Introduction aux rayons cosmiques

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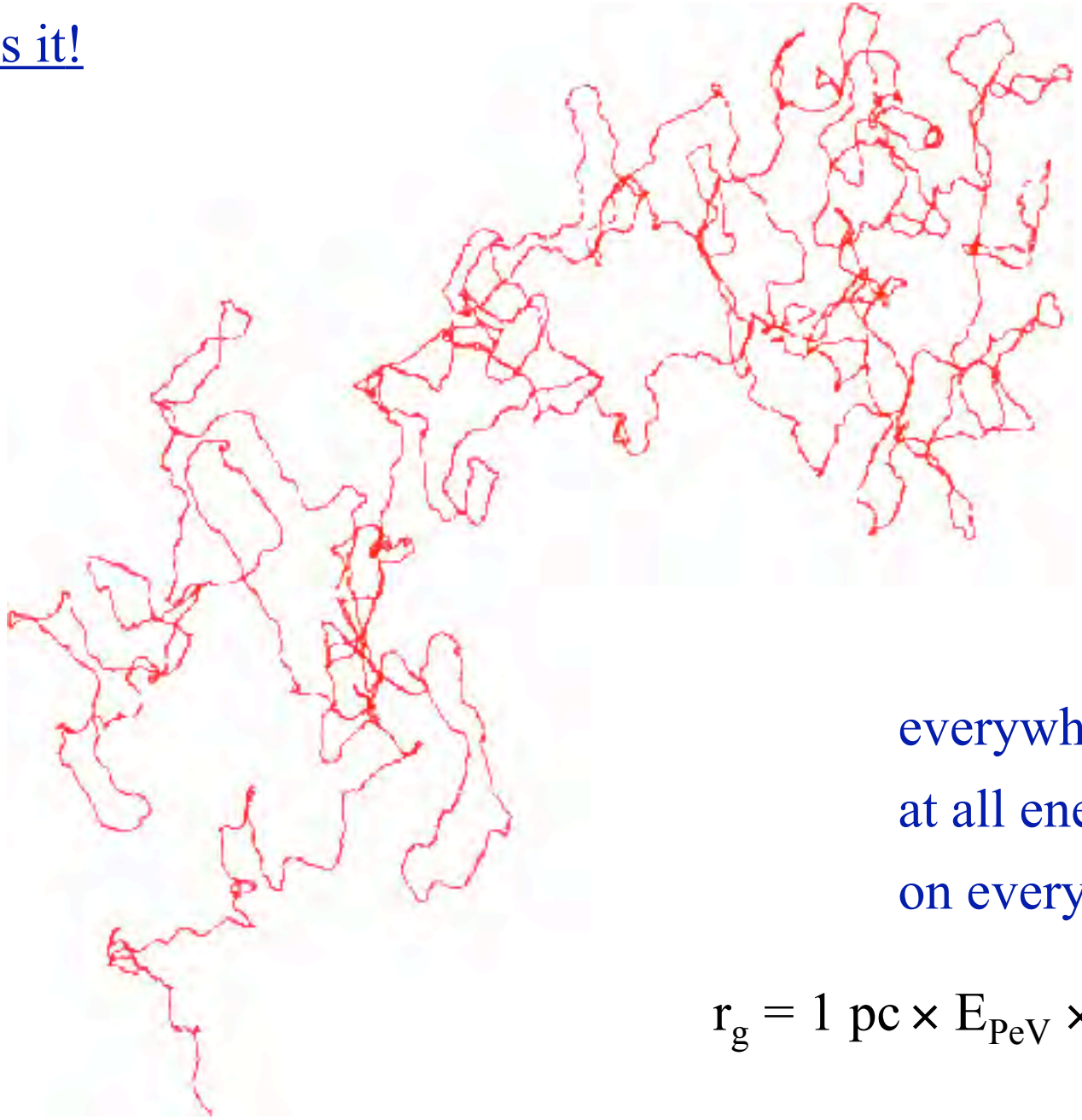
(APC - Univ. Paris 7)

This is it!



everywhere

at all energies

on every scale

$$r_g = 1\ \mathrm{pc} \times E_{\mathrm{PeV}} \times B_{\mu\mathrm{G}}^{-1}$$

Cosmic rays: "CRs"

- **Key subject in astrophysics!**
  - **One of the main components of the Galaxy (> 1 eV/cm^3)**
  - **CRs control the ionization of the interstellar medium**

  + heating + turbulent magnetic field + astro-chemistry!

  - **CRs regulate star formation** + LiBeB nucleosynthesis

- **Impact on the evolution of species and Earth climate**

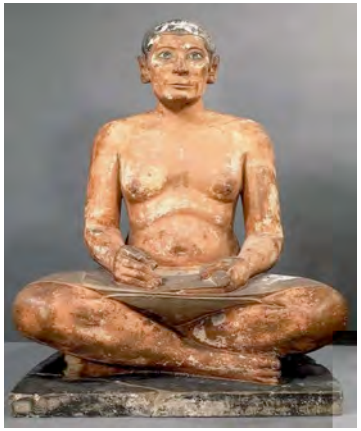
  + Herschel and price of wheat in England!

- **Still very poorly understood**

  ⟹ Why?

  NB: legitimate hopes for significant progress soon

Photon astronomy started millenaries ago with this instrument:



Cosmic ray physics started one century ago with this instrument:

Charged electroscope

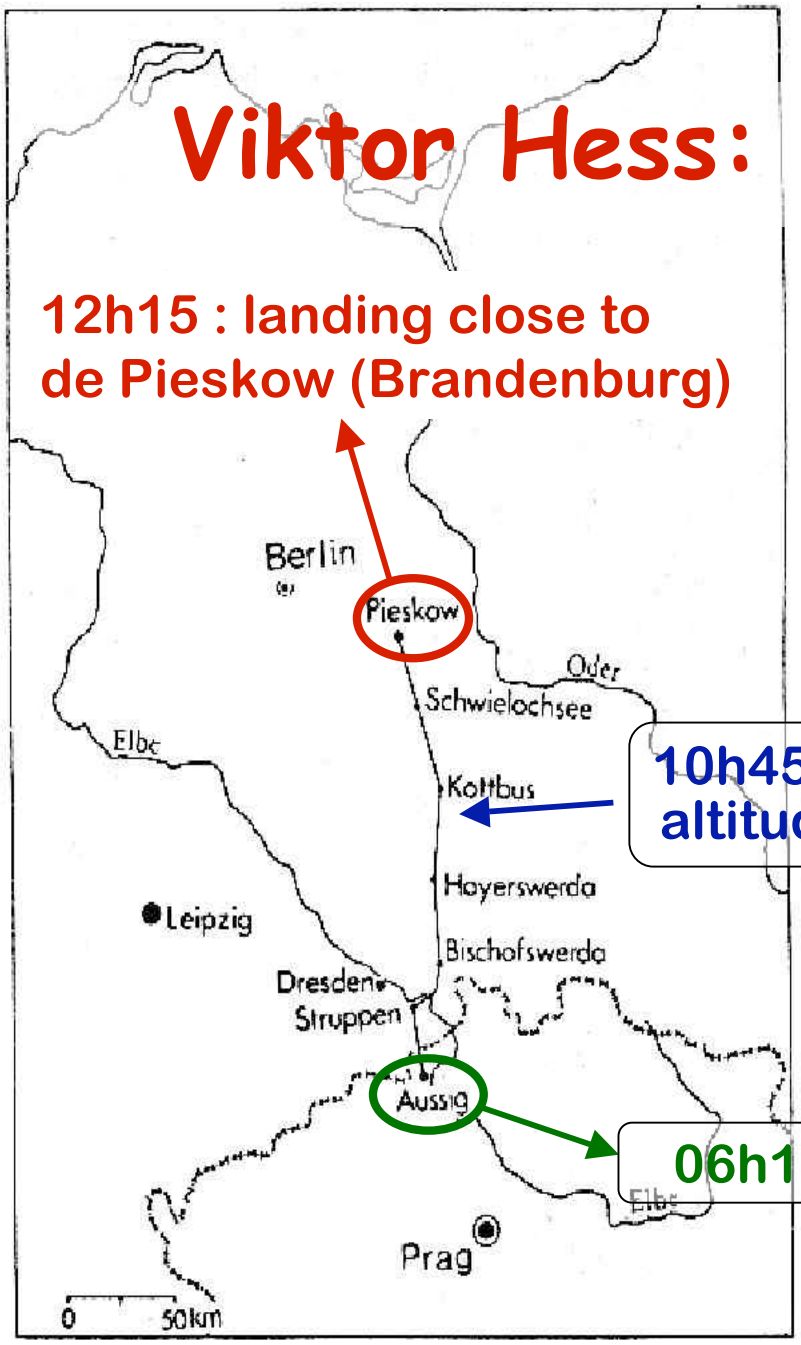
Discharged electroscope

"Spontaneous" discharge!

- **1901: Wilson notices that discharge is identical on the ground and underground (~7 div/hour)**
- **Rutherford shows that natural radioactivity (ground and contaminated apparatus) is responsible**

- 1910: Theodore Wulf (Jesuit and amateur physicist who builds the best electrometers) works on the top of the Eiffel tower

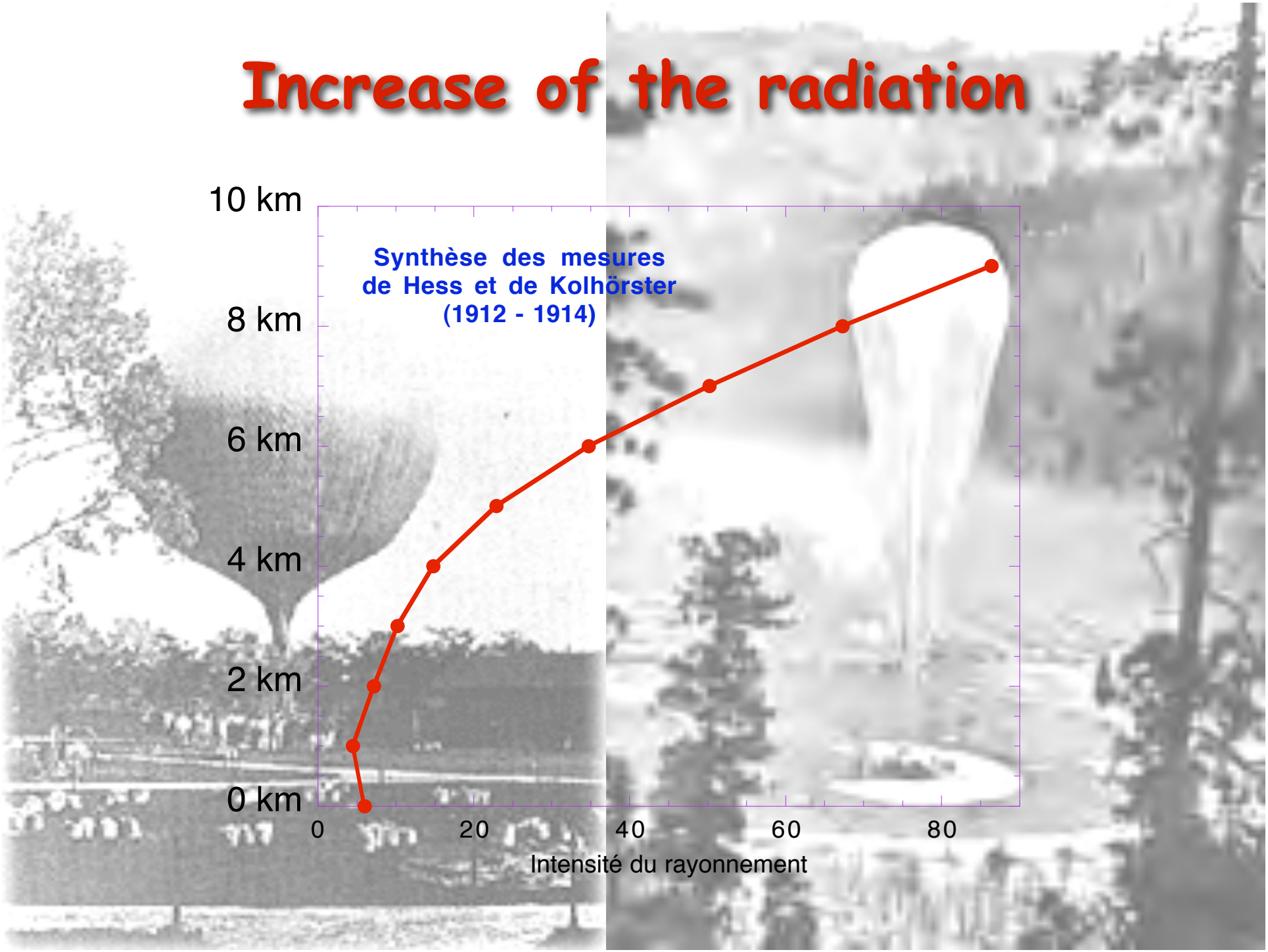
Viktor Hess: August, 7th 1912



oute des Entdeckungsfluges der kosmischen Strahlun

Hess bei Ballonlandung (1912).

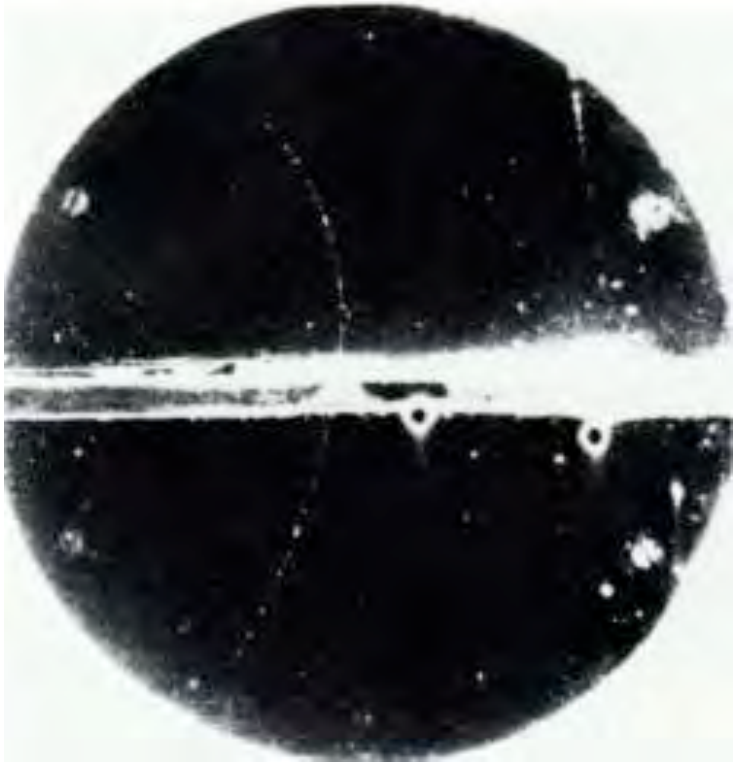
Increase of the radiation



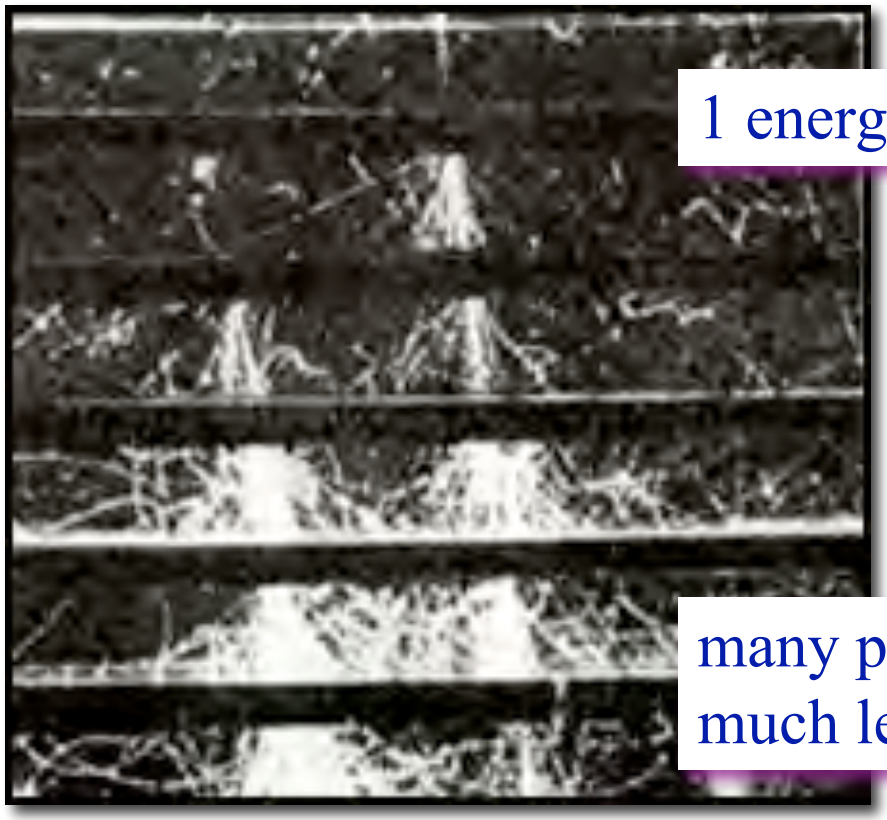
Then a long story began…

- 17 years to recognize that CRs are charged!
- 1932: Anderson discovers the positron (predicted in 1930 by Dirac) in a CR track
- 1936: Neddermeyer and Anderson discover the muon
- 1947: Powel discovers the pion (predicted in 1936 by Yukawa)

+ strange particles, etc.



Particle production

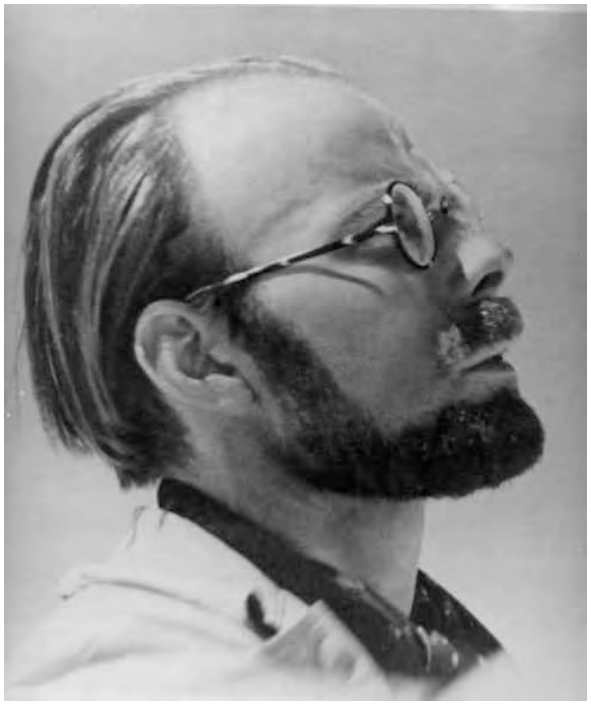


1 energetic particle

many particles, with much less energy!

→ particle "showers"

CR-induced atmospheric showers



Pierre Auger
discovers atmospheric
showers in 1938

⟹ CRs with $E > 10^{15}$ eV !!!

Une science est née !

(La physique des particules)

- **La liste des particules découvertes est longue**

1932	Positon ⇒ antimatière !
1936	Muon ⇒ la nature n'est pas si économe !
1947	Pions : π^0, π^+, π^-
1949	Kaons (K)
1949	Lambda (Λ)
1952	Xi (Ξ)
1953	Sigma (Σ)

Particules « étranges »

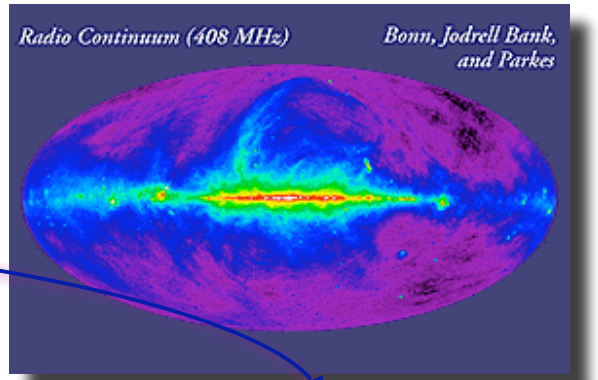
(Durée de vie beaucoup trop longue)

- **Tout cela, grâce aux rayons cosmiques…**
- **… dont on ignore toujours la nature et l'origine !!!**

Schism...

study of cosmic rays

1953



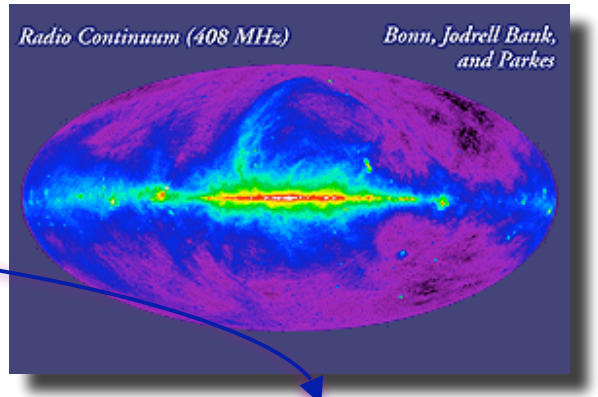
astrophysics

particle physics

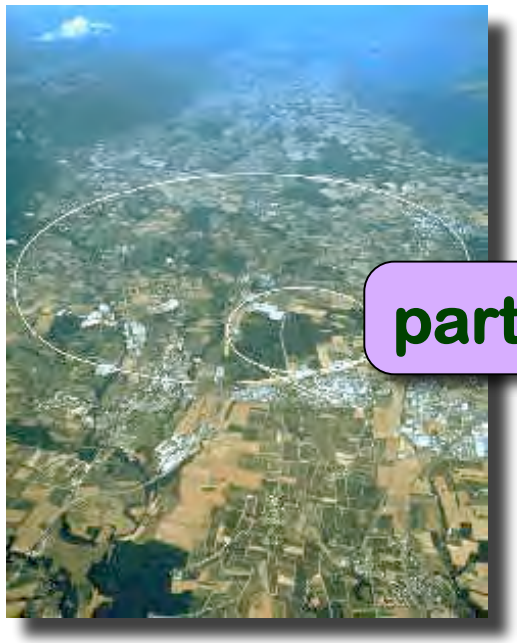
Schism... and ecumenism!

study of cosmic rays

1953



astrophysics



particle physics

> 2000

astroparticle physics

Les RCs sont (aussi) intéressants par eux-mêmes!

- Quels sont les primaires ?
- D'où viennent-ils ?
- Comment obtiennent-ils leur énergie ?
- Que nous révèlent-ils sur l'univers ?
- Peut-on les utiliser pour faire de l'astrophysique ?
- Peuvent-ils représenter des "messagers" intéressants en provenance de sources lointaines ?

Tout ce que nous savons, nous le tenons de la lumière !

- Nous connaissons des étoiles, des galaxies, le milieu interstellaire, des champs magnétiques cosmiques, des températures, des masses, des densités, des compositions, des vitesses, etc.
- Tout cela uniquement grâce aux photons atteignant la Terre depuis le cosmos !
- La lumière les messager cosmique par excellence…
- Mais elle n'est plus l'unique messager !
  - Pendant des dizaines de milliers d'années, la lumière visible a été notre seul accès au cosmos
  - Depuis 100 ans, il y aussi les rayons cosmiques !
  - Puis la lumière non visible, et maintenant les neutrinos, et bientôt les ondes gravitationelles !

L'astronomie est vivante !

