Energy spectrum and composition constraints on the transition from Galactic to extragalactic cosmic rays

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Based on:

Particle acceleration in GRBs: astro-ph/1409.1271 (MNRAS)
GCRs/UHECRs interplay, GCR/EGCR transition: astro-ph/1410.2655
Generic model of GCR/EGCR transition: 1505.01377 (Phys. Rev. D)

I- A working UHECR model

- ✓ i.e.: it accounts for the known phenomenology and reproduces the current data

→ its main features may be considered plausible, even though the underlying model and assumed UHECR sources may be wrong…

Particle acceleration in GRBs

- Internal shock model for the so-called prompt γ-ray emission of the GRBs
  - NB: not a fully successful model (none is!), but remains a viable scheme, of which we use only some general characteristics of the internal shocks
- Shock acceleration: consistent Monte-Carlo simulation, but requires some assumption about the ambient magnetic field
  - Diffusion of particles across the shock in "permanent" magnetic field (NB: requires rapid growth of turbulent modes, which is uncertain)
  - Includes particle escape
- Interaction of UHECRs during the acceleration itself

→ Composition and energy spectrum of the particles escaping the source

Outline of the acceleration model

- Modelling of internal shocks, following Daigne & Mochkovitch (1998)
  => estimate relevant physical quantities
  (few free parameters: global composition + partition of the energy)

- Calculation of the prompt emission (photon density and spectrum)
  following Daigne, Bosnjak & Dubus (2009)
  => these photons are targets for the accelerated cosmic-rays

- Particle acceleration at the resulting mildly relativistic shocks, following the numerical approach of Niemiec & Ostrowski (2004-2006)
  => with shock parameters given by the internal shock model

- Full calculation including energy losses (photo-hadronic and hadron-hadron) and escape out of the GRB
  => CR + neutrino output of individual GRBs as a function of luminosity

- Convolution with a GRB luminosity function & cosmological evolution
  (Piran & Wanderman 2010)
  => diffuse UHECR + neutrino fluxes

- Propagation of UHECRs to the Earth => propagated spectra/composition

Energy partition assumptions

◇ How to distribute the energy released in the internal shocks among cosmic-rays, electrons and magnetic field?

Model A

equipartition

$\varepsilon_e = \varepsilon_B = \varepsilon_{CR} = 1/3$

γ-ray efficiency ~5% ($L_\gamma \sim L_{wind}/20$)

$L_{wind} \leq 10^{51} - 10^{55}$ erg/s

$L_\gamma \leq 5\ 10^{49} - 5\ 10^{53}$ erg/s (iso)

↓

not enough power for UHECRs

Model B

low γ-ray efficiency

$\varepsilon_e << 1;\ \varepsilon_B = 0.1\ ;\ \varepsilon_{CR} = 0.9$

γ-ray efficiency: between 0.01% and 1%

$L_{wind} \leq 3\ 10^{53} - 3 10^{55}$ erg/s

$L_\gamma \leq 5\ 10^{49} - 5\ 10^{53}$ erg/s (iso)

↓

OK

Model C

low γ-ray efficiency

$\varepsilon_e << 1;\ \varepsilon_B = 1/3\ ;\ \varepsilon_{CR} = 2/3$

γ-ray efficiency: between 0.01% and 1%

$L_{wind} \leq 3\ 10^{53} - 3 10^{55}$ erg/s

$L_\gamma \leq 5\ 10^{49} - 5\ 10^{53}$ erg/s (iso)

↓

very good!

NB: only 3 times larger maximum wind power than equipartition

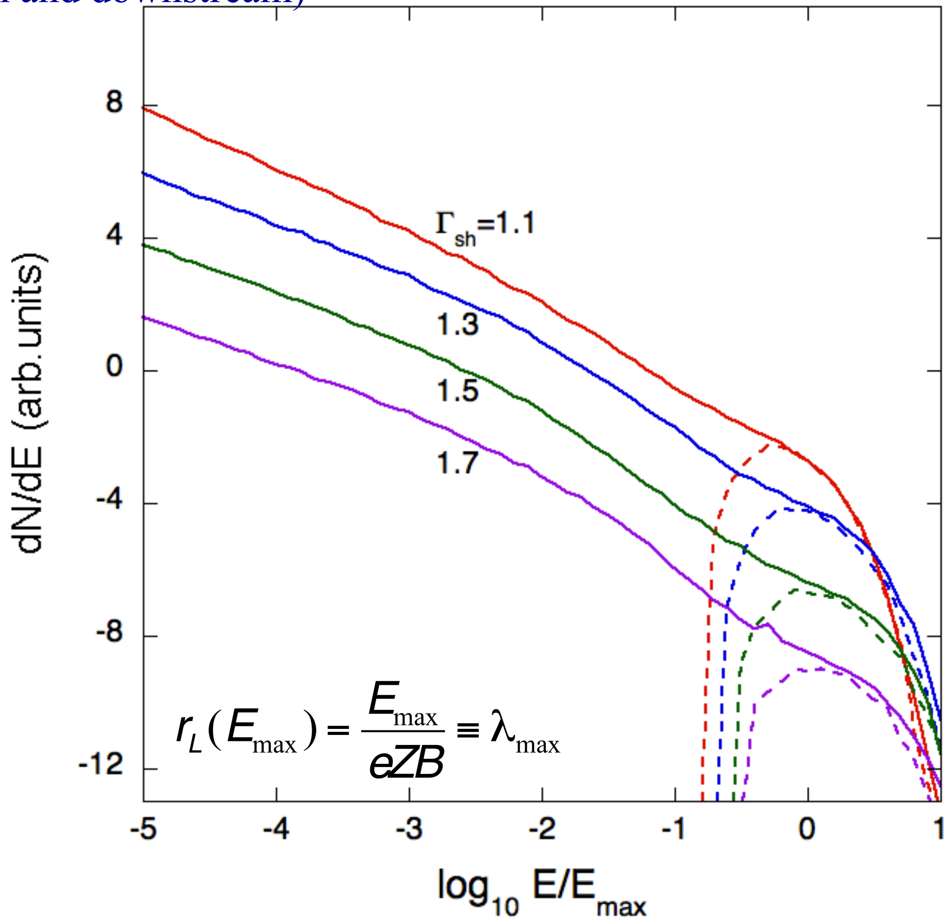
and smaller spread in wind power among GRBs

Particle acceleration at mildly relativistic shocks

- Monte Carlo simulation of Fermi acceleration:
  - Full calculation of particle trajectories and shock crossings => energy gains + particle escape (both upstream and downstream)

- Resulting spectra (no energy losses):

- Escape upstream : high pass filter (selects particles in the weak scattering regime)
- Escape downstream : becomes a high pass filter in the presence of energy losses (particles must leave before being cooled by energy losses)

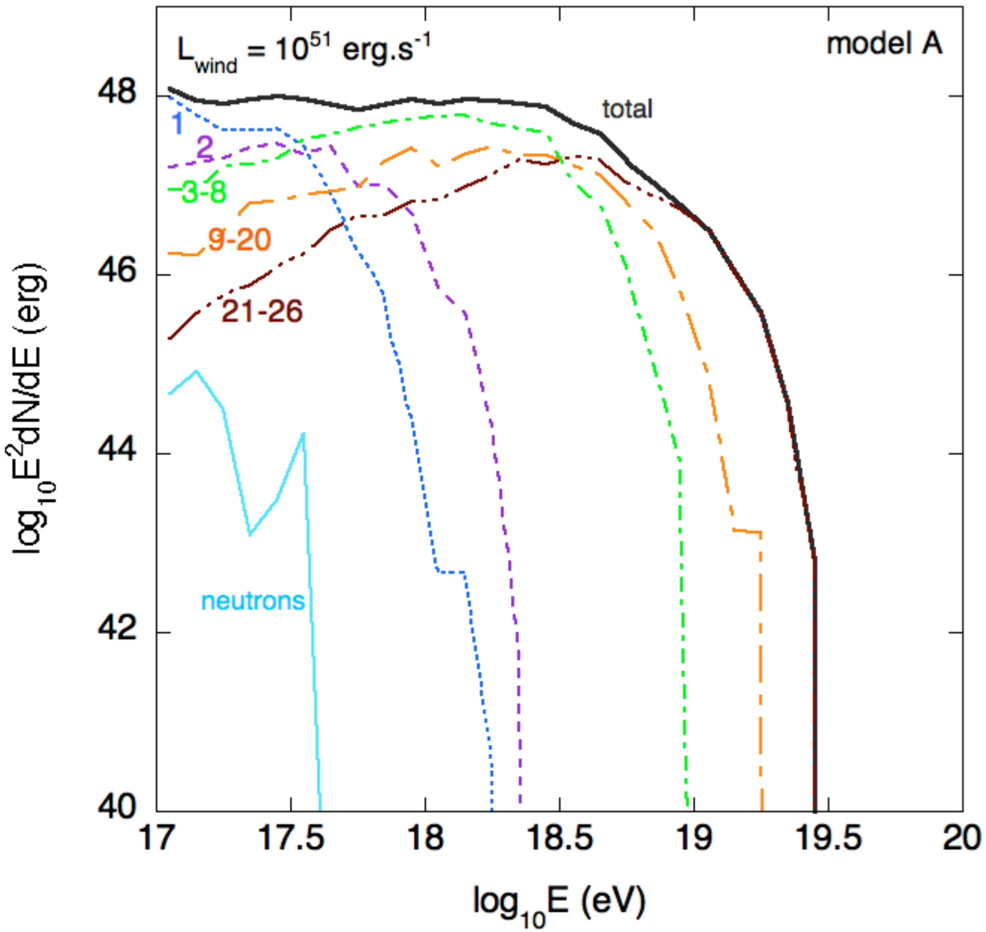


- Competition between acceleration and energy losses
  - Take into account all energy loss processes (expansion, synchrotron, pair production, photo-dissociation, photo-pion, hadronic interactions)

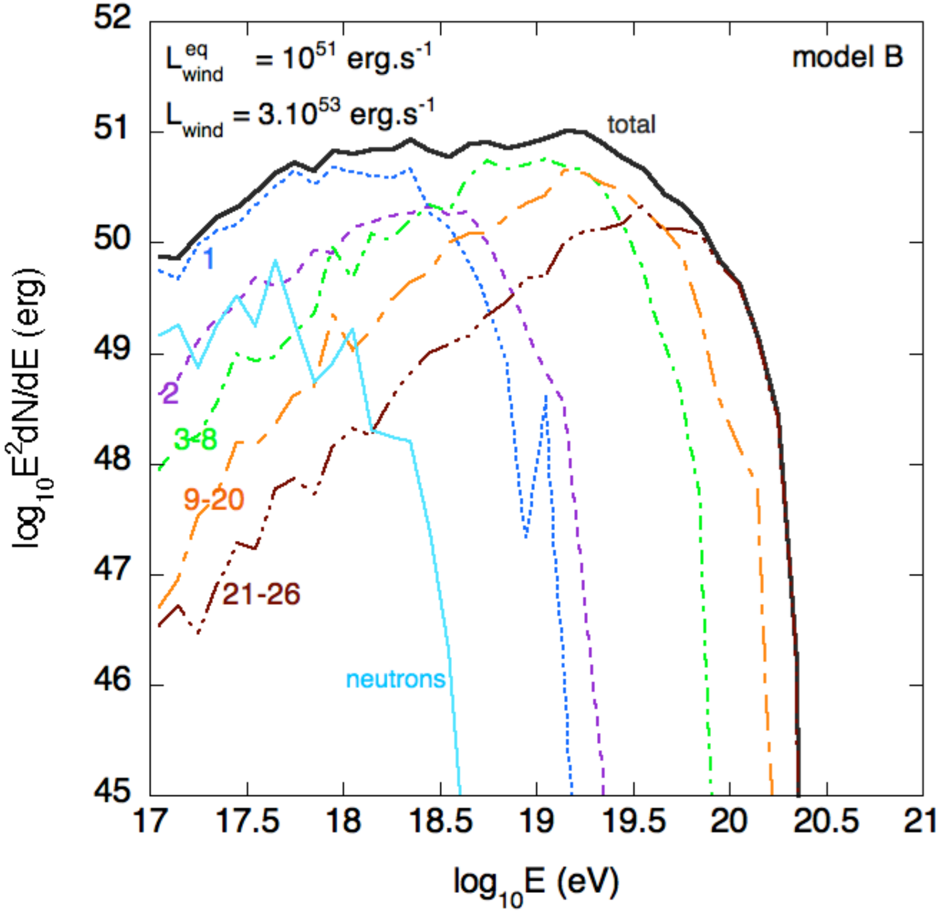
- Resulting spectra of escaping particles, integrated over the entire GRB evolution
  - For each GRB luminosity
  - For each energy partition model (A, B or C)

Escaping source spectra (incl. energy losses)

$L_{wind} = 10^{51}$ erg/s | $t_{wind} = 2$ s | metallicity = 10×GCRs



Equipartition



"Boosted"

