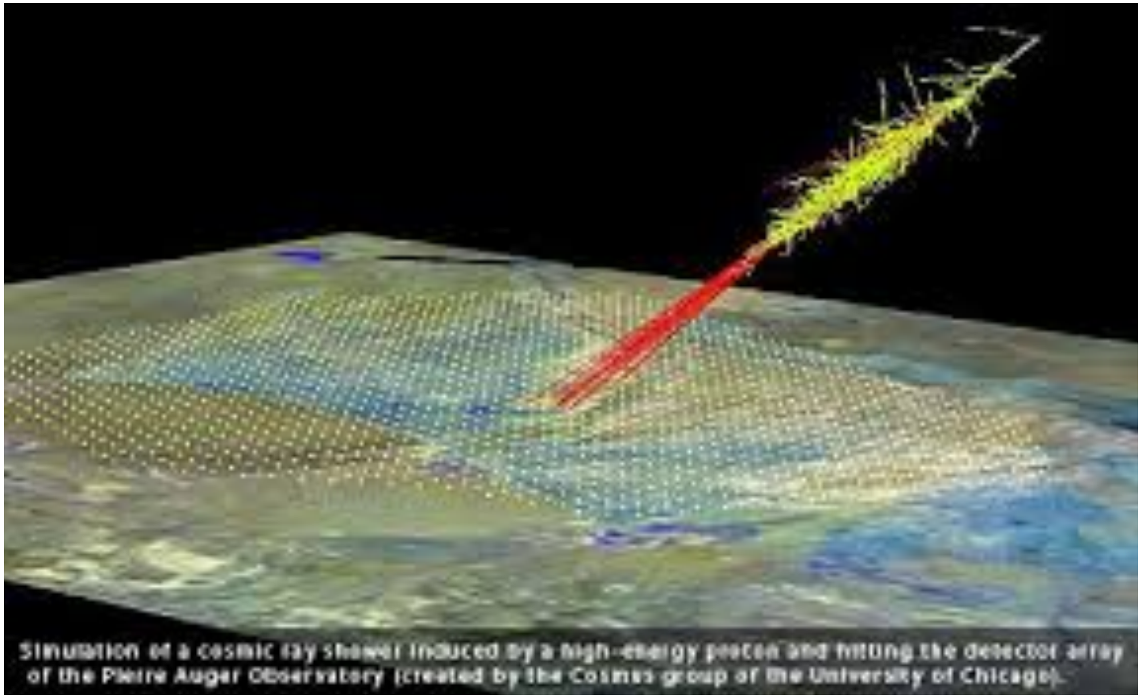
Ultra High Energy Cosmic Rays

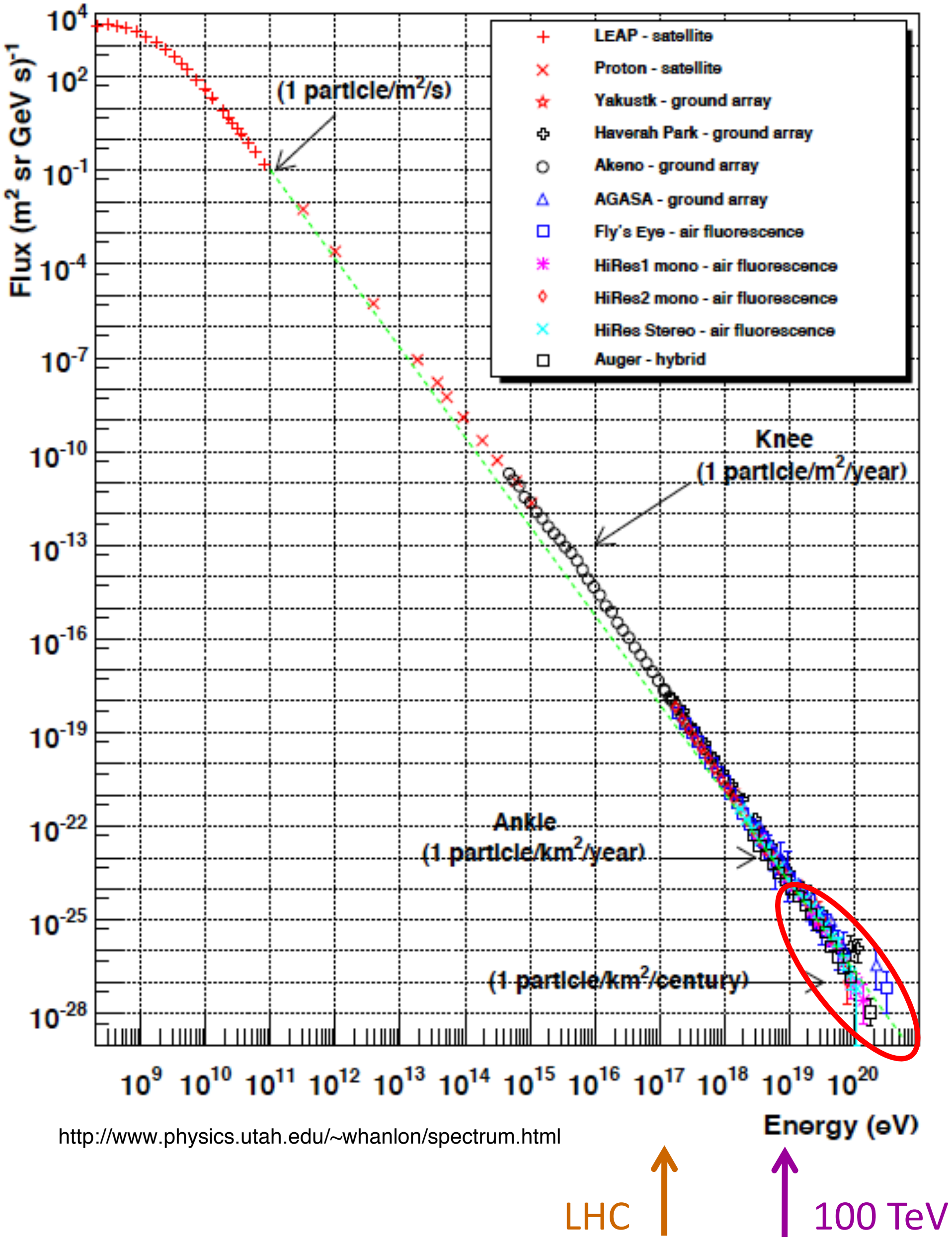


LIP

TÉCNICO LISBOA

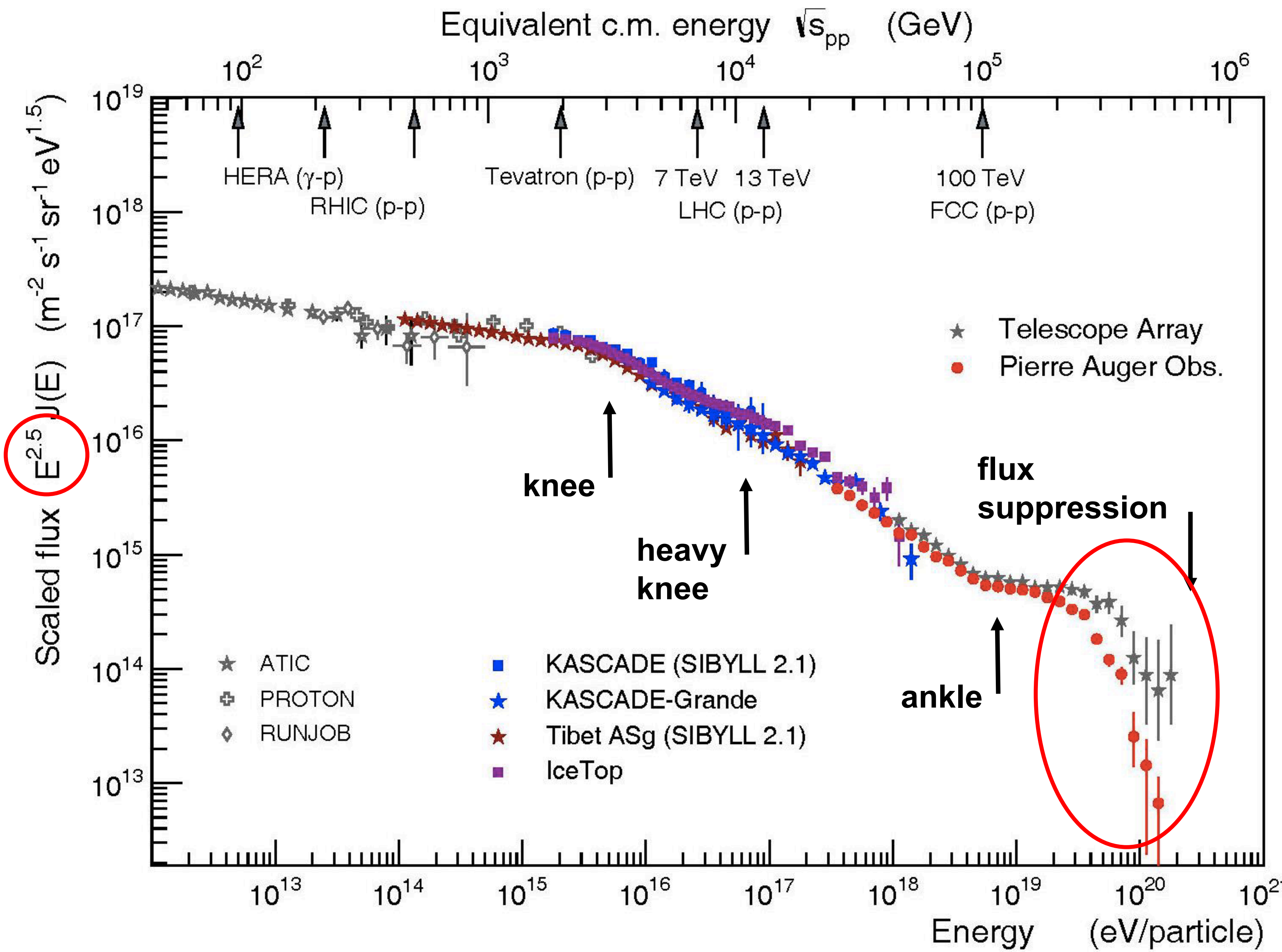
Mário Pimenta
1/2020, Asiago

High Energy Cosmic Rays

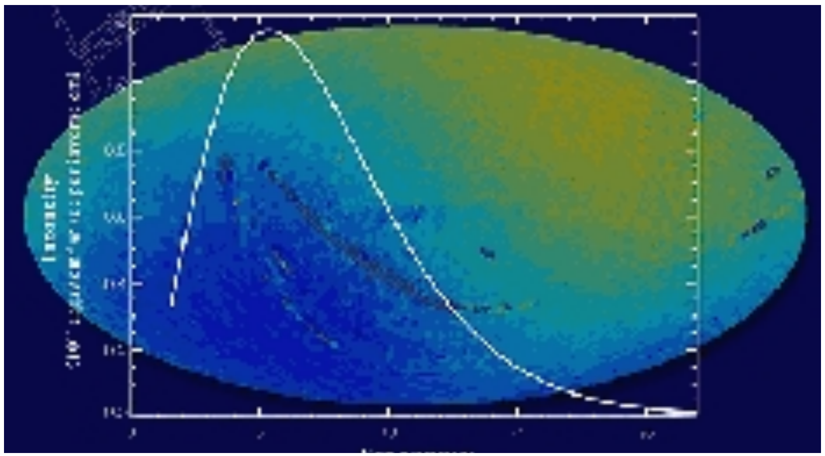


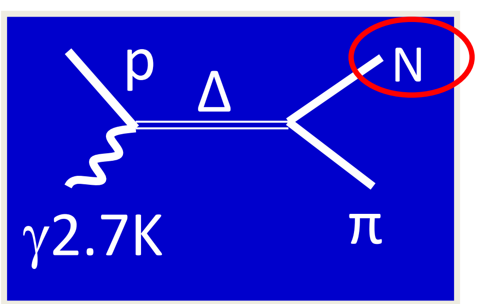
http://www.physics.utah.edu/~whanlon/spectrum.html

Energy spectrum ($E > 10^{14}$ eV)



Flux suppression?
The Greisen-Zatsepin-Kuzmin (GZK) cutoff



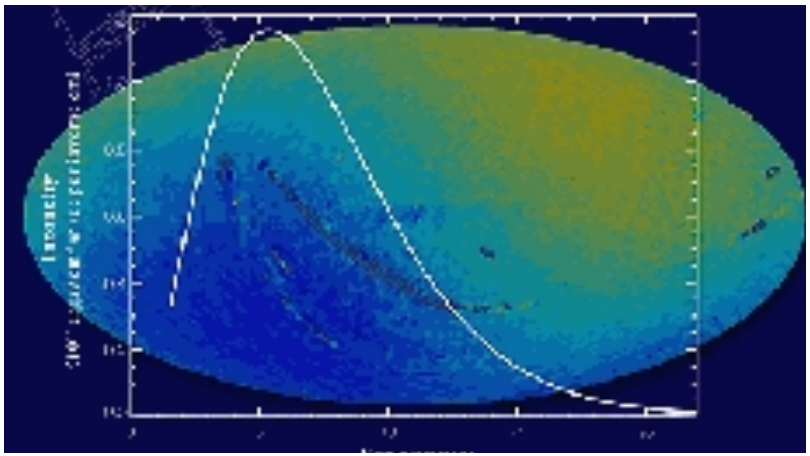


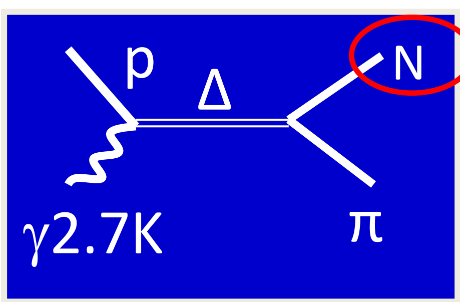
$E_p \approx 10^{20}\,\mathrm{eV}$

$$\lambda = \frac{1}{\sigma_{p\gamma}\,\rho_{CMB}}$$

$$\approx 6\ \mathrm{Mpc}$$

Flux suppression?
The Greisen-Zatsepin-Kuzmin (GZK) cutoff

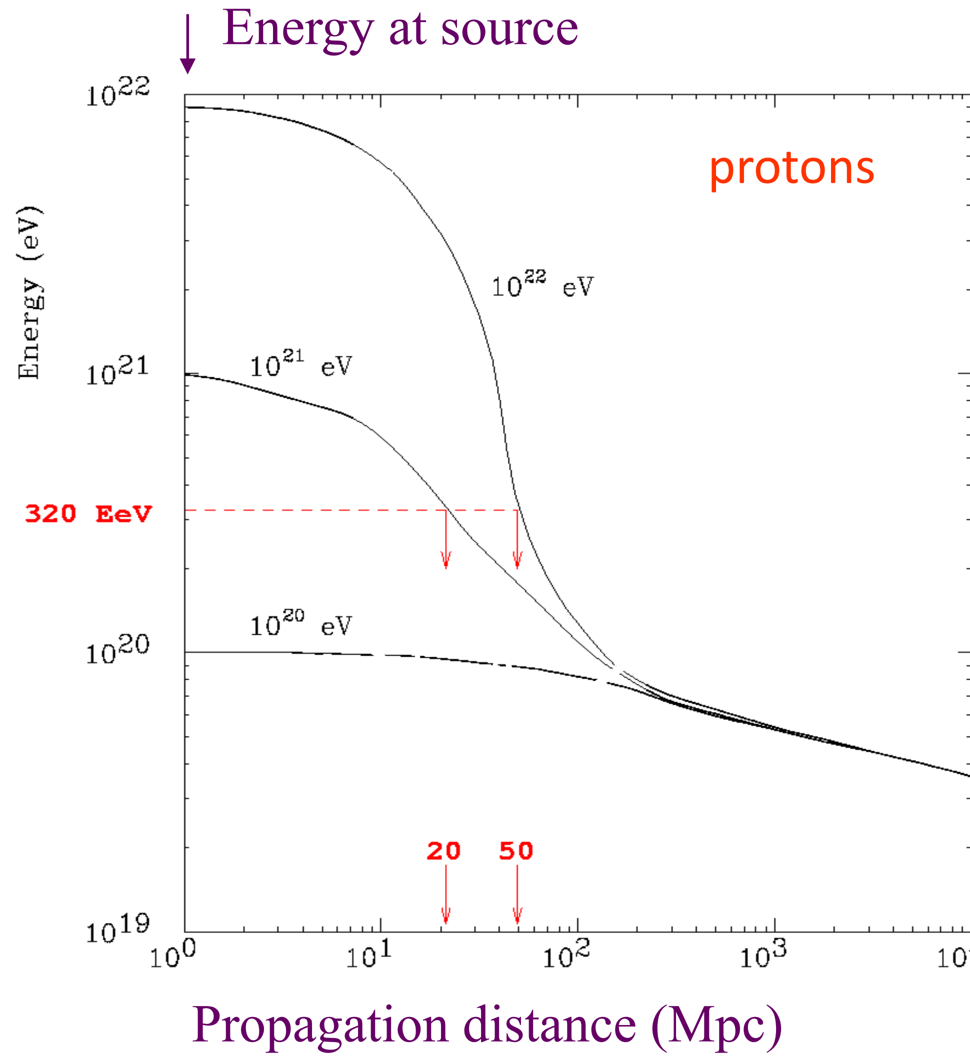




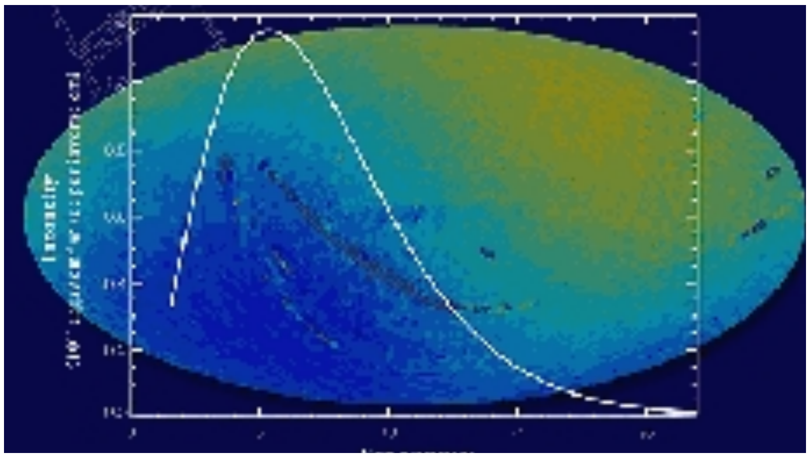
$E_p \approx 10^{20}\,\mathrm{eV}$

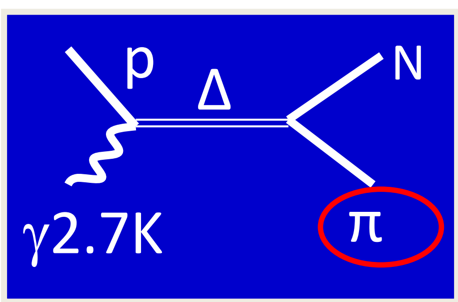
$$\lambda = \frac{1}{\sigma_{p\gamma}\,\rho_{CMB}}$$

$\approx$ 6 Mpc



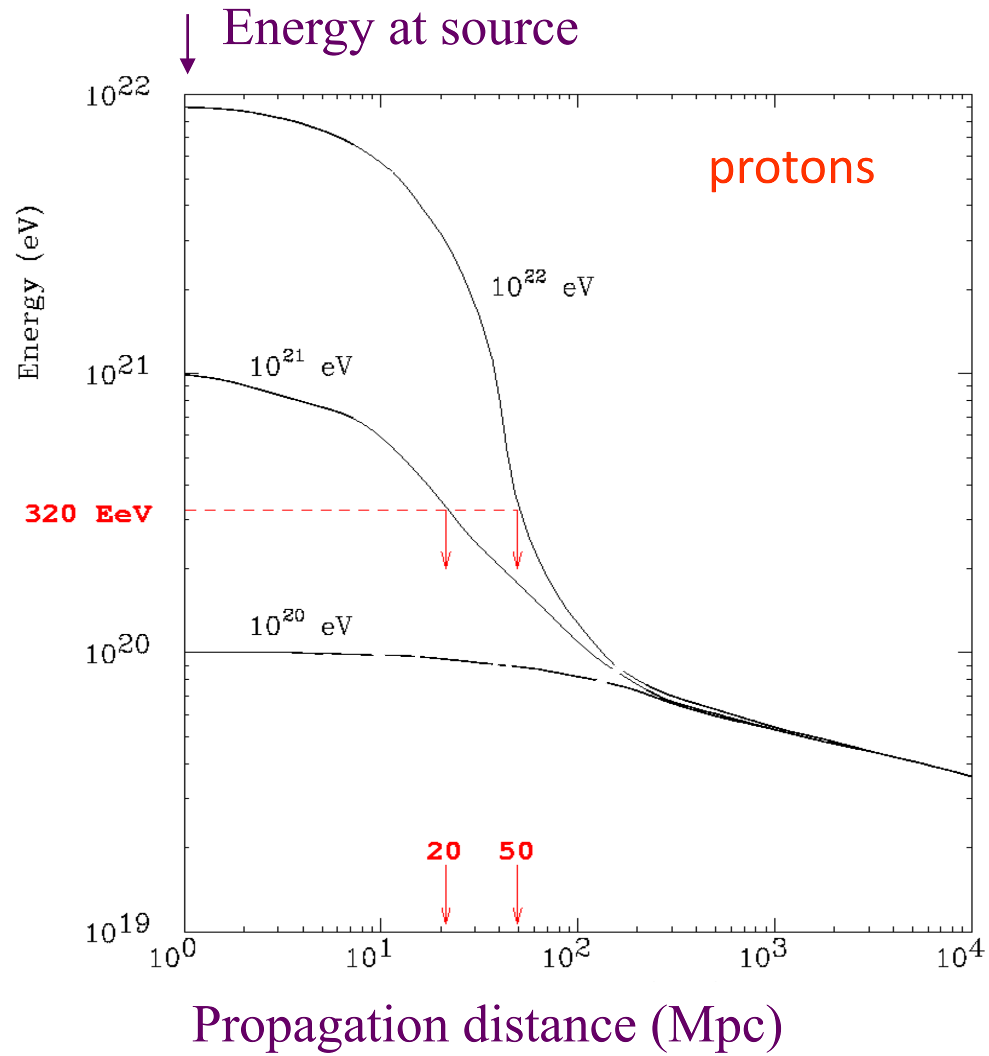
Flux suppression?
The Greisen-Zatsepin-Kuzmin (GZK) cutoff





$E_p \approx 10^{20}\,\mathrm{eV}$

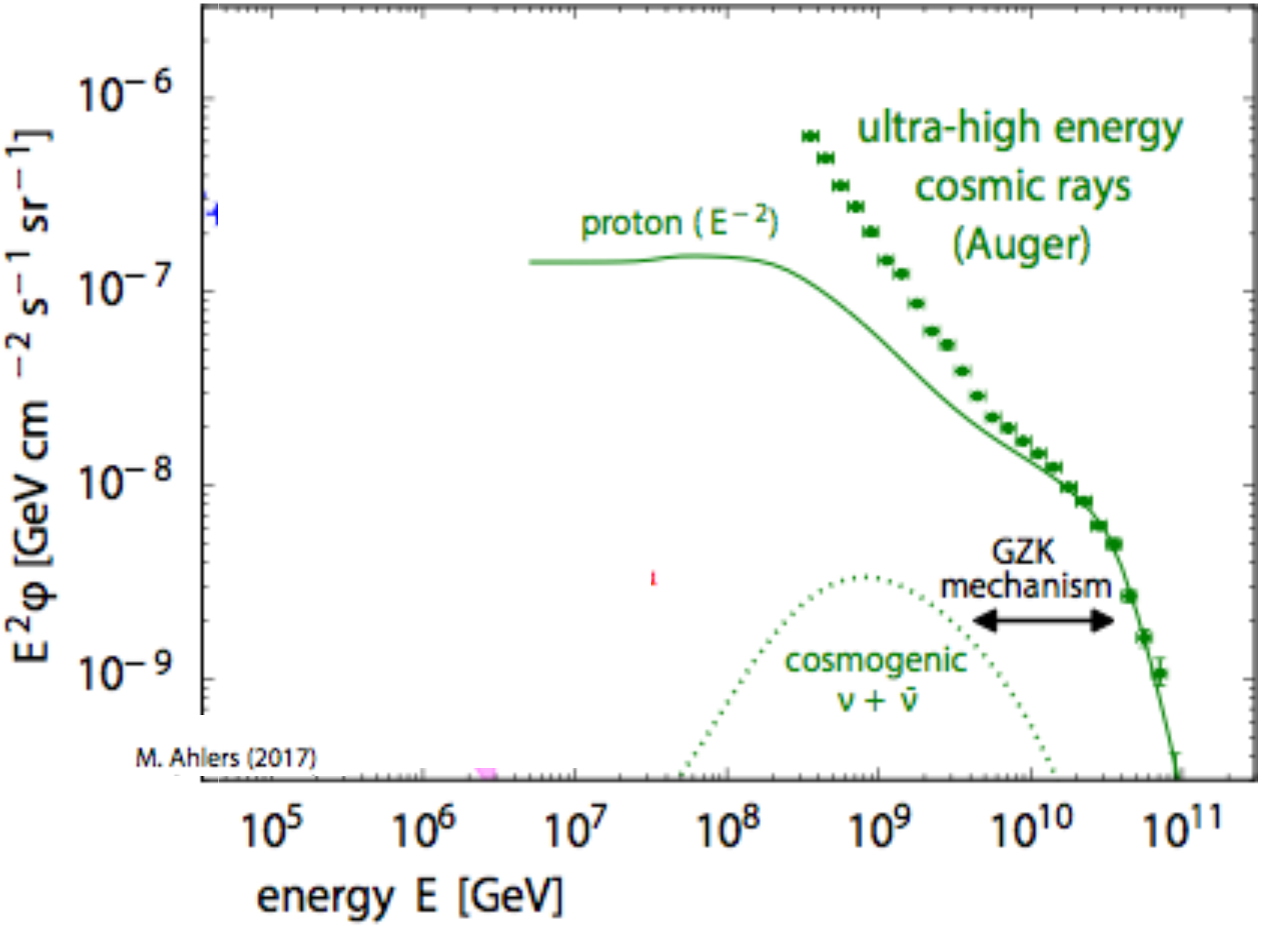
$$\lambda = \frac{1}{\sigma_{p\gamma}\,\rho_{CMB}} \approx 6\ \mathrm{Mpc}$$



$$\pi^0 \longrightarrow \gamma\gamma$$

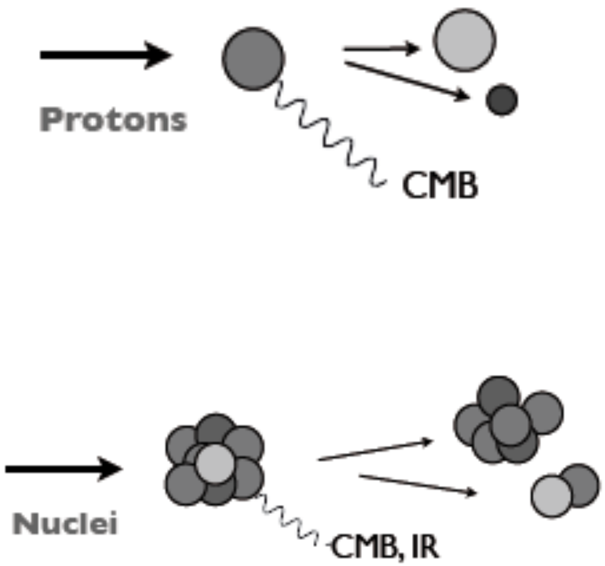
$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu$$

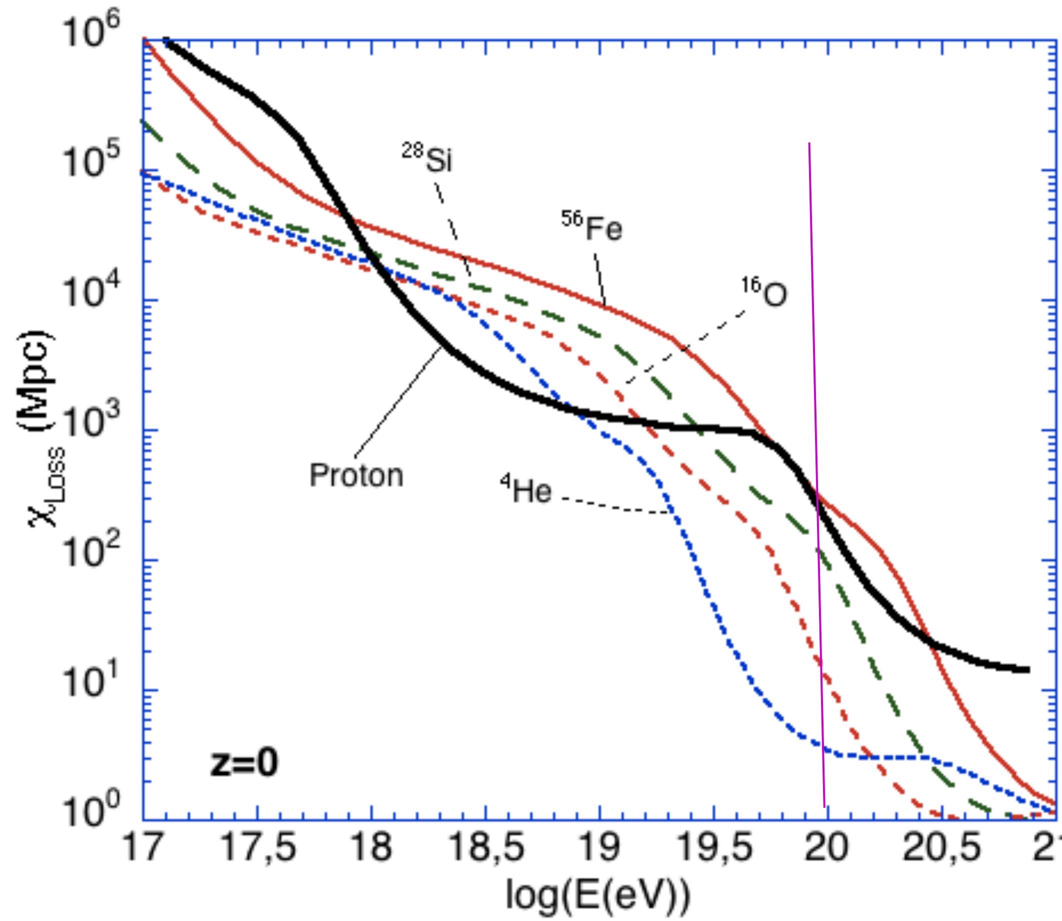
Predicted (and observed) Spectrum



No cosmogenic neutrinos observed so far

GZK vs nuclei photo-desimtegration

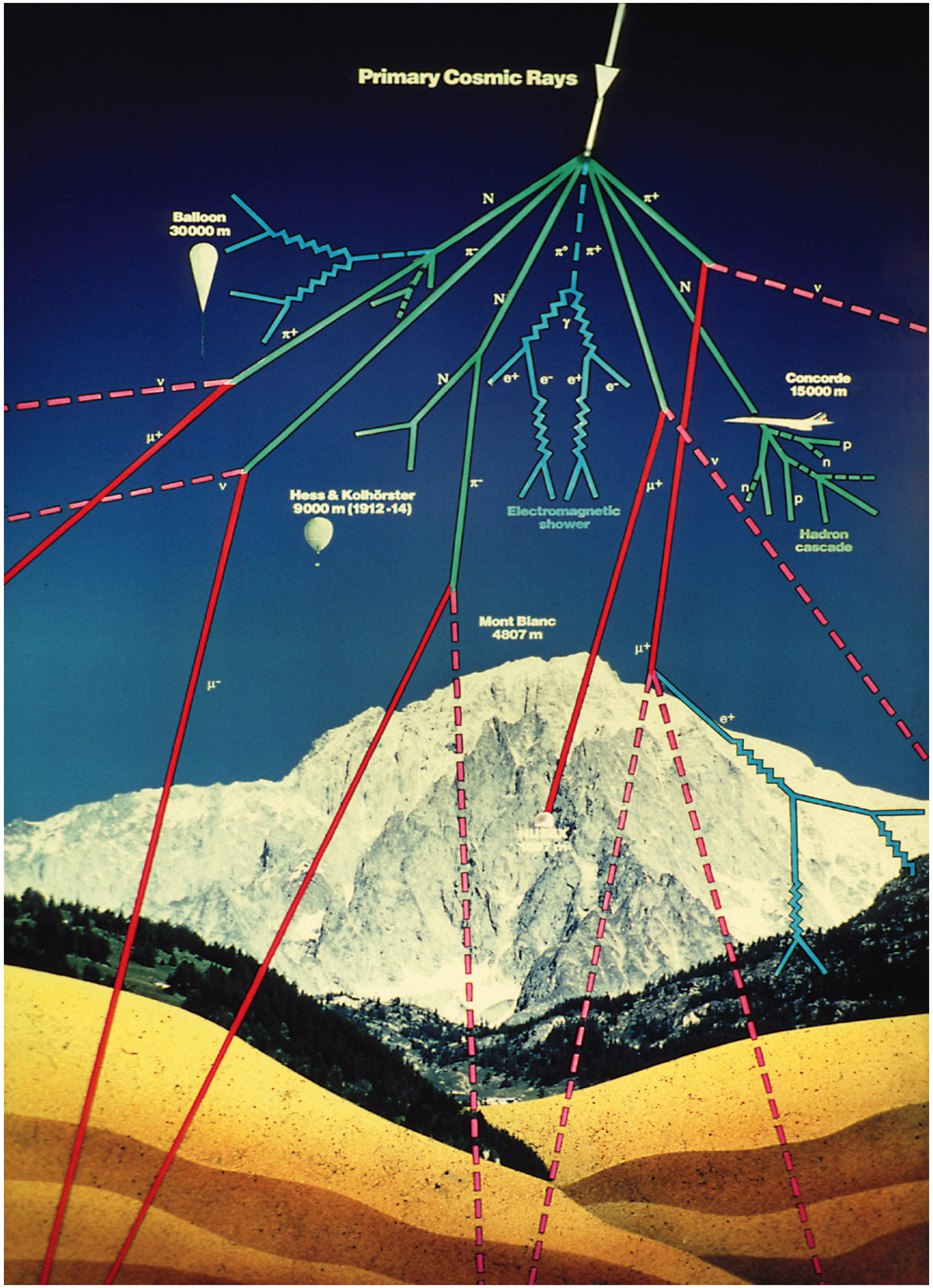




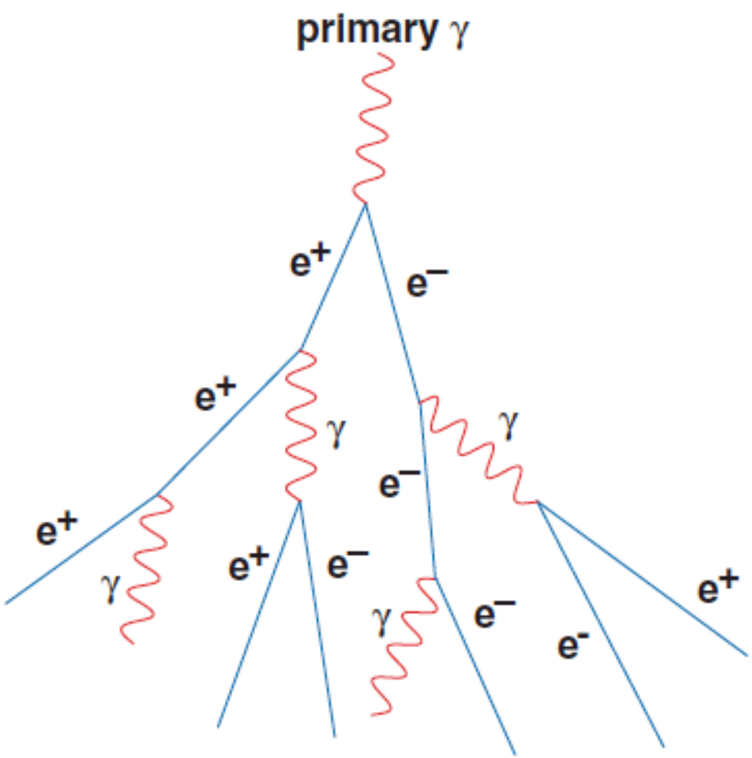
At 10^{20} eV proton and iron have similar attenuation lengths

