Cosmic-ray propagation - II

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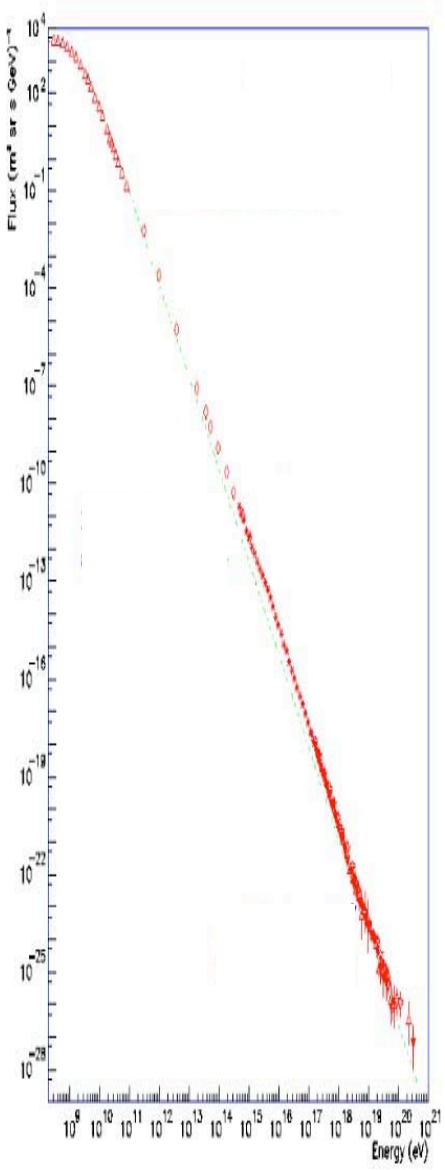
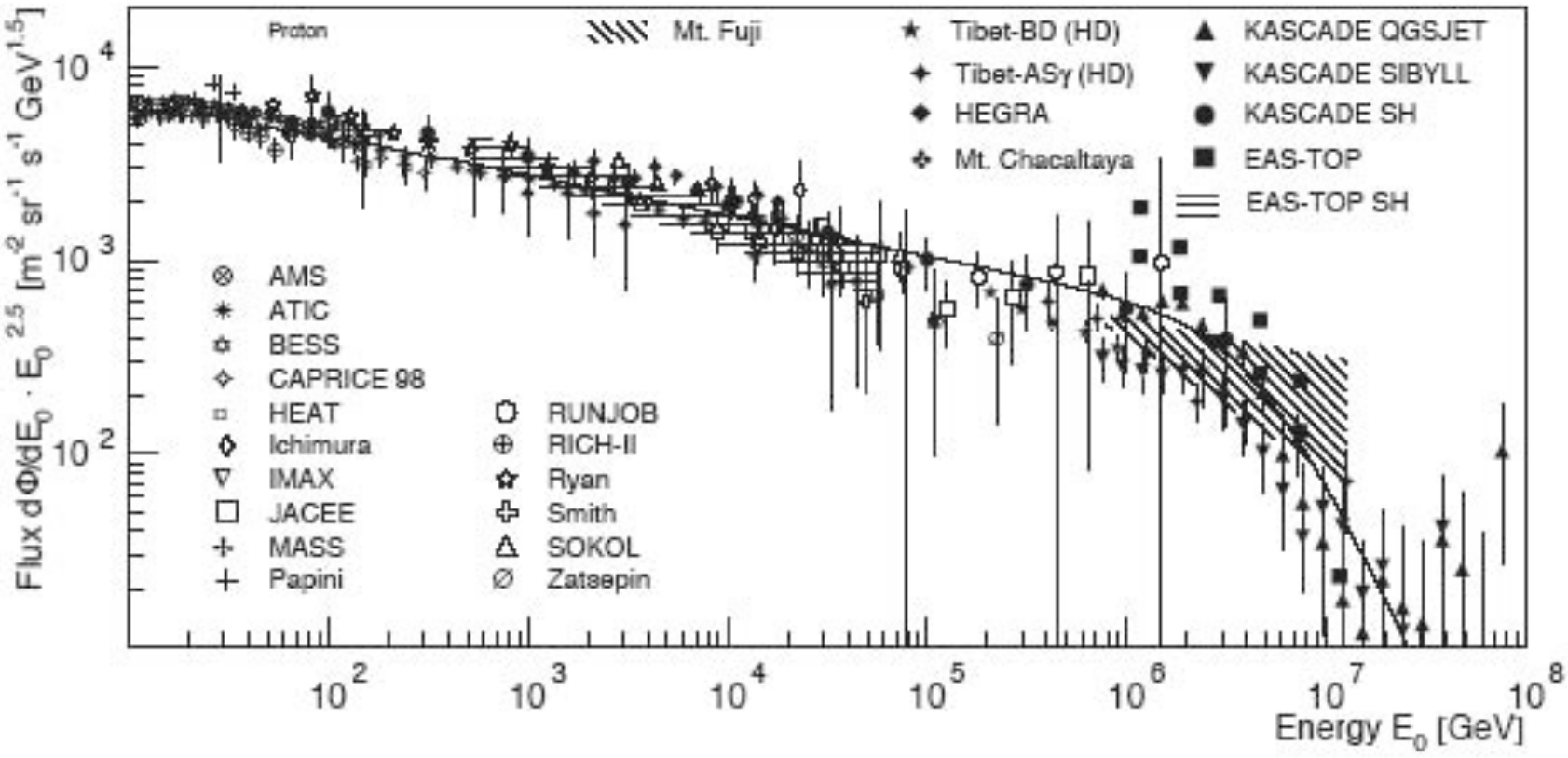
Final notes (lecture 1)

- Beware: all energetic particles (EPs) are not CRs…
- Some localized EP sources are known, but their phenomenology is often uncertain: more work is needed, obs. and theory, multi-messenger approach…
- Global CR phenomenology is not particularly problematic, but the sources are unknown (100 years after their discovery!)
- Secondary particles are extremely important: photons (non-thermal astronomy + diffuse backgrounds), nuclei (LiBeB nucleosynthesis!), neutrinos, antimatter, etc.
- Magnetic fields isotropize the CRs, and mix all sources… except at very high E!
- CRs at low E are Galactic (GCRs), while CRs at high E are extragalactic (EGCRs): the GCR/EGCR transition is a key!

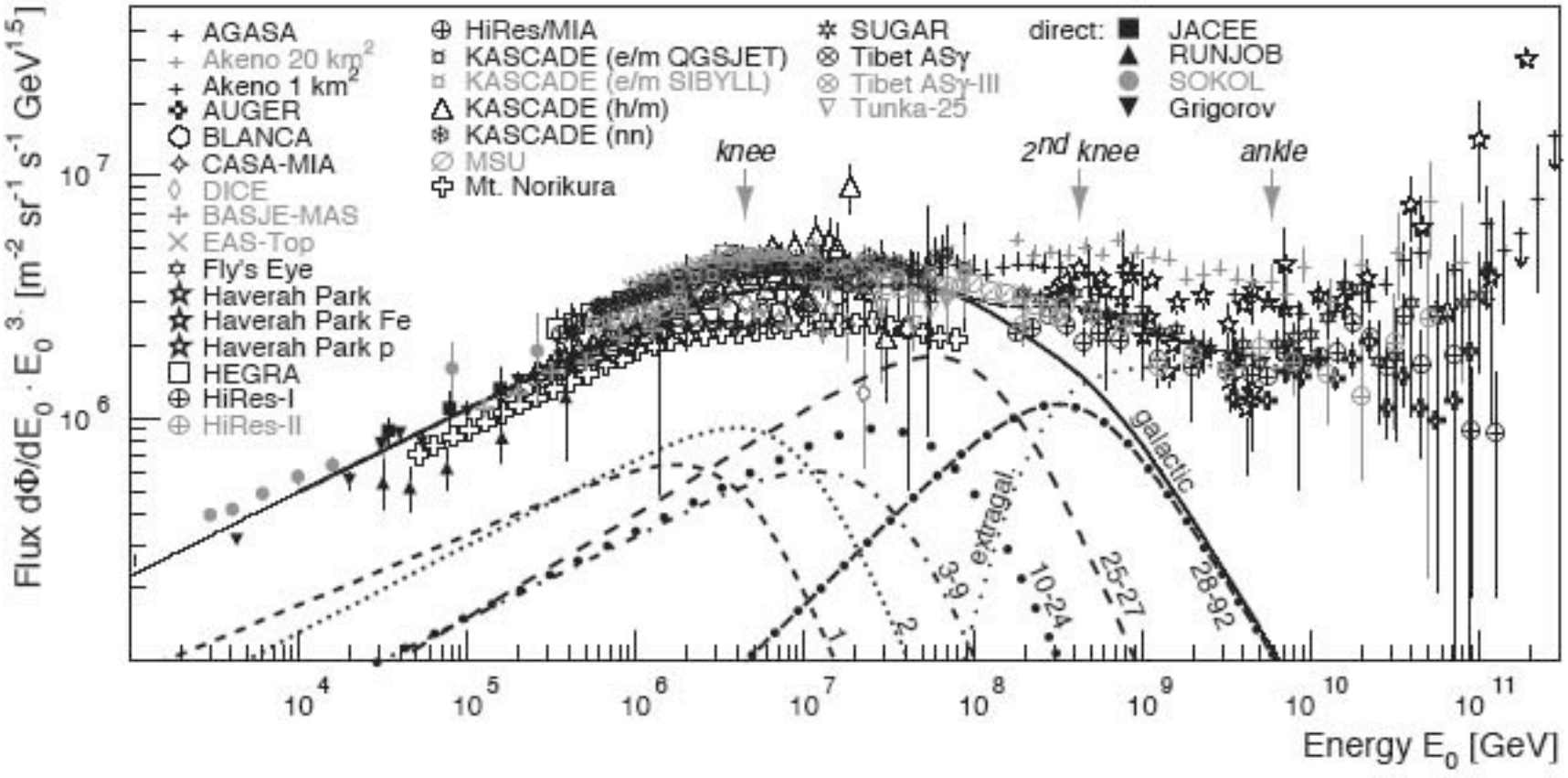
(Une des 7 merveilles du monde physique)



[CR flux] x $E^{2.5}$


Proton
Mt. Fuji
Tibet-BD (HD)
Tibet-ASγ (HD)
HEGRA
Mt. Chacaltaya
KASCADE QGSJET
KASCADE SIBYLL
KASCADE SH
EAS-TOP
EAS-TOP SH
AMS
ATIC
BESS
CAPRICE 98
HEAT
Ichimura
IMAX
JACEE
MASS
Papini
RUNJOB
RICH-II
Ryan
Smith
SOKOL
Zatsepin
Flux $d\Phi/dE_0 \cdot E_0^{2.5}$ [m^{-2} sr^{-1} s^{-1} $GeV^{1.5}$]
Energy E_0 [GeV]

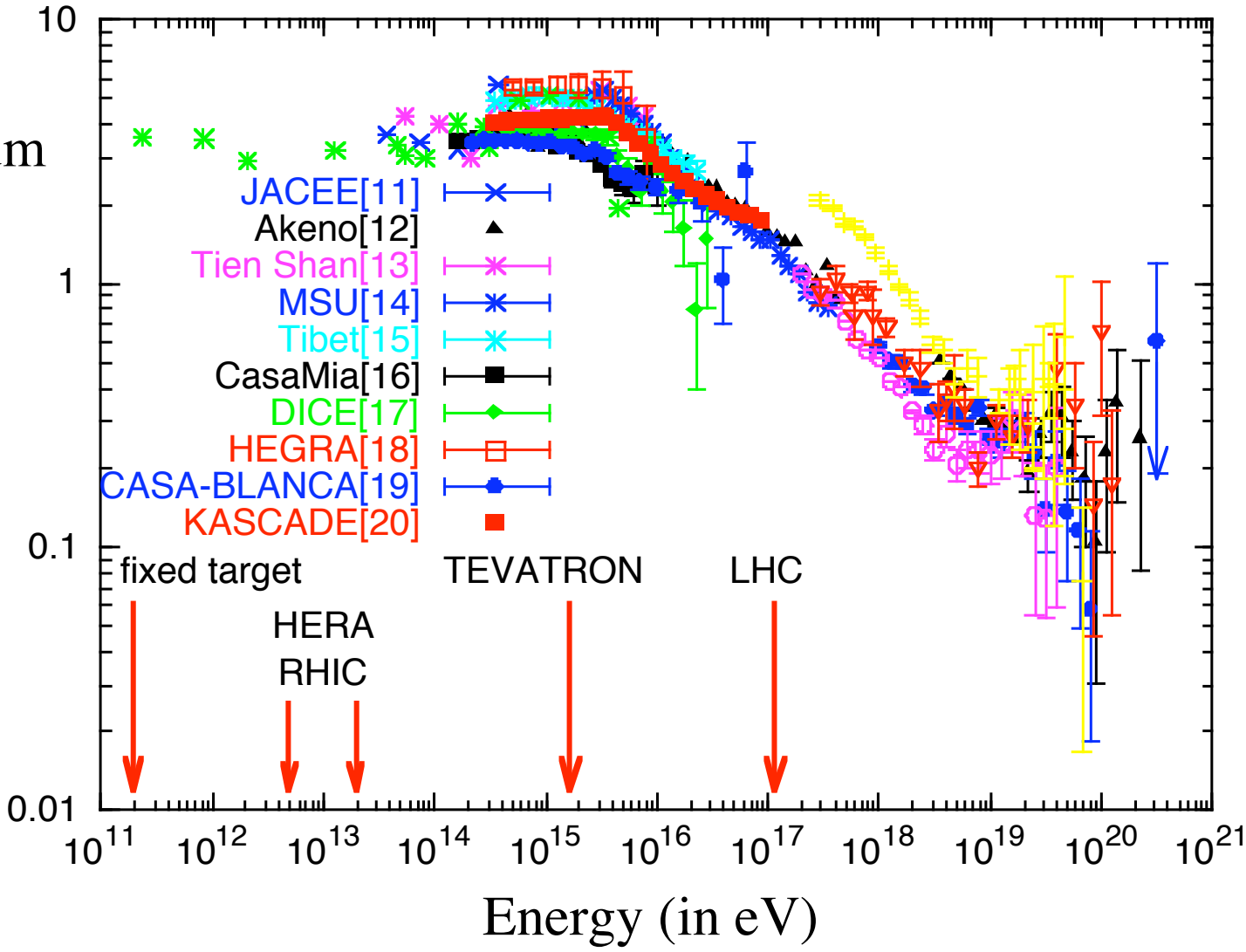
[CR flux] x E^3


AGASA
Akeno 20 km²
Akeno 1 km²
AUGER
BLANCA
CASA-MIA
DICE
BASJE-MAS
EAS-Top
Fly's Eye
Haverah Park
Haverah Park Fe
Haverah Park p
HEGRA
HiRes-I
HiRes-II
HiRes/MIA
KASCADE (e/m QGSJET)
KASCADE (e/m SIBYLL)
KASCADE (h/m)
KASCADE (nn)
MSU
Mt. Norikura
SUGAR
Tibet ASγ
Tibet ASγ-III
Tunka-25
direct:
JACEE
RUNJOB
SOKOL
Grigorov
knee
2nd knee
ankle
galactic
extragal.
1
2
3-9
10-24
25-27
28-92
Flux dΦ/dE0 · E0 3 [m-2 sr-1 s-1 GeV1.5]
Energy E0 [GeV]

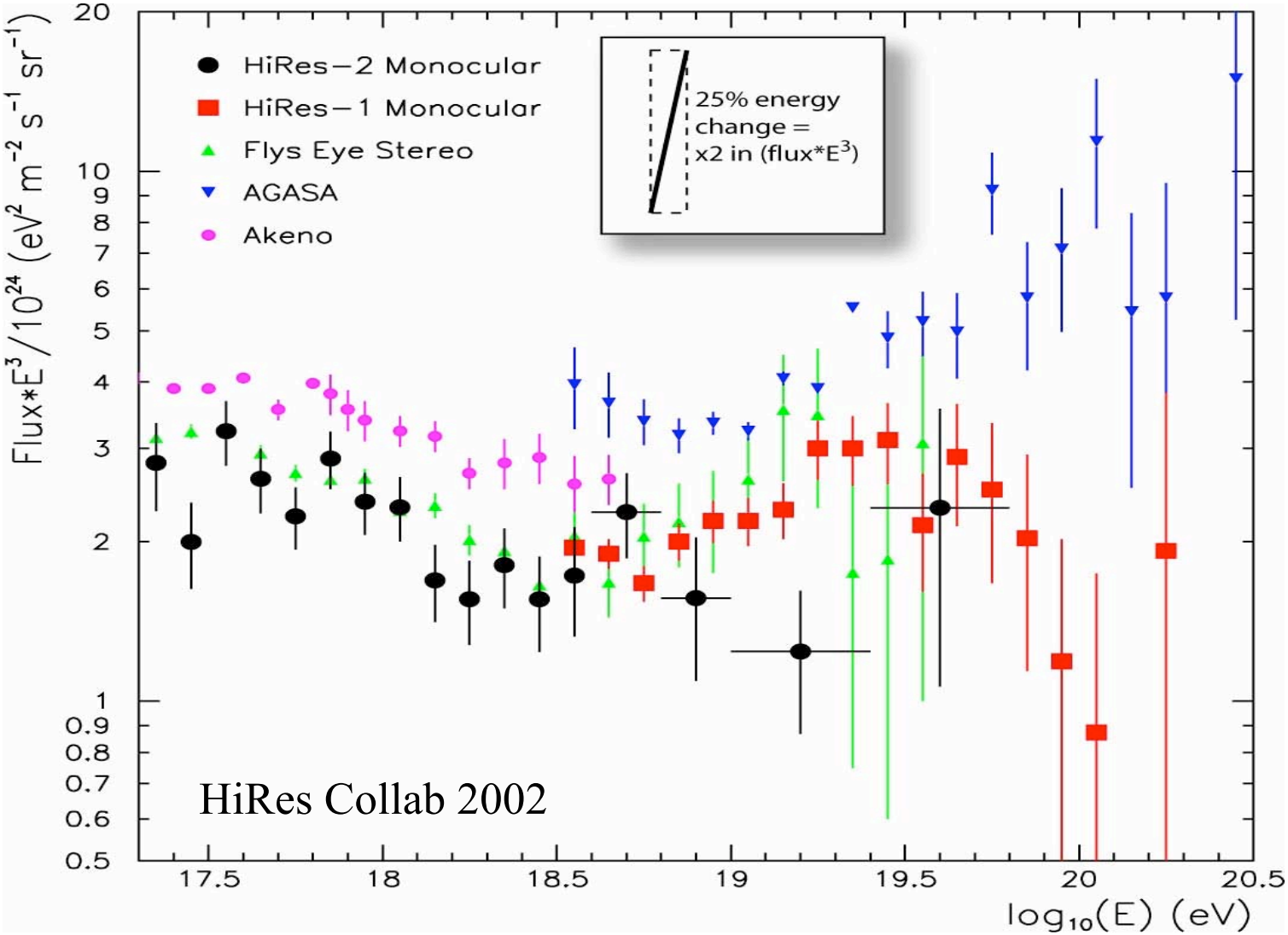
The 'knee' at 5×10^{15} eV

Tilted spectrum

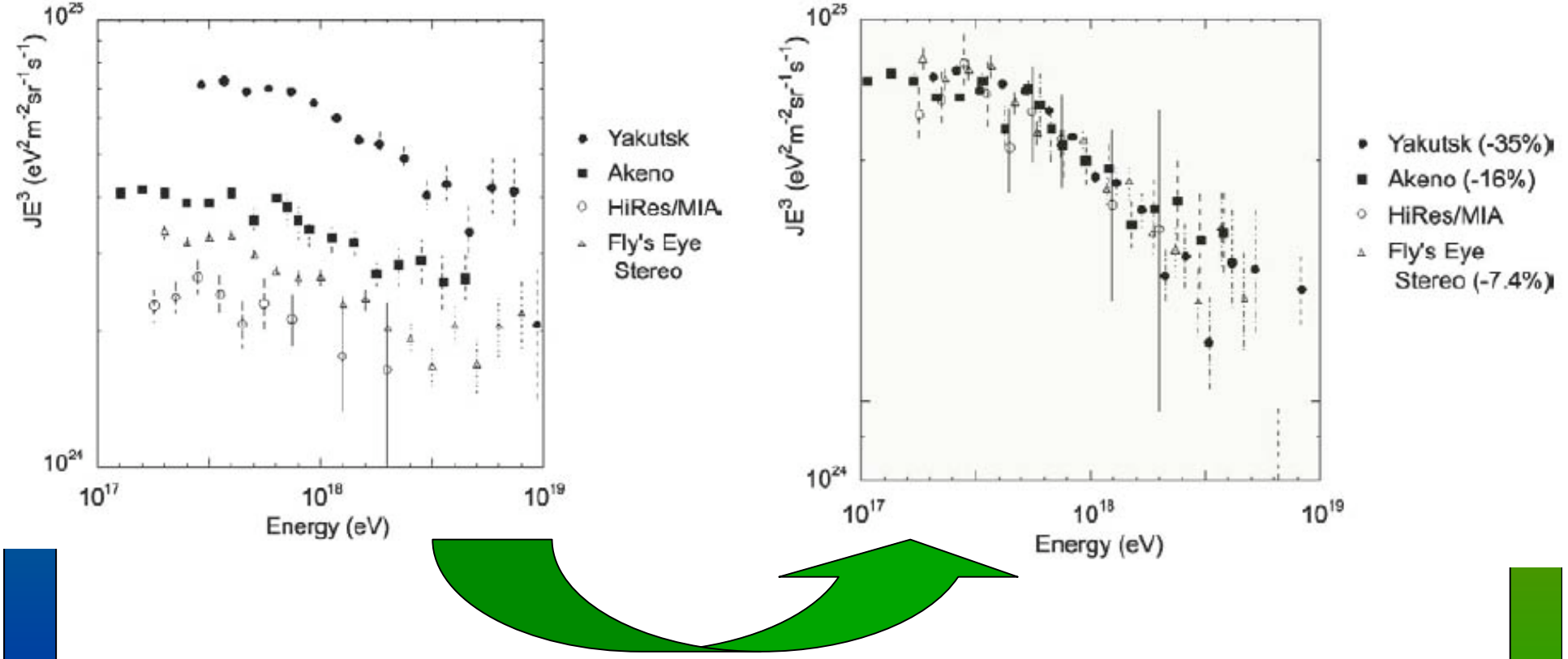
$\Phi(E) \times E^{2.7}$



Highest energies

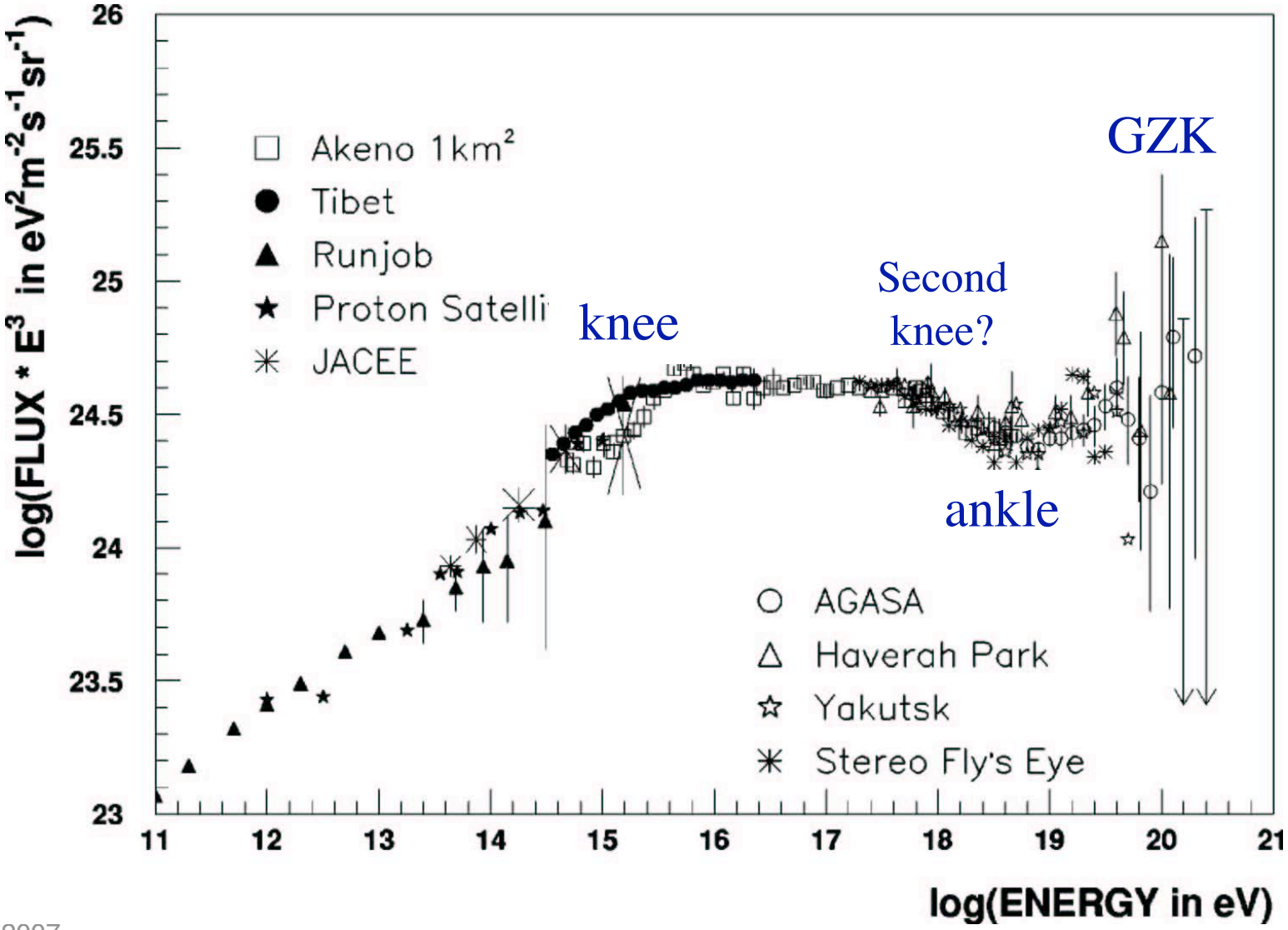


The 'second knee' at 5×10^{17} eV?



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

[CR flux] x E^3


log(FLUX * E^3 in eV^2 m^-2 s^-1 sr^-1)
log(ENERGY in eV)
Akeno 1km^2
Tibet
Runjob
Proton Satelli
JACEE
AGASA
Haverah Park
Yakutsk
Stereo Fly's Eye
knee
Second knee?
ankle
GZK

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]

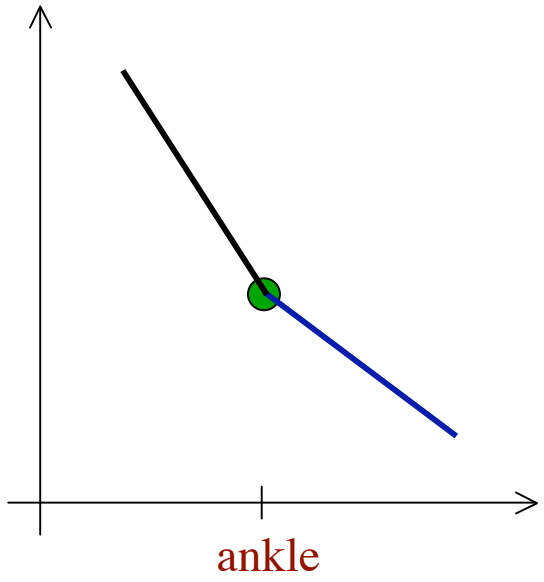
- Therefore a transition must occur!

