Explaining Knee by Cosmic Ray Escape from Galaxy

Ultra High Energy \\ Cosmic Rays

Dmitri Semikoz

APC , Paris

With G.Giacinti and M.Kachelriess

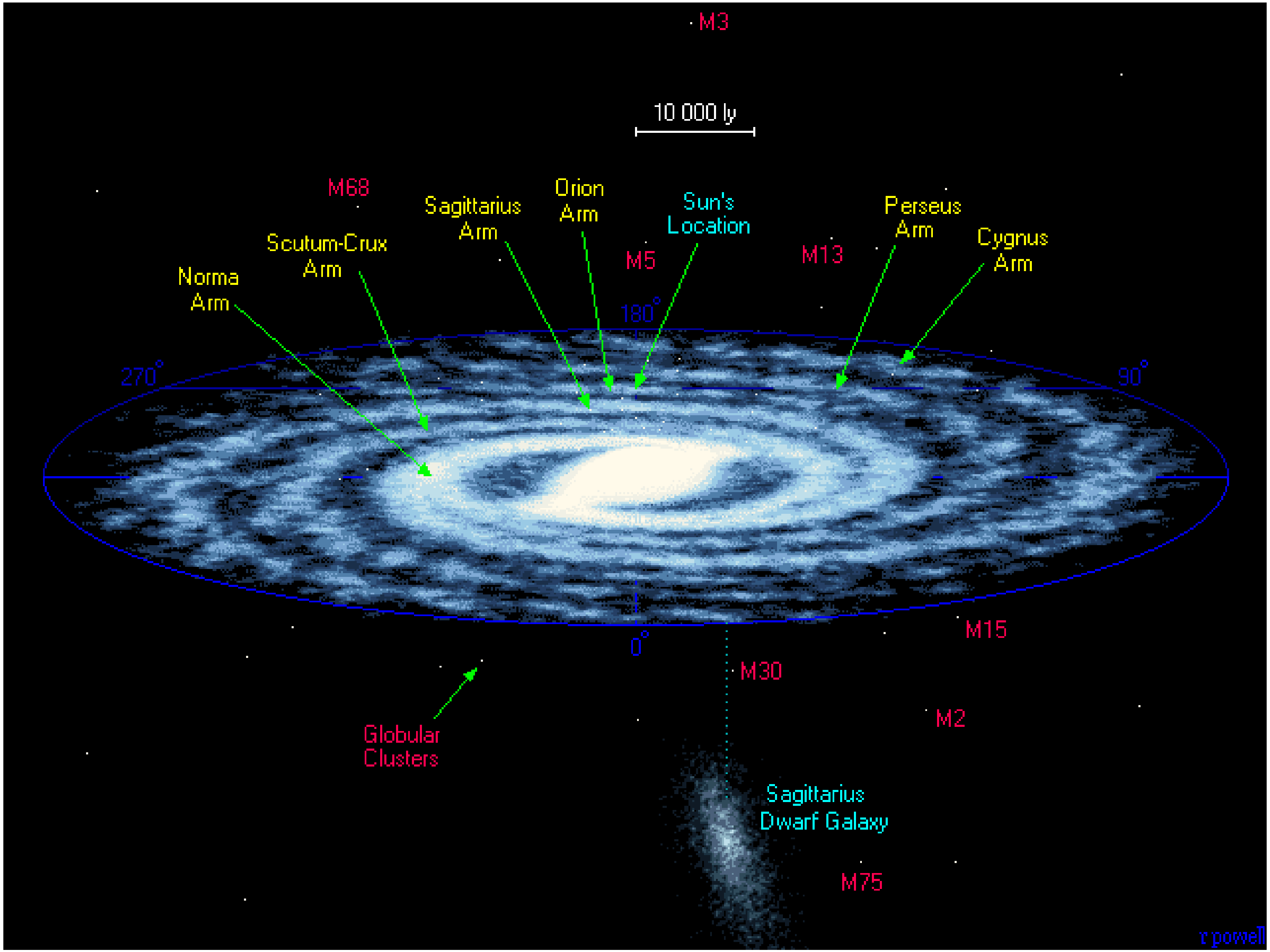
arXiv: 1403.3380 (to appear in PRD)

Overview:

- *Galactic Magnetic Field*
- *Cosmic ray diffusion around single source*
- *Cosmic ray escape from Galaxy: Knee region*
- *Galactic to extra-galactic cosmic ray transition*
- *Summary*

Galactic magnetic field

MILKY WAY GALAXY



Galactic magnetic field

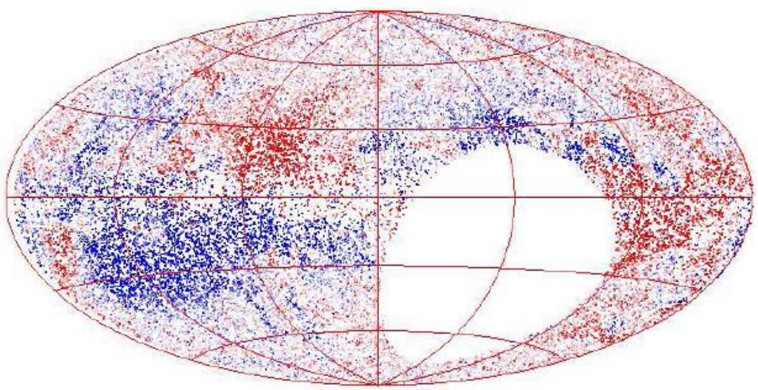
- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

Rotation measure

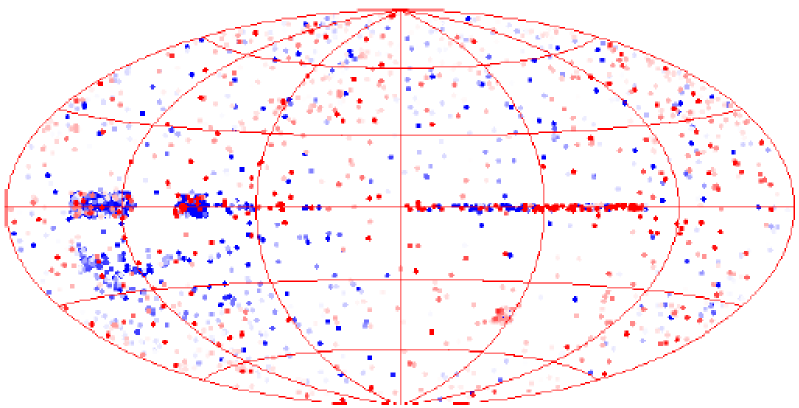
$$\mathrm{RM} \simeq 0.81 \int_0^L \left(\frac{n_e(l)}{\mathrm{cm}^{-3}}\right)\left(\frac{B_{||}(l)}{\mu\mathrm{G}}\right)\left(\frac{\mathrm{d}l}{\mathrm{pc}}\right)$$

$$\theta = \theta_0 + \mathrm{RM}\,\lambda^2$$

Galactic magnetic field measurement: RM



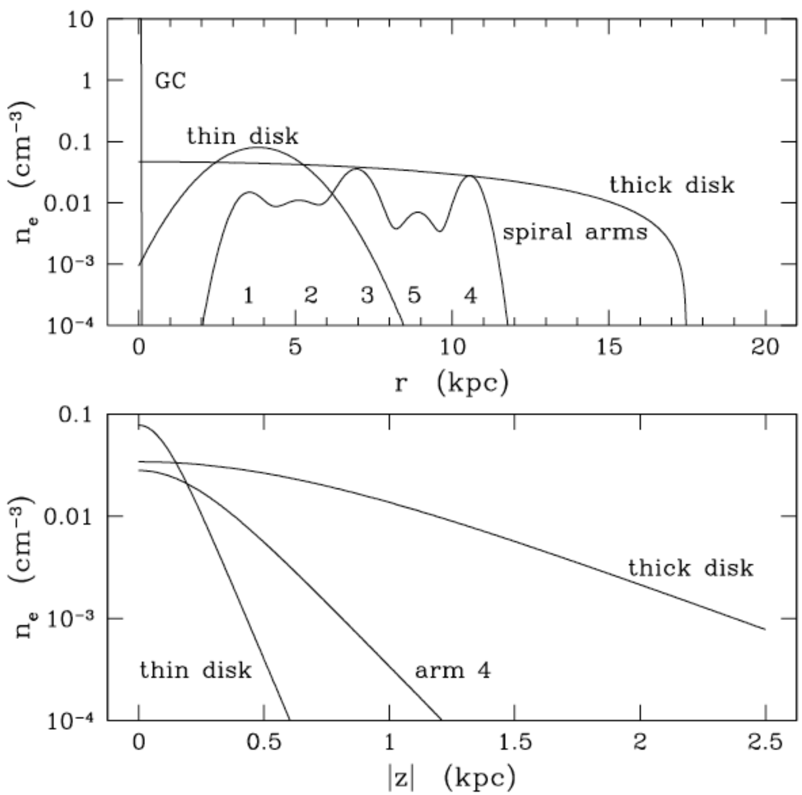
NVSS



Ph.Kronberg & Newton-McGee (2011)

From Pshirkov et al, **arXiv:1103.0814**

Free electrons 2001 model



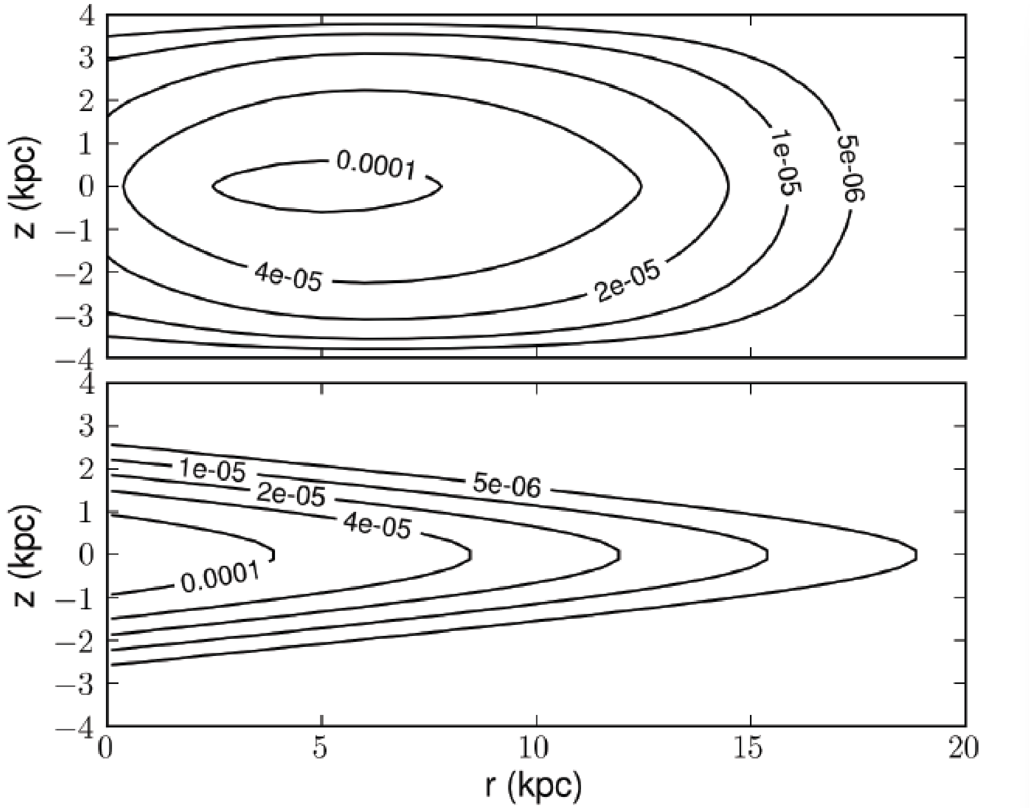
J.Cordes and T.Lazio, **astro-ph/0207156**

Polarized synchrotron emission

$$j_\nu \propto n_{cre} B_\perp^{\frac{1+s}{2}} \nu^{\frac{1-s}{2}}.$$

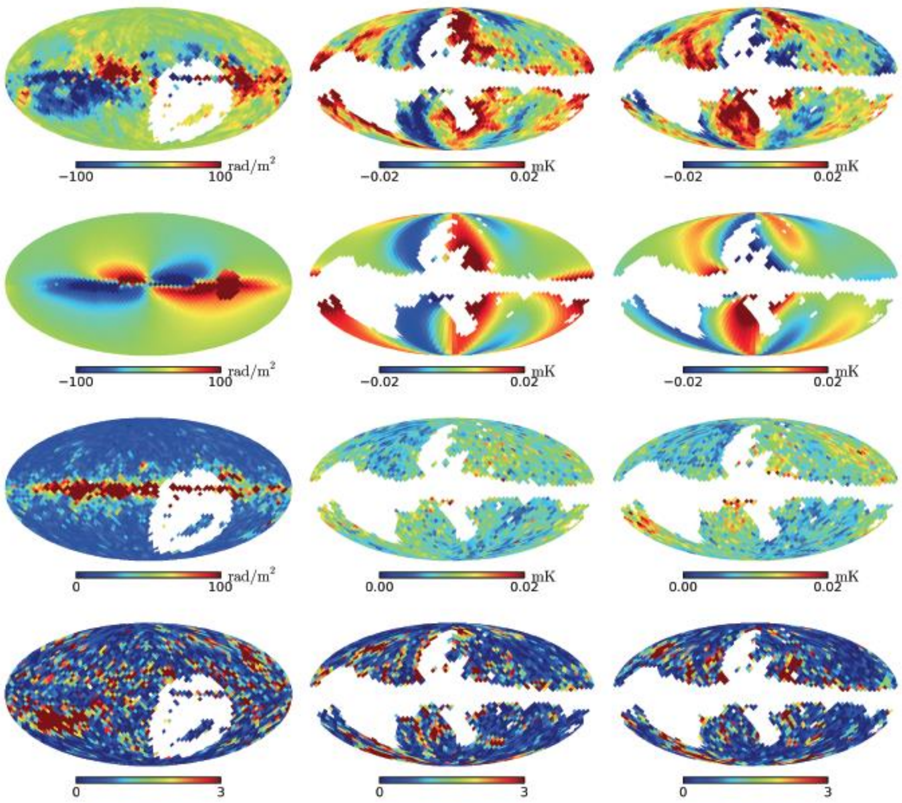
$$s = 3$$

Relativistic electrons



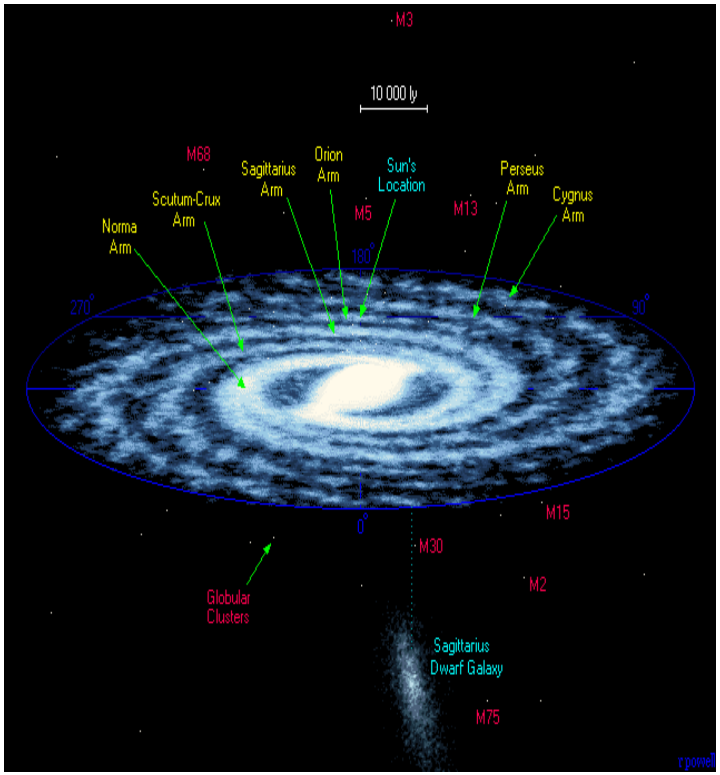
From R.Jansson & G.Farrar, arXiv:1204.3662

