ISAPP School 2018 : "LHC meets Cosmic Rays"

CERN, Geneva, Switzerland

(Oct. 29th – Nov. 2nd)

Extragalactic cosmic rays and the Galactic/extragalactic transition

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Mixity & gender equity

Extreme Universe Space Observatory

Overview

- UHECRs: very brief phenomenology
  - Acceleration
  - Propagation
  - Energy spectrum
  - Composition
  - Arrival directions (anisotropies)

UHECR = Ultra-high-energy cosmic rays

- The GCR/EGCR transition
  - What is the issue, why is it important?
  - How can we learn something about it?
  - What can we learn from it?

GCR = Galactic cosmic rays

EGCR = extragalactic cosmic rays

- Lessons from the GCR/GCR transition
  - General phenomenology of a transition
  - Lessons for the GCRs
  - Lessons for the EGCRs
  - An example of a "working", two-component model

Preliminary comment

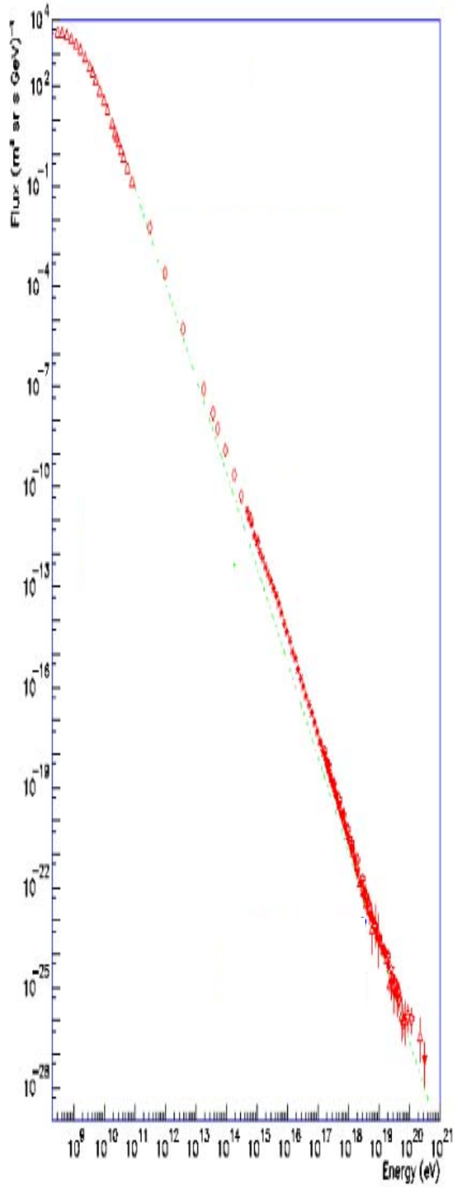
- Cosmic rays gave birth to Particle Physics
  - First window opened onto the subatomic world
  - Discovery of antimatter (1932)
  - Discovery of the muon (1936)
  - Discovery of pions (1947)
  - Discovery of "strange particles", K, Λ, Ξ, Σ… (1949–1953)
- Particle Physics repudiated cosmic rays
  - CERN created in 1954
  - Particle physics doesn't need cosmic rays anymore (so she believes!)
- Cosmic rays are back and welcome!
  - LHC: 10^{13} eV ; UHECRs: 10^{20} eV
  - Particle physics needs cosmic rays
  - Cosmic rays need particle physics (showers)

=> "LHC meets cosmic rays"… again!

- But cosmic rays are also interesting for themselves!

Cosmic rays

> 12 orders of magnitude!



4 per cm^2 per second

32 orders of magnitude (/m^2/sr/GeV)

1 per m^2 per billion years

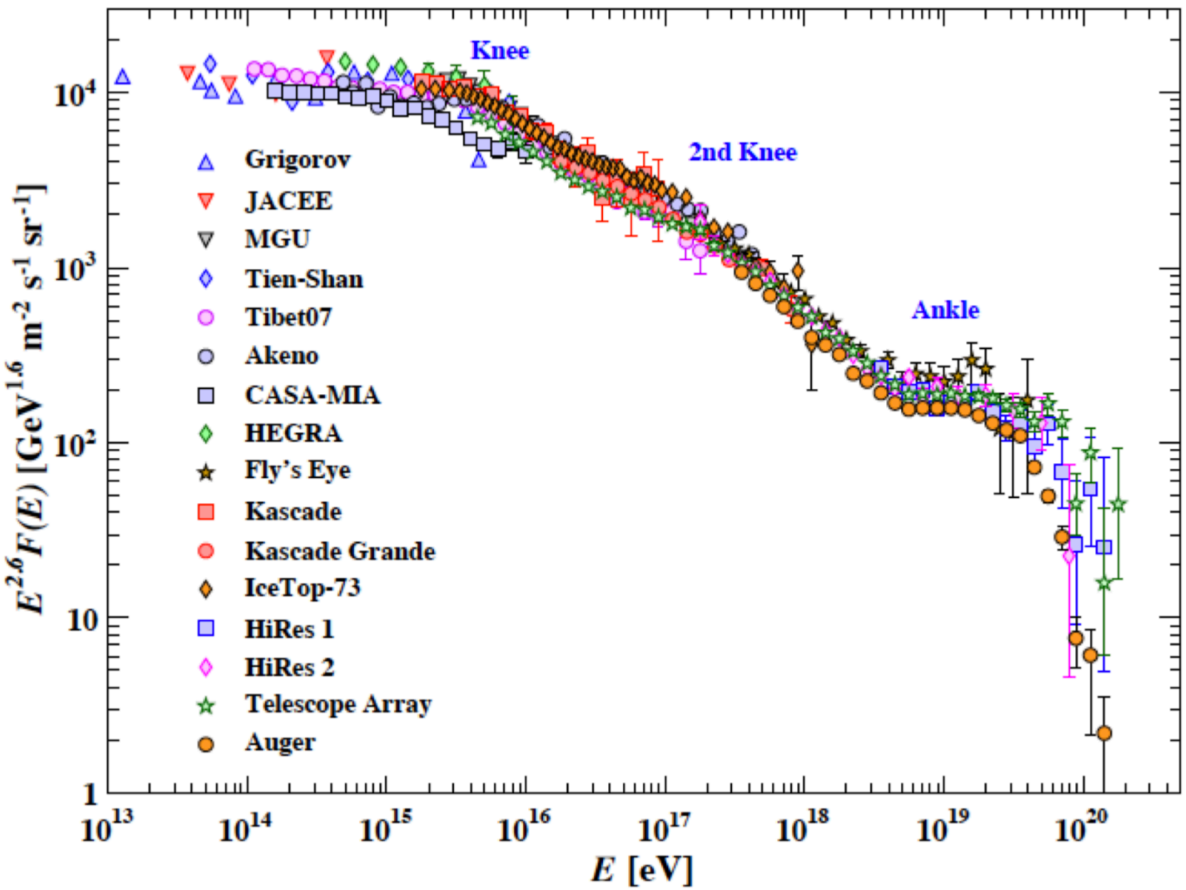
- **Major phenomenon !**
  - Universal
  - Out of equilibrium!!!
- **Major role in Galactic ecology !**
  - Energy density ~ star light, thermal, B field
  - Regulate the equilibrium between the different phases of the interstellar medium
  - Control ionisation, heating
  - Regulate star formation
  - Control astrochemistry
  - Generate turbulent magnetic field
  - Produce Li, Be and B!
- **Major unknown !**
  - Sources are unknown (Galactic and Extragal.)
  - Acceleration processes are uncertain

#IMHO: CRs are so important that our current state of ignorance is truly exciting!

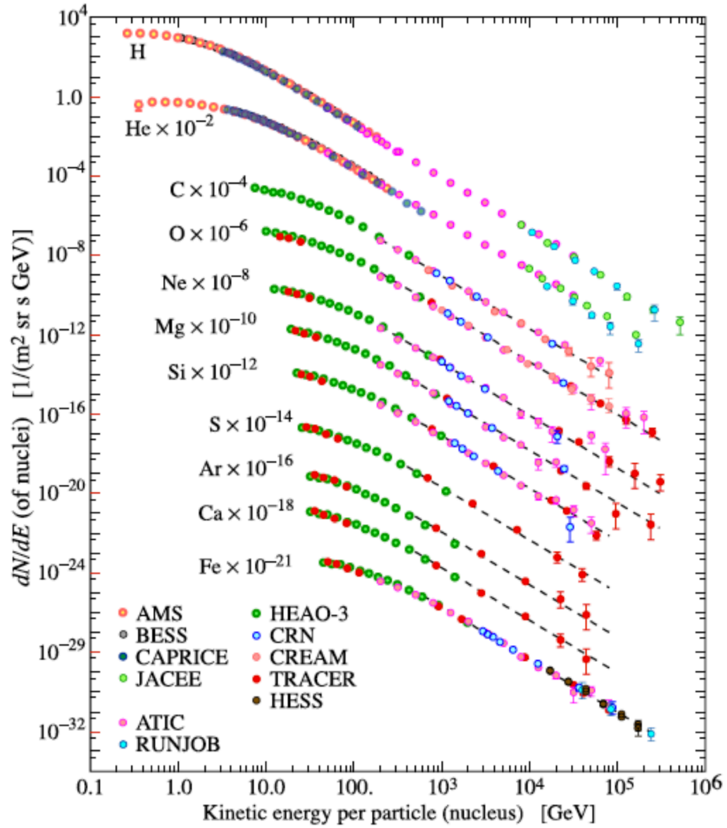
Cosmic rays

- A few significant structures

→ clues to understand/constrain underlying phenomena



NB: at "low" energy:



GCR/EGCR transition (1)

Galactic cosmic rays

extragalactic cosmic rays

GCR/EGCR transition

- Low-energy cosmic rays are Galactic!
  - Many possible sources → how could extragalactic sources dominate?

    Superbubbles, SNRs, pulsars, magnetic reconnection, AGN episodes, starburst episodes, GRBs, TDEs, etc.

  - Observational proof:

    Magellanic clouds have a lower gamma-ray emissivity from π^0 decay than the Milky-Way => lower cosmic ray flux => ∃ internal Galactic sources

    CR flux in LMC ~ 15% of GCR flux (even lower in SMC)

- Very-high-energy cosmic rays are (almost certainly) extragalactic
  - Loss of confinement in the Galaxy and its magnetic halo
  - Large anisotropy would result from active Galactic sources

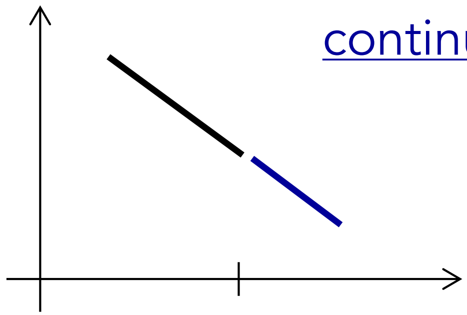
- So there must be a transition somewhere!

  → where?

Transition between two components

- Case 1: Same spectrum
  - Case 1.a: Same normalisation

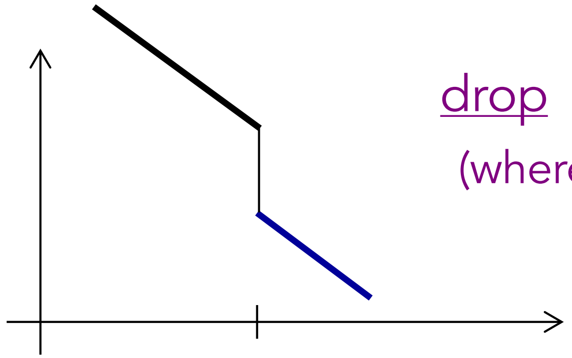
    very unlikely!



continuity

(→ Which one is which?)

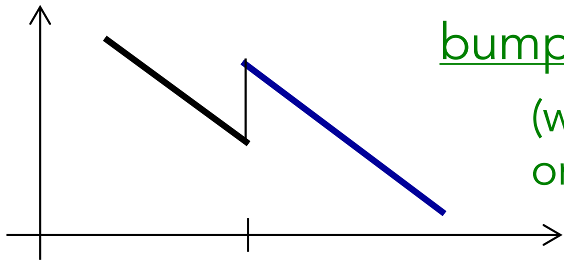
  - Case 1.b: First one is higher



drop

(wherever the first one stops)

  - Case 1.c: First one is lower

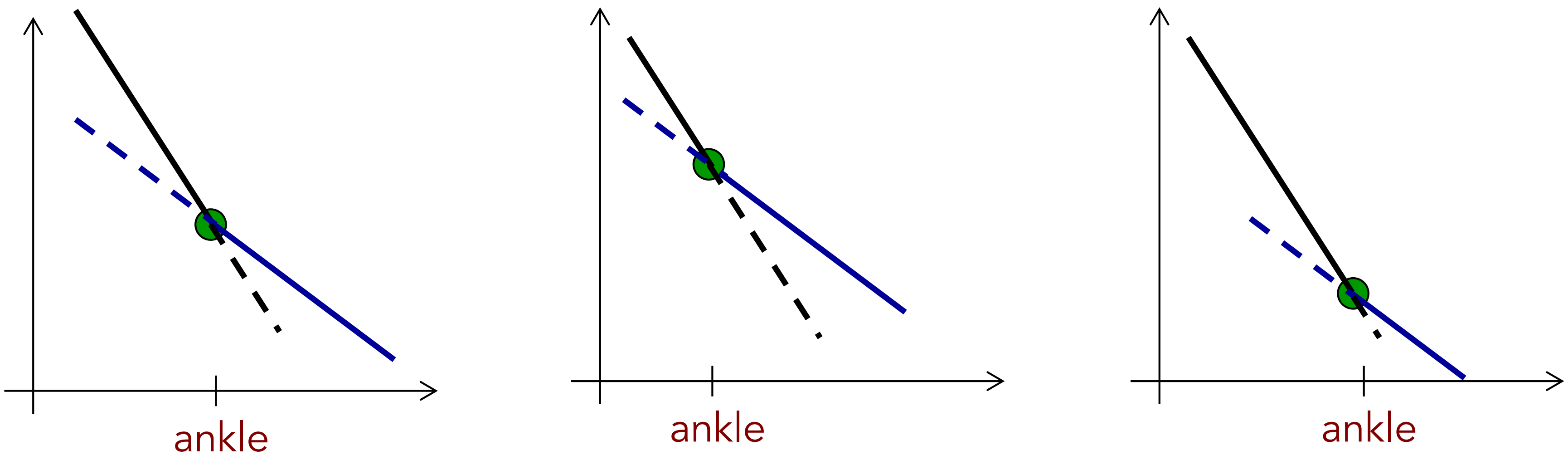


bump

(wherever the second one starts)

Transition between two components

✧ Case 2: from steeper to flatter, i.e. "ankle-like"

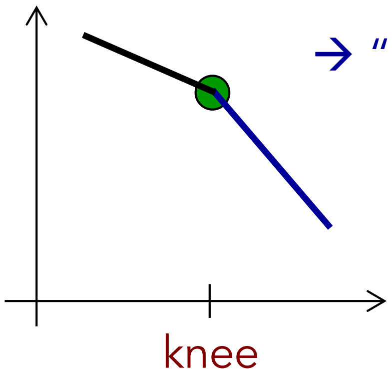


Produces an ankle at whichever energy where the second one overcomes the first one

→ very natural and simple phenomenology

Transition between two components

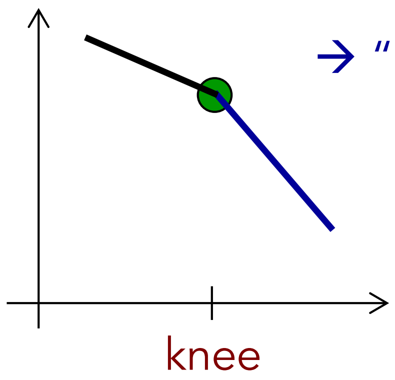
- Case 3: from flatter to steeper



→ "knee-like"?

Transition between two components

- Case 3: from flatter to steeper



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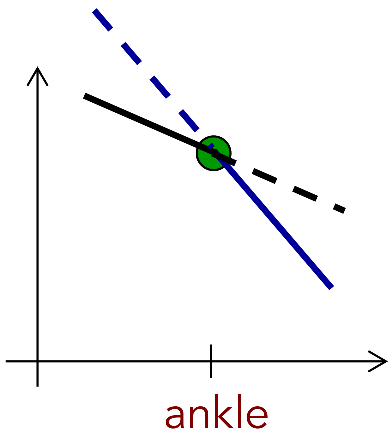
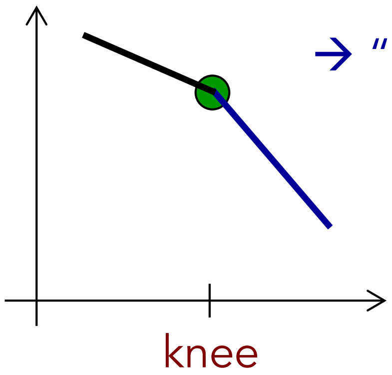


In fact no!

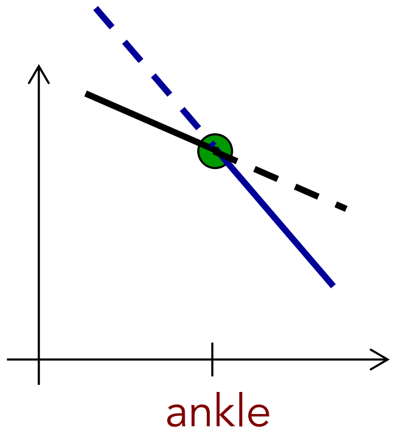
Ankle-like!

Transition between two components

- Case 3: from flatter to steeper



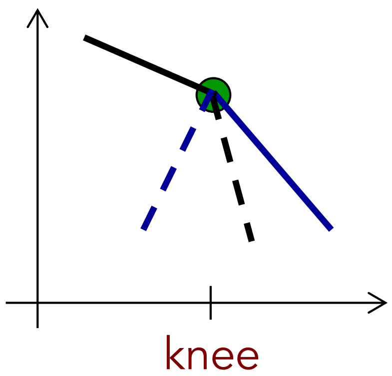
→ "knee-like"?

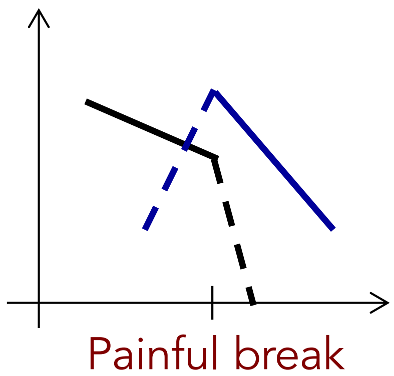


In fact no!

Ankle-like!

Unless the second one starts "exactly" where the first one stops…



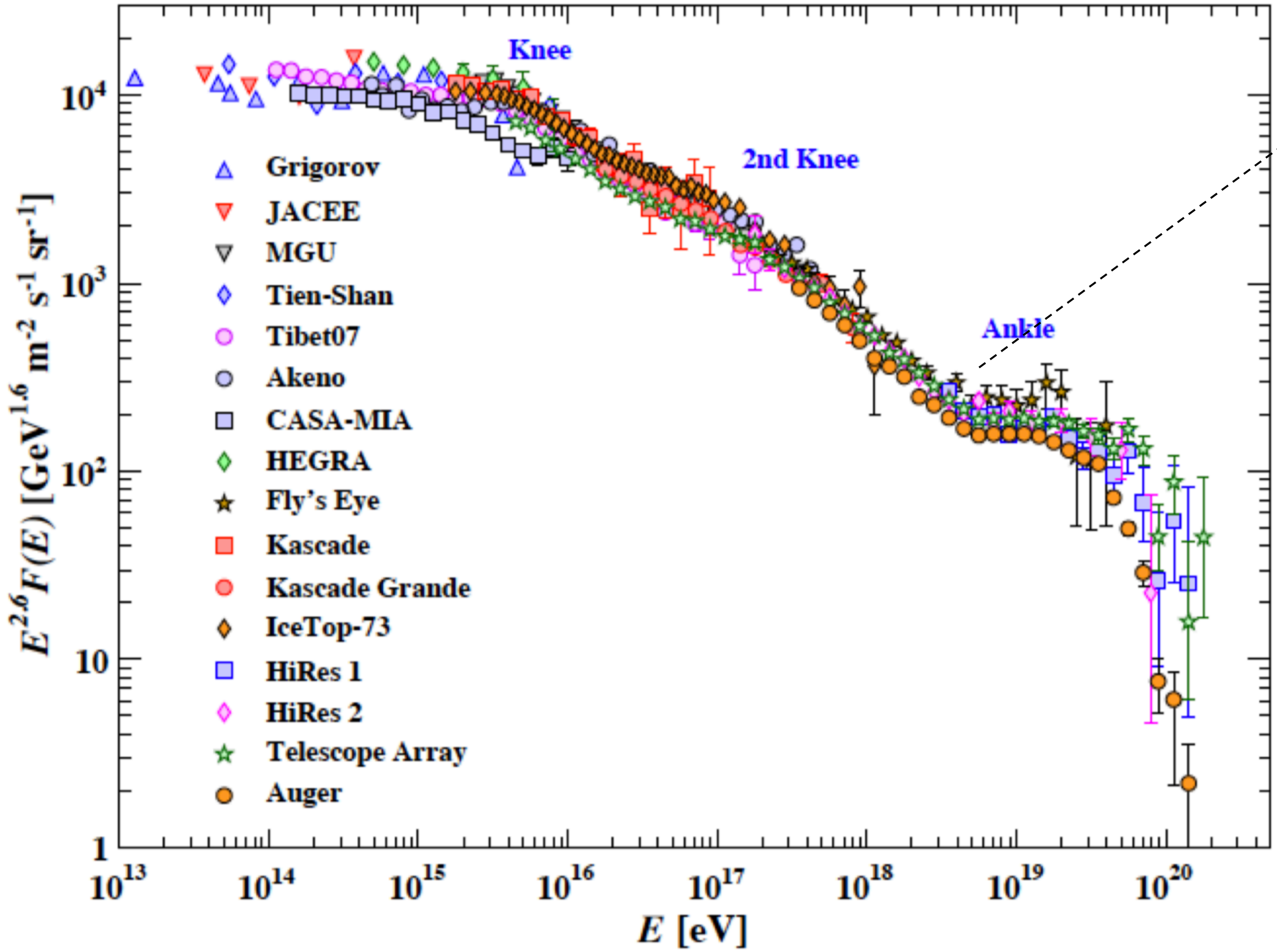


… and with the same flux!

=> very unlikely!

Transition in the data?

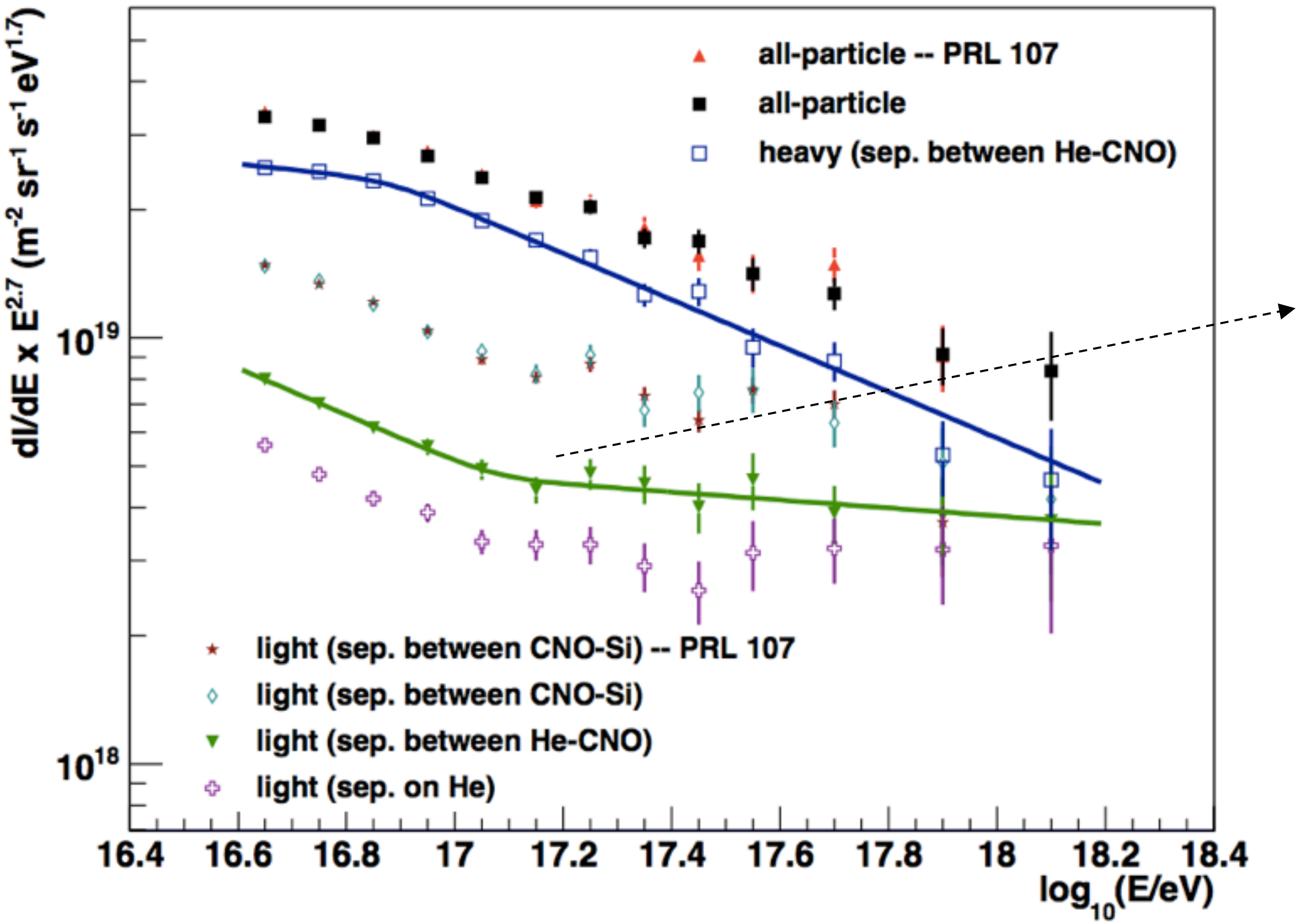
- All-particle data: there is an ankle indeed!



Natural candidate for the GCR/EGCR transition!

Transition in the data?

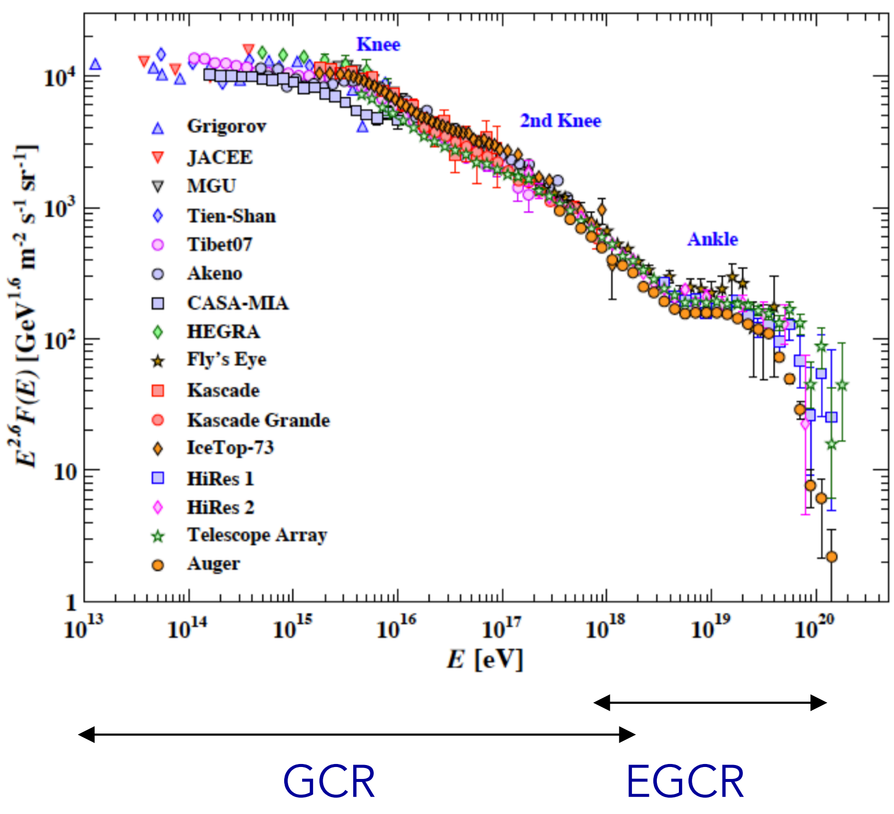
✧ KASCADE-Grande data: evidence for a "light-ankle" (protons?)



Natural candidate for a GCR/EGCR transition in the light component!

GCR/EGCR transition: a key issue!

- Immediate consequences
  - EGCRs must go as low in energy as the transition!
  - GCRs must go as high in energy as the transition!



- Forget PeVatrons: think EeVatrons!
  - Galactic sources must accelerate particles to much high energies than the knee → crucial constraint!
- Magnetic confinement
  - Galactic magnetic field should confine particles up to the ankle!
- Magnetic horizon
  - Extragalactic magnetic field should <u>not</u> prevent ankle particles from reaching us from extragalactic sources
- EGCR flux level & UHECR spectrum!

UHECRs:
crash course summary

UHECRs: crash course summary

- Observables: 3 spectral dimensions
  - Energy → energy spectrum
  - Nature of the cosmic ray → composition (or mass spectrum)
  - Arrival direction → anisotropies, angular spectrum
- Acceleration
  - What are the sources?
  - What is the acceleration process?
  - What is the power imparted to cosmic rays?
  - What is the energy spectrum at and out of the source?
  - What is the maximum energy? (or energies!)
  - What is the source composition?
- Propagation
  - Modification of the spectrum: energy losses
  - Modification of the composition: nucleon losses
  - Modification of the trajectories: pointing losses

UHECRs: crash course summary

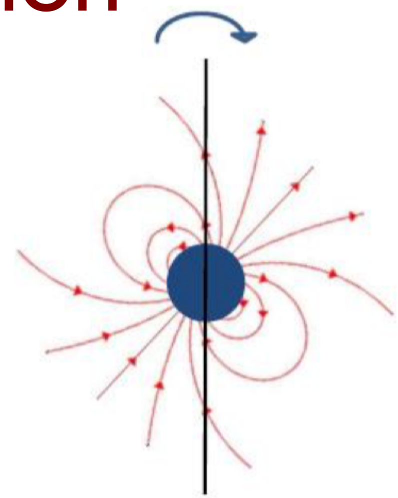
- Observables: 3 spectral dimensions
  - Energy → energy spectrum
  - Nature of the cosmic ray → composition (or mass spectrum)
  - Arrival direction → anisotropies, angular spectrum

Revolutionary data since ~10 years
New generation of detectors needed

- Acceleration
  - What are the sources? — Unknown
  - What is the acceleration process? — Unknown
  - What is the power imparted to cosmic rays? — few 10^{44} erg Mpc^{-3} yr^{-1}
  - What is the energy spectrum at and out of the source? — Unknown
  - What is the maximum energy? (or energies!) — Unknown
  - What is the source composition? — Unknown

- Propagation
  - Modification of the spectrum: energy losses — Well understood
  - Modification of the composition: nucleon losses — Well understood
  - Modification of the trajectories: pointing losses — Well understood, but unknown magnetic field!

Energy dimension: acceleration



- Acceleration up to 10^{20} eV is VERY challenging!
  - No permanent E fields in the universe, except at "machines" like pulsars/magnetars

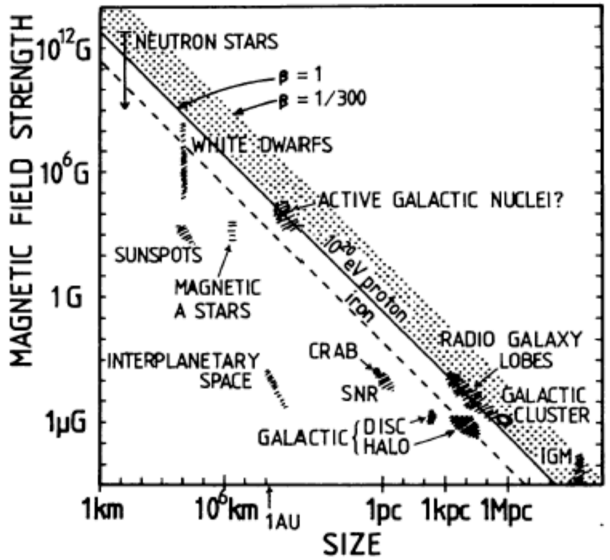
    $E_{max} < B\Omega R^2$

  - Transitory E fields: reconnection
  - "Change-of-frame acceleration" (shock waves + turbulence)
  - $E_{max} < ZuBL$
- Confinement problem
  - Keep the particles in the accelerator!

