Galactic Magnetic Field: some Puzzles

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with C.Becker, G.Giacinti, D.Semikoz, ...

Outline:

- Introduction: CRs as probe for the GMF
- GMF models
  - input: RM, $I_{\rm syn}$, and polarisation U, Q
  - status of models
- CR escape in GMF models *[Giacinti, MK, Semikoz '12ff]*
  - connection to diffusion picture
  - isotropic vs. anisotropic diffusion
- C-BASS and polarisation data *[Becker]*
- TeV halos
- Extended halo model
- Summary

CRs as probe for turbulent magnetic fields:

- Galactic magnetic field: regular + turbulent component
  turbulent: fluctuations on scales $l_{\max} \sim (10 - 150)\,\mathrm{pc}$ to $l_{\min} \ll l_{\max}$
- relevant scales:
  - fast modes with $kR_L \gg 1$: irrelevant
  - slow modes with $kR_L \ll 1$: act locally as uniform field B_0
  - CRs scatter on modes with $kR_L \sim 1$
- Larmor radius

$$R_{\mathrm{L}} = \frac{cp_\perp}{ZeB} = \frac{\mathcal{R}}{B} \simeq 1.08\,\mathrm{pc}\,\frac{\mathcal{R}}{\mathrm{PV}}\,\frac{\mu\mathrm{G}}{B}$$

$\Rightarrow$ CRs probe modes between $(10^{-7} - 1)\,\mathrm{pc}$

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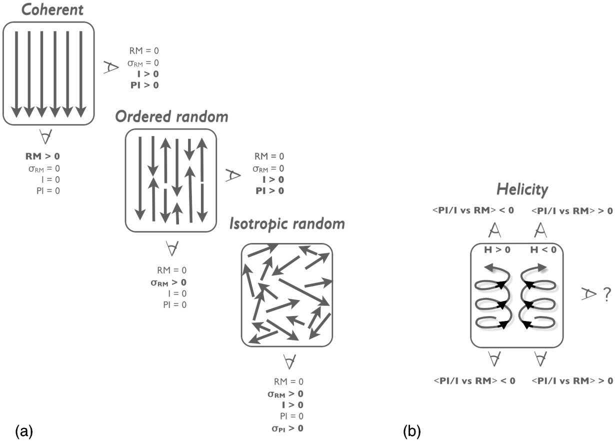
GMF observables

- unpolarised synchrotron intensity $I \sim \int_{\mathrm{L.o.S.}} ds\, n_{\mathrm{cre}}(\boldsymbol{x}, E) B_\perp^\alpha(\boldsymbol{x})$
- polarised synchrotron intensity P or Q, U
- rotation measure $\mathrm{RM} \sim \int_{\mathrm{L.o.S.}} ds\, n_e(\boldsymbol{x}) B_\parallel(\boldsymbol{x})$



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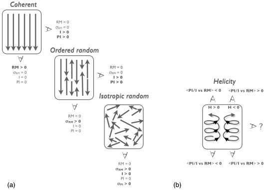
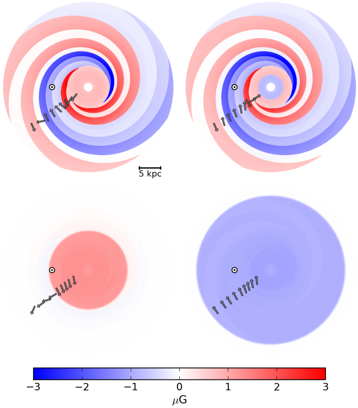


- standard approach:
  - only coherent field contributes to P and RM
  - CR electron density $n_{\rm cre}(\boldsymbol{x}, E)$: fixed, independent of GMF

Status of GMF models

JF12 has become a "standard":

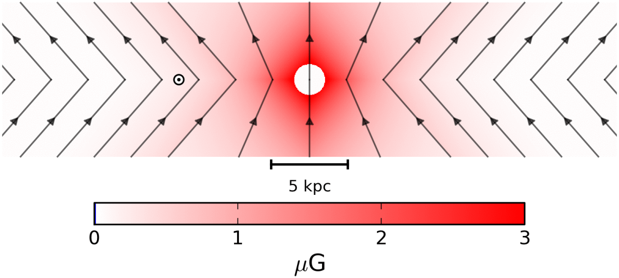
- fitted to RM and synchrotron data, 22 parameters for regular field
- (weak) spiral disk field:



Status of GMF models

JF12 has become a "standard":

- fitted to RM and synchrotron data, 22 parameters for regular field
- halo + X-field



- propagation along X field eases CR escape

Problems of GMF models I

- thermal electron density $n_e(\boldsymbol{x})$ poorly constrained by DM's
- CR electron density $n_{cre}(\boldsymbol{x}, E)$ fixed
- $L_c \sim 150$ pc and $L \simeq 7$ kpc $\Rightarrow N = L_{max}/L \sim 10$, $N_{eff} \sim$ few

