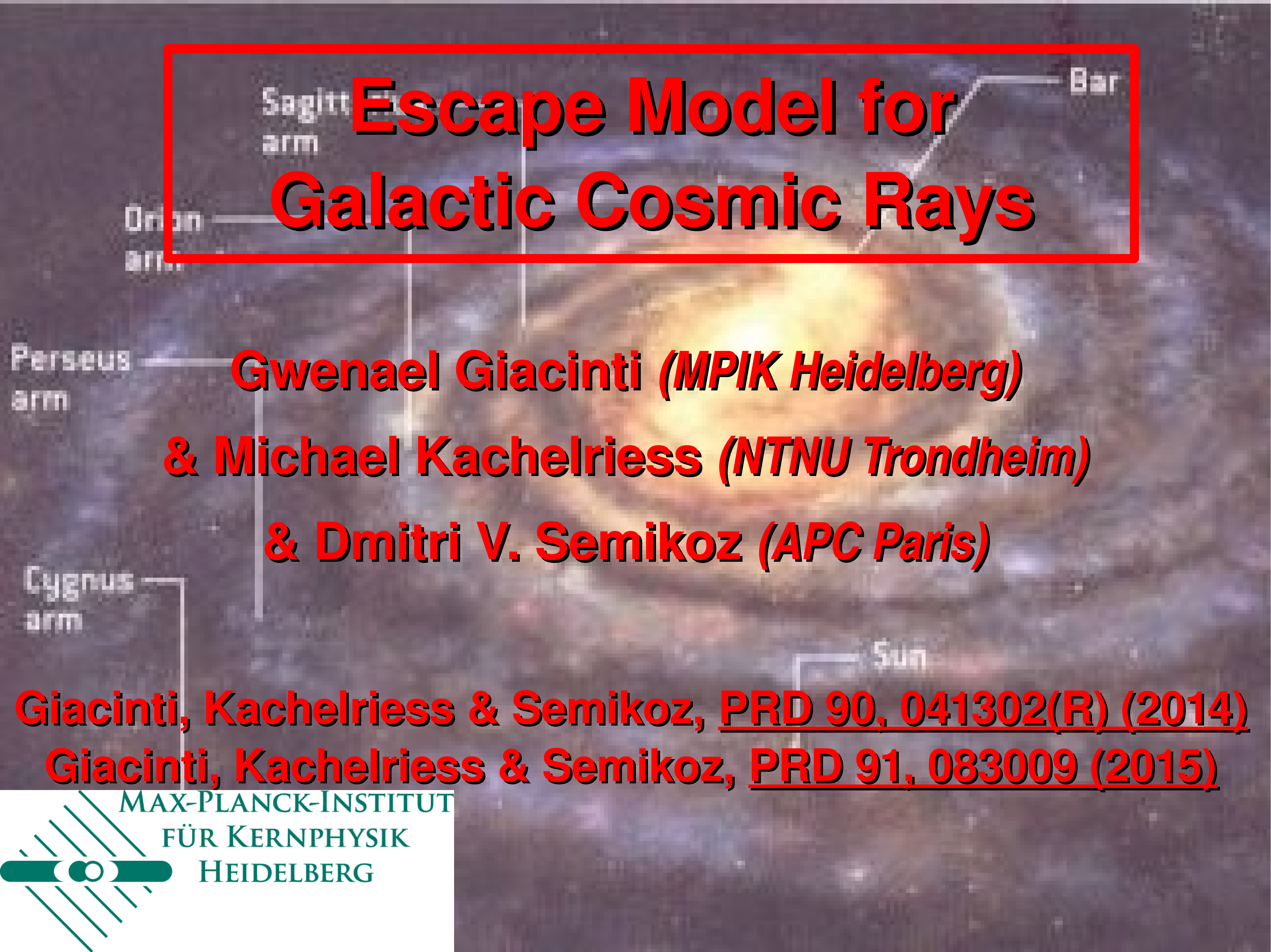


Escape Model for Galactic Cosmic Rays

Gwenael Giacinti *(MPIK Heidelberg)*

& Michael Kachelriess *(NTNU Trondheim)*

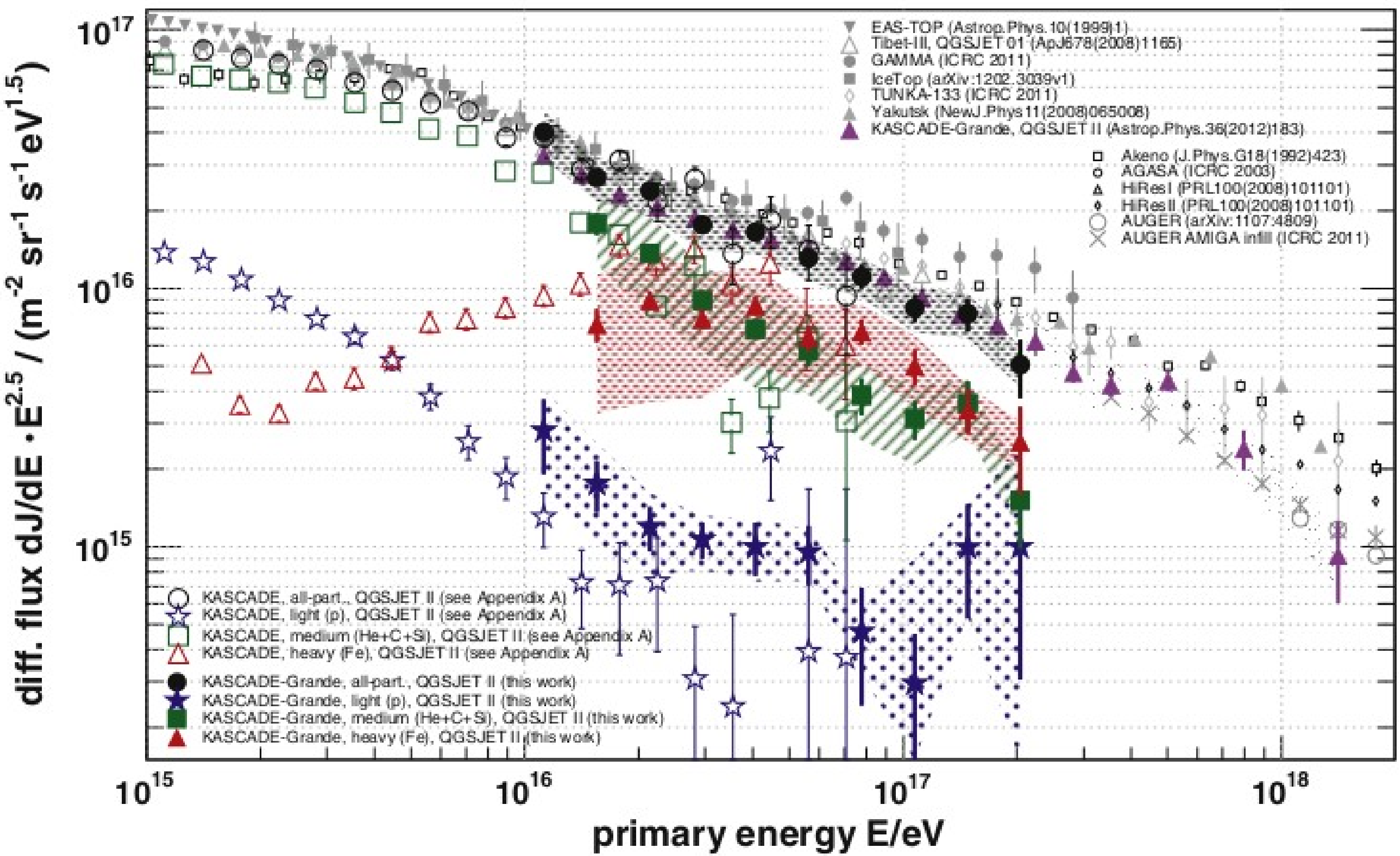
& Dmitri V. Semikoz *(APC Paris)*

Giacinti, Kachelriess & Semikoz, PRD 90, 041302(R) (2014)
Giacinti, Kachelriess & Semikoz, PRD 91, 083009 (2015)

Max-Planck-Institut für Kernphysik Heidelberg

Origin of the knee ?

W.D. Apel et al. / Astroparticle Physics 47 (2013) 54–66



E_{max} sources vs Energy at which $r_L = L_c$

Ginzburg & Syrovatski '64 ; Ptuskin et al. '93

Outline

I – Fit fluxes of individual elements around the knee

II – Transition Gal. → Extragal. ?

The turbulent Galactic magnetic field

Satisfies : <**B**(**x**)> = **0** **and** **<B(x)^2> = B$_{rms}^2$**

Power spectrum : $\mathcal{P}(k) \propto k^{-\alpha}$

Kolmogorov $\alpha = 5/3$

Kraichnan $\alpha = 3/2$

for $2\pi/L_{max} \leq k \leq 2\pi/L_{min}$

with L_{min} < 1 AU, **L_{max} ~ 10 pc - 100 pc (?)**

A&A 558, A72 (2013)
DOI: 10.1051/0004-6361/201322013
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Astronomy & Astrophysics

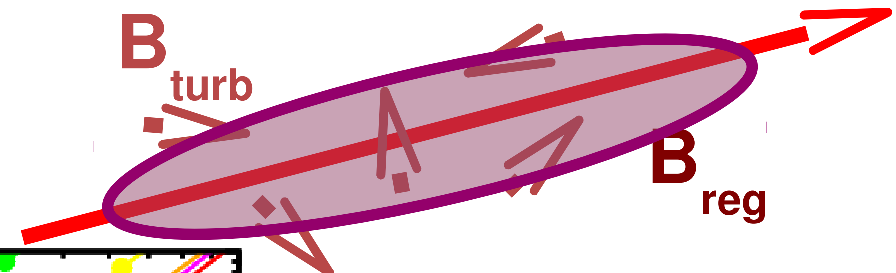
Studying Galactic interstellar turbulence through fluctuations in synchrotron emission

First LOFAR Galactic foreground detection

M. Iacobelli[1,2], M. Haverkorn[3,1], E. Orrú[2,3], R. F. Pizzo[2], J. Anderson[4], R. Beck[4], M. R. Bell[5], A. Bonafede[6], K. Chyzy[7], R.-J. Dettmar[8], T. A. Enßlin[9], G. Heald[2], C. Horellou[10], A. Horneffer[4], W. Jurusik[7], H. Junklewitz[9], M. Kuniyoshi[4], D. D. Mulcahy[4], R. Paladino[3,5], W. Reich[4], A. Scaife[11], C. Sobey[4], C. Sotomayor-Beltran[12]

