Search for the Origin of Cosmic Rays

Part 1: Cosmic Rays

Lecture at the J. Stefan Institute Ljubljana
within the course:
'Advanced particle detectors and data analysis'

Hermann Kolanoski
Humboldt-Universität zu Berlin and DESY

Zenith 0.150148
Azimuth 3.50723

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Overview of the lecture:

– **Part 1: Cosmic rays (CR) up to 10^{18} eV (EeV)**

– **Part 2: Neutrinos as Cosmic Ray messengers**

Part 1

– **Discovery of Cosmic rays (CR)**

– **How to measure CR – spectrum and composition**

– **Below the knee: direct measurements**

– **Above the knee: Extensive air showers (EAS)**

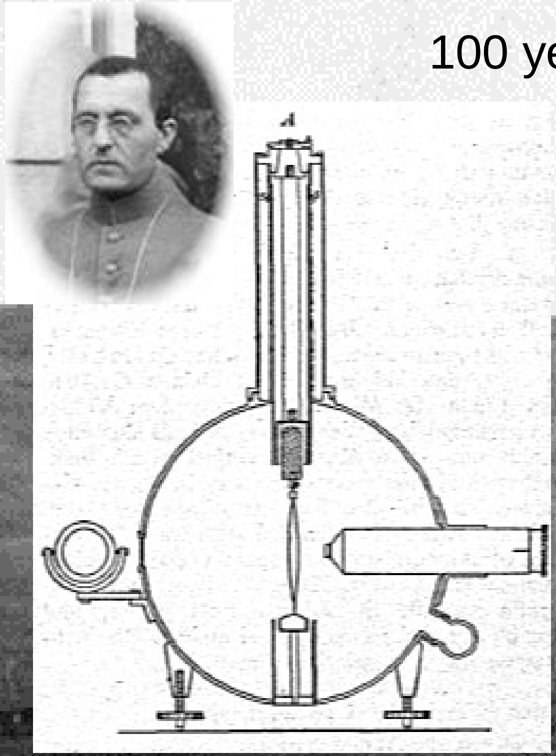
– **PeV-EeV: Spectrum and Composition**

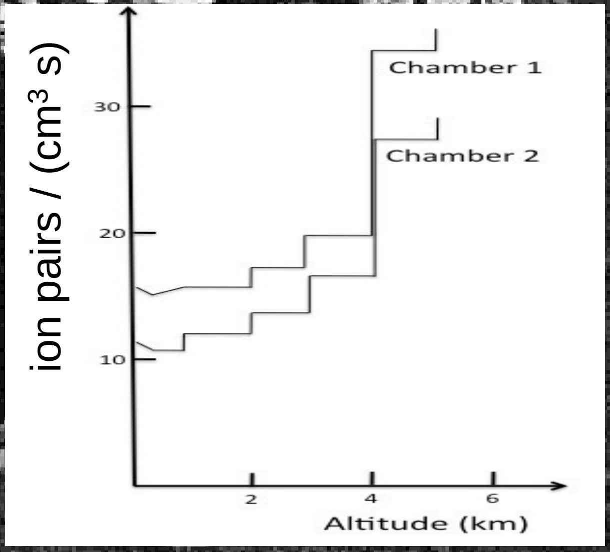
– **Anisotropy**

– **Possible sources**

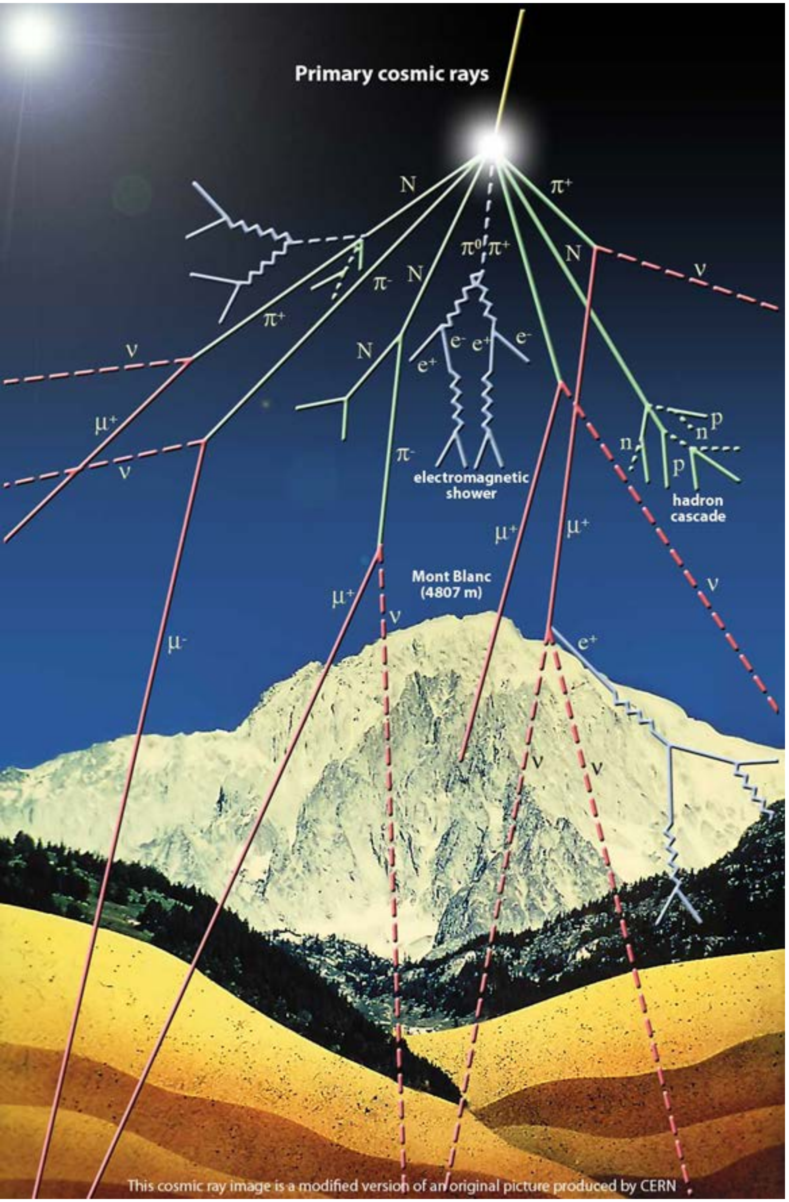
Cosmic Rays

100 years after their discovery not yet understood

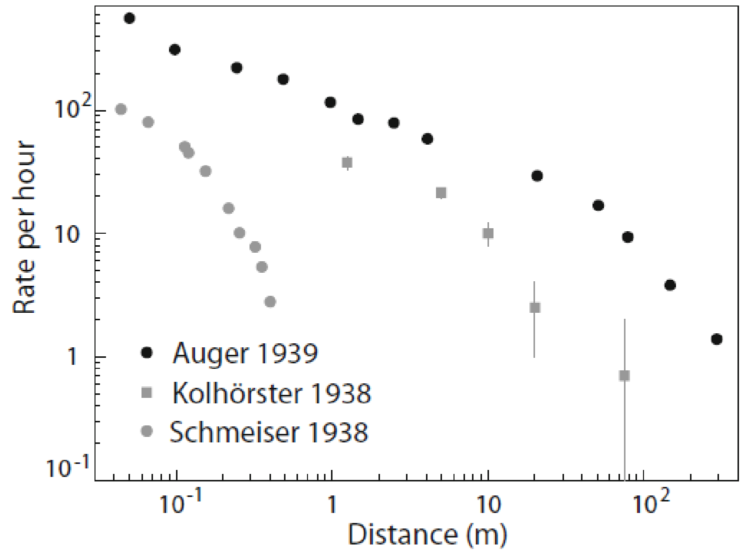


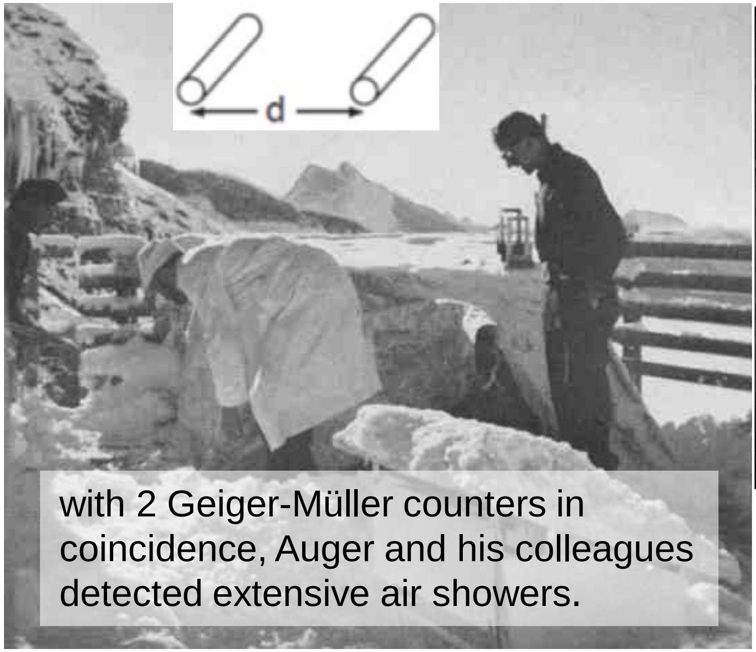


Extended Air Showers (EAS)

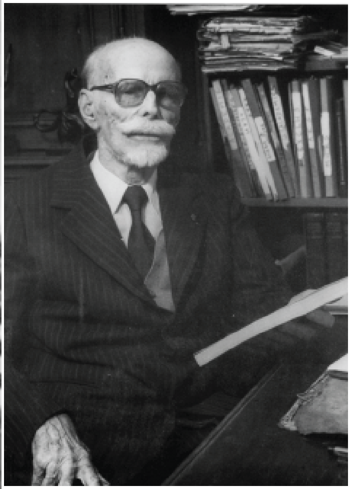


1938
Pierre Auger
discovered
EAS





with 2 Geiger-Müller counters in coincidence, Auger and his colleagues detected extensive air showers.



Zwicky's proposal for the CR Origin

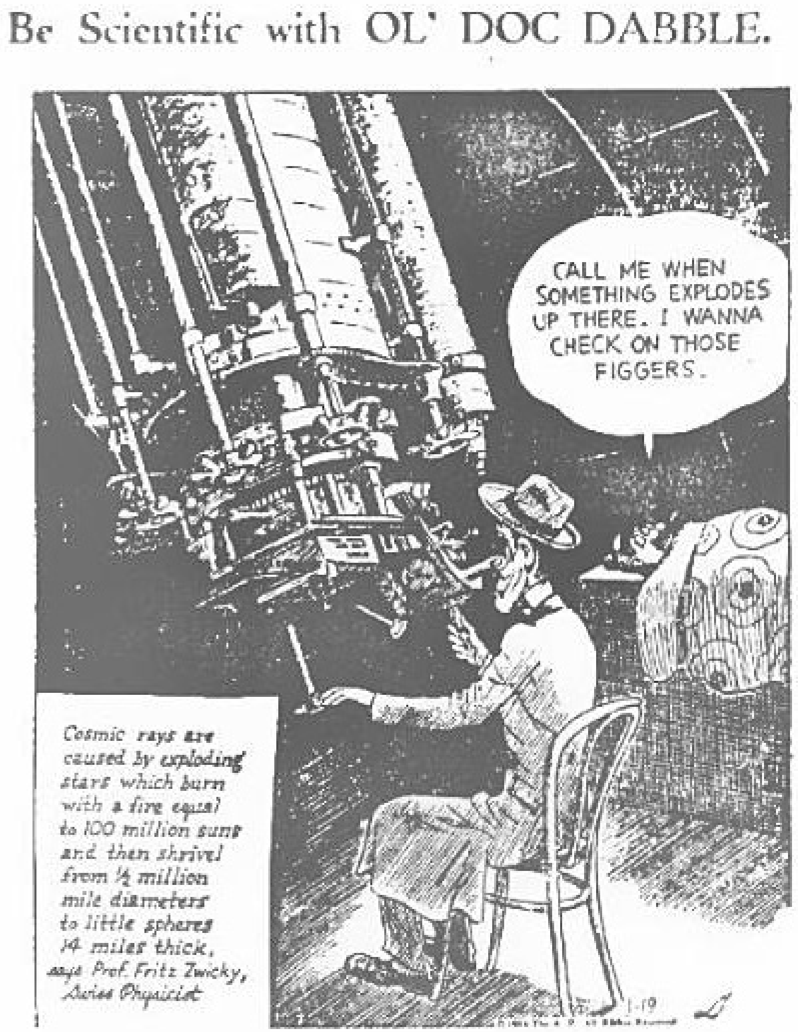
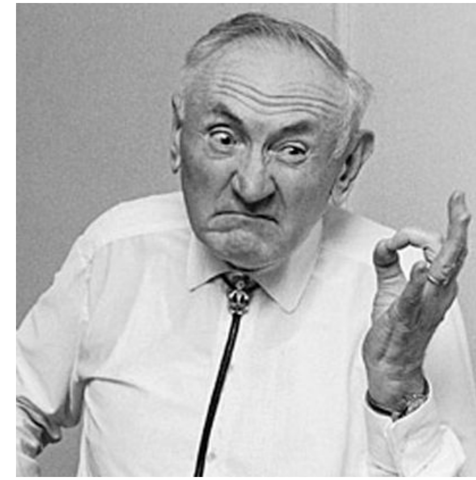


Figure 4.2: The cartoon which appeared in the *Los Angeles Times* of 19 January 1
strip entitled 'Be Scientific with Ol' Doc Dabble'.

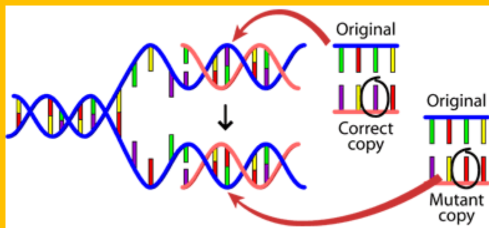
In Los Angeles Times, Jan. 1934

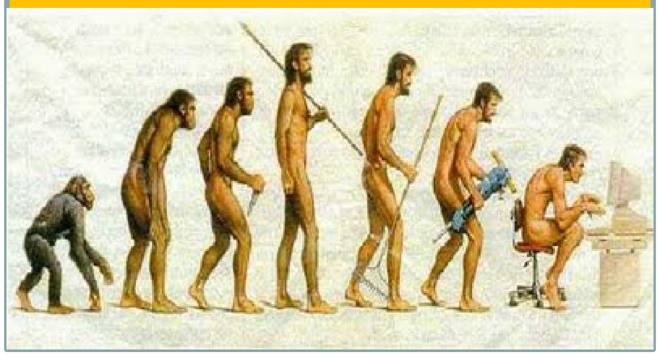


"Cosmic rays are caused by exploding stars which burn with a fire equal to 100 million suns and then shrivel from ½ million mile diameters to little spheres 14 miles thick."

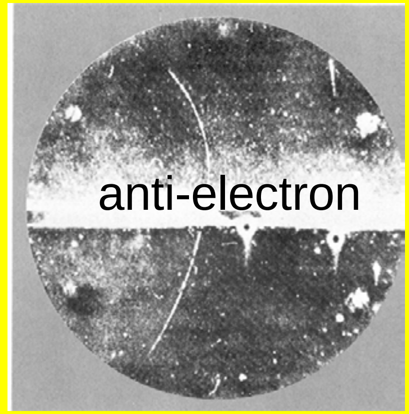
Useful Cosmic Rays

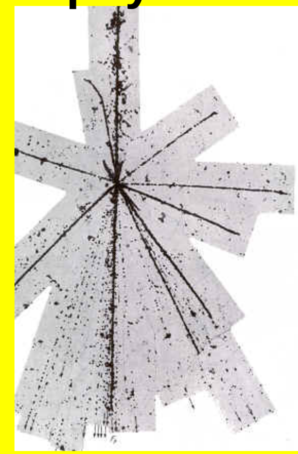
Motor of Evolution

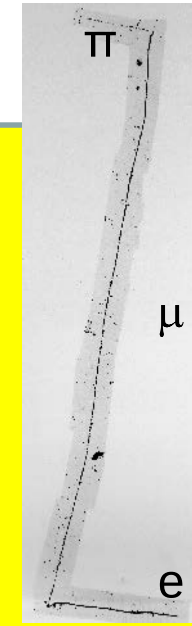




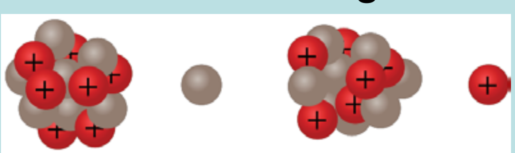
The cradle of particle physics





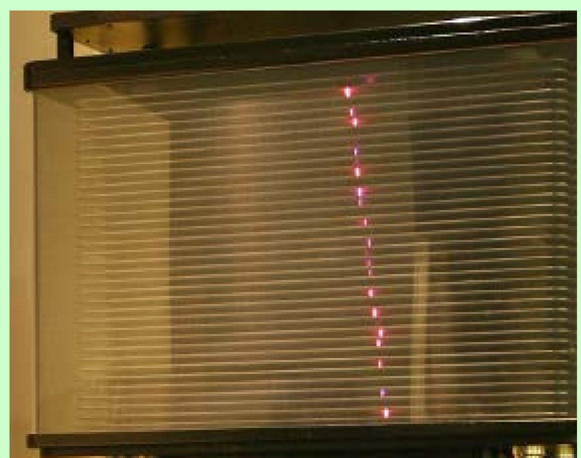


C-14 dating

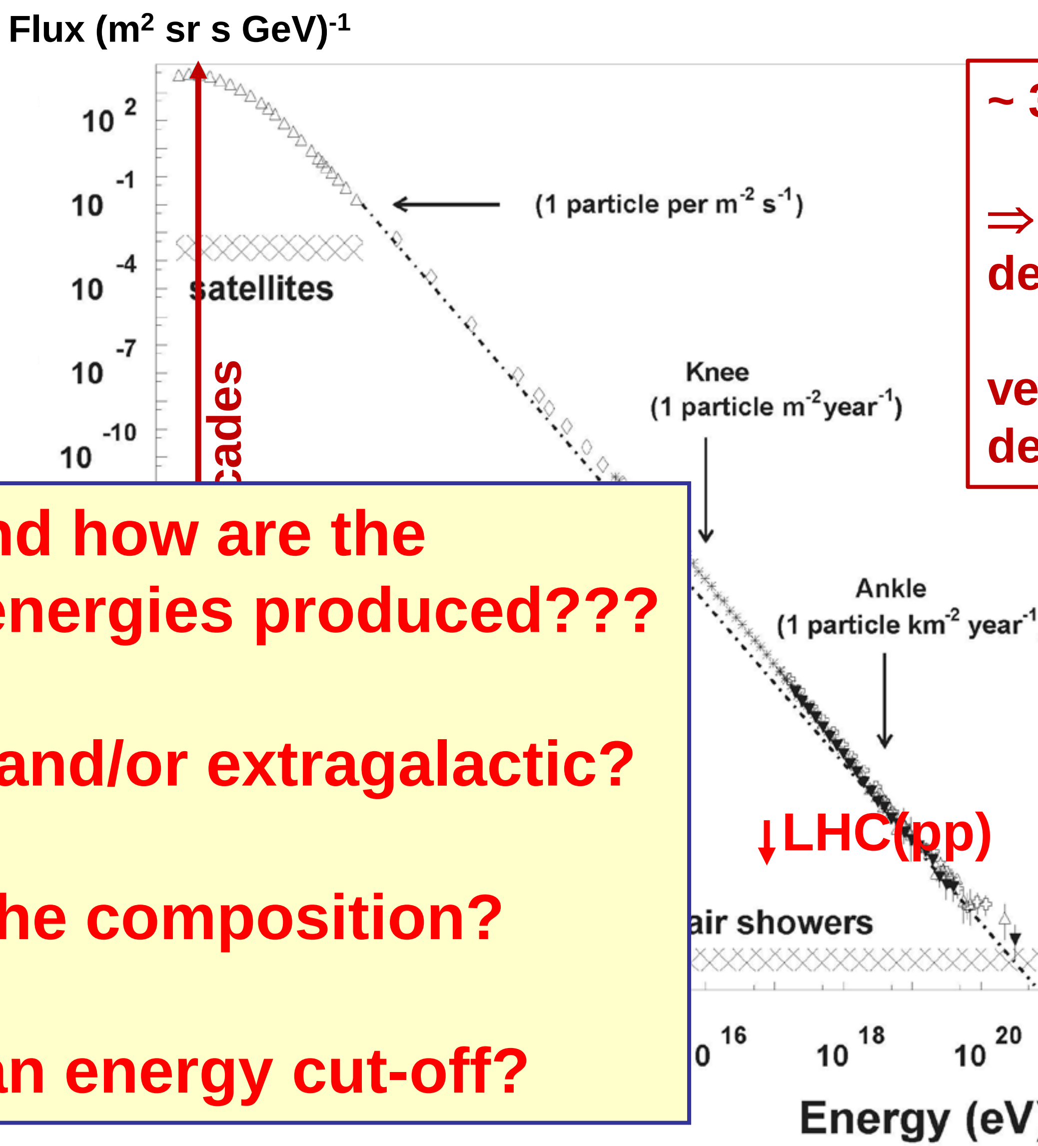


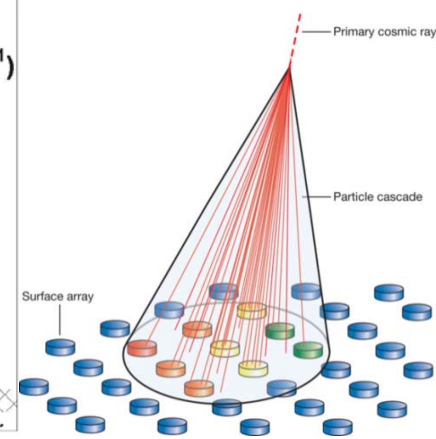
$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}p$$

Testing detectors, educational outreach, …



Charged Cosmic Ray Spectrum





~ 32 decades

⇒ very different detection methods

very different detector sizes

Where and how are the highest energies produced???

Galactic and/or extragalactic?

What is the composition?

Is there an energy cut-off?

Balloon Experiments

- volume up to 1 Million m^3
- pay load up to 3 to
- height up to 40 km.
- atmospheric depth 3-5 g/cm^2
- compare to λ_{int}(proton) = 90 g/cm^2

example:

Helium buoyancy of 1 kg/m^3 on ground

$\Rightarrow$ for a load of 2000 kg need 2000 m^3 helium

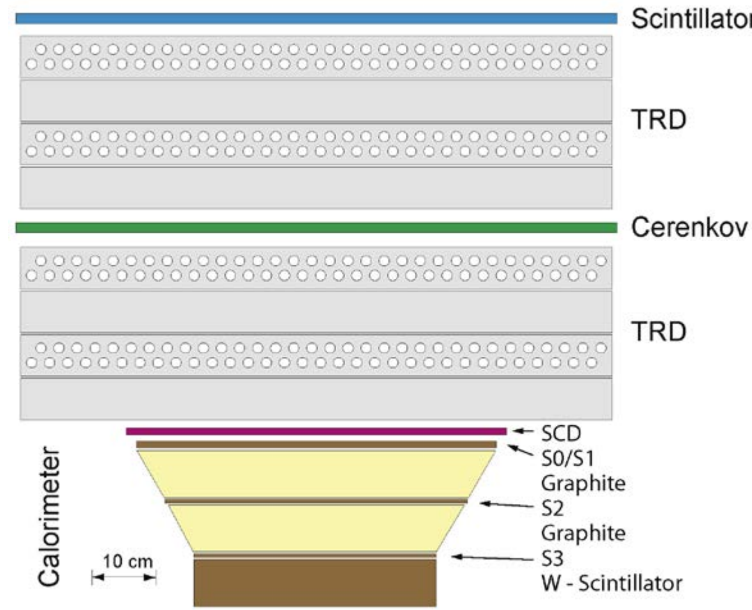
$\Rightarrow$ 400 000 m^3 at height of 5 g/cm^2

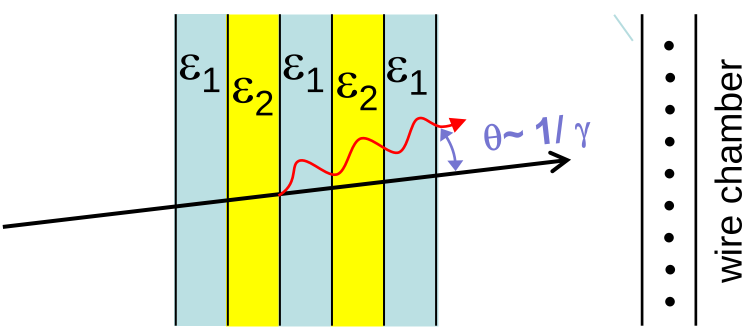
Balloon: Detectors

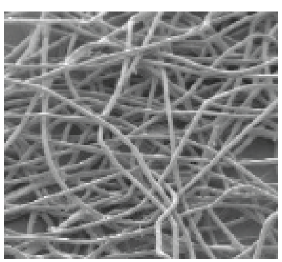
Identification without magnet:

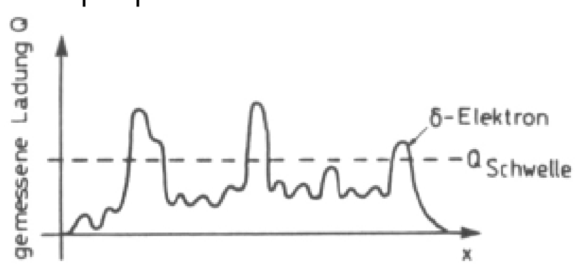
Transition Radiation

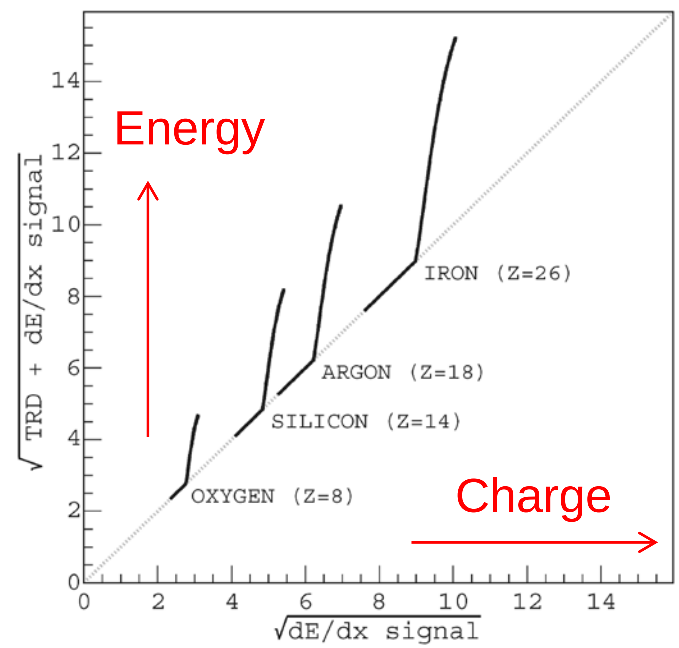
X-Ray Intensity $\sim \gamma = E/Mc^2$



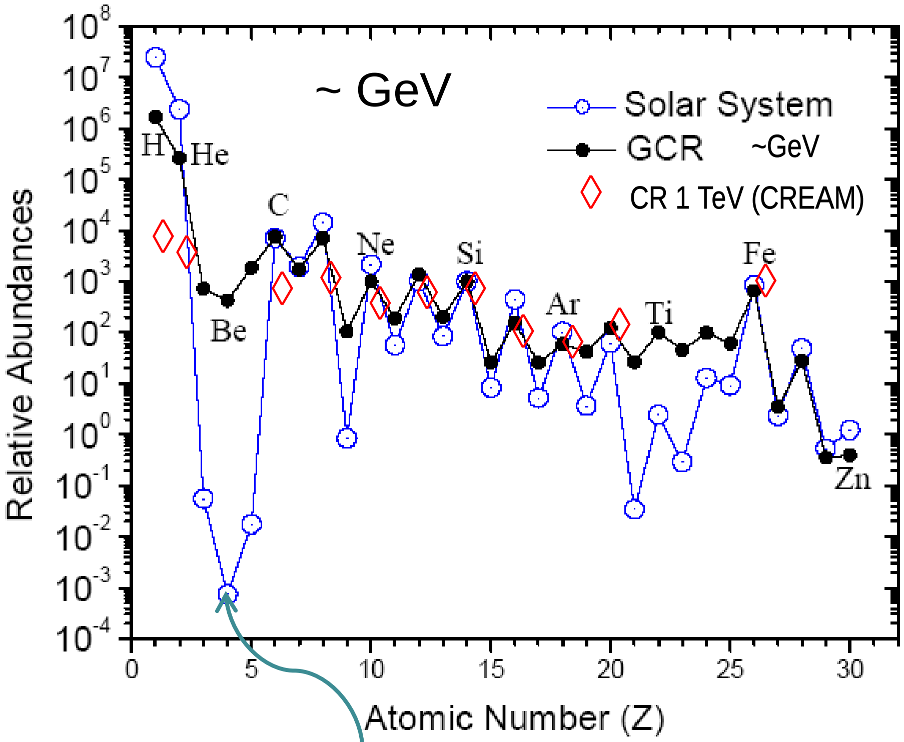






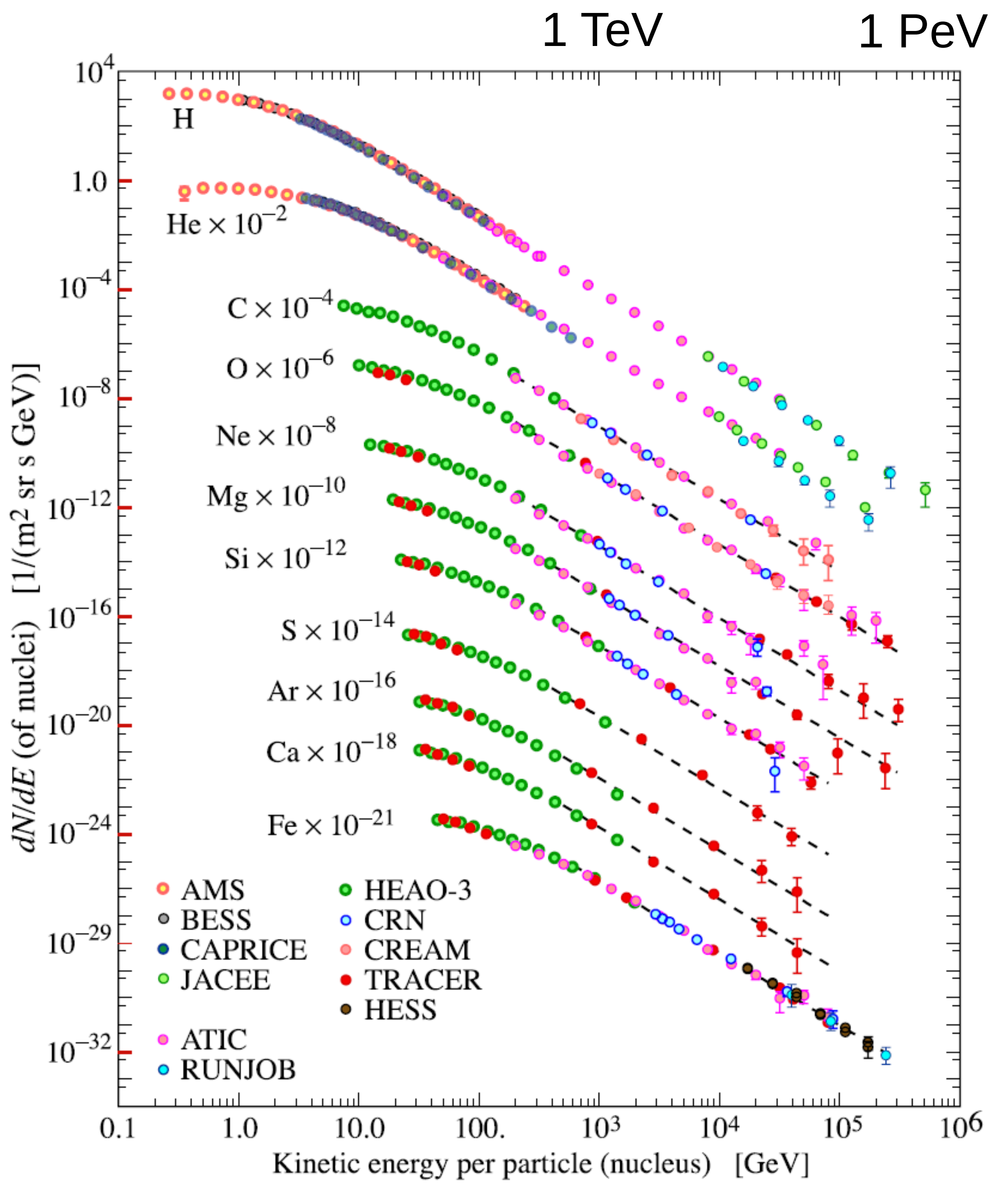


CR Composition up to ~100TeV



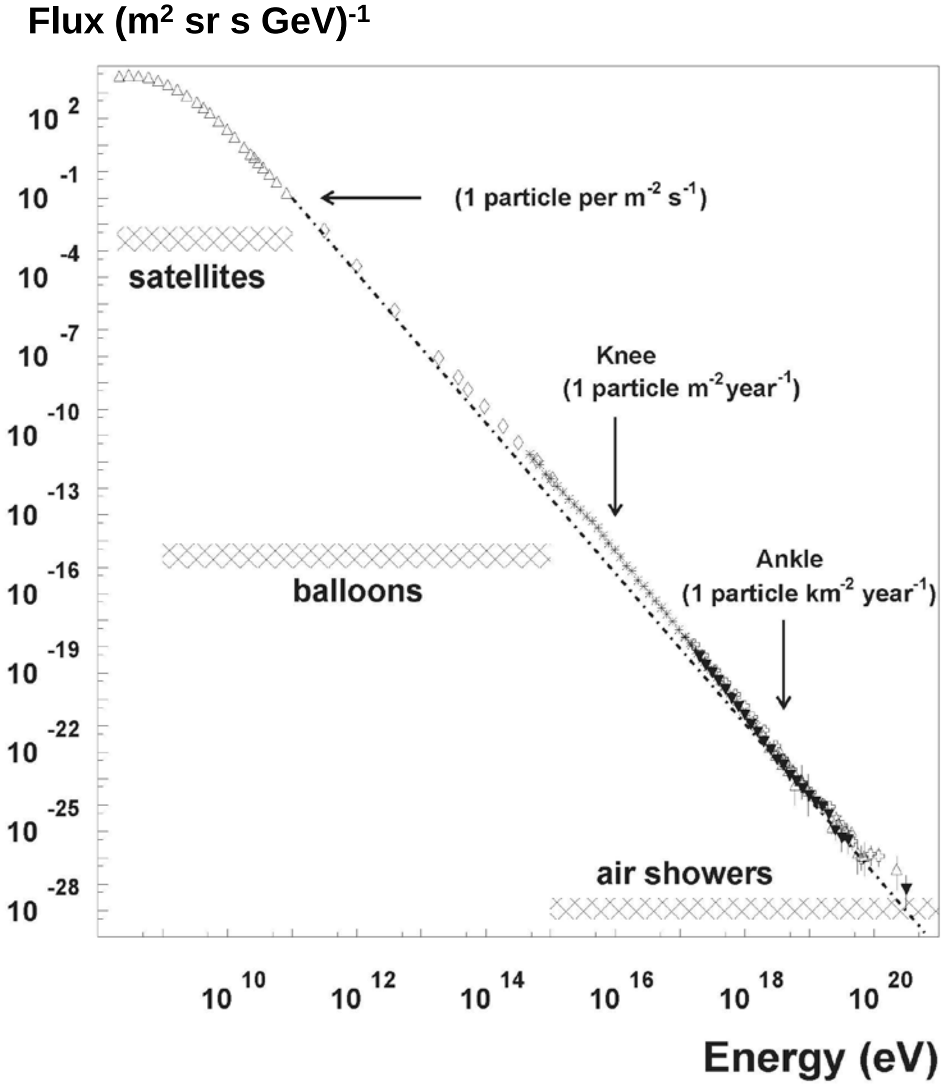
Filled due to interactions

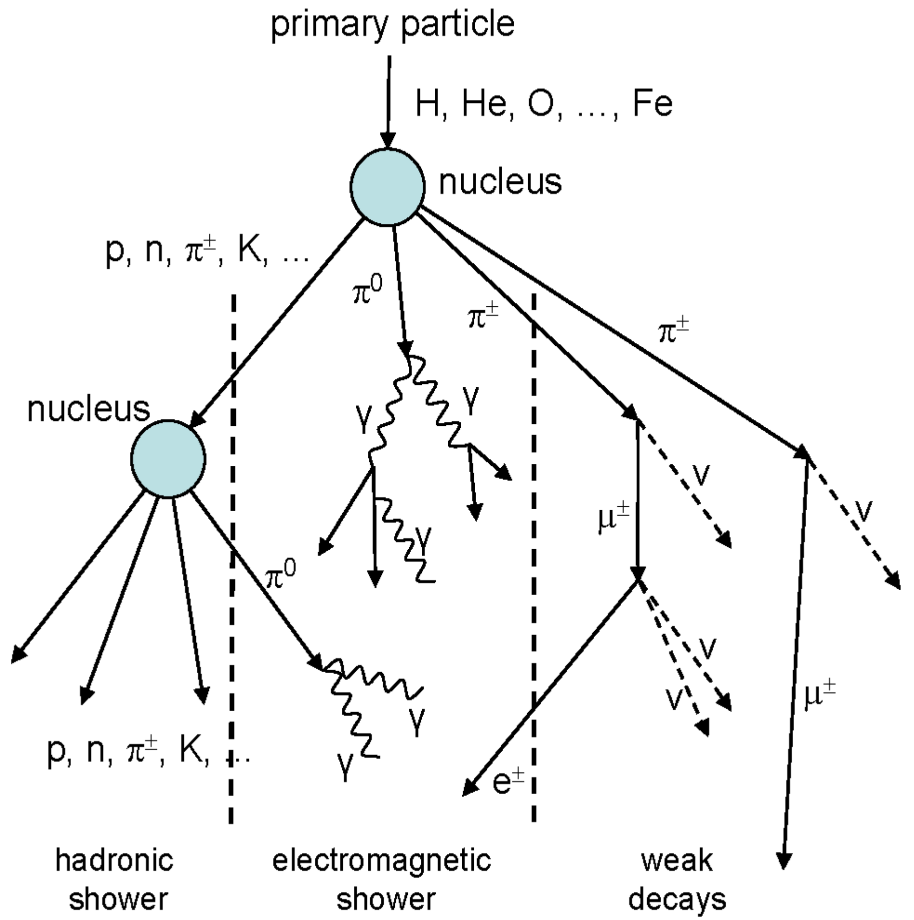
Li, Be, B surpressed in fusion



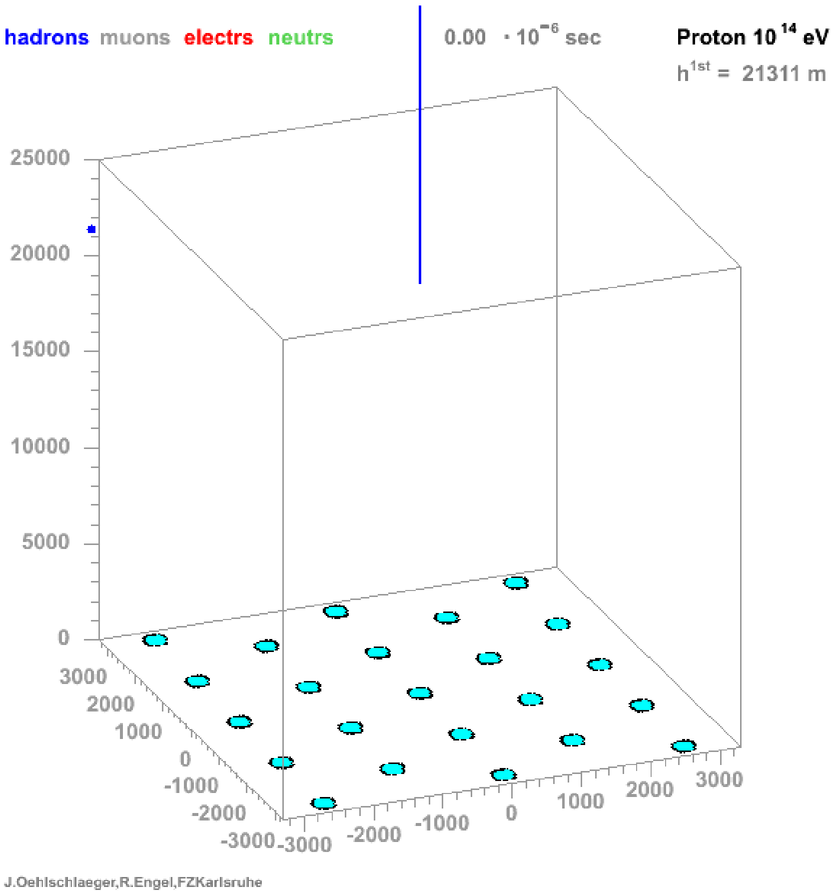
accelerated about 10^7 years ago
charged particles stay in galaxy
due to magnetic field

Extensive Air Showers





Air Shower Development



Atmospheric depth in g/cm²:

$$X(h) = \int_h^\infty \rho(z)dz \approx p(h)/g$$

Shower age:

$$s = \frac{3}{1 + \frac{2X_{\max}}{X}}$$

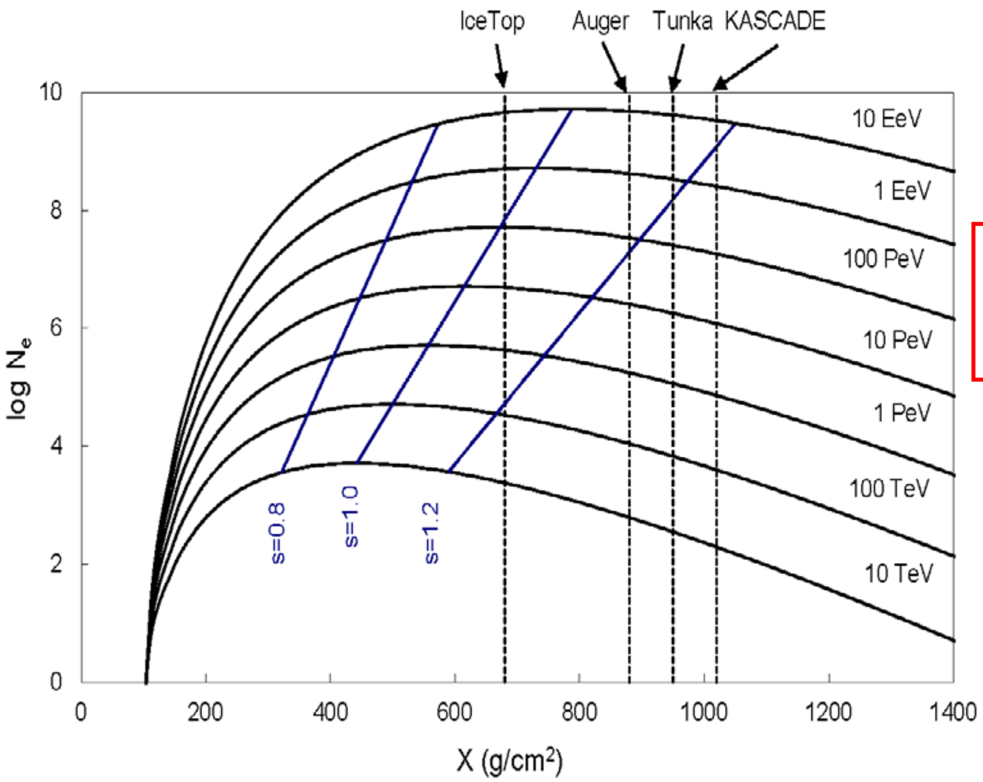
$$0 \leq s(X) \leq 3$$

$$s(X_{max}) = 1$$

$$\lambda'_a = \lambda_a \cdot \rho = \frac{A}{N_A \cdot \sigma} \approx 90\,\mathrm{g\,cm^{-2}}$$

$$\lambda'_a = X(h) = X_N \cdot e^{-h/H} \quad \Longrightarrow \quad h = H \cdot \ln \frac{X_N}{\lambda'_a} \approx 20.5\,\mathrm{km}$$

Longitudinal Shower Profile



Gaisser-Hillas Formula:

$$N_e(X) = N_{e,max} \left(\frac{X - X_1}{X_{max} - X_1} \right)^{\frac{X_{max} - X_1}{\Lambda}} \exp \frac{X_{max} - X}{\Lambda}$$

$N_{e,max}$, X_{max}, X_1, Λ are parameters

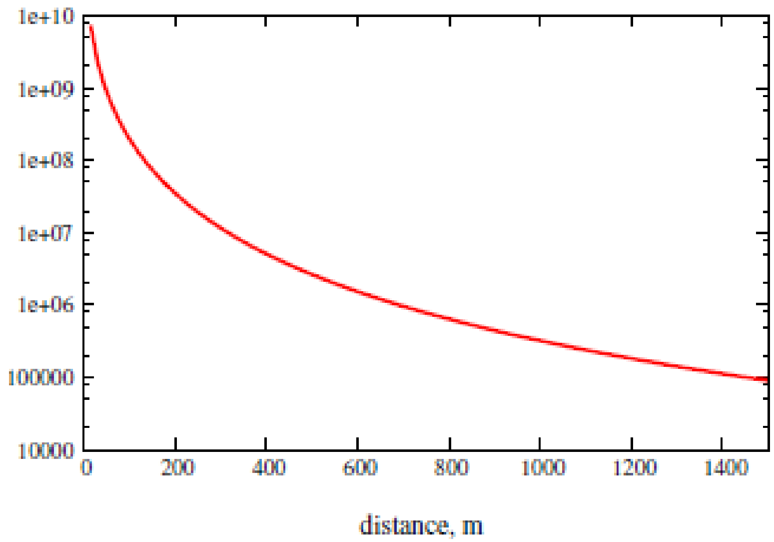
$\Lambda \approx 70$ g/cm^2 is an effective rad. length

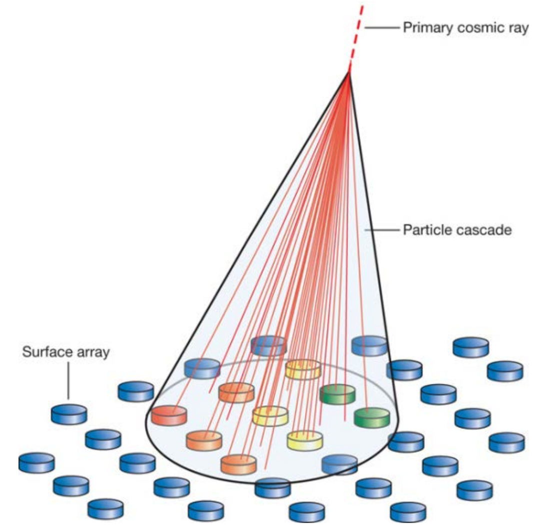
e.g.: at 100 PeV about 10^7 particles on sea level.

Shower profile can be seen with Cherenkov and fluorescence telescopes.

But mostly air shower detectors are calorimeters with only one readout plane.

Lateral Distribution Functions





NKG:

$$\frac{dN_e}{r\,dr\,d\varphi} = C(s) N_e(X) \left(\frac{r}{r_1}\right)^{s-2} \left(1+\frac{r}{r_1}\right)^{s-4.5}$$

$N_e(X)$ number of particles at depth X

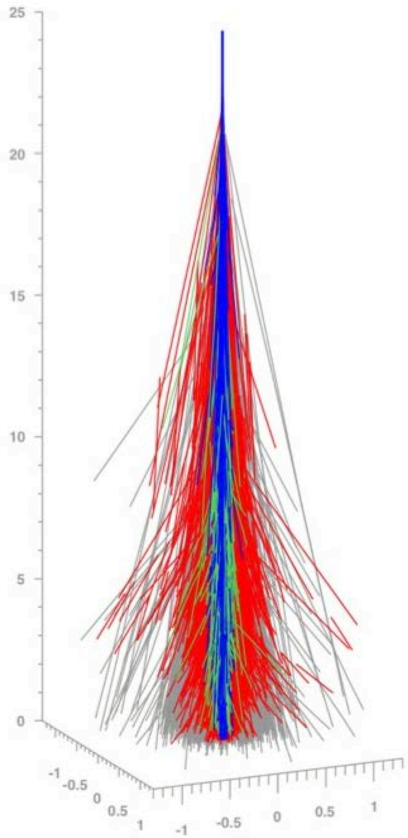
$s = 3/(1 + 2X_{max}/X)$ shower age

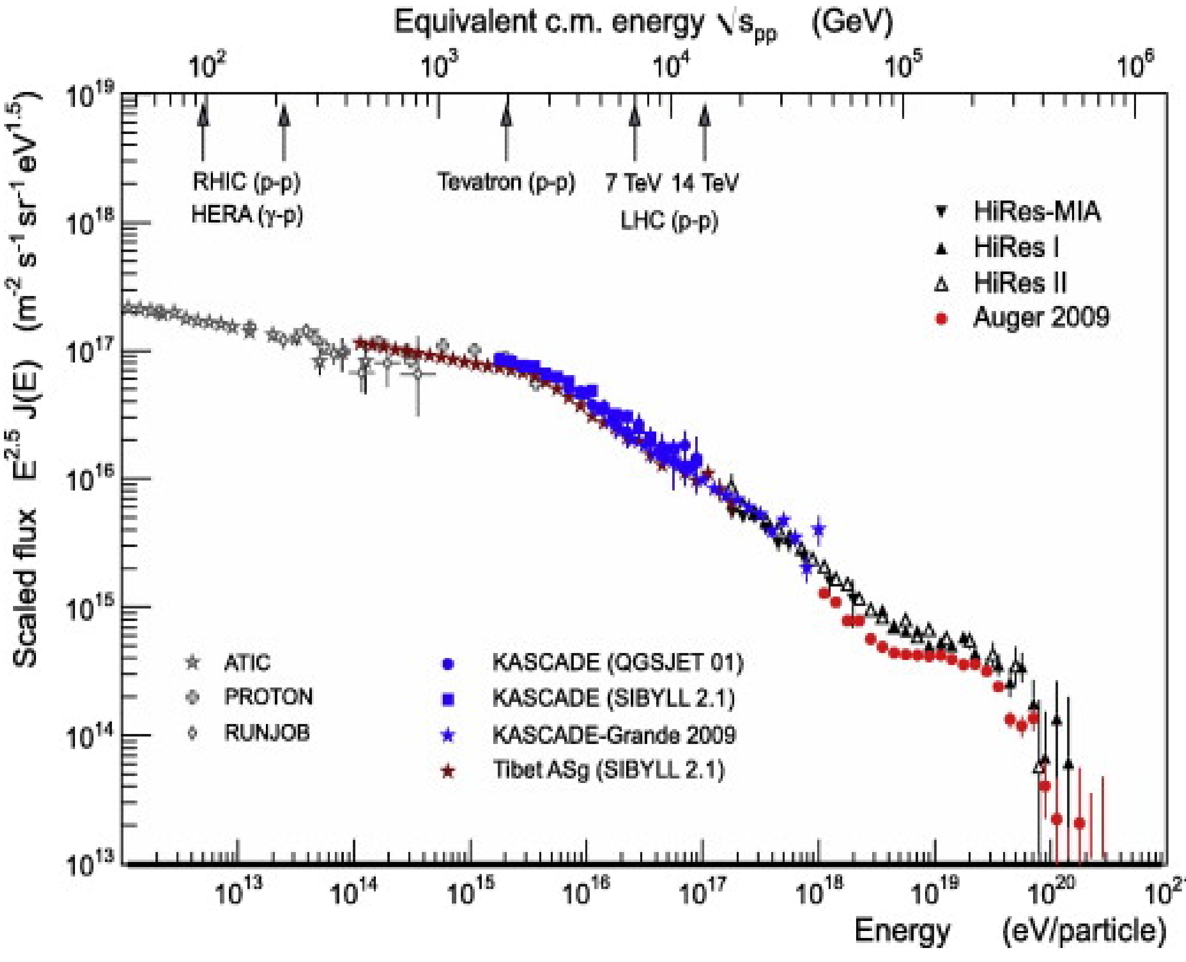
$r_1 = X_R E_s / E_c \approx 9.3\ \mathrm{g/cm^2}$ Molière radius

$C(s) = \Gamma(4.5-s)/[2\pi r_1^2 \Gamma(s) \Gamma(4.5-2s)]$ normalization

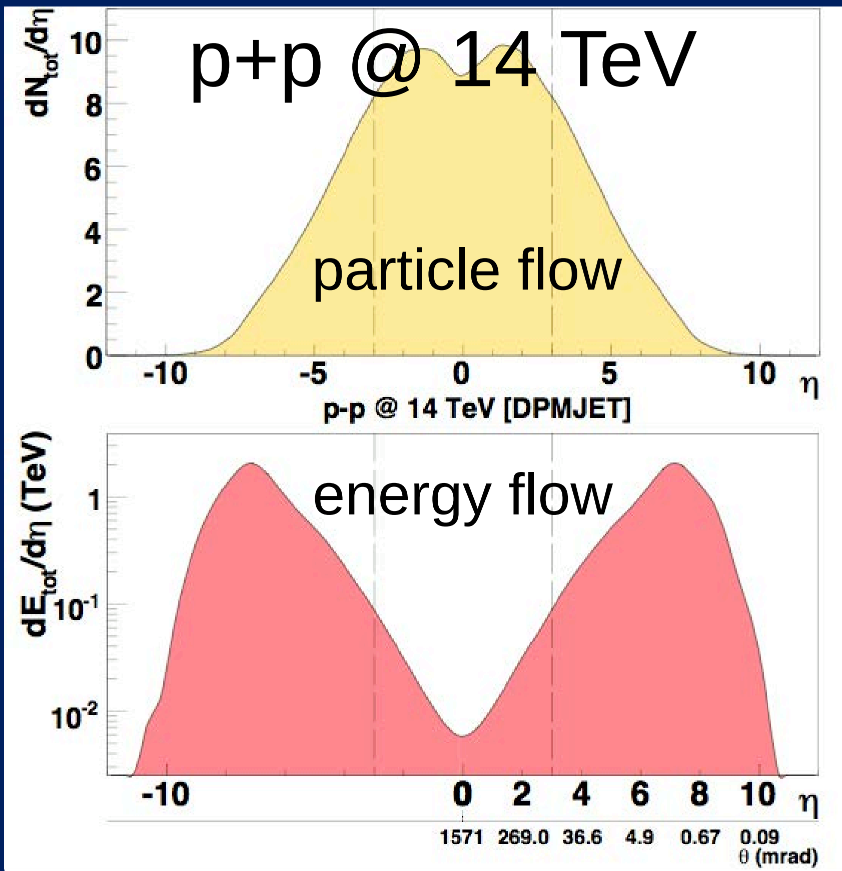
Shower Physics and Interaction Models

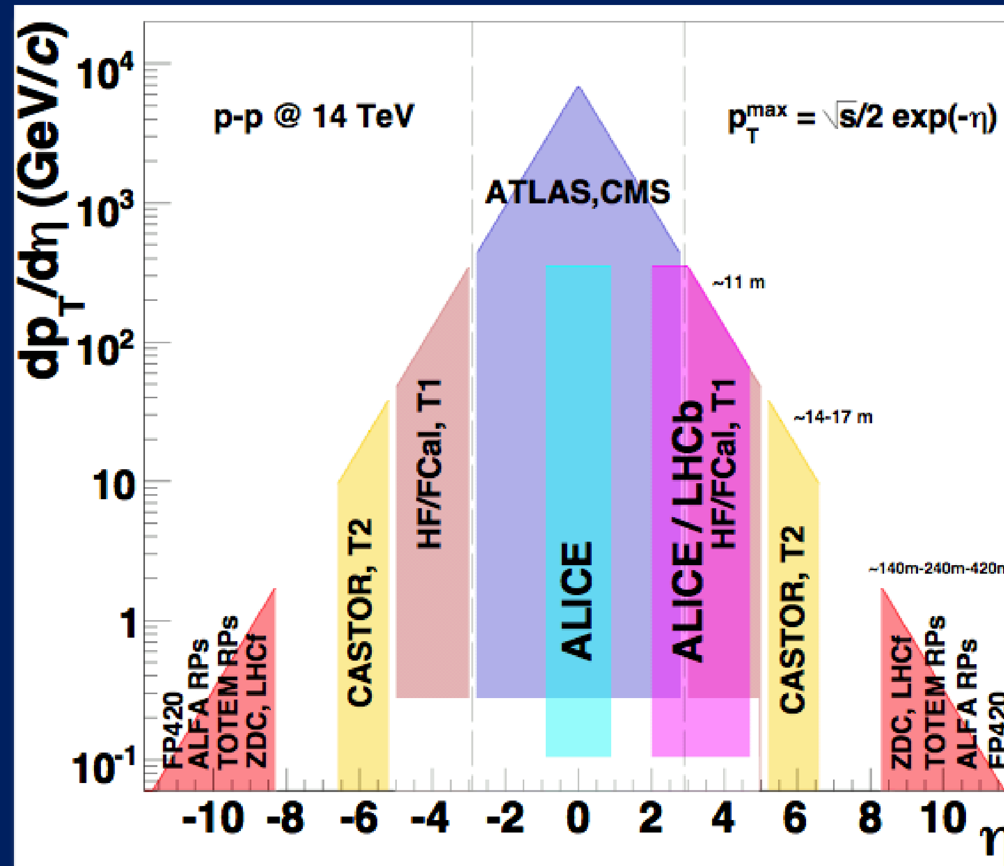
- hadronic interaction models: SYBILL, QGSJET, EPOS
- FLUKA for lower energies
- Tuning with LHC





Coverage of LHC Detectors





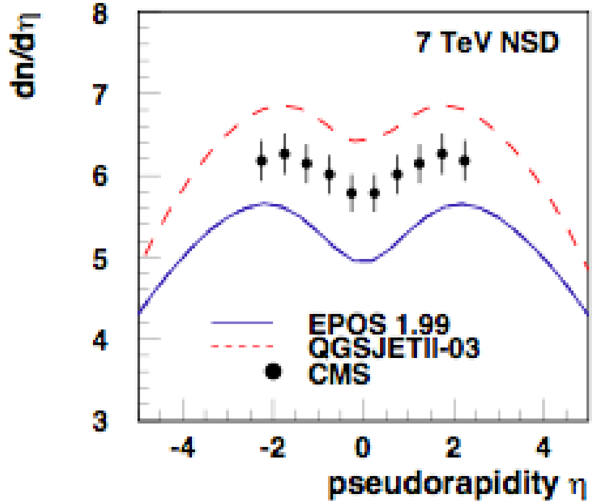
rapidity $$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right) = \text{arctanh}\left(\frac{p_L}{E}\right) \qquad y \to -\ln\left(\tan\frac{\theta}{2}\right) =: \eta$$

→ energy & particle flow at all rapidities

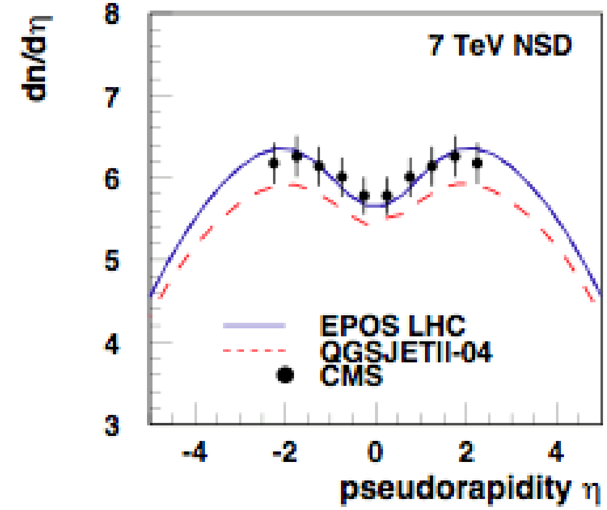
p_T, σ_{Tot}, σ_{inel}, σ_{diffr}, ...