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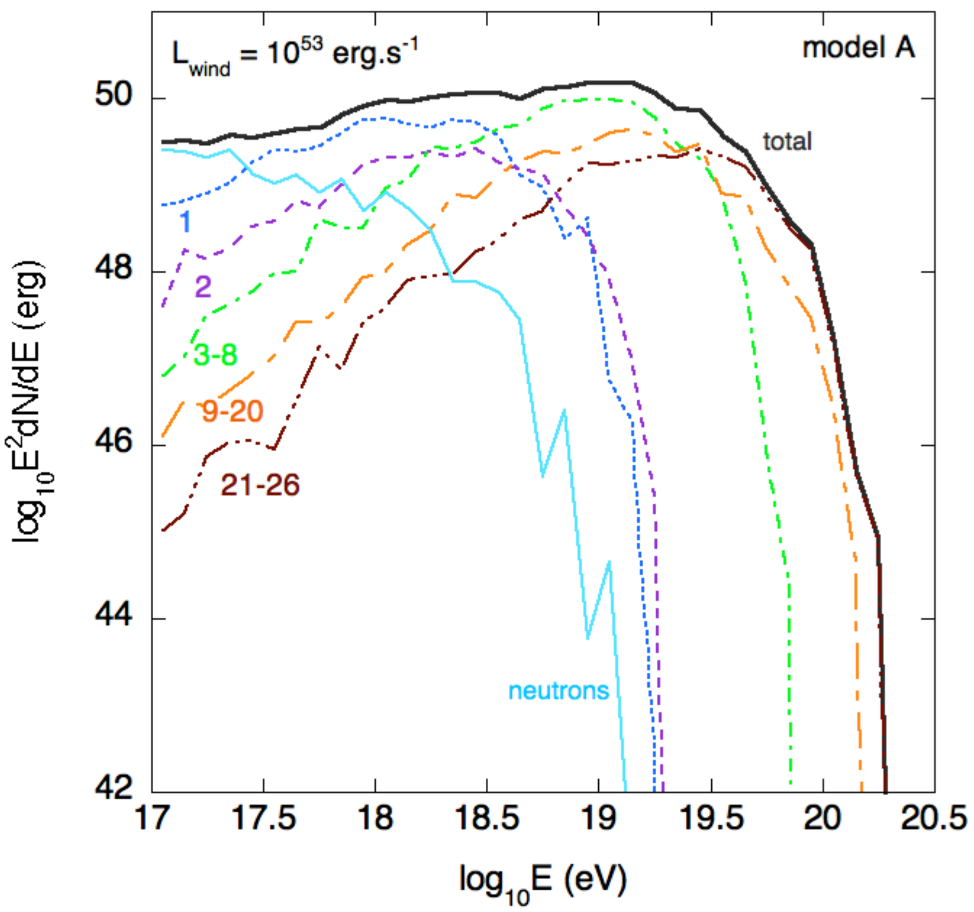

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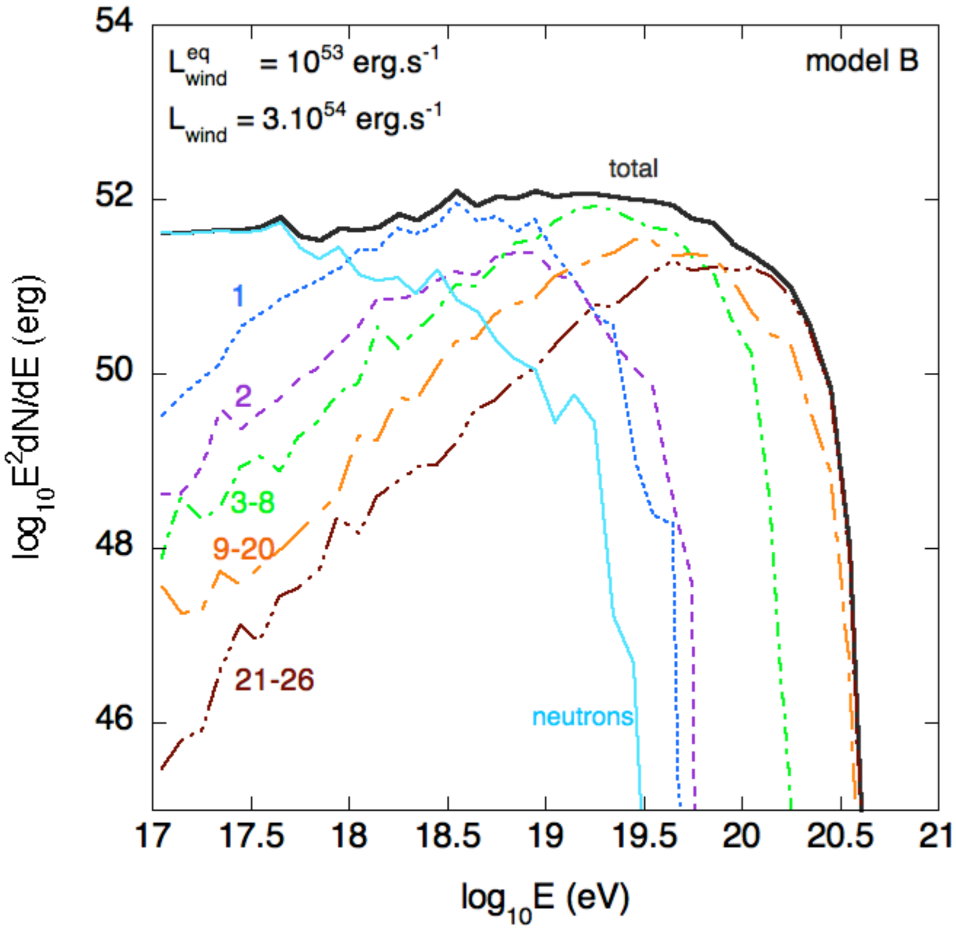

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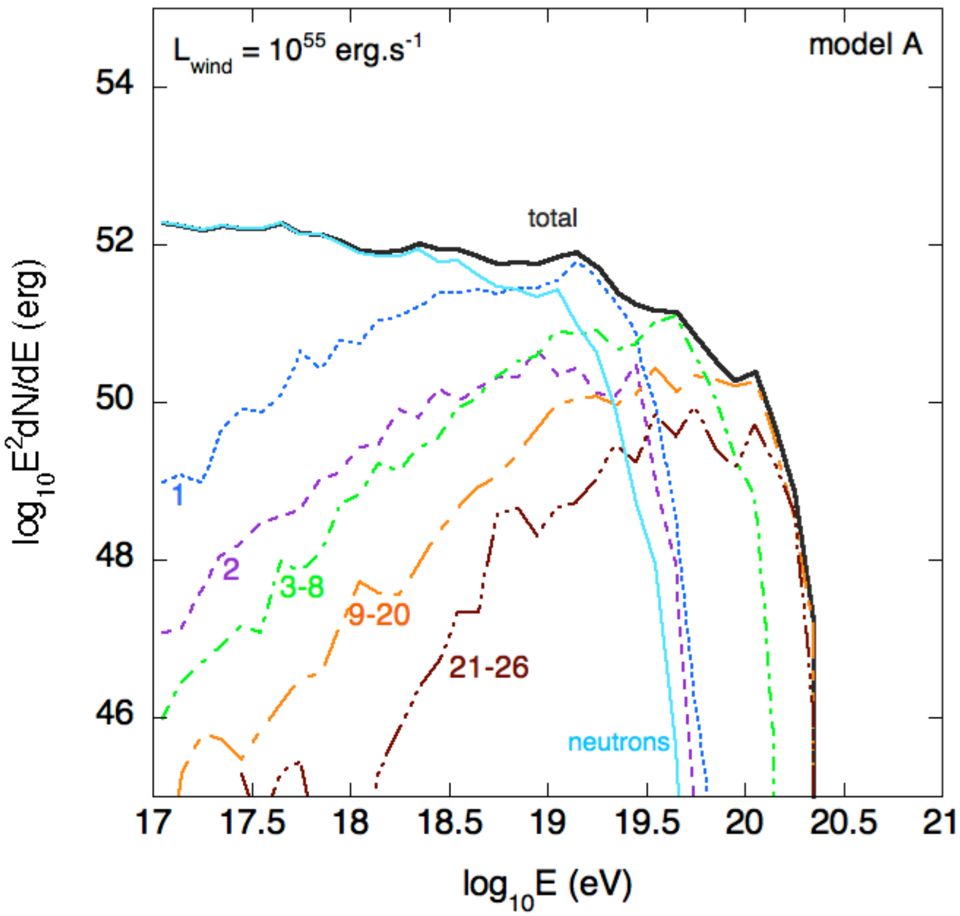
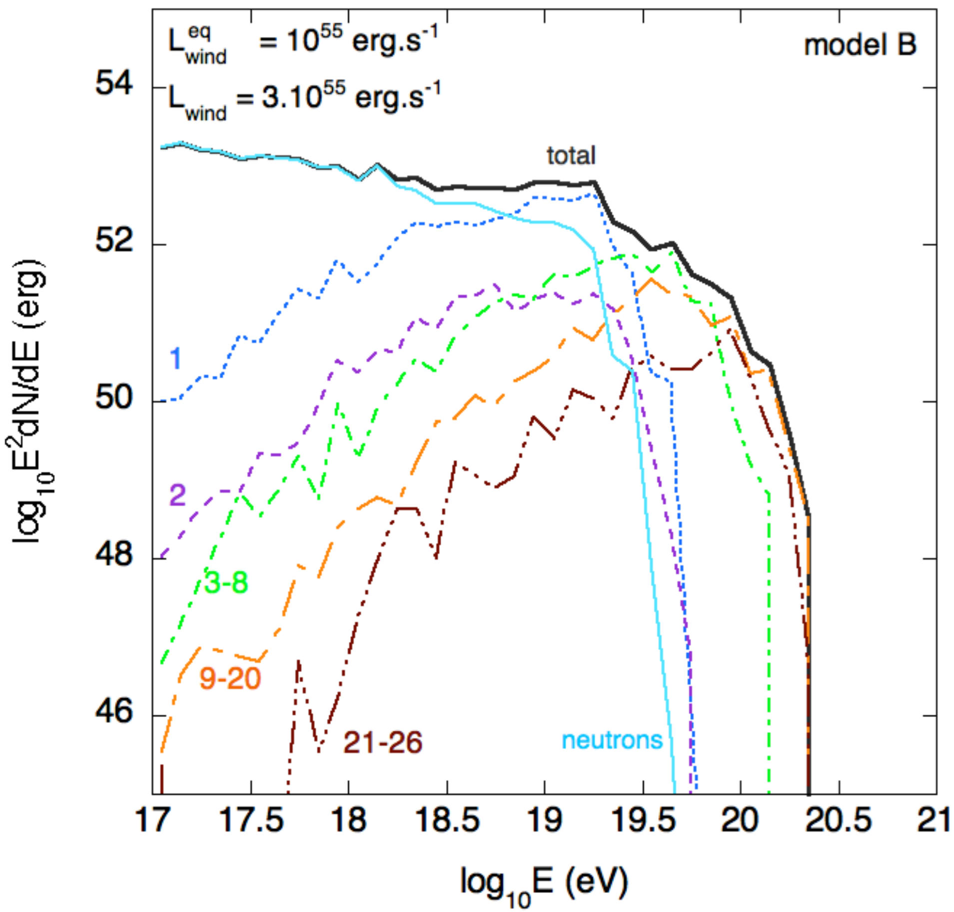




Equipartition

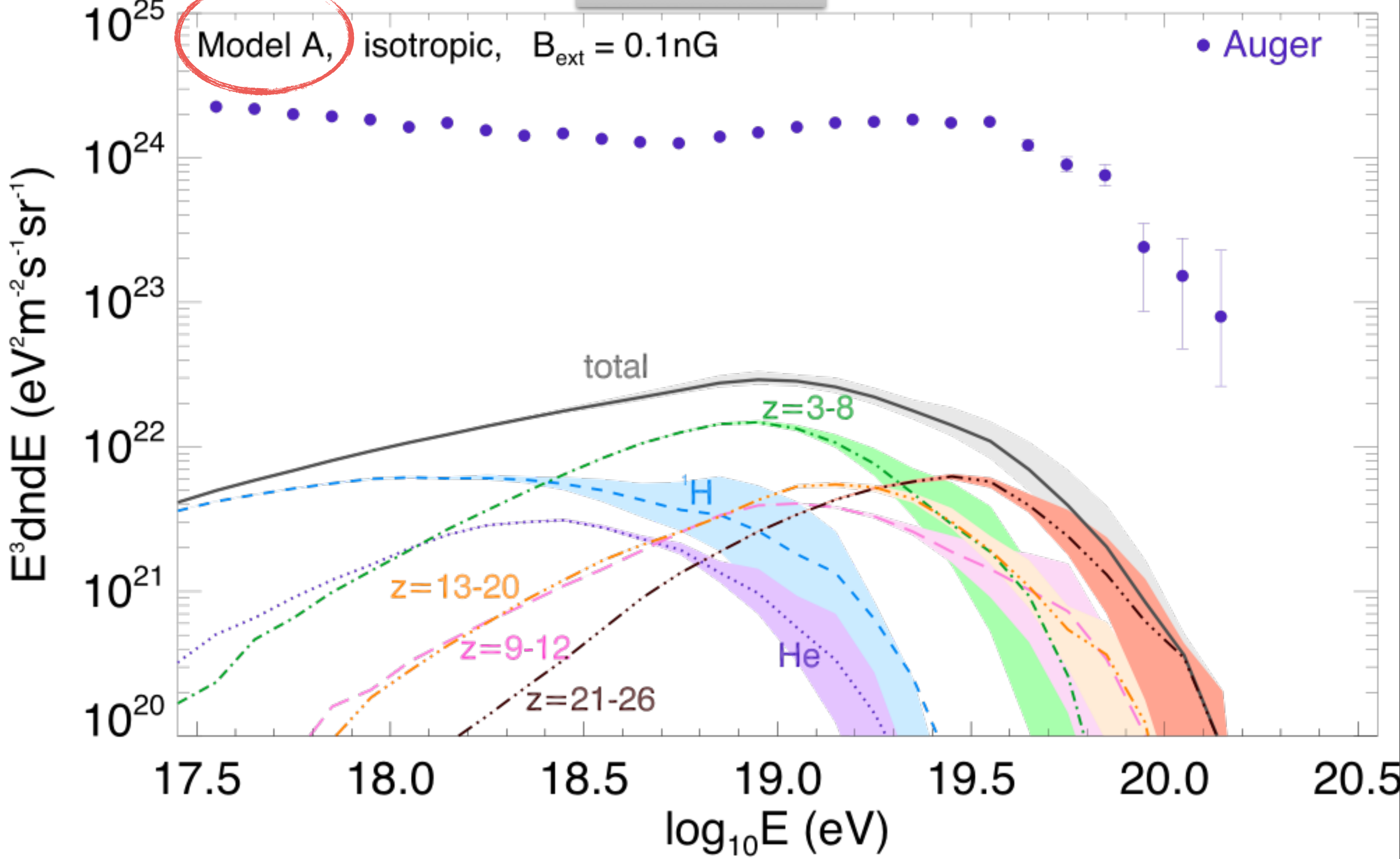
"Boosted"

LOOK AT THE NEUTRON COMPONENT!!!

