ULTRA-HIGH ENERGY COSMIC RAYS

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Outline

TODAY

Lect. 1

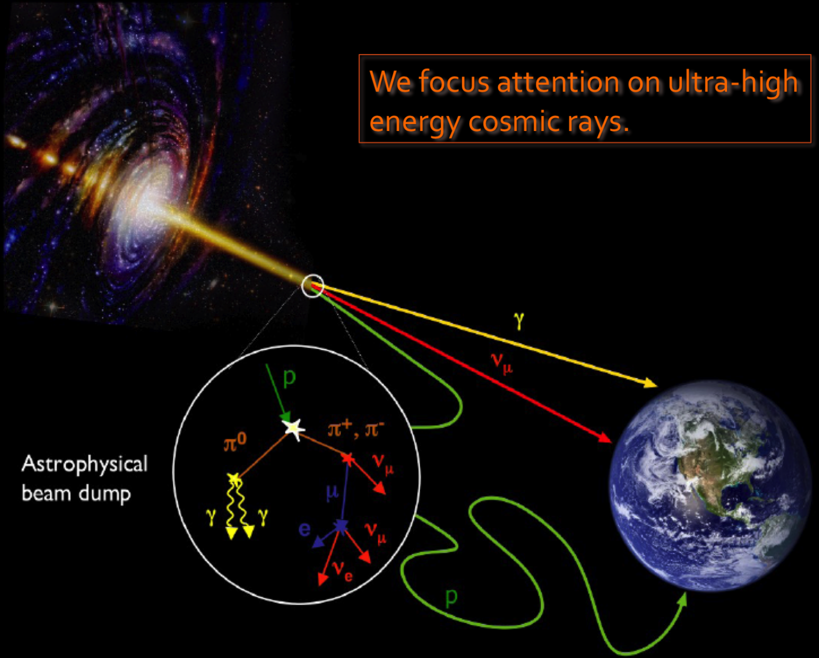
- ✓ Historical Introduction
- ✓ Acceleration mechanisms
- ✓ Propagation
- ✓ Detection Techniques: SD, FD, Hybrid
- ✓ Energy Spectrum: is there an end?

Lect. 2

- ✓ Cosmic ray astronomy?
- ✓ EAS phenomenology
- ✓ Composition of UHECR
- ✓ Neutral messengers
- ✓ Hadronic interactions in EAS

Astronomical Messengers

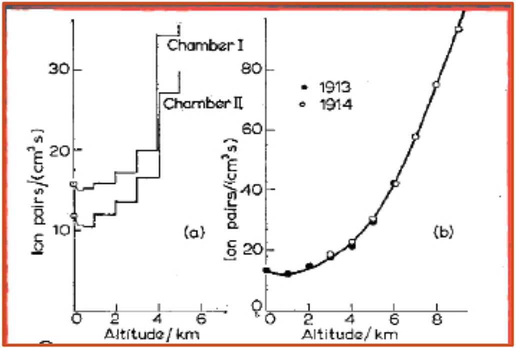
We focus attention on ultra-high energy cosmic rays.



Höhenstrahlung

- **1903 E.Rutherford and H Coke** *"30% of the ionization inside a closed vessel is due to an external radiation of great penetrating power"*
- **1910 Wulf**
- **1911 Gockel, Simpson and Wright, Pacini, Schrödinger…**
- **1912 Viktor Hess (Nobel prize 1936)**

Electroscope (circa 1787)

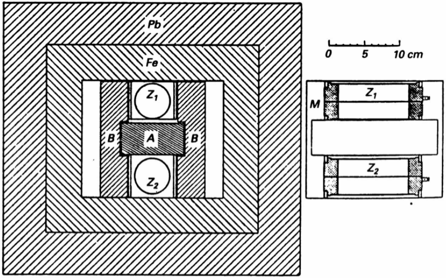


Pioneering studies

- 1927 Dimitry Skobelzyn using a cloud chamber photographed the first ghostly tracks left by cosmic rays

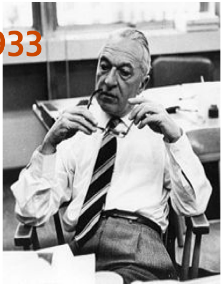
- 1929 Bothe y Kolhörster observed penetrating charged particles.

Coincidences in a pair of Geiger tubes with a thick gold layer in between.



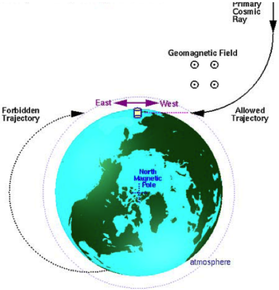
Bruno Rossi…ideas and experiments

- Main conclusions of his work in 1928-1933

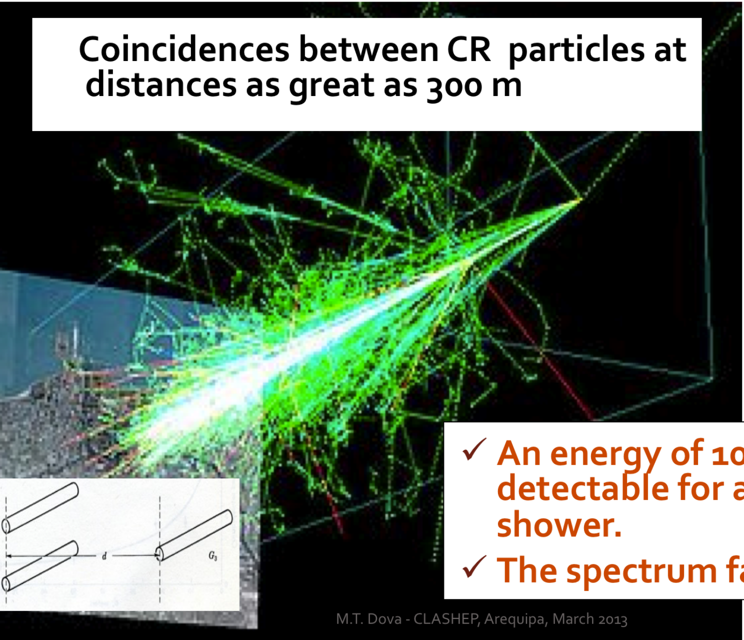


- ✓ Cosmic radiation cannot be understood of UHE gamma
- ✓ The radiation has the capability to produce secondaries of penetrating power.
- ✓ Anticipated how the magnetic field of earth was used as an analyzer of the properties of CR.

Cosmic rays predominantly charged and positive



Pierre Auger and Extensive Air Showers



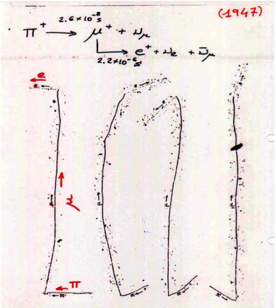
Coincidences between CR particles at distances as great as 300 m

(1938)

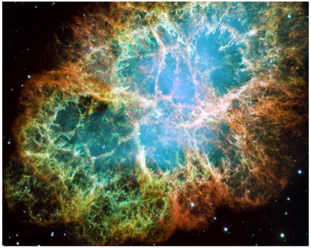
- ✓ An energy of 10^{14} eV was detectable for a single shower.
- ✓ The spectrum falls with E^{-2}

From CR to Accelerators

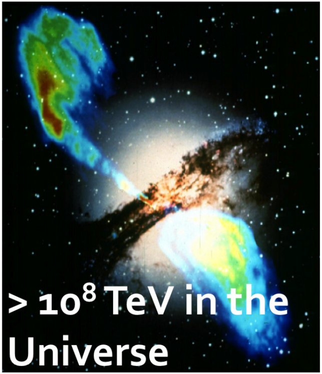
- 40´s: Boom of particle physics discoveries in CR desintegration.
- 50´s : Accelerators took over the study of particle physics **which was born in the search for the nature of CR.**



14TeV → LHC



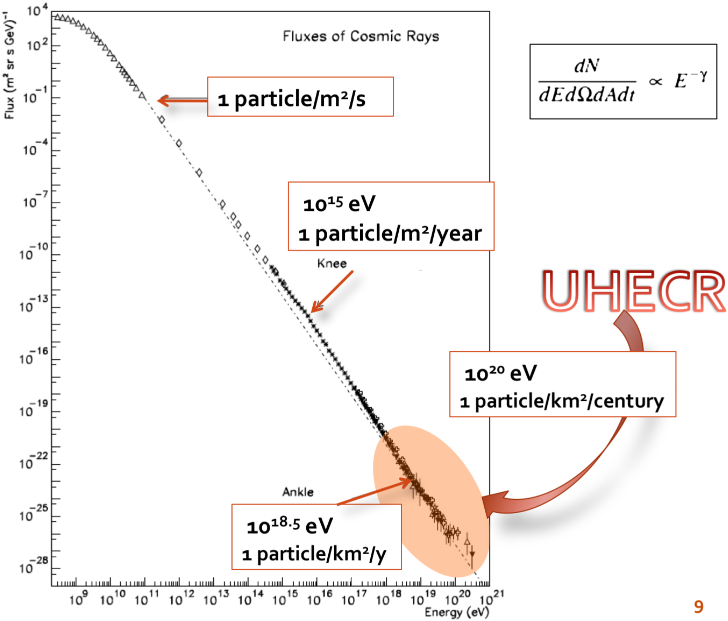
> 1000 TeV in the Galaxy



Cosmic Ray Spectrum

Simon Swordy (1954-2010)

http://astroparticle.uchicago.edu/crspec_info.txt



$$\frac{dN}{dE\,d\Omega\,dA\,dt} \propto E^{-\gamma}$$

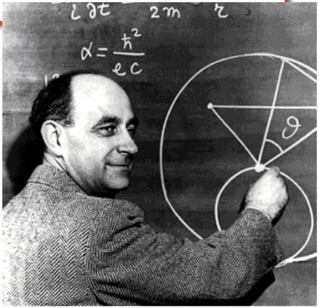
HYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 1[illegible], 1949

On the Origin of the Cosmic Radiation

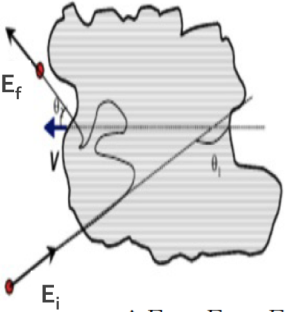
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

... yields naturally an inverse power law for the spectral distribution...



Fermi acceleration



In the rest frame of the moving cloud, the CR has energy:

$$E'_i = \Gamma_{\text{cloud}}\ E_i\ (1 - \beta_{\text{cloud}}\ cos\theta_i)$$

$E_i{}' = E_f{}'$

Transforming to laboratory frame:

$$E_f = \Gamma_{\text{cloud}}\ E'_f\ (1 + \beta_{\text{cloud}}\ cos\theta'_f)$$

Fractional energy change in lab frame:

$$\frac{\Delta E}{E} = \frac{E_f - E_i}{E_i} = \frac{1 - \beta_{\text{cloud}}\, cos\theta_i\ + \beta_{\text{cloud}}\, cos'\theta_f\ - \ \beta^2_{\text{cloud}}\, cos\theta_i\, cos'\theta_f}{1 - \beta^2_{\text{cloud}}}$$

Inside the cloud CR direction becomes randomized: $< cos\theta'_f >= 0$

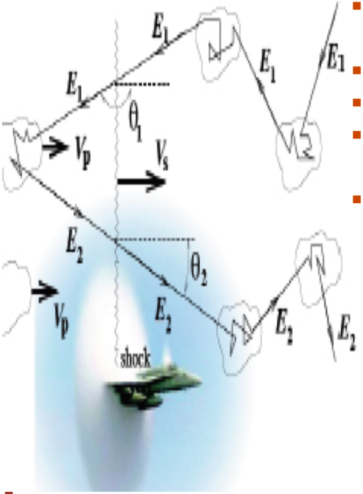
Probability of having a collision a θ_i : $\frac{dP}{d\Omega_i} \propto (1 - \beta_{\text{cloud}}\ cos\theta_i)$ → $< cos\theta_i >= -\beta_{\text{cloud}}/3$

Fractional energy $\frac{\Delta E}{E} = \frac{1 + \beta^2_{\text{cloud}}/3}{1 - \beta^2_{\text{cloud}}} 1 \approx \frac{4}{3}\beta^2_{\text{cloud}}$

$\beta_{cl} << 1$

- Energy gain
- Low efficiency

Shock wave acceleration



- During a SN explosion, material can move at ≈ 10^4 km/s
- much faster than speed of sound in ISM (10 km/s)
- a strong shock wave propagates radially out
- magnetic irregularities "pile up" in front of the shock
- particles can move back and forth across the shock and pick up more and more energy.

Fractional energy change in lab frame:

$$\frac{\langle \Delta E \rangle}{E} \simeq \frac{4}{3}\beta \simeq \frac{4}{3}\frac{V_P}{c} \simeq \frac{4}{3}\frac{(R-1)}{R}\frac{V_S}{c}$$

Compression factor→R = $\frac{v_1}{v_2} = \frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2}$

$\gamma = C_p/C_v = 5/3$

✓ First order in β → more efficient!

✓ lots of theoretical approaches in the last decade.

