Extra-Galactic magnetic fields and high energy cosmic rays

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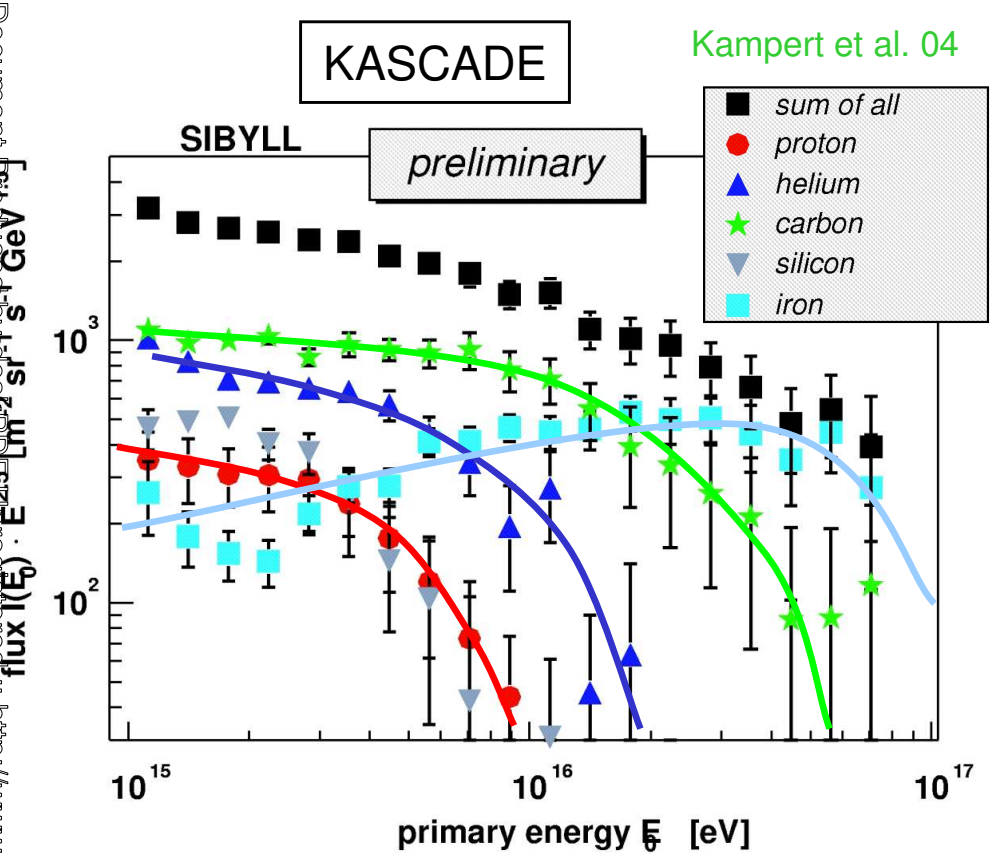
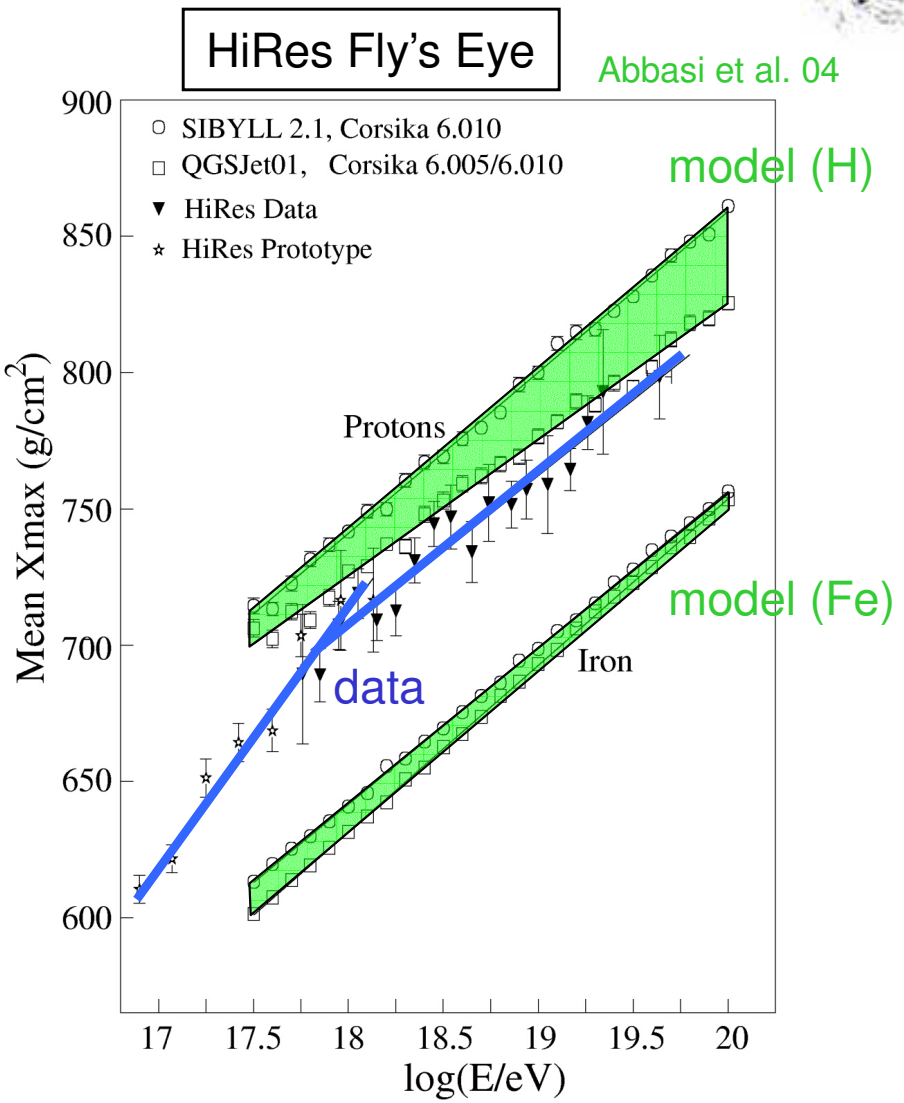
M. L., PRD 71:083007 (2005), astro-ph/0411173

