The Pierre Auger Observatory:

first steps towards proton astronomy

Etienne Parizot
(IPN Orsay - France)
parizot@ipno.in2p3.fr

Part 1

Overview of the cosmic rays

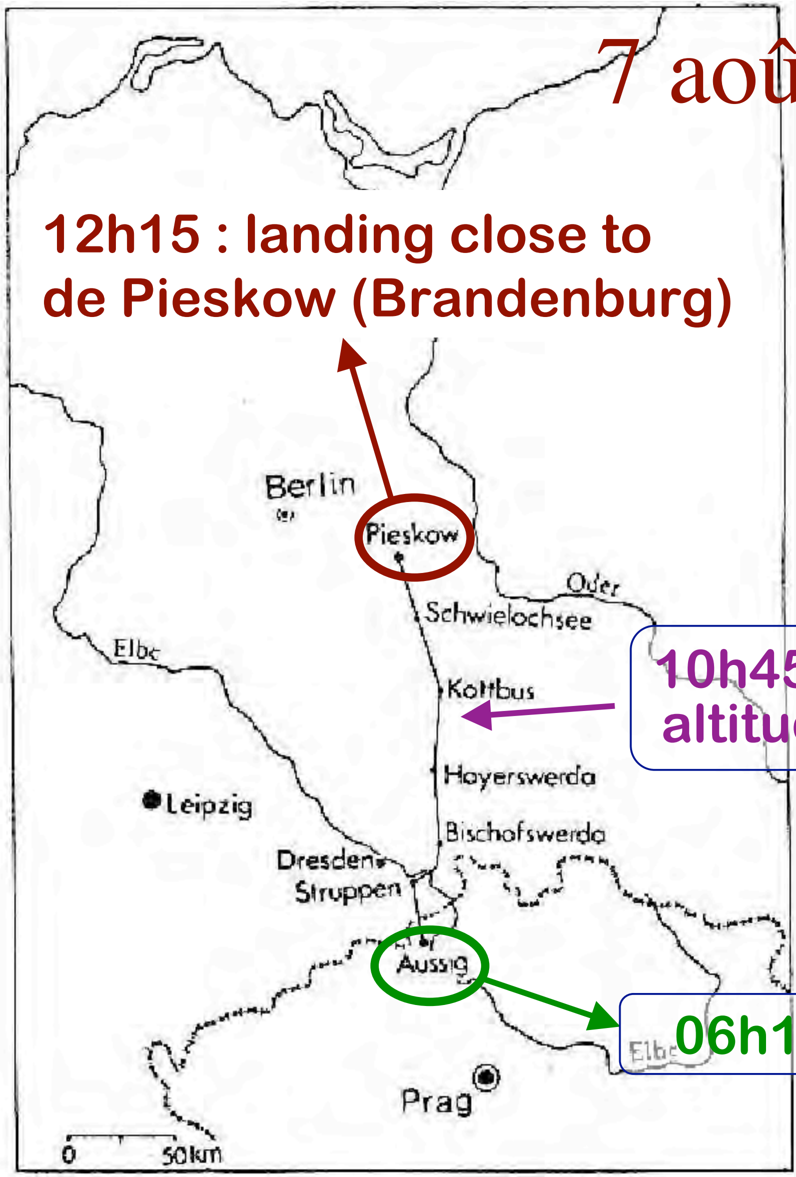
and their three spectral dimensions

7 août 1912

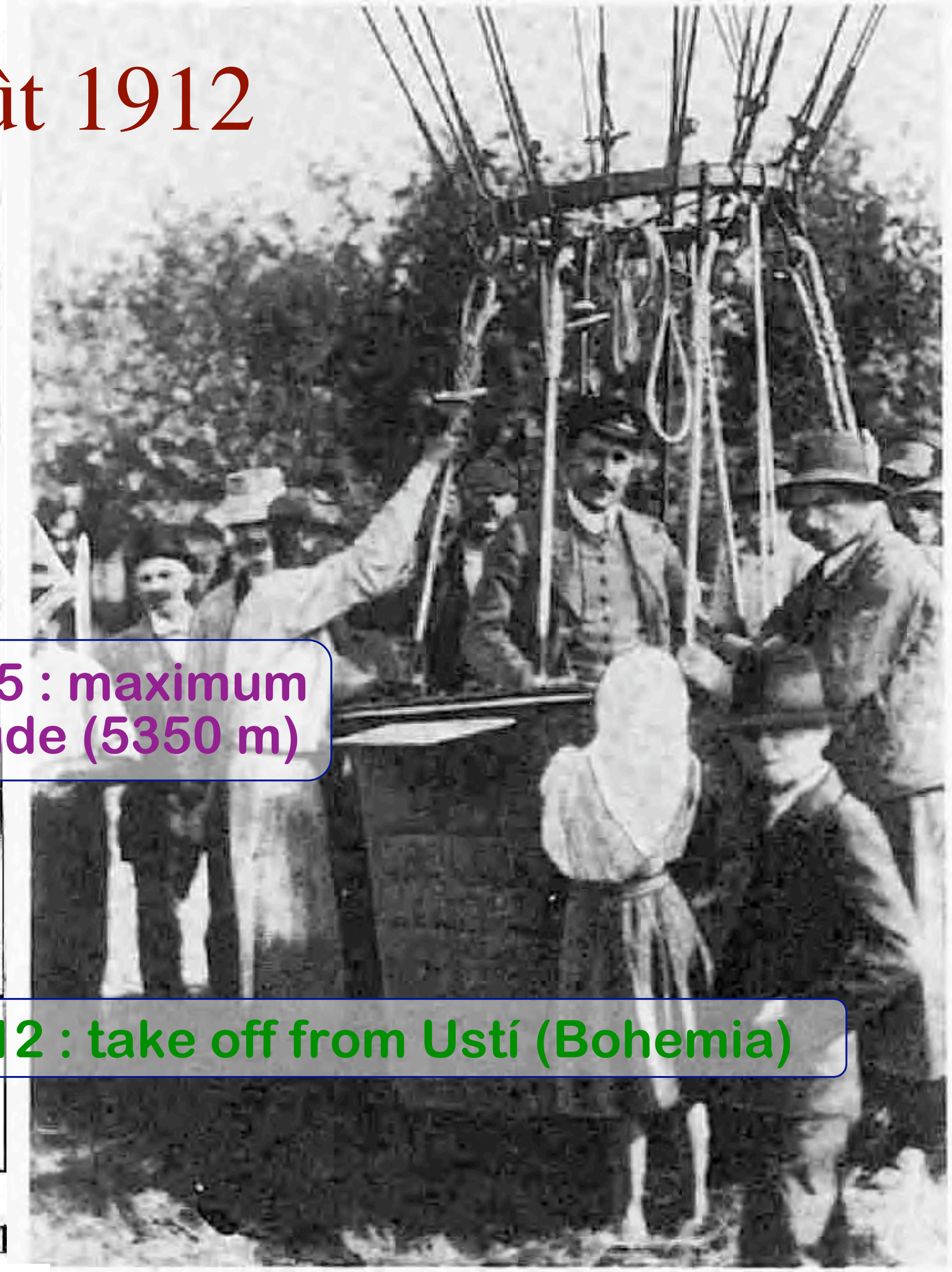
12h15 : landing close to
de Pieskow (Brandenburg)

10h45 : maximum
altitude (5350 m)

06h12 : take off from Ustí (Bohemia)

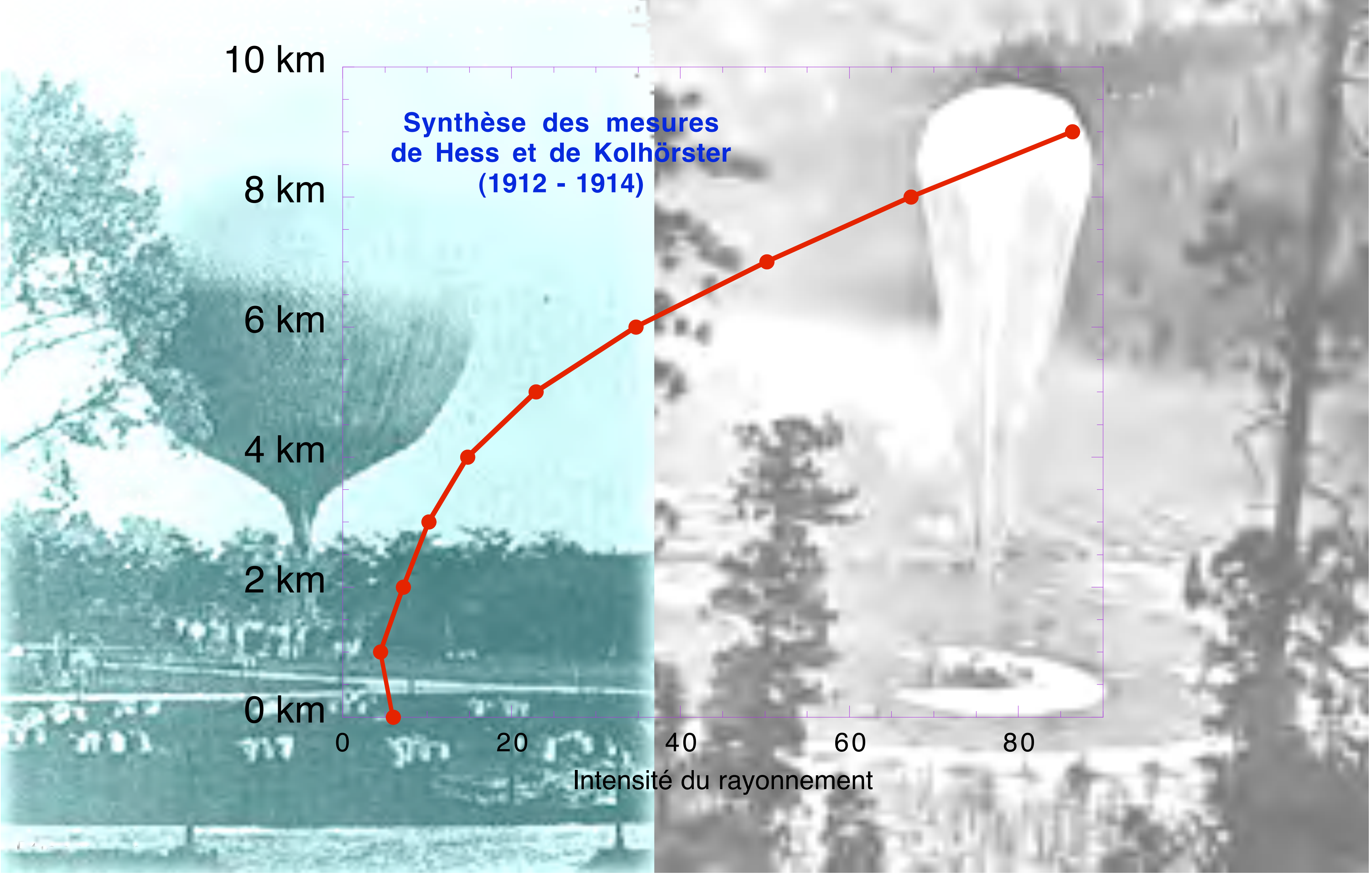


Route des Entdeckungsfluges der kosmischen Stral



Hess bei Ballonlandung (1912).

Increase of the radiation



Cosmic rays and particle physics

- Particle physics is the child of cosmic ray physics

1932 – Positron ⇒ antimatter !

1936 – Muon ⇒ Nature is not sparing!

1947 – Pions : π^0, π^+, π^-

1949 – Kaons (K)

1949 – Lambda (Λ)

1952 – Xi (Ξ)

1953 – Sigma (Σ)

(Kaons, Lambda, Xi, Sigma:) « strange » particles (lifetime is much too long)

All this, thanks to cosmic rays… whose nature and origin are still ignored!!!

→ schism between cosmic-ray physics and particle physics (CERN…)

CRs are (also) interesting by themselves!

- What are the primaries?
- Where do they come from?
- How do they get their energy?
- What do they reveal about the universe?
- Can they be used as tools for astrophysics?
- May they be valuable “messengers” from distant sources?

Everything in astrophysics is known from light!

- We know stars, galaxies, interstellar medium, magnetic fields, temperatures, masses, densities, compositions, velocities, etc.
- Only thanks to photons reaching the Earth from the cosmos!
- Light is the cosmic messenger "par excellence"…
- But it is not unique anymore!
  - For tens of thousands of years, visible light has been our only physical access to the cosmos
    - Since 100 years, cosmic rays tell us more, but ≠ astronomy!
  - And then non visible light, and now neutrinos, and soon gravitational waves!

Astronomy has two spectral dimensions

- “Binary astronomy”: something here, nothing there…
- Hipparcos (190 - 120 B.C.): magnitudes…
- > 1860: spectroscopy
  - Helium was discovered by Lockyer in 1889 (then on Earth by Ramsay in 1895)
  - Emission and absorption lines
  - Identification of elements, Doppler shifts, etc.

- Maxwell, Hertz…: discovery of invisible light!
  - Radio waves, infrared, UV, X, gamma

2 spectral dimensions: directions and energies

Cosmic-rays

A few grams of matter in a world of light!

- Everything we know in astrophysics comes from light…
- … and a few particles of extra-solar material: the cosmic-rays
- 4 CR/cm^2/s => 1 kg/year
- Extremely important for science, but not understood yet

3 spectral dimensions: directions, energies AND TYPE

Fundamental observables

1

Energy spectrum

↓

differential flux

2

Mass spectrum

↓

composition

3

Angular spectrum

↓

arrival directions

Fundamental observables

1

Energy spectrum

↓

differential flux

2

Mass spectrum

↓

composition

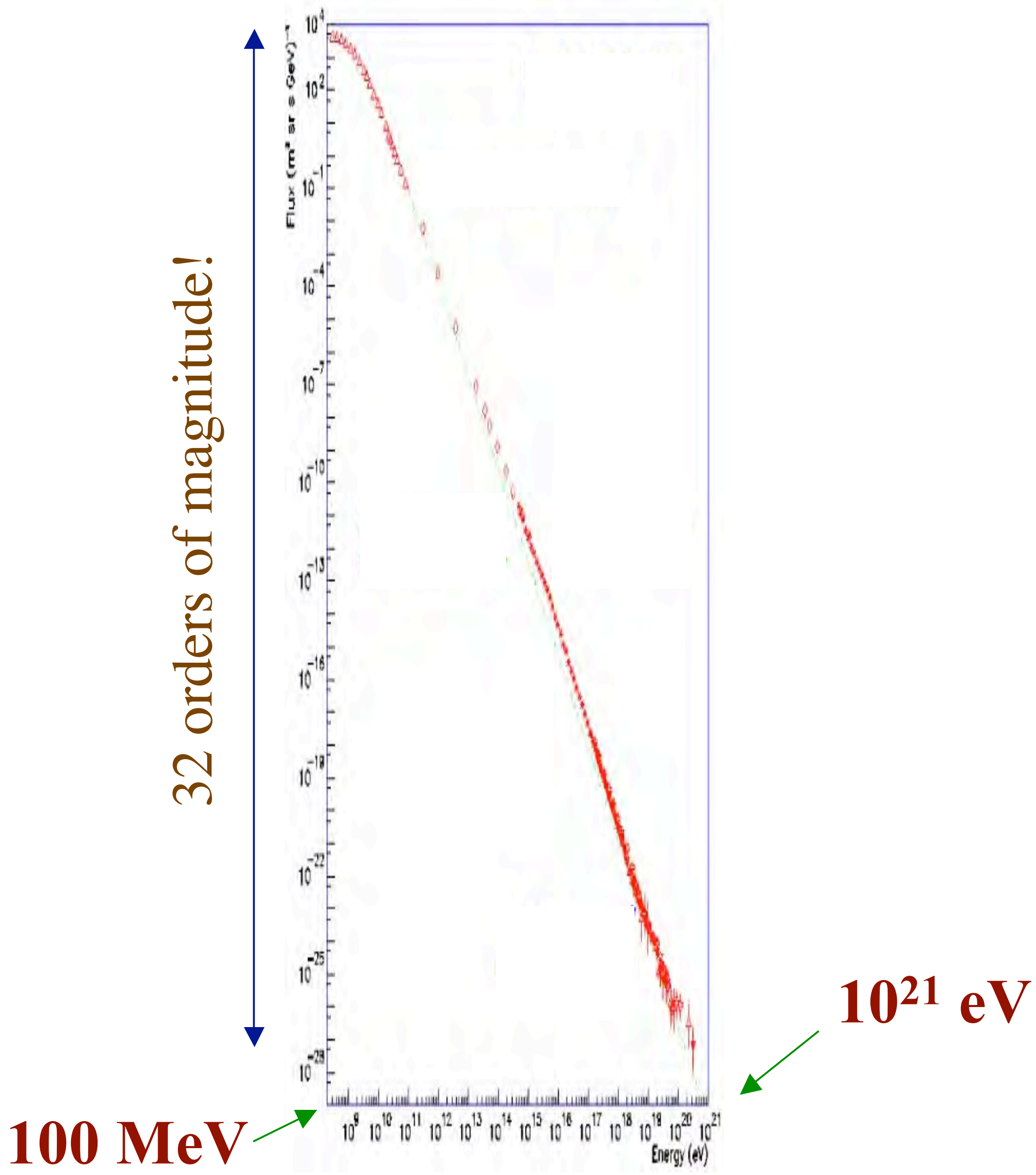
3

Angular spectrum

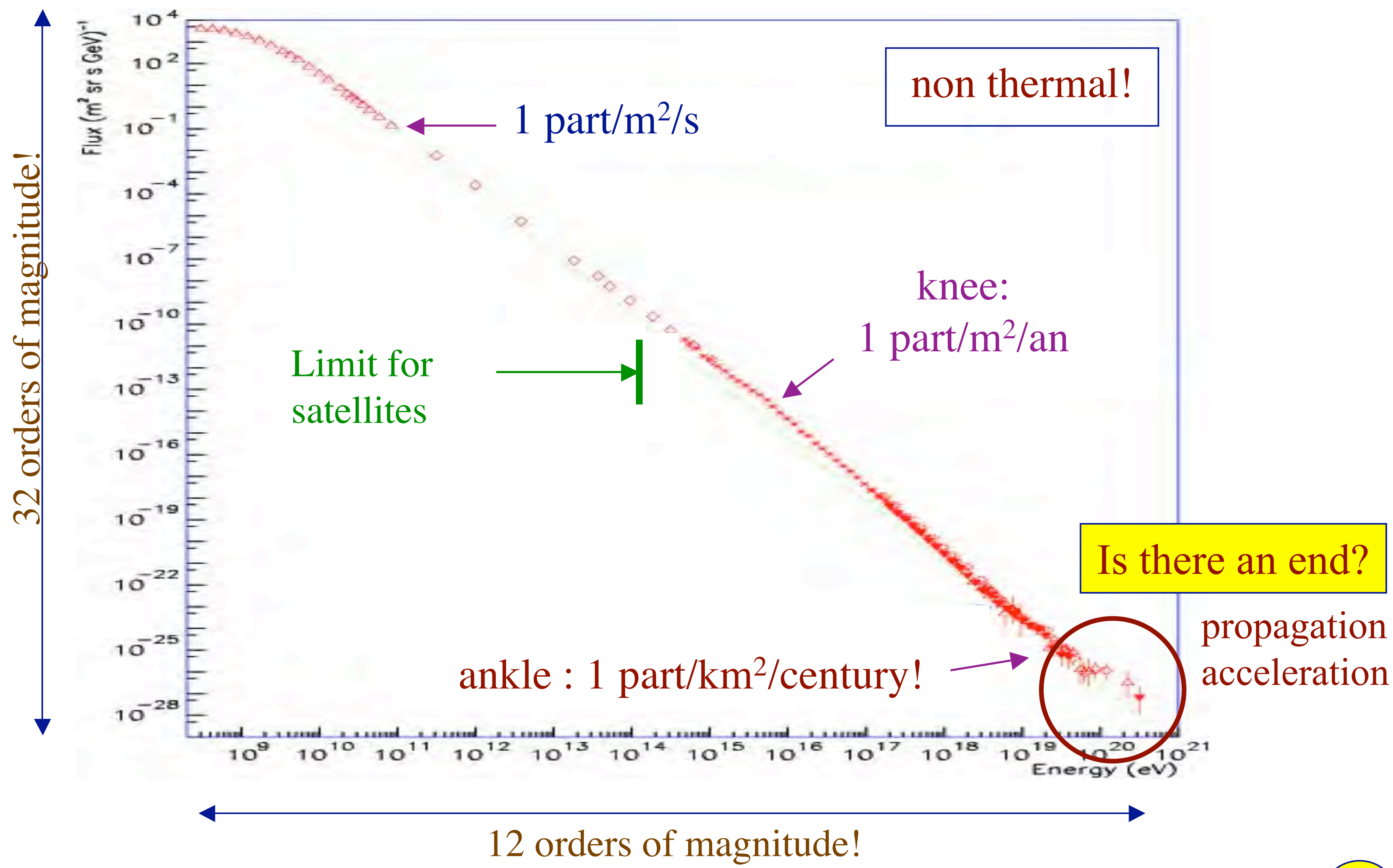
↓

arrival directions

The cosmic-ray energy spectrum



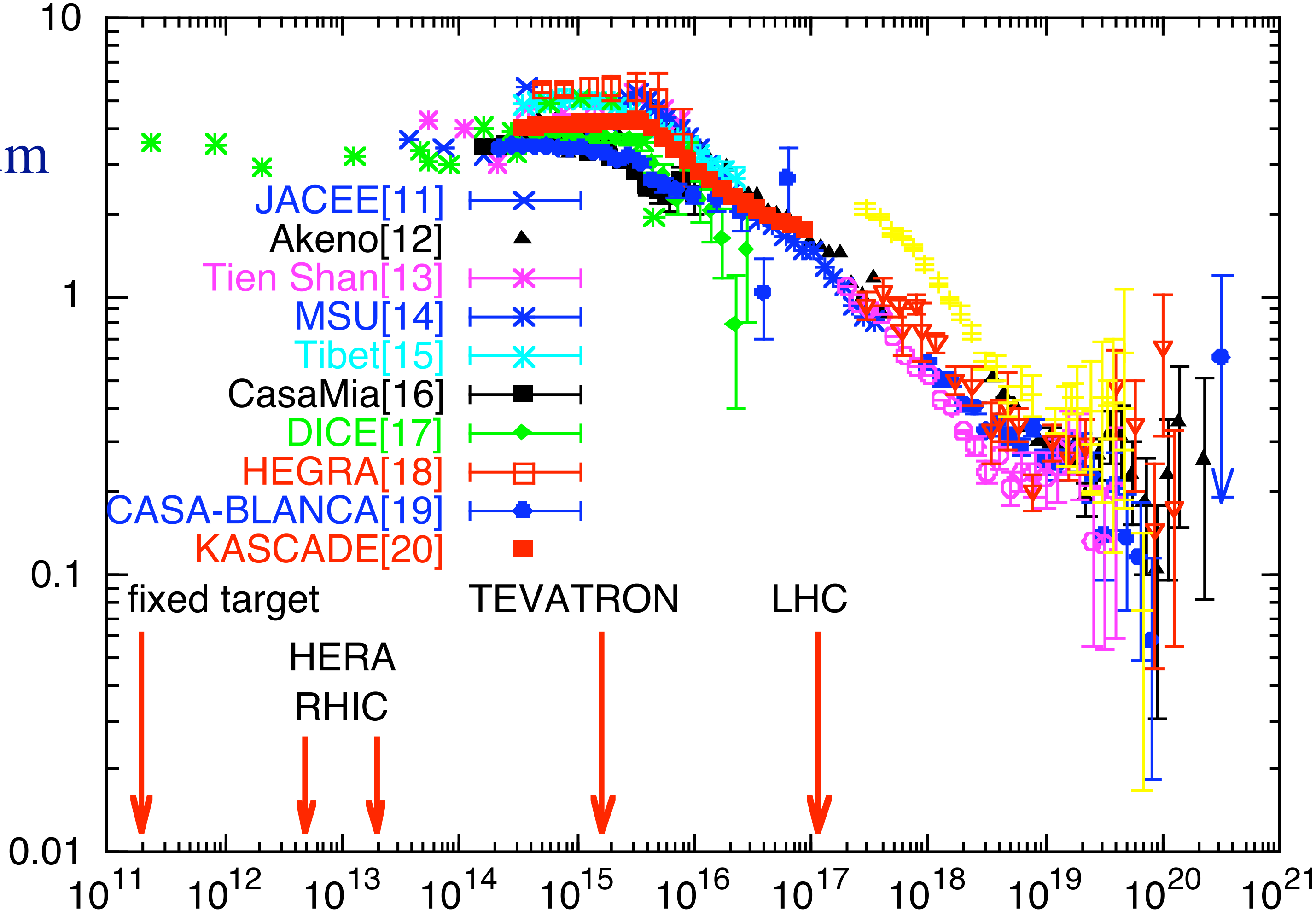
Energy spectrum (a one-century quest!)



The ‘knee’ at 5×10^{15} eV

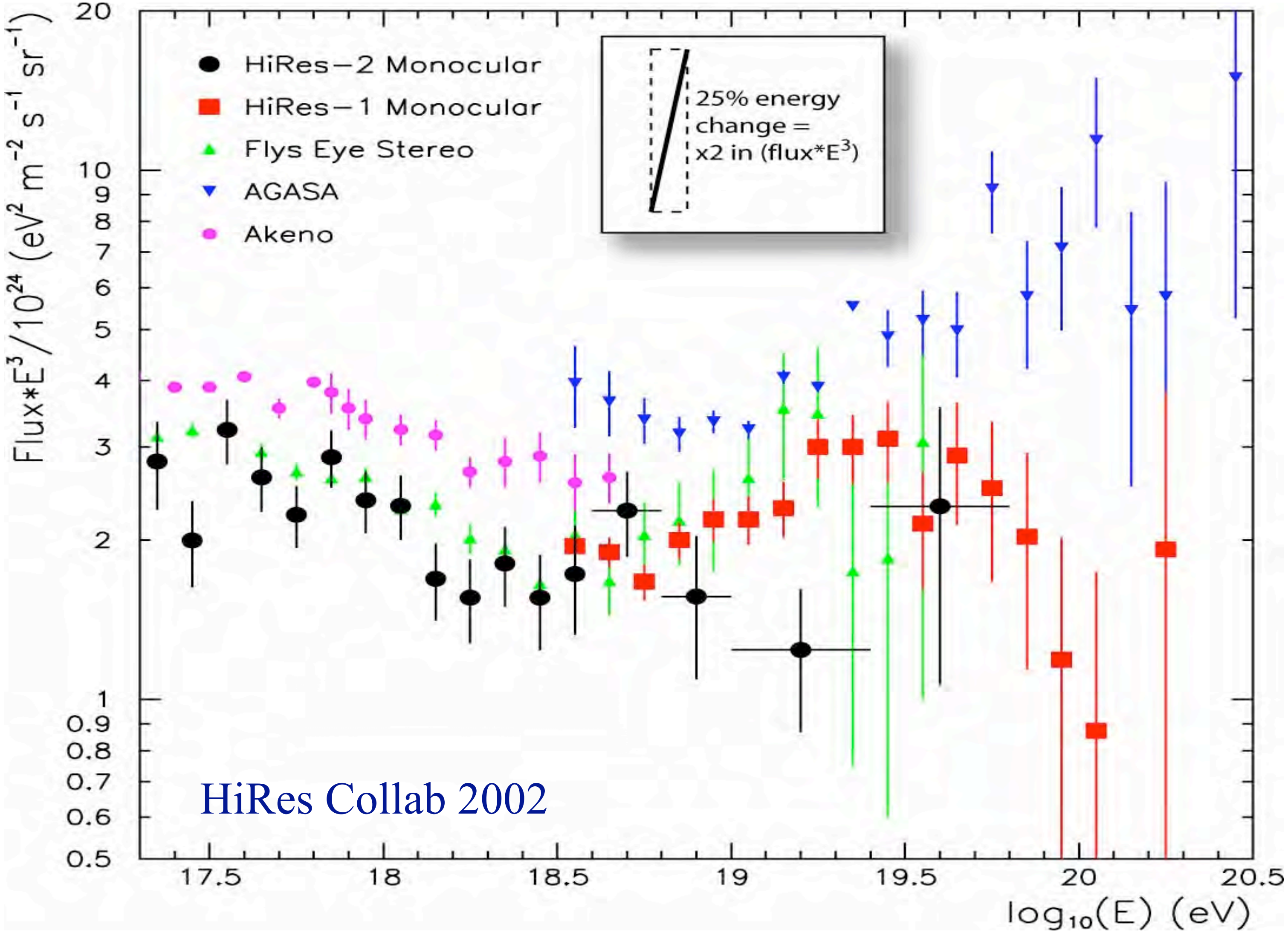
Tilted spectrum

$\Phi(E) \times E^{2.7}$

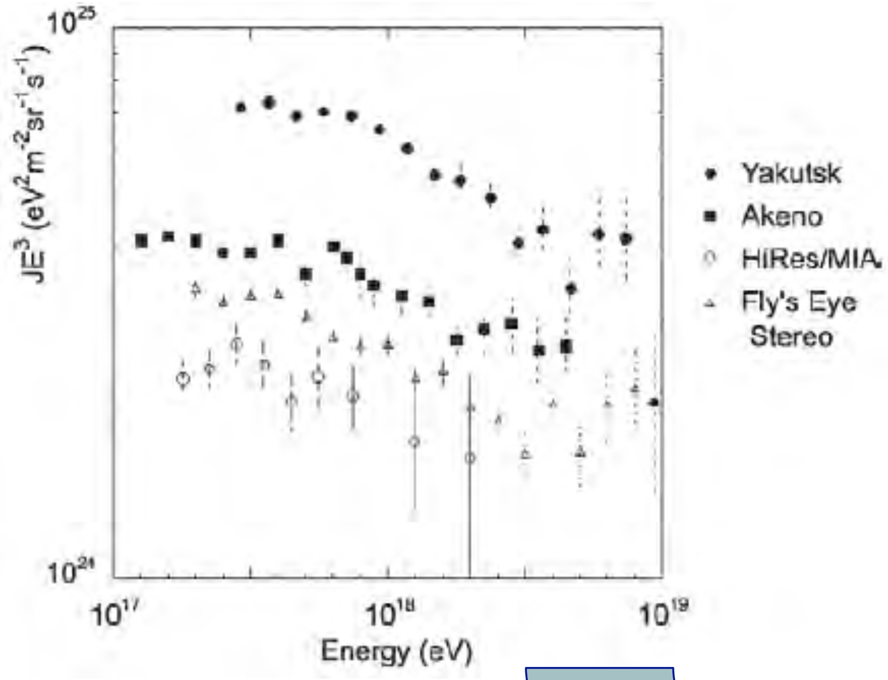


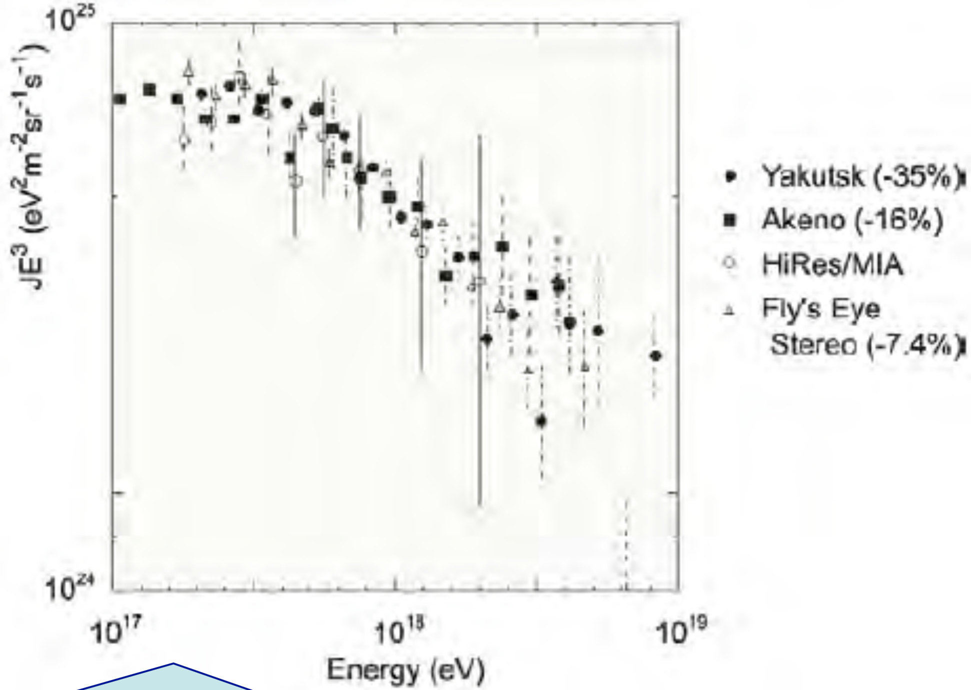
Energy (in eV)

Highest energies



The ‘second knee’ at 5×10^{17} eV?