Prediction of a power-law flux!

$$\frac{\Delta E}{E} \equiv \xi \quad \text{independent of energy} \; (\xi \simeq 4/3\, \beta_{cl}^2 \; \text{or} \; \beta_{cl} \;)$$

After n cycles (encounters)

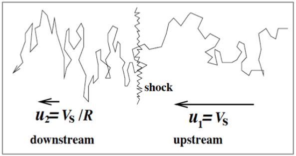
$$E_n = E_0 (1+\xi)^n \qquad n = \ln\left(\frac{E_n}{E_0}\right) / \ln(1+\xi)$$

P_{esc} probability of escape *in each cycle*

Number of particles that reach $E > E_n$:

$$N(>E_n) = N_0 \sum_n^{\infty} (1-P_{esc})^m \propto A \left(\frac{E_n}{E_0}\right)^{-\gamma}$$

In the shock frame of Vs

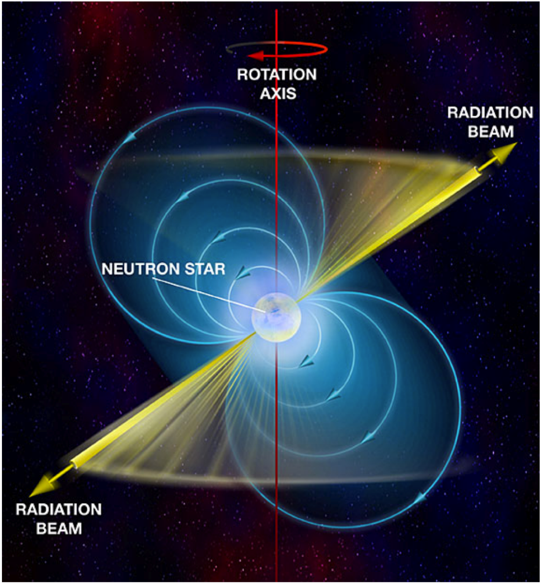


Shock Acceleration $\qquad P_{esc} = \frac{\rho_{CR} u_2}{c \rho_{CR}/4} = \frac{4 u_2}{c}$

$$\gamma = \frac{P_{esc}}{\xi} = \frac{3}{u_1/u_2 - 1} \sim 1 + O(M^{-2})$$

$$dN/dE \sim E^{-(2 + O(1/M^2))}$$

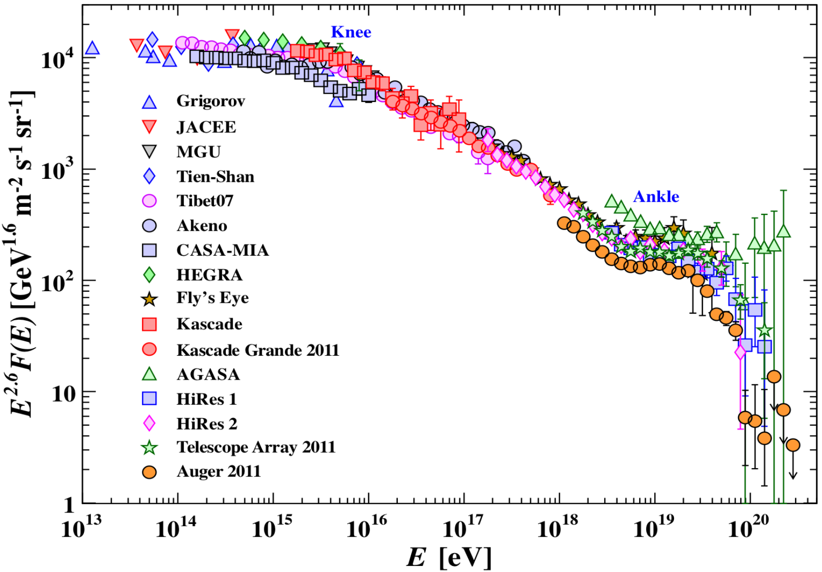
Unipolar inductors



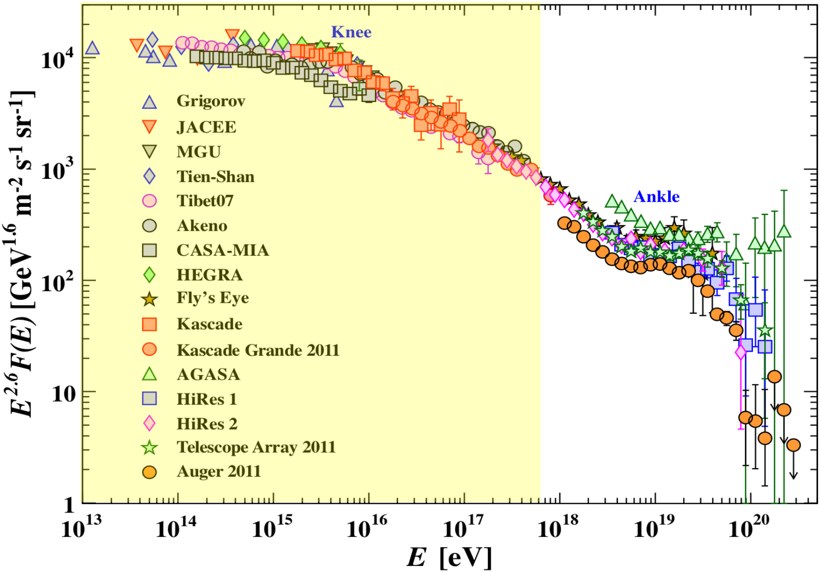
$$\vec{E} = \vec{V} \times \vec{B}$$

Very flat spectra

Cosmic Ray Spectrum (from PDG)



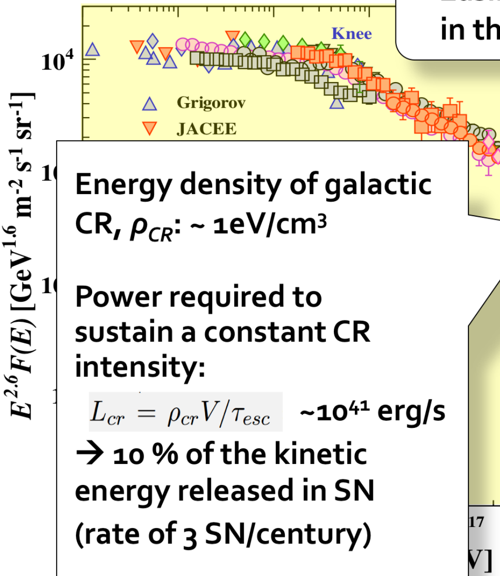
Galactic

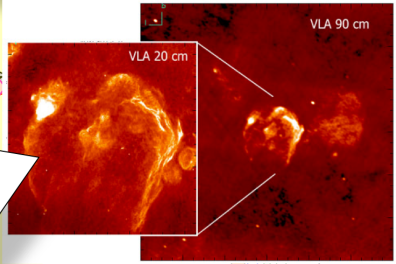


Knee
Ankle
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande 2011
AGASA
HiRes 1
HiRes 2
Telescope Array 2011
Auger 2011
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
10^4
10^3
10^2
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
E [eV]

"SM" of Galactic CR

✓Easily created and contained in the Galaxy.





Energy density of galactic CR, ρ_{CR}: ~ 1eV/cm^3

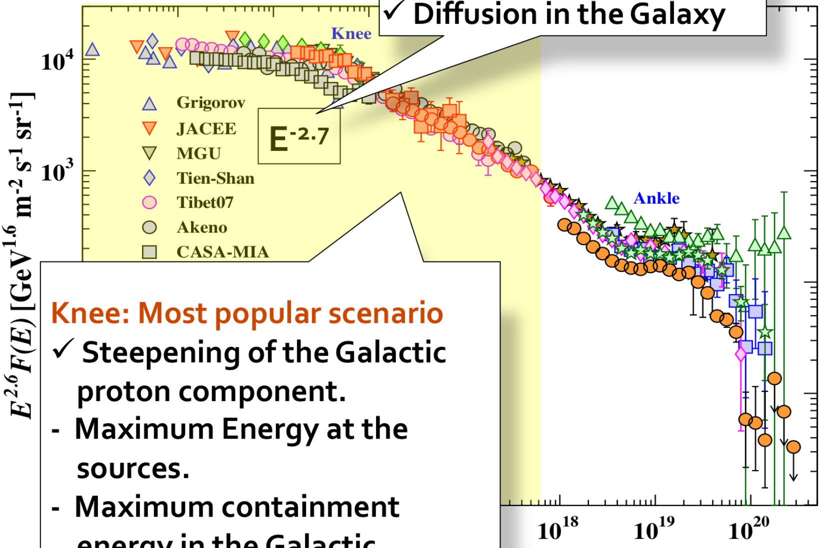
Power required to sustain a constant CR intensity:

$$L_{cr} = \rho_{cr} V / \tau_{esc}$$ ~10^{41} erg/s

→ 10 % of the kinetic energy released in SN (rate of 3 SN/century)

"SM" of Galactic CR

✓ Fermi acceleration
✓ Diffusion in the Galaxy



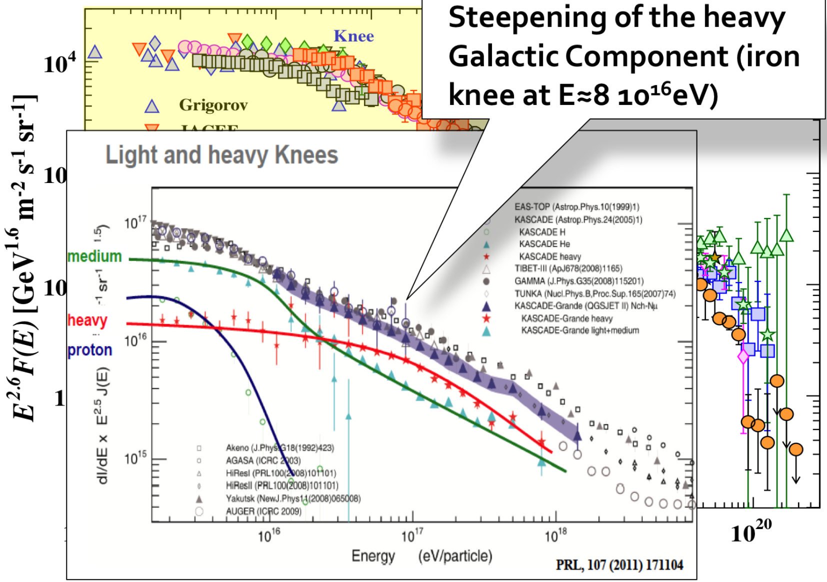
Knee: Most popular scenario

✓ Steepening of the Galactic proton component.

- Maximum Energy at the sources.
- Maximum containment energy in the Galactic Magnetic Field

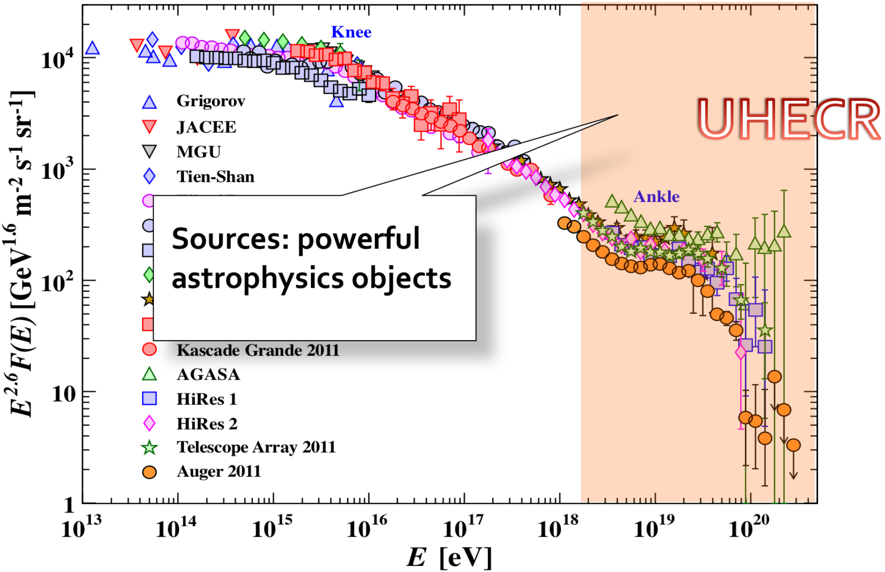
"SM" of Galactic CR

Steepening of the heavy Galactic Component (iron knee at E≈8 10^{16}eV)



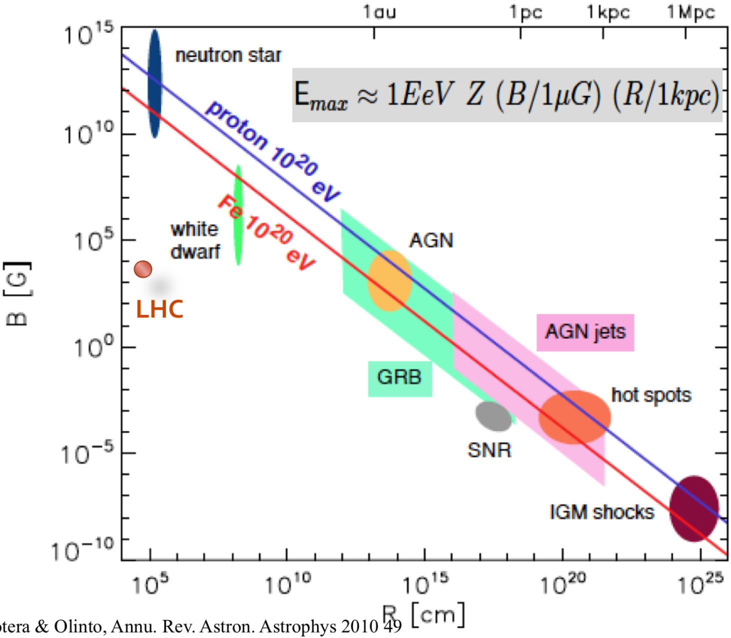
KASCADE-Grande Coll. PRL 107, 171104(2011)