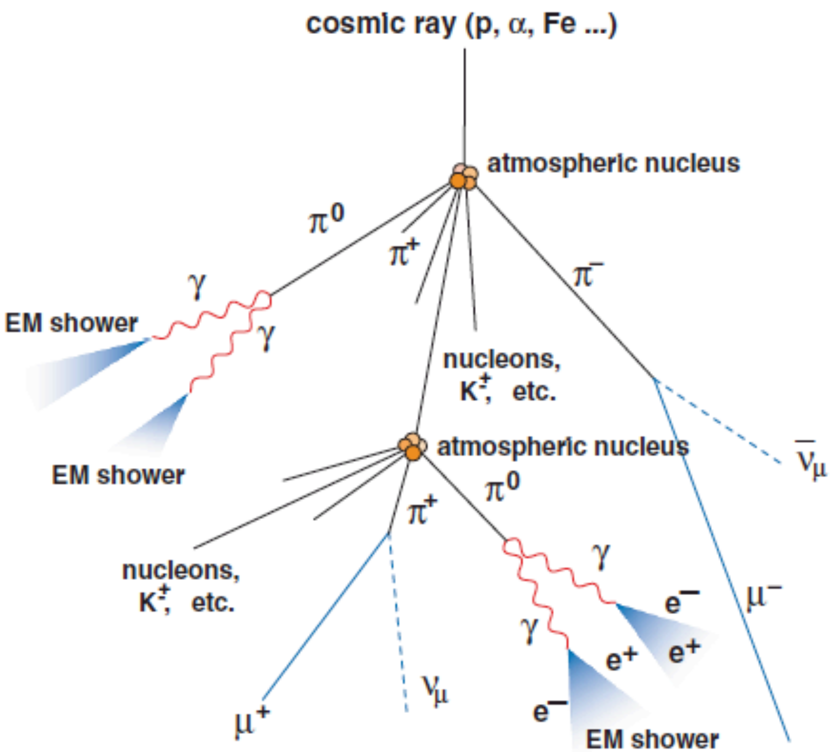
Arriving at Earth

p/nuclei



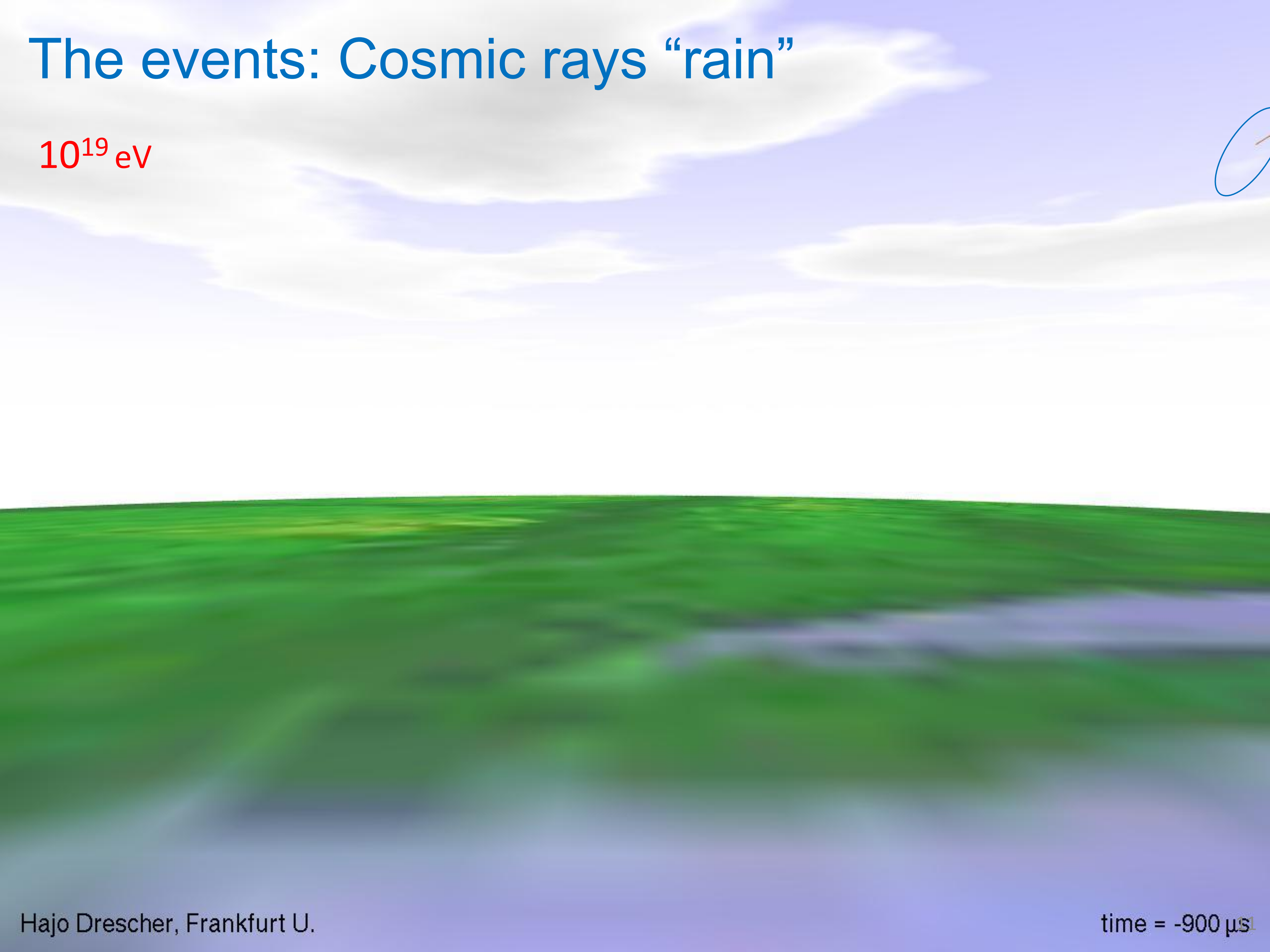
Shower cascades





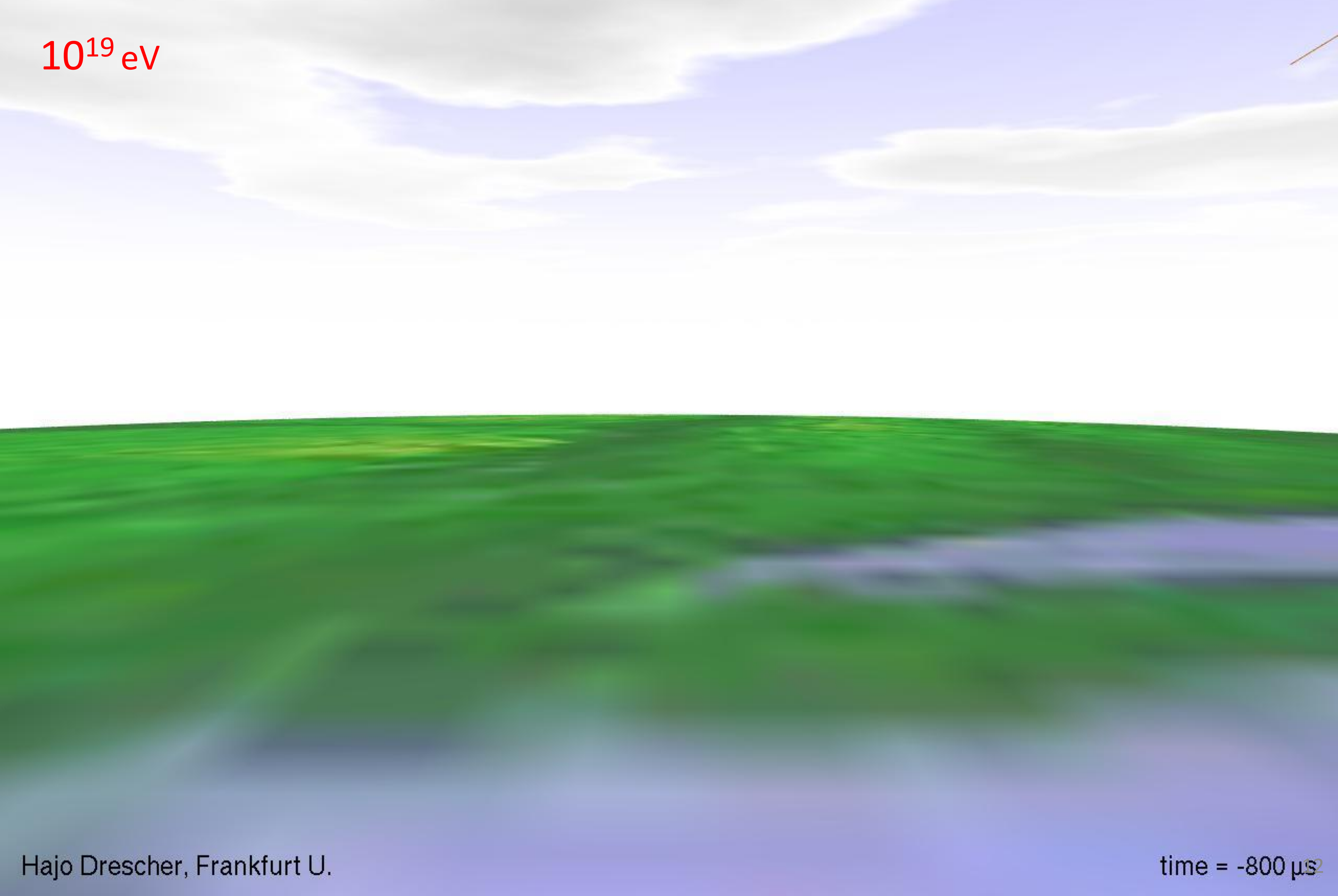
The events: Cosmic rays “rain”

10^{19} eV



The events: Cosmic rays “rain”

10^{19} eV

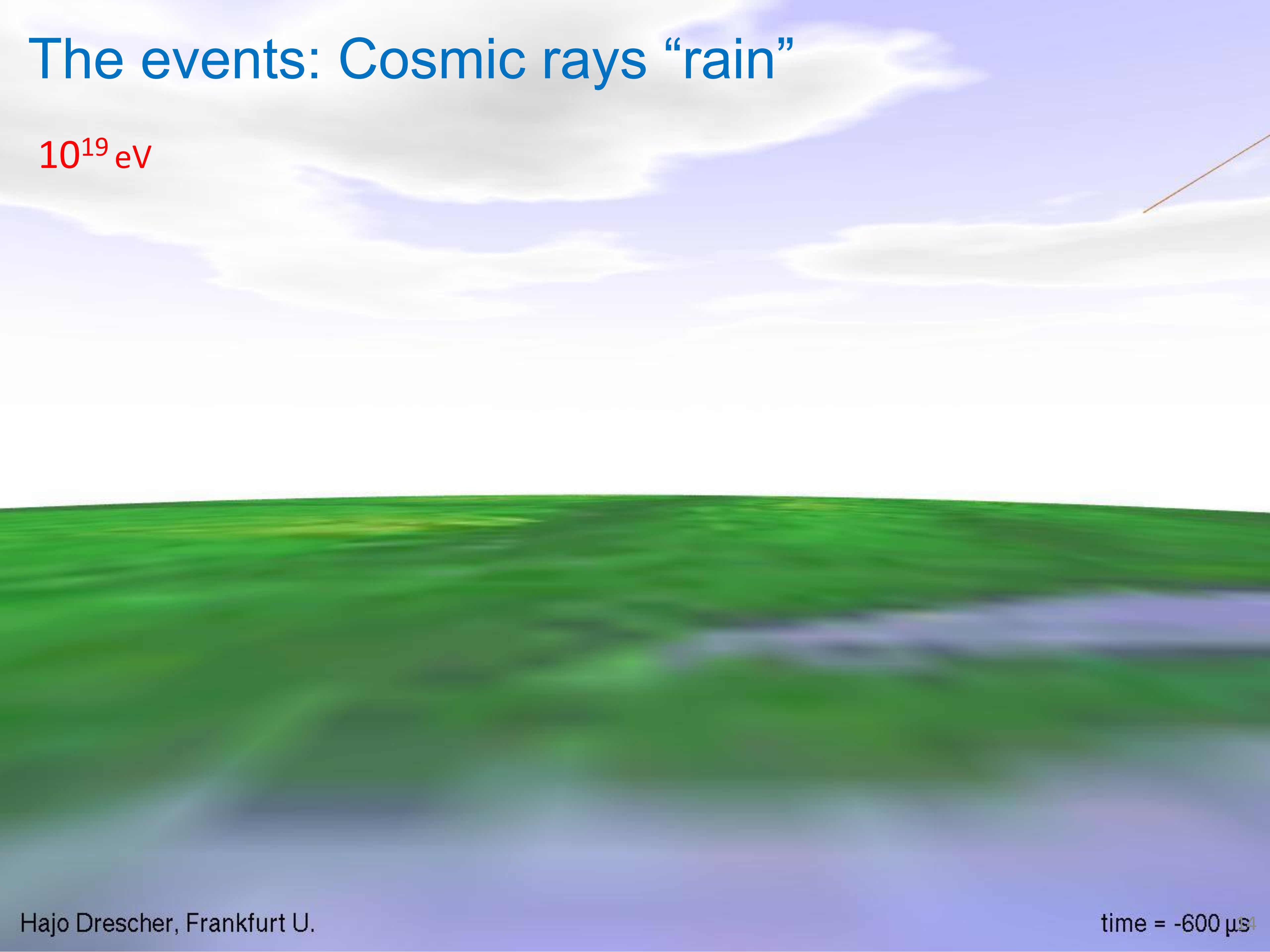


The events: Cosmic rays “rain”

10^{19} eV

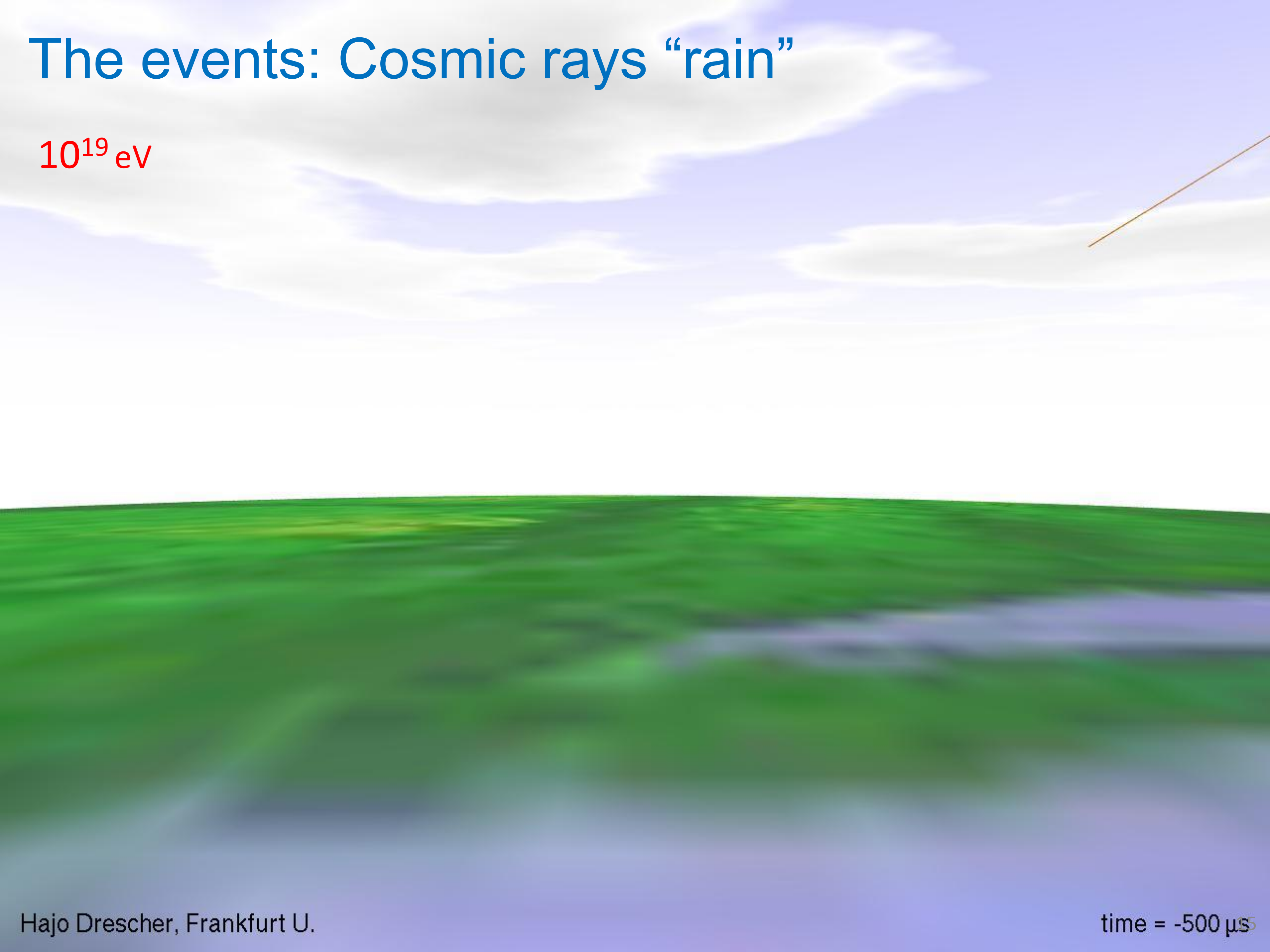
The events: Cosmic rays “rain”

10^{19} eV



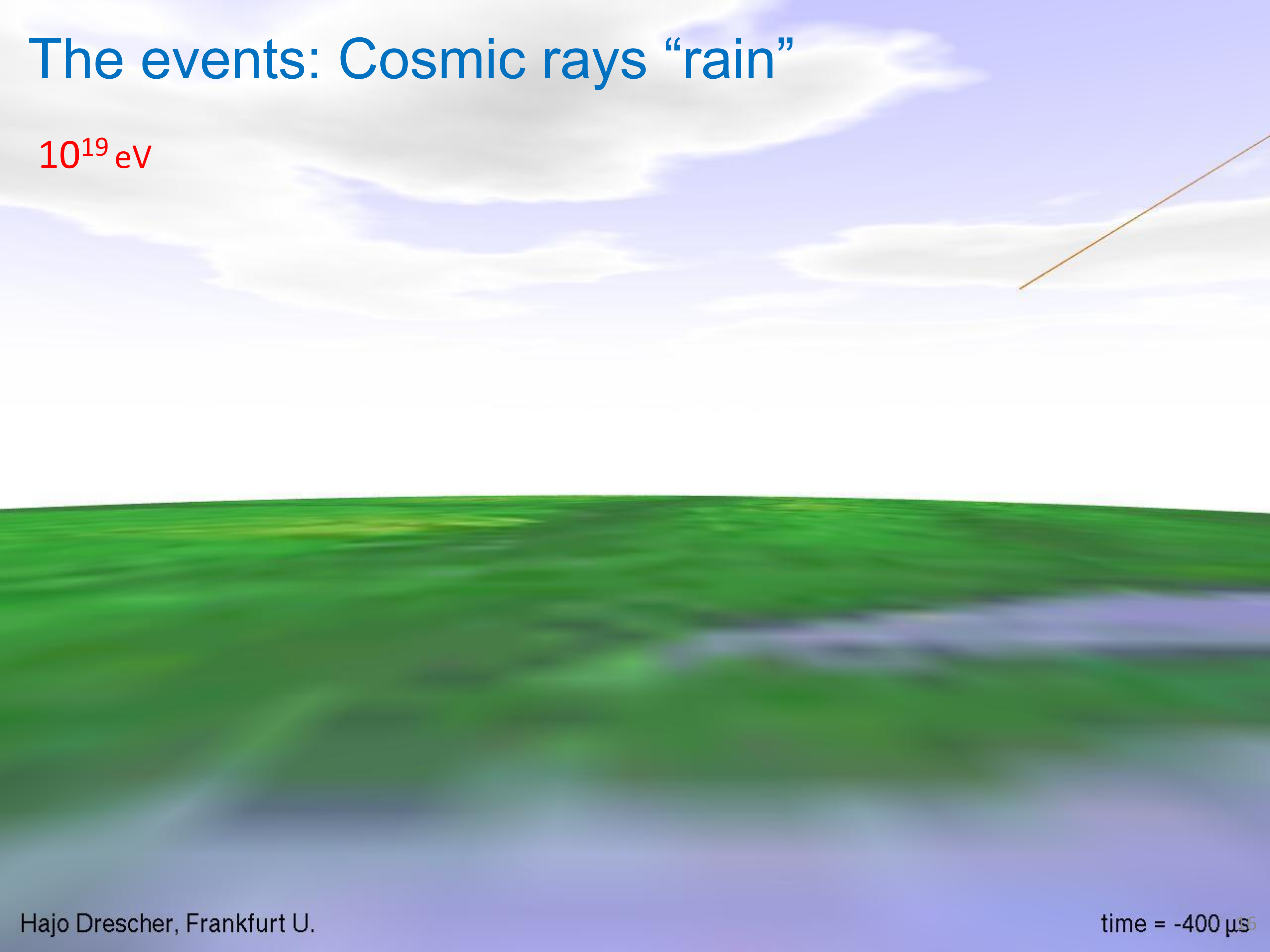
The events: Cosmic rays “rain”

10^{19} eV



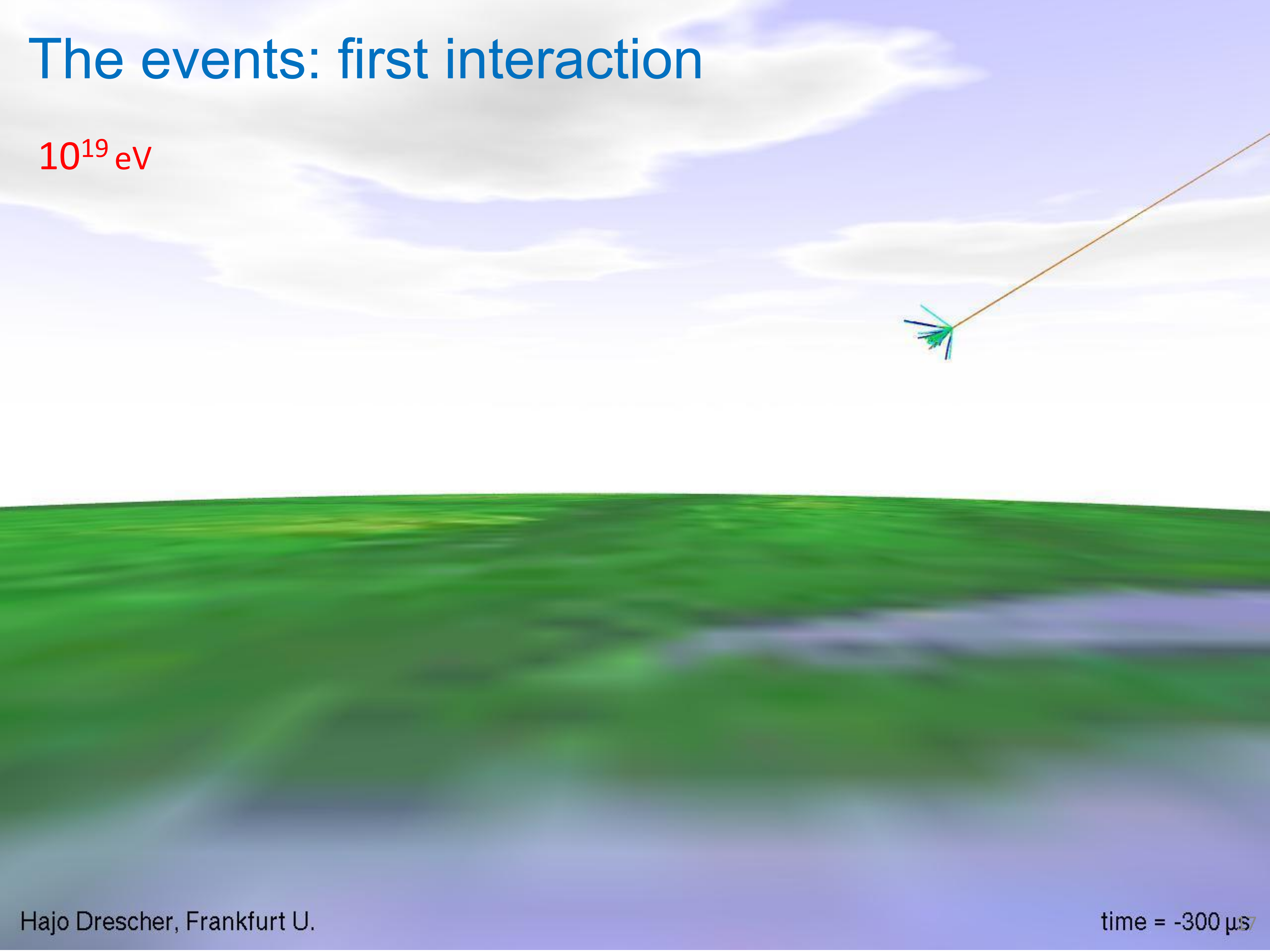
The events: Cosmic rays “rain”

10^{19} eV

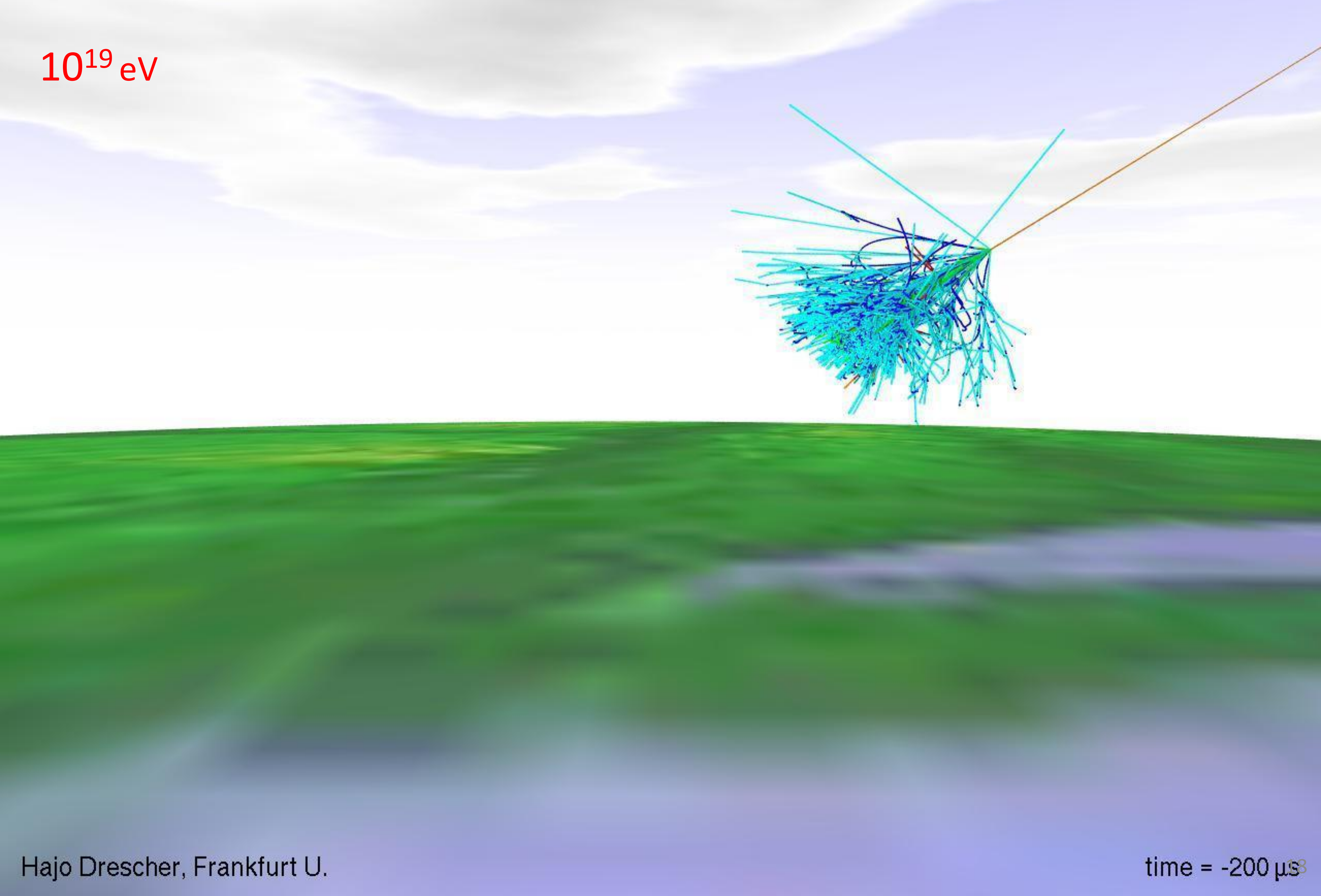


The events: first interaction

10^{19} eV

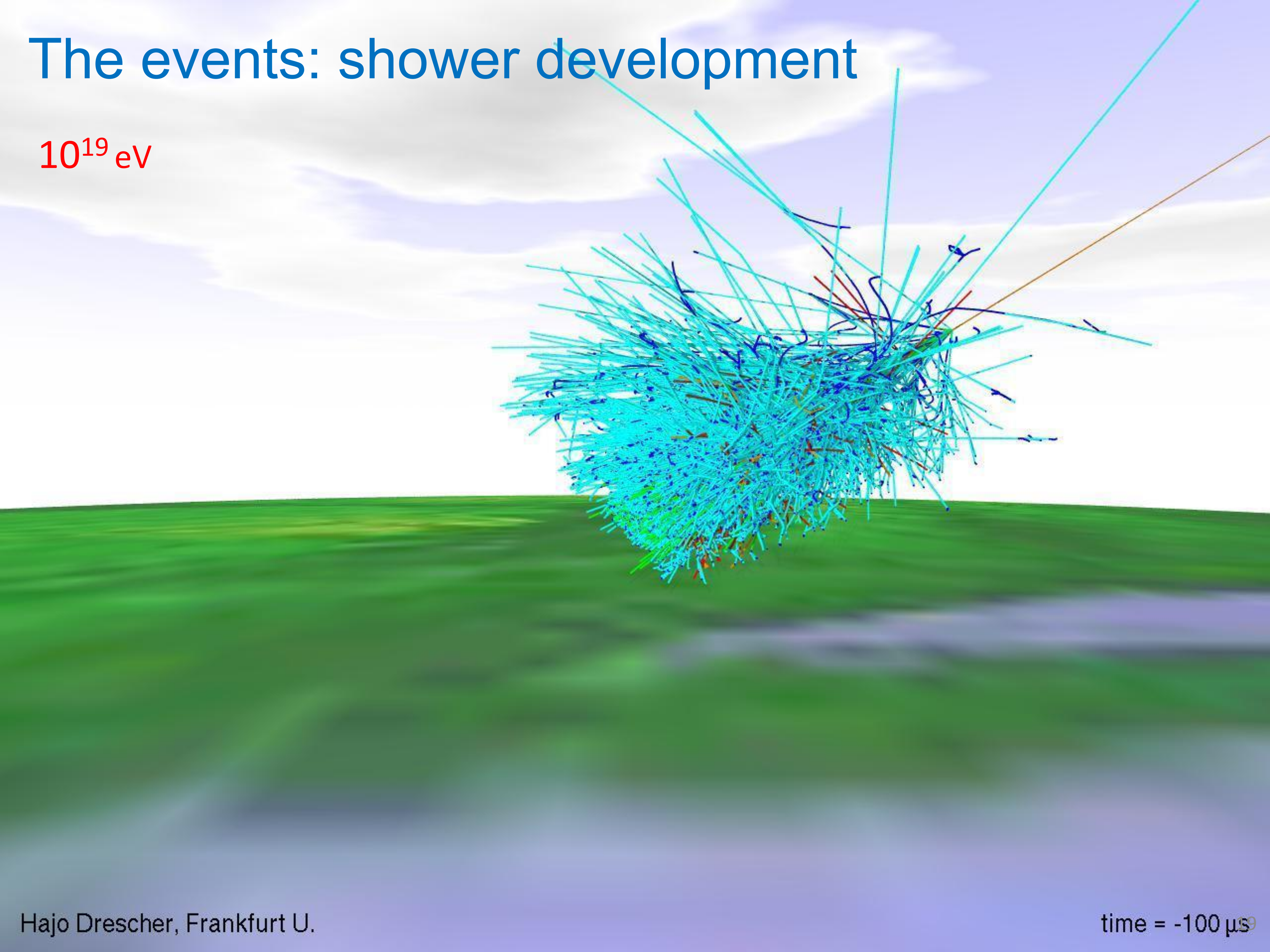


The events: shower development



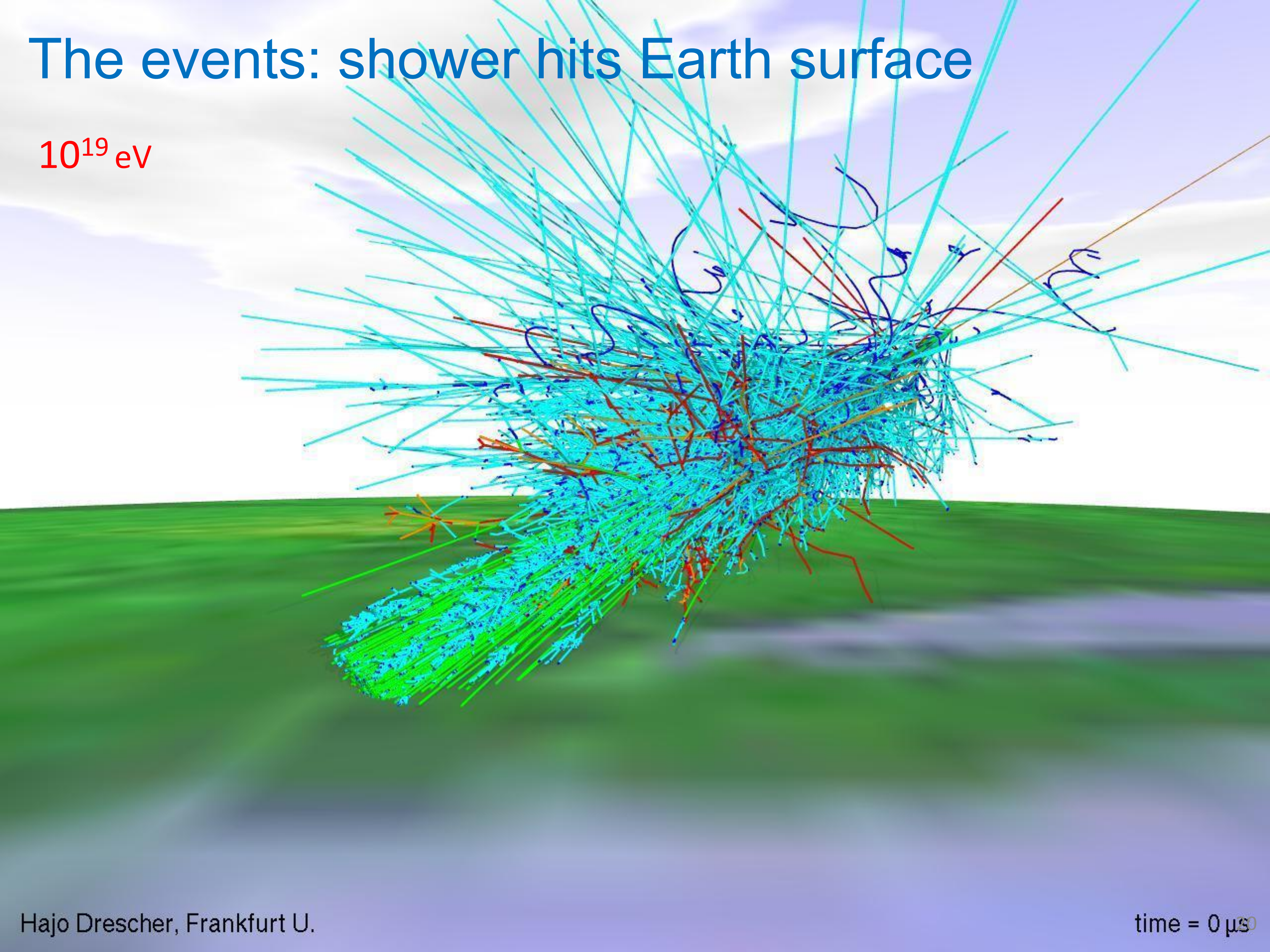
The events: shower development

10^{19} eV

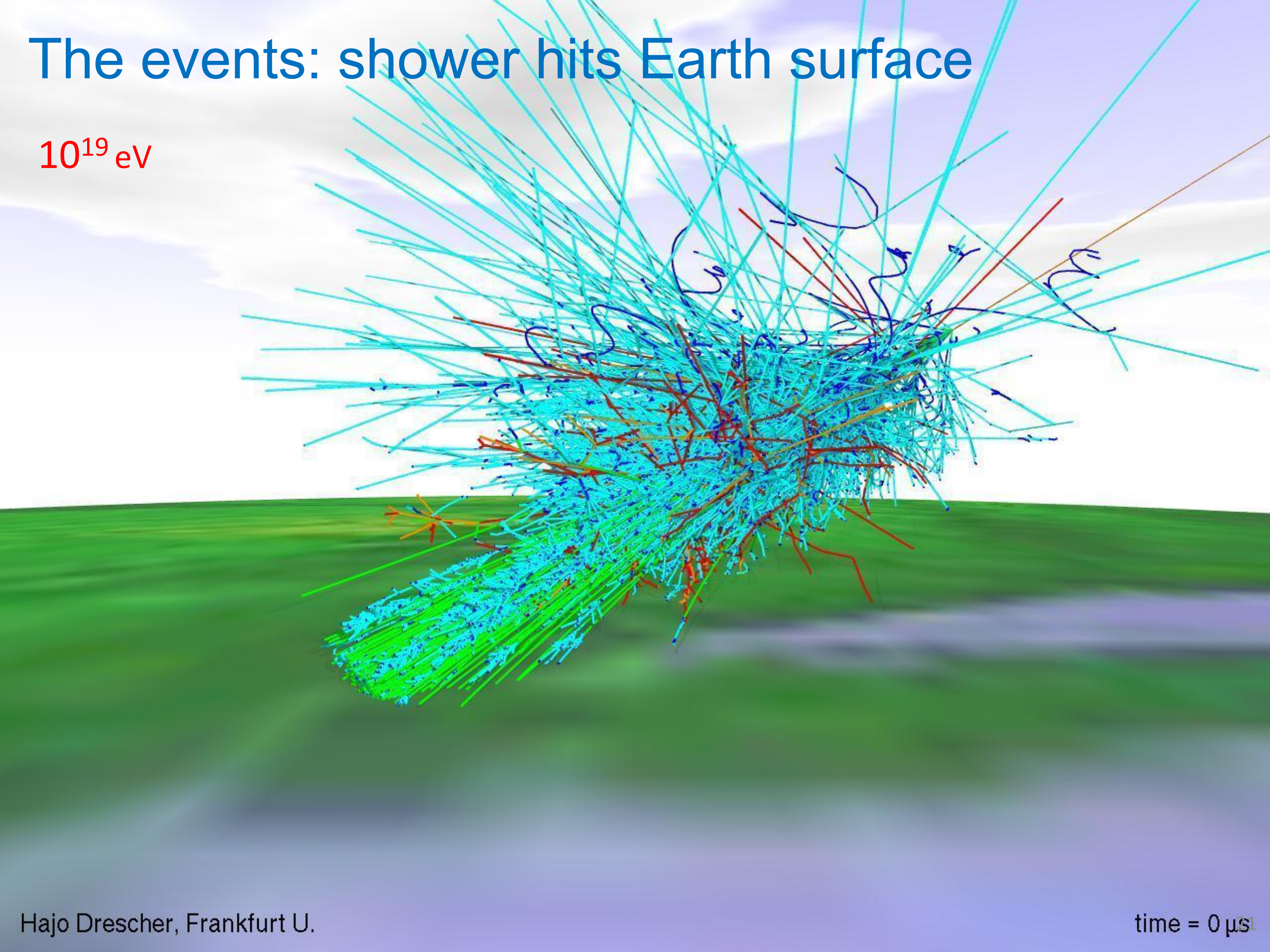


The events: shower hits Earth surface

10^{19} eV

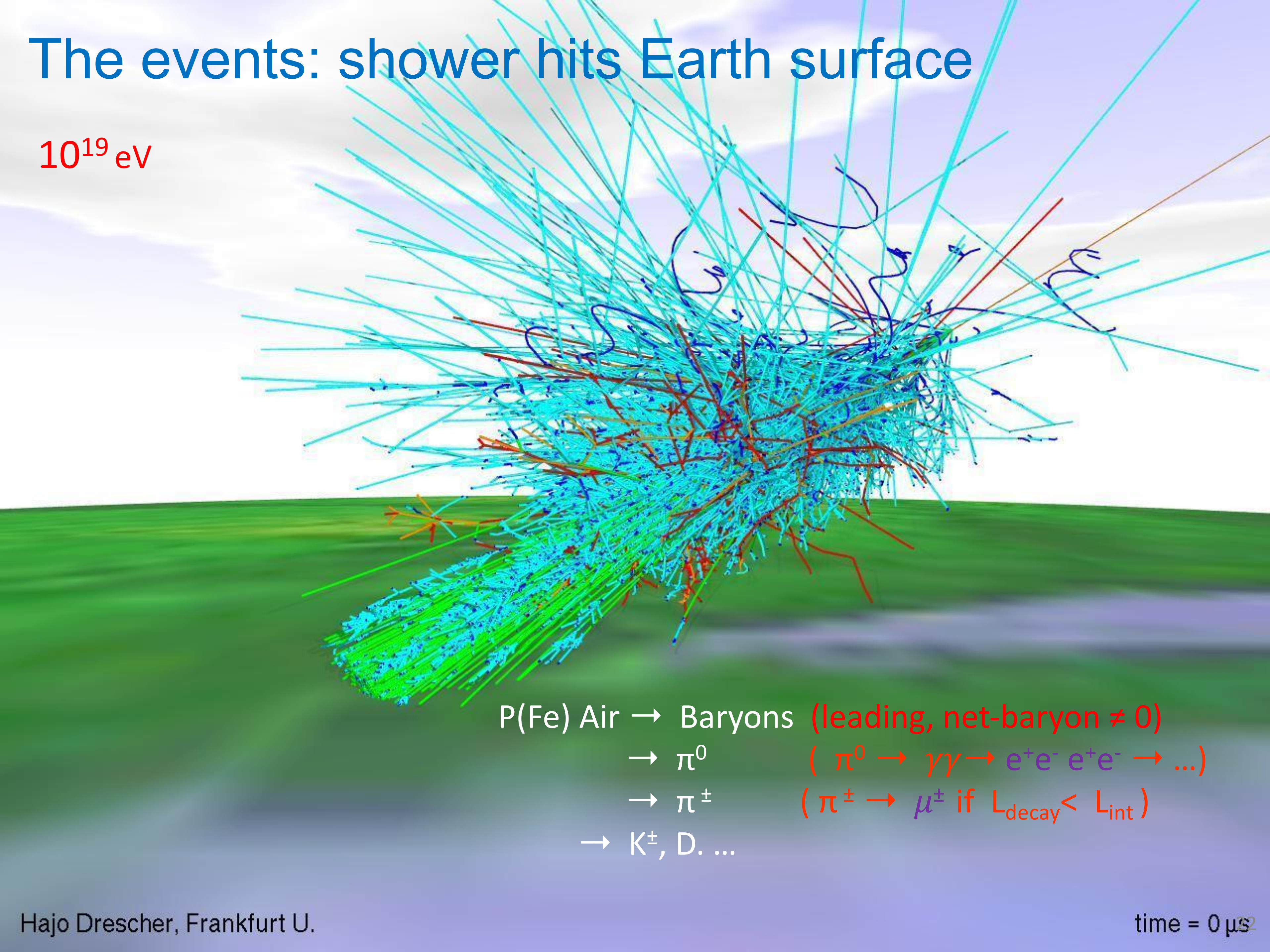


The events: shower hits Earth surface



The events: shower hits Earth surface

10^{19} eV



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

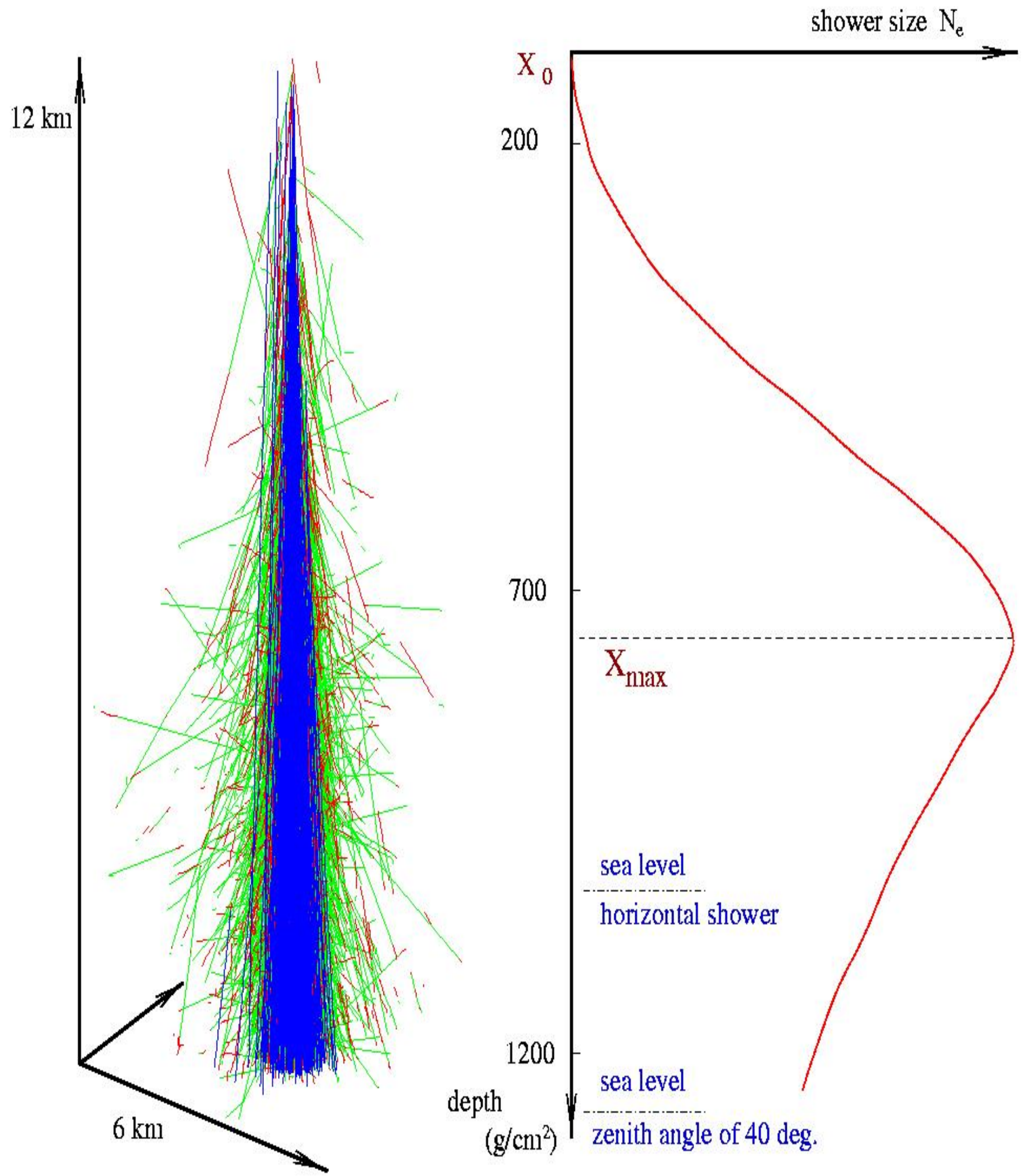
$\rightarrow \pi^0$ ($\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^- e^+e^- \rightarrow \ldots$)

