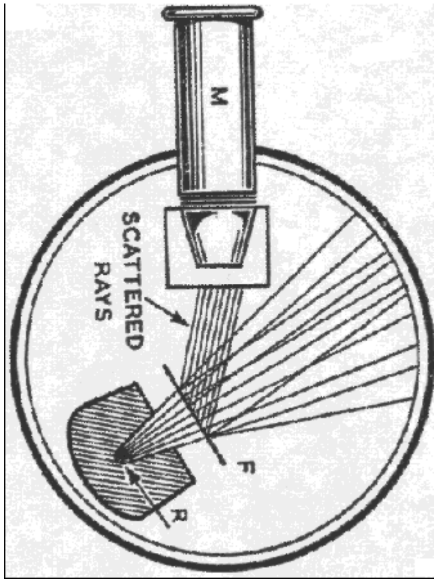
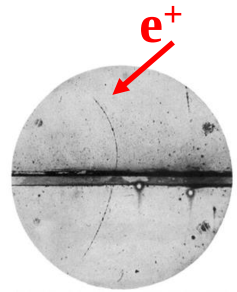
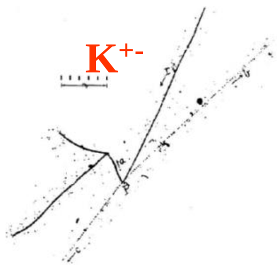
Particle Physics with High Energy Cosmic Rays

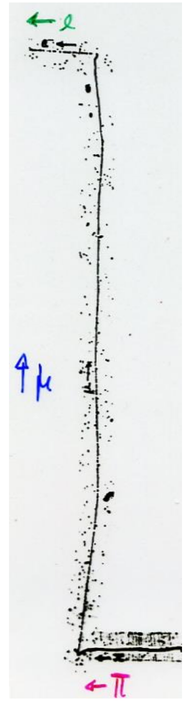
Mário Pimenta
Lisboa, April 2012

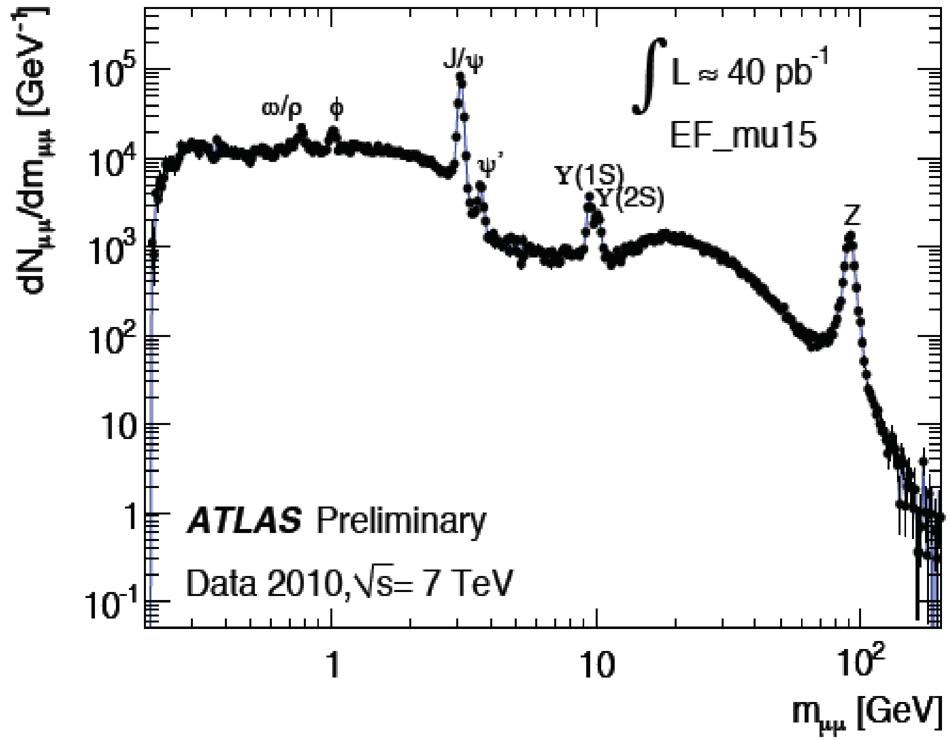
Particle Physics

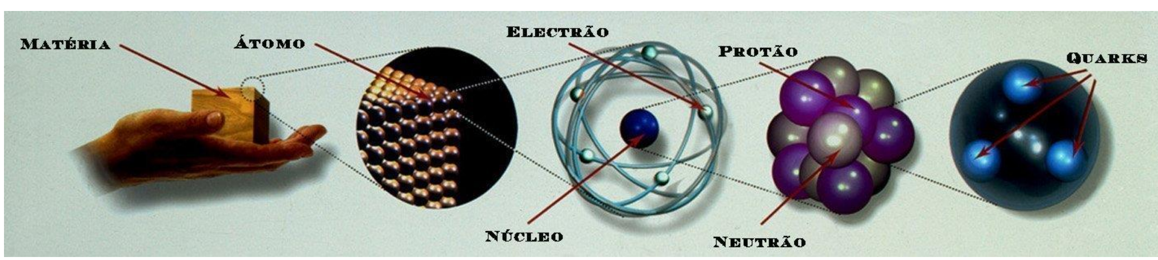


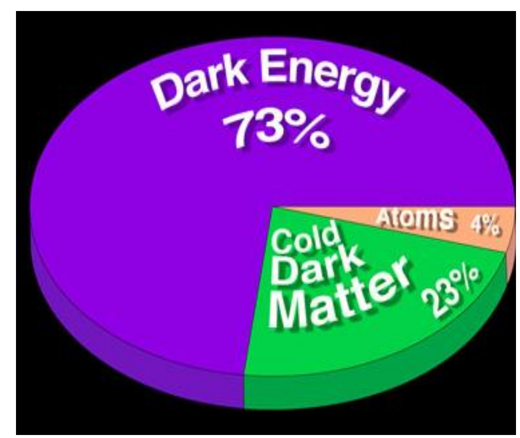










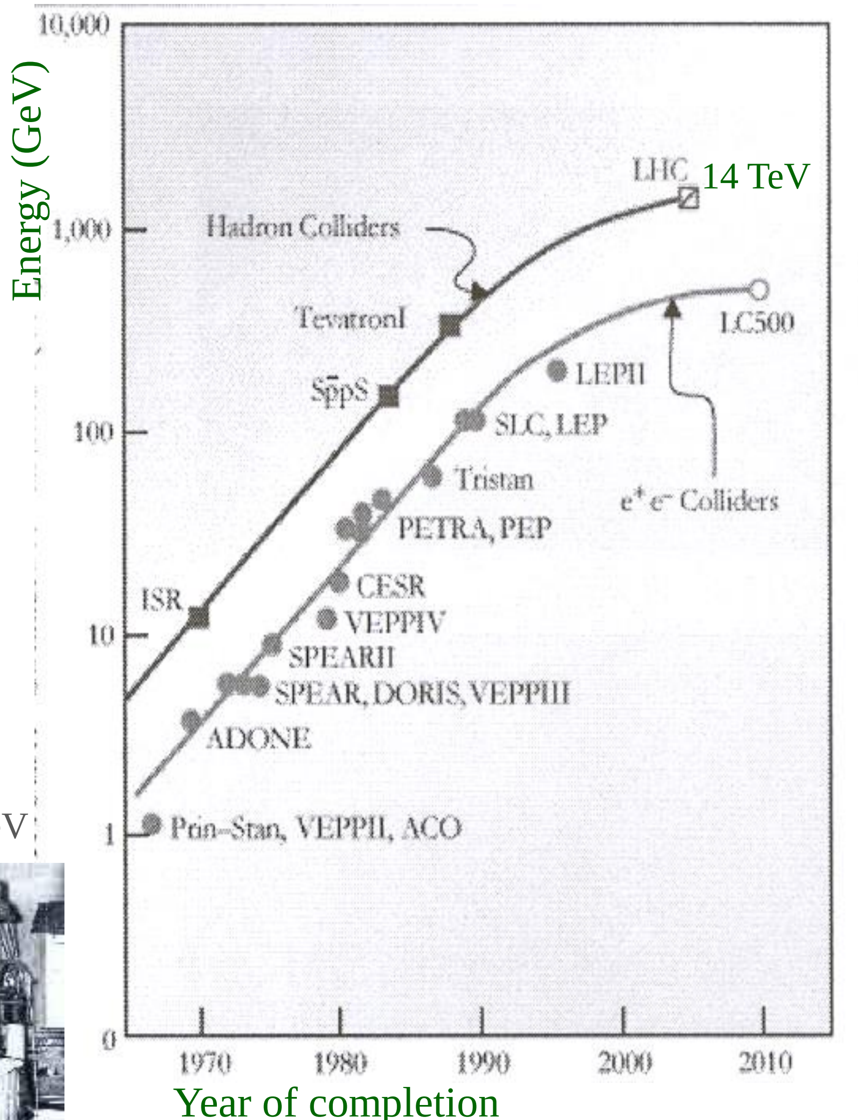


$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

H^0 ?

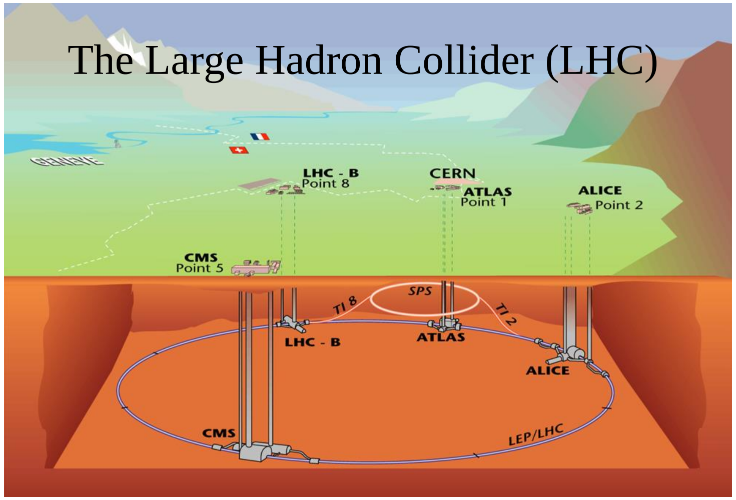
γ, W^+, W^-, Z^0 $G_1, \ldots, G_8$

Accelerators



~ 10 MeV

~1930

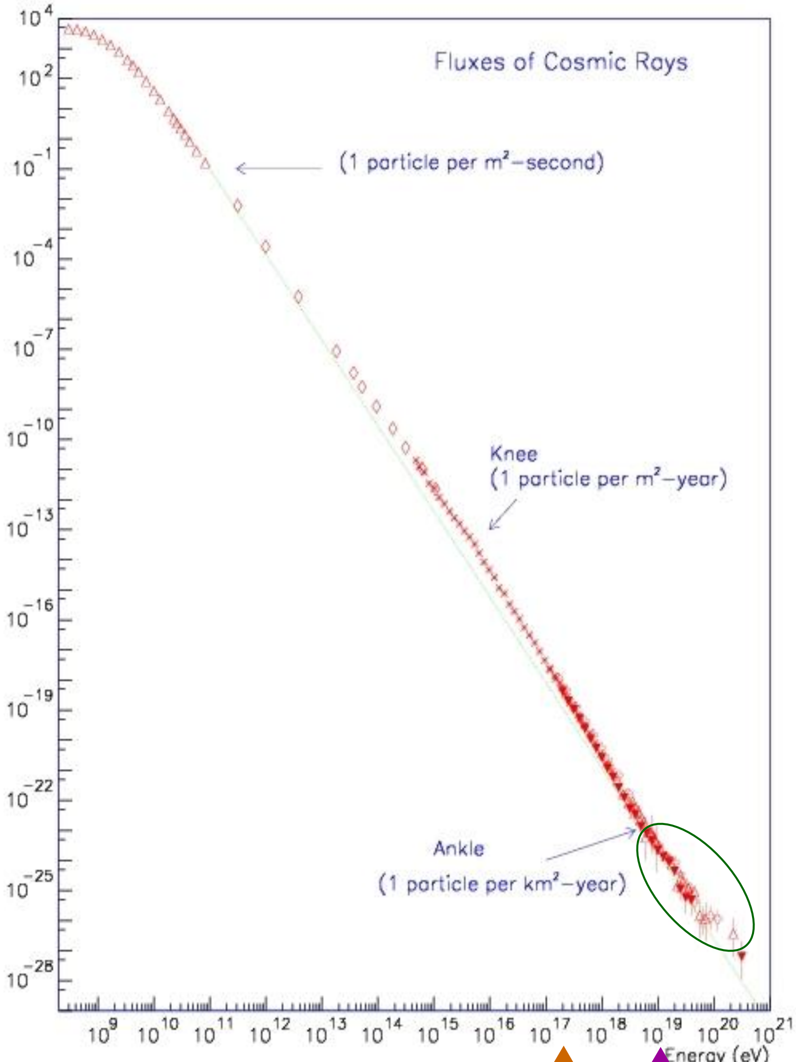


High Luminosity
Sophisticated detectors

Central region
Energy limited

Cosmic rays

Flux (m^2 sr s GeV)$^{-1}$



Energy (eV)

LHC

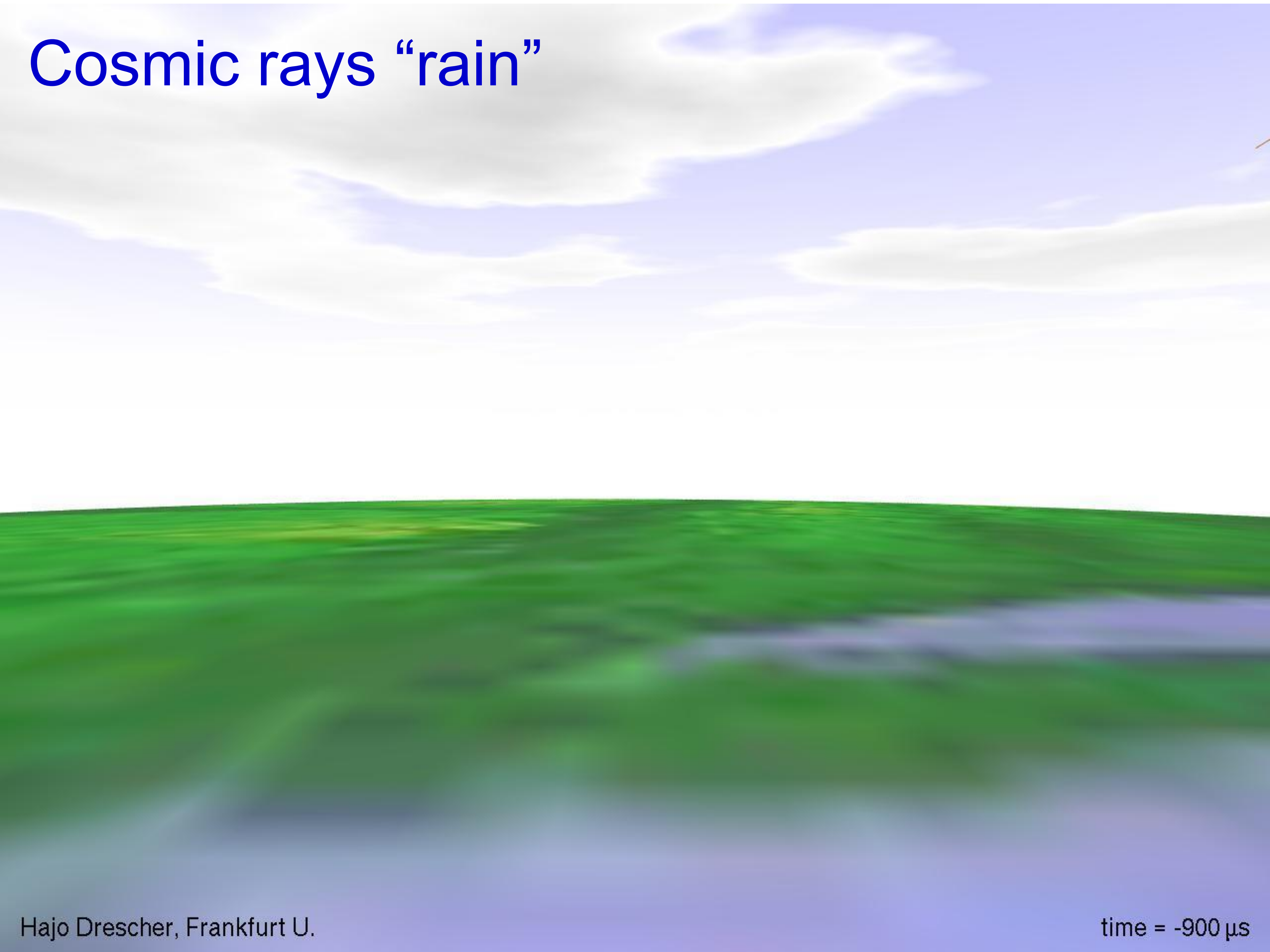
100 TeV

John Linsley, 1962

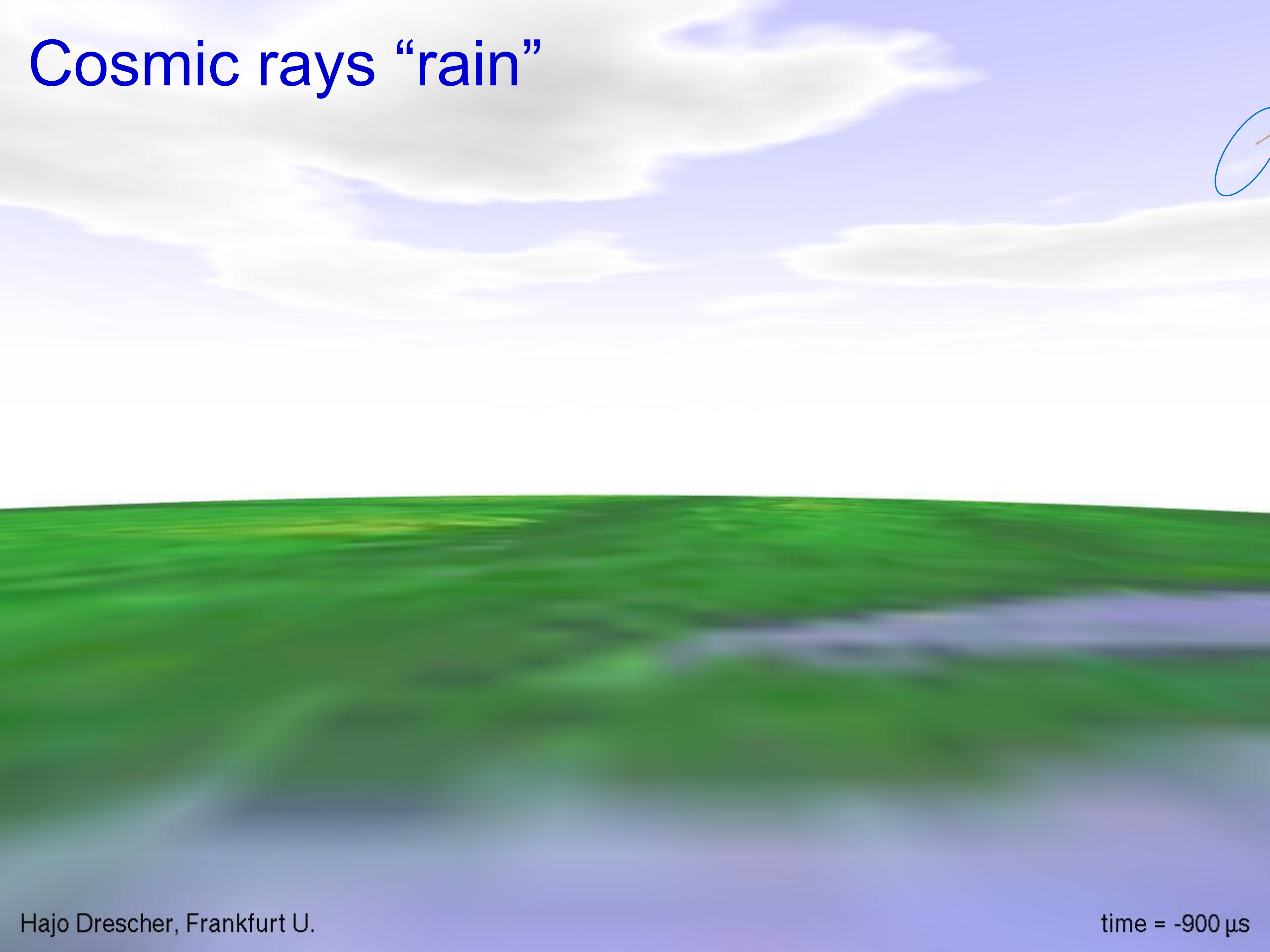
Forward Region
Extreme Energies

Small fluxes
indirect measurements

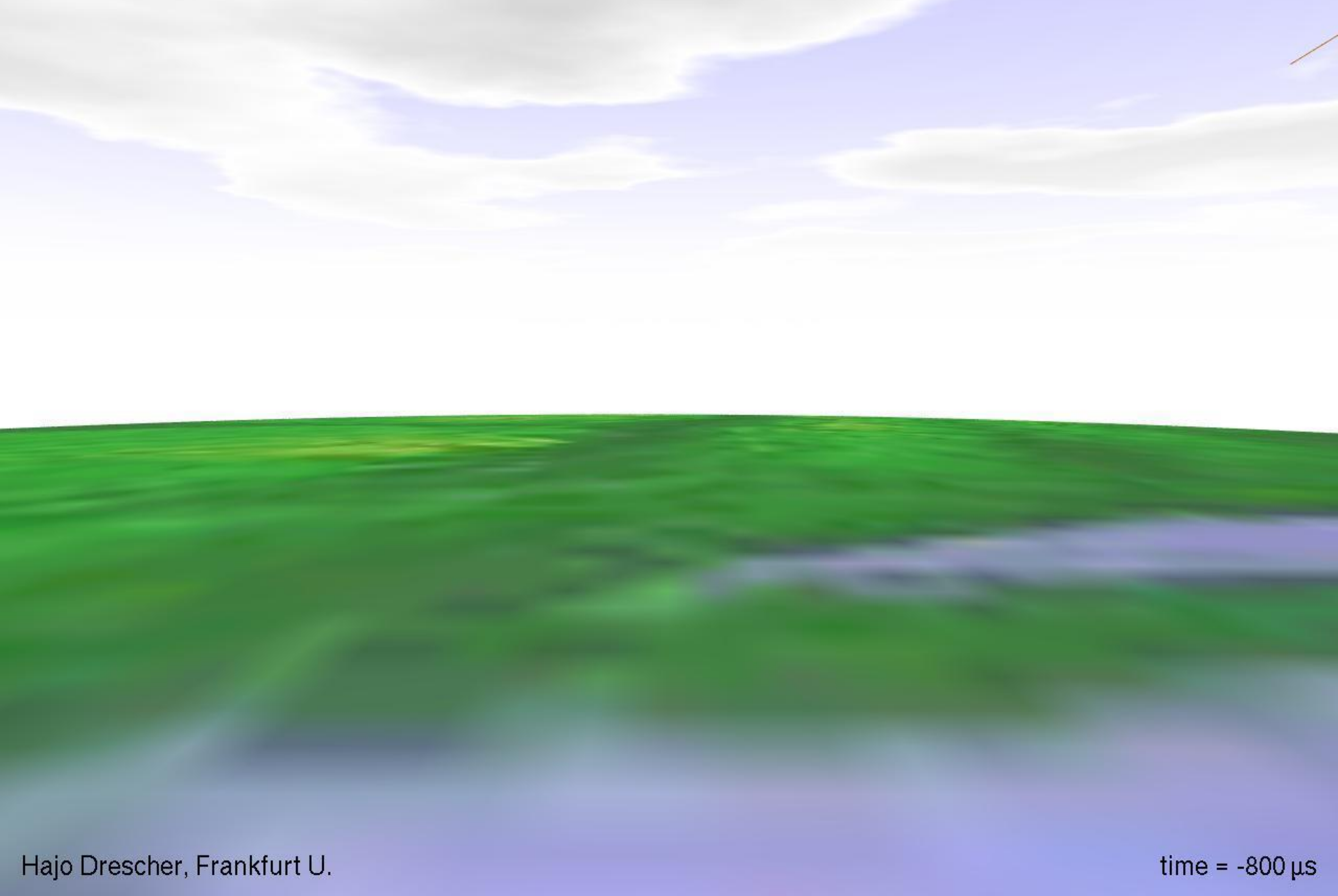
Cosmic rays “rain”