Extragalactic



Hillas criterium

Hillas, Ann. Rev. Astron. Astrophys. 22,425 (1984)



Kotera & Olinto, Annu. Rev. Astron. Astrophys 2010 49

Checklist for the sources of UHECR

- ✓ Extragalactic origin
- ✓ Acceleration to ultra-high energies
- ✓ Luminosity density (emissivity)
- ✓ UHECR survival during acceleration, escape and transport

Flux → $\frac{dN}{dE}$

Total flux = velocity X density

Density → $\rho = \frac{4\pi}{c}\int \frac{dN}{dE}dE$

Energy density → $\rho_E = \frac{4\pi}{c}\int E\frac{dN}{dE}dE$

Emissivity required to power UHECRs

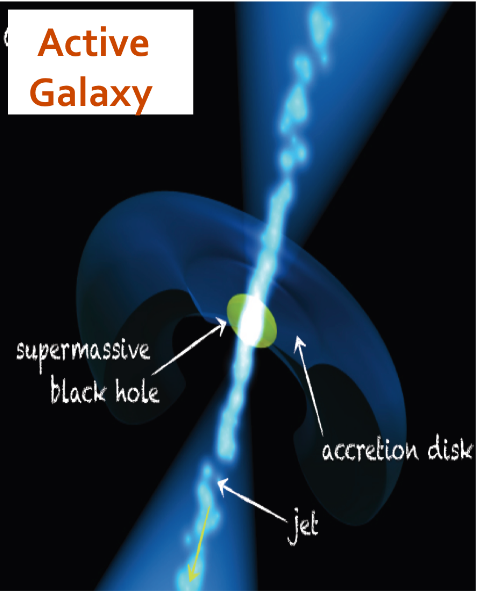
Energy density

$$\mathcal{E} = u_{uhecr}/t_{tot}$$

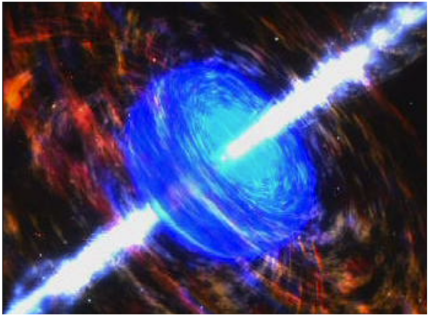
energy-loss mean time

For p → **@10^{20} eV → 0.4 10^{44} erg Mpc^{-3} y^{-1}**

C. Dermer, arXiv:0711.2804v2)

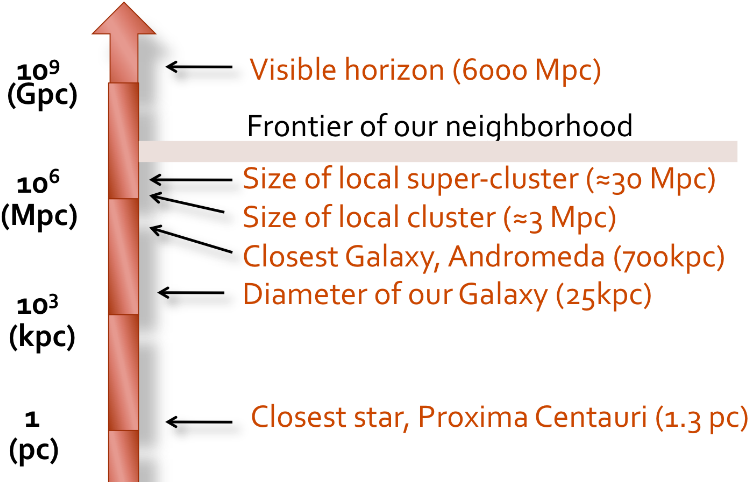


Collapse of massive stars produces a GRBs



The IceCube collaboration search for neutrinos emitted from 300 gamma ray bursts observed between May 2008 and April 2010.
They found none!

Some distance scales



1 parsec (pc) = 3.26 light-years
= 3×10^{13} km

1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New Yo

(Received 1 April 1966)

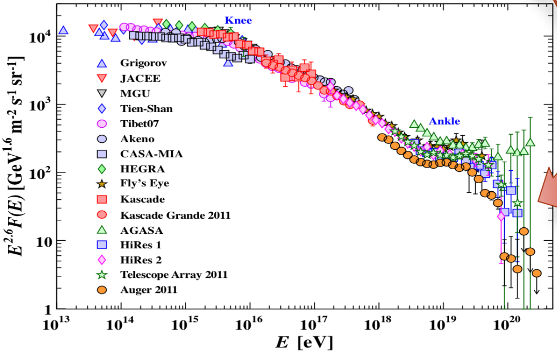
The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum ...

This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

... of the catastrophic cutoff ... intense isotropic radiation first detected by

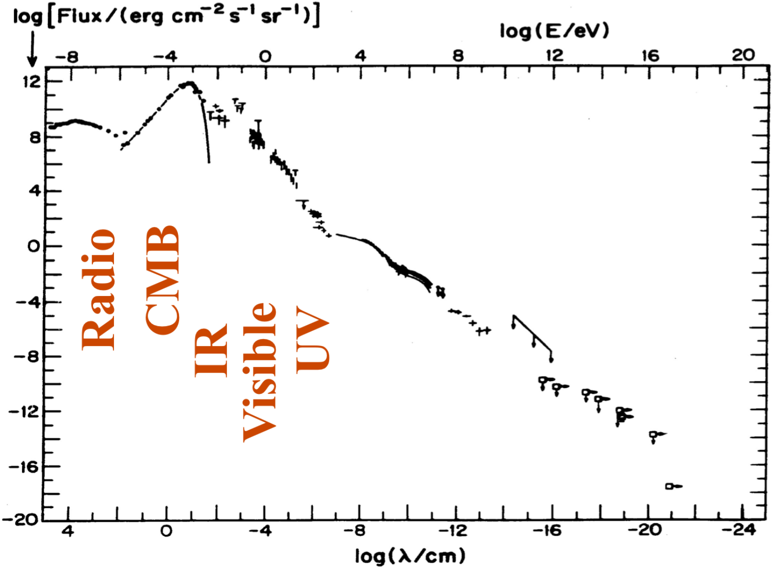
Penzias and ... and now co... measureme... cm wavelen... ent argume... conform ex... el outlined ... kinson[5]; wh... tion exists ... verse. The transparency of space at the pertinent wavelengths, and the consistency of intensity observations in numerous directions,

Opacity of the CMB to the propagation of UHECR



"Cosmologically meaningful termination"
→GZK?

"Background light"



Opacity of the CMB to protons

The fractional energy loss due to interactions with radiation fields

$$-\frac{1}{E}\frac{dE}{dt} = \frac{c}{2\Gamma^2}\sum_j \int_0^{\omega_m} d\omega_r \; y_j \; \sigma_j(\omega_r) \; \omega_r \int_{\omega_r/2\Gamma}^{\omega_m} d\omega \, \frac{n_\gamma(\omega)}{\omega^2}$$

Collisions with optical and infrared photons negligible

→ 2.7 K blackbody background radiation

$$-\frac{1}{E}\frac{dE}{dt} = -\frac{ckT}{2\pi^2\Gamma^2(c\hbar)^3}\sum_j \int_{\omega_{0_j}}^{\infty} d\omega_r \, \sigma_j(\omega_r) \, y_j \, \omega_r \, \ln(1 - e^{-\omega_r/2\Gamma kT})$$

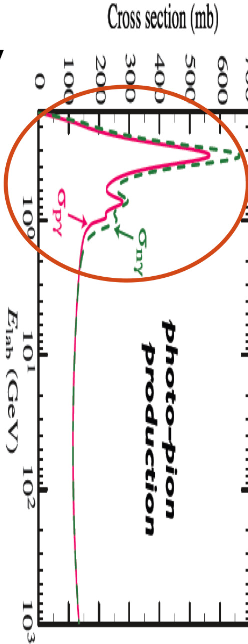
Pair Production $p\,\gamma \longrightarrow p\,e^+\,e^-$

E≤ 2. 10[18] eV

$$\sigma_{\rm BH}(\omega_r) = \frac{\pi}{12}\alpha\, r_0^2 \left(\frac{\omega_r}{m_e} - 2\right)^3 \qquad y_{\rm BH} = 2\,\frac{m_e}{m_p}$$

$$-\frac{1}{E}\left(\frac{dE}{dt}\right)_{\rm BH} = \frac{16c}{\pi}\frac{m_e}{m_p}\alpha\, r_0^2 \left(\frac{kT}{hc}\right)^3 \left(\frac{\Gamma kT}{m_e}\right)^2 \exp\left(-\frac{m_e}{\Gamma kT}\right)$$

Photopion production $p\gamma \longrightarrow N + n\pi$



- **Resonant region: $10^{10} \leq E \leq 10^{12}$ GeV**

$\sigma_\pi(\omega) \sim \Sigma$ B-W distributions

$$y_\pi(m_{R_0}) = 1 - \frac{1}{2^n}\prod_{i=1}^{n}\left(1 + \frac{m_{R_i}^2 - m_M^2}{m_{R_{i-1}}^2}\right)$$

$$-\frac{1}{E}\left(\frac{dE}{dt}\right)_\pi = A\exp[-B/E]$$

$A = (3.66 \pm 0.08) \times 10^{-8}\,\mathrm{yr}^{-1}$

$B = (2.87 \pm 0.03) \times 10^{11}\,\mathrm{GeV}$

- **High energy plateau $E > 10^{12}$ GeV**

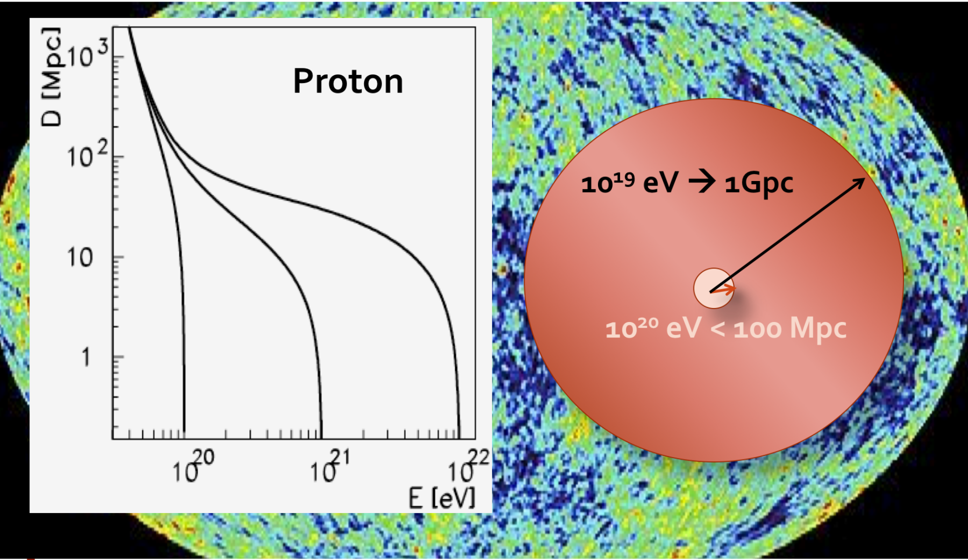
$$\sigma_\pi(\omega_r) = A + B\ \ln^2\left(\frac{\omega_r}{\mathrm{GeV}}\right) + C\ \ln\left(\frac{\omega_r}{\mathrm{GeV}}\right)\ \mathrm{mb}$$

$$y_\pi \sim 1/2$$

$$-\frac{1}{E}\left(\frac{dE}{dt}\right)_\pi = C = (2.42 \pm 0.03) \times 10^{-8}\ \mathrm{yr}^{-1}$$

Anchordoqui, MTD, Epele, Swain, Phys. Rev. D 55 (1998) 7103.

What is the CMB/GZK *wall* at ≈ 10^{20} eV?



Constraint on the proximity of UHECR (>5.10^{19} eV) sources

Evolution of the spectrum

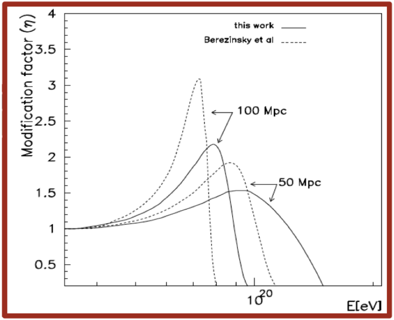
$$\frac{\partial N}{\partial t} = \frac{\partial (b(E)N)}{\partial E} + D\,\nabla^2 N + Q$$

$$Q(E) \; = \; \kappa\, E^{-\gamma}$$

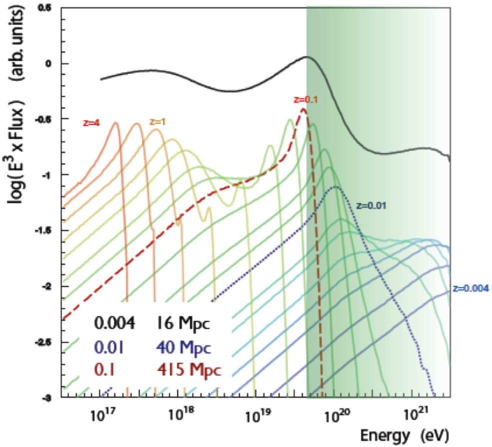
b(E): mean rate at which particles lose energy

$$\eta = \frac{\text{modified spectrum}}{\text{unmodified spectrum}}$$

Anchordoqui, MTD, Epele, Swain, Phys. Rev. D 55 (1997) 73-56



...but the GZK is a complex feature!



