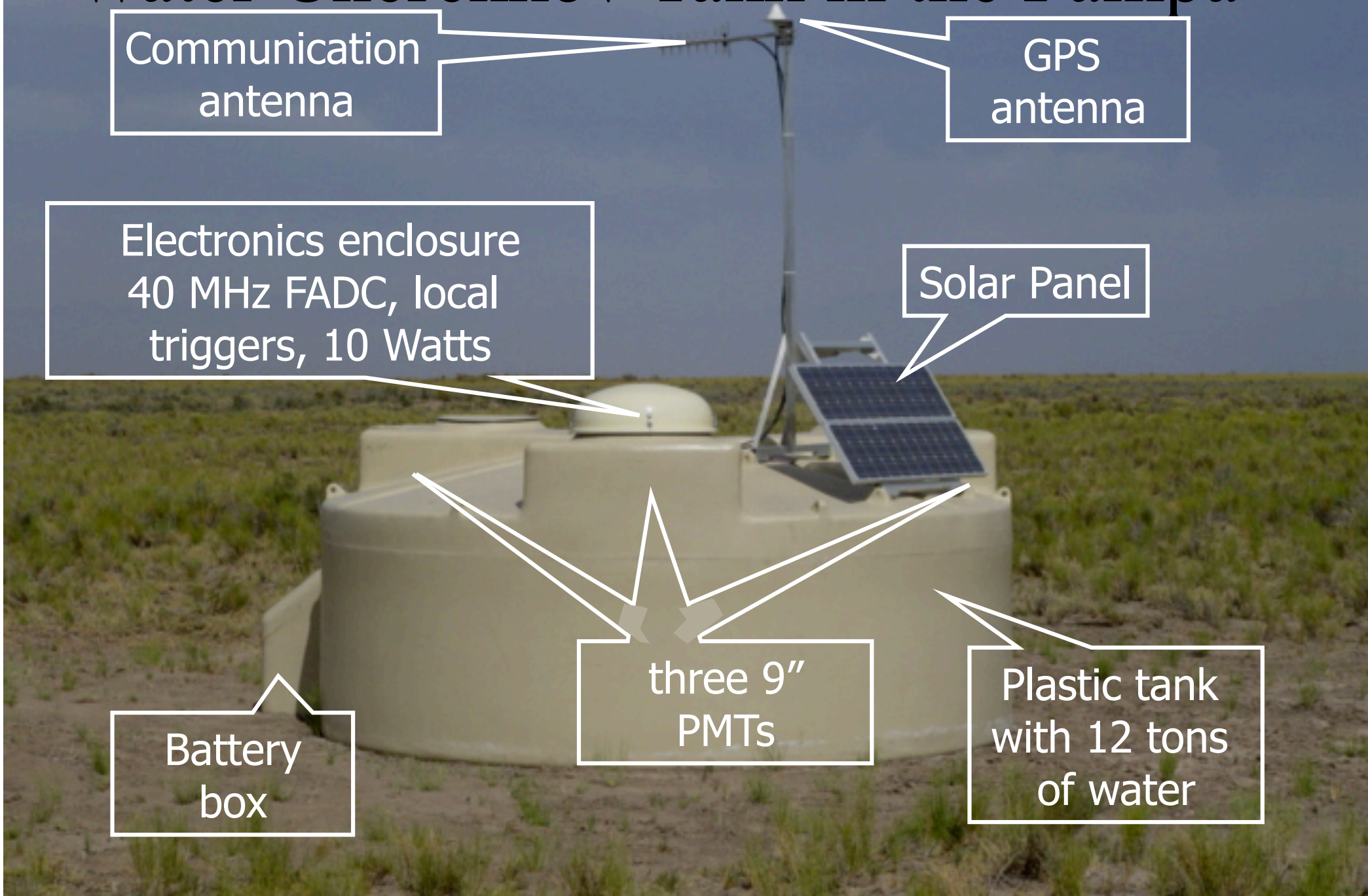
Electronics enclosure
40 MHz FADC, local
triggers, 10 Watts

Solar Panel

three 9"
PMTs

Battery
box

Plastic tank
with 12 tons
of water

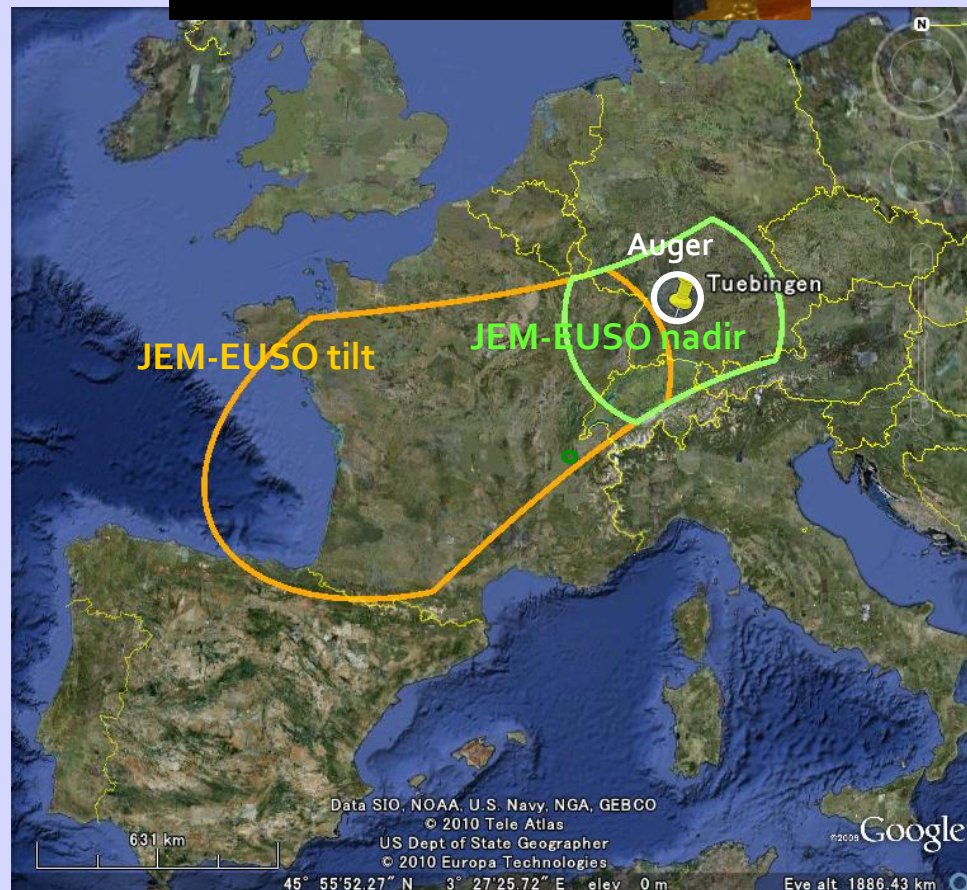


JEM-EUSO telescope

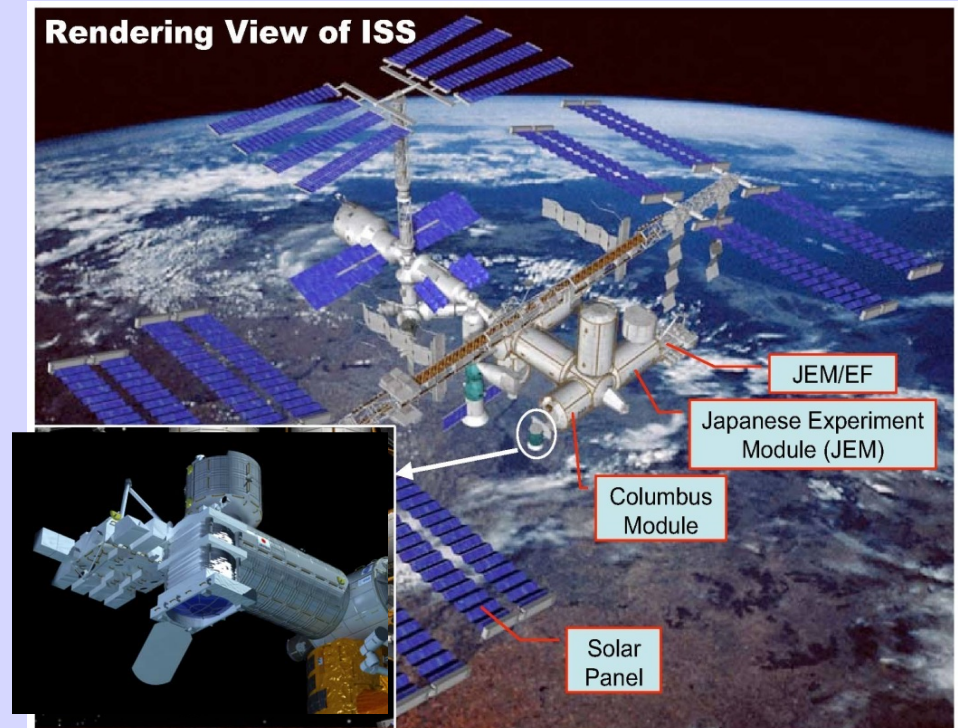
nadir



tilt

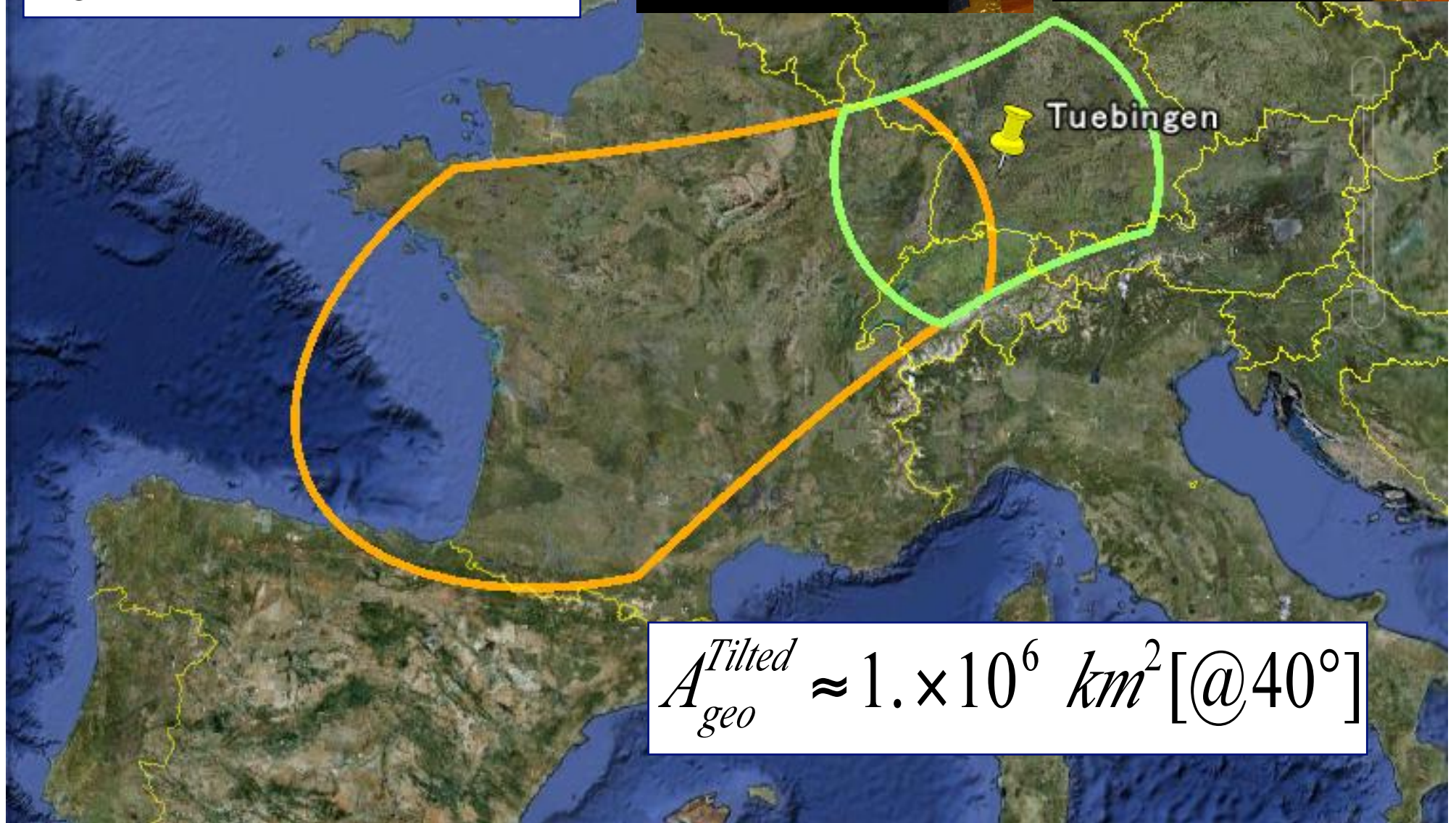


Rendering View of ISS



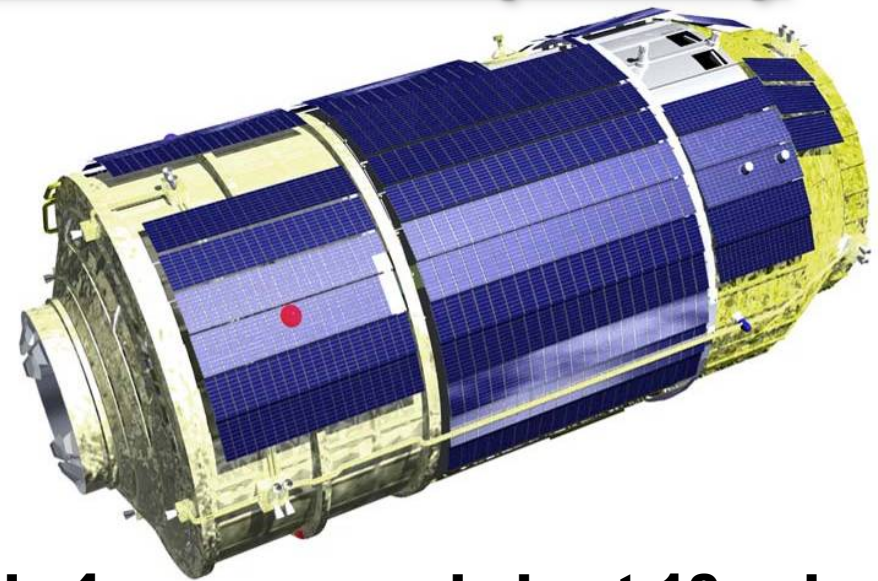
Two advantages:
1. Monitored area

$$A_{geo}^{Nadir} \approx 1.3 \times 10^5 \text{ km}^2$$



$$A_{geo}^{Tilted} \approx 1. \times 10^6 \text{ km}^2 [@40^\circ]$$

H-II Transfer Vehicle (HTV)

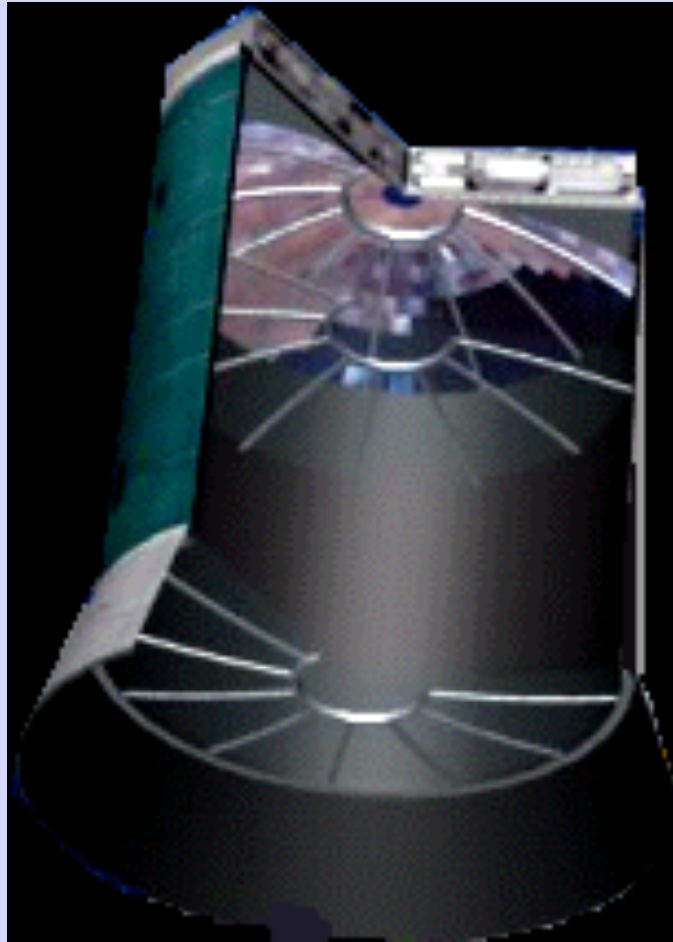


HTV is 4m across and about 10 m long



©JAXA

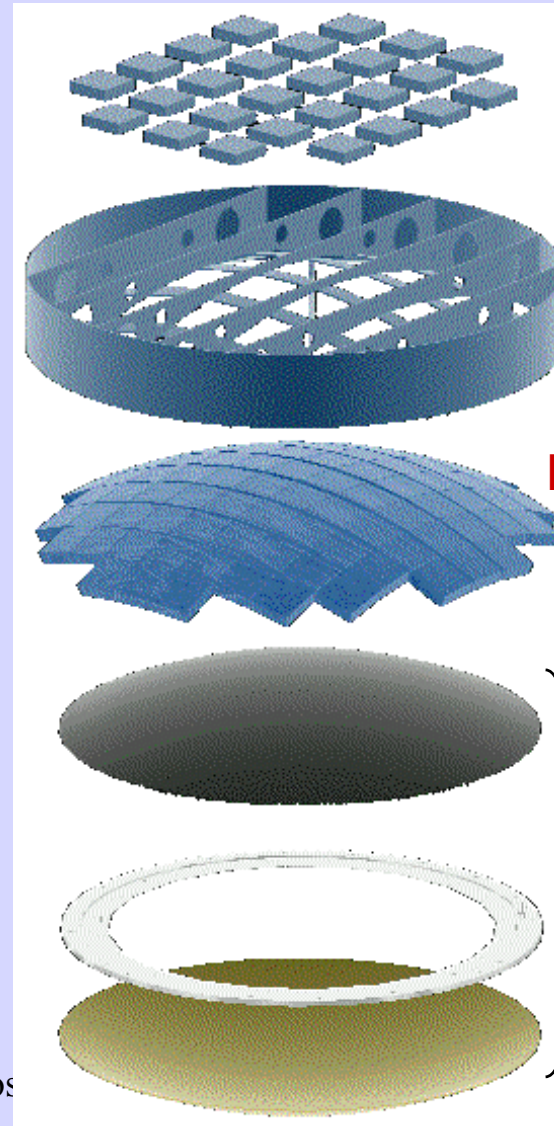
JEM-EUSO telescope and its structure



M. Bertagna

2.5m

Cos

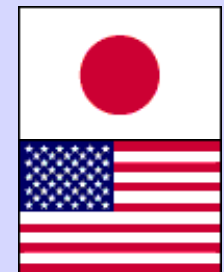
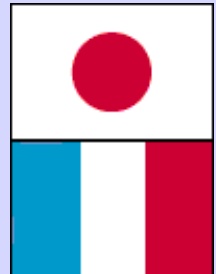
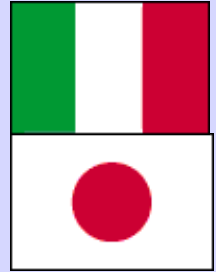


Electronics

Structure

Focal Plane

Optics





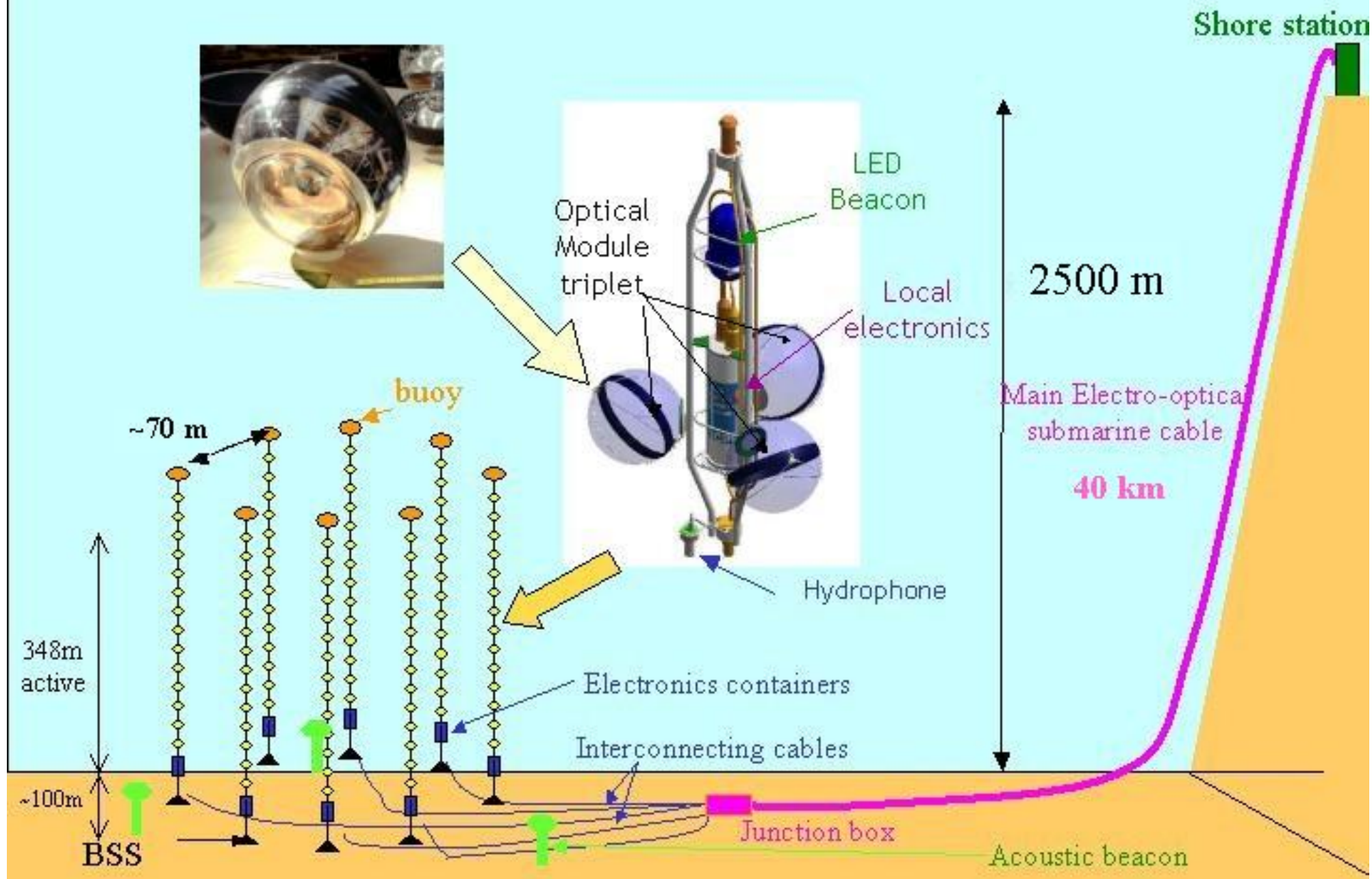
M. Bertaina

Cosmic Rays

12 lines of 25 storeys

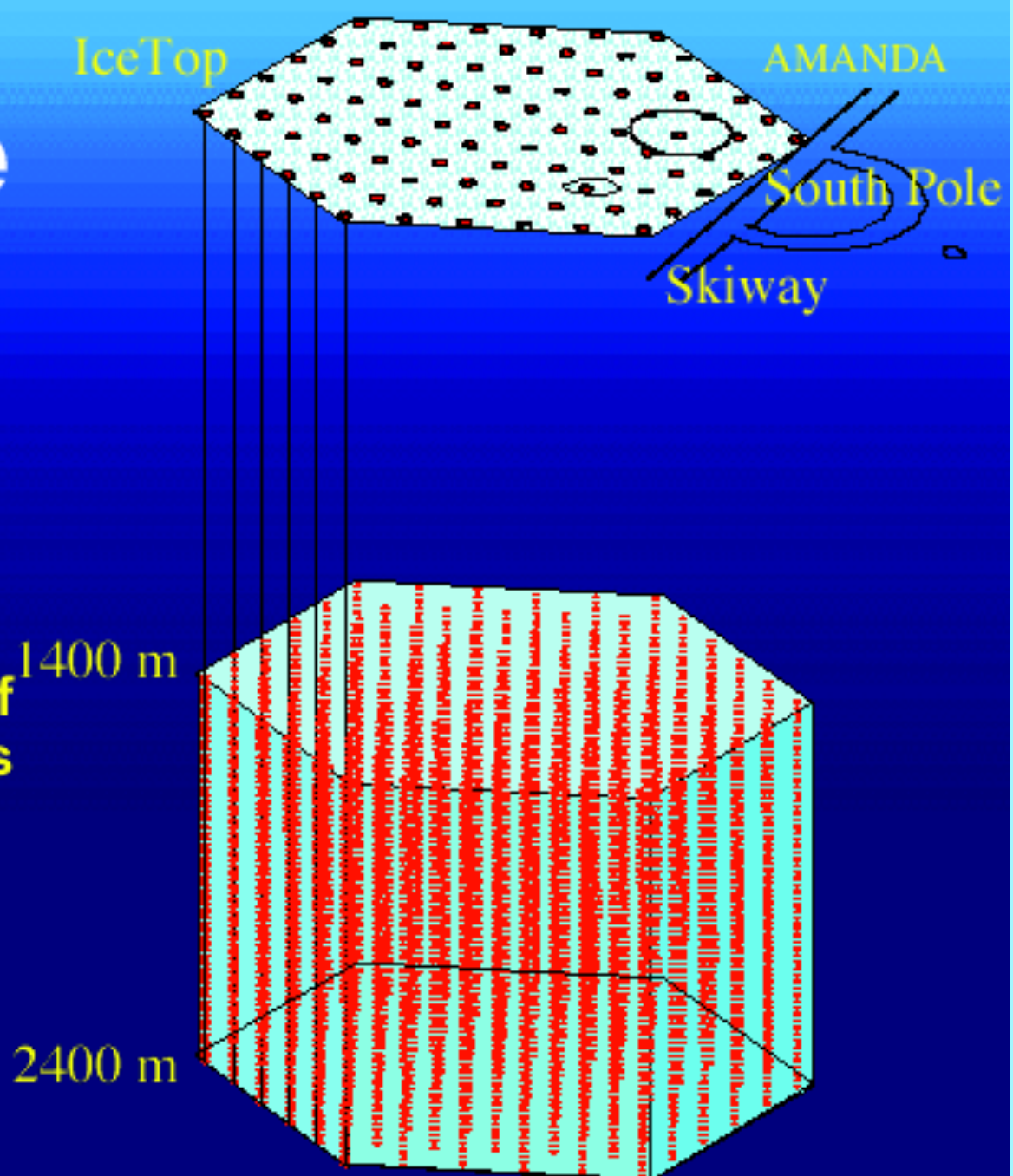
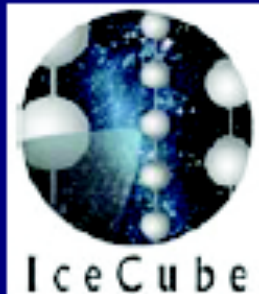
900 PMs

The ANTARES Detector



IceCube

- 80 Strings
- 4800 PMT
- Instrumented volume: 1 km³ (1 Gt)
- IceCube is designed to detect neutrinos of all flavors at energies from 10⁷ eV (SN) to 10²⁰ eV



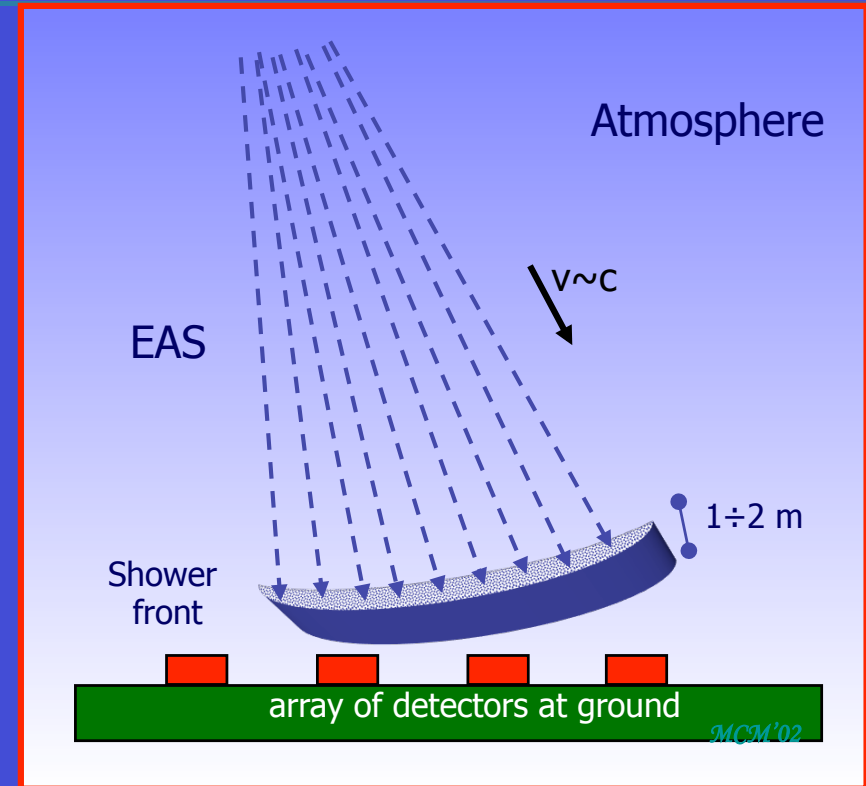
The methods “density sampling” and “fast timing”



The “Cosmic Ray Group” led by Bruno Rossi at M.I.T. defined new techniques to determine the energy and arrival direction of the primary CR originating the EAS:

“Density sampling”: the distribution of secondary particle density observed in different positions in an *array* of counters is used to localize the shower core, and derive the energy of the primary CR.

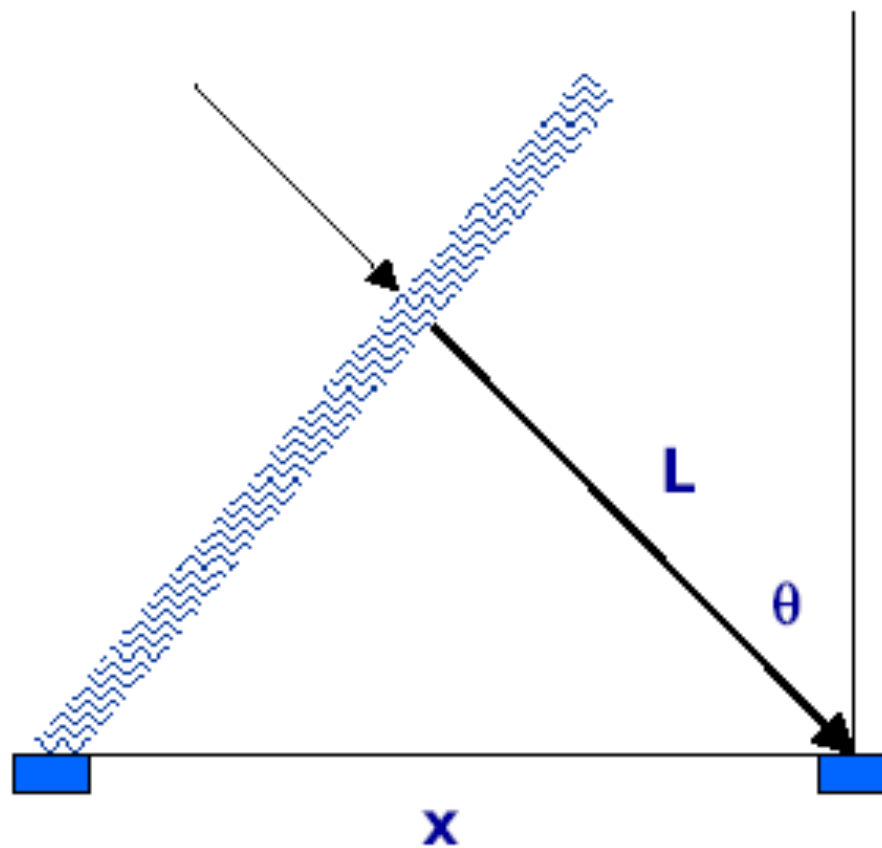
“Fast timing”: the arrival direction of primary CR (assumed coincident with shower axis) is determined by the differences among the arrival times of the shower front on the different detectors.



The technique of the “density sampling” and “fast timing” is at the basis of many experiments that use an *array* of particle detectors ...

Angular vs timing accuracy

Error of 65 nsec in timing causes ~ 2 deg error in direction estimate for shower at 45 deg and array with 1 km spacing:



Zenith angle $\theta=45.00$ deg

$X=1000\text{m}$, $L=707\text{m}$

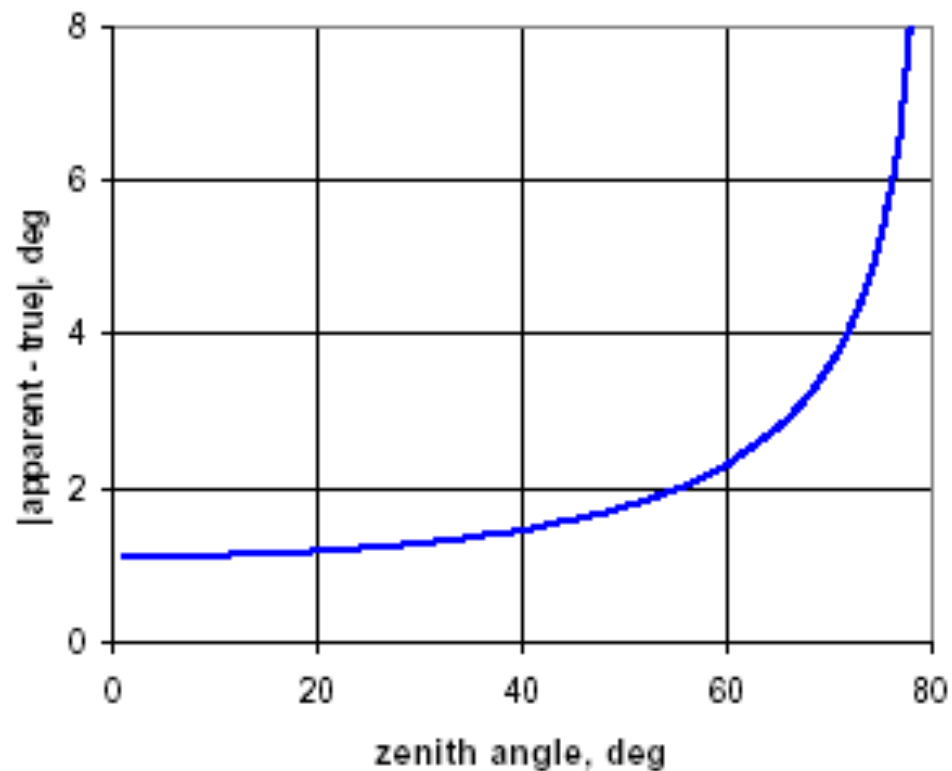
$\Delta t=L/c=2.36 \mu\text{sec}$

With timing error:

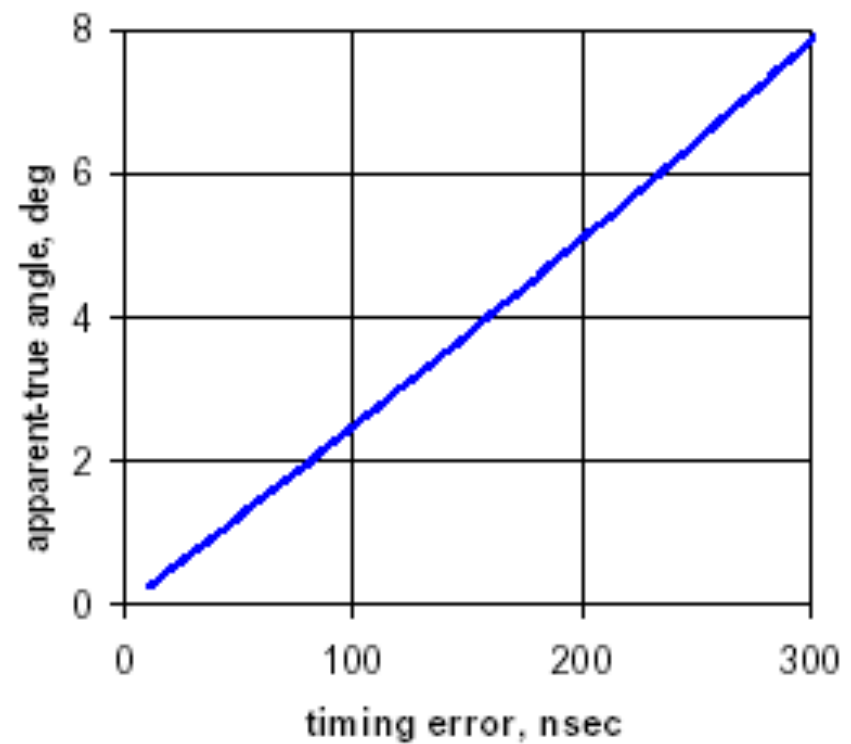
$\Delta t+65 \text{ nsec}=2.42 \mu\text{sec}$

- **apparent $L = 727 \text{ m}$**
- **apparent $\theta = 43.4 \text{ deg}$**
- **$\Delta\theta = 1.6 \text{ deg}$**

angular error vs zenith angle for
 $\delta t = 65$ nsec



Angular error vs timing error,
zenith angle = 45 deg



the e.m. shower array measure the density and arrival time of the particles (e, μ, γ) on a matrix of detectors at ground.

$T_1 < T_2 < T_3 \dots \rightarrow$ direction

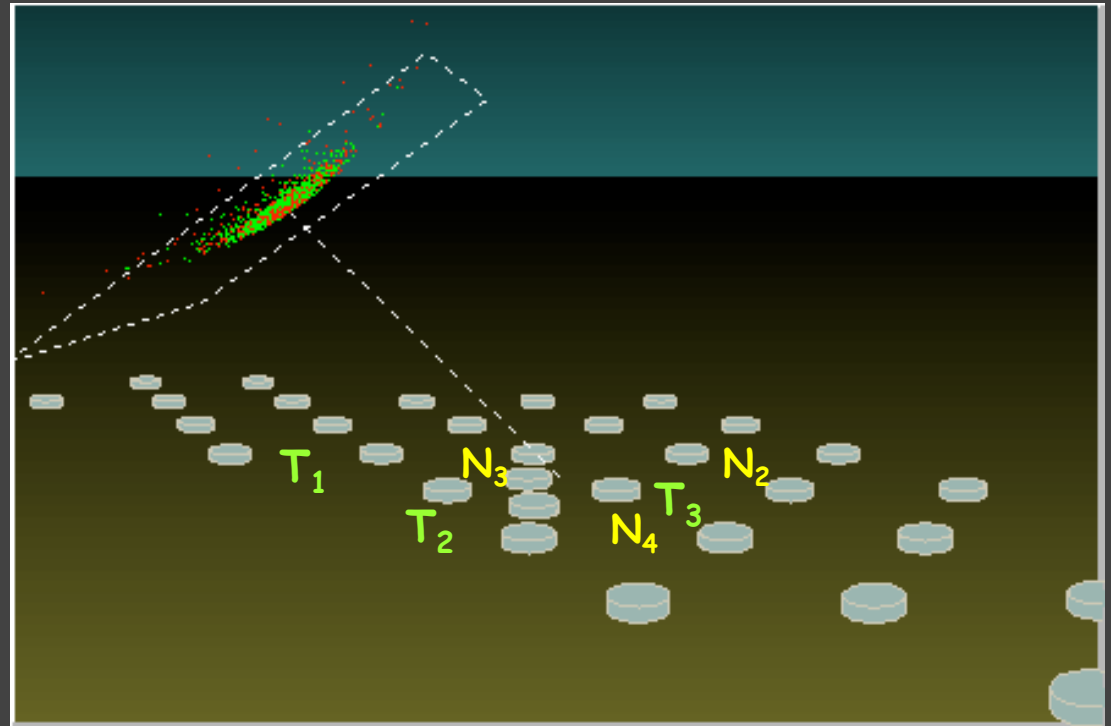
$N_3 > N_4 > N_2 \dots \rightarrow$ d.l.



