UHECR 2014

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On the GCR/EGCR transition and UHECR origin

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- astro-ph.HE: arxiv.org/abs/1410.2655 (Parizot, 2014)
- astro-ph.HE: arxiv.org/abs/1409.1271 (Globus et al., 2014)

I- GCR/EGCR transition

Please check Parizot (2014): astro-ph/1410.2655 and a forthcoming paper…

Important facts about Galactic CRs (some)

- ✧ CRs below the knee (at least!) come from the Galaxy
- ✧ The energy spectrum shows a break at the so-called "knee" and "2nd knee"
- ✧ The energy of the knee-like break is mass dependent
- ✧ The origin of GCRs is still unknown!
  - ➢ Please have a look at astro-ph.HE: arxiv.org/abs/1410.2655

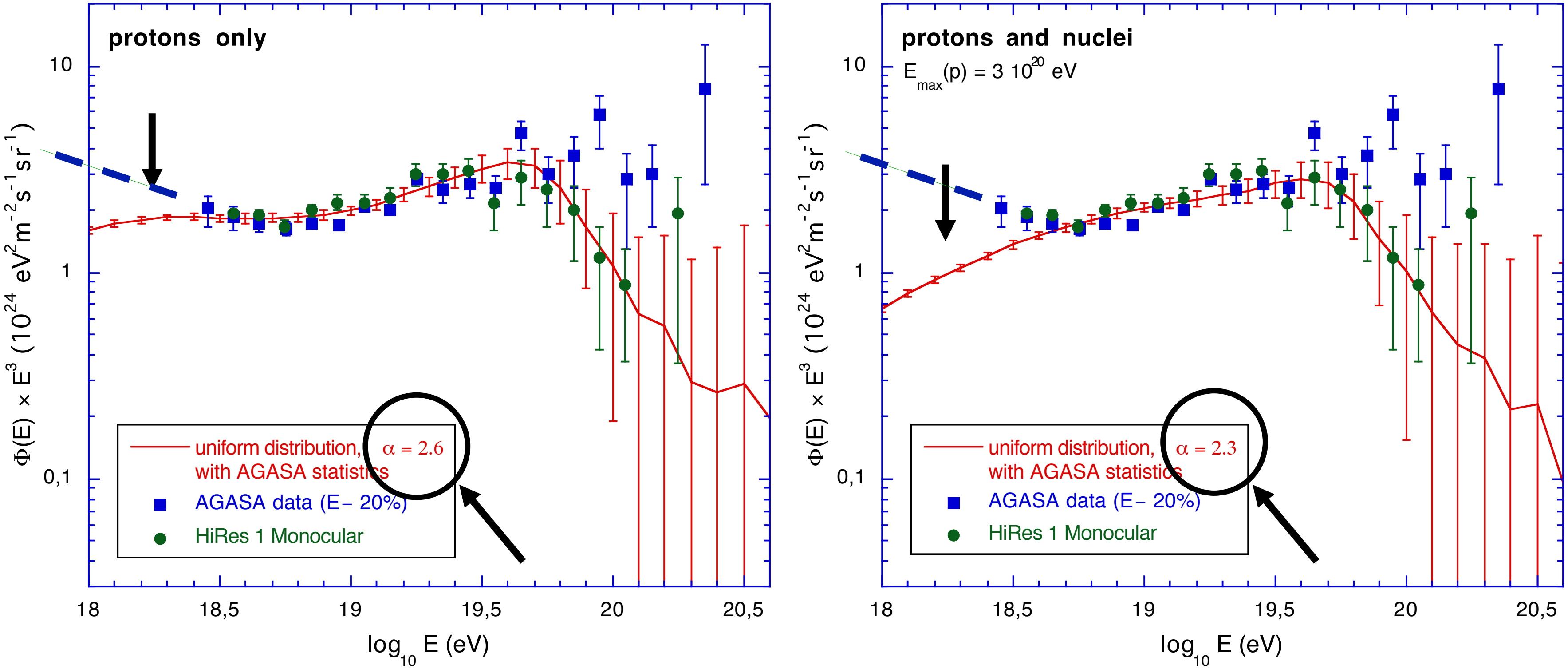
Important facts about UHECRs (some)

- ✧ The energy spectrum shows a cut-off where it is expected to be if the GZK effect applies (and it has to!)
- ✧ UHECRs show a gradual transition from a mixed composition (with dominant fraction of light nuclei) to a heavier and heavier composition, between ~10^{18} eV and ~3 10^{19} eV
- ✧ There is no significant small angular scale anisotropy
  - ➢ By the way, a large fraction of protons at the highest energies would be in contradiction with this result!

Implication for GCR/EGCR transition

- It is known since a long time that the presence of nuclei among UHECRs strongly suggest that the GCR/EGCR occurs at the ankle!

Allard et al. 2005



- An even harder source spectrum is needed in the case of a low proton E_{max}

The "low-proton E_{max}" scheme

- Very simple, natural and comforting generic interpretation of the UHECR data, which makes a lot of sense 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

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

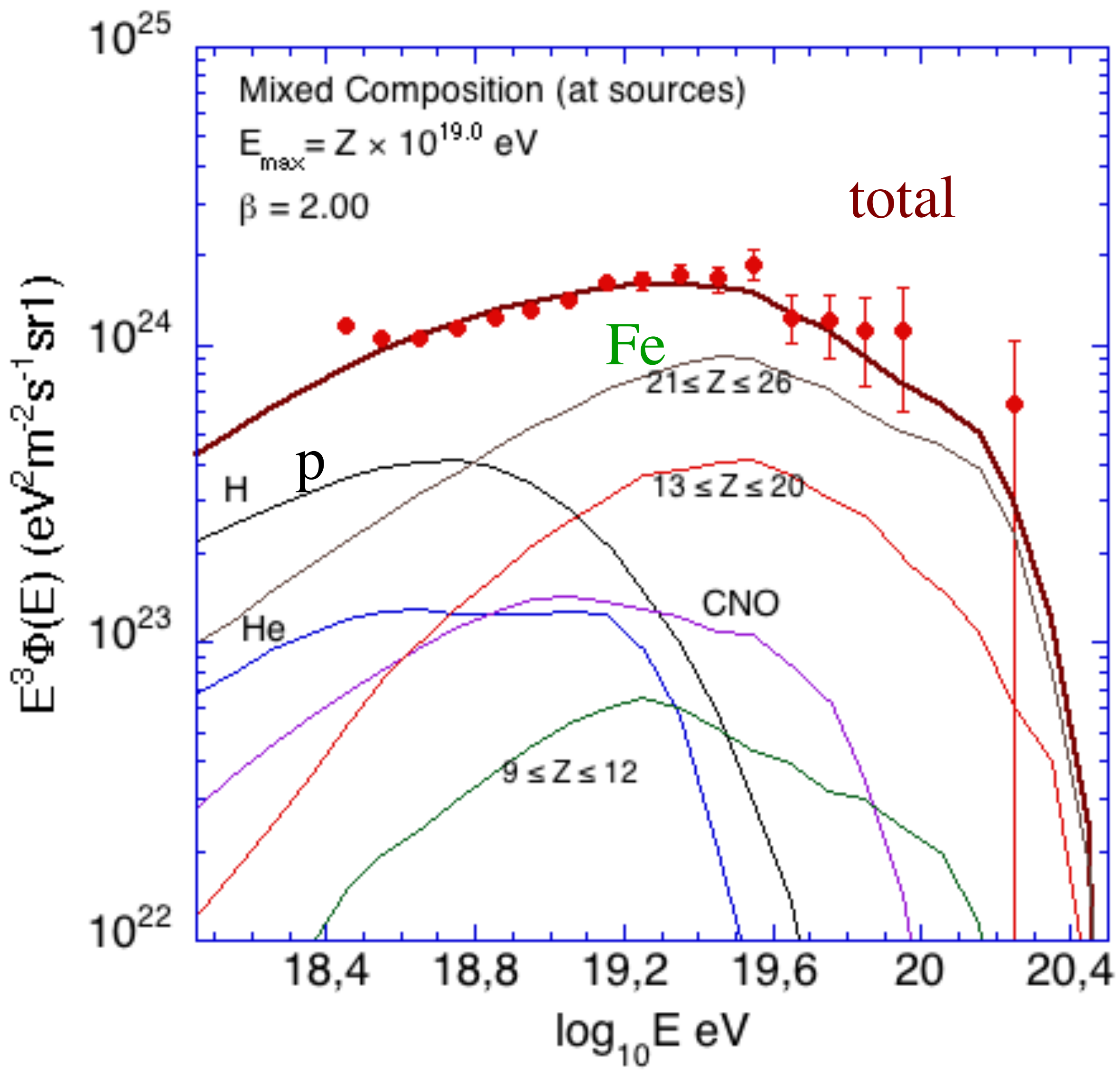
- Relaxes an old standing problem: very hard to build acceleration models providing maximum proton energies above 10^{20} eV!

  → More comfortable: $E_{max}(p) \sim$ between 4 10^{18} eV and 10^{19} eV

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

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

An example of low proton E_{max} model



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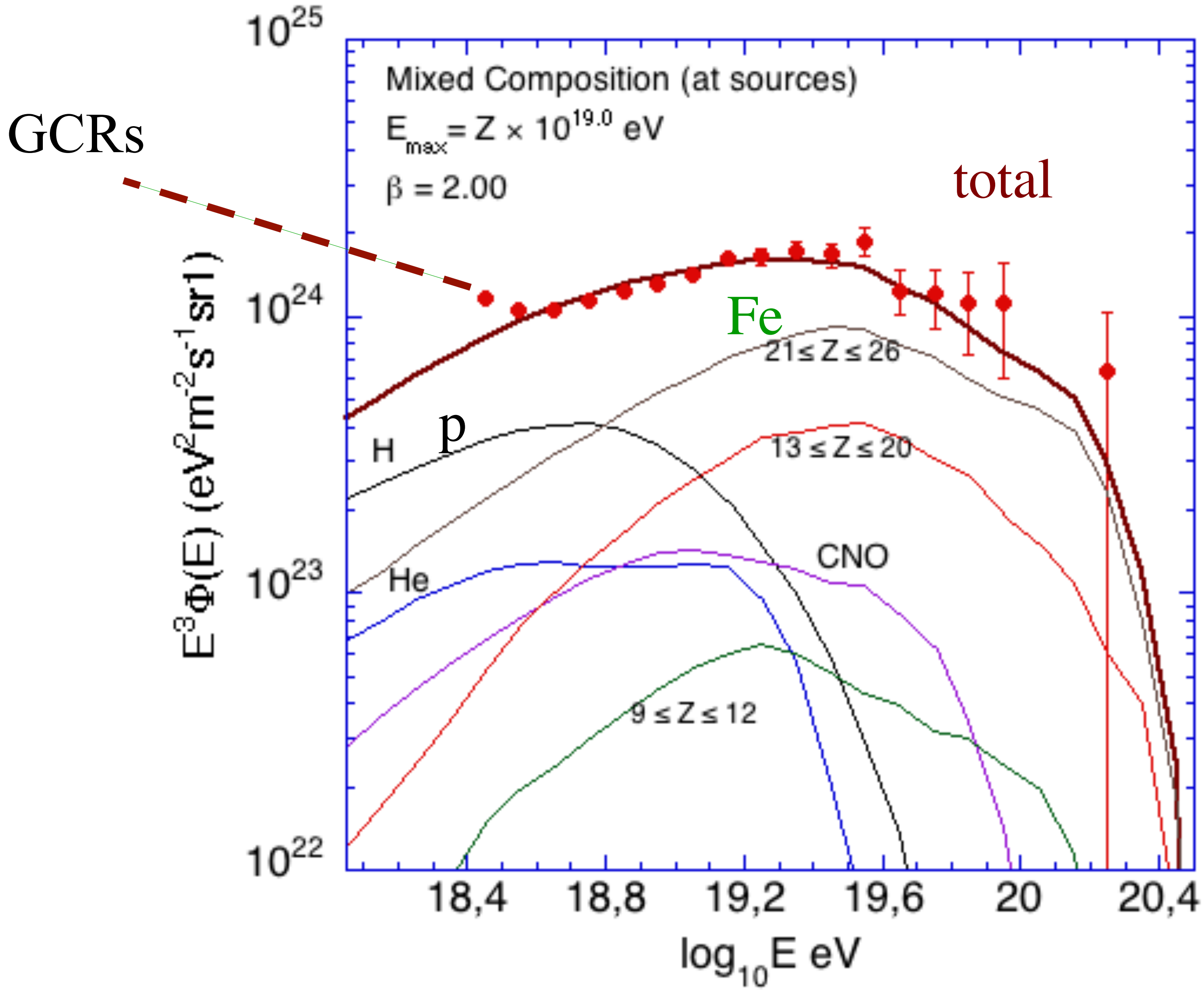
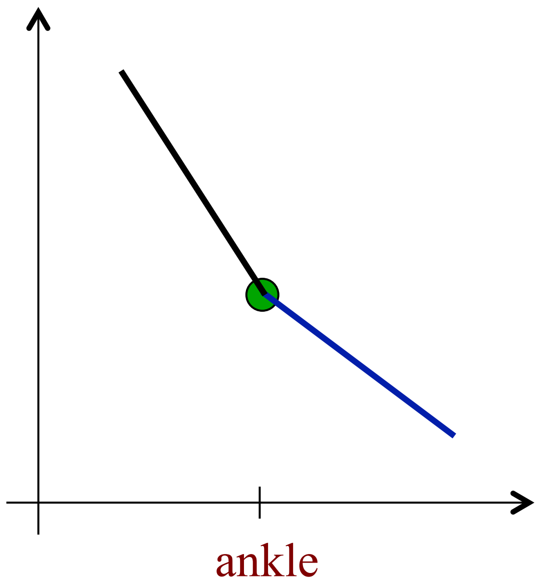


