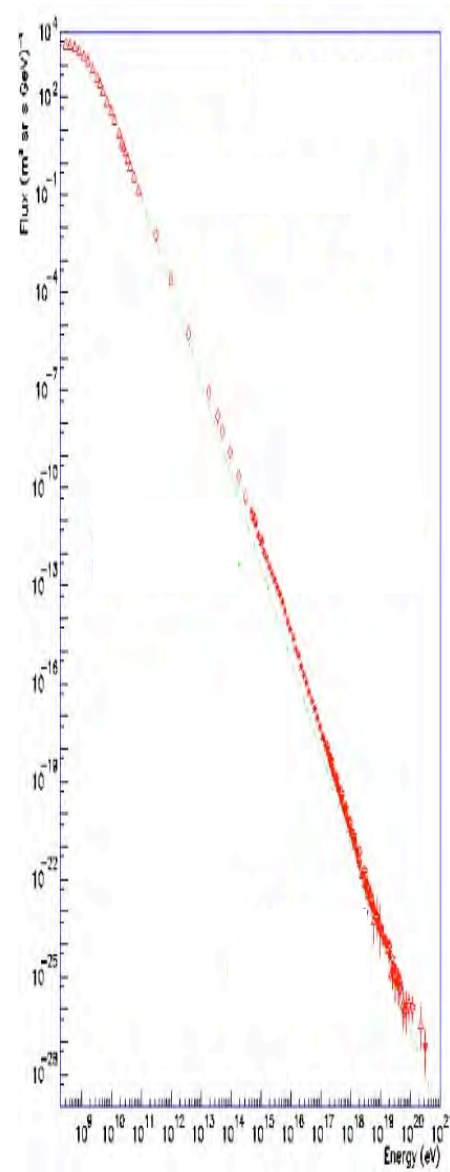
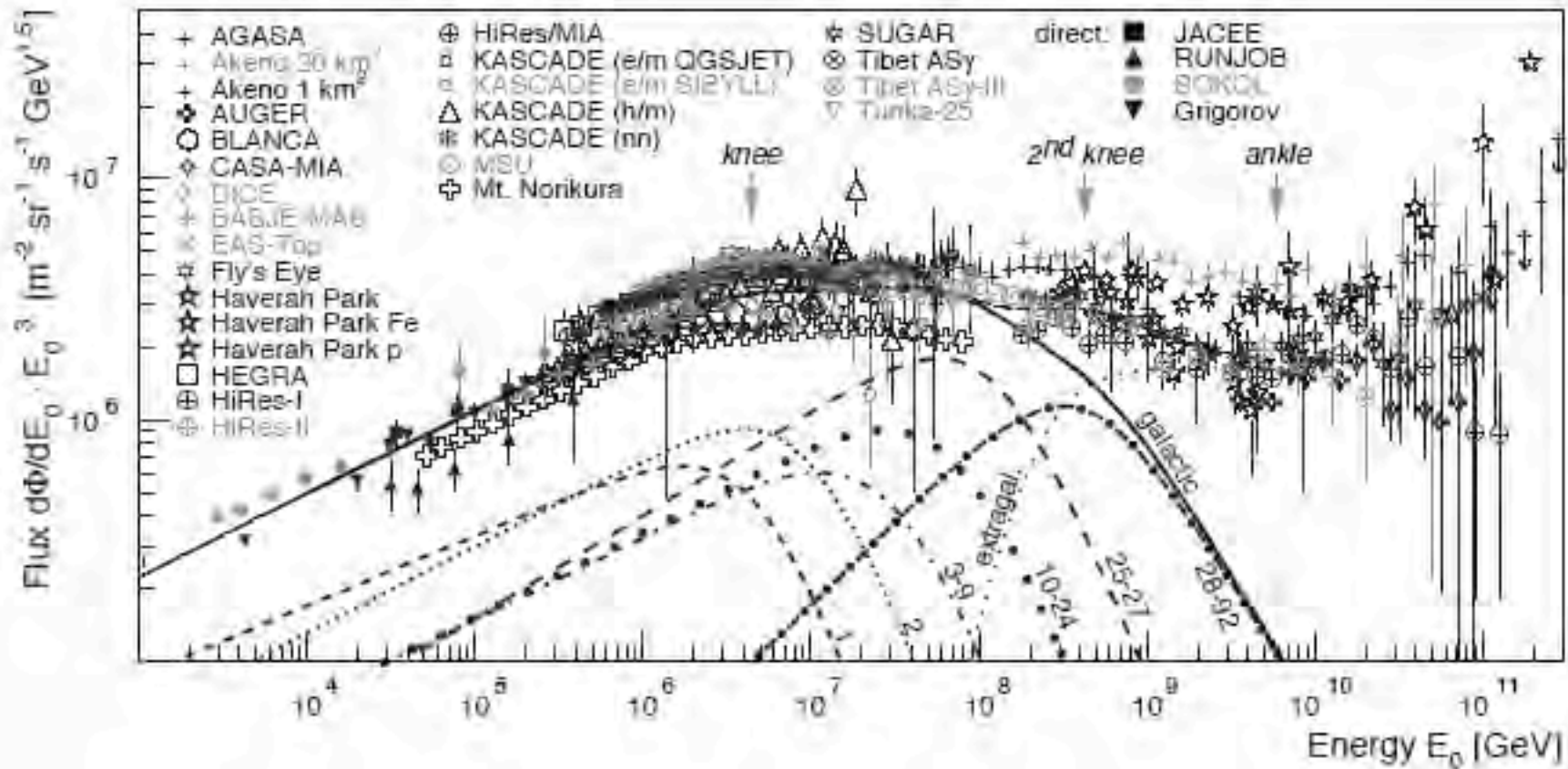


Transport des rayons cosmiques

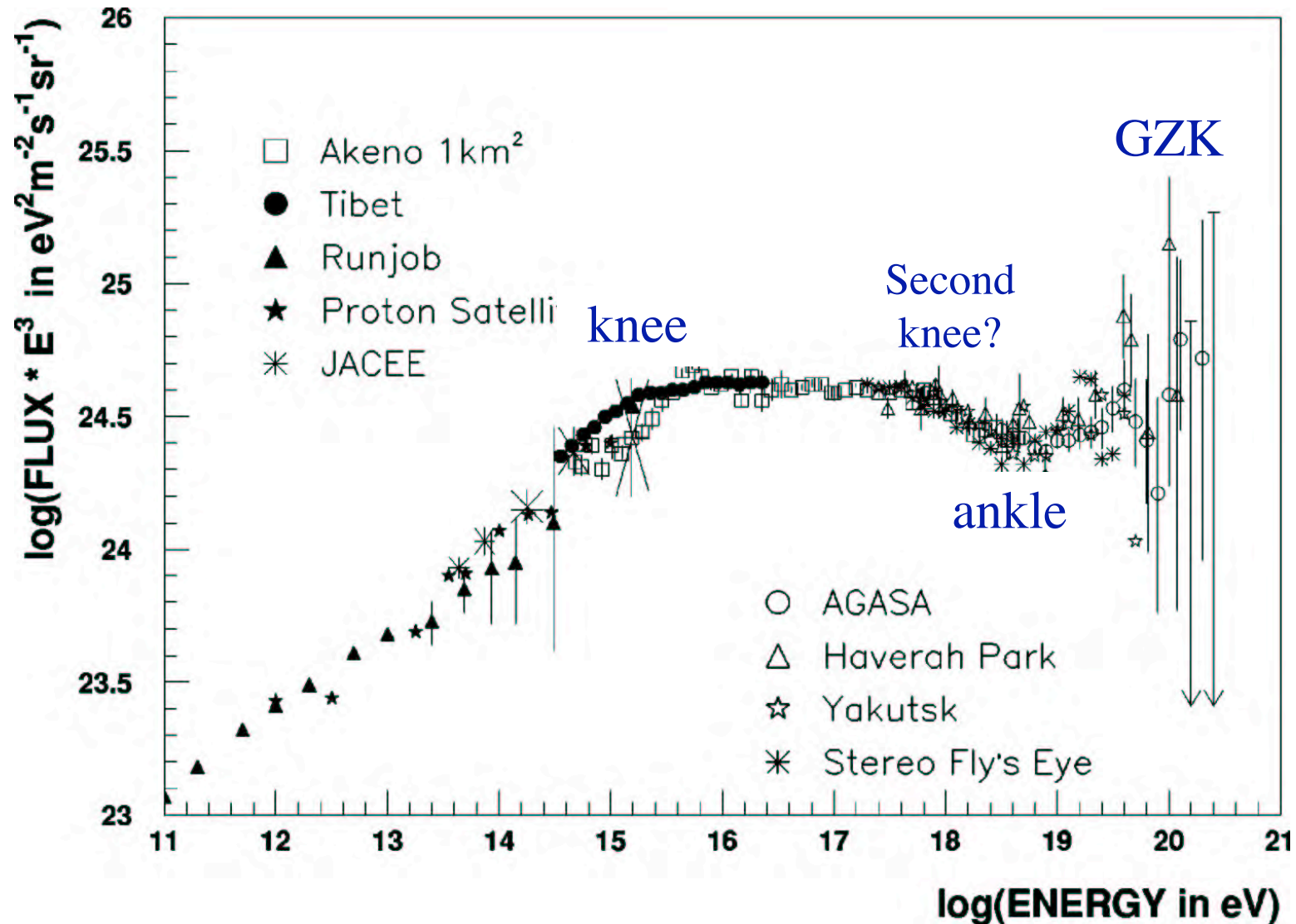
II - composante extragalactique



[CR flux] $\times E^3$



[CR flux] $\times E^3$



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!

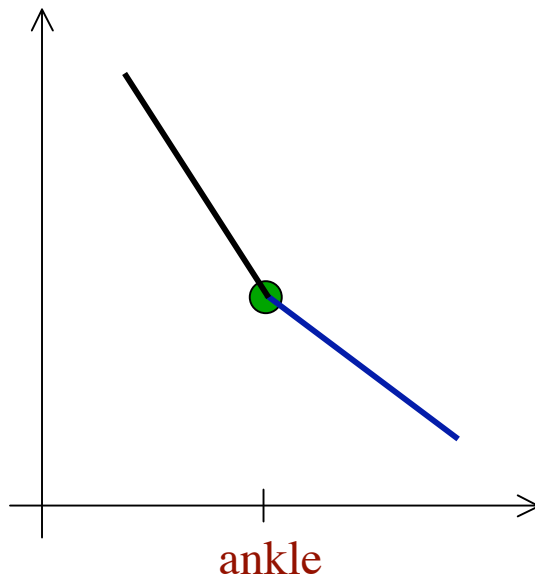
At what energy does it occur?

How does it show in the energy spectrum?

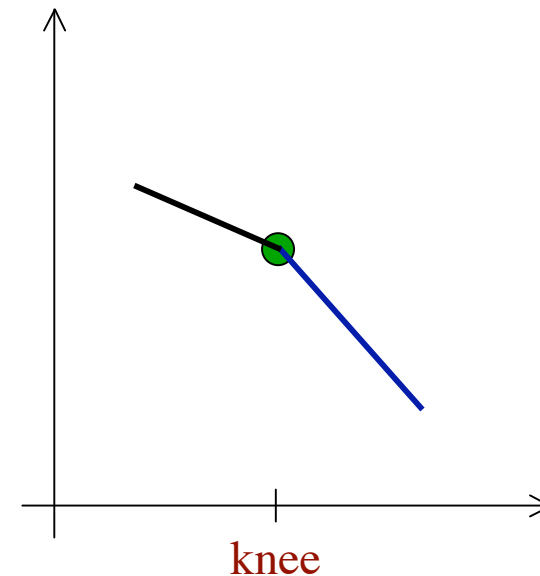
General phenomenology of transitions

- Two possibilities:

transition from a soft to a harder component



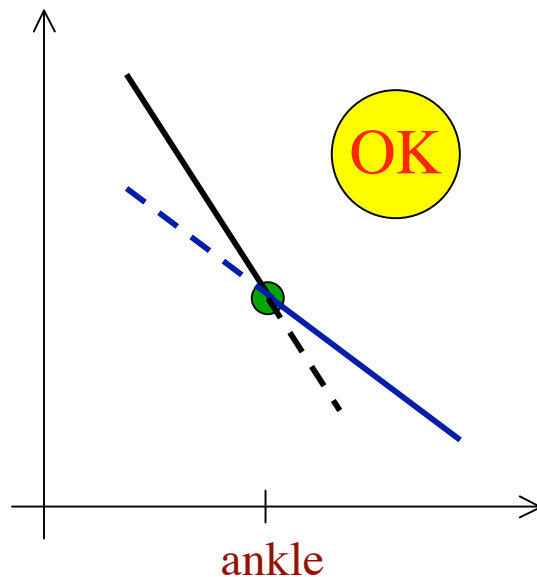
transition from a hard to a softer component



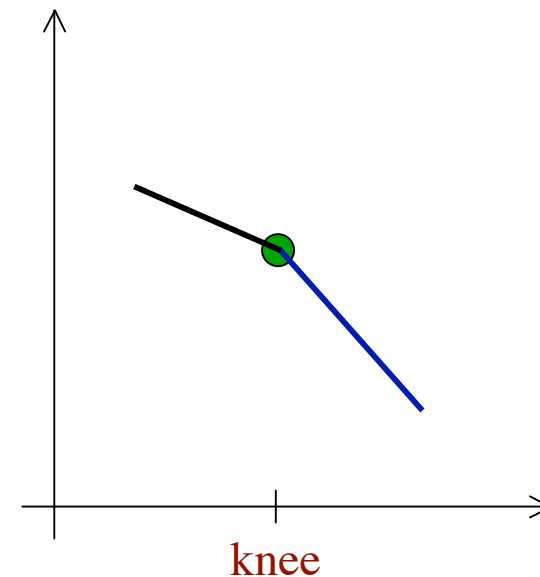
General phenomenology of transitions

- Two possibilities:

transition from a soft to a harder component



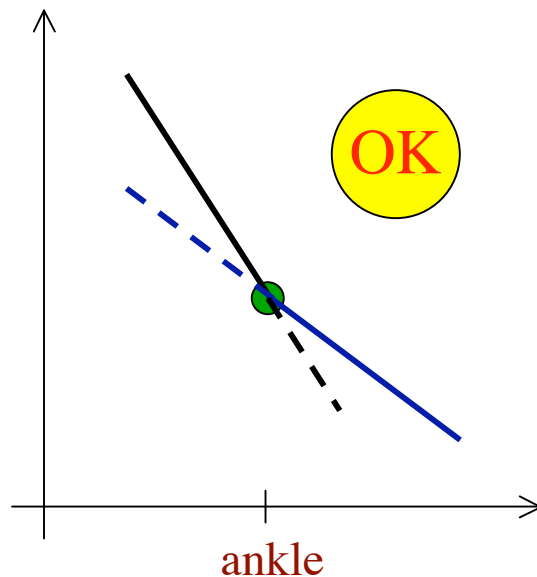
transition from a hard to a softer component



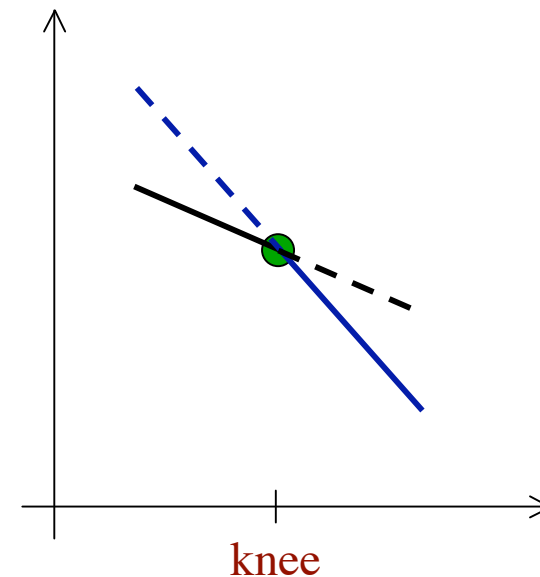
General phenomenology of transitions

- Two possibilities:

transition from a soft to a harder component



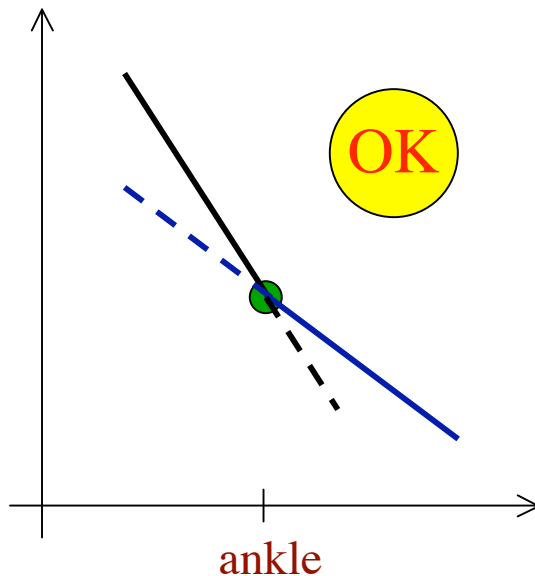
transition from a hard to a softer component



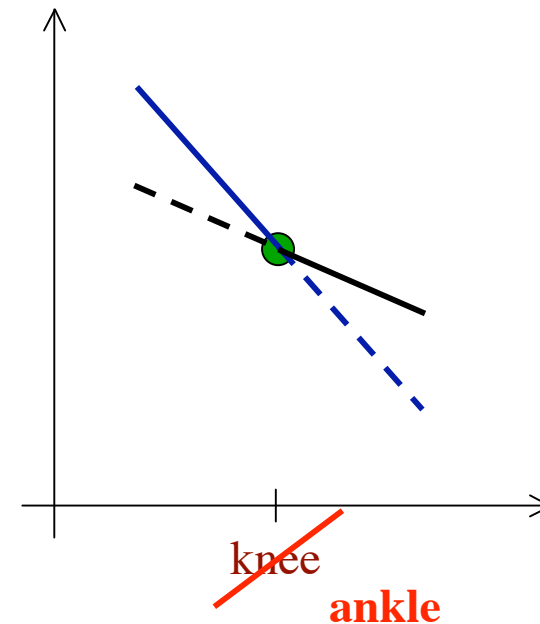
General phenomenology of transitions

- Two possibilities:

transition from a soft to a harder component



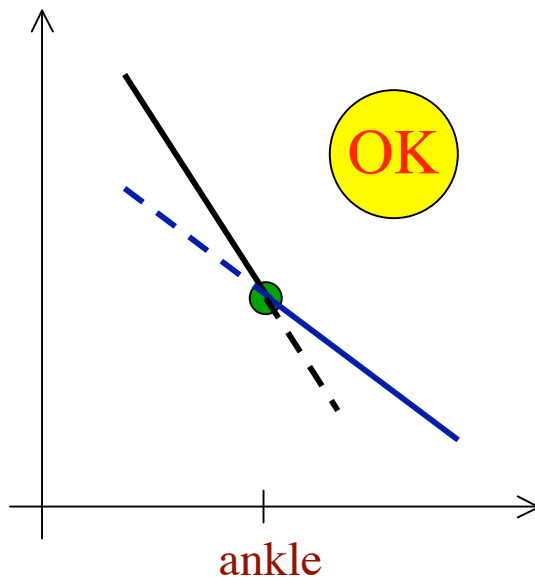
transition from a hard to a softer component



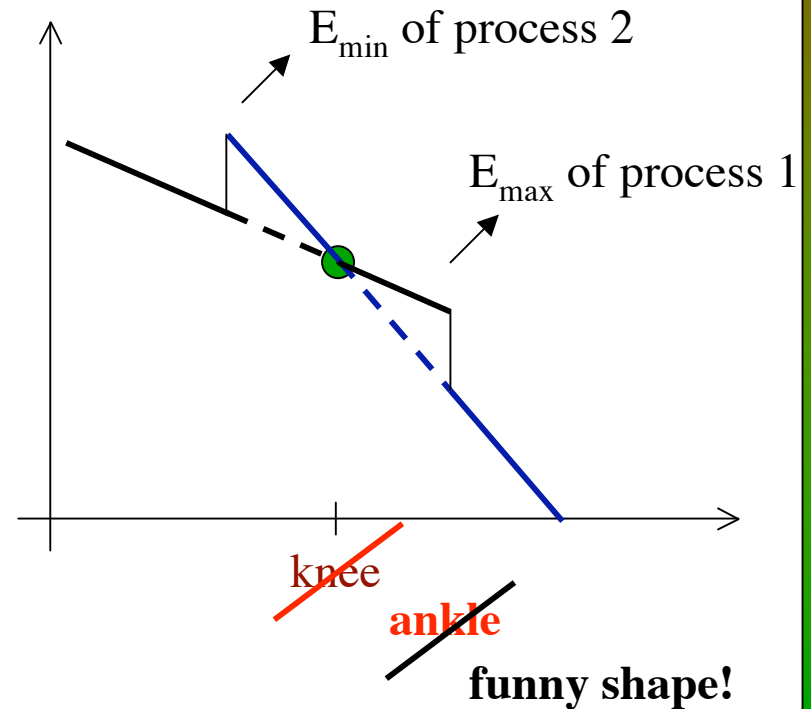
General phenomenology of transitions

- Two possibilities:

transition from a soft to a harder component

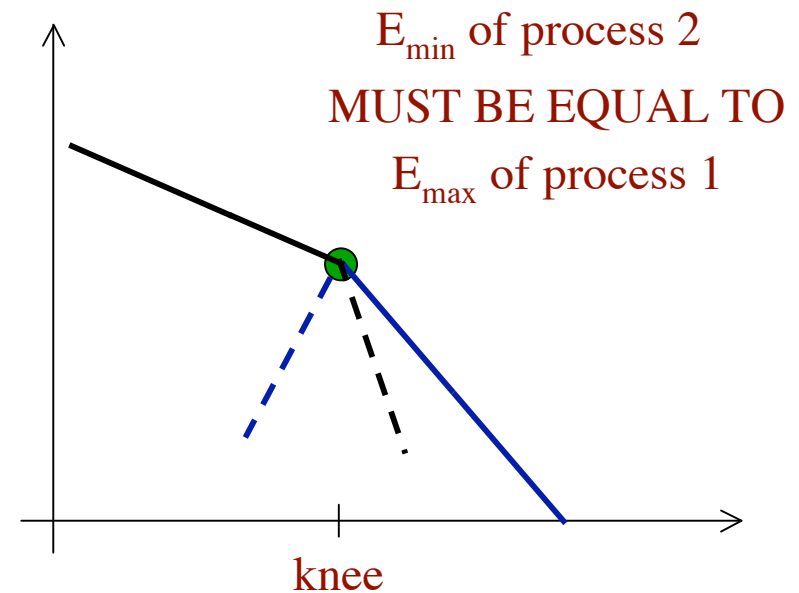
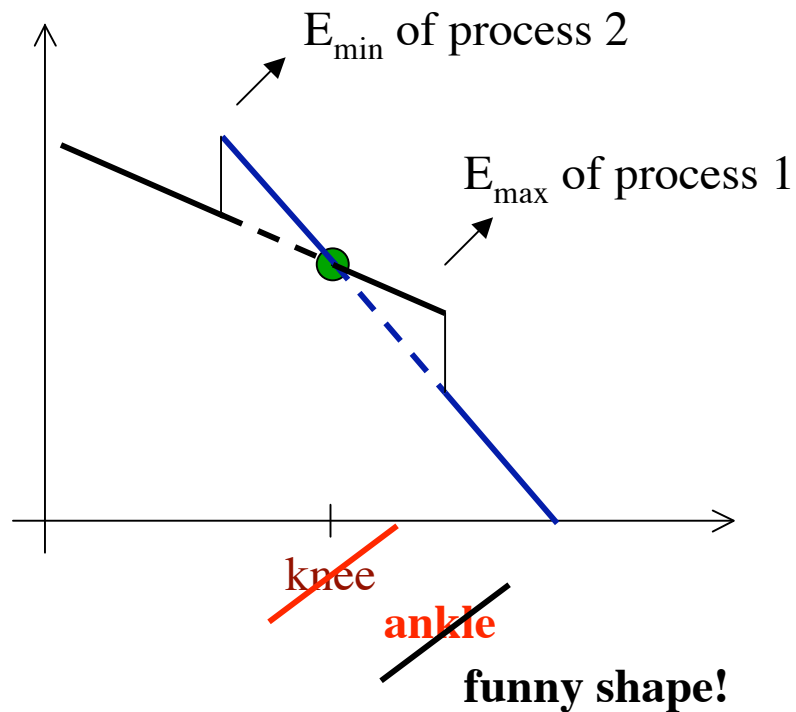


transition from a hard to a softer component



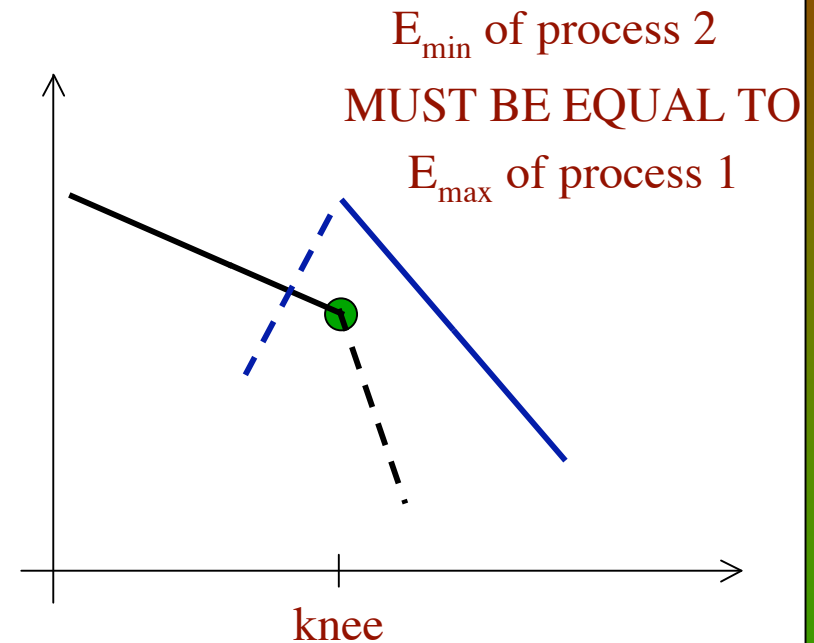
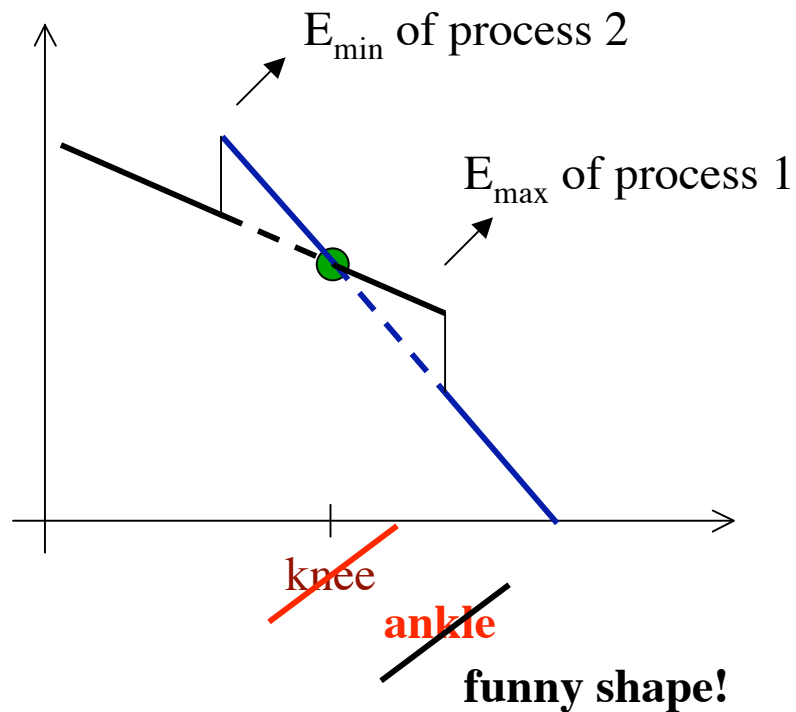
General phenomenology of transitions