Ne total number of particles



Primary Energy



2 parameters of the e.m. shower allow to separate light nuclei from heavy ones

N_{μ}/Ne

$X(Ne_{max})$

Shower maximum

$(N_{\mu}/Ne)_{Fe} > (N_{\mu}/Ne)_p$

M. Bertaina

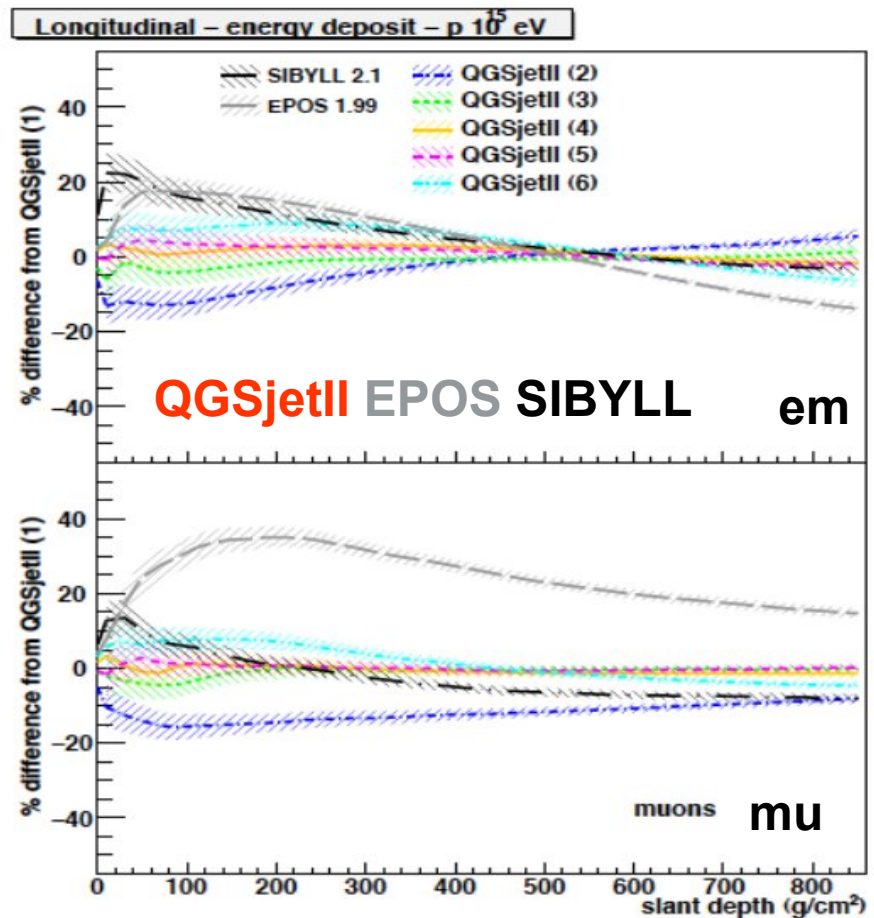
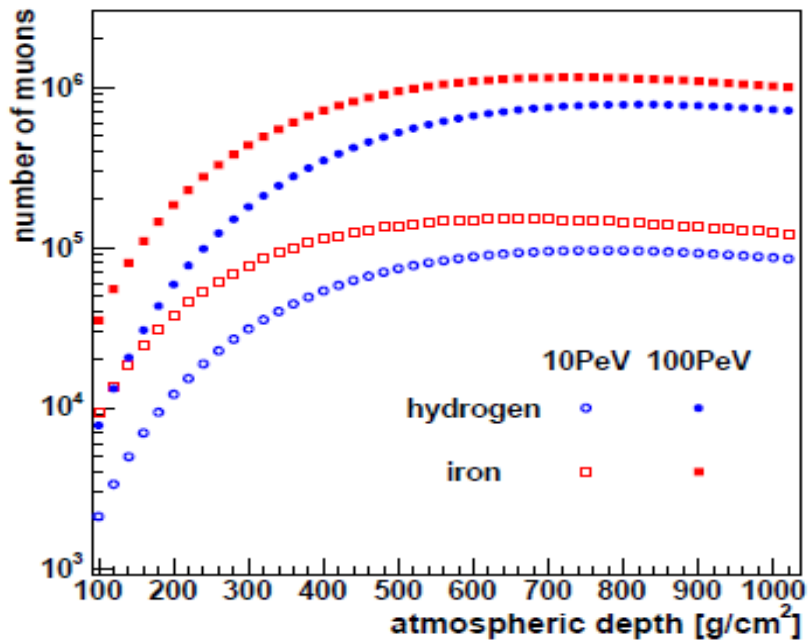
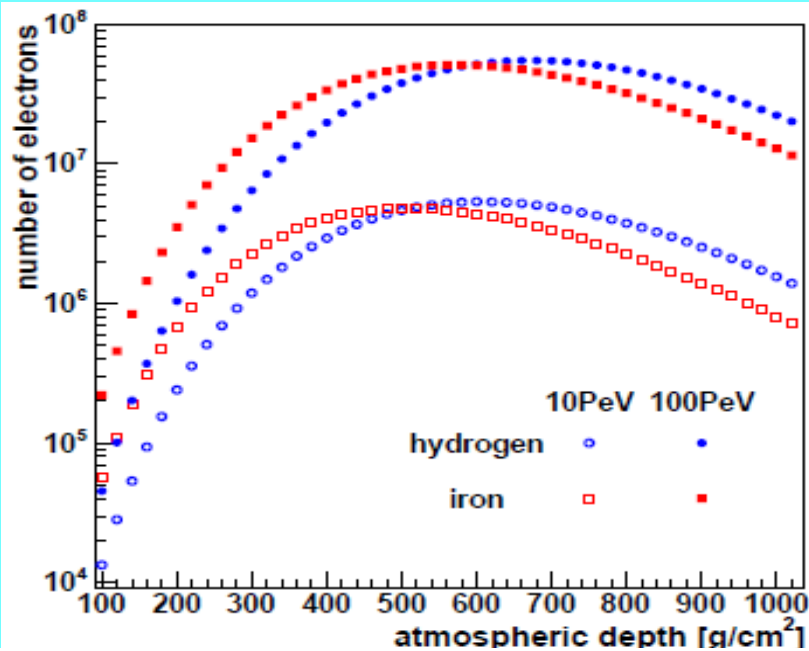
$X(Ne_{max})_{Fe} > X(Ne_{max})_p$

Cosmic Rays

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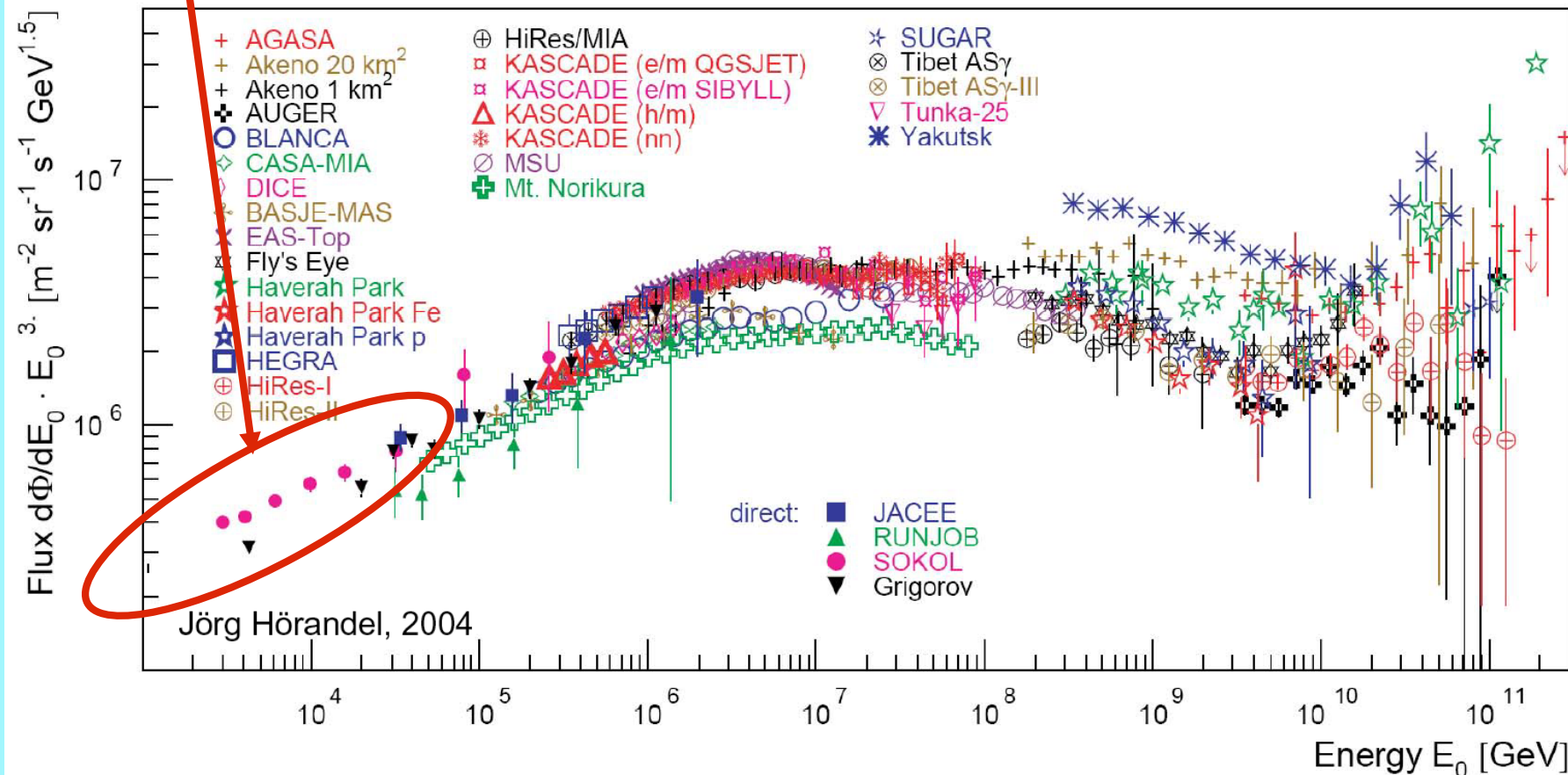
Longitudinal distribution of EAS

& model dependence



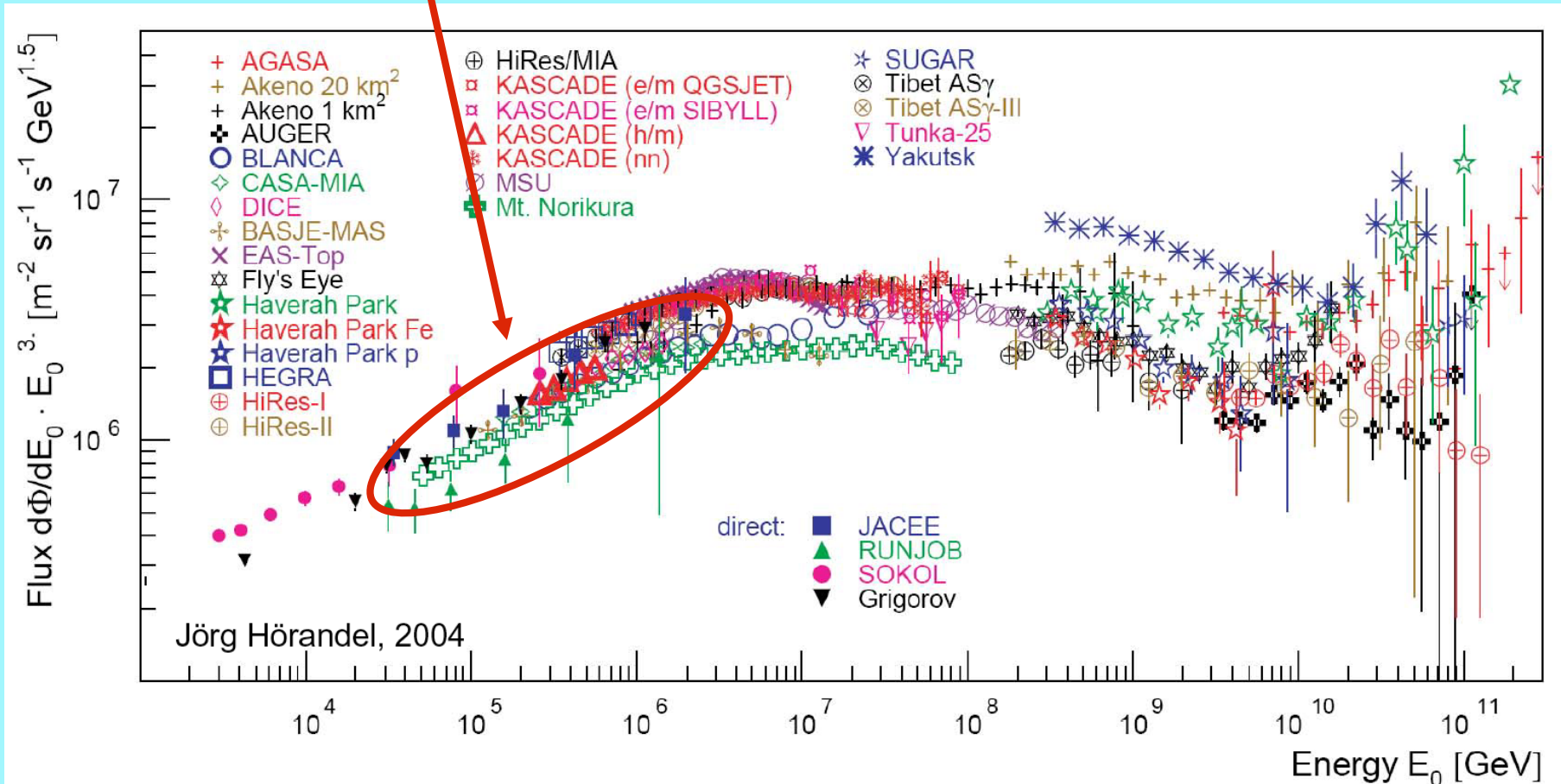
Features and problems: $S(E_0) \cdot E_0^3$

Interpretation of the new findings from direct experiments



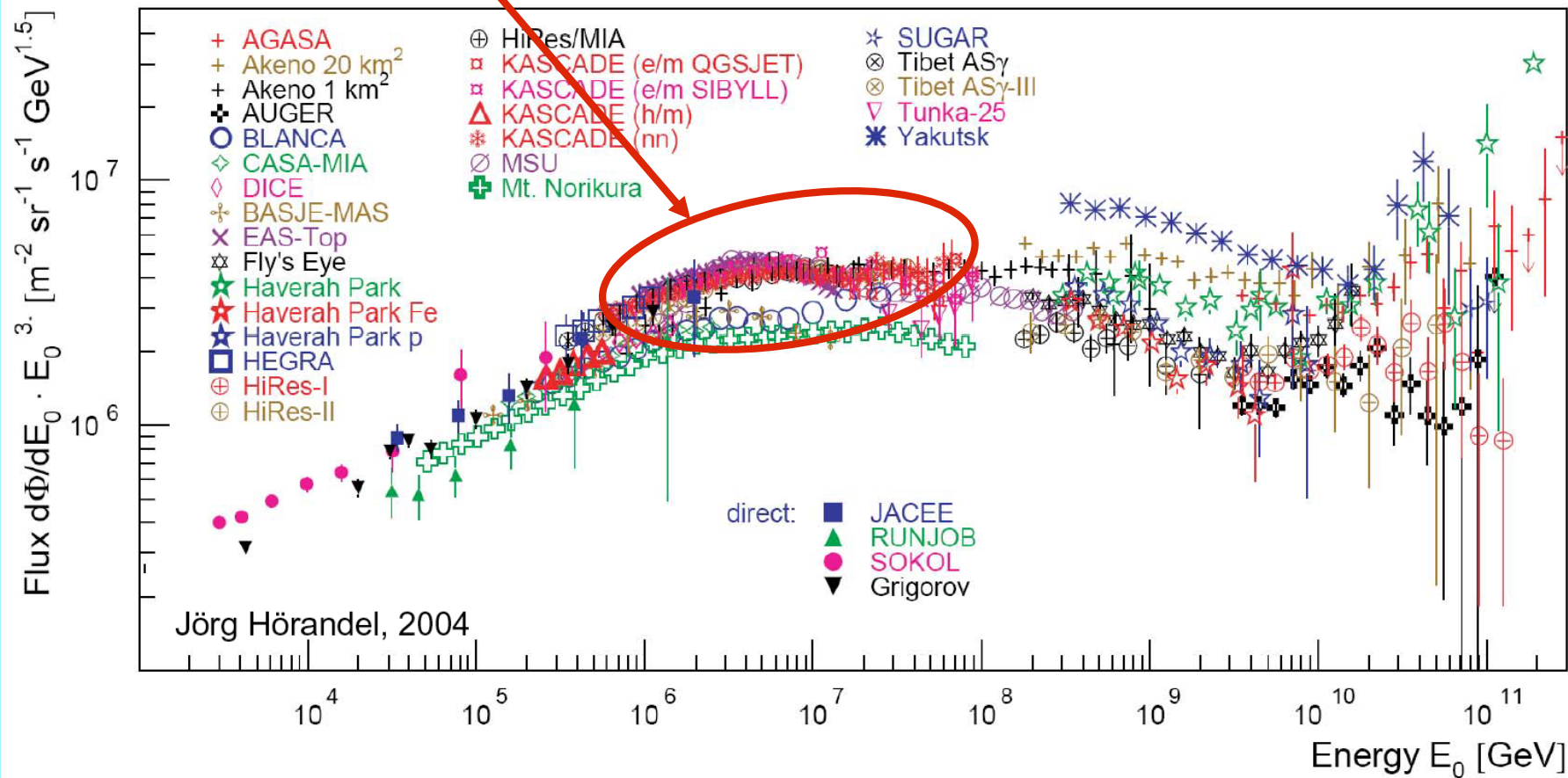
Features and problems: $S(E_0) \cdot E_0^3$

Technical: direct to ground based experiments



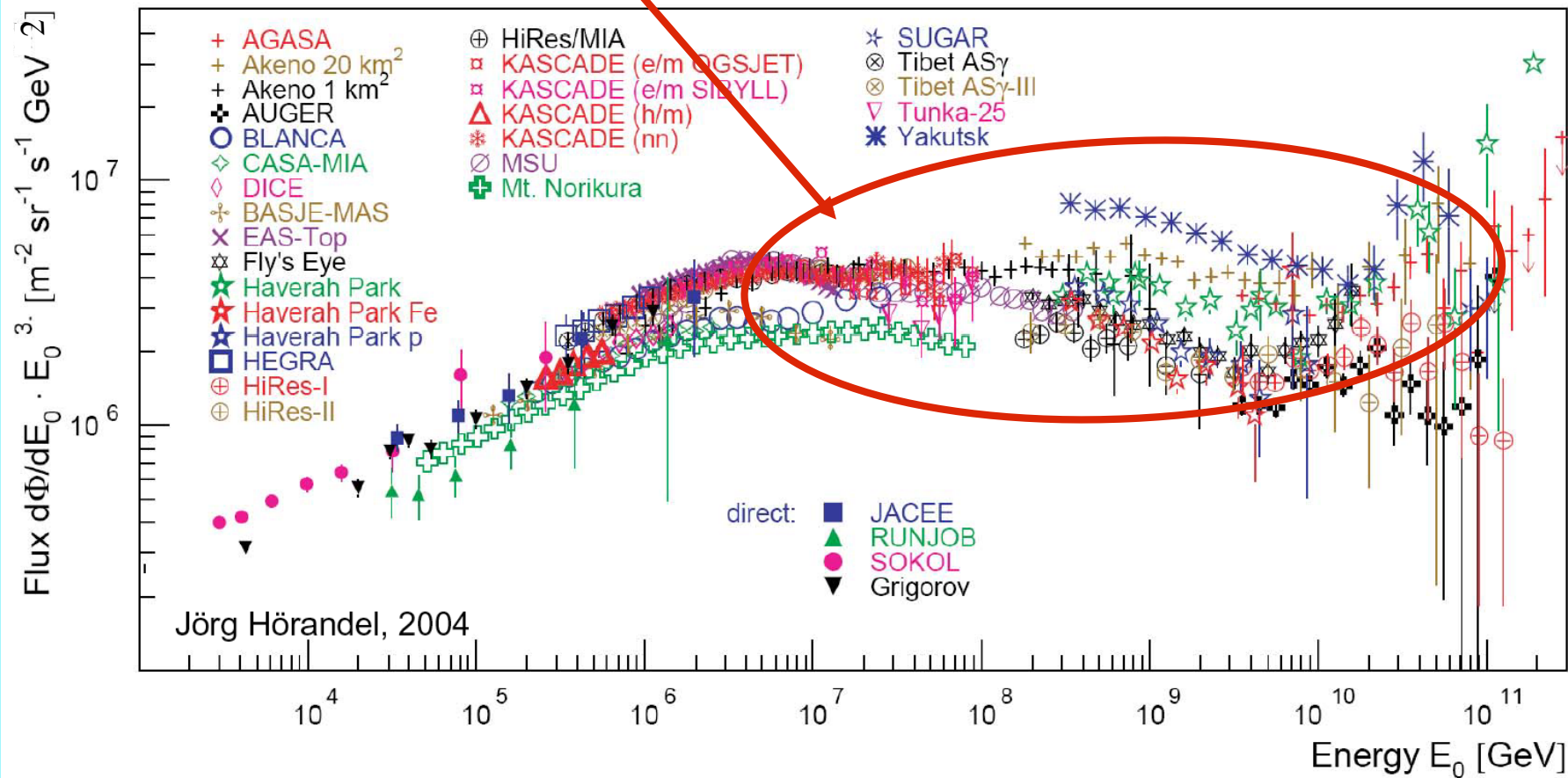
Features and problems: $S(E_0) \cdot E_0^3$

“knee”: origin?



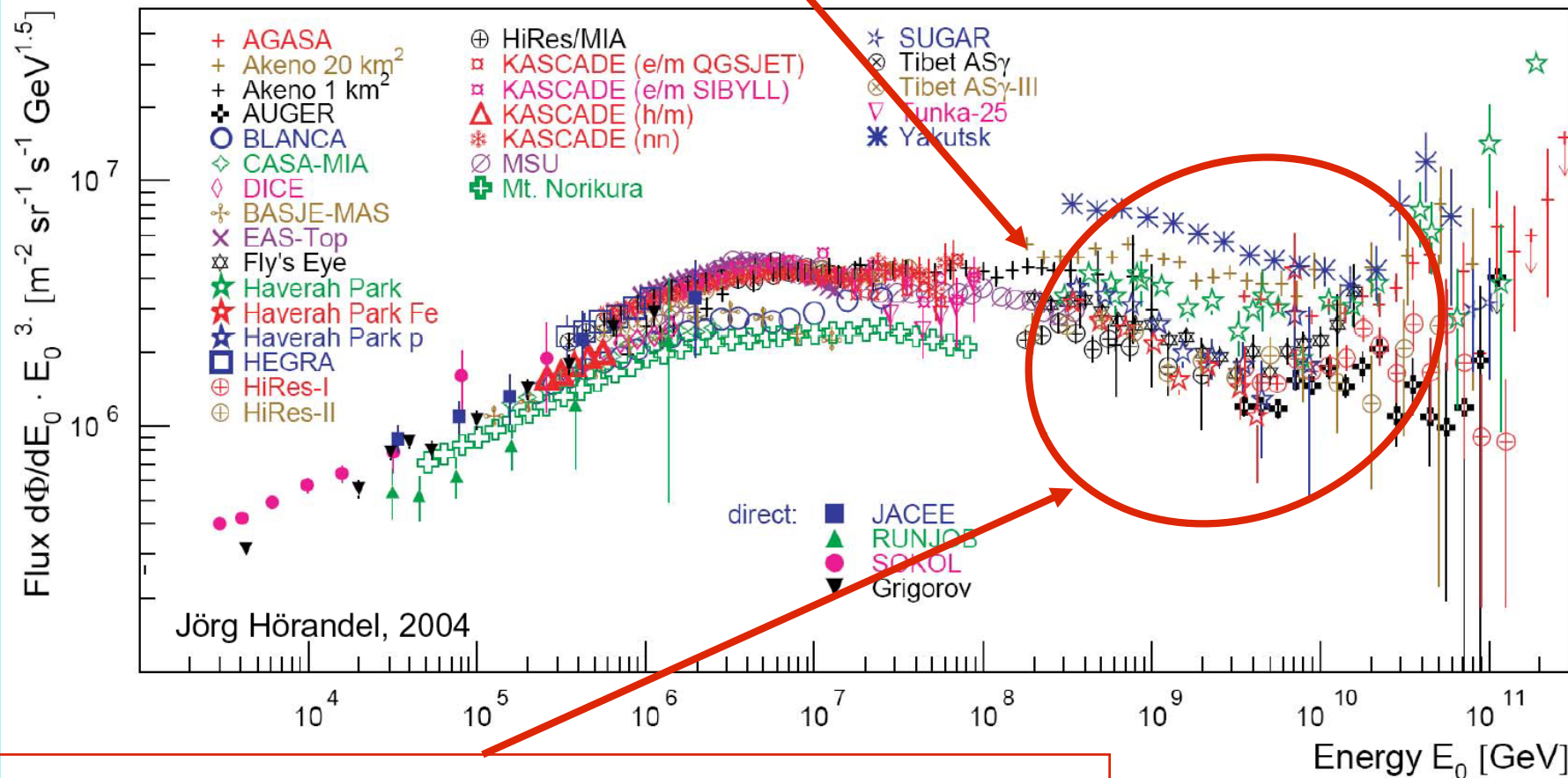
Features and problems: $S(E_0) \cdot E_0^3$

Composition / Hadronic interactions



Features and problems: $S(E_0) \cdot E_0^3$

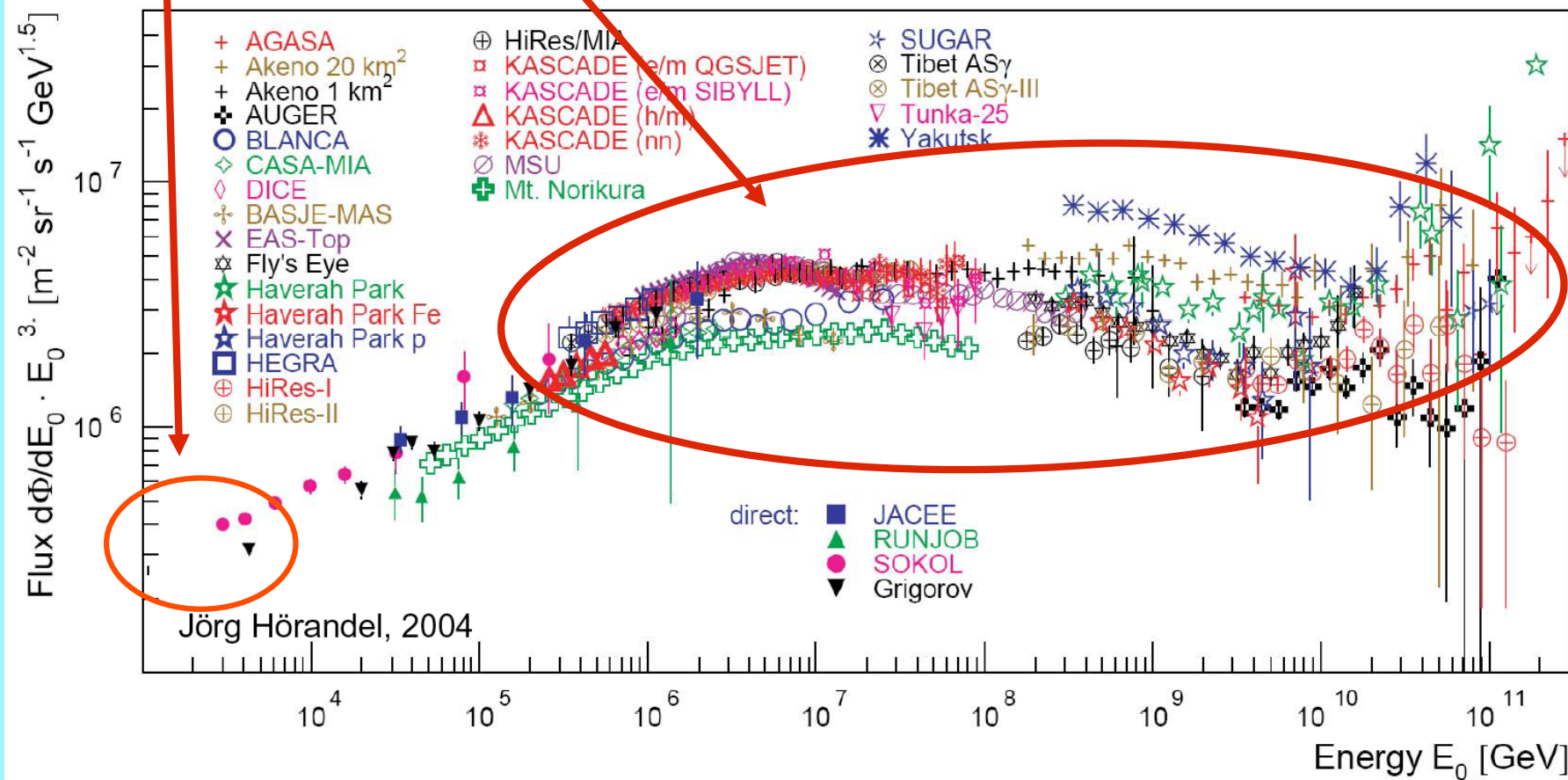
Technical: energy calibration



Sources: galactic to extragalactic? “ankle”?

Features and problems: $S(E_0) \cdot E_0^3$

Anisotropies



Techniques ($E < 10^{16}$ eV)

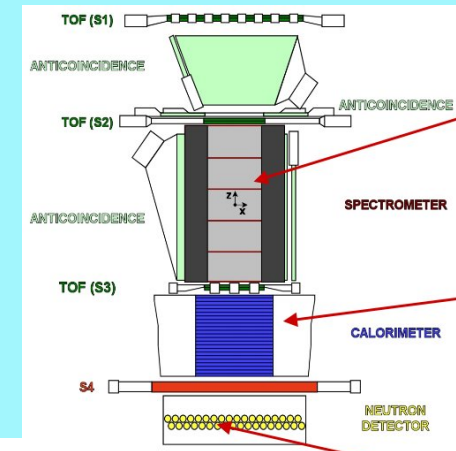
Type	Technique	Energy Range	Example of experiments & sensitive components
direct	spectrometer	1 - 1000 GeV	AMS (p,He), BESS (p,He), HEAO (CNO,Fe), PAMELA (p,He)
direct	calorimeter	30 GeV – 500 TeV	ATIC (all), CREAM (all), TRACER (O-Fe)
direct	emulsion chambers	10 – 500 TeV	JACEE, RUNJOB (all)
indirect	hadron calorimeter	500 GeV – 1 PeV	KASCADE, EAS-TOP (p)
indirect	muon spectrometer	100 GeV – 10 TeV	L3+C (mostly p & He)
indirect	Cherenkov	15 – 150 TeV	Hess (Fe)
indirect	Cherenkov + TeV μ	50 – 300 TeV	EAS-TOP/MACRO (p,He,CNO)
indirect	emulsion chambers, burst detectors	5 – 300 TeV	Tibet AS γ (p,He)
indirect	RPC carpet	5-250 TeV	ARGO (p+He)
indirect	Cherenkov	1PeV – 10 PeV	TUNKA-25 (all)
indirect	Ne-N $_{\mu}$ (GeV)	100 TeV – 10 PeV	GRAPES,EAS-TOP,KASCADE (all)

M. Bertina

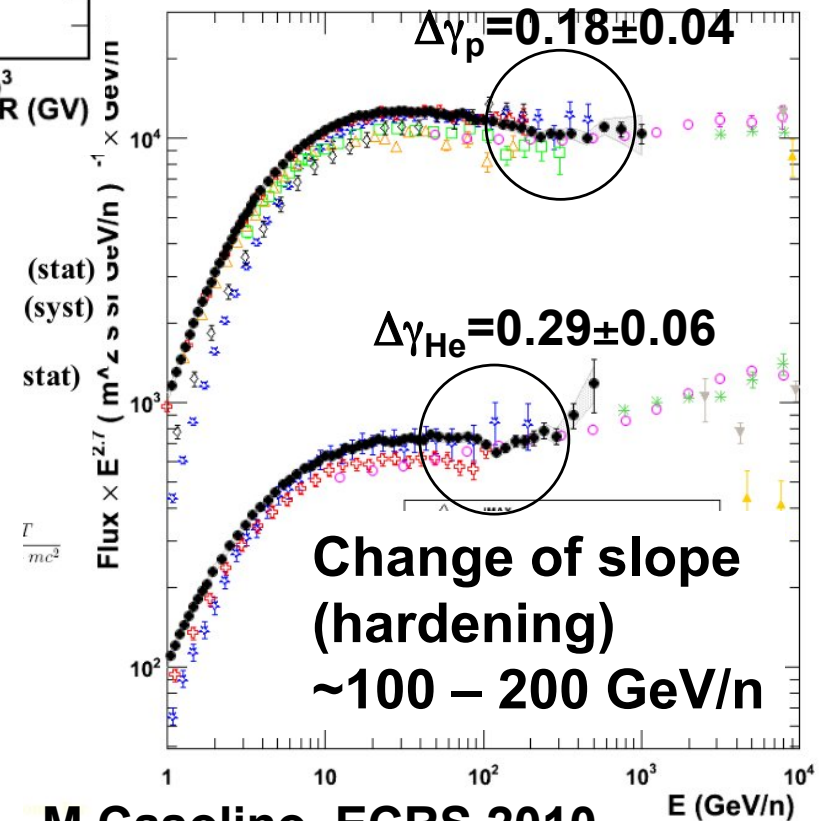
Cosmic Rays

75

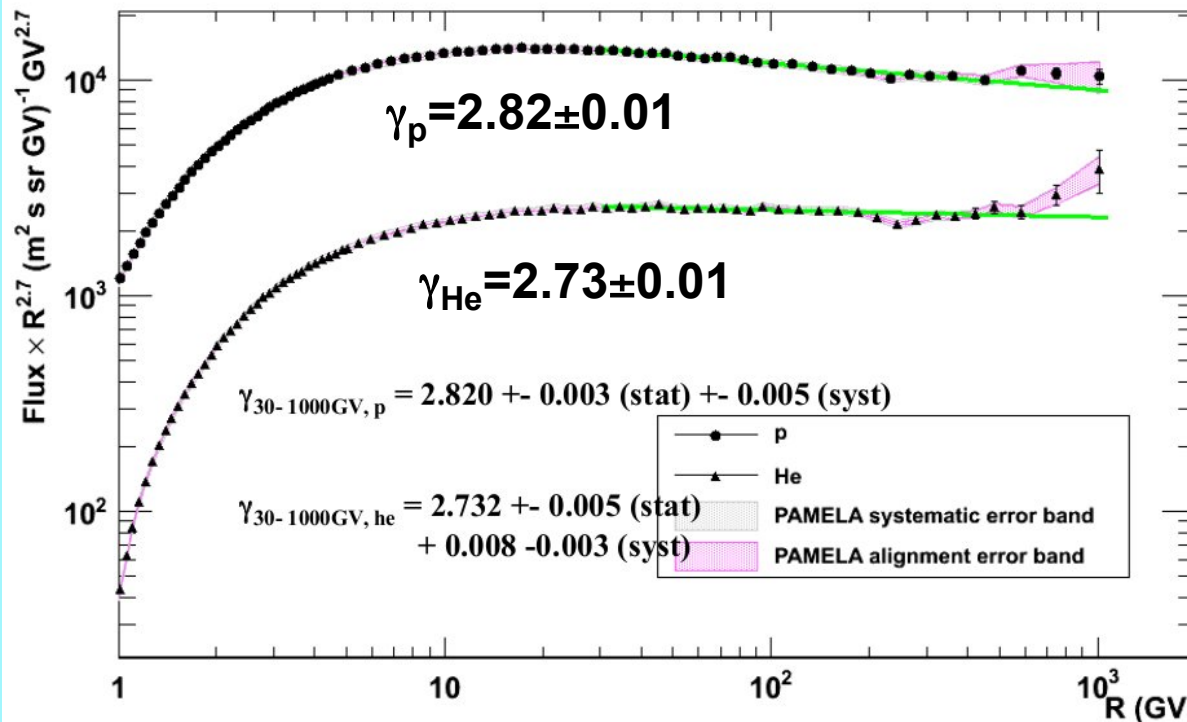
PAMELA $10^9 < E < 10^{12}$ eV



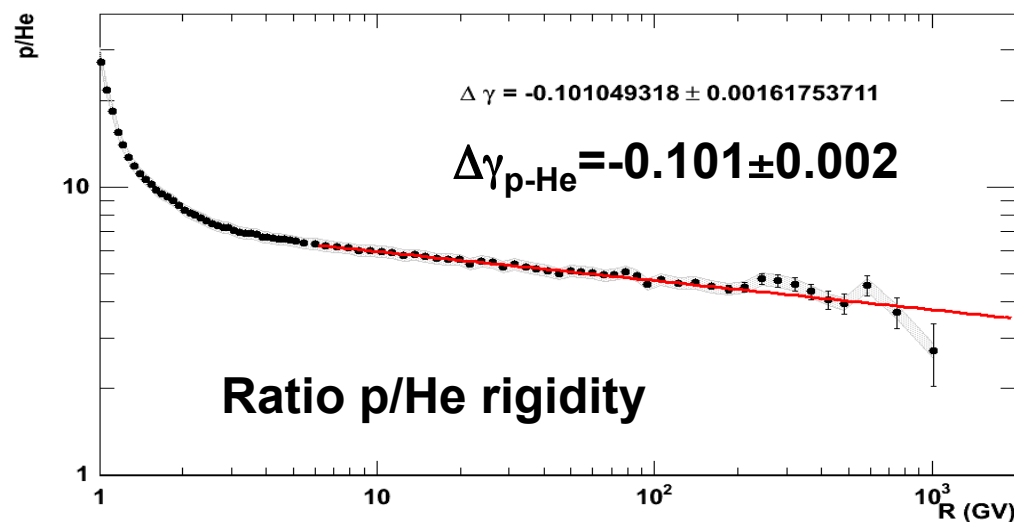
Comparison with previous experiments



M.Casolino, ECRS 2010



Different spectral index
between H and He

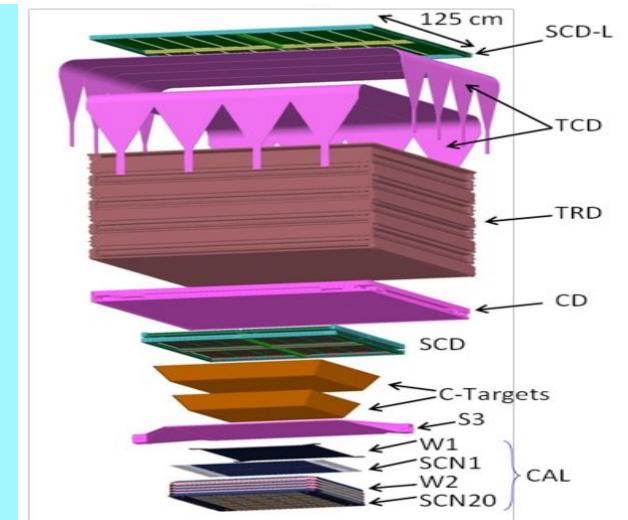
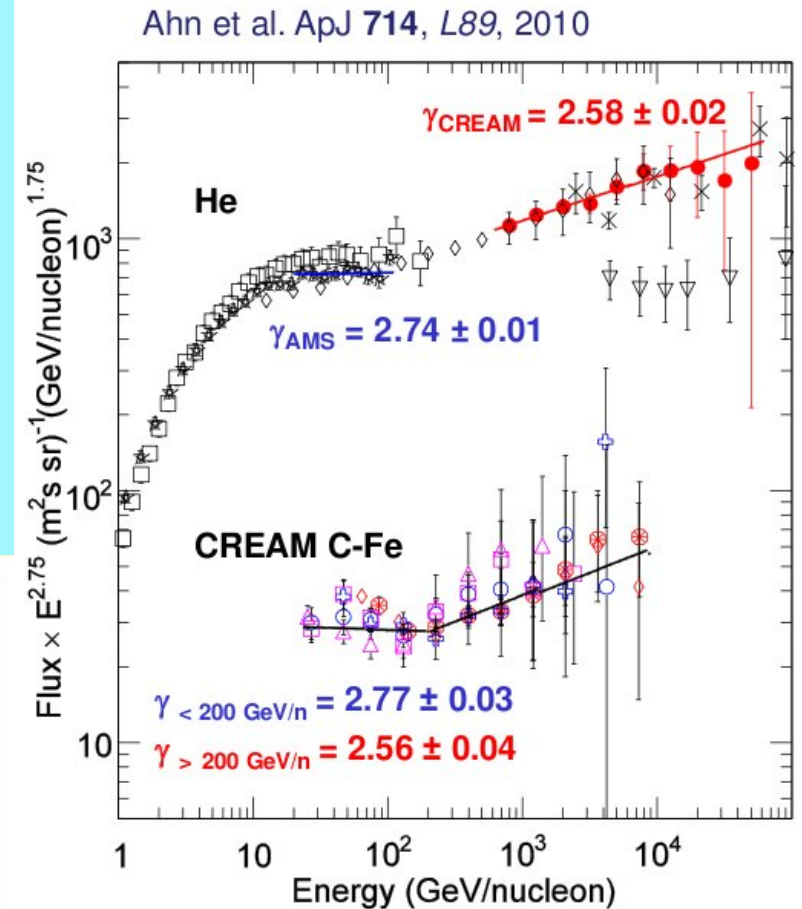
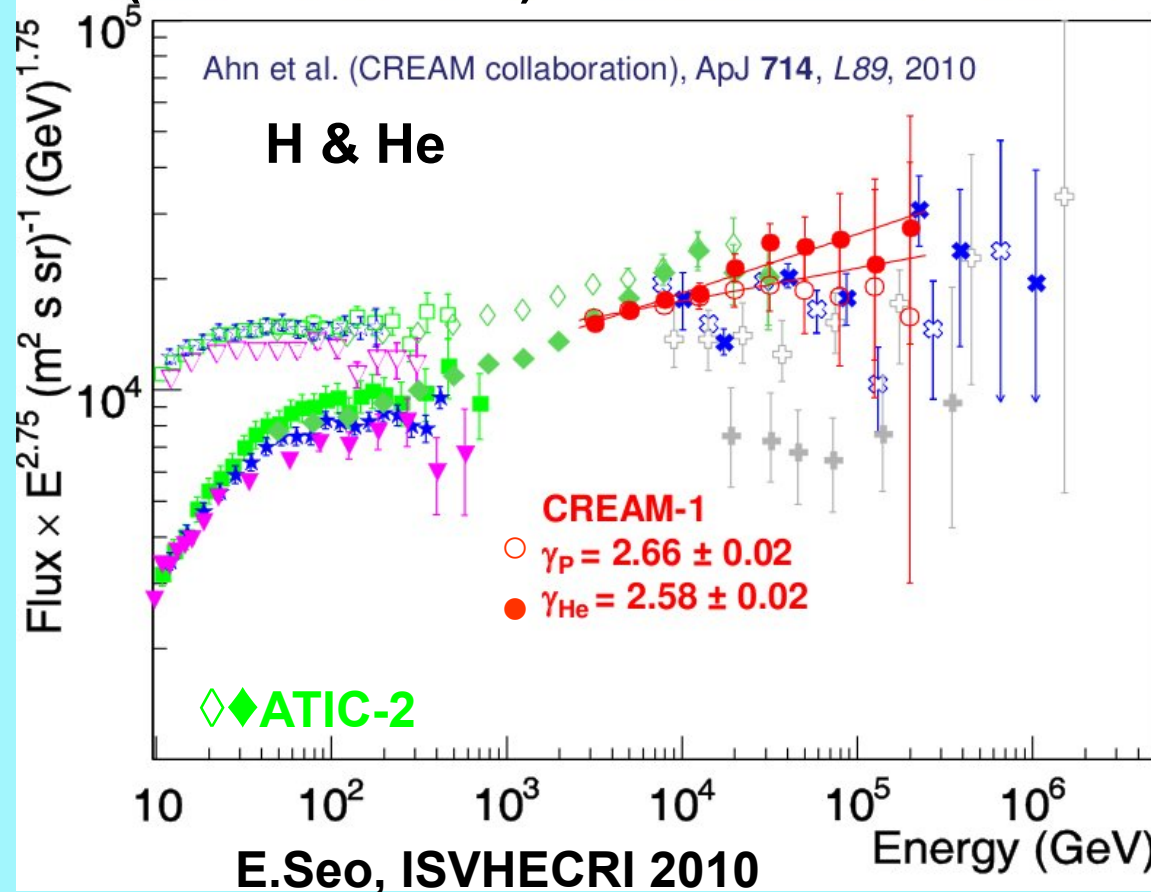