Resulting UHECR propagated spectra

Implementing the GRB rate, luminosity function, and redshift evolution from Wanderman & Piran (2010)

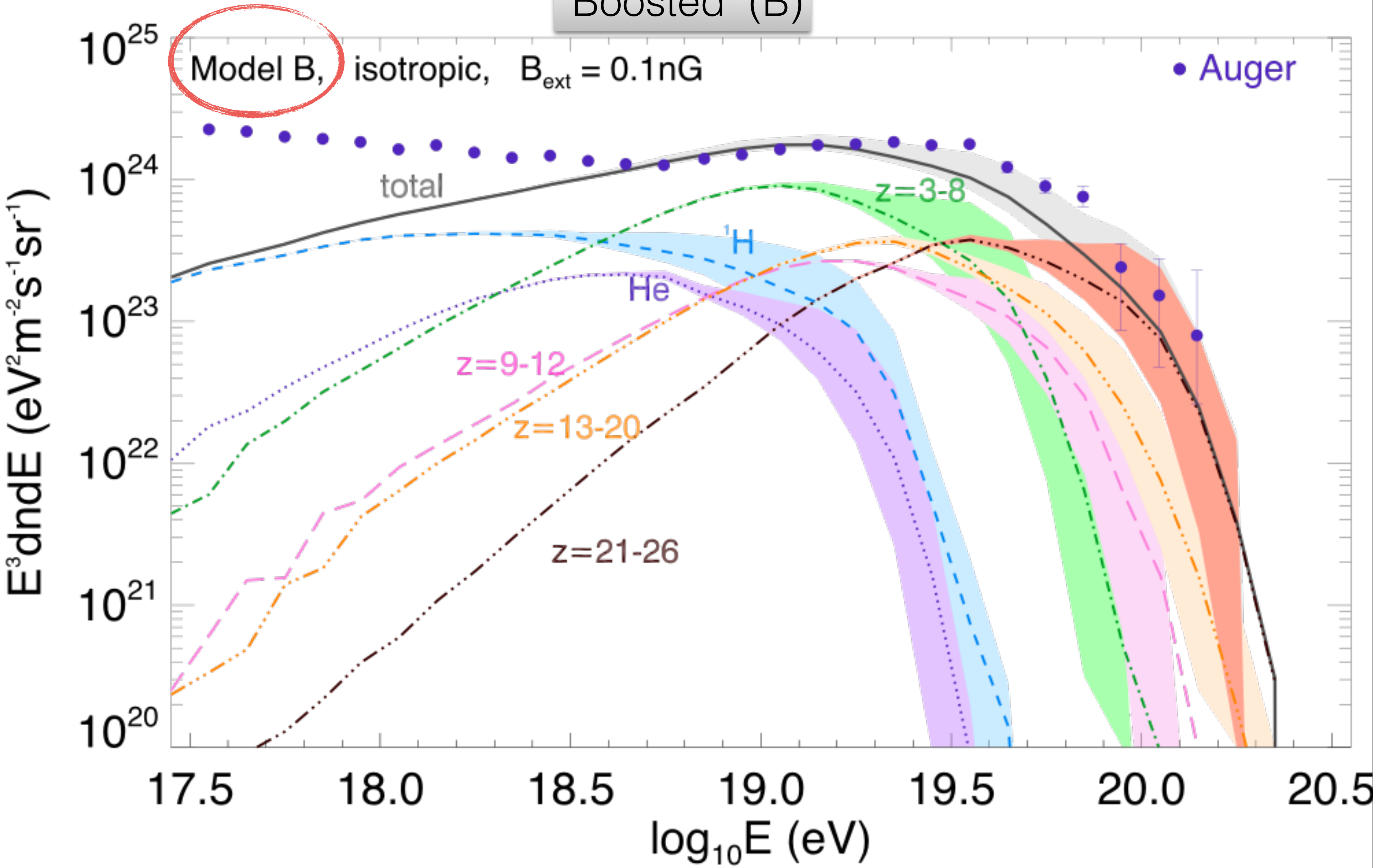
Equipartition



Resulting UHECR propagated spectra

Implementing the GRB rate, luminosity function, and redshift evolution from Wanderman & Piran (2010)

"Boosted" (B)



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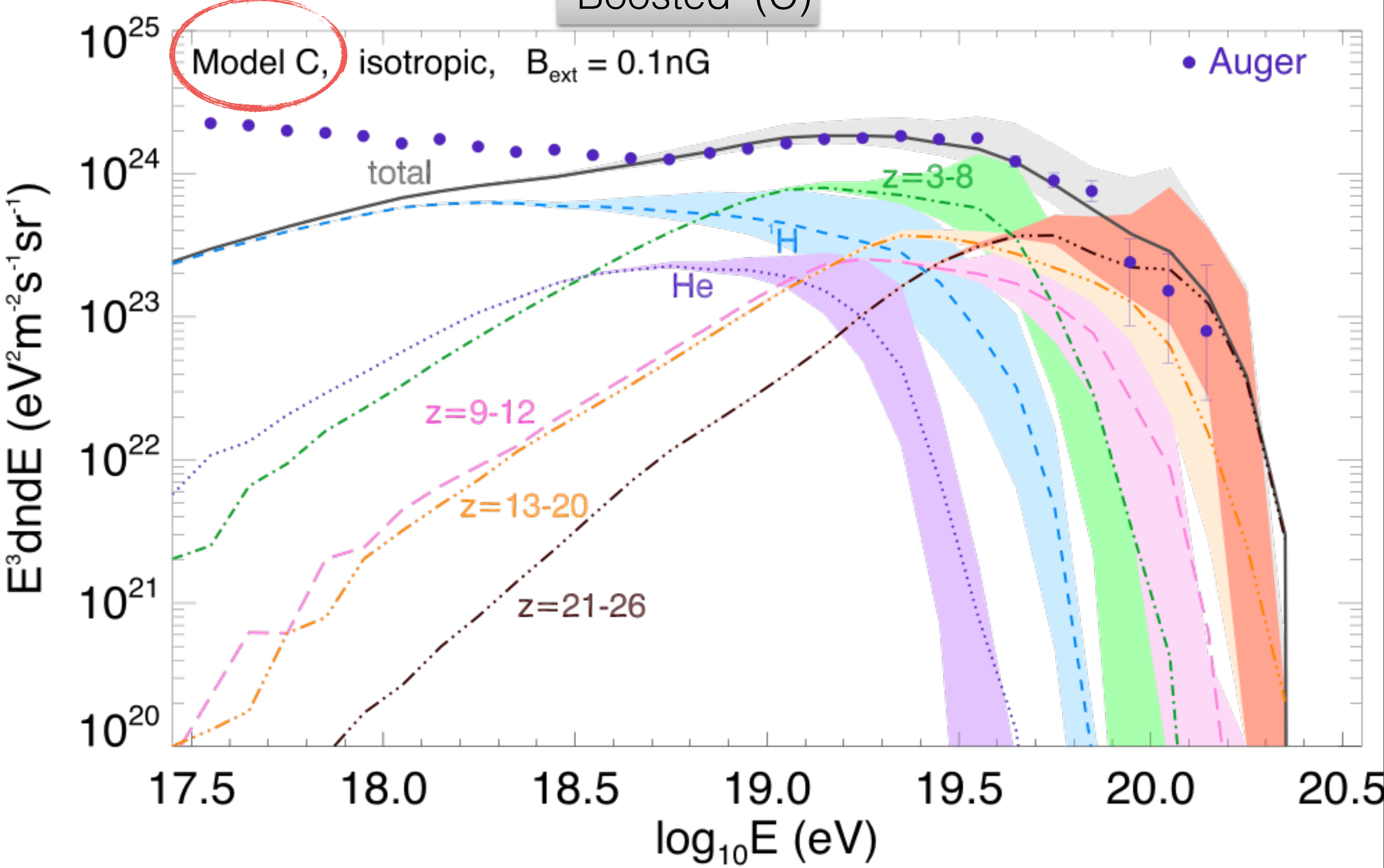
Implementing the GRB rate, luminosity function, and redshift evolution from Wanderman & Piran (2010)

"Boosted" (C)



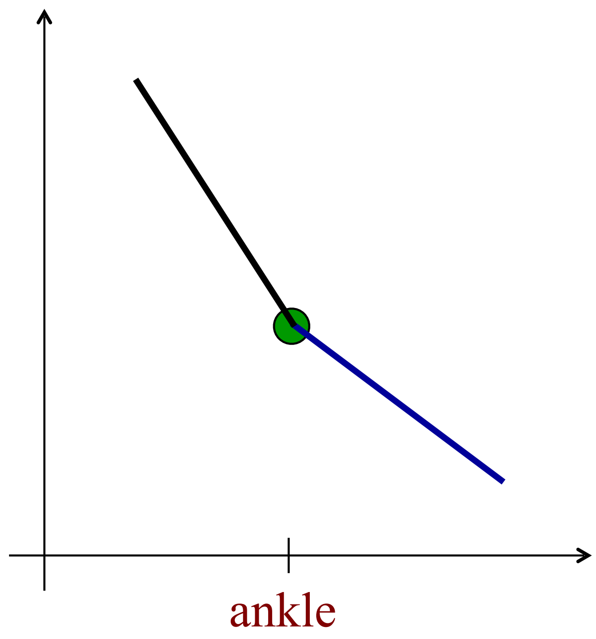
II- GCR/EGCR transition

- Low-E cosmic rays are Galactic
- High-E cosmic rays are extragalactic
- A transition must occur!
- An ankle-like feature is the most natural shape for a transition
- The complete cosmic-ray phenomenology (spectrum and composition) across the transition is easily and naturally described by invoking only 2 components of cosmic rays, one Galactic and one extragalactic

General phenomenology of transitions

- Two possibilities: the spectrum gets either harder or softer!

transition from a softer to a harder component



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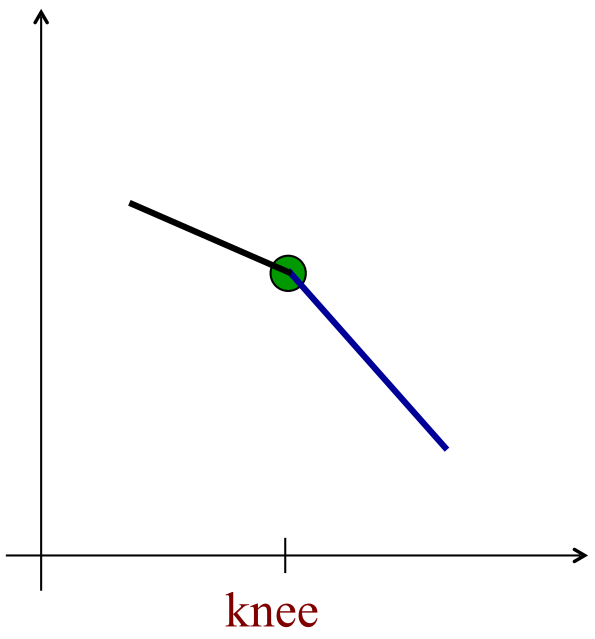

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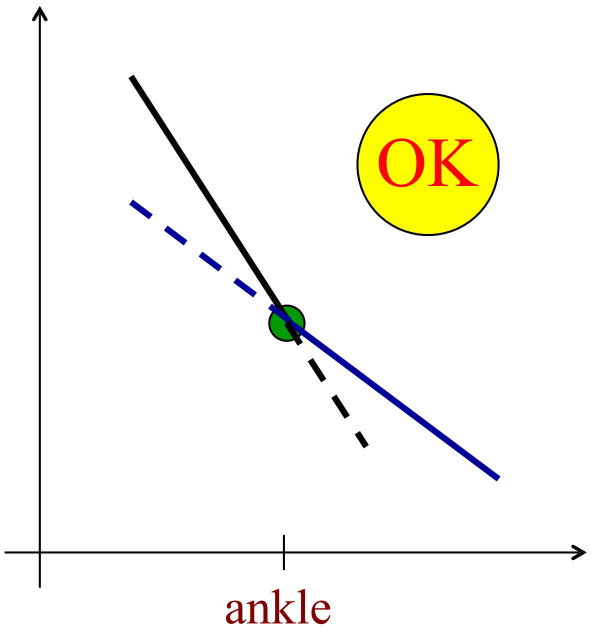