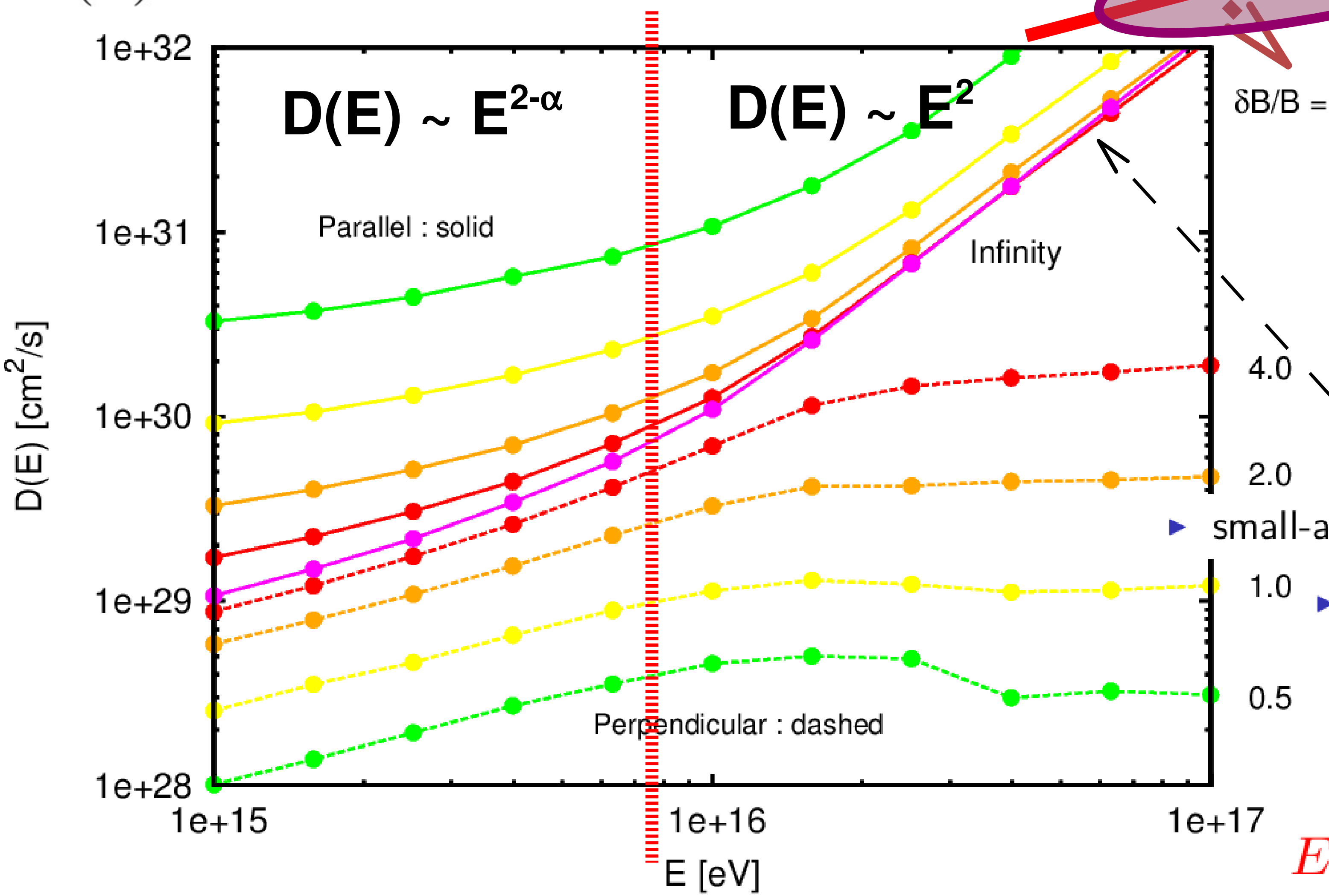
a variation of the ratio of random to ordered field as a function of Galactic coordinates, supporting different turbulent regimes.
Conclusions. We present the first LOFAR detection and imaging of the Galactic diffuse synchrotron emission around 160 MHz from the highly polarized Fan region. The power spectrum of the foreground synchrotron fluctuations is approximately a power law with a slope $\alpha \approx -1.84$ up to angular multipoles of $\lesssim 1300$, corresponding to an angular scale of ~8 arcmin. We use power spectra fluctuations from LOFAR as well as earlier GMRT and WSRT observations to constrain the outer scale of turbulence ($L_{\rm out}$) of the Galactic synchrotron foreground, finding a range of plausible values of 10–20 pc. Then, we use this information to deduce lower limits of the ratio of ordered to random magnetic field strength. These are found to be 0.3, 0.3, and 0.5 for the LOFAR, WSRT and GMRT fields considered respectively. Both these constraints are in agreement with previous estimates.

Perpendicular/Parallel diffusion coeffs.



$\mathcal{P}(k) \propto k^{-\alpha}$

$R_L \simeq l_c$



- small-angle scattering $D(E) \sim E^2$
- Hall diffusion $D(E) \sim E$

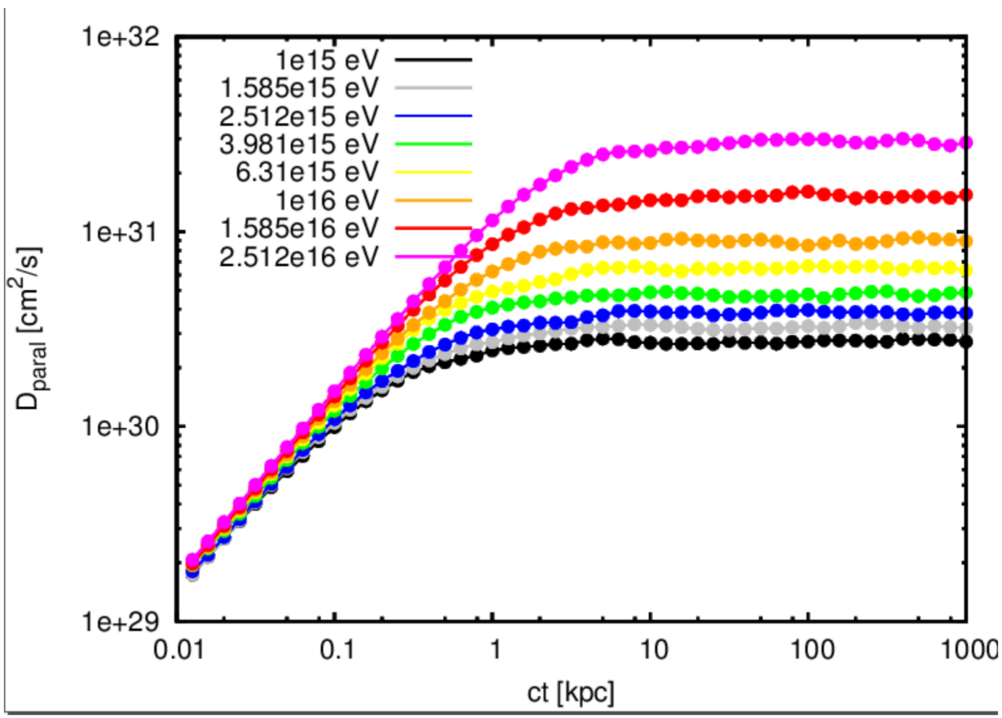
$$E_c/Z \sim 10^{15}\ \frac{B}{\mu G}\ \frac{l_c}{pc}$$

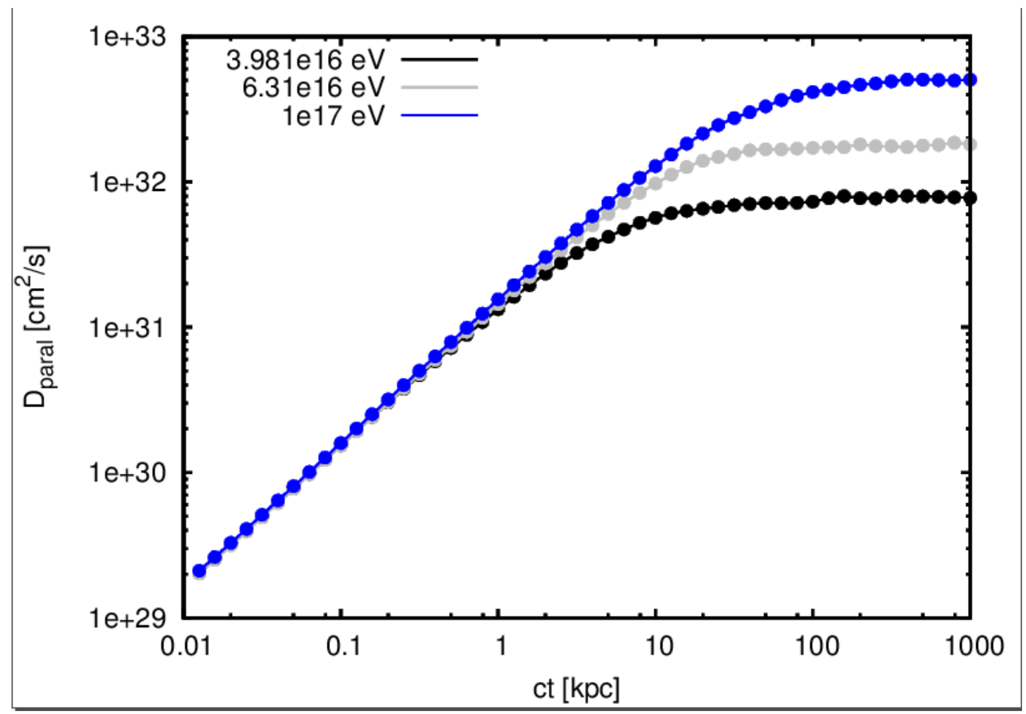
1 μG L_{max} = 150 pc Kolmogorov

Limitations ; Need for individual trajectories

+ Drifts (See also De Marco et al.)