General phenomenology of transitions

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

transition from a softer
to a harder component



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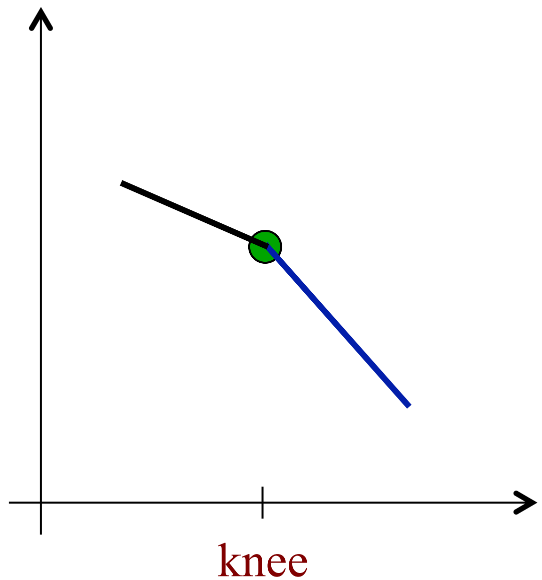

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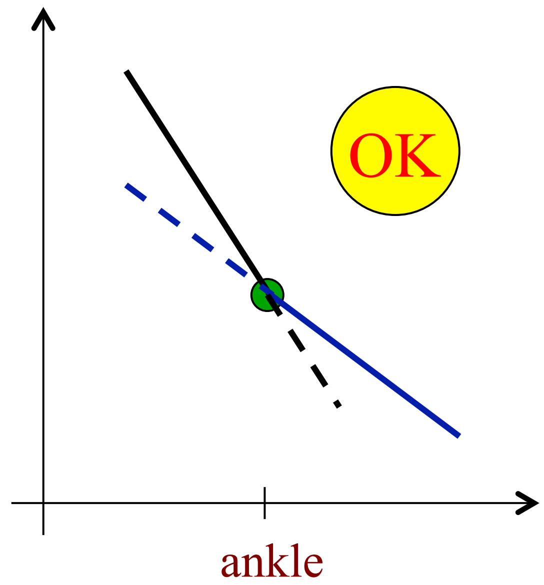

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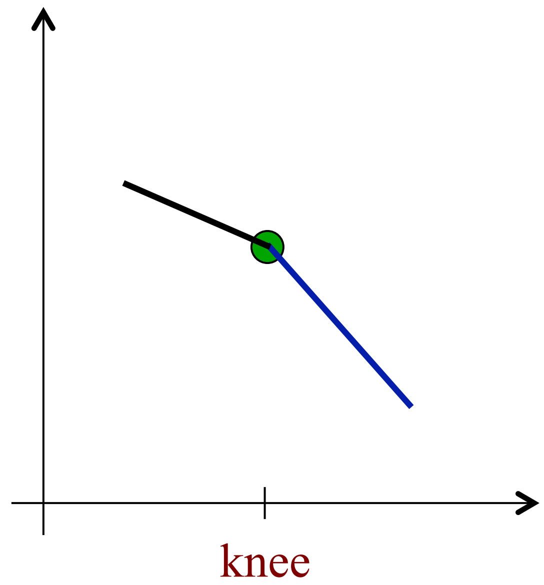

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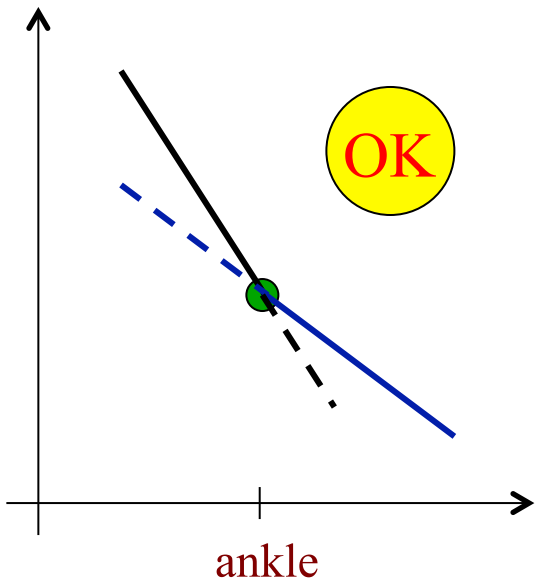

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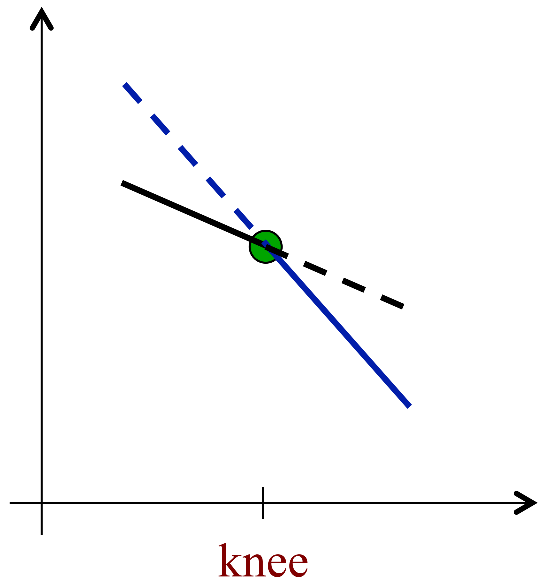

General phenomenology of transitions

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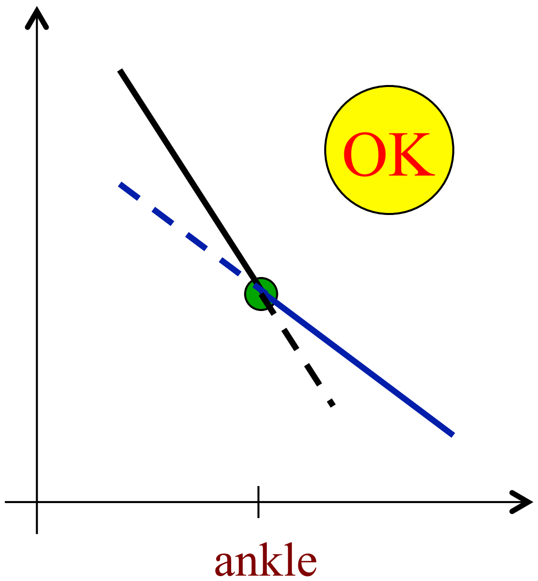

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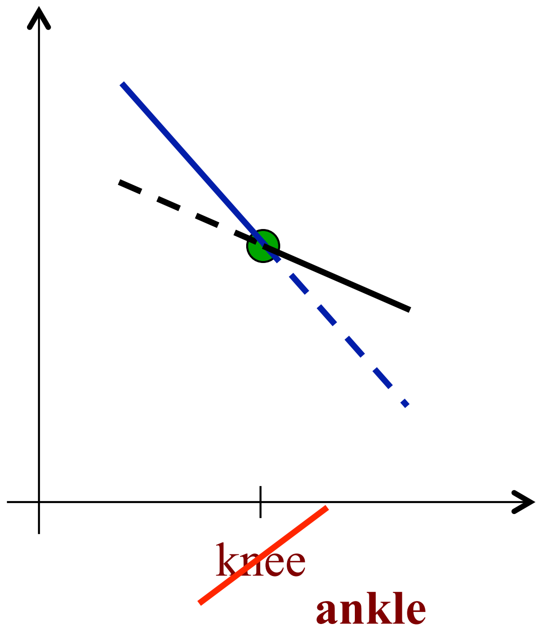
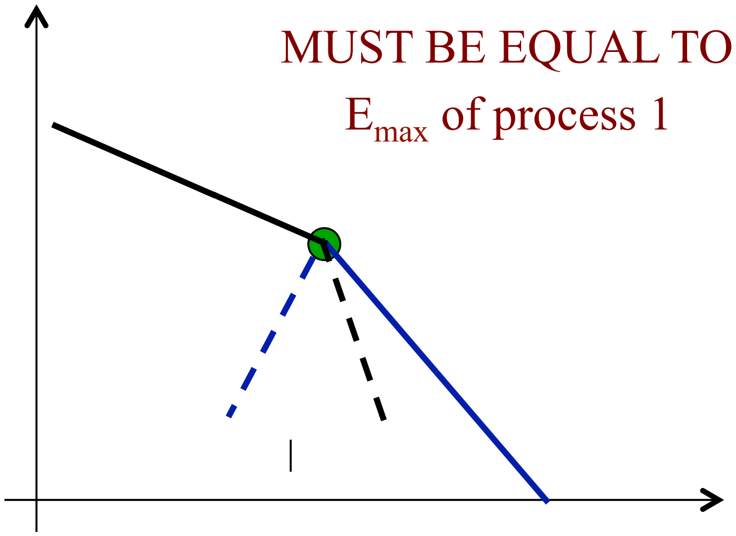


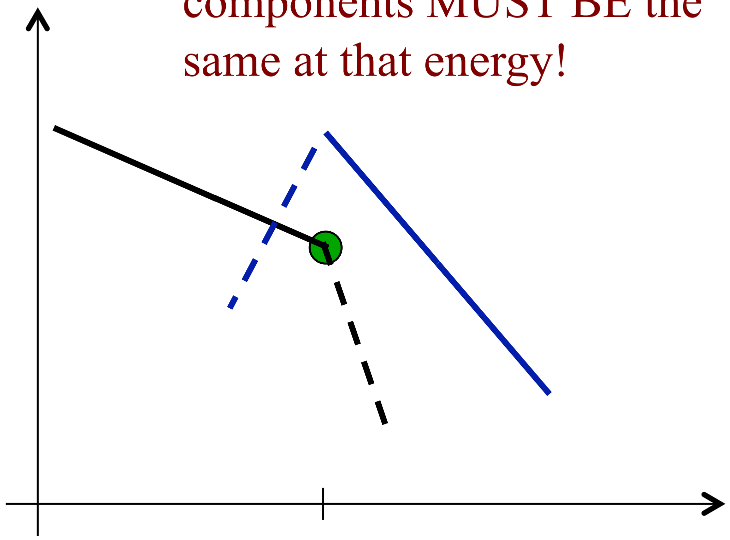
General phenomenology of transitions

- Requirements to obtain a knee-like transition:

E_{min} of process 2 MUST BE EQUAL TO E_{max} of process 1



AND the flux of the two components MUST BE the same at that energy!



AND the flux of the two components MUST BE comparable at that energy

General phenomenology of transitions

transition from a softer
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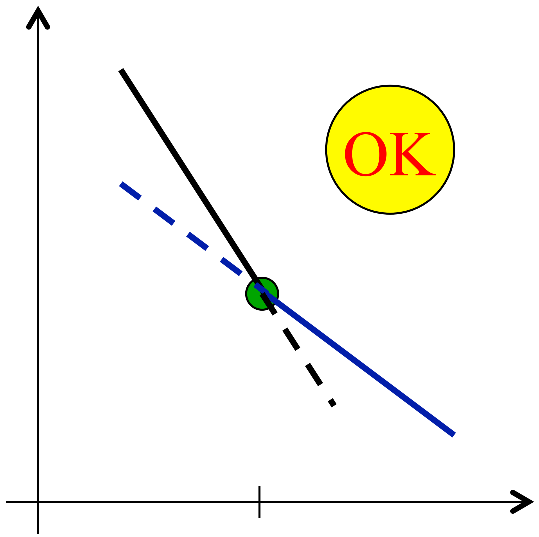
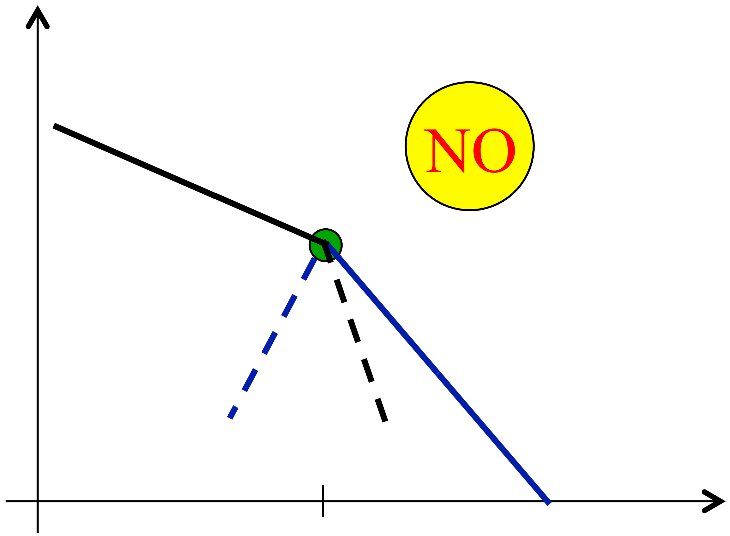


ankle

~~transition from a harder
to a softer component~~



knee

very improbable

Galactic/Extragalactic transition

- We know there must be a transition between GCRs and EGCRs
- It (almost certainly) must have an ankle shape.
- There is an ankle observed in the spectrum, at ~3 10^{18} eV
- This is precisely the energy range where you expect it when you consider GCRs!