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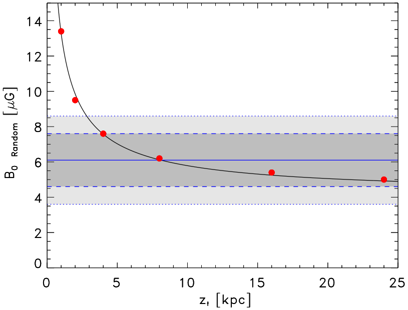
- B from RM is factor few smaller than from synchrotron:



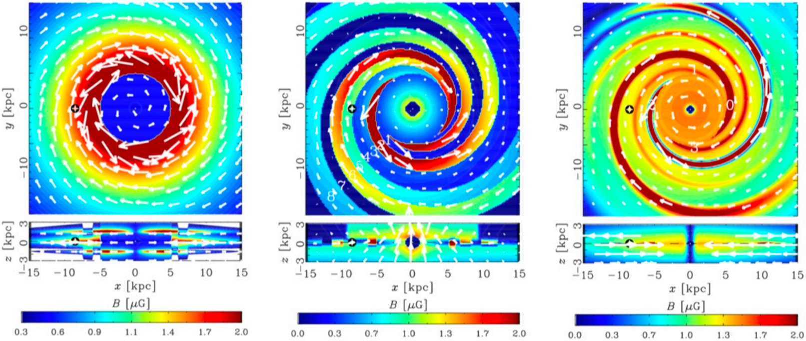
[*Di Bernardo et al. '19*]

$\Rightarrow\ b \gg B$

$\Rightarrow$ isotropic diffusion

Problems of GMF models II

- data are too sparse to constrain (severely) models



- new suit of 8 UF24 models $\Rightarrow$ talk by M. Unger

Approaches to CR propagation

1. UHECRs:
   - use model for Galactic Magnetic Field
   - calculate trajectories $\boldsymbol{x}(t)$ of individual CRs via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.
   - all fluctuations between $l_{\max}$ and $\sim R_L/10$ have to be included
     $\Rightarrow$ trajectory approach computationally very expansive for $E \searrow$
2. Galactic CR, low energies:
   - CRs as relativistic fluid
   - use effective diffusion picture
   - connection to GMF only indirect:
     - ★ use quasi-linear theory to connect $D(E)$ and $P(k)$
     - ★ D is factor 50-100 too small [*Strong, Ptuskin, Moskalenko '07*]
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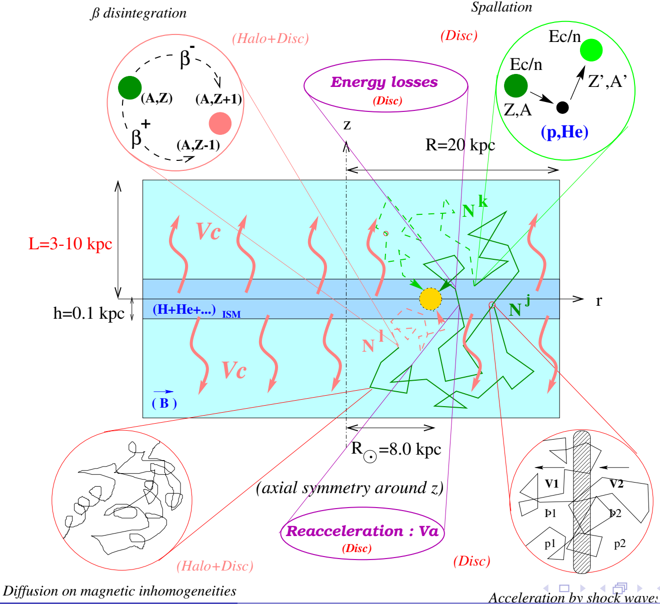

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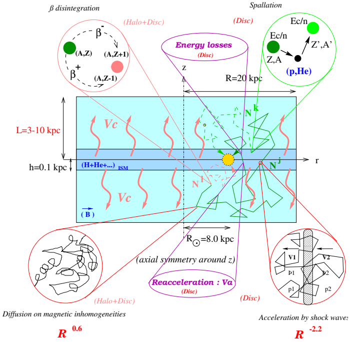

- effective approach invites for simplications:
- often $D_{ij}(E, \boldsymbol{x}) \to D(E), \quad \partial_t = 0$, etc.

How to connect diffusion and GMF?