- Diffusion approximation breaks down at **high energies**





→ **NEED FOR INDIVIDUAL CR TRAJECTORIES**

(Recent) Galactic magnetic field model

Regular MF

***Jansson & Farrar*, Astrophys. J. 757, 14 (2012)**

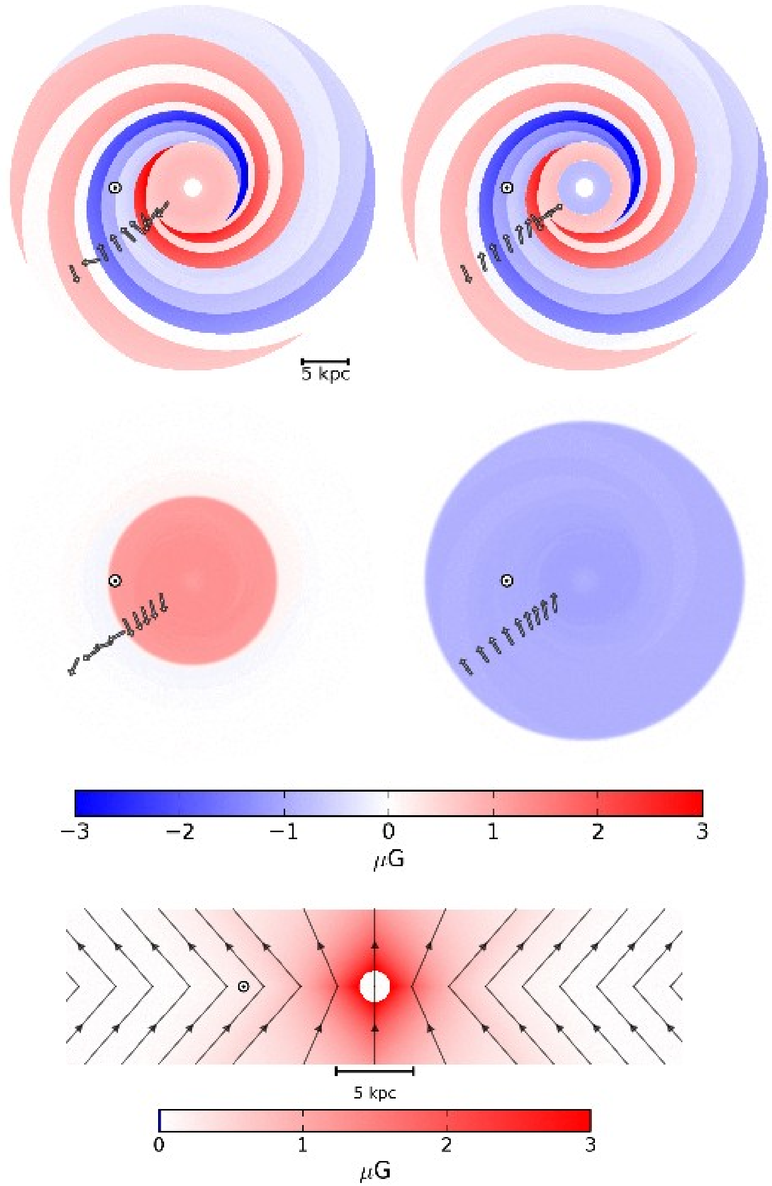
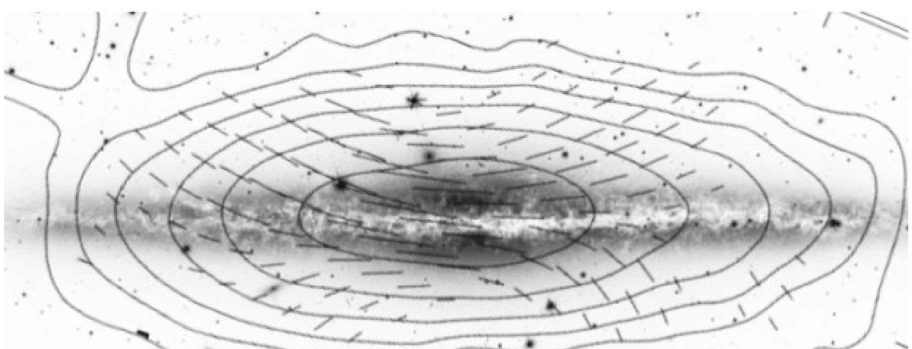


Table 1
Best-fit GMF parameters with $1-\sigma$ intervals.

Field	Best fit Parameters	Description
Disk	$b_1 = 0.1 \pm 1.8\,\mu$G	field strengths at $r = 5$ kpc
	$b_2 = 3.0 \pm 0.6\,\mu$G	
	$b_3 = -0.9 \pm 0.8\,\mu$G	
	$b_4 = -0.8 \pm 0.3\,\mu$G	
	$b_5 = -2.0 \pm 0.1\,\mu$G	
	$b_6 = -4.2 \pm 0.5\,\mu$G	
	$b_7 = 0.0 \pm 1.8\,\mu$G	
	$b_8 = 2.7 \pm 1.8\,\mu$G	inferred from $b_1, ..., b_7$
	$b_{\rm ring} = 0.1 \pm 0.1\,\mu$G	ring at 3 kpc $< r <$ 5 kpc
	$h_{\rm disk} = 0.40 \pm 0.03$ kpc	disk/halo transition
	$w_{\rm disk} = 0.27 \pm 0.08$ kpc	transition width
Toroidal halo	$B_{\rm n} = 1.4 \pm 0.1\,\mu$G	northern halo
	$B_{\rm s} = -1.1 \pm 0.1\,\mu$G	southern halo
	$r_{\rm n} = 9.22 \pm 0.08$ kpc	transition radius, north
	$r_{\rm s} > 16.7$ kpc	transition radius, south
	$w_{\rm h} = 0.20 \pm 0.12$ kpc	transition width
	$z_0 = 5.3 \pm 1.6$ kpc	vertical scale height
X halo	$B_{\rm X} = 4.6 \pm 0.3\,\mu$G	field strength at origin
	$\Theta^0_{\rm X} = 49 \pm 1°$	elev. angle at $z = 0, r > r^{\rm c}_{\rm X}$
	$r^{\rm c}_{\rm X} = 4.8 \pm 0.2$ kpc	radius where $\Theta_{\rm X} = \Theta^0_{\rm X}$
	$r_{\rm X} = 2.9 \pm 0.1$ kpc	exponential scale length
striation	$\gamma = 2.92 \pm 0.14$	striation and/or $n_{\rm cre}$ rescaling



NGC 891, Krause (2009)

(Recent) Galactic magnetic field model

Turbulent MF

Jansson & Farrar
Astrophys. J. 761, L11 (2012)

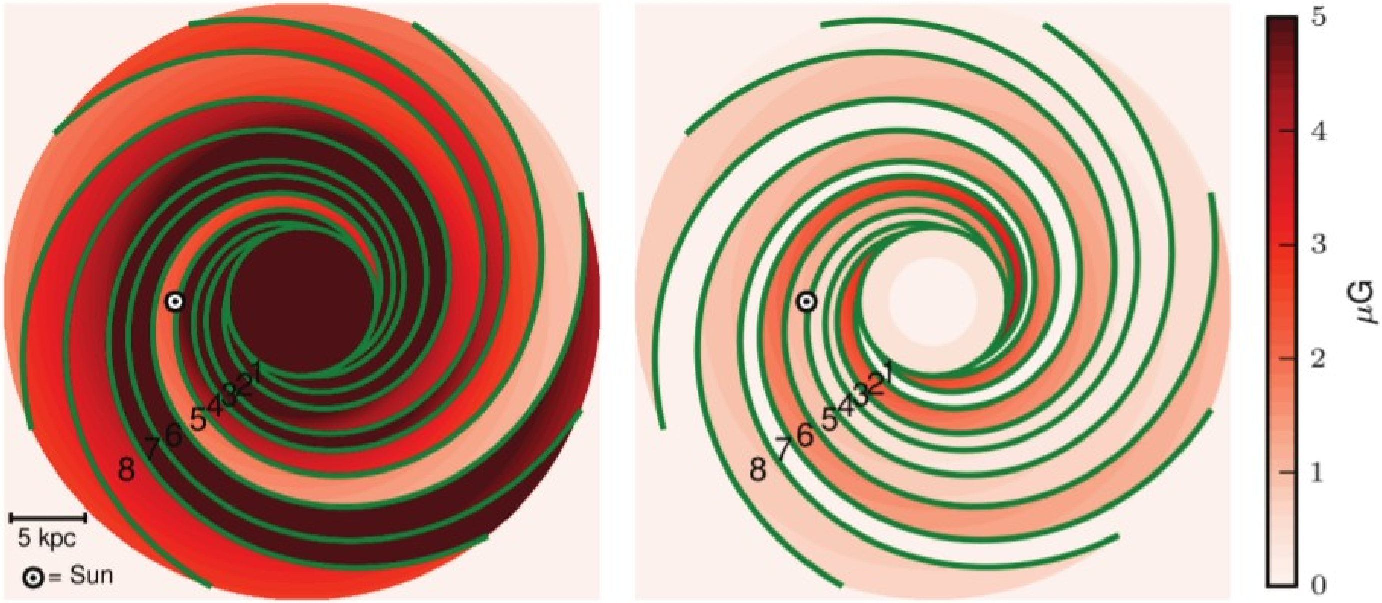


Table 1
Best-fit parameters of the random field, with $1-\sigma$ intervals.

Field	Best fit Parameters	Description
Disk component	$b_1 = 10.81 \pm 2.33\,\mu$G	field strengths at $r = 5$ kpc
	$b_2 = 6.96 \pm 1.58\,\mu$G	
	$b_3 = 9.59 \pm 1.10\,\mu$G	
	$b_4 = 6.96 \pm 0.87\,\mu$G	
	$b_5 = 1.96 \pm 1.32\,\mu$G	
	$b_6 = 16.34 \pm 2.53\,\mu$G	
	$b_7 = 37.29 \pm 2.39\,\mu$G	
	$b_8 = 10.35 \pm 4.43\,\mu$G	
	$b_{\rm int} = 7.63 \pm 1.39\,\mu$G	field strength at $r < 5$ kpc
	$z_0^{\rm disk} = 0.61 \pm 0.04$ kpc	Gaussian scale height of disk
Halo component	$B_0 = 4.68 \pm 1.39\,\mu$G	field strength
	$r_0 = 10.97 \pm 3.80$ kpc	exponential scale length
	$z_0 = 2.84 \pm 1.30$ kpc	Gaussian scale height
Striation	$\beta = 1.36 \pm 0.36$	striated field $B^2_{\rm stri} \equiv \beta B^2_{\rm reg}$