Ratio p/He rigidity

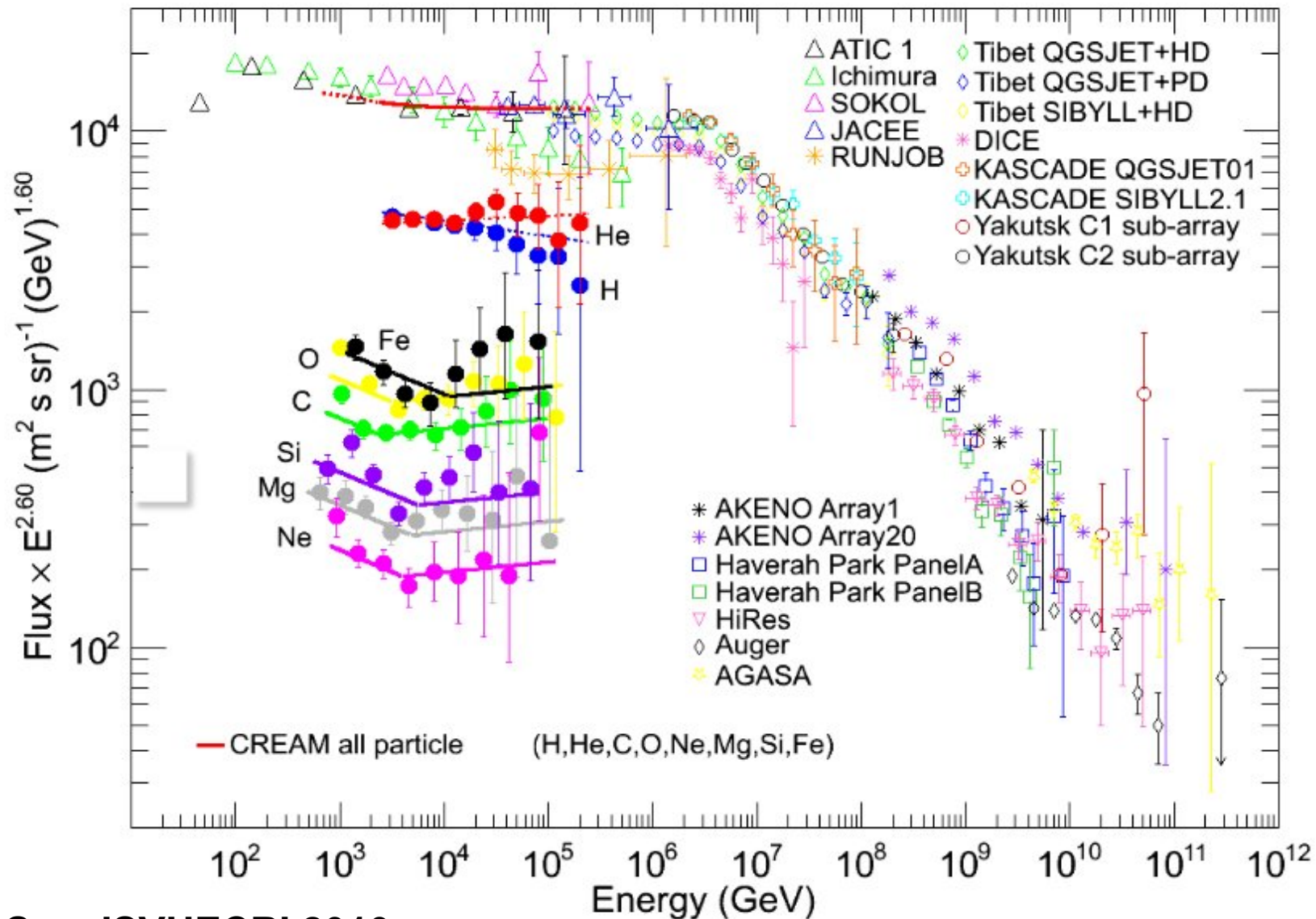
CREAM $10^{12} < E < 10^{14}$ eV

also sees different spectral index
between H and the other elements

The change of spectral index occurs
also for C-Fe in the same energy range
(100-200 GeV/n) as for PAMELA



Single and All-particle spectra by CREAM



What does all this mean ?

Some interpretations:

Is the spectral difference between H and He an indication that there are different types of sources or mechanisms of acceleration?

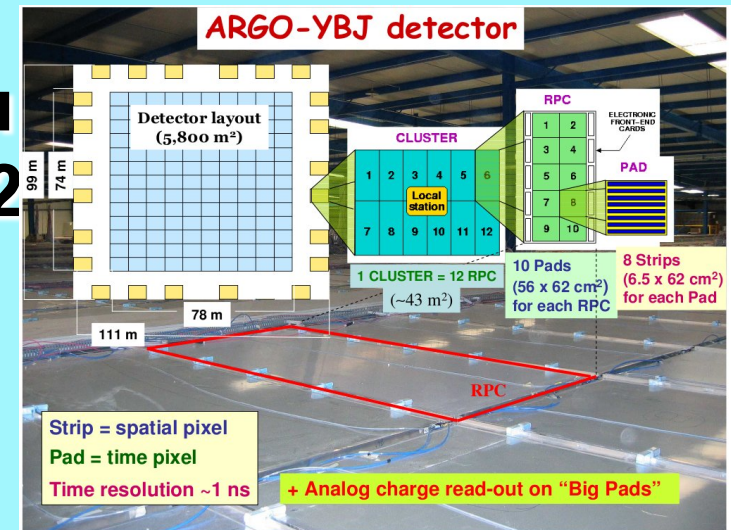
(Biermann, *A&A* **271**, 649, 1993; Biermann et al. *PRL* **103**, 061101, 2009; *ApJ* **710**, L53, 2010)

The flattening of the elemental spectra is an indication that:

- a) The source spectra are harder than previously thought?**
- b) The concavity around 200 GeV/n is an indication of the c.r. interaction with the shock?** (Ellison et al. *ApJ* **540**, 292, 2000; Allen et al. *ApJ* **683/2**, 773, 2008).
- c) If it is not acceleration or propagation related, are we seeing a local source?** (Erlykin & Wolfendale *A&A* **350**)
- d) Is it due to acceleration by multiple remnants?** ((Medina-Tanco & Opher *ApJ* **411**, 690, 1993)

Light-component spectrum measured by ARGO (5-2

Measurement of the *light-component* (p+He) spectrum of primary CRs in the energy region (5 – 250) TeV via a Bayesian unfolding procedure



CREAM p+He

EAS-TOP + MACRO

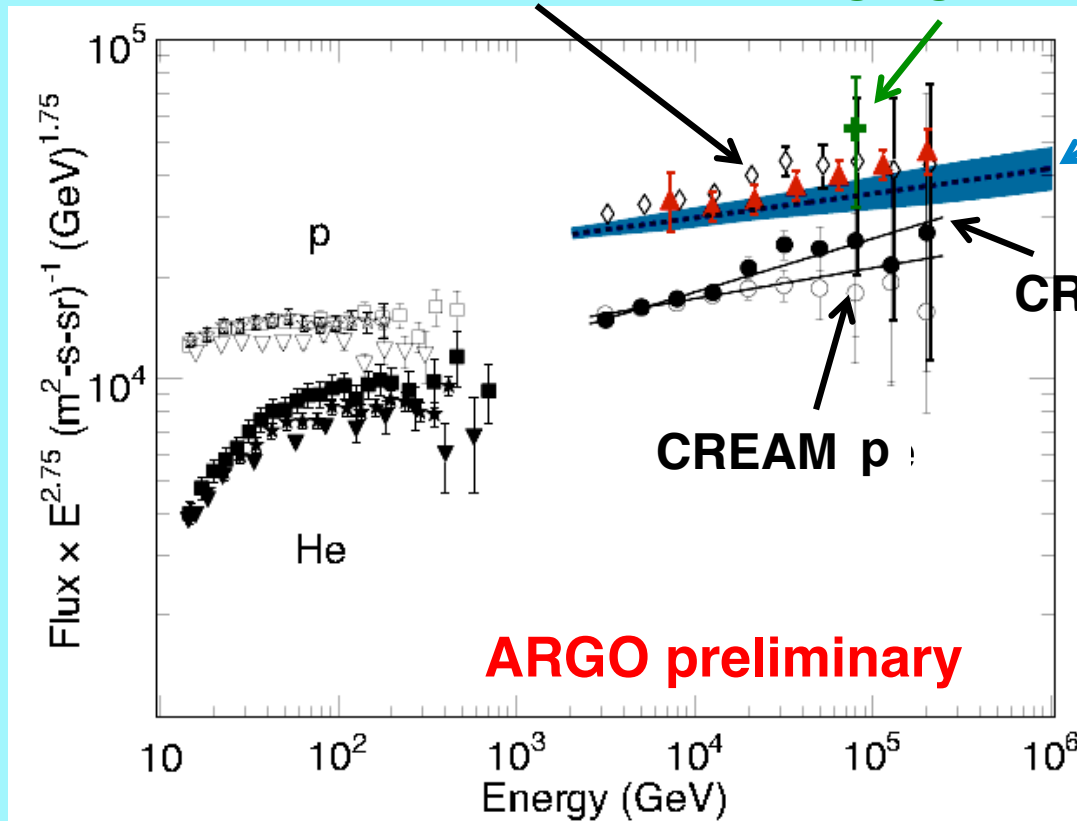
Horandel p+He

CNO < 2%

CREAM He

ARGO data agree with CREAM results

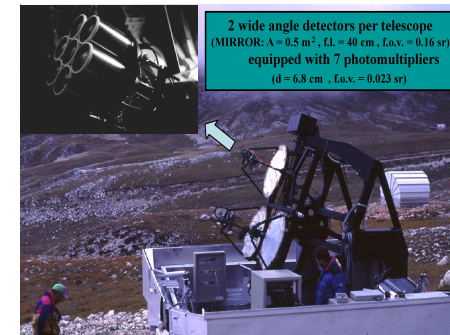
Evidence that the proton spectrum is flatter than in the lower energy region



MACRO and EAS-TOP are separated by 1100 - 1300 m of rock corresponding to a threshold $E_{\mu} \approx 1.3 - 1.6$ TeV.

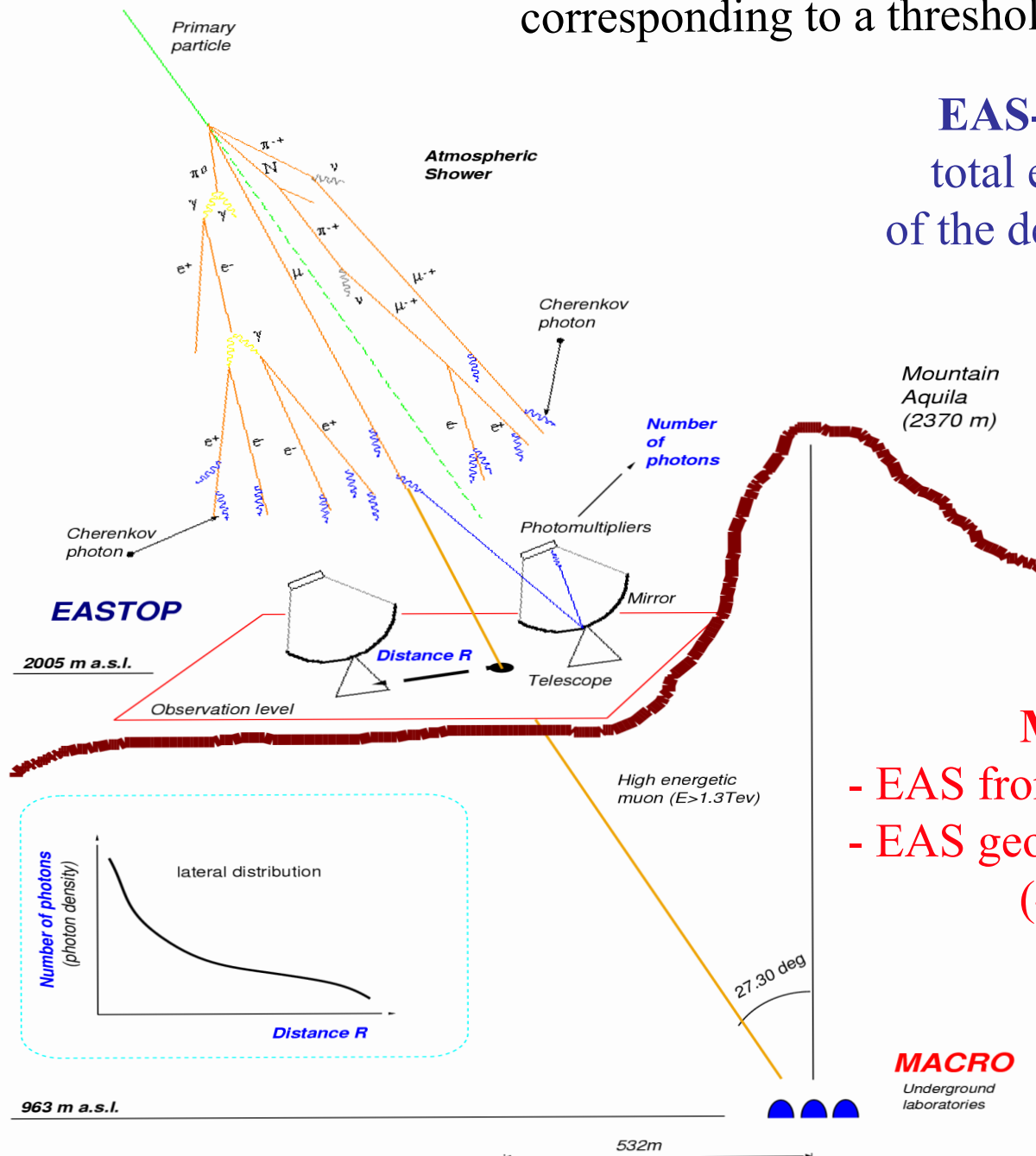
EAS-TOP (Cherenkov detector):
total energy through the amplitude of the detected Cherenkov light signal.

THE EAS-TOP CHERENKOV DETECTOR



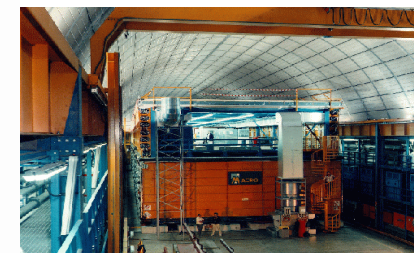
Trigger threshold: $N_{\text{photo}} = 120 \text{ phe / mirror}$ ($E_{\text{thr}} = 40 \text{ TeV}$ at $r = 130 \text{ m}$)
Trigger rate: 7 Hz/telescope
Cherenkov event: coincidence in $\Delta T = 30 \text{ ns}$, between any 2 corresponding PMs.

5

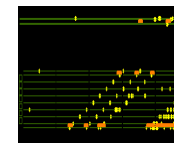


MACRO (as a μ detector):

- EAS from primaries with $E_n > 1.3 \text{ TeV/n}$
- EAS geometry through the μ track ($\sim 20 \text{ m}$ uncertainty) .



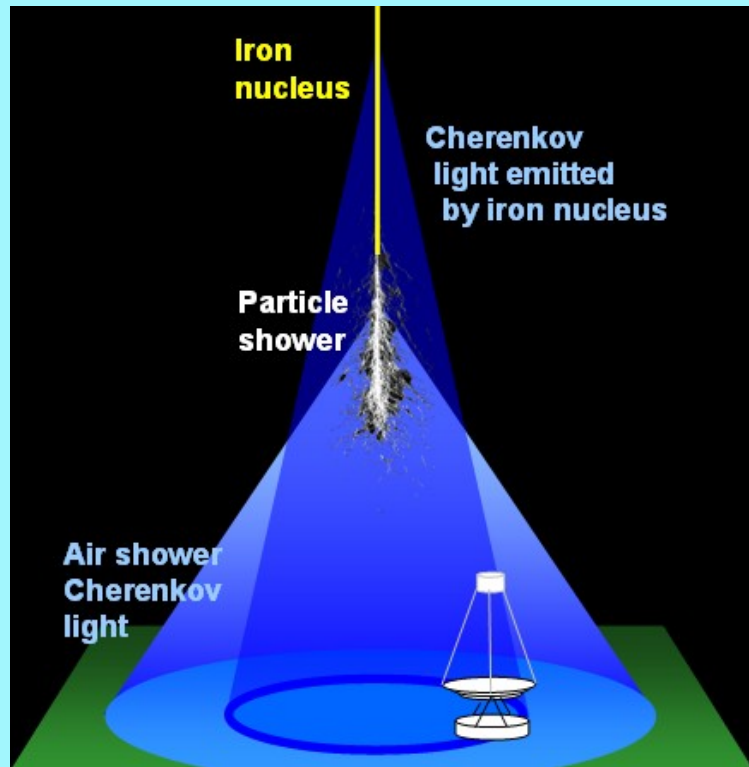
depth: 3100 m w.e.
 $E_{\mu}^{\text{thr}} \sim 1.3 \text{ TeV}$
 $76.6 \times 12 \times 4.8 \text{ m}^3$
 $\sigma_0 < 1^\circ$
20 m at surface level



1

Cherenkov light: H.E.S.S. Iron: 15 – 150 TeV

Cherenkov Light $\propto Z^2$

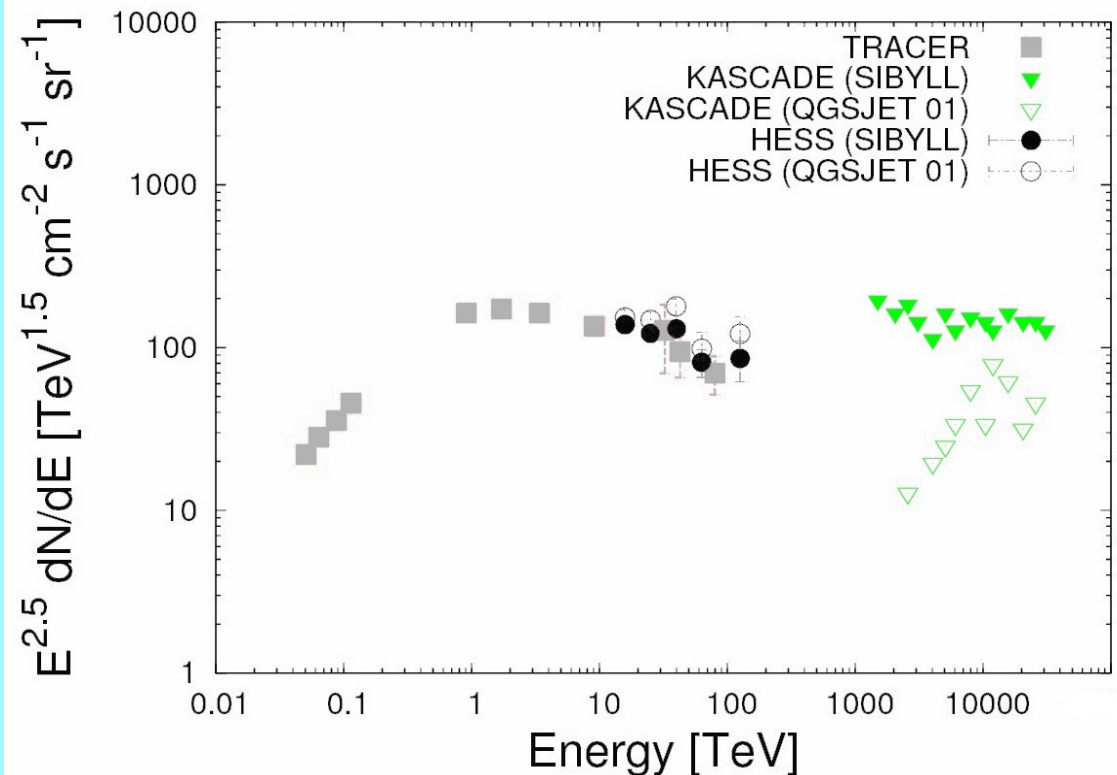
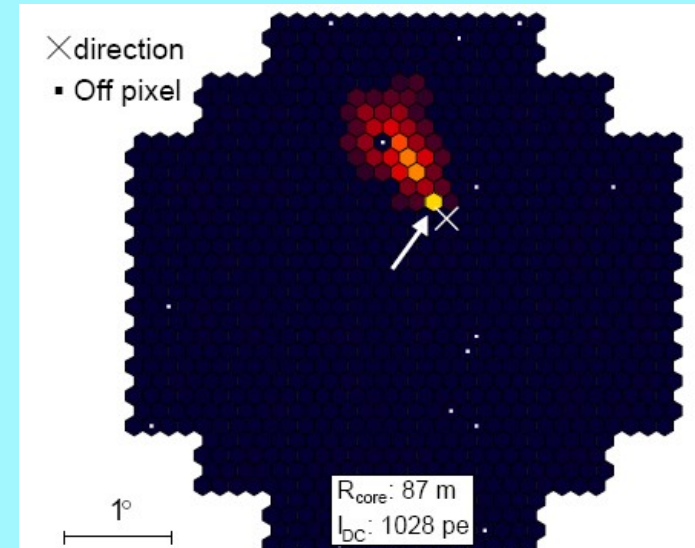


Good agreement with other exper.

- Hadronic model $\approx 20\%$ on normal.
- Power-law Index

QGSJET = 2.62 ± 0.11

SIBYLL = 2.76 ± 0.11

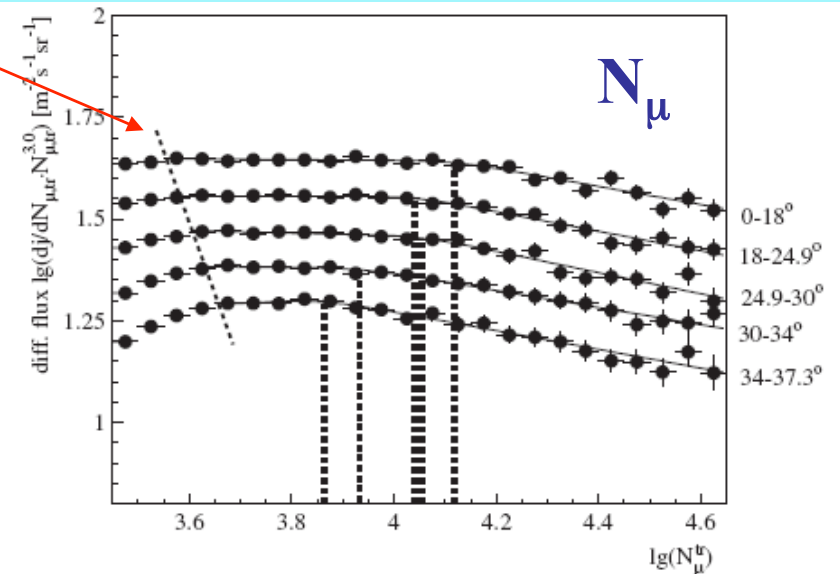
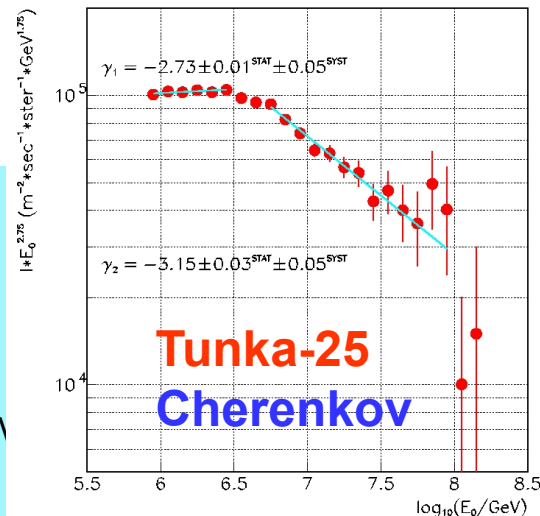
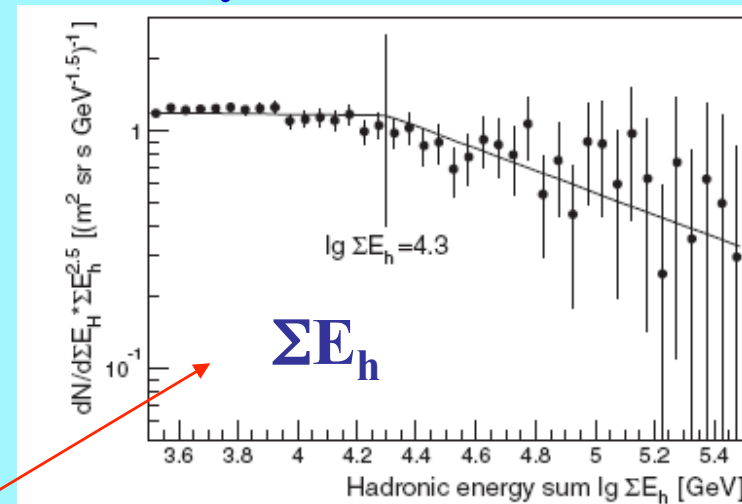
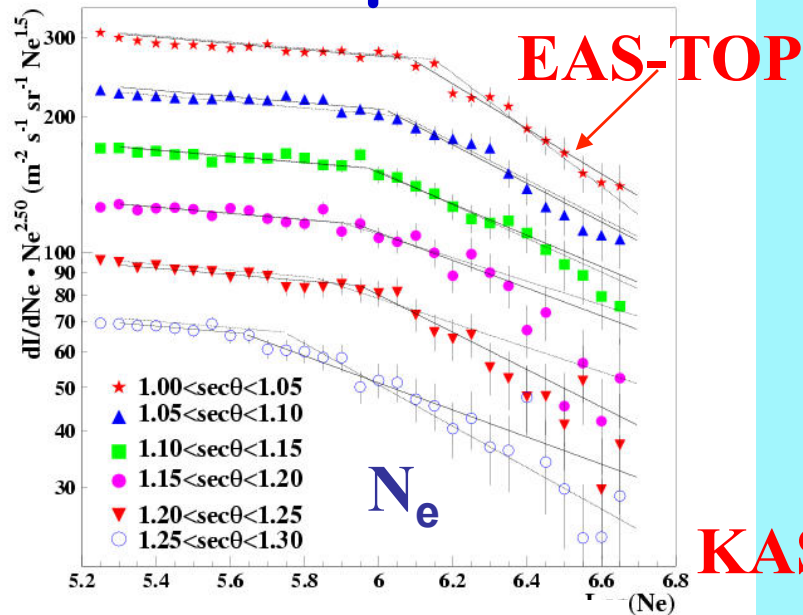


Cosmic Rays

Aharonian et al., 2007

Experimental results at knee energies

The change of slope is observed in the spectra of all EAS components



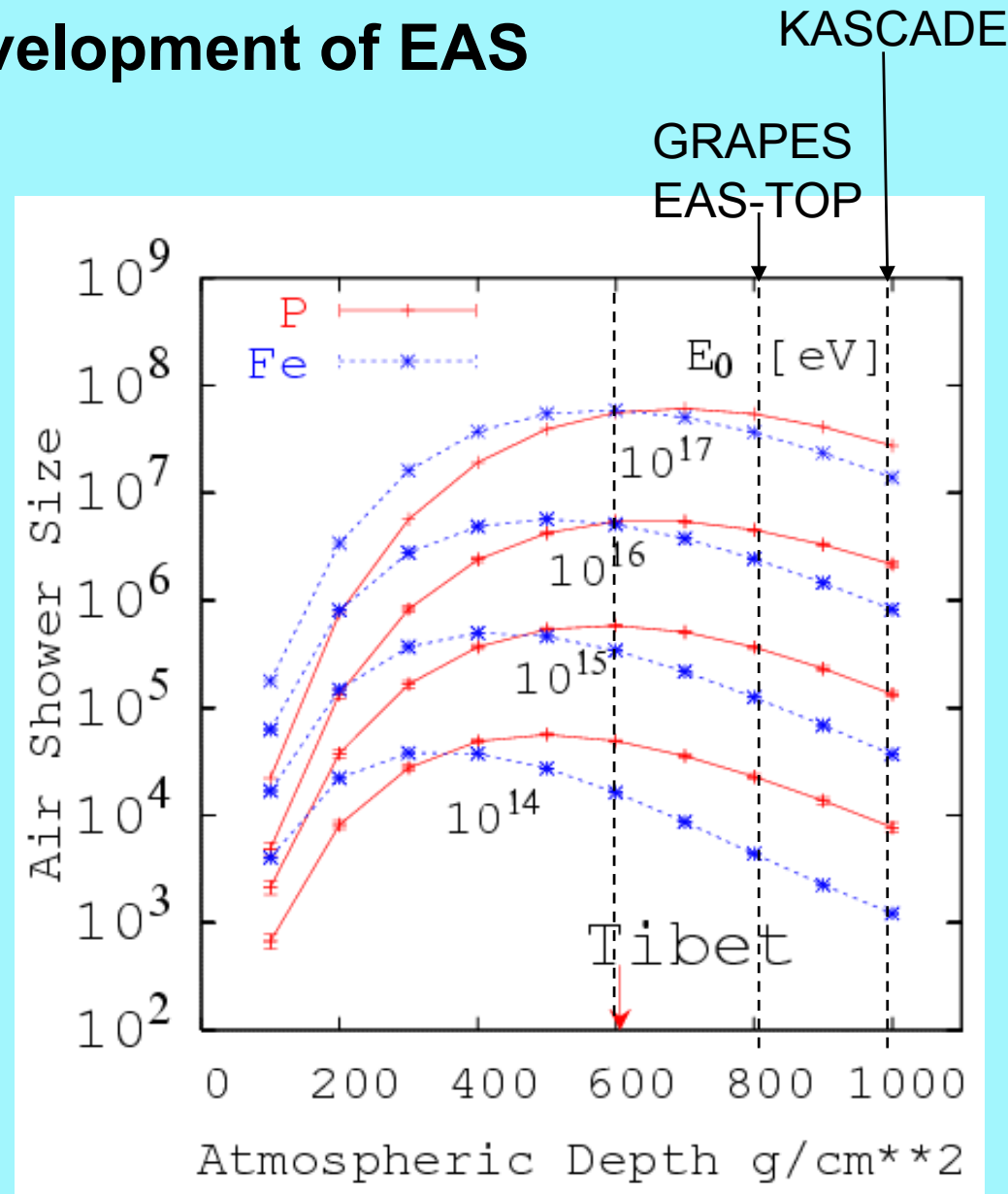
Cosmic Ray

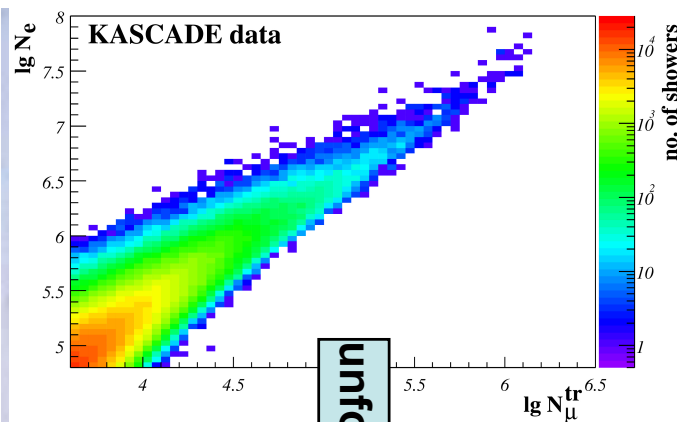
Longitudinal development of EAS

In the knee region:

At high mountain the shower is at maximum
less fluctuations

Sea level is better
for composition studies
because **H – Fe**
separation is easier

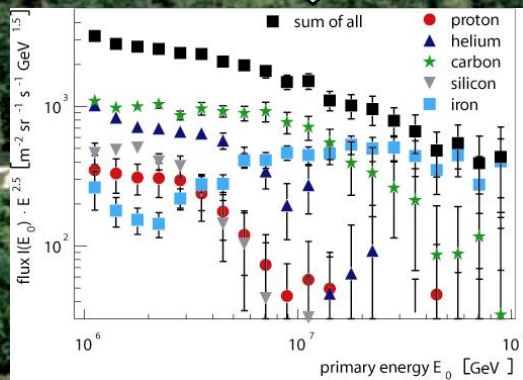




Mass group spectra
from Ne – N_μ (GeV):
E = 1 - 30 PeV

KASCADE (110 m a.s.l.)