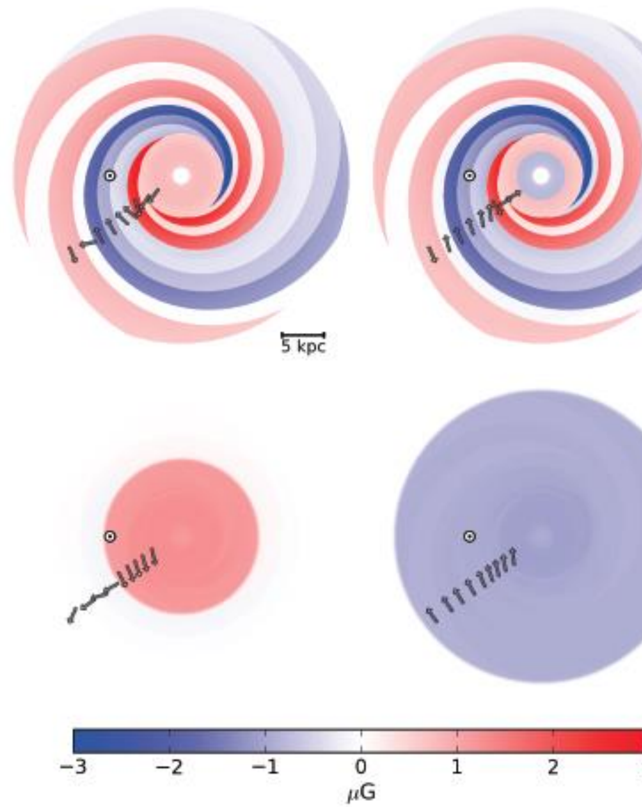
Synchrotron/RM maps



From R.Jansson & G.Farrar, arXiv:1204.3662

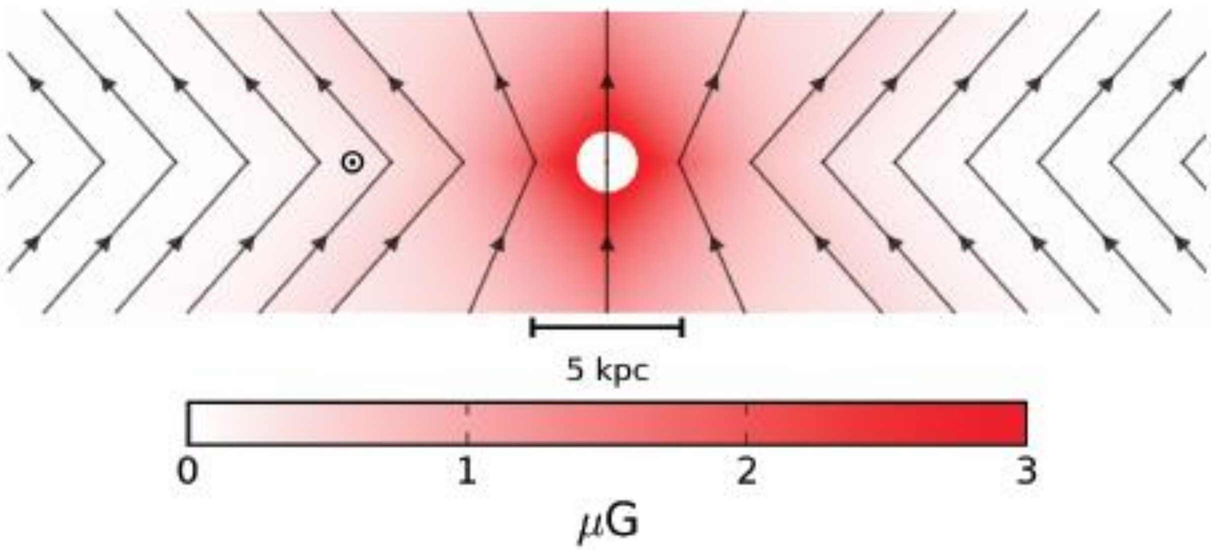
Galactic magnetic field: disk





R.Jansson & G.Farrar, arXiv:1204.3662

Galactic magnetic field halo: x-shape



R.Jansson & G.Farrar, arXiv:1204.3662

GMF regular field parameters

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 $z = 0, r > r^c_{\rm X}$
	$r^c_{\rm X} = 4.8 \pm 0.2$ 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

R.Jansson & G.Farrar, arXiv:1204.3662

Galactic magnetic field

- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

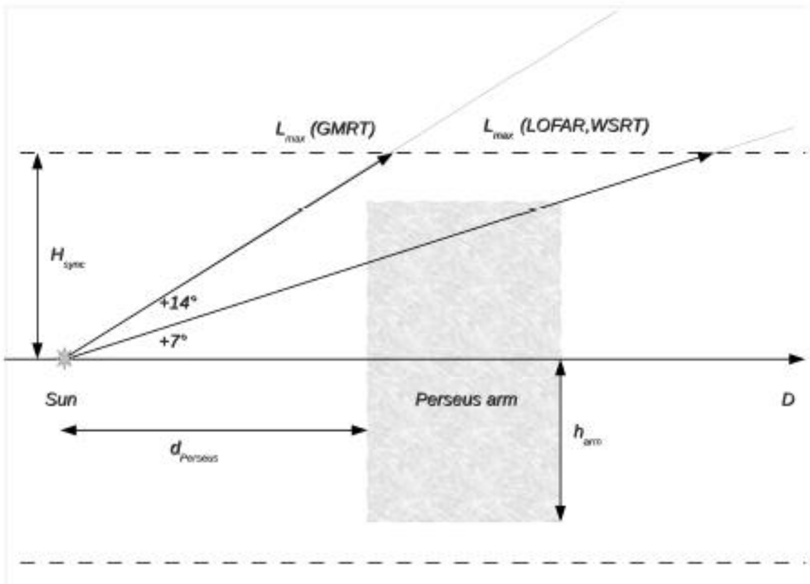
Galactic magnetic field: turbulent component

- Field with $\langle B(r) \rangle = 0$ $\langle B(r)^2 \rangle \equiv B_{\rm rms}^2 > 0.$
- Power spectrum $\mathcal{P}(k) \propto k^{-\alpha},$ $|B(k)|^2 \propto k^{-\alpha-2}$
- With index $\alpha = 5/3, 3/2$ for Kolmogorov/Kraichnan cases
- Correlation length

$$L_c = \frac{L_{\max}}{2} \frac{\alpha - 1}{\alpha} \frac{1 - (L_{\min}/L_{\max})^{\alpha}}{1 - (L_{\min}/L_{\max})^{\alpha-1}} .$$

- Where
- $L_{\min} = 1\,\mathrm{AU}$ Lmax=25-100 pc

LOFAR measurement of maximum scale of turbulent GMF in disk



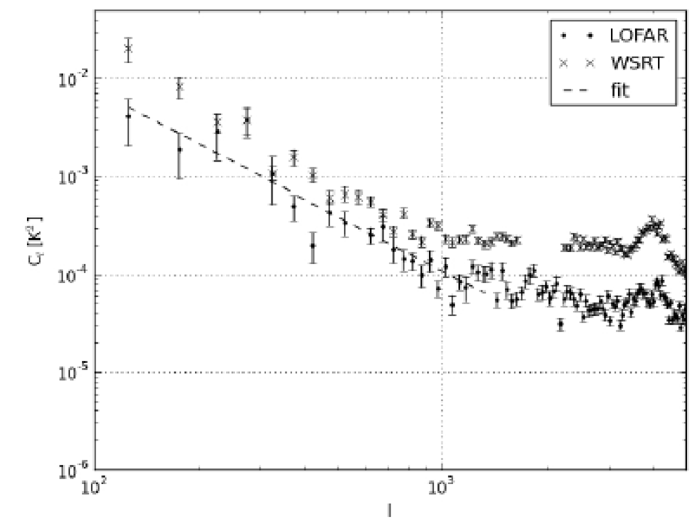


Fig. 9. Power spectra of total intensity from the LOFAR (dots) and WSRT (crosses) observations. The error bars indicate statistical errors at 1σ. The fitted power law (dashed line) with a spectral index $\alpha = -1.84 \pm 0.19$ for $\ell \in [100, 1300]$ is also shown.

arXiv: 1308.2804

Lmax ~ 20 pc +-6 pc in disk

Galactic magnetic field: turbulent component

- For G.Farrar model there is dedicated paper on turbulent component arXiv:1210.7820

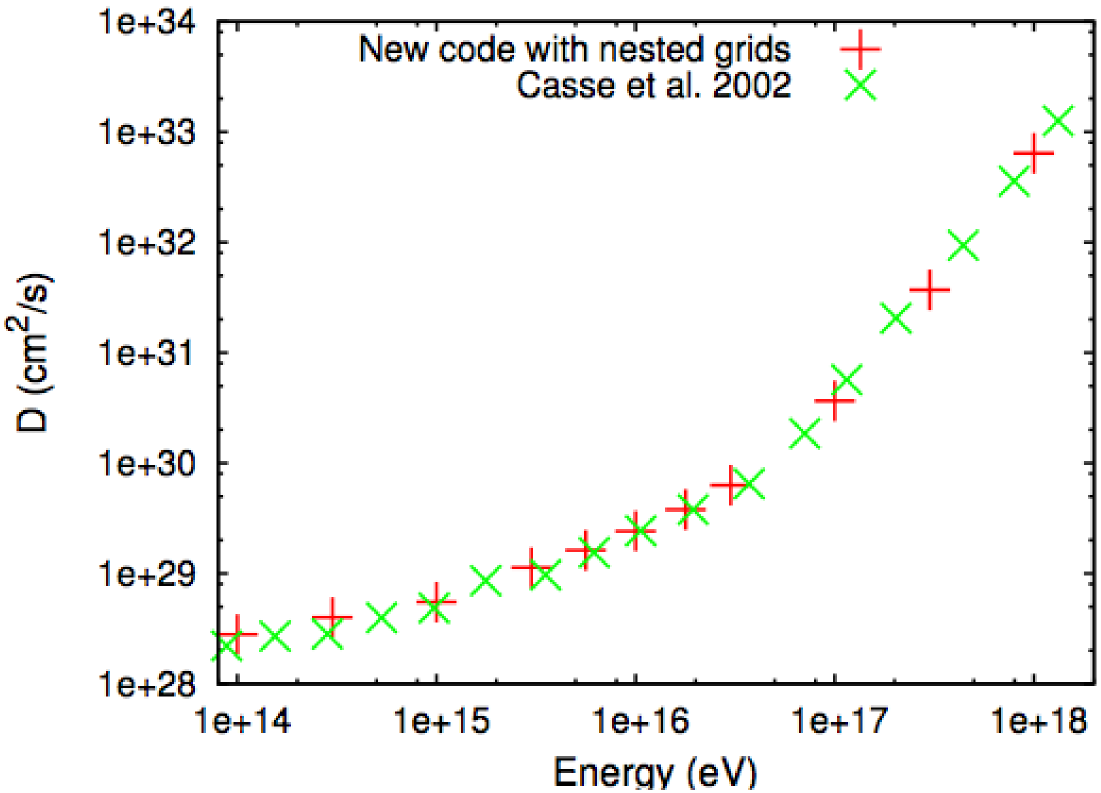
- For Pshirkov et al only deflection map in arXiv:1304.3217

$$B_{\rm rms}(r,z) = B(r)\exp\left(-\frac{|z|}{z_0}\right)$$

$B(r) = B_0 = 6\ \mu G$ $z_0 = 1.8$ kpc

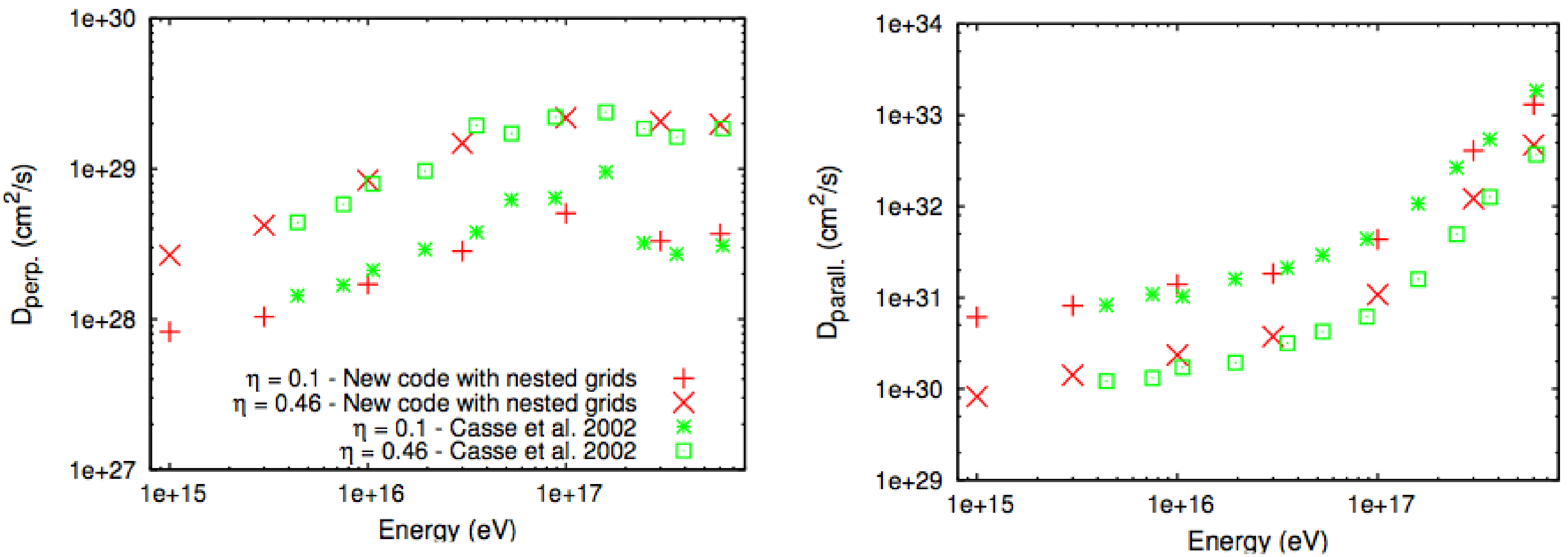
Thanks to G.Farrar and P.Tinyakov for discussion