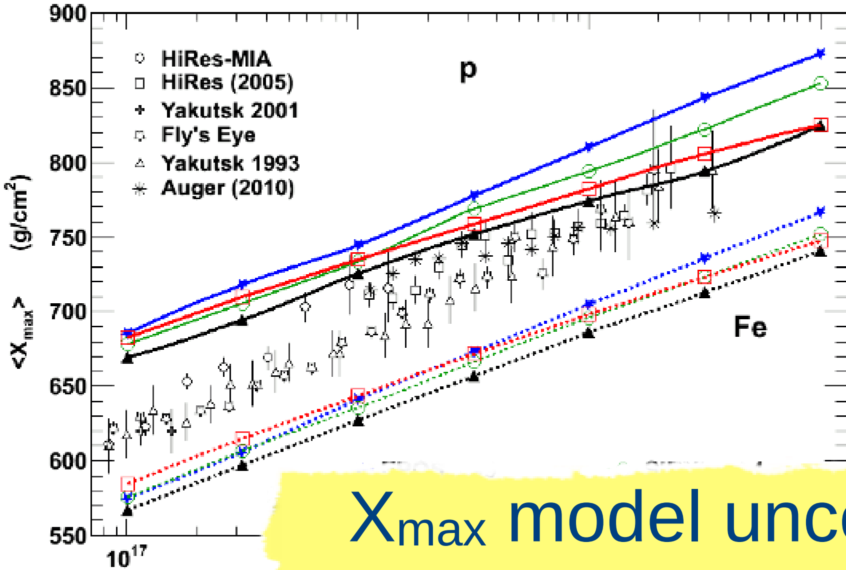
Improvements in Models thanks to LHC

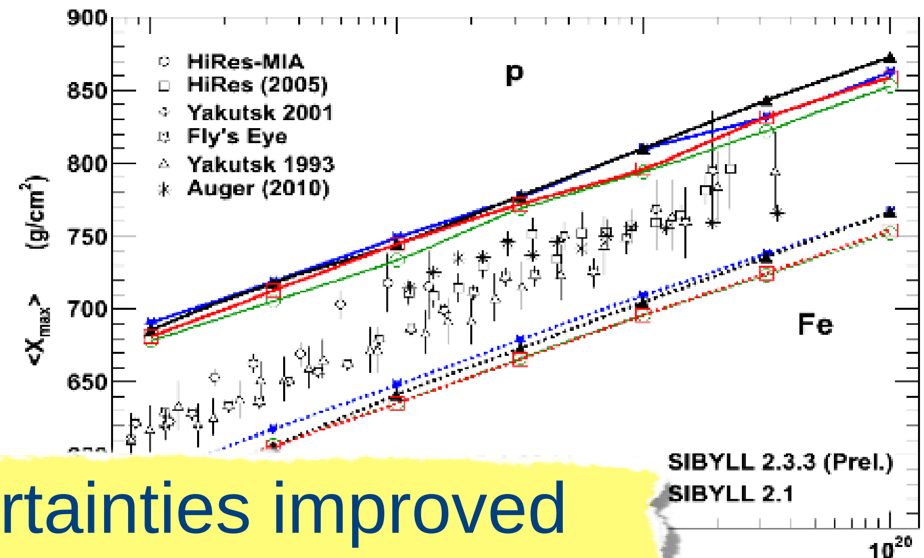
Before LHC



Now

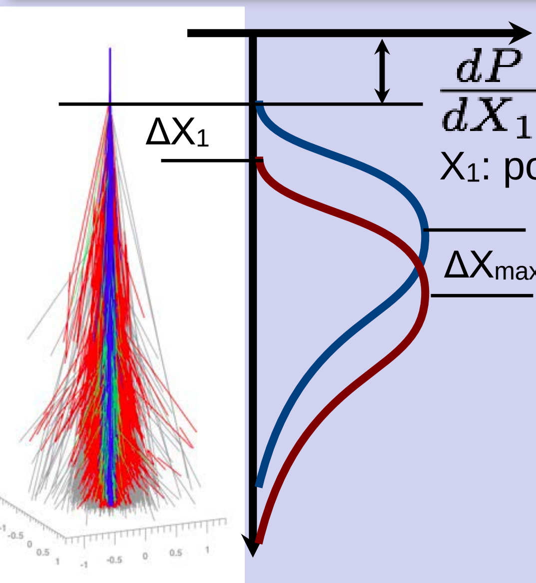






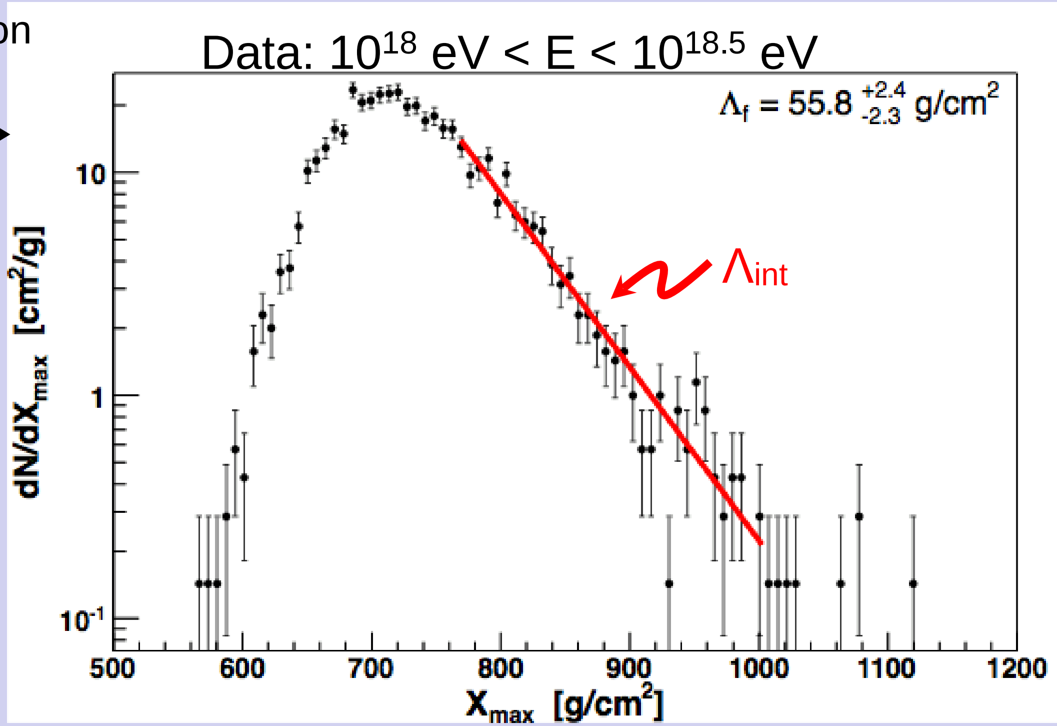
X_{max} model uncertainties improved from ~ 50 g/cm² to ~ 20 g/cm²

p-Air Cross-Section from X_{max} distribution



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

X_1: point of 1st interaction



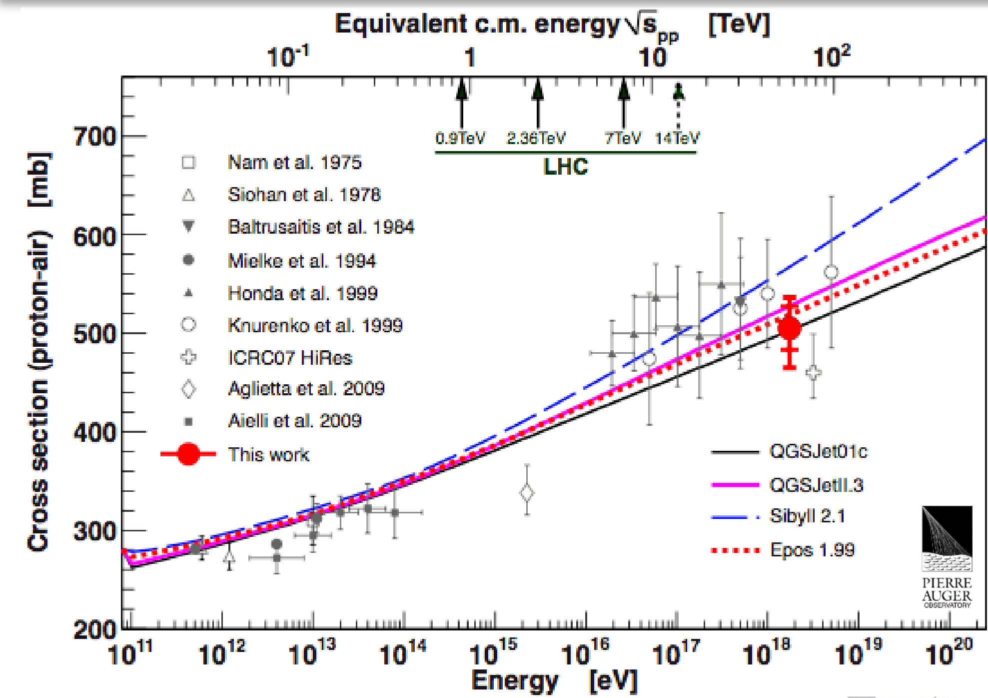
In practice: $\sigma_{p\text{-}Air}$
by tuning models to
describe Λ seen in data

$$\sigma_{p-air} = \frac{\langle n_{air} \rangle}{\lambda_{int}}$$

Difficulties:

- mass composition can alter Λ
- fluctuations in Xmax
- experimental resolution ~ 20 g/cm^2

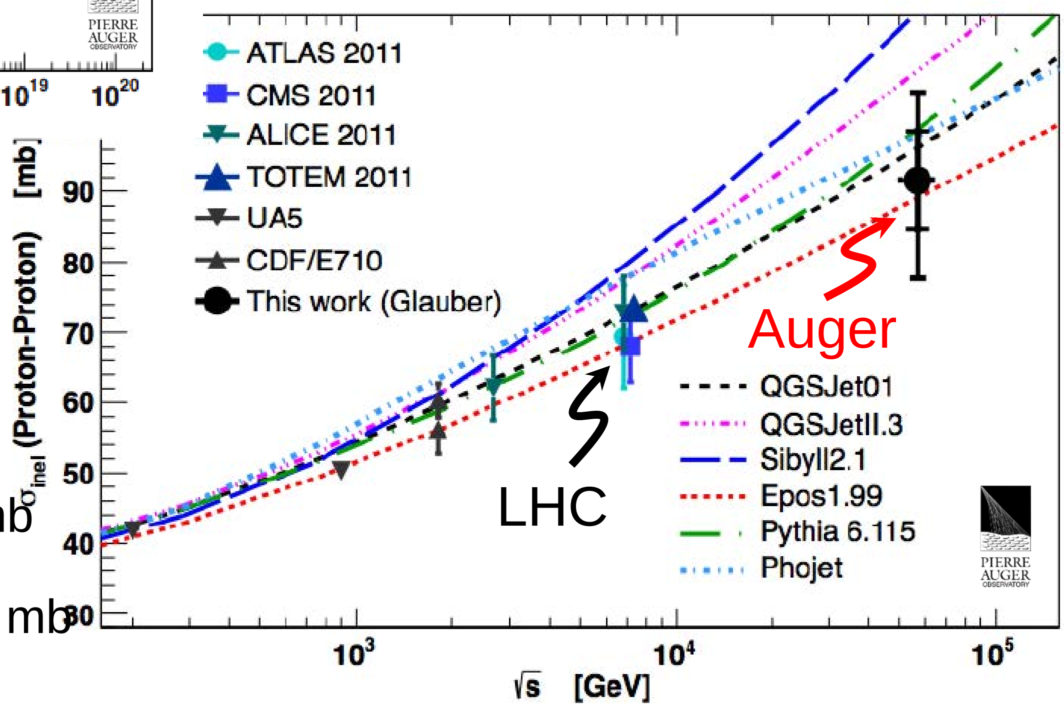
p-Air and pp Cross section @ √s=57 TeV



Auger Collaboration, PRL 109, 062002 (2012)

Conversion from p-air to p-p cross section by Glauber-approach

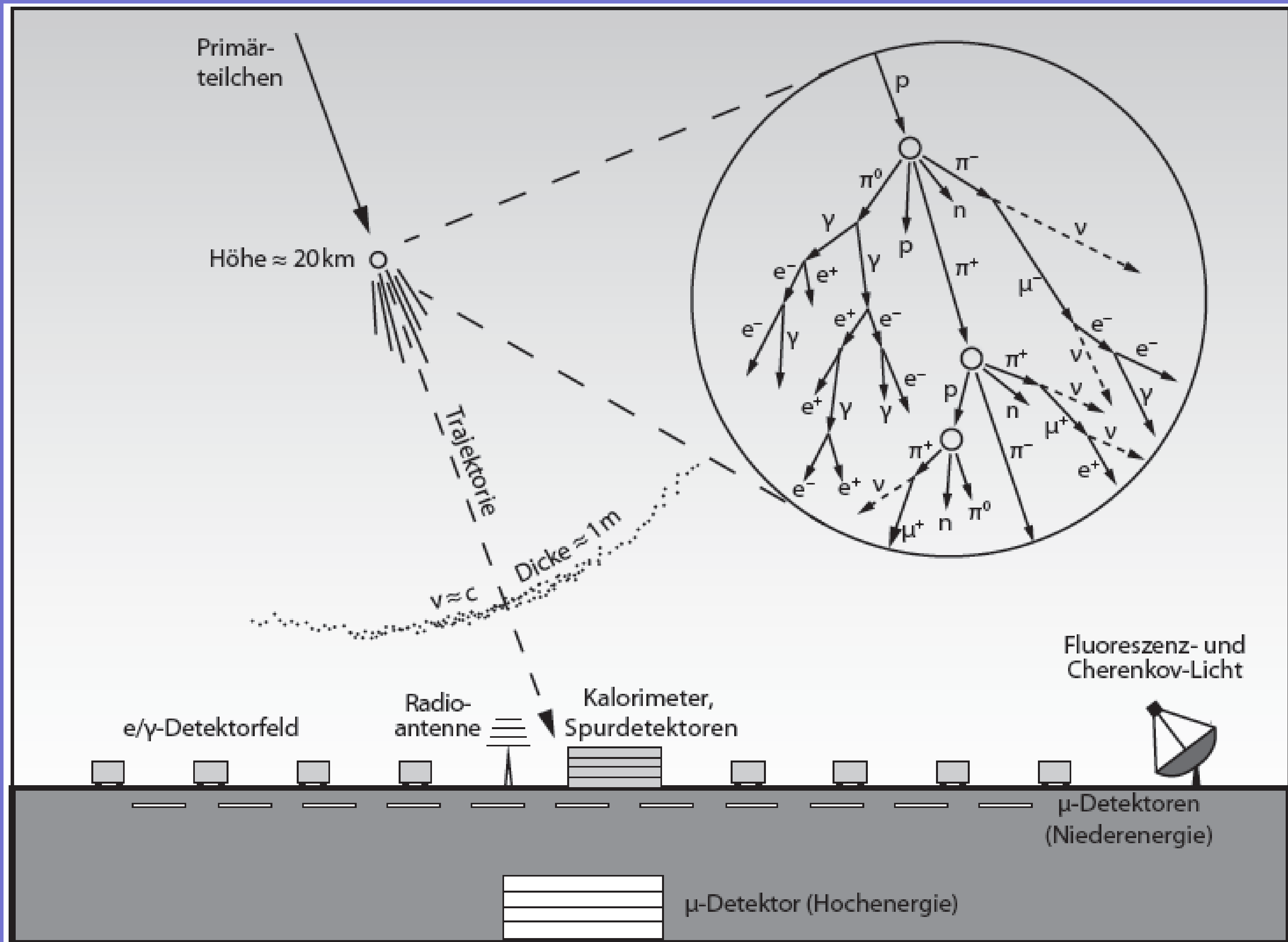
$$\sigma_{p\text{-}Air} = (505 \pm 22_{stat}\,(^{+26}_{-34})_{sys}\,)\ \mathrm{mb}$$



$$\sigma^{inel}_{pp} = [92 \pm 7_{stat}\,(^{+9}_{-11})_{sys} \pm 7.0_{Glauber}]\ \mathrm{mb}$$

$$\sigma^{tot}_{pp} = [133 \pm 13_{stat}\,(^{+17}_{-20})_{sys} \pm 16_{Glauber}]\ \mathrm{mb}$$

Detecting Extensive Air Showers

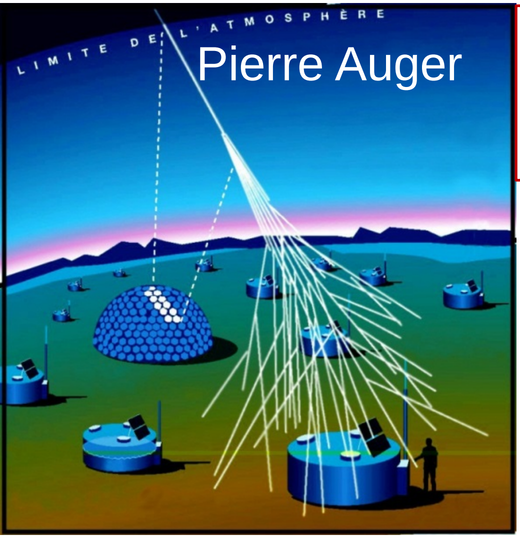


Detector sizes

very high particle densities in air showers → take only samples

distance	7.5 m
size	40000 m^2
energies	10 TeV – 1 PeV

distance	13 m
size	40000 m^2
energies	100 TeV – 10 PeV

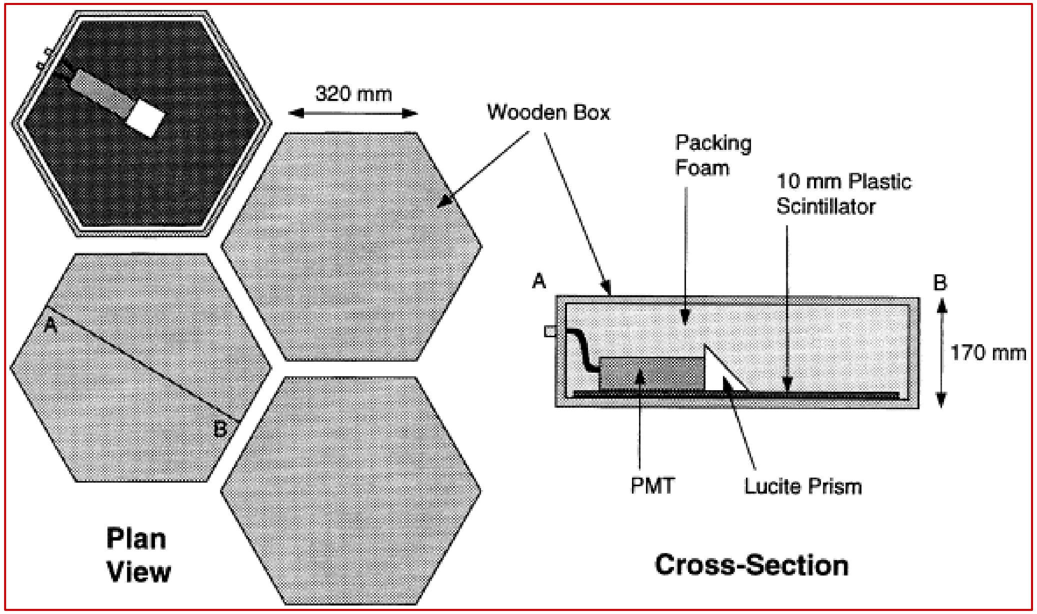


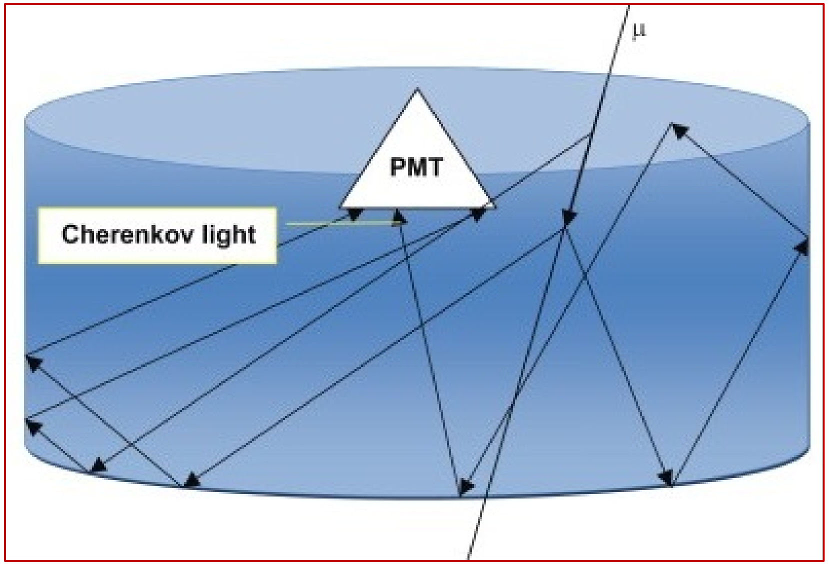
distance	1500 m
size	3000 km^2
energies	EeV – 100 EeV

distance	125 m
size	1 km^2
energies	PeV – EeV

Sampling Detectors

Sampling on the surface



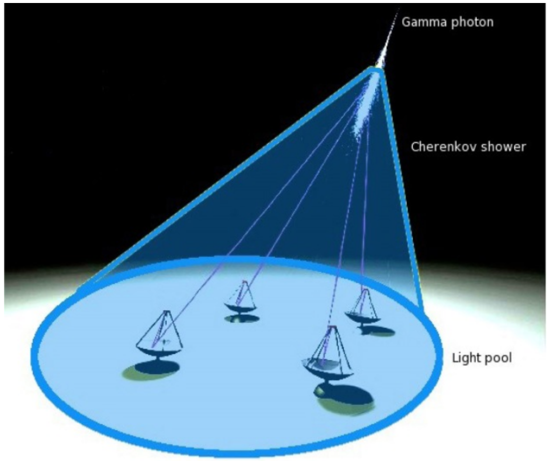


scintillation counters
measure: **number of particles**

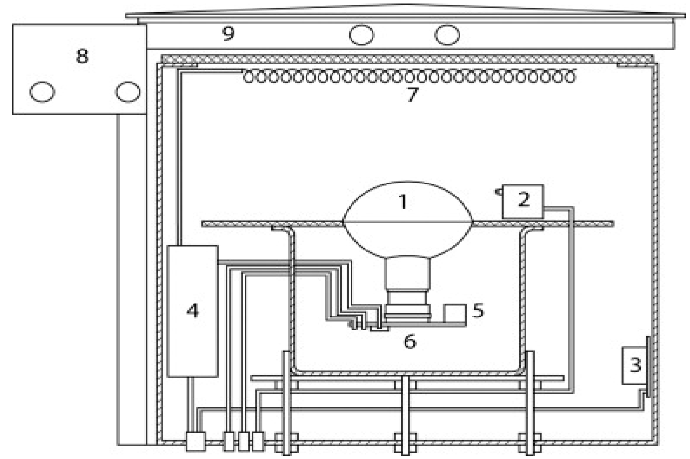
water/ice Cherenkov detectors
measure: calorimetric energy

Sampling of longitudinal shower profile

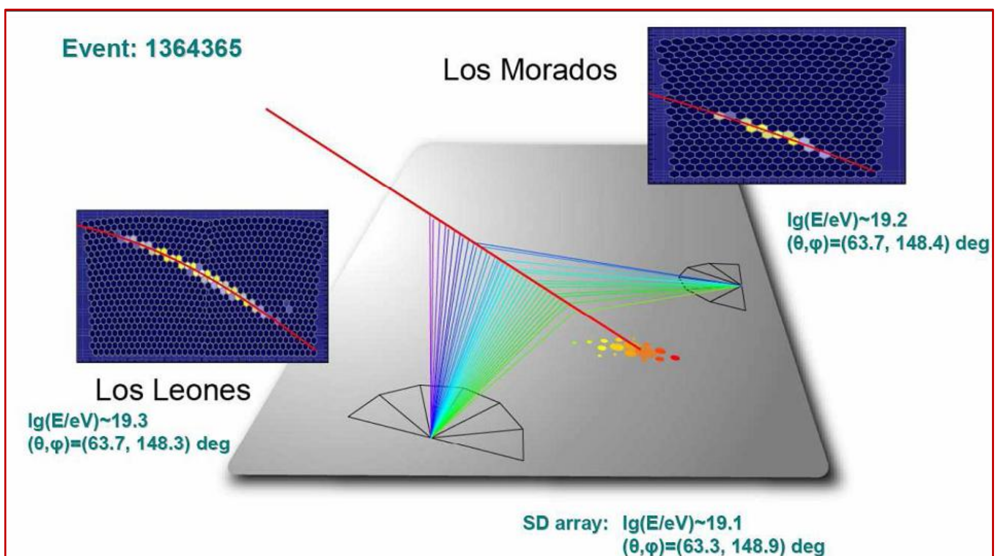
imaging Cherenkov

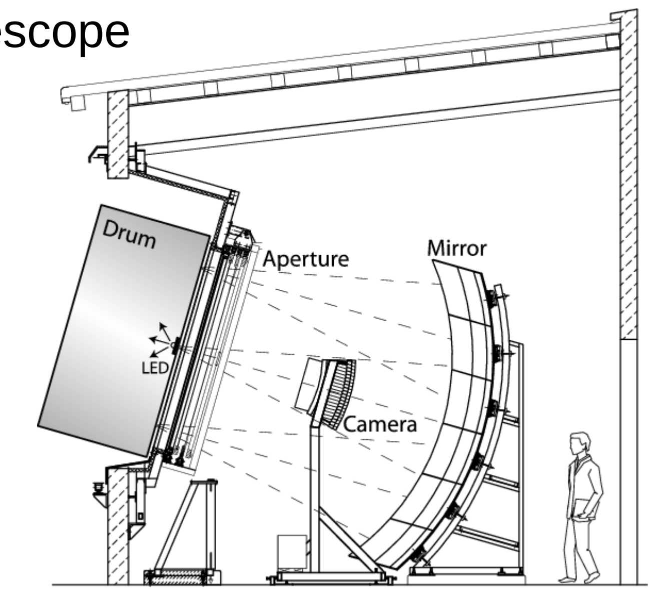


non-imaging Cherenkov

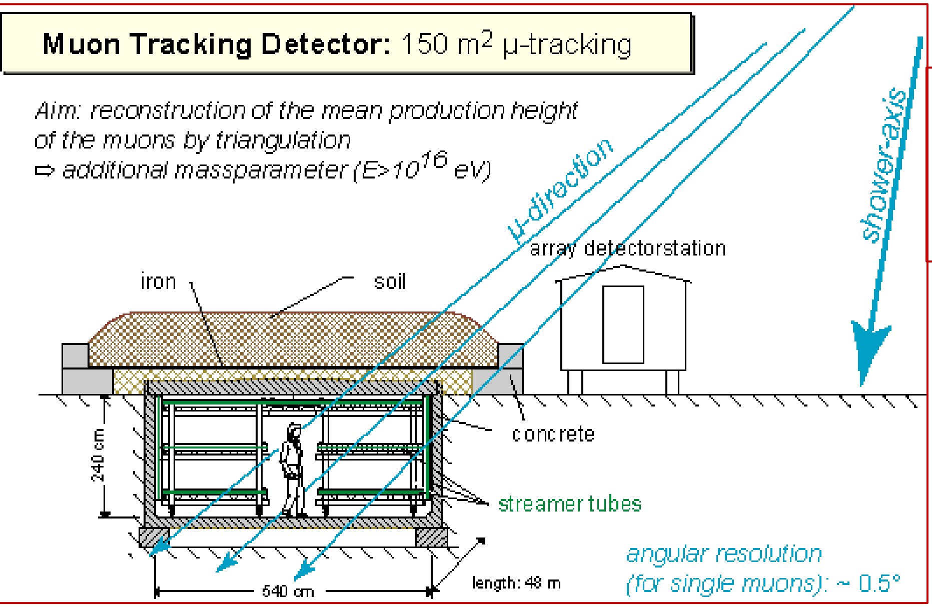


fluorescence telescope

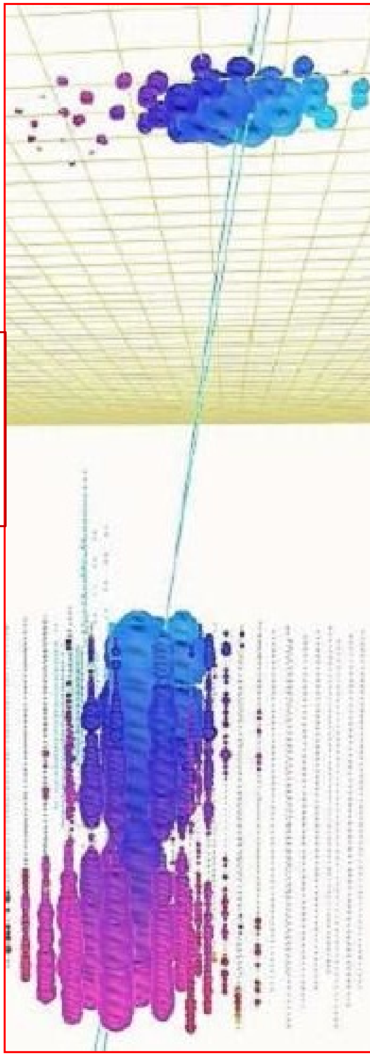




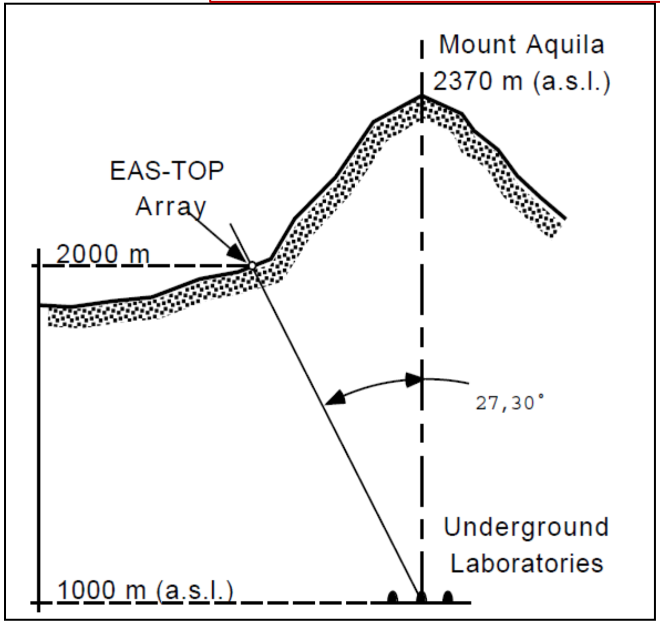
muon detectors



GeV muons from shower products



TeV muons from first interaction, near shower axis



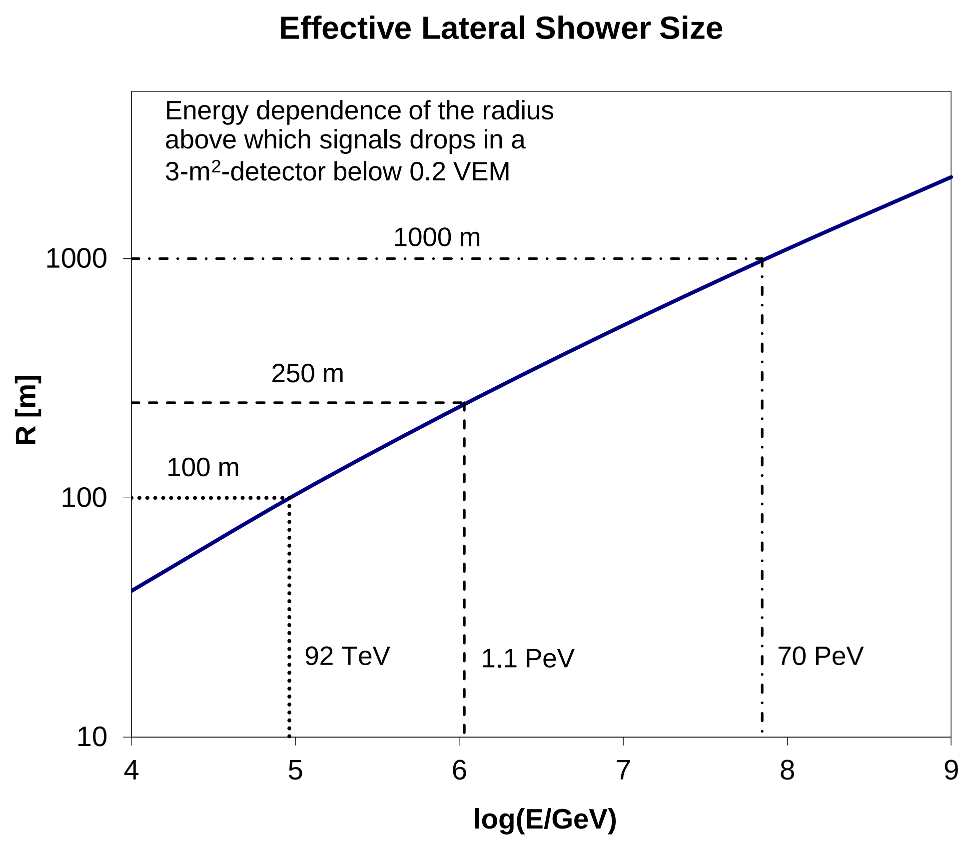
muon number is composition sensitive:

for HE nucleus each nucleon interacts independently
$\Rightarrow$ higher hadron multiplicity
$\Rightarrow$ higher meson decay rate
$\Rightarrow$ higher muon rate