Composition studies by KASCADE collaboration:
Astrop.Phys. 24 (2005) 1 , Astrop.Phys. 31 (2009) 86



Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

→ solve the inverse problem

$$g(y) = \int K(y, x) p(x) dx$$

with y=(N_e, N_μ^{tr}) and x=(E, A)

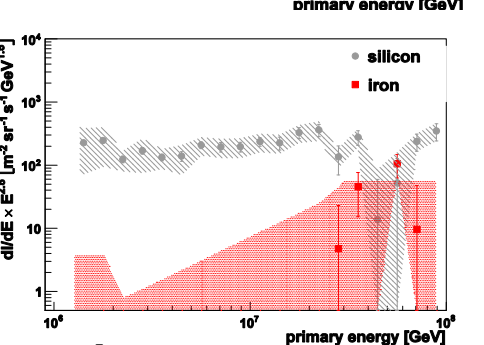
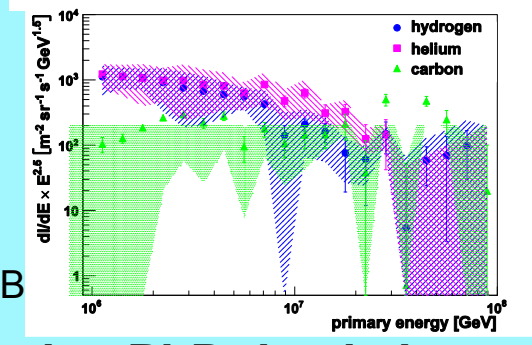
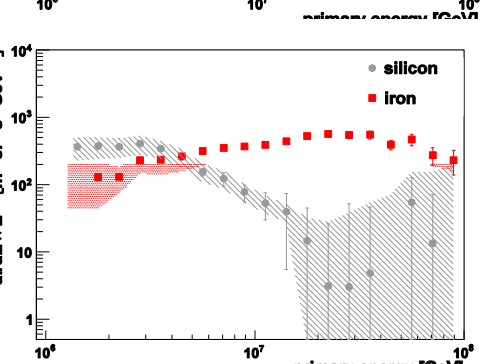
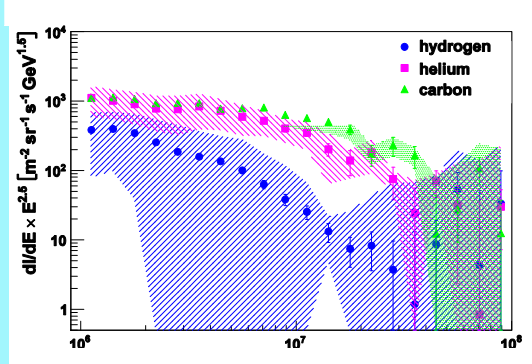
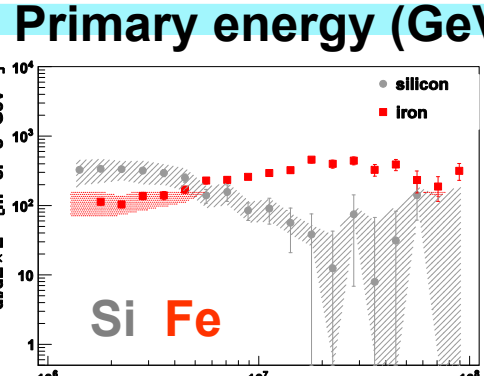
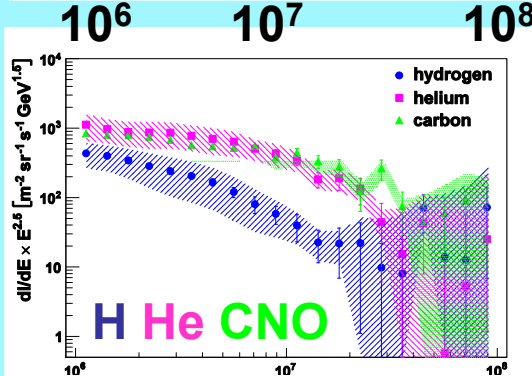
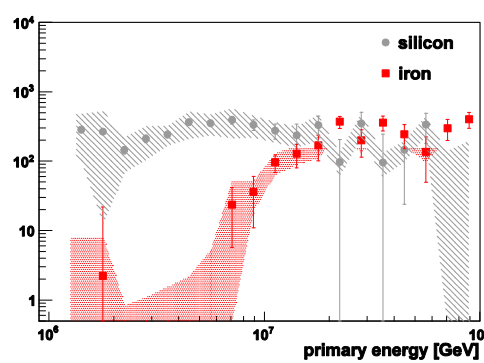
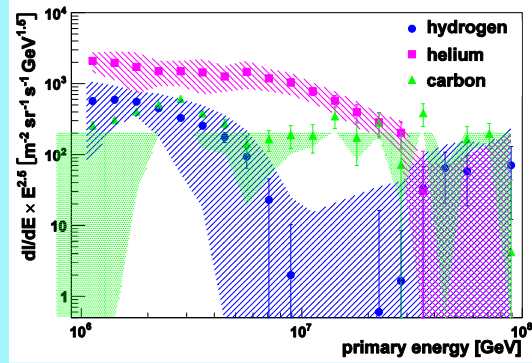


e/γ - detector
(liquid scintillator)

lead/iron absorber

muon detector
(plastic scintillator)

$dN/dE \times E^{2.5} [m^{-2}s^{-1}sr^{-1}GeV^{1.5}]$



KASCADE

QGSjet01/FLUKA

Knee H $\sim (3 - 4 \times 10^{15} \text{eV})$

Knee He $\sim 8 \times 10^{15} \text{eV}$

No knee in other spectra

QGSjetII/FLUKA

Knee H $\sim (3 - 4 \times 10^{15} \text{eV})$

Knee He $\sim 8 \times 10^{15} \text{eV}$

Knee CNO $\sim (2-3 \times 10^{16} \text{eV})$

Knee Si $\sim 4 \times 10^{15} \text{eV}$

SIBYLL/FLUKA

Knee H $\sim (3 - 4 \times 10^{15} \text{eV})$

Knee He $\sim 8 \times 10^{15} \text{eV}$

Knee CNO $\sim (2-3 \times 10^{16} \text{eV})$

Knee Si $\sim 4 \times 10^{15} \text{eV}$

EPOS1.99/FLUKA

Knee H $\sim (6 - 7 \times 10^{15} \text{eV})$

No knee in other spectra

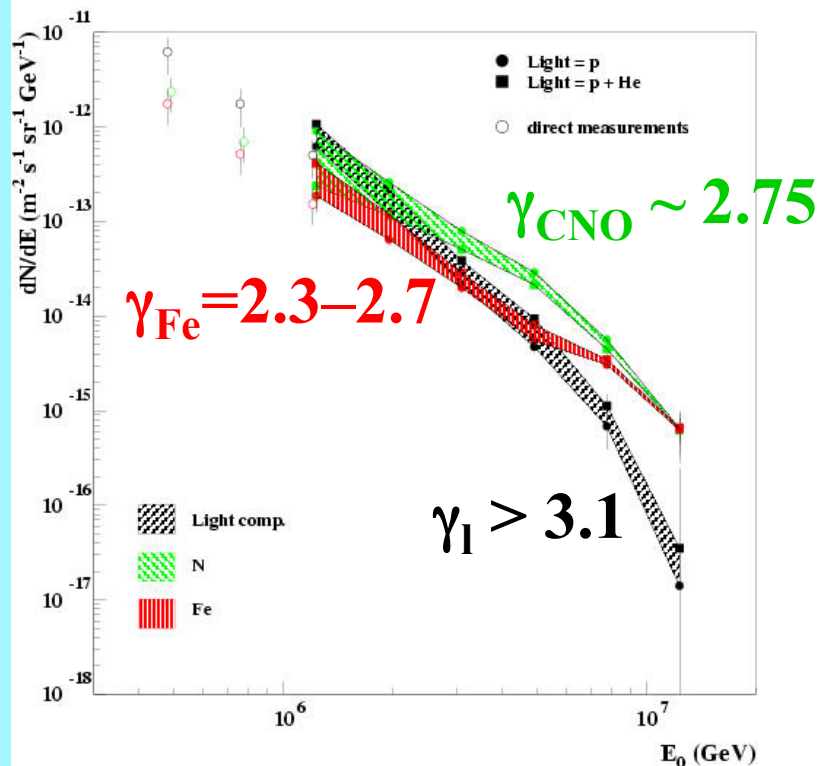
Almost no Fe

M. B

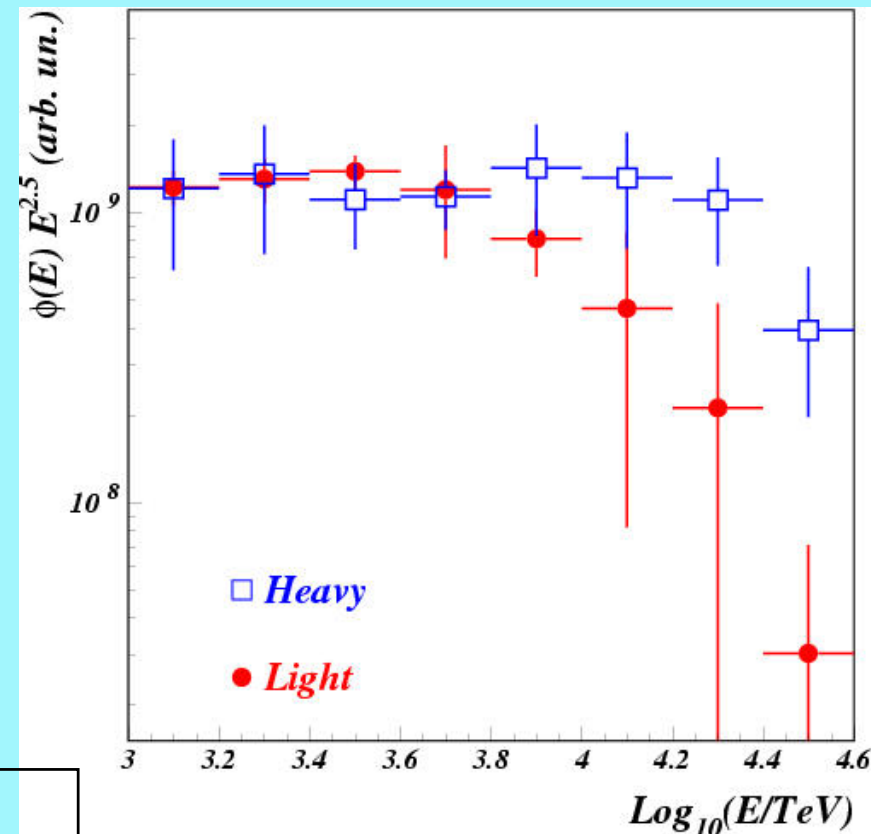
M. Fingler, PhD thesis in preparation

EAS-TOP (2005 m a.s.l.) & MACRO

EAS-TOP Ne-N μ (GeV)



EAS-TOP/MACRO Ne-N μ (TeV)



Average power low index
 of different mass groups (γ)
 Heavier primary spectra harder

$\rightarrow E_p \propto Z$?
 M. Bertaina

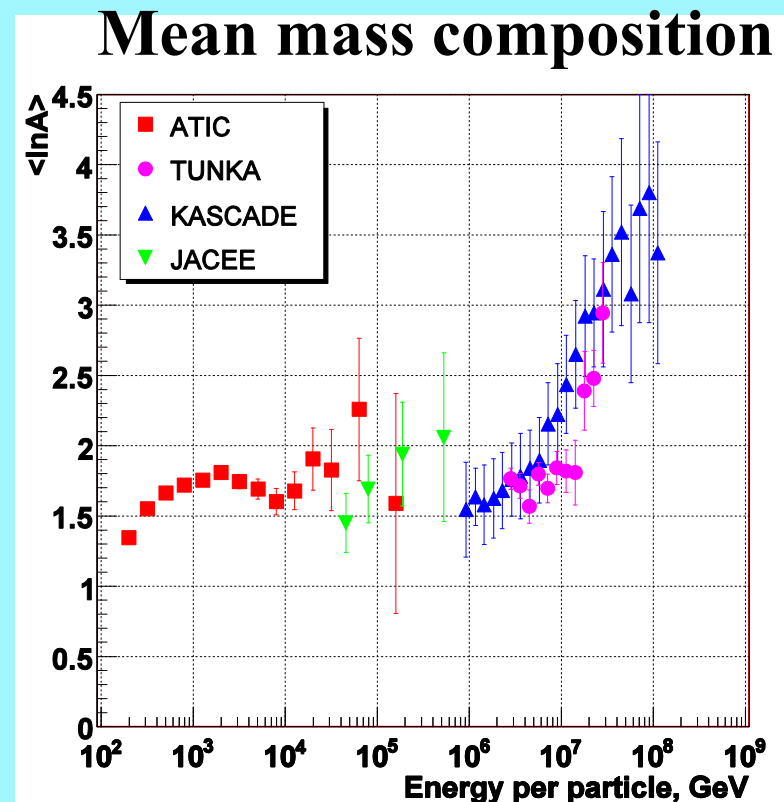
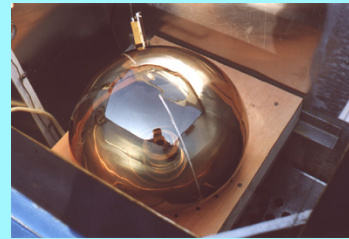
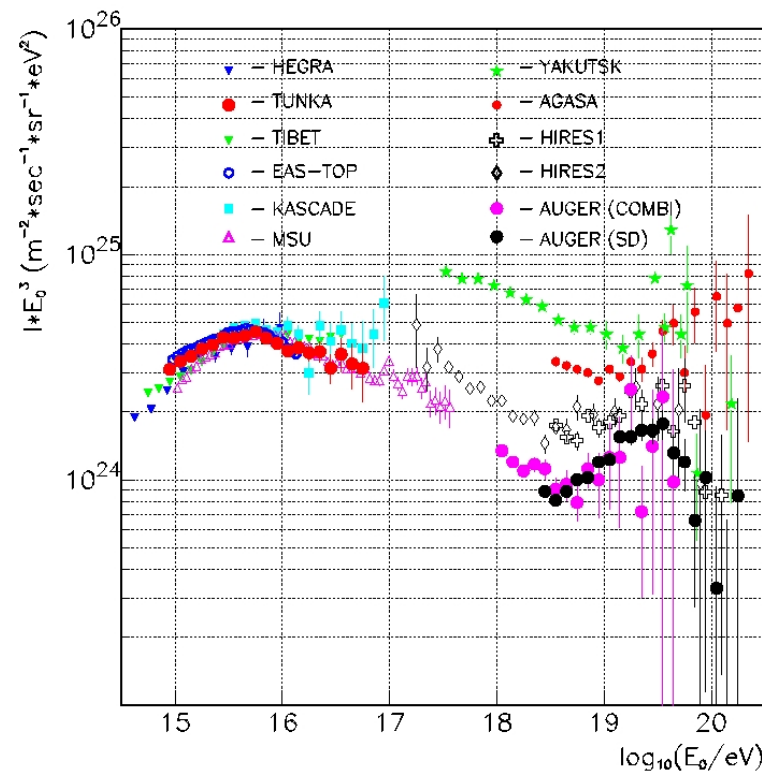
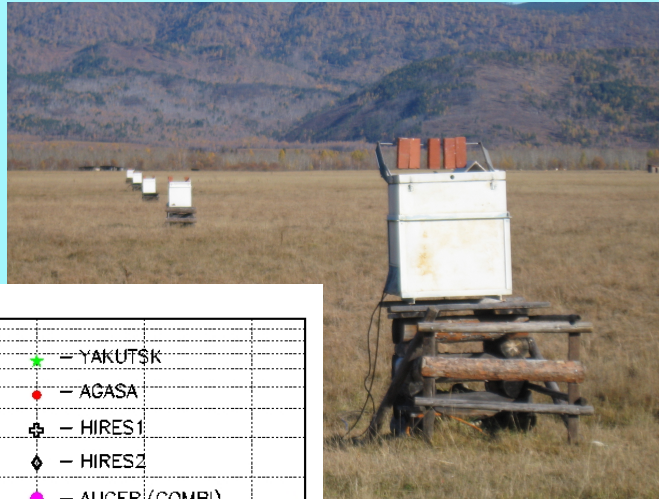
Cosmic Rays

$L = p + \text{He}$ $H = \text{Mg} + \text{Fe}$

Astrop. Phys. 20 (2004) 641

Astrop. Phys. 21 (2004) 583

TUNKA-25 Cherenkov array, Siberia 675 m a.s.l.



V. Prosin, *Highlights of
Astroparticle Physics*
Torino, 2010

1. Composition before the knee and in the knee is light 70% of p + He, 30% of others.

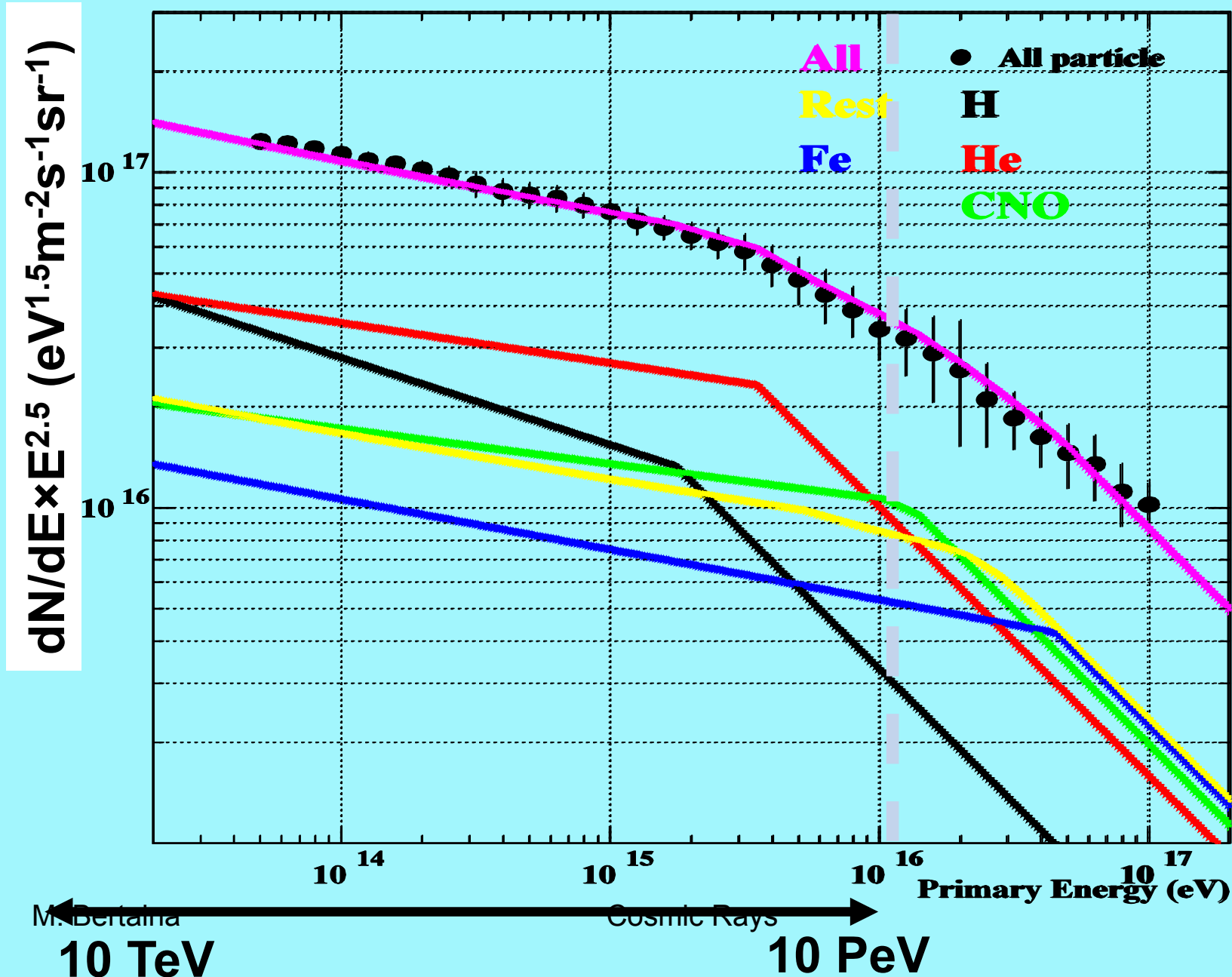
M. Bertaina

Cosmic Rays

88

2. Composition at $3 \cdot 10^{16}$ is heavy 30% of p+He, 70% of others.

All particle spectrum (10 TeV – 10 PeV)

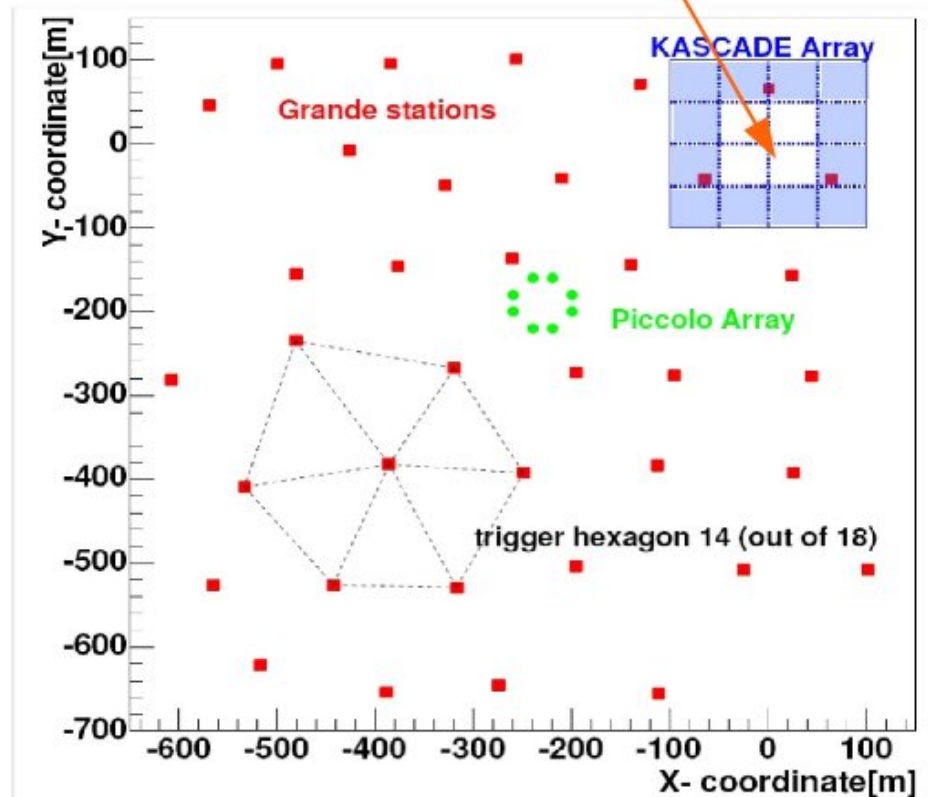


KASCADE-Grande features and performances

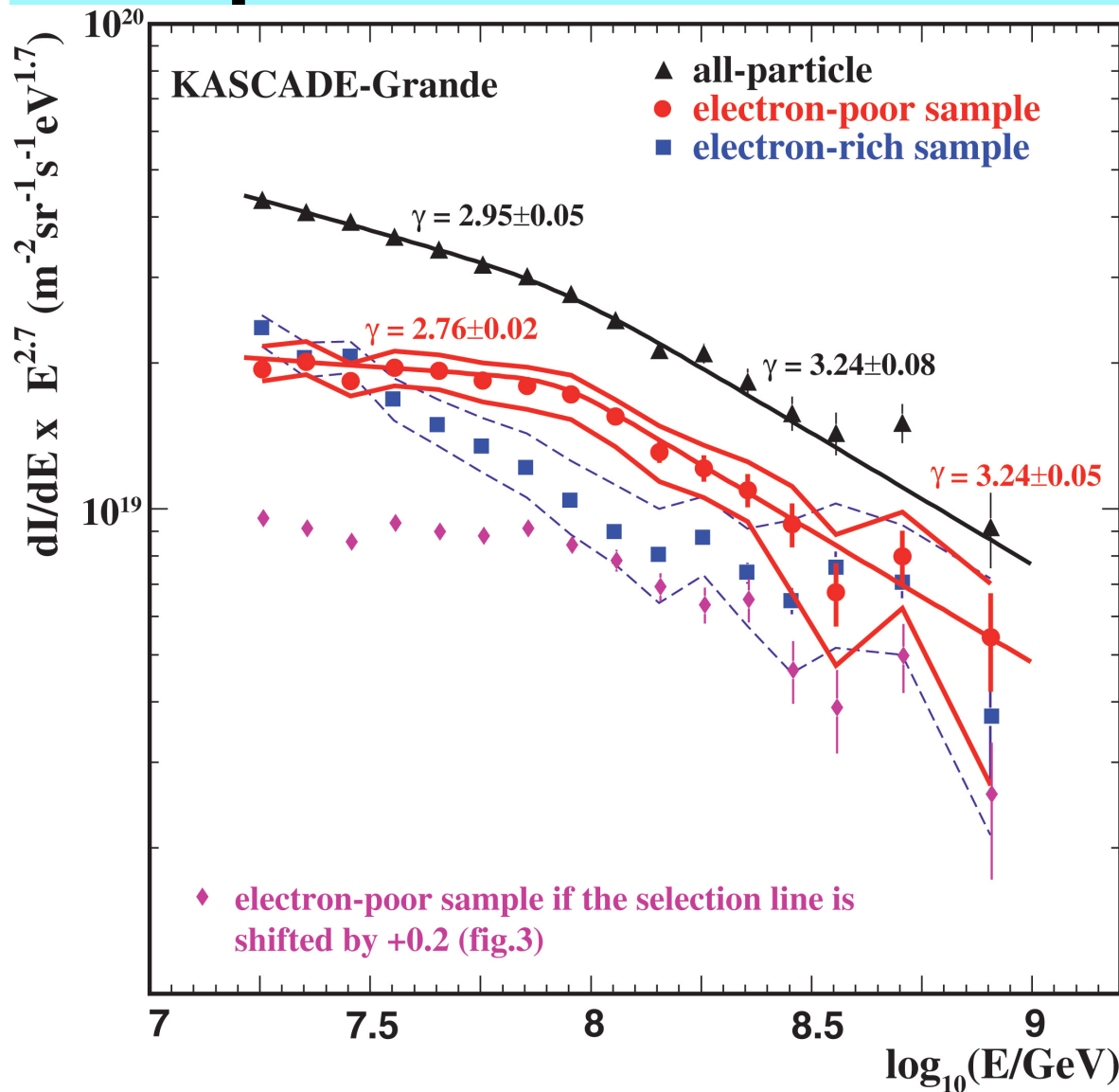
- **KASCADE:**
 - energy range $10^{14} - 10^{16}$ eV
 - 252 detector stations over 200×200 m²
 - in a station: measurement of e and μ separately with **two co-located types of detector scintillators**
- **Grande:**
 - 37 detector stations 10 m² each spread over 700×700 m²
 - in a station: measurement of all-charged e + μ
 - 18 hexagonal clusters. 7 out-of-7 coincidence triggers data acquisition



Upper view and Bottom view of a Grande station



Spectra of individual mass groups :



- spectra of individual mass groups:

→ steepening close to 10^{17}eV (2.1σ) in all-particle spectrum

→ steepening due to heavy primaries (3.5σ)

→ light+medium primaries show steeper spectrum,
 → fit by power law okay
 → but possibility for hardening above 10^{17}eV

→ spectrum of more enhanced heavy sample has harder spectrum before break.

KASCADE-Grande collaboration, PRL 107 (2011)

171103 M. Bertina

Cosmic Rays

91

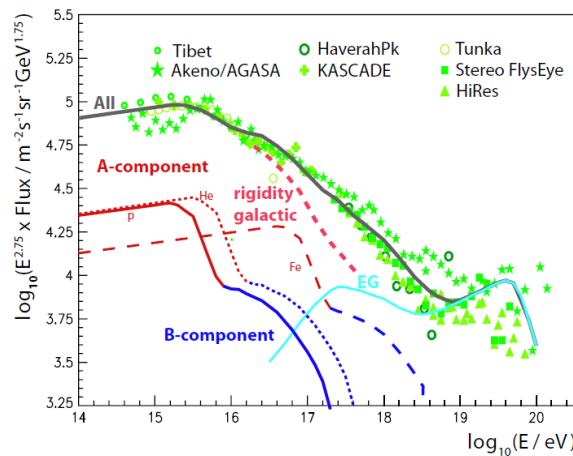
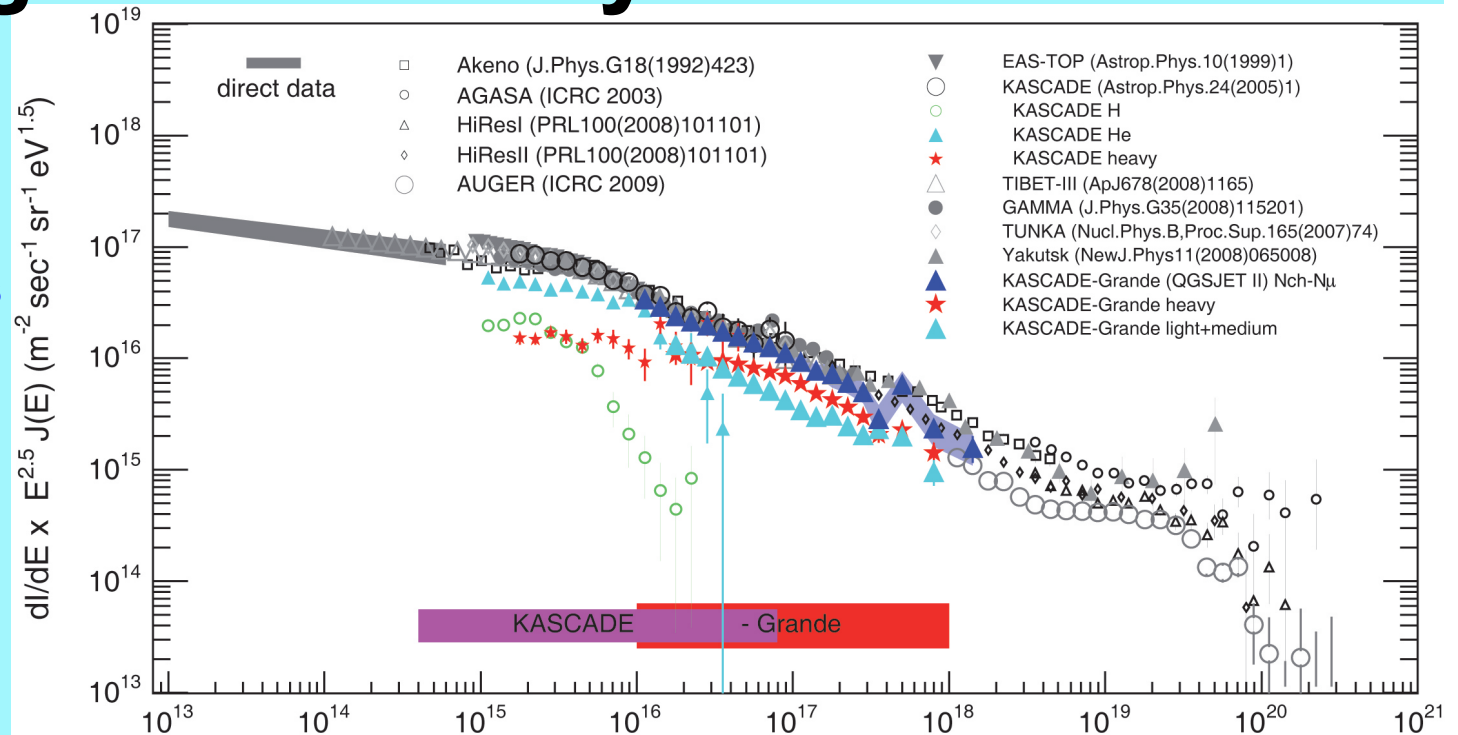
Light and Heavy Knees

→ KASCADE:
knee of light primaries at
 $2-4 \cdot 10^{15} \text{ eV}$

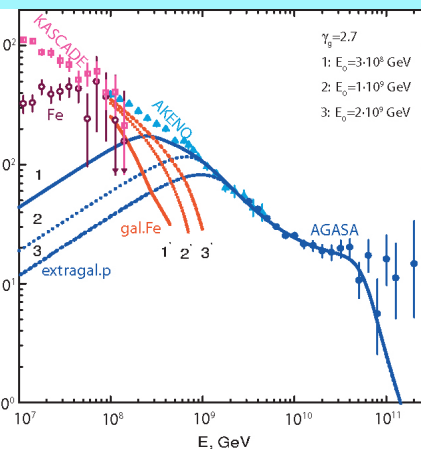
→ KASCADE-Grande:
knee of heavy primaries
at $8-9 \cdot 10^{16} \text{ eV}$

→ both:
medium primaries
needed in the range of
 $10^{15} - 4 \cdot 10^{17} \text{ eV}$ (QGSJet)

arXiv:1107.5885



A.M. Hillas, J. Phys. G: Nucl. Part. Phys.
31 (2005) R95



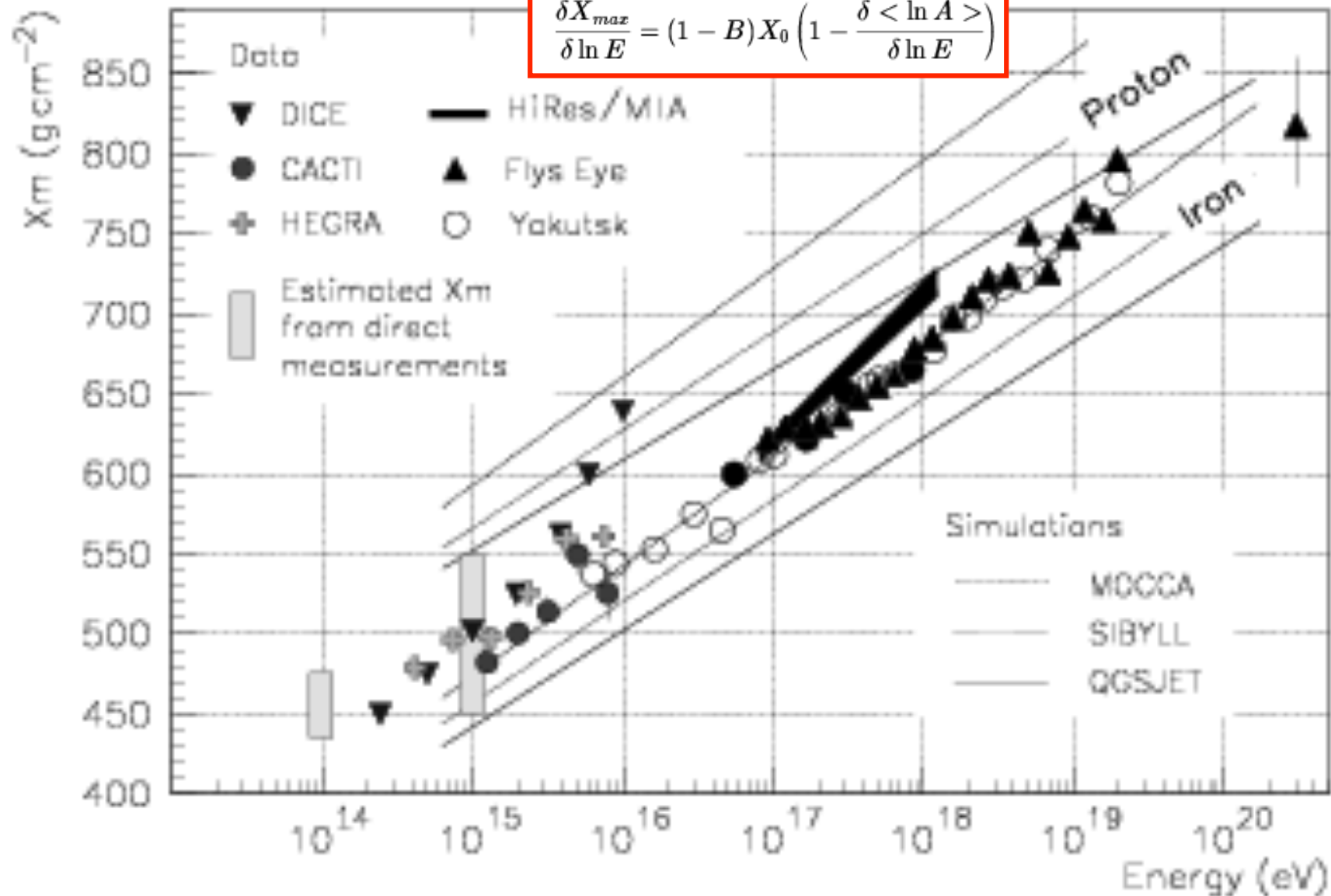
V. Berezhinsky, astro-ph
0403477

→ Questions:

- which astrophysical model describes the data?
- exact composition above heavy knee?
- spectral forms of mass groups?
- recovery of protons above 10^{17} eV ?

$$X_{max} = (1 - B)X_0 \left(\ln \frac{E}{\epsilon} - \langle \ln A \rangle \right)$$

$$\frac{\delta X_{max}}{\delta \ln E} = (1 - B)X_0 \left(1 - \frac{\delta \langle \ln A \rangle}{\delta \ln E} \right)$$