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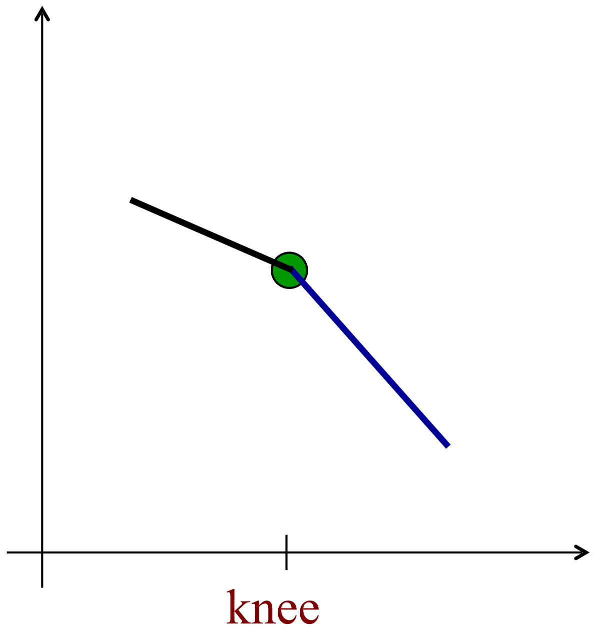

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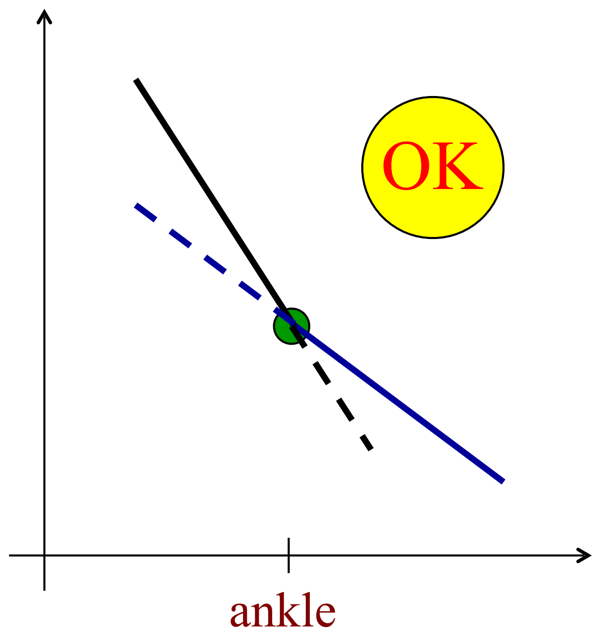
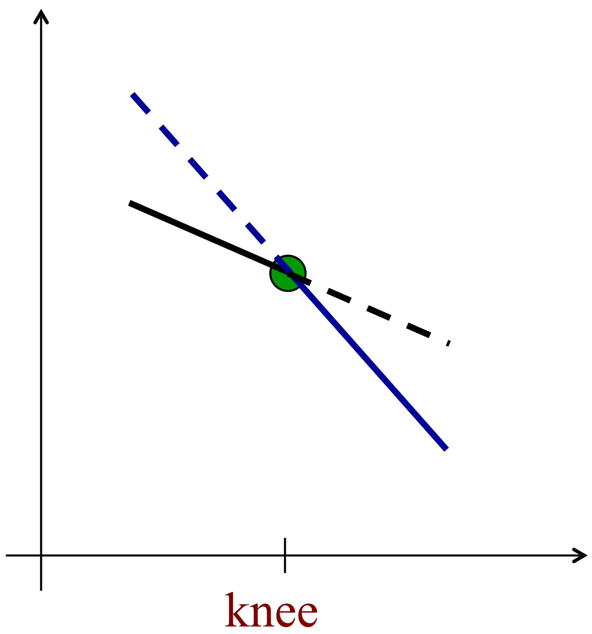


transition from a harder to a softer component



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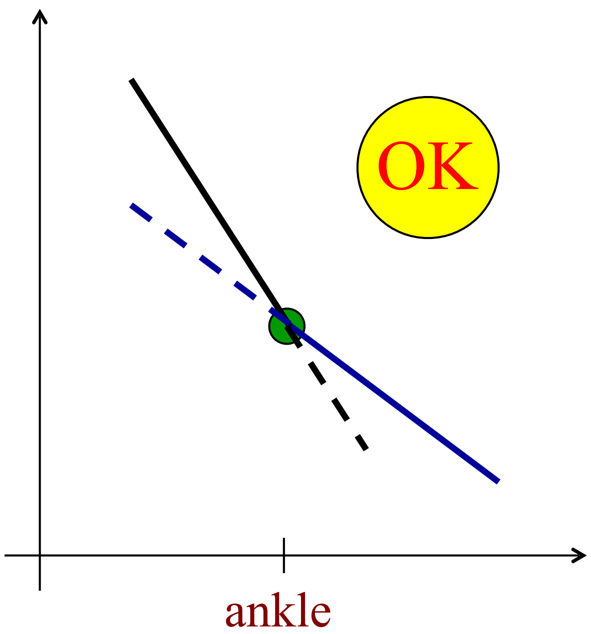

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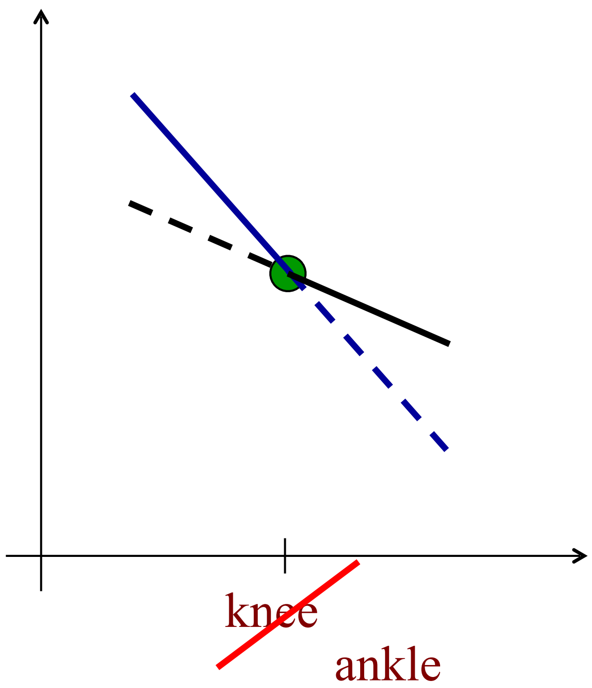
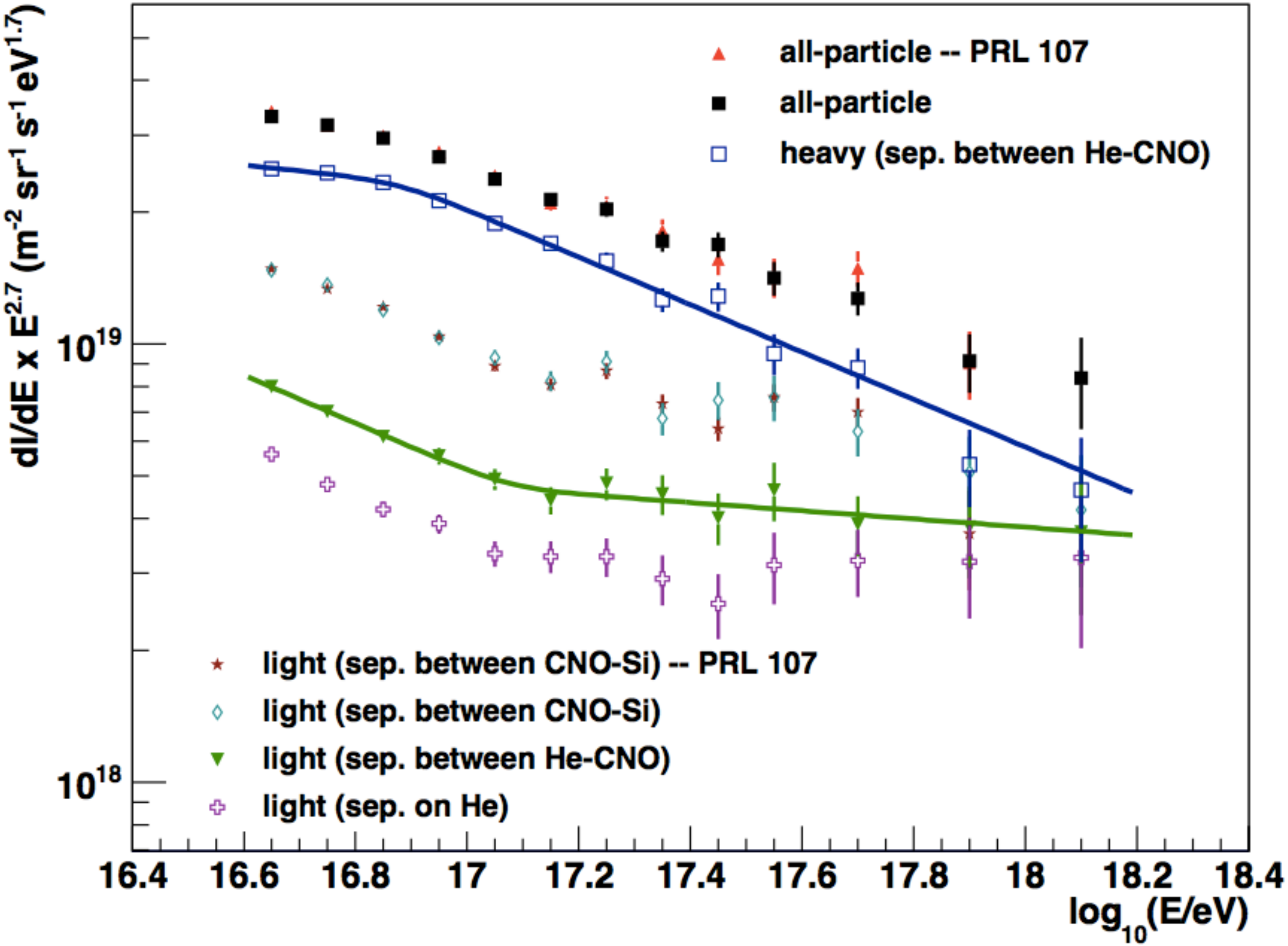


Kascade-Grande results

Kascade Grande Collaboration (2013)



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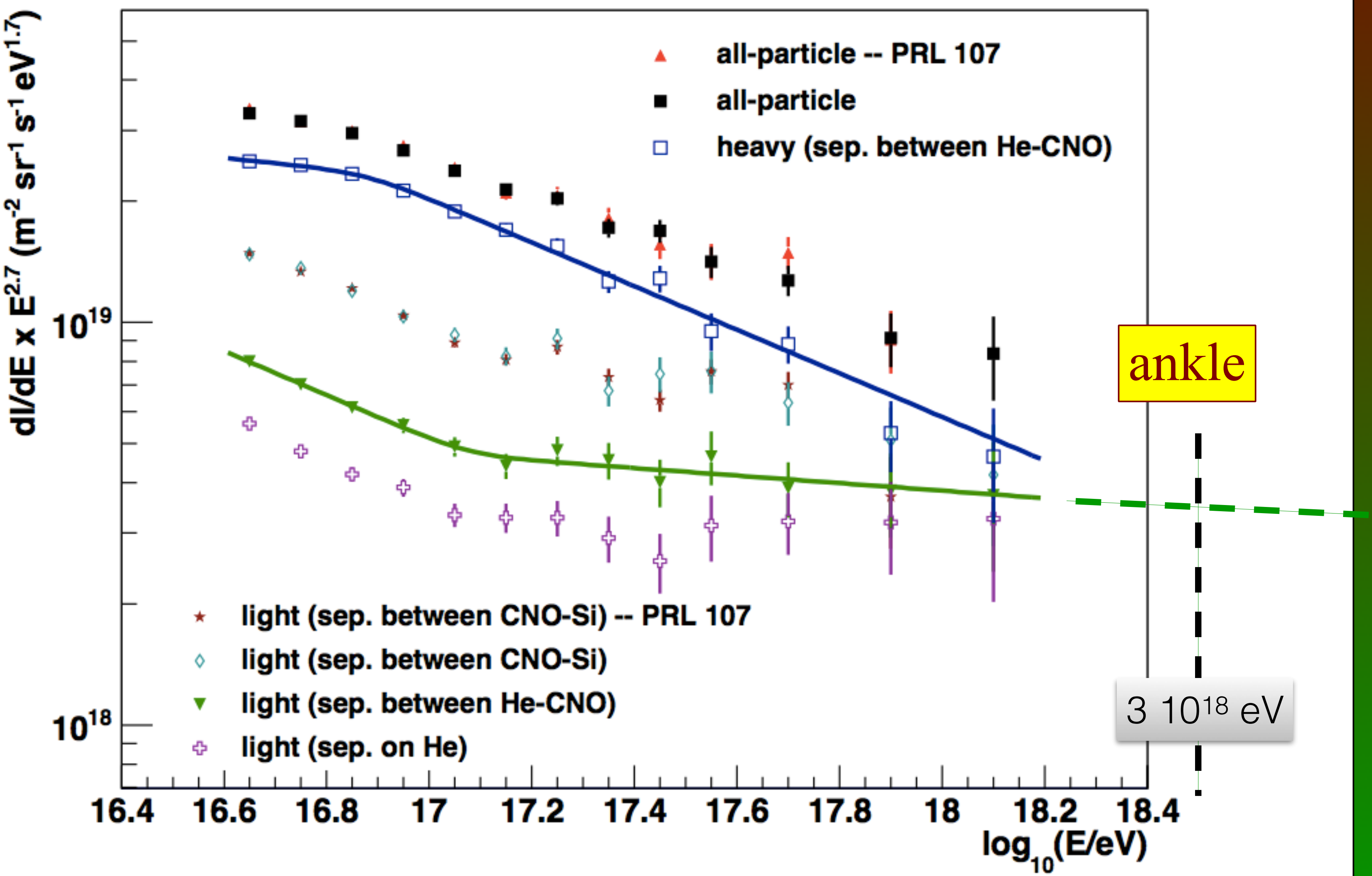

