Magnetic fields in the Milky Way and their signature in polarization observations

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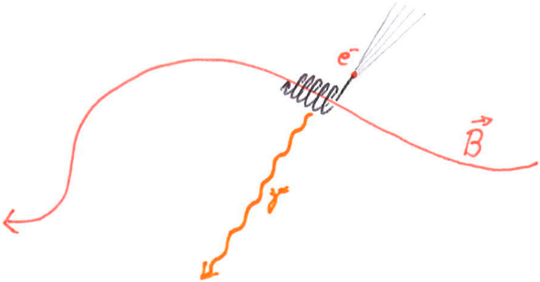
GBT Dark Energy workshop, Beijing, 2013-12-12

Outline

- Relevant observables
- Current knowledge
- Correlations and helicity
- Possible advancements using 21 cm surveys

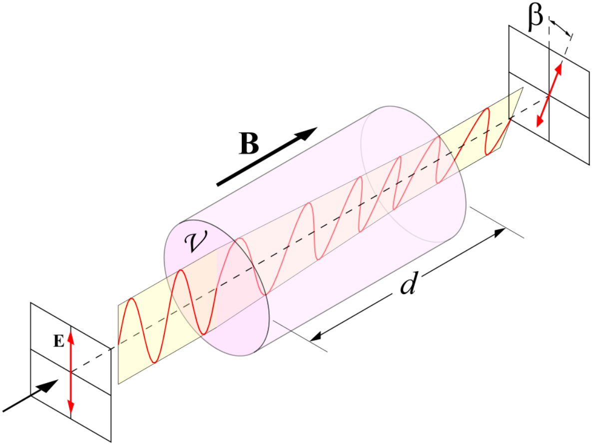
Synchrotron radiation



for $n_{\mathrm{CRE}}(E) \propto E^{-\gamma}$:

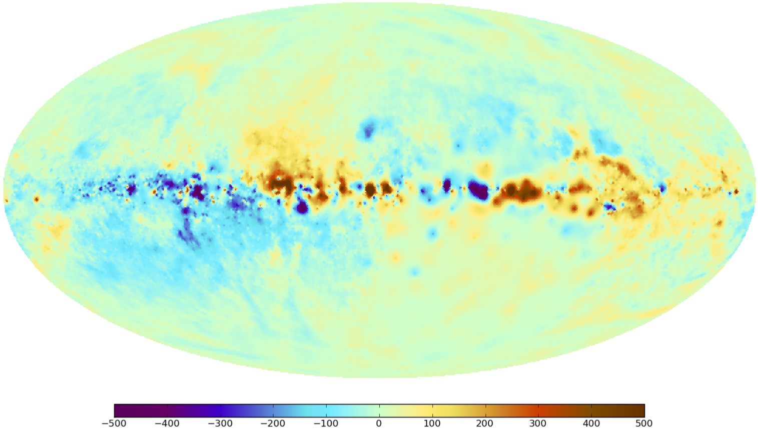
$$P(\lambda) \propto \lambda^{\frac{\gamma-1}{2}} \int \mathrm{d}z \, n_{\mathrm{CRE}} \, B_{\perp}^{\frac{\gamma+1}{2}} \, \mathrm{e}^{2i\left(\arctan\left(\frac{B_y}{B_x}\right)+\frac{\pi}{2}\right)}$$

Faraday rotation



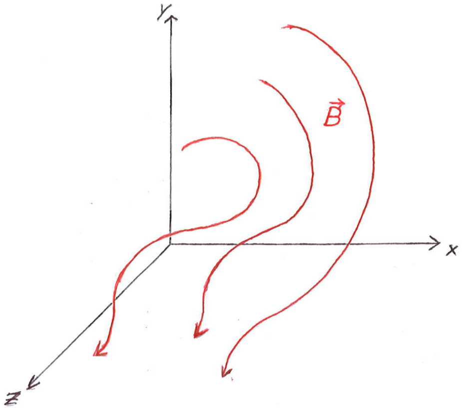
$$\beta \propto \lambda^2 \underbrace{\int_0^\infty \mathrm{d}z\, n_\mathrm{e}\, B_z}_{\propto \phi}$$