Sampling distance

- you need large areas,
- but need not completely covered because of high particle densities
- for O(m^{2}) detector find range of suitable signals, see →
- chose sampling distance such that that detector does not limit energy and angle resolution

Estimate for IceTop:

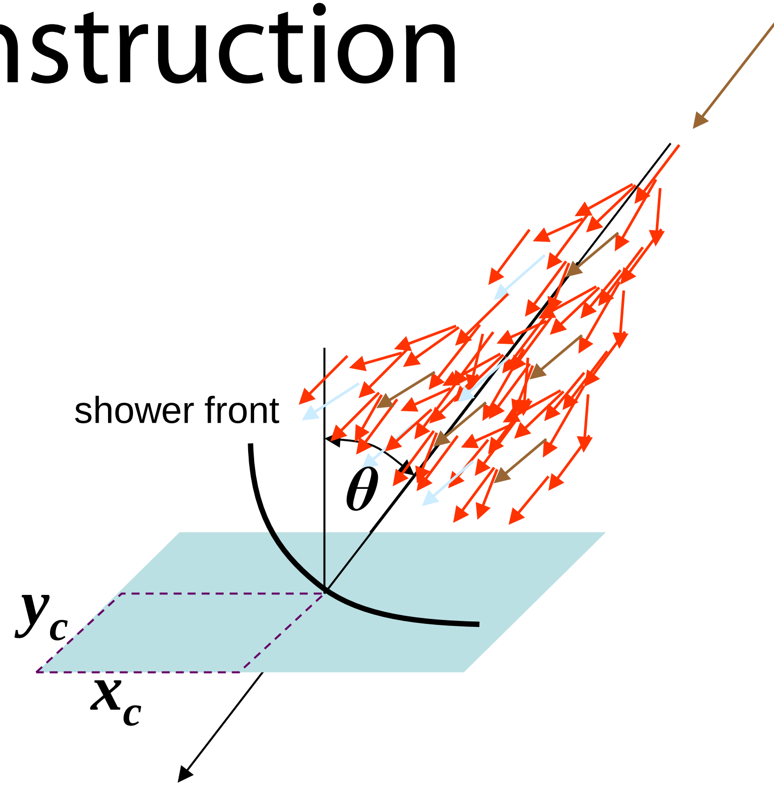


Air Shower Reconstruction

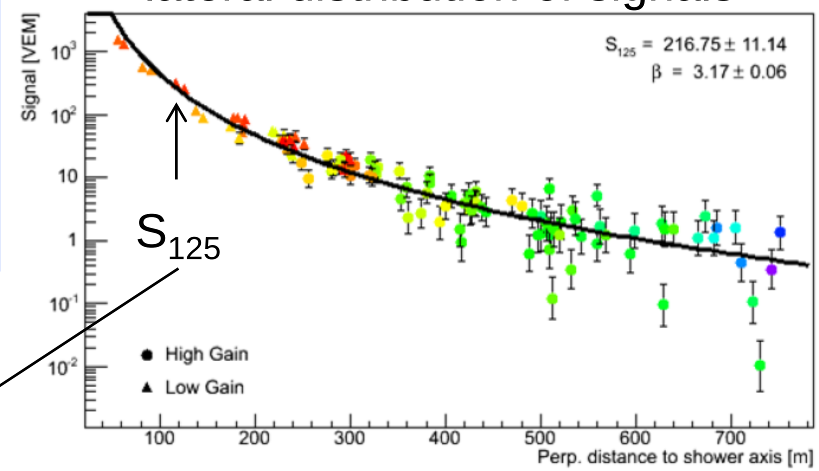
N signals $(s_i, \vec{x}_i, t_i)$

$\Downarrow$

- shower direction: θ, φ
- shower centre x_c, y_c
- shower size $\Rightarrow E_0$ (with ***mass hyp.)***
- shower age: $\Rightarrow X_{max}$

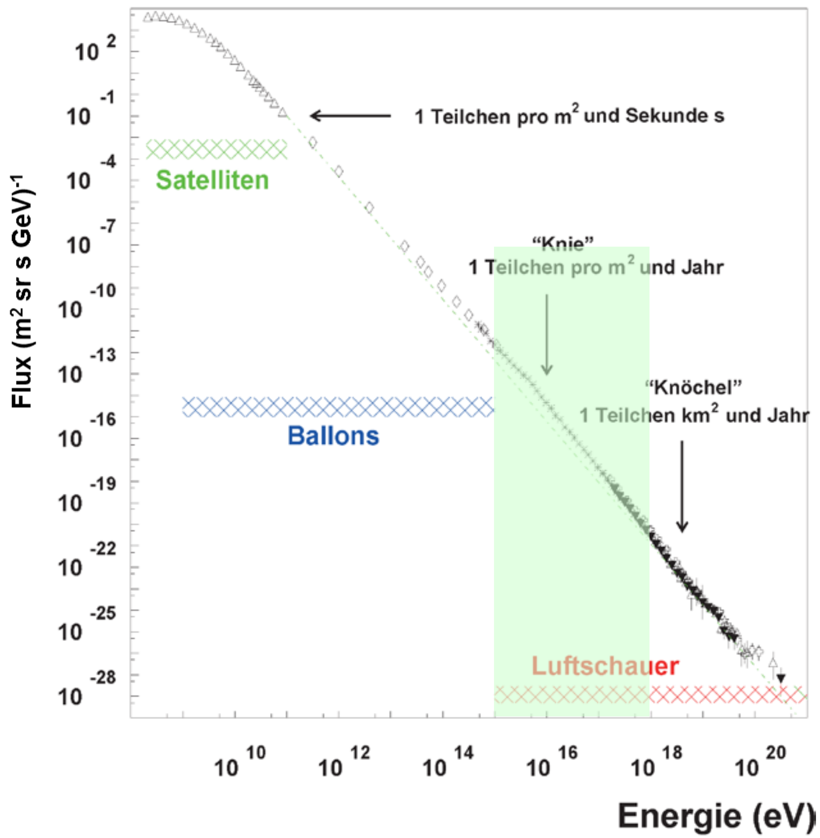


lateral distribution of signals



reference signal size at R=125 m

Detectors in the PeV to EeV Range



Typical size ~ 1 km^2

e.g. Kaskade-Grande, Tunka, IceTop,

What limits a 1 km^2 detector?

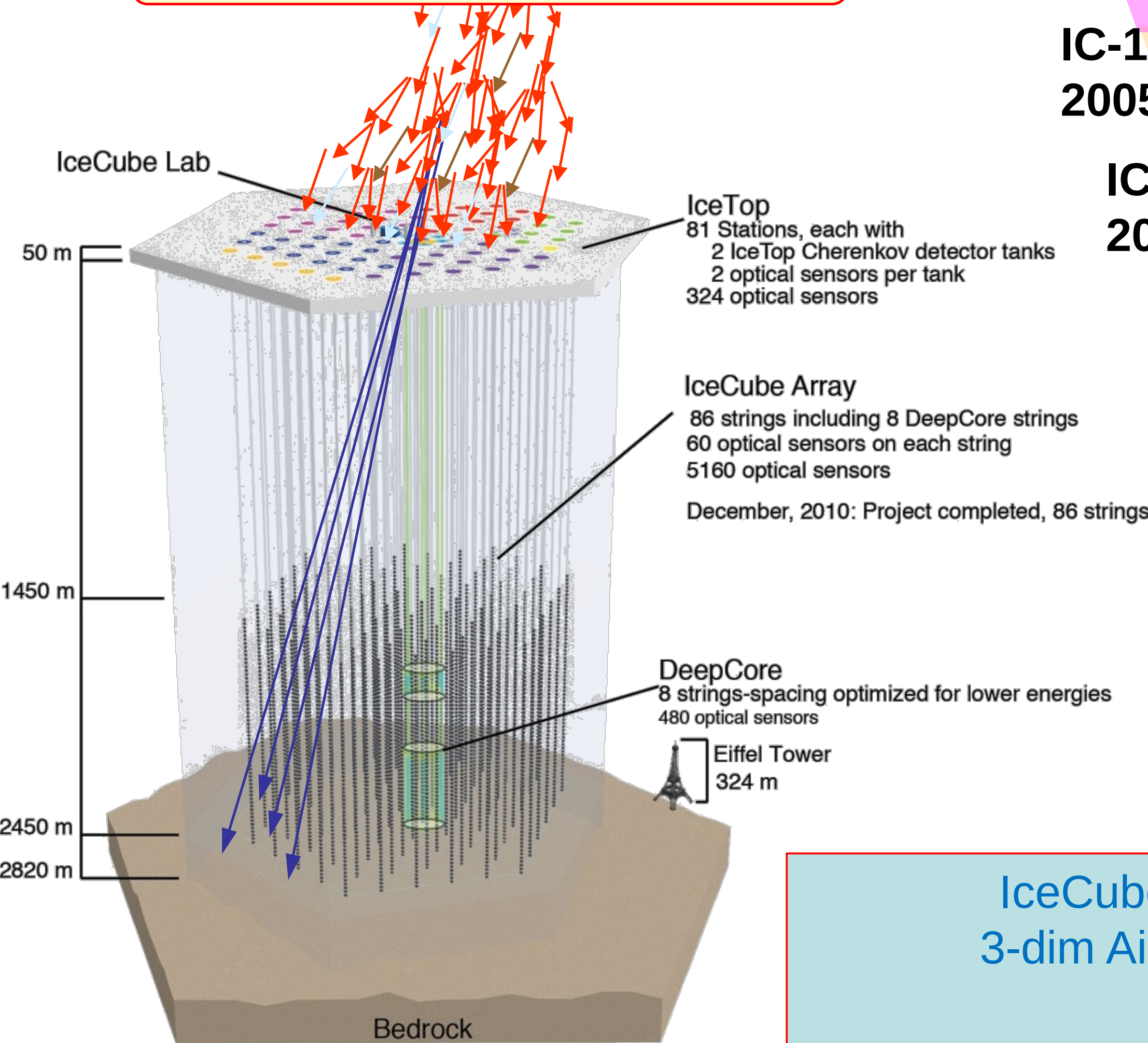
at 1 EeV: $F=1.5\times10^{-21}$ $(m^2\ sr\ s\ GeV)^{-1}$

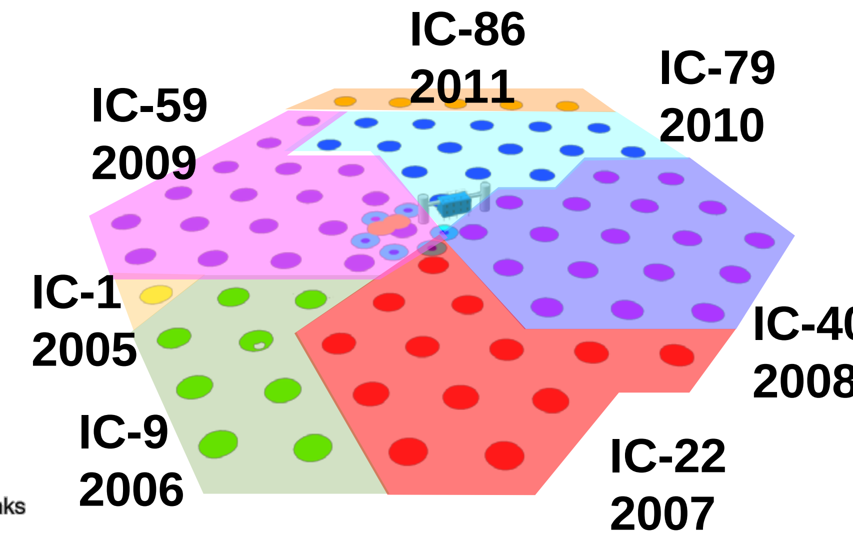
for $\Delta\log E = 0.1$; $\Delta\Omega=1.8$ sr ($\theta<45°$); $A=1\ km^2$

you get about 8 events per year

IceCube Detector

Detector Completion Dec 2010





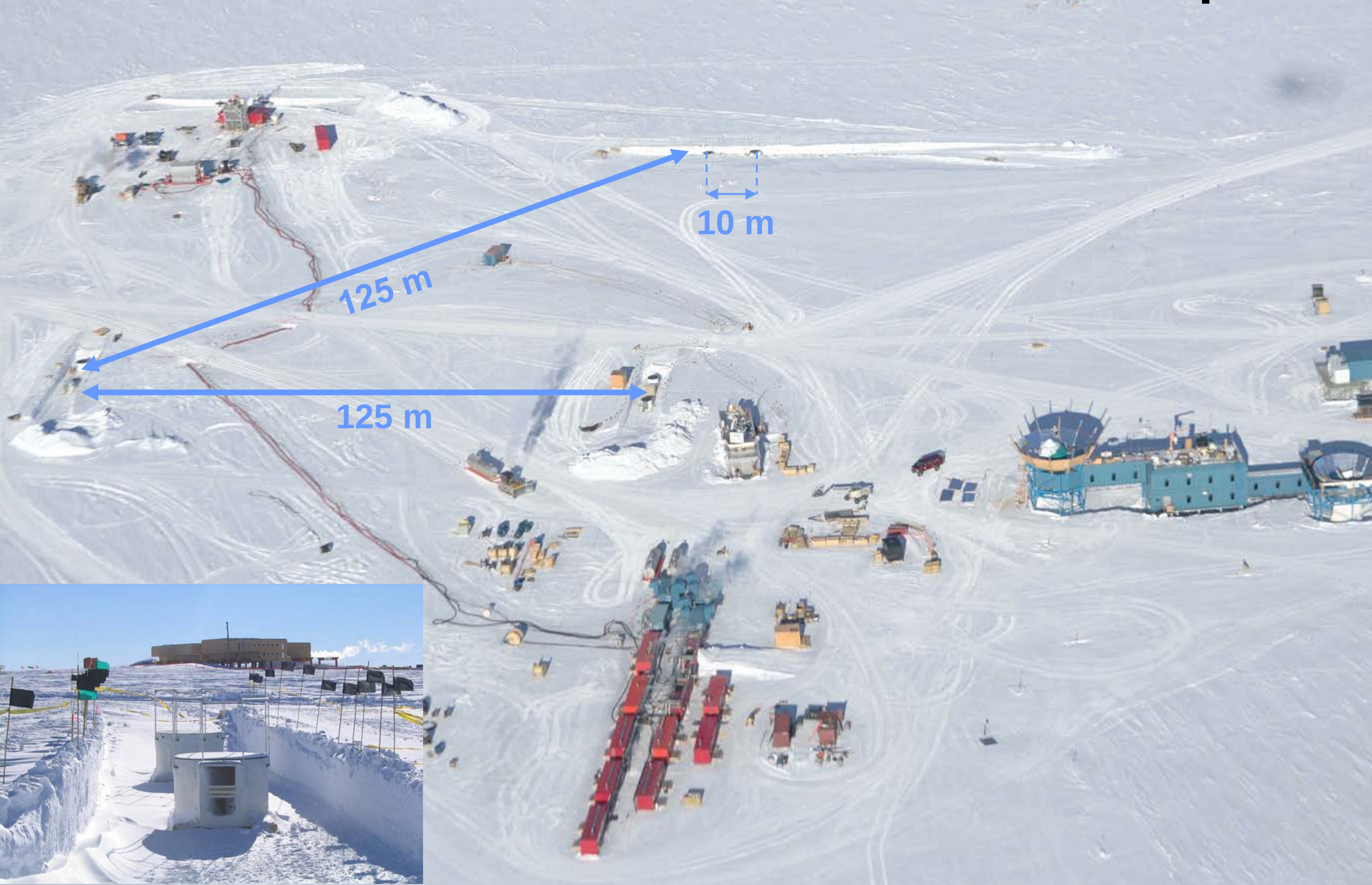
CR Analyses

- air showers in IceTop
- muon (bundle)s in IceCube
- atm. neutrinos in IceCube
- IceCube - IceTop coinc.

IceCube with IceTop is a
3-dim Air Shower Detector

unprecedented volume

Aerial view of IceCube/IceTop



DOM – Digital Optical Module

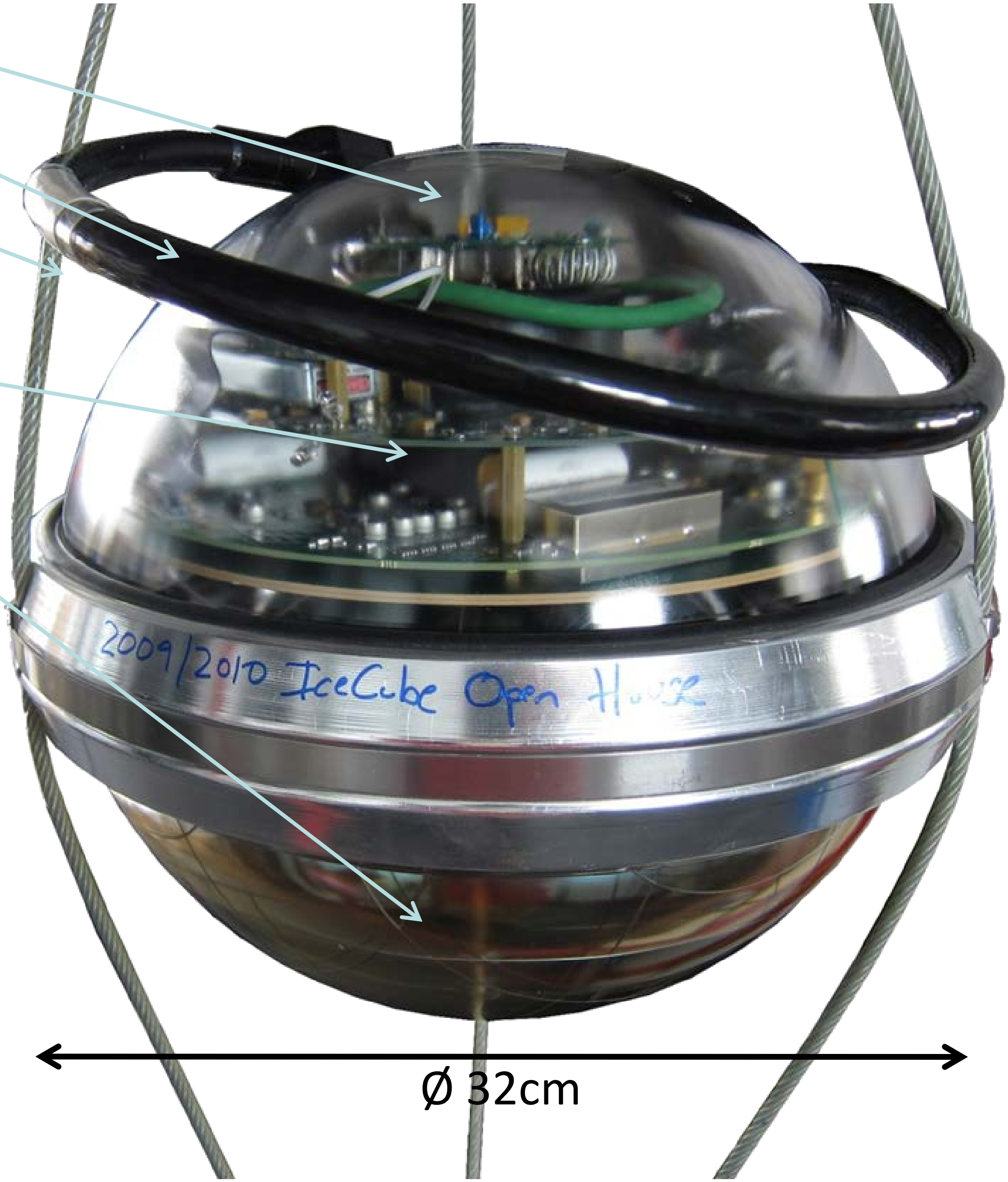
pressure glas sphere

junction cable

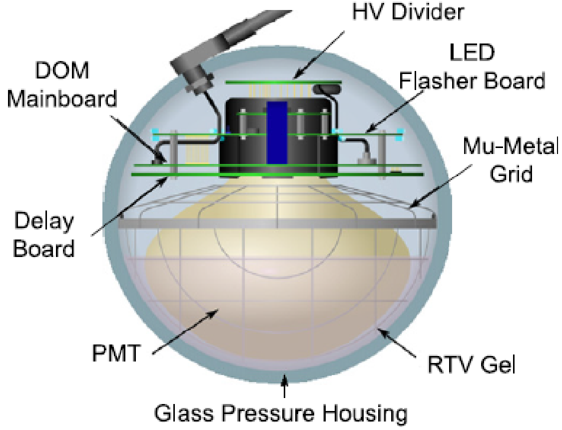
harness

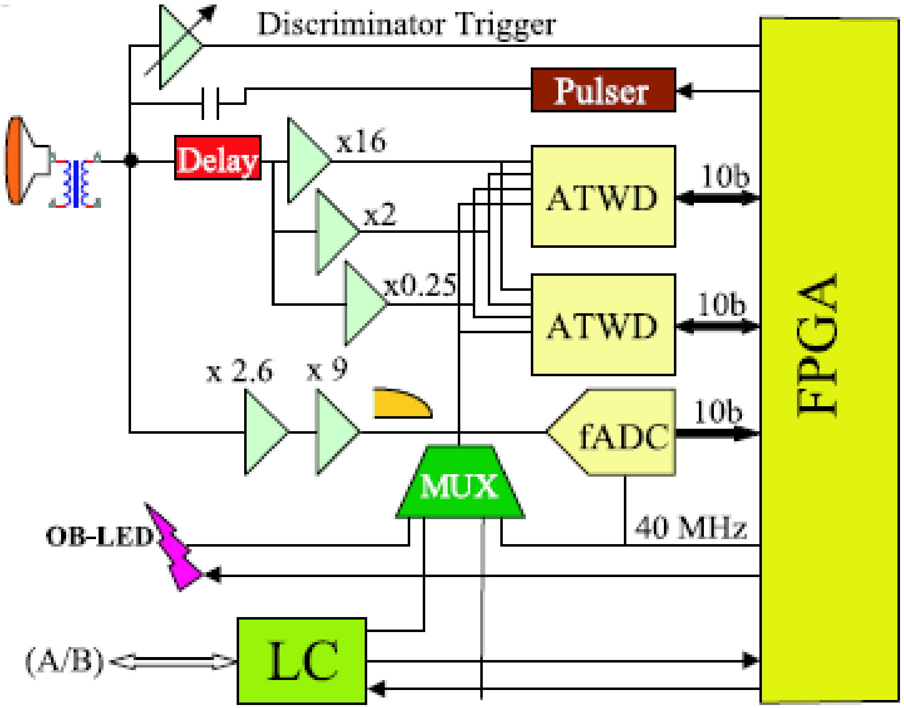
elektronics:
high voltage,
digitalization,
data transfer

photomultiplier = light sensor



DOM – Frontend Electronics





PMT with integrated HV-converter

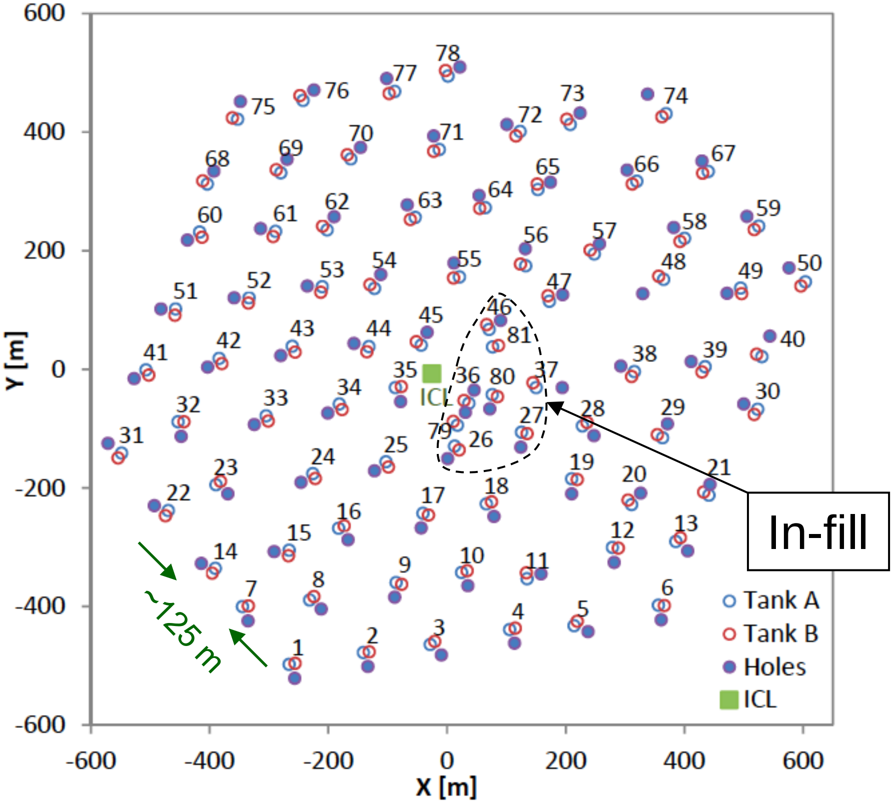
- Onboard Digitalisation
  - o ATWD, 128 Samples in 422 ns
  - o FADC, 256 samples in 6.4 µs
- Local Coincidence with neighbors
- Onboard calibration and tests
- Autonomous operation