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

$\rightarrow K^\pm$, D. …

Extensive Air Showers (EAS)

10^{19} eV

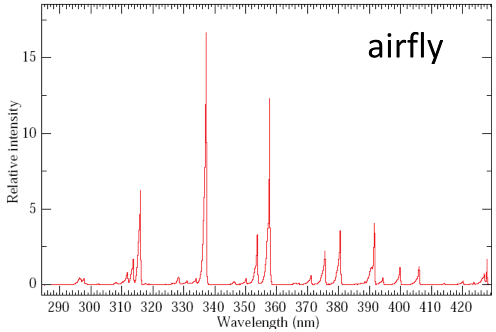


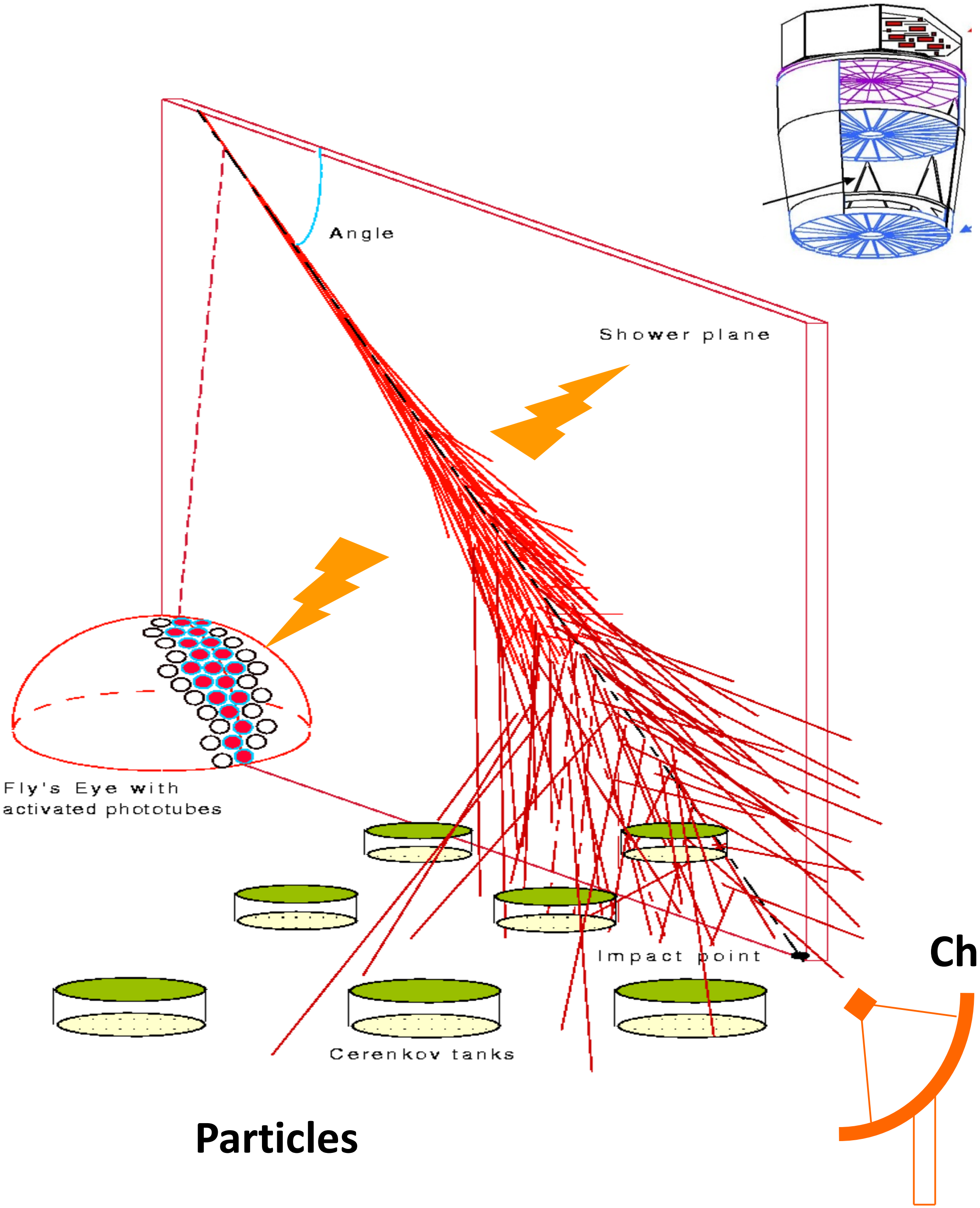
$$X(l) = \int_0^l \rho(x) dx$$

EAS detection

Fluorescence

electrons excite N_2 molecules



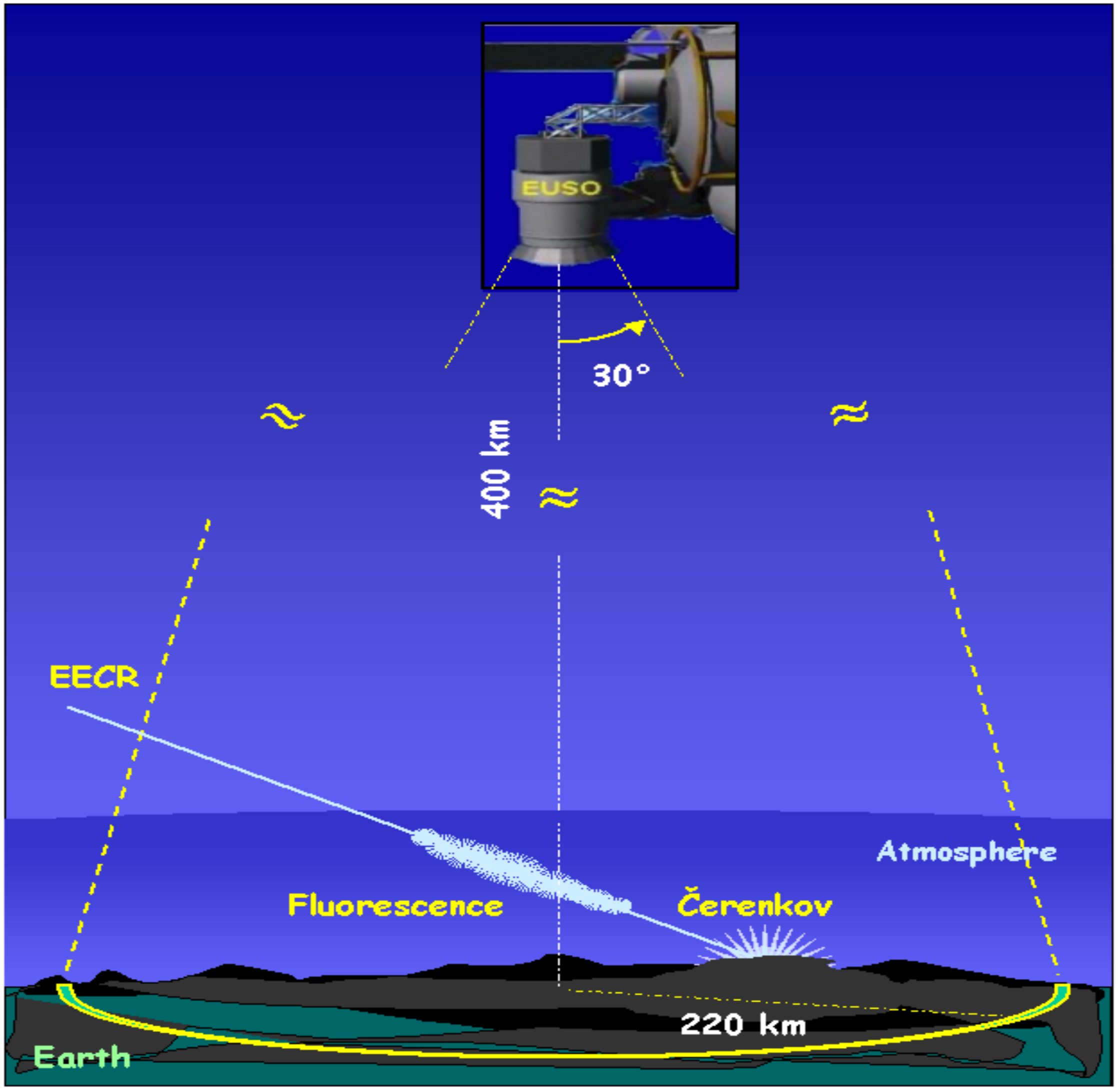


Cherenkov

Particles

Fluorescence from space

JEM-EUSO

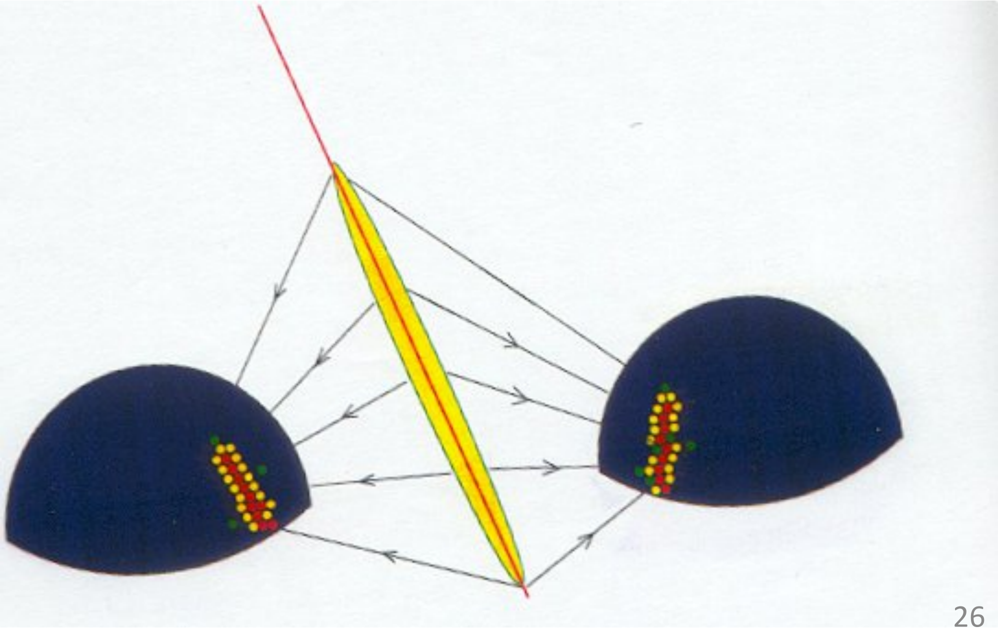


Fluorescence from Earth

Fly's Eye

Air shower

stereo image

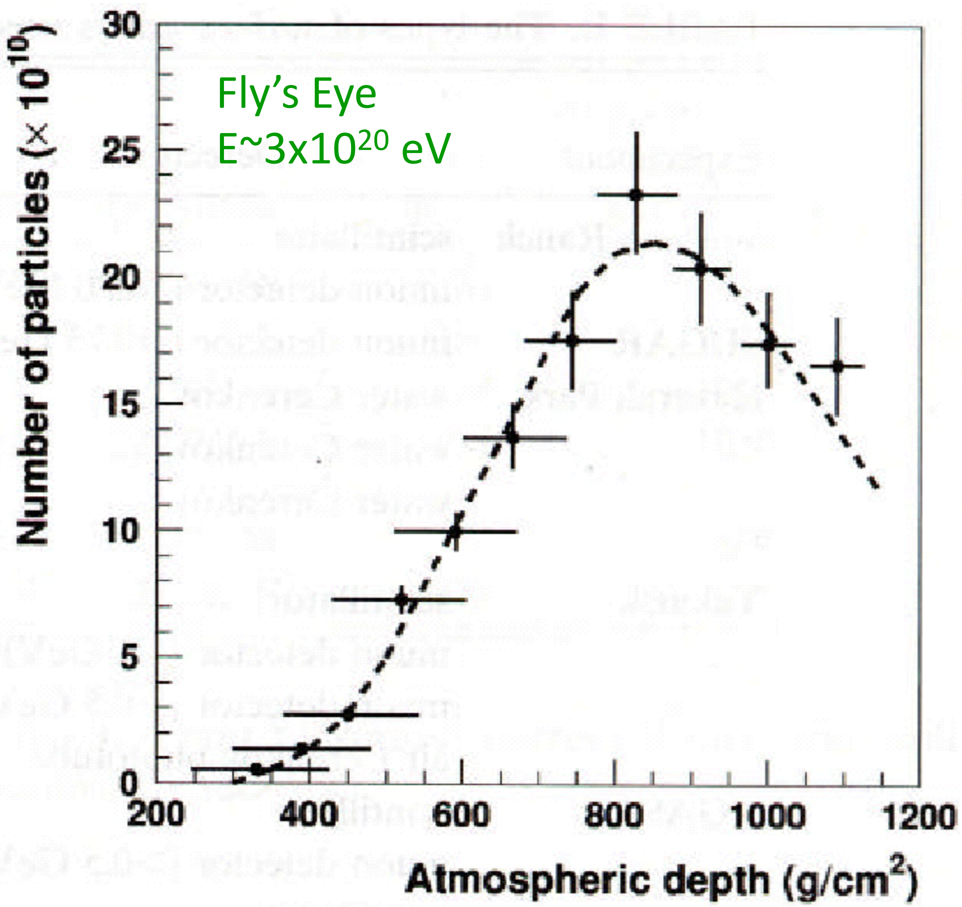


Fluorescence detectors measurements

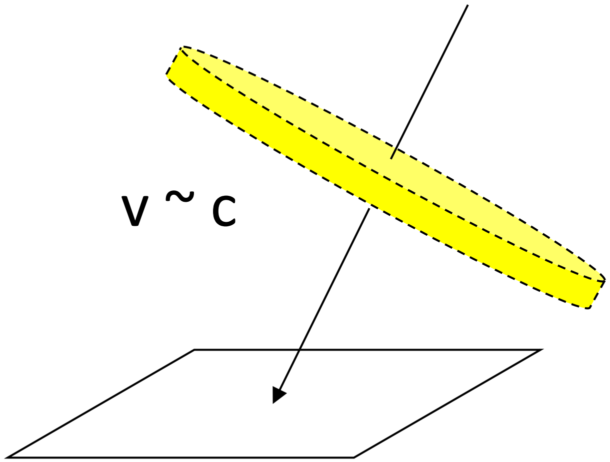
The direction
The X_{max}
The Energy

$$E \propto Ne$$

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

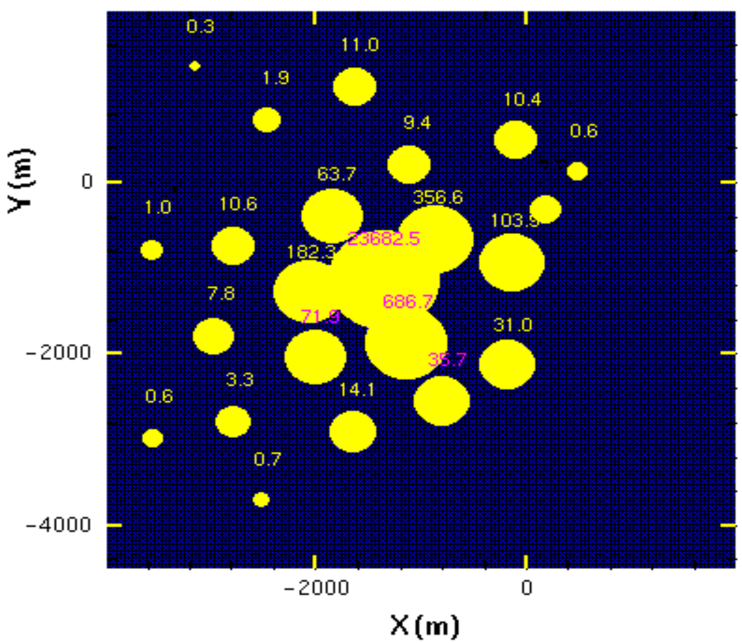


Ground arrays measurements

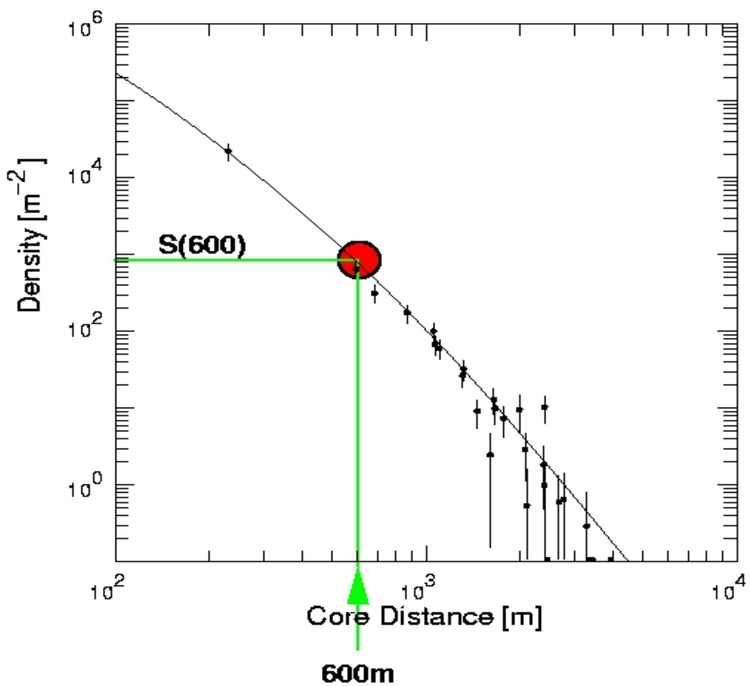


From (n_i, t_i):

The direction
The core position
The Energy



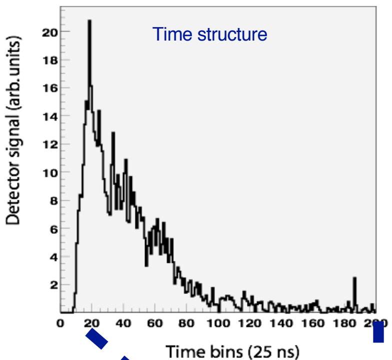
The LDF



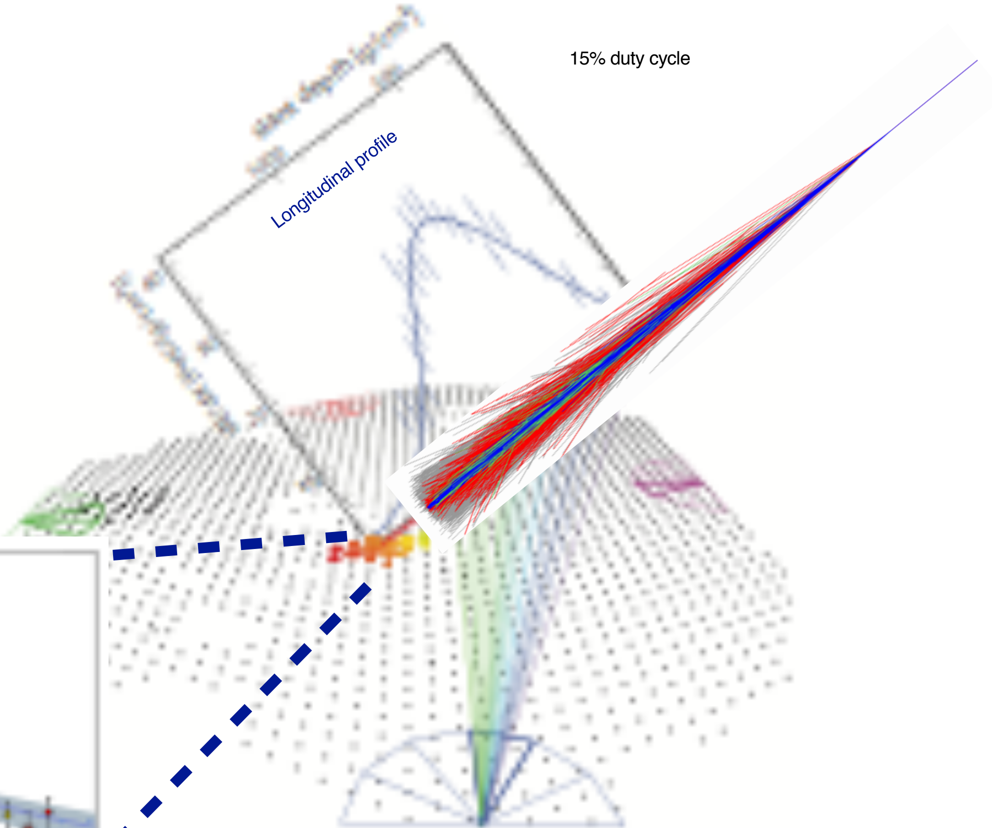
Measurements by an Hybrid detector at Earth

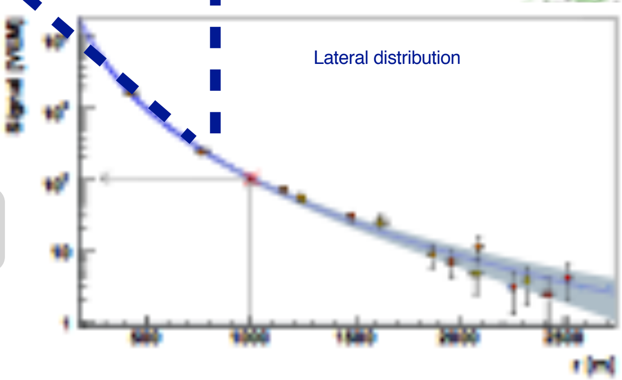
$$E_{cal} = \int_0^{\infty} \left(\frac{dE}{dX}\right)_{obs} dX$$

15% duty cycle



100% duty cycle





$$E_{rec} = f(S_{1000}, \theta)$$

Example: event observed with Auger Observatory

Earth Observatories

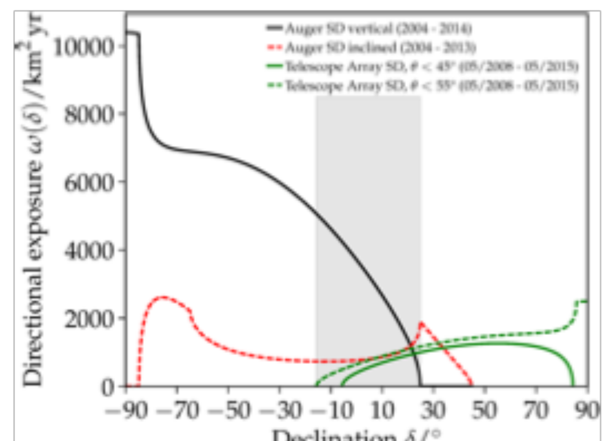
Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

Auger:
- 6.7×10^4 km^2 sr yr (spectrum)
- 9×10^4 km^2 sr yr (anisotropy)

TA:
- 8.1×10^3 km^2 sr yr (spectrum)
- 8.6×10^3 km^2 sr yr (anisotropy)

Together full sky coverage



Telescope Array (TA)

Area ~ 680 km^2

3 fluorescence telescopes

507 double-Layer scintillators

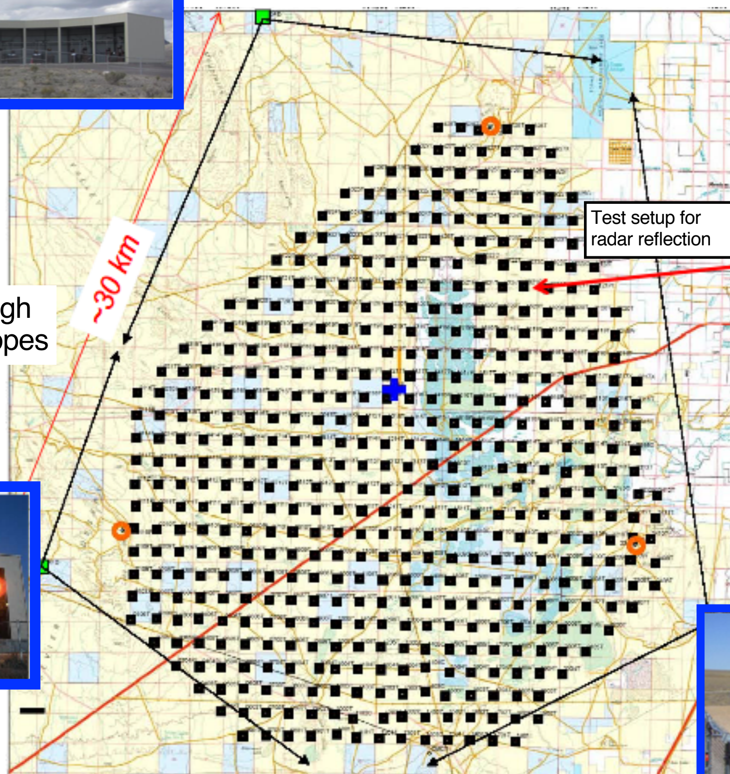
Talk by Abu-Zayyad

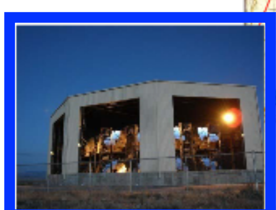
Middle Drum: based on HiRes II

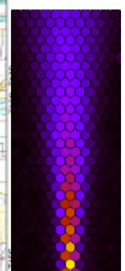
TALE (TA low energy extension)

LIDAR
Laser facility

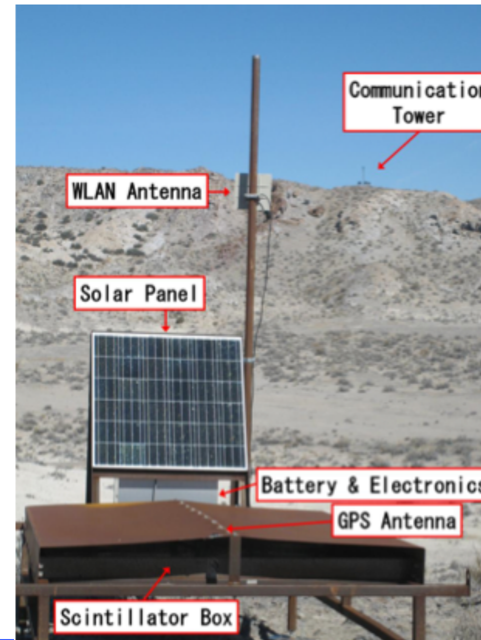
Infill array and high elevation telescopes