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

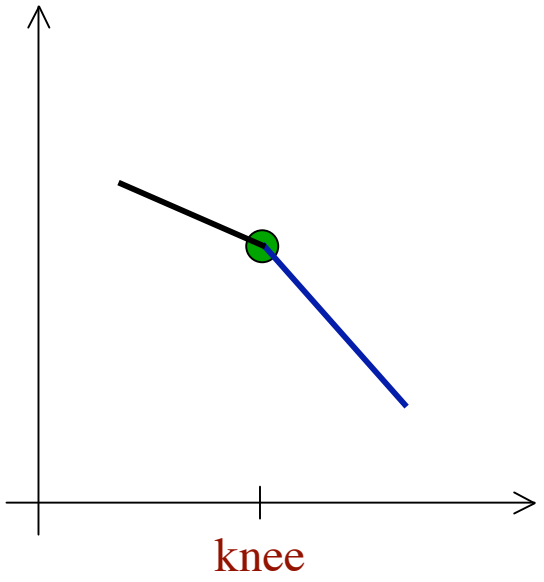
General phenomenology of transitions

- Two possibilities:

transition from a soft
to a harder component



transition from a hard
to a softer component



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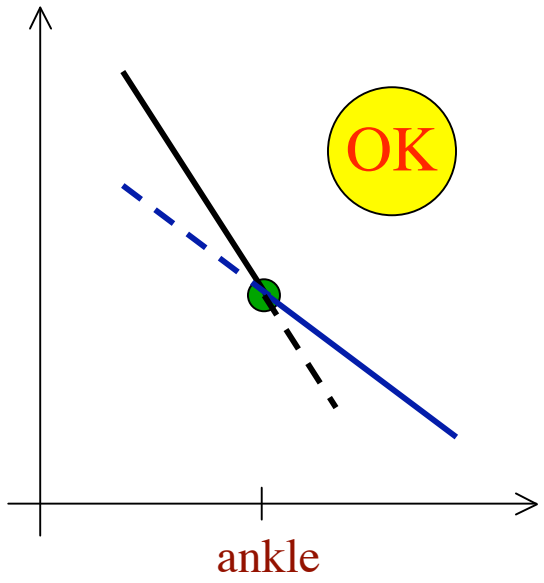
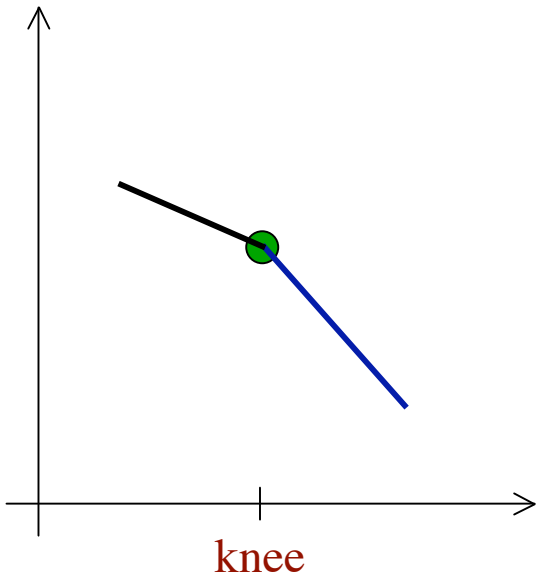


transition from a hard
to a softer component



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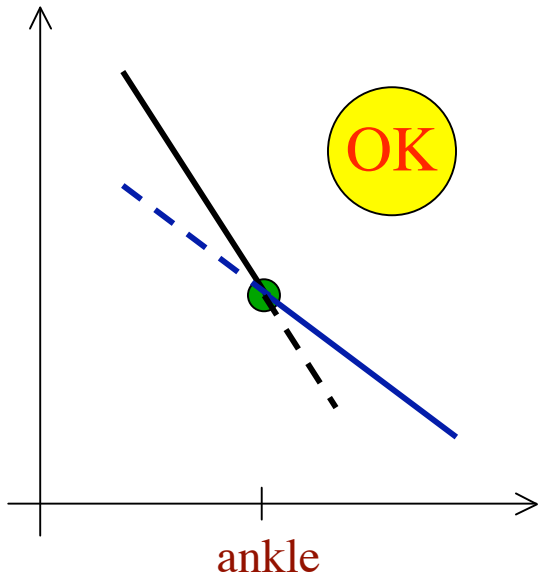

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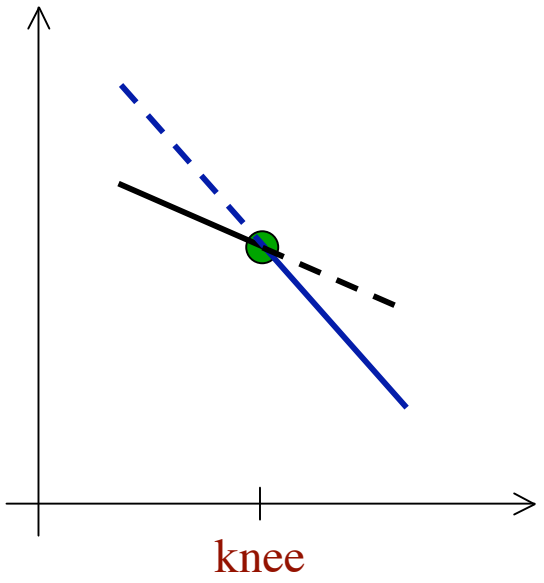

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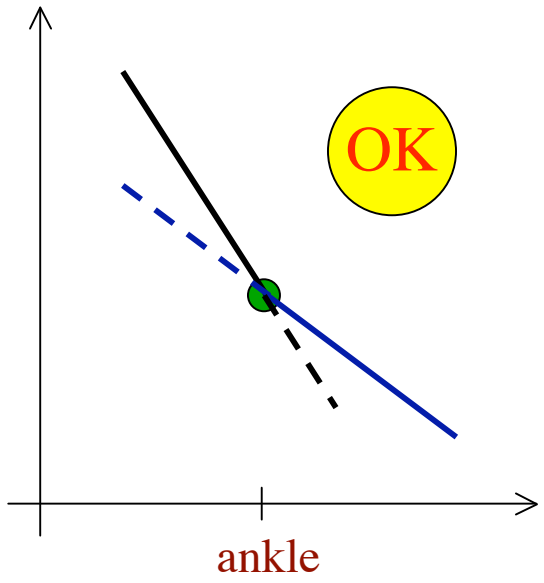
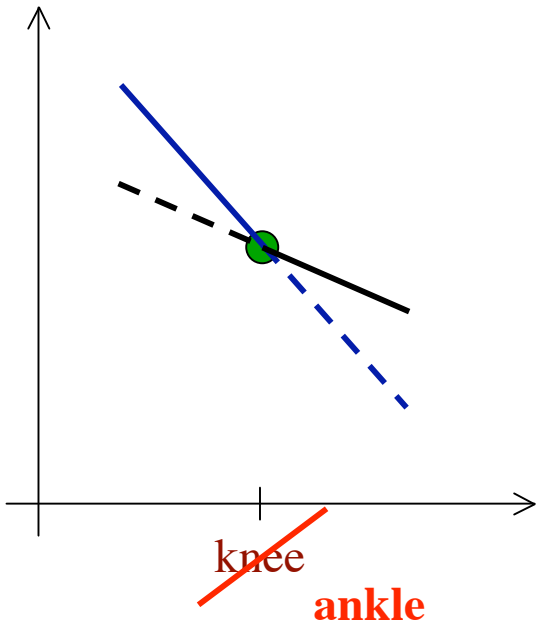


transition from a hard to a softer component



General phenomenology of transitions

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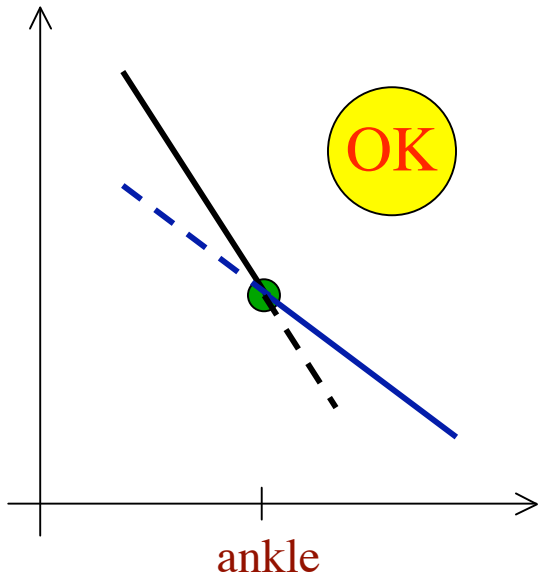
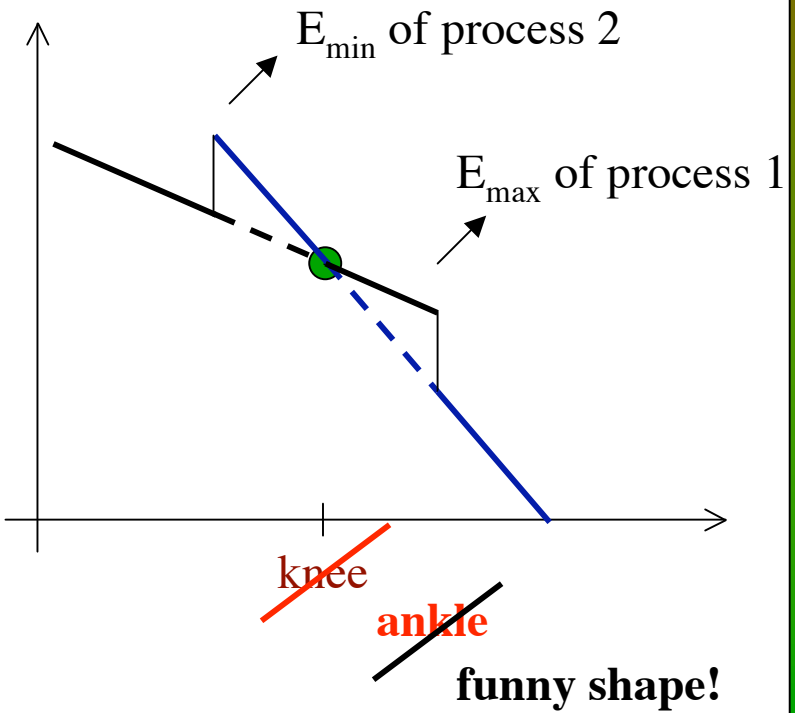
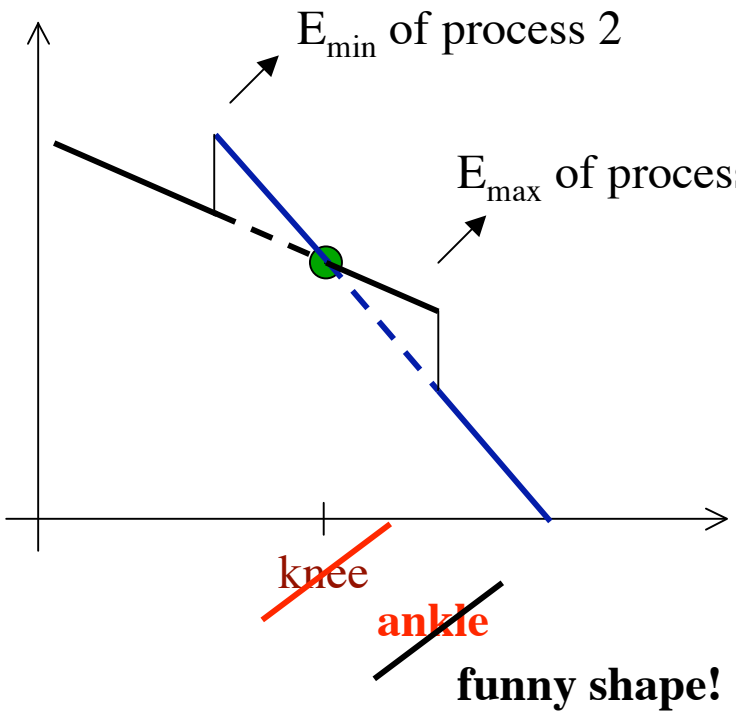


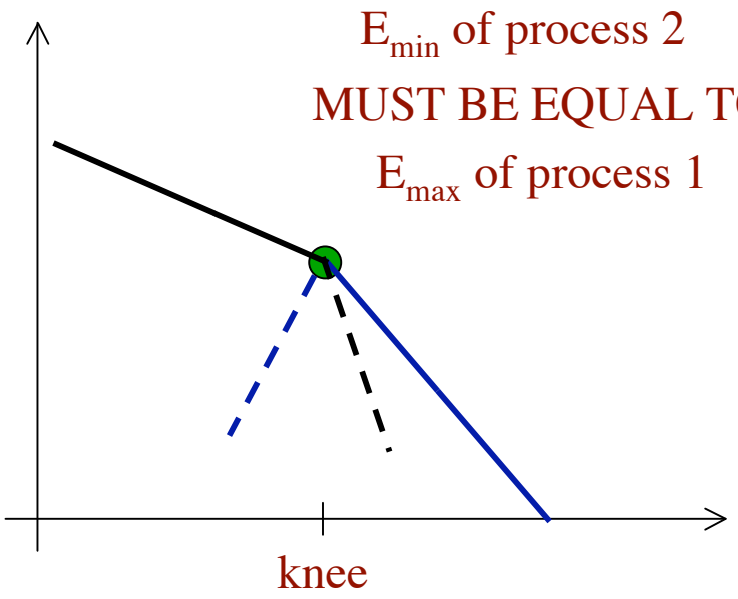
transition from a hard to a softer component



General phenomenology of transitions

- Requirements to obtain a knee-like transition:





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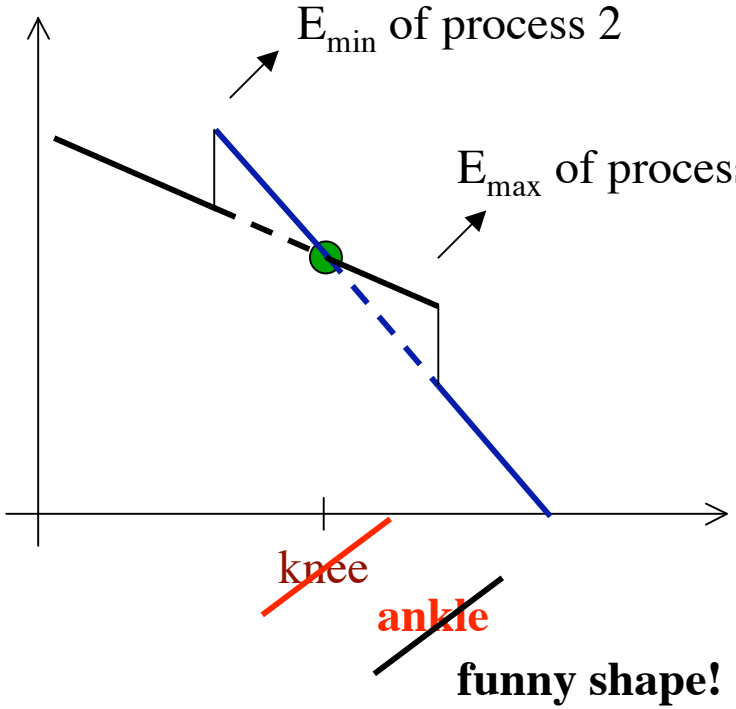
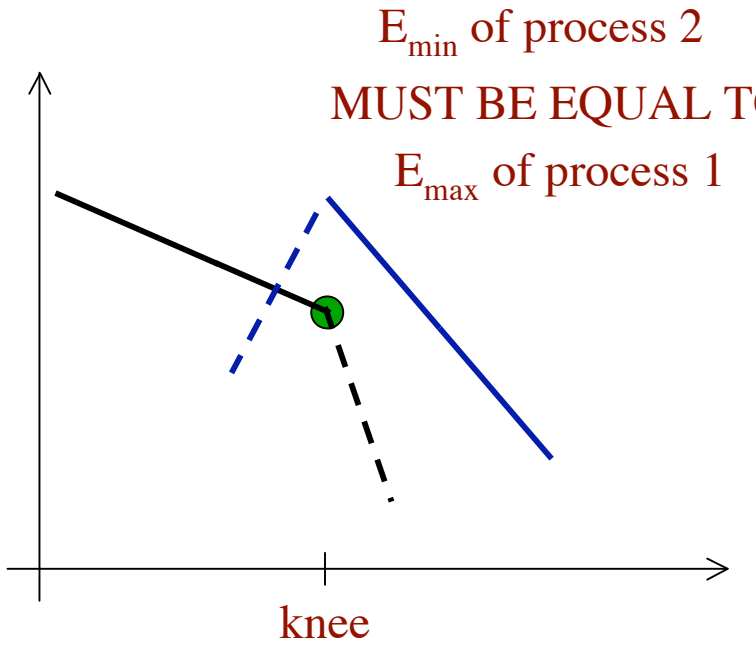
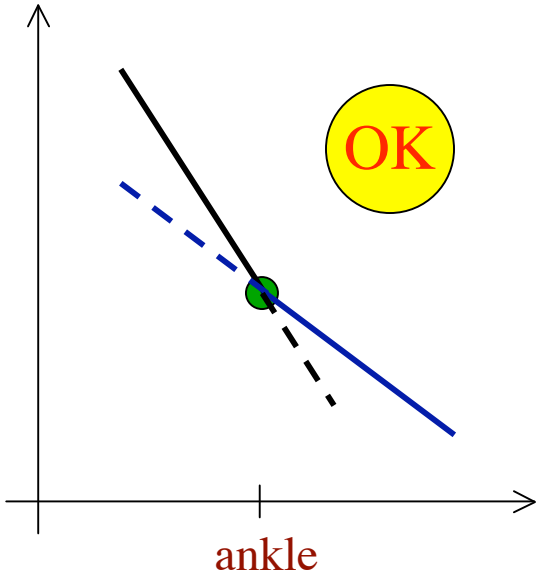




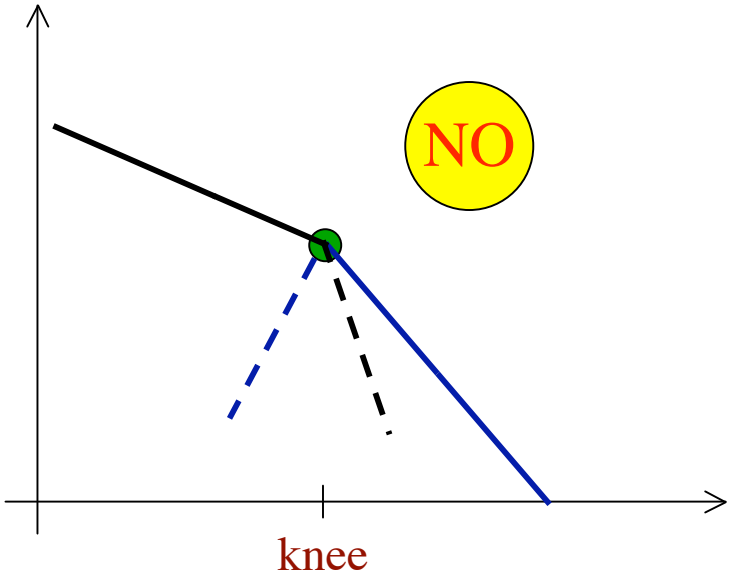
AND the flux of the two components MUST BE EQUAL precisely at THAT energy

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 ~3 10^{18} eV
- …precisely in the energy range where you expect it!

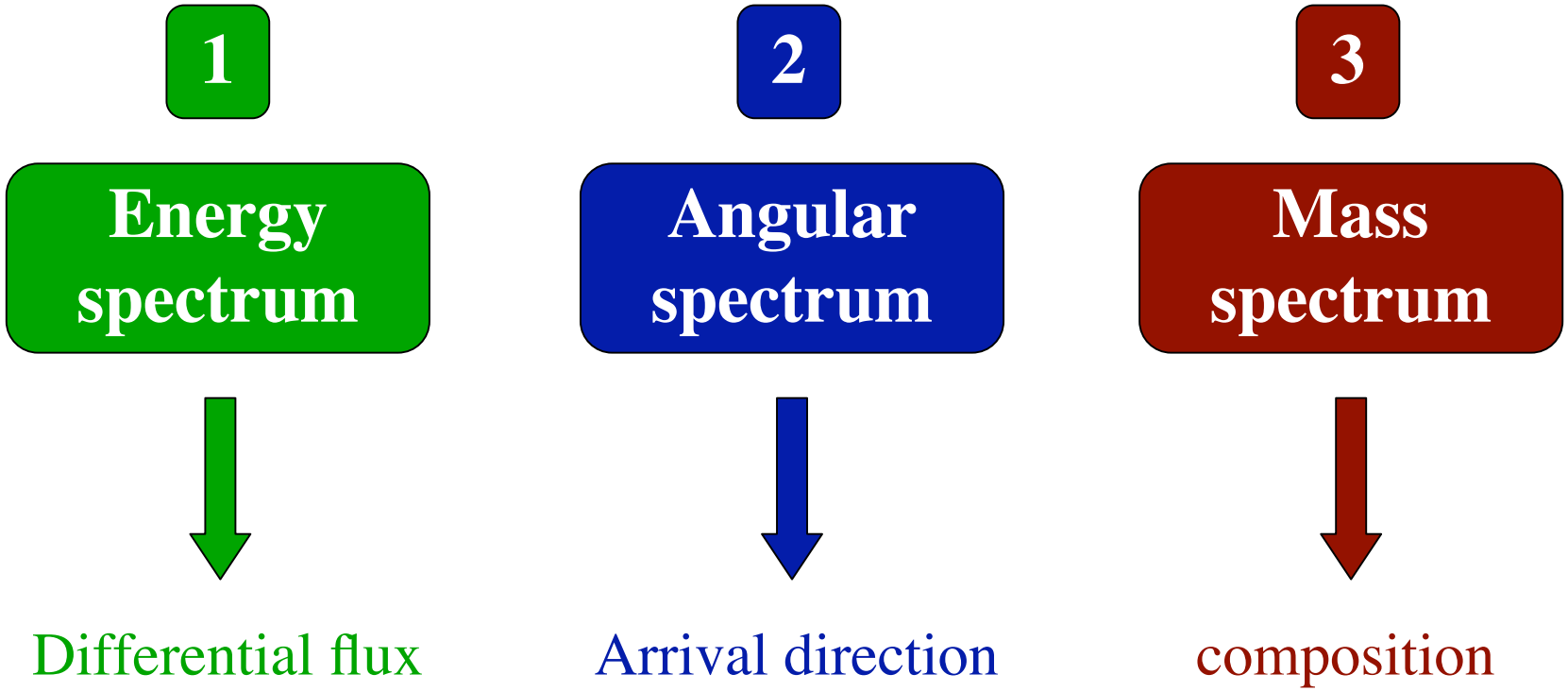
It could not be at much higher energy,
because Galactic CRs escape anyway

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

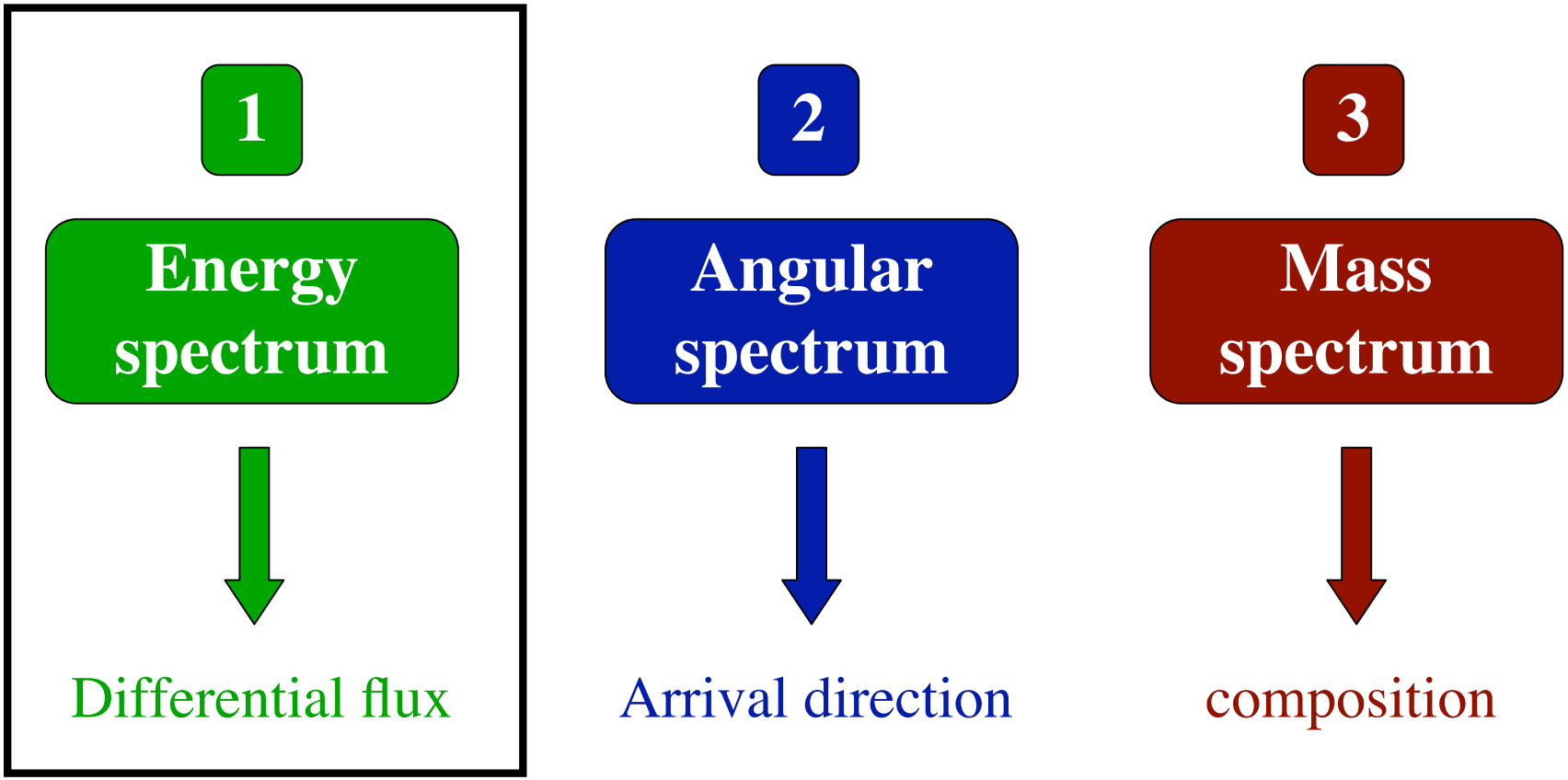
Propagation of extragalactic "UHECRs" (ultra-high-energy cosmic rays)