- comparison of $D_{ij}(E)$:
  - analytical calculation: only approx. & limiting cases
  - numerical calculation straight-forward
- observable: grammage $\tau_{\rm esc}(E) = L^2/(2D) \propto 1/X$

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Our approach:

- use model for Galactic magnetic field: Jansson-Farrar, Psirkhov et al.,...
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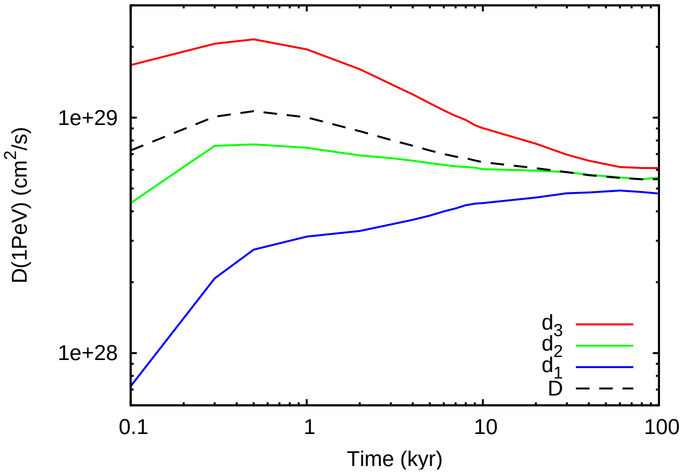
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.
- as preparation, let's calculate diffusion tensor in pure, isotropic turbulent magnetic field

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

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



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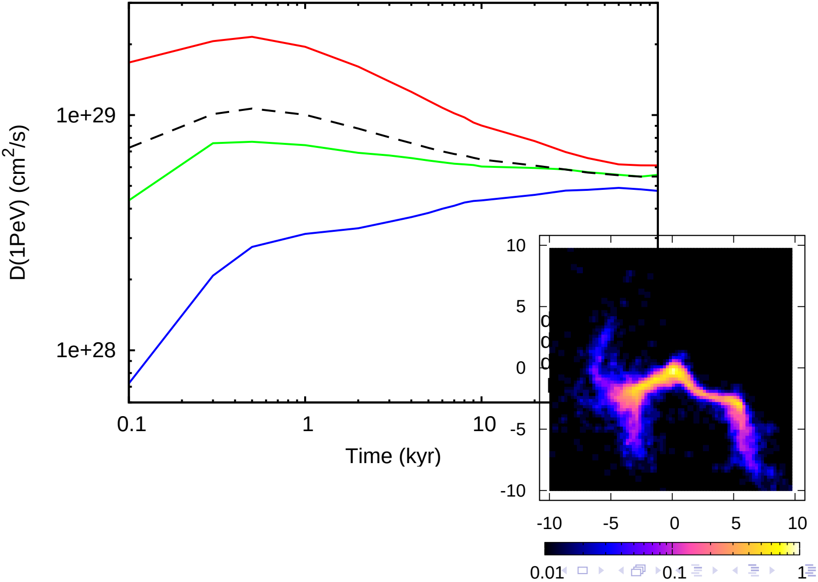

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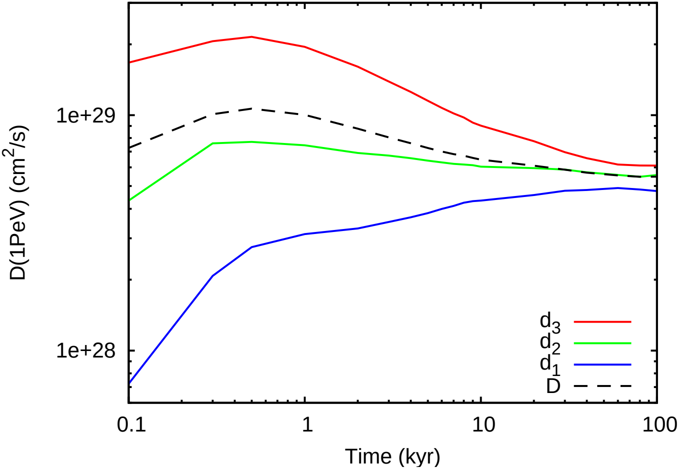

- asymptotic value is ~ 50 smaller than standard value

Is isotropic diffusion possible?

- for isotropic diffusion:

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

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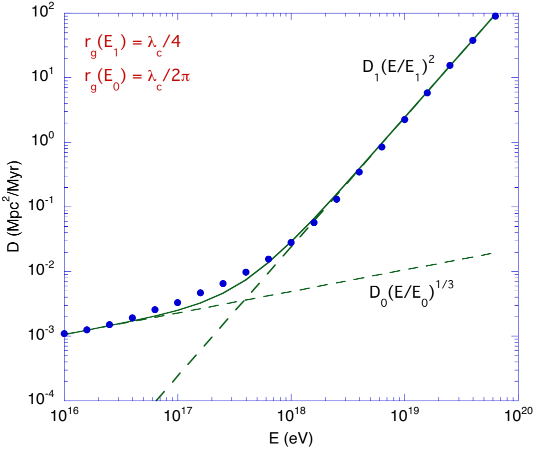
- for isotropic diffusion: for $\alpha = 5/3$

$$D = \frac{cL_0}{3}\left[(R_{\rm L}/L_0)^{1/3} + (R_{\rm L}/L_0)^2\right] \qquad \text{with } L_0 \simeq L_c/(2\pi)$$