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

→ It could not be at much lower energy, because extragalactic CRs probably don't fill the whole universe at lower energies

- This is also precisely the energy range where you expect it when you consider UHECRs!

→ The most natural models accounting for the data (spectrum & composition) at the highest energies do it only above the ankle [because of the hard spectrum required]

Galactic/Extragalactic transition

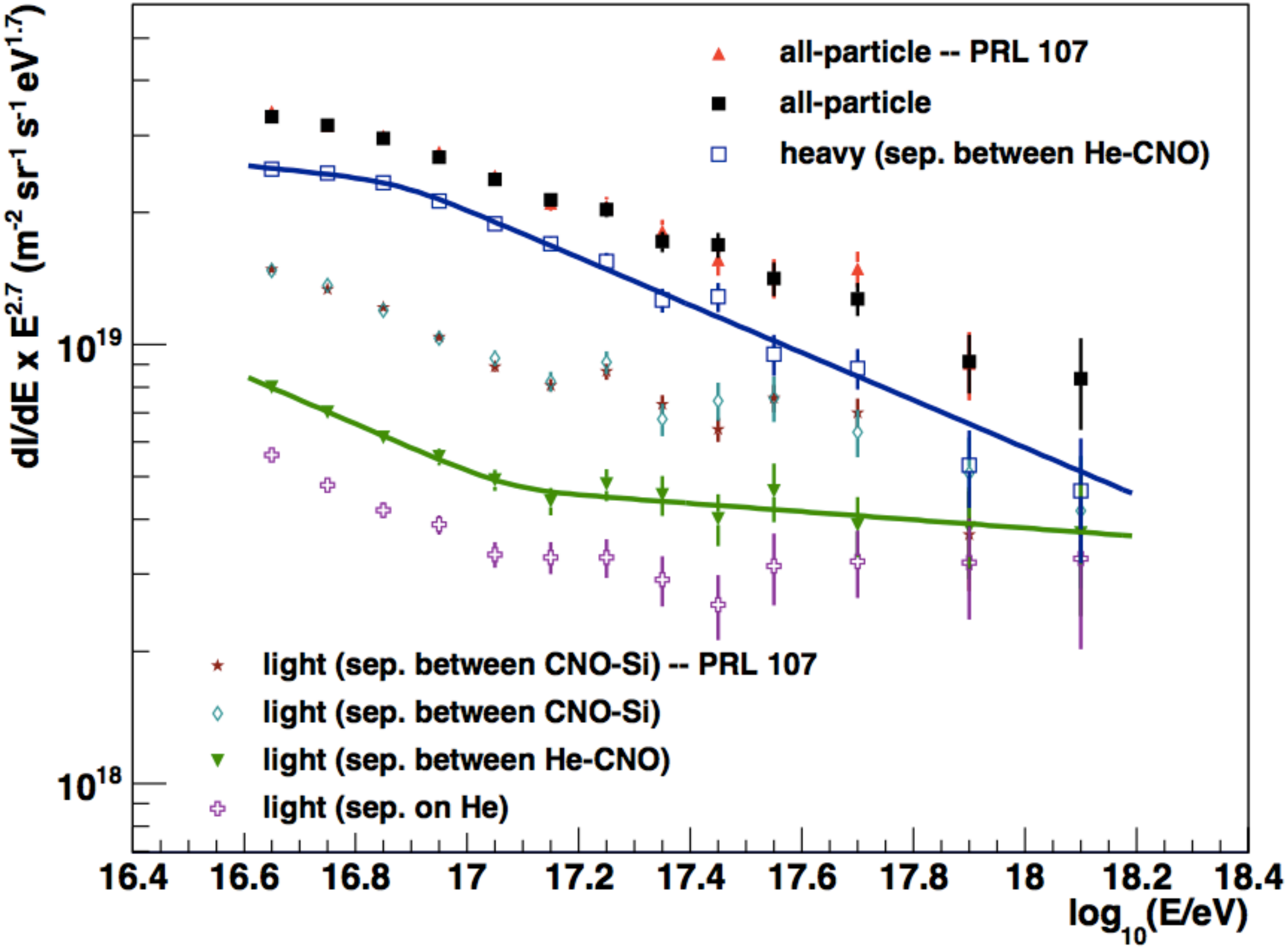
- If the transition is at the ankle (~ 3-5 10^{18} eV), the Galactic component of CRs must extend up to that energy.
- The end of the Galactic component is most probably dominated by Fe nuclei.

  This is both expected from the structure of the knee, and required by the confinement and anisotropy properties of the CR distribution at 10^{18} eV (cf. Auger results)
- Galactic protons do not need to reach such high energies, but only 26 times lower energies.
- → Galactic protons should be present at 10^{17} eV.

  Can we see them? → YES!
  Better than that: we even (probably) see the proton (light) GCR/EGCR transition, at a energy much lower than the ankle, as expected!

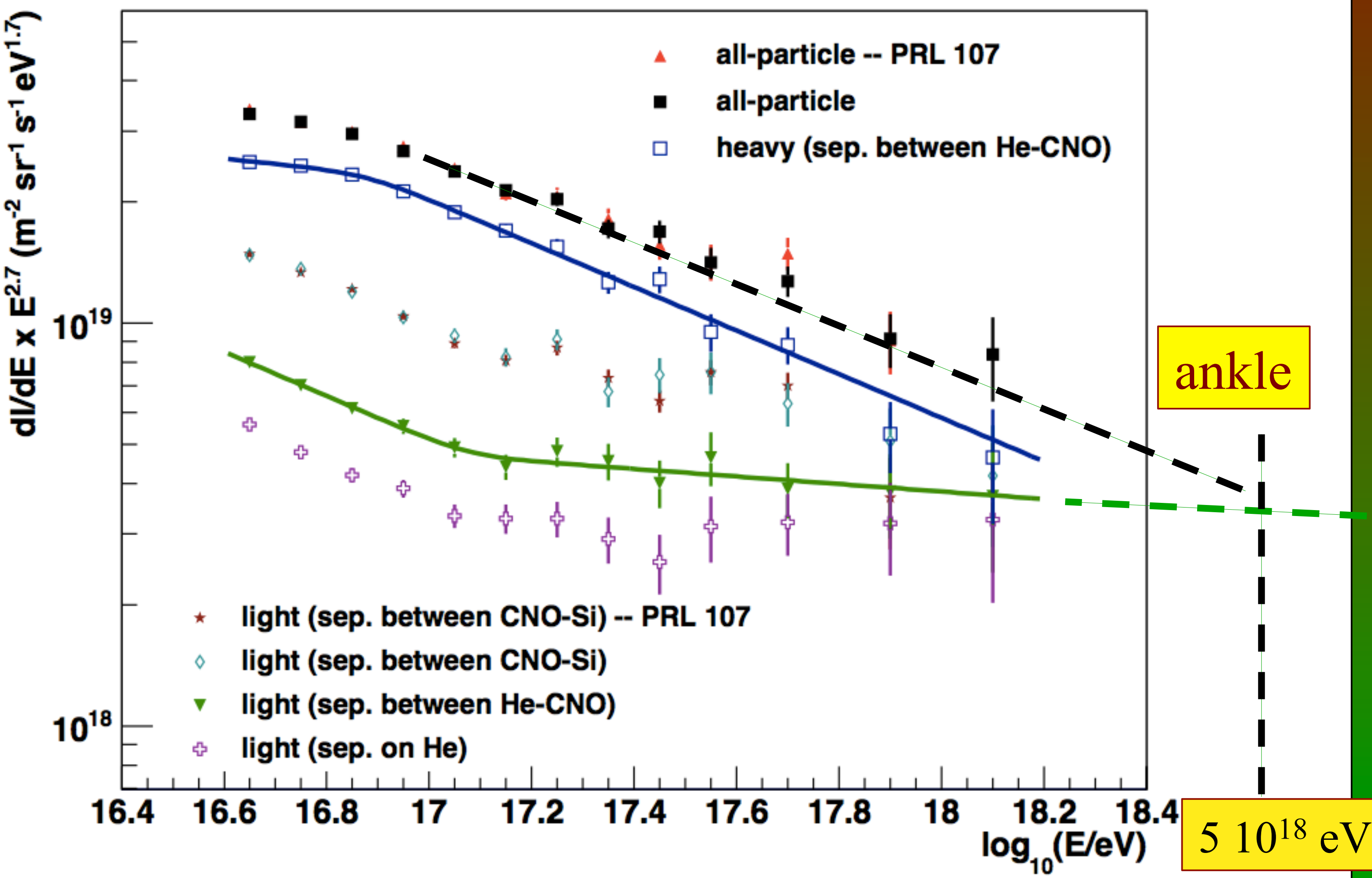
Kascade-Grande results

Kascade Grande Collaboration (2013)

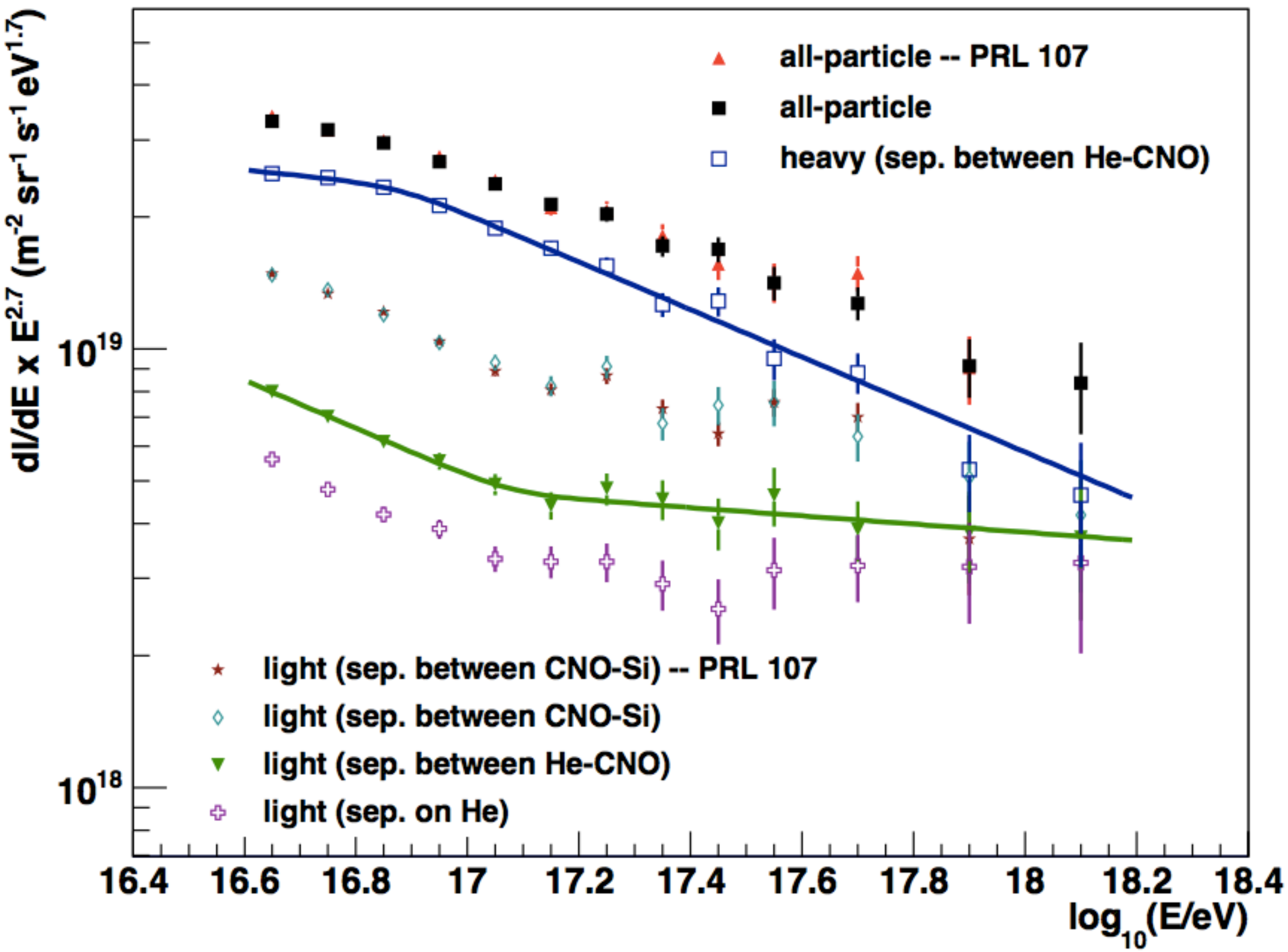


Kascade-Grande results

Kascade Grande Collaboration (2013)