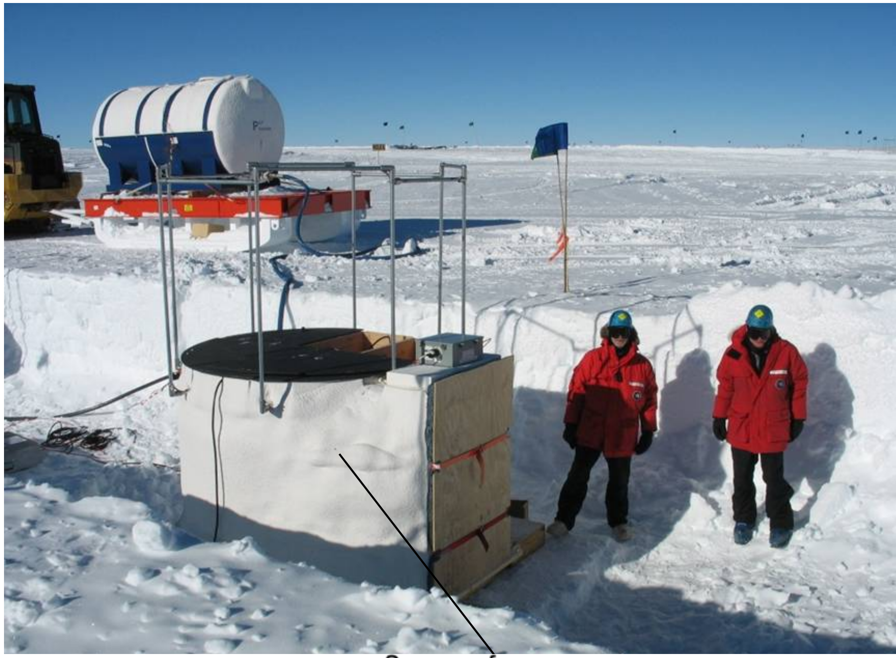
<u>3 amplifications:</u>

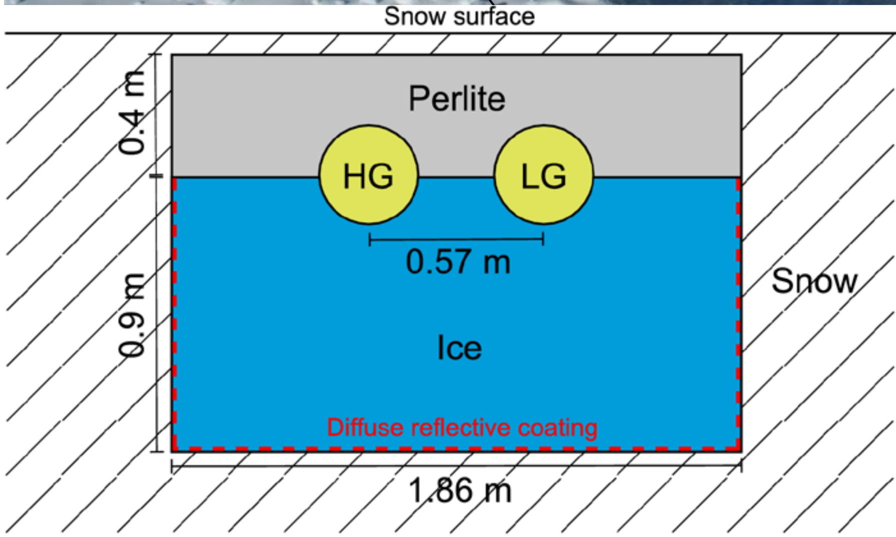
least significant bit (LSB):	0.15 pe	(photoelectronen)
saturation HG DOM	8000 pe	⇒ effective 16 bit
saturation LG DOM	125000 pe	⇒ effective 20 bit

~ 10^6 steps

Final IceTop Detector Array 2011







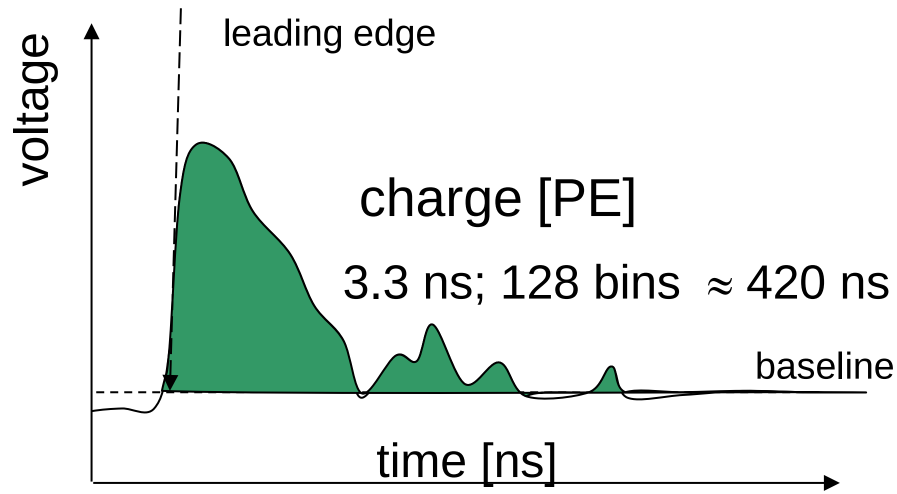
final detector:

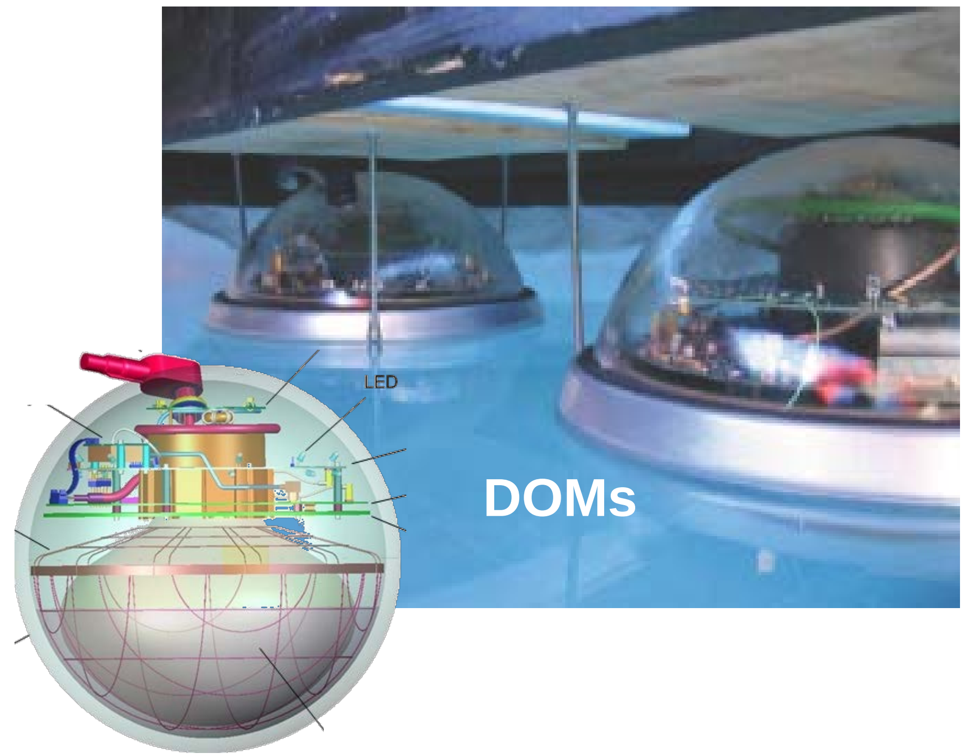
81 stations (162 tanks)

mostly ~ 125 m;

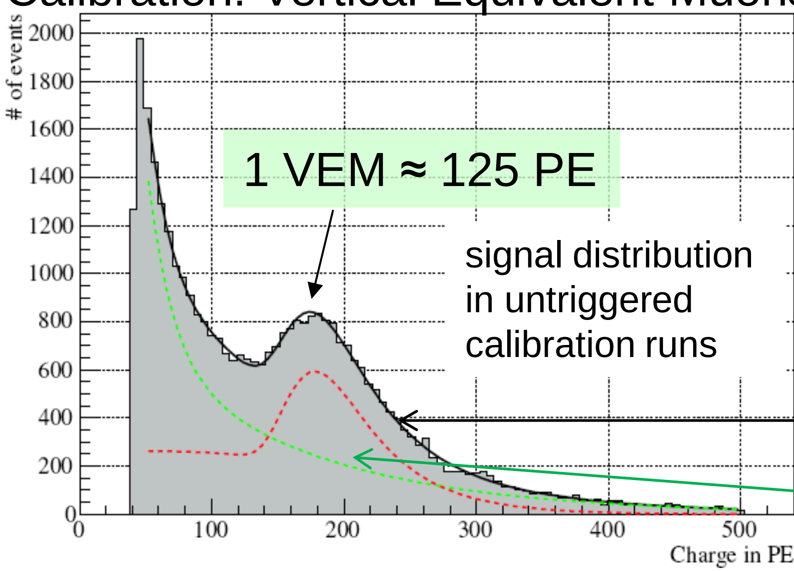
In-fill array: 3 inserts +5 closest stations

IceTop Signal Recording





Calibration: Vertical Equivalent Muons

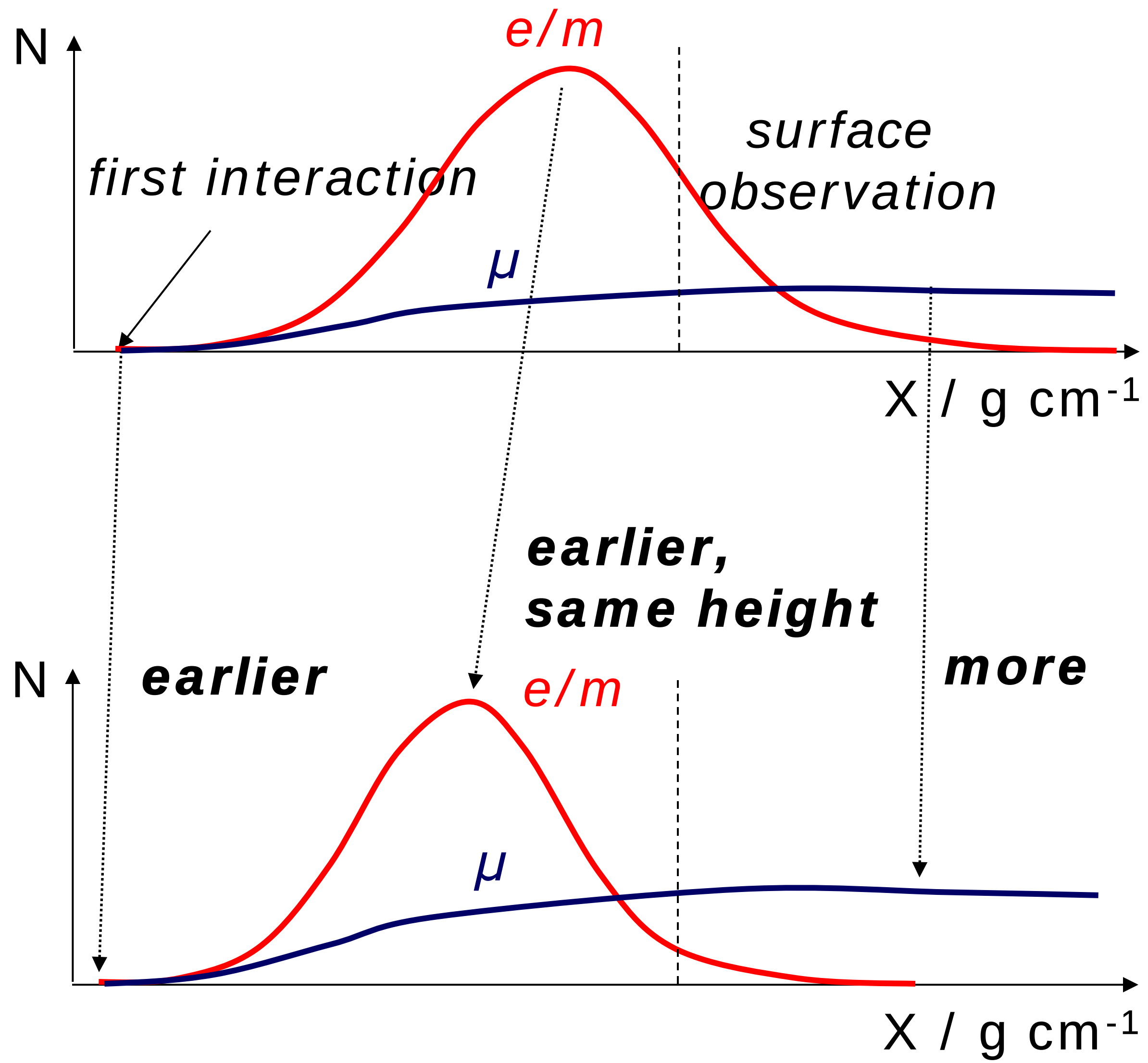


muon signal

e.m. background

⇒ snow height on tanks

Shower Development for Different Nuclei

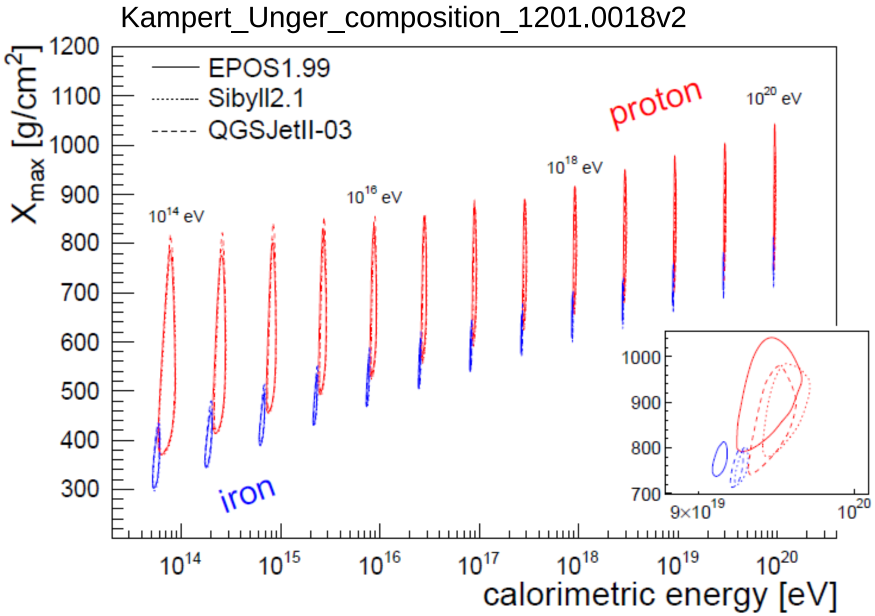


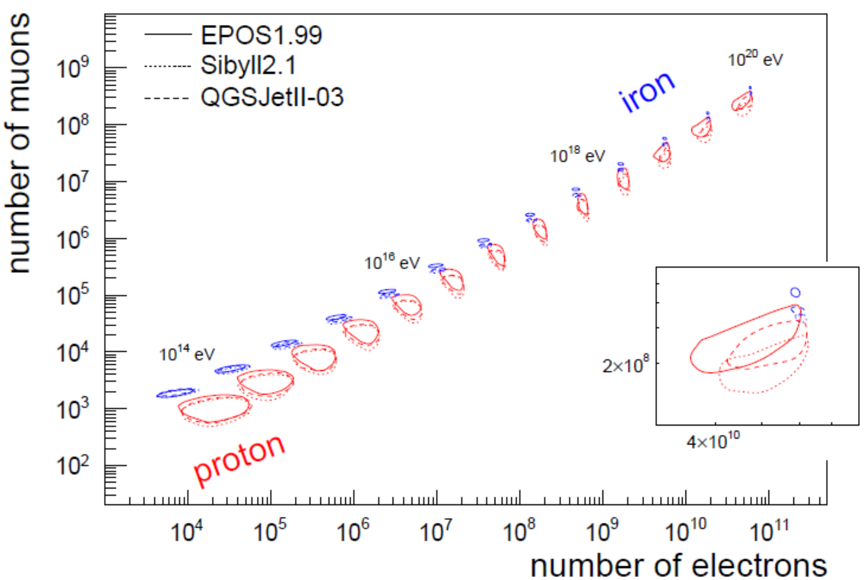
proton

heavier nucleus:

- earlier maximum
- more muons

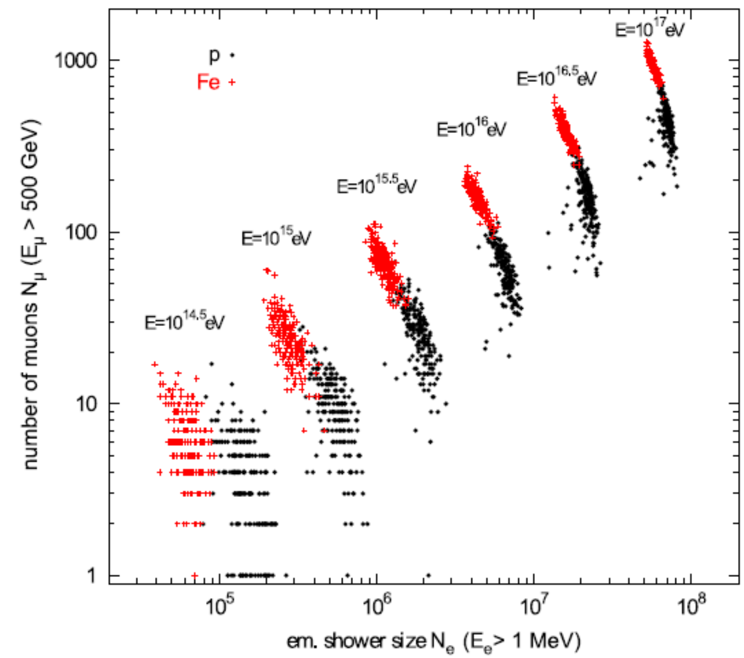
Composition dependent Observables





Muon Multiplicity

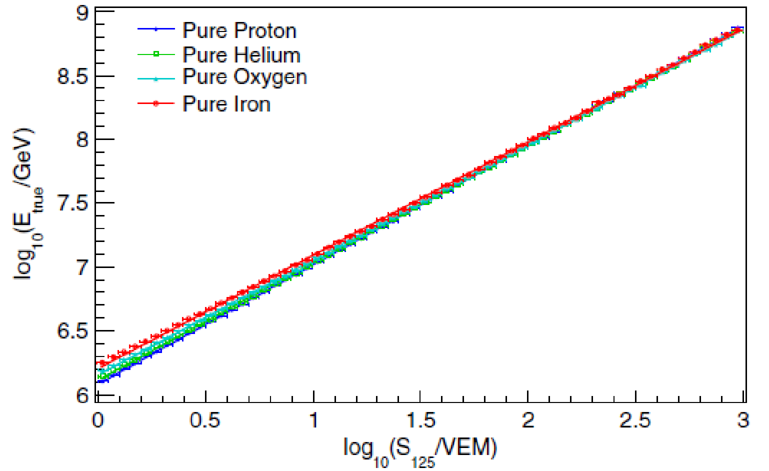
$$N_\mu \sim A^{0.23}\, E^{0.77}$$



Derived Spectrum Depends on Composition:

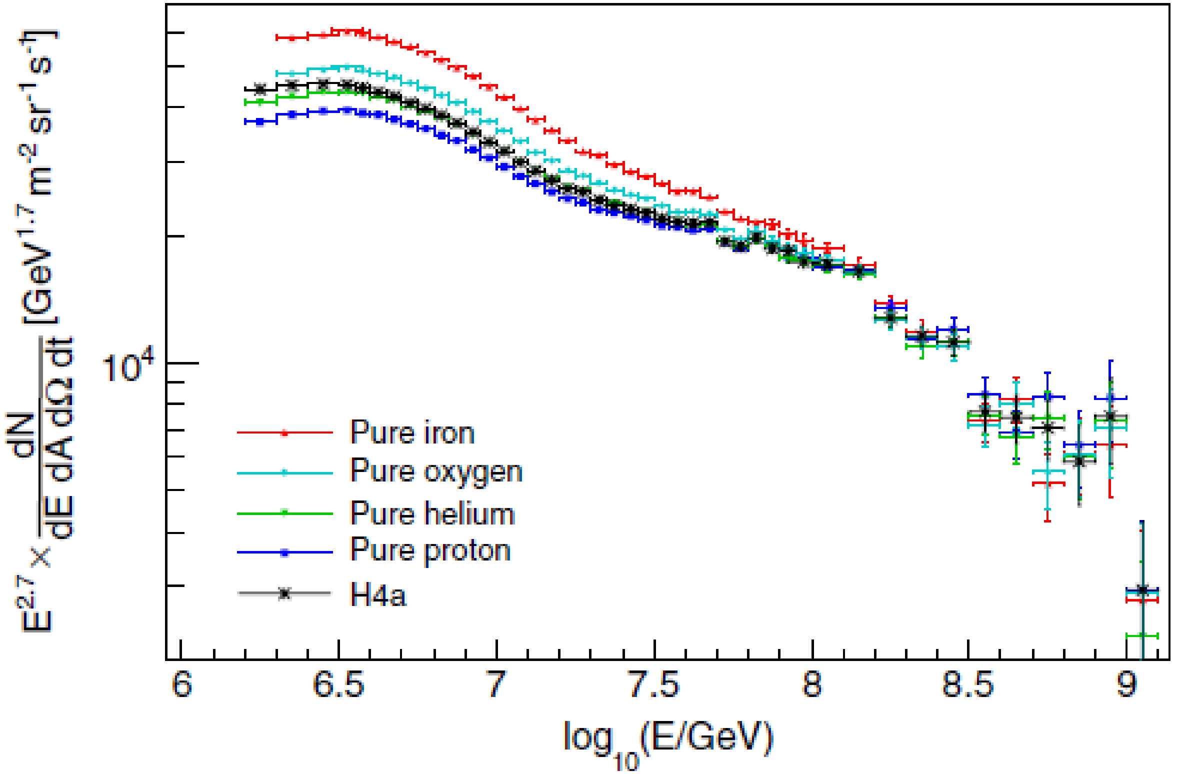
flux of primary CR:

$$J(E) = \frac{dN}{dE\,dA\,d\Omega\,dt}$$

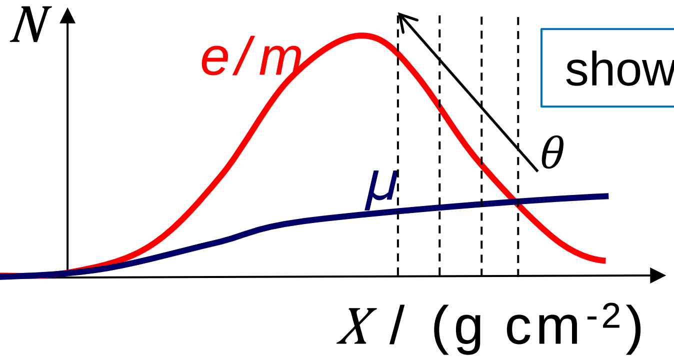


shower size

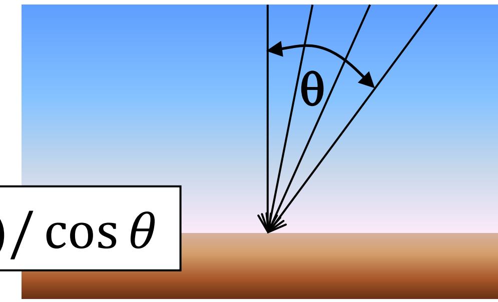
Different shower age of different elements



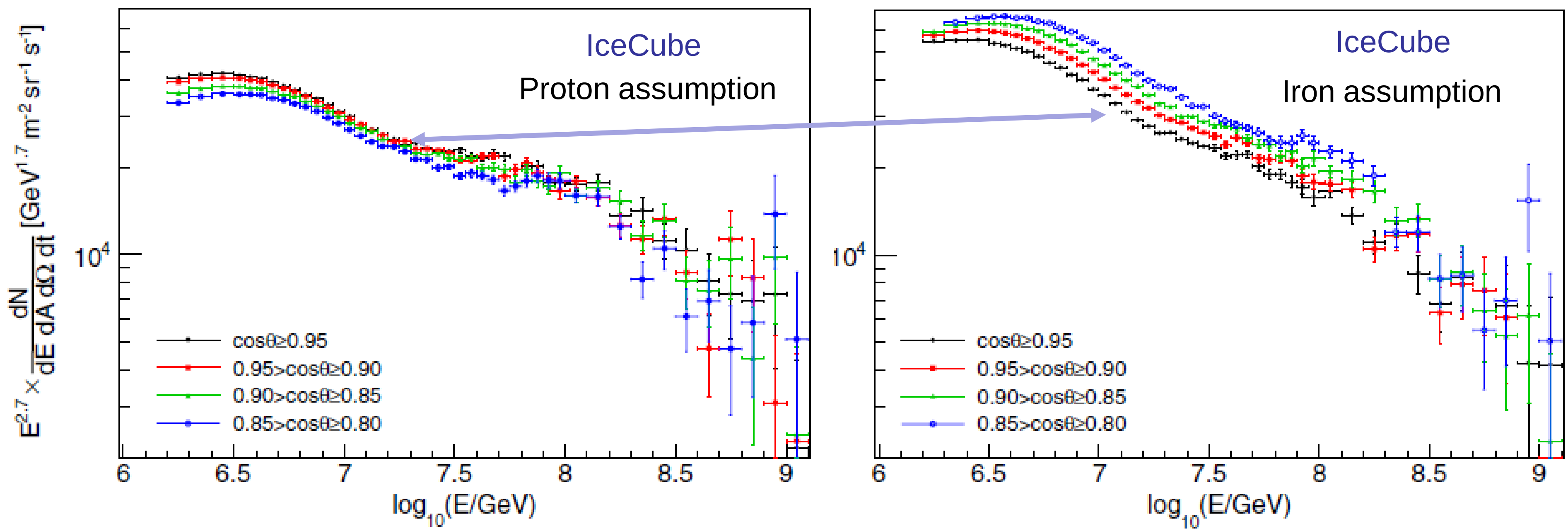
Composition Sensitivity of Slant Depth



shower size depends on zenith angle



Slant depth = $X(\theta) = X(0)/\cos\theta$



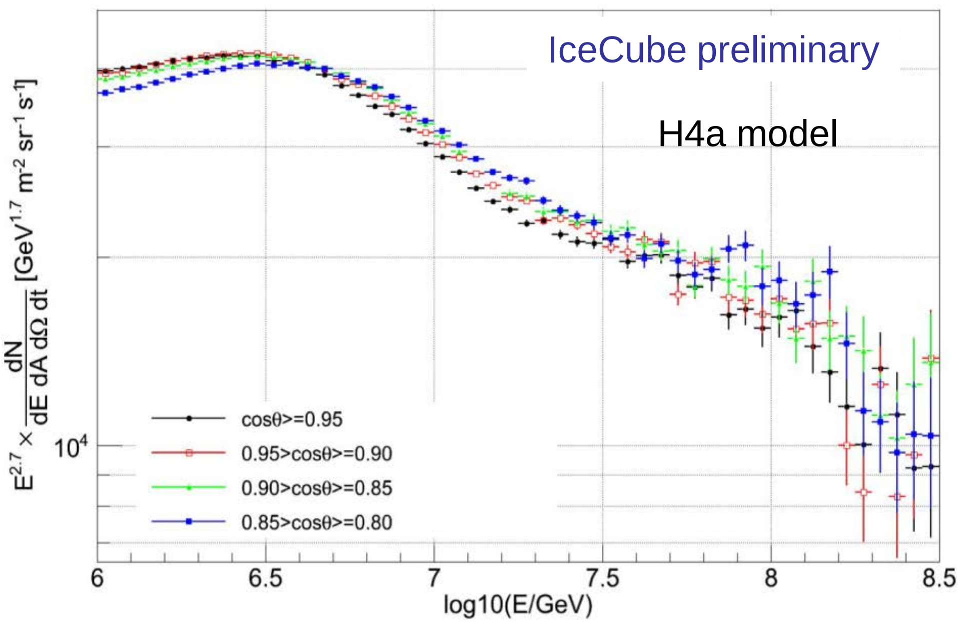
→ Flux not isotropic for proton or iron only assumptions

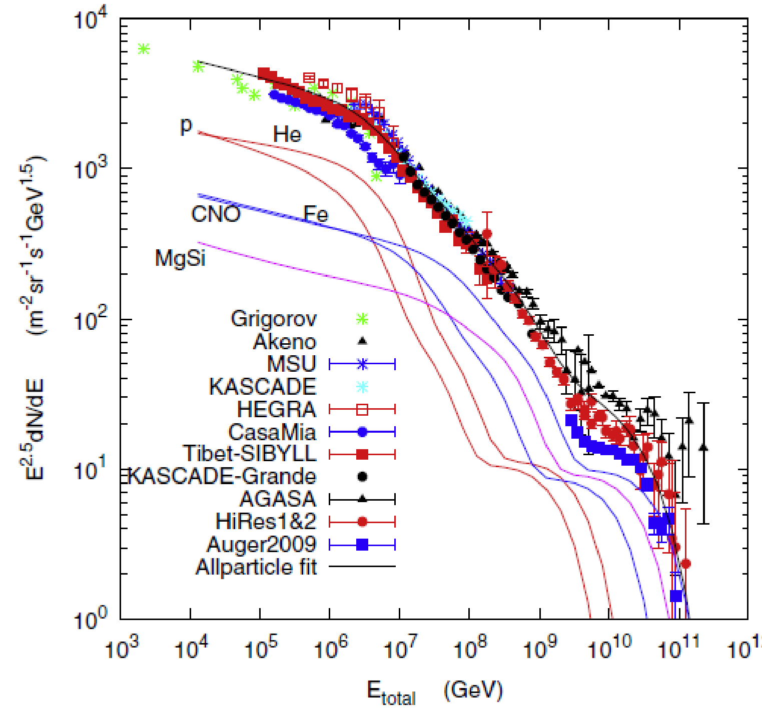
→ Mixed composition needed!

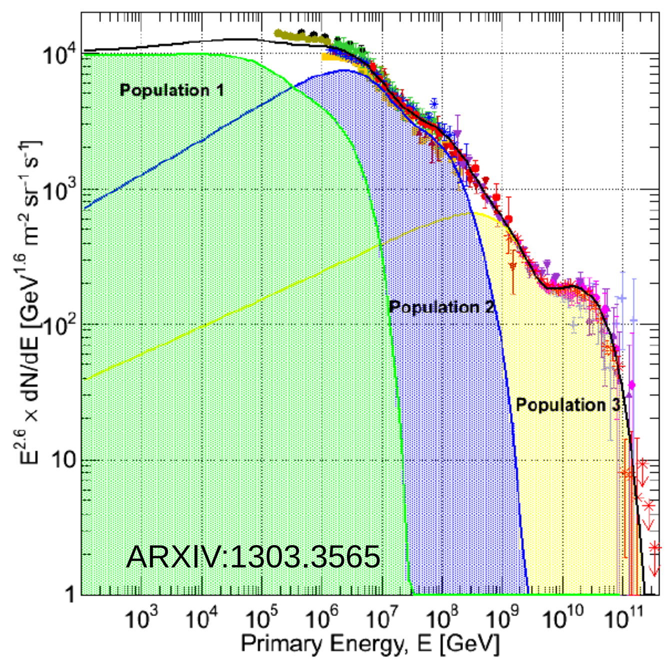
→ Isotropy requirement leads to composition sensitivity with surface detector only!