    $E_{max} < ZuBL$

  - => large magnetic fields and/or large size needed!

Hillas 1984



Energy dimension: acceleration

- Acceleration up to 10^{20} eV is VERY challenging!

- Source power
  - Magnetic energy passing through the source

$$P_{mag} = uL^2 \left(\frac{B^2}{2\mu_0}\right)$$

  - Minimum power requirement:

$$E_{\max} < ZuBL \longrightarrow P_{source} > P_{mag} = \left(\frac{Z}{6}\right)^{-2} \left(\frac{E_{\max}}{100\mathrm{EeV}}\right)^{2} \left(\frac{u}{c}\right)^{-1} 4 \times 10^{42}\ \mathrm{erg\ s^{-1}}$$

- Put in efficiencies and loss processes!

- Conclusion: VERY challenging indeed… especially for protons!

But E_{max} (Fe) = 26 × E_{max} (proton) (if no losses or photo-dissociation)

Energy dimension: propagation

(= transport from the sources to the Earth)

- Interaction of Galactic cosmic rays with the ambient medium
  - At low energy: spallation, ionisation losses, Bremsstrahlung, pion production, Inverse Compton… (cf. Pasquale Blasi's lecture)
  - At high energy, say above 10 GeV : negligible!

(GRCs leak out of the Galaxy unaffected)

- Steepening of GCR spectrum through energy-dependent confinement

Simplified propagation equation ("leaky box")

$$\frac{\mathrm{d}N(E)}{\mathrm{d}t} = Q(E) - \frac{N(E)}{\tau_{\rm esc}(E)}$$

source term

$$Q(E) \propto E^{-x}$$

confinement time

$$\tau_{\rm esc}(E) \propto E^{-a}$$

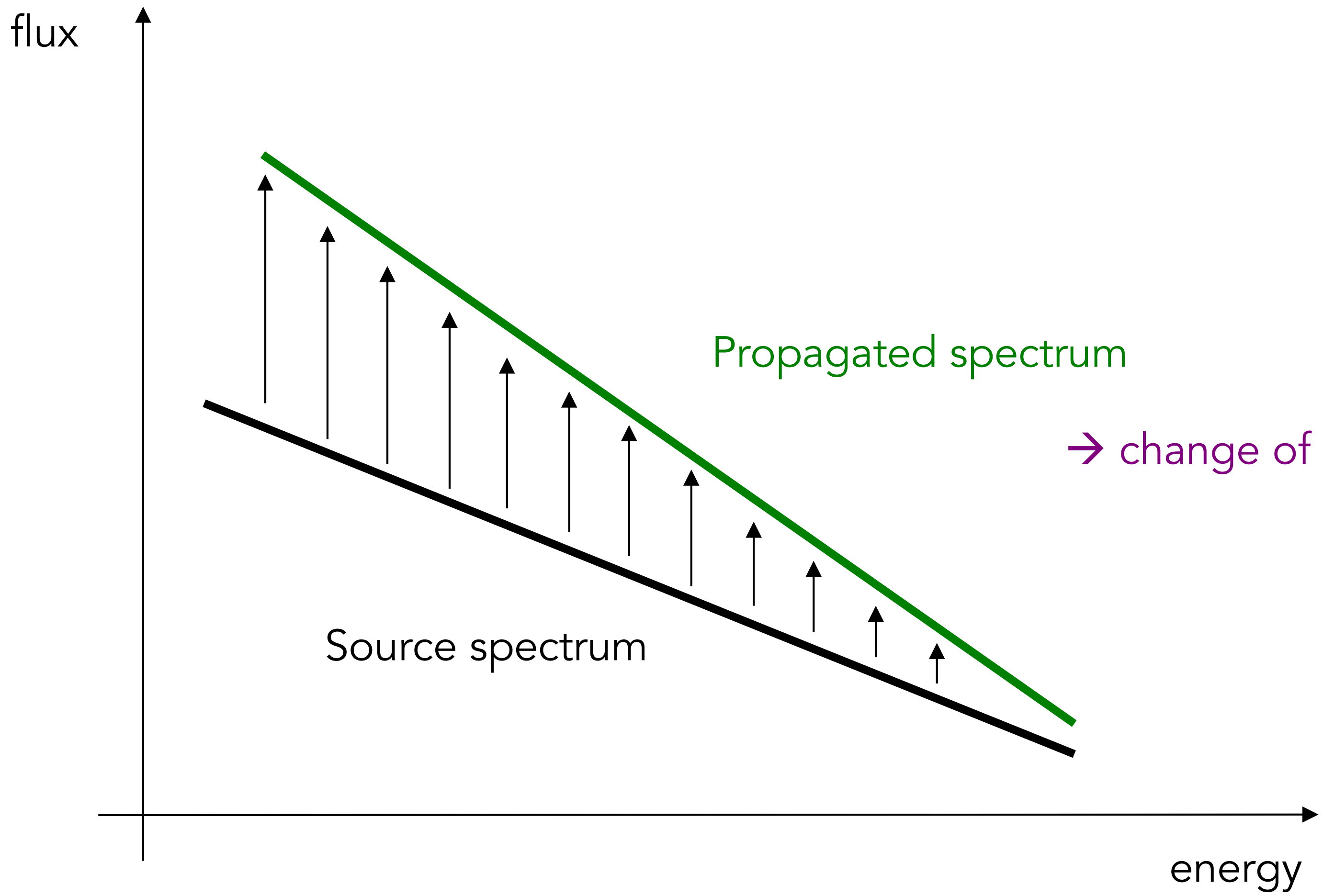
Steady state solution

$$N(E) = Q(E) \times \tau_{\rm esc}(E)$$

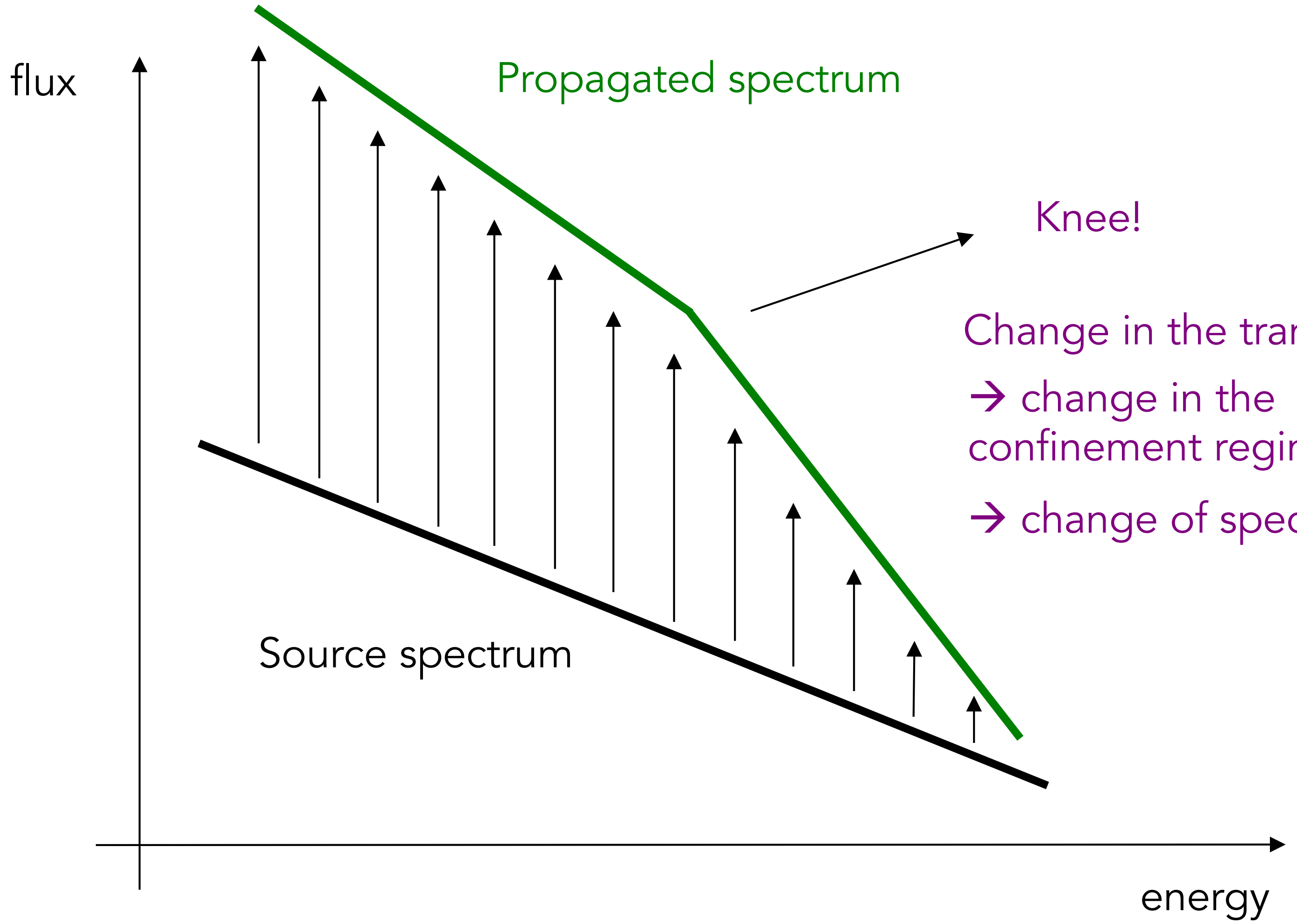
steeper spectrum:

$$N(E) \propto E^{-(x+a)}$$

Energy dimension: propagation



Energy dimension: propagation



Knee!

Change in the transport regime

→ change in the confinement regime!

→ change of spectral index!

UHECR propagation

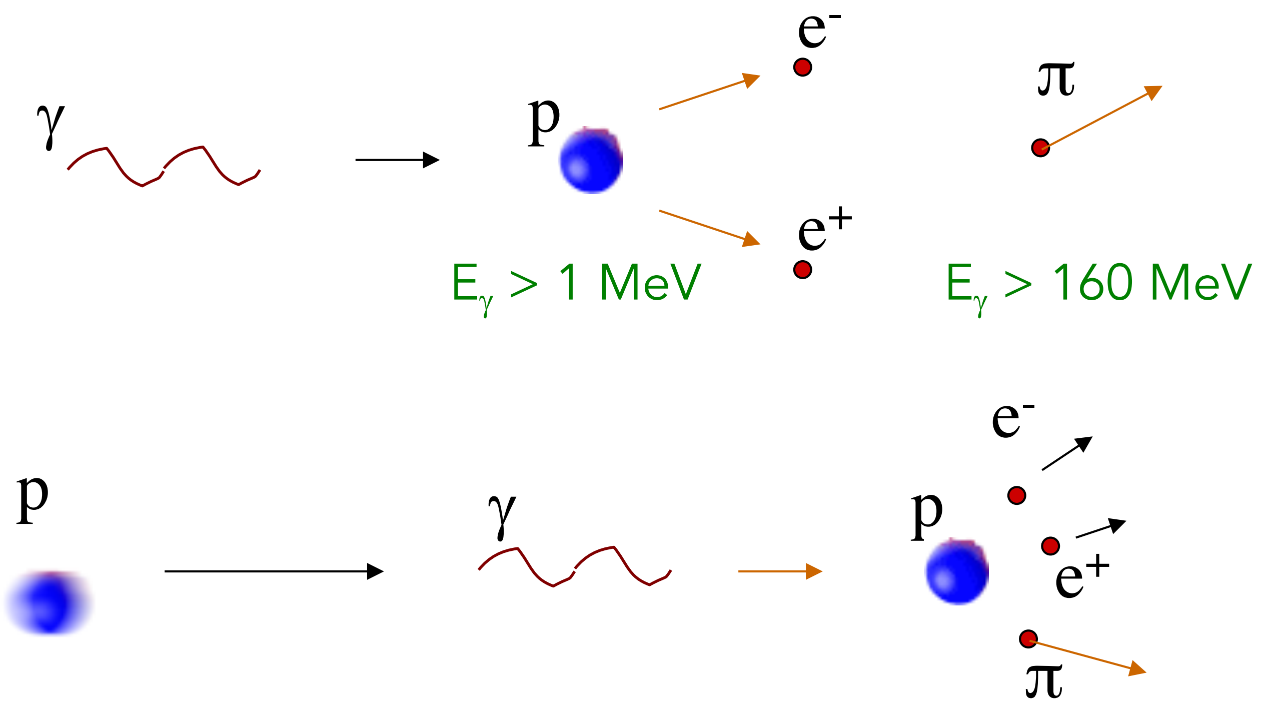
- Interaction of extragalactic cosmic rays with the ambient medium
  - It's almost empty… but full of photons! → The GZK effect! (Greisen, Zatsepin, Kuz'min)

Cosmological microwave background (CMB)

UHE protons

Proton rest frame

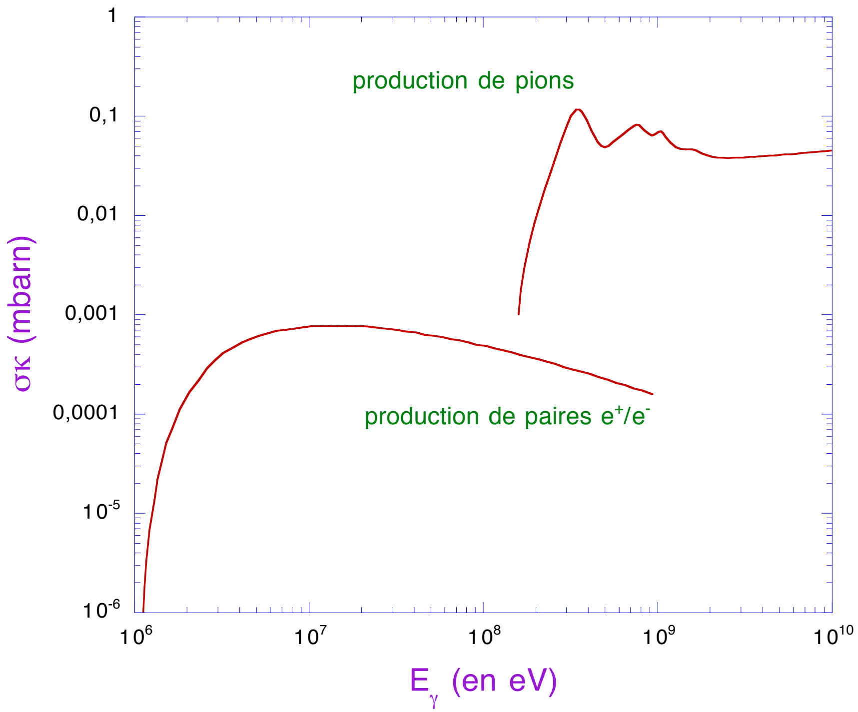
"Cosmic frame"



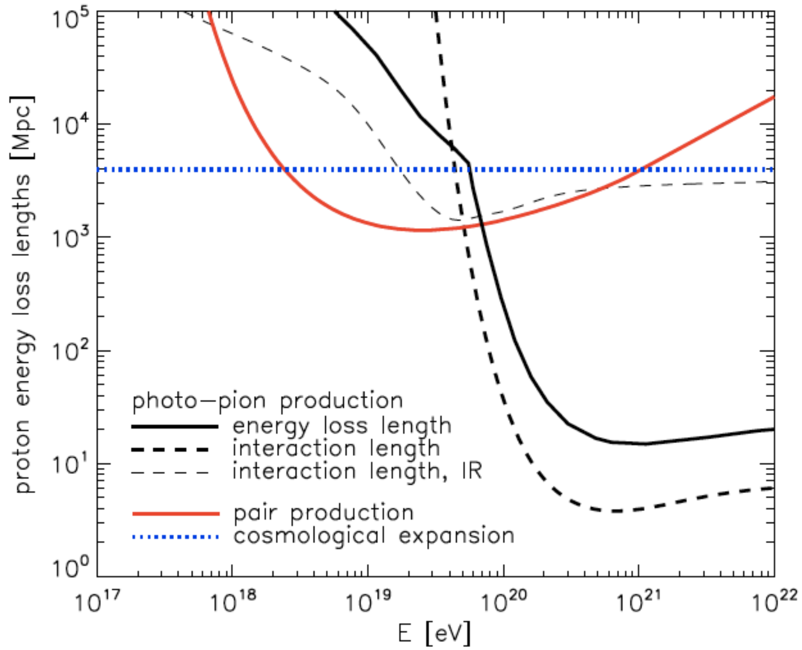
UHECR propagation

- The GZK effect for protons

[cross section] x [inelasticity]



Attenuation length



UHECR propagation

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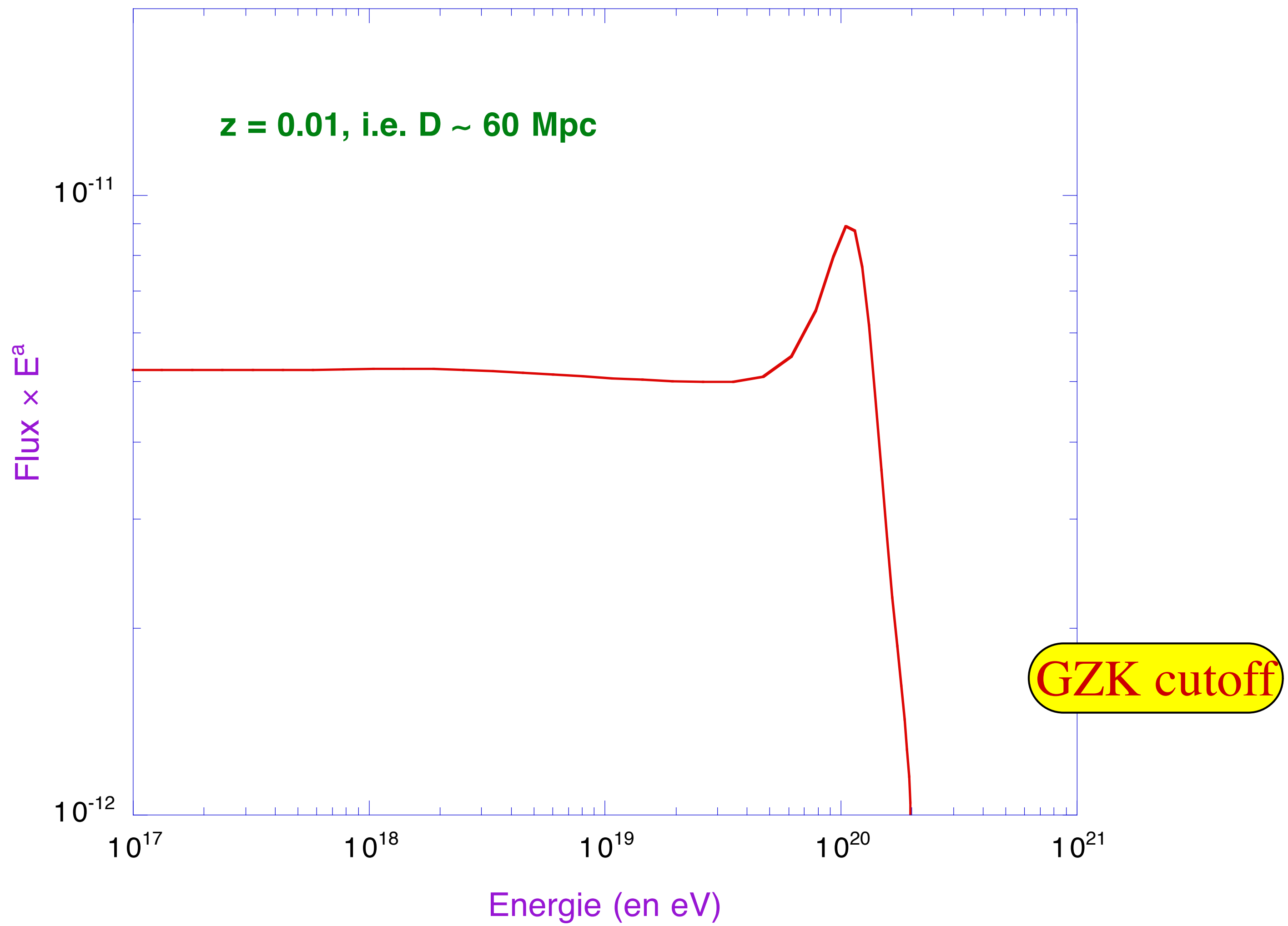

UHECR propagation

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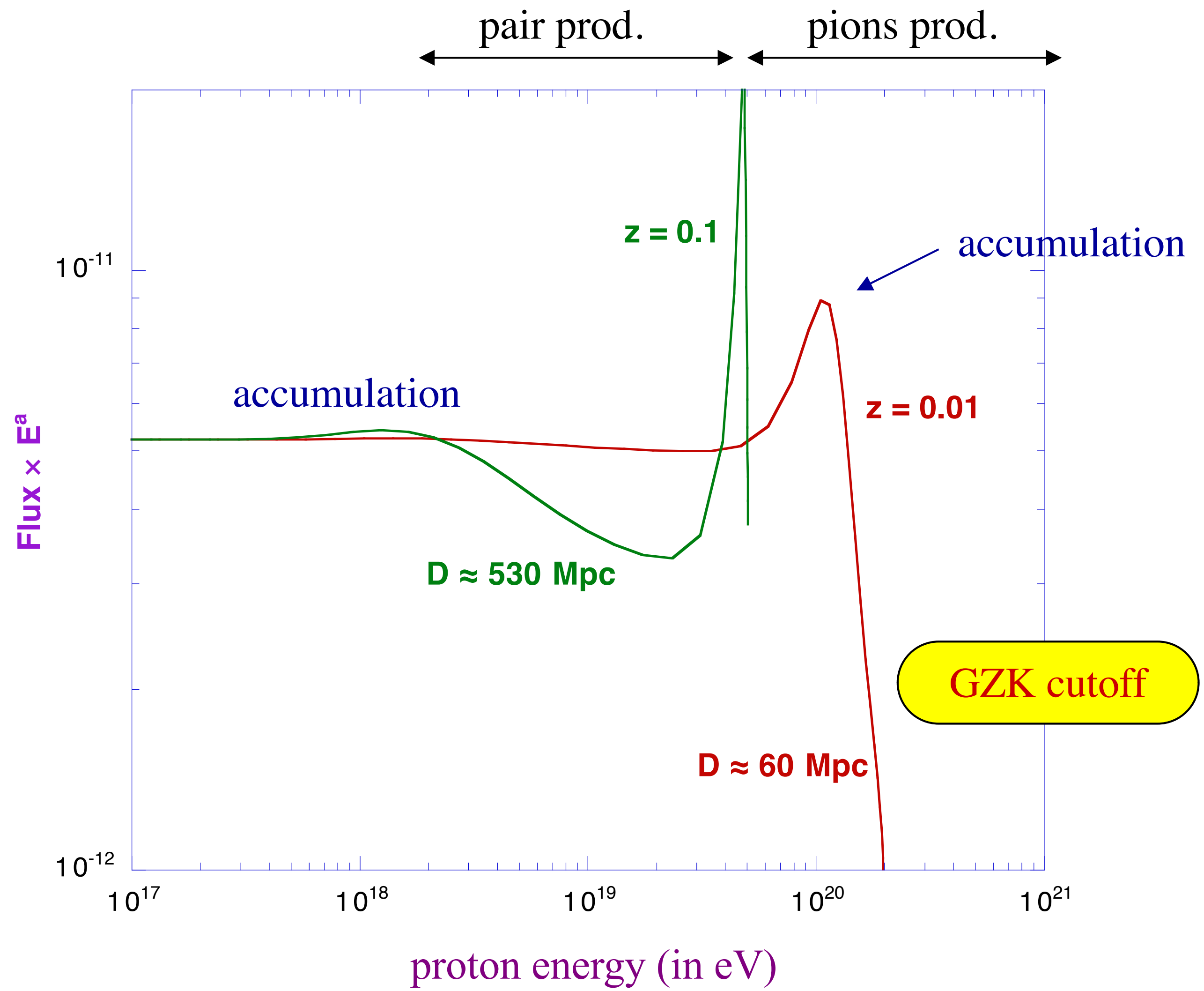
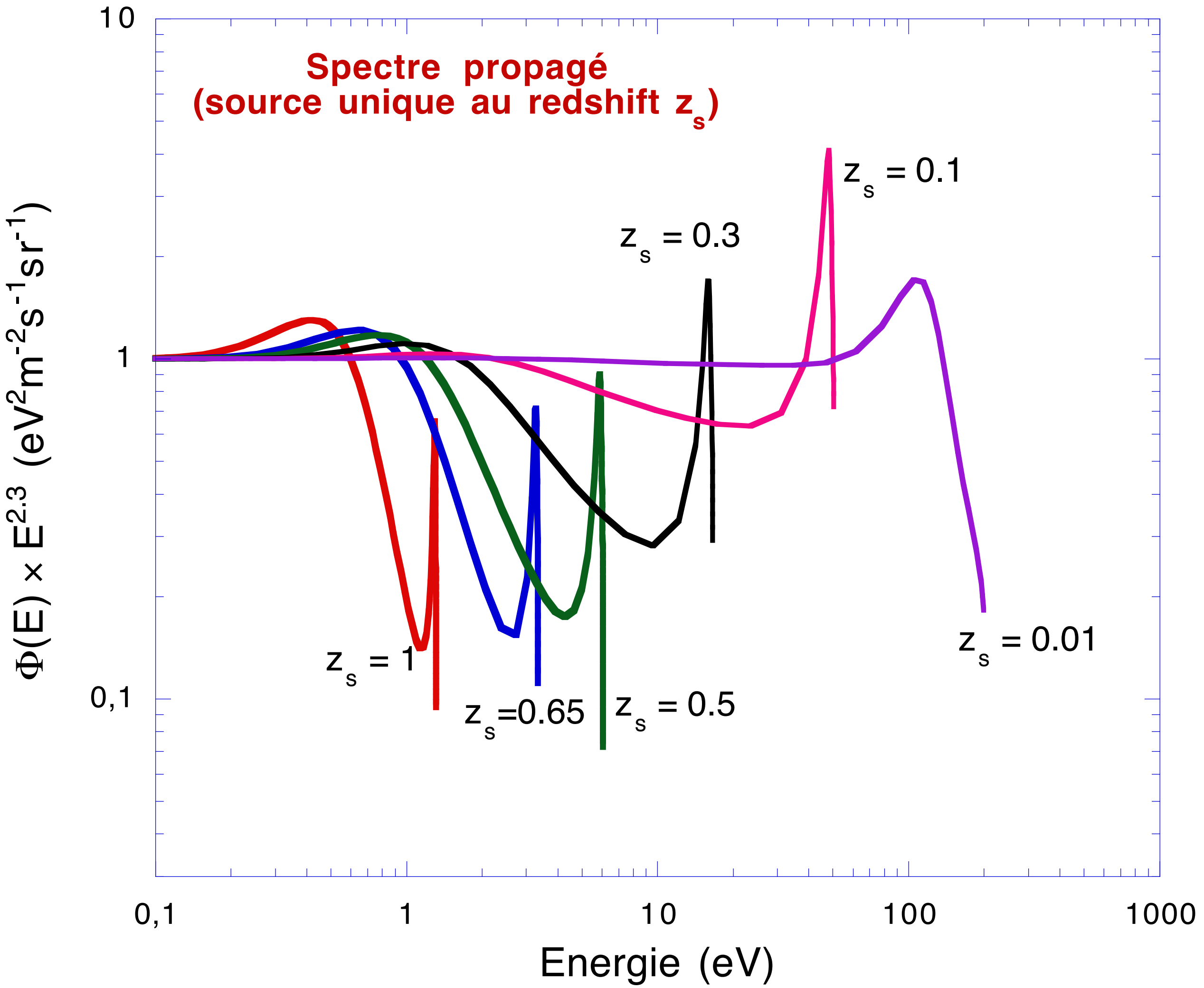


