Charged Cosmic Rays up to the knee region and beyond (III)

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Outline of the lecture

Introduction

Origin, acceleration and propagation of cosmic rays

Models of the knee

Extensive Air Showers

Energy spectrum and composition: measurement and results

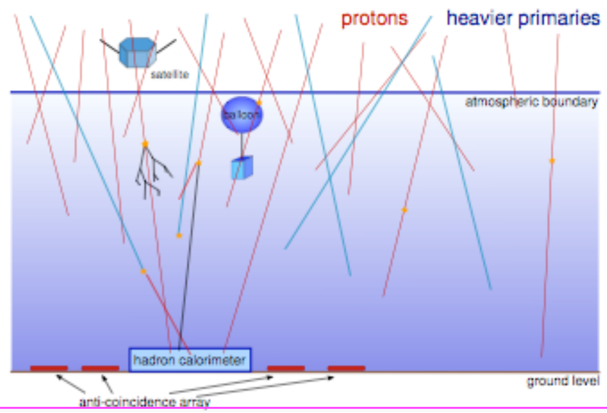
The measurement of the p-Air cross section

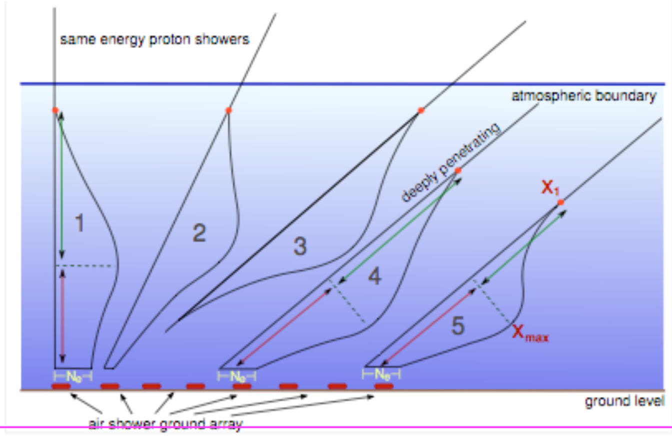
Anisotropy studies with EAS arrays

The Galactic to Extragalactic transition

Future projects

The measurement of $\sigma^{p\text{-}Air}$





Unaccompanied hadrons

Measure the unaccompanied hadron flux at 2 different atm depths

Balloons on top, calorimeters at ground level

$\Lambda_{att} = (X_{top} - X_{ground}) / \ln(\Phi_{top} - \Phi_{ground})$

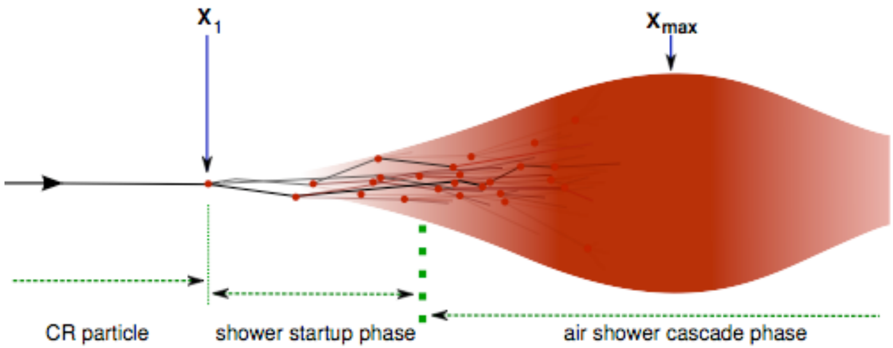
N_μ-N_e from surface detectors

Constant Nμ fix E0

Constant Ne fix development stage

$f(\theta) \propto \exp\{-x_o\ (\sec\theta - 1)/\Lambda_{obs}\}$

$\Lambda_{obs} = \lambda_{int} K_{EAS}$



X_{max}

Directly observed

$P(X_{max}^{rec}) \propto \exp\{-X_{max}^{rec}/\Lambda_{obs}\}$

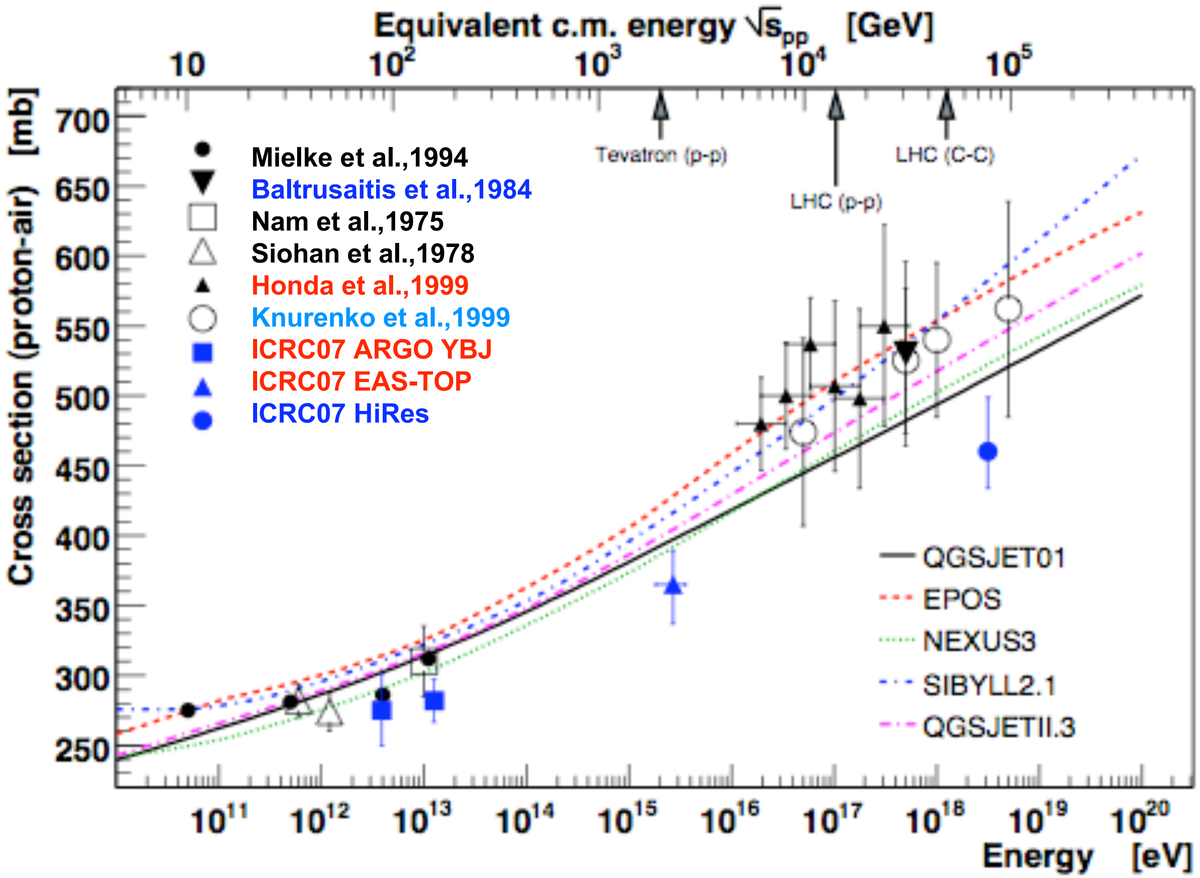
$\Lambda_{obs} = \lambda_{int} K_X$

smaller fluctuations

Xmax shape from fluorescence

Xmax fluct from Cerenkov

The measurement of $\sigma^{p\text{-}Air}$



Unaccompanied hadrons

N_μ-N_e from surface detectors

Xmax shape from fluorescence

Xmax fluct from Cerenkov

$K(N_e N_\mu) \neq K(X_{max})$
K strongly depends on models
p/He uncertain

$\Lambda_{abs}^{EXP} > \Lambda_{abs}^{MC}$:
deeper penetration of EAS in atm respect to predictions

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- The Galactic to Extragalactic t
- Future projects

Anisotropy from diffusion
Compton-Getting effect
The method and the experimental challenge
The low and high energy region
Hints for the transition region

Anisotropy studies with EAS arrays

T=time for a cosmic ray to reach Earth from its source in straight line
τ=actual time needed by the cosmic ray

Anisotropy $\delta = \tau / T$

100% anisotropy if $\tau = T$, CR directly to Earth
100% isotropy if $\tau = \infty$, complete isotropization

Any $\delta \neq 0$ implies a motion

Propagation of the CR from the source in the intergalactic space

Motion of the Earth/Sun system in an isotropic gas (e.g. the CR one): the **Compton-Getting effect:**

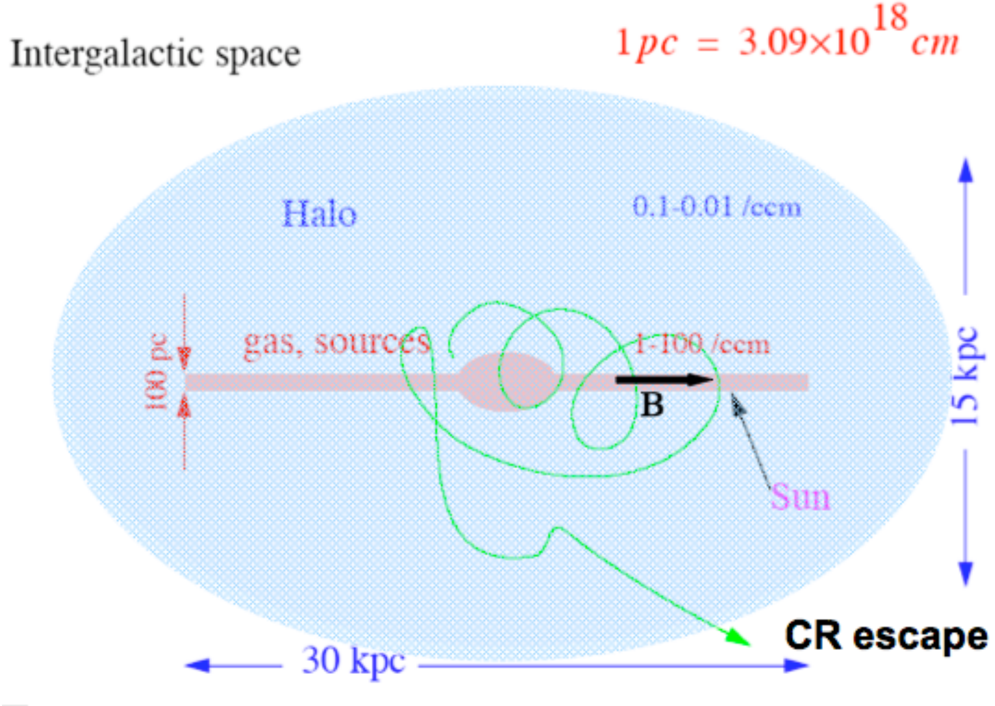
Anisotropy from Diffusion

Cosmic rays propagate in the Galaxy guided by magnetic fields $\vec{B}(\vec{r}) = \vec{B}_{reg}(\vec{r}) + \vec{B}_{turb}(\vec{r})$

They are confined in the Galaxy up to ~10^{18} eV, since the curvature in a Galactic magnetic field of ~3 μG is

$$r_g[pc] = \frac{E_{15}[10^{15} eV]}{B[\mu G]Z}$$

(1 EeV proton r_g ~ thickness of Galactic disk)



$$D = \frac{1}{3}\lambda_D v$$

diffusion coefficient

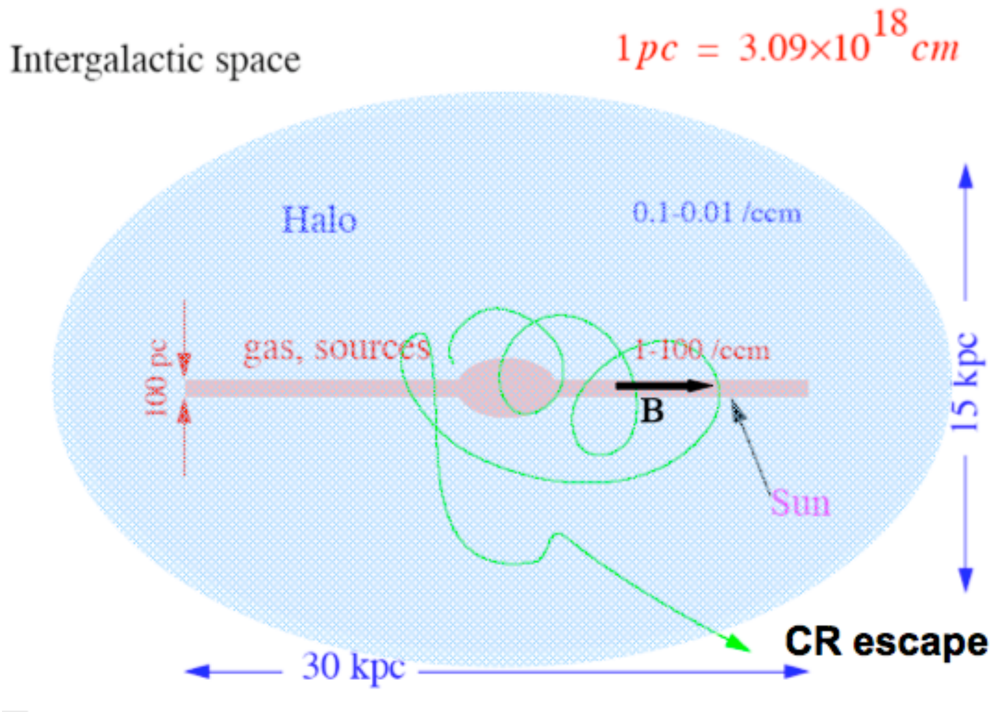
λ_D=diffusion mean free path ~ scale of ISM inhomegeneities (0.1-0.3 pc)

$$\delta = \lambda_D \frac{\partial N}{\partial x}\frac{1}{N} = \frac{3D}{v}\left|\frac{\nabla N}{N}\right|$$

If diffusion is present, density gradients appear, since CRs flow away from the Galactic plane, and there is anisotropy

$$\lambda_{esc} = \rho v h H / D = \rho v h / v_D = \rho v \tau_{esc} \propto R^{-m} = (E/Z)^m$$

v = particle velocity
ρ = disk density = 1/cm^3
H = halo scale height ~ 700 pc
D/H = v_D = escape velocity ~ 1.5 10^6 cm/s
D ~ 10^{28} cm^2/s



D increases with E,
hence δ increases with E

$\delta \sim v_D/v \sim 10^{-4}$
level of expected anisotropy

Compton-Getting effect

Motion of Earth and Solar System in an isotropic gas in the rest frame

Earth orbiting around the Sun (in solar time):

expected $\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\frac{v}{c}\cos\vartheta$

measured $\frac{\Delta I}{\langle I \rangle} \sim 0.047\%$

galactic CR anisotropy

Solar System moving through the cosmic rays "gas" (in sidereal time)

galactic CR anisotropy

Solar System moving with V~350 km/s through the CMB rest frame

extragalactic CR anisotropy

$\frac{\Delta I}{\langle I \rangle}$ (exp) ~0.6%

At Earth:

I= CR intensity

γ=slope ~2.7

V_{det} ~ 30 km/s

θ=Angle between the detector motion and the CR arrival direction

Anisotropy studies with EAS arrays

EAS arrays have

uniform exposure in right ascension α (due to Earth rotation),

not uniform exposure in declination δ : $\Delta\delta = f$(array geographical position, zenith angle dependence of the shower detection and reconstruction)

Method: analysis in α, through the harmonic analysis of the counting rate within a defined δ band [formalism of Rayleigh]

amplitude A $A = \delta \cos d$ (d=declination of observation)

phase Φ (hour angle of the maximum intensity)

probability P to detect a spurious amplitude

Experimental challenge:

- expected amplitudes very small (10^{-3} - 10^{-4})
  need long term observations and large collecting areas
- spurious effects have to be kept as small as possible
  need area uniformity and time stability, continuity of operation
- dependence on pressure and temperature

Many consistency checks are needed

Experimental challenge:

- expected amplitudes very small (10^{-3} - 10^{-4})
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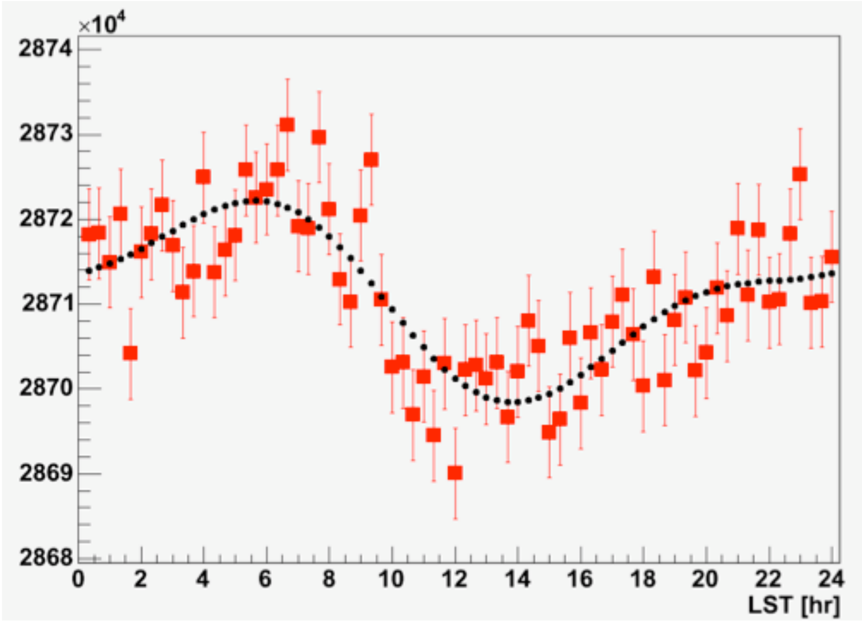
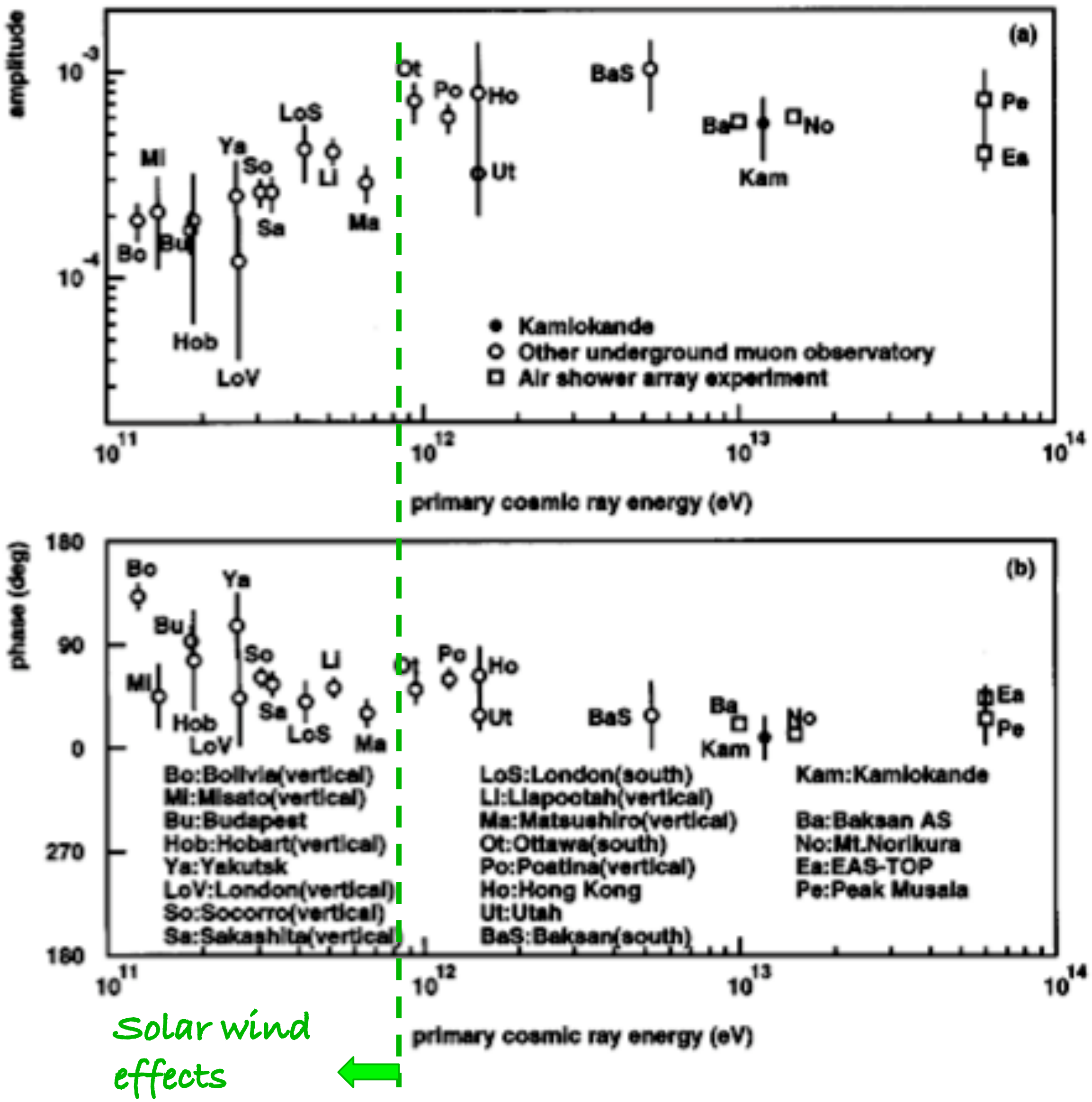
Experimental method:

- ✓ For each EAS :
  arrival time and direction, α and δ, E
- ✓ Correct the counting rates for P,T
- ✓ Apply some safety cuts
- ✓ Make consistency checks
  (antisidereal time distribution,
  Compton-Getting effect, etc.)





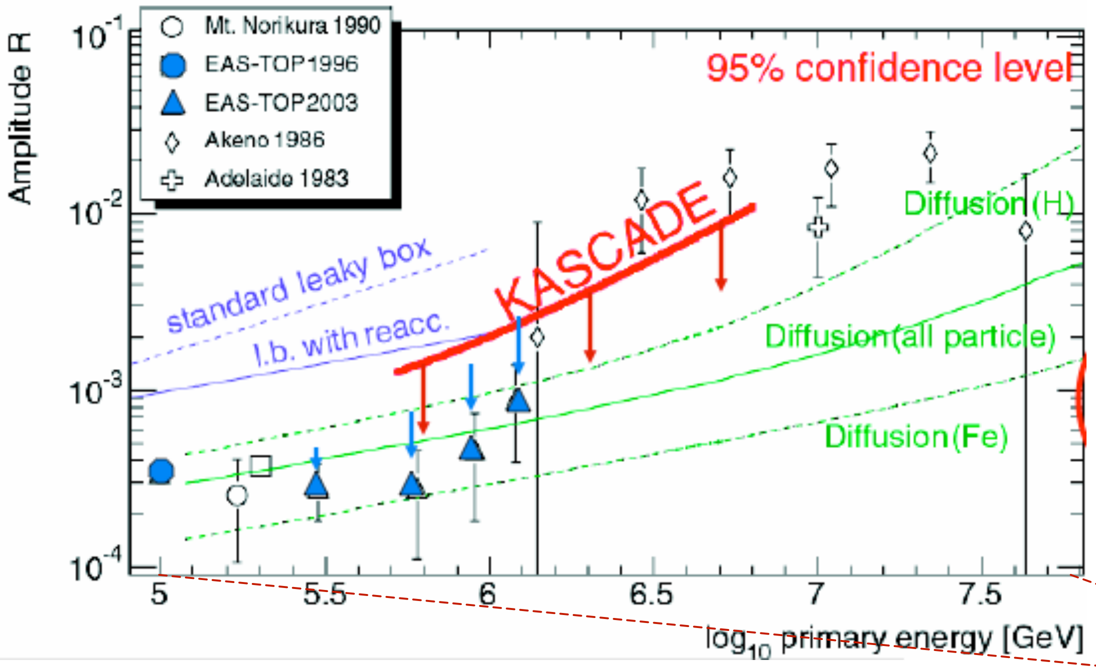
The "low" energy range

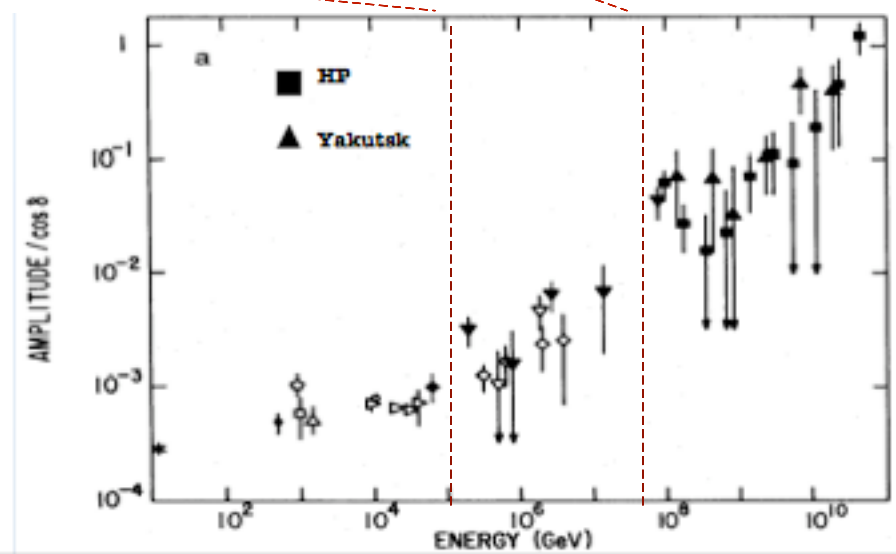
The measurements are made underground or with high altitude detectors below 10 TeV and with EAS arrays above

All data on sidereal anisotropy show good consistency up to 100 TeV

They are consistent with large scale diffusive propagation in the Galaxy

The high energy range





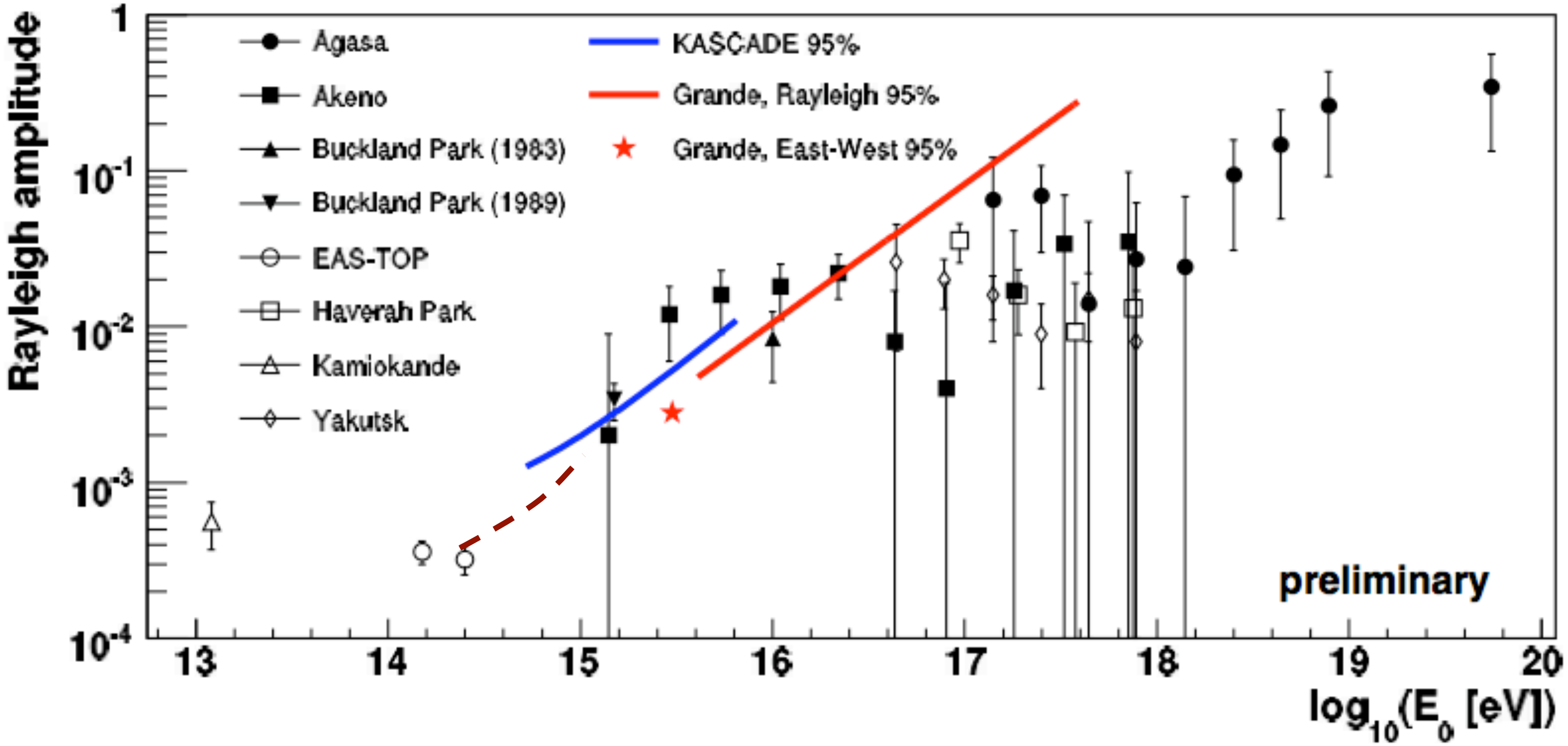
Old data seemed to suggest an increasing of amplitude

...but increasing amplitude where decreasing number of events!

Even for new results, data suffer from statistics and systematic uncertainties

[M.Aglietta et al.,
T.Antoni et al.,Ap.J. 604 (2004) 687.]

The transition region



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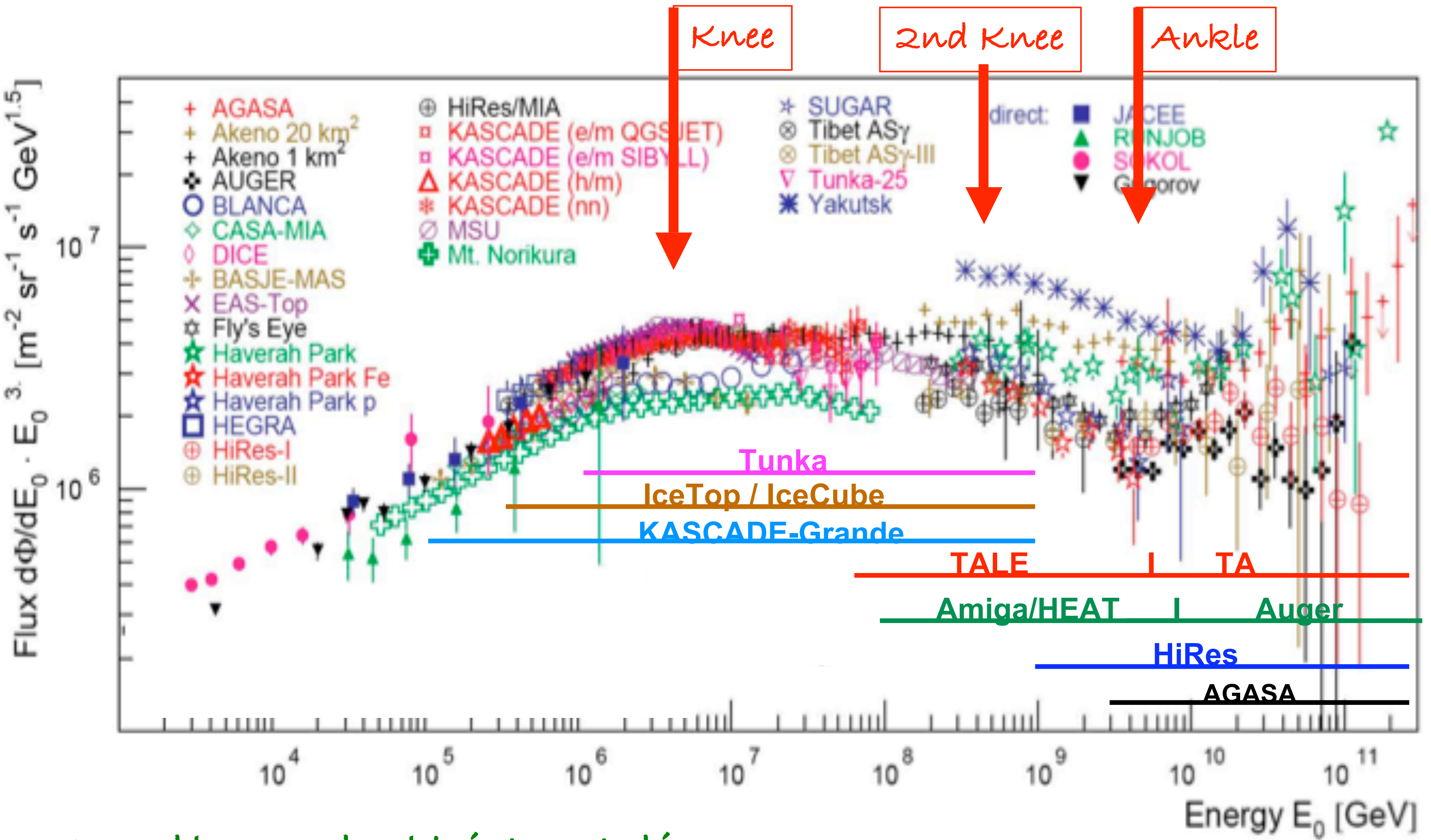
The existing data
4 different models
Energy and Composition constraints