Composition Model H4a

T.K.Gaisser. "Spectrum of cosmic-ray nucleons, kaon production, and the atmospheric muon charge ratio." Astropart. Phys. 35 (2012) 801.



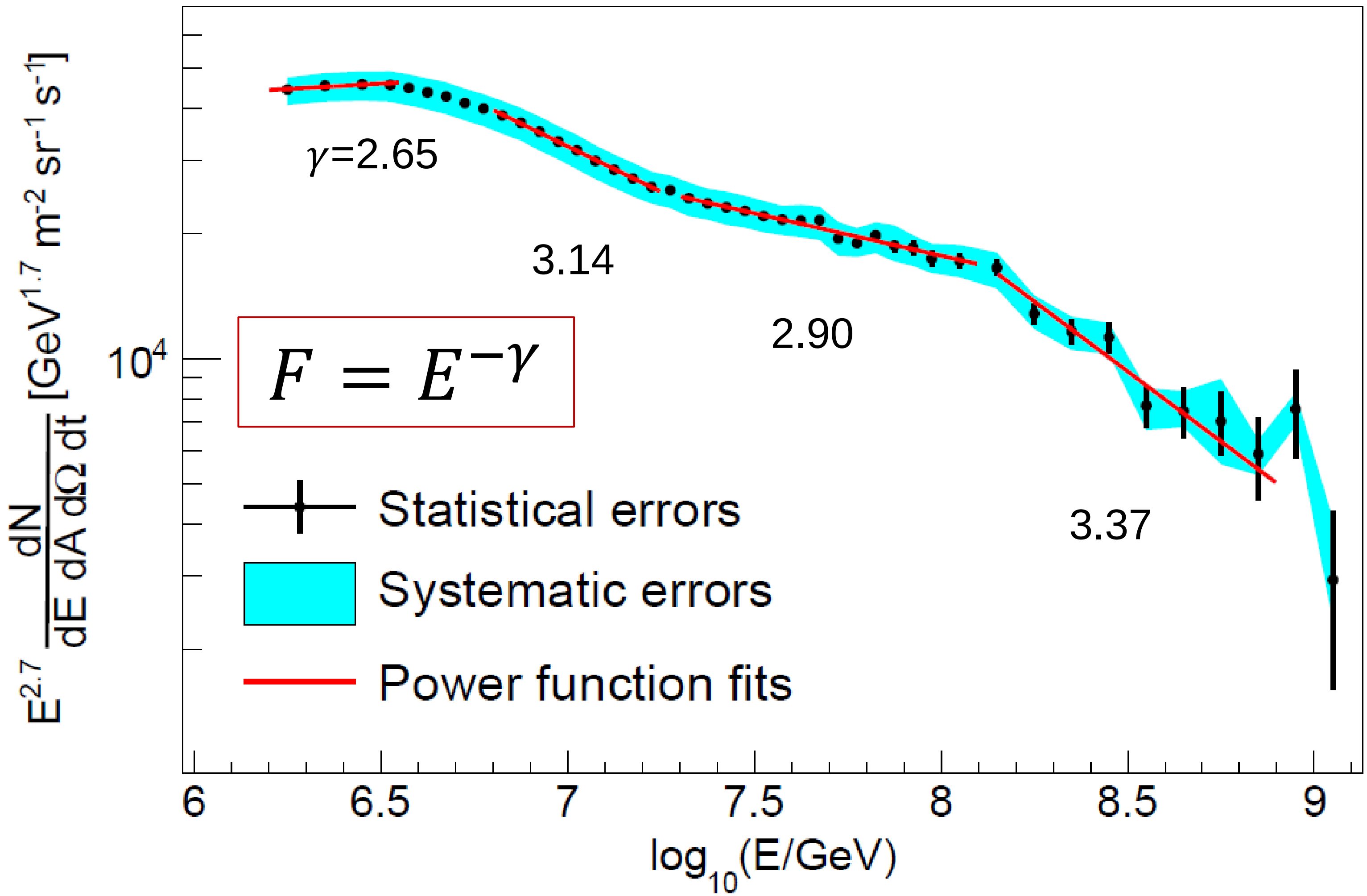




Data require at least 2 galactic contributions and in addition an extragalactic one

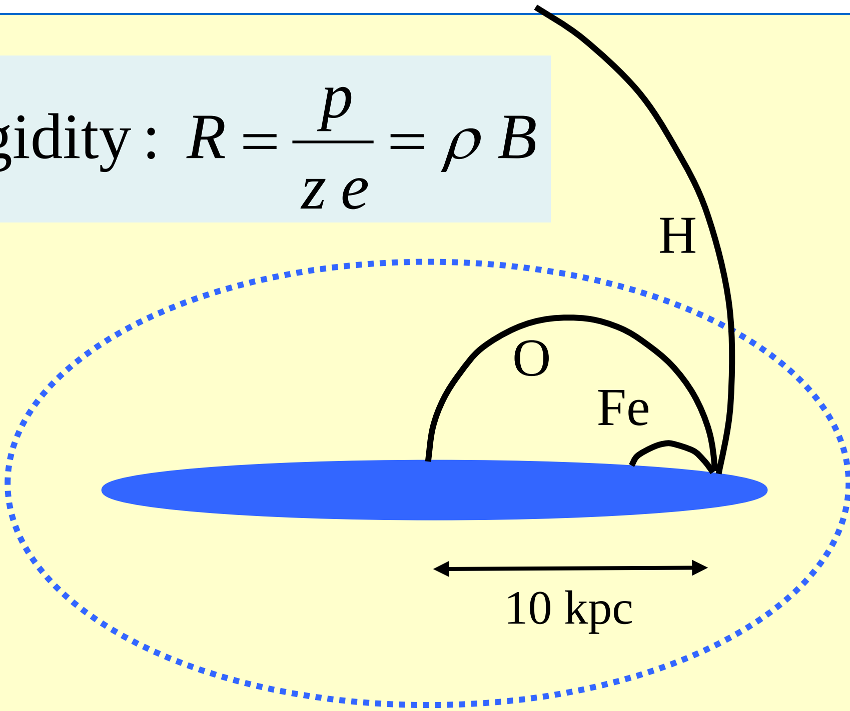
PeV to EeV

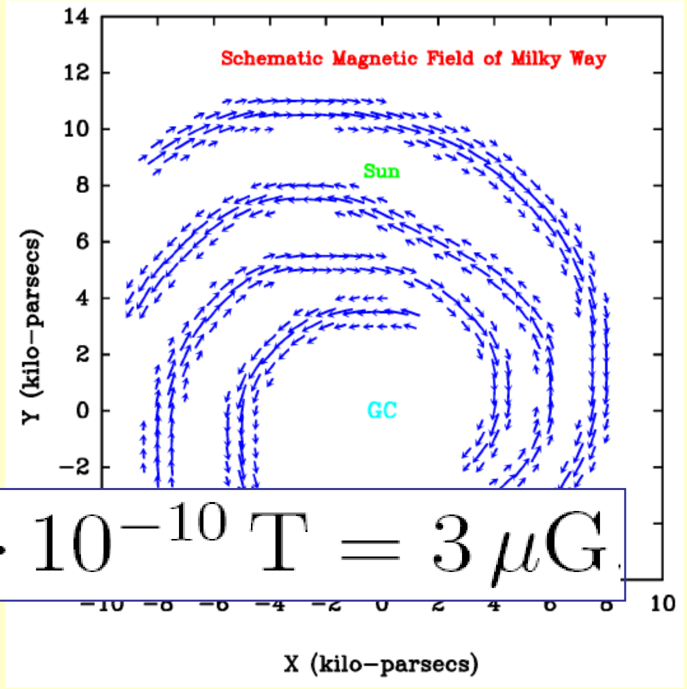
The fine structure in the spectrum



Confinement in the Galaxy

Rigidity : $R = \frac{p}{z\,e} = \rho\,B$





$$3 \cdot 10^{-10}\,\mathrm{T} = 3\,\mu\mathrm{G}$$

$E_{max} \sim Z \;\Rightarrow\; E_{max}(\mathrm{Fe}) \approx 26\,E_{max}(\mathrm{H})$

CR in galaxy: mean lifetime 10^7 years

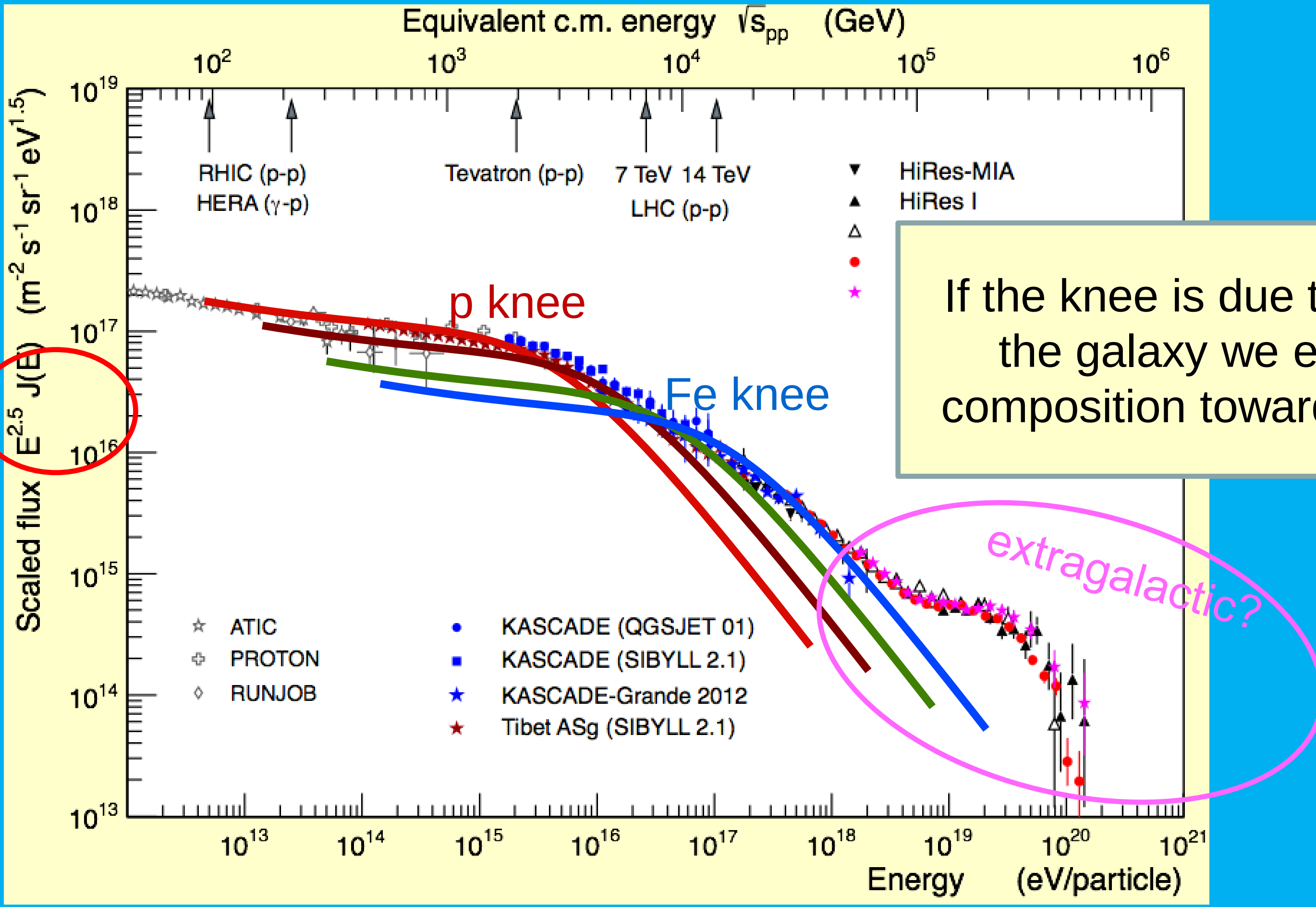
Energy has to be refueled.

Where, how?

energy densities in galaxy

	MeV/m^3
cosmic rays	0.5
optical star light	0.6
CMB	0.26
galactic B-field	0.25

Origin and Physics of the knee(s)

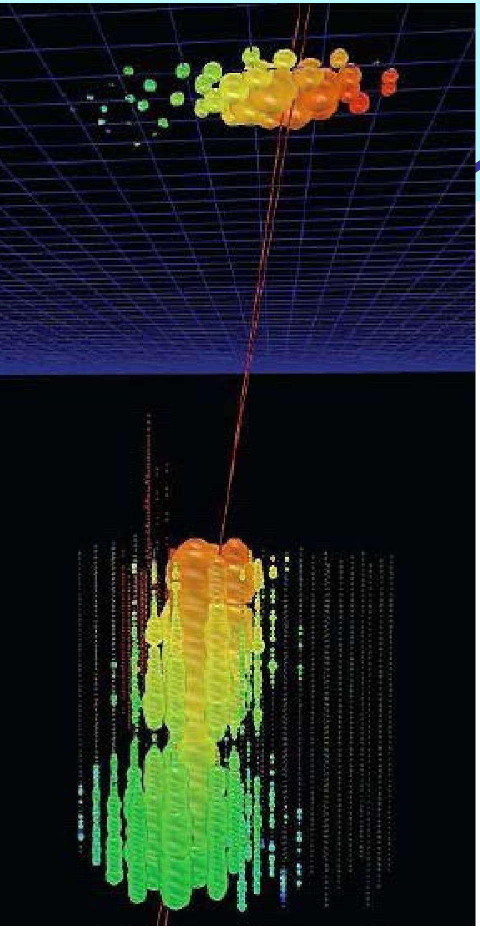


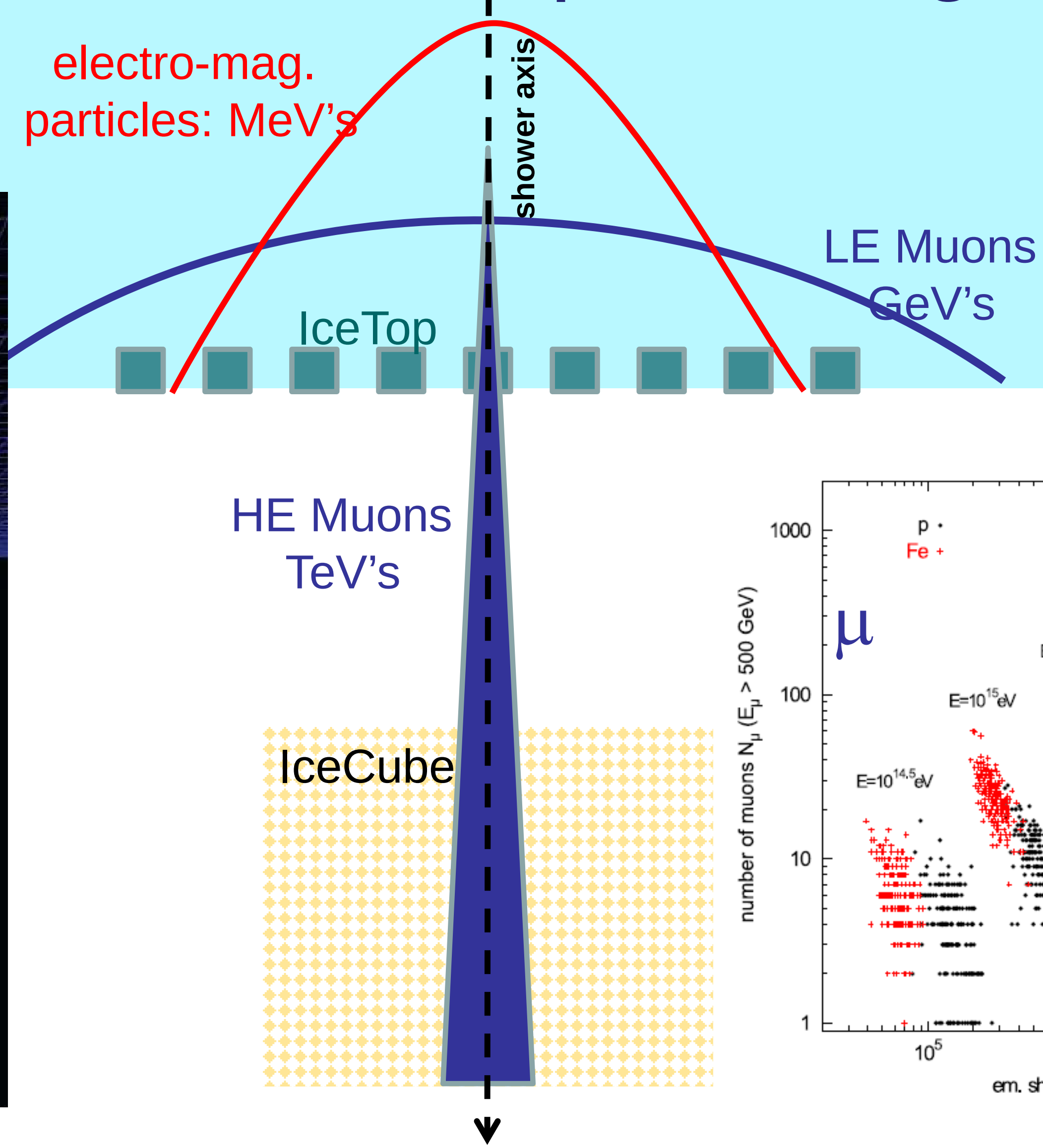
If the knee is due to the diffusion out of the galaxy we expect a change in composition towards heavier elements

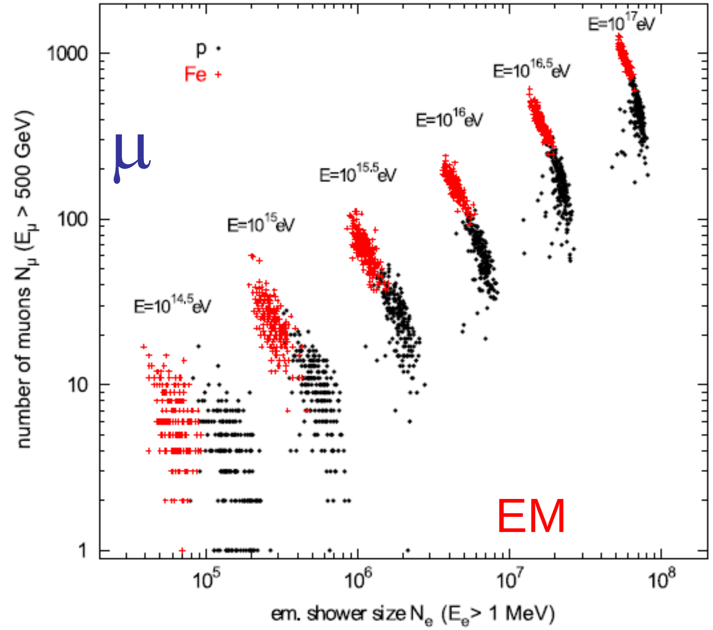
spectrum below the knee: well known by direct measurements; above the knee: indirect measurements via air showers, difficult