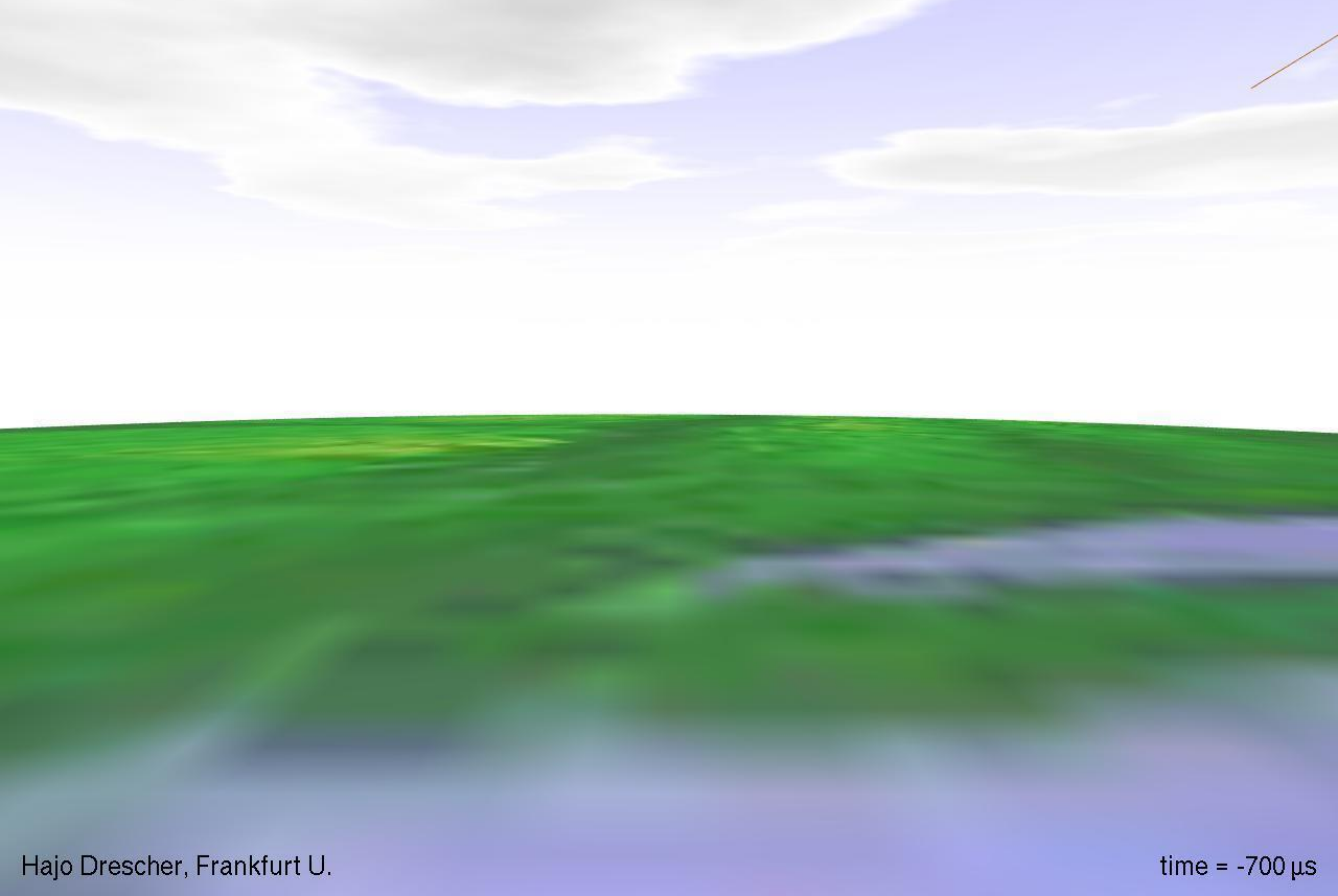
Cosmic rays “rain”



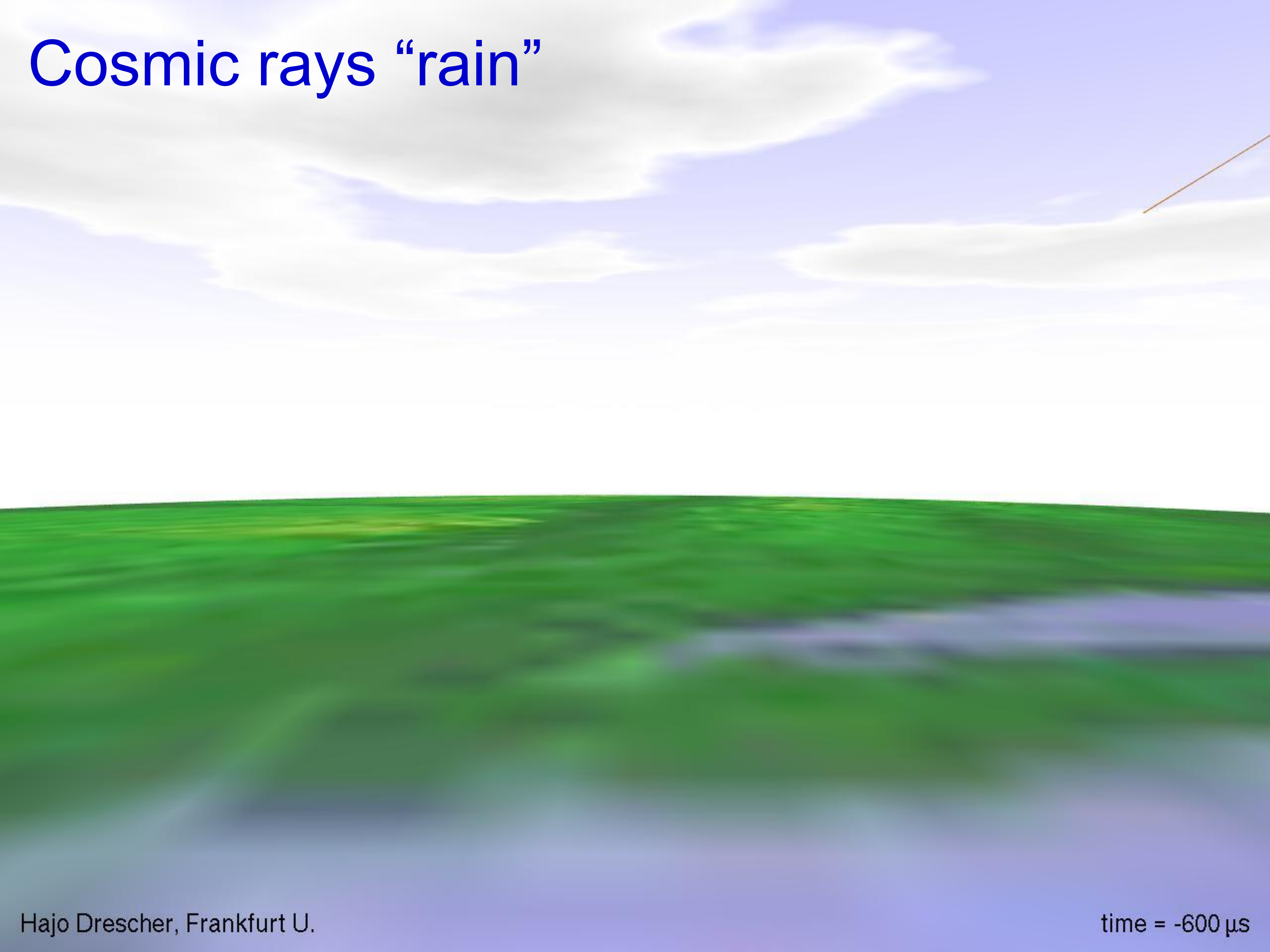
Cosmic rays “rain”



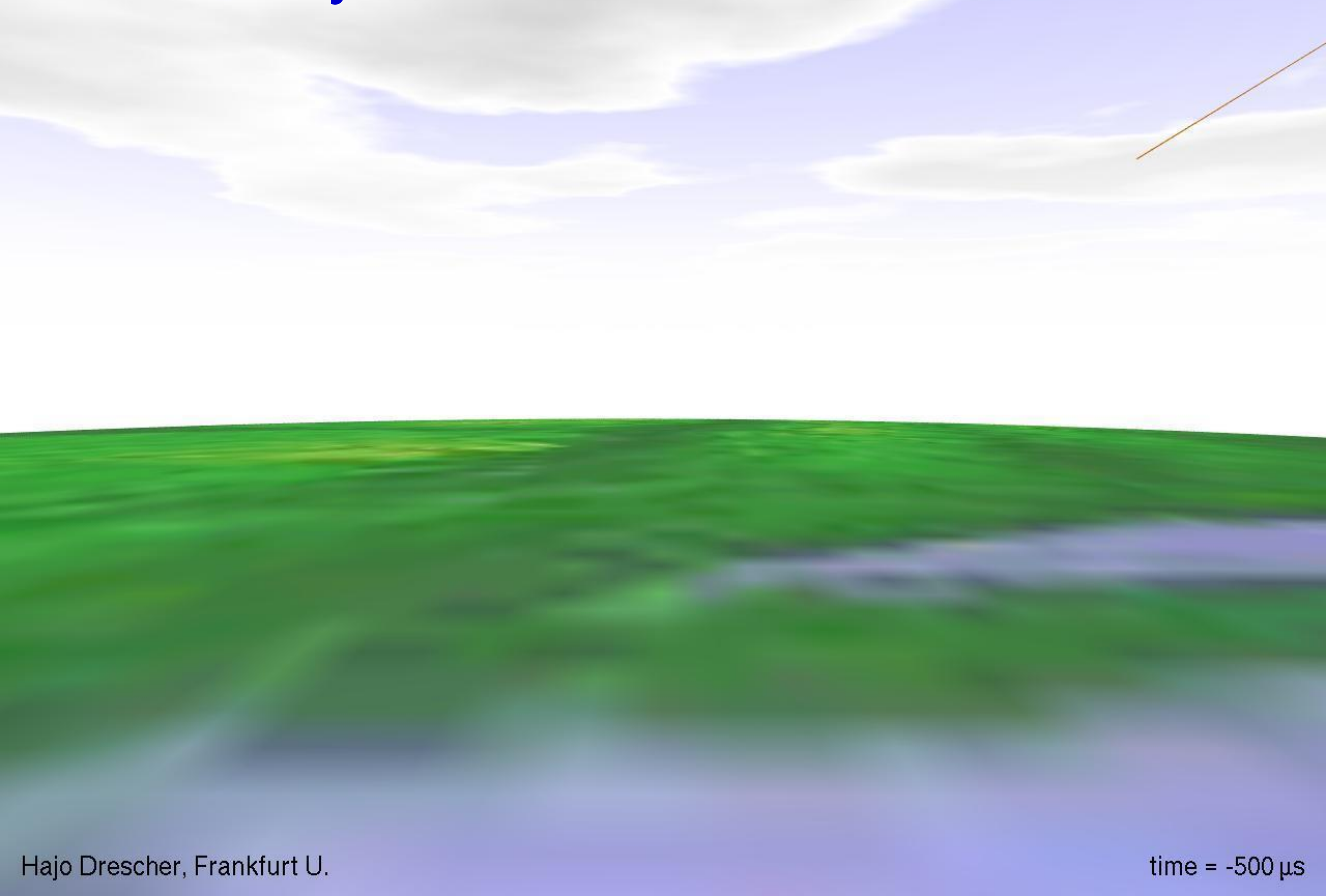
Cosmic rays “rain”



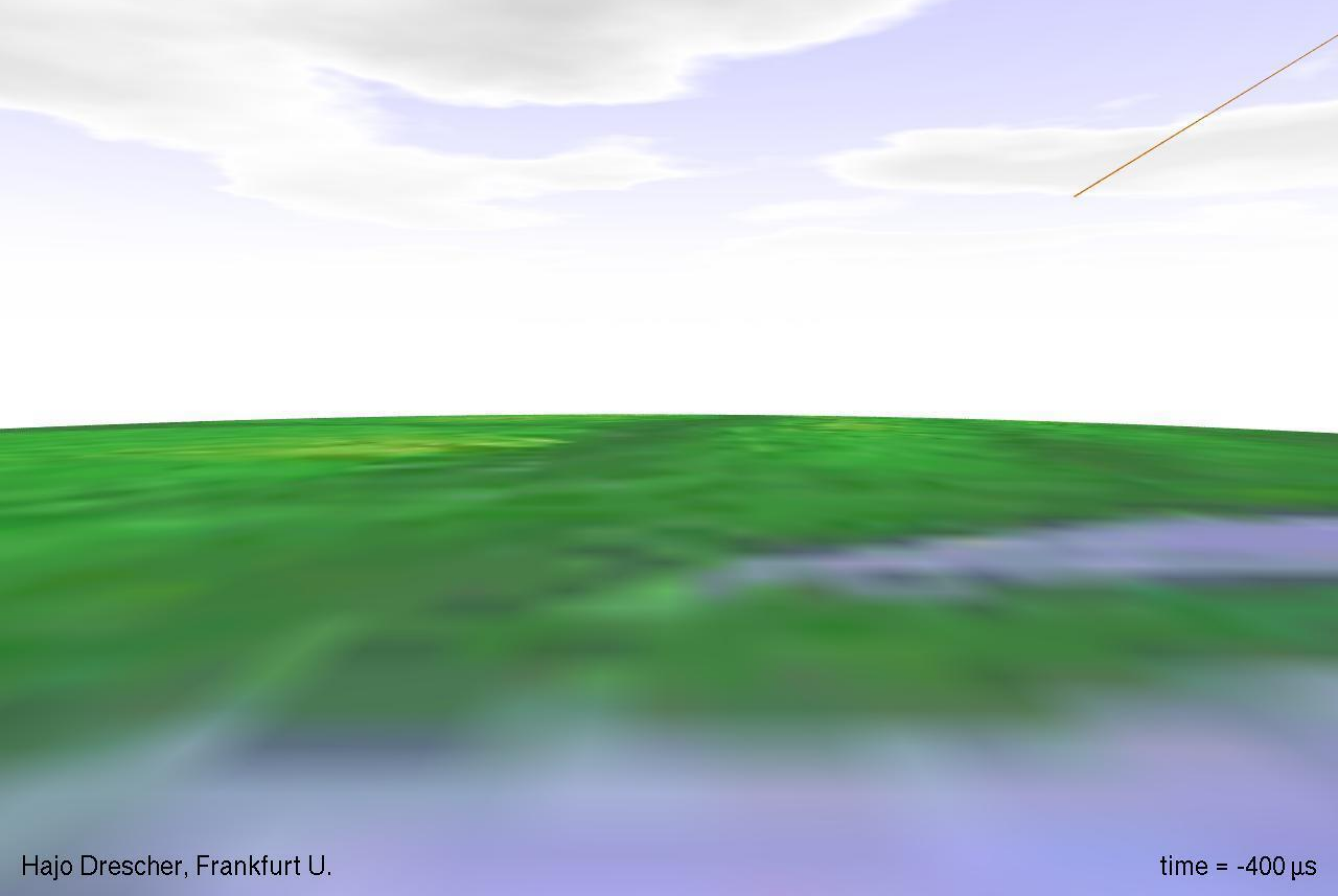
Cosmic rays “rain”



Cosmic rays “rain”



Cosmic rays “rain”



Cosmic rays “rain”

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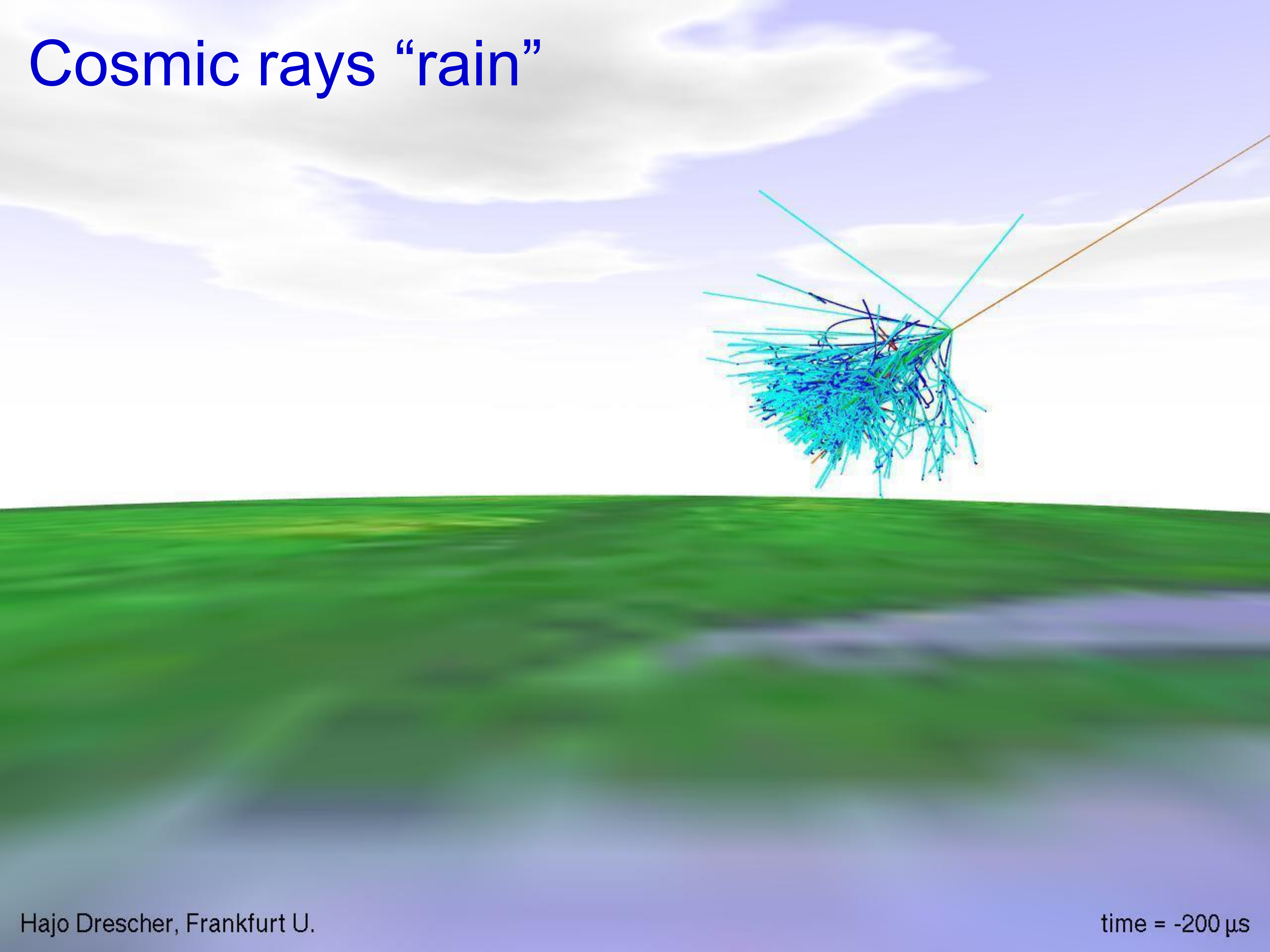
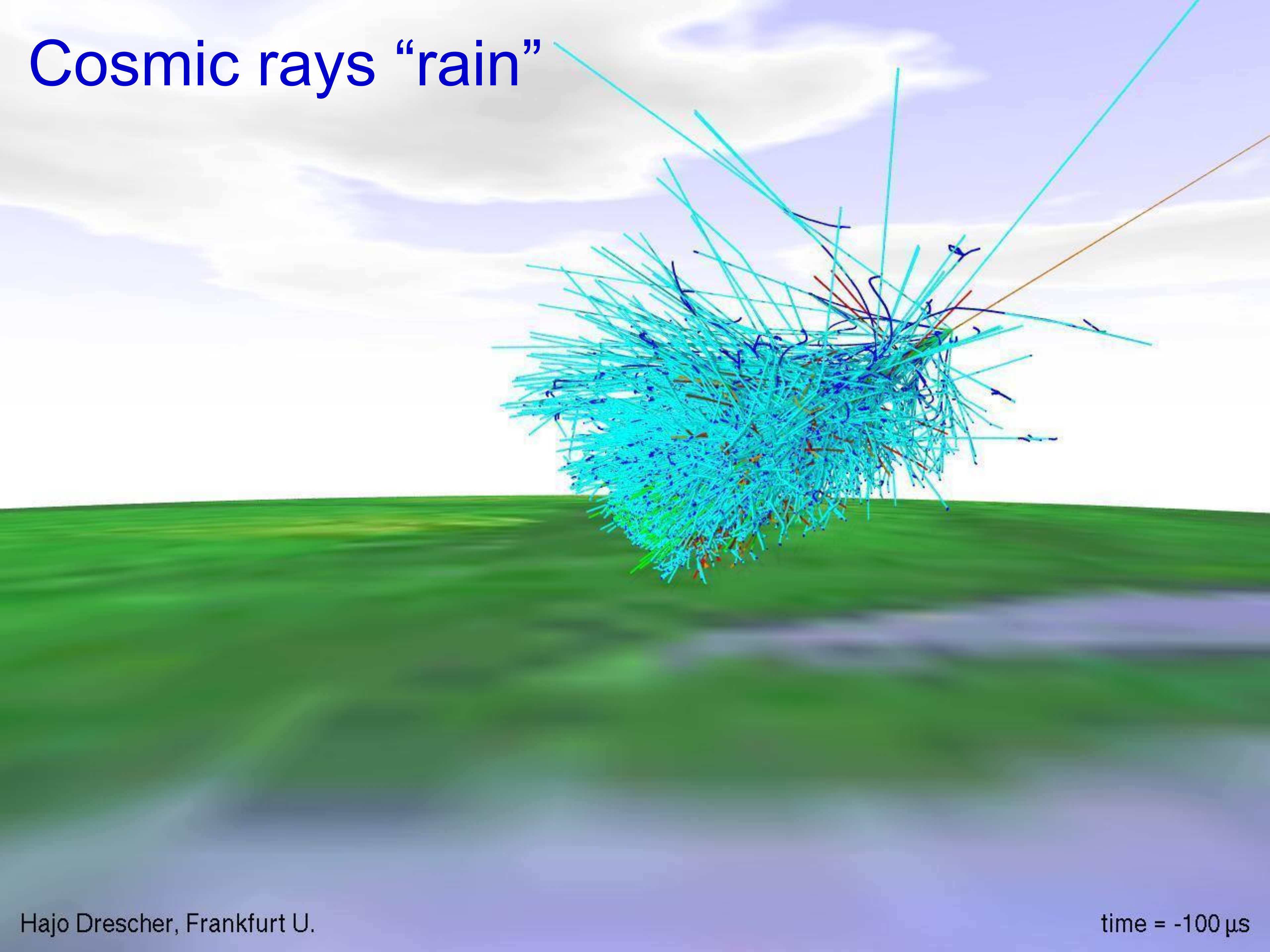
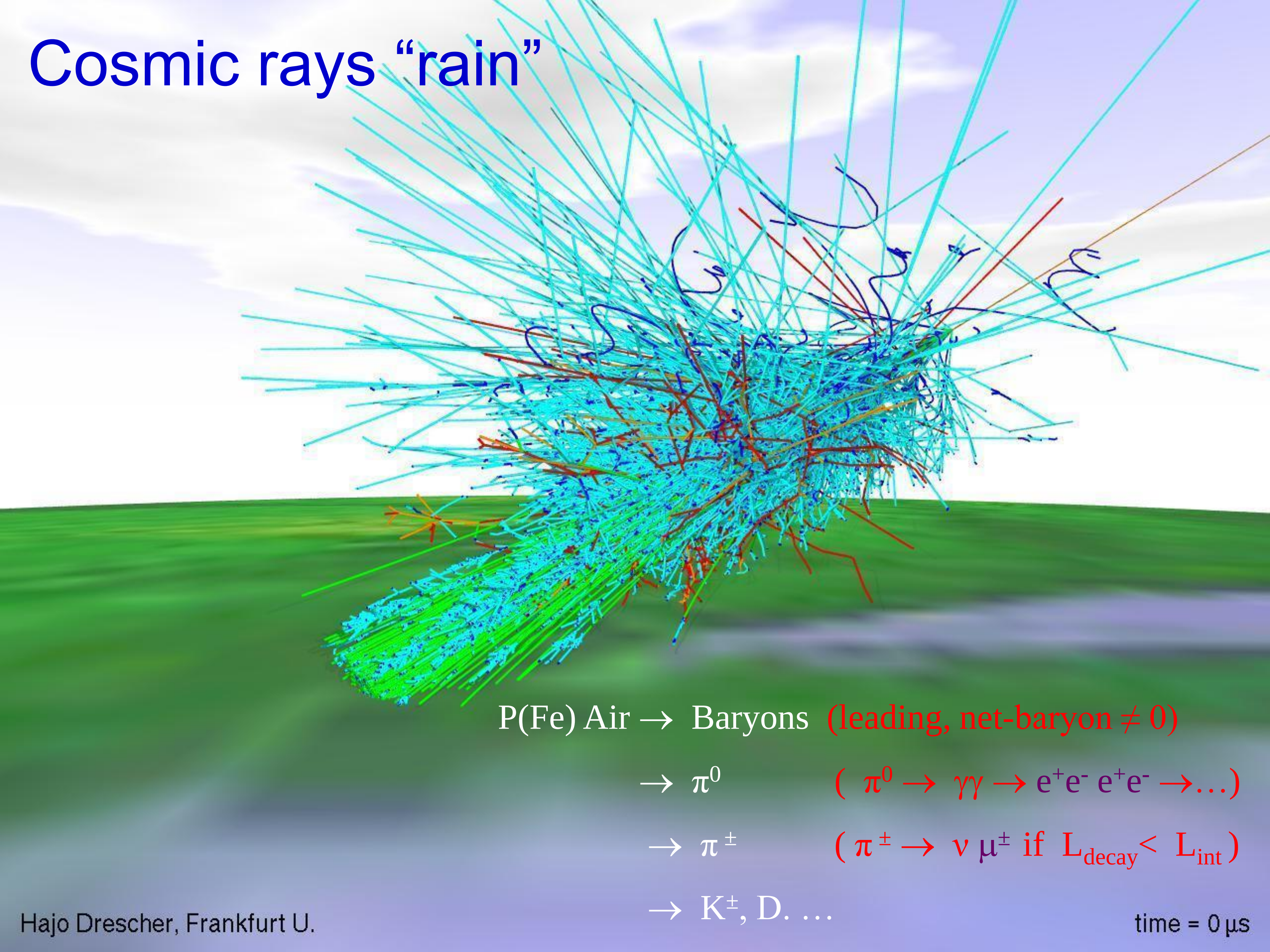