The connection between All-particle flux and All-nucleon flux

$$\frac{d\phi(E_0)}{dE_0} = \sum_i K_i E_0^{-\gamma}$$

sum running on
different mass groups

$$E_{nuc} = E_0/A$$

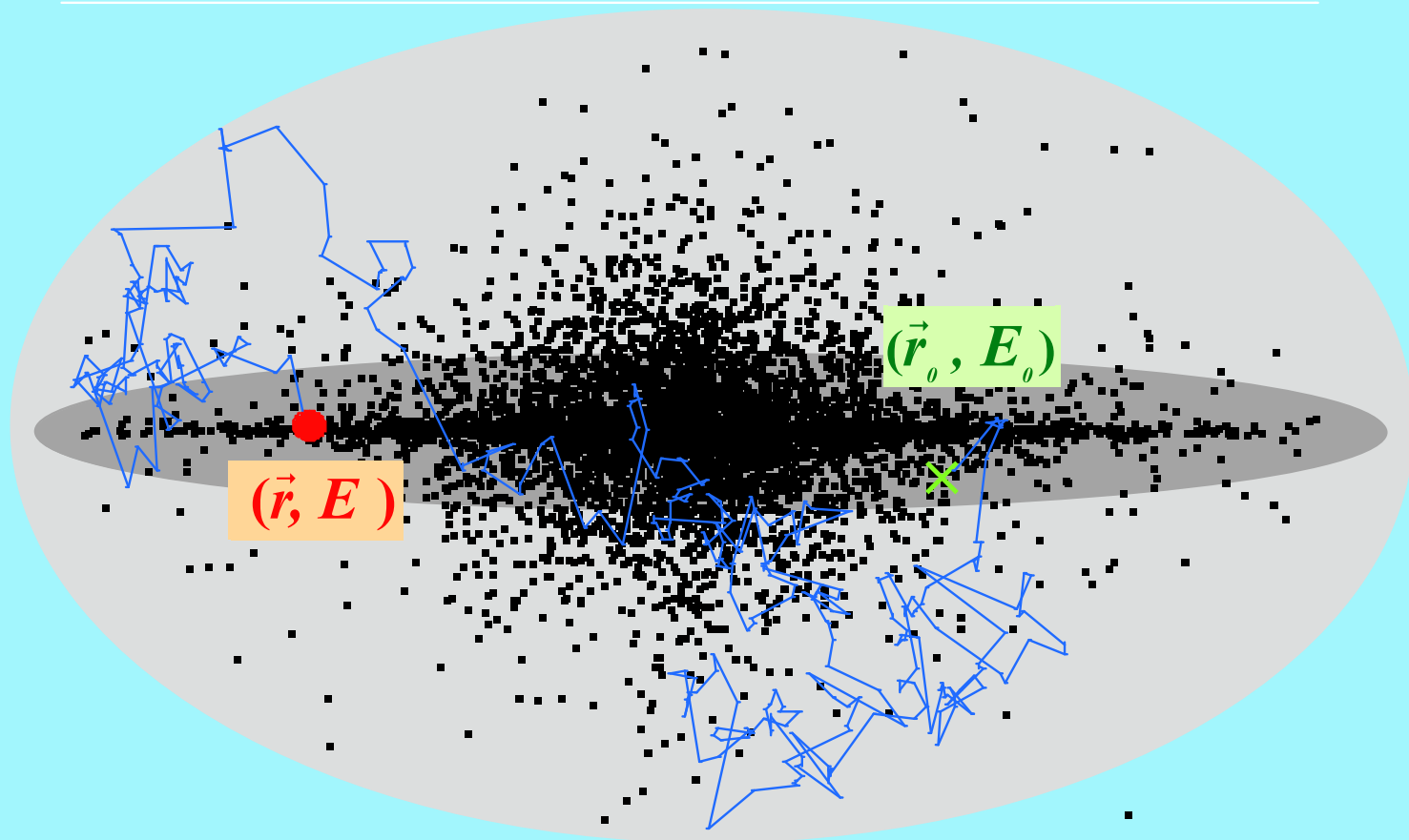
(A = mass number)

$$\frac{d\phi(E_{nuc})}{E_{nuc}} = \frac{d\phi(E_0)}{dE_0} \frac{dE_0}{dE_{nuc}}$$

$$\frac{d\phi(E_{nuc})}{E_{nuc}} = \sum_i K_i (A_i E_{nuc})^{-\gamma} A_i$$

$$\frac{d\phi(E_{nuc})}{E_{nuc}} = \sum_i K_i A_i^{\gamma-1} E_{nuc}^{-\gamma}$$

$\Phi (r, E; r_0, E_0)$: structure function

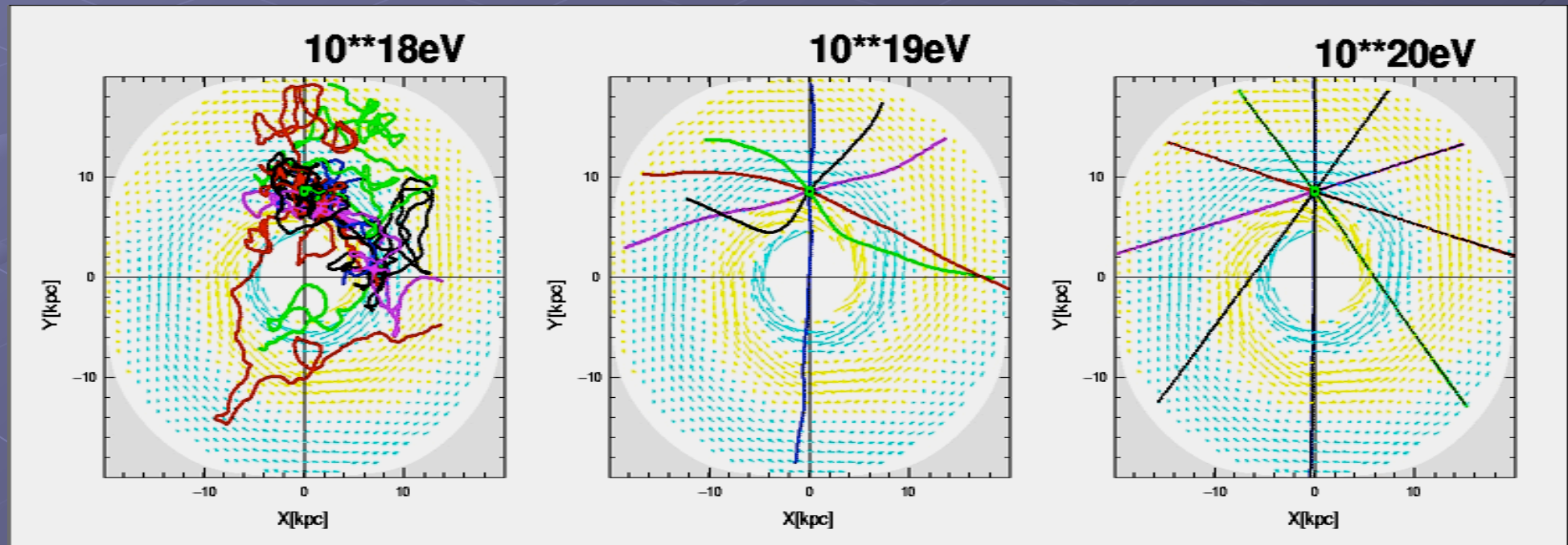


● : solar system $\vec{r} (r \approx 10\text{kpc}, z \approx 0)$

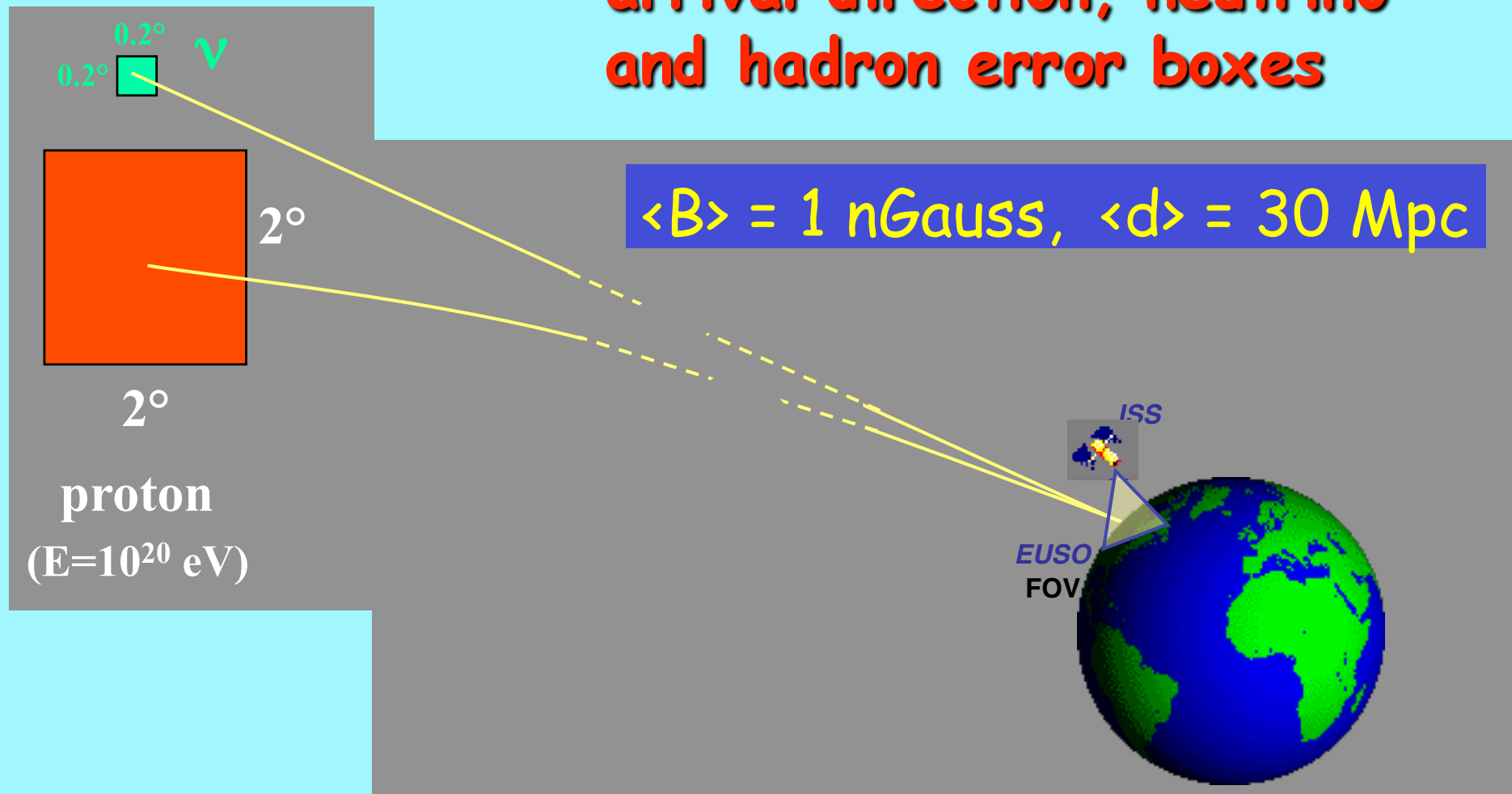
× : source $\vec{r}_0 (r_0, z_0)$

Cosmic Ray Propagation in our Galaxy

- Deflection angle < 1 degree at 10^{20}eV



arrival direction, neutrino and hadron error boxes



The neutrino error box is limited only by the instrument angular resolution, the proton error box is dominated by the intergalactic magnetic fields.

AGN Unified Model

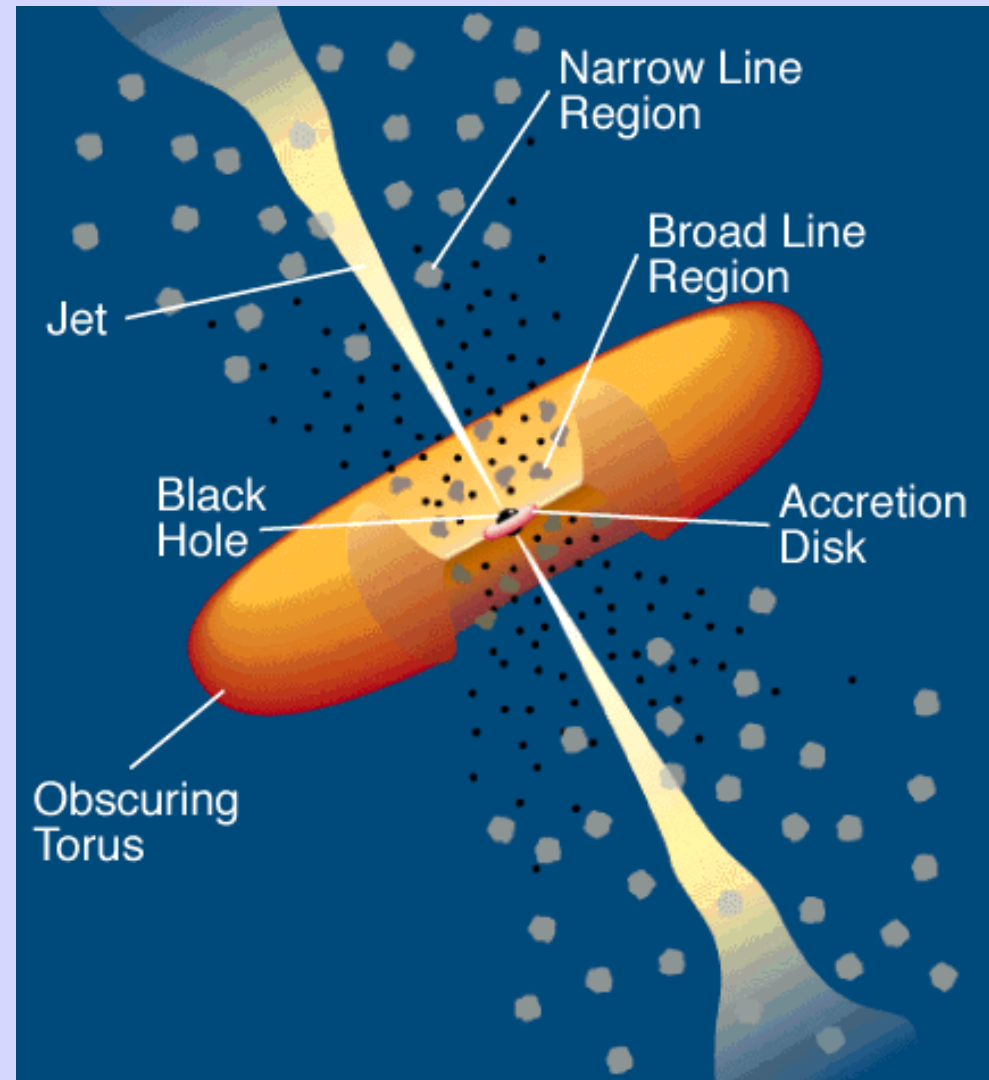
According to the Unified Model all AGNs share the same fundamental mechanism.

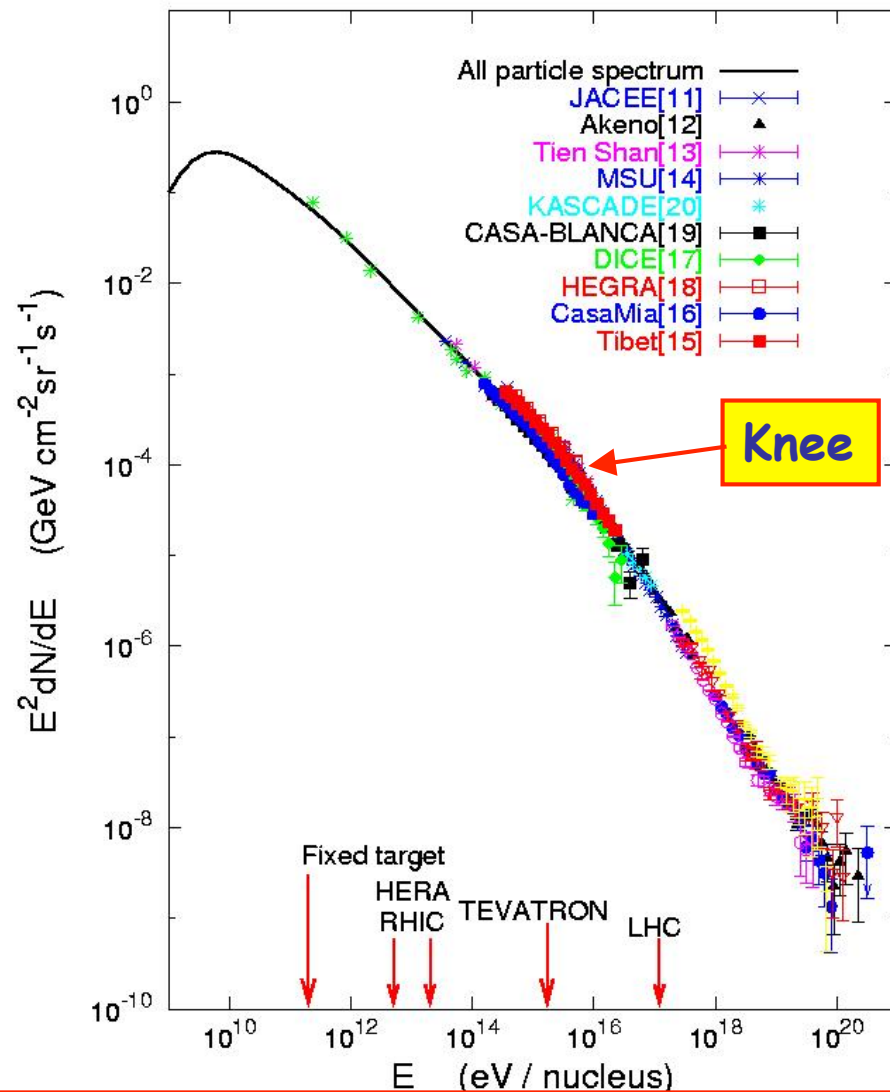
Source of energy:

super massive black hole
 $\sim 10^6$ - 10^9 solar masses

+ accretion disk

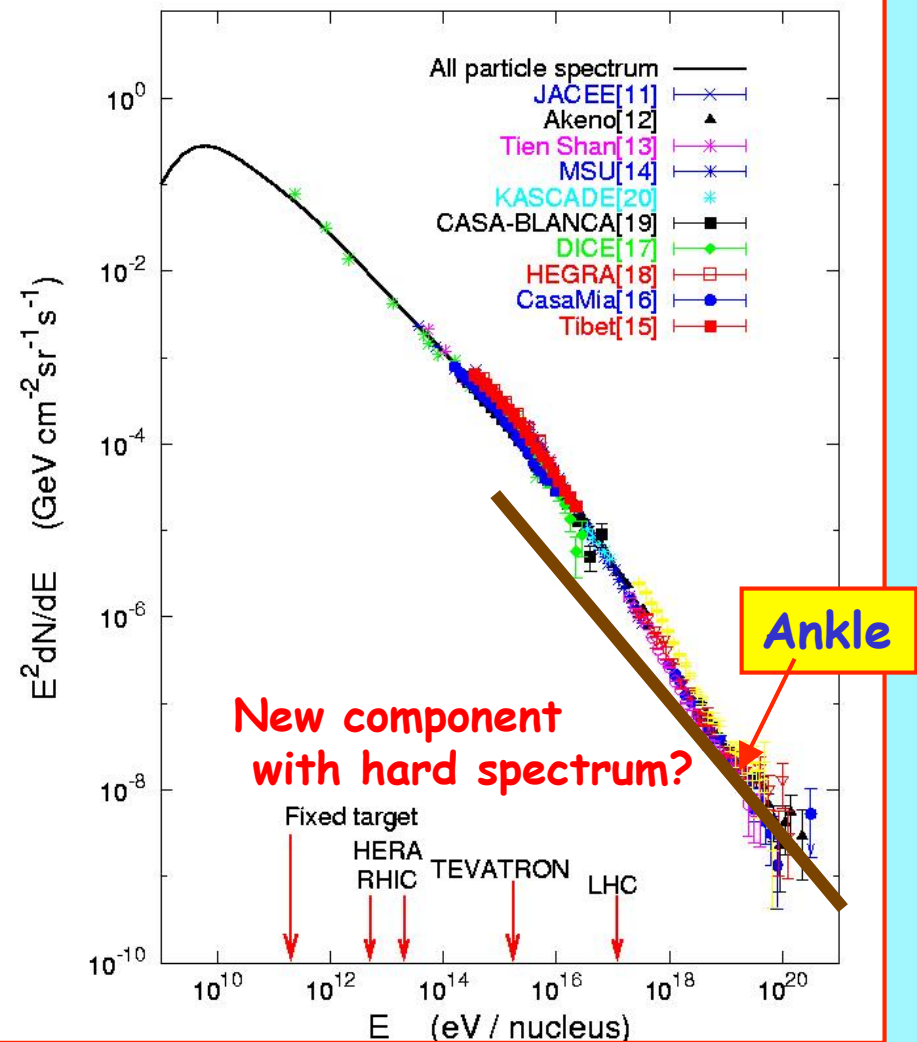
Fuel: 1-10 solar masses /year





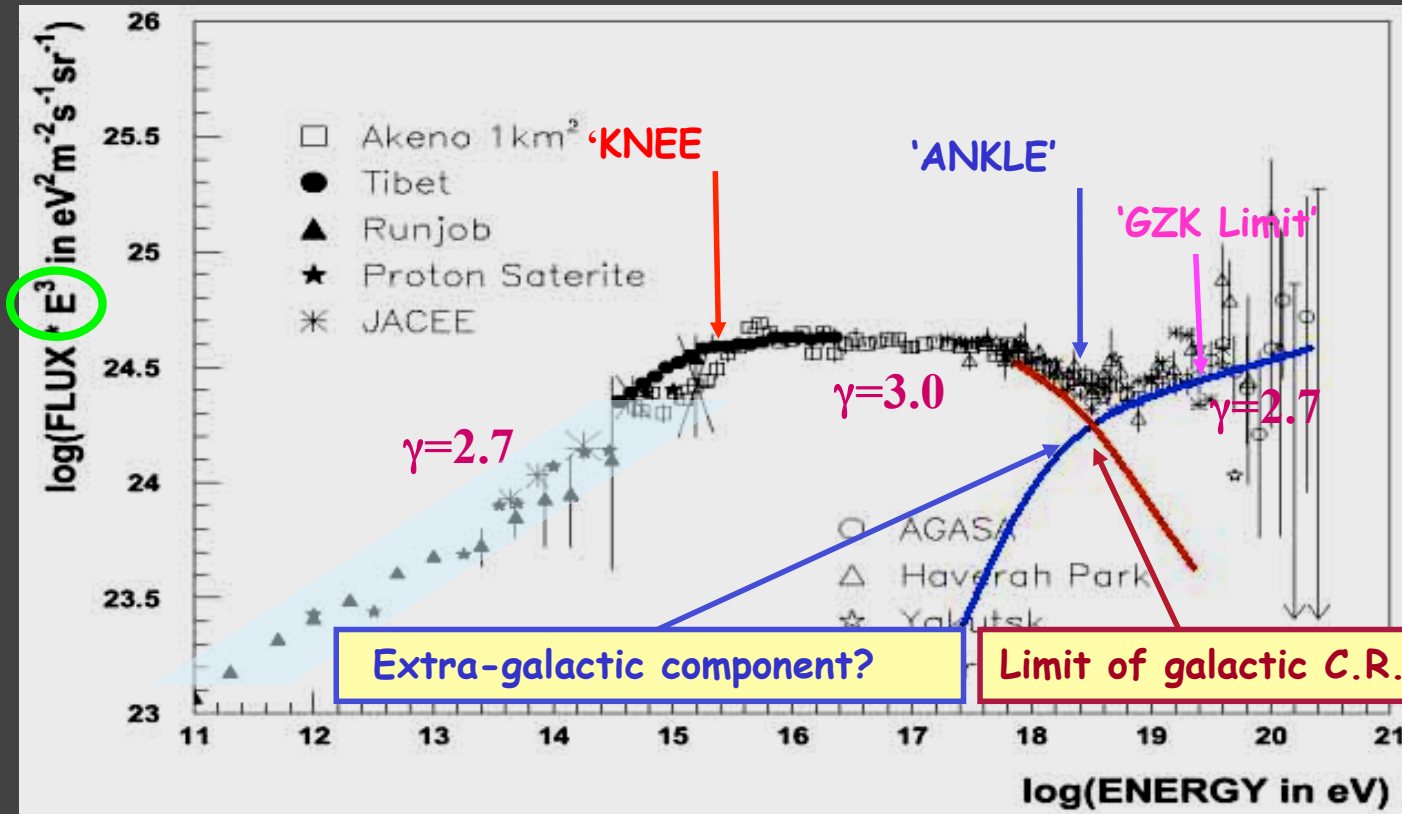
M. Bertaina

Cosmi



2

...the ankle marks the transition between galactic and extra galactic cosmic rays ?



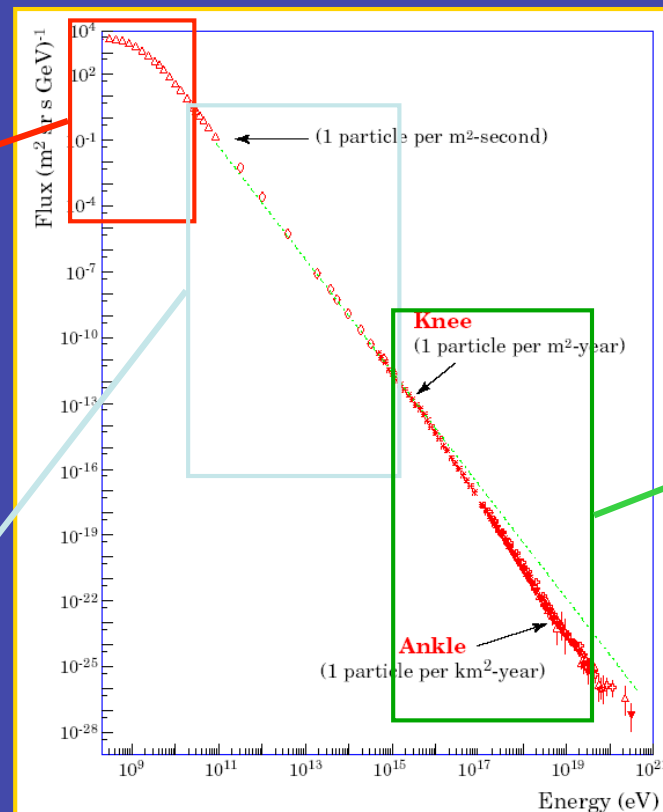
On the origin of cosmic rays (within GZK limit)

The identification of the sources is connected with the energy of the cosmic rays.

For energies within the GZK limit, the cosmic rays are produced in places where intense magnetic fields exist, which are capable of accelerating nuclei at high energies or they are produced during the explosion of a star.

$10^9 \div 10^{10}$ eV:
solar origin

$10^{10} \div 10^{15}$ eV:
Galactic origin
(SuperNovae explosion)



**$10^{15} \div 5 \times 10^{19}$ eV
(limite GZK):**

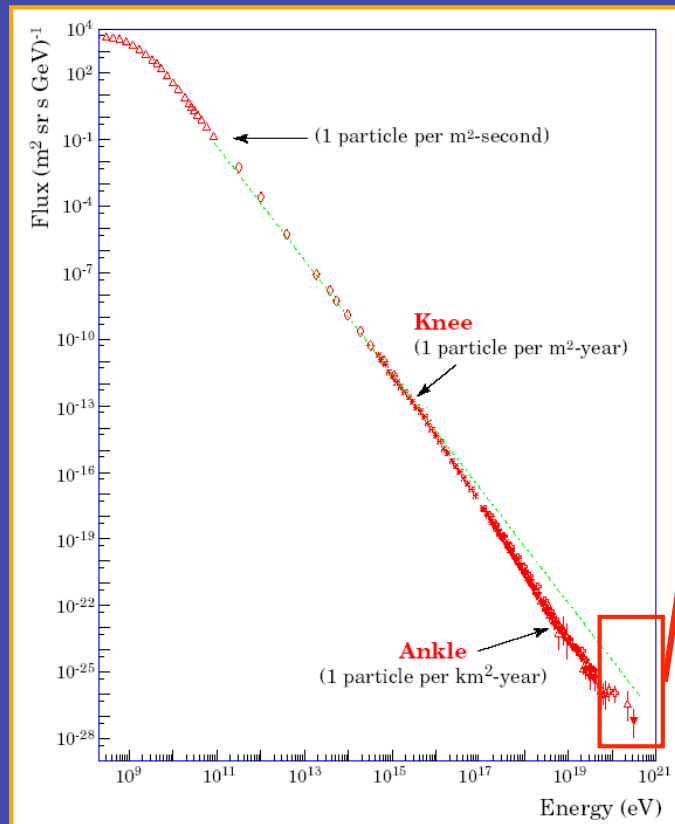
Extragalactic origin
(explosions of Super
Novae, pulsar with
intense magnetic
fields, black holes,
active galactic nuclei)

On the origin of cosmic rays (beyond the GZK limit)

For energies $E_0 > \sim 5 \times 10^{19}$ eV the origin of primary cosmic rays becomes a mystery.

Possible sources are:

- Collisions among galaxies or clusters of galaxies, radio galaxies. But the presence of the cosmic microwave background (CMB) prevent the particles of extreme high energy to cross cosmological distances (GZK effect); the maximum distance they could come from is comparable to Virgo cluster (M87). But this is in contradiction with the almost **isotropic arrival direction of the EHECR phenomenon**.
- Decay of particles originated just after Big Bang. In this case the majority of EHECR cosmic rays might be **neutrinos**.



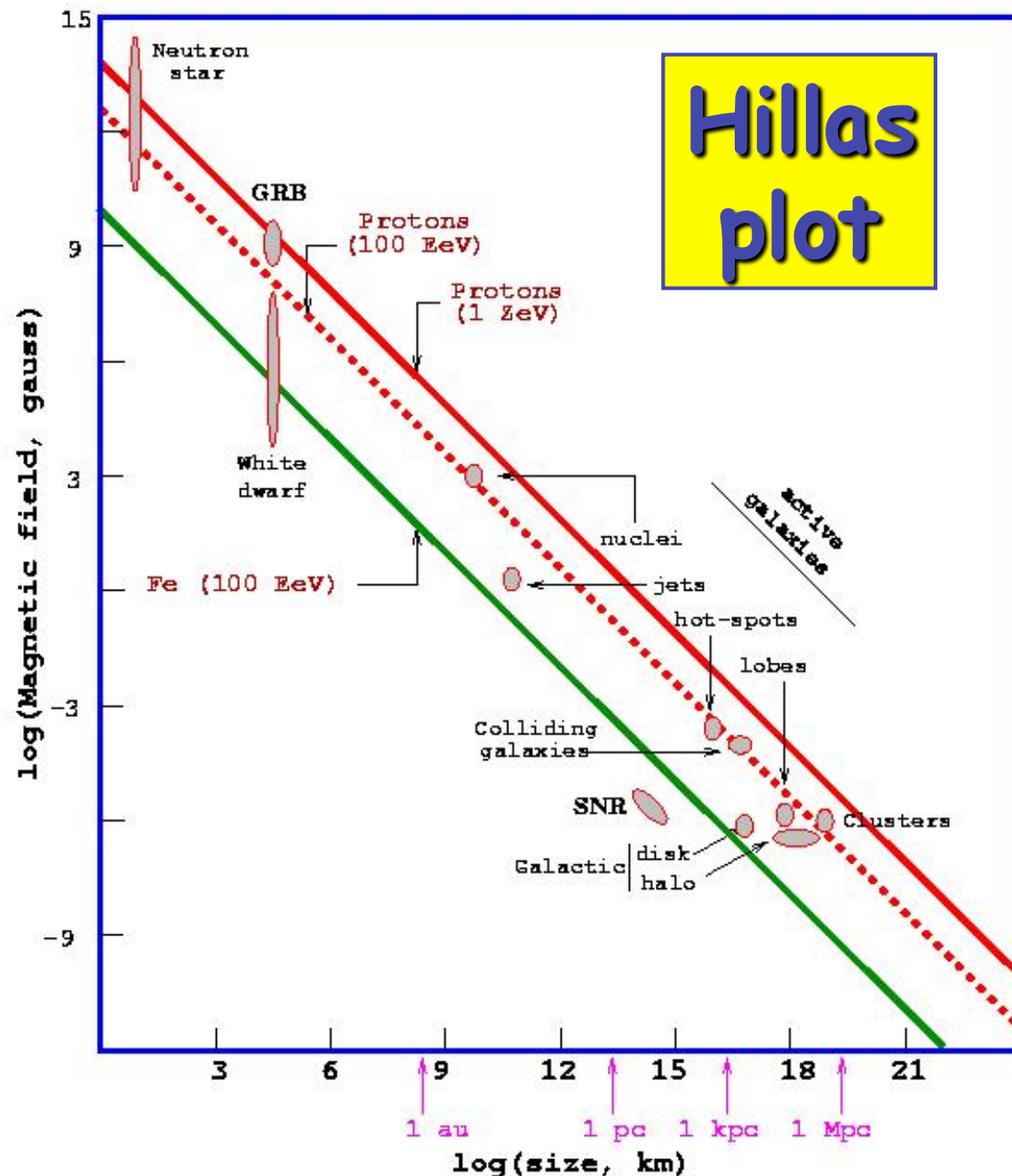
Few sources survive to the criteria

$$B \cdot L > E/Z$$

- Neutron stars
- GRB
- AGN
- Radio lobes
- Clusters
- collisions among Galaxies/Clusters

$$E_{MAX} \propto \gamma ZBL$$

M. Bertaina

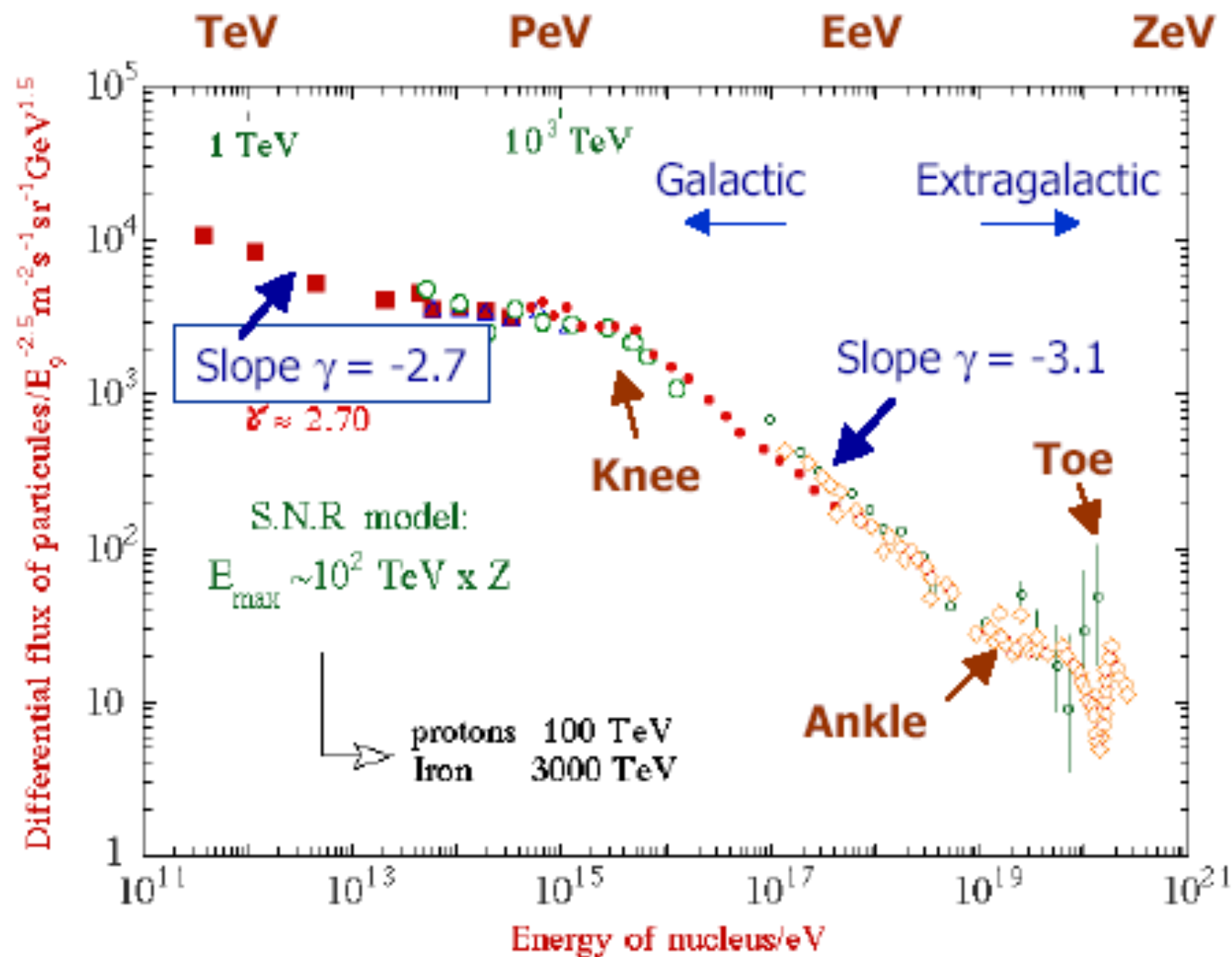


→ Atmosphere is required for the primary particle to interact and develop **shower** with a production of :

- Cherenkov light
- fluorescence light

→ Details of the **UV** light production yield details of the primary particle :

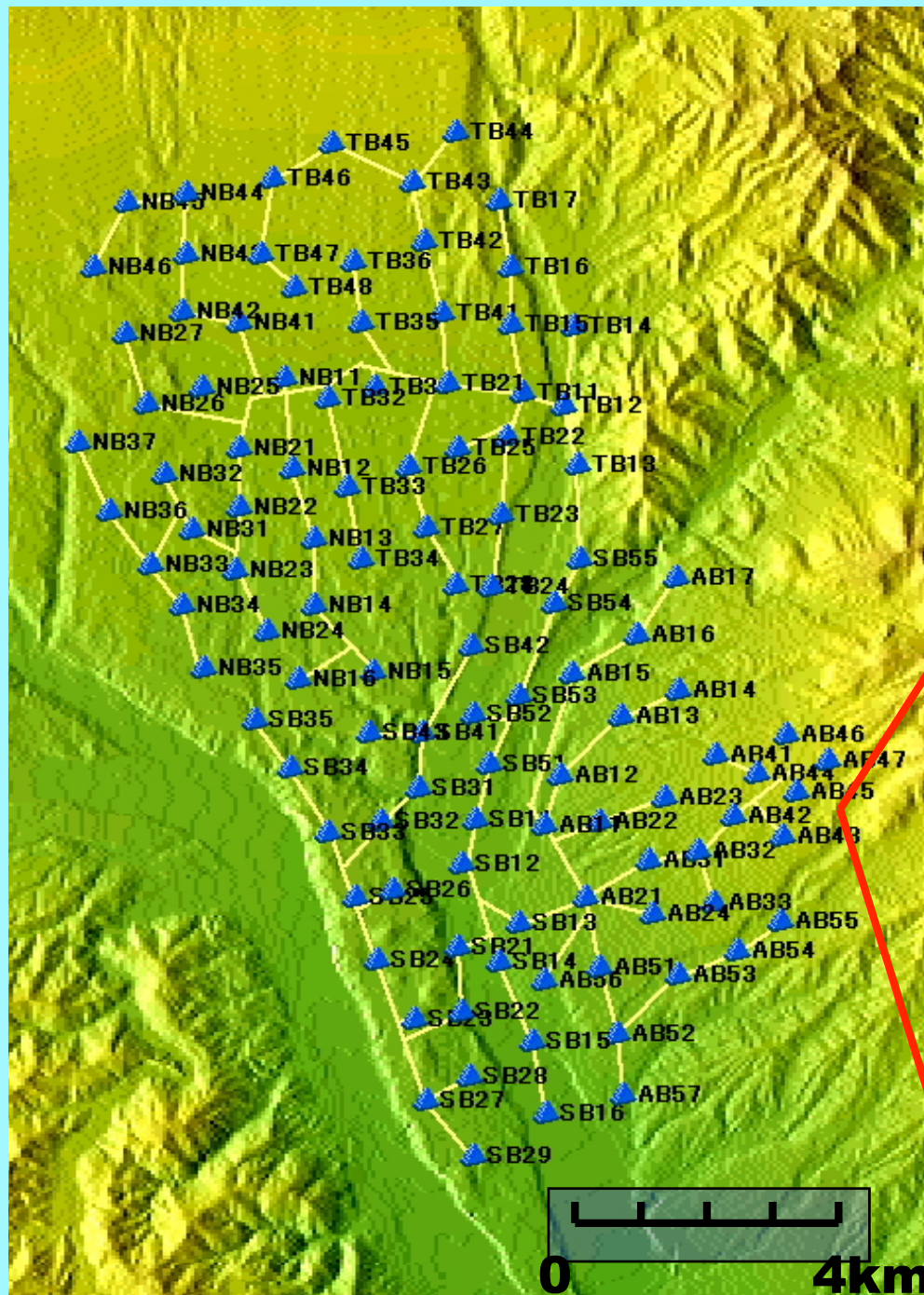
- the amount of UV light produced is proportional to the particle's energy
- the shape of the shower profile and the atmospheric depth of the shower maximum contain information about particle mass composition



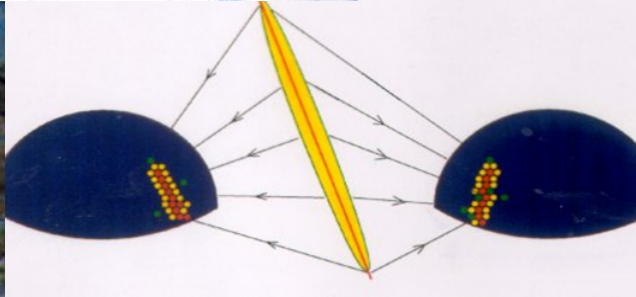
AGASA

Akeno Giant Air
Shower Array

111 Electron Det.
27 Muon Det.



- Les premières détections
 - Fly 's eye (US, 81-92)



- 67 miroirs de 1.6 m de diamètre

- Point focal à 140 m de 12 x 12 m

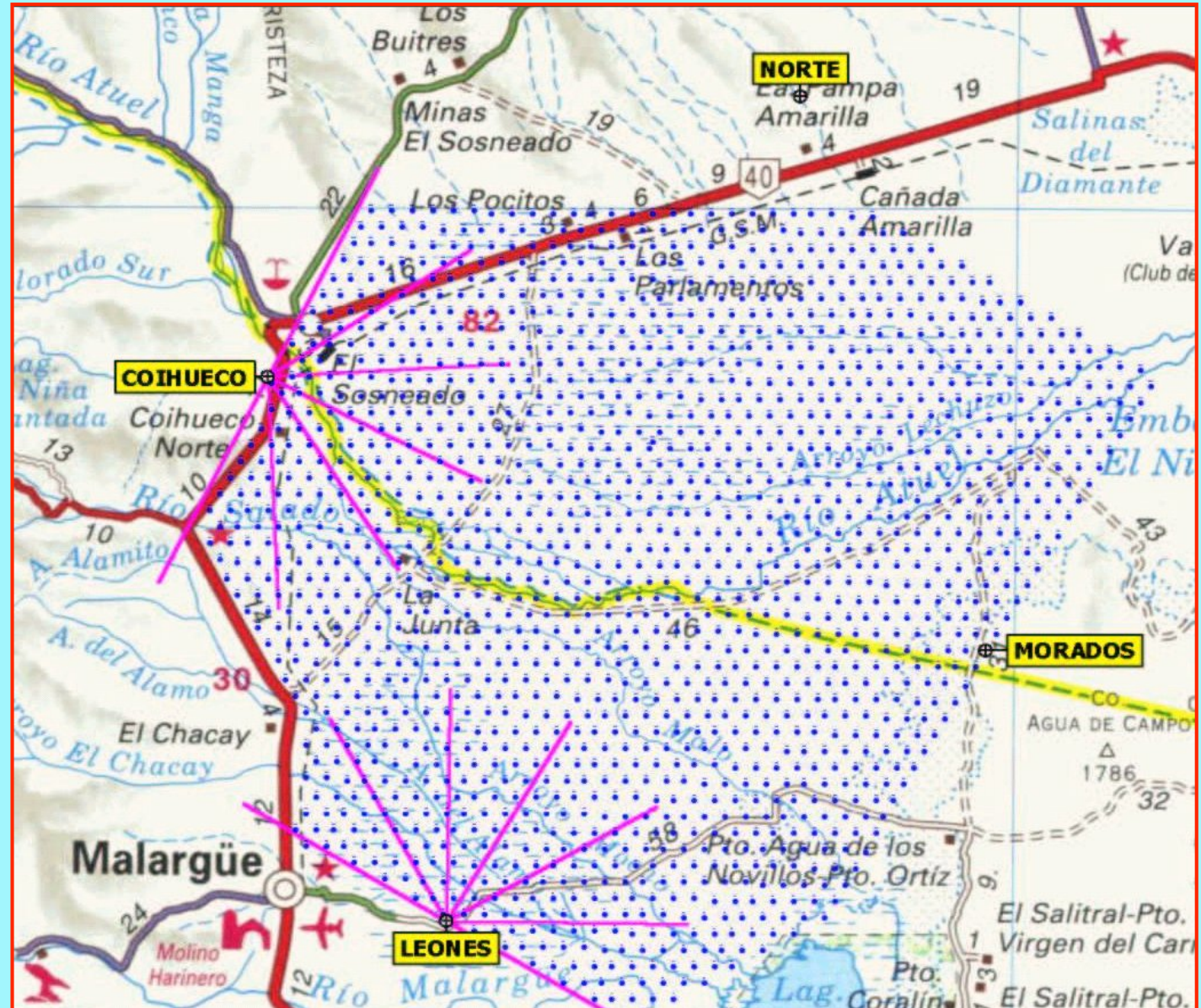
1 rayon cosmique d'énergie de $3 \cdot 10^{20}$ eV