Electron light source (ELS):
~40 MeV



Northern hemisphere: Utah, USA

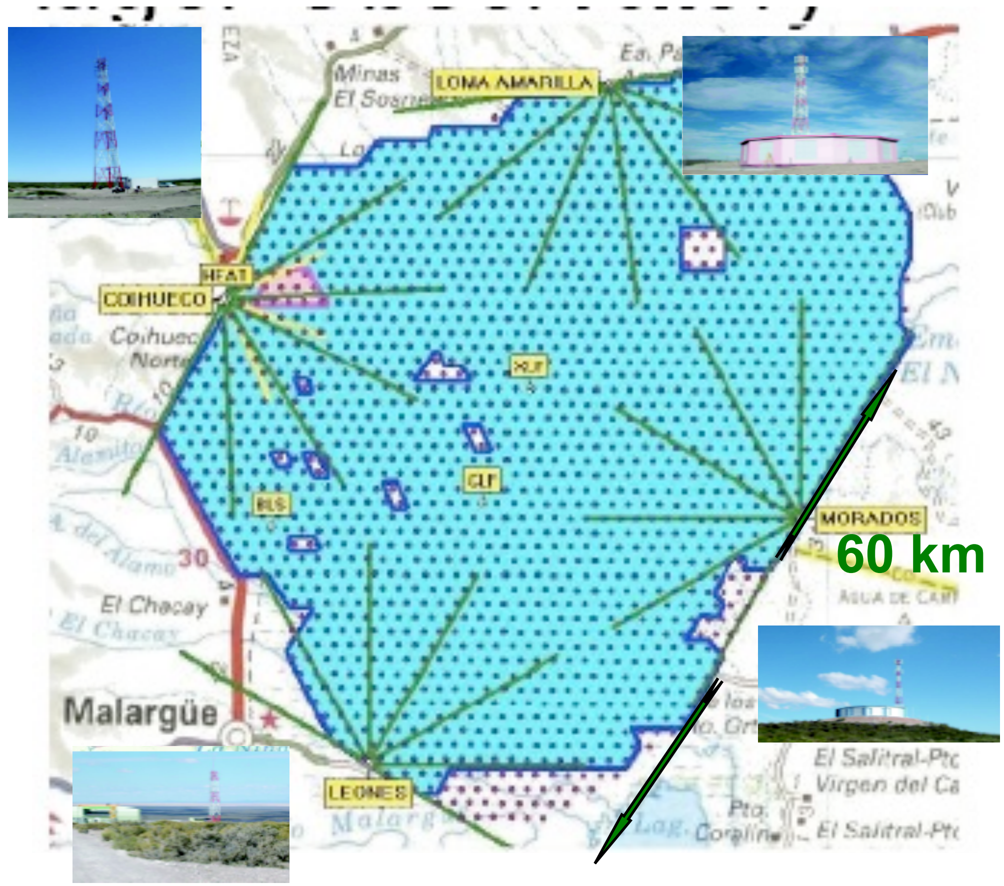
The Pierre Auger Observatory

South Hemisphere

Area ~ 3000 km2

24 fluorescence telescopes

1600 water Cerenkov detectors

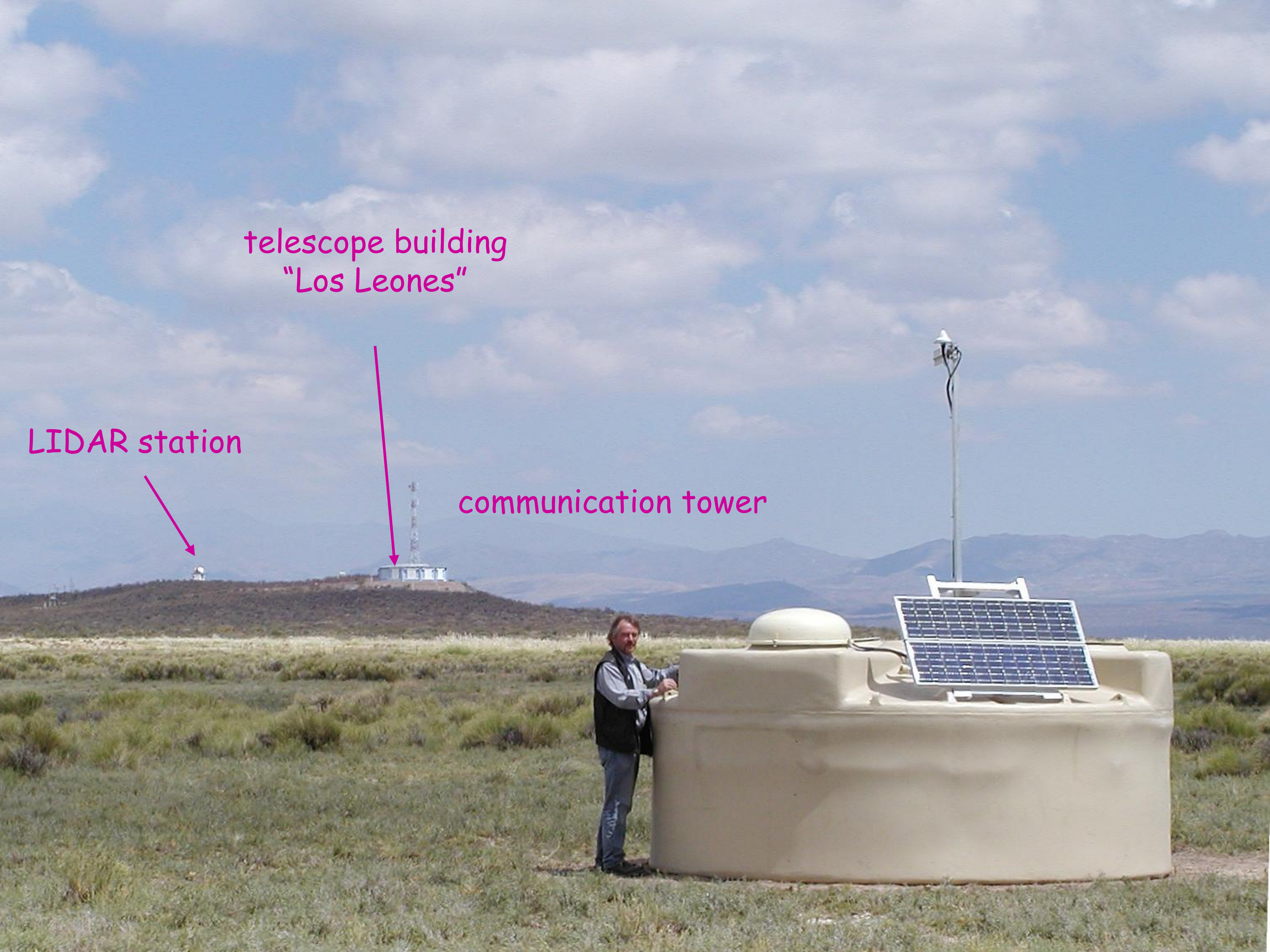


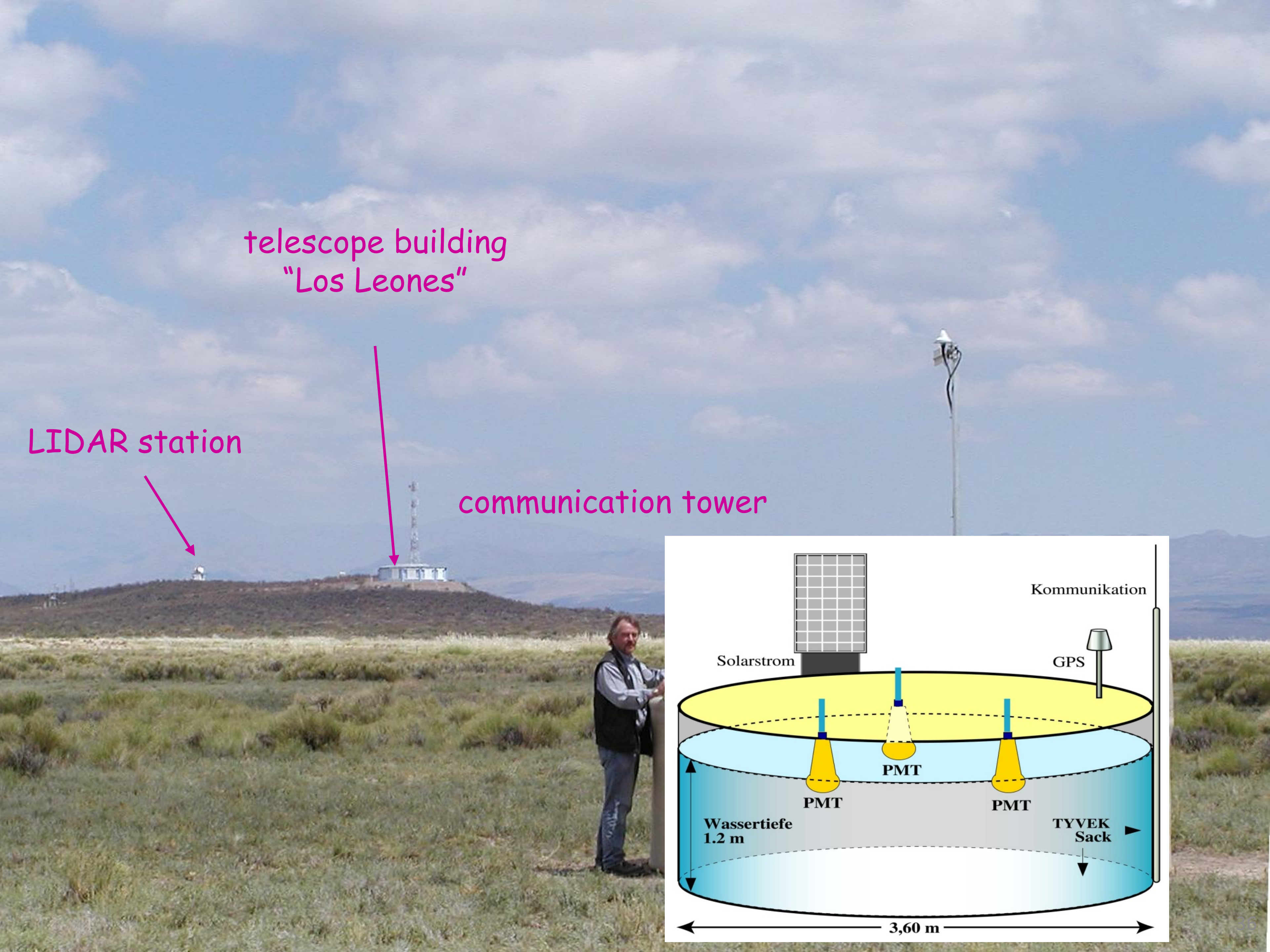
Malargüe, Argentina

Nov 2009


Escuela Nº 4-190
Dr. James W. Cronin
MALARGÜE - MENDOZA

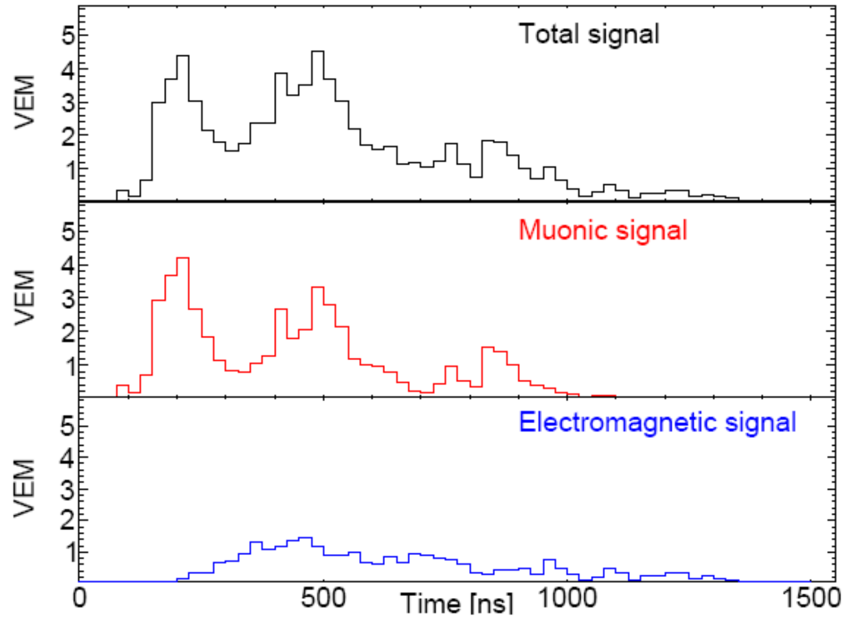
Tanks aligned seen from Los Leones

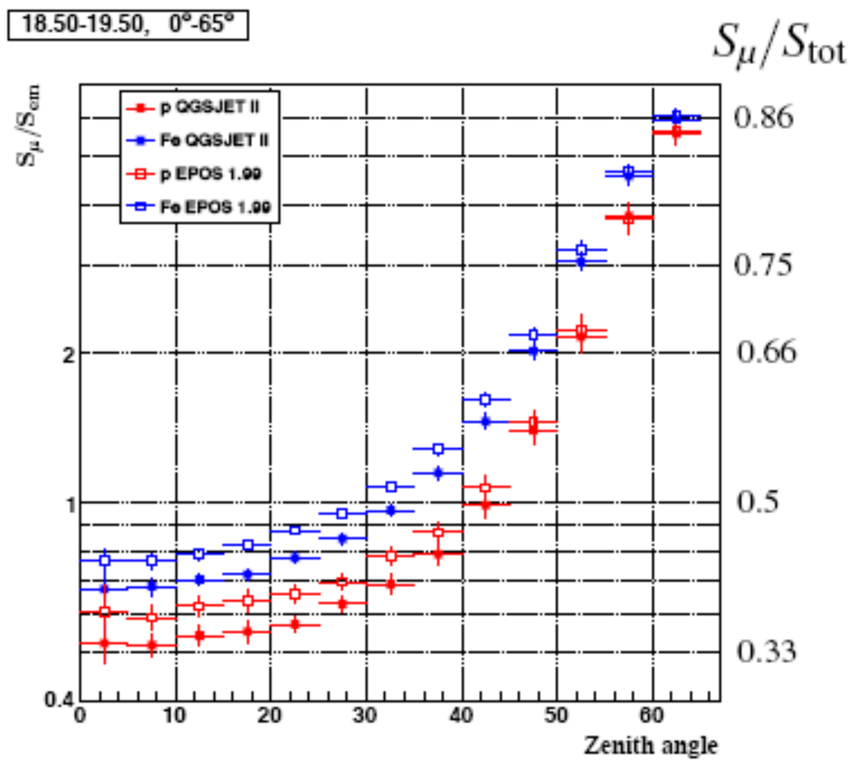

telescope building
“Los Leones”
LIDAR station
communication tower


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

E.M. and μ signal at the SD

Individual time traces

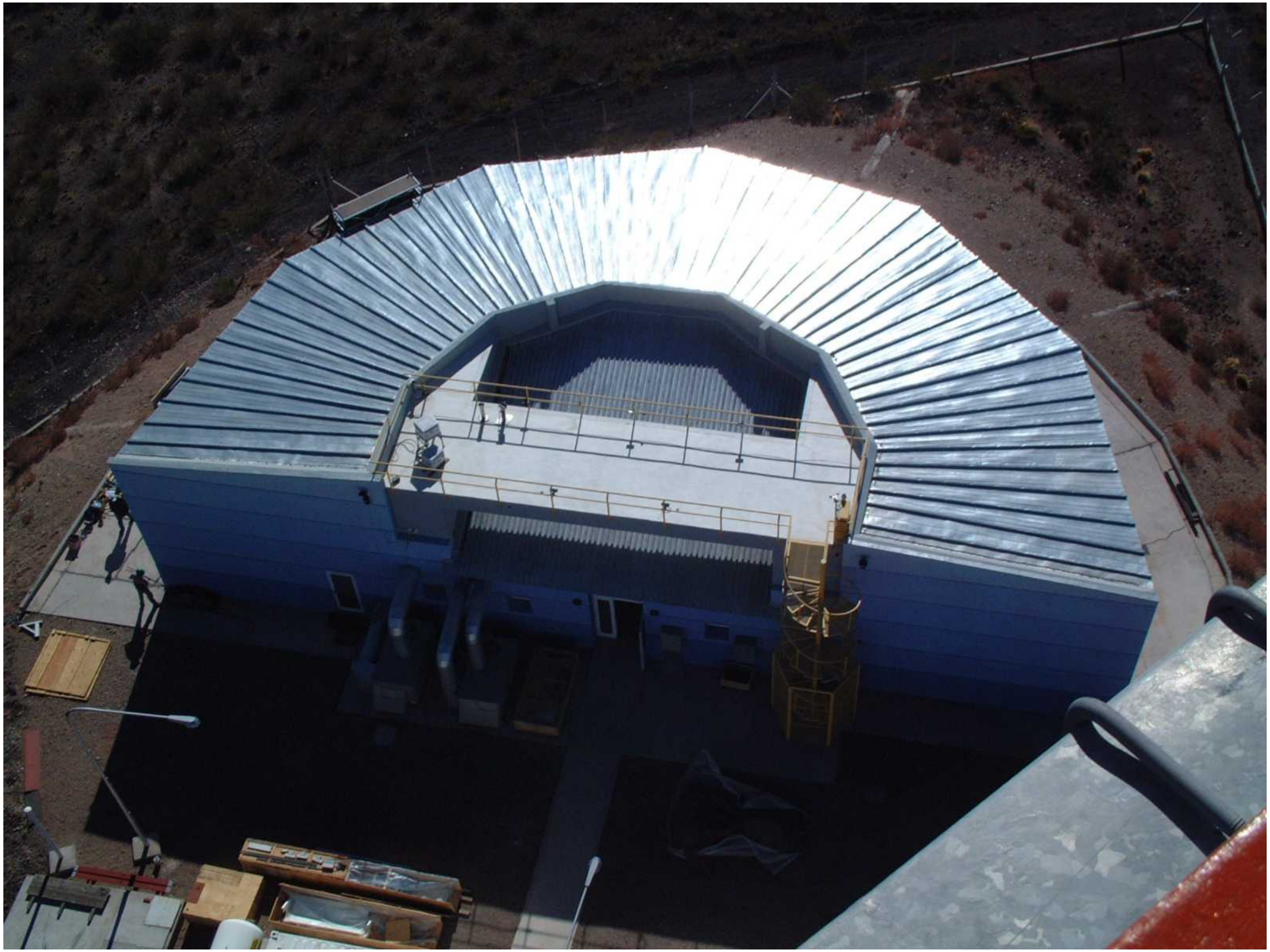




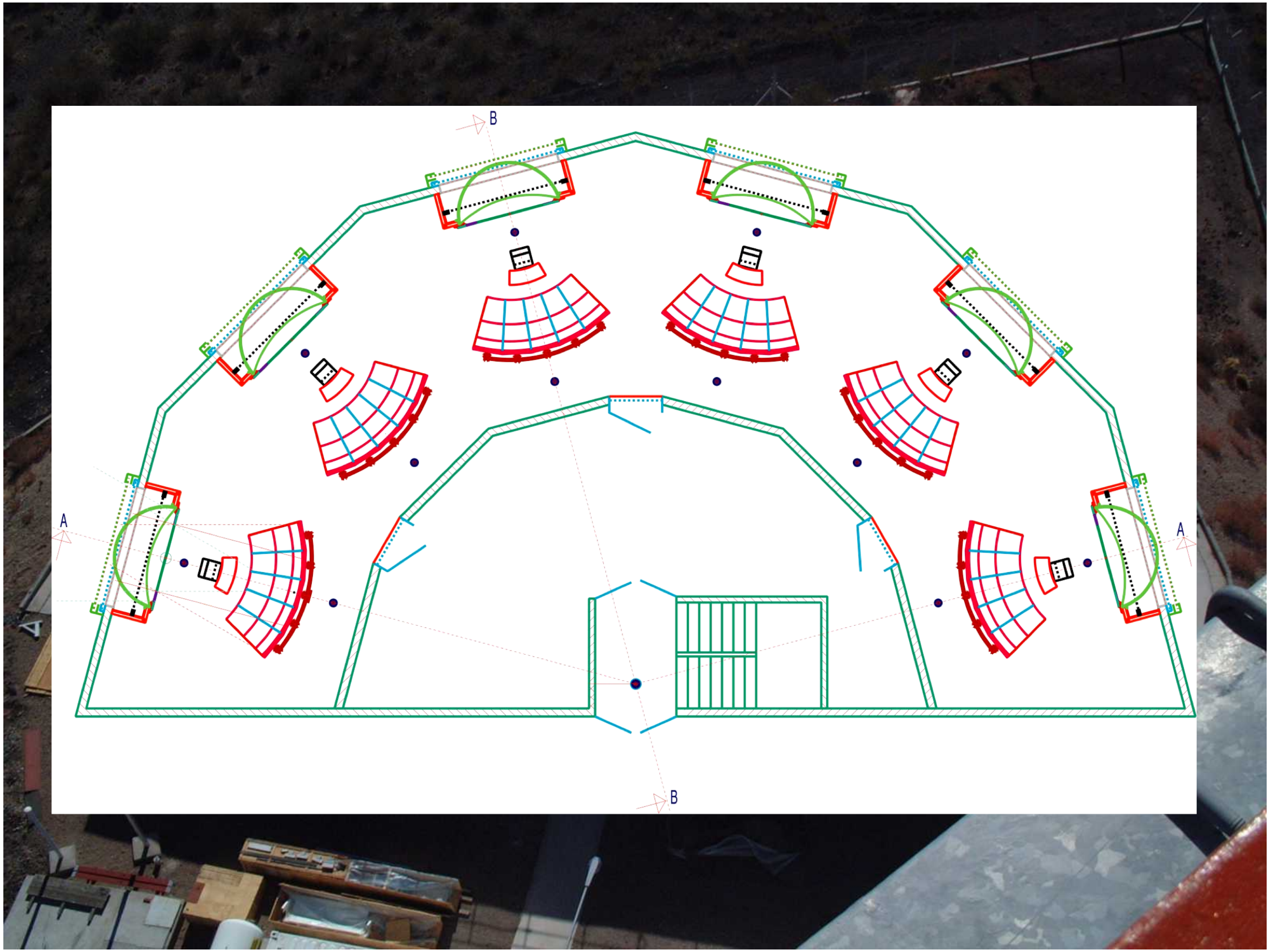
Proton, Θ =45º , E= 10^{19} eV ,
d= 1000m

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

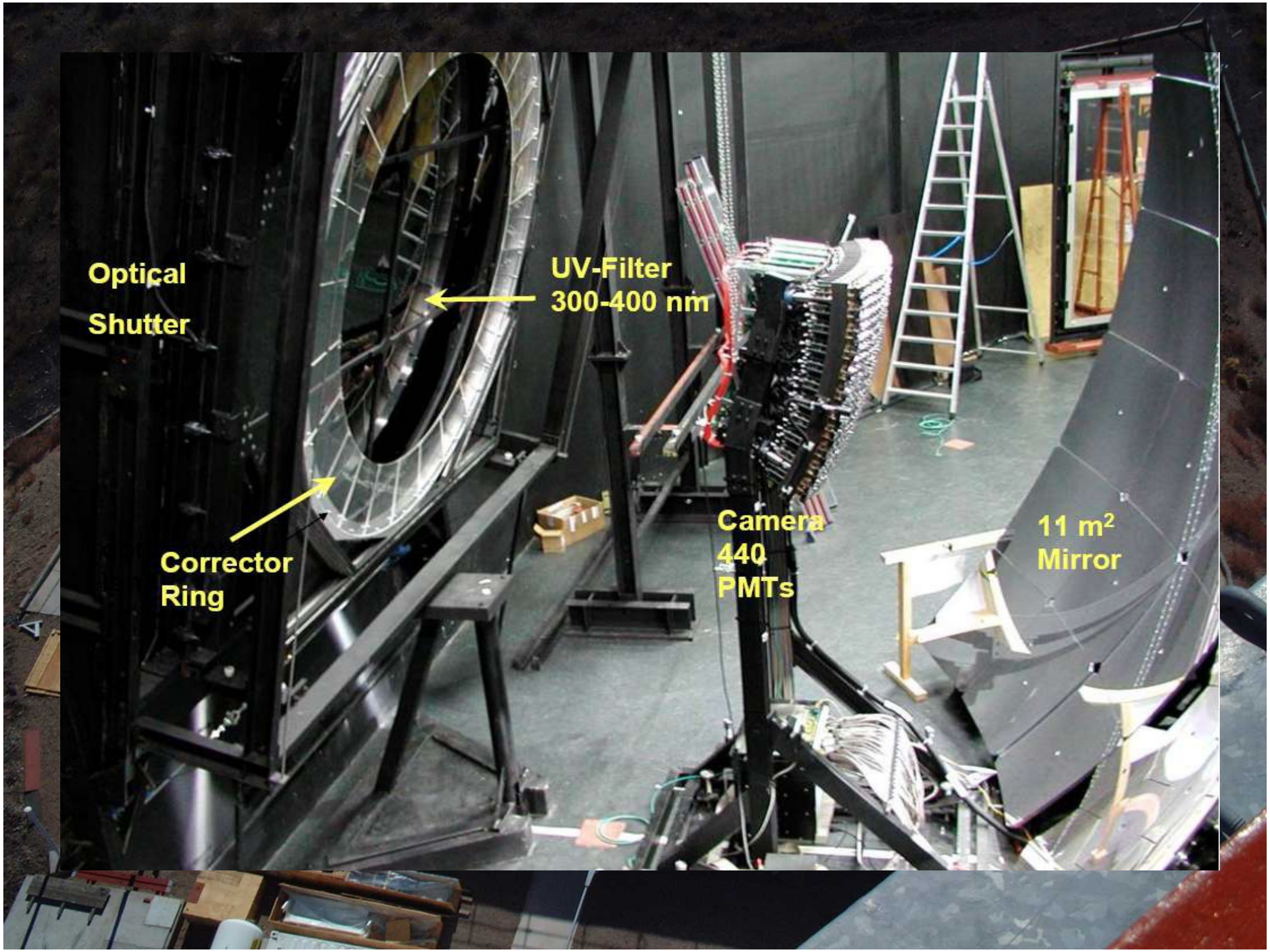
The fluorescence detectors (FD)



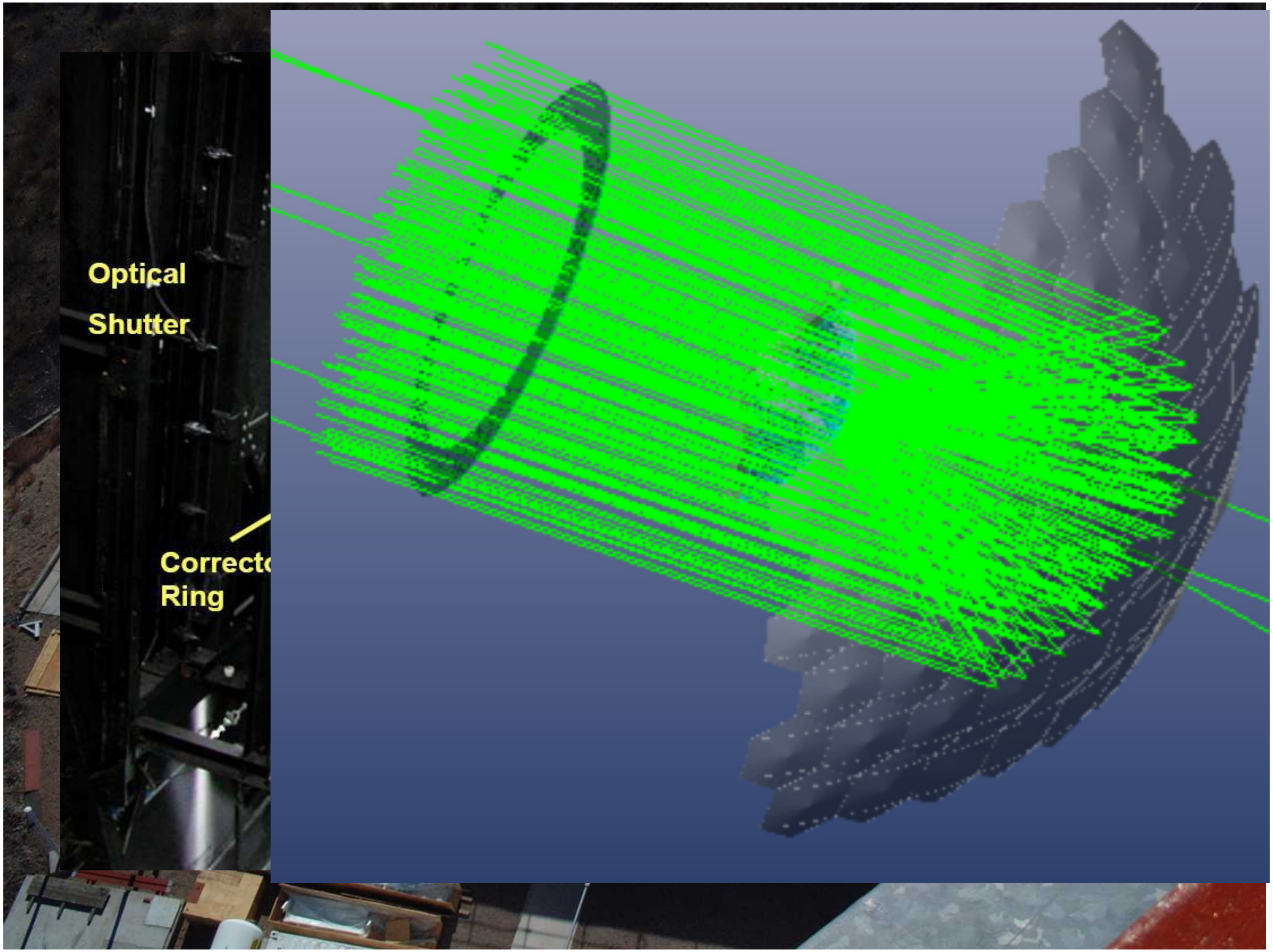
The fluorescence detectors (FD)



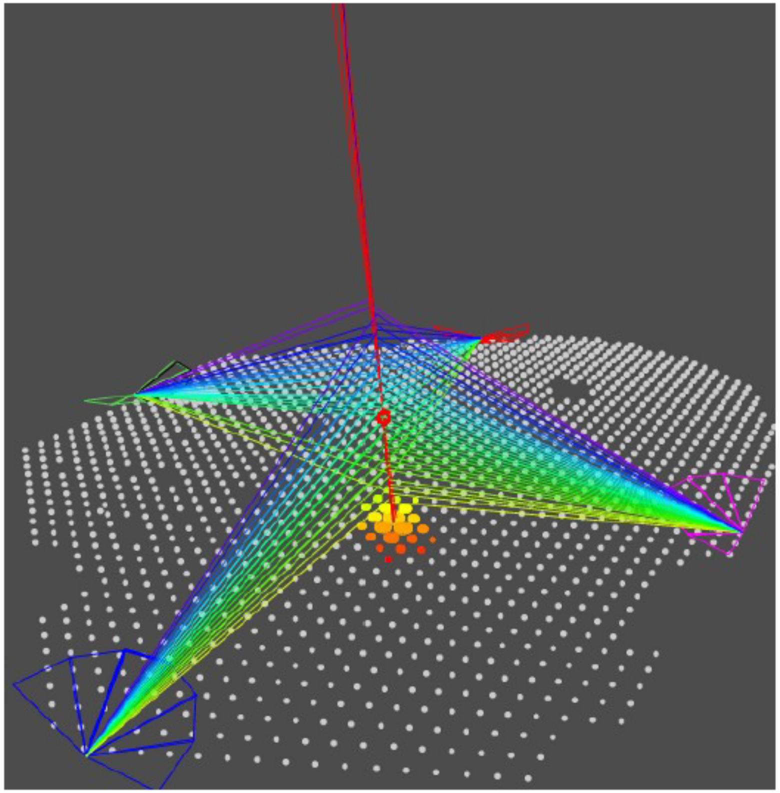
The fluorescence detectors (FD)

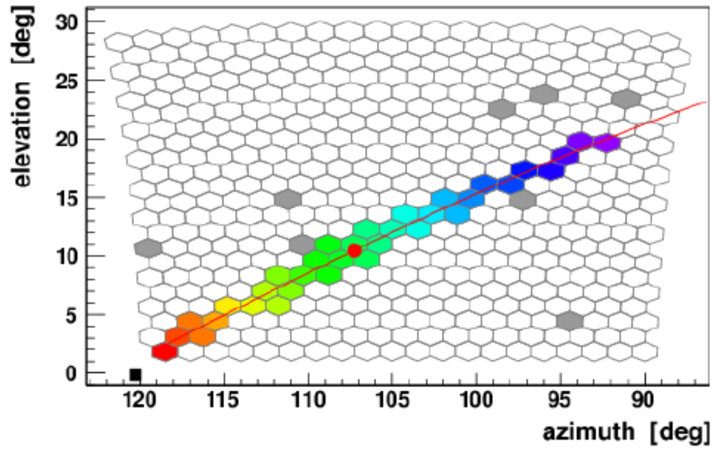


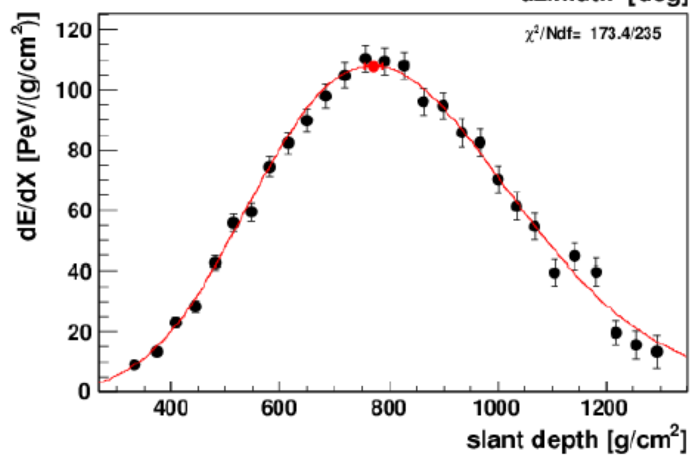
The fluorescence detectors (FD)

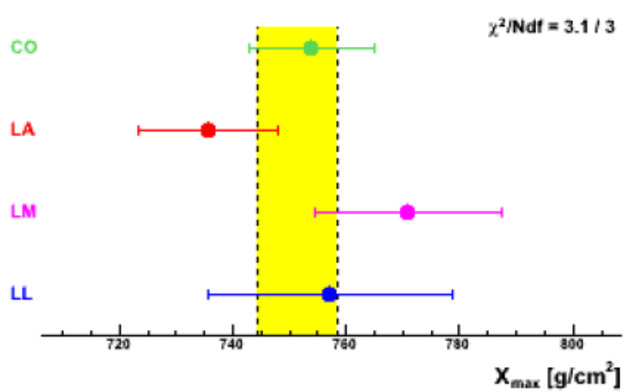


A 4 eyes hybrid event !









Energy

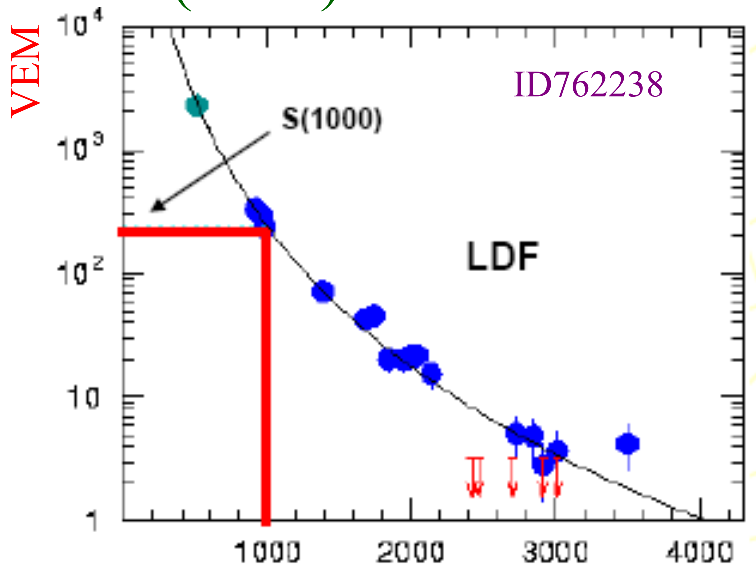
E = (7.1± 0.2) 10^{19} eV

Depth of the maximum

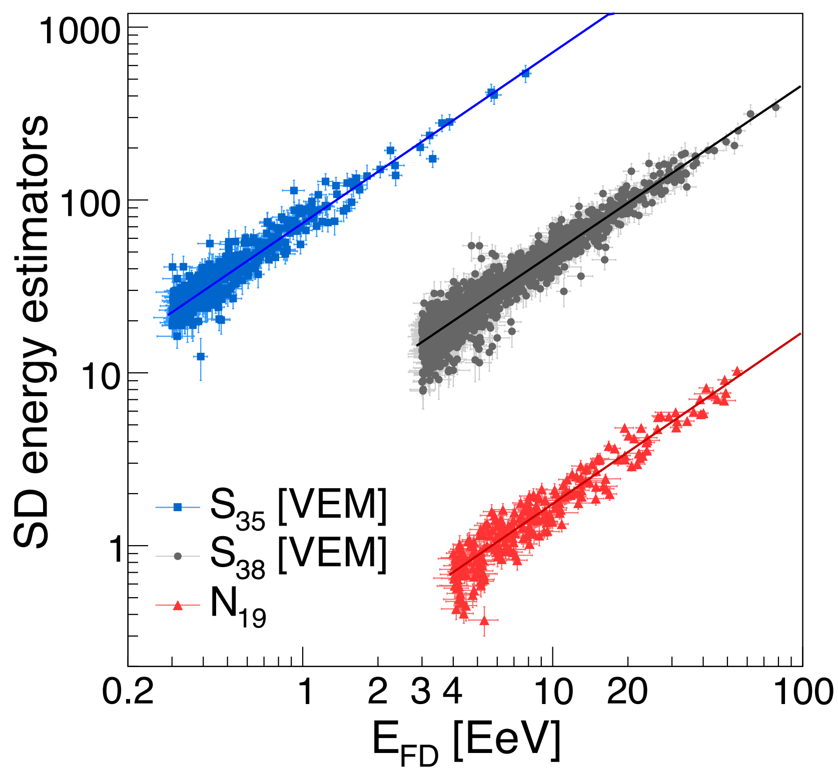
X_{max} = (752 ± 7) g/cm²

Energy determination in Auger

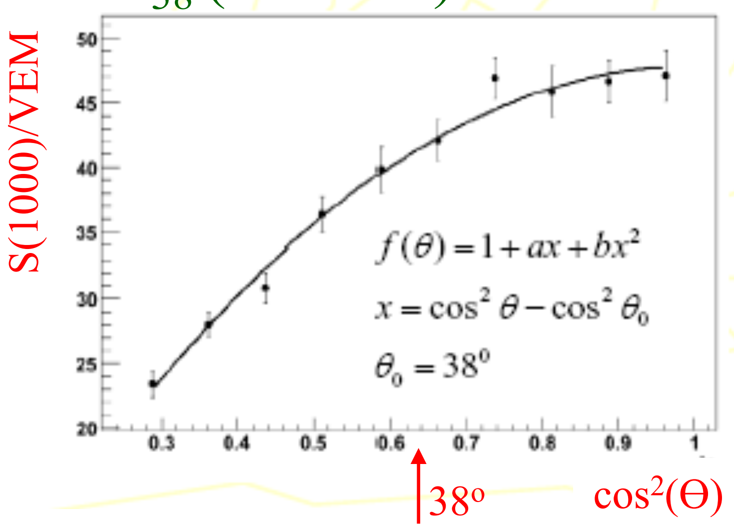
S(1000)



Calibration



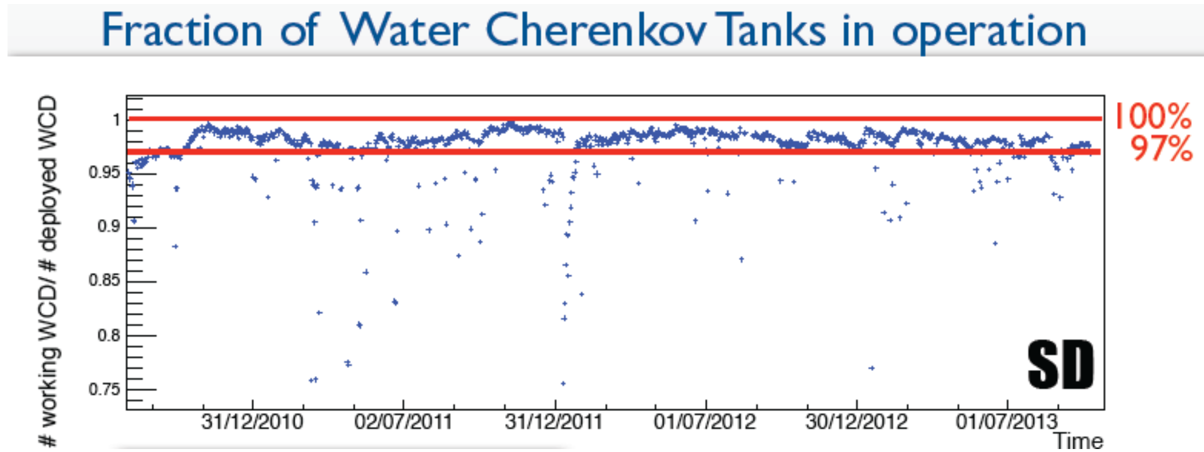
S_{38} (das CIC)



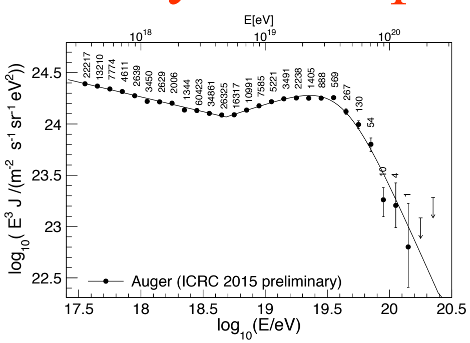
$\sigma_E \sim 10\%$

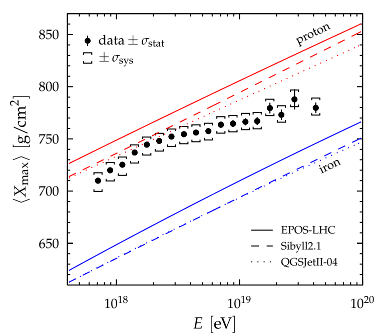
Auger is running smoothly

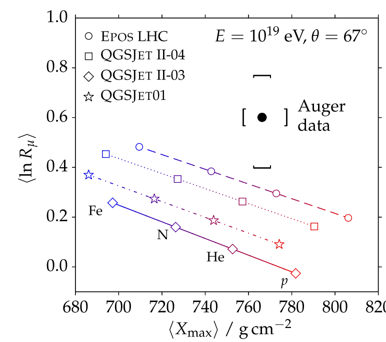
The Swiss clock!

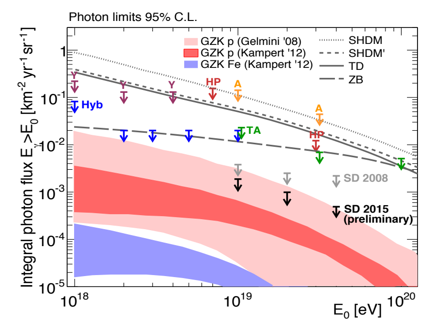


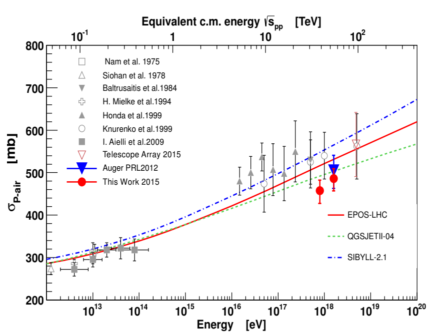
Many and important results !