UHECR propagation

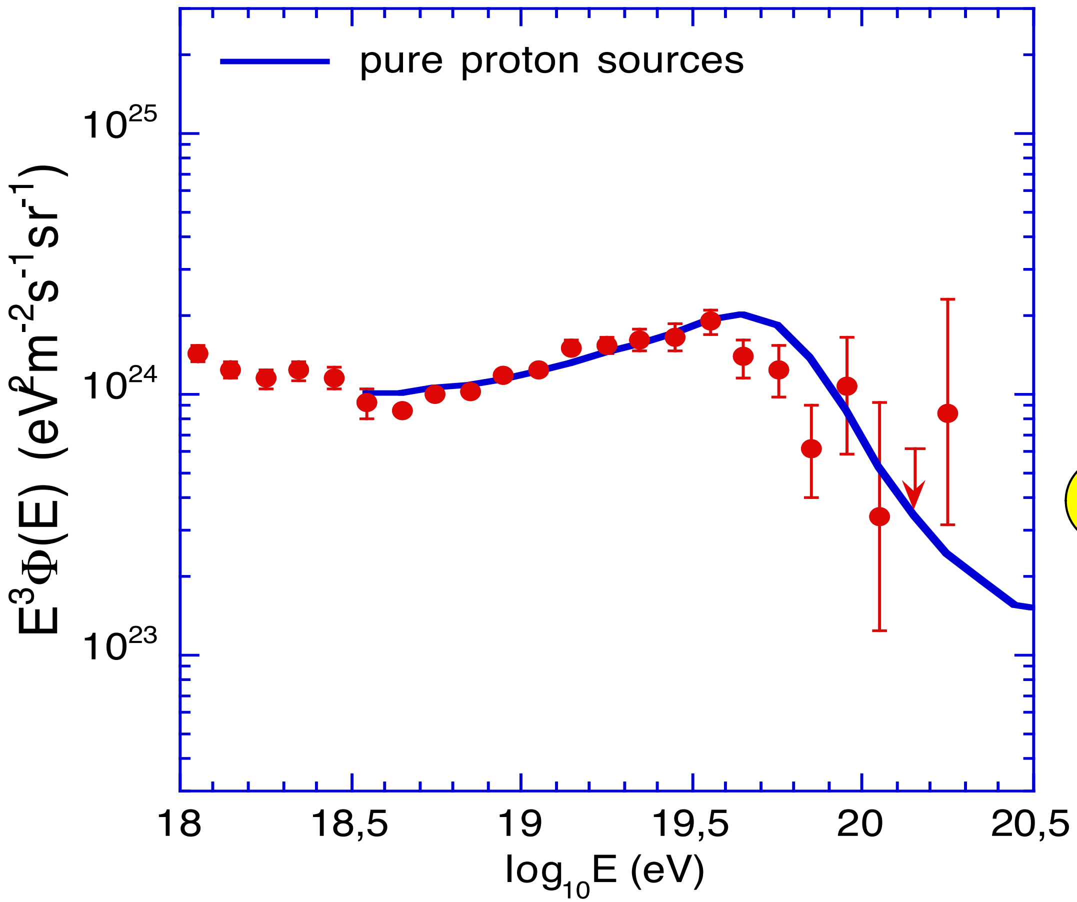
- The GZK effect for protons



UHECR propagation

- The GZK effect for protons

With a uniform source distribution



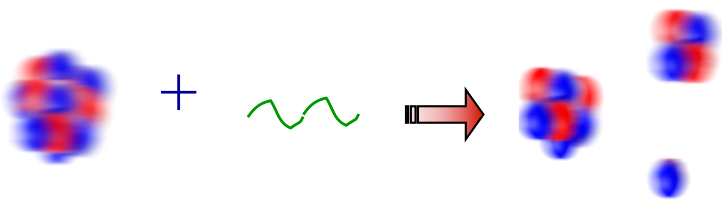
GZK suppression

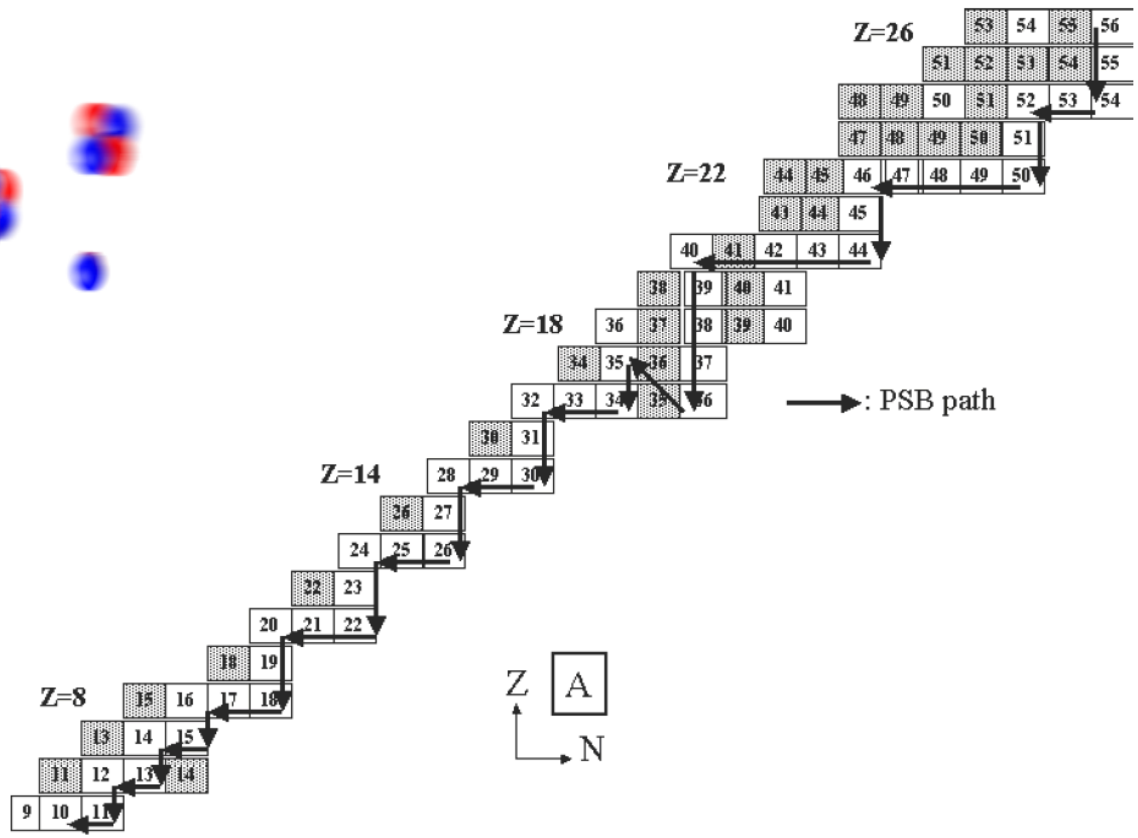
UHECR propagation

- The GZK effect for nuclei

  Nuclei interact with CMB and IR photons

  → photo-dissociation + energy losses





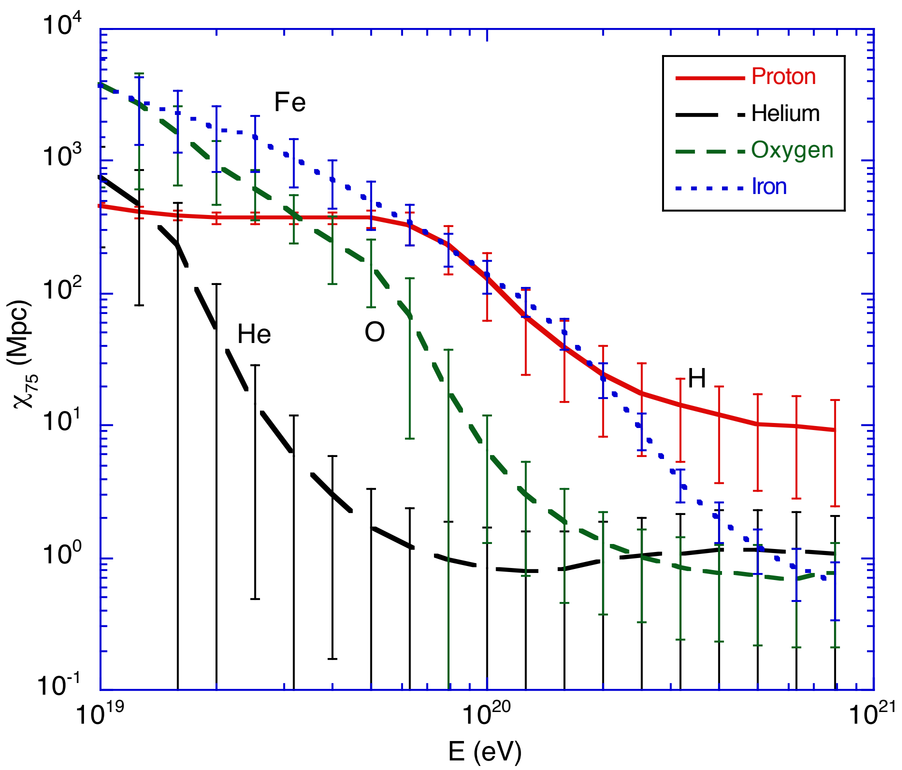
- Nuclear cascade in the intergalactic medium

UHECR propagation

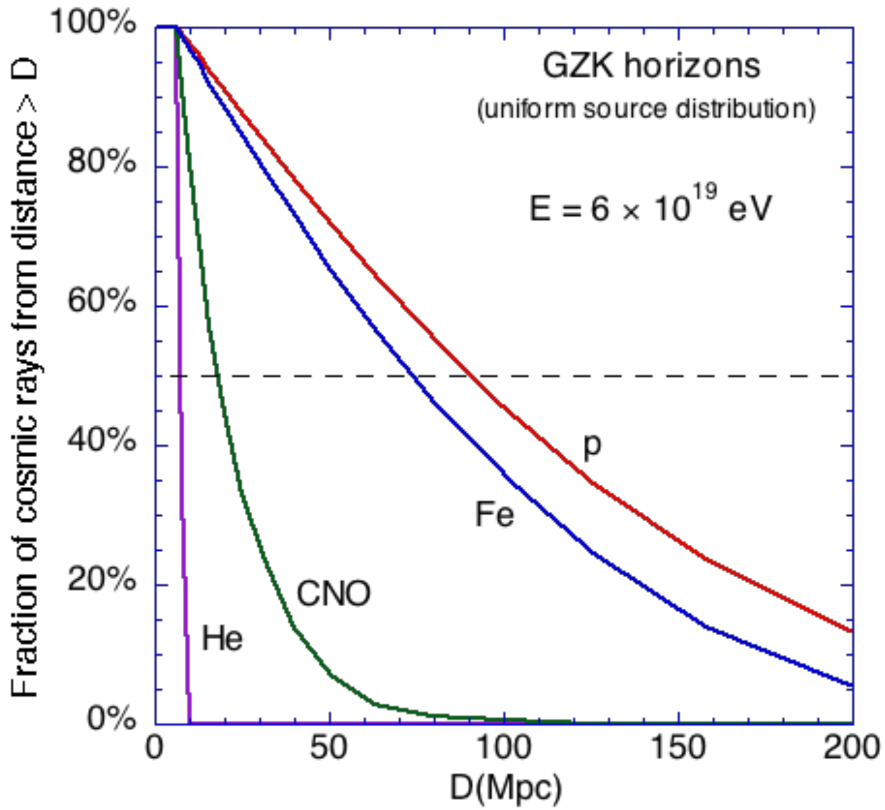
- The GZK effect for nuclei

Horizon effect, similar to that of protons

Attenuation length

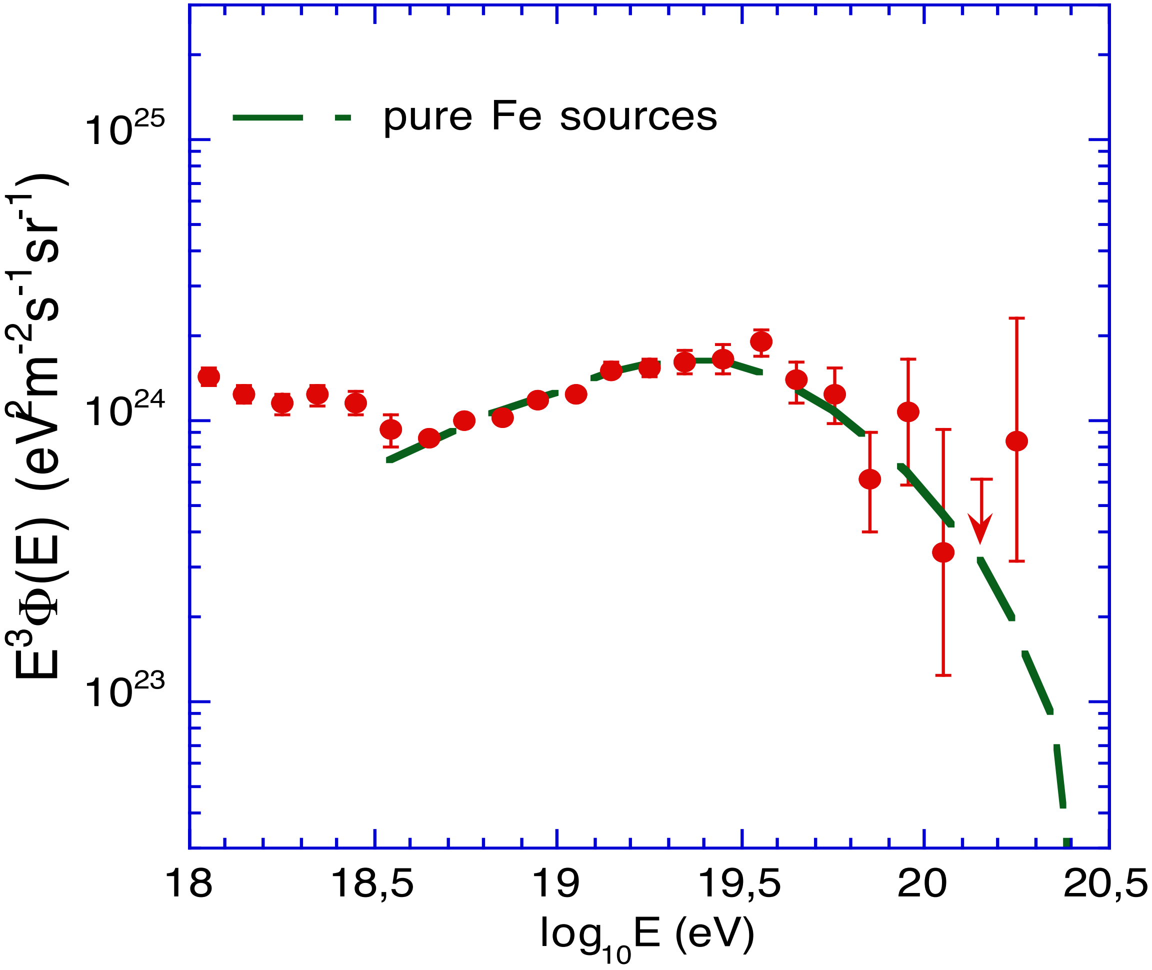


Horizon effect



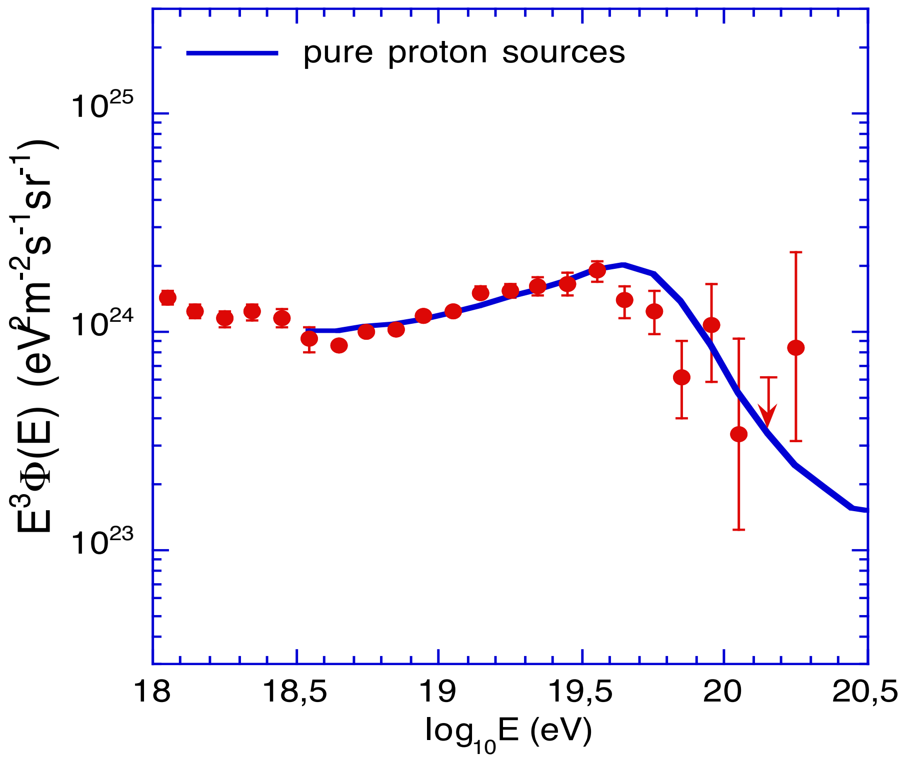
UHECR propagation

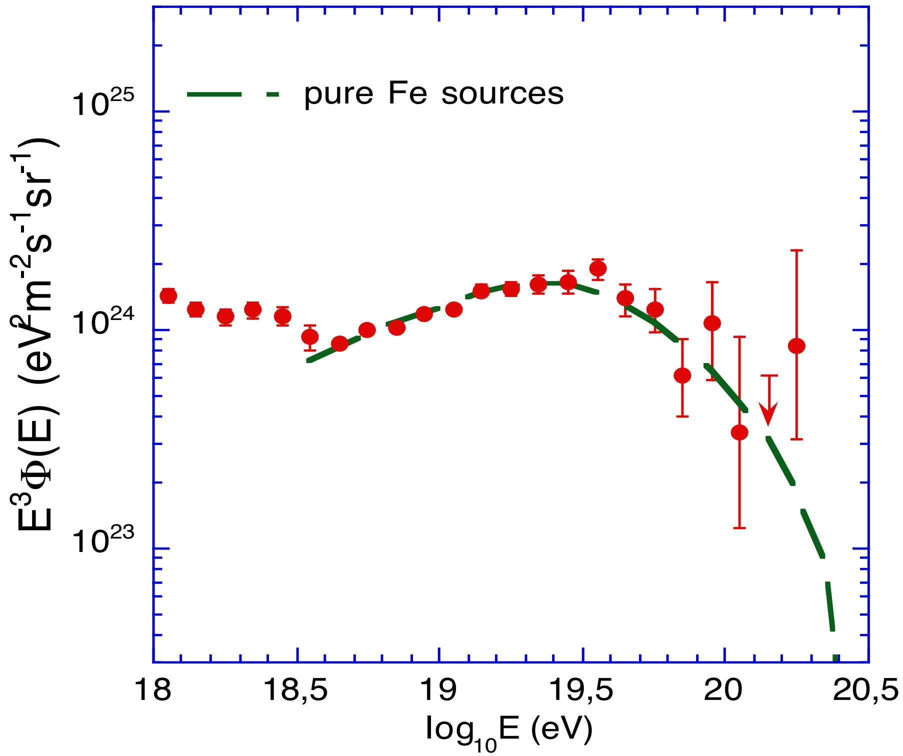
- The GZK effect for nuclei



UHECR propagation

- Evidence for a GZK feature in the UHECR spectrum

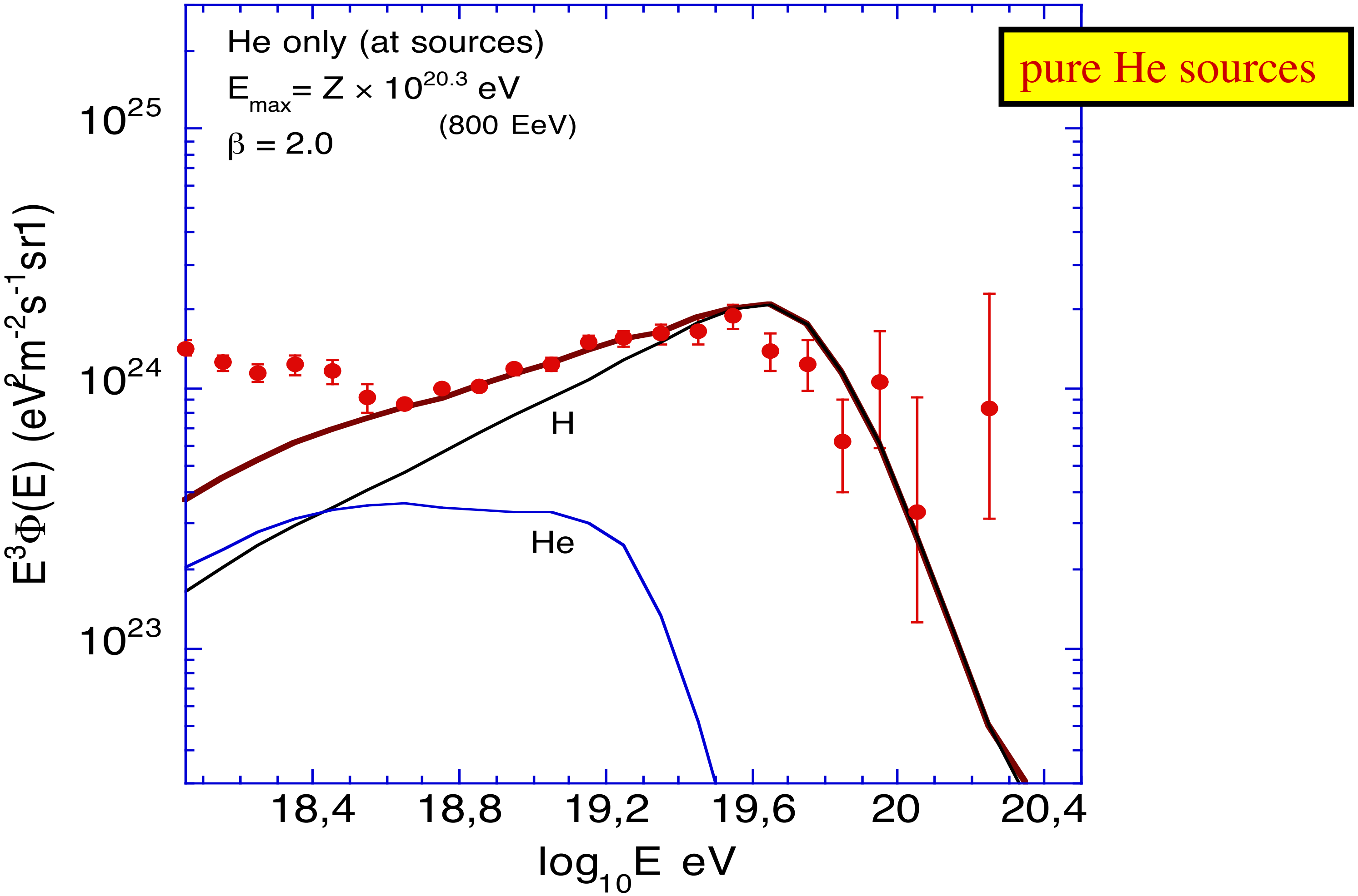




→ but no information on the source composition!

UHECR propagation

- Just for fun!



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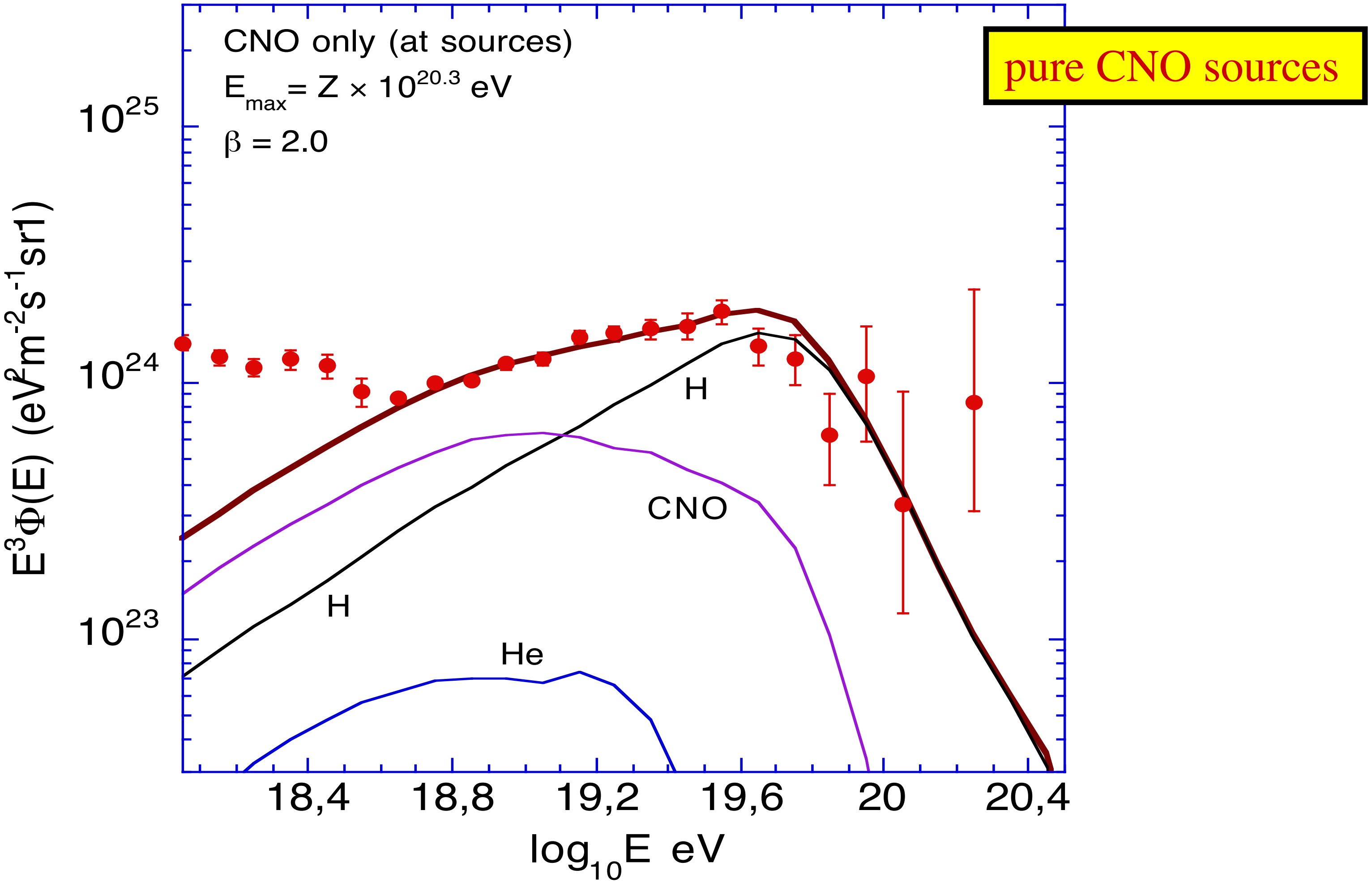

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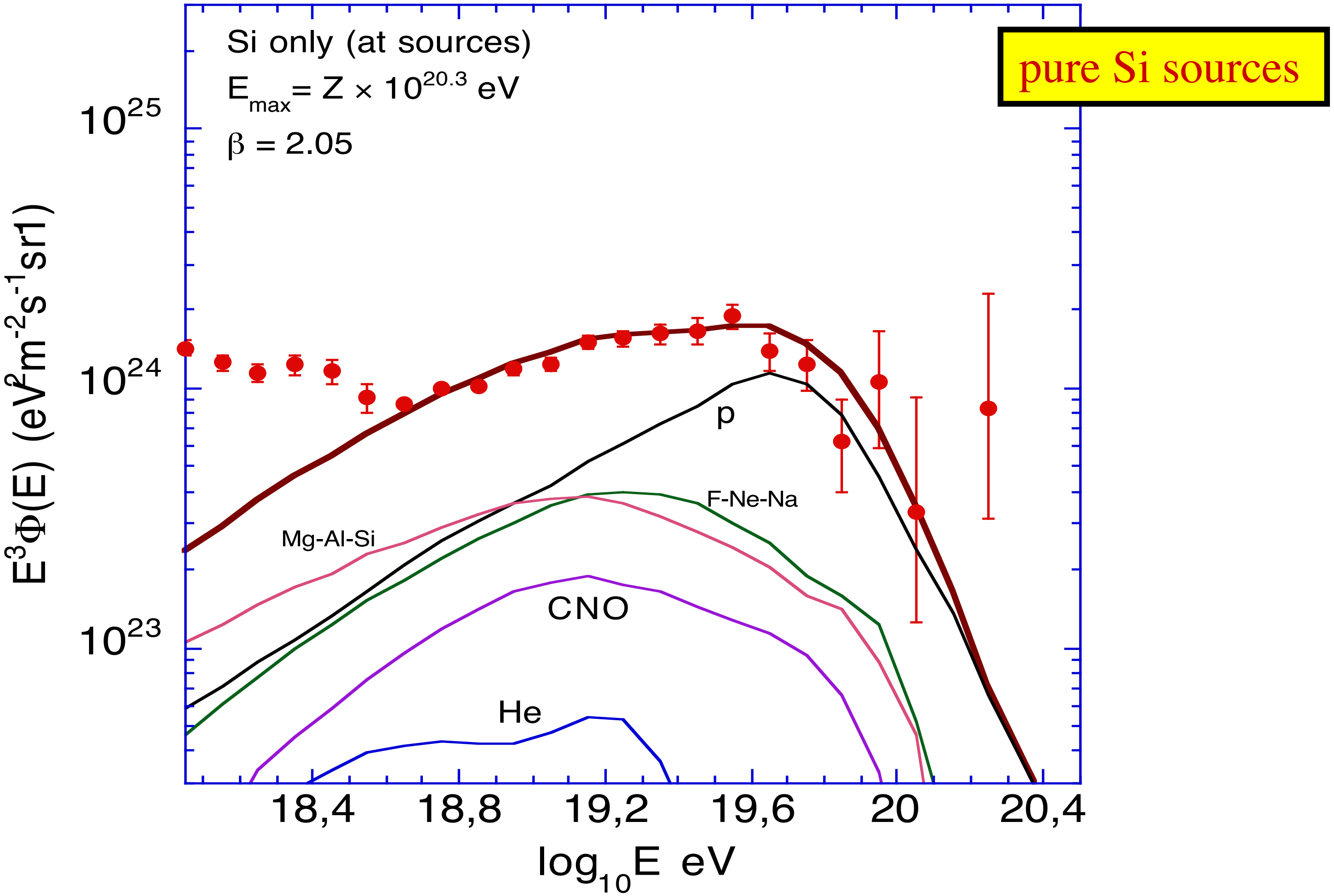

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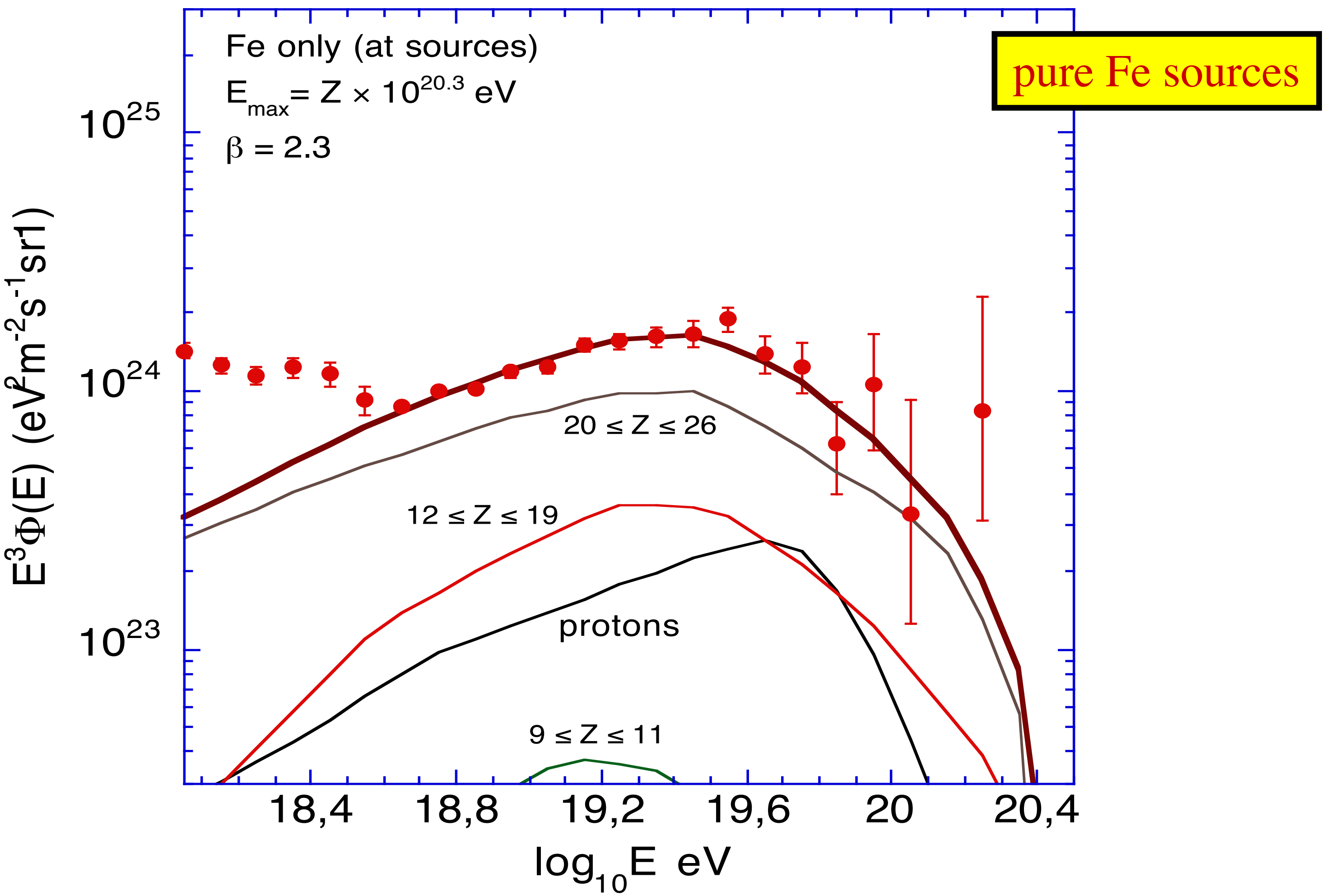