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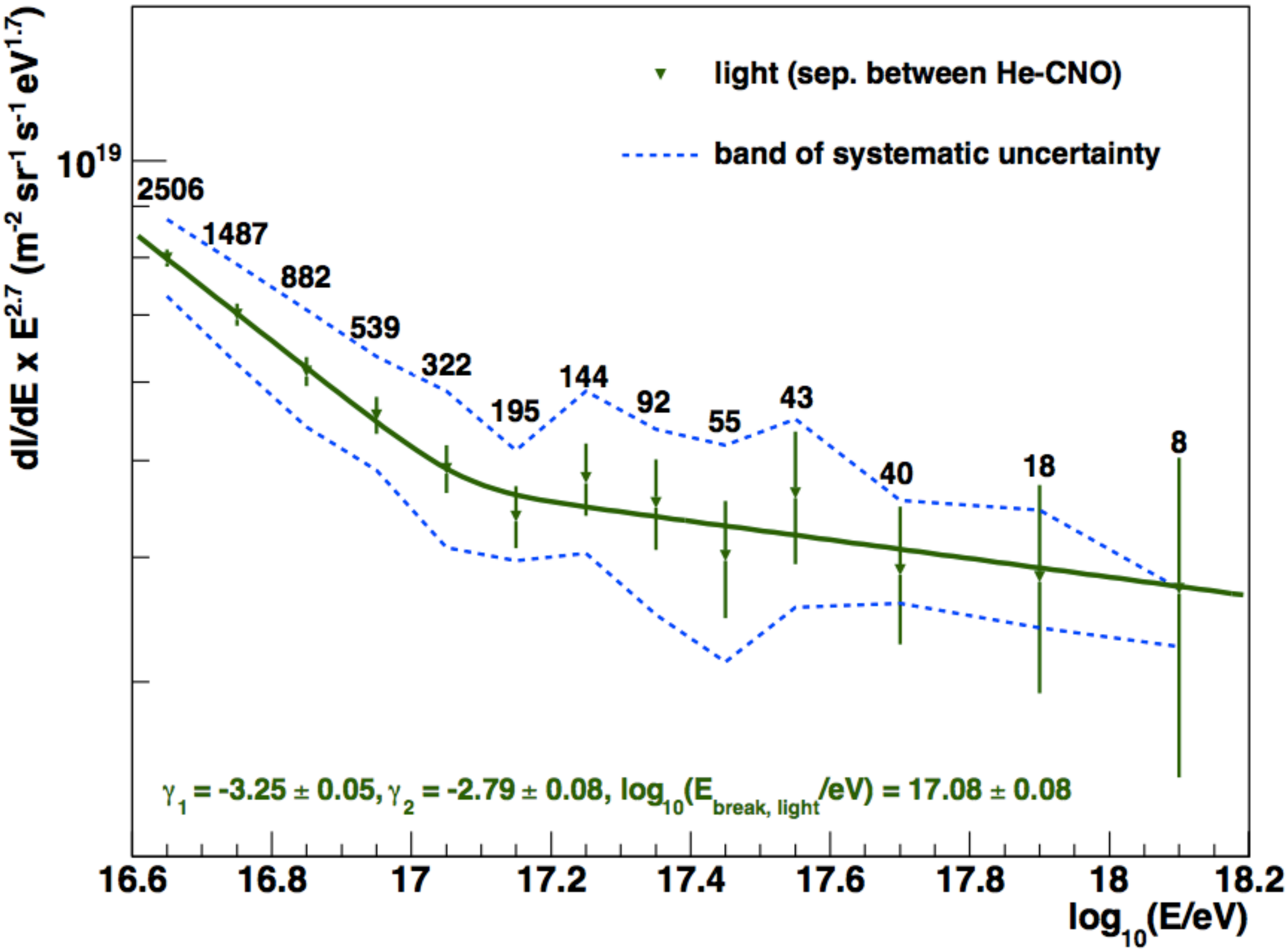
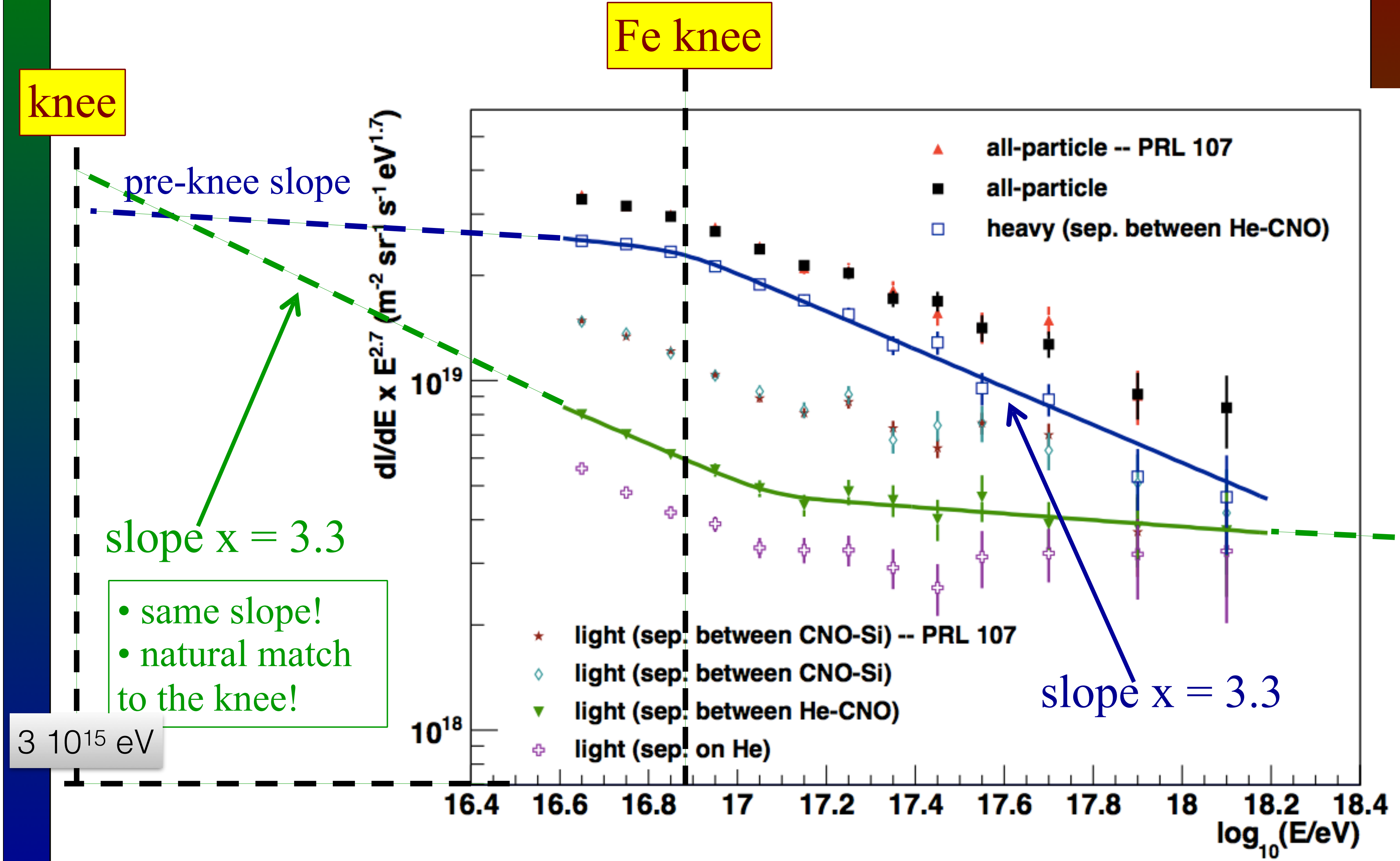
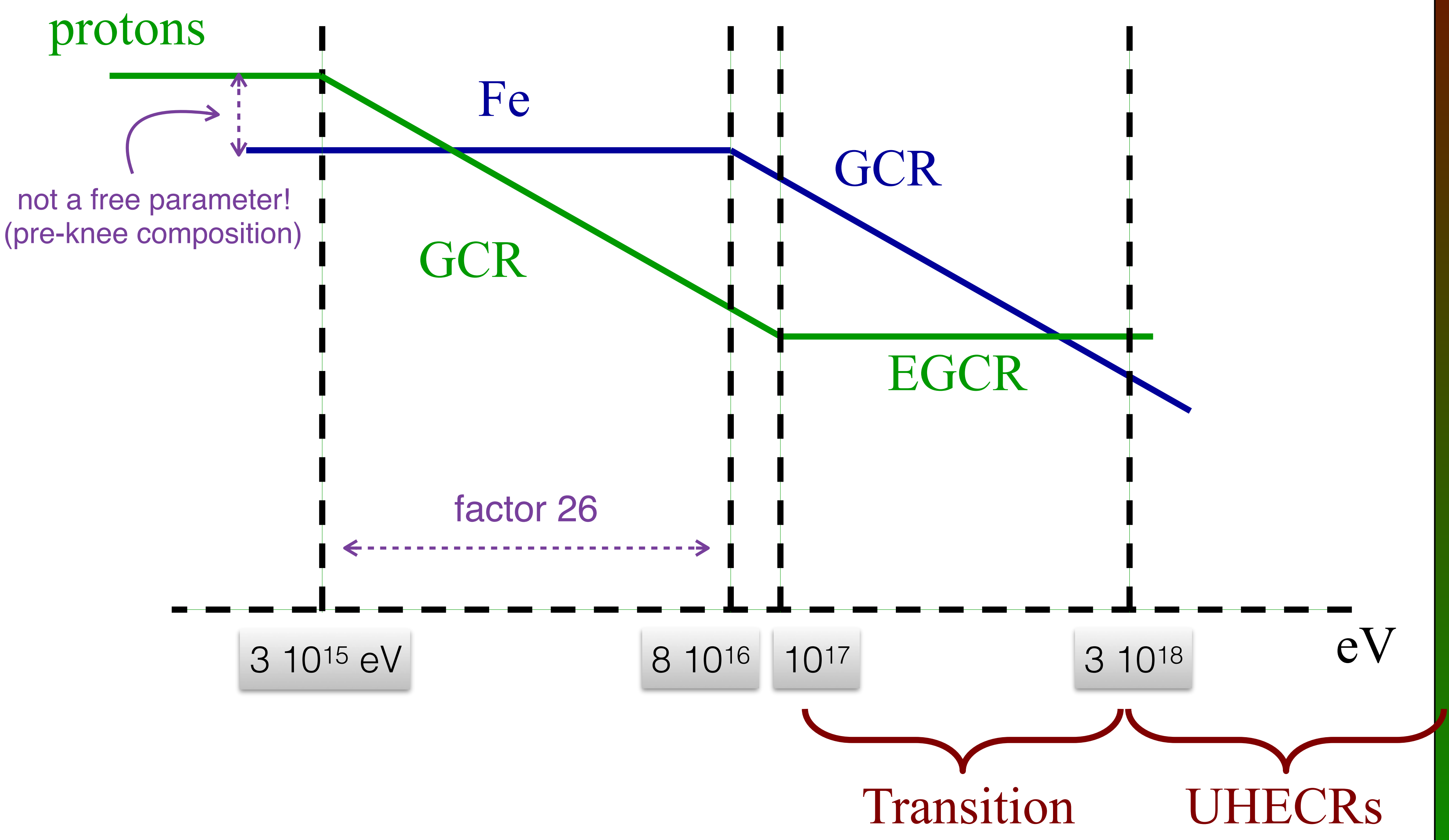


Quite a simple and natural picture!



