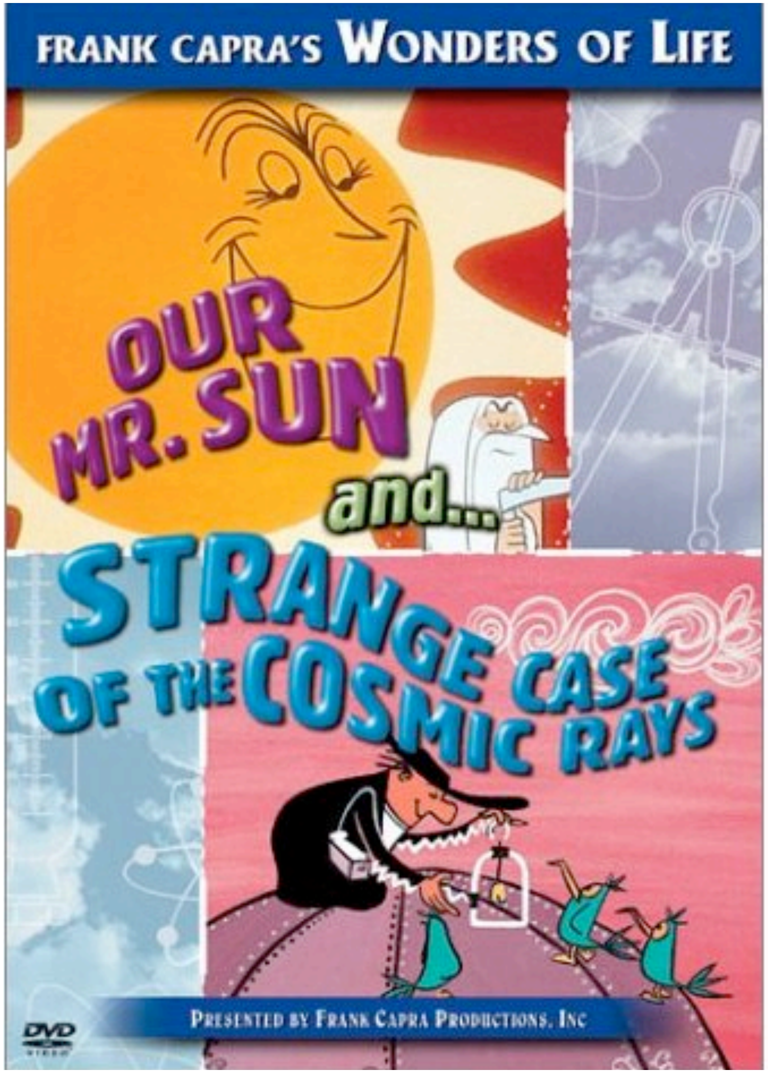
1957 written by Anderson & Rossi

Cosmic Rays

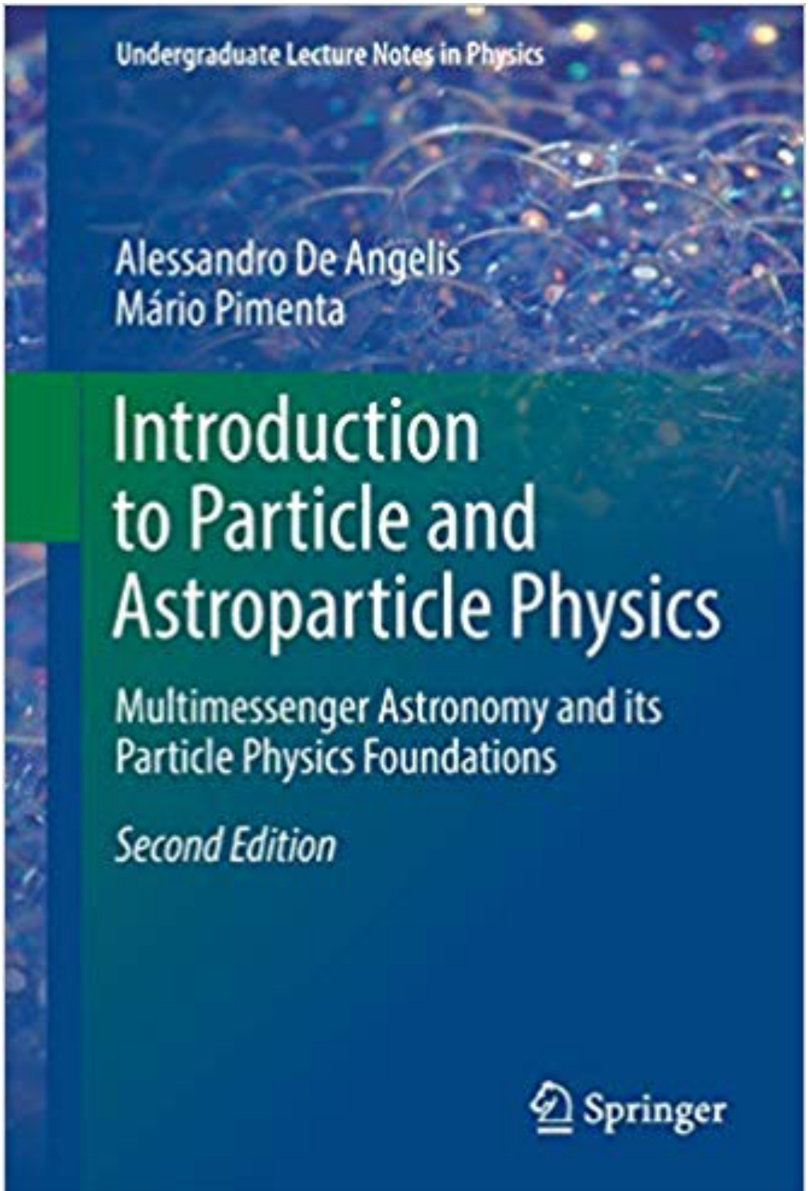


I. History, sources, acceleration, propagation, interaction in atmosphere

II. Detection from space (AMS), UHECR: detection and results

LIP TÉCNICO LISBOA

Mário Pimenta,
Otranto, May 2019

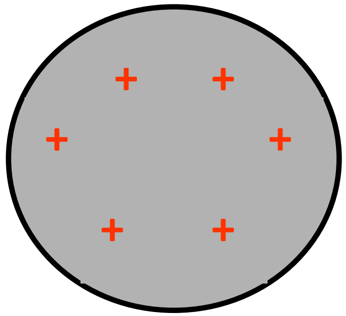


"Introduction to Particle and Astroparticle Physics"

Alessandro De Angelis, Mário Pimenta, Springer (2nd edition, 2018)

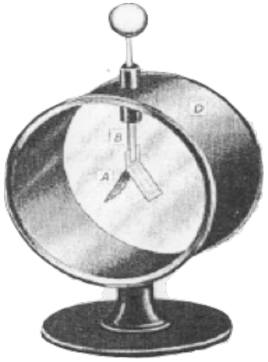
Free electrical charges in the atmosphere !!!

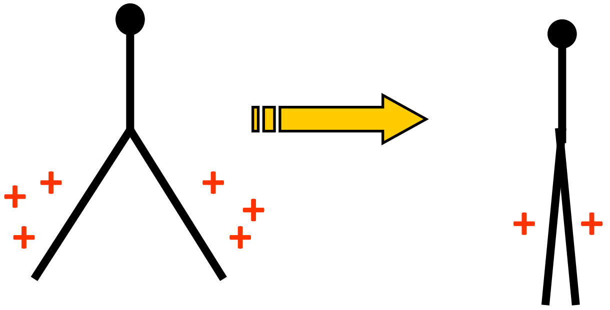
Coulomb, 1785



Discharge of charged conductors ...

End of XIX century

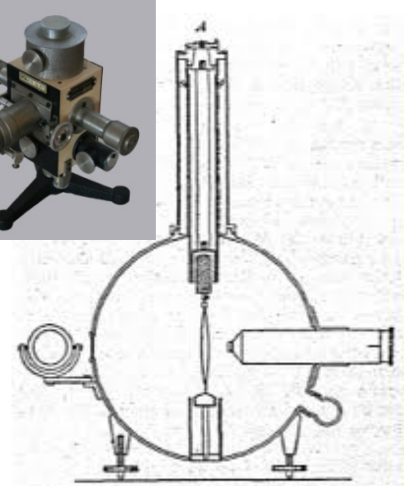




Radioactivity ?

Make good electroscopes!

The two friends Julius Elster and Hans Geiter, gymnasium teachers in Wolfenbuttel, around 1900



Theodor Wulf, German Jesuit, perfected the electroscope in 1908-09, up to a sensitivity of 1 volt

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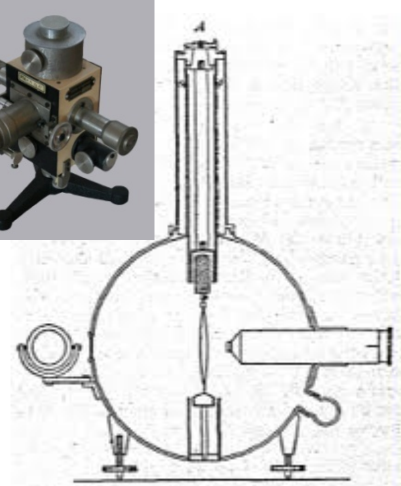

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By sea and by sky

Wulf 1909-
1910

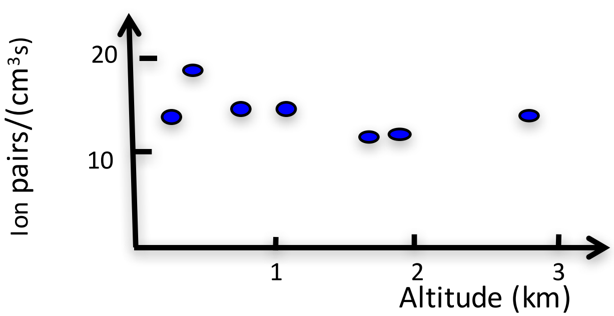
Results not
conclusive

By sea and by sky

Wulf 1909-1910

Gockel 1909

Results not conclusive

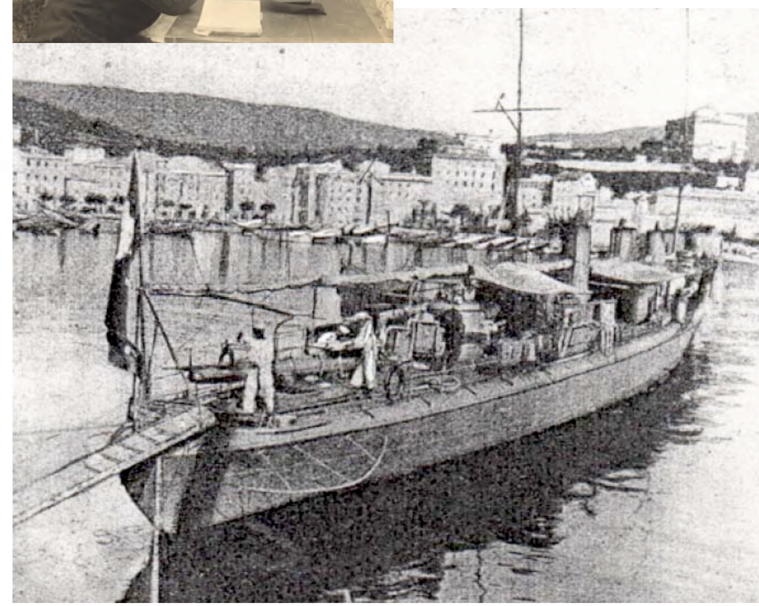


By sea and by sky

Wulf 1909-1910

Gockel 1909

Domenico Pacini1911



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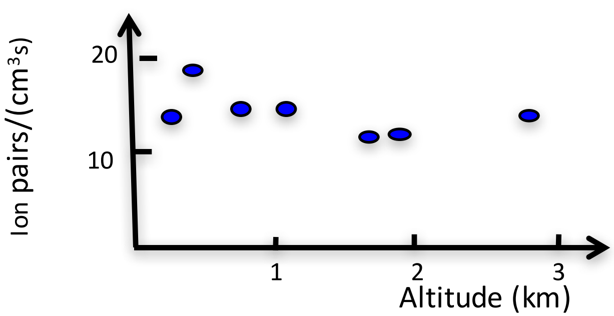


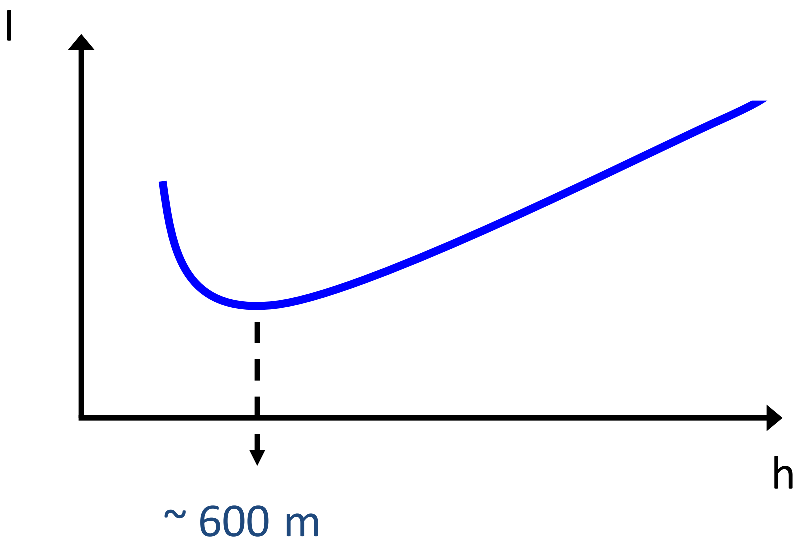
the winning idea !!!: immersing an electroscope 3m deep in the sea Pacini finds a significant (20% at 4.3σ) reduction

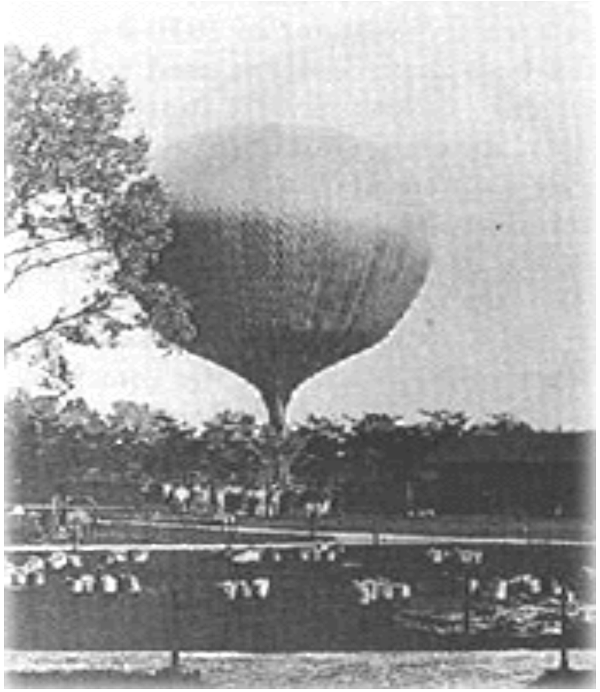
The radiation comes from the sky !!!

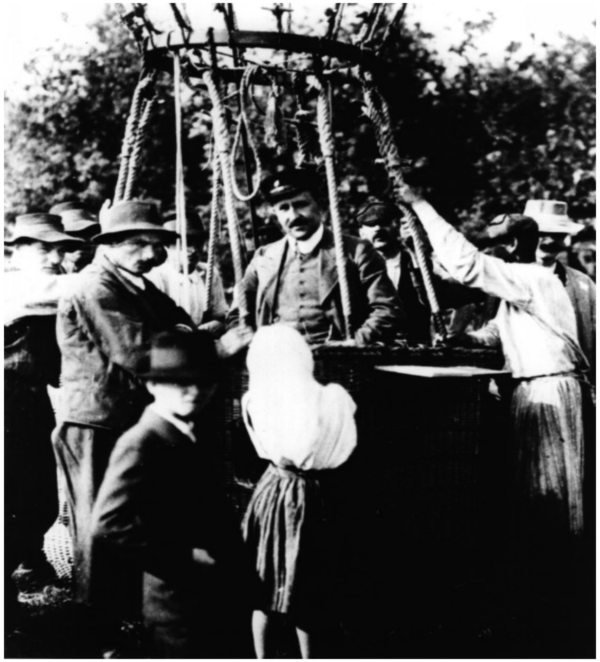
Viktor Hess, 1912

Several flights up to 6 Km

Day/night, eclipses, ...



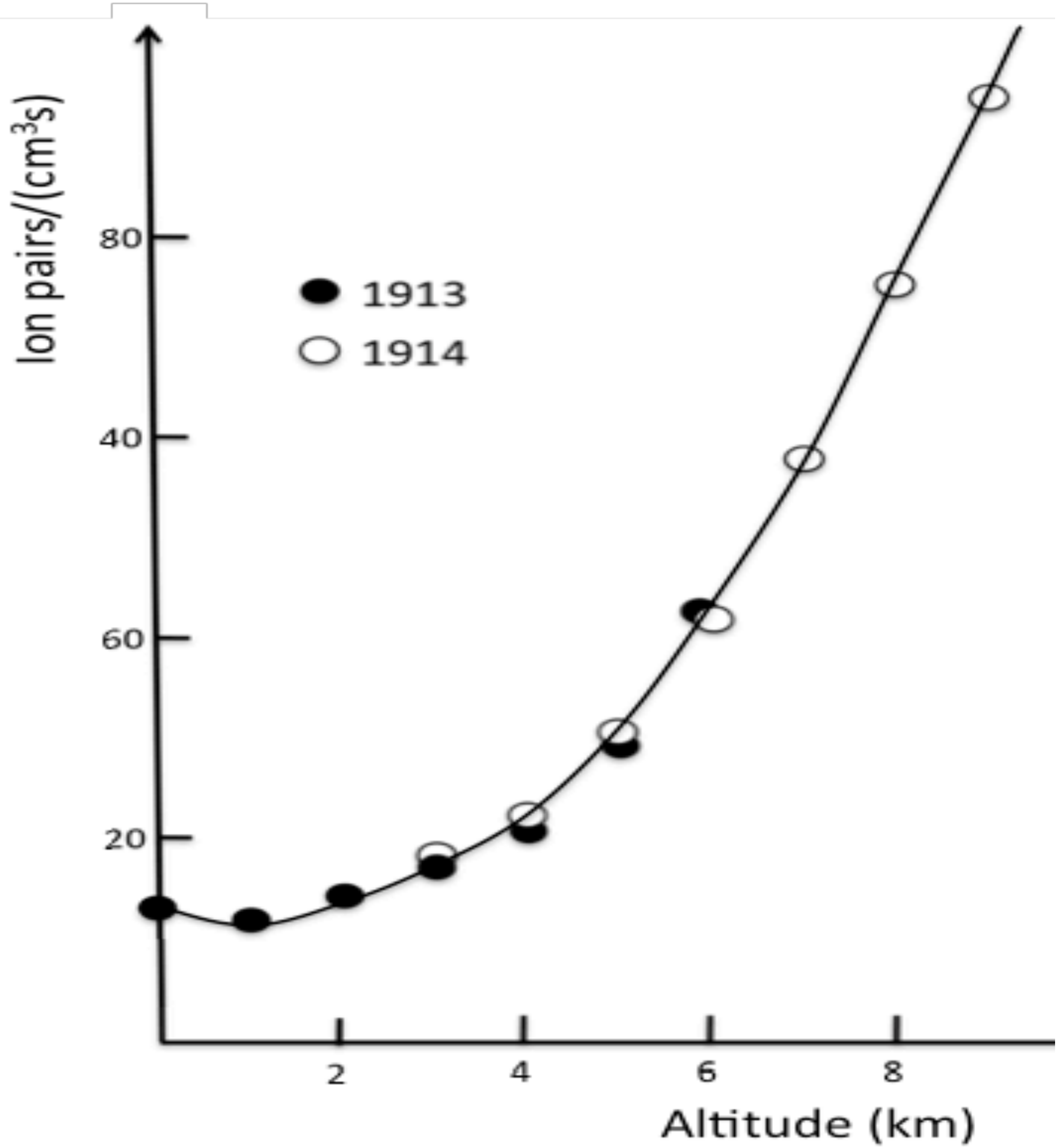




"Cosmic Rays" ! (Milikan)

The confirmation

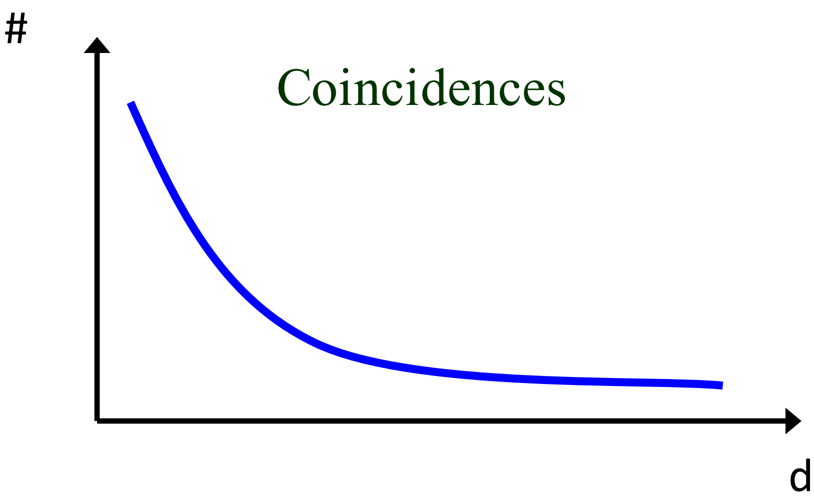
Kolhörster

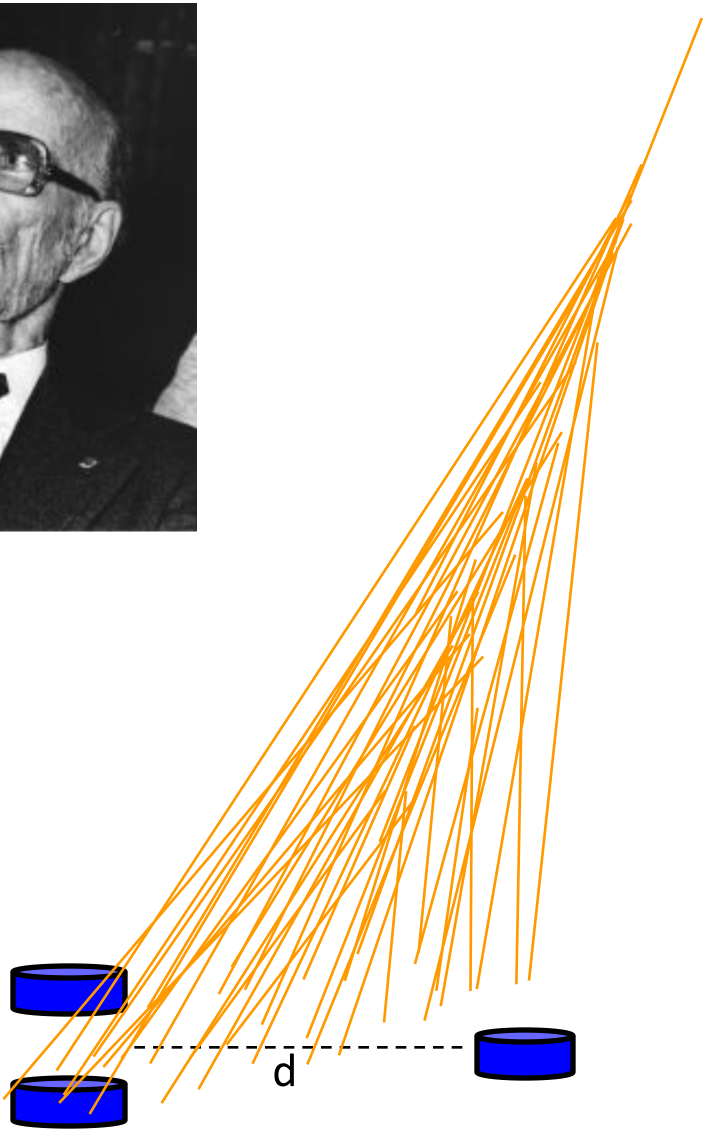


Flights up to 9200 m !!!

Particle showers

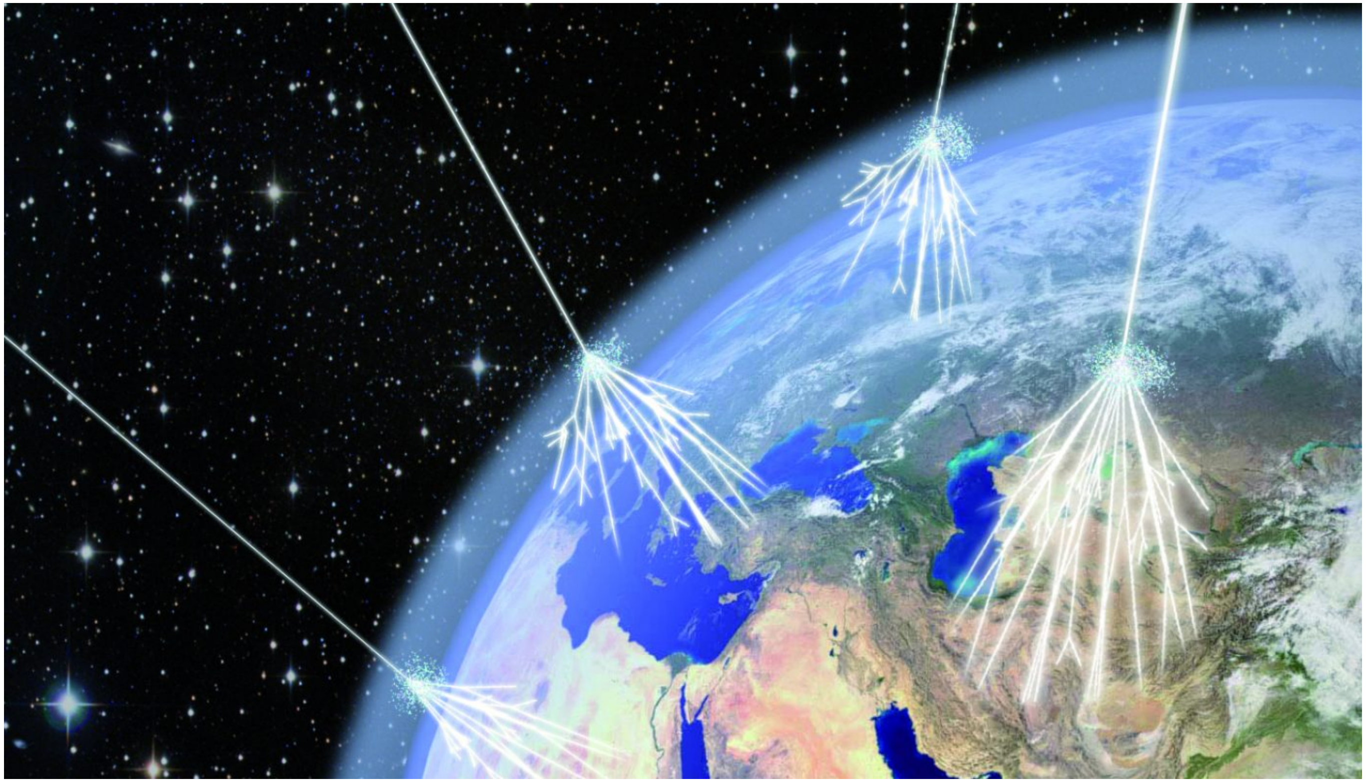
Pierre Auger, 1938





First shower energy estimates !

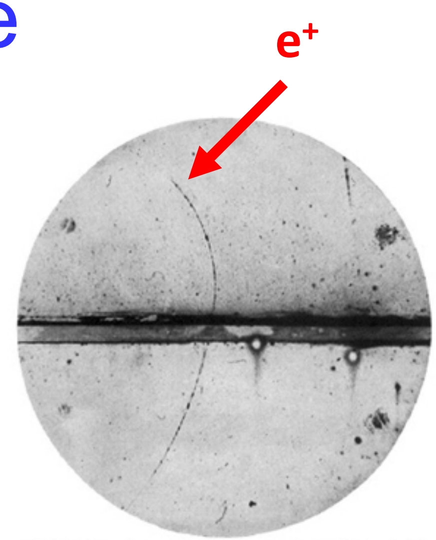
Messengers from the Universe

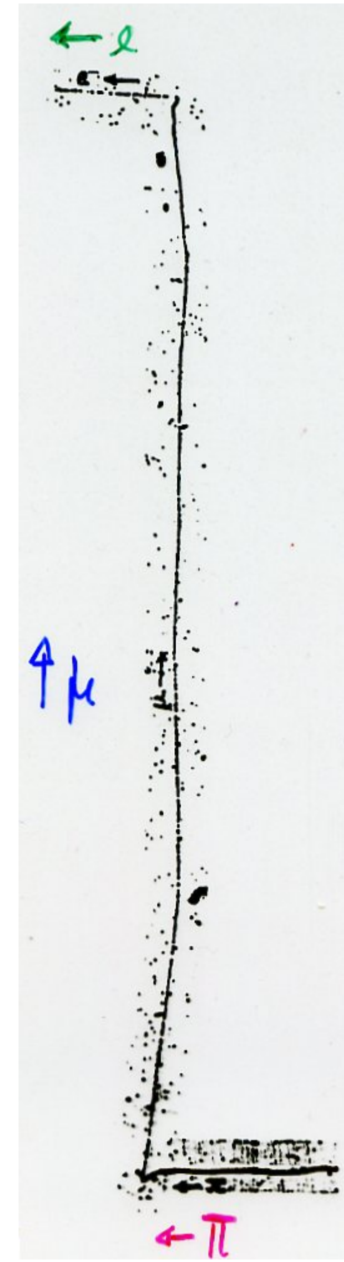


20% of the natural radiation at ground is due to cosmic radiation!!!

Can we use these **"cosmic rays"** for science?

YES (the birth of Particle Physics)





Positron (Anderson 1932)

Antimatter! (Dirac)

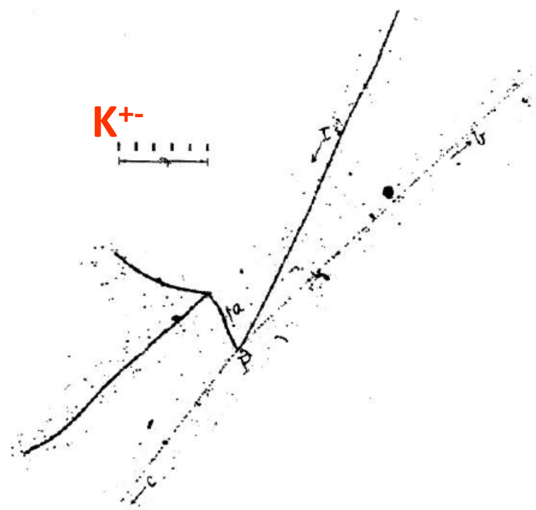
$\gamma \rightarrow e^+e^-$ (Einstein)

μ (Anderson 1937)

Rossi, 1940:
Muon life time.
Time dilation!

π (Lattes, Powell 1947)

Strong interactions (Yukawa)



K, Λ, ... (Leprince Ringuet 1944, Rochester , Butter 1947, ...)

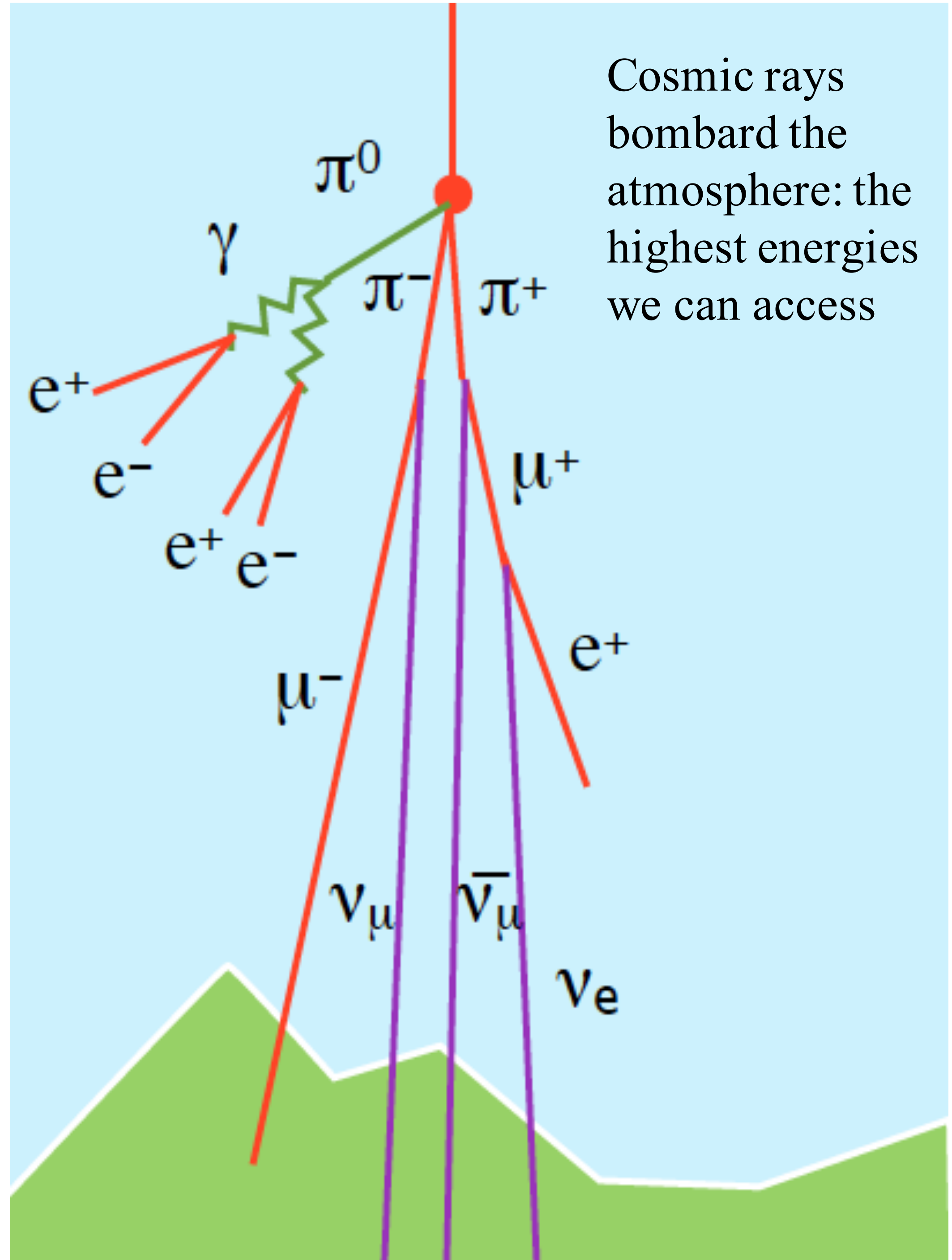
Strangeness

YES, it allows accessing the highest energies

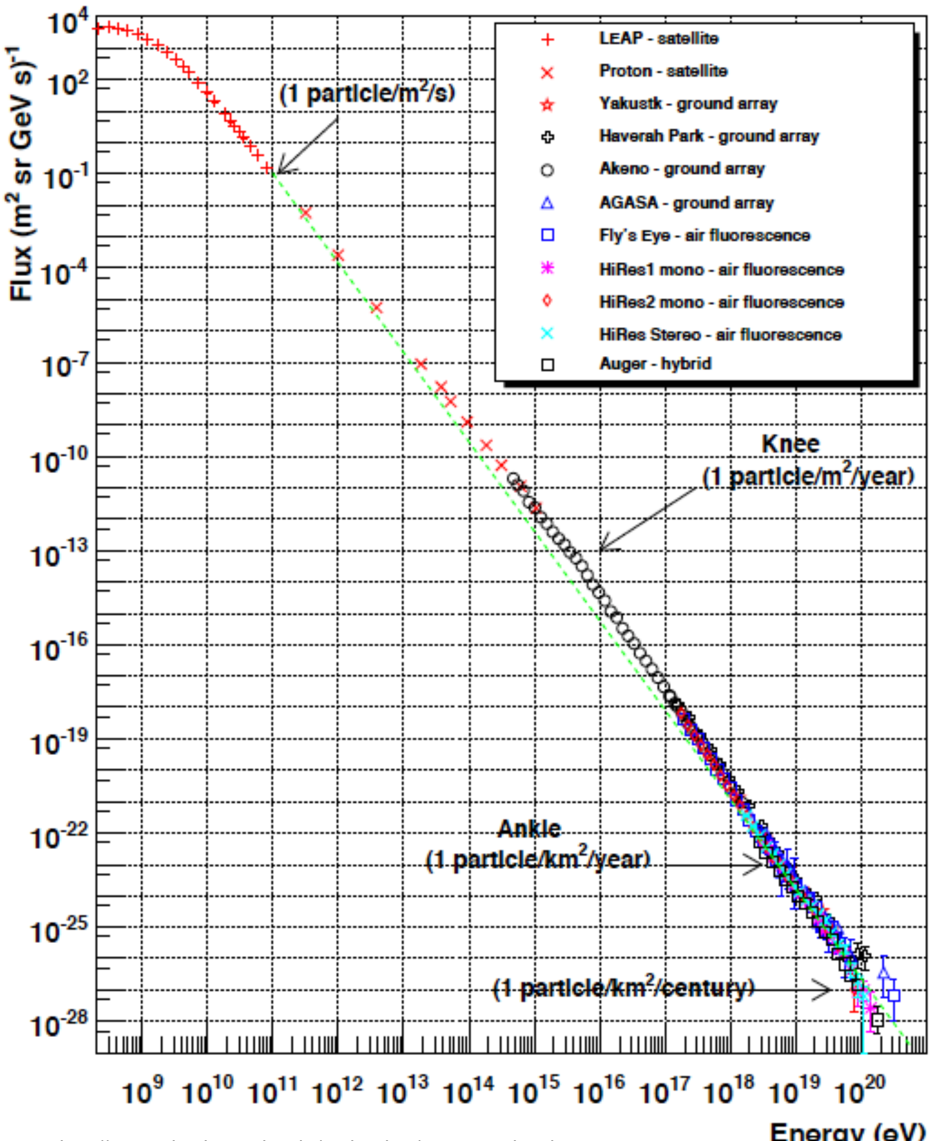
Detected protons 10^8 times more energetic than LHC

Detected gamma-rays 10^4 times more energetic than human-made

Detected neutrinos 10^5 times more energetic than human-made



Charged cosmic rays (p/nucleus)



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

$$\frac{dN}{dE} \propto E^{-\alpha}$$

$$\alpha = \begin{cases} 2.7 & E < 10^{16} \\ 3.0 & 10^{16} < E < 10^{18} \\ 2.7? & E > 10^{18} \end{cases}$$

Energy spectrum ($10^9 < E < 10^{15}$ eV)

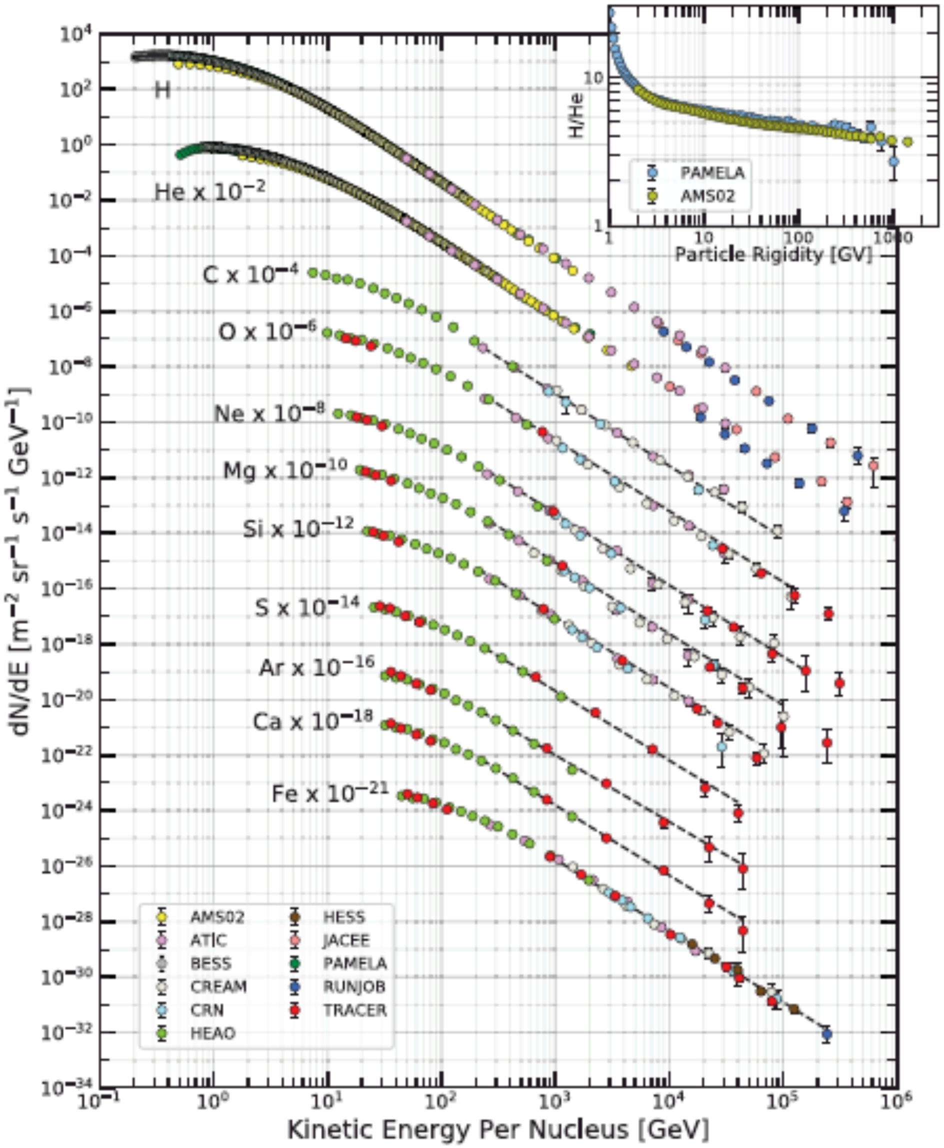


Figure 29.1: Fluxes of nuclei of the primary cosmic radiation in particles per energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [2–13]. The inset shows the H/He ratio at constant rigidity [2,4].

70% p

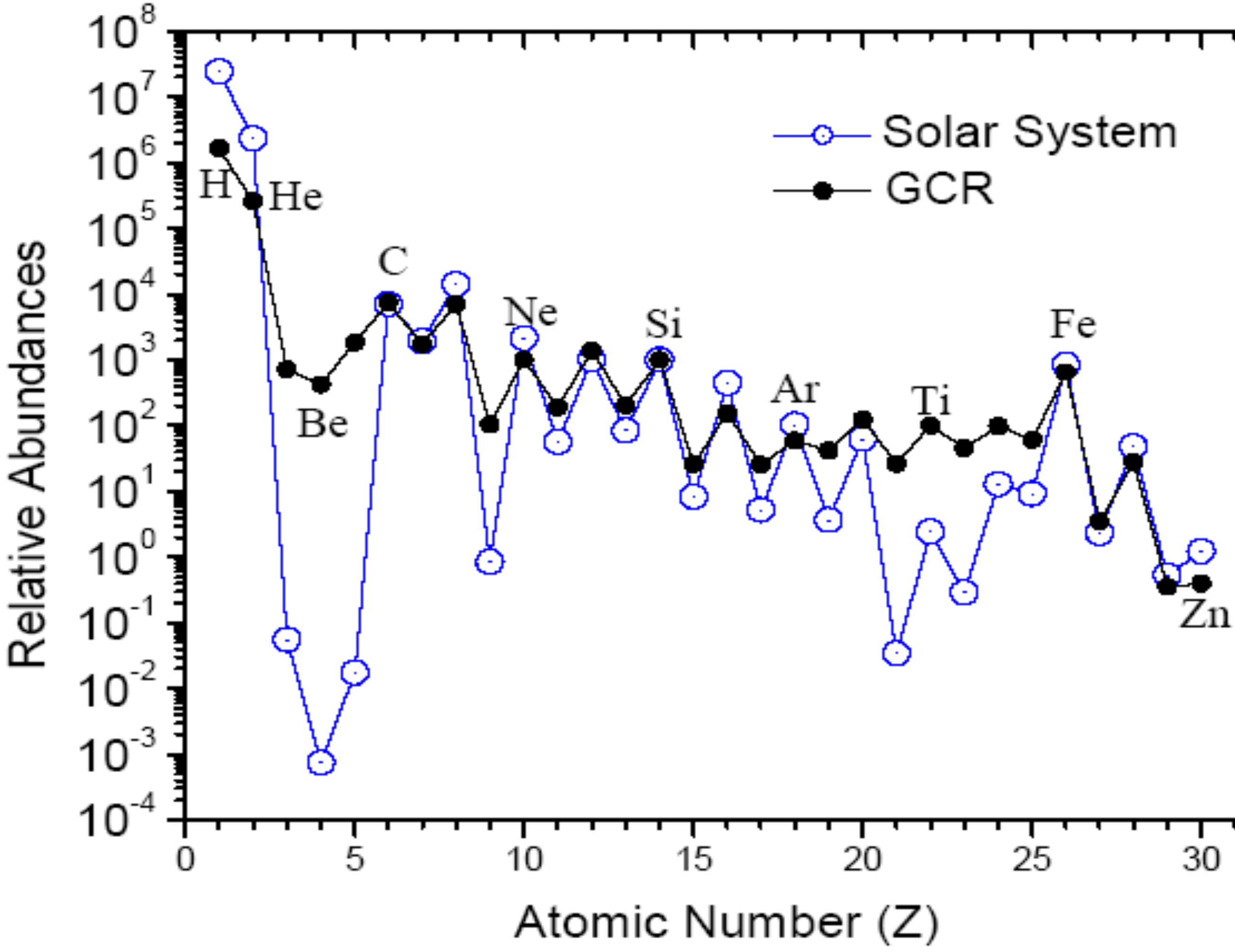
20% He

Rigidity

$$R = \frac{pc}{Ze} = r_L B \,.$$

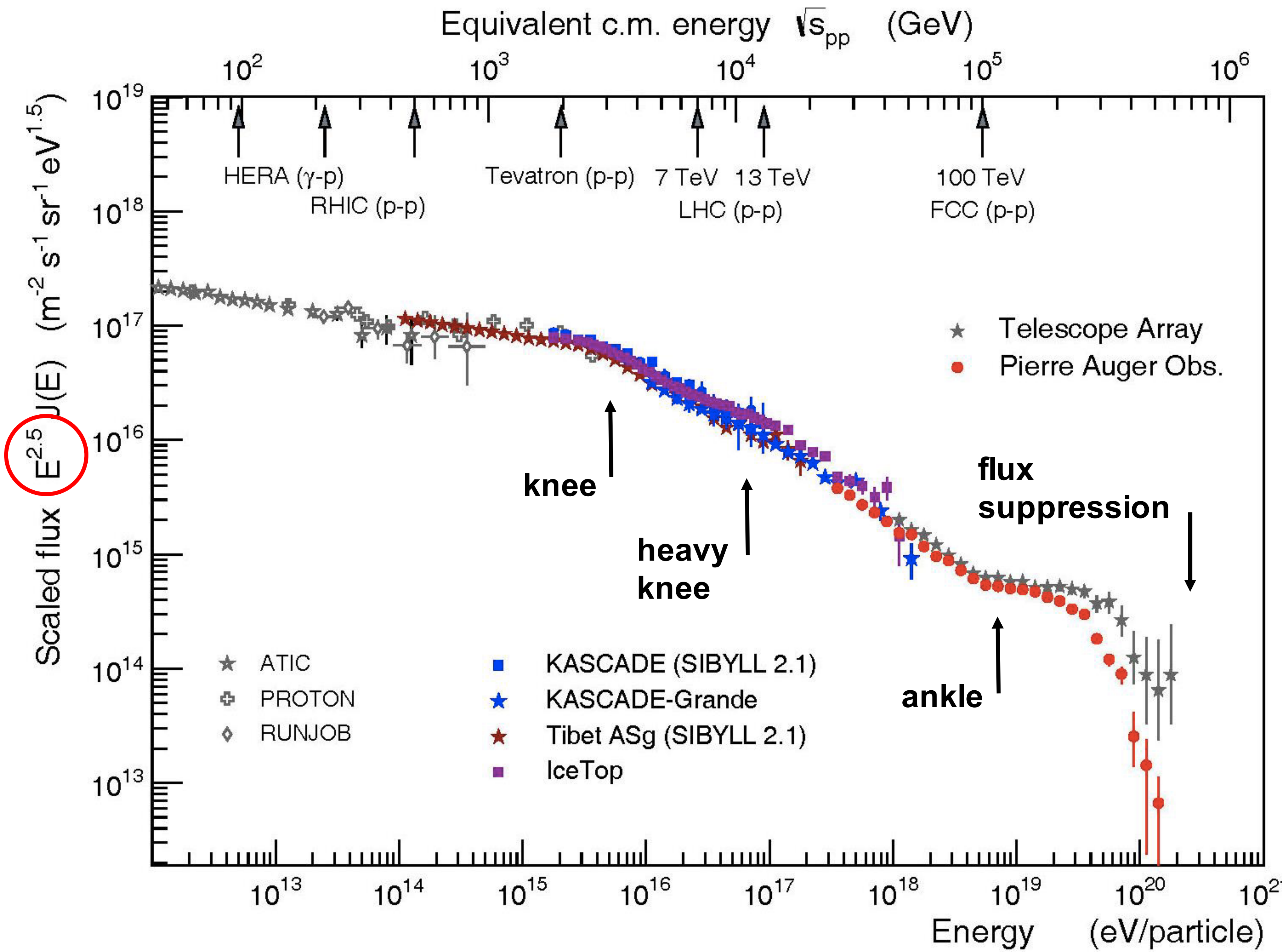
J. Beringer et al (PDG) PR D86 010001 (2012)

Solar vs Galactic Cosmic Rays

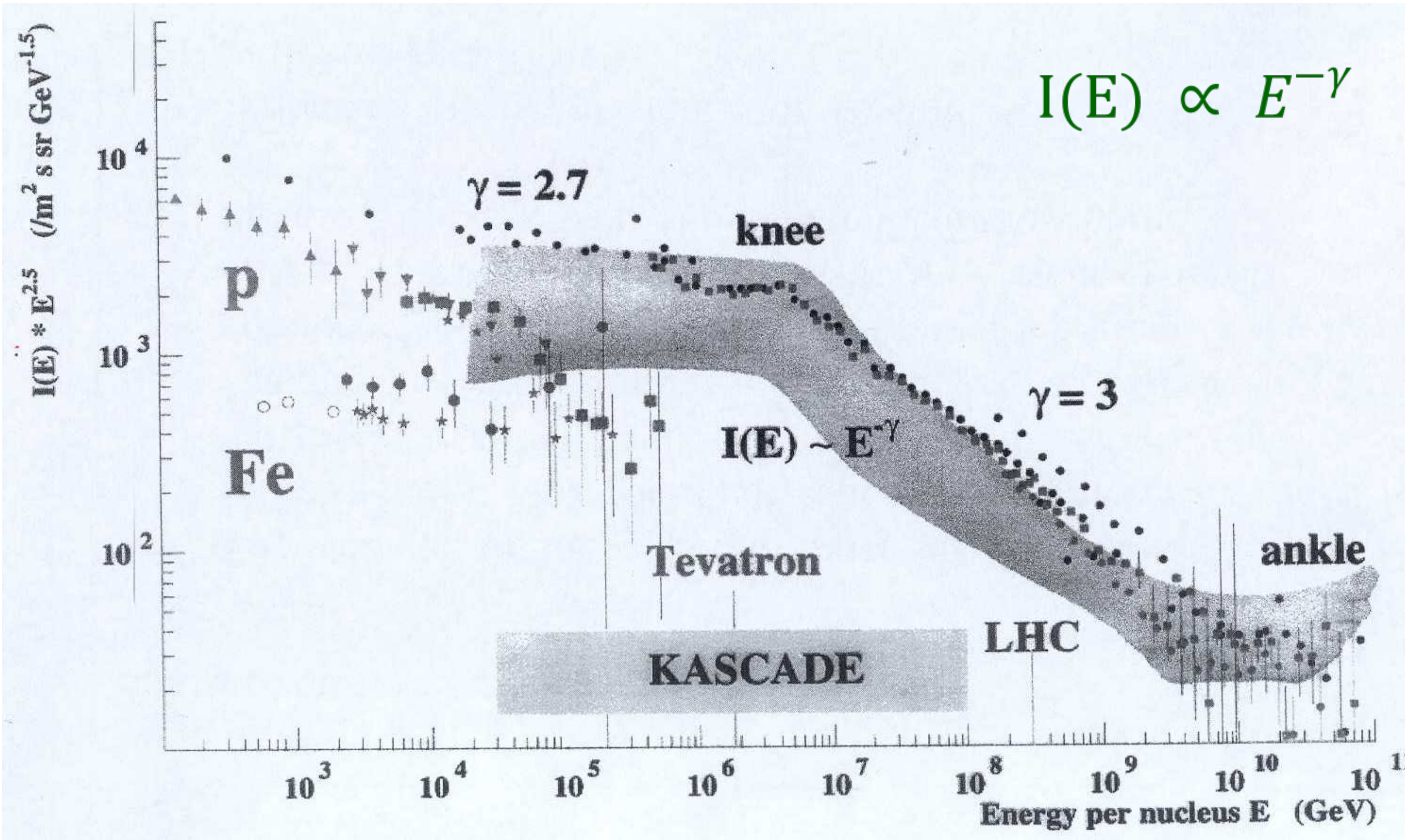


ACE News 83 (2004) - NASA

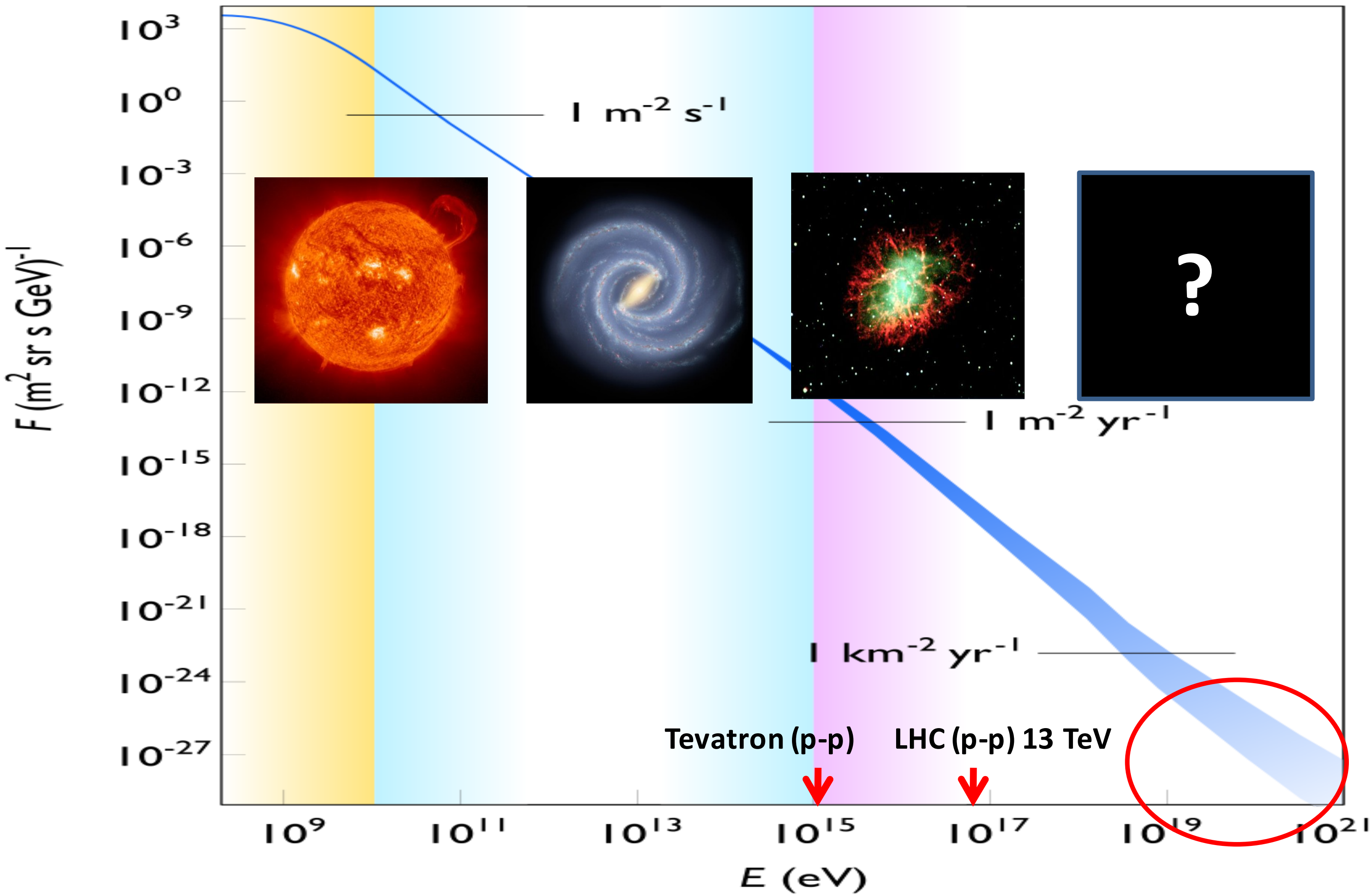
Energy spectrum (E >10^{14} eV)



Anthropomorphic representation



Origin ! ?



1 m-2 s-1
1 m-2 yr-1
1 km-2 yr-1
?
Tevatron (p-p)
LHC (p-p) 13 TeV
F (m2 sr s GeV)-1
E (eV)

Zwicky conjectures (1933)

(Zwicky in1930)

1. Heavy enough stars collapse at the end of their lives into super-novae
2. Implosions produce explosions of cosmic rays
3. They leave behind neutron stars

Origin (E ~<10^{15} eV)?