(Bergmann et al., PLB 2006)

Opacity of the CMB to nuclei

- **Photodesintegration rate**

$$A\,\gamma \to (A-1)\,n$$
$$A\,\gamma \to (A-2)\,(pn)$$

$$R_{Ai} = \frac{1}{2\Gamma^2}\int_0^\infty dw\,\frac{n(w)}{w^2}\int_0^{2\Gamma w} dw_r\, w_r \sigma_{Ai}(w_r)$$

- **Parameterization → Fit to photoabsortion σ**

$$R(\Gamma)\big|_{\rm Fe} \approx \begin{cases} 3.25\times10^{-6}\,\Gamma^{-0.643}\exp(-2.15\times10^{10}/\Gamma)\ {\rm s}^{-1} & \Gamma\in[1.0\times10^{9},\ 3.68\times10^{10}] \\ 1.59\times10^{-12}\,\Gamma^{-0.0698}\ {\rm s}^{-1} & \Gamma\in[3.68\times10^{10},\ 1.0\times10^{11}] \end{cases}$$

Negligible for $\Gamma > 10^{10}$

- **Fractional Energy Loss**

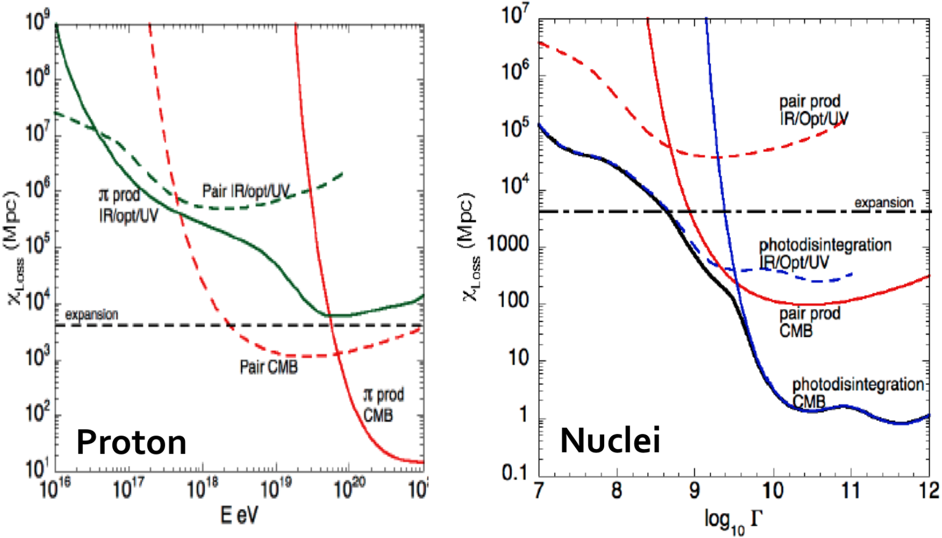
$$-\frac{1}{E}\frac{dE}{dt} = \frac{1}{\Gamma}\frac{d\Gamma}{dt} + \frac{R}{A}$$

$$\left.\frac{dA}{dt}\right|_A \sim \left.\frac{dA}{dt}\right|_{\rm Fe}\left(\frac{A}{56}\right) = R\big|_{\rm Fe}\left(\frac{A}{56}\right)$$

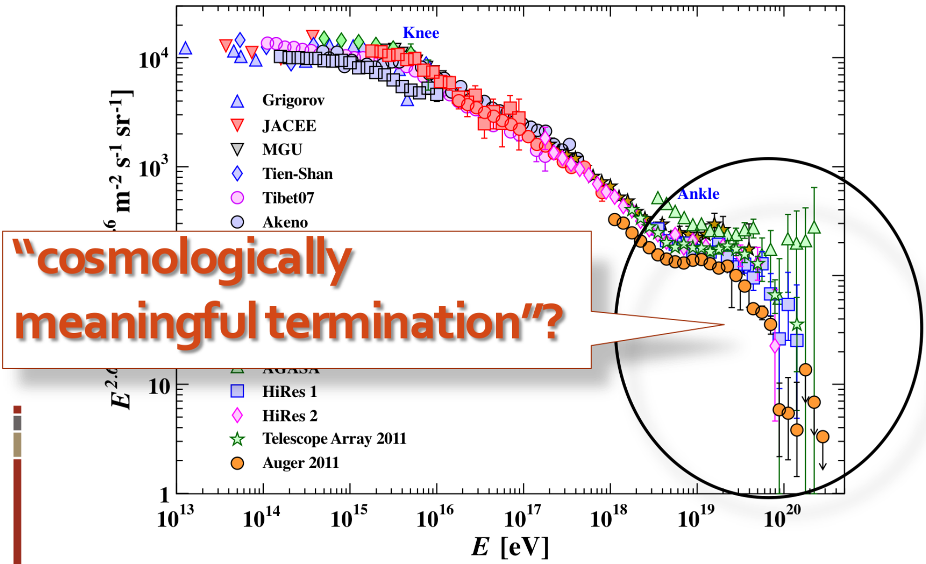
$$E(t) \sim 938\ A(t)\ \Gamma\ {\rm MeV} \sim E_0\, e^{-R(\Gamma)|_{\rm Fe}\, t/56}$$

Anchordoqui, MTD, Epele, Swain, Phys. Rev. D 55 (1998) 7103.

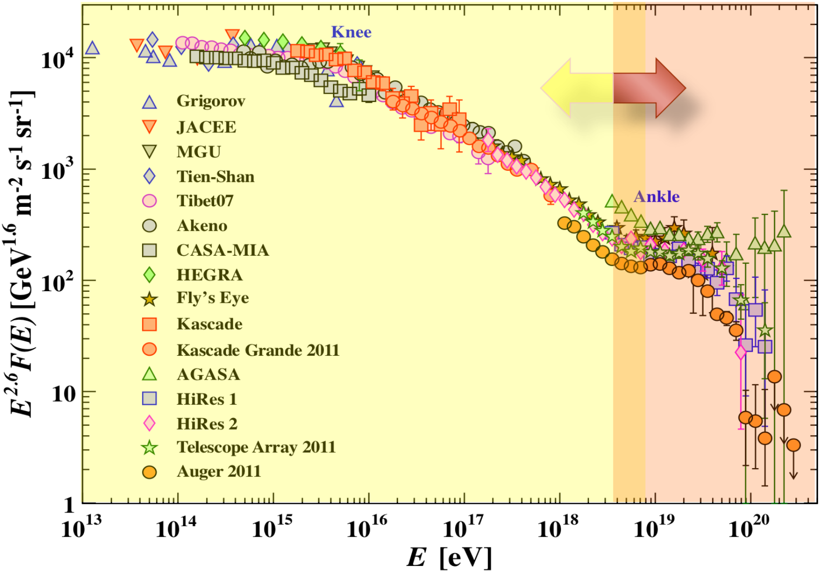
How far UHECRs can travel through space



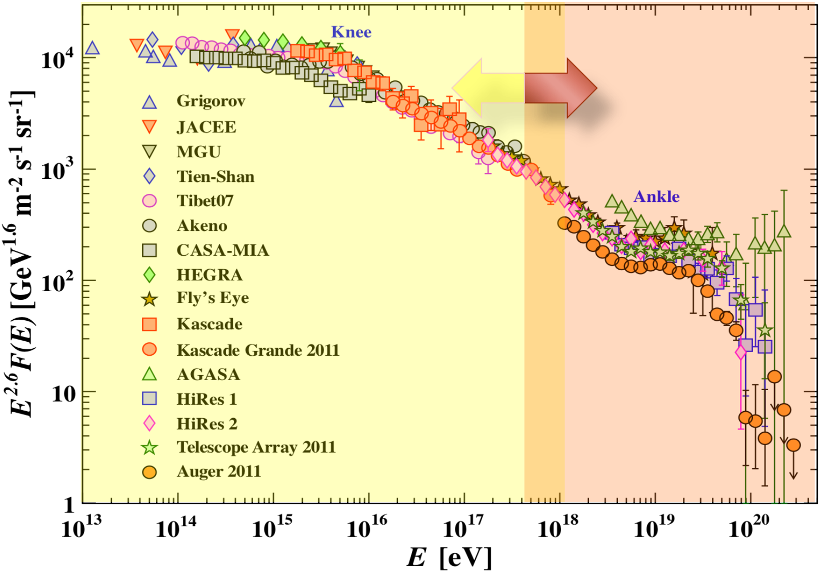
D. Allard, 2011


Knee
Ankle
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
HiRes 1
HiRes 2
Telescope Array 2011
Auger 2011
E [eV]
"cosmologically meaningful termination"?

Galactic to Extragalactic transition

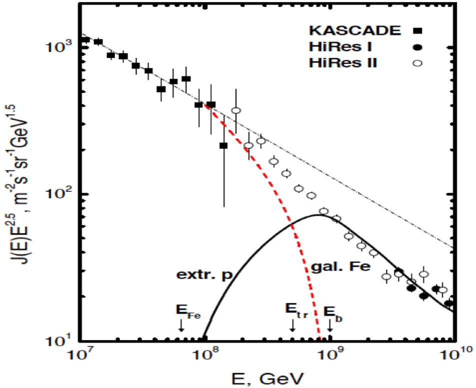


Galactic to Extragalactic transition



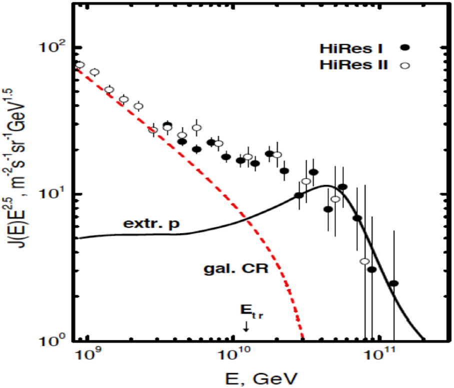
Models for the ankle & transition G→EG

Dip Model: V.Berezinsky, Phys.Rev.D74 (2006) 043005



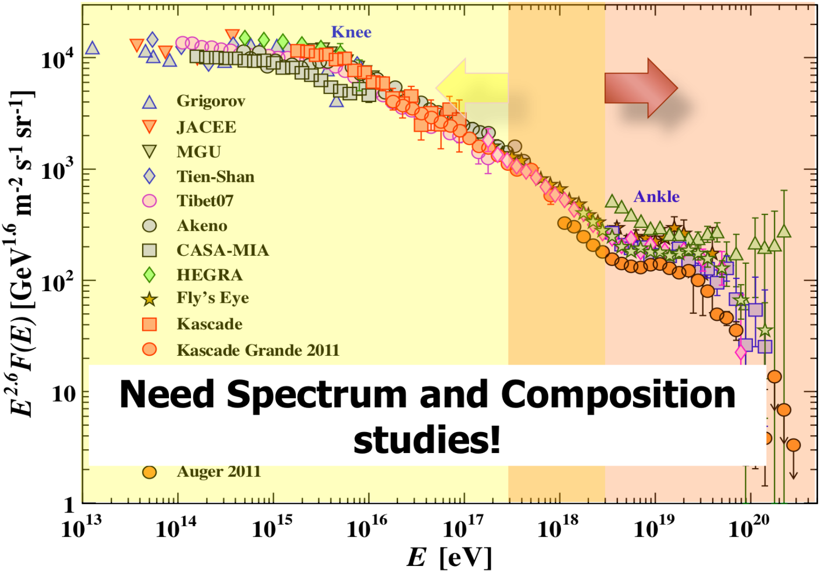
- Almost pure proton composition
- Pair production Dip
- Transition @ (5 – 7) 10^{17} eV

Ankle Models: Waxman 1999, Wibig and Wolfendale 2005, Hillas 2005, 2006



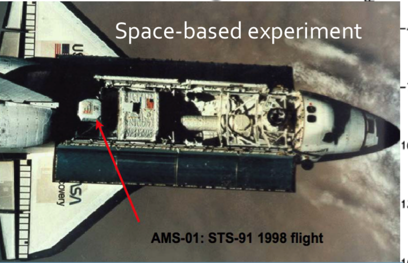
- Transition @ 0.3-1. 10^{19} eV
- Additional mechanisms to fill the gap between the iron knee and the onset of the EG component.

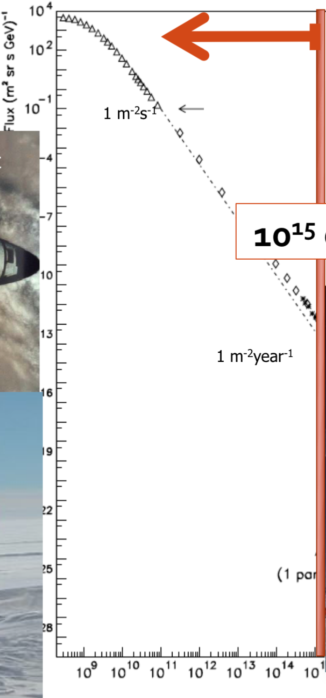
Galactic to Extragalactic transition



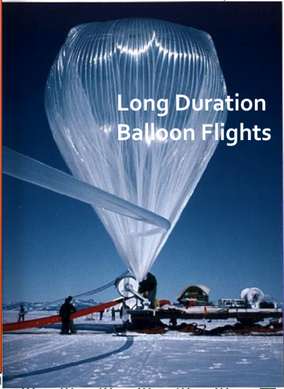
Need Spectrum and Composition studies!