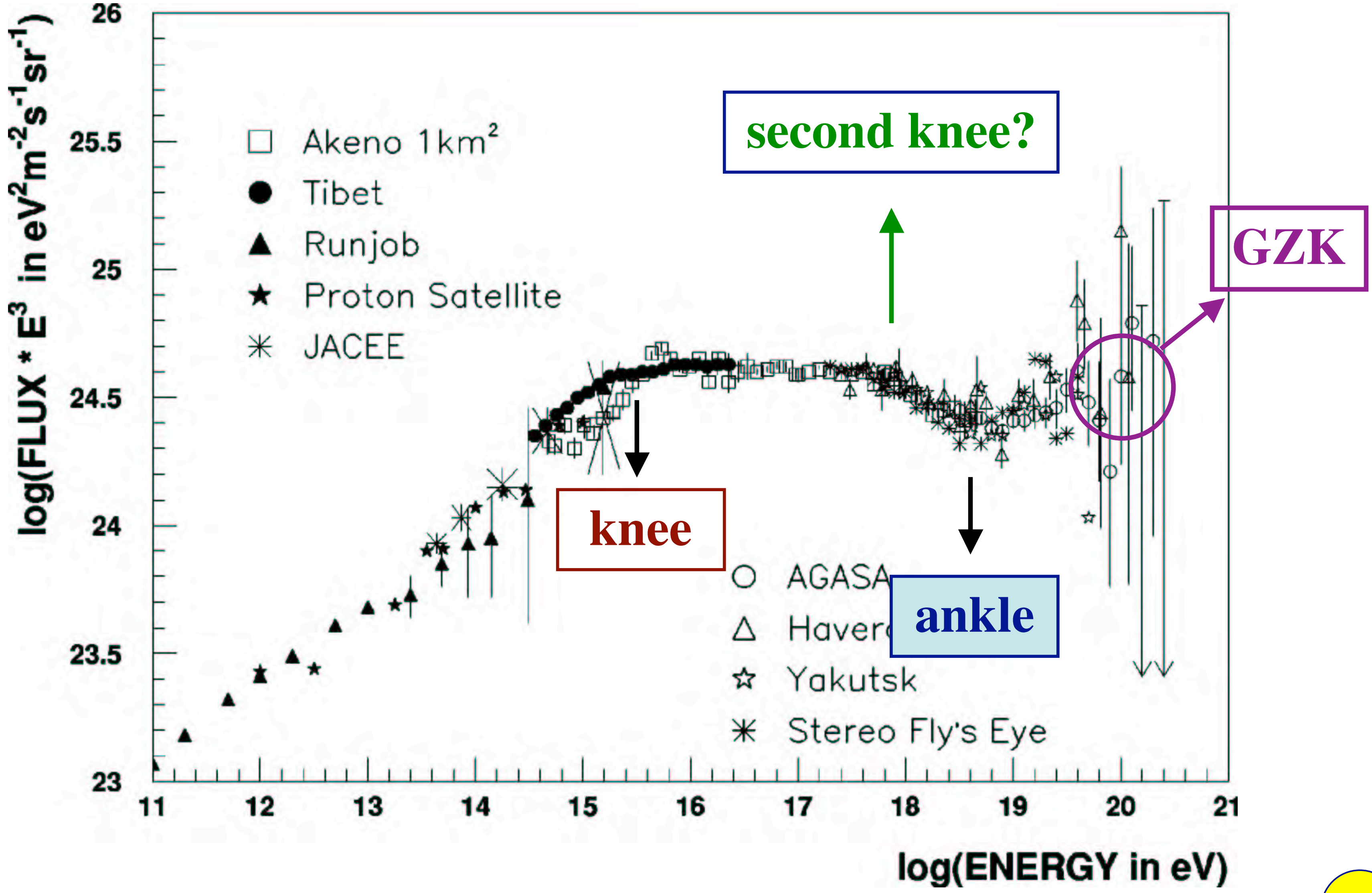


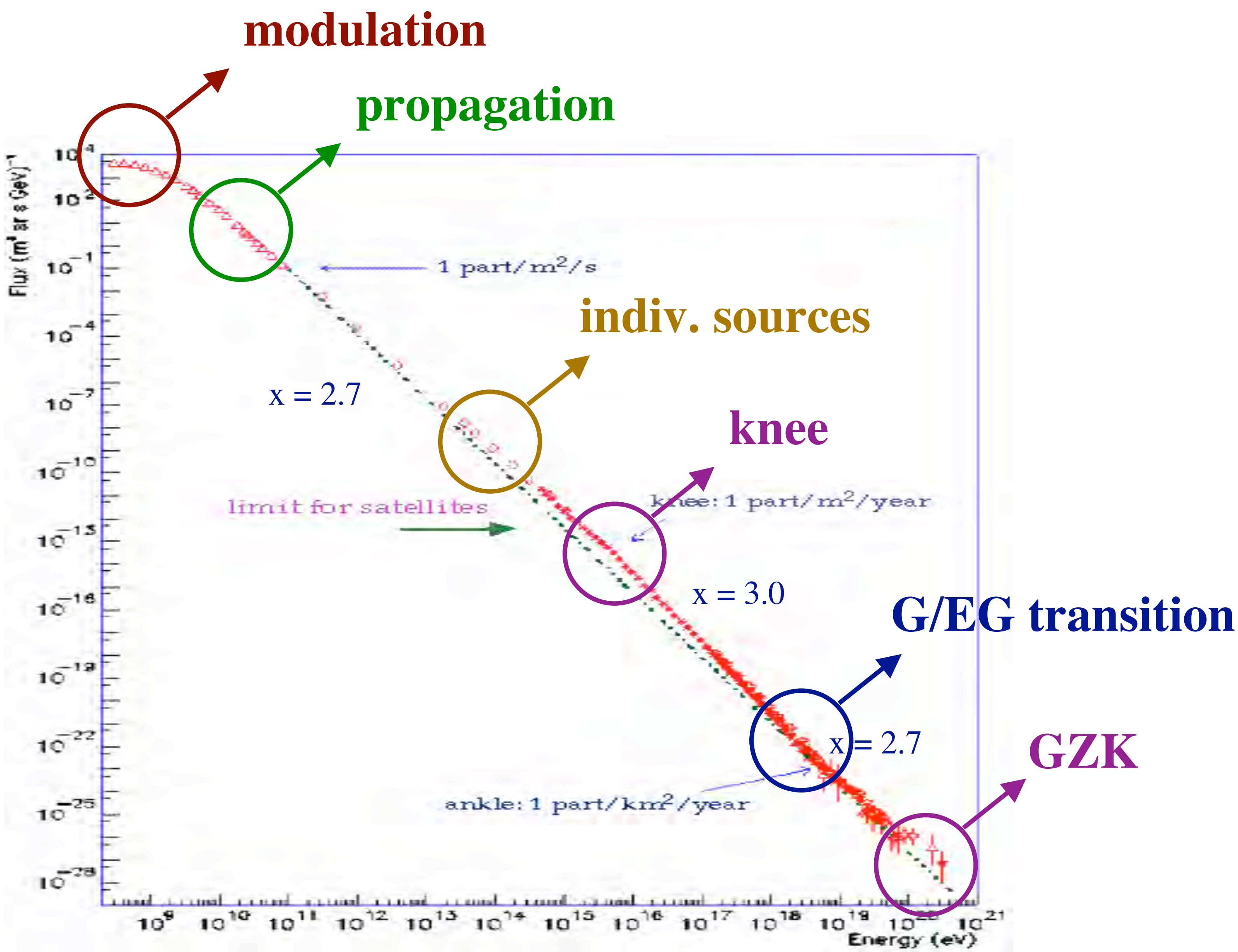


- Rescaling game…

- But you need to assume that systematics do not depend on E…

Tilted energy spectrum (× E^3)




modulation
propagation
1 part/m²/s
indiv. sources
x = 2.7
knee
knee: 1 part/m²/year
limit for satellites
x = 3.0
G/EG transition
x = 2.7
GZK
ankle: 1 part/km²/year
Flux (m² sr s GeV)⁻¹
Energy (eV)

Fundamental observables

1

Energy spectrum

↓

differential flux

2

Mass spectrum

↓

composition

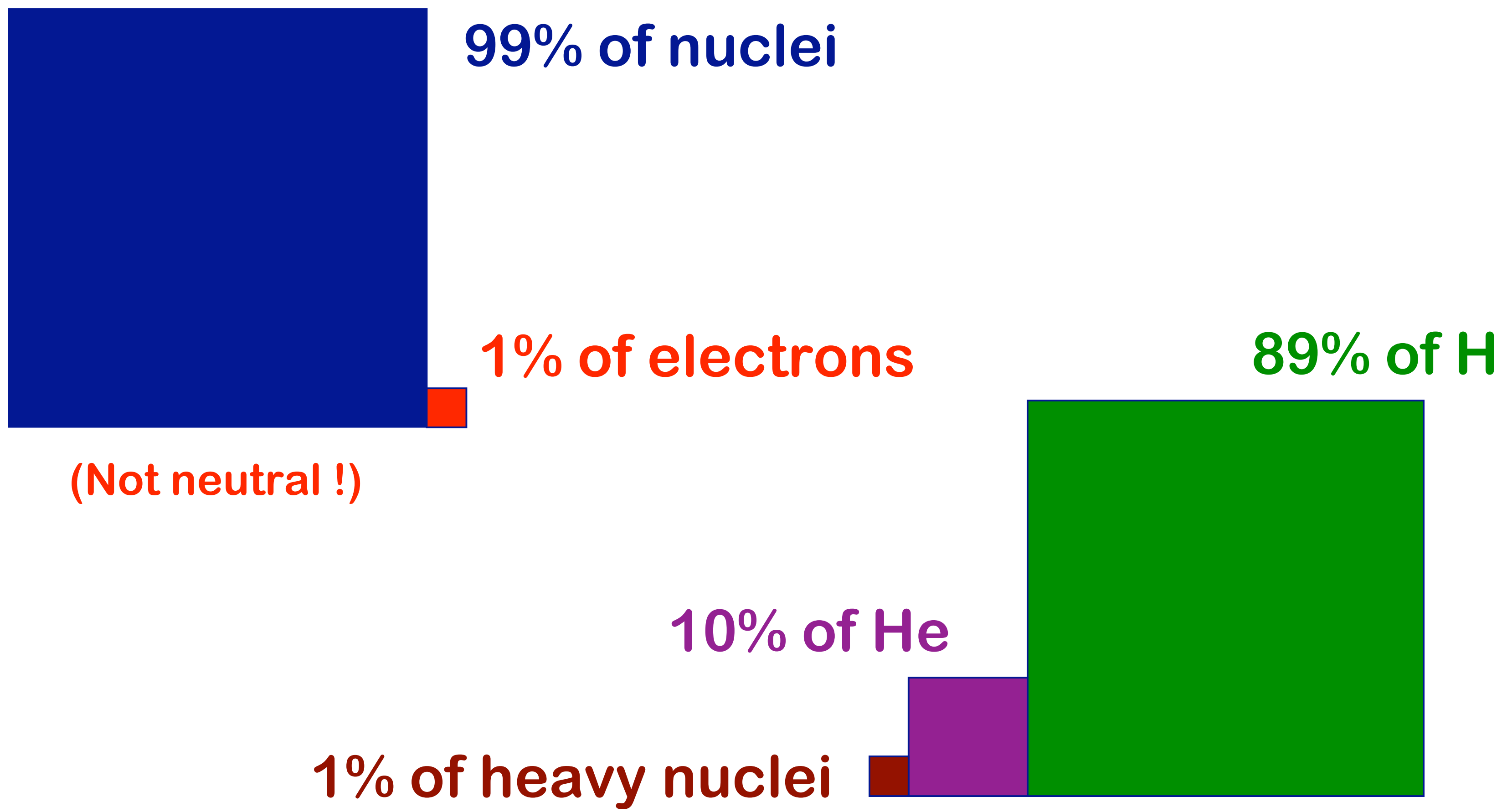
3

Angular spectrum

↓

arrival directions

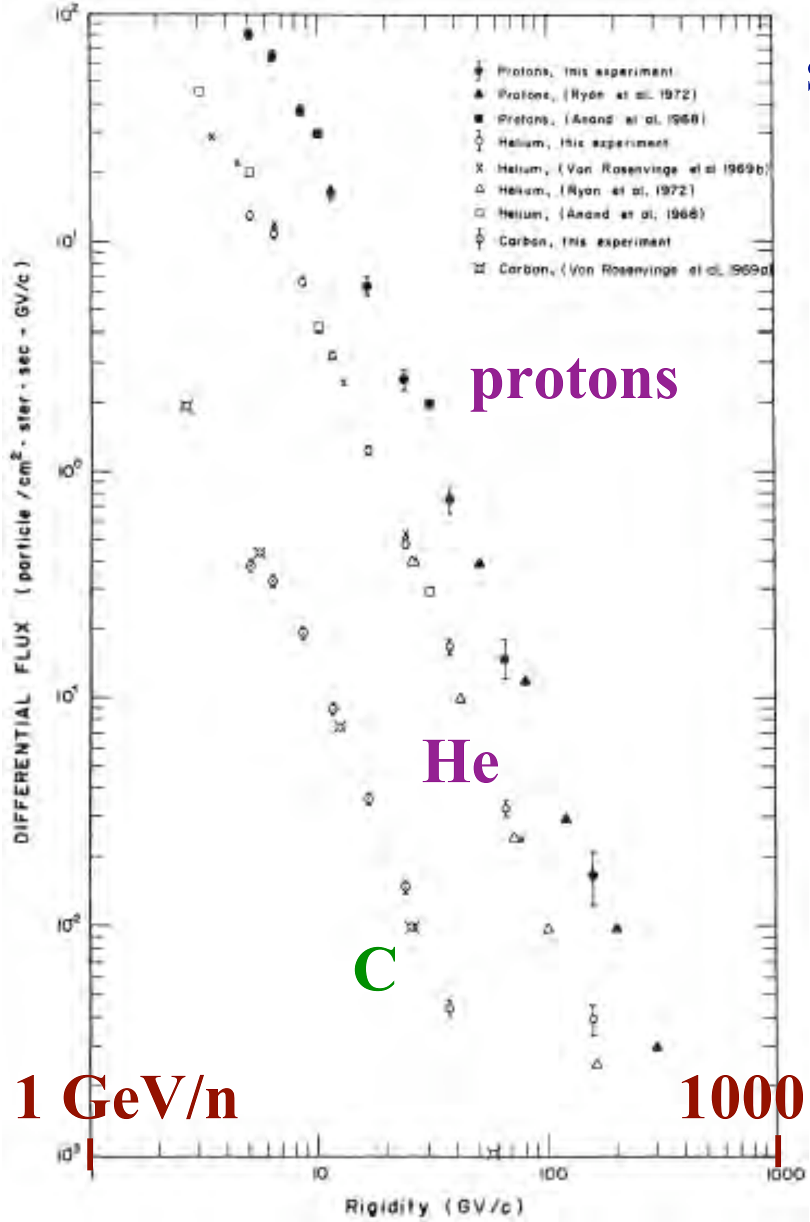
Cosmic-ray composition



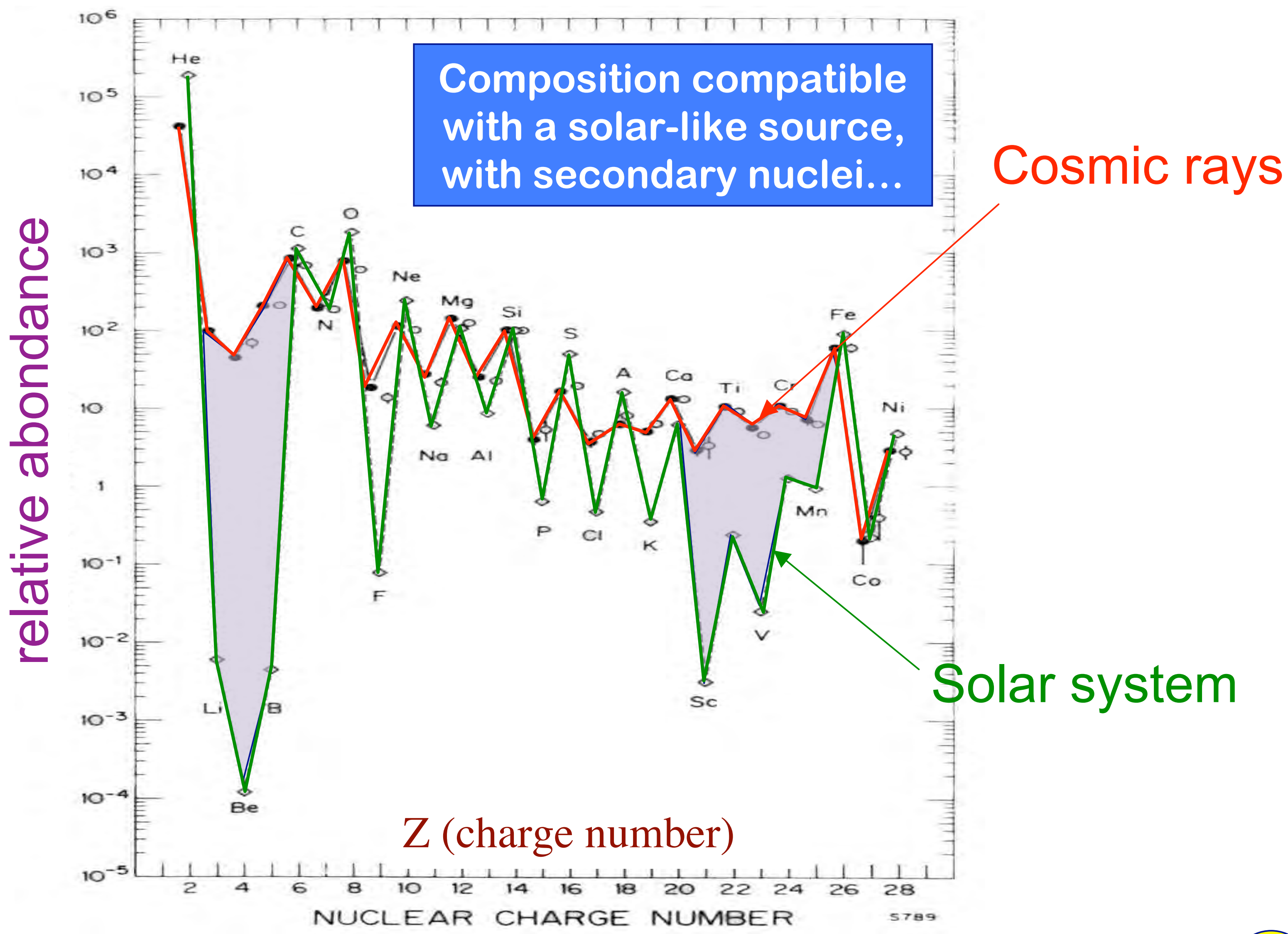
Same spectrum for all elements

(apart from specific spectral structures)

Smith et al. (1973)



CR vs solar system



Cosmic rays are not immutable!

Bonus track: previously unreleased!

- Opens extraordin … spective: the composition of CRs recor … t of their history!
- Nucl … actions in space: information about the … r gone through!
- In addition, secondary nuclei can be radioactive: cosmic-ray clocks!
- We should really make the most of this new spectral dimension!

Fundamental observables

1	2	3
Energy spectrum	**Mass spectrum**	**Angular spectrum**
↓	↓	↓
differential flux	composition	arrival directions

Angular distribution

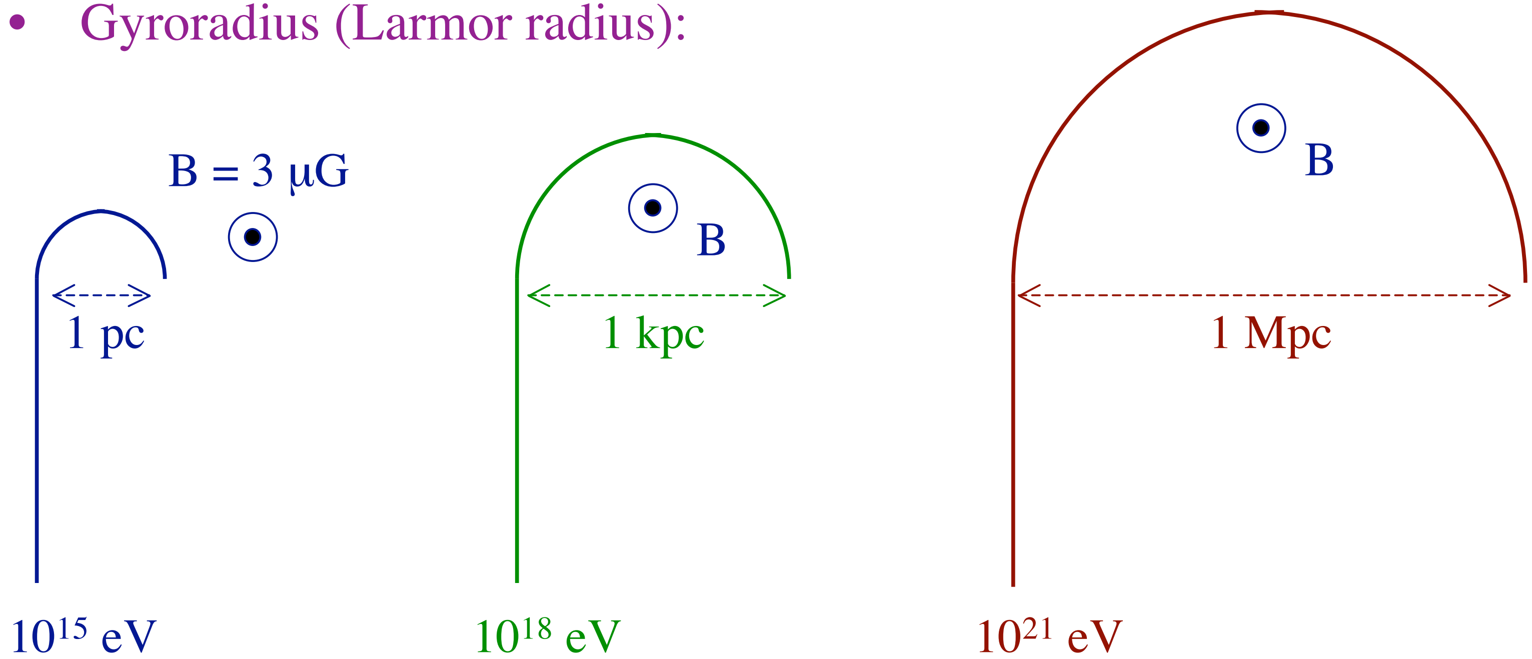
- Isotropic!

(→ no information about sources)

no astronomy!

Non rectilinear propagation!

- Galactic magnetic field: ~ 3 μG (3.10^{-10} T)
- Gyroradius (Larmor radius):



Supernova remnant

Disk + Galactic halo

>> galaxy

→ proton astronomy?

Galactic/extragalactic transition

- Low-energy cosmic rays have a galactic origin

  This is certain, because we can see that they
  are less numerous in the Magellanic clouds…

- High-energy cosmic rays have an extragalactic origin

  This is (almost) certain, because they cannot
  be confined in the galaxy

  [Unless they are VERY heavy
  nuclei, or the sources are in the halo]

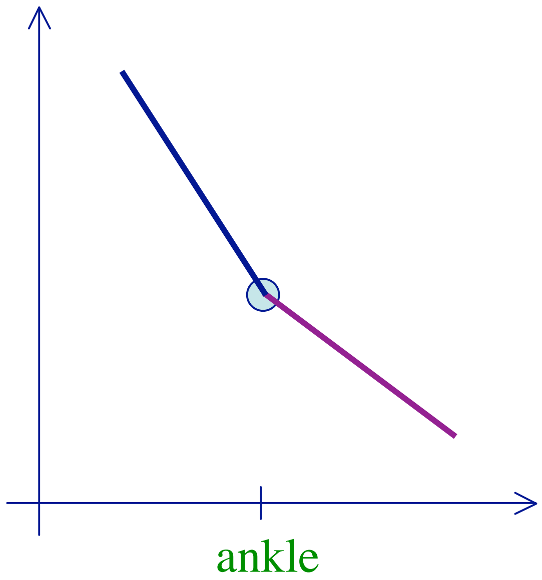
- Therefore a transition must occur!

  At what energy does it occur?
  How does it show in the energy spectrum?