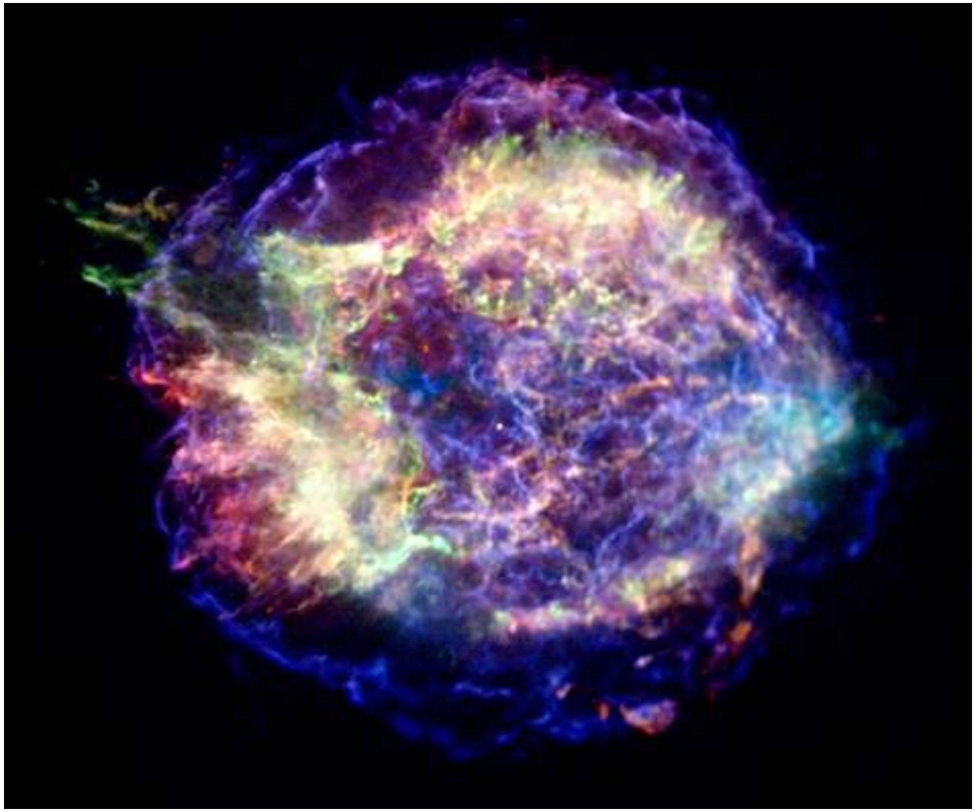
Energy density (cosmic rays)

$$\rho_E \sim \int E \frac{dN}{dE} dE \sim 10^{-12}\,\mathrm{erg}/cm^3$$

$$\sim 1\,\mathrm{eV}/cm^3$$

$$P \sim \frac{\rho_E V_{galaxy}}{\tau_{esc}} \sim 5.10^{40} erg/s$$

For example, power dissipated by a Supernova (the remnant of a collapsed star) of 10 $M_{sun.}$

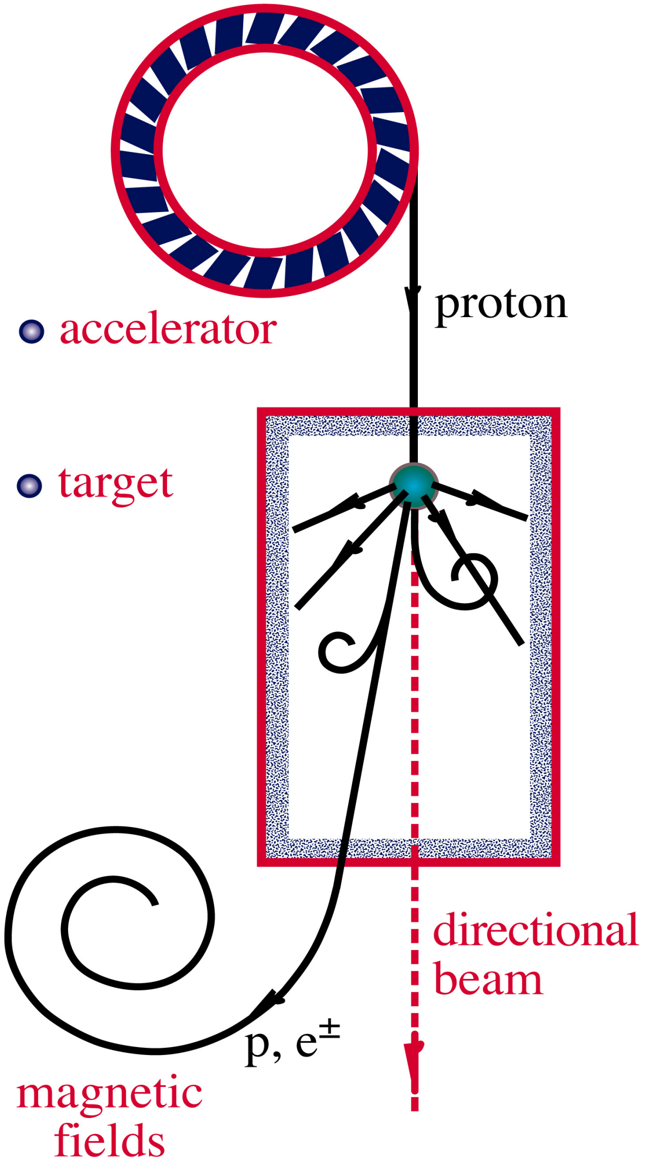


E ~10^{53} erg

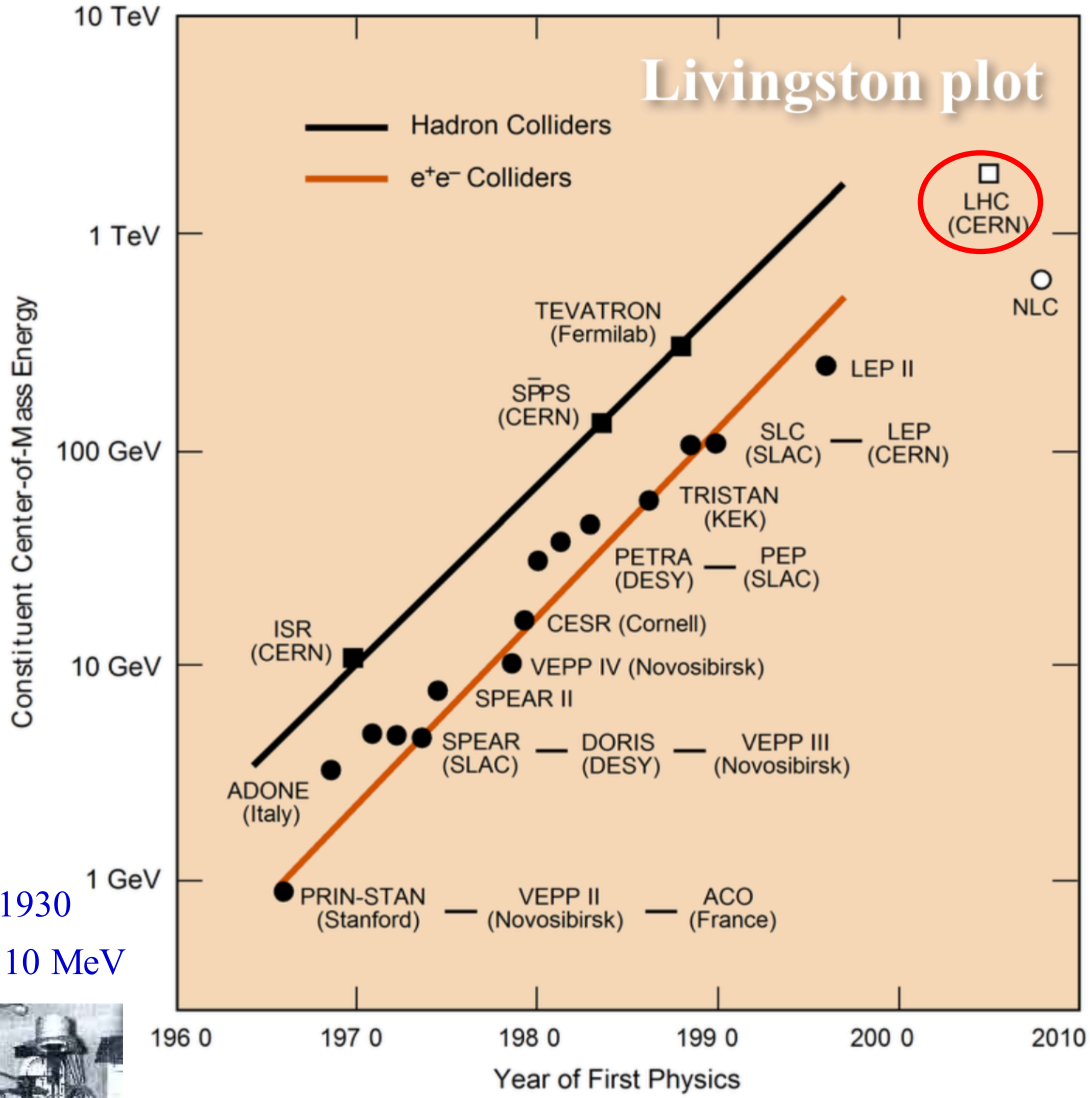
Supernovae in our Galaxy

1 SN ~30 Years ~10^{-9} s^{-1}

Charged particle production



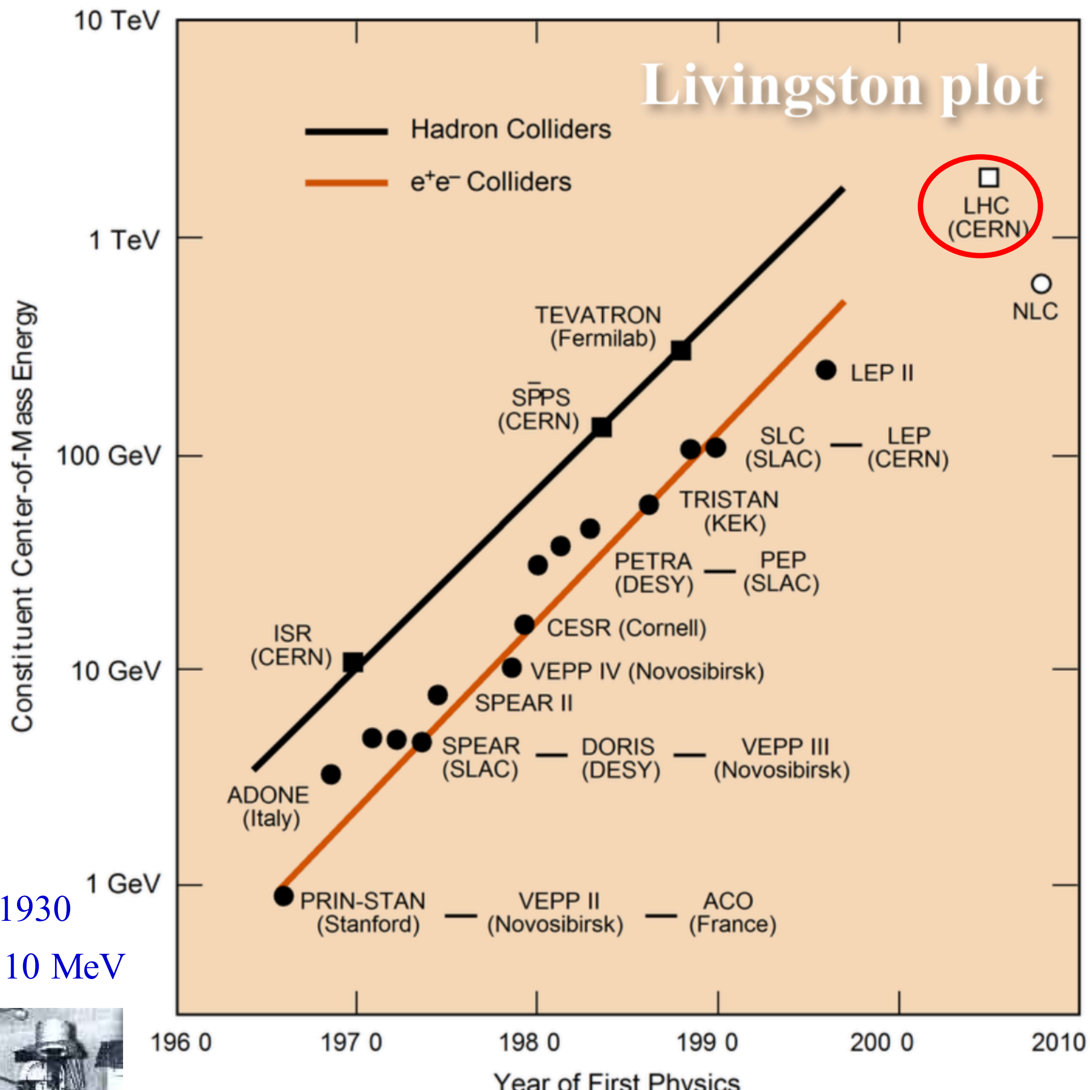
Human-made accelerators



~1930

~ 10 MeV

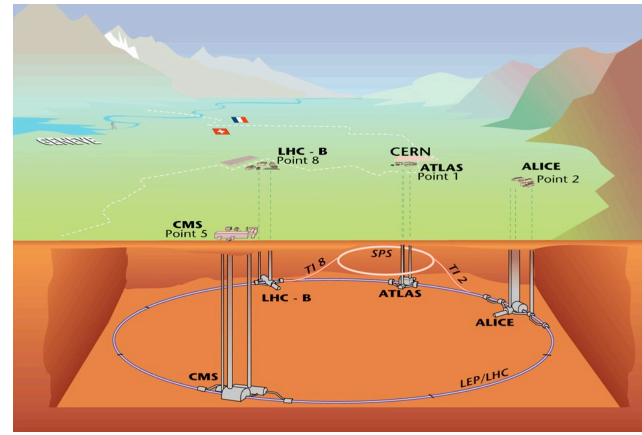
Human-made accelerators



~1930

~ 10 MeV

The Large Hadron Collider (LHC)



R ~10 km, B ~ 10 T

E $\propto$ BR ~ 10 TeV

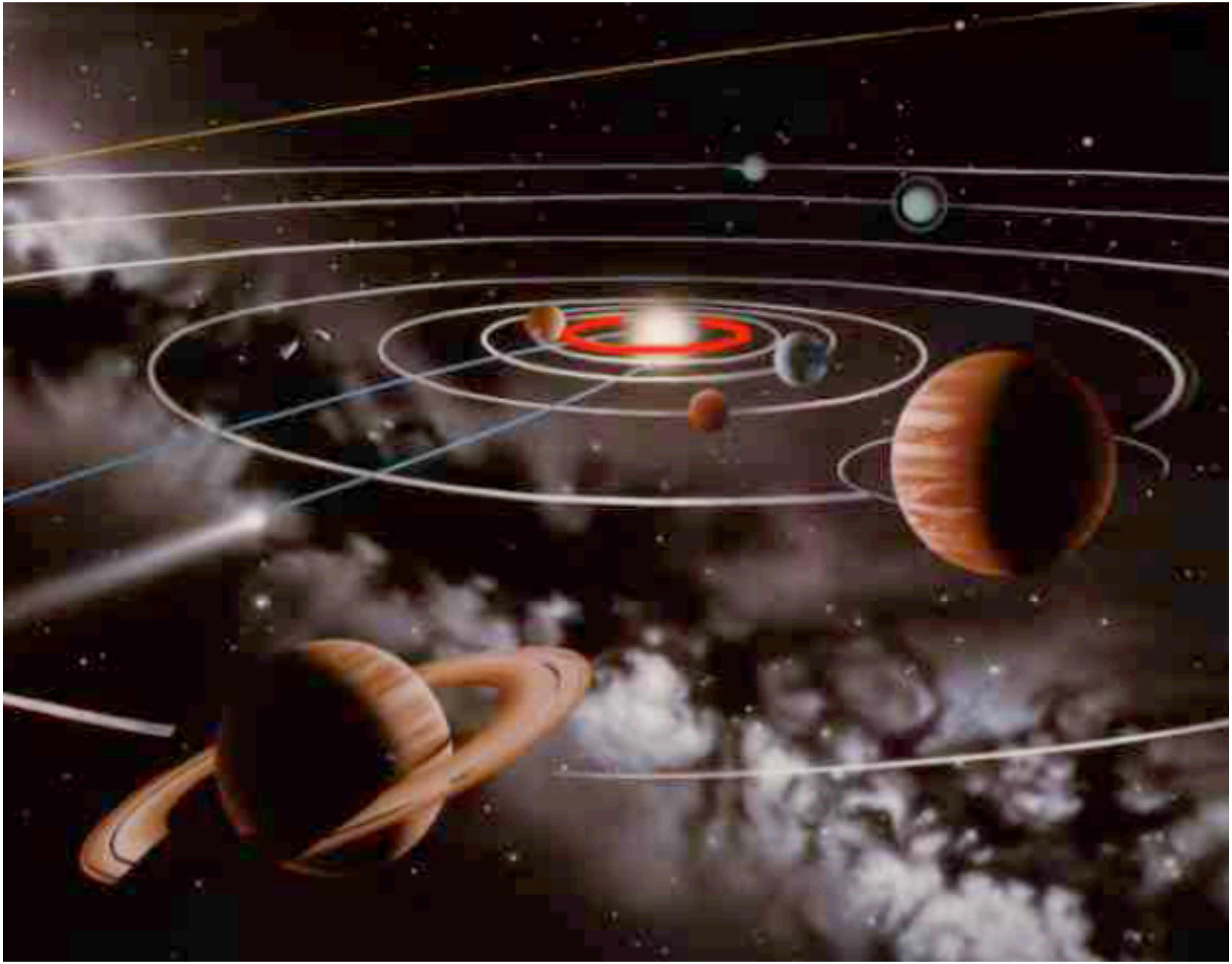
High Luminosity

Sophisticated detectors

Central region

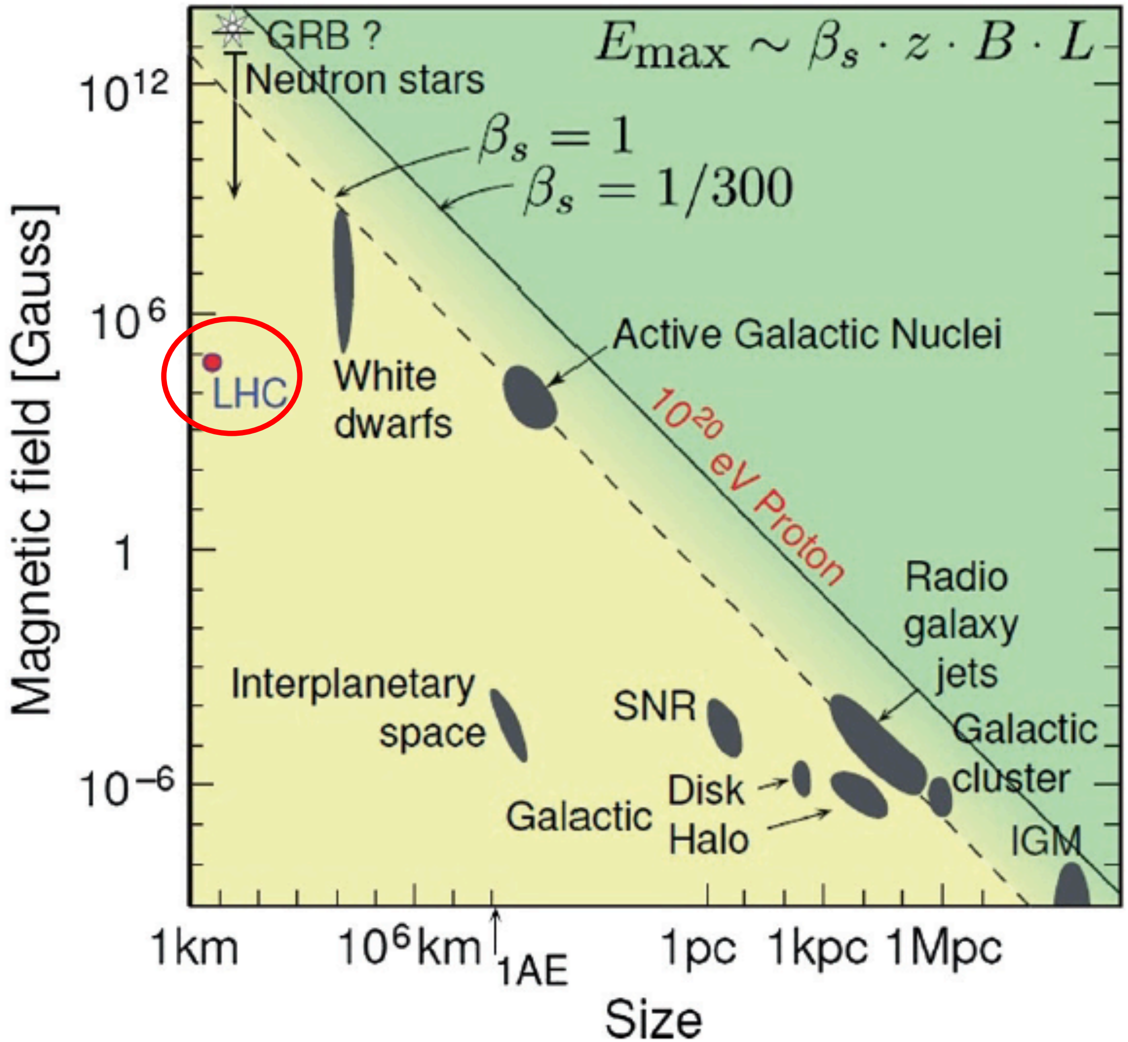
Energy limited

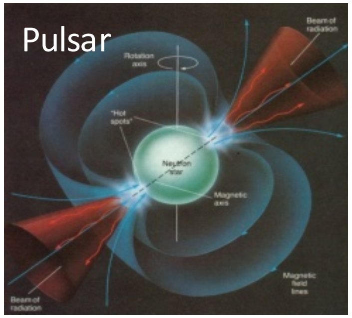
A Mercury orbit LHC !

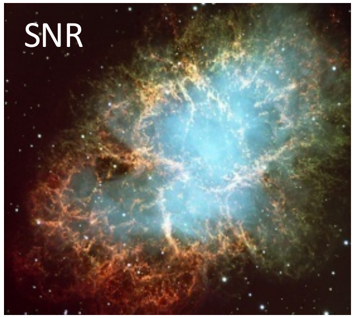


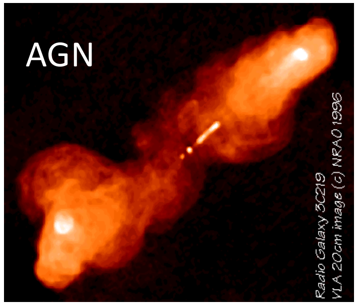
Where can be these accelerators in the Universe?

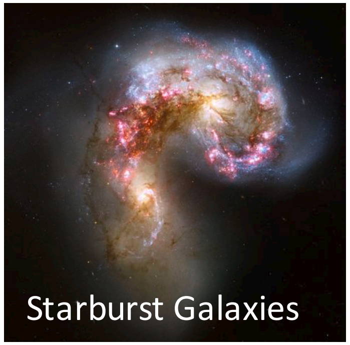
Hillas plot





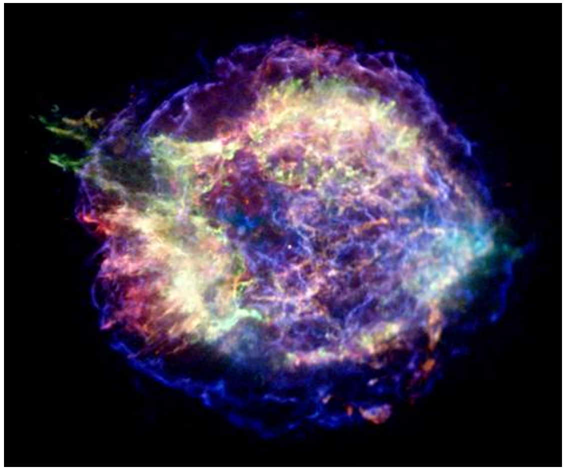




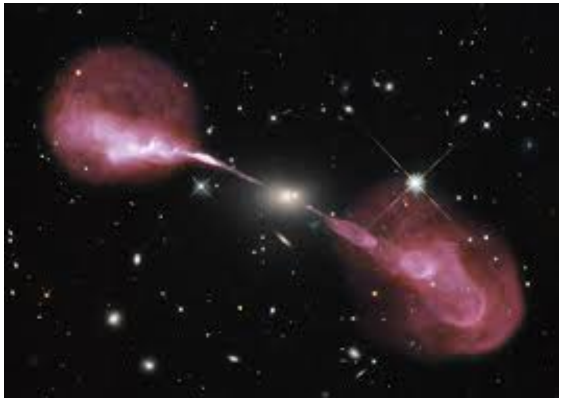


Pulsars, SNRs, AGNs

- Stellar end-products. A star heavier than the Sun collapses at the end of its life into a neutron star (R ~ few km, which can be pulsating – a pulsar) or into a BH, and ejects material in an explosion (SuperNova Remnant).
  - Very large B fields are in the pulsar; magnetic fields also in the SNR

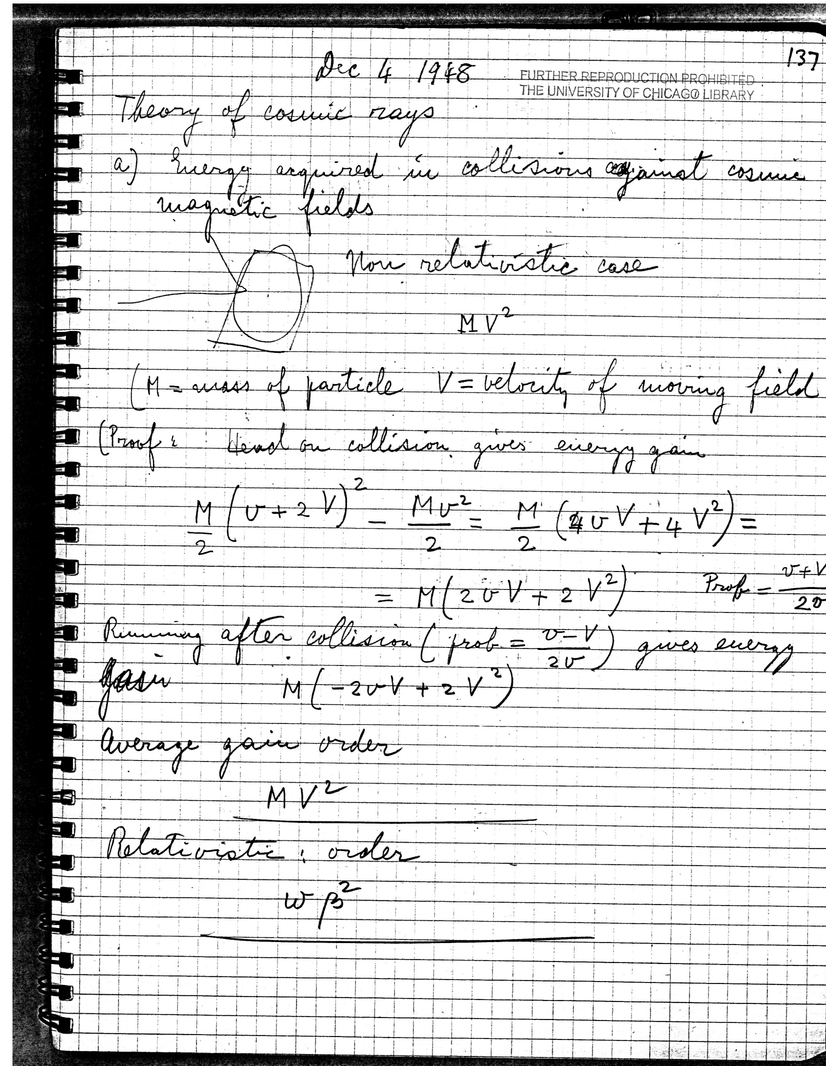


- The centres of galaxies host black holes, often supermassive (millions or even billion solar masses). They might accrete at the expense of the surrounfing matter, and accelerate particles in the process. When they are active, they are called Active Galactic Nuclei.



How to generate bottom-up energies much higher than thermal?

Enrico Fermi, Werner Heisenberg and Wolfgang Pauli



137

Dec 4 1948

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV + 2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision $\left(\text{prob} = \frac{v-V}{2v}\right)$ gives energy gain

$$M(-2vV + 2V^2)$$

Average gain order

MV^2

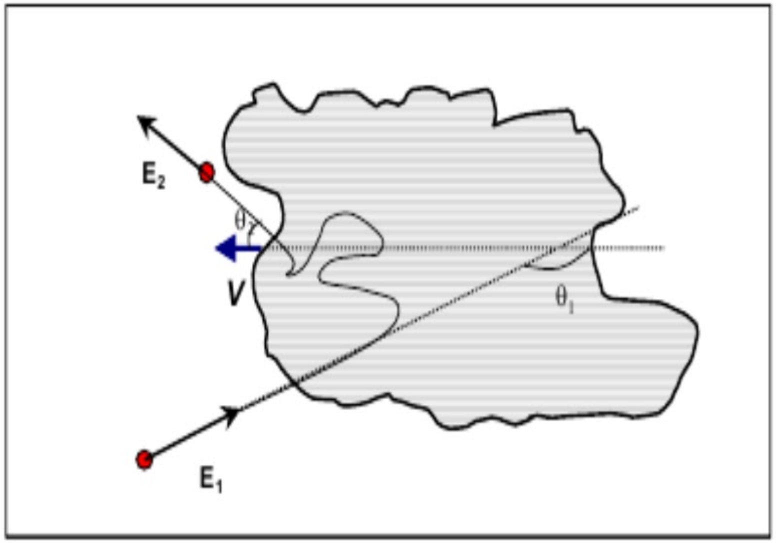
Relativistic: order

$w\beta^2$

Acceleration mechanism

Fermi 2nd order (1949)

particles accelerated in stochastic collisions with massive interstellar clouds (collisions to a moving diffusive wall!)



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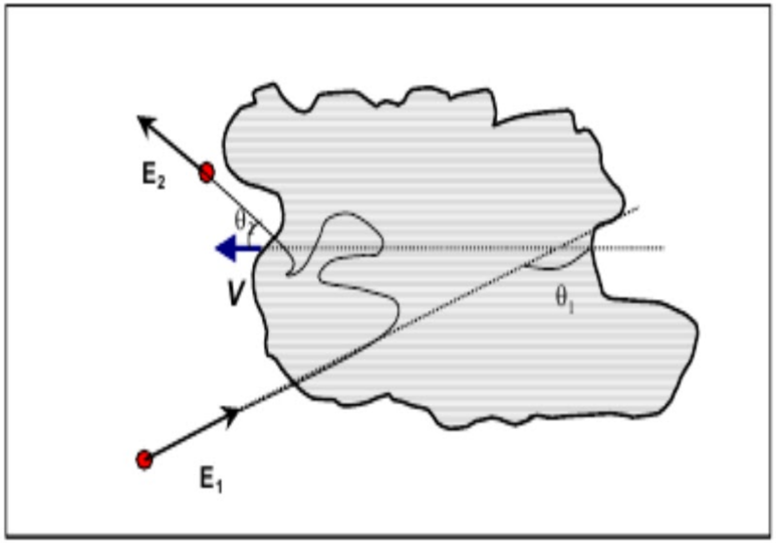

In the cloud reference frame

$$E_1^* = \gamma\, E_1 (1 - \beta \cos\theta_1)$$
$$E_2^* = E_1^*$$

Back to the Lab reference frame

$$E_2 = \gamma\, E_2^* \,(1 + \beta \cos\theta_2^*)$$

Then:

$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2^* - \beta^2 \cos\theta_1 \cos\theta_2^*}{1 - \beta^2} - 1$$

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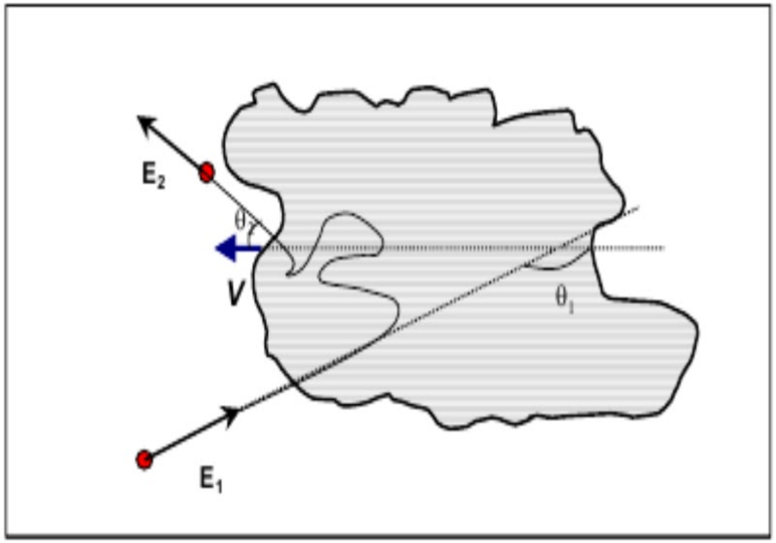

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But:

$$\langle \cos\theta_2^* \rangle = 0$$

Probability

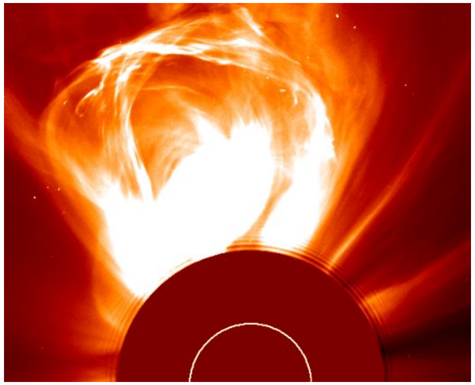
$$\langle \cos\theta_1 \rangle = \frac{\int_{-1}^{1} \cos\theta_1 (1 - \beta\cos\theta_1)\, d\cos\theta_1}{\int_{-1}^{1} (1 - \beta\cos\theta_1)\, d\cos\theta_1} = -\frac{\beta}{3}$$

$$\left\langle \frac{\Delta E}{E} \right\rangle \simeq \frac{4}{3}\beta^2$$

$\beta \sim 10^{-4}$!!!

Acceleration mechanism

Solar coronal mass ejection 9 Mar 2000



Fermi 1st order

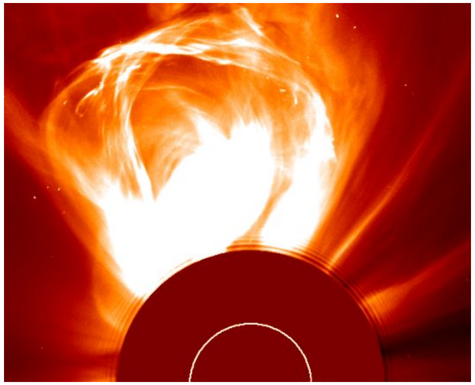
Shock formation :

- Sudden release of Energy (CMEs, SNRs, GRBs,…)
- Supersonic flow hits an obstacle (AGNs jets, pulsar winds, …)

Acceleration mechanism

Fermi 1st order

Solar coronal mass ejection 9 Mar 2000

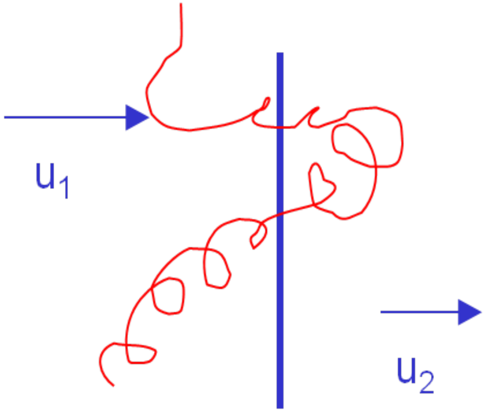


Shock formation :

- Sudden release of Energy (CMEs, SNRs, GRBs,…)
- Supersonic flow hits an obstacle (AGNs jets, pulsar winds, …)

Particles gain energy by consecutive crossings of the shock front!

$$\frac{\Delta E}{E} = \frac{1 - \beta \cos\theta_1 + \beta \cos\theta_2^* - \beta^2 \cos\theta_1 \cos\theta_2^*}{1 - \beta^2} - 1$$



Acceleration mechanism

Fermi 1st order

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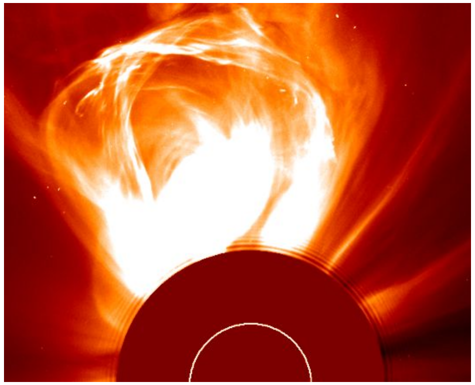

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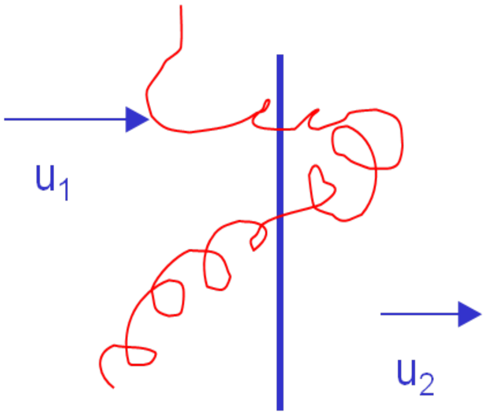


$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2^* - \beta^2\cos\theta_1\cos\theta_2^*}{1-\beta^2} - 1$$

Crossing probability α cos(θ)

Now (plane shock front):

$$\langle\cos\theta_1\rangle = \frac{\int_{-1}^{0}\cos^2\theta_1\, d\cos\theta_1}{\int_{-1}^{0}\cos\theta_1\, d\cos\theta_1} = -\frac{2}{3}$$

$$\langle\cos\theta_2^*\rangle = \frac{\int_{0}^{1}\cos^2\theta_2^*\, d\cos\theta_2^*}{\int_{0}^{1}\cos\theta_2^*\, d\cos\theta_2^*} = \frac{2}{3}$$

$$\left\langle\frac{\Delta E}{E}\right\rangle \simeq \frac{4}{3}\beta$$

The power law

In each cycle the particle gains a small fraction of energy ε. After n cycles:

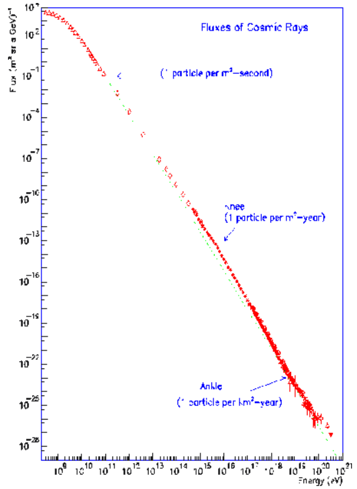
$$E_n = E_0 (1+ \varepsilon)^n$$

Or the number of cycles to attain an energy E is:

$$n = \ln(E/E_0)/\ln(1+\varepsilon)$$

$$\frac{dN}{dE} \propto E^{-\gamma}$$

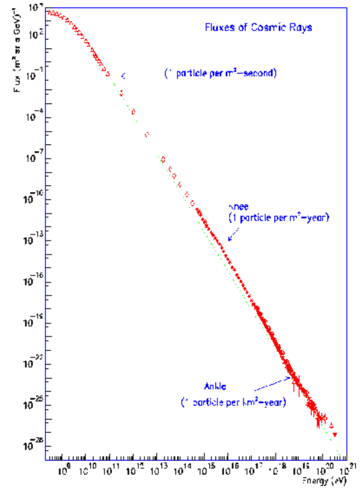
$$(N > E) \propto E^{-\gamma+1}$$



The power law

$$\frac{dN}{dE} \propto E^{-\gamma}$$

$$\left(N > E\right) \propto E^{-\gamma+1}$$



In each cycle the particle gains a small fraction of energy ε. After n cycles:

$$E_n = E_0 (1+ \varepsilon)^n$$

Or the number of cycles to attain an energy E is:

$$n = \ln(E/E_0)/\ln(1+\varepsilon)$$

The particle may escape from the shock region with some probability P_i .Then the probability to escape with $E>E_n$ is:

$$P_{E_n} = P_i \sum_{j=n}^{\infty} (1-P_i)^n = (1-P_i)^n$$

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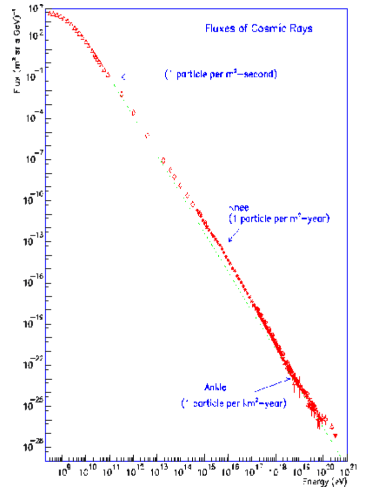

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$$P_{E_n} = (1-P_e)^{\ln\left(\frac{E}{E_0}\right)/\ln(1+\epsilon)}$$

$$\ln P_{E_n} = \frac{\ln\left(\frac{E}{E_0}\right)}{\ln(1+\epsilon)} \ln(1-P_e) = \frac{\ln(1-P_e)}{\ln(1+\epsilon)} \ln\left(\frac{E}{E_0}\right)$$

$$\frac{N}{N_0} = P_{E_n} = \left(\frac{E}{E_0}\right)^{-\alpha} \qquad \alpha = -\frac{\ln(1-P_i)}{\ln(1+\epsilon)} \cong \frac{P_i}{\epsilon}$$

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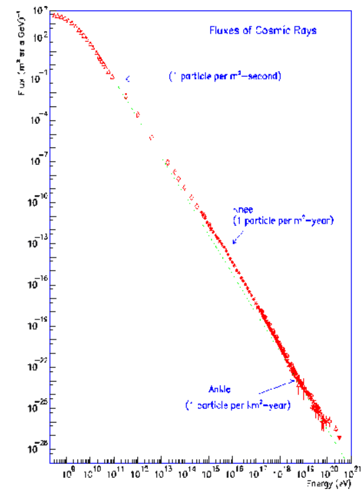

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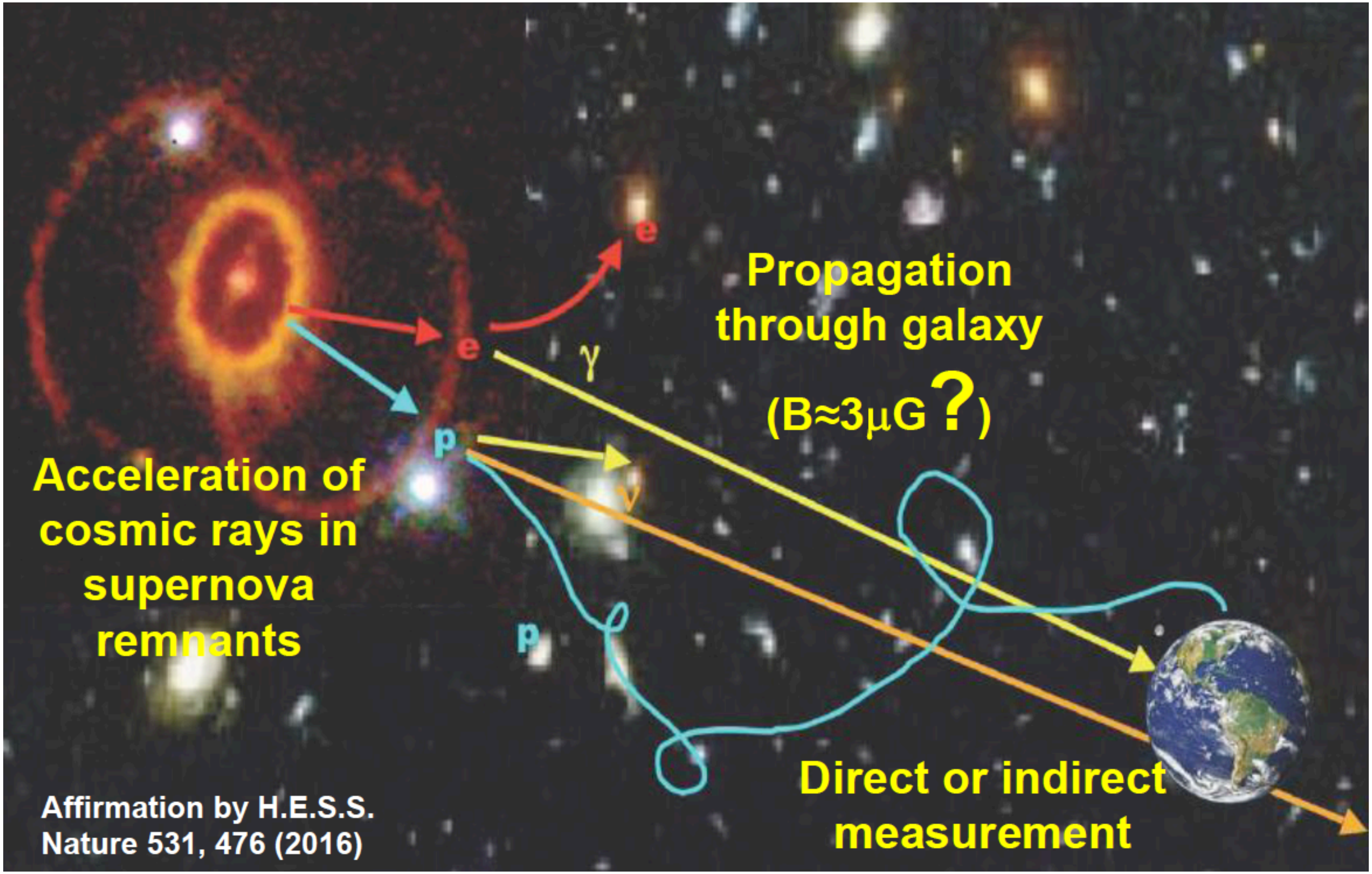
$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

$\gamma=\alpha+1$

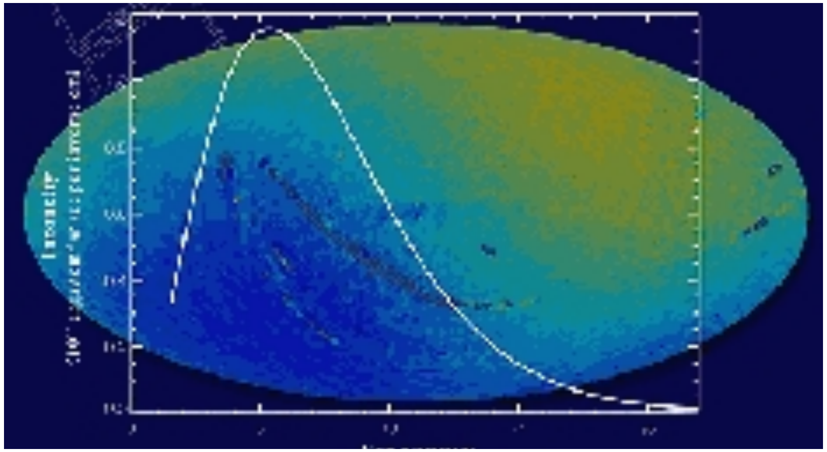
$$\left(\frac{dN}{dE}\right)_{Source} \approx E^{-2}$$

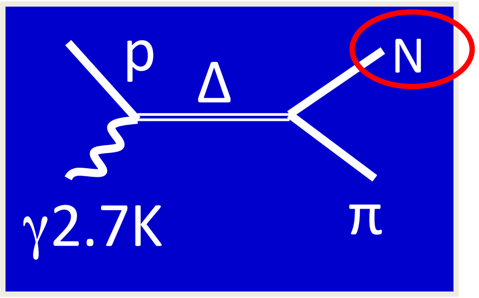
$$\left(\frac{dN}{dE}\right)_{Earth} \propto \left(\frac{dN}{dE}\right)_{Source} . \tau_{esc}(E) \propto E^{-2.7}$$

Propagation of cosmic rays



The Greisen-Zatsepin-Kuzmin (GZK) cutoff



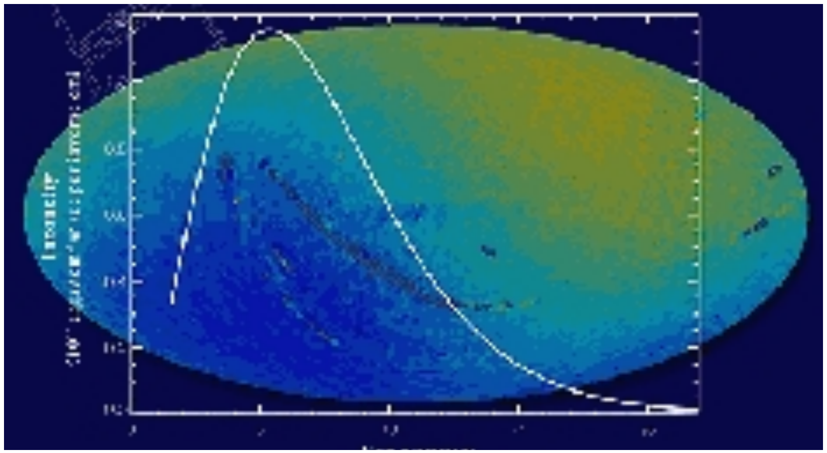


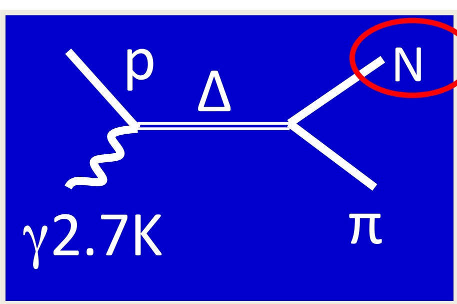
$$E_p \approx 10^{20}\,\mathrm{eV}$$

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

» 6 Mpc

The Greisen-Zatsepin-Kuzmin (GZK) cutoff





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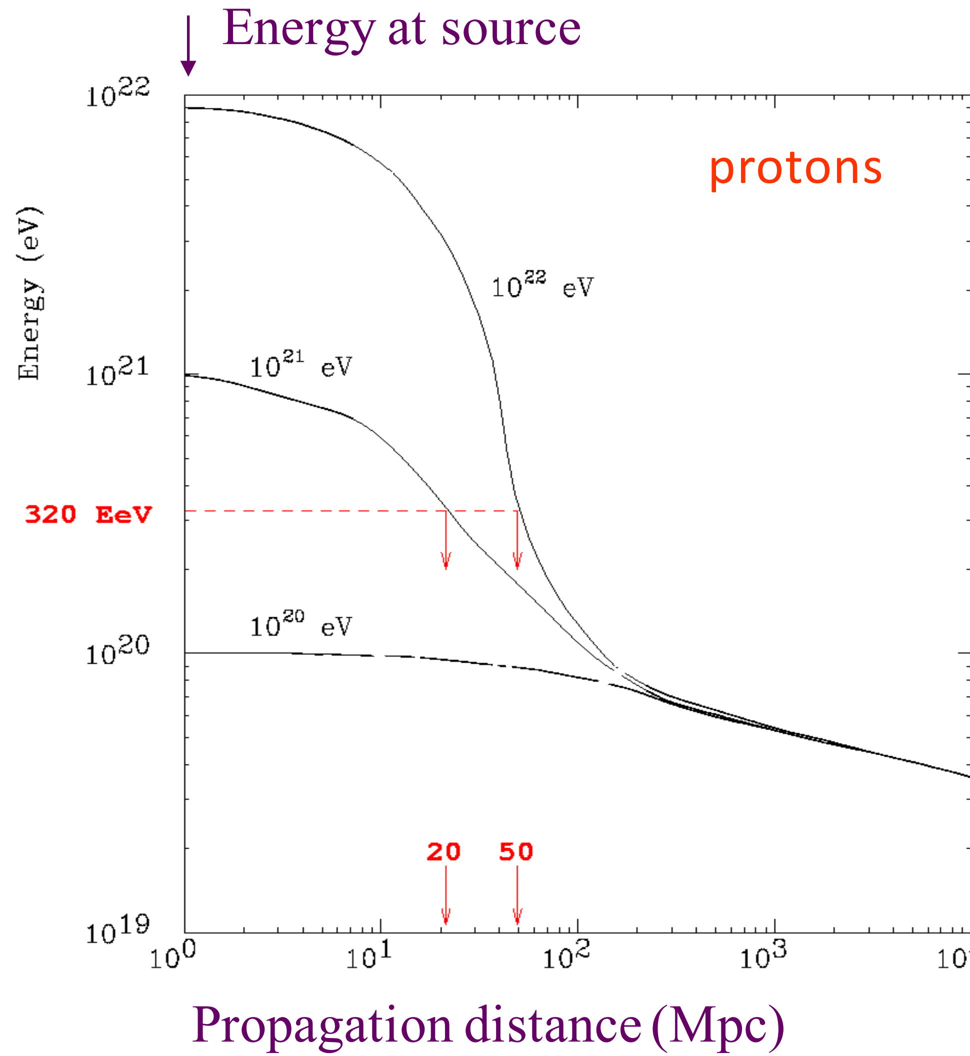

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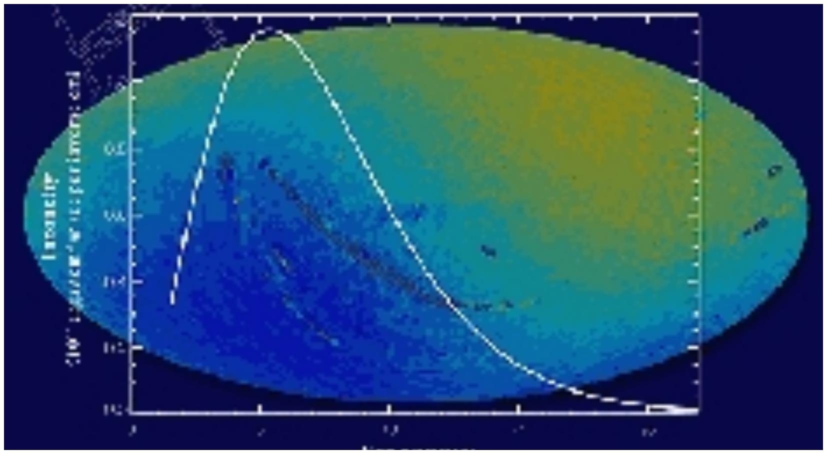

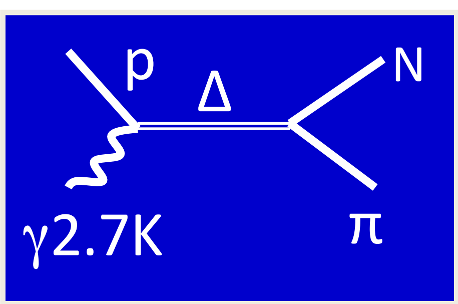

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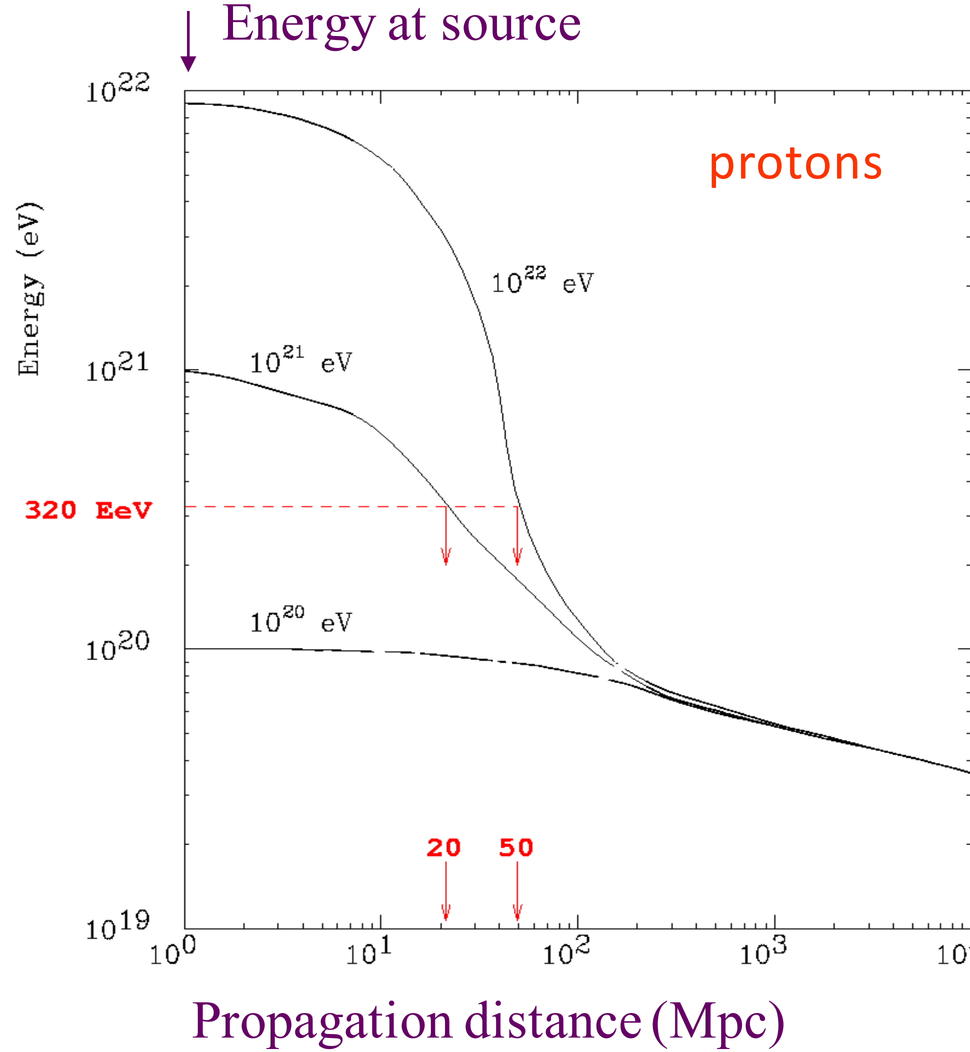
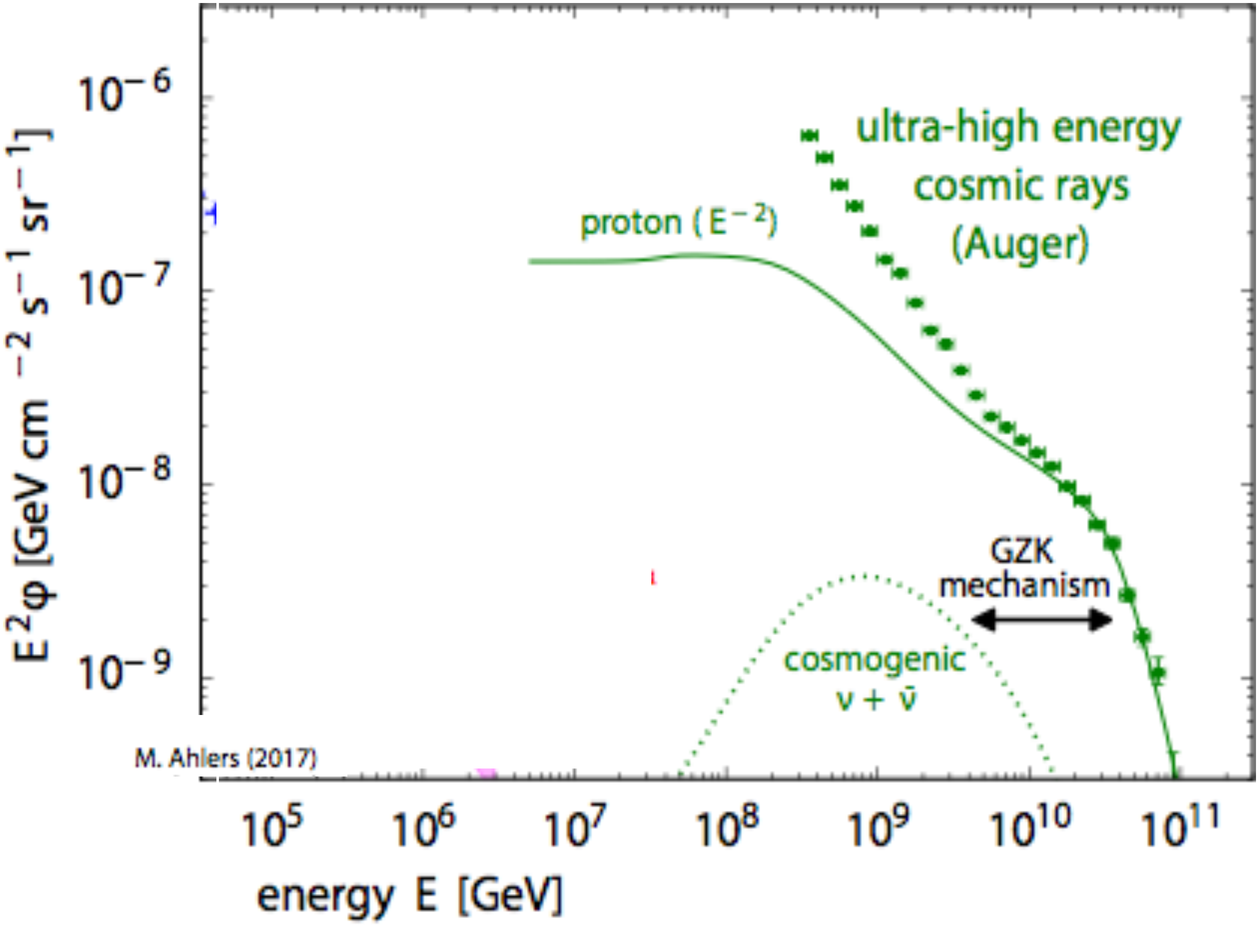


$\pi^0 \longrightarrow \gamma\gamma$

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

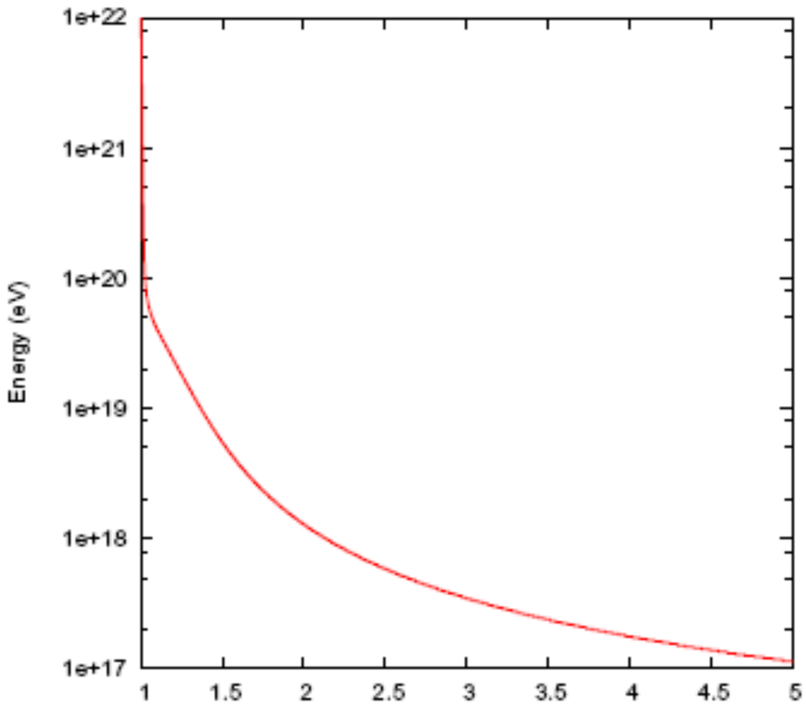
Predicted (and observed) Spectrum



No cosmogenic neutrinos observed so far

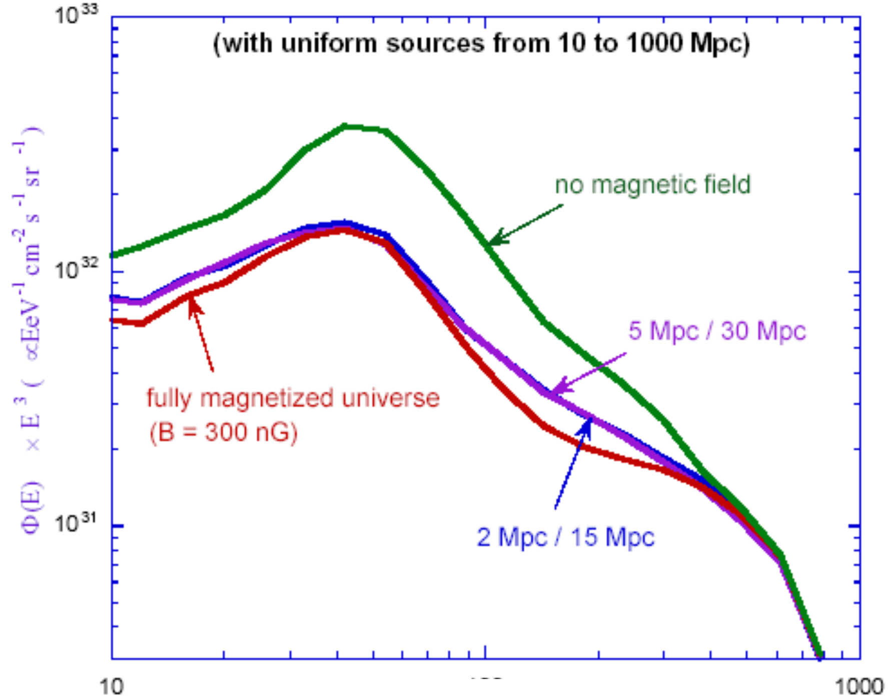
GZK is model dependent

GZK cutoff Energy – Stecker and Scully



1 + z

GZK and magnetic fields (protons)
Deligny, Parizot, Letessier-Selvon



Energy (in EeV)

Sources type and distribution

Primary composition

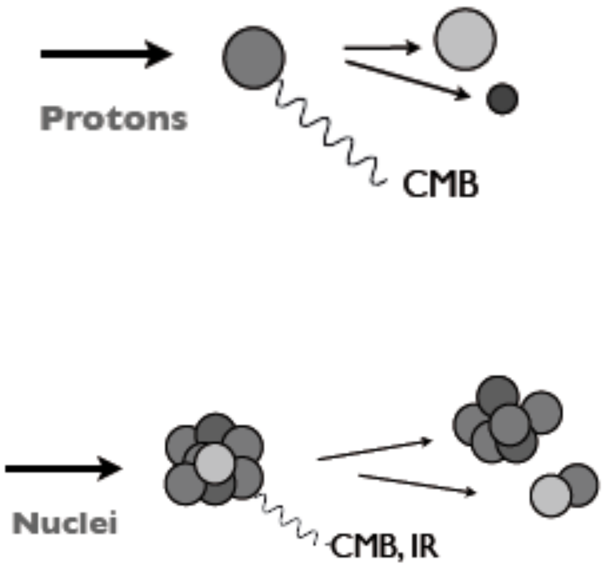
Magnetic fields

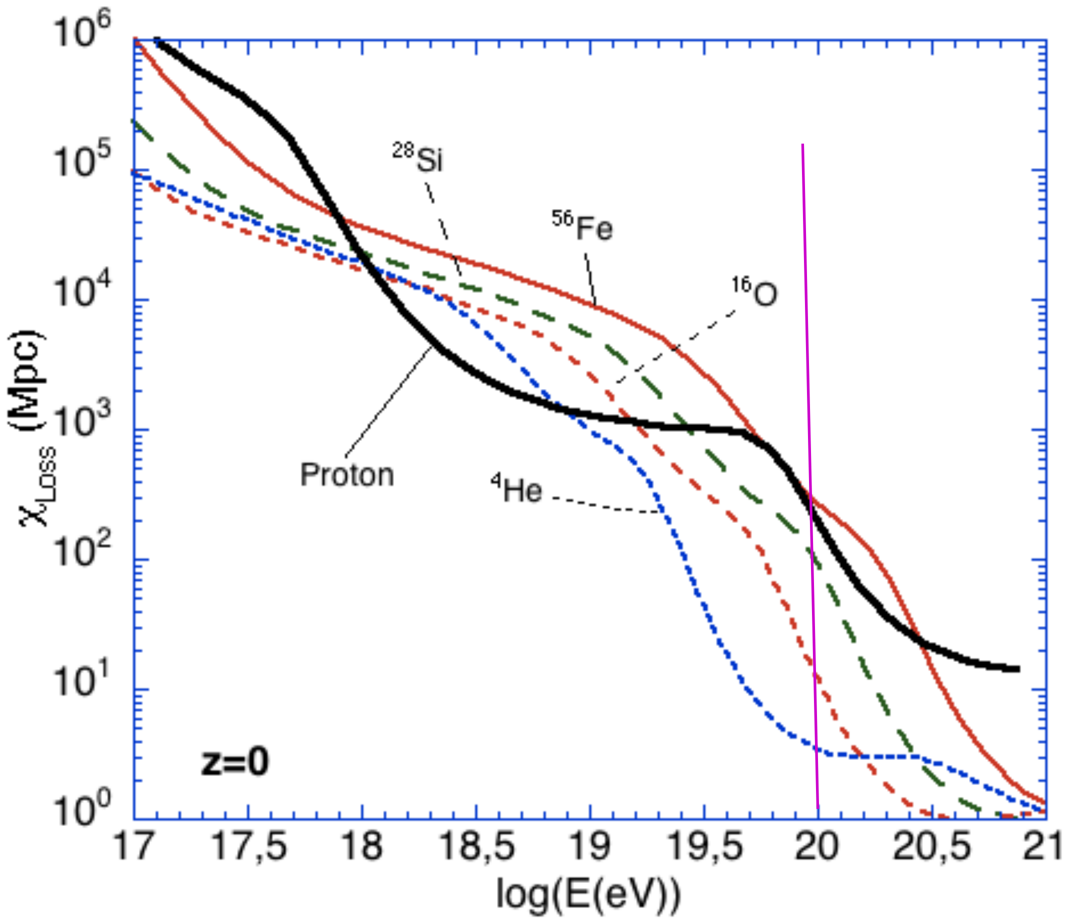
Not a true cutoff !

Pileup

Recovery of the spectrum at higher energies ?