- « Astronomie binaire » : quelque chose ici, rien là…
- Hipparcos (190 - 120 B.C.) : magnitudes…
- > 1860: spectroscopie
  - Helium découvert par Lockyer en 1889 (puis sur Terre par Ramsay in 1995)
  - Raies d'émission et d'absorption
  - Identification des éléments, décalages Doppler, etc.

- Maxwell, Hertz…: découverte de la lumière invisible !
  - Ondes radio, infrarouge, UV, X, gamma

2 dimensions spectrales : directions et énergies

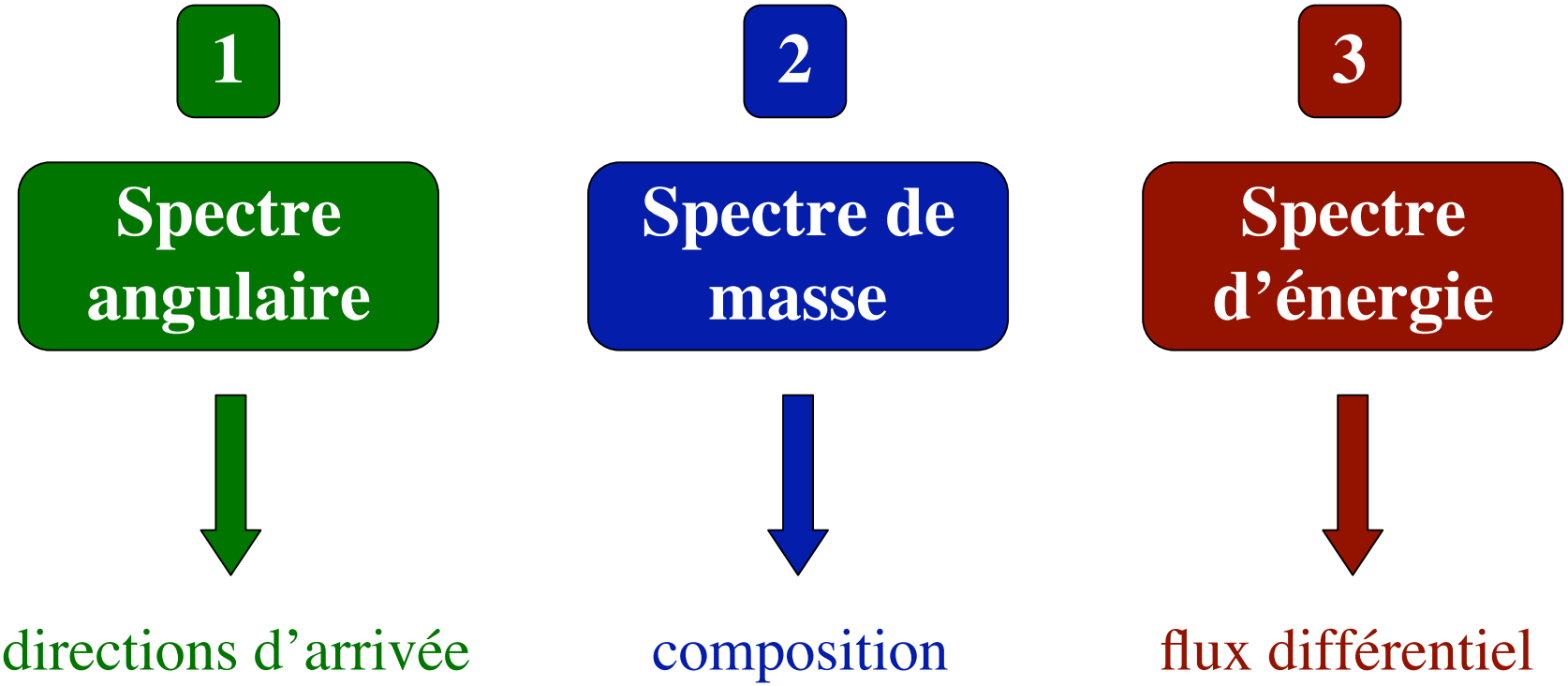
Les rayons cosmiques

Quelques grammes de matière dans un monde lumineux !

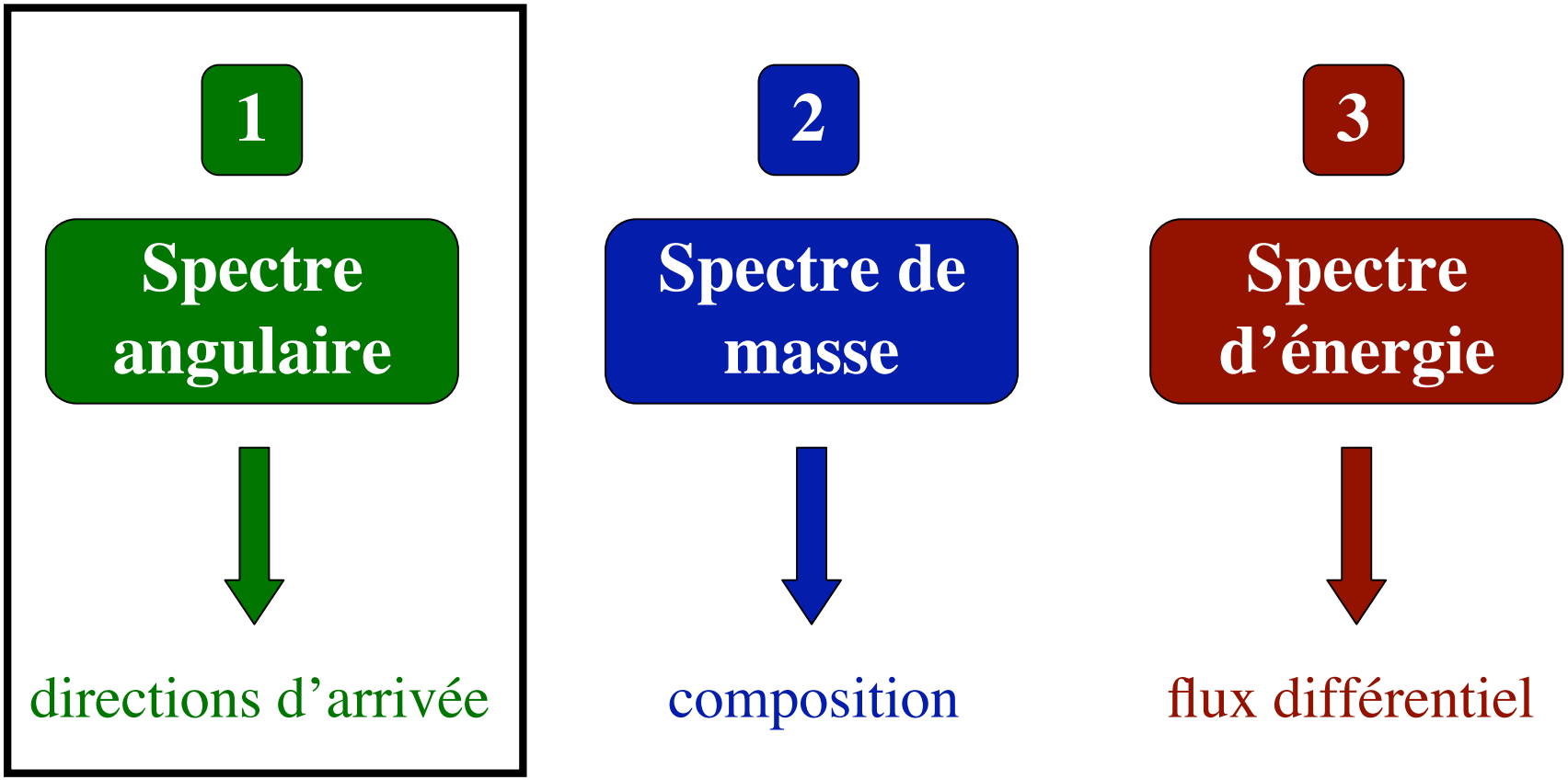
- Toute ce que nous savons en astrophysique vient de la lumière…
- … et de quelques particules de matière extra-solaire : les rayons cosmiques
- 4 CR/cm^2/s => 1 kg/an
- Extrêmement importants pour le science, mais toujours incompris !

3 dimensions spectrales : directions, énergies, + nature physique

Observables fondamentales



Observables fondamentales



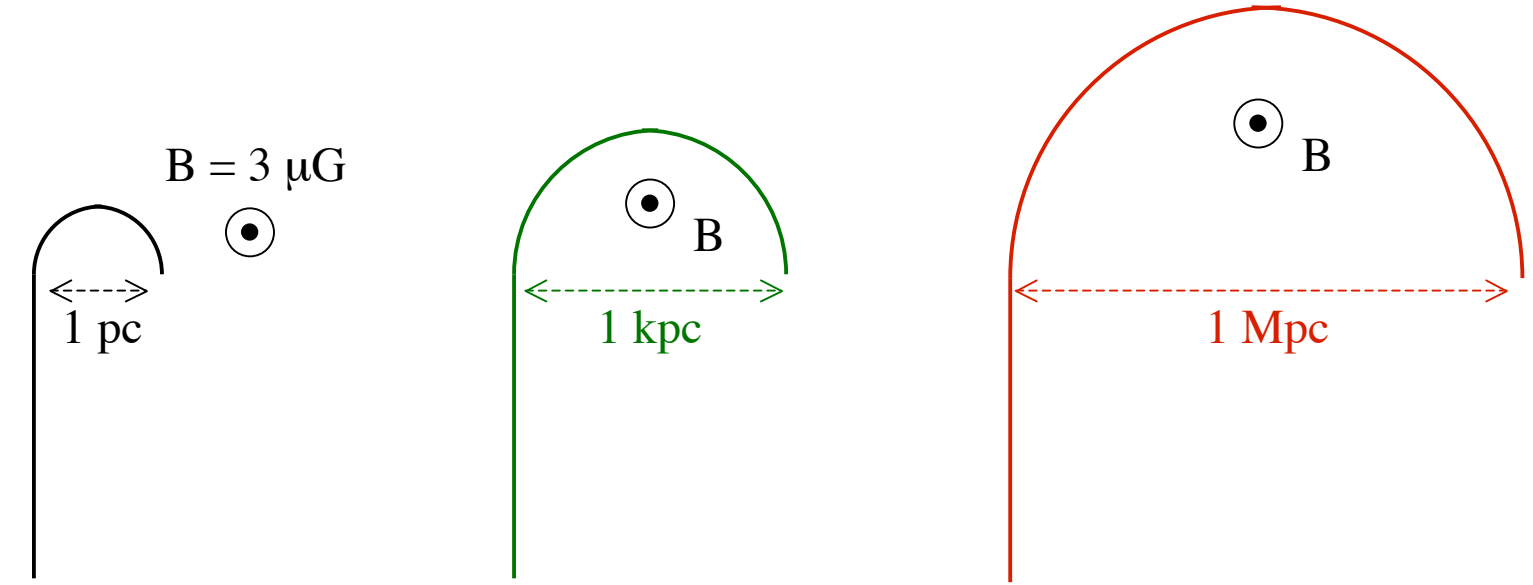
Distribution angulaire

- **Isotrope !**

(→ aucune information sur les sources)

Propagation non rectiligne !

- **Champ magnétique galactique : ~ 3 μG** **(3.10^{-10} T)**
- **Rayon de giration :**



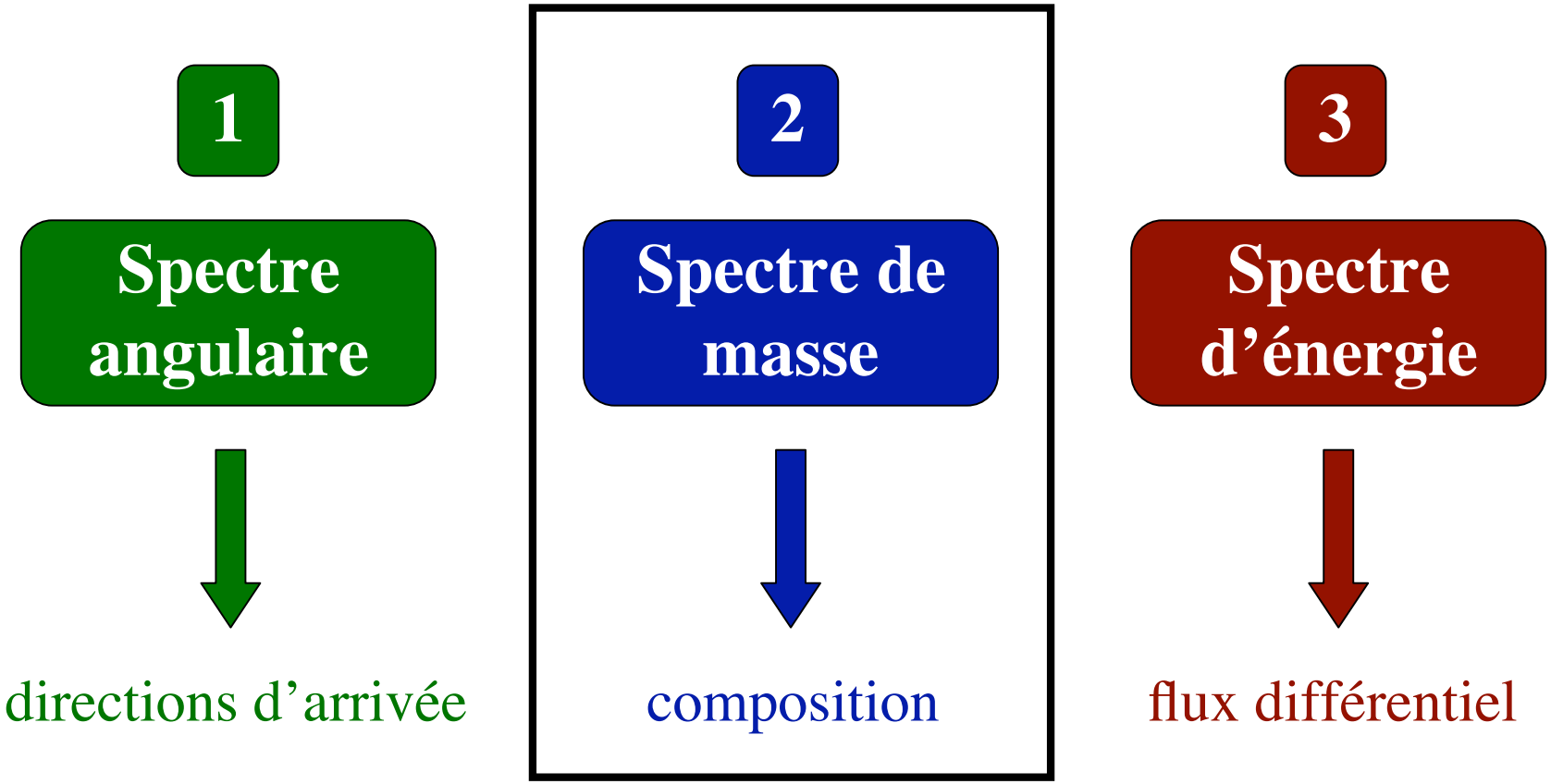
10^{15} eV — Reste de supernova

10^{18} eV — Disque + halo galactique

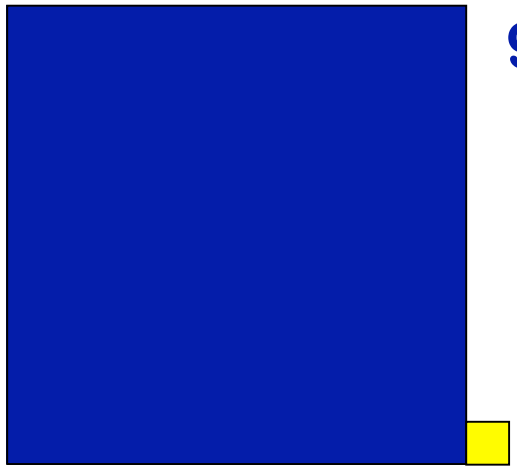
10^{21} eV — >> galaxie

→ astronomie proton ?

Observables fondamentales



Composition des rayons cosmiques



99% de noyaux

1% d'électrons

(Pas neutre !)

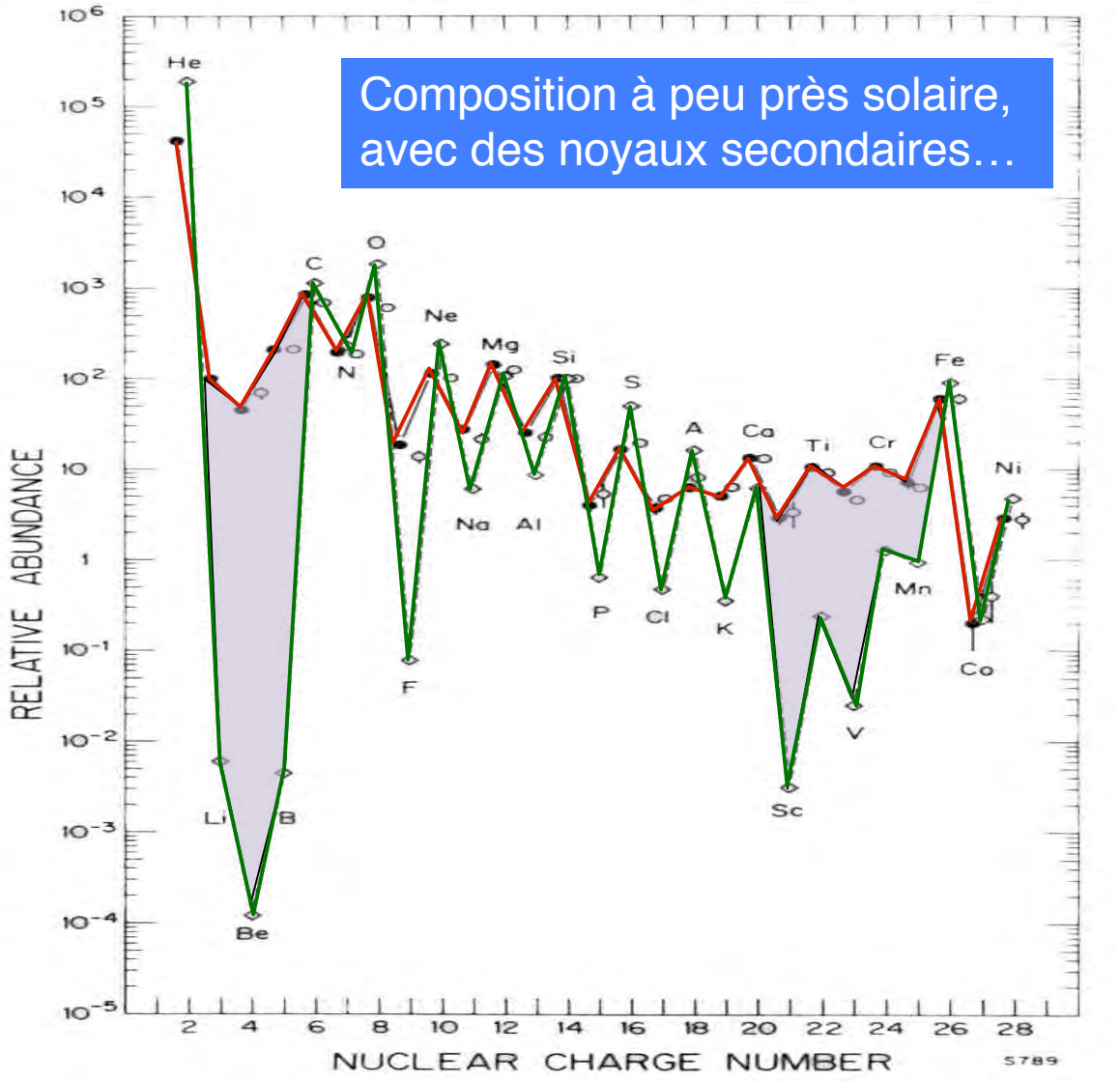
89% de H

10% de He

1% de noyaux lourds

Flux : 4 RC/cm^2/s ⇒ 1 kg/an « 40 000 tonnes/an (météorites)

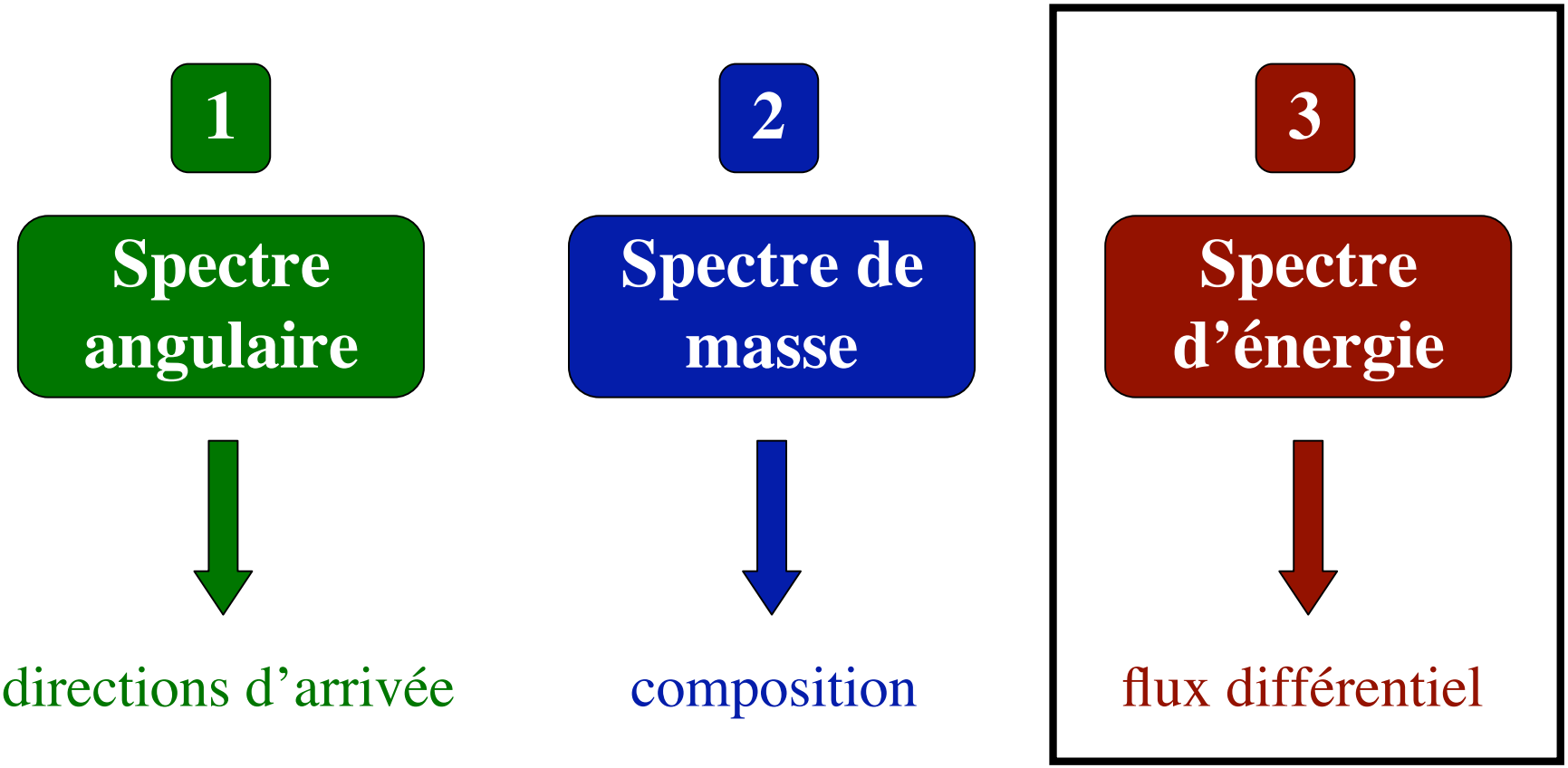
CR vs système solaire



Composition à haute énergie ?