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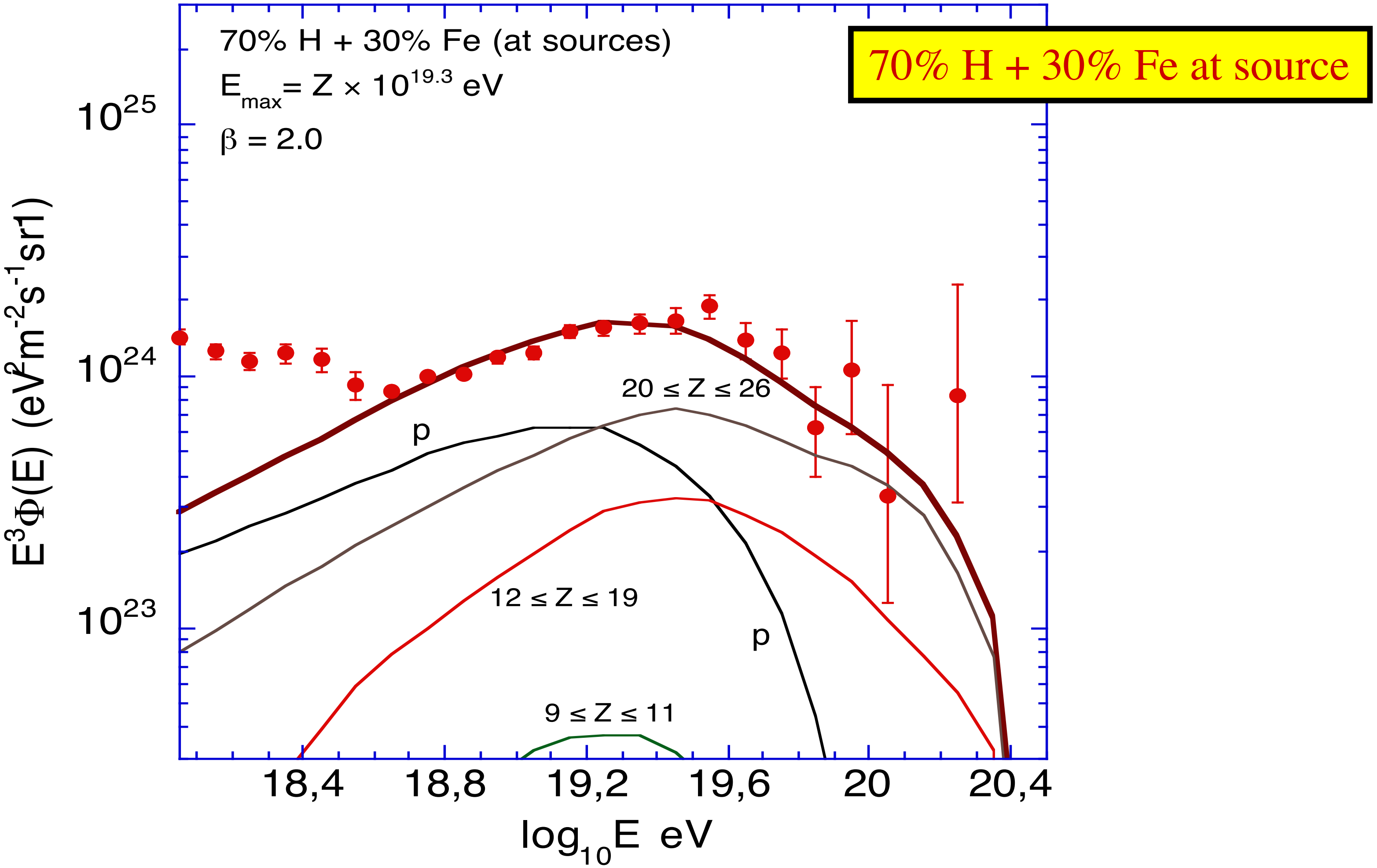
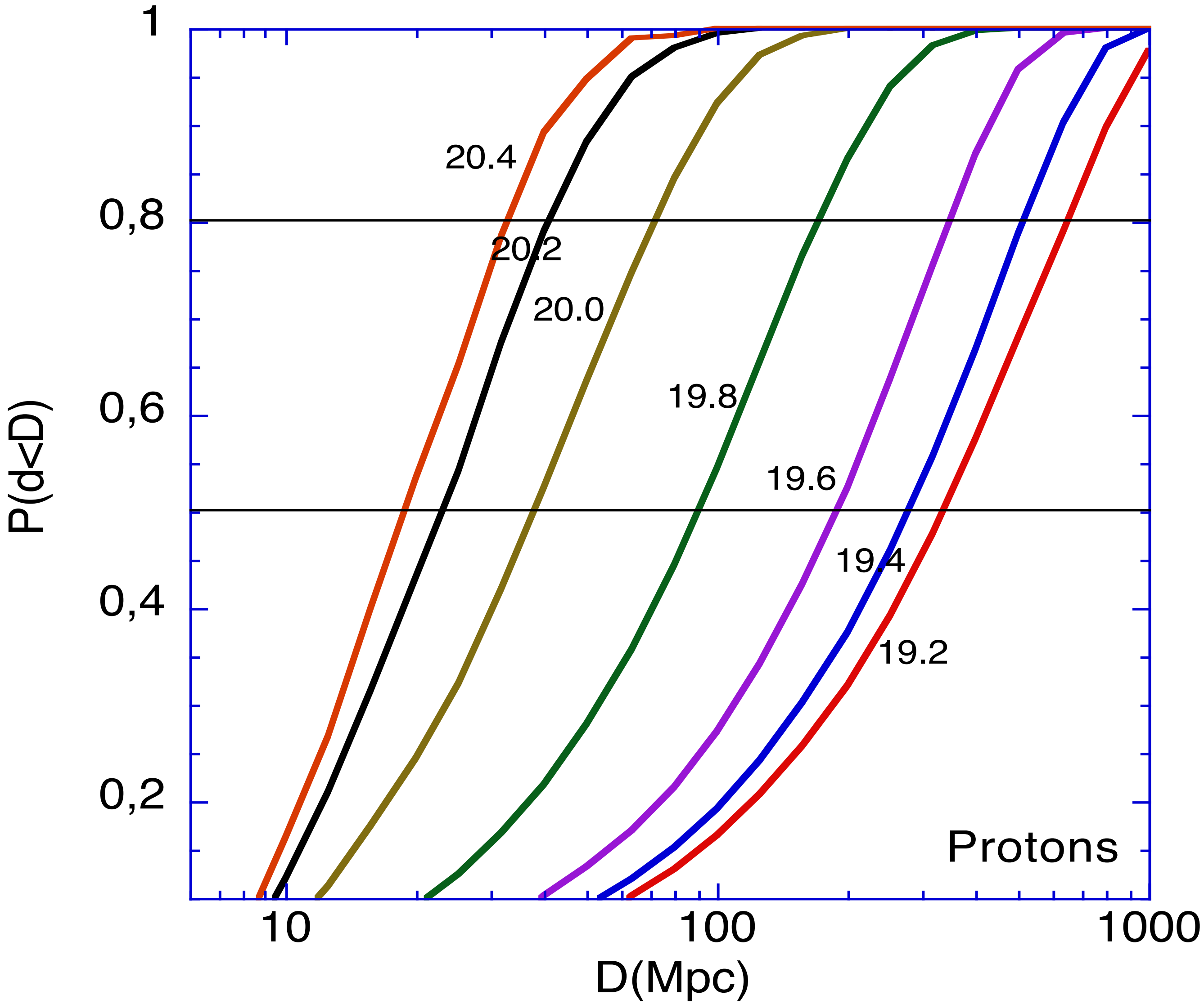


GZK horizon effect



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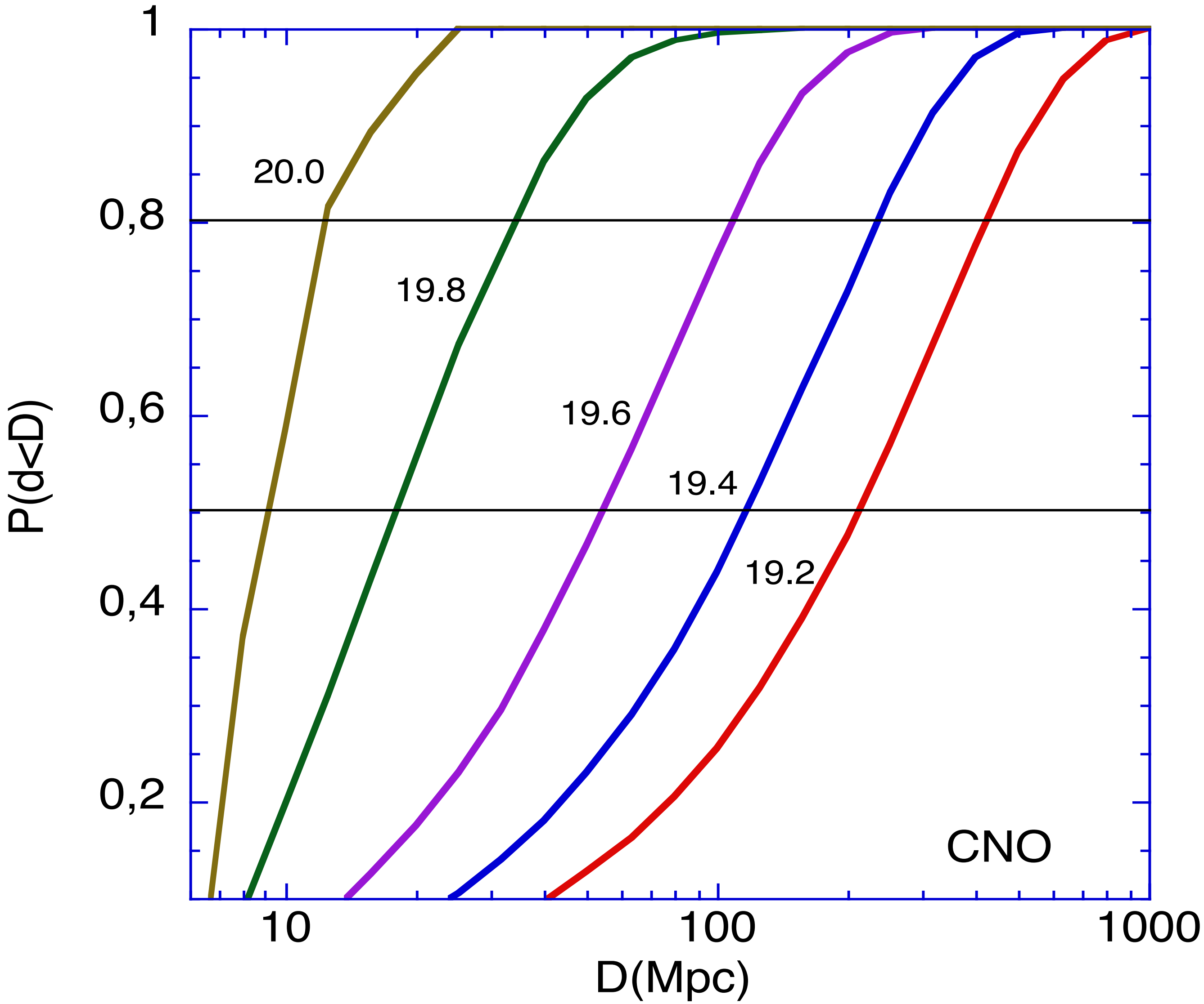
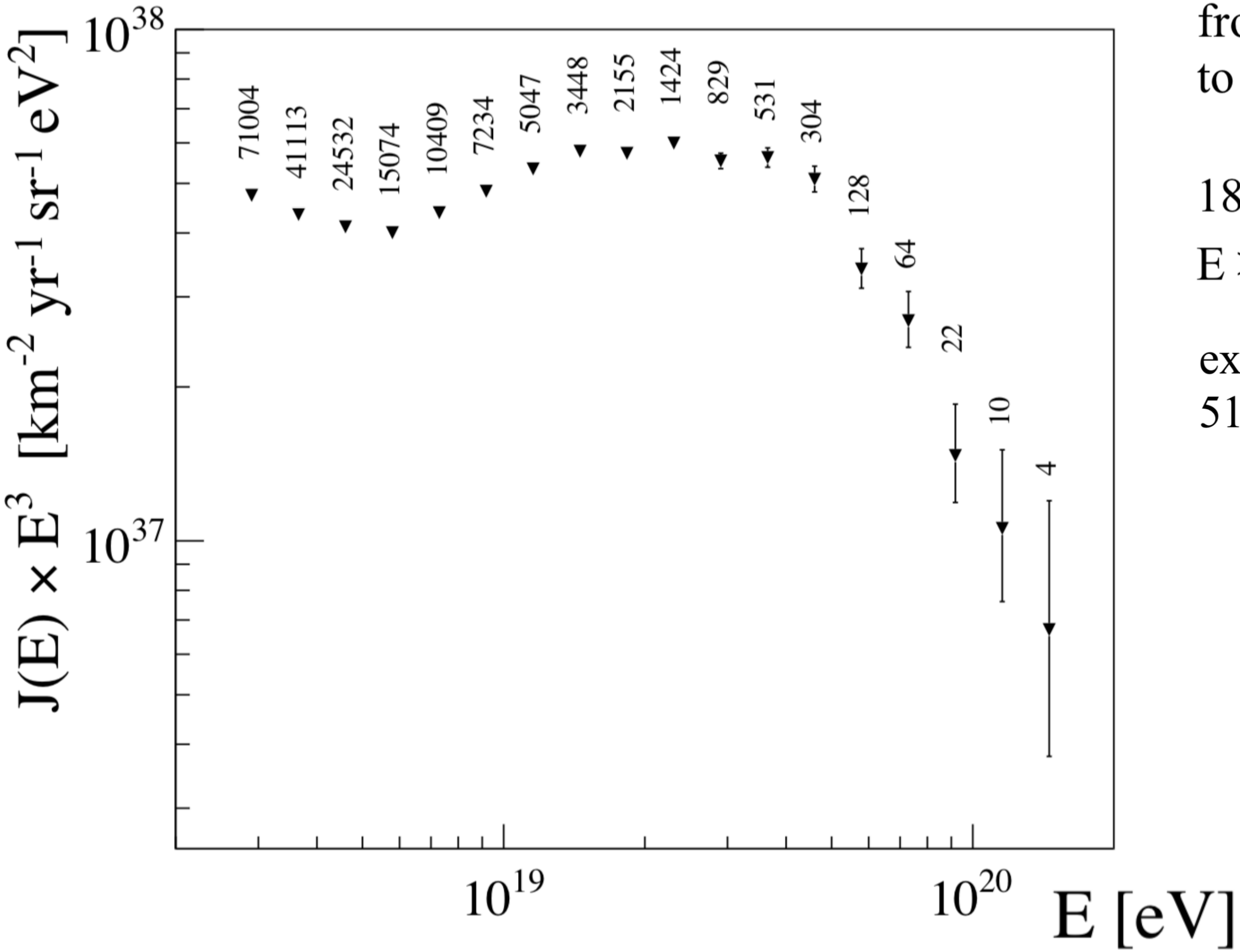


What do the data say?

- Energy spectrum measured at the Pierre Auger Observatory



from Jan 2004 to Dec 2016

183332 events

E >$10^{18.4}$ eV

exposure 51588 km^2 yr sr

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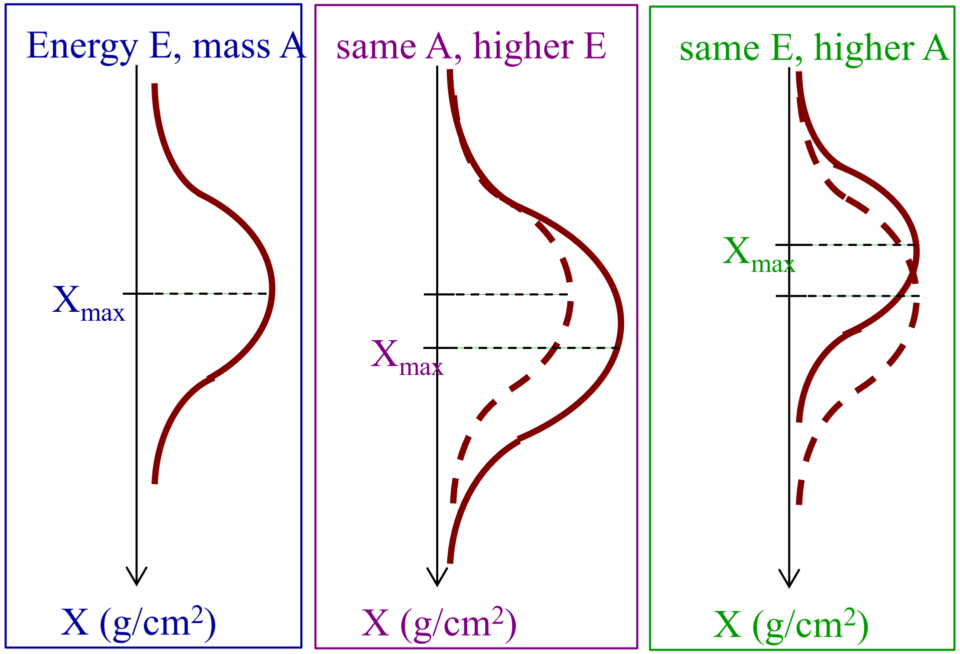


Higher energy => deeper shower

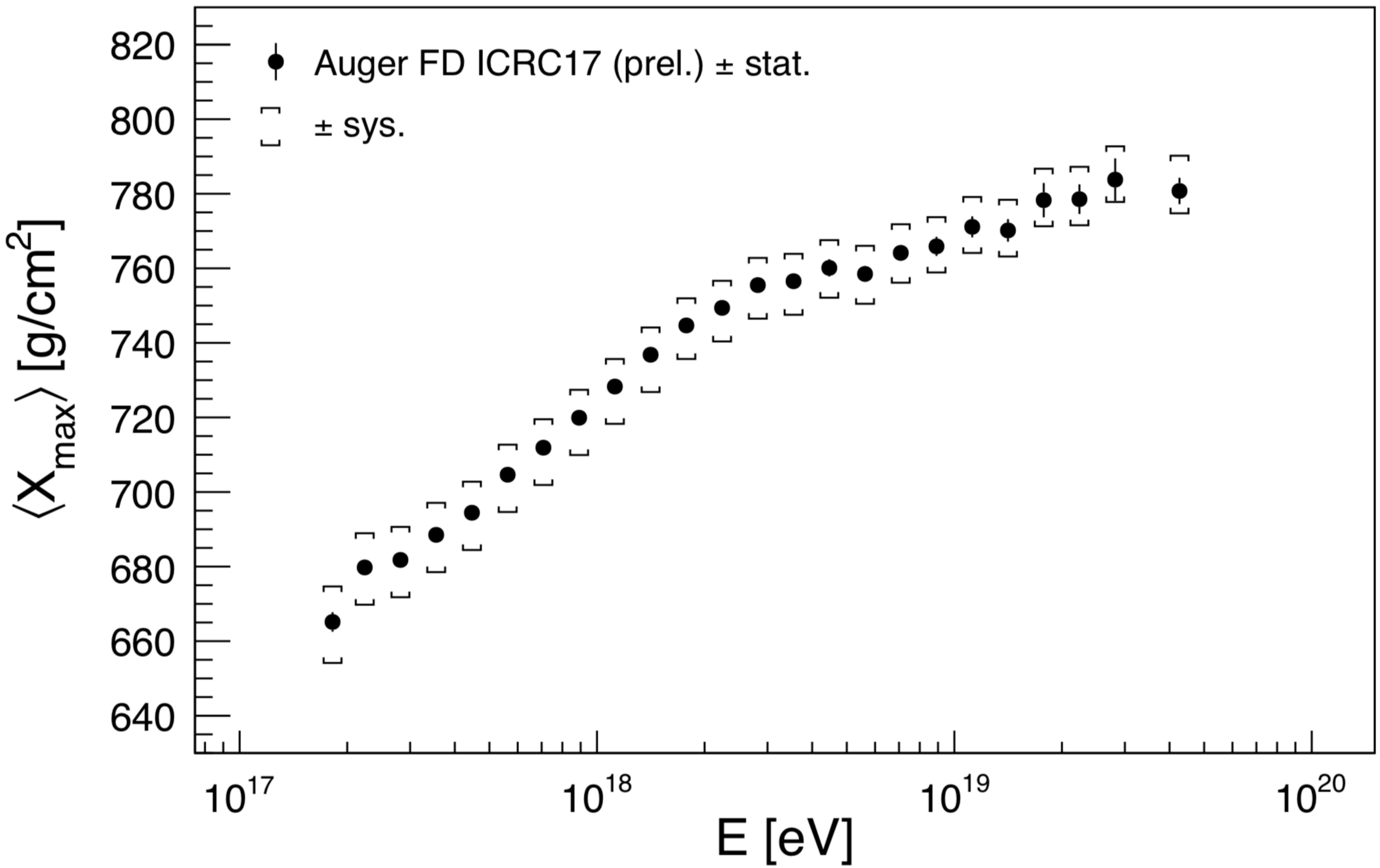
Higher mass => shallower shower

Higher mass => smaller fluctuations

What do the data say?

- CR composition estimated at the Pierre Auger Observatory

Pierre Auger Coll., PRL 2011, PRD 2014; update at ICRC17



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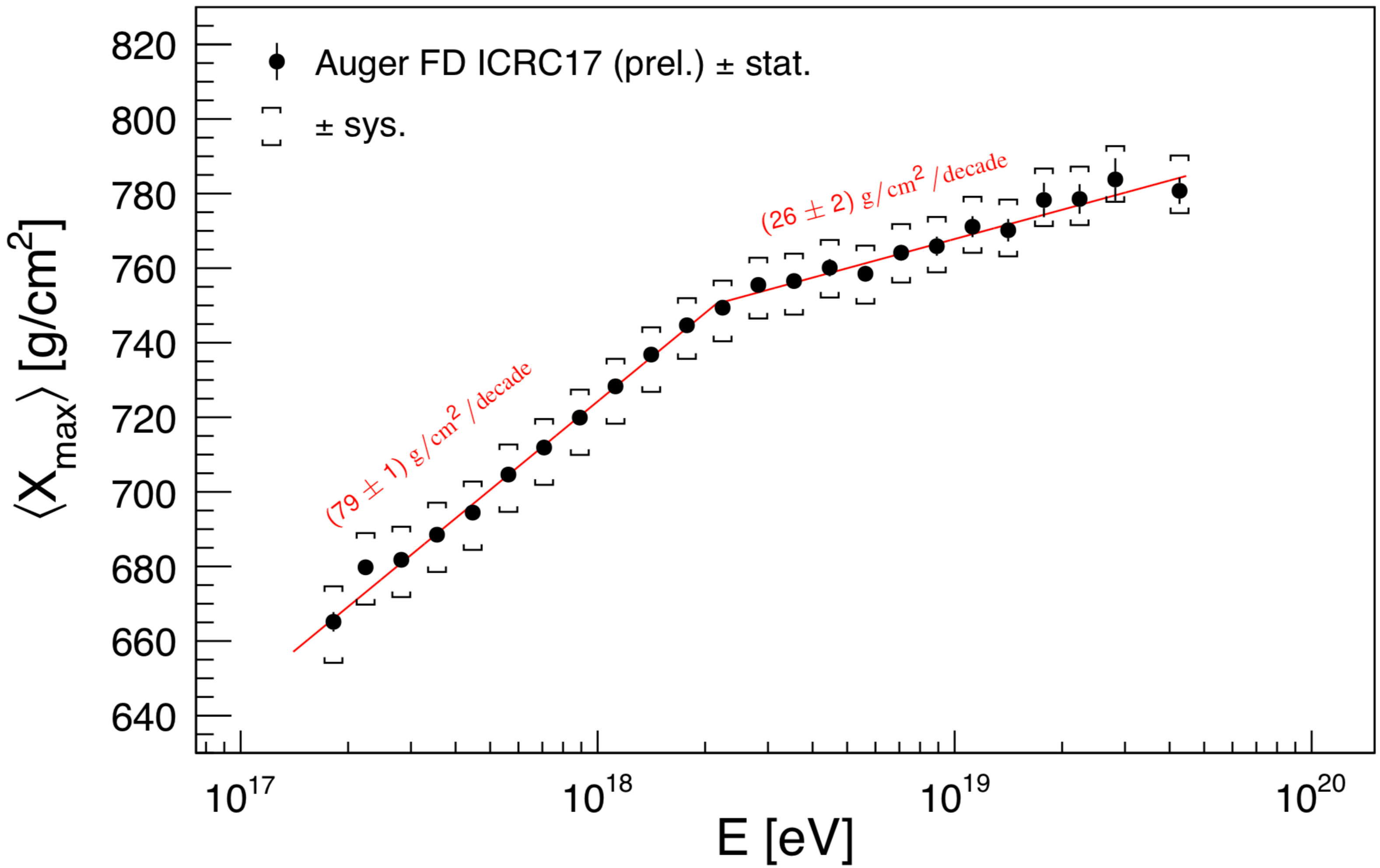

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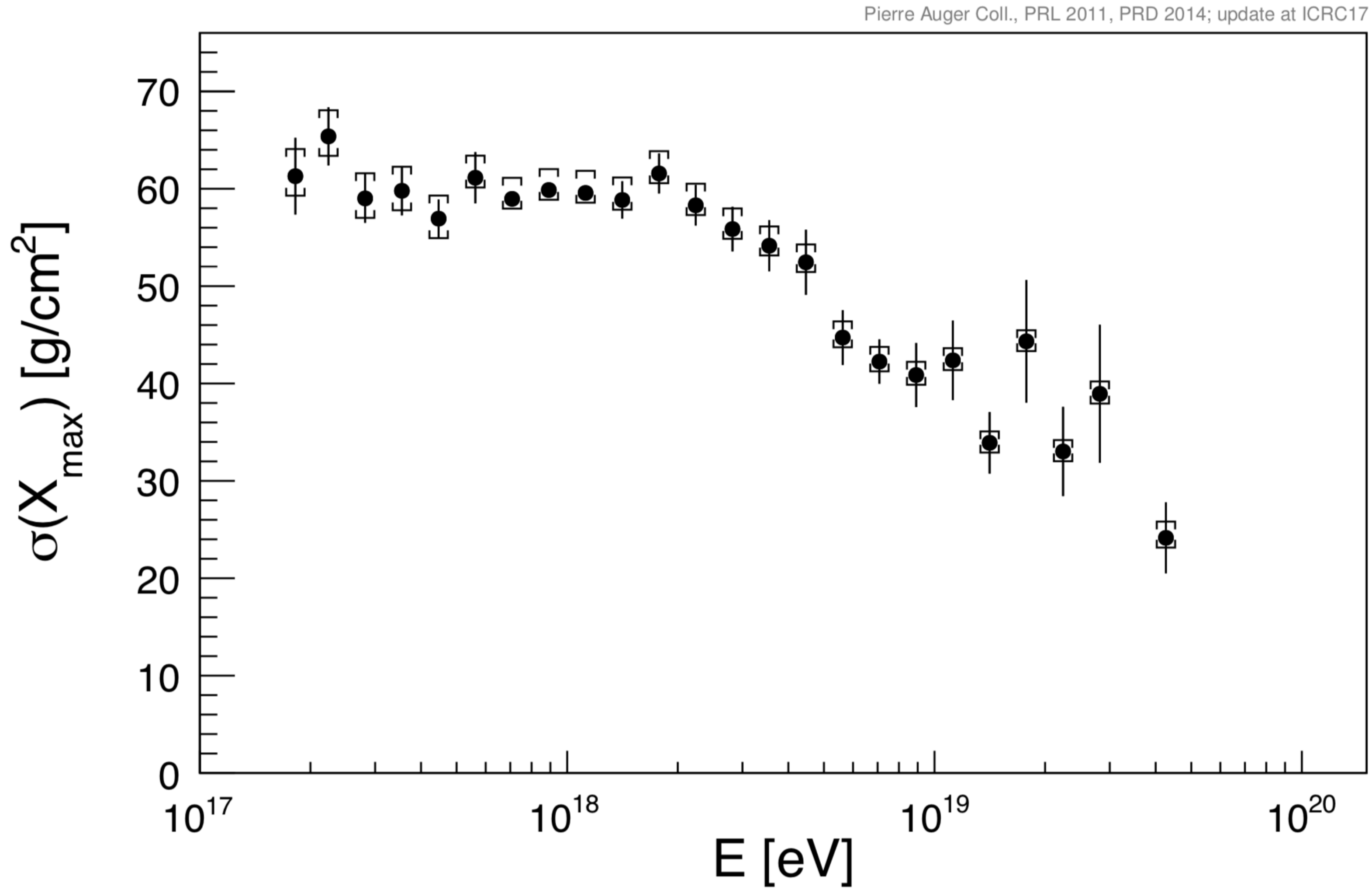
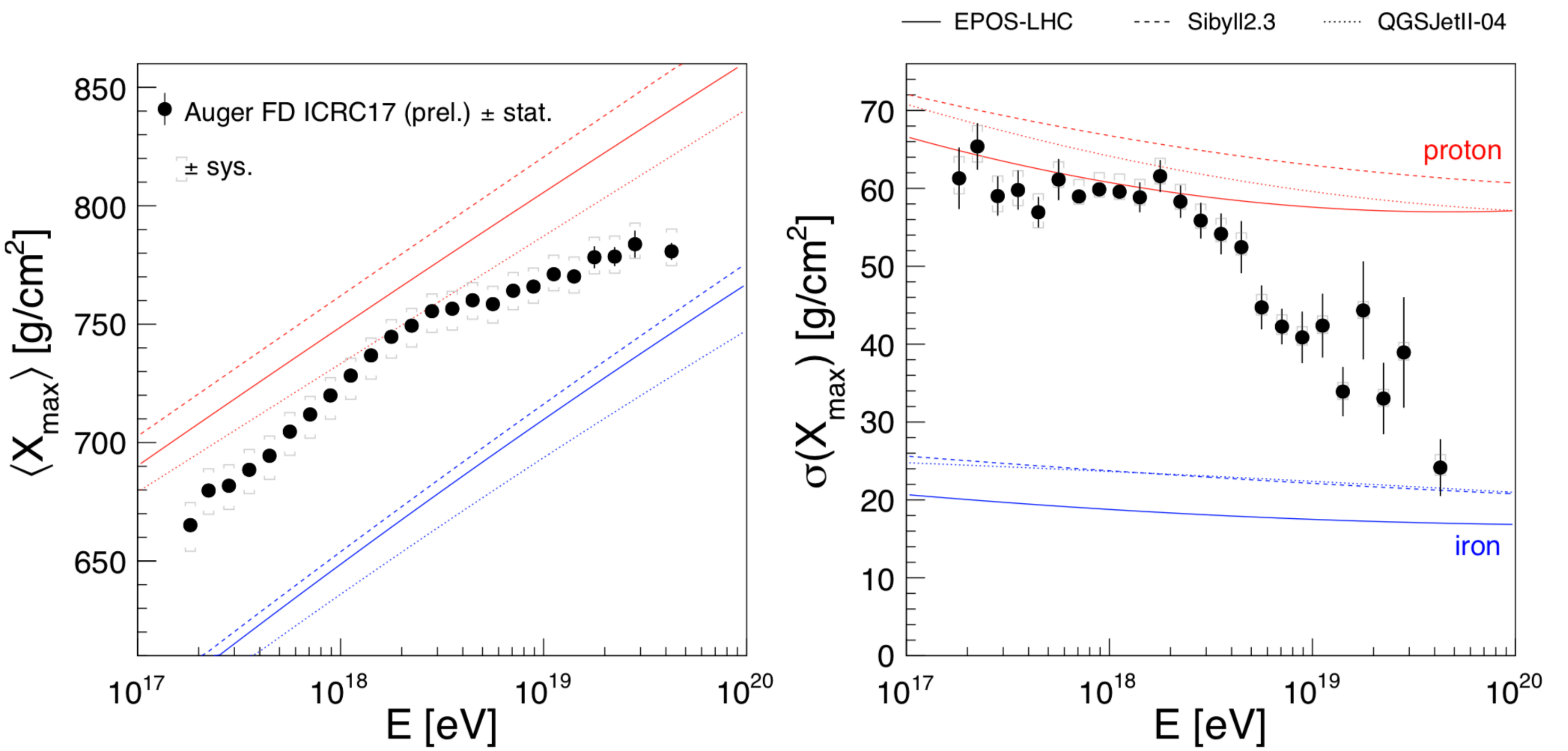


What do the data say?

- CR composition estimated at the Pierre Auger Observatory



Natural interpretation: low proton E_{max}

✧ The Auger results clearly show a transition towards a heavier composition around a few 10^{18} eV

✧ This is either puzzling…

- because protons are by far the most abundant nuclear species in the universe
- because the transition occurs at energies much lower than the expected GZK cut-off (so it cannot be due to a propagation effect)

✧ …or very easy to understand – and very comforting!

- there is a "non GZK" cut-off of the protons

→ it must be at the source!

→ simple, generic and natural explanation: the low proton E_{max} scheme!

Natural interpretation: low proton E_{max}

- Very sensible interpretation, from the astrophysical point of view!