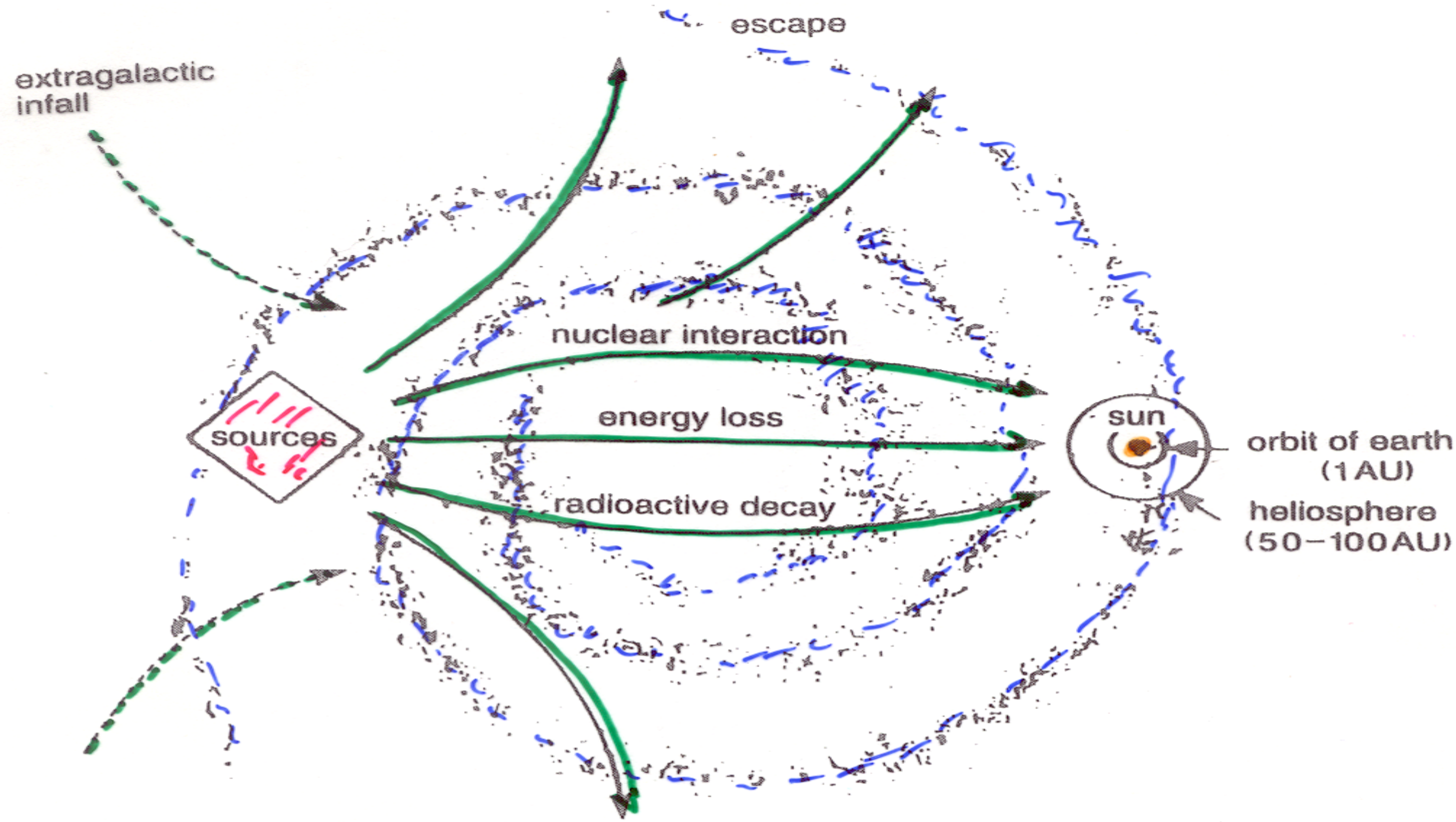
GZK vs nuclei photo-desimtegration





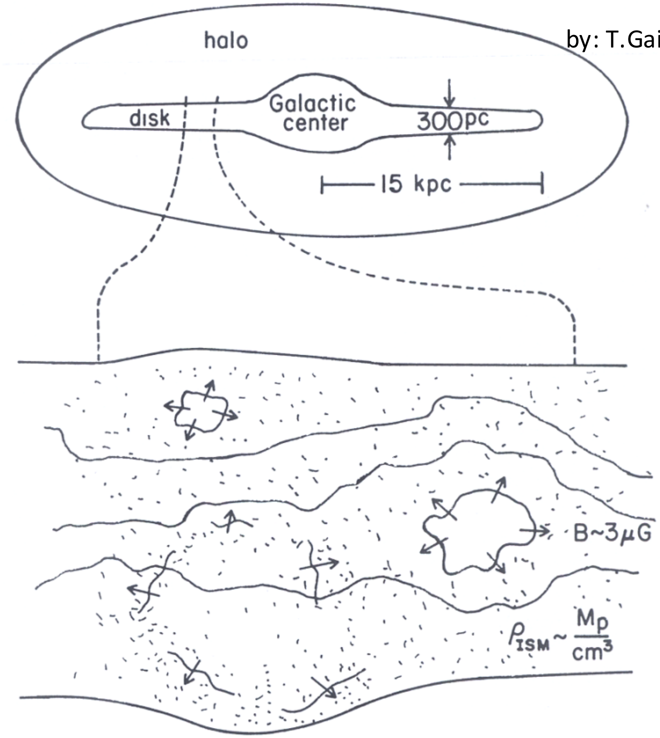
At 10^{20} eV proton and iron have similar attenuation lengths

The propagation in our galactic



Propagation

by: T.Gaisser



Charged cosmic rays diffuse and interact in the Galactic randomly magnetized ISM . Confinement times are quite long ($t\sim10^7$ years) and directions become basically isotropic.

Transport equation :

$$\frac{\partial N_i}{\partial t} = Q_i + \vec{\nabla}\cdot\left(D\,\vec{\nabla}N_i - \vec{V}\,N_i\right) + \frac{\partial}{\partial E}\left(b(E)N_i\right) - \frac{N_i}{\tau_i} + \sum_{j>i}\frac{P_{ji}N_j}{\tau_j} - \ldots$$

Sources

Diffusion

Convection

Energy gains and losses

escape

Spallation gains

Spallation and decay losses

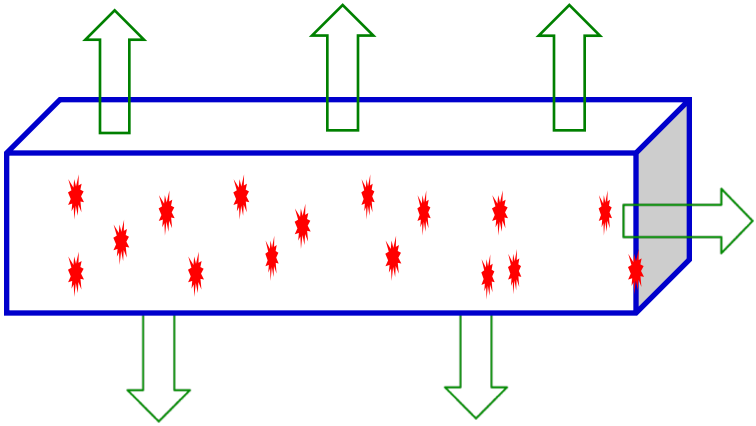
$$\frac{\partial N_i}{\partial t} = C_i + \nabla \cdot (D\nabla N_i - \mathbf{V} N_i) + \frac{\partial}{\partial E}\left(b\left(E\right) N_i\right) +$$

$$- \left(n\beta_i c\sigma_i^{\text{spall}} + \frac{1}{\gamma_i \tau_i^{\text{decay}}} + \frac{1}{\hat{\tau}_i^{\text{esc}}}\right) N_i +$$

$$+ \sum_{j>i} \left(n\beta_j c\sigma_{ji}^{\text{spall}} + \frac{1}{\gamma_j \tau_{ji}^{\text{decay}}}\right) N_j \,.$$

Leaky-Box

A box where charged cosmic rays freely propagates having however some probability to escape by the walls. The sources are uniformely distributed.



Interaction lengths >> escape length

Simplified stationary equation :

$$0 = Q_i + \sum_{j>i} N_j \left\{ \rho\beta c\, \sigma_{ji}^{spall} + \frac{1}{\gamma\tau_{ji}^{decay}} \right\} - N_i \left\{ \rho\beta c\, \sigma_{i}^{spall} + \frac{1}{\gamma\tau_{i}^{decay}} + \frac{1}{\tau_{i}^{esc}} \right\}$$

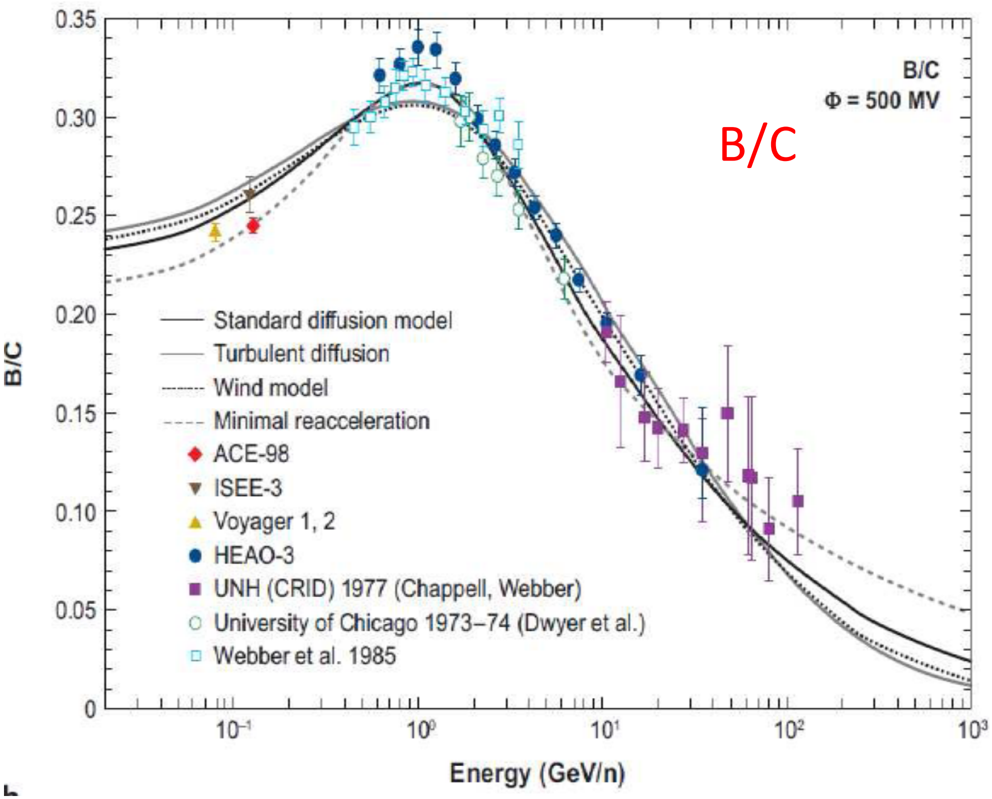
Sources

Spallation and decays gains

Spallation, decays and escape losses

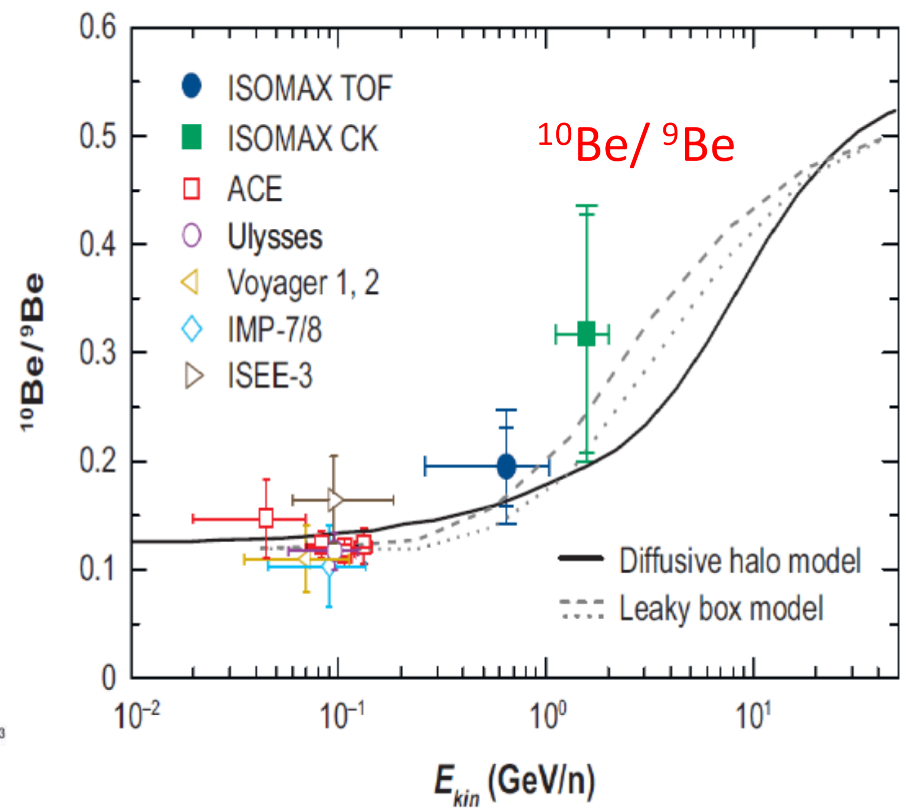
Constraining propagation models

Secondary/primary ratios



Box size, Diffusion coef., escape time, ...

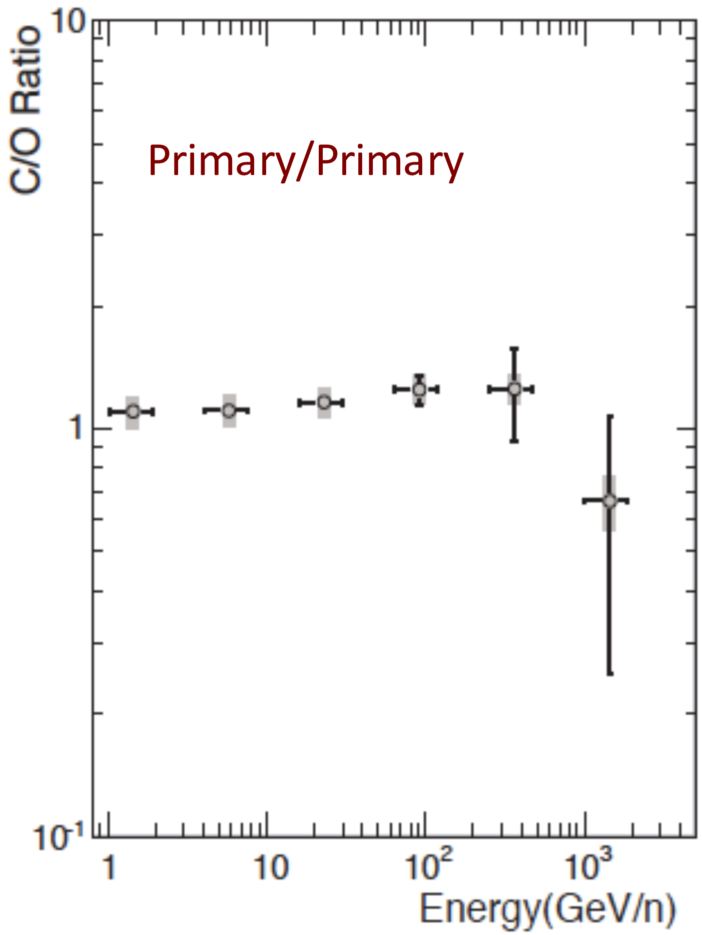
Unstable/stable isotopos

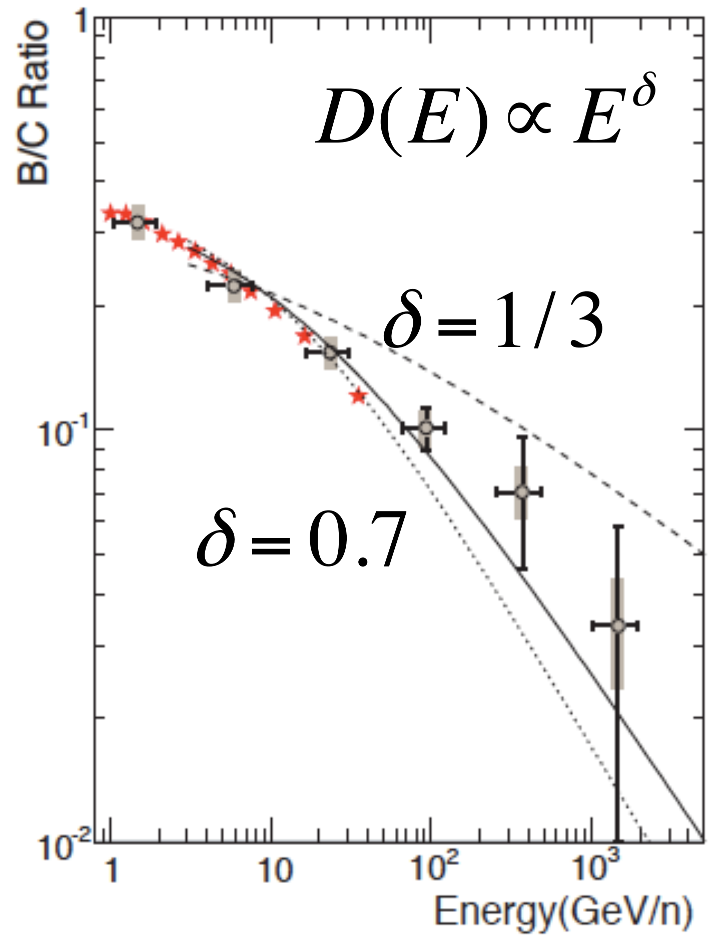


Radioactive clocks

Energy dependence (τ_{sc})

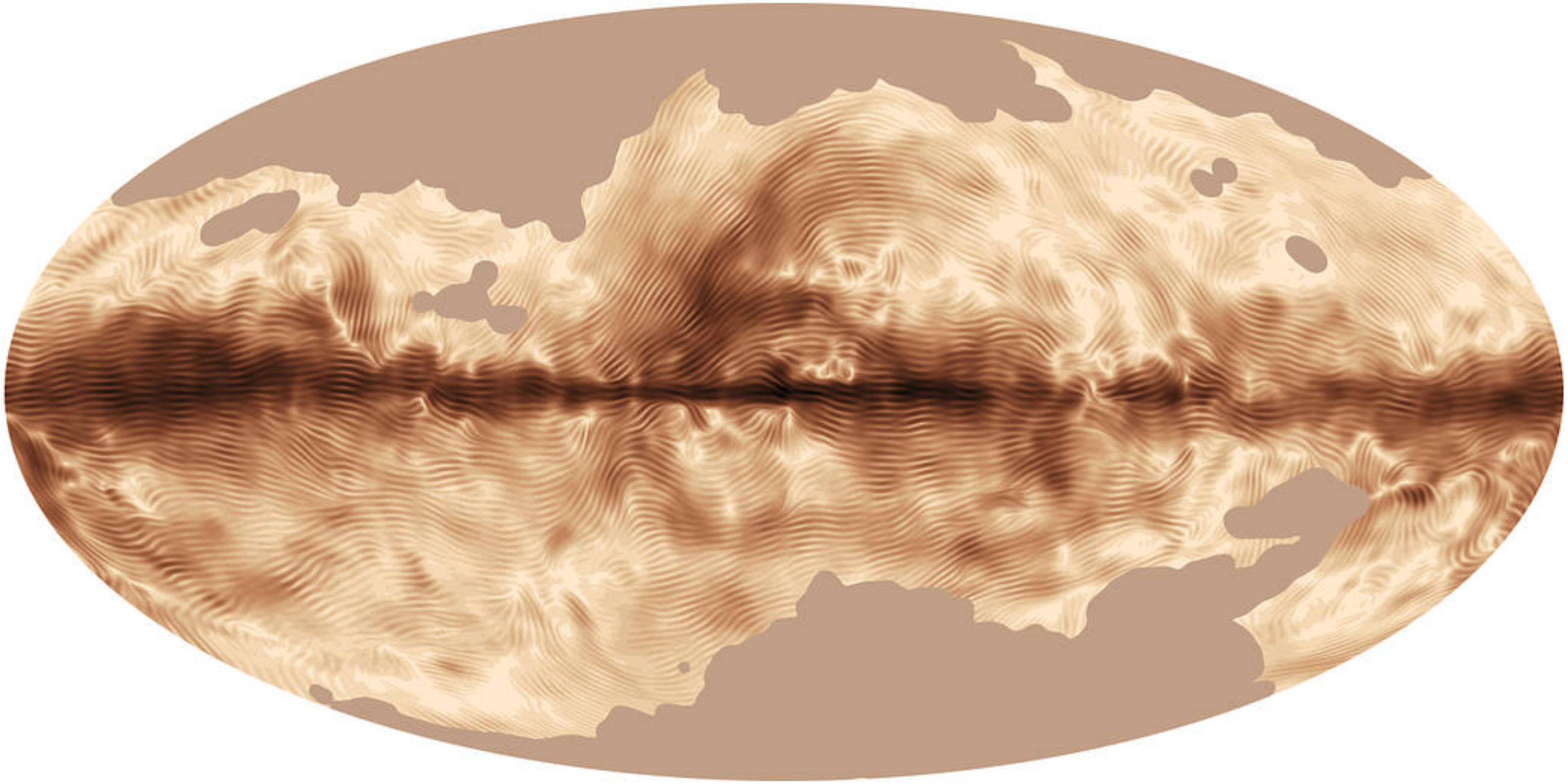
CREAM 2008





Milky Way Galactic Magnetic Field

as seen by Planck satellite

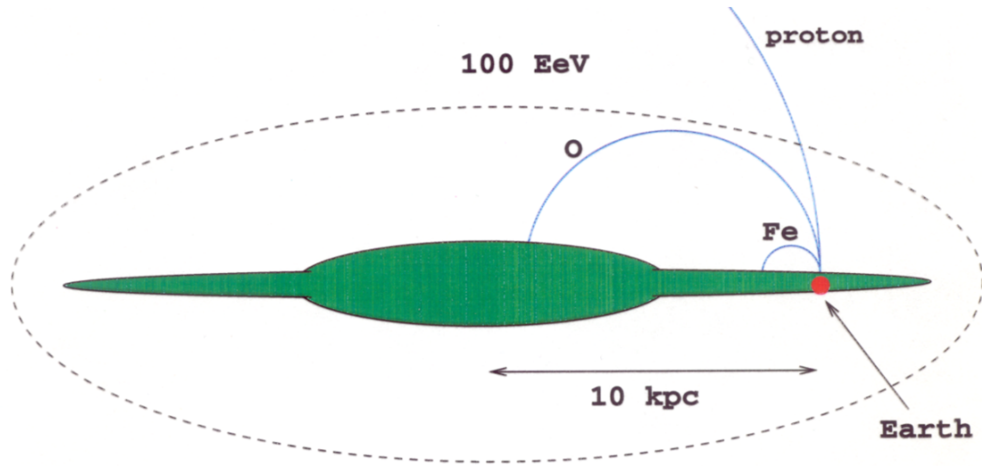


Galactic $B \sim 10^{-6}$ G
Extra-Galactic $B \leq 10^{-9}$ G

Confinement and composition

Magnetic Field:

Galactic ~ 1-3 μG
Intergalatic 1 nG > B > 1fG

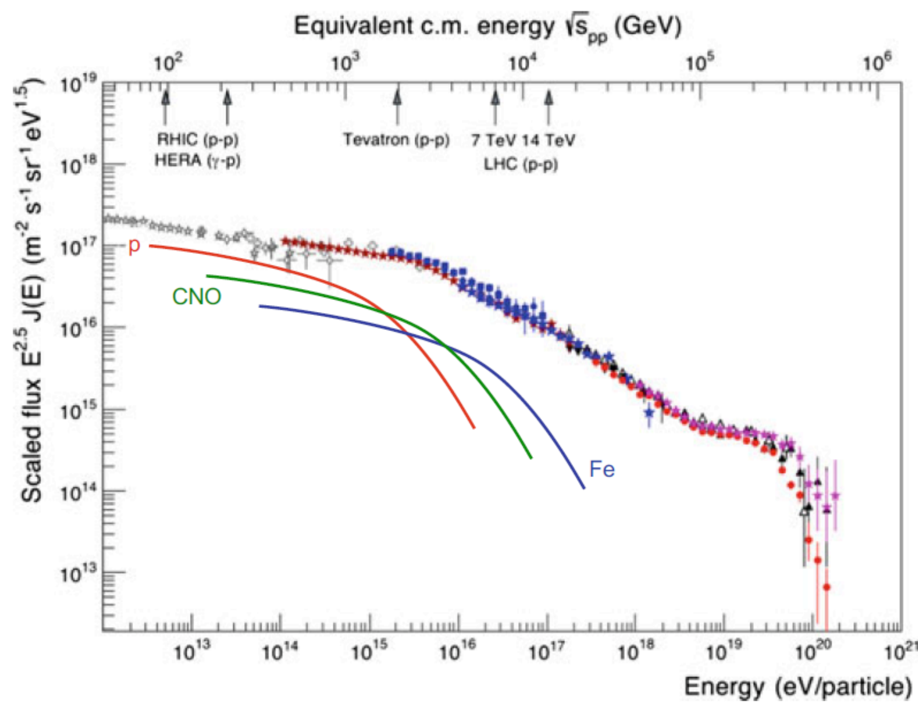


Larmor Radius:

$$R = \frac{E}{ZeB}$$

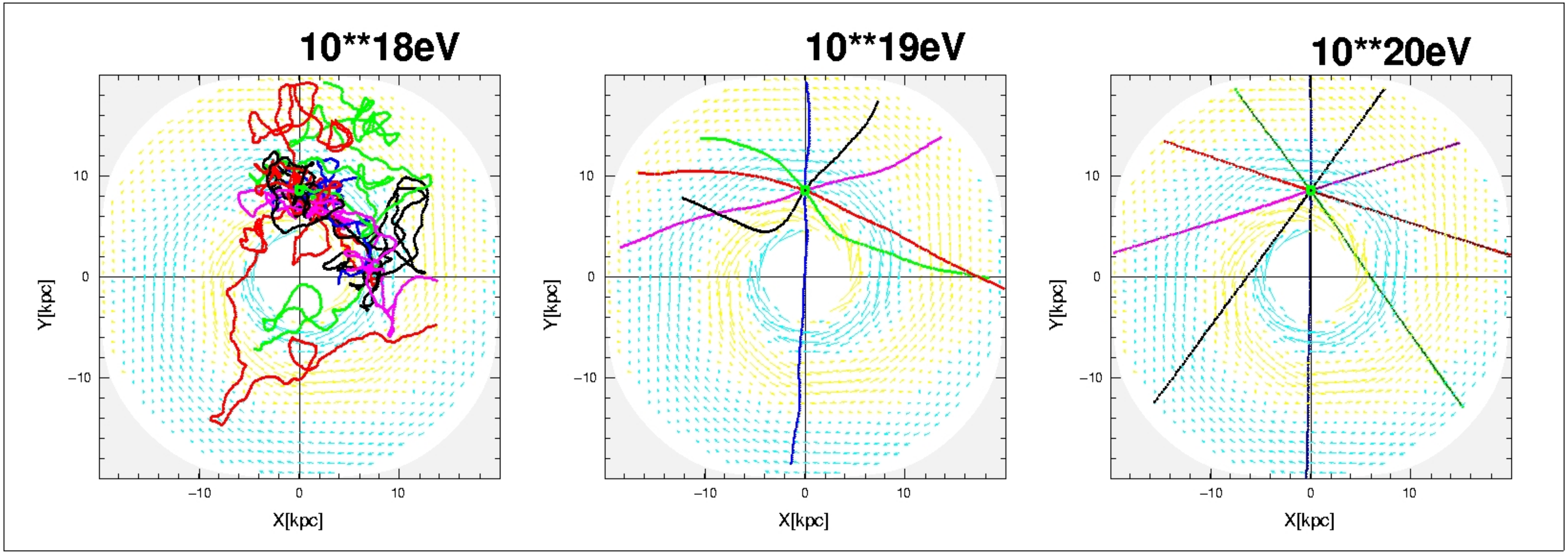
Several knees?

Convolution of the escape probability in the galaxy with the acceleration efficiencies of the sources ..



Galactic Magnetic Field deflection (p)

T.Stanev

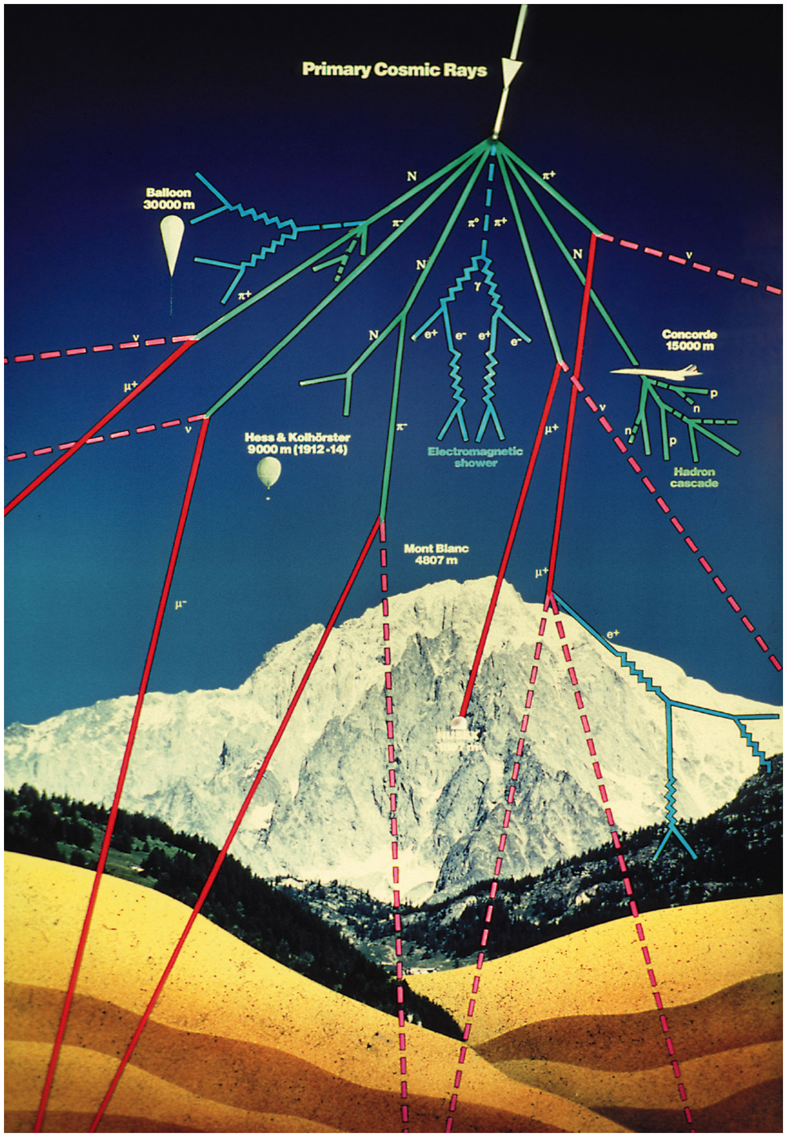


Above 10^{19} : Astronomy !

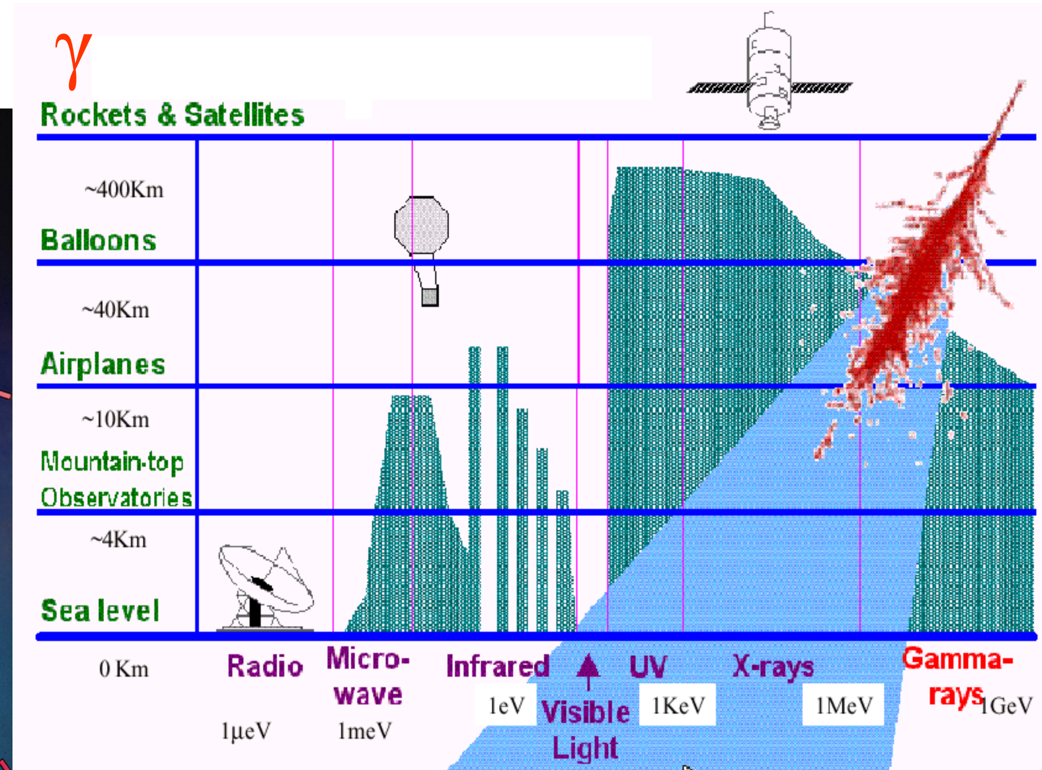
An unique opportunity to measure the galactic magnetic field ?

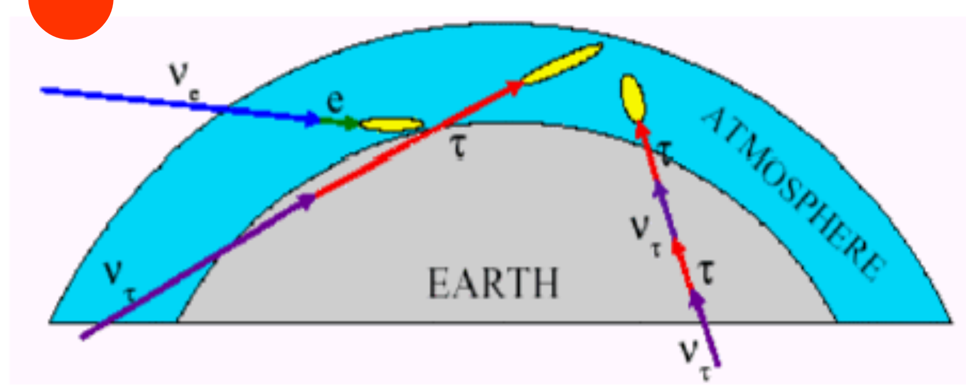
Arriving at Earth

p/nuclei

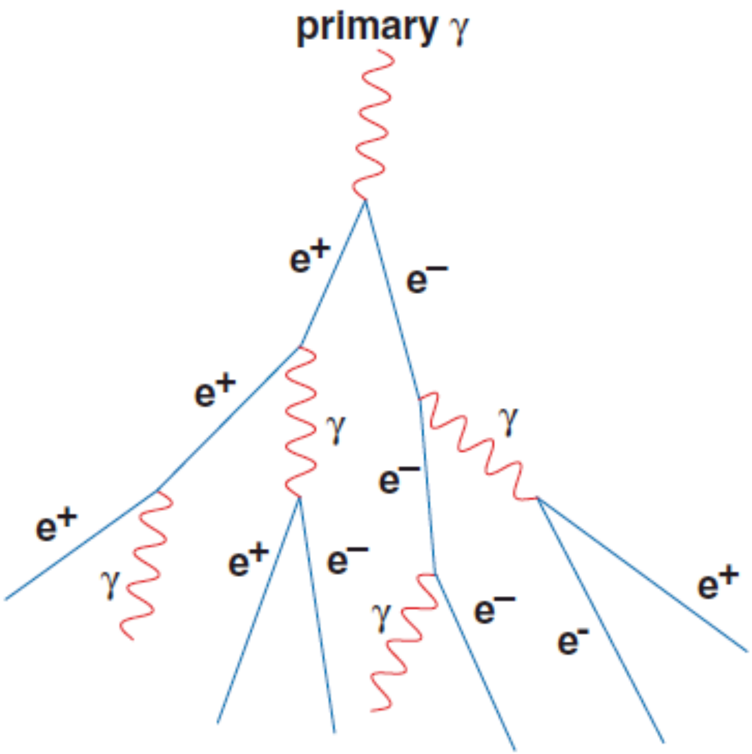


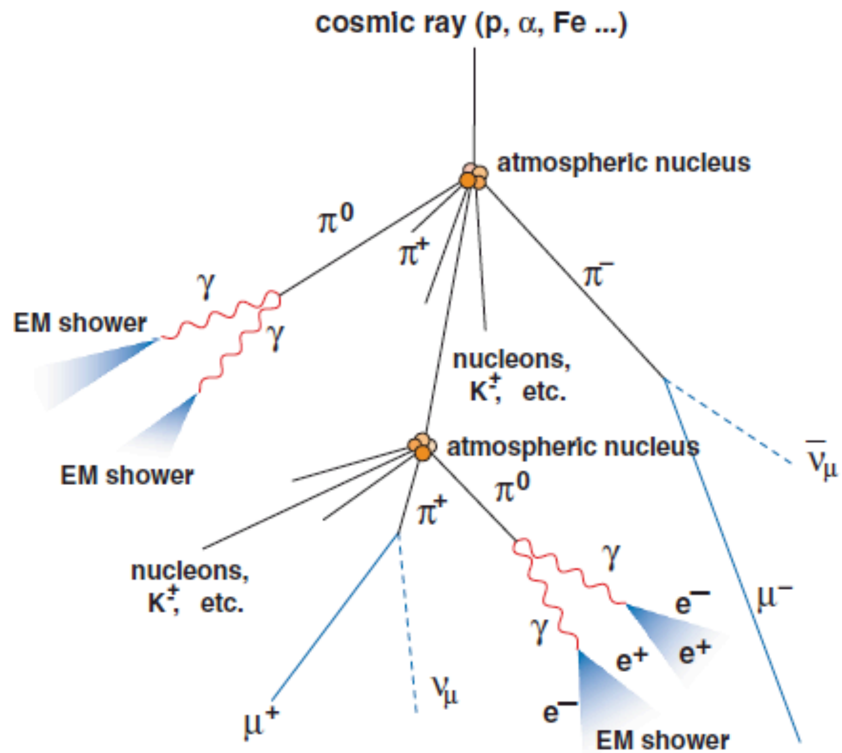
γ





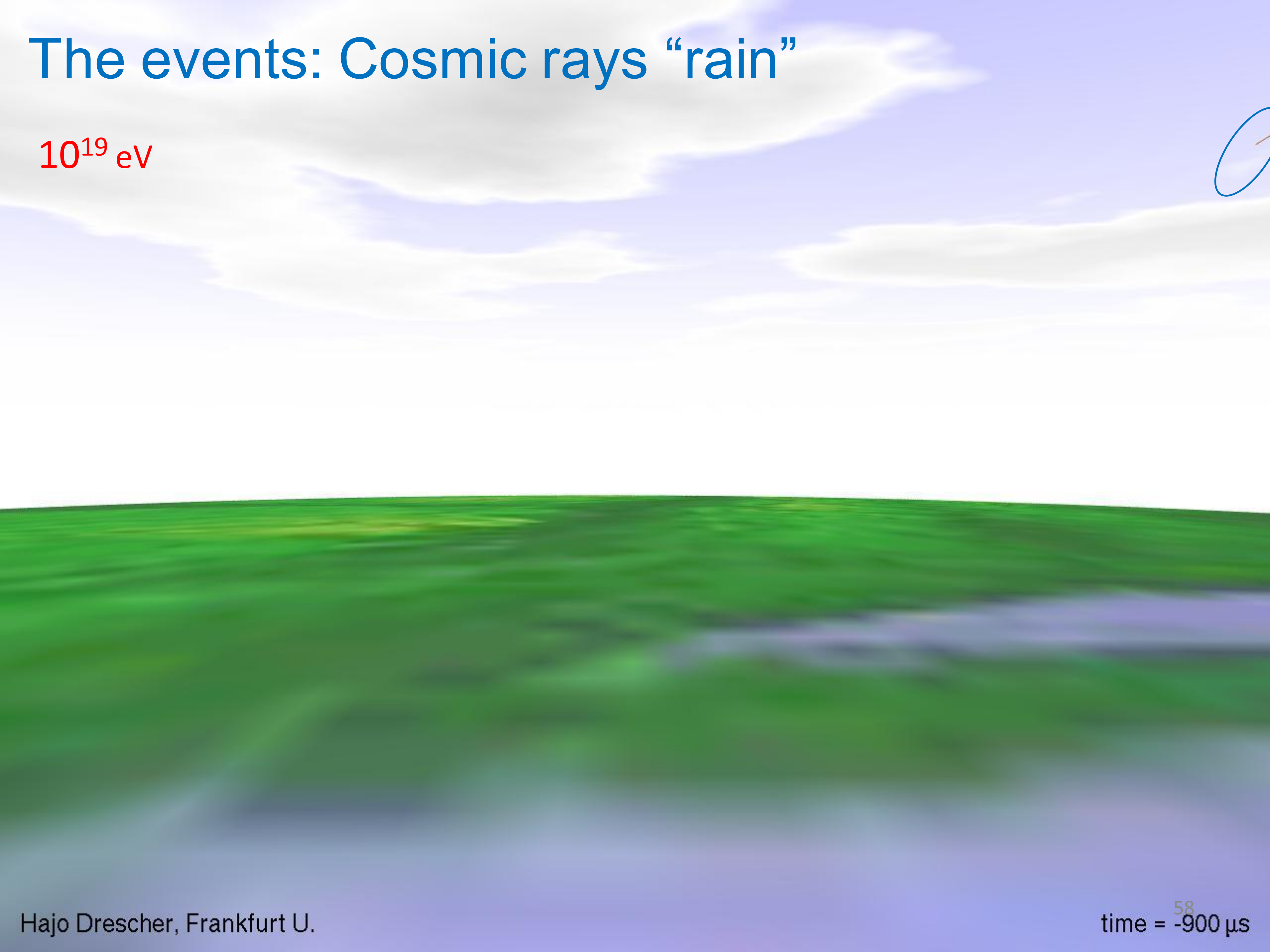
Shower cascades





The events: Cosmic rays “rain”

10^{19} eV



The events: Cosmic rays “rain”

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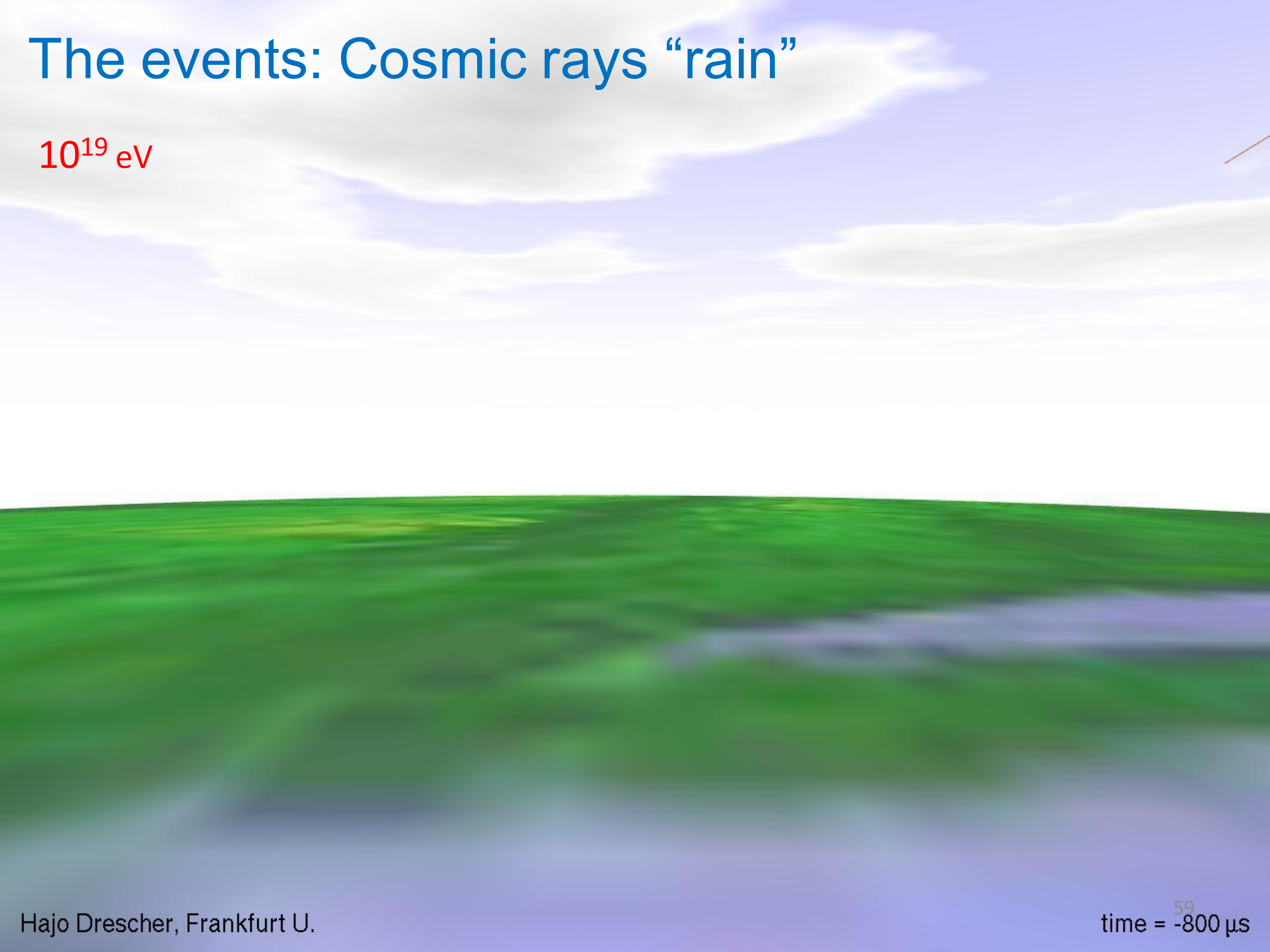

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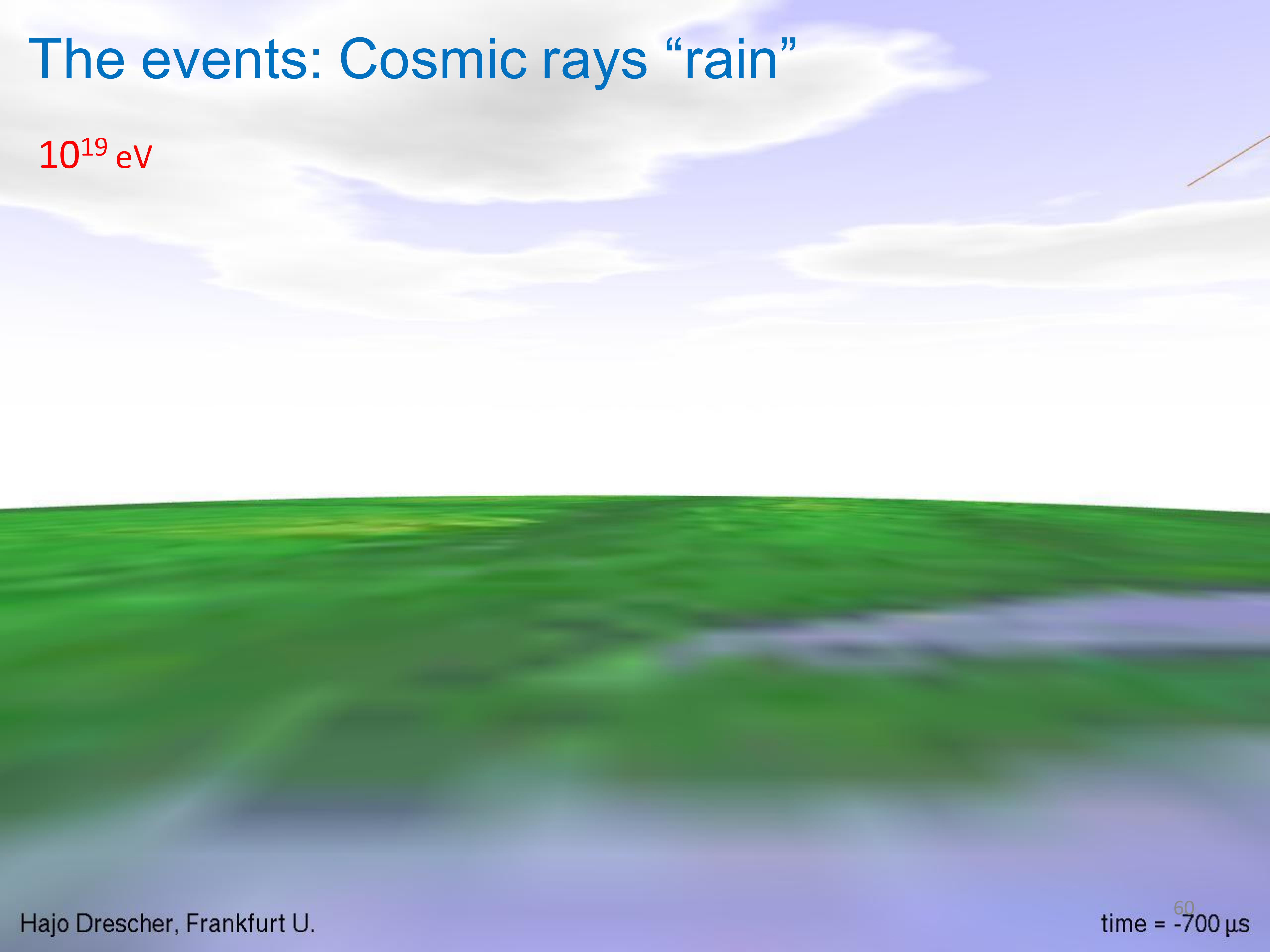

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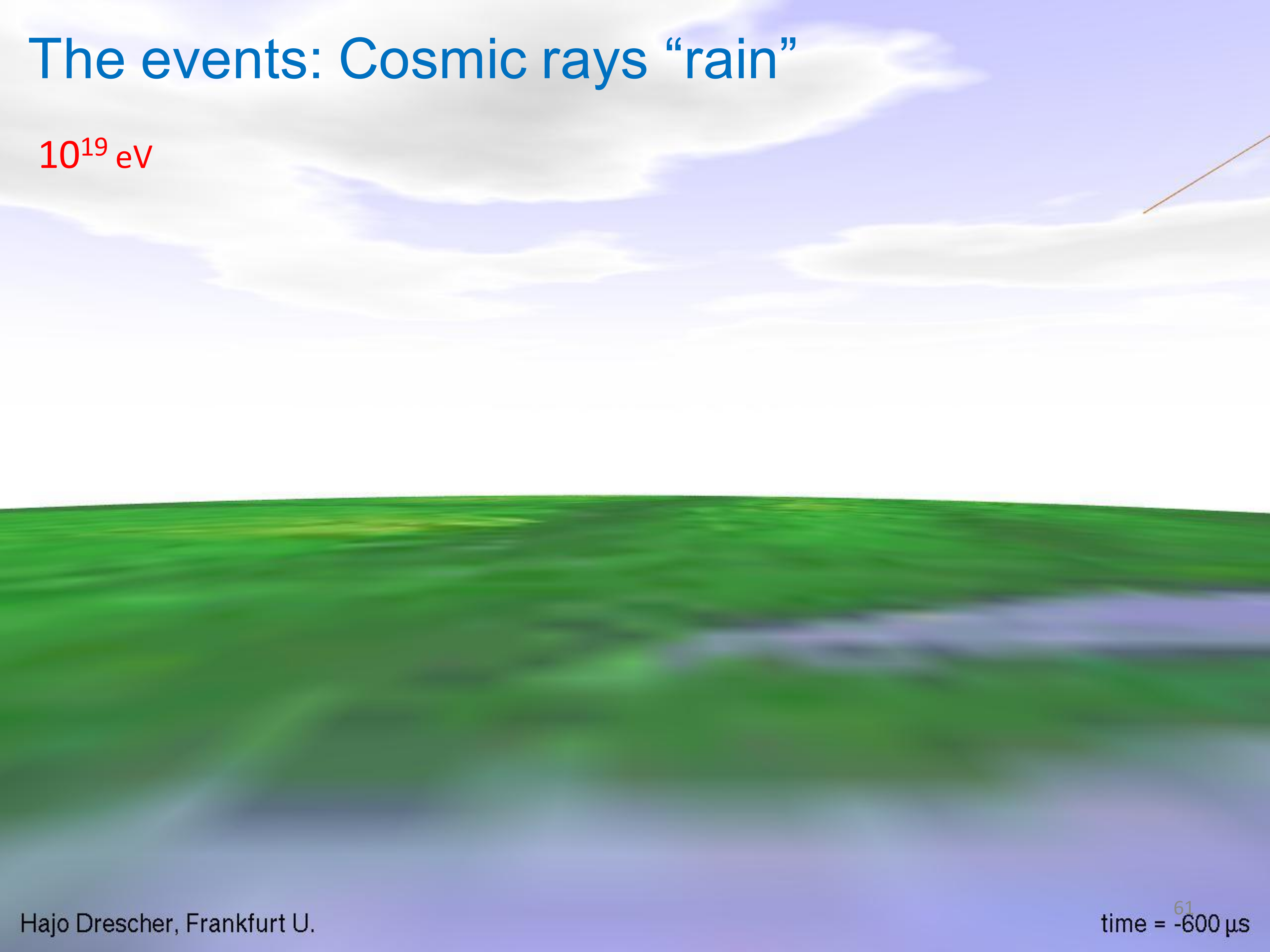
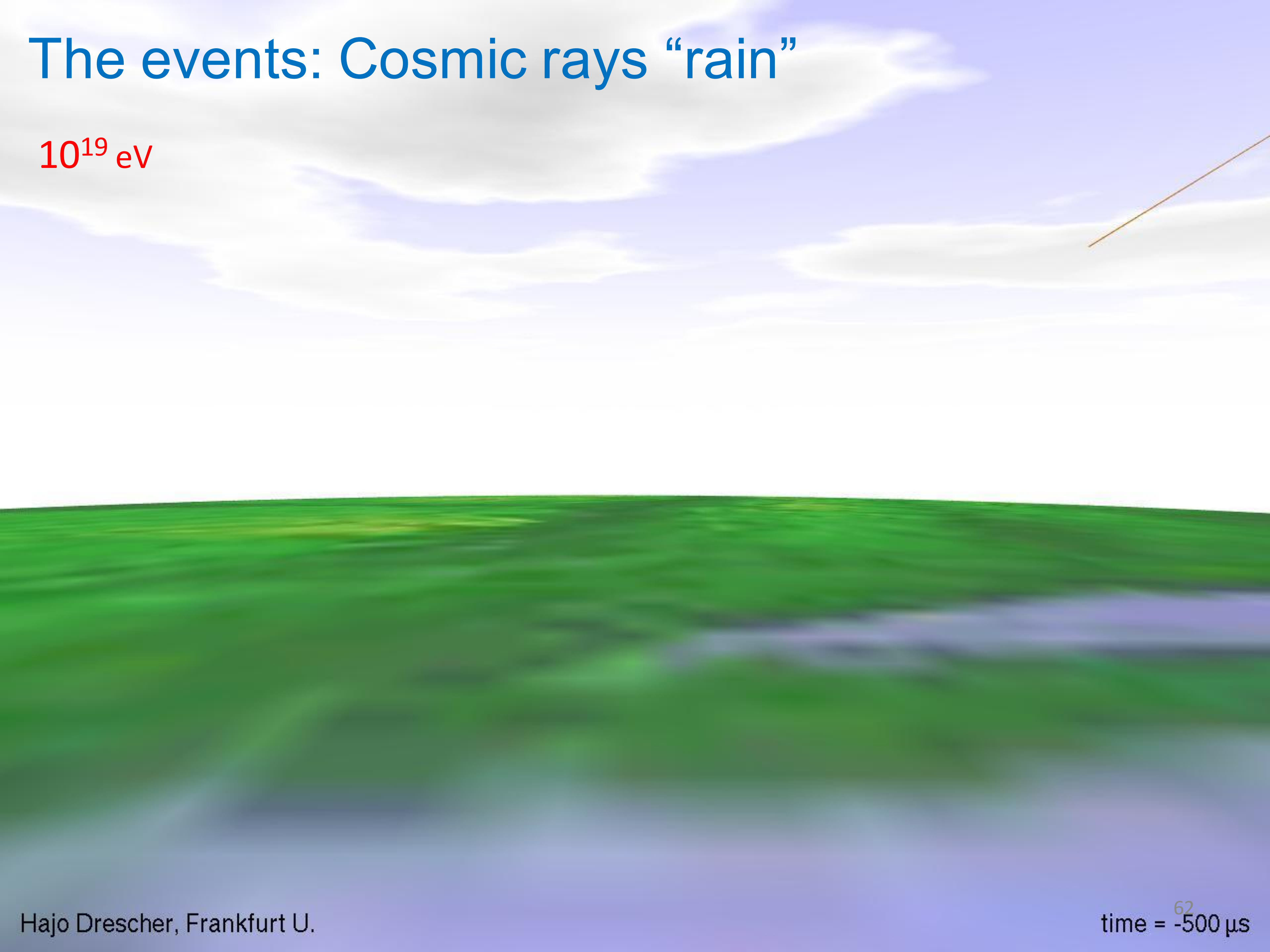
10^{19} eV



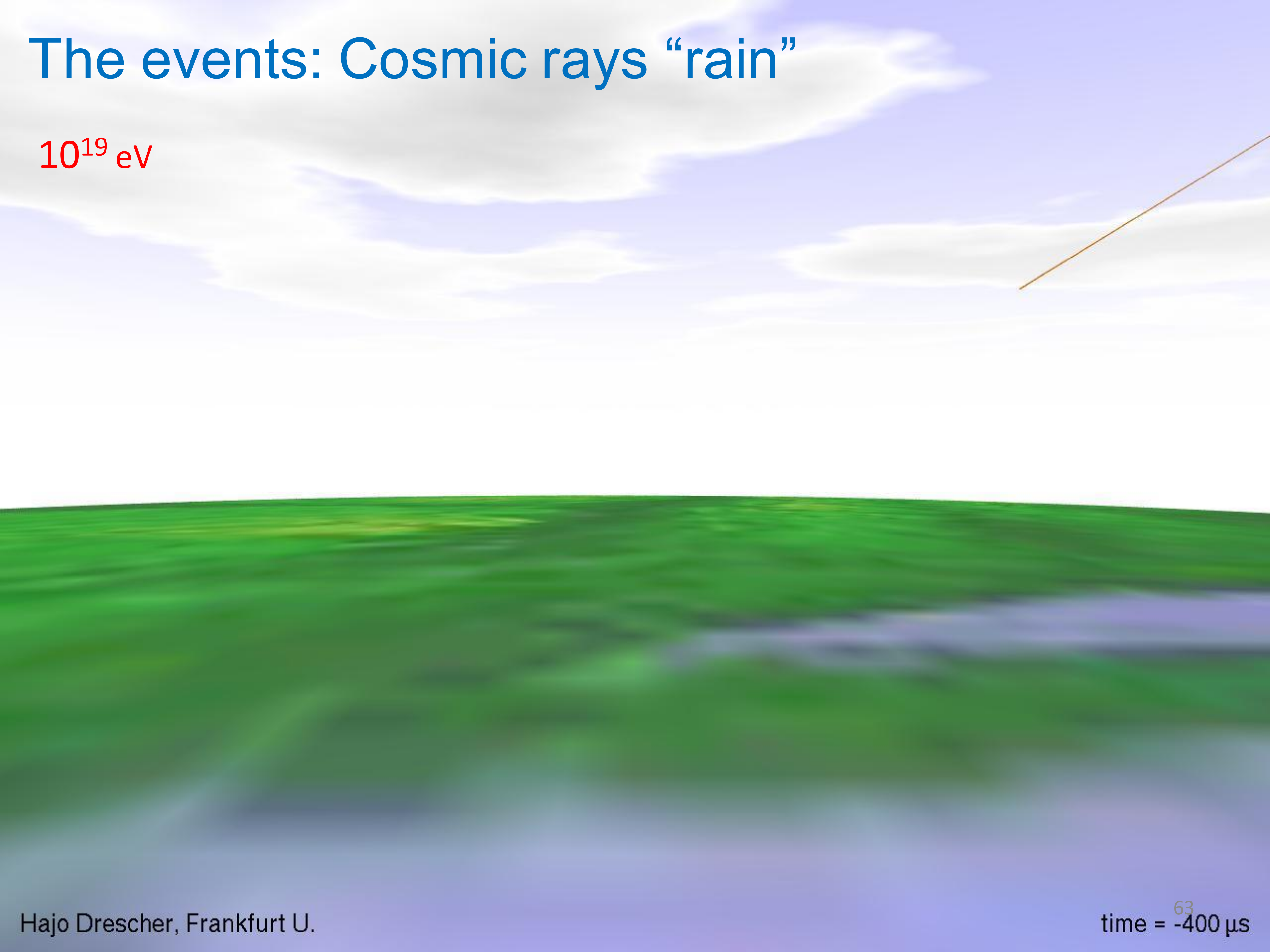
The events: Cosmic rays “rain”

10^{19} eV



The events: Cosmic rays “rain”