- Requirements to obtain a knee-like transition:



General phenomenology of transitions

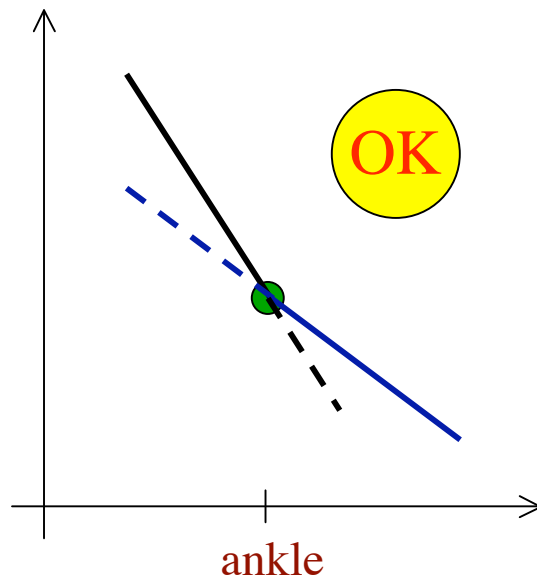
- Requirements to obtain a knee-like transition:



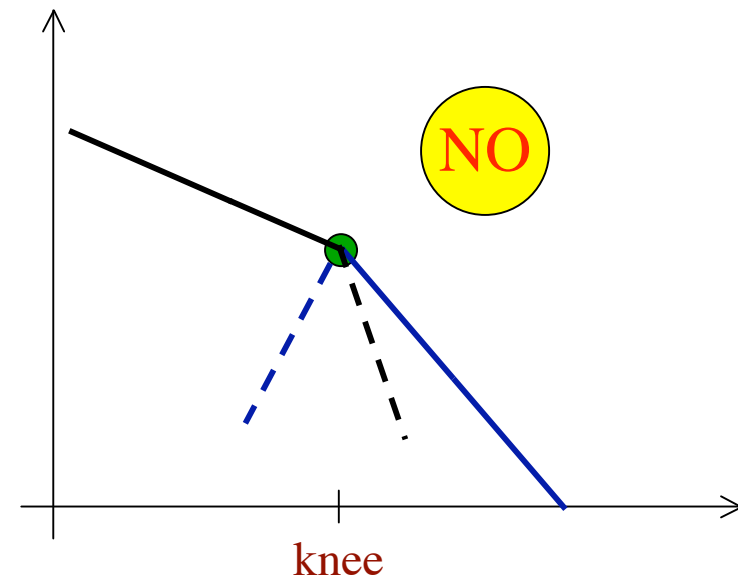
AND the flux of the two components MUST BE EQUAL precisely at THAT energy

General phenomenology of transitions

transition from a soft
to a harder component



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



virtually impossible
(extremely improbable)

General phenomenology of transitions

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

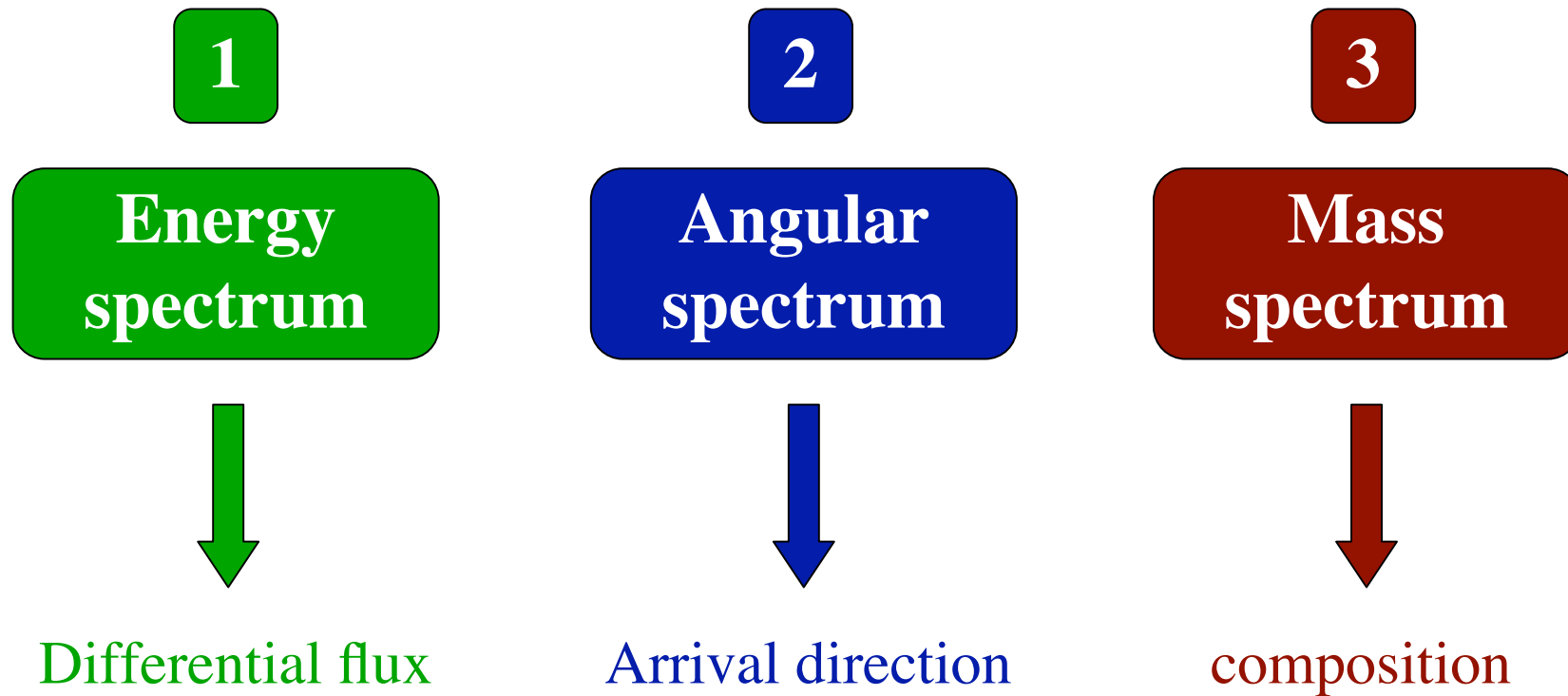
It could not be at much higher energy,
because Galactic CRs escape anyway

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

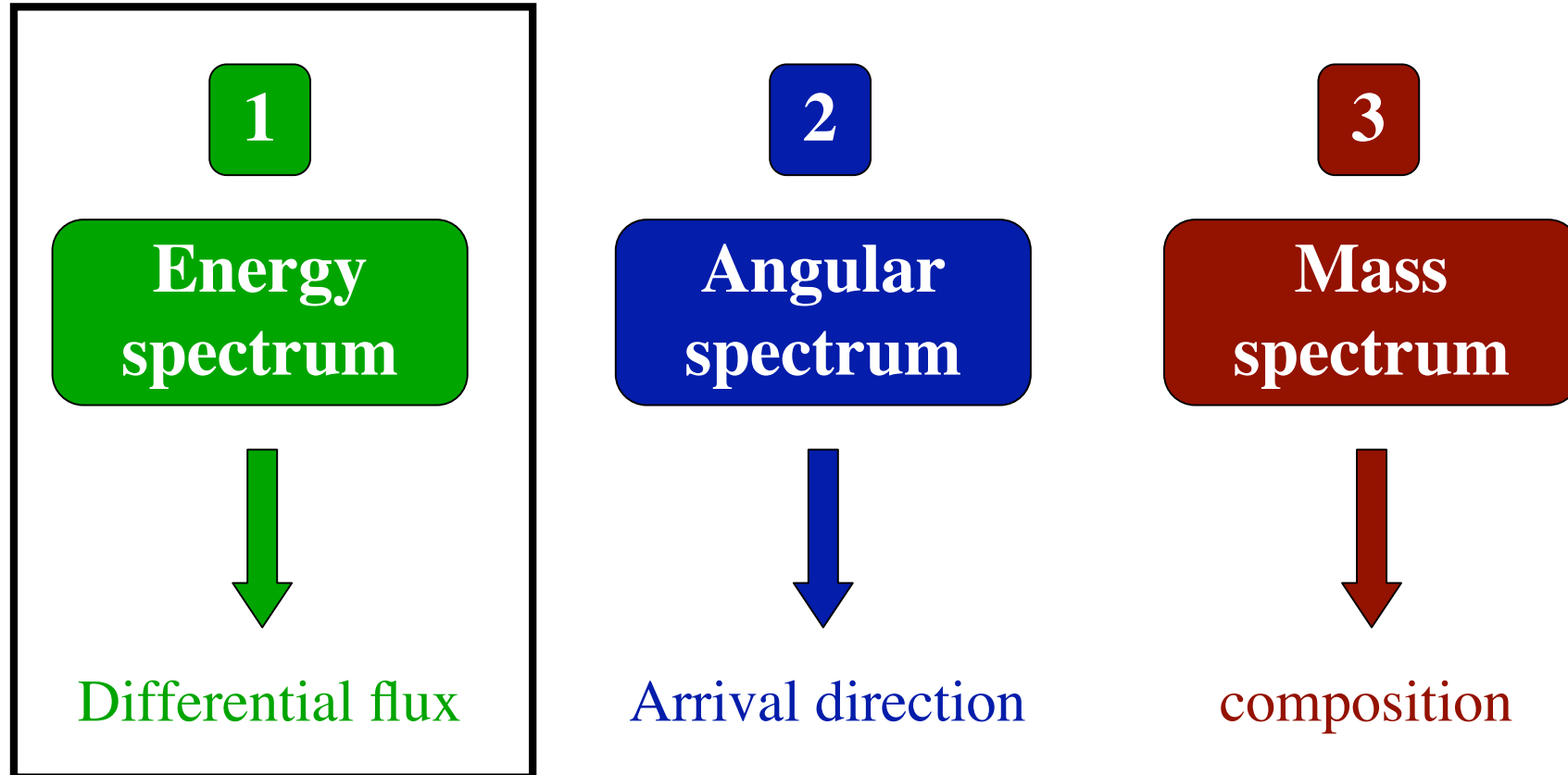
Propagation of extragalactic “UHECRs” (ultra-high-energy cosmic rays)

- Phenomenology similar to that of low-energy CRs
- Energy losses and nuclear reactions with photons as targets instead of interstellar nuclei... (and no escape!)
- Same 3 “spectral dimensions”: transport in angular space, mass space, and energy space

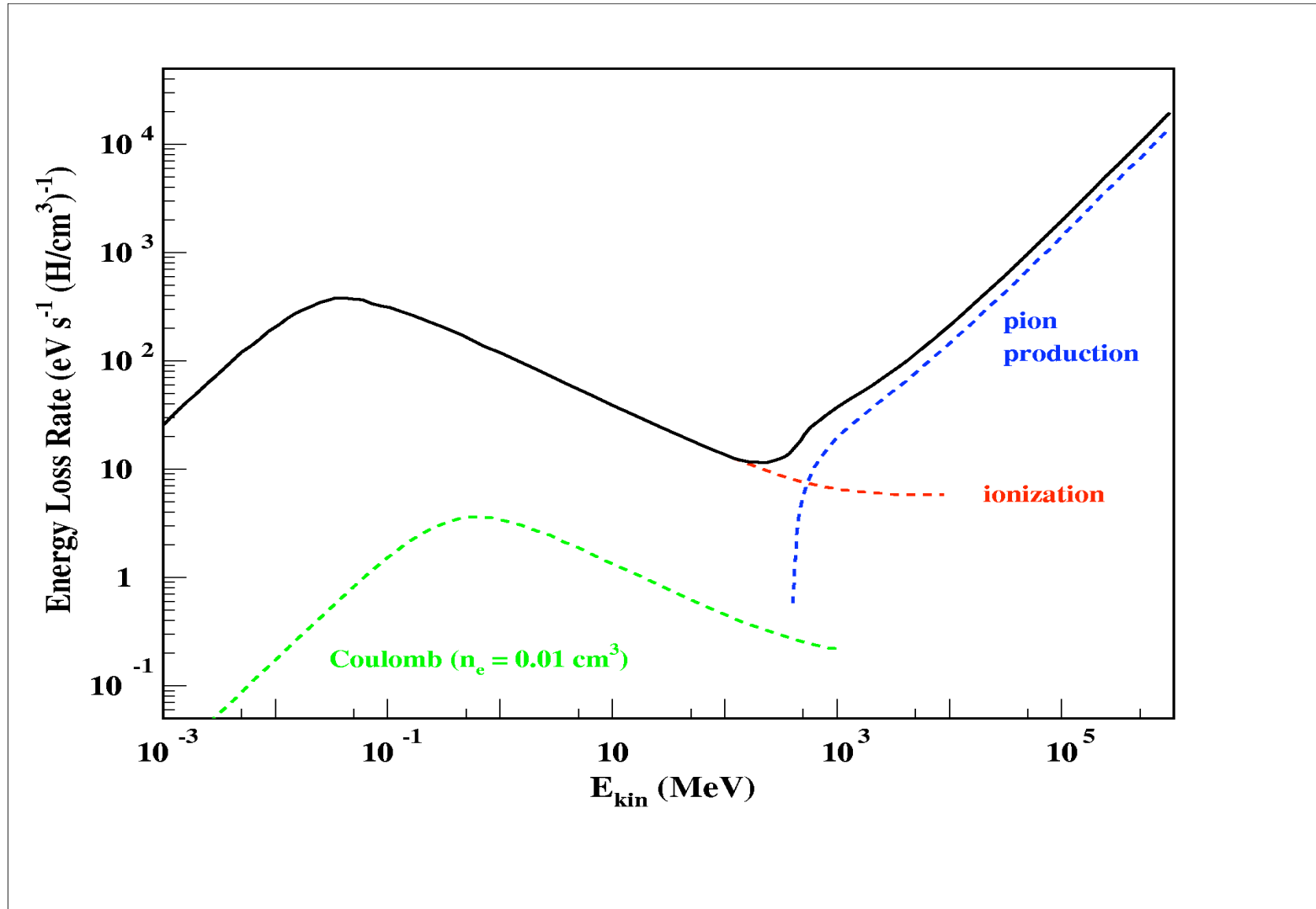
Cosmic-ray primary observables



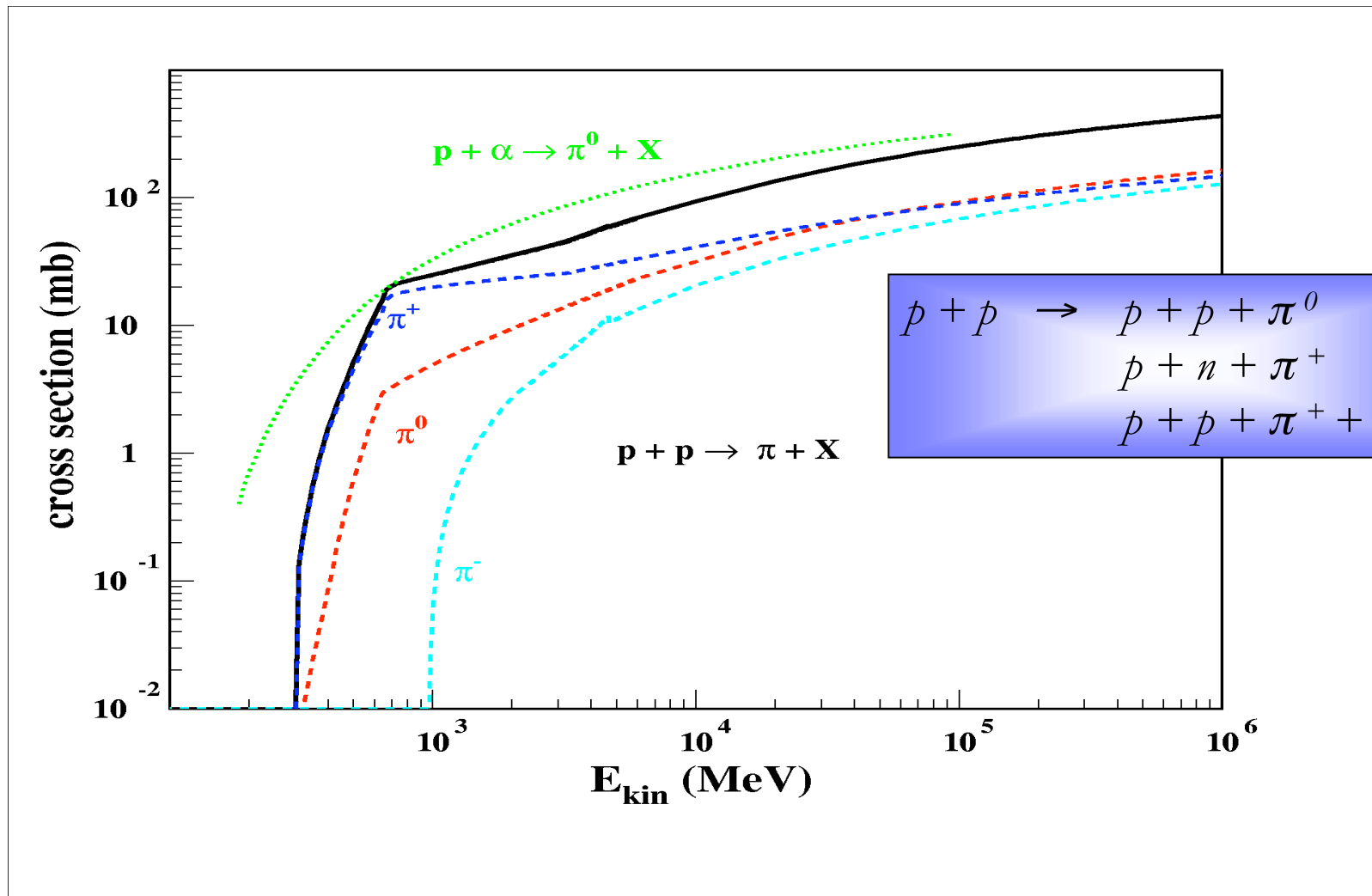
Cosmic-ray primary observables



Reminder: energy losses at low E

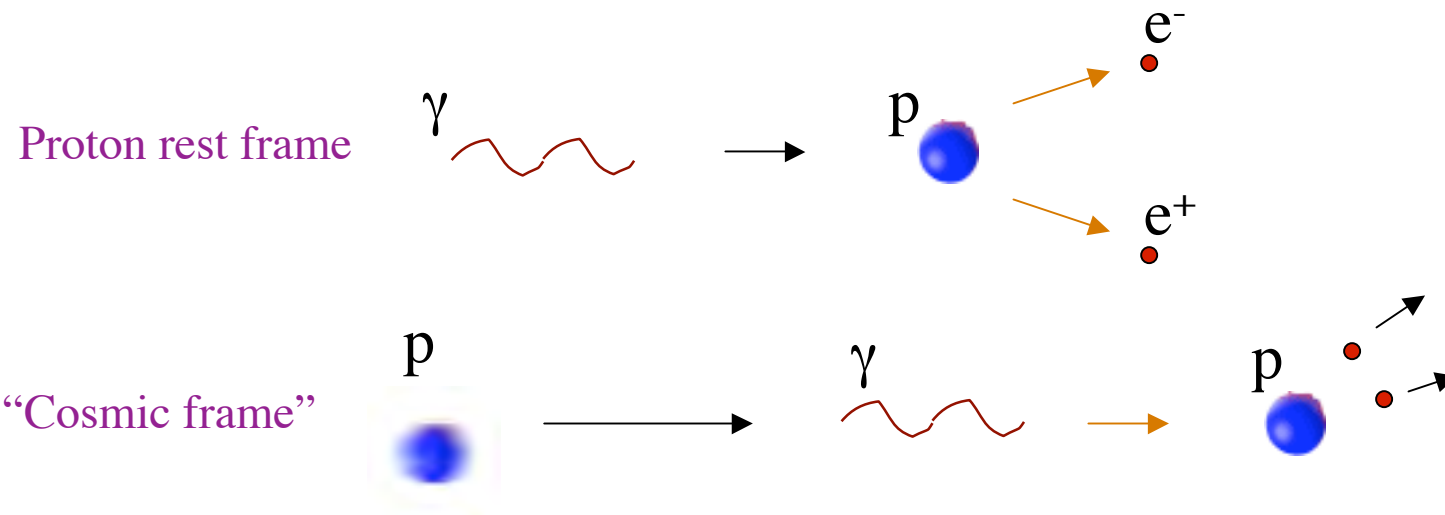


Nuclear interactions



The GZK effect

- Greisen (1966) + Zatsepin & Kuz'min (1966)
- Energy losses through e^+/e^- pair and pions production on CMB photons!



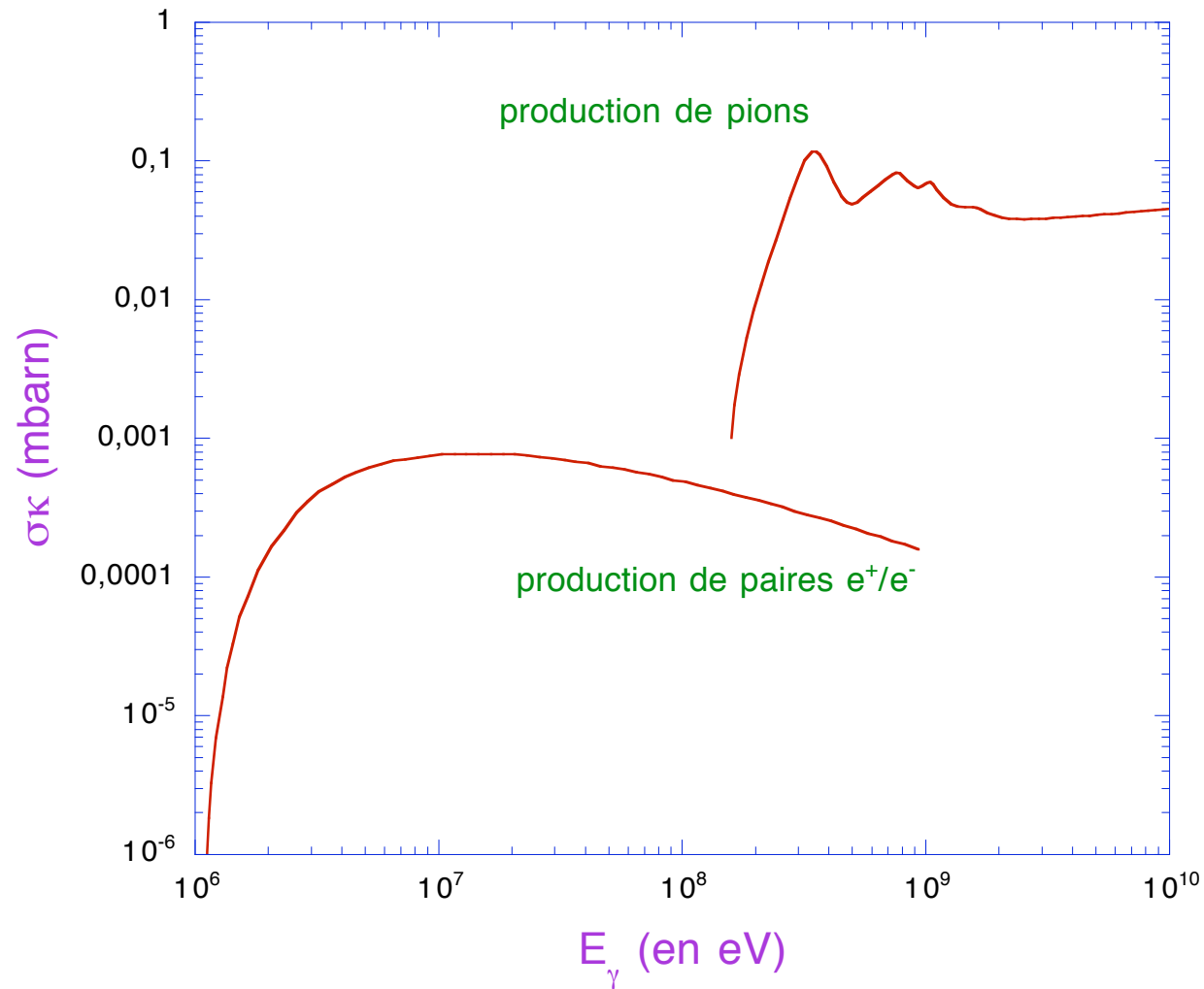
- Threshold : $E_\gamma \approx 2 m_e c^2$ in the proton rest frame