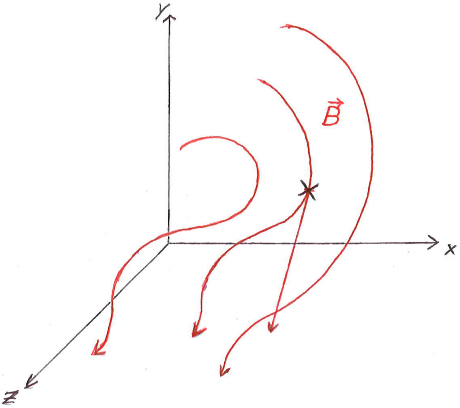
Faraday rotation

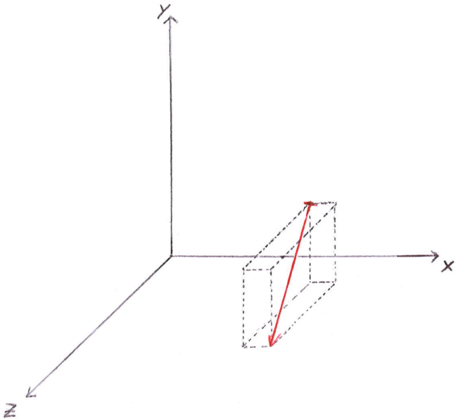


Oppermann et al. (2012)

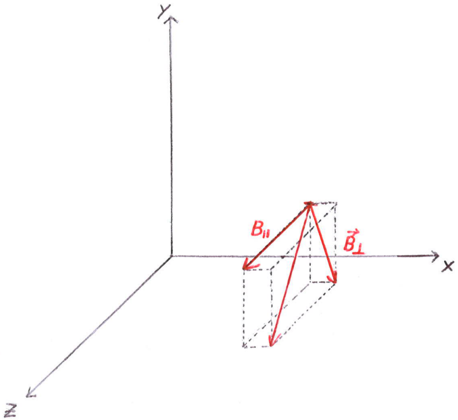
all-sky map of Galactic contribution to Faraday depth in rad/m^2

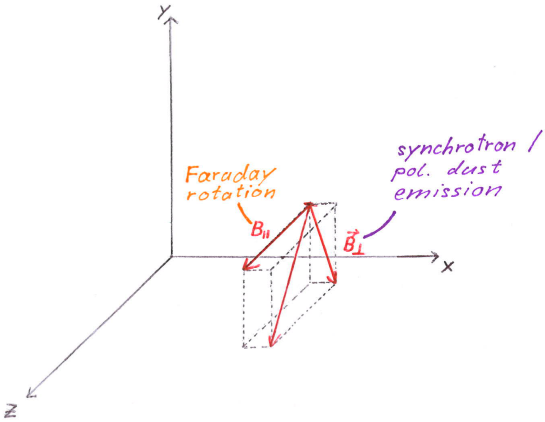

y
x
z
$\vec{B}$

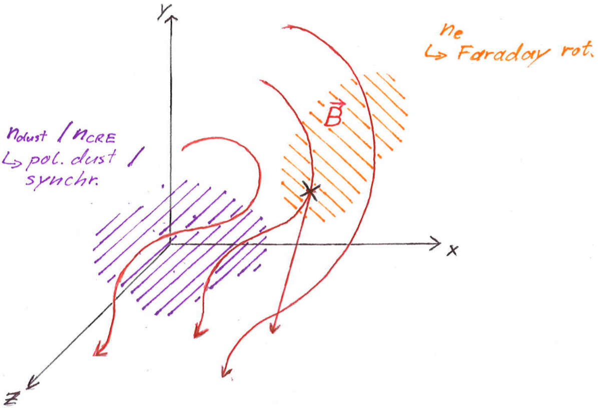

y
x
z
$\vec{B}$



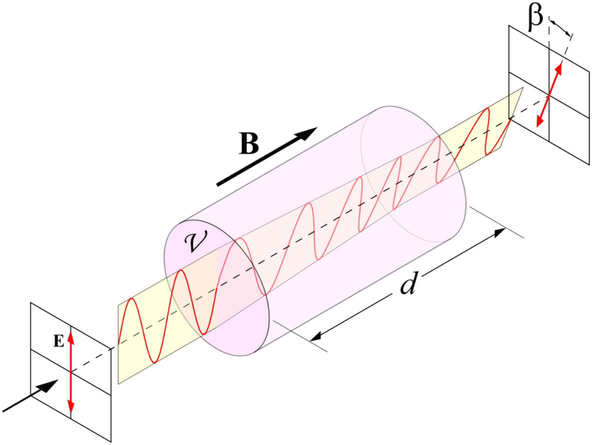
Y
X
Z


Y
$B_{\parallel}$
$\vec{B}_{\perp}$
X
Z


y
x
z
Faraday rotation
$B_{\parallel}$
synchrotron / pol. dust emission
$\vec{B}_{\perp}$