- Très controversé
- Essentiellement inconnu au delà de 10^{16} eV

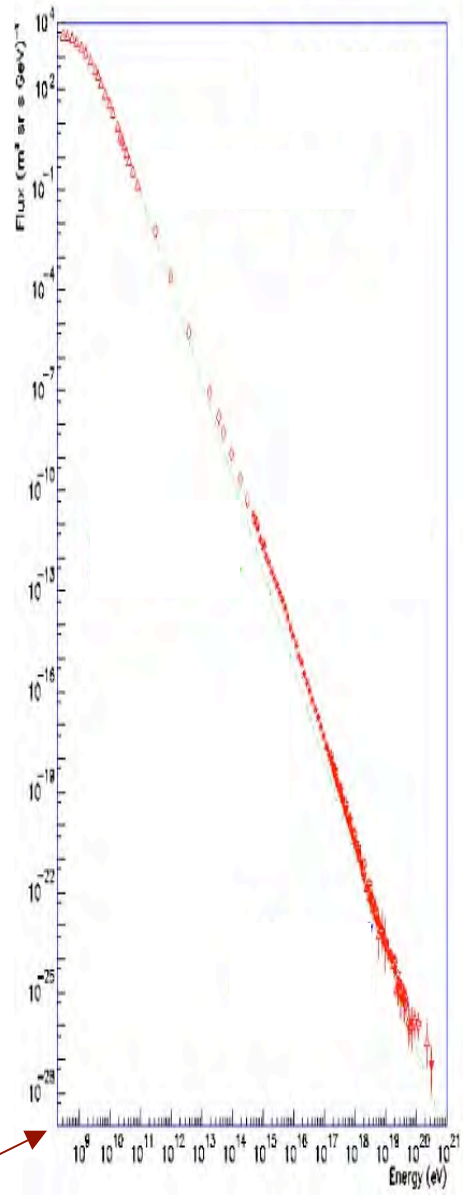
Observables fondamentales



Le spectre d'énergie des rayons cosmiques

Une des sept merveilles du monde physique !

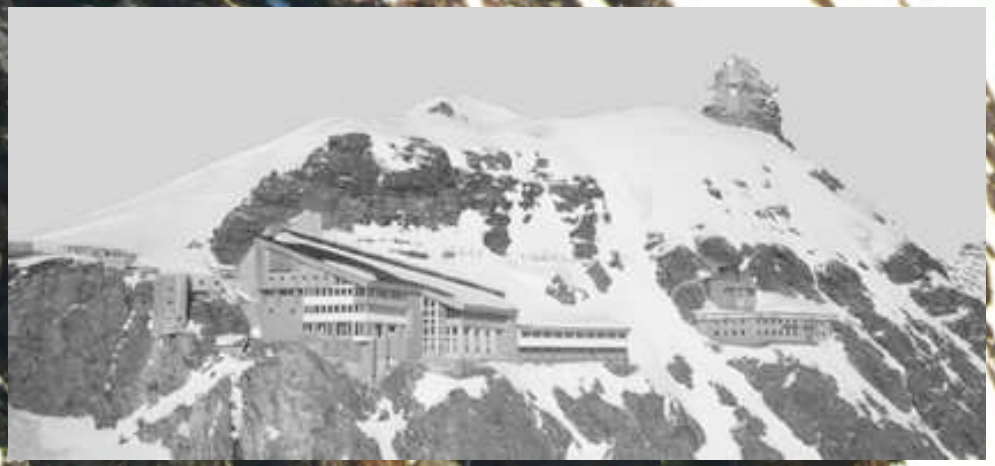
Le spectre d'énergie des RC



100 MeV

10^{21} eV

Laboratoire de Jungfraujoch (3500 m)



Plateau Rosa (3400 m)

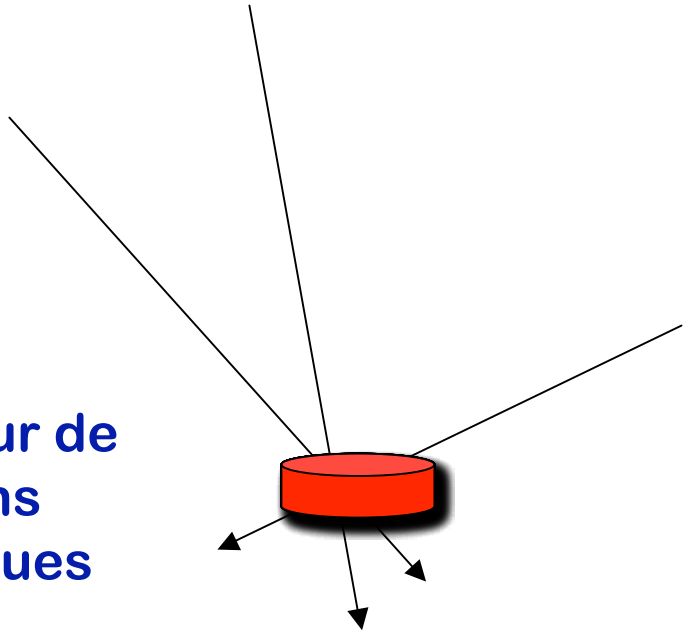
Chacaltaya (Bolivie, 5300 m)

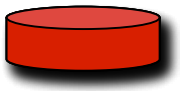
Chacaltaya (Bolivie, 5300 m)

Pierre Auger à la montagne…
(1937-1938)

Pierre Auger
et les gerbes atmosphériques

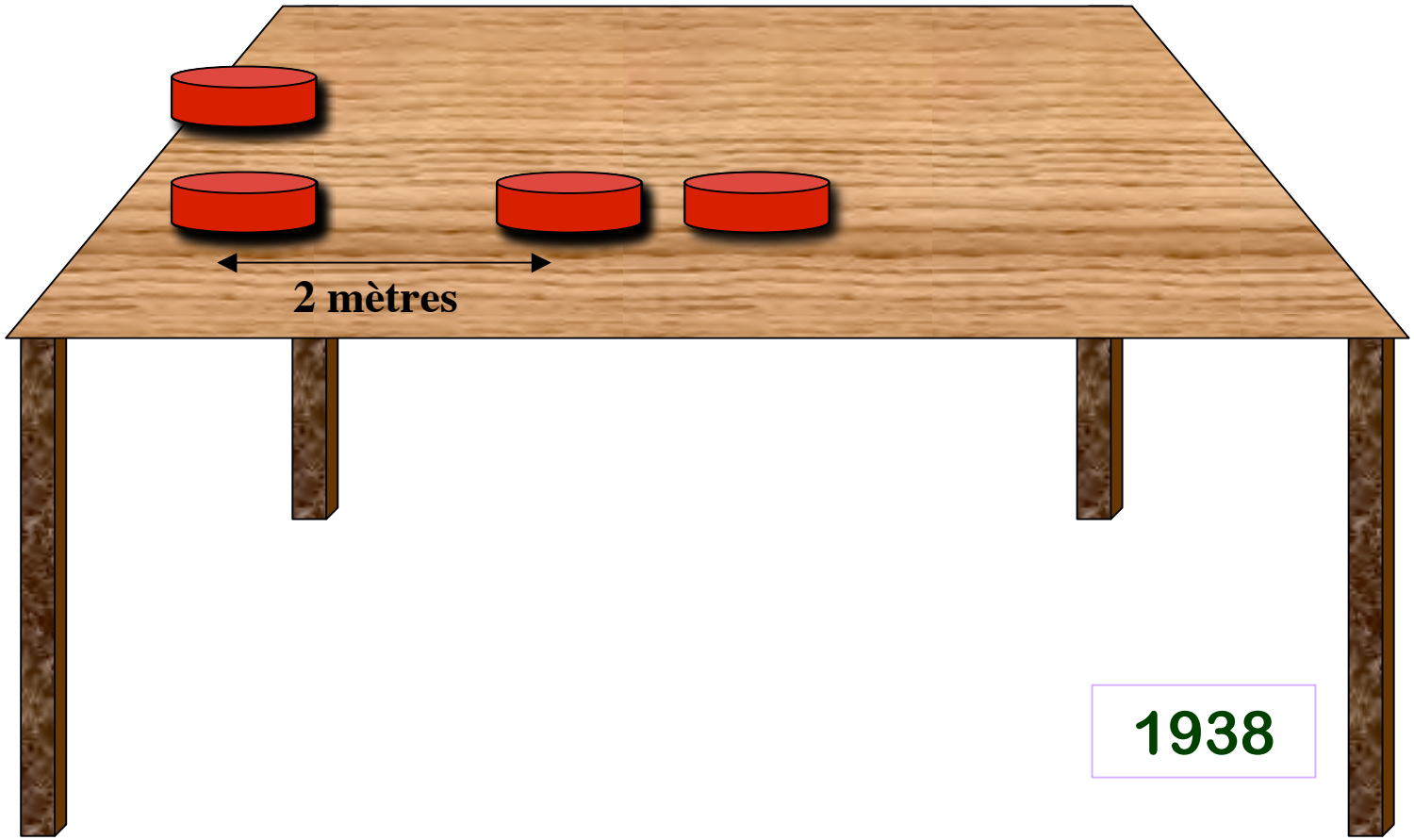
détecteur de
rayons
cosmiques





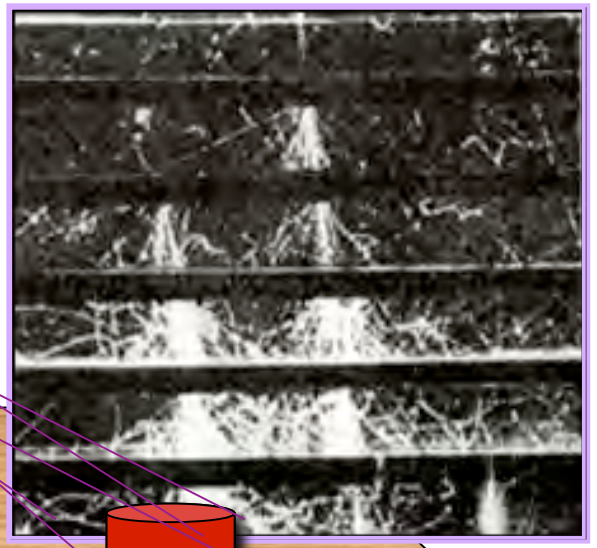
1938

Coïncidences de détection



1938

5 mètres, 10 mètres...



10 mètres

gerbe atmosphérique !

Des énergies stupéfiantes !

$\Rightarrow E > 10^{15}$ eV

$\Rightarrow \Gamma > 10^{6}$

1 seconde = 3 semaines

1 km = 1 mm

« On voit d'après ces résultats que les averses soudaines de rayons cosmiques décrites ici peuvent couvrir des surfaces de l'ordre de 1000 m^2, et comportent donc plusieurs dizaines de milliers de corpuscules, dont une moitié environ peut traverser 5 cm de plomb. »

Académie des sciences, séance du 18 juillet 1938

Jusqu'où cela peut-il aller ?

5 mètres → 40 minutes en moyenne

20 mètres → 1h15 en moyenne

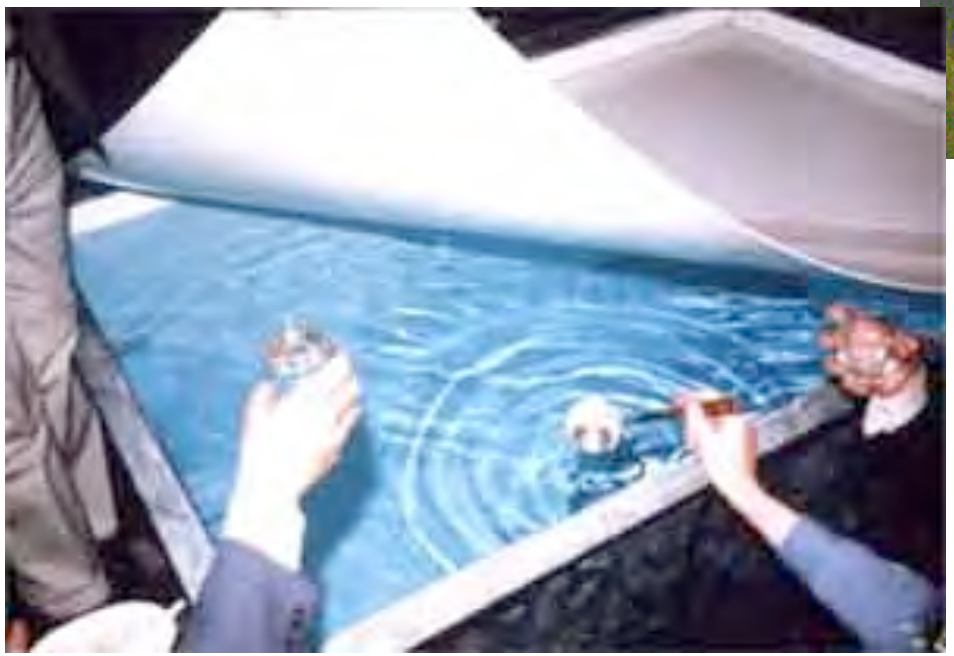
...

1 km → des années !!!


Des réseaux de détecteurs...
58 détecteurs
sur 12 km²
450 mètres
Georgi Zatsepin

Haverah Park (UK)

- Réseau de 12 km^2 de détecteurs constitués de cuves d'eau à effet Cherenkov
  - En opération 20 ans jusqu'à 1987
  - Enregistre quelque 1000 gerbes atmosphériques
  - Jusqu'à 10^{20} eV...



Dégustation de l'eau après 20 ans:
« a little bit stale… »


Volcano ranch (Nouveau-Mexique)
John Linsley chasse les serpents !
1962
Un rayon cosmique d'énergie supérieure à 10^{20} eV !!! !!! !!! !!! !!!

Invraisemblable !

- 10^{20} eV, c'est…
- … plusieurs Joules = énergie macroscopique !
- … l'énergie d'une balle de tennis à 100 km/h !
- … un facteur de Lorentz de 10^{11} !
- … une seconde qui dure 3500 ans !
- … la distance Terre-Soleil ramenée à 1,50 m !

- En un mot, c'est fou !

- Mais la quête n'est pas terminée…

La technique de fluorescence

- Les rayons cosmiques ionisent (c'est comme ça qu'on les a découverts !). Donc ils produisent de la fluorescence.

- Une gerbe à 10^{20} eV, c'est 100 milliards de particules dans l'atmosphère
- En regardant bien, par nuit noire, on peut détecter le rayonnement UV associé

L'œil de mouche (Utah)

L'œil de mouche (Utah)

15 octobre 1991
Un événement à 3.2×10^{20} eV

Le plus énergétique à ce jour…

High Resolution Fly's Eye: HiRes

- 21 Miroirs
  - 360 deg en azimuth
  - 3-17 deg en élévation
- Sample & Hold DAQ
- Observation jusqu'à juin 1997

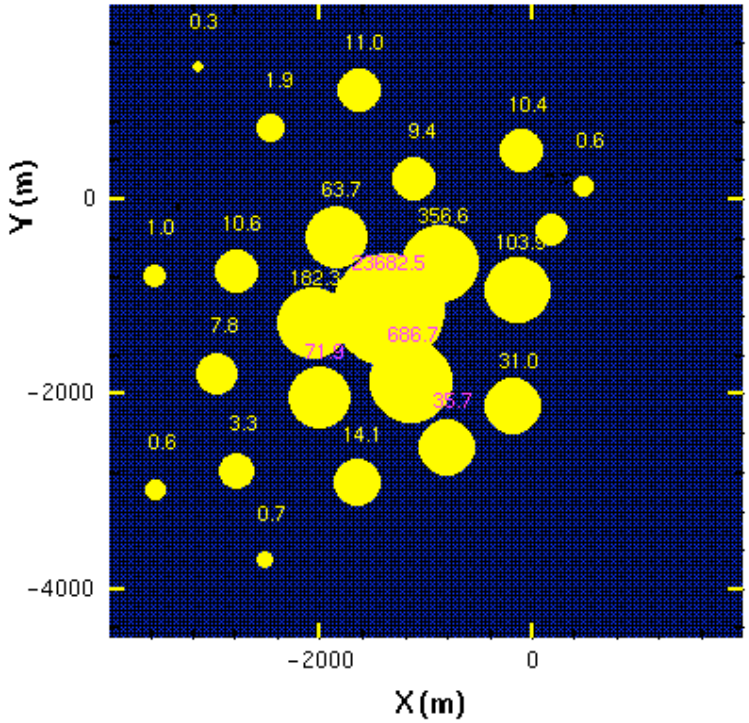
- 42 Miroirs
  - 360 deg en azimuth
  - 3-33 deg en élévation
- FADC DAQ
- Observation depuis october 1999

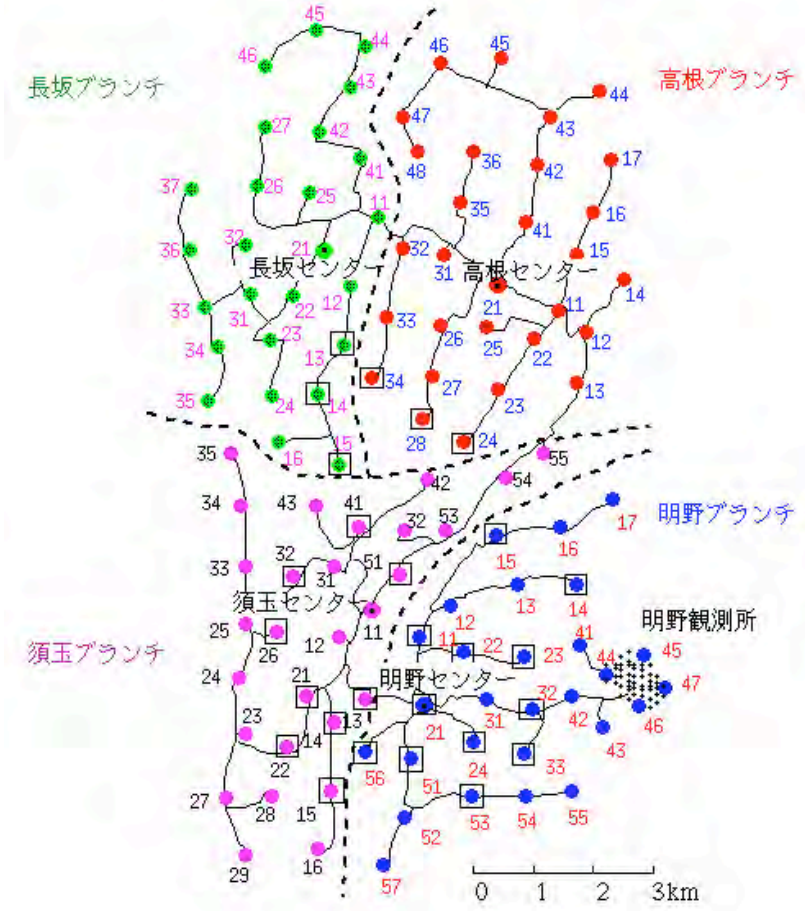
AGASA

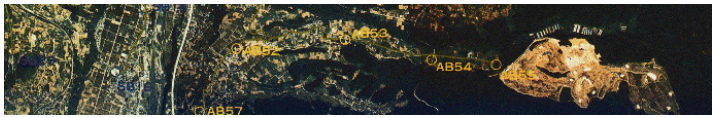
Akeno Giant Air Shower Array

100 km²

technique des scintillateurs







Le spectre d'énergie des rayons cosmiques

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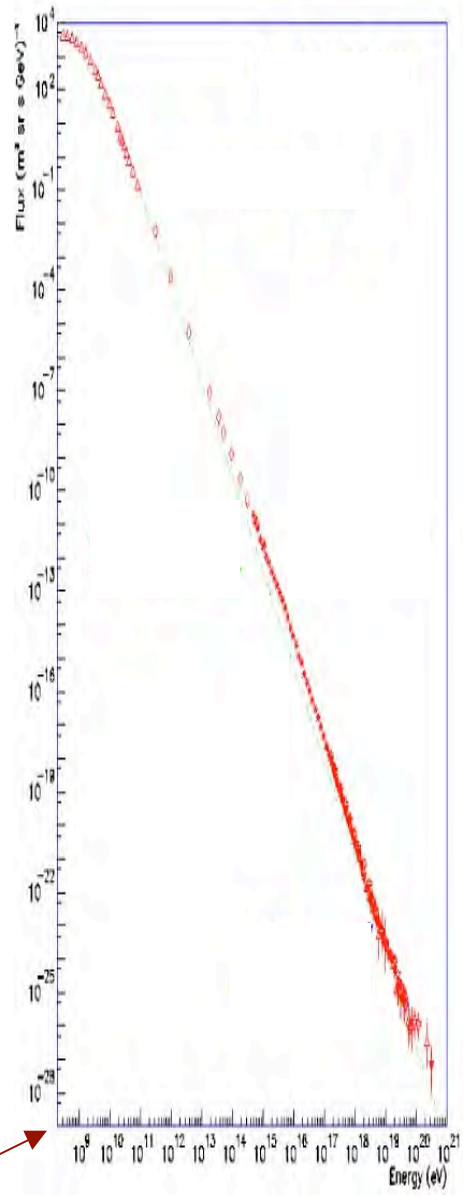


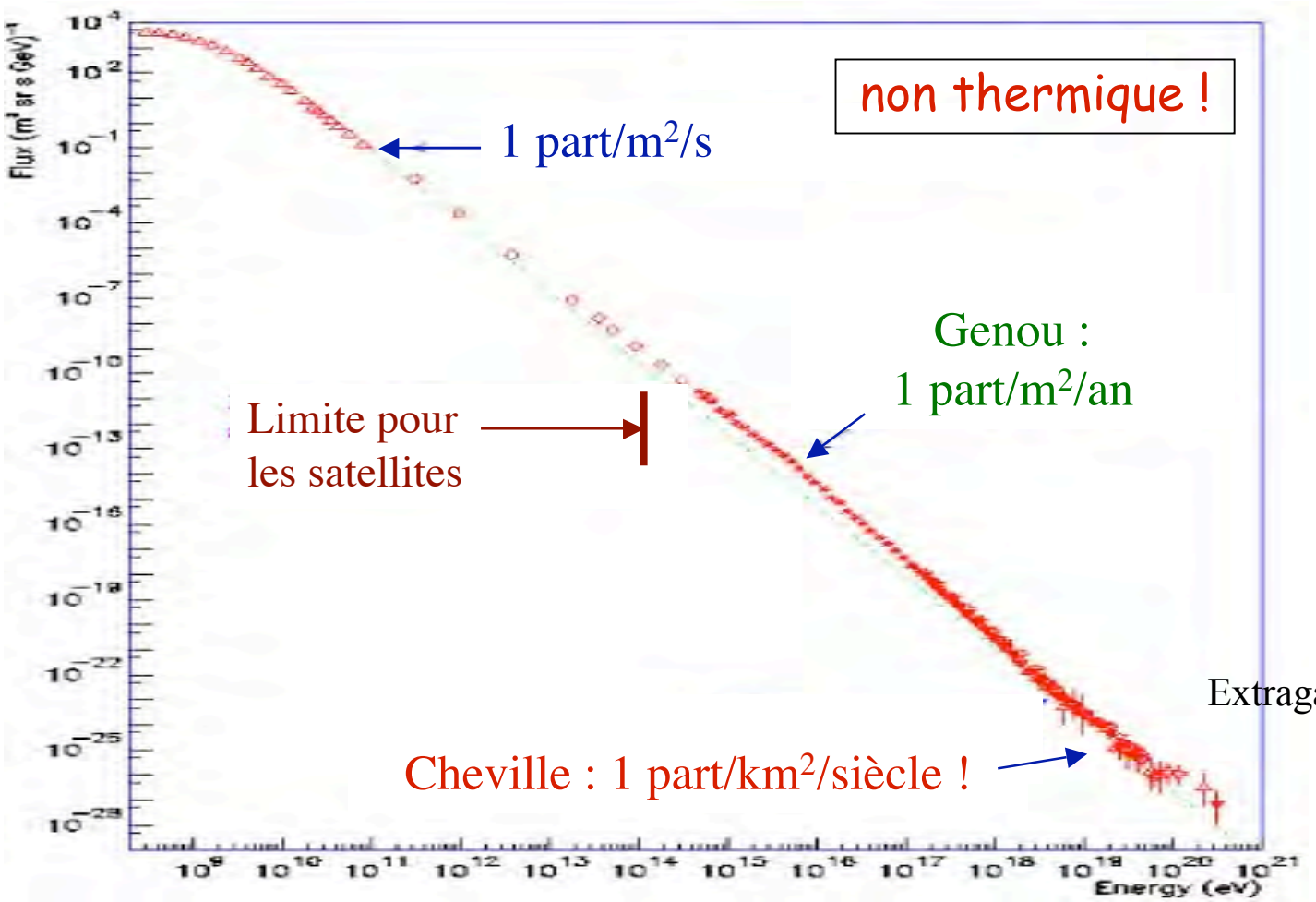
100 MeV

10^{21} eV

Spectre d'énergie

de 1 cheveu à 10 milliards d'années lumière !