$$E_\gamma > 1 \text{ MeV}$$

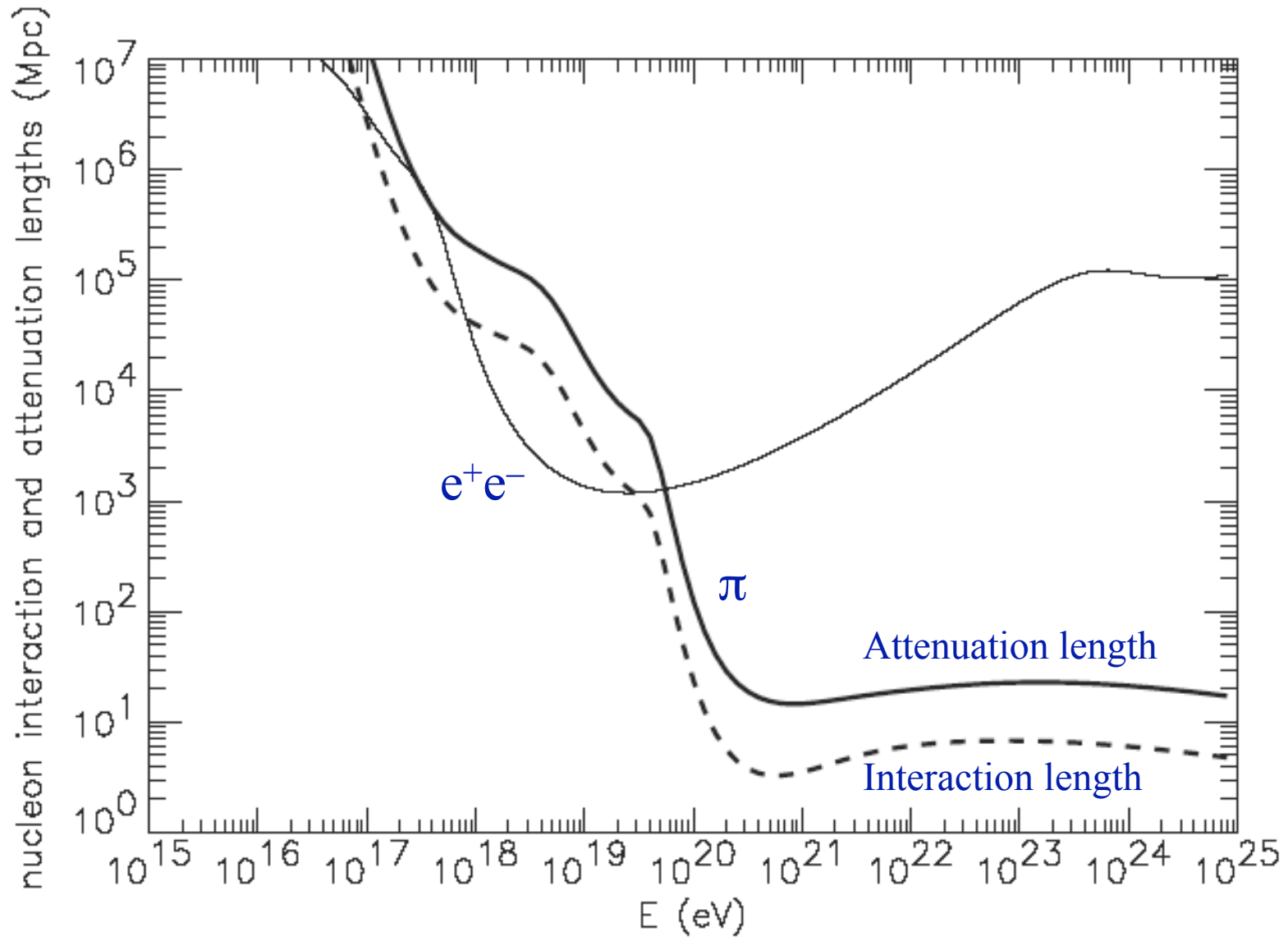
- Threshold : $E_\gamma \approx m_\pi c^2$ in the proton rest frame

$$E_\gamma > 160 \text{ MeV}$$

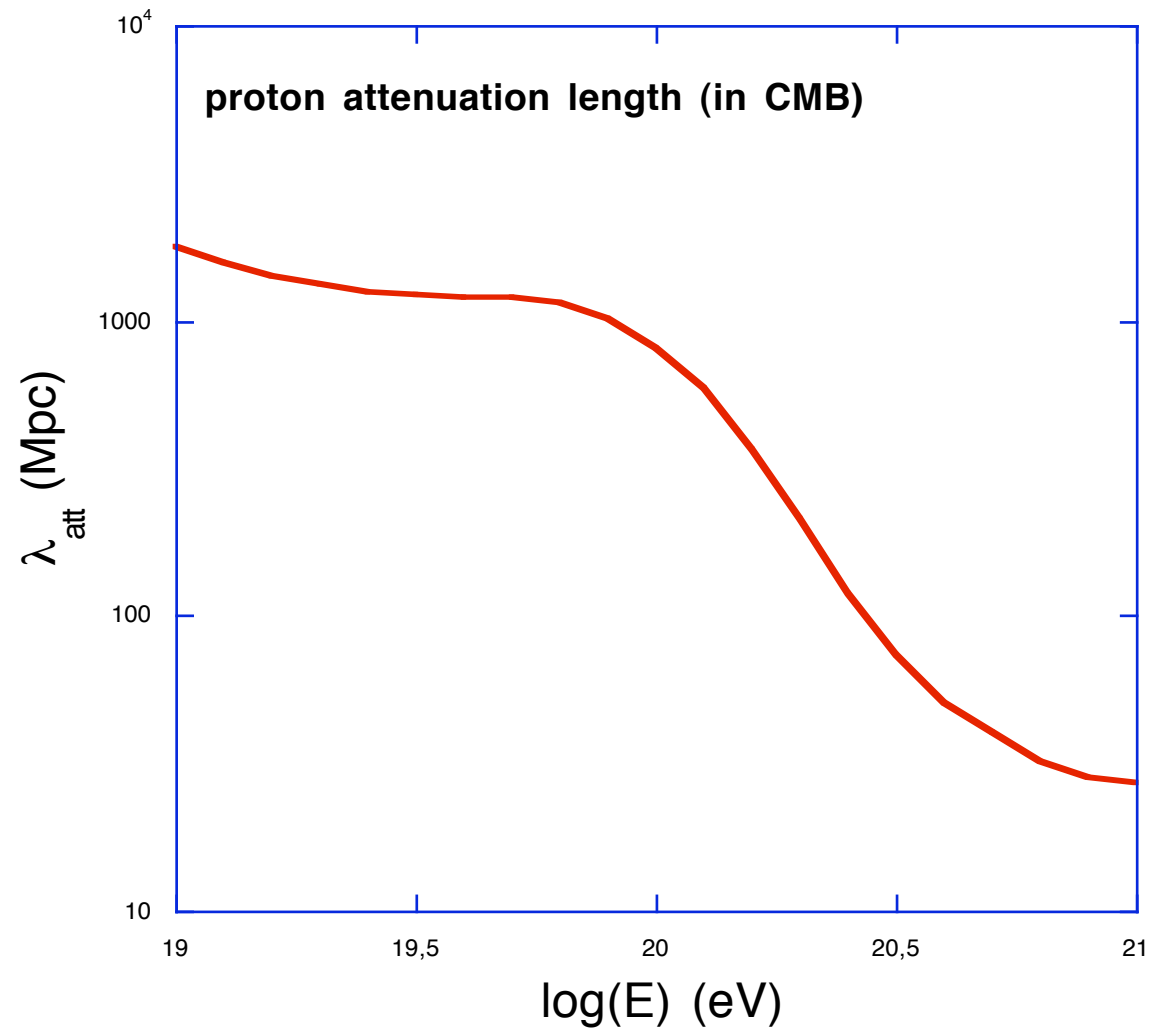
[cross section] × [inelasticity]