Only turbulent diffusion



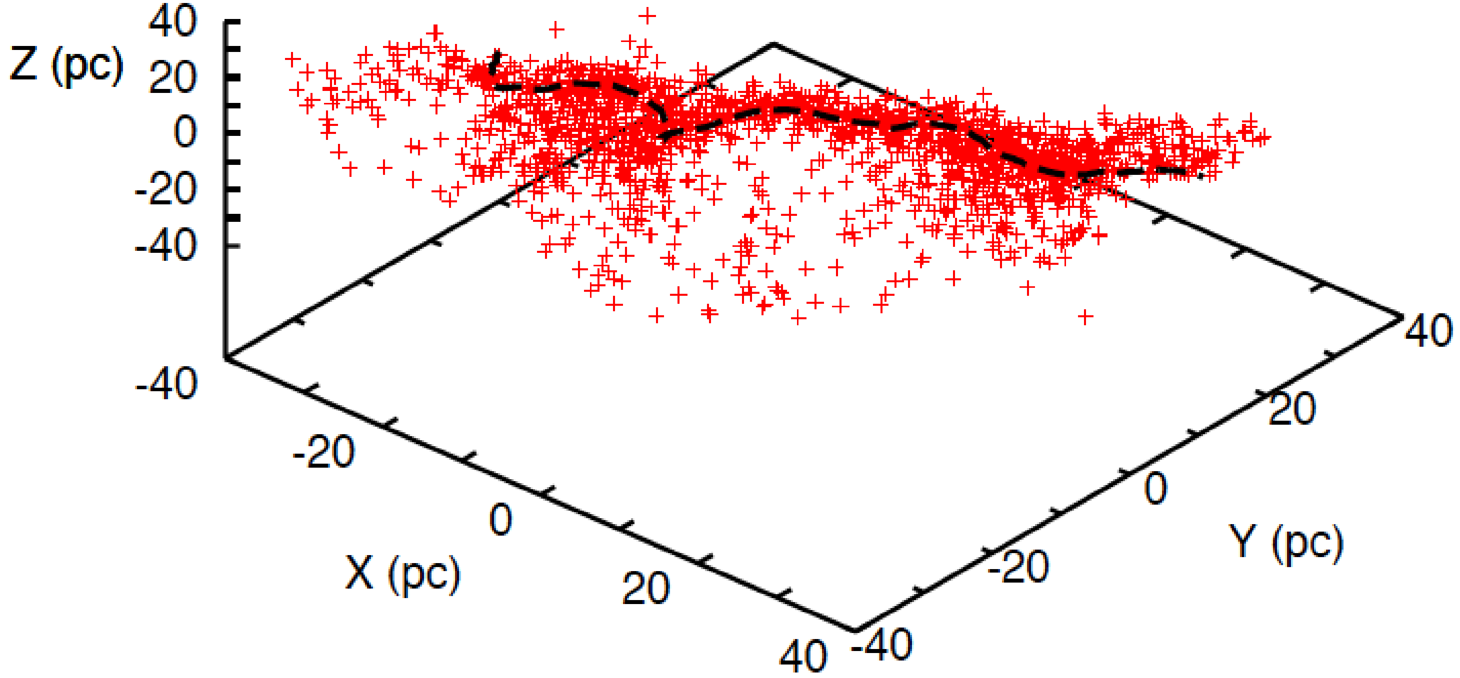
G.Giacinti et al, arXiv:1112.5599

Regular and turbulent diffusion

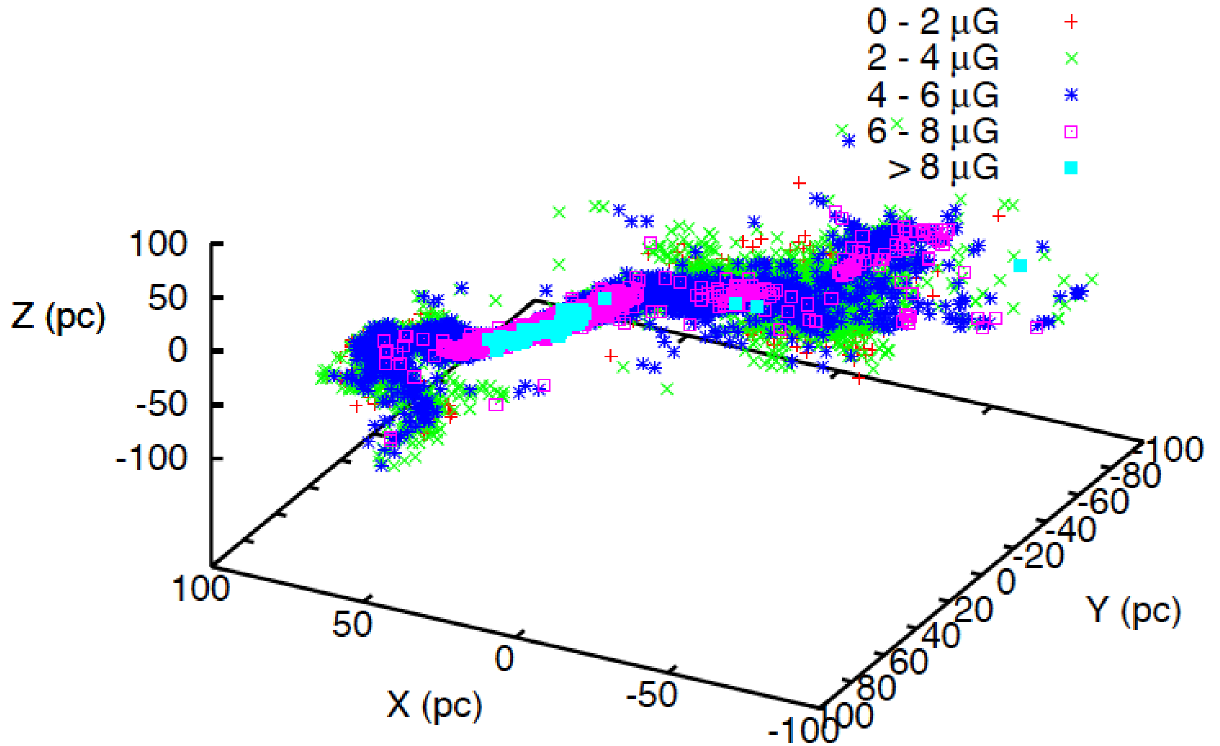


Cosmic ray diffusion from single source

3D spatial distribution of 1PeV protons 500 yr after escape from source



3D spatial distribution of 1PeV protons 1000 yr after escape from source



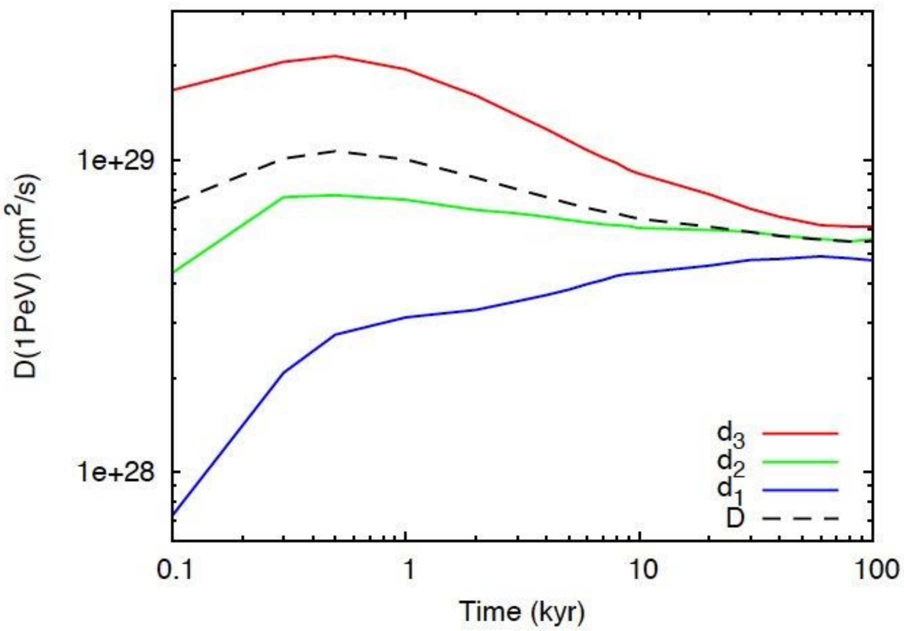
Eigenvalues of diffusion tensor

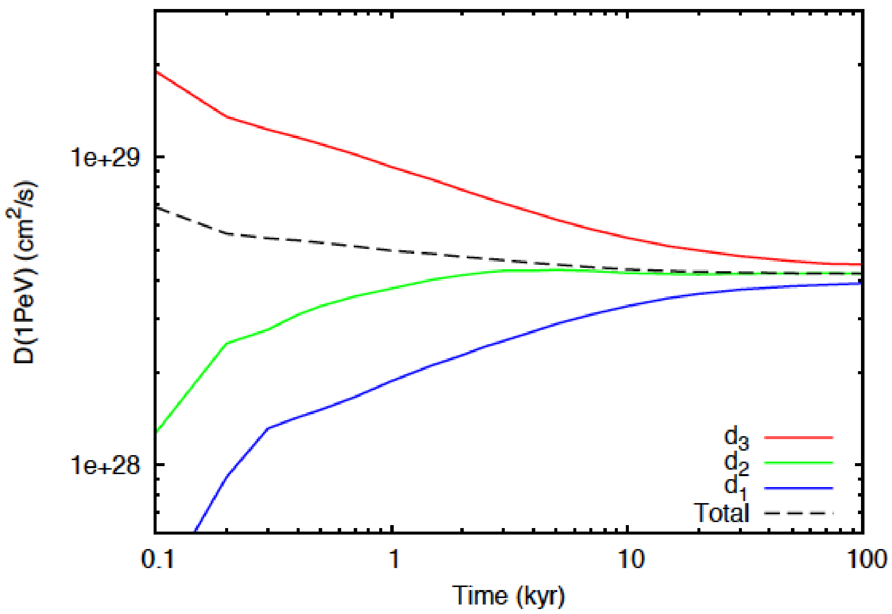
- Diffusion tensor $D_{ij}^{(b)} = \frac{1}{2Nt}\sum_{a=1}^{N} x_i^{(a)} x_j^{(a)}$

  3 eigenvalues $d_1^{(b)} < d_2^{(b)} < d_3^{(b)}$

  Average only after diaganalization $d_i = \frac{1}{M}\sum_{b=1}^{M} d_i^{(b)}$

Evolution of eigenvalues of diffusion tensor at 1 PeV





Kolmogorov case Kraichnen case

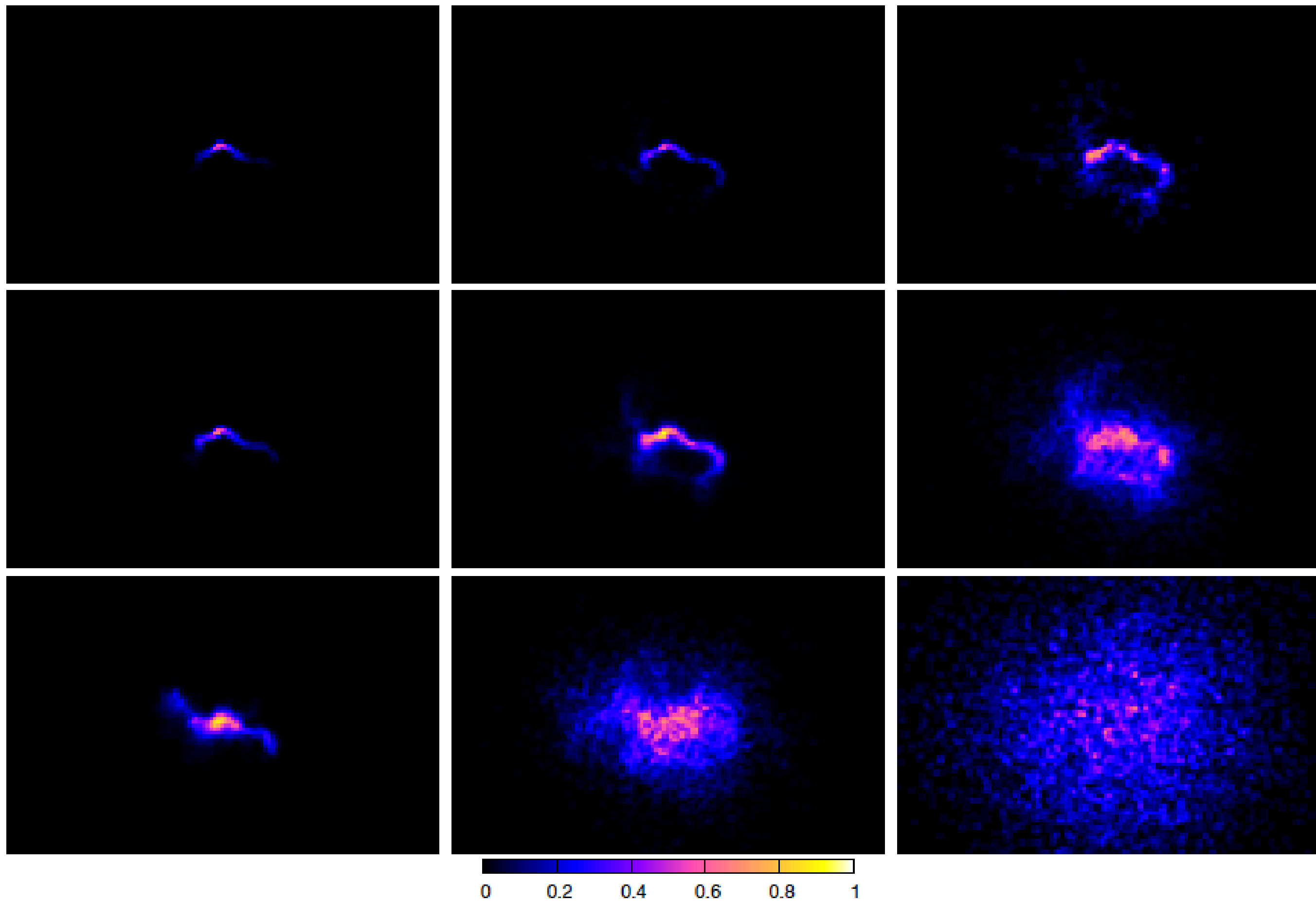
G.Giacinti, M.Kachelriess and D.S., PRL, **arXiv:1204.1271**