Second knee and ankle interpreted in

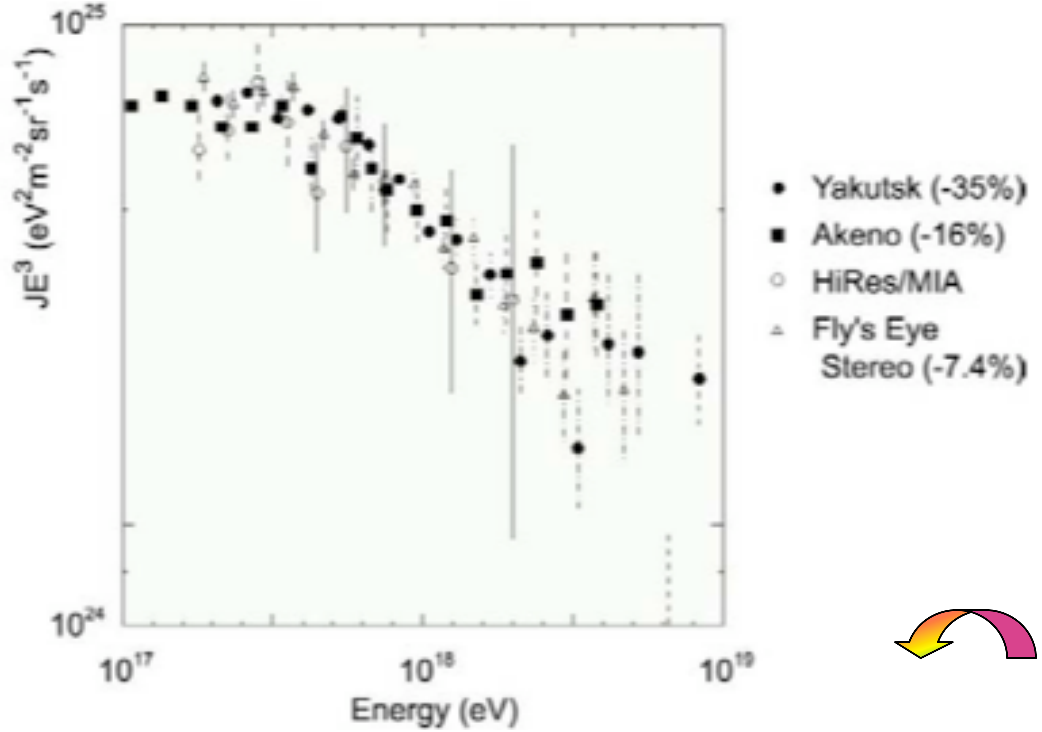
Ankle model [M.Hillas, J.Phys.G31 (2005) R95 and ref.therein]

Mixed composition model [D.Allard et al., Astrop.Phys.27 (2007) 61]

Dip model [V.Berezinsky et al., Phys.Rev.D74 (2006) 043005]

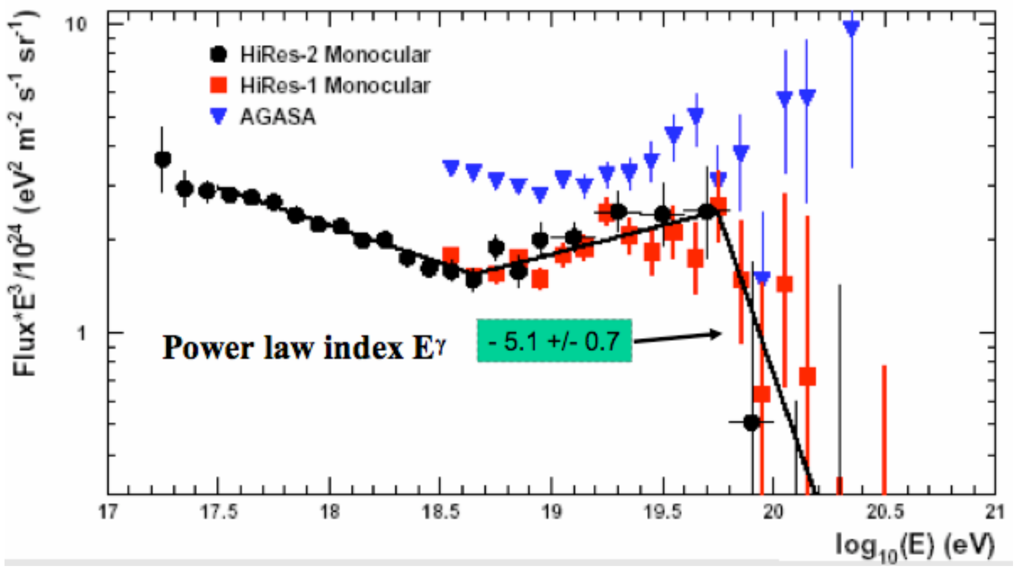
Check with existing data !!!

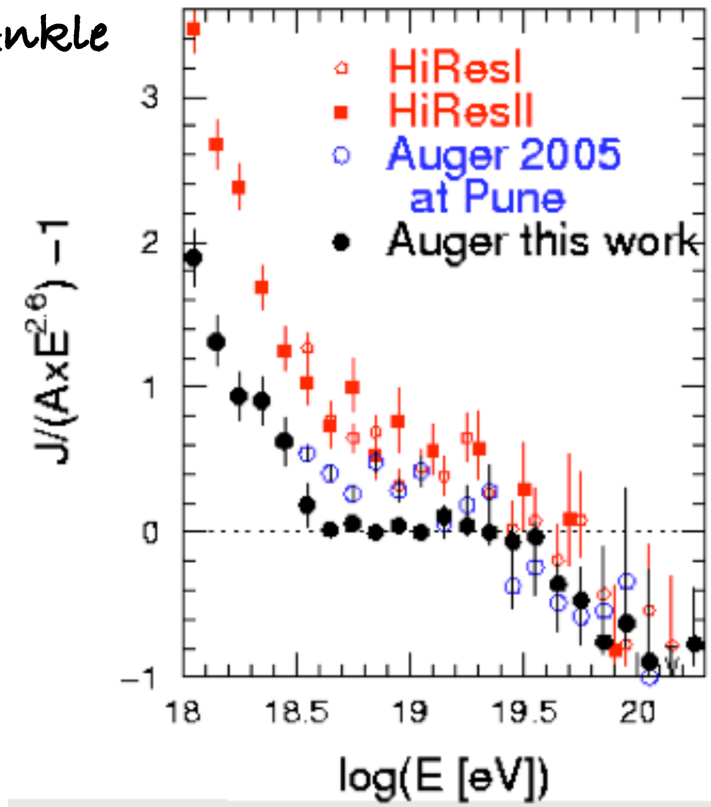
Existing data



Second knee

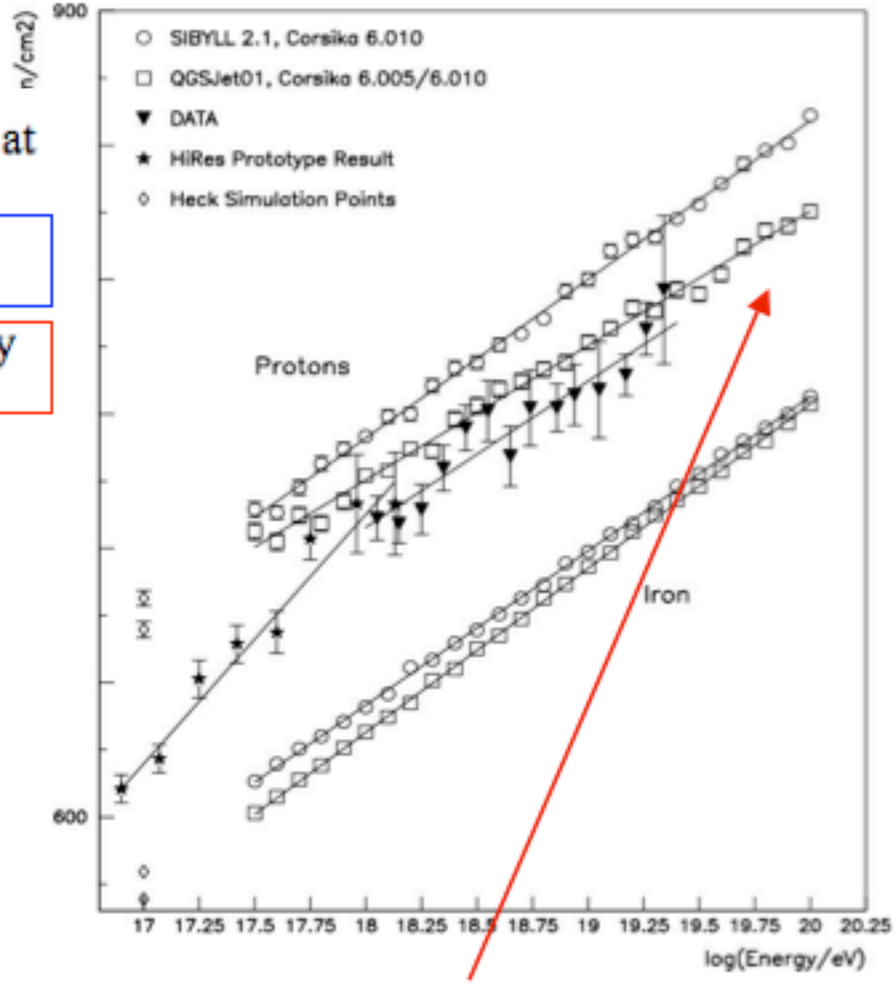
Ankle





HiRes Composition Measurement

- There is a **model-independent** break in slope at about 10^{18} eV.
- Heavy (galactic) nuclei decrease, give way to light (extragalactic) composition.
- Galactic/extragalactic transition is complete by about 10^{18} eV.
- Fits, plus QGSJet predictions, yield model of proton fraction as a function of energy.
- All fluorescence measurements of X_{max} are consistent.
- Only fluorescence experiments SEE X_{max}.

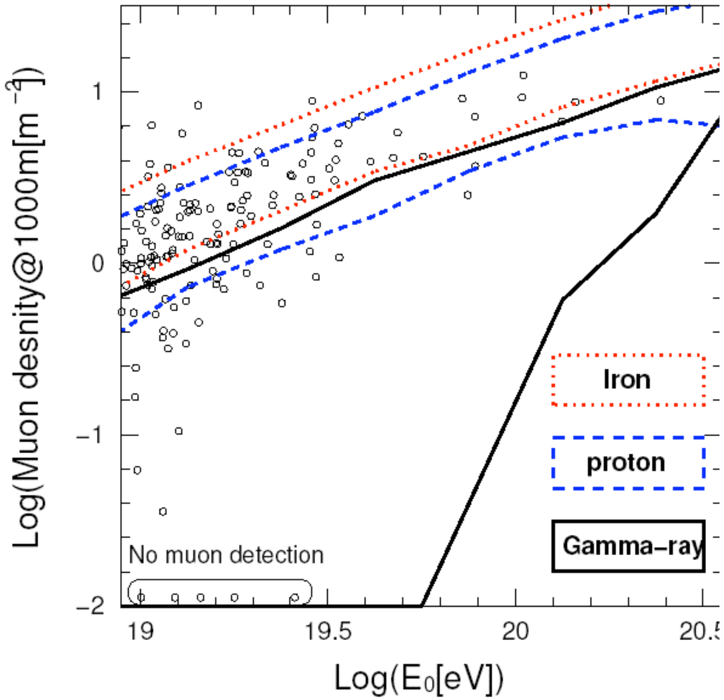


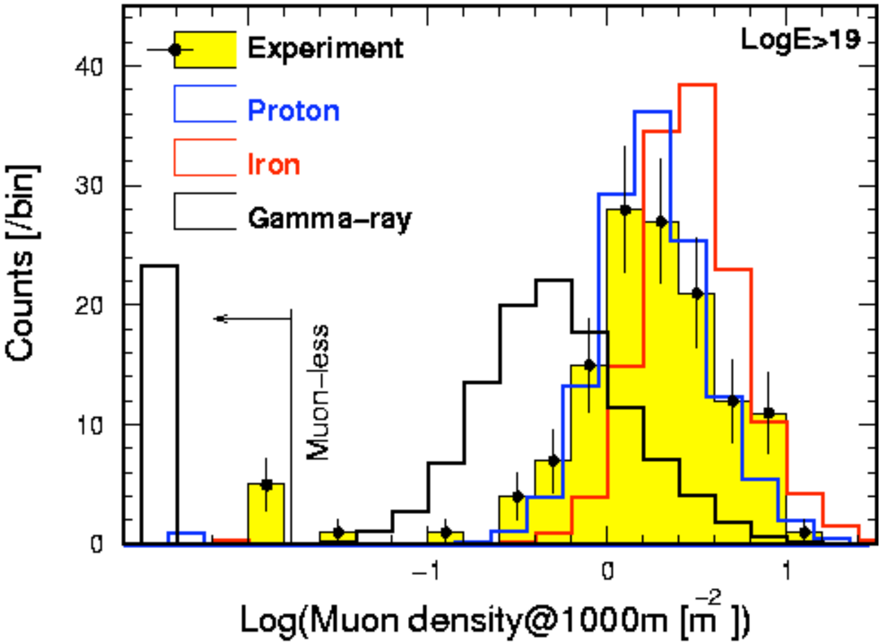
- ***Higher statistics needed to extend analysis up to the GZK Threshold!***

The muon content from AGASA

Primary mass estimator: the muon density at 1 km $\rho_\mu(1000)$

Average relationship $\rho_\mu(1000)[m^{-2}] = (1.26 \pm 0.16)(E_0[eV]/10^{19})^{0.93 \pm 0.13}$



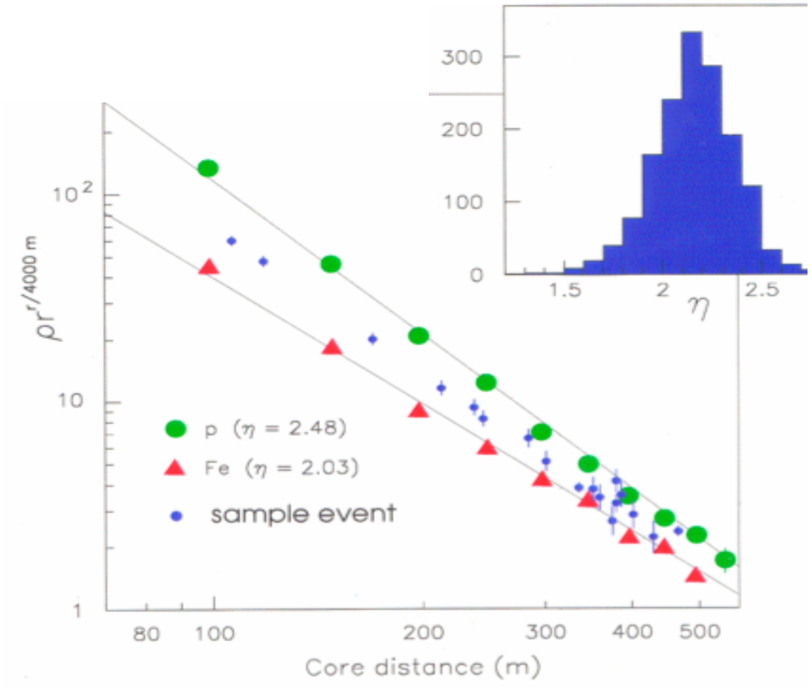


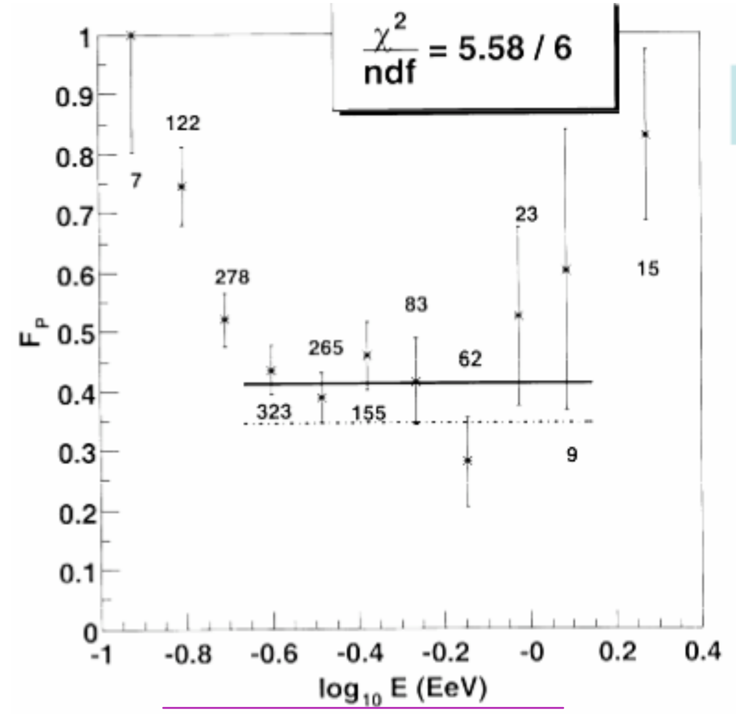
Gradual decrease of %Fe between $10^{17.5}$ & 10^{19}eV

Fe frac.: <35% (10^{19} –$10^{19.5}$ eV)

<76% (above $10^{19.5}$eV)

The muon ldf from Haverah Park





.22 1.6 EeV

$\rho_\mu(r) \sim r^{-(\eta + r/4000)}$

η= steeper for EAS developing later. Compare its spread with Expectations from different primary masses

.

