Signatures of a Local Cosmic Ray Source

Michael Kachelrieß

NTNU, Trondheim

with G.Giacinti, A.Nernov, V.Savchenko, D.Semikoz

Outline of the talk

1. Introduction: CR propagation
   - Diffusion approach
   - Trajectory approach
2. Escape model and anisotropic diffusion
   - Connecting $D(E)$ and GMF
   - Fluxes of groups of CR nuclei & knee
   - Consequences of anisotropic diffusion
3. A recent nearby SN?
   - Anisotropy
   - Antimatter fluxes
   - Nuclei fluxes and B/C
4. Conclusions

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   - use model for Galactic Magnetic Field
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  all fluctuations between $l_{\rm max}$ and $\sim 1/10 R_L$ have to be included
  $\Rightarrow$ makes trajectory approach computationally very expansive

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- slope of power spectrum $\mathcal{P}(k) \propto k^{-\alpha}$ determines energy dependence of diffusion coefficient for $B_{\rm reg} = 0$ as $D(E) \propto E^{\beta}$ as $\beta = 2 - \alpha$:

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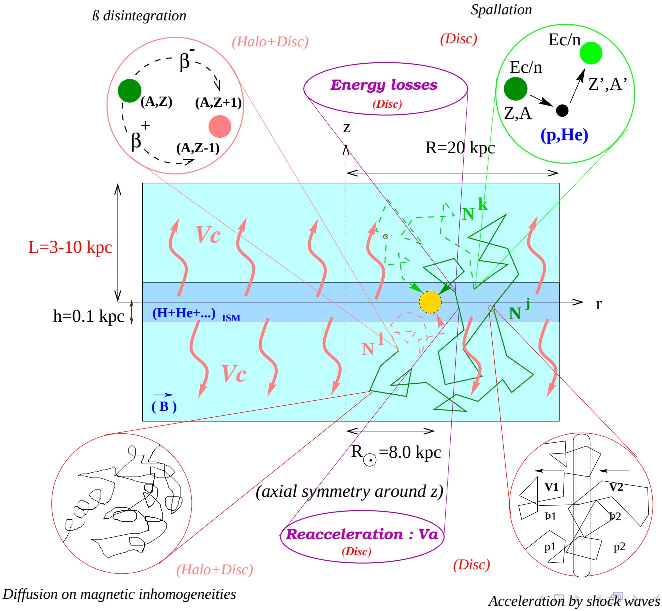
- injection spectrum $dN/dE \propto E^{-\delta}$ modified to $dN/dE \propto E^{-\delta-\beta}$
- anisotropy $\delta = -3D_{ij}\nabla_i \ln(n) \propto E^{\beta}$

Standard diffusion approach:



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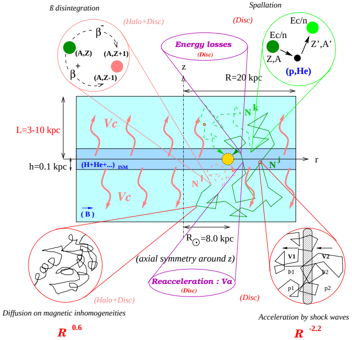

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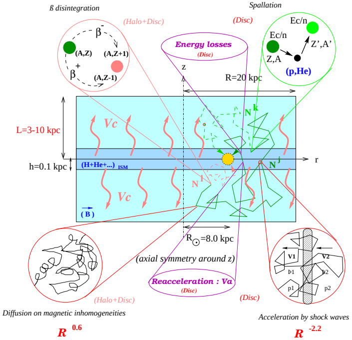

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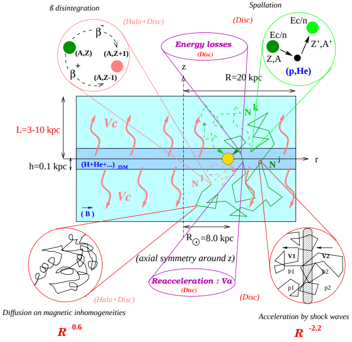

- often emphasis on interactions
- GMF enters only indirectly via $D(E)$ and L
- good approximation for many "average" quantities: $I_\gamma(E), \ldots$
- how important are deviations, local effects?

How to connect diffusion and GMF?

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- diffusion picture: $D(E)$ strongly degenerated with $I(E) \propto E^{\alpha}$ and L
- better observable: $\tau_{\rm esc}(E) = L^2/(2D) \propto 1/X$

Our approach:

- use model for Galactic magnetic field: Jansson-Farrar, Psirkhov et al.,. . .
- calculate trajectories $x(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.