M. L. & B. Revenu, in preparation

Recent data: knee → ankle





rigidity dependent knee: $E_{knee} \sim Z \times 2 \cdot 10^{15}$ eV

change of chemical composition:

iron → $10^{17.5}$ eV (∼ second knee!)
proton $10^{17.5}$ eV → …?

A new interpretation for the ankle...

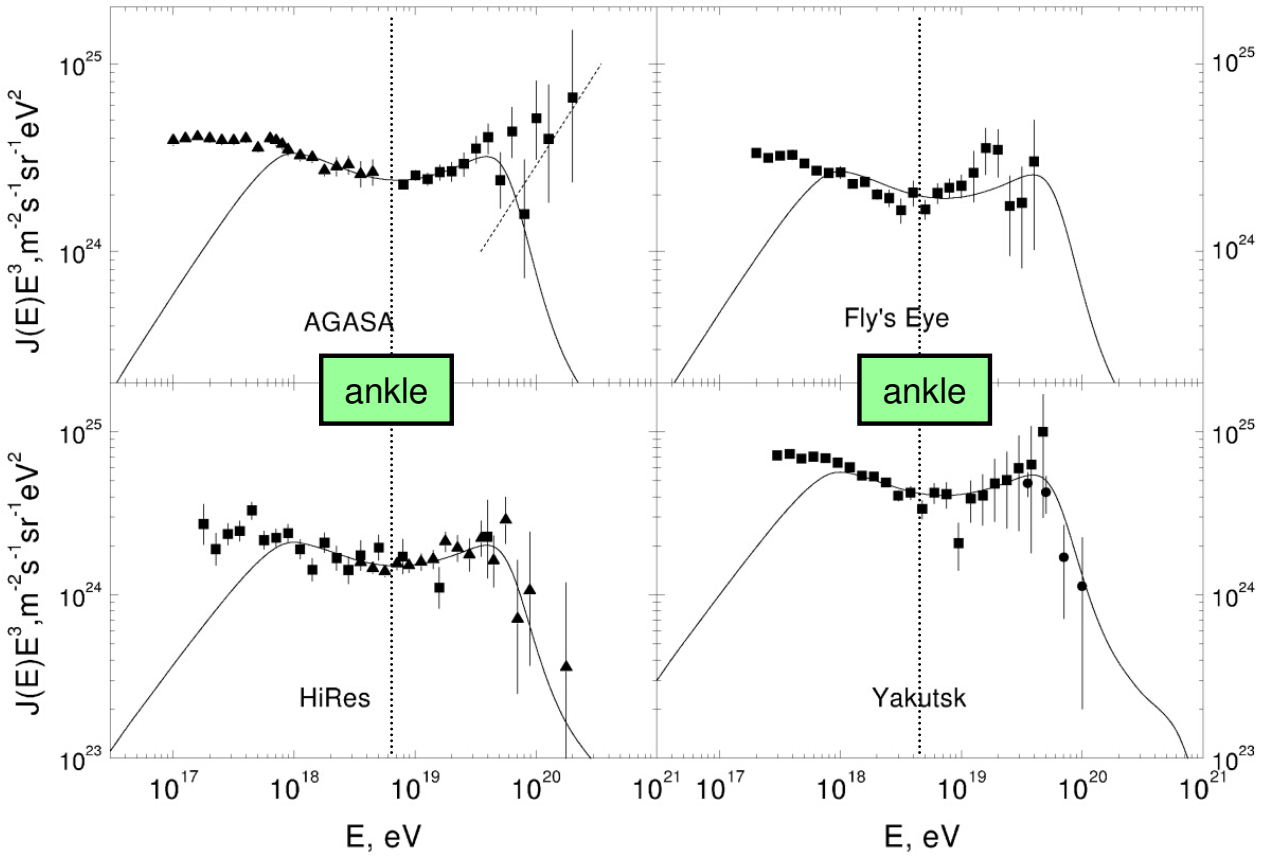
Berezinsky & Grigoreva 88
Berezinsky et al. 02, 03, 04, 05

a population of sources at cosmological distances
+
proton pair production on CMB: $p + \gamma_{CMB} \rightarrow p + e^+e^-$

$\Downarrow$

dip in the spectrum at $E \sim 10^{19}$ eV ~ ankle!

ankle = pair production dip ⇒ GZK cut-off !