10^{19} eV

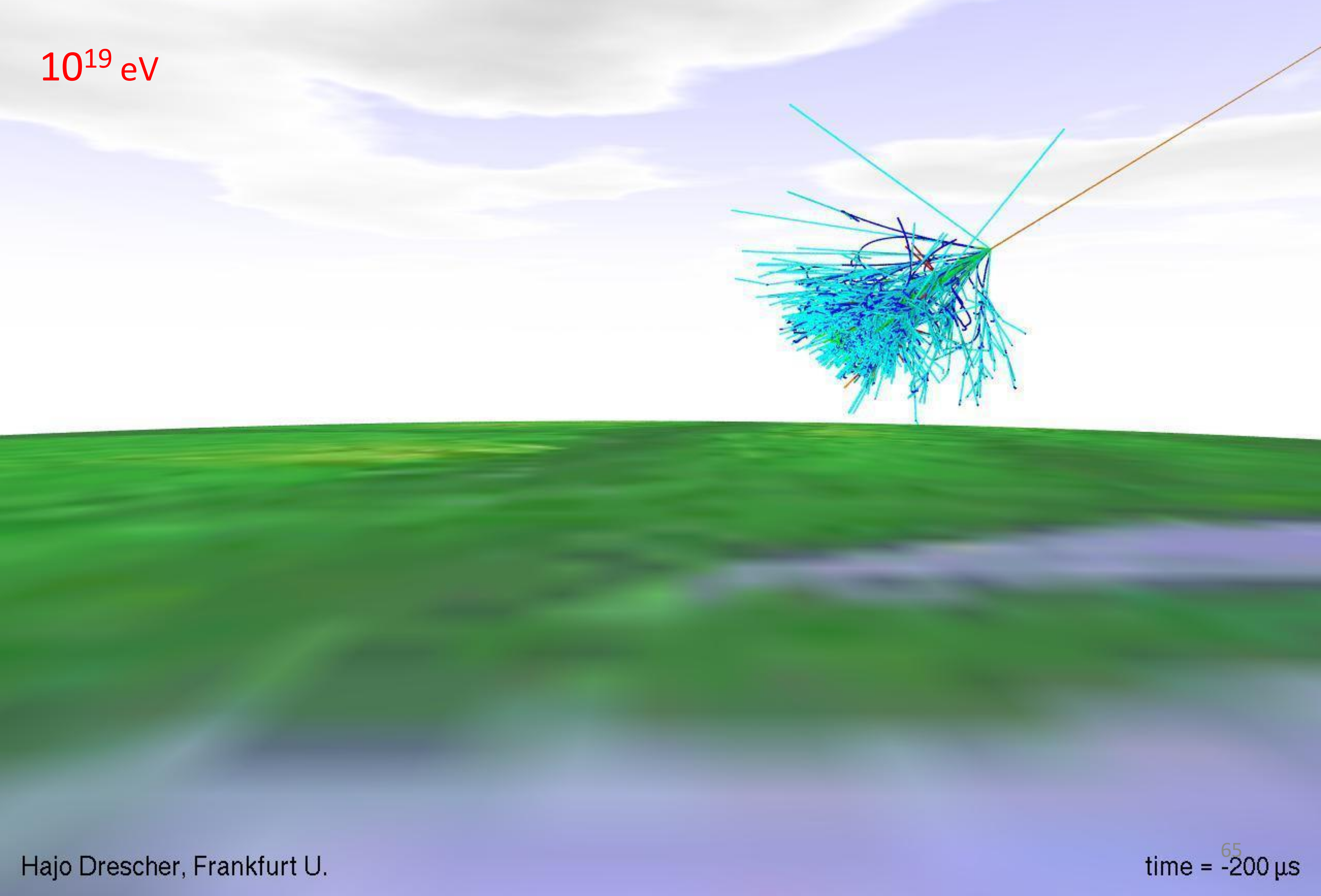


The events: first interaction

10^{19} eV

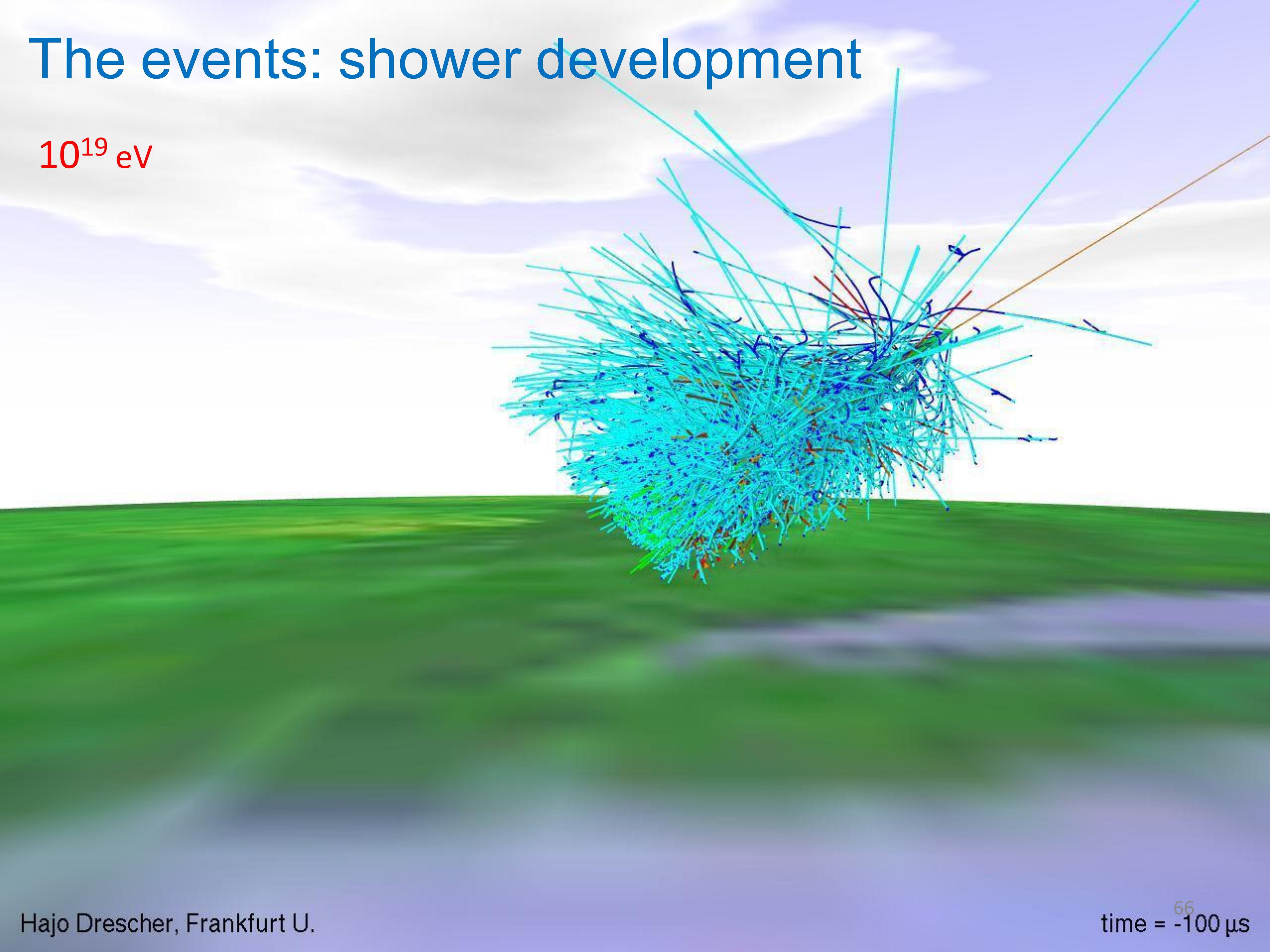
The events: shower development

10^{19} eV



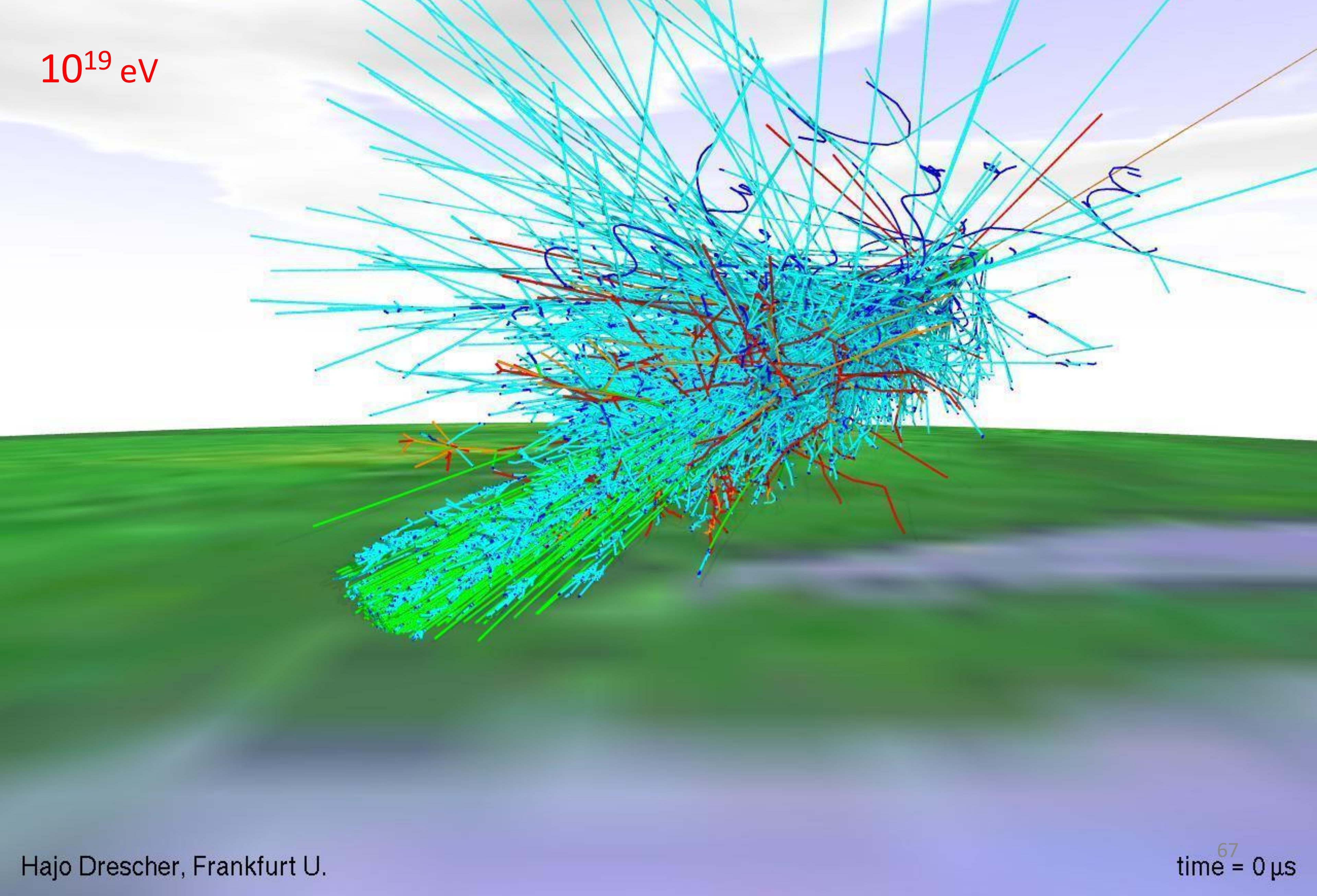
The events: shower development

10^{19} eV



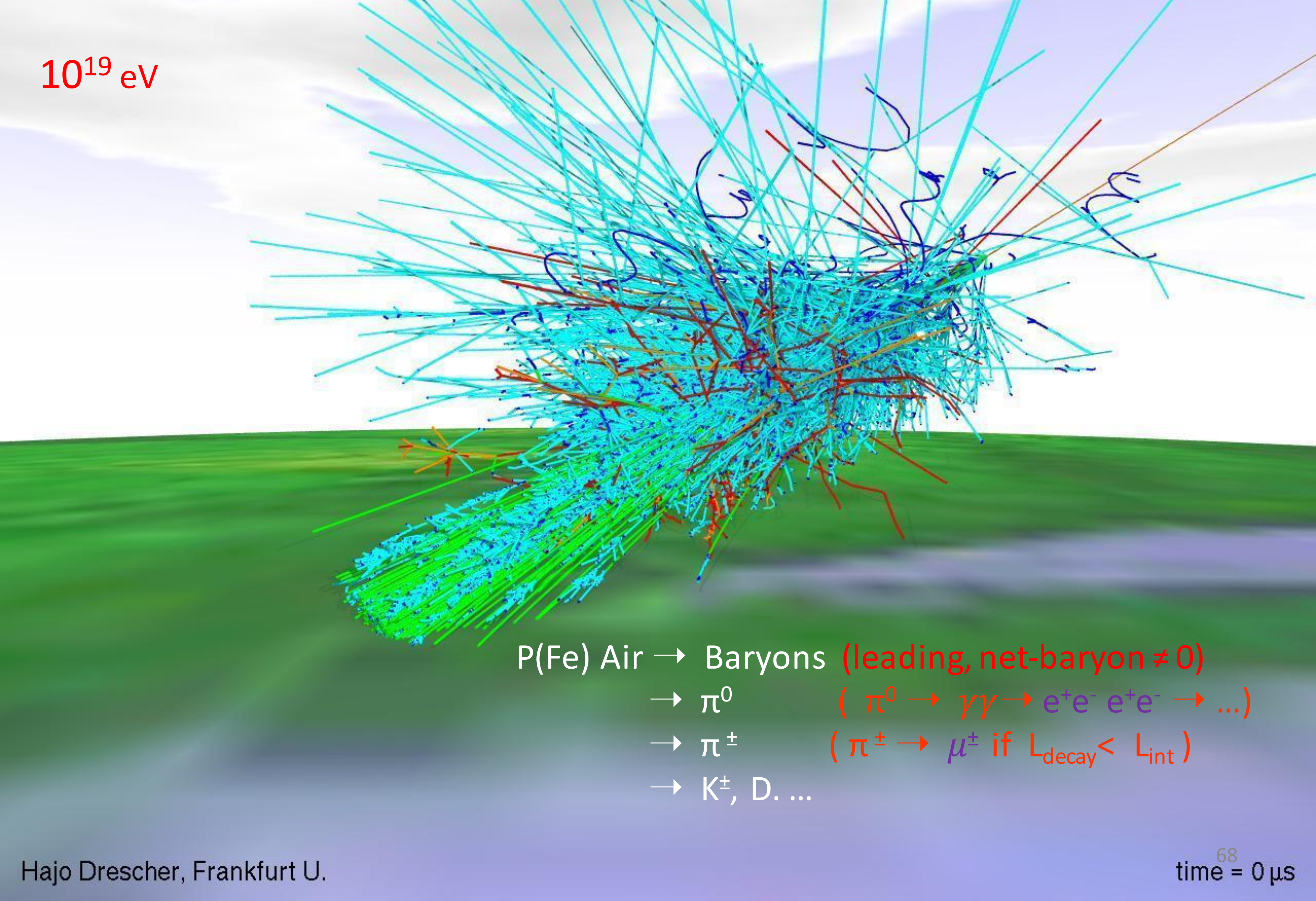
The events: shower hits Earth surface

10^{19} eV



The events: shower hits Earth surface

10^{19} eV



P(Fe) Air → Baryons (leading, net-baryon ≠ 0)

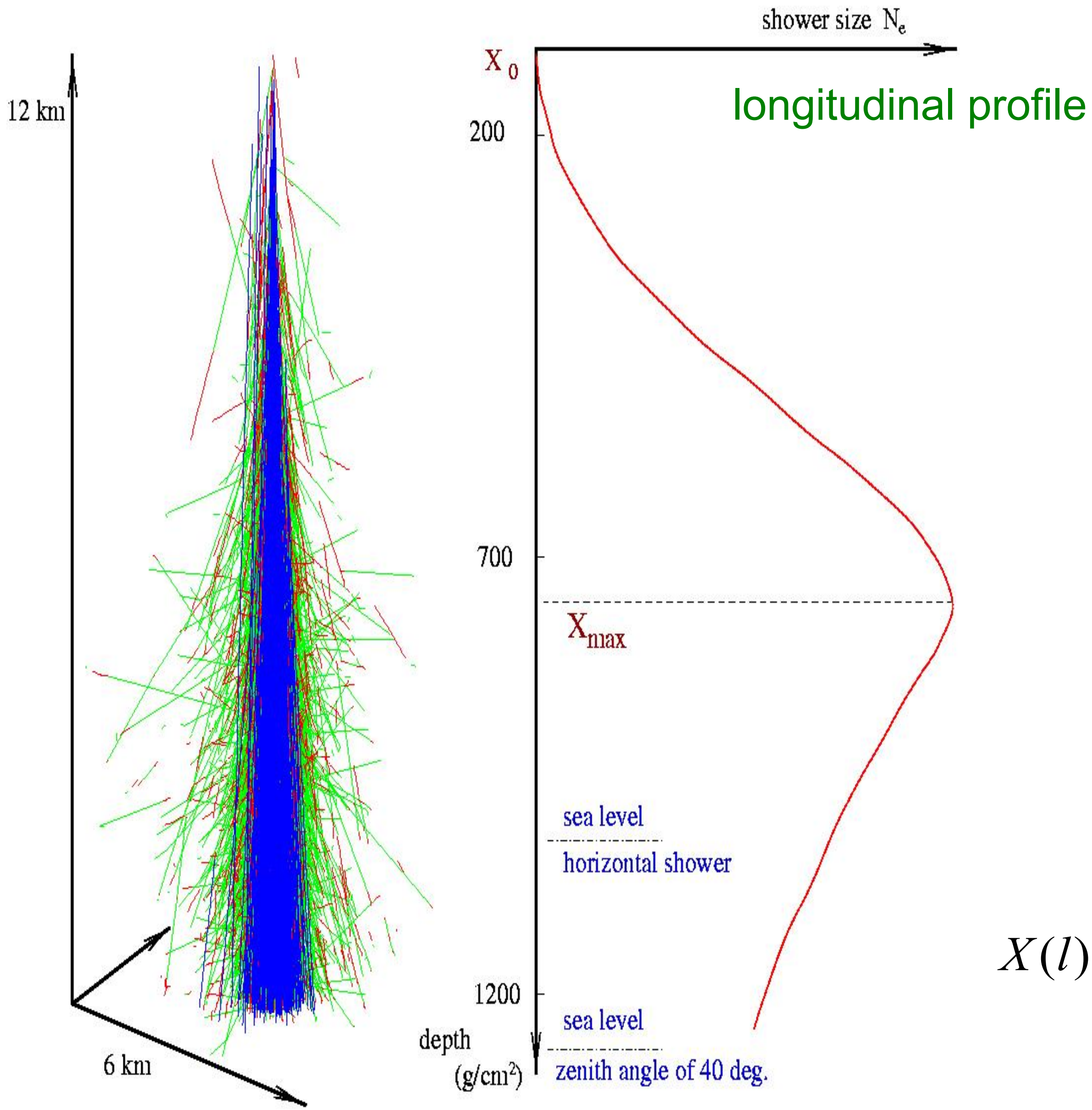
→ π^0 ($\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^-\ e^+e^- \rightarrow \ldots$)

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

→ $K^\pm$, D. …

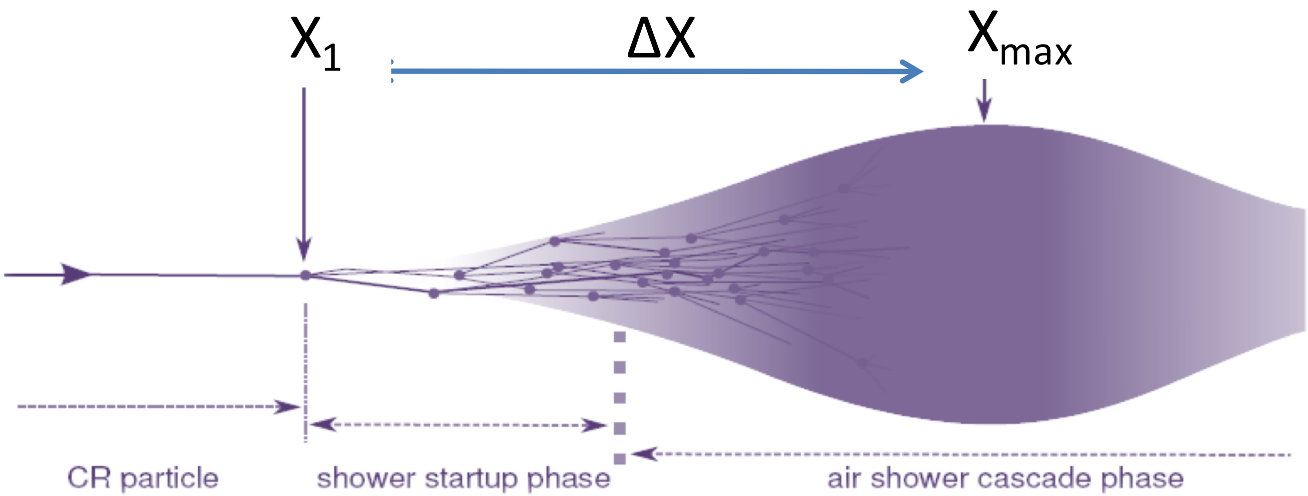
Extensive Air Showers (EAS)

10^{19} eV

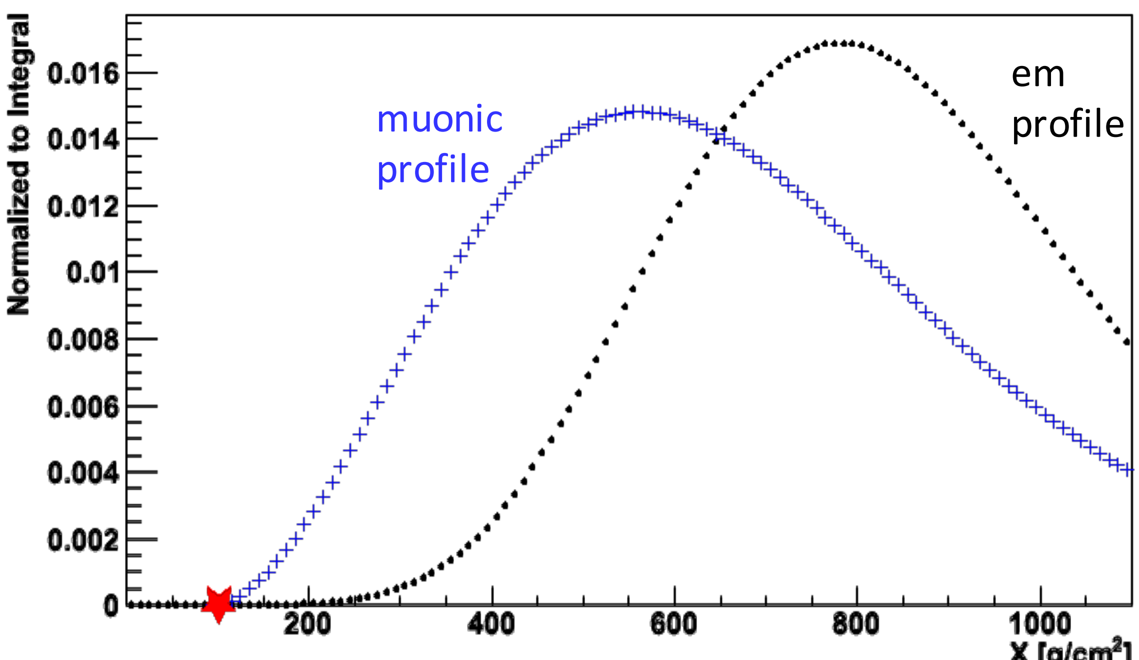


$$X(l) = \int_0^l \rho(x)dx$$

Shower development



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



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

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

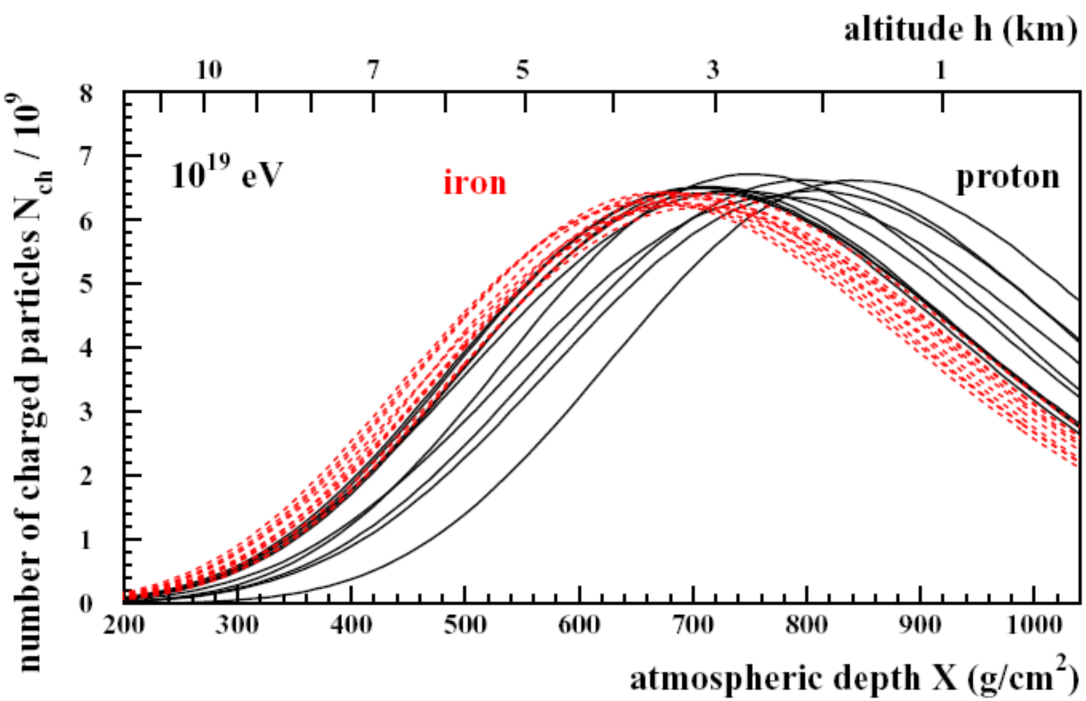
EAS longitudinal profiles

Gaisser

$$N_e = N_e^{max}\left(\frac{X - X_1}{X_{max} - \lambda}\right)^{\frac{X_{max}-\lambda}{\lambda}} e^{-\left(\frac{X-X_1}{\lambda}\right)}$$

$N_e^{max} \propto E$

$X_{max} \propto \ln E$



Iron ~ 56 nucl(E/56)

Smaller fluctuactions

Smaller X_{max}

EAS transverse profiles

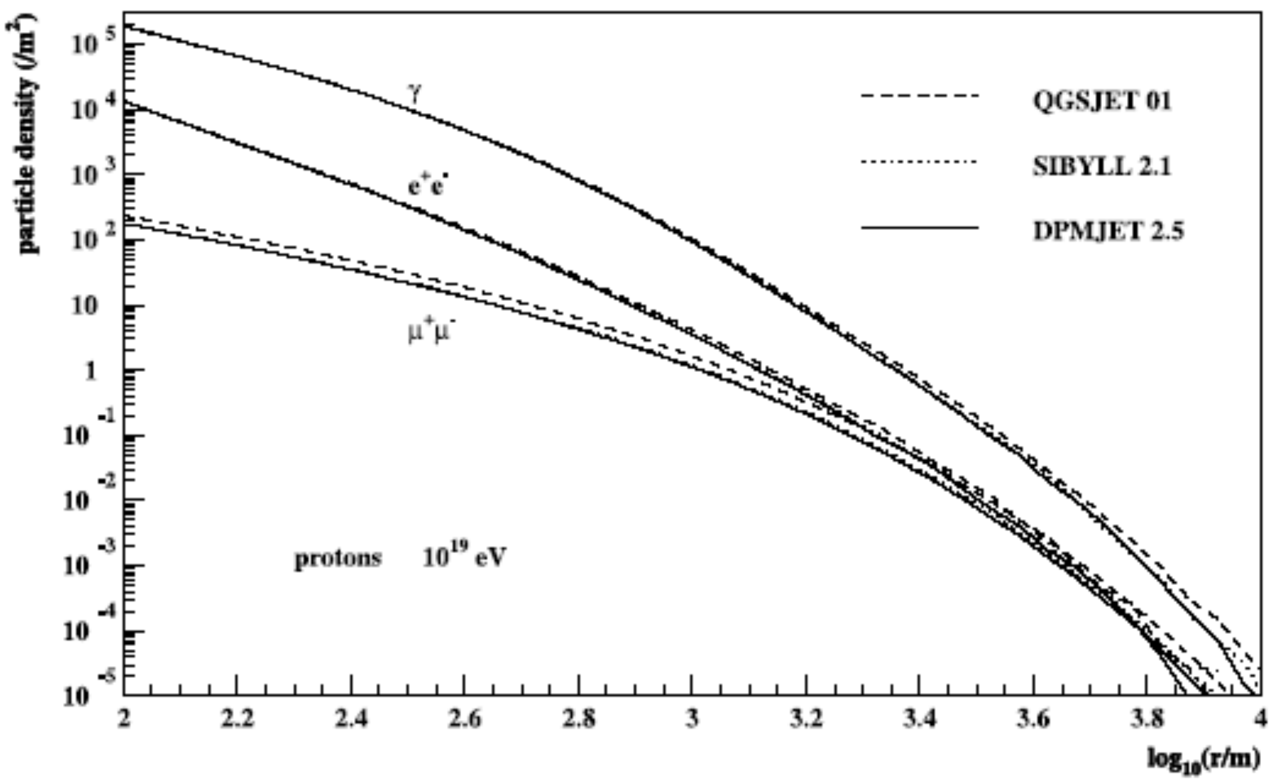
NKG (Nishimura, Kamata, Greisen)

$$\rho(r) = c(s) N_e / r_0^2 (r/r_0)^{s-2} (1 + r/r_0)^{s-4.5}$$

r_0: Moliére radius

s : shower age

J. Knapp et al. / Astroparticle Physics 19 (2003) 77–99



P_t distributions

Multiple Coulomb scattering

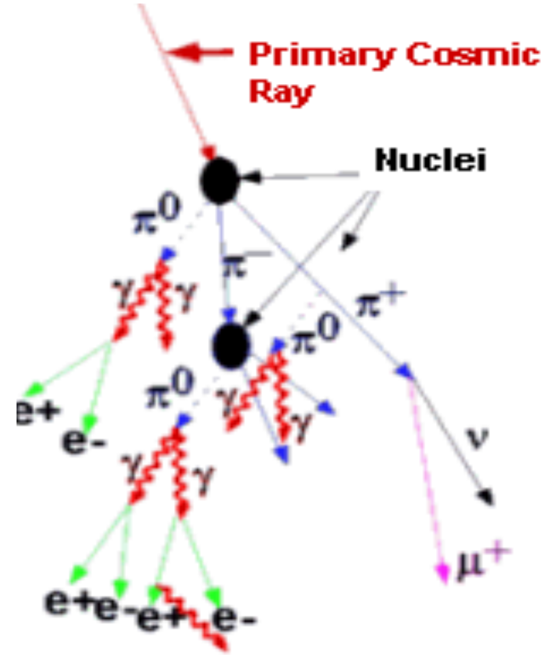
Particle interactions

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

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

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

$\rightarrow K^\pm$, D. ...



e.m. and weak interations

- well known !

hadronic interations

- large uncertainties !
- forward region, small p_t, very high $\sqrt{s}$
- main parameters: σ_{in}, k_{in}, <n>, (fraction π^0, Nb of Baryons, ...)

Nuclear fragmentation

- Nuclei are not just a superposition of nucleons !

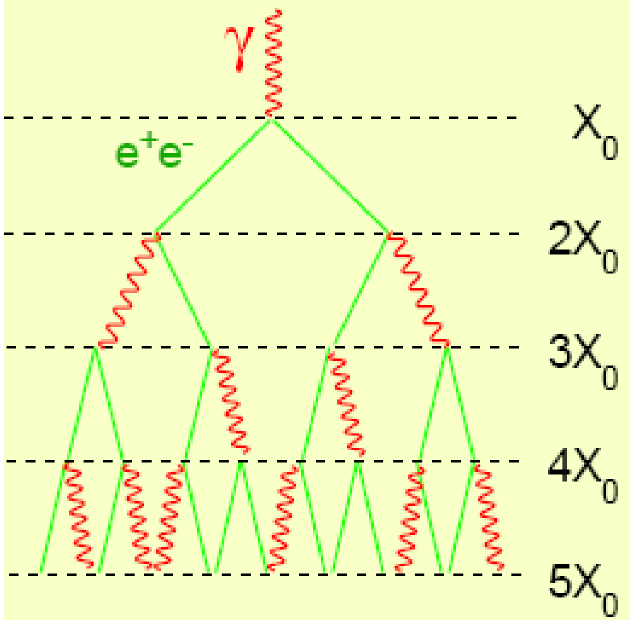
Missing Energy

- 5% to 10% ...

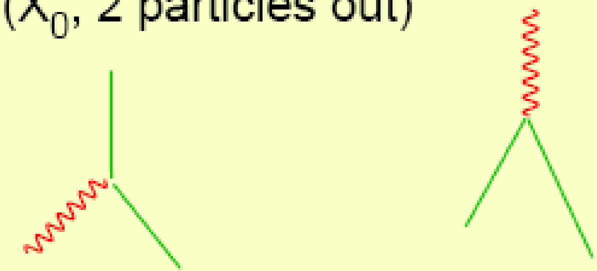
Electromagnetic interactions

J. Knapp

A simple (el.mag.) shower model:



Bremsstrahlung & Pair production
(X_0, 2 particles out)



$N(t) = 2^t$ t is depth in X_0

$E(t) = E_0/2^t$

$N_{max} = E_0/E_{crit} = 2^{t_{max}}$

$E_{crit} = E_0/N_{max} = E_0/2^{t_{max}}$

$t_{max} = \ln(E_0/E_{crit}) / \ln 2$

... reproduces shower behaviour rather well

but: X_0 for bremsstrahlung, 0.78 X_0 for pair production,
both processes produce energy spectra,
δ-electrons, ionization, scattering ...
Reality is more complicated, ... needs a MC simulation.

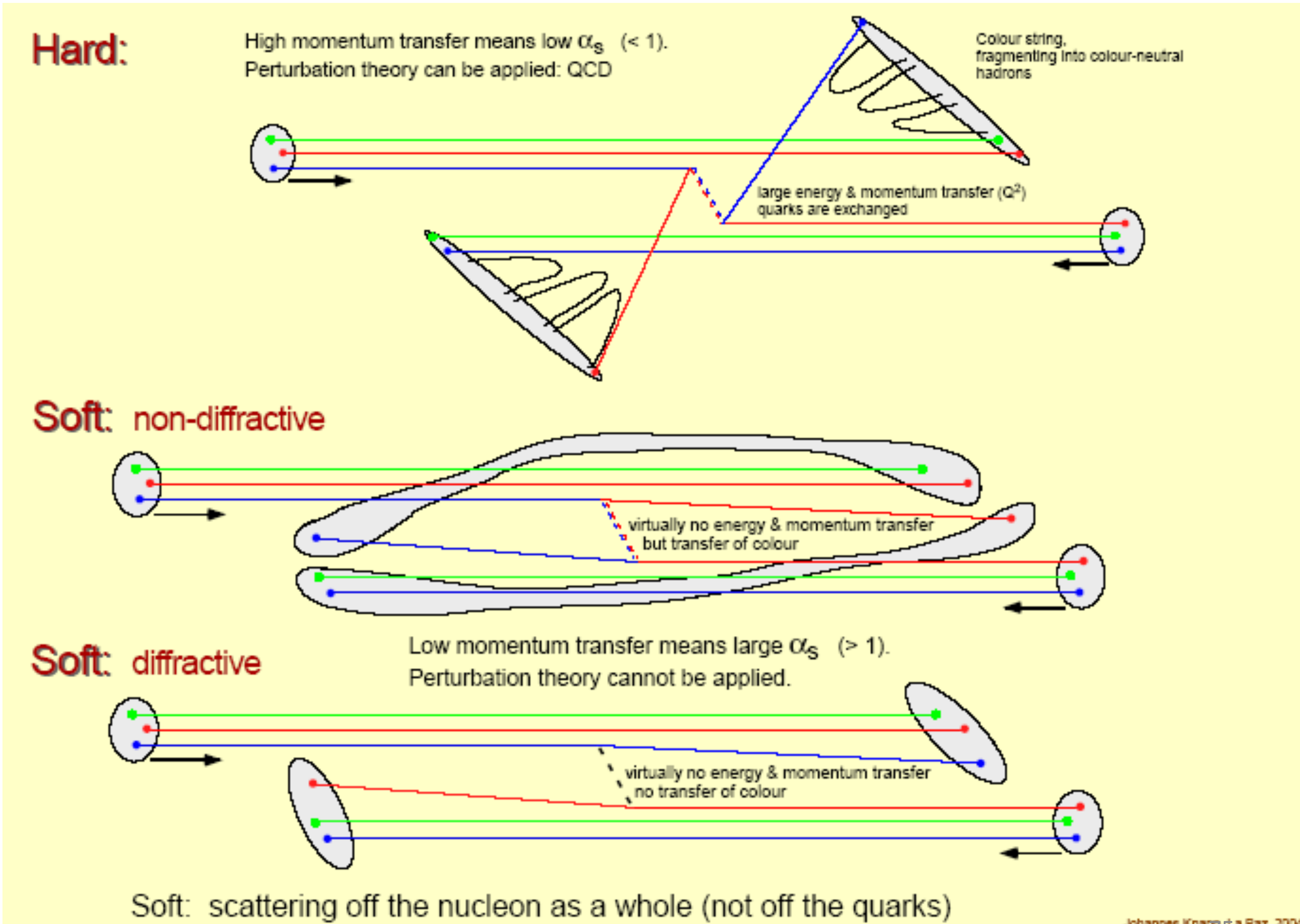
Hard and soft hadronic interactions

J. Knapp

Perturbative QCD

↕

Pomeron exchange GRT

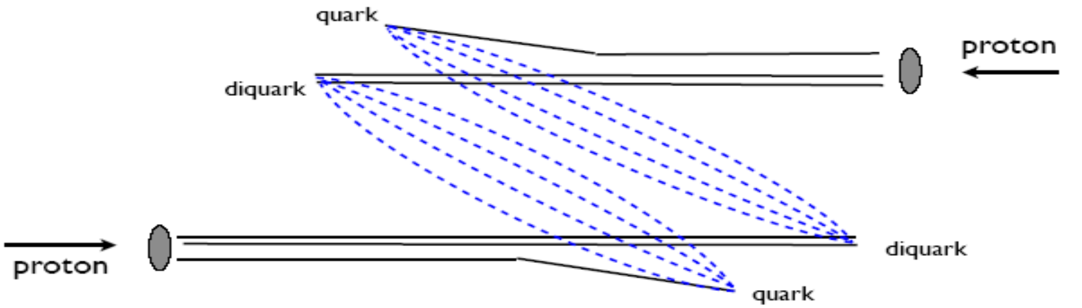


“Standard” Hadronic models (low pt)

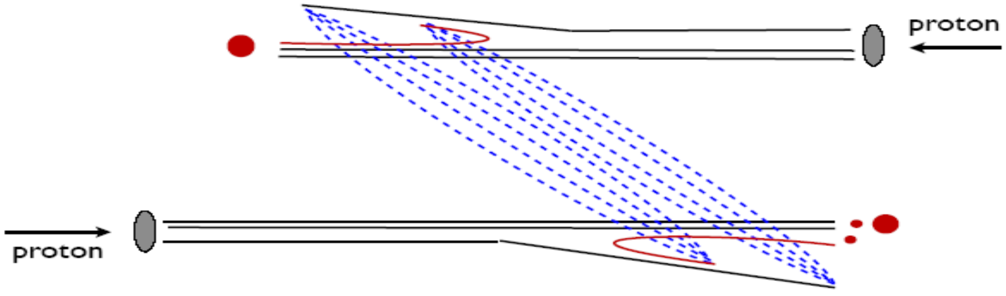
Minimum string configuration

Ralph Engel

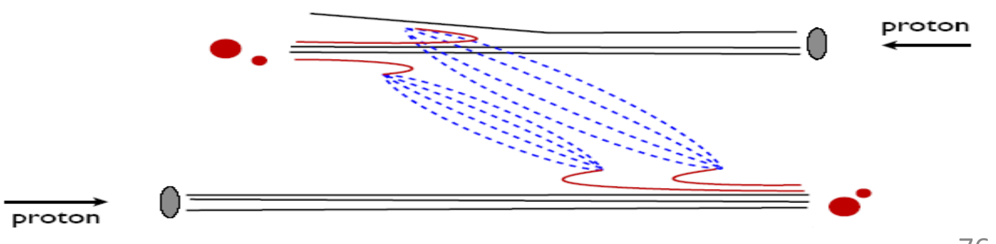
SIBYLL



QGSJET



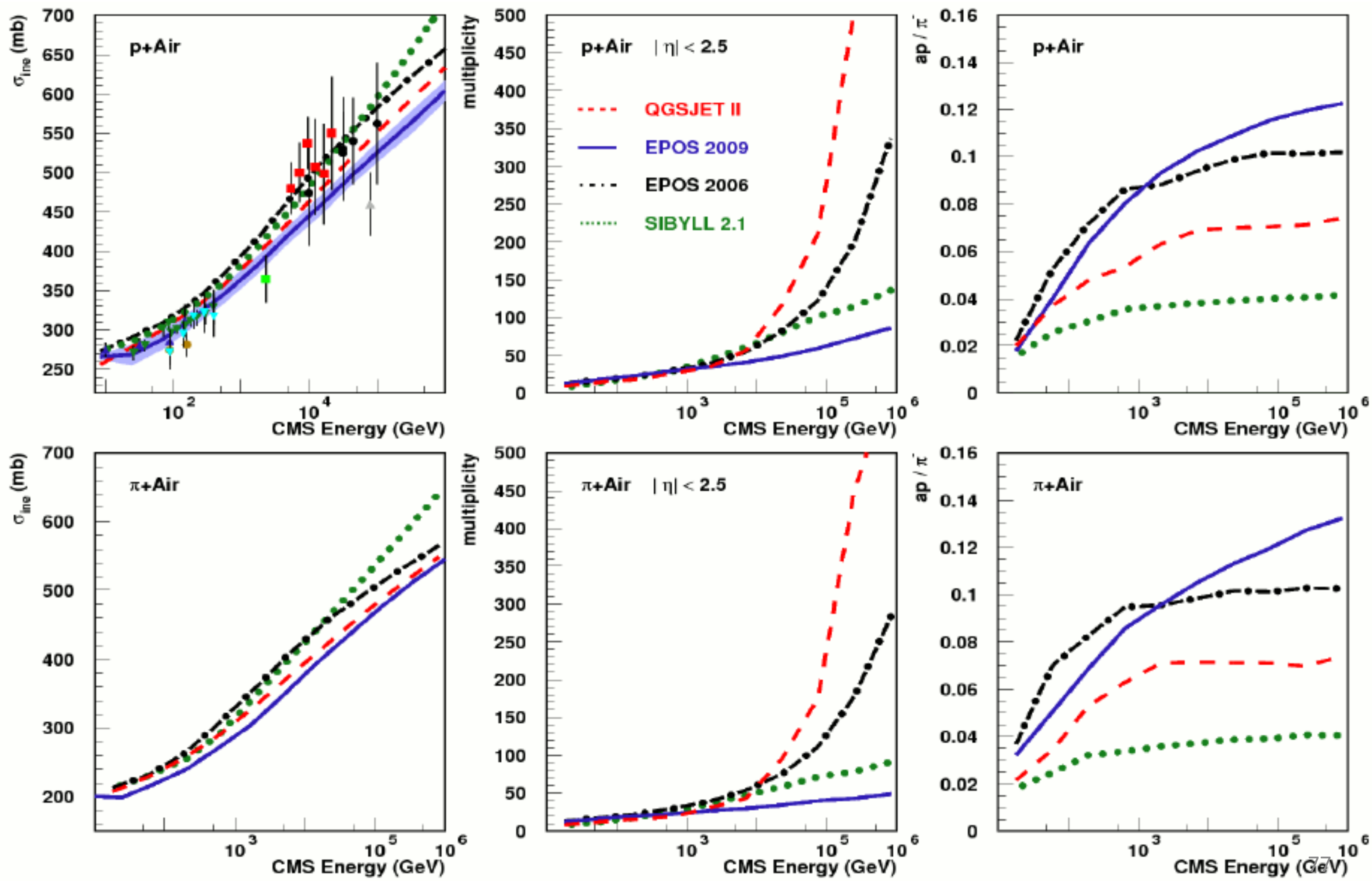
EPOS



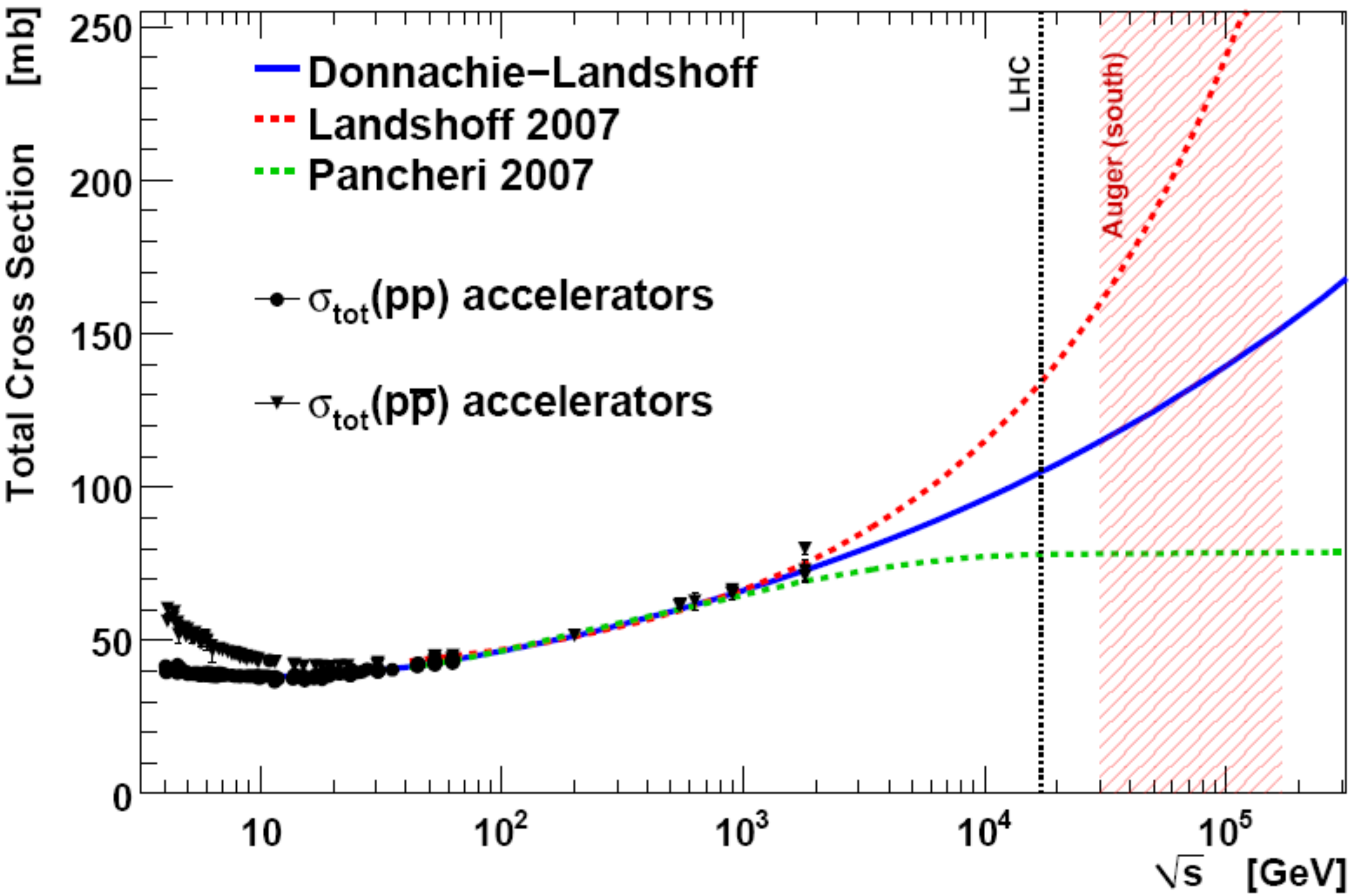
Hadronic models parameters

P.Tanguy

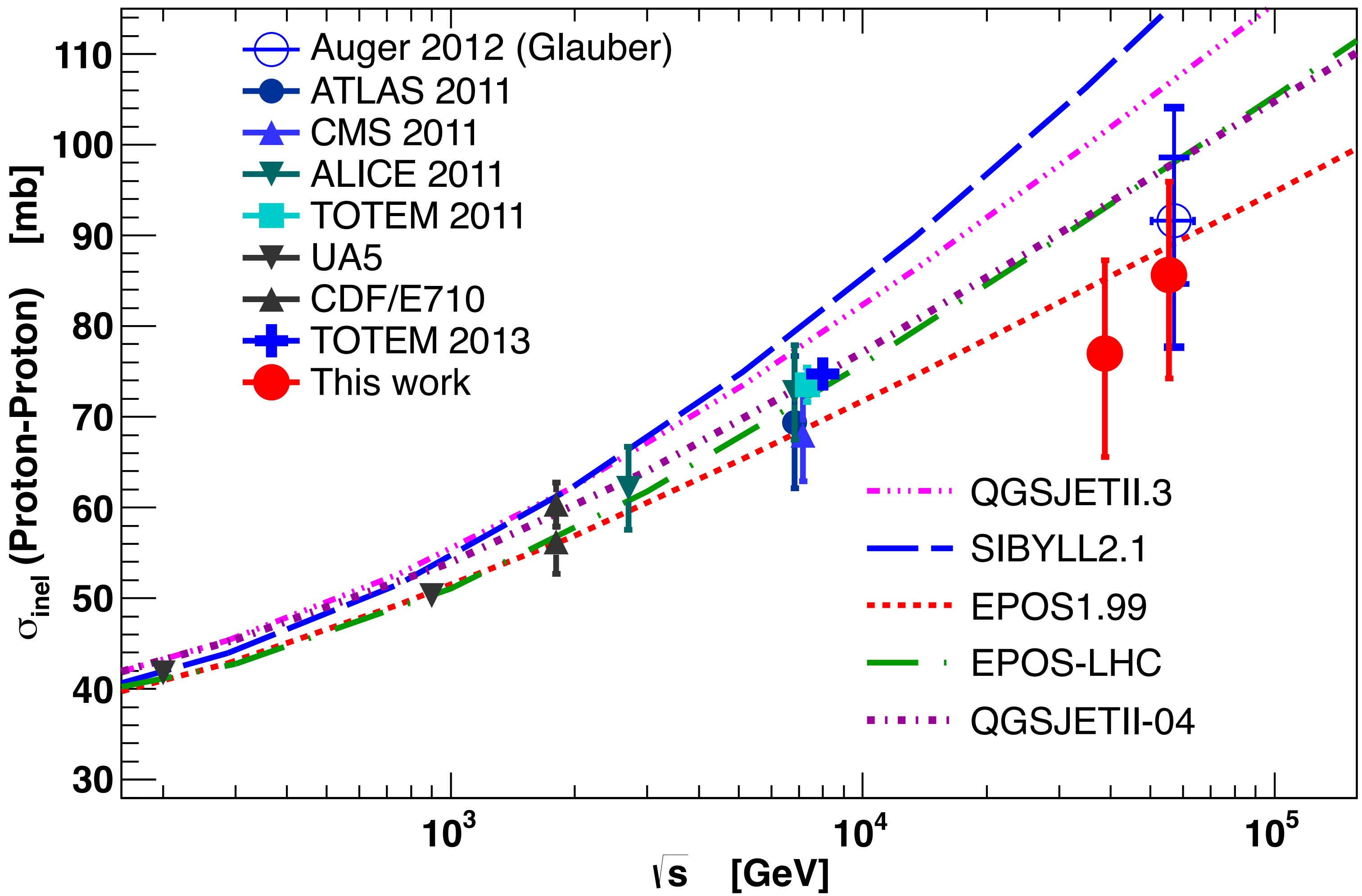
p air



Cross sections extrapolations (before LHC)

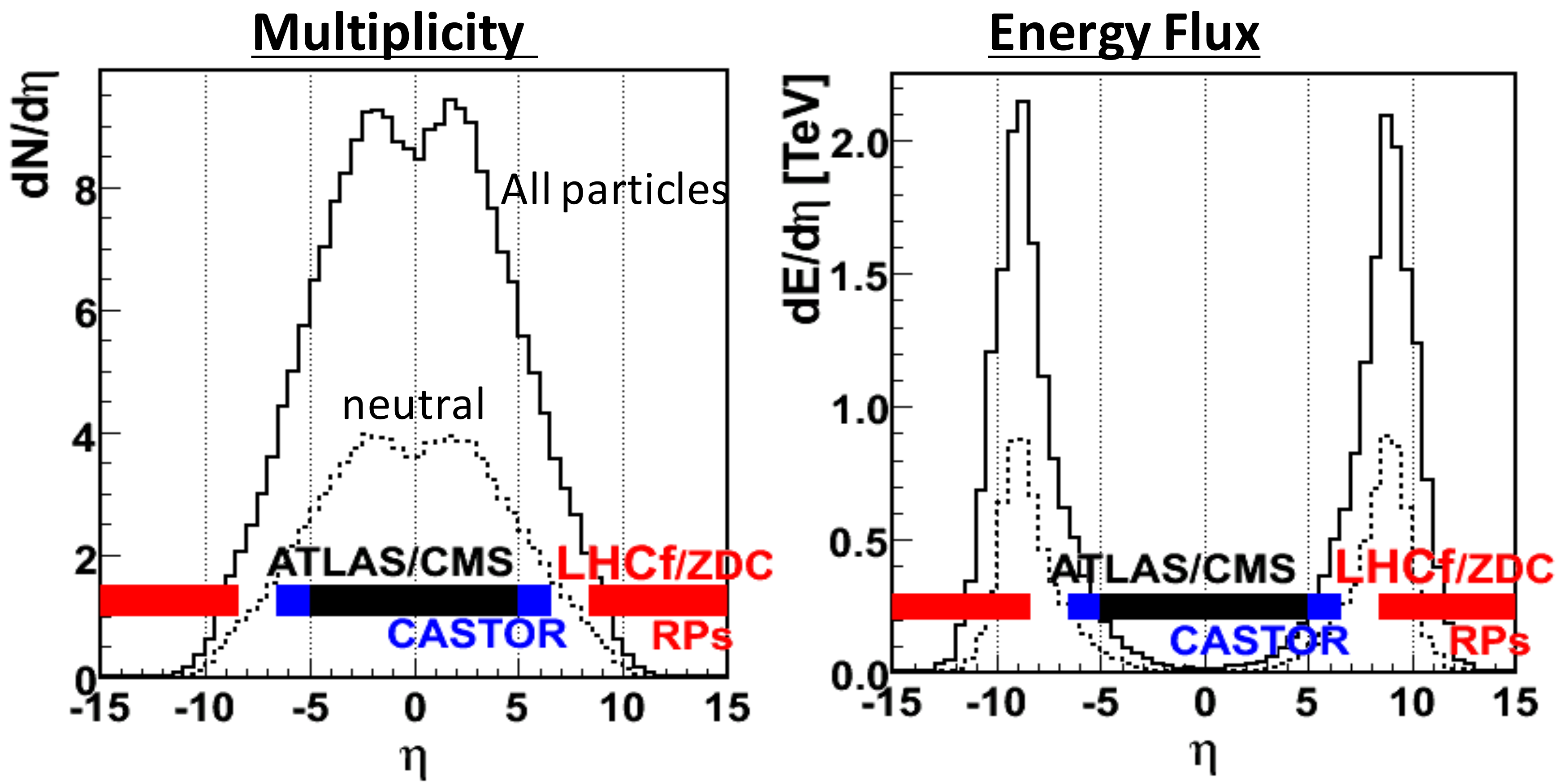


Cross sections extrapolations (after LHC)



LHC Kinematics (14 TeV)

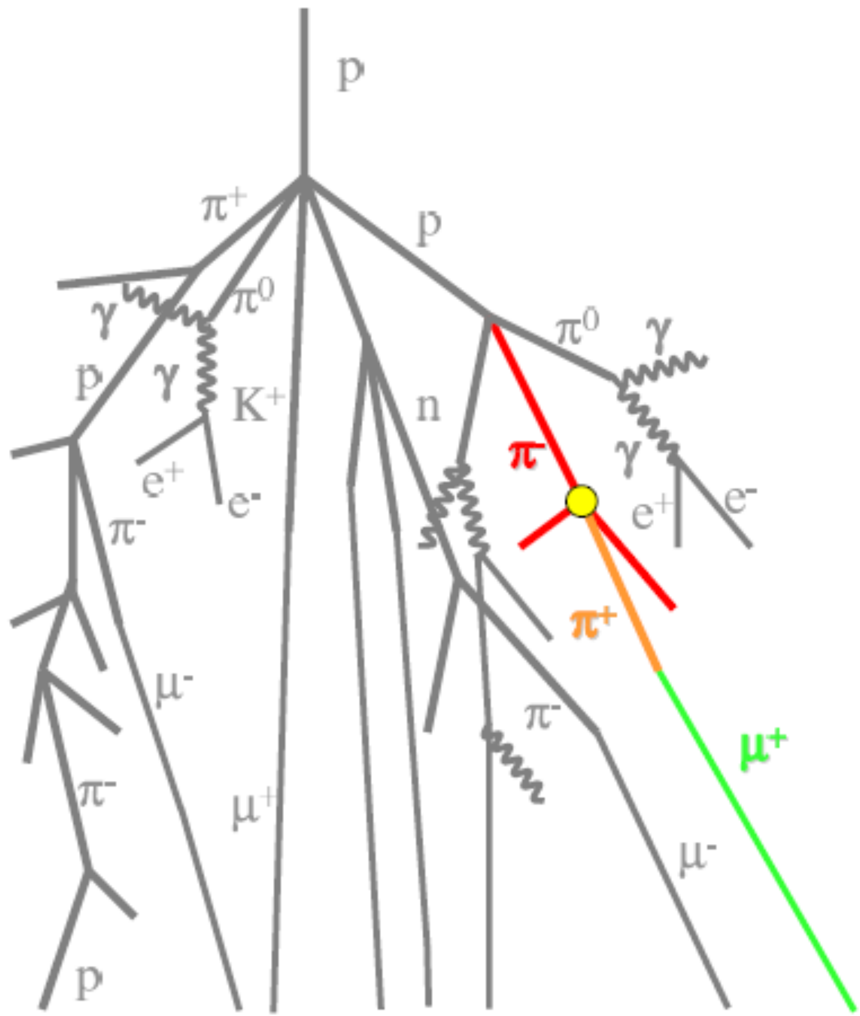
Takashi SAKO



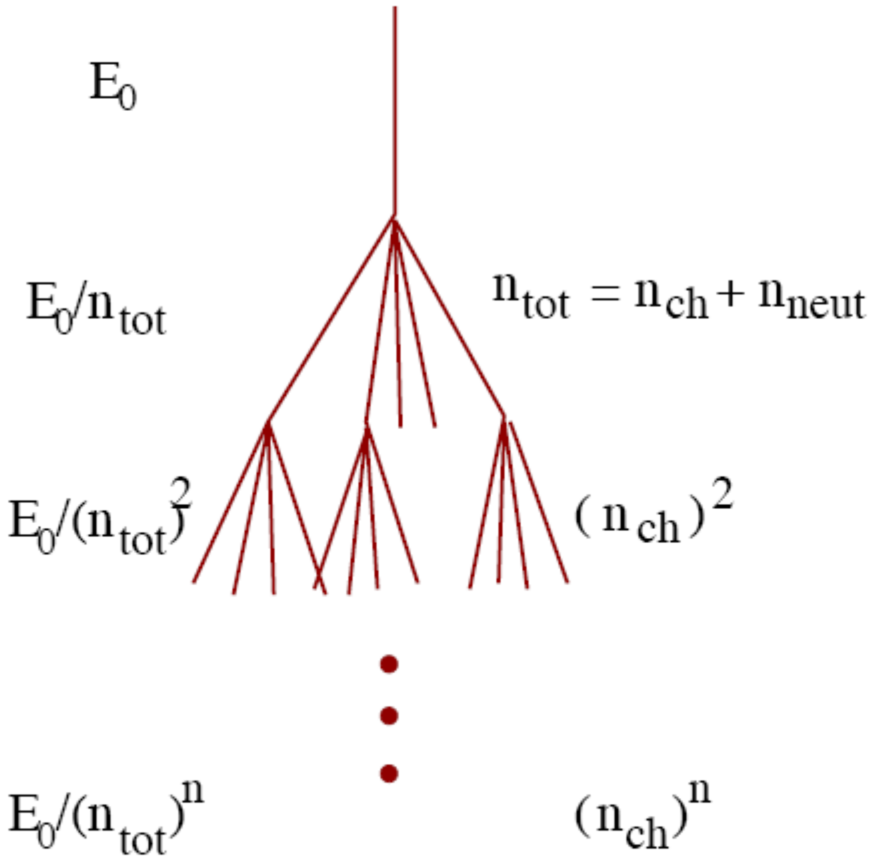
pseudo-rapidity; $\eta = -\ln(\tan(\theta/2))$

Most of the energy flows into very forward region

The μ_s



Muon production



Primary particle proton

π^0 decay immediately

$\pi^{\pm}$ initiate new cascades

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha$$

$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

- cascade stops at $E_{part} = E_{dec}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Fluxes in the atmosphere

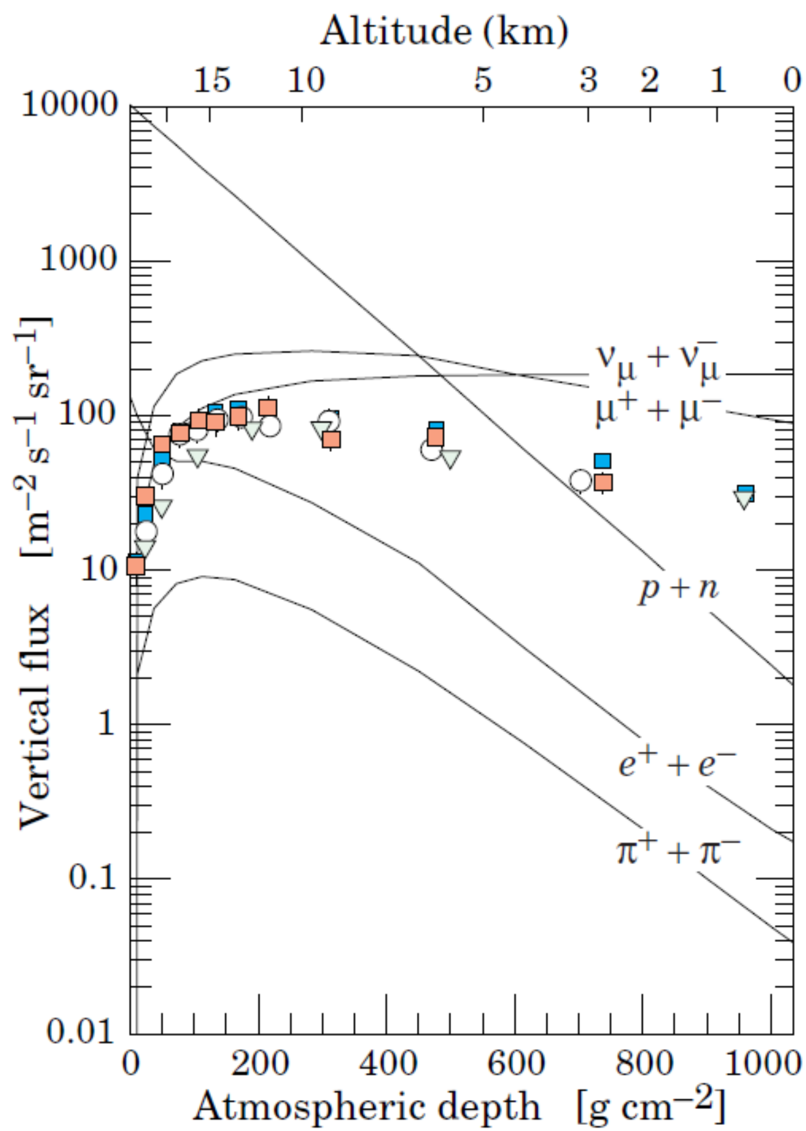


Figure 26.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (26.2). The points show measurements of negative muons with $E_\mu > 1$ GeV [32–36]. **J. Beringer et al (PDG) PR D86 010001 (2012)**

Muon spectrum at Earth Surface

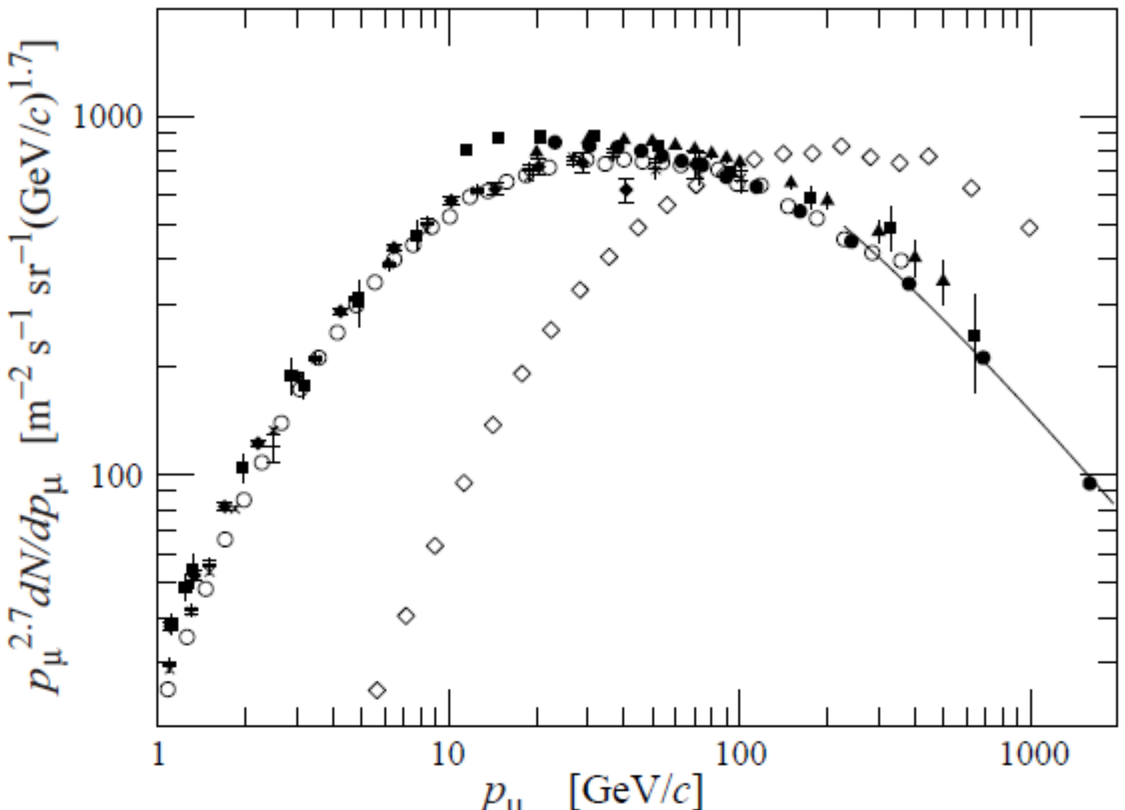


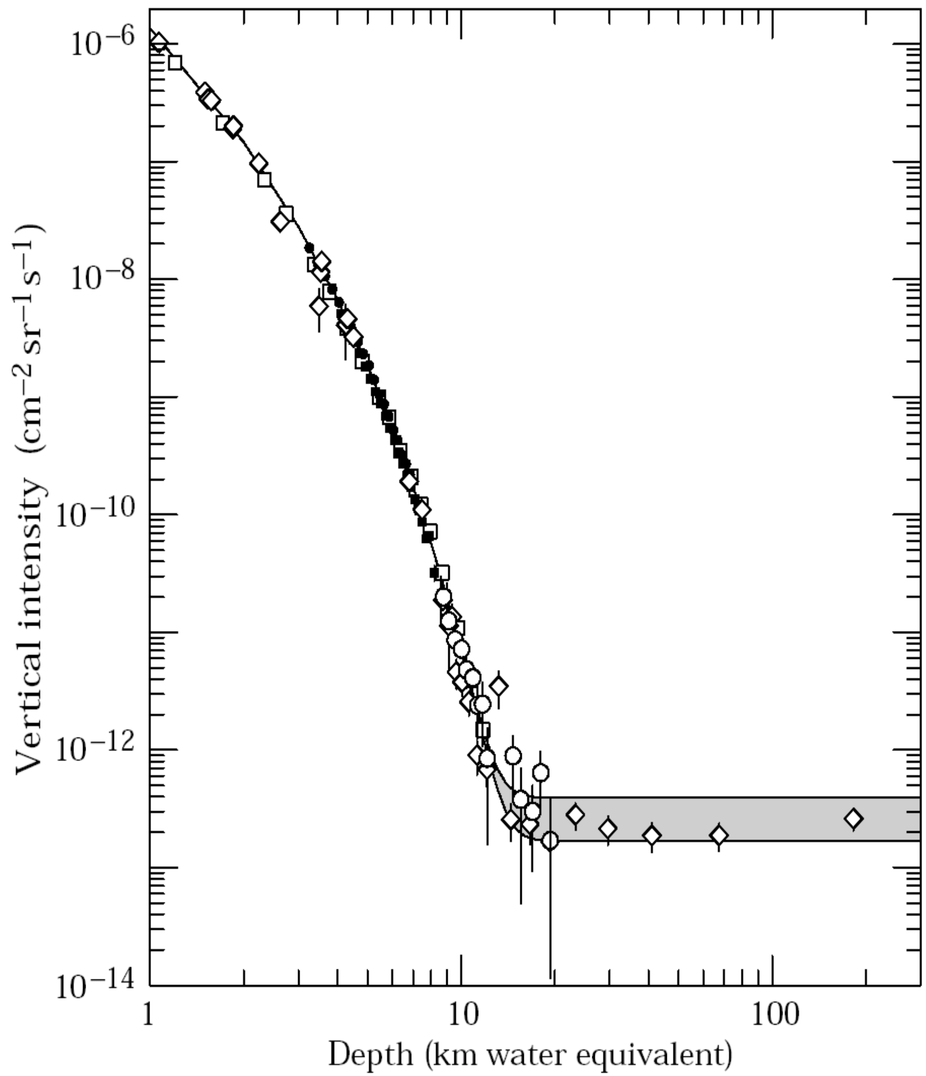
Figure 26.4: Spectrum of muons at $\theta = 0°$ (♦ [41], ■ [46], ▼ [47], ▲ [48], ×, + [43], ○ [44], and ● [45] and $\theta = 75°$ ◊ [49]) . The line plots the result from Eq. (26.4) for vertical showers. **J. Beringer et al (PDG) PR D86 010001 (2012)**

Under Earth

At the Earth surface :

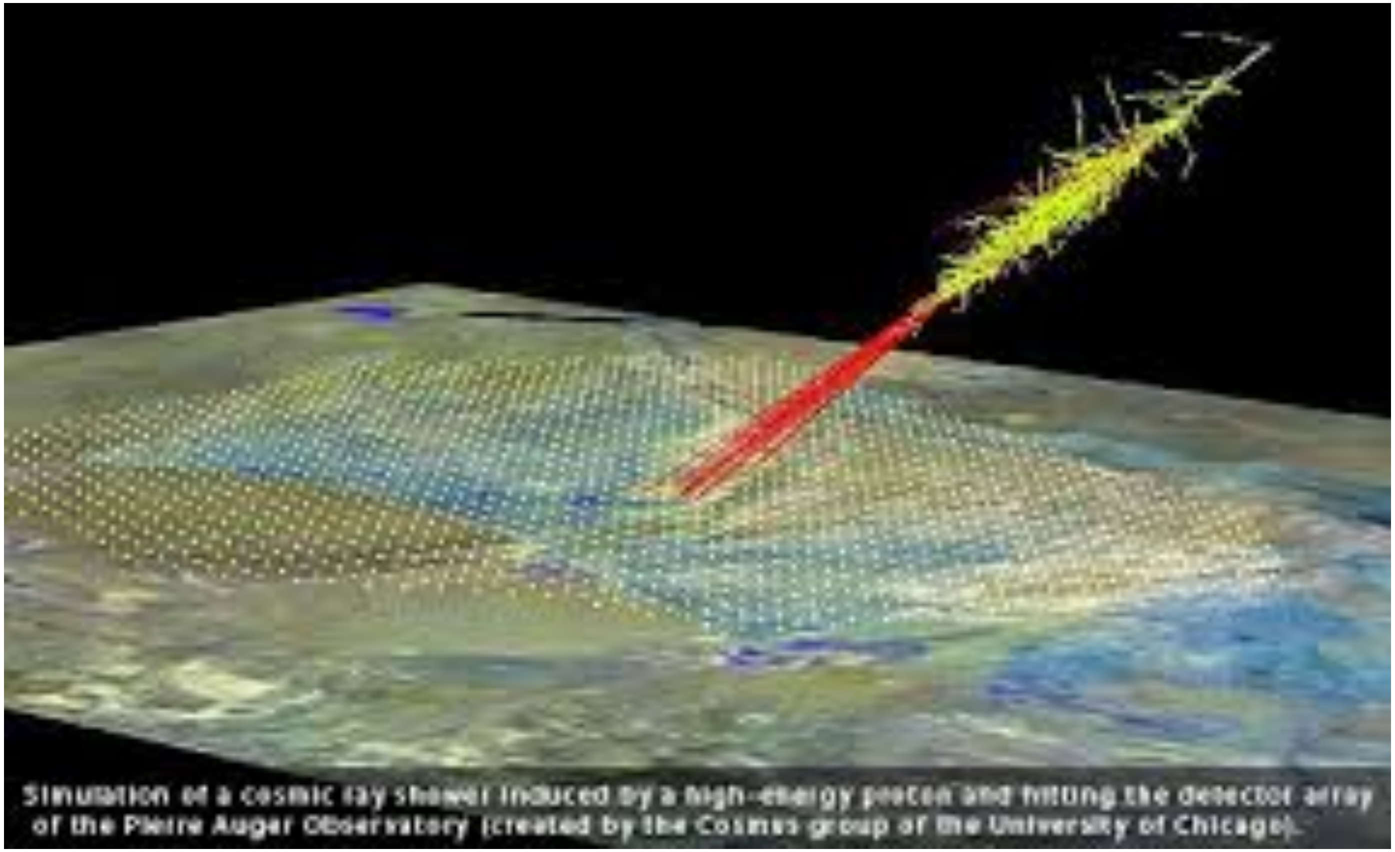
~70 m^{-2} s^{-1} sr^{-1}

~1 cm^{-2} min^{-1} (W~p)



Place	Depth(KmWater)	Threshold(TeV)
Mt.Blanc	~ 5	~ 3
GranSasso	~ 3.5	~ 2
Kamiokande	~ 2.7	~ 1

Cosmic rays (II)



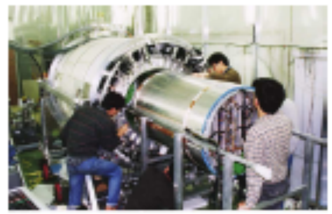
Simulation of a cosmic ray shower induced by a high-energy proton and hitting the detector array of the Pierre Auger Observatory (created by the Cosmus group of the University of Chicago).