[Parizot '04]

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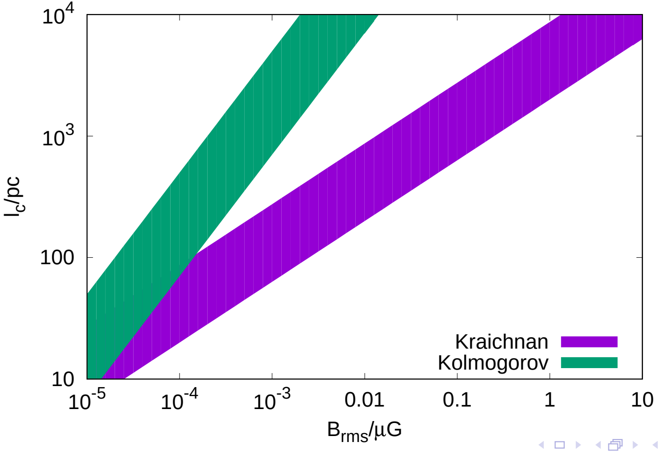

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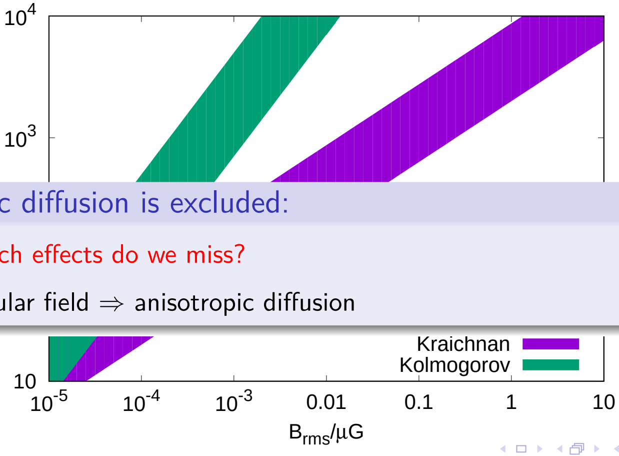

isotropic diffusion is excluded:

- which effects do we miss?
- regular field $\Rightarrow$ anisotropic diffusion

Anisotropic diffusion – 2 options:

- anisotropic turbulence
- dominance of regular field, $B_{\rm rms} = \eta B_0 \ll B_0 \;\Rightarrow\; D_{\|} \gg D_{\perp}$

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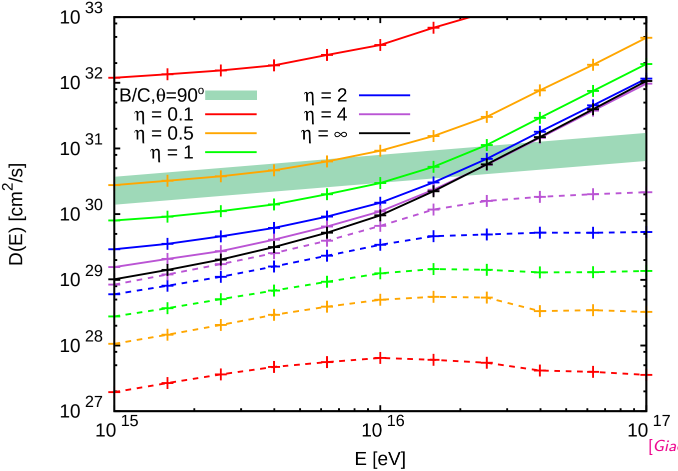

[Giacinti, MK, Semikoz '17]

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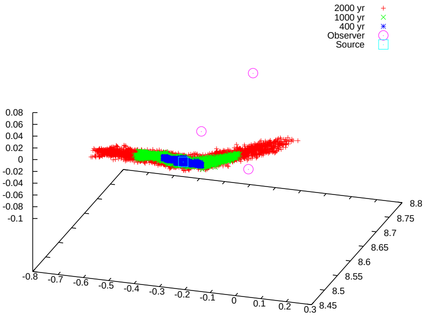
$\Rightarrow$ anisotropic CR propagation



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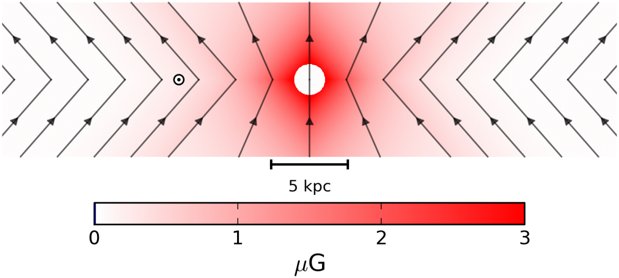
$\Rightarrow$ anisotropic CR propagation

$\Rightarrow$ $D_{\|} \sin(2\vartheta)$ reduces grammage



How dominant is the regular field?