Experimental Techniques

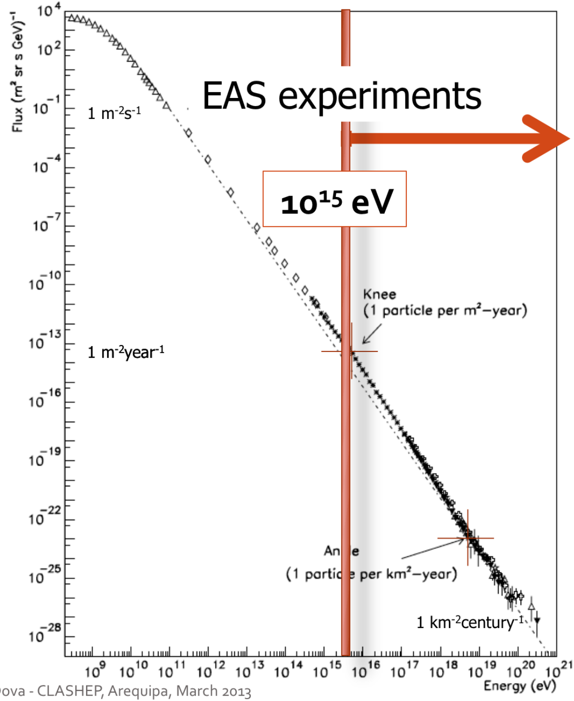


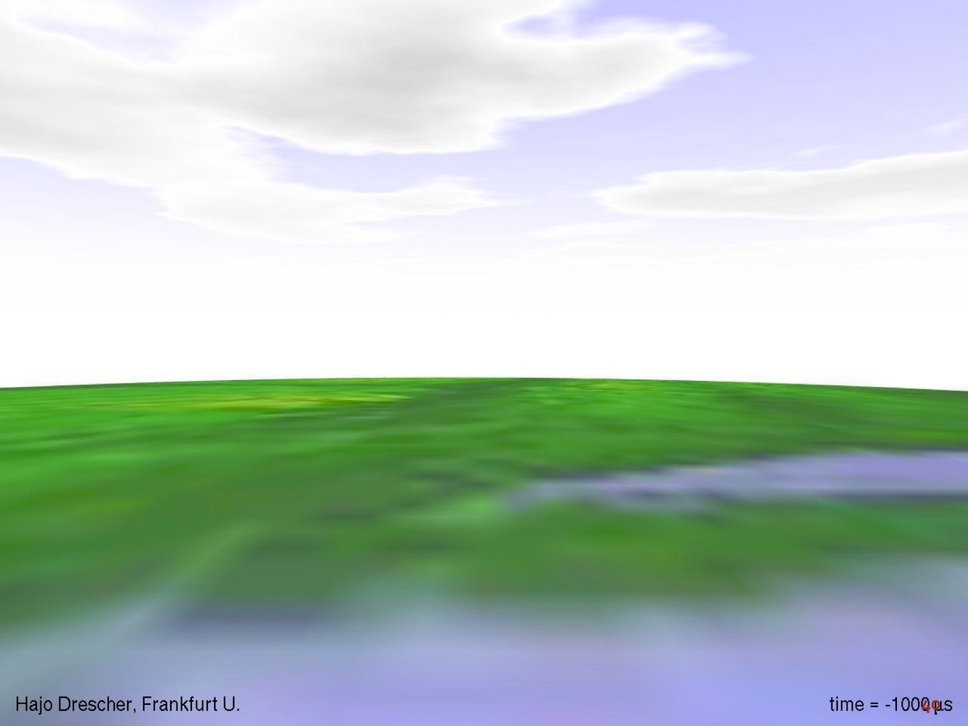


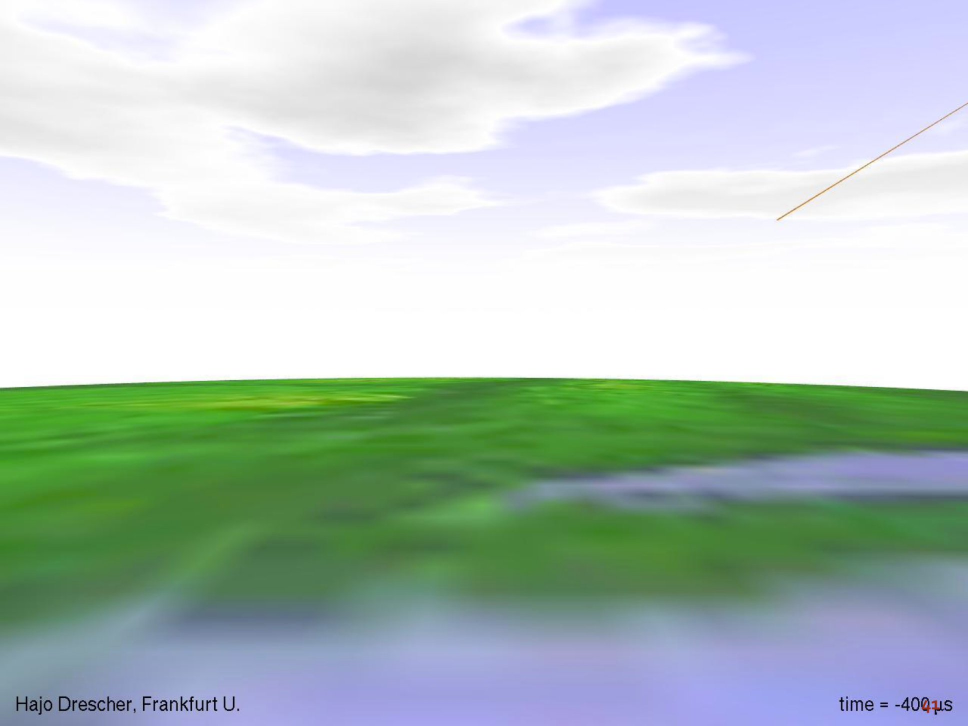
Satellite and Balloon experiments



Experimental Techniques above the "knee"




Hajo Drescher, Frankfurt U.
time = -1000 µs


Hajo Drescher, Frankfurt U.
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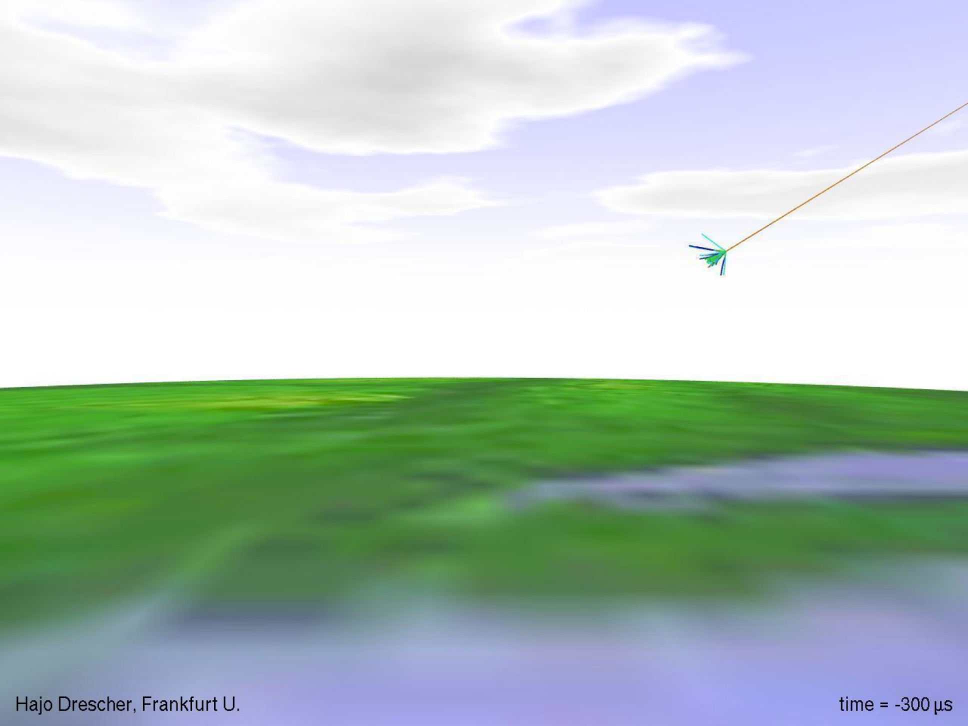
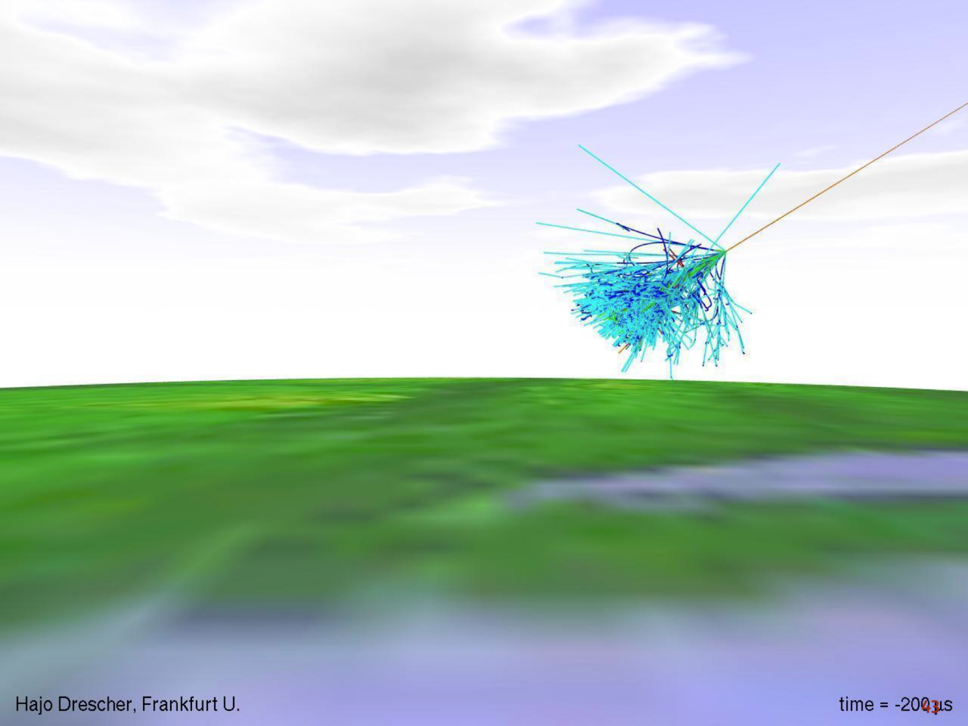
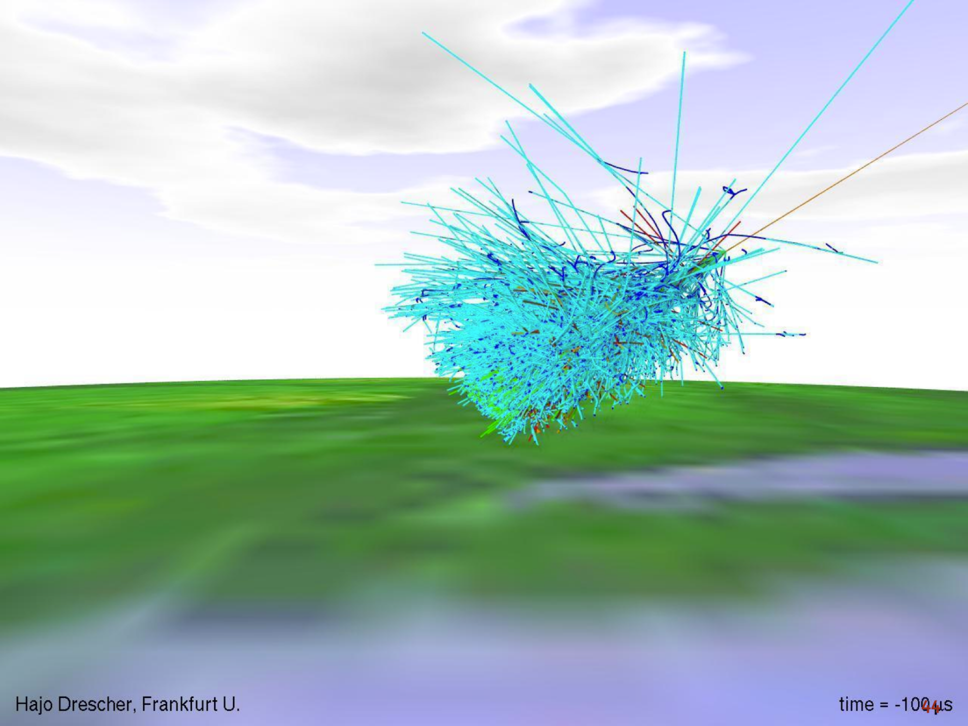
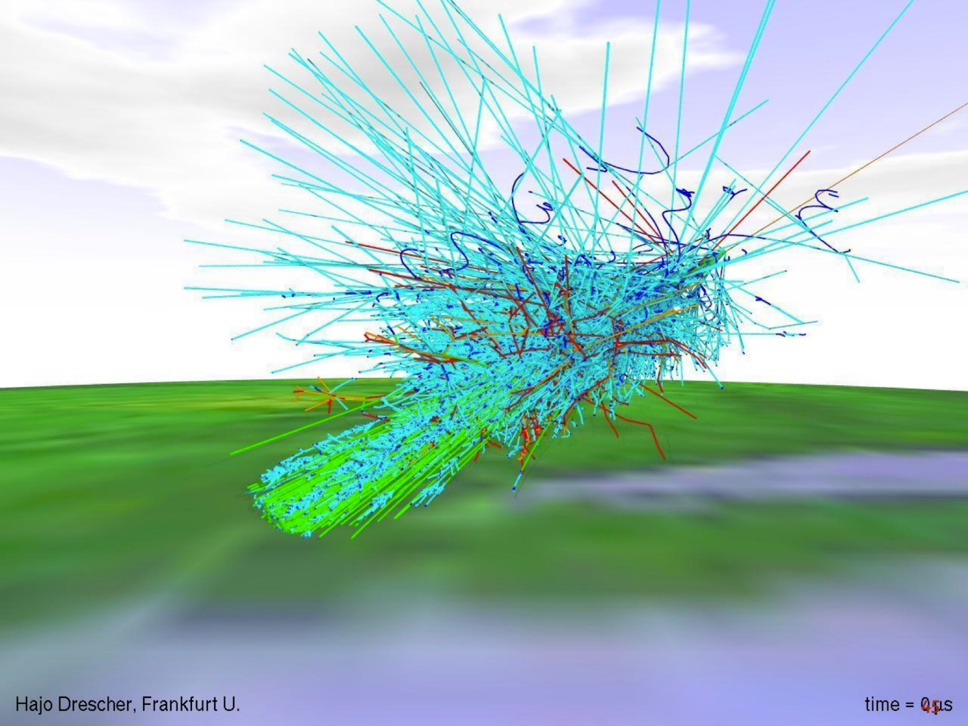
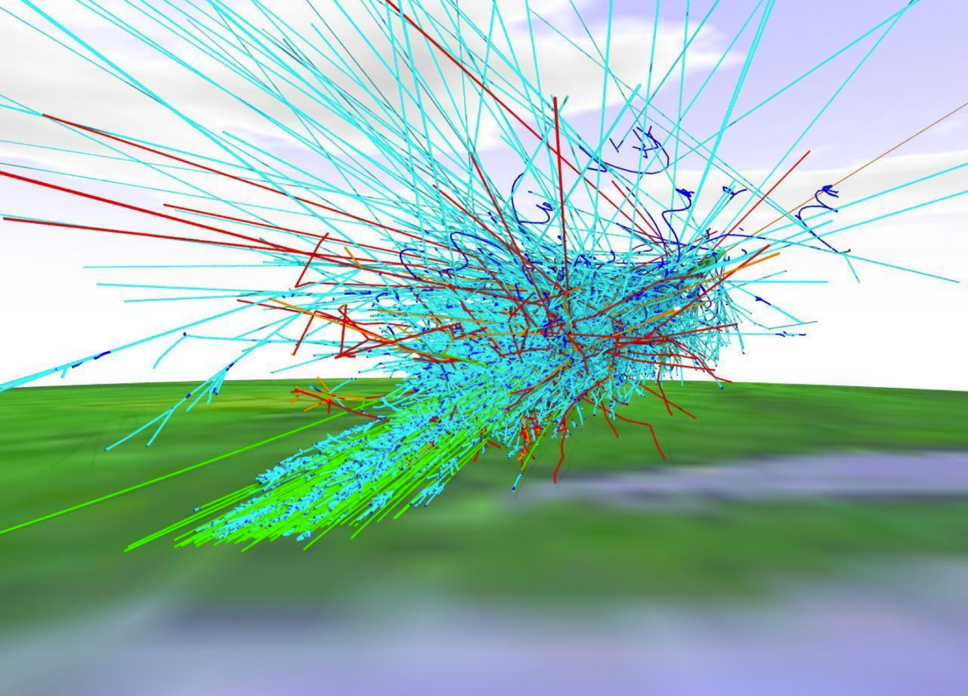