- 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

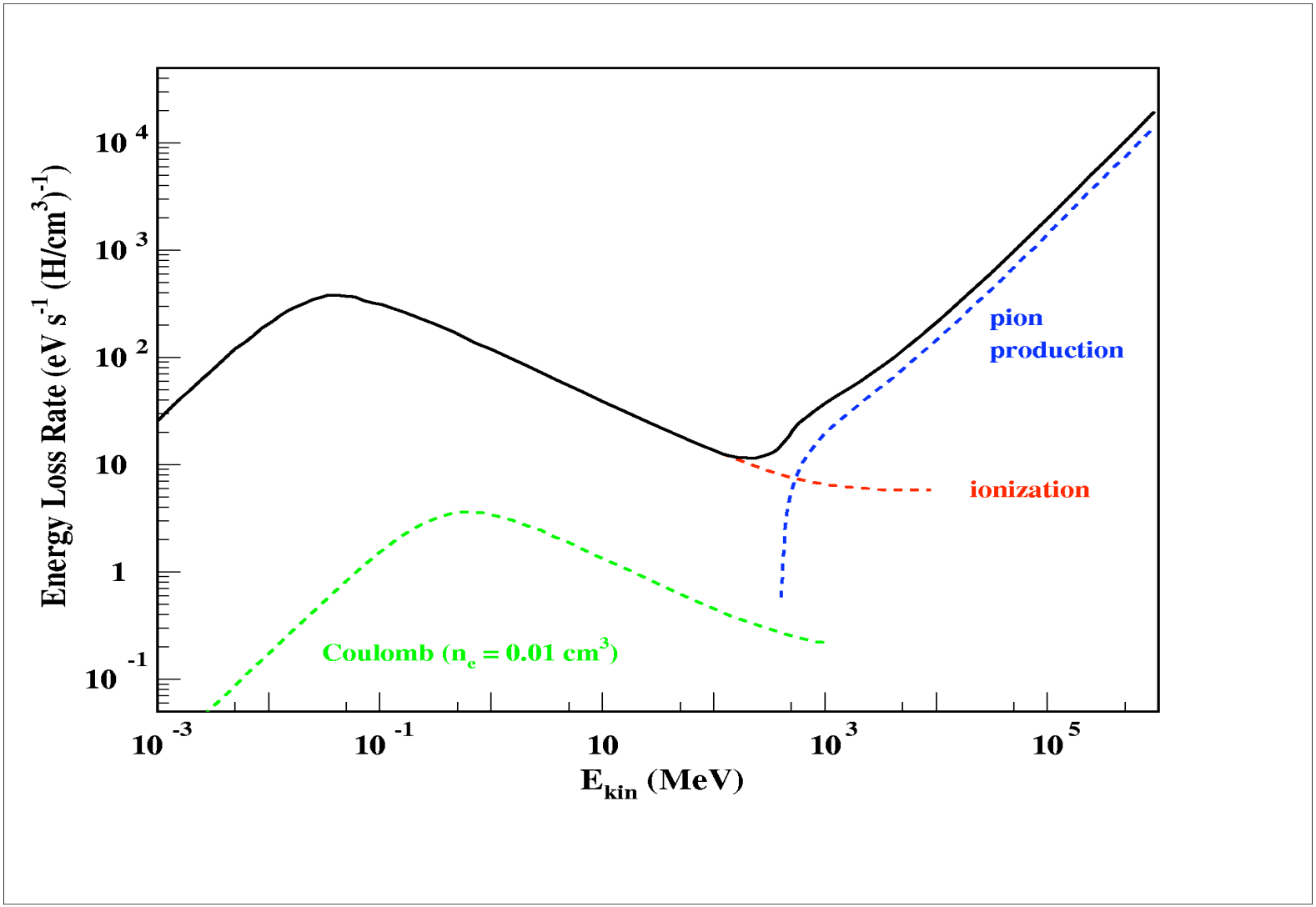
Cosmic-ray primary observables



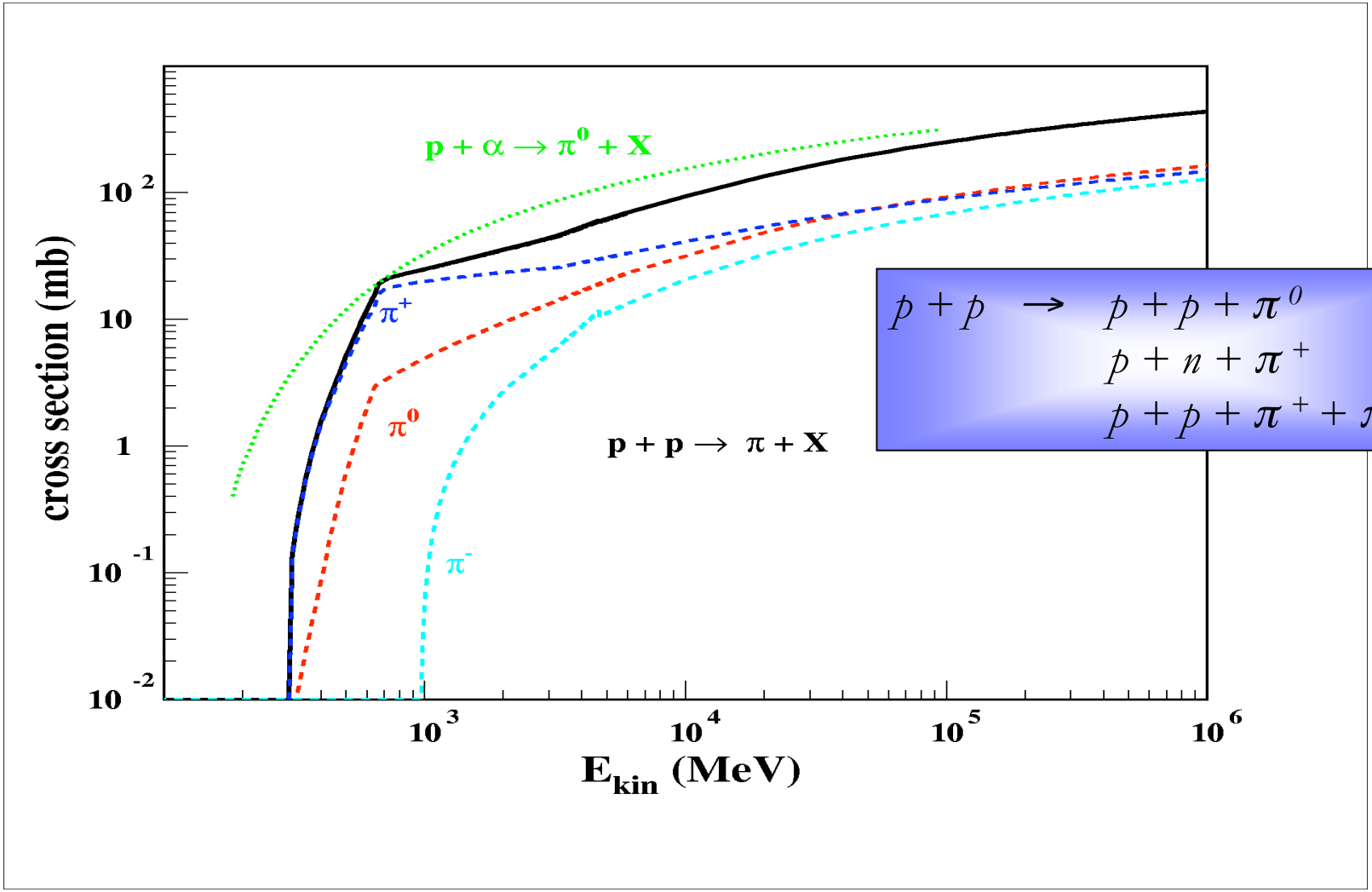
Cosmic-ray primary observables



Reminder: energy losses at low E

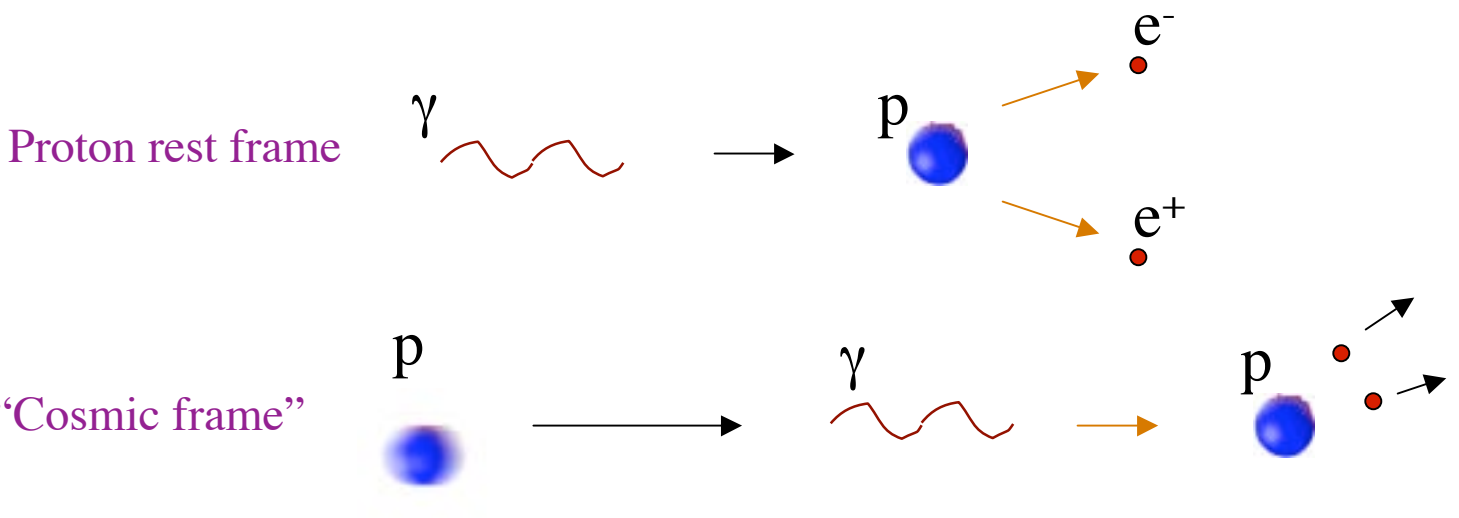


Nuclear interactions



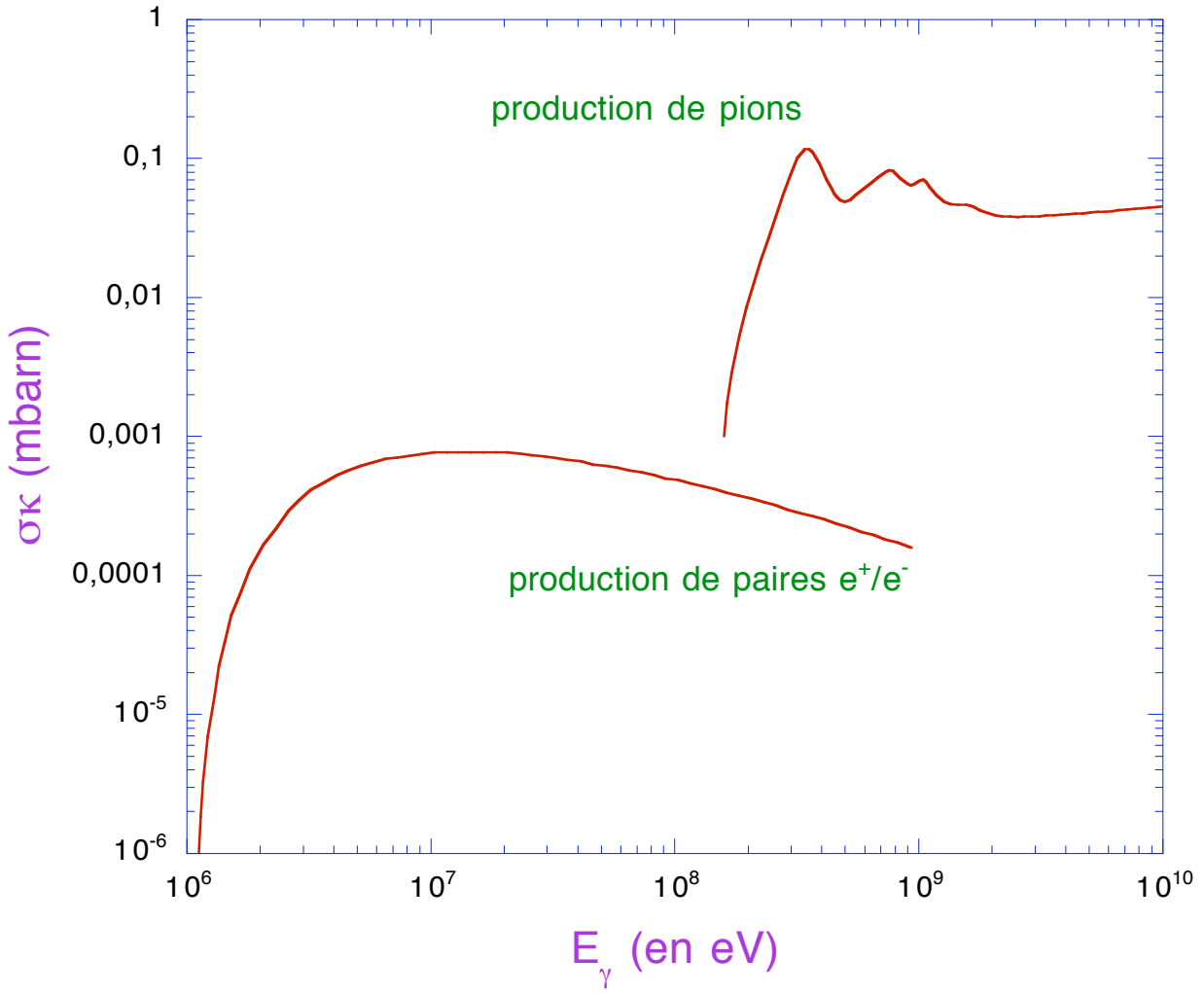
The GZK effect

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

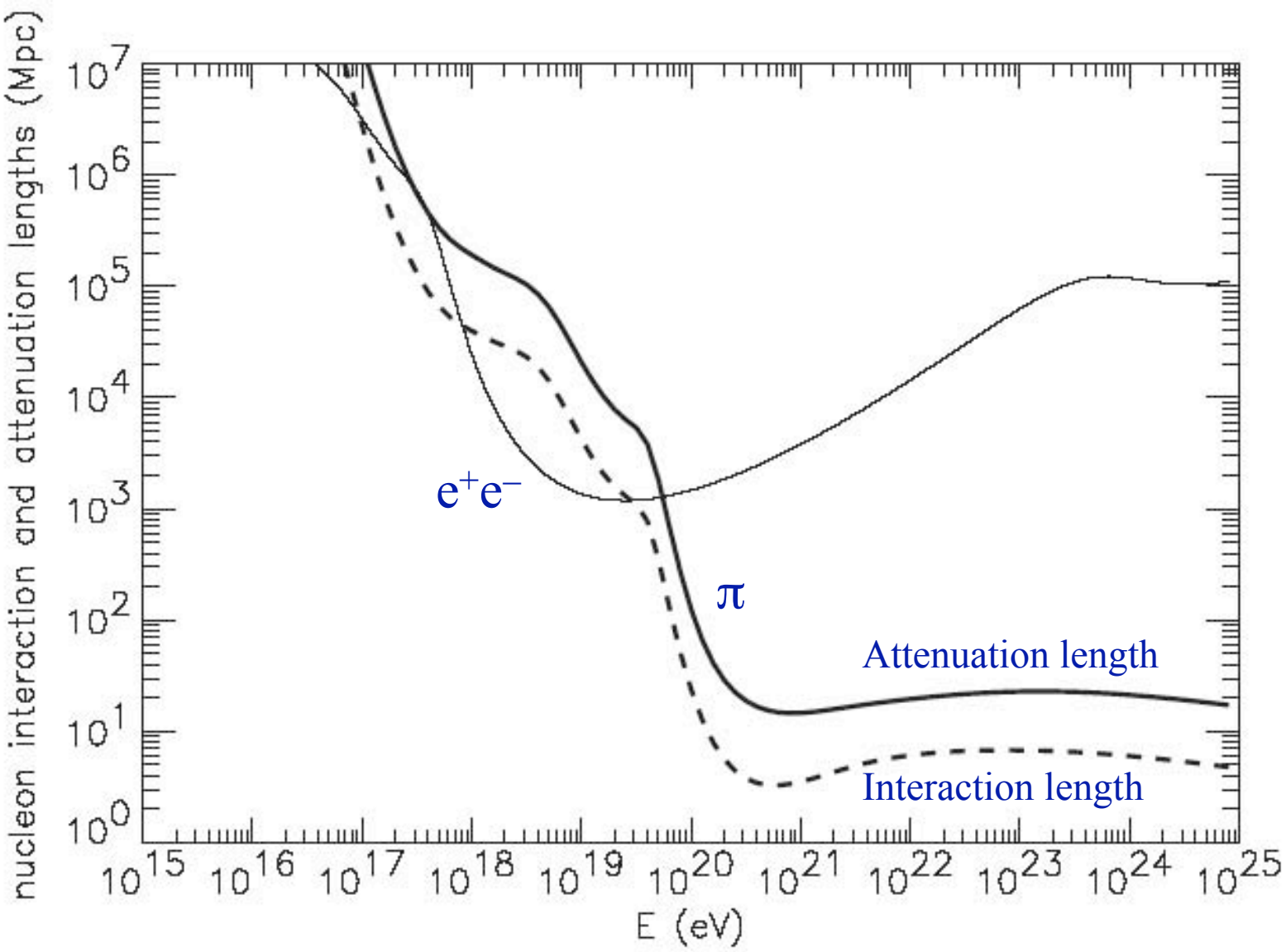


- Threshold : $E_\gamma \approx 2\, m_e c^2$ in the proton rest frame $\quad E_\gamma > 1$ MeV
- Threshold : $E_\gamma \approx m_\pi c^2$ in the proton rest frame $\quad E_\gamma > 160$ MeV

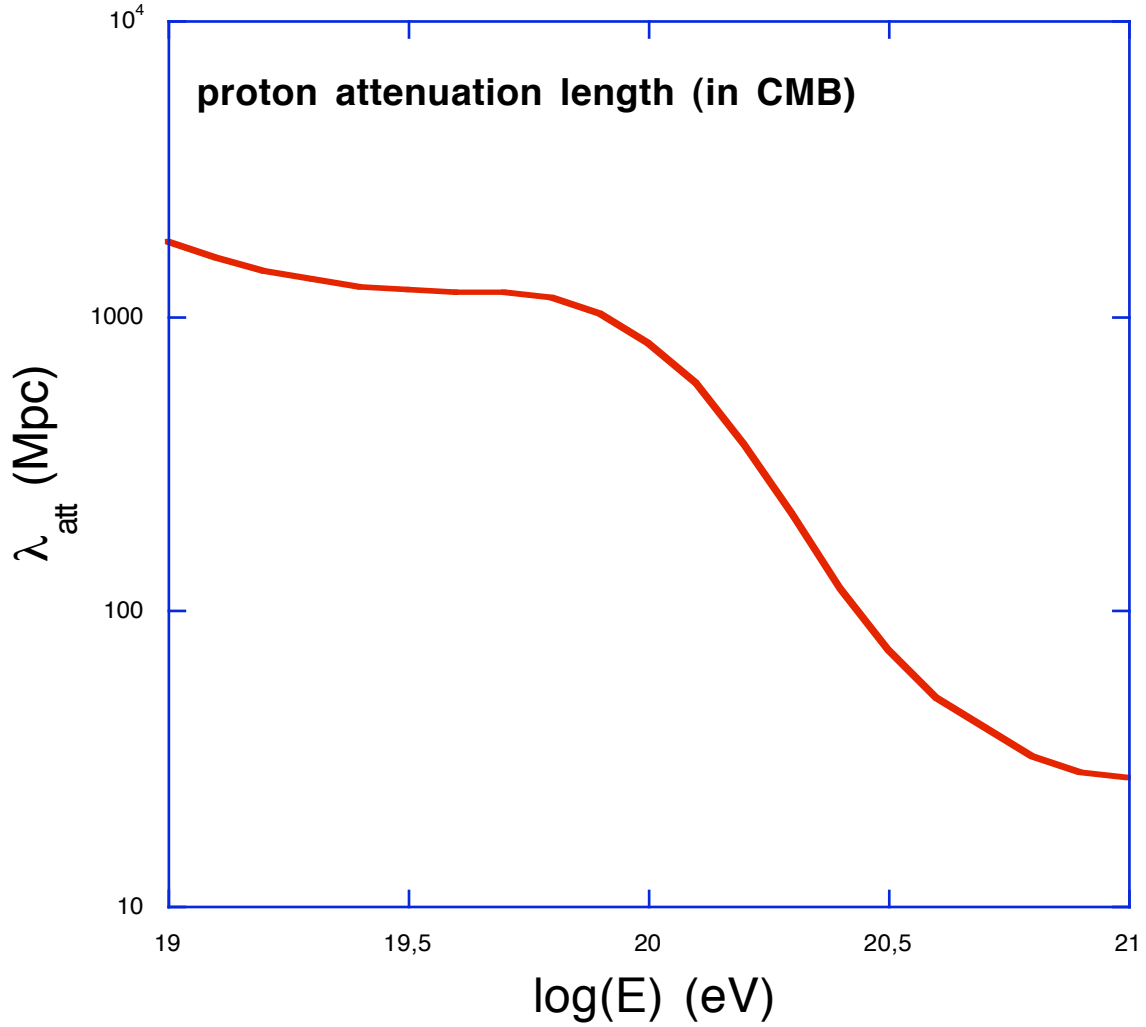
[cross section] x [inelasticity]