Cosmic ray direct detection in space

'96 '97 '98 '99 '00 '01 '02 '03 '04 '05 '06 '07 '08 '09 '10 '11

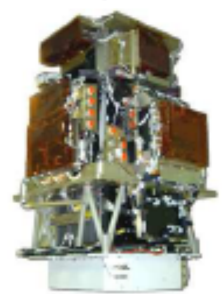
STS-91 flight (Jun 98)

BESS-POLAR (2004, 2007-08)

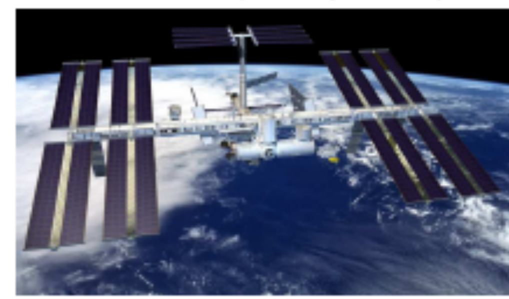


FERMI (June 2008)

PAMELA (June 2006)

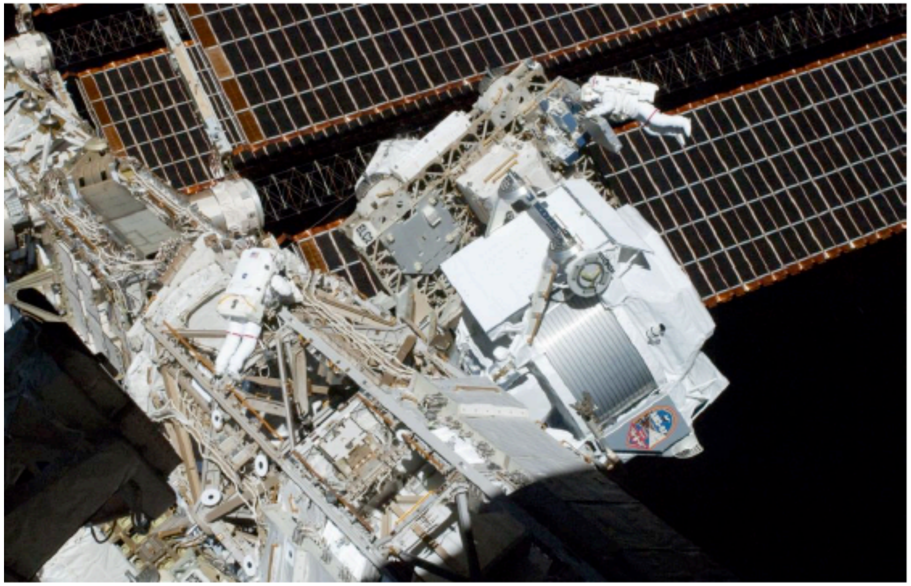


AMS to ISS (Feb-Apr/2011)

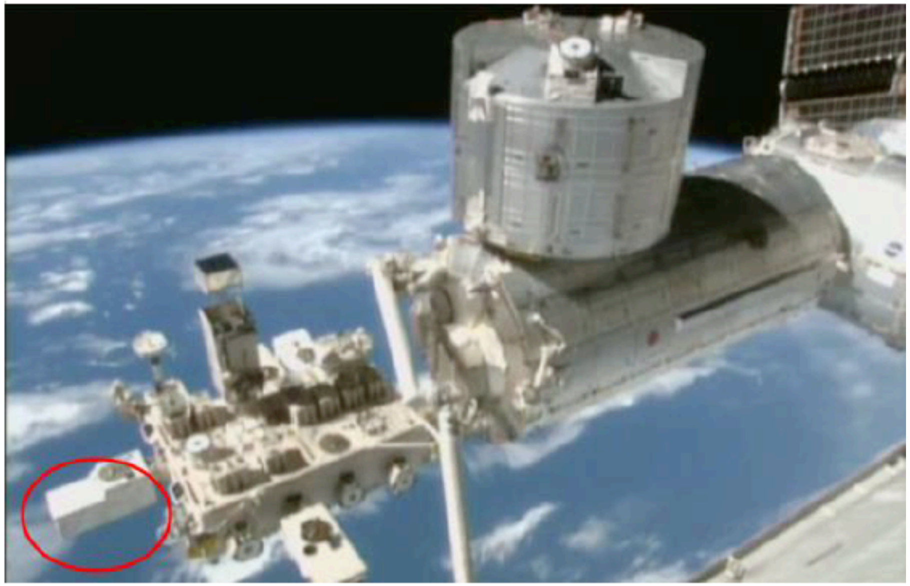


Space-born Cosmic Ray Experiments in operation

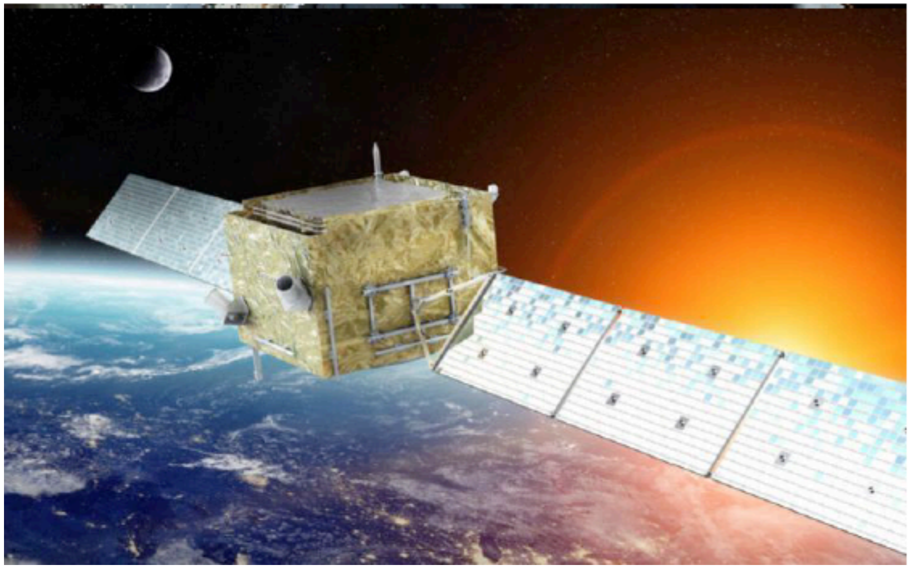
AMS, started May 2011



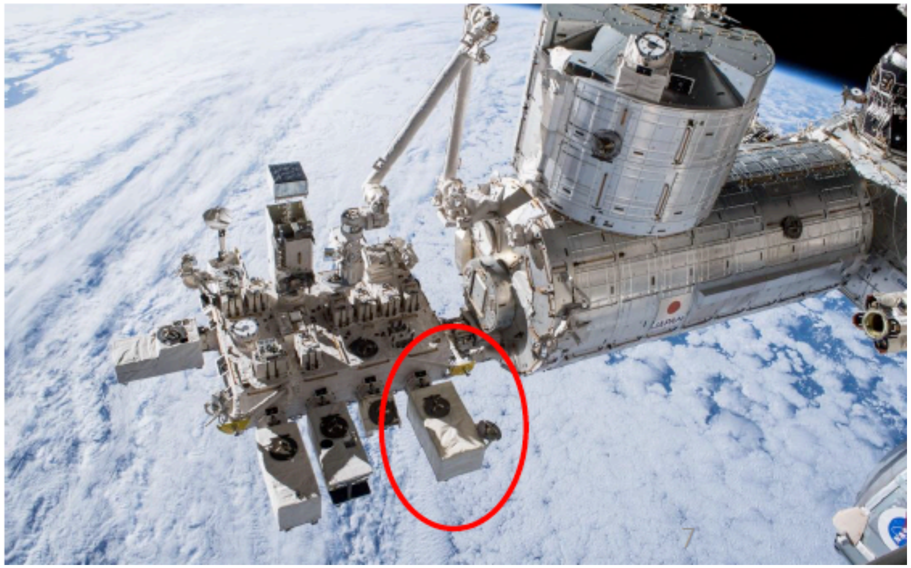
CALET, started August 2015



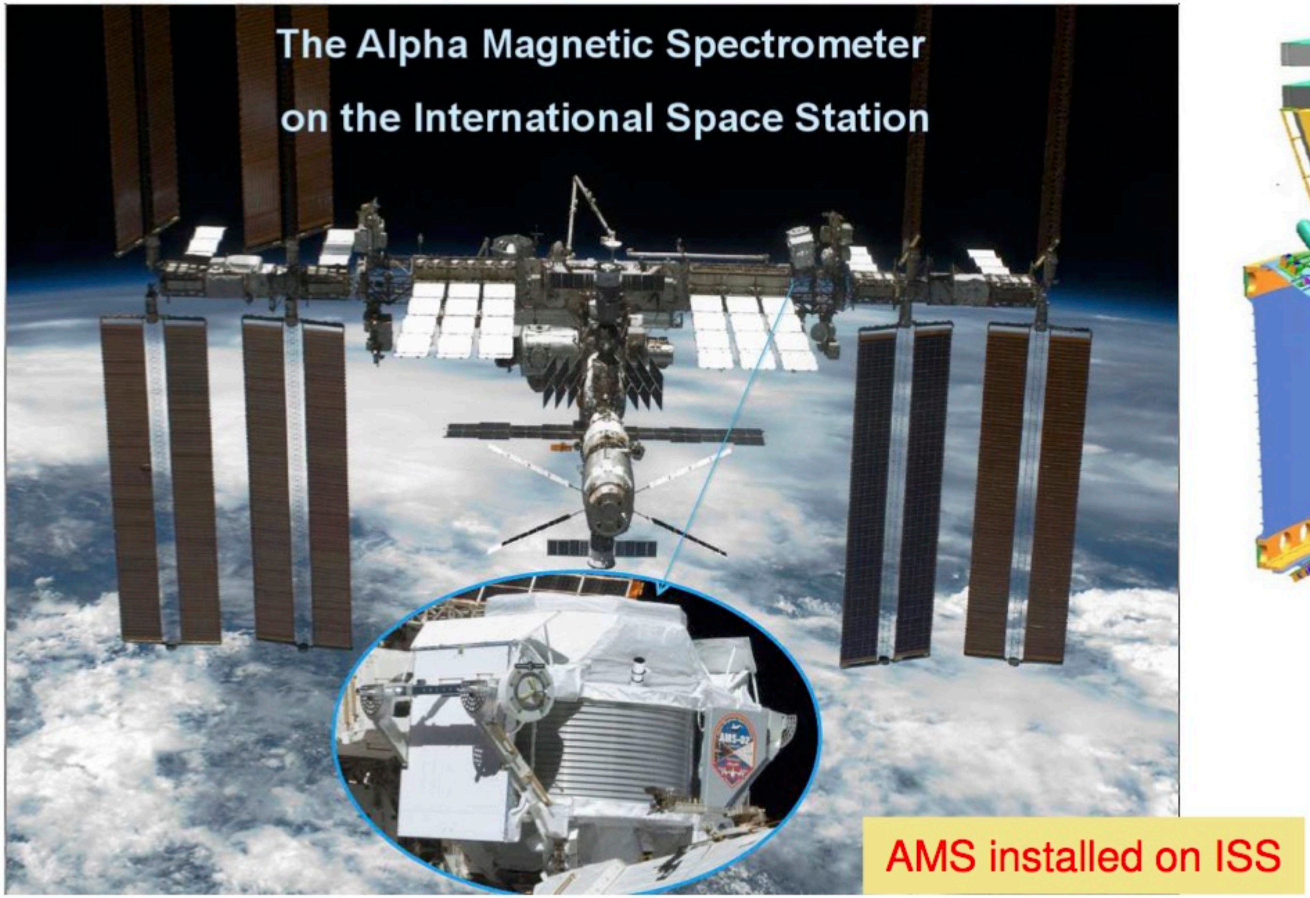
DAMPE, started December 2015

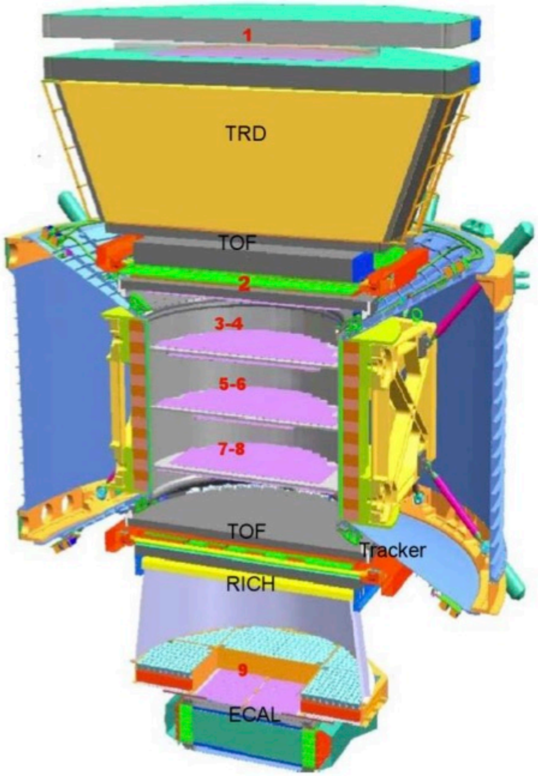


ISS CREAM, started August 2017

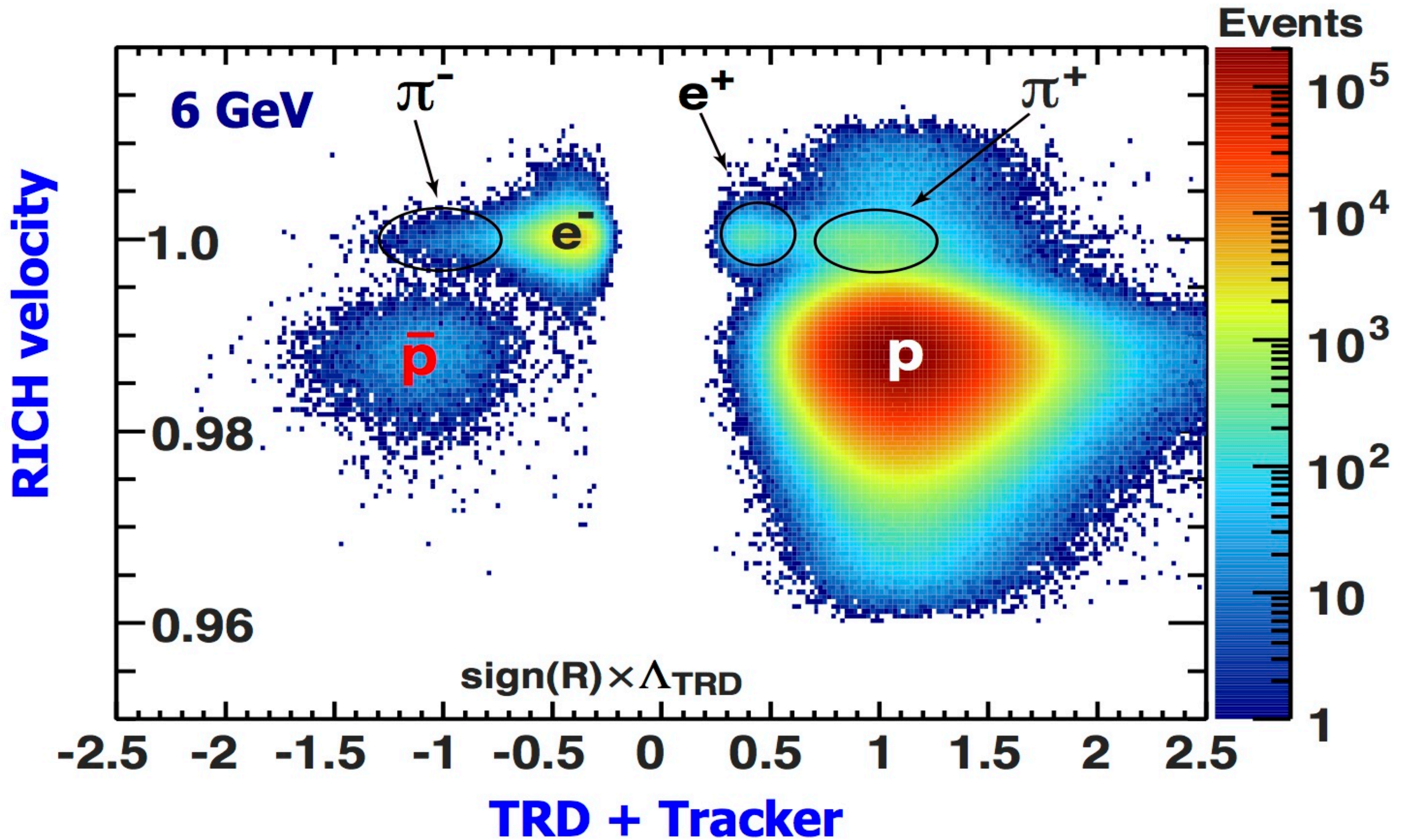


AMS

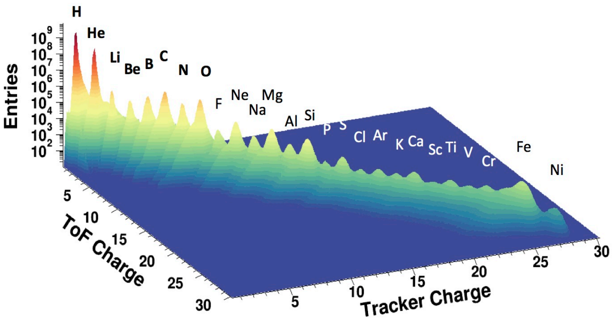

The Alpha Magnetic Spectrometer
on the International Space Station
AMS installed on ISS


1
TRD
TOF
2
3-4
5-6
7-8
TOF
Tracker
RICH
9
ECAL

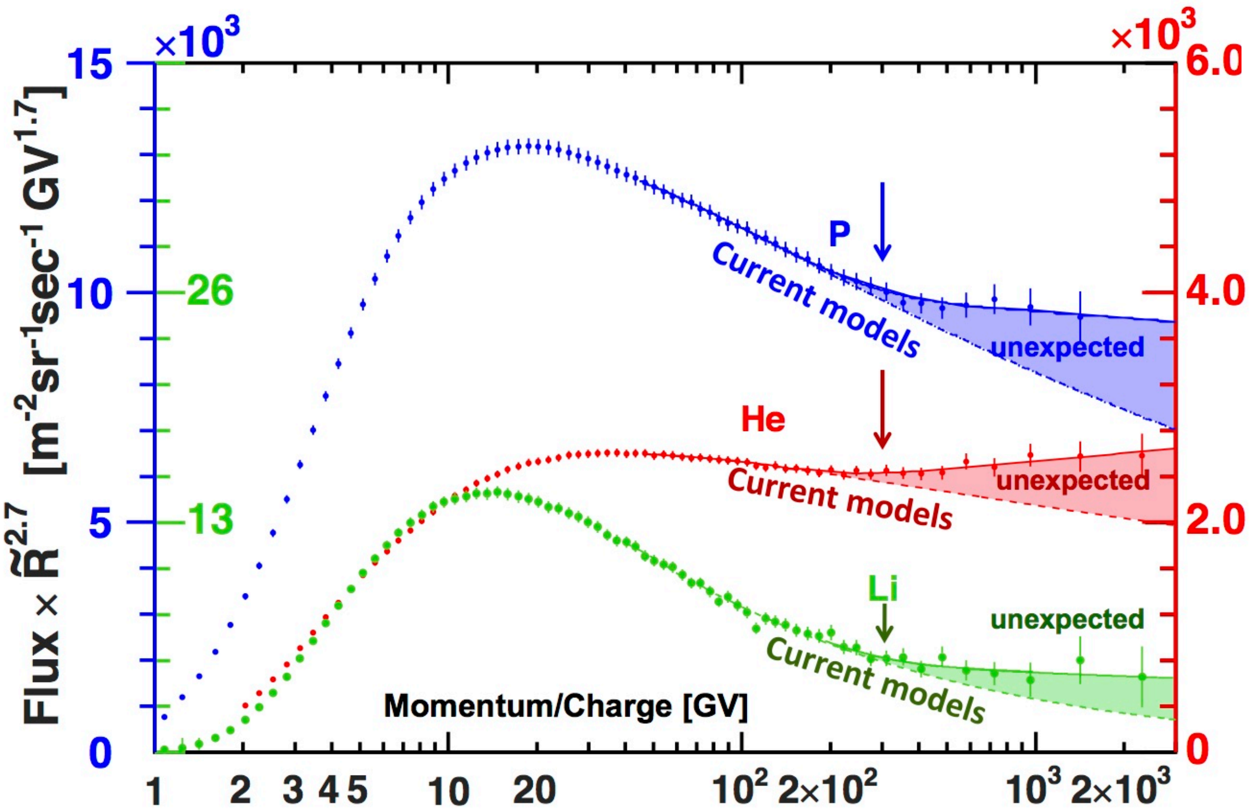
Particle identification



Nuclei …

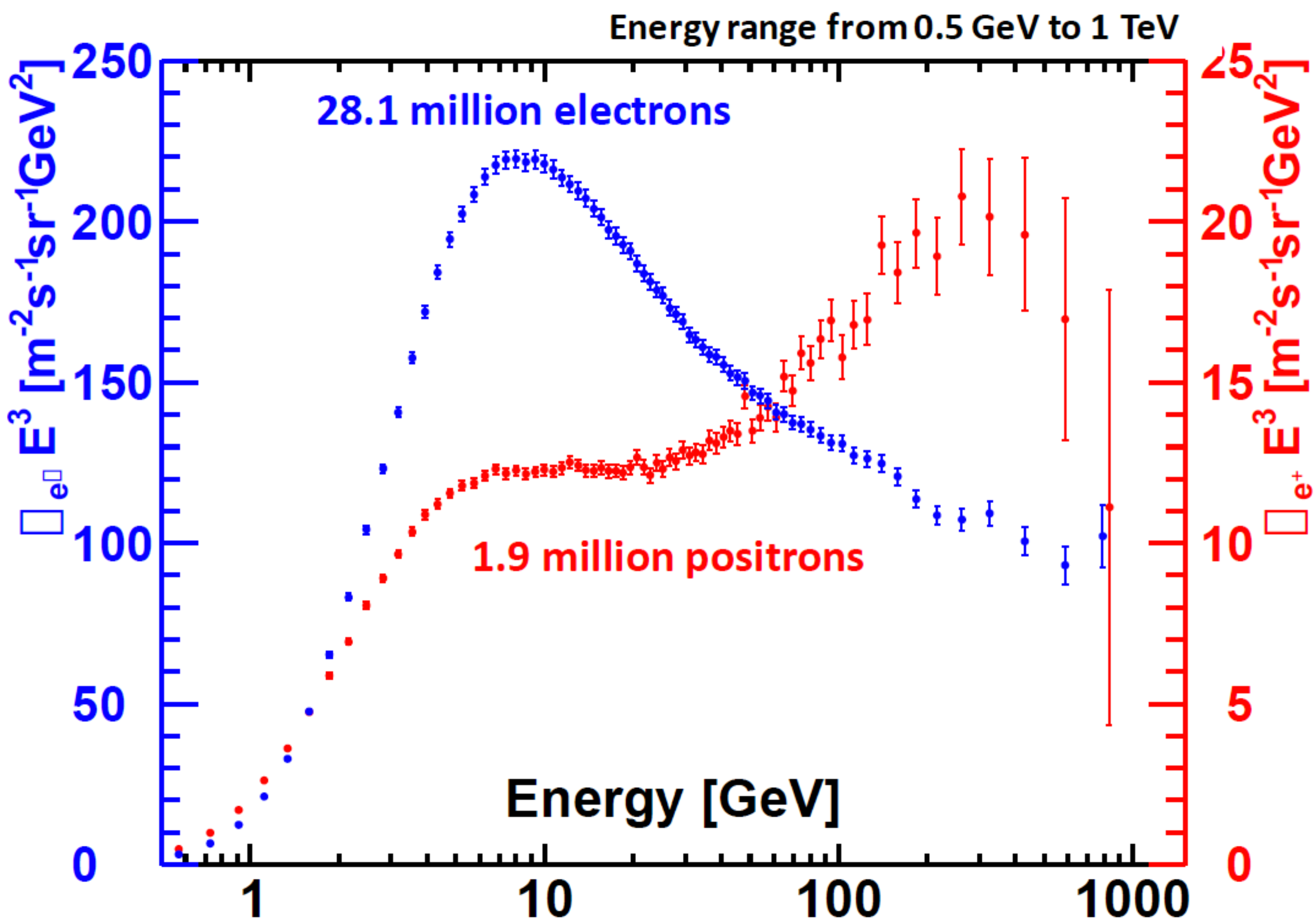


H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Fe
Ni
Entries
ToF Charge
Tracker Charge



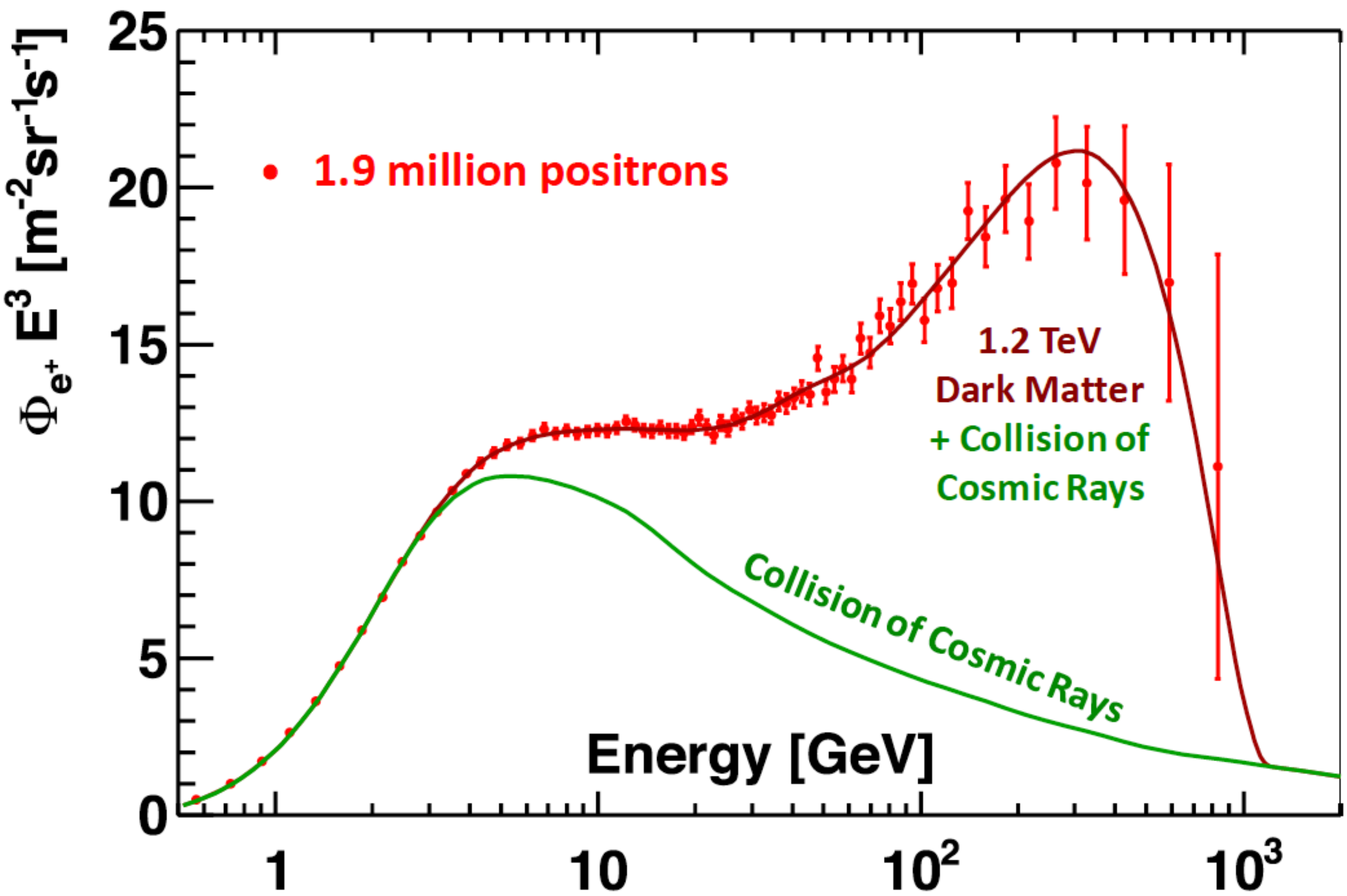
×10³
×10³
15
10
5
0
26
13
6.0
4.0
2.0
0
Flux × R̃^2.7 [m^-2sr^-1sec^-1 GV^1.7]
P
Current models
unexpected
He
Current models
unexpected
Li
unexpected
Current models
Momentum/Charge [GV]
1
2
3
4
5
10
20
10²
2×10²
10³
2×10³

Electron, positron spectrum

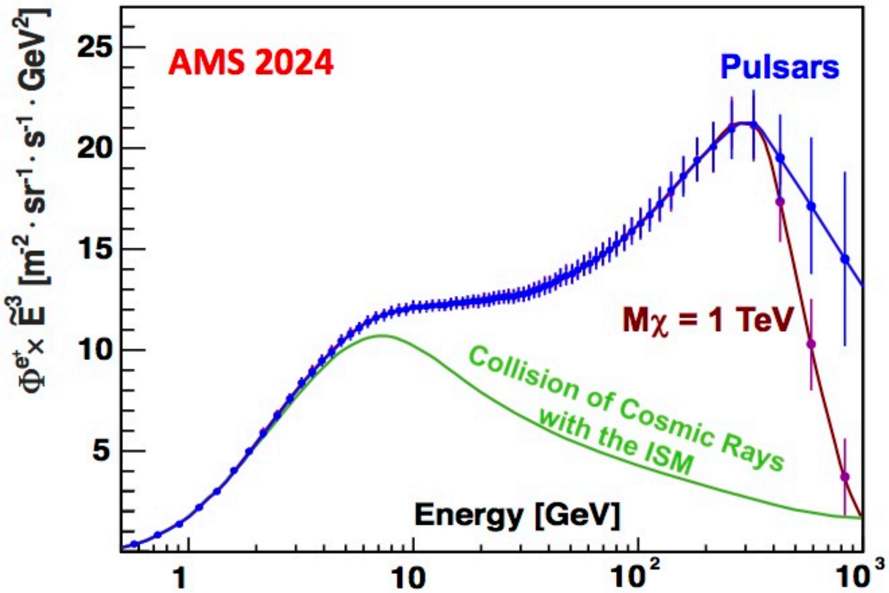


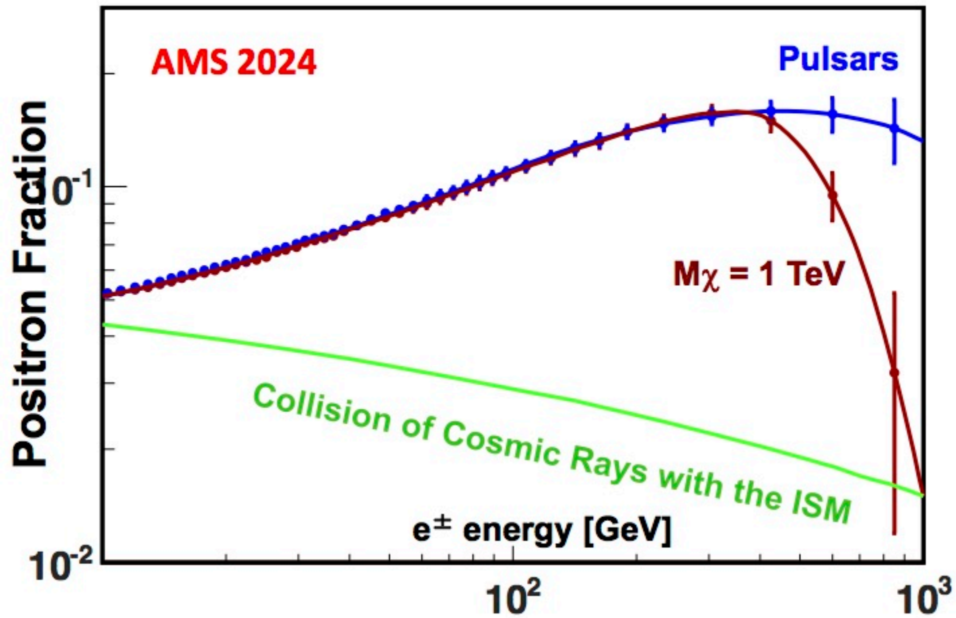
Dark matter signal?

The positron flux appears to be in agreement with predictions from a 1.2 TeV Dark Matter model (*J. Kopp, Phys. Rev. D 88, 076013 (2013)*)



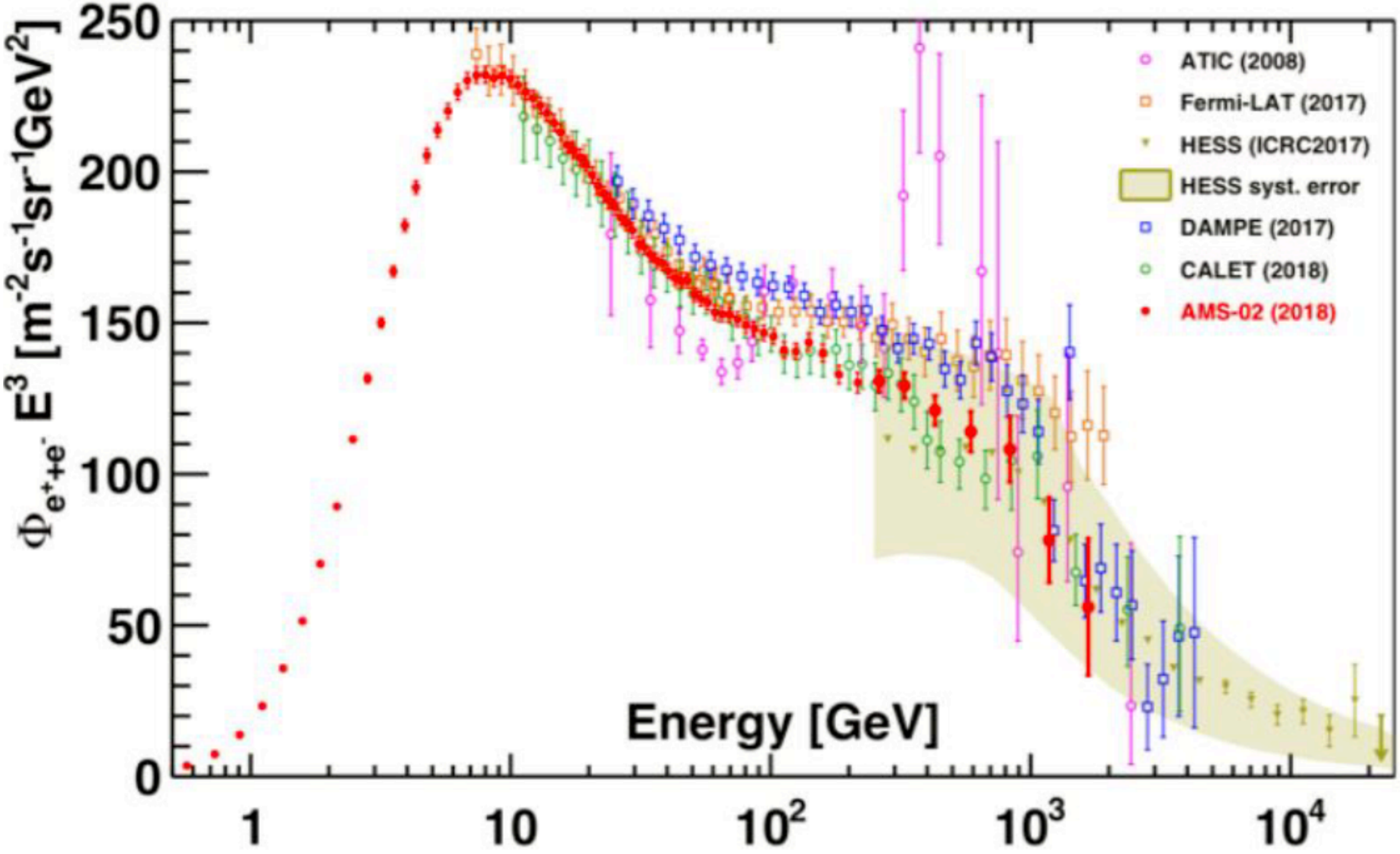
Wait for 2024 …



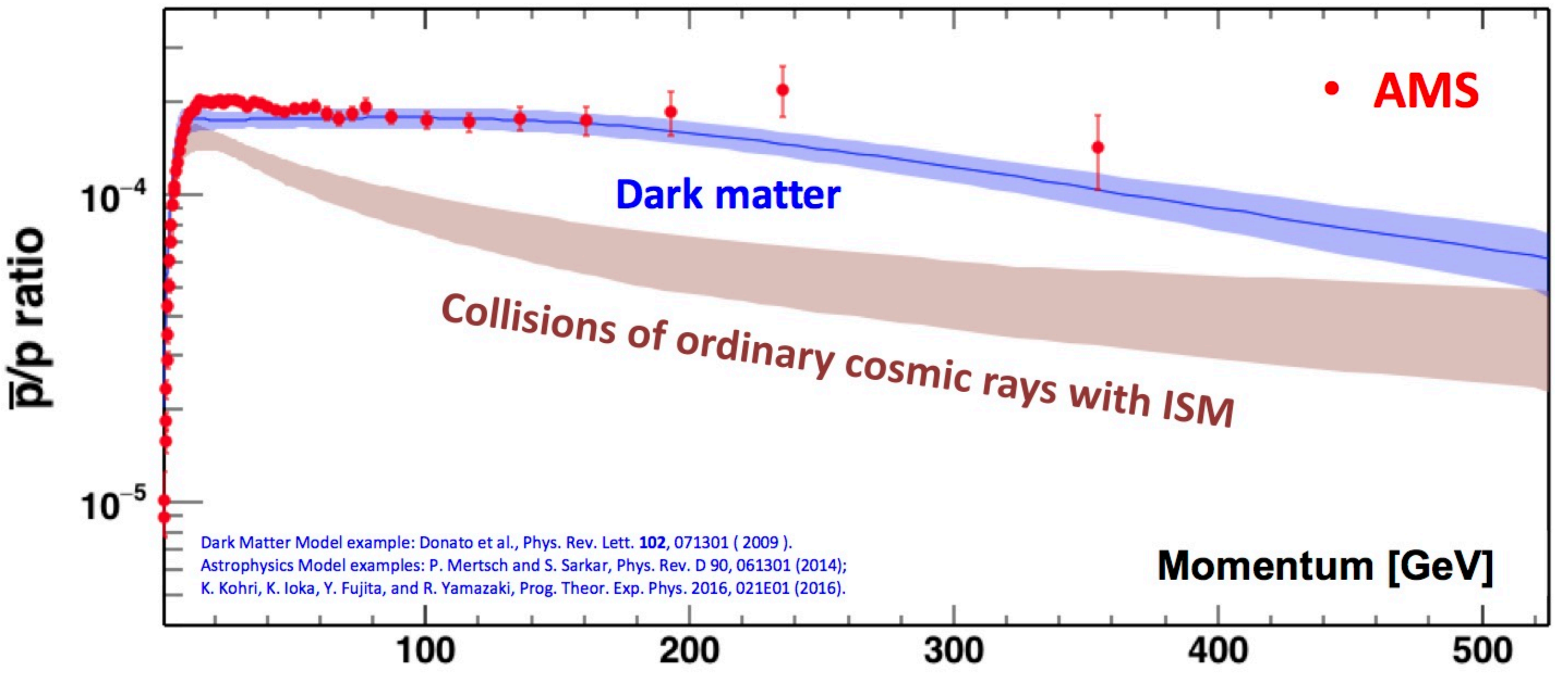


Meanwhile …

$(e^+ + e^-)$ AMS data: comparison with other detectors

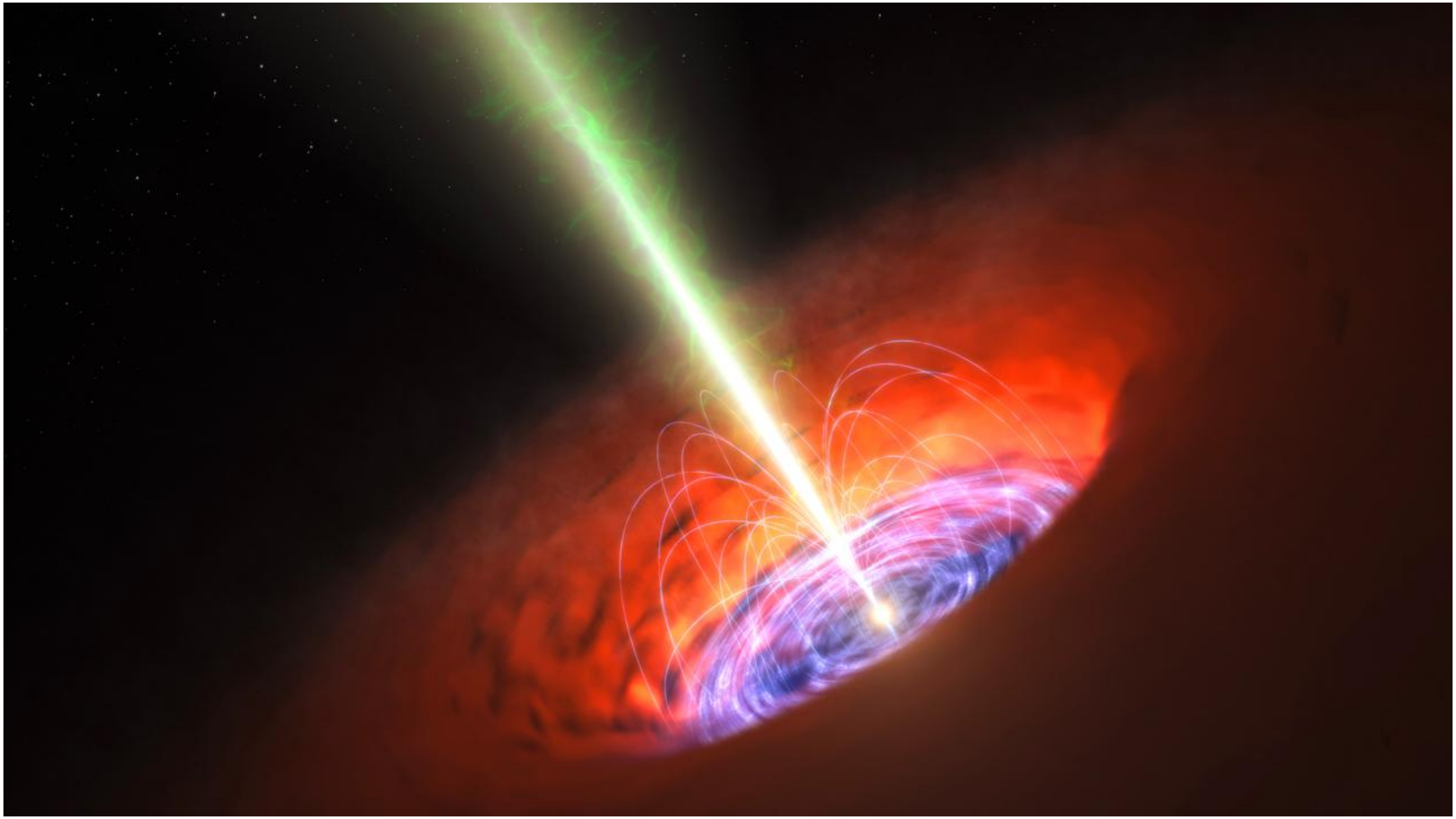


anti-proton/proton ratio

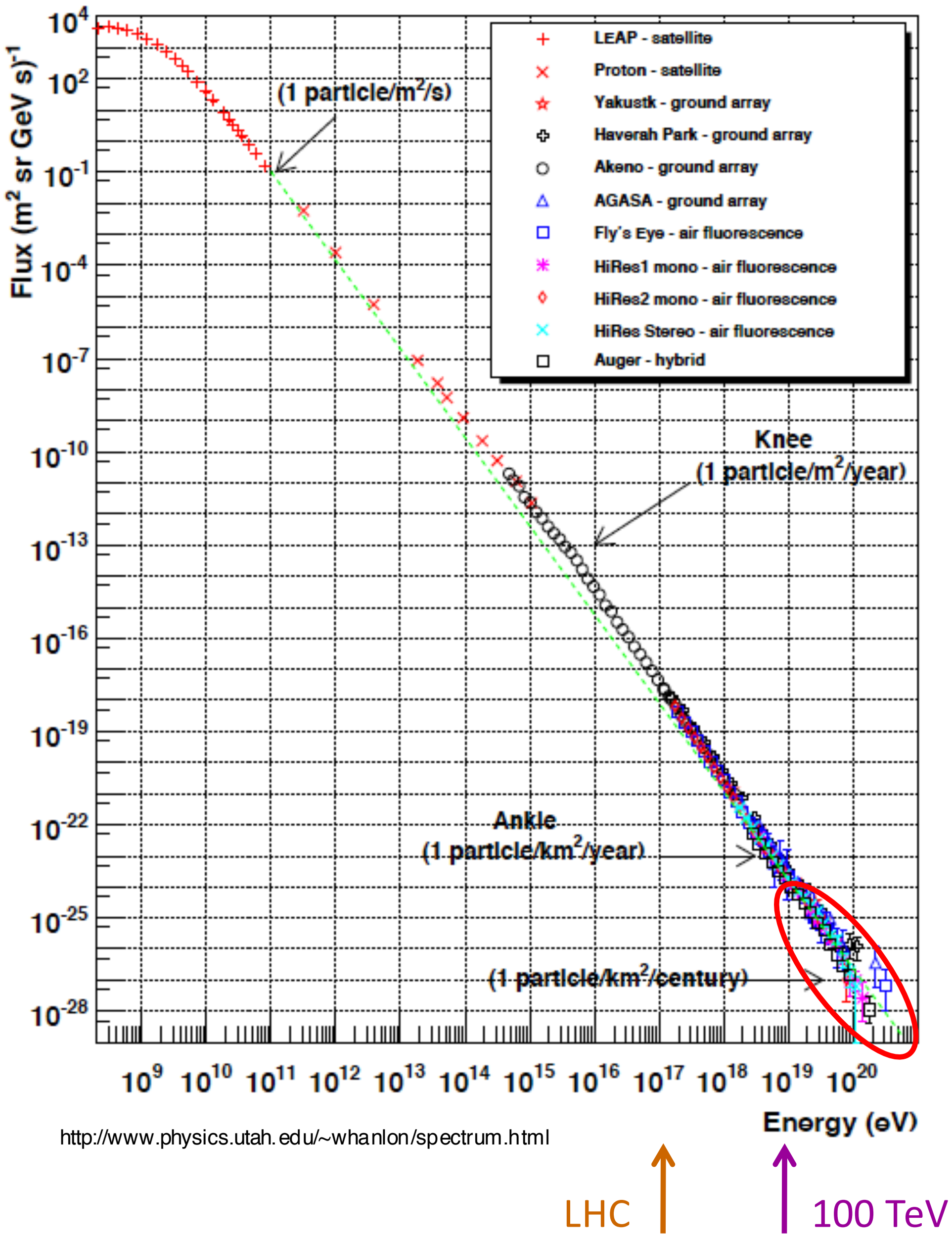


Not easily explained by pulsars ...

The Extreme Universe



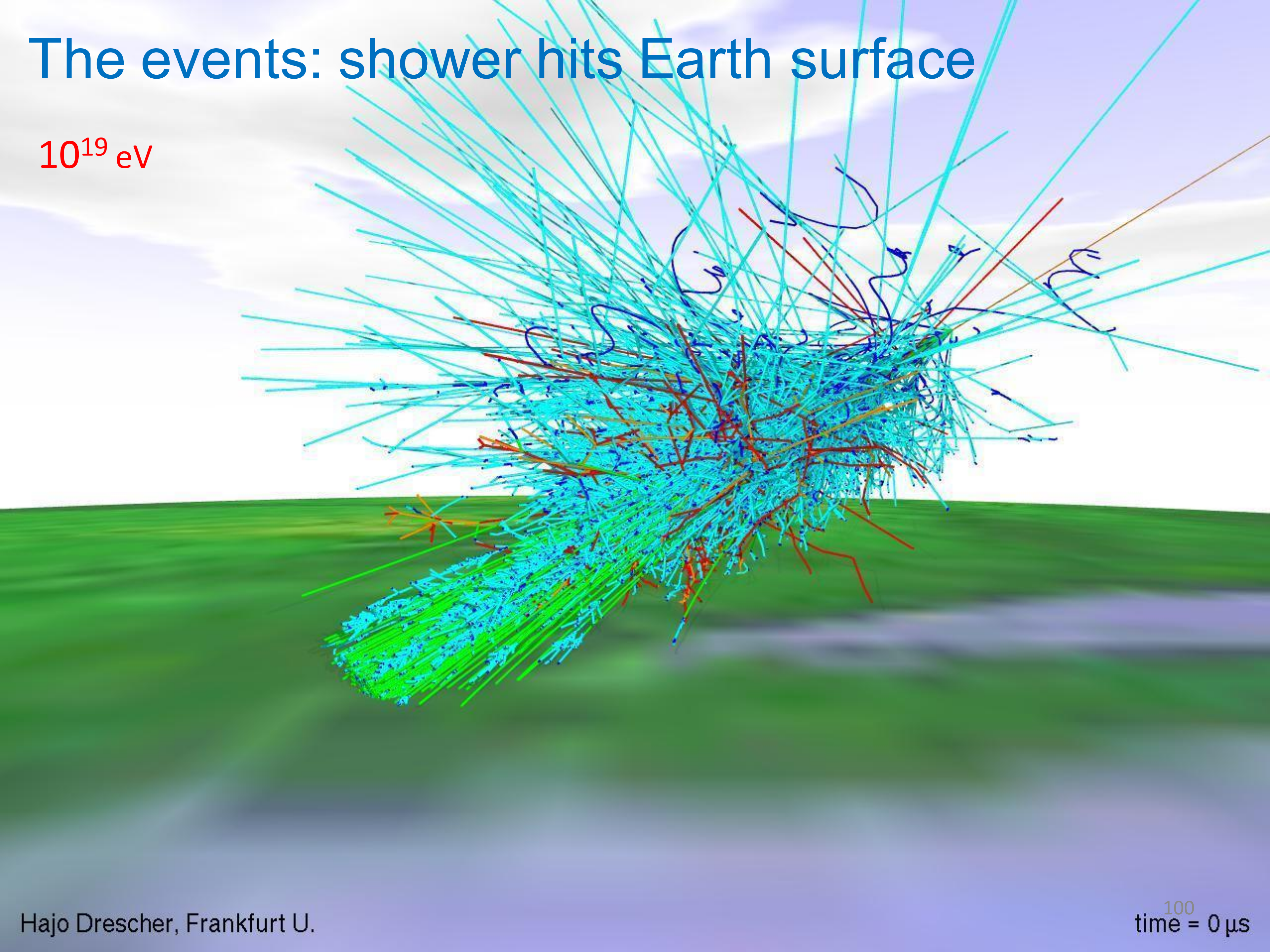
High Energy Cosmic Rays



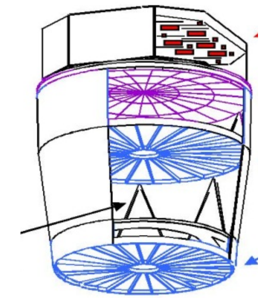
http://www.physics.utah.edu/~whanlon/spectrum.html