32 ordres de grandeur !



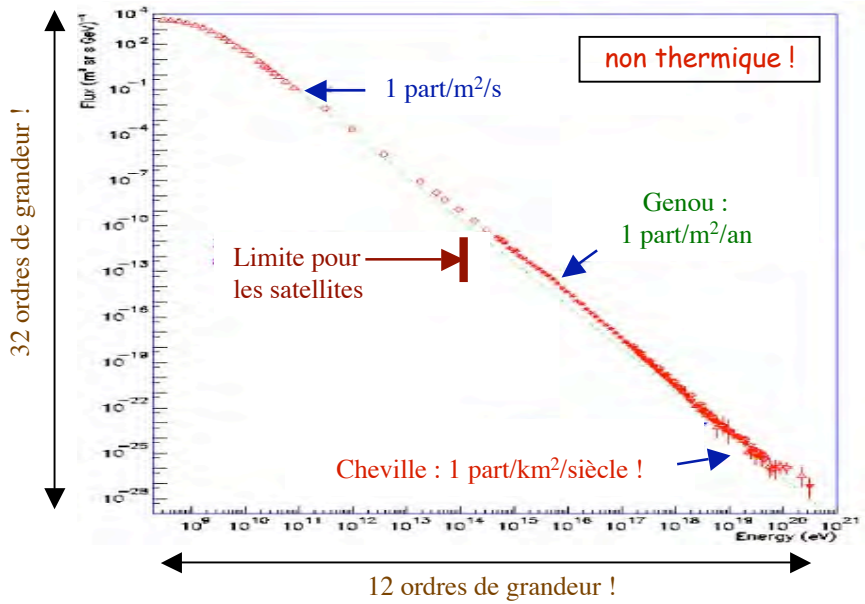
12 ordres de grandeur !

de 1 cheveu à 100 000 km !

Limite à haute énergie ?

Où s'arrête le spectre ?

Pourra-t-on faire de l'astronomie proton ?

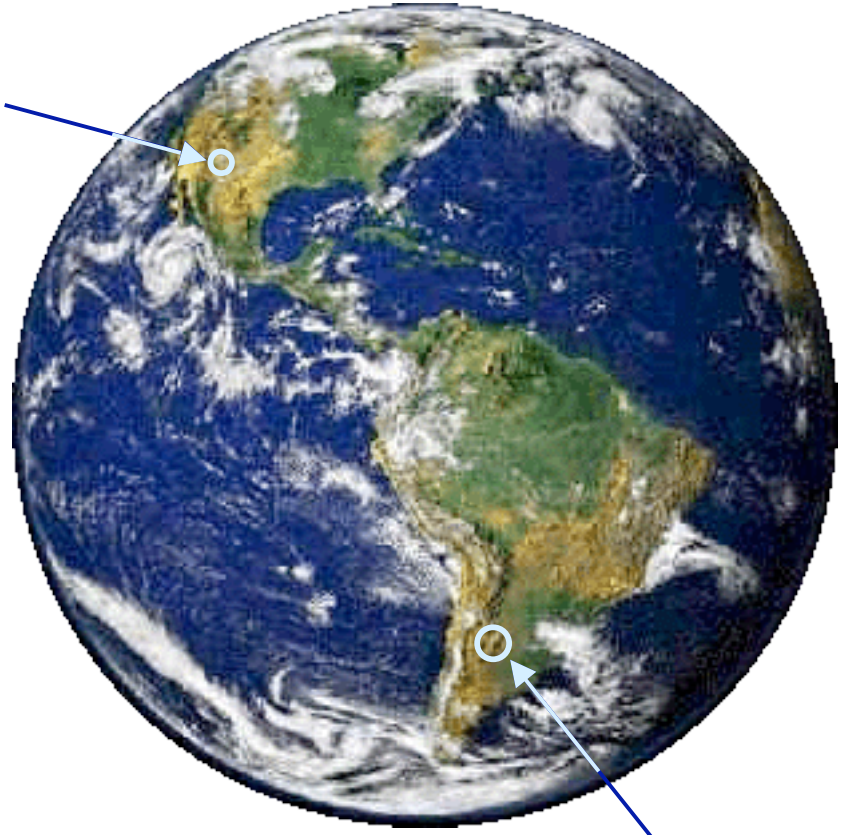


Énergies extraordinaires, permettant de tester la physique à des énergies inaccessibles sur Terre !


CR detection at the
Pierre Auger Observatory
¡ Bienvenida en la tierra cósmica !

The Pierre Auger Observatory

Northern site
20 000 km^2
(still to be funded)



63 Institutions
369 Scientists

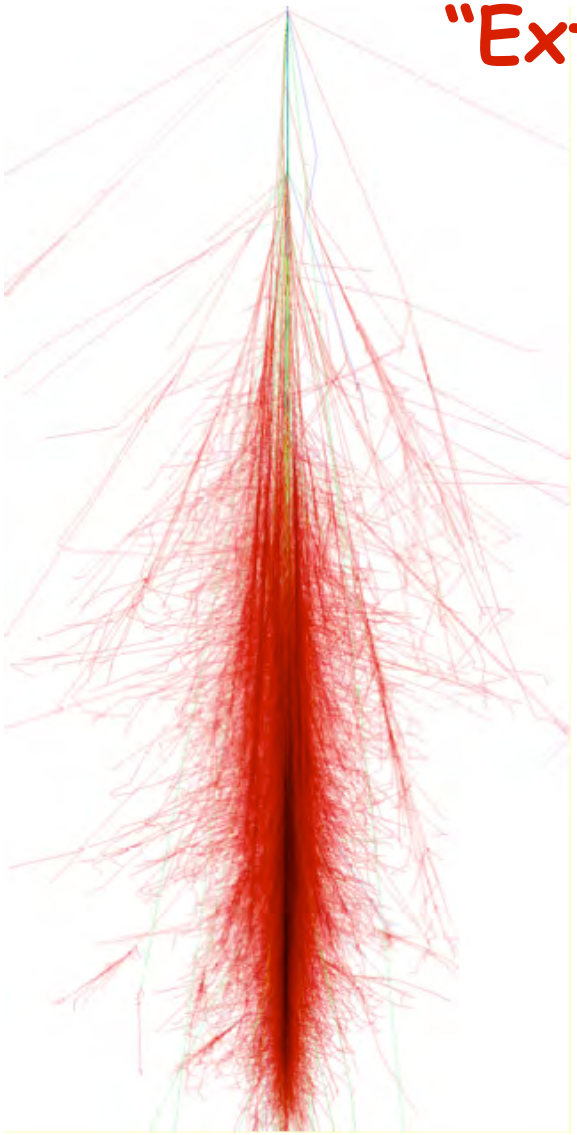
- ***Participating Countries***

- Argentina
- Australia
- Brazil
- Czech Republic
- France (+ Vietnam)
- Germany
- Italy
- Mexico (+ Bolivia)
- Netherlands
- Poland
- Portugal
- Slovenia
- Spain
- United Kingdom
- USA

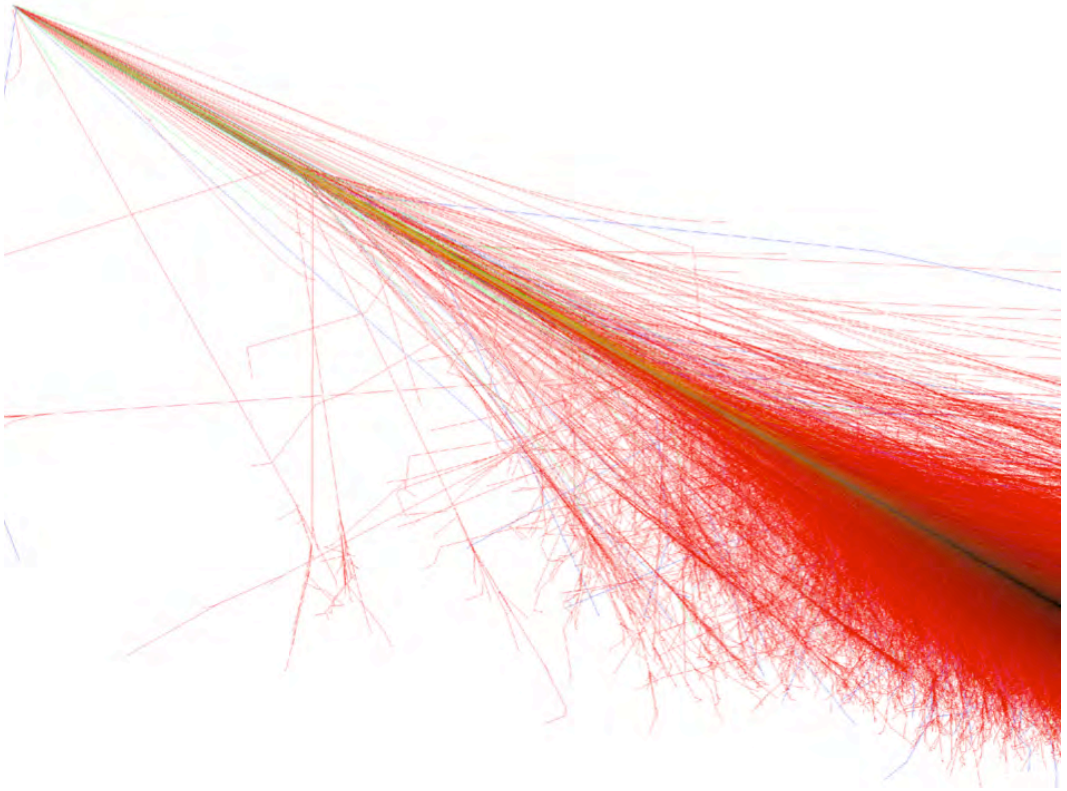
3 000 km^2

Southern site

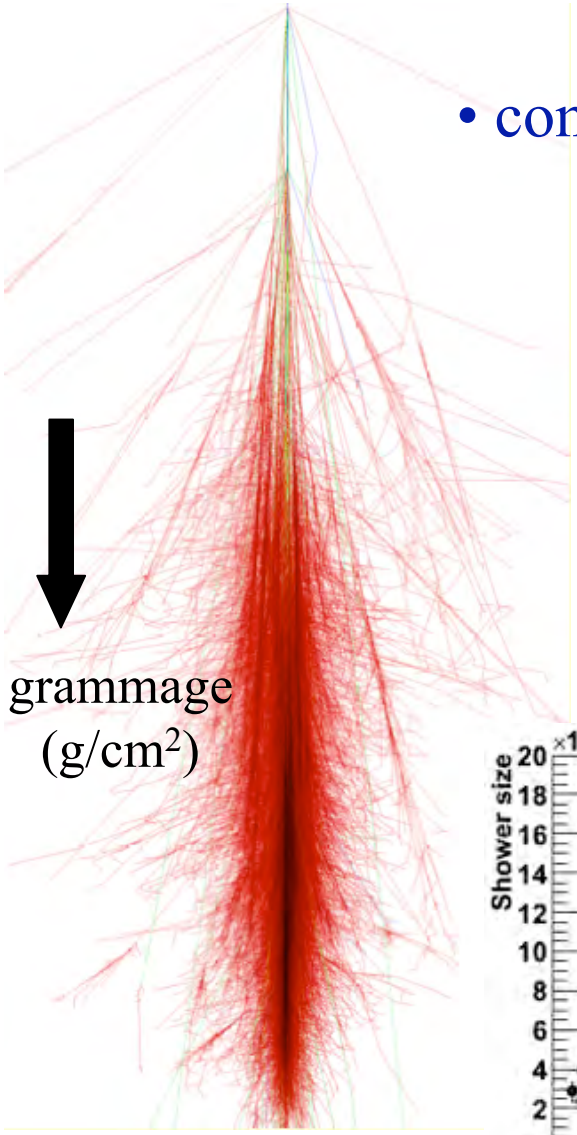
Indirect CR detection through "Extensive Air Showers"



- Induced by cosmic rays in the atmosphere



High-energy CR detection



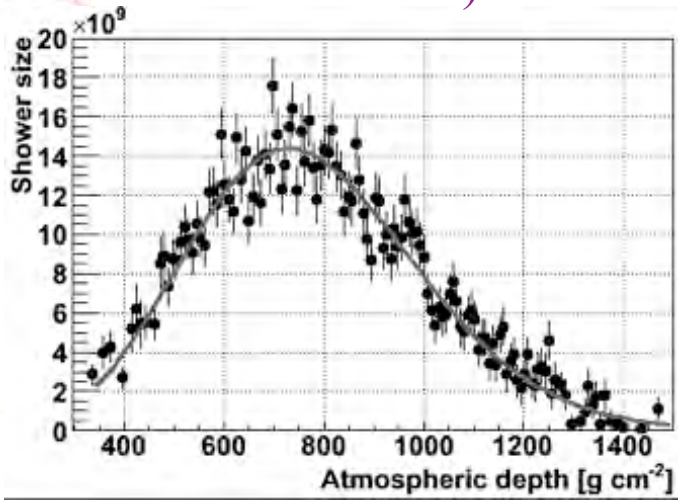
grammage
(g/cm^2)

- comparison of observables with MC simulations

Fluorescence photons from atmosphere

→ longitudinal shower development

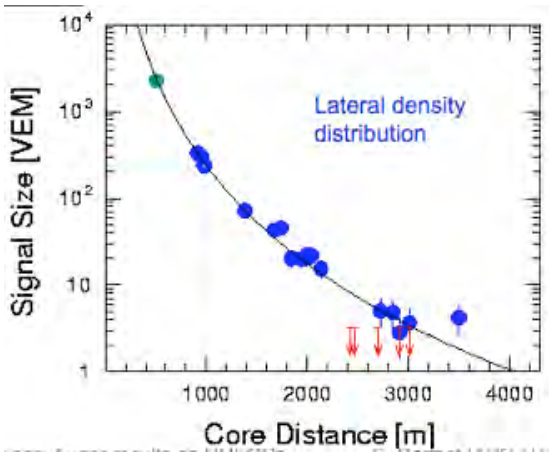
(sensible to EM sub-shower)



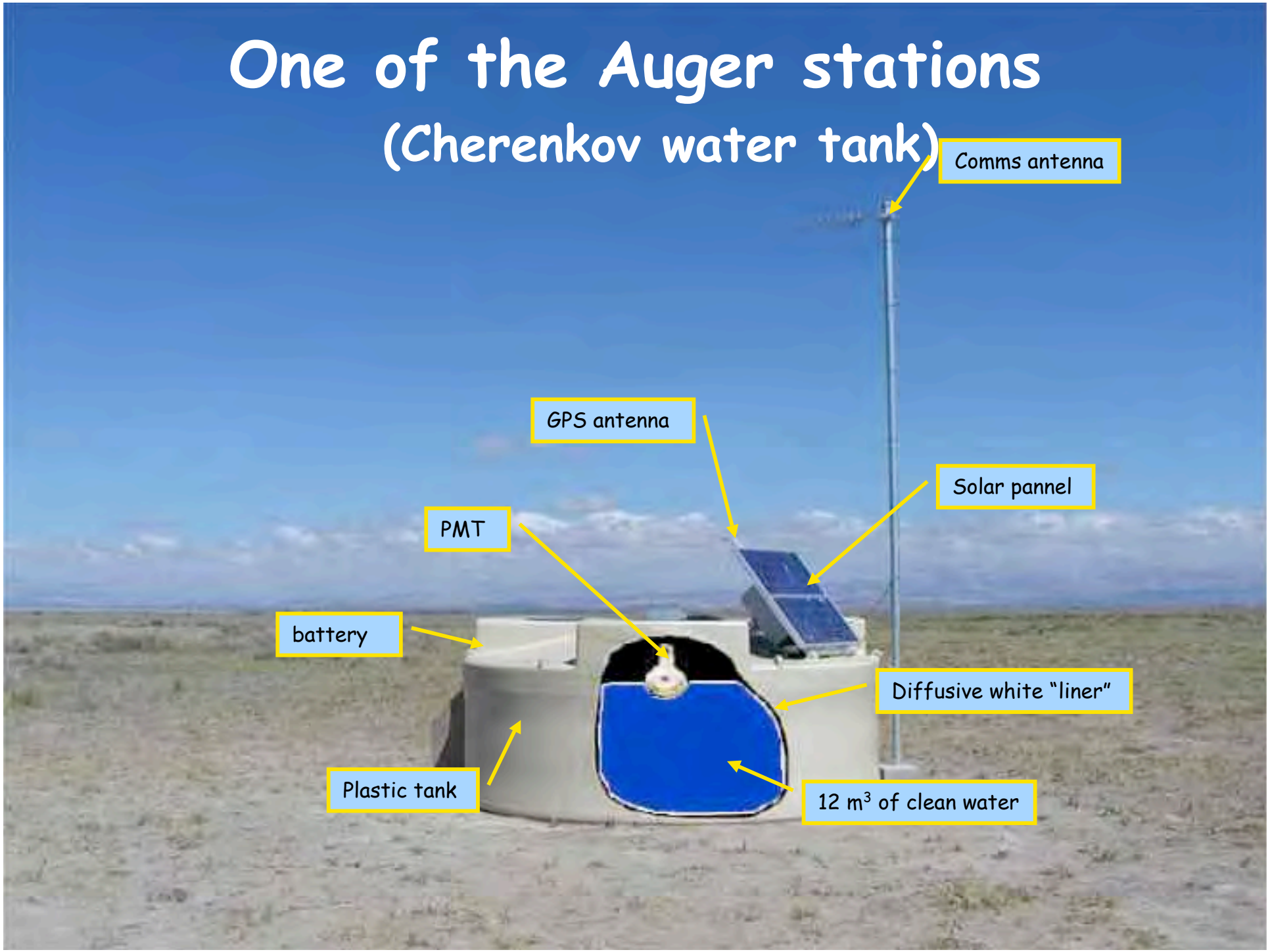
Density of shower particles on the ground

→ lateral distribution

(sensible to EM and hadronic sub-showers)



One of the Auger stations
(Cherenkov water tank)



Hexagonal array (1.5 km spacing, 3000 km^2)

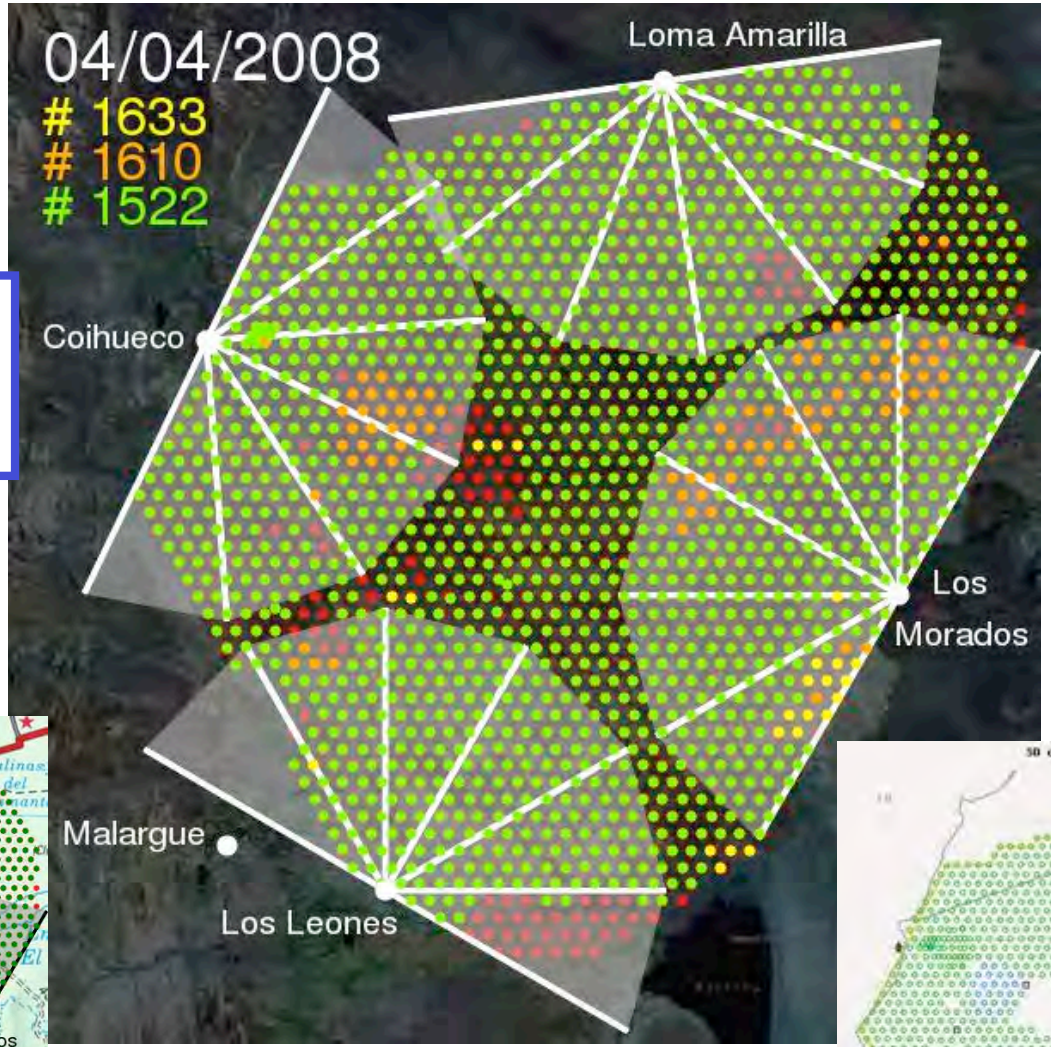
Déployer des cuves sur la pampa…

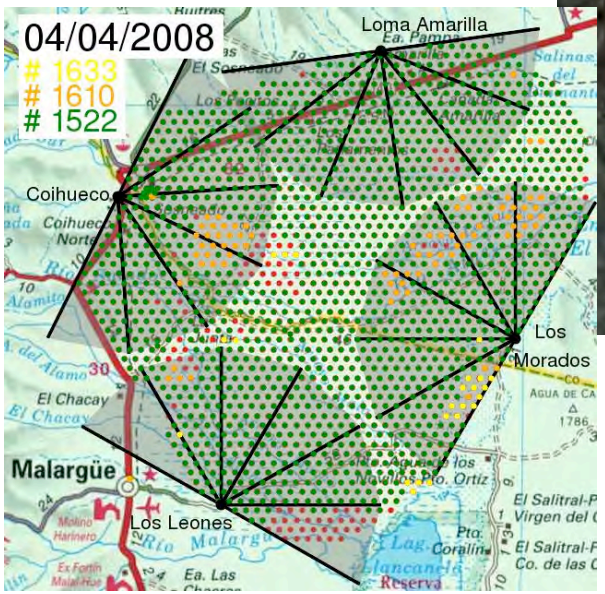
…pas si simple!