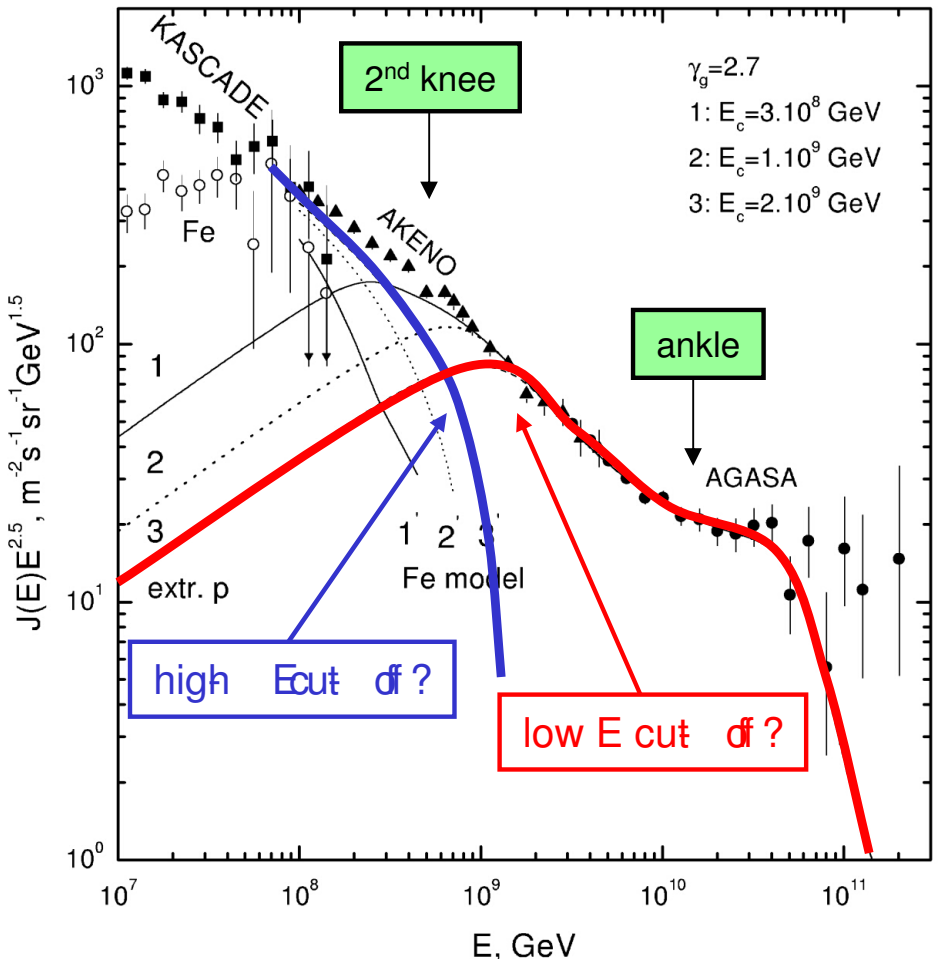


index: s = 2.7
cut off below 10^{18} eV

... but transition from Galactic → extra-Galactic CRs?

low-energy cut-off → transition between Galactic and extra-Galactic CRs at second knee !

Berezinsky et al. 04



however: requires fine-tuning !? … physical meaning of low-energy cut-off ?

A natural solution : extra-Galactic magnetic fields

M. L., PRD71:083007 (2005); Aloisio & Berezinsky 05

- A natural and economical interpretation for high E cut-off of Galactic CRs:

  knee = maximal energy at source ⇒ high E cut-off at Fe knee

- A new interpretation for low E cut-off of extra-Galactic CRs:

  extra-Galactic magnetic fields shield detector from extra-Galactic CRs at E $\lesssim 10^{18}$ eV

  - length traveled by diffusing on B inhomogeneities in a Hubble time:

    $L \simeq (\lambda_{diff}\, c/H_0)^{1/2} \sim 65$ Mpc $(\lambda_{diff} / 1$ Mpc$)^{1/2}$ [λ_{diff}(E,B,…): scattering length]