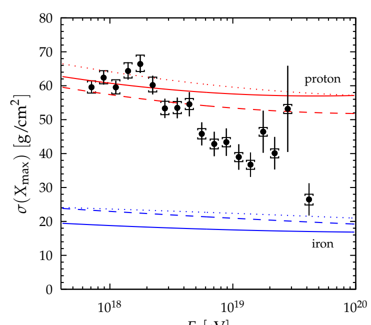


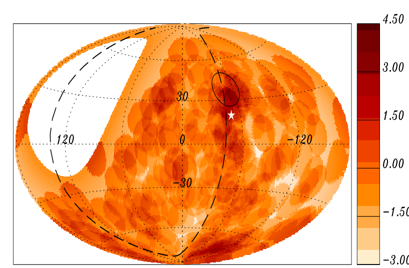


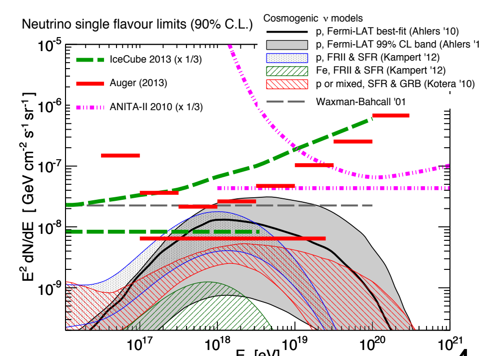




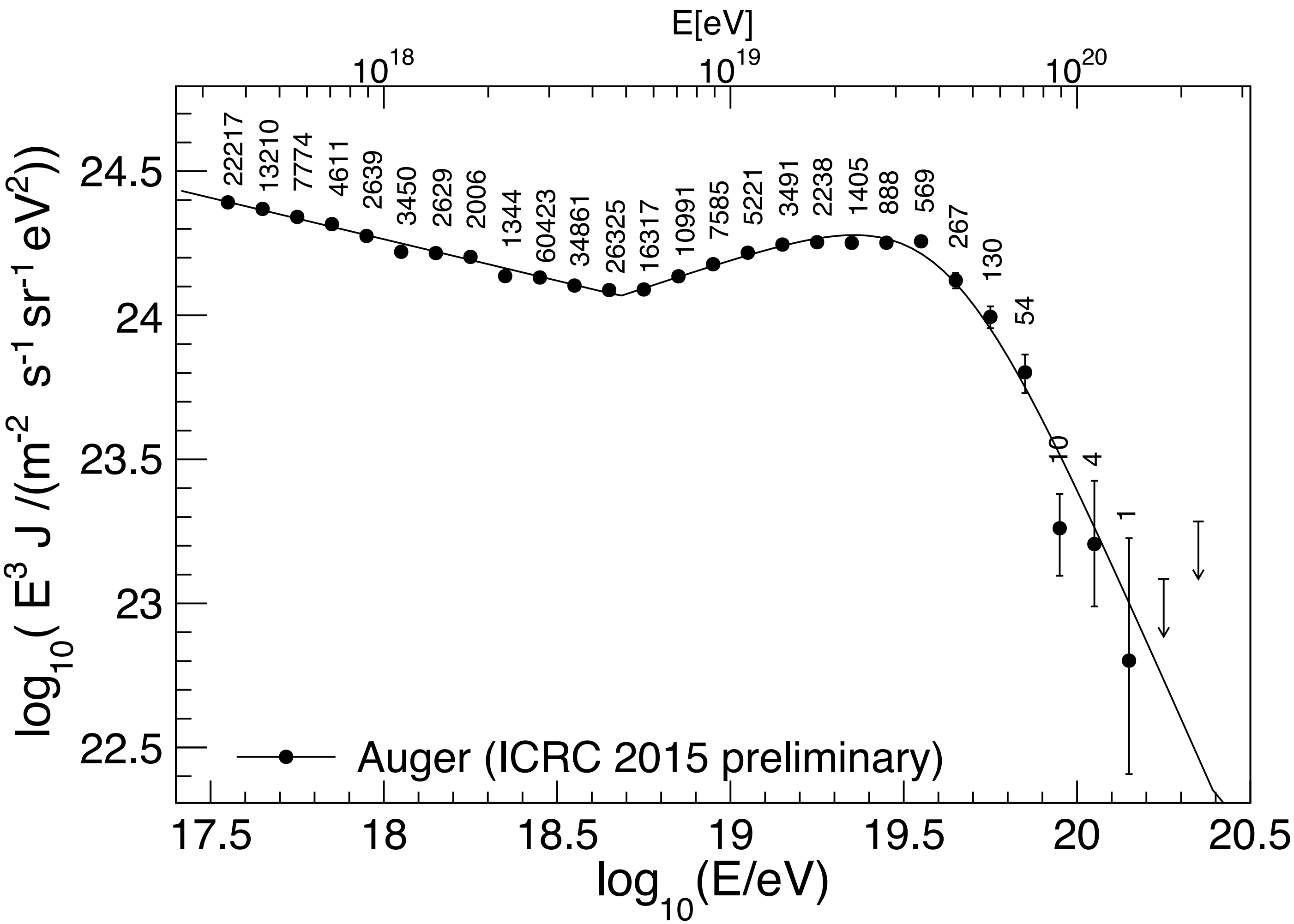


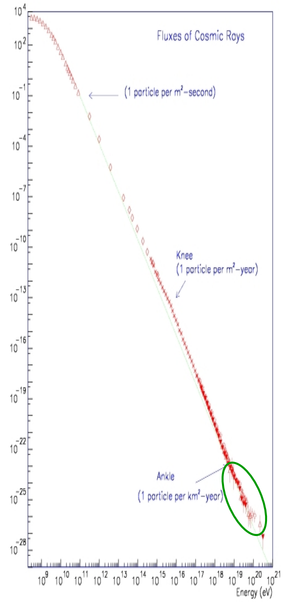






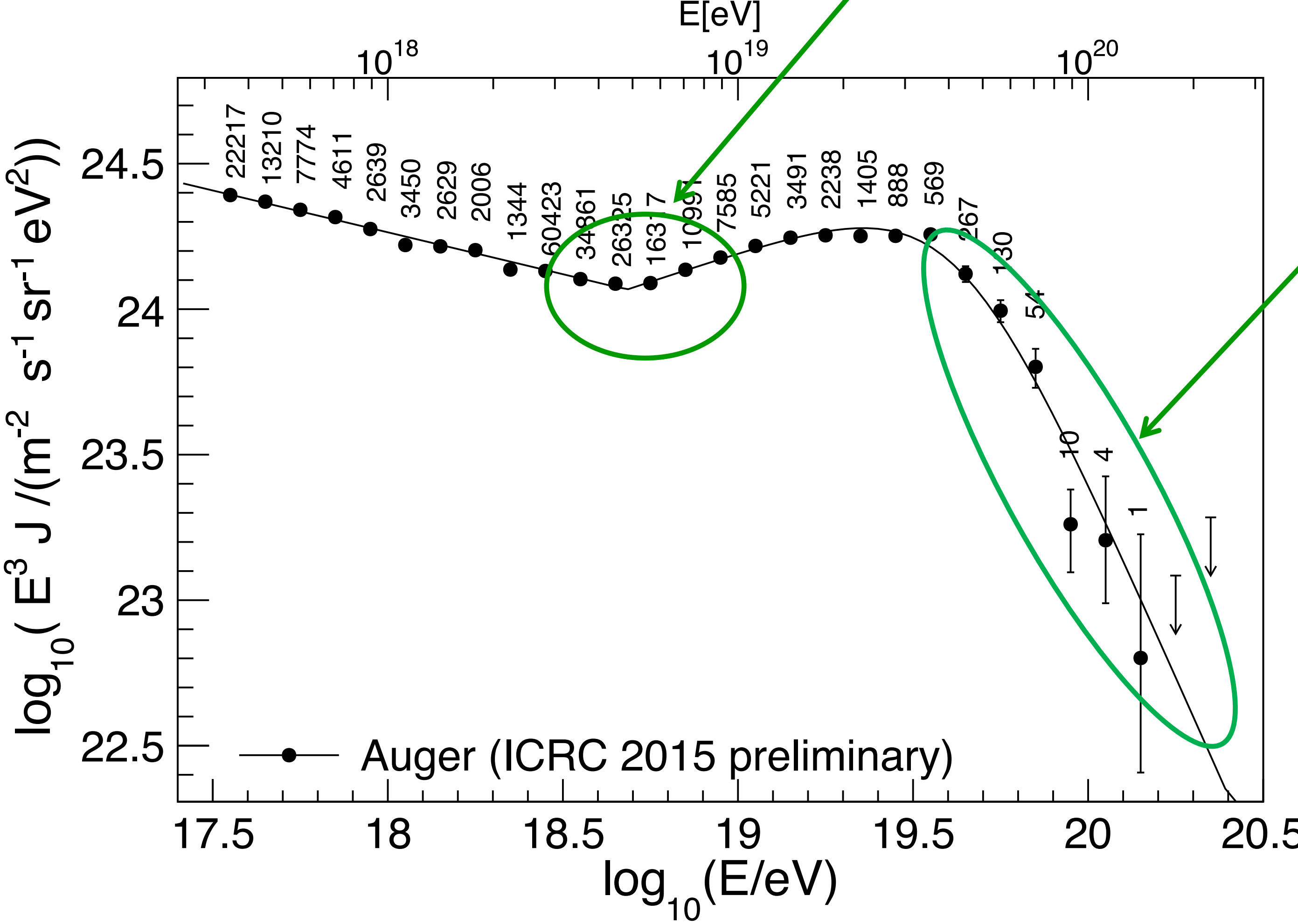
Energy spectrum

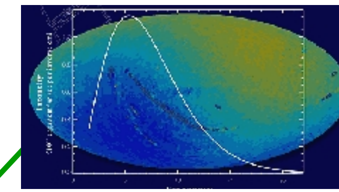


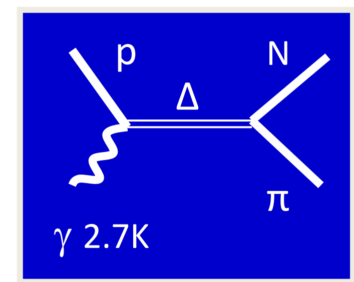


Energy spectrum

Ankle

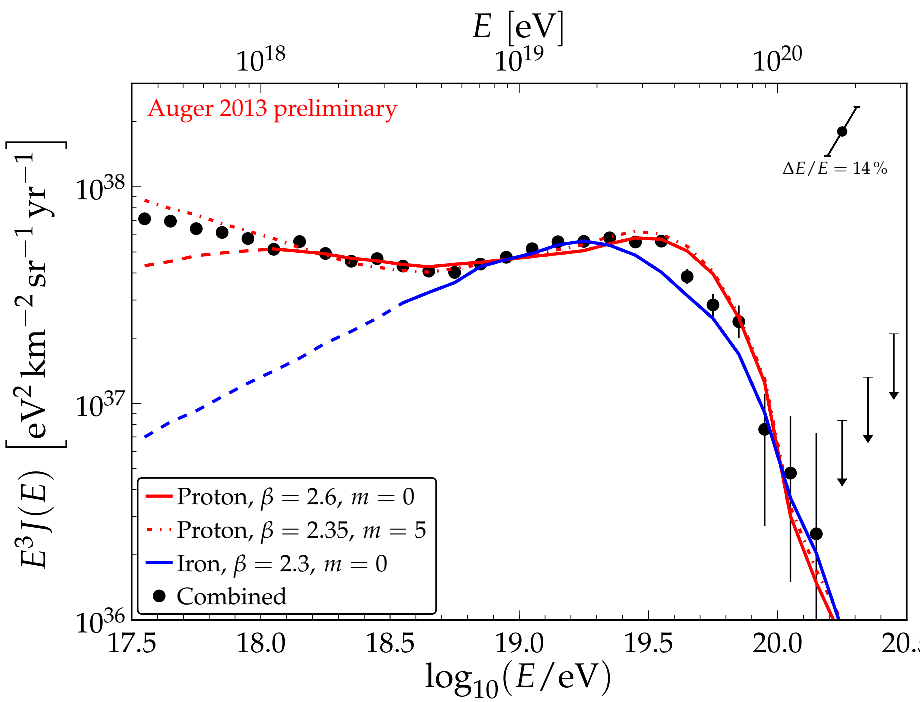


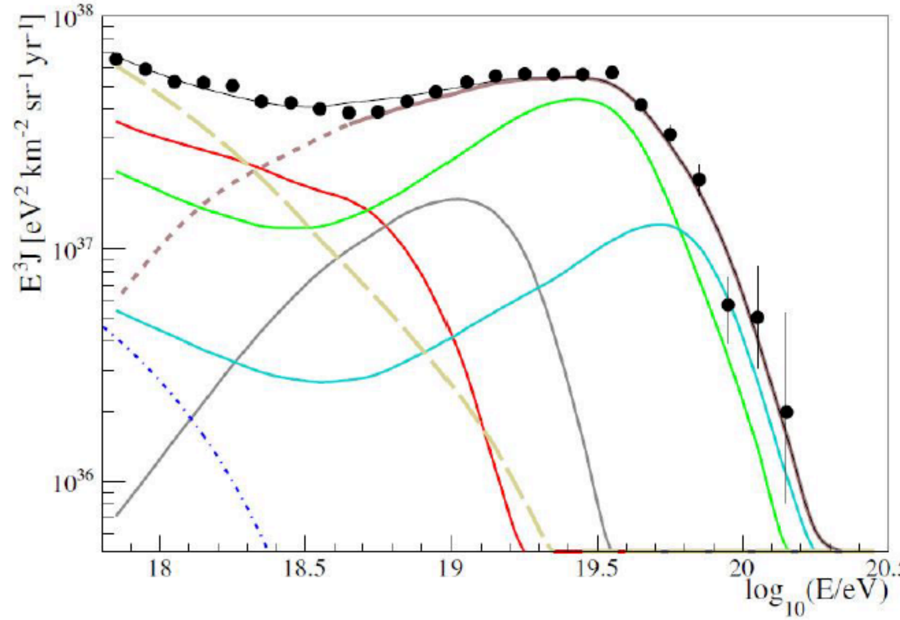




GZK like suppression !!!

GZK or the exhaustion of sources ???



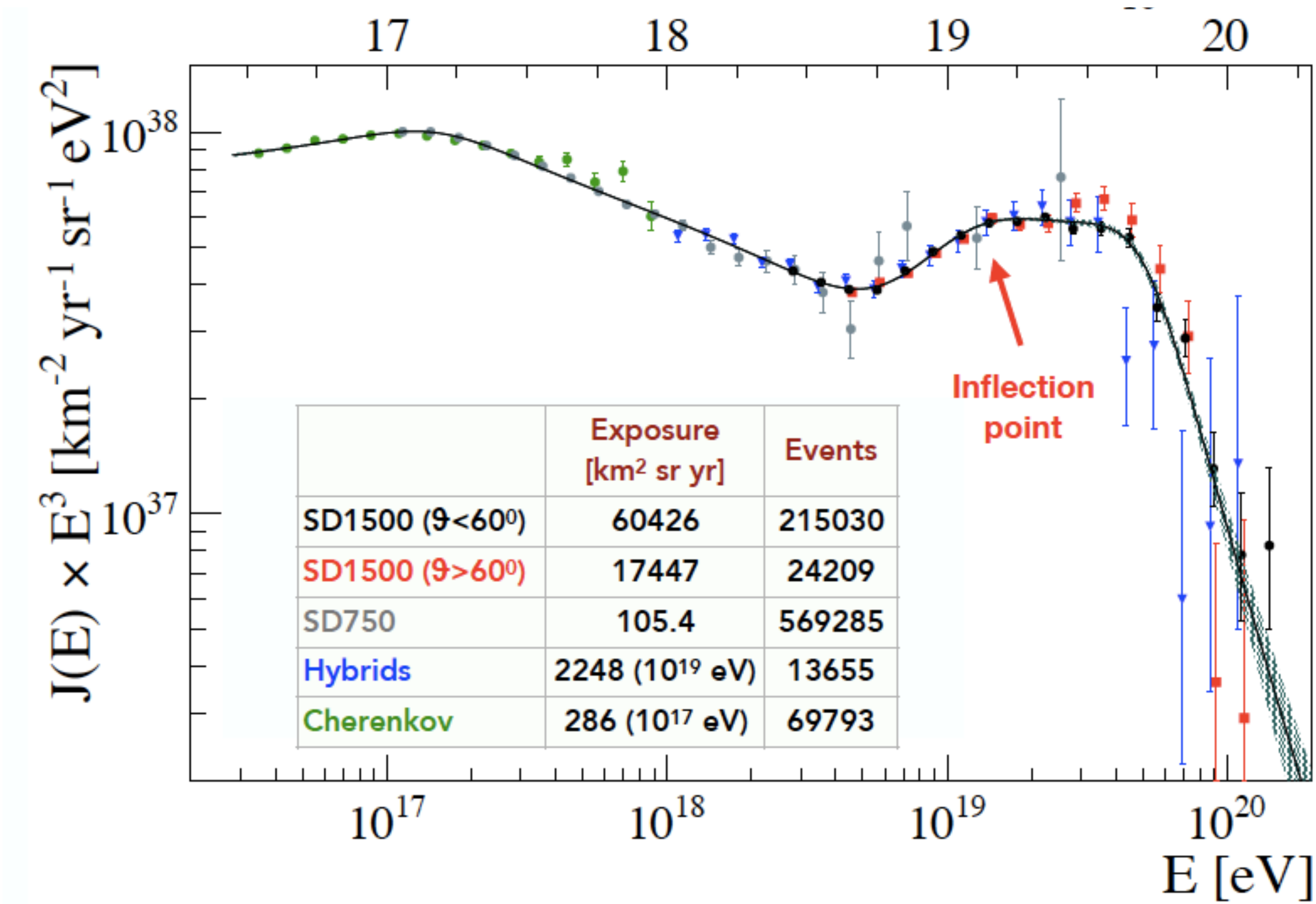


H^1 (red) , He^4 (grey), N^{14} (green), Si^{28} (cyan), Fe^{56} (blue)

Auger Collab., *JCAP*, **04**, 038 (2017).

Composition is the key to disentangle the two scenarios!

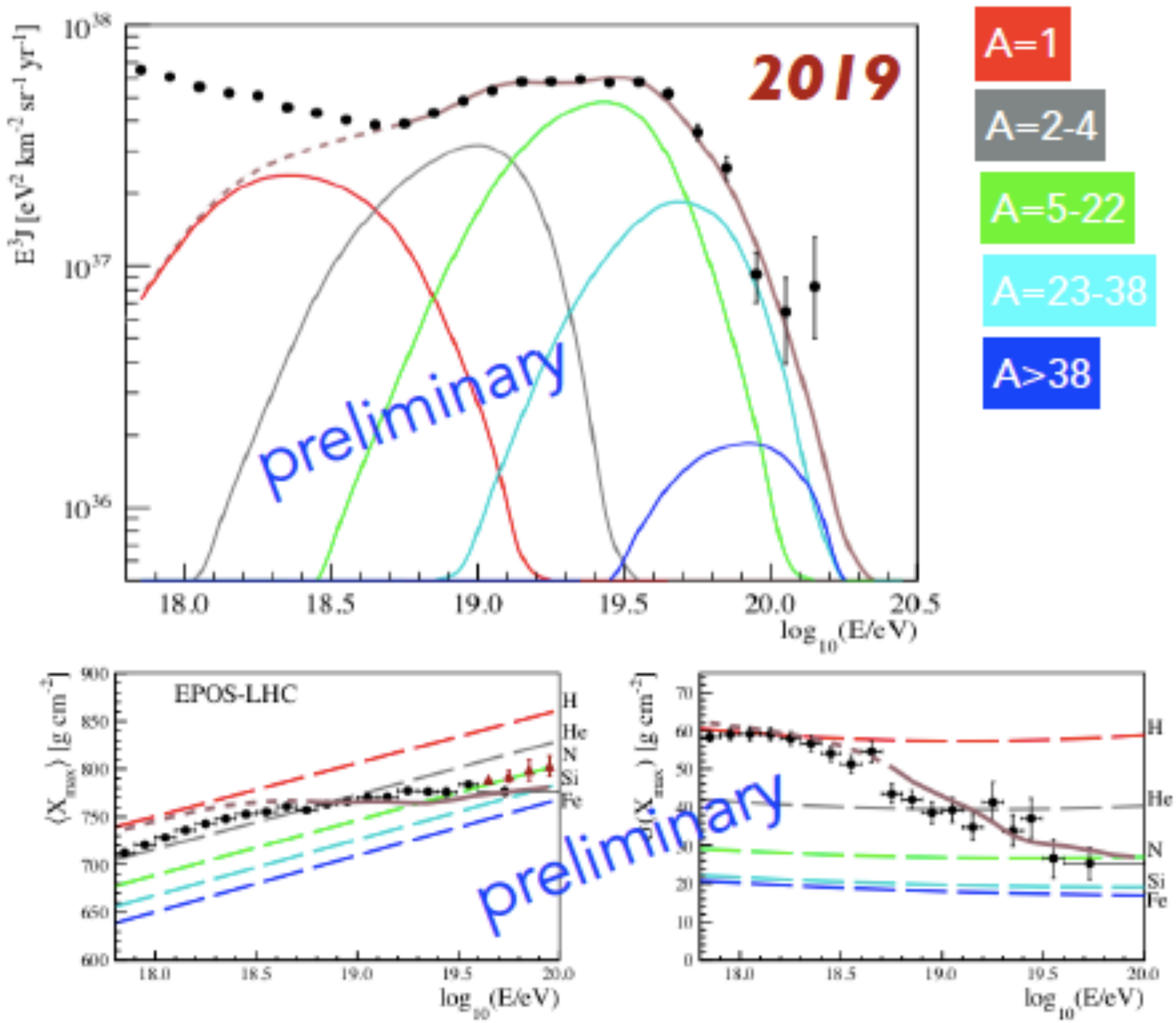
Auger 2019 – energy spectrum



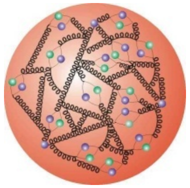
	Exposure [km^2 sr yr]	Events
SD1500 ($\vartheta<60^0$)	60426	215030
SD1500 ($\vartheta>60^0$)	17447	24209
SD750	105.4	569285
Hybrids	2248 (10^{19} eV)	13655
Cherenkov	286 (10^{17} eV)	69793

The presence of the inflection point strongly constrains proton single models …

Auger 2019 – composition fit - energy spectrum



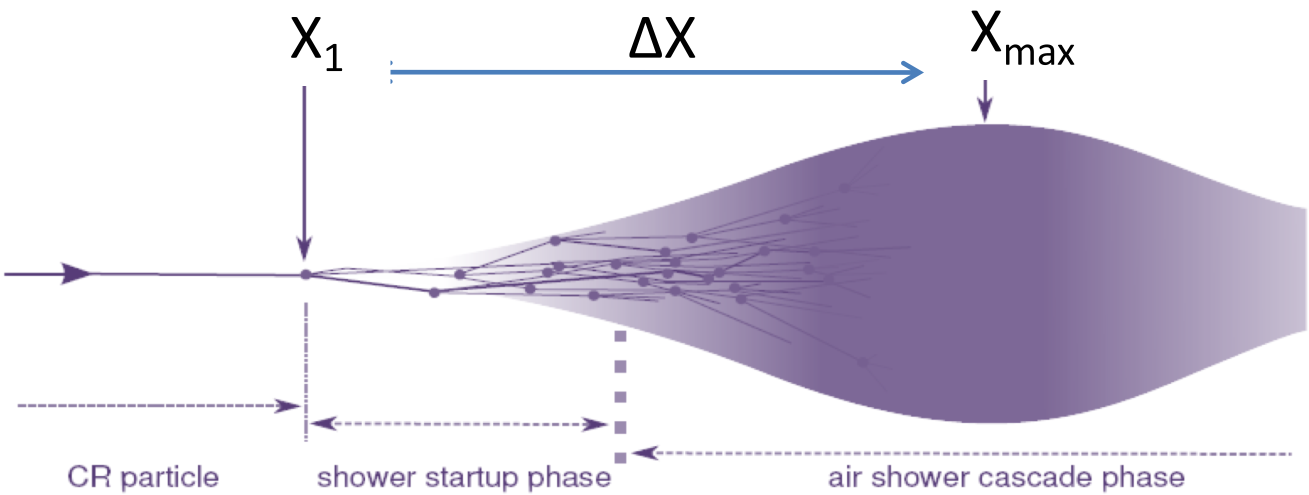
X_{max} and the “beam composition”



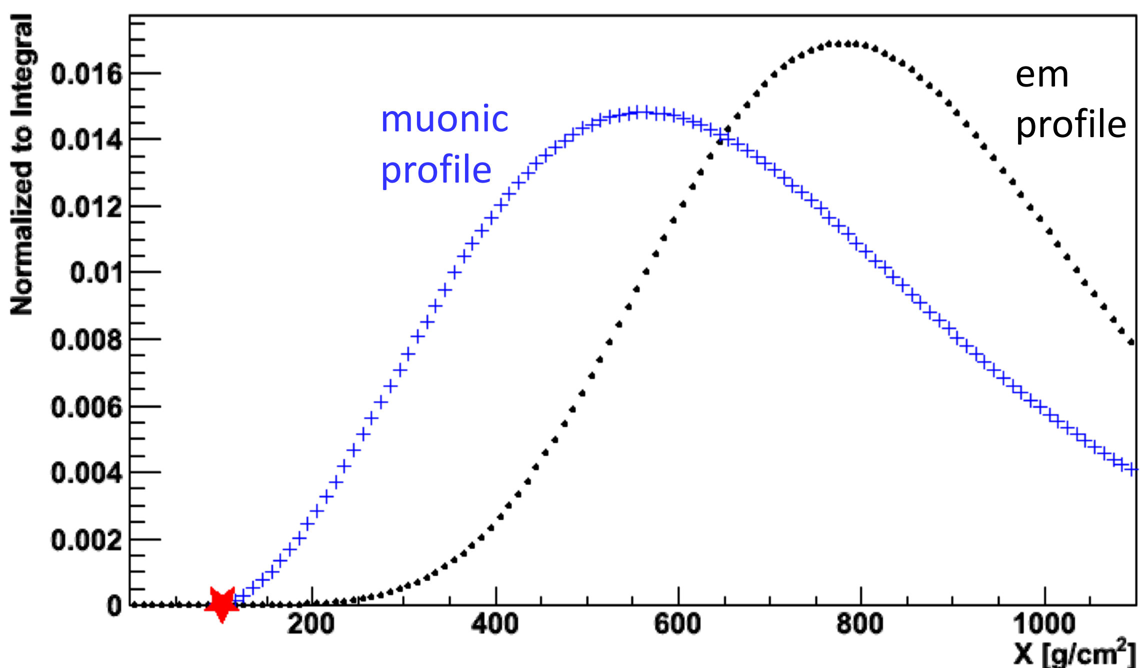
Proton

Nuclei (
Iron, …)

Shower development



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

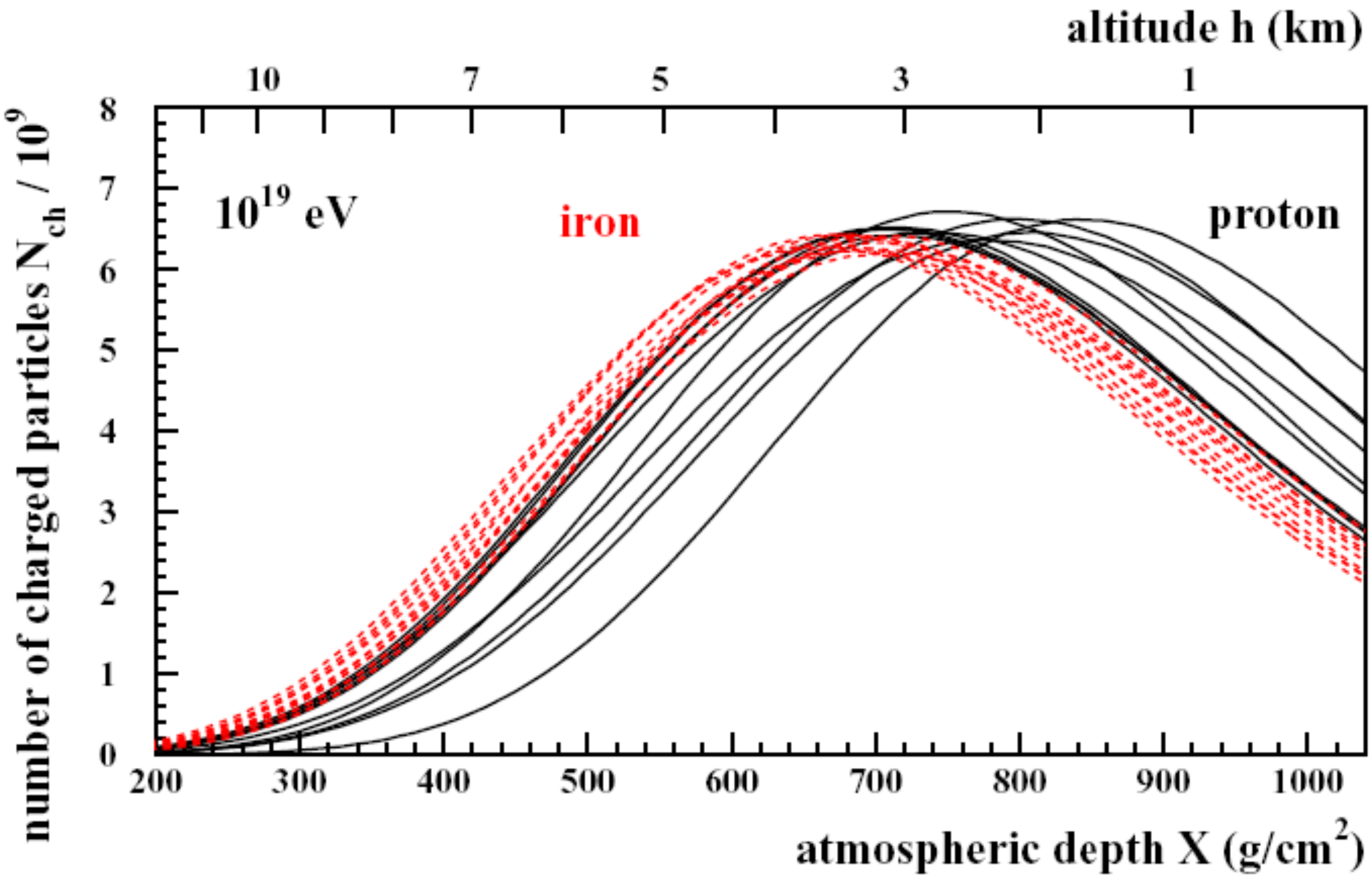


$E \propto Ne$

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

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

Fe/p longitudinal profiles



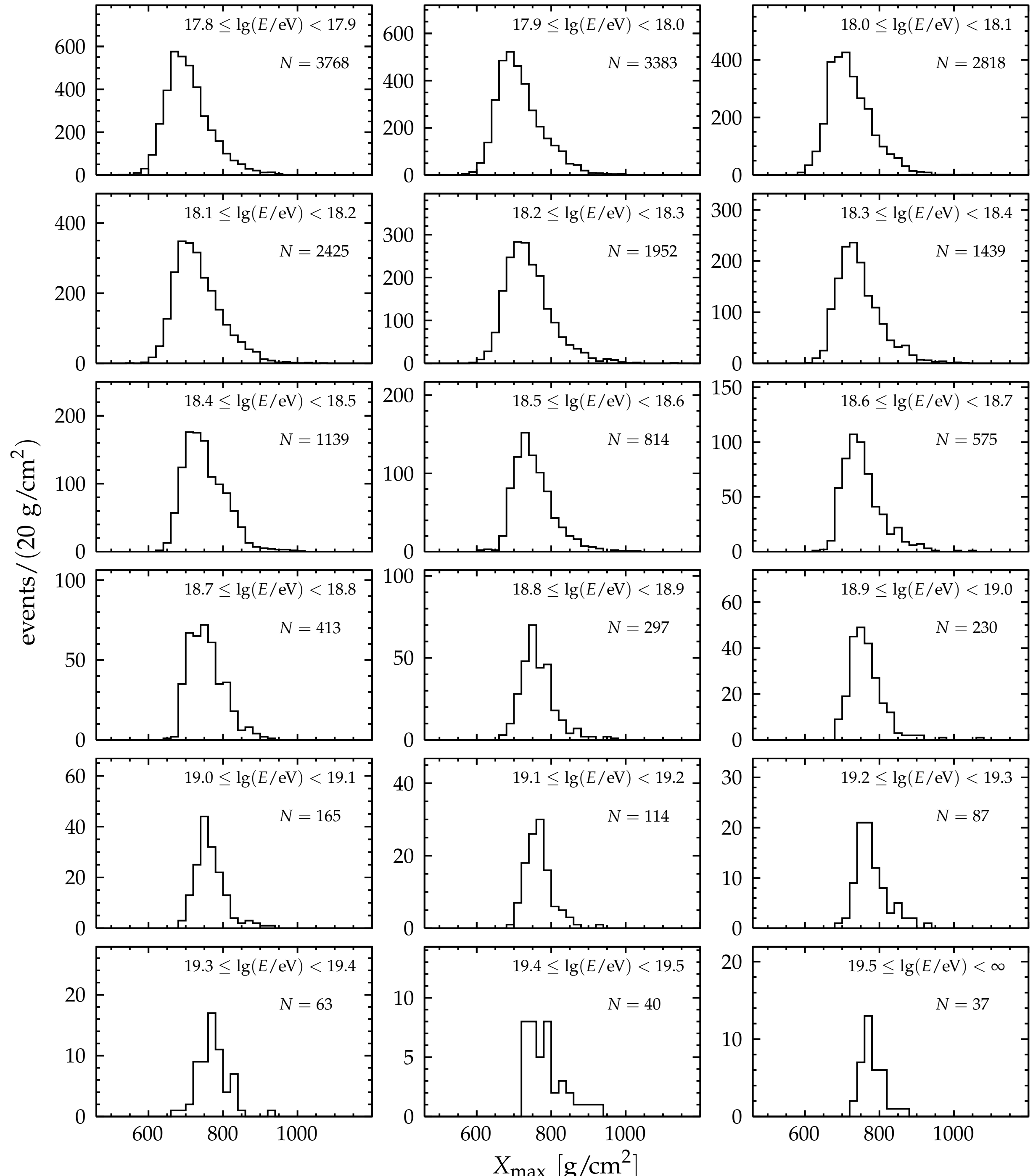
Iron ~ 56 nucl(E/56)

Smaller fluctuactions

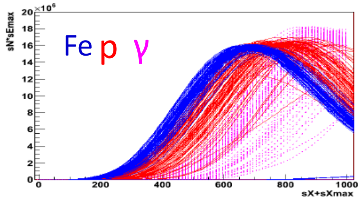
Smaller X_{max}

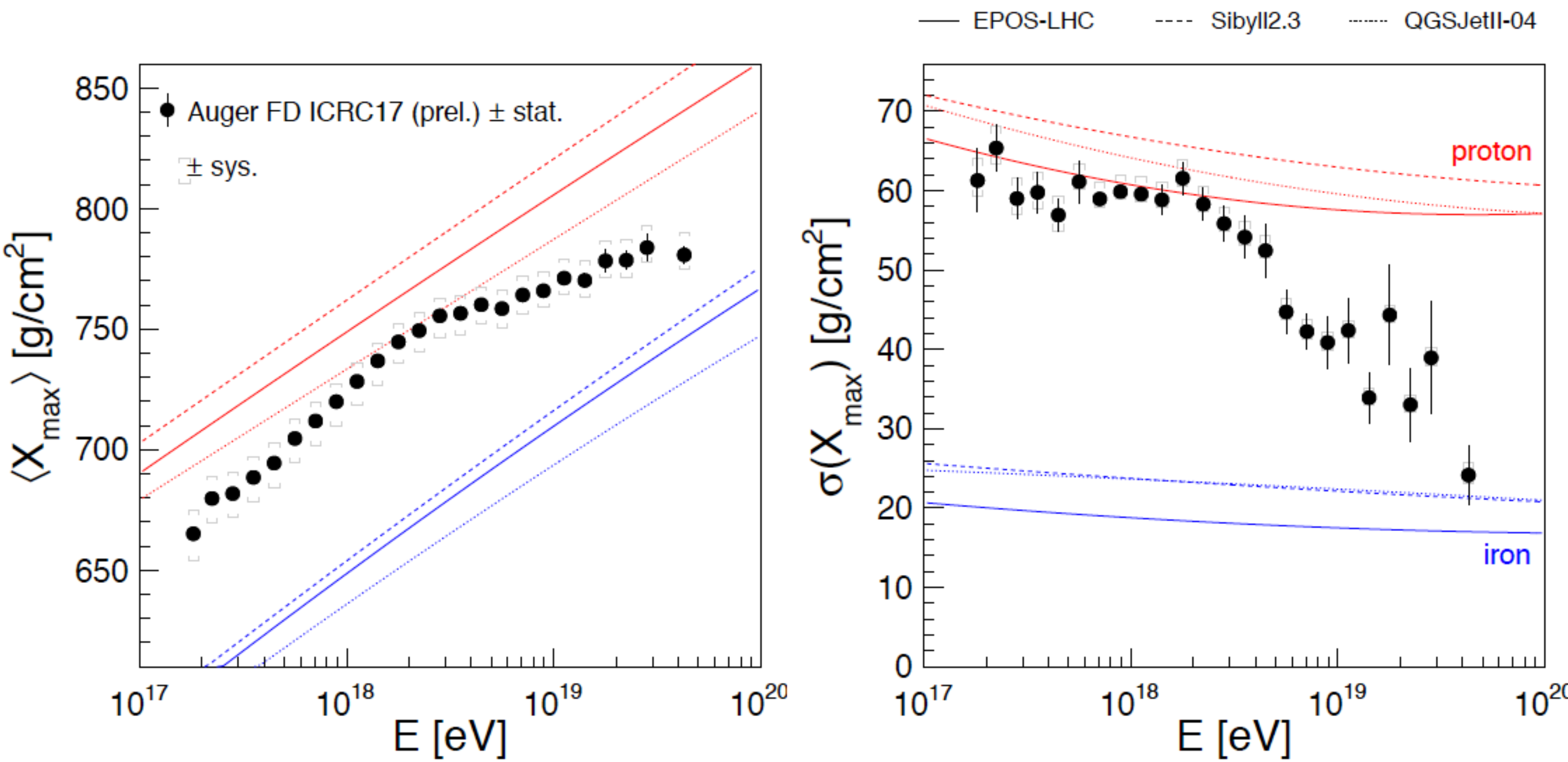
X_{max} distributions

As the energy increases the distributions become narrower !!!