- LOFAR: $l_{\rm coh} \lesssim 10\,$pc in disc
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- determine magnitude of random $\boldsymbol{B}_{\rm rms}(\boldsymbol{x})$ from grammage $X(E)$

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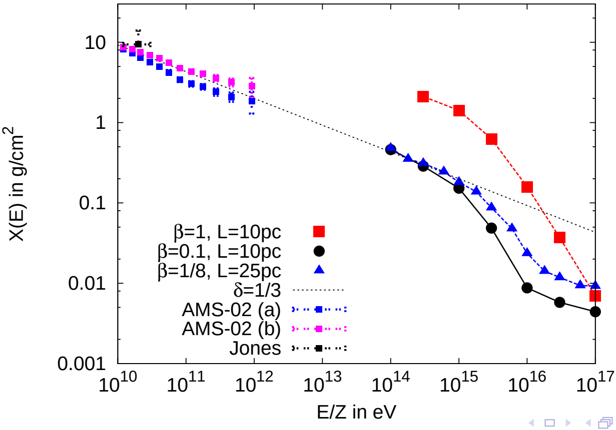

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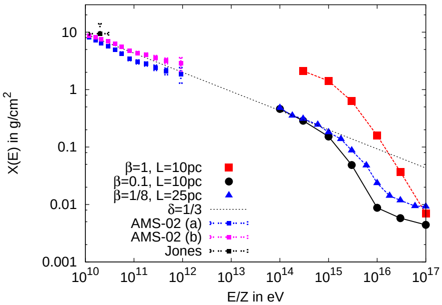
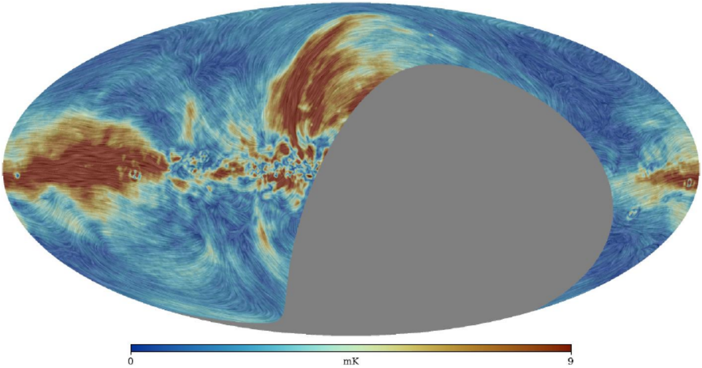


⇒ prefers weak turbulent fields

⇒ contradiction to synchrotron intensity

C-BASS polarisation experiment at 5 GHz: [P. Leahy '23]



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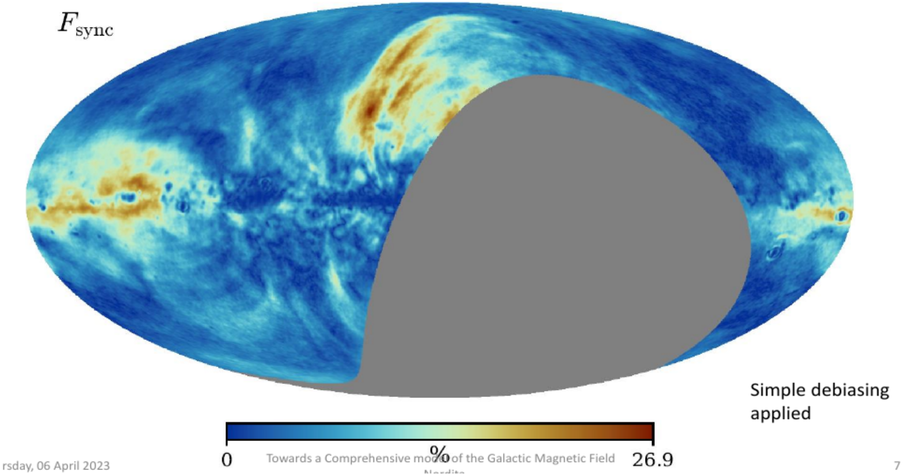


C-BASS polarisation experiment at 5 GHz:

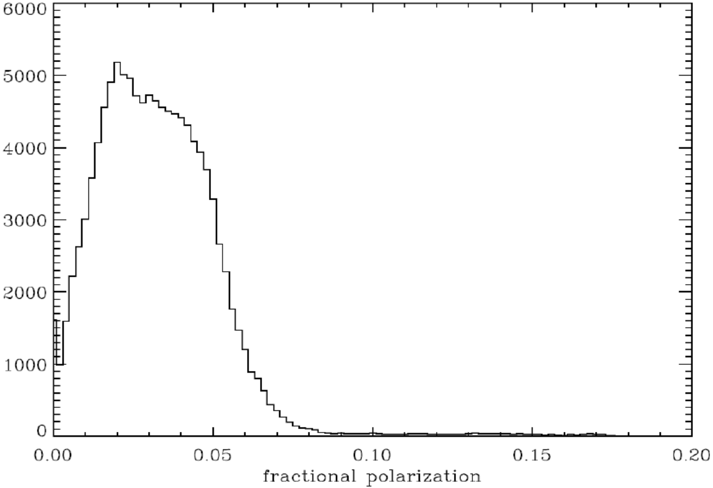
[P. Leahy '23]

High-latitude sky mask

- $b > 30°$
- Avoids obvious structures:
  - Loop I
  - Loop III
  - Virgo A

C-BASS: Polarisation degree per pixel

[P. Leahy '23]



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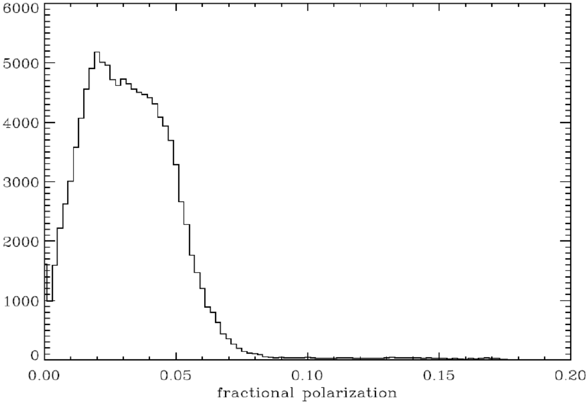
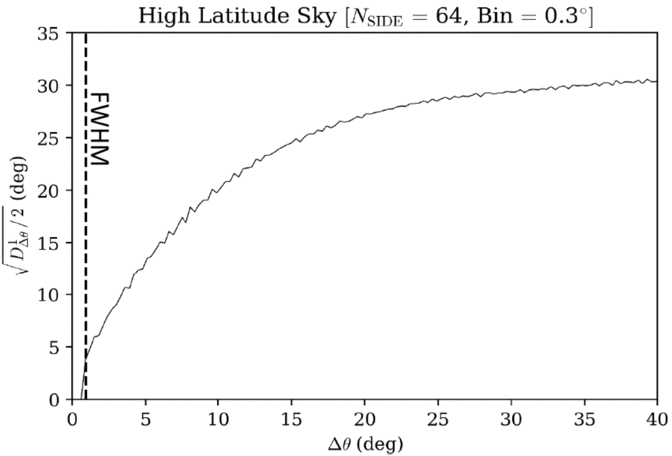


- average polarisation $\langle P \rangle \simeq 3.3\%$, almost everyhere $< 10\%$.
- Local Spur, fan regions: $P \sim 30\%$

C-BASS: Structure function

[P. Leahy '23]



- typical angular scale $\vartheta \simeq 15°$

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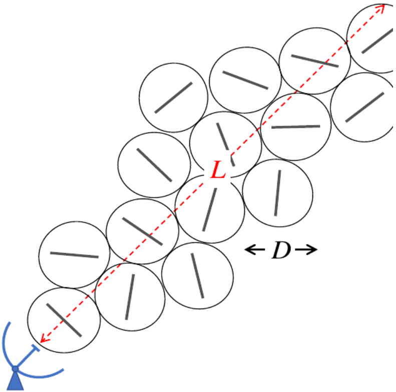

- typical angular scale $\vartheta \simeq 15^\circ$
- $\sin \vartheta/2 \simeq D/L \simeq 1/N$

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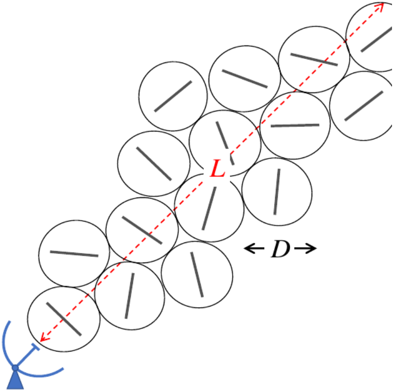

- typical angular scale $\vartheta \simeq 15°$
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- $\vartheta \simeq 15° \Rightarrow N \simeq 8$