SD deployment (initial goal: 1600 tanks)

21st April 2008

1637 deployed
1610 filled with water
1566 with electronics



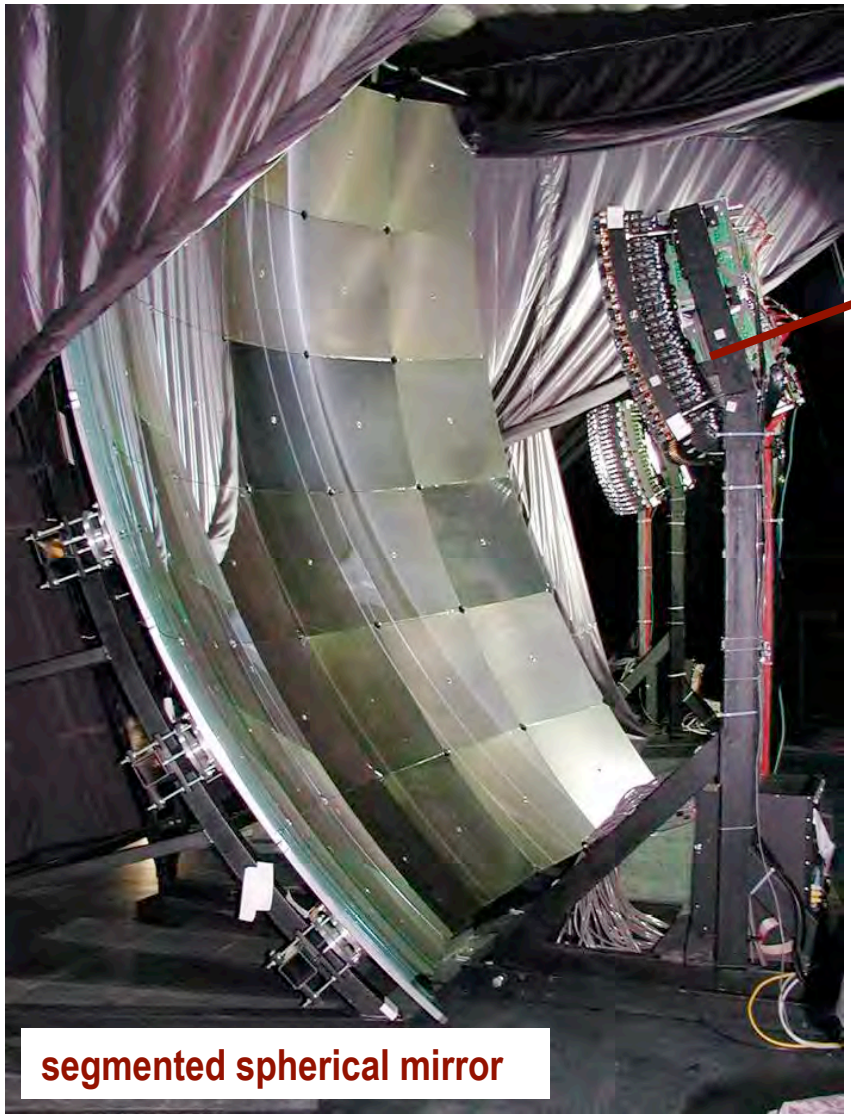


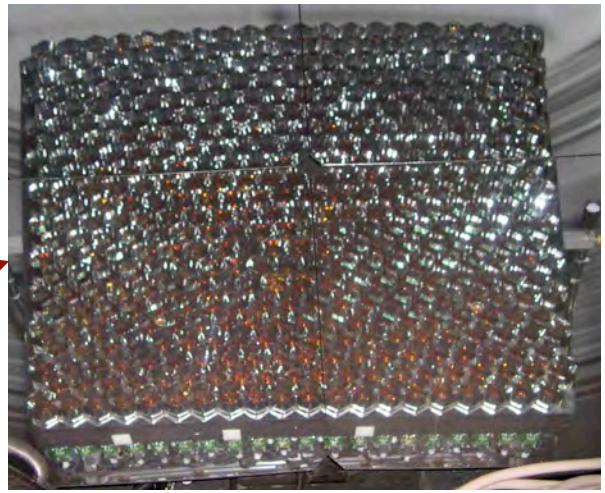
Aerial view of Los Leones fluorescence station

4 times 6 telescopes overlooking the site

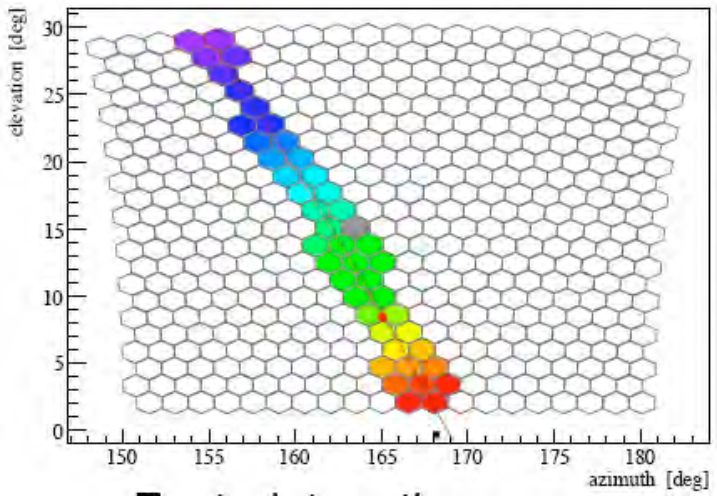
Completed!

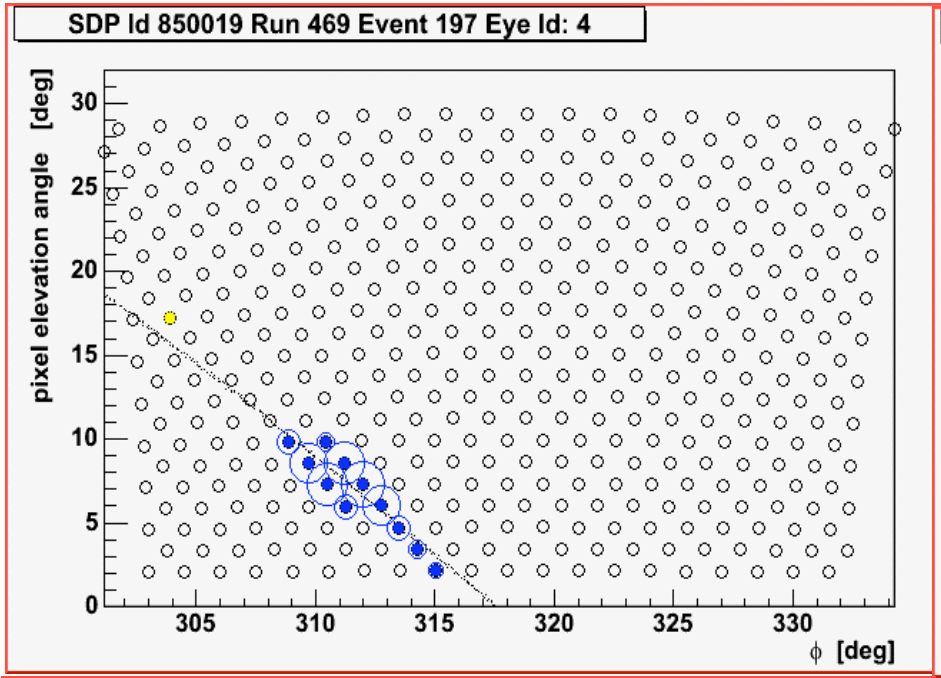
One of the fluorescence eyes

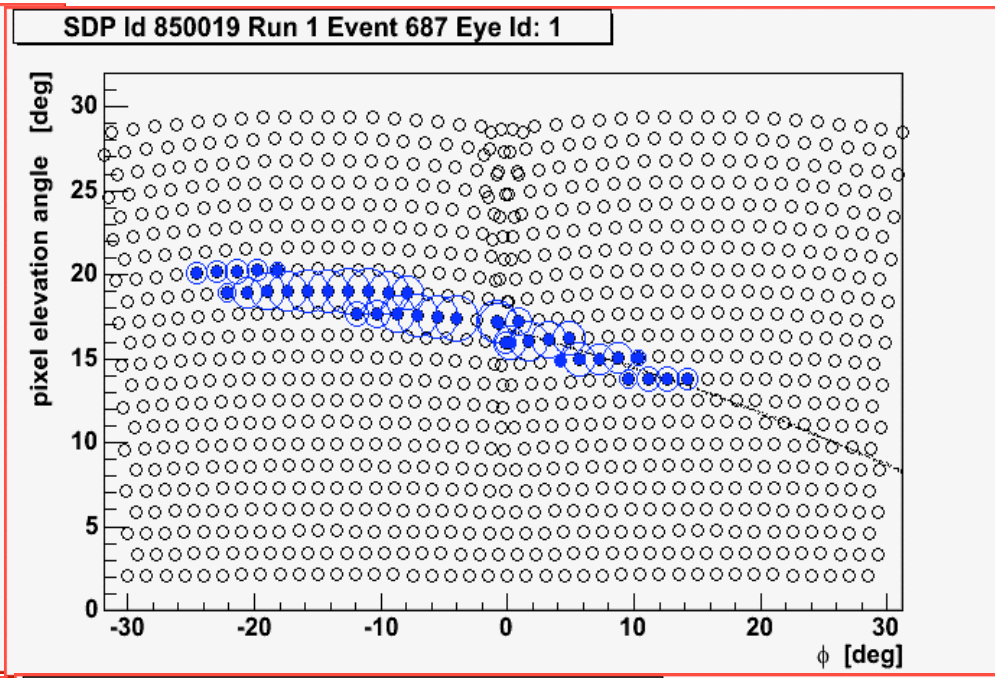


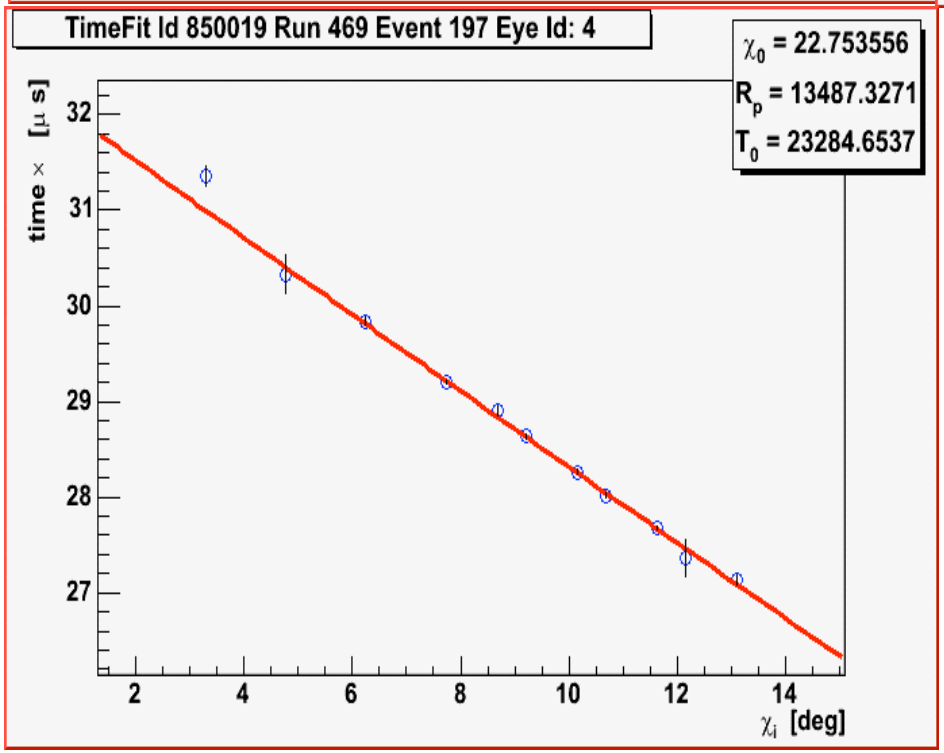


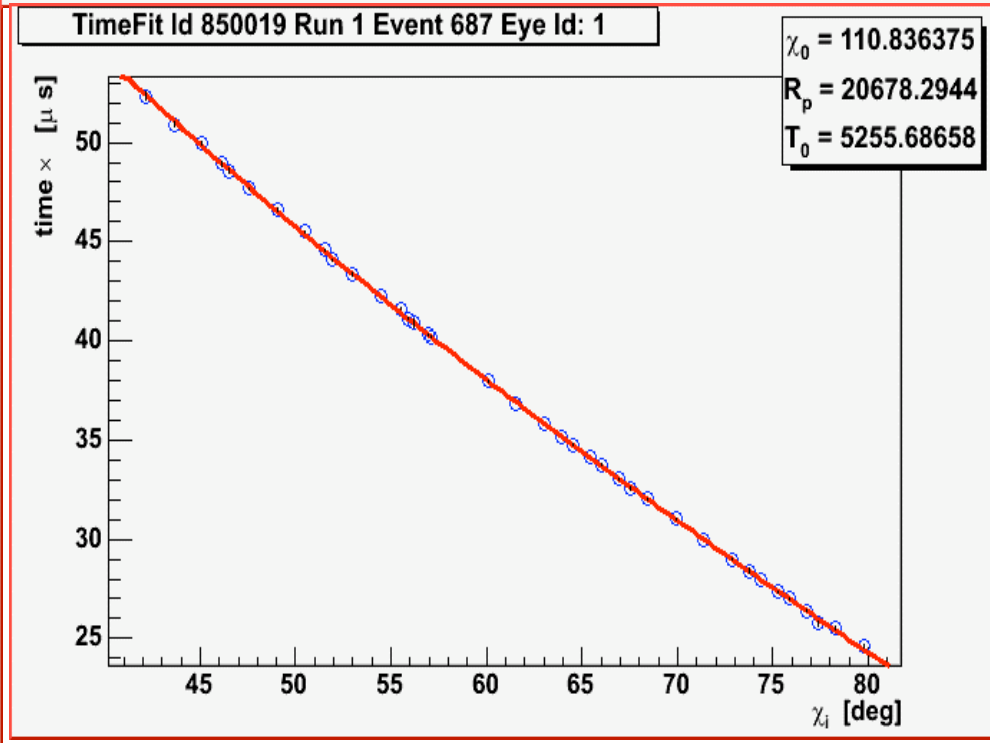
440 PMT camera 1.5° per pixel



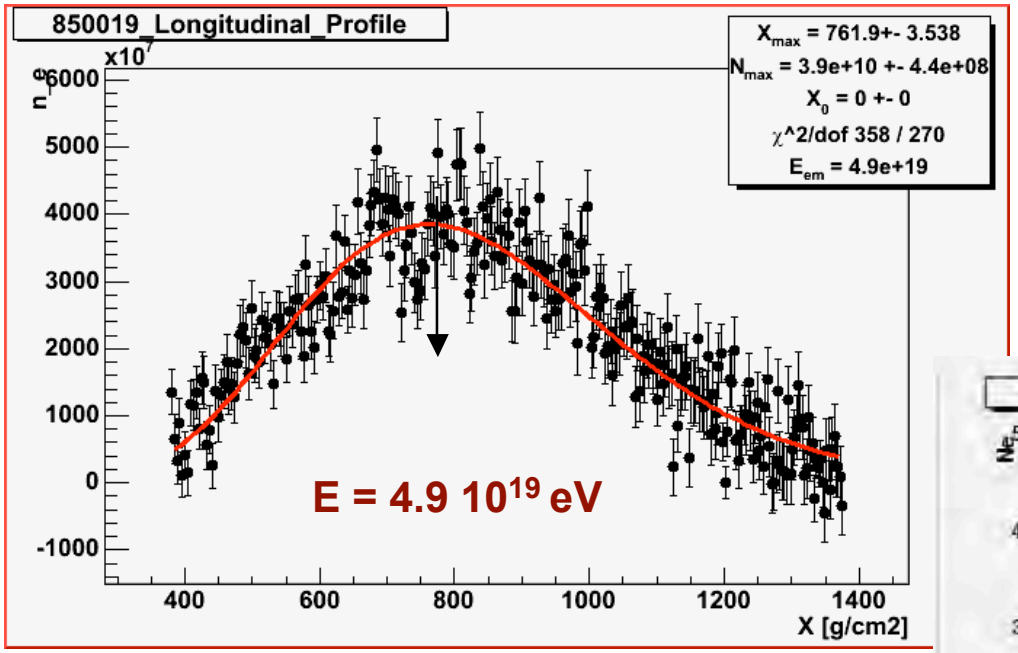

SDP Id 850019 Run 469 Event 197 Eye Id: 4
pixel elevation angle [deg]
ϕ [deg]


SDP Id 850019 Run 1 Event 687 Eye Id: 1
pixel elevation angle [deg]
ϕ [deg]

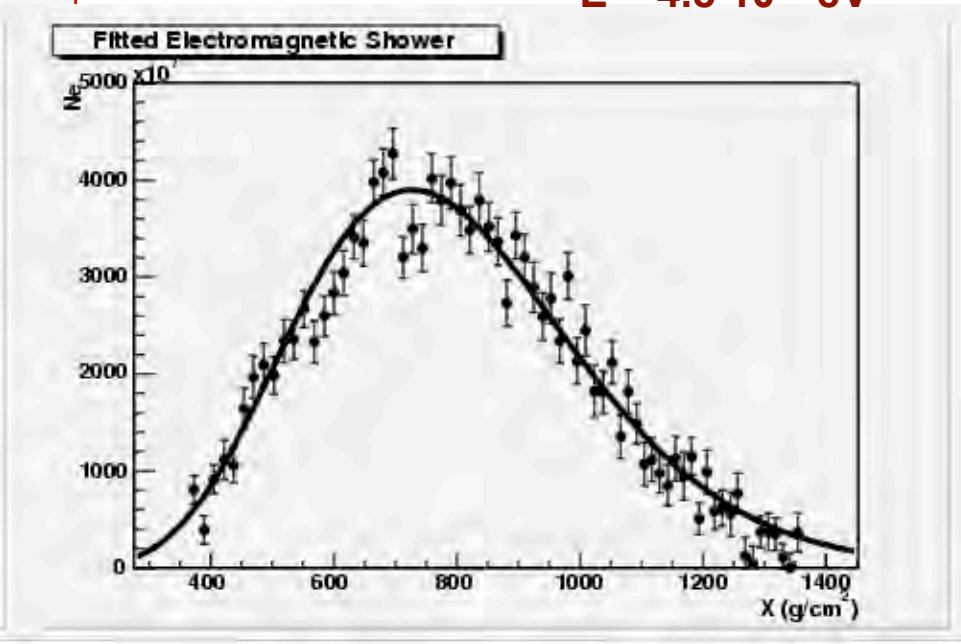

TimeFit Id 850019 Run 469 Event 197 Eye Id: 4
χ0 = 22.753556
Rp = 13487.3271
T0 = 23284.6537
time × [μ s]
χi [deg]

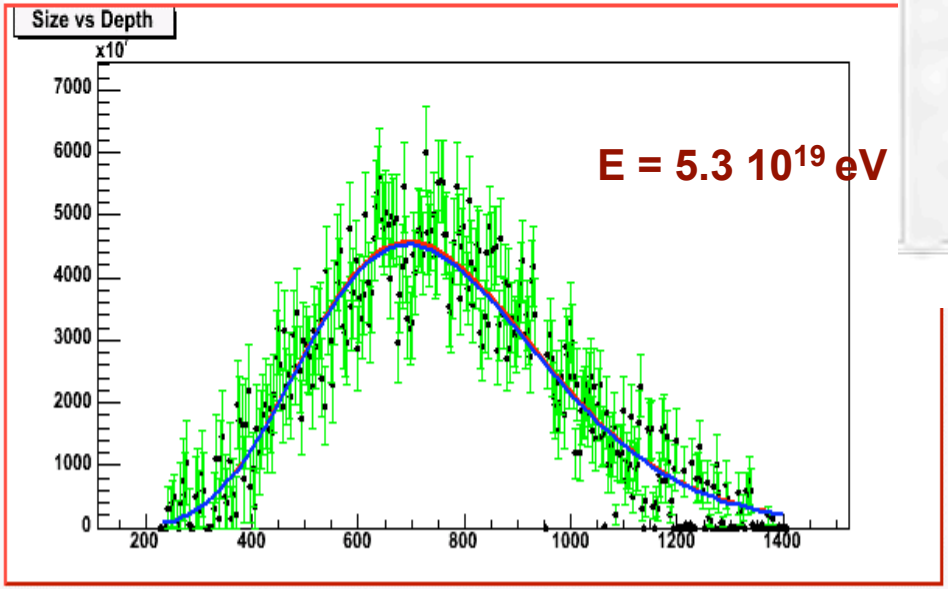

TimeFit Id 850019 Run 1 Event 687 Eye Id: 1
χ0 = 110.836375
Rp = 20678.2944
T0 = 5255.68658
time × [μ s]
χi [deg]