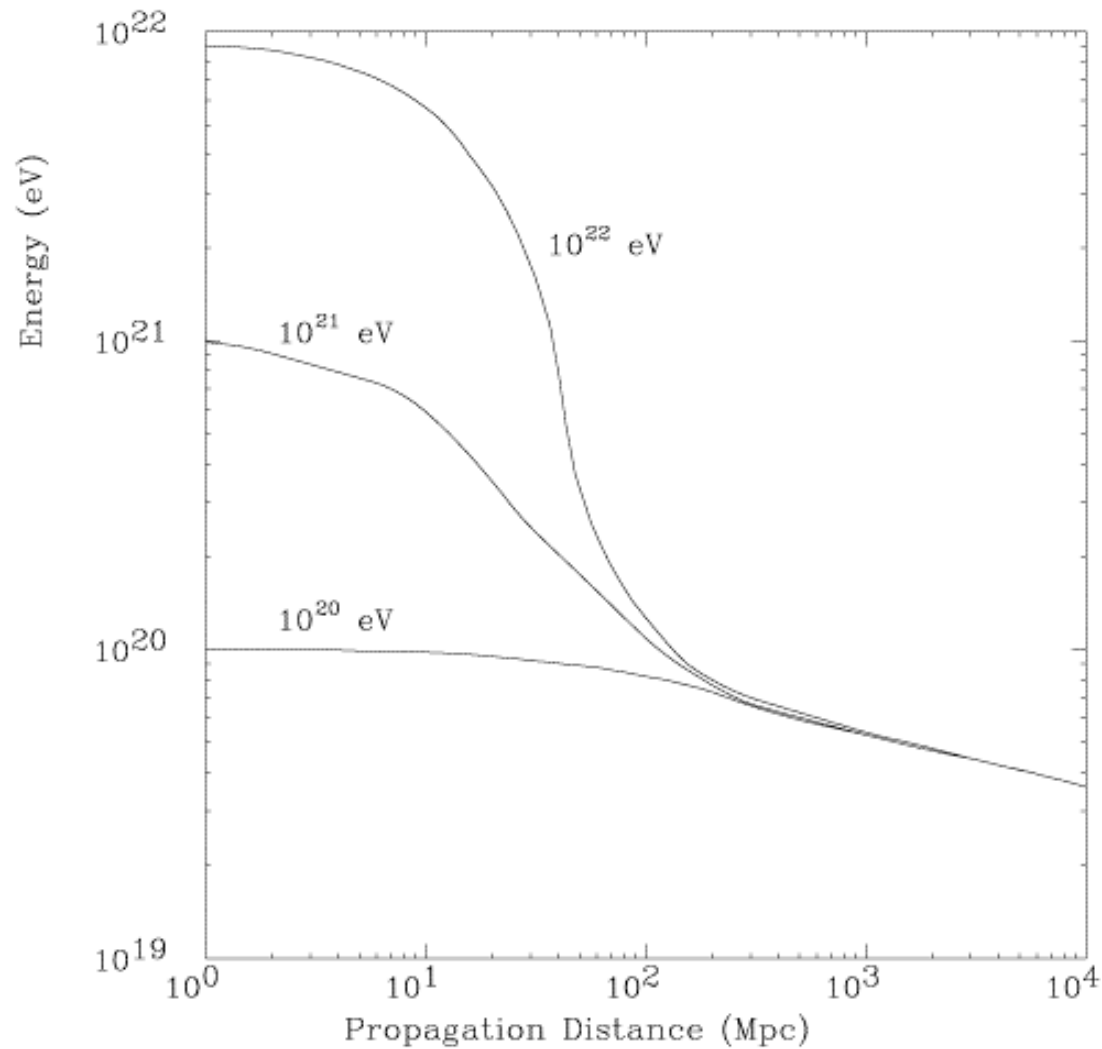
Attenuation length



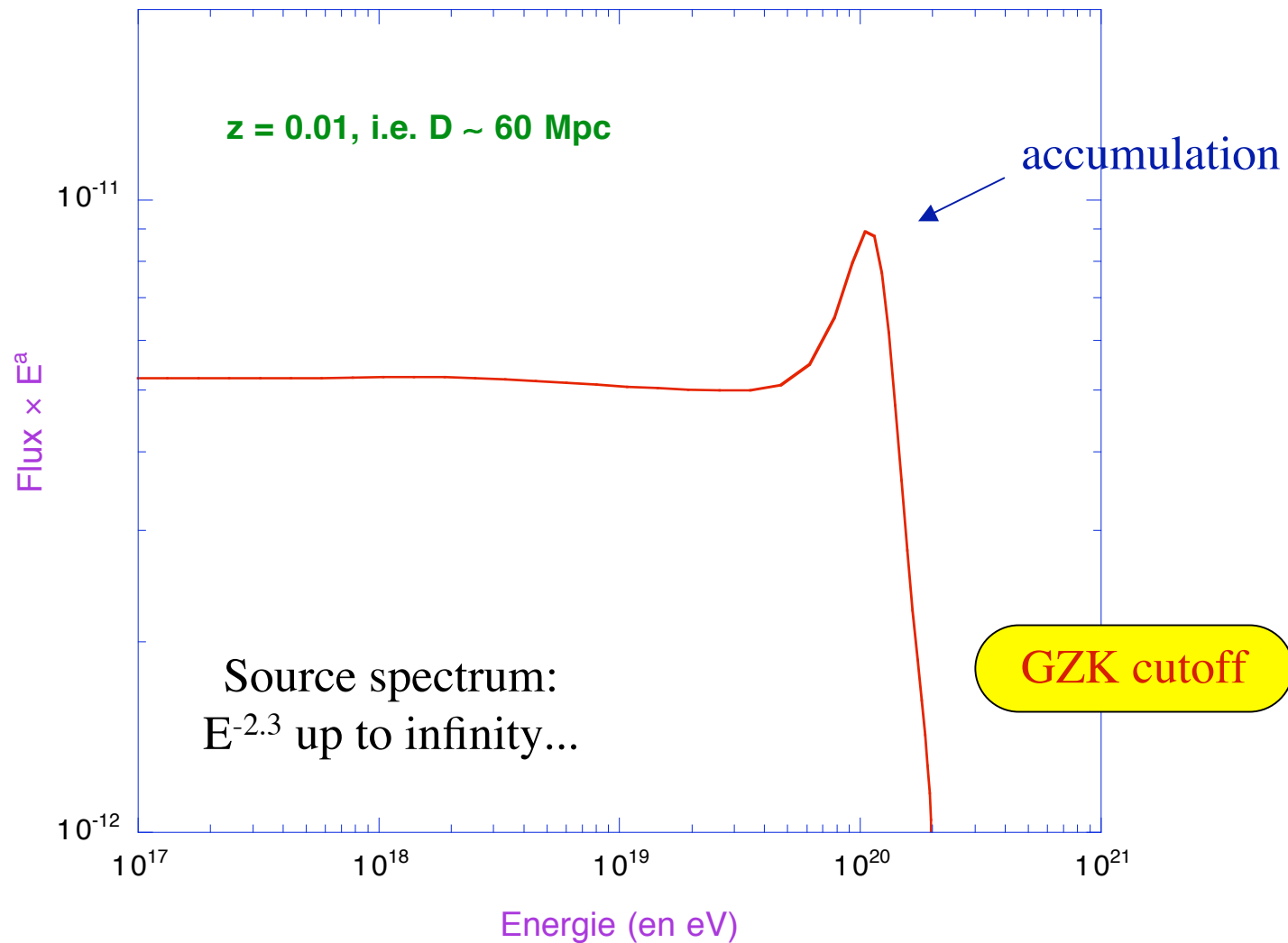
Attenuation length - horizons

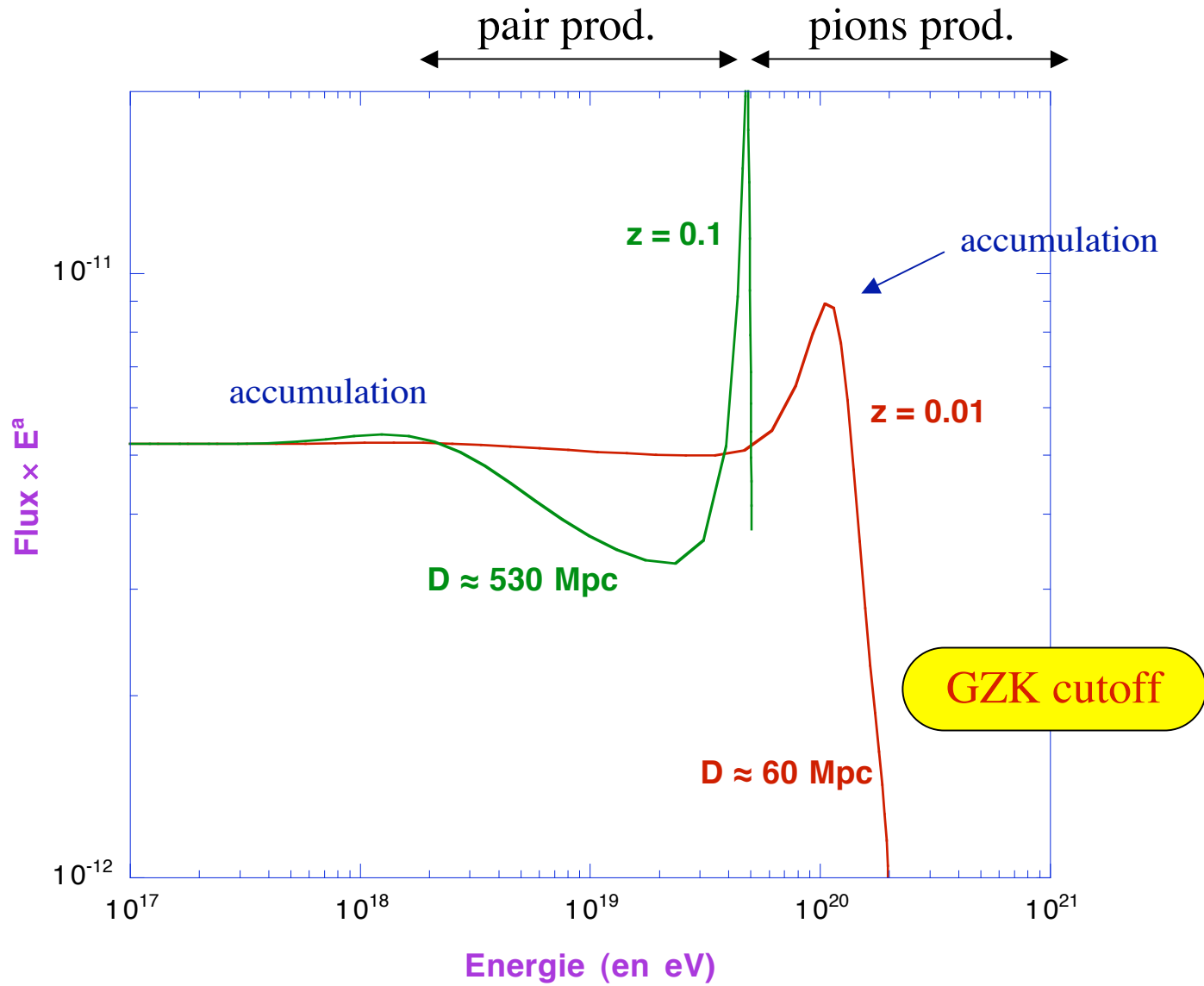


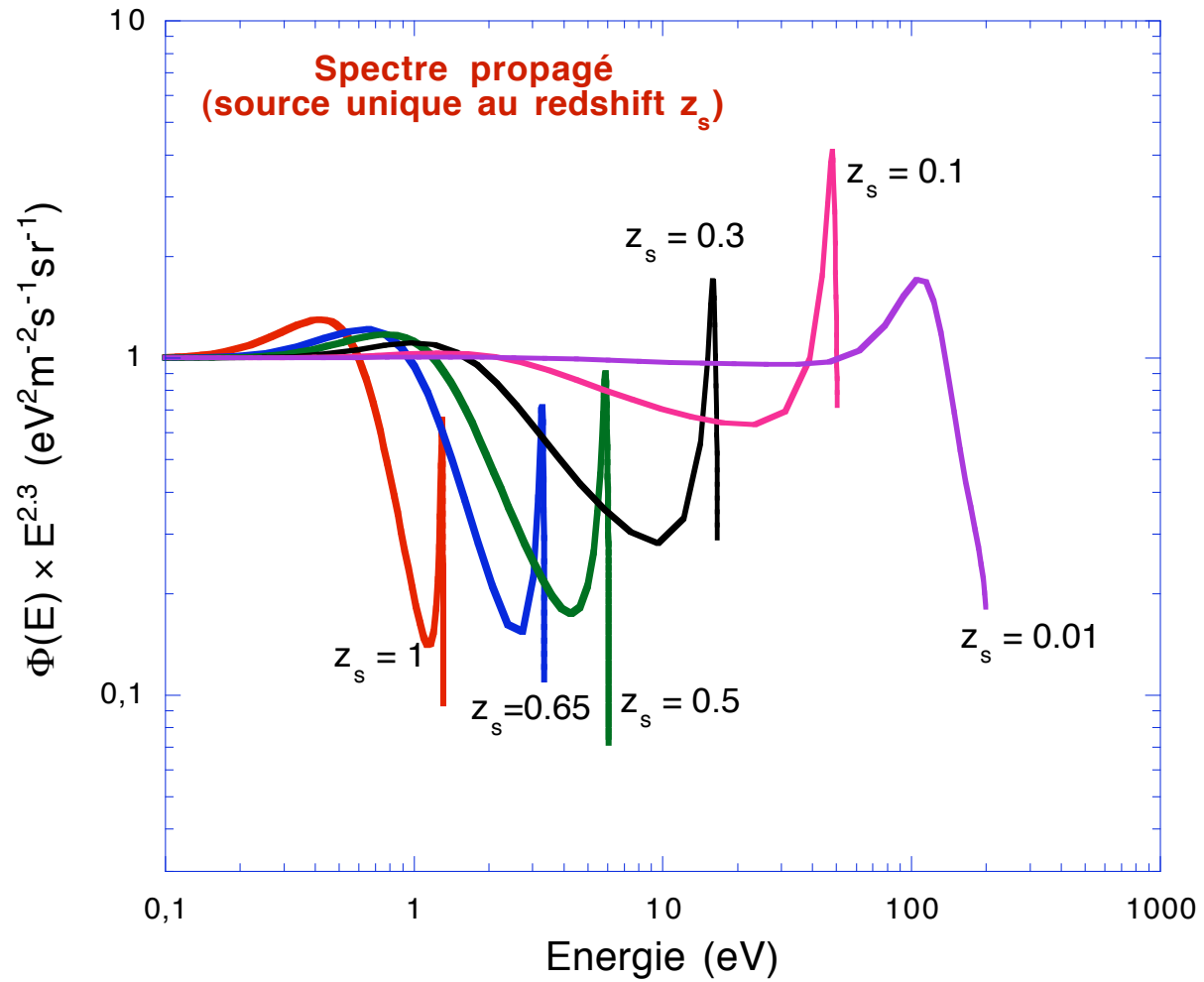
Evolution of the CR energy



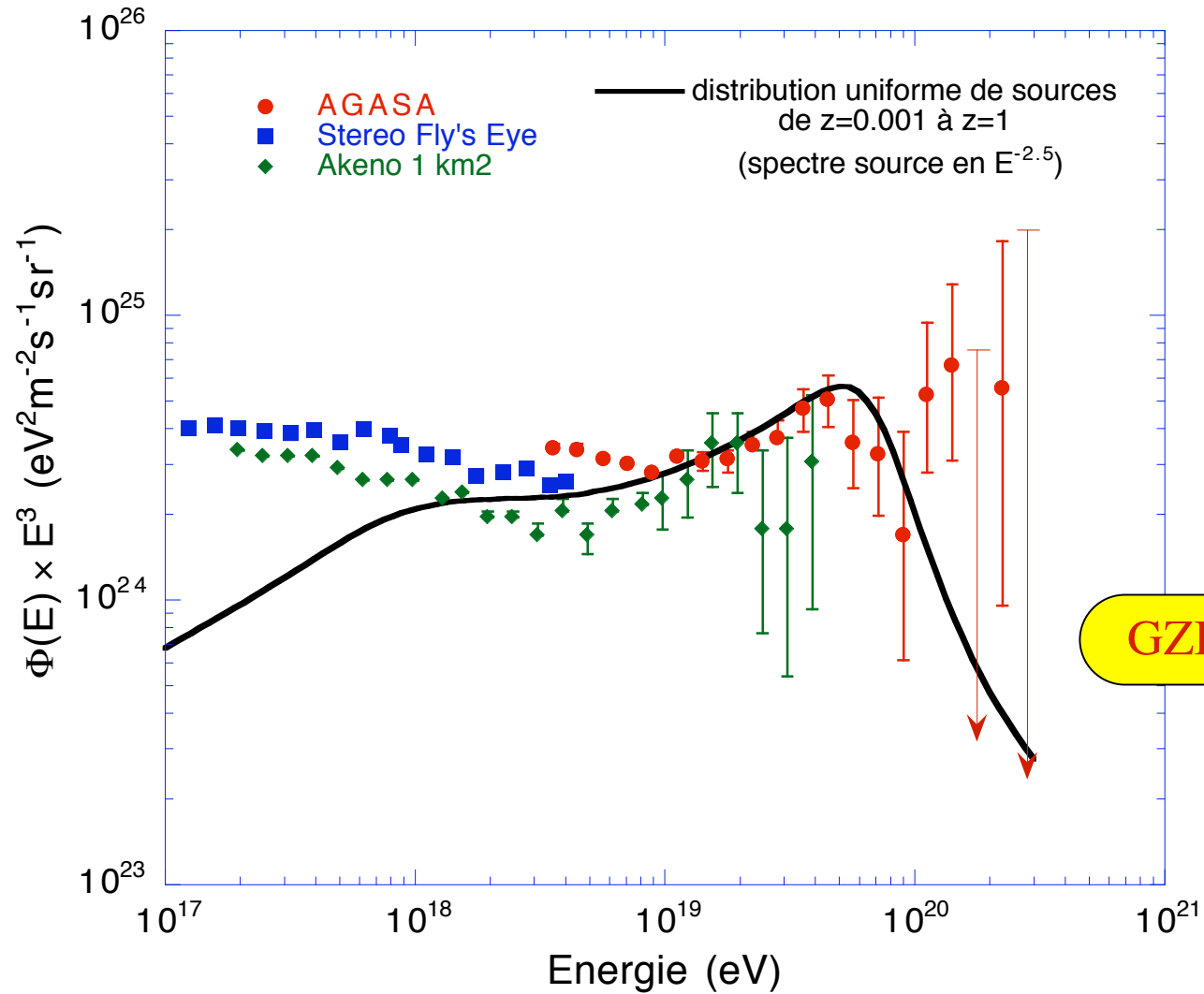
"Propagated" spectrum





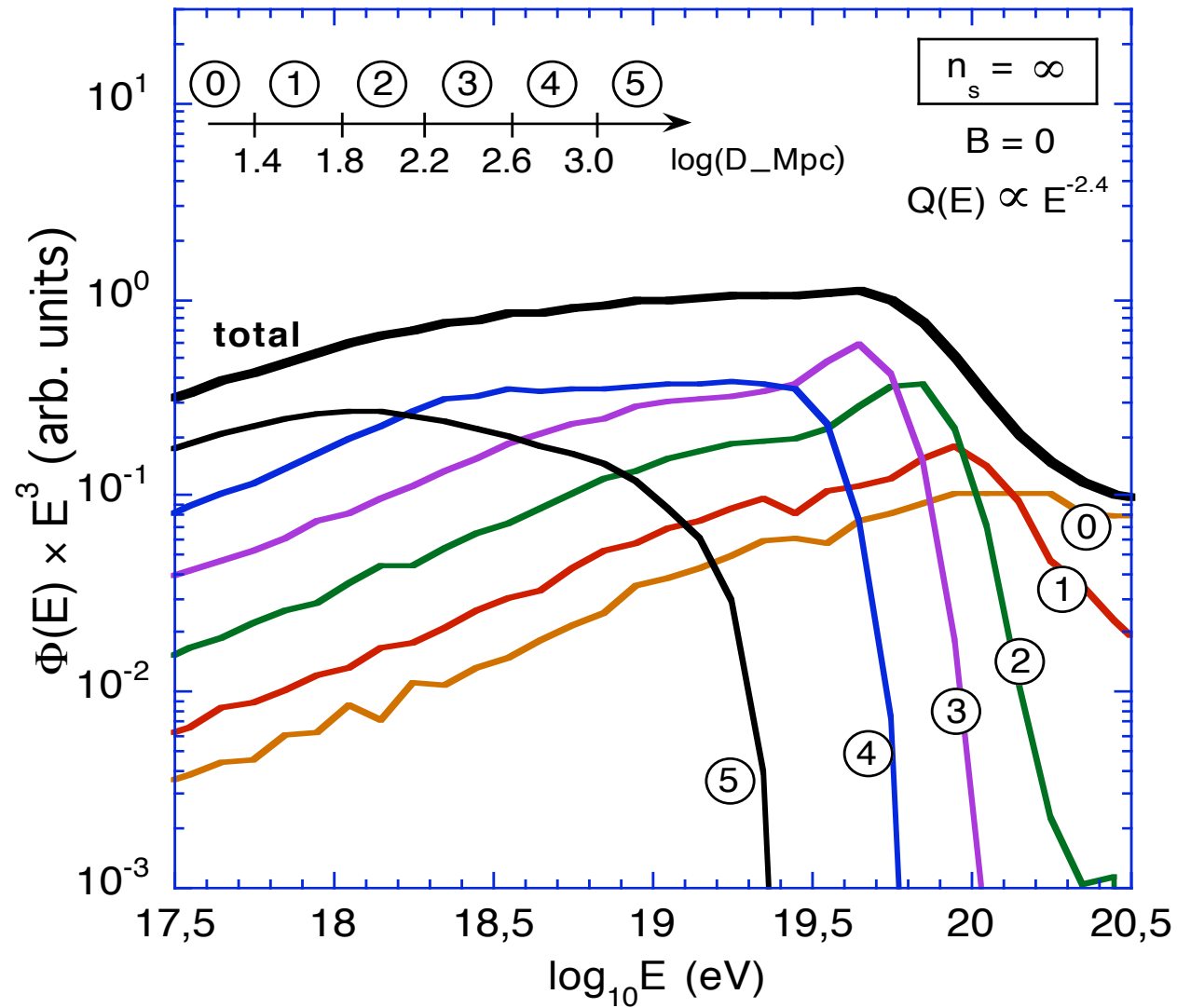


Uniform source distribution

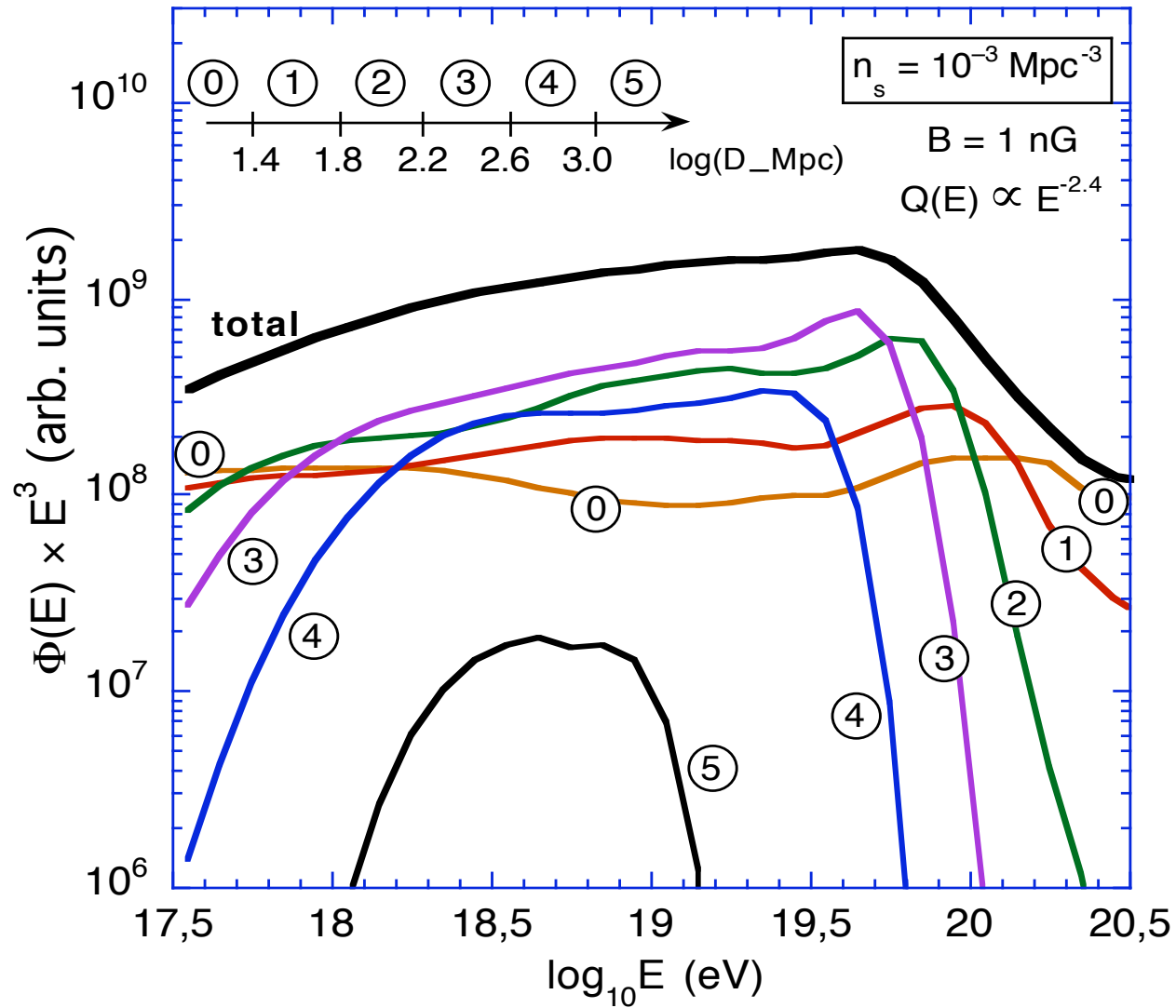


GZK cutoff

Contribution of different injection redshifts



Contribution of different injection redshifts



Cosmic-ray primary observables

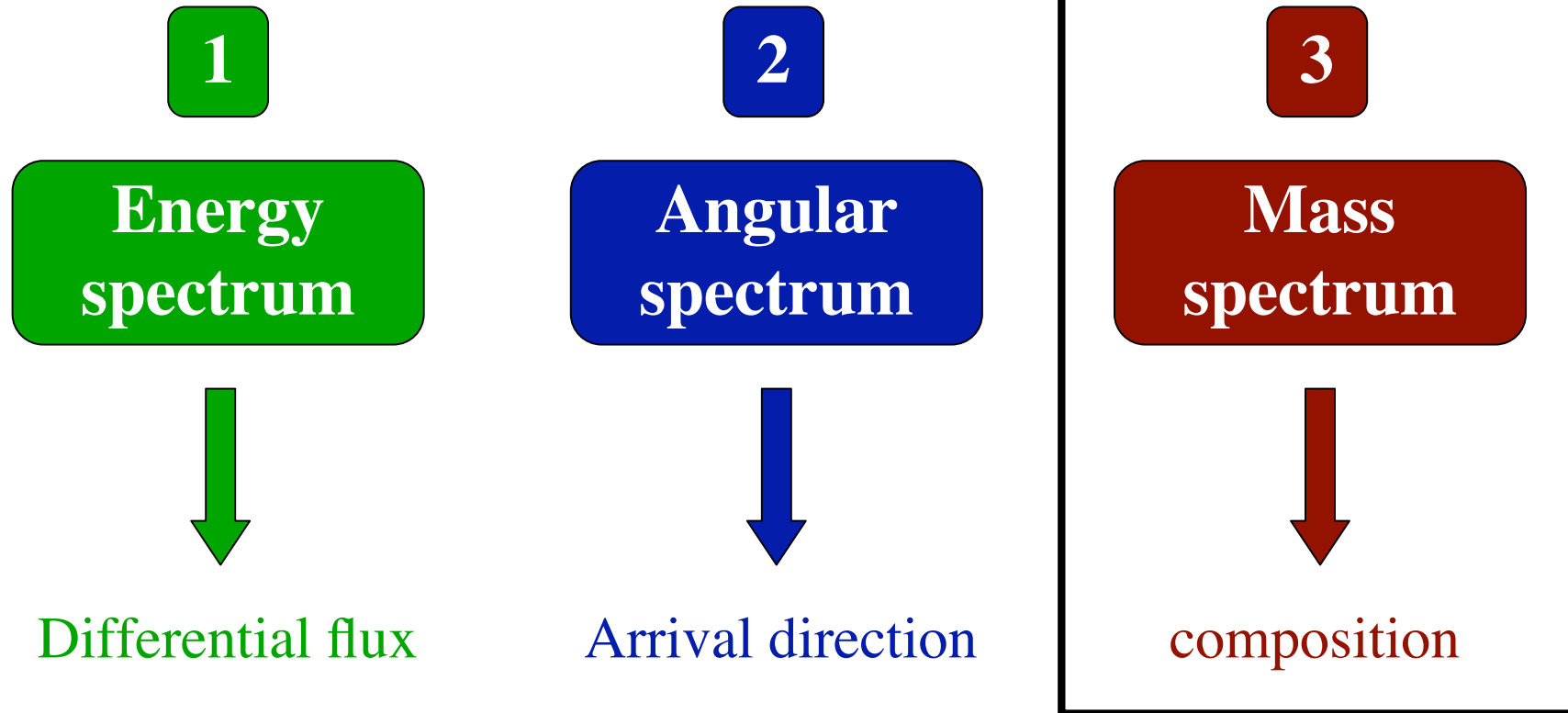
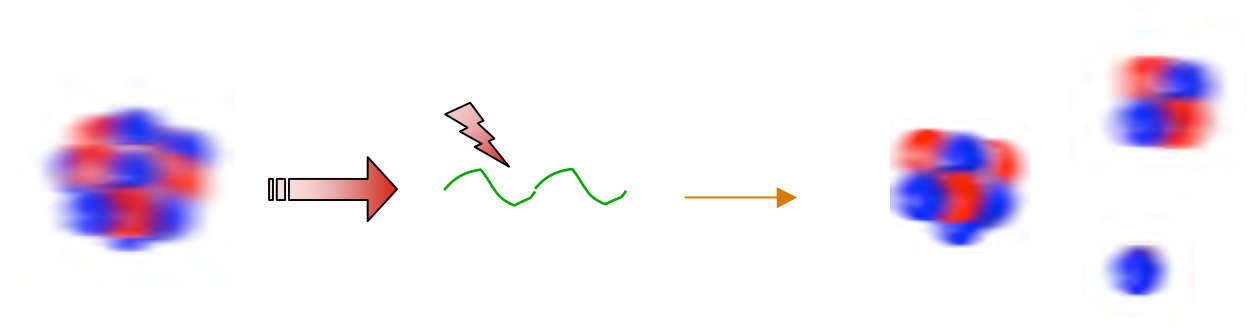
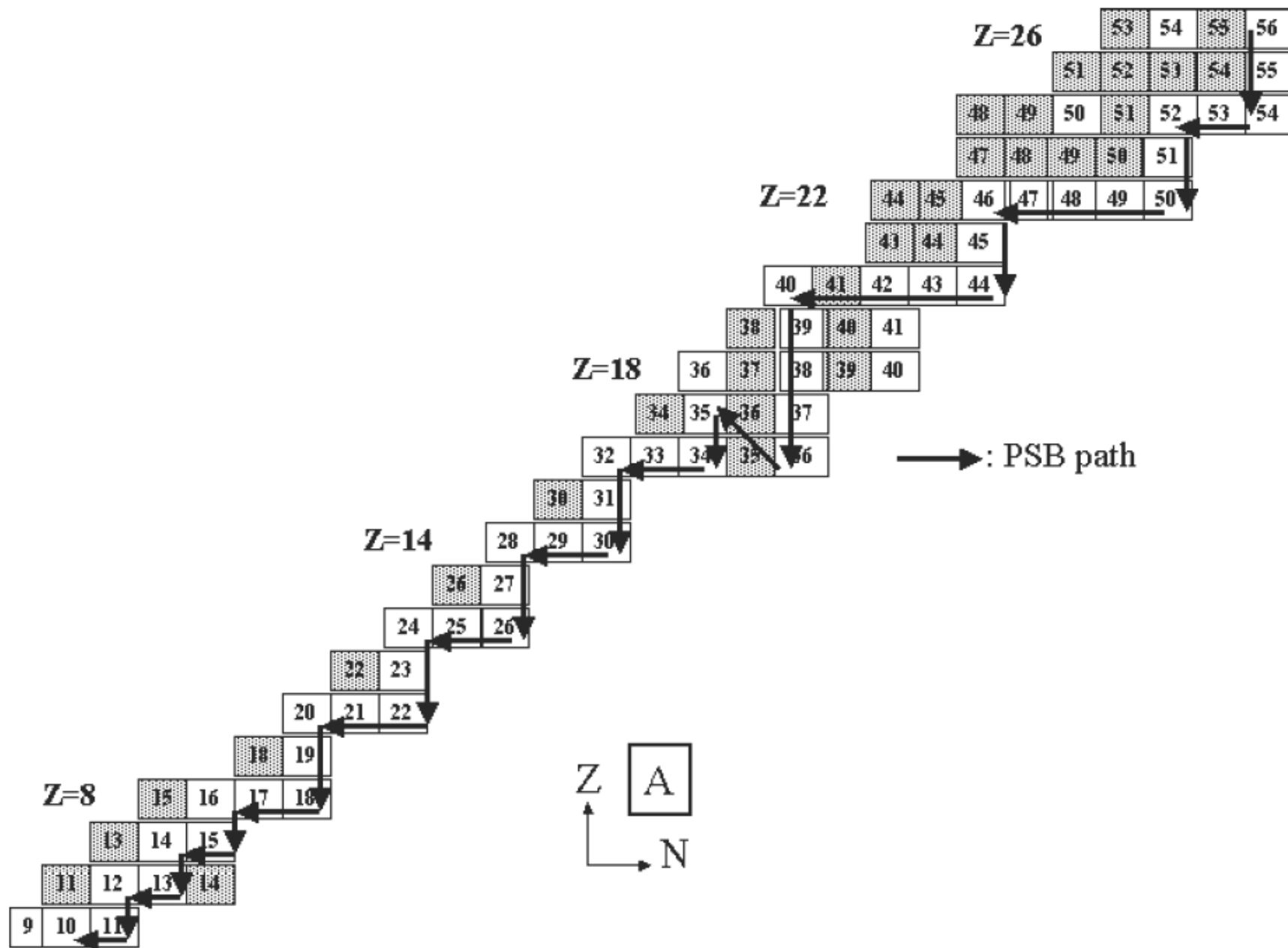


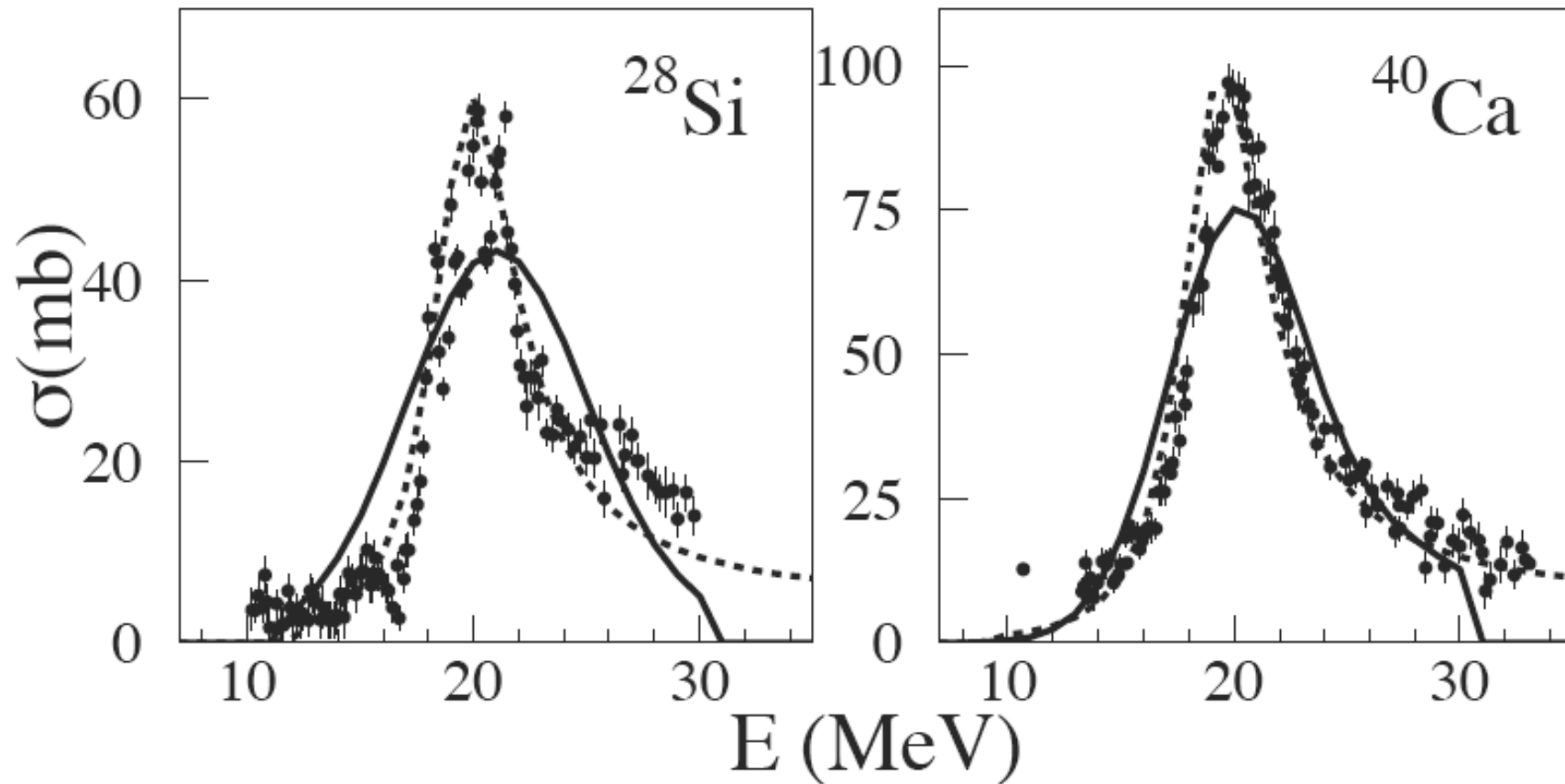
Photo-disintegration of nuclei



2D nuclear scheme

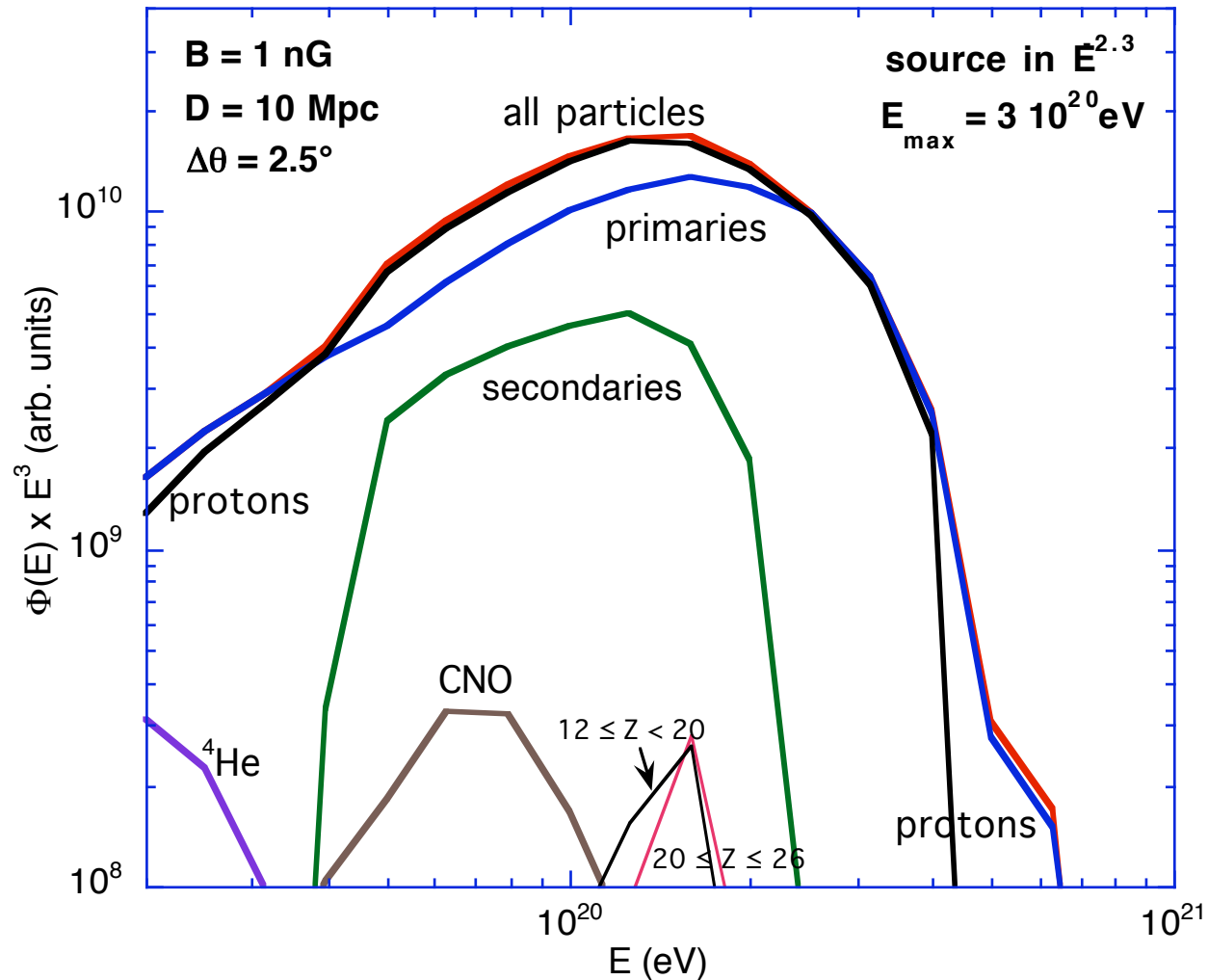


New cross sections

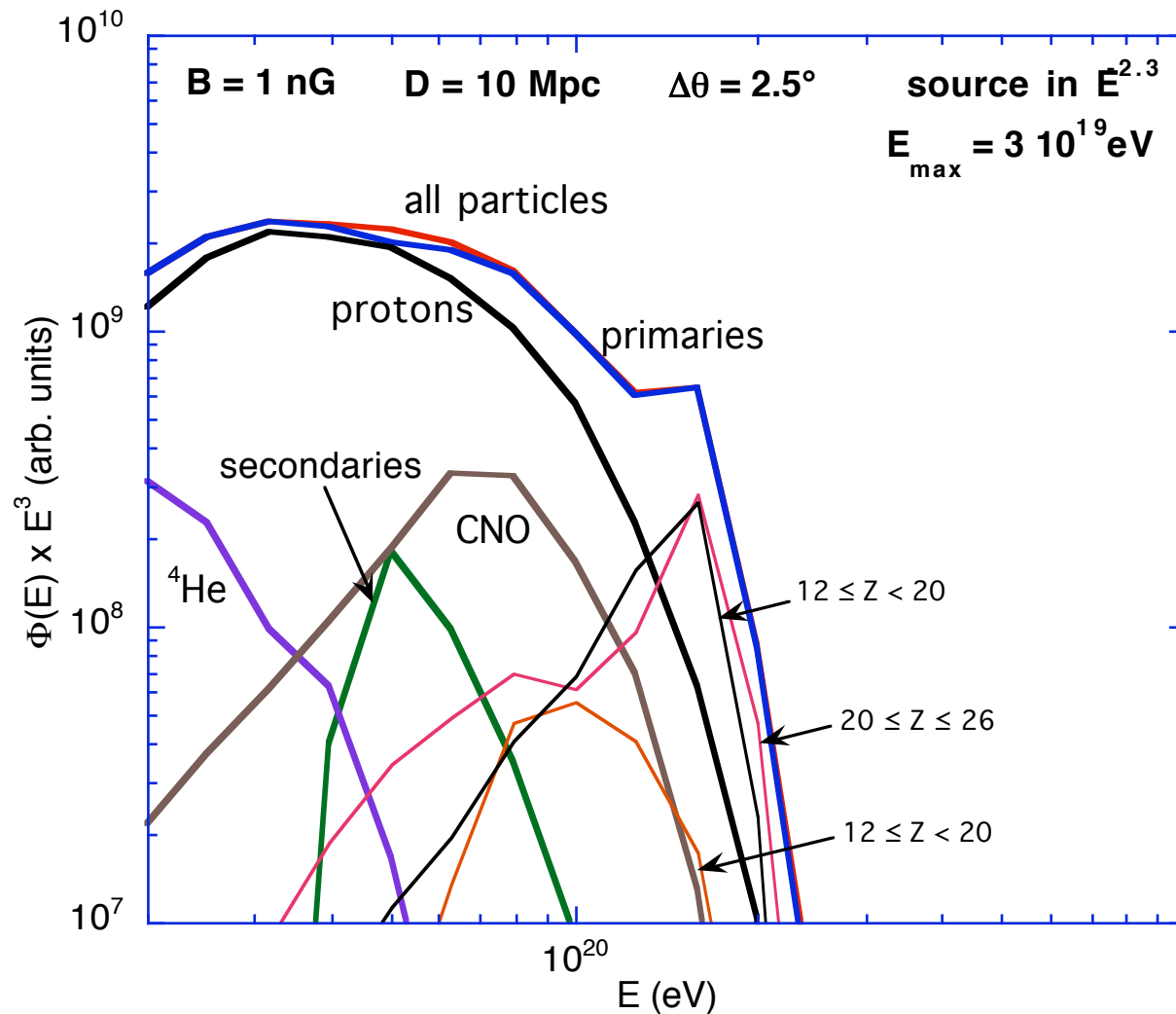


- Puget, Stecker, Bredekamp (1976)
- - - Khan et al. (2004)