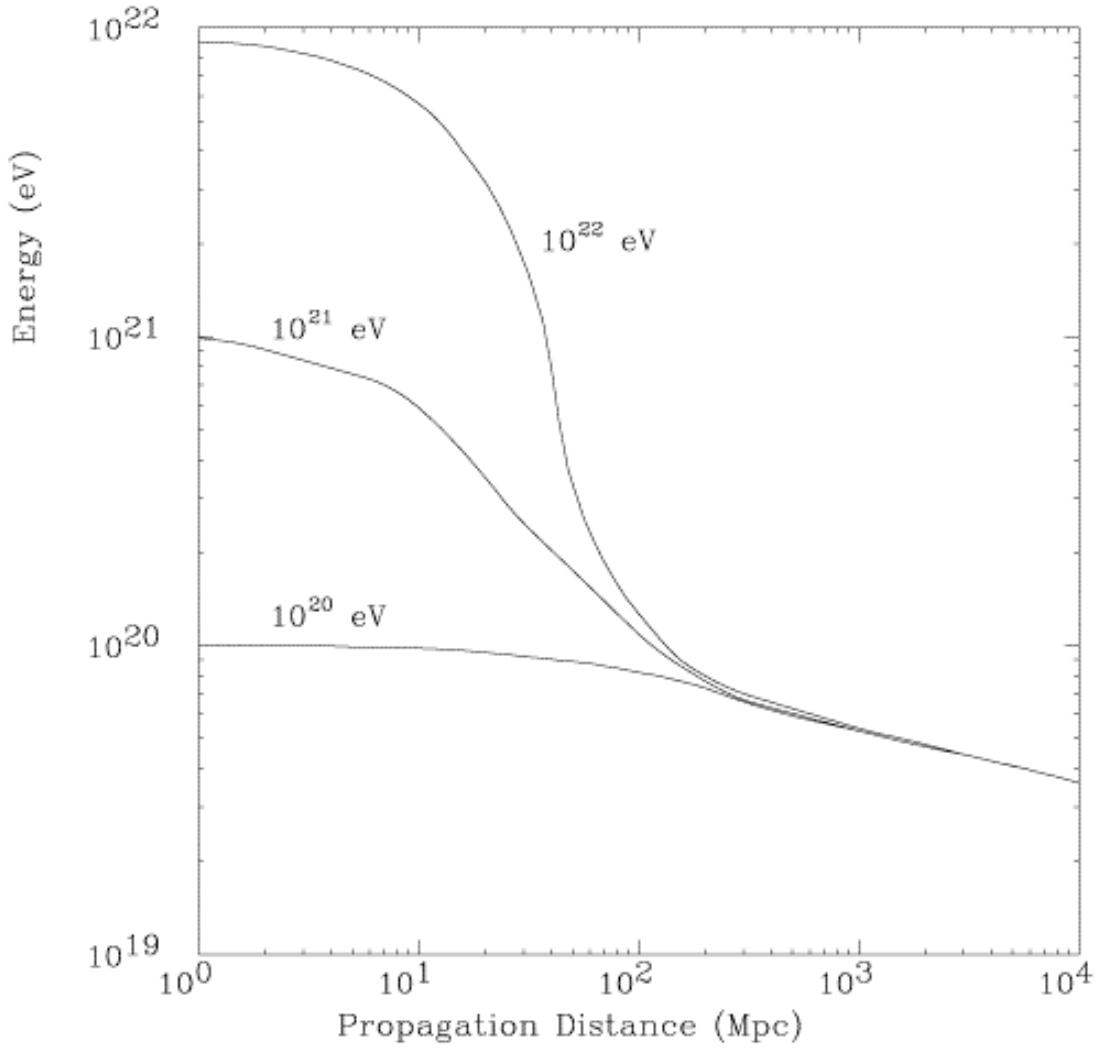
Attenuation length



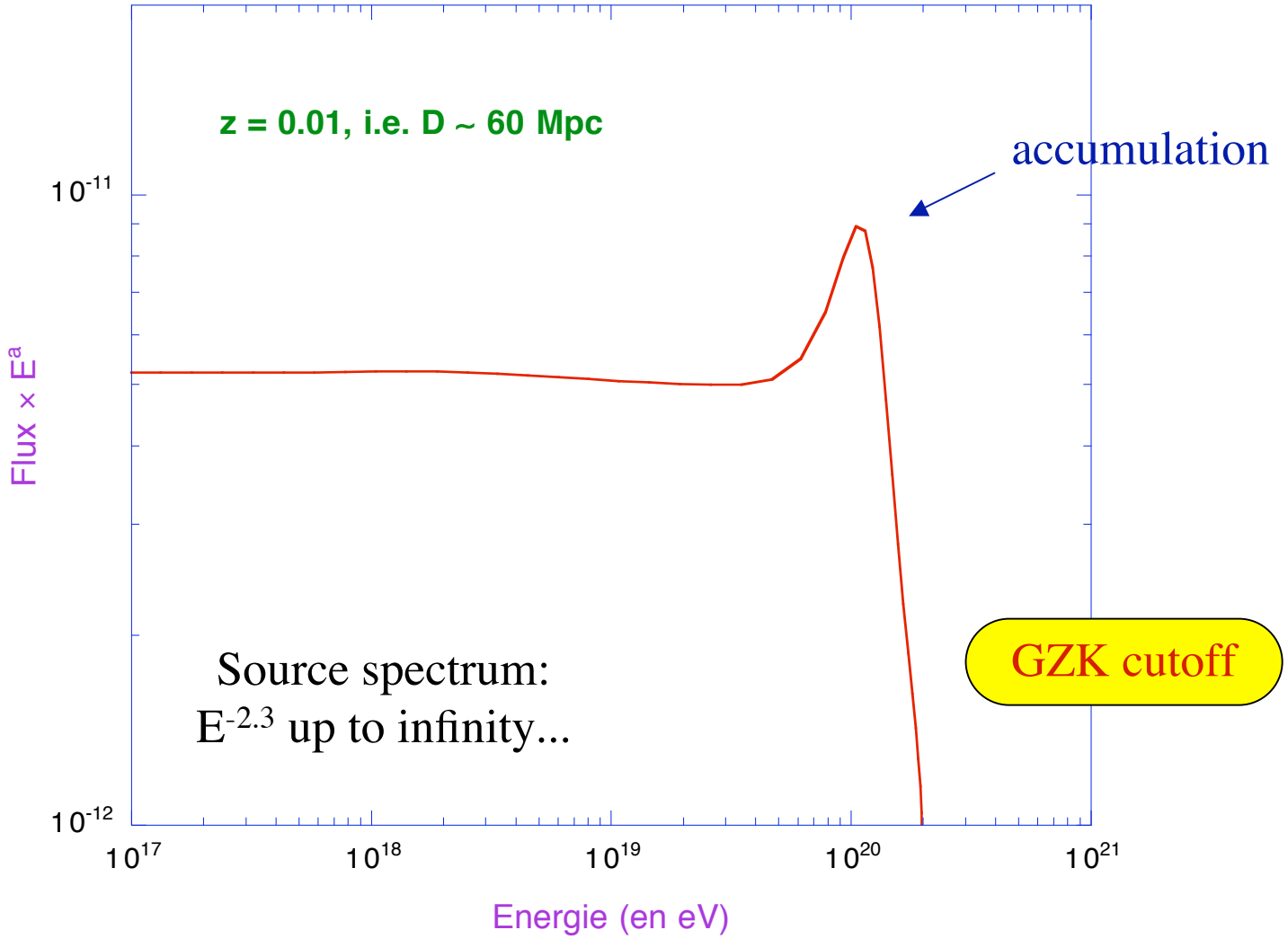
Attenuation length - horizons

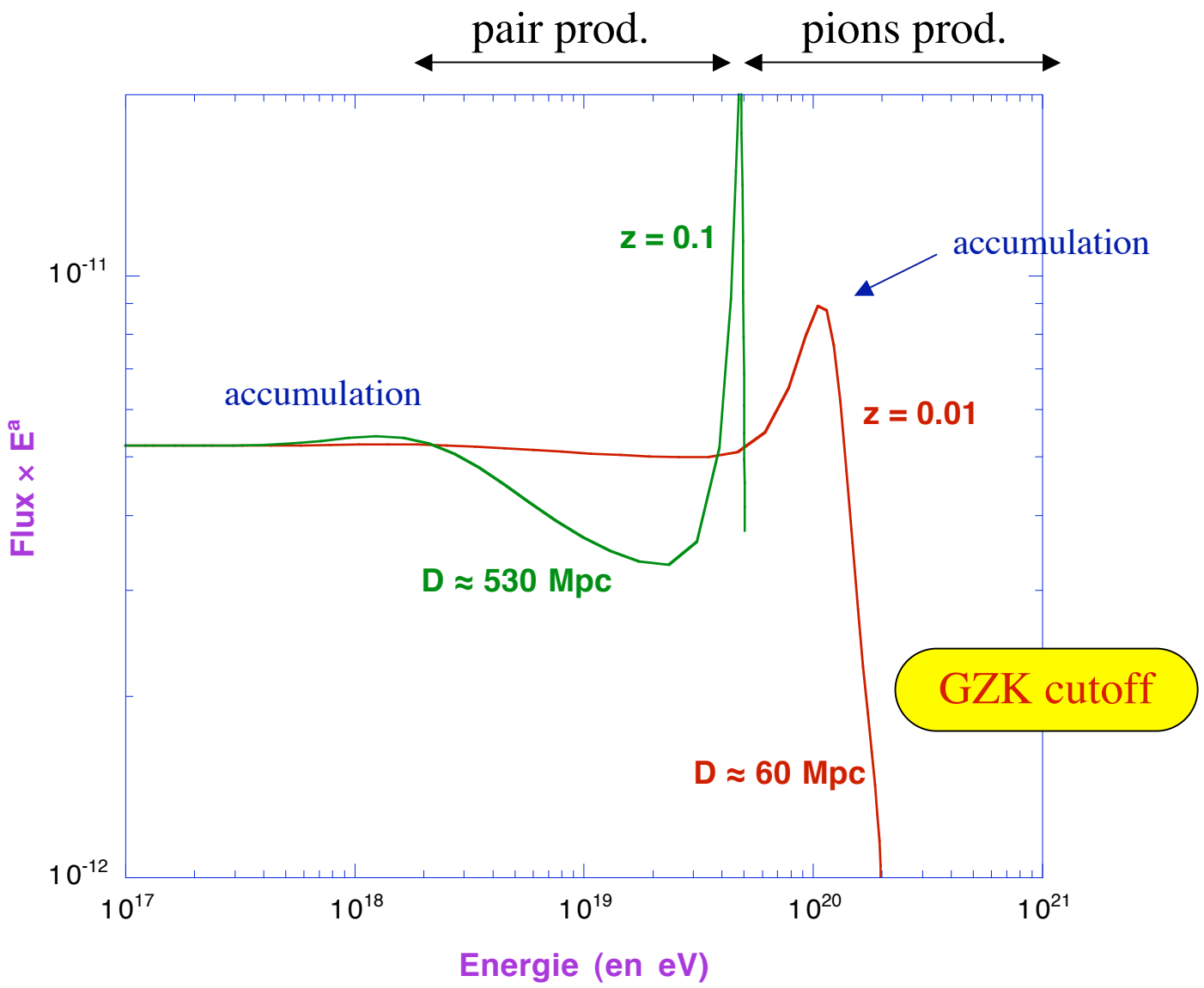


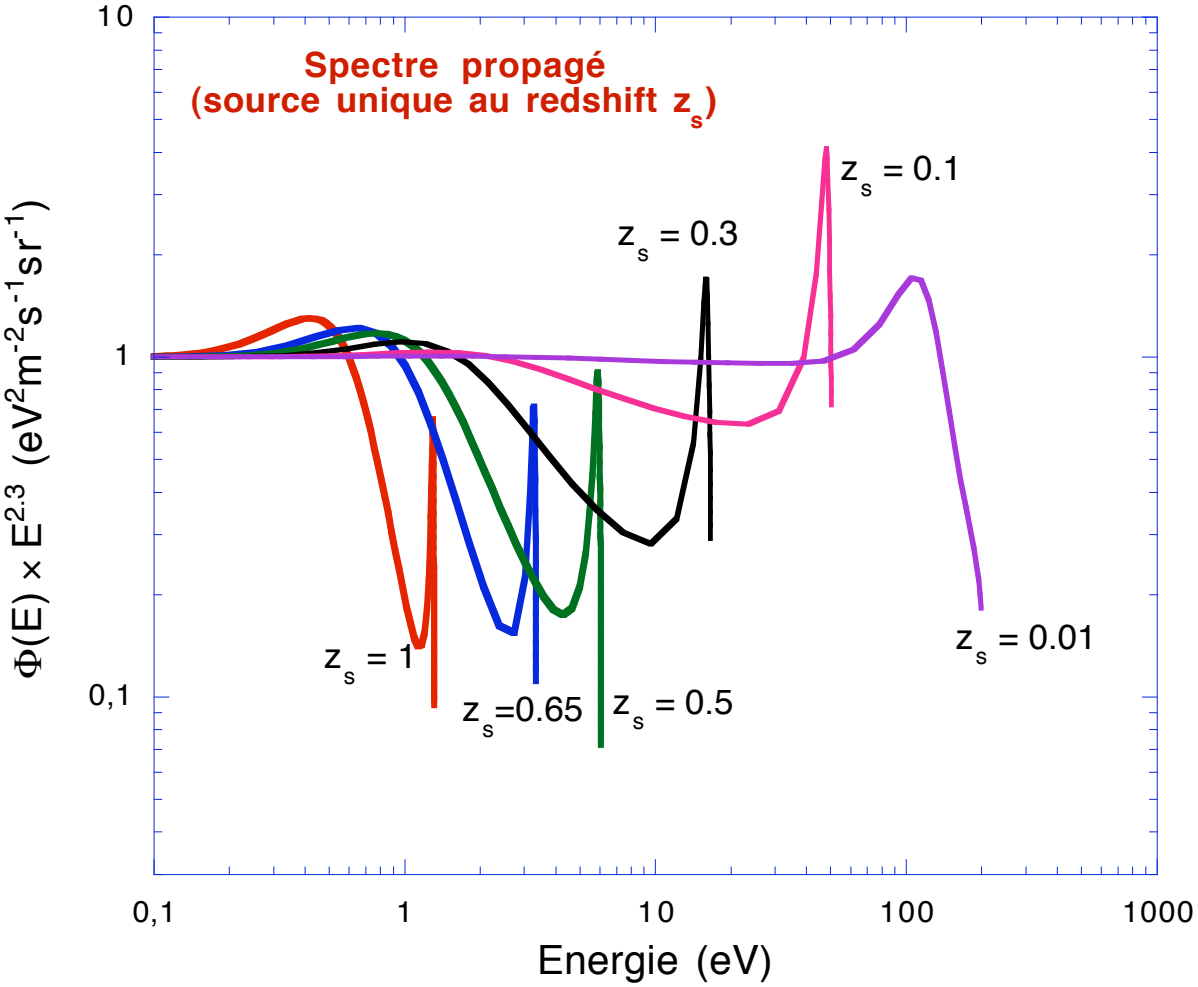
Evolution of the CR energy



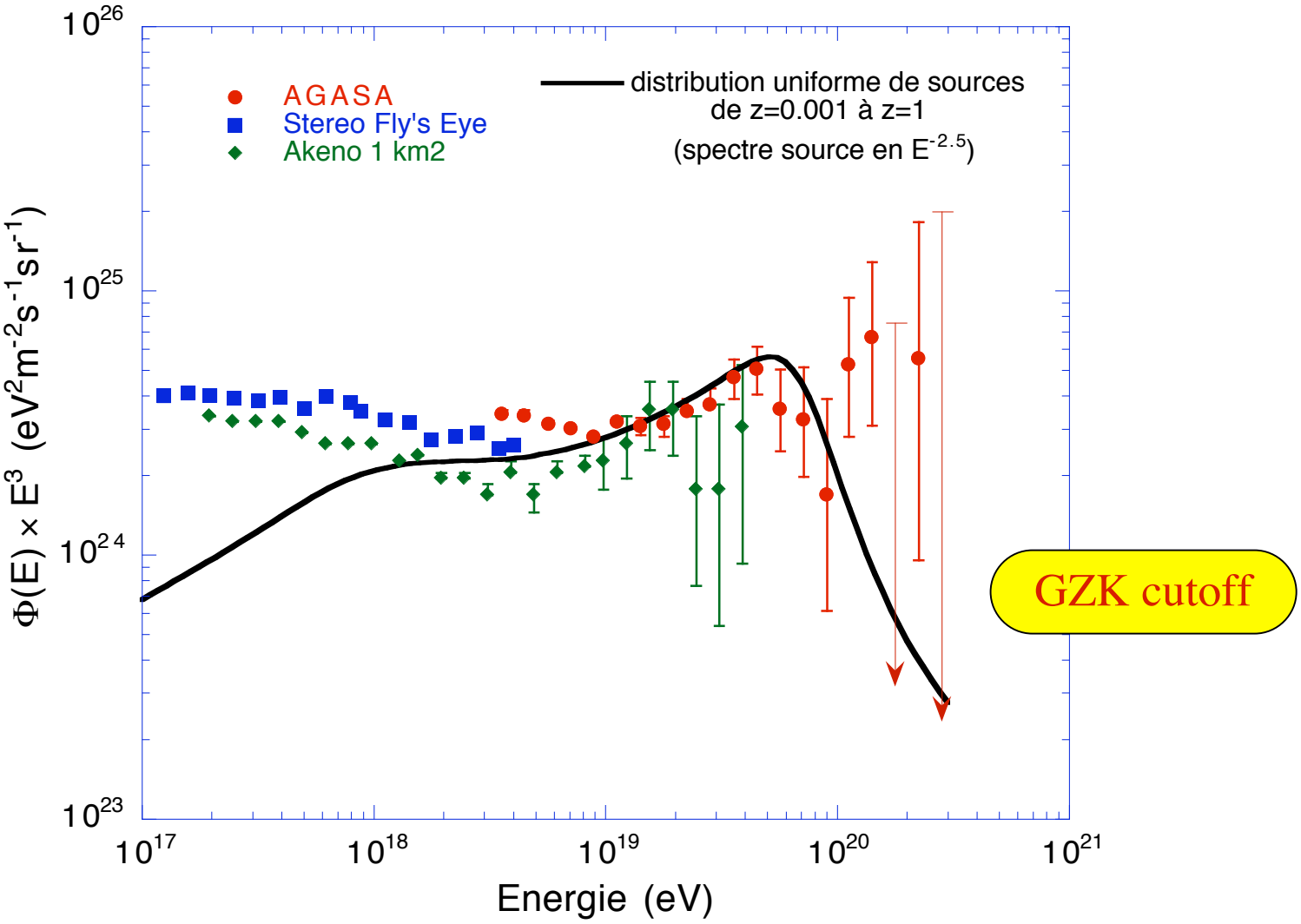
"Propagated" spectrum



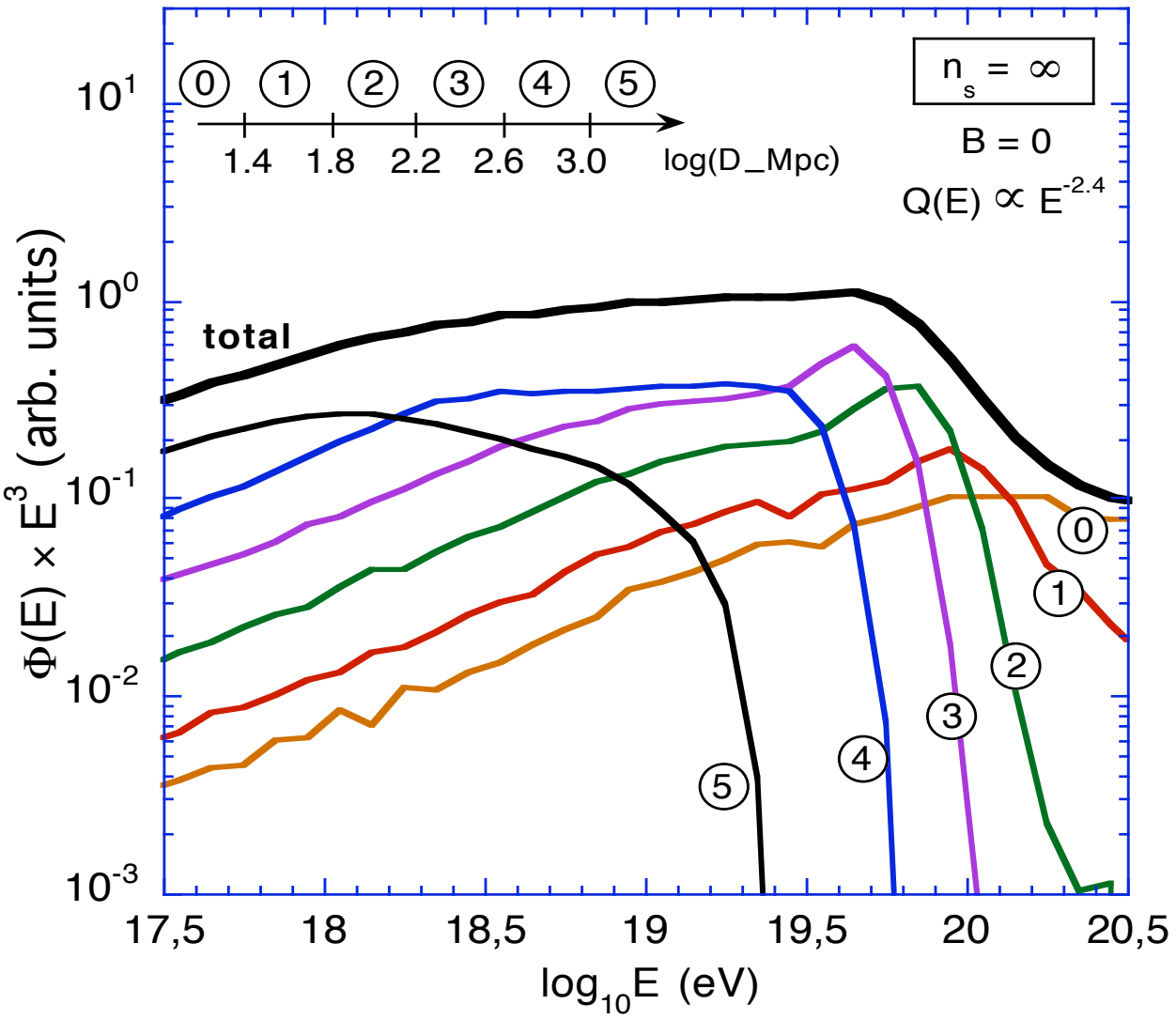

pair prod.
pions prod.
z = 0.1
accumulation
accumulation
z = 0.01
D ≈ 530 Mpc
GZK cutoff
D ≈ 60 Mpc
10^-11
10^-12
10^17
10^18
10^19
10^20
10^21
Flux x E^a
Energie (en eV)


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

Uniform source distribution



Contribution of different injection redshifts



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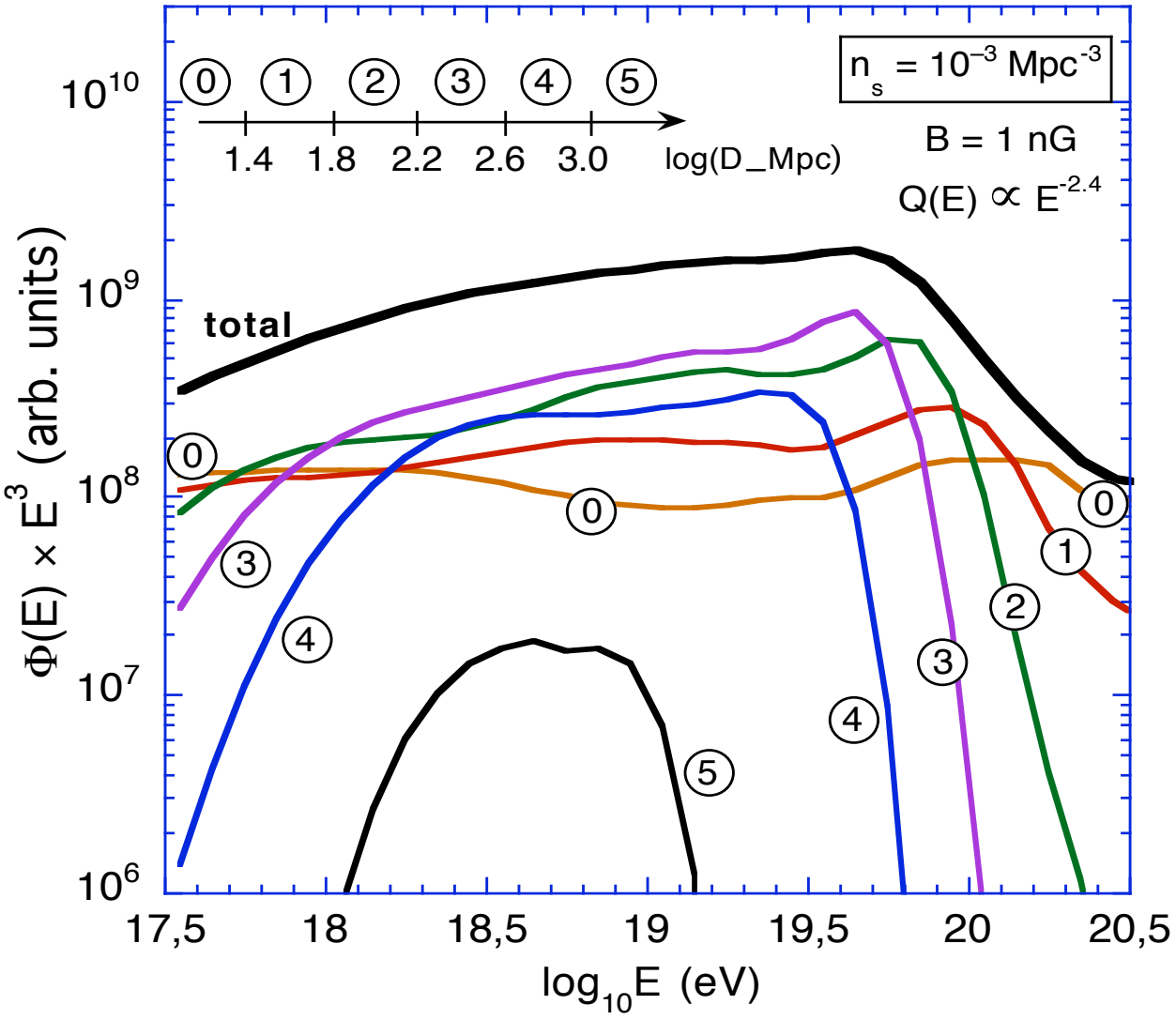


Cosmic-ray primary observables

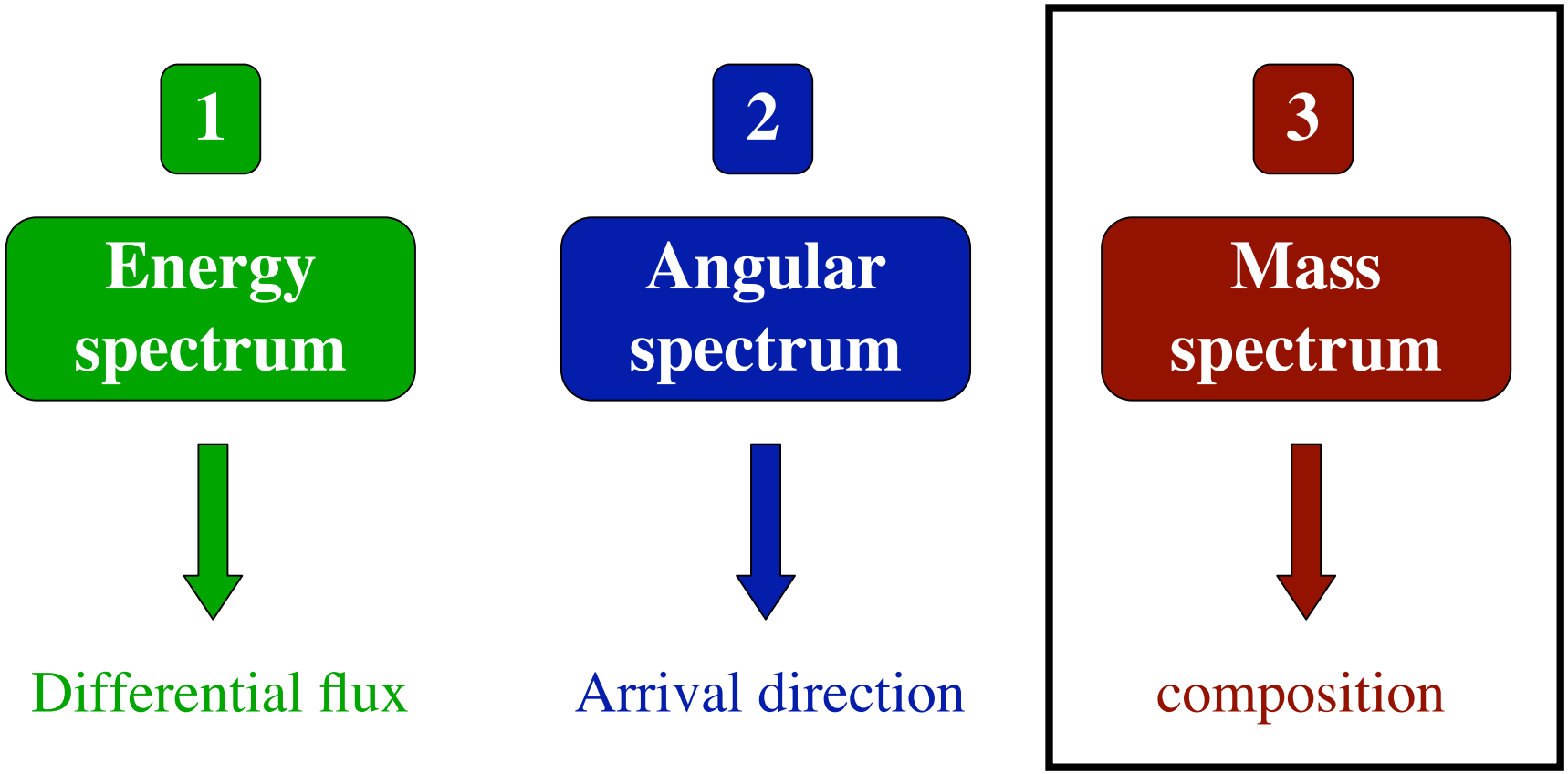
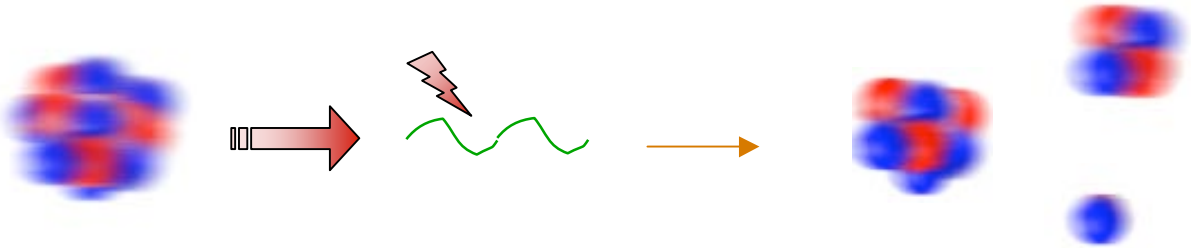
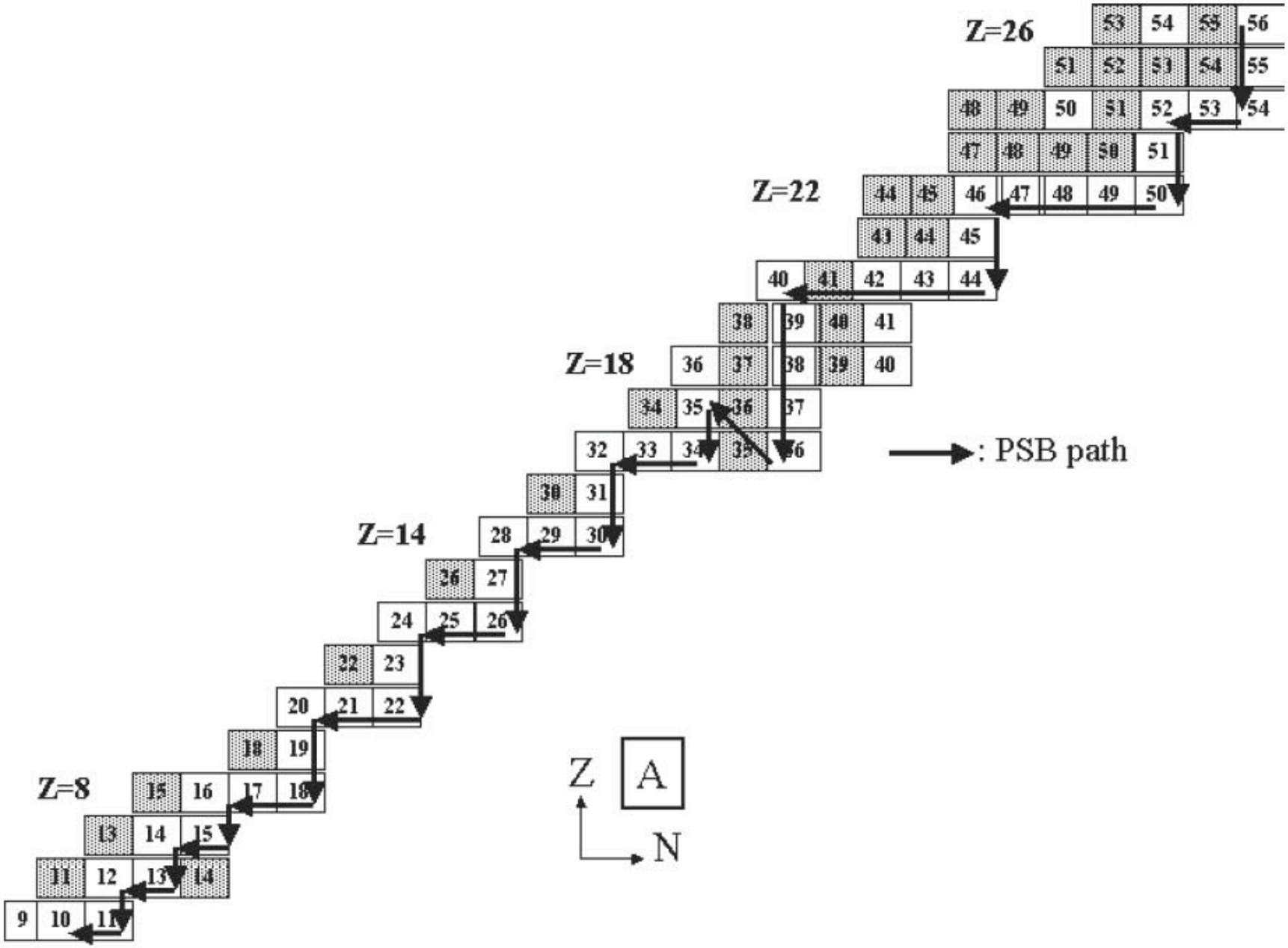