- Maximum energy at the source proportional to *Z* for different nuclei

  Charged particles trajectories and energy gains only depend on rigidity

  $$E_{max}({}^{Z}_{A}X) = Z \times E_{max}(p)$$

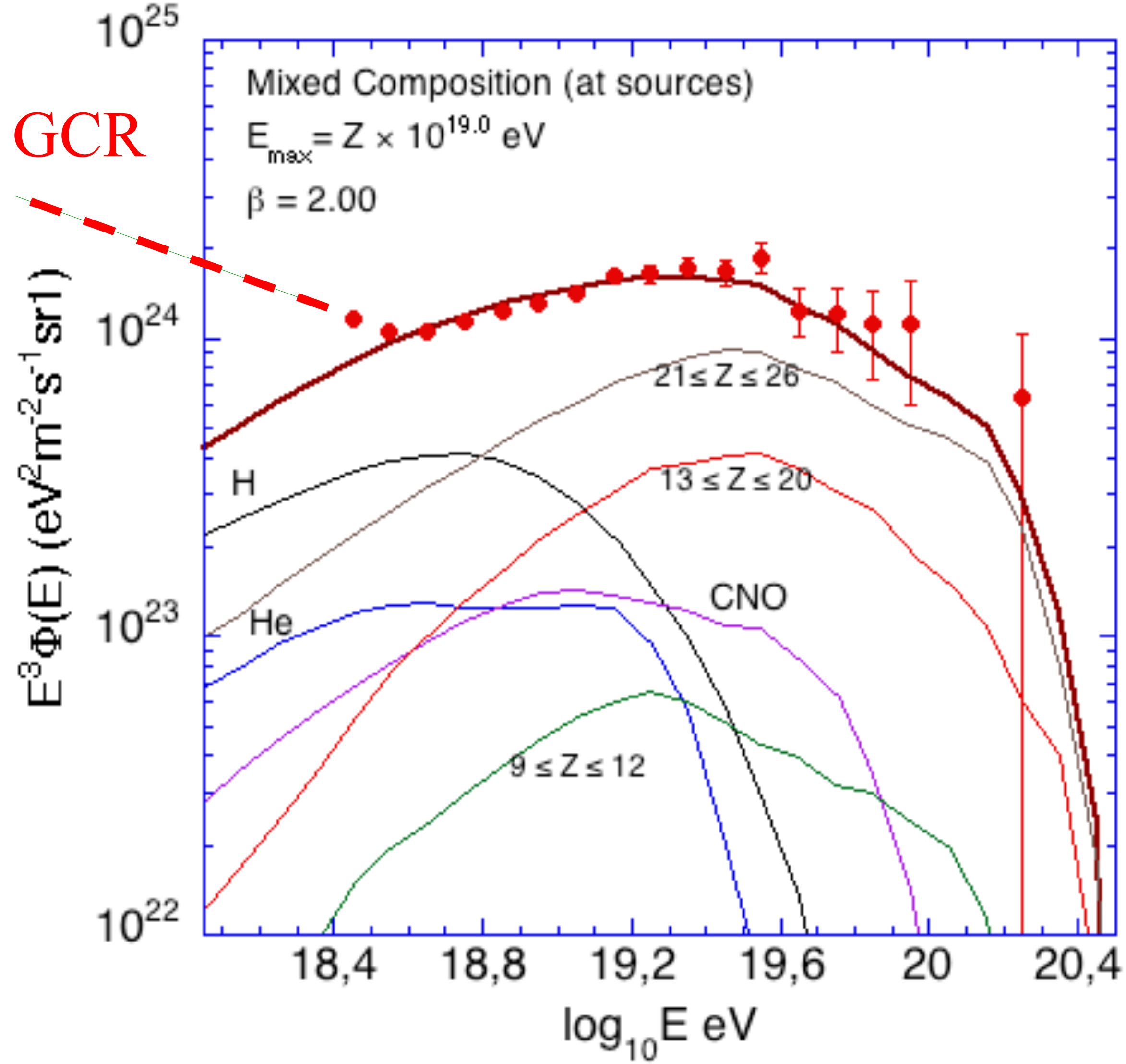
- Relaxes a critical problem: very hard to build acceleration models providing maximum proton energies above10^{20} eV!

  → More "comfortable" to have E_{max}(p) ~ between a few 10^{18} eV and 10^{19} eV

- → transition towards heavier component by extinction of the light one!

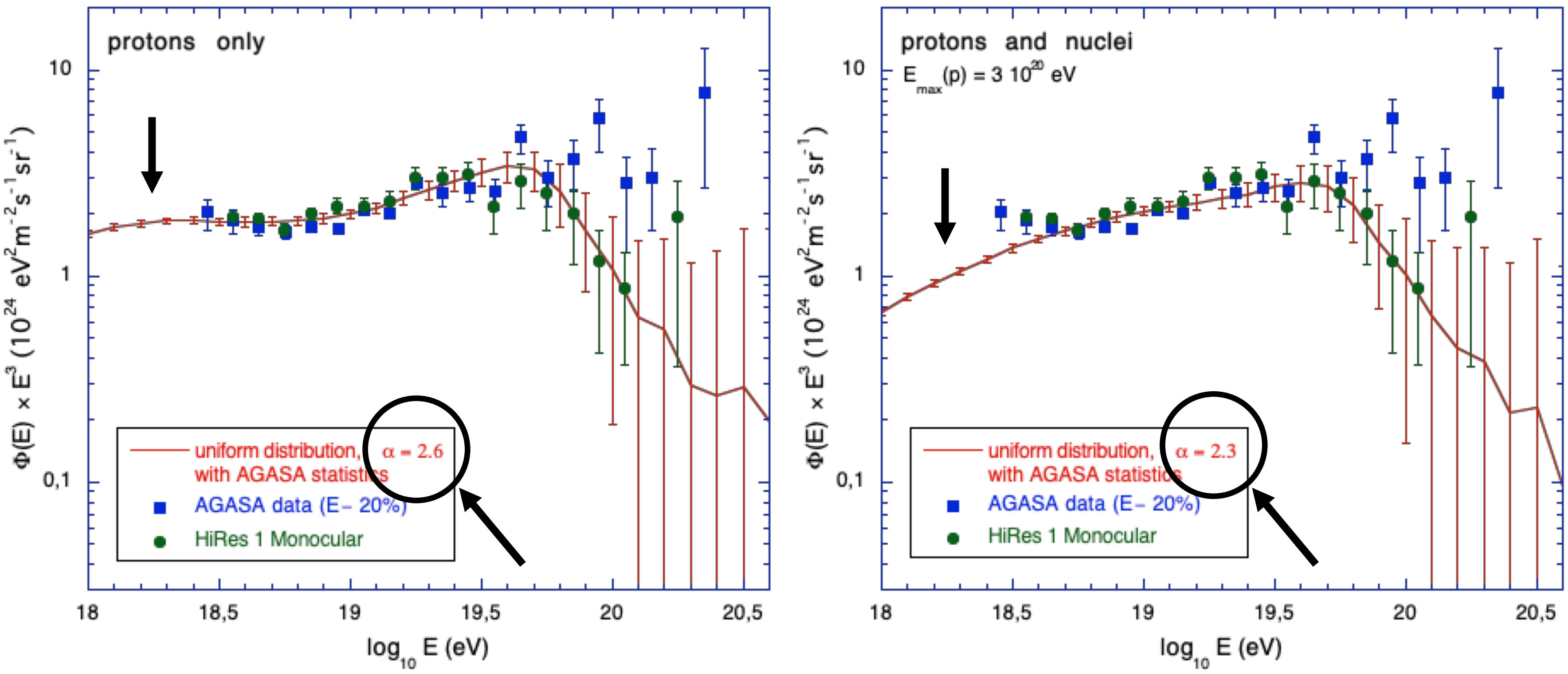
- NB: also in line with the absence of any marked anisotropy in the UHECR sky (would be hard to explain within a p-dominated scenario!)

Natural interpretation: low proton E_{max}



Natural interpretation: low proton E_{max}

Allard et al. (2005)



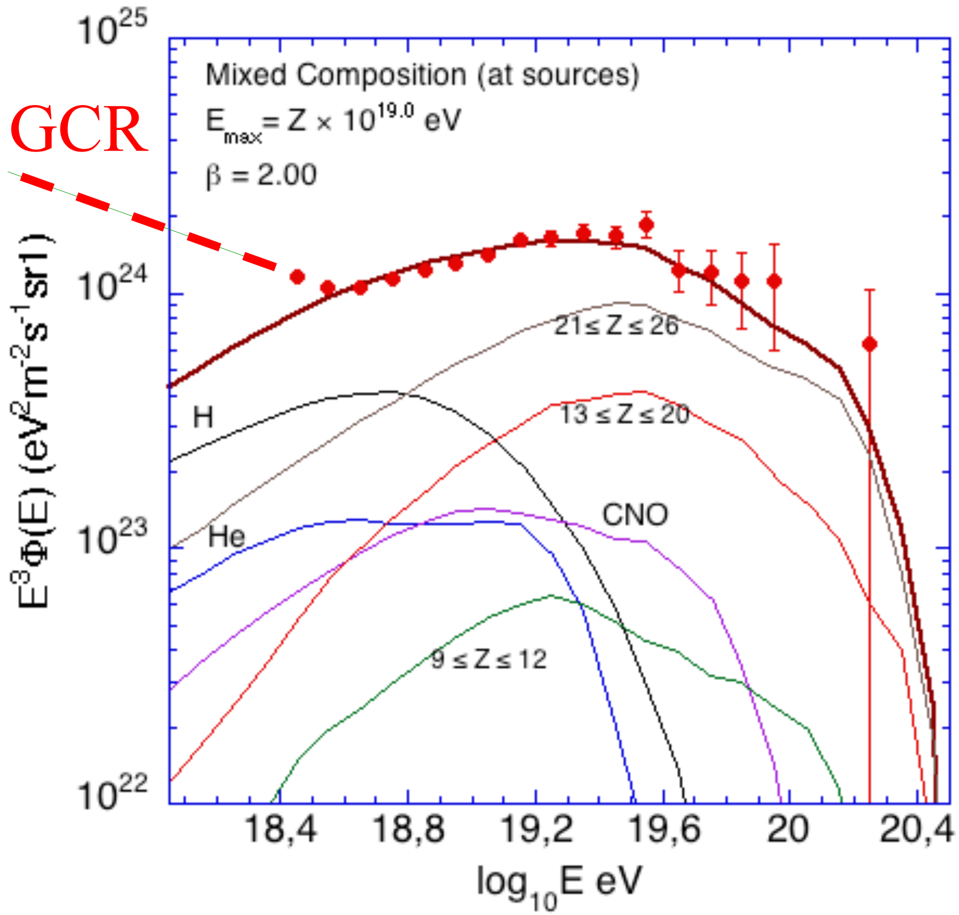
- source spectrum & acceleration
- Interpretation of the ankle

Natural interpretation: low proton E_{max}

✧ But this has an important implication:

The source spectrum must be hard! $$Q(E) \propto E^{-x}$$

with x < 2 or even x ~ 1



✧ Not a problem!

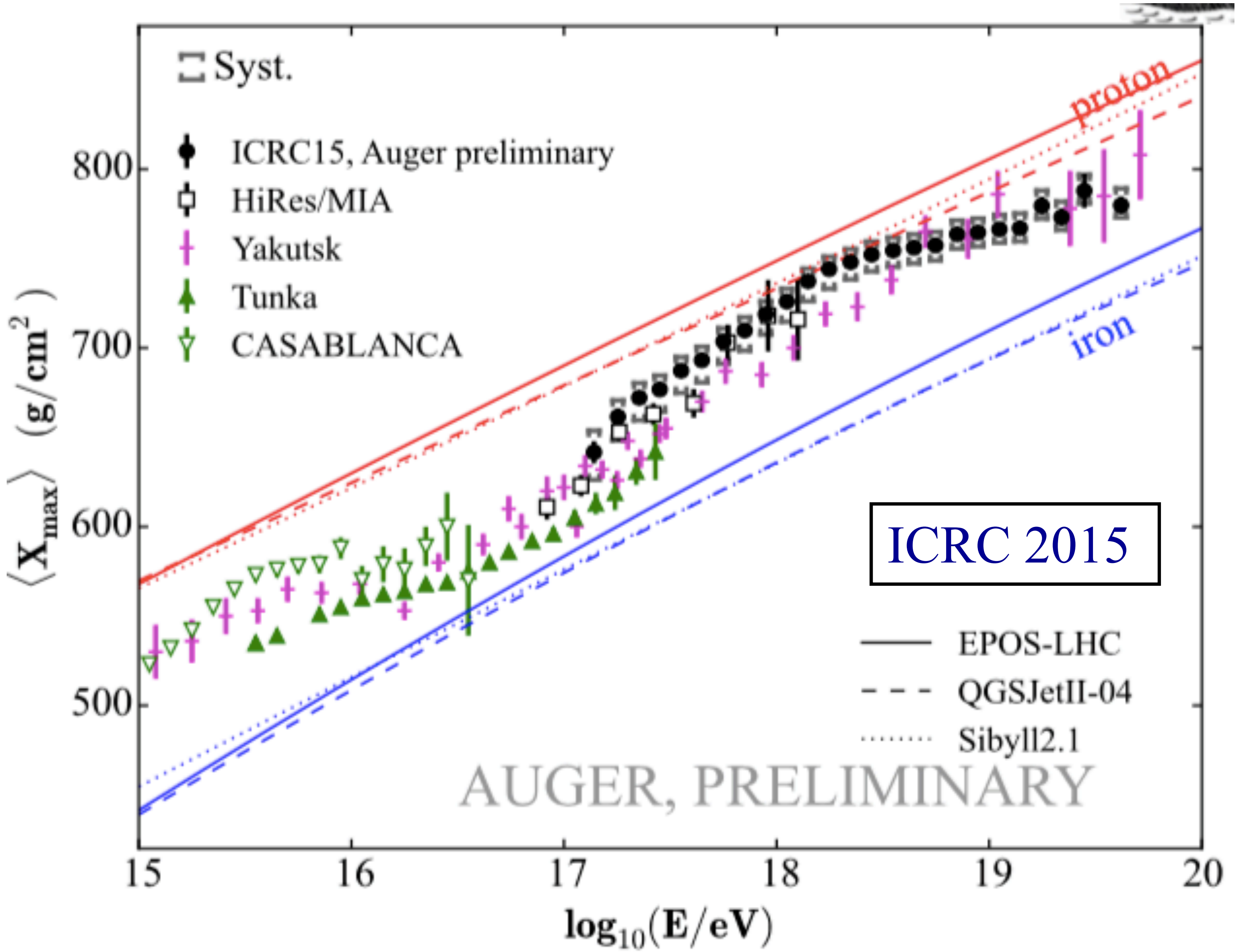
- requires less energy in total
- obtained in a natural way in some models

✧ But a hard proton spectrum implies a low EGCR proton fraction at 10^{18} eV…

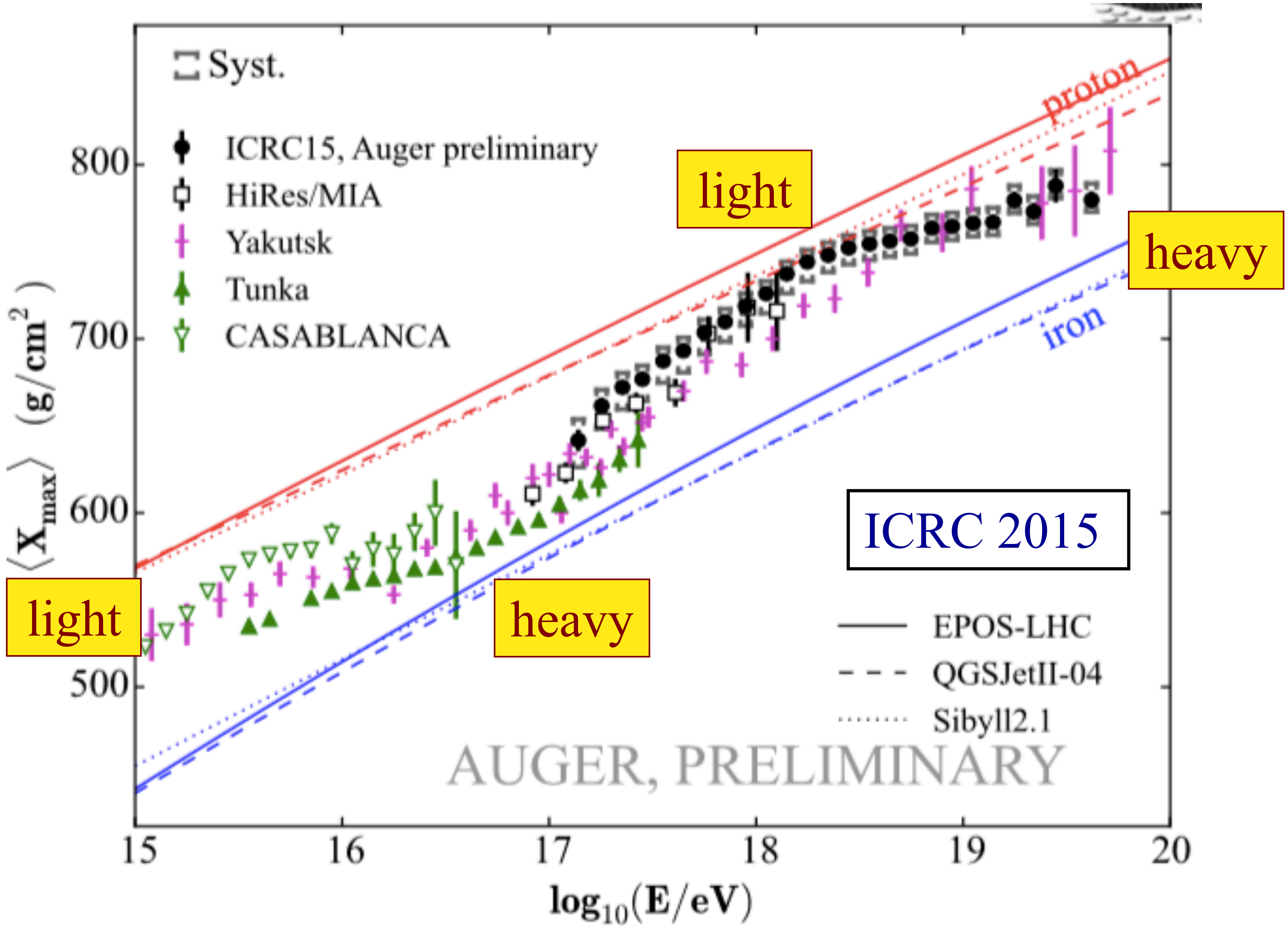
✧ And GCRs must reach the ankle > 10^{18} eV!

Back to the GCR/EGCR transition

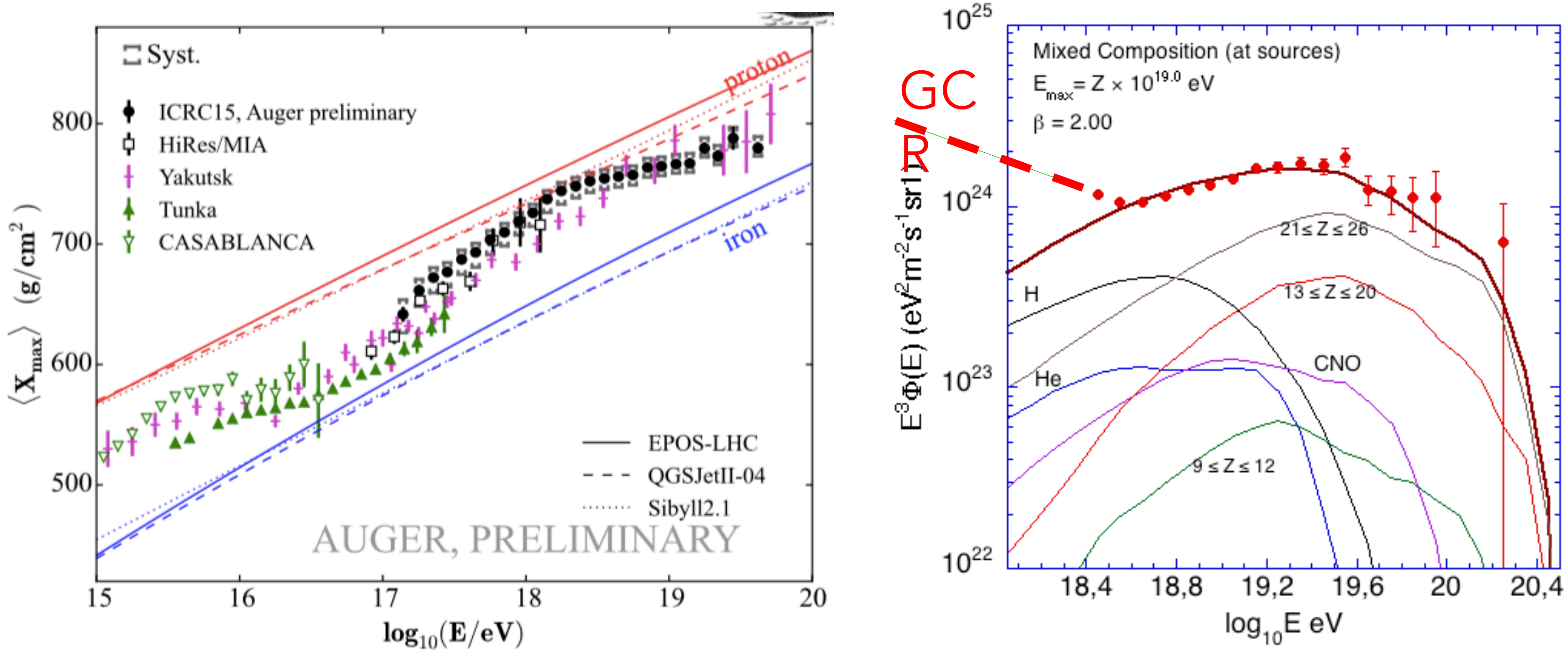
Combined composition data



Combined composition data



Is there a proton crisis at the ankle?



✧ Important constraint: CRs are light-dominated at 10^{18} eV

But light CRs at 10^{18} eV cannot be Galactic! → that would violate isotropy data! (Auger results)

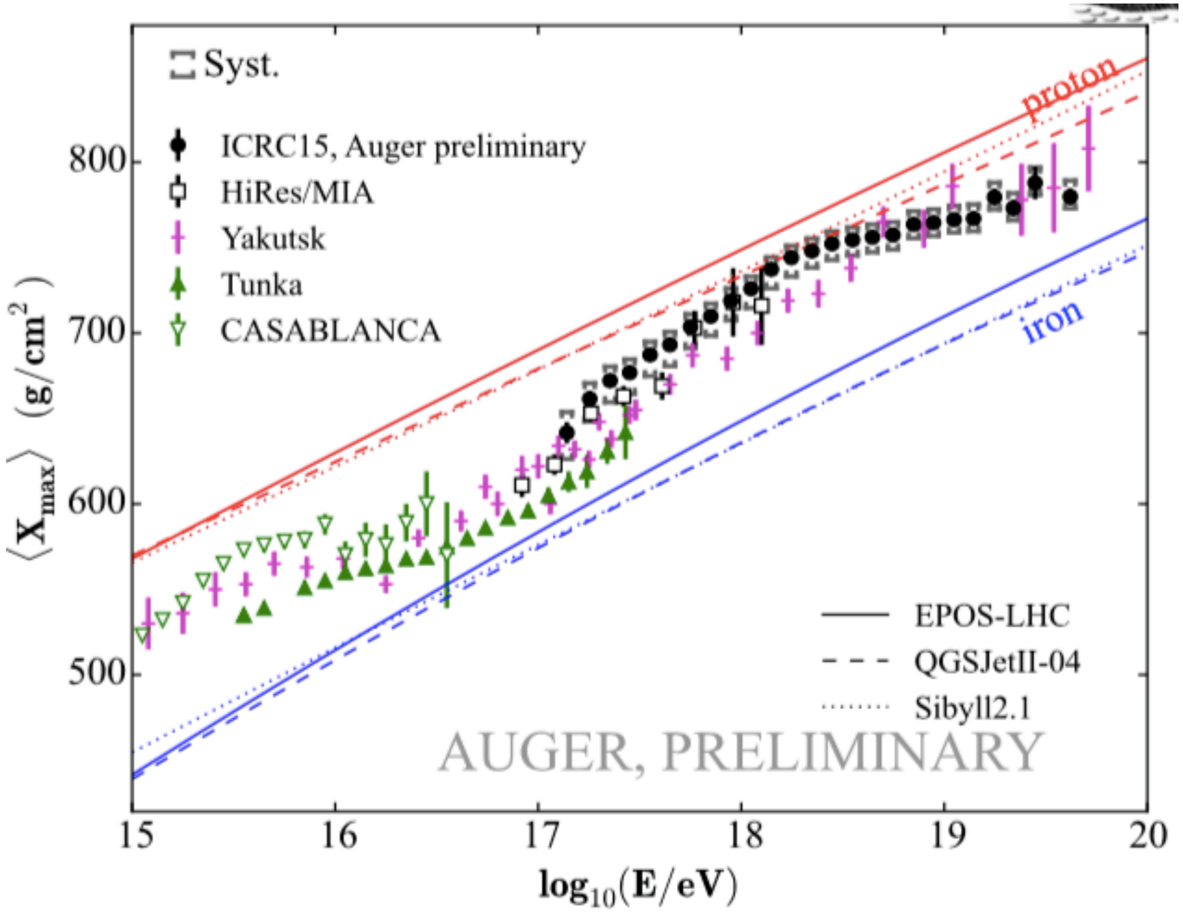
And light CRs at 10^{18} eV cannot be extragalactic if they have the hard spectrum inferred from the light-to-heavy UHECR transition!

✧ => either there is an additional component to fill the gap, or the spectrum of light elements is different!

GCR/EGCR transition is key!

Lessons from GCRs

→ Can we attack the problem from below the ankle?
→ The knee + new data from KASCADE-Grande!



→ GCRs become heavier at the knee

What is the GCR knee?

✧ Is it a feature of the acceleration process?

- Cut-off at the source?

→ usually advocated by people who hold SNRs responsible for the GCRs

- Change of slope due to reducing number of sources?

→ in some versions of the SNR-GCR connection scheme

✧ Is it a feature of cosmic ray propagation/confinement?

- Change of diffusion regime?

→ expected due to maximum turbulence scale (→non resonant scattering off magnetic inhomogeneities)

- Influence of a Galactic wind?

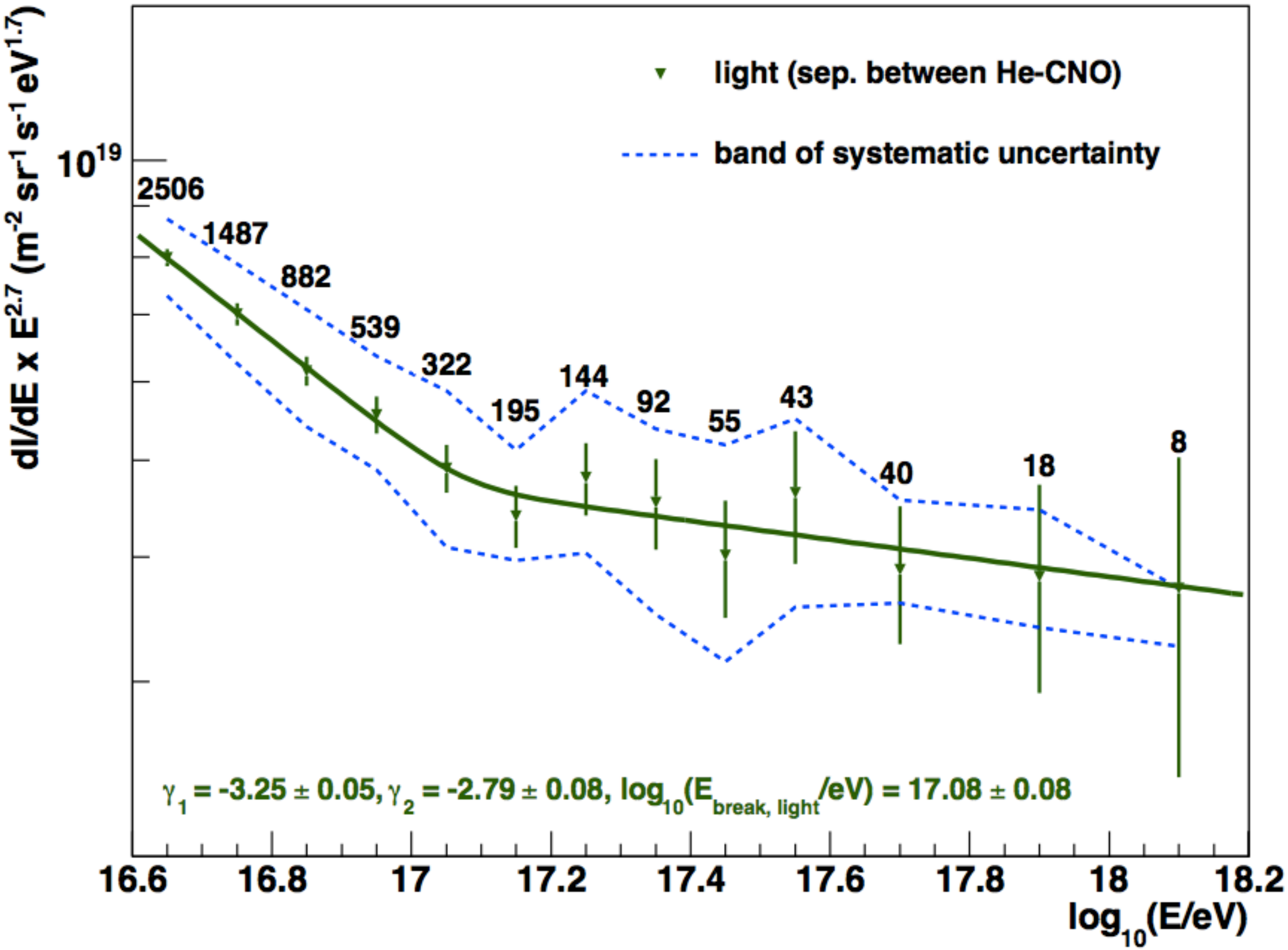
→ advection?

✧ Is it a local effect (space-time distribution of sources)?

✧ In all cases, a rigidity-dependent effect can be expected…

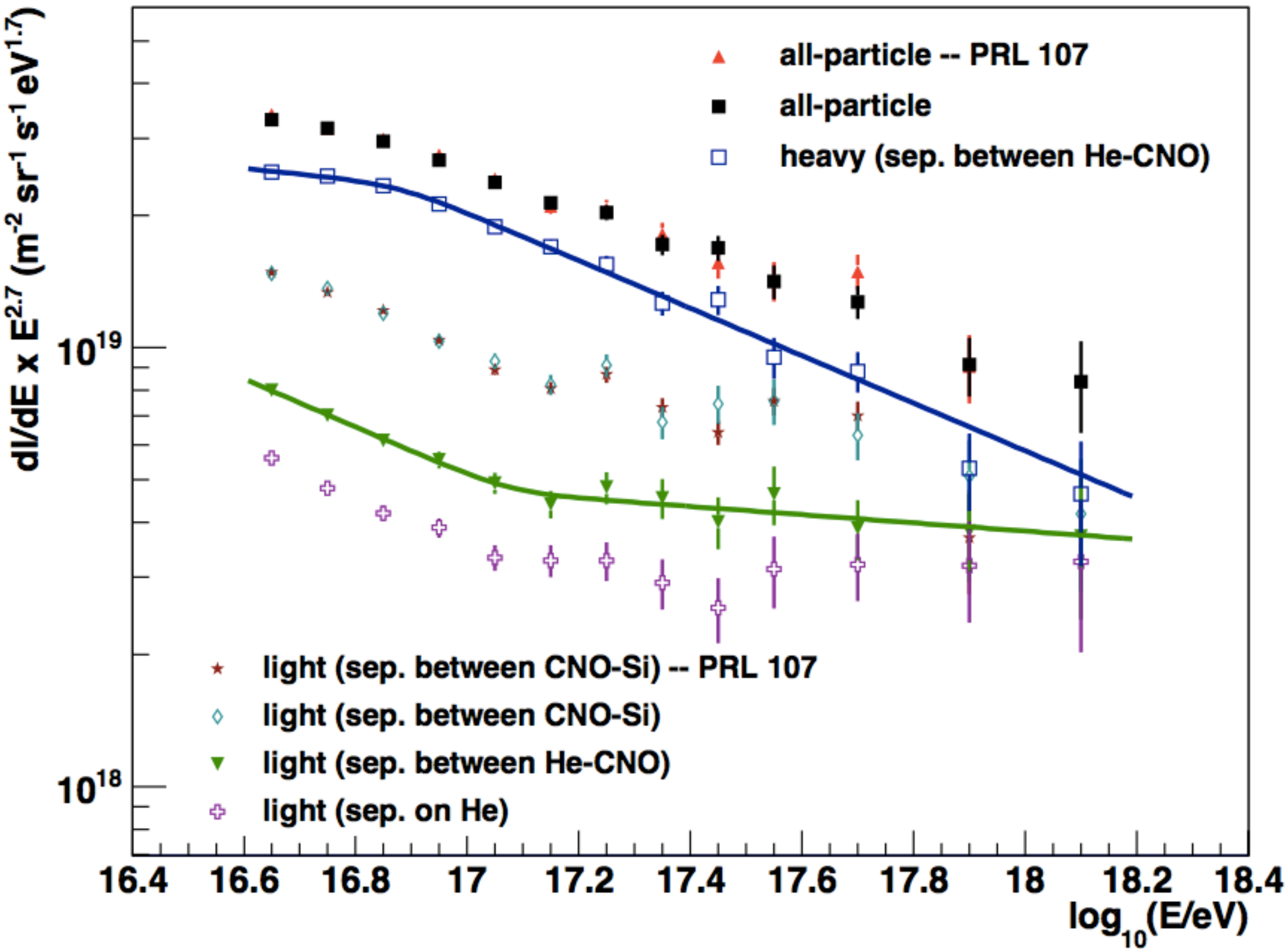
Kascade-Grande: the light ankle!