We try l_c = 1 pc to 10 pc
& Kolmogorov spectrum

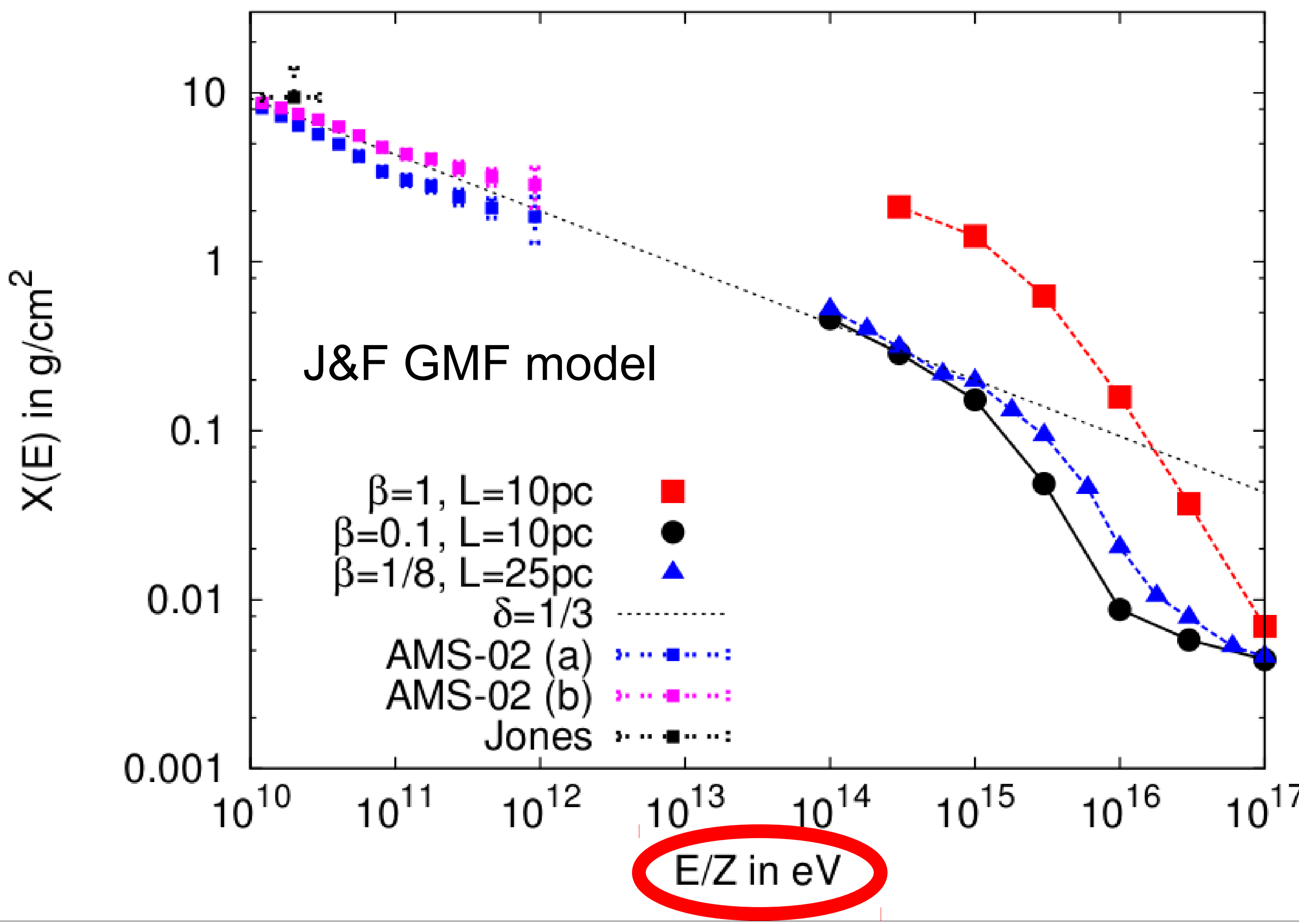
Knee

Gaz distribution :

$n(z) = n_0 \exp(-(z/z_{1/2})^2)$ with $n_0 = 0.3/\mathrm{cm}^3$ at $R_\odot$ and $z_{1/2} = 0.21\,\mathrm{kpc}$

$n = 10^{-4}\mathrm{g/cm}^3$ ↔ Minimum, up to z = +/- 10 kpc

Sources : $n(r) \propto (r/R_\odot)^{0.7} \exp\left[-3.5(r - R_\odot)/R_\odot\right]$ D. A. Green, arXiv:1309.3072



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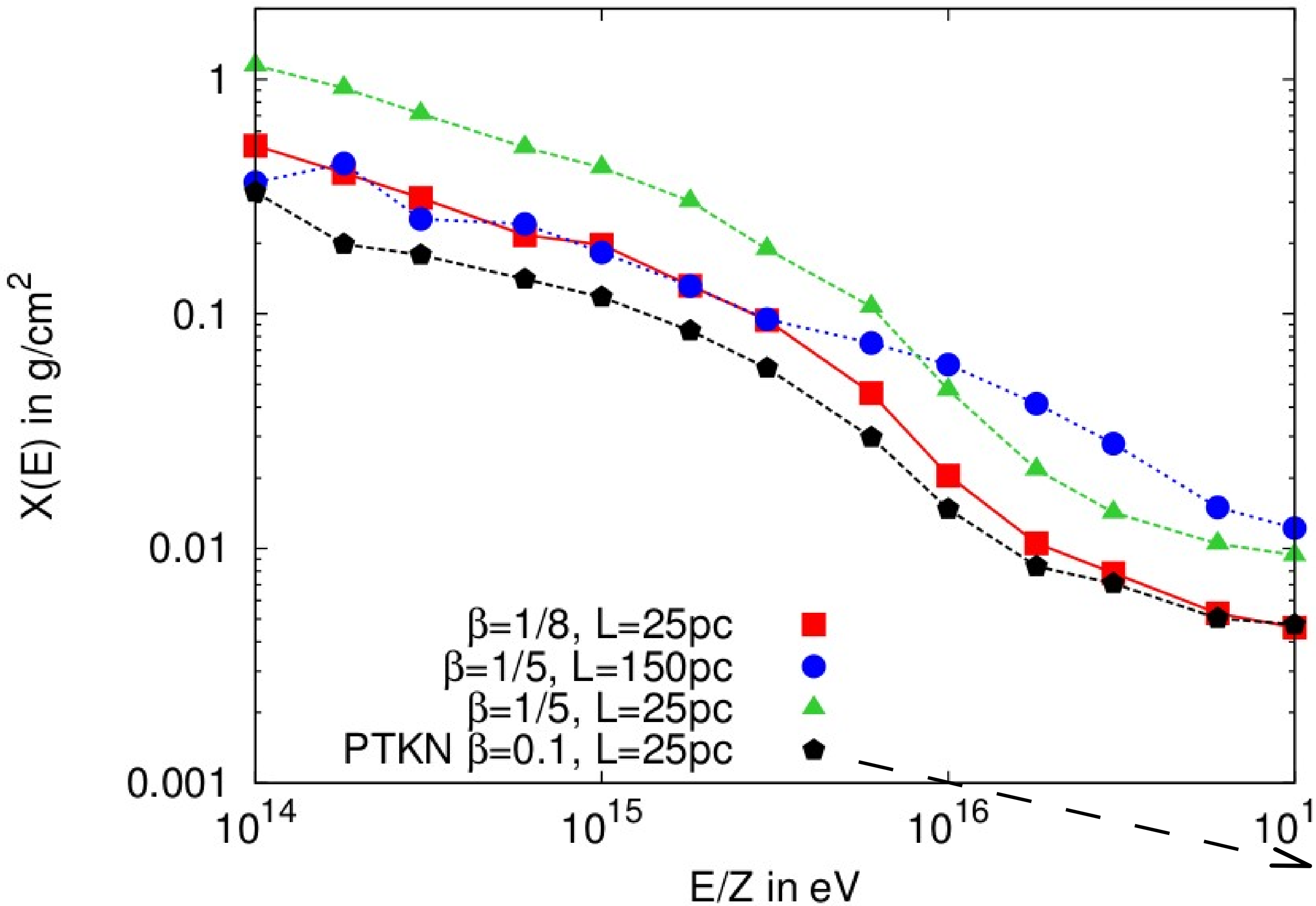
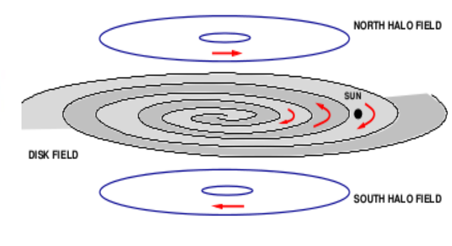
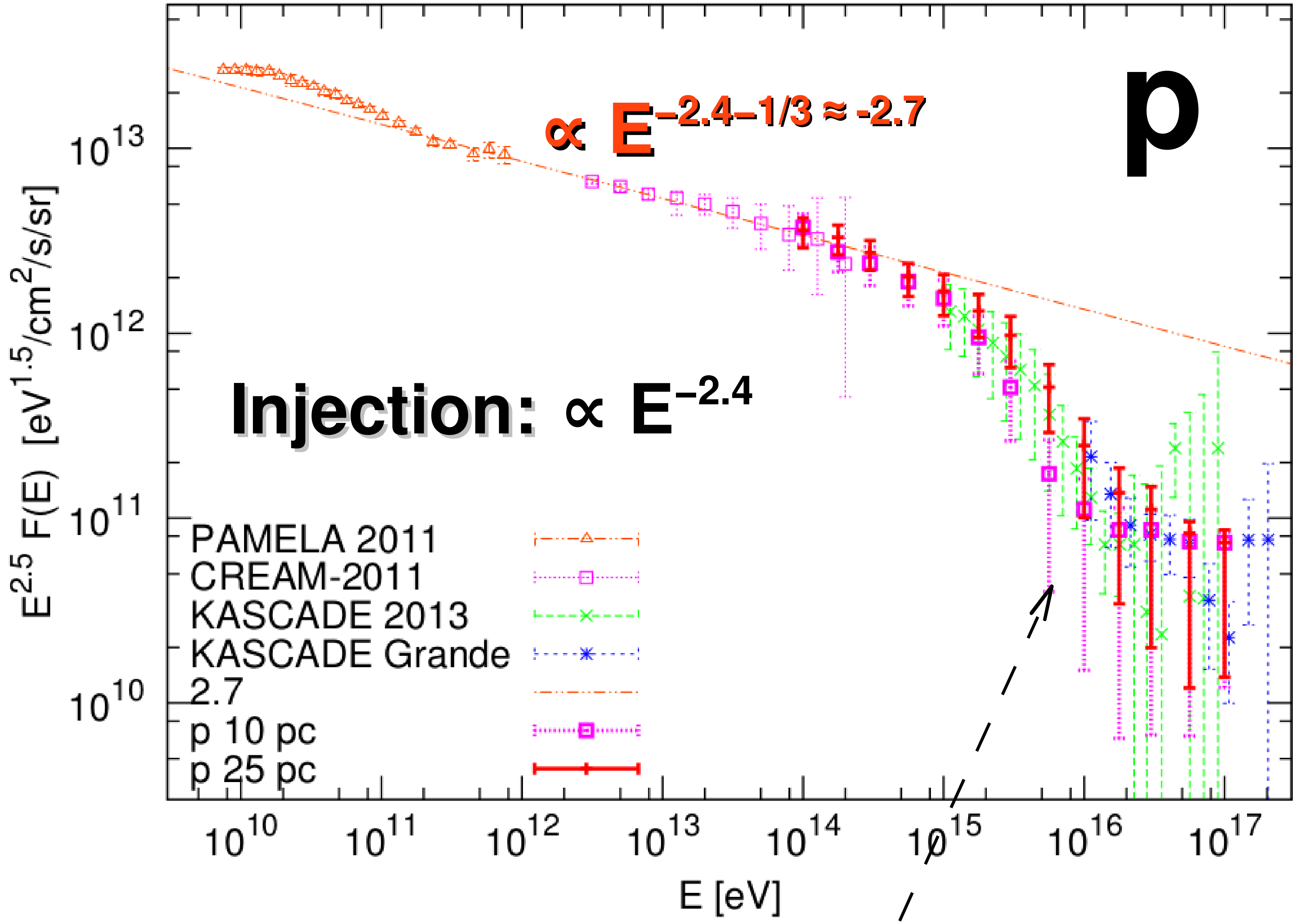




IG. 4.— Sketch of the structure of the galactic magnetic field.