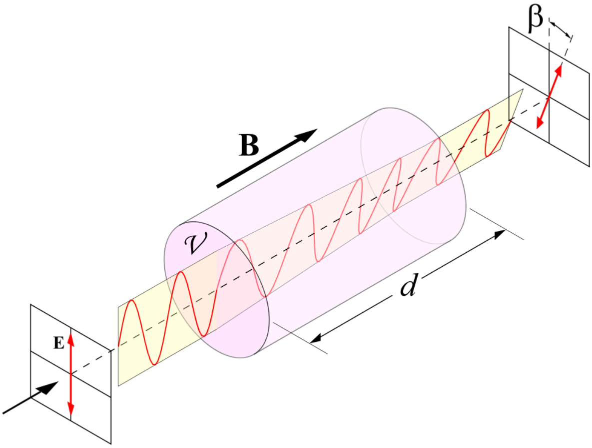

y
x
z
n_e
↳ Faraday rot.
$\vec{B}$
n_{dust} / n_{CRE}
↳ pol. dust /
synchr.

Faraday rotation



$$\beta \propto \lambda^2 \underbrace{\int_0^\infty \mathrm{d}z \, n_\mathrm{e} \, B_z}_{\propto \phi}$$

Faraday rotation



$$\beta \propto \lambda^2 \underbrace{\int_0^{z} \mathrm{d}z' \, n_{\mathrm{e}} \, B_z}_{\propto \phi(z)}$$

synchrotron radiation

for $n_{\mathrm{CRE}}(E) \propto E^{-\gamma}$:

$$P(\lambda) \propto \lambda^{\frac{\gamma-1}{2}} \int_0^\infty \mathrm{d}z \, n_{\mathrm{CRE}} \, B_\perp^{\frac{\gamma+1}{2}} \, \mathrm{e}^{2i\left(\arctan\left(\frac{B_y}{B_x}\right)+\frac{\pi}{2}\right)}$$

Faraday rotated synchrotron radiation

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Faraday rotated synchrotron radiation

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$$= \int_0^\infty \mathrm{d}z\, p(z)\, \mathrm{e}^{2i\,\lambda^2\,\phi(z)}$$

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$$= \int_0^\infty \mathrm{d}z \, p(z) \, \mathrm{e}^{2i\,\lambda^2\,\phi(z)}$$

$$= \int_{-\infty}^\infty \mathrm{d}\phi \, p(\phi) \, \mathrm{e}^{2i\,\lambda^2\,\phi(z)}$$

Faraday rotated synchrotron radiation

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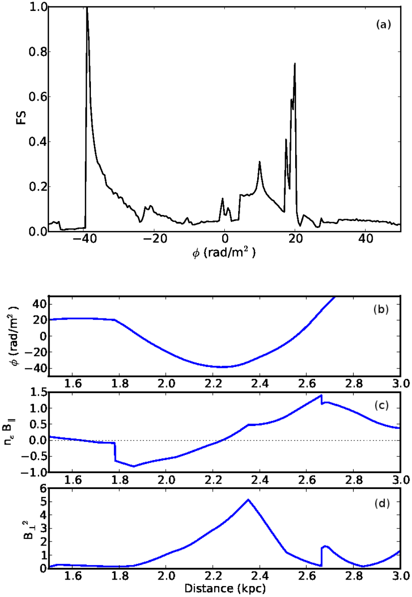
$$P(\lambda) \propto \lambda^{\frac{\gamma-1}{2}} \int_0^\infty \mathrm{d}z\, n_{\mathrm{CRE}}\, B_\perp^{\frac{\gamma+1}{2}}\, \mathrm{e}^{2i\left(\arctan\left(\frac{B_y}{B_x}\right)+\frac{\pi}{2}\right)}\, \mathrm{e}^{2i\,\lambda^2 \int_0^z \mathrm{d}z'\, n_{\mathrm{e}}(z')\, B_z(z')}$$

$$= \int_0^\infty \mathrm{d}z\, p(z)\, \mathrm{e}^{2i\,\lambda^2\,\phi(z)}$$

$$= \int_{-\infty}^\infty \mathrm{d}\phi\, p(\phi)\, \mathrm{e}^{2i\,\lambda^2\,\phi(z)}$$