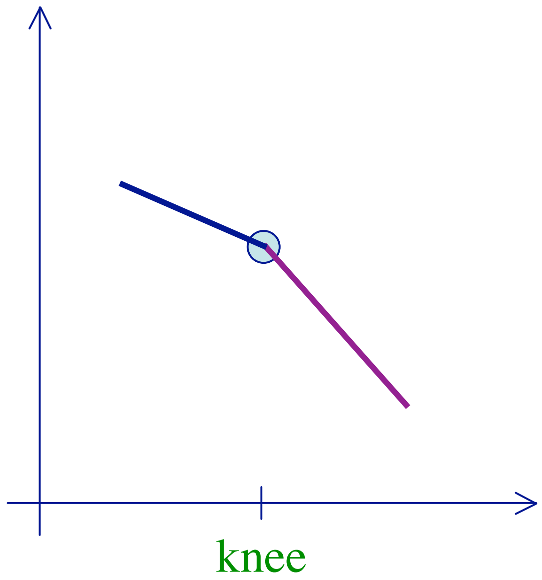
General phenomenology of transitions

- Two possibilities:

transition from a soft
to a harder component



transition from a hard
to a softer component



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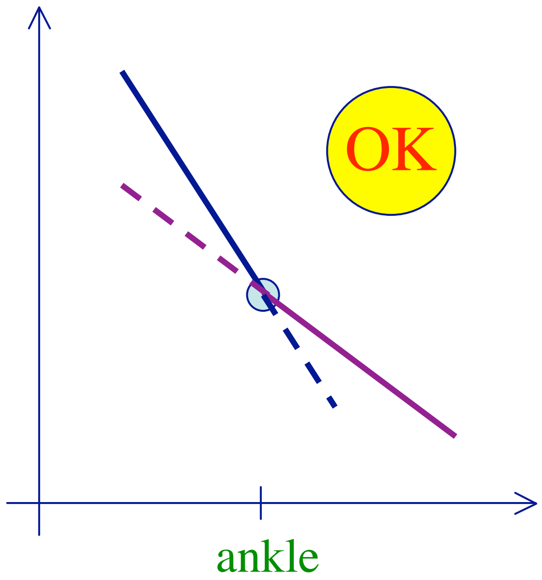

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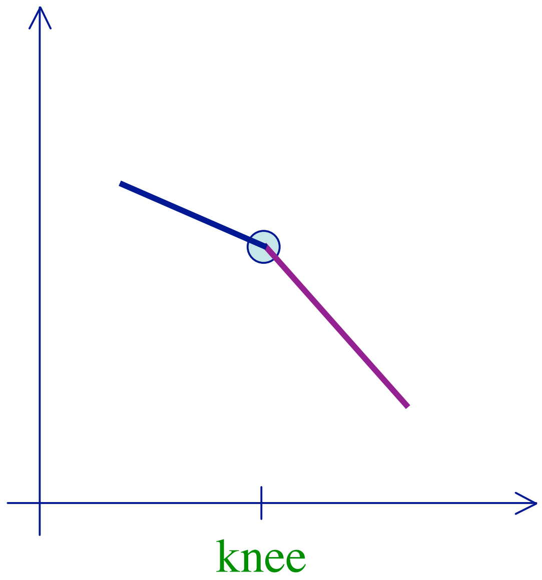

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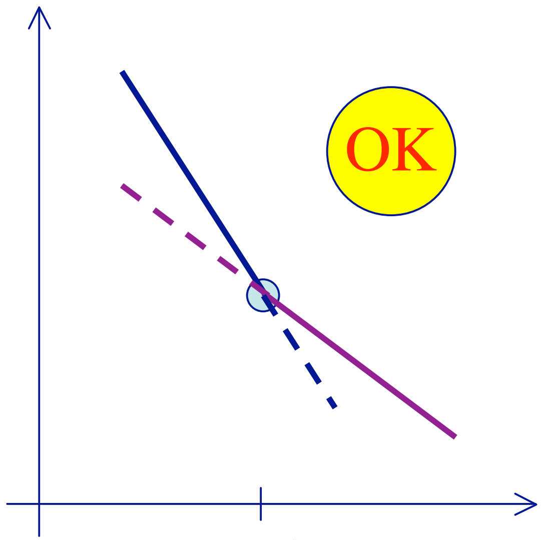
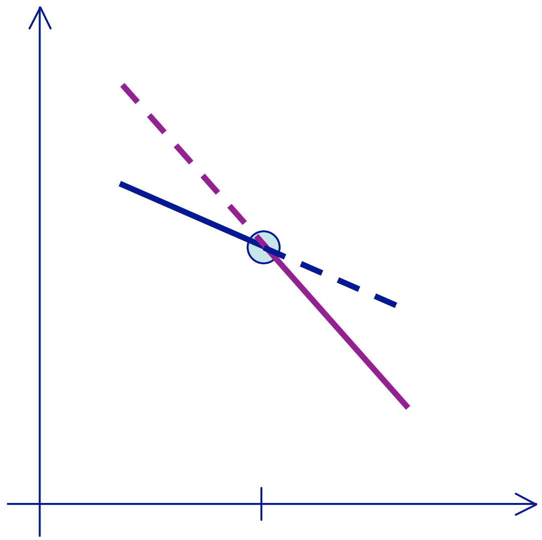


ankle

transition from a hard
to a softer component



knee

General phenomenology of transitions

- Two possibilities:

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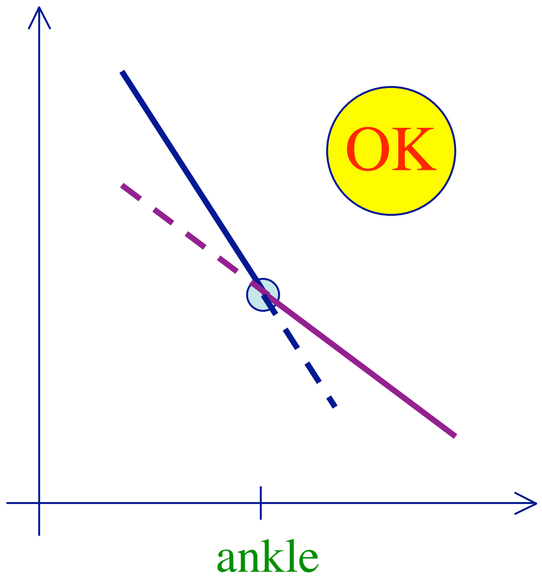
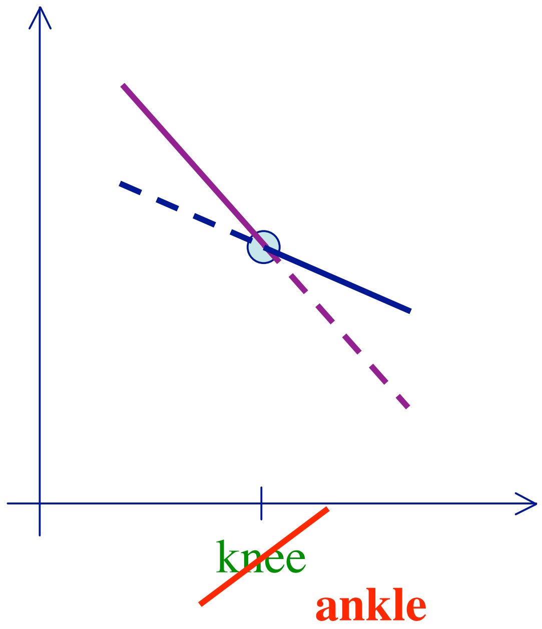
to a harder component



transition from a hard
to a softer component



General phenomenology of transitions

- Two possibilities:

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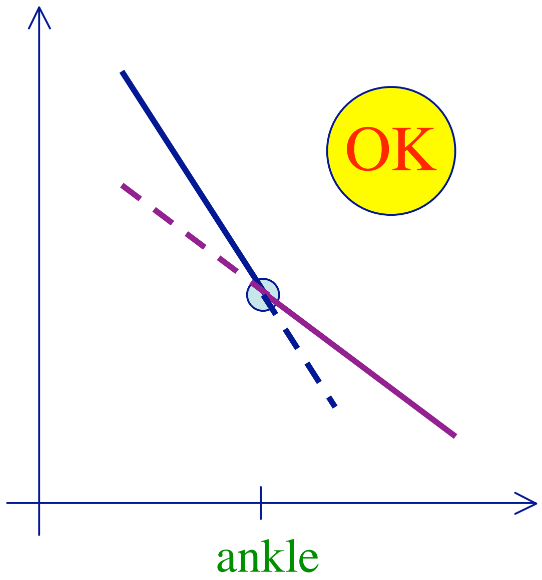
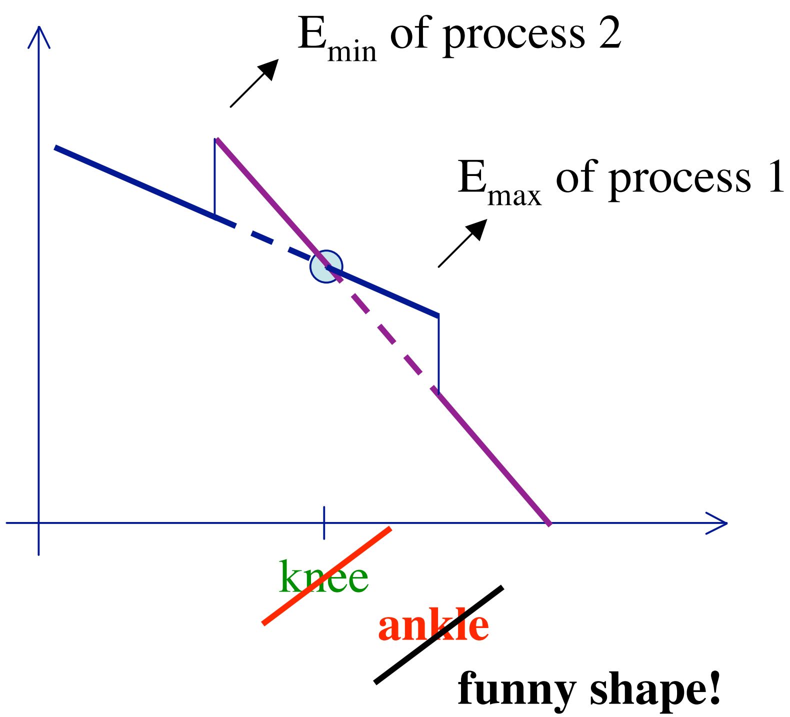
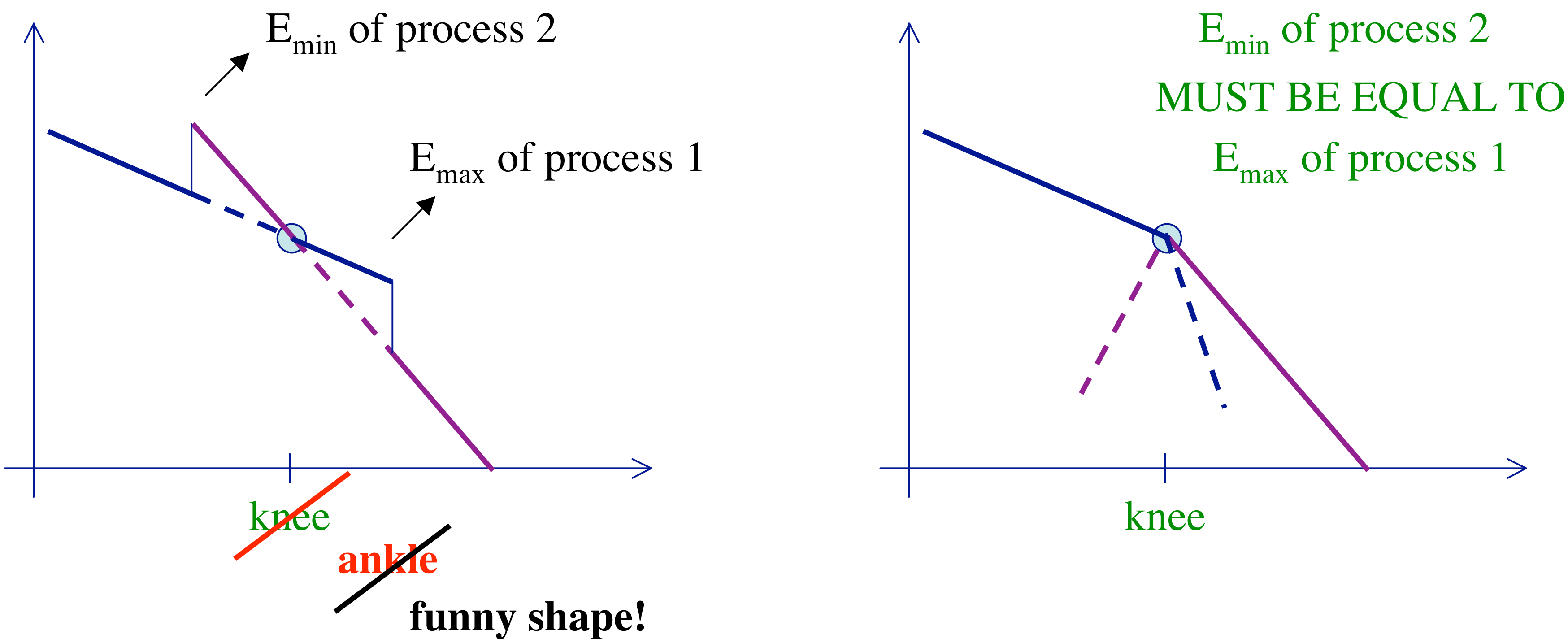


transition from a hard to a softer component



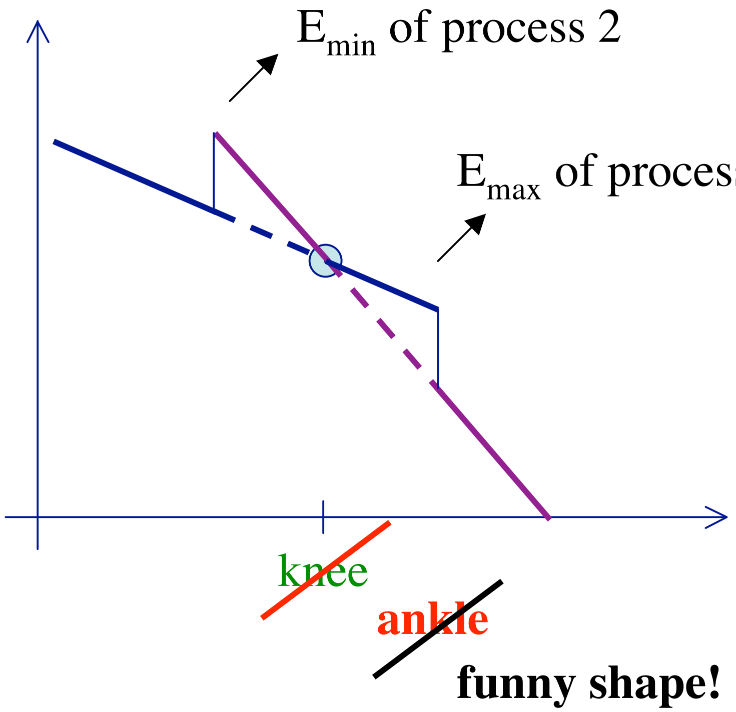
General phenomenology of transitions

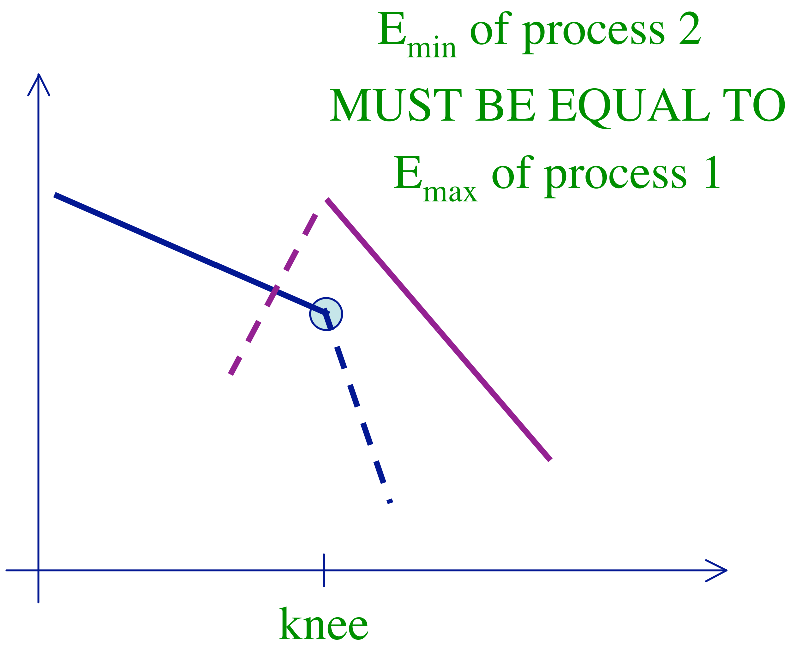
- Requirements to obtain a knee-like transition:



General phenomenology of transitions

- Requirements to obtain a knee-like transition:

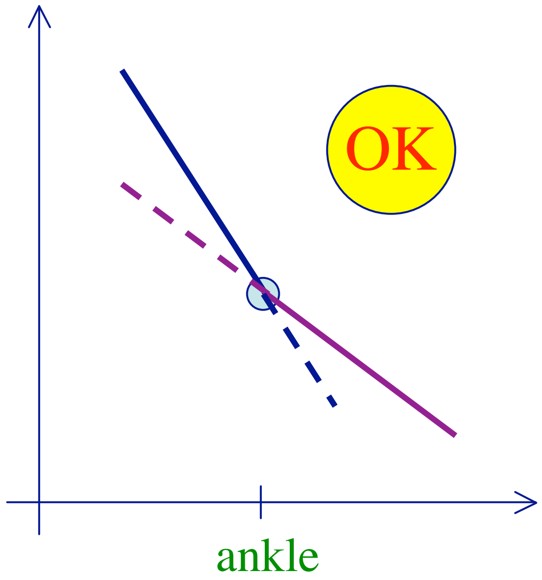




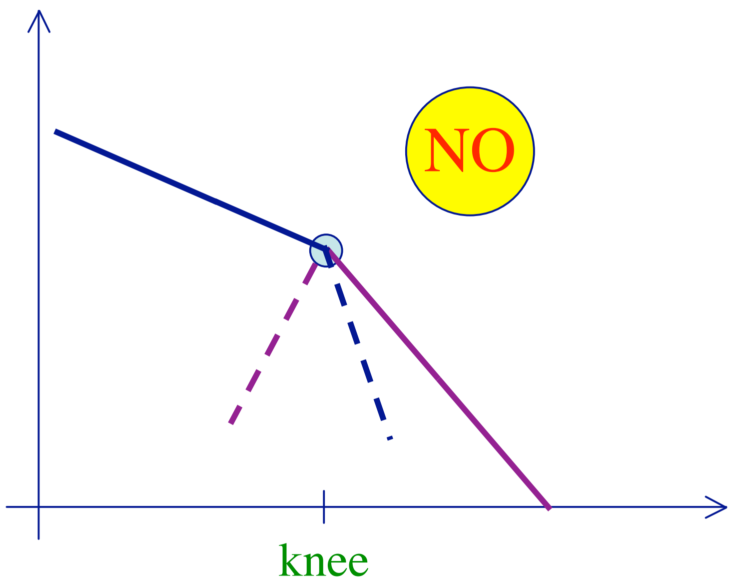
AND the flux of the two components MUST BE EXACTLY EQUAL precisely at THAT energy

General phenomenology of transitions

transition from a soft
to a harder component



~~transition from a hard
to a softer component~~



virtually impossible
(extremely improbable)

Galactic/extragalactic transition

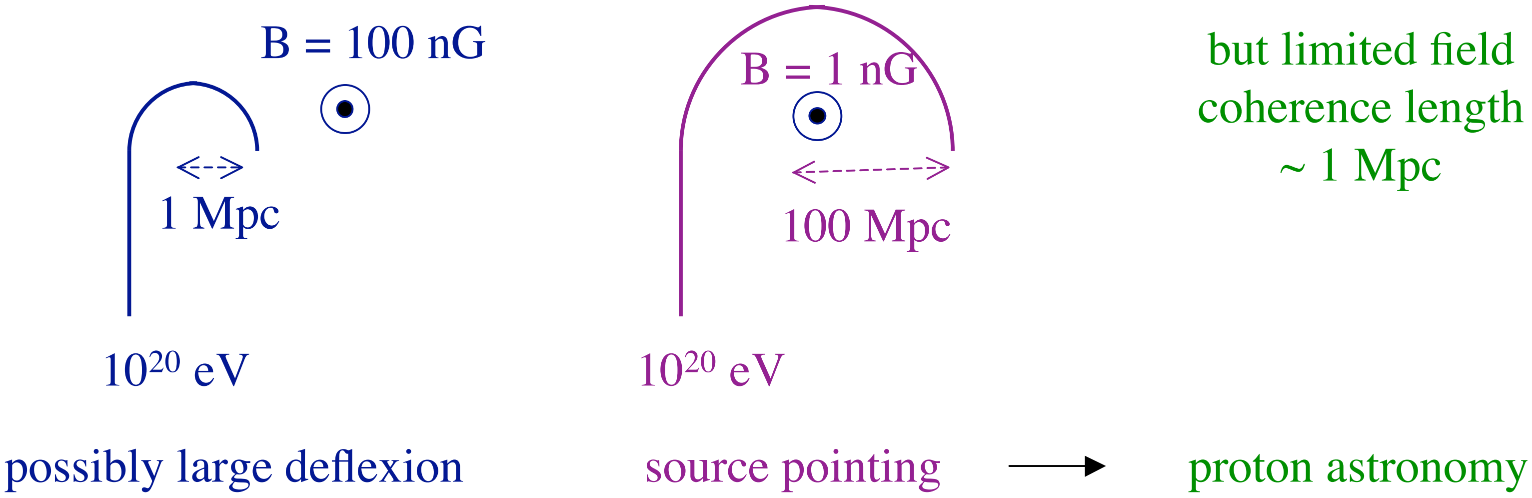
- There certainly must be a transition
- It (almost) certainly must have an ankle shape
- There is an ankle observed in the spectrum, at ~3 10^{18} eV
- This is precisely the energy range where you expect it!

It could not be at much higher energy, because galactic CRs escape anyway

It could not be at much lower energy, because extragalactic CRs are suppressed anyway

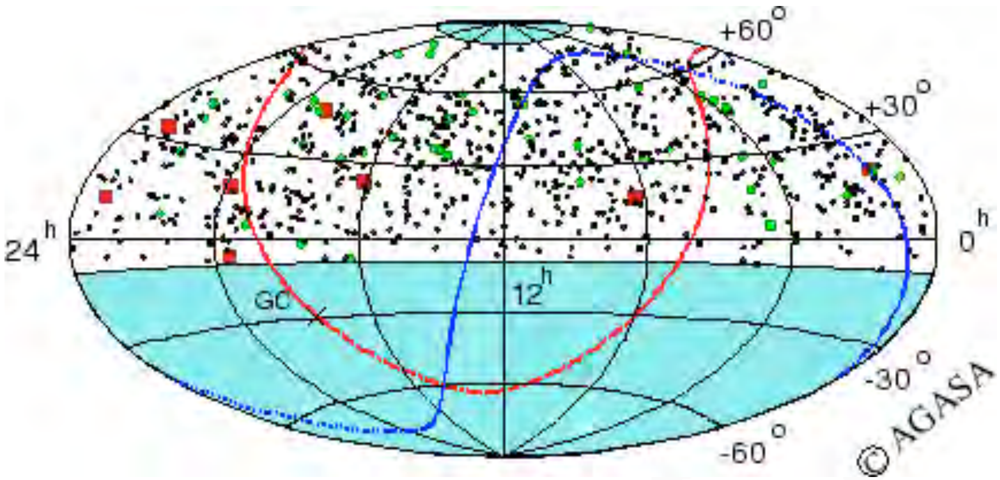
Extragalactic CRs and proton astronomy

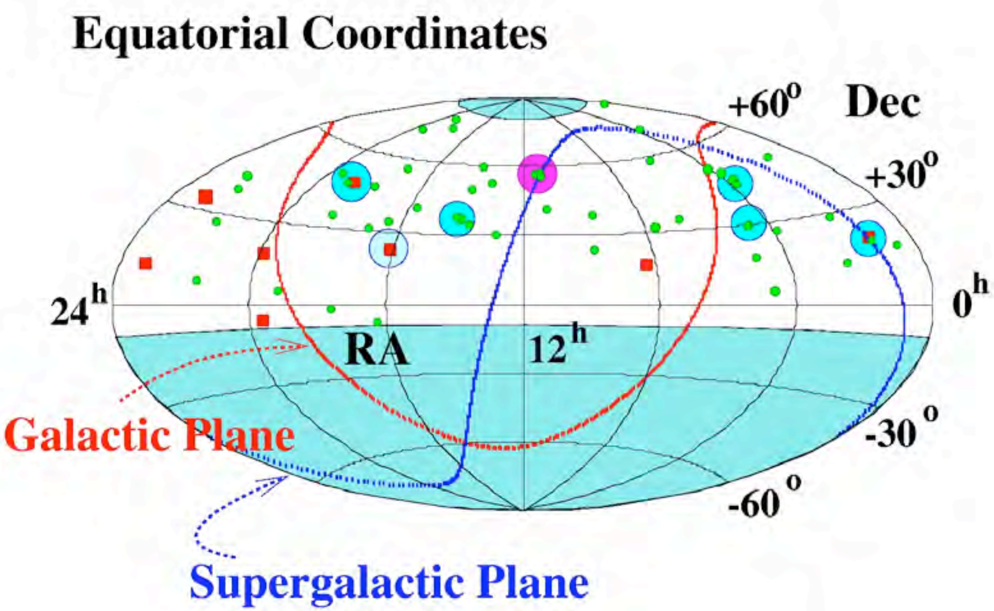
- Galactic magnetic field: ~ 3 μG (3.10^{-10} T)
- Extragalactic magnetic field: unknown… from 1 nG to 100 nG?



- At very high energy, if the CR flux is isotropic, it must be because the sources are isotropically distributed, not because of isotropisation, as at low energy.
- But isotropy can only be approximate + that does not prevent us from seeing individual sources!!!

Are there multiplets in the data?





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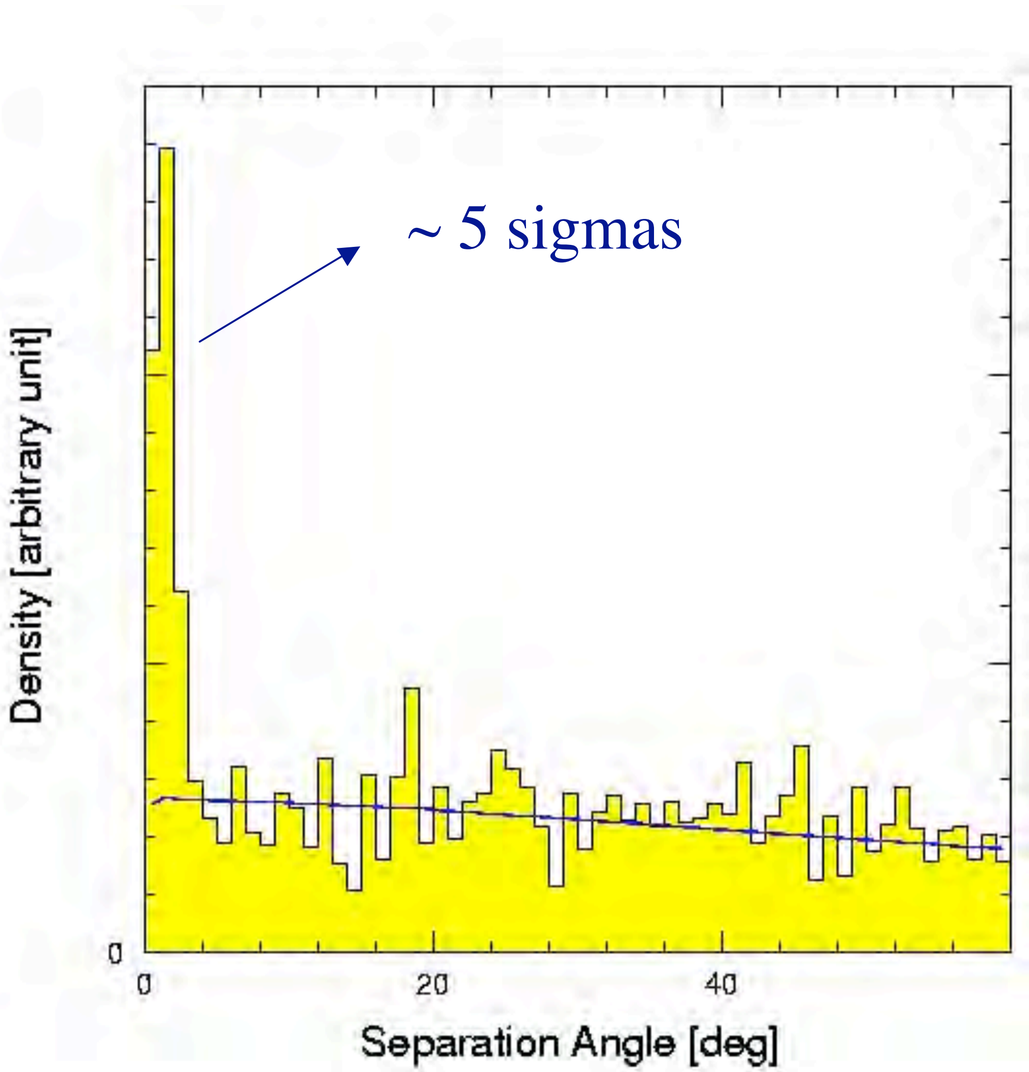
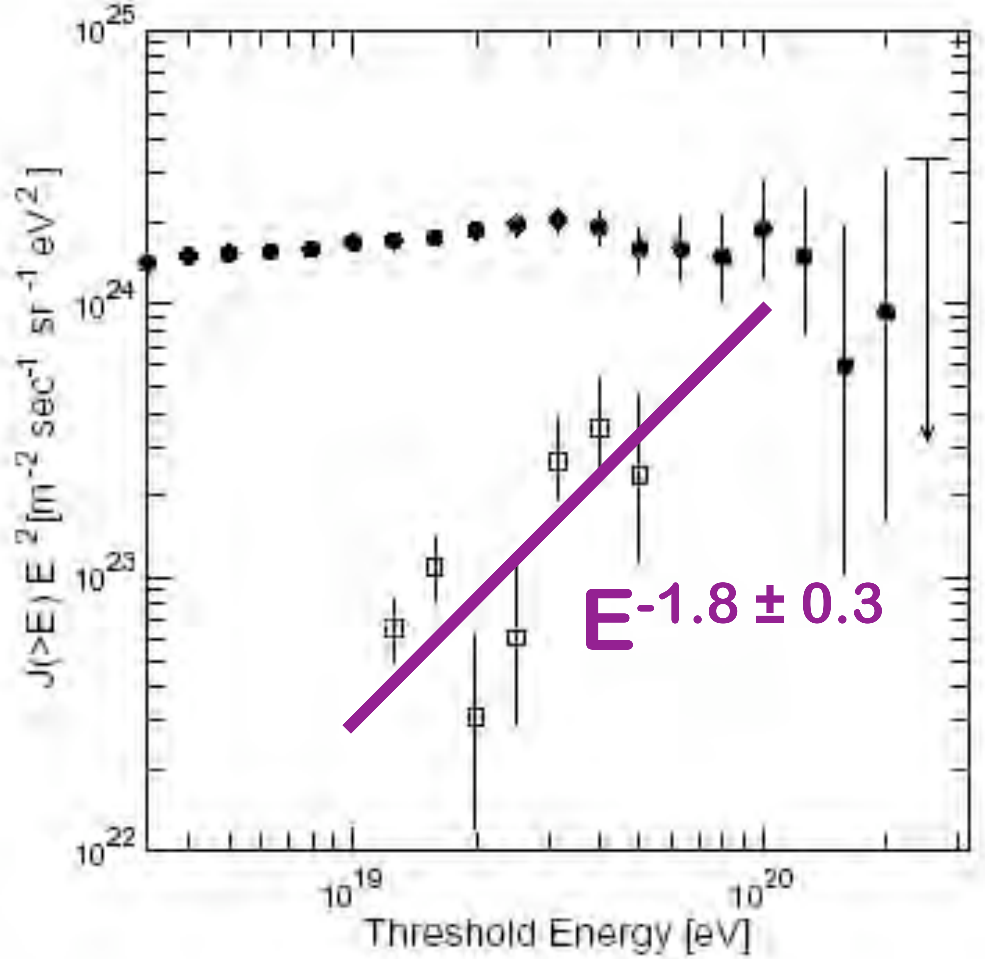