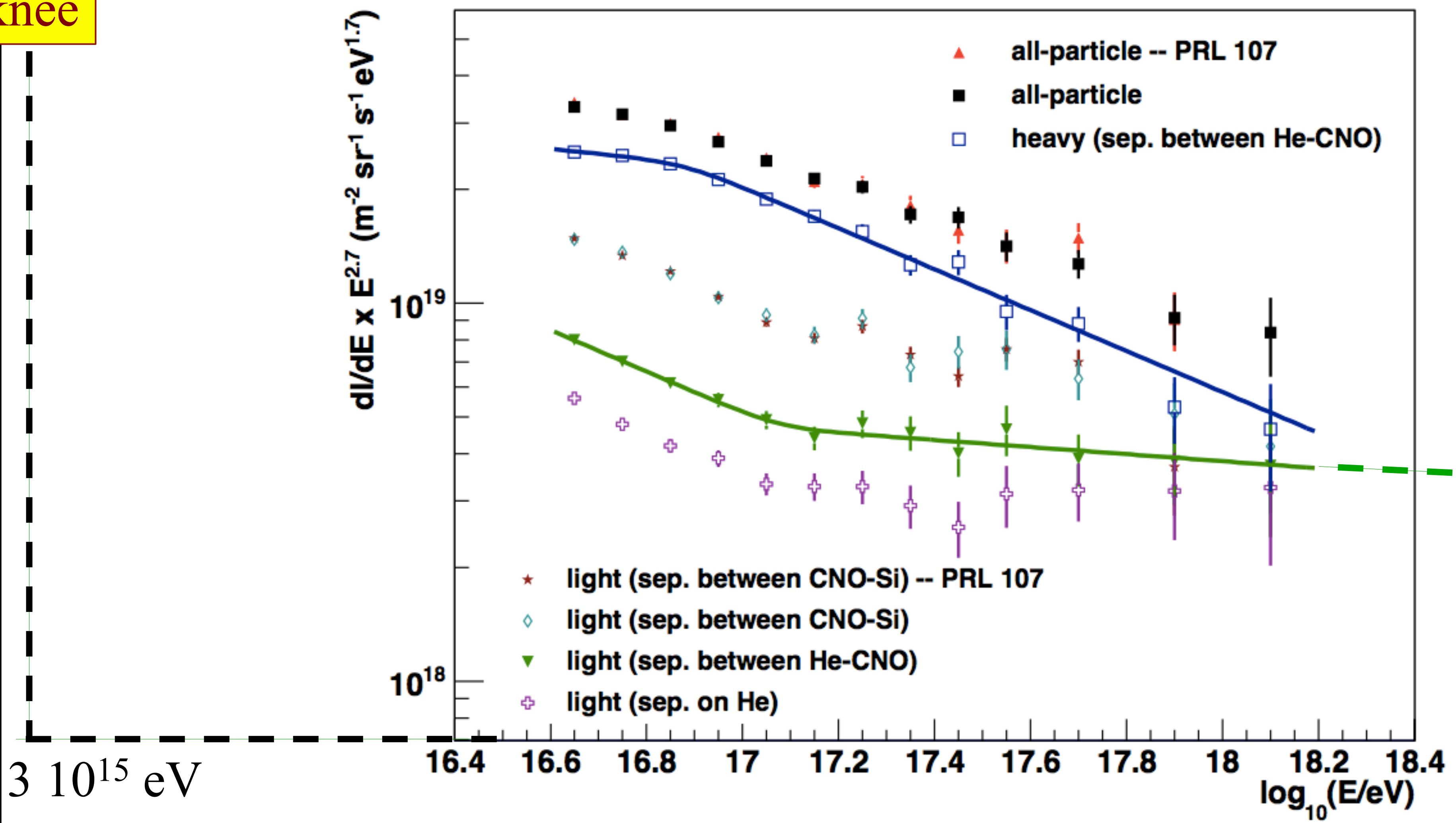


Quite a simple and natural picture!



Quite a simple and natural picture!

knee



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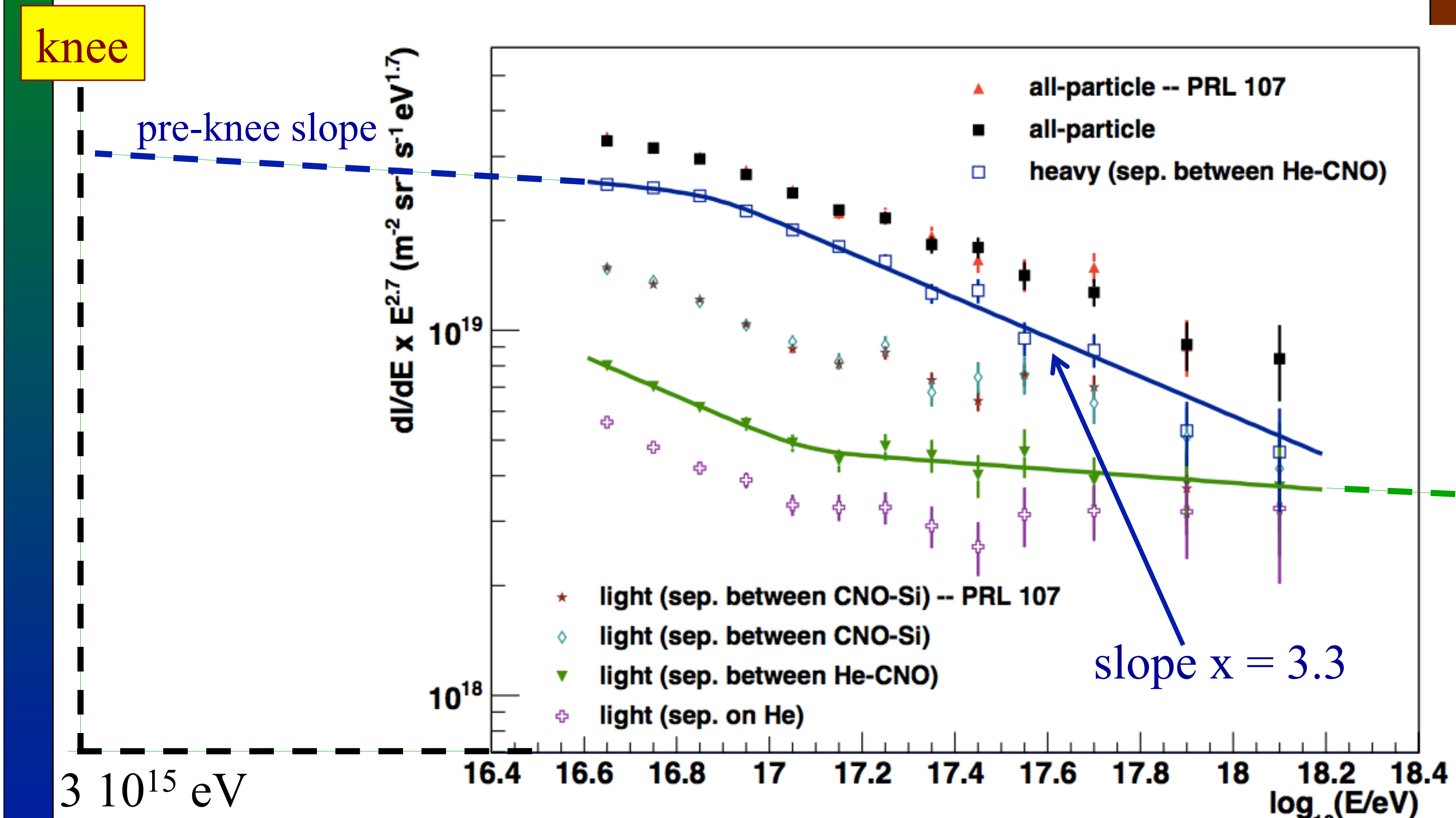

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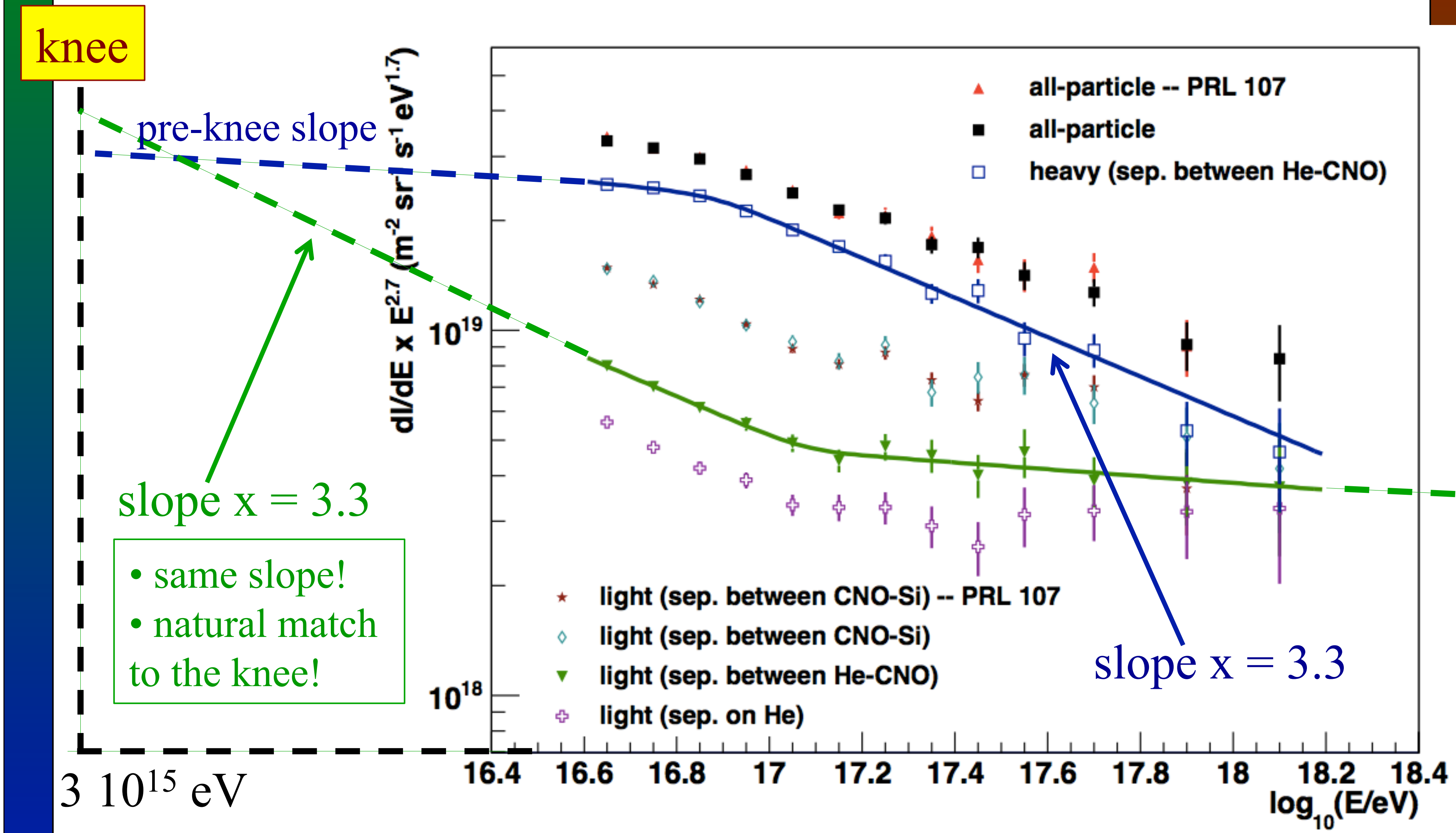