⇒ 800 Tm couvrant le ciel



Area $\approx 3000 \text{ km}^2$ Aperture $\approx 7400 \text{ km}^2 \text{ sr}$

- M. Bertaina



EUSO



Greisen, Zatsepin and Kuzmin (1960) pointed out that there ought to be a "cutoff" in the cosmic ray spectrum around 10^{20} eV:

- The universe is filled with Cosmic Background Radiation (CBR), relic photons from the Big Bang
- CBR photons have an energy spectrum characteristic of a blackbody at $\sim 3\text{K}$, so they are in the ~ 0.001 eV (microwave) energy range
- But in the rest frame of a 10^{20} eV proton, they look like high energy (10^9 eV) gamma rays!
- Protons and nuclei have a high probability (cross section) for interacting with GeV gamma rays and getting smashed into other (lower energy) particles

Many hypotheses have been offered, suggesting UHE CRs are due to:

- Bottom-up models: some variant of the same mechanism valid for lower energies
- Top-down models: created at UHE - due to decay of a very heavy parent particle (GUT or supersymmetry models), or perhaps due to topological defects in the Universe
- Neutrino interactions in intergalactic space
- Exotic astrophysics: AGNs, , jets, GRBs - little is known about gamma ray bursters or UHE CRs, so maybe there is a connection!
- Magnetic field models: maybe intergalactic space has a larger magnetic field than expected, so charged particles do not point back to sources even at UHE
- Violation of Lorentz invariance - would solve the GZK puzzle

The cosmic microwave background at 3 °K makes the Universe opaque to the cosmic rays of extreme energy
K. Greisen - G.T.Zatsepin & V.A.Kuz'min (1966)

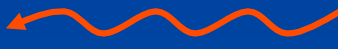
GZK Cutoff

$p + \gamma \rightarrow p + \pi^0$
 $p + \gamma \rightarrow n + \pi^+$
 $E_{\text{thr}} = 6.8 \cdot 10^{19} \text{ eV}$
 $l = 1/\sigma\rho = 6 \text{ Mpc}$
 $\rho \sim 410 \text{ } \gamma/\text{cm}^3$
 $\sigma = 135 \text{ mbarn}$

Cosmic rays with energy $E > 7 \cdot 10^{19} \text{ eV}$ must have their sources within 50 Mpc

Propagation : interaction des RC avec le CMB

- ◆ Ces photons sont inoffensifs, car d'énergie très faible...
... à moins de se jeter sur eux à toute allure !!!

	proton	photon
Système du laboratoire	10^{20} eV 	0.5 meV 
Référentiel du proton	$E_{\text{cin}}=0$ 	300 MeV 

Interaction des RC avec le CMB

♦ Interaction des protons

- photoproduction de pions :

$$p + \gamma_{2,7K} \rightarrow \Delta \rightarrow n + \pi^+$$

$$p + \gamma_{2,7K} \rightarrow \Delta \rightarrow p + \pi^0$$

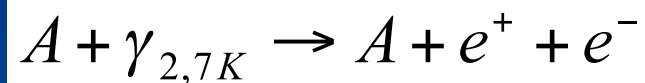
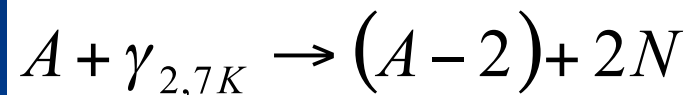
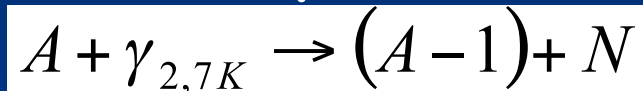
$$p + \gamma_{2,7K} \rightarrow \Delta \rightarrow p + e^+ + e^-$$

- À chaque interaction, perte d'environ 22% d'énergie
- Processus se répète jusqu'à ce que l'énergie totale p- dans leur centre de masse soit inférieure au seuil de production de la résonance :

c'est l'effet Greisen-Zatsepin-Kuzmin (1966)
ou effet GZK

Propagation : interaction des RC avec le CMB

- ◆ Les noyaux ultra-énergétiques se brisent sur les photons du rayonnement fossile



- Energie d'excitation plus faible, mais sont les noyaux les plus stables : étapes moins connues

◆ Photons

- Seuil de création de paires e^+e^- atteint rapidement. Coupure GZK vers 10^{12-13} eV

◆ Neutrinos

- Parfaitement insensible à tous les obstacles : sondes idéales... oui, mais extrêmement difficile de les détecter

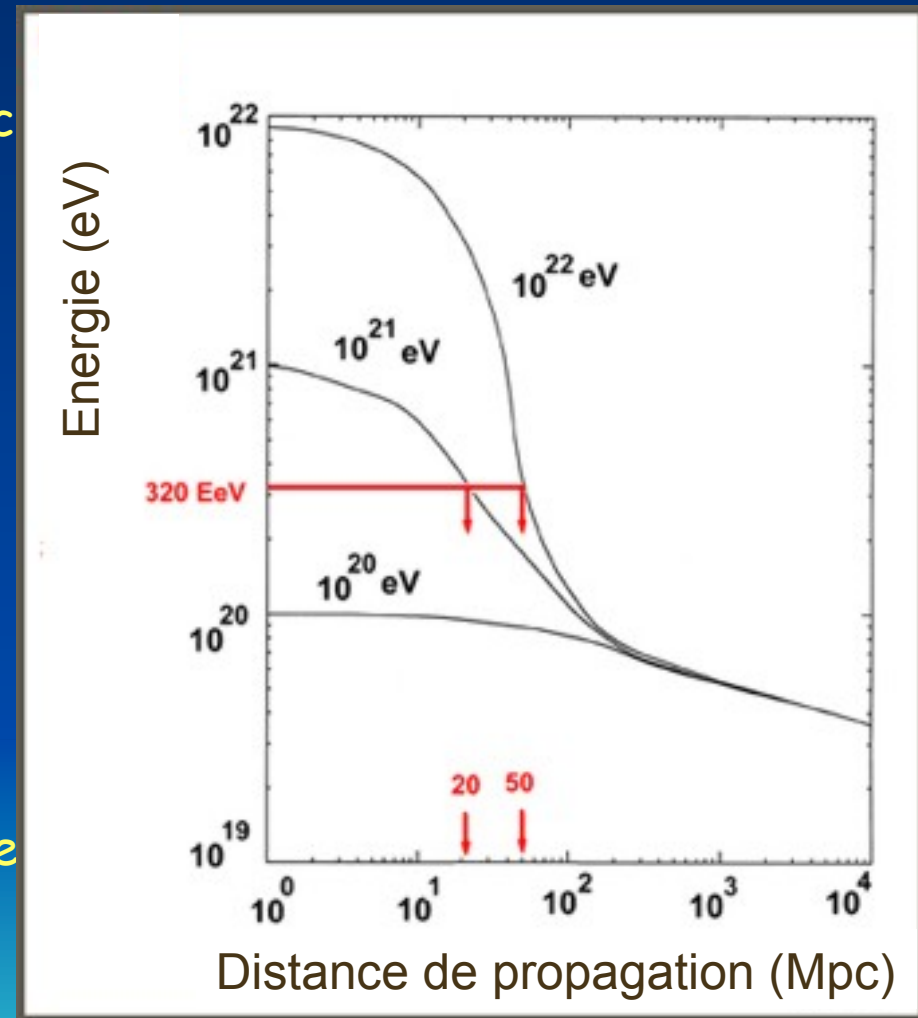
Conséquences de l'effet GZK sur les protons

◆ Libre parcours moyen

- Au dessus de $5 \cdot 10^{19}$ eV : 10Mpc
(1 pc = $3.09 \cdot 10^{16}$ m)

◆ Brutalité de la coupure GZK:

- à partir de 100Mpc, toutes les énergies sont ramenées sous 10^{20} eV
- record à $3 \cdot 10^{20}$ eV $\Rightarrow$
 - Source dépassant largement cette énergie
 - Ou située à quelques dizaines de Mpc
- Problème : on ne connaît pas de telle source !!!



THE GZK EFFECT



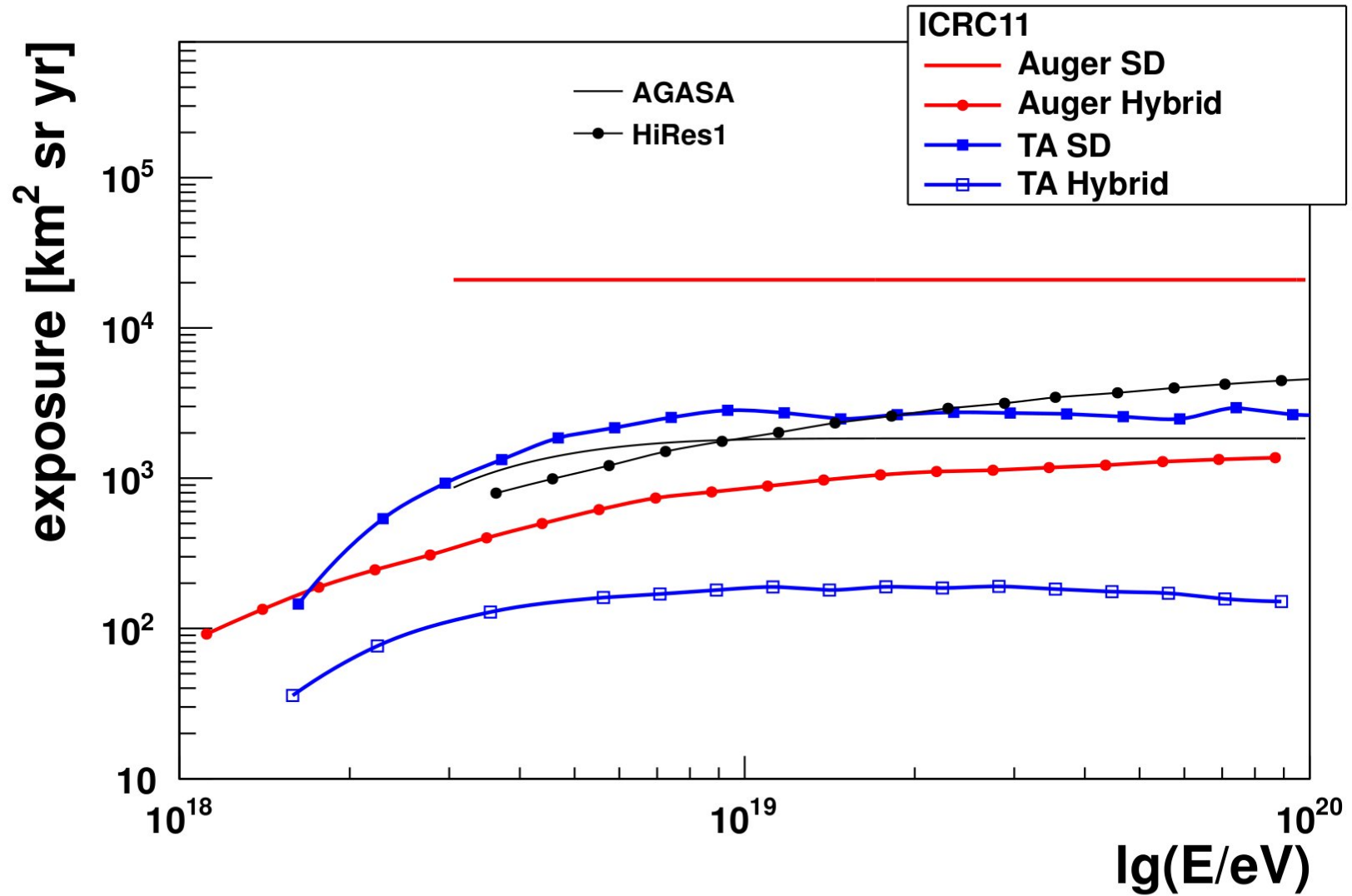
Energy and attenuation factor ($e^{-x/\lambda_{\text{GZK}}}$) are:

$$E_{\text{GZK}} \sim 5 \cdot 10^{19} \text{ eV}$$

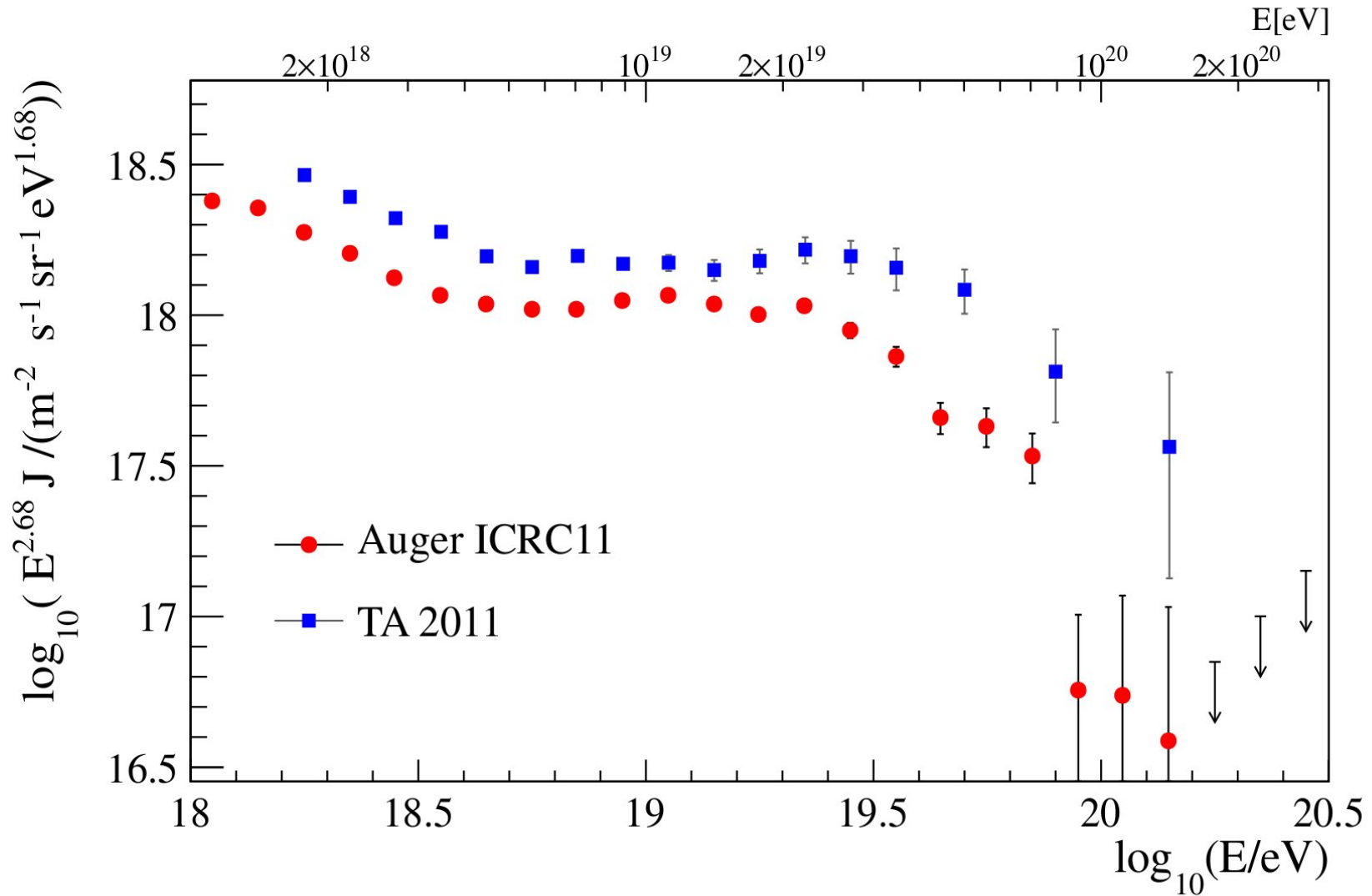
$$\lambda_{\text{GZK}} \sim 30 \text{ Mpc}$$

- Super-GZK hadrons from distant sources will lose energy and pile-up at sub-GZK energies.
- If UHE CR are protons, they show the highest value for the Lorentz factor ($\gamma \sim 10^{11}$) observed in nature.

Comparison of Exposures

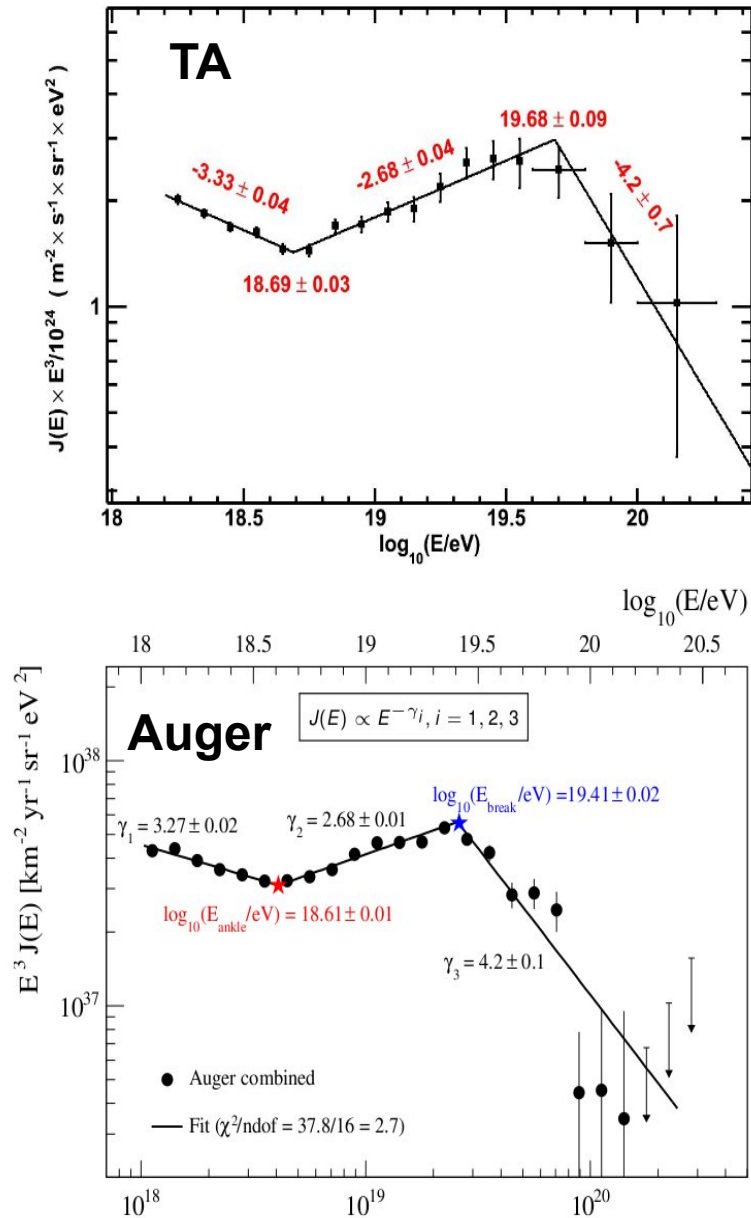


Comparison of Spectra



energy scale difference of $\sim 20\%$?

Comparison of spectral features



	TA	Auger
γ_1	3.33 ± 0.04	3.27 ± 0.02
γ_2	2.68 ± 0.04	2.68 ± 0.01
γ_3	4.2 ± 0.7	4.2 ± 0.1
$\lg(E_1/\text{eV})$	18.69 ± 0.03	18.61 ± 0.01
$\lg(E_2/\text{eV})$	19.68 ± 0.09	19.41 ± 0.02

B. Stokes [TA Coll.], icrc1297

F. Salamida [Auger Coll.], icrc893

Energy Scale Uncertainties

Auger R. Pesce, icrc1160

calibration	9.5%
reconstruction	10%
atmospheric	8%
fluorescence yield*	14%
invisible energy [†]	4%
tot. quad. sum	22%

Telescope Array D. Ikeda, icrc1264

calibration	10%
reconstruction	10%
atmospheric	11%
fluorescence yield**	11%
invisible energy ^{††}	
tot. quad. sum	21%

total syst. of energy scale difference

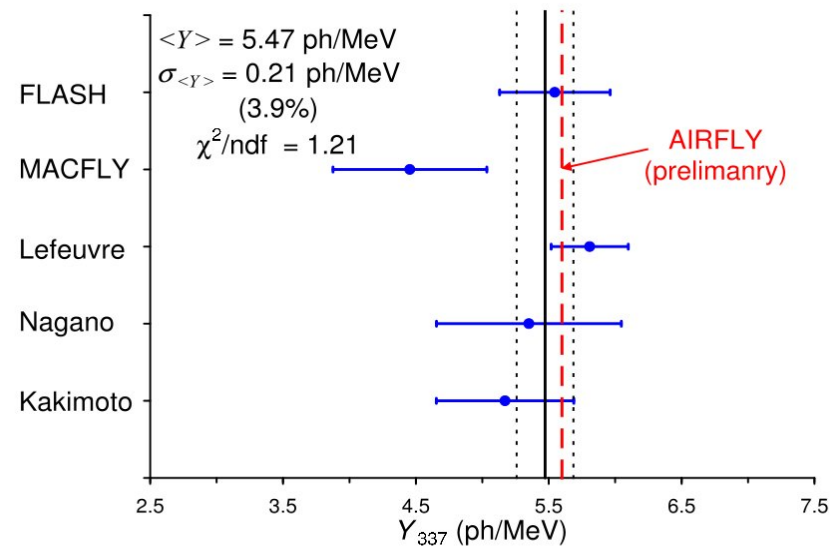
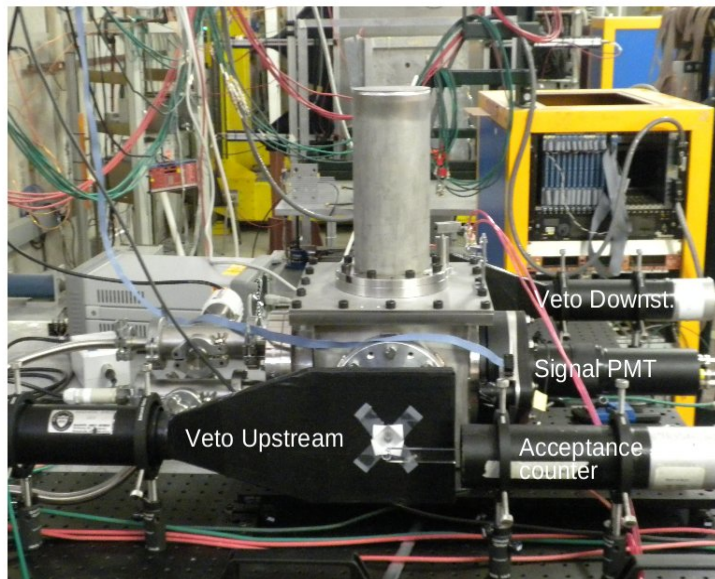
$$\sigma_{\text{sys}}(E_{\text{Auger}} - E_{\text{TA}}) = 30\%$$

without fluorescence yield:

$$\sigma_{\text{sys}}(E_{\text{Auger}} - E_{\text{TA}}) = 24\%$$

* yield: Nagano, spectrum: AIRFLY ** yield: Kakimoto, spectrum: Bunner [†] QGSJet mixed ^{††} QGSJet proton

Fluorescence Yield Measurement by AIRFLY



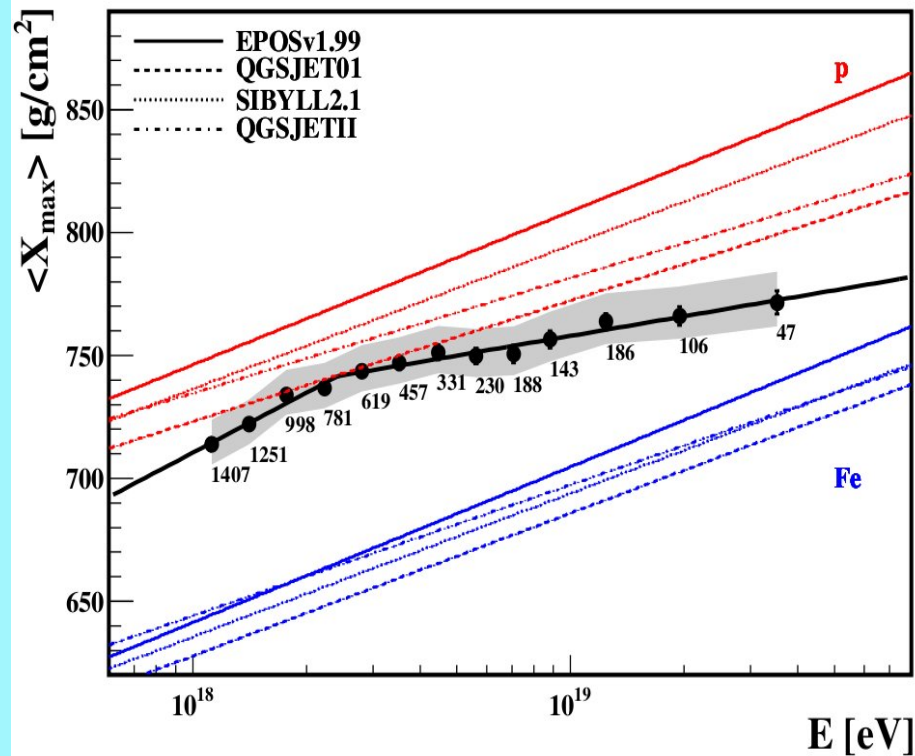
F. Arqueros et al., icrc442

$$Y_{\text{air}} = 5.67 \pm 0.07(\text{stat.}) \pm 0.21(\text{syst.}) \text{ phot}_{337}/\text{MeV}$$

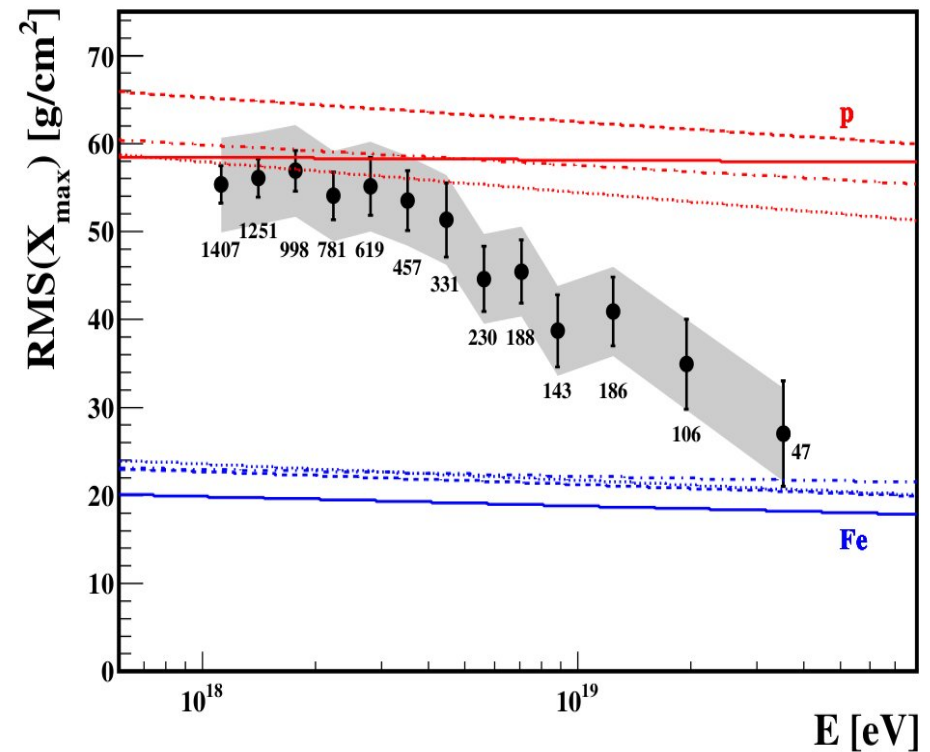
Auger: 5.05 phot₃₃₇/MeV, i.e. energy scale goes *down* by 10%

Longitudinal EAS Development with Auger FD

average depth



fluctuations

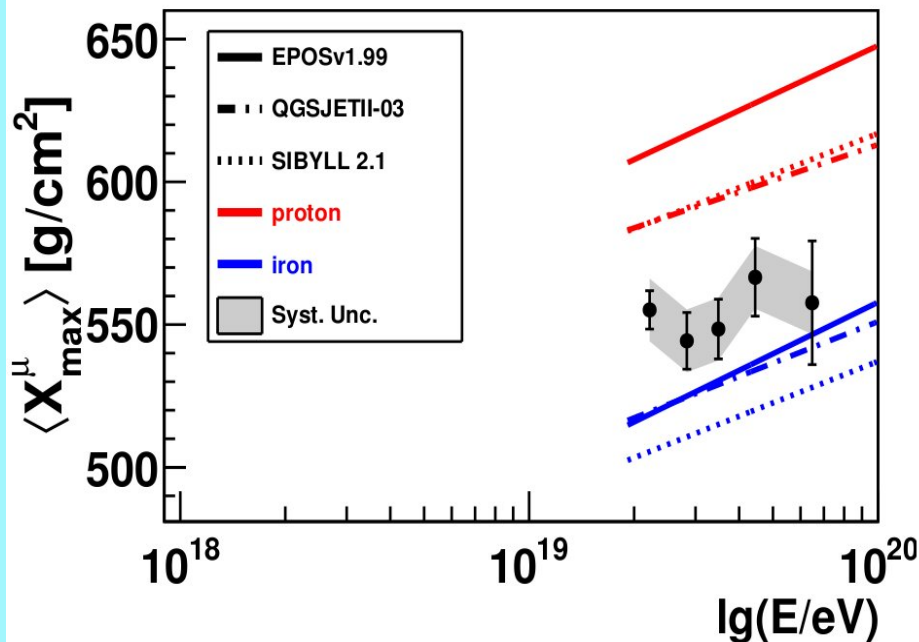


P. Facal [Auger Coll.], icrc725

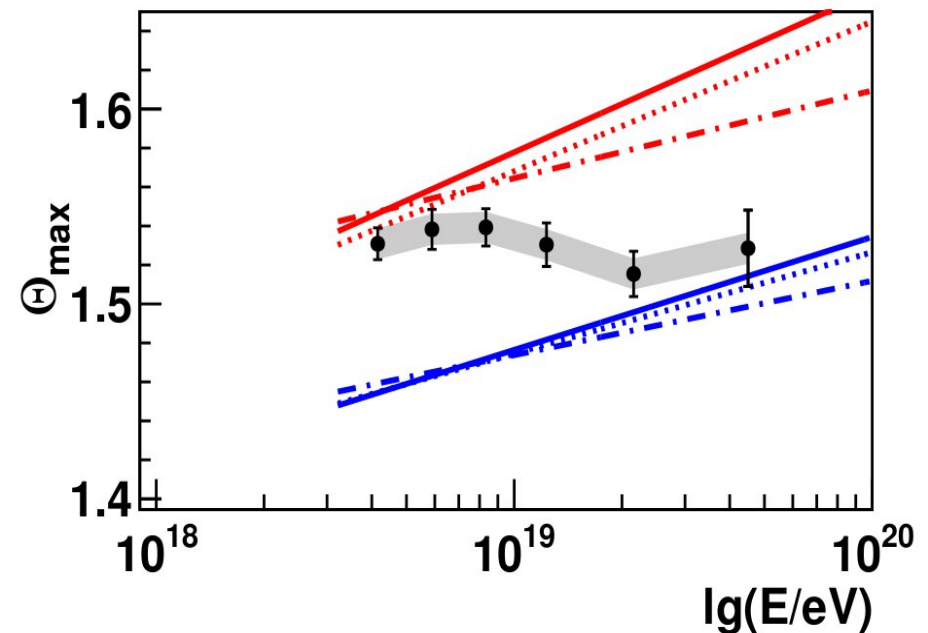
Longitudinal EAS Development with Auger SD

muon production depth

θ -dep. of risetime asymmetry



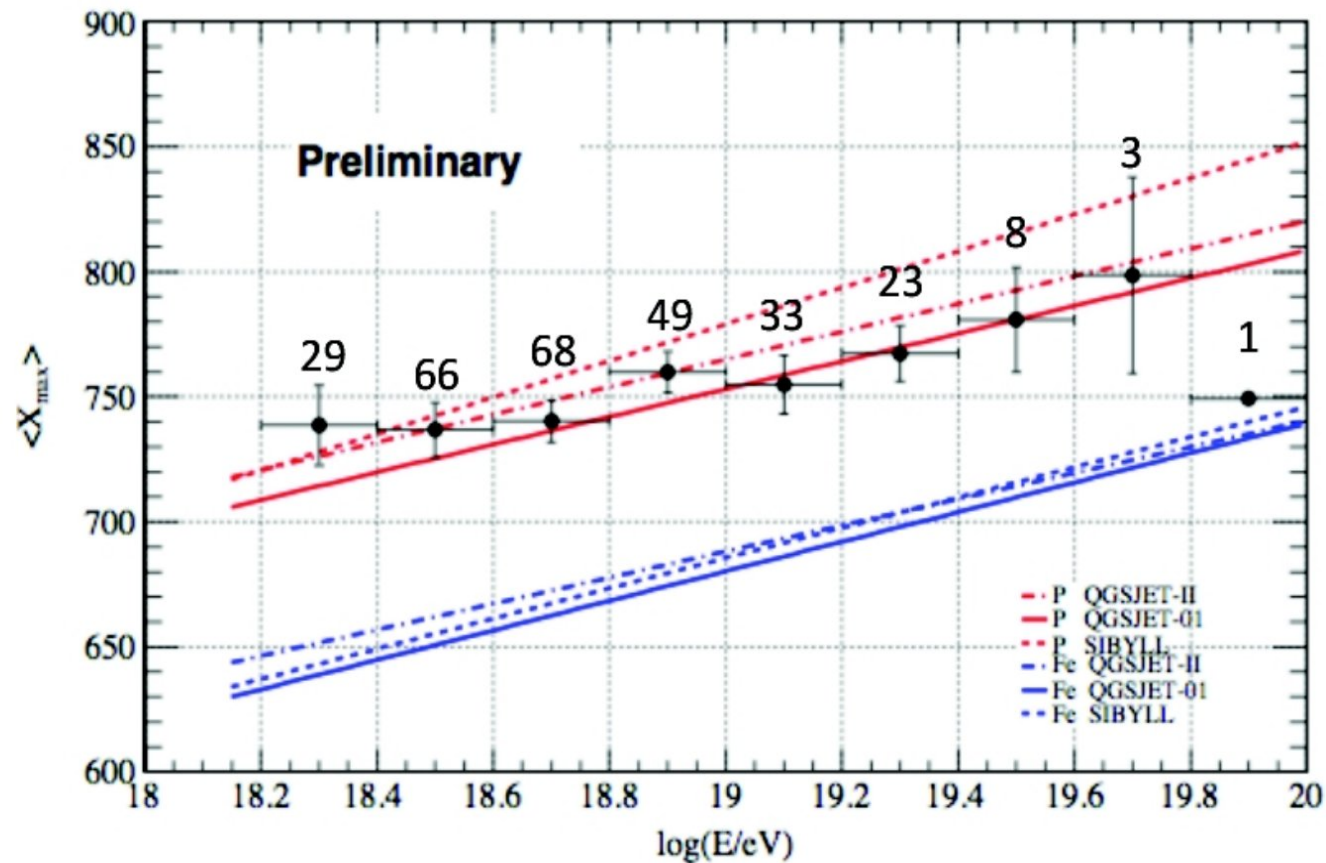
D. Garcia-Gamez [Auger Coll.], icrc735



D. Garcia-Pinto [Auger Coll.], icrc709

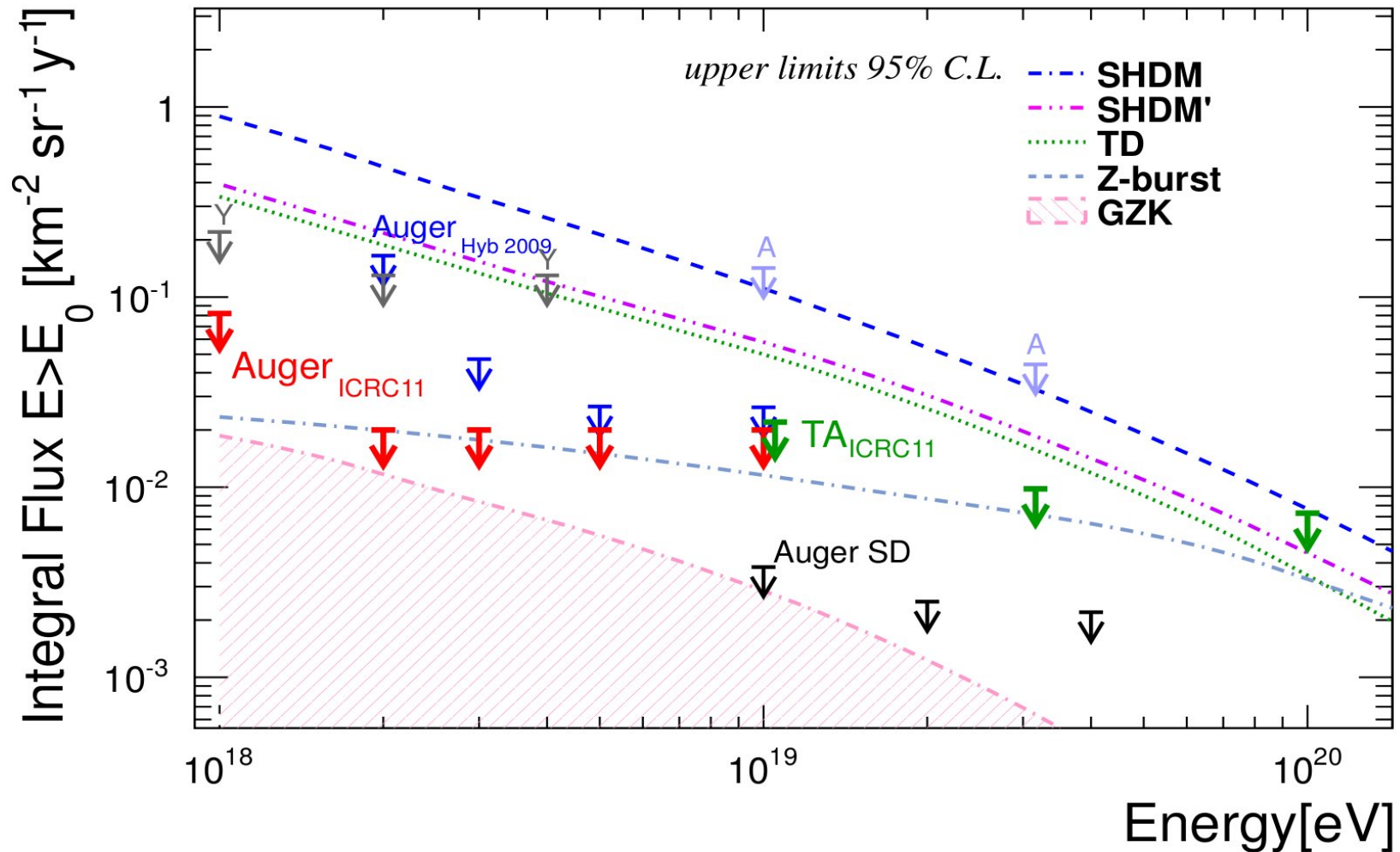
- reach to higher energy
- syst. independent of FD

Longitudinal EAS Development with TA Stereo FD



A. Tameda [TA Coll.], icrc1268

Photon Search Results

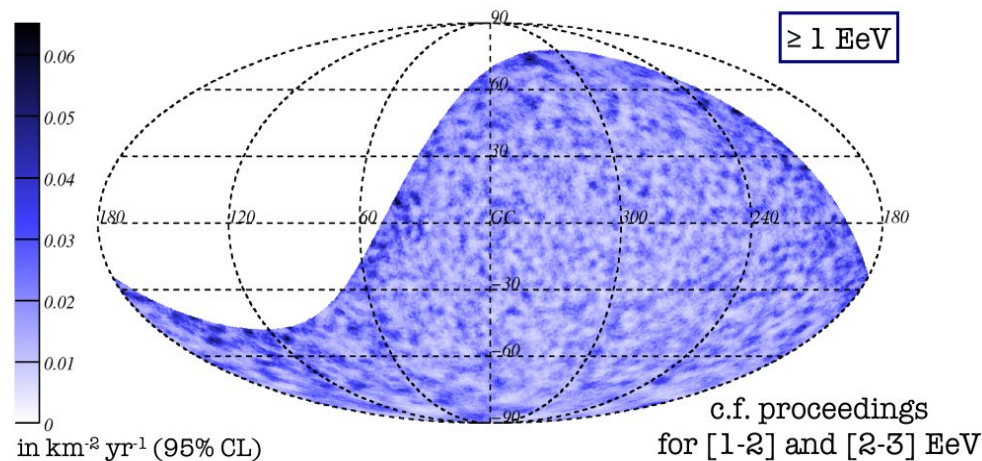


G.I. Rubtsov [TA Coll.], icrc1266

M. Settimo [Auger Coll.], icrc393

Search for Anisotropies in the EeV range

Galactic neutron sources?