Hajo Drescher, Frankfurt U.
time = -300 µs


Hajo Drescher, Frankfurt U.
time = -200 µs

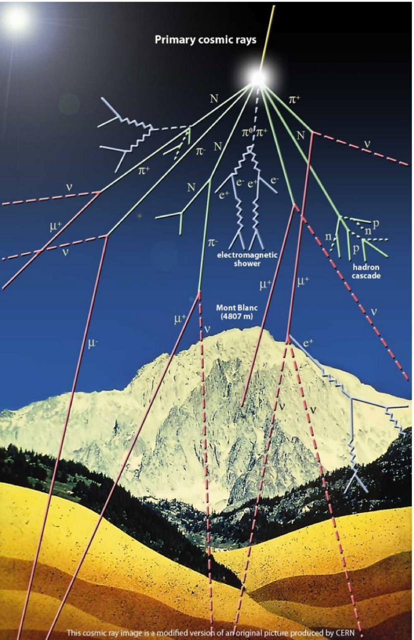

Hajo Drescher, Frankfurt U.
time = -100 µs

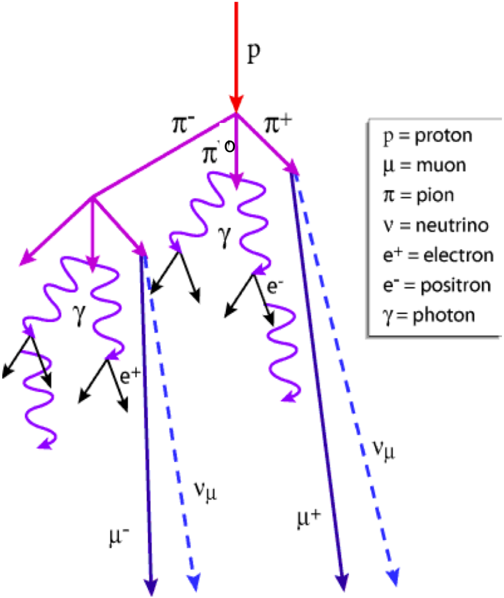

Hajo Drescher, Frankfurt U.
time = 0 μs



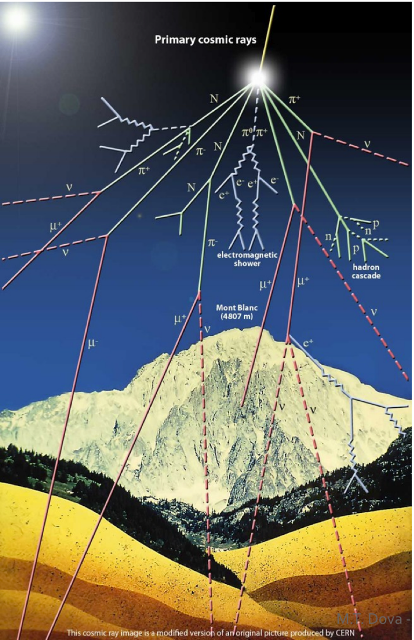
Hajo Drescher, Frankfurt U.

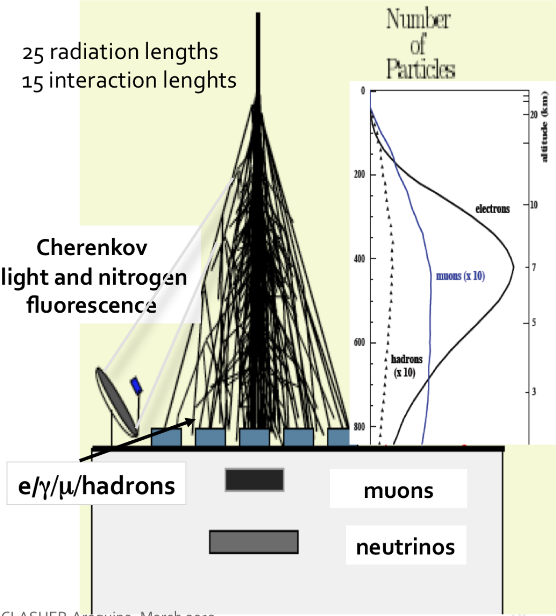
The atmosphere as particle detector





The atmosphere as particle detector

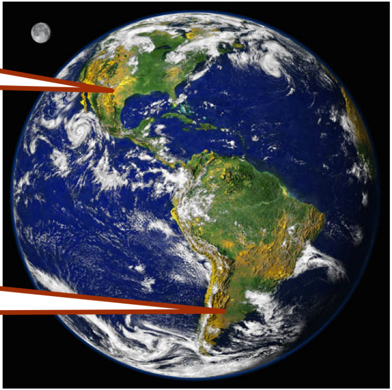




UHECR current experiments

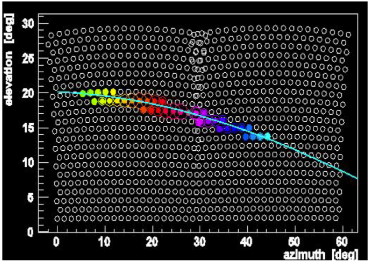
Utah
USA

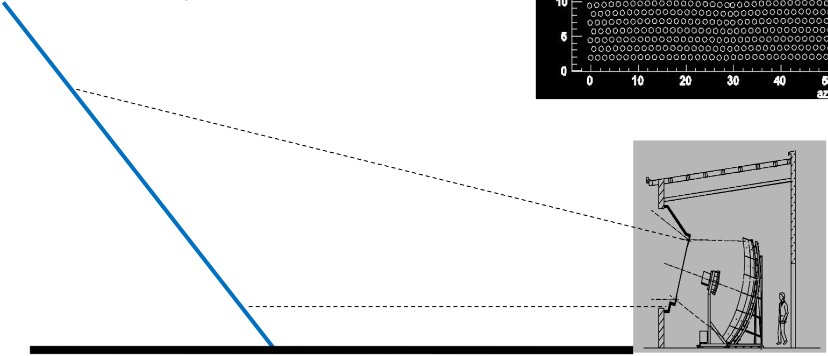
Mendoza,
Argentina



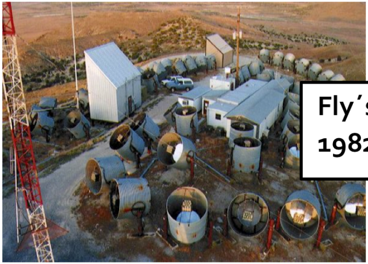
Fluorescence technique

Fluorescence telescope “see” the UV light emitted by N2 molecules excited by shower electrons

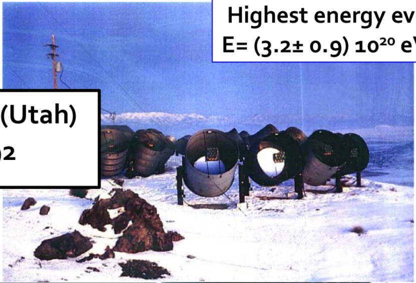




Fluorescence Detectores (I)



Fly´s Eye(Utah)
1982-1992



Highest energy event
E= $(3.2 \pm 0.9)\ 10^{20}$ eV

HiRes (Utah)
1997-2006

Fluorescence detectors (II)

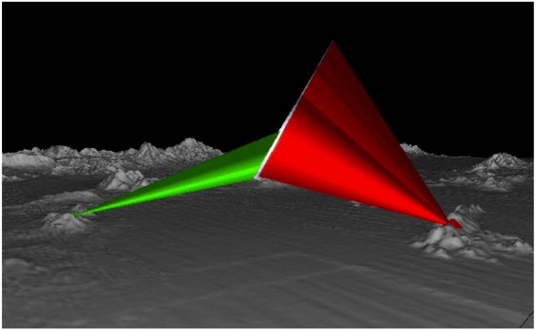
27 telescopes

440 PMTs 30ºX30º

38 telescopes

258 PMTs 15ºX18º

Detection using Fluorescence technique

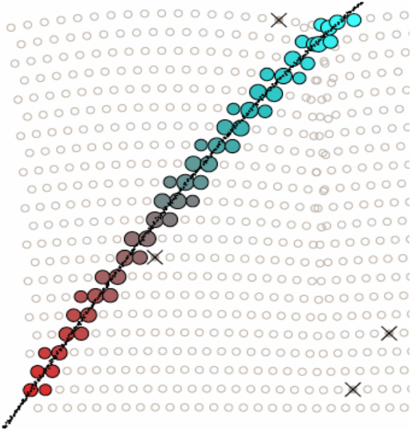


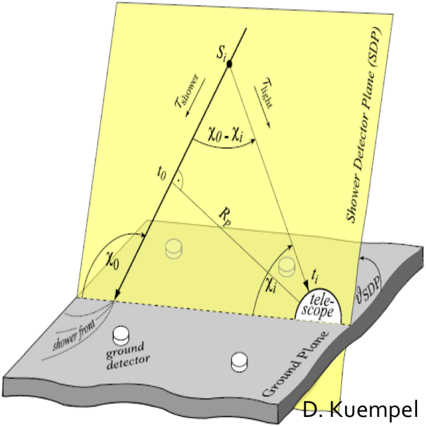
- Energy measurement is calorimetric
- Low duty-cycle
- Atmospheric uncertainties
- Fluorescence yield
- Aperture is not easily determined

Geometry from Fluorescence technique

Use direction and timing information from FD pixels

$$t_{i,exp} = t_0 + R_p / c \ \tan[(\chi_0 - \chi_i)/2]$$





D. Kuempel

EM energy from shower development

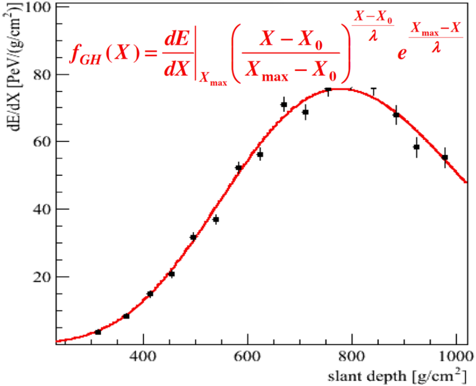
ADC counts vs t → γ vs t → γ vs slant depth → $E_{deposited}$

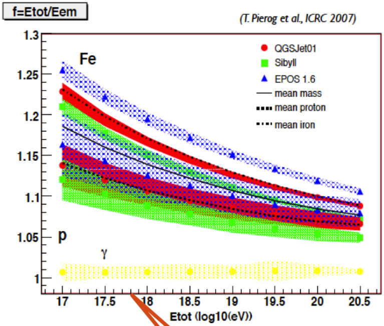
Detector calibration

Atmosphere

fluorescence yield ≈ 5γ's /MeV

$$\frac{d^2 N_\gamma}{dX\,d\lambda} = Y(\lambda, P, T, e_v) \cdot \frac{dE_{tot}^{dep}}{dX}$$

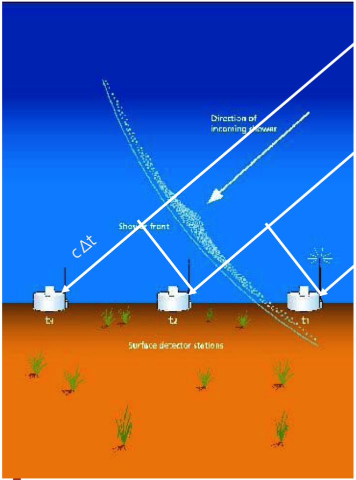




$$E_{em} = \int_0^\infty f_{GH}(X)\,dX$$

$$E_{FD} = f_{inv}\, E_{em}$$

Surface Arrays

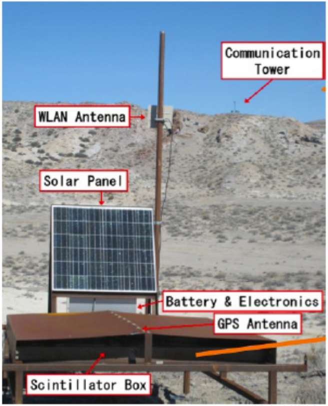


- ✓ 100% duty cycle
- ✓ Aperture well defined and large.
- ✓ Direction by time delay of arrival times
- ✓ Energy by signal intensities
- ✓ Energy measurement relies on assumptions about interaction models.