Cosmic rays “rain”



Cosmic rays “rain”



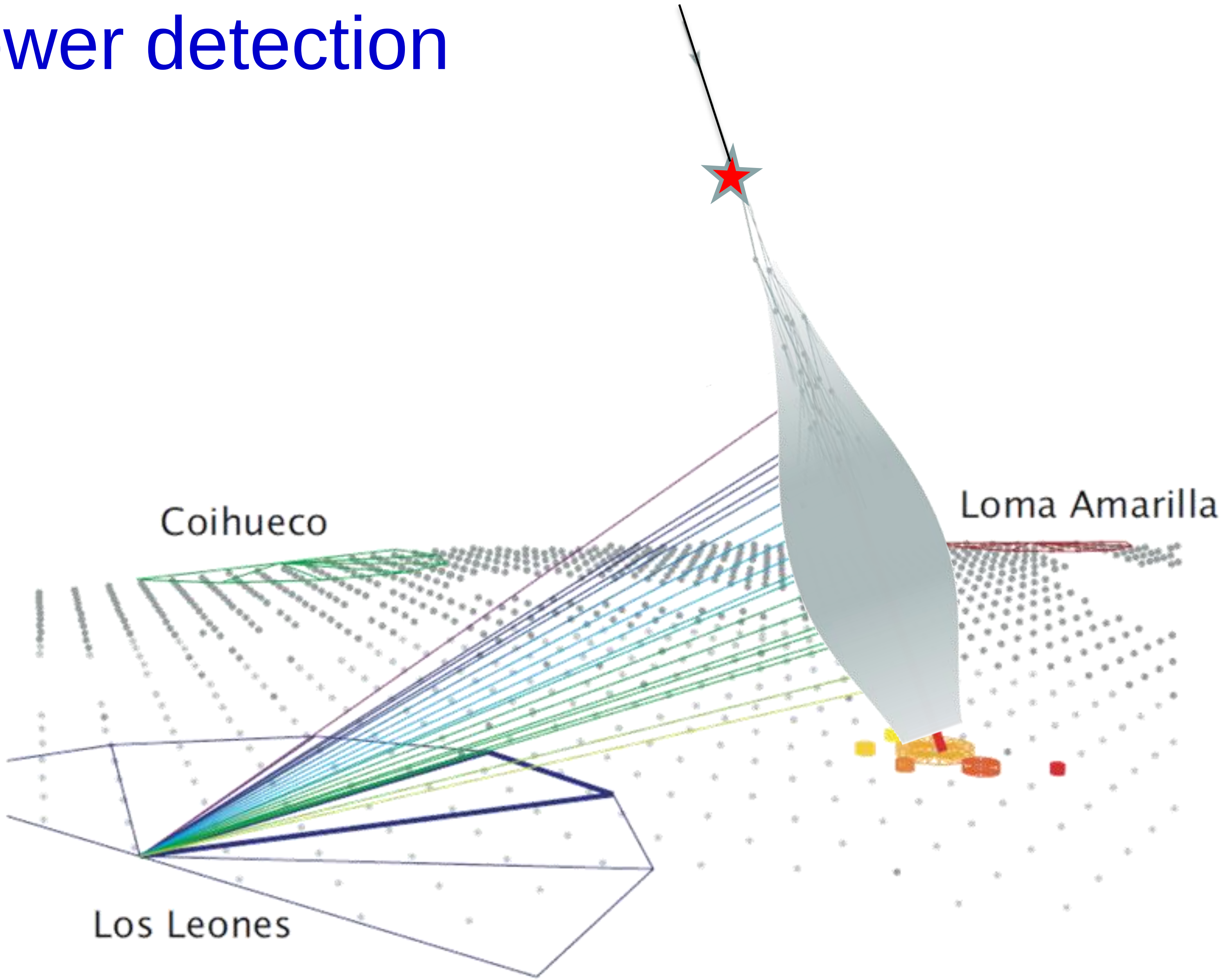
$P(Fe)\ Air \rightarrow$ Baryons (leading, net-baryon $\neq 0$)

$\rightarrow \pi^0$ $(\ \pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^-\ e^+e^- \rightarrow \ldots)$

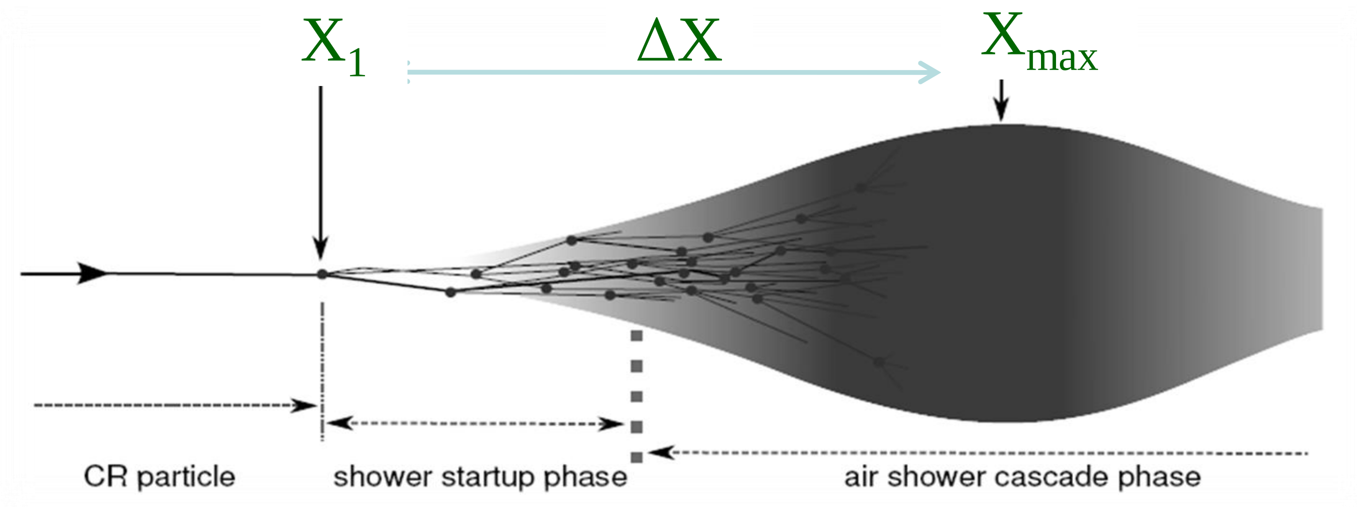
$\rightarrow \pi^{\pm}$ $(\pi^{\pm} \rightarrow \nu\ \mu^{\pm}$ if $L_{decay} < L_{int})$

$\rightarrow K^{\pm}$, D. …

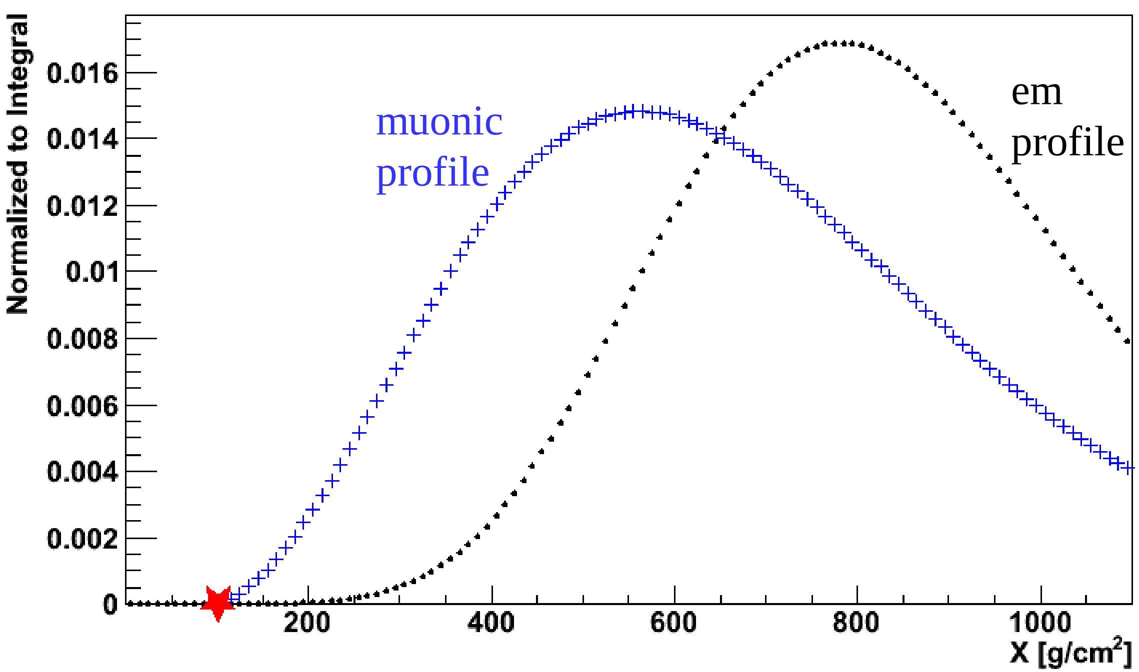
Shower detection



Shower development



$$X_{max} = X_1 + \Delta X$$



$$E \propto Ne \propto \int \frac{dN_e}{dX} dX$$

$$N_\mu \cong \int \frac{dN_\mu}{dX} dX$$

$$X(l) = \int_0^l \rho(x) dx$$

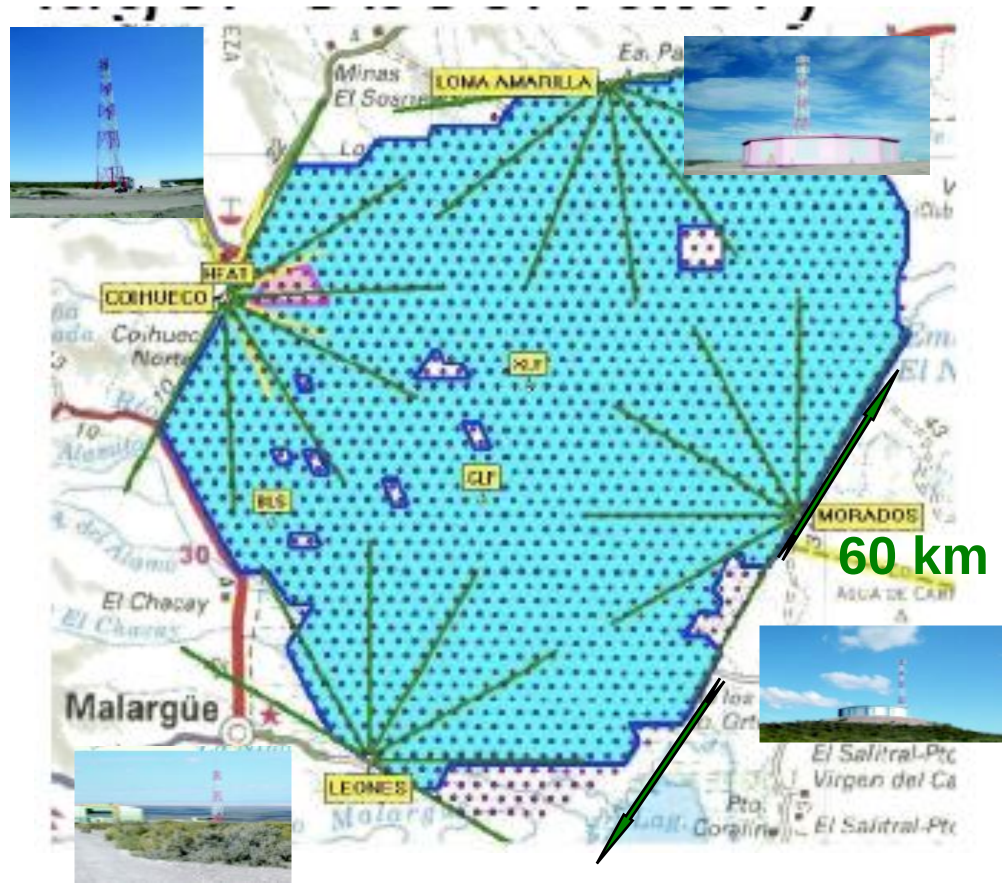
The Pierre Auger Observatory

South Hemisphere

Area ~ 3000 km2

24 fluorescence telescopes

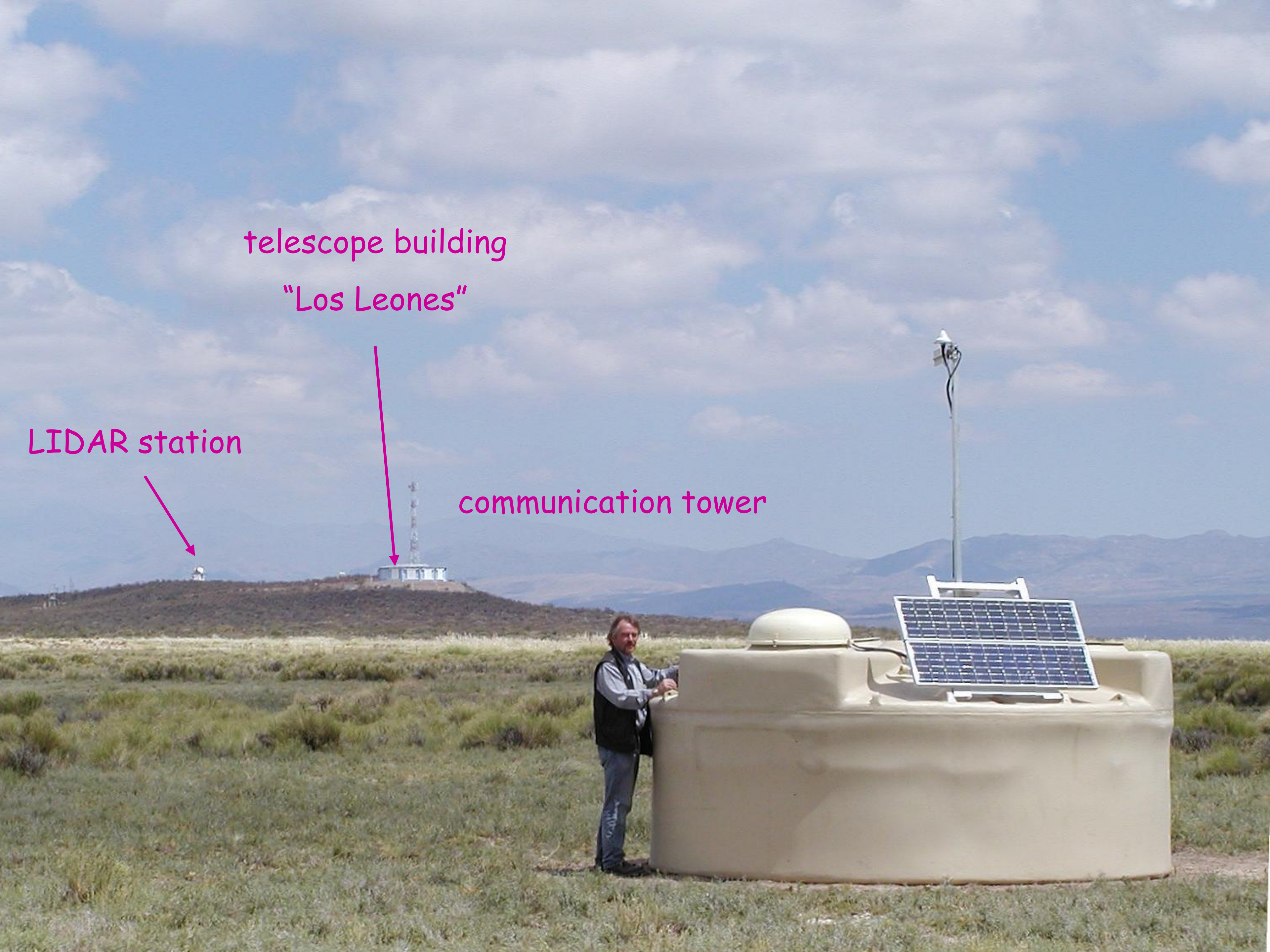
1600 water Cerenkov detectors

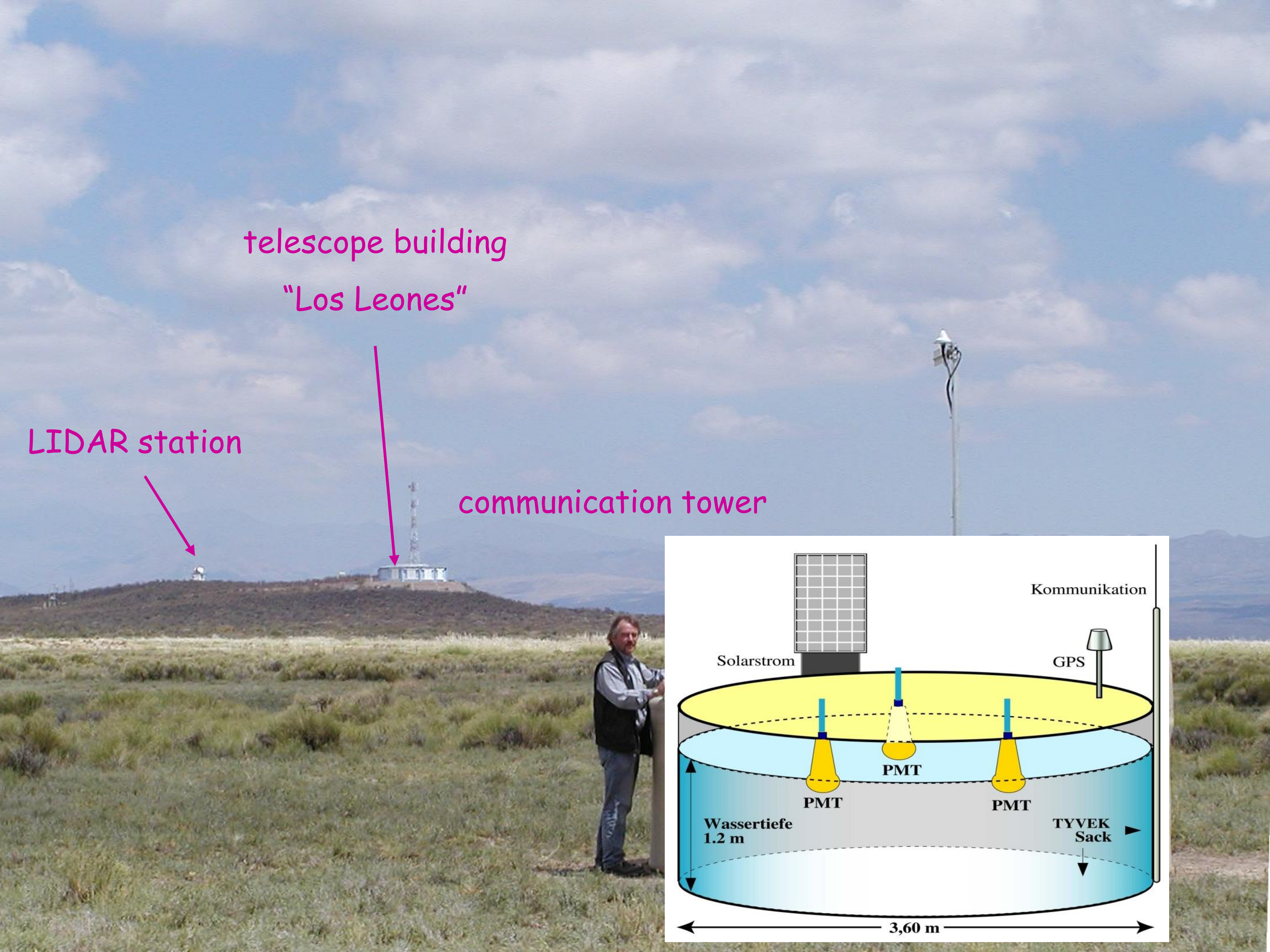


Malargüe, Argentina

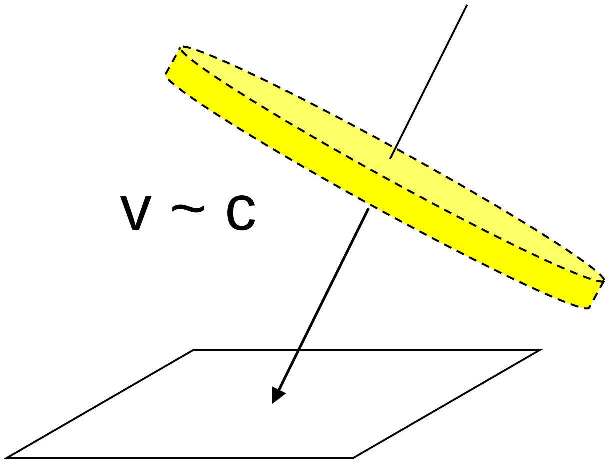
Nov 2009


1.5 km

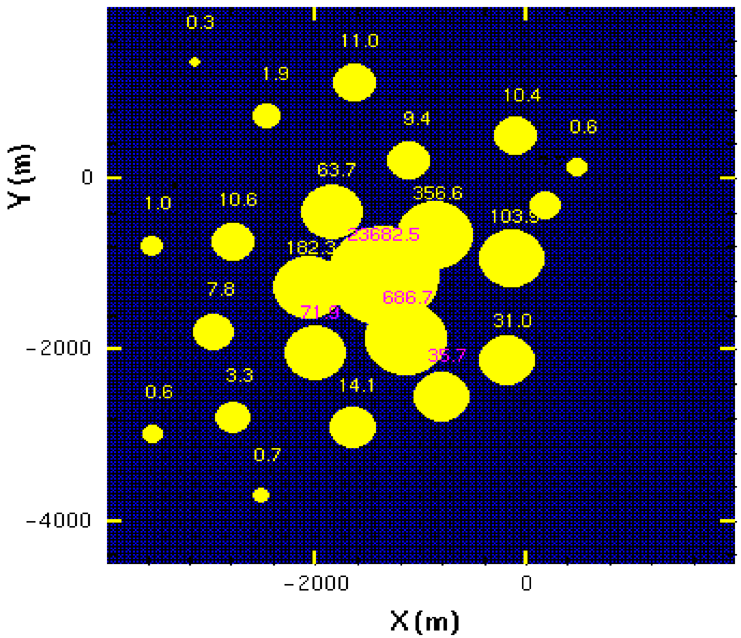

telescope building
"Los Leones"
LIDAR station
communication tower

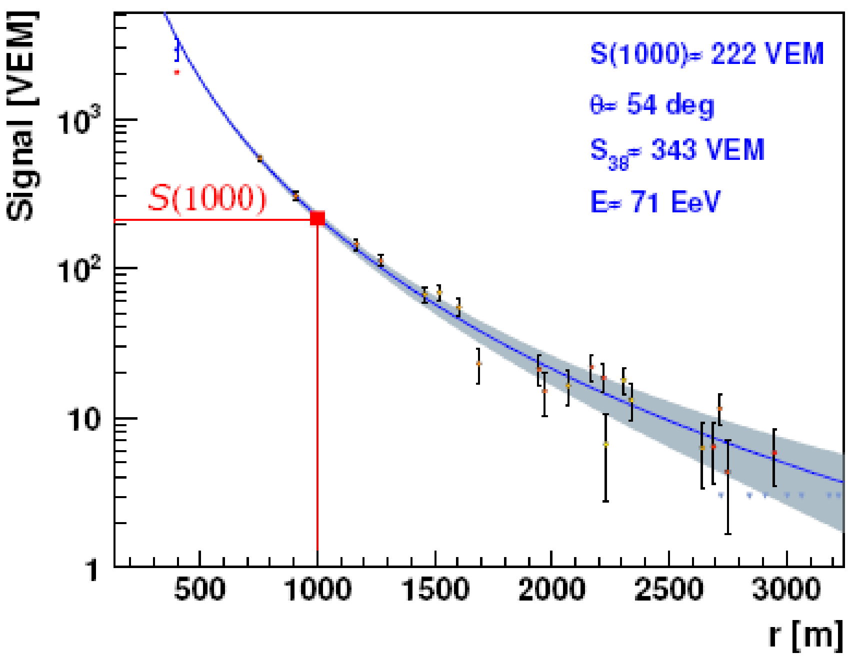

telescope building
"Los Leones"
LIDAR station
communication tower
Kommunikation
Solarstrom
GPS
PMT
PMT
PMT
Wassertiefe
1.2 m
TYVEK
Sack
3,60 m