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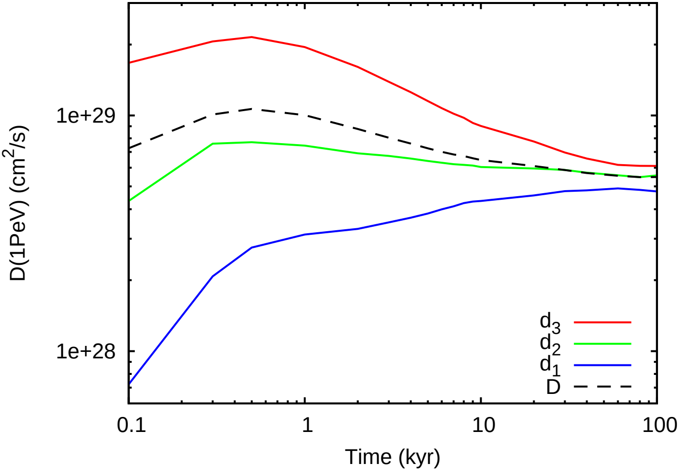
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.
- as preparation, let's calculate diffusion tensor in pure, isotropic turbulent magnetic field

Eigenvalues of $D_{ij} = \langle x_i x_j \rangle / (2t)$ $\quad E = 10^{15}$ eV, $B_{\rm rms} = 4\mu$G

[*Giacinti, MK, Semikoz ('12)*]



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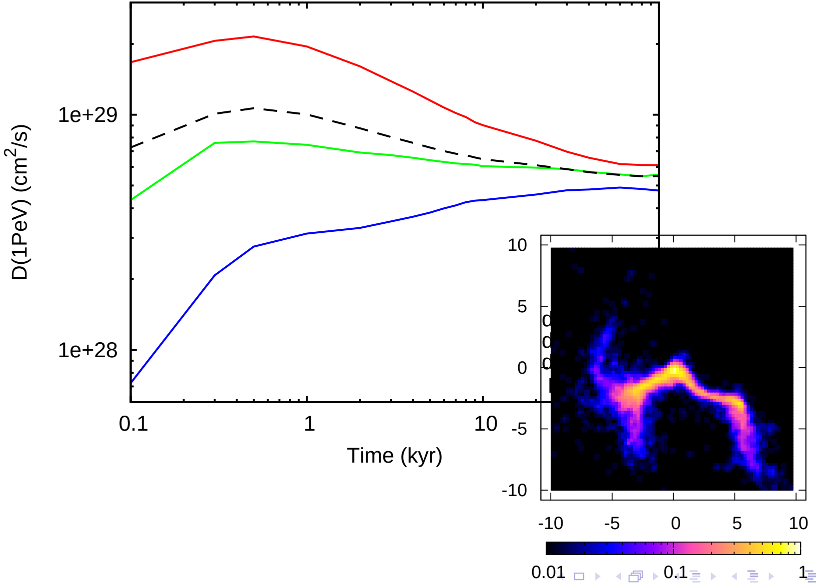

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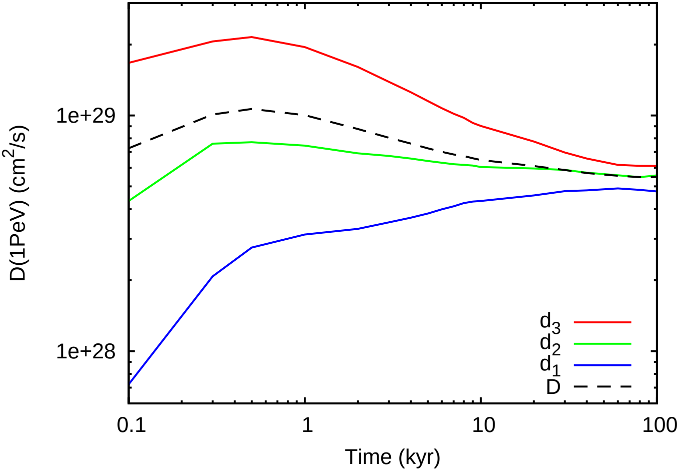

- asymptotic value is ~ 50 smaller than standard value

Is isotropic diffusion possible?