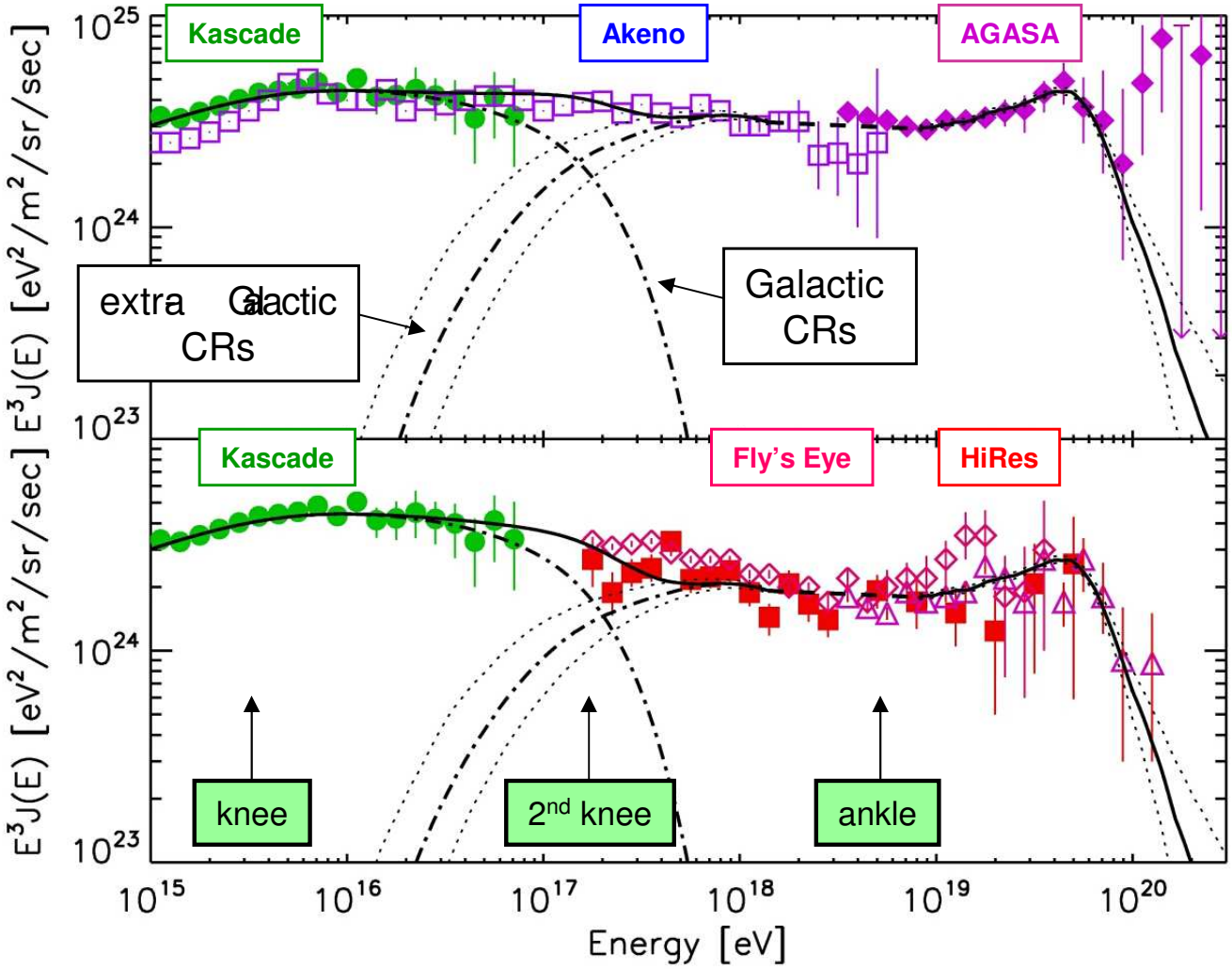
  - if closest source distance $\gtrsim$ L ⇒ sources outside CR horizon ;
    then, since λ_{diff} growing function of E ⇒ low-energy cut-off

  - Note 1: $\text{for } R_L \gg l_{coh},\quad \lambda_{diff} \sim \frac{R_L^2}{l_{coh}} \sim 0.1\,\text{Mpc} \left(\frac{E}{10^{17}\,\text{eV}}\right)^2 \left(\frac{B\sqrt{l_{coh}}}{0.1\,\text{nG.Mpc}^{1/2}}\right)^{-2}$

  - Note 2: expected source distance scale ∼ 50-100 Mpc Yoshiguchi et al. 03; Blasi & De Marco 04; Kachelriess & Semikoz 05