Kascade Grande Collaboration (2013)



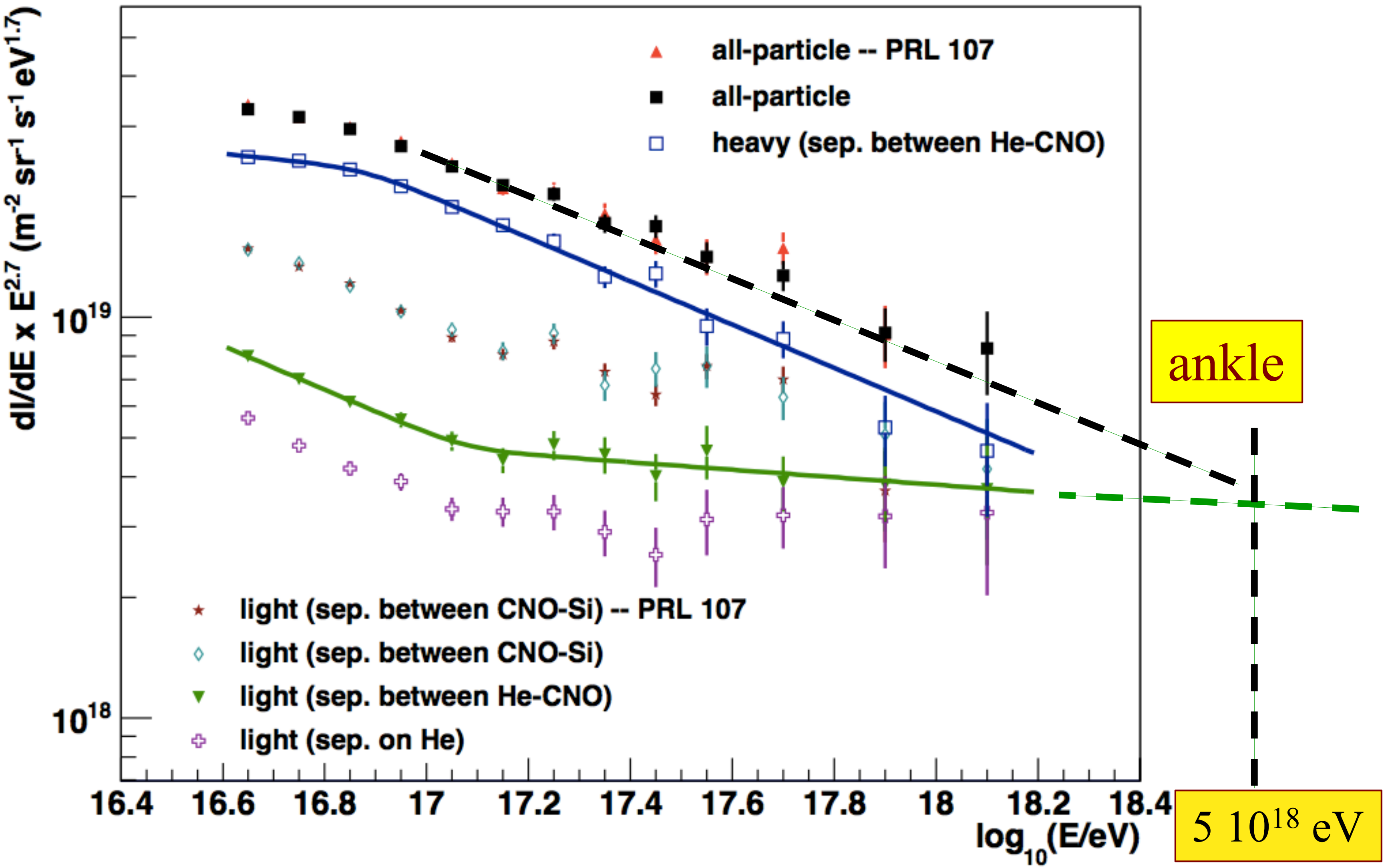
Kascade-Grande: light ankle/heavy knee

Kascade Grande Collaboration (2013)

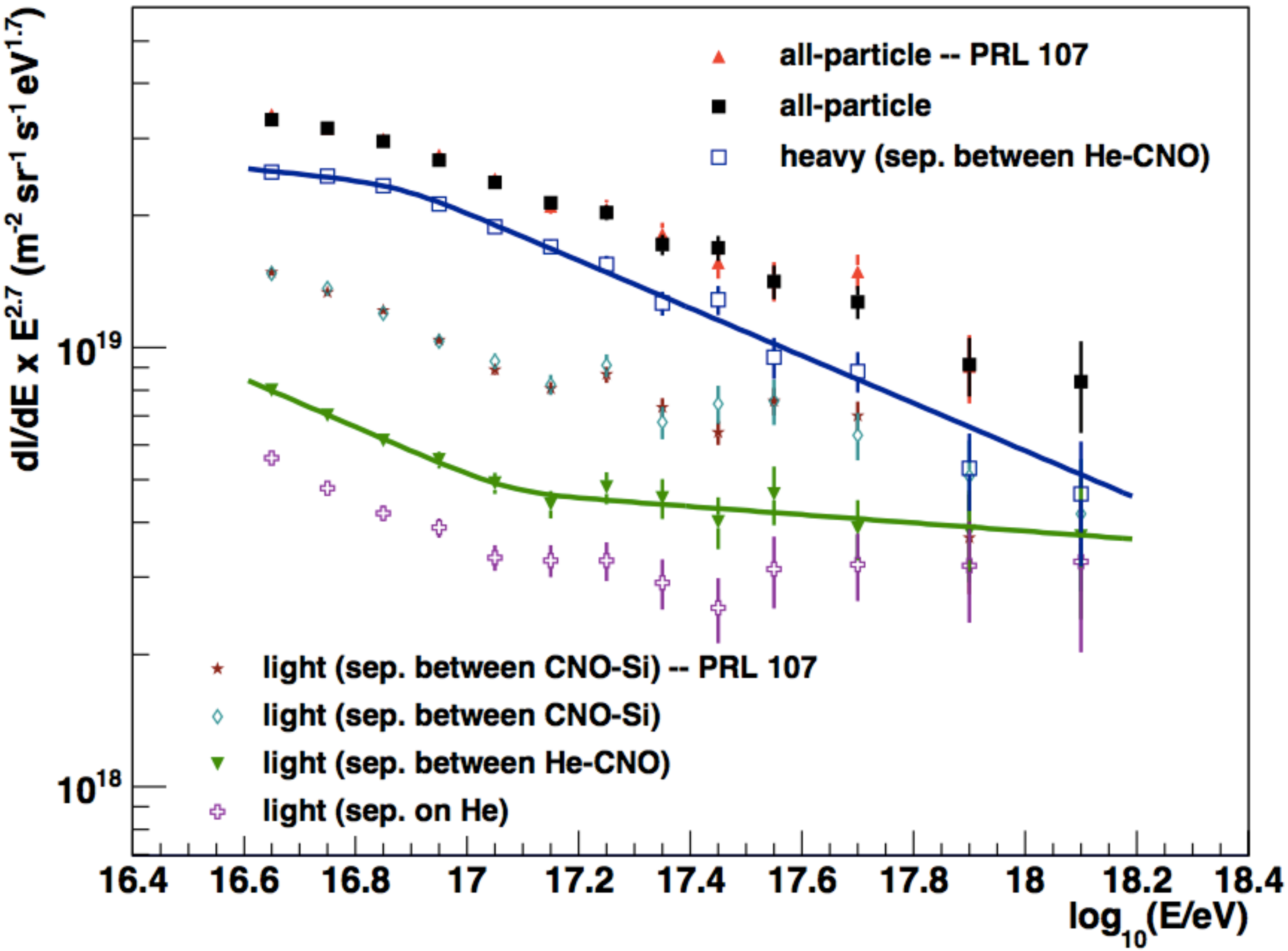


Kascade-Grande results

Kascade Grande Collaboration (2013)



Quite a simple and natural picture!



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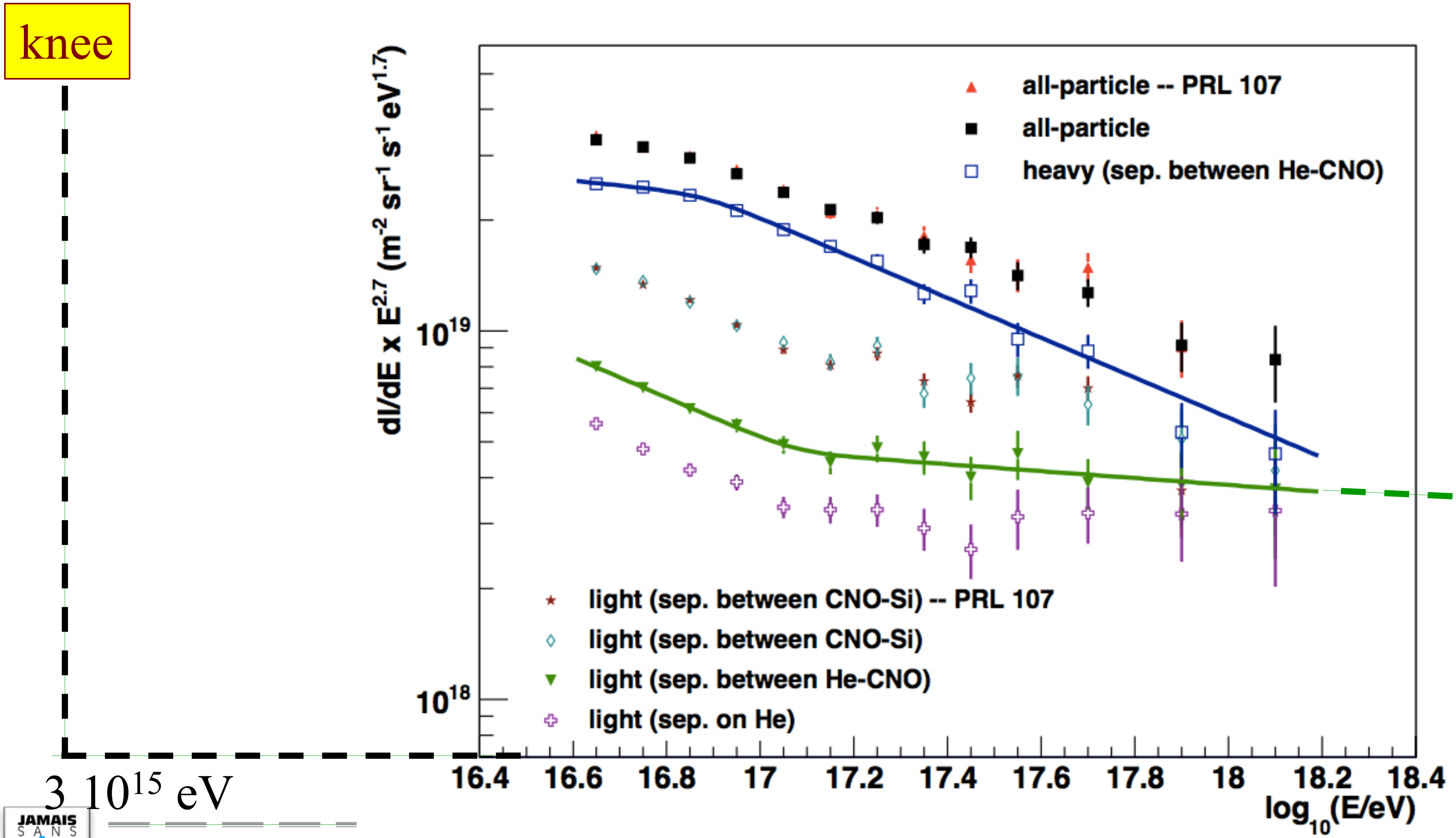

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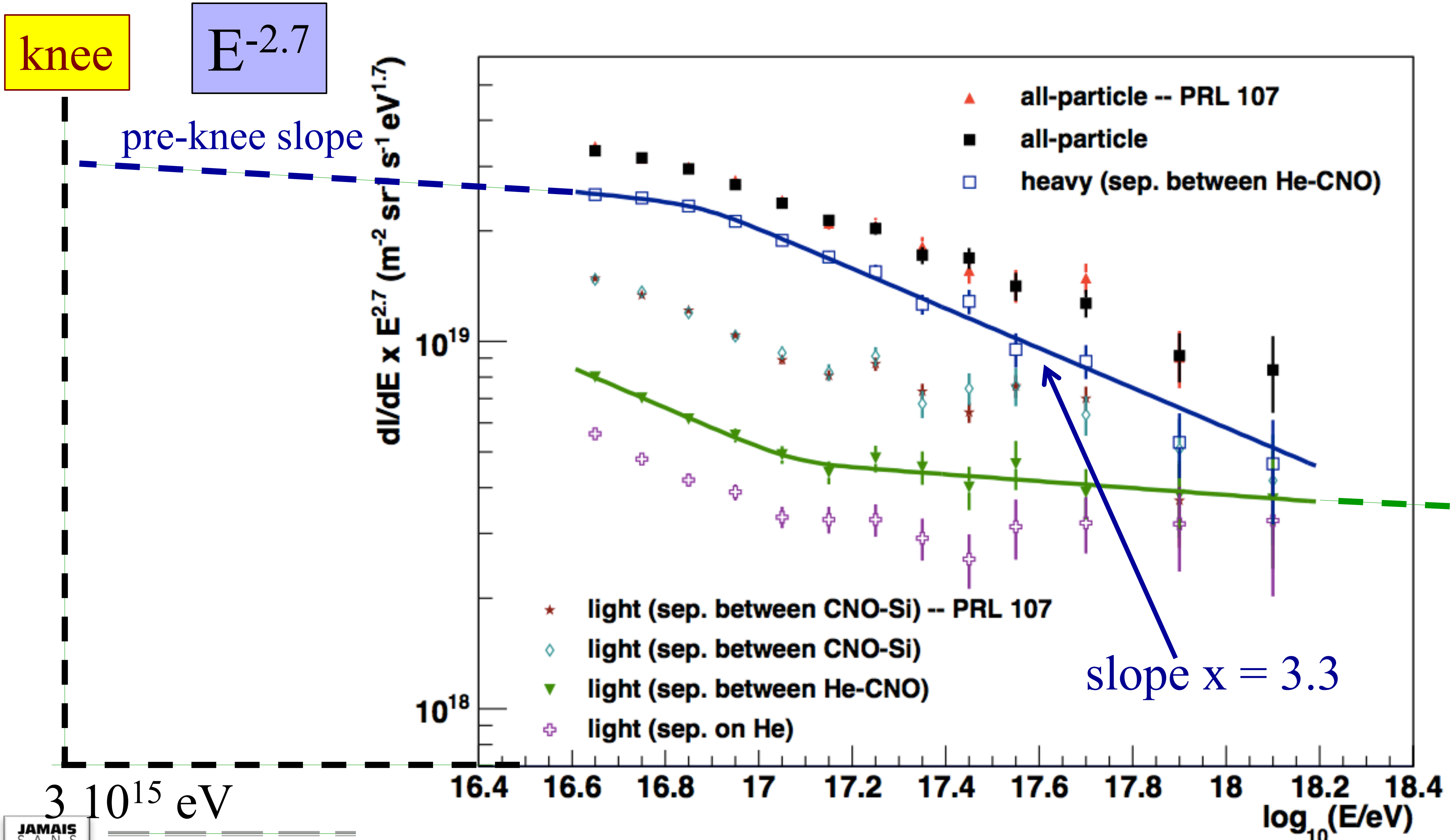

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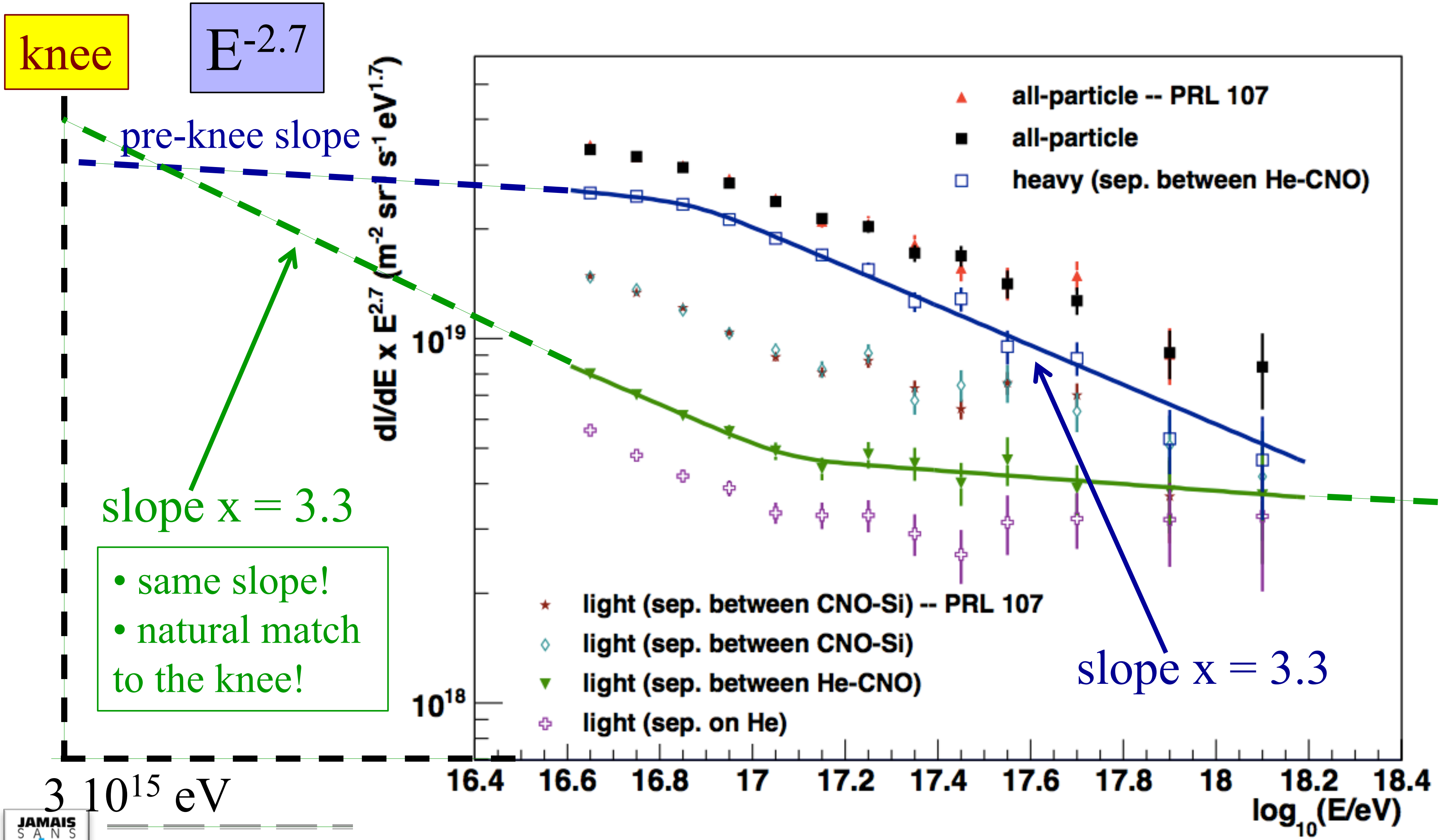

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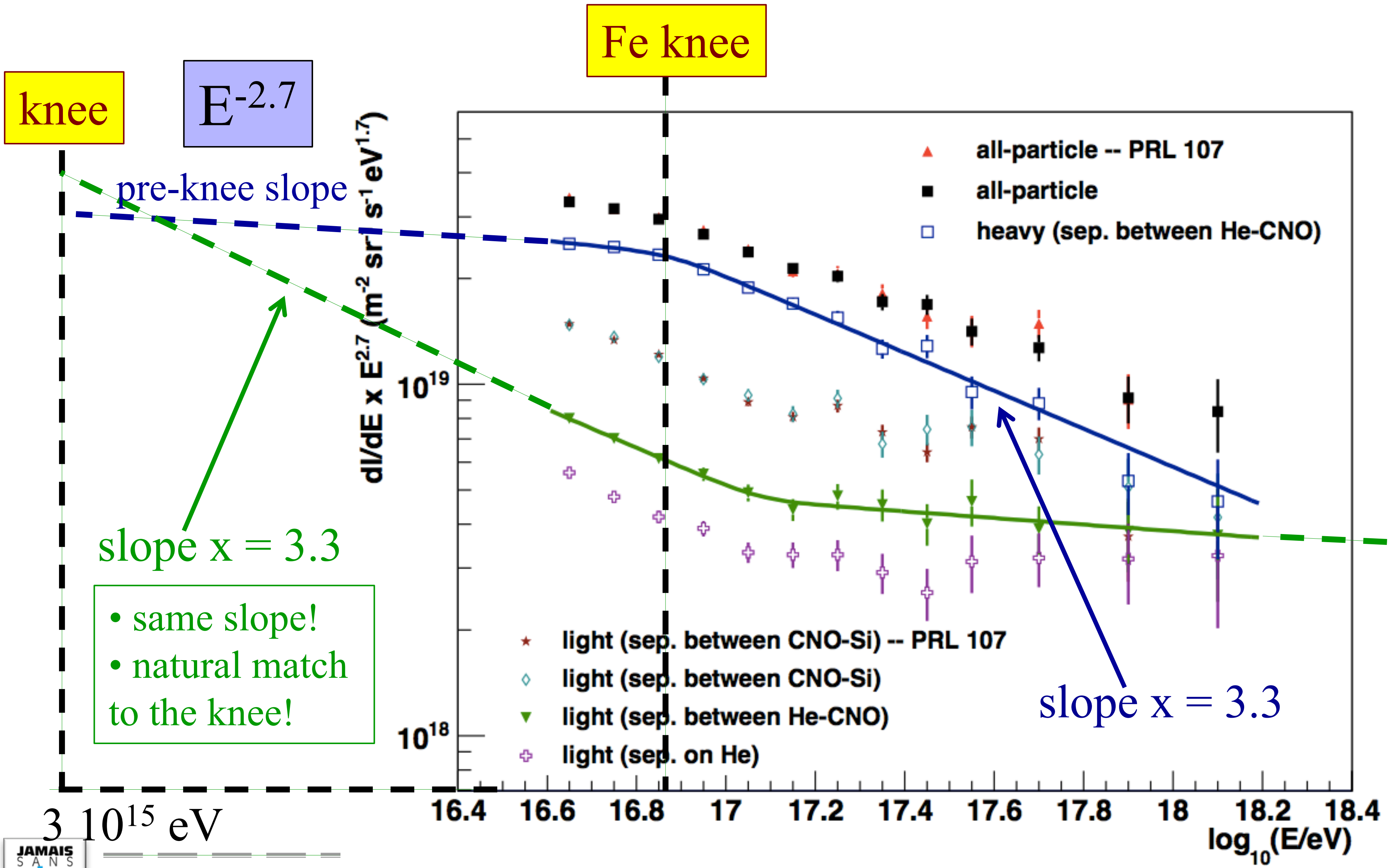
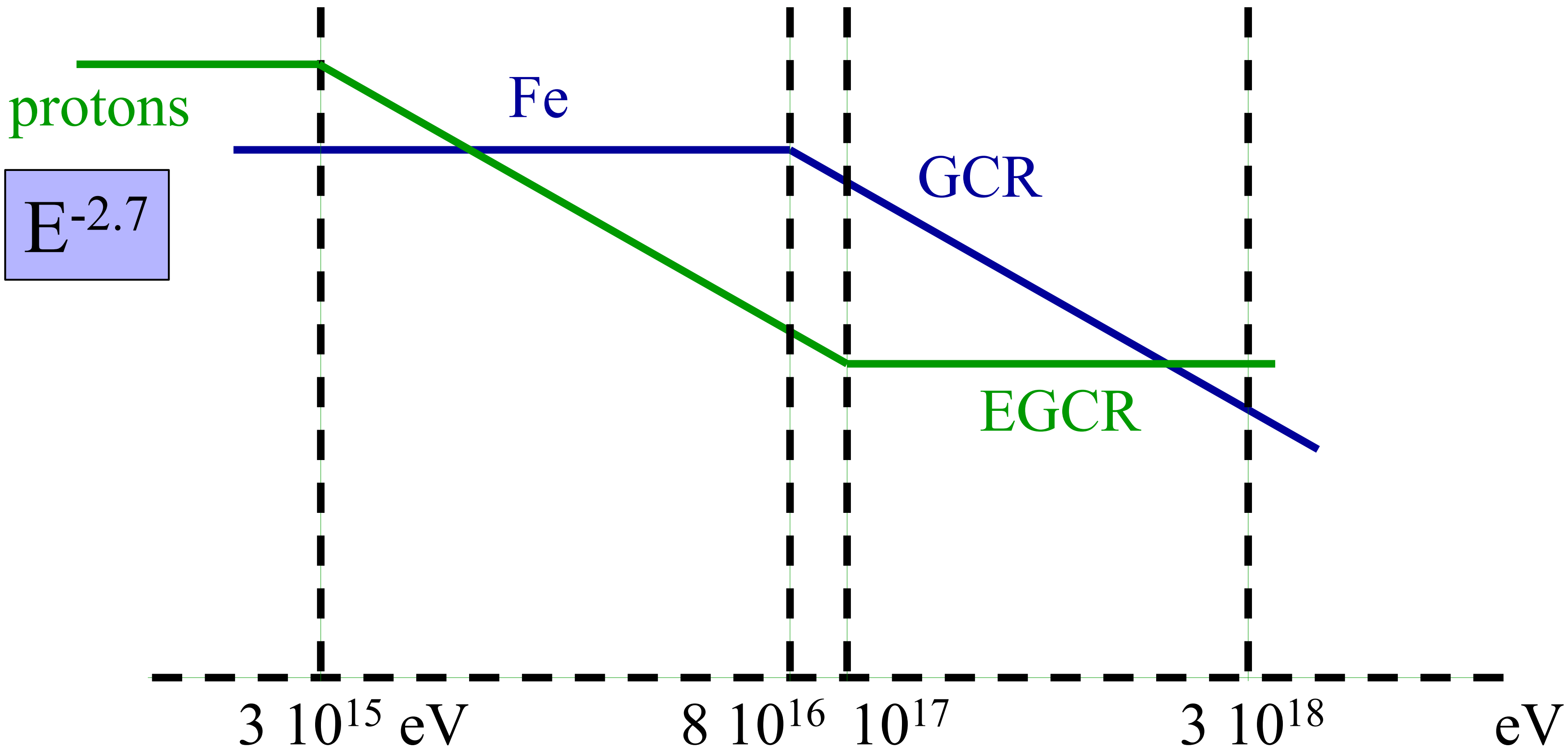
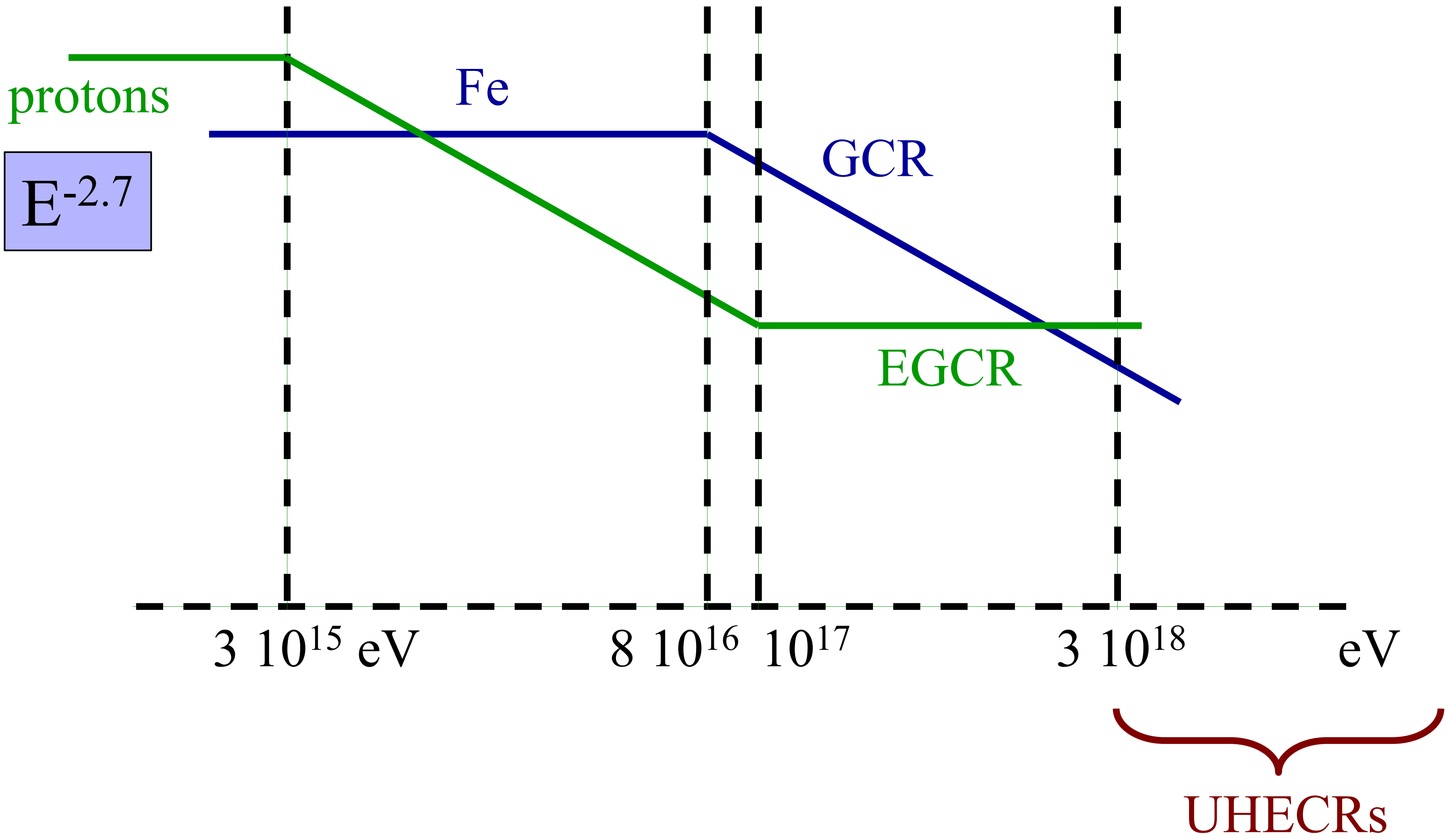