The integrated « spectrum » of multiplets



Part 2

Cosmic-ray phenomenology: propagation in the three spectral dimensions

Propagation of cosmic rays

1 **Energy space**

energy losses
re-acceleration
confinement

modification of the spectrum

2 **Nuclear space**

nuclear reactions
transmutations

modification of the composition

3 **Angular space**

interaction with magnetic field

isotropy → source pointing

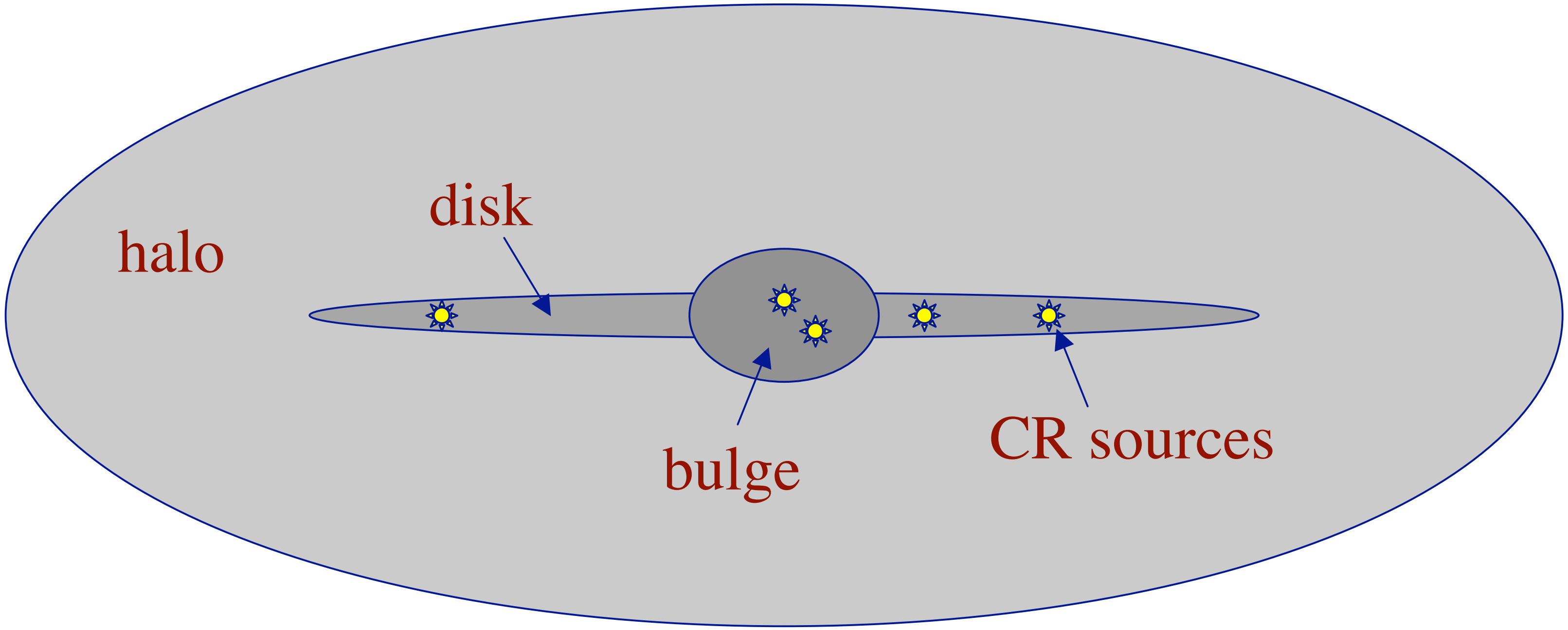
Galactic cosmic rays (low energy)

1	2	3
Energy space	**Nuclear space**	**Angular space**
↓	↓	↓
Coulombian losses re-acceleration	spallation secondary nuclei	diffusive regime confinement $t \propto D^{-1} \propto E^{-\beta}$

Result:
- source spectrum in $E^{-2.35}$
- confinement time in $E^{-0.36}$
- source composition ~ standard interstellar medium

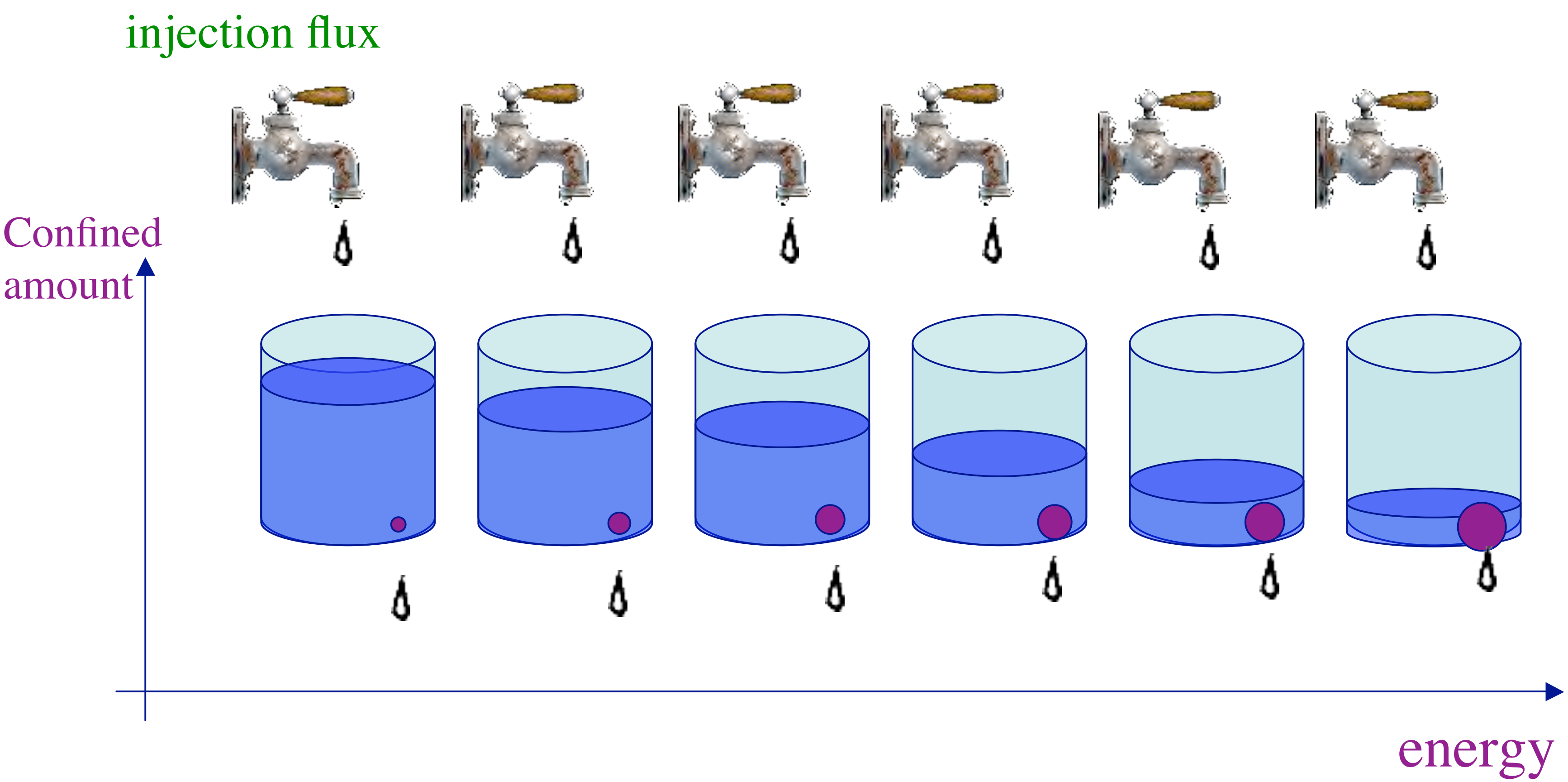
Confinement and escape

- For a given injection rate, the particles that remain confined longer are more numerous!



- Low-energy CRs stay longer in the galaxy (high-energy CRs escape quicker)!

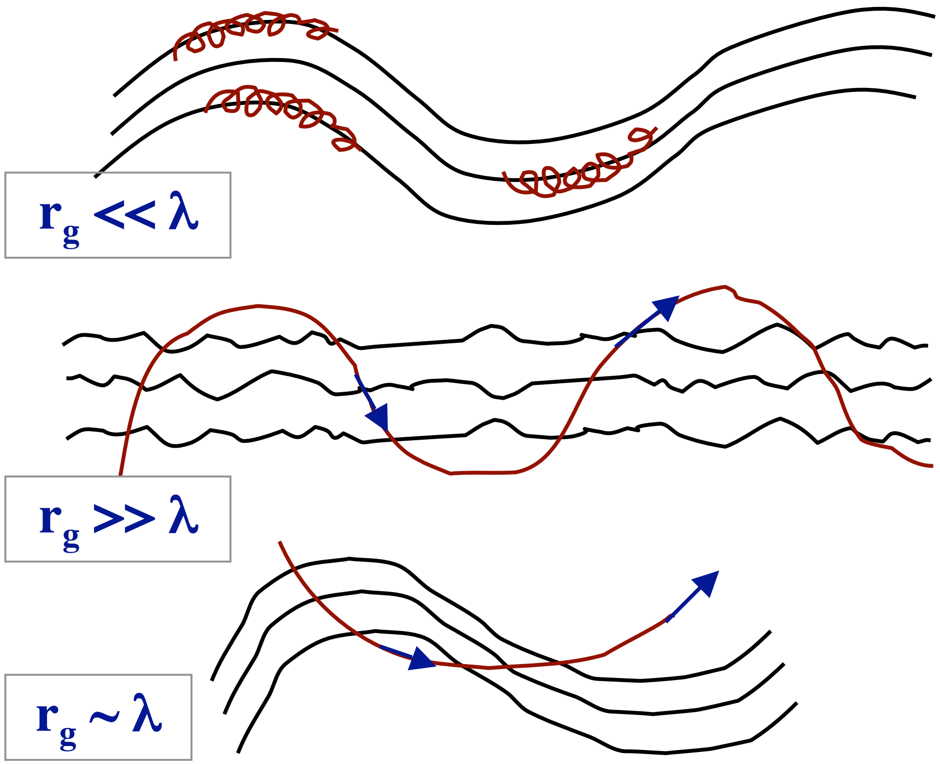
Spectrum modification



- Amplification of low-energy cosmic rays
  $\Rightarrow$ steepening of the spectrum

Transport of charged particles in B field

- Interaction with the ambient magnetic field
  - regular field / turbulent field — magnetic waves

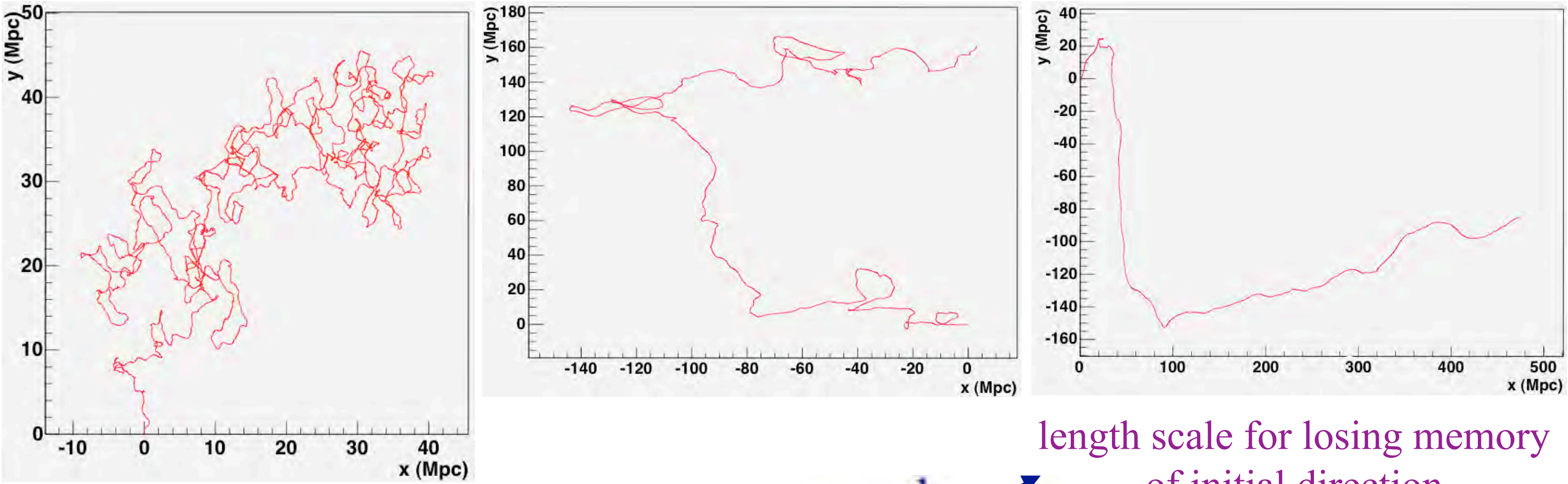


Adjustment of first adiabatic invarient:
$p_\perp^2 / B \sim \text{cst}$

Nothing spécial…
(pitch angle ~ constant)

pitch-angle diffusion:
$\Delta\alpha \sim B_1/B_0$
Drift of the guiding centre:
$r \sim r_g \, \Delta\alpha$

Diffusive regime: "random walk"



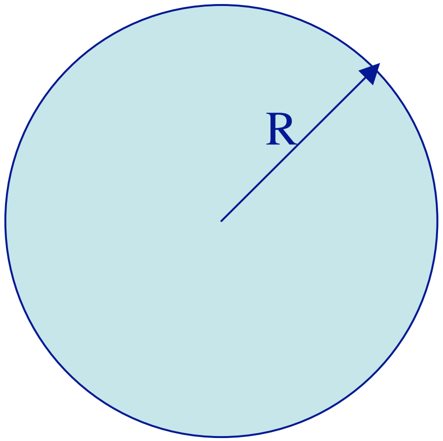
length scale for losing memory of initial direction (~ significant deflection)

- Random walk process $D = \frac{1}{3}\lambda_{\rm diff}\, v$
- Bohm regime $\lambda_{\rm diff} = r_{\rm g} \longrightarrow D_{\rm B} = \frac{1}{3} r_{\rm g} c$
- Quasilinear theory of resonant diffusion
  - At low energies, $r_g << \lambda_c$ $D(E) \simeq \frac{1}{3} r_{\rm g} c \frac{\langle B^2 \rangle}{\int_{1/r_{\rm L}}^{\infty} {\rm d}k B^2(k) k^2}$

$B^2(k)k^2 \propto k^{-5/3} \longrightarrow D(E) \propto E^{1/3}$

Confinement and escape

- Diffusive regime: $< r^2 > = 6Dt \propto E^{\alpha}$



- Confinement time in the galaxy (typical size R)

$$\tau_{conf} = R^2/6D \propto E^{-\alpha}$$

Cosmic ray spectrum slope steepening

- Confinement time of cosmic rays of energy E:

$$\tau_{\text{conf}} \propto E^{-\alpha}$$

- Injection rate in the whole Galaxy:

$$\frac{dN(E)}{dt} \propto E^{-x}$$

- Resulting number in the Galaxy (steady-state)

$$N(E) = \tau_{\text{conf}} \times \frac{dN(E)}{dt} \propto E^{-(x+\alpha)}$$

slope steepening

- Observed spectrum: $E^{-2.71}$ ➔ $x + \alpha = 2.71$

Result from CR study at low E

- The cosmic-ray spectrum and composition
- The abundance ratios of secondary and primary nuclei
- The abundance of radioactive secondary nuclei (produced by nuclear interactions during CR propagation)

- Everything can be very well reproduced, at all energies (where measurements are possible), with the following "best fit" parameters

- Source spectrum power law index: $x = 2.35$
- Confinement time energy dependence: $\alpha = 0.36$

↓

remarkably close to 1/3

Extragalactic cosmic rays (high energy)

1 — Energy space

↓

interaction with CMB

↓

GZK cutoff

2 — Nuclear space

↓

interaction with CMB

↓

photo-disintegration

3 — Angular space

↓

interaction with magnetic field

↓

isotropy → source pointing

Extragalactic cosmic rays (high energy)

1

Energy space

interaction with CMB

↓

GZK cutoff

2

Nuclear space

interaction with CMB

↓

photo-disintegration

3

Angular space

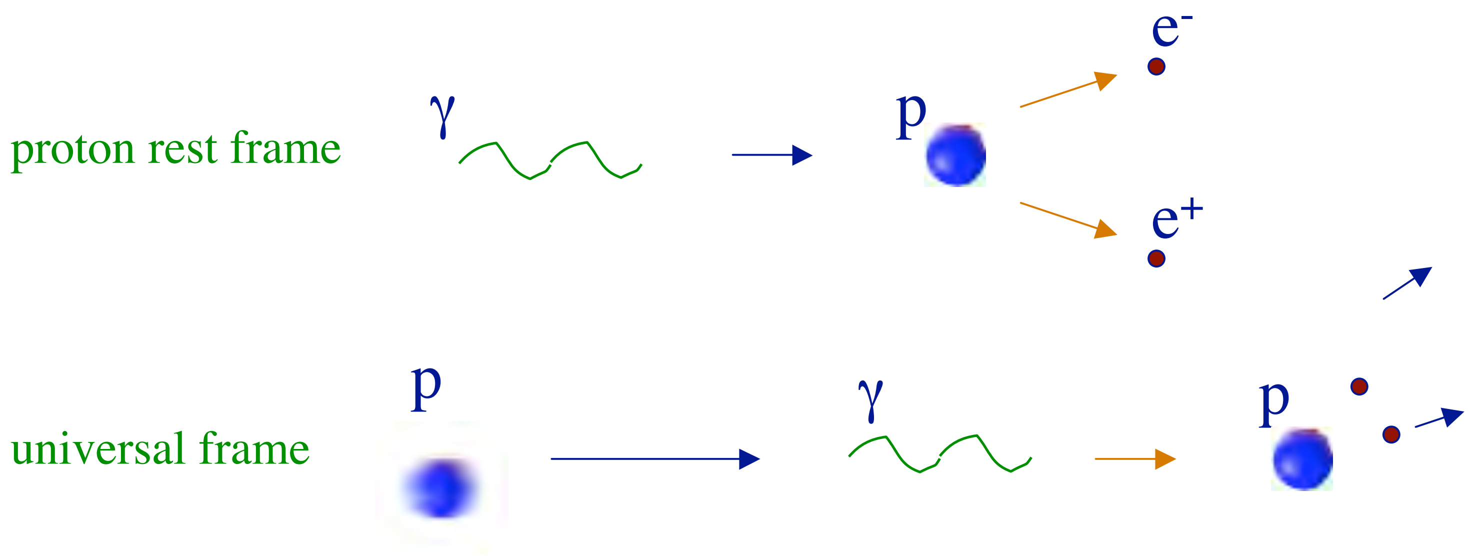
interaction with magnetic field

↓

isotropy → source pointing

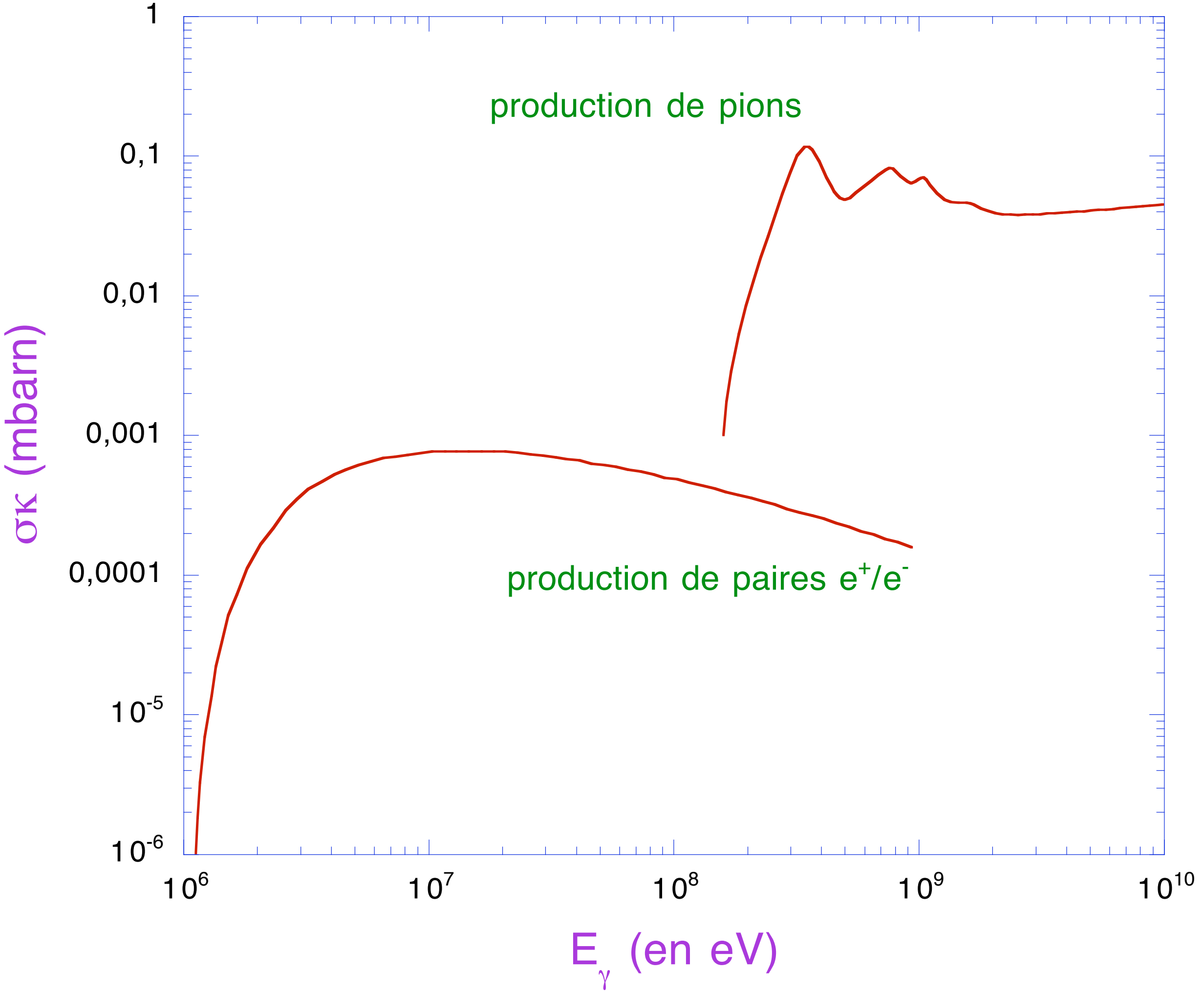
The GZK effect

- Greisen (1966) + Zatsepin & Kuz'min (1966)
- Energy losses due to pion and e^+/e^- pair production