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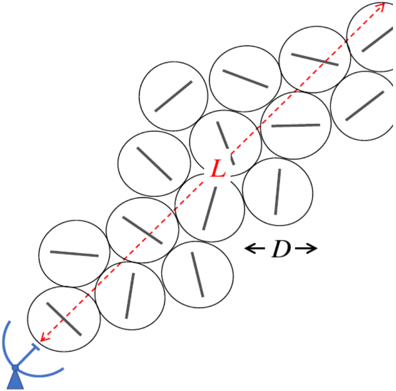
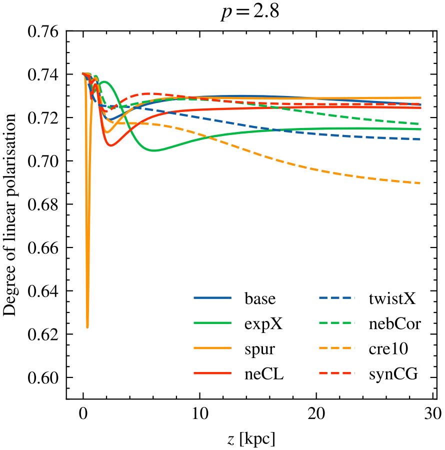


- typical angular scale $\vartheta \simeq 15^\circ$
- $\sin\vartheta/2 \simeq D/L \simeq 1/N$
- $\vartheta \simeq 15^\circ \Rightarrow N \simeq 8$
- but $N \simeq 8$ gives $\langle P\rangle \simeq 0.7/\sqrt{N} \simeq 27\%$

Polarisation degree in UF24 models

- regular field B_0 from UF24 model



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- regular field B_0 from UF24 model
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Polarisation degree in UF24 models

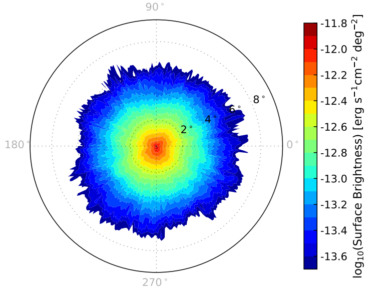
- regular field B_0 from UF24 model
- add turbulent field b such that locally RMS $b = \beta B_0$
- calculate P for various field realisations:

β	base	neCL	expX	spur	cre10	synCG	twistX	nebCor
1	0.36	0.37	0.36	0.39	0.33	0.39	0.36	0.35
1.5	0.22	0.23	0.22	0.24	0.2	0.24	0.22	0.21

- agrees with $\langle P \rangle$ in Local Spur & fan regions $|b| > 30^\circ$
- small $\langle P \rangle$ would require $b \gg B_0$

TeV halos (around PWNe?)

- HAWC: slow diffusion around Geminga: $D \sim D_0/100$



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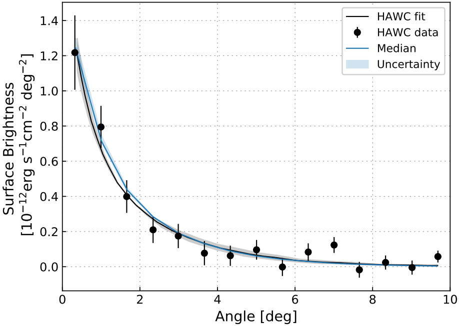

[*López-Coto, Giacinti '17*]

TeV halos (around PWNe?)

- HAWC: slow diffusion around Geminga: $D \sim D_0/100$
- consistent with expectation for isotropic diffusion, $B = 3\mu$G and $L_c = 1\,$pc
- three options:
  - regular field "expelled" around SNR
  - self-generated turbulence close to SNR/PWNe
  - typical situation in disk

Three-component model for the GMF:

add extended halo/corana field:

- disk field: small L_c & turbulent dominated such $D \simeq D_{\rm iso} \sim D_0/100$
- halo field: large L_c, dominated by regular field, $\sin(2\vartheta)D_{\|} \simeq D_0$
- extended halo/corona: large L_c, turbulent field up to 200 kpc

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simplifications:

- power law $dN/dE \sim E^{-p}$ for $e^{\pm}$
- profiles $B(z) \sim \exp[-(z-z_0)/z_t]$ and $B_{\rm min}$
- determine $n_e(z)$ from stationary 1d advection-diffusion equation

Stationary 1d advection-diffusion equation

- solution for $v = 0$:

$$n(z) = n_0 - j_0 \int_0^z \frac{dz'}{D(z')}$$

- use $D(z) = D_0 \exp(z/z_0)$:

$$n(z) = n_0 + \frac{j_0 z_0}{D_0} \left[\exp(-z/z_0) - 1\right]$$

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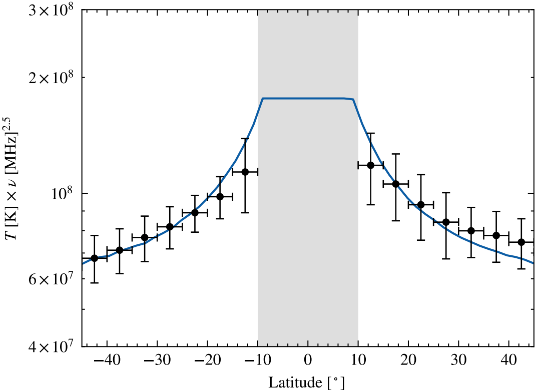
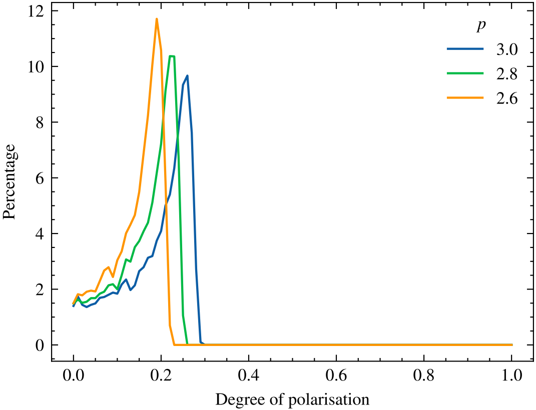
- two cases:
  - $j_0 z_0 / D_0 n_0 > 1$: free-escape boundary
  - $j_0 z_0 / D_0 n_0 < 1$: non-zero $n(z)$ for $z \to \infty$

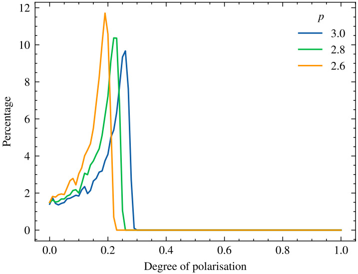
Three-component model for the GMF: fit to synchrotron



Three-component model for the GMF: polarisation



Three-component model for the GMF: polarisation



distribution of P:

- very small P requires partial cancellation of disk and halo contribution

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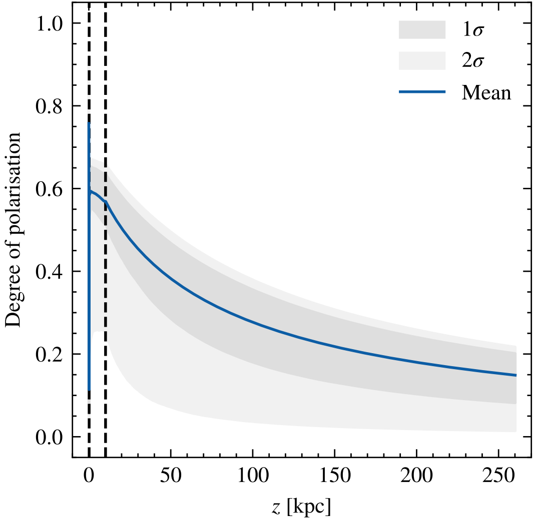

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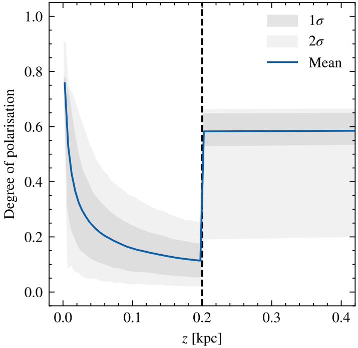

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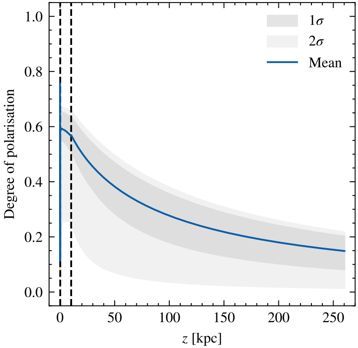
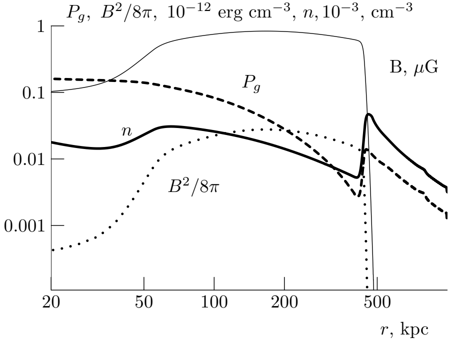


- representative values: $B_{\rm min} = 0.1\mu$G and $n_{\rm min} = 0.1 n_0$
- compatible with CR escape

Other suggestions for an extended halo

- ..., Taylor et al. '14
- Zirakashvili, Ptuskin, Rogovaya '23:



Consequences:

- additional time-delays (and deflections) for UHECRs
- diffuse photon and neutrino fluxes

Conclusions

1. CR escape requires fast diffusion
   - regular field should dominate in halo
   - total contribution to I subdominant
2. Polarisation degree in C-Bass very low
   - large contribution to intensity from turbulent dominated region
   - region should be large $N = L/L_c \gg 1$
3. disk turbulent dominated
   - $N = L/L_c \simeq$ few
4. shape of CR sources in photons:
   - disk: spherical
   - halo: elongated

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