A natural solution : extra-Galactic magnetic fields

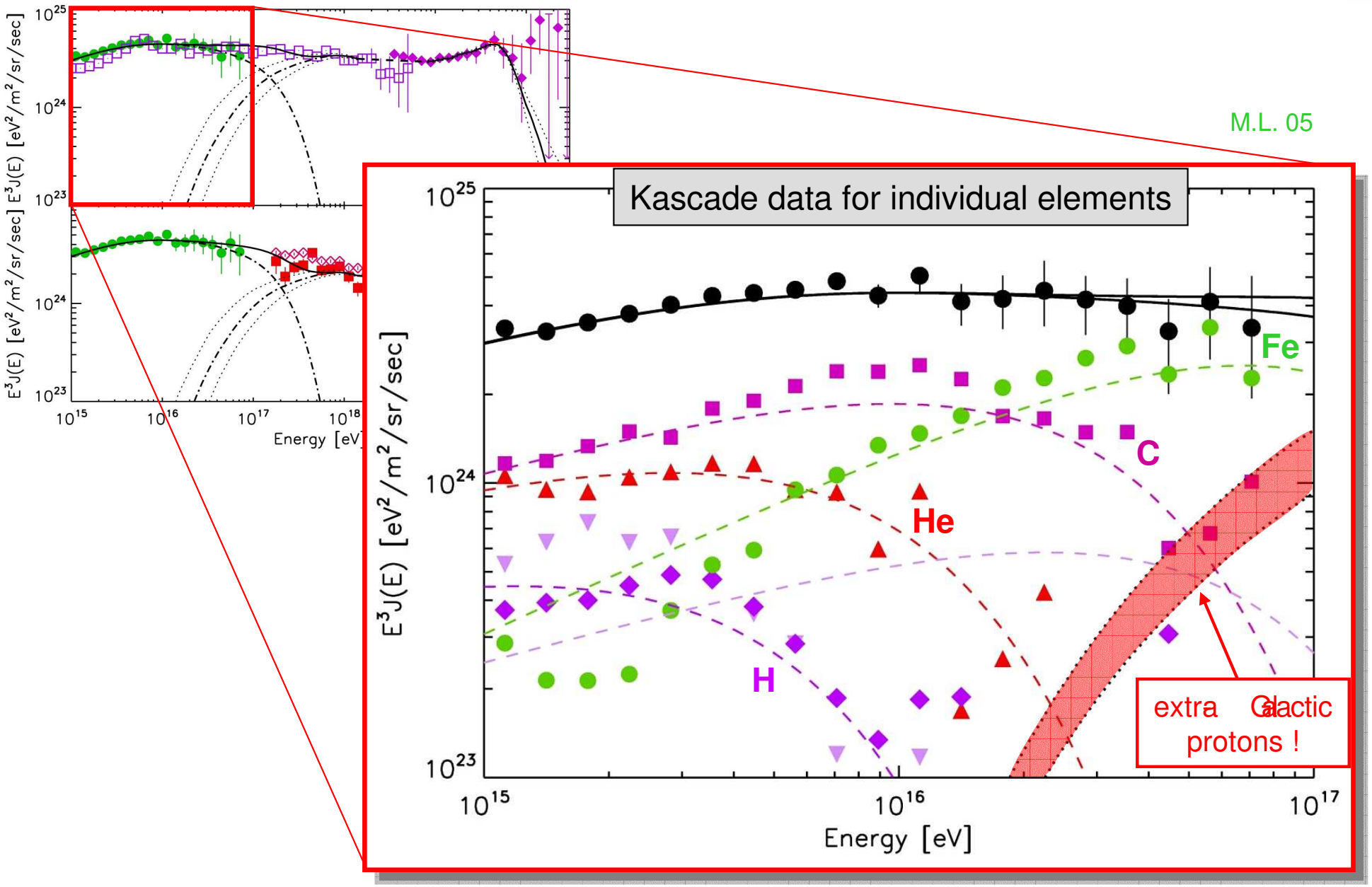
two free parameters: $s \simeq 2.6, \quad B\sqrt{l_{\rm coh}} \simeq 0.2\,{\rm nG.Mpc}^{1/2}$



M.L. 05

- Note: B $l_{coh}^{1/2} \sim 0.3$ nG.Mpc$^{1/2} \ll$ observational upper limit ~ 10 nG.Mpc$^{1/2}$
- Note: this scenario not applicable to γ–ray bursts sources: closest source $\in$ Milky Way

A natural solution : extra-Galactic magnetic fields



Other models for the transition at the second knee

- modulation of cosmic-ray flux: Muraishi et al. 05

  strong Galactic magnetic field in halo forbids entry to extra-Galactic CRs below:

  $E_{min} \sim Z \times 6 \cdot 10^{15}$ eV $(B_{\mu G}\, R_{100kpc}\, V_{300km/s} / \eta_{100})$ (too low ?!)