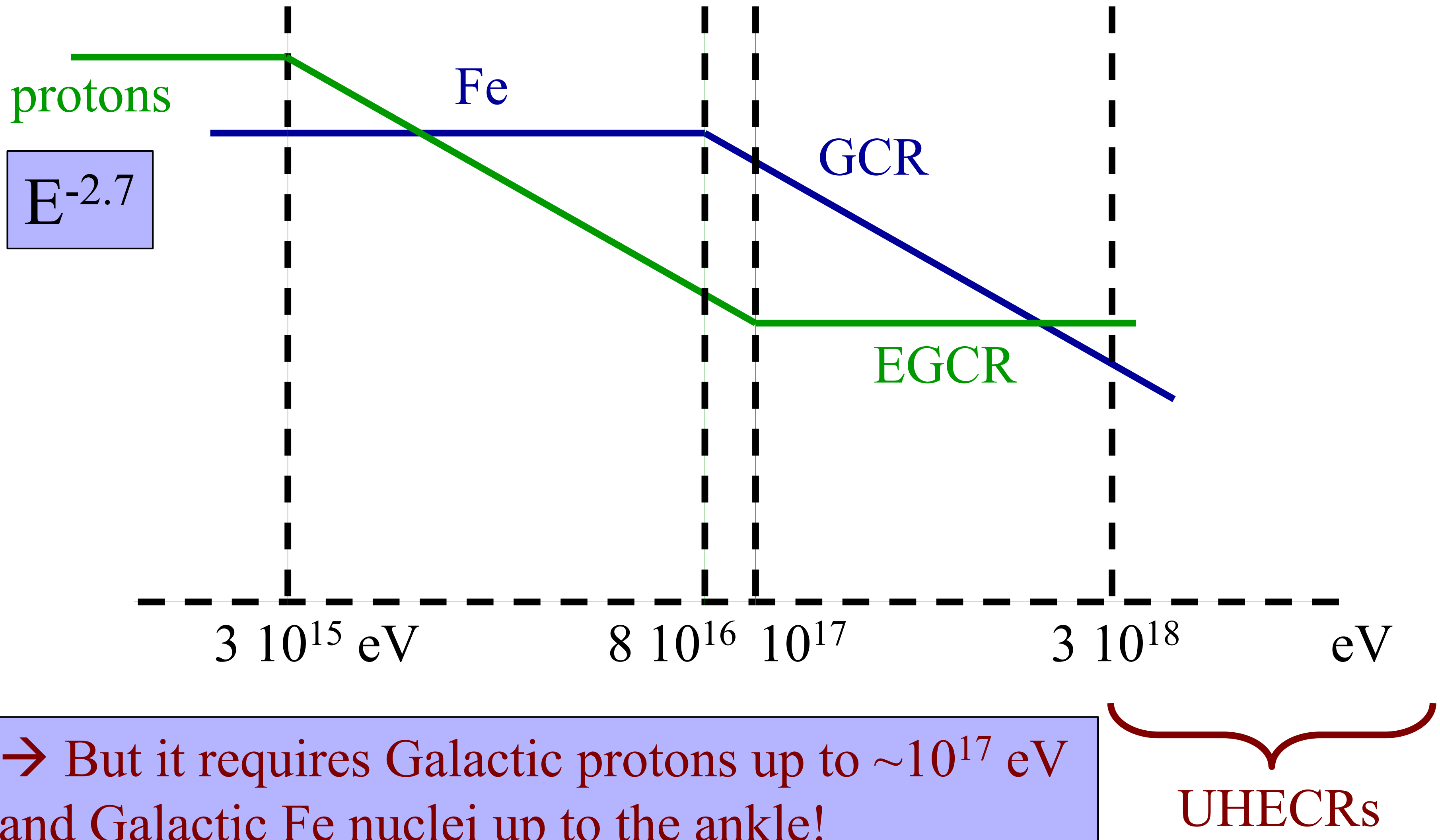
Very appealing GCR/EGCR transition picture



Very appealing GCR/EGCR transition picture



Very appealing GCR/EGCR transition picture

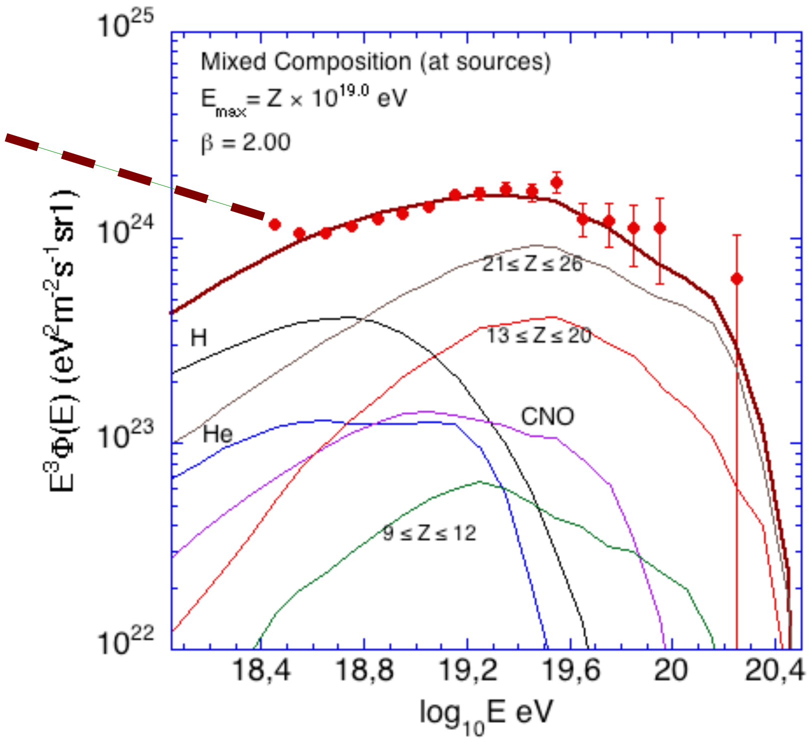


→ But it requires Galactic protons up to ~10^{17} eV and Galactic Fe nuclei up to the ankle!

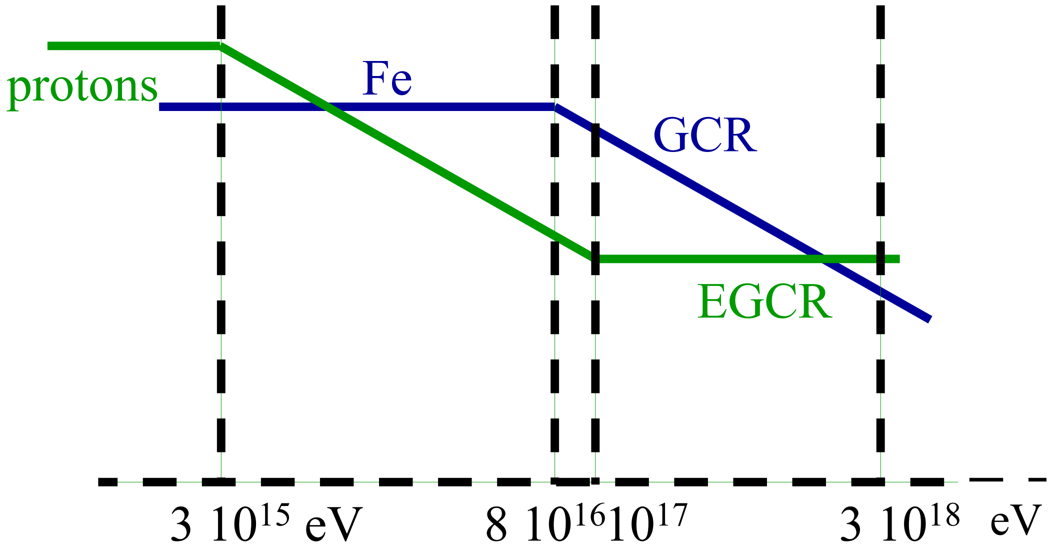
Not SNRs! → Is there a second GCR component?

Do we have a hardness crisis?

Low proton E_{max} models imply hard source spectra



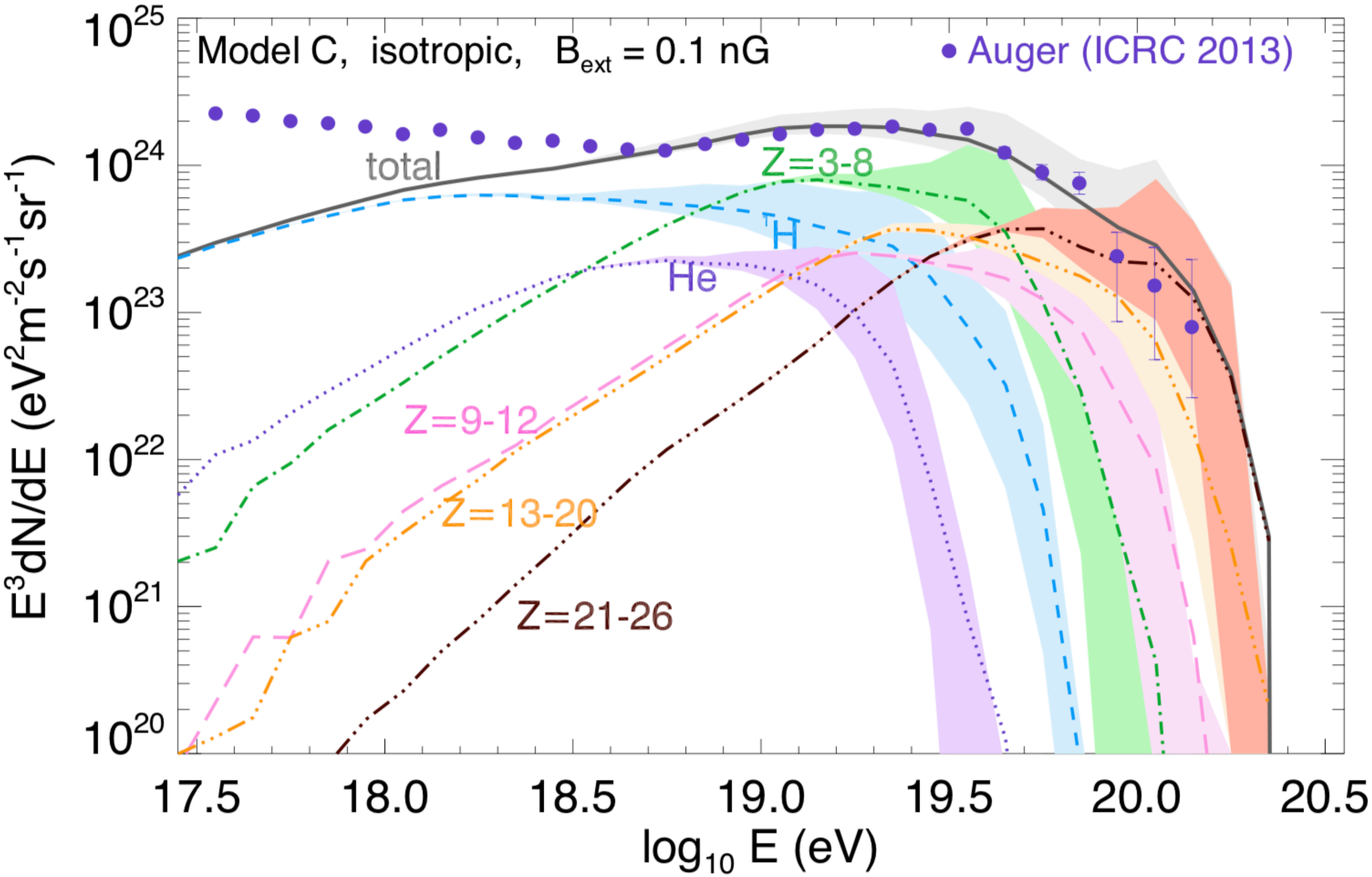
The EGCR proton component seems to be much softer!



<u>Does this require an additional component?</u>

In fact, no: a softer spectrum for EGCR protons (compared to EGCR nuclei) works as well!

Example: acceleration model in GRBs



Example of a simple, generic model
that meets the transition and UHE constraints

- One single GCR component, with rigidity dependence only
- One single EGCR component, from a GRB source model

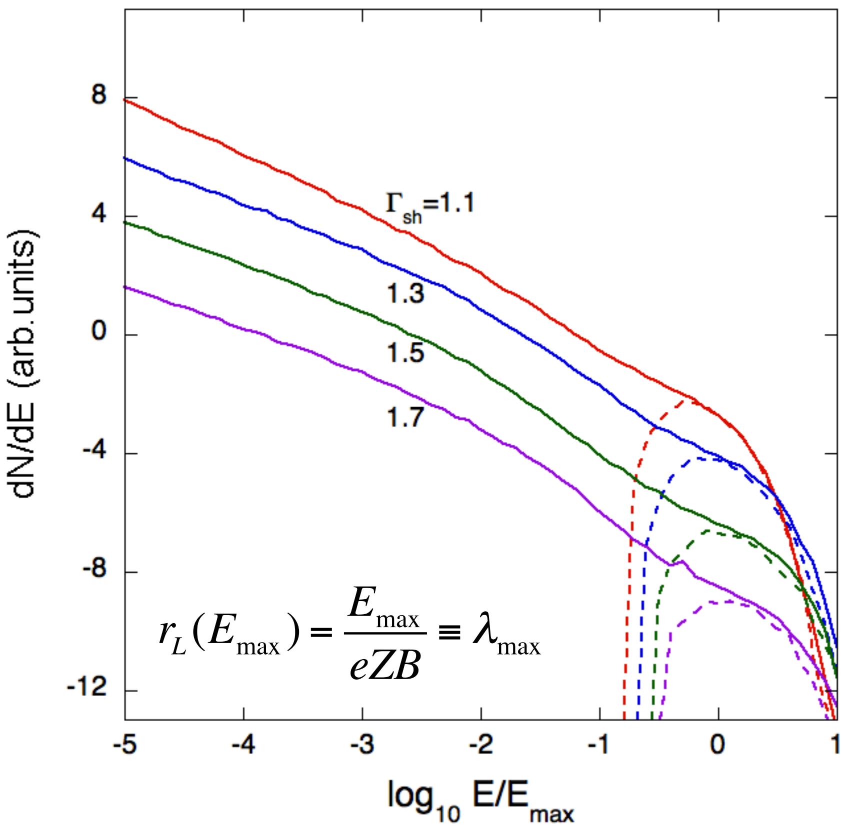
↓

gamma-ray burst

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 : should become a high pass filter in the presence of energy losses (particles must leave before being cooled by energy losses)

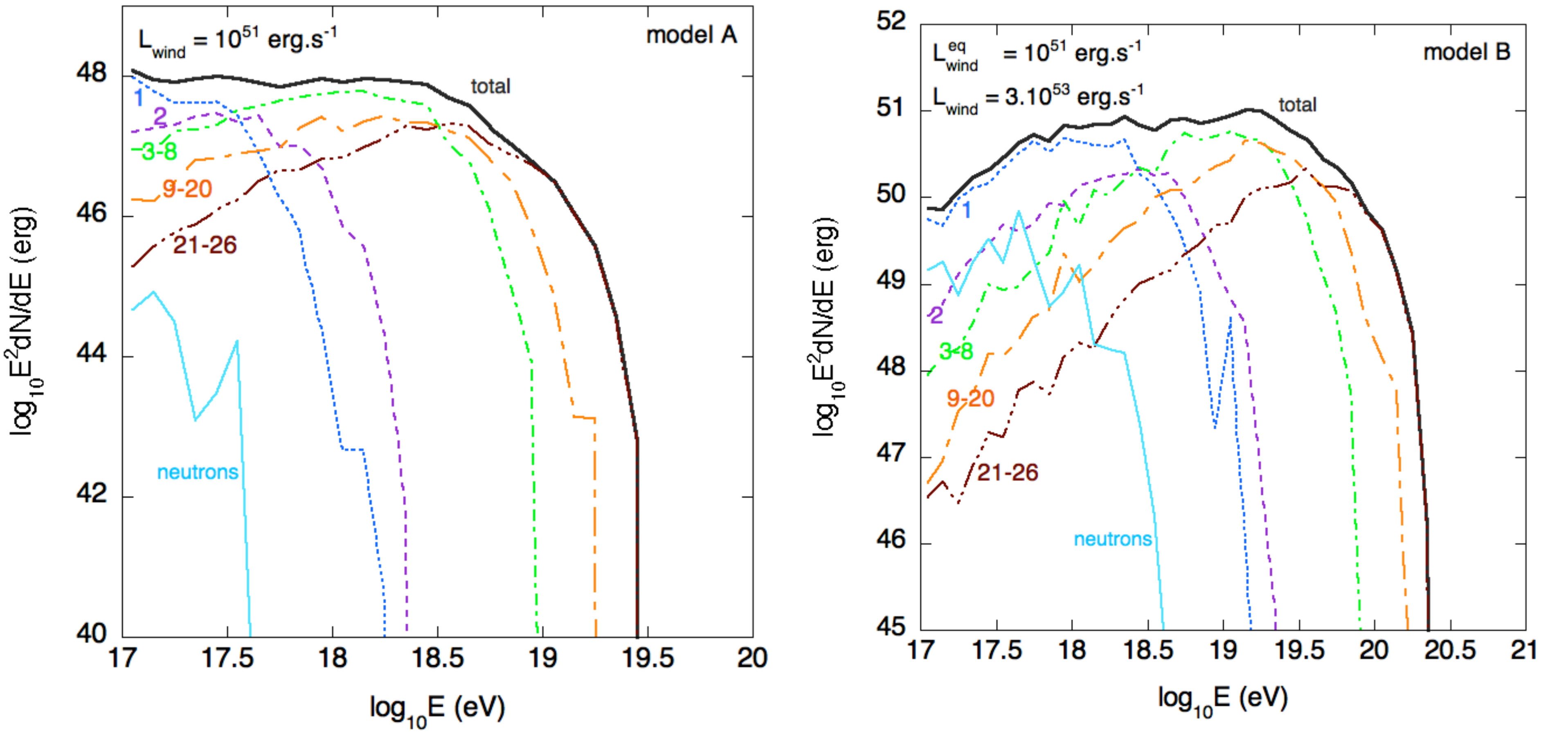
Particle acceleration with energy losses

- 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 whole GBR evolution
  - For each GRB luminosity
  - For each of three different energy partition models (A, B and C)

Particle acceleration with energy losses

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



mass hierarchy for E_{max} + very hard spectrum!

Particle acceleration with energy losses

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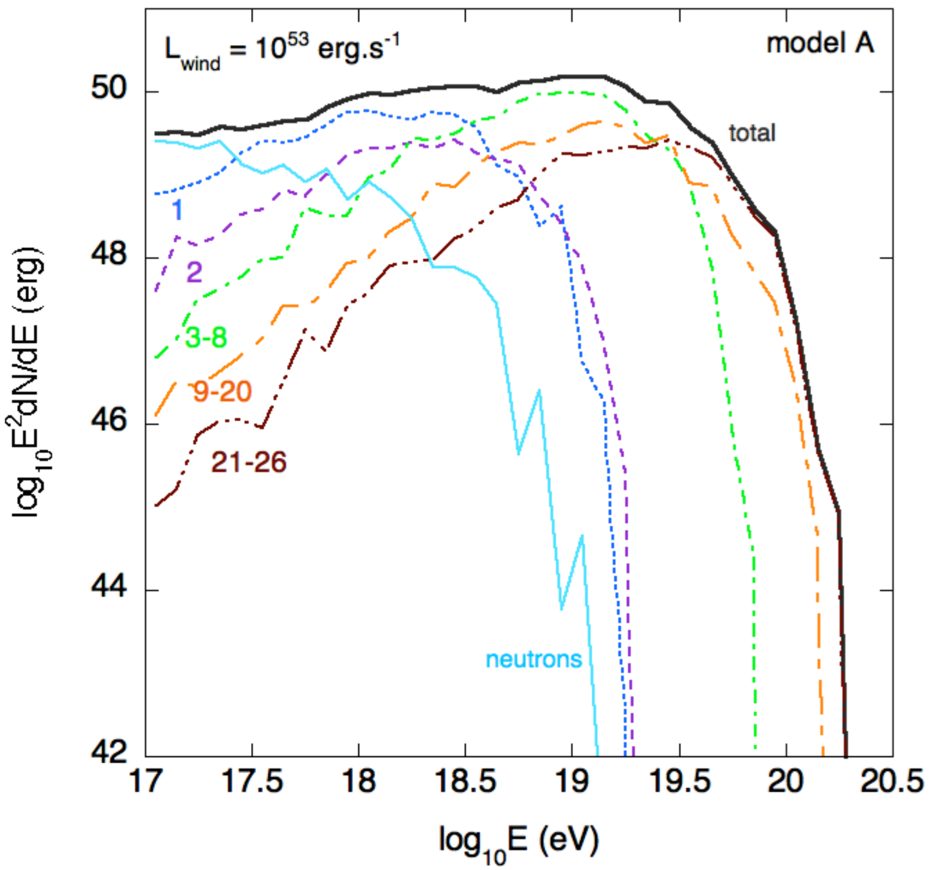

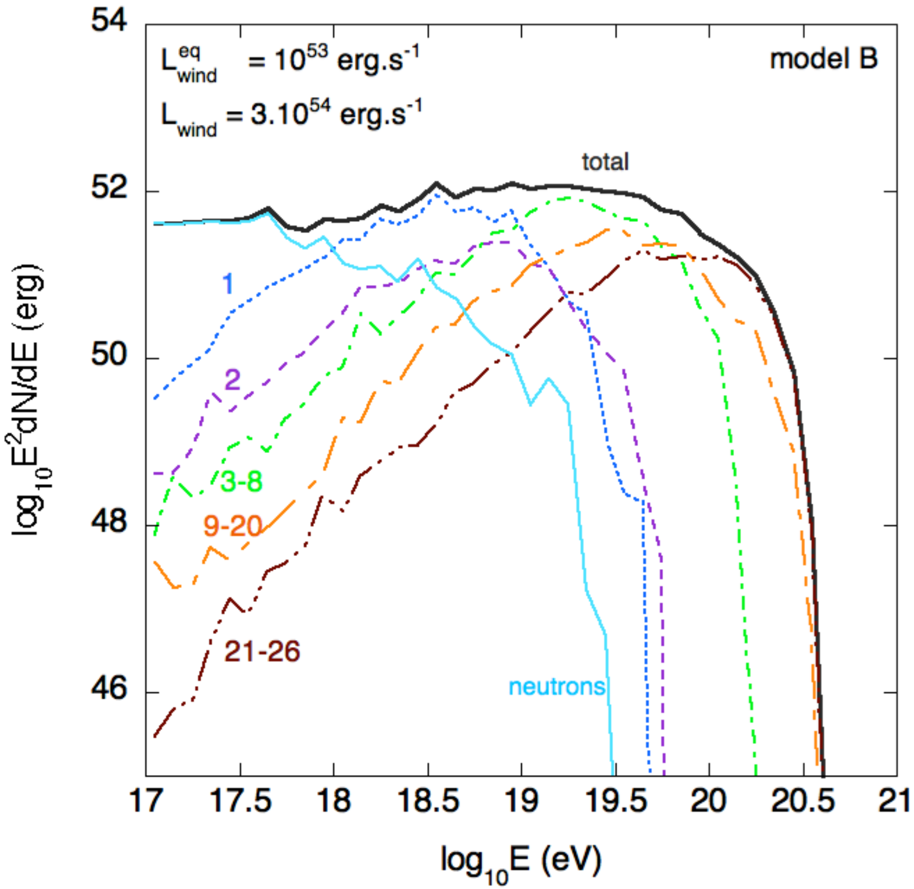

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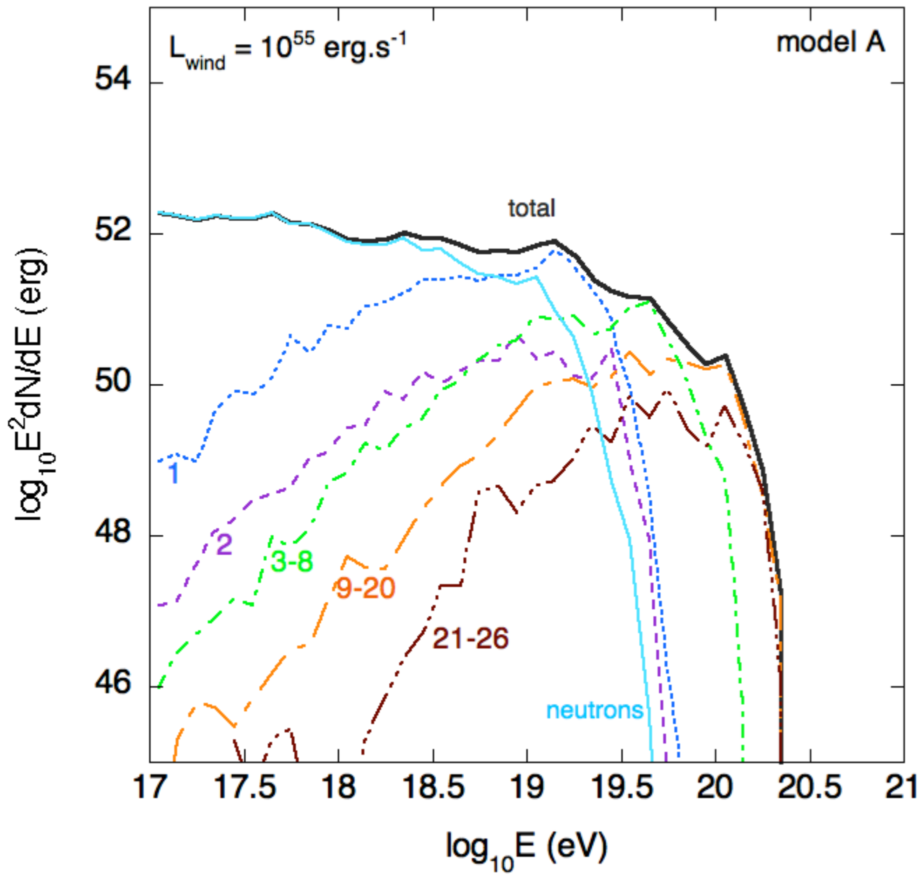
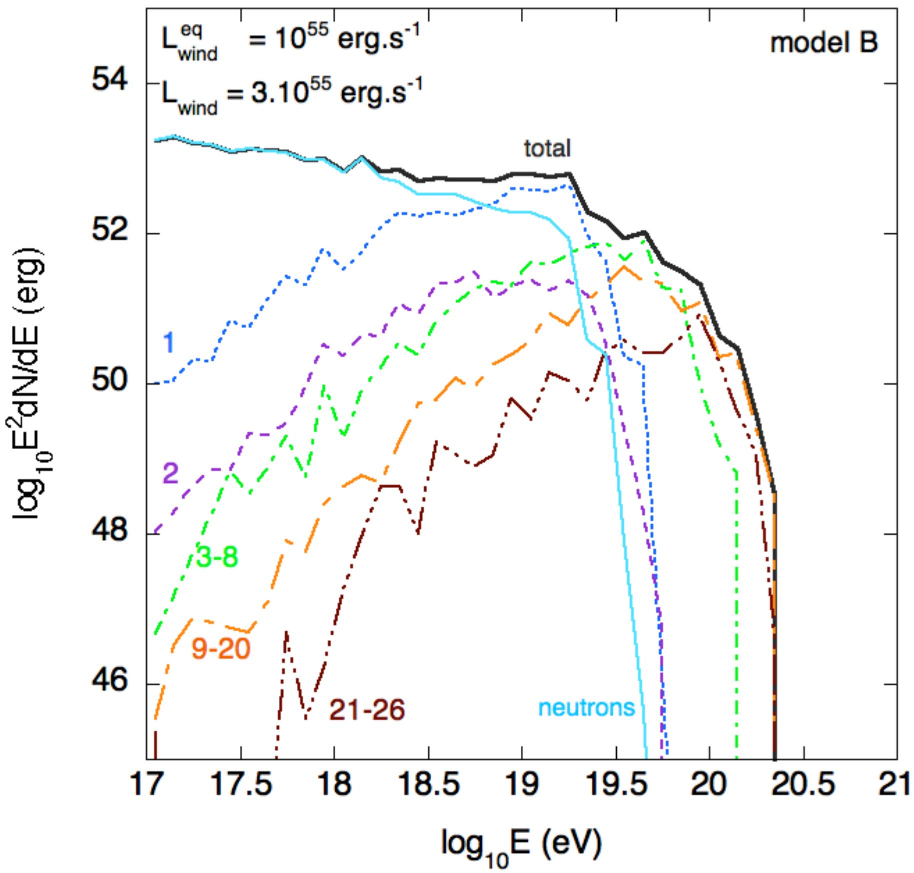




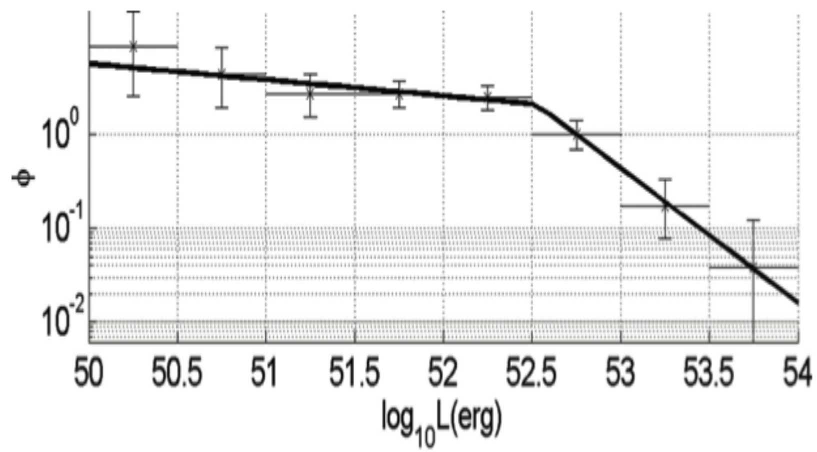
LOOK AT THE NEUTRON COMPONENT!!!