Ground array measurements



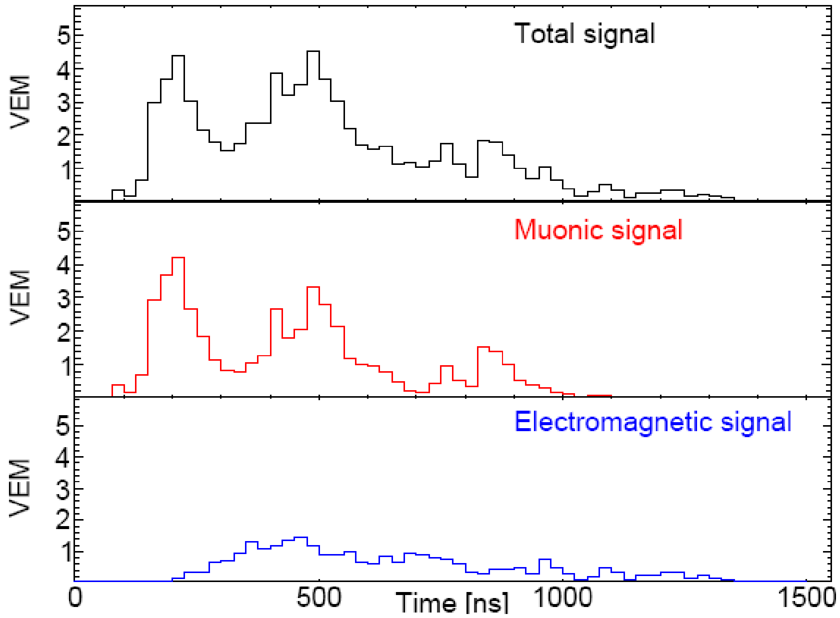
From (n_i, t_i):
The direction
The core position
The Energy

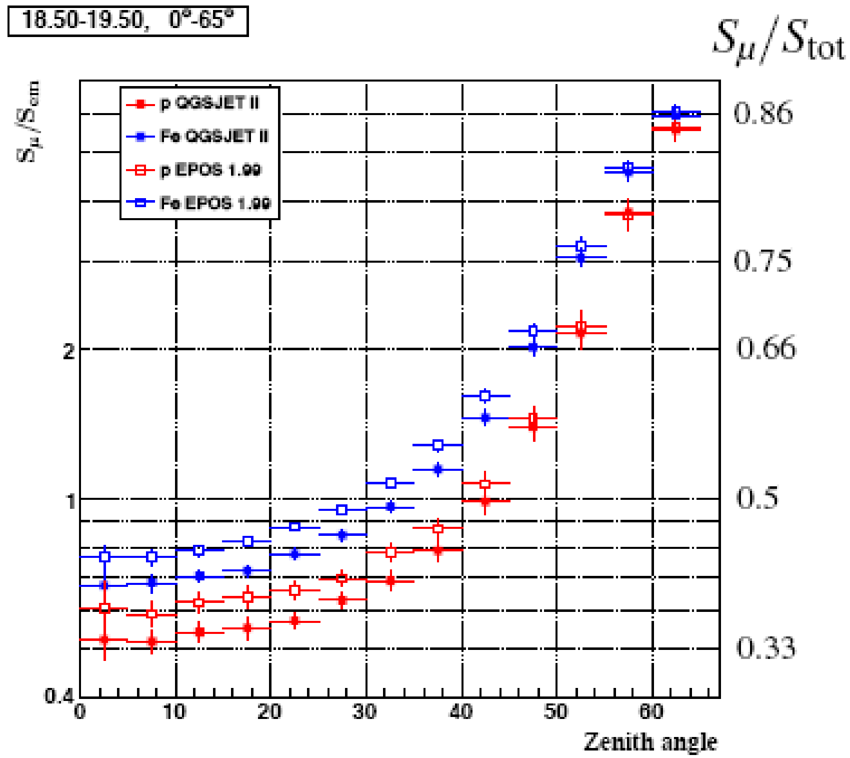




E.M. and μ signal at the SD

Individual time traces

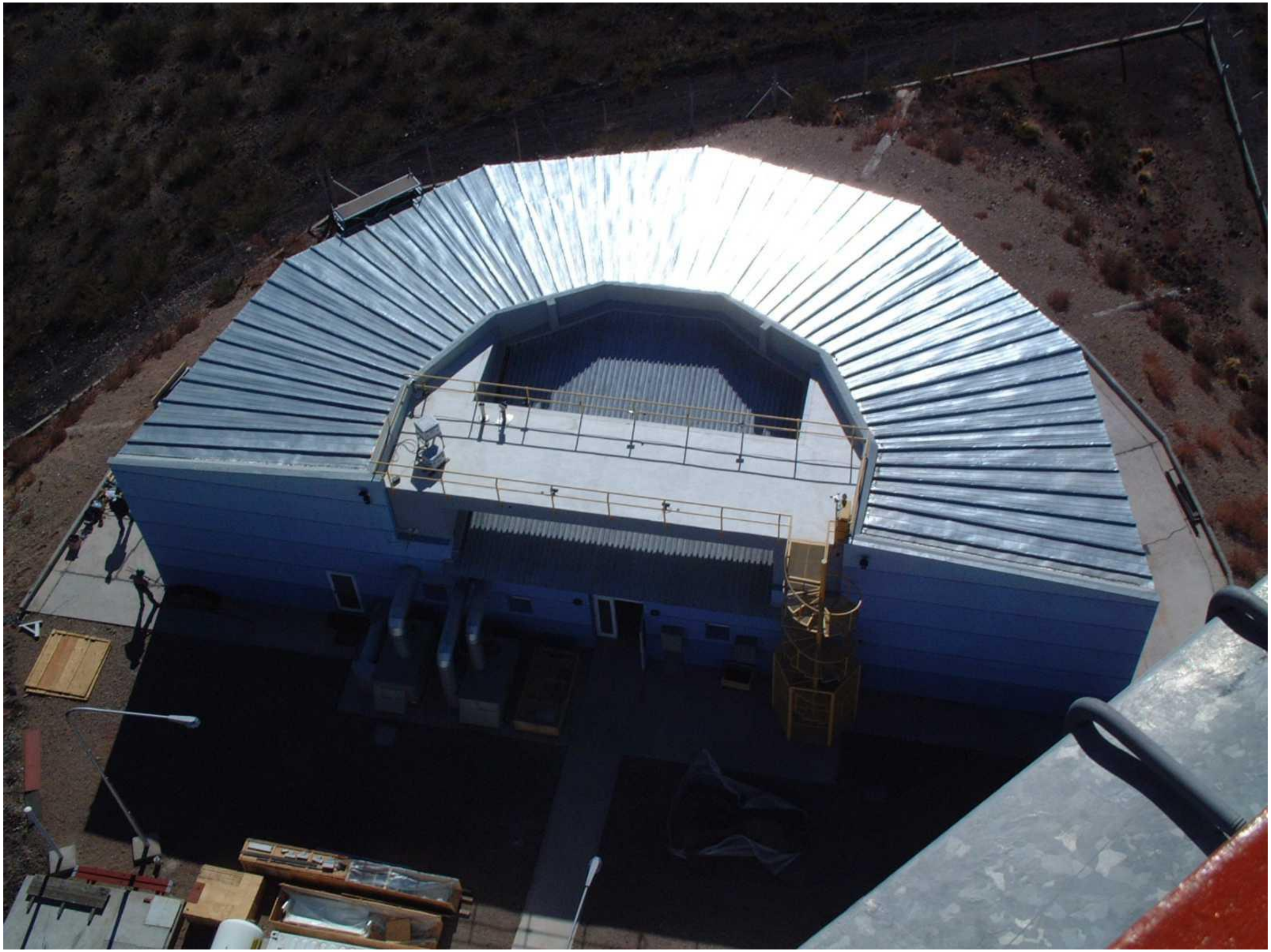




Proton, Θ =45°, E= 10^{19} eV ,
d= 1000m

$$S_{\mathrm{MC}}(E,\theta,X_{\mathrm{max}}) = S_{\mathrm{em}}(E,\theta,DG) + N_\mu^{\mathrm{rel}} S_\mu^{\mathrm{QGSII,p}}(10^{19}\,\mathrm{eV},\theta,DG)$$

The fluorescence detectors (FD)



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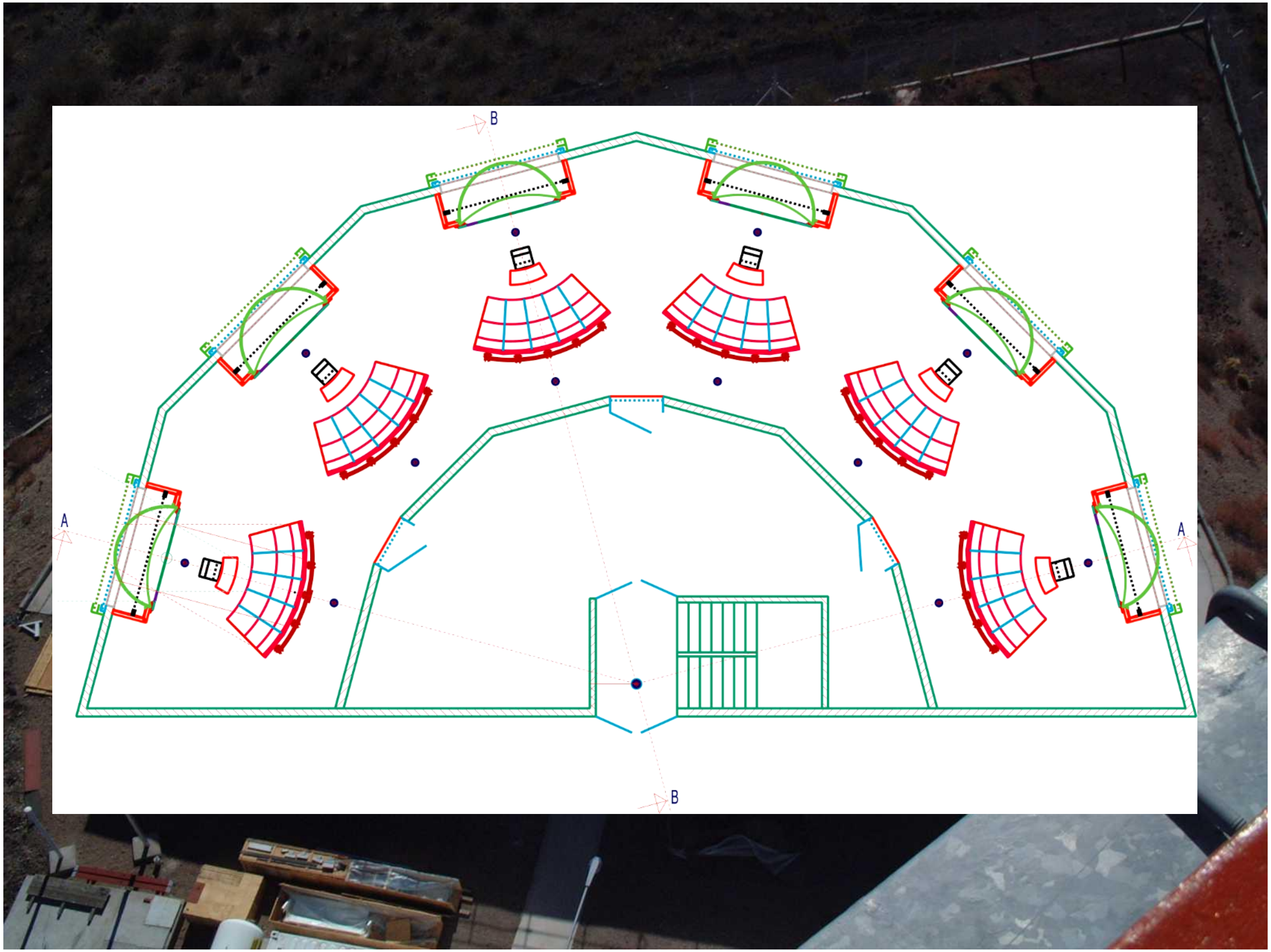

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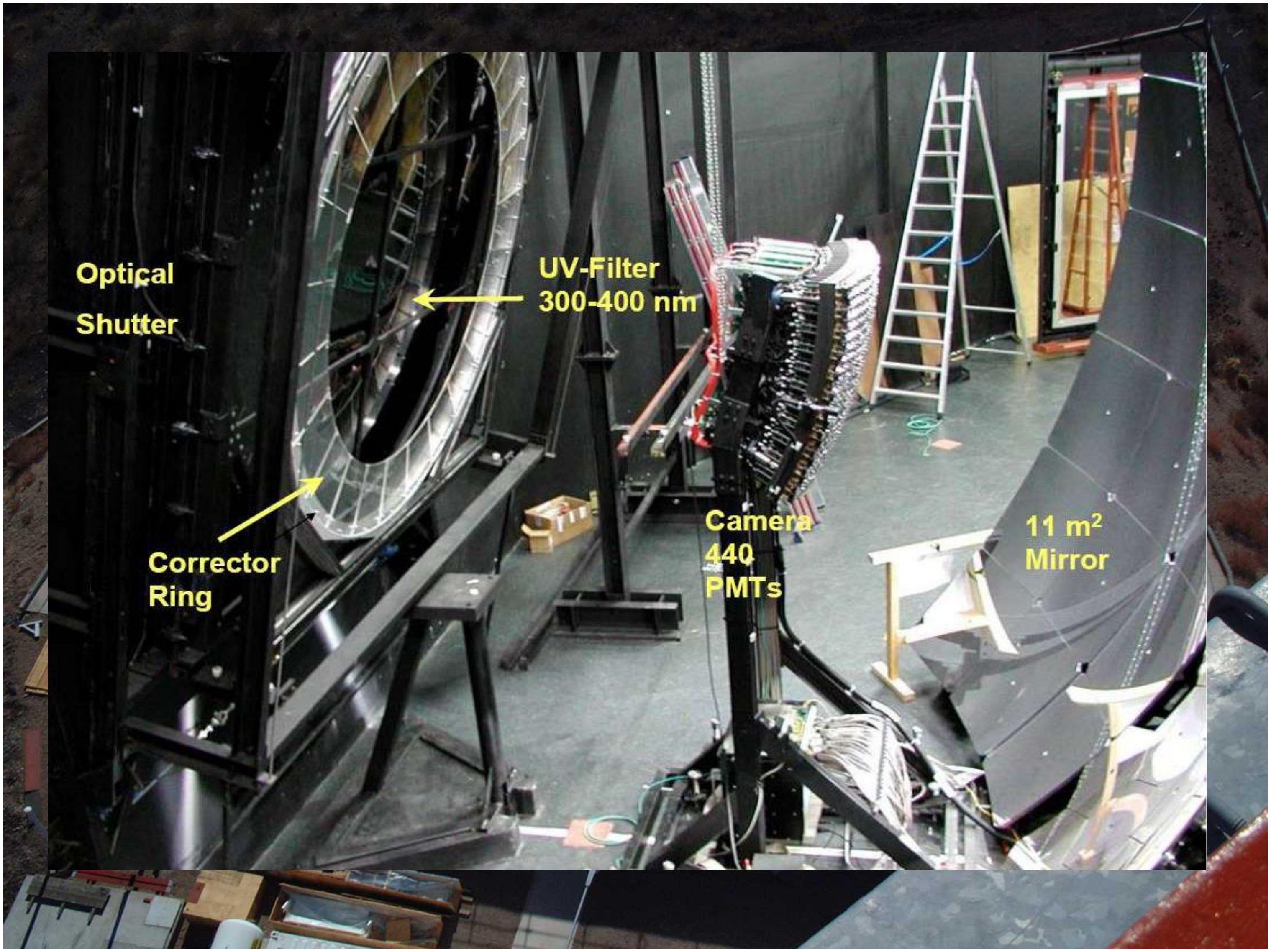


Fluorescence detector measurements

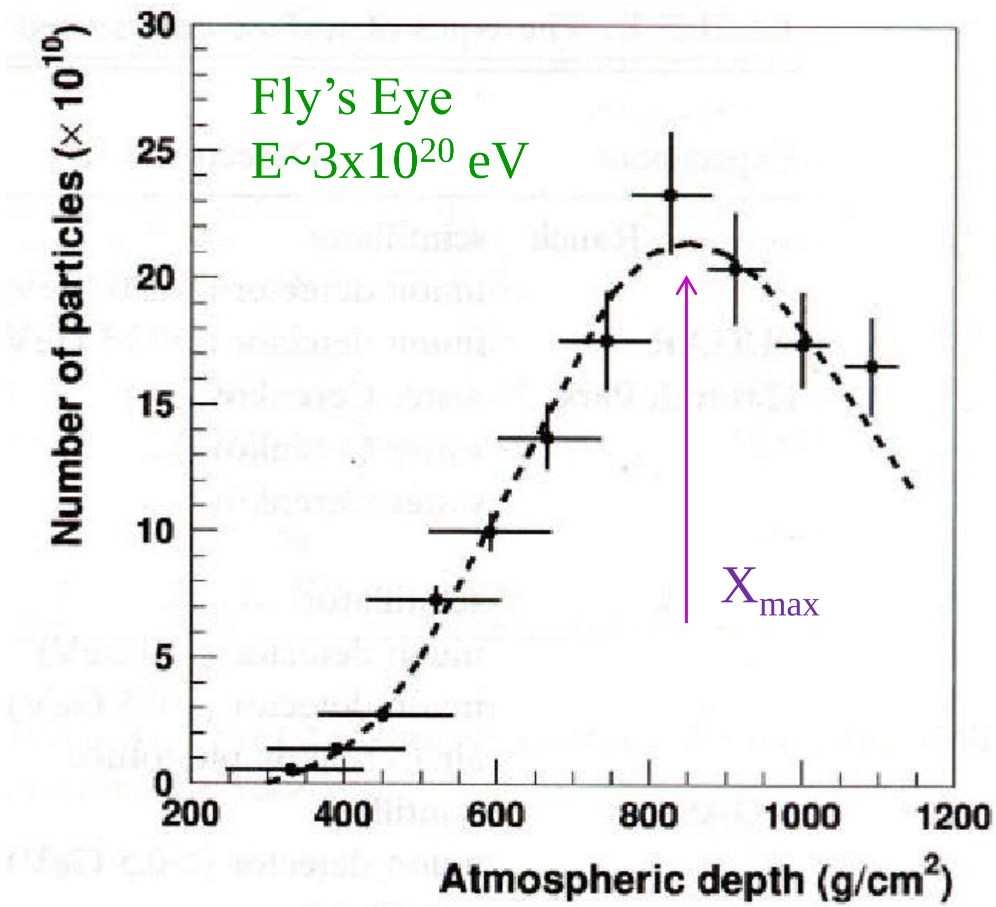
The direction

Light profiles

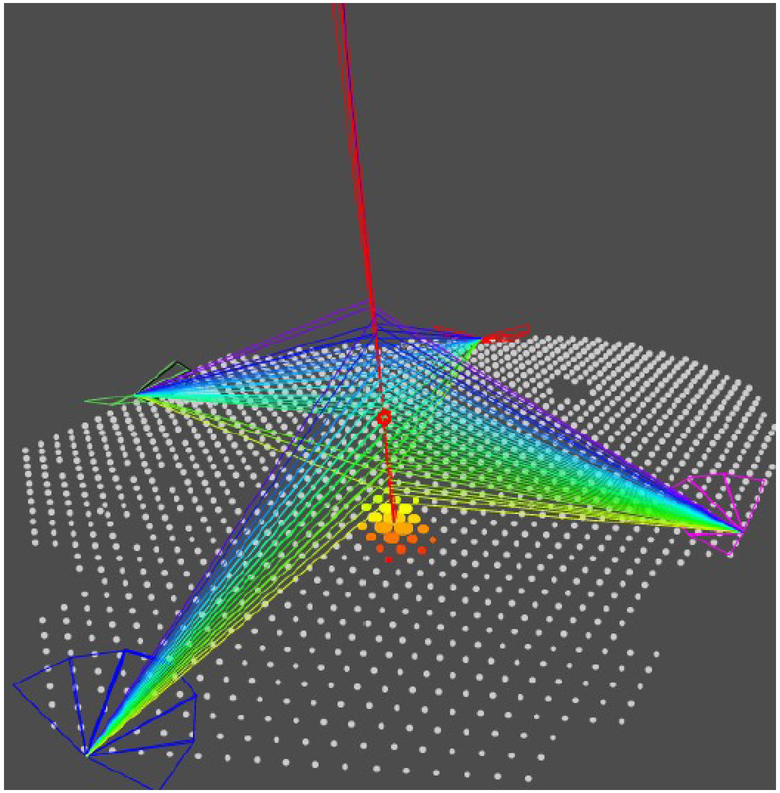
(X_{max}, Energy, …)

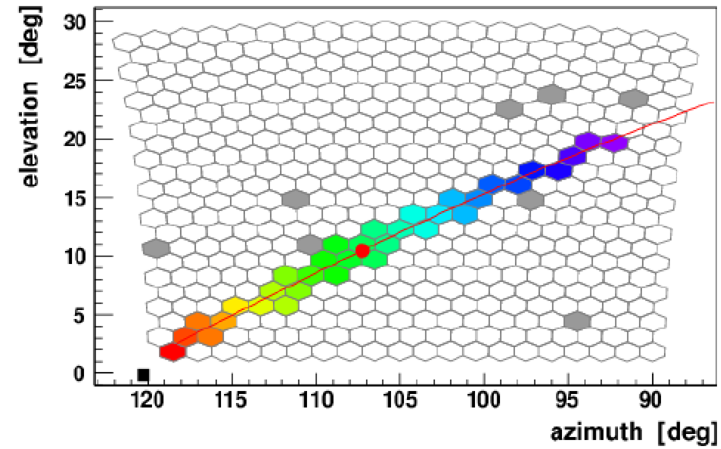
$$E \propto Ne$$

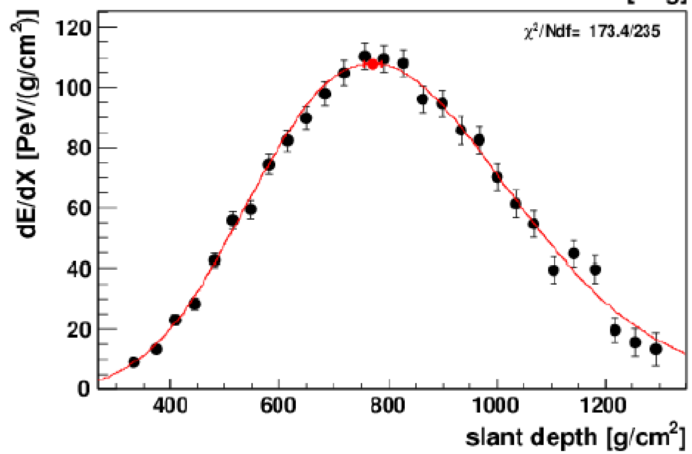
$$\propto \int N(t)$$

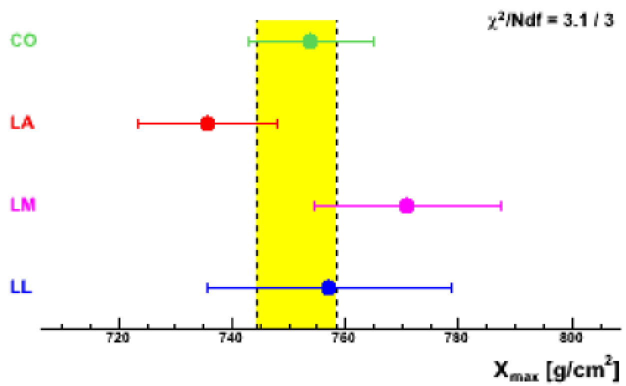


A 4 eyes hybrid event !