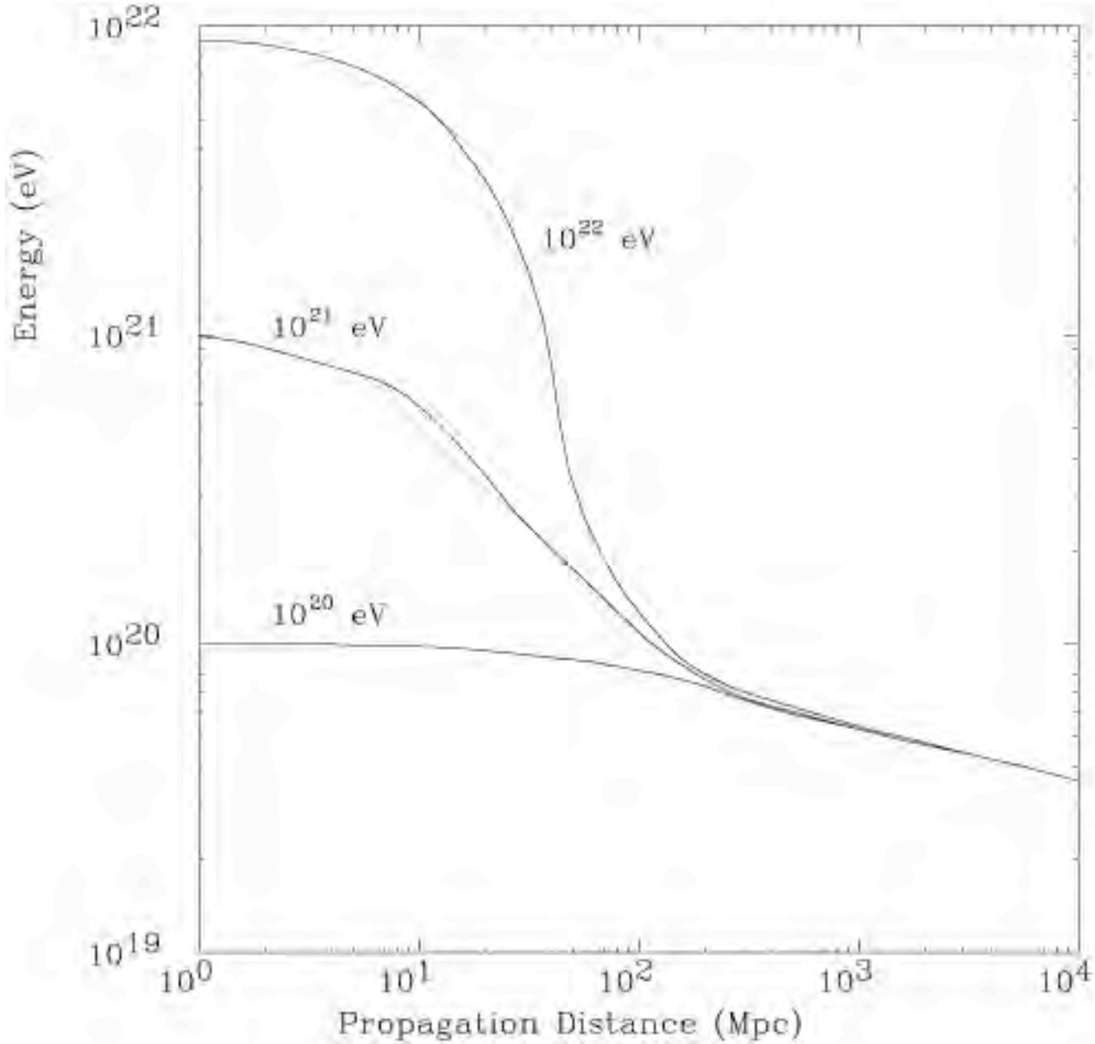


- Threshold: $E_\gamma = 2\ m_e c^2$ or $2m_\pi c^2$ in the proton rest frame

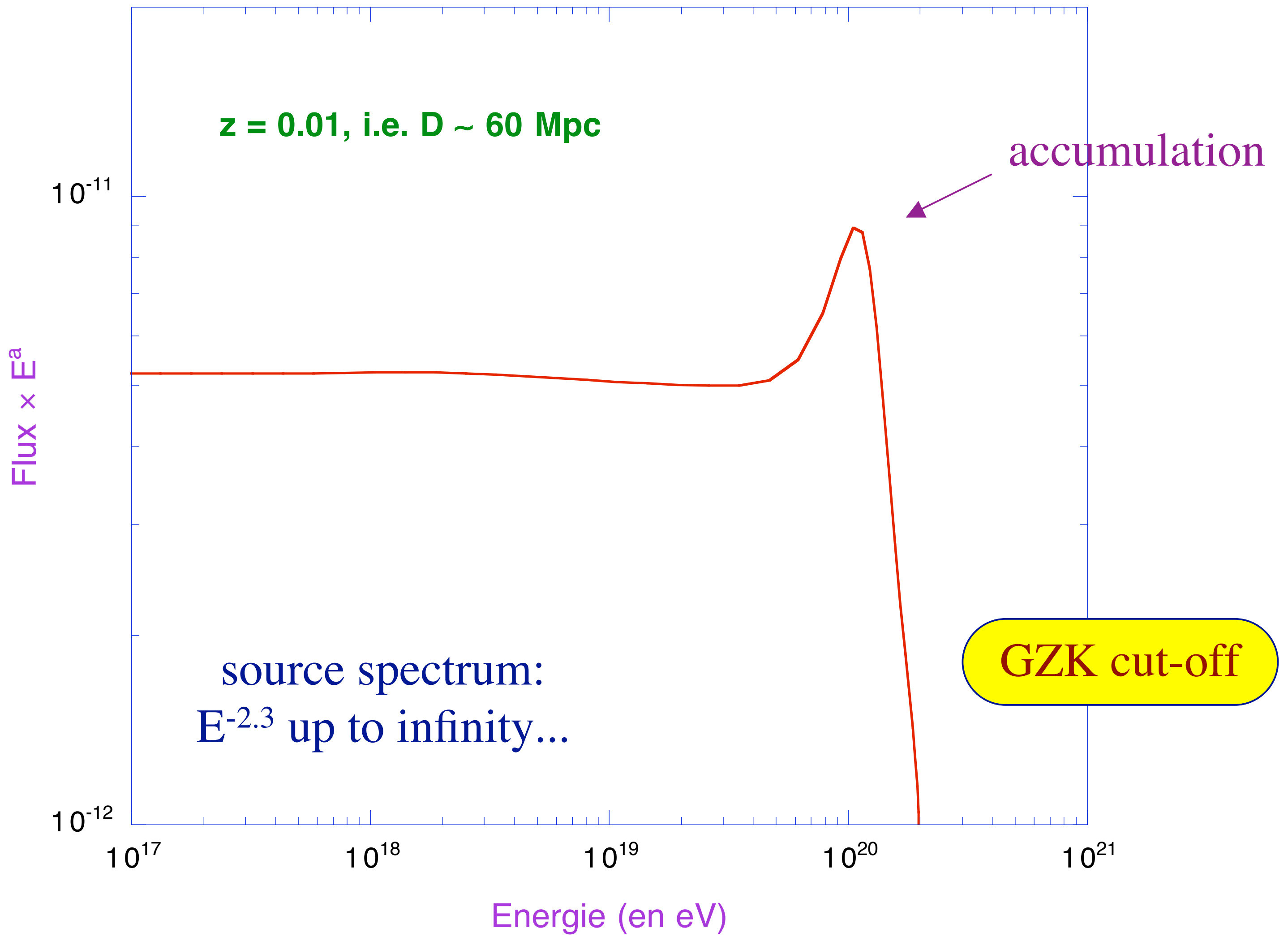
Cross section for energy losses

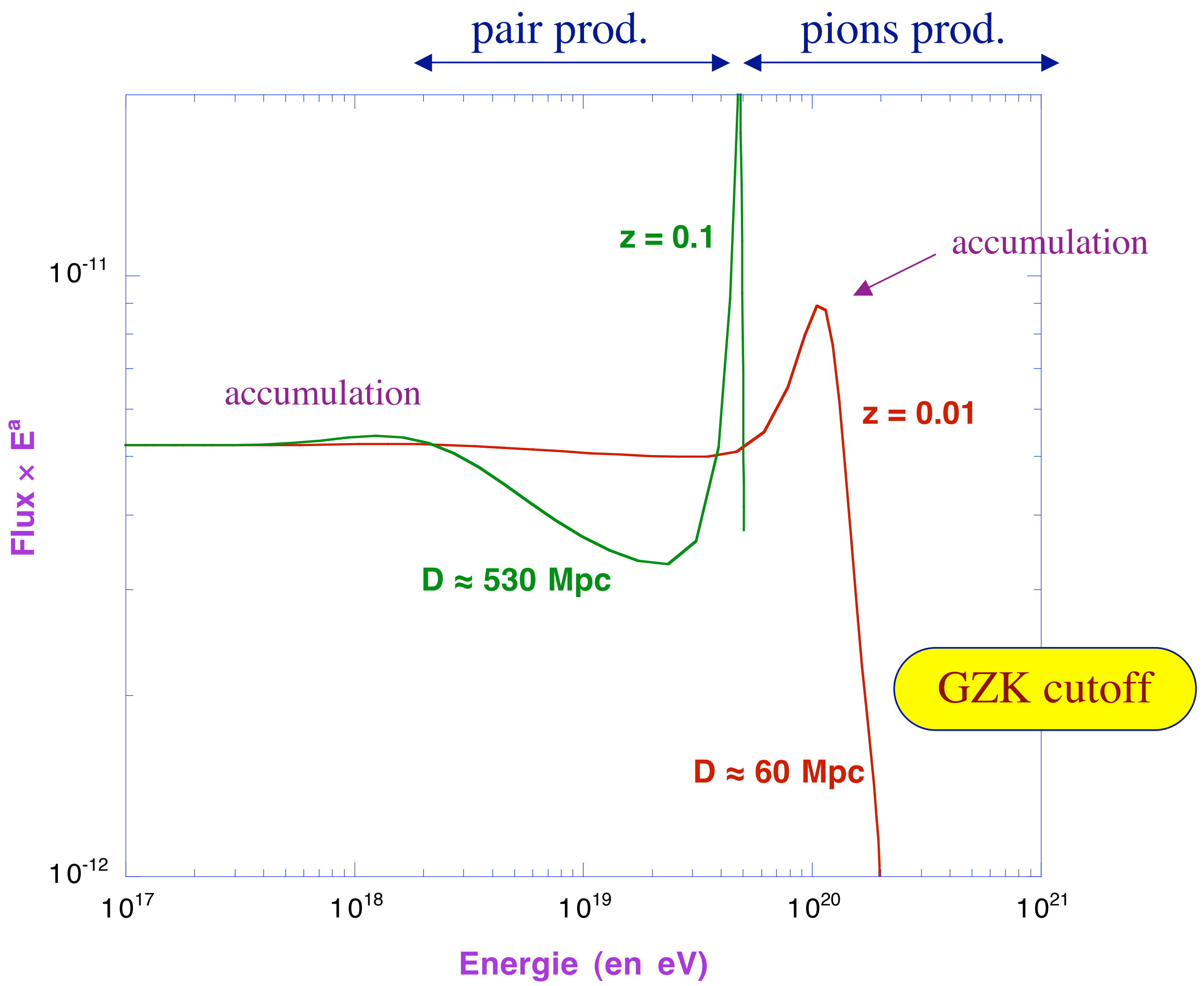


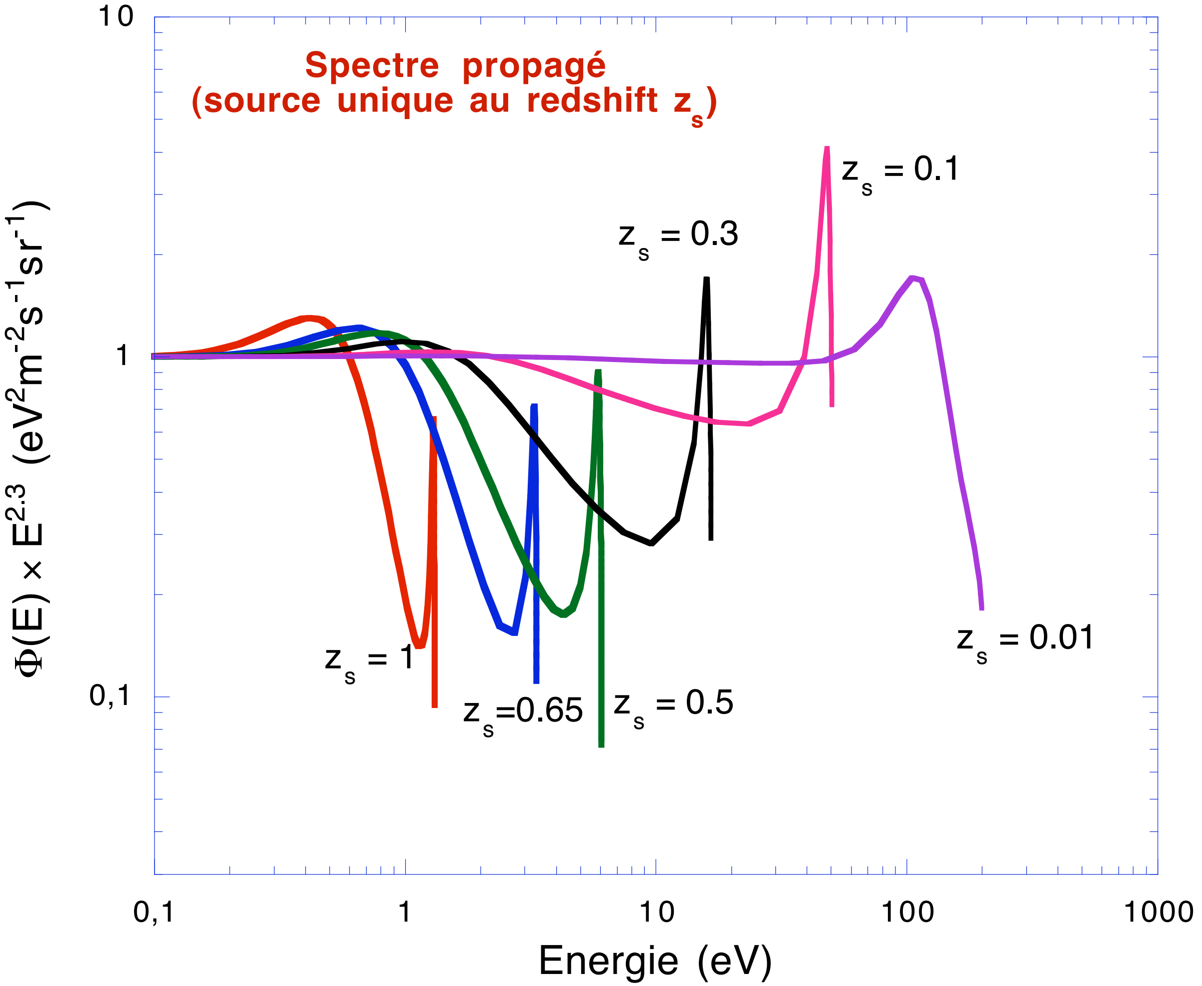
Energy evolution of a cosmic ray



“Propagated spectrum”

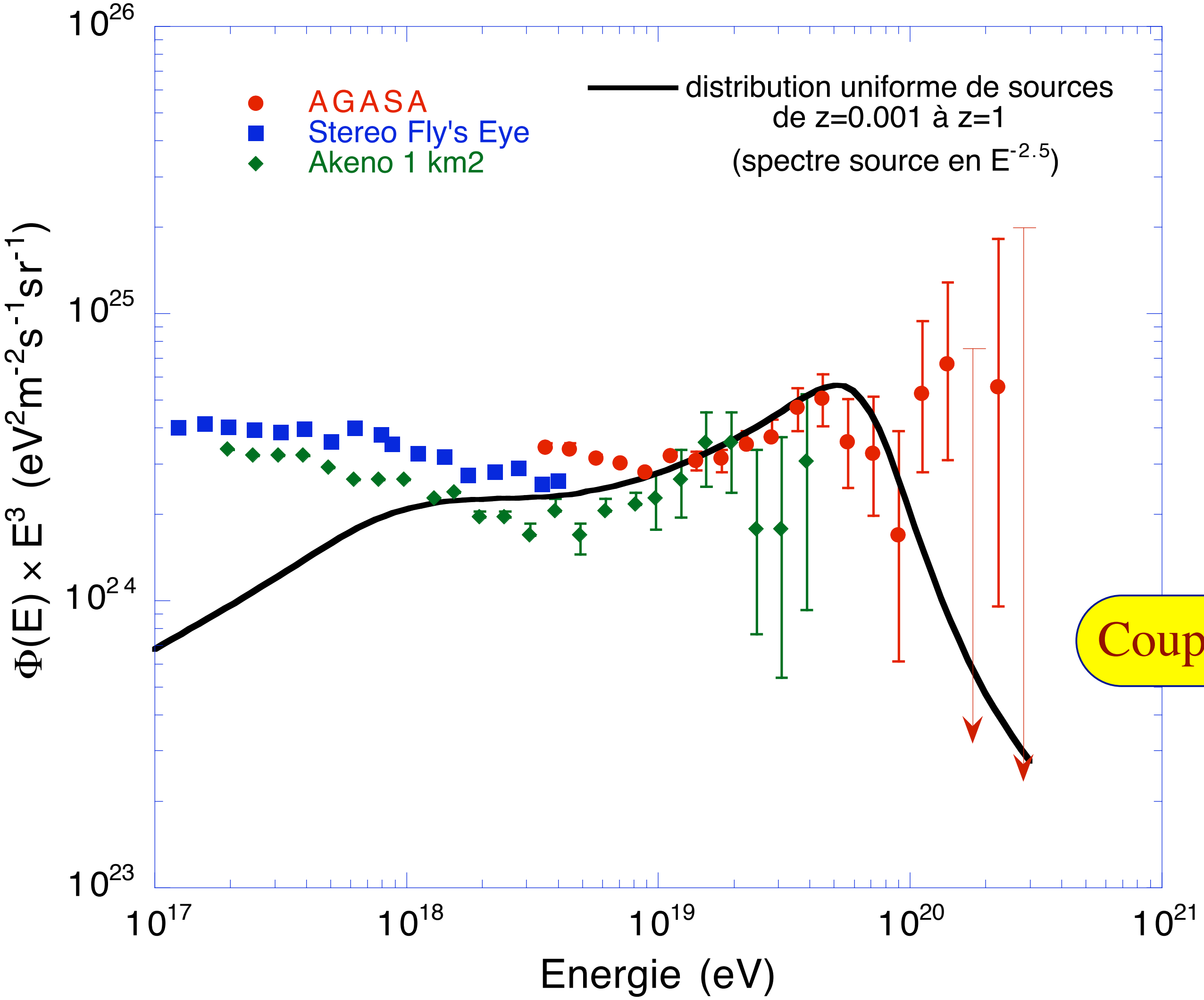



pair prod.
pions prod.
accumulation
z = 0.1
accumulation
z = 0.01
D ≈ 530 Mpc
GZK cutoff
D ≈ 60 Mpc
10-11
10-12
1017
1018
1019
1020
1021
Flux × Ea
Energie (en eV)



Spectre propagé
(source unique au redshift z_s)
z_s = 0.1
z_s = 0.3
z_s = 1
z_s=0.65
z_s = 0.5
z_s = 0.01
10
1
0,1
0,1
1
10
100
1000
Energie (eV)
$\Phi(E) \times E^{2.3}$ ($eV^2m^{-2}s^{-1}sr^{-1}$)

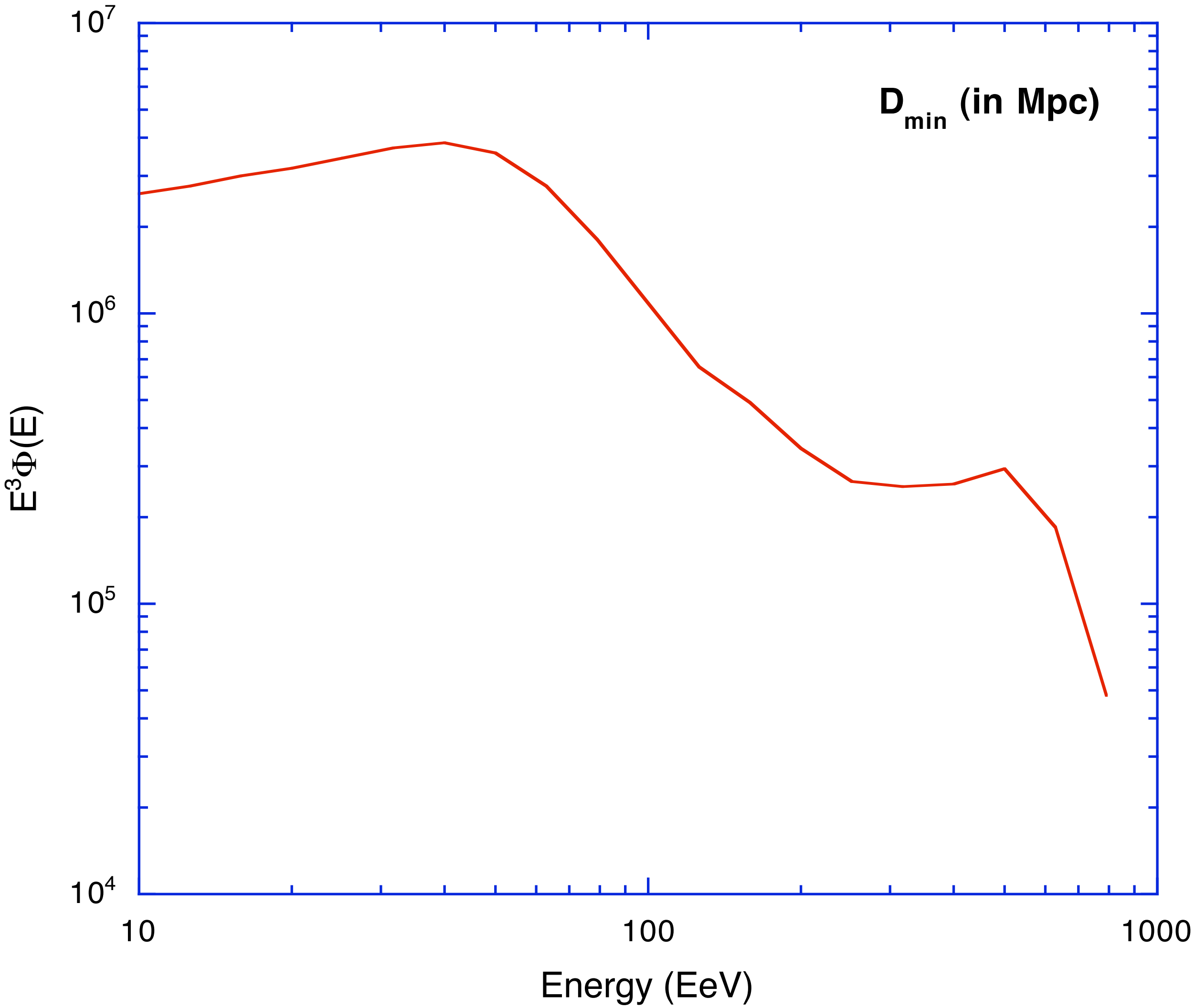
Uniform source distribution



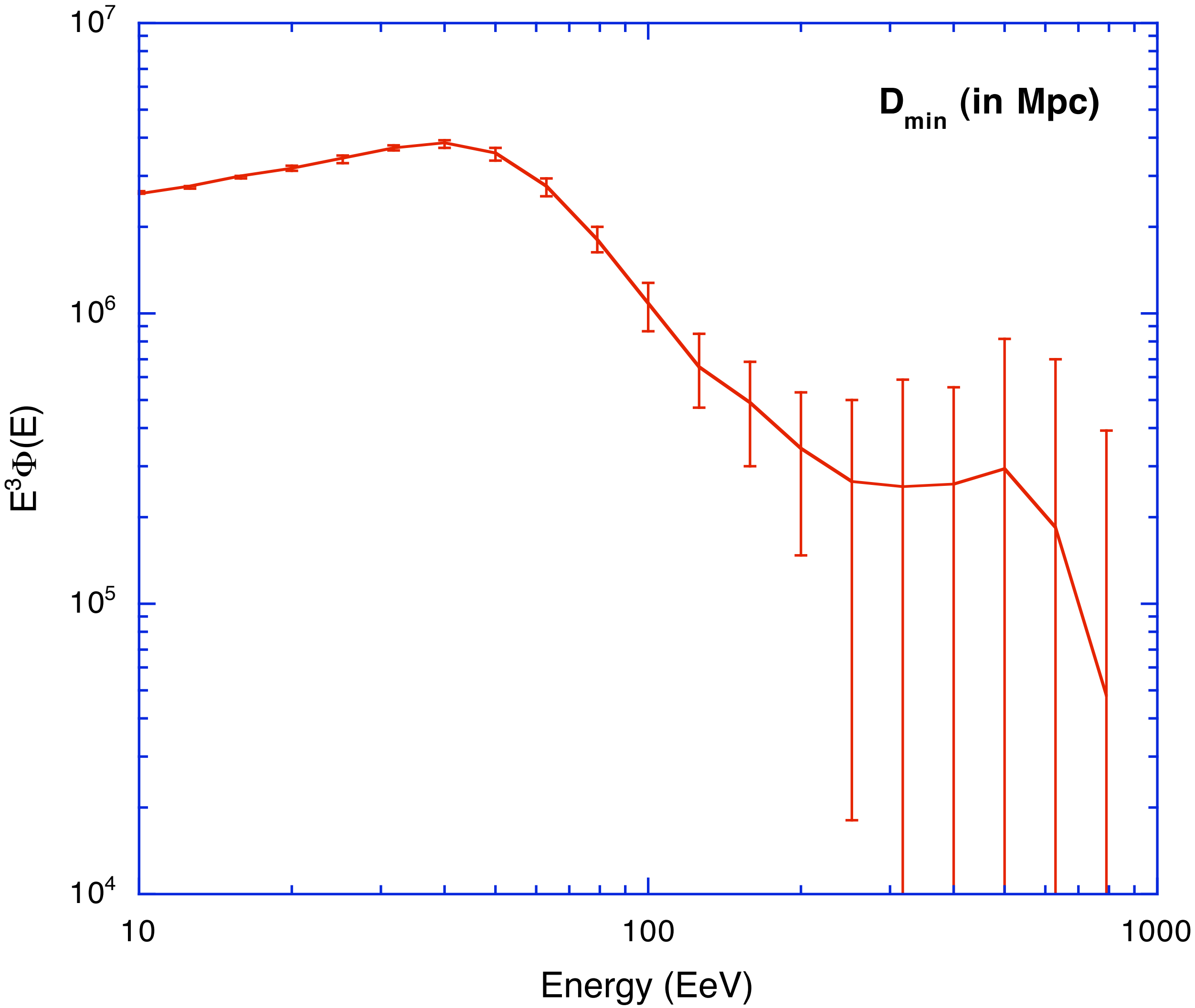
Coupure GZK

"flux recovery" (from nearby sources)

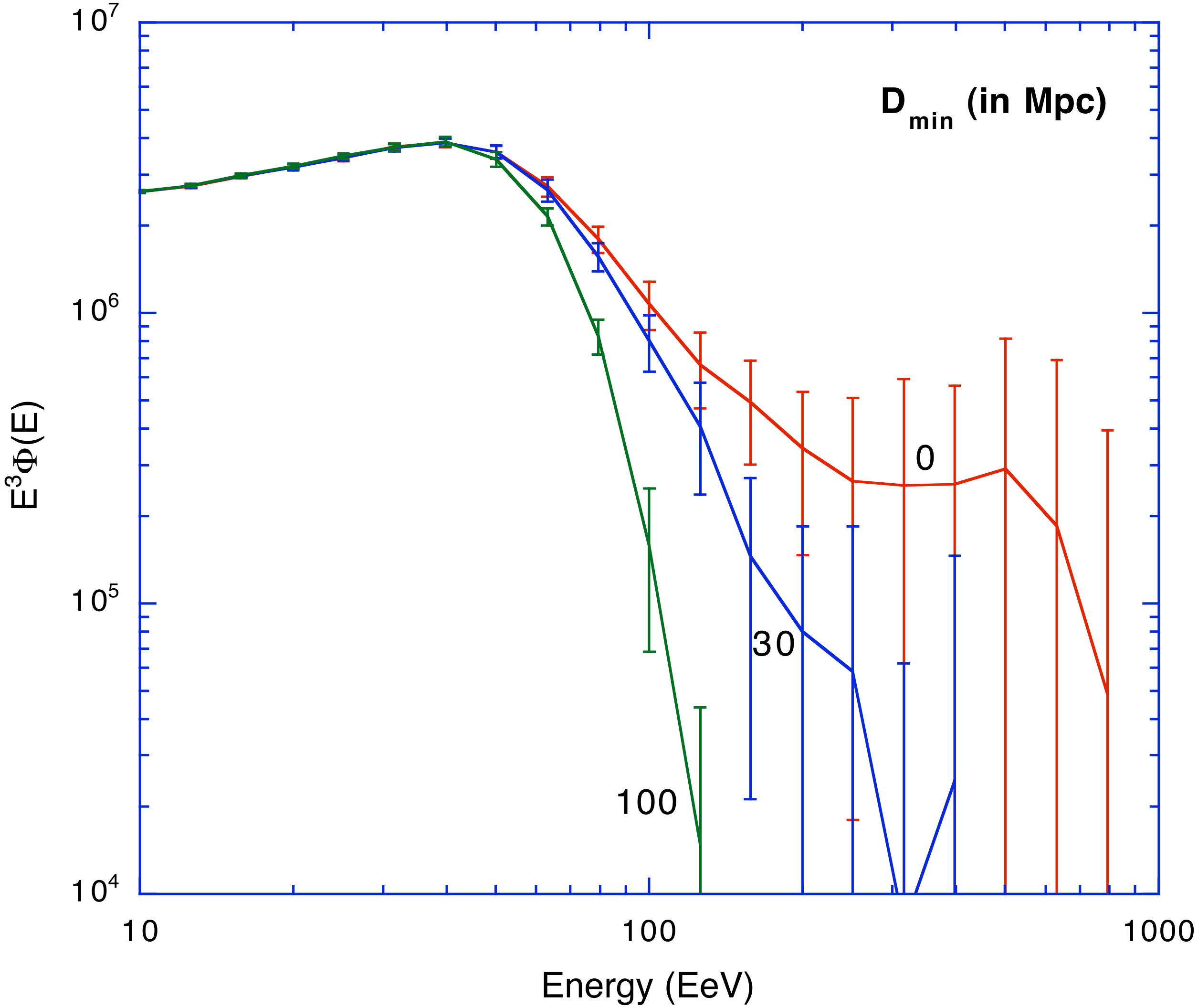
- GZK protons lose energy by pion production in a discrete way: $\Delta E/E \sim 20\%$



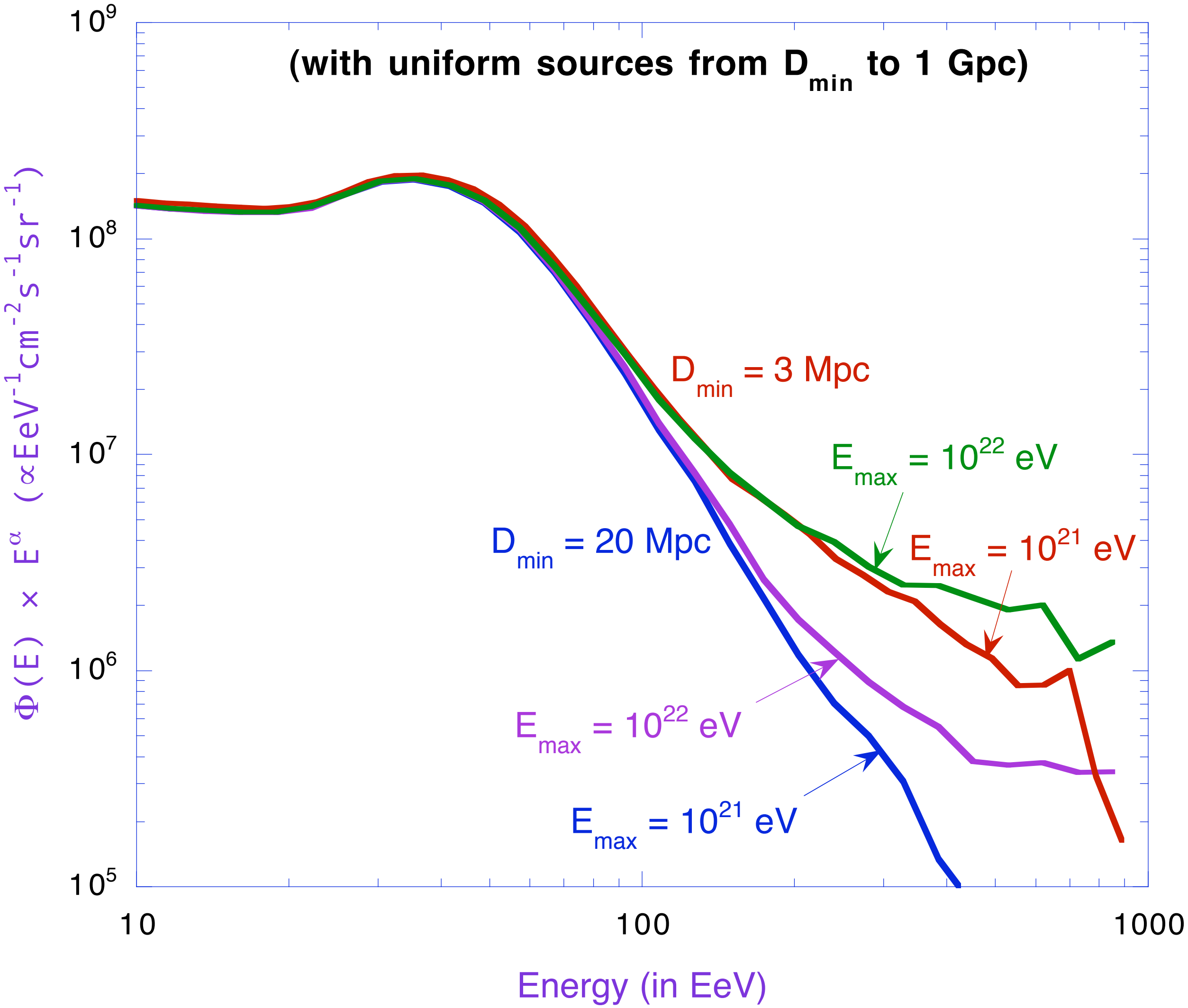
Stochastic propagation and limited data set



Influence of source granularity (D_{min})

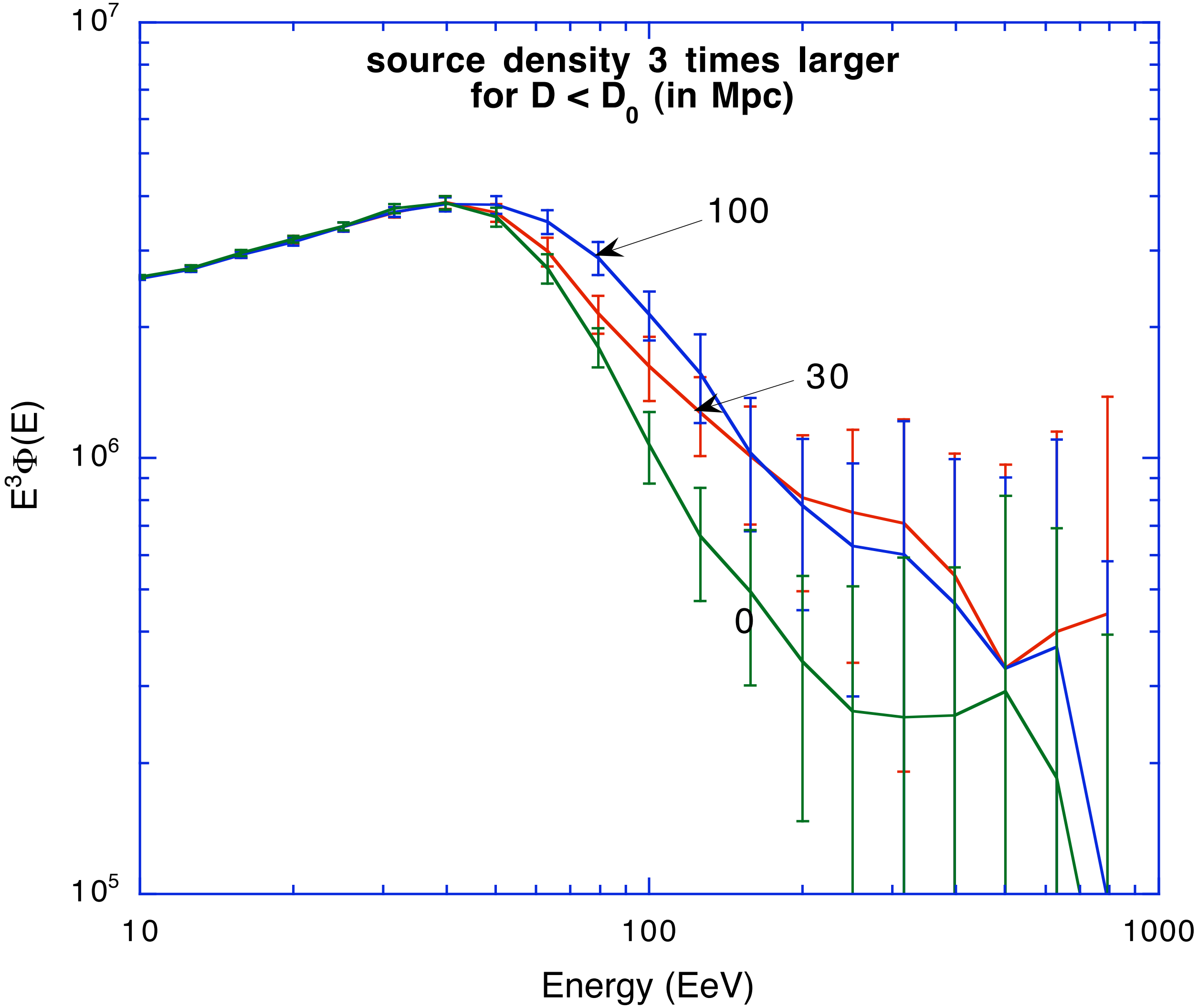


Influence de E_{max}

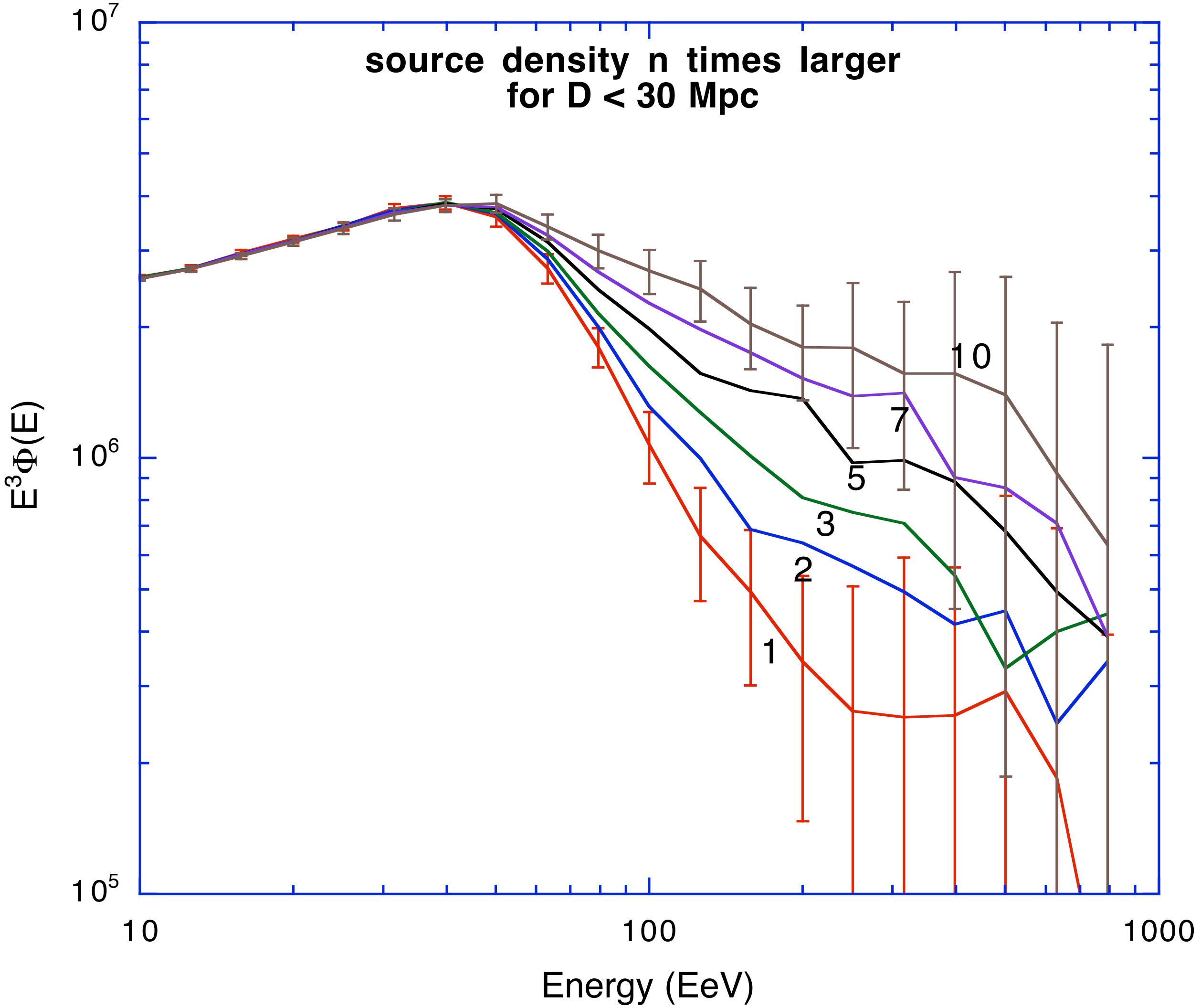


+ the source spectrum does not have to be a power law?