Pshirkov et al., ApJ 738, 192 (2011)

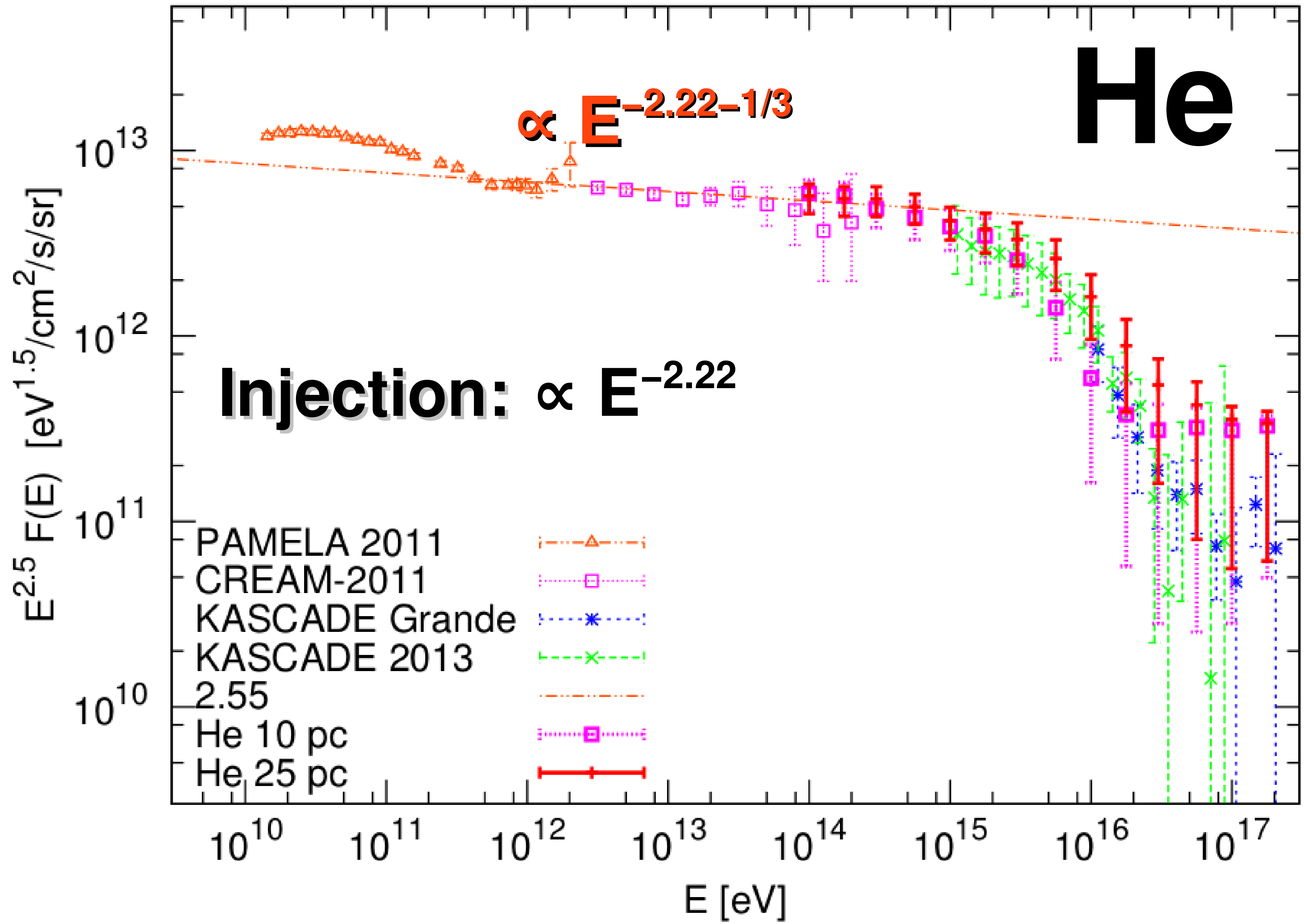
Composition - Fluxes



K-G p flux ~ 40% larger than KASCADE

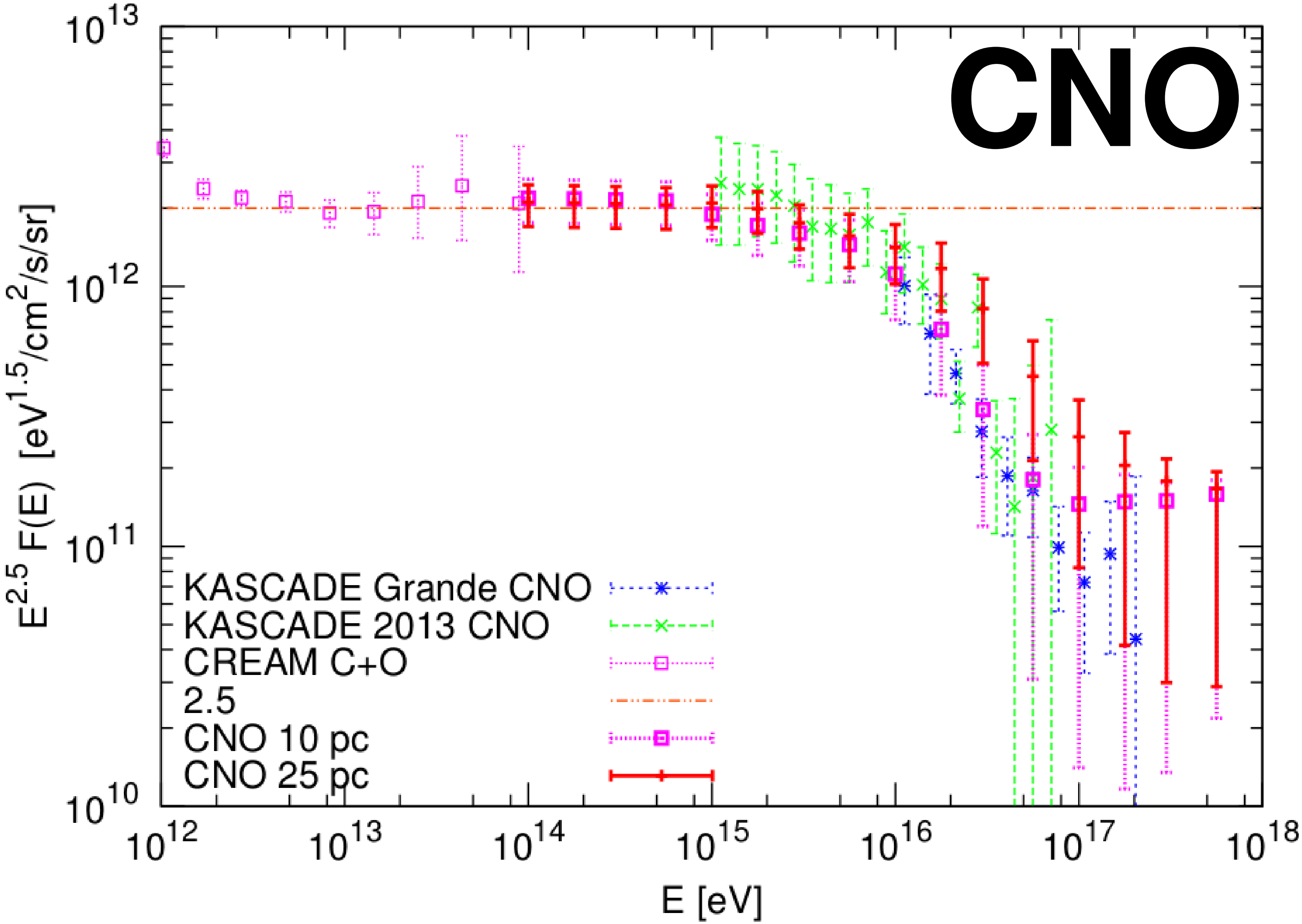
10 – 30 PeV: Reduced **p** flux of KASCADE-Grande by 40%, and added this difference to the **He** flux

Composition - Fluxes



Injection nuclei : $\alpha = -2.17$ or 2.22 & maximal energy ZxE_p

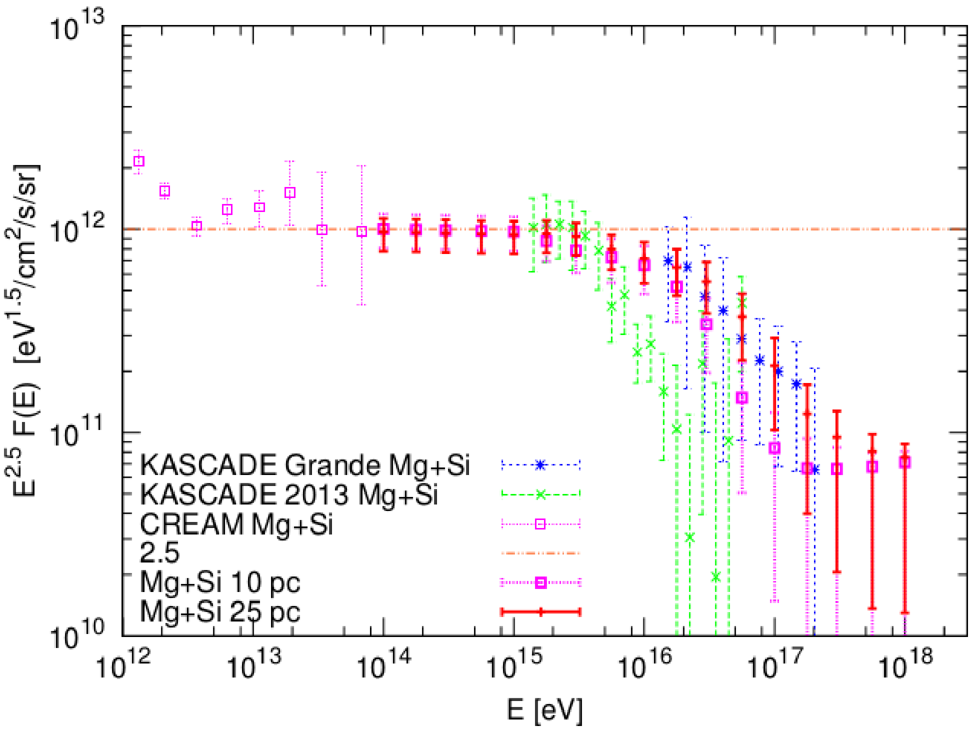
Composition - Fluxes



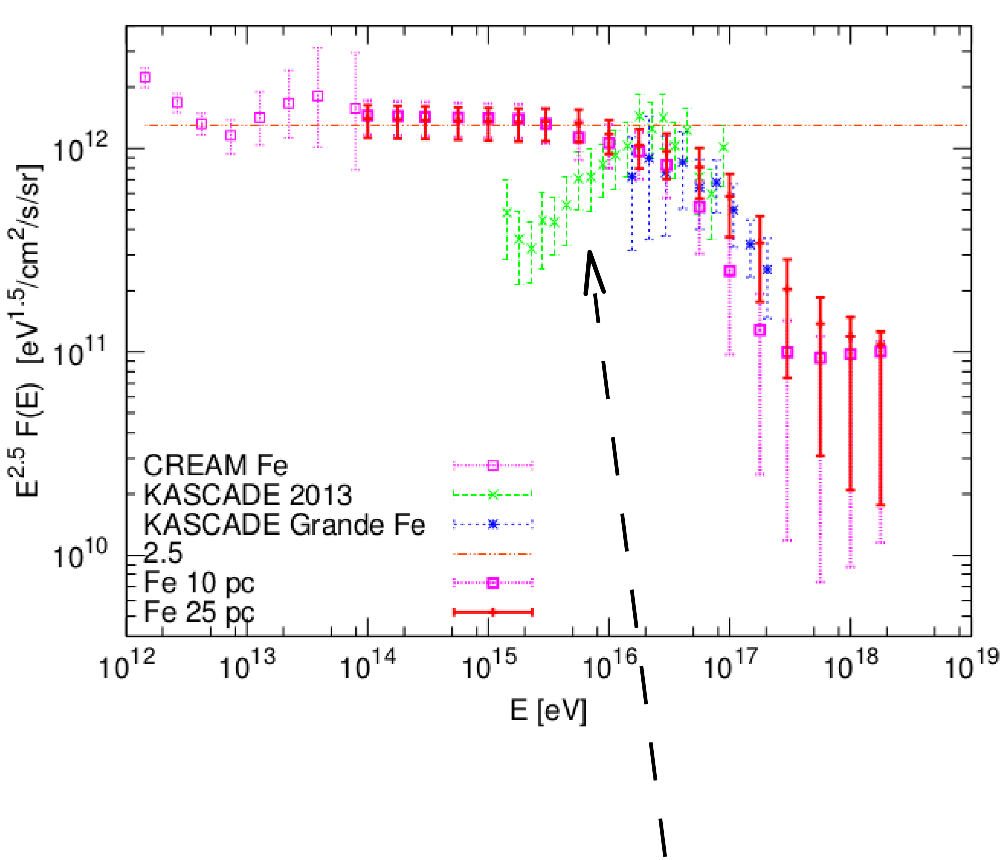
CREAM flux = Sum of its C and O fluxes, using C energy bins for the binning, and interpolating the O flux to these bins.