Energy

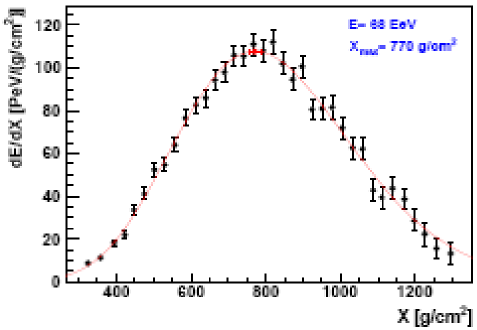
$E = (7.1 \pm 0.2)\ 10^{19}$ eV

Depth of the maximum

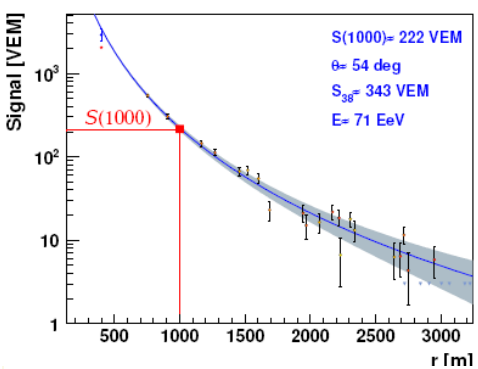
$X_{max} = (752 \pm 7)$ g/cm^2

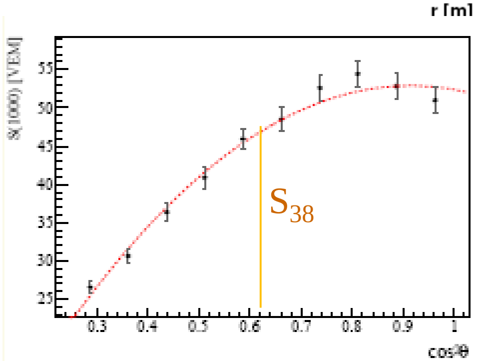
SD Energy Calibration

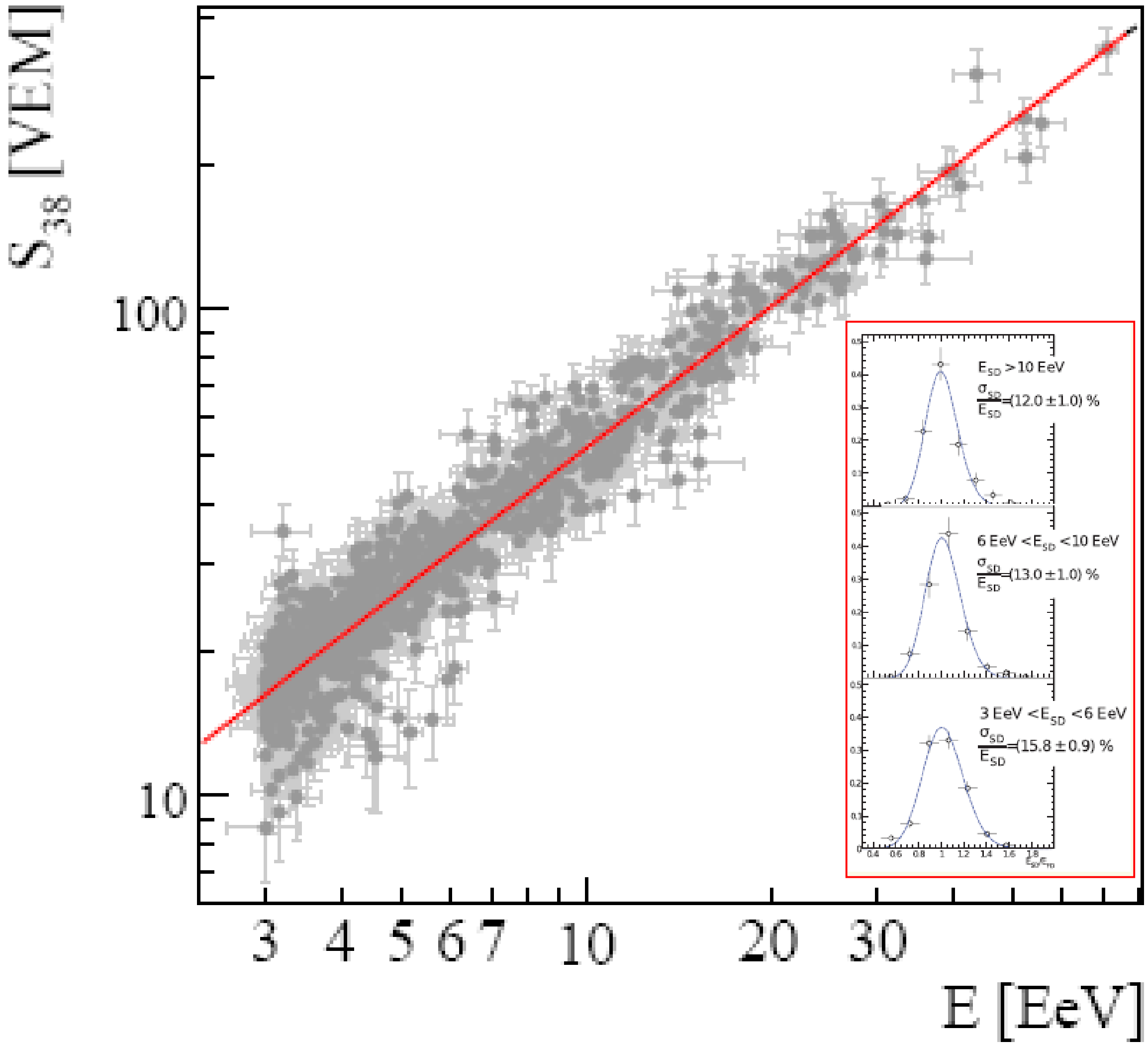
FD



SD

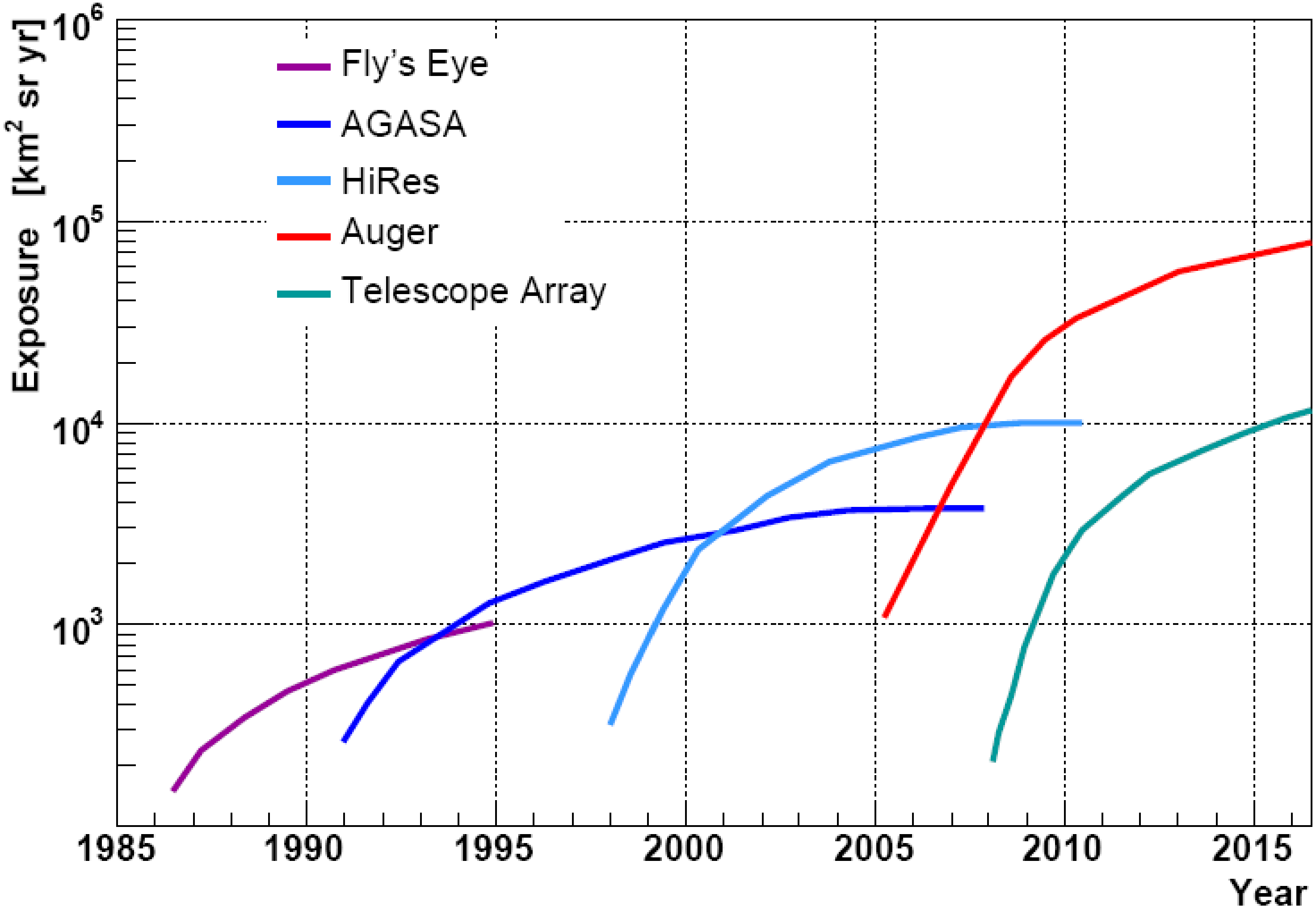






Total Energy uncertainty: 22%

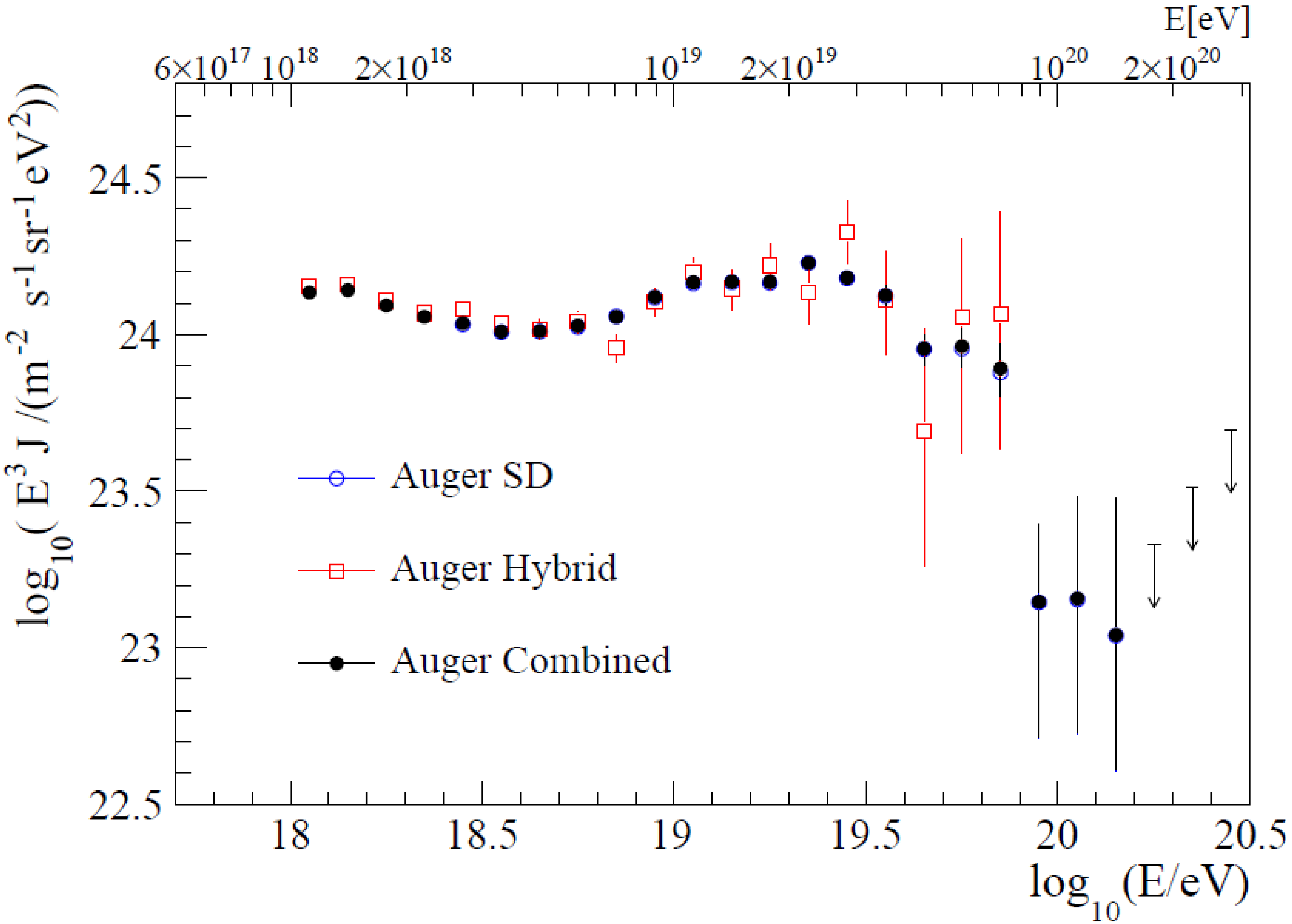
Exposure

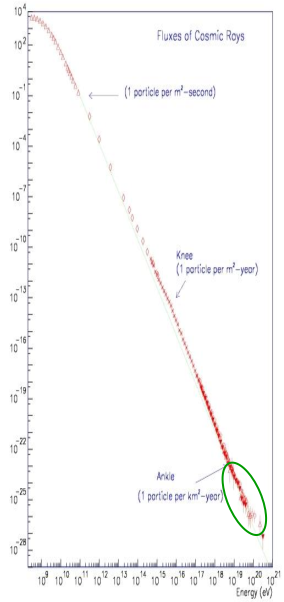


Auger has already more than 10 times the Agasa Exposure

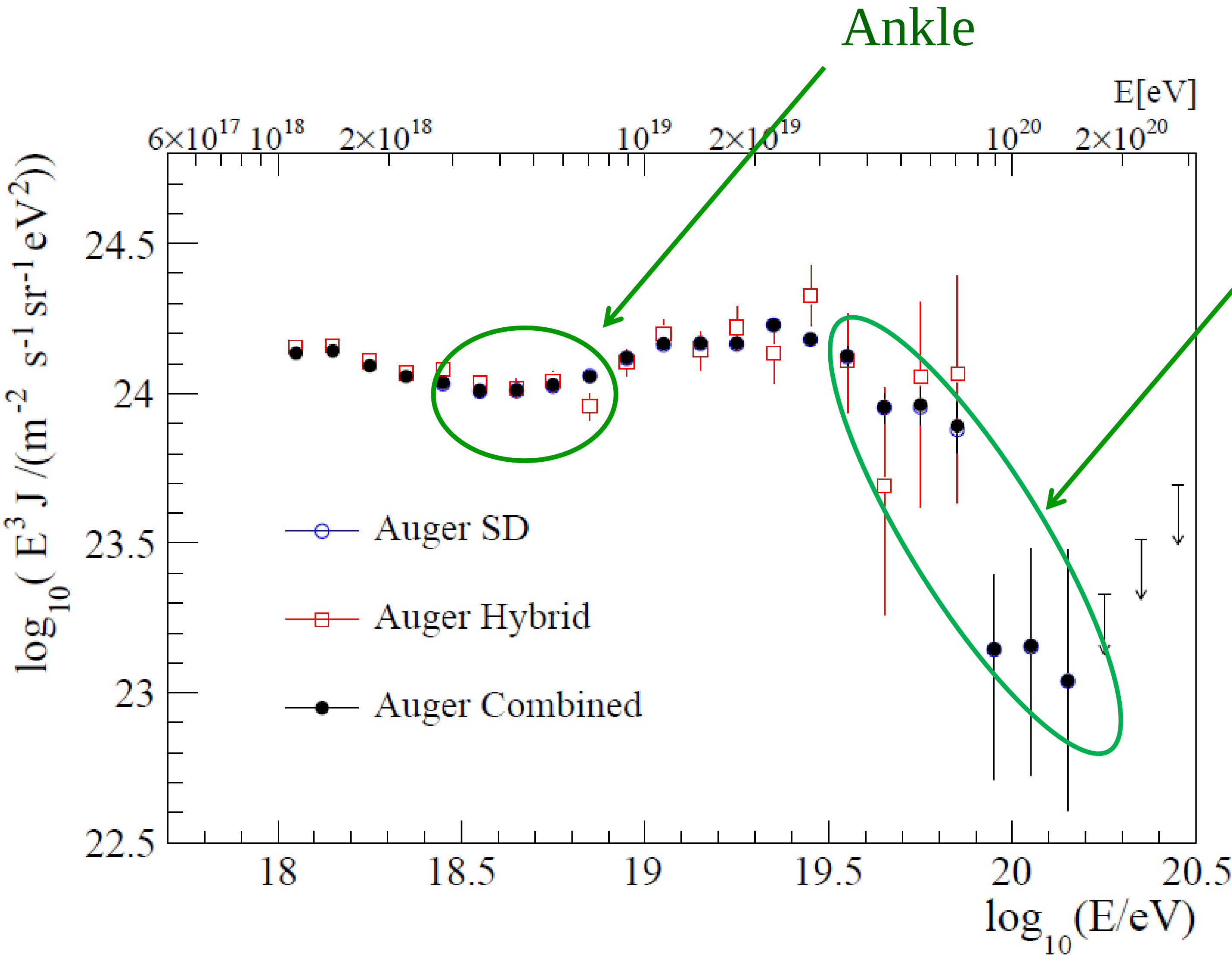
The results

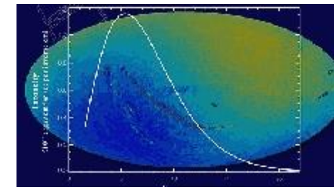
Energy spectrum

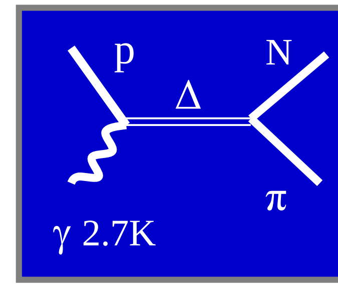




Energy spectrum



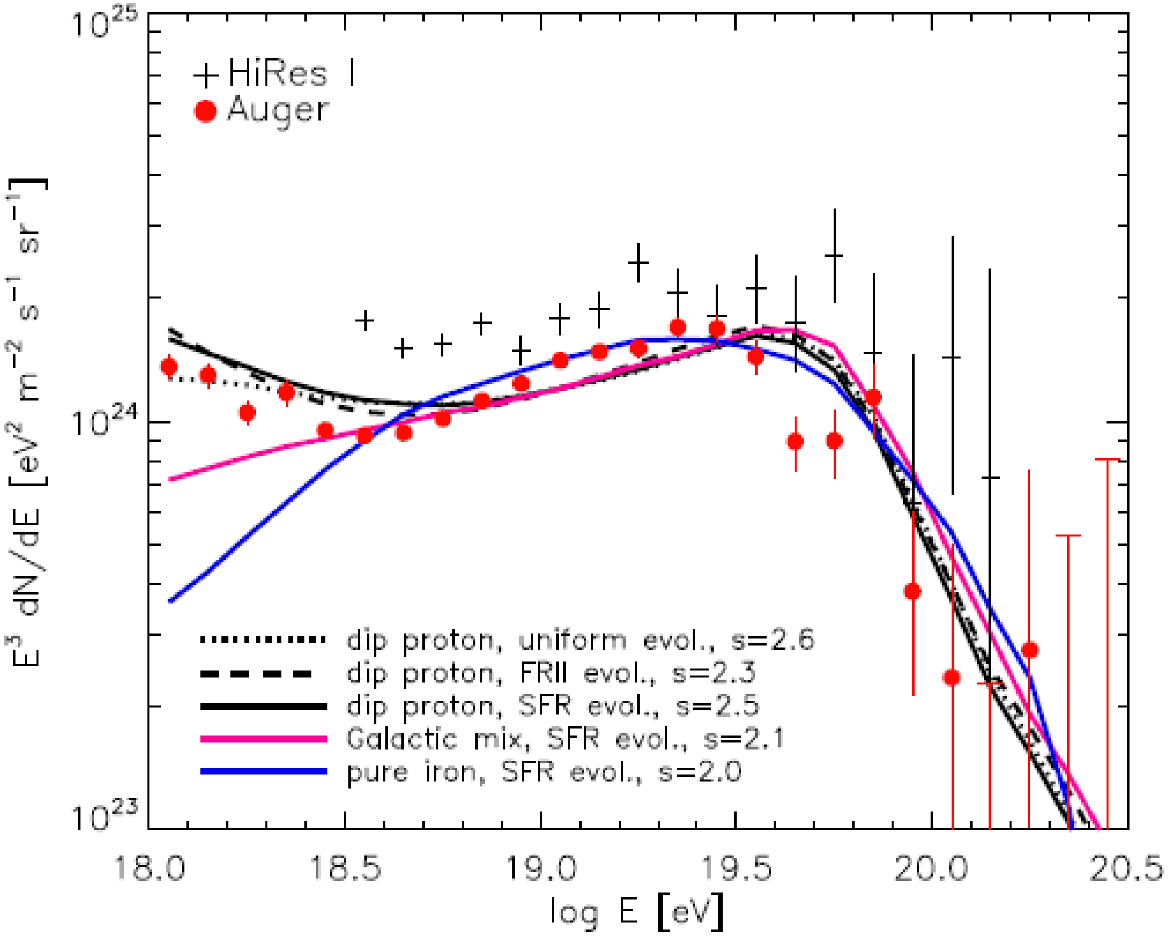




GZK like
suppression !!!