Very appealing GCR/EGCR transition picture



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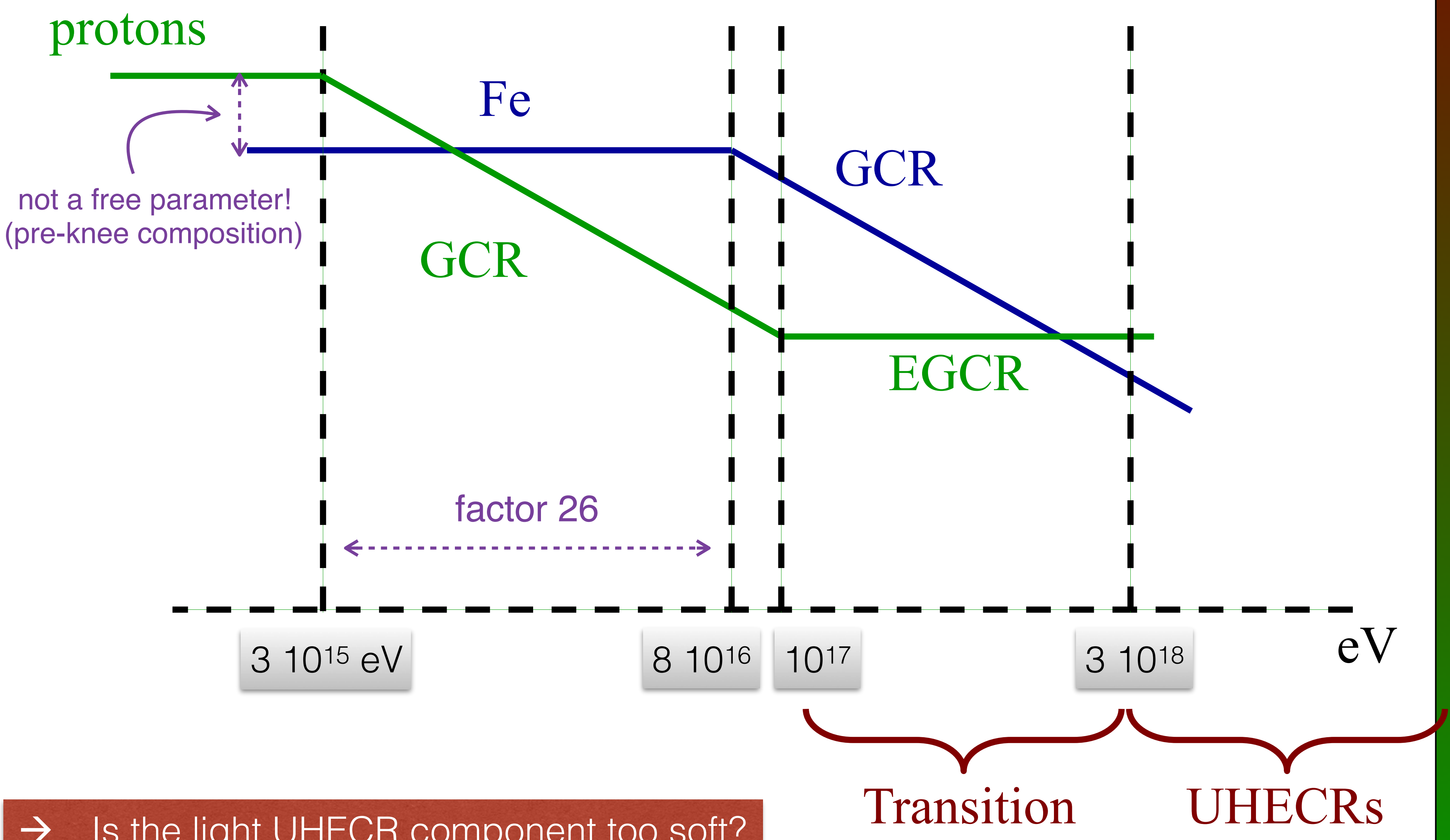
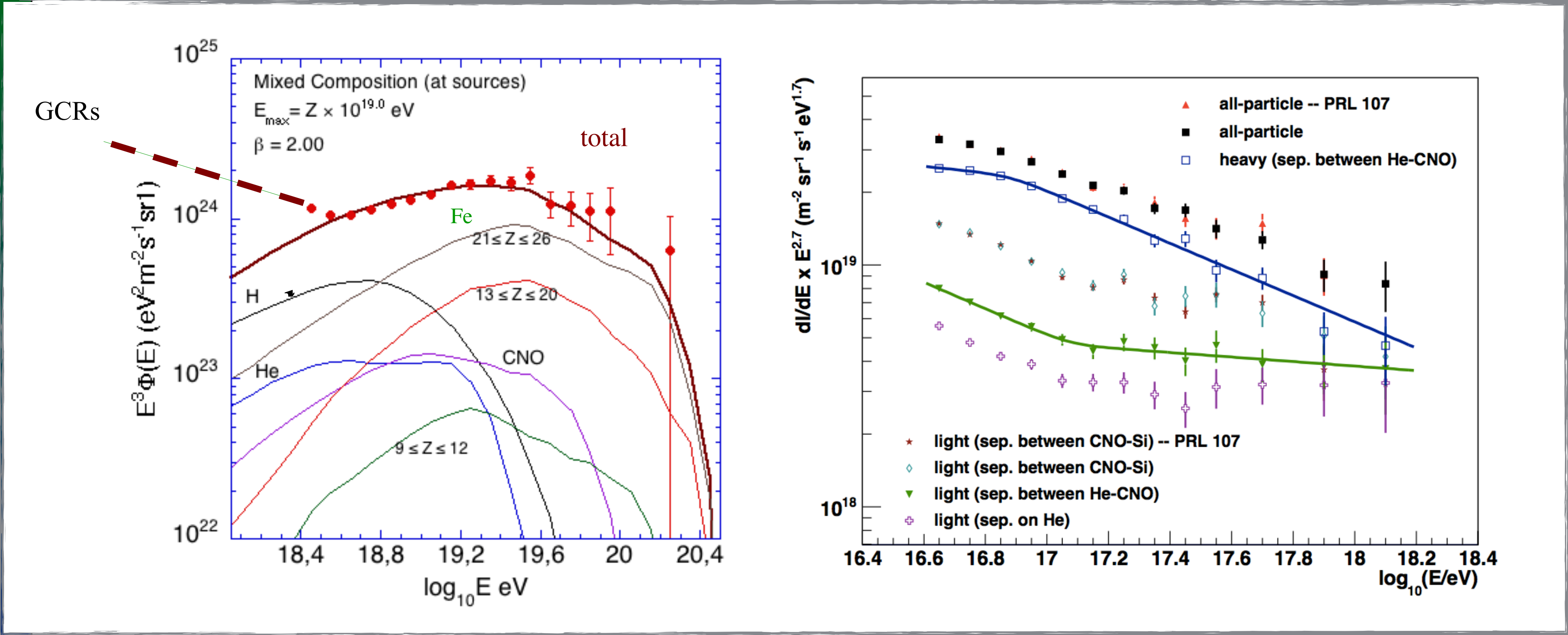


→ Is the light UHECR component too soft?

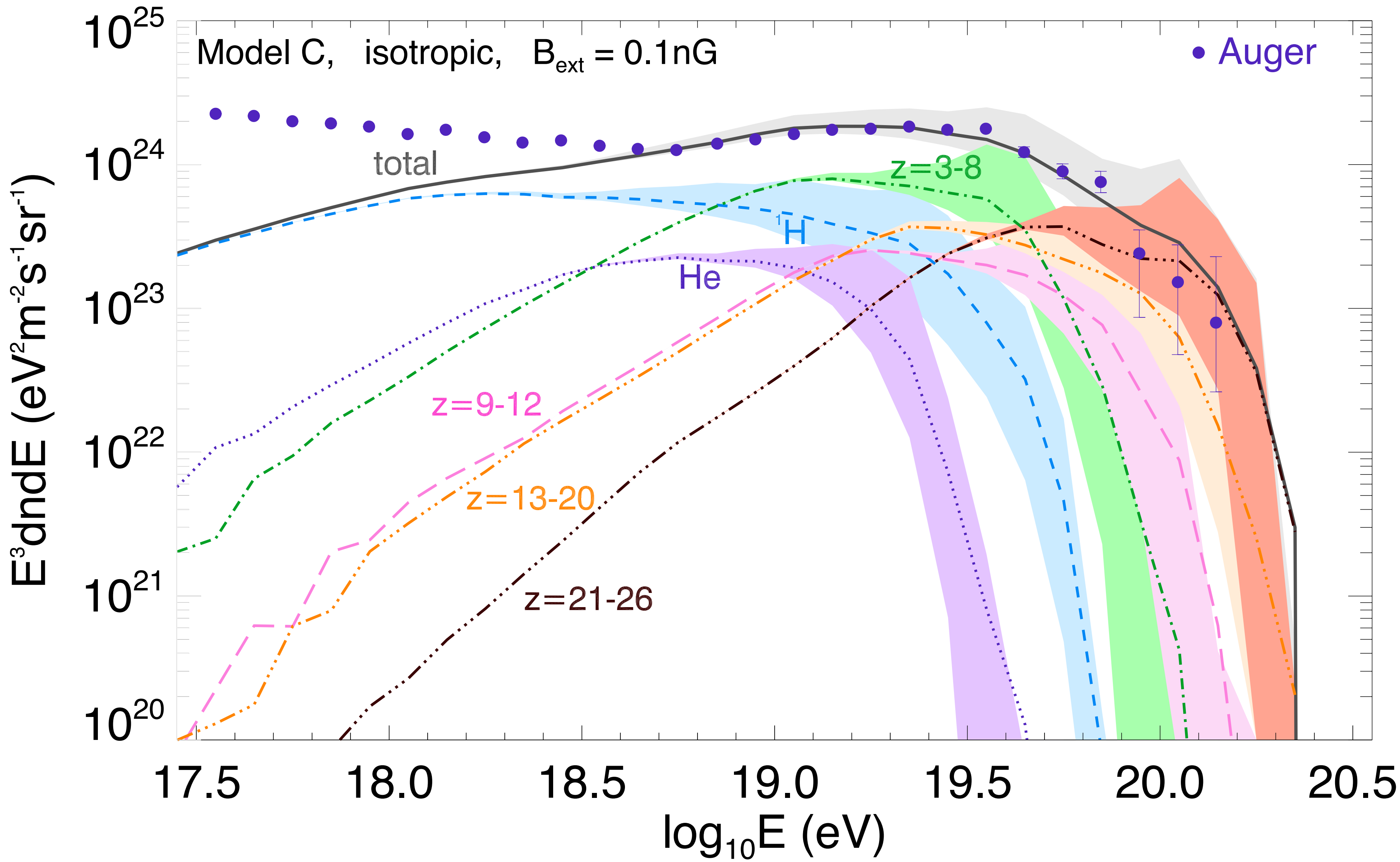
Reminder: low proton E_{max} models imply very hard source spectra



…but the EGCR proton component can be much softer!

→ no need for an additional component!

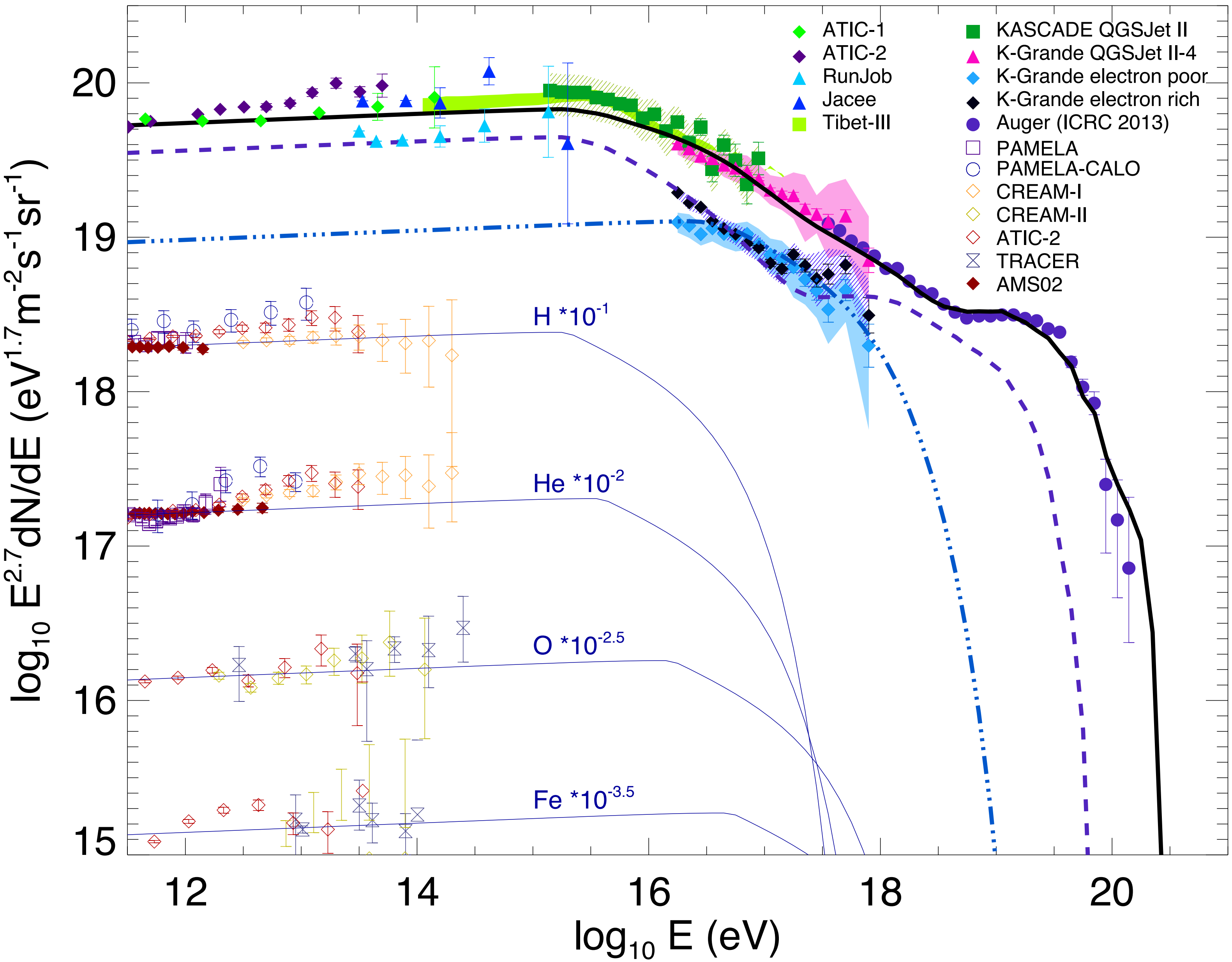
Example of spectrum from GRB model



III - Global description of the cosmic-ray composition and spectrum

- Galactic CR model: a spectrum depending only on rigidity: power-law with a break at the knee (caused by whatever phenomenon at the source or during propagation) and an exponential cutoff at $E_{max}(Z) = Z \times E_{max}(p)$
- Extragalactic CR model: e.g. our generic UHECR spectrum from the GRB acceleration model (not critical: anything else with similar features could do)