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



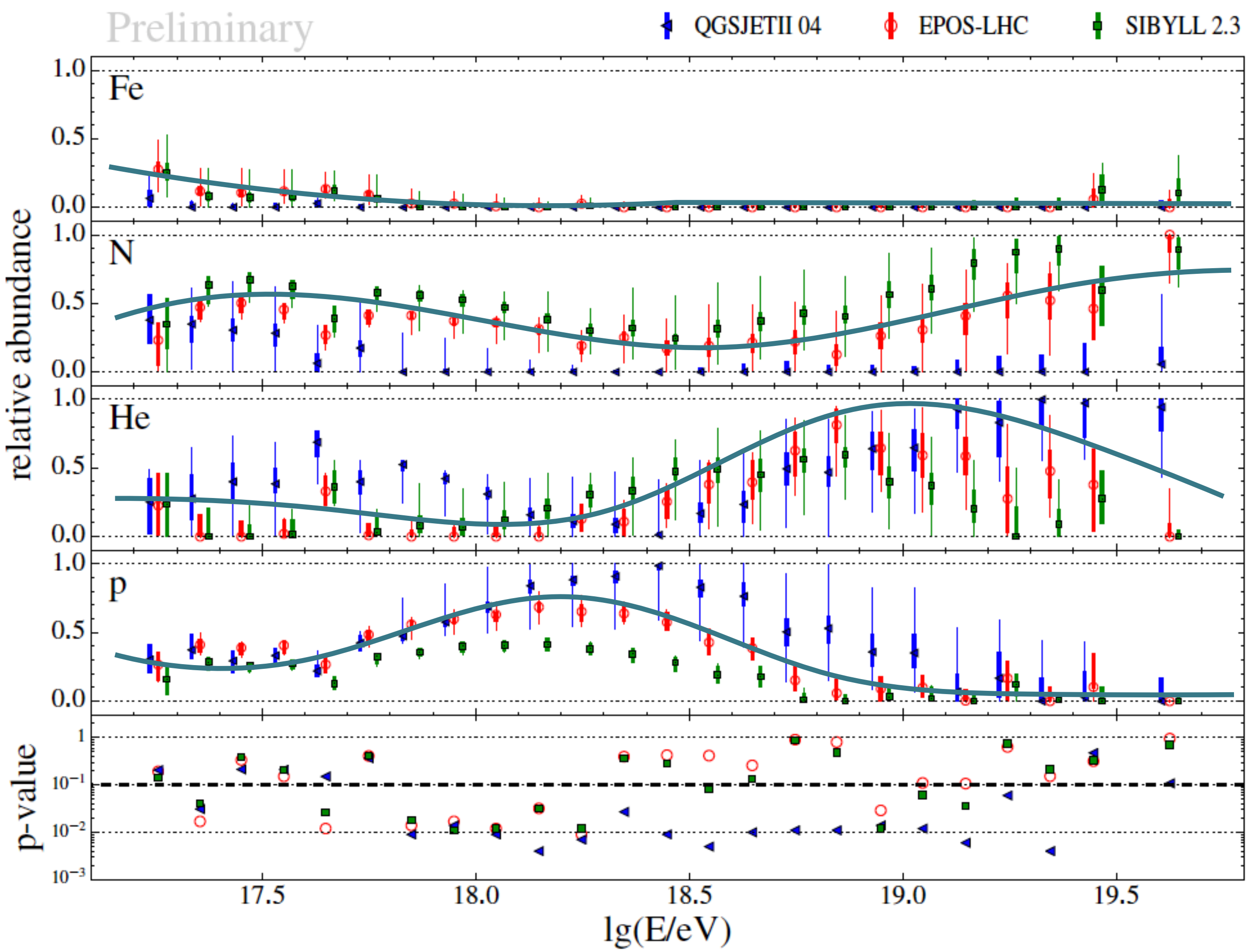


A clear change above 3 10^{18} eV

Mass composition

Auger, preliminary

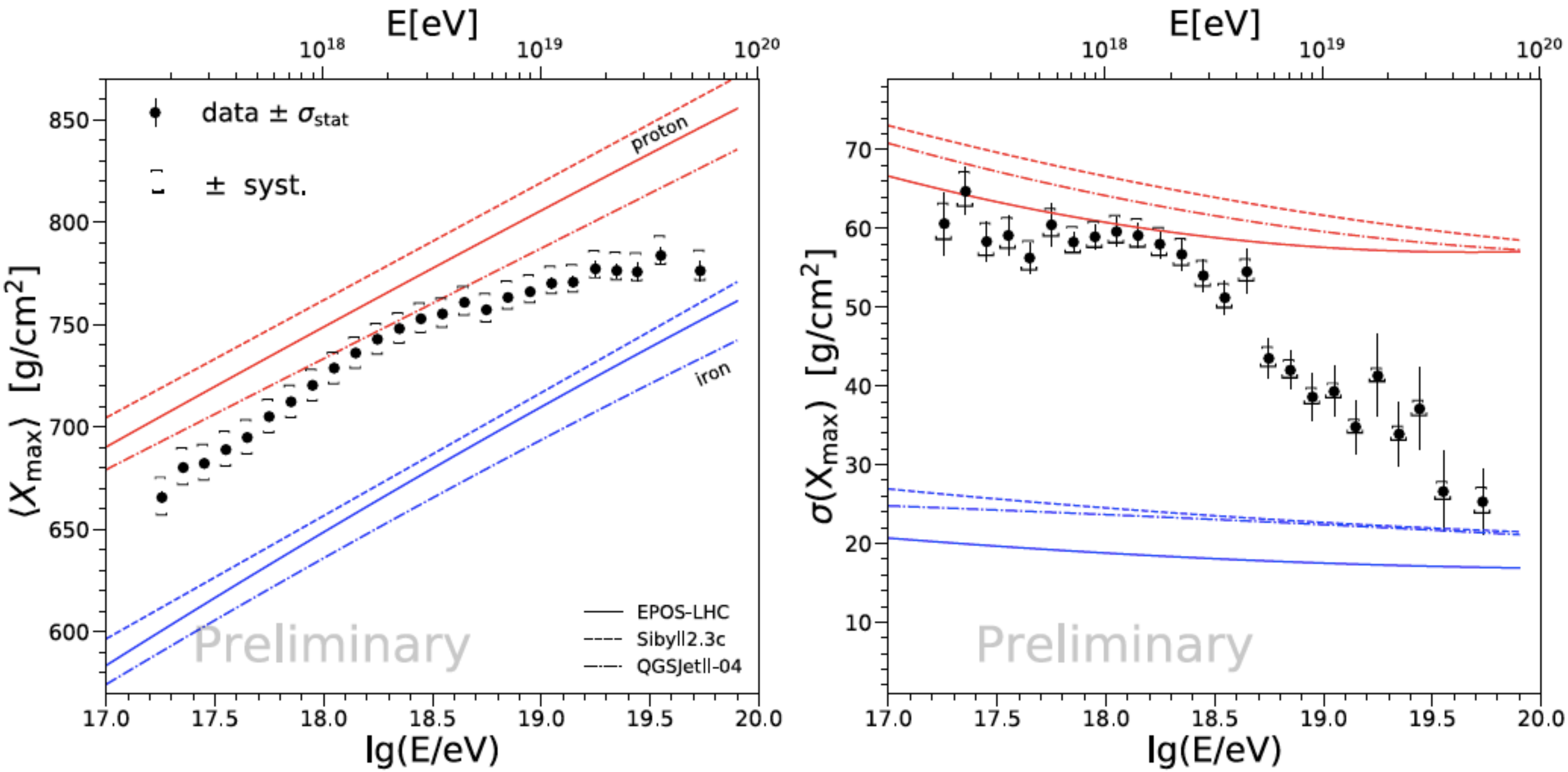
fluorescence telescope data (15% duty cycle)



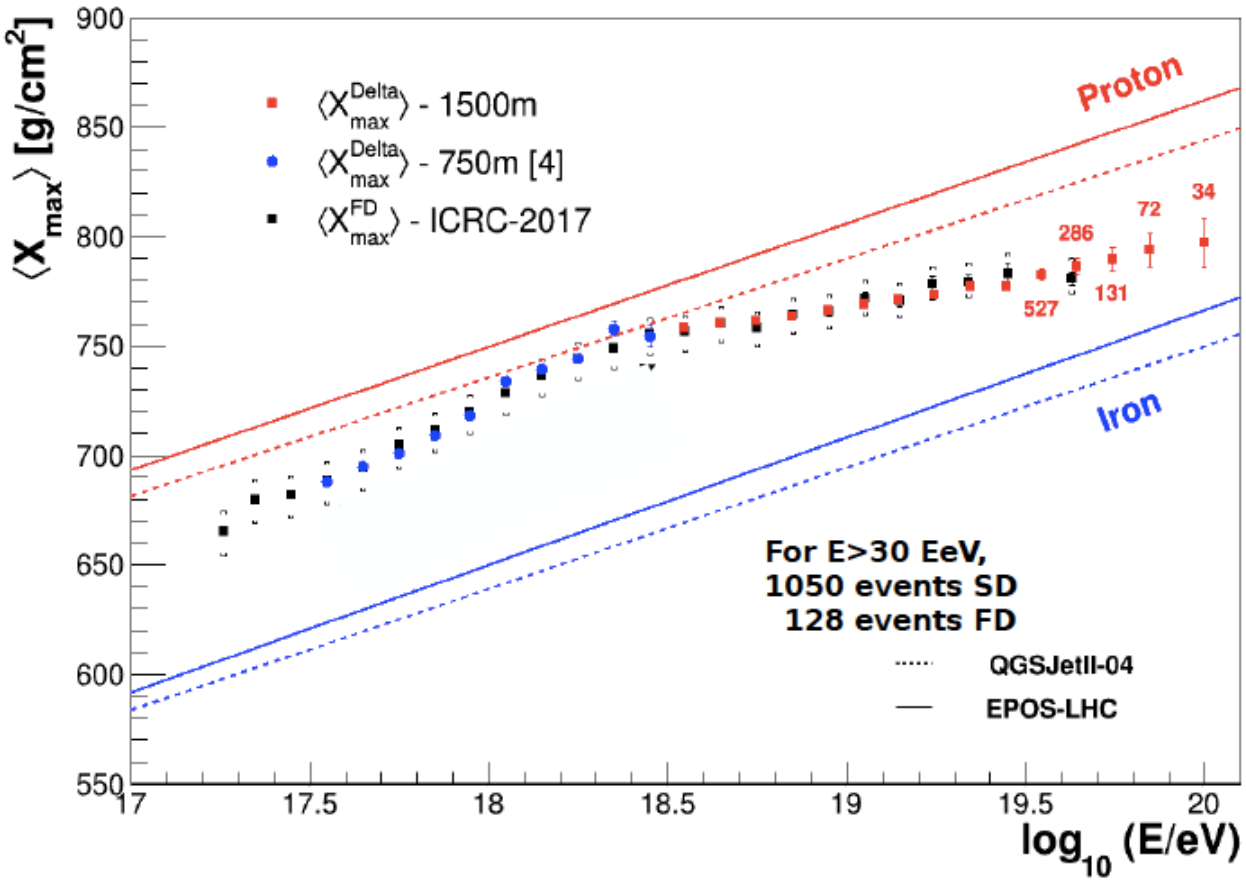
Pierre Auger Coll., PRD 90 (2014) 12, 122006; update at ICRC17 [1

Composition could be explained by disintegration of ~ C or Si nuclei, very hard energy spectrum at injection favored (~ E^{-1}) ...

Auger 2019 – <Xmax> data



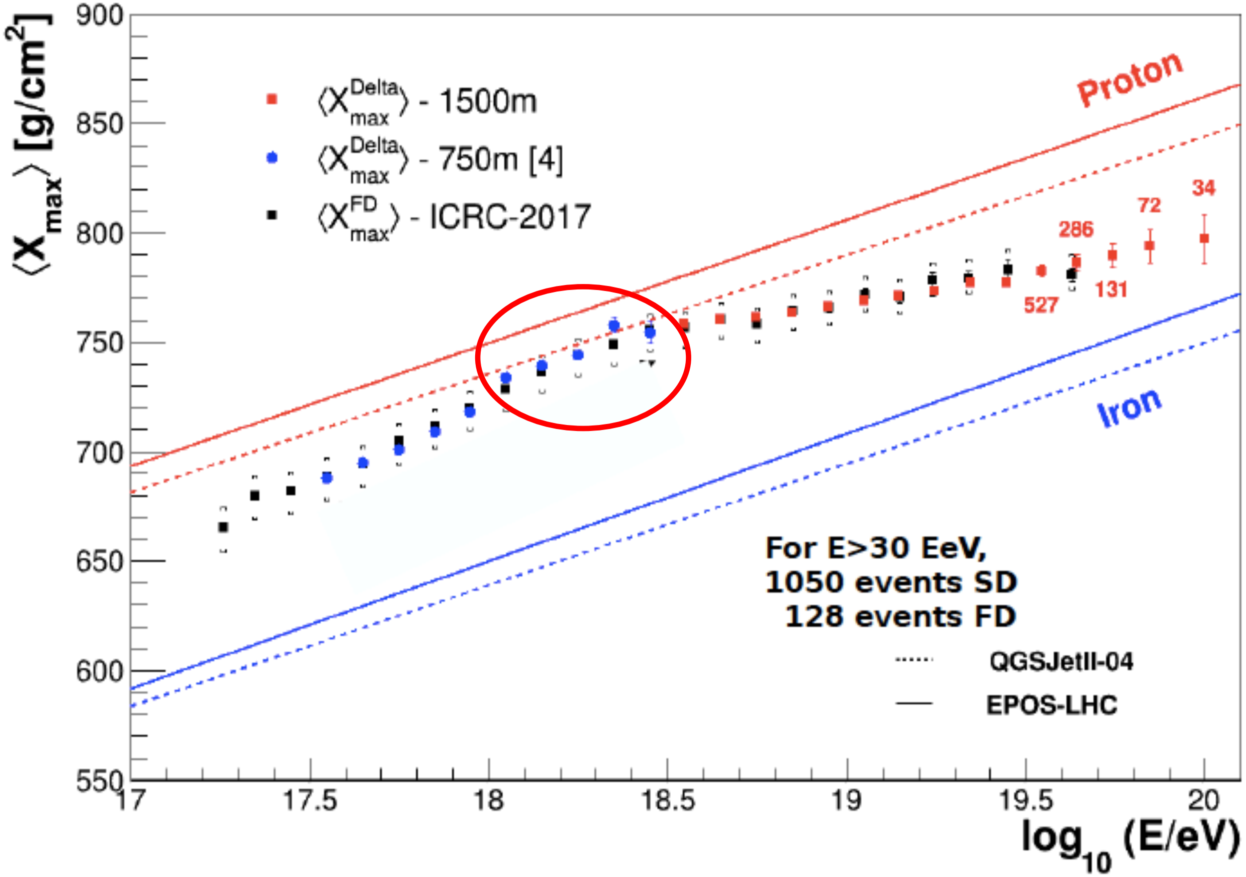
Auger 2019 – <Xmax> FD and SD data



$\log_{10}$(E/eV)	SD
18.5-18.6	45872
18.6-18.7	27783
18.7-18.8	17011
18.8-18.9	11631
18.9-19.0	7960
19.0-19.1	5489
19.1-19.2	3582
19.2-19.3	2290
19.3-19.4	1473
19.4-19.5	864
19.5-19.6	527
19.6-19.7	286
19.7-19.8	131
19.8-19.9	72
>19.9	34
Total	125005

Surface detector data:
only average composition

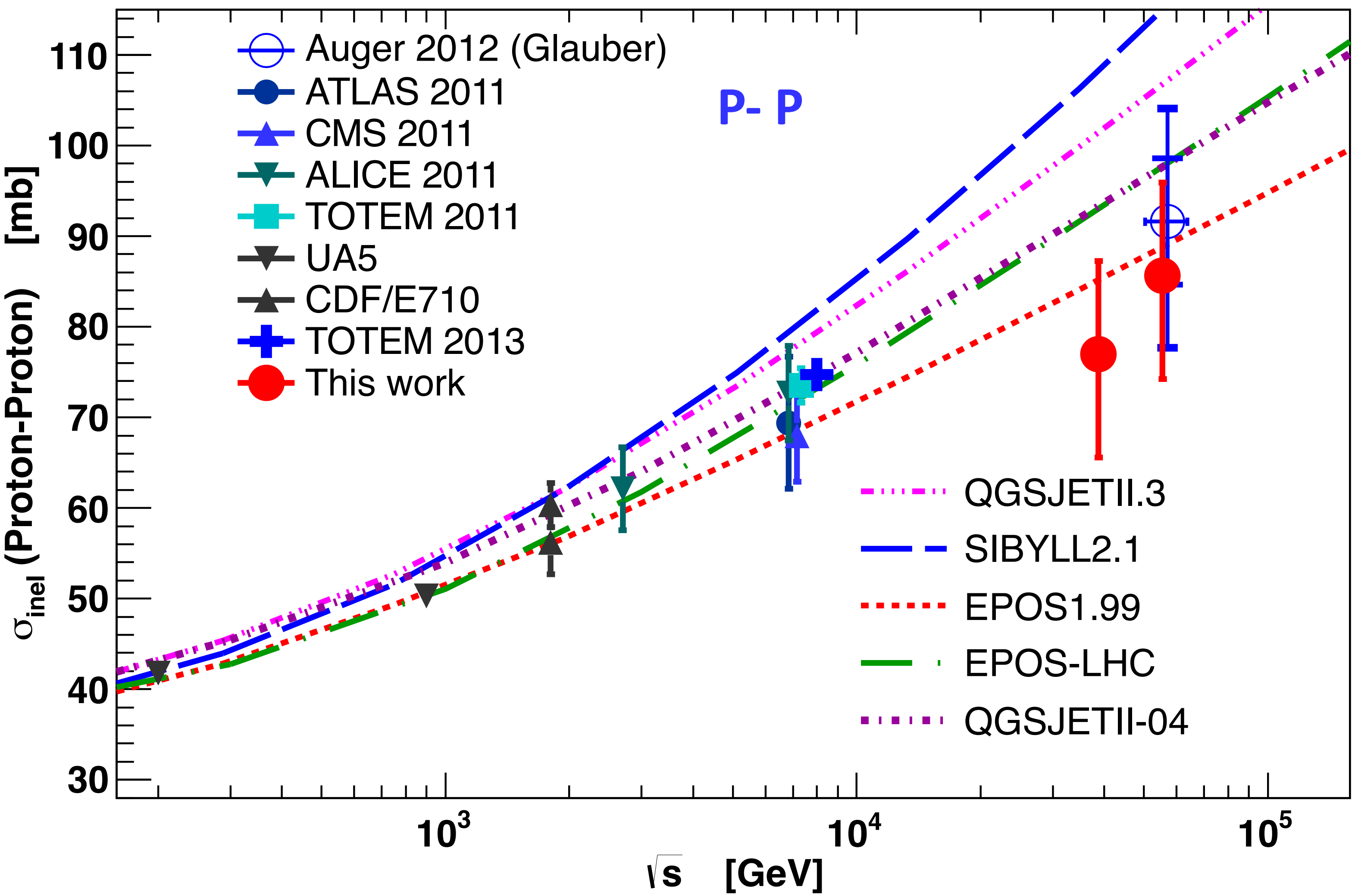
Auger 2019 – <Xmax> FD and SD data



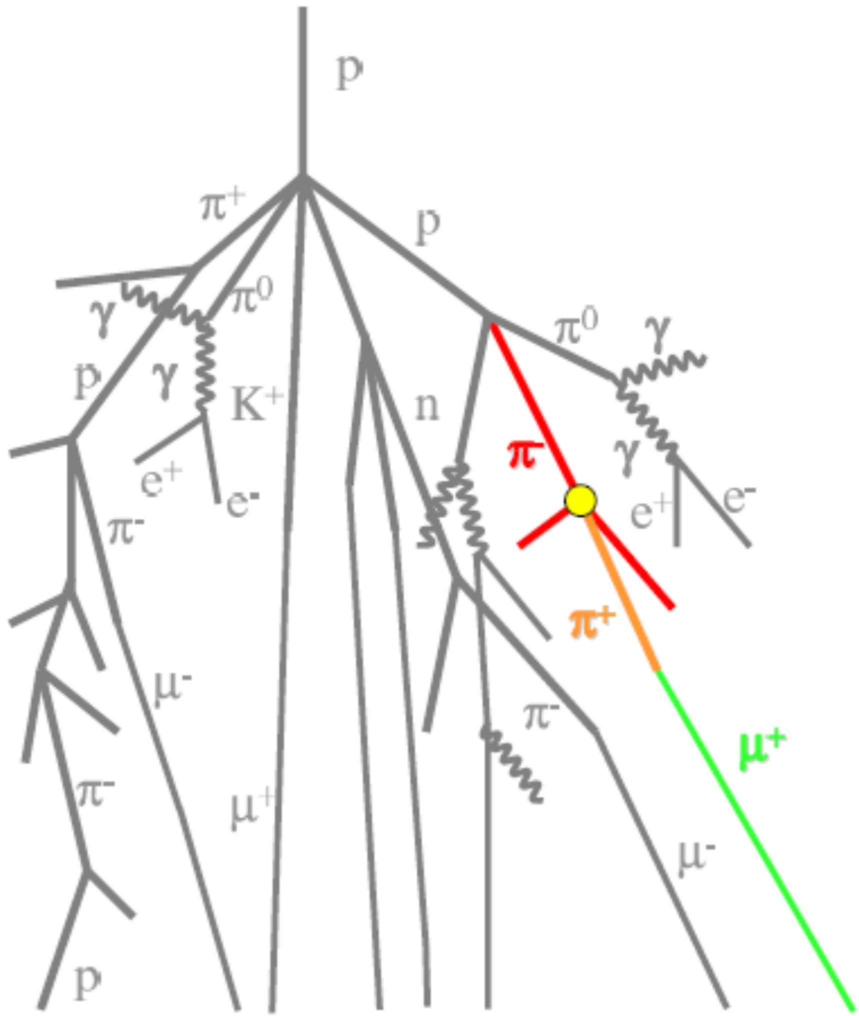
$\log_{10}$(E/eV)	SD
18.5-18.6	45872
18.6-18.7	27783
18.7-18.8	17011
18.8-18.9	11631
18.9-19.0	7960
19.0-19.1	5489
19.1-19.2	3582
19.2-19.3	2290
19.3-19.4	1473
19.4-19.5	864
19.5-19.6	527
19.6-19.7	286
19.7-19.8	131
19.8-19.9	72
>19.9	34
Total	125005

Surface detector data:
only average composition

Proton cross-section

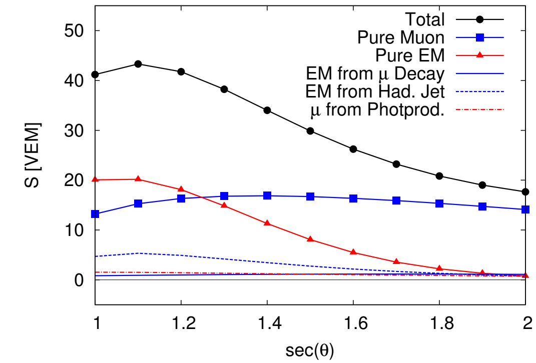


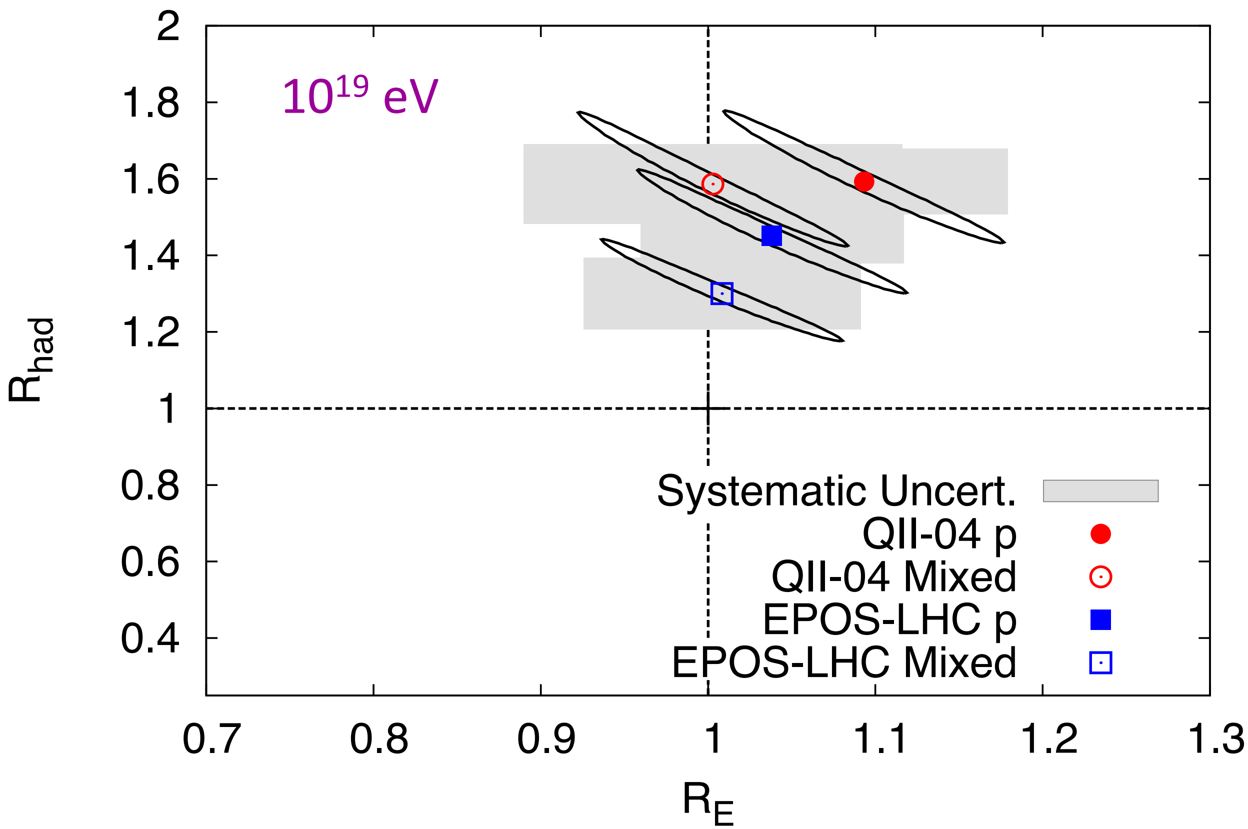
The “number of μ_s



The “number of μ_s (“vertical” showers)

$$S_{\rm resc}(R_E, R_{\rm had})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\rm had}\, R_E^{\alpha}\, S_{{\rm had},i,j}$$

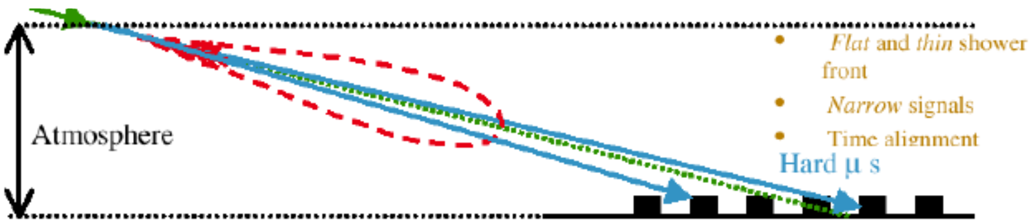


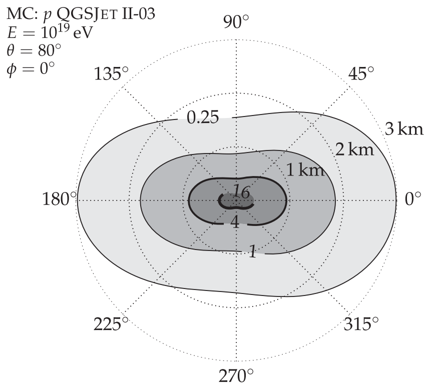


Model	R_E	$R_{\rm had}$
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

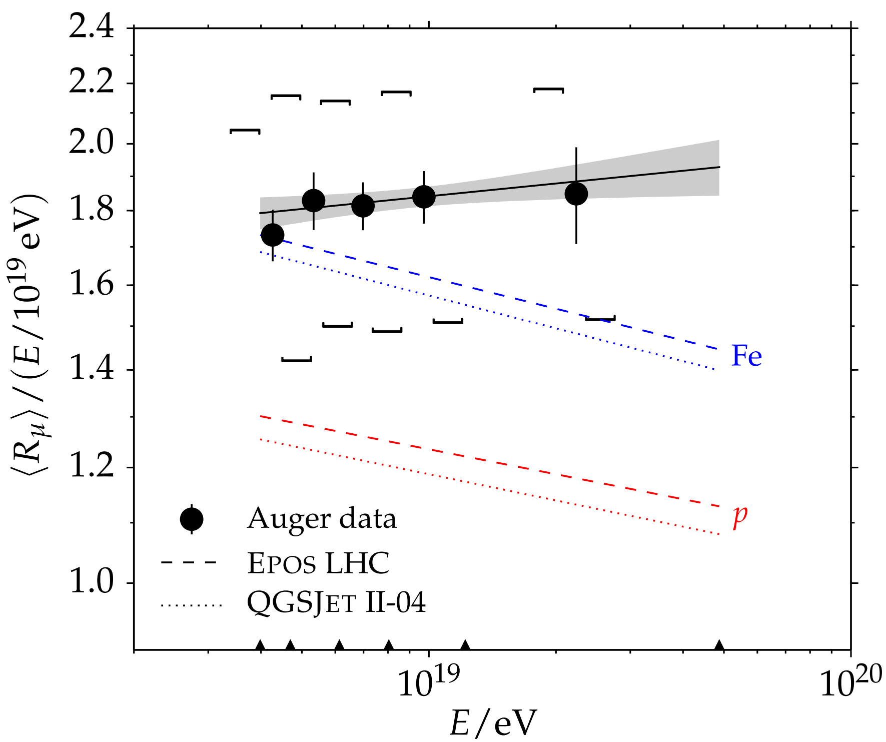
Hadronic signal in data
is significantly larger

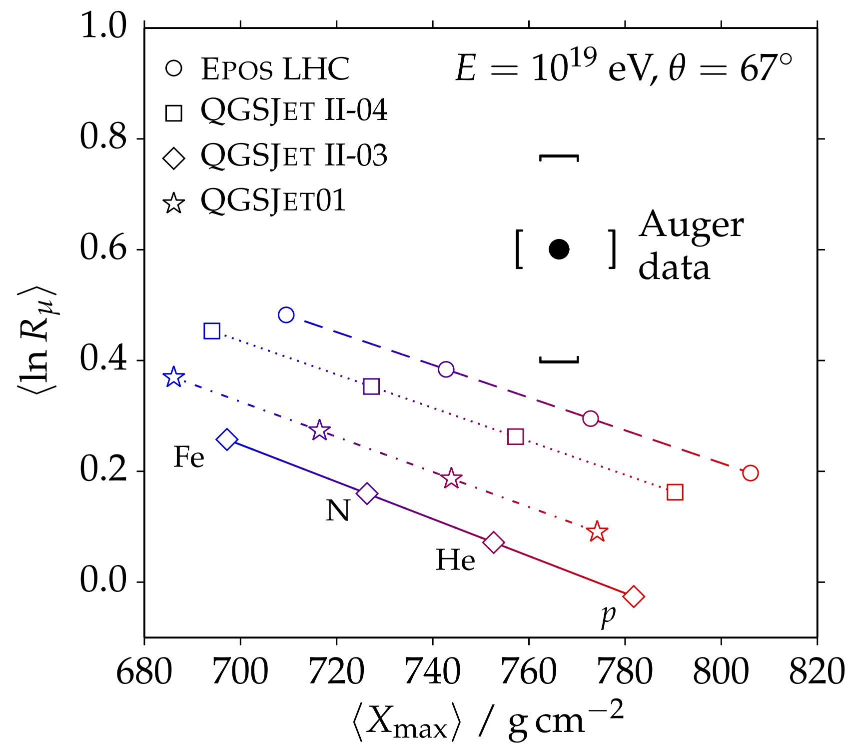
The “number of μs (inclined showers)





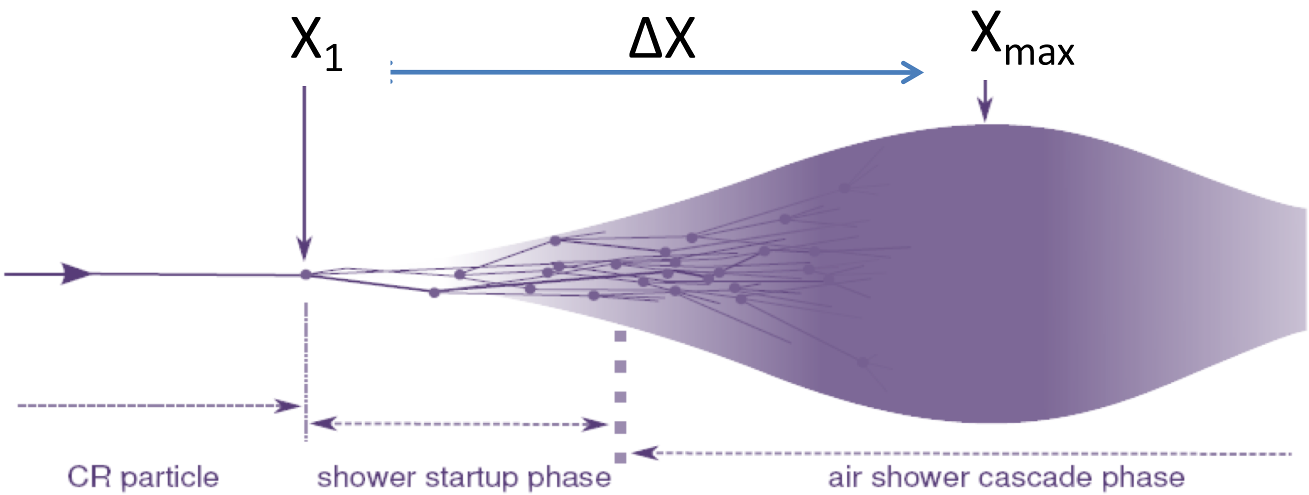
$$R_\mu = N_\mu^{true} / N_\mu^{map}(\theta, \phi) = N_{19}^{true}$$



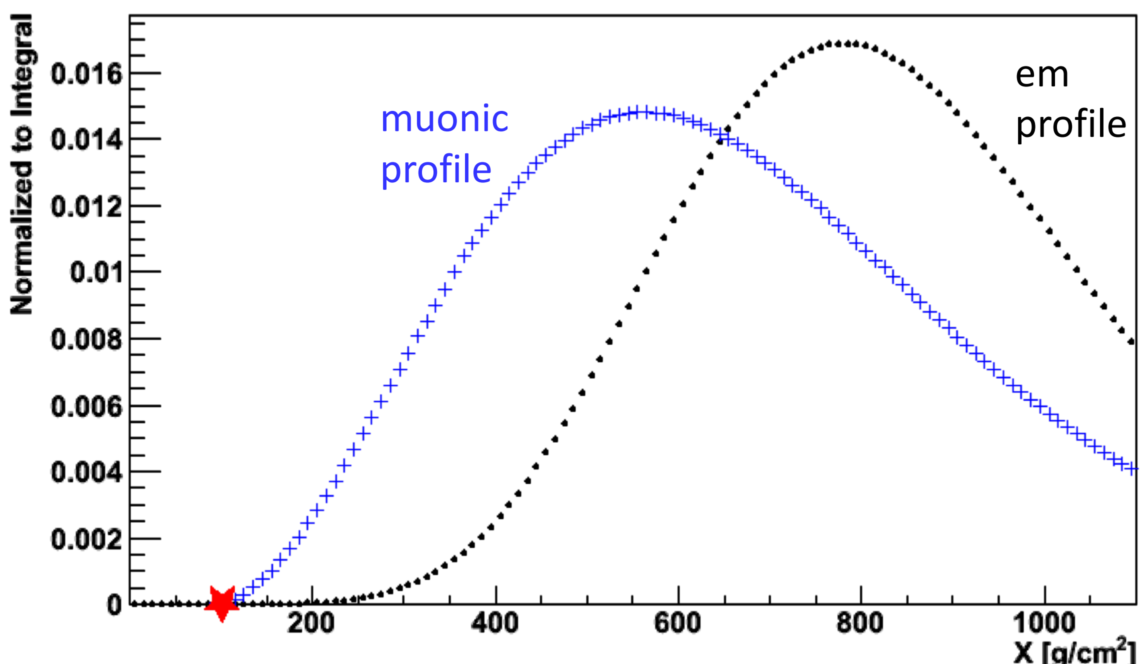


Tension between data and all hadronic interaction models !!!

Shower development



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



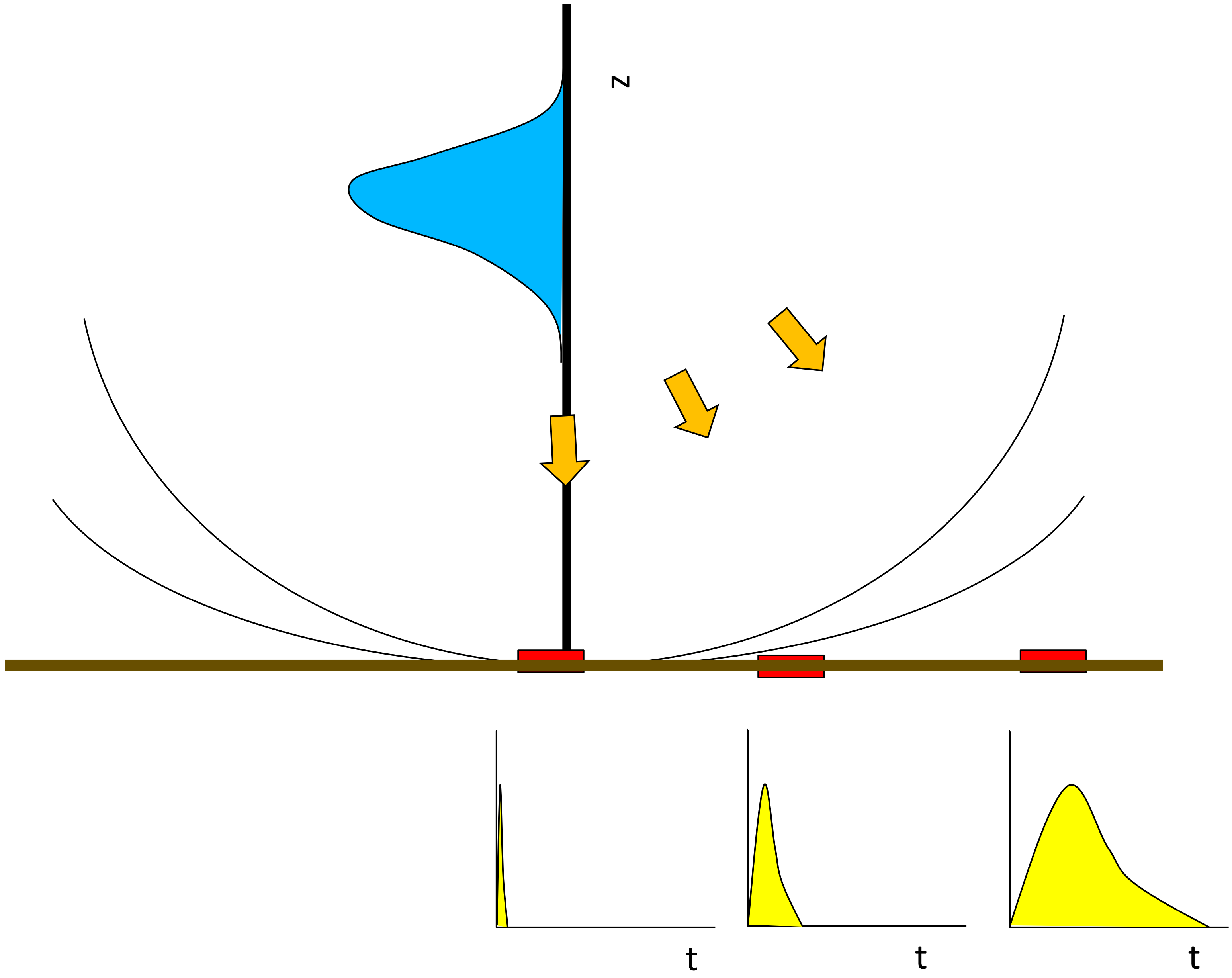
$E \propto Ne$

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

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

Muon Production Depth (MPD)

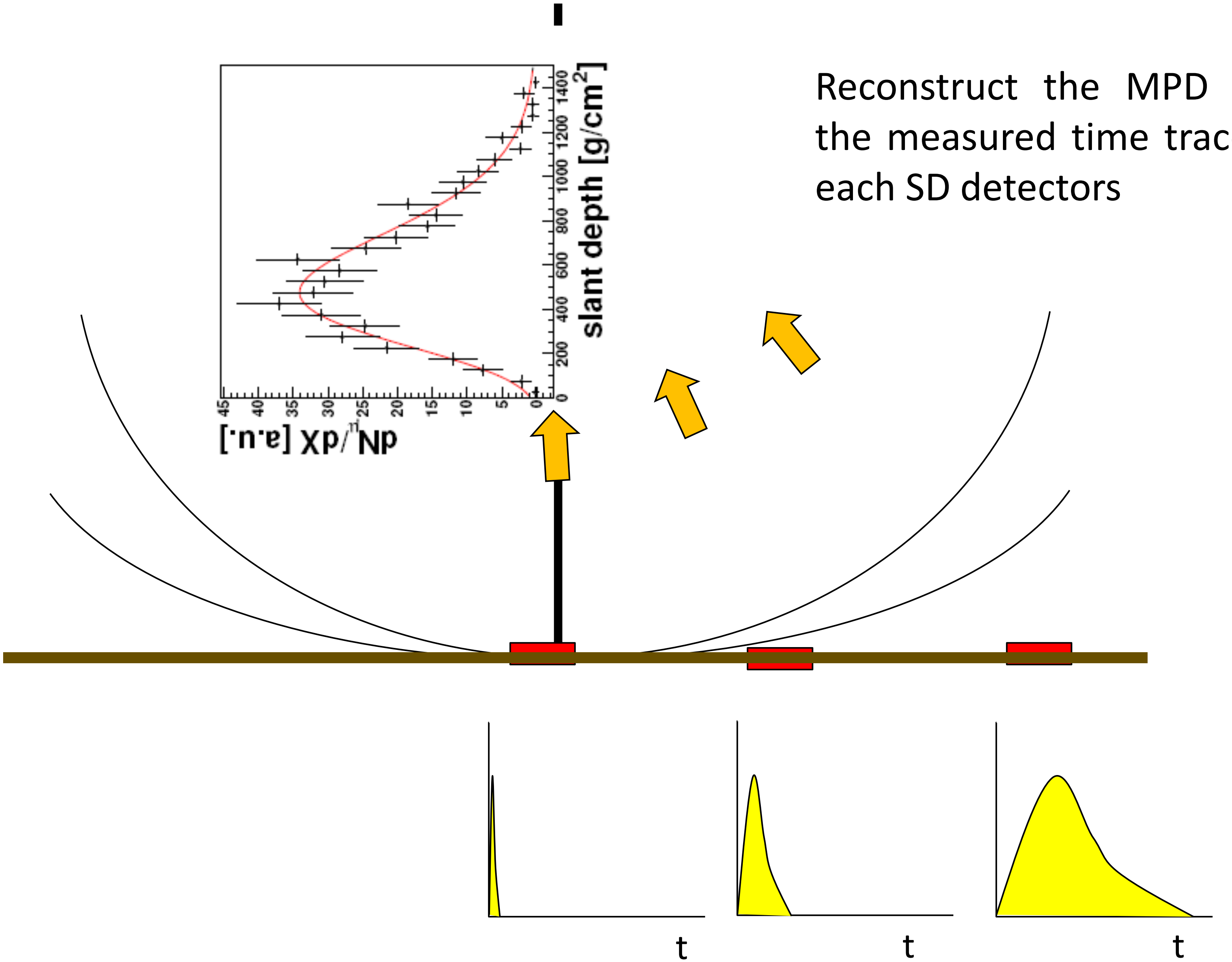
L. Cazon, R.A. Vazquez, A.A. Watson, E. Zas, Astropart.Phys.**21**:71-86 (2004)
L.Cazon, PhD Thesis (USC 2005)