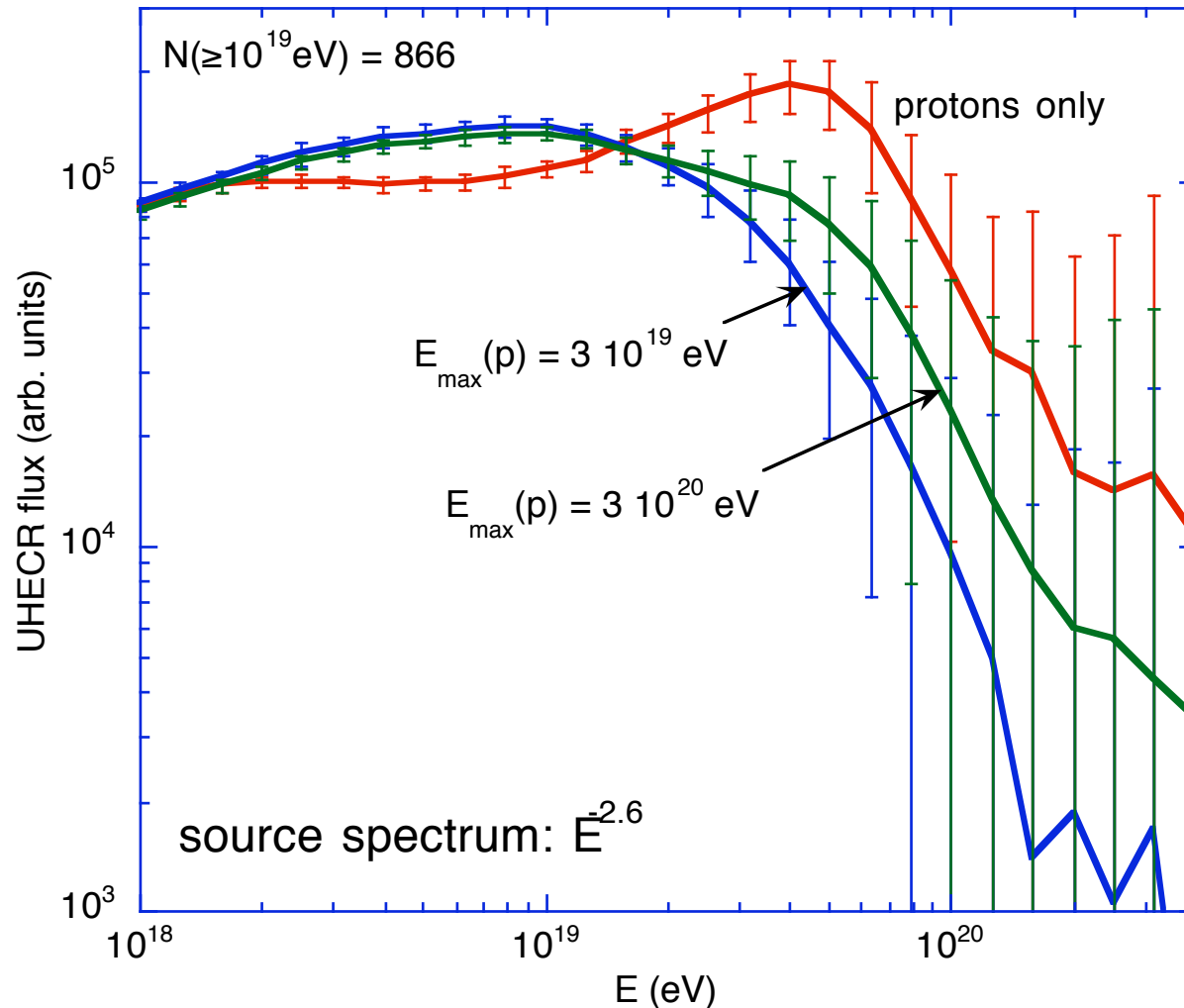
Individual sources



Individual sources

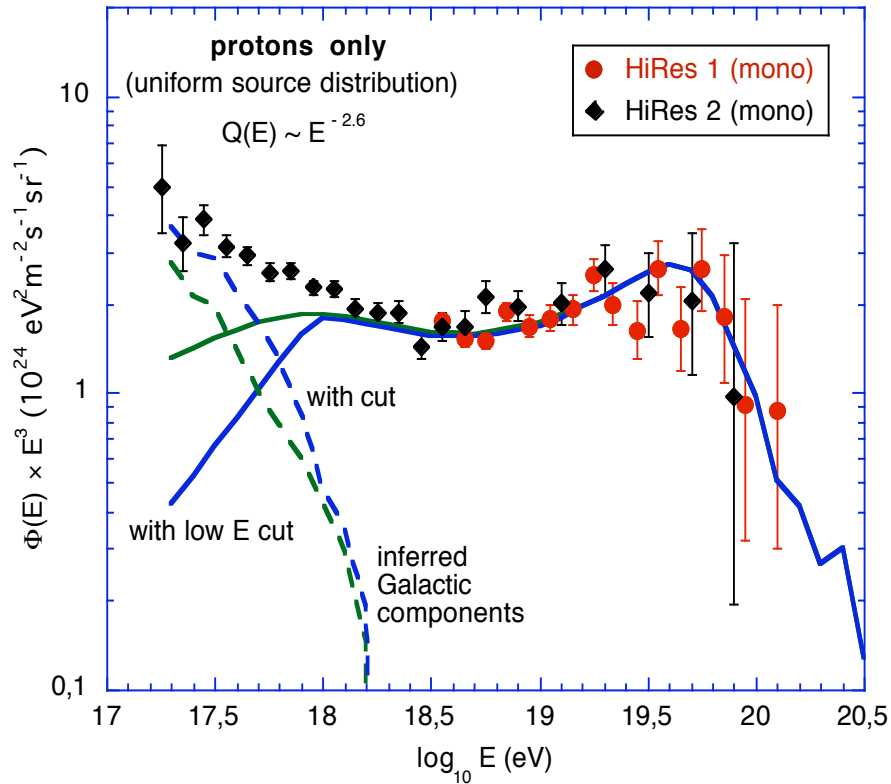


Examples of "propagated" spectra



Are there nuclei among EGCRs?

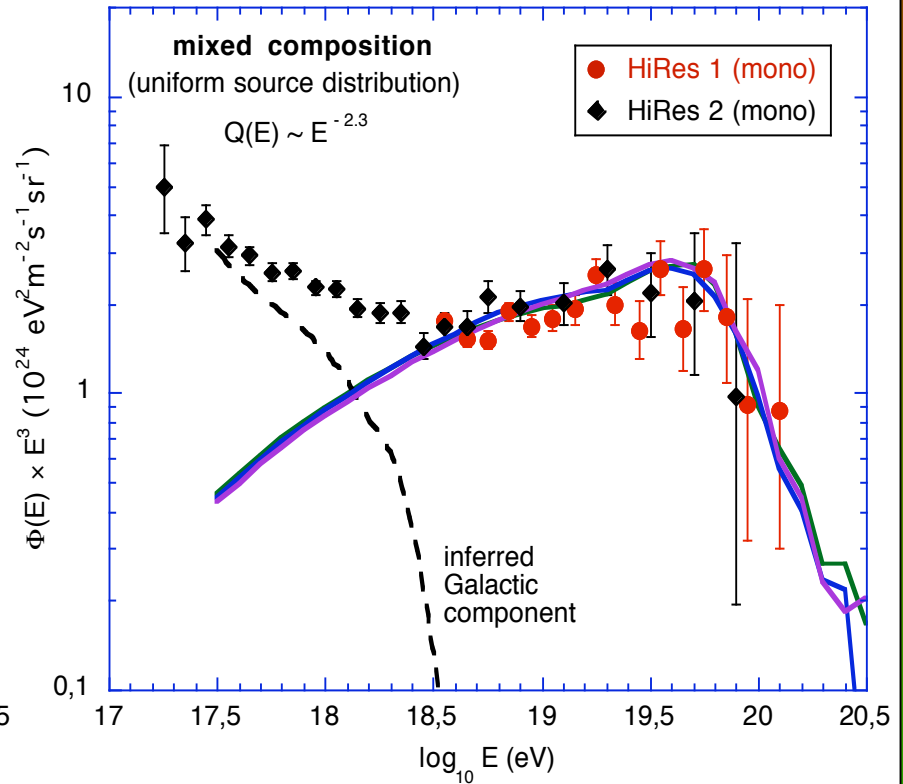
Pure protons (cf. Berezhinsky et al.)



Source spectrum in $E^{-2.6}$

Ankle = "pair production dip"

Mixed composition (Allard et al.)



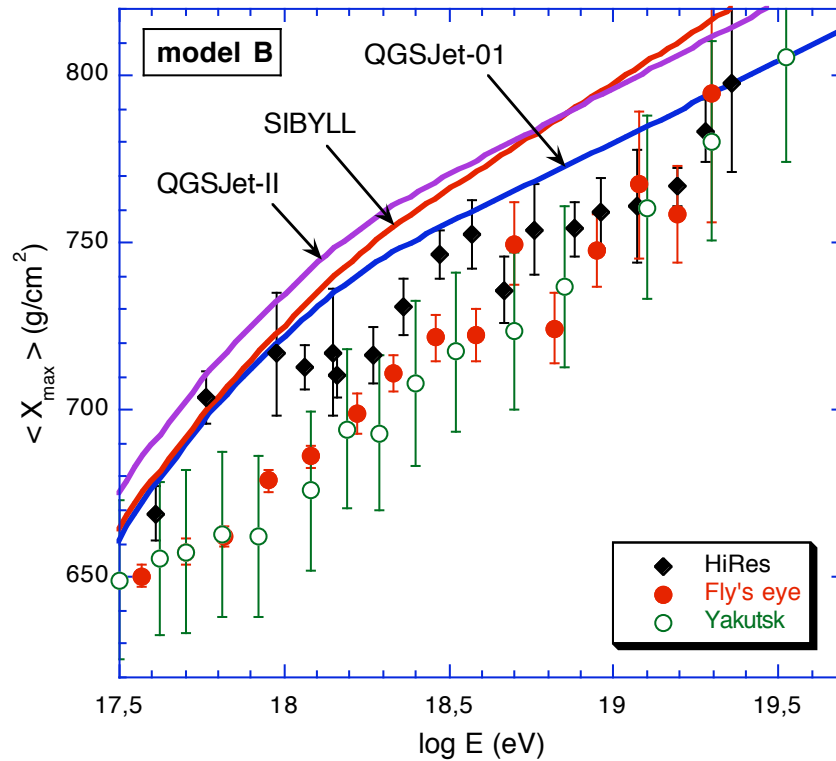
Source spectrum in $E^{-2.3}$

Ankle = gal./extragal. transition

Composition observables

(Galactic/Extragalactic transition)

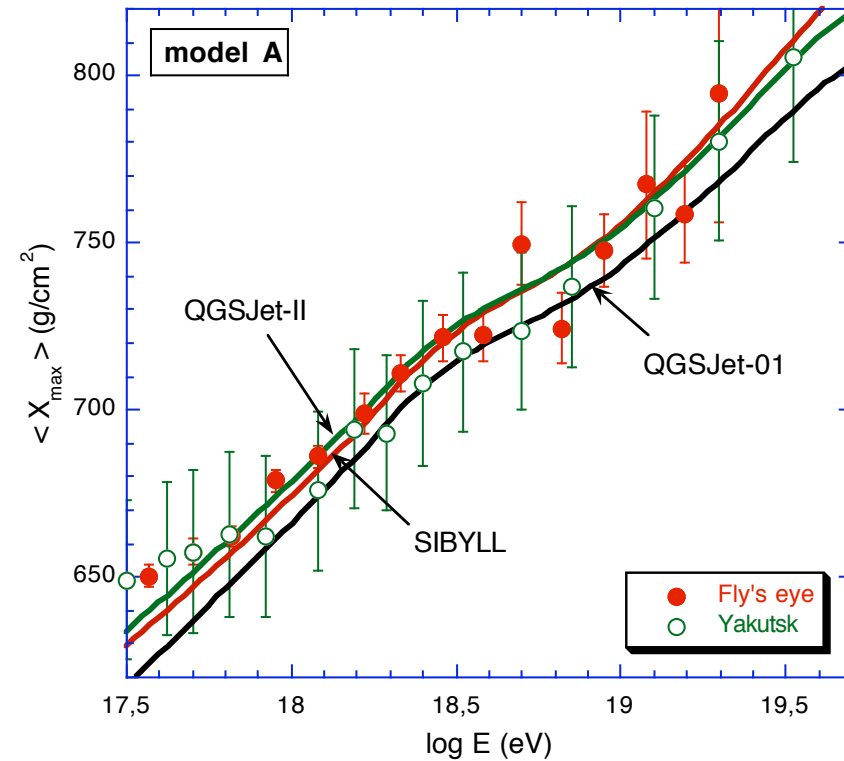
Pure protons (cf. Berezhinsky et al.)



Source spectrum in $E^{-2.6}$

Ankle = "pair production dip"

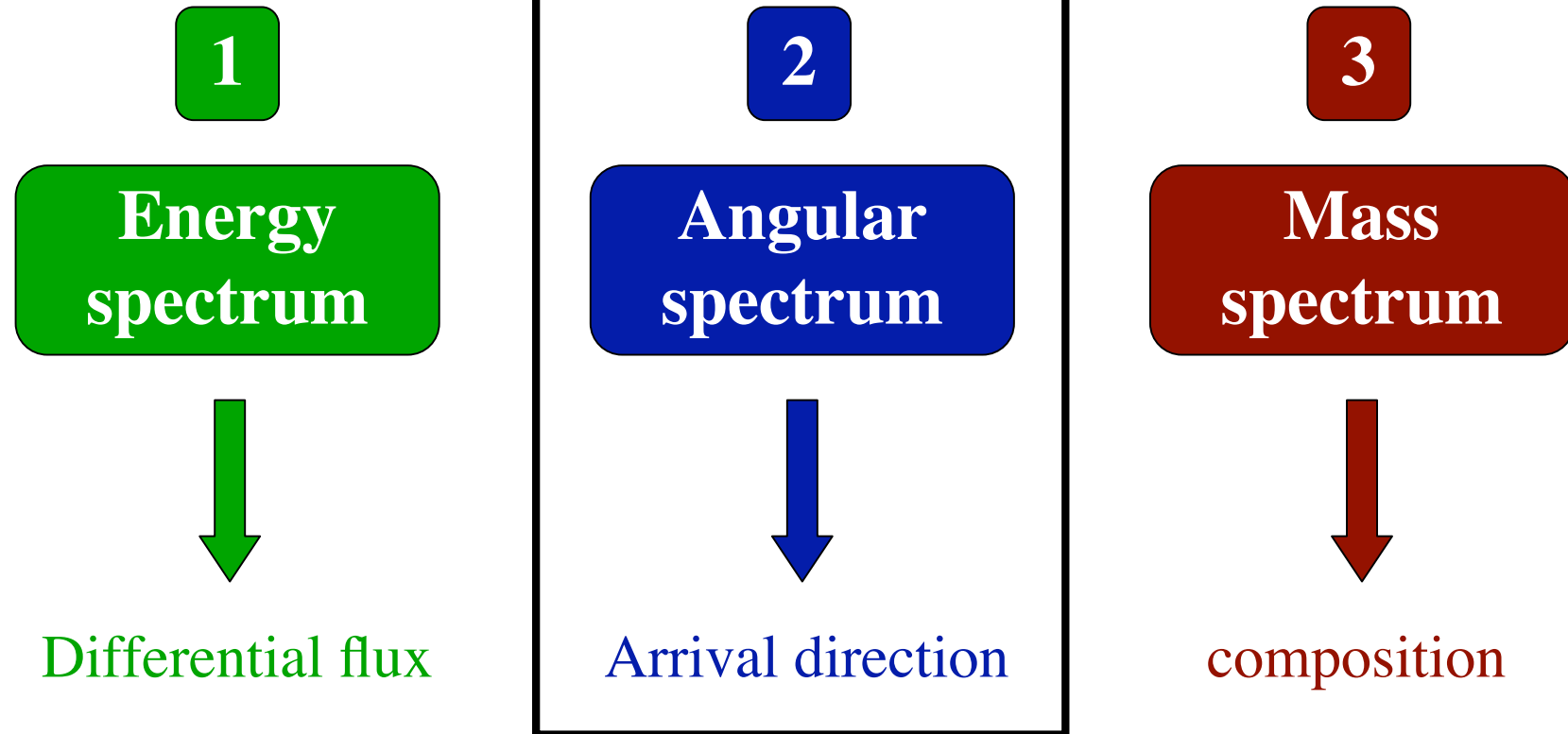
Mixed composition (Allard et al.)