Composition - Fluxes

Mg + Si

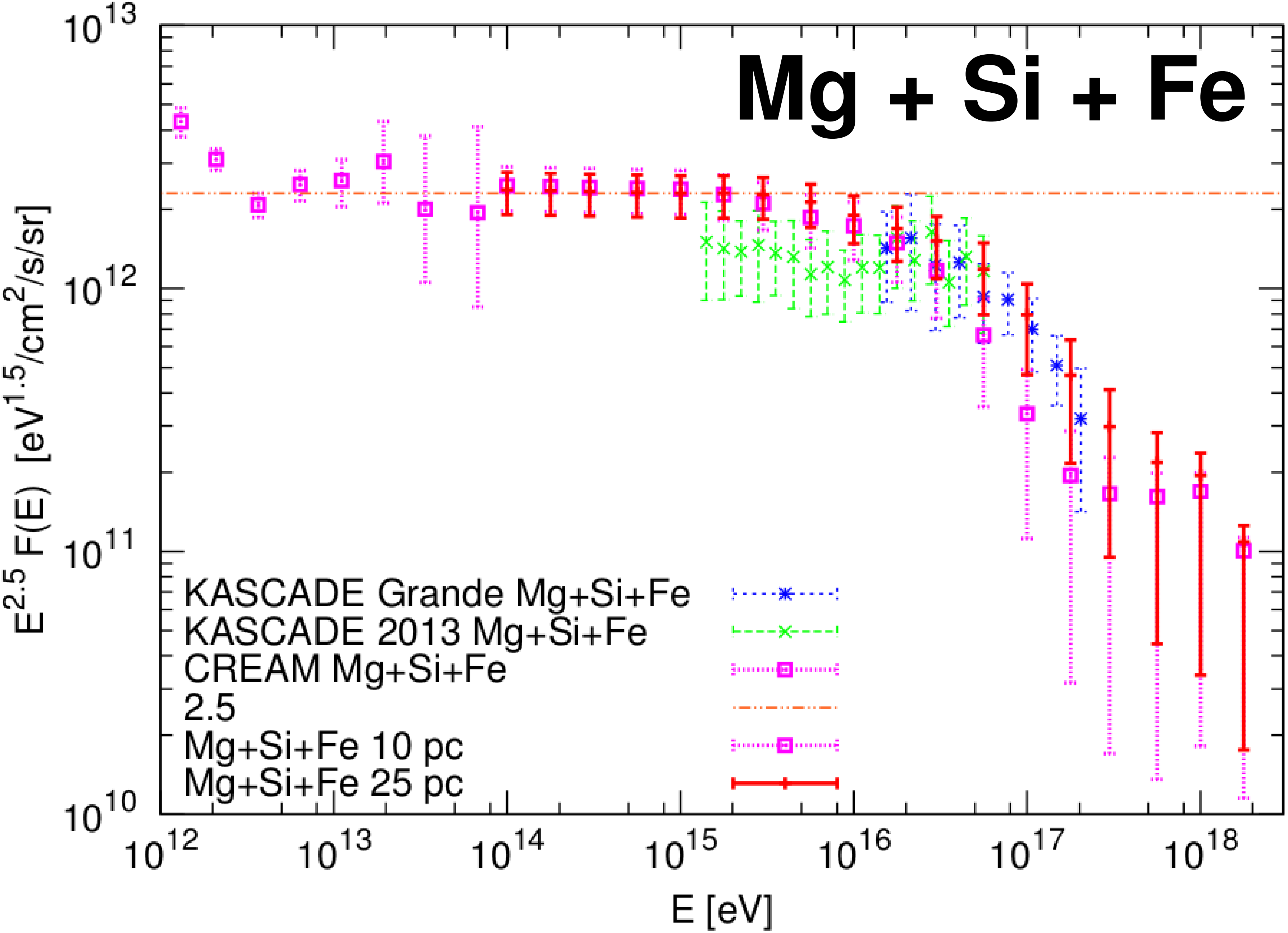


Fe

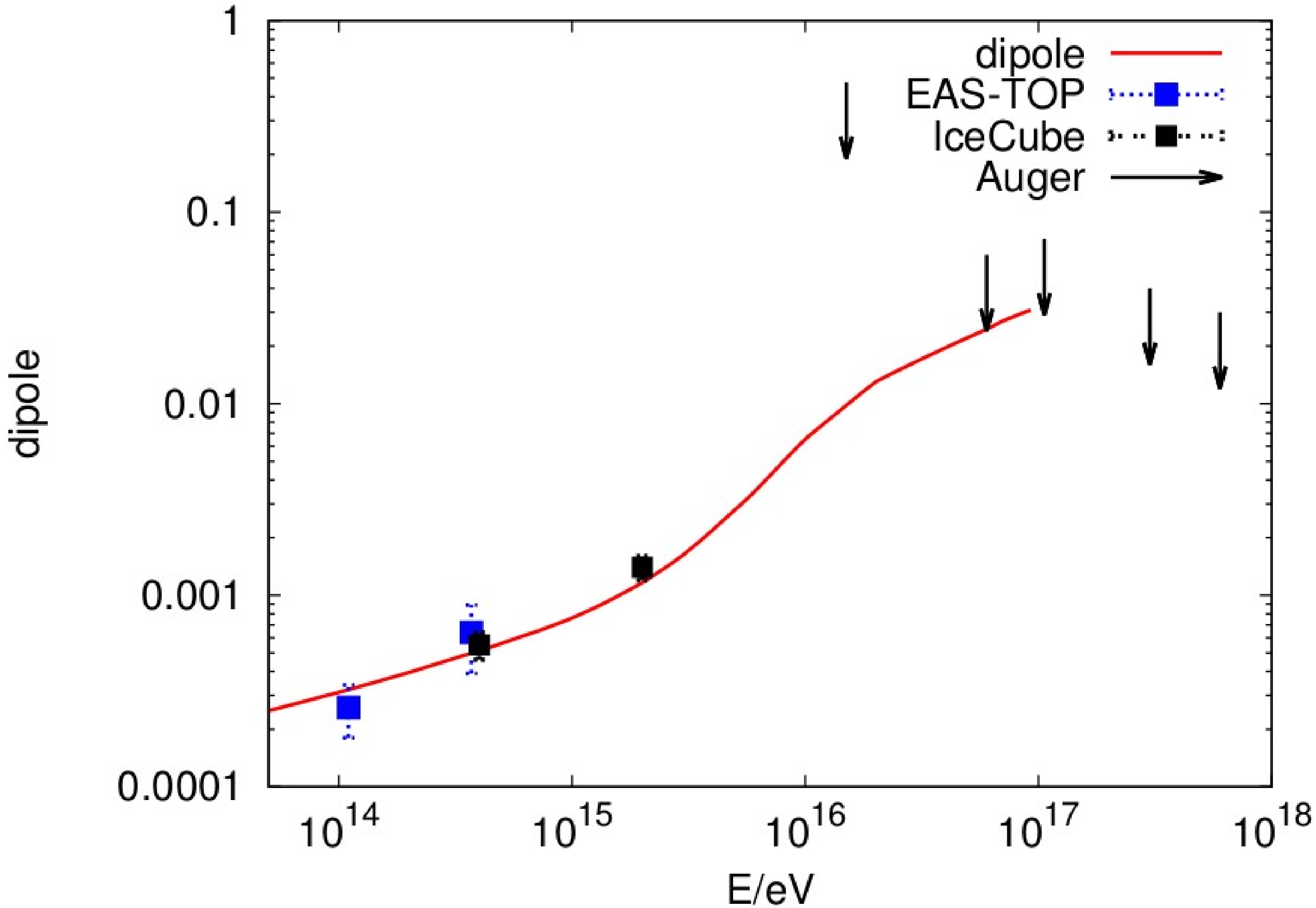


Likely to be due to the difficulty for KASCADE to distinguish between Si and Fe nuclei => We sum up Mg, Si and Fe fluxes.