Diffusion of protons from single source

100 TeV

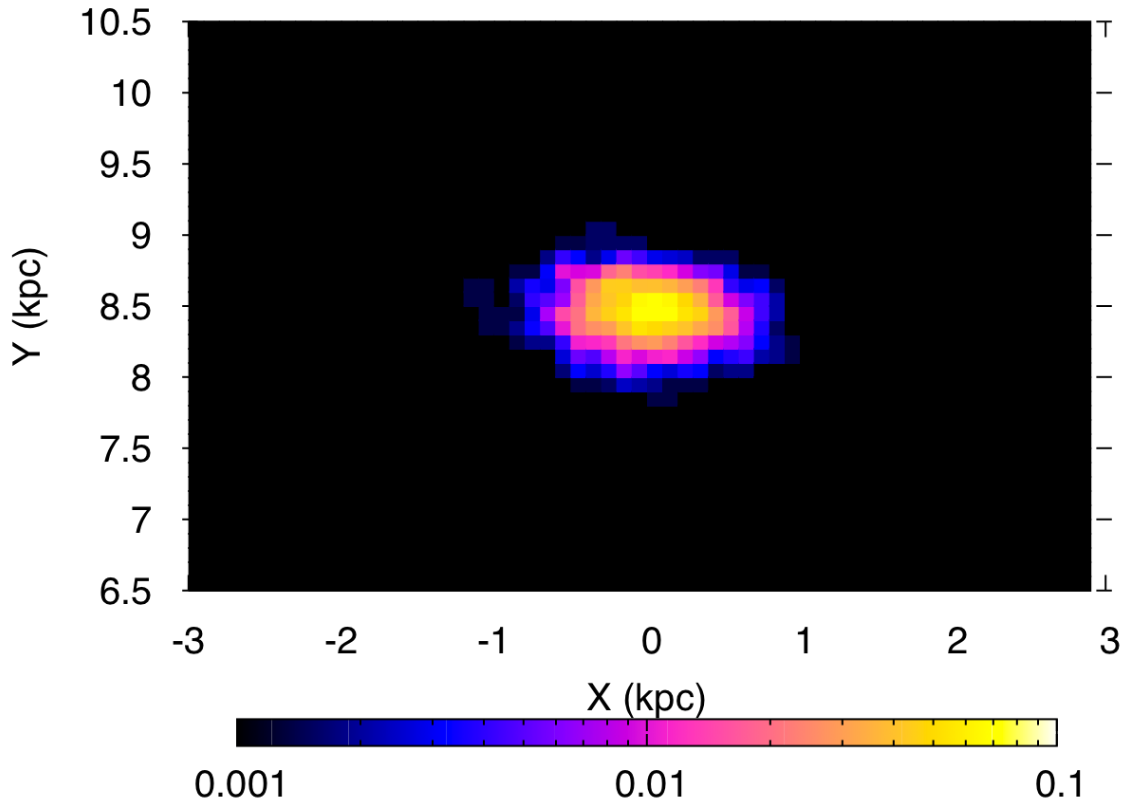
1 PeV

10 PeV

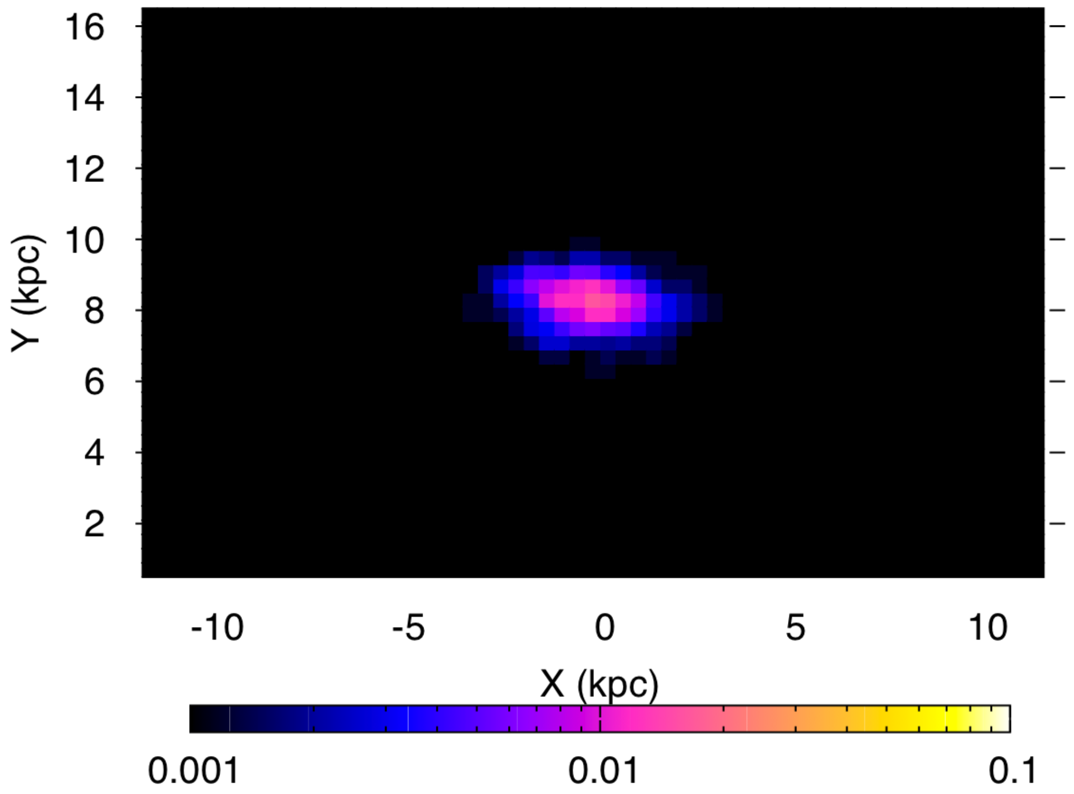


500 yr 2 kyr 7 kyr

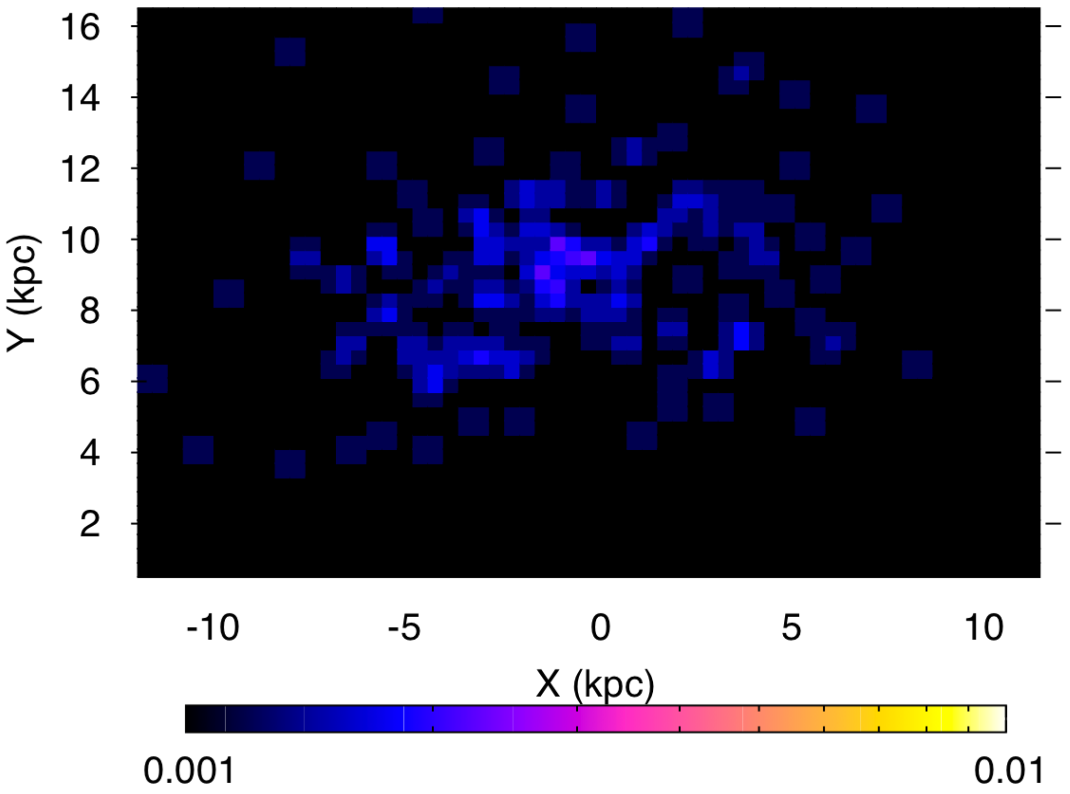
40 PeV protons from single source: 10 kyr



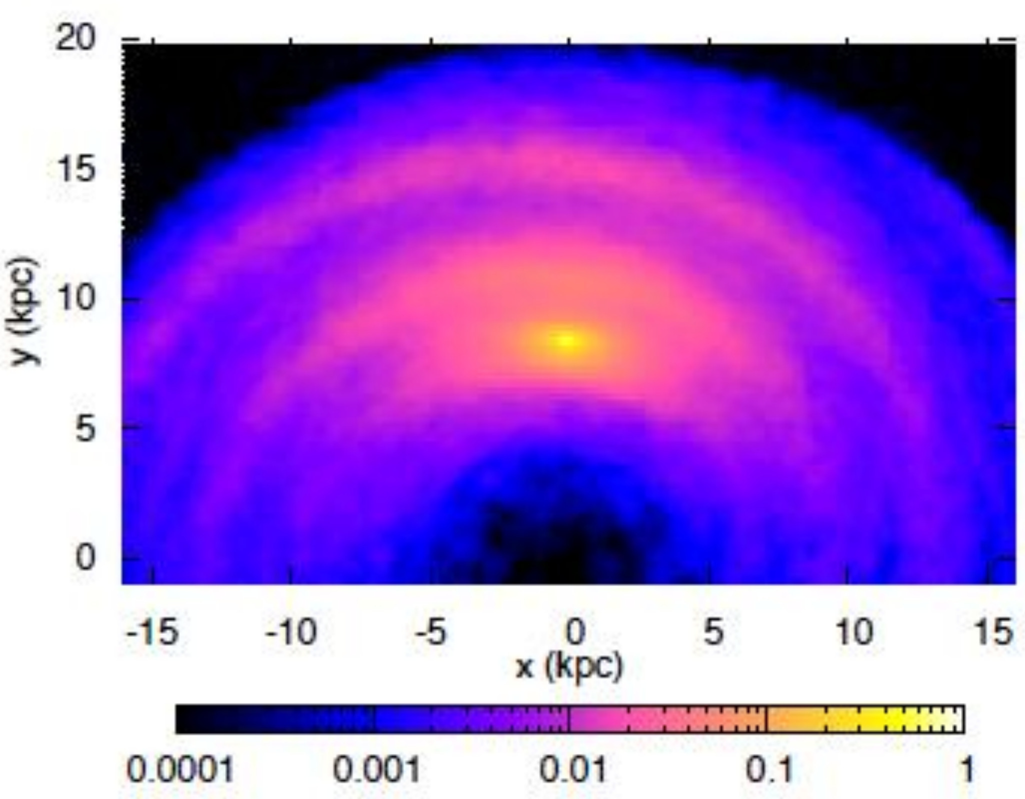
40 PeV protons from single source: 100 kyr



40 PeV protons from single source: 1 Myr



40 PeV protons from single source: all times (up to several Myr)



G.Giacinti et al, **arXiv:1112.5599**

Knee in the cosmic ray spectrum

ESCAPE MODEL:

- Idea: V. L. Ginzburg and S. I. Syrovatskii, *1962-1964; small angle diffusion approximation*
- Developement: V. S. Ptuskin et al., Astron. Astrophys. 268, 726 (1993); J. Candia, E. Roulet and L. N. Epele, JHEP 0212, 033 (2002); J. Candia, S. Mollerach and E. Roulet, JCAP 0305, 003 (2003). *Hall diffusion approximation*

Cosmic Ray Knee

.

- change of interactions at multi-TeV energies: excluded by LHC
- maximal energy of dominant CR sources – Hillas model
- knee at $R_L(E/Z) \simeq l_{\rm coh}$:

$\Rightarrow$ change in diffusion from $D(E) \sim E^{1/3}$ to

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

Cosmic Ray Knee

- change of interactions at multi-TeV energies: excluded by LHC
- maximal energy of dominant CR sources – Hillas model
- knee at $R_L(E/Z) \simeq l_{\rm coh}$:

$\Rightarrow$ change in diffusion from $D(E) \sim E^{1/3}$ to

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

our approach:

  - use model for Galactic magnetic field
  - calculate trajectories $x(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.

Cosmic Ray Knee

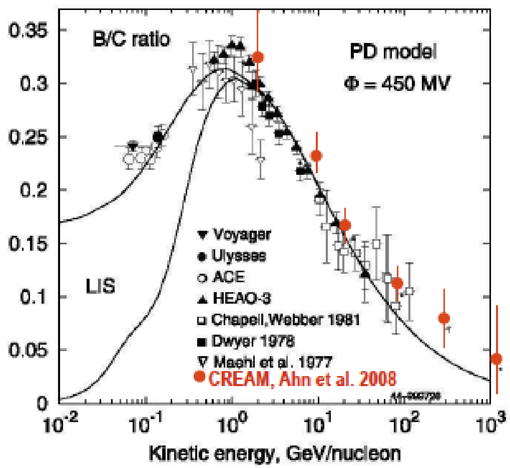
- $l_{\rm coh}$ and regular field $\boldsymbol{B}(\boldsymbol{x})$ fixed from observations
- determine magnitude of random $\boldsymbol{B}_{\rm rms}(\boldsymbol{x})$ from grammage $X(E)$

B to C ratio

B/C ratio in three models of cosmic ray propagation

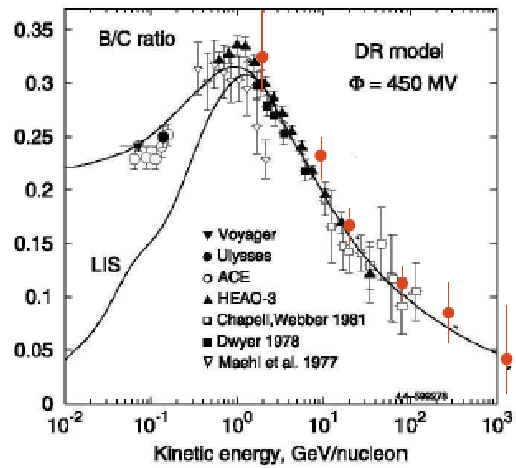
plain diffusion, "unphysical" break

$D \sim (p/Z)^{0.6}$
$Q_{cr} \sim (p/Z)^{-2.1}$



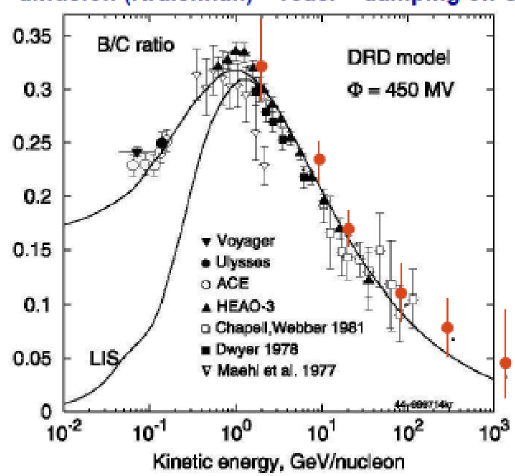
diffusion (Kolmogorov) + reacceleration

$D \sim (p/Z)^{0.3}$
$Q_{cr} \sim (p/Z)^{-2.4}$



diffusion (Kraichnan) + reac. + damping on CR

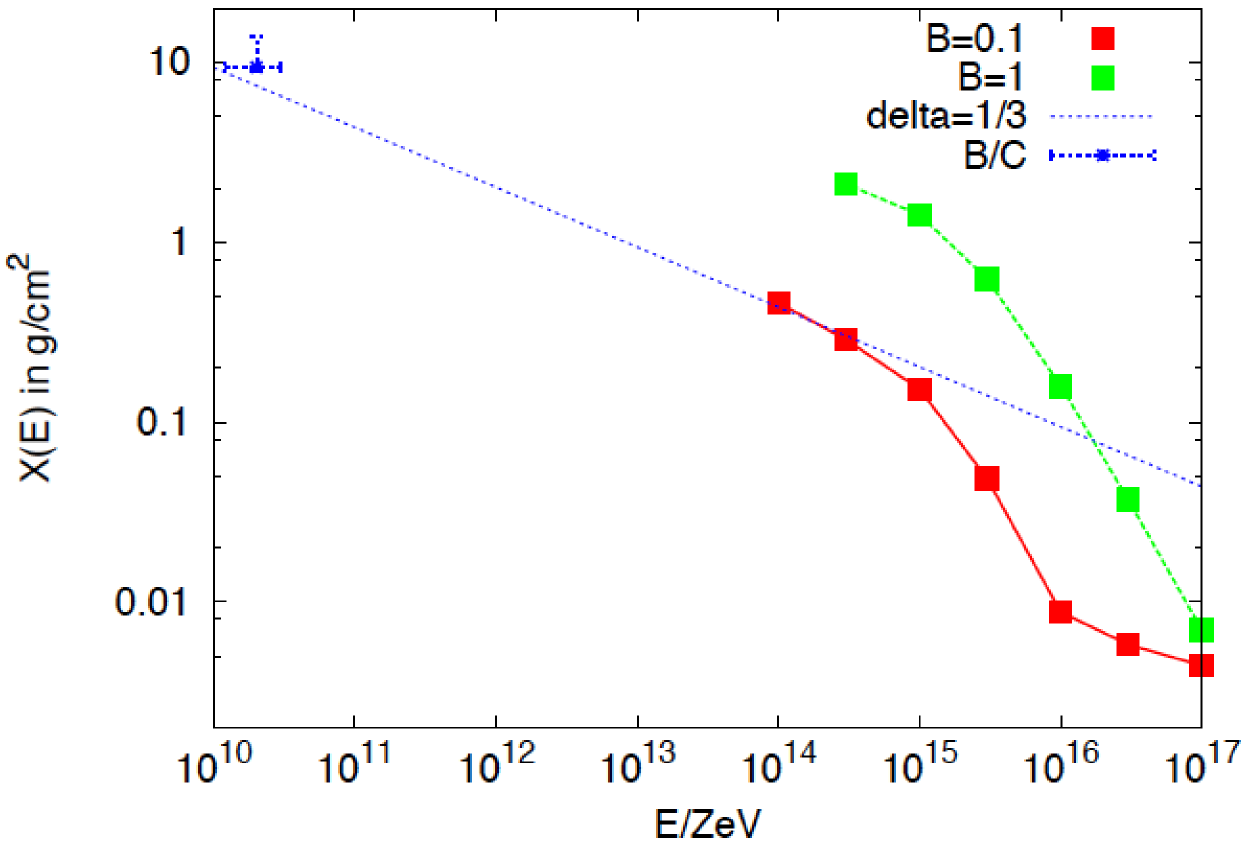
$D \sim (p/Z)^{0.5}$
$Q_{cr} \sim (p/Z)^{-2.2}$