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$$D = \frac{cL_0}{3} \left[(R_{\rm L}/L_0)^{2-\alpha} + (R_{\rm L}/L_0)^2 \right]$$

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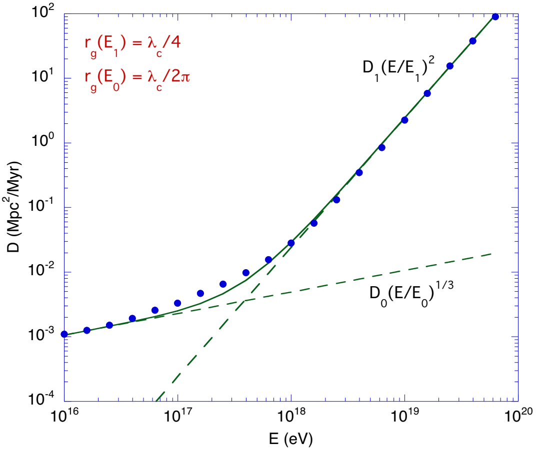

[Parizot '04]

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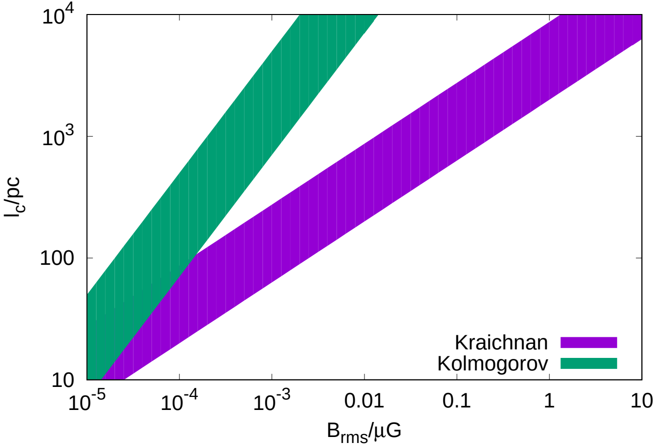

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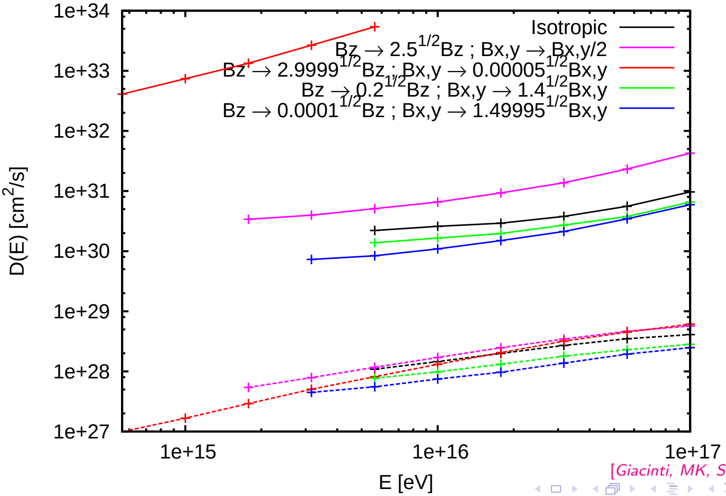

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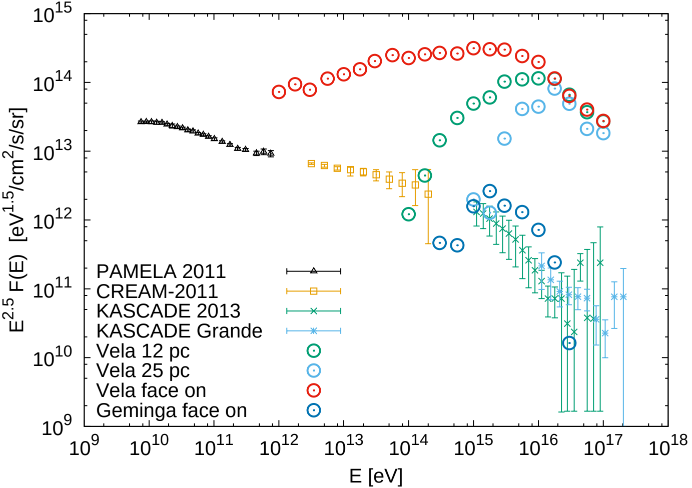
$\Rightarrow$ relative importance of single sources is changed

Consequences of anisotropic propagation:



$\Rightarrow$ local sources contribute only, if $d_\perp$ is small

Fitting the grammage X

[Giacinti, MK, Semikoz ('14,'15)]