Composition - Fluxes



Anisotropy

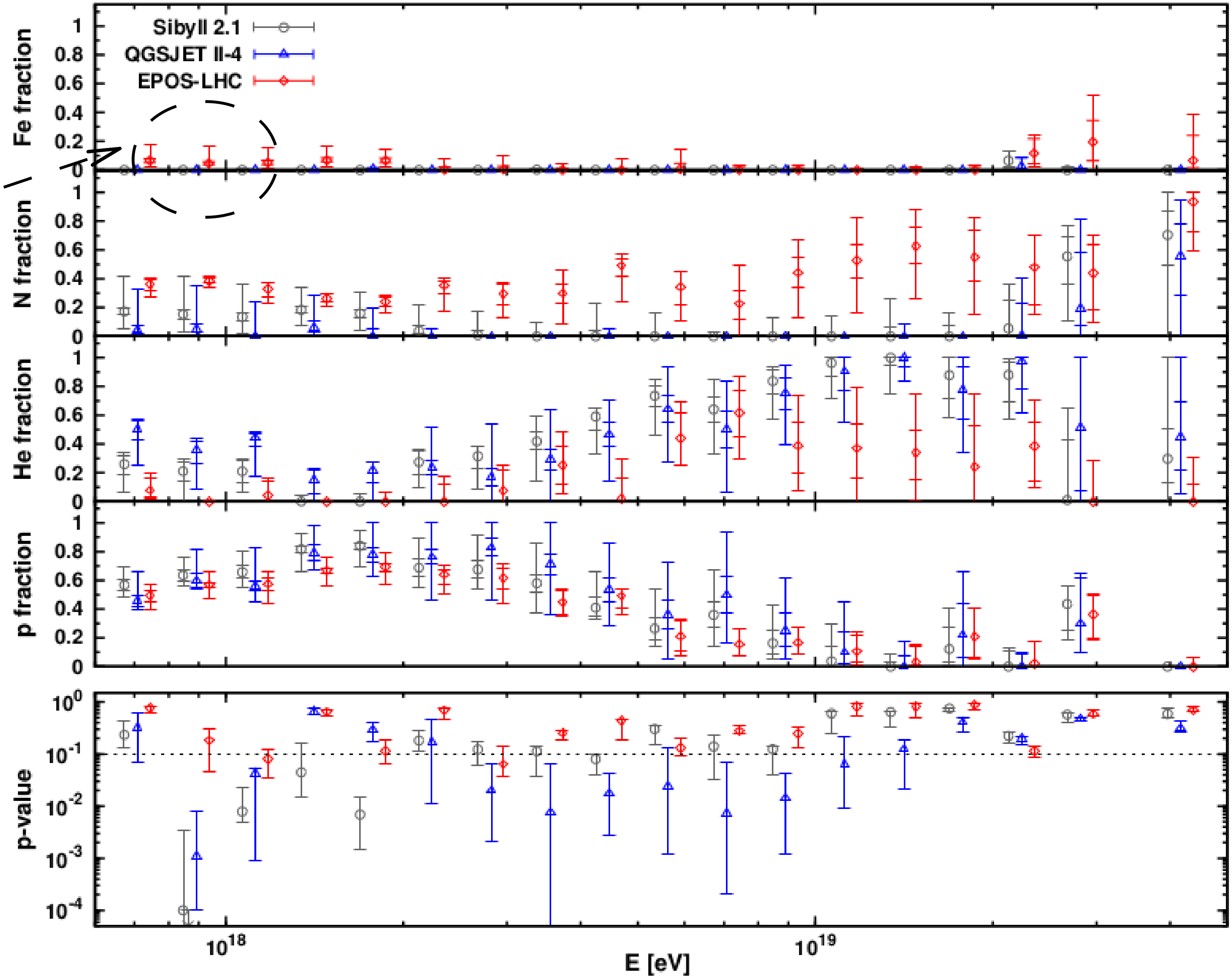


β = 1/10 and
L_{max} = 10 pc

→ See talk by
Michael Kachelriess

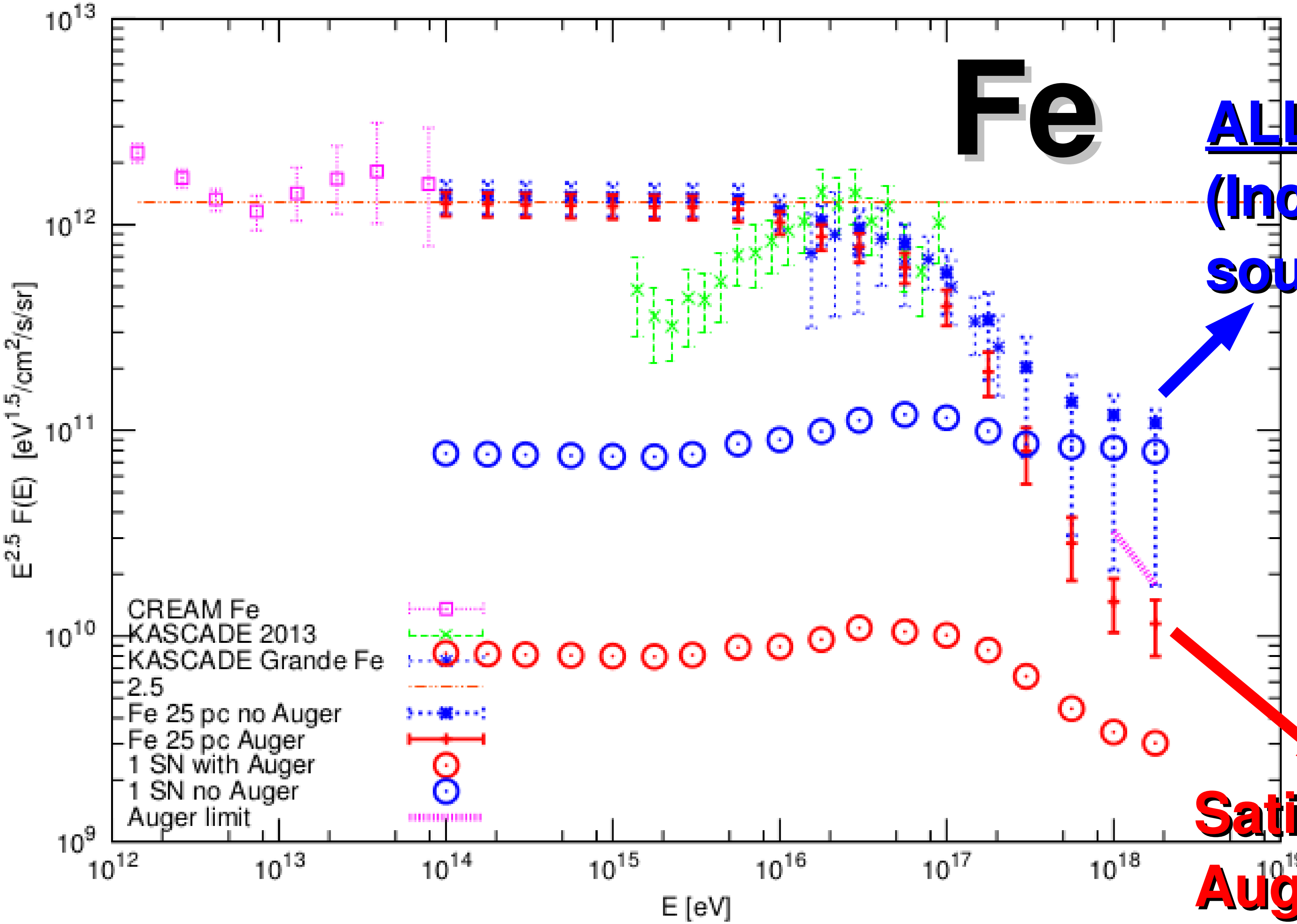
Auger composition

Fe fraction above 6×10^{17} eV is <~ 20%



arXiv:1409.5083

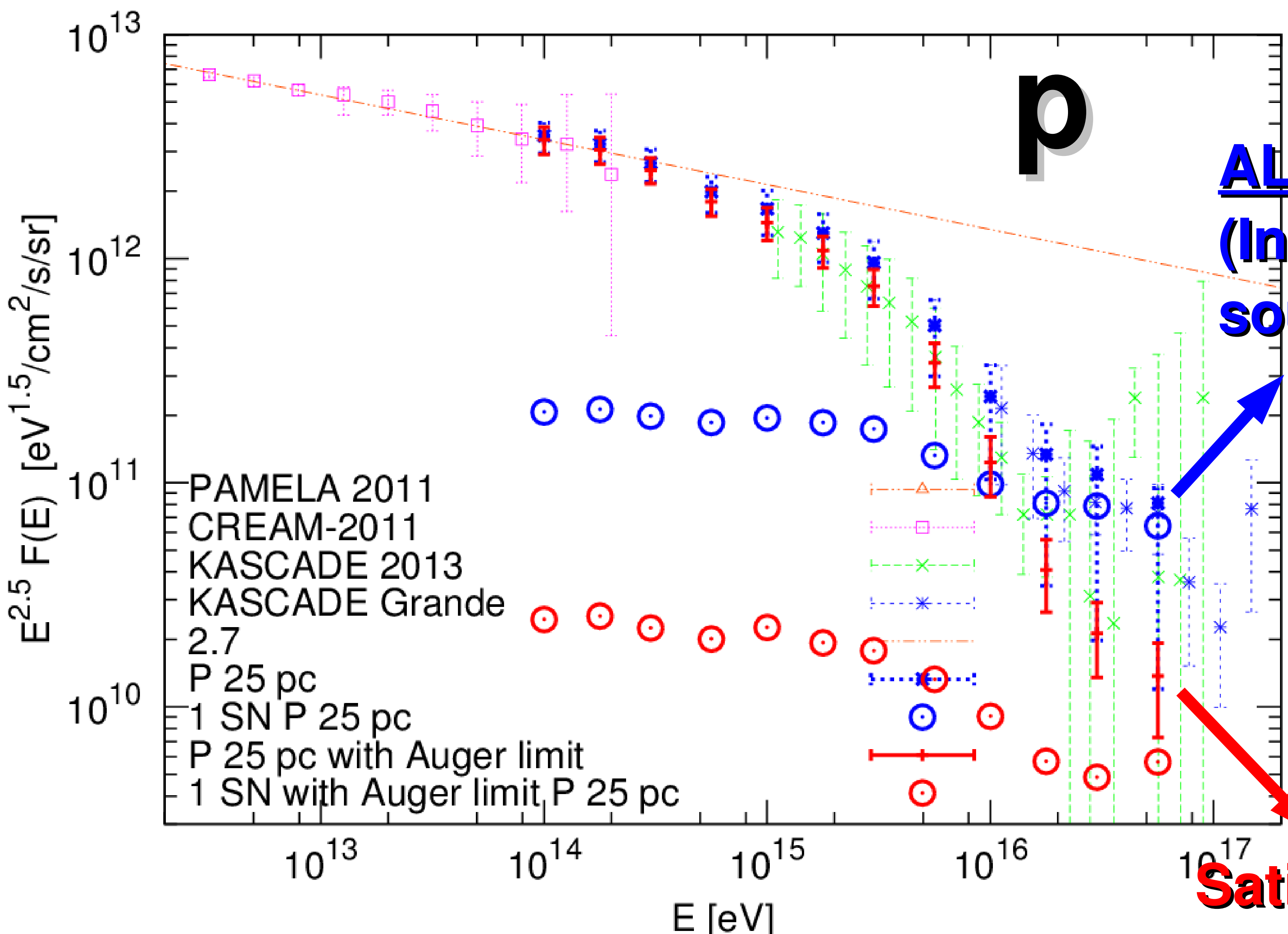
Auger limits on Fe fraction



ALL configs (Incl. nearby source)