Energy spectrum (interpretation)

Kotera &Olinto



GZK:

$p\ \gamma \rightarrow \Delta \rightarrow p\ N$

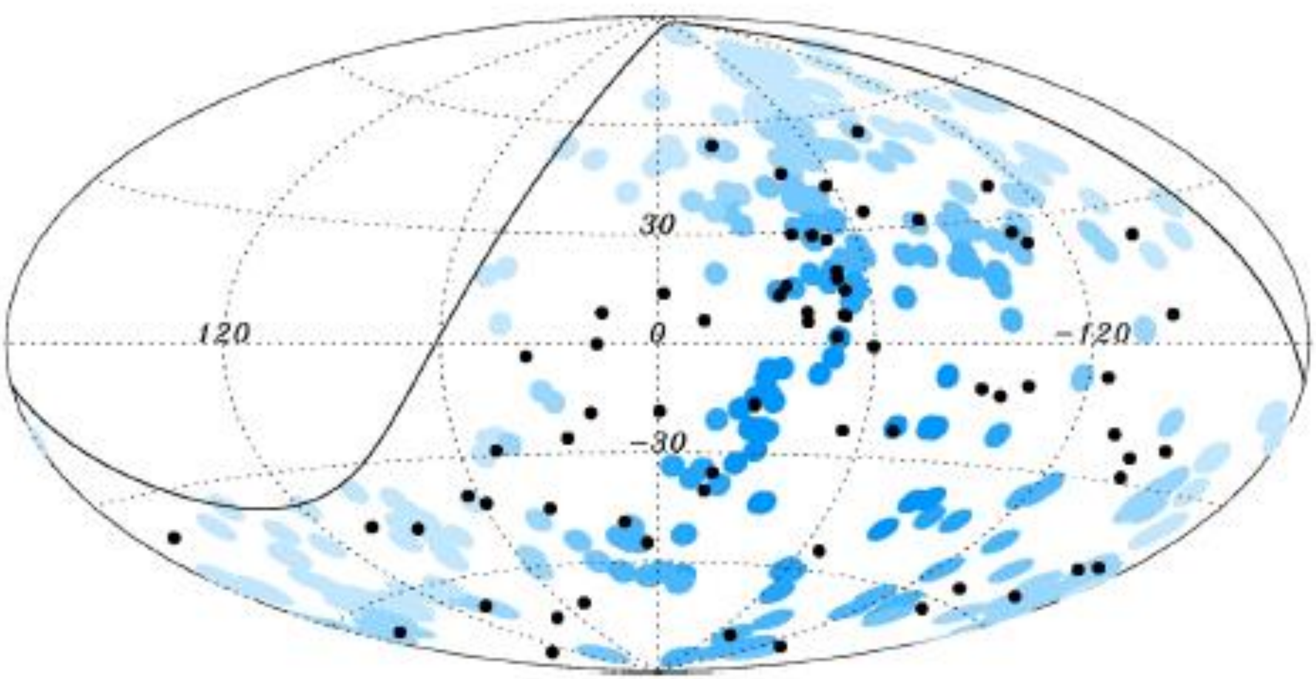
Dip (Berezinsky et al) :

$p\ \gamma \rightarrow p\ e^+ e^-$

Mixed models:
fine tuning!

Spectrum of UHECRs multiplied by E^3 observed by HiRes I and Auger. Overlaid are simulated spectra obtained for different models of the Galactic to extragalactic transition and different injected chemical compositions and spectral indices, s.

Correlation with AGNs

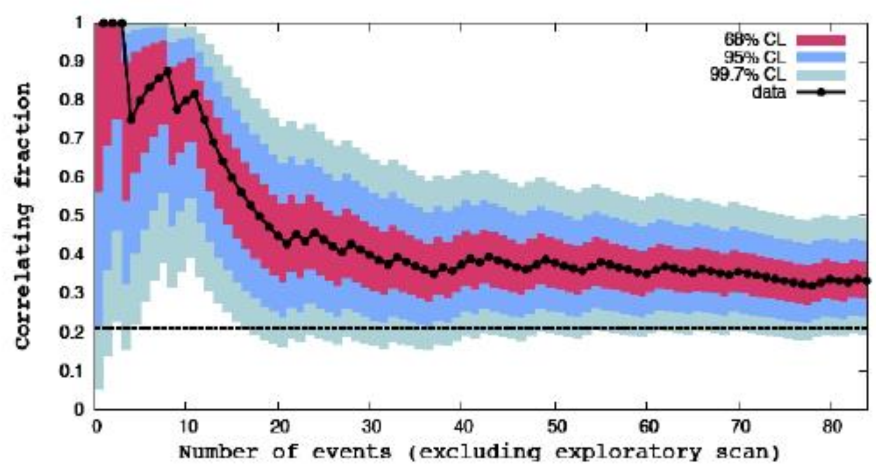


28 out of 84 correlates

Vernon-Cetty-Vernon AGN catalog

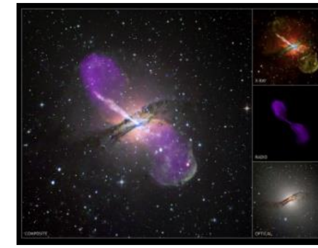
E> 57 EeV, z<0.018, distance < 3.1 deg.

P = 0.006, f = 33 ± 5%



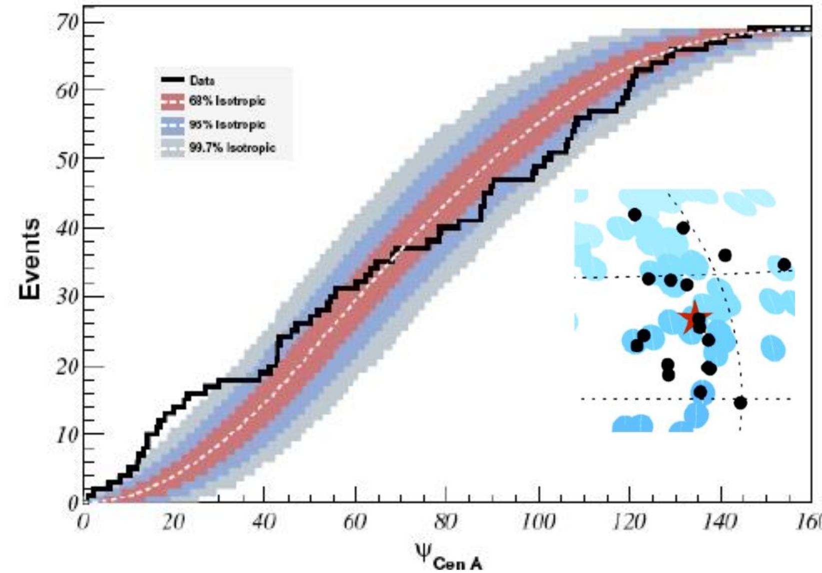
Cen A

Closest (4.6 Mpc) powerful radio galaxy with characteristics jets and lobes, candidate for UHECR acceleration



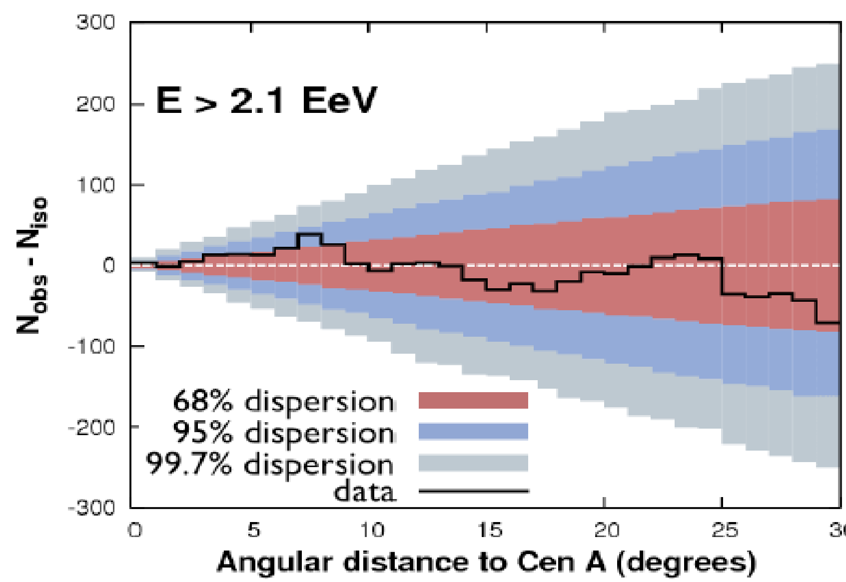
E> 57 10^{18} eV

13/62 within 18 deg., expect 3.2



Lower energies

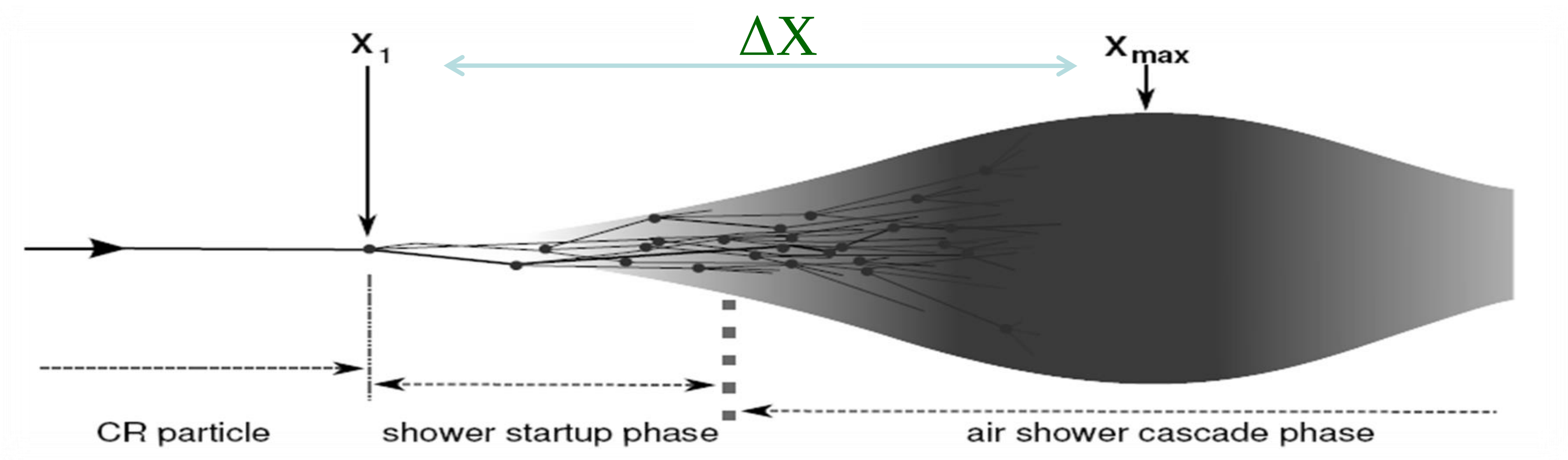
No significant anisotropies

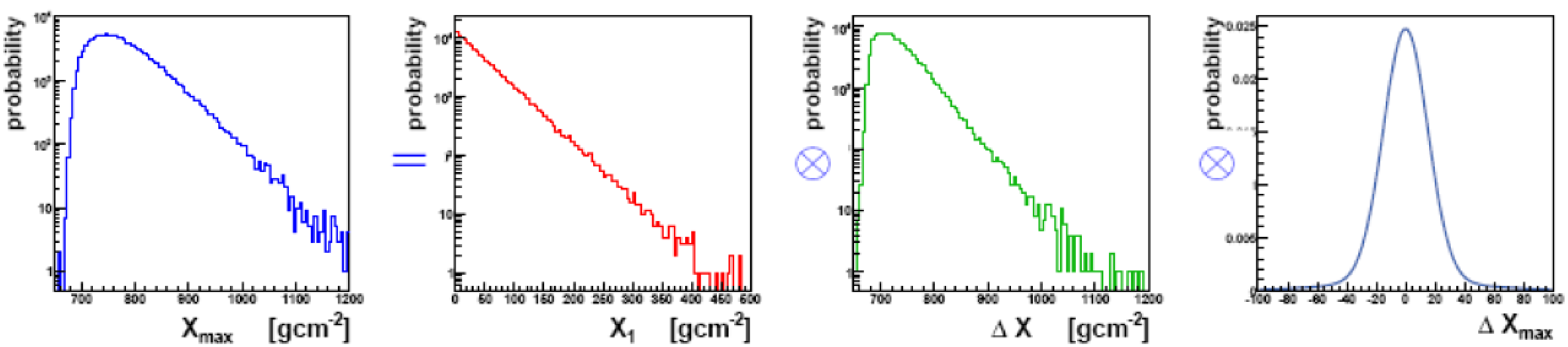


But particles with the same rigidity (E/Z) follows the same paths !!!

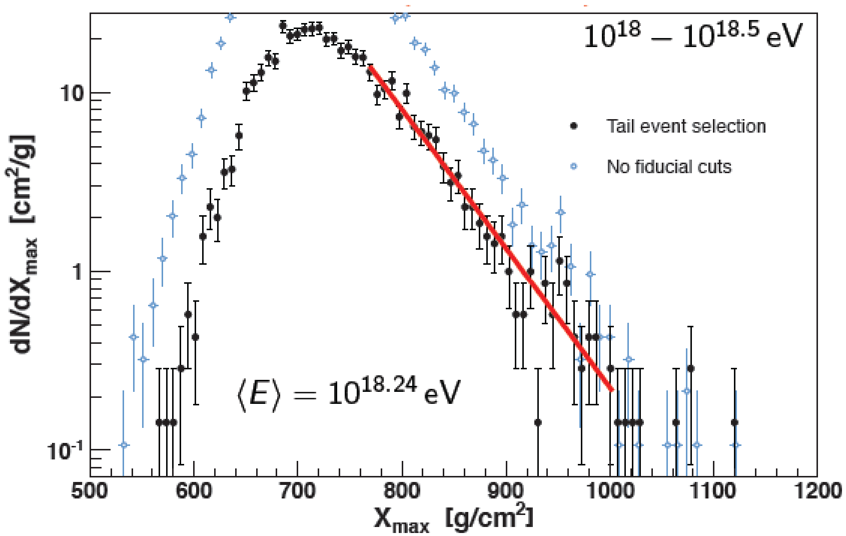
scenarios in which high energy anisotropies are caused by heavy primaries and having a significant light component at lower energies are disfavoured

X_{max} distributions



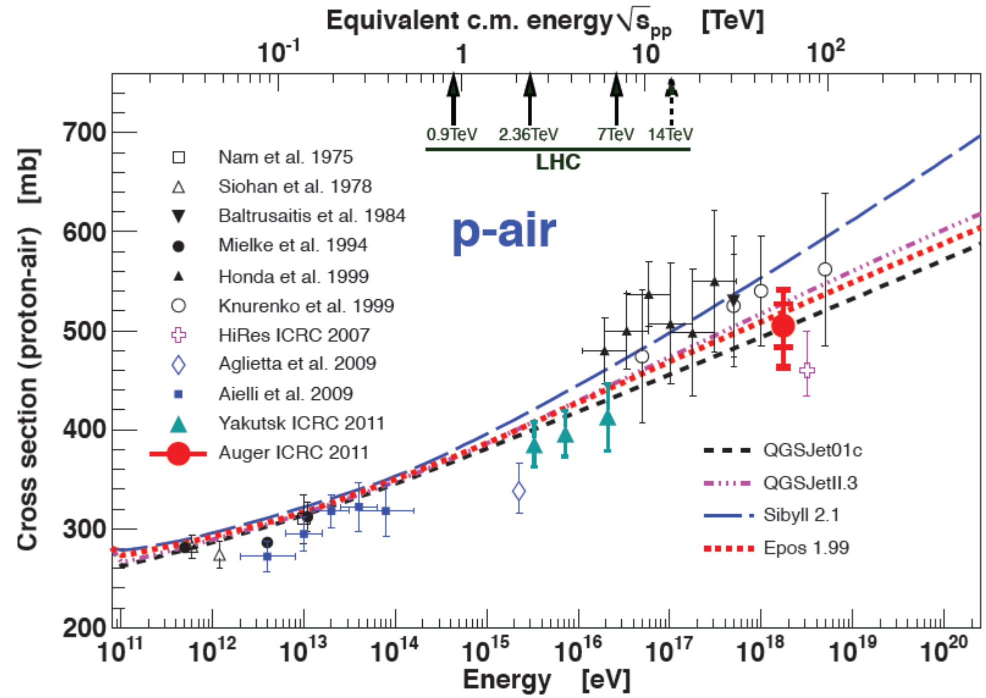


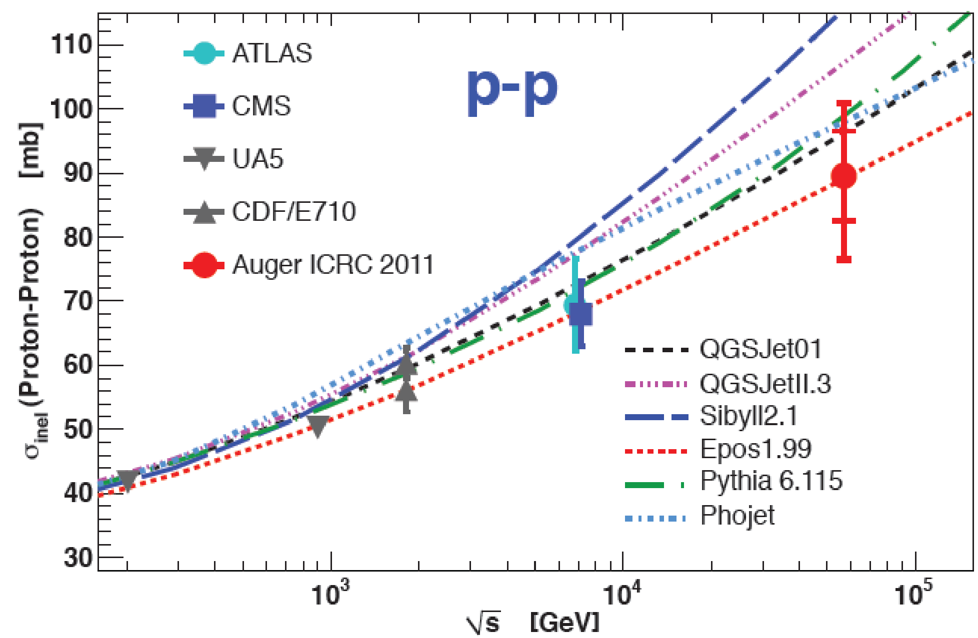
Proton cross-section



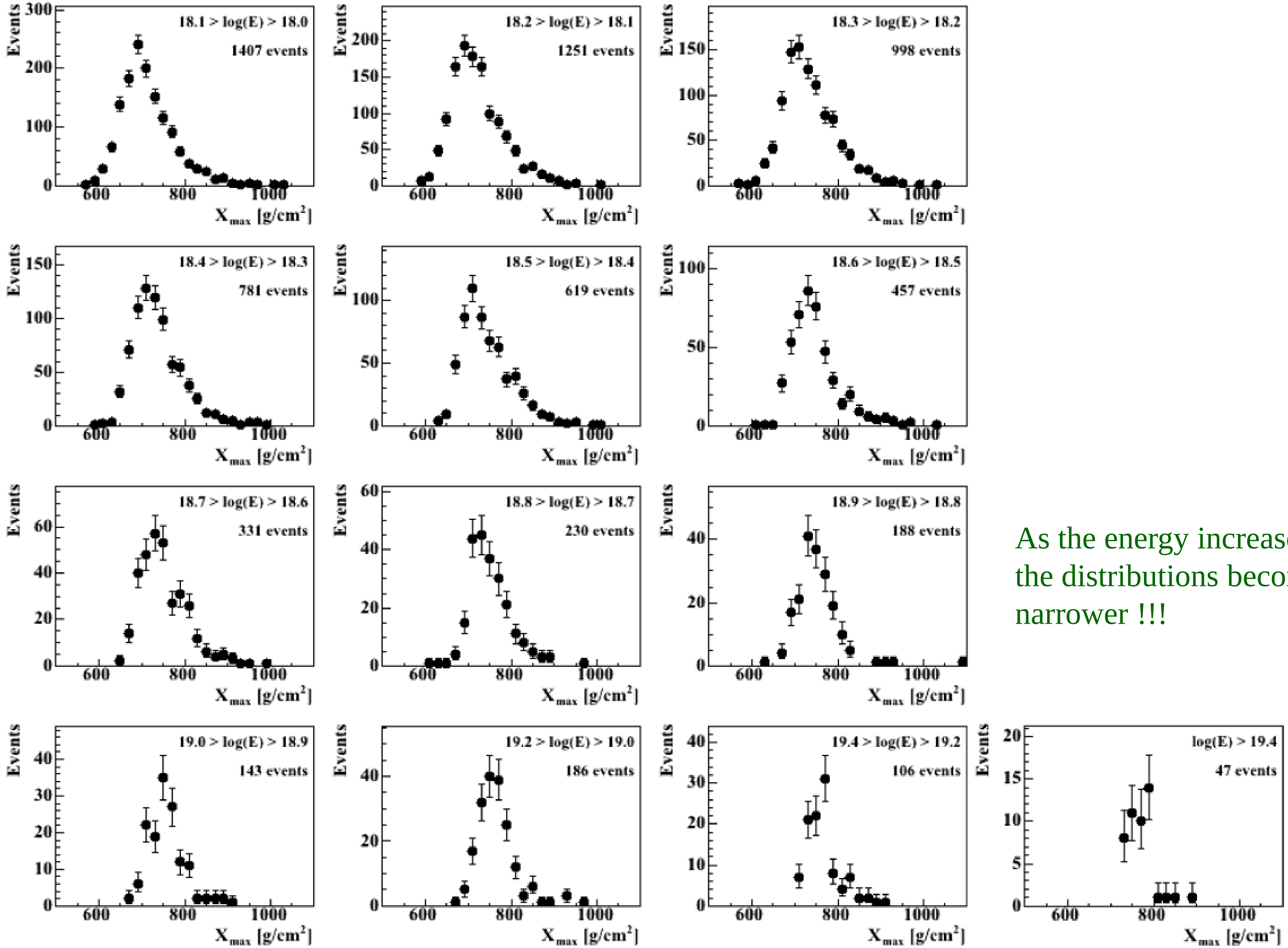
If % p > 20%, % He < 25%

Slightly lower than expected by most of the models but in good agreement with recent LHC data.