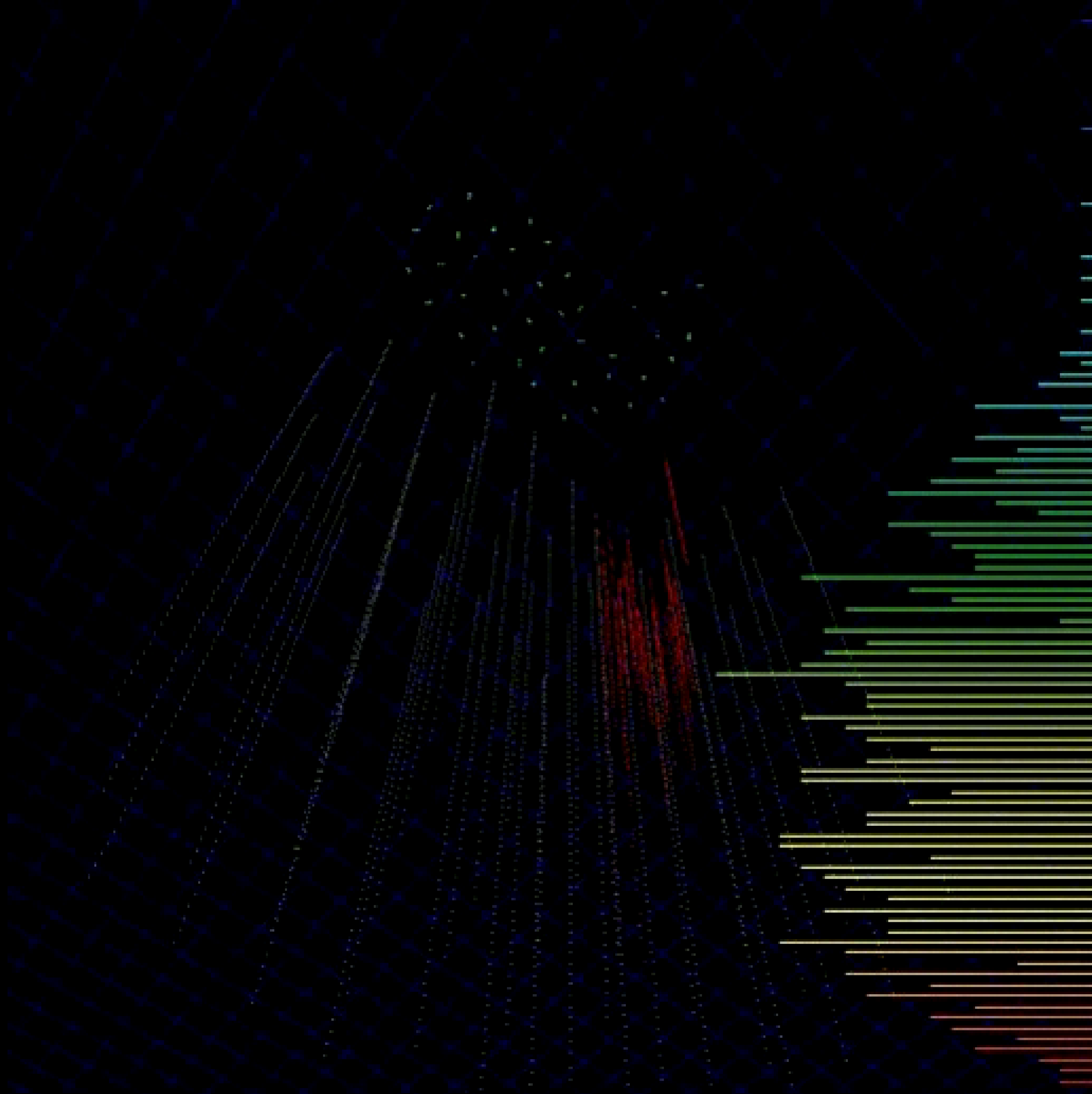
Spectrum and Composition

IceCube/IceTop's Strength

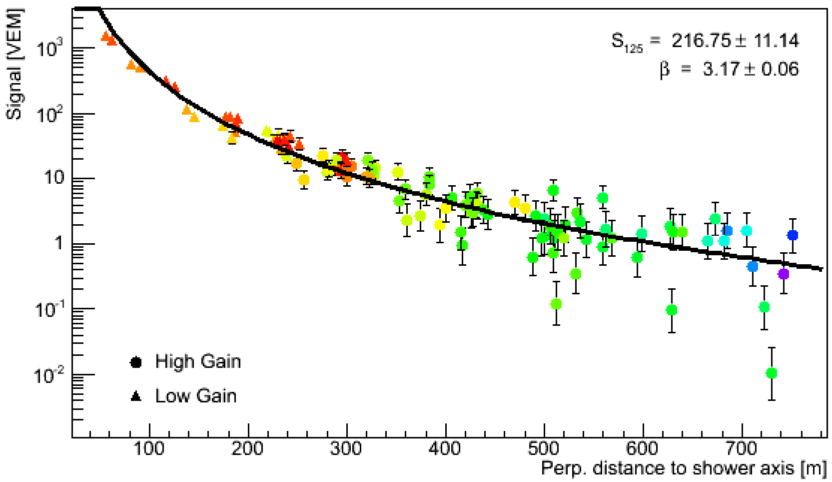


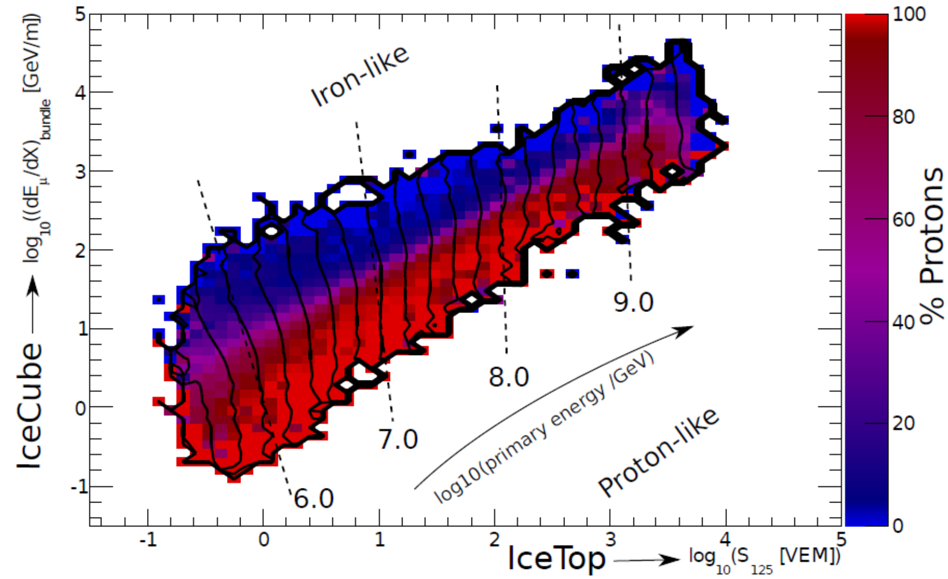


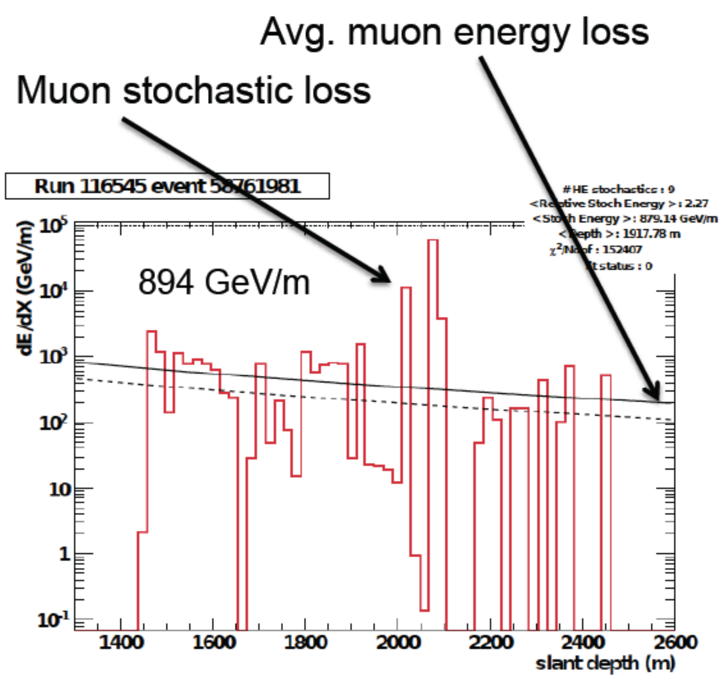


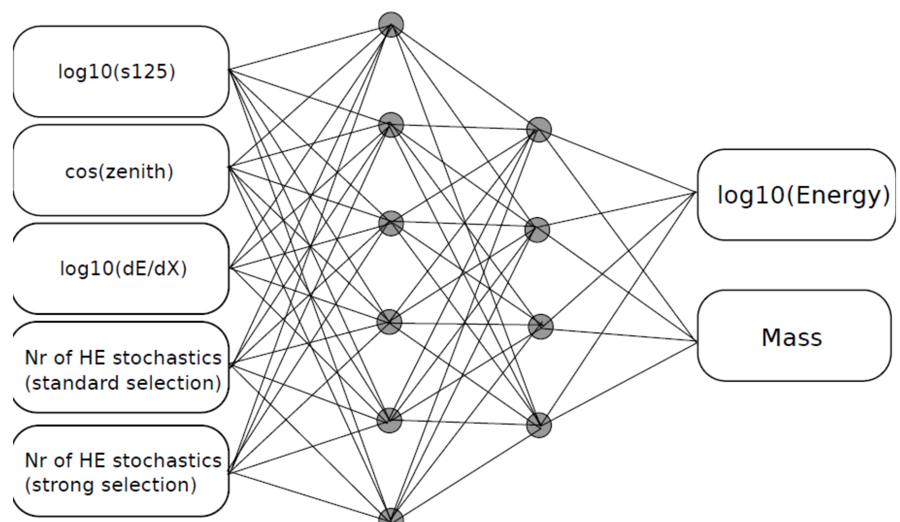


IT73/IC79 Composition Analysis

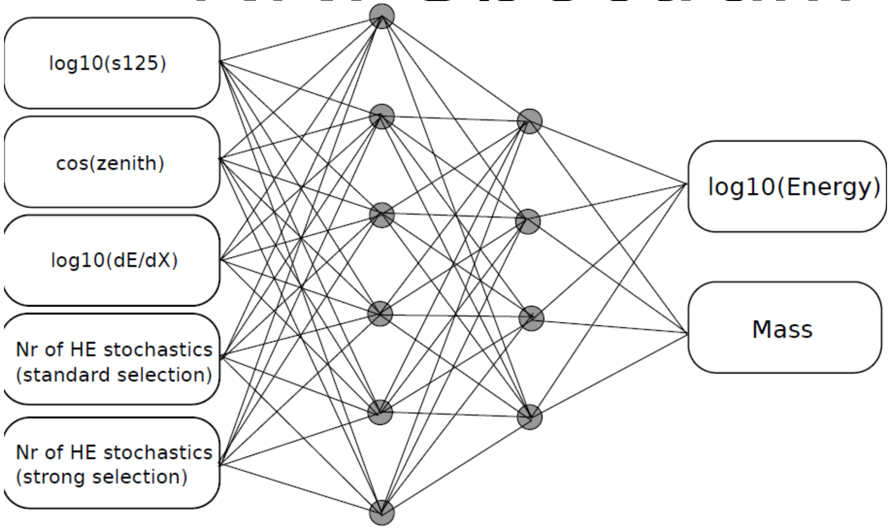


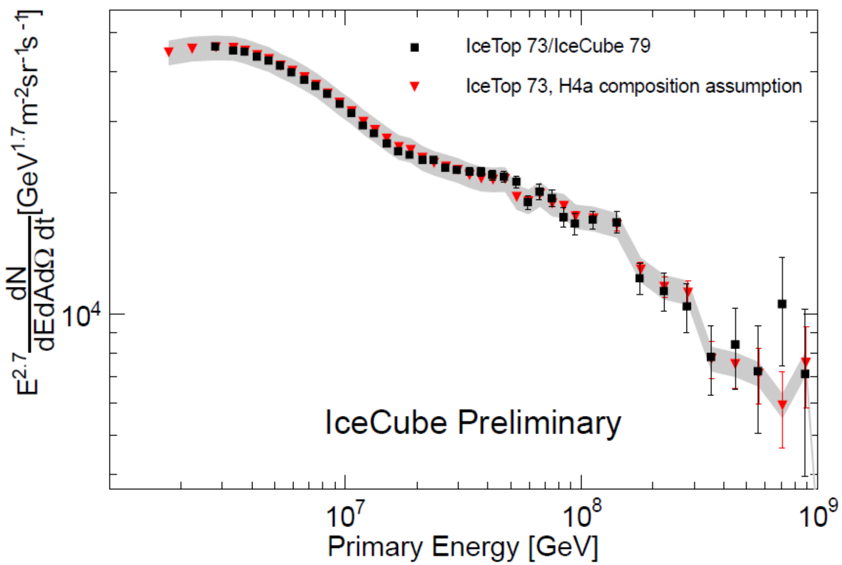


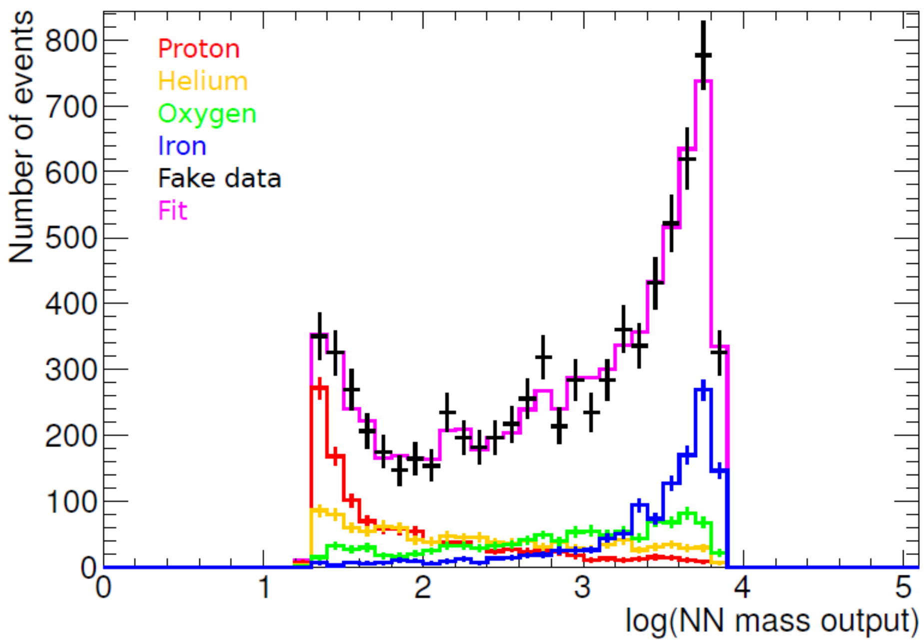


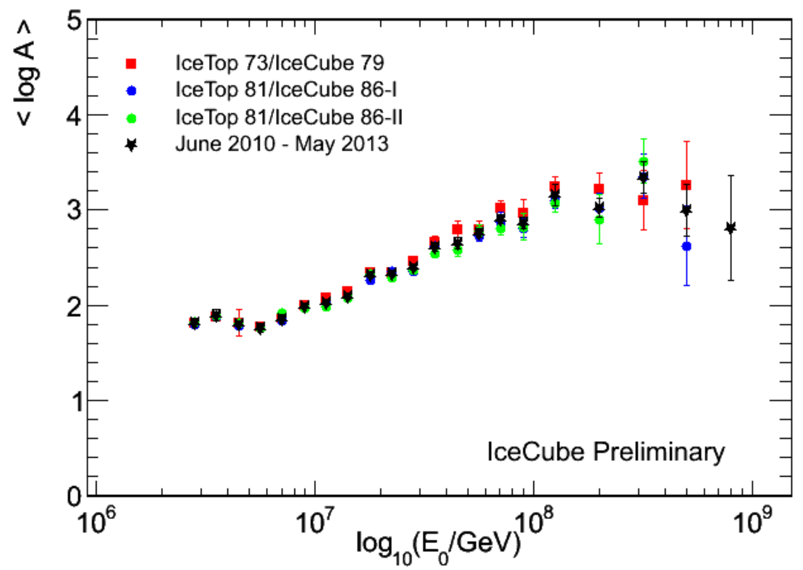


NN: Spectrum and Composition



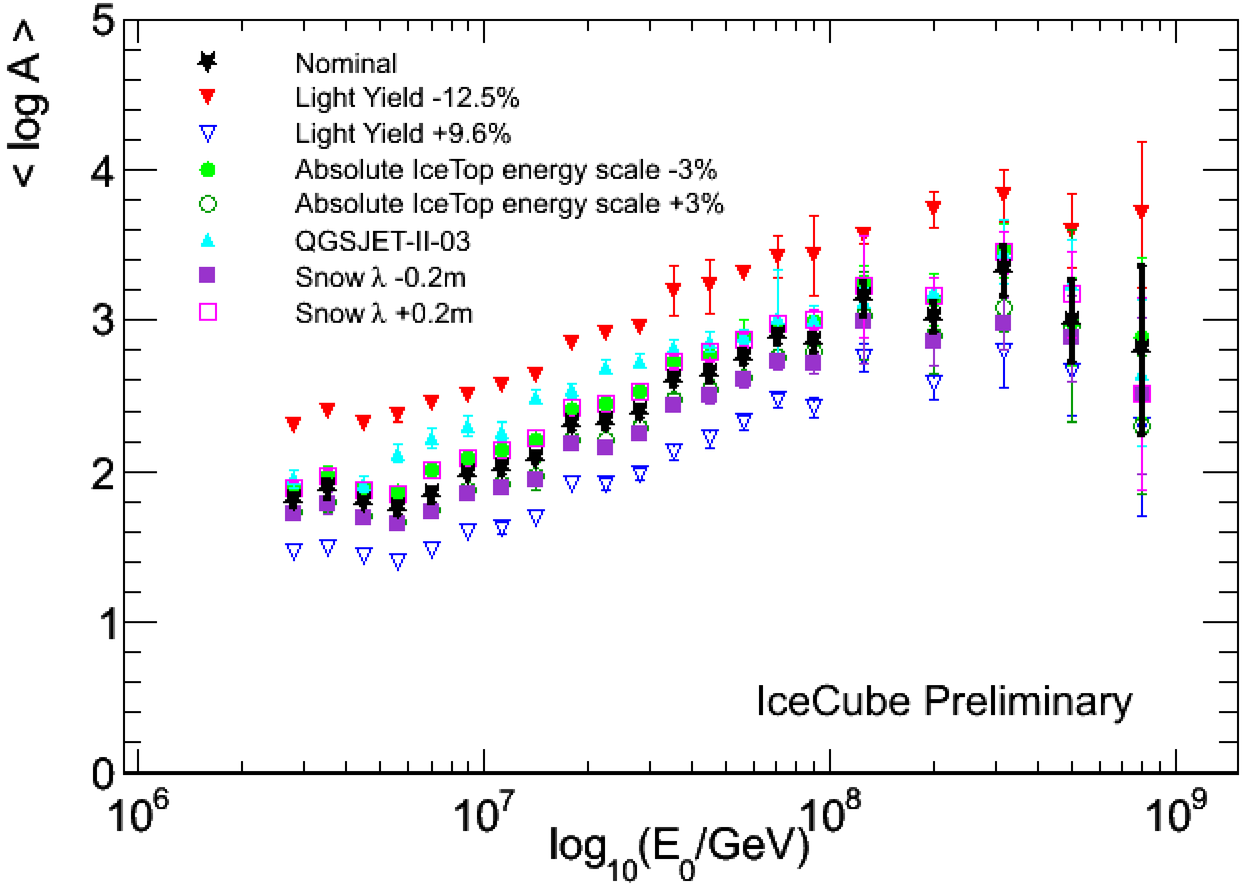




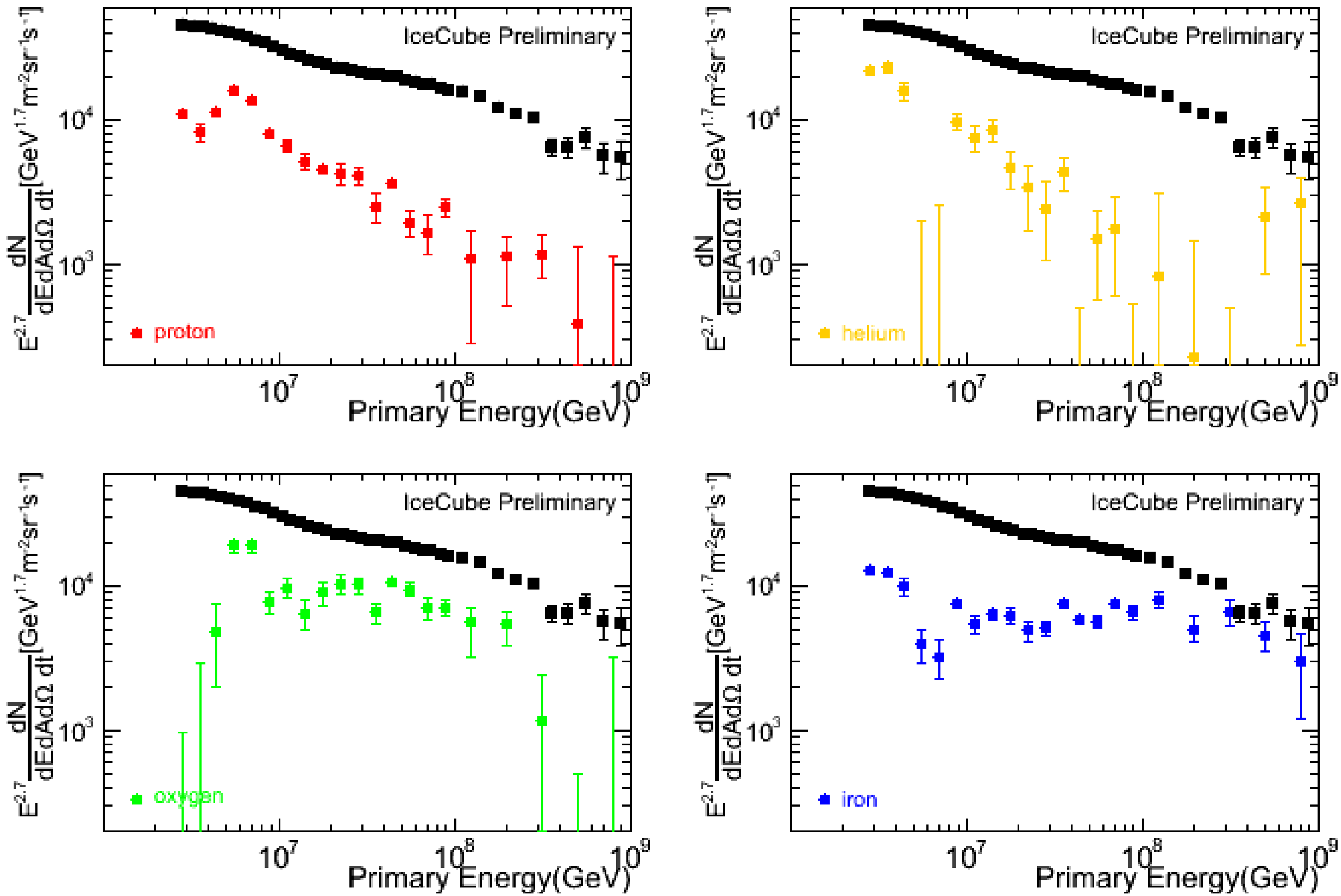


Average Mass Composition

Systematics are still Large



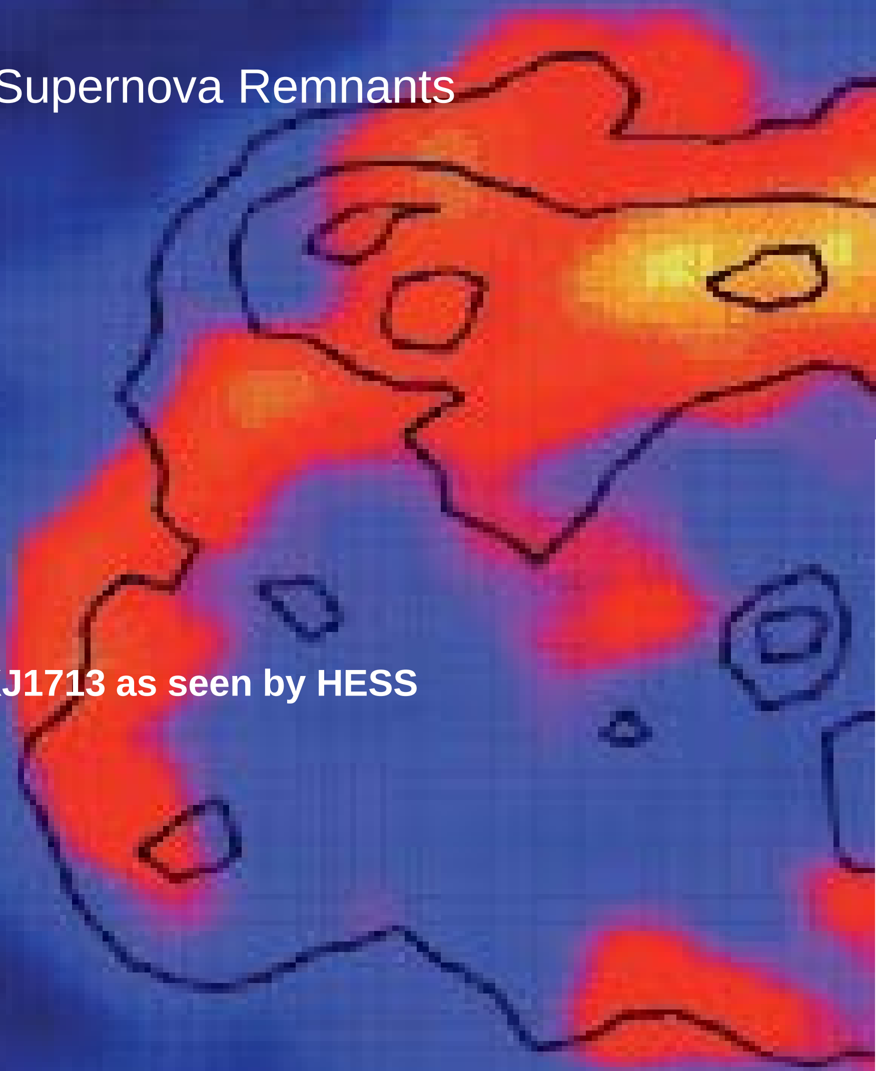
Mass Spectra



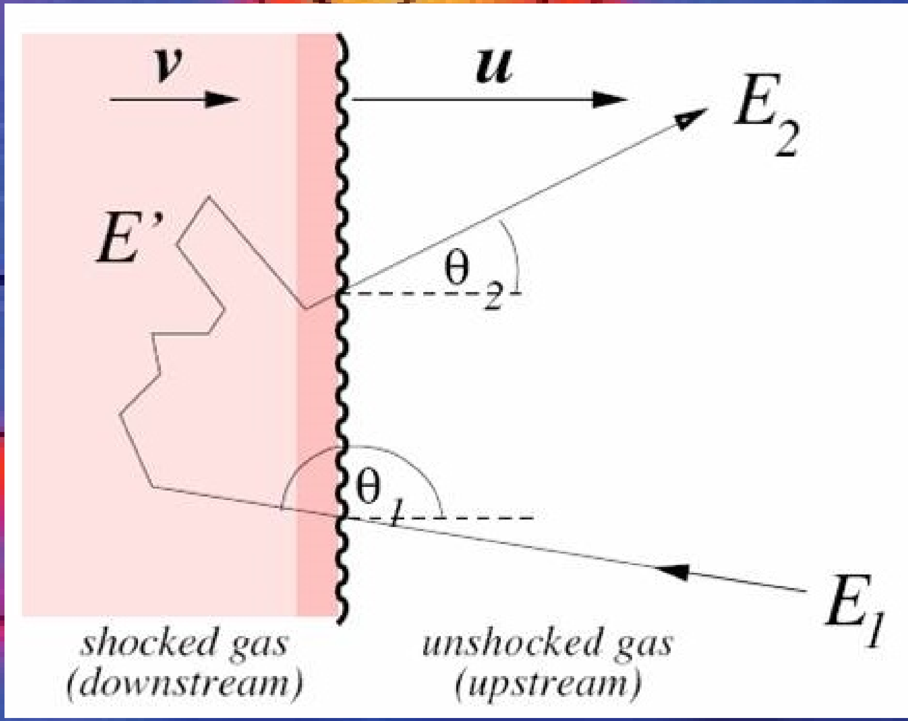
Cosmic Accelarators

Supernova Remnants

Fermi acceleration
at shock front



RXJ1713 as seen by HESS



Efficiency of SNR for Cosmic Rays

$\rho_E^{CR} \approx 0.5$ MeV/m^3 CR energy density
$\tau_G^{CR} \approx 10^7$ years time spent in galaxy
$V_G \approx 10^{61}$ m^3 volume of galaxy ($r \approx 15$ kpc, $h \approx 0.5$ kpc)

Reqired acceleration power:

$$L_{CR} \approx V_G\, \rho_E^{CR} / \tau_G^{CR} \approx 3\times 10^{33} \text{ J/s}$$

Total power of supernova explosions:

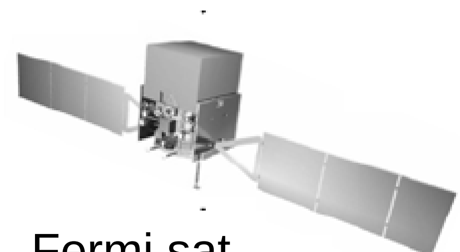
$\tau_G^{SN} \approx 30\text{-}50$ years time between SN explosions in milky way
$E^{SN} \approx 3\times 10^{46}$ J energy per SN

$$L_{SN} \approx E^{SN} / \tau_G^{SN} \approx 3\times 10^{35} \text{ J/s}$$

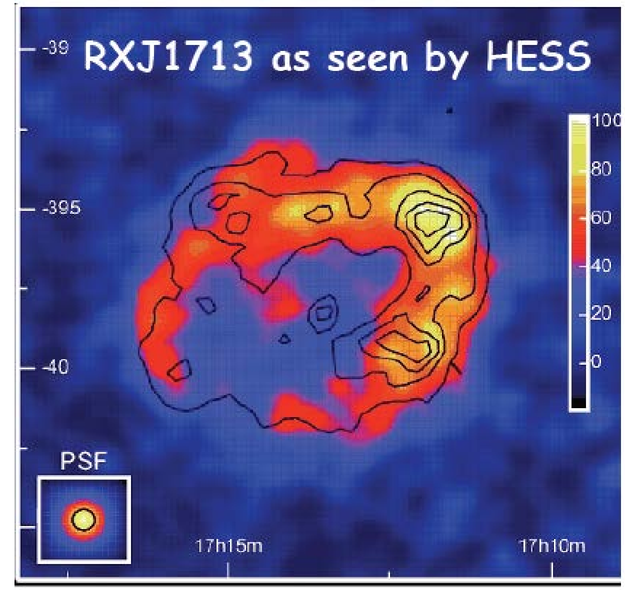
With 1% efficiency of SN all cosmic rays can be explained

Acceleration of Nuclei in SNR?

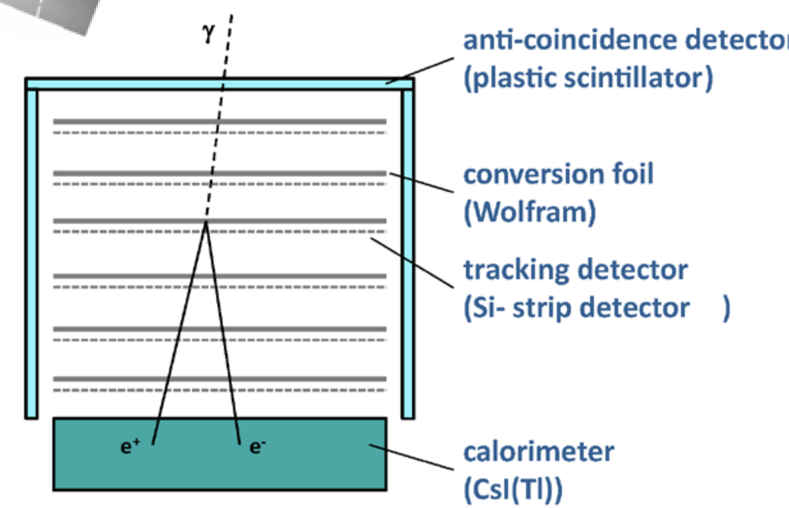
TeV gamma telscope



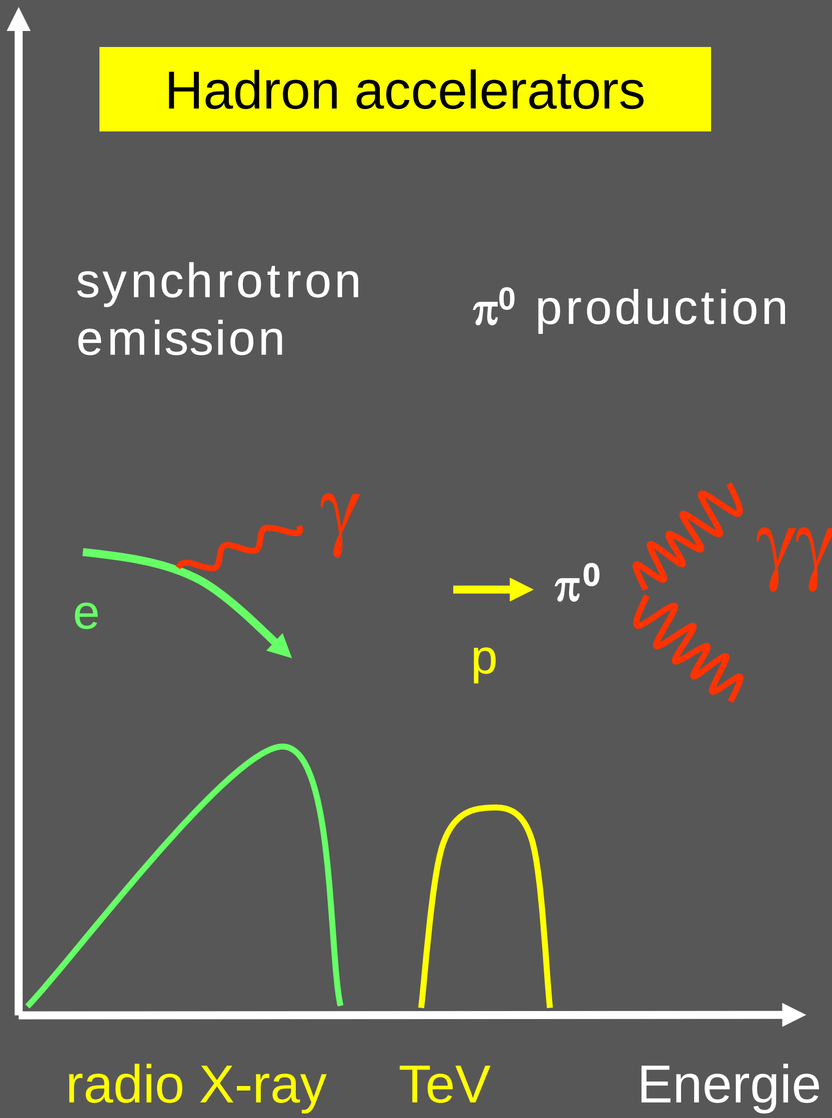
Fermi sat.

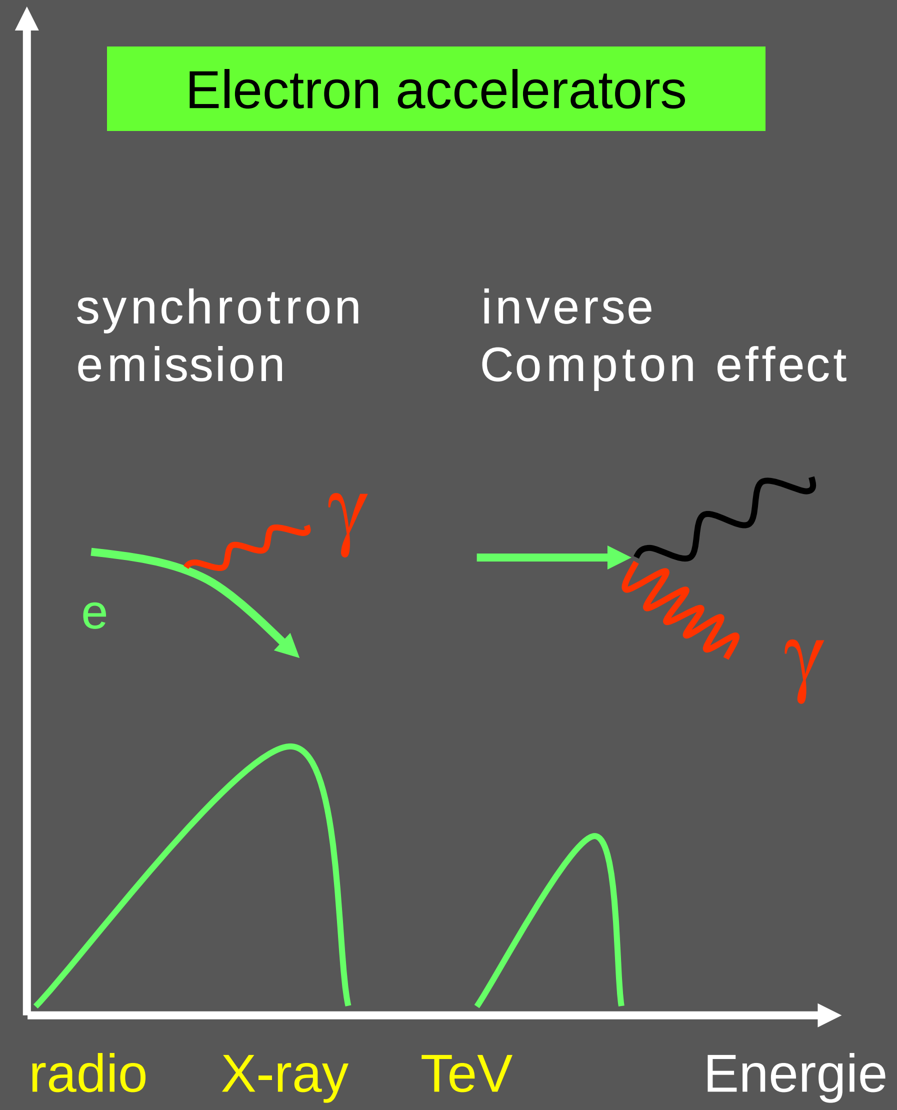


Fermi LAT



Acceleration of Nuclei in SNR?

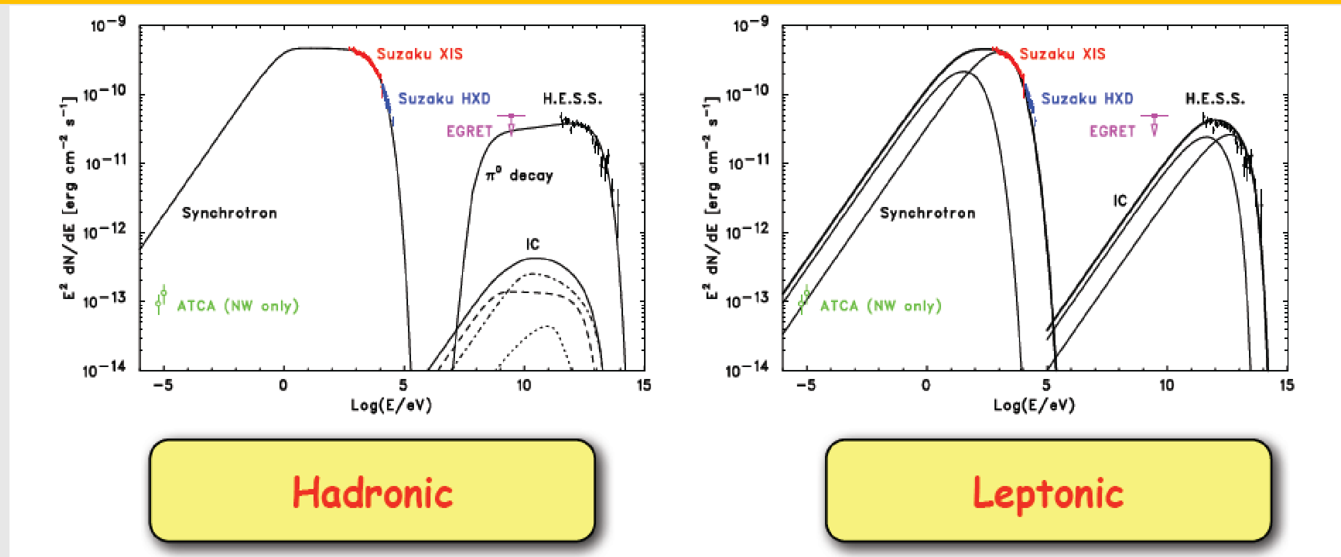




Hadronic or Leptonic?