- fix $l_{\rm coh}$ and regular field $\boldsymbol{B}(\boldsymbol{x})$, e.g. JF model
  - LOFAR: $l_{\rm coh} \lesssim 10\,\mathrm{pc}$ in disc
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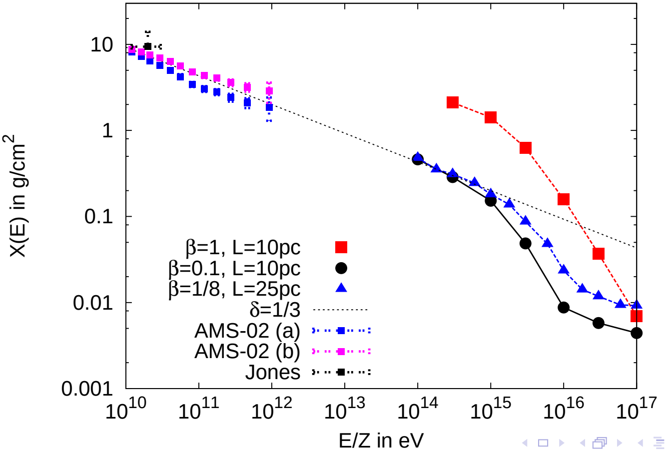

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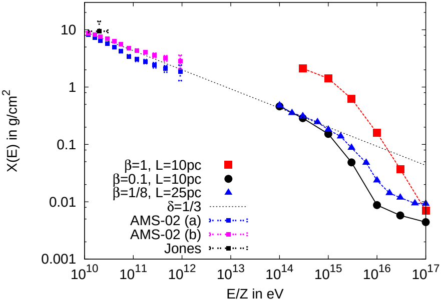

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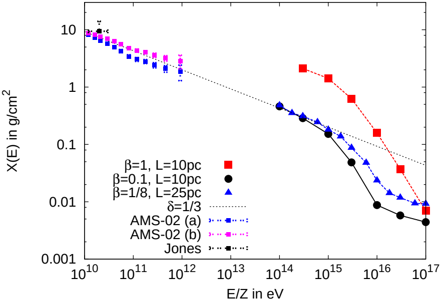

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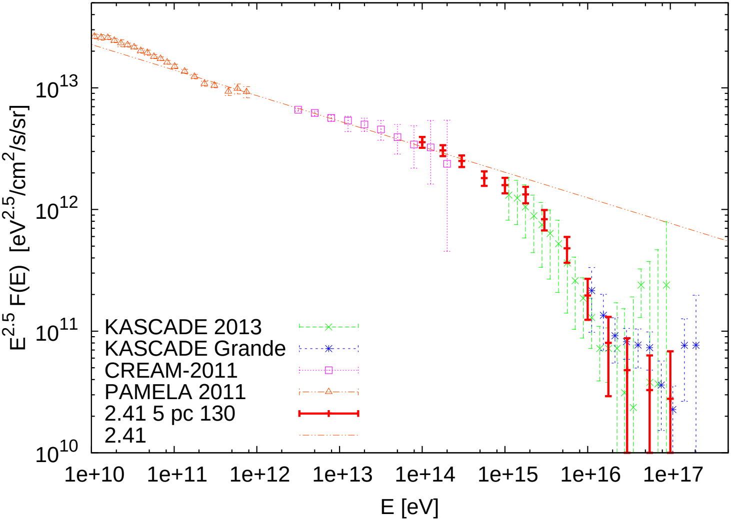
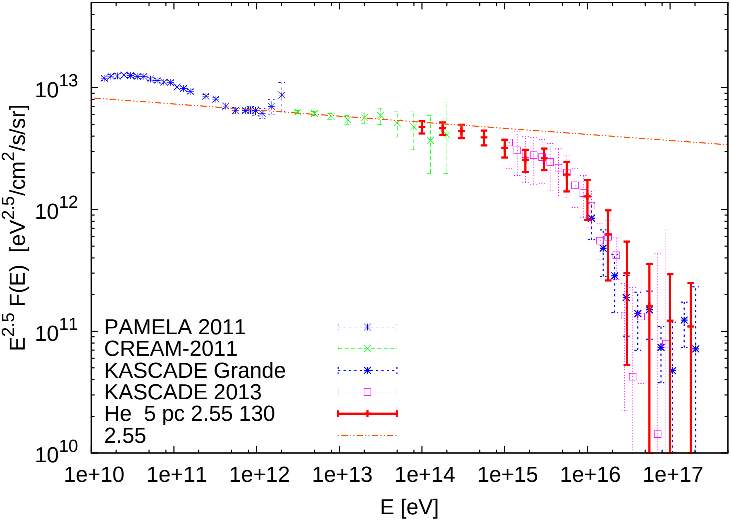
- test: fluxes $I_A(E)$ of all isotopes fixed by low-energy data