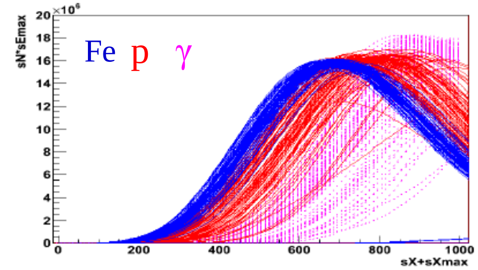


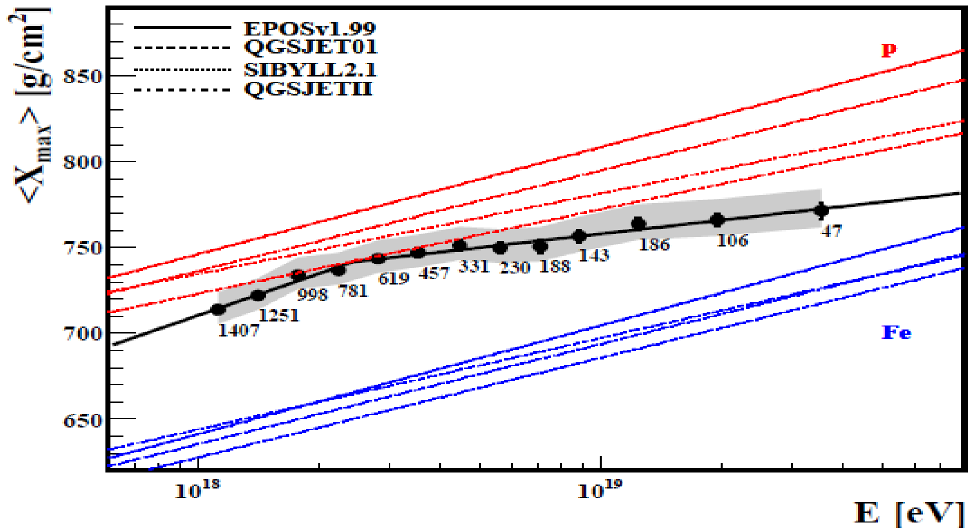
X_{max} distributions

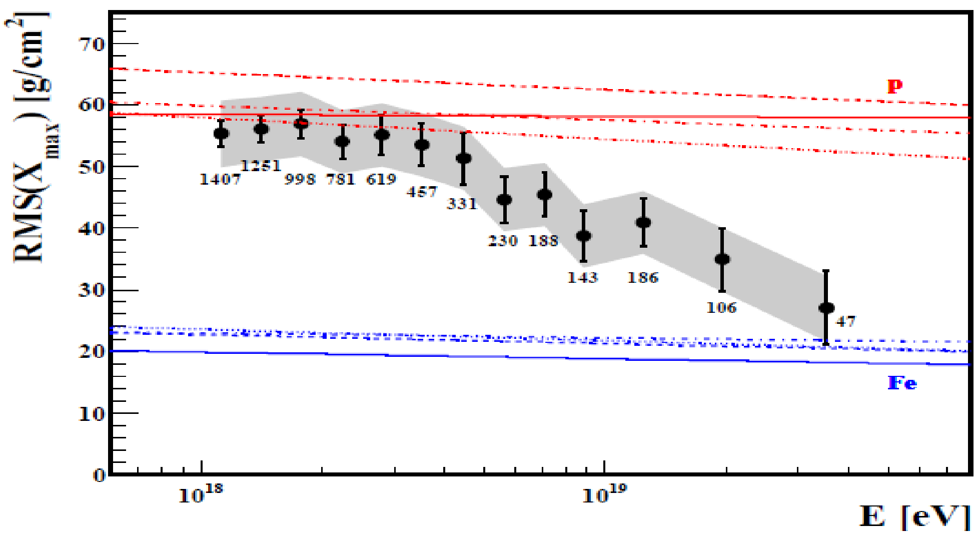


As the energy increases the distributions become narrower !!!

$\langle X_{max} \rangle$ and RMS(X_{max})

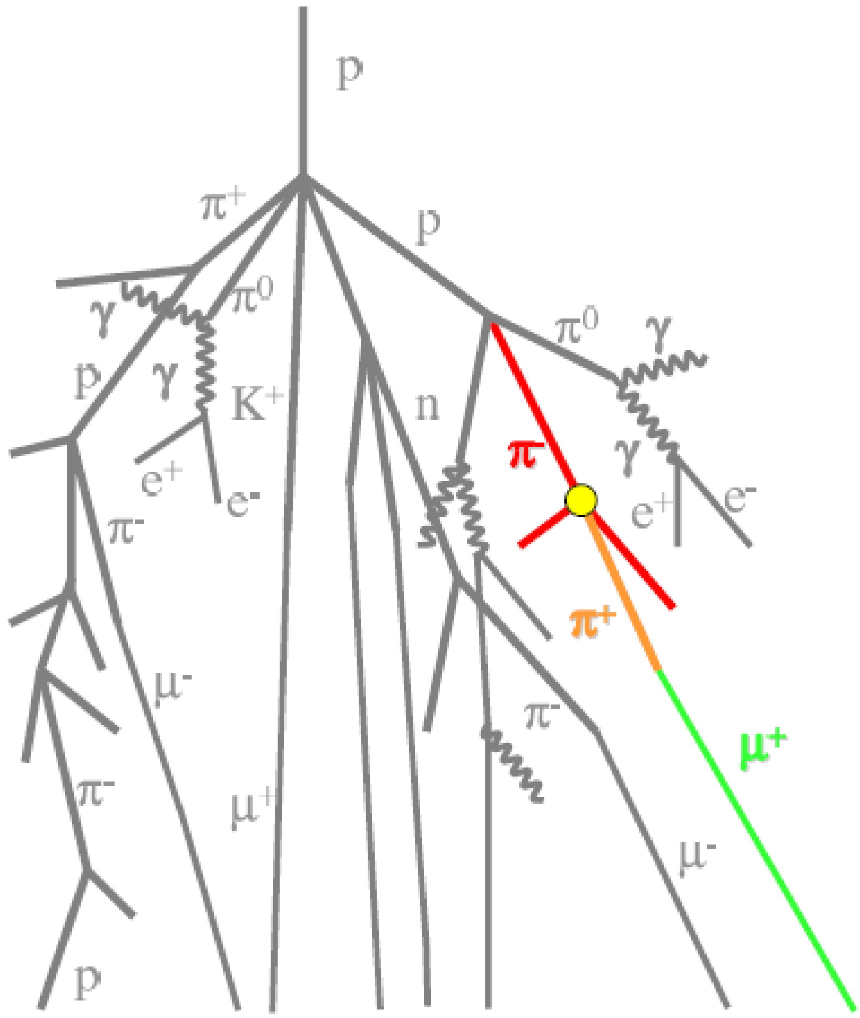




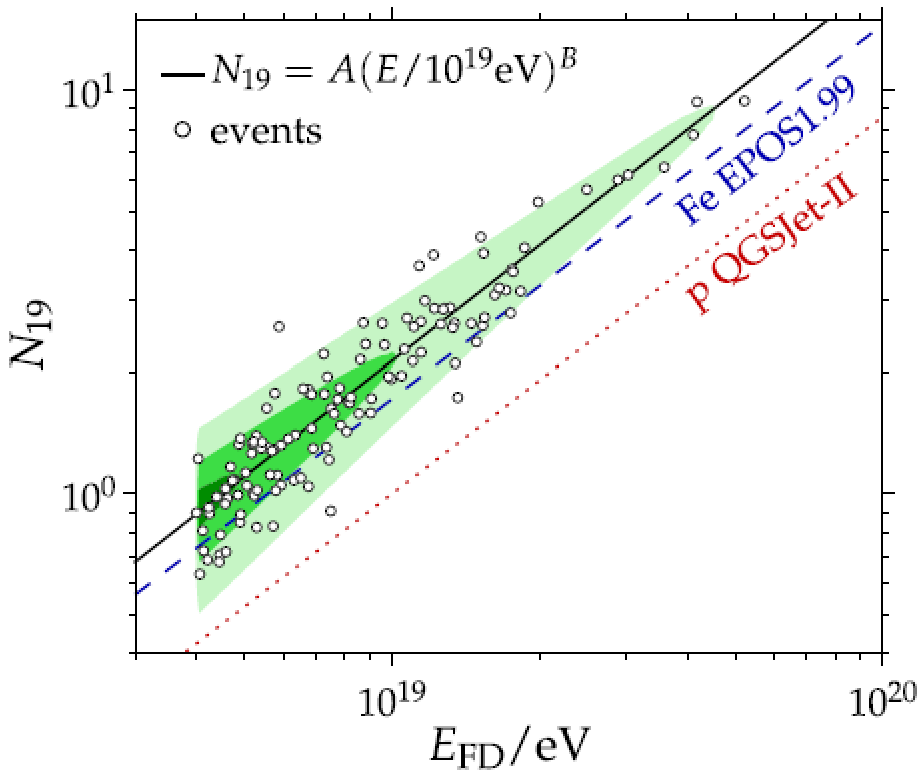


Heavy nuclei ?
Wrong Physics models ?

The “number of μ”

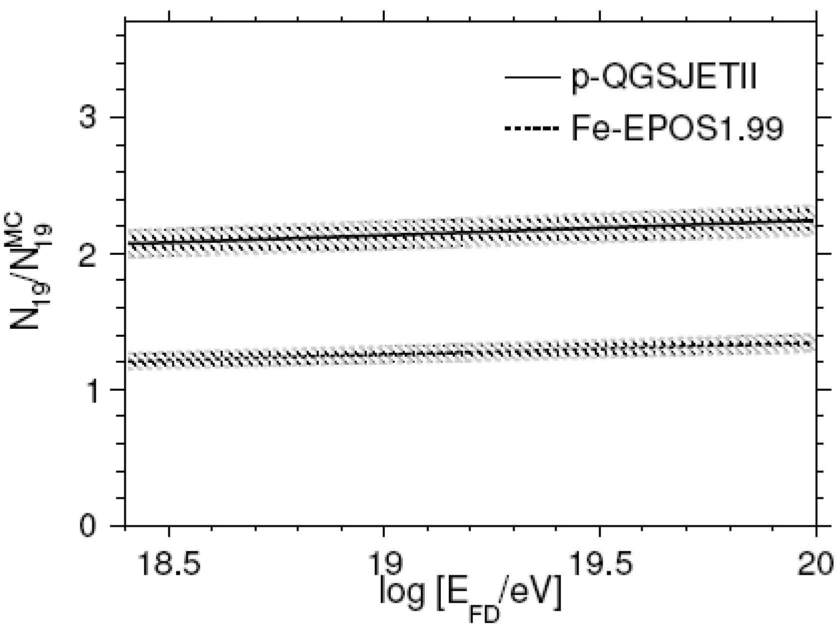


N_μ - Inclined showers



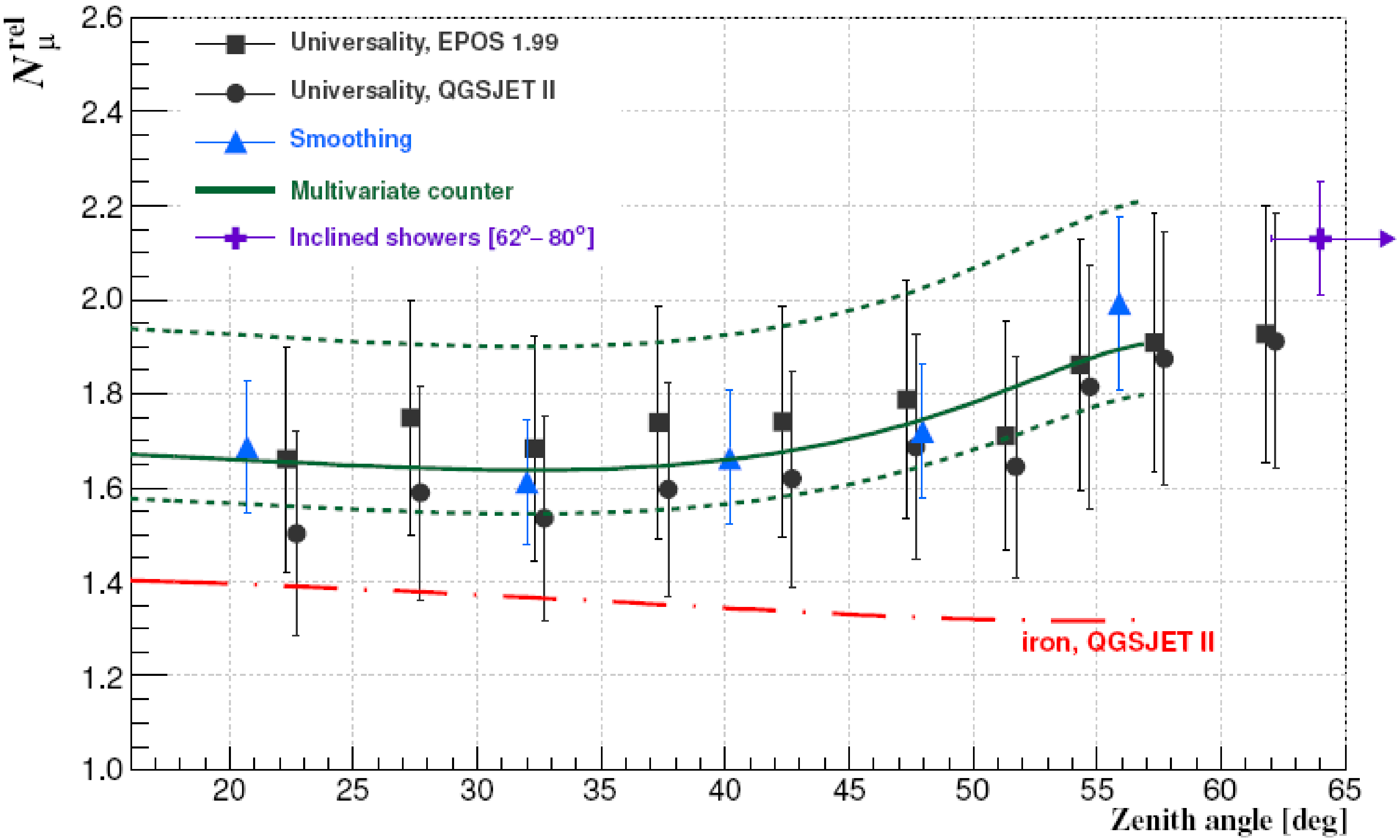
$N_\mu^{rel} = 2.13 \pm 0.04(\text{stat}) \pm 0.11(\text{sys})$

with respect to p QGSJET II at 10 EeV



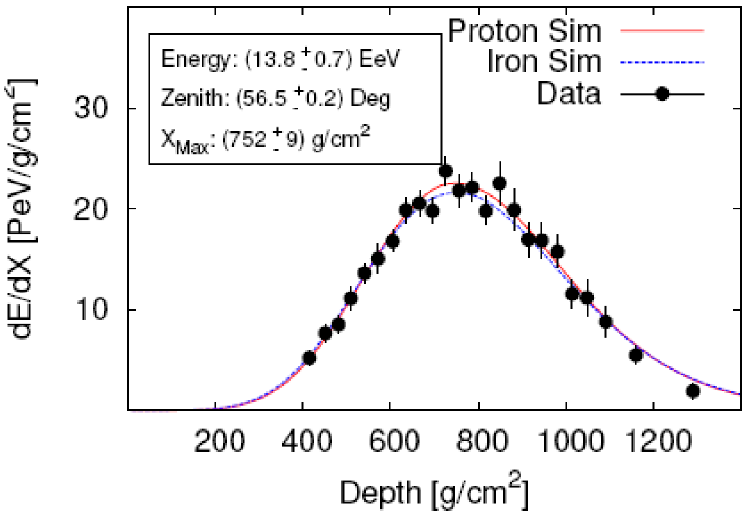
$N_\mu \sim E^{095}$

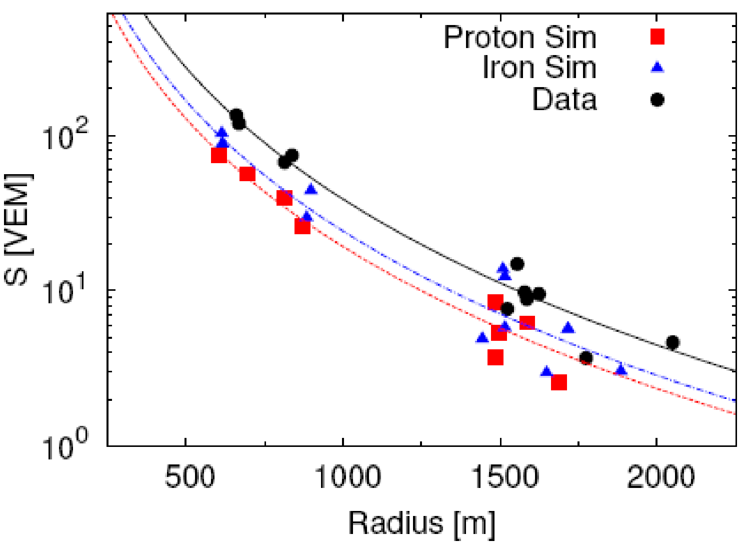
N_μ - all θ (from SD)



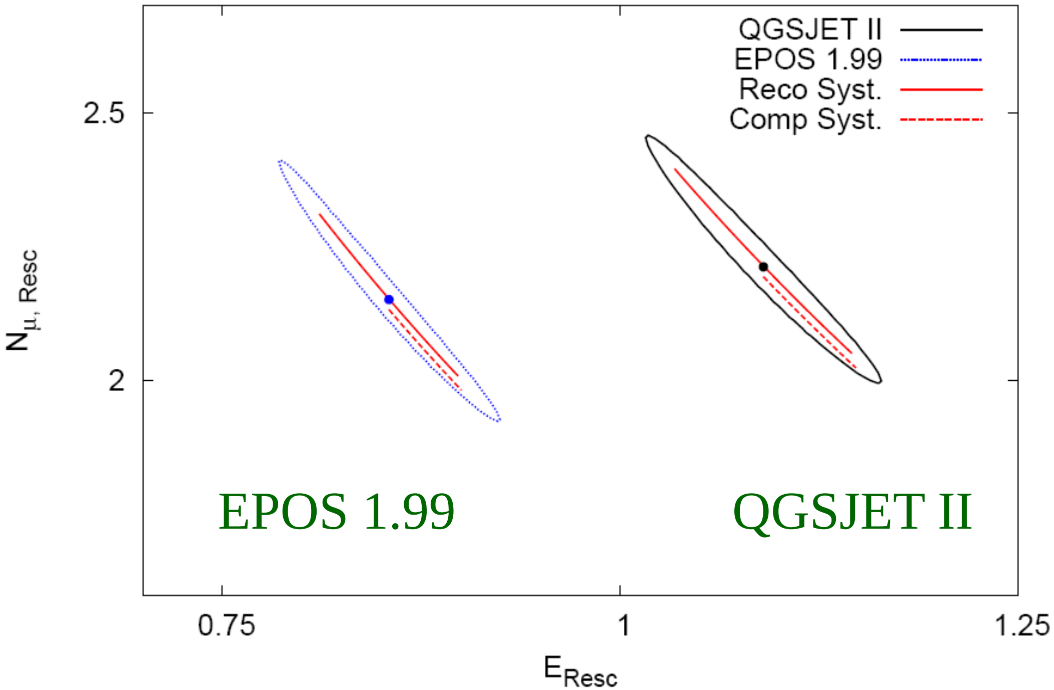
N_μ^{rel} — number of muons with respect to QGSJET II protons at 10 EeV

Hybrid events





N_μ , E_{resc}



$$S_{\rm fit} = N_{\mu,\,\rm resc} E^{\alpha}_{\rm resc} S_{\mu,\,\rm sim} + E_{\rm resc} S_{\rm em,\,sim}$$

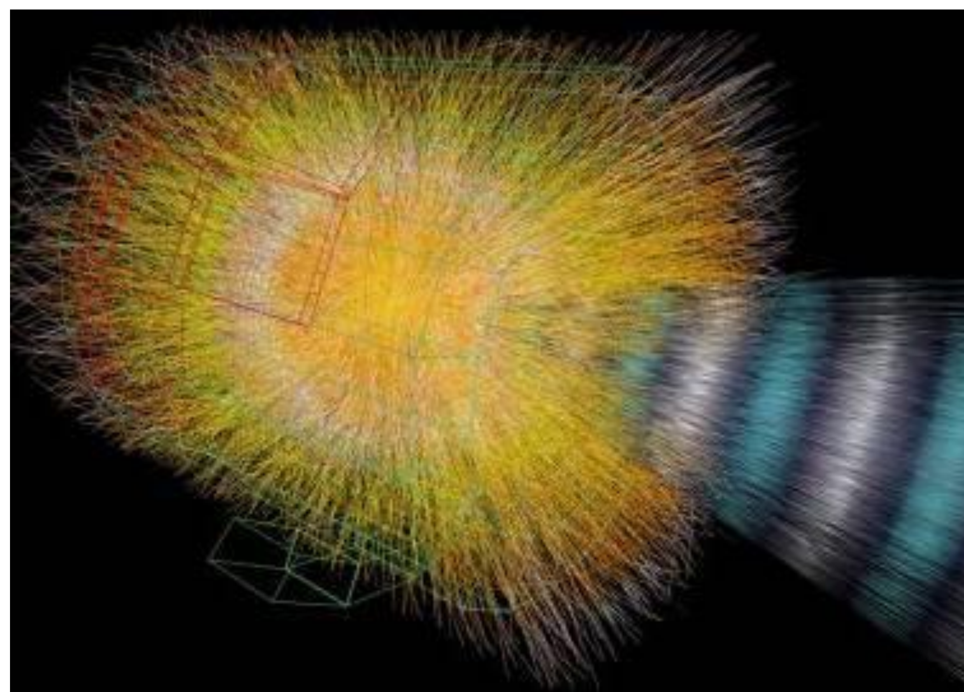
The puzzle

“beam composition” ???

Proton

Nuclei
(Iron, …)

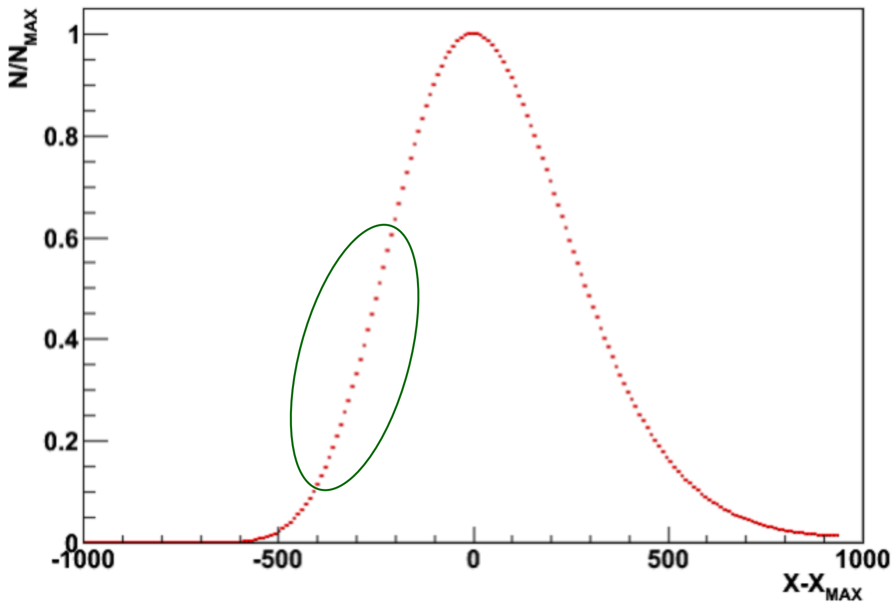
“New” interactions ???