Independent analyses of stereo events



E = 4.8 10^{19} eV

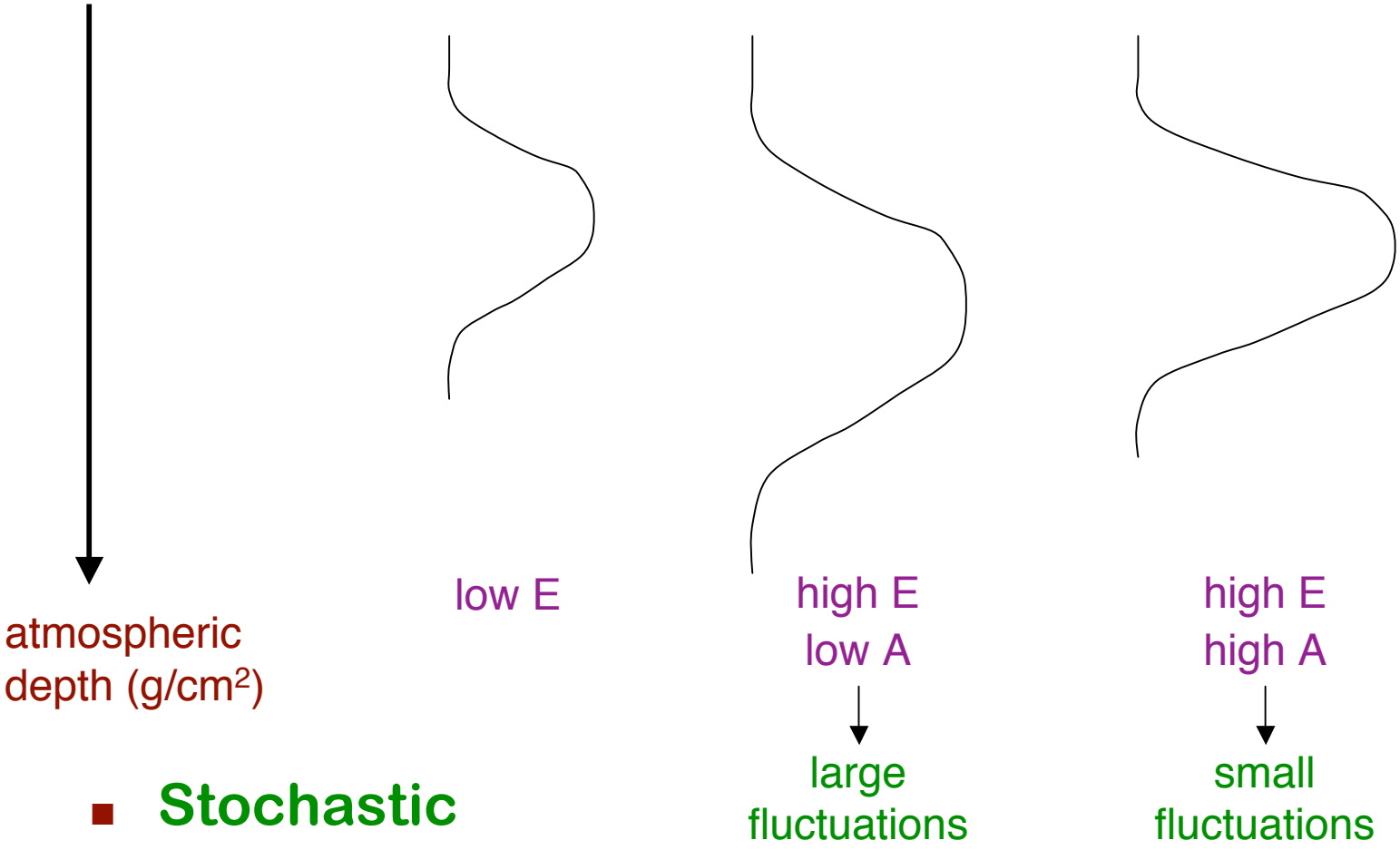




E_{em} calculated by fitting a GH profile and integrating

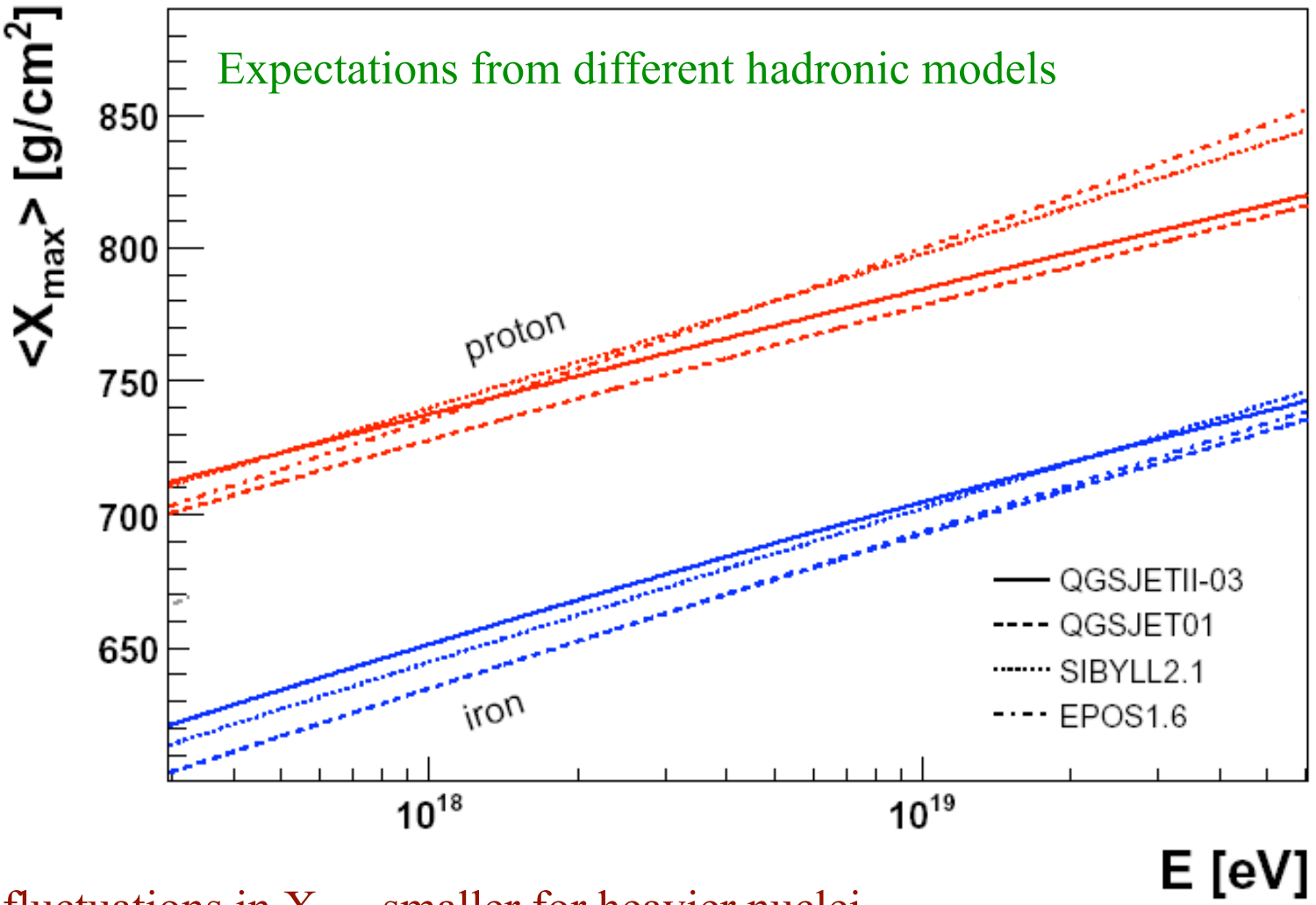
Composition-sensitive observable

- **Depth of shower maximum development: X_{max}**



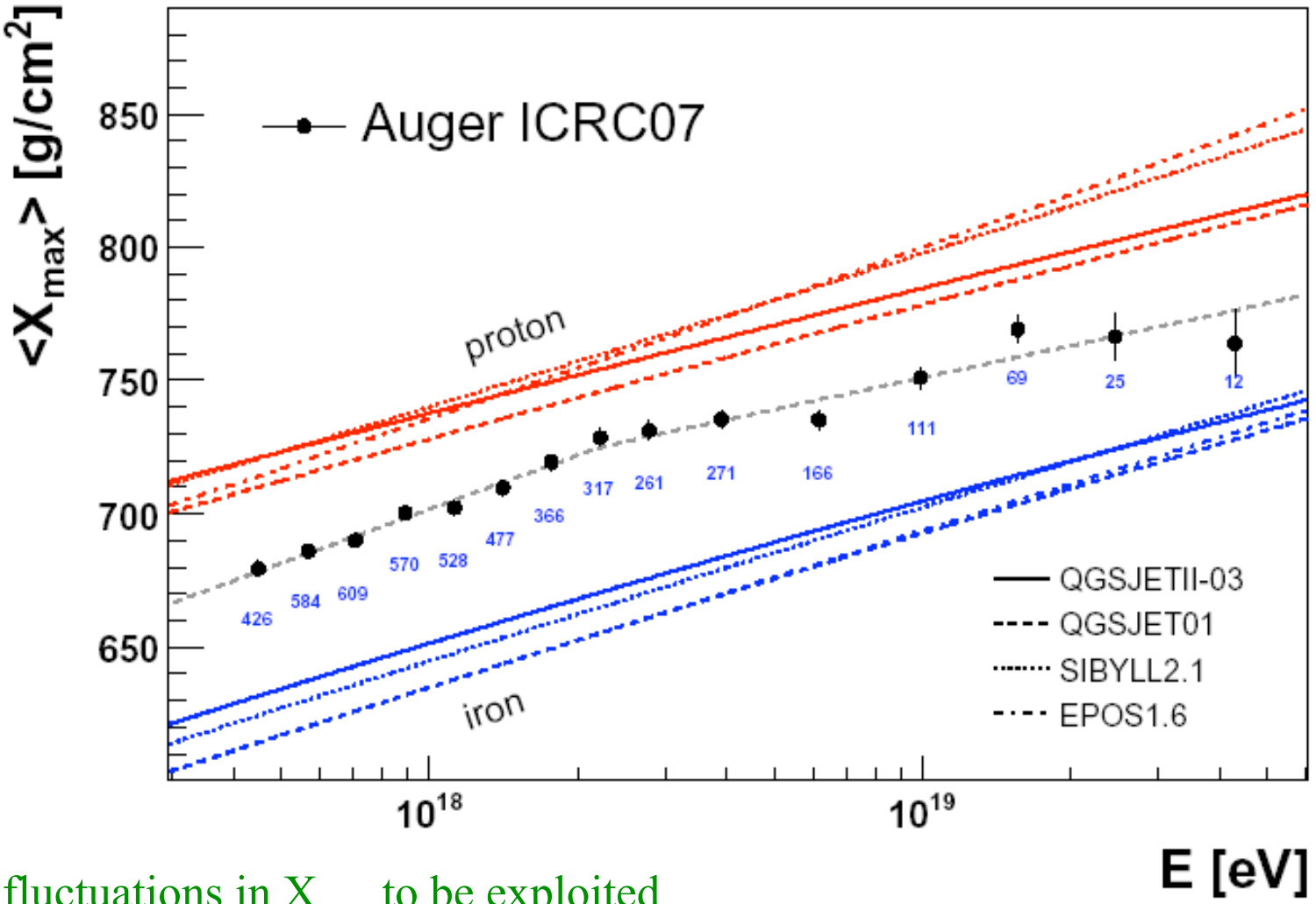
- **Stochastic process**

Atmospheric depth of shower maximum



+ fluctuations in X_{max} smaller for heavier nuclei

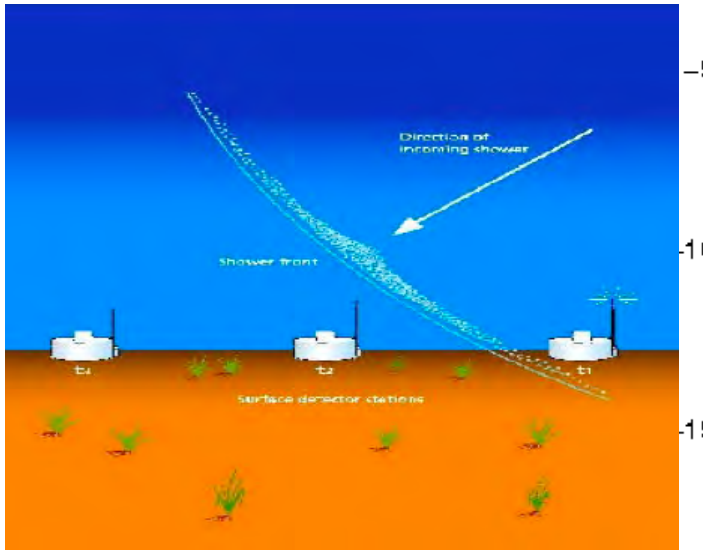
Shower maximum
measured over 2 decades in E



+ fluctuations in X_{max} to be exploited

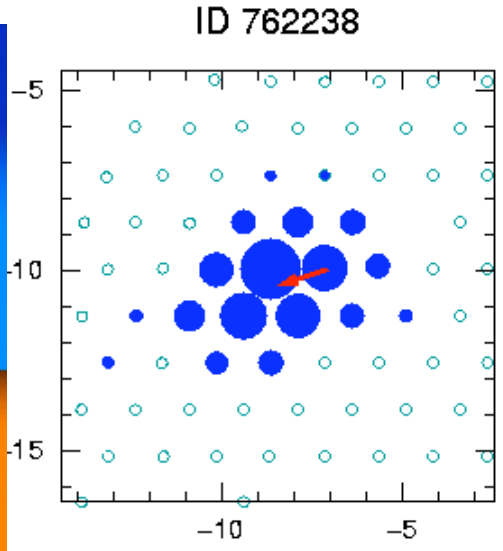
Energy reconstruction with surface detector

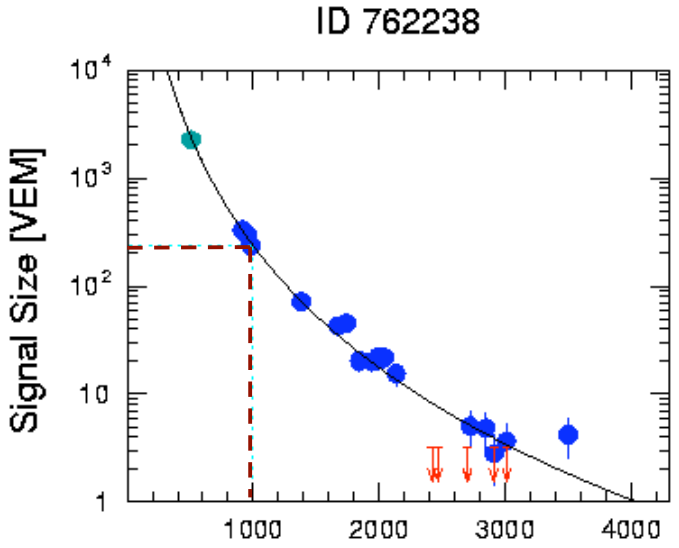
- **SD energy estimator:** interpolated signal in a tank at 1000 meters and 38°

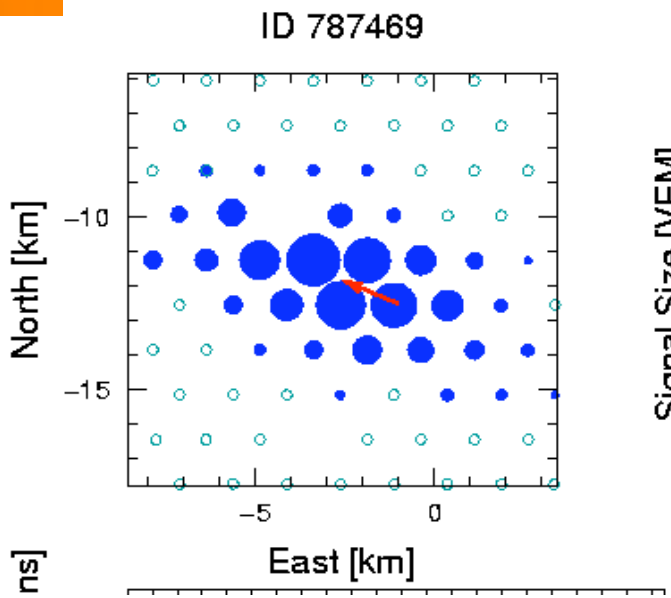


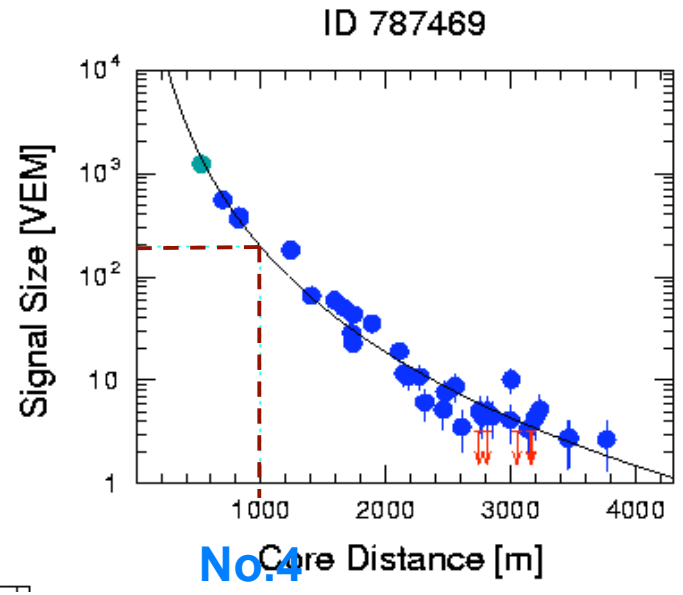
timing information
available for triangulation

geometry reconstruction
(arrival direction)

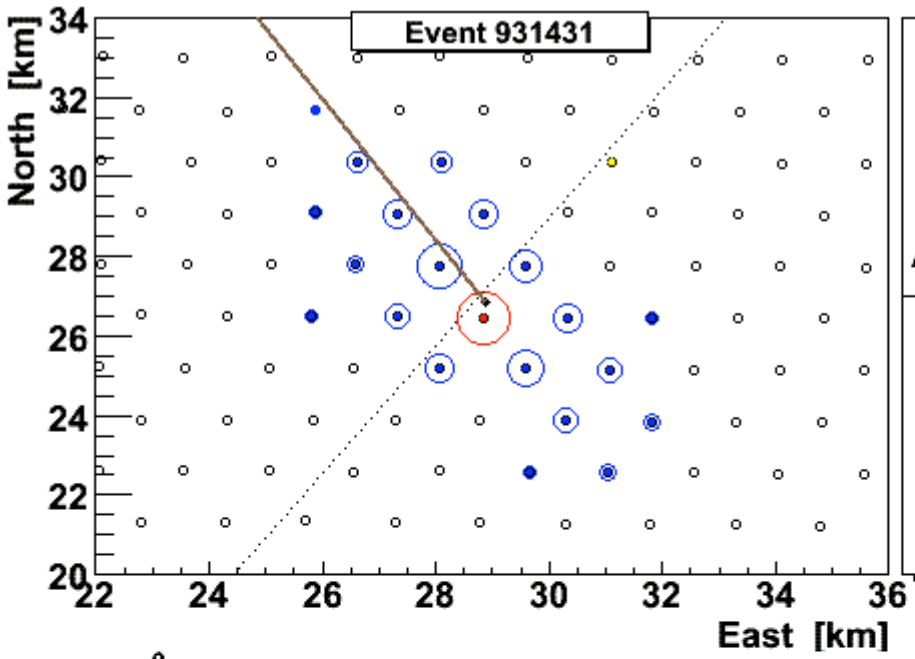








Example of a Hybrid Event



Core location

Easting 468693 ± 59

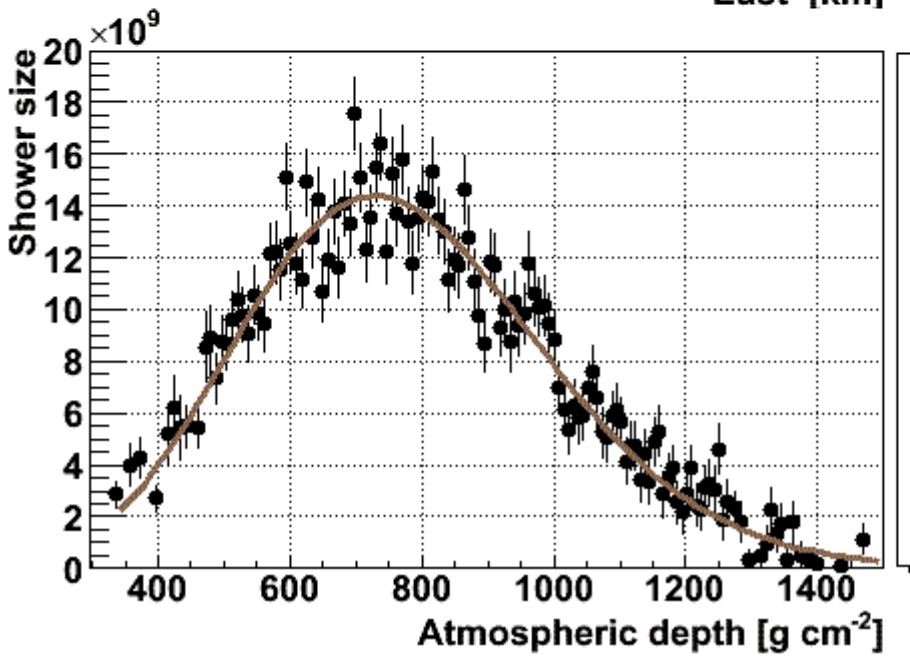
Northing 6087022 ± 80

Altitude = 1390 m a.s.l.

Shower Axis

$\theta = (62.3 \pm 0.2)^{\circ}$

$\phi = (119.7 \pm 0.1)^{\circ}$



Energy Estimate:

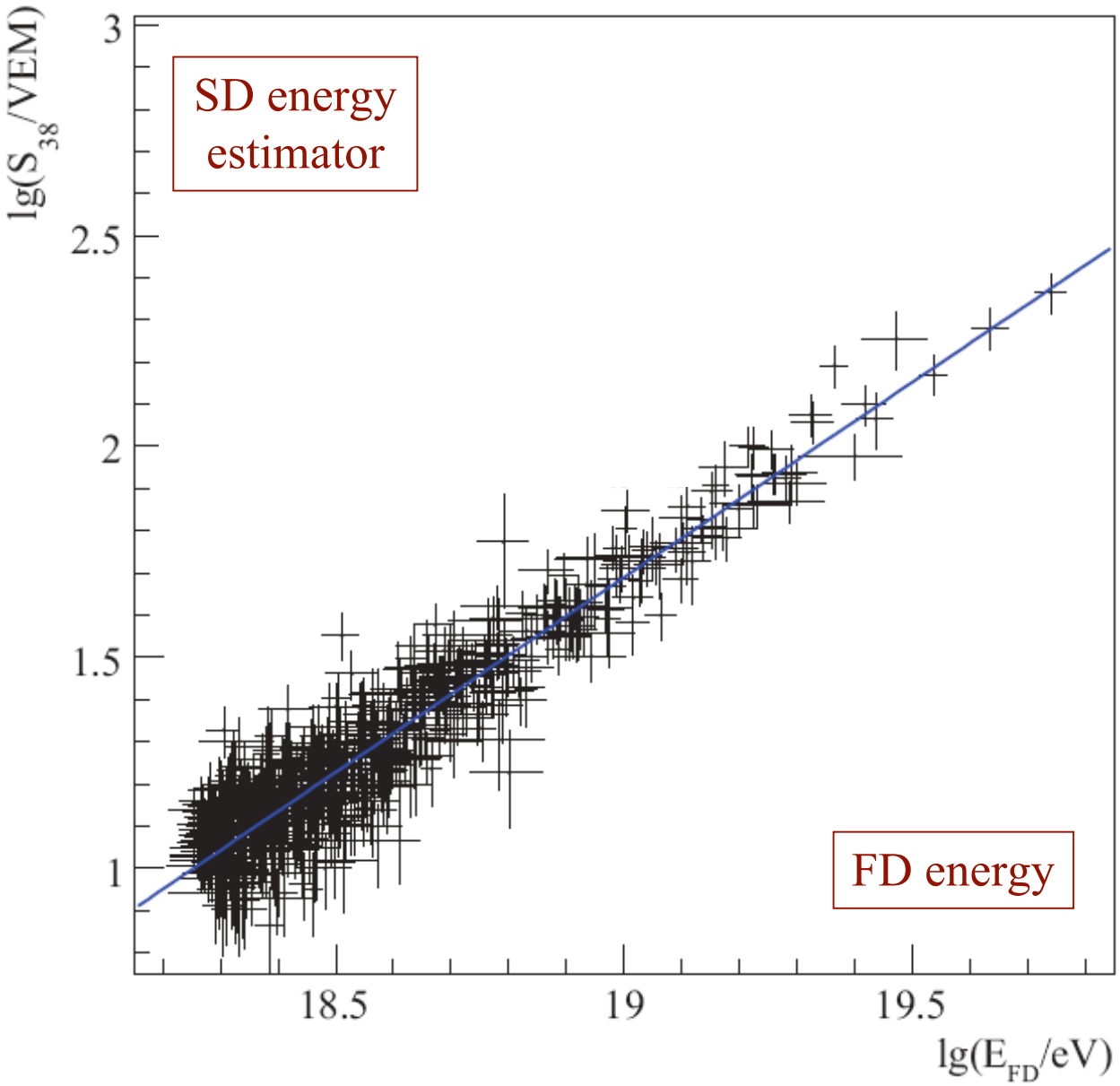
$X_{max} = (728 \pm 20)$ g cm^{-2}

χ^2/dof = 258 / 134

$E_{em} = (21 \pm 5)$ EeV

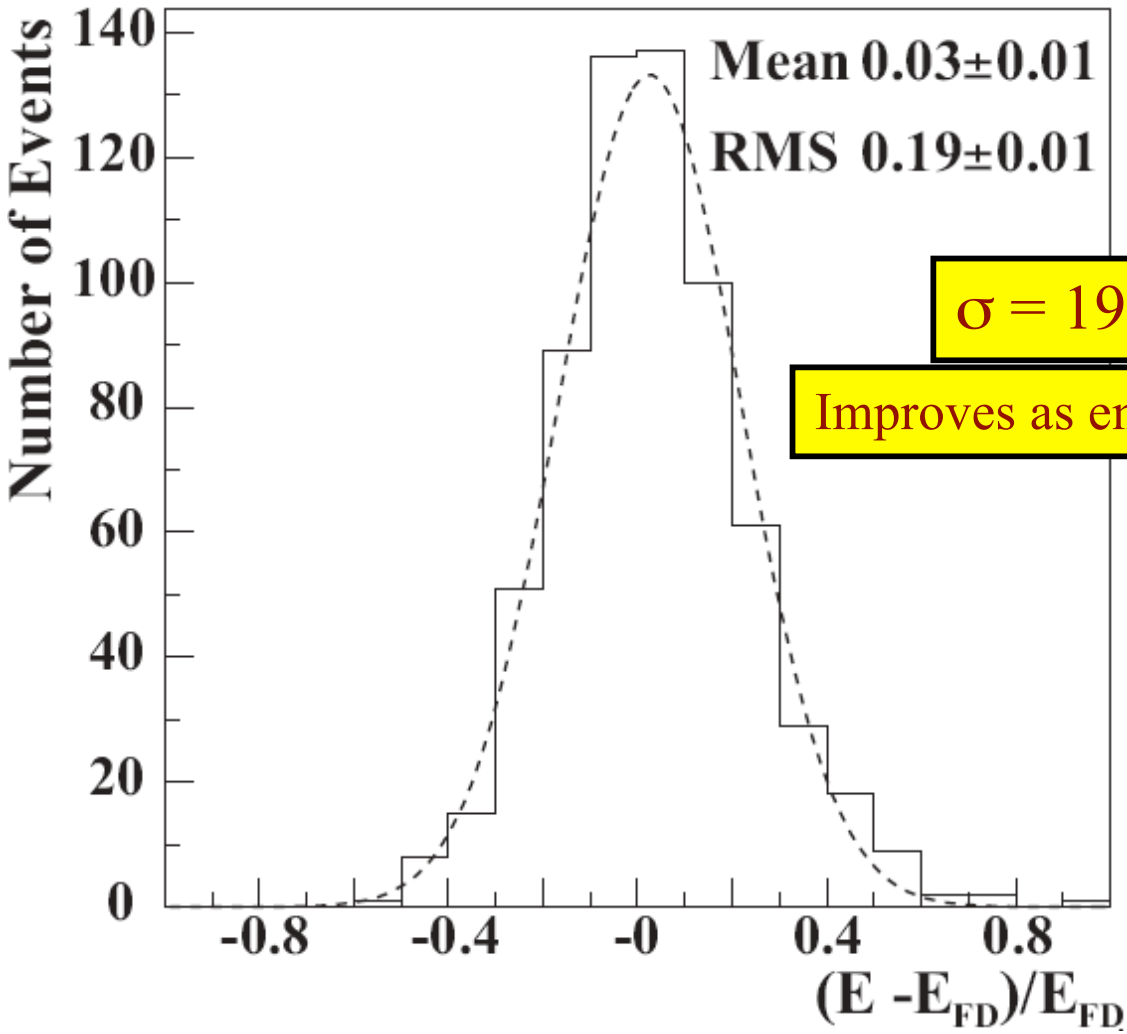
$E_{tot} = (23 \pm 6)$ EeV

Cross-calibration of the detectors



Cross-calibration of the detectors

Fractional dispersion of FD/SD energy estimates

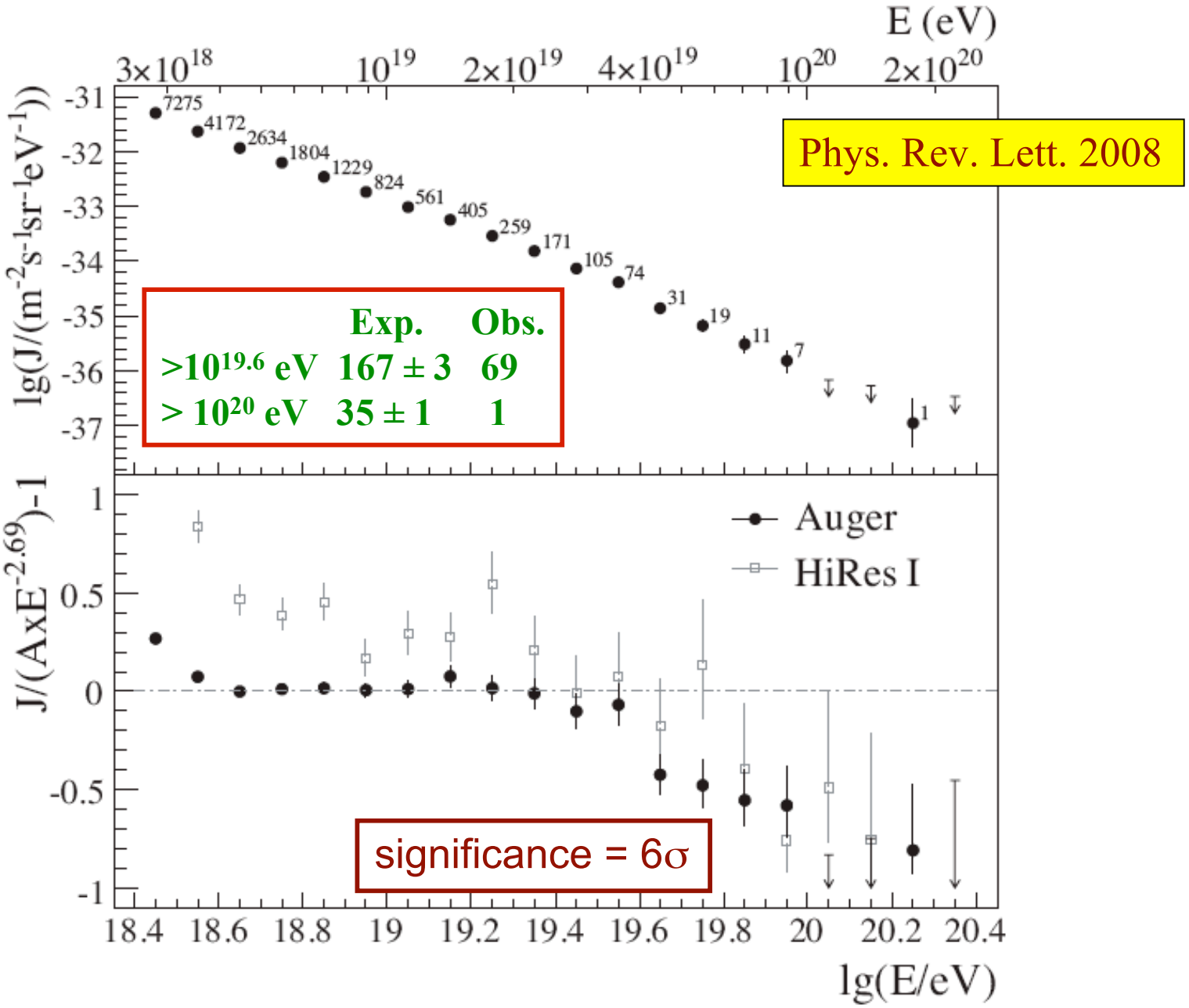


σ = 19%

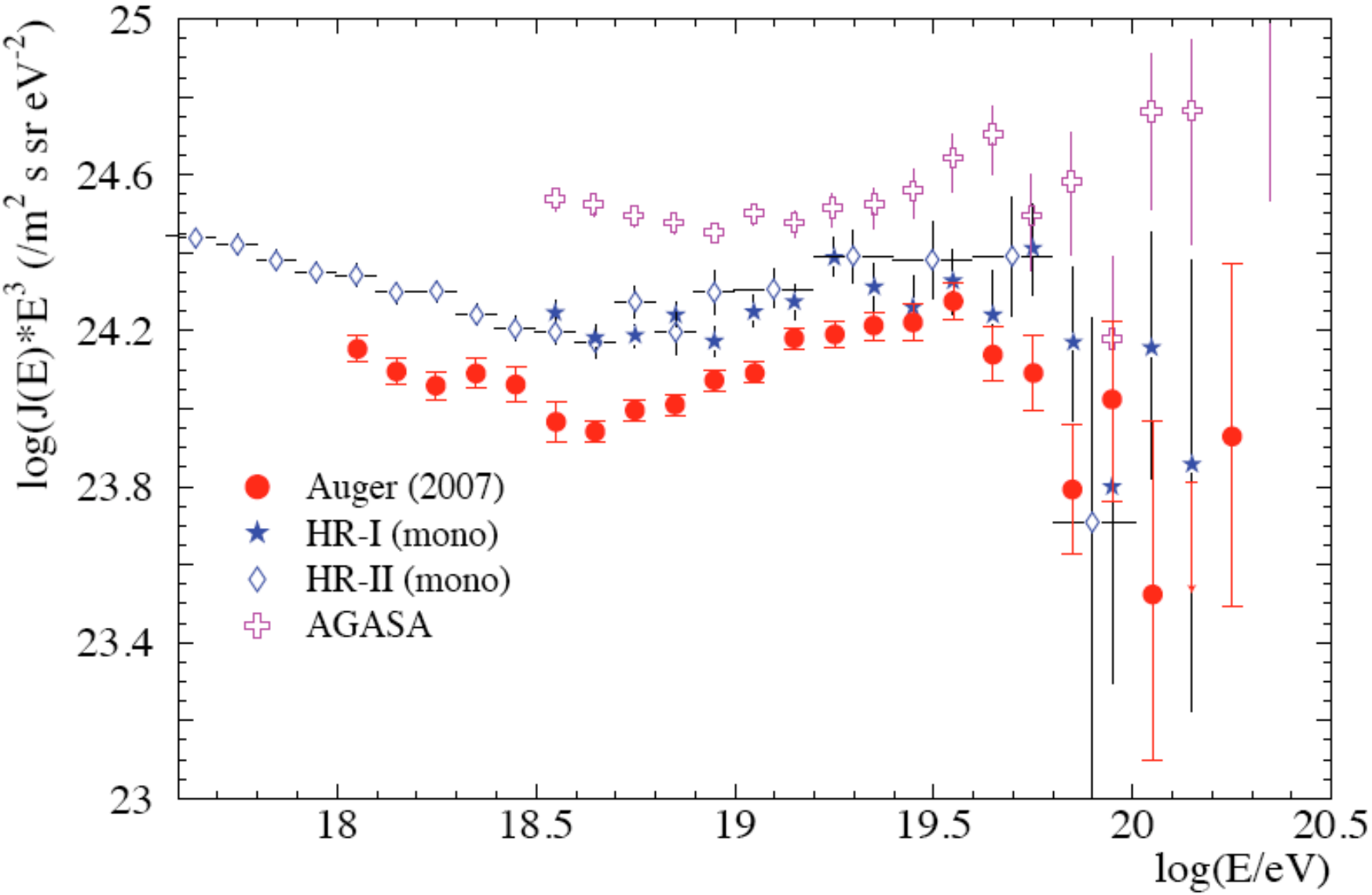
Improves as energy increases!

Very good estimator !

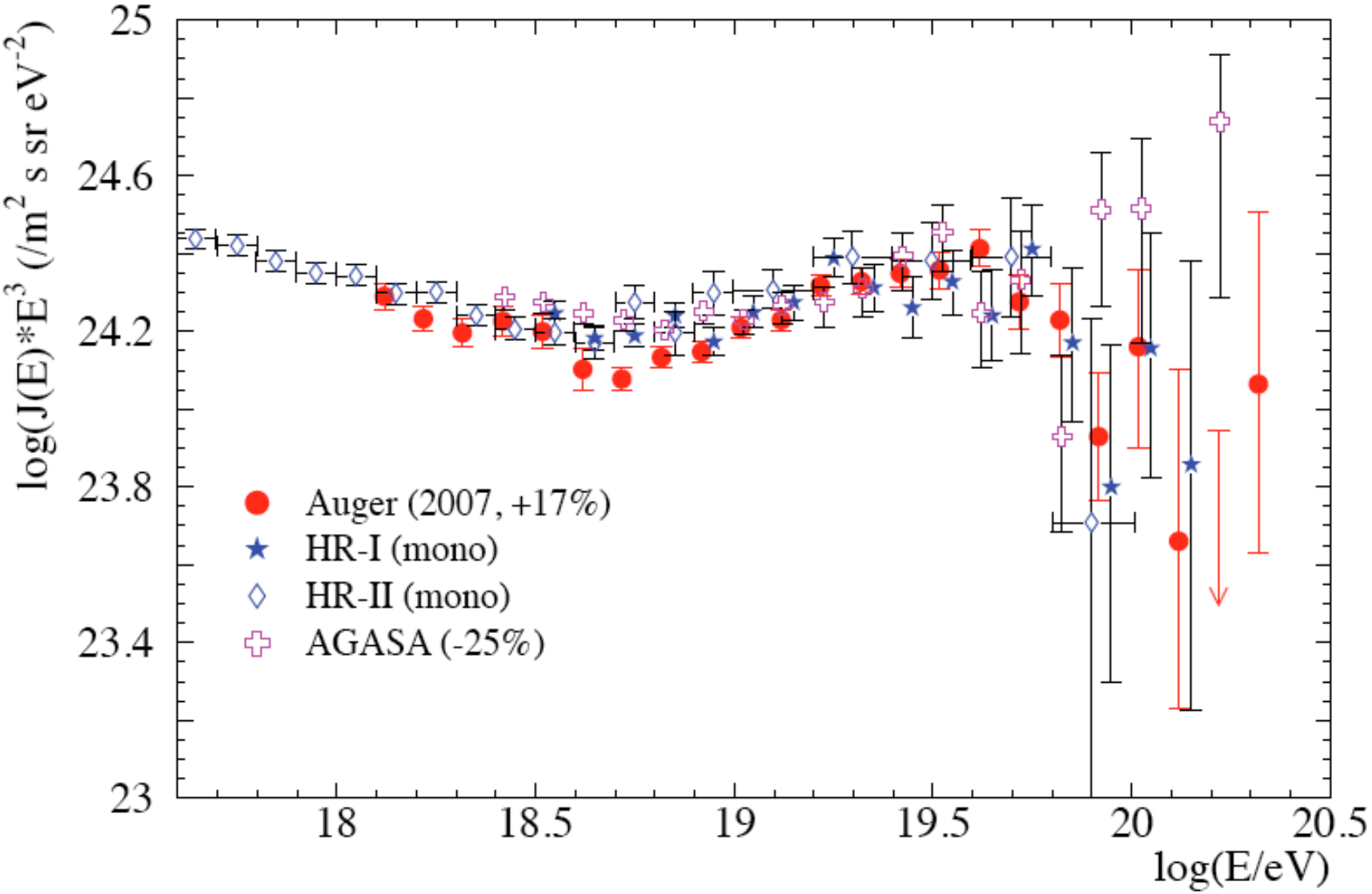
Energy spectrum from SD showers with $\theta \leq 60°$



Energy spectrum



Energy spectrum



Auger anisotropy results

- Angular resolution of ~1°: good enough!
- No large-scale signal (dipole) at any energy above 1 EeV

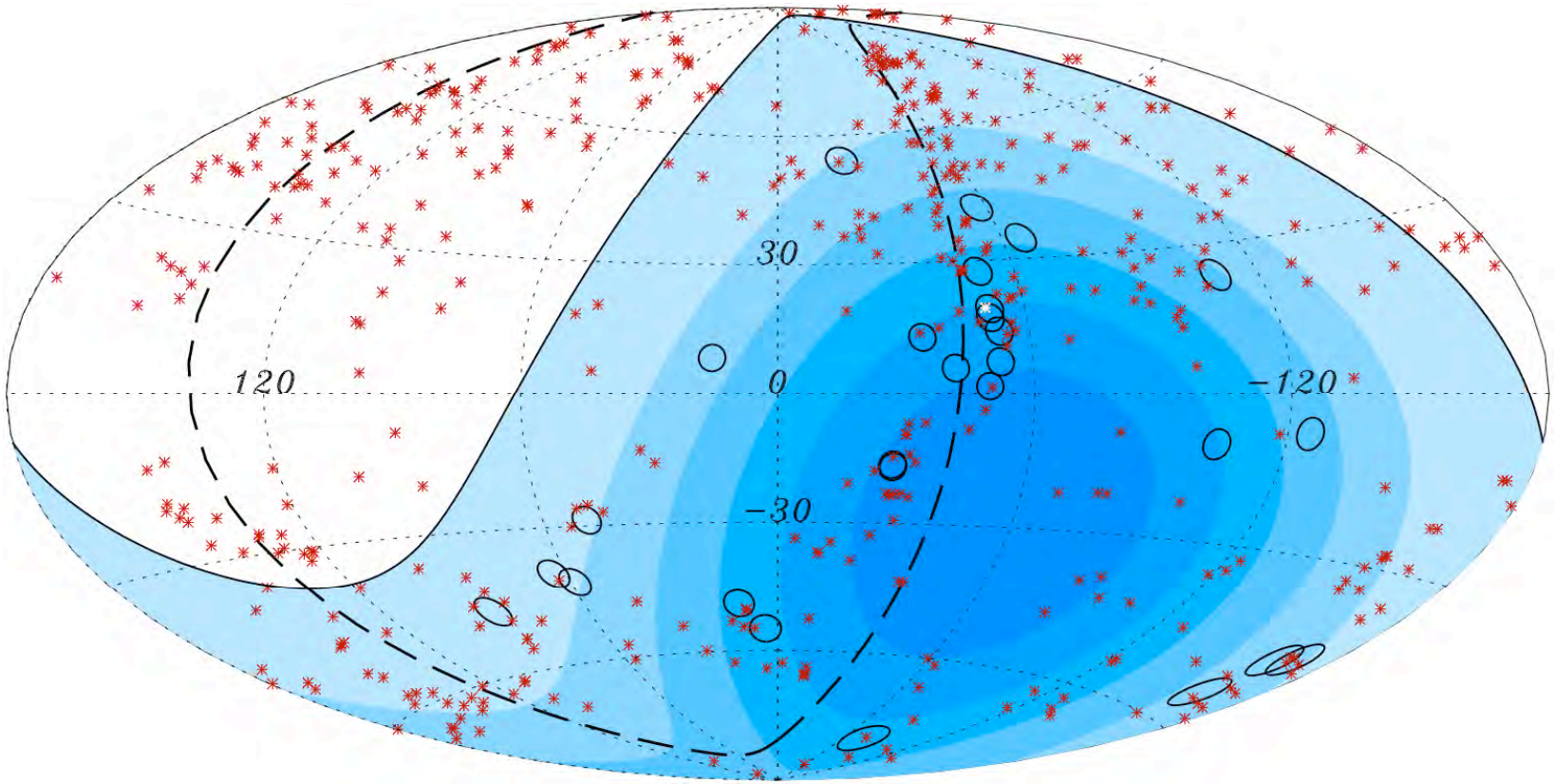
  e.g. $\alpha < 0.7\%$ for $1 \text{ EeV} \leq E \leq 3 \text{ EeV}$
- No significant excess emission from Galactic center
- No signal from BL-Lacs as possibly seen by HiRes

⟹ none of the previous reports have been confirmed…

Auger main anisotropy result

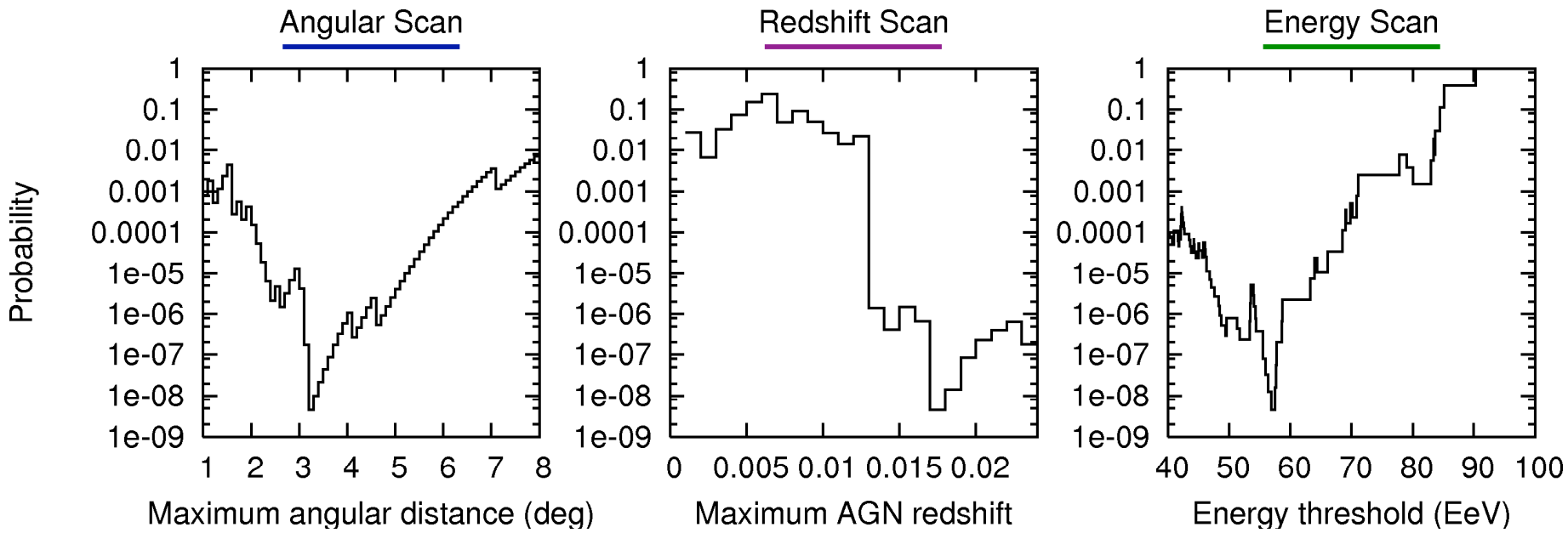
- Highest energy cosmic rays have an anisotropic distribution!
- First evidence that cosmic-ray astronomy is indeed possible!
- Correlation with nearby matter distribution
  - seen through an AGN catalog
- Opening of a new era:
  - Study of particle acceleration in high-energy astrophysical sources
  - Multi-messenger study of sources
  - High-energy physics!