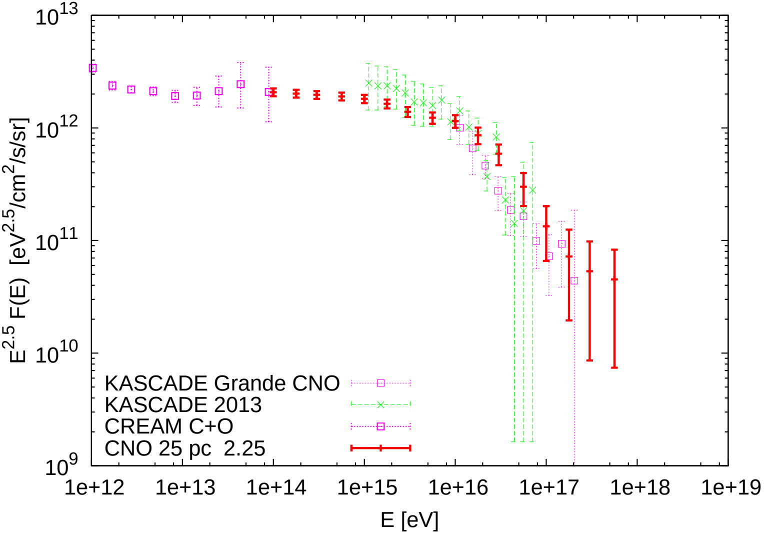
Knee from Cosmic Ray Escape: proton energy spectra



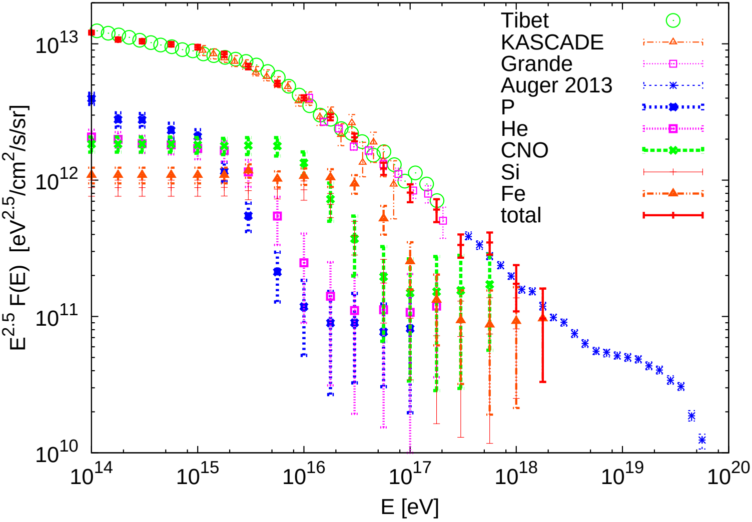
Knee from Cosmic Ray Escape: He energy spectra



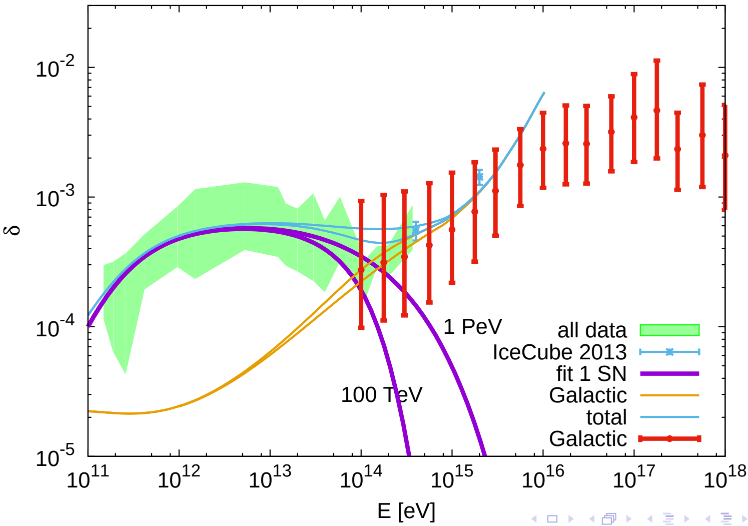
Knee from Cosmic Ray Escape: CNO energy spectra