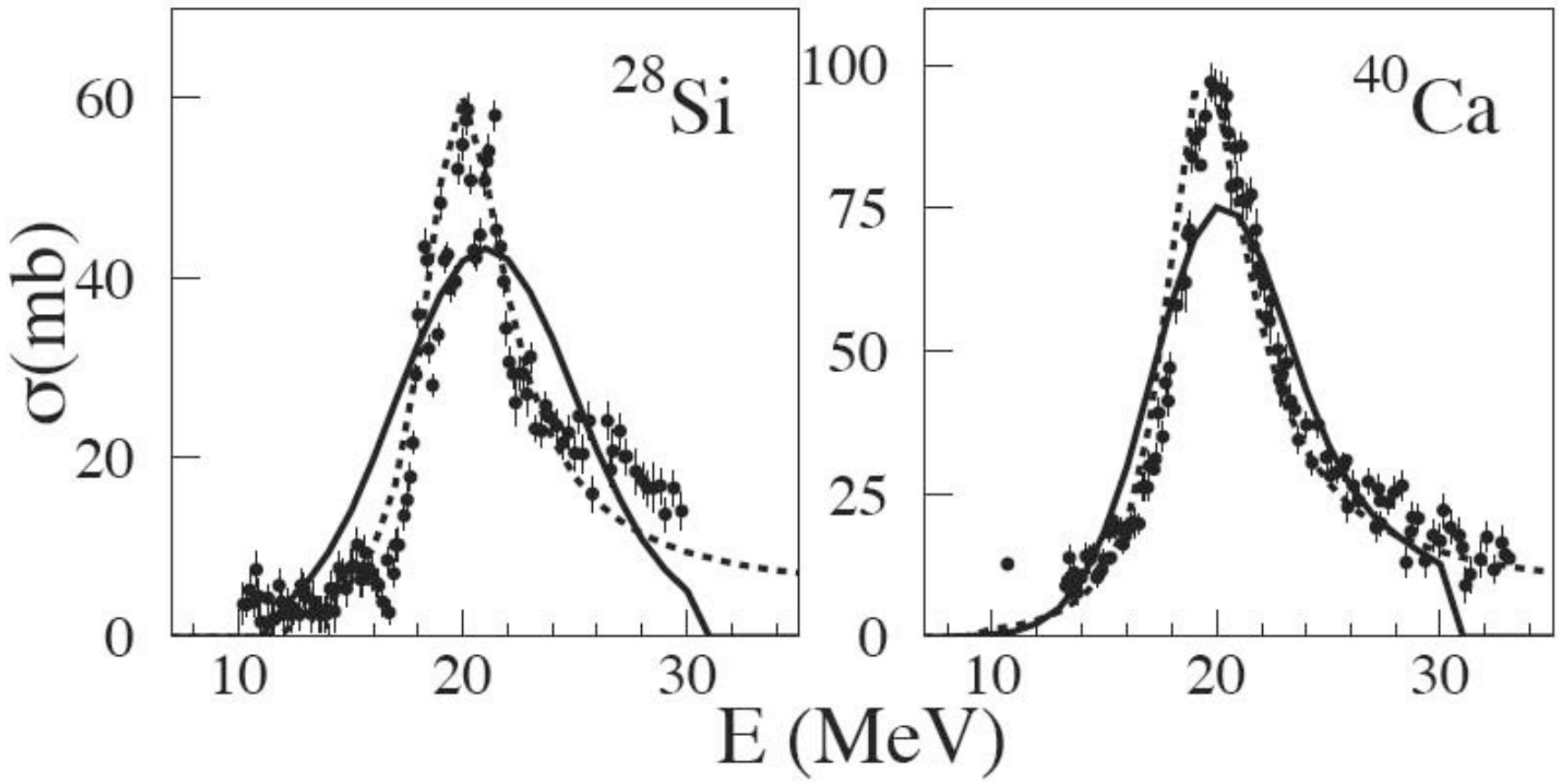
Photo-disintegration of nuclei



2D nuclear scheme



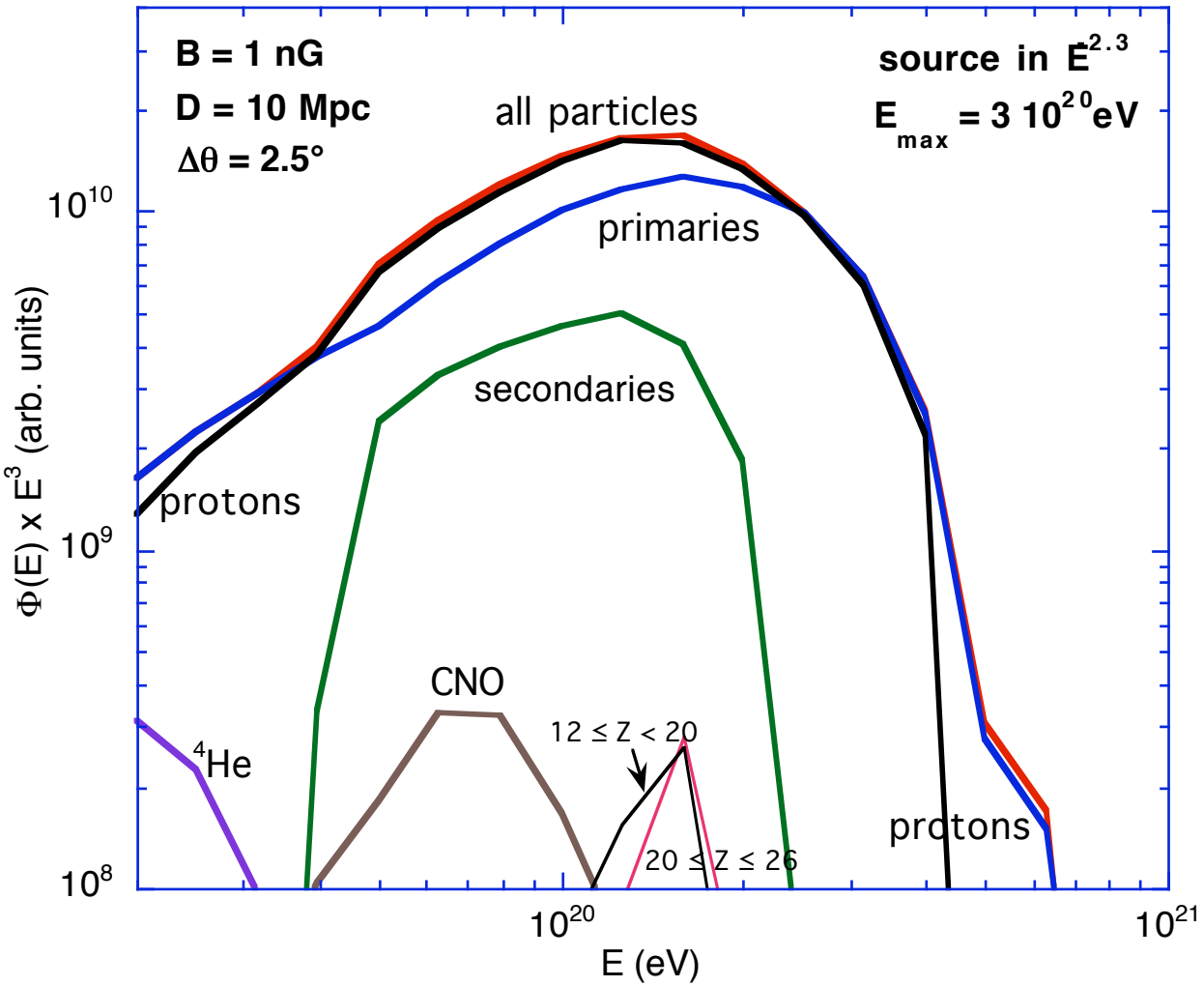
New cross sections



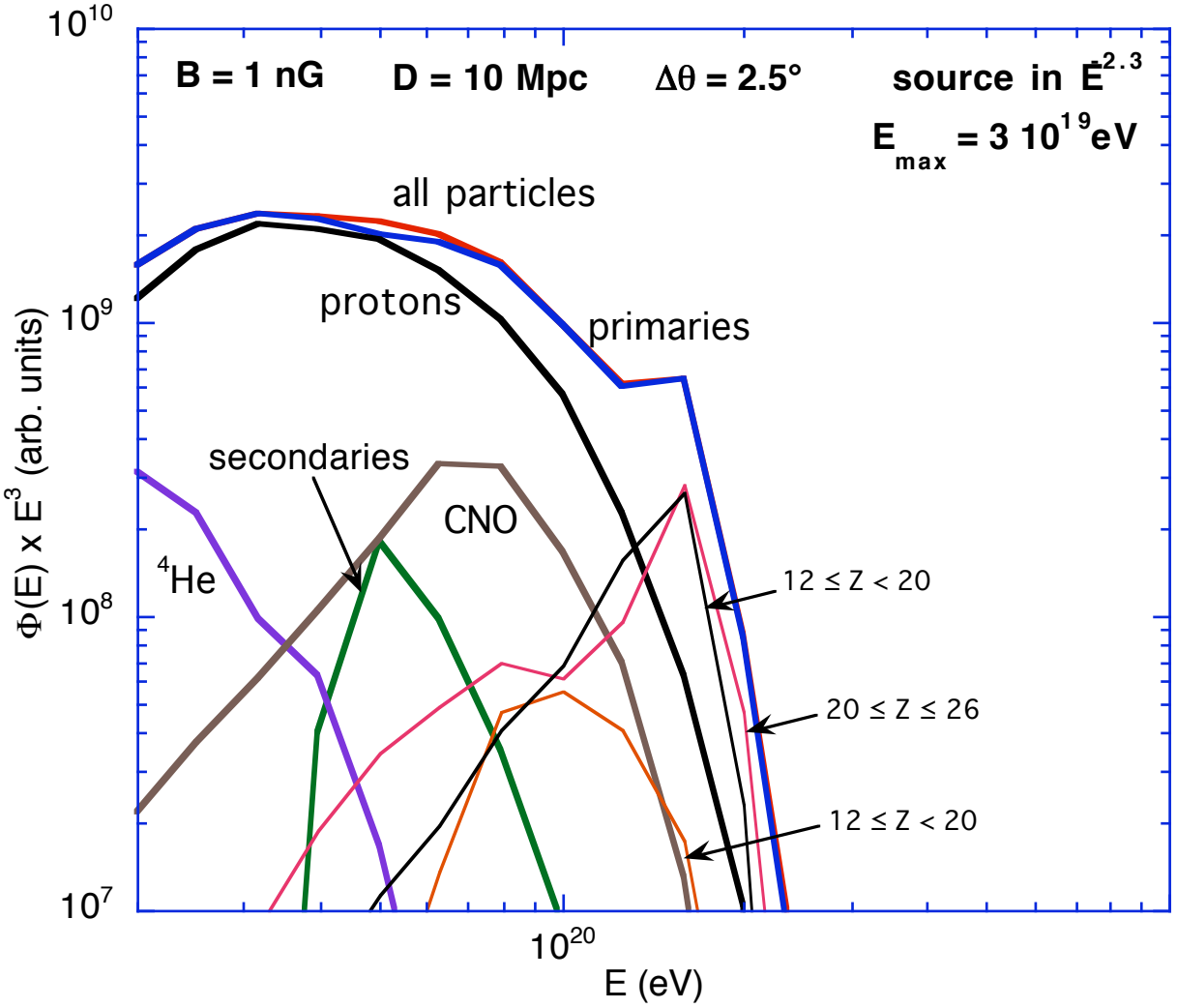
Puget, Stecker, Bredekamp (1976)

Khan et al. (2004)

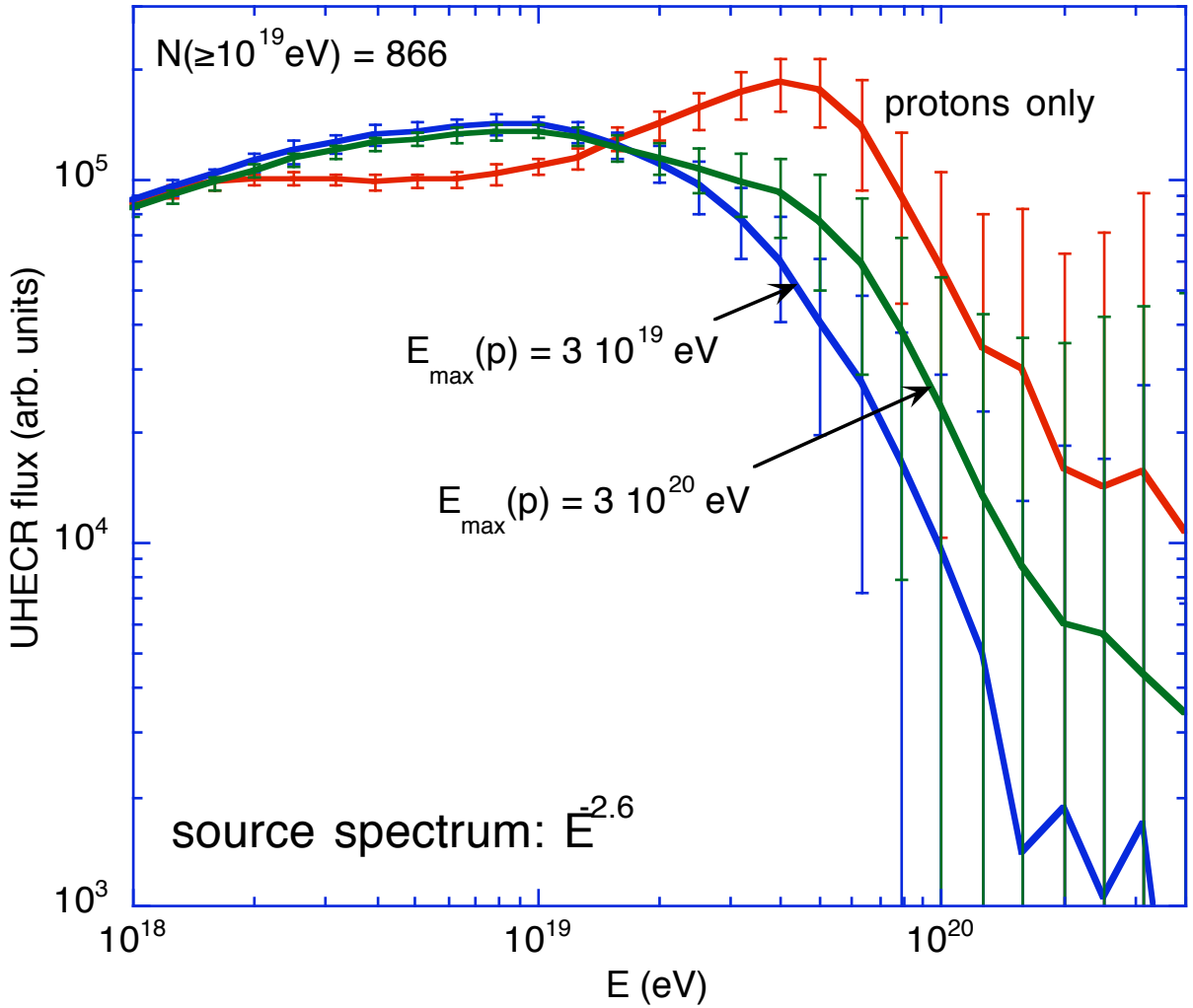
Individual sources



Individual sources

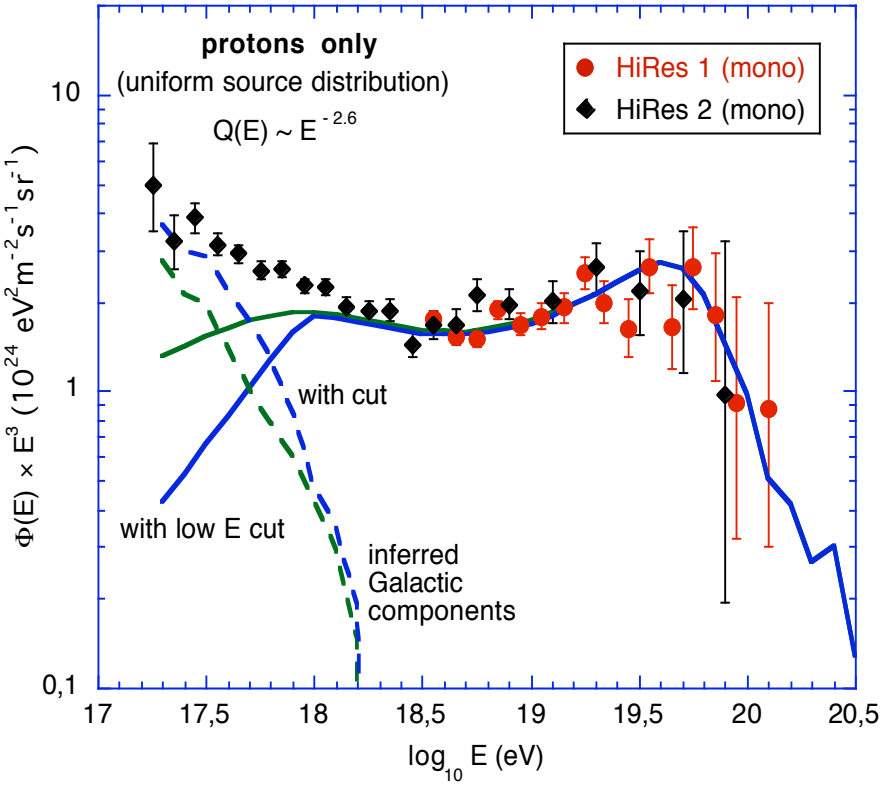


Examples of "propagated" spectra



Are there nuclei among EGCRs?

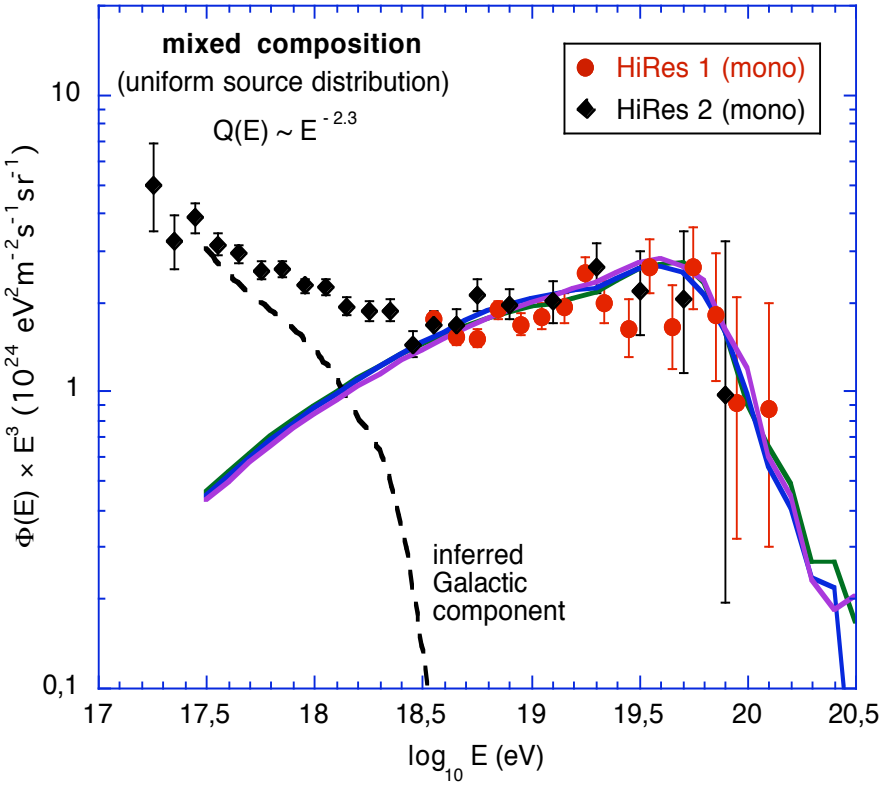
Pure protons (cf. Berezinsky et al.)



Source spectrum in $E^{-2.6}$

Ankle = "pair production dip"

Mixed composition (Allard et al.)



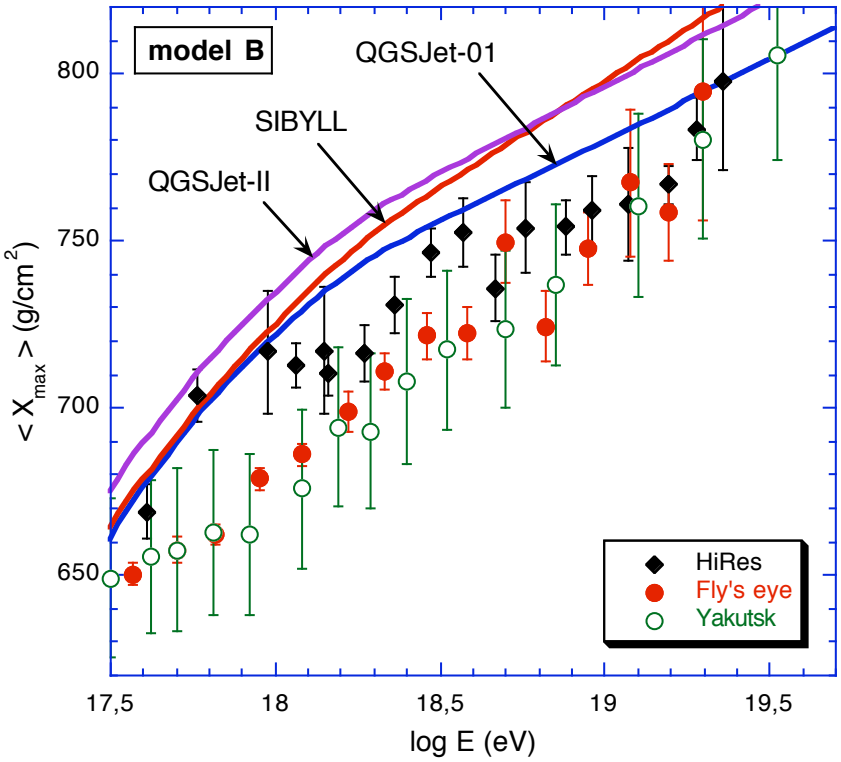
Source spectrum in $E^{-2.3}$

Ankle = gal./extragal. transition

Composition observables

(Galactic/Extragalactic transition)

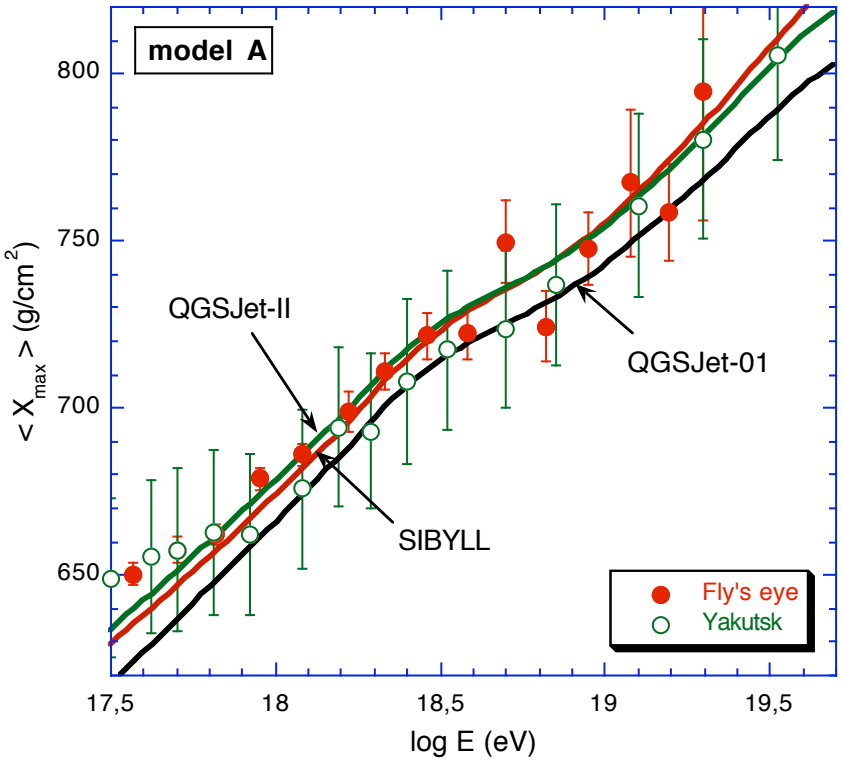
Pure protons (cf. Berezinsky et al.)



Source spectrum in $E^{-2.6}$

Ankle = "pair production dip"

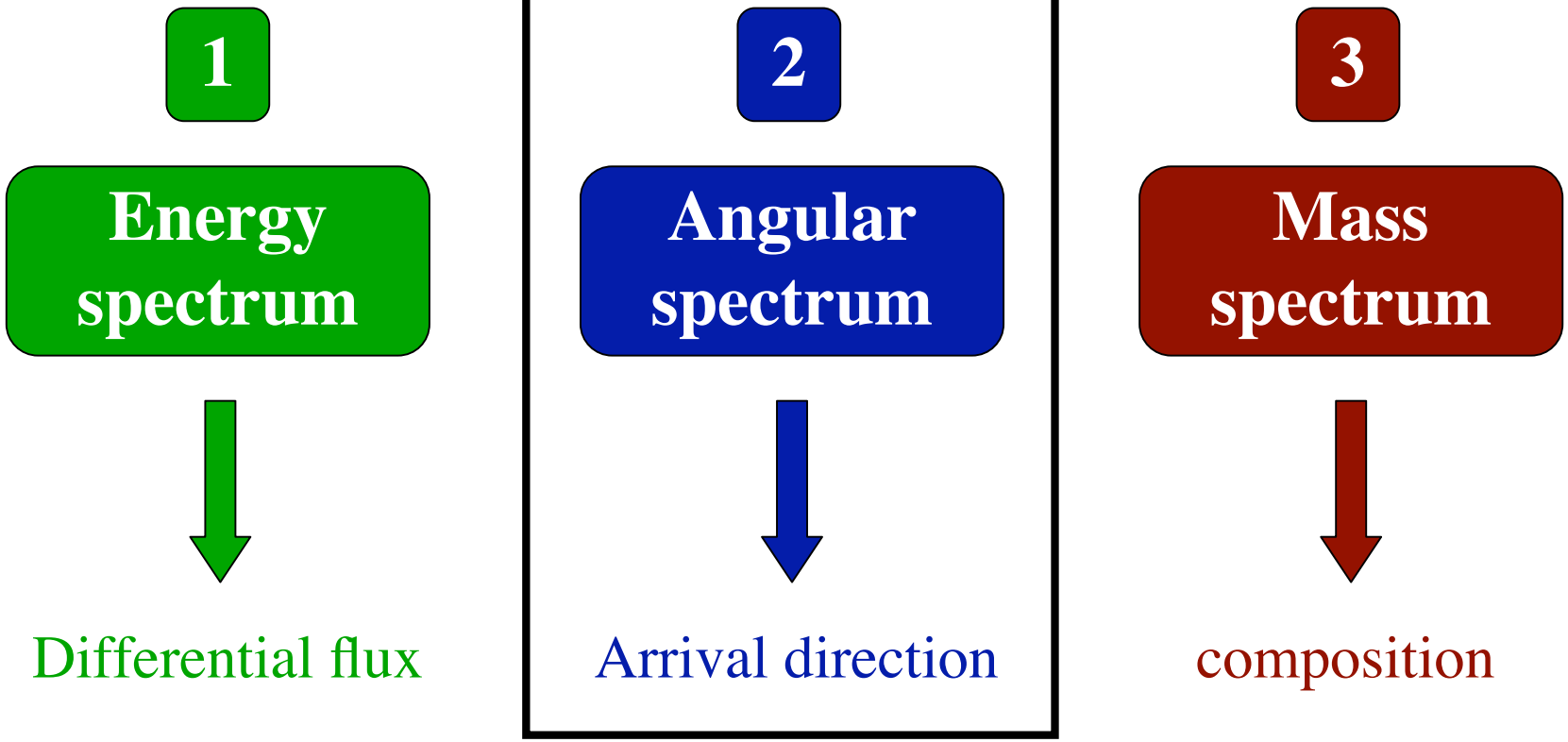
Mixed composition (Allard et al.)