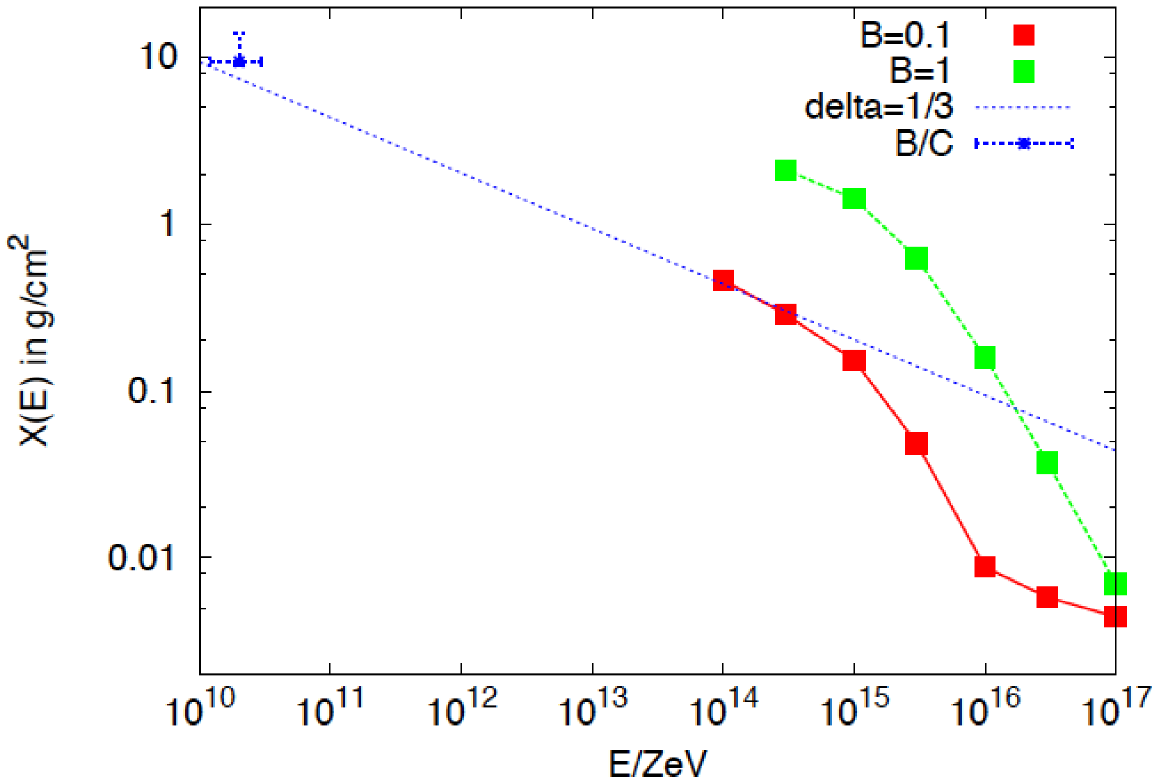
derived exponent of source spectrum at high energies 2.1...2.2 or 2.4

Cosmic Ray Knee

- $l_{\rm coh}$ and regular field $B(x)$ fixed from observations
- determine magnitude of random $B_{\rm rms}(x)$ from grammage $X(E)$



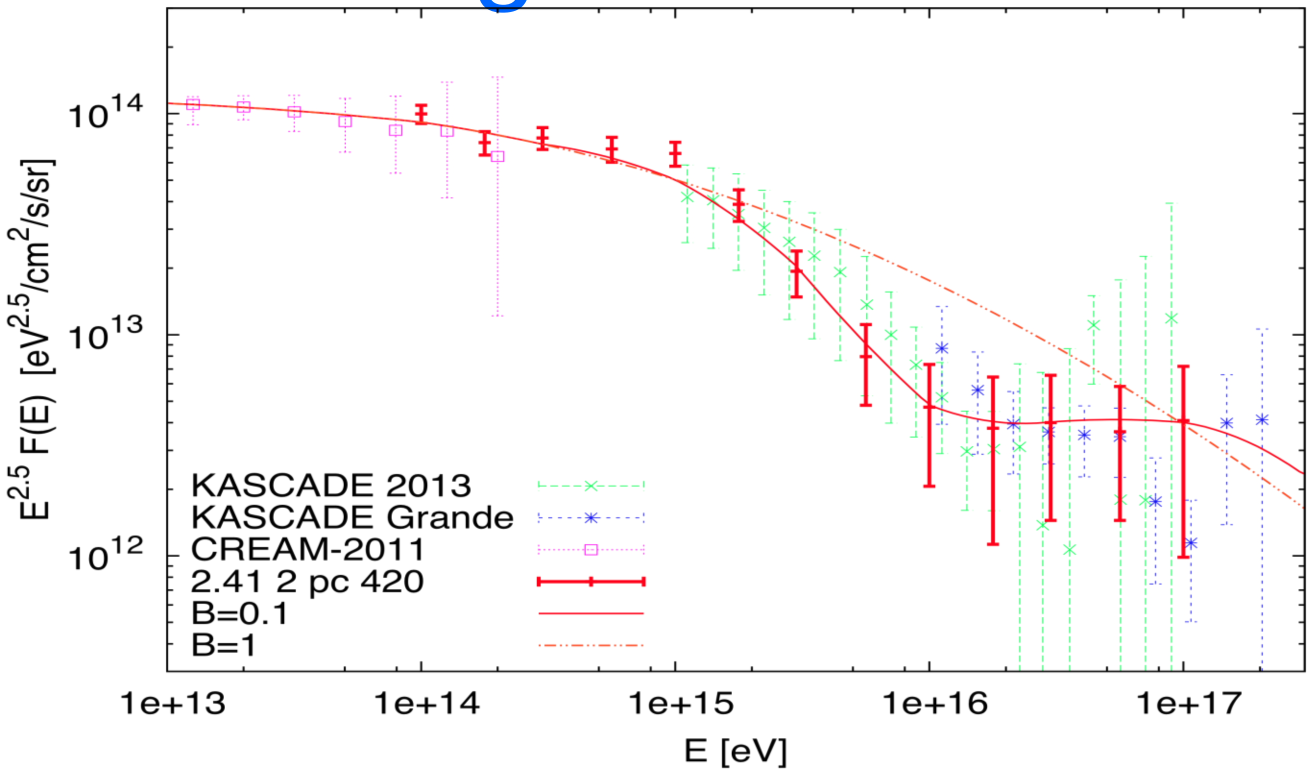
Cosmic Ray Knee



$\Rightarrow$ prefers weak random fields

$\Rightarrow$ fluxes $I_A(E)$ of all isotopes fixed by low-energy data

Escape model does not work with large turbulent field

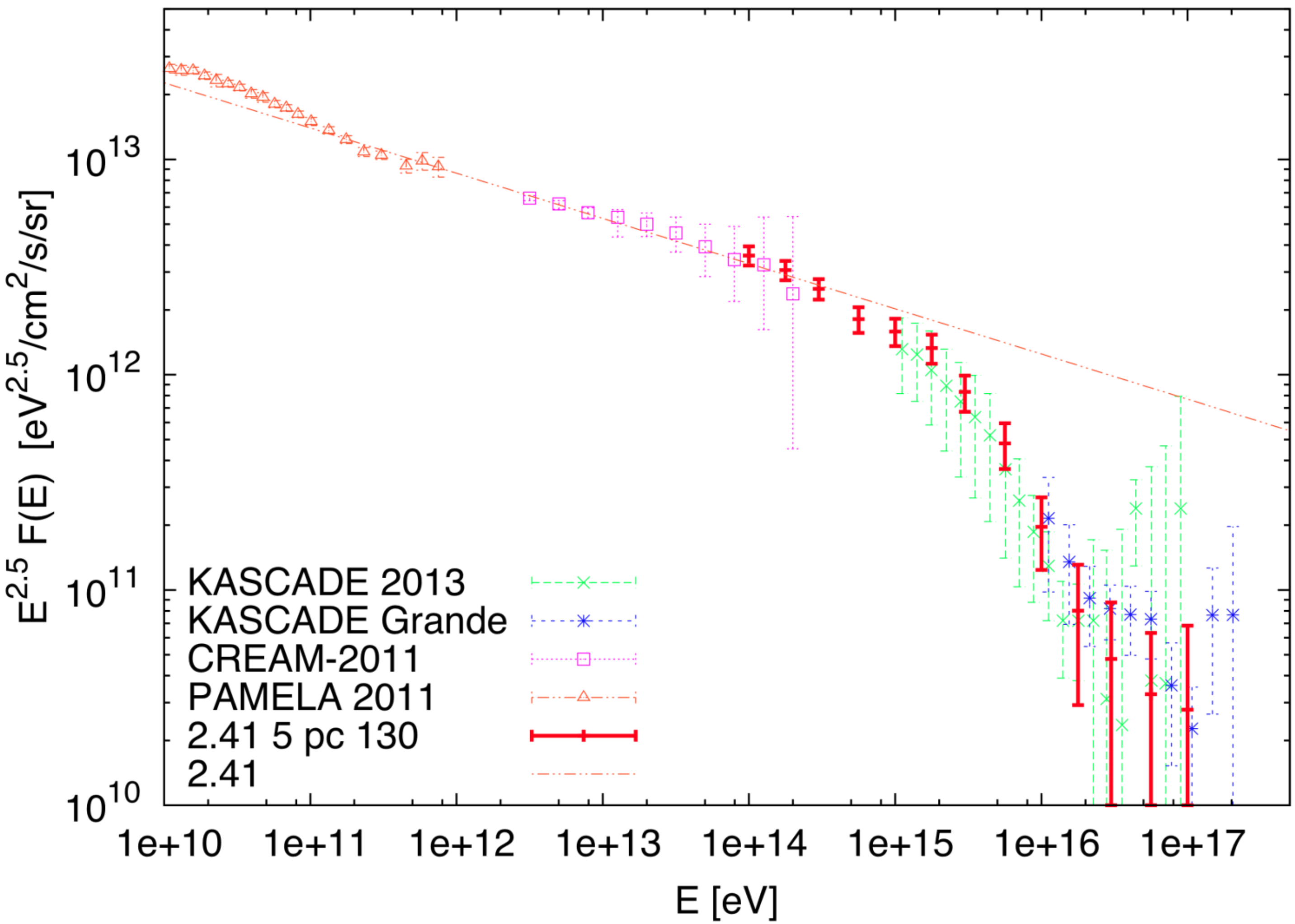


Magnetic field will be reduced by factor 5 in next generation models. Thanks to G.Farrar for discussion.

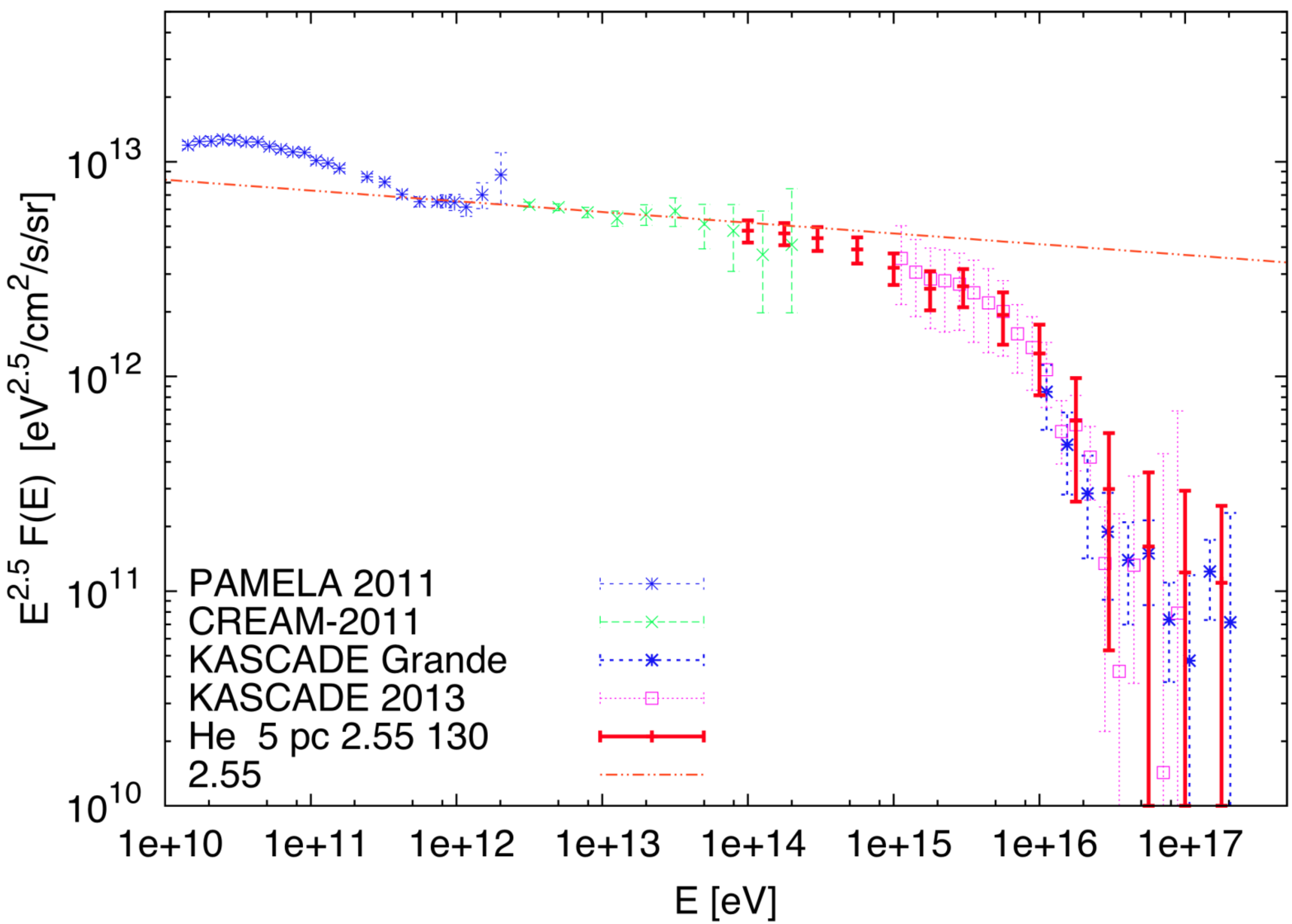
Model

- Sources with power law spectrum fitted to CREAM data at TeV region. $1/E^{\alpha}$
- Emax $=10^{17}$ eV $\alpha=2.4$ protons $\alpha=2.25$ nuclei
- Distributed as SN in Galaxy
- Turbulent field in disk with Kolmogorov turbulence and Lmax =10 pc or 25 pc
- GMF of G.Farrar with reduced turbulent field 5 or 10 times.