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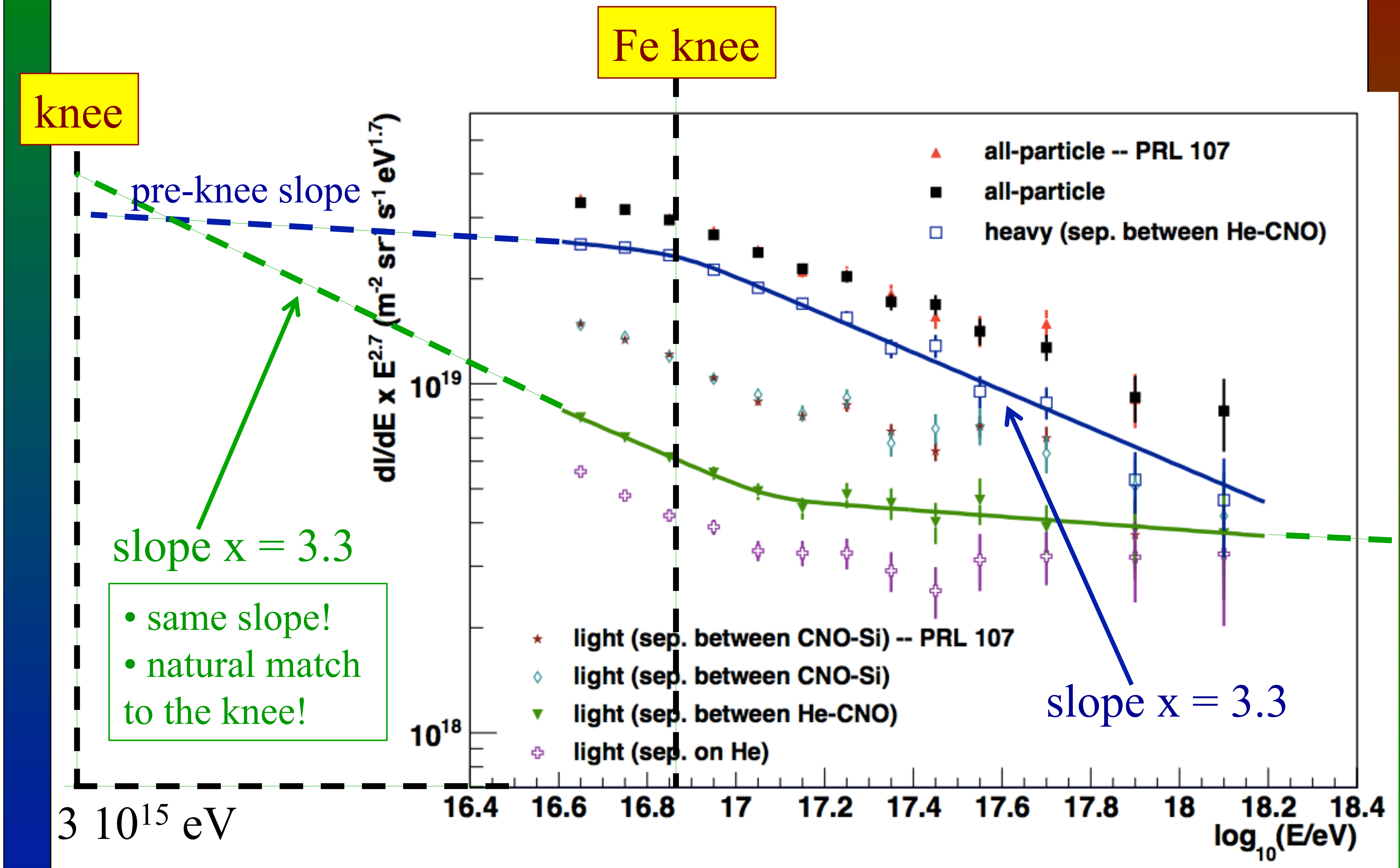
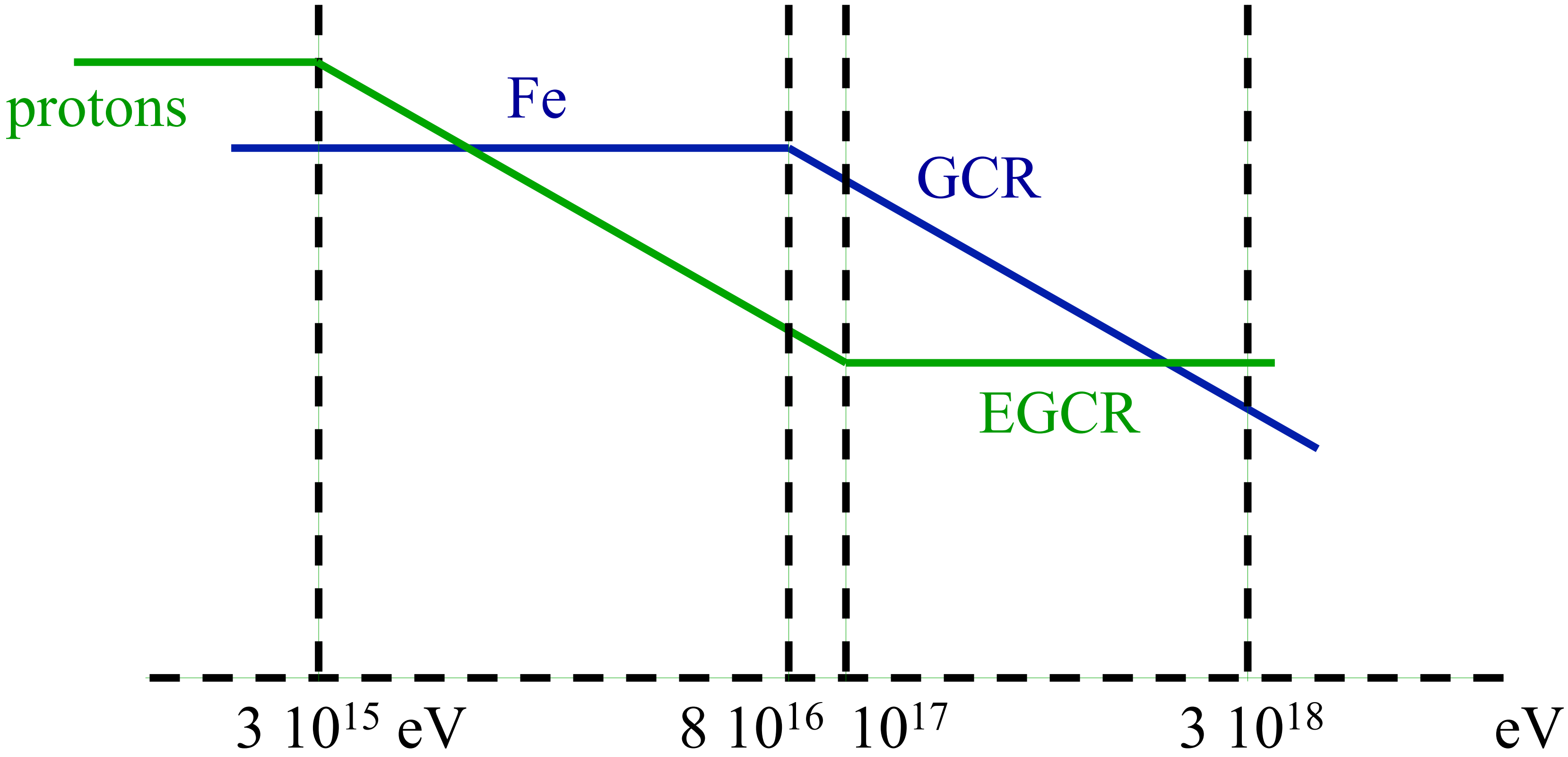


Very appealing GCR/EGCR transition picture



Very appealing GCR/EGCR transition picture

- The GCR component gives way to the EGCR component at an ankle-like spectral feature.

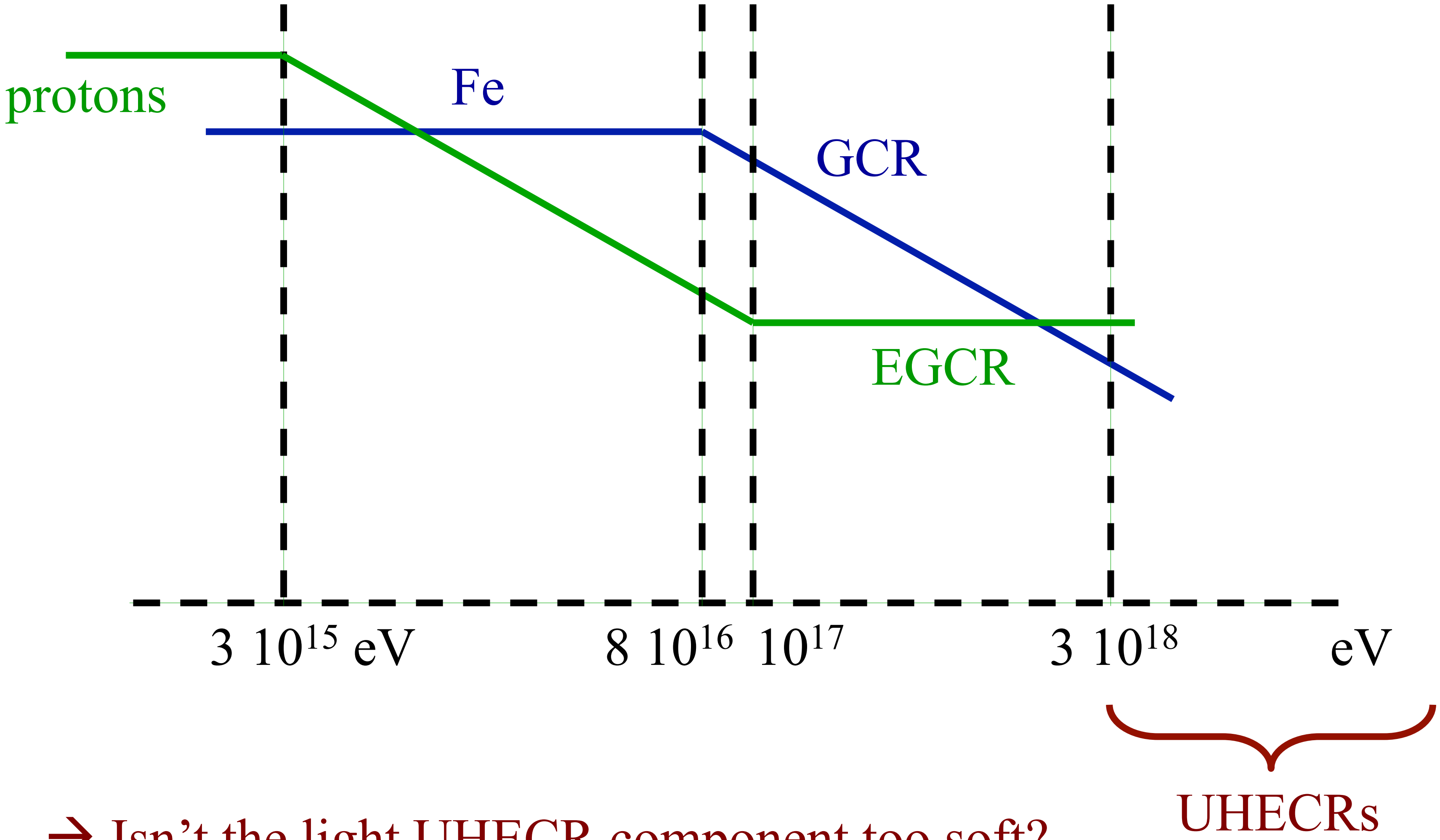
  The harder EGCR component simply becomes dominant at some point…

- The proton/light component first steepens by $\Delta x \sim 0.5$ at the "proton knee" (~3 PeV), and then becomes exceeded by the EGCR proton component at $\sim 10^{17}$ eV

- The Fe/heavy component does exactly the same at 26 times higher energies!

- → clear, simple and consistent picture

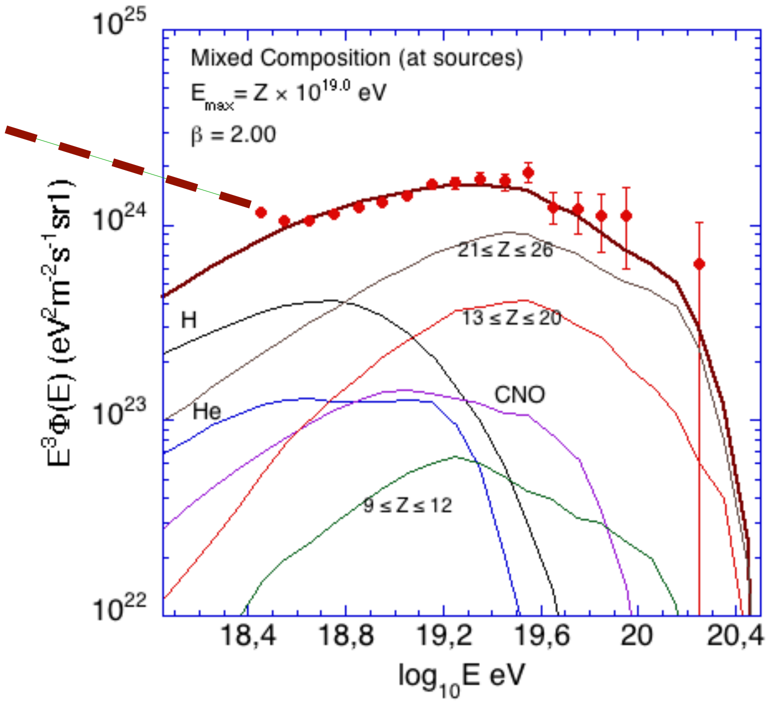
Very appealing GCR/EGCR transition picture



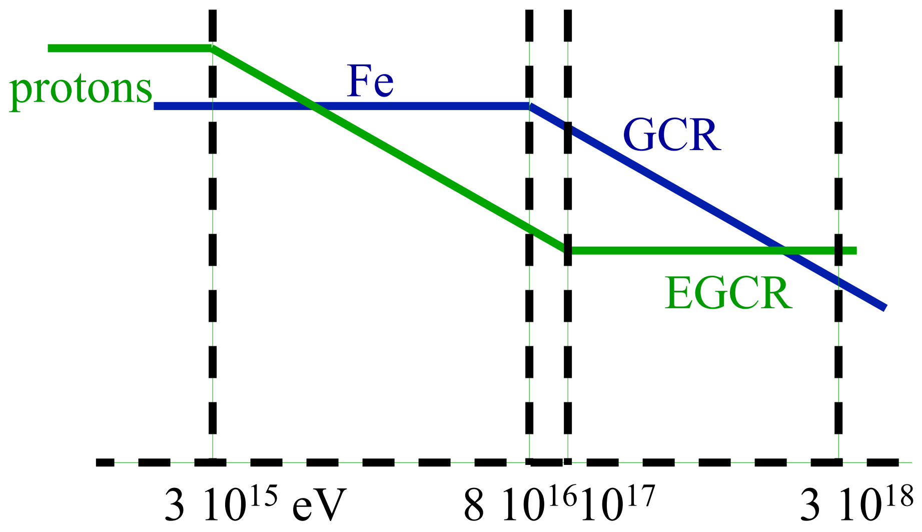
→ Isn't the light UHECR component too soft?