Resulting UHECR propagated spectra

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

$$\frac{dN_{\rm GRB}}{dL_\gamma}(L_\gamma) \propto \begin{cases} L_\gamma^{-\alpha} & \text{for } L_\gamma \leqslant L_\star \\ L_\gamma^{-\beta} & \text{for } L_\gamma > L_\star \end{cases}$$

$\alpha = 1.2$
$\beta = 2.4$

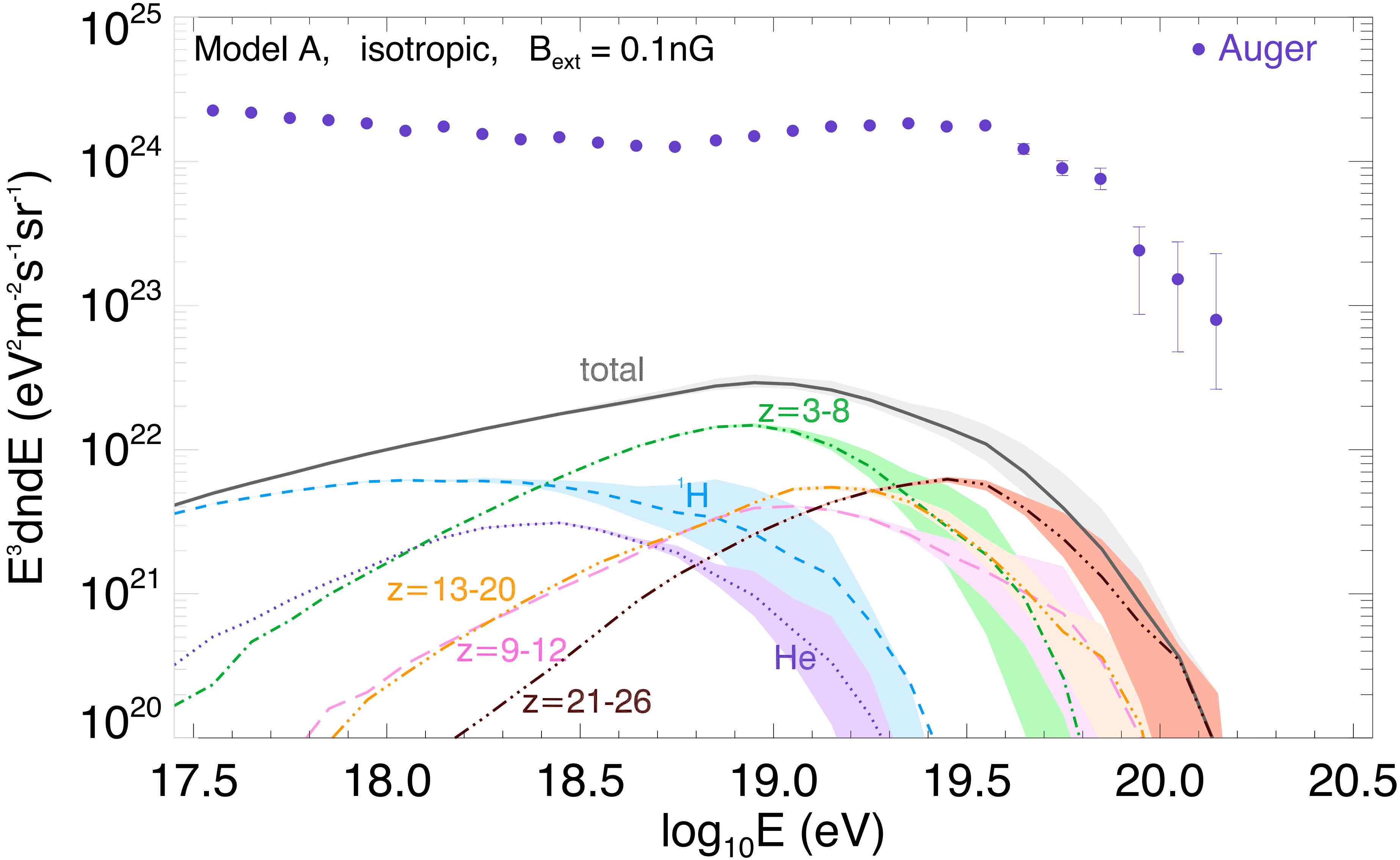


$$\rho_{GRB}(z) = \rho_{GRB}(0) \times \begin{cases} (1+z)^{n_1} & \text{for } z \leqslant z_\star \\ (1+z_\star)^{n_1-n_2} \times (1+z)^{n_2} & \text{for } z > z_\star \end{cases}$$

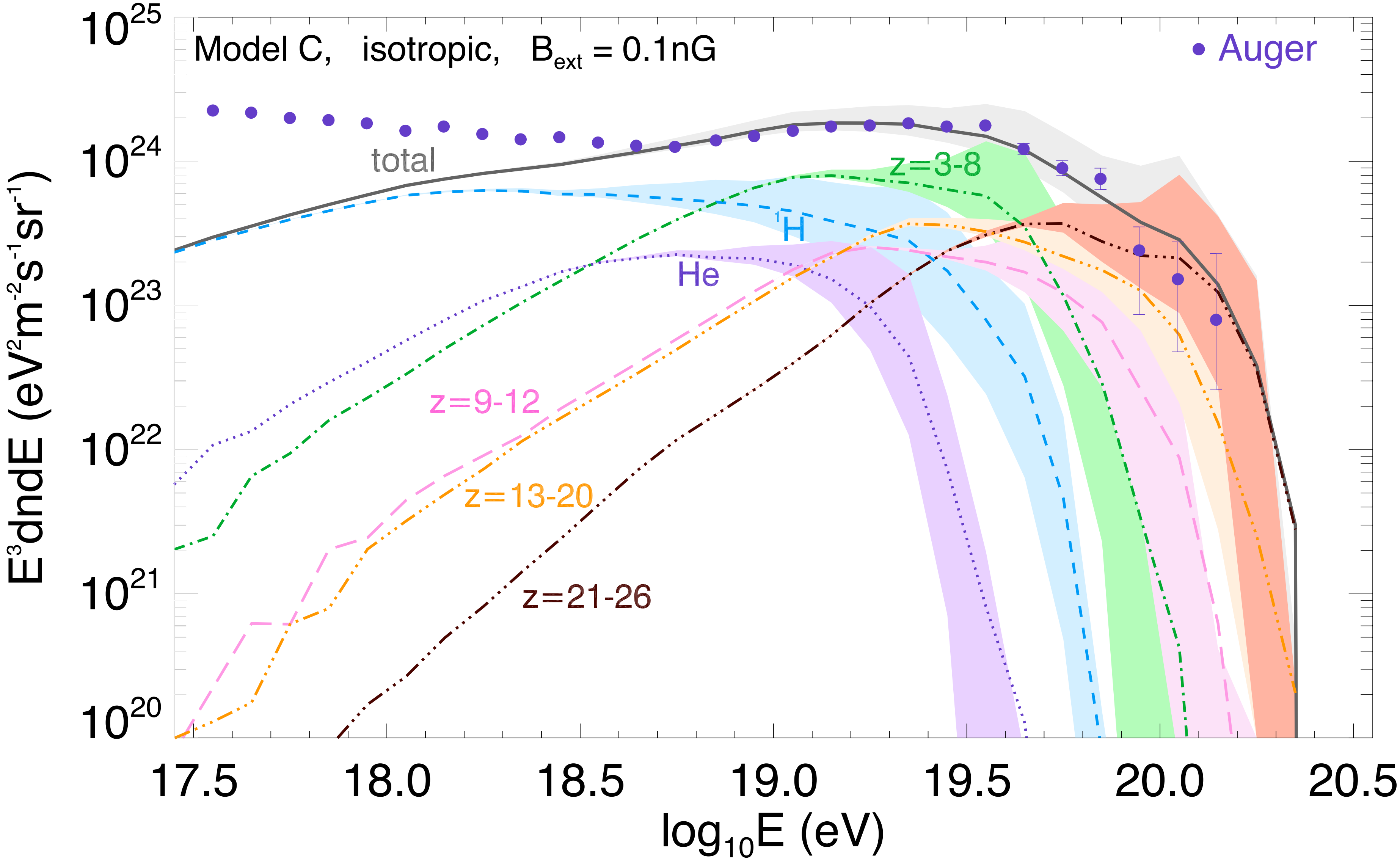
$$\rho_{\rm GRB}(0) = 1.3\,{\rm Gpc^{-3}\,yr^{-1}}$$

$n_1 = 2.1$
$n_2 = -1.4$
$z_* = 3$

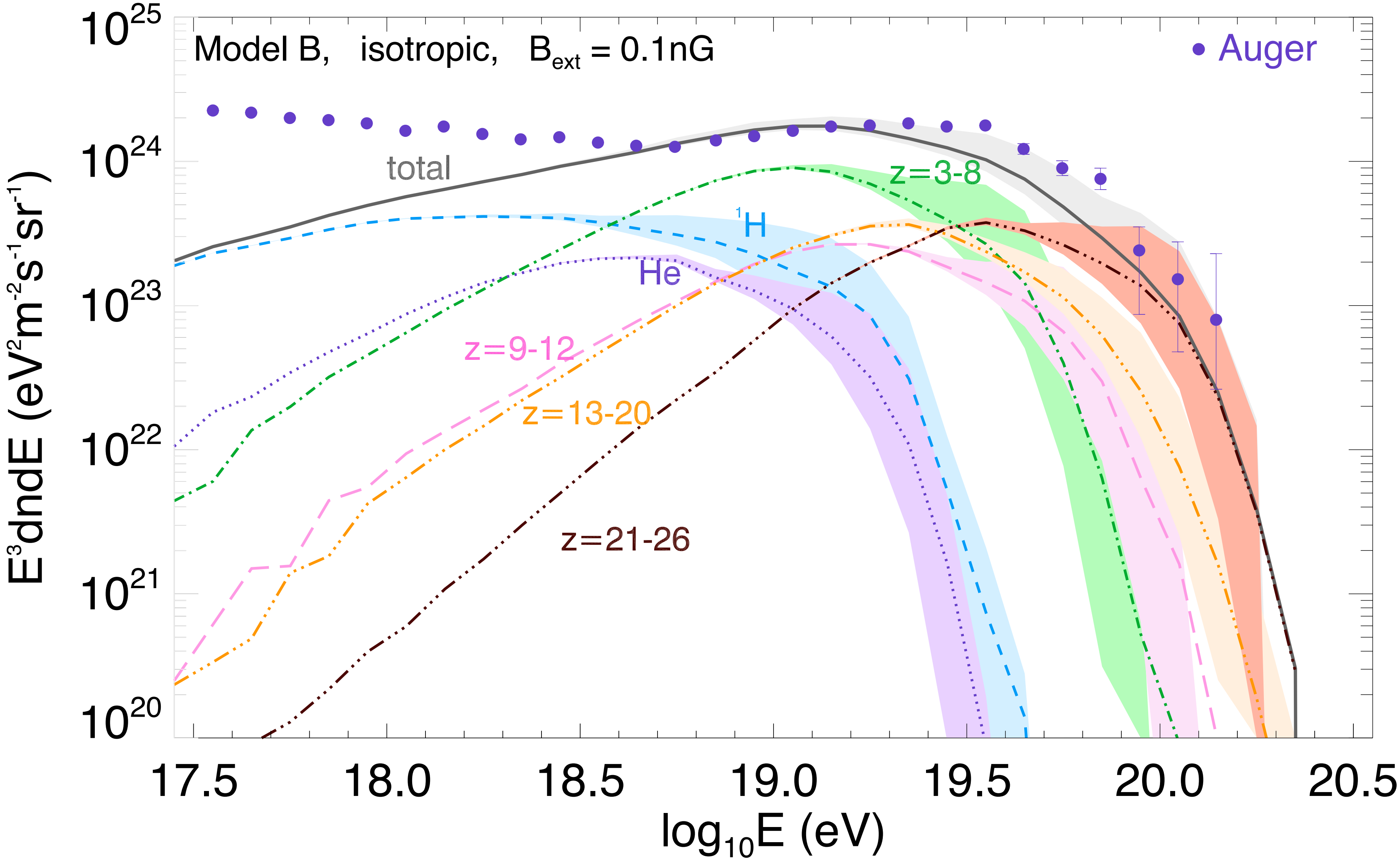
Resulting UHECR propagated spectra



Resulting UHECR propagated spectra



Resulting UHECR propagated spectra



Global GCR/EGCR model

Globus, Allard & EP (Phys. Rev. D, 2015)

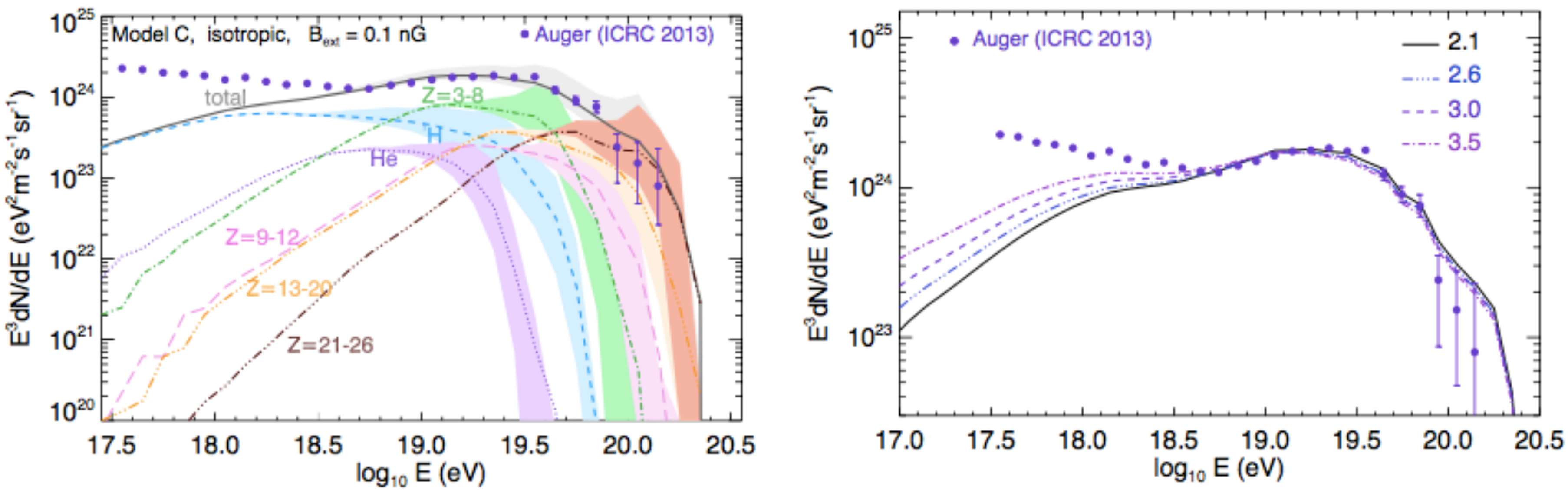
- Let's put GCR and EGCR models together!
- IT WORKS!
- All the spectral features and composition measurements can be reproduced, both qualitatively and quantitatively!
- Only two components are needed: 1 GCR + 1 EGCR

Global GCR/EGCR model

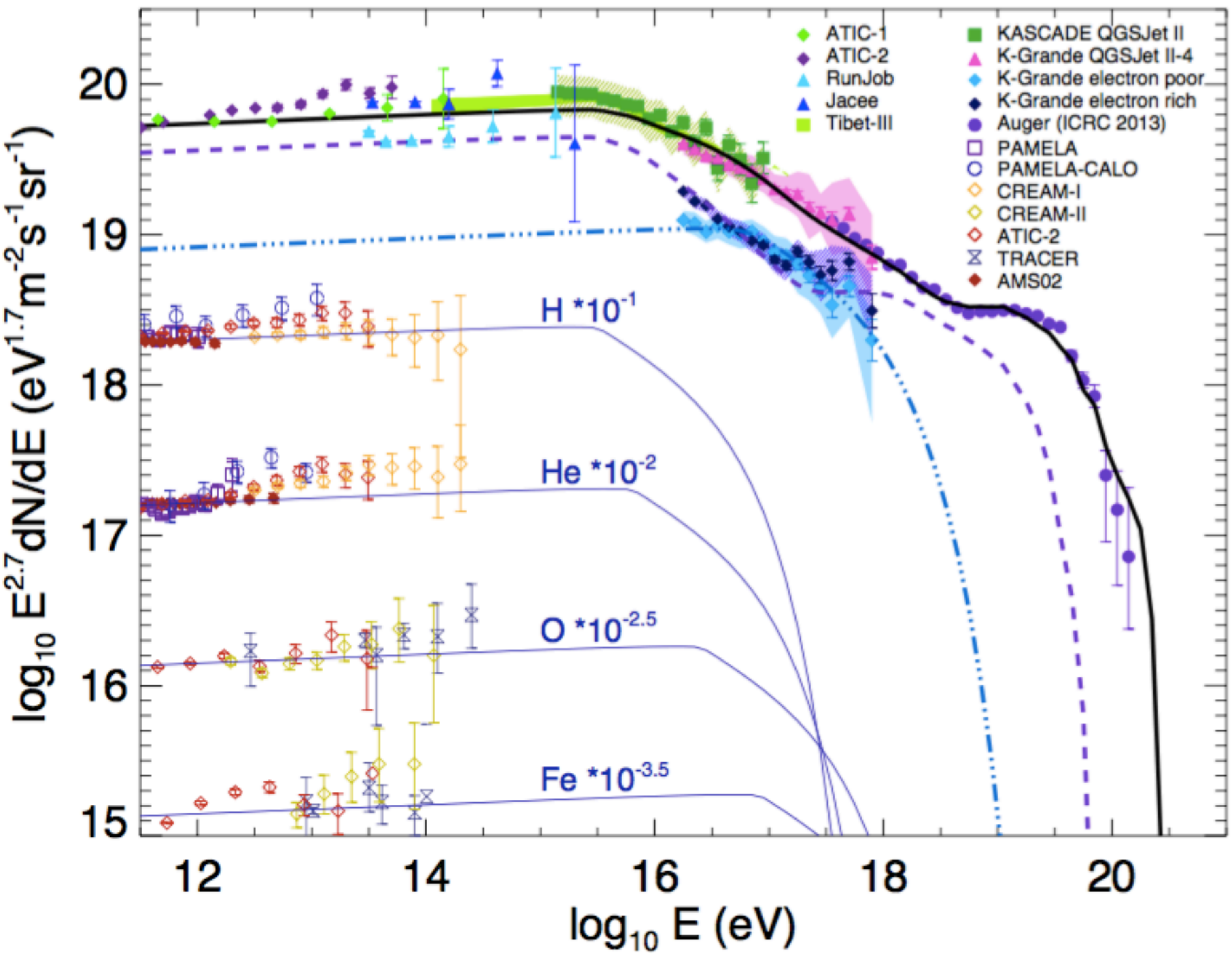
- GCRs: broken power law at the knee (either source or propagation effect), with measured abundances at low E (below the knee): purely rigidity-dependent spectrum

- EGCRs: fit of Auger spectrum data with the GRB acc. model

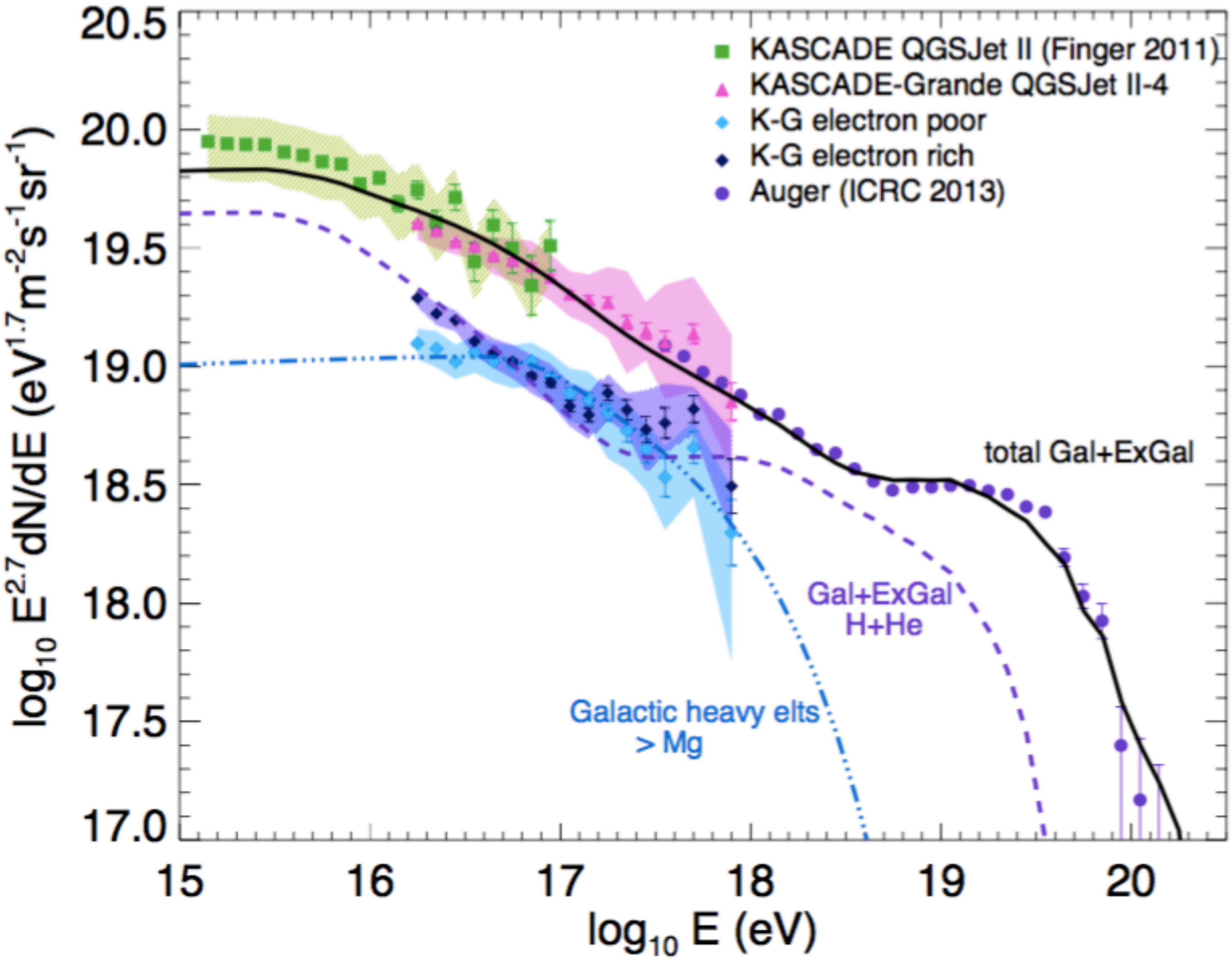
  + cosmological evolution of the sources (but could be different GRB wind model, etc.) → 1 extra parameter



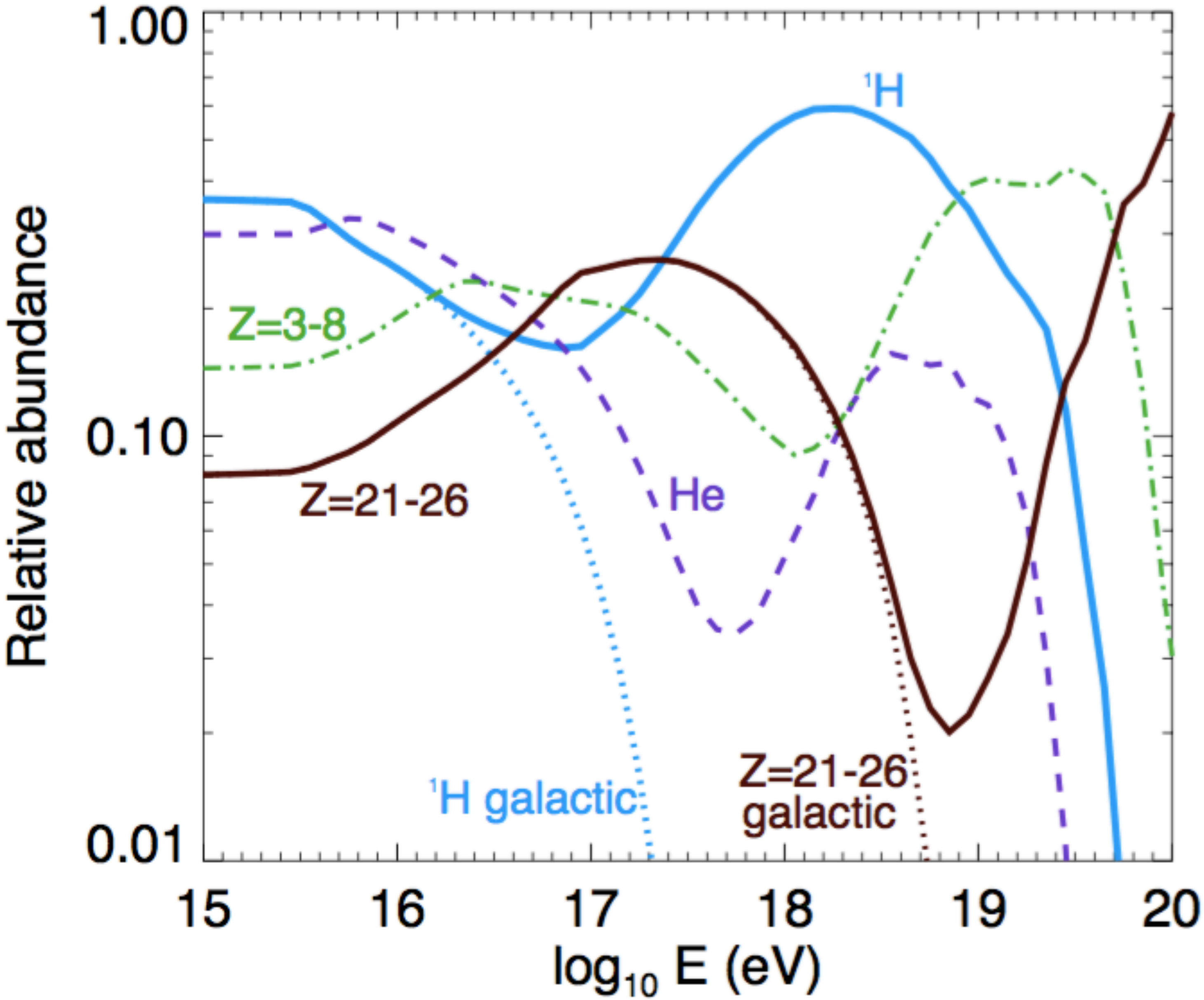
Global GCR/EGCR model: spectrum



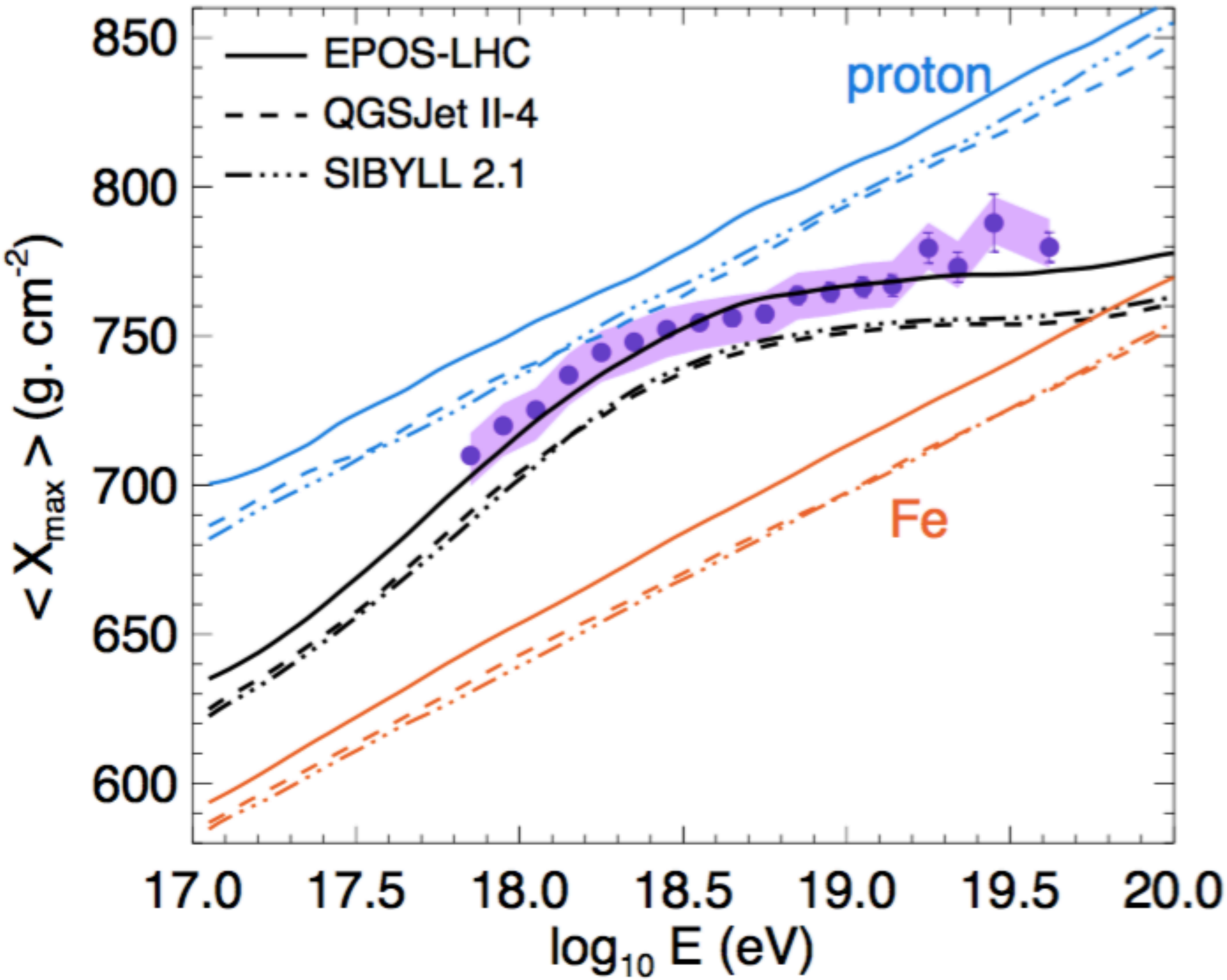
Global GCR/EGCR model: spectrum



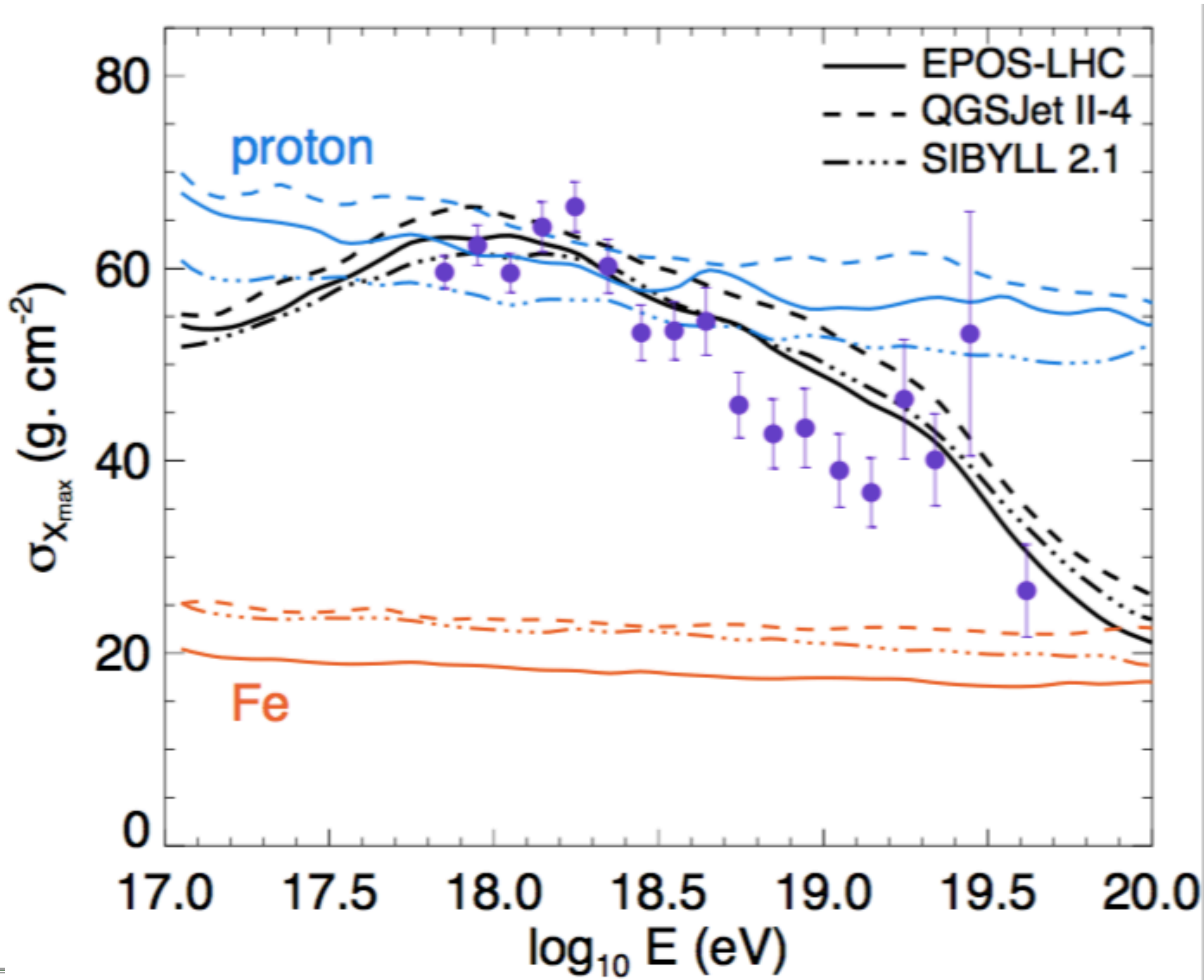
Global GCR/EGCR model: composition



2. Global GCR/EGCR model: composition



2. Global GCR/EGCR model: composition



Implications

- ✧ Two dominant components are sufficient to account for the general CR phenomenology over the entire spectrum

- ✧ But then the EGCR component must have a low maximum energy (with a charge/mass dependence) and softer proton spectrum

- ✧ The GCR proton component should extend up to ~10^{17} eV

  → Seems very hard for SNR models
  (which have other severe problems, by the way!)

- ✧ NB: the GRB acceleration model is probably not unique: strongly magnetized media with high photon density would produce the same key features (presumably)

- ✧ Other schemes are possible, with additional components
  → other types of implications and questions

Main message

- ✧ The GCR/EGCR transition region is very important to study
- ✧ It is constrained from above by EGCRs and from below by GCRs
- ✧ In turn, it constraints GCRs and EGCRs!
- ✧ Studies must involve energy spectrum, composition and anisotropies (and their energy evolution)

Perspectives

- ✧ More data are needed on the GCR/EGCR transition region
- ✧ The knee needs to be understood → data needed!
- ✧ Detailed anisotropy studies will be important (at all energies)
- ✧ Find GCR sources! → keep an open mind beyond isolated SNRs!
- ✧ Find EGCR sources! → take advantage of the GZK horizon effect: look deep into the cut-off, with larger exposure and full sky coverage

  NB: important efforts of the JEM-EUSO Collaboration to develop space-based UHECR studies → stay tuned ;-)

- ✧ Develop multi-messenger astronomy!

  Cosmogenic neutrinos + electromagnetic cascades → neutrino and gamma-ray backgrounds + individual sources