LDF reanalyzed with recent models:

Fraction of protons:

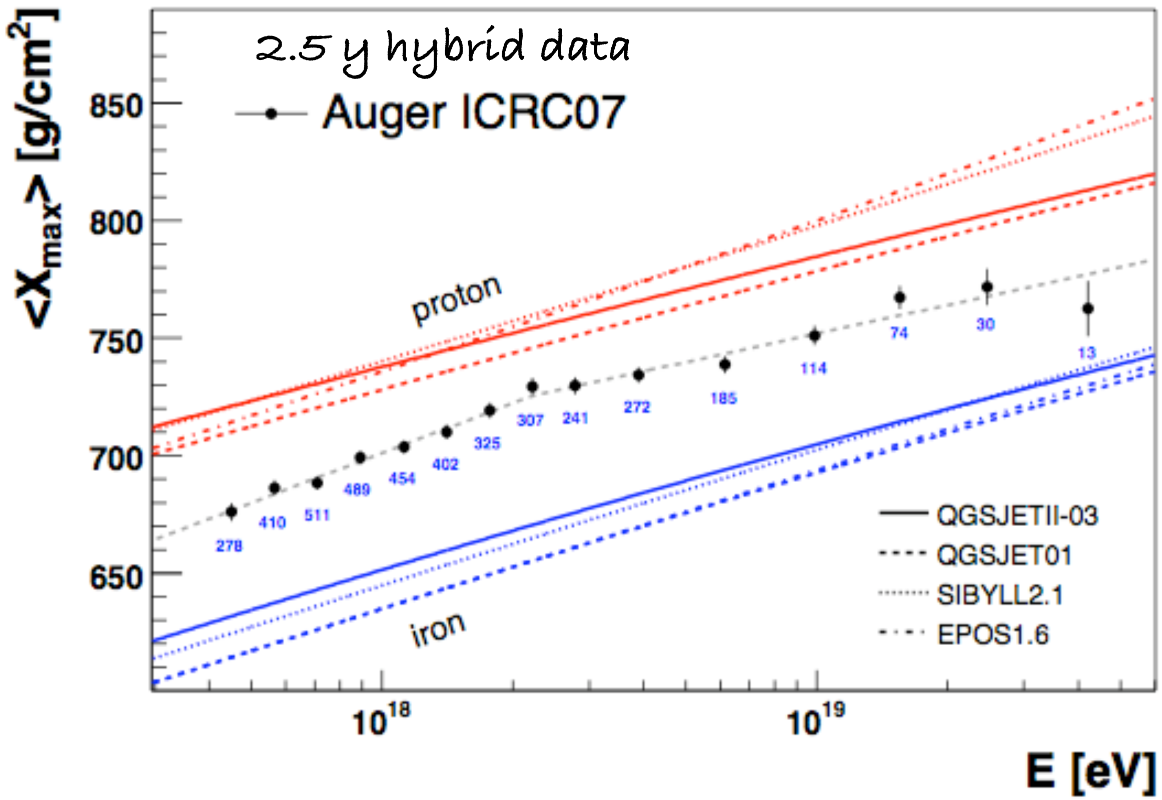
(34 ± 2)% with QGSJet98.

Increase to 48% with QGSJet01.

The X_{max} distribution from Auger

$$\langle X_{\max}\rangle = D_{\rm p}\left[\ln\left(E/E_0\right) - \langle \ln A\rangle\right] + c_{\rm p},$$

D_p and c_p (average depth of a proton) depend on models

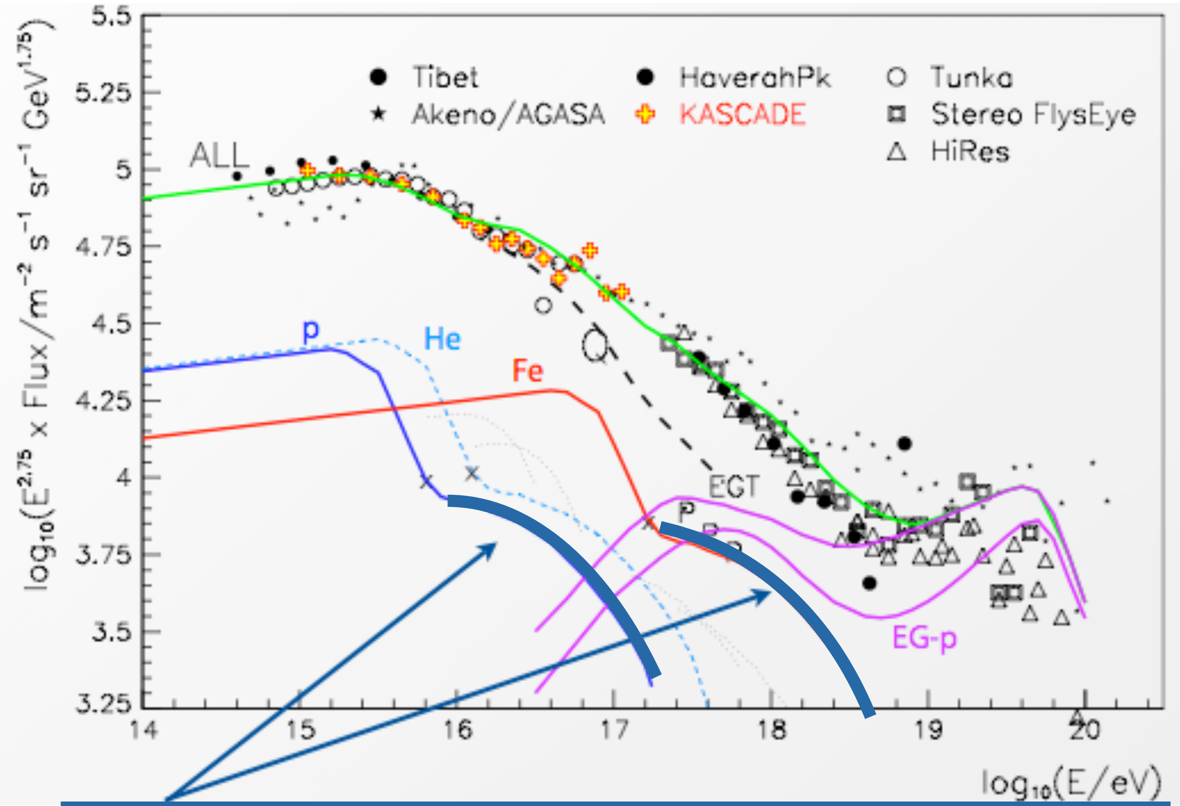


$E_{break} \sim 10^{18.35}$ eV

D10= (71±5) g cm^{-2} below
D10= (40±4) g cm^{-2} above

Result compatible with Previous ones (but already Better statistics!)

Systematics <15 (11) g cm^{-2} atm+detector
22% uncertainty in FD energy scale



Ankle Model

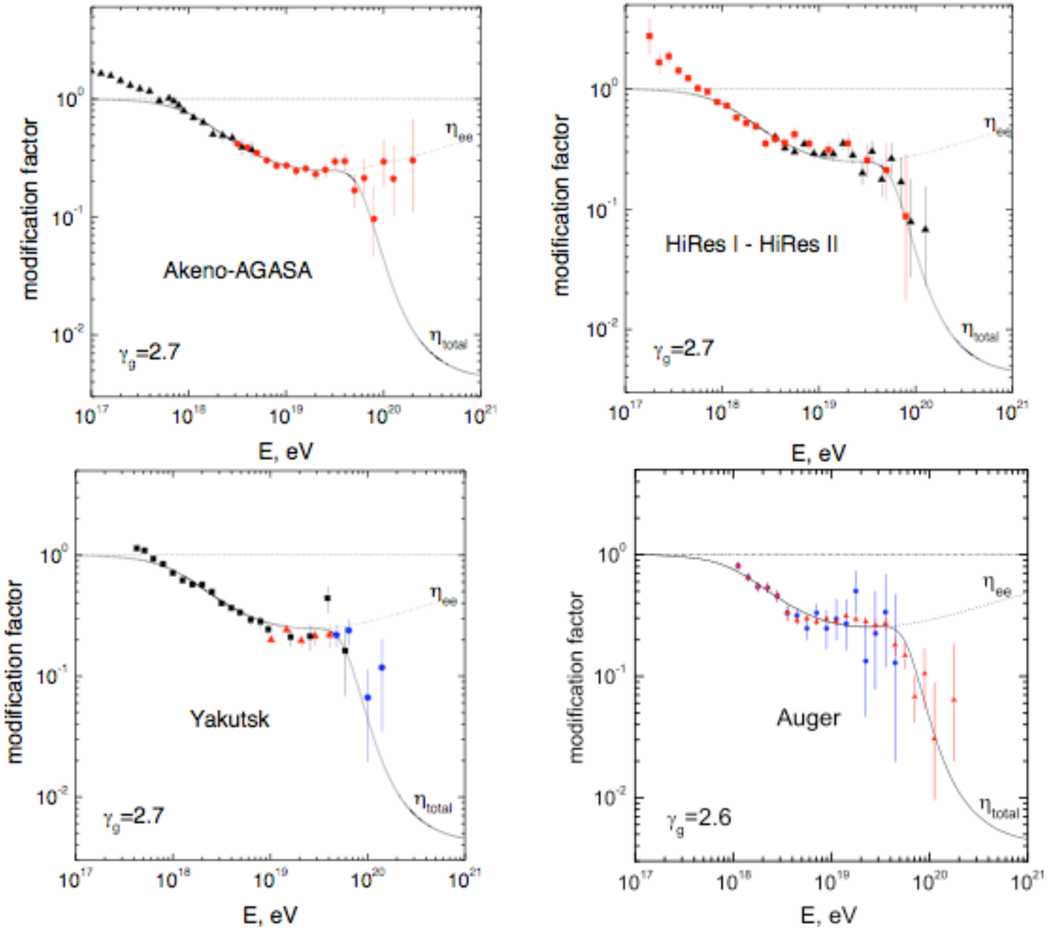
- GCR sum of all components with same rigidity
- EGCR **protons** (+ some He)
- Source spectrum Q(E)
  α=2.3
  Similar to predictions from DSAM
- **Transition at the ankle**
  Most natural shape of a transition

Needs additional component to link with SM

Galactic: modified DSAM with E_{MAX} 100 times >
Bell-Lucek model: acceleration by type II SN whose precursor star emits a dense wind before explosion

[M.Hillas, J.Phys.G31 (2005) R95 and ref.therein,]

Dip Model



- EGCR sources accelerate only **protons**
- Pair production dip in the propagated spectrum ($p+\gamma_{CMB} \rightarrow e^+e^-$)
  The dip is seen by all experiments
  Ankle is a natural feature included in the dip
- The GCR/EGCR transition occurs at the second knee
  Very nice link to standard GCR model (transition close to E_{knee}^{Fe})

... but

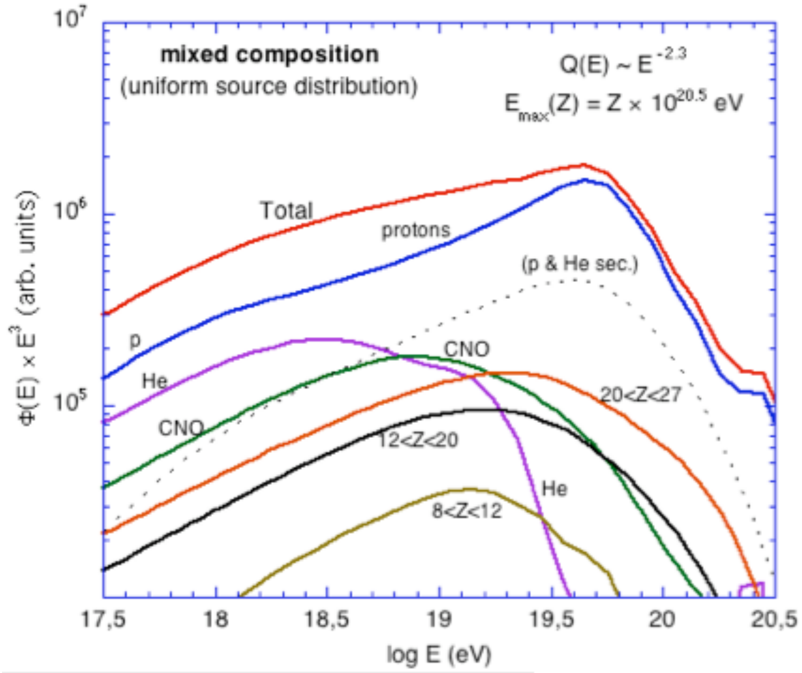
Source spectrum agrees with data if $Q(E) \propto E^{-\alpha}$ with α=2.6-2.7

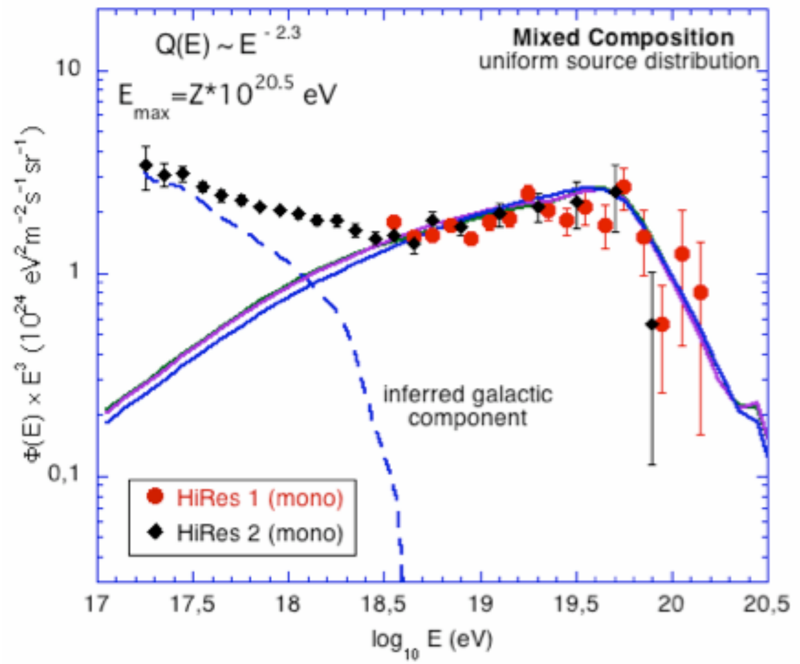
Nuclei admixture>10-15% destroys the agreement dip/data

Modification factor:

$$\eta(E) = J_p(E) / J_p^{un\,mod}(E)$$

[V.Berezinsky, 27st ICRC Conference, Merida (2007)]



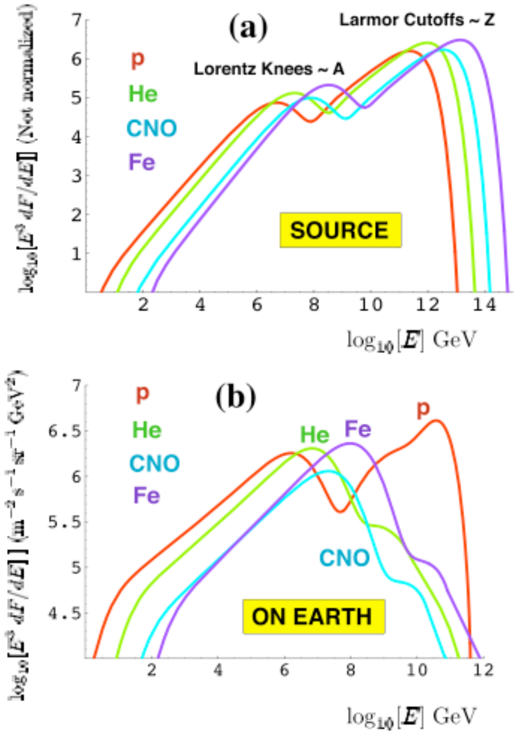


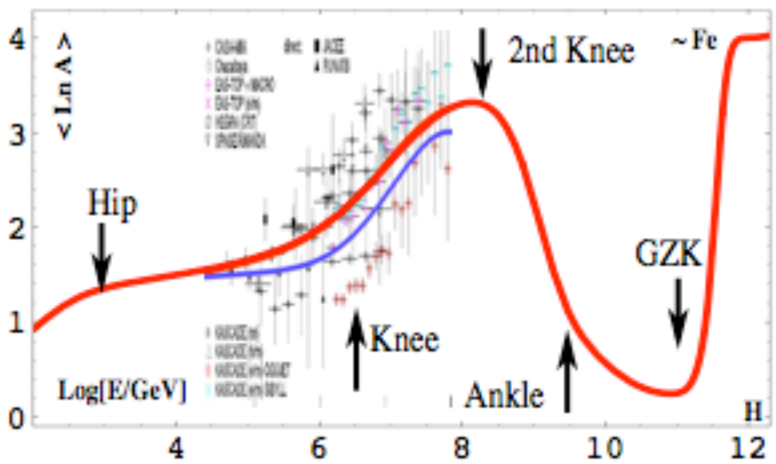
Mixed composition model

- Abundance ratios at source are similar to the GCR ones: **mixed composition**
- Source spectrum $Q(E) \propto E^{-\alpha}$ adjusted to fit data: $\alpha=2.3$
  Agreement with predictions from DSAM
- **The ankle = end of GCR/EGCR transition**
- The dip is filled by contribution of elements other than protons
- The propagated spectra are not sensitive to a small change in composition (less He or more Fe)

...but injection spectrum ∝ A ? composition?