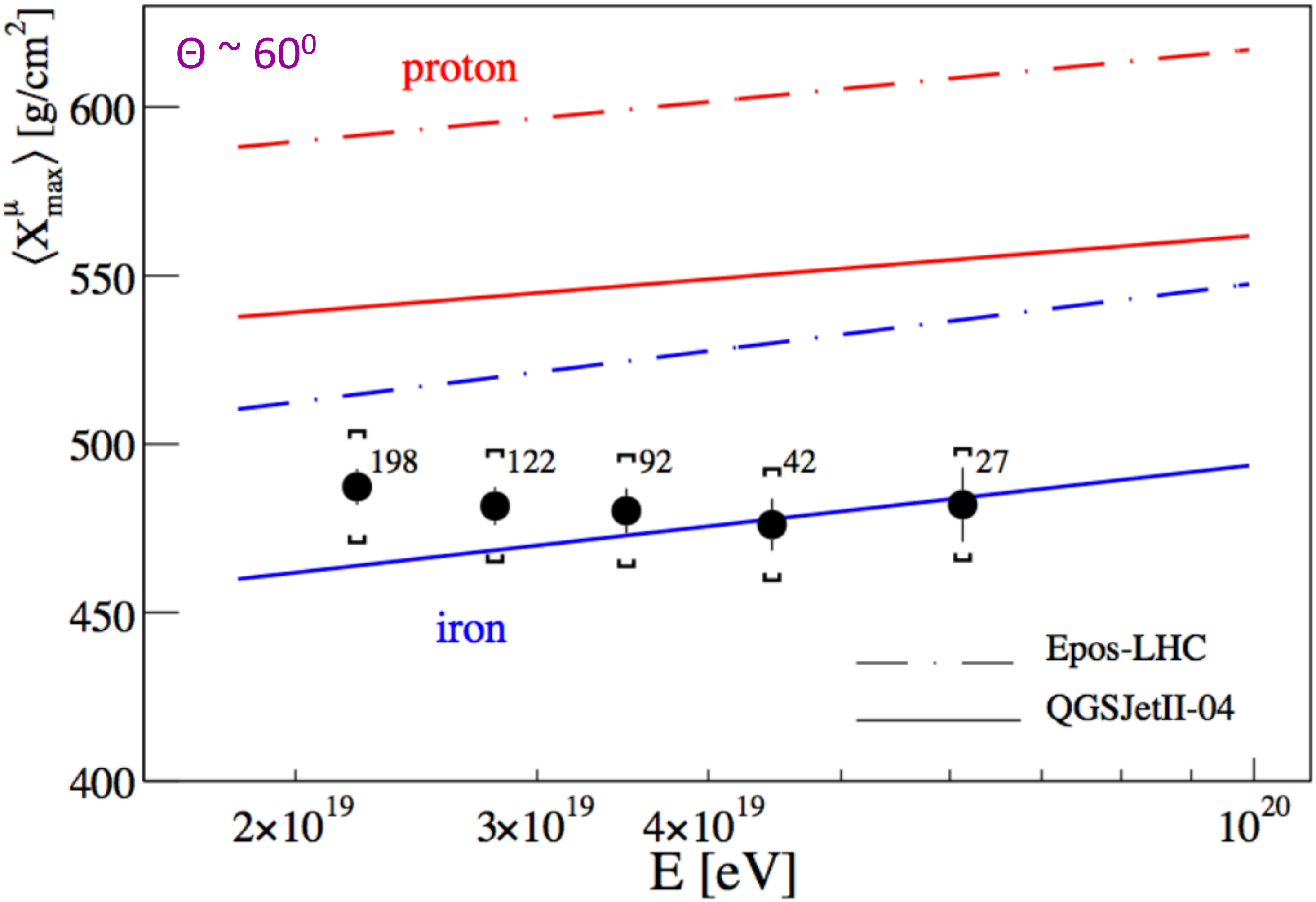
Muon Production Depth (MPD)

L. Cazon, R.A. Vazquez, A.A. Watson, E. Zas,
Astropart.Phys.**21**:71-86 (2004)
L.Cazon, PhD Thesis (USC 2005)

Reconstruct the MPD from the measured time traces at each SD detectors

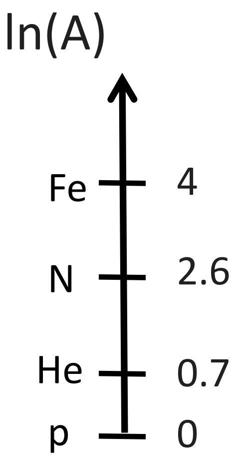


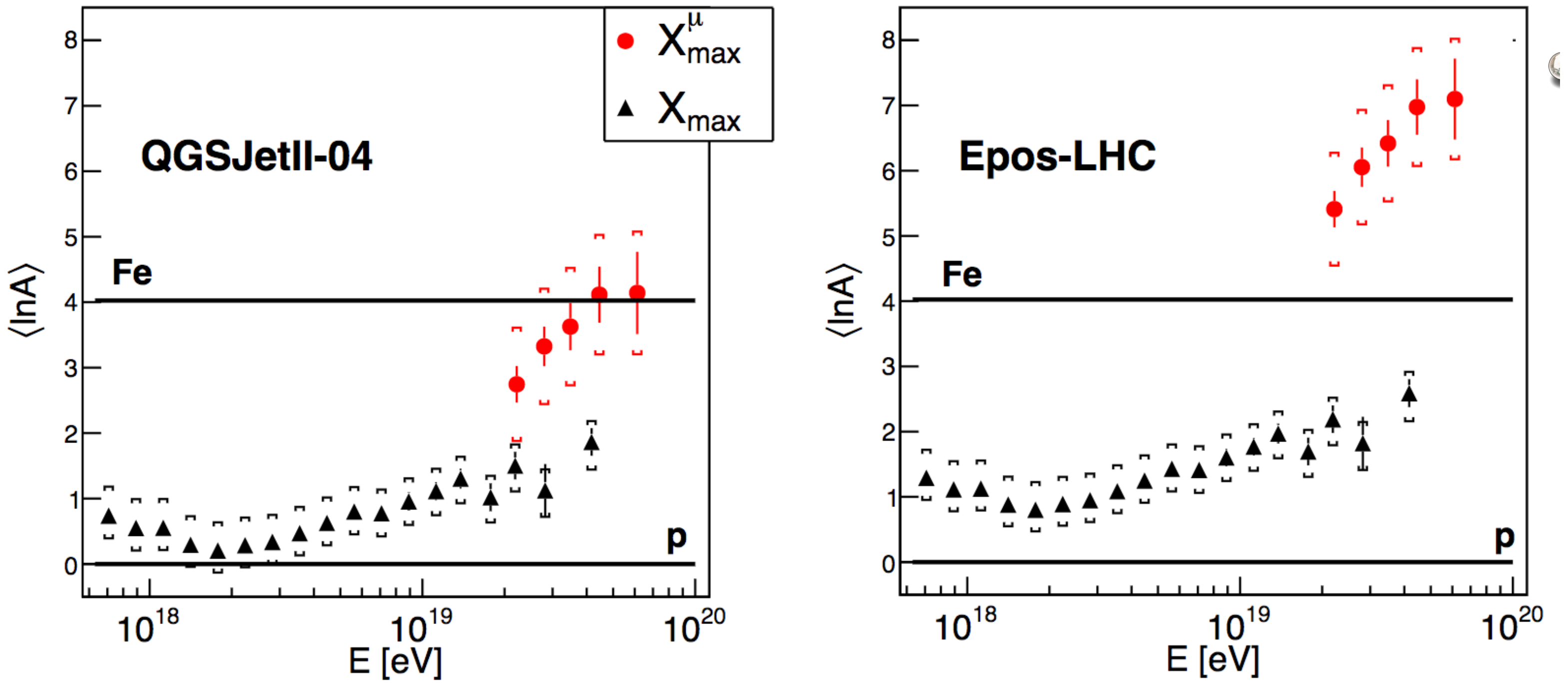
$<X^{\mu}_{max}>$



Θ ~ 60⁰
proton
iron
198
122
92
42
27
Epos-LHC
QGSJetII-04
⟨X^μ_max⟩ [g/cm²]
600
550
500
450
400
2×10^19
3×10^19
4×10^19
10^20
E [eV]

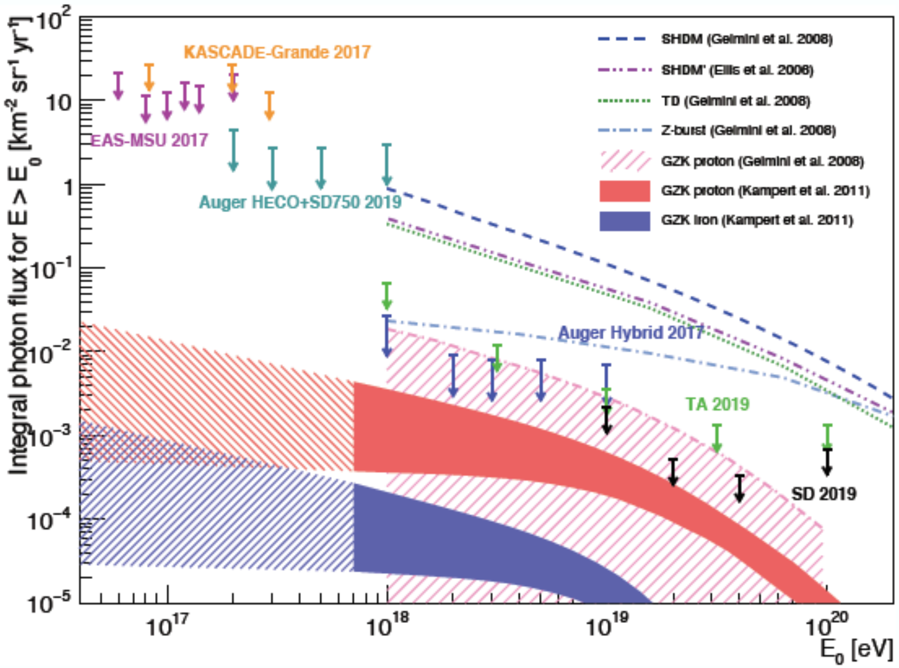
<ln A> from X_{max} and X^{μ}_{max}

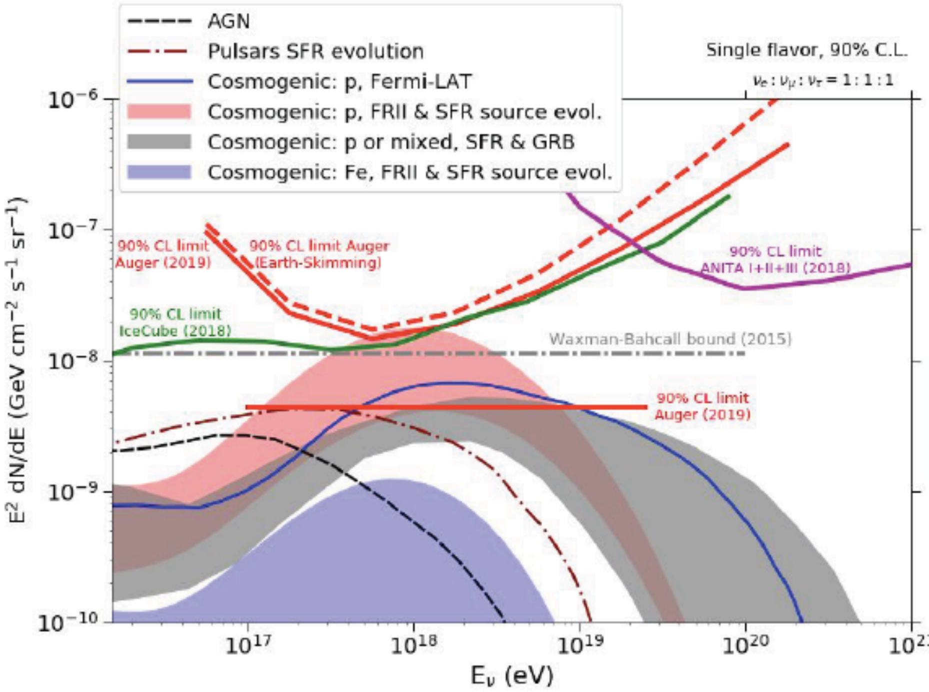




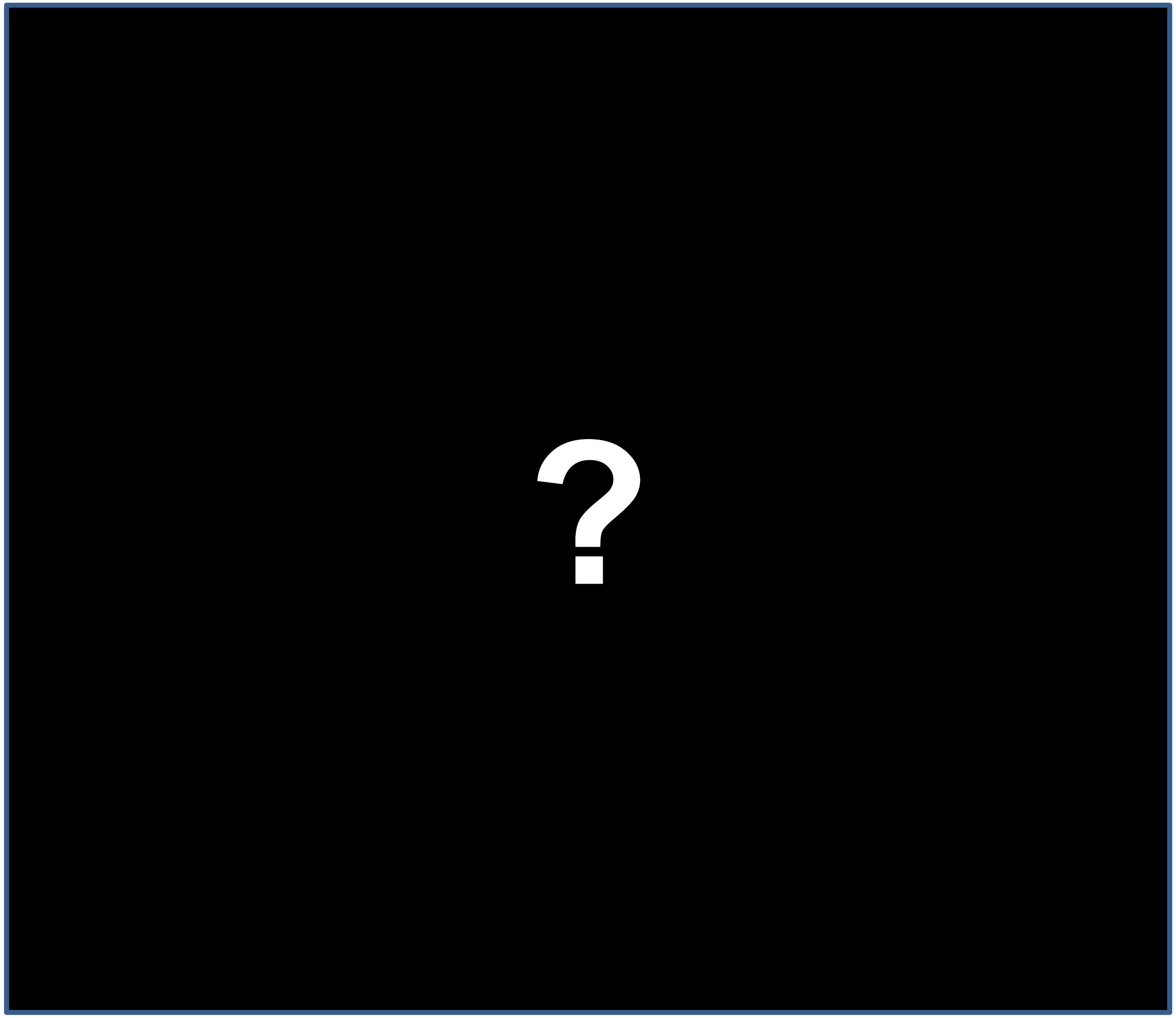
(X_{max} , X^{μ}_{max}) is sensitive to hadronic development of the shower (rapidity distributions, …)

Auger 2019 – γ and ν

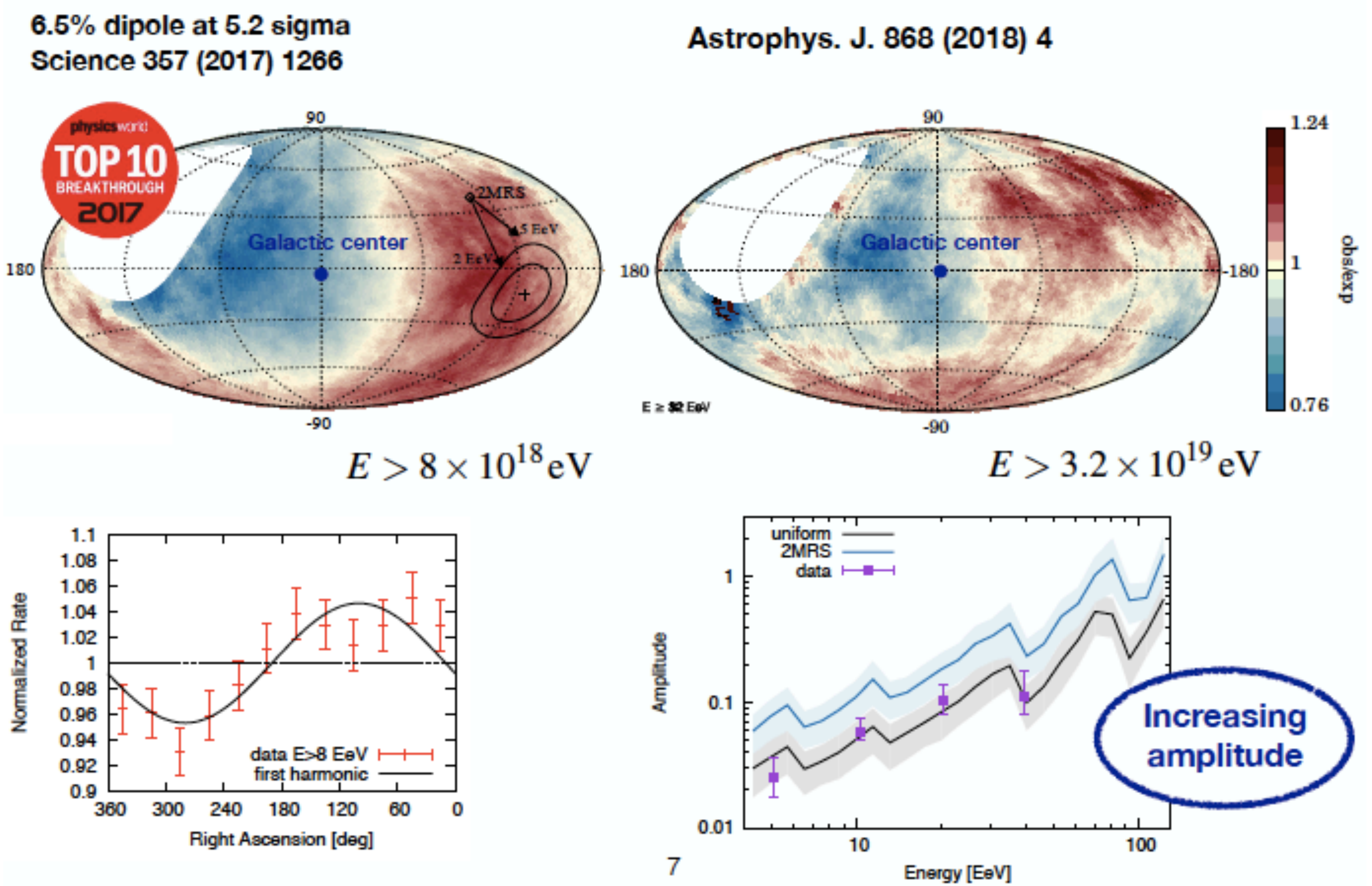




Origin

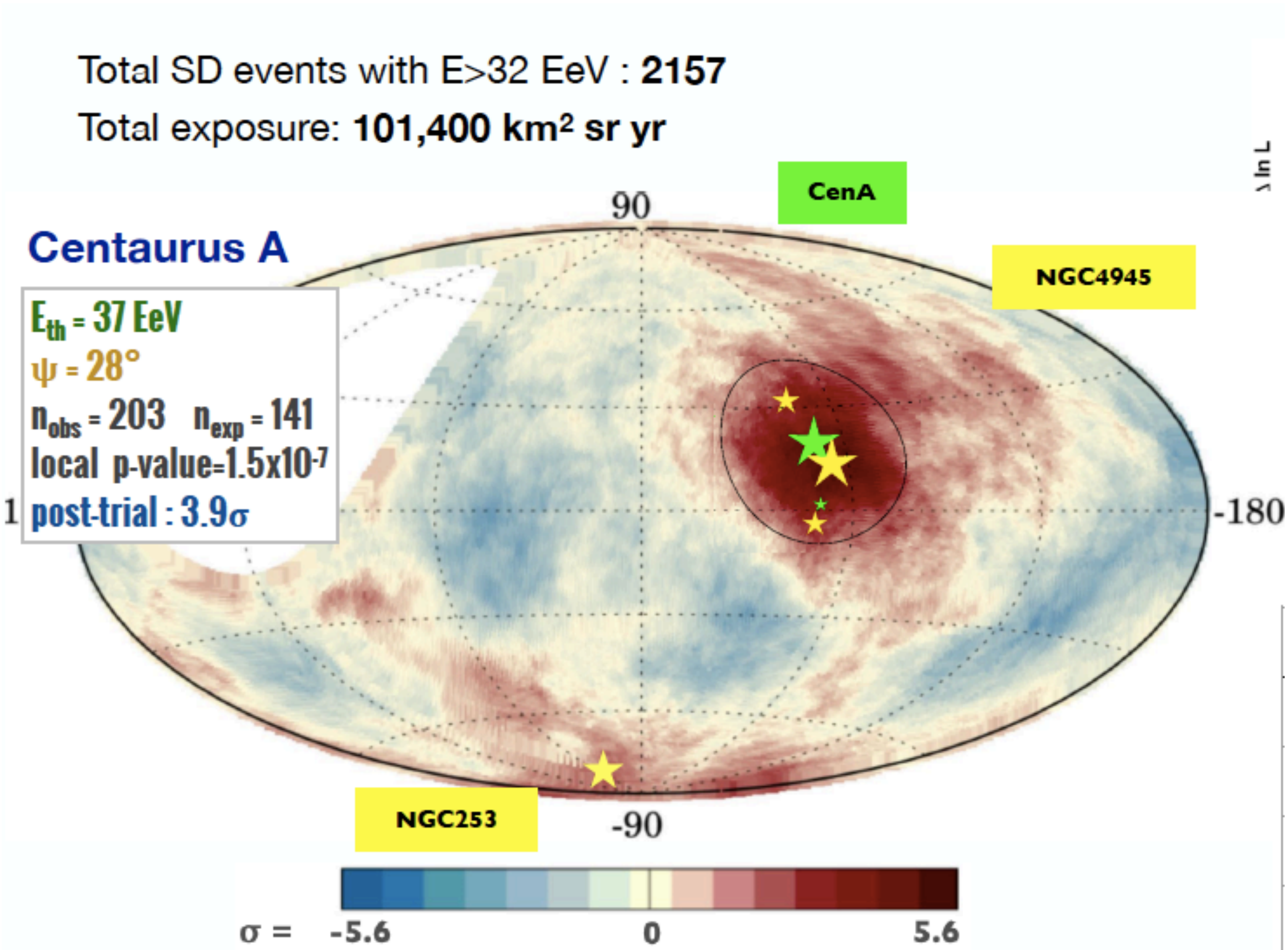


Extragalactic Origin



Arrival directions follow mass distribution of near-by galaxies

Auger 2019 – Cen A

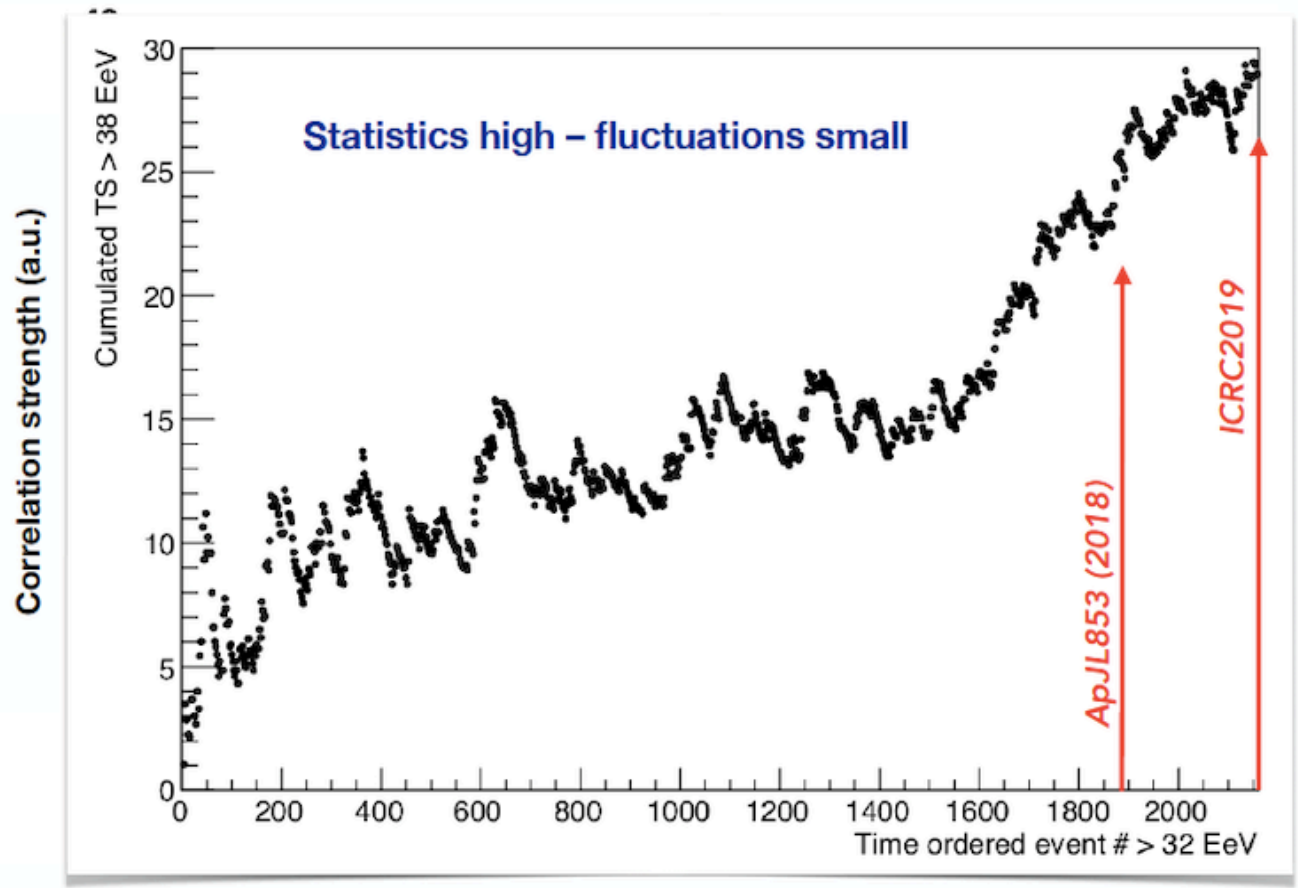


Highlight: correlation with starburst galaxies

4.0 σ

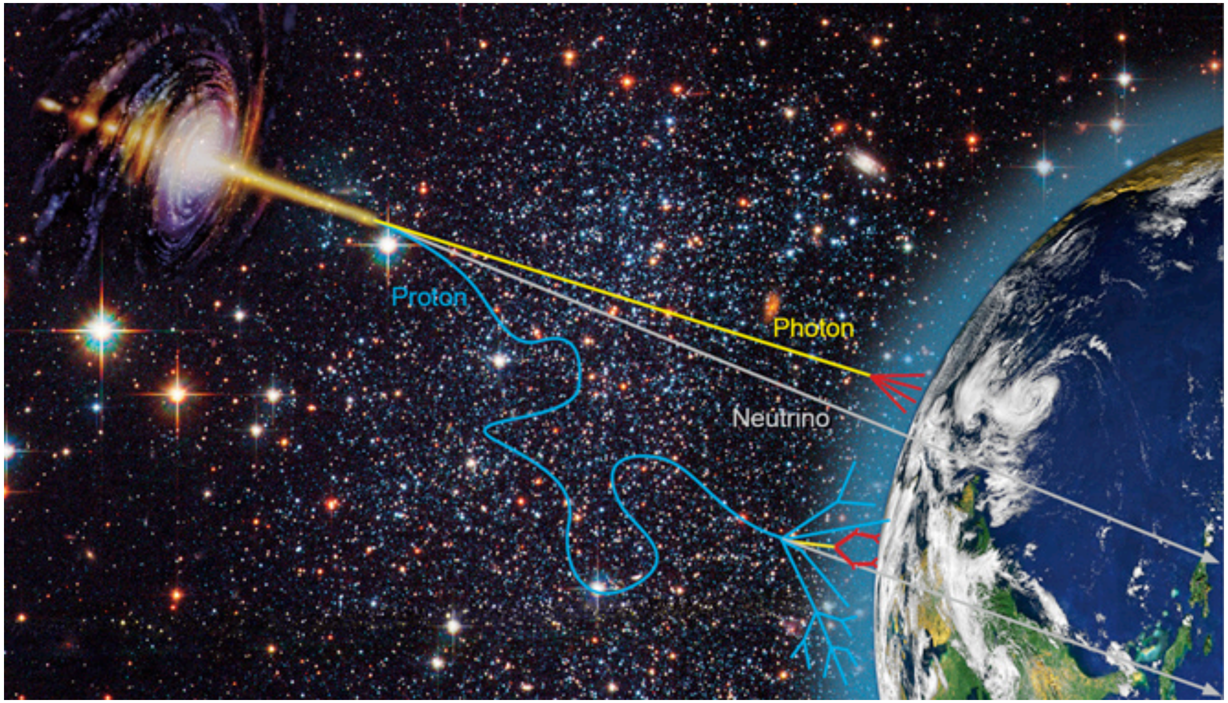
3.2 σ

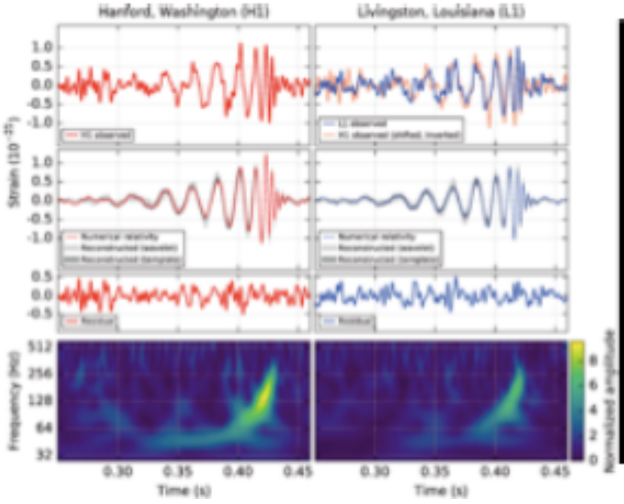
Significance of correlation with starburst galaxies

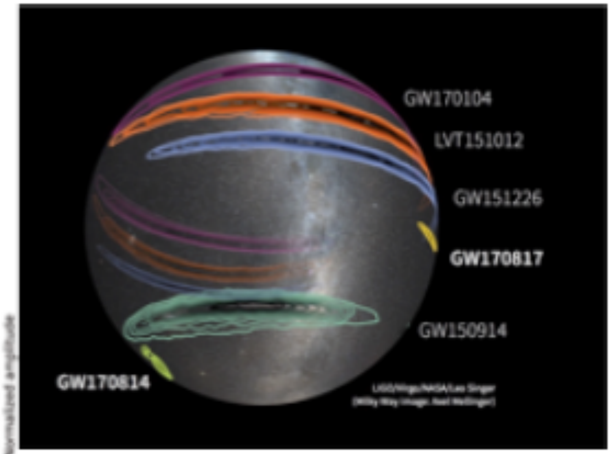


(Auger, ICRC 2019)

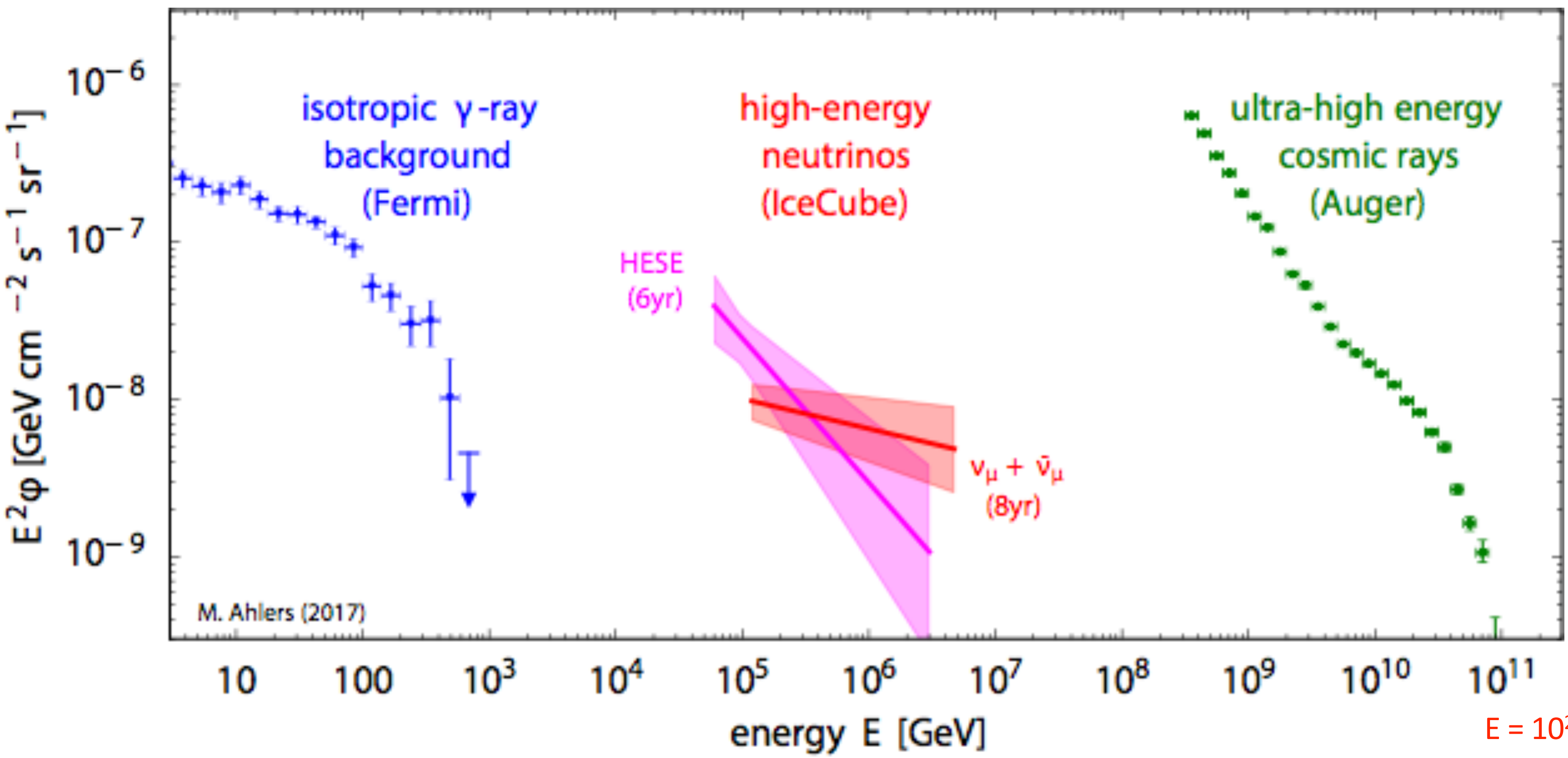
The Multi-messenger Era







The Universe at the highest energies !