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) would do!

Mass dependent spectra!

- By studying UHECR acceleration in GRBs, we have discovered a very interesting feature
  - NB: see also yesterday's talk by Ke Fang (UHECR acceleration by newly-born neutron stars)
- The source spectrum predicted from the acceleration model is different for nuclei and for protons!
  - Because most protons are secondary particles (escaping as neutrons)
- UHE protons injected into the extragalactic medium have a much softer spectrum than UHE nuclei!
  - This is exactly what we need!
- NB: this is a generic feature of acceleration models in high radiation density environment!

II- Particle acceleration in GRBs

Please check Globus et al. (2014): astro-ph: 1409.1271

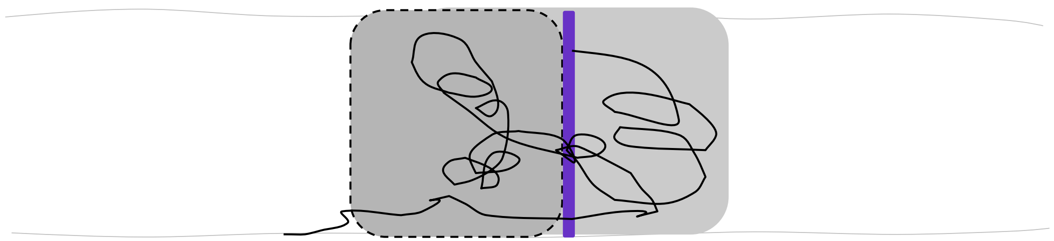
Particle acceleration in GRBs

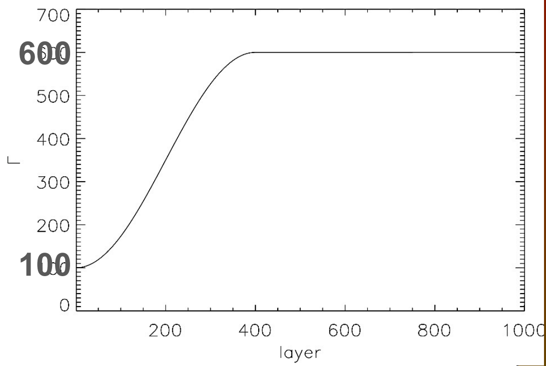
✧ First complete treatment (within the internal shock model)

- Modelling of internal shocks, following Daigne & Mochkovitch (1998)
  => estimates of the physical quantities (few free parameters)
- 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 by a GRB luminosity function & cosmological evolution (Piran & Wanderman 2010)
  => diffuse UHECR + neutrino fluxes
- Propagation of UHECRs to the Earth => propagated spectra/composition

Modelling of internal shocks

We follow Daigne & Mochkovitch 1998 : a relativistic wind with a varying Lorentz factor is decomposed in discretized solid layers
$\Rightarrow$ Layers collisions mimic the propagation of a shock in the wind





Lorentz factor profile

Free parameters of the wind:
wind luminosity L_{wind}, wind duration t_{wind} (in the following we use t_{wind}=2s and $L_{wind}=10^{51}-10^{55}$ erg.s^{-1} isotropic)

Free parameters associated to the shock:
ε_e, ε_B, ε_{CR} equipartition factors for the released energy

...needed for acceleration

B_{rms}, Γ_{shock}, Γ_{res}

...needed for energy losses

r_{shock},

$$\frac{1}{E}\frac{dE}{dt} = t_{exp}^{-1} = \frac{\Gamma_{res}\,c}{r_{shock}}$$

density,
photon background...

Energy partition models

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

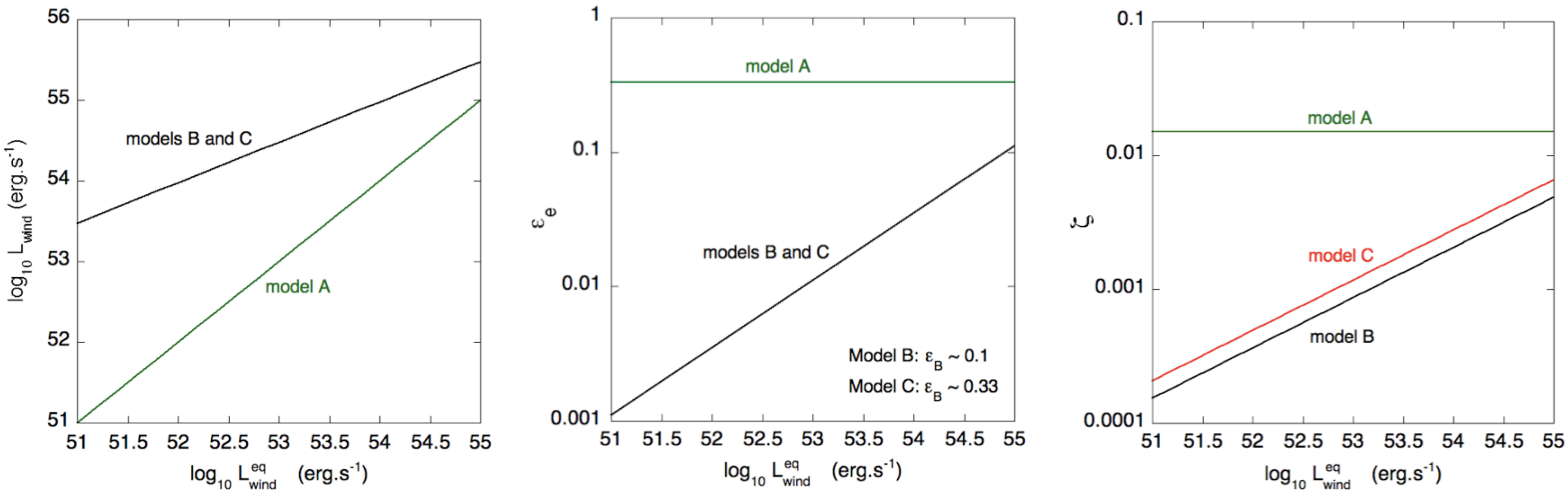
- ✧ Model A: equipartition: $\varepsilon_{e},= \varepsilon_{B}= \varepsilon_{CR}= 1/3$
  - ➢ Gamma-ray production efficiency ~5% ($L_{\gamma} \sim L_{wind}/20$)
  - ➢ 10^{51} erg/s $\leq L_{wind} \leq 10^{55}$ erg/s => $5\ 10^{49}$ erg/s $\leq L_{\gamma} \leq 5\ 10^{53}$ erg/s (iso)

- ✧ Models B and C: low γ-ray efficiency: $\varepsilon_{e} << 1$
  - ➢ $3\ 10^{53}$ erg/s $\leq L_{wind} \leq 3\ 10^{55}$ erg/s => $5\ 10^{49}$ erg/s $\leq L_{\gamma} \leq 5\ 10^{53}$ erg/s (iso)
  - ➢ Gamma-ray production efficiency: between 0.01% and 1%

- ✧ Model B: $\varepsilon_{B}= 0.1$, $\varepsilon_{CR}= 0.9$
- ✧ Model C: $\varepsilon_{B}= 1/3$, $\varepsilon_{CR}= 2/3$

Energy partition models

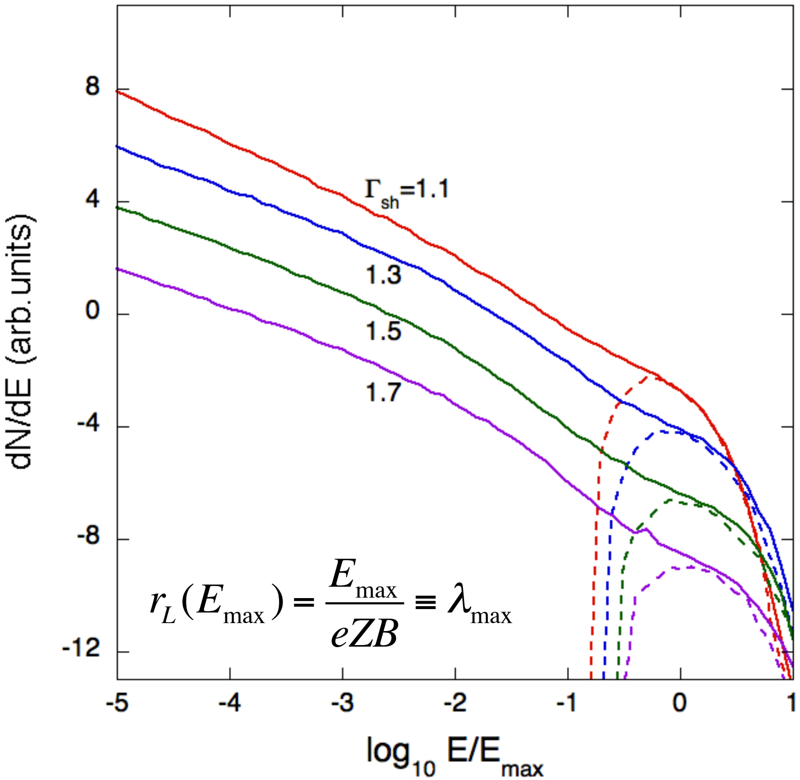
- NB: Model A is more "standard", but mostly by simplicity…
- Models B & C are not crazy a priori!



- Largest assumed wind power only a factor of 3 higher than in model A
- Smaller spread in the wind powers of different GRBs
- Fraction of electrons accelerated between $\sim 10^{-4}$ and $\sim 10^{-2}$

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):



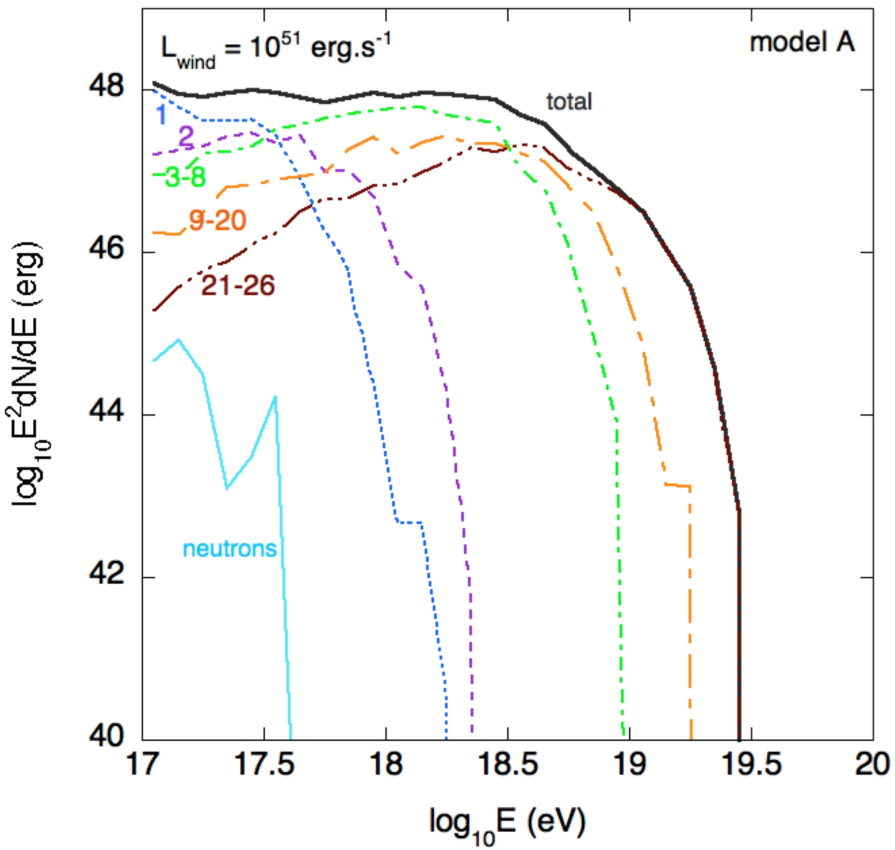
- ➢ Escape upstream : high pass filter (selects particles in the weak scattering regime)
- ➢ Escape downstream : should become a high pass filter in the presence of energy losses (particles must leave before being cooled by energy losses)