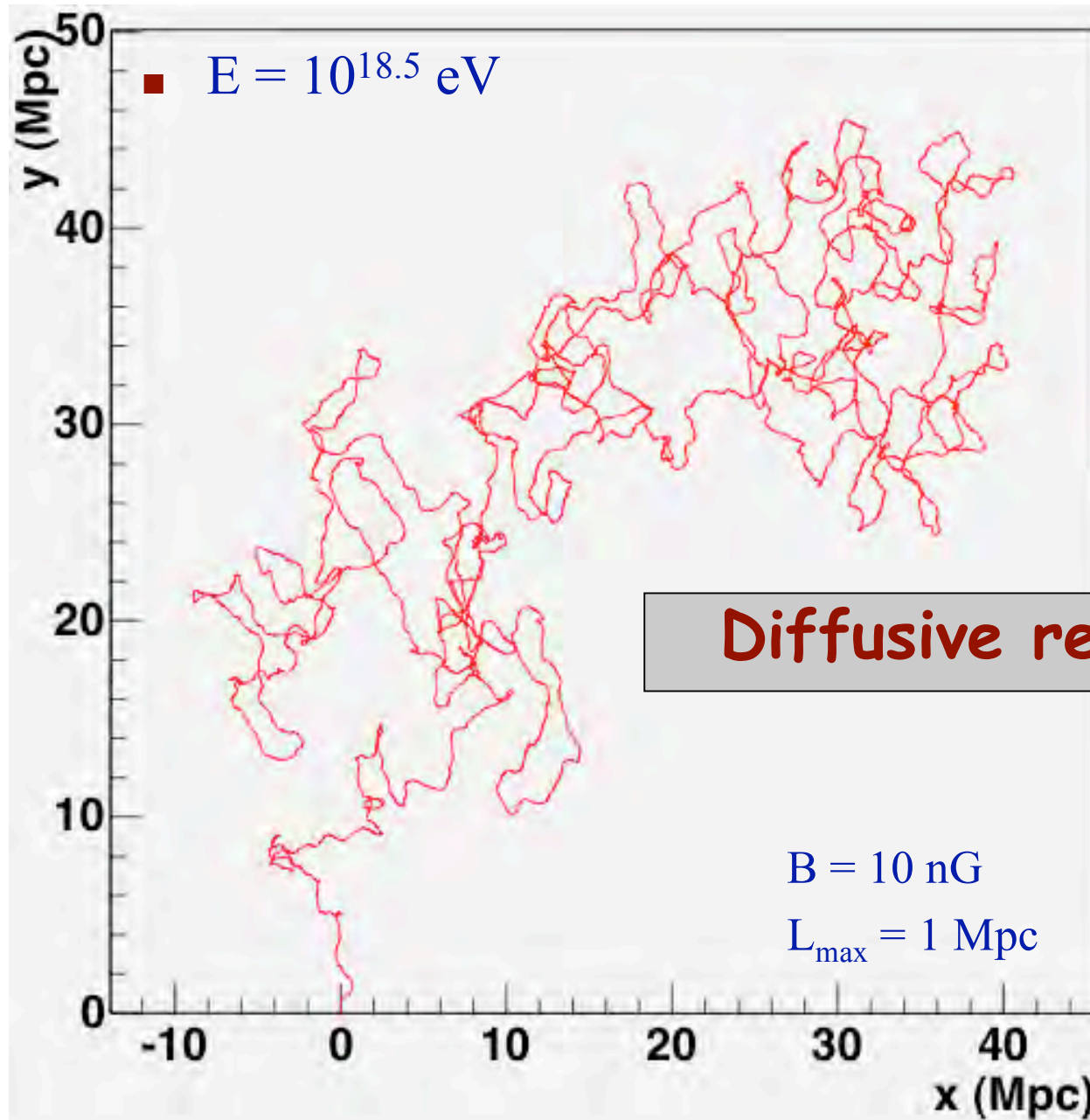


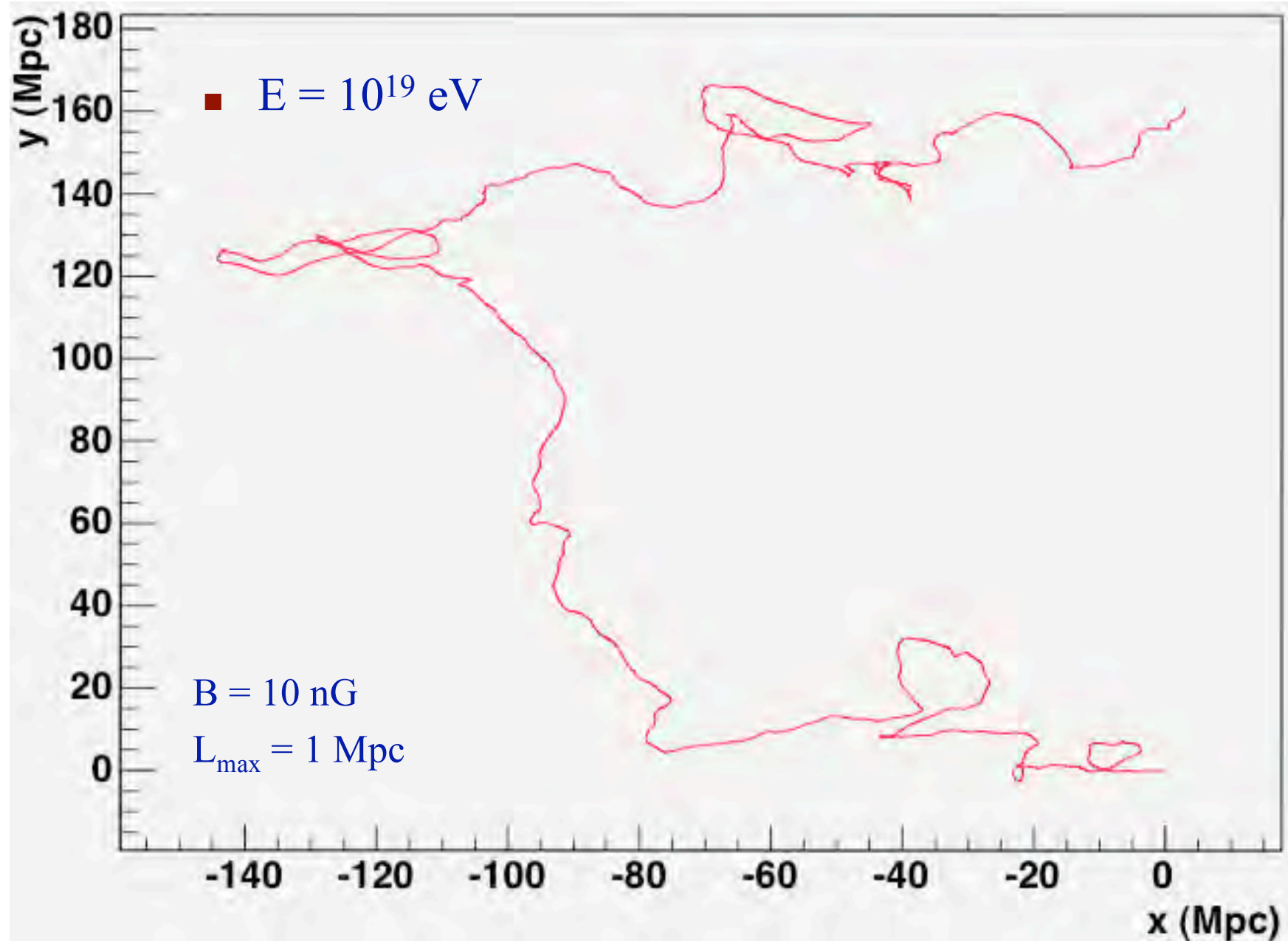
Source spectrum in $E^{-2.3}$

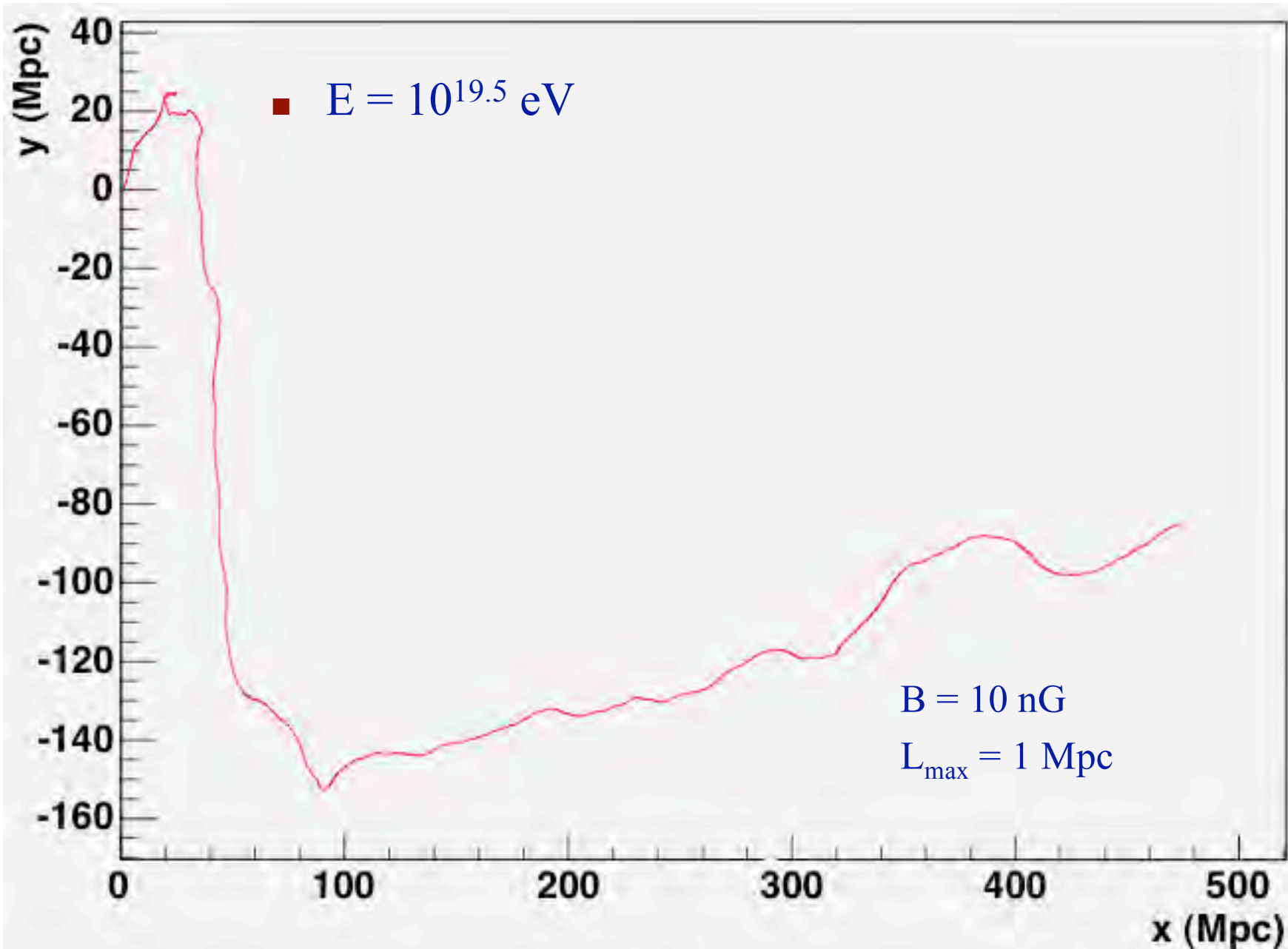
Ankle = Gal./extragal. transition

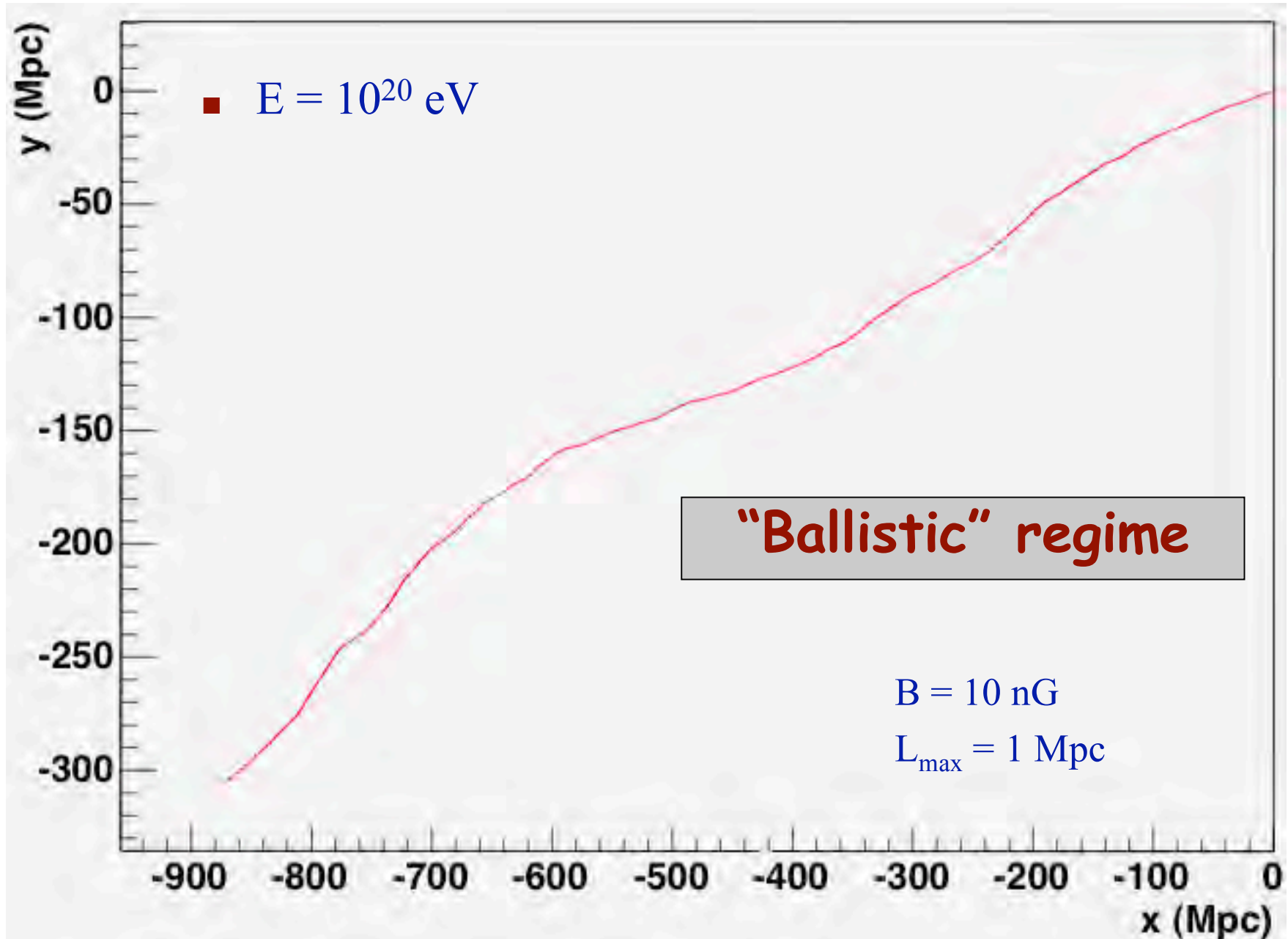
Cosmic-ray primary observables



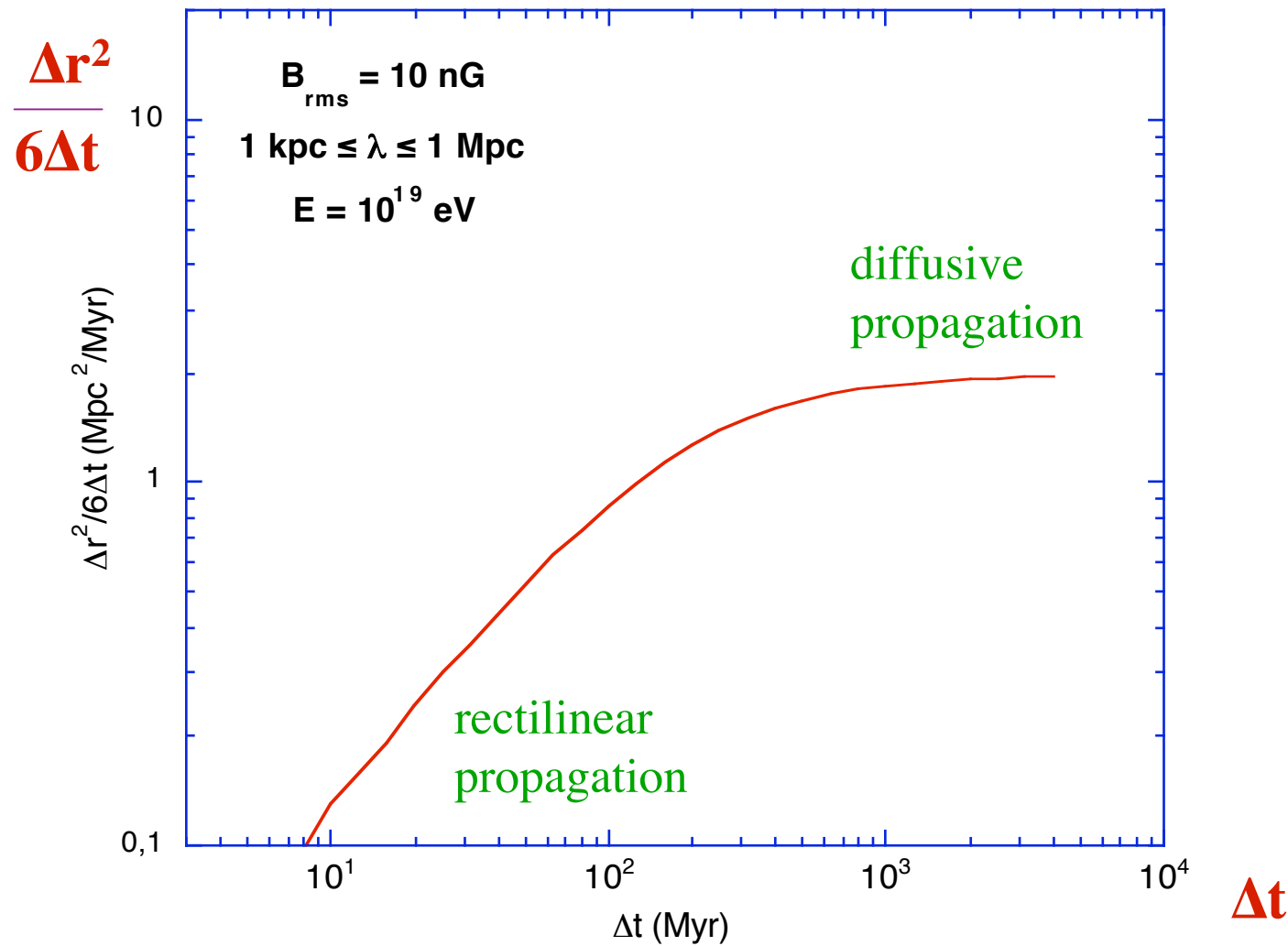




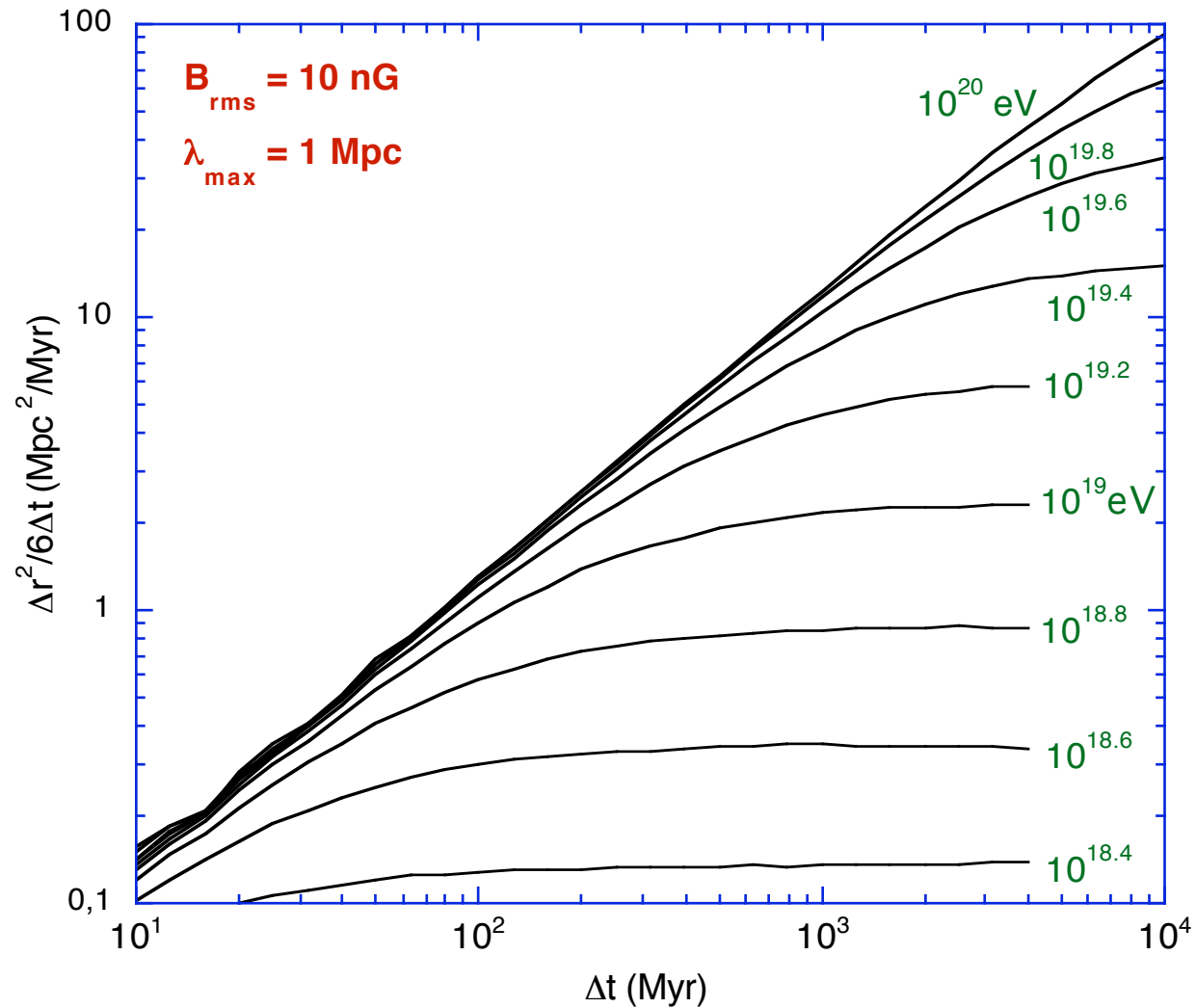




Reaching the diffusive regime



Reaching the diffusive regime

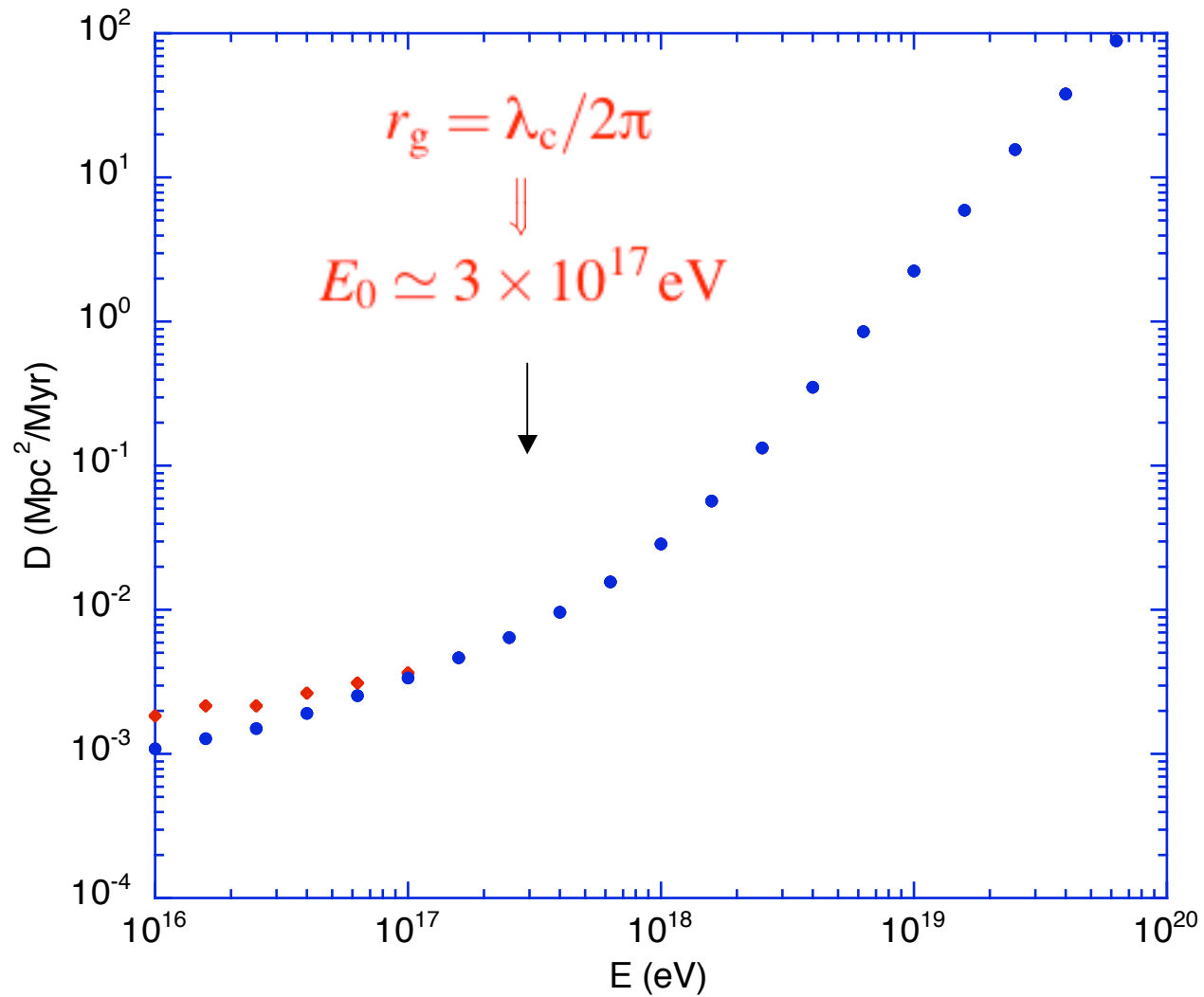


$B = 10 \text{ nG}$

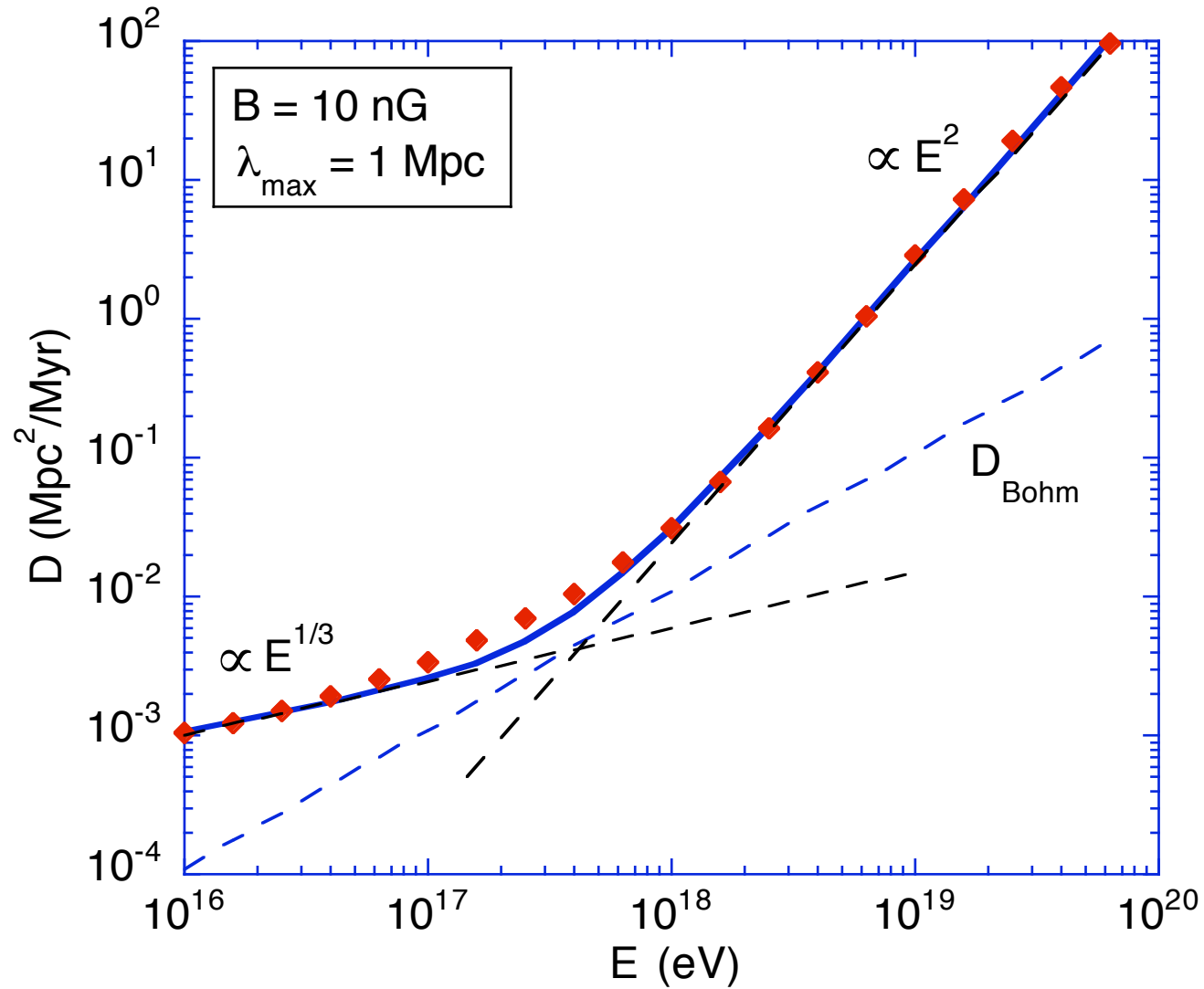
$L_{\text{max}} = 1 \text{ Mpc}$

$D(E)$

Diffusion coefficient



D(E)