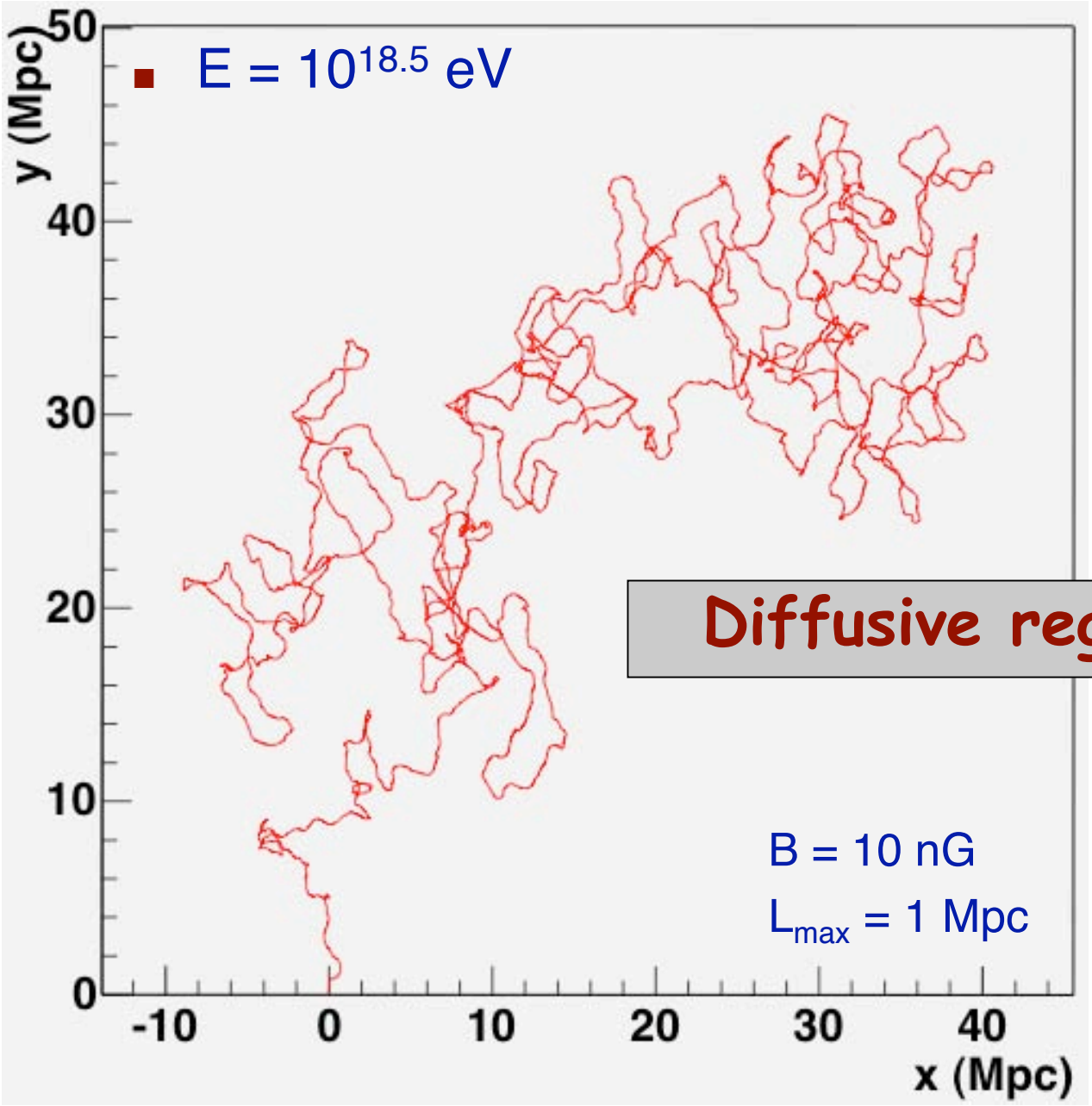


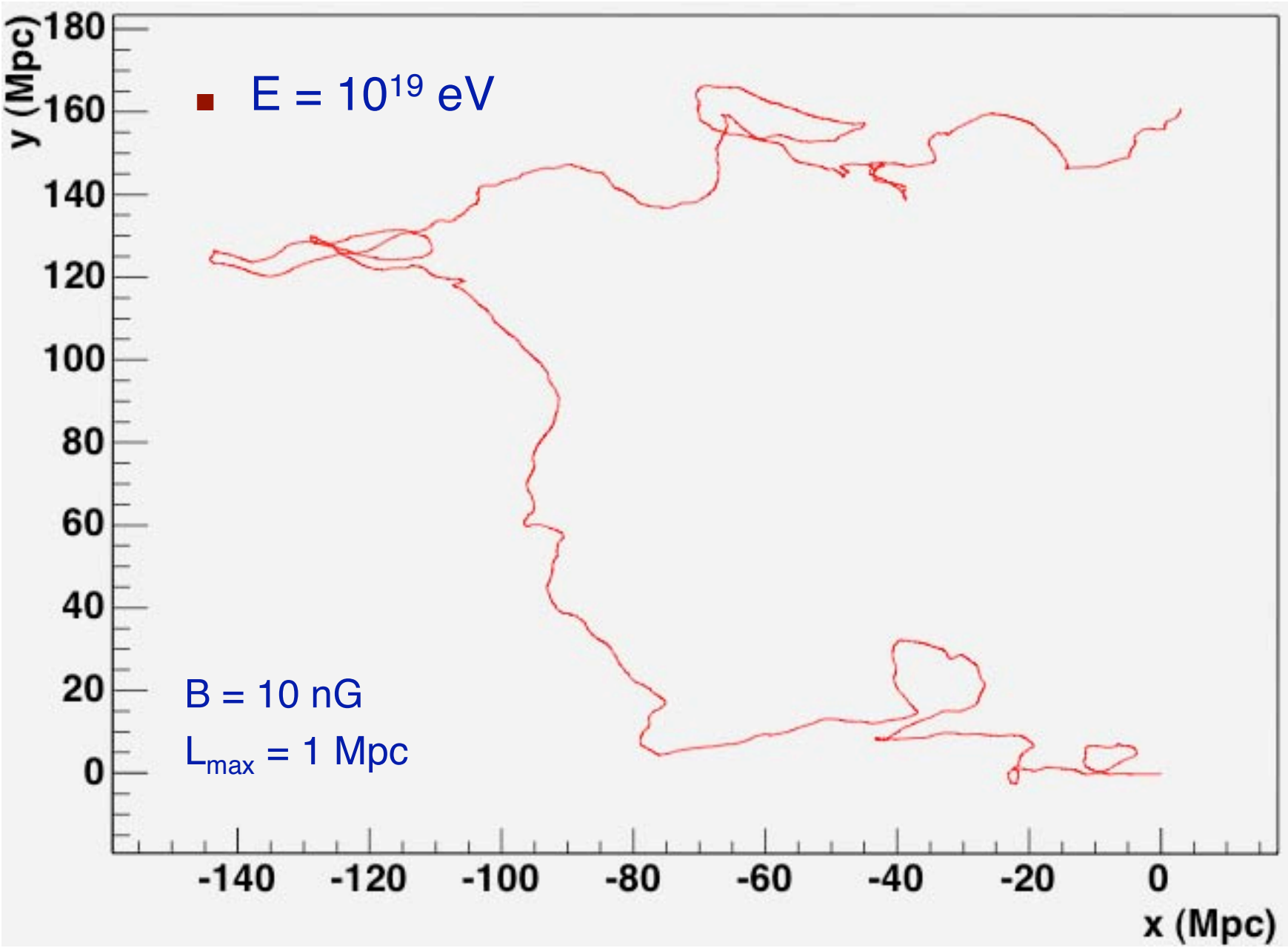
Source spectrum in $E^{-2.3}$

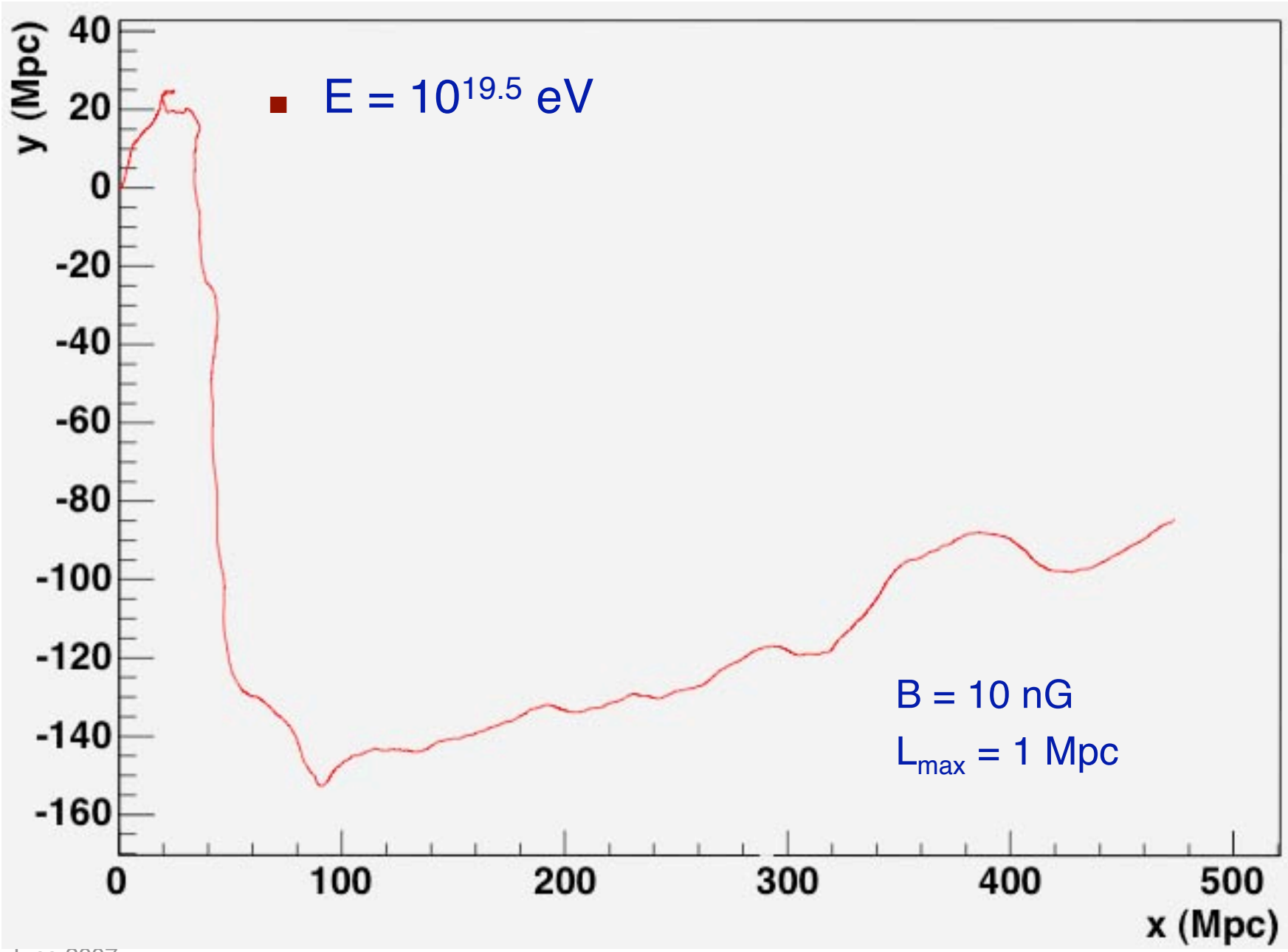
Ankle = Gal./extragal. transition

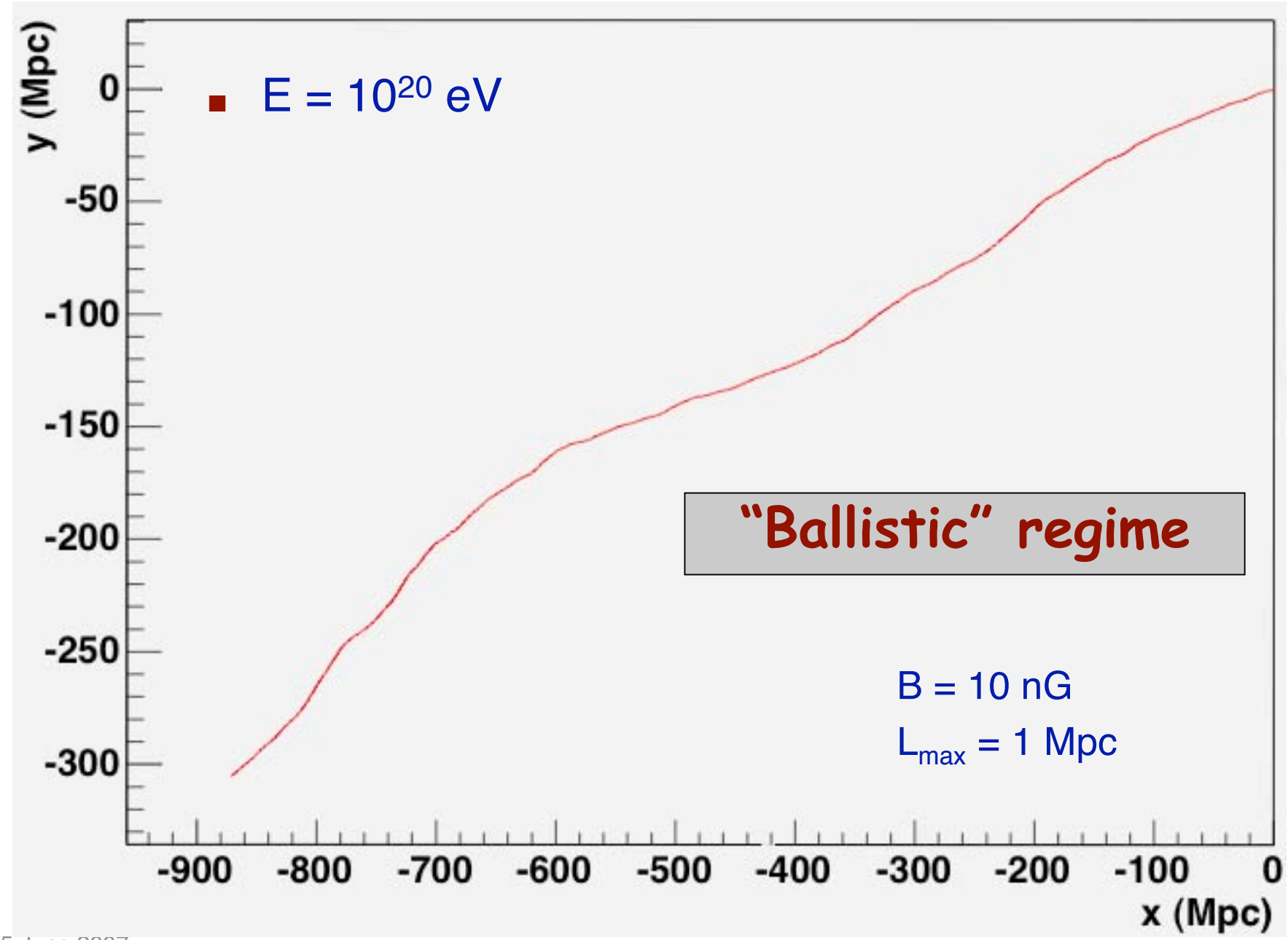
Cosmic-ray primary observables



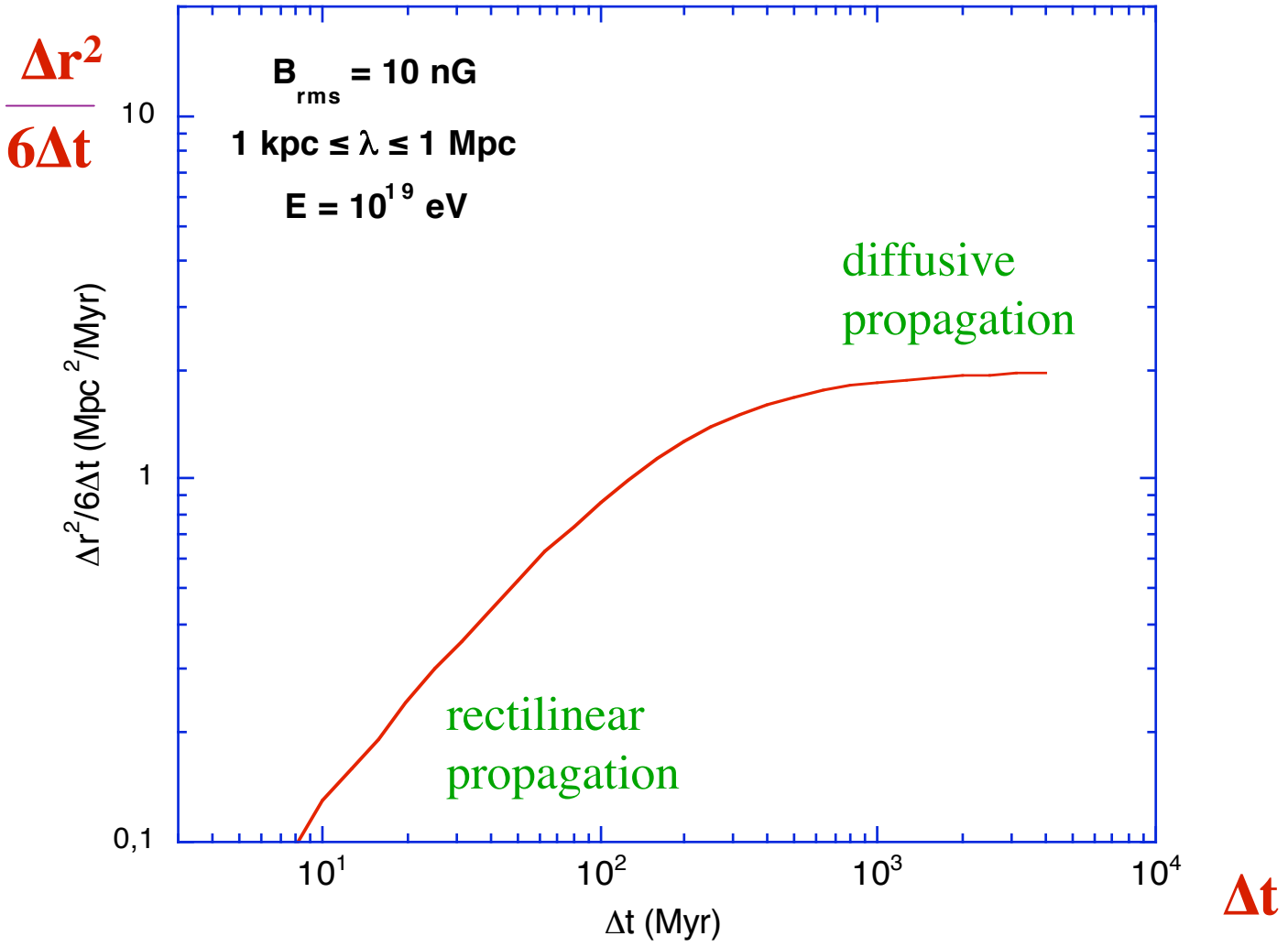

E = 10^18.5 eV
y (Mpc)
50
40
30
20
10
0
-10
0
10
20
30
40
x (Mpc)
Diffusive regime
B = 10 nG
L_max = 1 Mpc


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)

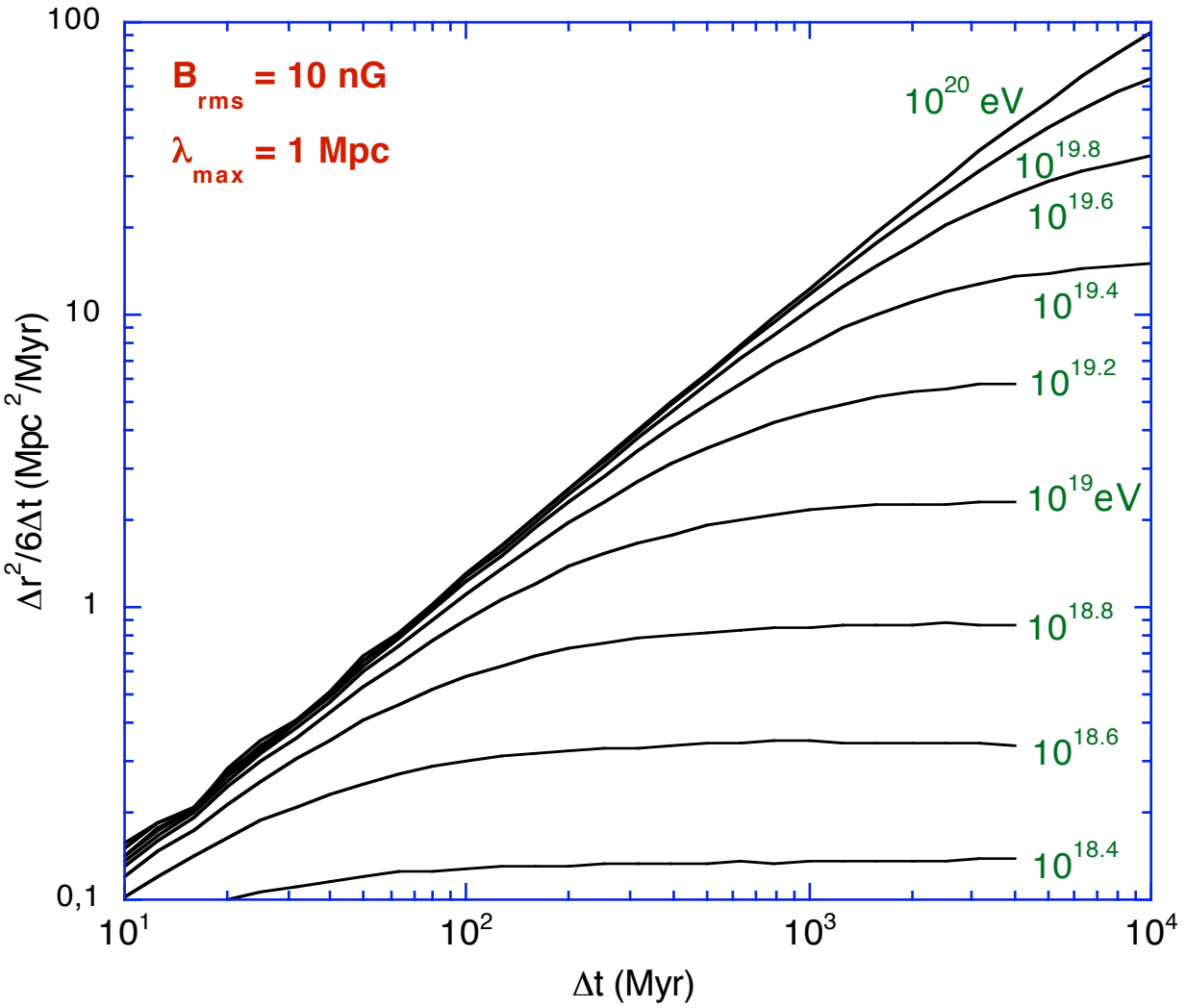

E = 10^19.5 eV
B = 10 nG
L_max = 1 Mpc
y (Mpc)
x (Mpc)
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
0
100
200
300
400
500


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

Reaching the diffusive regime



Reaching the diffusive regime

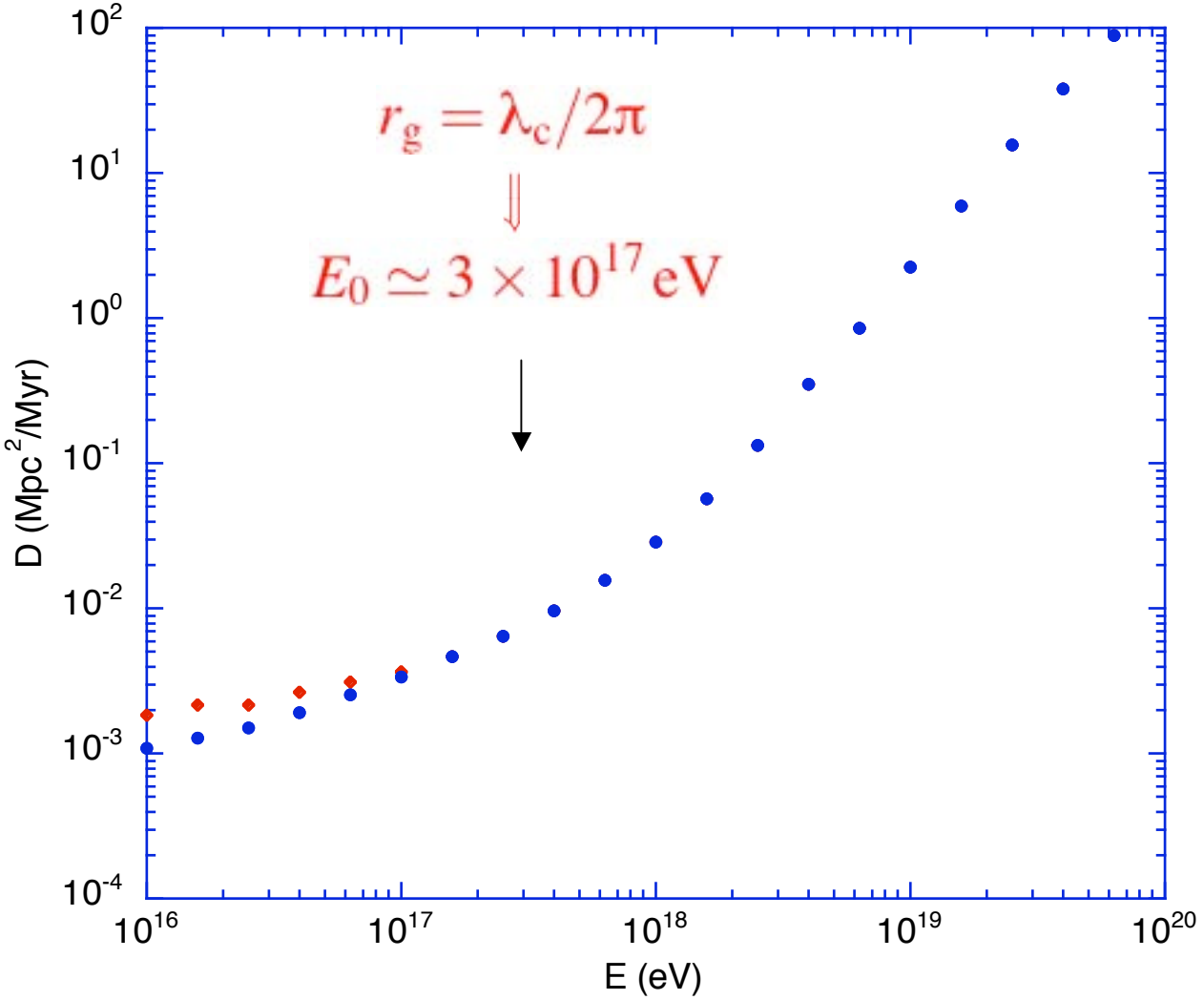


B = 10 nG

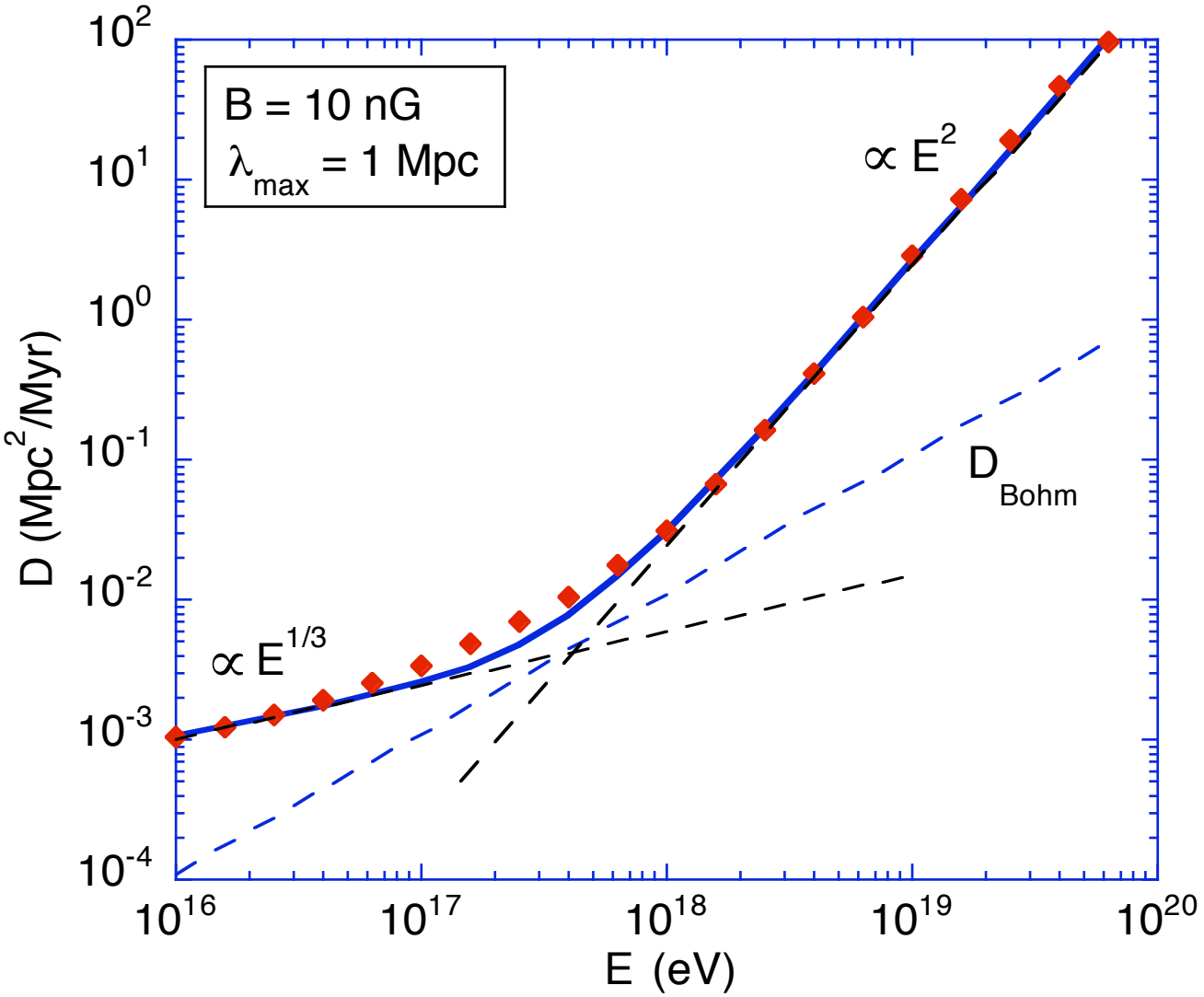
L_{max} = 1 Mpc

D(E)

Diffusion coefficient



D(E)


B = 10 nG
λmax = 1 Mpc
∝ E2
∝ E1/3
DBohm
D (Mpc2/Myr)
E (eV)
10-4
10-3
10-2
10-1
100
101
102
1016
1017
1018
1019
1020