[N.Globus et al., A&A 437 (2007) 1]





Cannonball model

CB of ordinary matter plasma is emitted when part of the accretion disk falls onto the compact object

$\gamma_{CB} \sim 10^3$ to agree with observations

$E_{jet} \sim 1.5\ 10^{51}$ erg (5 CB/jet)

Fluxes at 1st knee: $E_p \sim 4\ 10^{15}$ eV,

$E_A \sim A\ E_p$

Flux at 2nd knee: dominated by Galactic Fe

Extragalactic protons above 10^{19} eV.

Acceleration stops when $r_L \sim r_{CB}$, (2-6) 10^{11} Z GeV

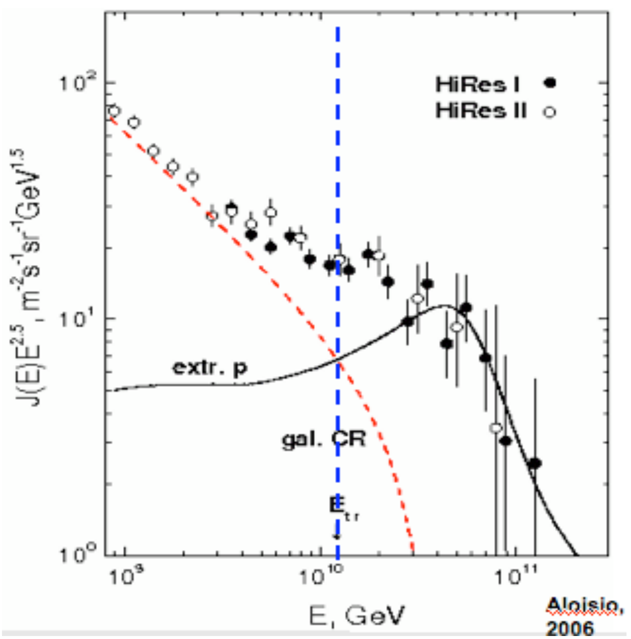
The expected X_{max} is intermediate between dip and mixed composition models

Transition in all models : a steep galactic spectrum intersecting a flatter extragalactic one

All models must explain the measured spectrum and composition and agree with the Standard Model of Galactic Cosmic Rays

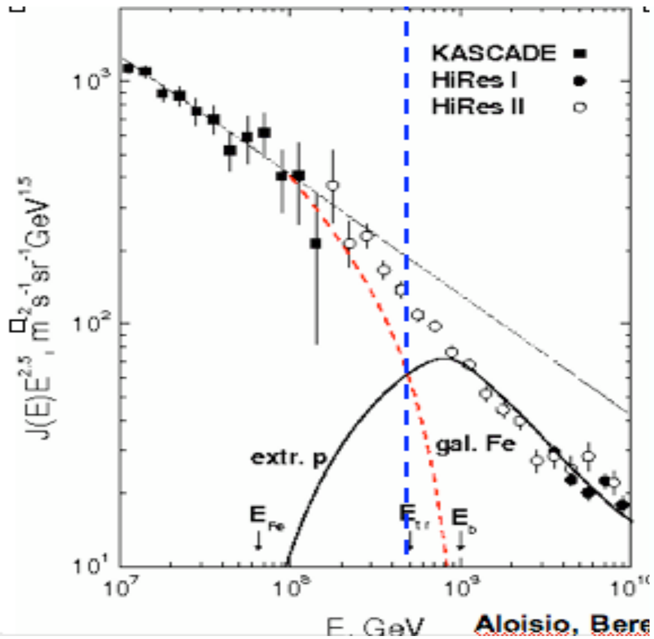
Ankle Model:

- Transition at ankle
- GCR > 10^{19} eV, Fe dominated.
- additional GCR needed
- p, can include heavy nuclei



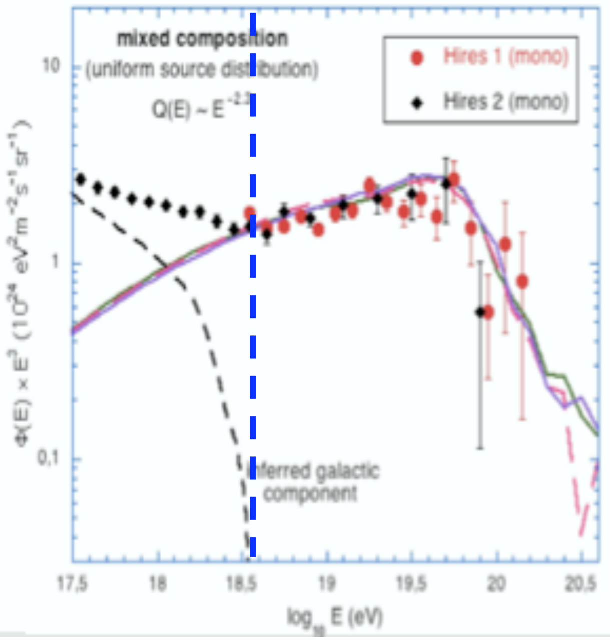
Dip model:

- Transition at second knee
- Ankle as part of the dip ($p+\gamma_{CMB} \rightarrow e^+e^-$)
- pure proton composition



Mixed composition:

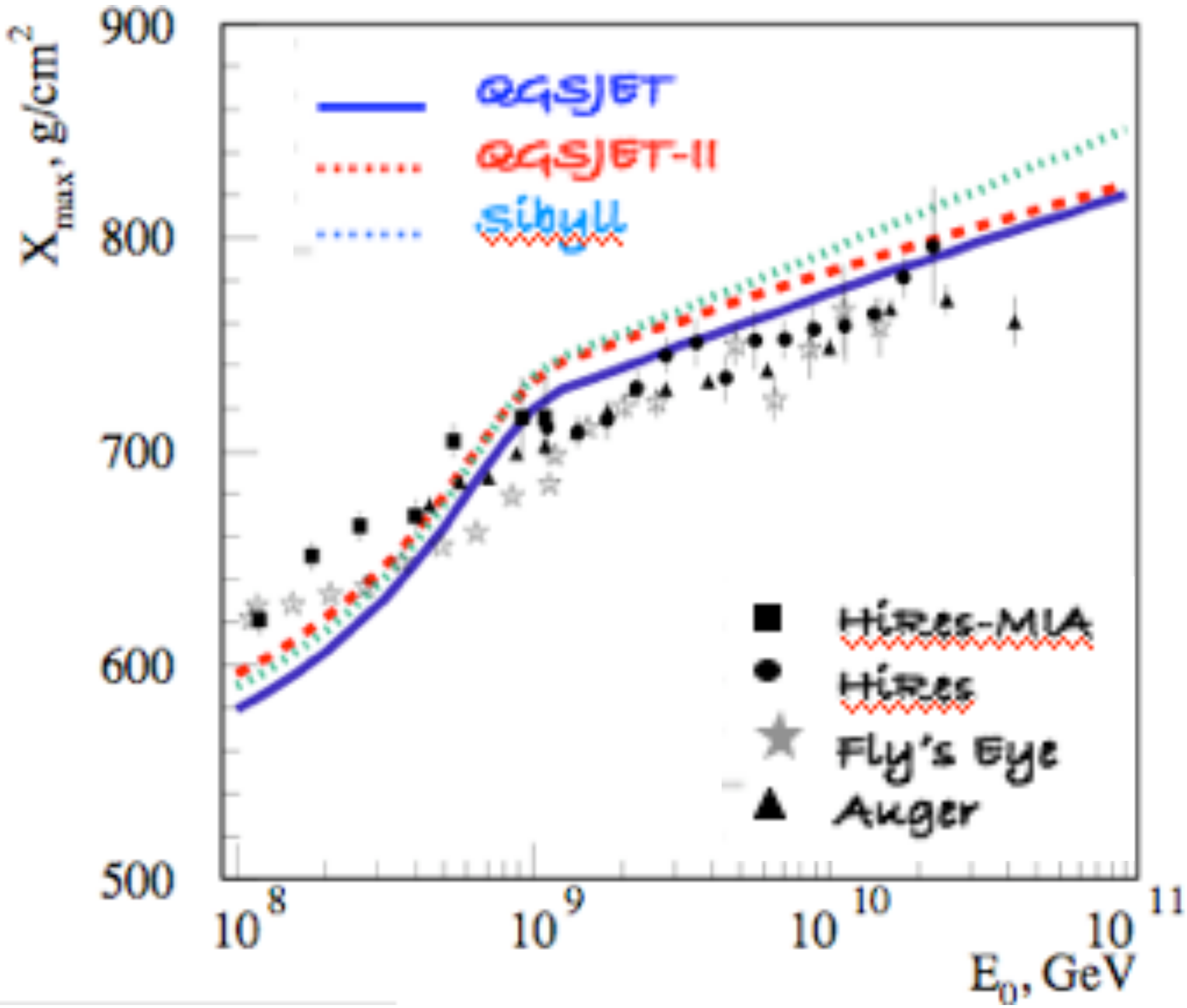
- Transition at ankle
- source spectrum as predicted by DSAM
- mixed composition



Before the transition → anisotropy is expected to increase (r_L ~ galactic disk thickness)

After the transition → large scale isotropy

Composition constraints

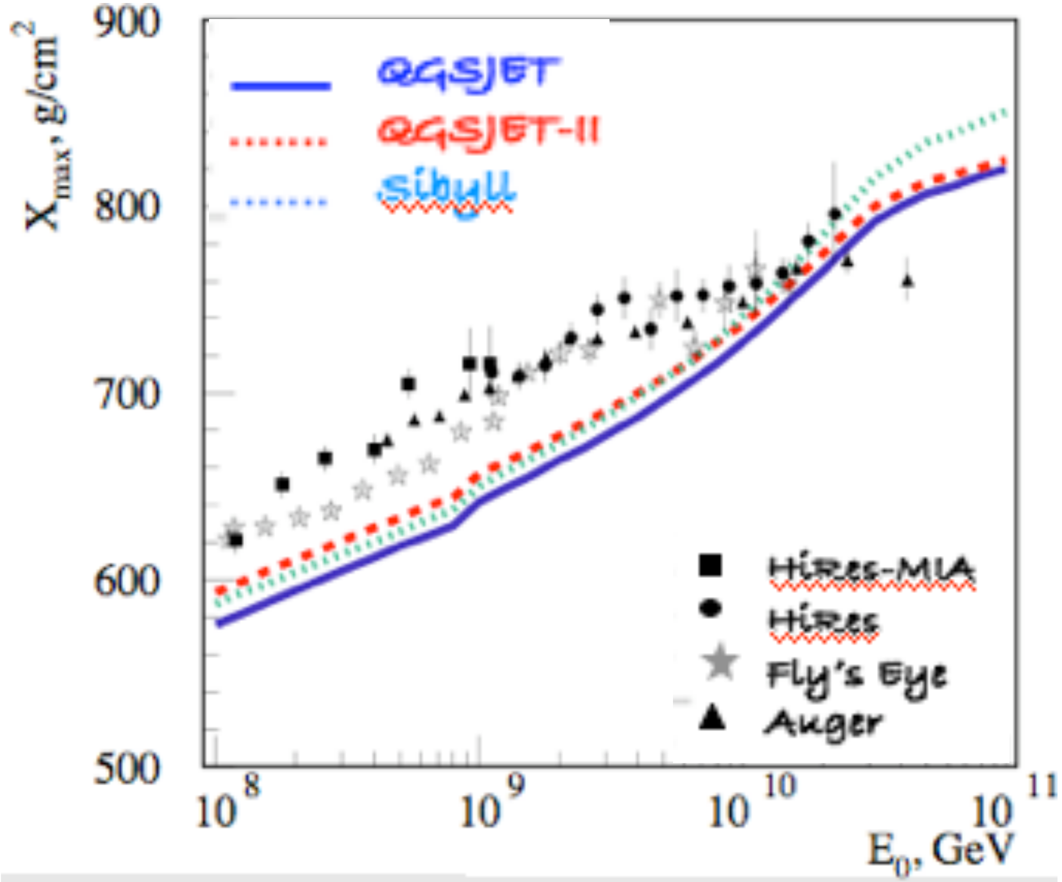


Dip-based model

Sharp rise 10^{17} - 10^{18} eV due to sharp transition from Galactic Iron to extragalactic protons.

Systematic errors on X_{max} ~20-25 g cm^{-2}

Composition constraints

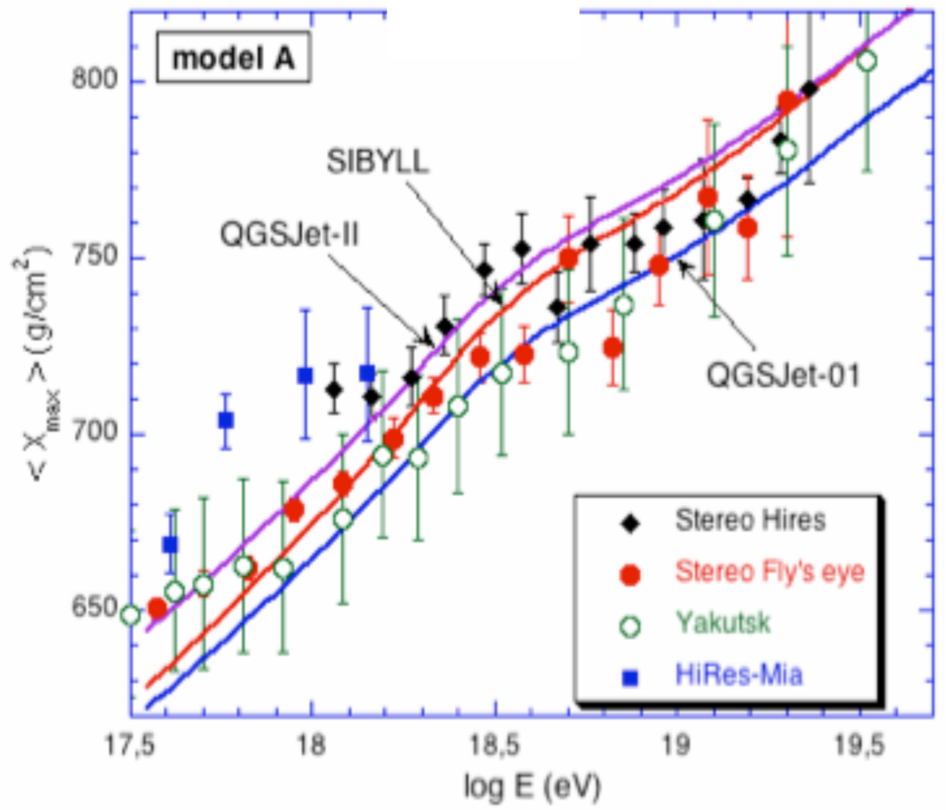


Ankle model

The transition is much smoother, the composition becomes proton-dominated only above 10^{19} eV.

Clear underestimation of X_{max}

Composition constraints

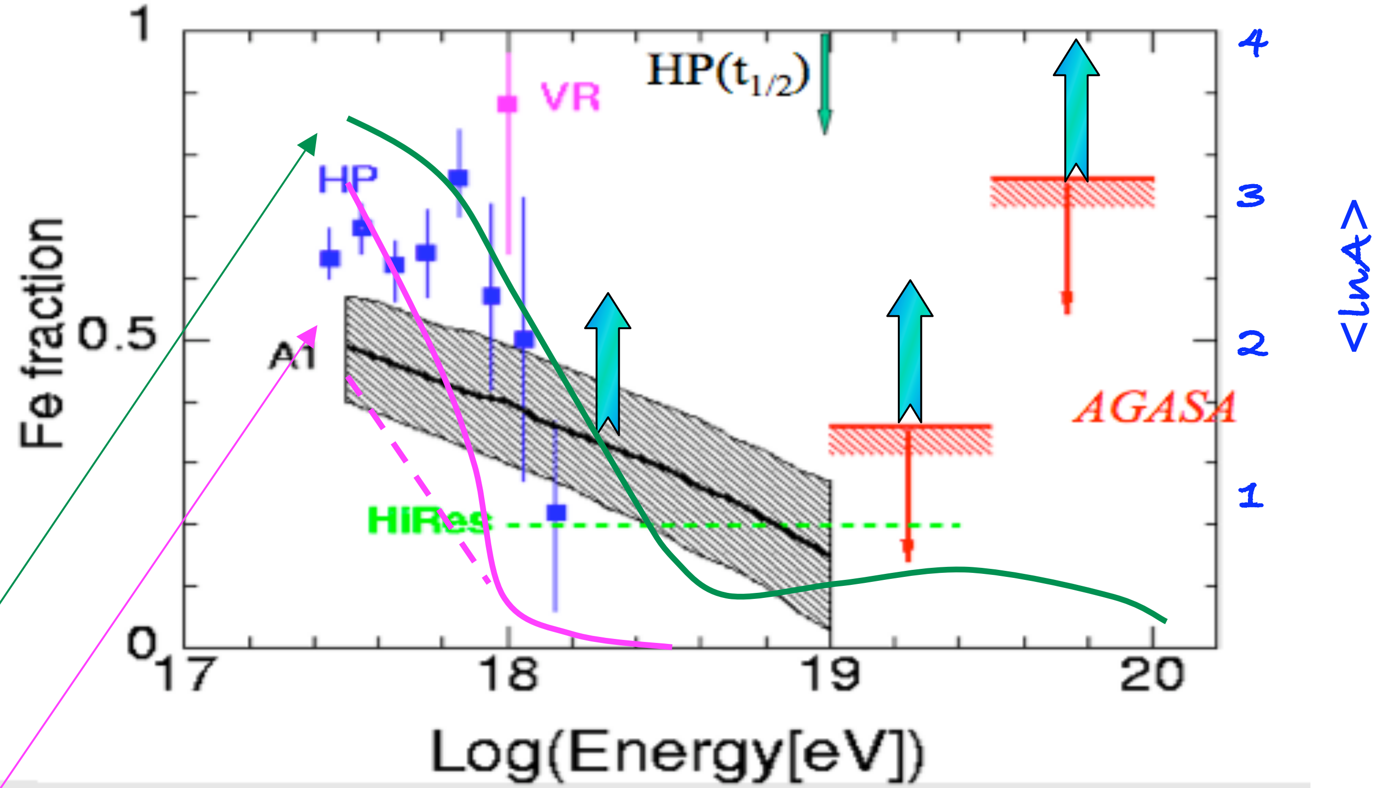


Mixed comp.model

Good fit of Fly's Eye and Yakutsk.