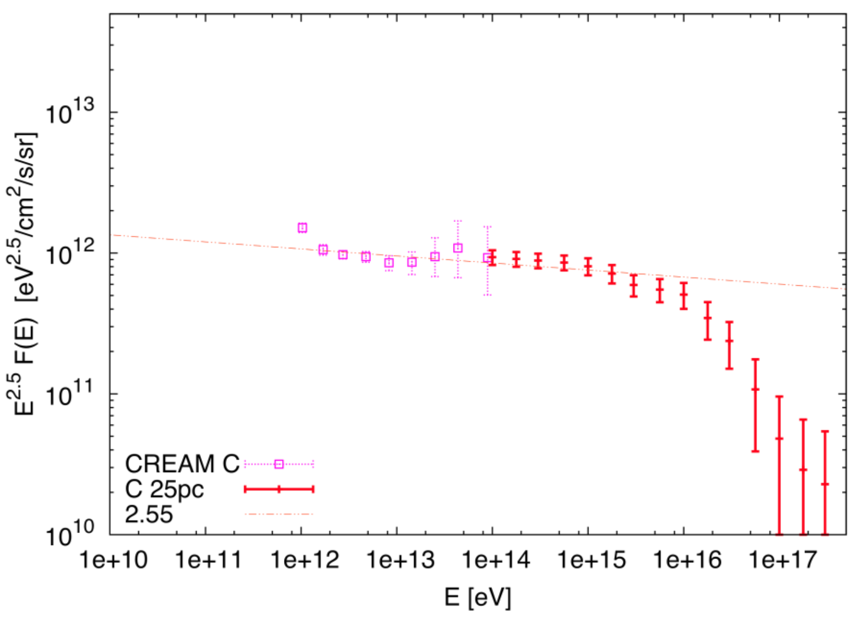
Cosmic Ray Knee: protons

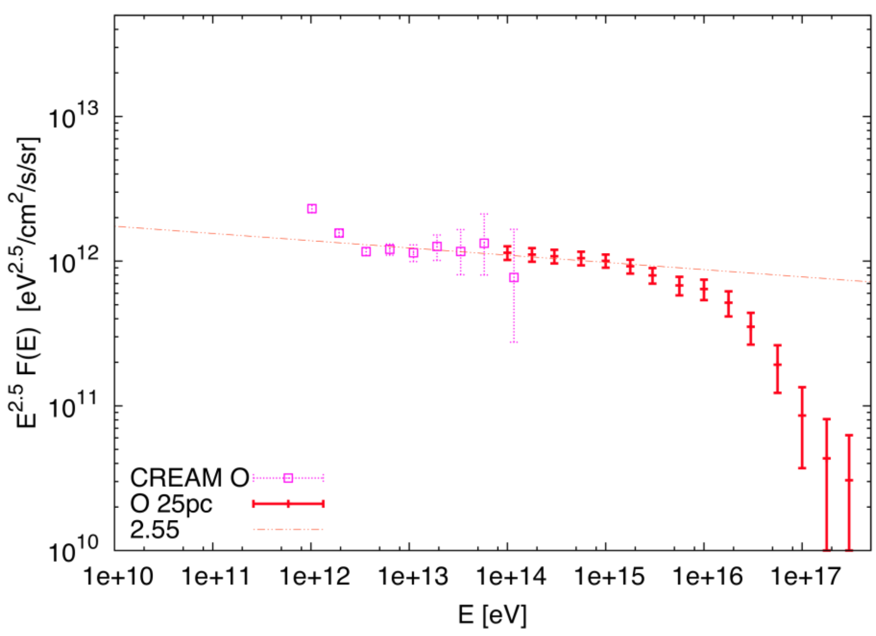


Cosmic Ray Knee: He

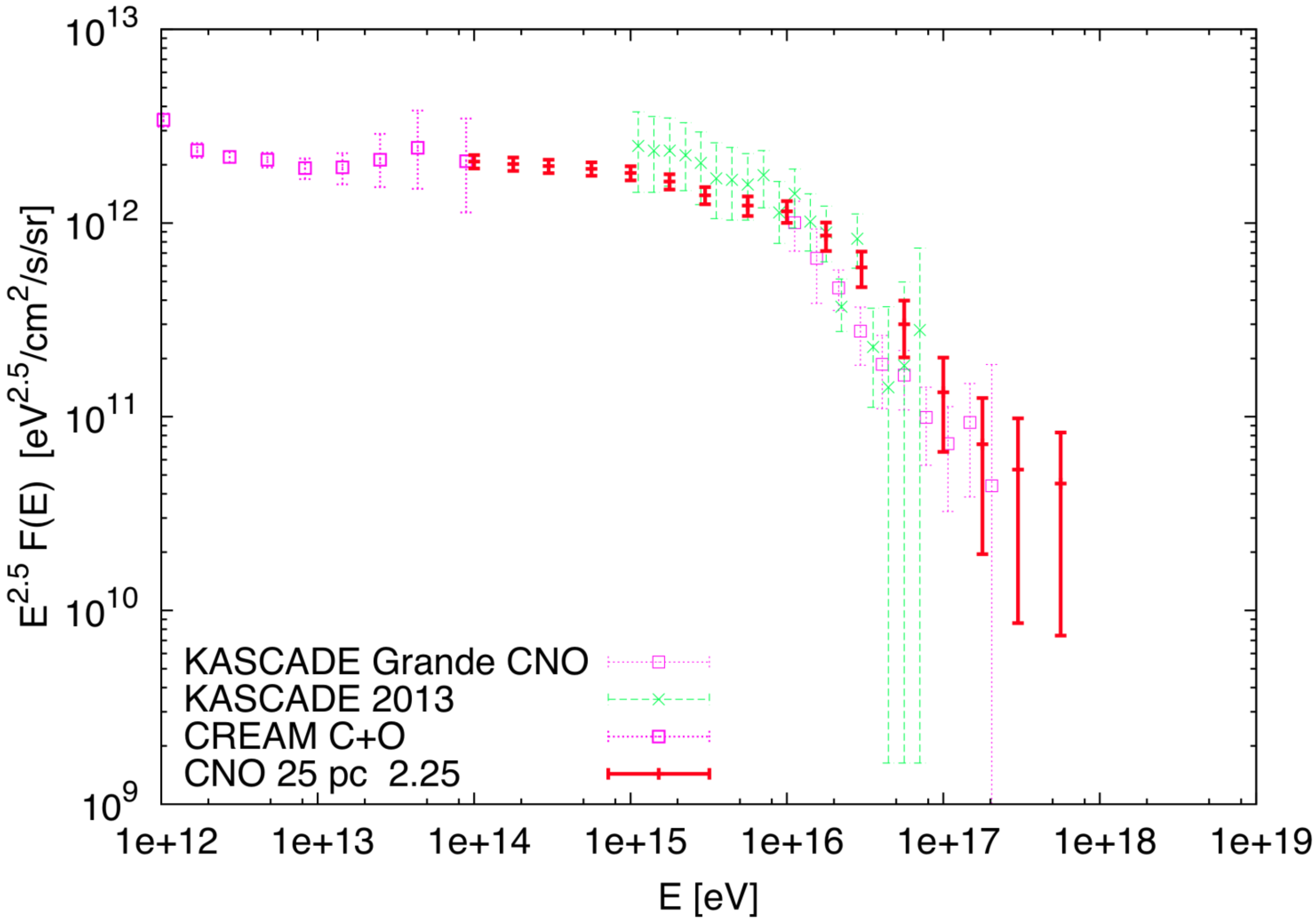


Cosmic Ray Knee: C and O

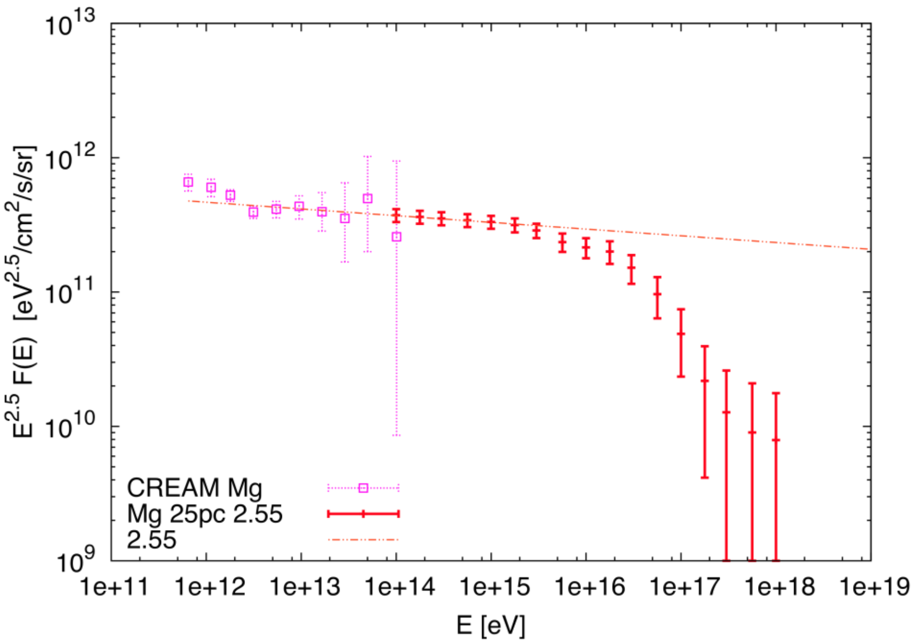


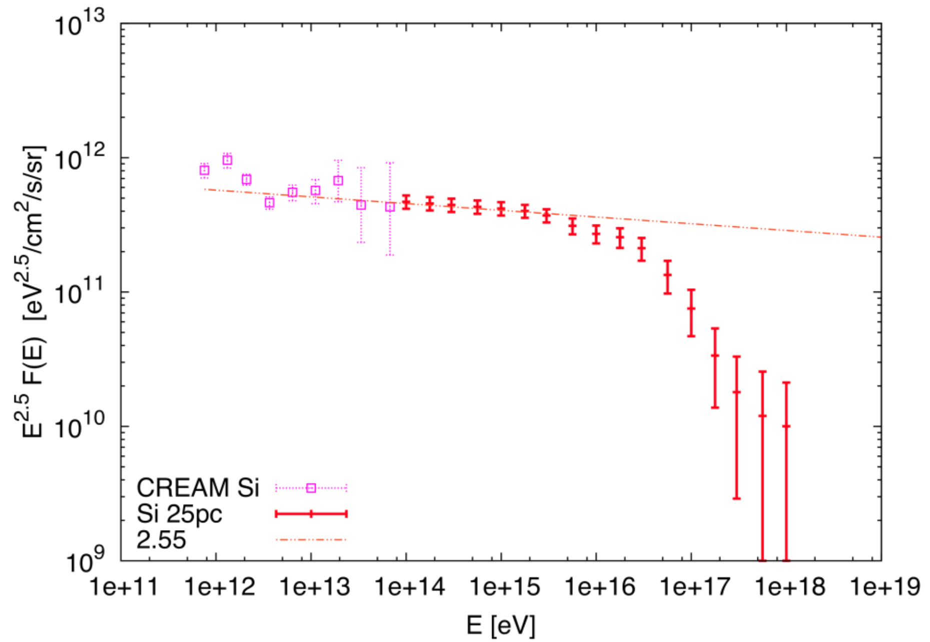


Cosmic Ray Knee: CNO

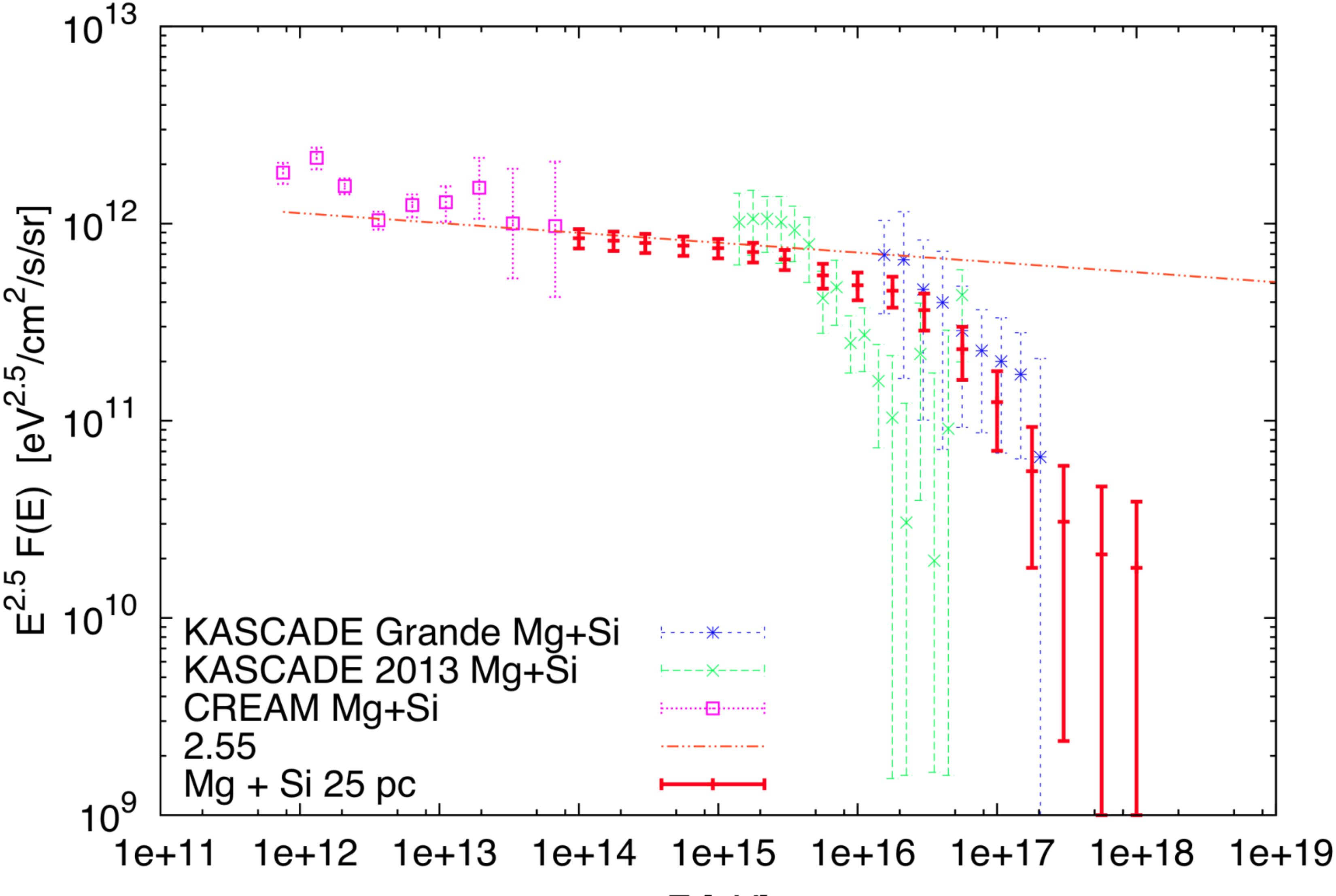


Cosmic Ray Knee: Mg and Si

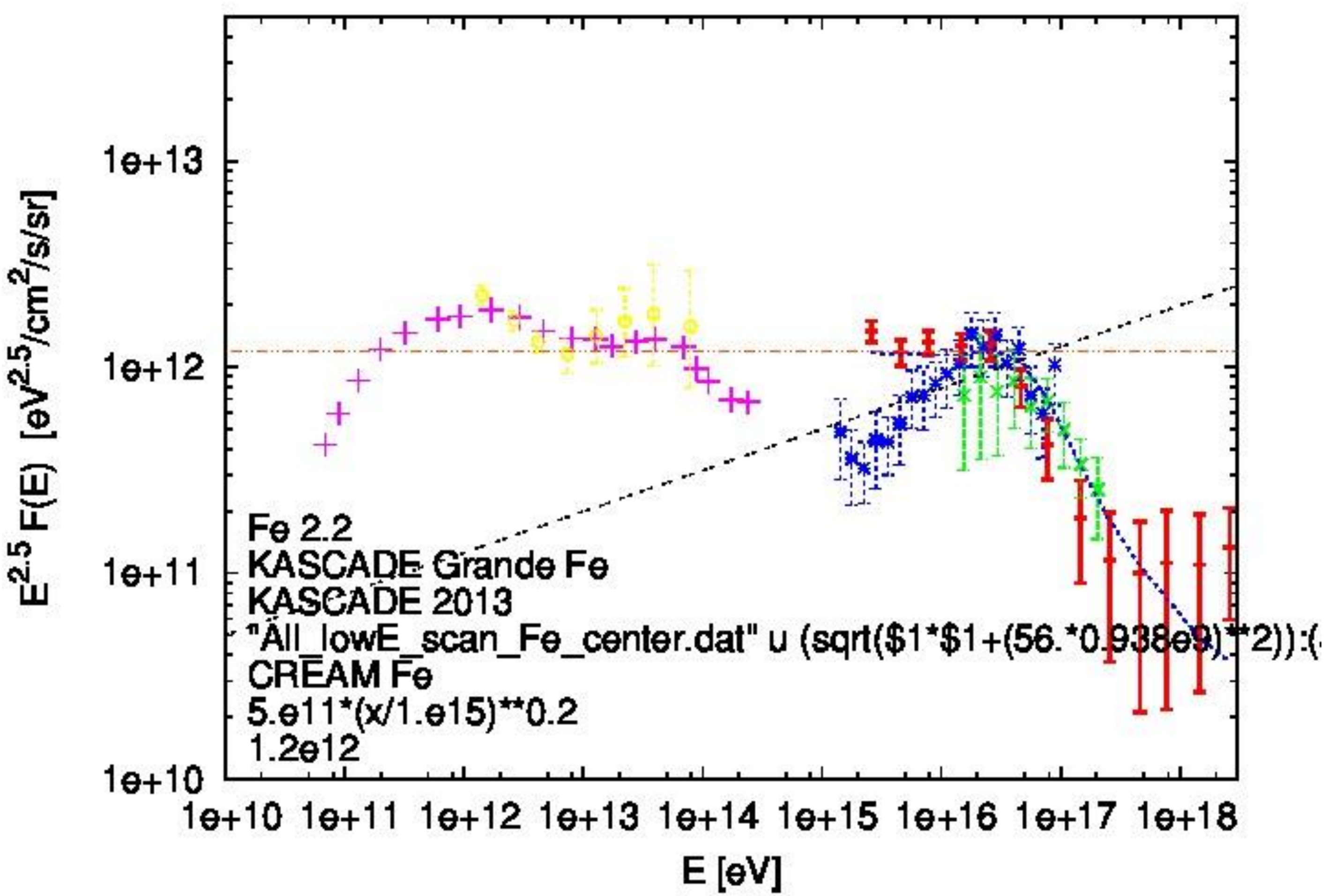




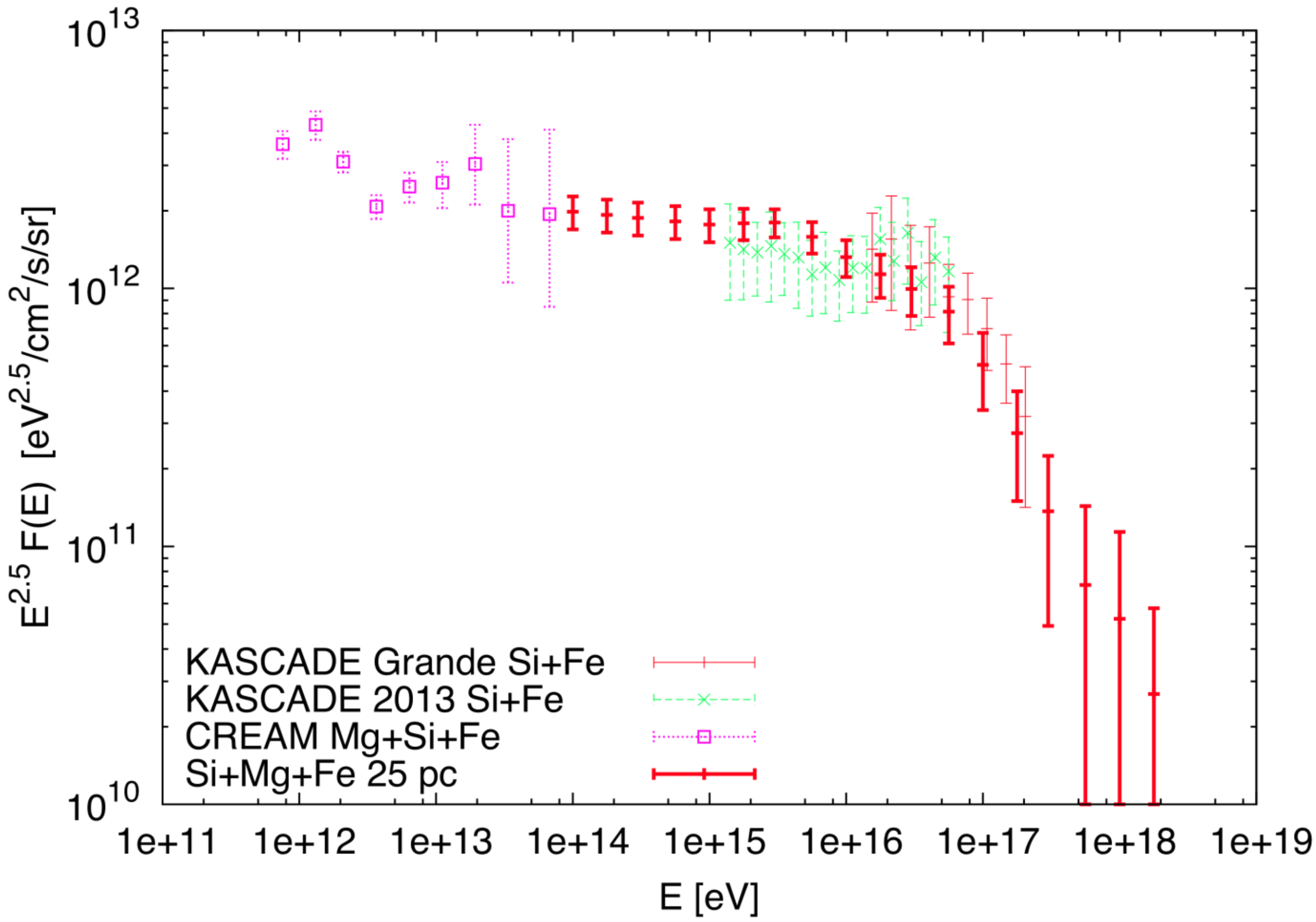
Cosmic Ray Knee: Mg+Si



Cosmic Ray Knee: Fe

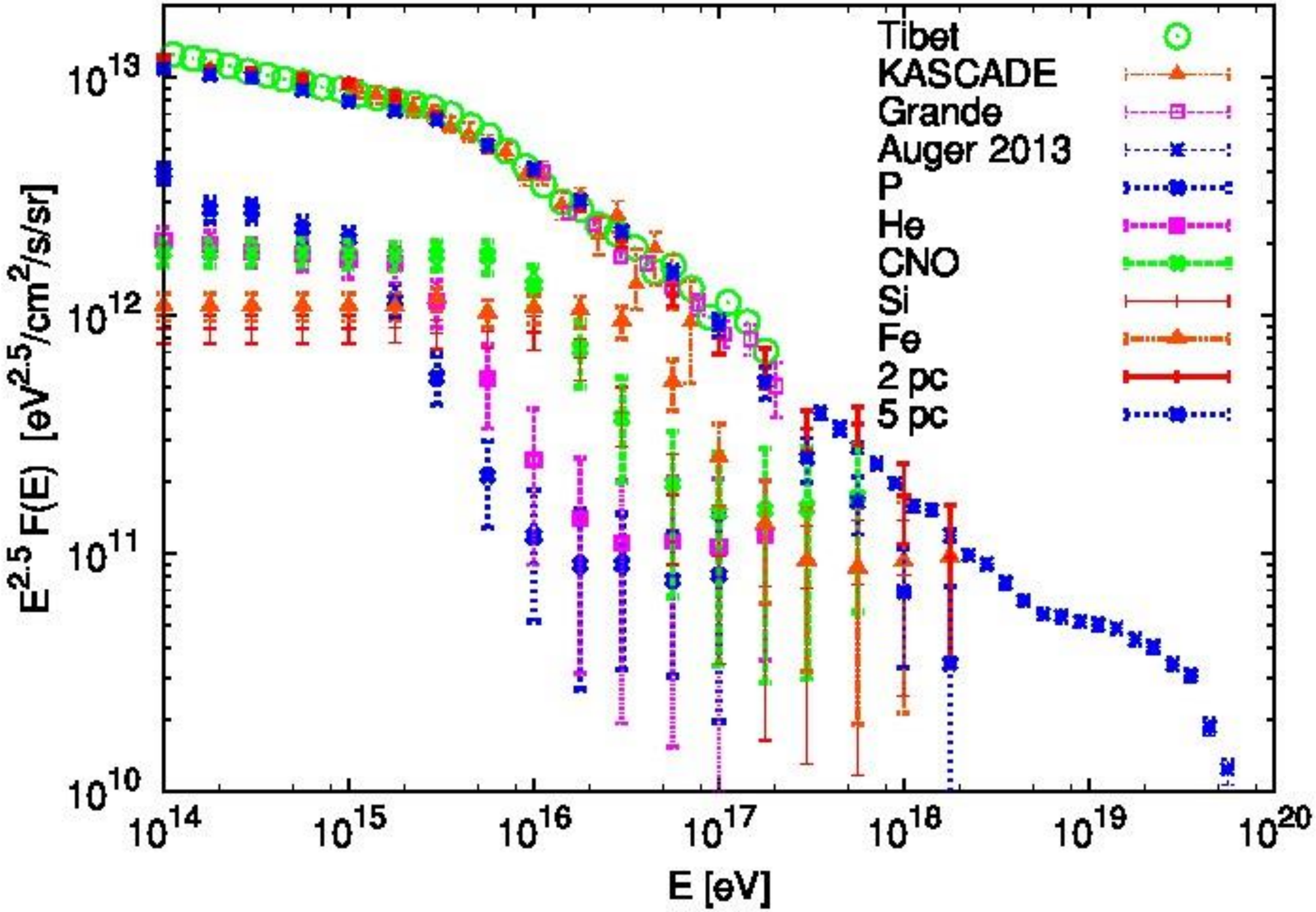


Cosmic Ray Knee: Mg+Si+Fe



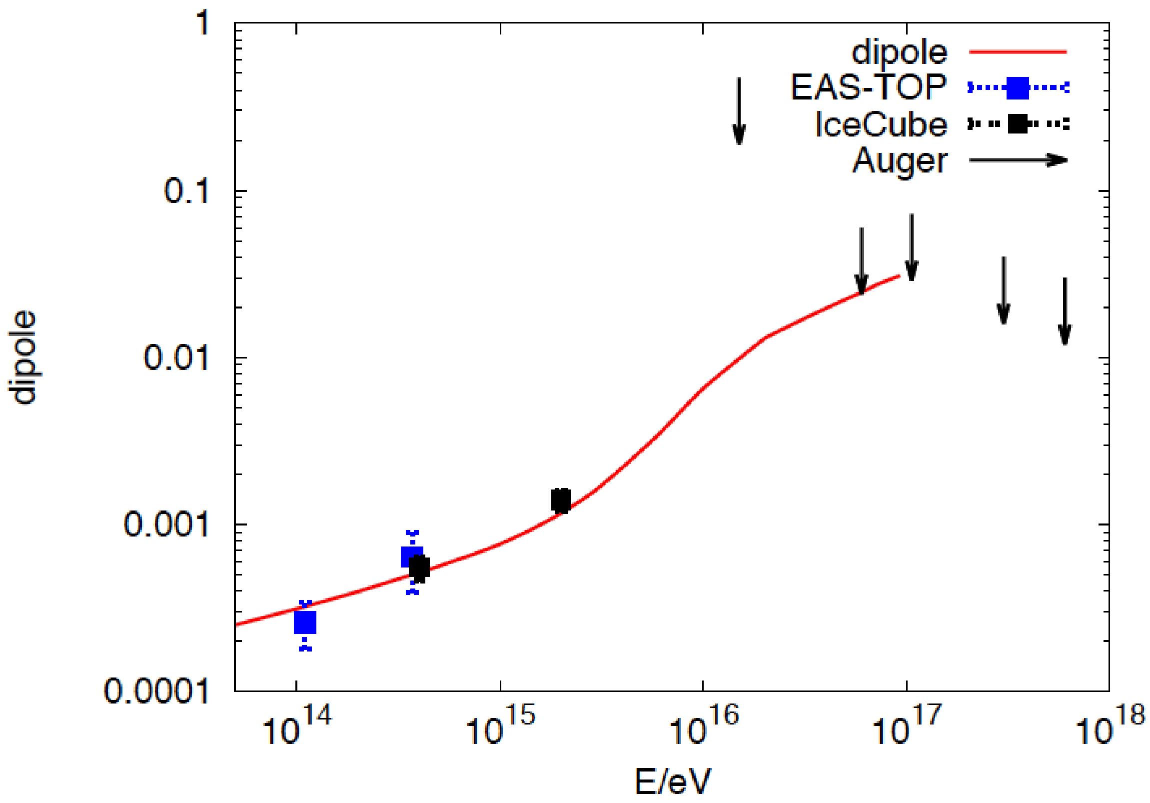
Thanks to Andreas Haungs for discussion

Cosmic Ray Knee: all particles



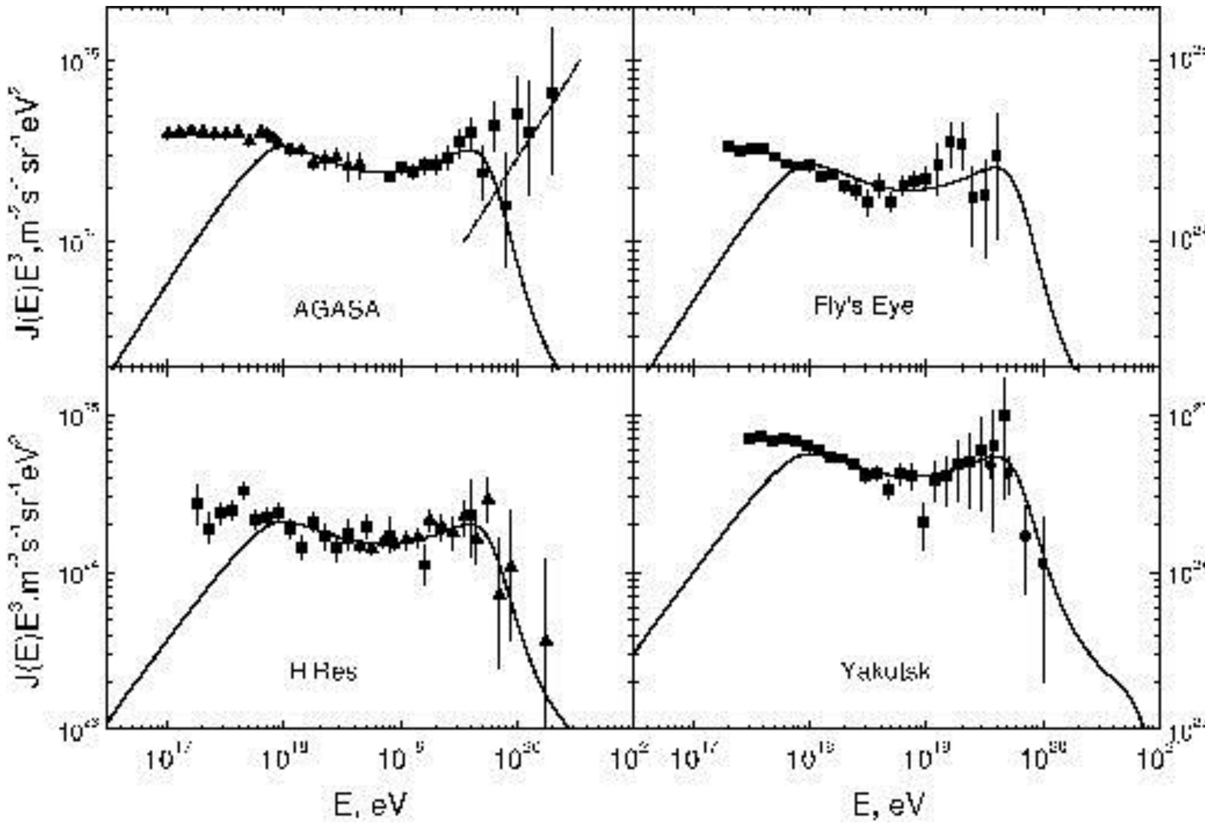