Local overdensity of sources - 1

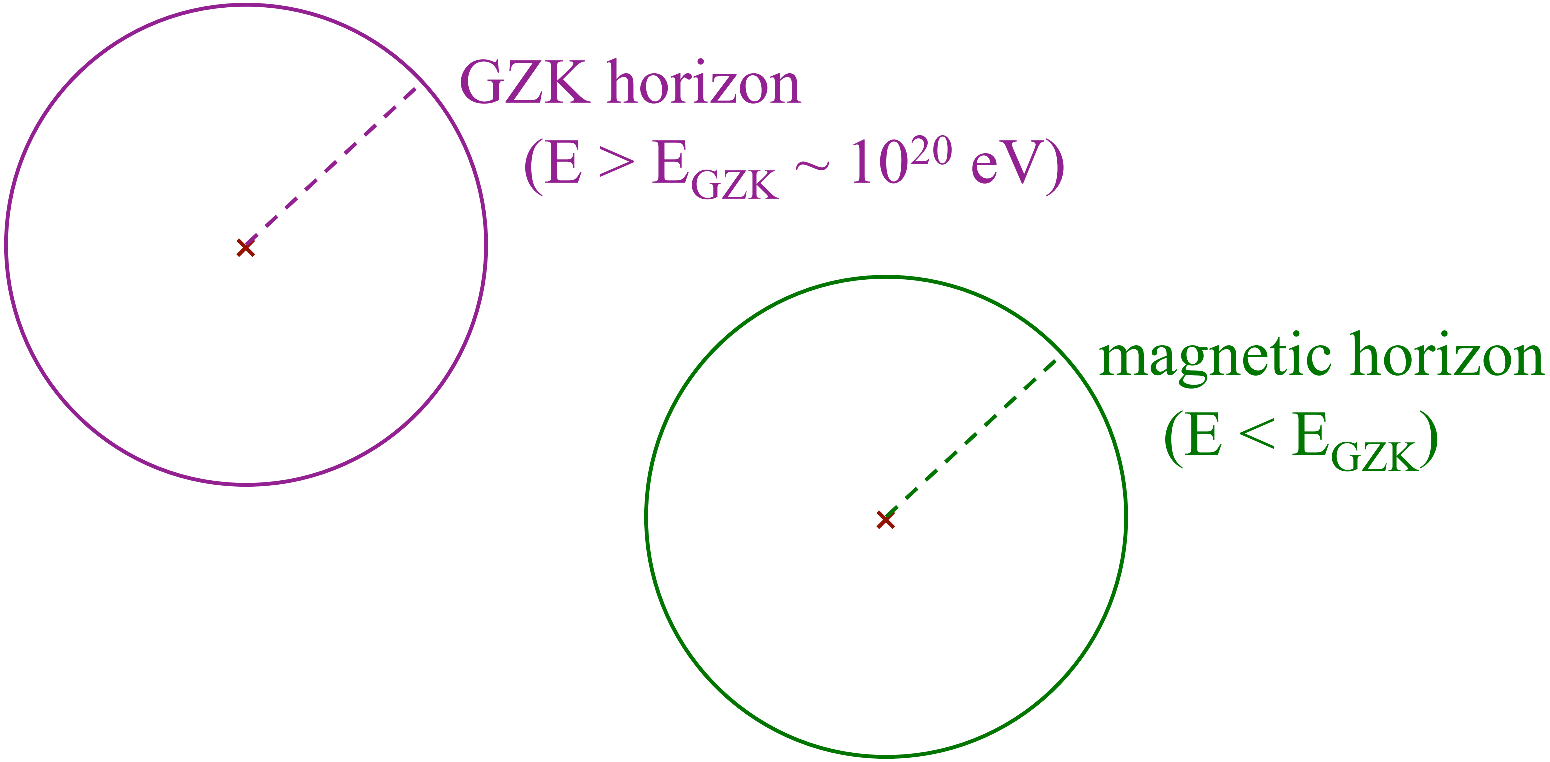


Local overdensity of sources - 2



Influence of the magnetic field

- If B is large, the diffusion coefficient is small and the particles may not have had enough time pas to reach us from distant sources!

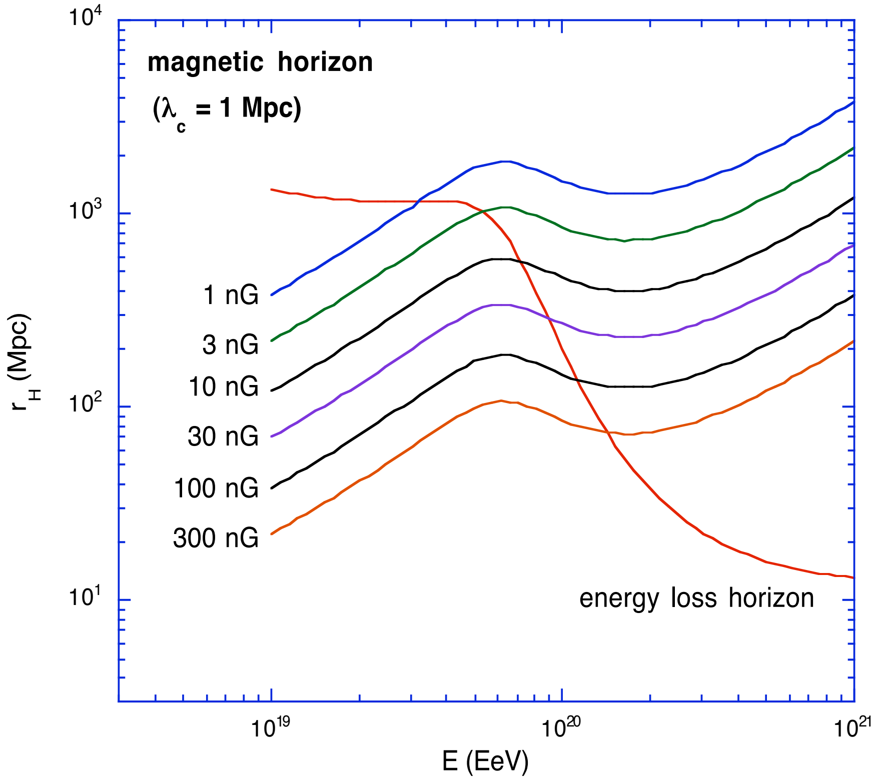


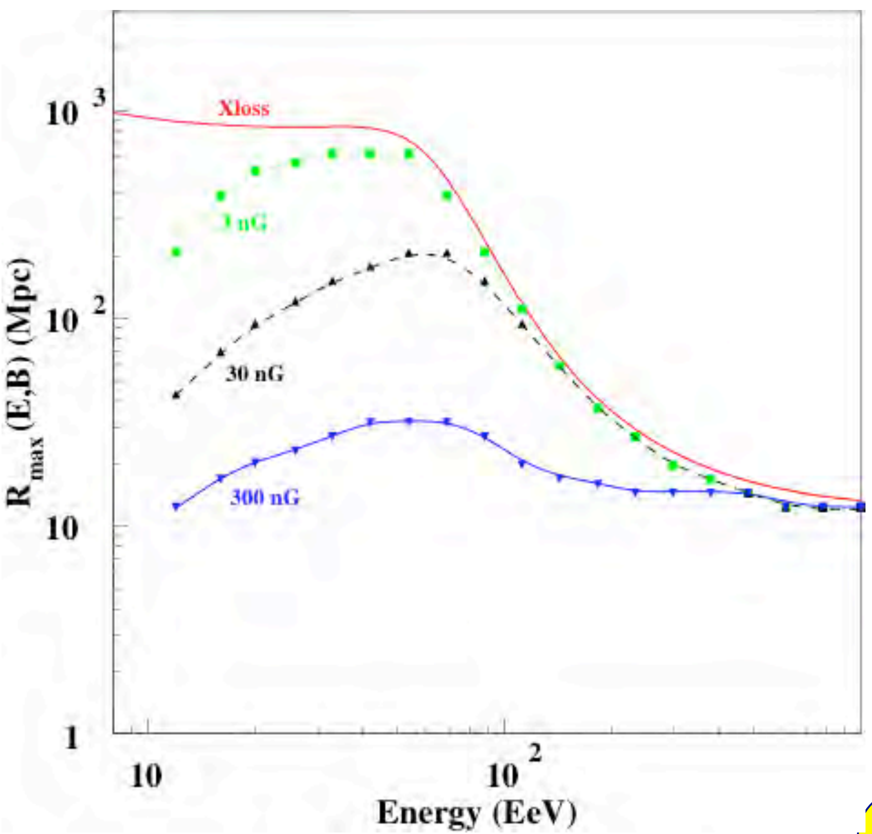
→ the source distance is limited at **all** energies!

Magnetic horizons

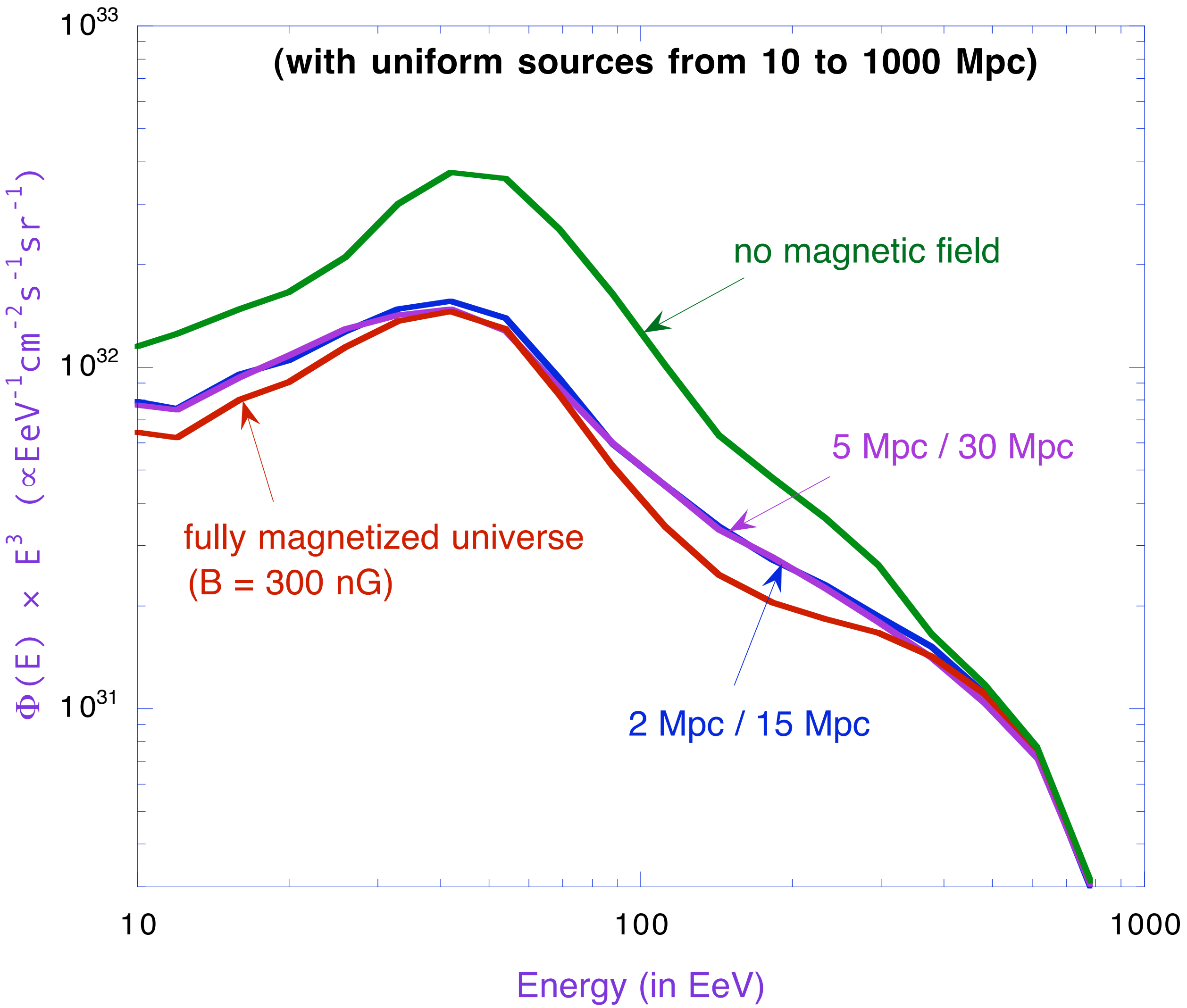
$$r_H \simeq \lambda_{diff} \left(\frac{\tau_{loss}}{\tau_{diff}} \right)^{1/2}$$

$$r_H \simeq 0.58\,\mathrm{Mpc} \left(\frac{\tau_{loss}}{1\,\mathrm{Myr}} \right)^{1/2} \left(\frac{E/Z}{10^{18}\mathrm{eV}} \right) \left(\frac{B}{1\,\mathrm{nG}} \right)^{-1/2}$$





Reduction of the GZK cutoff



- Do not say “**THE** GZK cutoff”, but “**the** GZK cutoffs” !

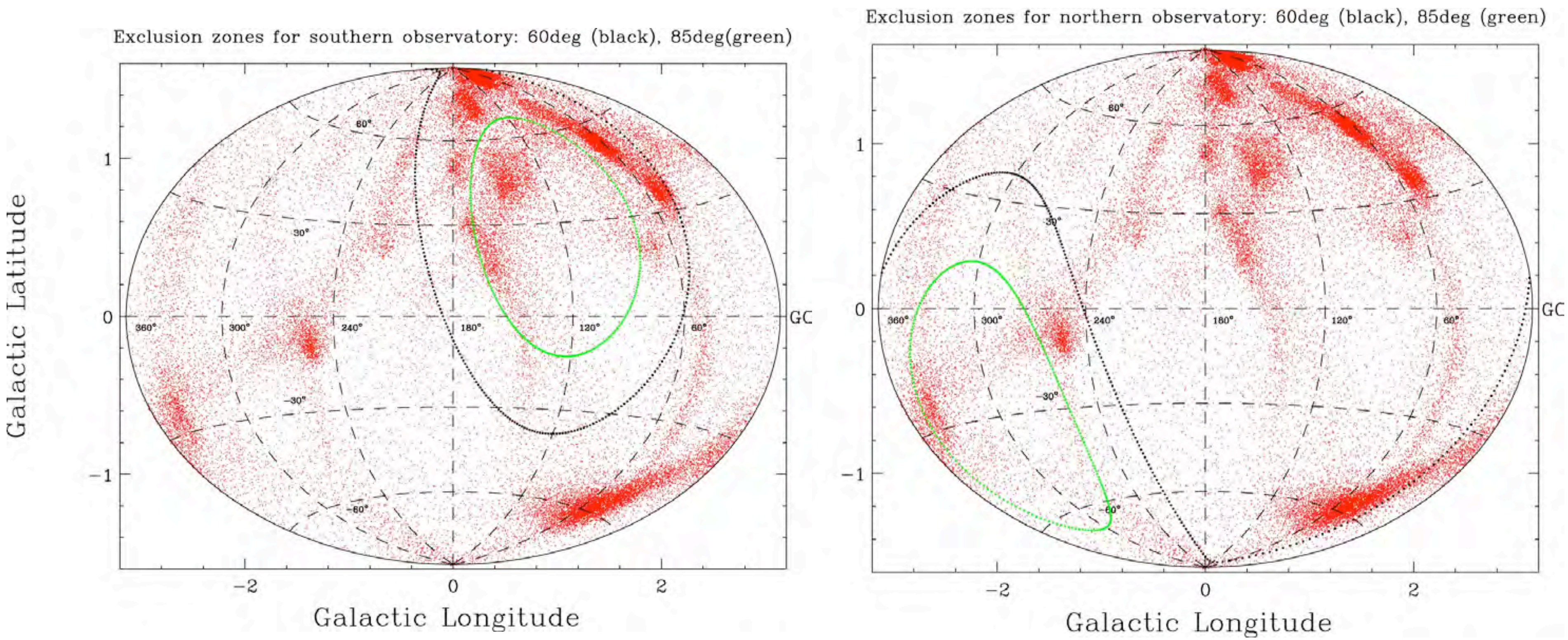
- The Pierre Auger Observatory does not have to find whether **THE** GZK cutoff is there or not:

- The Pierre Auger Observatory has to measure **which** GZK cutoff is actually realised in Nature

- + the shape of the extragalactic spectrum: ankle, e^+e^- dip, etc.

Not the same spectrum everywhere!!!

Galaxy distribution 7-21 Mpc



Southern site **Northern site**

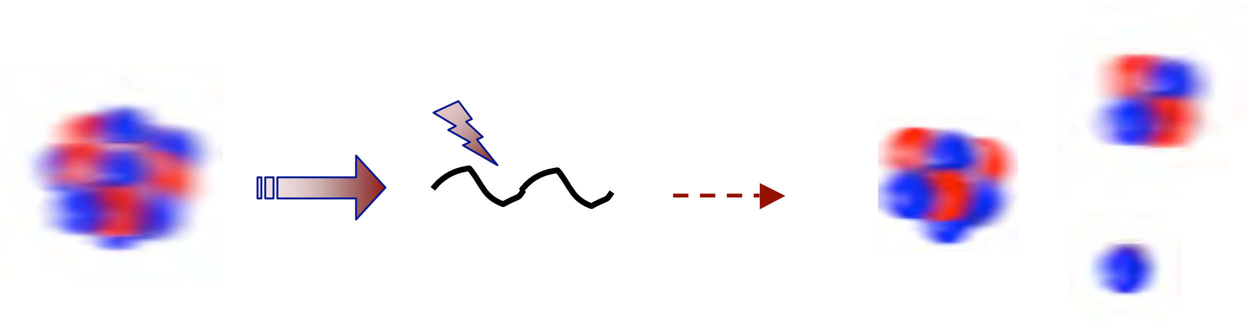
Necessity of a global sky coverage ➔
Northern site of the Pierre Auger Observatory

Extragalactic cosmic rays (high energy)

1	2	3
Energy space	**Nuclear space**	**Angular space**
↓	↓	↓
interaction with CMB	interaction with CMB	interaction with magnetic field
↓	↓	↓
GZK cutoff	photo-disintegration	isotropy → source pointing

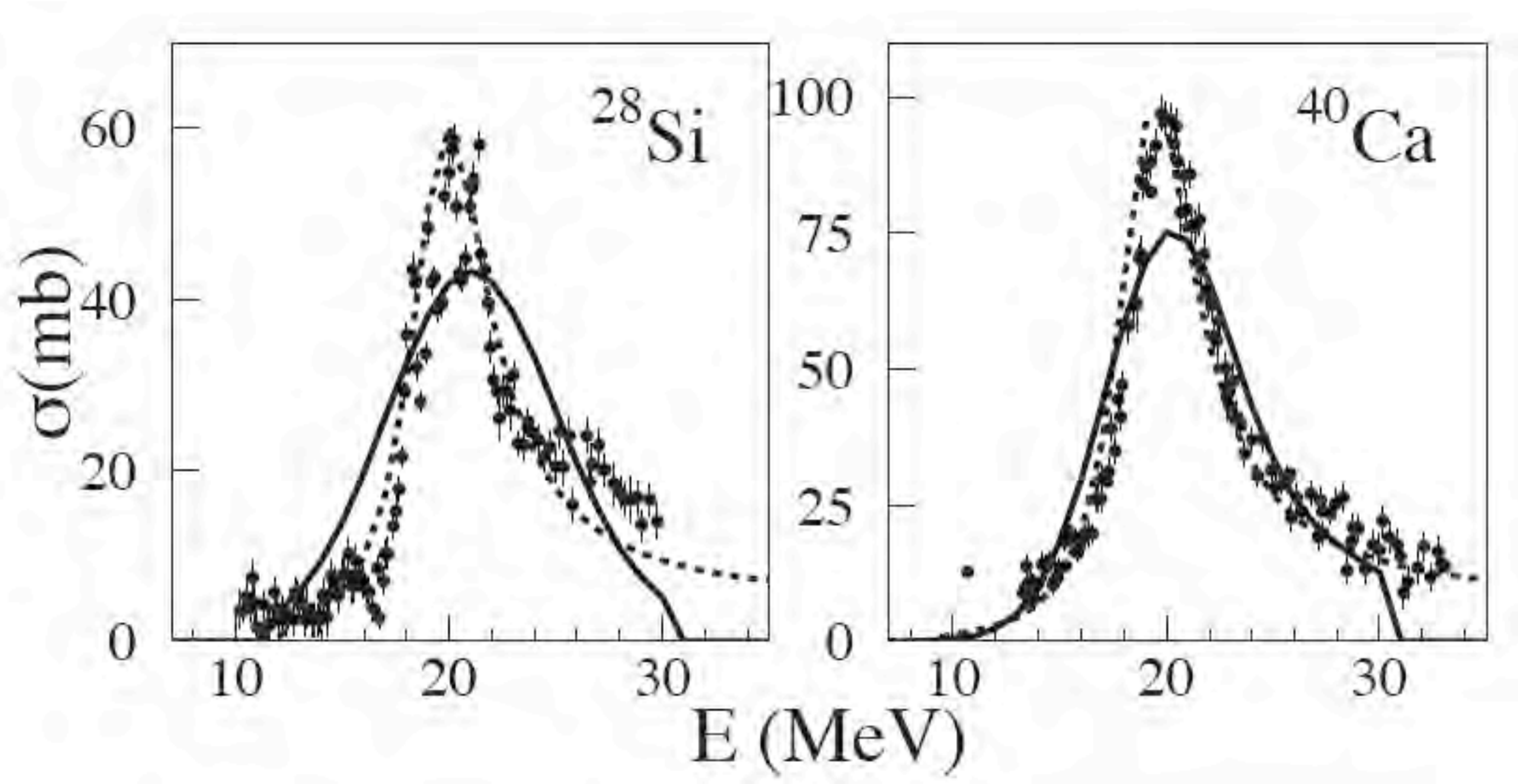
Photo-disintegration of nuclei

- Ultra-energetic nuclei get photodisintegrated by the photons of the cosmological microwave background (CMB)



- Recent work in collaboration with nuclear physicists (IPN Orsay)
  - New cross sections (1st revision since 1976)
  - 2D propagation in the nuclear space: A and Z

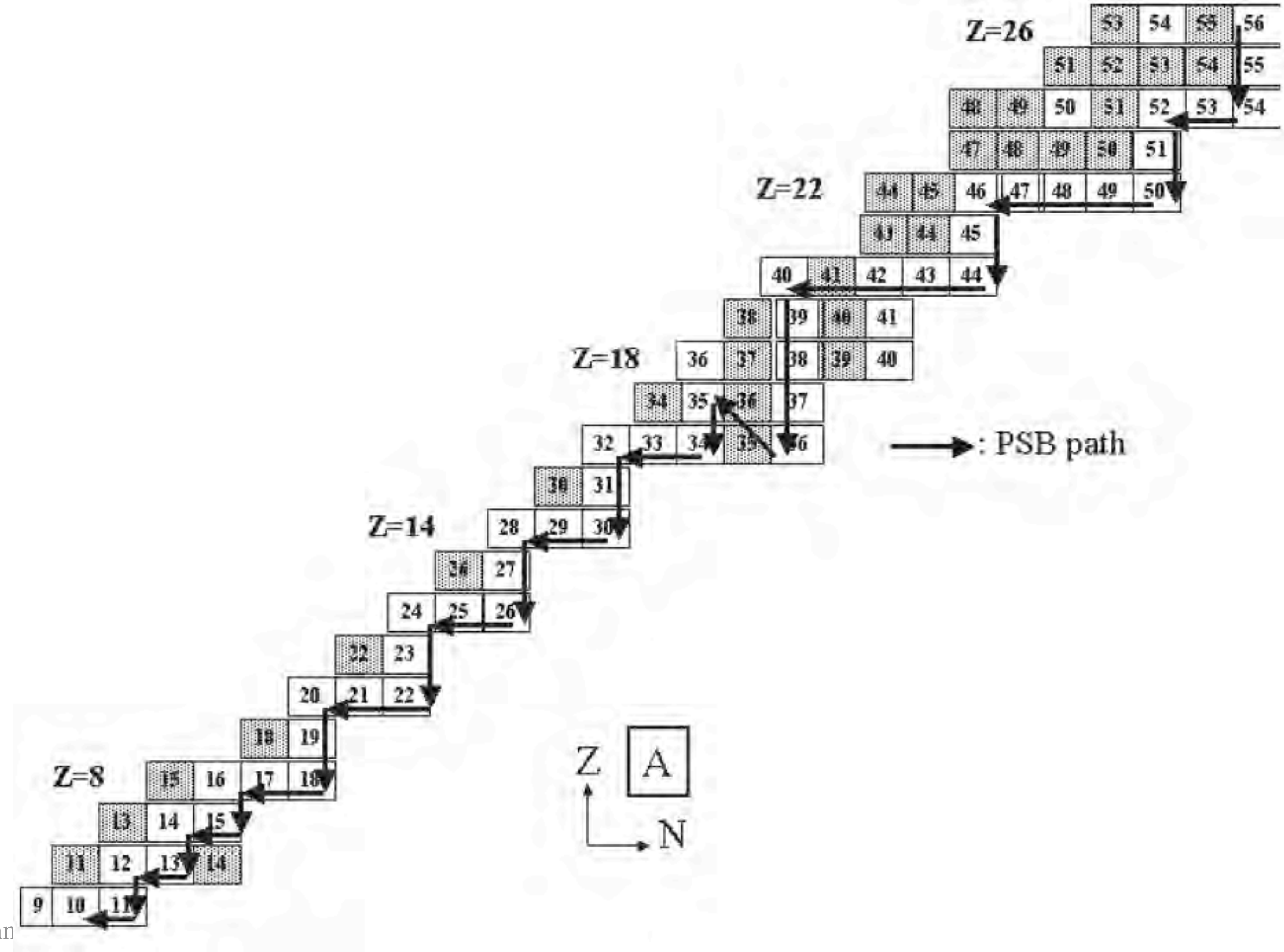
New cross sections



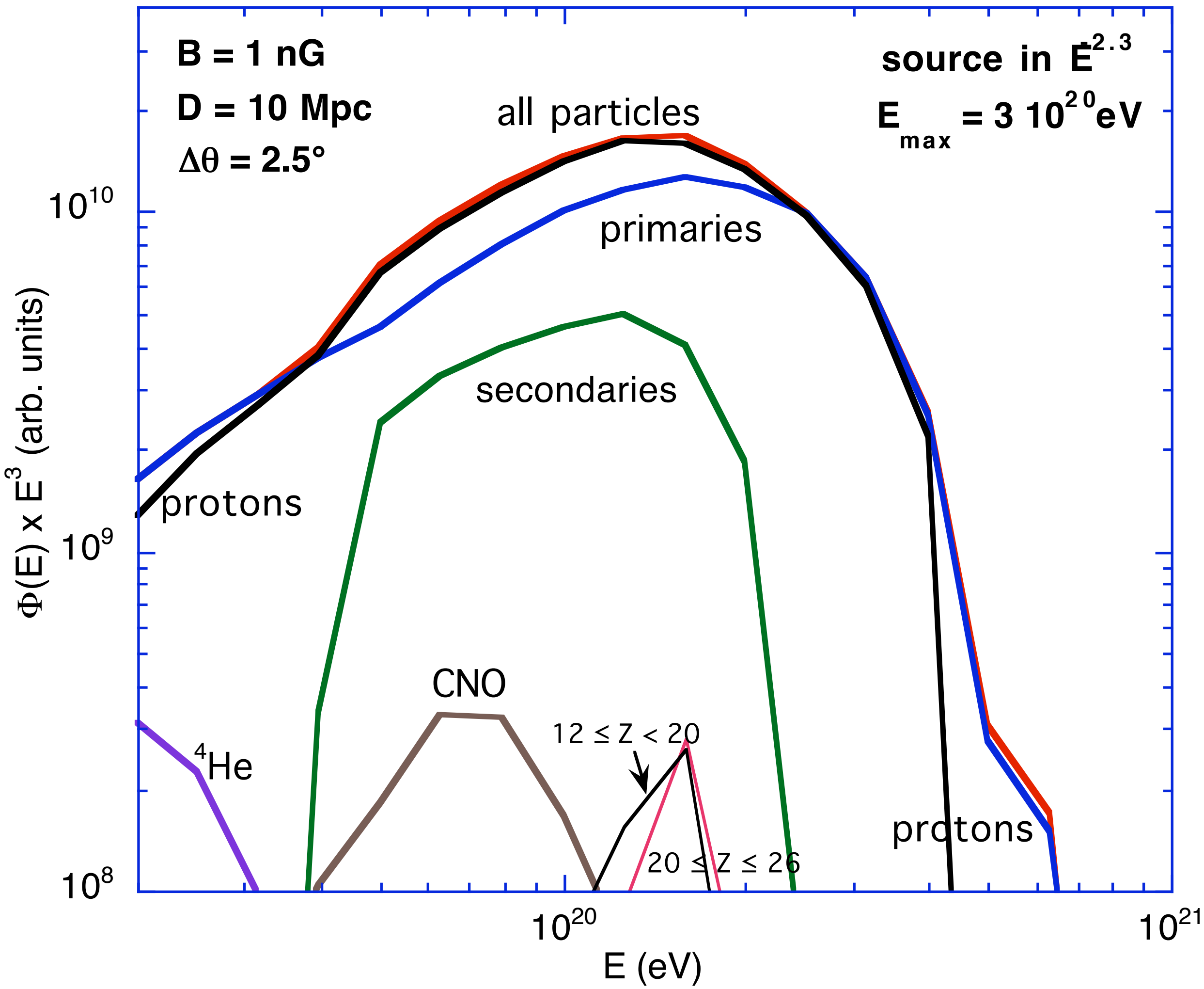
Puget, Stecker, Bredekamp (1976)