Differencies within 20 g cm^{-2}

Composition constraints



(A) Mixed comp.model — Fe very large up to 3 10^{17} eV; >50% up to 10^{18} eV
Significant fraction of Fe above 10^{18} eV

(B) Dip based model — ~45% Fe and 55% p at 3 10^{17} eV; ~10% Fe at 10^{18} eV
(—— with harder spectrum $\propto E^{-2}$ below 10^{18} eV,
- - - with spectrum $\propto E^{-2.6}$ below 10^{18} eV)

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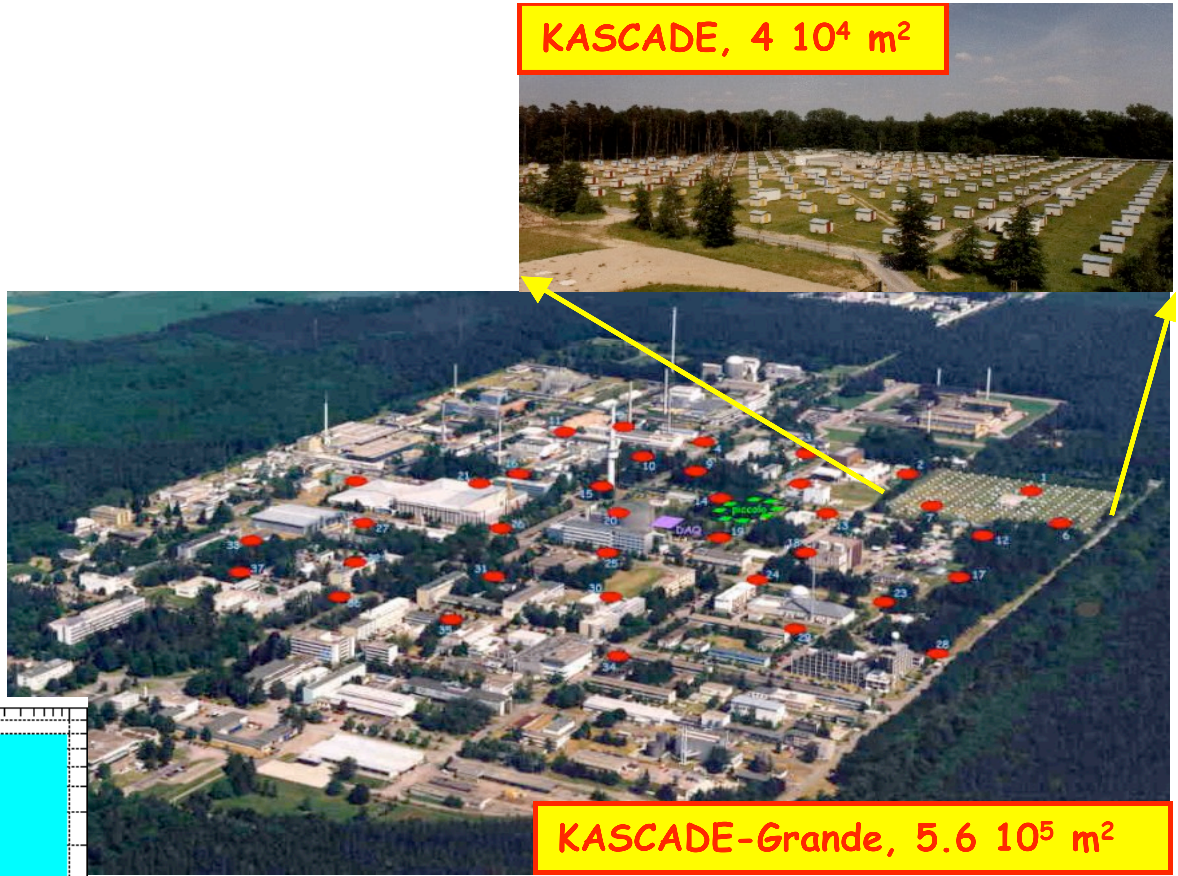
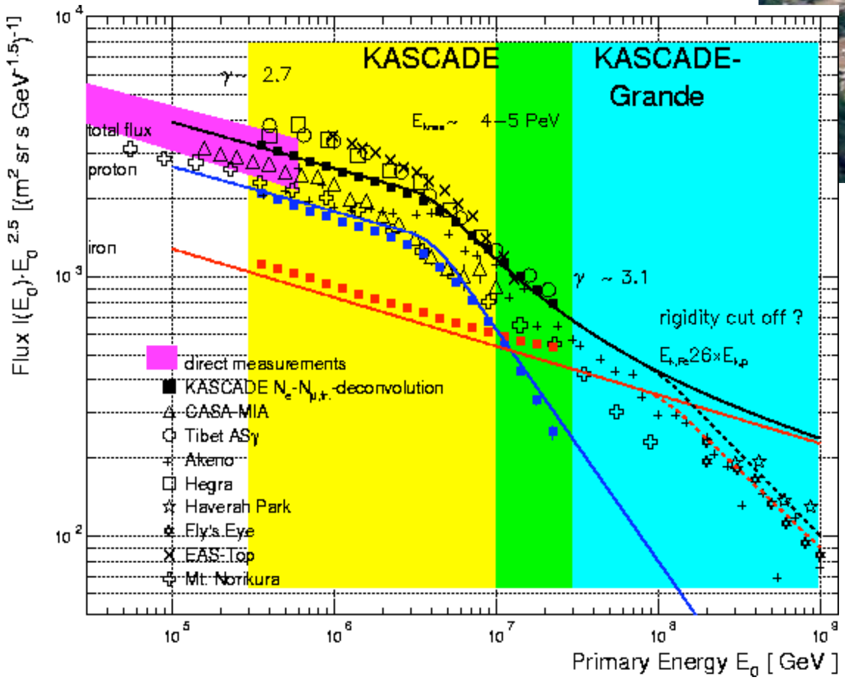
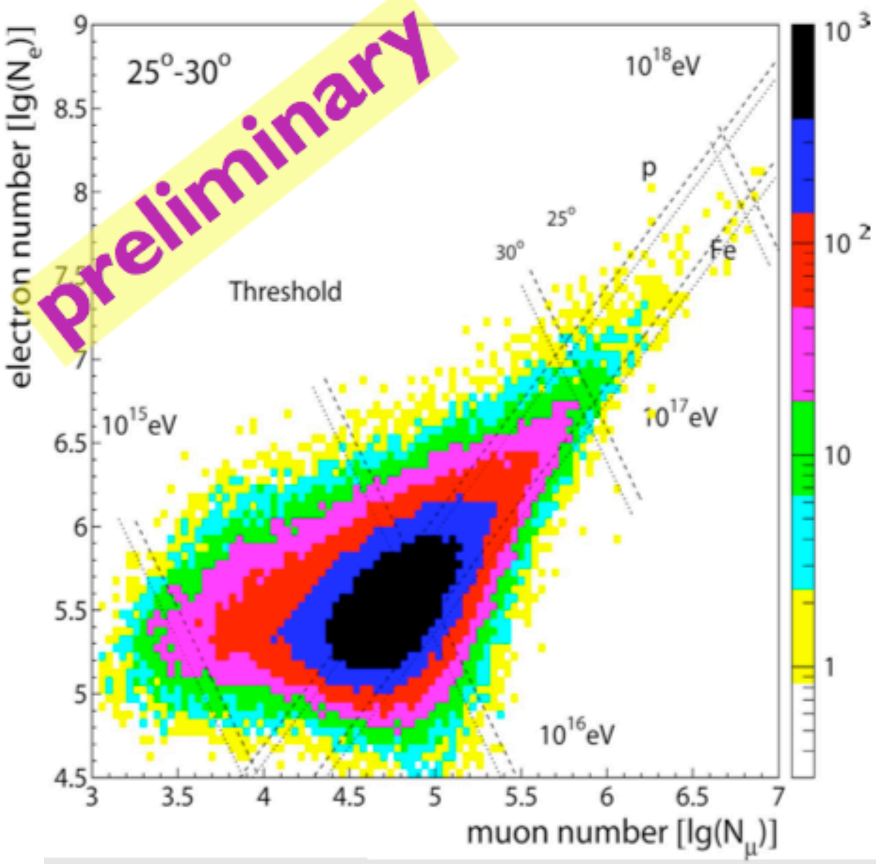
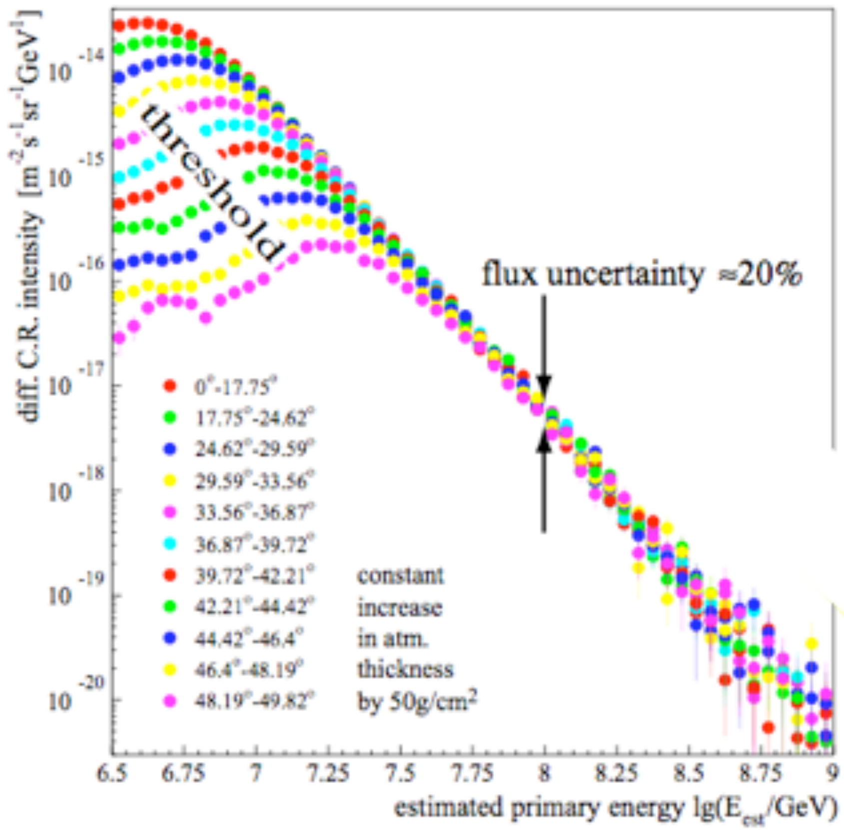
Kascade-Grande

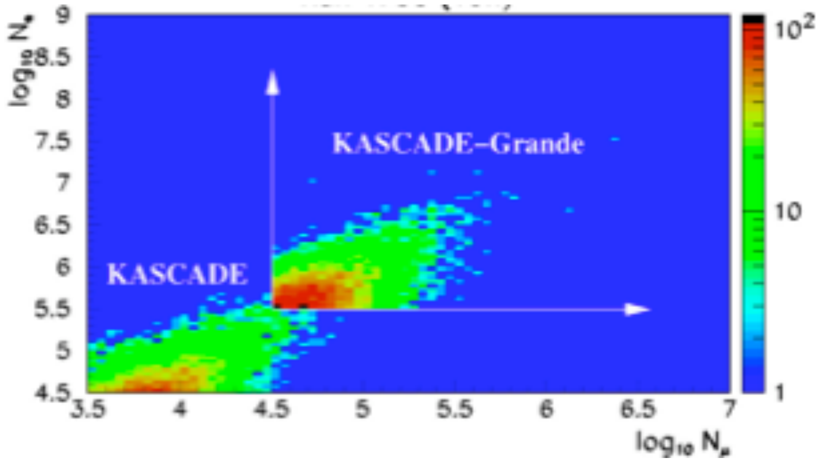
- Study of the elemental composition up to 10^{18} eV
- Search for Fe cut-off (Fe knee)
- Study of the 2nd knee











Electron and mon numbers

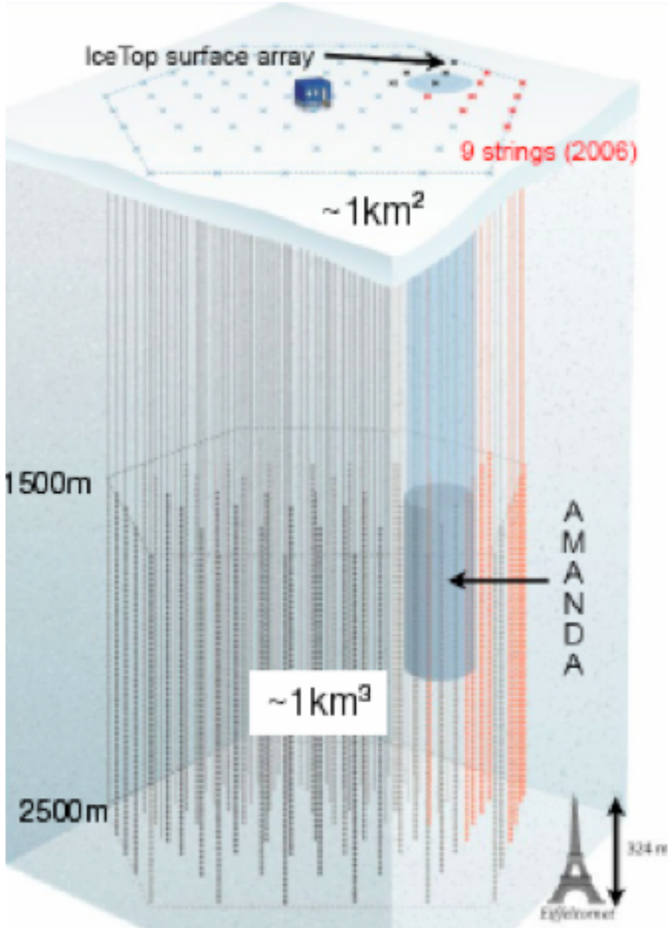
- All particl energy spectrum from their combination
- Unfolding is possible : composition

IceTop & IceCube

IceTop: 80 pairs of frozen water tanks, 2 DOMs/tank
- 26 completed in 2007
E deposition at surface

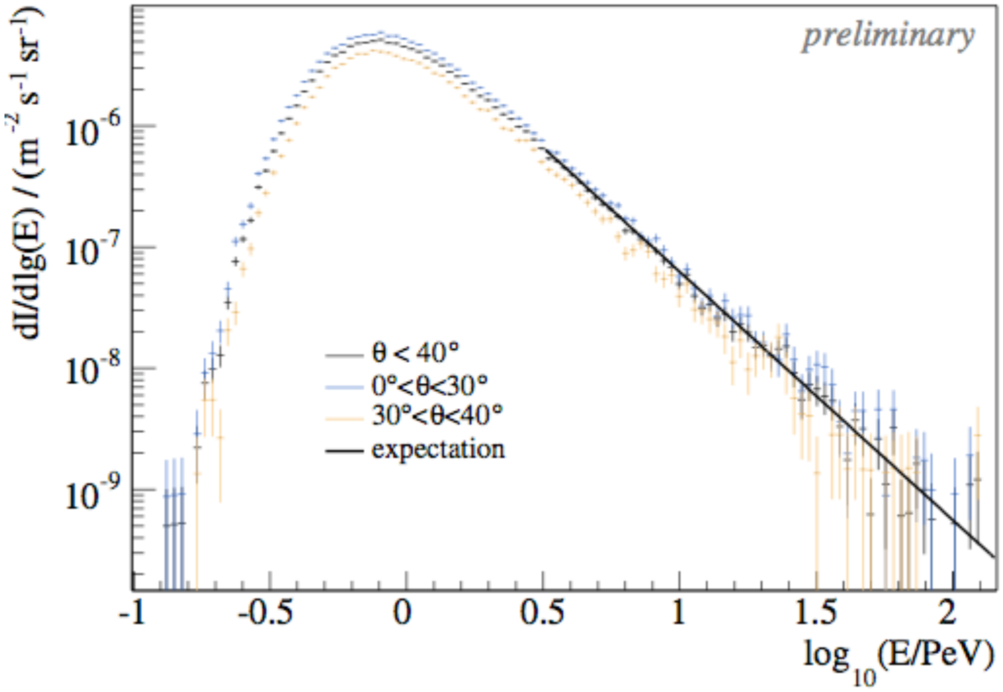
IceCube: 80 strings of 60 digital optical modules (DOM)
cables each 17m, 1 IceTop pair/IceCube string
- 22 completed in 2007
Cerenkov light from μ bundles