SD installation in the North….

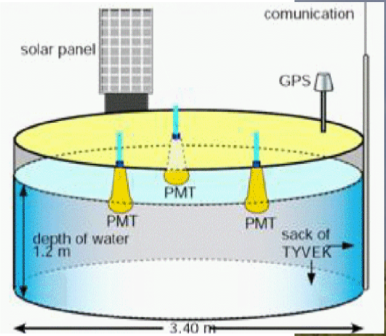
Thin scintillators

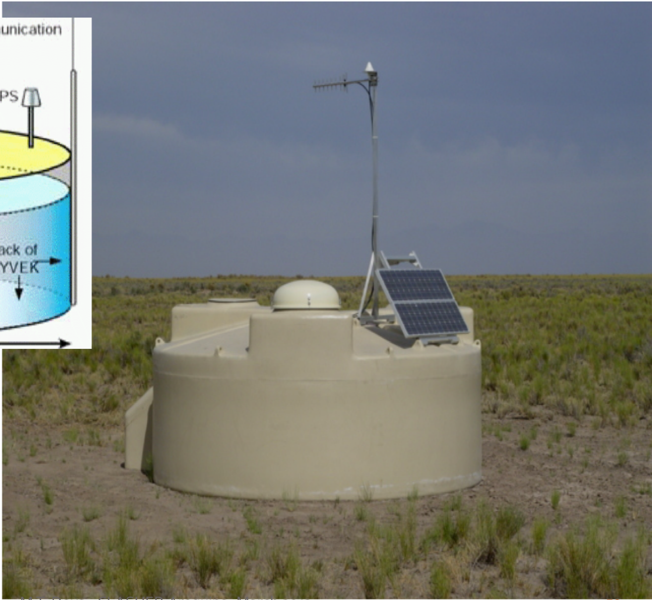
- 507 detectors, ≈700km²
- 3 m² / SD
- 2 layers of plastic scintillator
- 1 PMT for each layer.



Installation in the South…

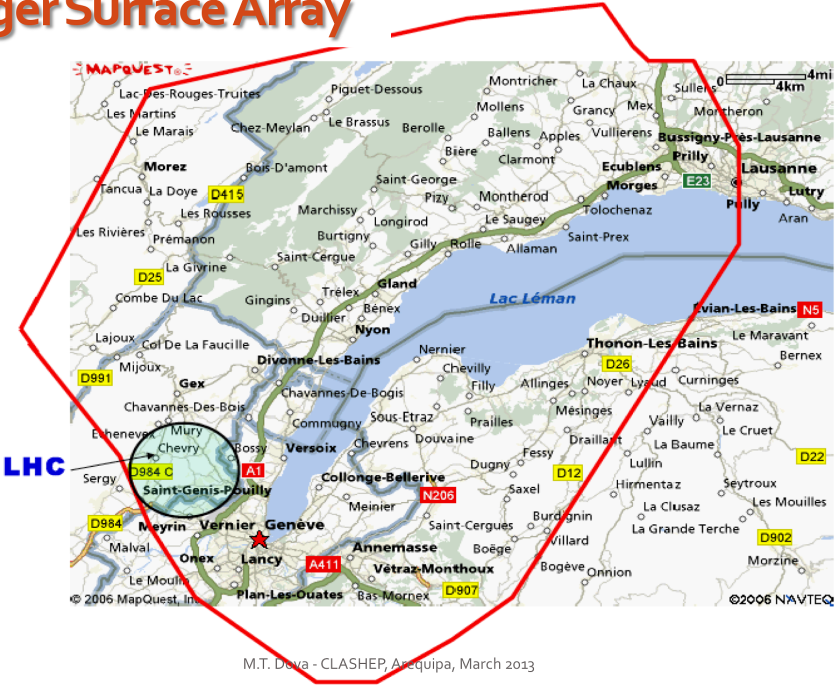
AUGER: water Cerenkov station



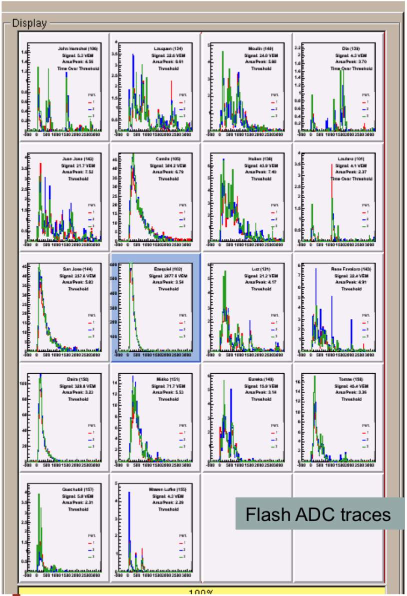


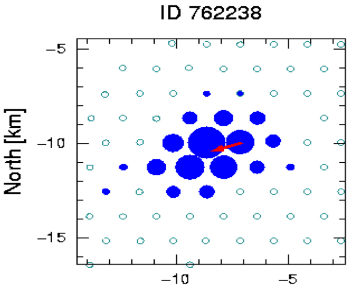
- **large acceptance to inclined showers**

Auger Surface Array

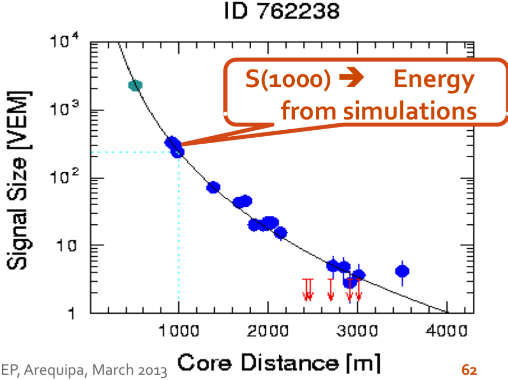


Energy from SD





Lateral density distribution

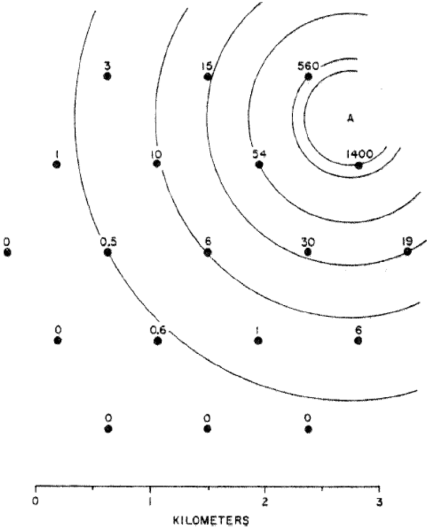


Volcano Ranch (1962-1972): First E>10^{20}eV

10km² scintillators array

$$S_{vr}(r) = \frac{N}{r_m^2} C(\alpha,\eta) \left(\frac{r}{r_m}\right)^{-\alpha} \left(1 + \frac{r}{r_m}\right)^{-(\eta-\alpha)}$$

$$C = \frac{\Gamma(\eta-\alpha)}{2\pi\Gamma(2-\alpha)\Gamma(\eta-2)}$$



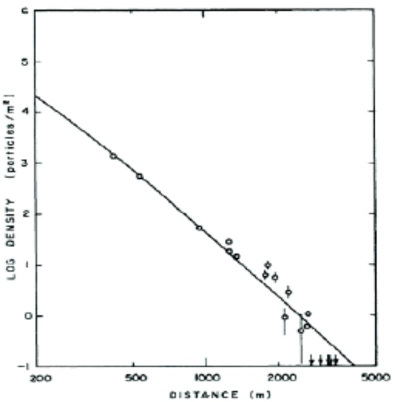
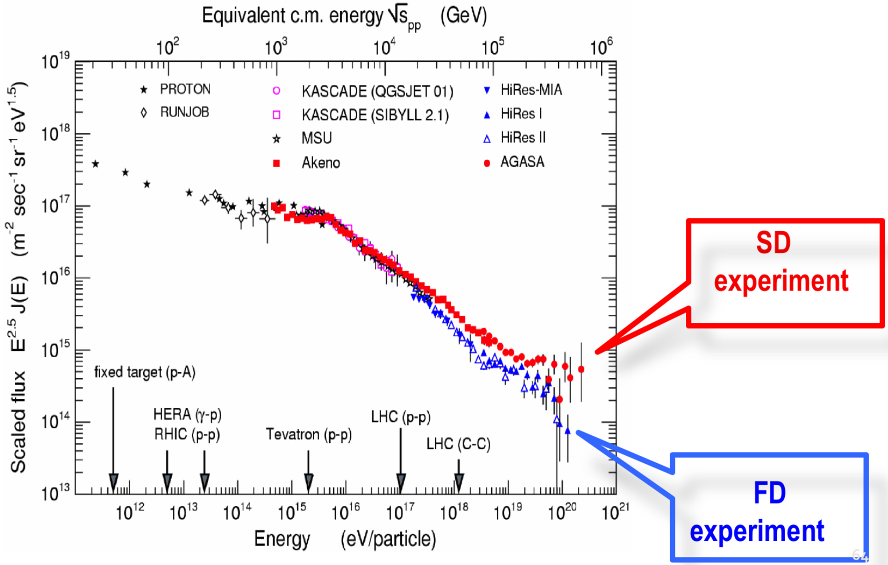


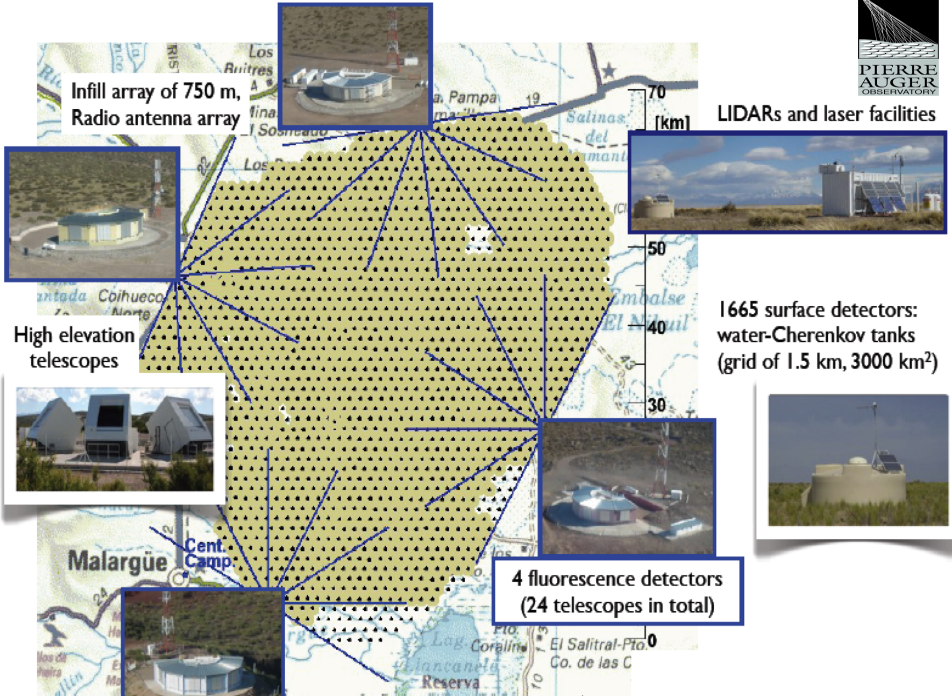
FIG. 2. Observed shower densities as a function of distance from the shower axis. The curve is the Greisen approximation of the Nishimura-Kamata lateral distribution for $s = 1.0$, $N = 5 \times 10^{19}$.

The cosmic ray spectrum some years ago…is there an end?