Angular effects of B

- deflection



- angular diffusion

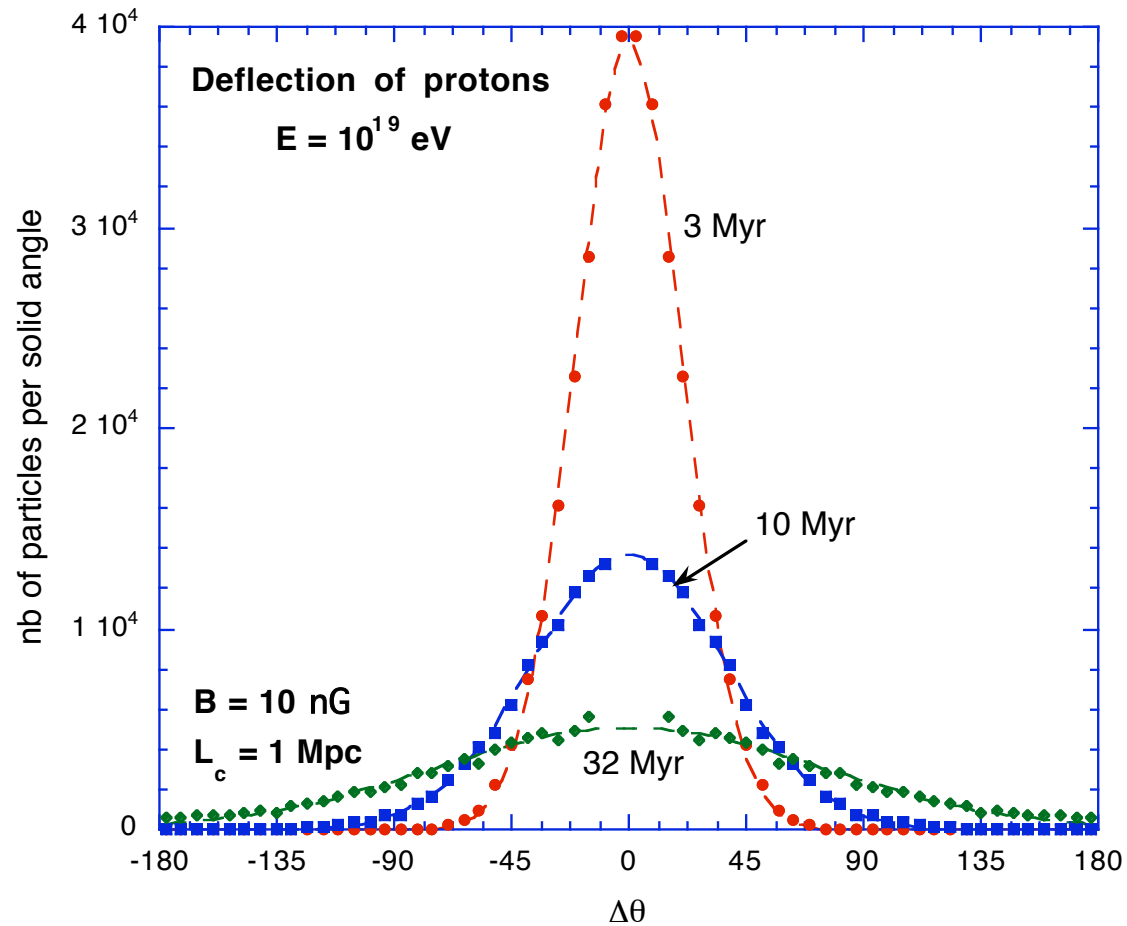


- isotropization

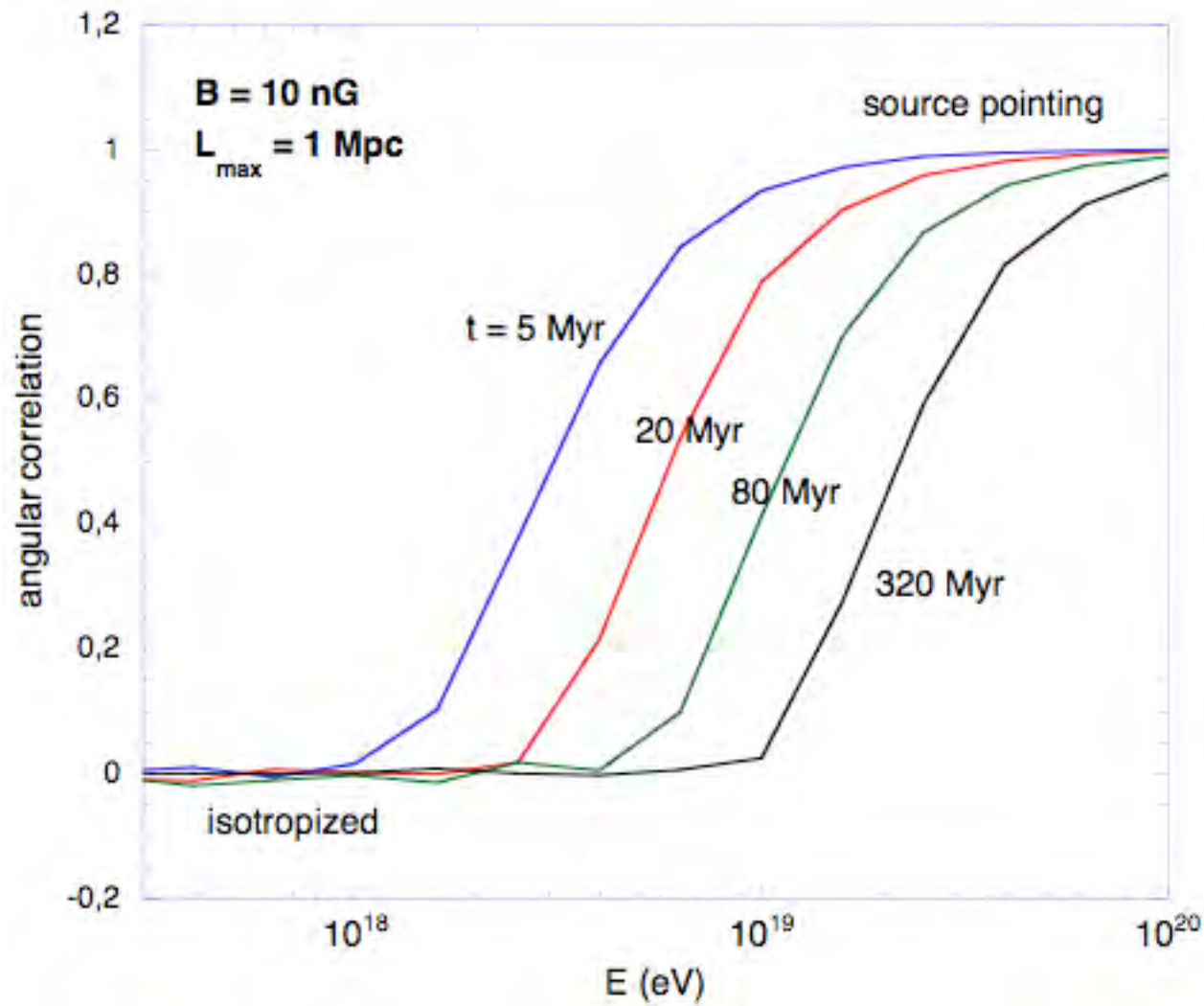


- diffusion in space

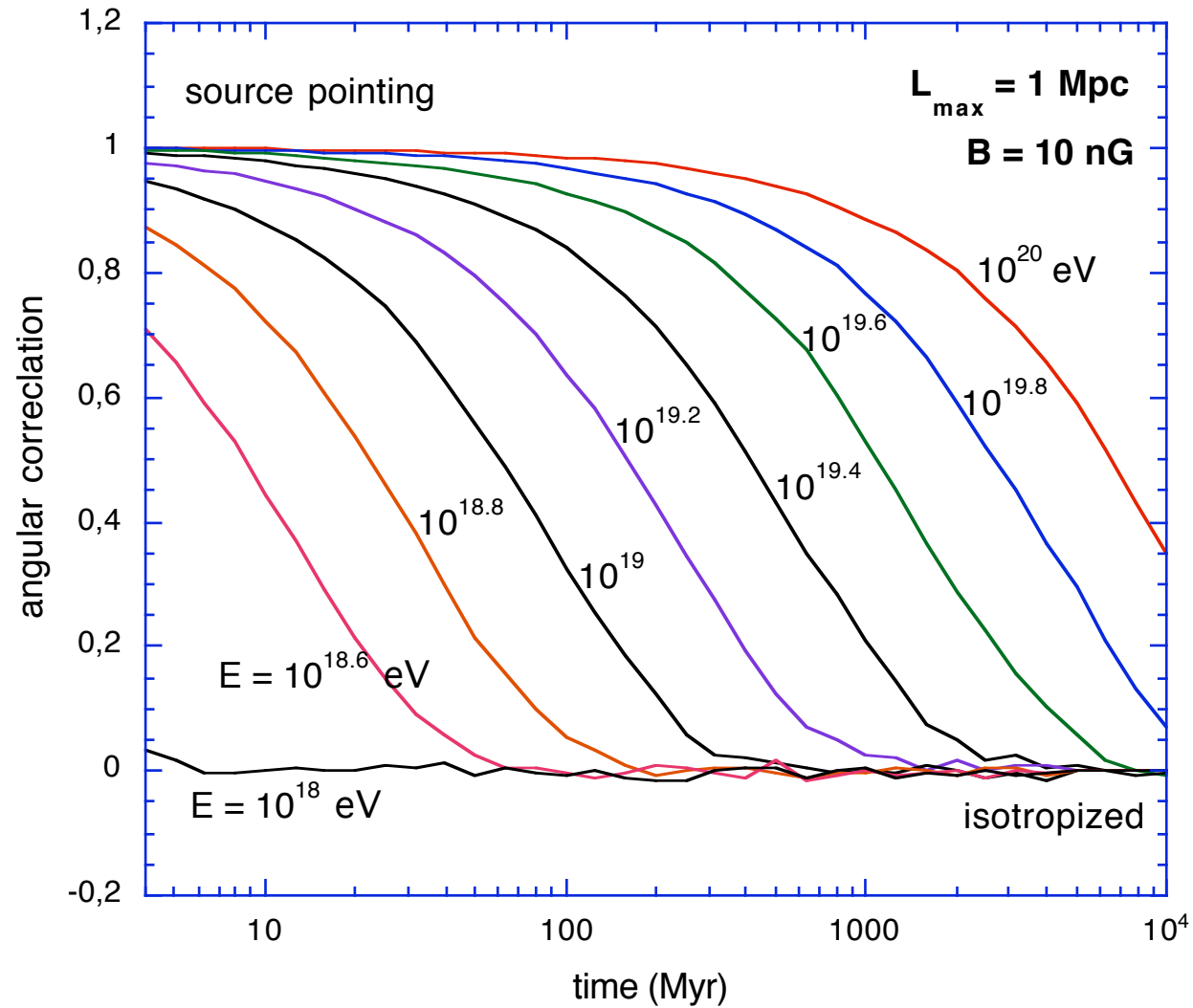
Angular diffusion



Angular de-correlation

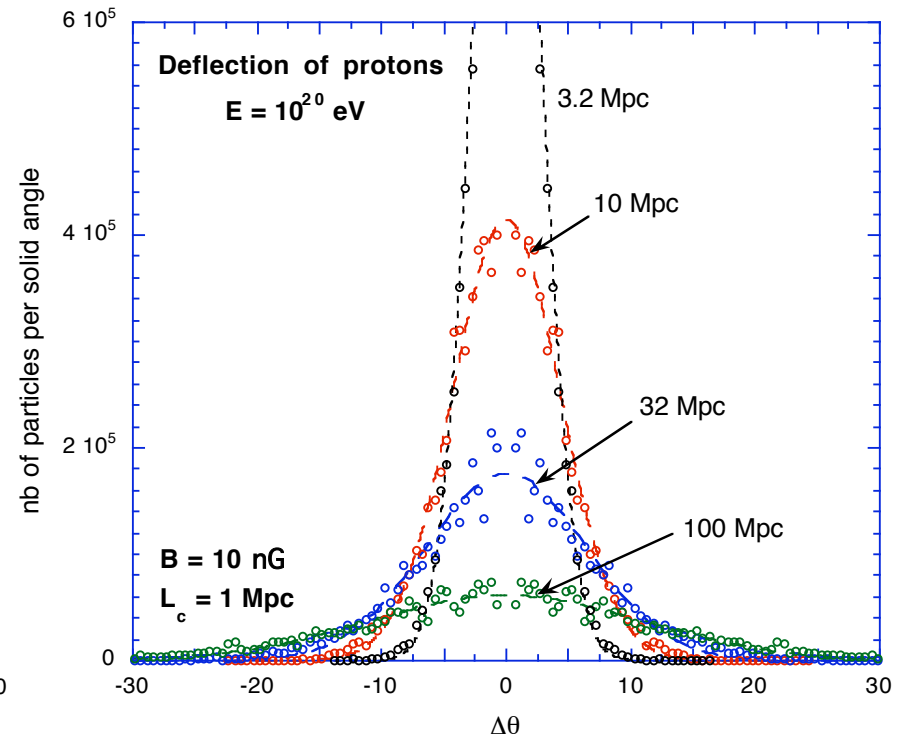
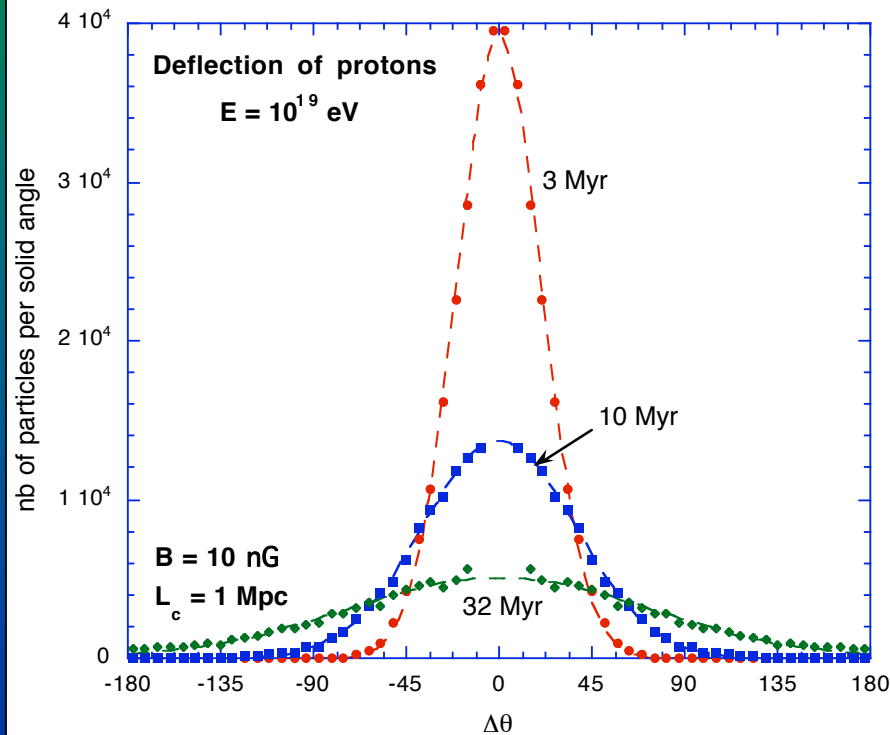


Angular de-correlation

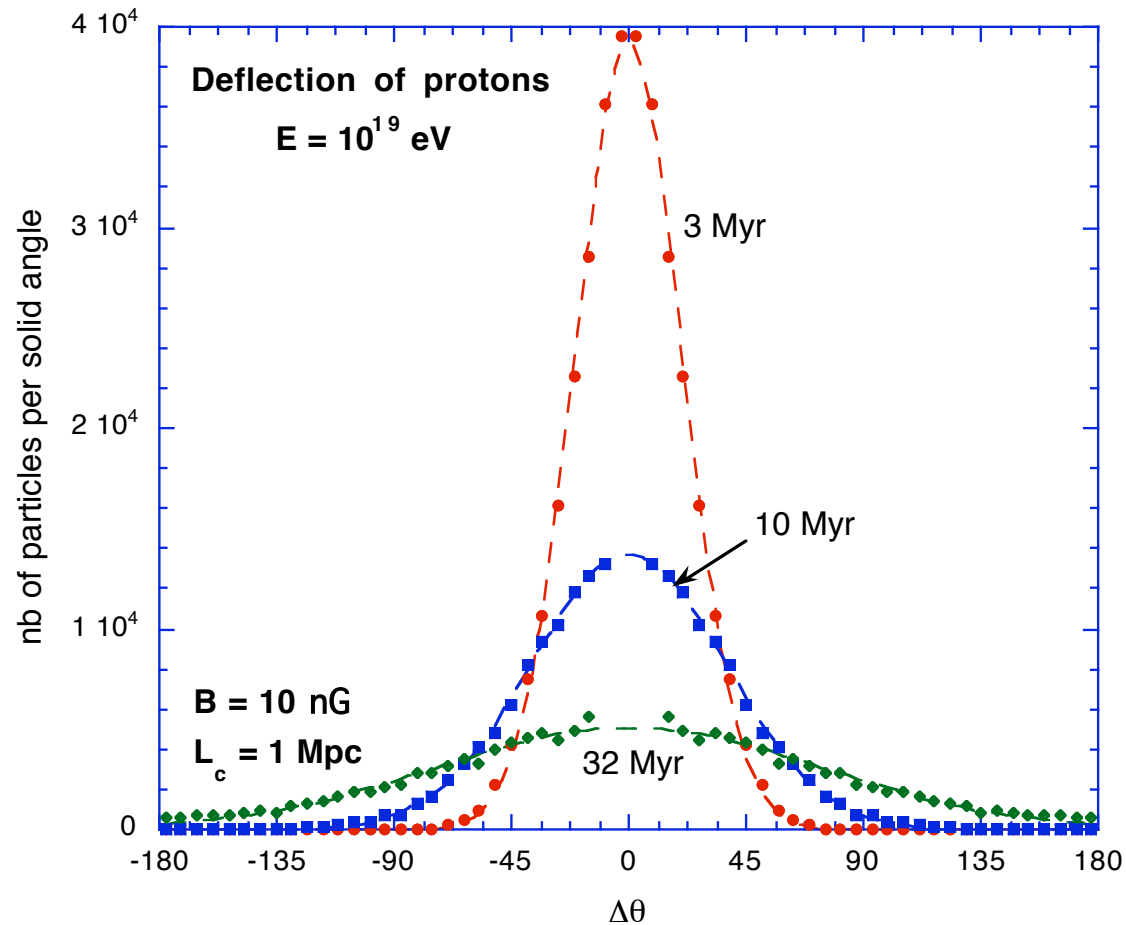


Angular diffusion regime

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



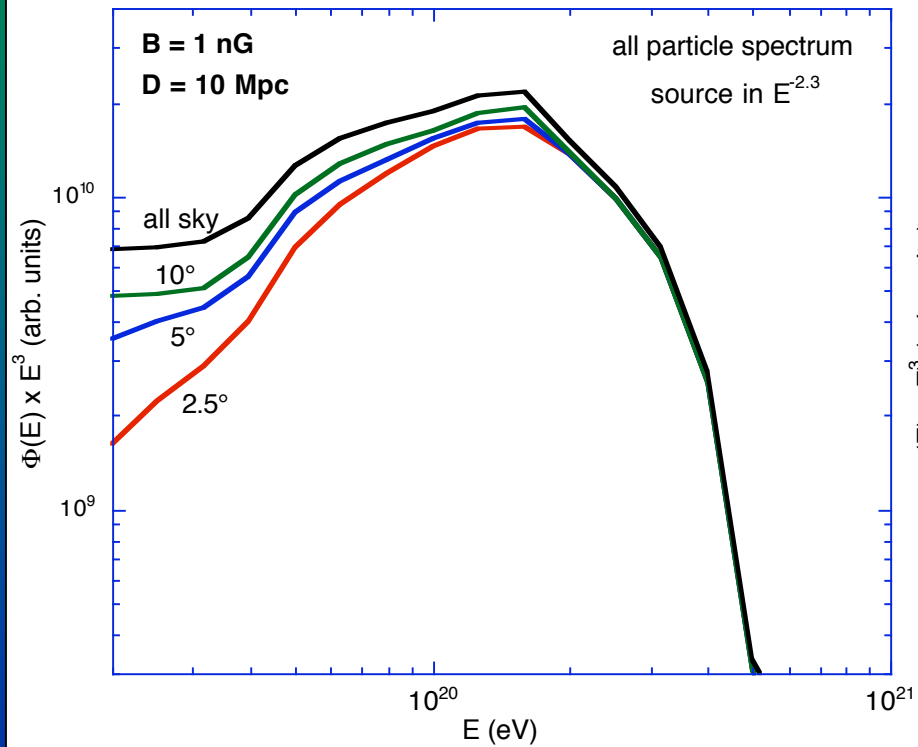
High-pass filter effect



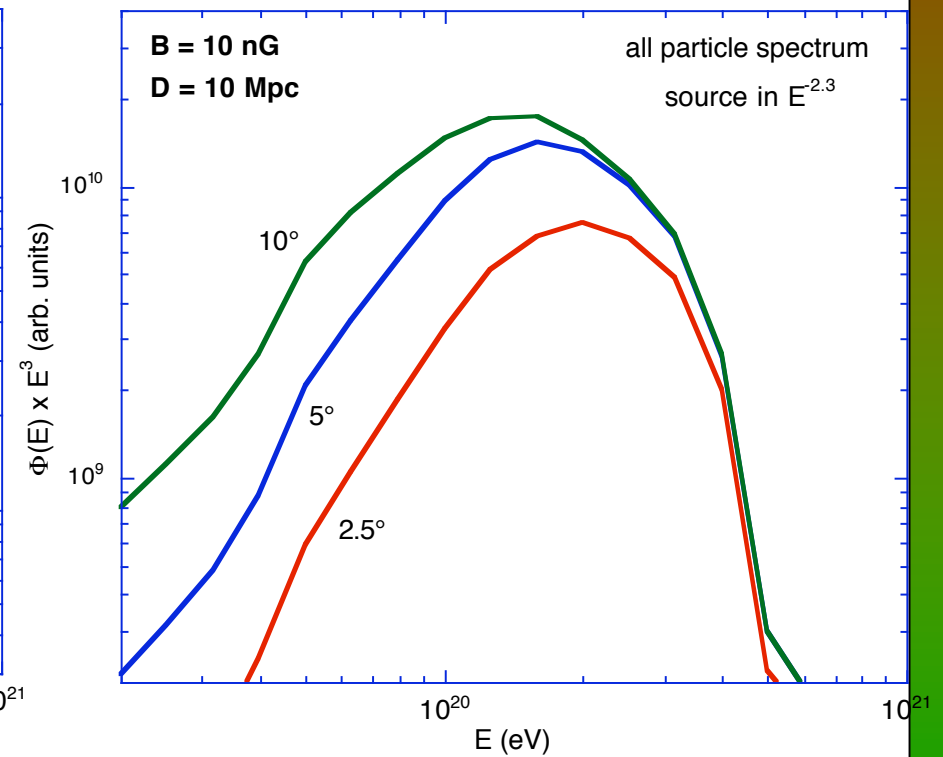
- High energies are less spread out
- Nearby sources are less spread out
- Different spectra are to be expected

Individual sources

Weak field

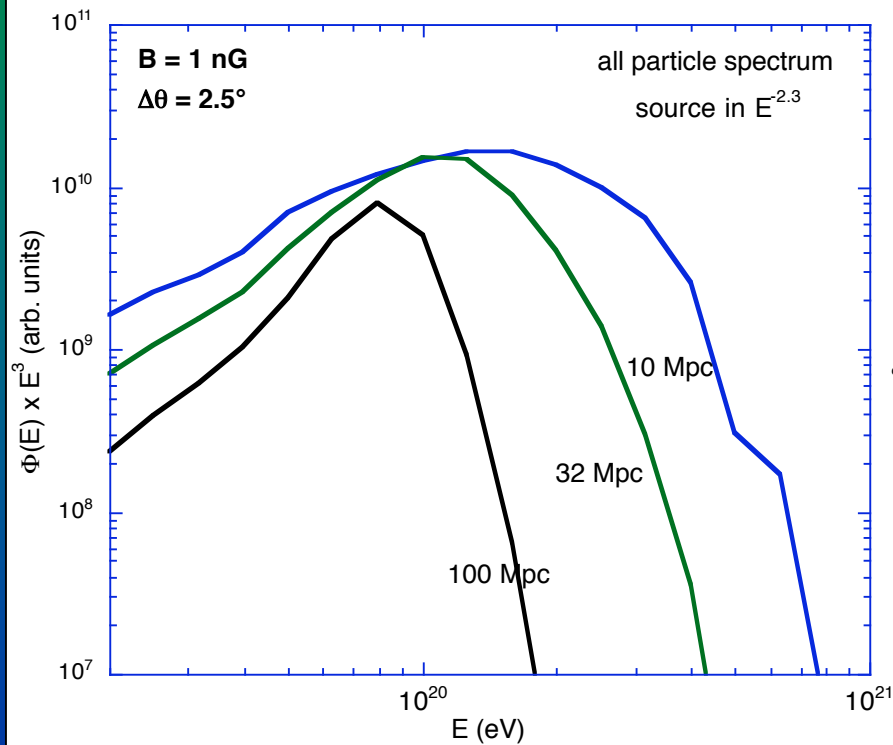


Strong field

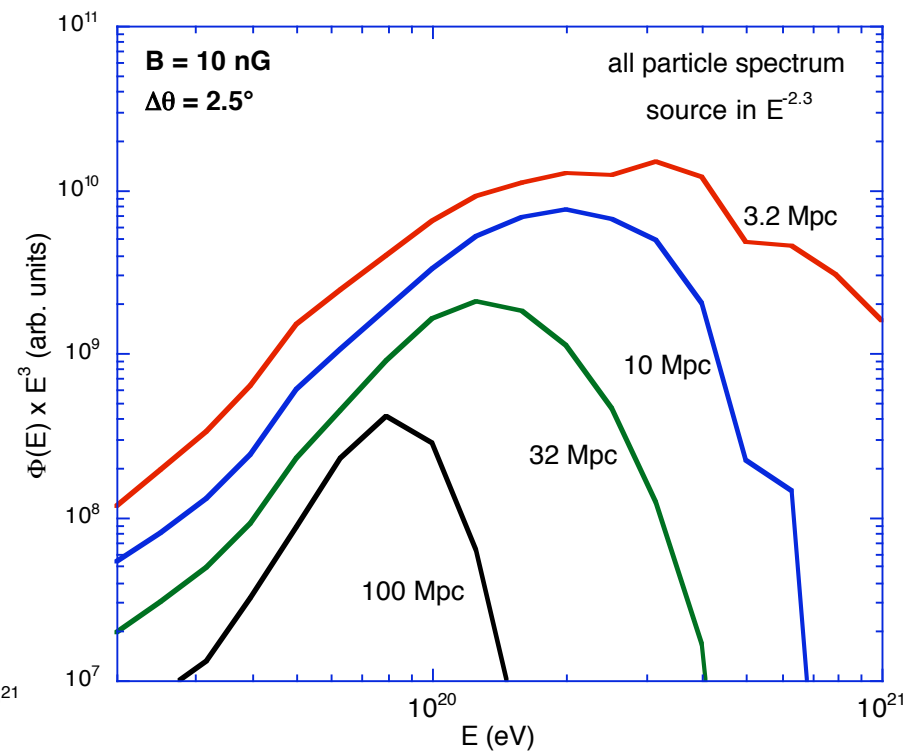


Individual sources

Spectrum of particles within 2.5° of a cluster



Weak field

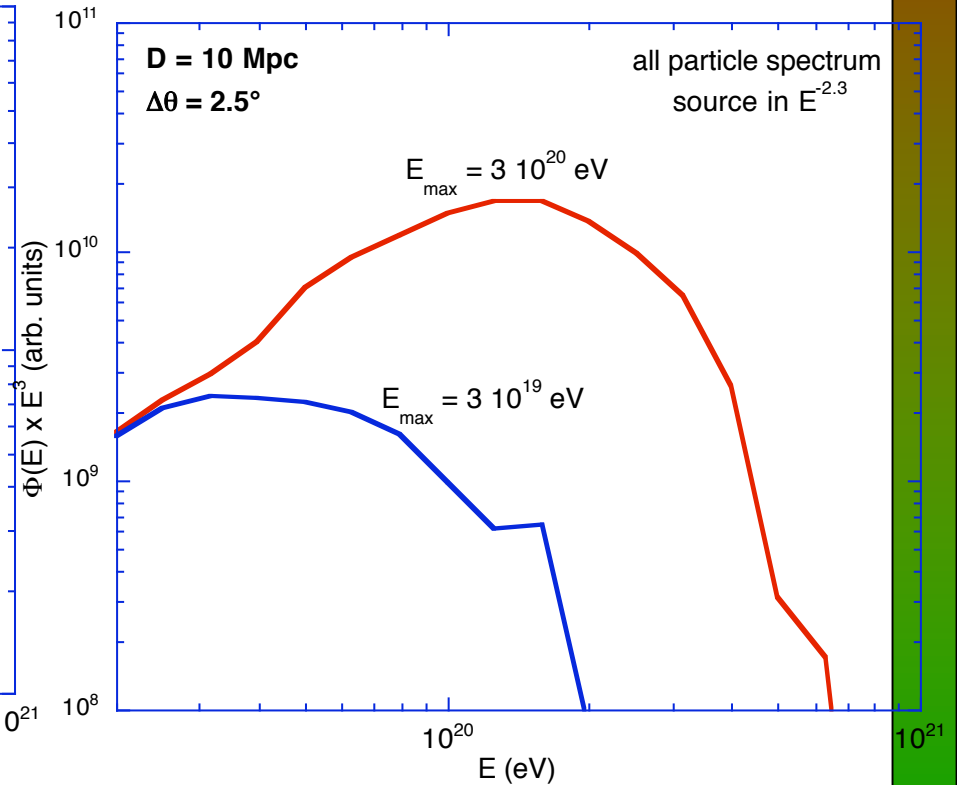
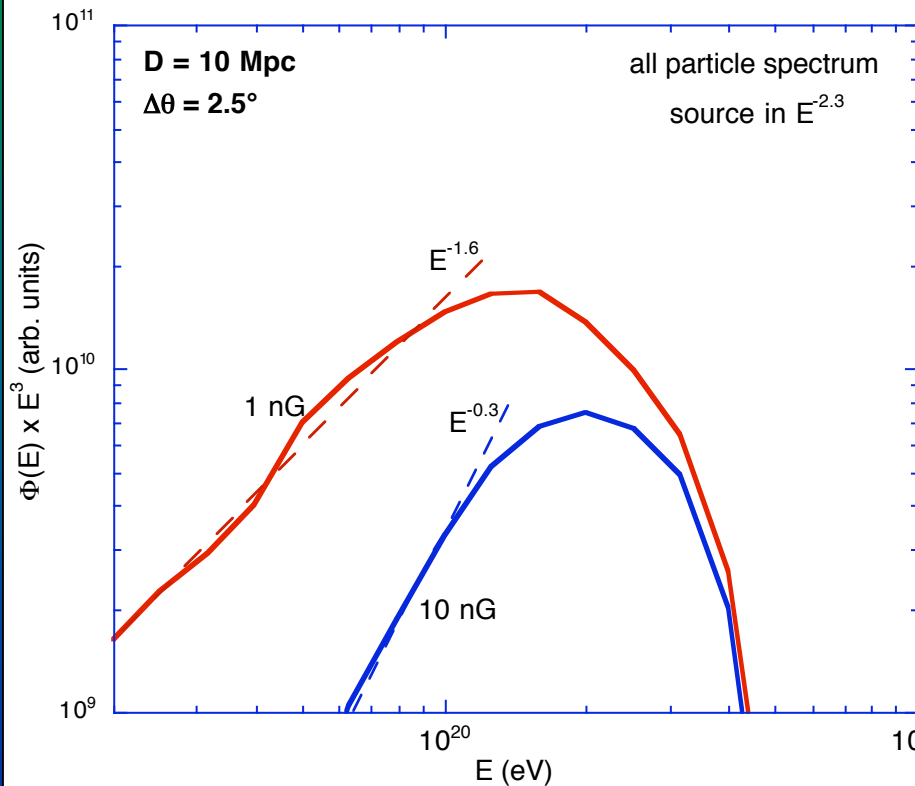


Strong field

Individual sources

Measure of the magnetic field?

Source maximum energy...



Auger: déjà des résultats majeurs !

5165 km² sr yr ~ 0.8 année du détecteur complet

1

**Spectre
de masse**

Y a-t-il ou non des
noyaux lourds parmi
les RC de très haute
énergie ?

Crucial pour la
phénoménologie des RC et
de la transition Gal./Extragal.

2

**Spectre
d'énergie**

La coupure GZK
tant discutée est-
elle observée ?

Intense débat théorique et
expérimental + implications
pour la physique

3

**Spectre
angulaire**

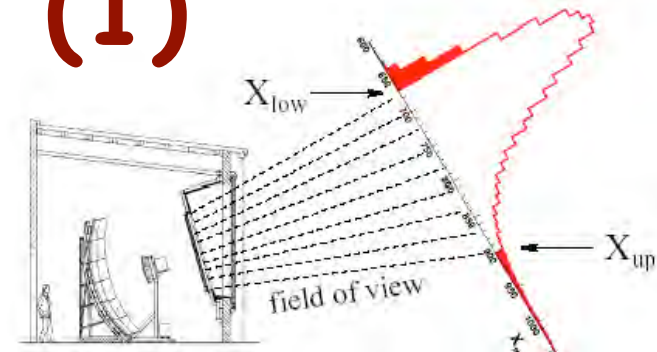
La distribution
angulaire des RC à
très haute est-elle
toujours isotrope ?

L'astronomie proton est-elle
à notre portée ?