Auger main anisotropy result



Auger main anisotropy result

3 free parameters in the definition of the correlation



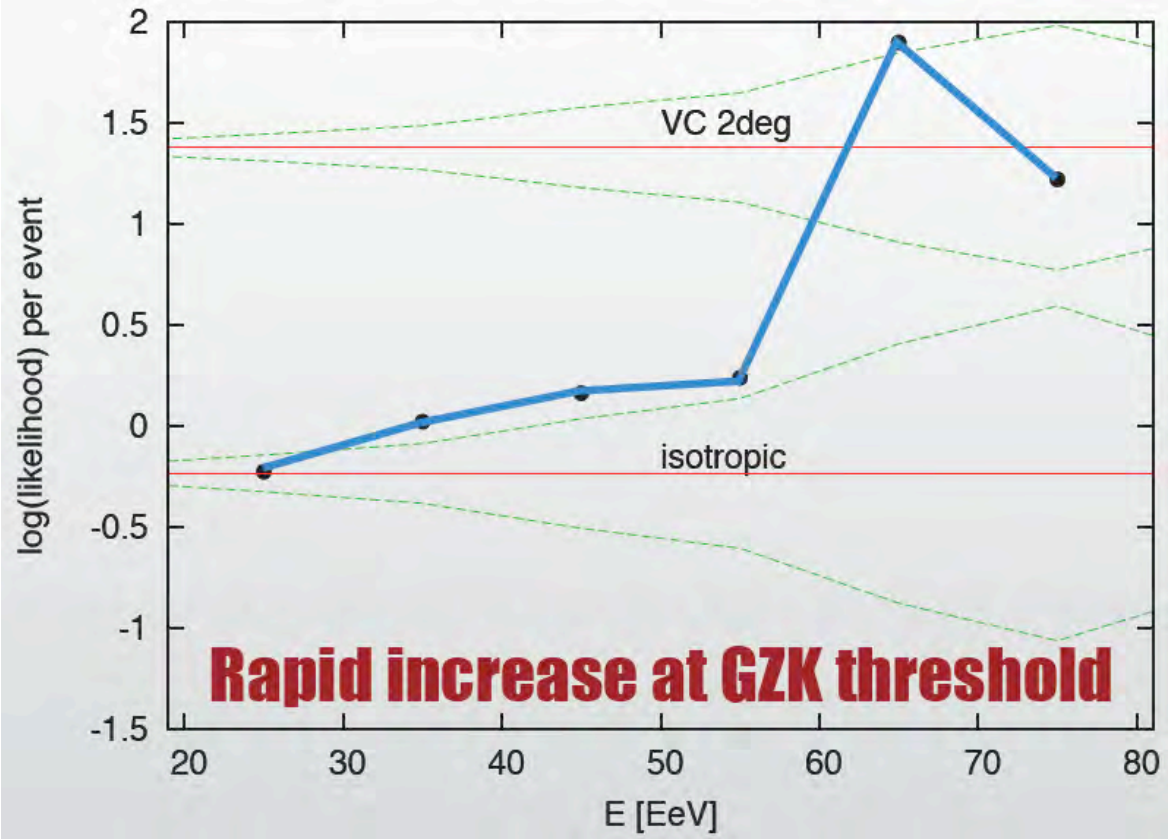
$\Delta\theta \leq 3.1°$

$z \leq 0.018$

$(D \leq 75$ Mpc$)$

$E \geq 56$ EeV

Auger main anisotropy result



The energy above which the correlation is most significant corresponds to an energy where the CR flux drops… (supporting the GZK interpretation)

Astrophysical implications?

- **Not clear yet! (very low statistics to check against any model, whether naive or sophisticated)**
- **Can UHECRs come from AGNs?** ➡ YES

  But we knew that before!
- **Do UHECRs have to come from AGNs?** ➡ NO!
- **NB: no claim from Auger!**

Summary of Auger results

composition

some nuclei,
no photons, no
neutrinos yet

matches astrophysical expactations

Implications for gal./extragal. **transition**?

Unity with the CR science and sources at low E?

Makes HECR studies even **richer**!

E spectrum

ankle +
GZK cutoff

Excellent news!
40 years-old prediction!

⇒ nearby sources
⇒ « proton astronomy »!
+ isolated sources!

+ high-energy physics
study of showers (muons, hadronic models, energy scale)

cf. knee + **LHC** !

directions

anisotropic sky

One of the most important results since 100 years!

⇒ some sort of "cosmic-ray astronomy" is possible (it just began!)

⇒ cosmic rays to be integrated into the scientific *corpus* of astrophysics

Cosmic rays, year zero!

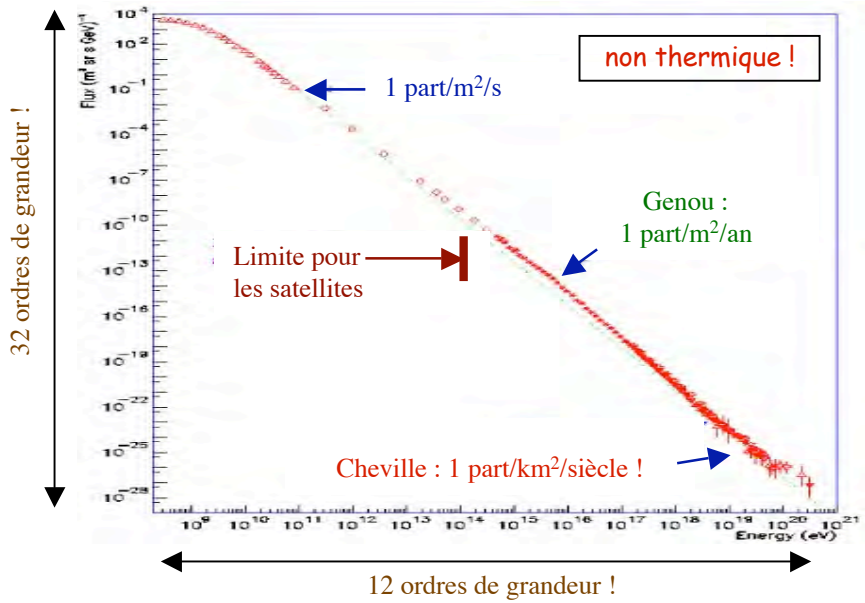
- **Historical opening of a non-photonic astronomy!**
  - **Eventually: identification and study of individual sources**
  - **Necessary to increase collecting power at the highest energies** ⟹ Auger Nord (Lamar, Colorado)

    (sources are there: let's go and get them!)

    ⟹ Shower detection from space (JEM-EUSO, S-EUSO…)
- **Many questions**
  - **sources, CR origin, acceleration mechanisms, behaviour of energetic sources in the universe, link with low-energy CRs and galactic ecology**
  - **study of high-energy physics (LHC results are awaited!)**

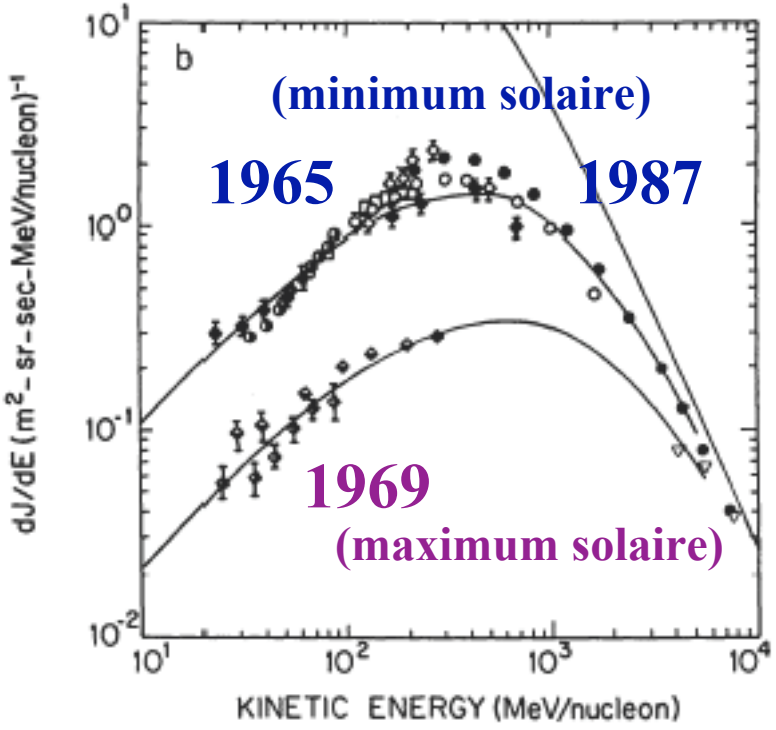
Limite à basse énergie ?

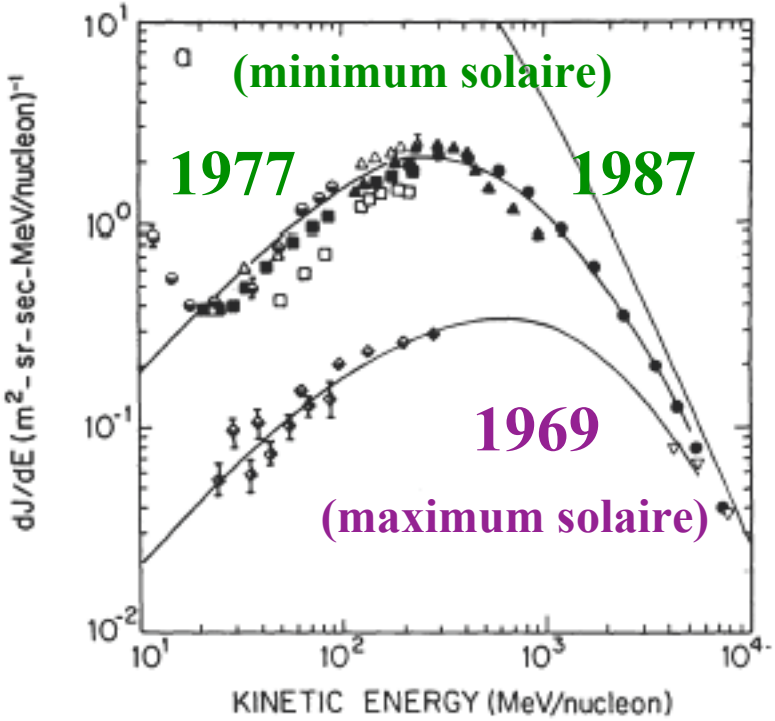
Rayons cosmiques les plus nombreux et les plus importants pour l'astrophysique galactique…



MAIS : Phénomène de modulation solaire…

Modulation solaire



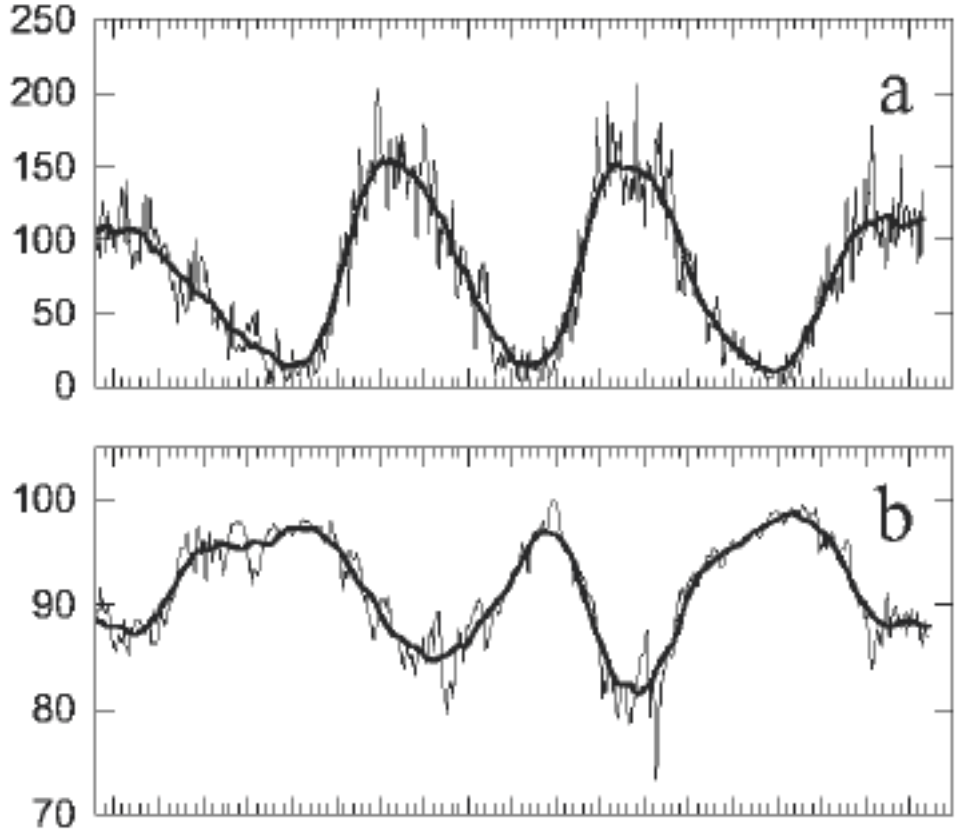


Solar modulation

- Flux variation in coincidence with solar cycles

Sun spot activity

CR intensity



Modulation solaire : données de Voyager et de Pioneer

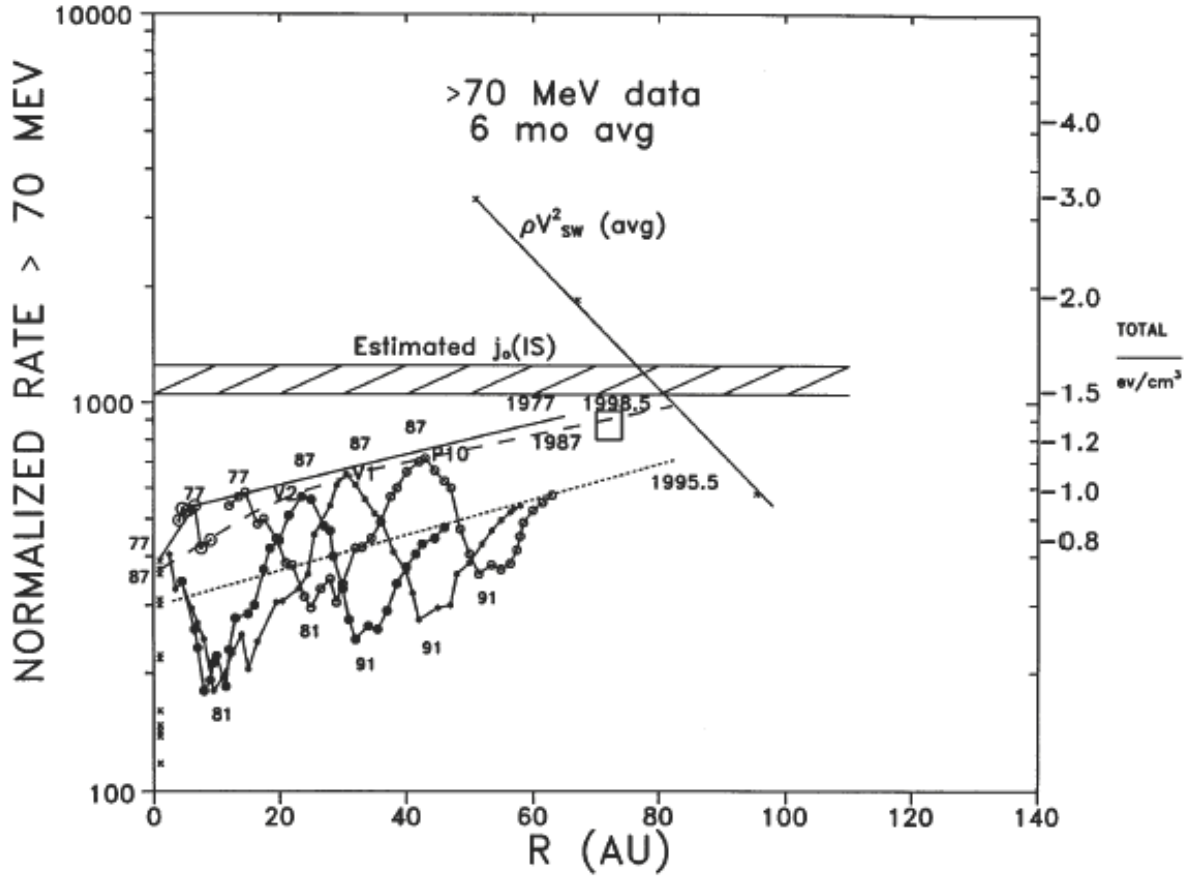
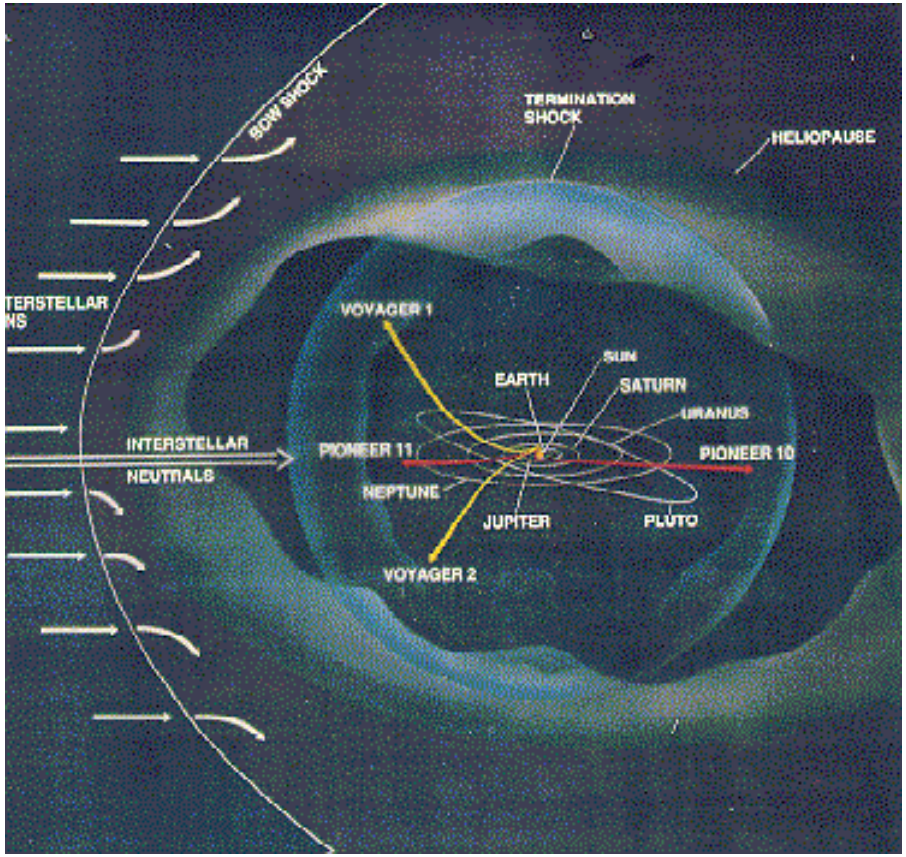
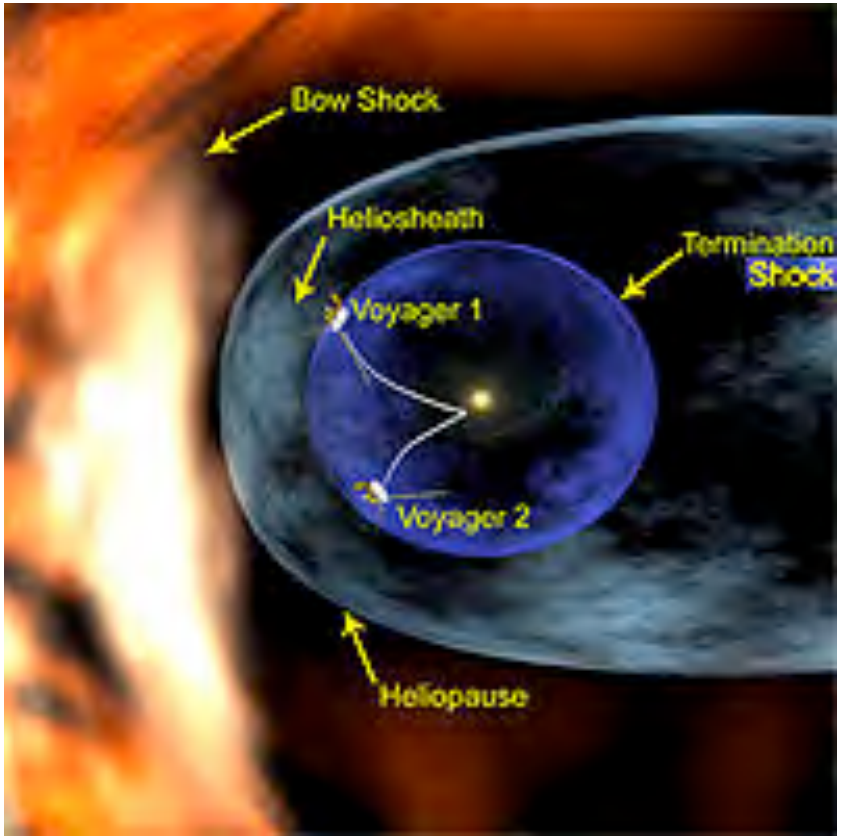


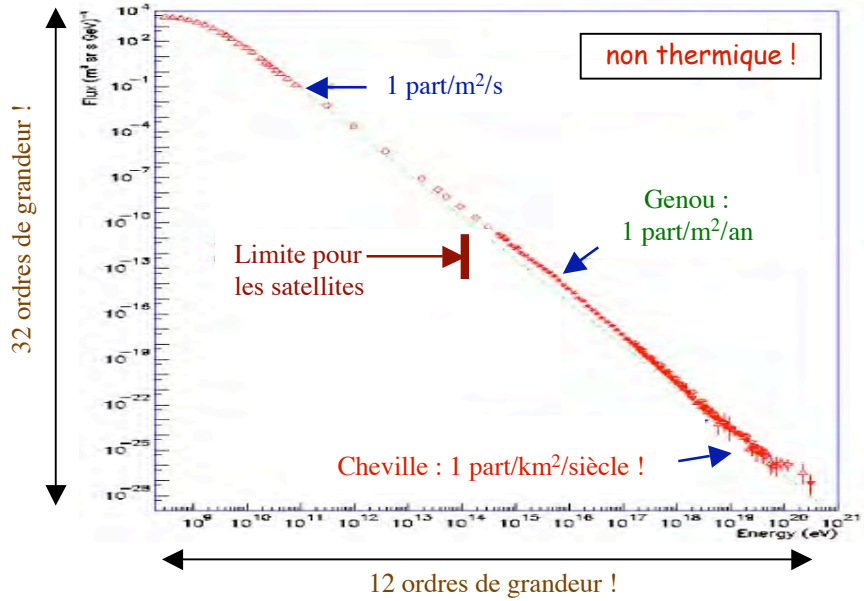
FIG. 1.—Counting rates of greater than 70 MeV cosmic rays vs. distance measured on *Voyager* and Pioneer spacecraft from 1977 to 1995. These integral rates, converted to energy densities are shown on the right-hand axis. The estimated interstellar counting rate is shown as a hatched region. The average energy density contained in the solar wind is also shown.


BOW SHOCK
TERMINATION SHOCK
HELIOPAUSE
TERSTELLAR
NS
VOYAGER 1
SUN
EARTH
SATURN
URANUS
INTERSTELLAR
NEUTRALS
PIONEER 11
PIONEER 10
NEPTUNE
JUPITER
PLUTO
VOYAGER 2


Bow Shock
Heliosheath
Termination Shock
Voyager 1
Voyager 2
Heliopause

Limite à basse énergie ?

Rayons cosmiques les plus nombreux et les plus importants pour l'astrophysique galactique !



- Ionisation du milieu interstellaire (MIS)
- Chauffage du MIS
- Production du champ magnétique
- Contrôle de l'astrochimie (→ panspermie ?)
- Régulation de la formation d'étoiles
- Nucléosynthèse des éléments légers

Domaine inaccessible à une mesure directe !
→ recours à l'astronomie photonique
→ toute l'astronomie non thermique et des hautes énergies…