A HYBRID DETECTOR

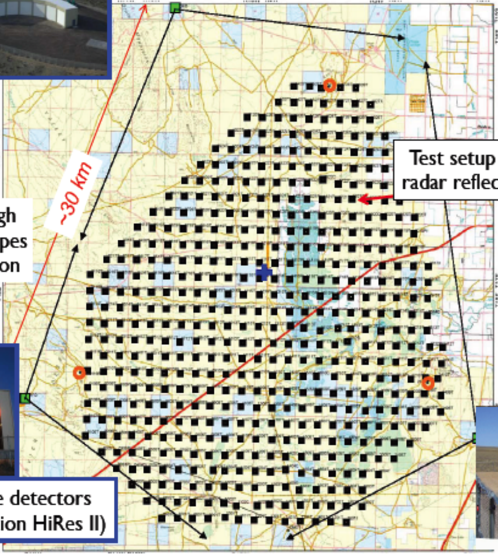
Surface + Fluoresnce is more than 2 detectors!



Infill array of 750 m,
Radio antenna array
LIDARs and laser facilities
High elevation telescopes
1665 surface detectors: water-Cherenkov tanks (grid of 1.5 km, 3000 km^2)
4 fluorescence detectors (24 telescopes in total)
70
[km]
50
40
30
0
Malargüe
Cent. Camp.
Coihueco
Los Buitres
Salinas del Amarillo
Embalse El Nihuil
Lag. Coralino
El Salitral-Pto.
Co. de las C
Reserva
PIERRE AUGER OBSERVATORY

Telescope Array (Utah, US)

Middle Drum: based on HiRes II



LIDAR
Laser facility

Infill array and high elevation telescopes under construction

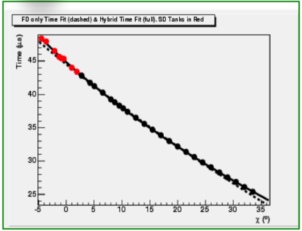
3 fluorescence detectors (2 new, one station HiRes II)

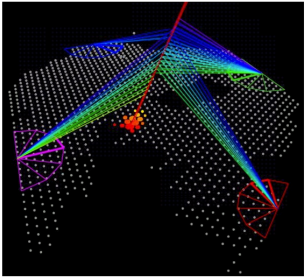
507 surface detectors: double-layer scintillators (grid of 1.2 km, 680 km^2)

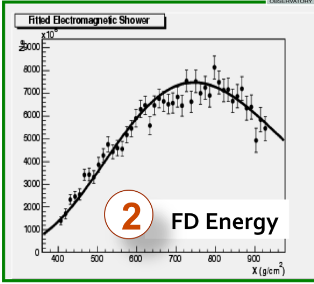
Electron light source (ELS): ~40 MeV

Hybrid Data: Absolute energy calibration

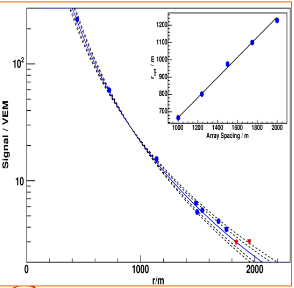
1 Hybrid geometry



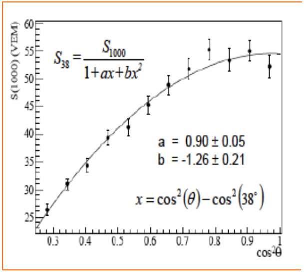




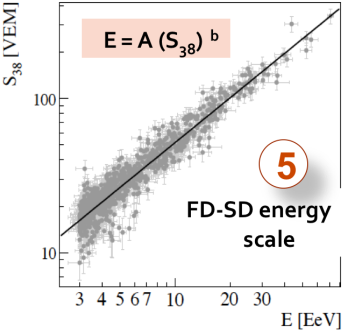
2 FD Energy



3 SD parameter (S1000)

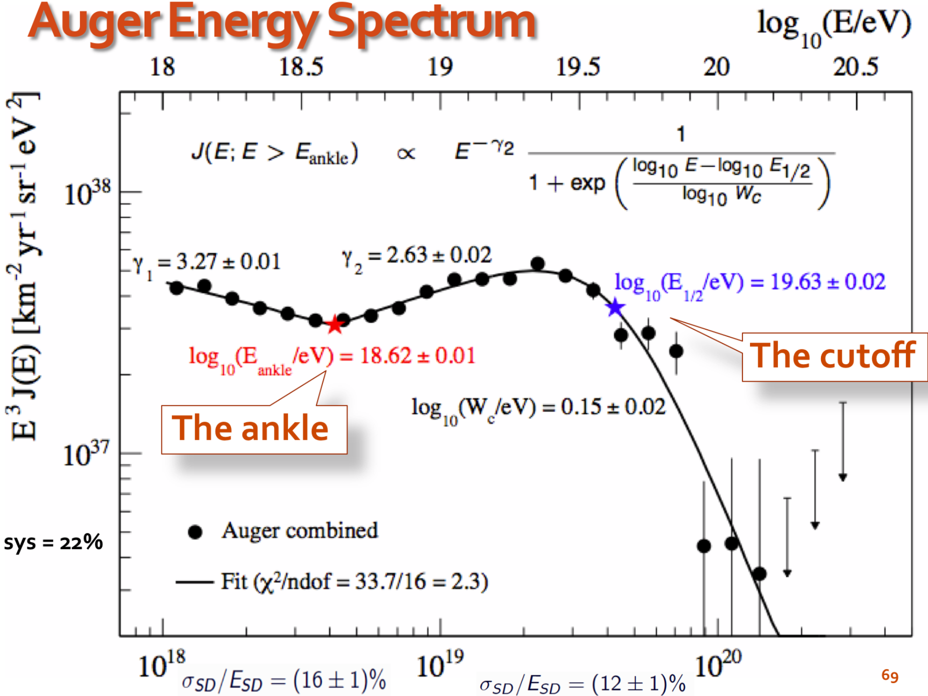


4 Zenith angle dependence of s1000



5 FD-SD energy scale

Auger Energy Spectrum

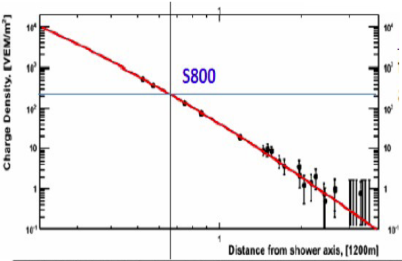


ΔE sys = 22%

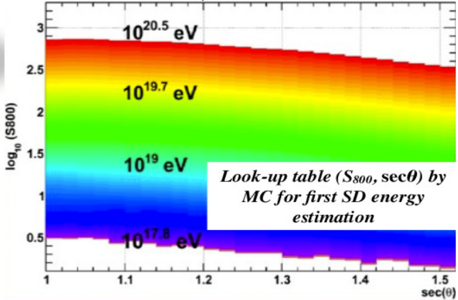
TA energy calibration

1 FD Energy: Calorimetric measurement

2

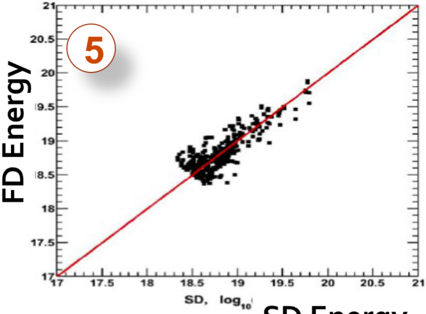


3



4 MC lookup table to determine SD Energy

5

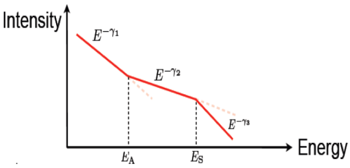


$$E_{\mathrm{SD}} = \frac{1}{\left\langle \frac{E'_{\mathrm{SD}}}{E_{\mathrm{FD}}} \right\rangle_{\mathrm{hyb}}} E'_{\mathrm{SD}}$$

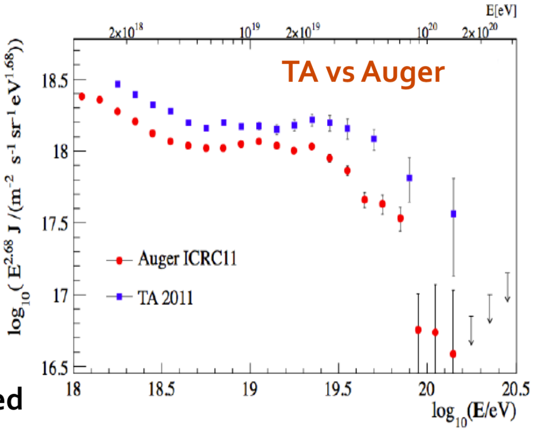
27% less than E from MC

YOSHIKI TSUNESADA, ICRC 2011

3 power-law fit

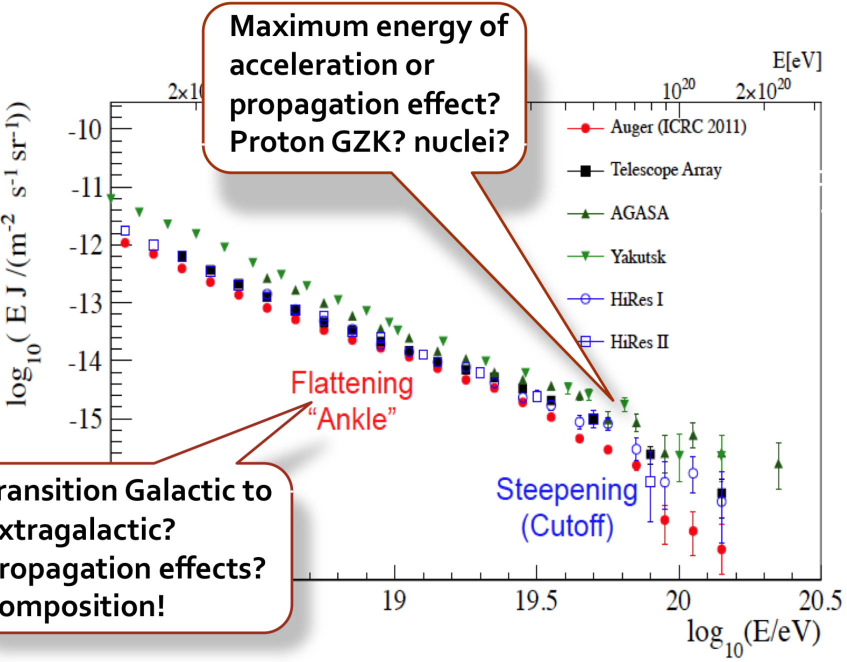


- Ankle: Confirmed
- Suppression: Confirmed
- 20% diff not fully explained



	γ_1	γ_2	γ_3	$\log E_A$	$\log E_S$
HiRes	3.25 (0.01)	2.81 (0.03)	5.1 (0.7)	18.65 (0.05)	19.75 (0.04)
Auger	3.27 (0.02)	2.68 (0.01)	4.2 (0.1)	18.61 (0.01)	19.41 (0.02)
TA	3.33 (0.04)	2.68 (0.04)	4.2 (0.7)	18.69 (0.03)	19.68 (0.09)

HiRes: *PRL*, **100**, 101101 (2008); Auger: ICRC2011 (icrc893); TA: ICRC2011 (icrc1297)


Maximum energy of acceleration or propagation effect? Proton GZK? nuclei?
Transition Galactic to Extragalactic? Propagation effects? Composition!
Flattening "Ankle"
Steepening (Cutoff)
E[eV]
10^{20}
2×10^{20}
$\log_{10}(E\,J/(m^{-2}\ s^{-1}\ sr^{-1}))$
-10
-11
-12
-13
-14
-15
19
19.5
20
20.5
$\log_{10}(E/eV)$
Auger (ICRC 2011)
Telescope Array
AGASA
Yakutsk
HiRes I
HiRes II

UHECR DATA

- Sources must be extreme objects
- Energy loss during propagation

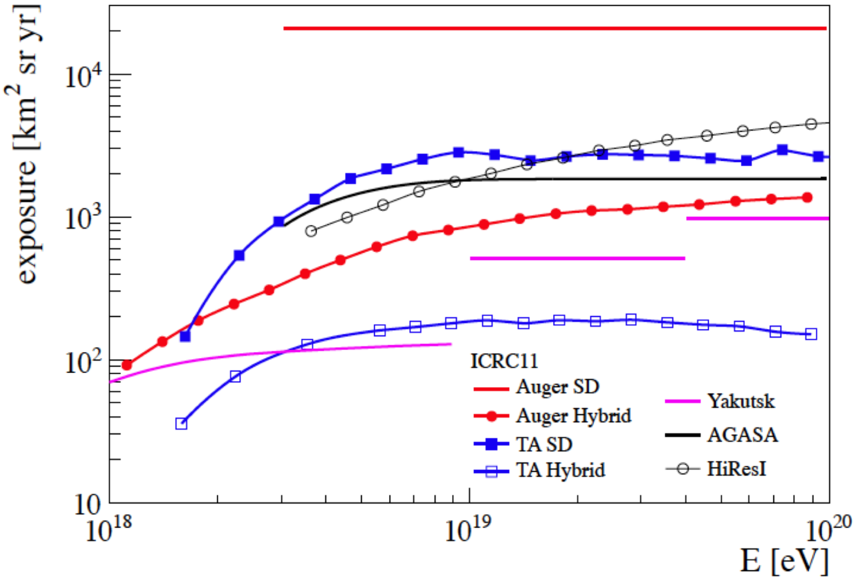
- Phenomenology of the EAS
- Proton, iron? Estimate of composition of UHECR needs hadronic models

...more Tomorrow!

BACKUP

Exposures

(M.Unger, KIT)



Many possible models

(Kotera & Olinto, 1101.4256)