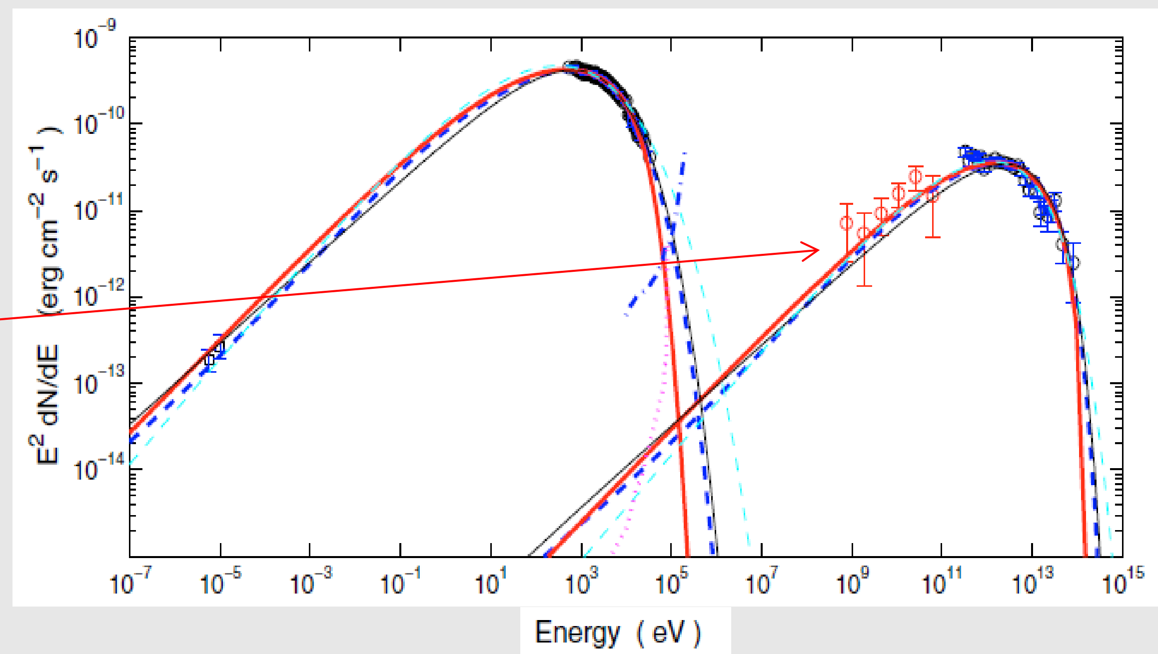
example:

RXJ1713

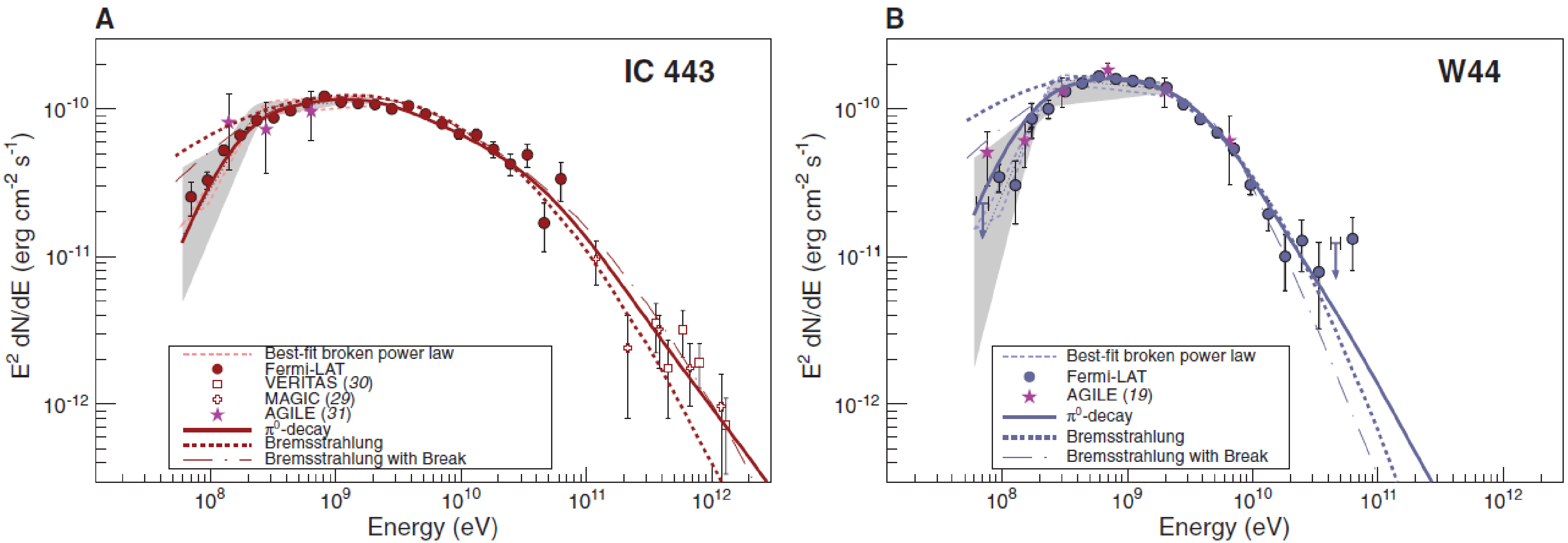


after Fermi measurements:

Leptonic



Detection of the Characteristic Pion-Decay Signature in Supernova Remnants using Fermi LAT



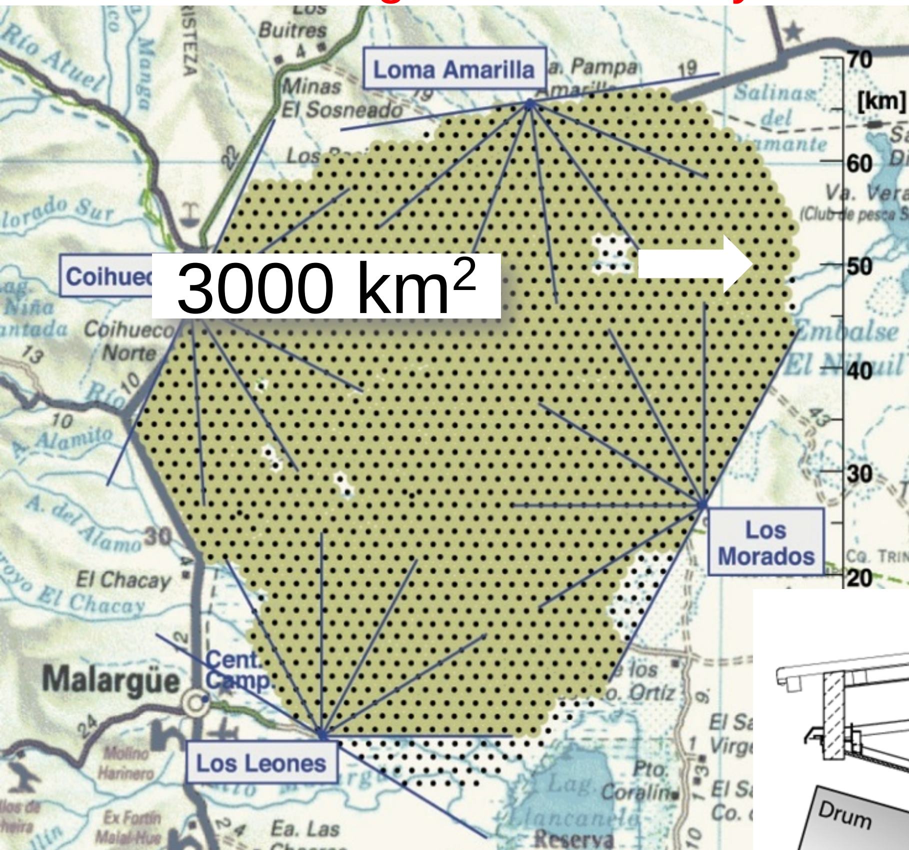
Solid lines: best fit pion-decay gamma-ray

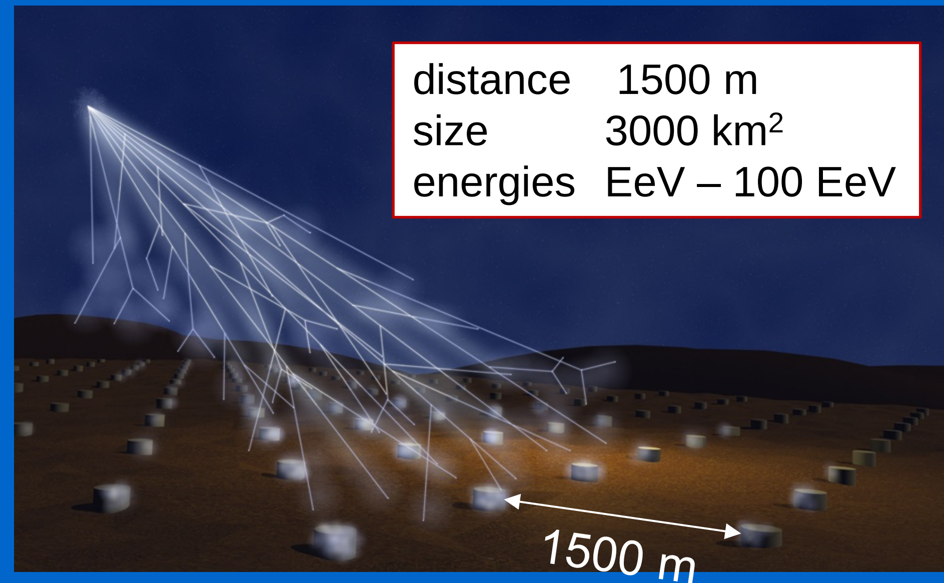
Dashed lines: denote the best-fit bremsstrahlung

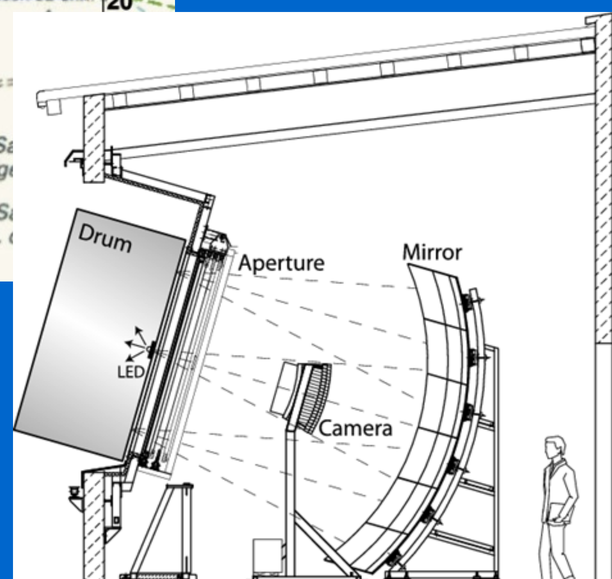
UHECR

The highest energies in nature

Pierre Auger Observatory

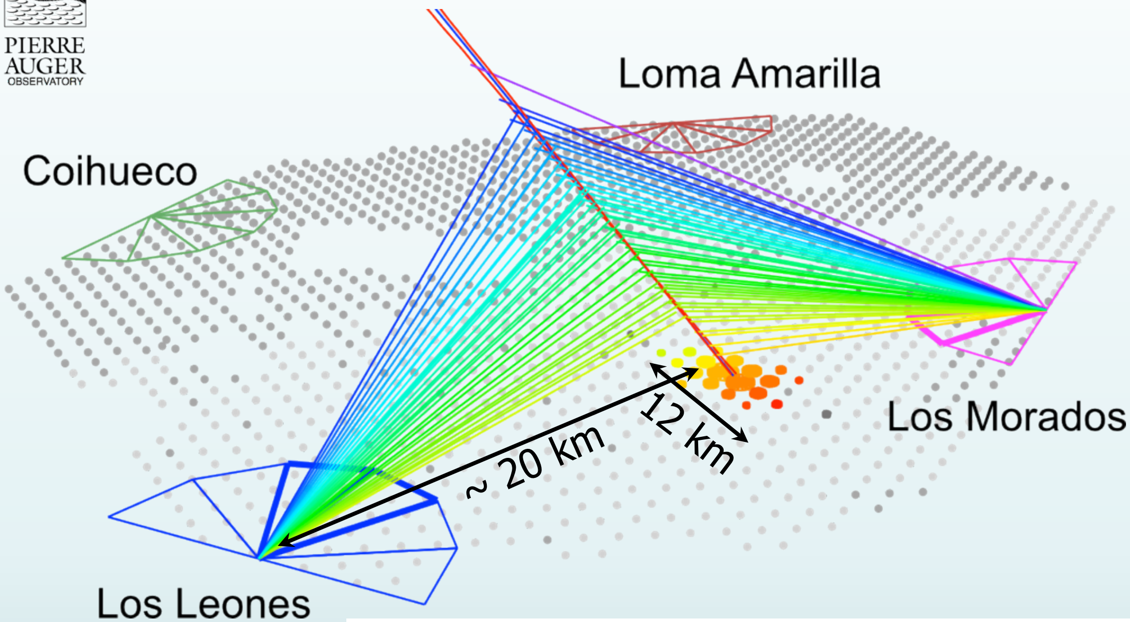


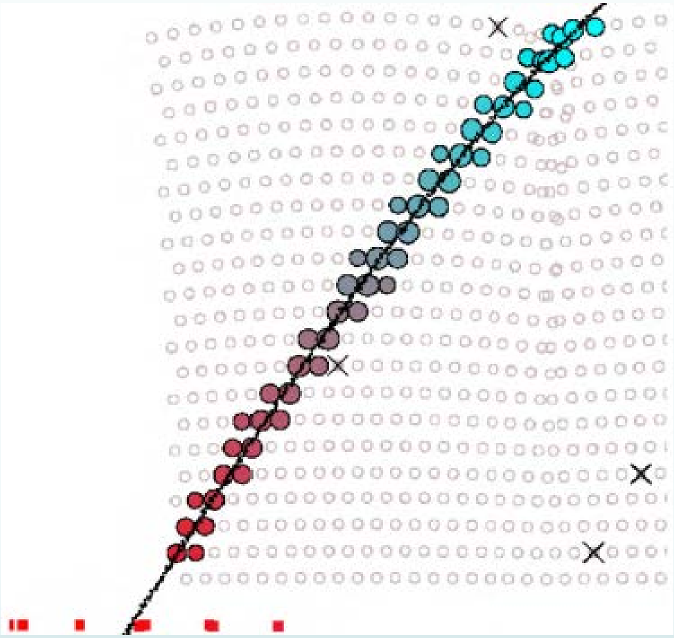


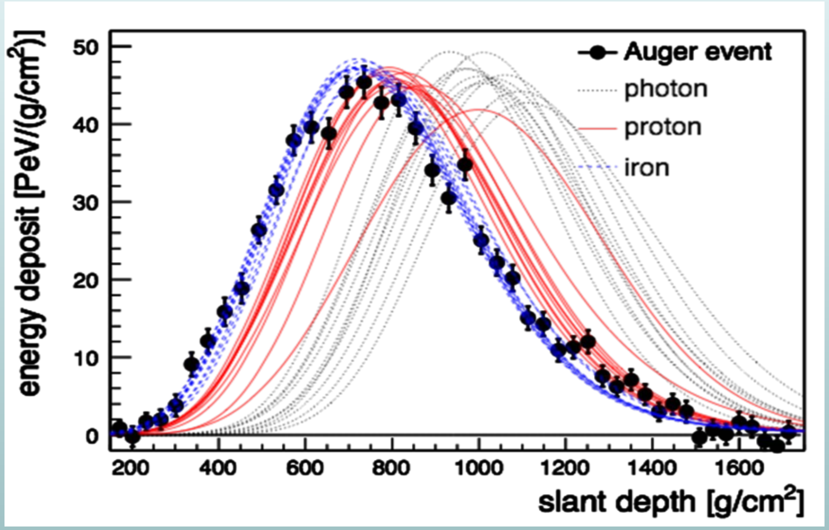


Event Example in Auger Observatory

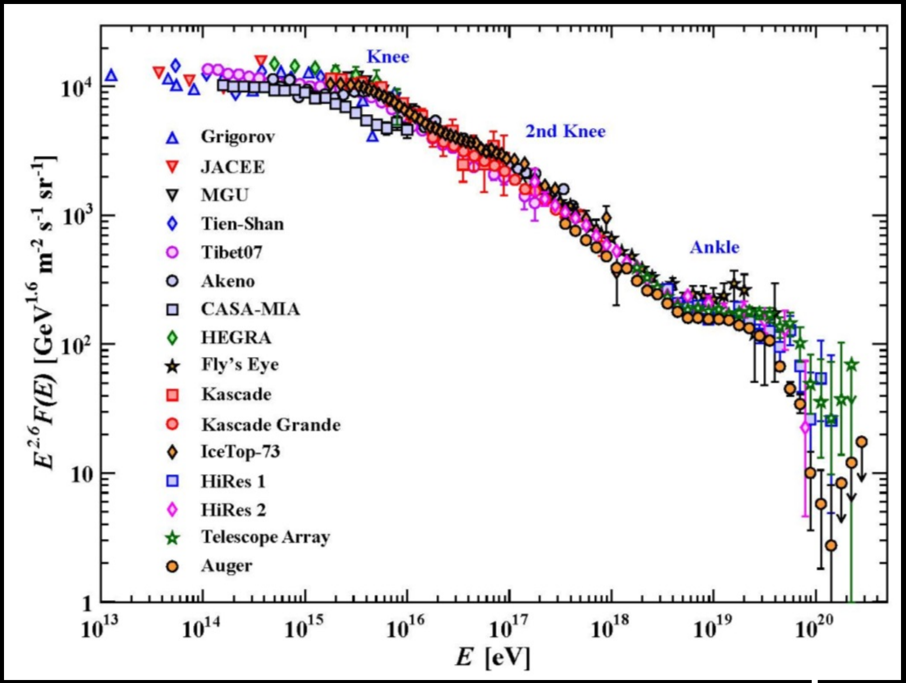
PIERRE AUGER OBSERVATORY

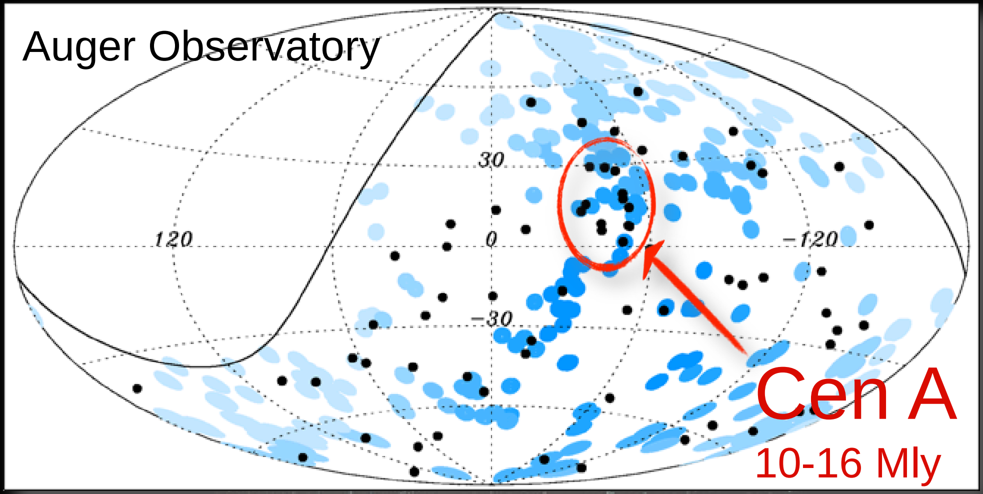






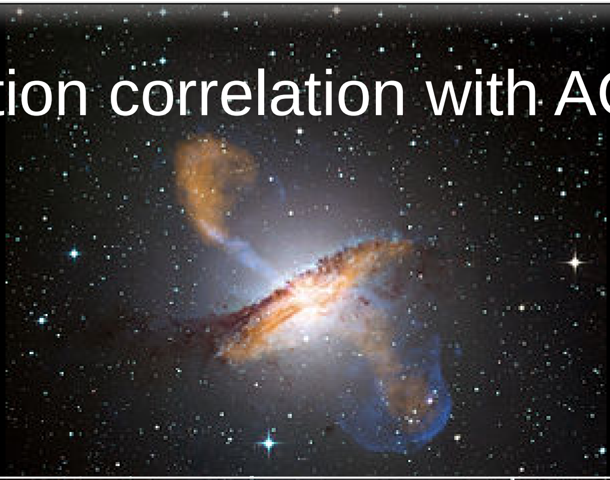
Summary of UHECR Results





cut-off at 10^{20} eV definitely observed

direction correlation with AGN?

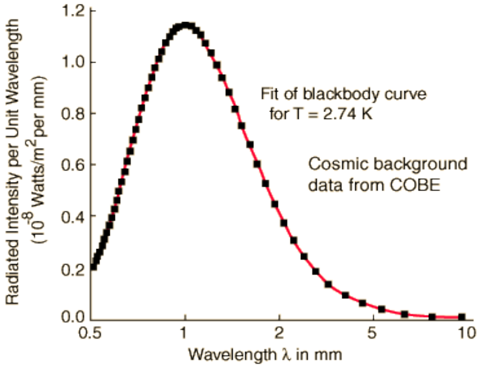


GZK or source power limited?

(GZK = Greisen-Zatsepin-Kuzmin)

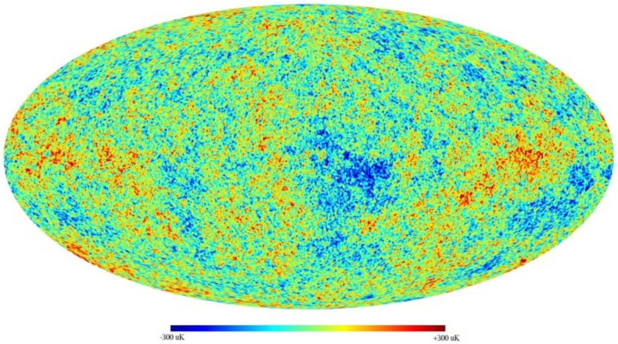
28/84 = 33%
isotropic background = 21%
➙ <1 % chance probability

Cosmic Rays, CMB Photons and Neutrinos



Cosmic Microwave Background (CMB):

perfect blackbody at 2.74 K



Greisen-Kuzmin-Zatsepin (GZK) Cut-Off

$$\gamma_{cmb}\, p \rightarrow \Delta^+ \rightarrow \begin{array}{l} n\,\pi^+ \rightarrow n\,\mu\nu \\ p\,\pi^0 \rightarrow p\,\gamma\gamma \end{array}$$

CMB 2.7 K $\rightarrow$ threshold $E_p \approx 4\times10^{19}$ eV

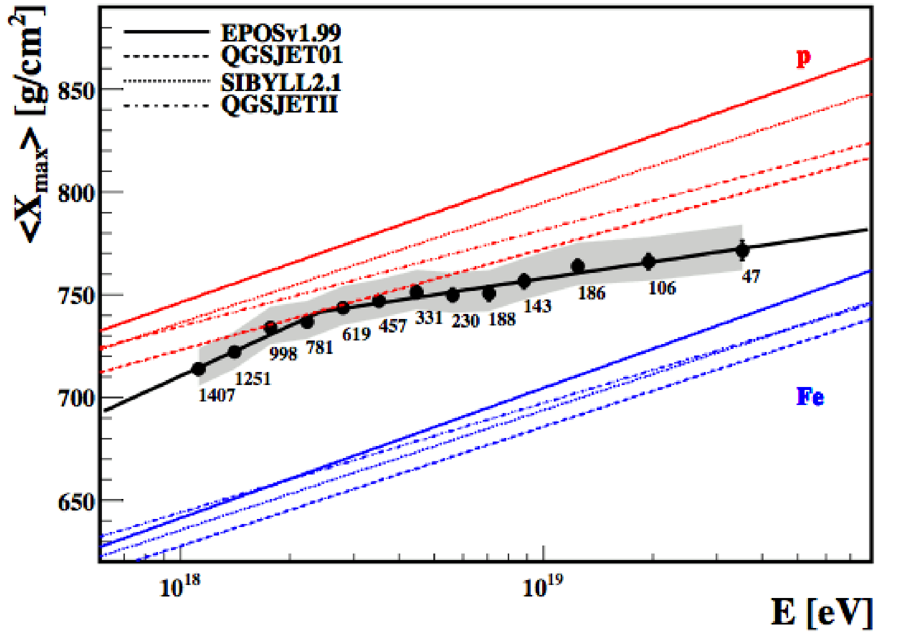
“GZK horizon” ~160 Mly

Nature of the Cutoff?

Is this the "GZK cutoff"?
Energy loss by collison with CMB photons?

Or do accelerators run out of steam?
$\Rightarrow$ composition becomes heavier $\rightarrow$ Fe

Auger: X_{max} with florescence detectors



data suggest change of composition from light to heavy

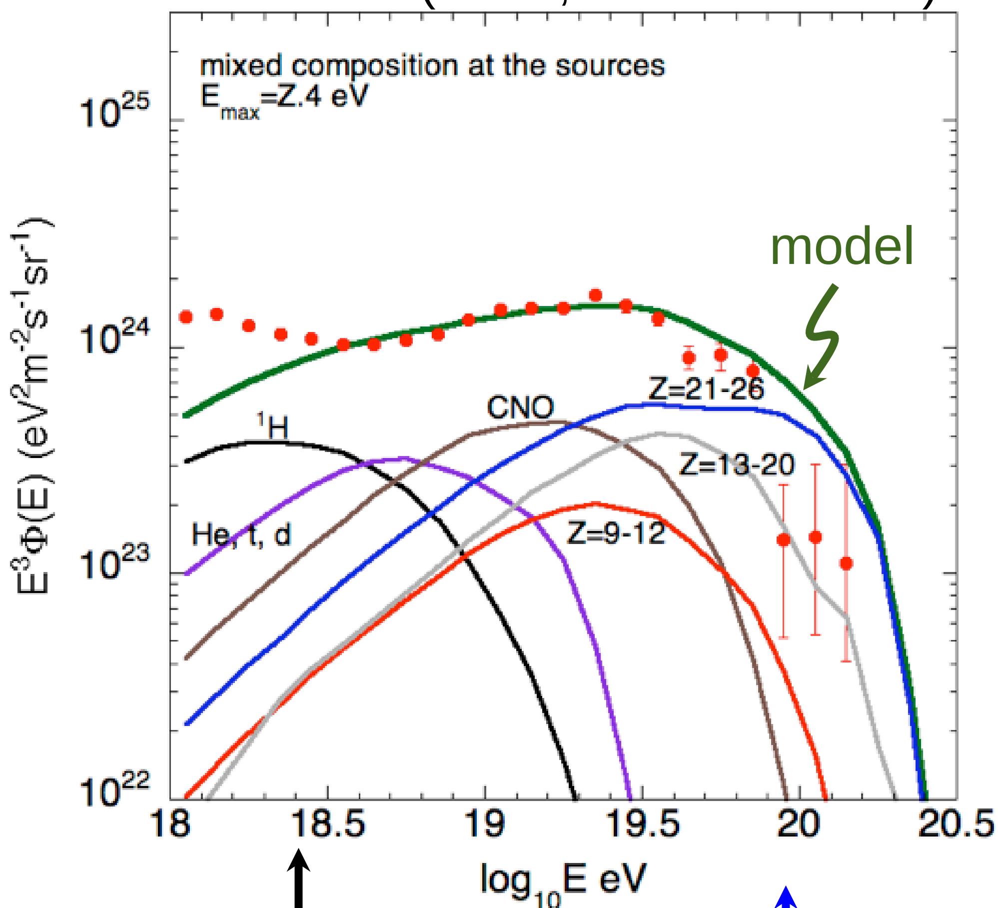
Not GZK cutoff?

Clarification from other messengers?

Are there GZK neutrinos?

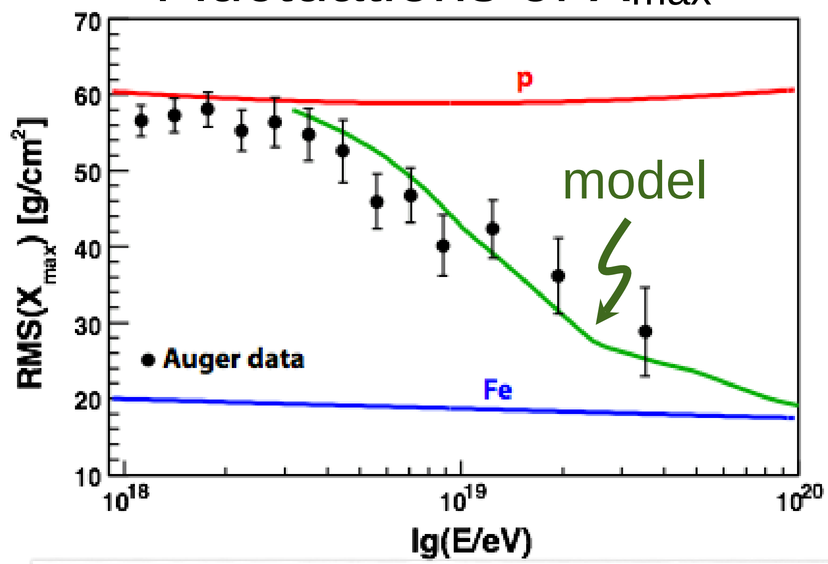
Limiting energy of CR sources ?

(Allard, arXiv:1111.3290)



Natural transition to heavier composition at high energy !

Fluctuations of X_{max}



Note: In this picture flux is not suppressed by GZK!

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

Iron $E_{max, Fe} = 26\ E_{max,p}$

$= 10^{20}$ eV


The End
of Part 1