Coincidence rate ~0.2 Hz
At completion → 300 TeV - 1 EeV



Preliminary Energy Spectrum

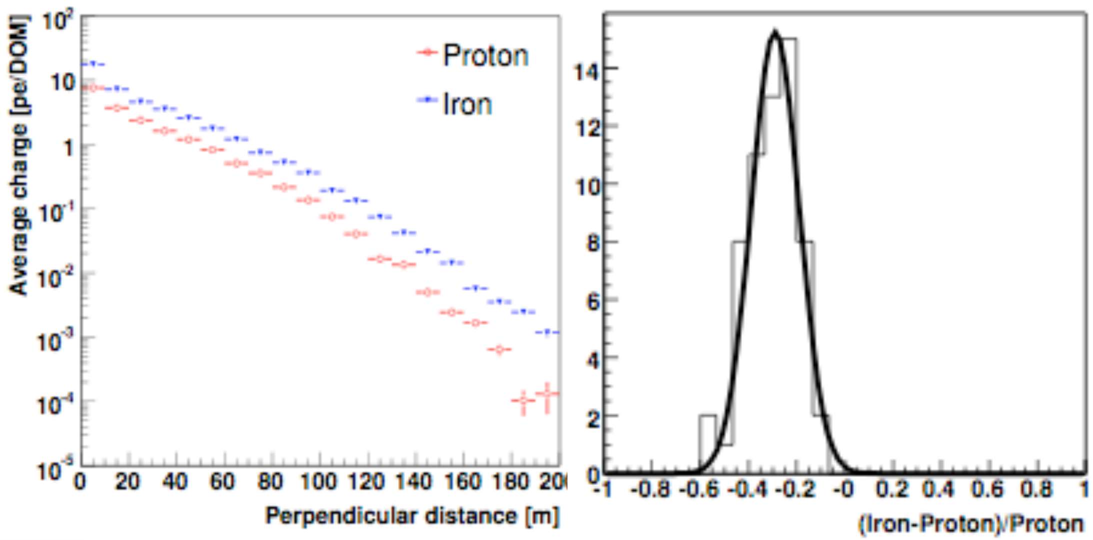
Cerenkov photons in the 2.45 m^3 tank ice :
S(100) estimated by LDF fit
With MC : S(100) ⟶ E



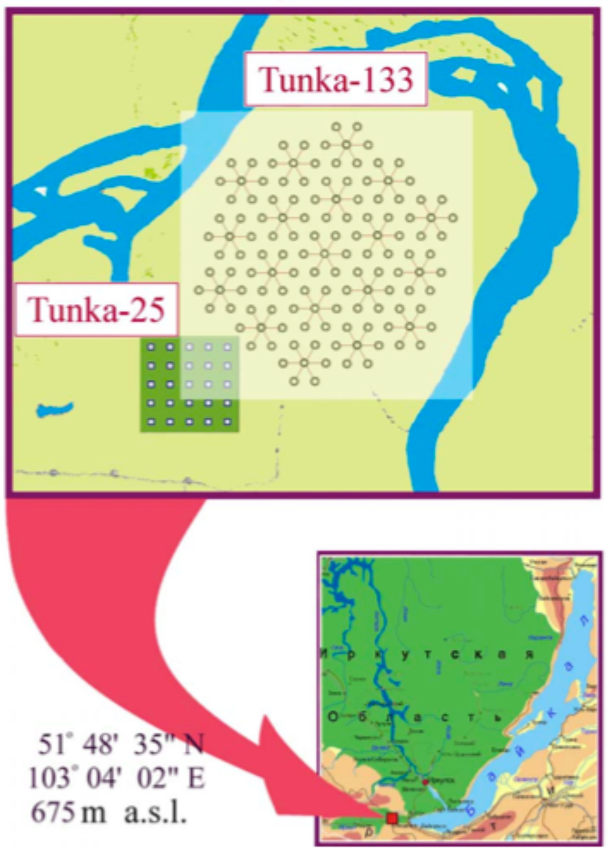
Composition study - MC

Only muons reach IceCube
Average charge/in-ice DOM

Slope of the residual times distribution



Tunka 133

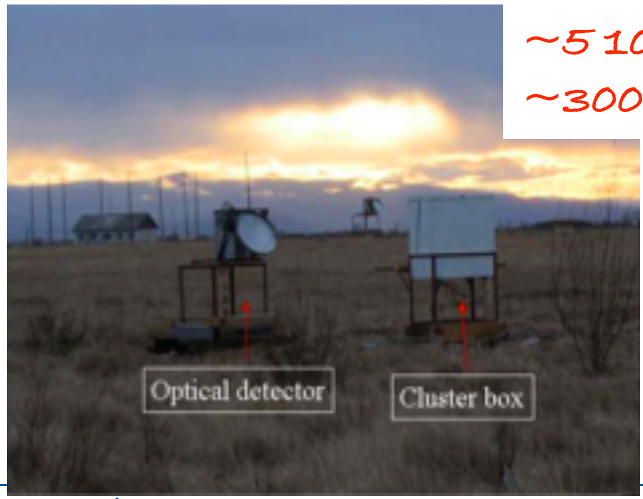


a

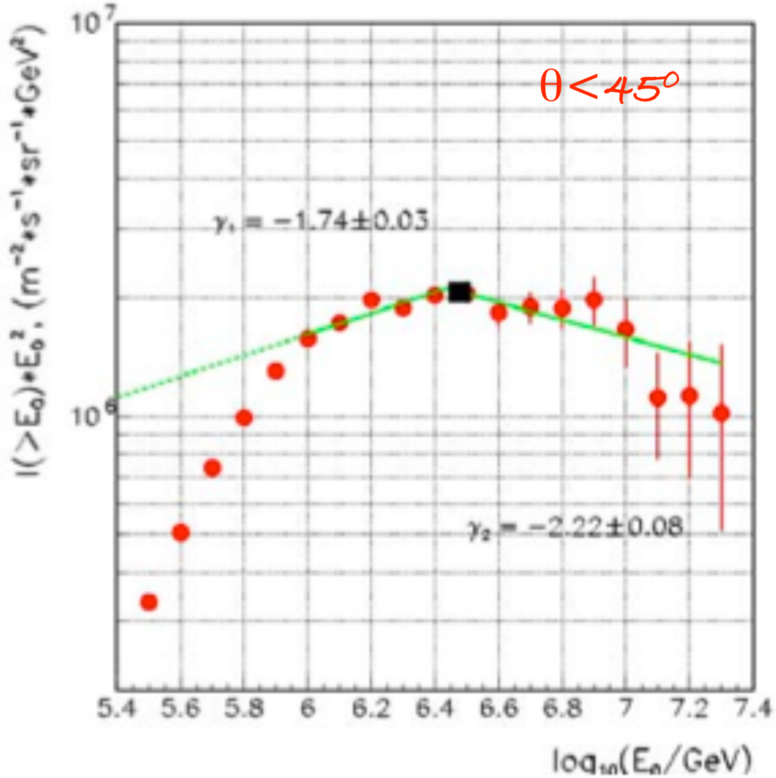
$E = 10^{15} - 10^{18}$ eV

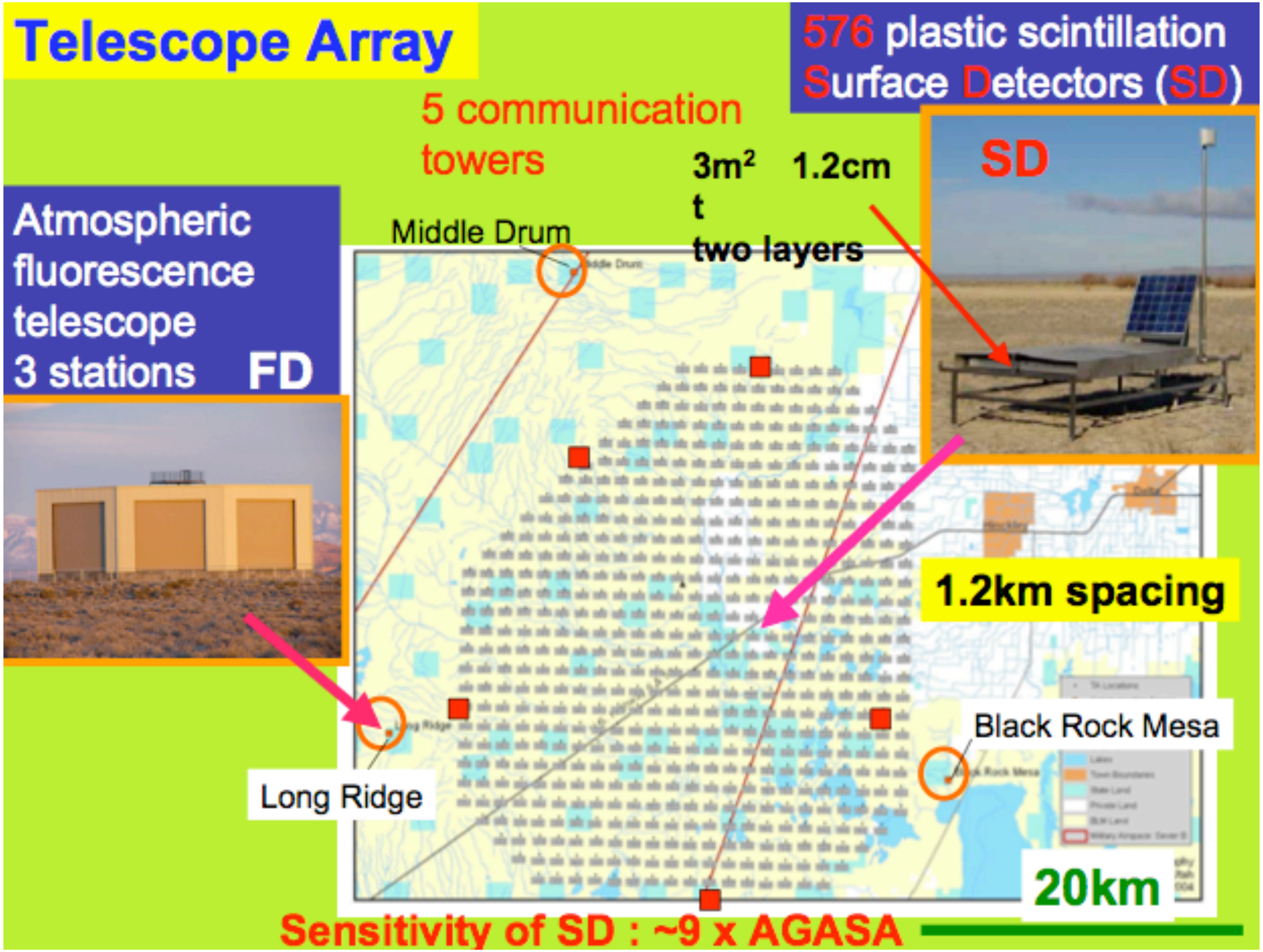
133 optical detectors with PMT in 19 clusters, 7 detectors each.Detector separation 85 m

5-6 water tanks (10 m^2, 90 cm h)



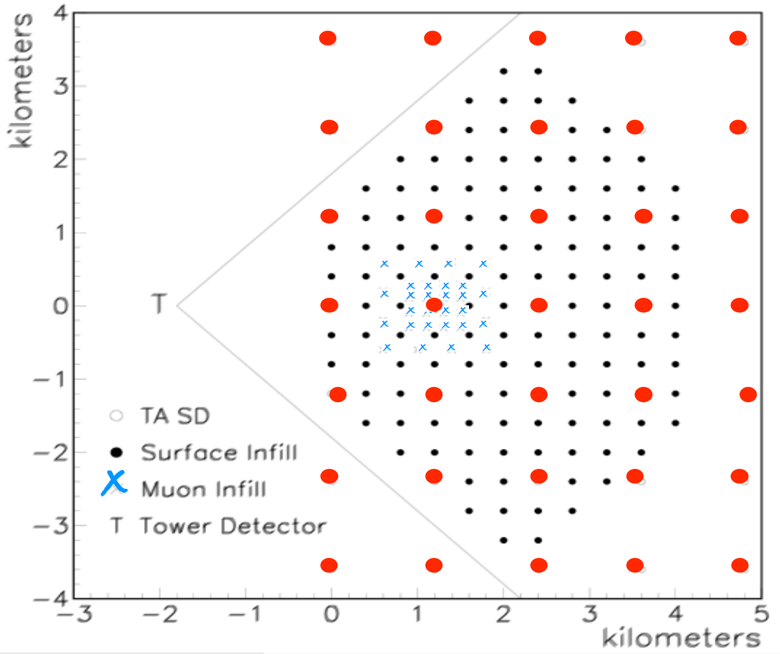
~5 10^5 ev/y > 3 10^{15} eV
~300 ev/y >10^{17} eV

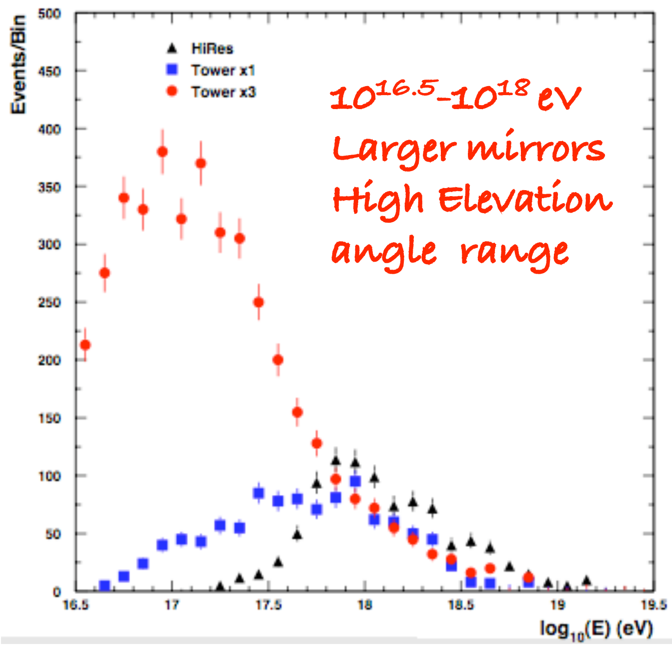



Telescope Array
576 plastic scintillation Surface Detectors (SD)
5 communication towers
3m² 1.2cm t two layers
SD
Atmospheric fluorescence telescope
3 stations FD
Middle Drum
1.2km spacing
Black Rock Mesa
Long Ridge
20km
Sensitivity of SD : ~9 x AGASA

TALE

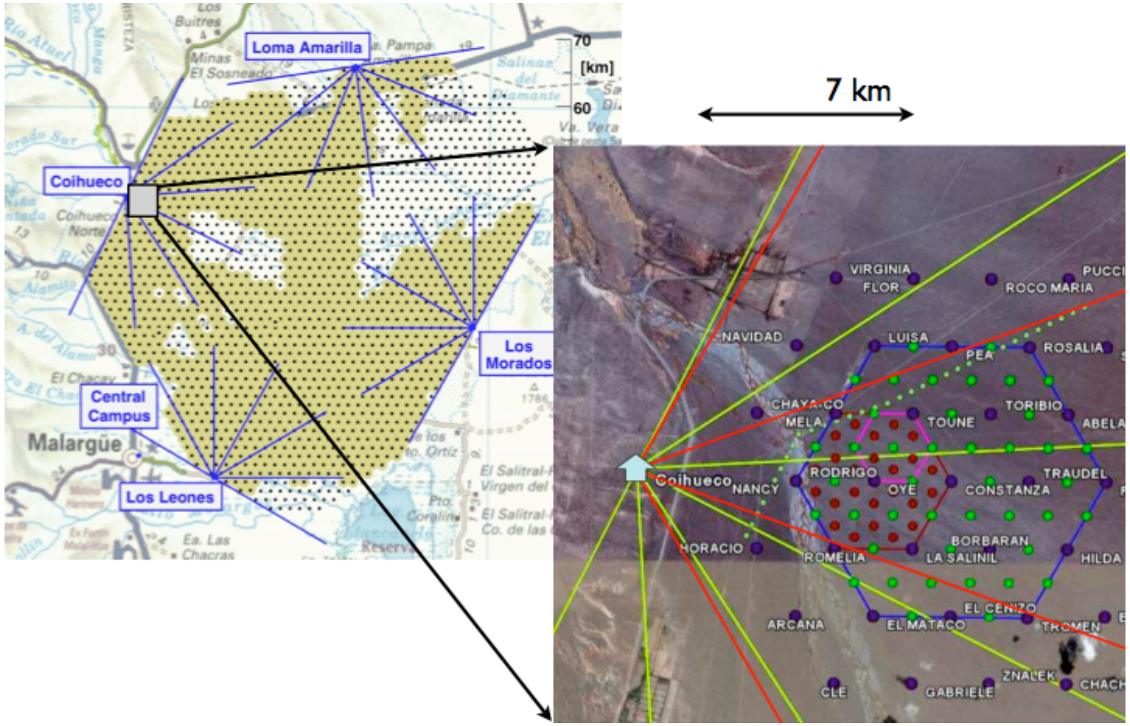
Telescope Array Low Energy extension
- 2 sets of fluorescence detectors viewing 3-31°
- 1 fluorescence detector (Tower) viewing 31-71°
- 100 surface detectors infill array (400 m spacing)
- 28 μ stations 3 km away from Tower
  (inner part 200 m spacing)