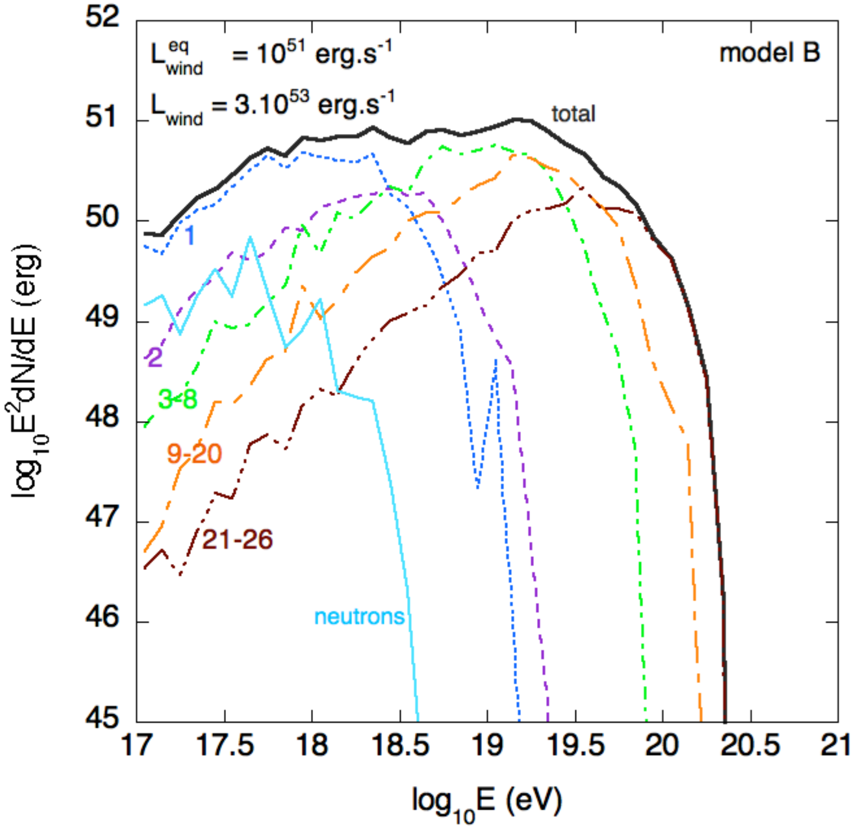
Particle acceleration with energy losses

- 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 energy partition model (A, B or C)

Particle acceleration with energy losses

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





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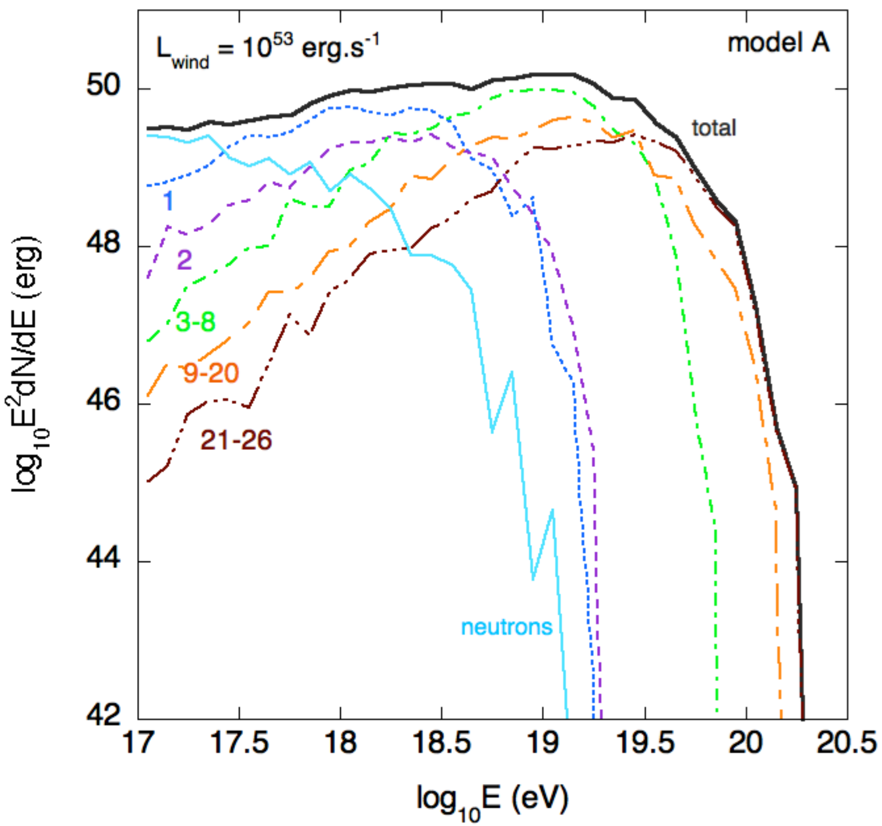

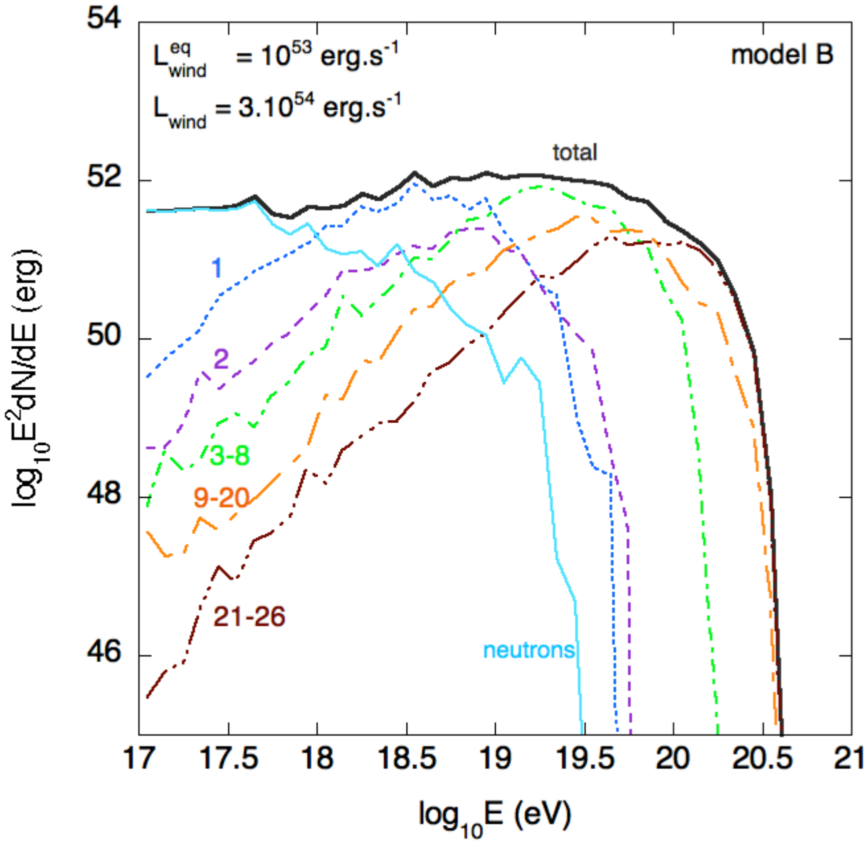

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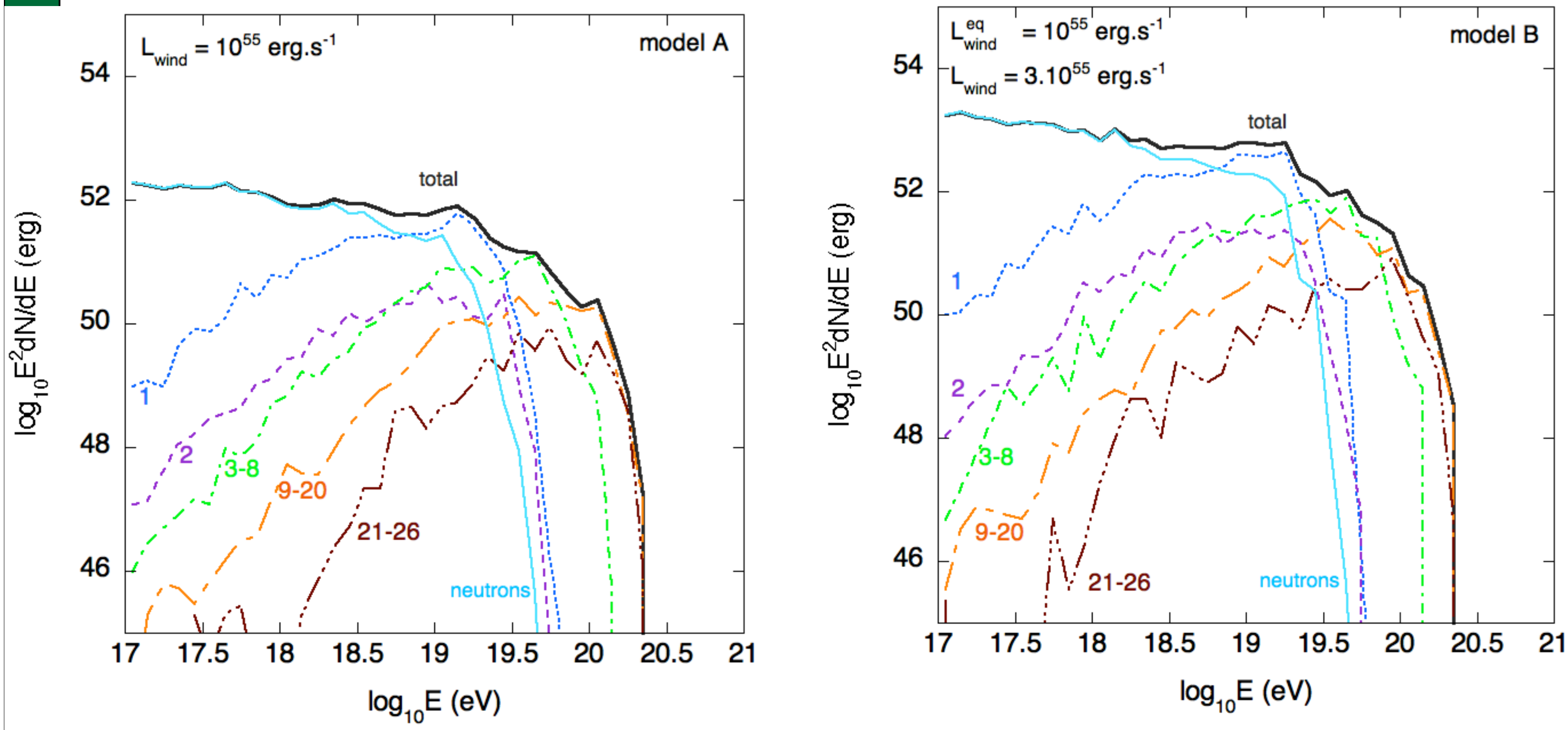


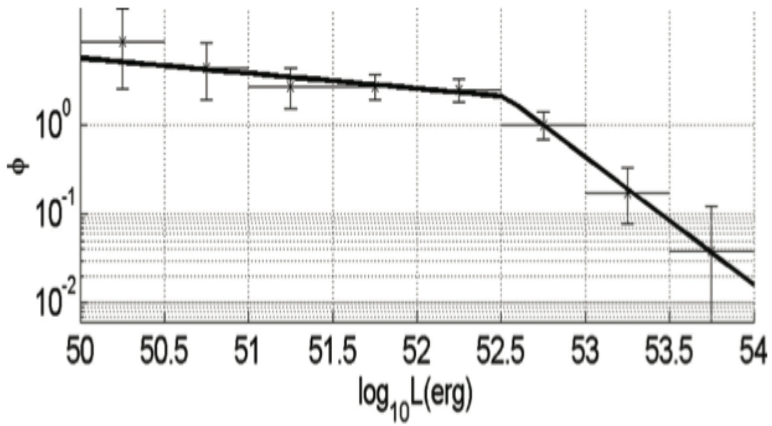
LOOK AT THE NEUTRON COMPONENT!!!