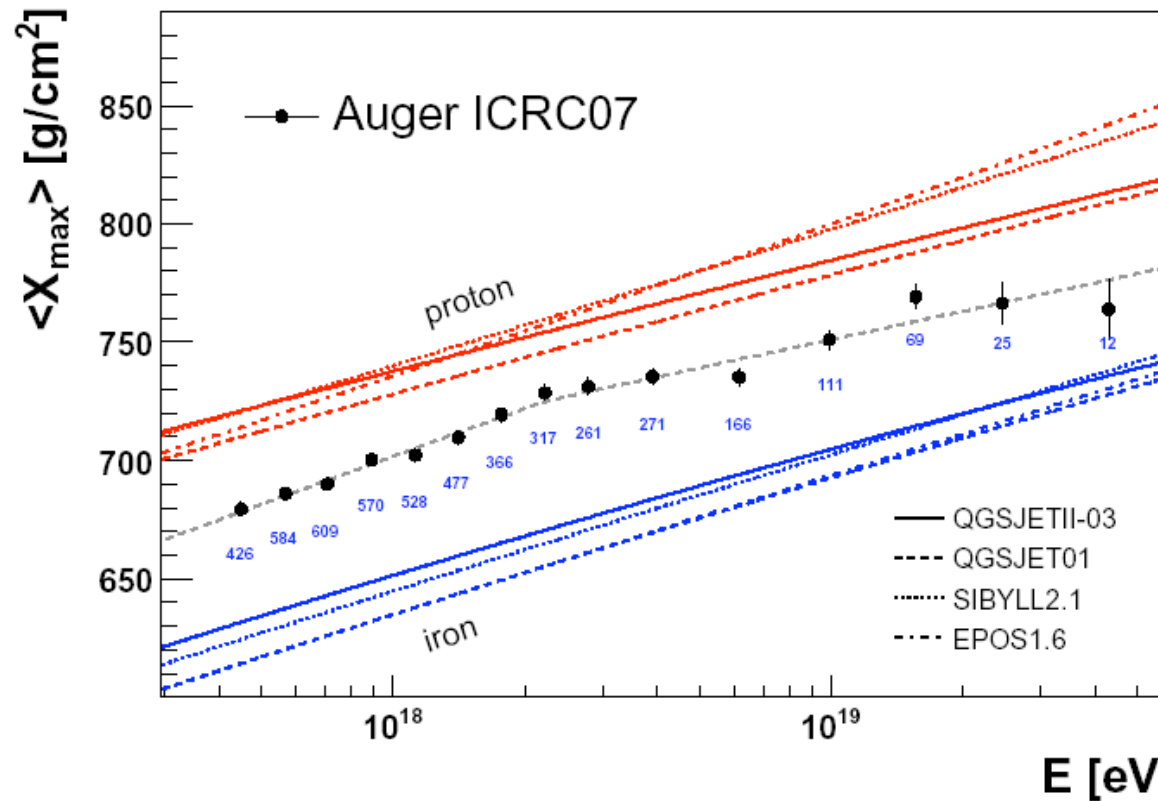
Composition (1)

Apparemment...

Présence de noyaux !



Profondeur de pénétration



énergie

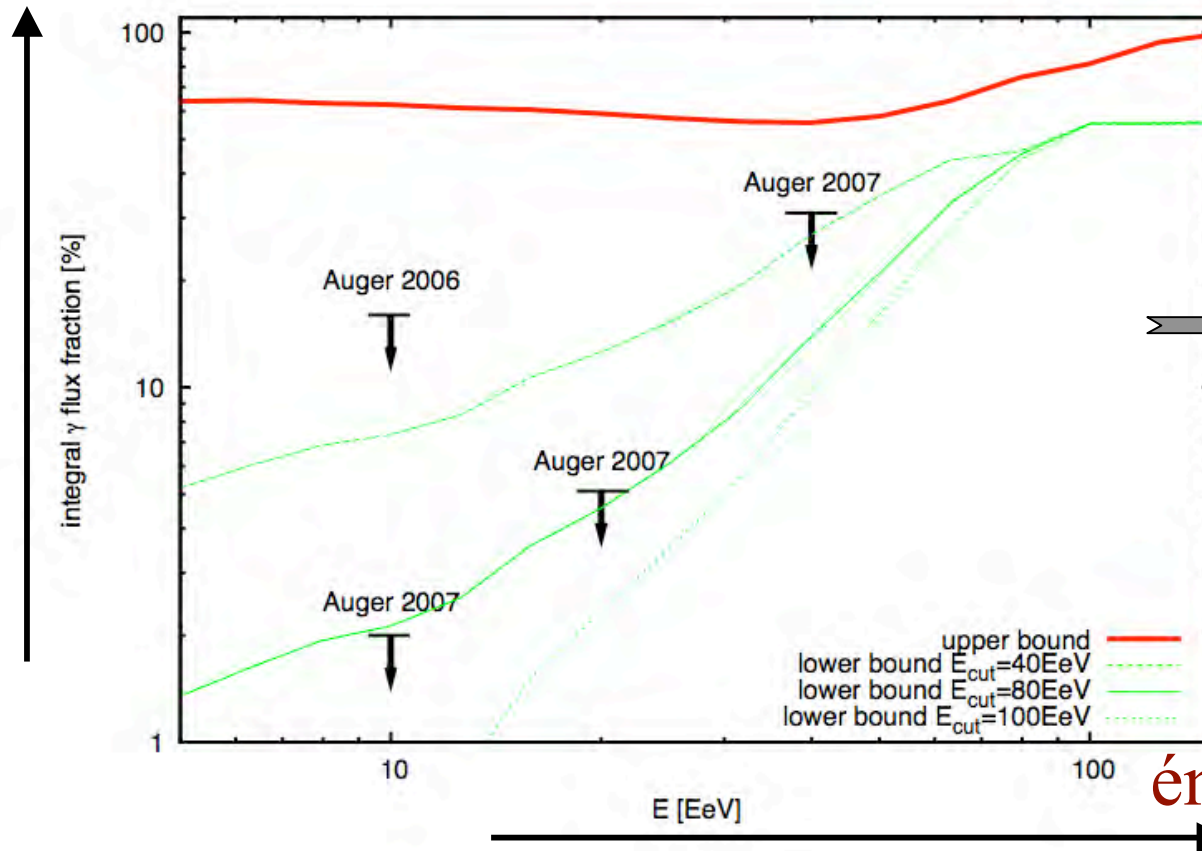
Composition (2)

Modèles « top-down » (SHDM ou TD) prédisent des flux de photons abondants



Les gerbes induites par des photons sont très spécifiques...

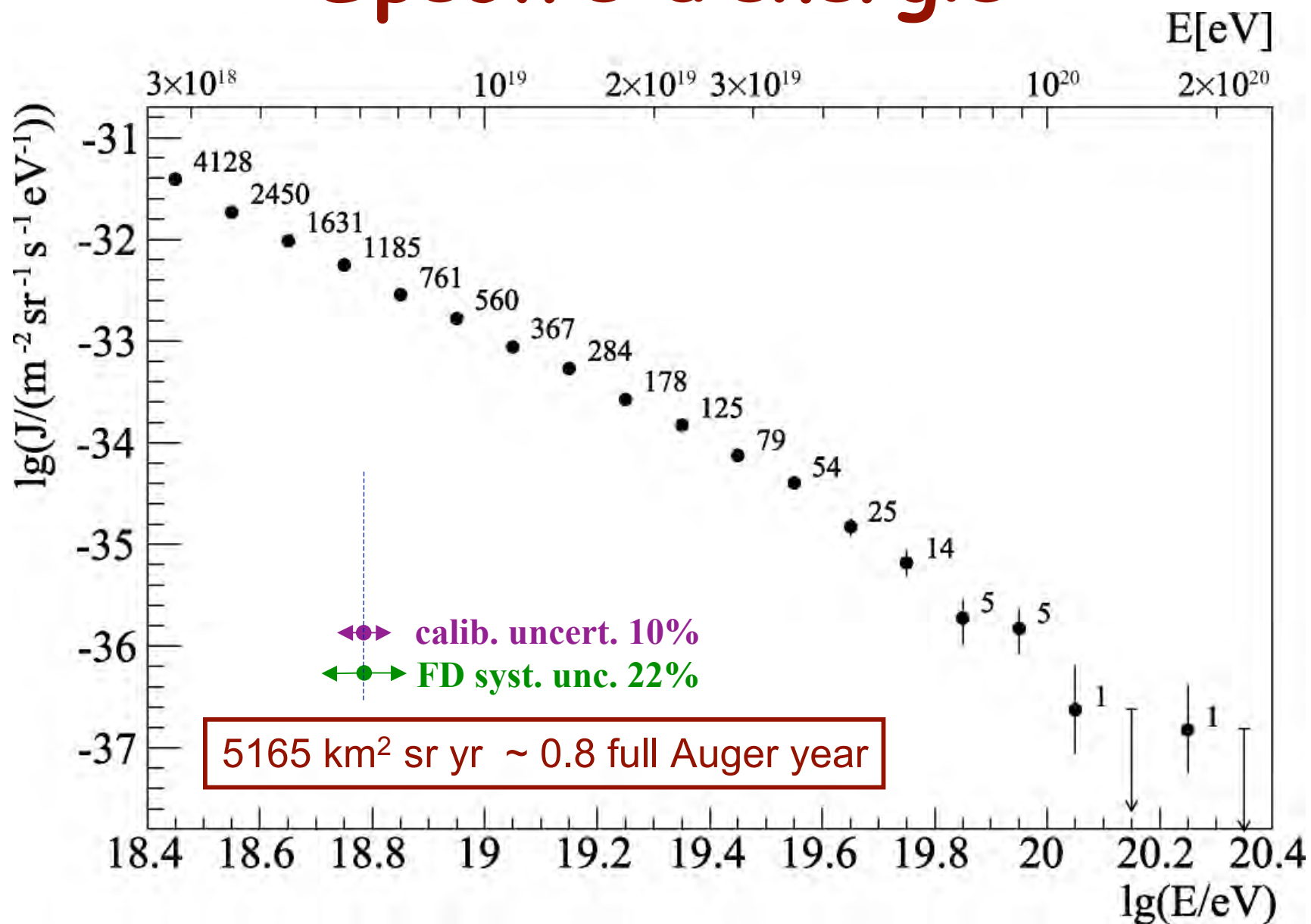
fraction de photons



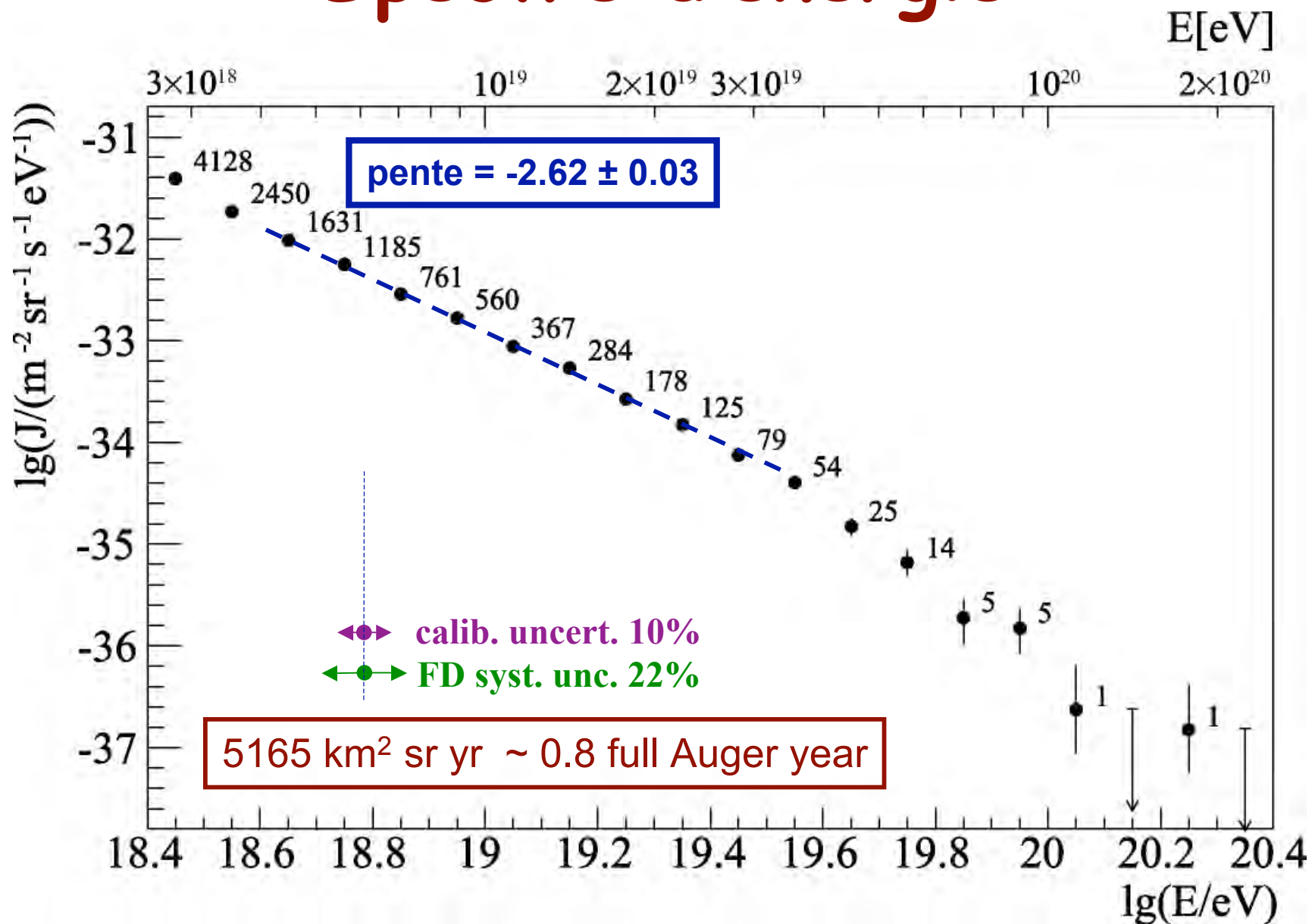
Les modèles top-down à matière noire supermassive sont exclus !

énergie

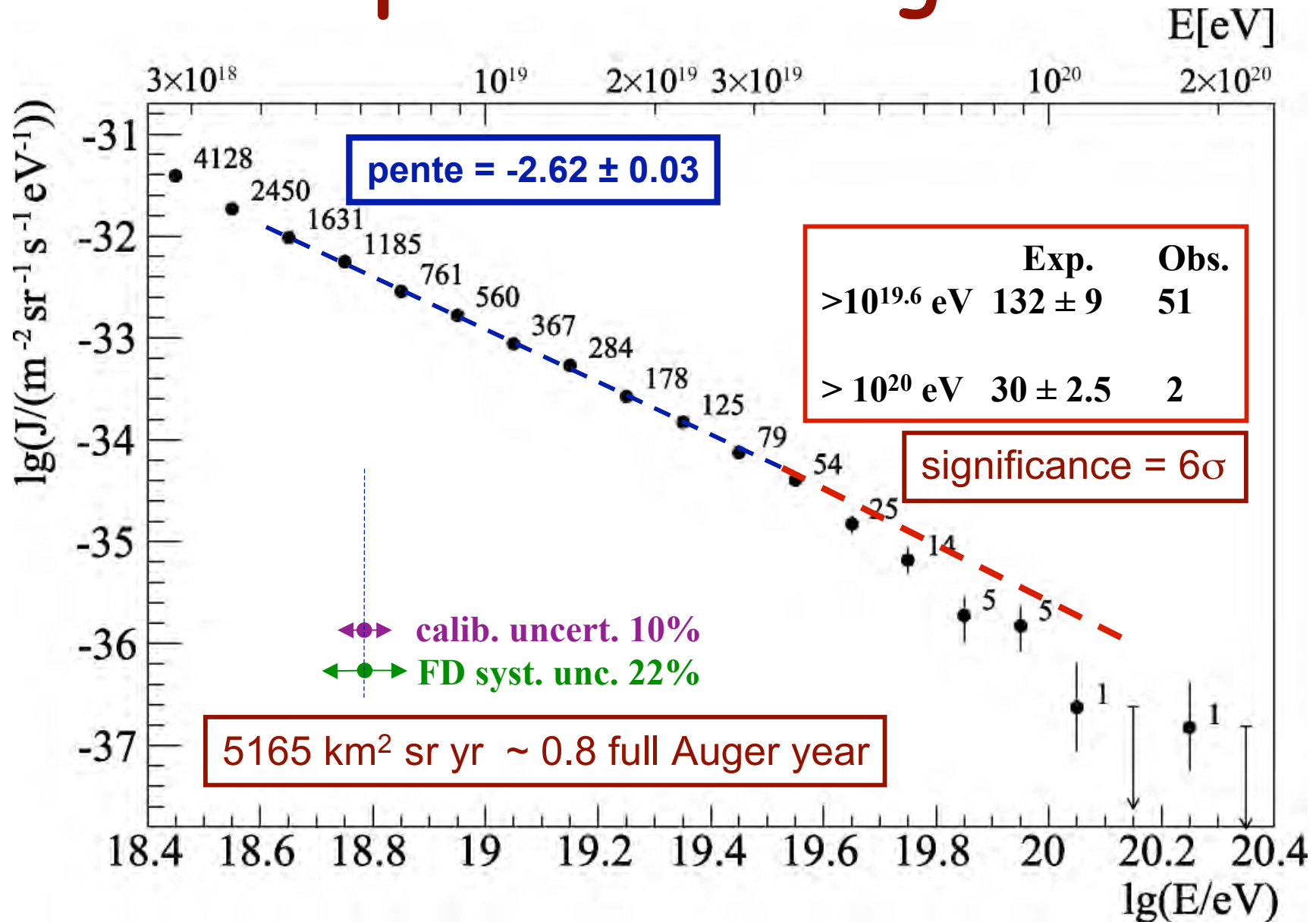
Spectre d'énergie



Spectre d'énergie



Spectre d'énergie



Distribution angulaire

Les rayons cosmiques ultra-énergétiques sont anisotropes !

- Au-delà d'une certaine énergie, les RC ont une distribution incompatible avec l'isotropie (significativité établie à partir d'une prescription *a priori*, sur un lot de données indépendant)
- Un lien peut être établi (globalement) entre les directions d'arrivée des rayons cosmiques les plus énergétiques et des structures extragalactiques relativement proches
- Corrélation avec la direction d'AGN (noyaux actifs de galaxies) proches (≤ 100 Mpc) : sources ou simples traceurs ?

Résumé : résultats majeurs d'Auger

masse

des noyaux,
peu de photons

Conforme aux attentes
astrophysiques

Résout certains
problèmes liés à la
transition gal./extragal.

Unité avec le reste de la
science des rayons
cosmiques et des sources

Richesse supplémentaire
pour le domaine
(dimension spectrale !)

énergie

cheville +
coupure GZK

Excellente nouvelle !
Prédiction de 40 ans !

⇒ sources proches
⇒ « astronomie proton » !
+ isolement des sources !

+ physique à haute énergie
étude des gerbes (muons,
modèles hadroniques,
échelle d'énergie...)

cf. genou + **LHC** !

direction

ciel anisotrope

**Résultat le plus important
depuis 100 ans !**

⇒ « l'astronomie rayons
cosmiques » est possible
(elle vient de débuter !)

⇒ rayons cosmiques
intégrés au *corpus*
scientifique de
l'astrophysique

Rayons cosmiques, année zéro !

- Ouverture historique d'une astronomie non photonique !

- ◆ À terme, identification et étude de sources individuelles
- ◆ Nécessité d'augmenter la puissance de collection à haute énergie

➡ Auger Nord (Lamar, Colorado)

(les sources sont là : allons les chercher !)

- Nombreuses questions

- ◆ sources, origine des RC, mécanisme d'accélération, fonctionnement des sources énergétiques de l'univers, écologie galactique, équilibre des composantes (champ magnétique, rayonnement, phases du milieu interstellaire, formation d'étoiles, chimie interstellaire...), lien avec les autres rayonnements (radio, X, gamma, neutrinos...)

- Tout cela commence aujourd'hui !

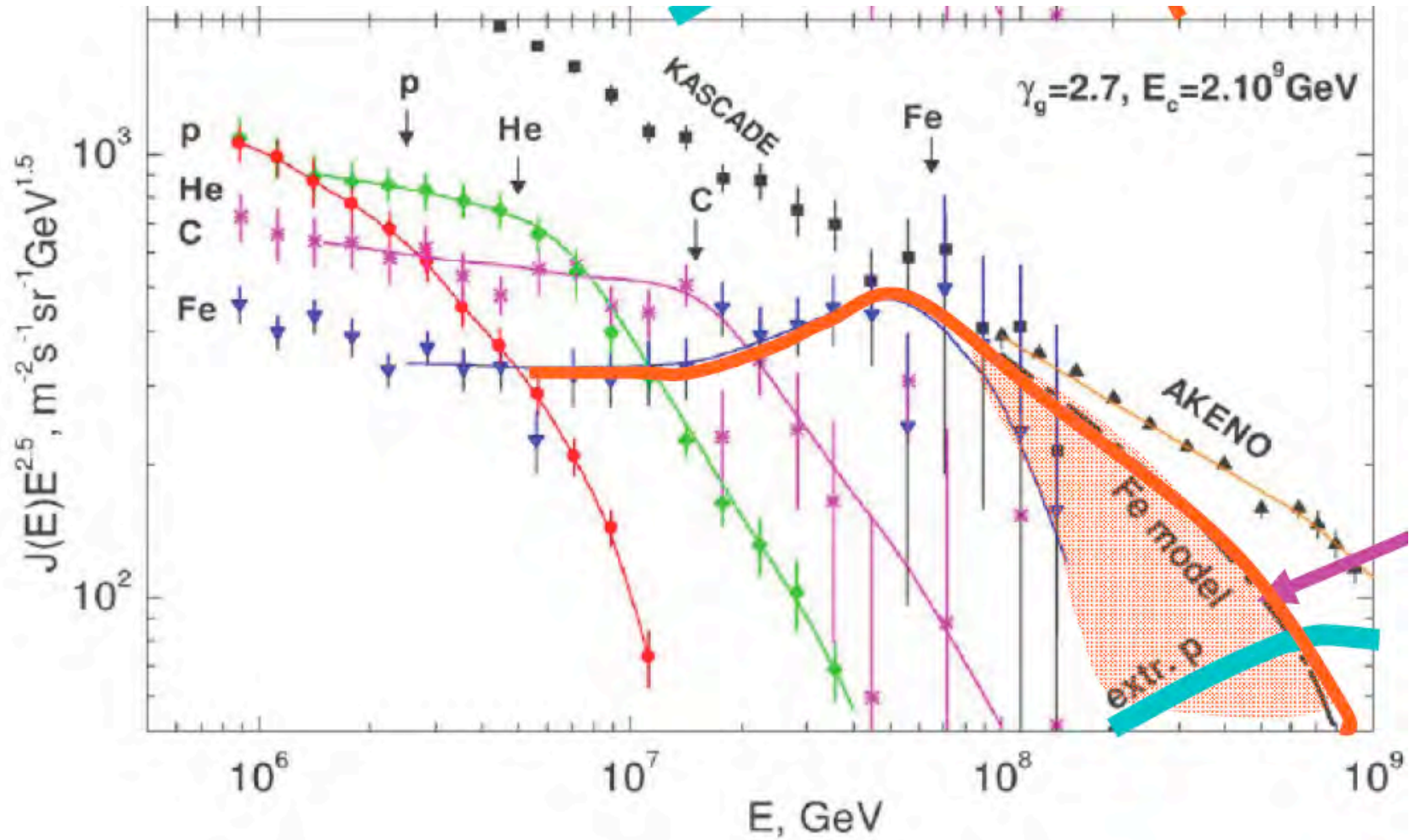
À propos du genou...

Un mystère à éclaircir...

Domaine très riche, avec plusieurs possibilités intéressantes...

- Énergie maximale à l'accélération
- Changement de régime de propagation
- Changement de régime à l'accélération
- Inexistence du genou ! (Physique au TeV...)
- Contribution contingente d'une source locale
- NB: Genou en Z vs. Genou en A

Elemental knees



Berezinsky, et al. (2004)

Elemental knees

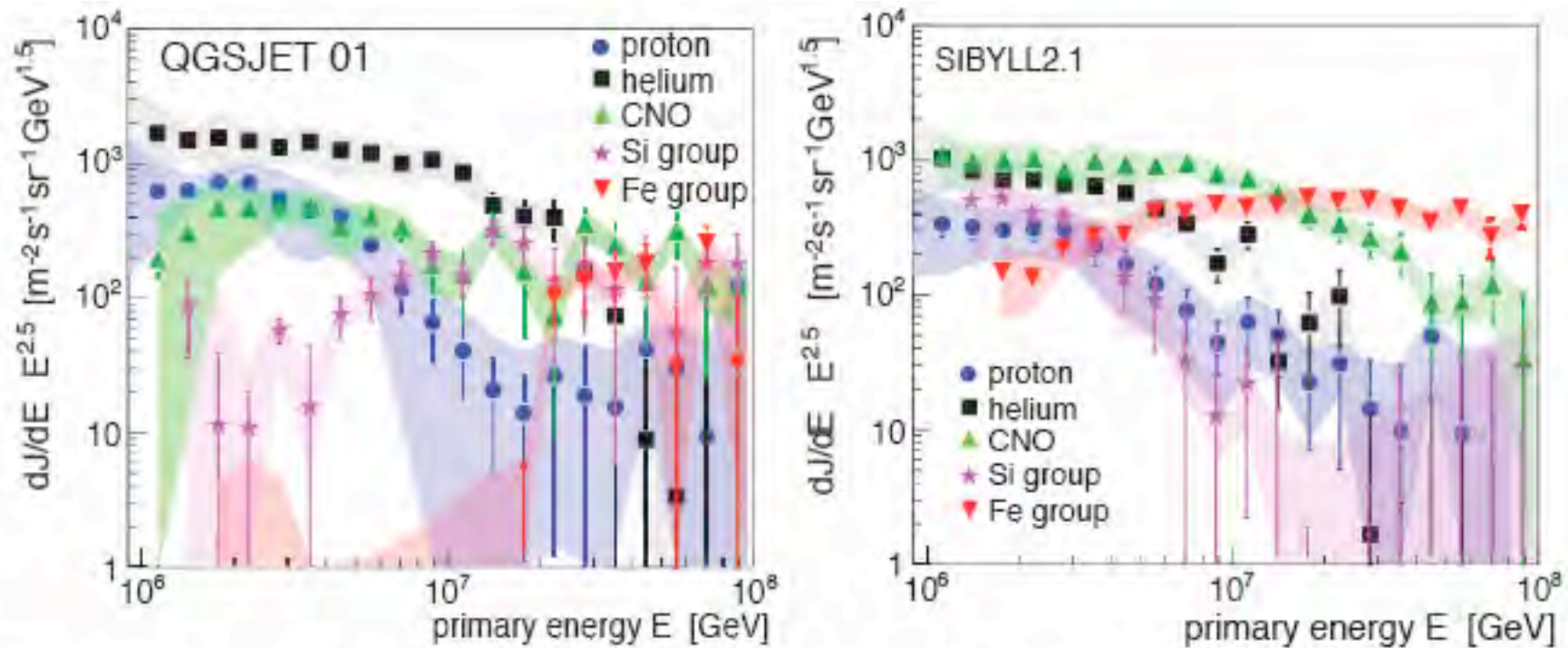


Fig. 7. Energy spectra for elemental groups as obtained by the KASCADE experiment, using two different models (QGSJET 01 and SIBYLL 2.1) to interpret hadronic interactions in the atmosphere [54].

from Hörandel (astro-ph/0611387)