Satisfying Auger Limits

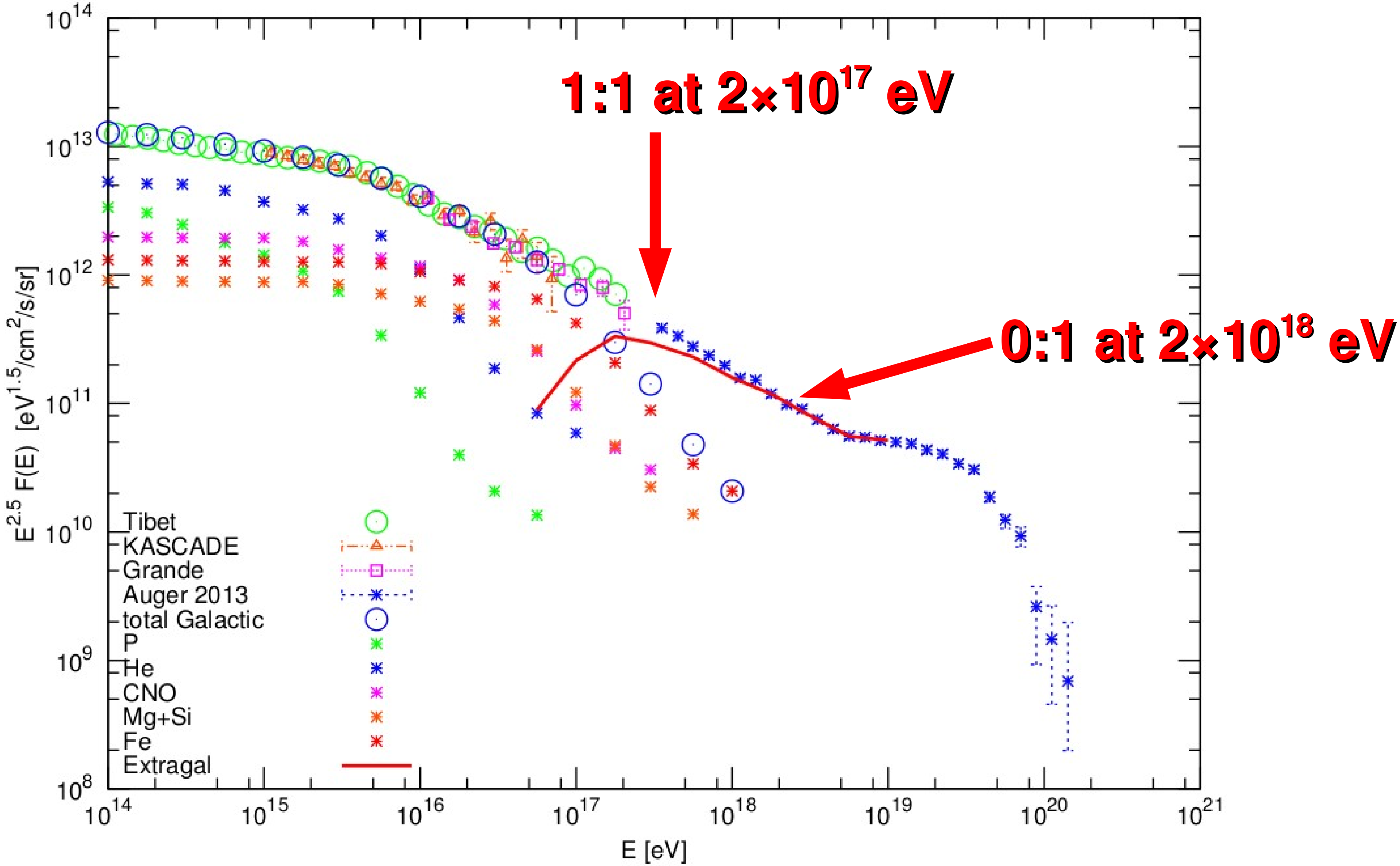
Auger limits on Fe fraction



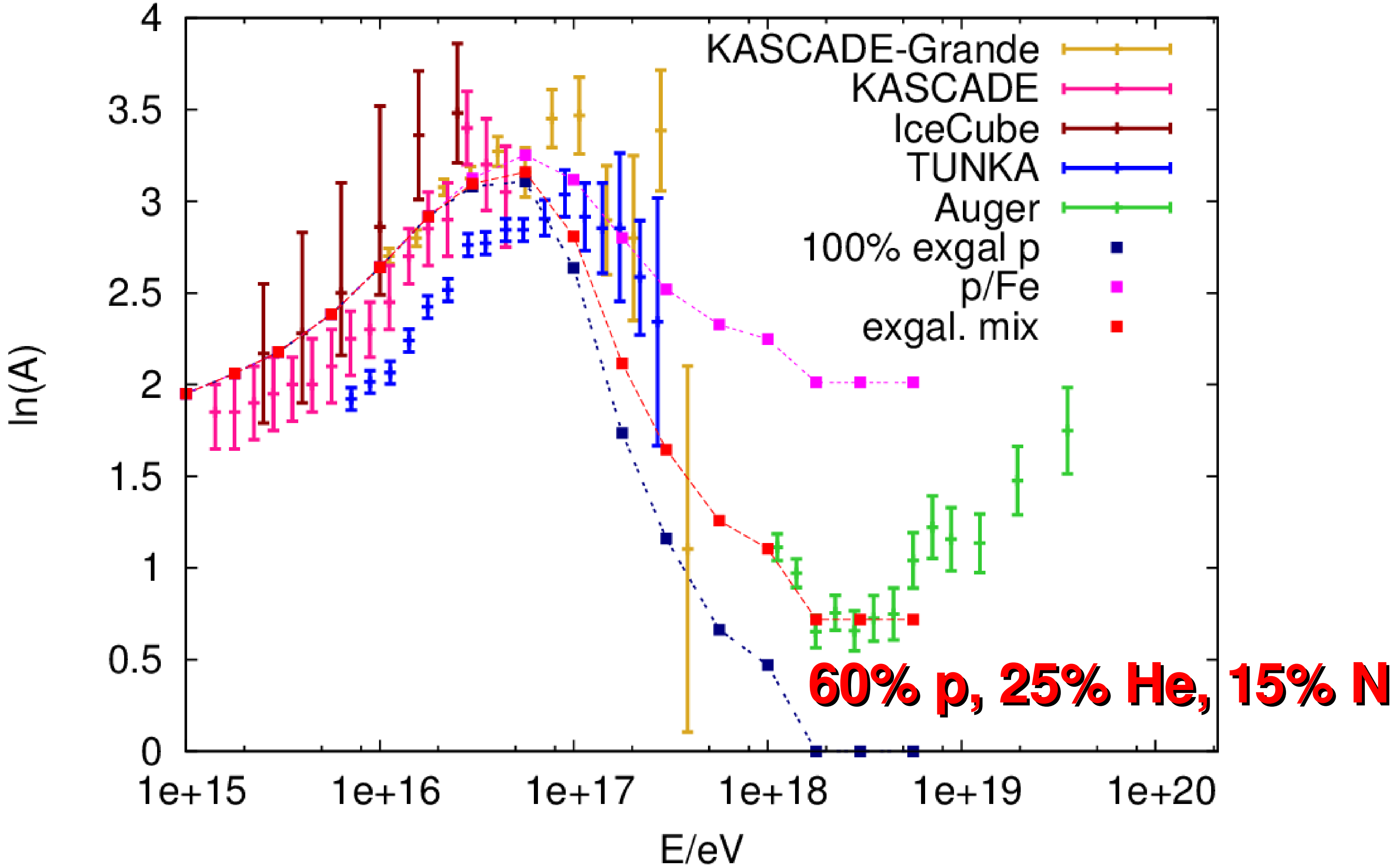
ALL configs (Incl. nearby source)

Satisfying Auger Limits

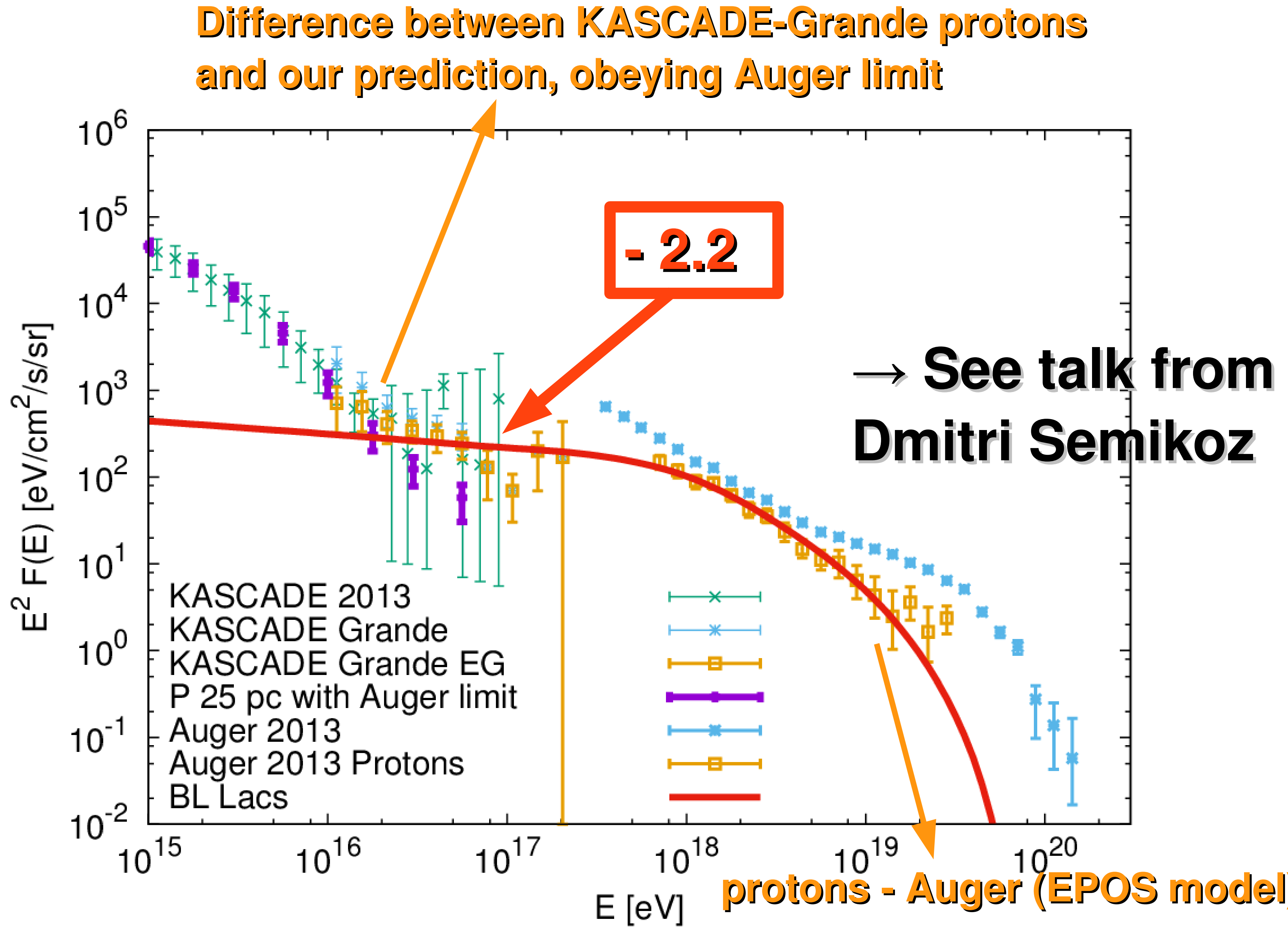
Galactic / Extragalactic CRs



Composition - ln(A)



Extragalactic CR protons



Conclusions

- 'Escape model' can fit all recent CR data / observables, notably spectrum of individual elements around the knee

- Can be tested (e.g. Auger anisotropy at 'low' energies)

- Transition to extragal. CRs no later than at a few x 10^{17} eV
  Extragal. Protons above a few 10s PeV.