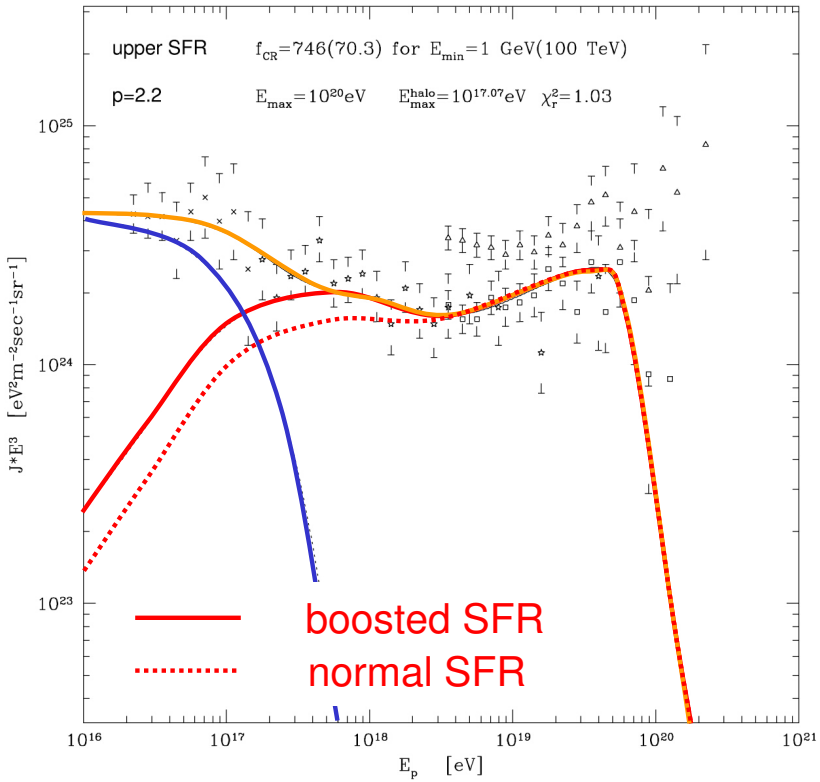
- cut-off at source: Berezinsky et al. 02

  source magnetic field ? M.L. 05
  … requires B ~ μG on L ~ 100 kpc

- strong evolution of source luminosity:
  Wick et al. 04
  De Marco & Stanev 05

  $L_{source} \propto (1+z)^m$, with m ~ 3-4
  « harder » spectrum s ~ 2.2 - 2.4

  note: this exceeds strong upper bound on cosmic SFR from SN ν background
  (Strigari et al. 05)



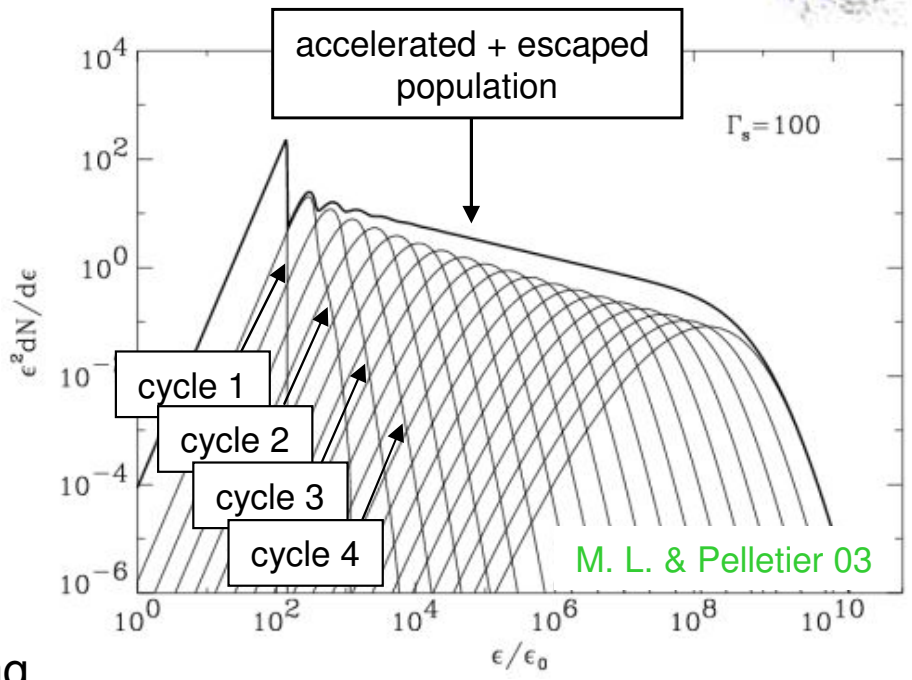
Relativistic shock acceleration and spectral index s