Knee from Cosmic Ray Escape: total energy spectra



Knee from Cosmic Ray Escape: dipole anisotropy



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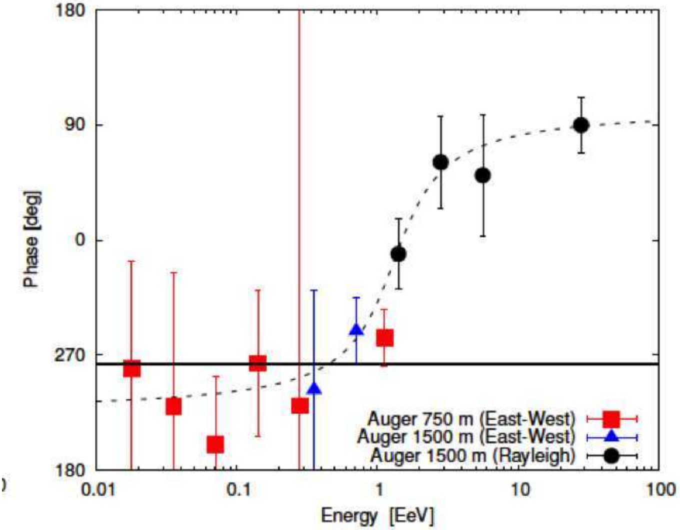
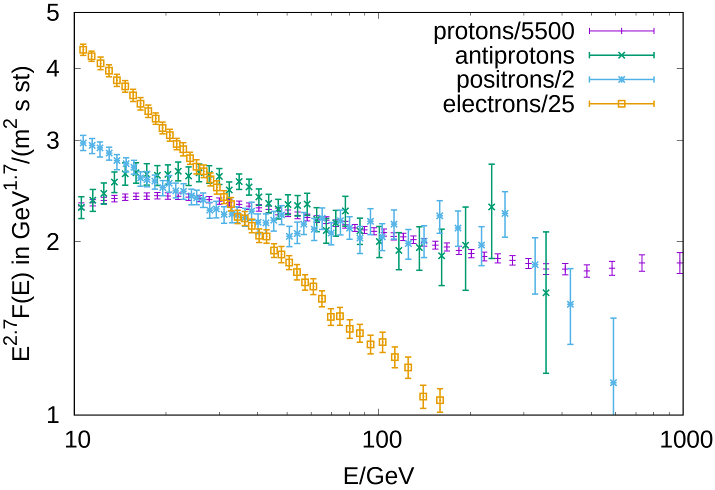


Evidence for dominance of local sources:



Evidence for dominance of local sources:

- secondary $\bar{p}$ and e^+ flux have same shape as p
  - $\bar{p}$ diffuse as $p \Rightarrow$ leads to constant $\bar{p}/p$ ratio
  - $\bar{p}/p$ ratio fixed by source age $\Rightarrow$ $\bar{p}$ flux is predicted
  - e^+ flux is predicted
  - relative ratio of $\bar{p}$ and e^+ depends only on their Z factors

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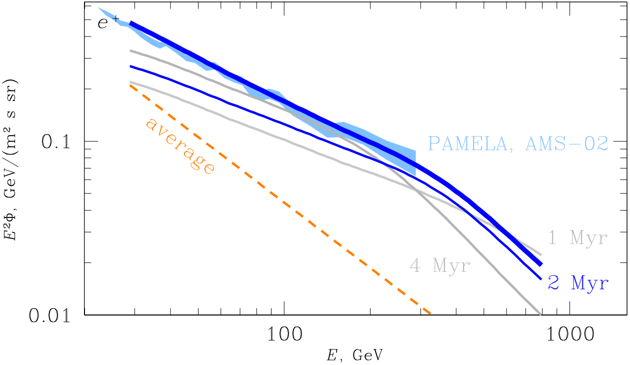

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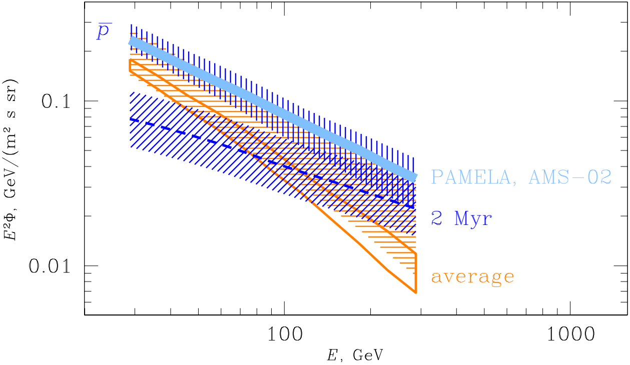

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- B/C consistent? CR anisotropy?