The events: shower hits Earth surface

10^{19} eV

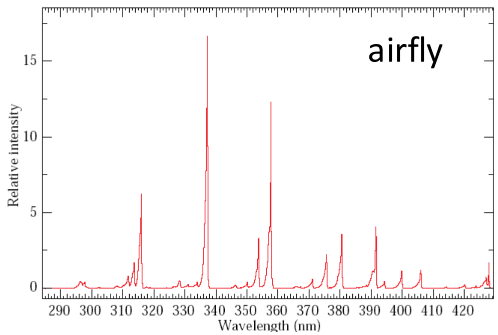


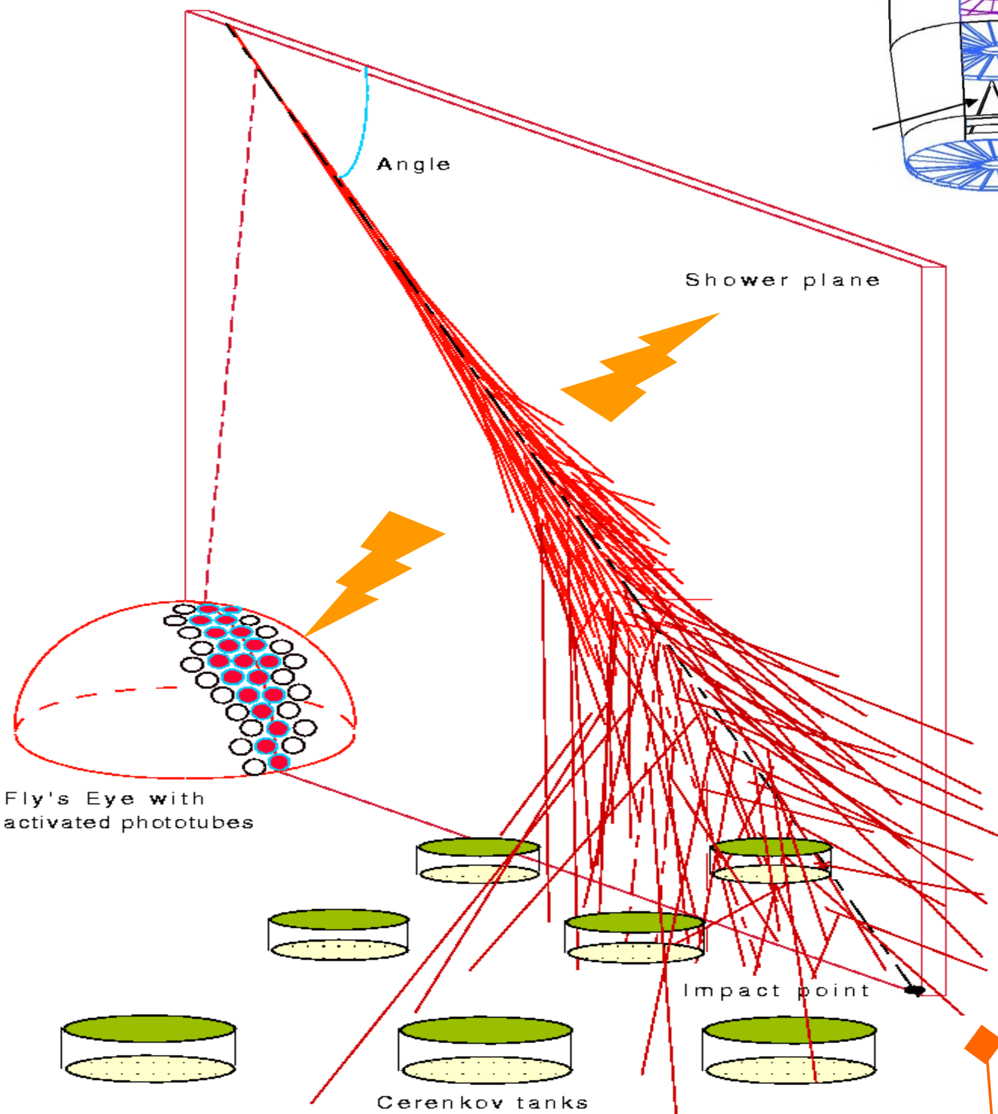
EAS detection



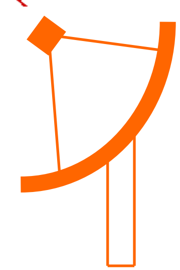
Fluorescence

electrons excite N_2 molecules





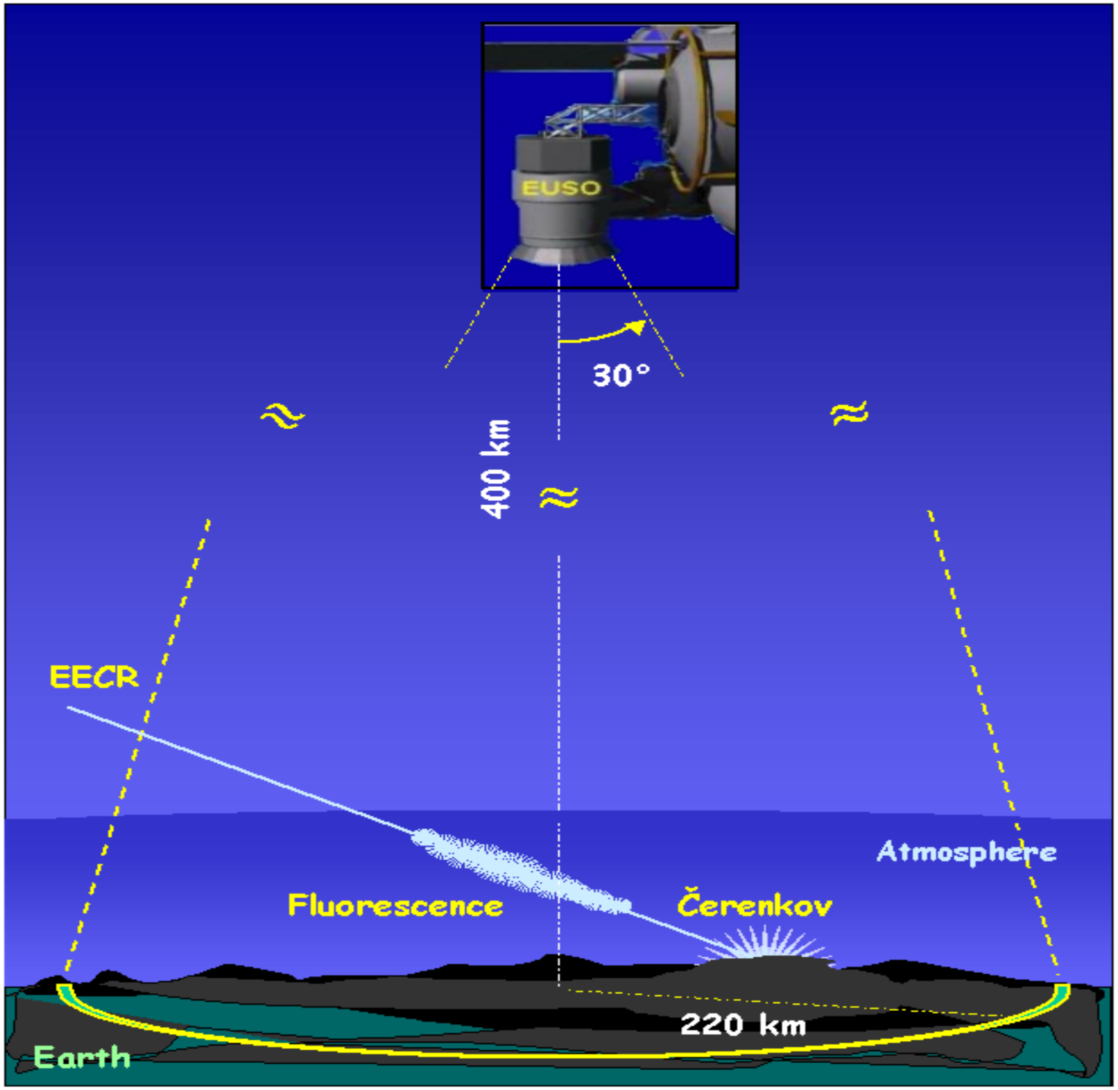
Cherenkov



Particles

Fluorescence from space

JEM-EUSO



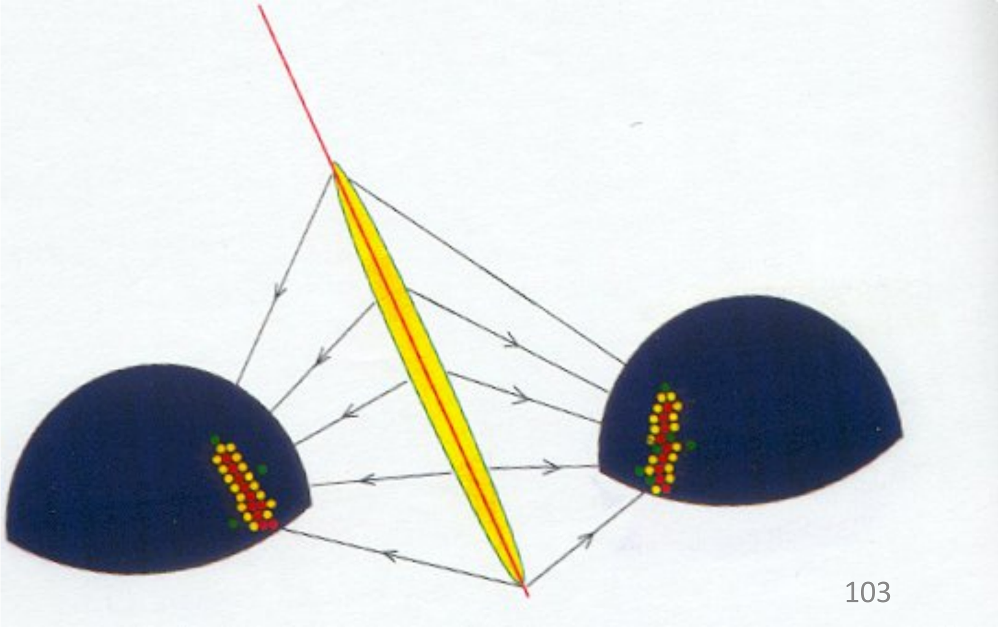
Fluorescence from Earth

Fly’s Eye

HiRes

Air shower

stereo image



Fluorescence detectors measurements

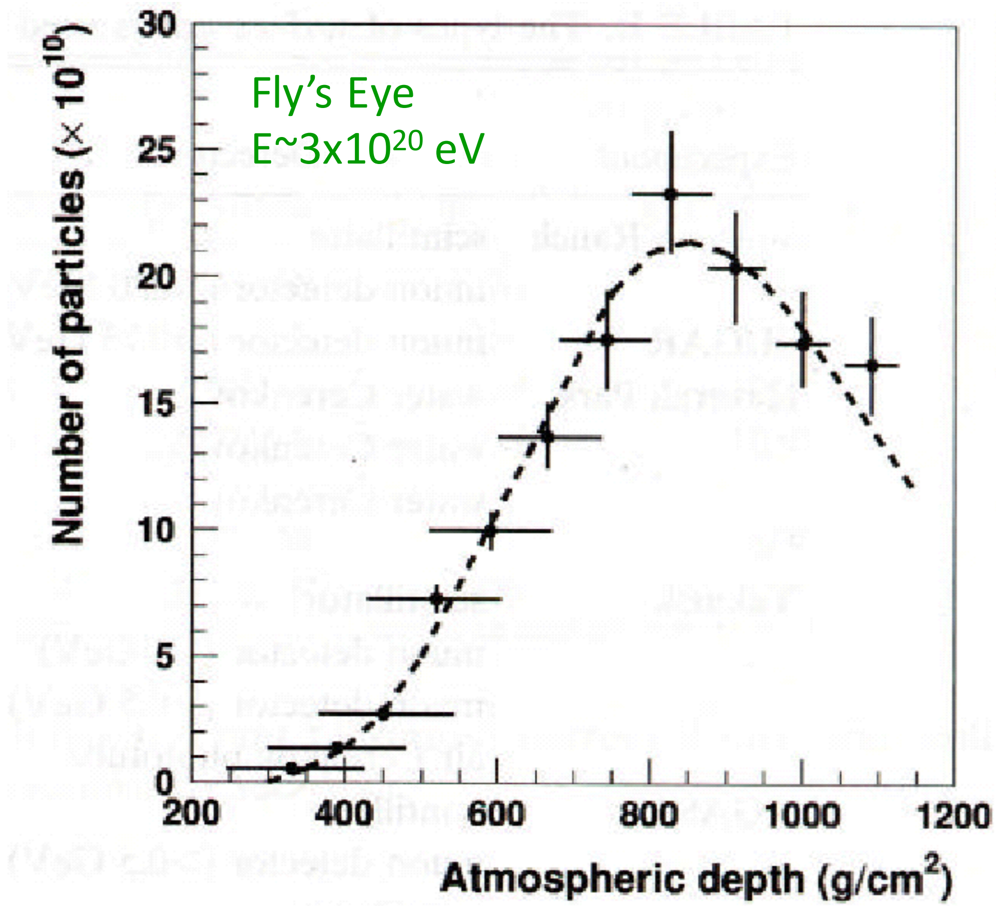
The direction

The X_{max}

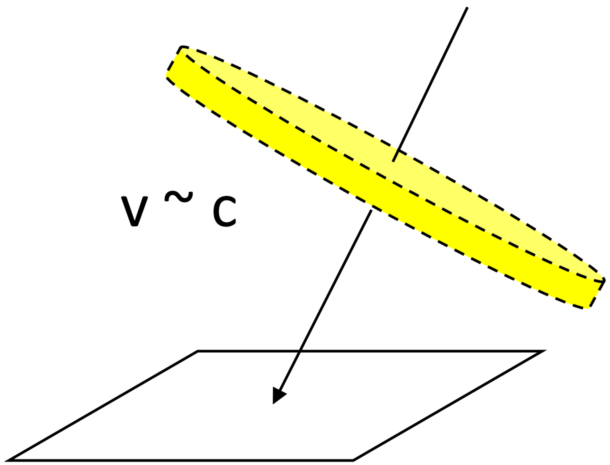
The Energy

$$E \propto Ne$$

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



Ground arrays measurements

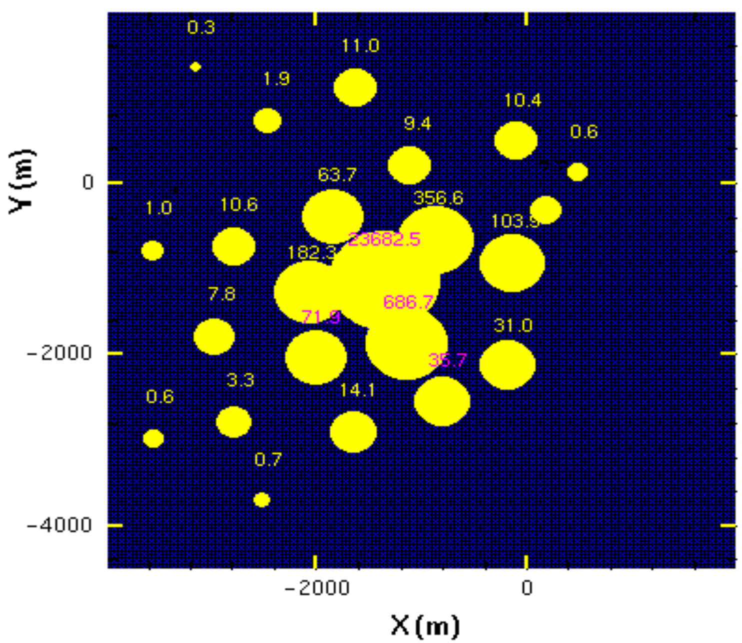


From (n_i, t_i):

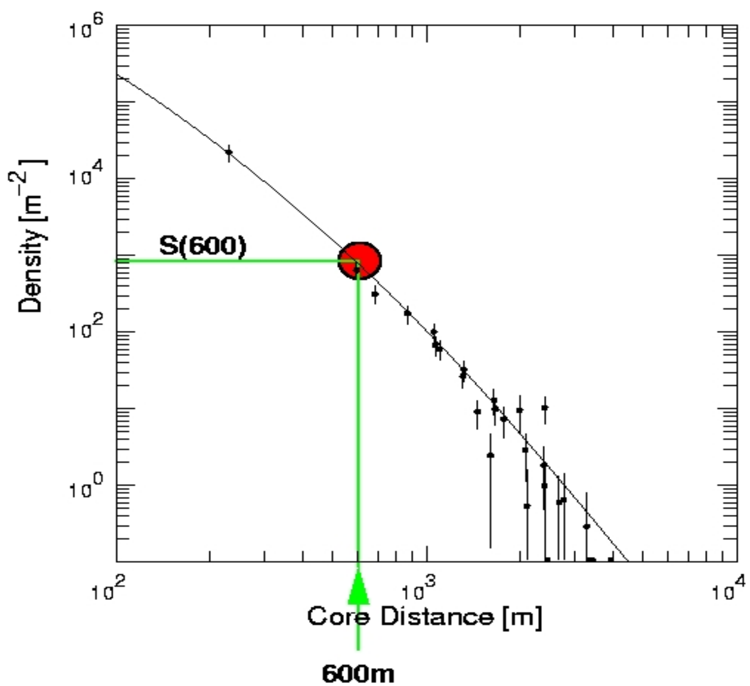
The direction

The core position

The Energy

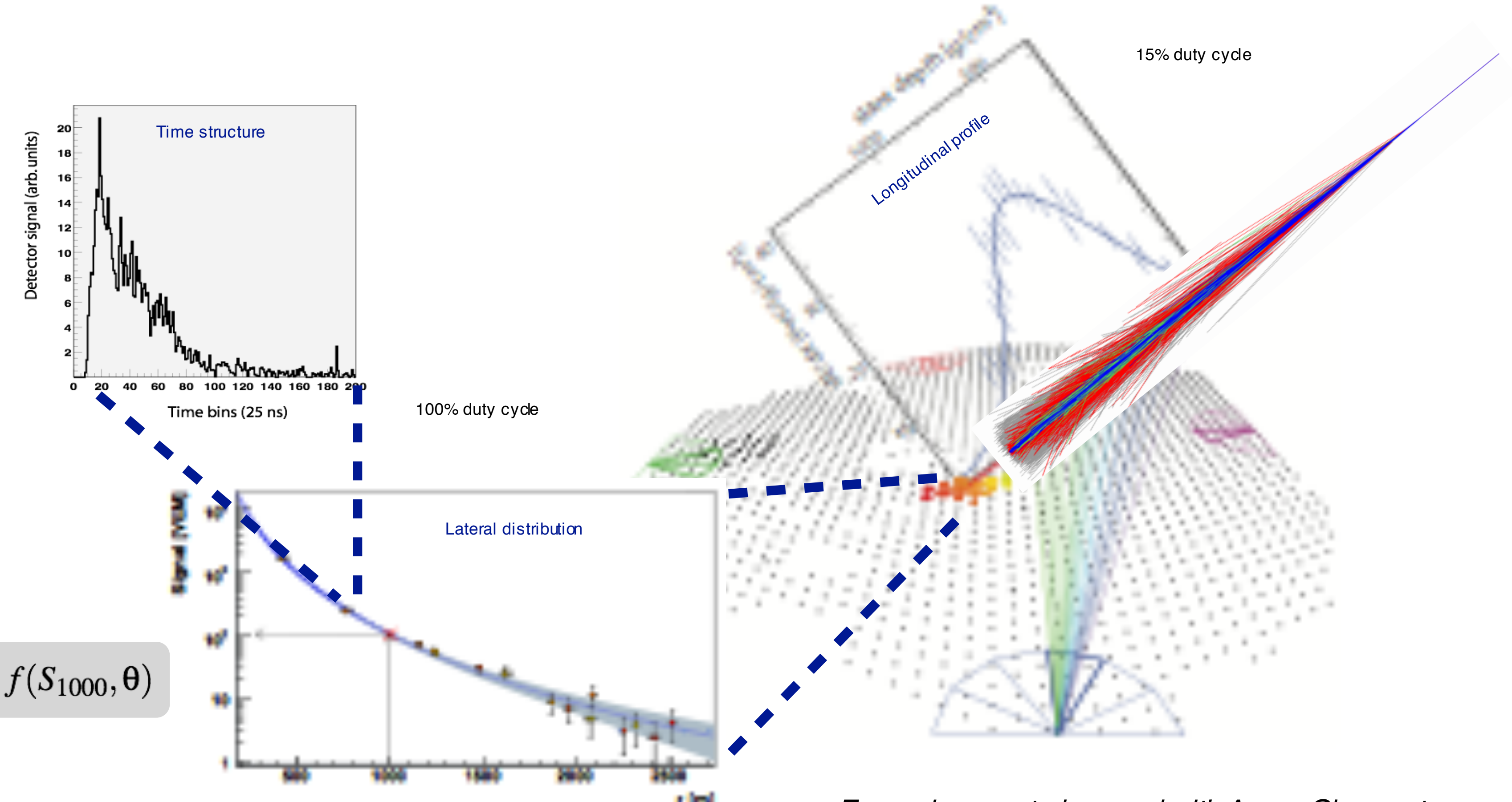


The LDF



Measurements by an Hybrid detector at Earth

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



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

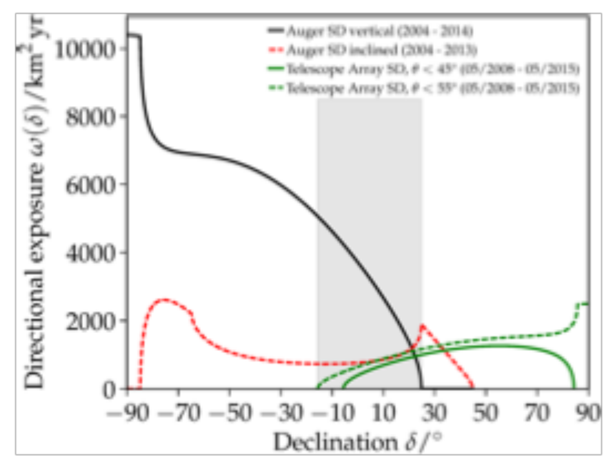
Example: event observed with Auger Observatory

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

Together full sky coverage



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)

Telescope Array (TA)

Area ~ 680 km^2

3 fluorescence telescopes

507 double-Layer scintillators

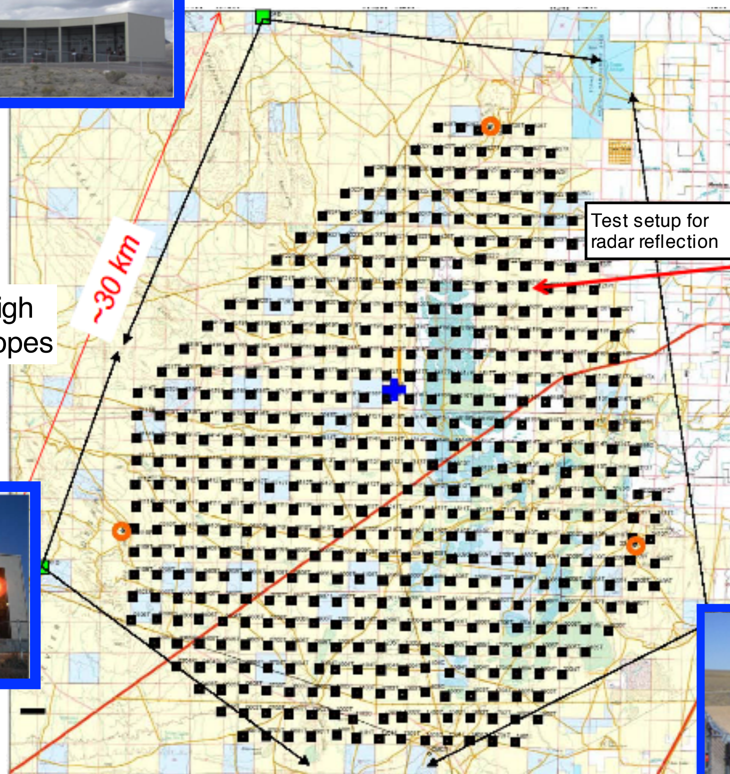
Talk by Abu-Zayyad

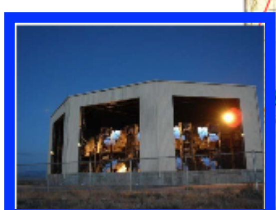
Middle Drum: based on HiRes II

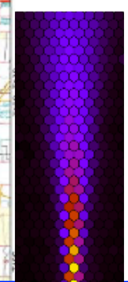
TALE (TA low energy extension)

LIDAR
Laser facility

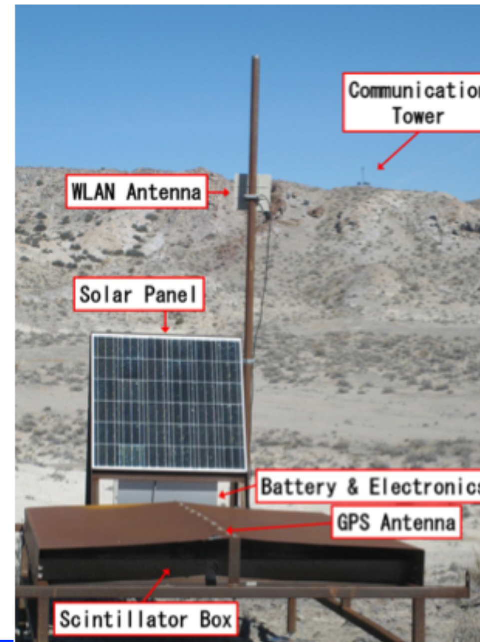
Infill array and high
elevation telescopes







Electron light
source (ELS):
~40 MeV



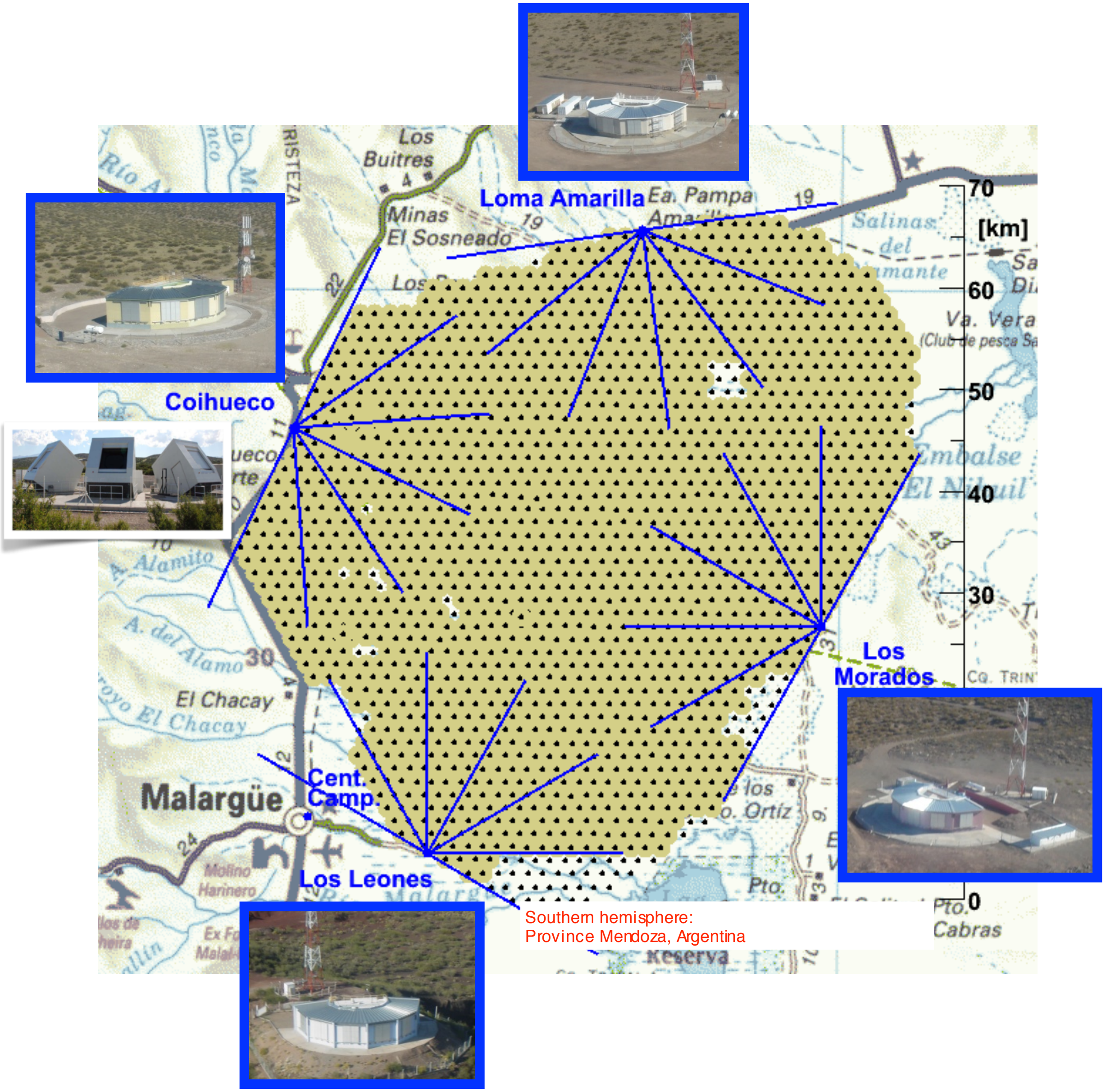
Northern hemisphere: Utah, USA

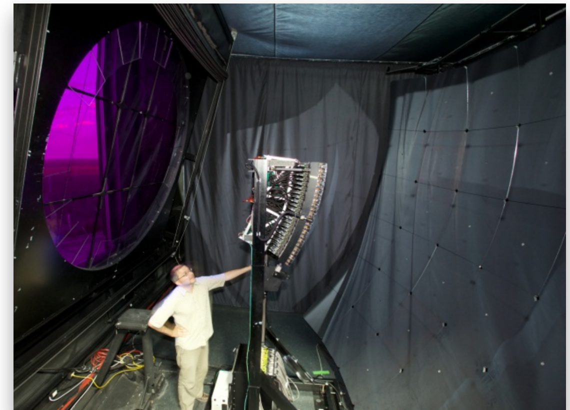
Pierre Auger Observatory

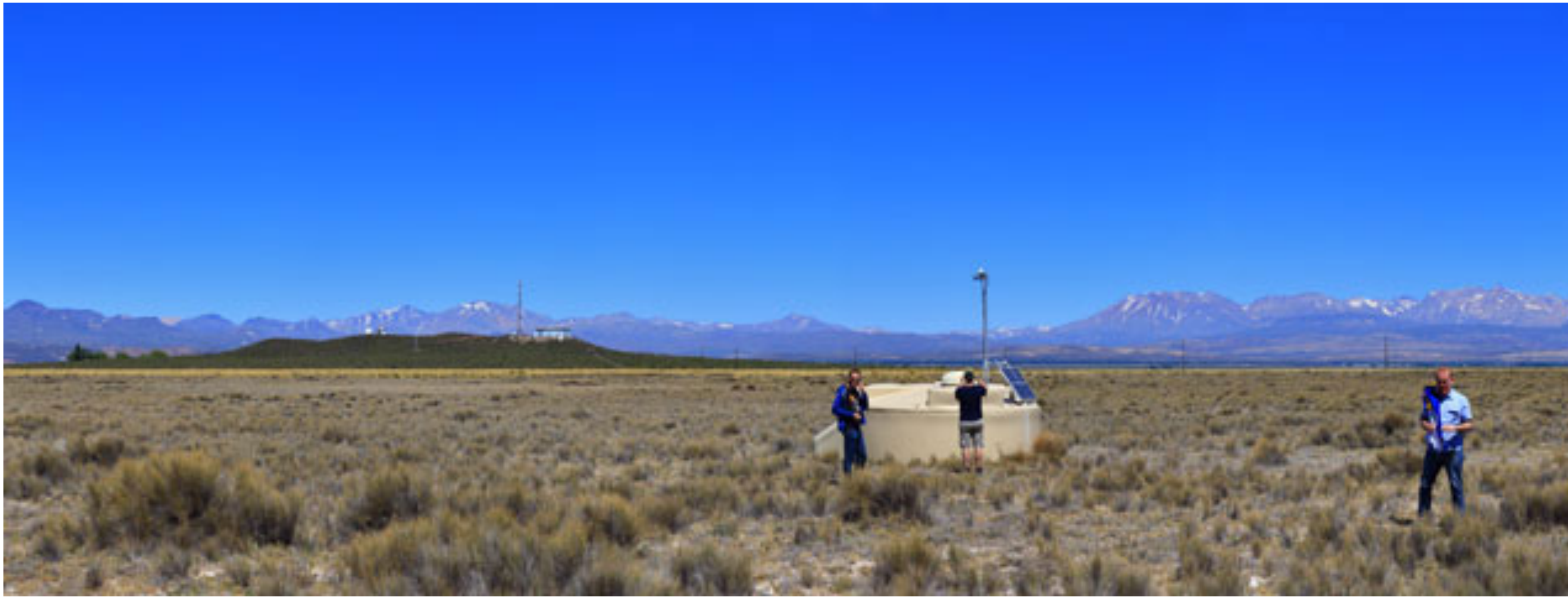
Area ~ 3000 km^2

24+3 fluorescence telescopes

1600 water Cerenkov detectors

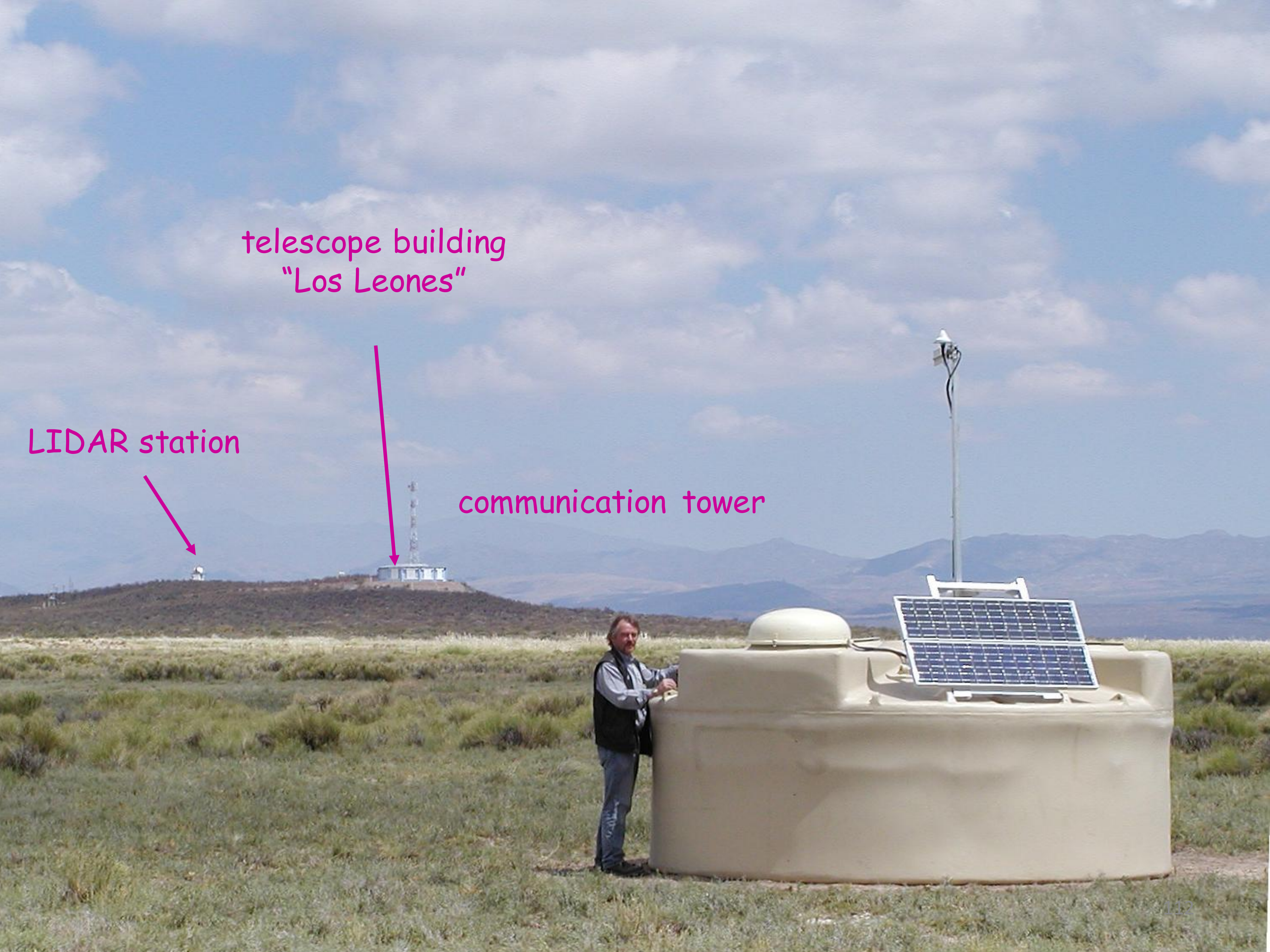


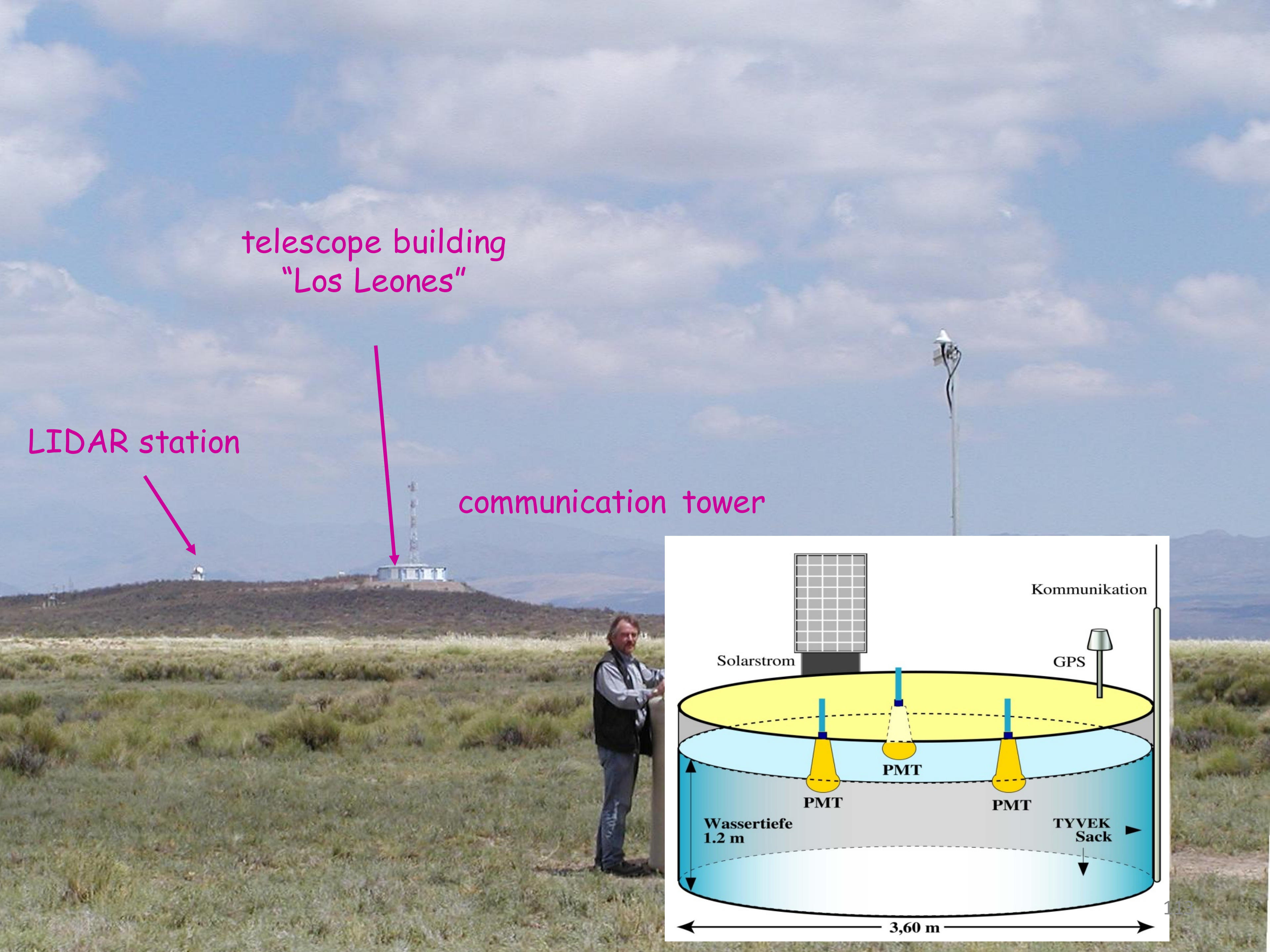





Escuela Nº 4-190
Dr. James W. Cronin
MALARGÜE - MENDOZA

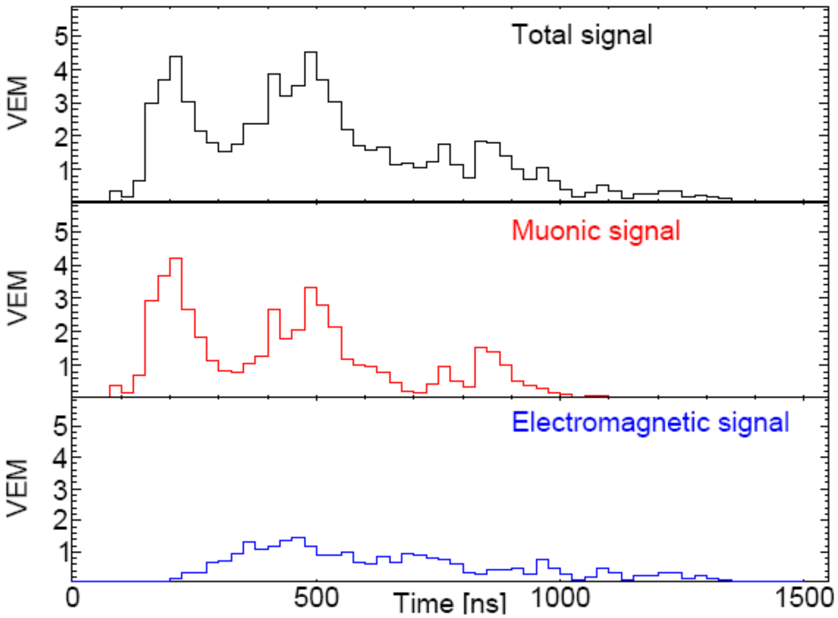
Tanks aligned seen from Los Leones

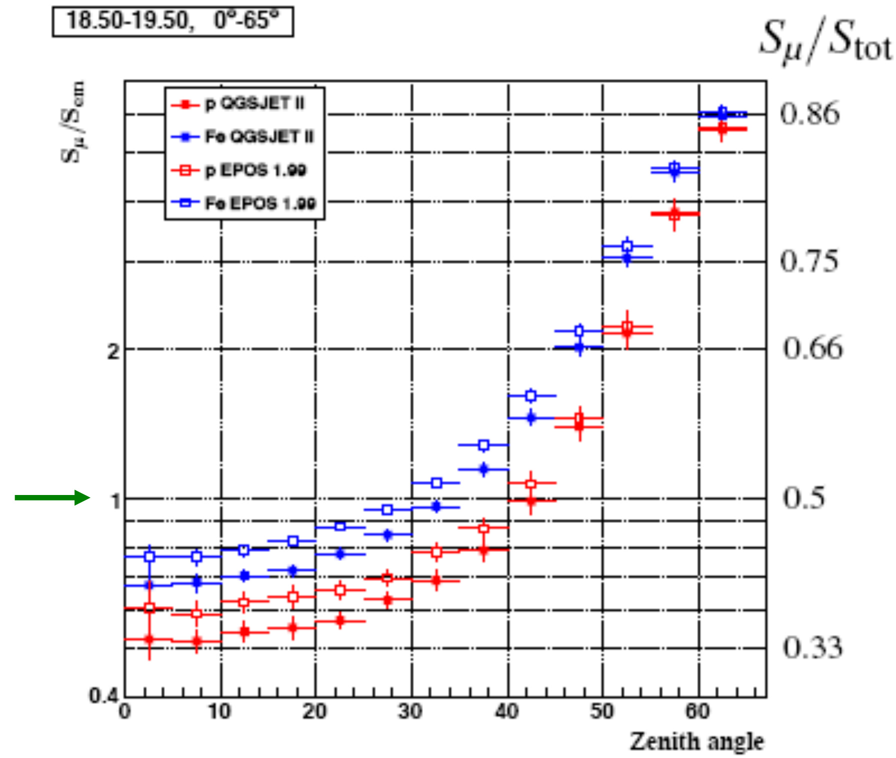

telescope building
"Los Leones"
LIDAR station
communication tower


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 in the WCDs

Individual time traces

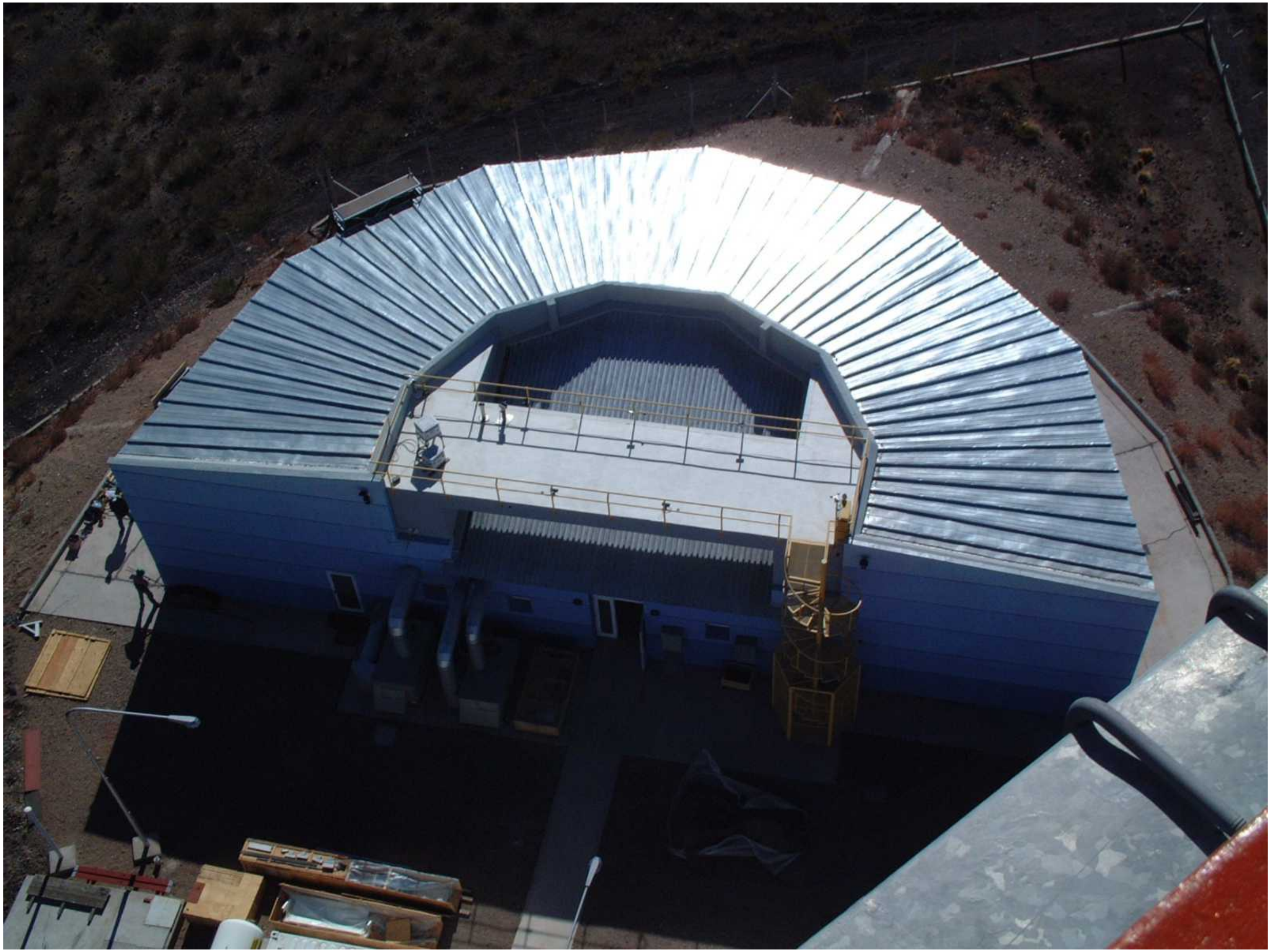




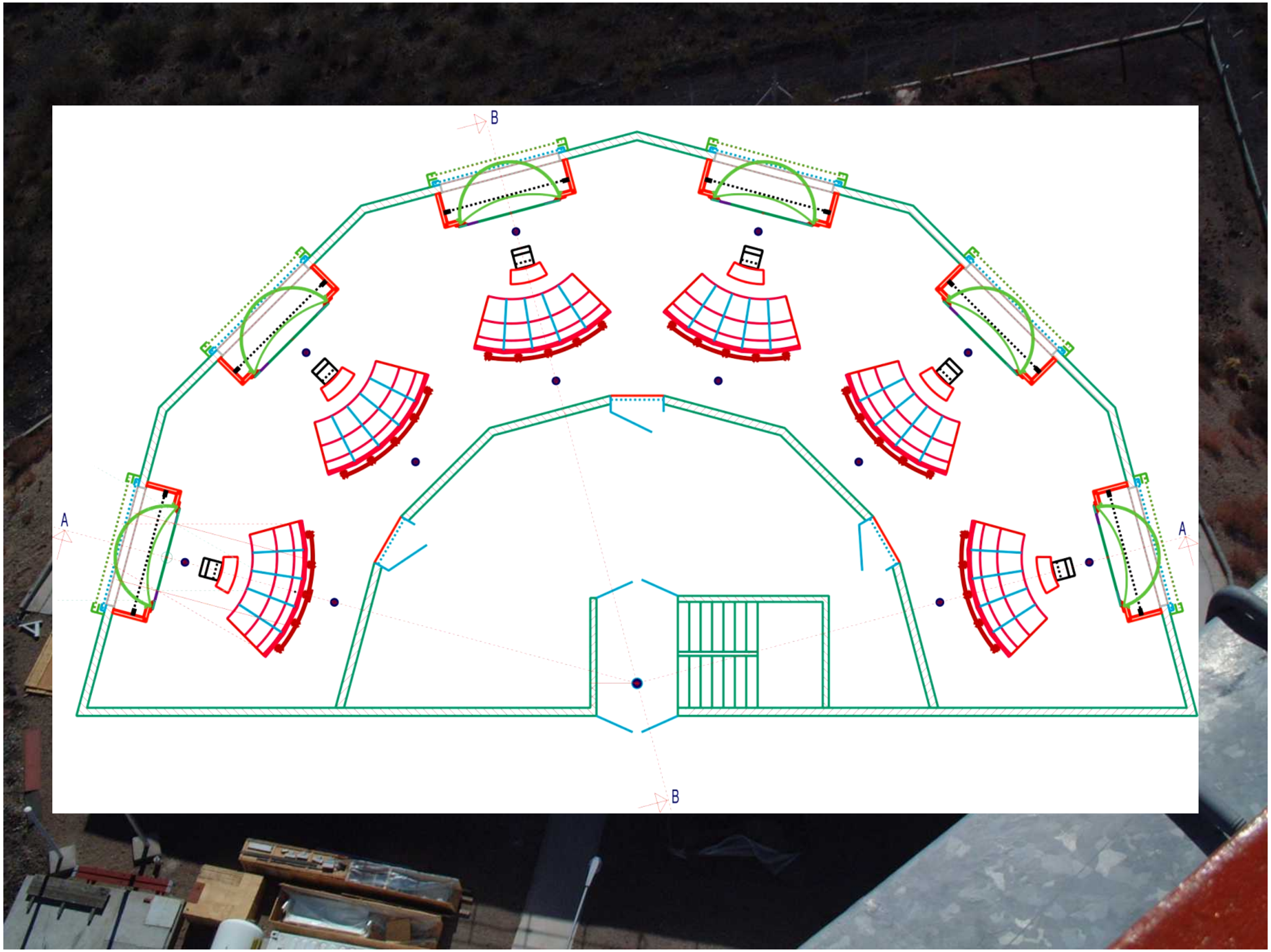
Proton, ϴ =45°, E= 10^{19} eV, d= 1000m

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

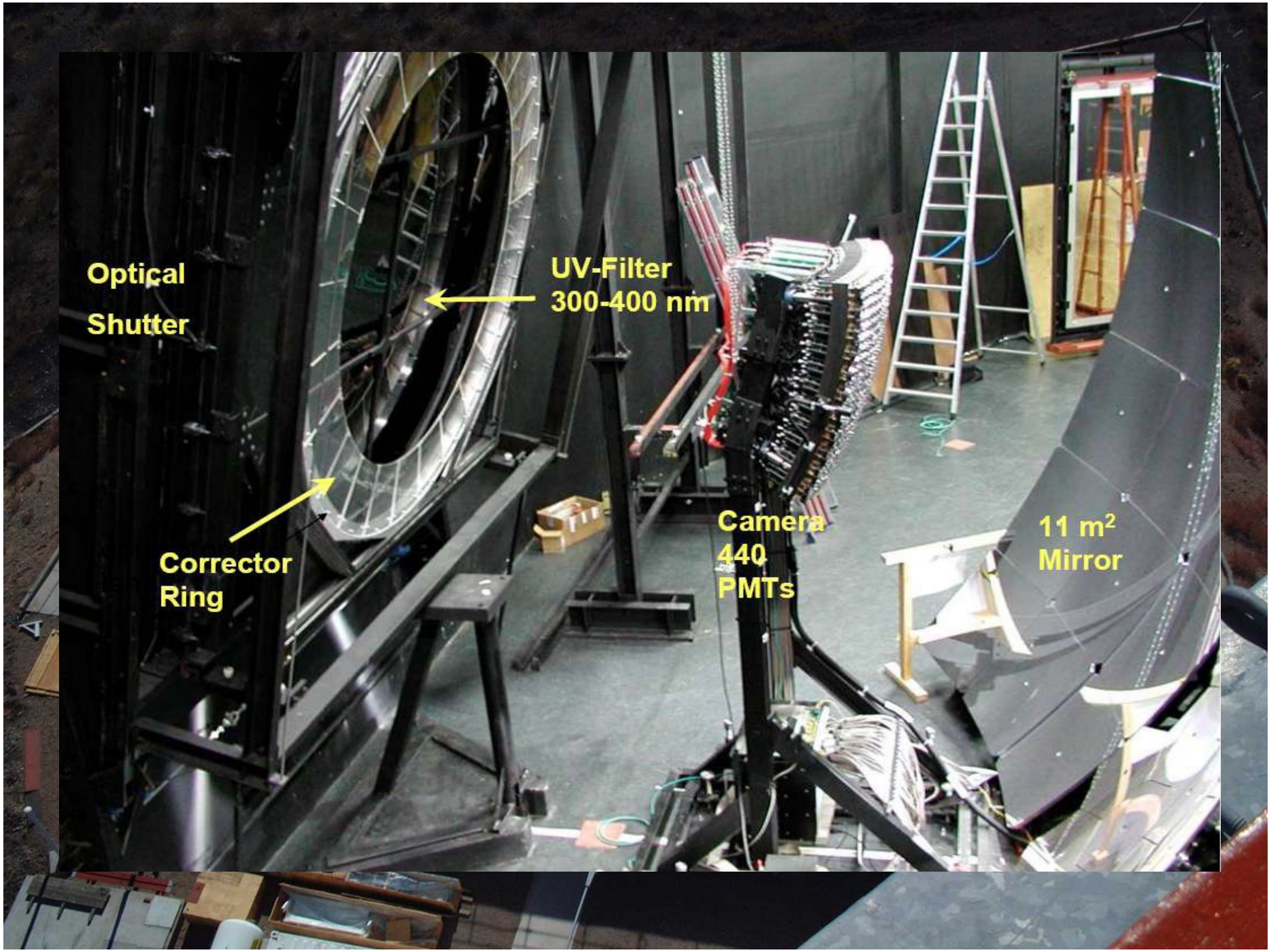
The fluorescence detectors (FD)



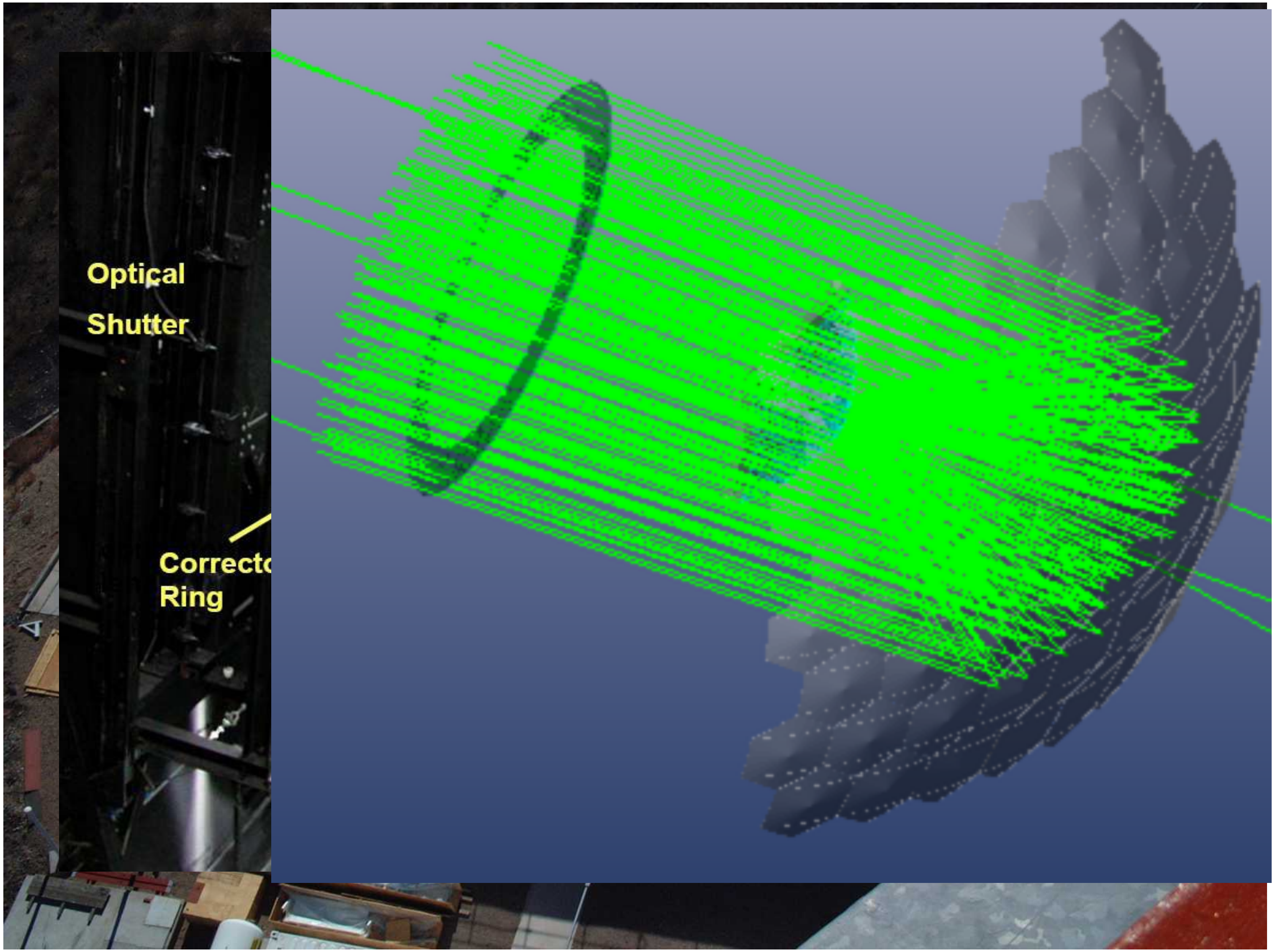
The fluorescence detectors (FD)



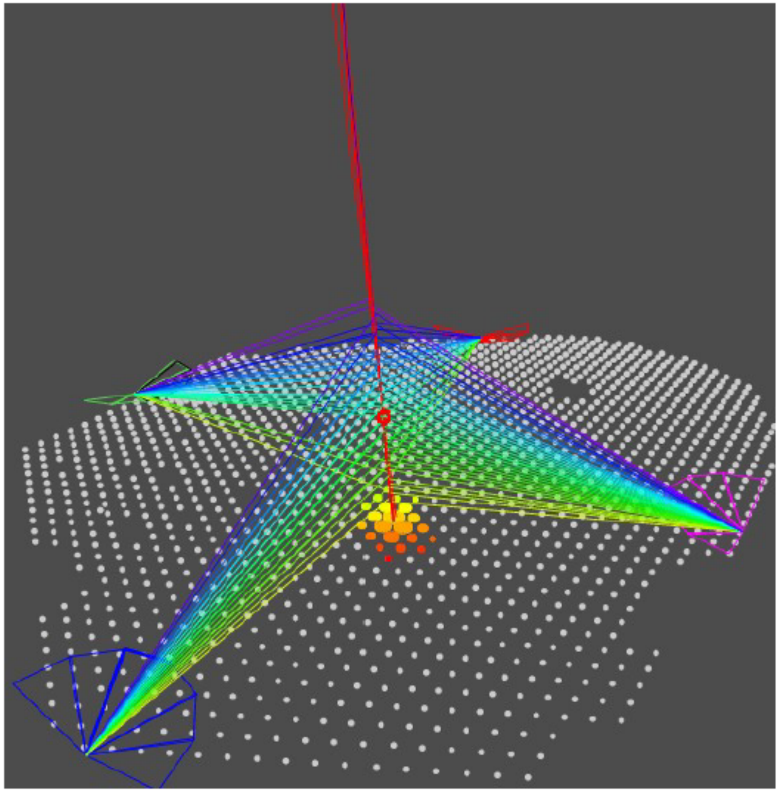
The fluorescence detectors (FD)

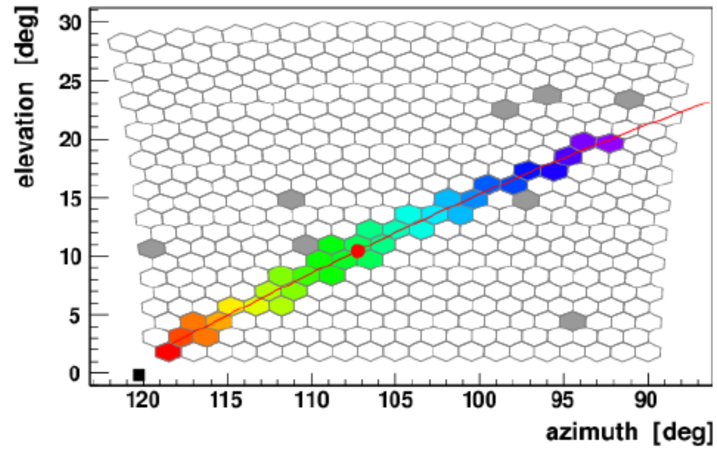


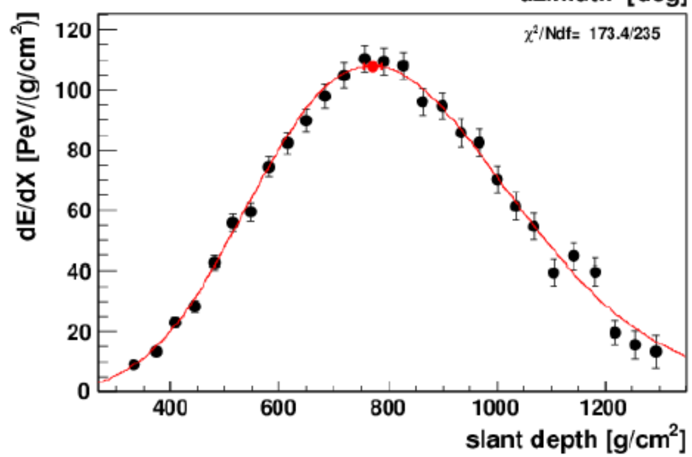
The fluorescence detectors (FD)

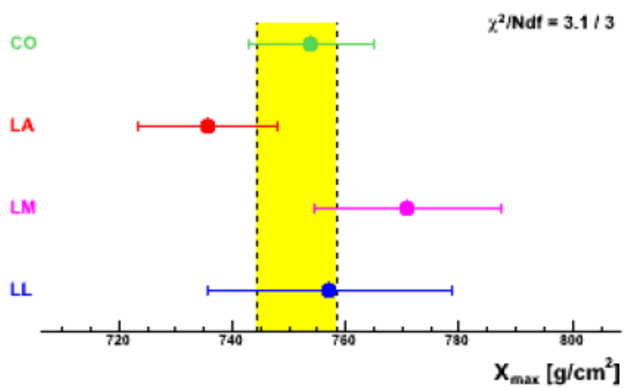


A 4 eyes hybrid event !









Energy

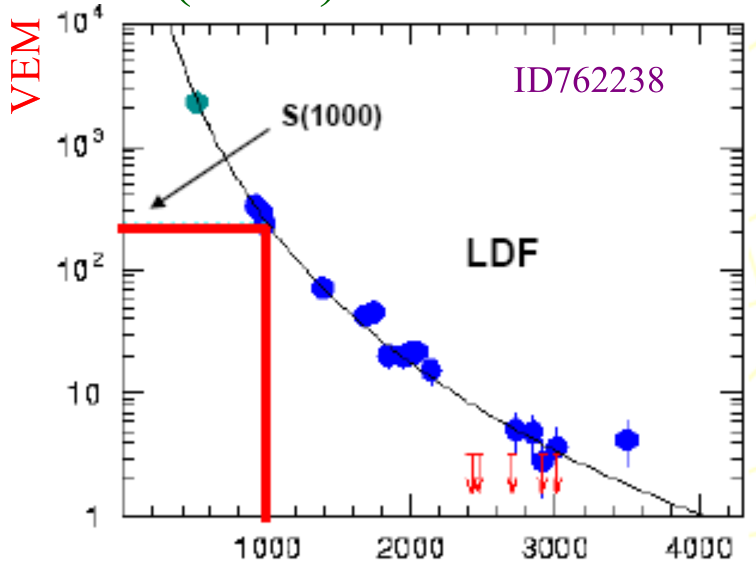
$E = (7.1 \pm 0.2)\ 10^{19}$ eV

Depth of the maximum

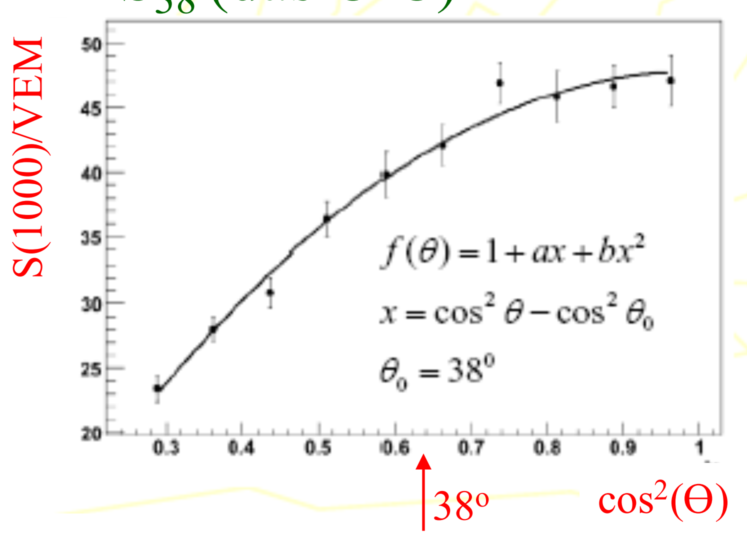
$X_{max} = (752 \pm 7)$ g/cm^2

SD Energy calibration in Auger

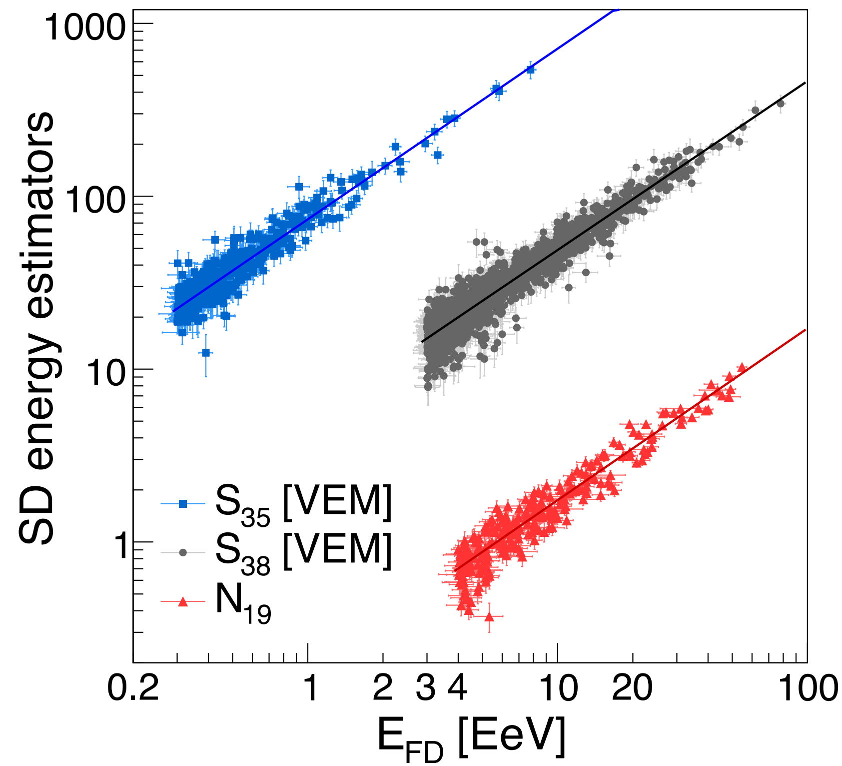
S(1000)



S_{38} (das CIC)



Calibration

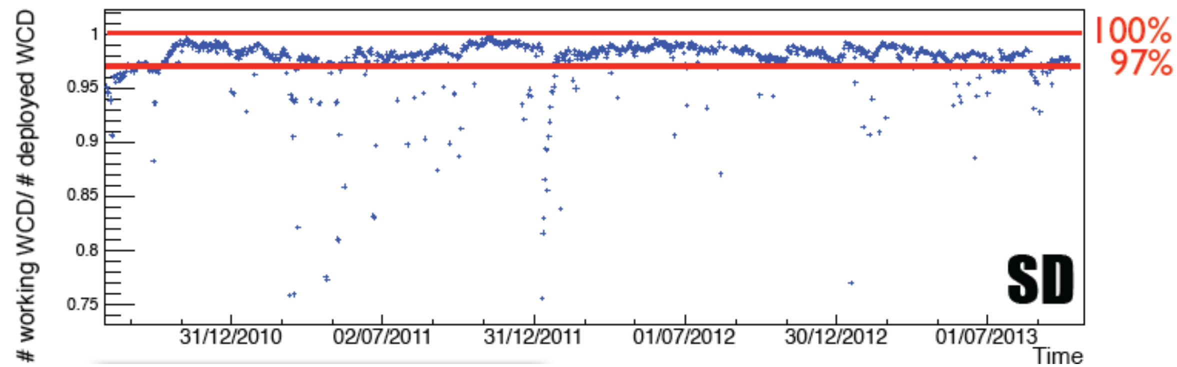


$\sigma_E < 10\%$

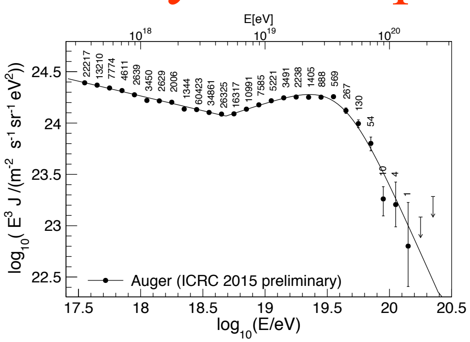
Auger is running smoothly

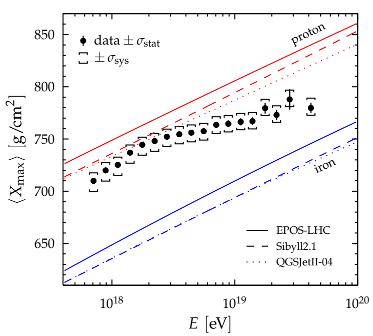
The Swiss clock!