Resulting UHECR propagated spectra

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

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

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

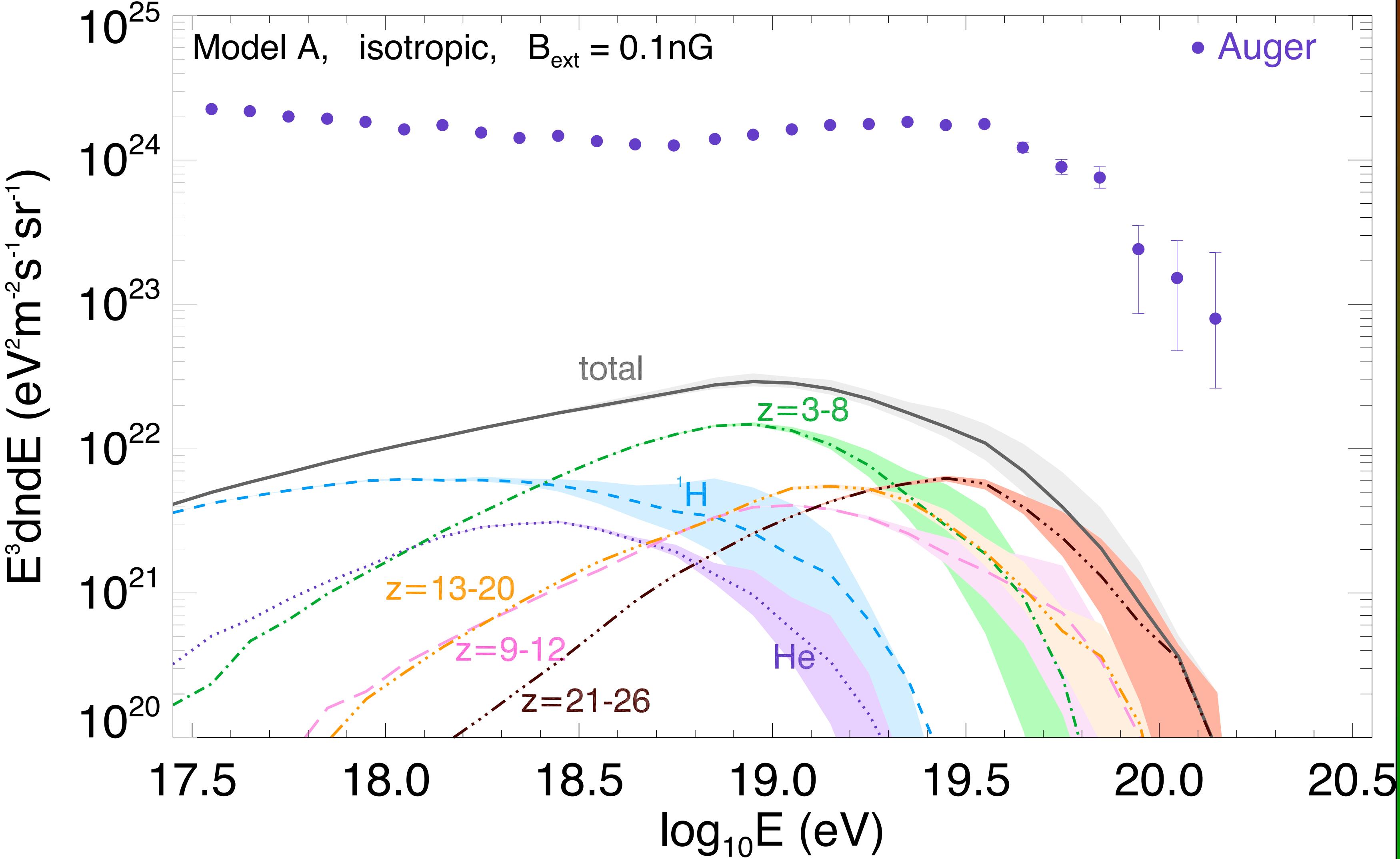


$$\rho_{GRB}(z) = \rho_{GRB}(0) \times \begin{cases} (1+z)^{n_1} & \text{for } z \leqslant z_\star \\ (1+z_\star)^{n_1-n_2} \times (1+z)^{n_2} & \text{for } z > z_\star \end{cases}$$

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

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

Resulting UHECR propagated spectra



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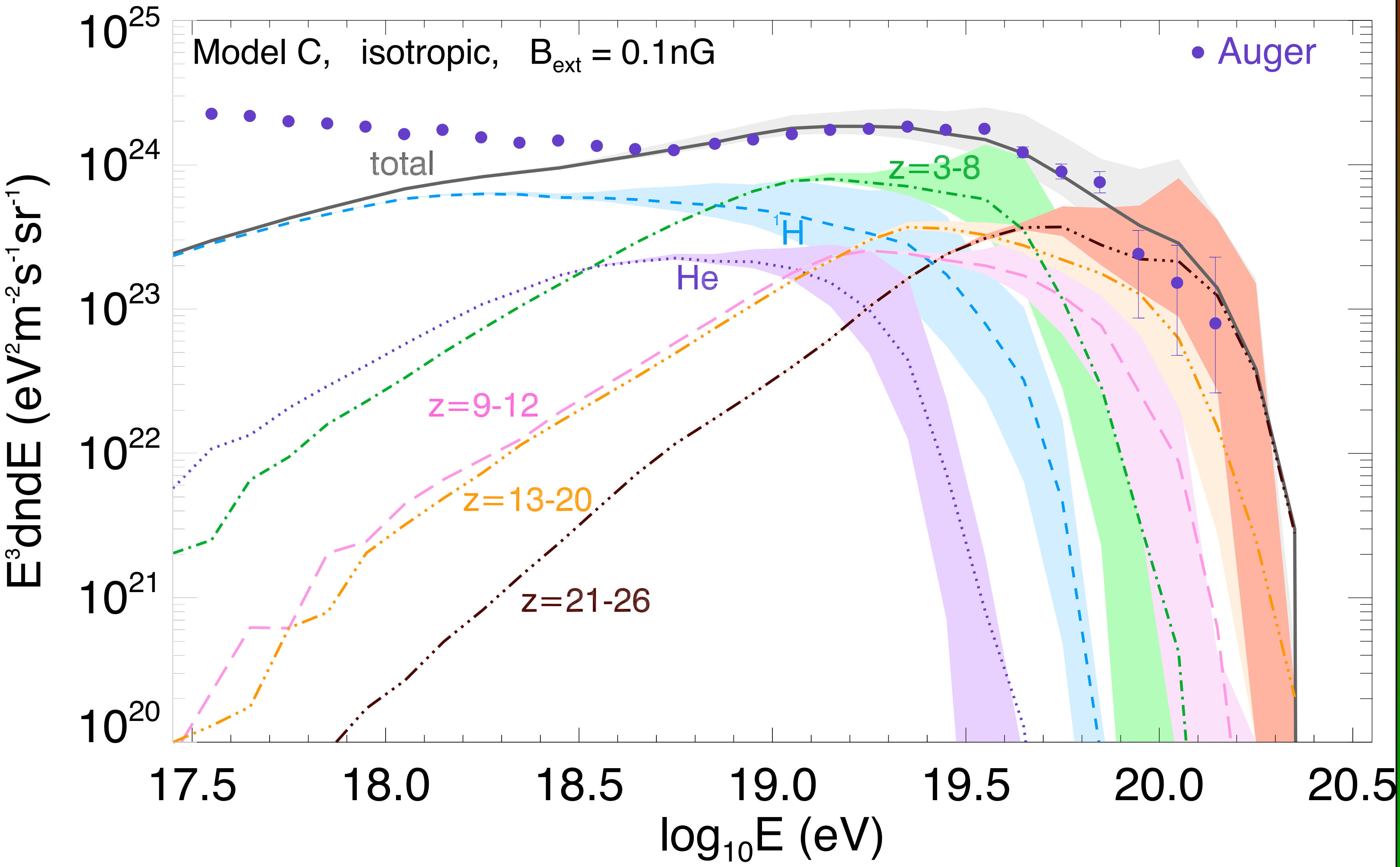

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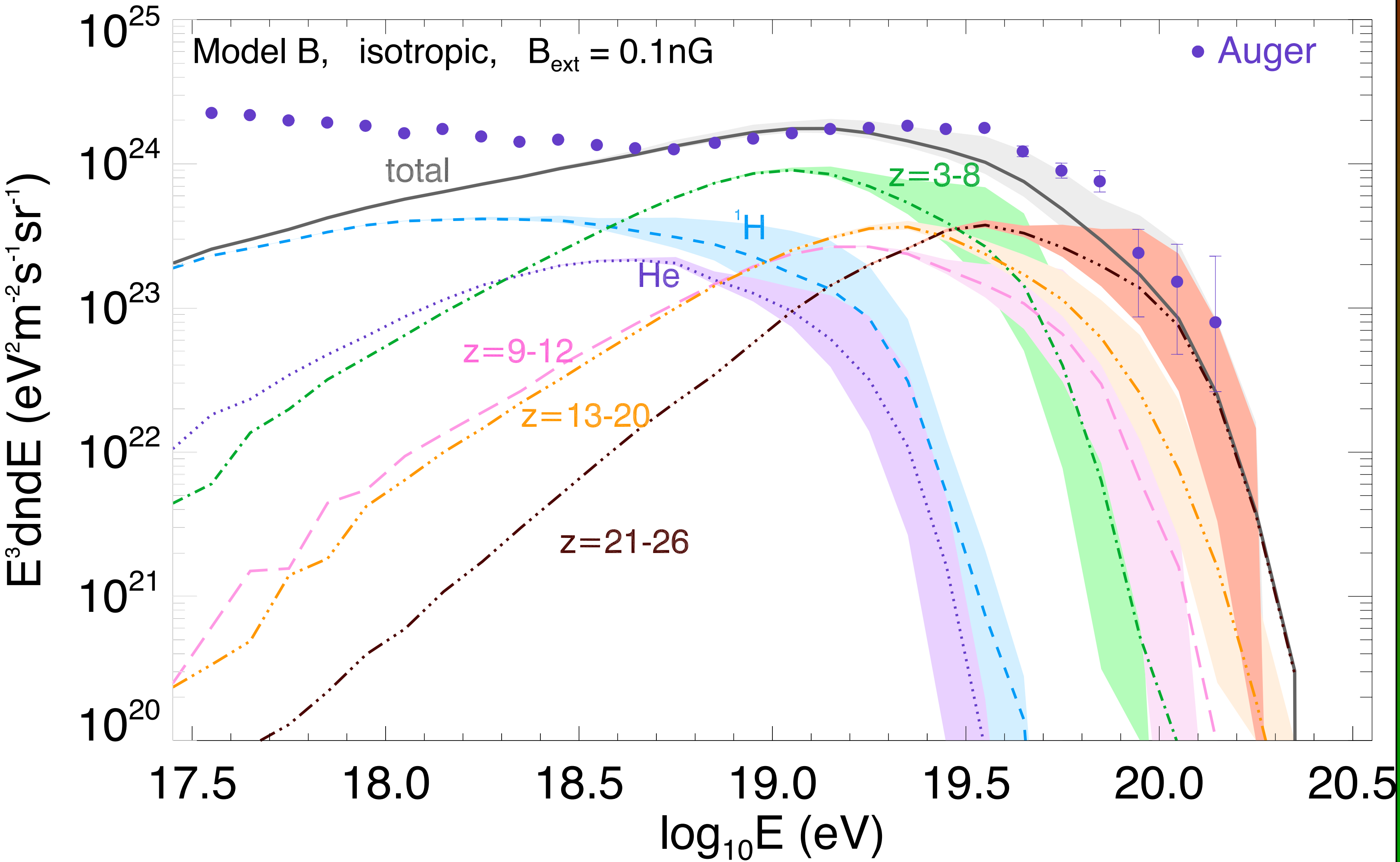
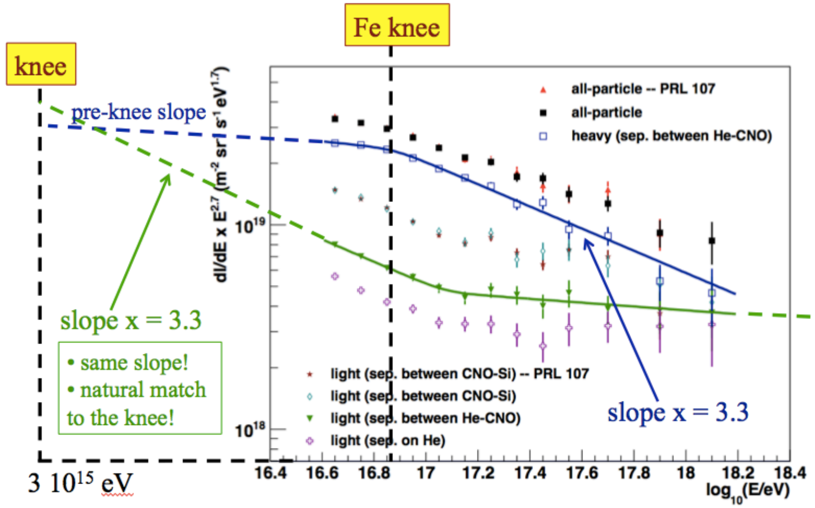
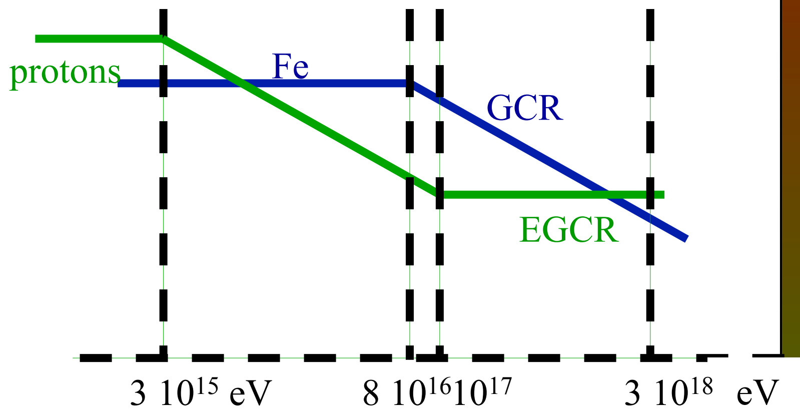


Summary

✧ There is a very simple, natural, and beautiful picture of the GCR/EGCR transition, nicely consistent with GCR data and UHECR data





✧ Particle acceleration at GRB internal shocks can account for the UHECR phenomenology, with a given assumption about energy partition between electrons, B field and CRs

✧ Key feature: the proton spectrum is softer than the nuclei spectra!