Khan et al. (2004)

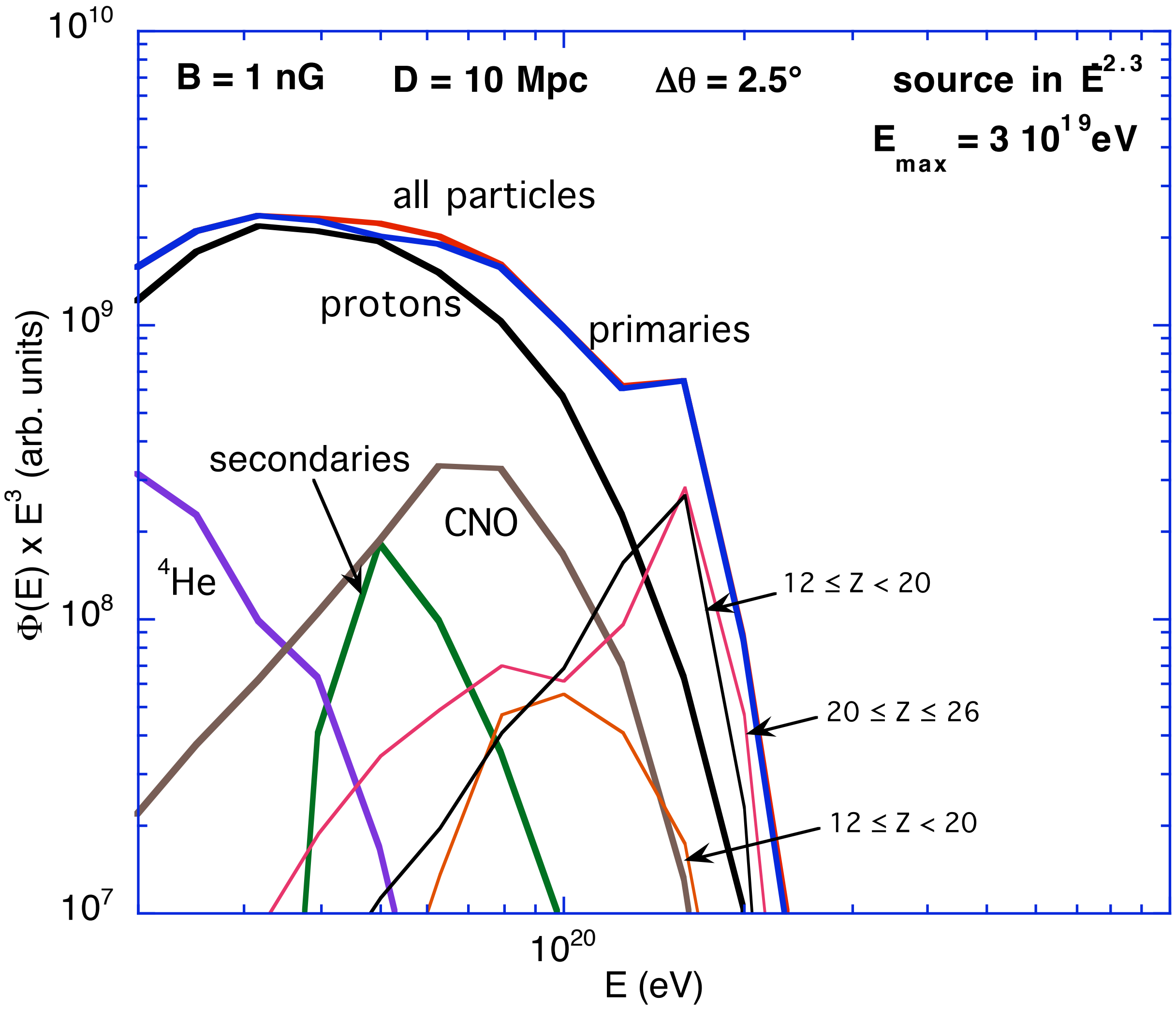
Access to all nuclei



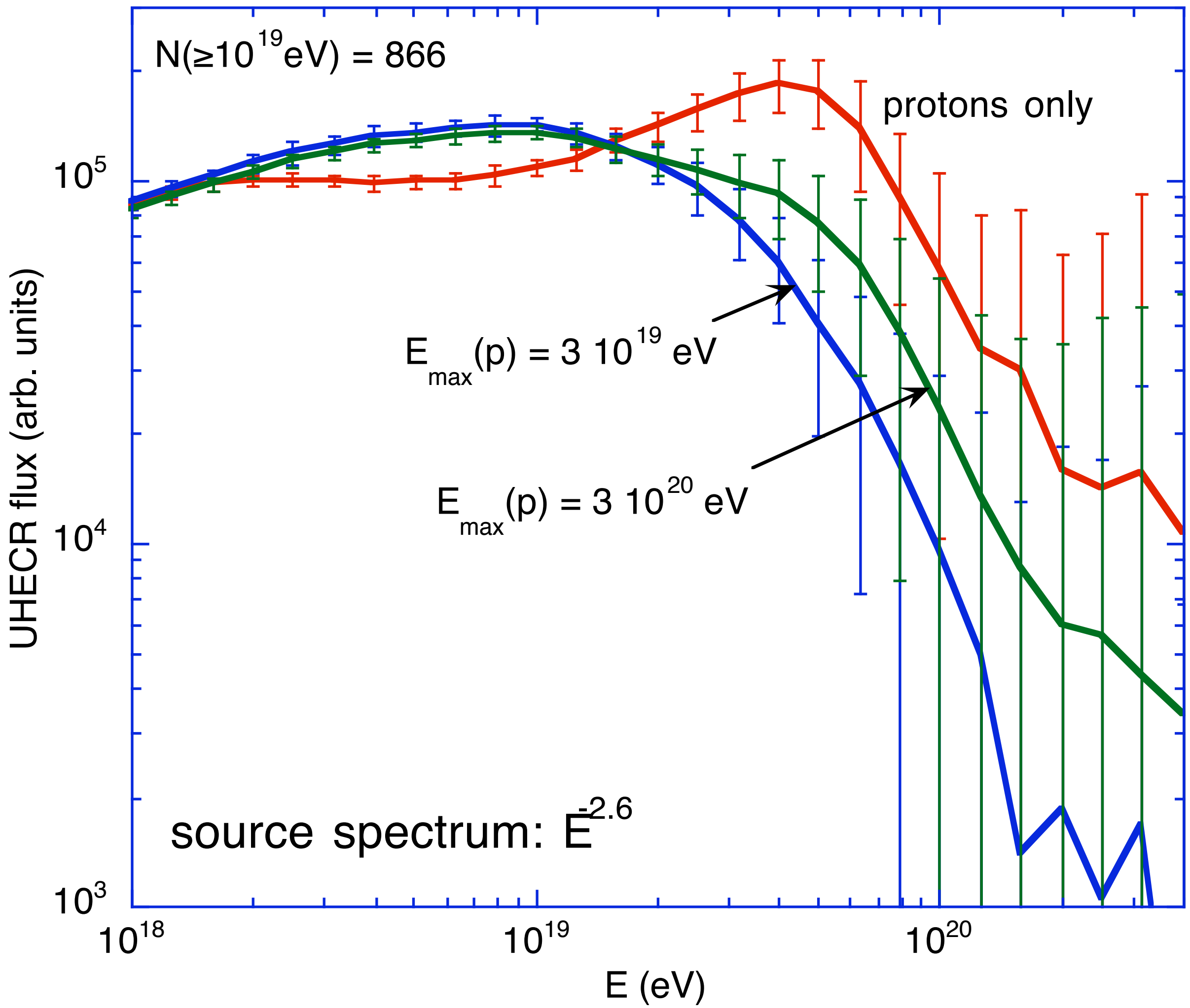
Individual sources



Individual sources

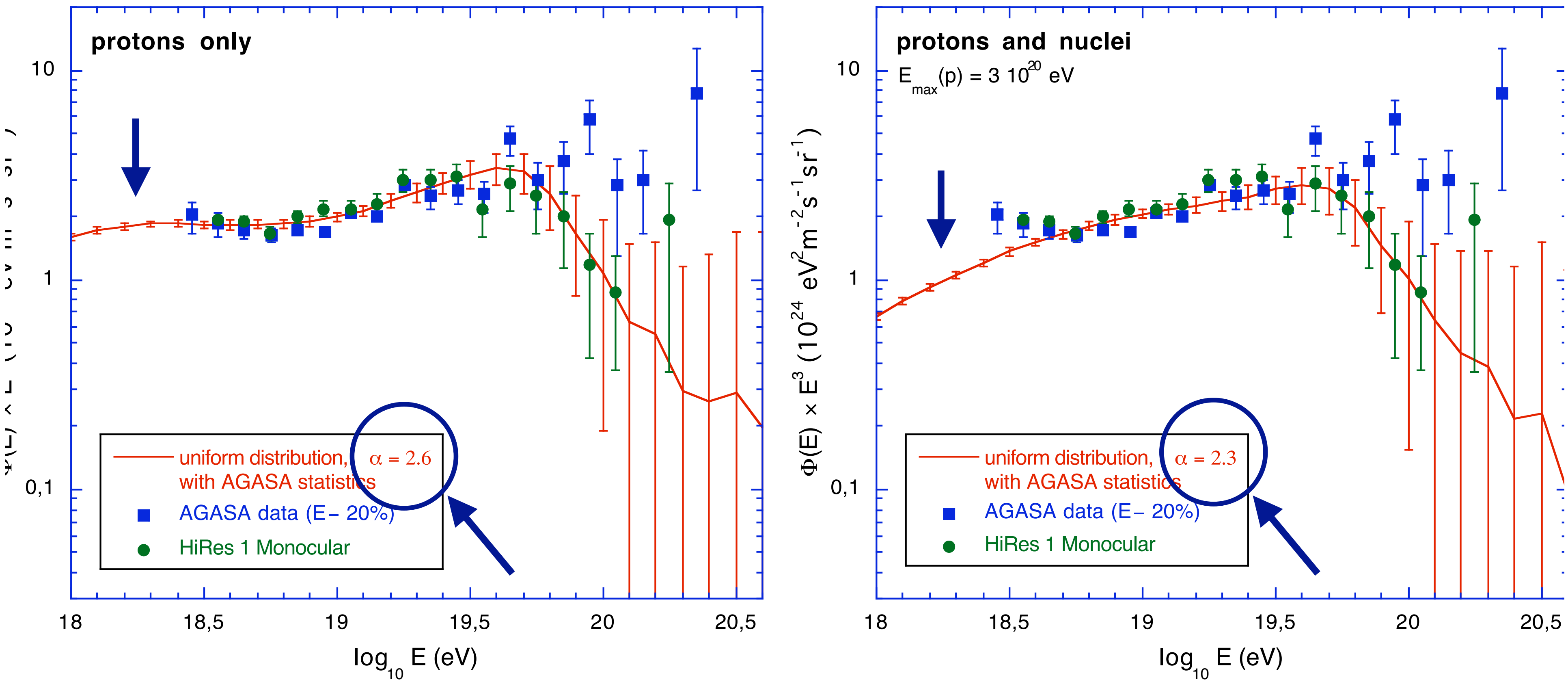


Examples of propagated spectra



Are there nuclei among extragalactic CRs?

Allard et al. (2005)



- source spectrum & acceleration
- Interpretation of the ankle

Extragalactic cosmic rays (high energy)

1

Energy space

↓

interaction with CMB

↓

GZK cutoff

2

Nuclear space

↓

interaction with CMB

↓

photo-disintegration

3

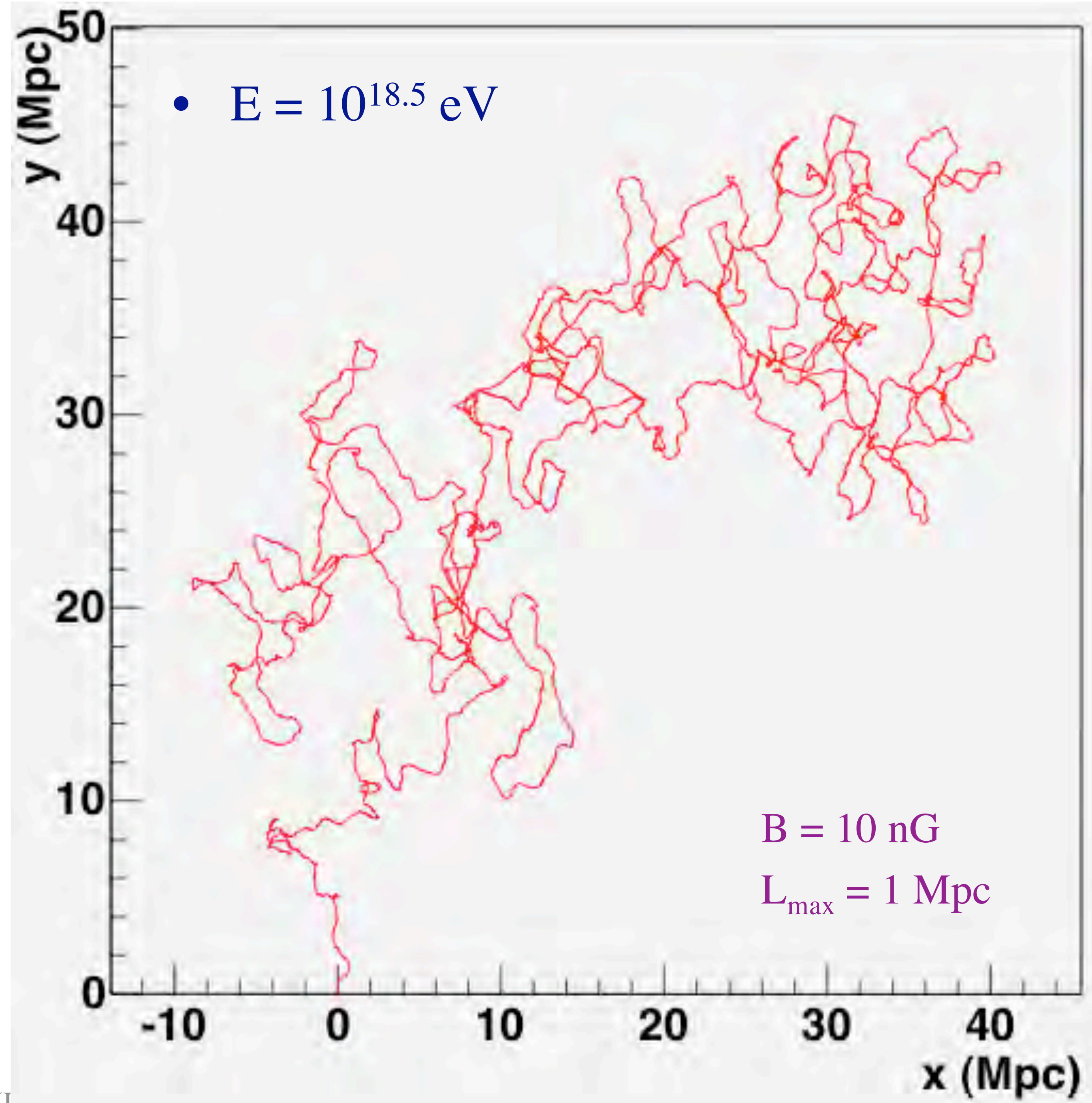
Angular space

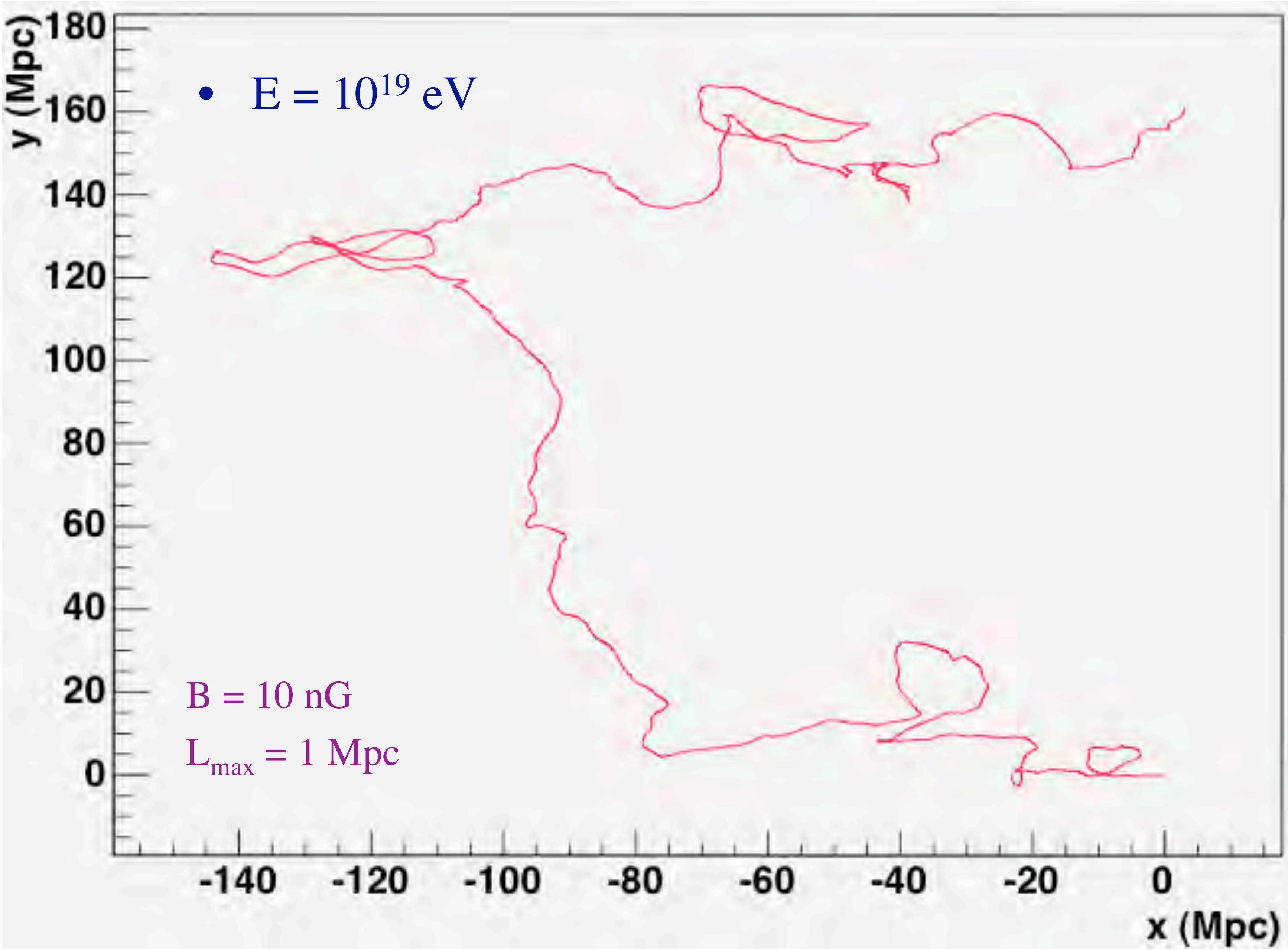
↓

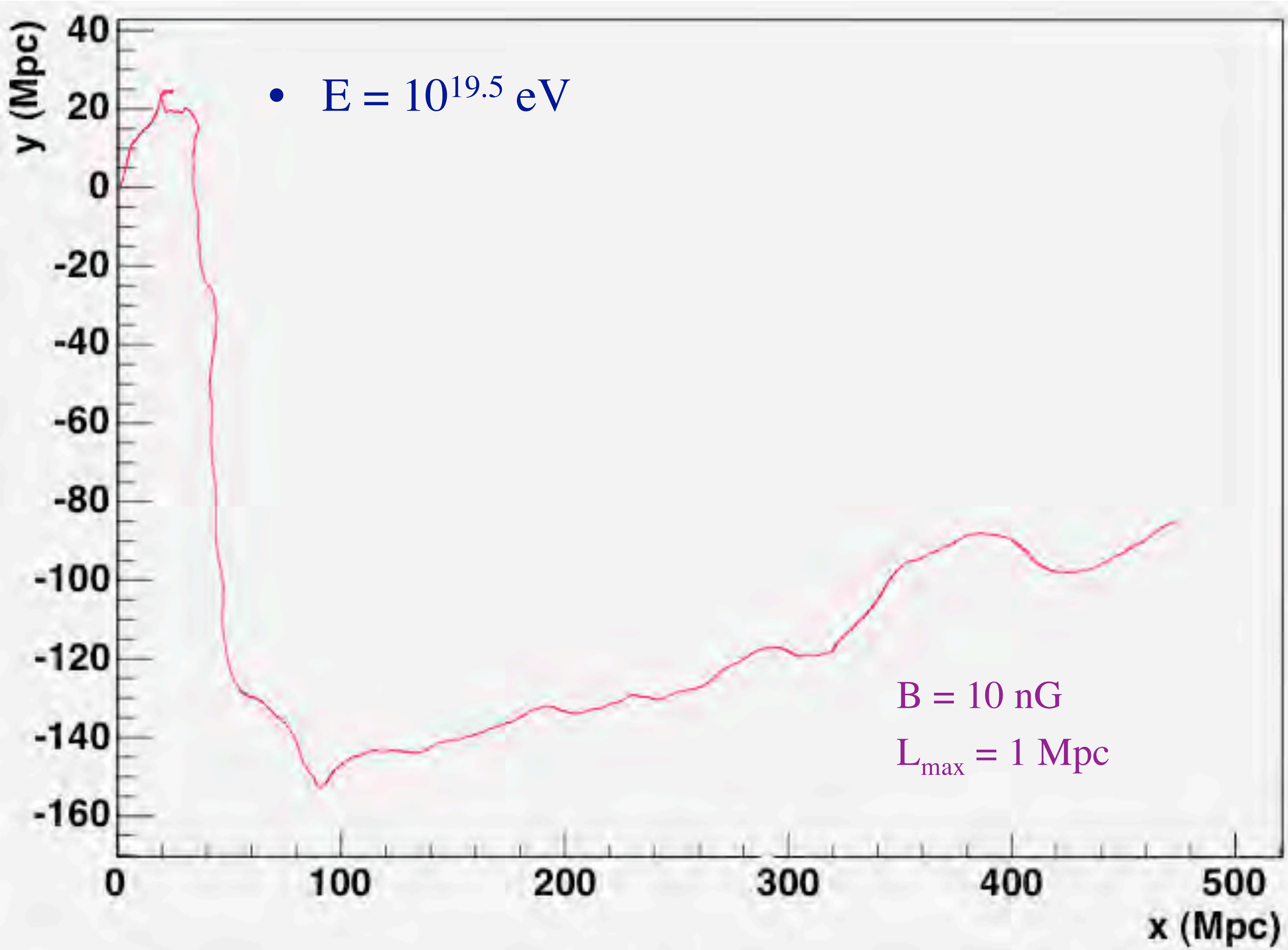
interaction with magnetic field

↓

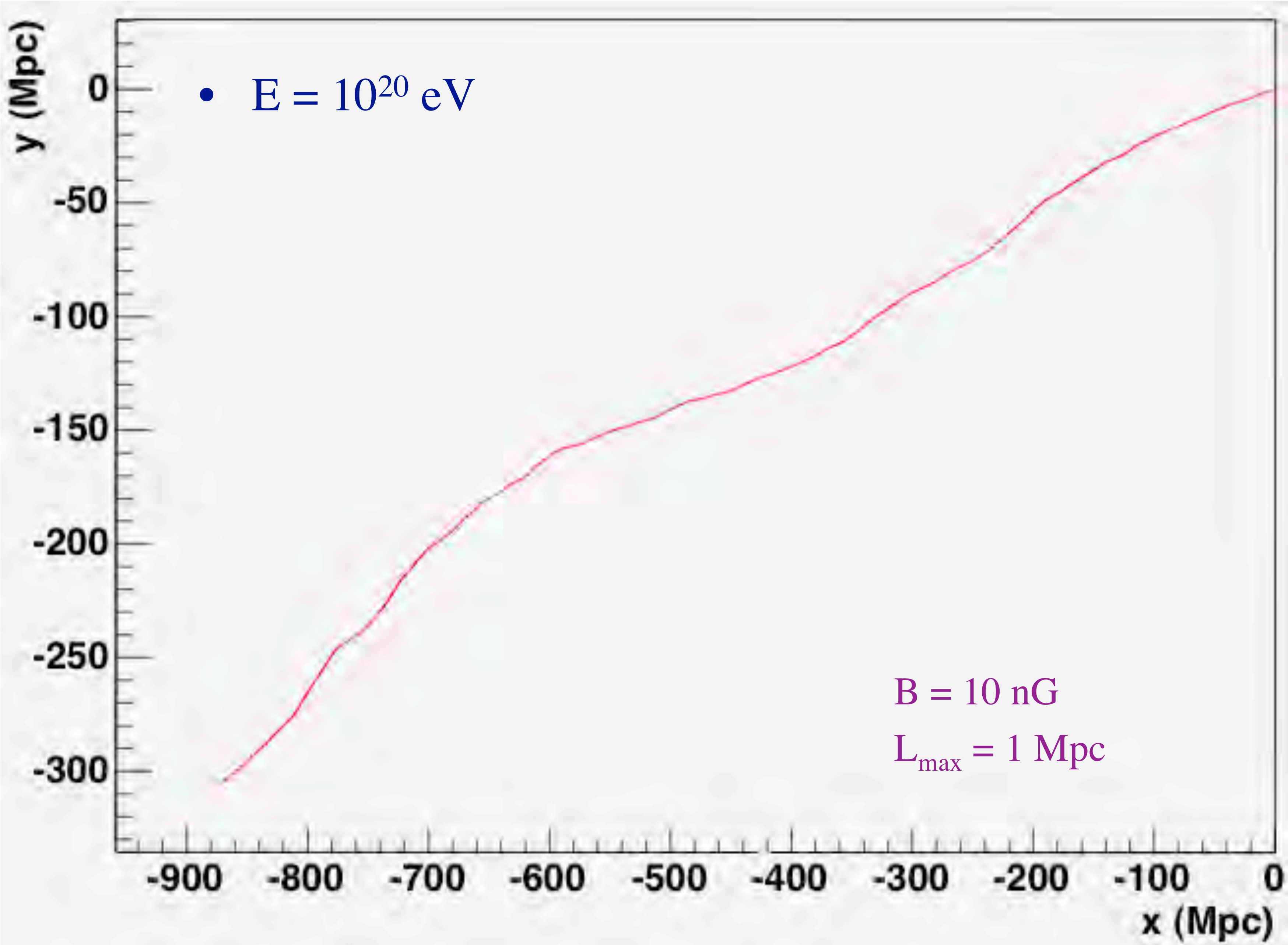
isotropy → source pointing


• E = 10^18.5 eV
B = 10 nG
L_max = 1 Mpc
y (Mpc)
x (Mpc)
0
10
20
30
40
50
-10
0
10
20
30
40


• E = 10^{19} eV
B = 10 nG
L_{max} = 1 Mpc
y (Mpc)
180
160
140
120
100
80
60
40
20
0
-140
-120
-100
-80
-60
-40
-20
0
x (Mpc)