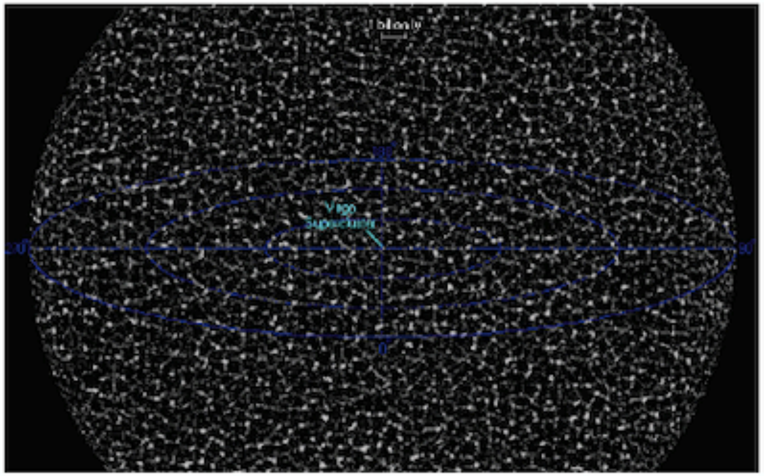
E = 10^{20} eV

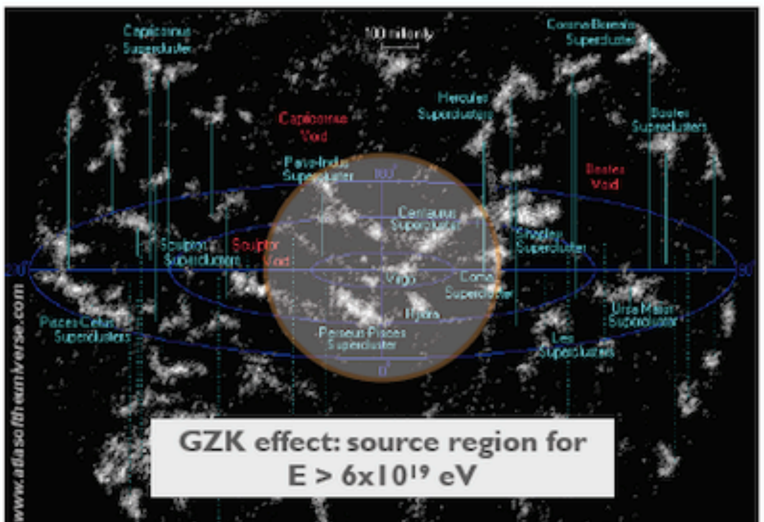
Energy density per decade similar in all three messenger particles

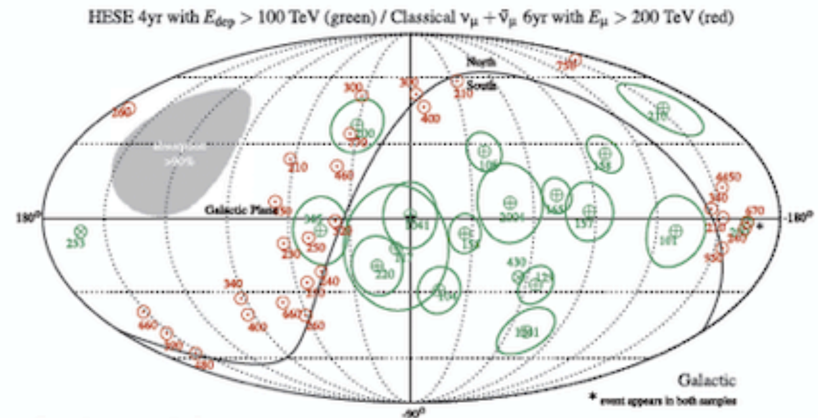
$$E^2 \frac{\mathrm{d}N}{\mathrm{d}E} = E \frac{\mathrm{d}N}{\mathrm{d}\ln E} \qquad \rho_{\mathrm{decade}} = \int_{\mathrm{decade}} E \frac{\mathrm{d}N}{\mathrm{d}\ln E}\, \mathrm{d}\ln E$$

Ralph Engel

Complementarity of UHE cosmic rays and neutrinos

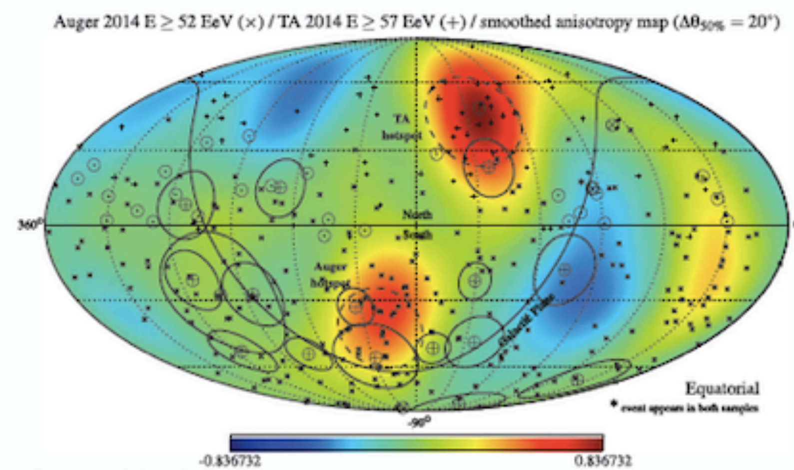






Neutrinos (transient events)

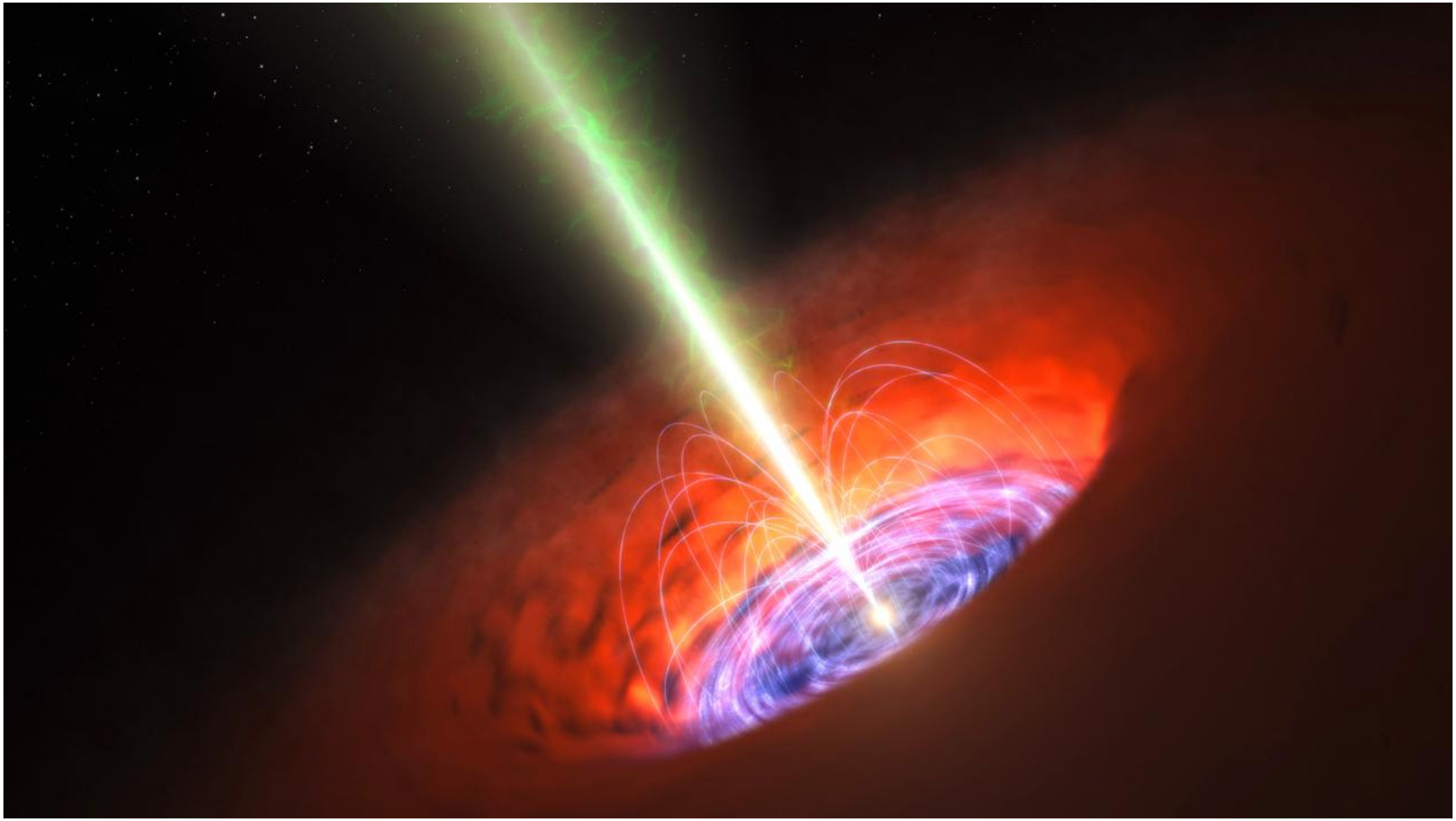
(Ahlers & Halzen, PTEP 2



Cosmic rays (back-tracking)

906.06233.pdf

The Extreme Universe

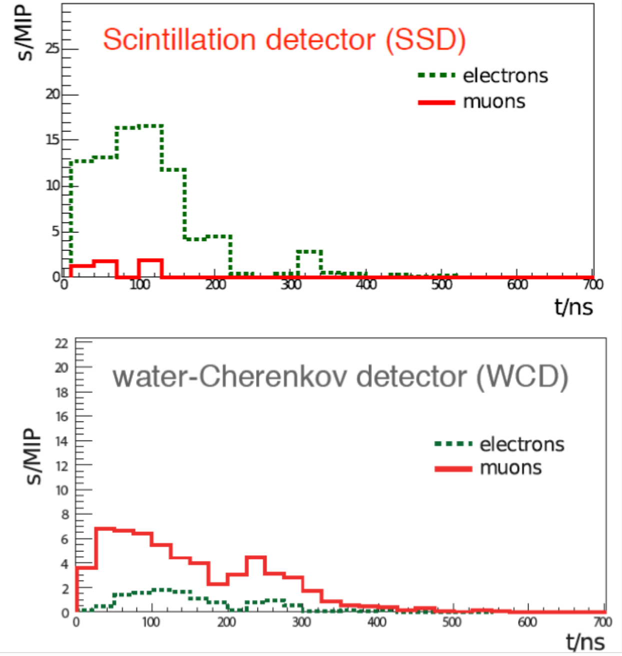


Auger Prime

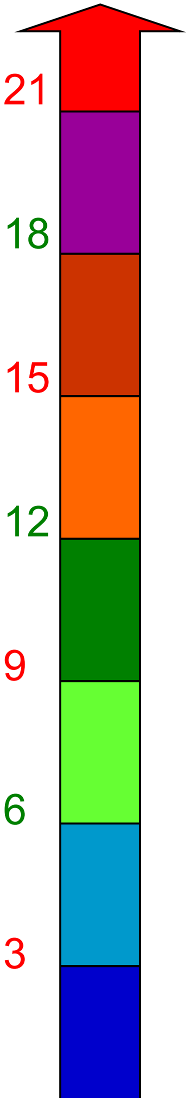
- "Primary cosmic Ray Identification through Muons and Electrons"

- Two complementary detectors:
  - Scintillator on top of the tank: signal dominated by e.m. component
  - WCD sensitive to e.m. + muons

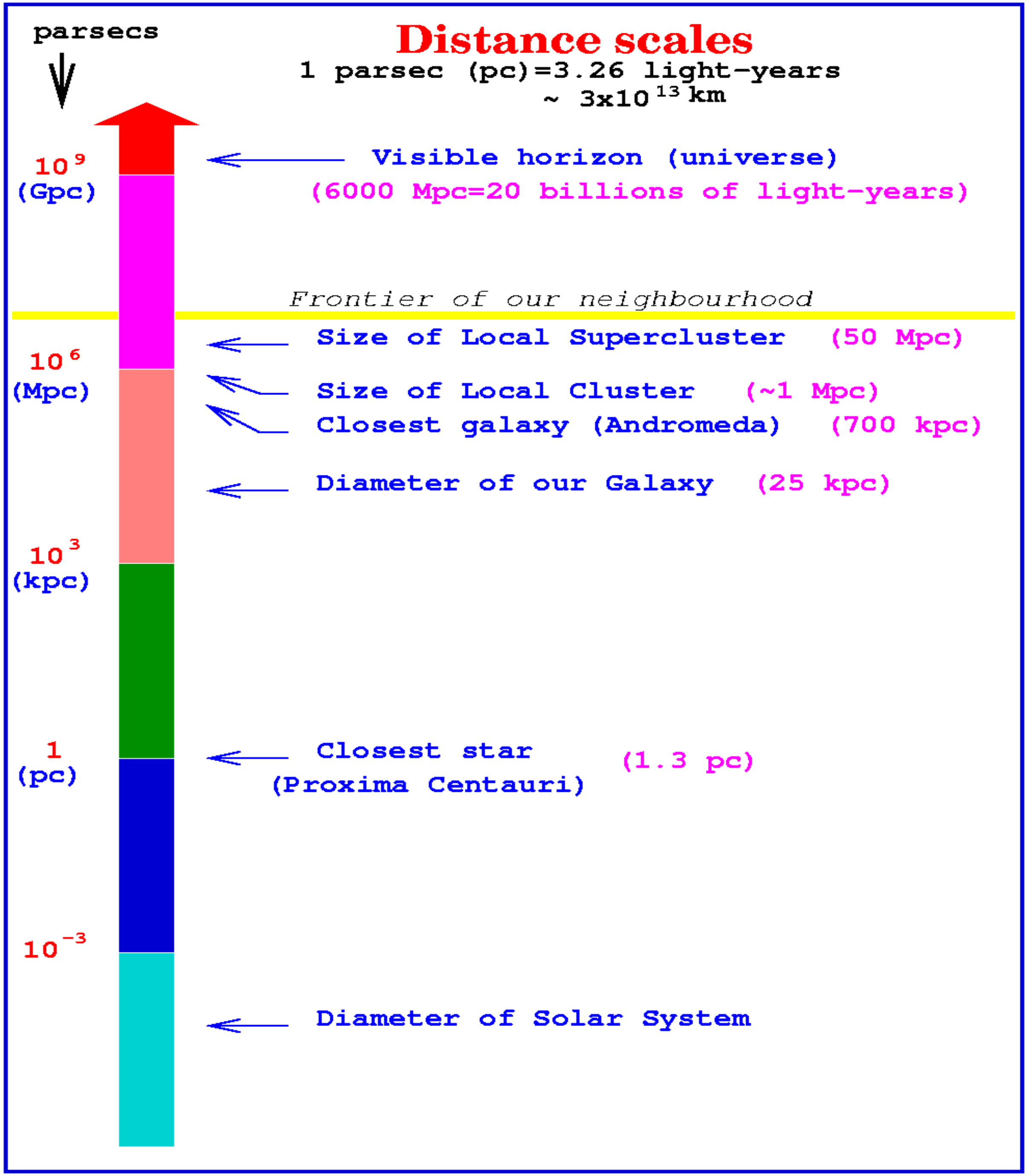
- The goal:
  - Enhance primary identification
  - Improve shower description
  - Reduce systematic uncertainties



Energy scales

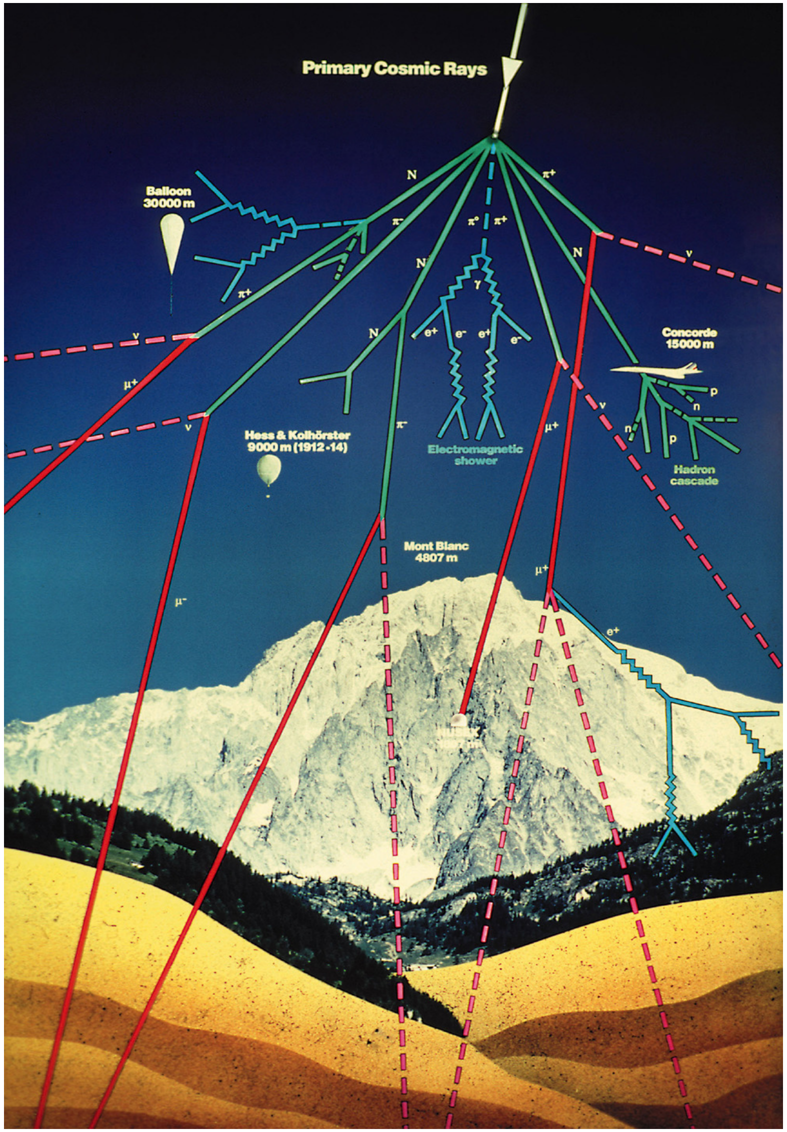


10^{21}	ZeV (zeta)	
10^{18}	EeV (exa)	Black holes / AGN
10^{15}	PeV (peta)	Supernovae's
10^{12}	TeV (tera)	Man-made accelerators
10^{9}	GeV (giga)	Proton mass
10^{6}	MeV (mega)	Nuclear rectors
10^{3}	KeV (kilo)	X rays, TV
1	eV	Battery

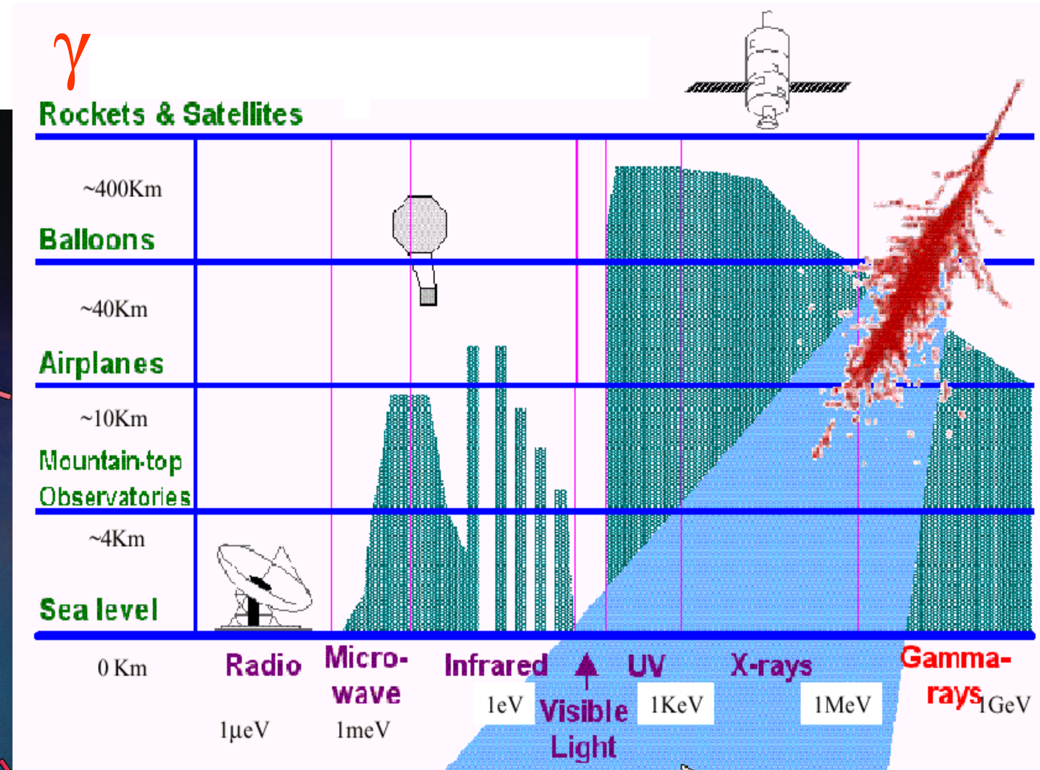

parsecs
Distance scales
1 parsec (pc)=3.26 light-years
~ 3x10 13 km
10 9
(Gpc)
Visible horizon (universe)
(6000 Mpc=20 billions of light-years)
Frontier of our neighbourhood
10 6
(Mpc)
Size of Local Supercluster (50 Mpc)
Size of Local Cluster (~1 Mpc)
Closest galaxy (Andromeda) (700 kpc)
Diameter of our Galaxy (25 kpc)
10 3
(kpc)
1
(pc)
Closest star
(Proxima Centauri)
(1.3 pc)
10 -3
Diameter of Solar System

Arriving at Earth

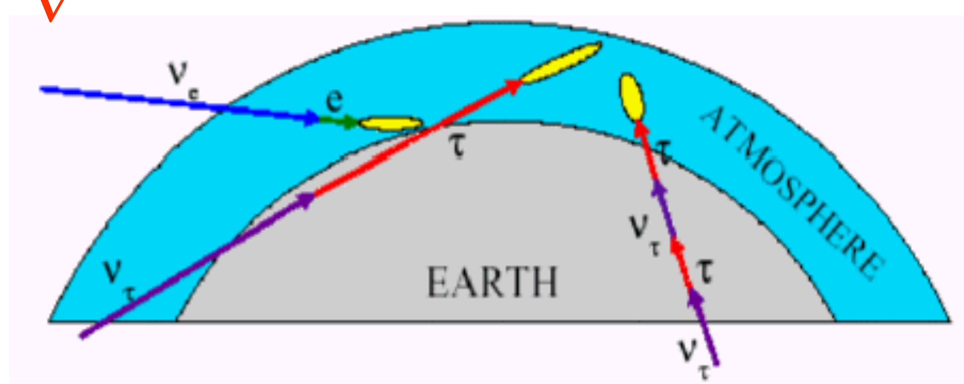
p/nuclei



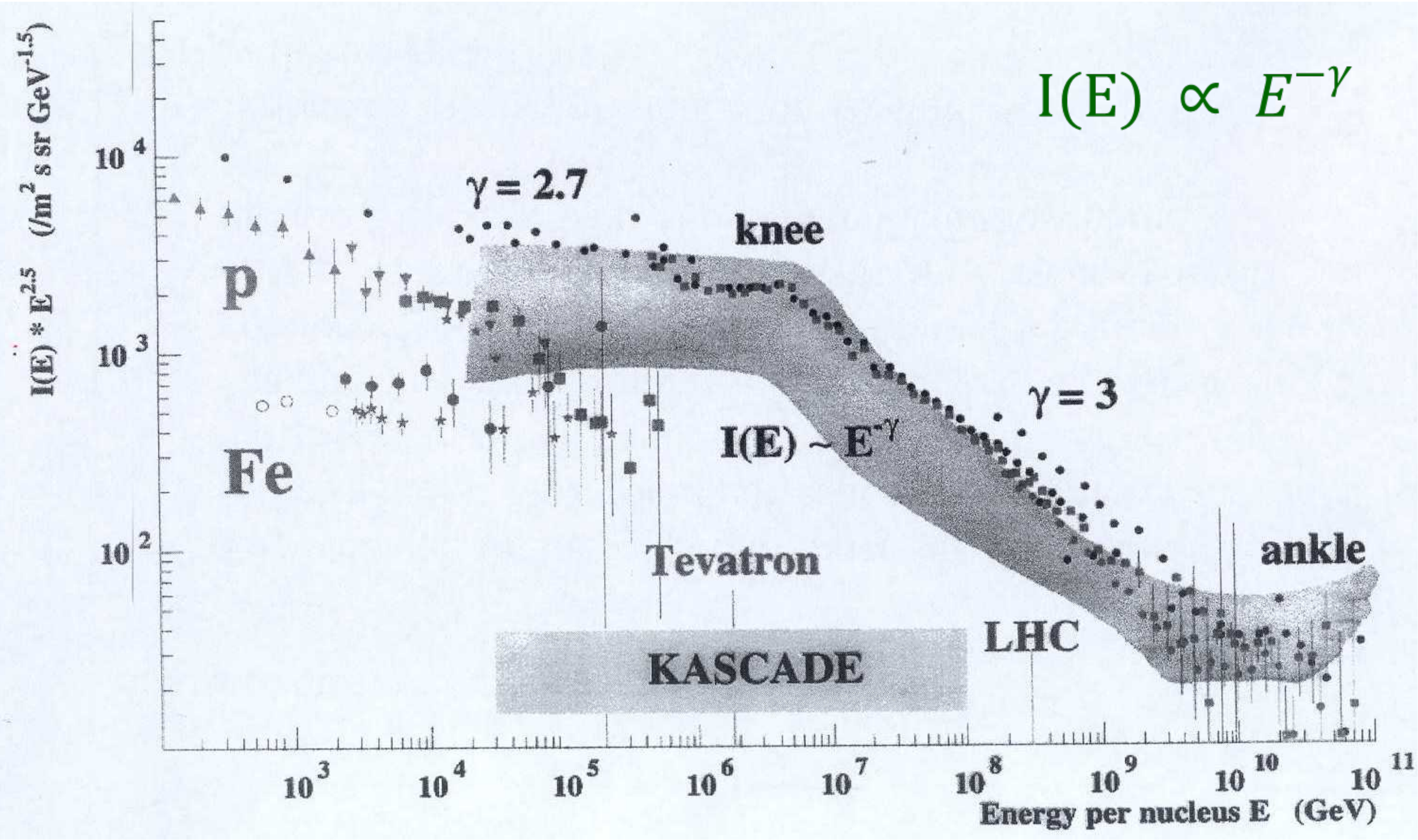
γ



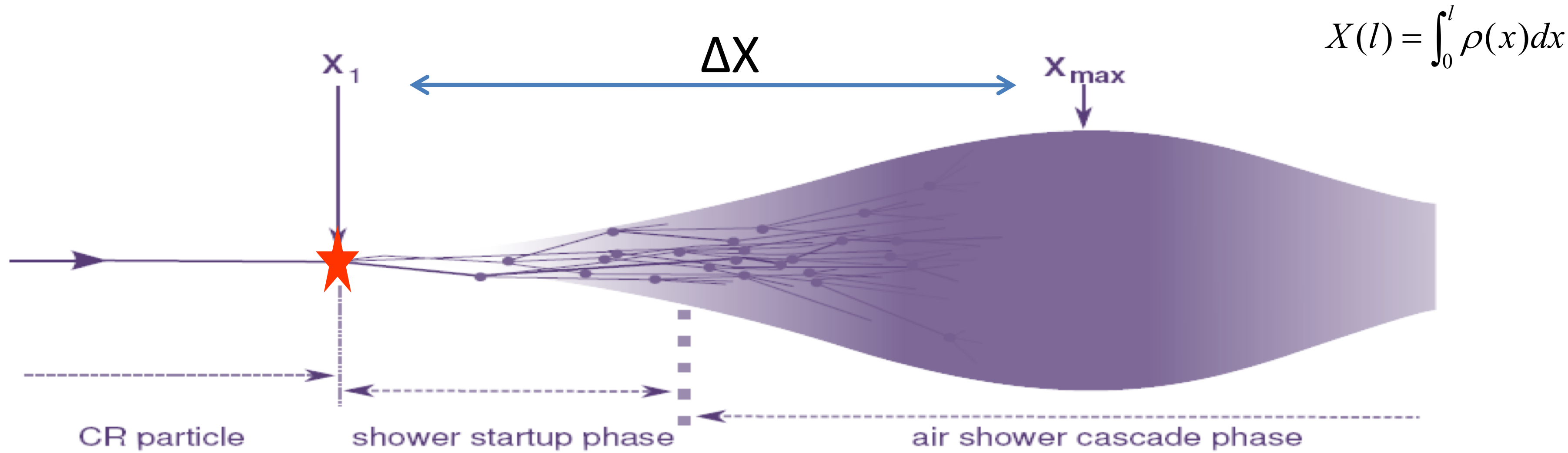
ν



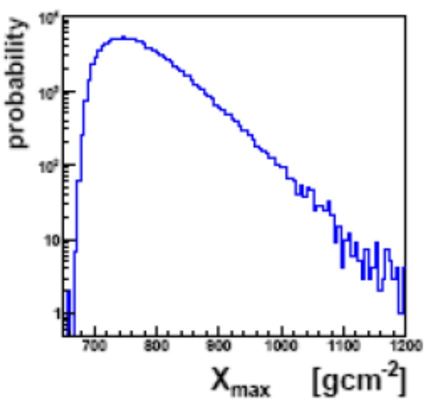
Anthropomorphic representation



$<X_{max}>$distribution

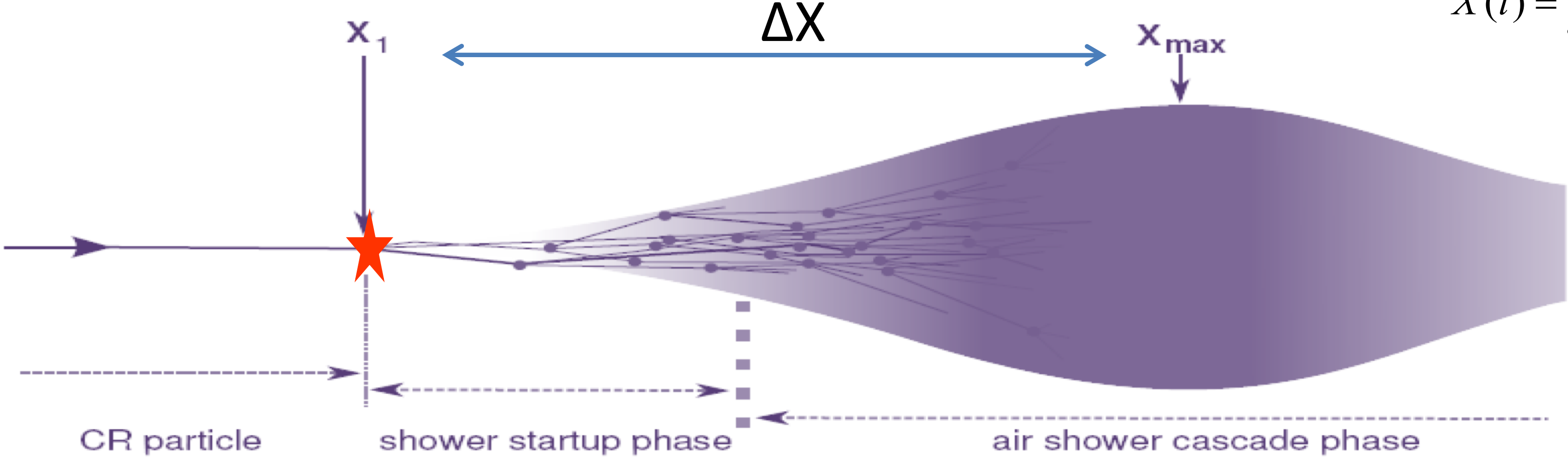


$$X_{max} = X_1 + \Delta X$$



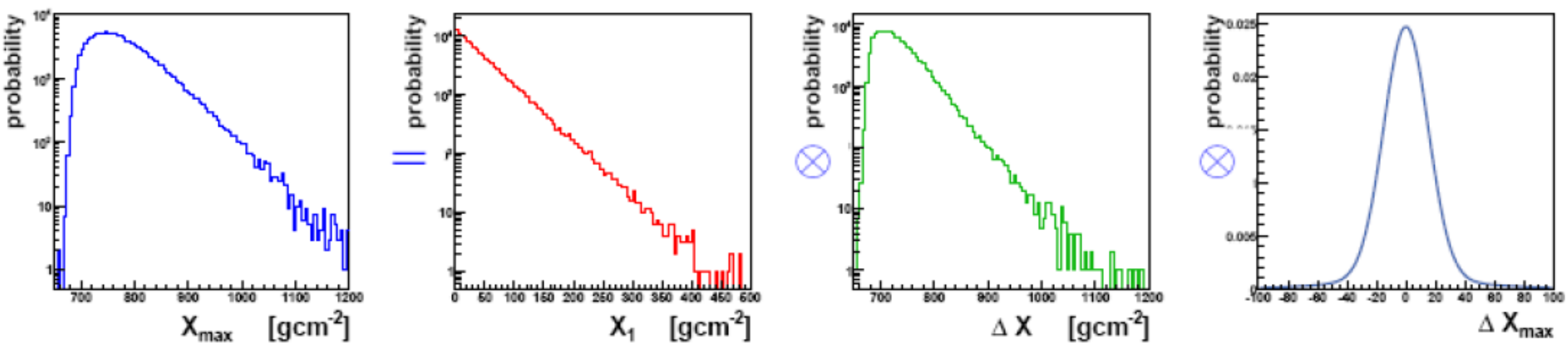
<X_{max} >distribution

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

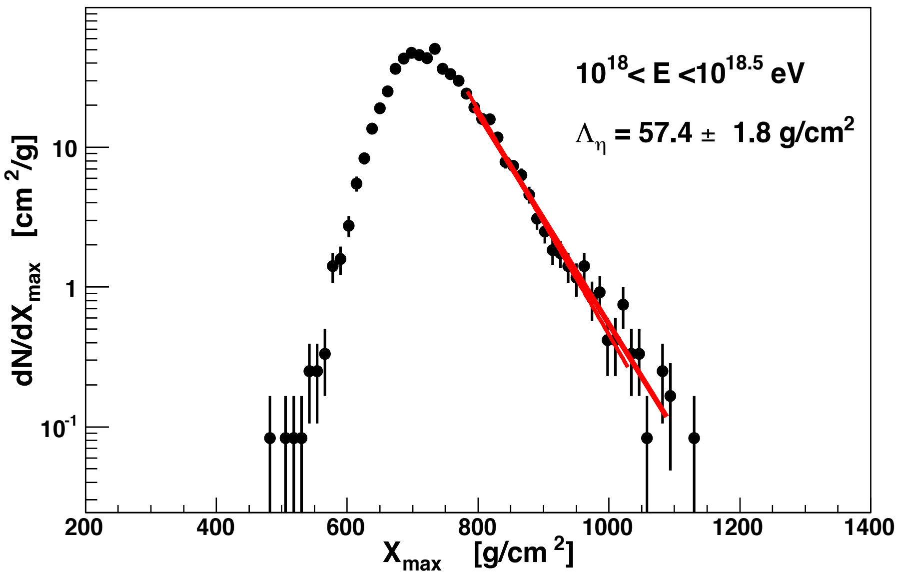


$$X_{max} = X_1 + \Delta X$$

X_1 ΔX Experimental resolution

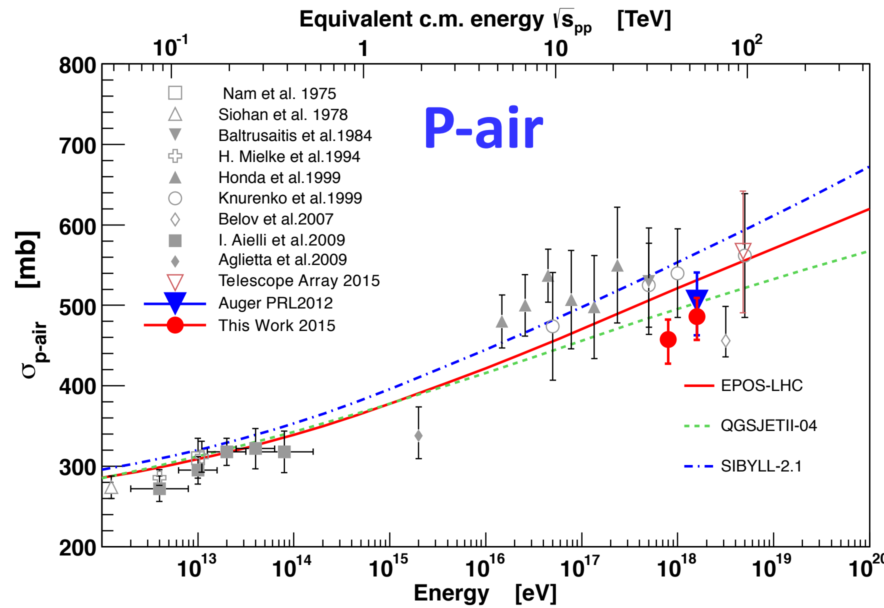


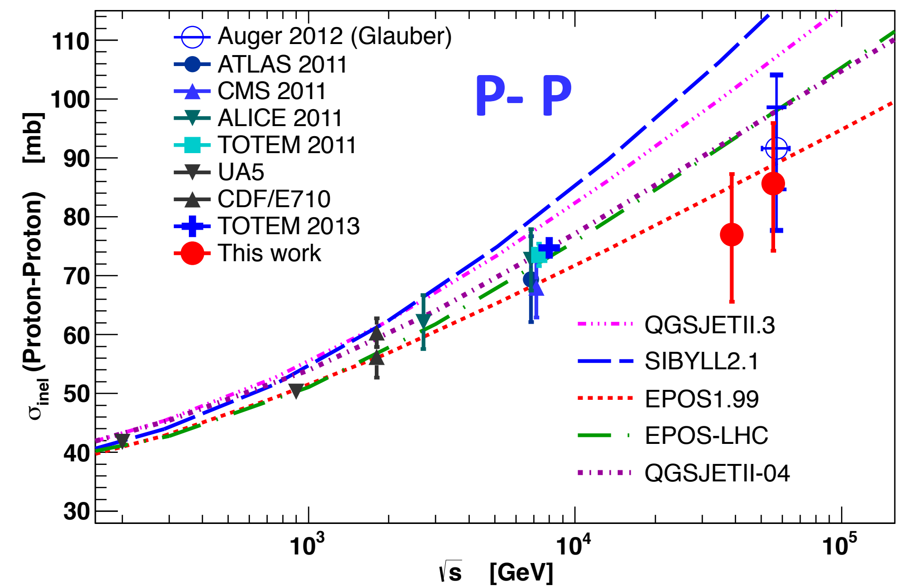
Proton cross-section



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

Slightly lower than it was expected at the time by most of the models, but in good agreement with recent LHC data.

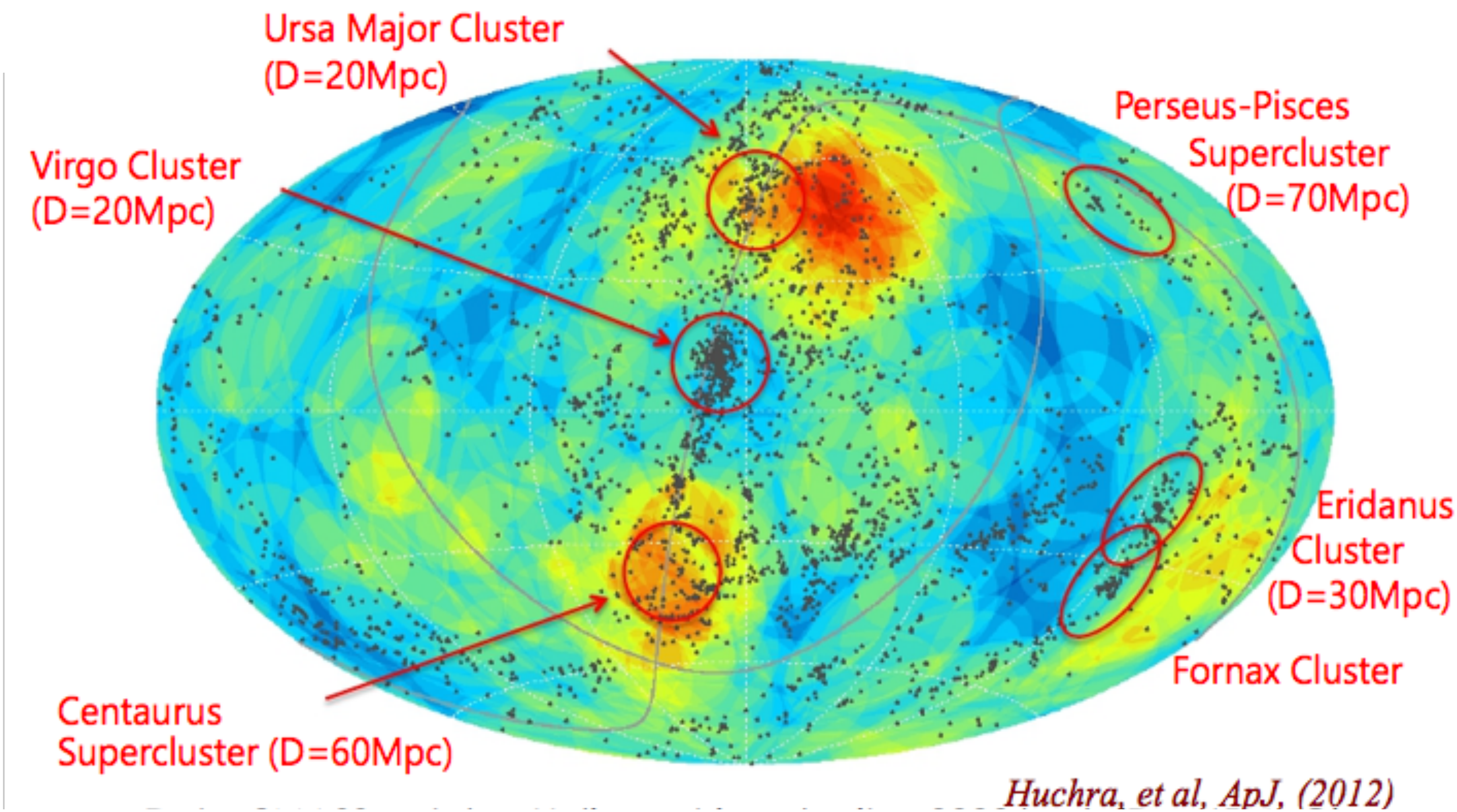




Hot/Warm spots

$E > 6 \times 10^{19}\,\mathrm{eV}$

TA and Auger: over-densities ~20° size



Galaxies with D < 45 Mpc
(2MASS catalog)