$10^{16.5}$-10^{18} eV
Larger mirrors
High Elevation angle range

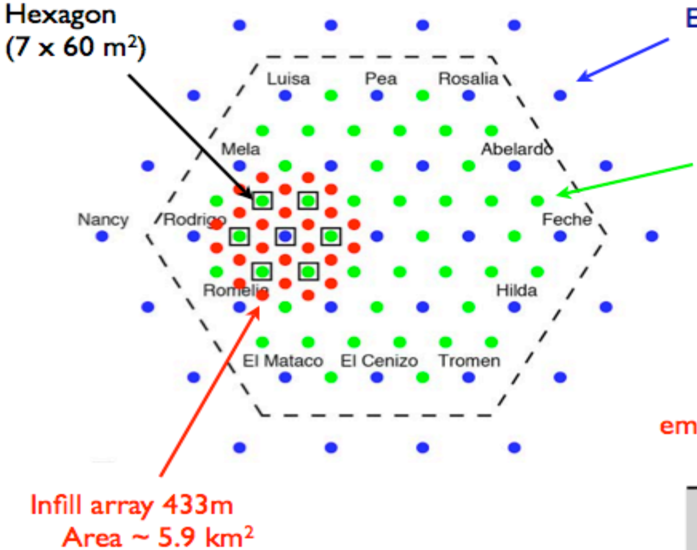
- Hybrid reconstruction of EAS down to few 10^{16} eV
- Study of primary composition $10^{16.5}$ -$10^{18.5}$ eV



Auger AMIGA infill

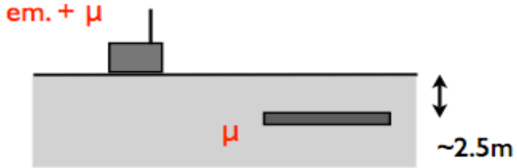
0.1-100 EeV

Prototype cluster 2008
750 m infill 2009
433 m infill ?



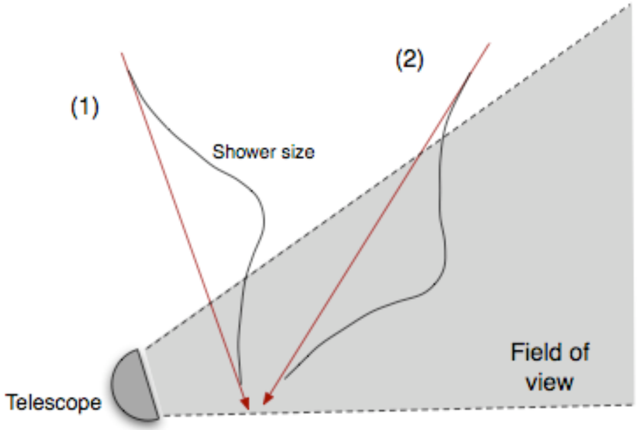
Muon detector
54 (30m²) + 7 (60m²)
Cherenkov tanks: 61
Area ~ 23 km²

E_o [EeV]	Area [km^2]	No. events year^{-1}
0.1	5.9	16000
0.3	23.5	8500

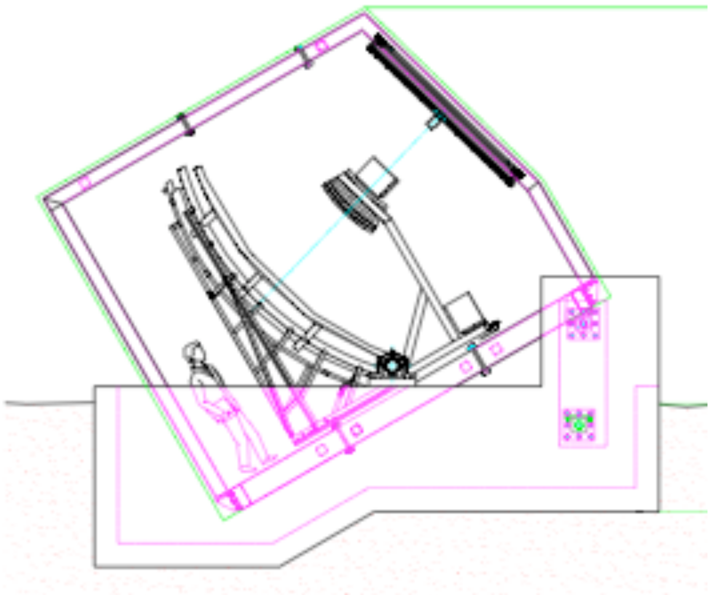


Detector pairs

Auger - HEAT



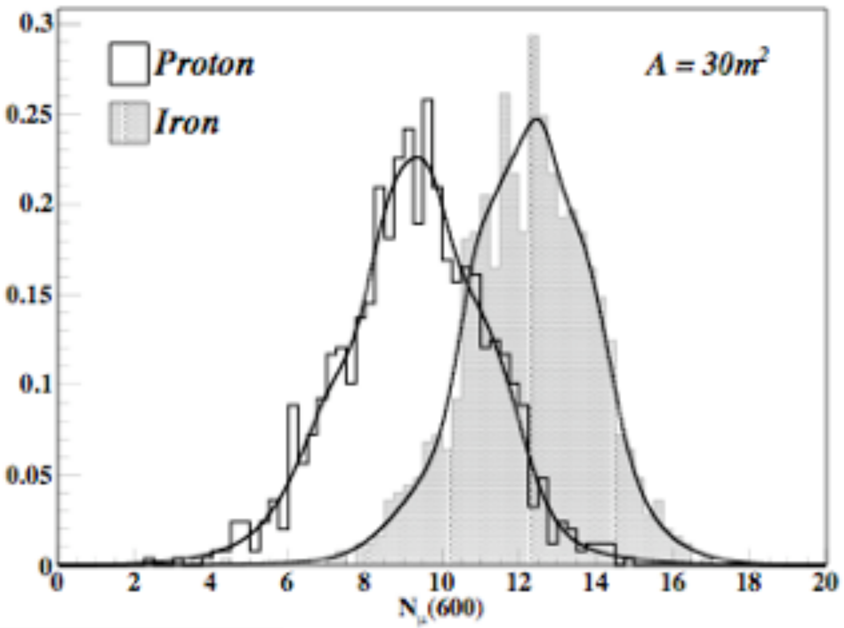
At low elevation field of view, the X_{max} of low energy EAS is seen only at large distance



3 additional fluorescence detectors with elevated field of view; 30°-60° above horizon

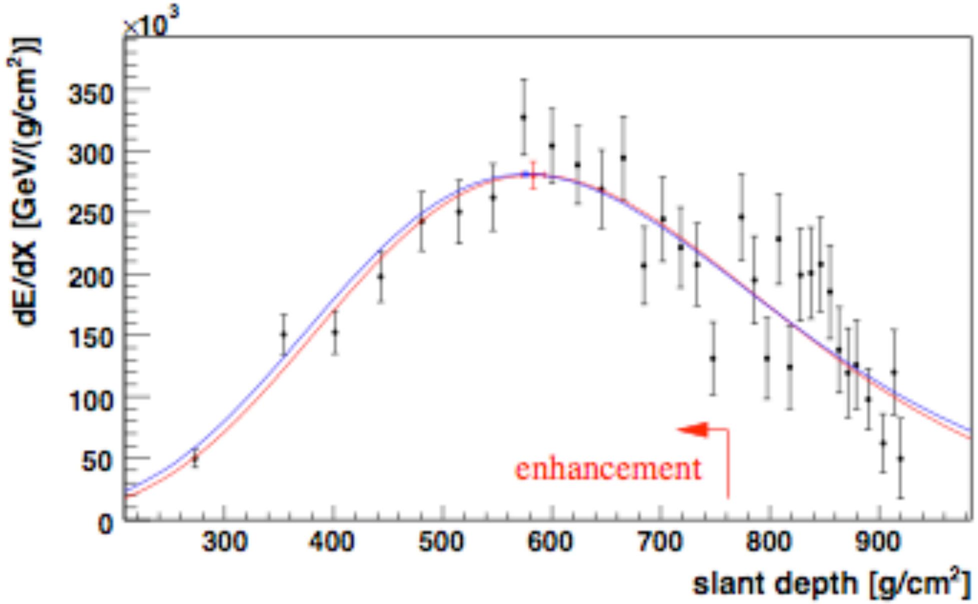
Energy range widens down to 10^{17} eV

Hybrid mode HEAT/AMIGA: ~200 events/y ~10^{18} eV



AMIGA

Simulation:
μ count rates at 10^{18} eV, 30^0
5000 events/year expected
for E>$10^{17.5}$ eV



HEAT

Simulation:
longitudinal profile of a shower

$E^{17.25}$ eV, core distance 1.2 km

Summary on the transition region

The transition region is of the utmost importance to understand the global picture of origin, acceleration and propagation of GCR +EGCRs

Different models can be distinguished using their prediction on composition, spectral shape and anisotropy

The present HiRes X_{max} results seem to confirm the proton-dominant composition expected in the frame of the dip model. Auger data are In agreement within errors.

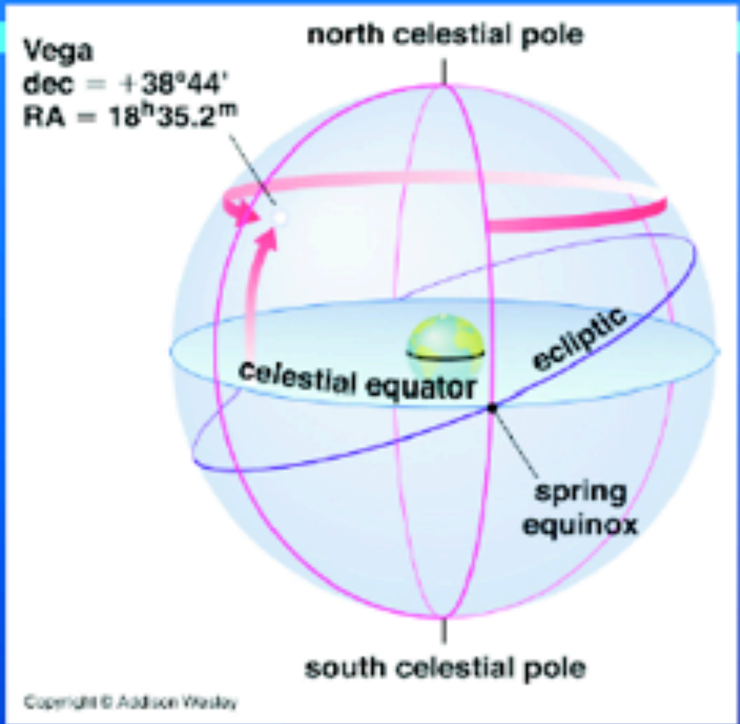
All 3 models need adjustment to match the Galactic spectrum, but some ways out can be found

Future projects, first Kascade-Grande and TALE, and in the future the Auger low energy enhancements, will give us a powerful tool to clarify the problem

THE END ?

....of course NOT !!!

Right ascension and declination



A sidereal day (time the Earth takes to rotate once wrt to the stars) lasts 23h 56'

Declination δ

$$S_D = \sin\delta_L \cos\vartheta + \cos\delta_L \sin\vartheta \sin\varphi$$

$$C_D = (1 - S^2{}_D)^{1/2}$$

$$\delta = \tan\frac{S_D}{C_D}$$

δ_l=*latitude of the array*

Right ascension r.a.

$$S_H = -\cos\varphi$$

$$C_H = -\sin\varphi\sin\delta_L + \tan\vartheta\cos\delta_L$$

$$r.a. = t_s - \tan\frac{S_H}{C_H}$$

t_s=*local sidereal time*

r.a. is measured in units of sidereal time

The Fourier analysis:

A serie of experimental data x(t) measured in the time interval T

$$x(t) = \frac{a_0}{2} + \sum_{1 \le k \le \infty} \left(a_k \cos\frac{2\pi kt}{T} + b_k \sin\frac{2\pi kt}{T} \right)$$

$$x(t) = \frac{a_0}{2} + r_i \sin\left(\frac{2\pi t}{T} + \varphi_i\right) + \ldots + r_k \sin\left(\frac{2\pi kt}{T} + \varphi_i\right) + \ldots$$

And for identical dt:

$$a_k = \frac{2}{N} \sum_{1 \le i \le N} x_i \cos\frac{2ki\pi}{N} \qquad b_k = \frac{2}{N} \sum_{1 \le i \le N} x_i \sin\frac{2ki\pi}{N}$$

$$r_k = \sqrt{a_k^2 + b_k^2} \qquad \tan\varphi_k = \frac{a_k}{b_k}$$

Amplitude and phase of the k-th harmonic

The Rayleigh formula

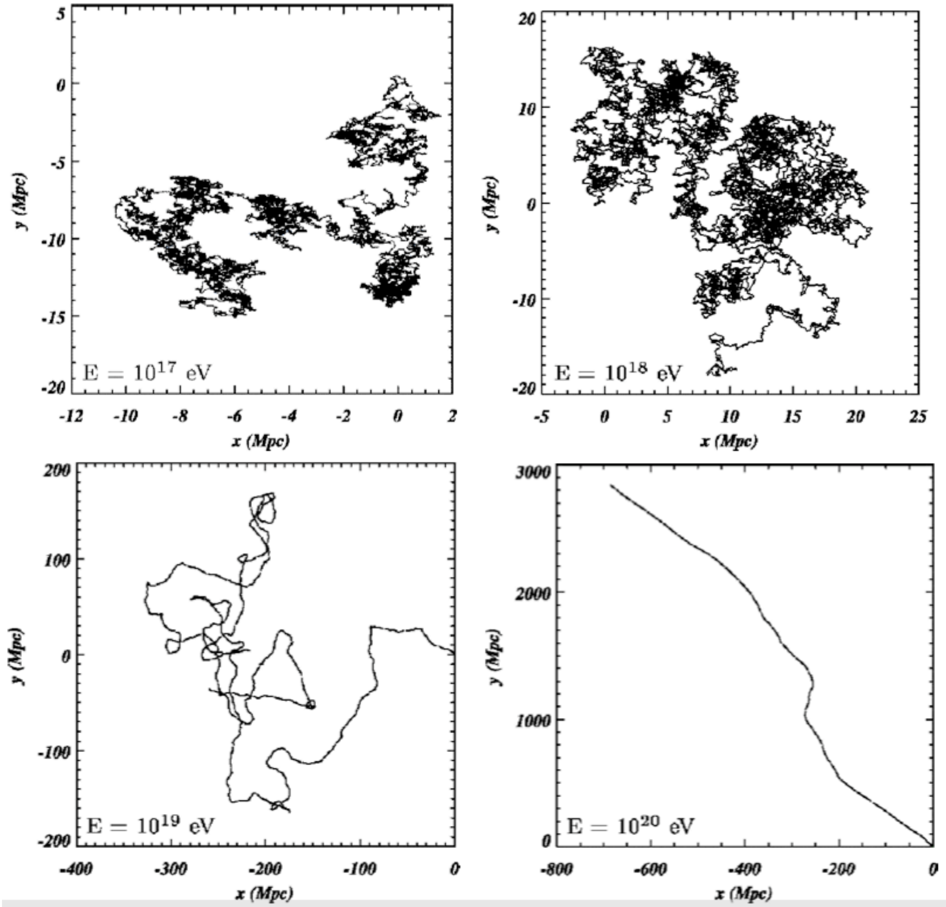
If a first harmonic amplitudine r≠0 is detected, the probability of it being the result of a fluctuation in an isotropic distribution is (for N data points)

$$P(>r) = \exp\left(\frac{-r^2 N}{4}\right)$$

with a significance

$$k = \frac{r^2 N}{4}$$

The EG magnetic field



EGMF poorly constained
Current upper limits: < few nG

Individual trajectories depend only on $r_g \sim 1.1$ Mpc E_{EeV}/ZB_{nG}

- **Ballistic regime:**
  deflections small,
  distance from source d~ct
- **Diffusive regime:**
  Isotropized particles undergo diffusive propagation, $d \sim \sqrt{Dt}$

Magnetic horizon = maximum distance CR travel away from their source in a MF

$$R_{magn}(E) \approx \sqrt{4D(E)\min(\tau_{90}, t_s)}$$

At "low" energies (10^{17}-10^{18} eV) possible suppression of the flux !