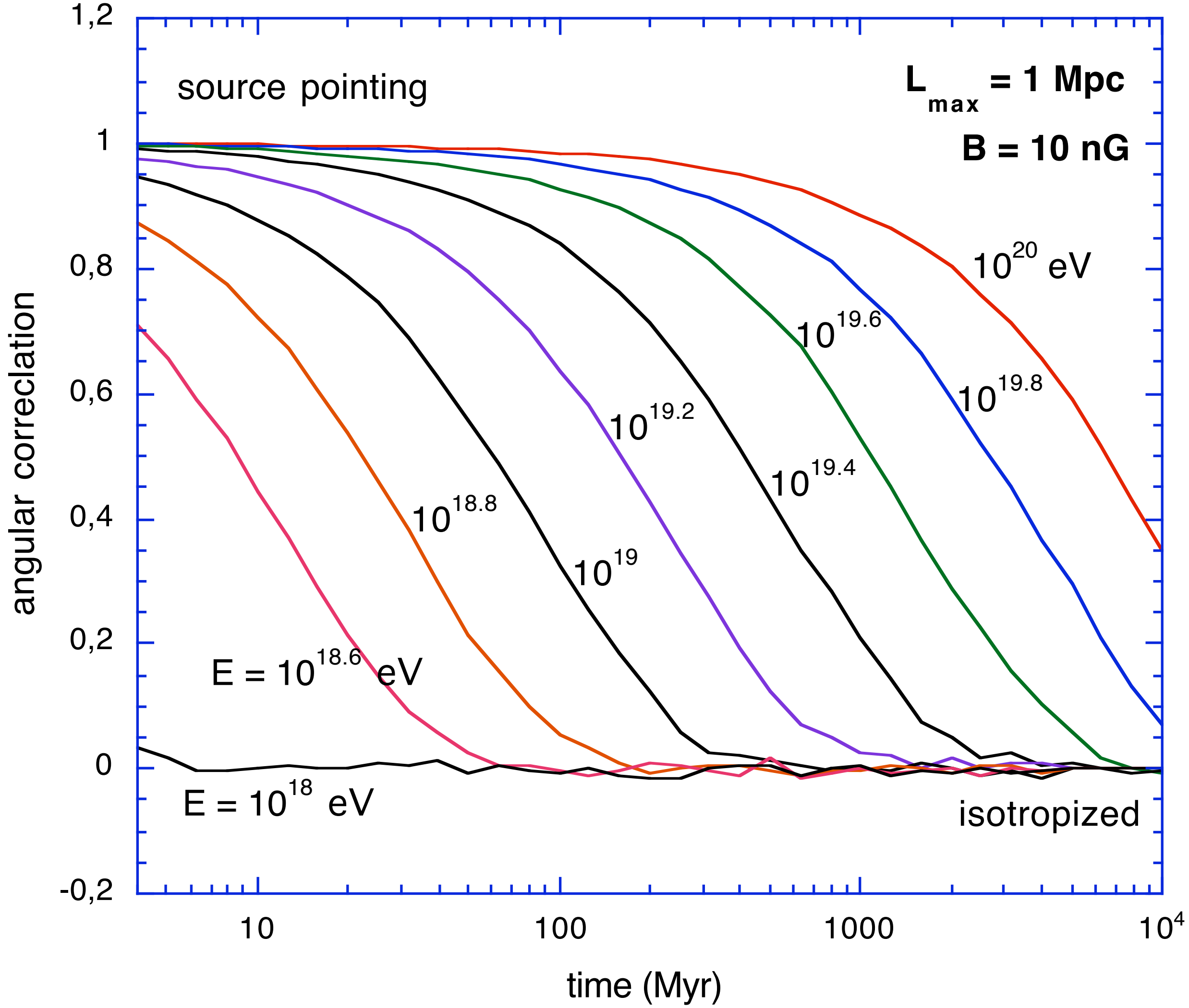
y (Mpc)
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
0
100
200
300
400
500
x (Mpc)
• E = 10^19.5 eV
B = 10 nG
L_max = 1 Mpc


y (Mpc)
0
-50
-100
-150
-200
-250
-300
• E = 10^20 eV
B = 10 nG
L_max = 1 Mpc
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
x (Mpc)

Angular effects of the magnetic field

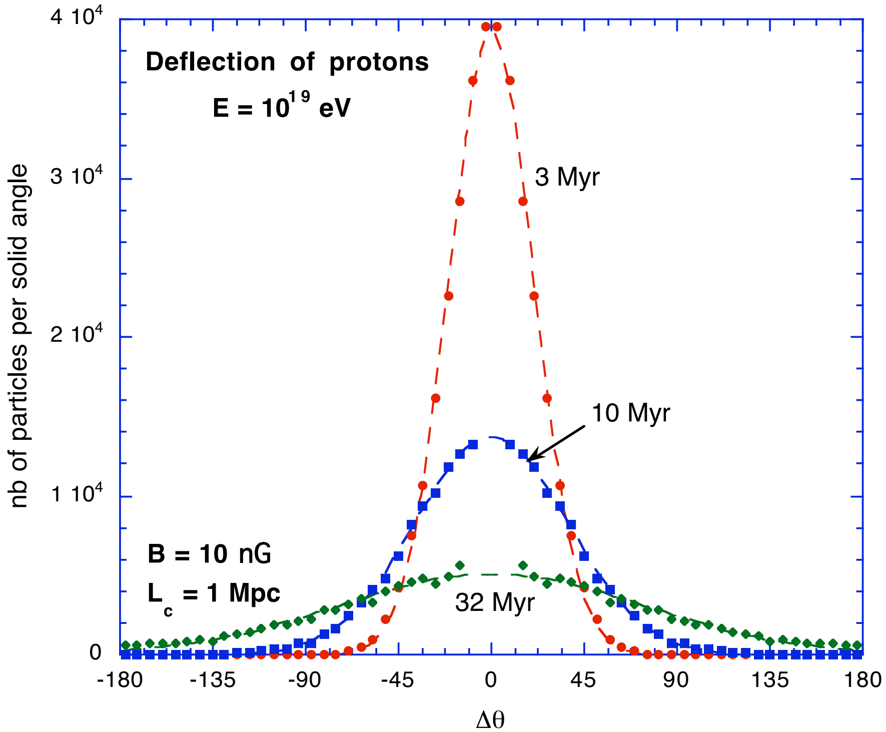
- deflexion
    - angular diffusion
        - isotropisation
            - spatial diffusion

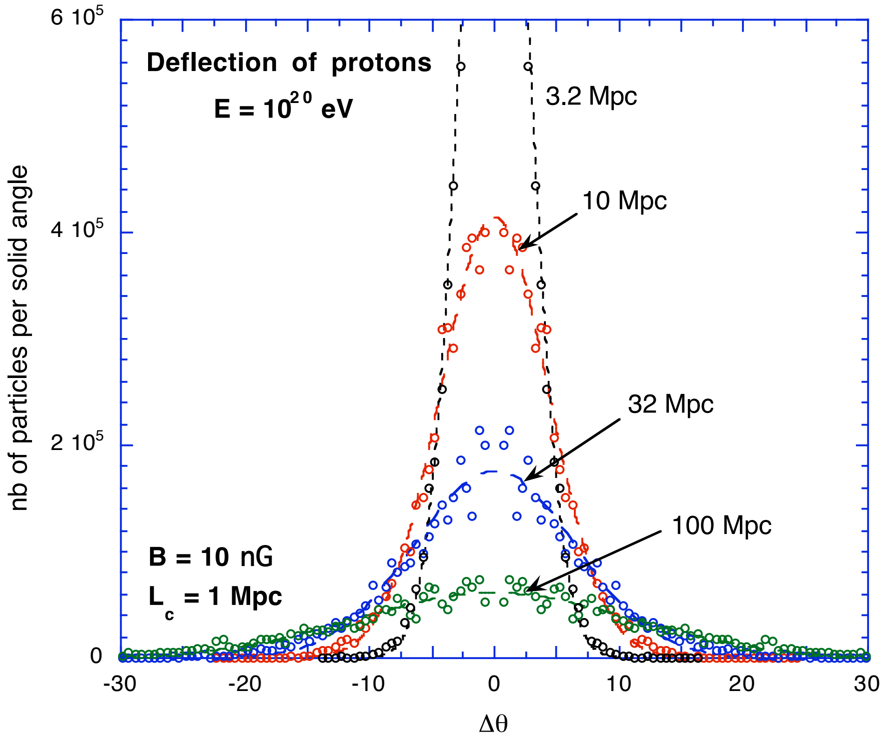
Angular decorrelation



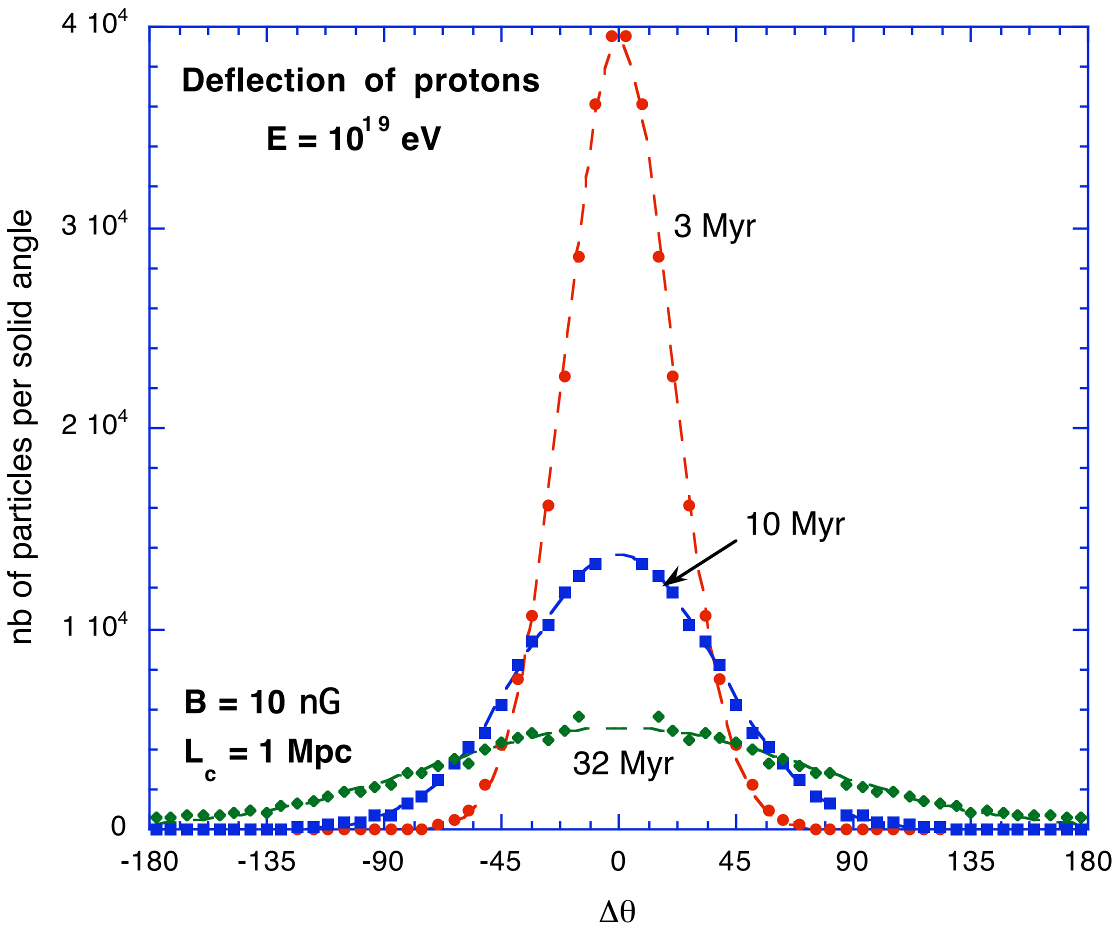
Angular diffusion regime

$\sigma_\theta \propto D^{1/2}$





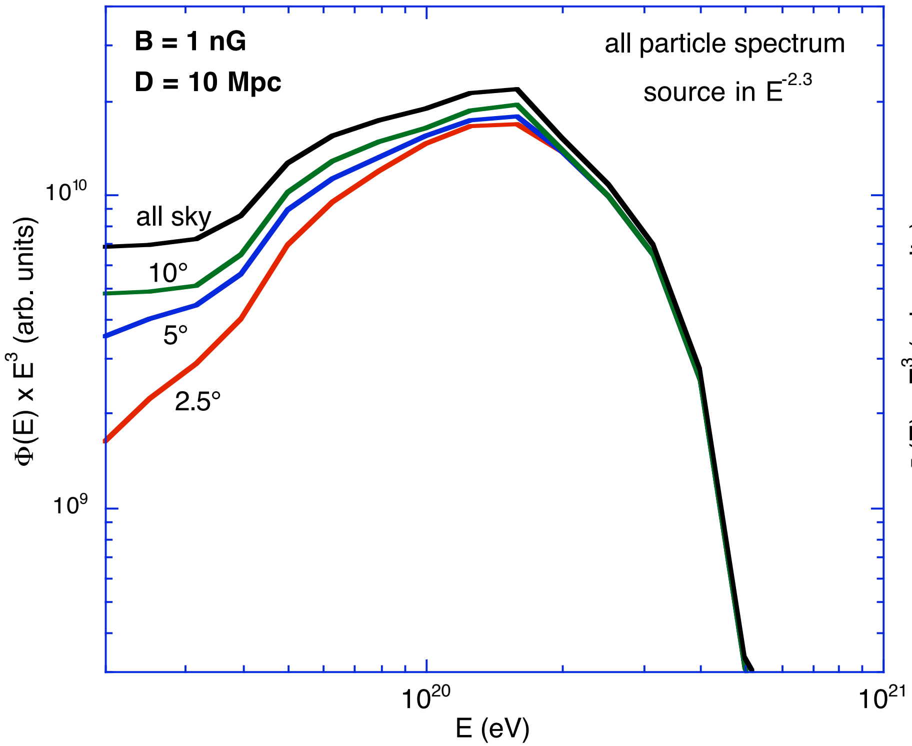
Low-cut filter effect in multiplets of events



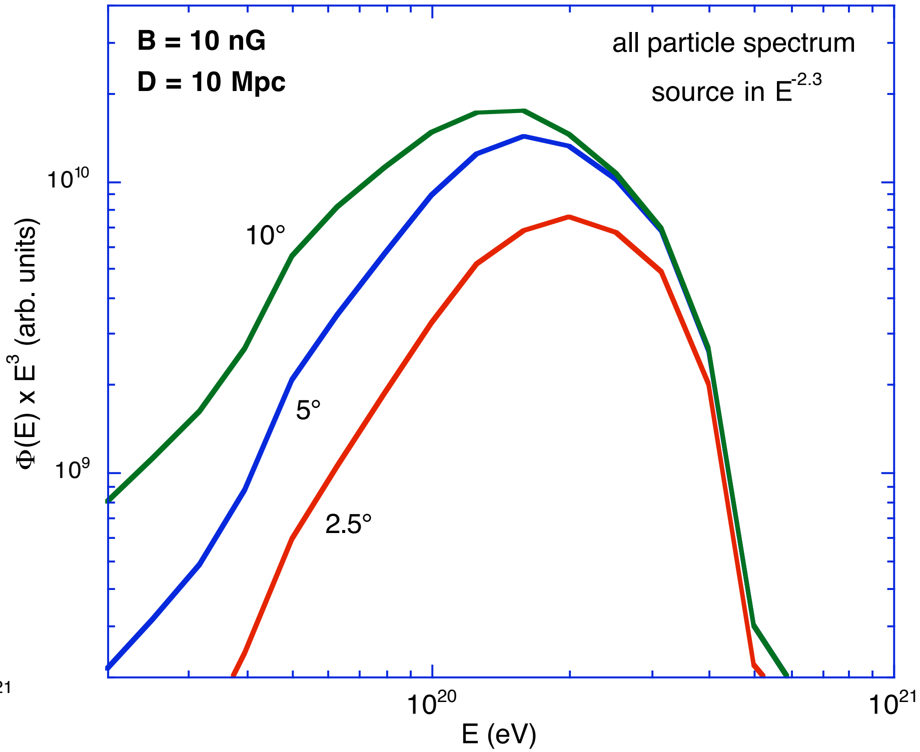
- High energies are less spread
- Nearby sources are less spread
- different expected spectra

Individual sources

Cosmic-ray spectrum in a cluster of events

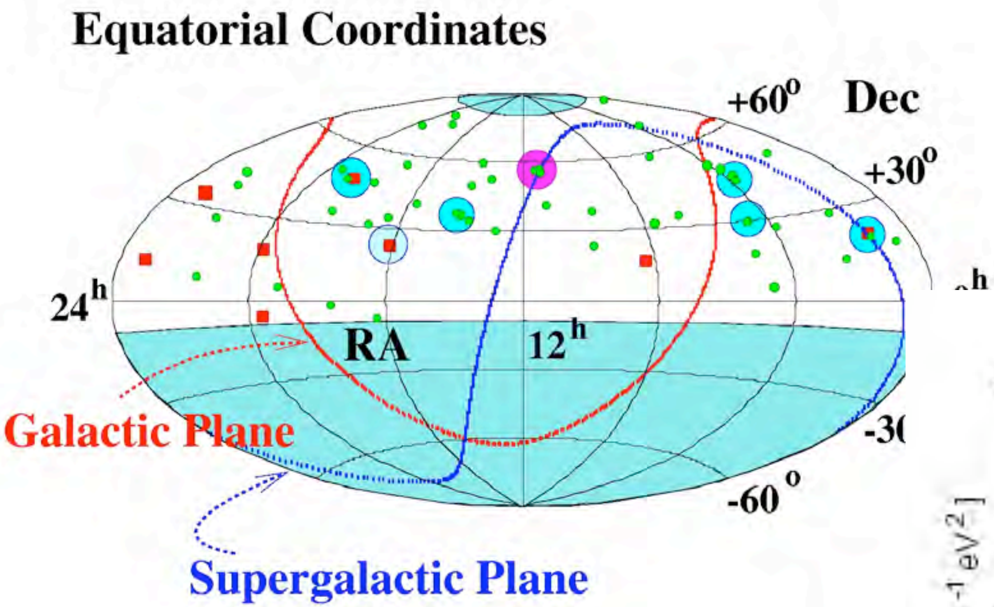


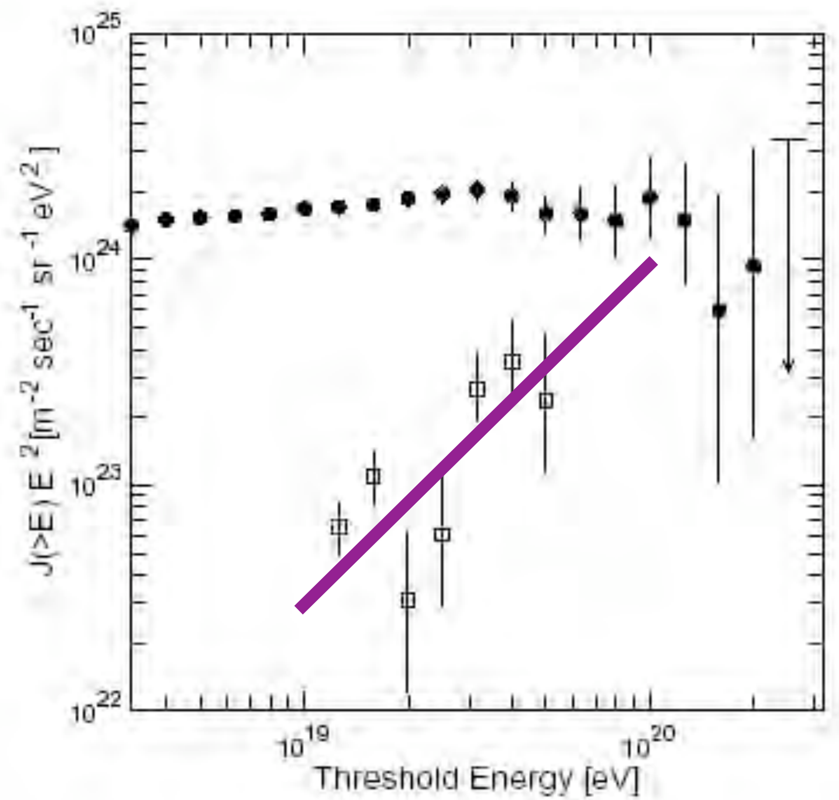
Low magnetic field



High magnetic field

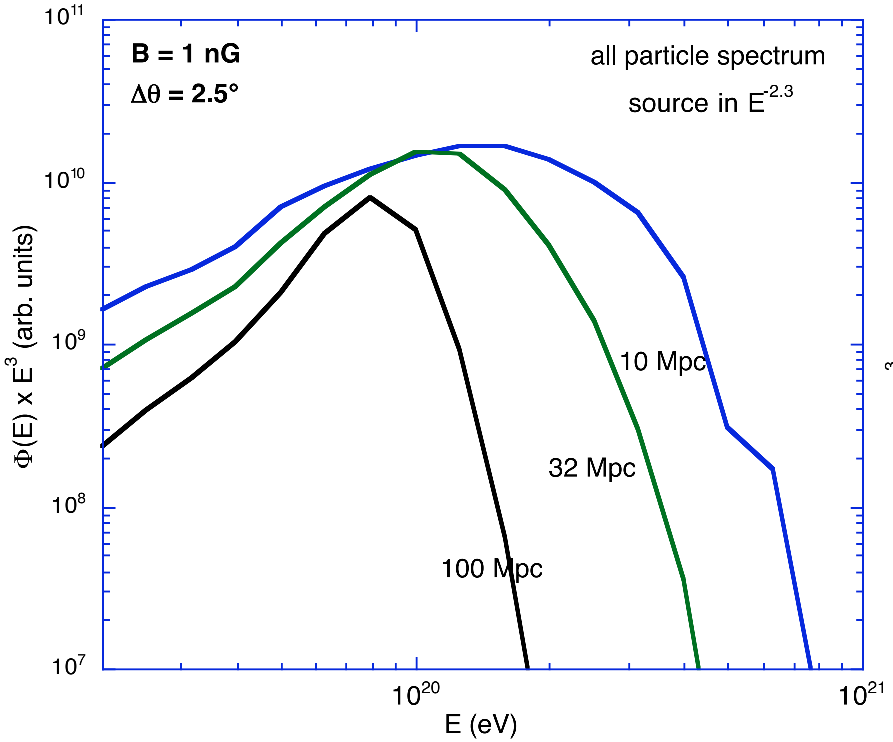
AGASA multiplets



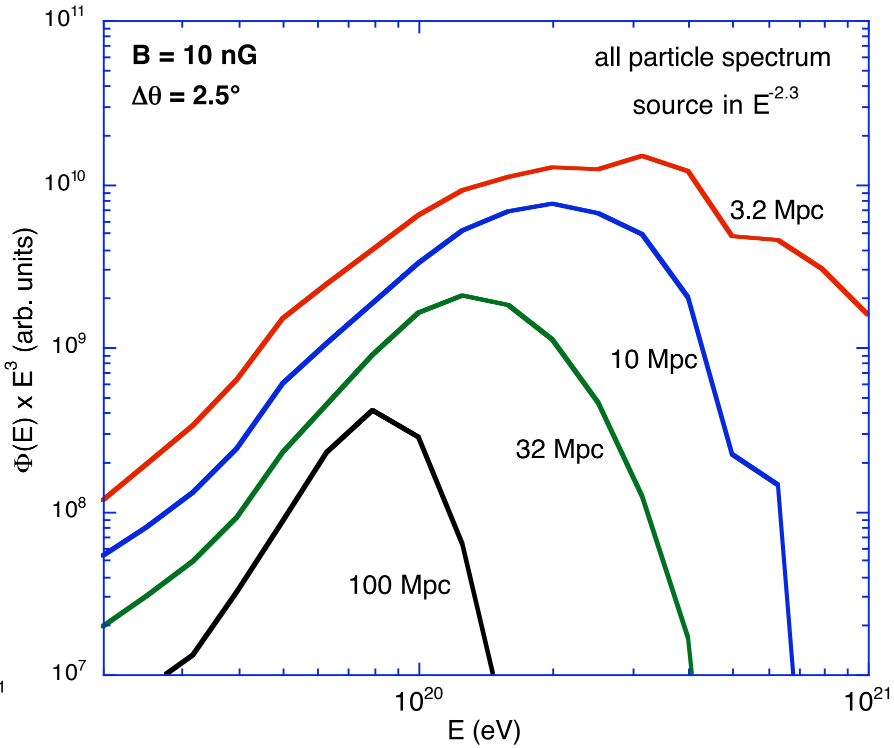


Individual sources

CR spectrum in a cluster of events at 2.5°



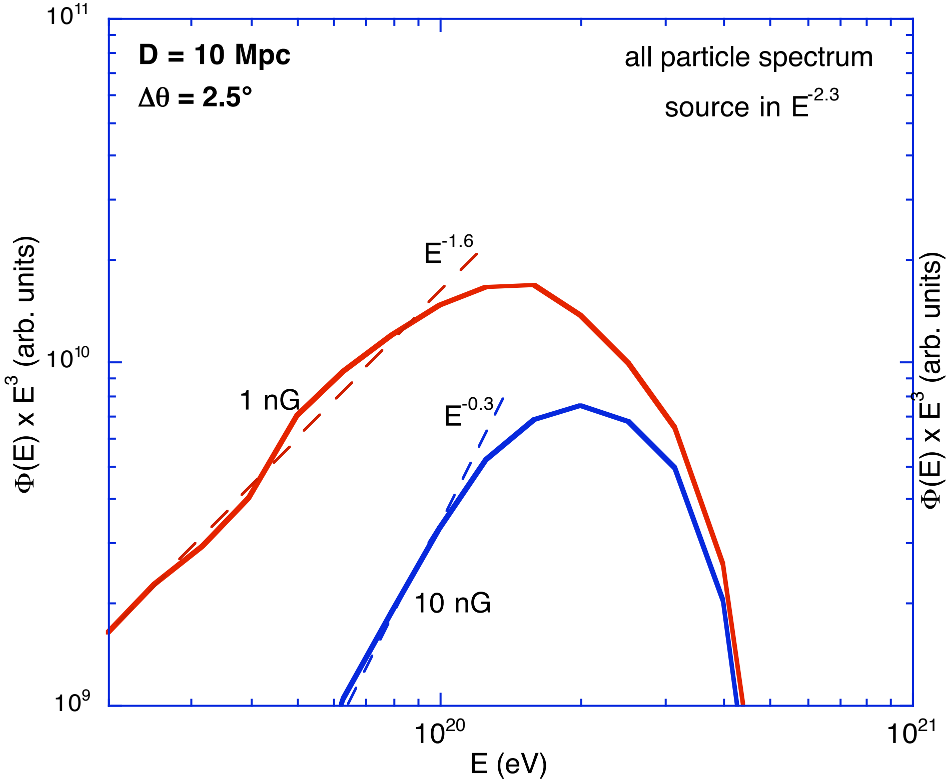
Low magnetic field



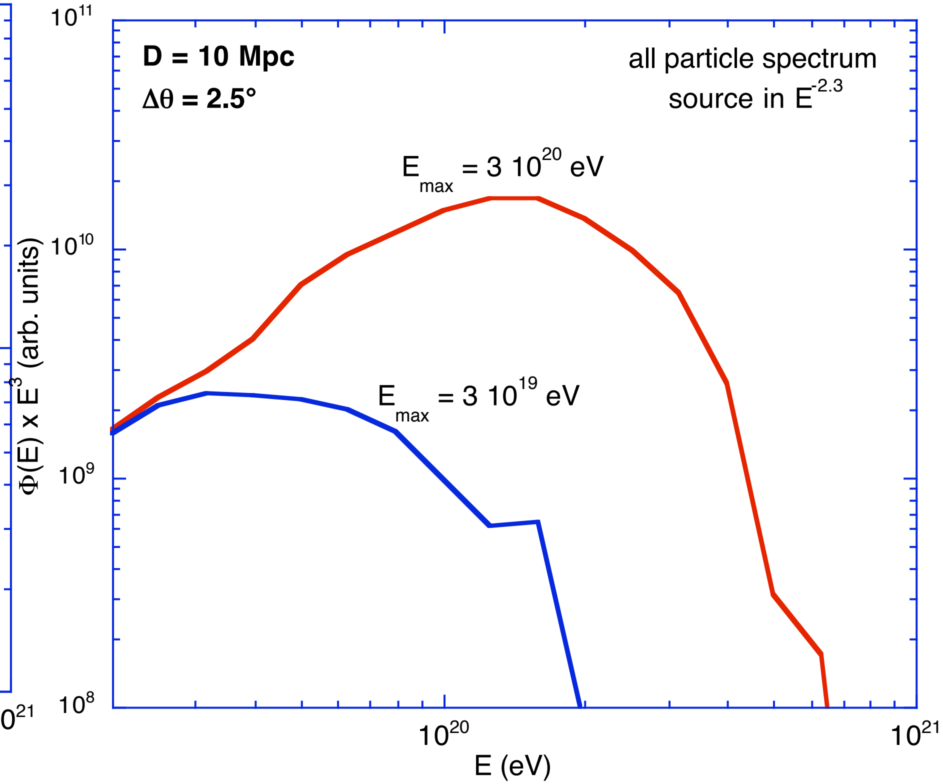
High magnetic field

Individual sources

Measure the magnetic field ?



Maximal energy…



Some conclusions…

- The detailed study of CR propagation allows one to go beyond the **naive view** of a universal GZK cutoff:
  - Source distribution
  - Source spectrum (power law, E_{max})
  - Most nearby sources
  - Role of the magnetic field
  - Presence of nuclei
- Proton astronomy is opened!
  - Spectra of different sky regions! (need for Auger North)
  - Spectra of individual sources! (~100 events with the Auger Observatory)
  - Will provide strong constraints on extragalactic magnetic field (measurements!)
  - Transition from diffusive to rectilinear propagation
- Global cosmic-ray phenomenology:
  - Transition from galactic to extragalactic cosmic rays: MOST IMPORTANT!
  - Nature and shape of the ankle
  - Extreme importance of anisotropy measurements (constraints on the ankle)
- Associate the 3 spectral dimensions: energy, composition and angular features are expected both at the ankle and at the highest energies!

  ==> build the Northern site of Auger is a MUST!