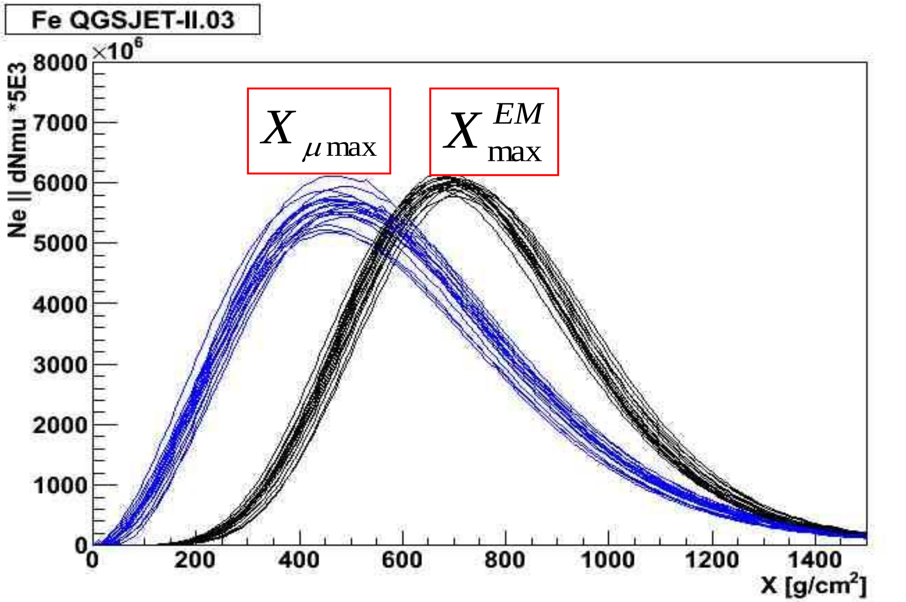
Further investigations

New analysis methods @ LIP

Explore the sensitivity of the first part of the normalized longitudinal shower profile to composition and hadronic interaction models



Reconstruct the Muon Production Depth (MPD) from the measured time traces at each SD detectors



SiPM

FACT

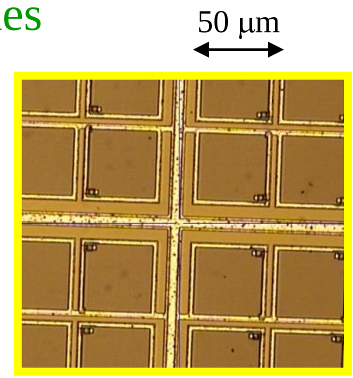
First G-**A**PD **C**herenkov **T**elescope

An array of Geiger avalanche photodiodes

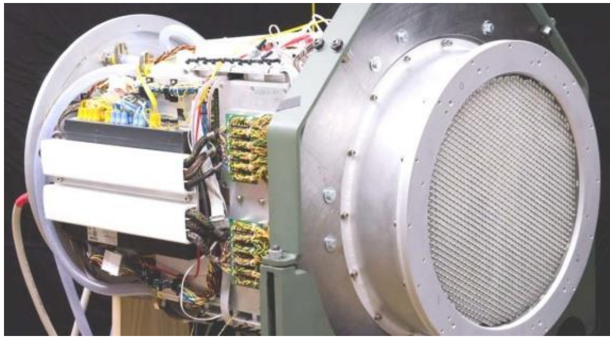
PMT typ. peak PDE 25%

SiPM could reach ~60%

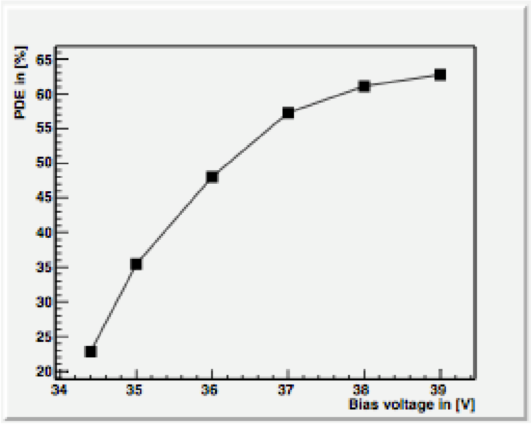
SiPM getting better (higher PDE, lower dark noise, lower crosstalk,…) and cheaper
New packages (denser) being released



Microscope view of a SiPM



1440 pixels, 4.5 degree FOV

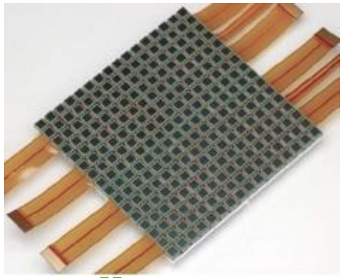


Measurement of a “Dolgoshein” prototype

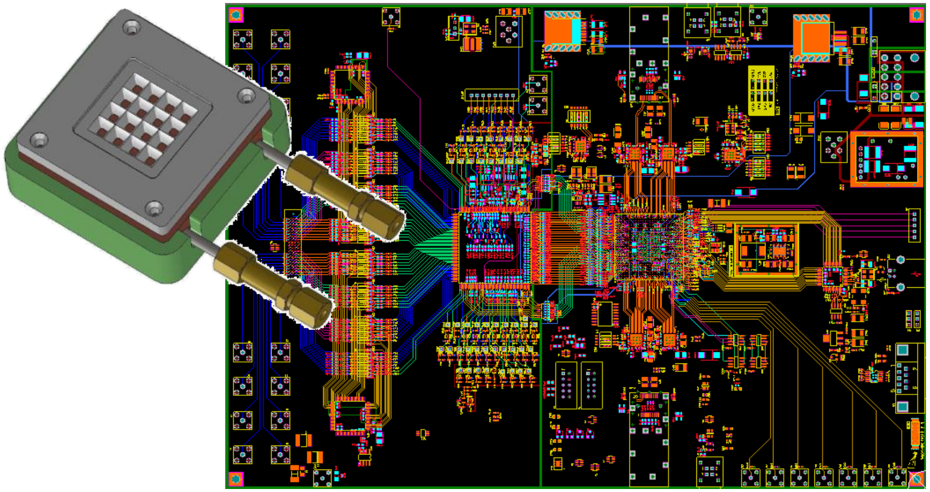
Towards a FS with SiPM

Collaboration LIP, Aachen, MPI, Granada, Palermo, to develop a SiPM based Focal Surface

Zecotek array

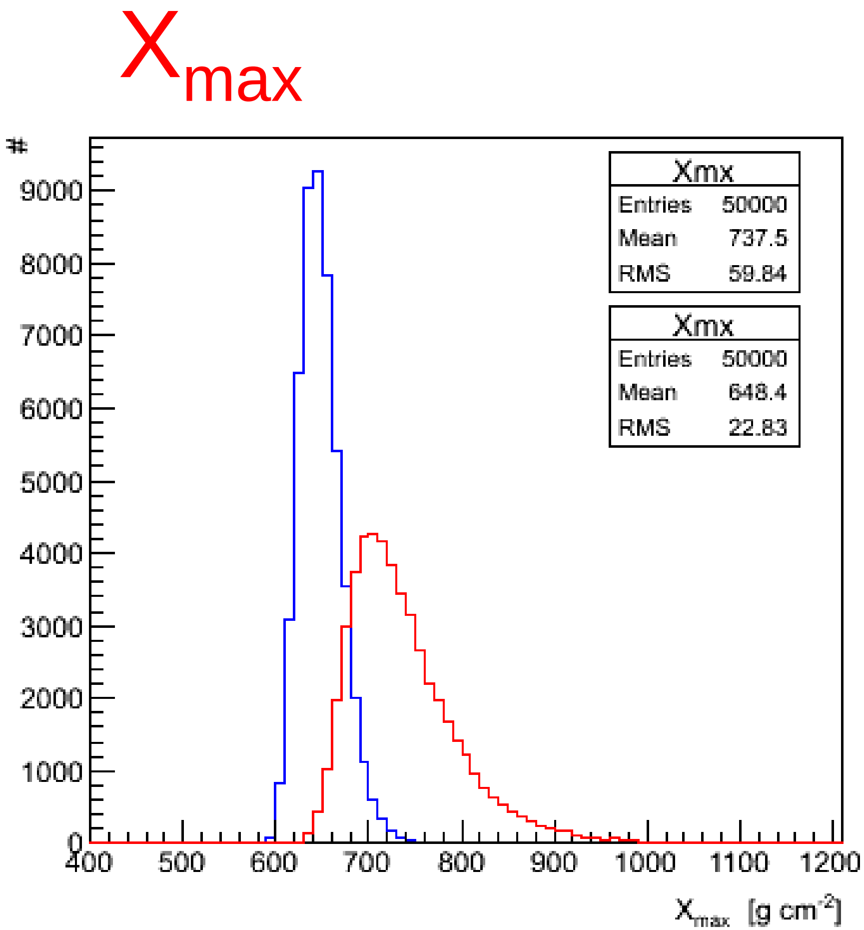


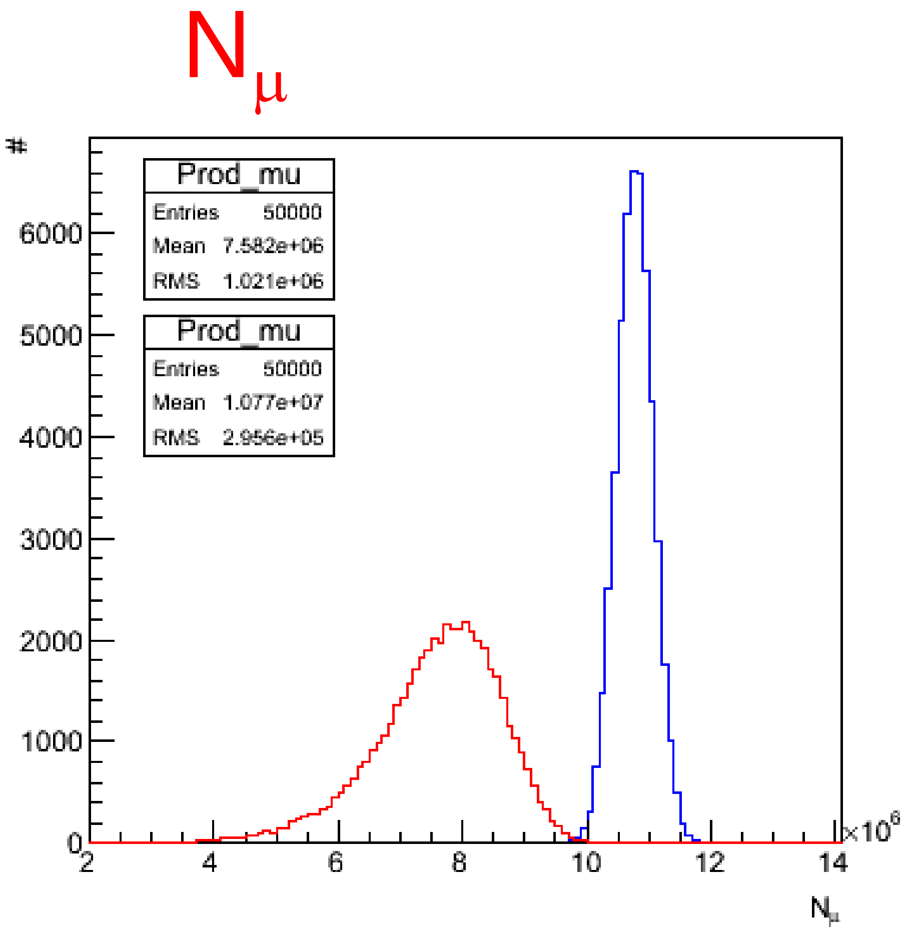
Hamamatsu array



N_μ

QGSJETII

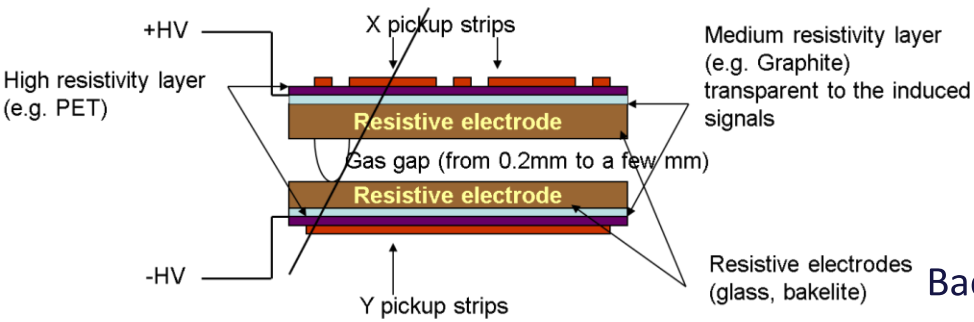




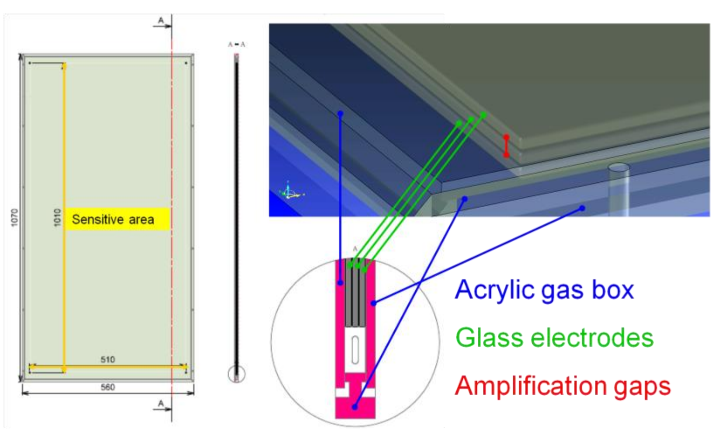
50% Fe - 10^{18} eV

“autonomous”RPCs

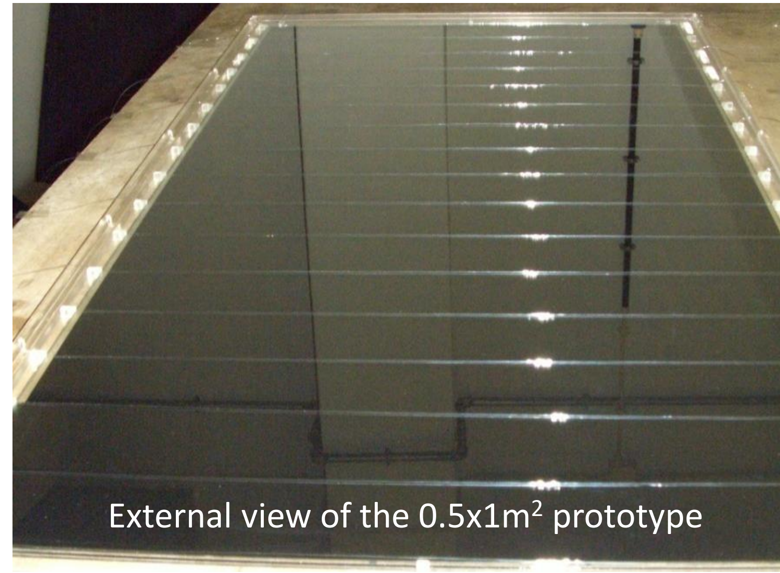
Resistive Plate Chambers (RPCs) are rugged and reliable gaseous detectors, widely used in High Energy and Nuclear Physics experiments.
- excellent time resolution
- can be produced in large areas
- cheap



Generic RPC architecture

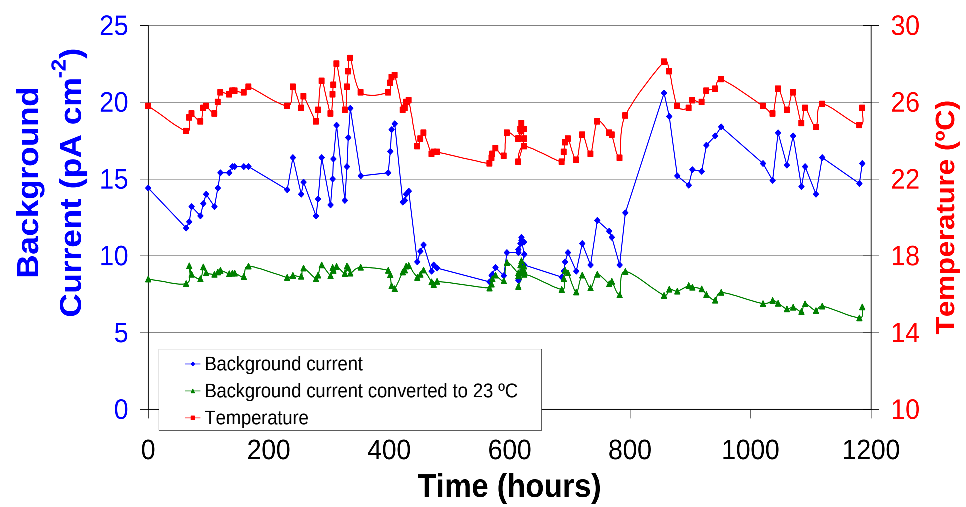


Structure of the prototype



External view of the 0.5x1m^2 prototype

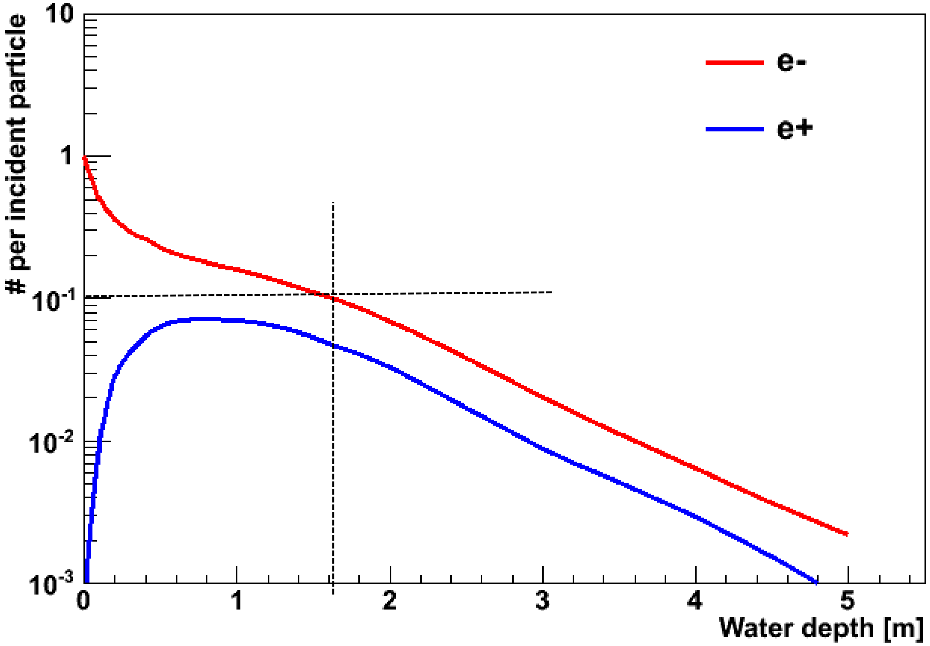
Background current at a gas flow of 1 kg/year of R134a.

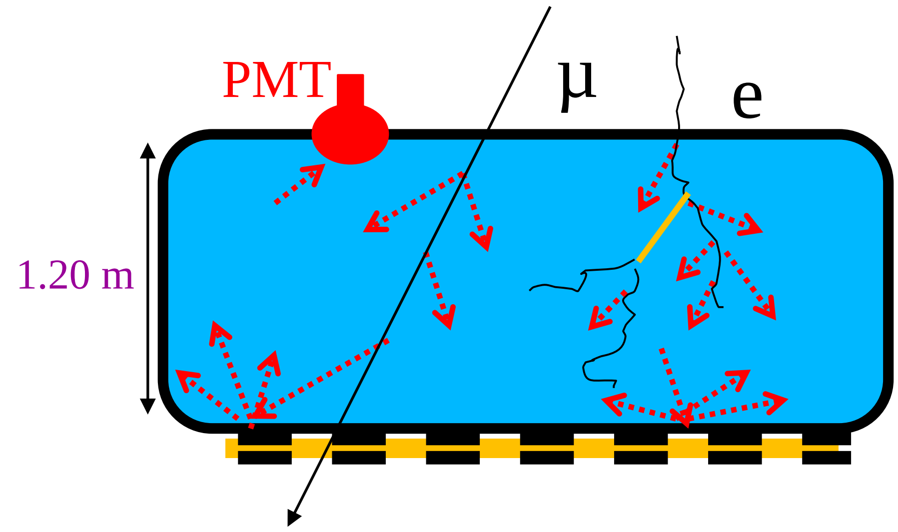


At a constant temperature the current is stable, demonstrating the operation of the chamber at a very low gas flow.

“em” supression

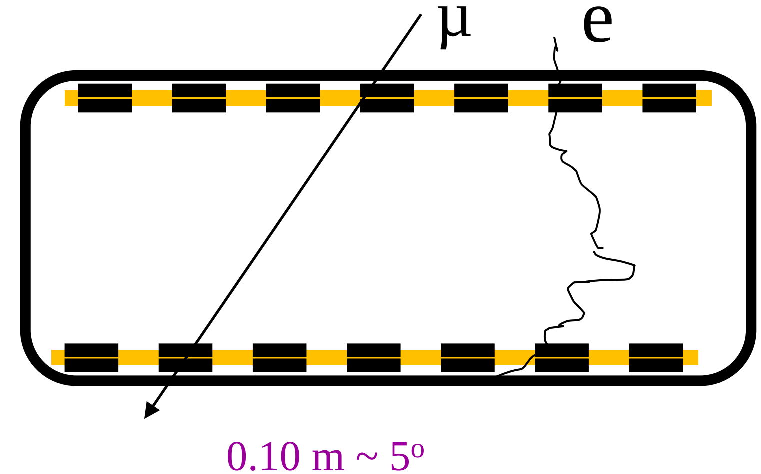
Under an absorber ...





2 plane “telescope”

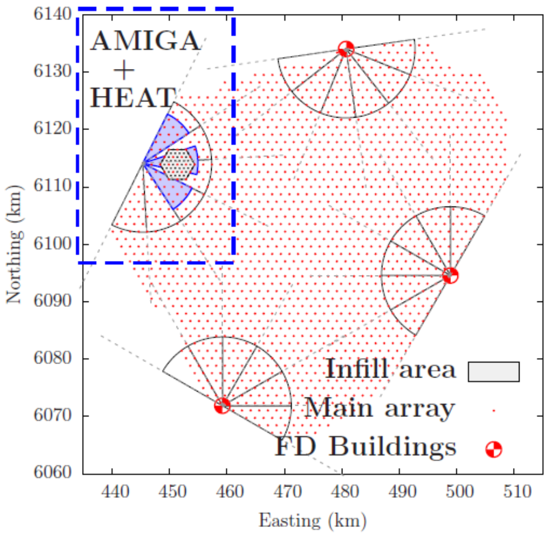
To discriminate straight pointing trajectories from the shower axis

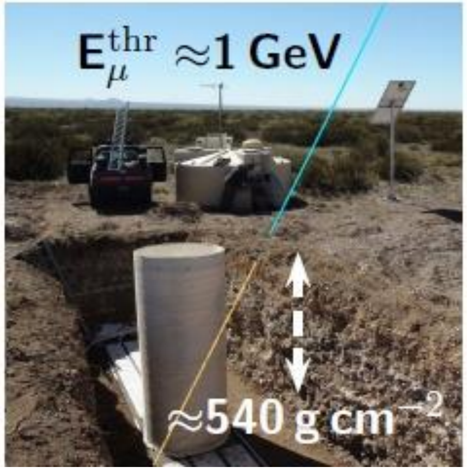


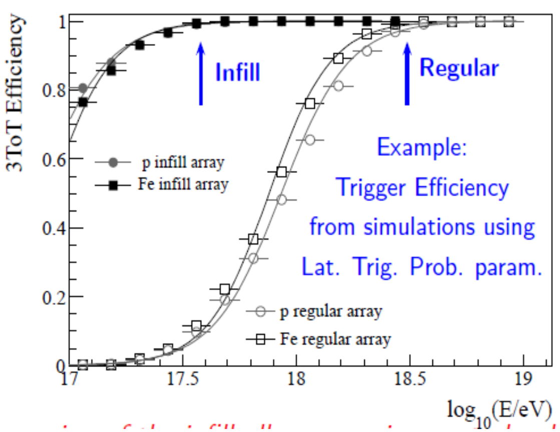
We are exploring the 100 TeV energy scale, well beyond LHC, and may be we are touching something fundamental!

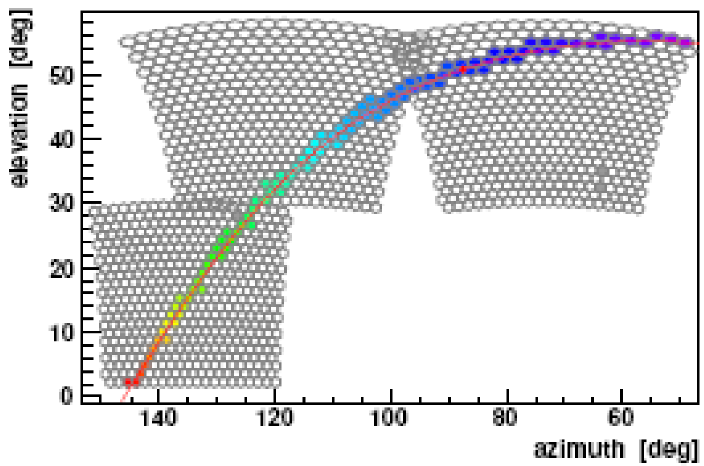
AMIGA/HEAT

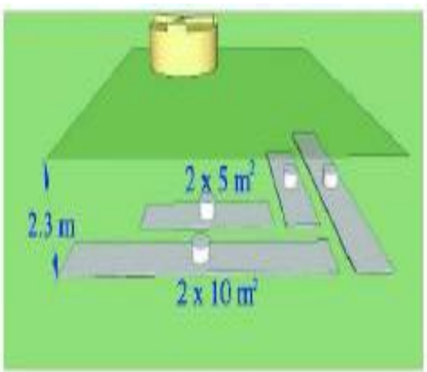
23.5 km2, 42 extra SDs on 750m grid (infill array) associated with 30m2 buried scintillators, 3 extra FD telescopes tilted upwards 30











E ~ 3 × 10^{17} eV
with full efficiency