Global description of the CR data



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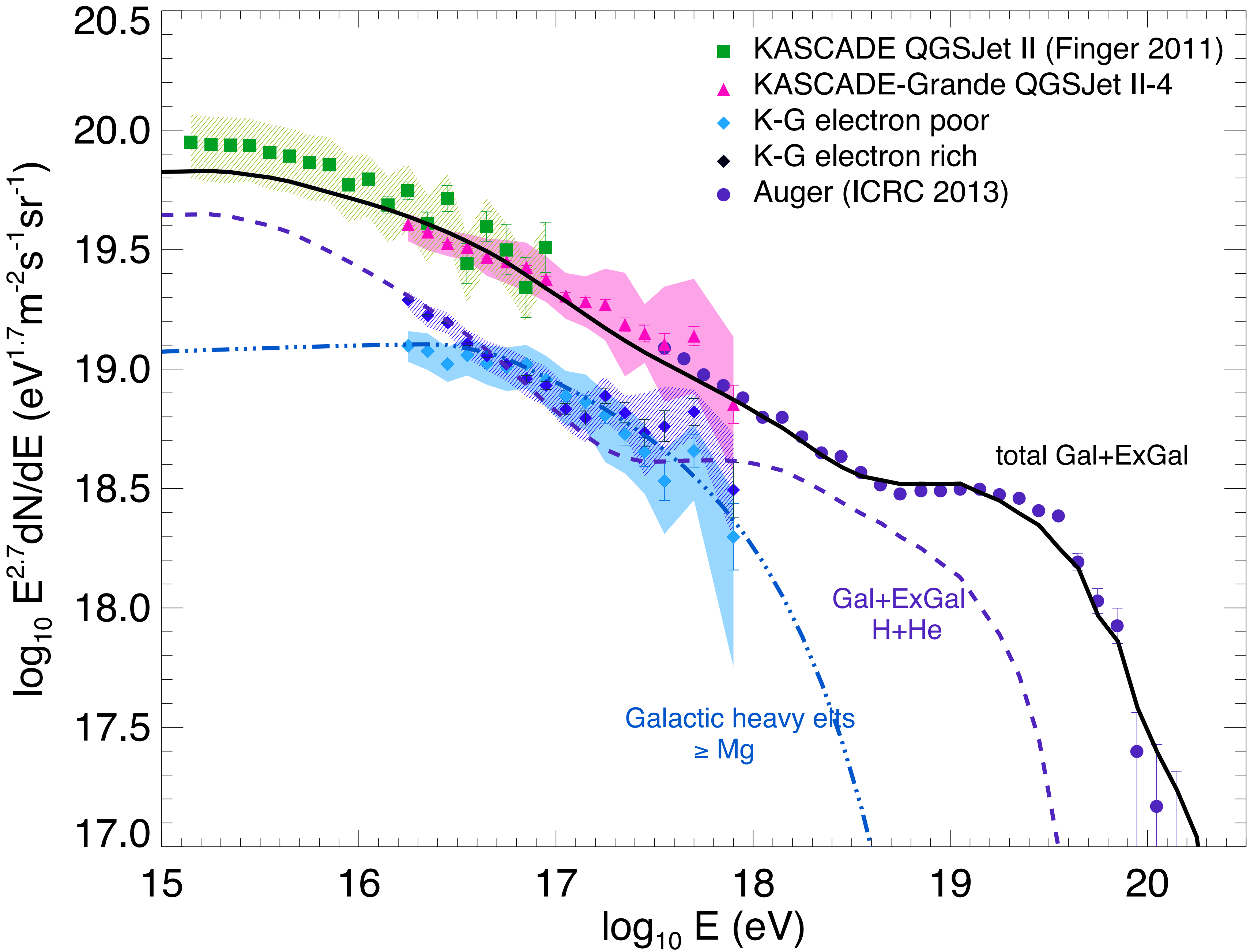
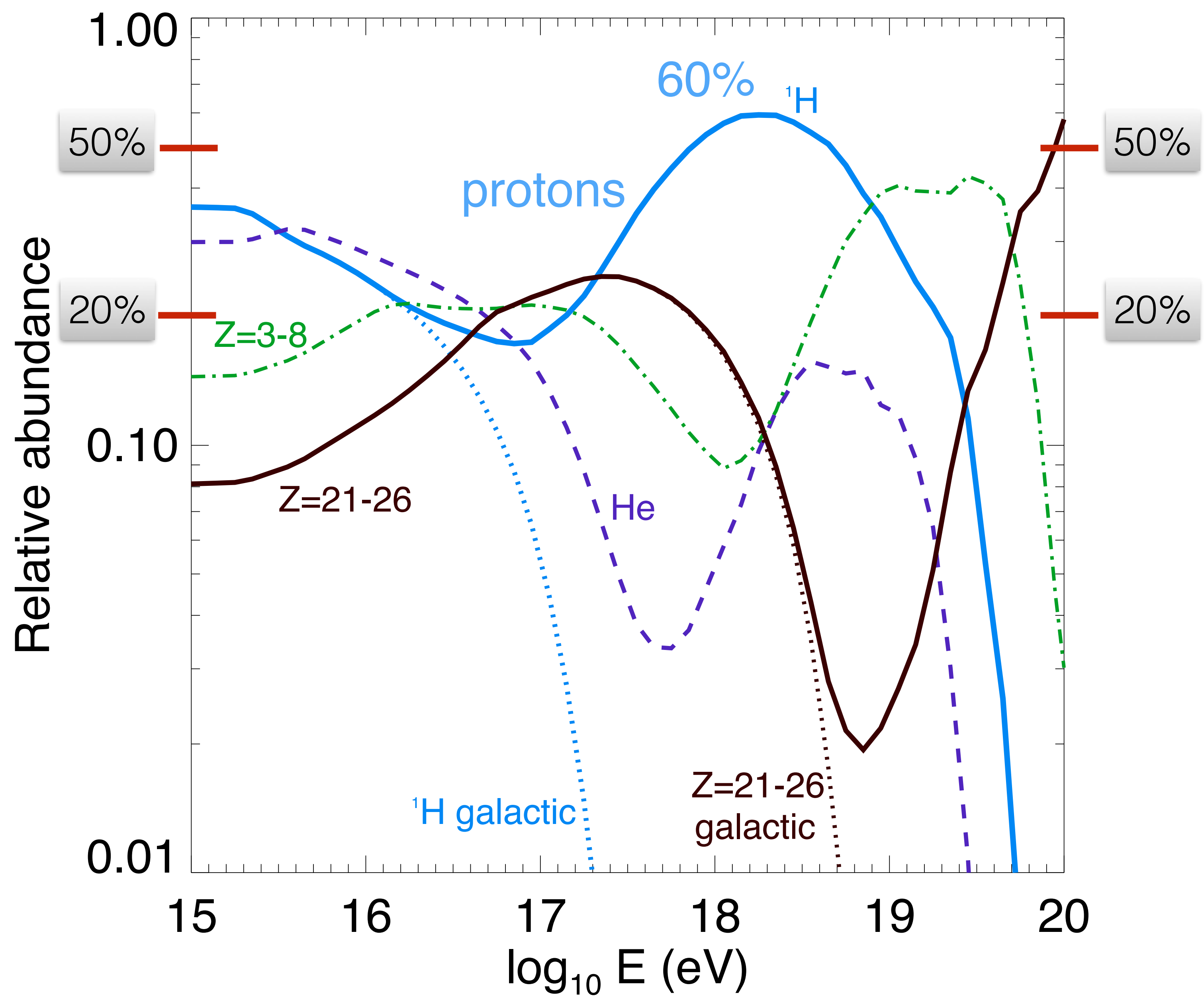


Resulting evolution of the CR composition



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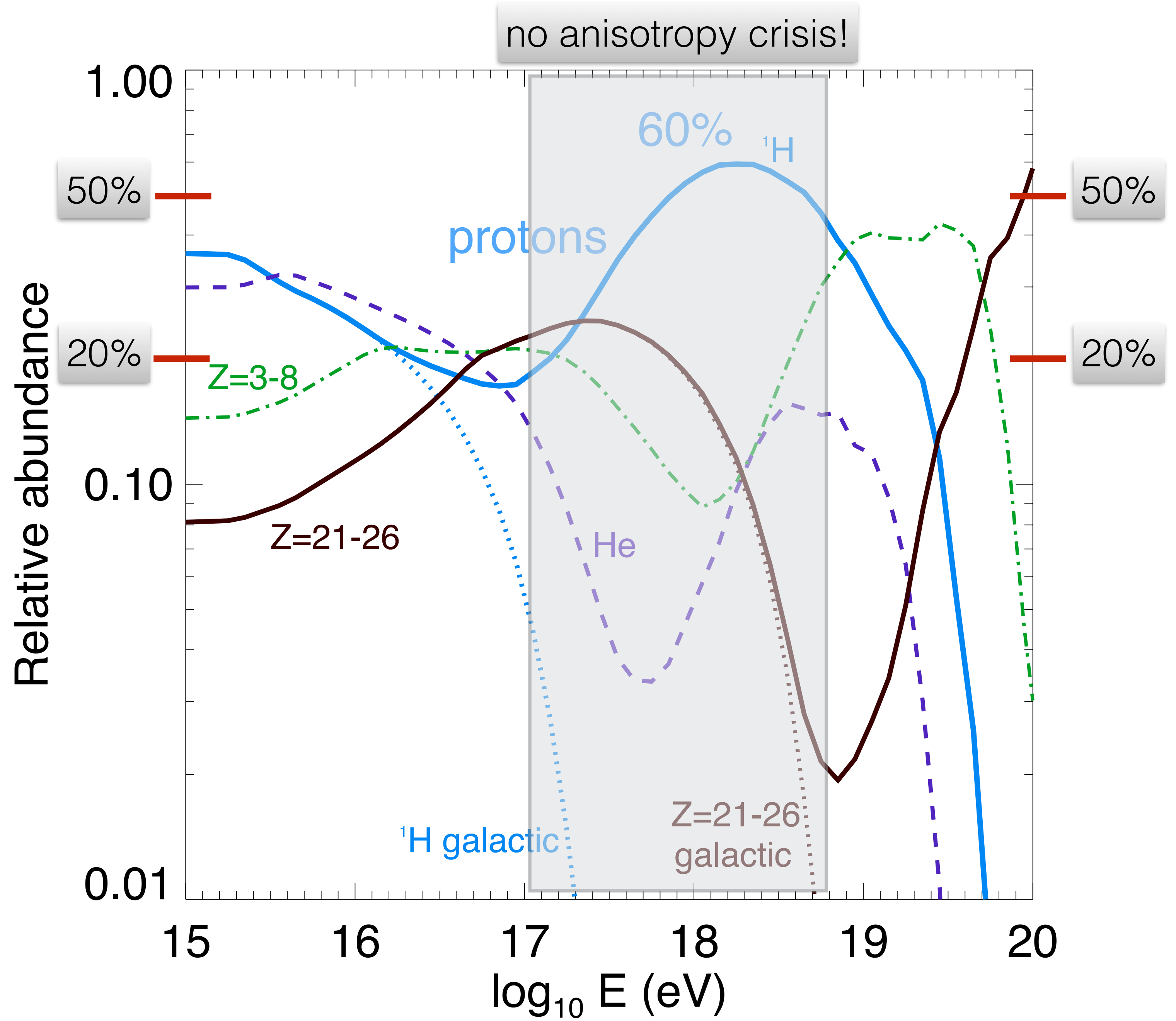
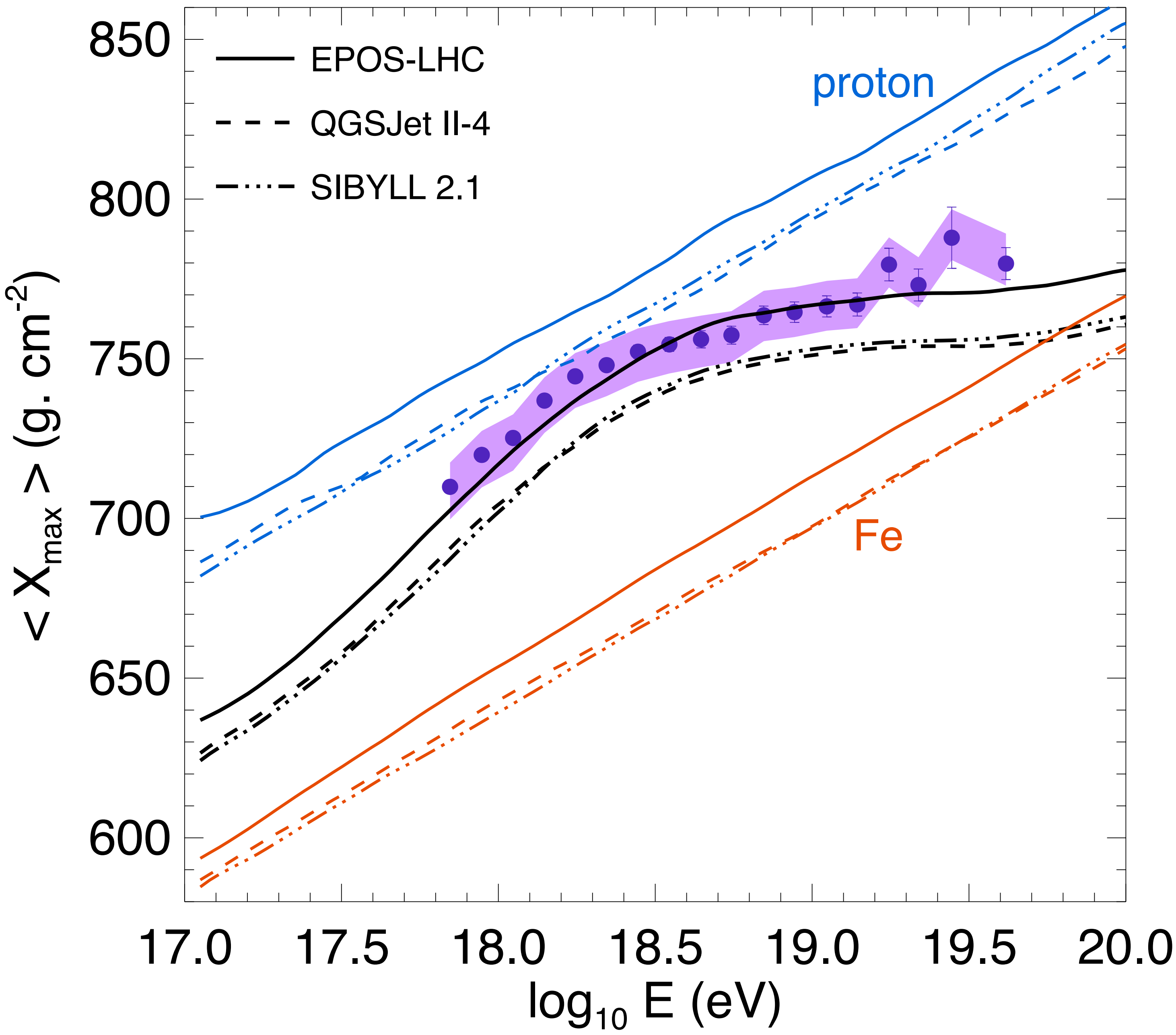