Anisotropy in arrival directions

Cosmic Ray Knee: anisotropy



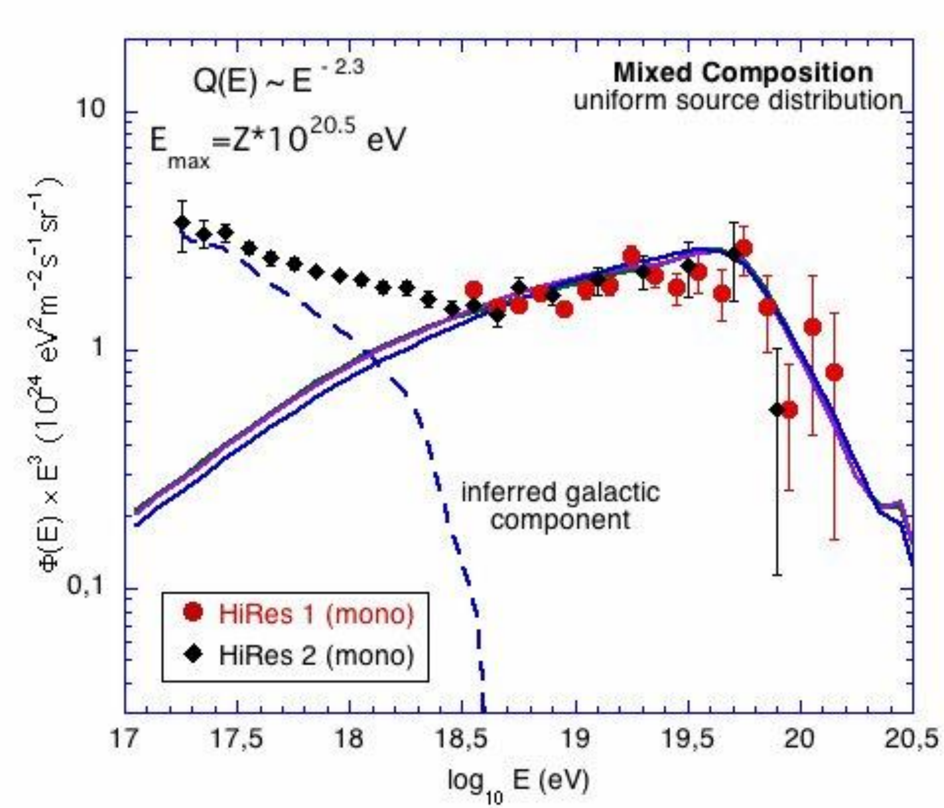
Transition from galactic to extragalactic cosmic rays

Dip model: Protons can fit UHECR data



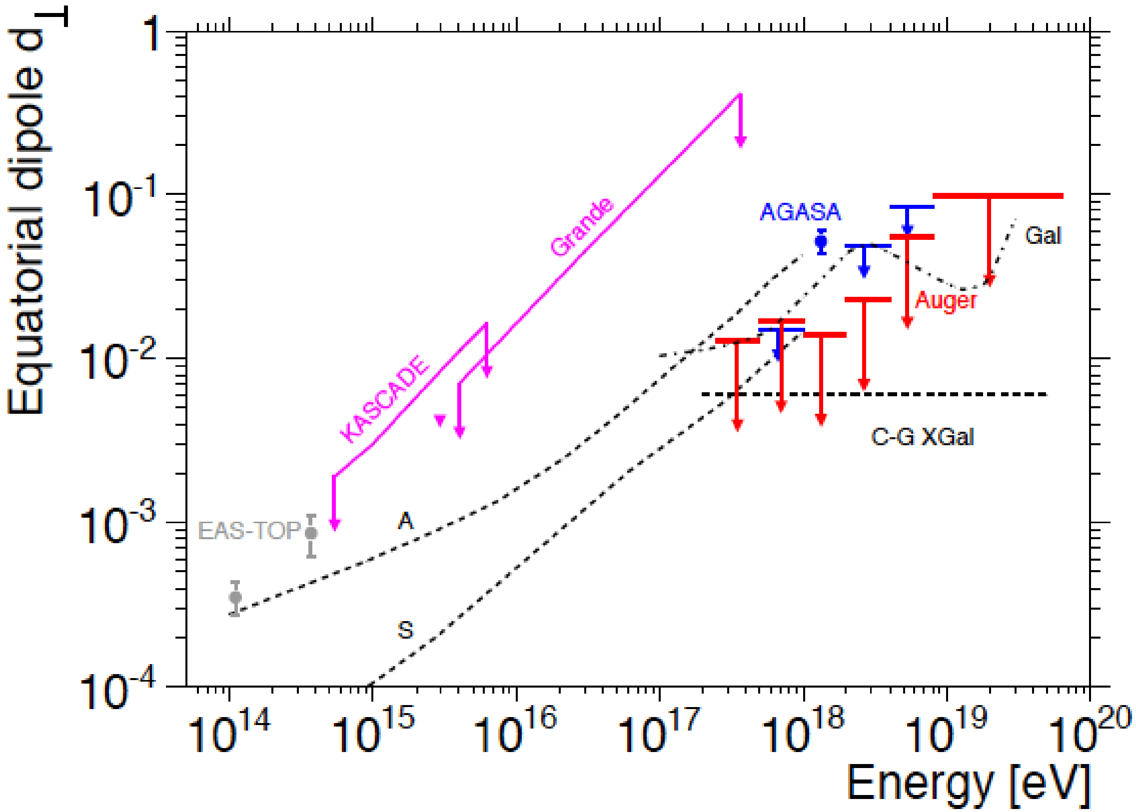
V.Berezinsky , astro-ph/0509069

Mixed composition model



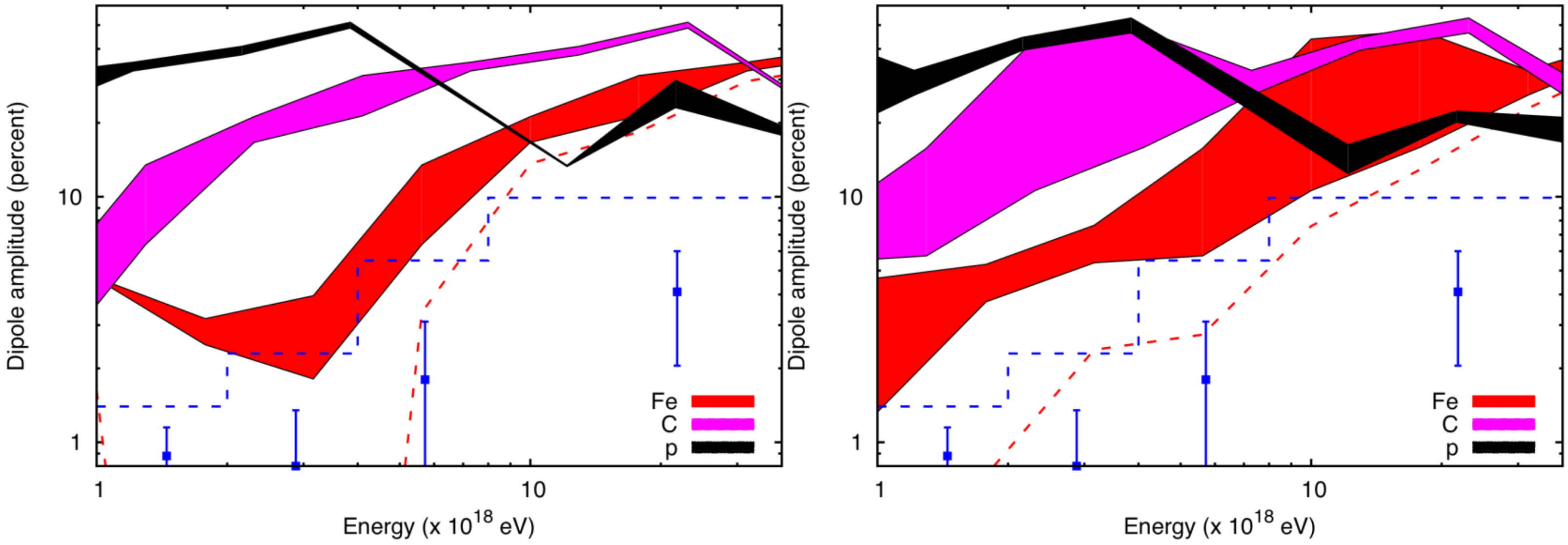
D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Anisotropy towards Galactic plane



Pierre Auger Collaboration, arXiv:1103.2721

Dependence on parameters

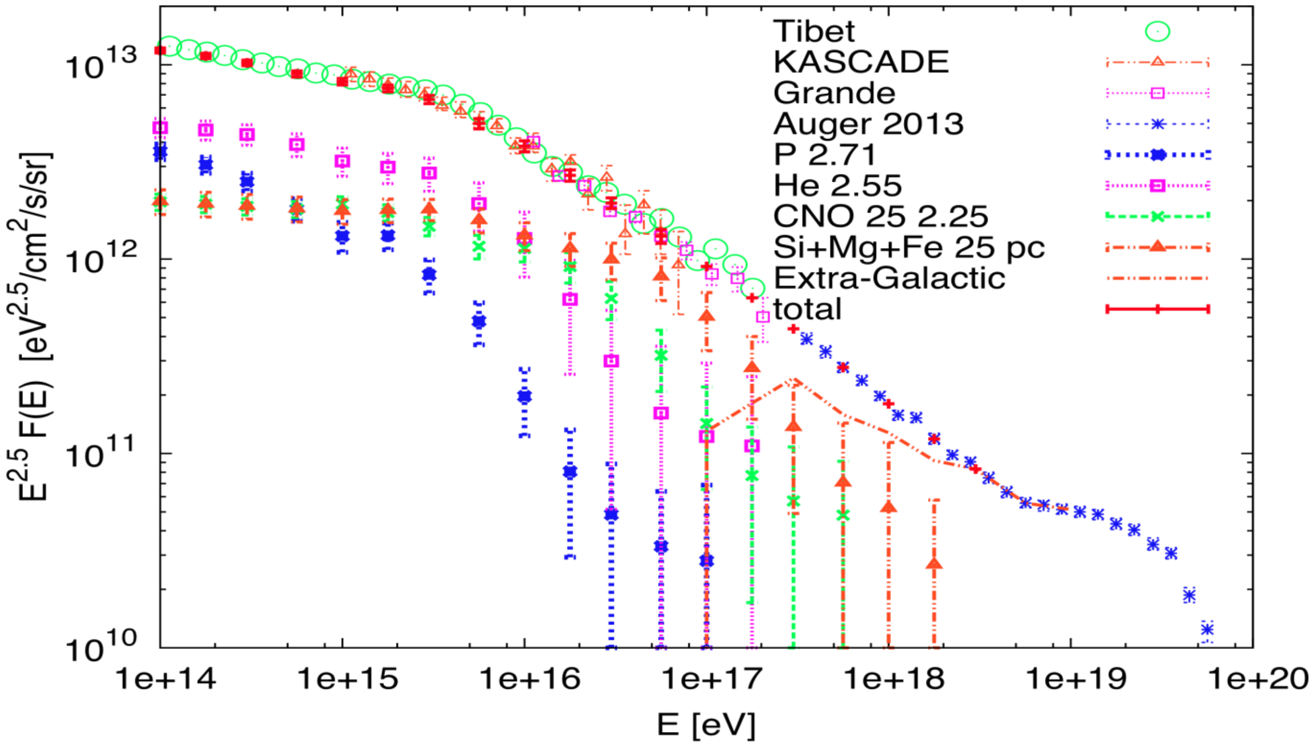


Turb. Magn. Field spectrum
Kolmogorov/Kraichnan

Lmax = 100-300 pc

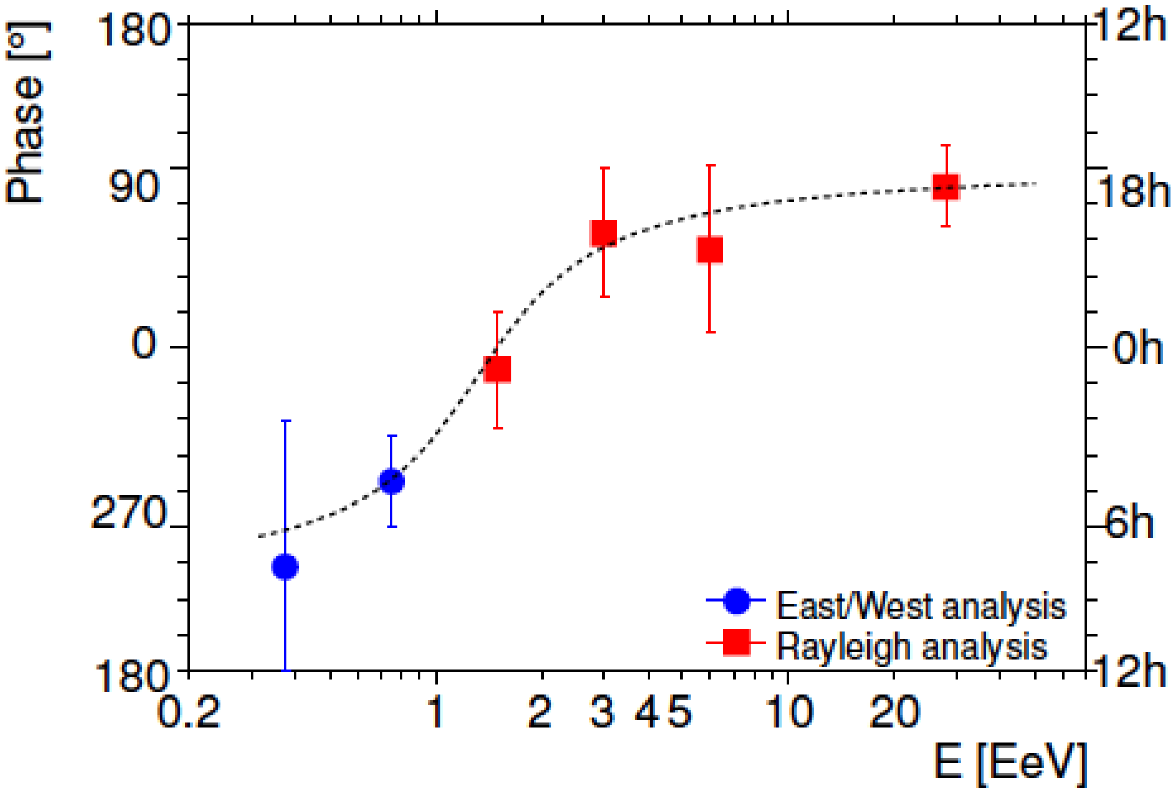
G.Giacinti et al, **arXiv:1112.5599**

Contribution of extra-Galactic sources



G.Giacinti et al, in preparation

Auger dipole phase consistent with escape model



Conclusions

- Present GMF models for turbulent field are in contradiction with B/C measurements, unless average turbulent GMF is 5-10 times smaller. Those changes are expected in next generation of GMF models.
- Knee for all individual nuclei can be explained by escape of cosmic rays from Galaxy.
- Existing limits on anisotropy forbid large (conservatively 10% or more) fraction of Galactic protons at 1 EeV. In combination with light nuclei domination at 1 EeV this mean that EG transition happened at energies below 1 EeV
- In escape model extragalactic cosmic rays dominate at energies around 1 EeV .