Anisotropy of a single source

- if only turbulent field:
  diffusion = random walk = free quantum particle
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$$\delta = \frac{3D}{c}\frac{\nabla n}{n} = \frac{3R}{2T}$$
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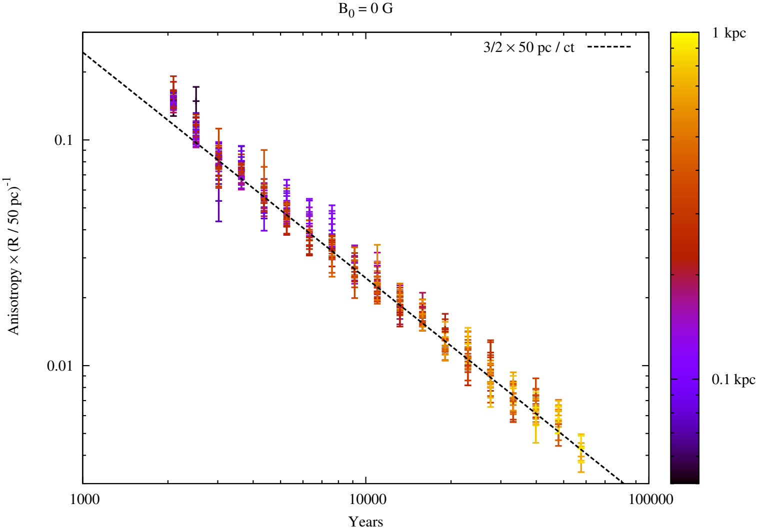
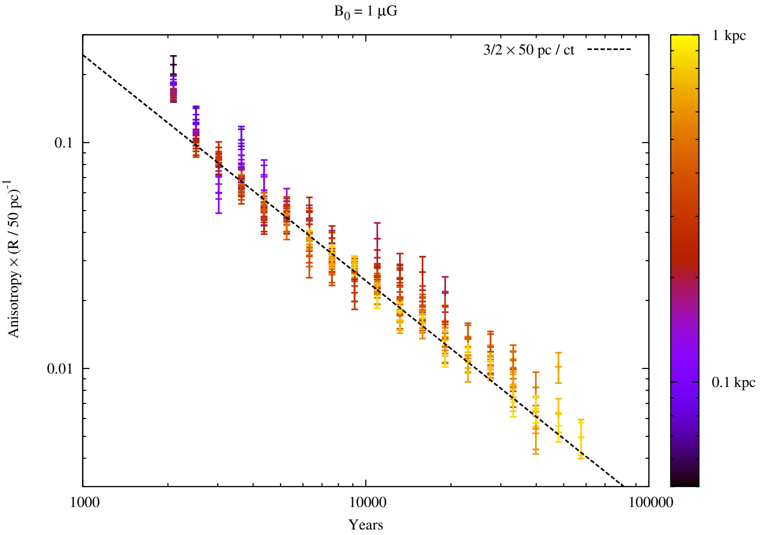


[*Savchenko, MK, Semikoz '15*]

Anisotropy of a single source: plus regular



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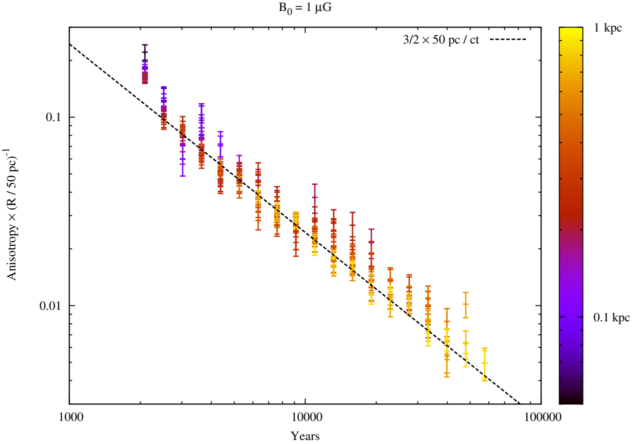