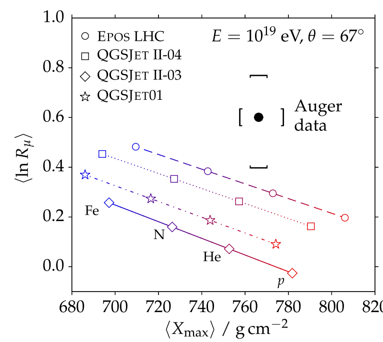
Fraction of Water Cherenkov Tanks in operation

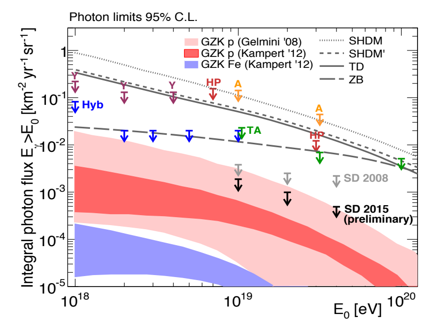


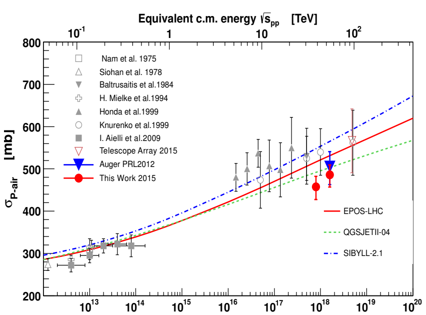
Many and important results !

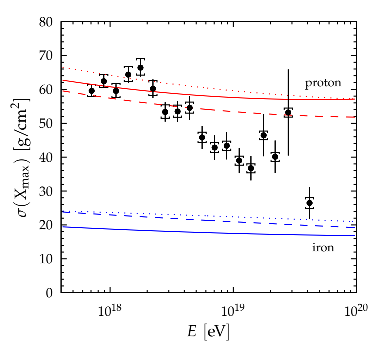


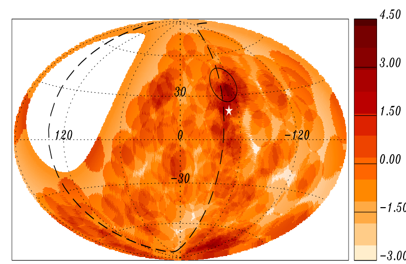


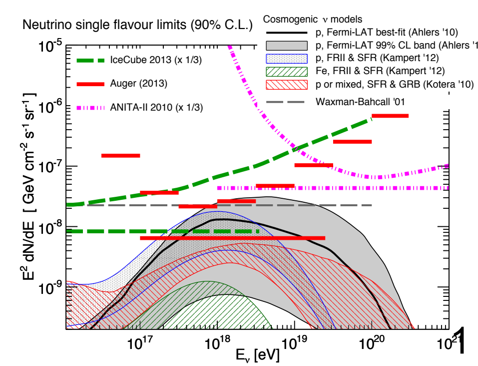




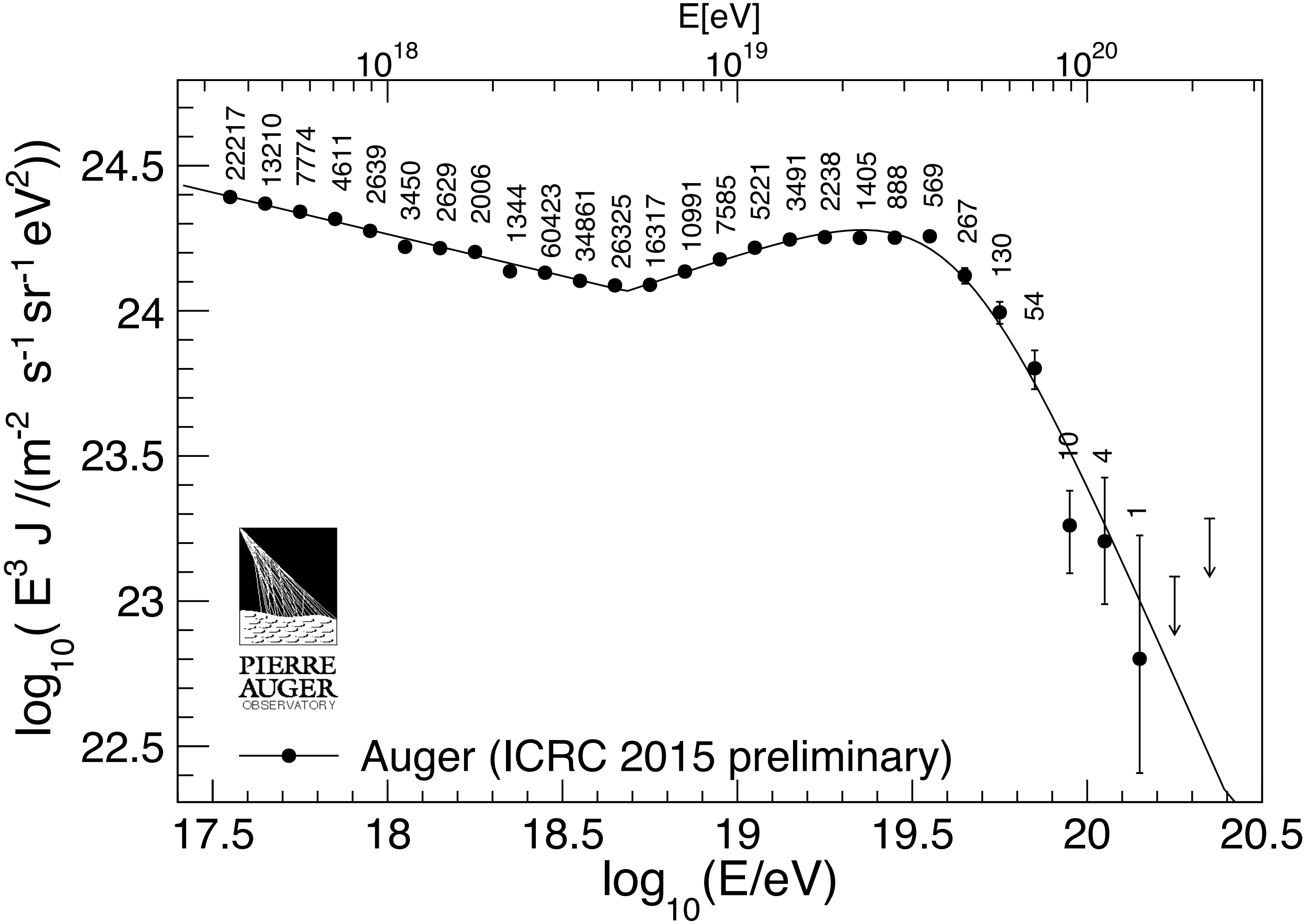


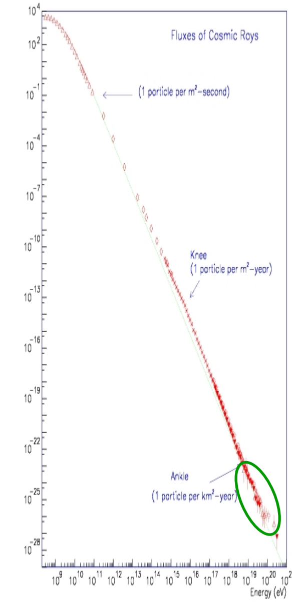




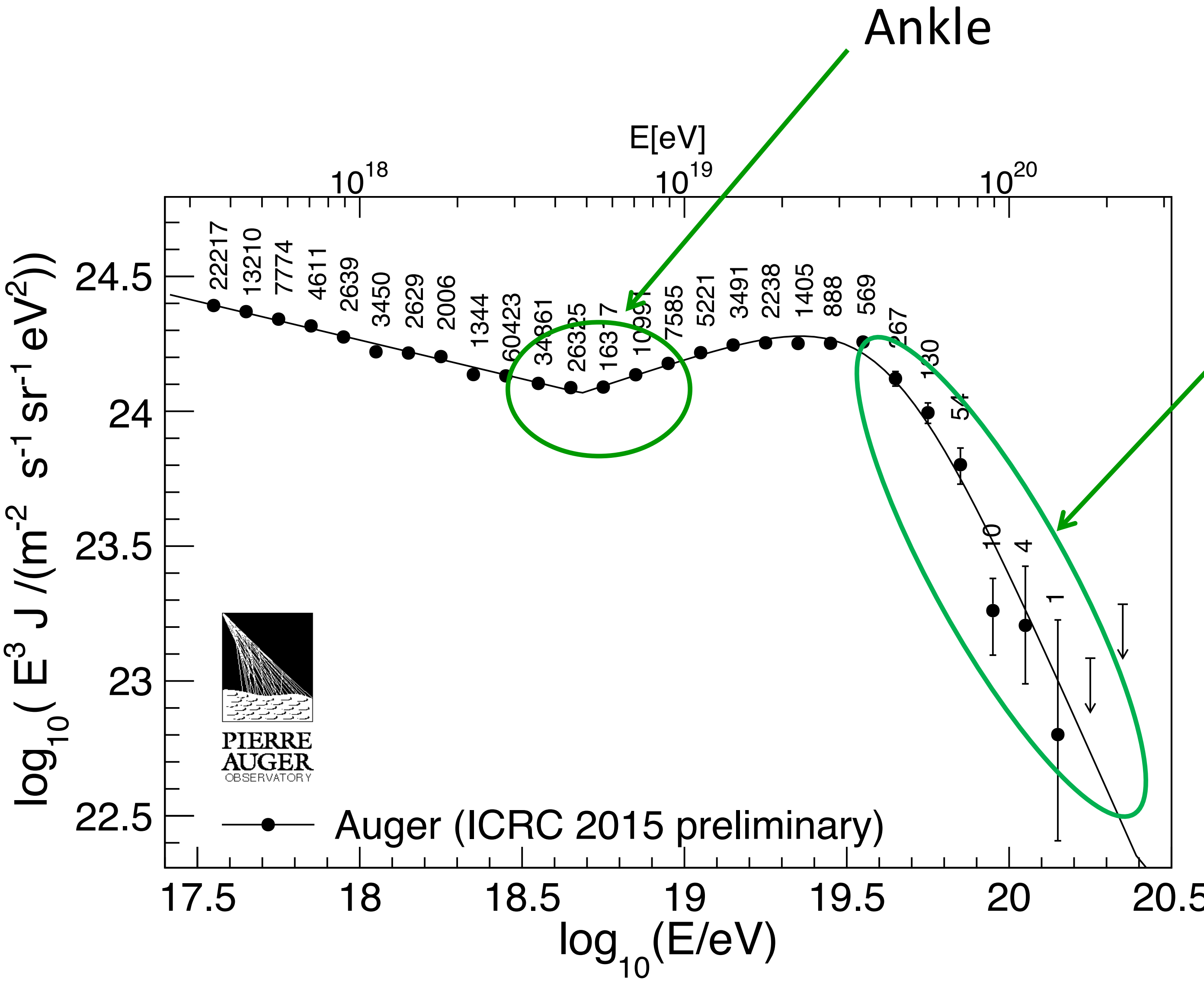


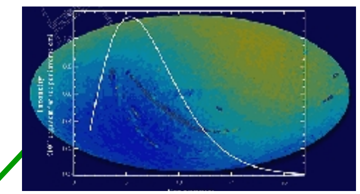
Energy spectrum

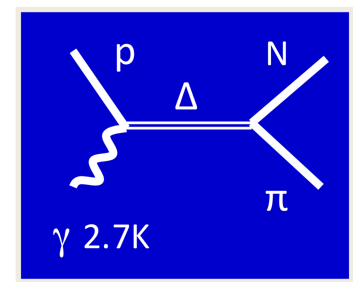




Energy spectrum

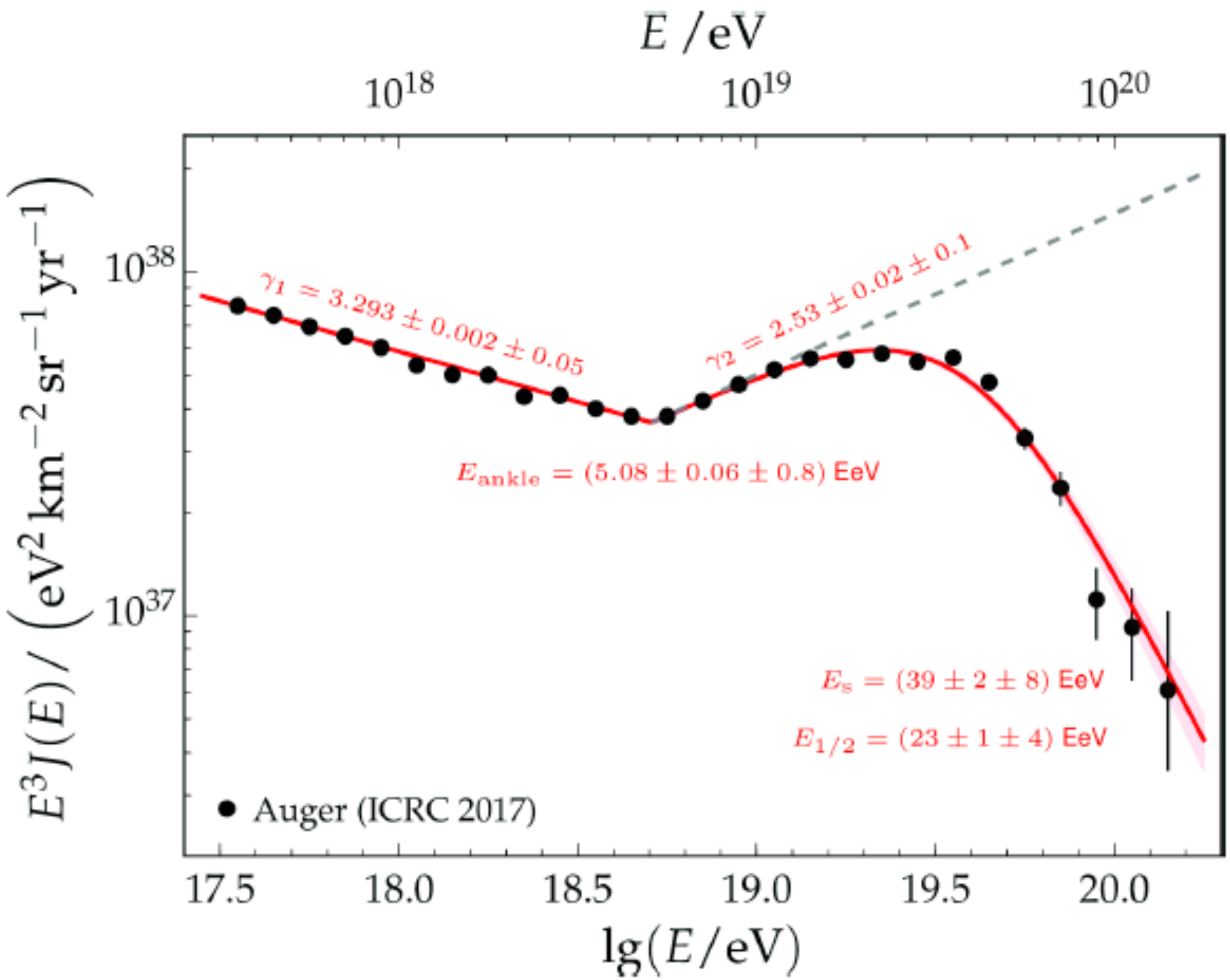




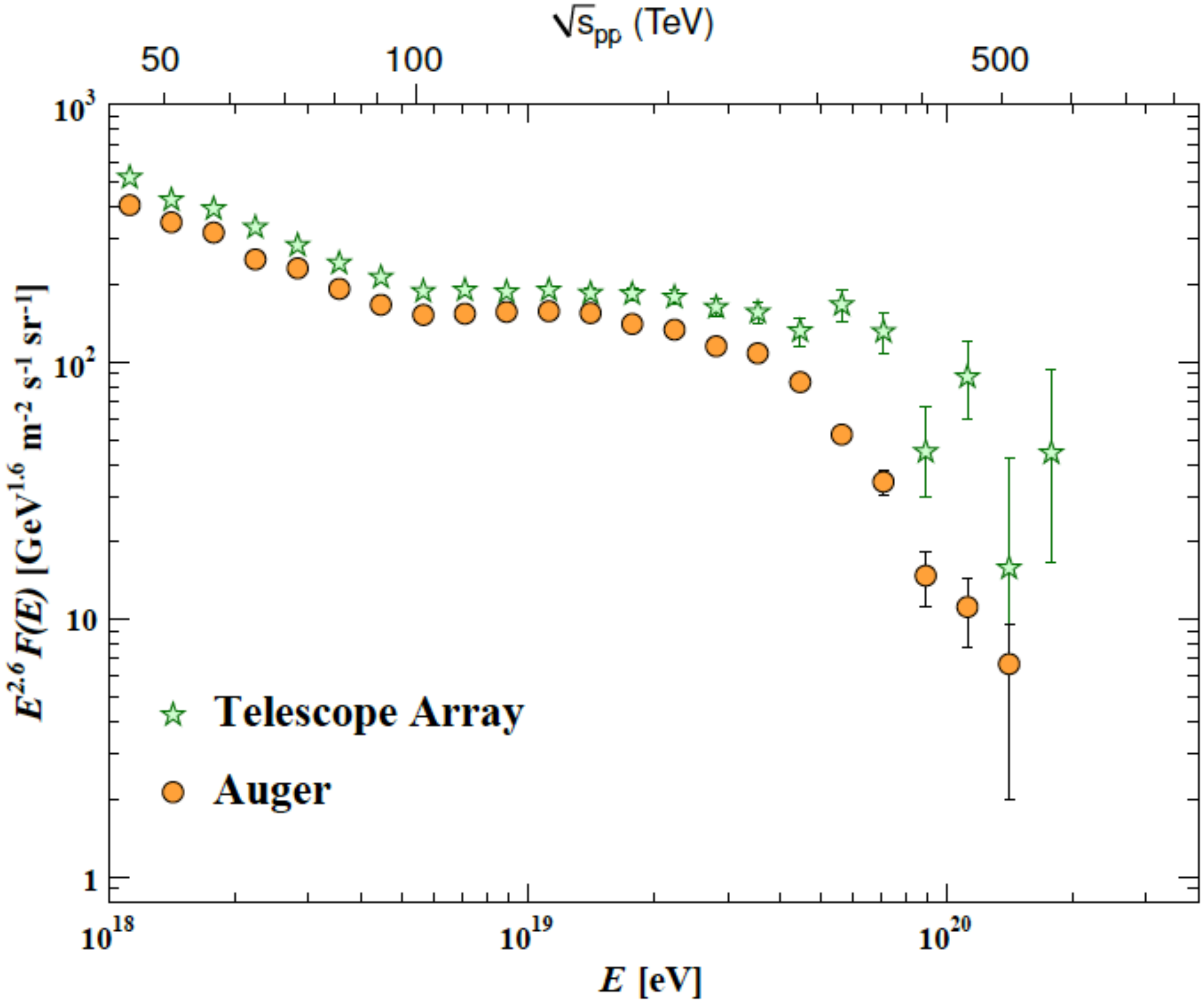


GZK like suppression !!!

Energy spectrum



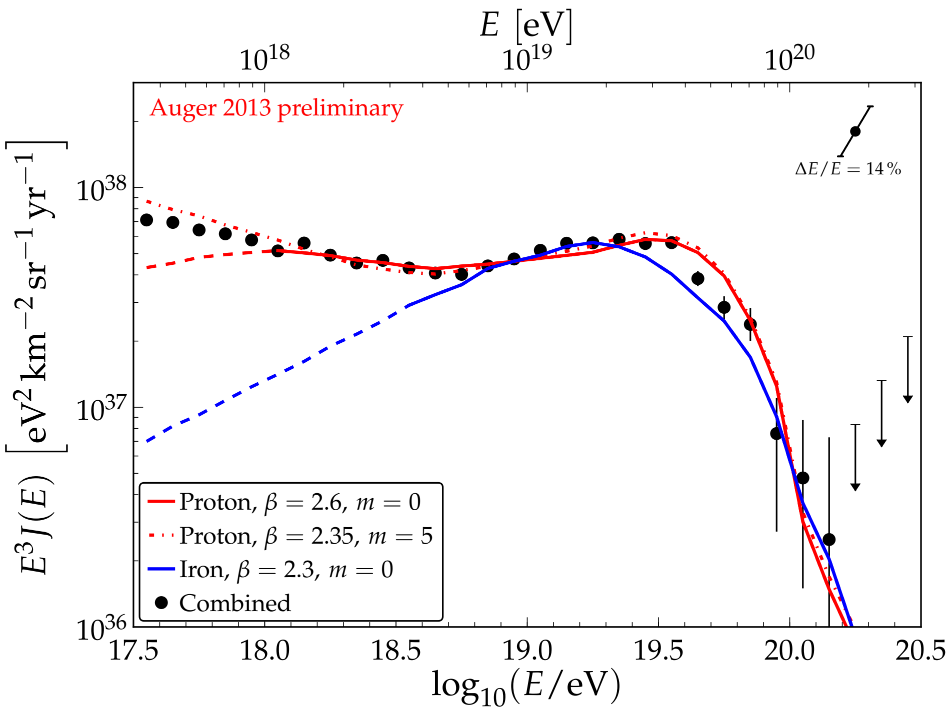
Auger vs TA

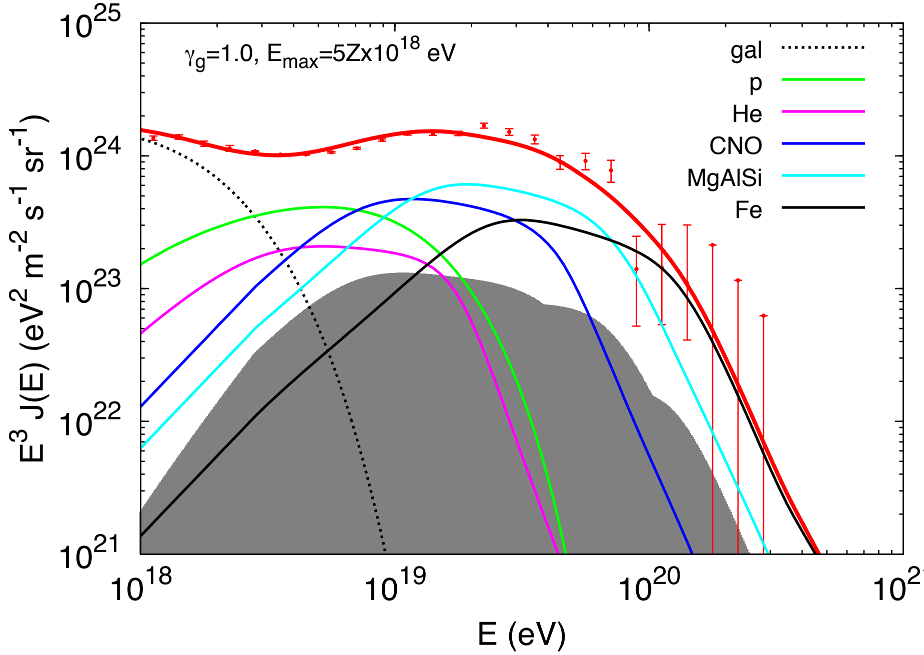


$\sqrt{s_{pp}}$ (TeV)
50
100
500
10^3
10^2
10
1
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
Telescope Array
Auger
10^{18}
10^{19}
10^{20}
E [eV]

GZK or the exhaustion of sources ???

Old Data

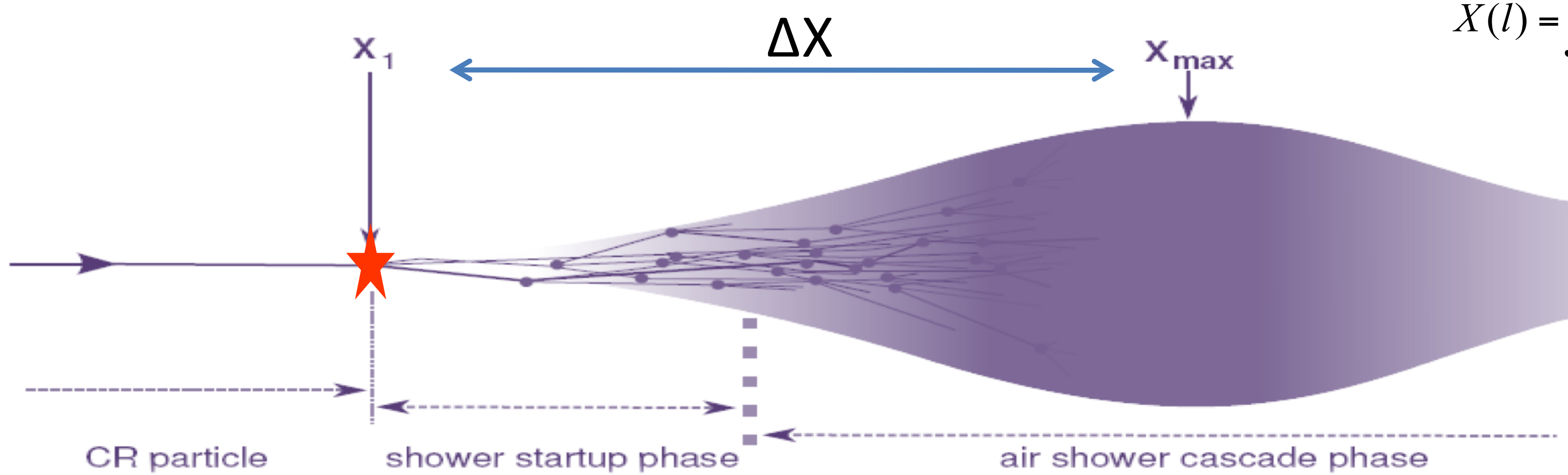




Composition is the key to disentangle the two scenarios!

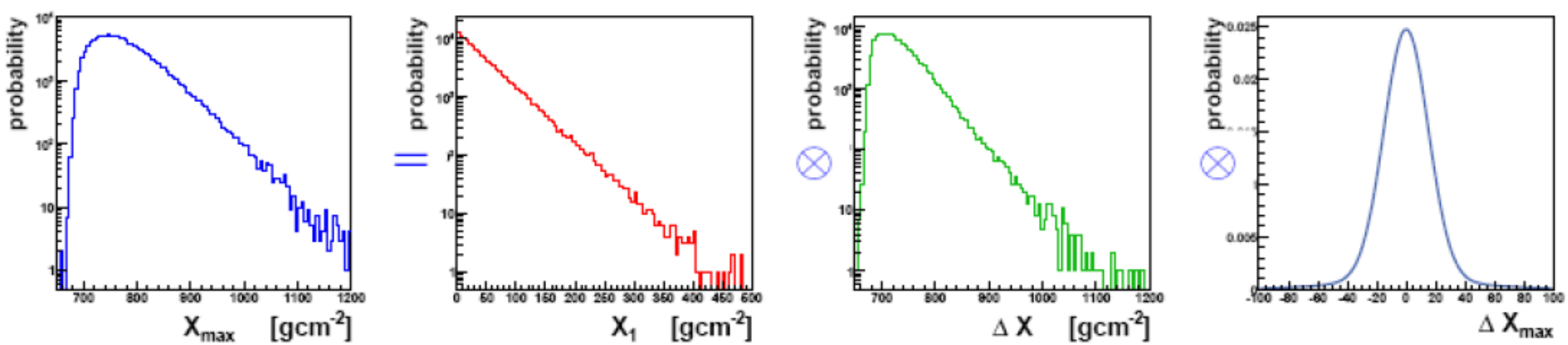
$\langle X_{max} \rangle$ distribution

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

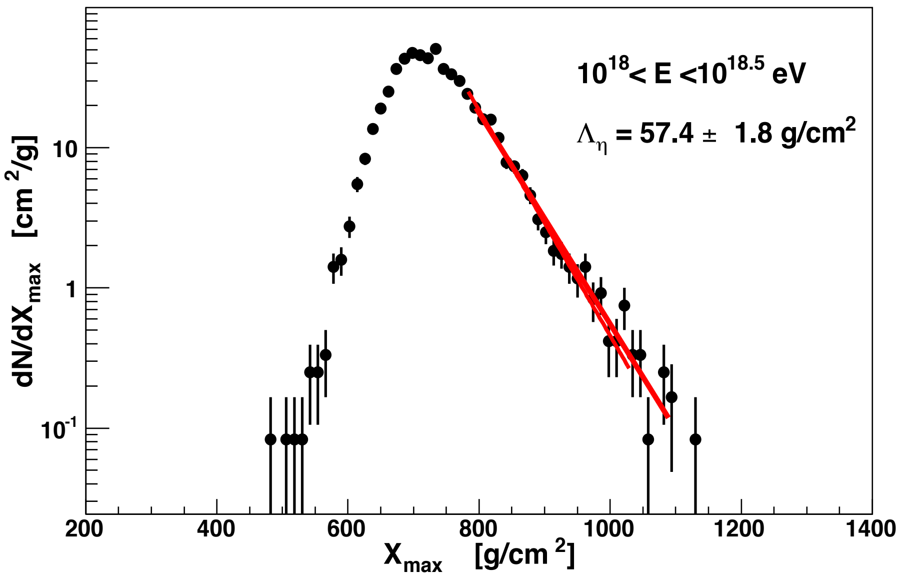


One Energy bin

X_1 ΔX Experimental resolution

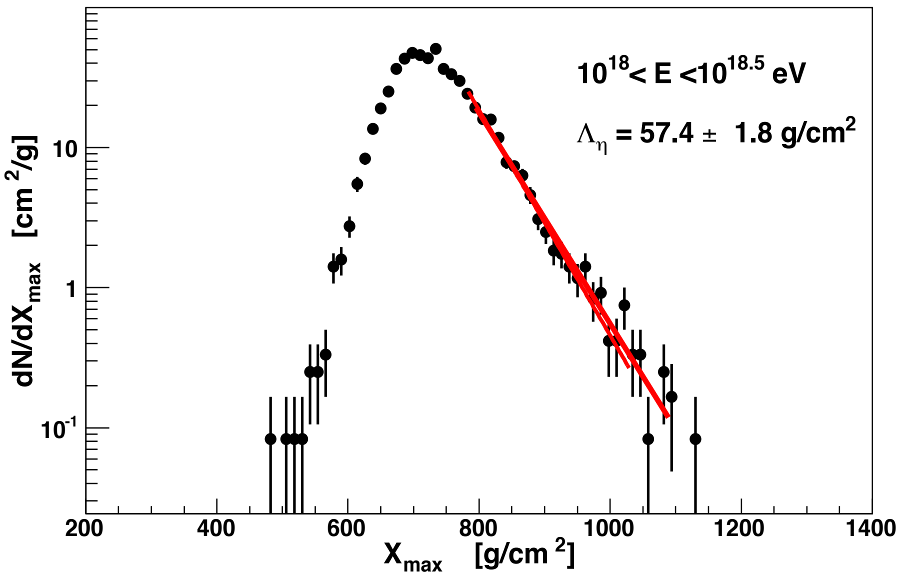


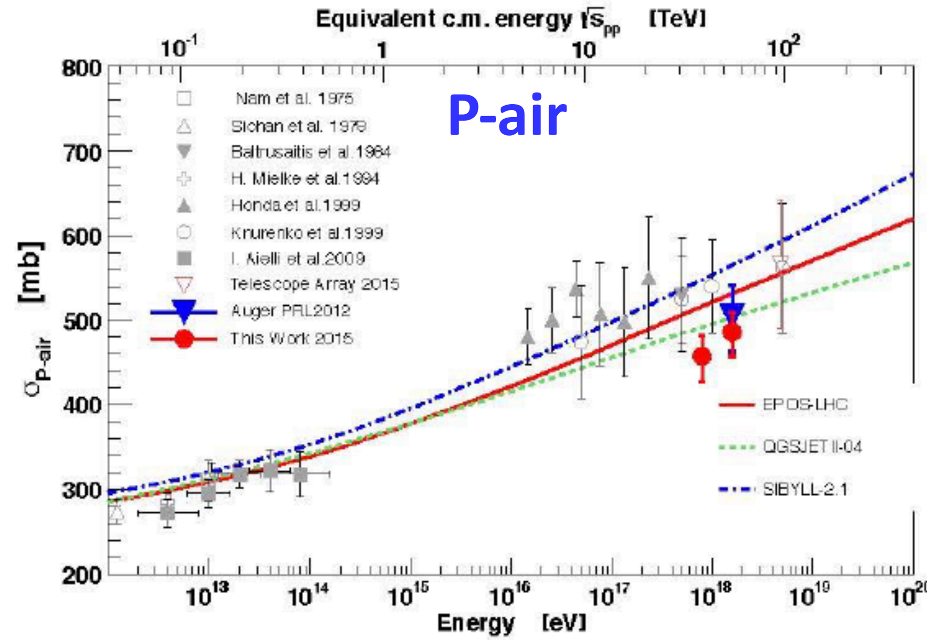
Proton cross-section

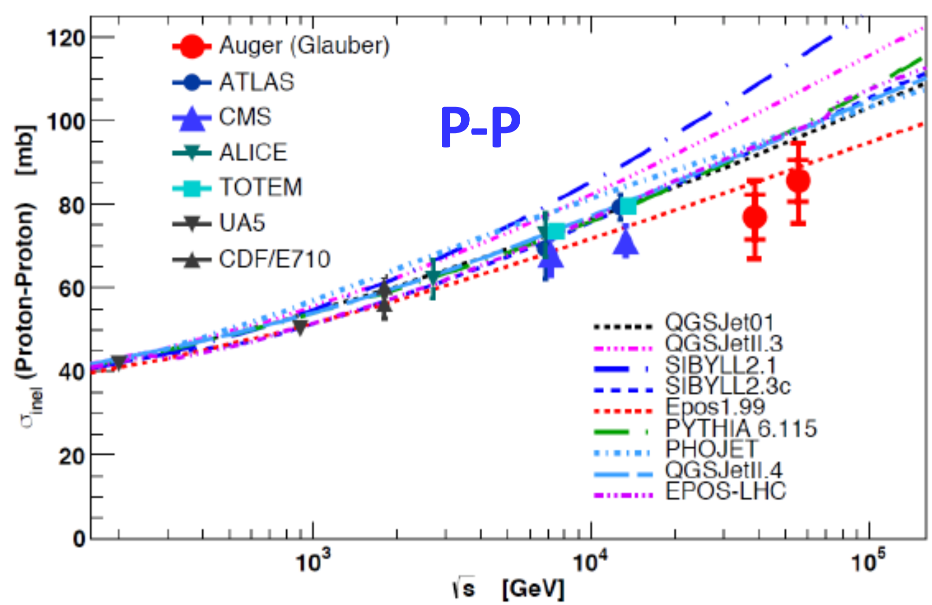


Proton cross-section

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

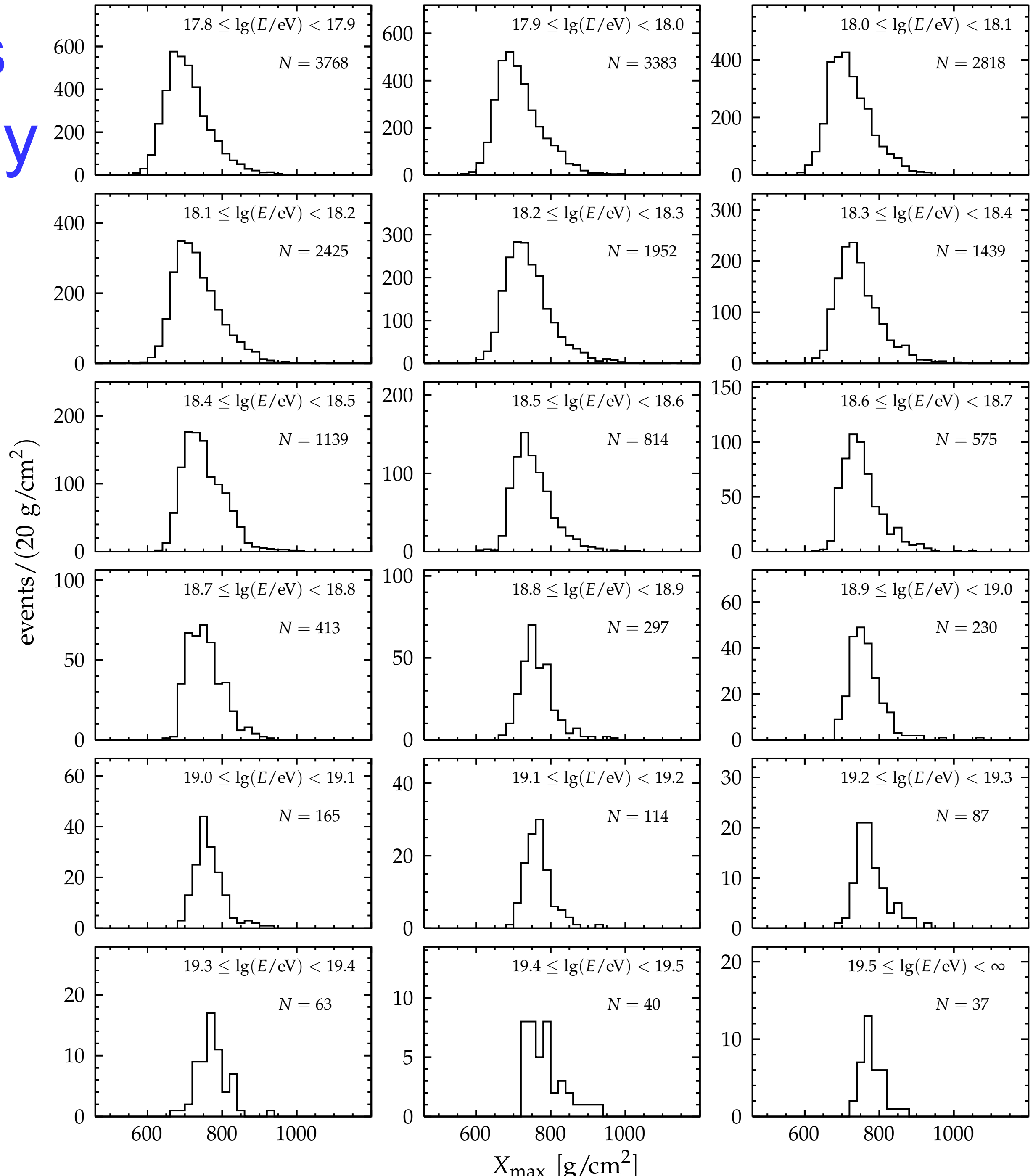




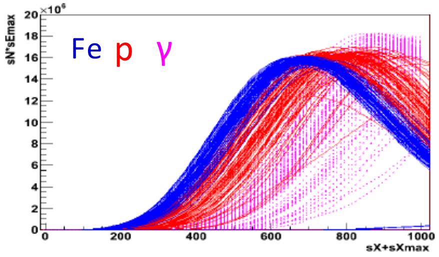


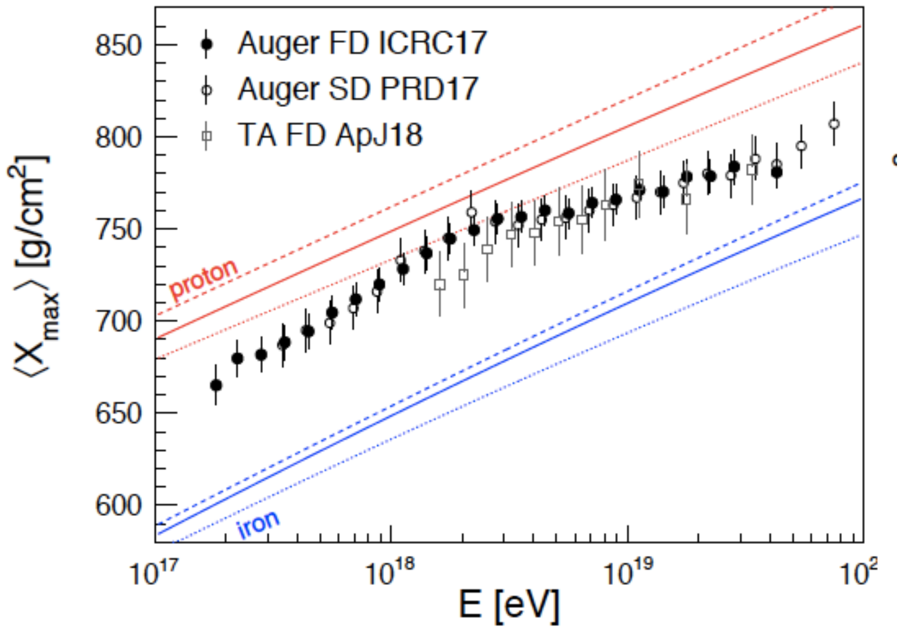
X_{max} distributions for several energy bins

As the energy increases the distributions become narrower !!!

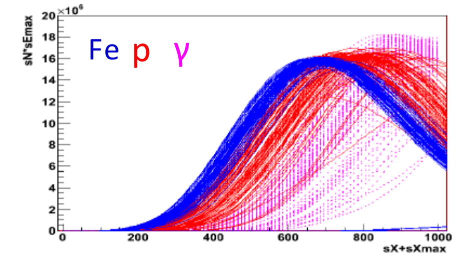


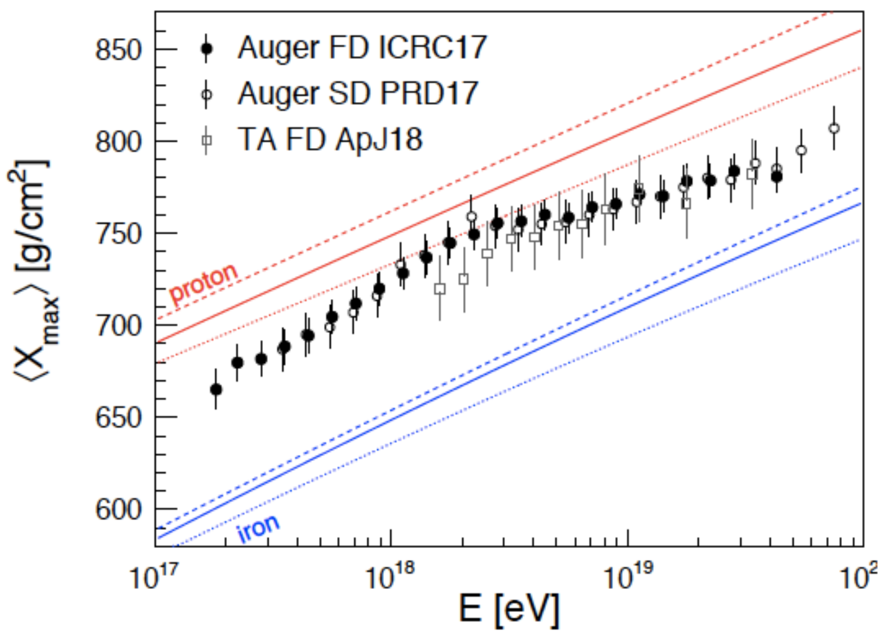
<X_{max}>

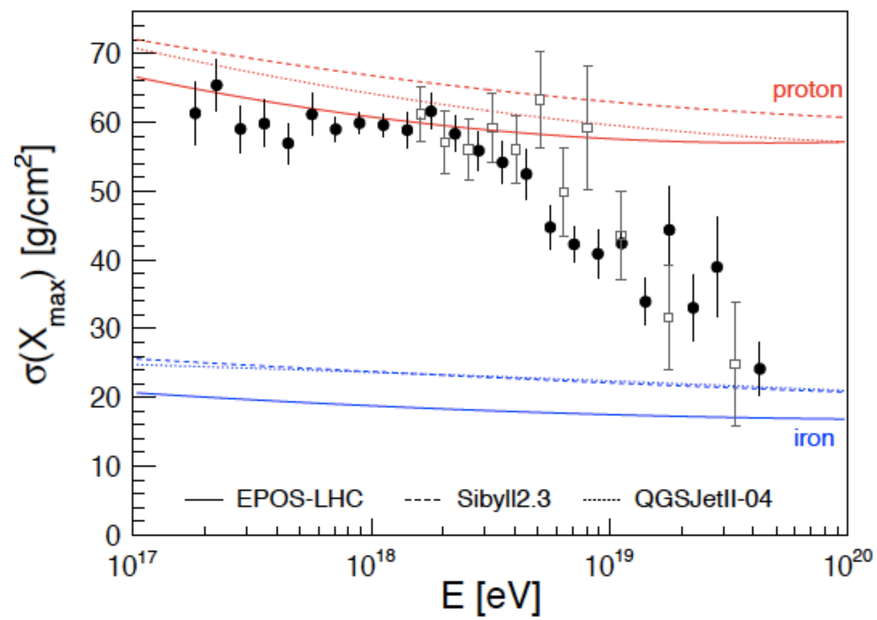

Fe p γ
sN*sEmax
sX+sXmax


Auger FD ICRC17
Auger SD PRD17
TA FD ApJ18
proton
iron
⟨Xmax⟩ [g/cm2]
E [eV]

<X_{max}> and RMS(X_{max})





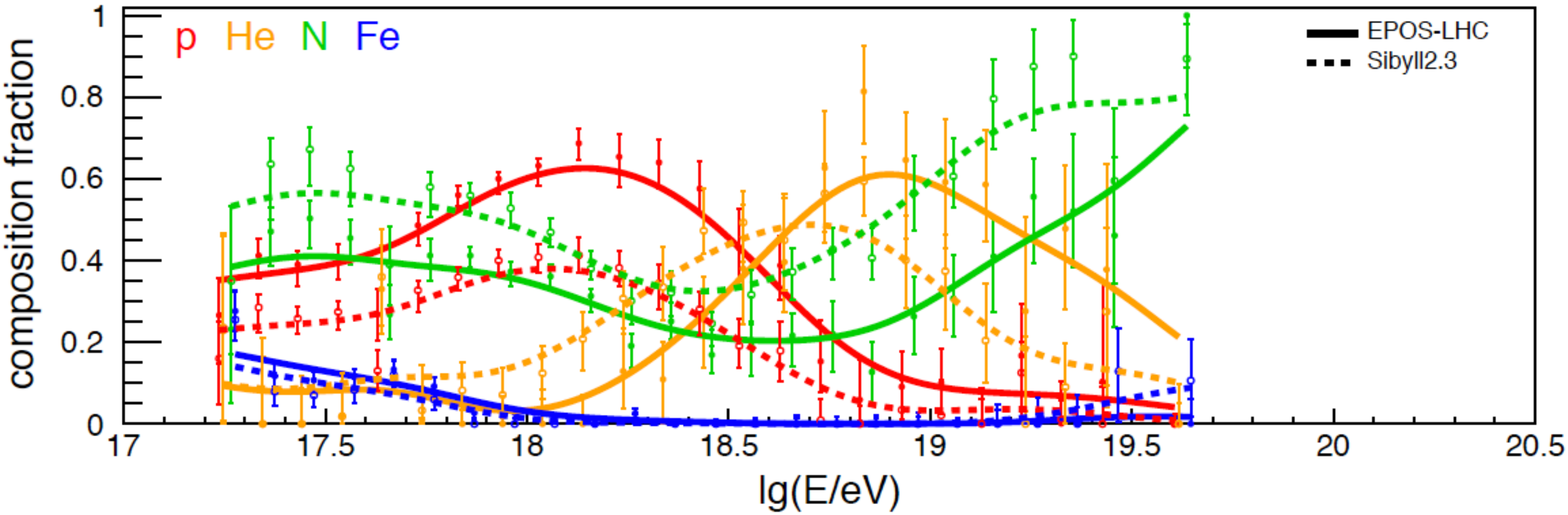


A clear change above 3 10^{18} eV

Beam composition ??? Hadronic interactions???

Mass composition

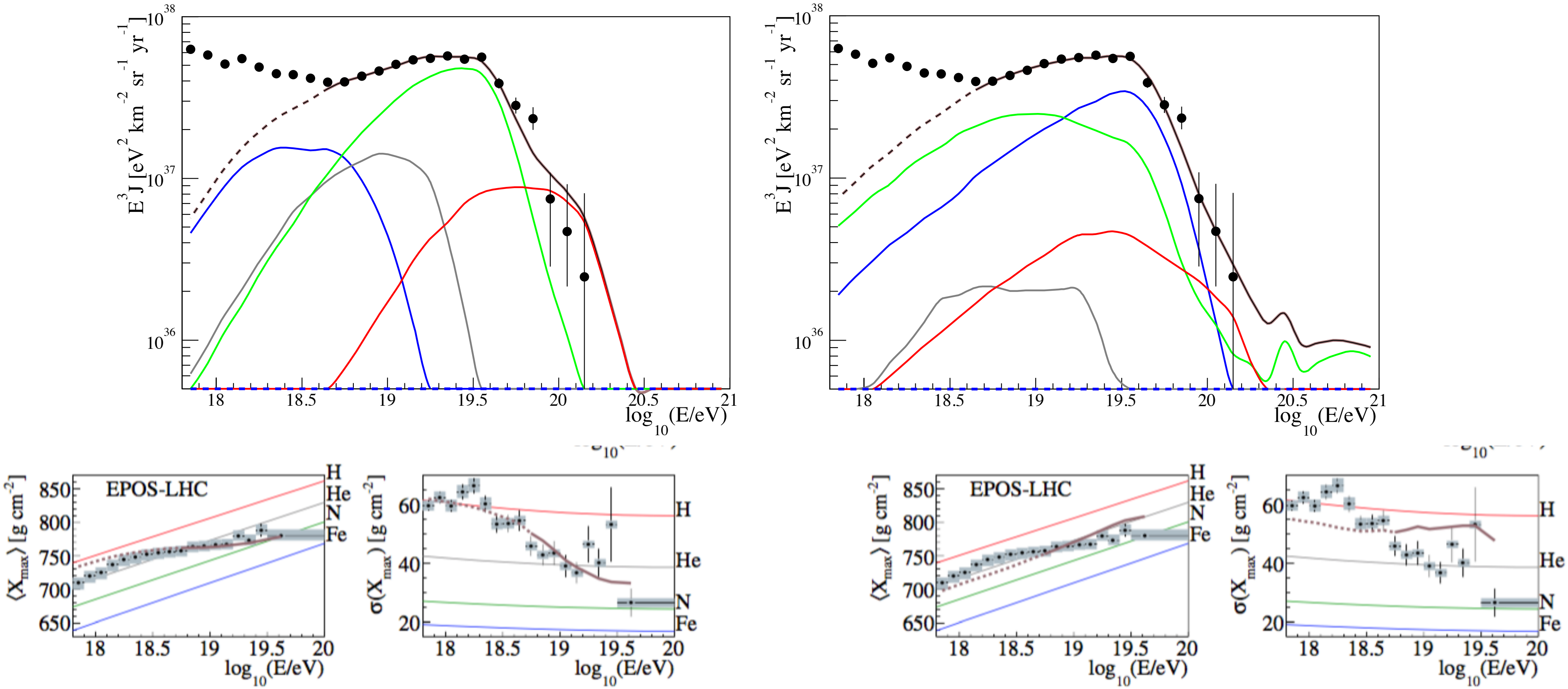
fluorescence telescope data (15% duty cycle)



Combined fits

A. di Matteo for the Pierre Auger Coll., Proc 34th ICRC (2015)

Protons (blue)
Helium (gray)
Nitrogen (green)
Iron (red)



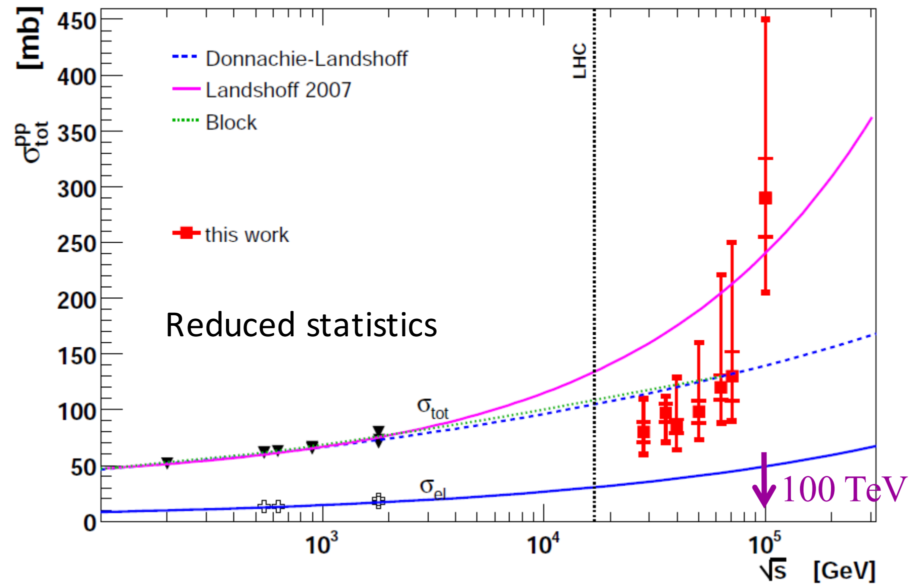
A Fit (spectrum, <X_{max}>, RMS(X_{max})) is always possible but it requires a very unusual metallicity and a very hard energy spectrum of the sources!

The "Particle Physics" interpretation …

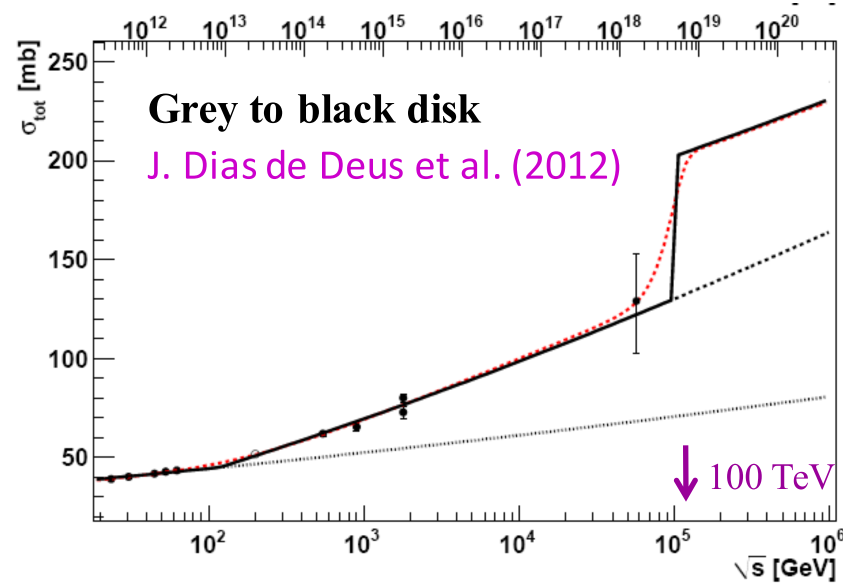
R.Ulrich (2008)

If just proton …

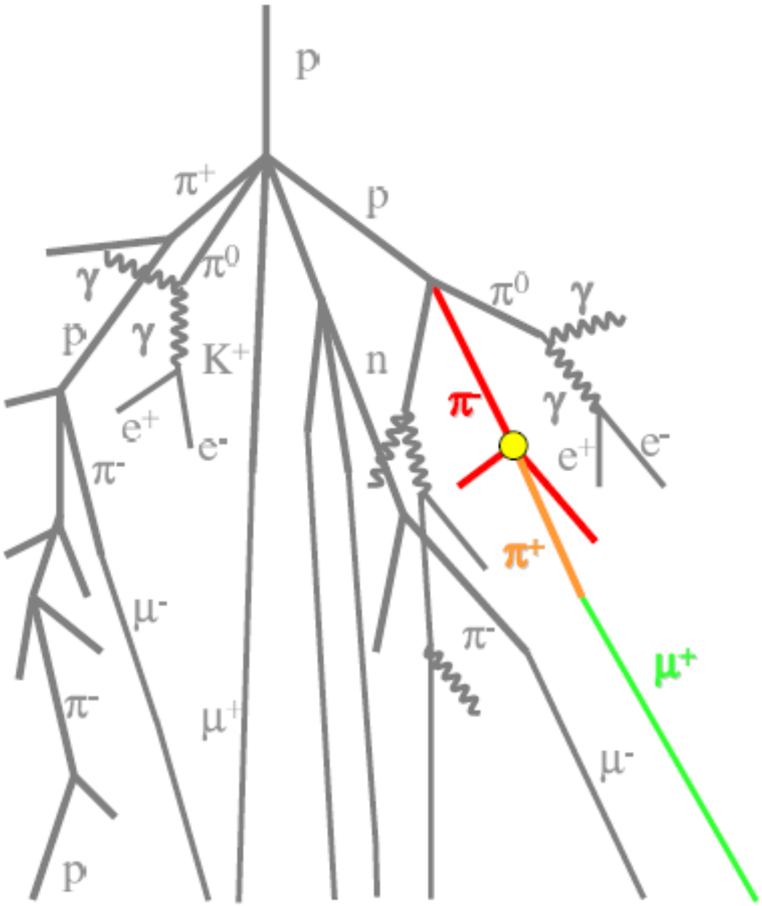
A dramatic increase in the proton-proton cross section



But no violation of the Froissart bound !