B. Orfeuil [Auger Coll.], icrc713

Right Ascension Modulation?

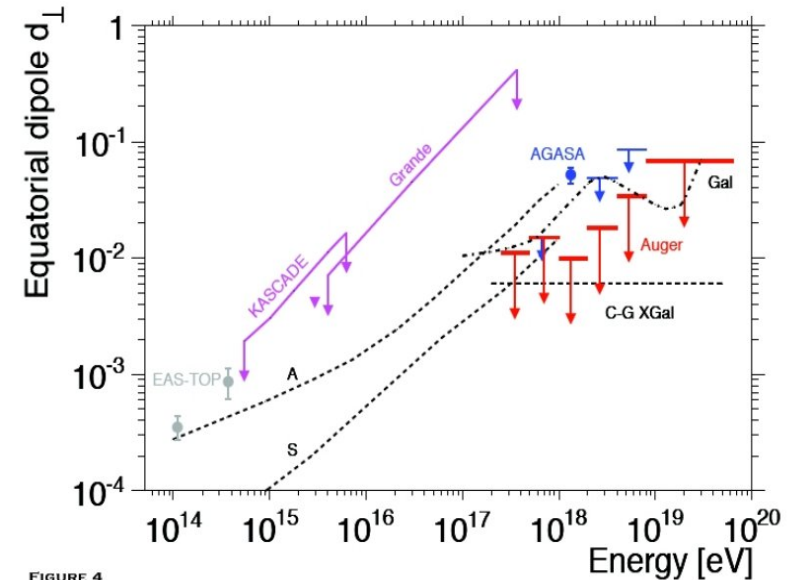
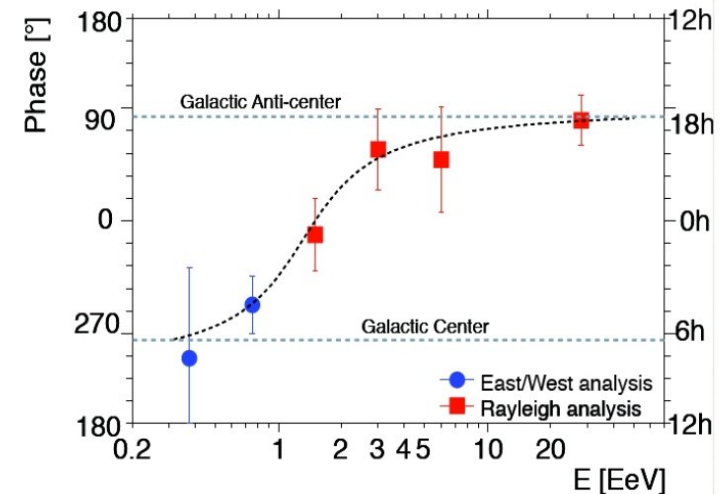


FIGURE 4

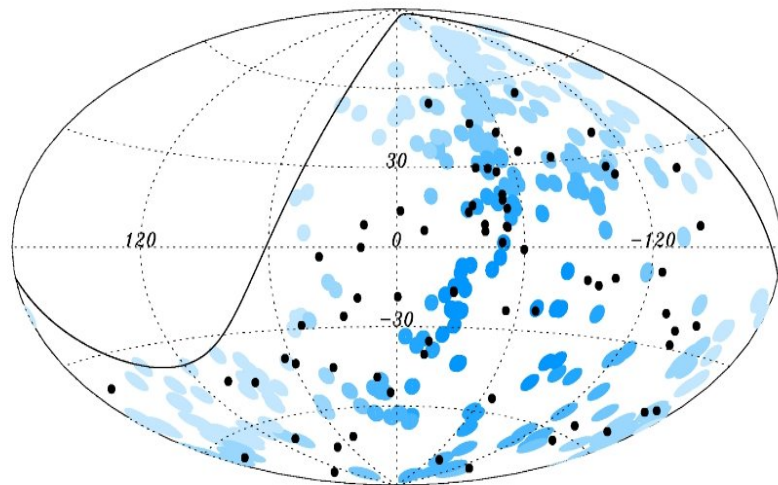


H. Lyberis [Auger Coll.], icrc493

UHE Correlation with AGNs within GZK-sphere?

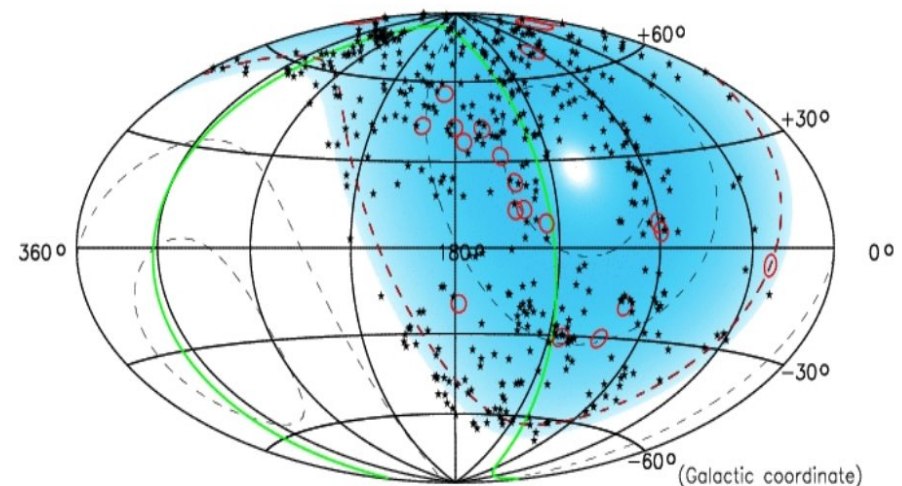
VCV catalogue, $E > 57 \text{ EeV}$, $z < 0.018$, distance $< 3.1 \text{ deg}$.

Auger



28 out of 84 correlate

TA

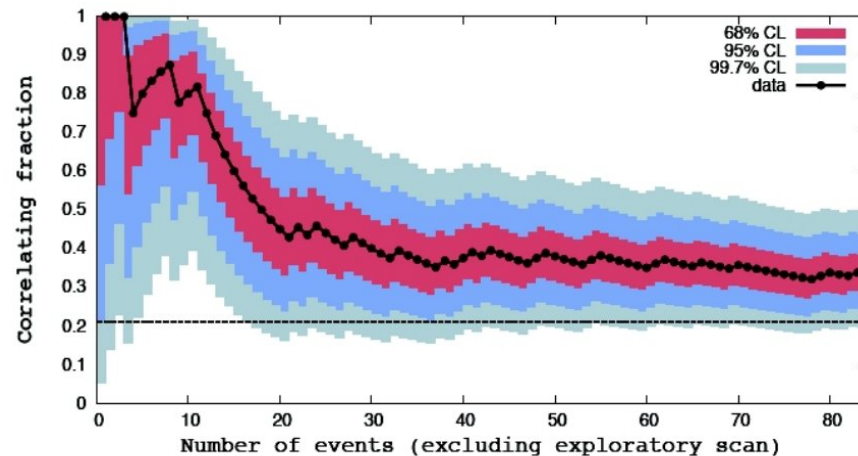


8 out of 20 correlate

UHE Correlation with AGNs within GZK-sphere?

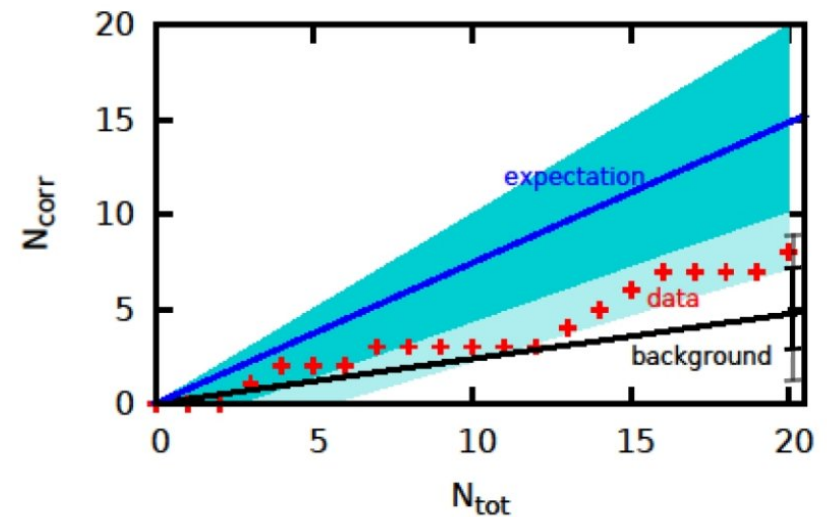
VCV catalogue, $E > 57 \text{ EeV}$, $z < 0.018$, distance $< 3.1 \text{ deg}$.

Auger



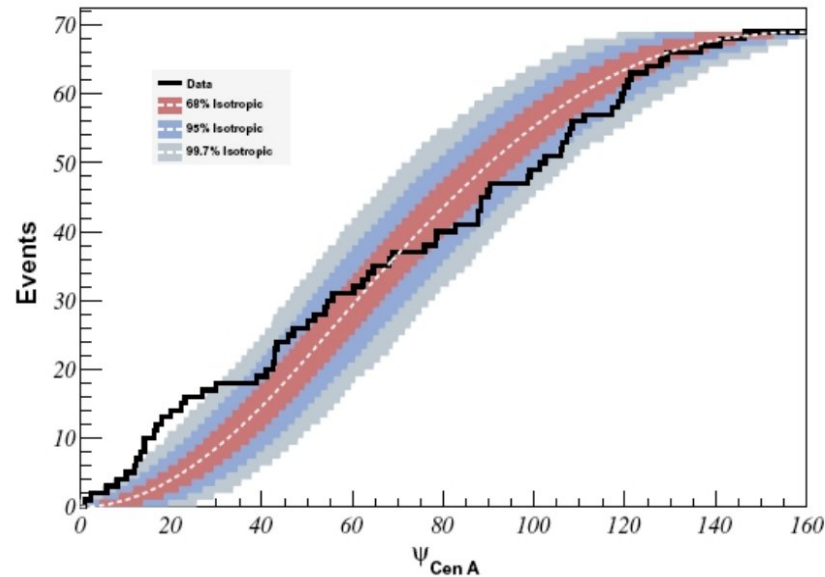
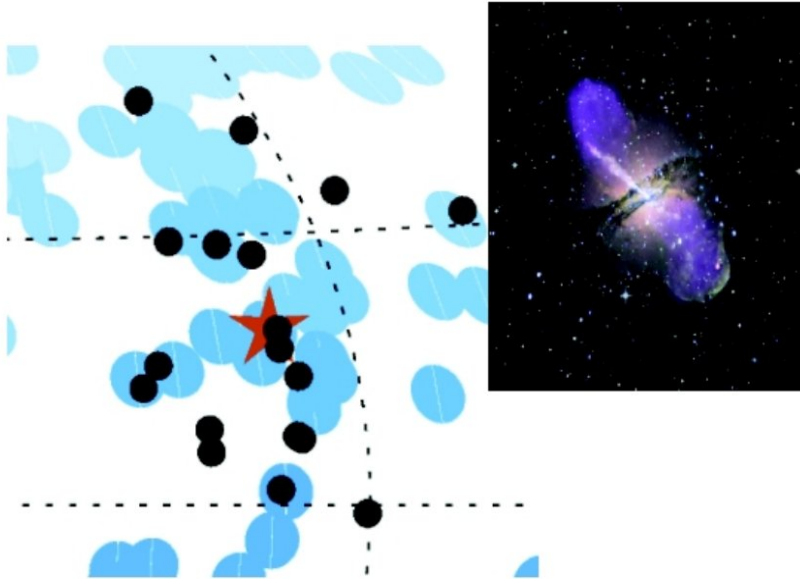
$$P = 0.006, f = 33 \pm 5\%$$

TA



compatible with isotropy and
updated (!) Auger

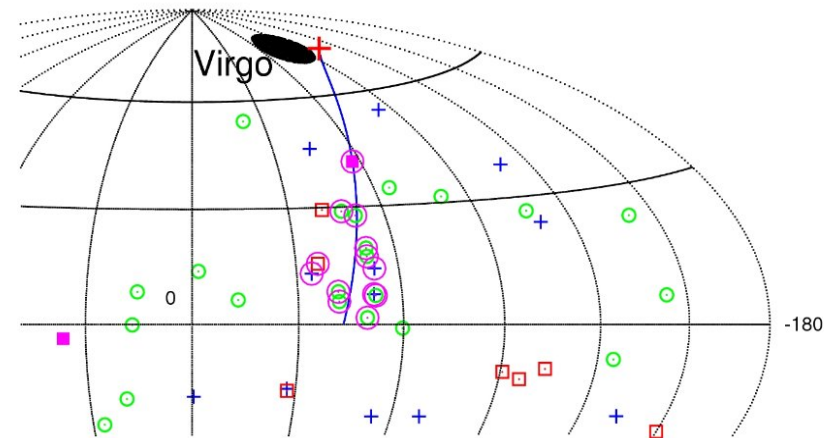
UHERs from CenA?



13/62 within 18 deg., expect 3.2
limits on source composition?

E.M. Santos [Auger Coll.], icrc868

... or Virgo?

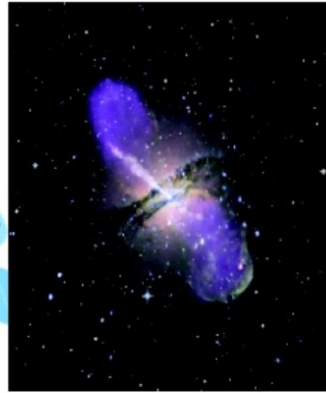
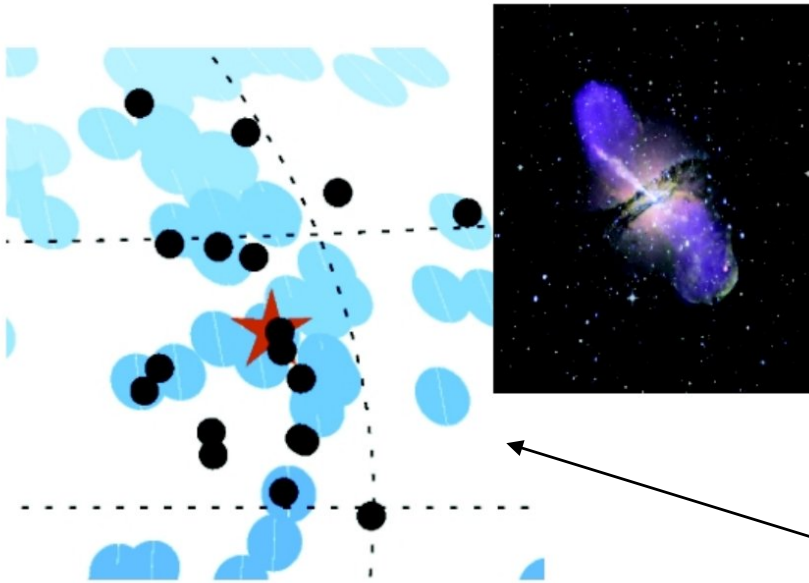


Giacinti&Semikoz, icrc171

Energy Spectrum

1. Cutoff and dip established.
2. Energy scale error $\sim 20\%$.
3. Power law fits agree among exp..
4. Spectral shapes seem differ above $10^{19.5}$ eV
 - Auger is based on muon (water tank)
 - HiRes, TA and Yaktsuk are based on e/ γ (Air Fluor., plastic scint.)
 - CIC, MC zenith att. By MC, calorimetry

UHERs from CenA?

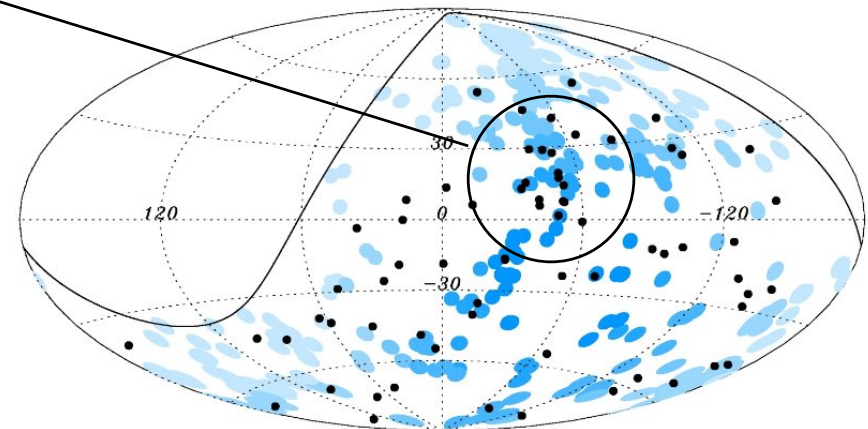
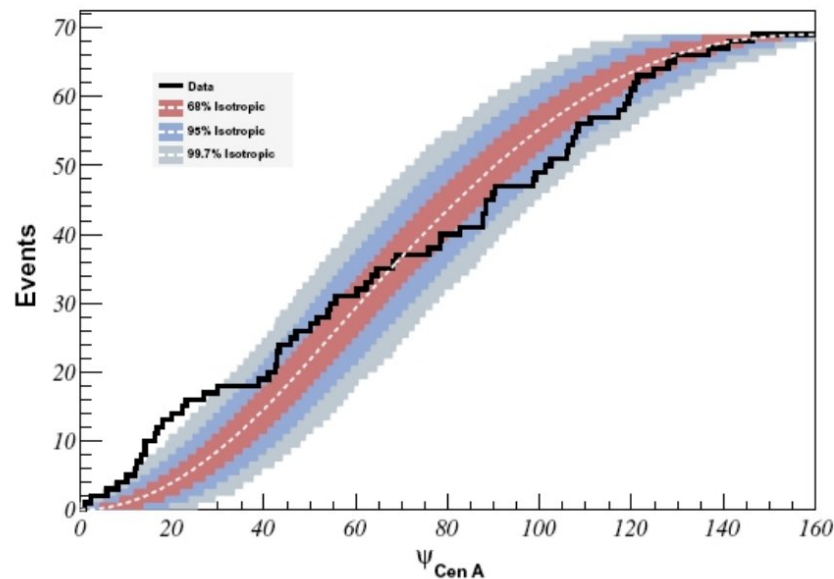


VCV Catalogue, $E > 57 \text{ EeV}$,
 $Z < 0.018$, distance $< 3.1^\circ$

13/62 within 18 deg., expect 3.2
limits on source composition?

E.M. Santos [Auger Coll.], icrc868

Auger



28 out of 84 correlate

Anisotropy

- ▶ No anisotropy established with certainty; however, various hints exist
- ▶ Expectations depend crucially on the actual mass composition of UHECR
- ▶ $O(10)$ increase in statistics, together with reasonable improvements in other parameters, is needed for definitive progress

... clarifying several aspects of the puzzle. **Be patient.**

UHECR status in just one word

Previous to Auger / HiRes :

$$\frac{1 \text{ particle}}{100 \text{ km}^2 \text{ yr sr}}$$



Key Auger / HiRes result:

$$\frac{1 \text{ particle}}{\cancel{100} \text{ km}^2 \text{ yr sr}}_{1000}$$

A quantitative jump in exposure

(orders of magnitude: e.g., $10^3 \rightarrow 10^5$ km² yr sr)

**is needed to effectively open such an
astronomical window @ $E > 10^{20}$ eV**

At current rate $\sim 30/\text{yr}$ $E > 60 \text{ EeV}$
need over 30 years!

Need Significant Increase in Statistics
at the highest energies.

Scratching the Surface

Increase Exposure!

Antares, ANITA, Rice

HE neutrinos

IceCube

UHE cosmic rays

Cen A??

Auger, TA

JEM-EUSO

ARA, ARIANNA, KM3Net

JEM EUSO: AN OBSERVATORY OF UHECRs FROM SPACE

Instantaneous aperture: up to $\sim 10^6 \text{ km}^2 \text{ sr}$



**Main Objective:
ASTRONOMY and ASTROPHYSICS
THROUGH PARTICLE CHANNEL**

An experimental pathfinder with
outstanding scientific capability

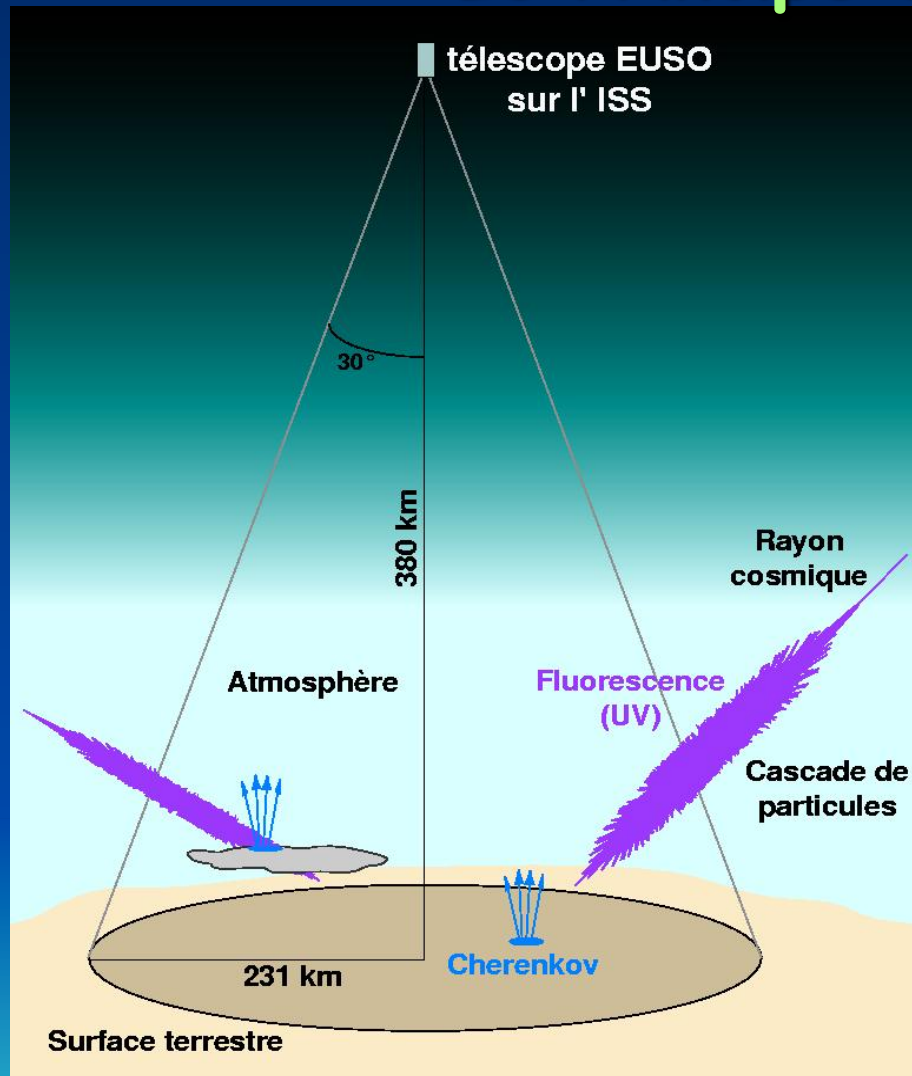
JEM-EUSO Exposure

using Universitetsky Tatiana satellite data

Observatory	Aperture km ² sr	Status	Start	Lifetime	Duty cycle	Annual Exposure km ² sr yr	Relative to Auger
Auger	7,000	Operations	2006	4 (16)	1	7000	1
TA	1,200	Operations	2008	2 (14)	1	1,200	0.2
TUS	30,000	Developed	2012	5	0.14	4,200	0.6
JEM-EUSO ($E \approx 10^{20}$ eV)	430,000	Design	2017	5	0.14	60,000	9
JEM-EUSO (highest energies) Tilted mode 35°	1,500,000	Design	2017	5	0.14	200,000	28

- 2013: launch JEM-EUSO balloon from Kiruna
- 2017: launch to ISS using Japanese HII Transfer Vehicle (HTV)?

Le Principe de détection



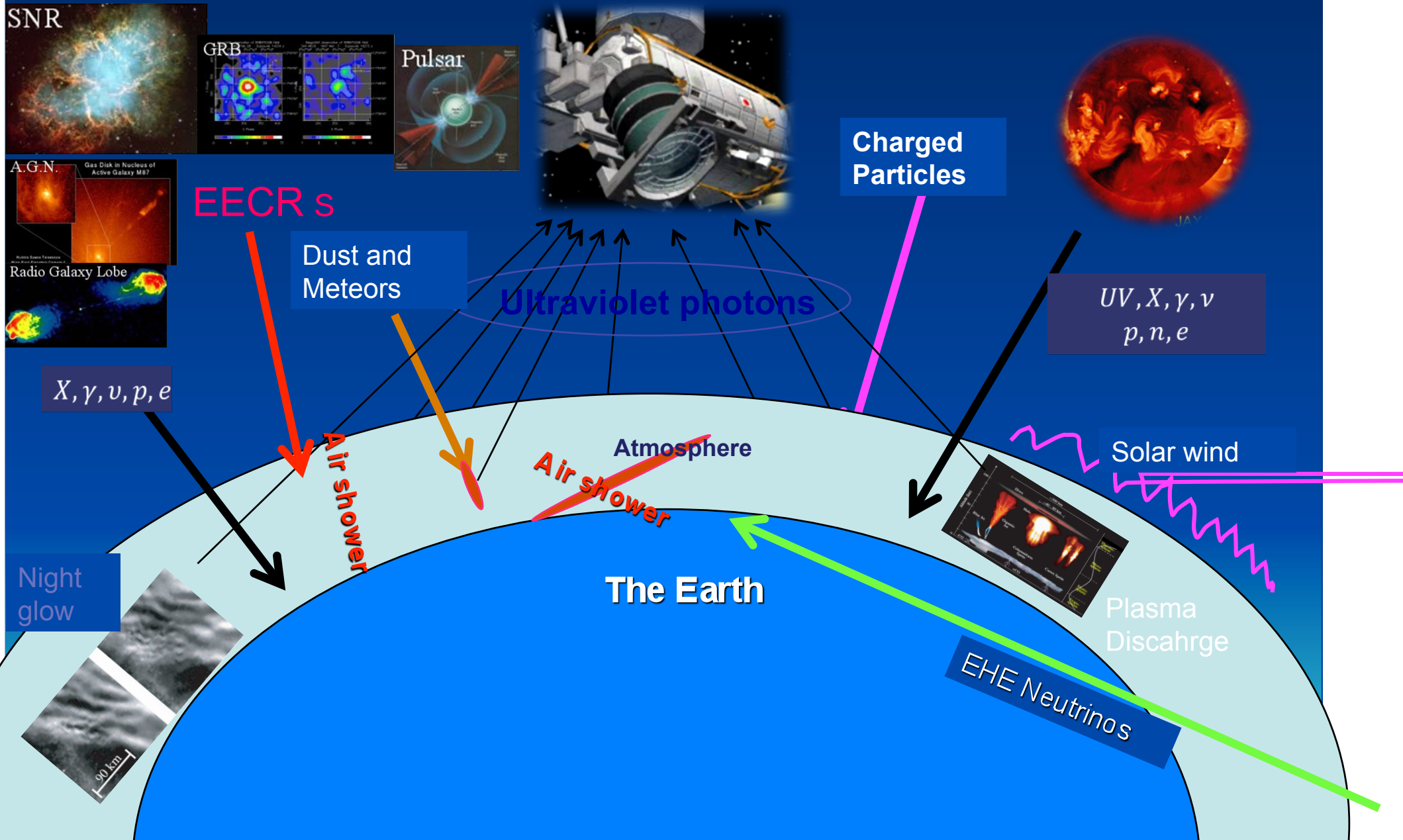
◆ Grandes surface d'observation et masse de cible

◆ Mesure de la fluorescence produite par les molécules d'azote excitées par les particules chargées de la gerbe

◆ Détection du Cherenkov produit par les particules chargées relativistes et réfléchi (sol, nuages)

→ détection de photons dans l'UV (300-400nm)

JEM-EUSO is an Astronomical Earth Observatory from Space



Science Objectives

Main Objective :

Astronomy and astrophysics through particle channel with extreme energies ($E > 5 \times 10^{19} \text{eV}$)

Identification of **sources** by the high statistics arrival direction analysis

Measurement of the **energy spectra** from individual sources to constrain acceleration or emission mechanisms

Exploratory objectives :

Detection of extreme energy **gamma-rays**

Measurement of extreme energy **neutrinos**

Study of the Galactic **magnetic field**

Verification of the **relativity** and the **quantum gravity** effect in extreme energy

Global observation of **atmospheric** phenomena: nightglows, lightning and plasma discharges

CR energy spectrum

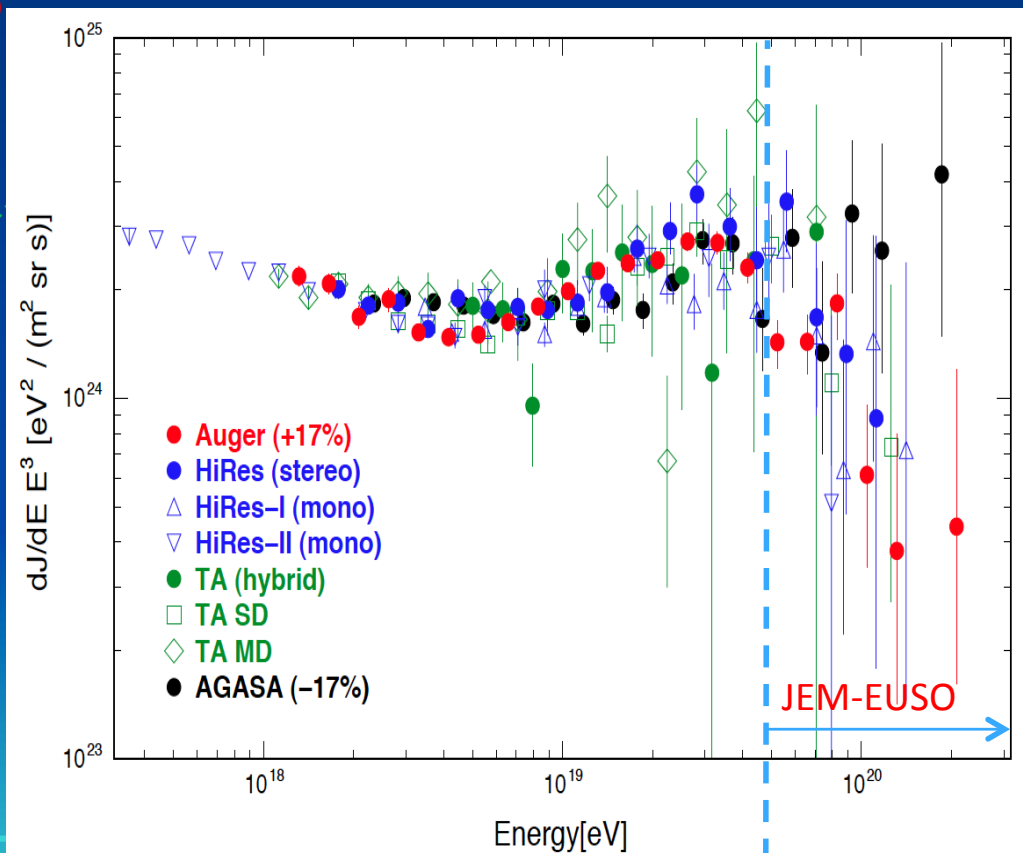
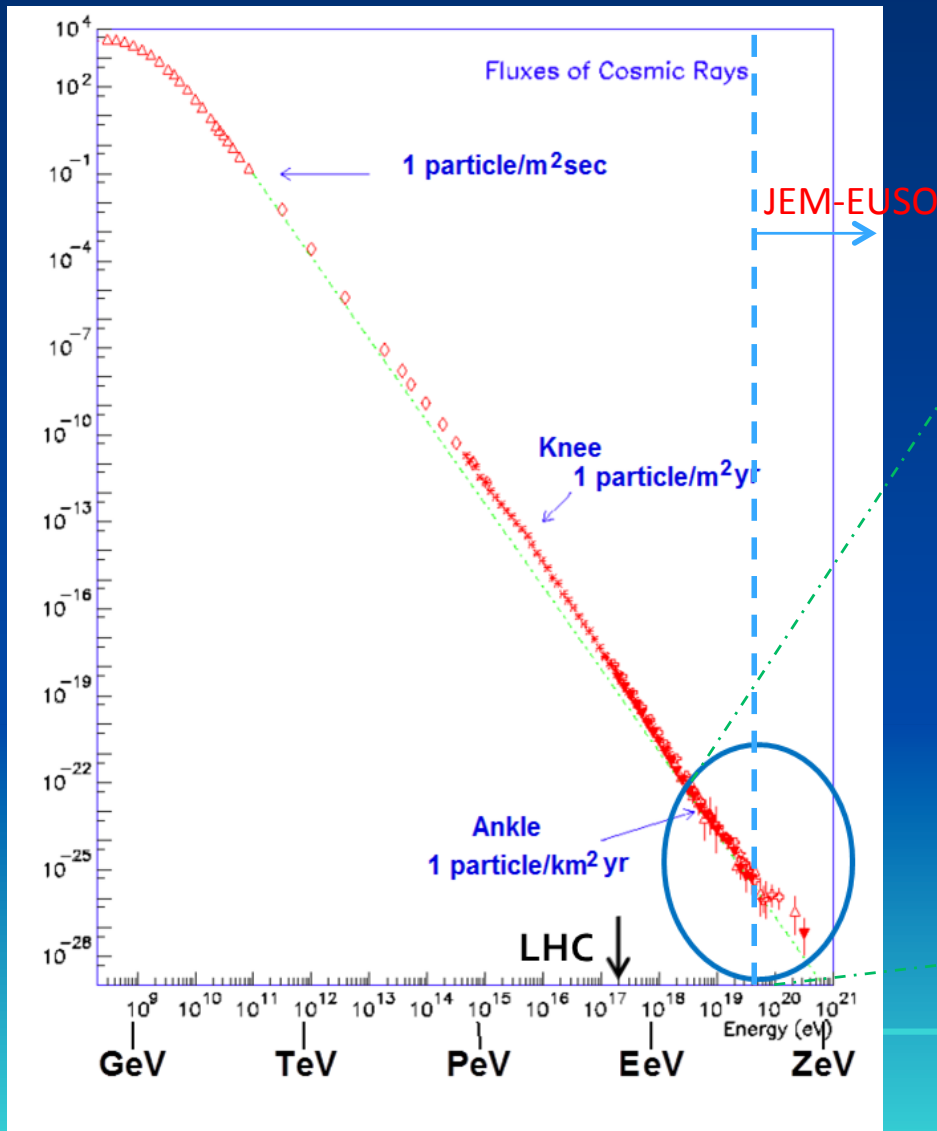
Integral flux:

$E > 10^{11} \text{ eV} \sim 1 \text{ part./m}^2\text{/second}$

$E > 5 \cdot 10^{15} \text{ eV} \sim 1 \text{ part./m}^2\text{/year}$

$E > 5 \cdot 10^{18} \text{ eV} \sim 1 \text{ part./km}^2\text{/year}$

$E > 10^{20} \text{ eV} \sim 1 \text{ part./km}^2\text{/millennium}$

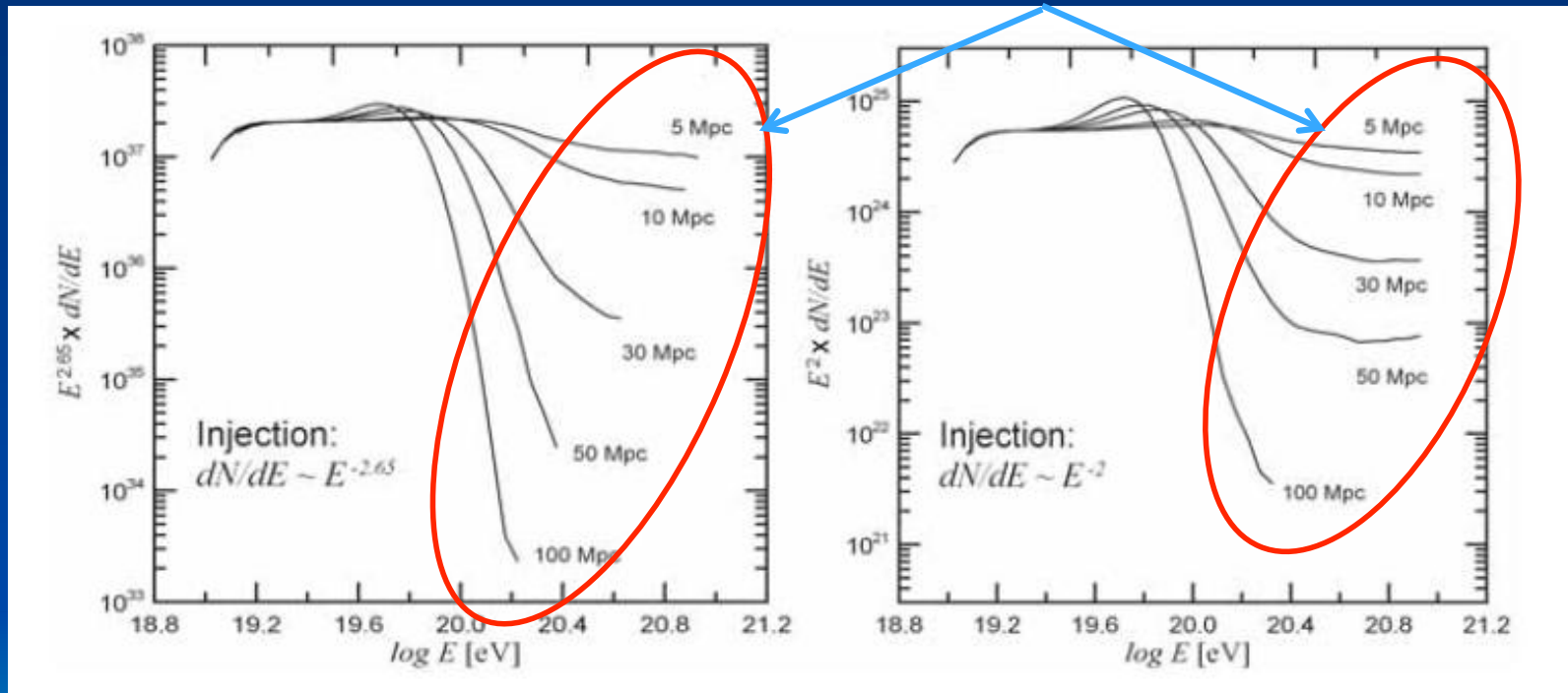


Spectral steepening



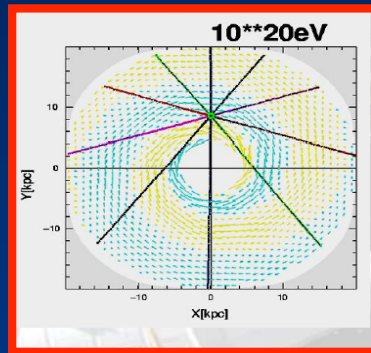
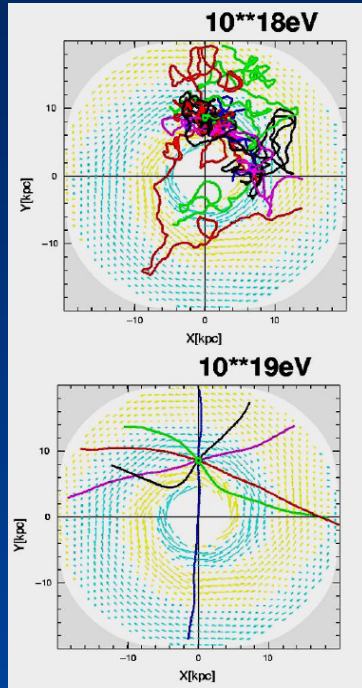
$$E_{GZK} \simeq 5 \times 10^{19} \text{ eV}$$

GZK features strongly depend on the distances to the sources



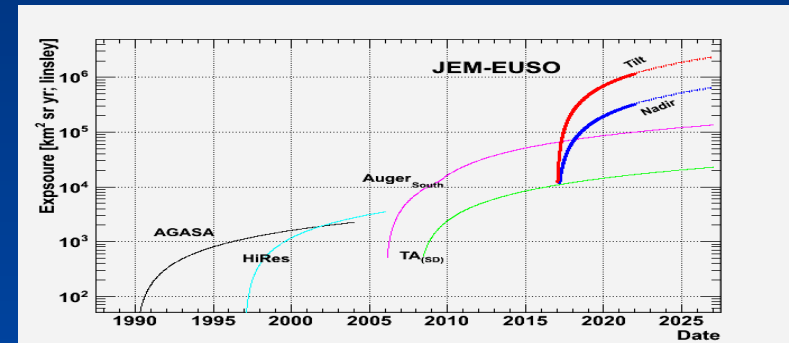
GZK cut-off suppress Energy spectrum in case of isotropic sources

Anisotropy analysis

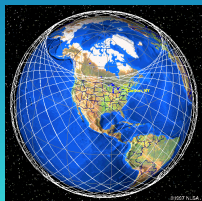


$E > 10^{20}$ eV: particles do not bend significantly

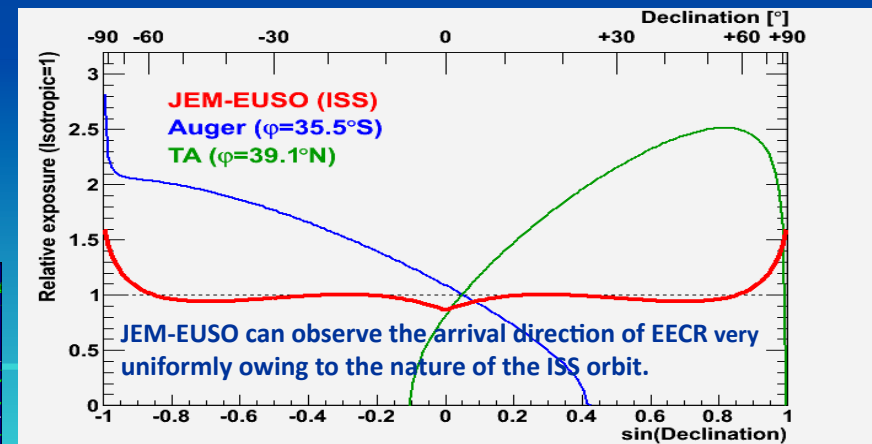
- **Point source analysis:** very high statistics (500÷800 events in 3 years) at the highest energies, should identify several dozen individual clusters with tens of events associated to each of them, which will allow correlating the sources with known astronomical objects .