- Fermi I acceleration in relativistic shocks:

$$\left.\begin{array}{r} P_{return} \simeq 0.4 \\ \langle p_{i+1}/p_i \rangle_{cycle\ i} \simeq 2 \end{array}\right\} \Rightarrow \text{canonical slope } s \simeq 2.2\text{-}2.3$$

Bednarz & Ostrowski 98
Kirk et al. 00
Achterberg et al. 01
M. L. & Pelletier 03
Keshet & Waxman 04

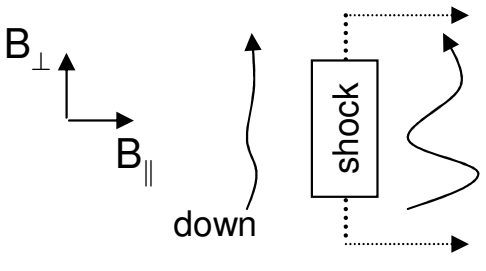
assumes isotropic scattering !



but: { coherent B field $\Rightarrow$ anisotropic scattering
shock compression $\Rightarrow$ anisotropic turbulence

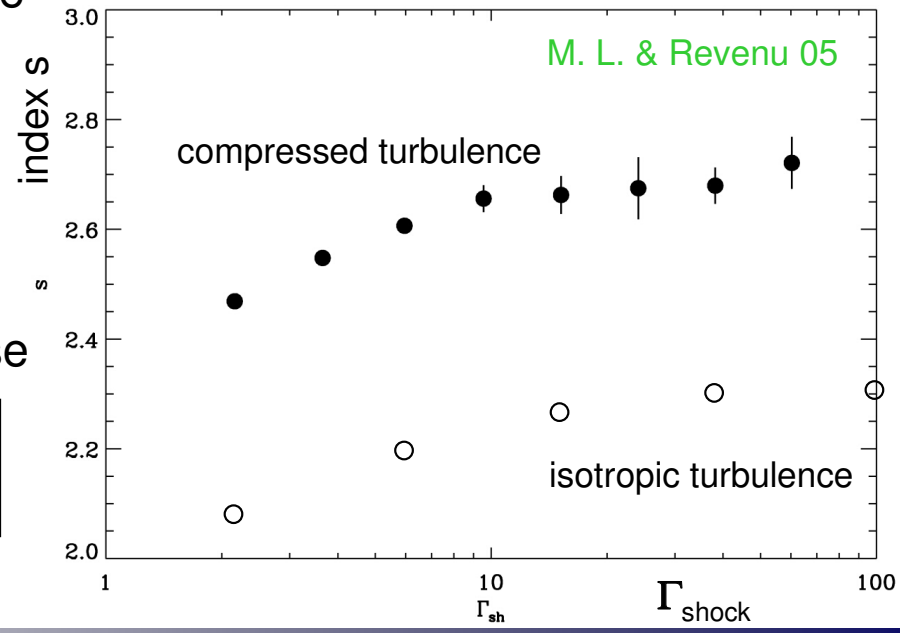
- Acceleration including compression effects:

$$\frac{B_{\perp,\mathrm{down}}}{B_{\perp,\mathrm{up}}} \simeq \Gamma_{\mathrm{shock}}\sqrt{8} \quad (\Gamma_{\mathrm{shock}} \gg 1)$$



$\Rightarrow B_{down} \sim$ transverse

pure Kolmogorov:
$s \sim 2.7$ ($\Gamma_{sh} \gg 1$)



Conclusions ...

- Emergence of extra-Galactic CRs at second knee $\sim 10^{18}$ eV ?
  … sources at cosmological distances ?
  … ankle ~ pair production on CMB ?
- Extra-Galactic magnetic fields responsible for the transition ?
  … implications : - Auger/HiRes: charged particle astronomy
  - Kascade-Grande: estimate of $\lambda_{diff}(E)$