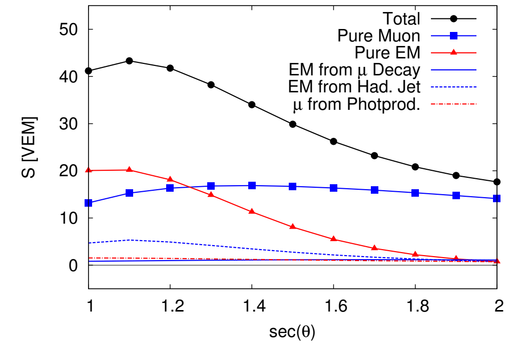


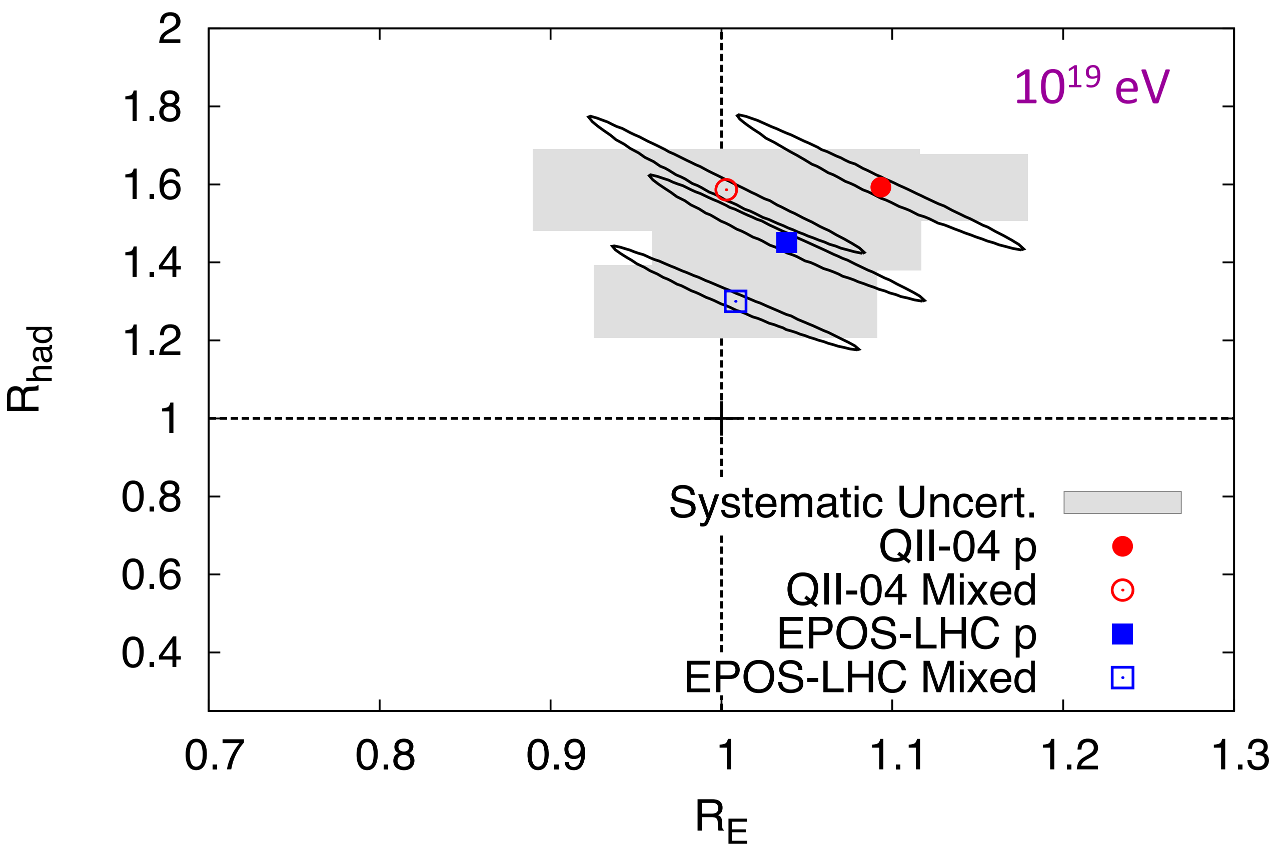
The “number of μ_s



The "number of μ_s

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

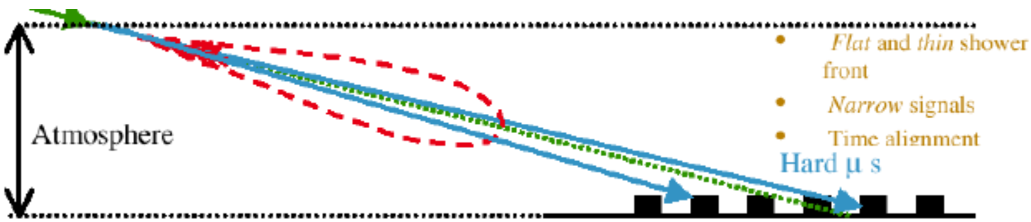


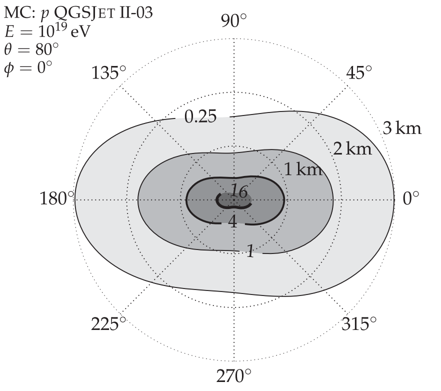


Model	R_E	$R_{\rm had}$
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

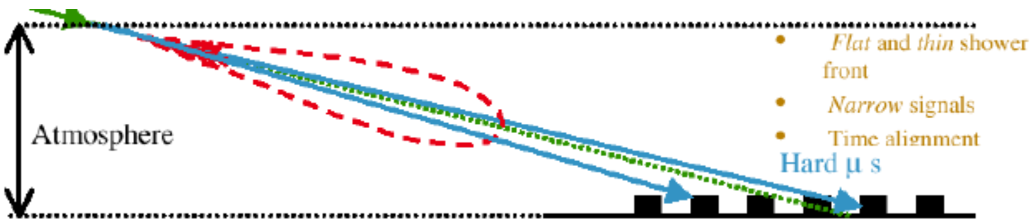
Hadronic signal in data
is significantly larger

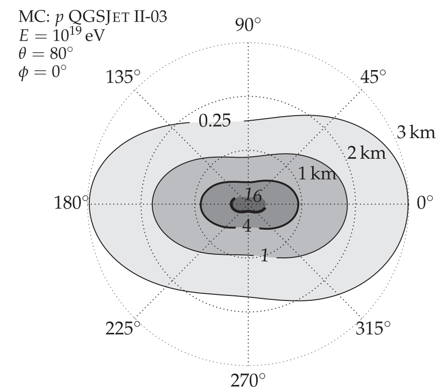
The “number of μ_s (inclined showers)



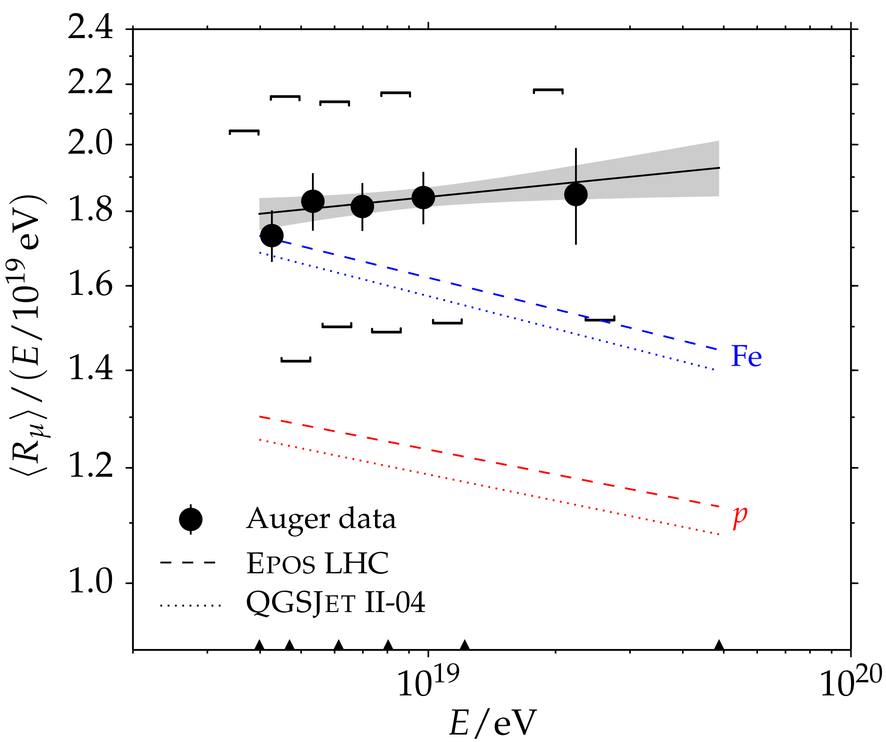


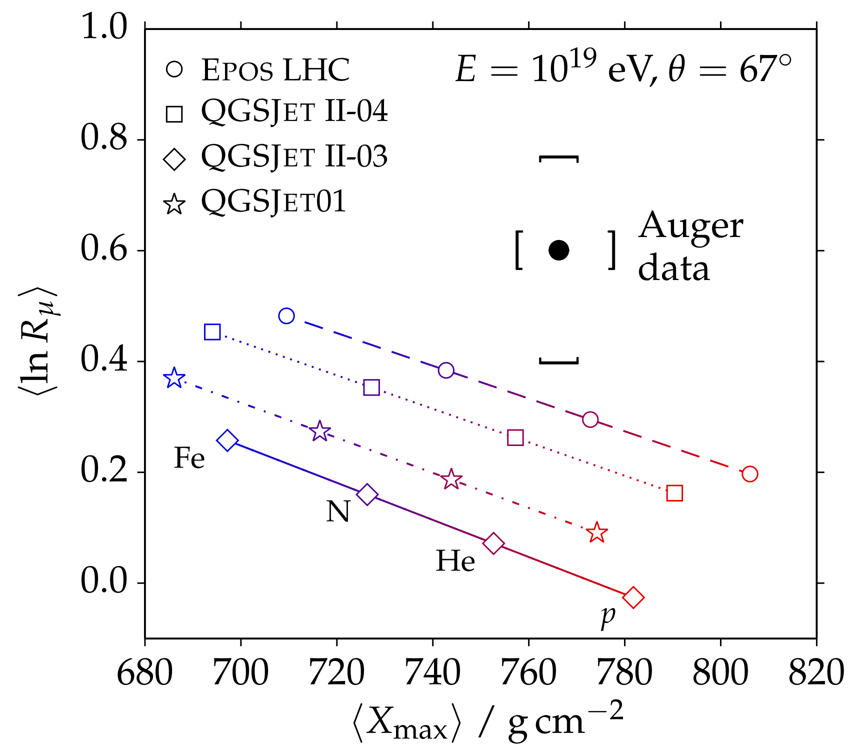
The “number of μ_s (inclined showers)





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

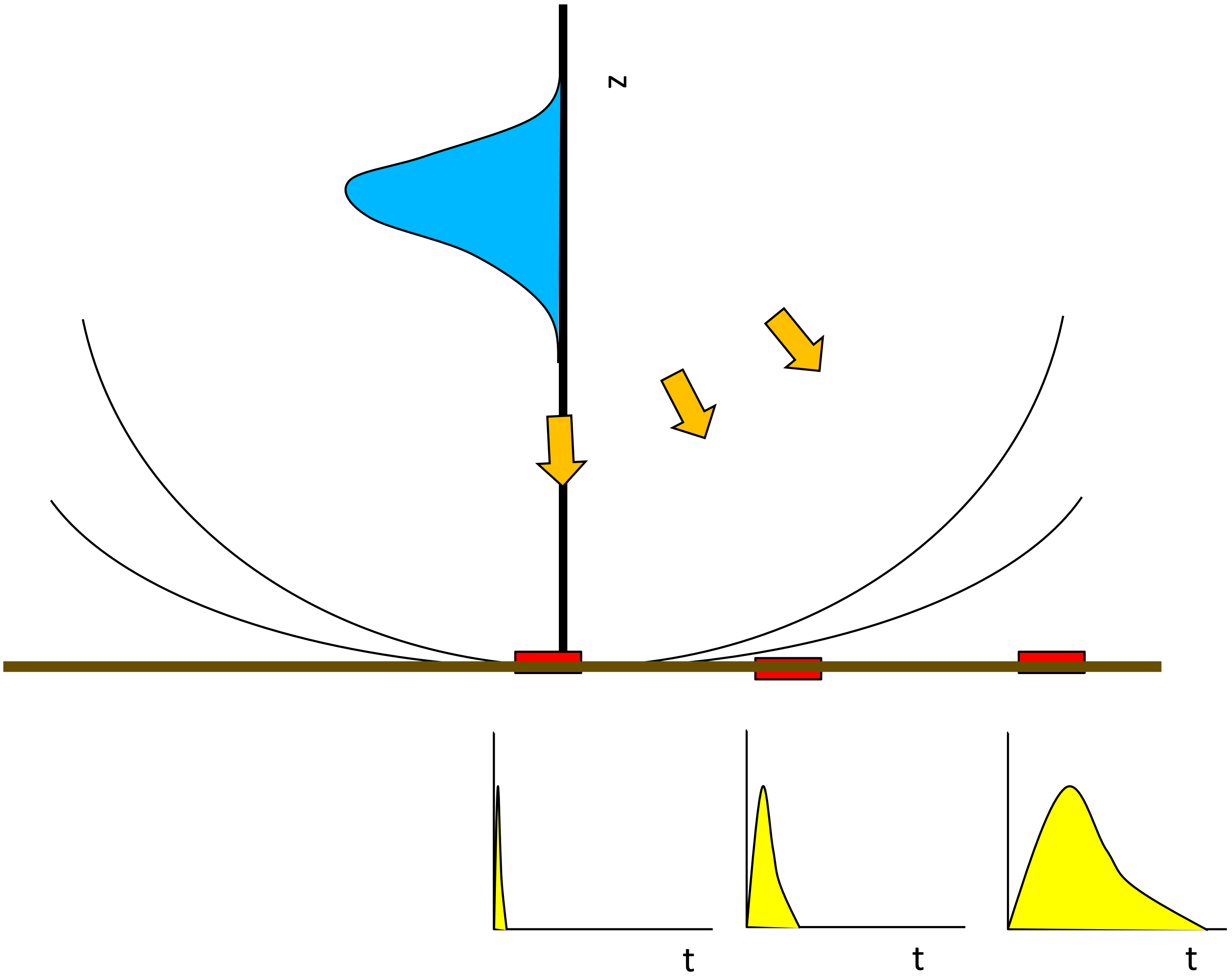




Tension between data and all hadronic interaction models !!!

Muon Production Depth (MPD)

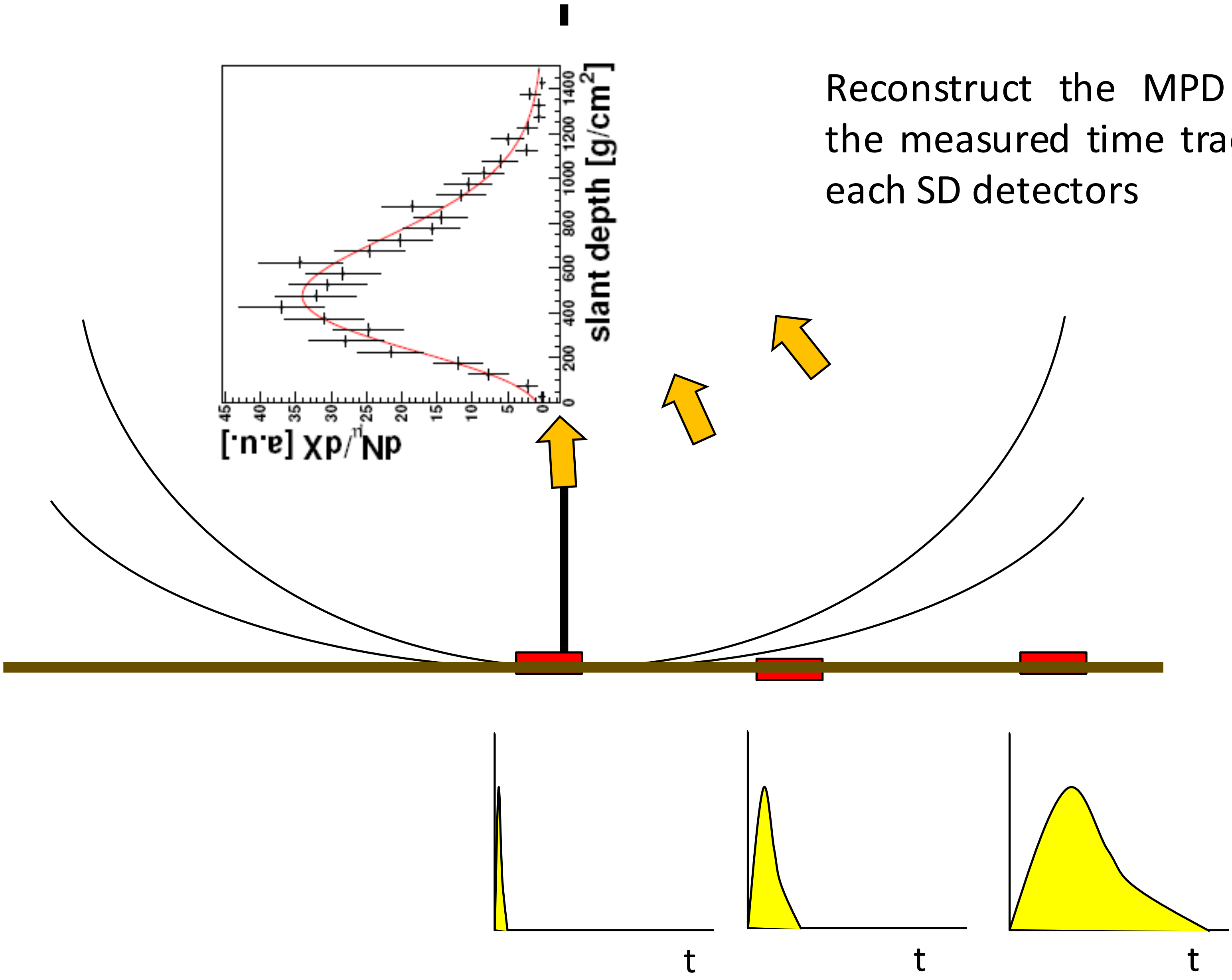
L. Cazon, R.A. Vazquez, A.A. Watson, E. Zas,
Astropart.Phys.**21**:71-86 (2004)
L.Cazon, PhD Thesis (USC 2005)



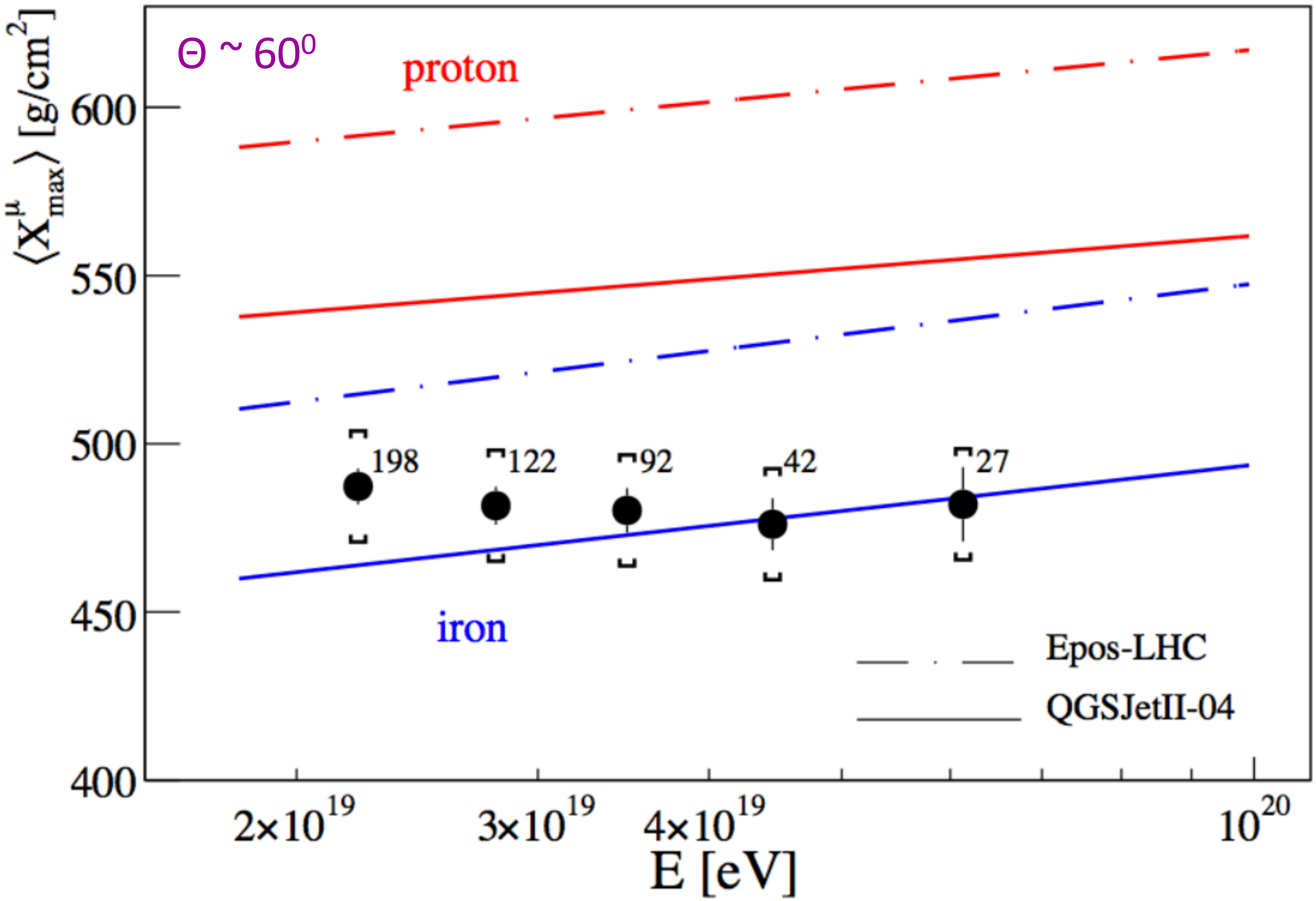
Muon Production Depth (MPD)

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

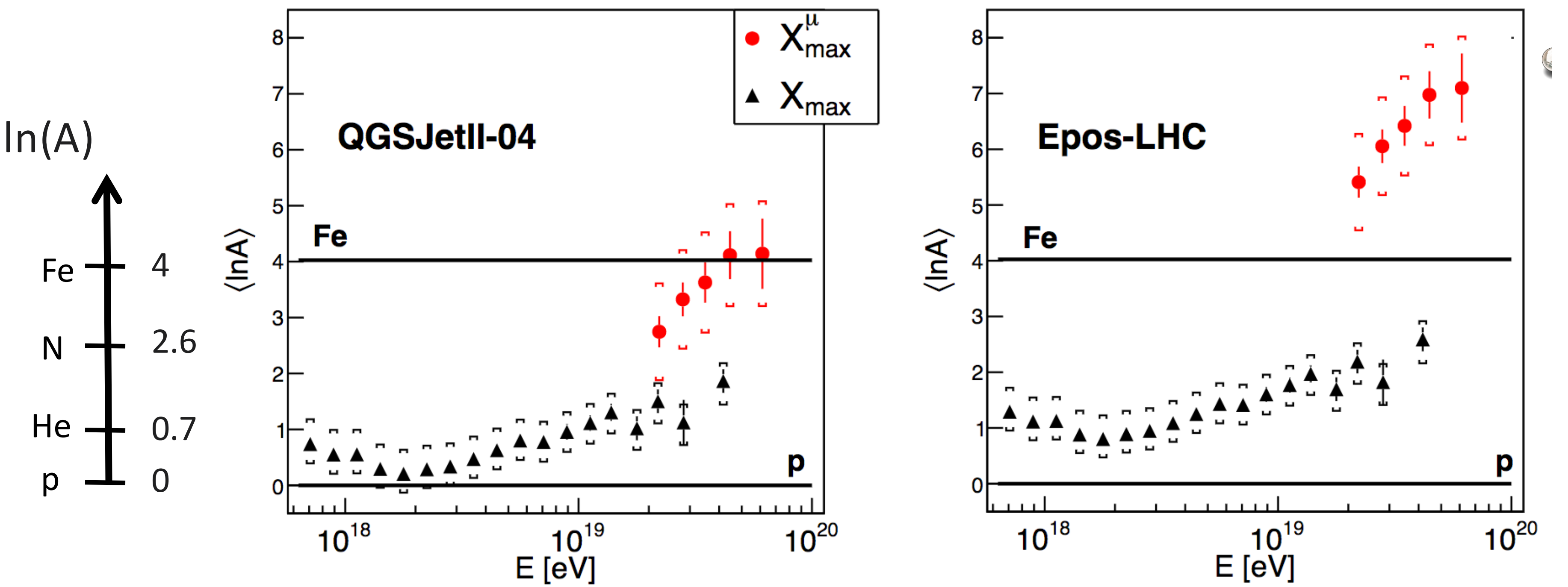


$<X^{\mu}_{max}>$



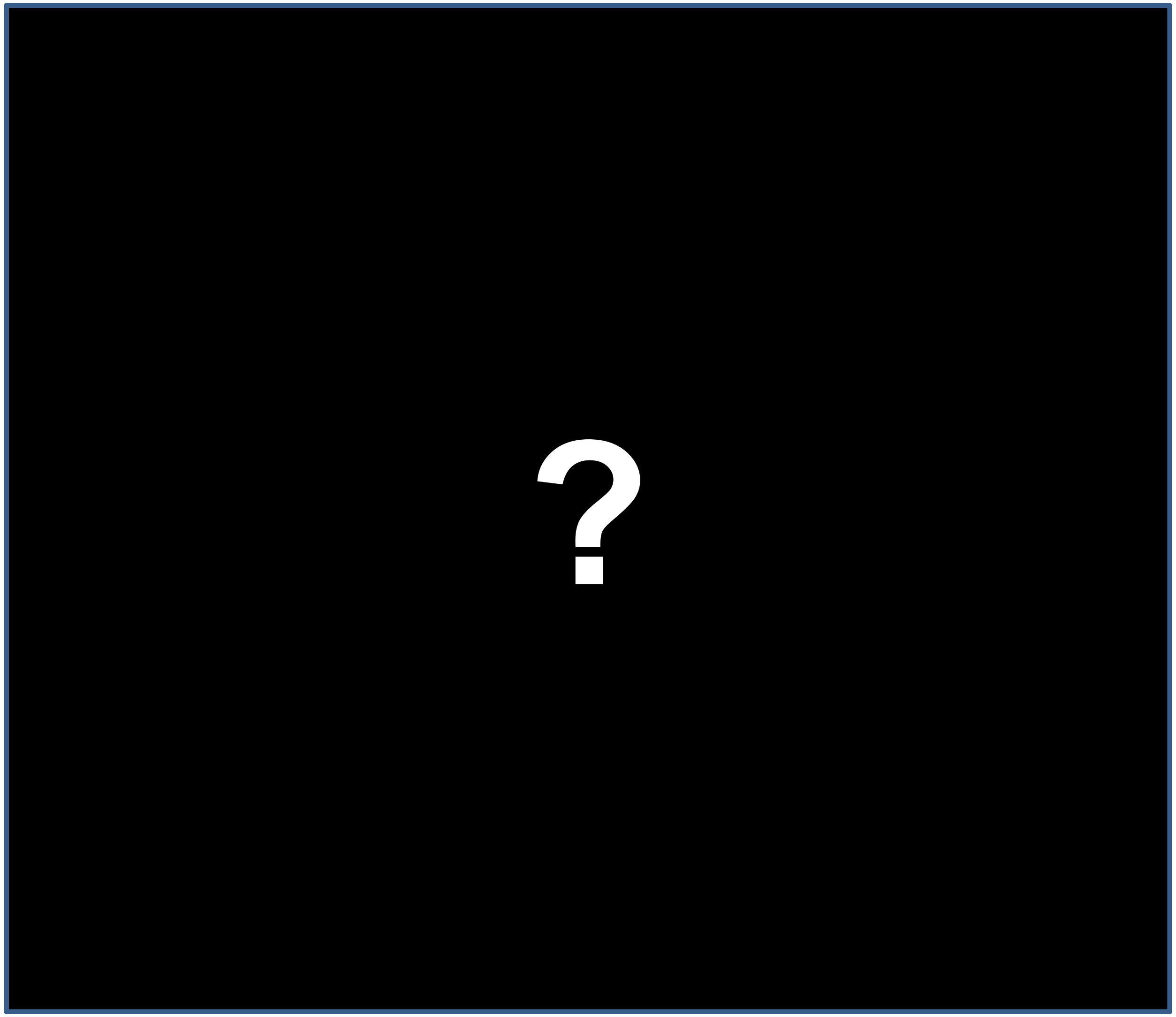
Θ ~ 60⁰
proton
iron
198
122
92
42
27
Epos-LHC
QGSJetII-04
⟨X^μ_max⟩ [g/cm²]
600
550
500
450
400
2×10^19
3×10^19
4×10^19
10^20
E [eV]

<ln A> from X_{max} and X^{μ}_{max}



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

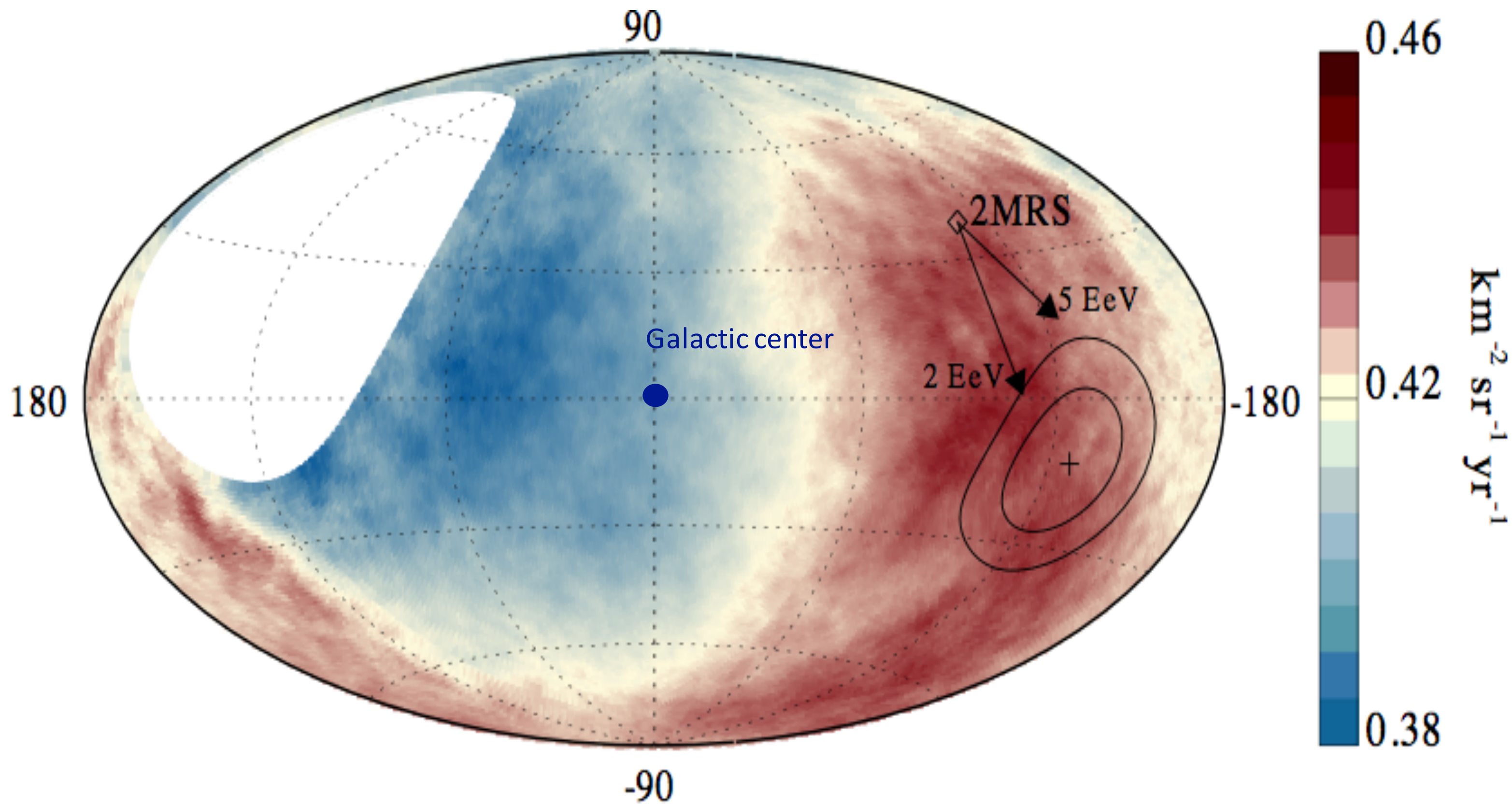
Origin



Extragalactic Origin

$E > 8 \times 10^{18}\,\text{eV}$

Auger - 6.5% dipole at 5.2 sigma

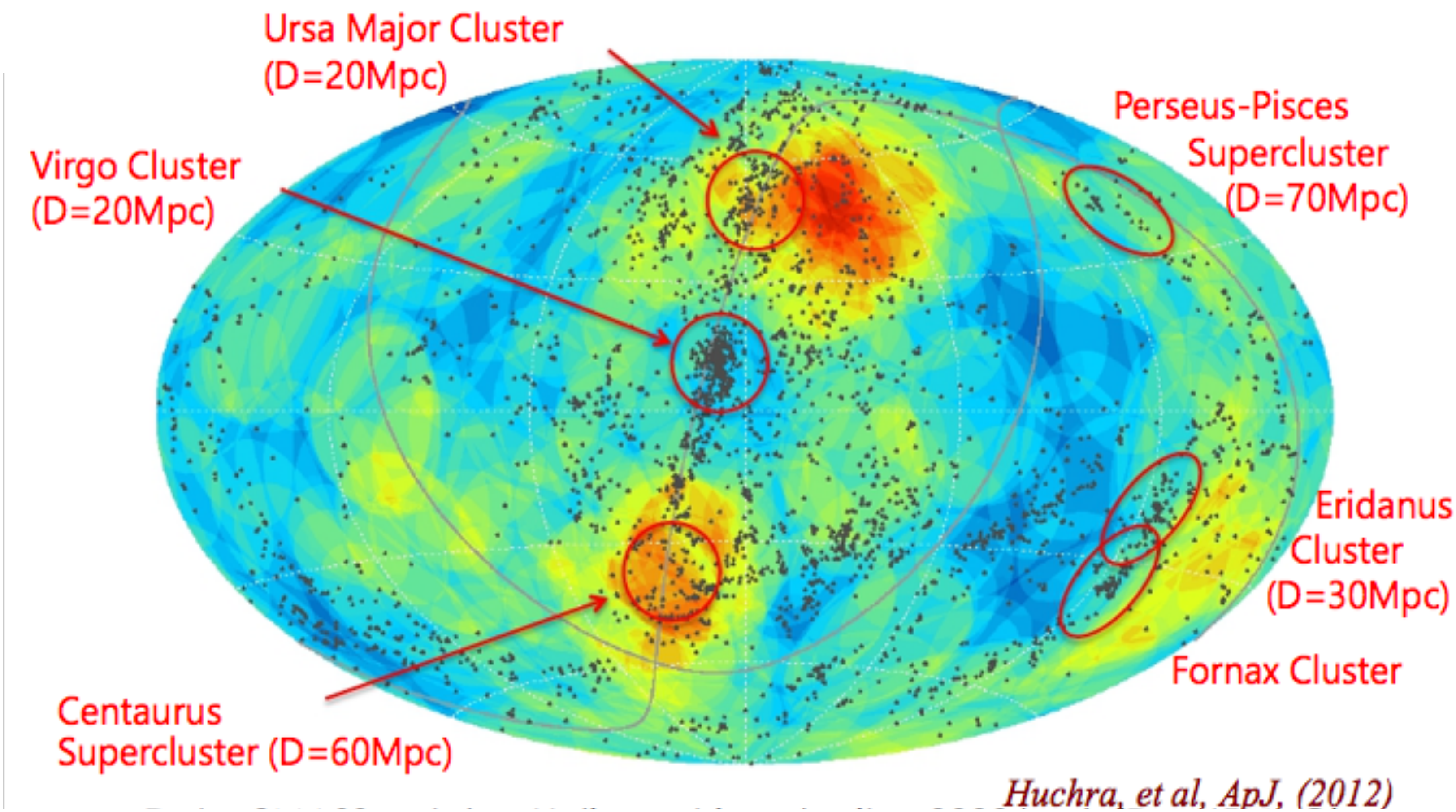


Arrival directions follow mass distribution of near-by galaxies

Hot/Warm spots

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

TA and Auger: over-densities ~20° size

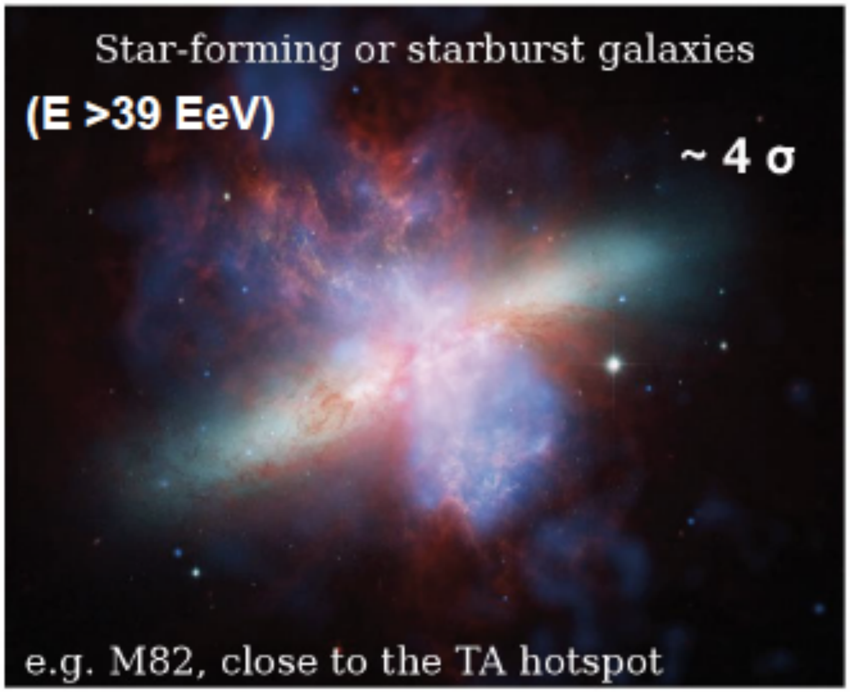


Huchra, et al, ApJ, (2012)

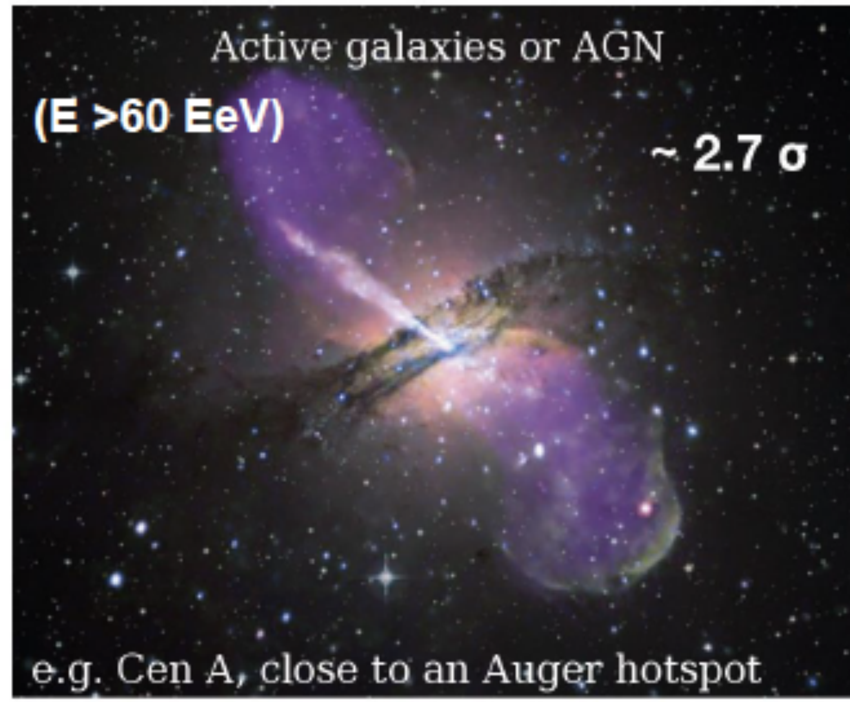
Galaxies with D < 45 Mpc
(2MASS catalog)

Anisotropies – Correlation with catalogs (Auger)

Starburst galaxies



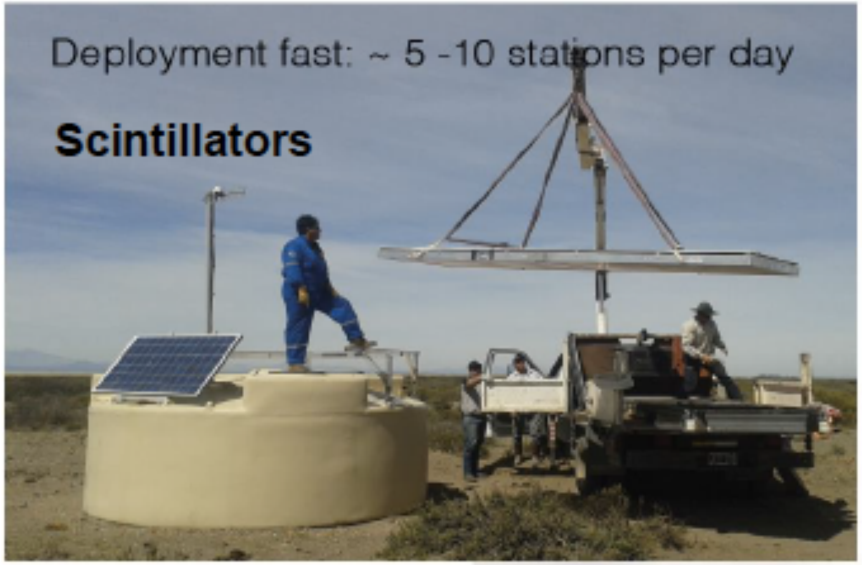
AGNs



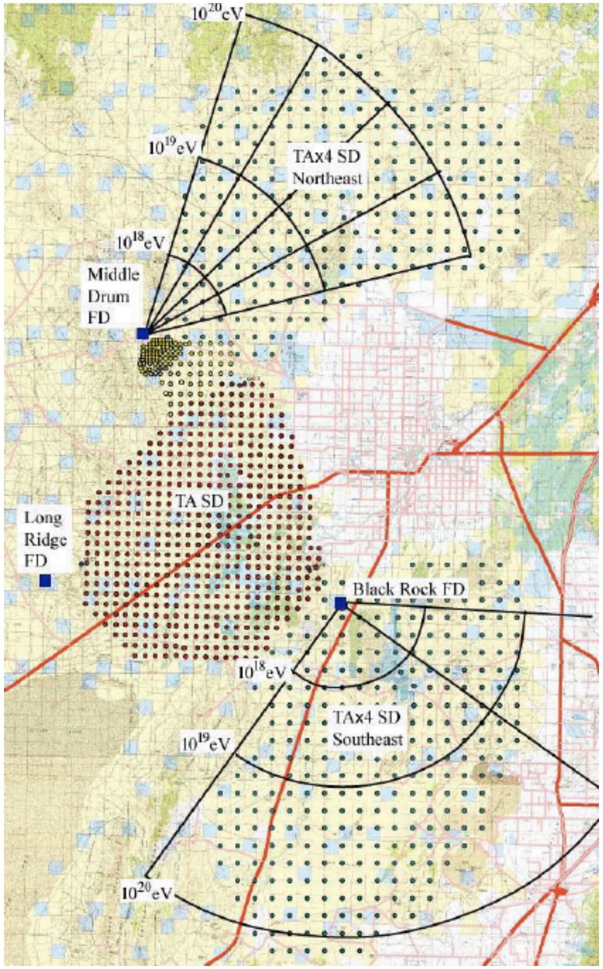
(Giaccari ICRC 2017)

Auger and TA upgrades

Auger Prime

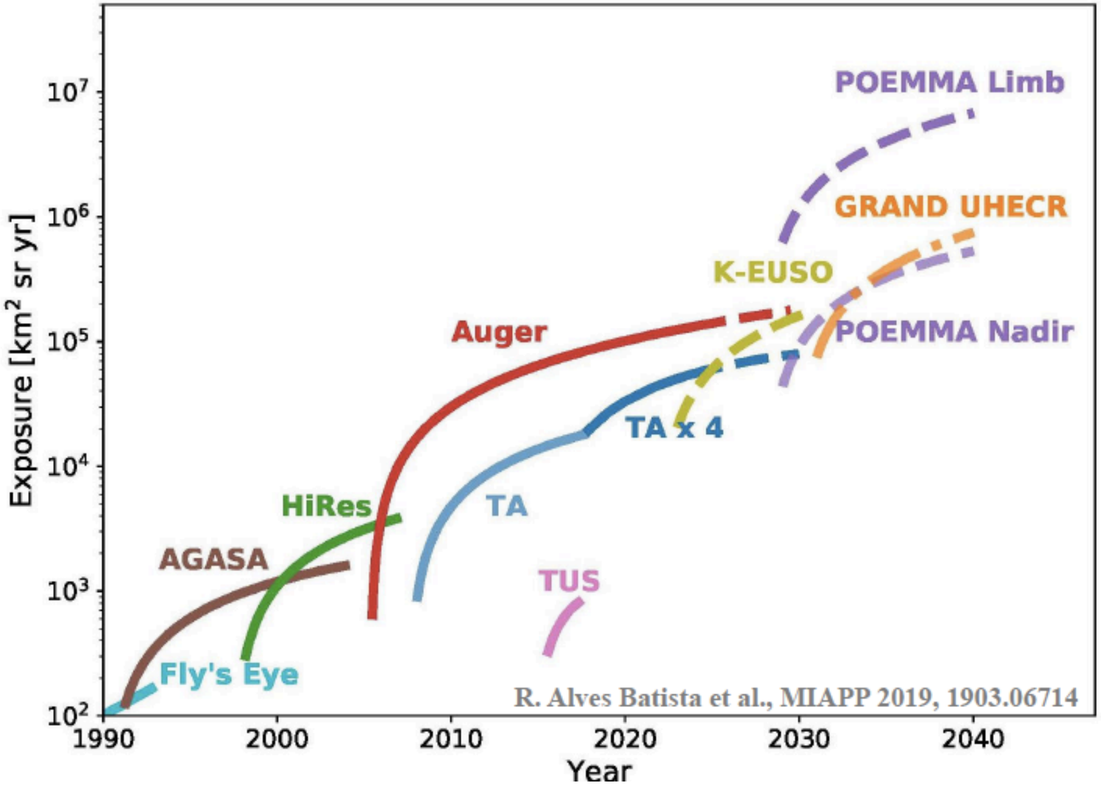


TAx4



Past, present and future

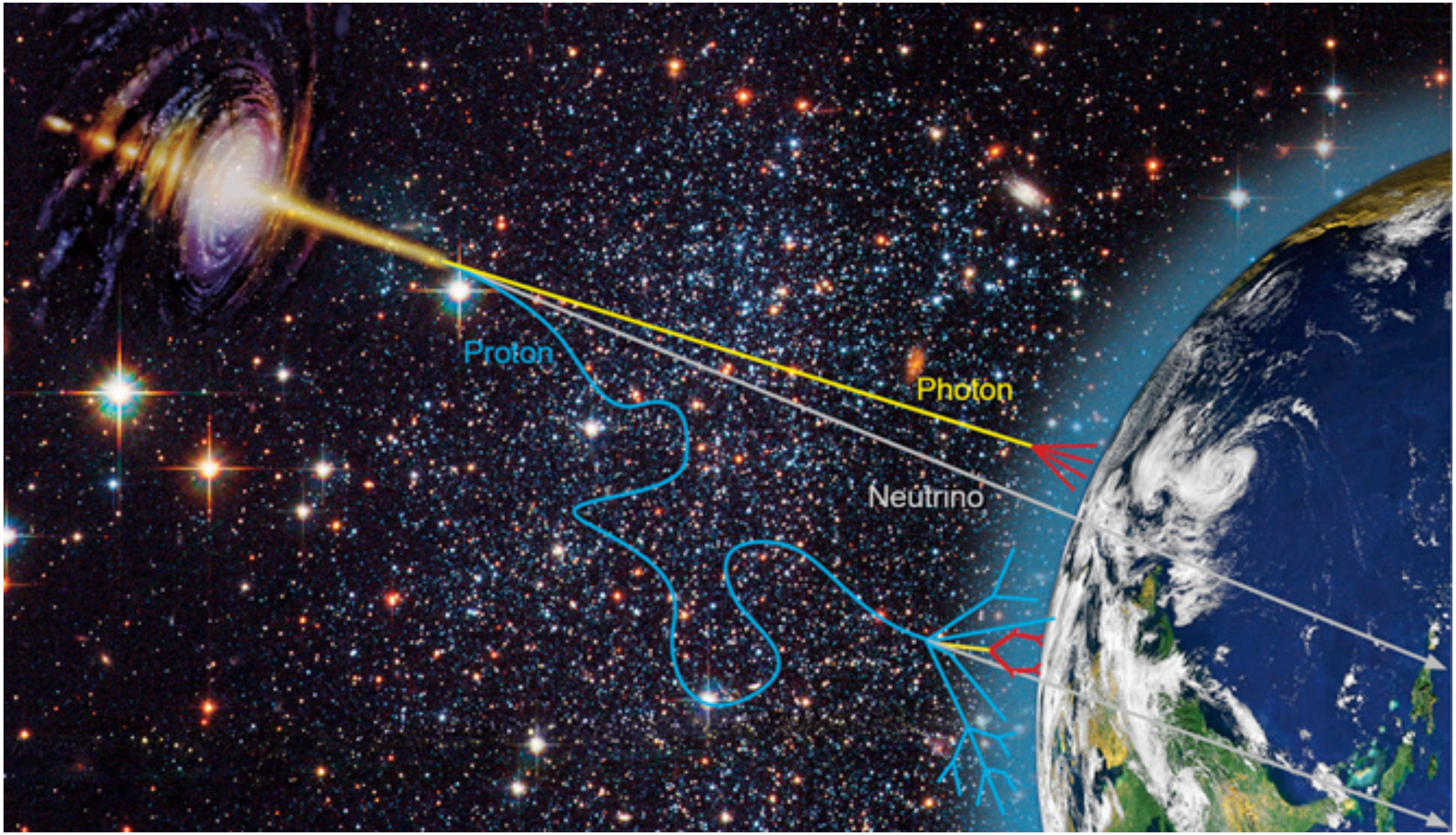
Exposures



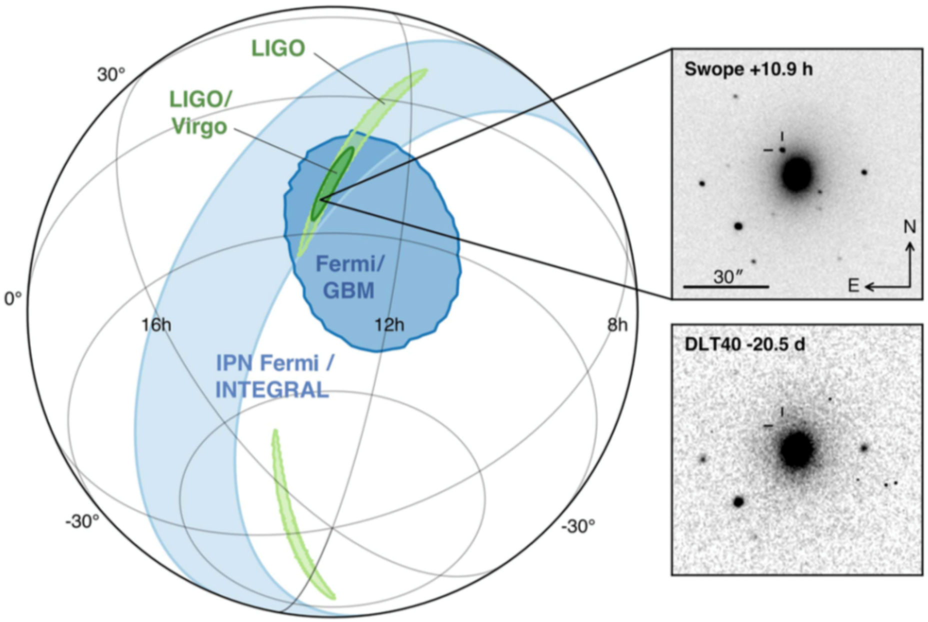
Open Questions

- origin
- mass composition,
- the end of the energy spectrum
- the transition from Galactic to extragalactic
- the effect of magnetic fields
- arrival directions anisotropies
- hadronic interactions at ultrahigh energies
- Looking for new physics - LIV

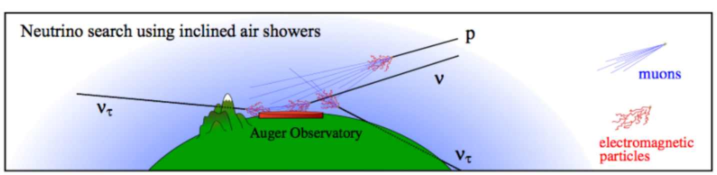
The Multimessager Era

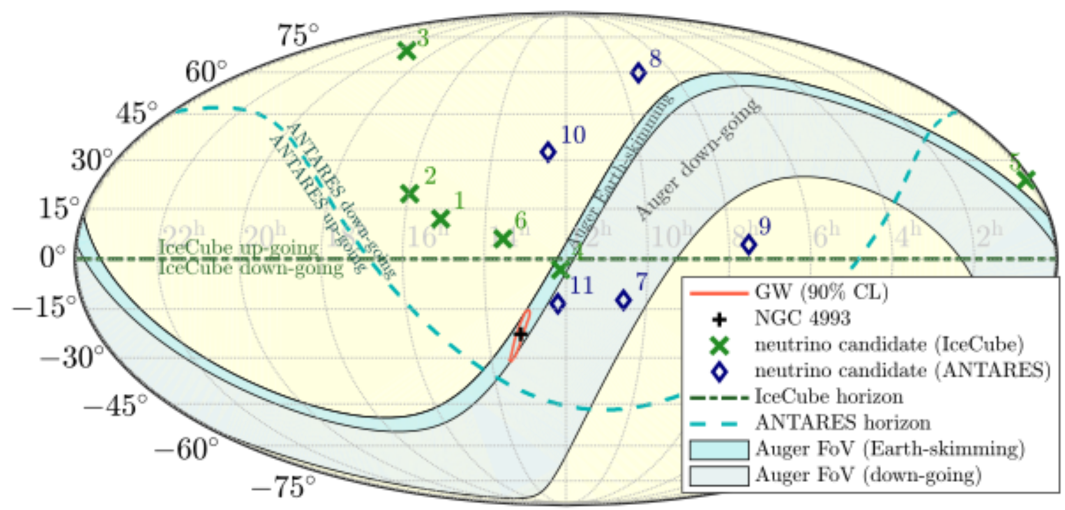


GW170817

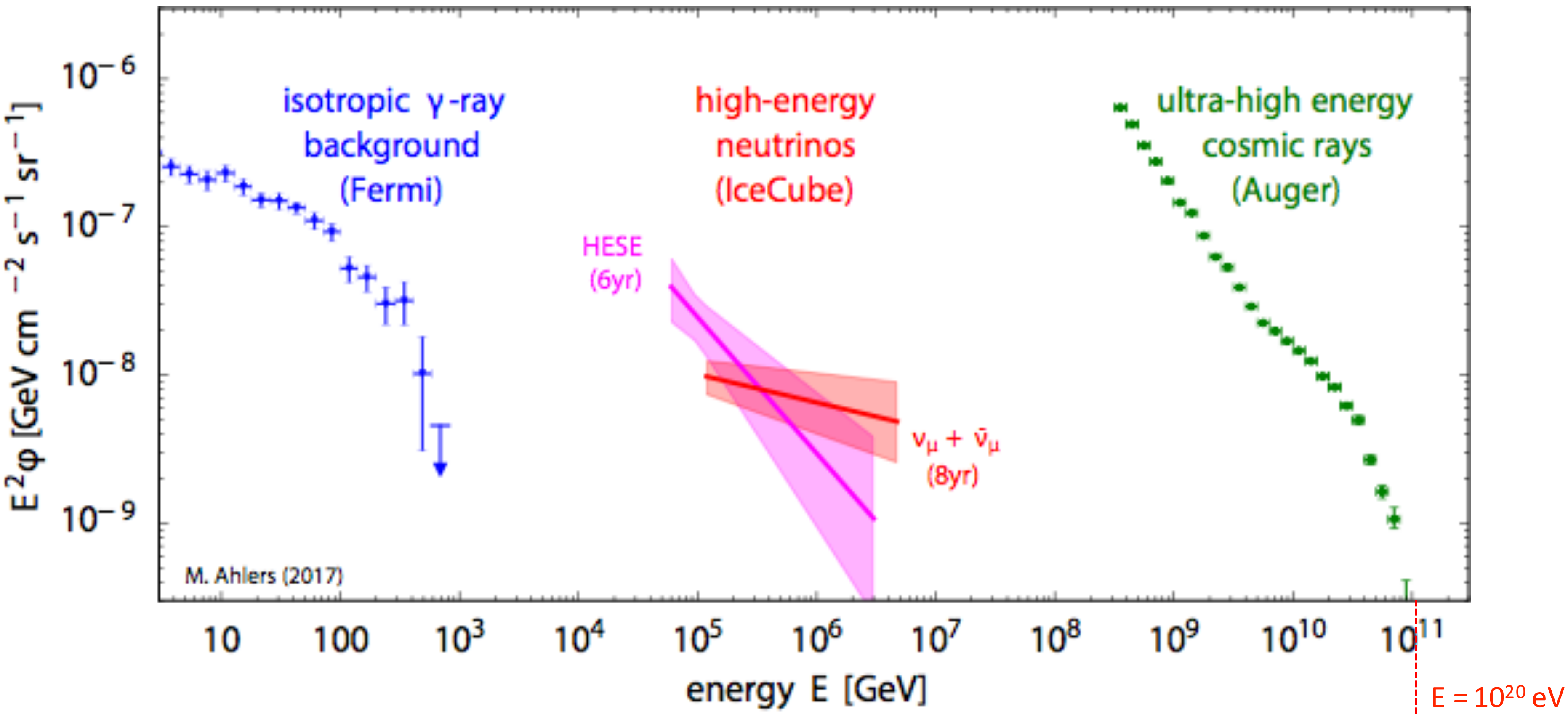


The first multimessenger discovery of a binary neutron star merger





The Universe at the highest energies !



$$E^2 \frac{dN}{dE} = E \frac{dN}{d\ln E}$$

$$\rho_{\text{decade}} = \int_{\text{decade}} E \frac{dN}{d\ln E}\, d\ln E$$

Energy density per decade similar in all three messenger particles

Open Questions

- origin
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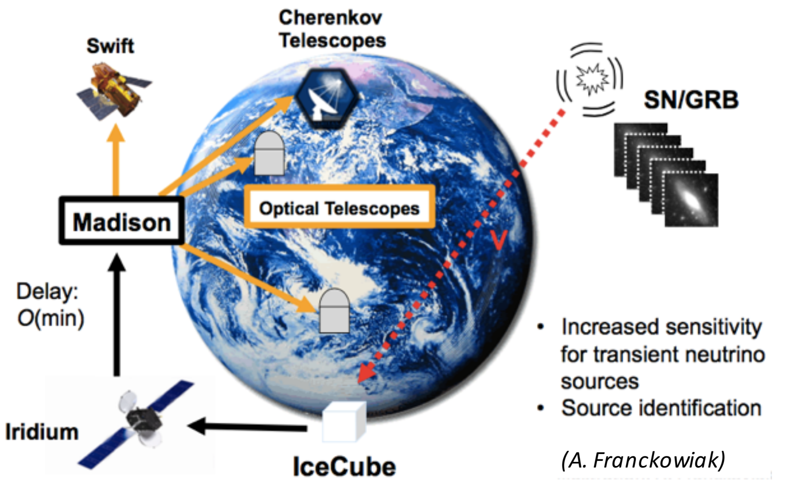
- Looking for new physics - LIV ...

First source of astrophysical neutrinos at high energy?

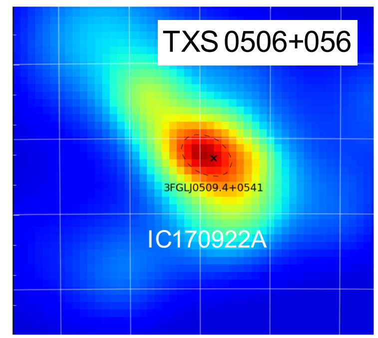


- Increased sensitivity for transient neutrino sources
- Source identification

(A. Franckowiak)

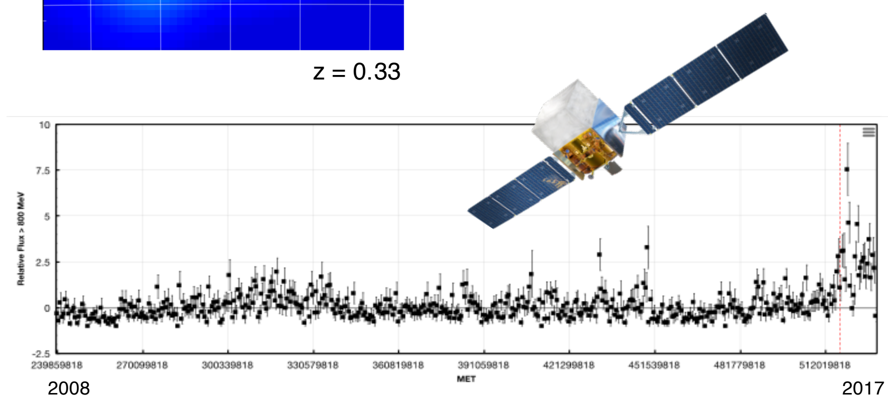
09.05.18, 13:33

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of  Maryland) report on
behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability
of being of astrophysical origin. The event was identified by the  Extremely High Energy
(EHE) track event selection. The IceCube detector was in a normal operating state. EHE events
typically have a neutrino interaction vertex that is outside the detector, produce a muon
that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert
(https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with the direction refined
to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible
astrophysical source for the candidate neutrino.
```



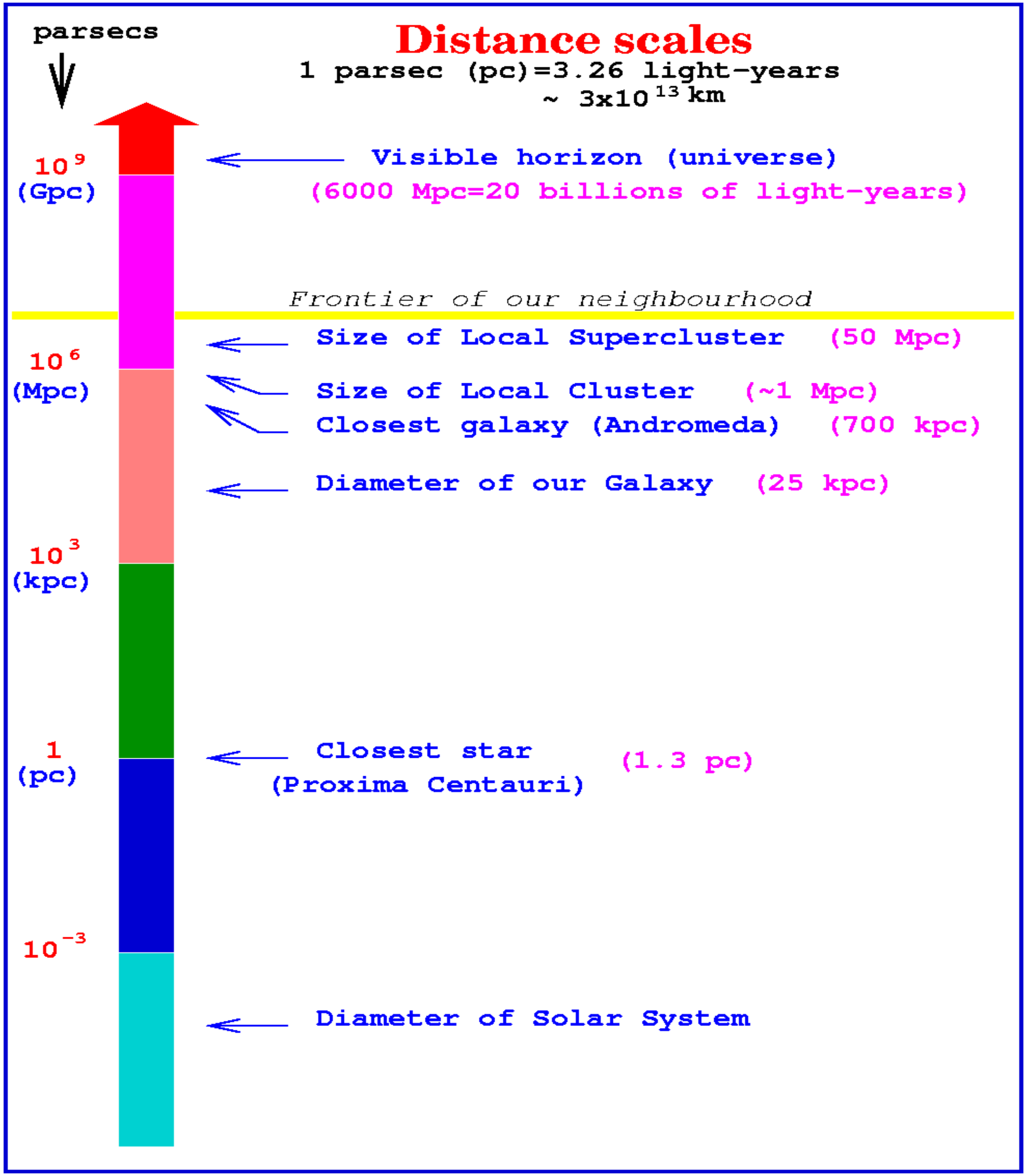
z = 0.33

MAGIC: flare E > 100 GeV

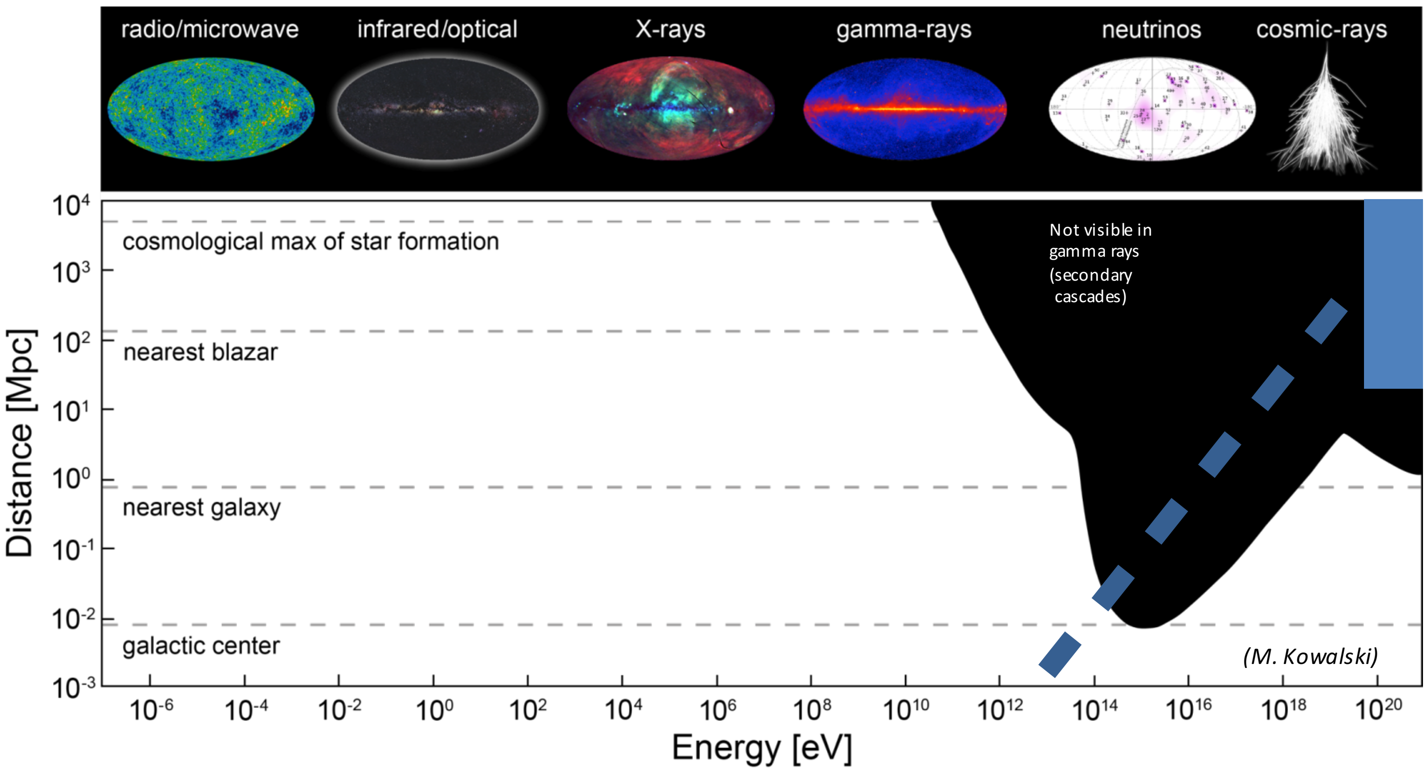


FERMI: flare (found 6 days later)

IceCube 1709922A, publications in preparation


Distance scales
1 parsec (pc)=3.26 light-years
~ 3x10^13 km
parsecs
10^9
(Gpc)
Visible horizon (universe)
(6000 Mpc=20 billions of light-years)
Frontier of our neighbourhood
Size of Local Supercluster (50 Mpc)
10^6
(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

Propagation distances of different messenger particles



Not visible in
in cosmic rays
(energy loss effects)

Cosmological evolution
of sources important

Magnetic horizon for cosmic rays
(diffusion time exceeds lifetime of Galaxy / Universe)