Comparison with Auger results



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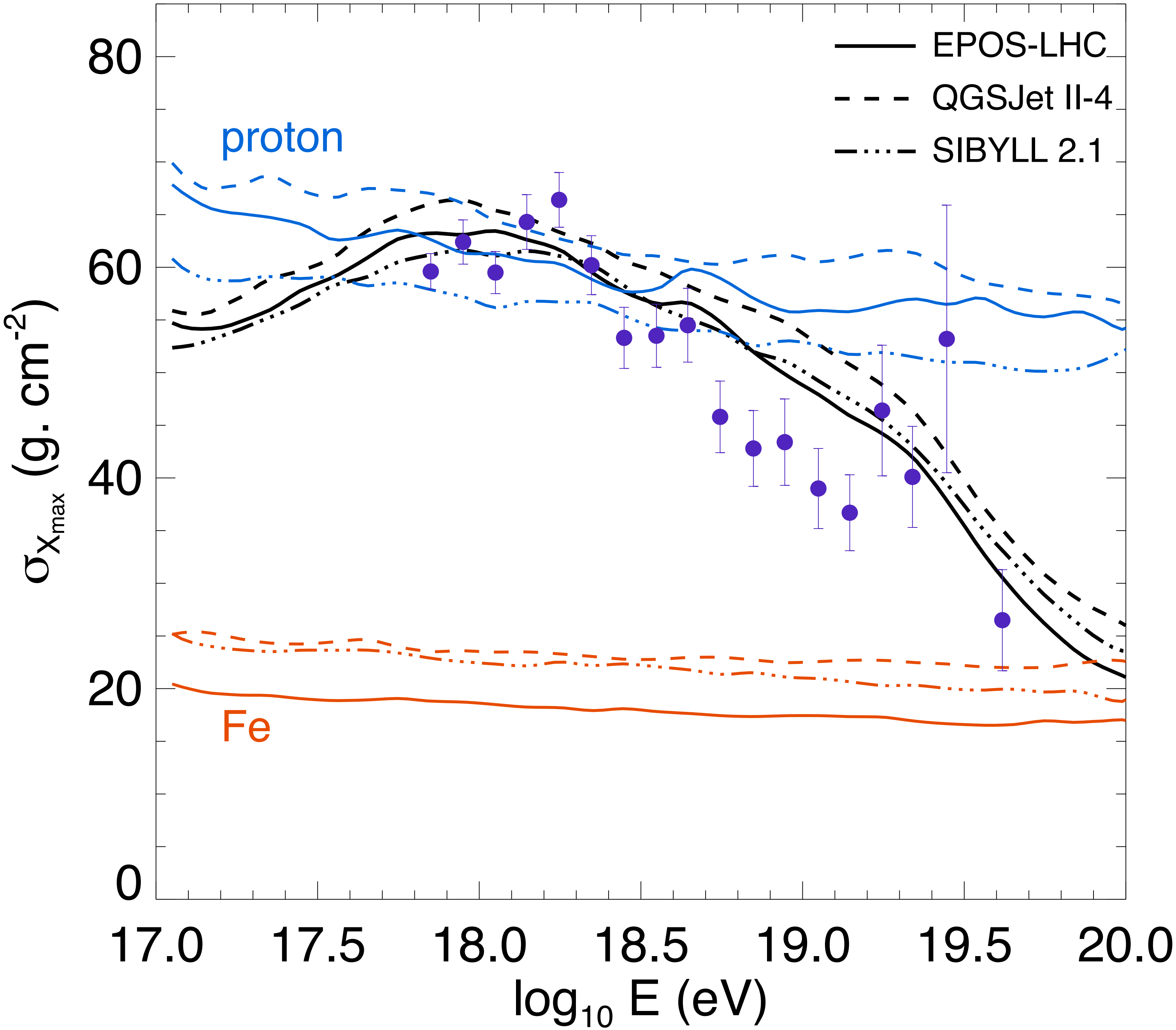

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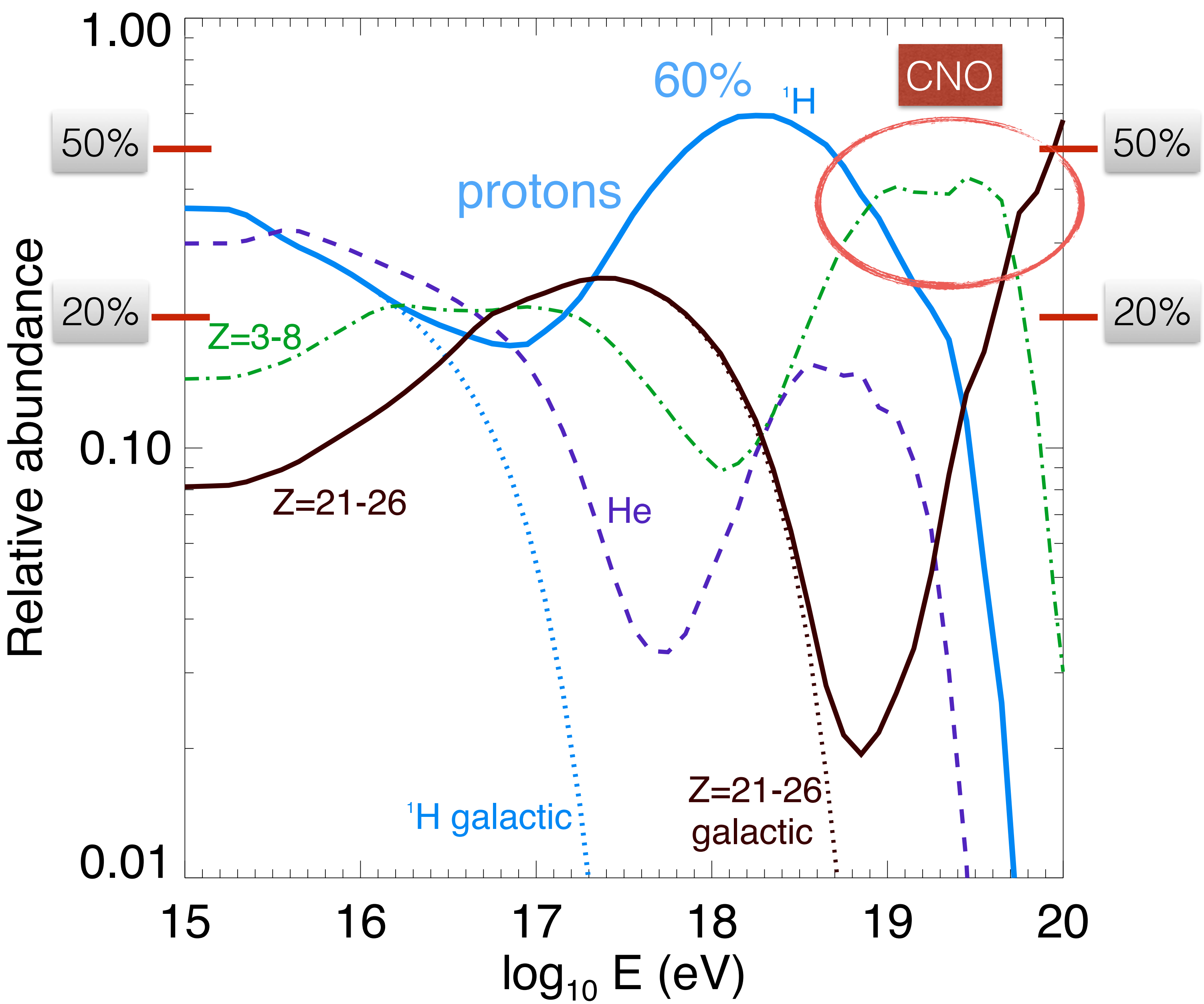


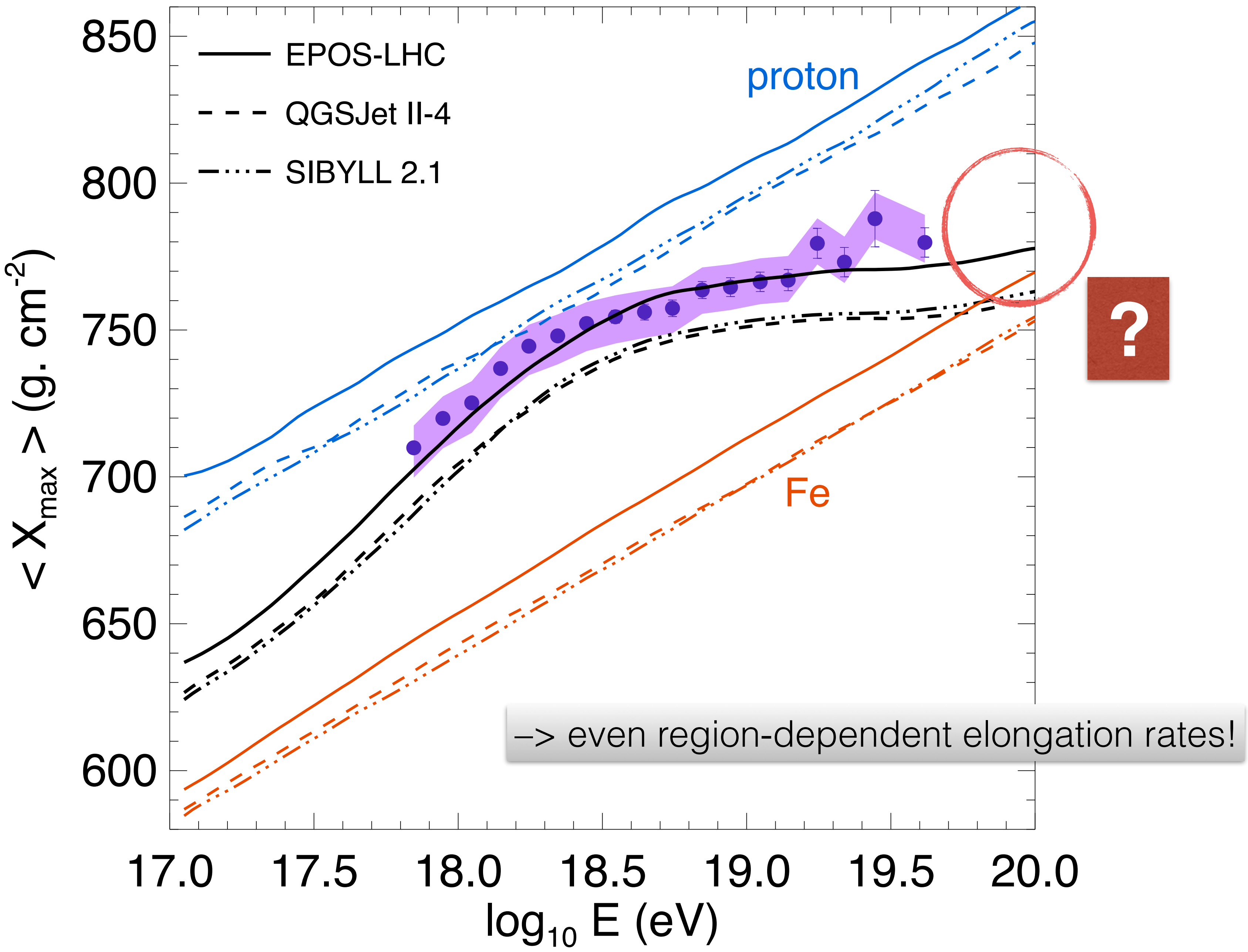
Comments about the composition at highest energies

- CNO is the main class of UHECRs at 10–50 EeV
- The Fe and sub-Fe dominate (> 60 EeV)

- NB: the rigidity of UHECRs is highest at intermediate energies!
  - C at 50 EeV: R = 8.3 EV
  - Fe at 100 EeV: R = 3.8 EV
  - NB: TA hotspot has none of the events with E > 100 EeV

- JEM-EUSO could add crucial data points on the $< X_{max} >$ plot!
  - 10 times Auger => 100 times Auger FD !
  - X_{max} measurement difficult from space, but the error on $< X_{max} >$ will be low!
  - Precision: between 20 g/cm2 (at 50 EeV) and 30 g/cm2 (at 100 EeV)

JEM-EUSO could add crucial points!



Summary

- UHECR acceleration in high photon density environments (at least in our acceleration model at internal shocks of GRBs) produce **hard nuclei spectra** with **low proton E_{max}** and a **much softer proton spectrum**

- The mere superposition of the **only one GCR and one EGCR** components (based on data at the knee and up to the ankle) allows to reproduce both the **spectral and composition features over the whole energy range**

- An important implication is that the Galactic sources must **accelerate protons up to ~50 PeV**: this is a **serious challenge for standard GCR source models** based on diffusive shock acceleration in isolated SNRs

- More data on the CR composition at all energies will be very helpful. **JEM-EUSO could provide crucial data points** in the "elongation rate" plot!

- Extragalactic UHECR studies have **very important implications on the understanding of GCRs and of particle acceleration in the universe**, which is of utmost importance for high-energy astrophysics and astroparticle physics!