- **Global anisotropy analysis:** very uniform exposure over the whole sky (ISS inclination $\approx 51.6^\circ$). If extreme particles come from cosmological distances, as those of GRBs and AGNs, several dozen sources uniformly distributed in the sky will be discovered

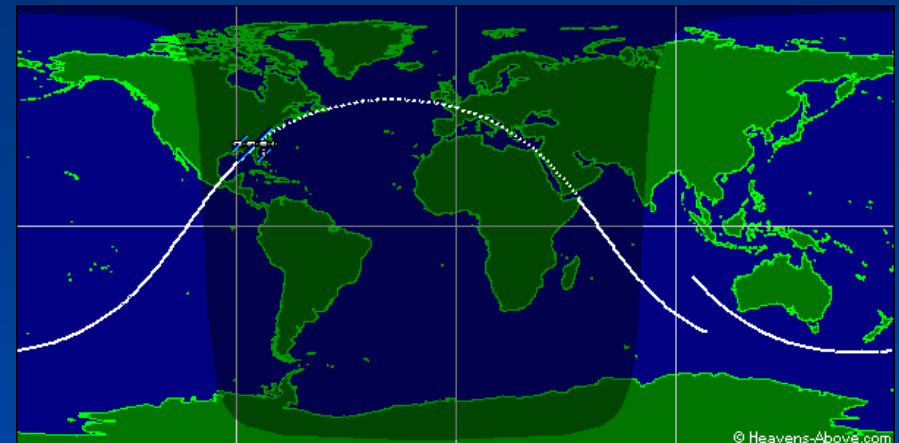
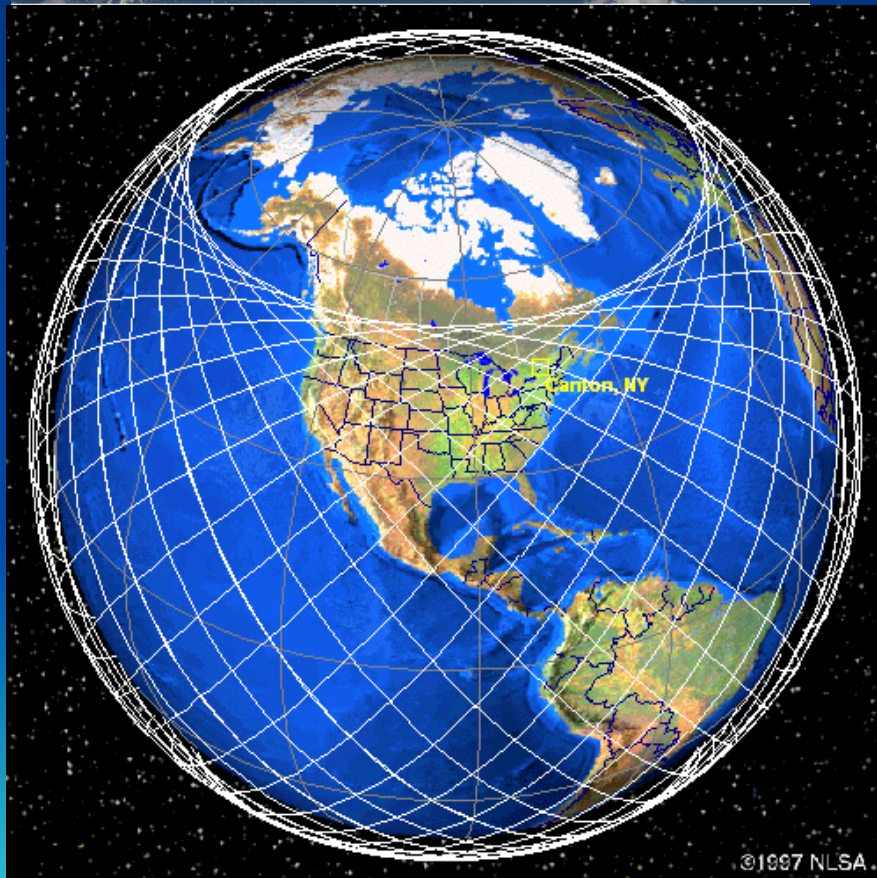


Inclination: 51.6°
Height: ~ 400 km





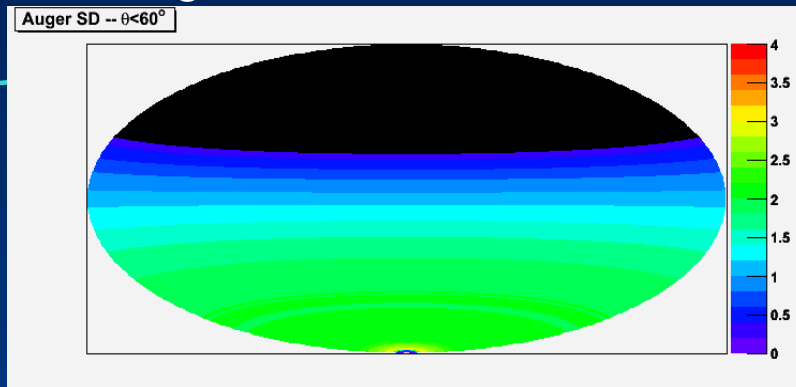
ISS Orbit



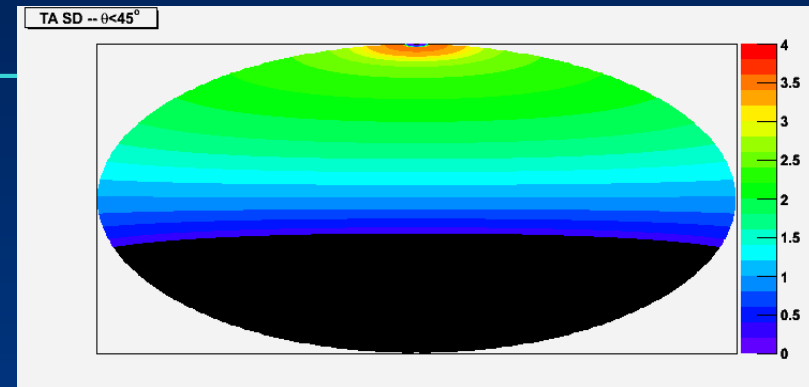
Inclination: 51.6°
Height: $\sim 400\text{km}$

JEM-EUSO can observe the arrival direction of EECR very uniformly owing to the nature of the ISS orbit.

Auger

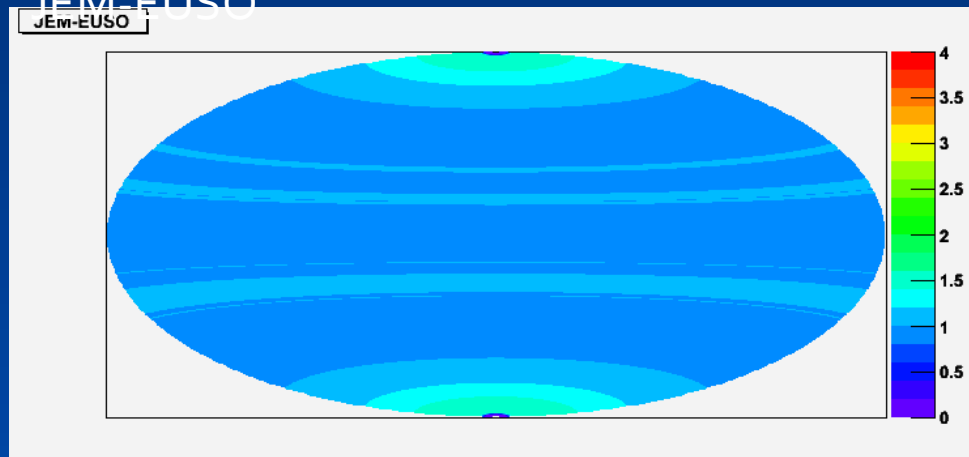


TA

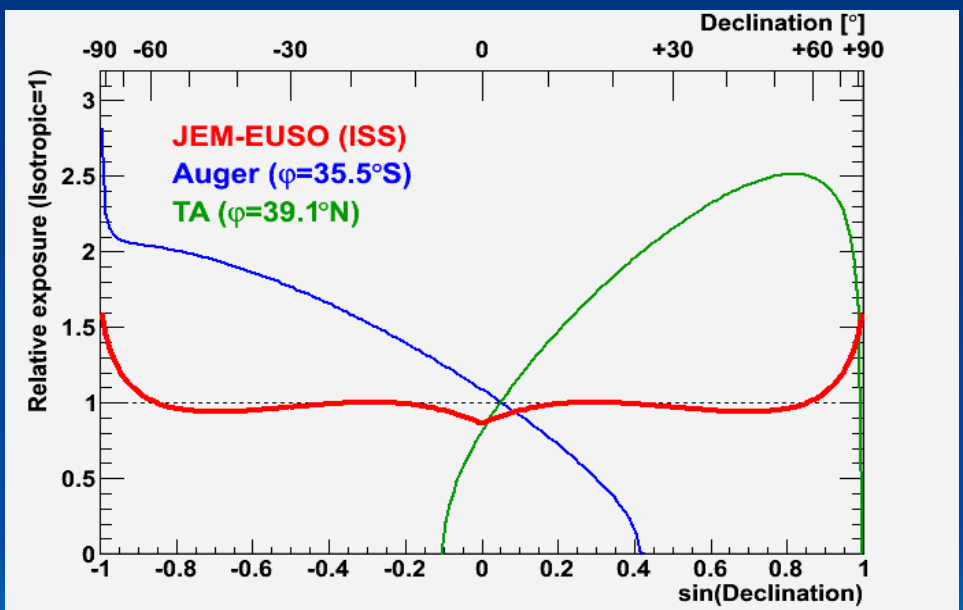


Color scale represents the excess or deficit of exposure relative to the fully isotropic exposure

JEM-EUSO

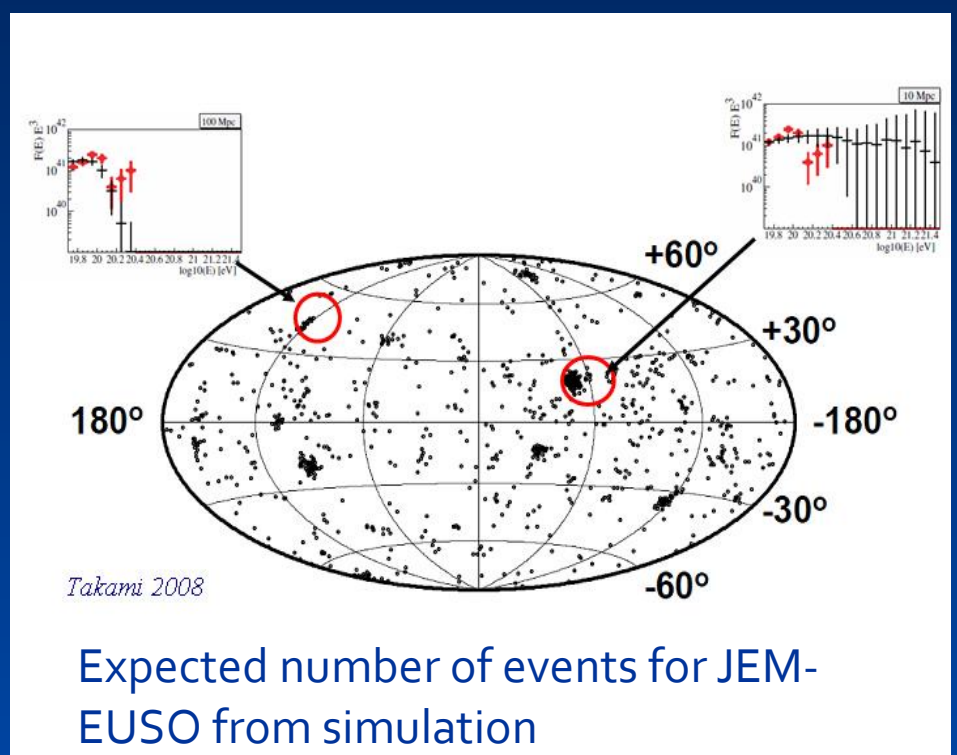
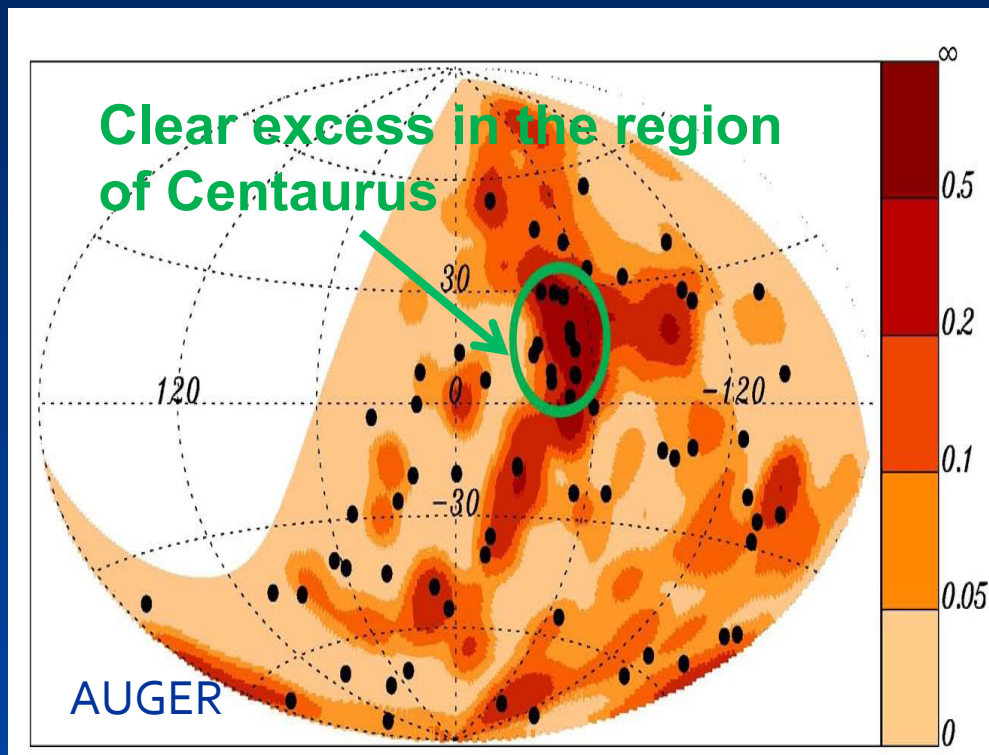


Different from ground experiments, JEM-EUSO covers entire Celestial Sphere with almost constant exposure



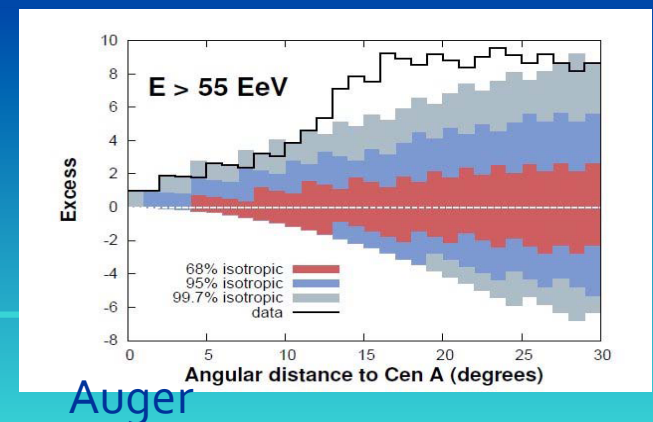
Curves in the right-bottom show the relative exposure (same as color scale) as a function of sin (declination), which corresponds to solid area in the sky. In all cases, the average in [-1:1] is 1 and deviations represent non-uniformity. JEM-EUSO serves almost flat exposure in most part of the sky. Small excesses in polar region are due to the fact JEM-EUSO stays higher latitudes N and S within inclination more times that equatorial region. In TA & Auger excess in exposure may reach 2—3 times from uniformity at maximum, while large zenith angle region is not observable.

Searching for excesses



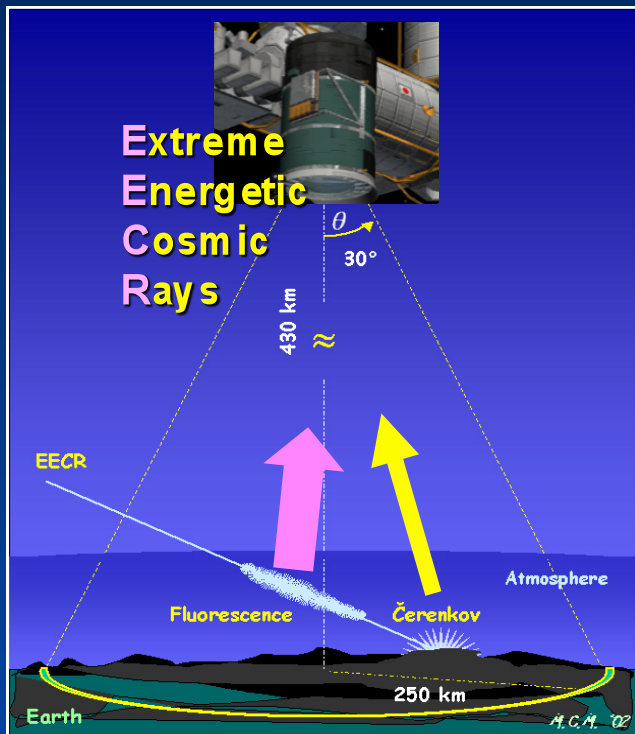
Auger. **Events for $E > 55$ EeV** superimposed on the Swift – BAT density map smoothed with angular scale of 5 degrees
Distance less than 200 Mpc.

Within 18° from Cen A we have 13 events (20% of the total) while we expect 3.2 for isotropic distribution.



Cen-A AGN @ 4 Mpc (Centaurus Cluster @ 40-50 Mpc)

JEM-EUSO Observational Principle

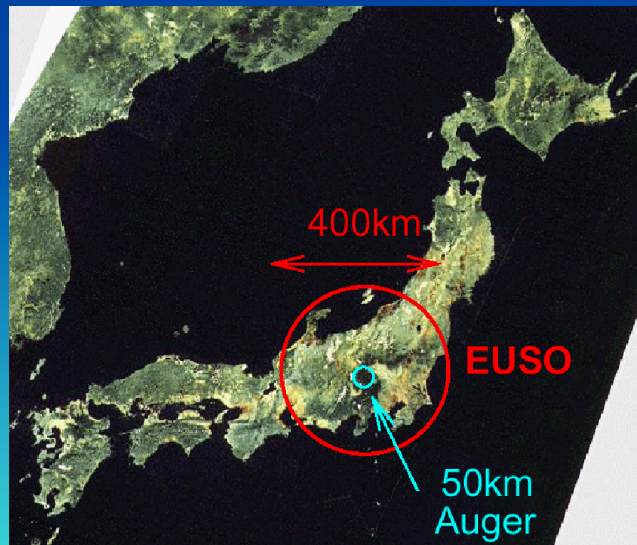


JEM-EUSO is a new type of observatory on board the International Space Station (ISS), which observes transient luminous phenomena occurring in the Earth's atmosphere

- Orbiting at $\sim 8 \text{ km s}^{-1}$ with inclination of 51.6° , at a nominal altitude of $\sim 400 \text{ km}$.
- Super wide FoV (60°) and a large diameter (2.5 m).
- Covers both northern and southern hemisphere.
- 1 orbit every 90 minutes.

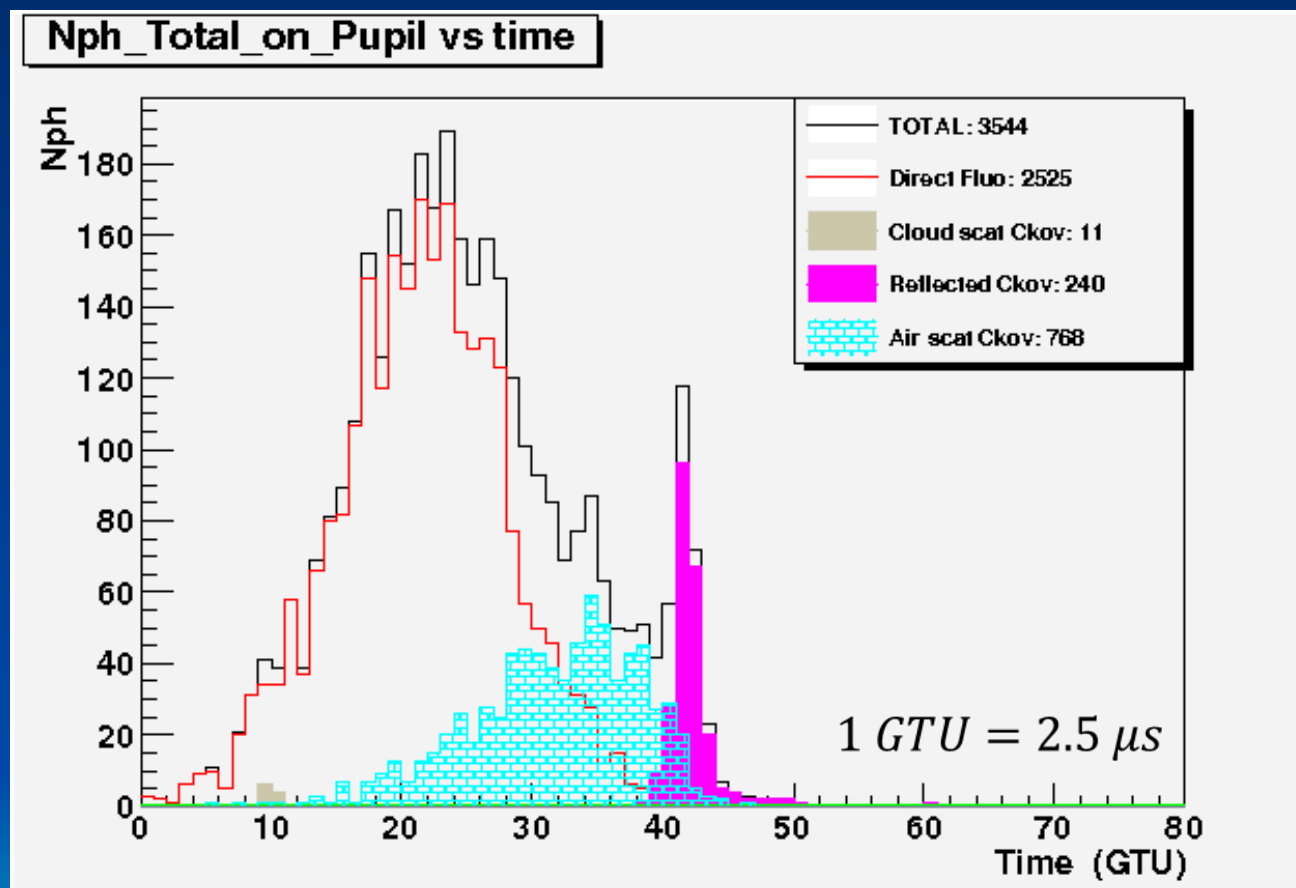
Viewing night atmosphere in $> 2 \cdot 10^5 \text{ km}^2$ area (instantaneous aperture 66 times greater than Auger)

- Target volume about 10^{12} tons (1000 km^3 of H_2O)



Time profile of photons from a typical EAS

($E = 10^{20}$ eV, $\theta = 60^\circ$)

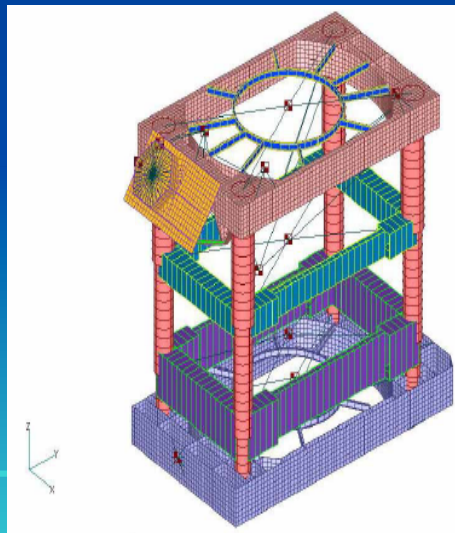
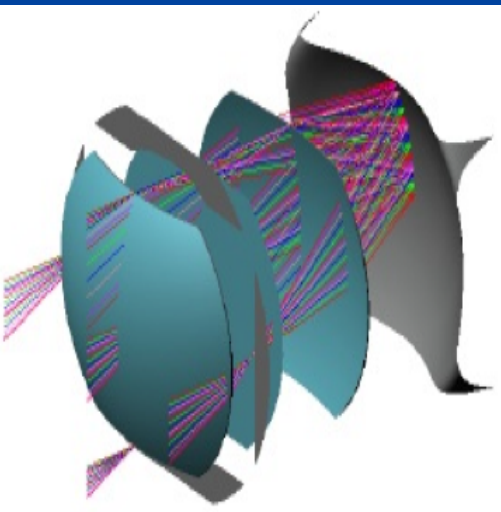
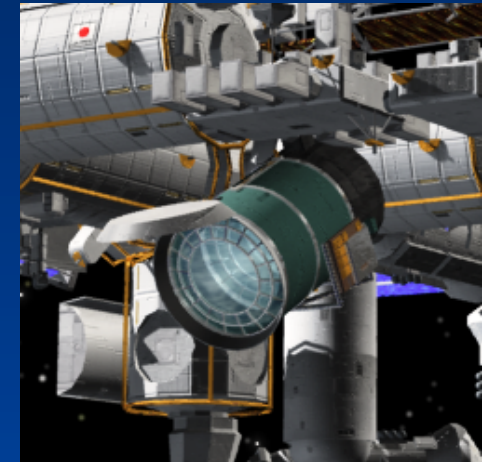


Time profile of photons from a typical EAS. The black line represents all photons with fluorescence component shown by the red line. Cherenkov components, scattered in the atmosphere and diffused from the surface, are shown in cyan and magenta shaded histograms, respectively.

The JEM-EUSO System

MISSION PARAMETERS

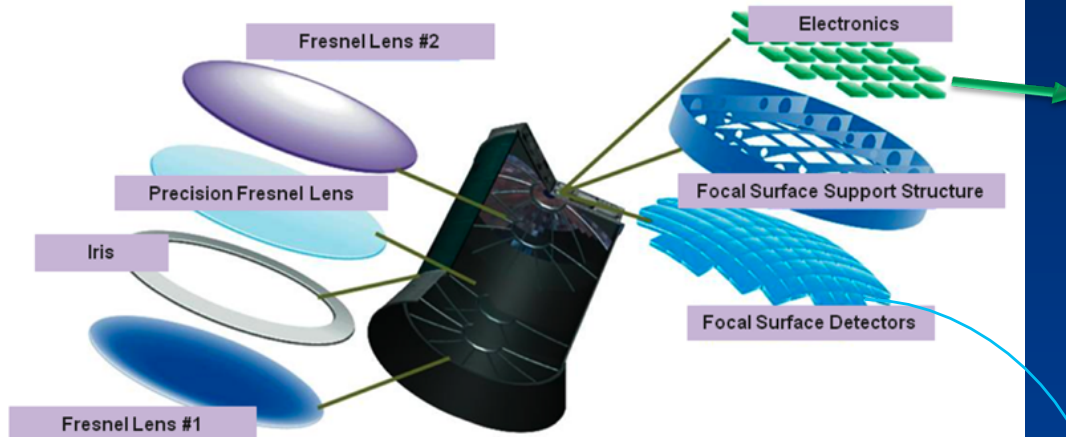
- Time of launch: year 2016 - 2017
- Operation Period: 3 years (+ 2 years)
- Launching Rocket : H2B
- Transportation to ISS: un-pressurized Carrier of H2 Transfer vehicle (HTV)
- Site to Attach: Japanese Experiment Module/ Exposure Facility #2
- Height of the Orbit: ~400km
- Inclination of the Orbit: 51.64°
- Mass: 1983 kg
- Power: 926 W (operative), 352 W (non-operative)
- Data Transfer Rate: 285 kpbs + on-board storage



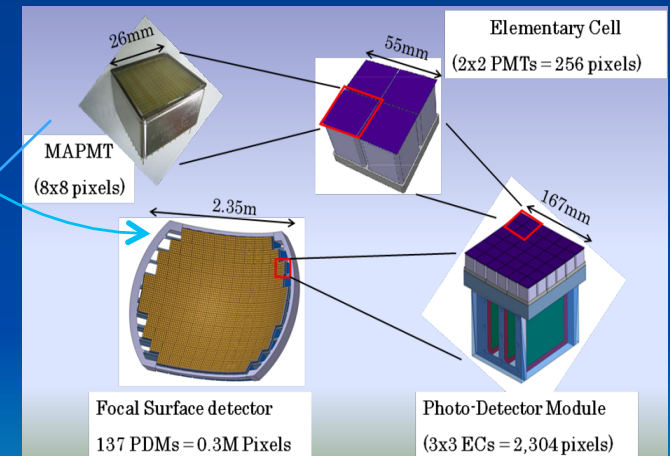
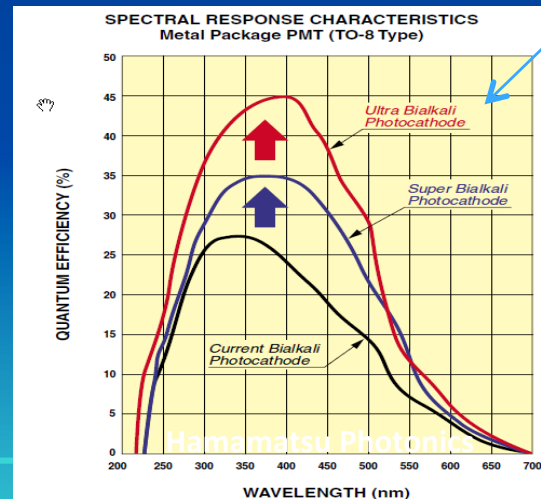
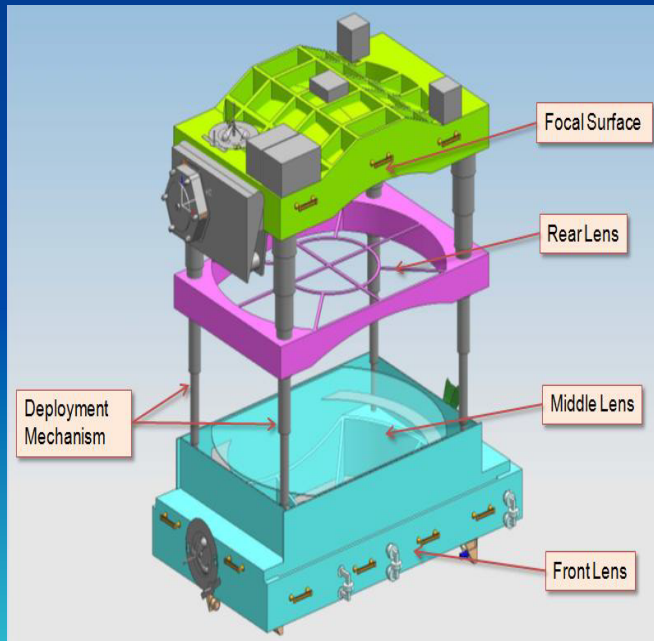
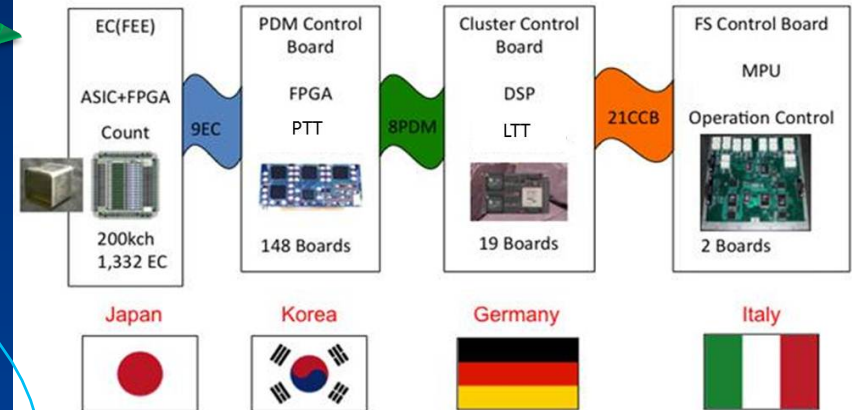
INSTRUMENTS PARAMETERS

- Field of view: $\pm 30^\circ$
- Aperture diameter: 2.5 m
- Optical bandwidth: 330 – 400 nm
- Angular resolution: 0.07°
- Pixel size: 2.9 mm
- Number of pixels: $\sim 3.0 \times 10^5$
- Pixel size at ground: ~ 500 m
- Duty cycle: $\sim 20\%$
- Observational area: $1.9 \times 10^5 \text{ km}^2$

The JEM-EUSO Telescope



JEM-EUSO Data Acquisition Core Outline



JEM-EUSO
UBA M64 Q.E. ~ 38%
pixel size 2.9 mm

THE END



BOTTOM - UP PROCESSES

Here acceleration of low energy particles occurs in objects such as AGN and their radio lobes, interacting galaxies or highly magnetized neutron stars (an extreme case in this class are GRBs).

The observation of a direction of arrival and time coincidence of a GRB and an extreme energy neutrino ($E > 10^{19}$ eV) would provide a crucial test for the identification of GRBs as the UHE CR sources, in spite of their location at distances well beyond the GZK limit.

Other Bottom-Up Hyp.

Cosmological and Low luminosity
Gamma-Ray Bursts

Heavy Nuclei from astrophysical sources
With heavy composition and accelerated
under conditions preventing dissociation.

Fe could have a cutoff ~ 200 EeV instead
of the ~ 60 for protons 



TOP - DOWN PROCESSES

One way to overcome the many difficulties with the acceleration of EECR is to introduce a new, unstable supermassive particle called the X-particle. The decay of these particles is thought to produce copious amounts of photons, neutrinos and leptons, and a smaller fraction of protons and neutrons which could be detected as UHE CR.

The X-particles themselves could be produced by the decay of topological defects or supermassive relic particles produced at the end of the GUT phase transition stage of the universe.

The “Top-Down” alternatives

–Relics of GU Era: Topological Defects

Localized regions where extreme densities of mass-energy are trapped.
 $M > 10^{23}$ eV decaying into GUT Higgs, superheavy fermions or leptiquarks

–“Z-bursts”

UHE neutrinos could produce interacting with relic neutrinos, particles fragmenting into burst of Z^0 . Does a halo of neutrinos exist? (there are problems anyway)

–UltraHeavy Dark Matter Particles



UHE CR PRODUCTION MECHANISMS

Observations and Experiments are needed to answer to the questions remaining open

Bottom – up signatures

- Protons/nuclei
- Power law spectrum
- counterparts

Top – down signatures

- Photons/neutrinos
- Non-power law spectrum
- No counterparts/repeats
- Halo distribution

Proton - neutrino discrimination

Proton spectrum according to $E^{-2.7}$, 3 years of data taking
Neutrino spectrum : E^{-1} $3 \cdot 10^{19} - 10^{21}$ (arbitrary large statistics)

The probability of neutrino interaction in atmosphere is proportional to the atmospheric density.