Angular effects of B

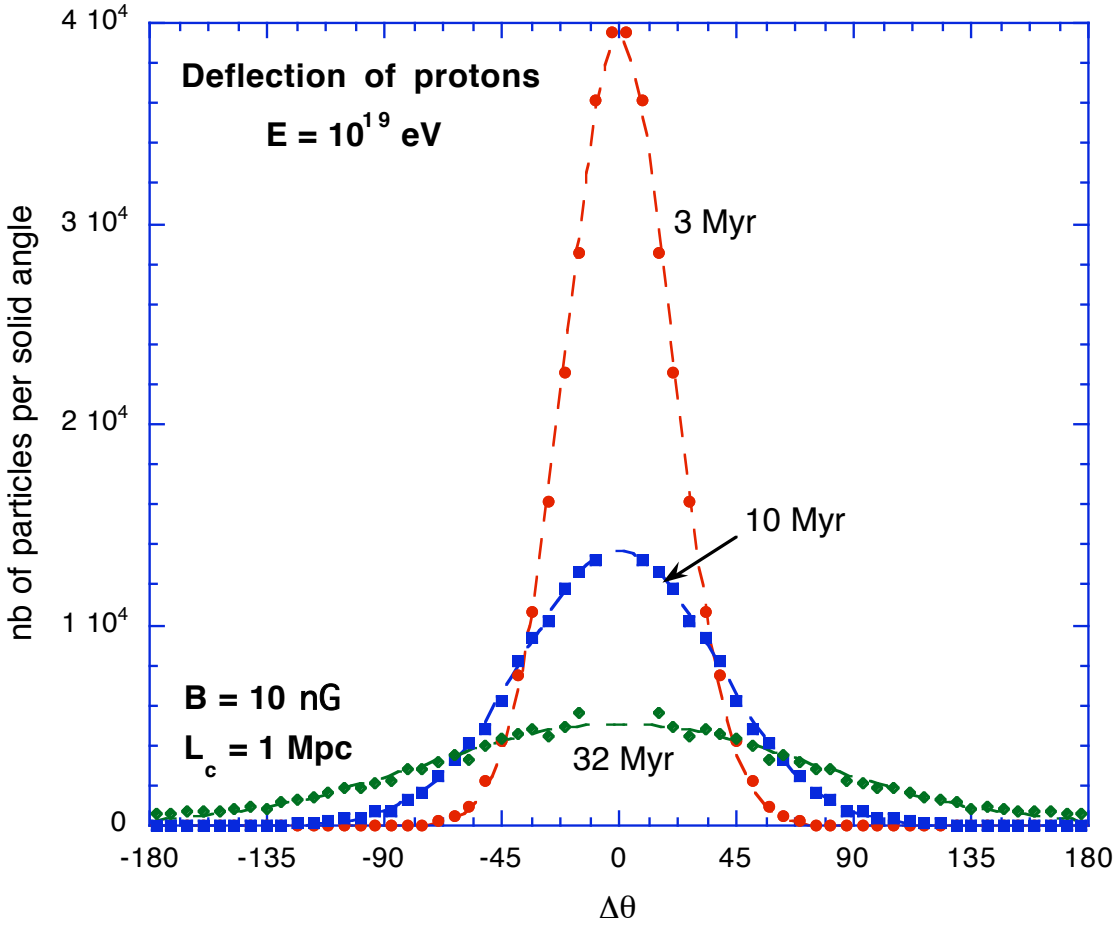
- deflection

- angular diffusion

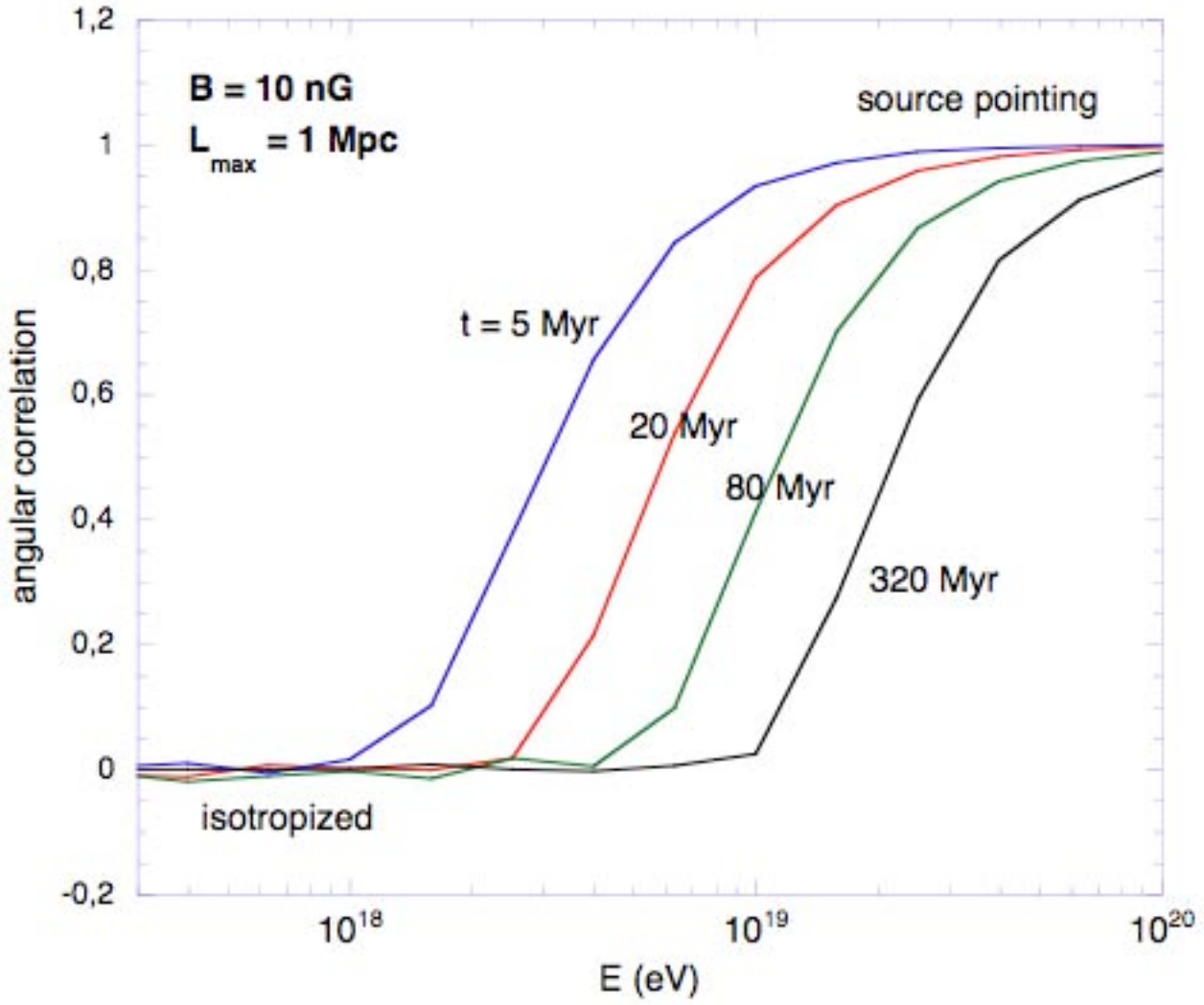
- isotropization

- diffusion in space

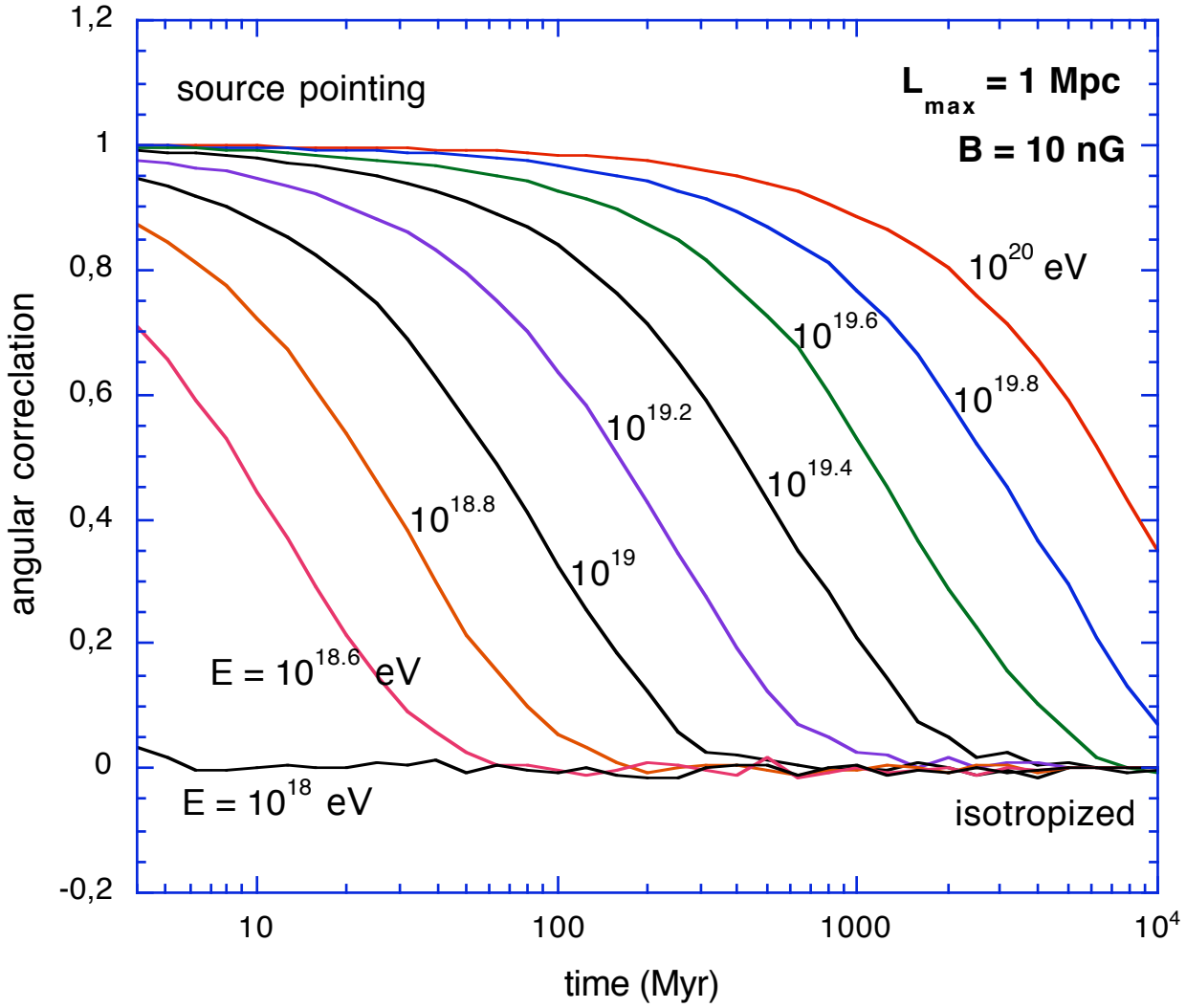
Angular diffusion



Angular de-correlation

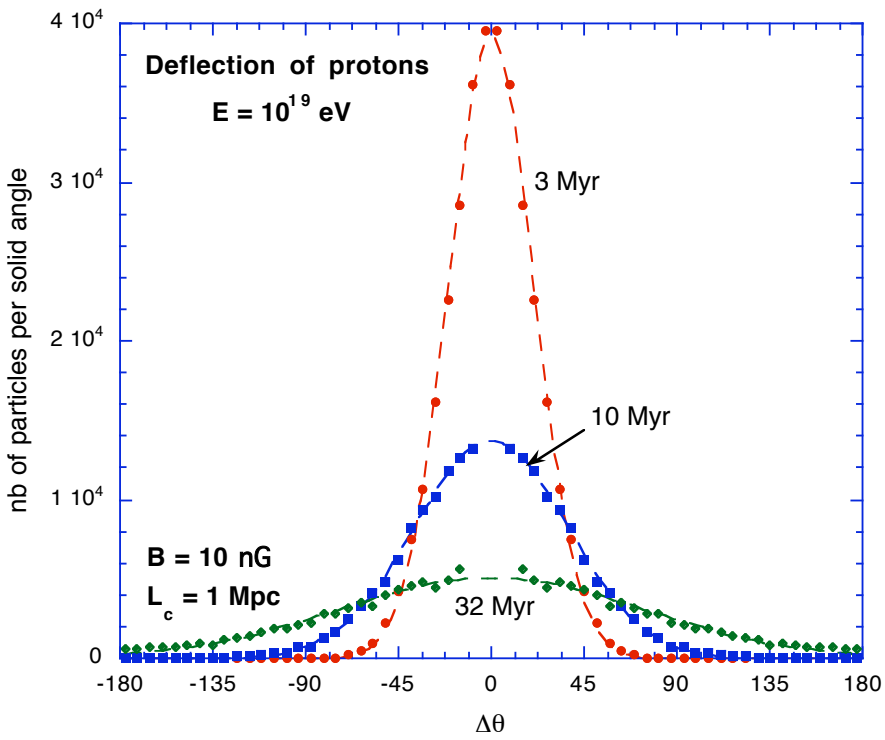


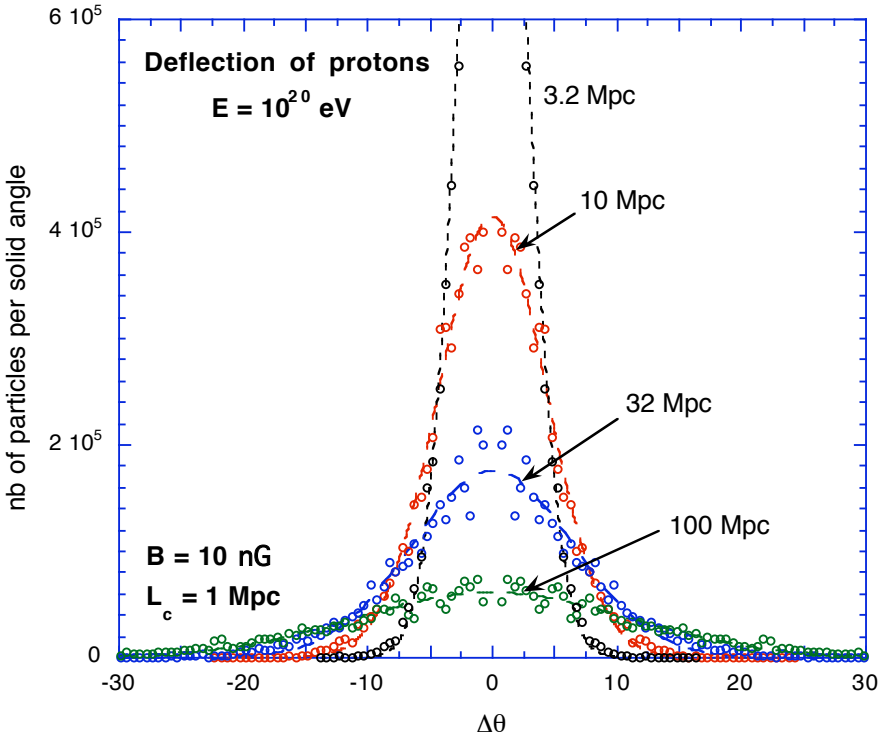
Angular de-correlation



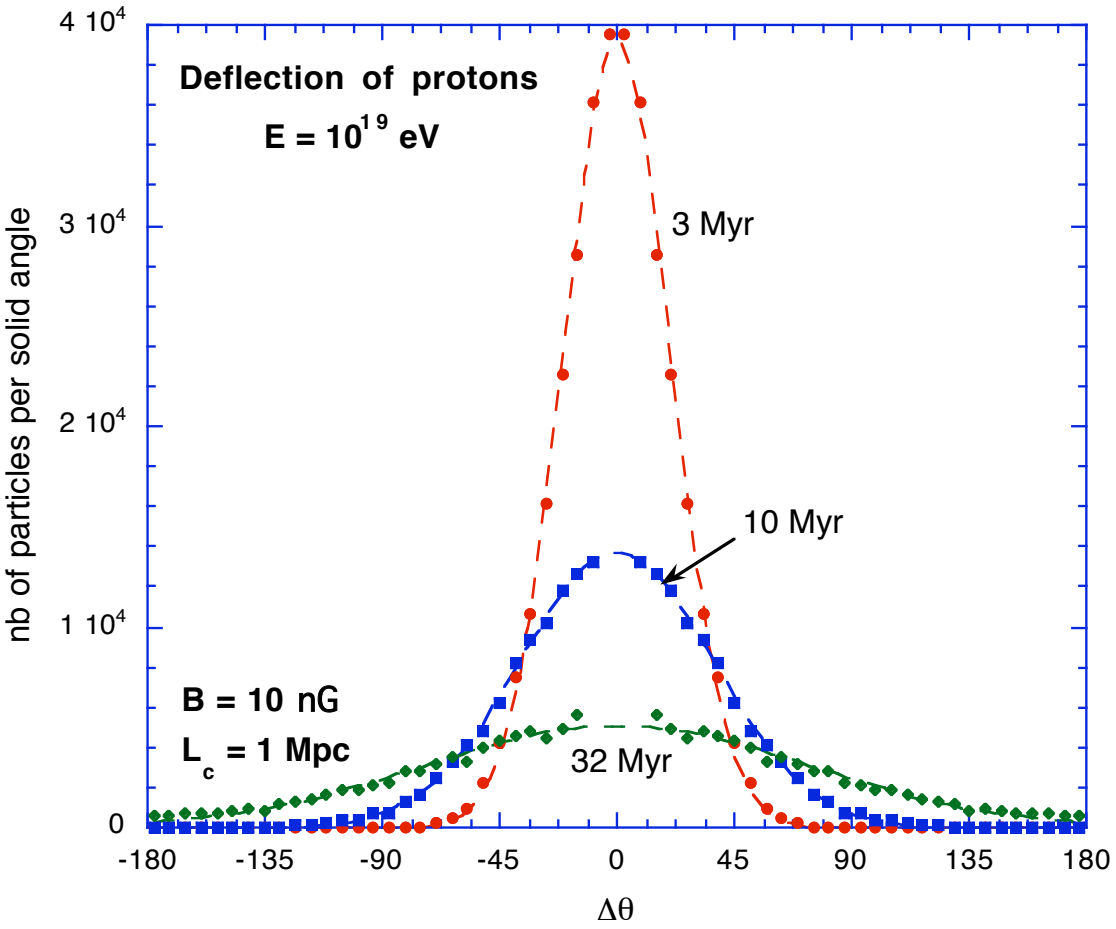
Angular diffusion regime

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





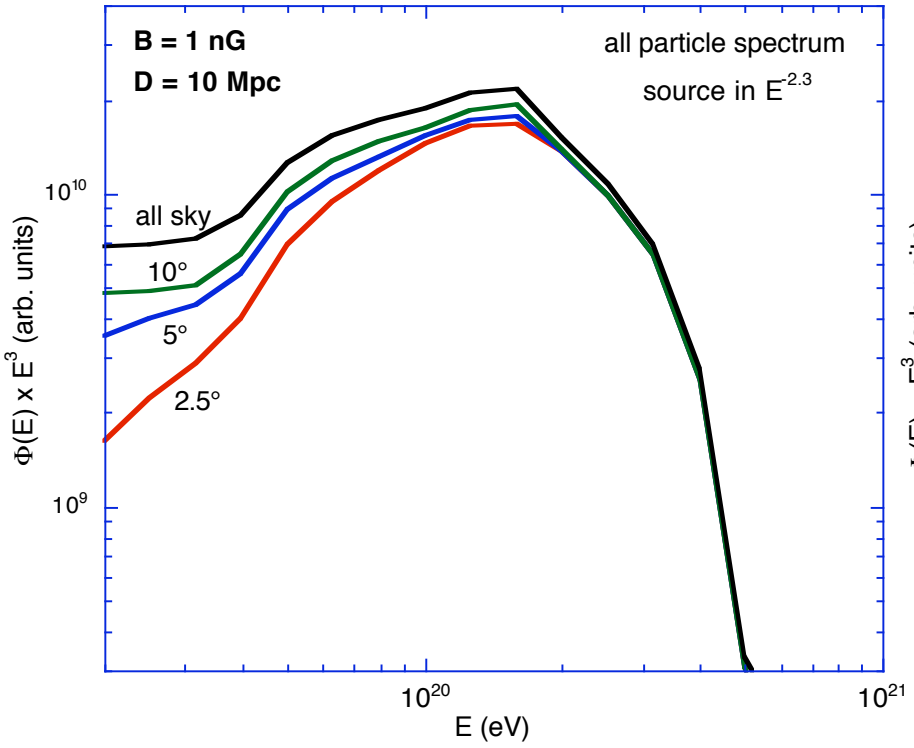
High-pass filter effect



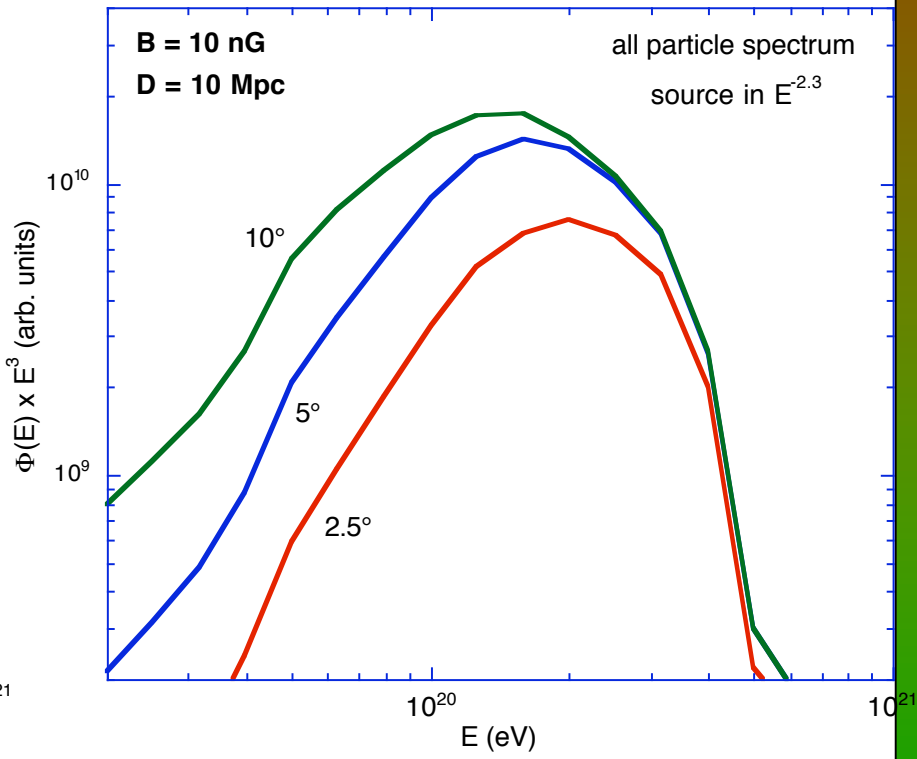
- High energies are less spread out
- Nearby sources are less spread out
- Different spectra are to be expected

Individual sources

Weak field

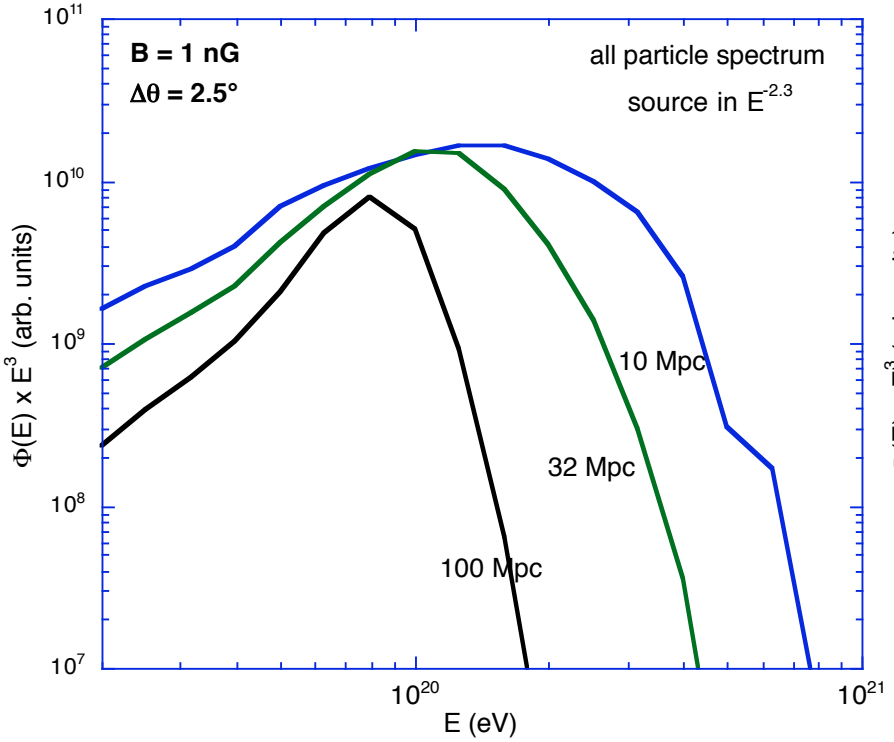


Strong field

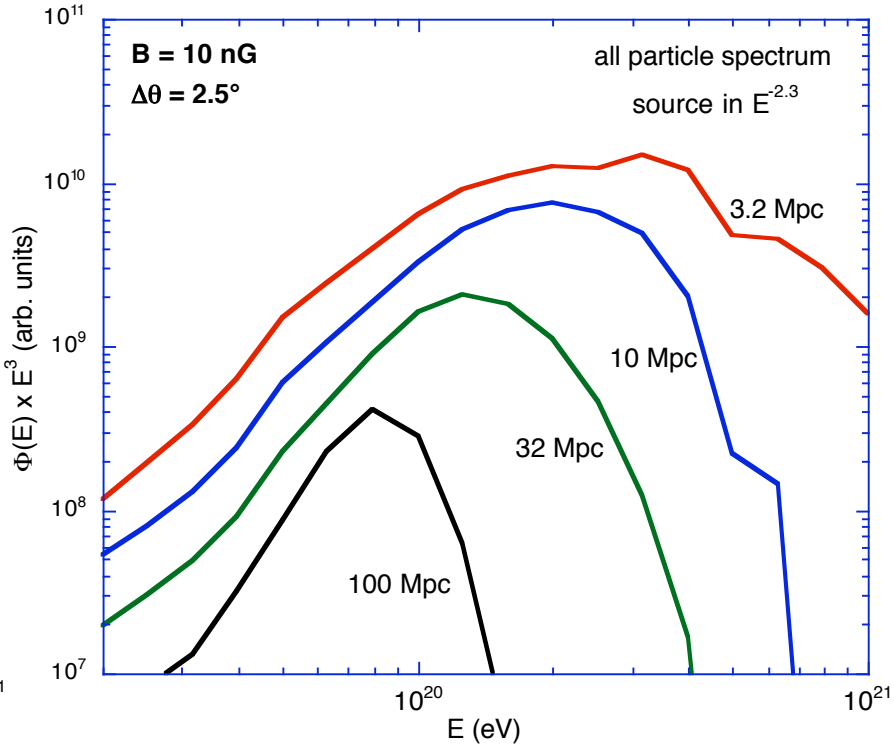


Individual sources

Spectrum of particles within 2.5° of a cluster



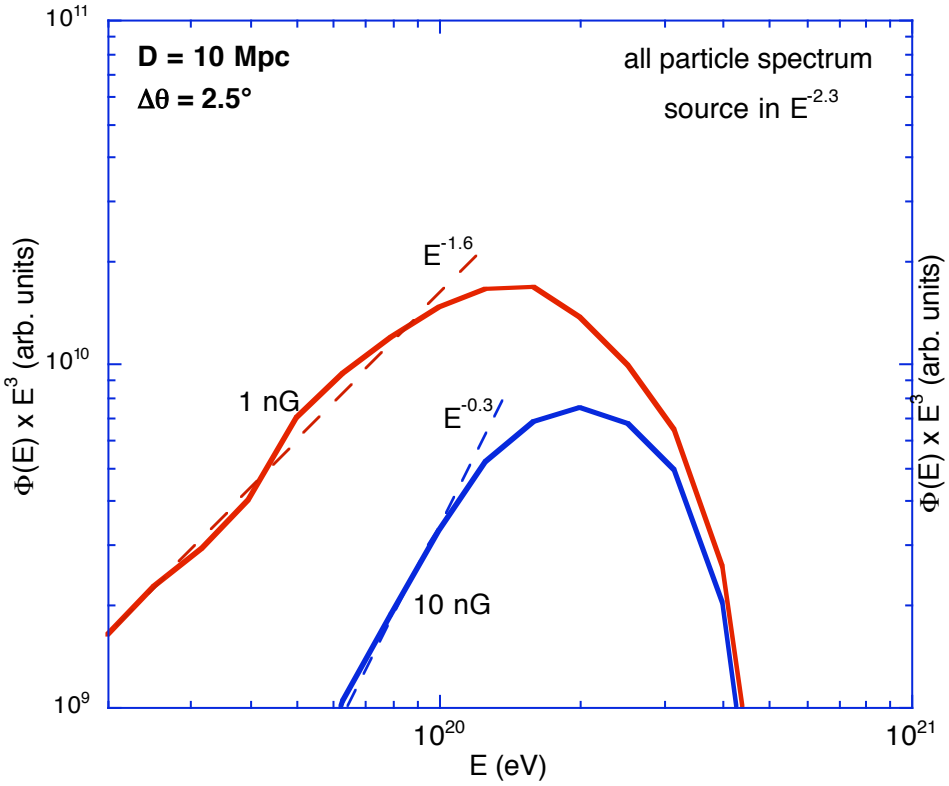
Weak field



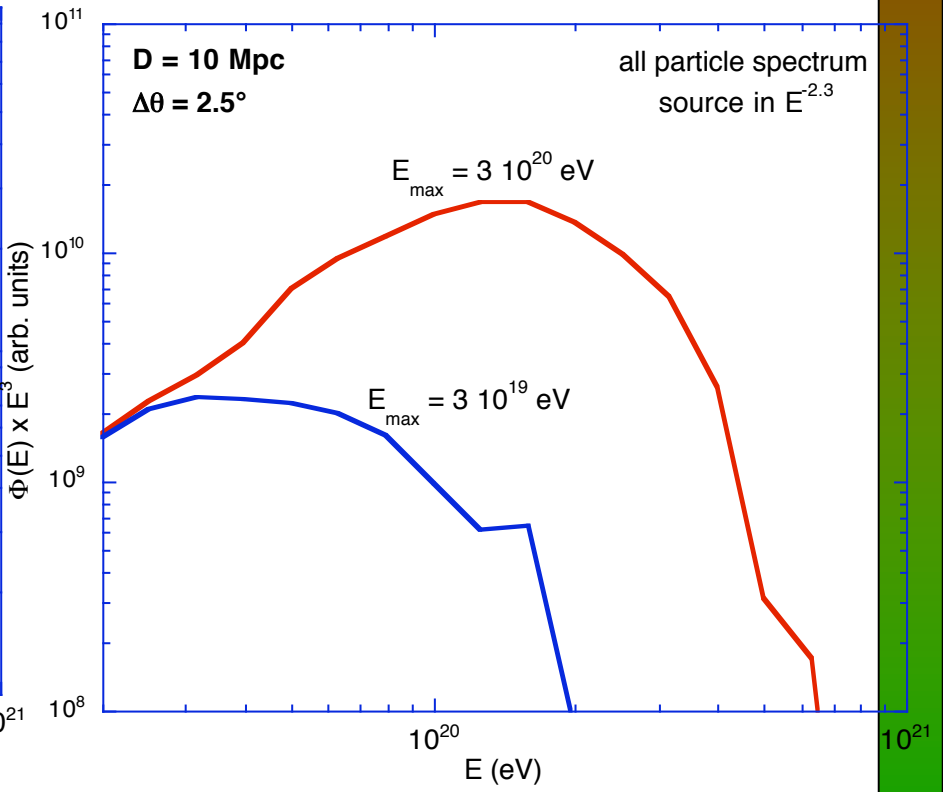
Strong field

Individual sources

Measure of the magnetic field?