- regular field changes $n(\boldsymbol{x})$, but keeps it Gaussian

  $\Rightarrow$ no change in δ

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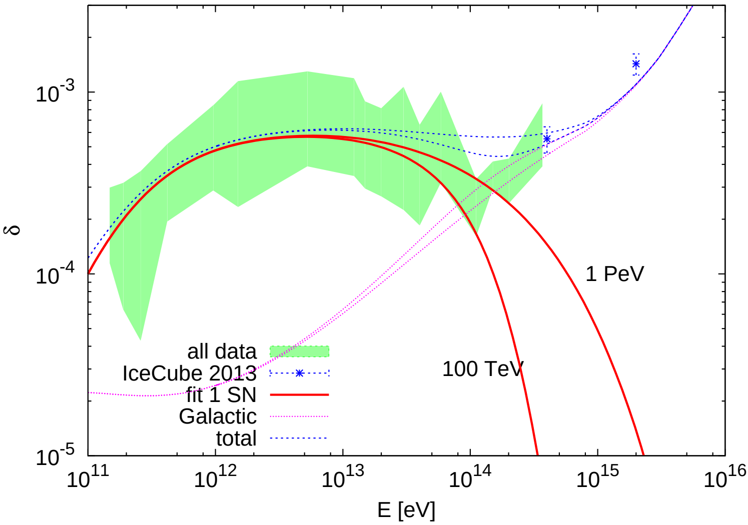

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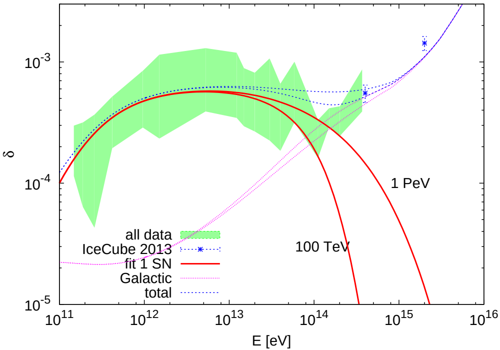

[Savchenko, MK, Semikoz '15]

- suggests low-energy cutoff ⇒ source is off-set

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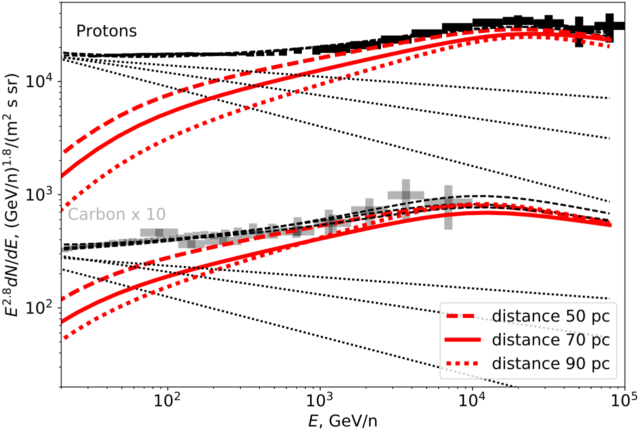
- relative normalisation of "local source" $F^{(1)}(\mathcal{R})$ and "average" $F^{(2)}(\mathcal{R})$ varies,

$$F_A(\mathcal{R}) = C_A^{(1)} F^{(1)}(\mathcal{R}) + C_A^{(2)} F^{(2)}(\mathcal{R})$$

Local source: nuclei fluxes

⇒ explains breaks and variation of rigidity spectra



[MK, Neronov, Semikoz, *in prep.*]

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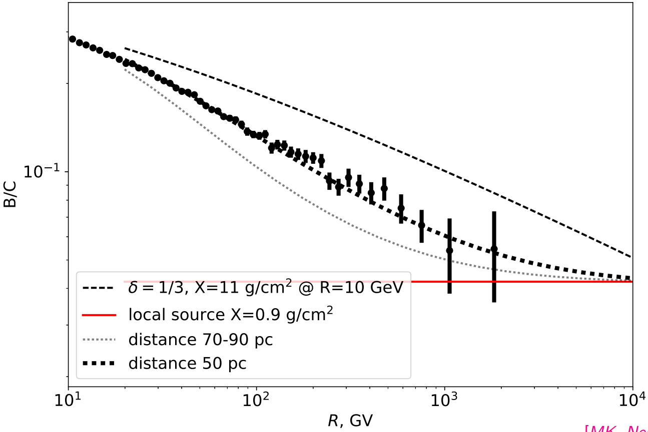

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Conclusions I

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  - isotropic diffusion leads to too large X
  - recovery of fluxes as suggested by KASCADE-Grande
  - probes GMF: suggests small $l_{\rm coh}$
  - transition to light-intermediate extragalactic CRs completed at 10^{18} eV
  - propagation feature is unavoidable, but possible to shift to higher energies
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Conclusions II

1. Single source: anisotropy
   - dipole formula $\delta = 3R/2T$ holds universally in quasi-gaussian regime
   - plateau of δ points to dominance of single source
2. Single source: primary and secondary fluxes
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