Source maximum energy…



Auger: déjà des résultats majeurs !

5165 km^2 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

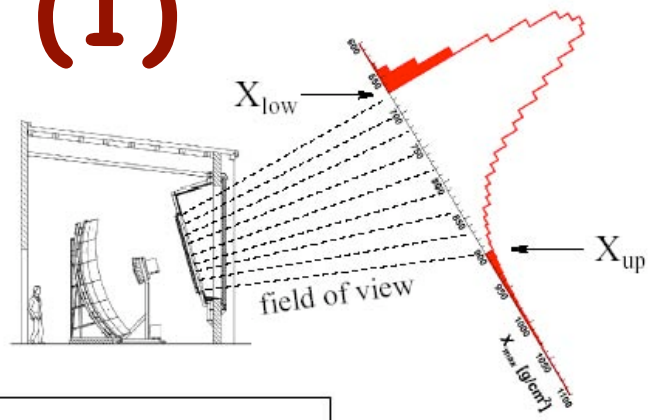
La distribution angulaire des RC à très haute est-elle toujours isotrope ?

L'astronomie proton est-elle à notre portée ?

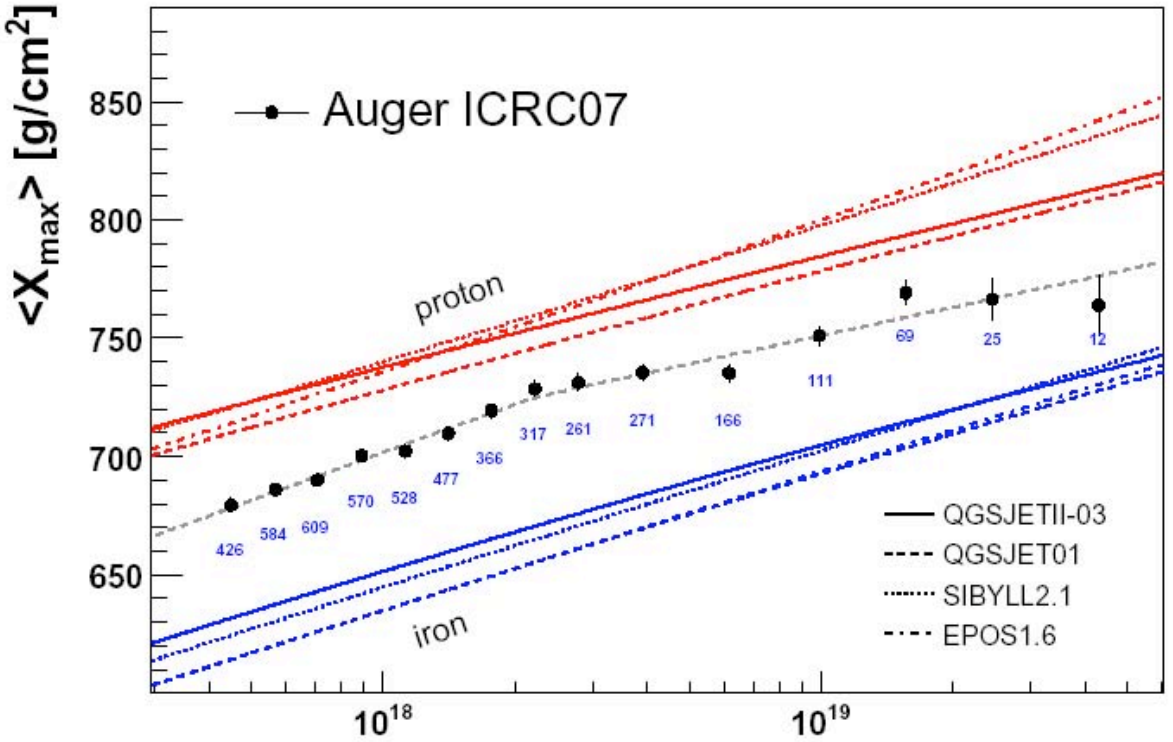
Composition (1)

Apparemment…

Présence de noyaux !



Profondeur de pénétration



énergie

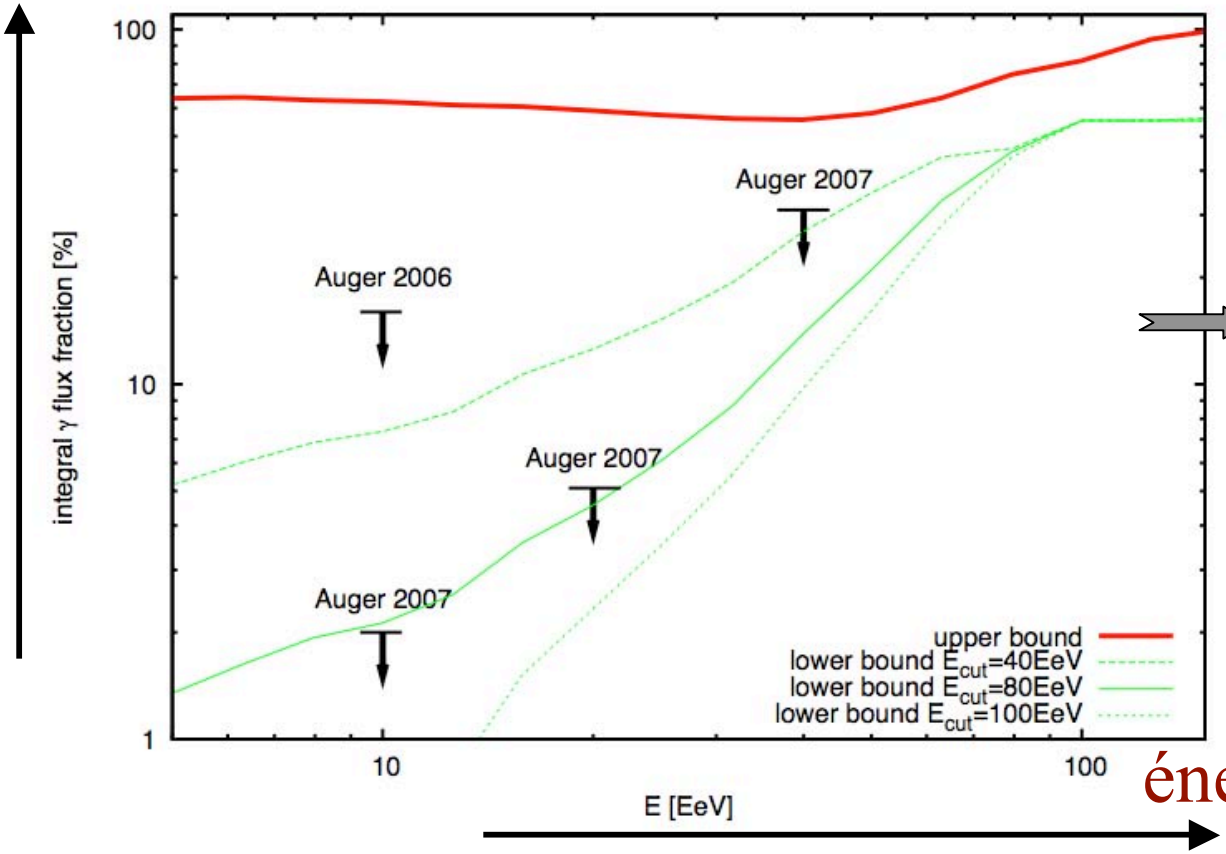
Composition (2)

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

+

Les gerbes induites par des photons sont très spécifiques…

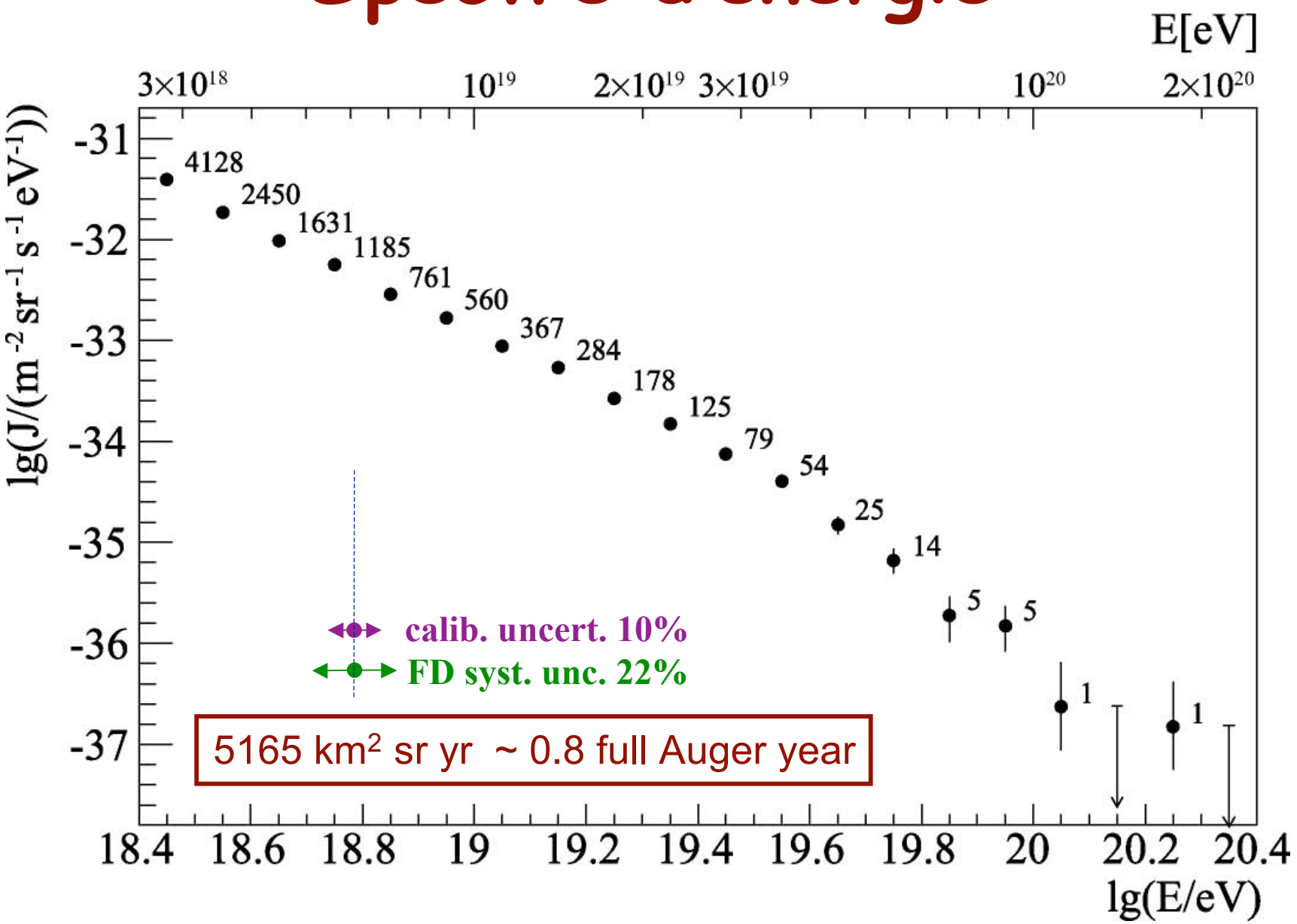
fraction de photons



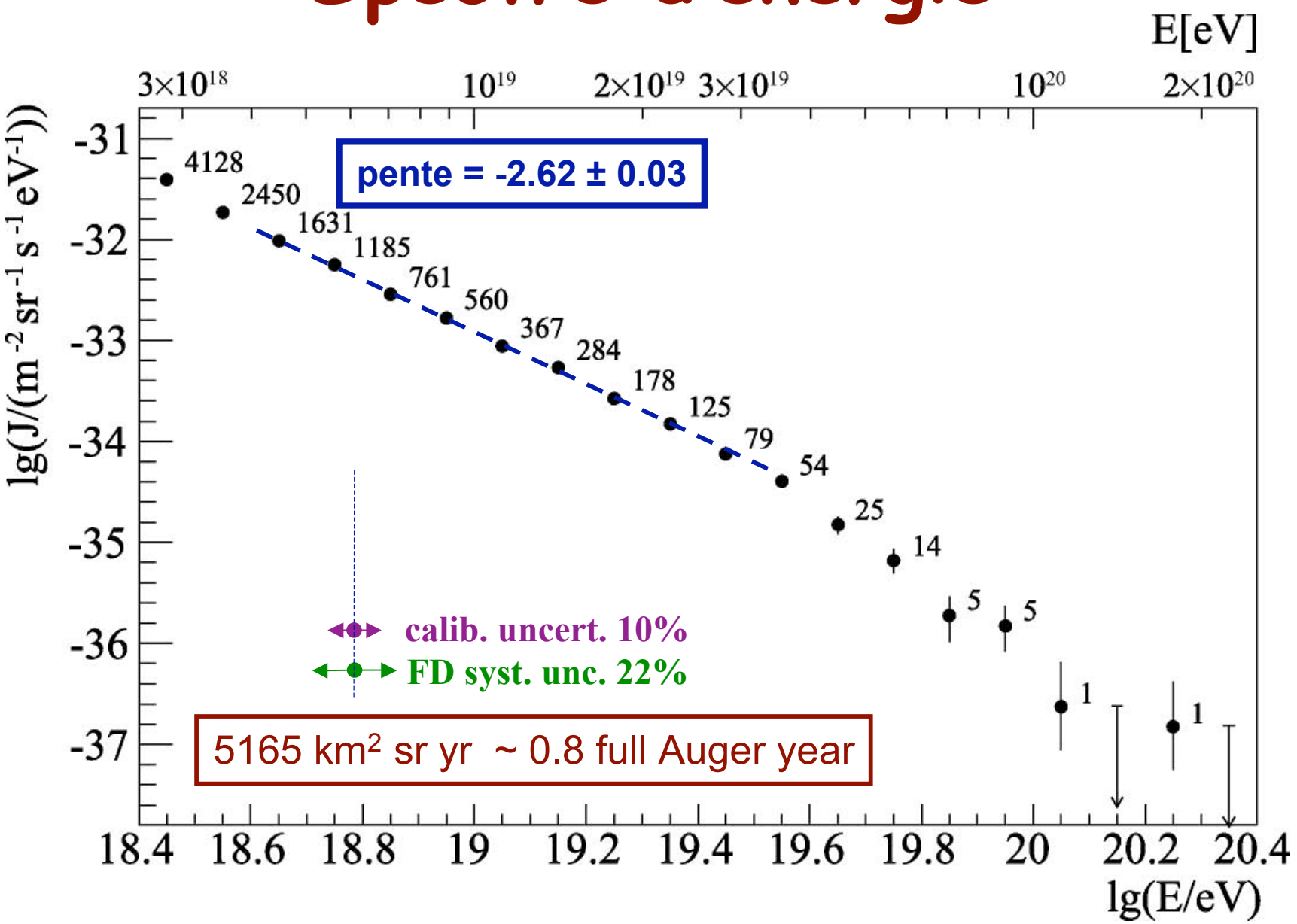
énergie

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

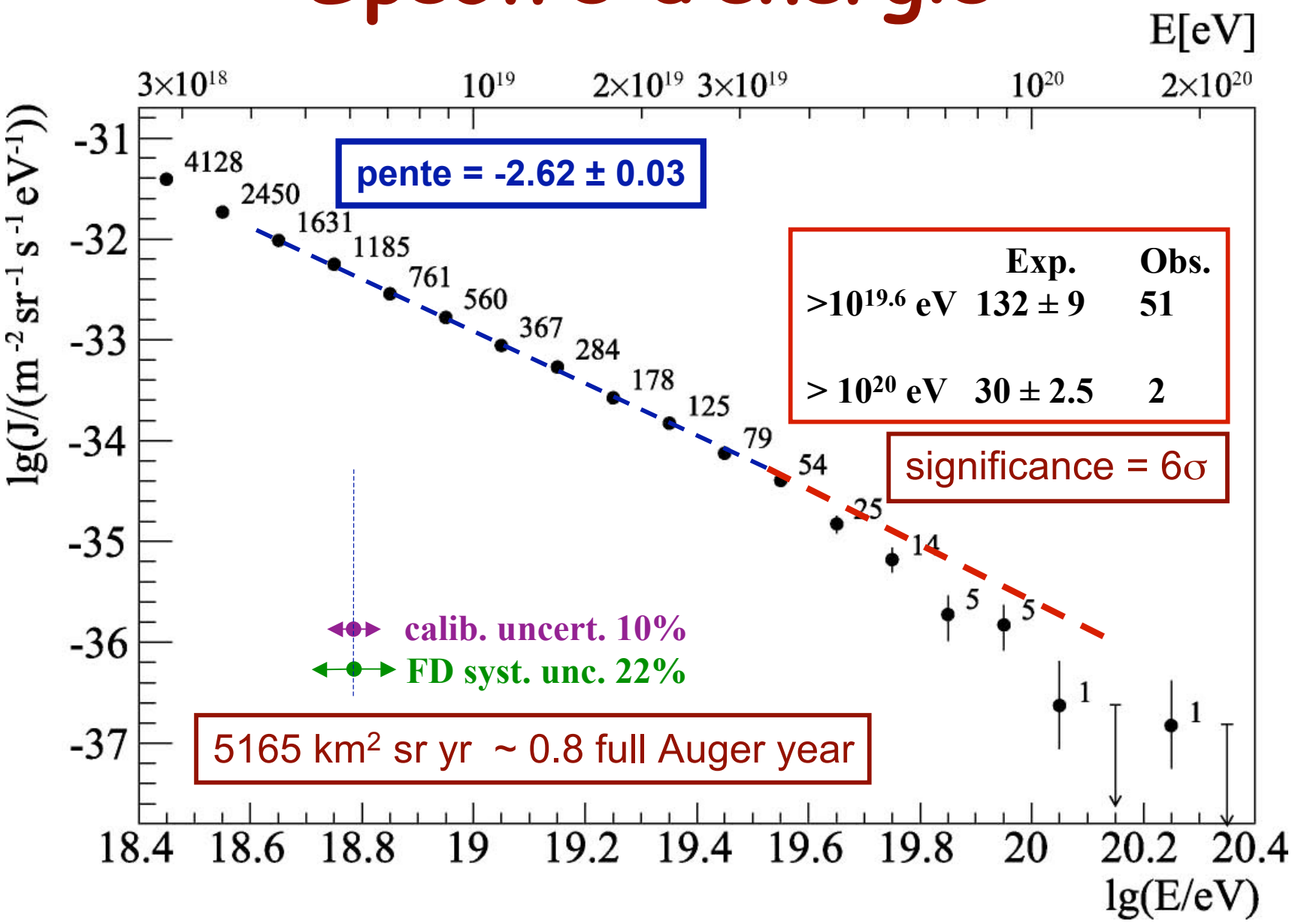
Spectre d'énergie



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

- Une série d'articles est en cours de finition
(merci d'attendre un peu pour les détails ;-))

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 !

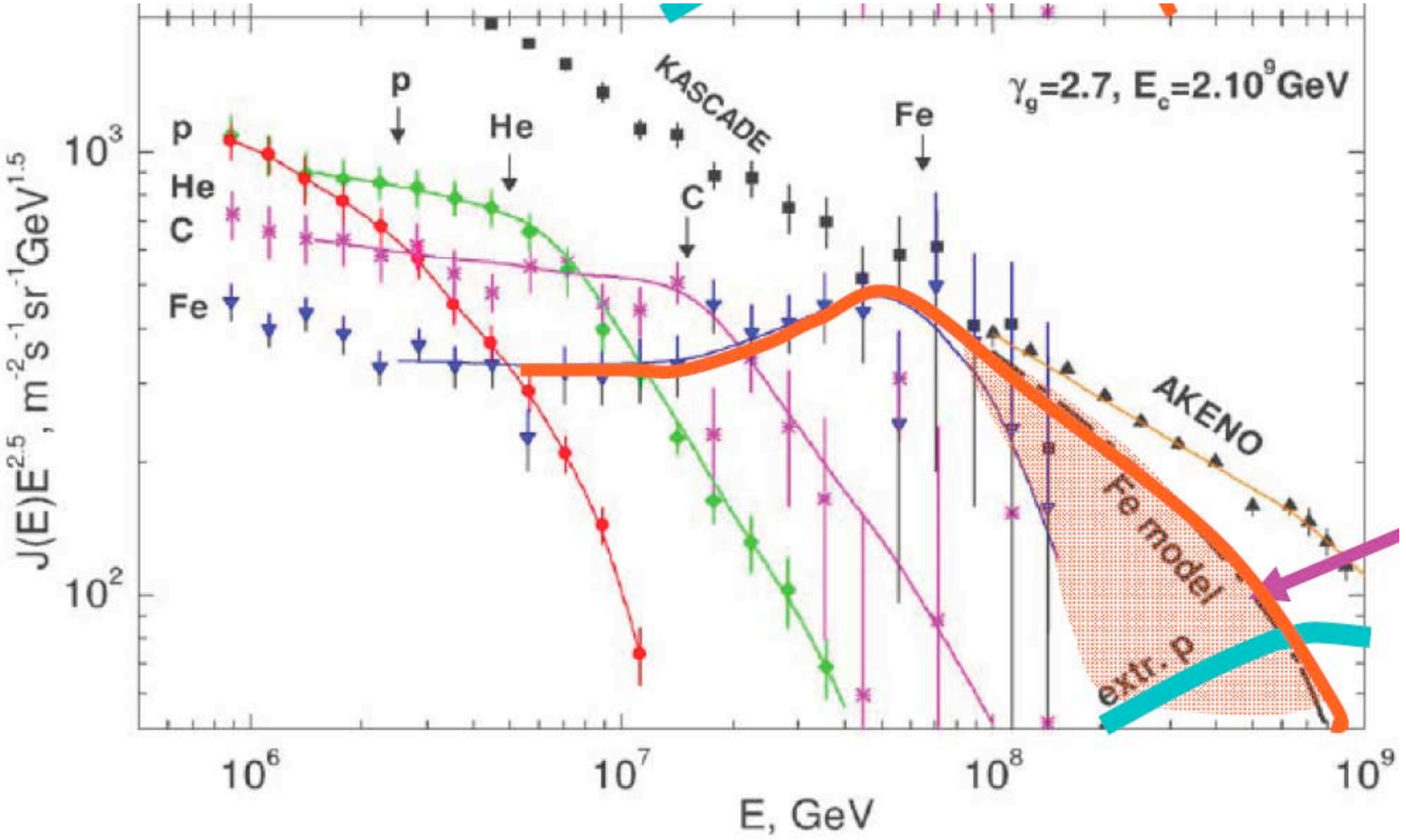
À propos du genou…

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

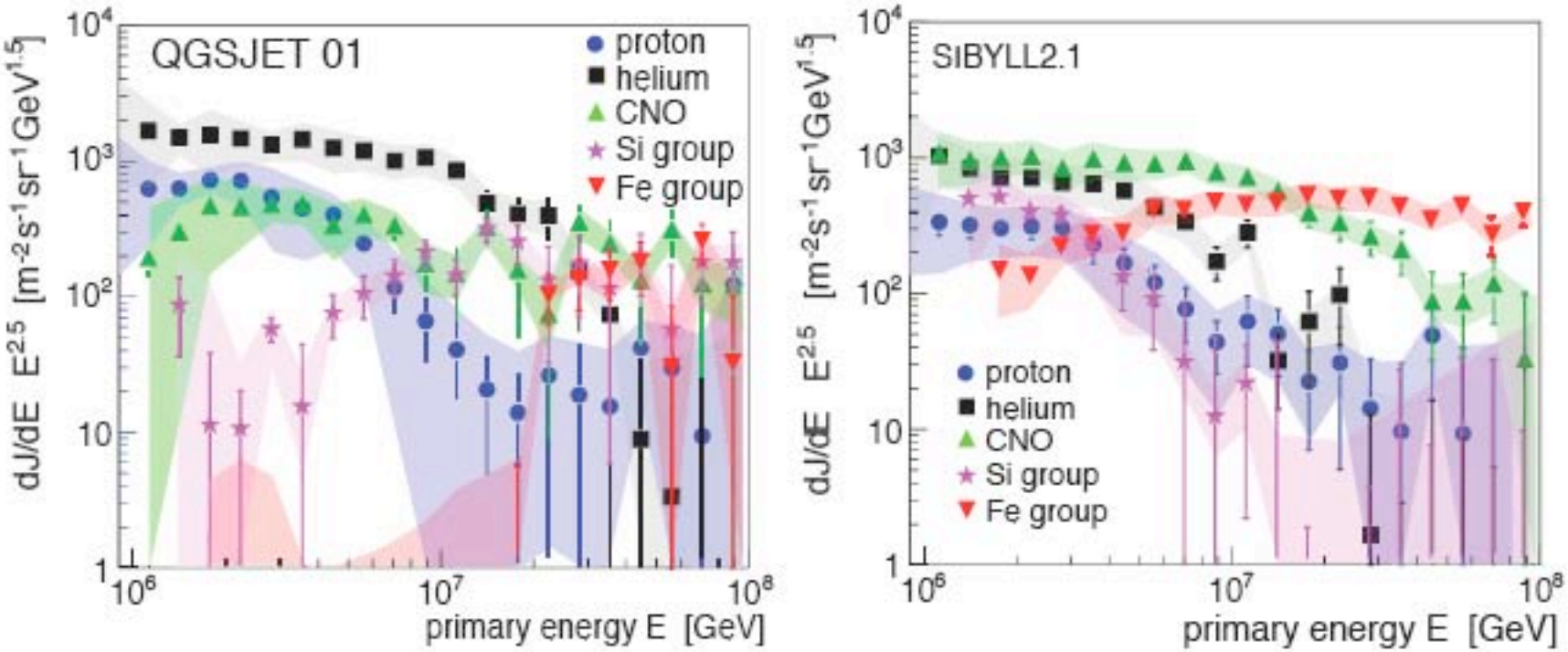


Fig. 7. Energy spectra for elemental groups as obtained by the KASCADE experiment, using two different models (QGSJET 01 and SIBYLL 2.1) to interpret hadronic interactions in the atmosphere [54].

from Hörandel (astro-ph/0611387)

Merci !