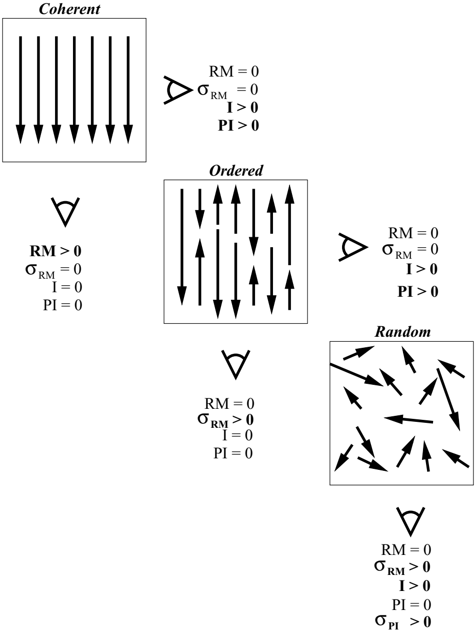
$$\Rightarrow \quad p(\phi) = \int_{-\infty}^\infty \mathrm{d}\lambda^2\, \mathrm{e}^{-2i\,\lambda^2 \phi}$$



Bell et al. (2011)

Outline

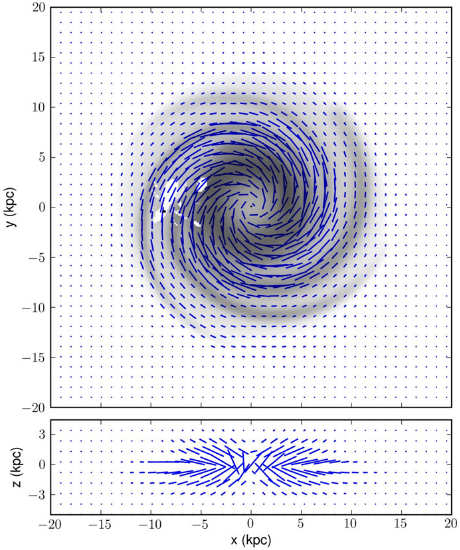
- Relevant observables
- Current knowledge
- Correlations and helicity
- Possible advancements using 21 cm surveys



Jaffe et al. (2010)

- parametric models
- see Jansson & Farrar (2012a,b)
- fit to WMAP synchrotron map and extragalactic RMs

Coherent component



Random components

- $B_{\mathrm{ordered}} \approx 1.35 B_{\mathrm{coherent}}$
- $B_{\mathrm{isotropic}} \approx B_{\mathrm{ordered}}$
- $\Rightarrow \quad B^2_{\mathrm{ordered}} + B^2_{\mathrm{isotropic}} > B^2_{\mathrm{coherent}}$

Jansson et al. (2012)

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How random is random?

- correlation structure of the magnetic field
- cross-correlation of the field components

Magnetic correlation tensor

$$\left\langle B_i(\vec{x})\, B_j(\vec{x}')\right\rangle = M_{ij}(\vec{x}, \vec{x}')$$

Magnetic correlation tensor

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assumptions

statistical homogeneity:

$$M_{ij}(\vec{x}, \vec{x}') = M_{ij}(\vec{x} - \vec{x}')$$

$$\Leftrightarrow \quad M_{ij}(\vec{k}, \vec{k}') = (2\pi)^3\ \delta^{(3)}(\vec{k} - \vec{k}')\, f_{ij}(\vec{k})$$

Magnetic correlation tensor

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$$\Leftrightarrow \quad M_{ij}(\vec{k}, \vec{k}') = (2\pi)^3\, \delta^{(3)}(\vec{k} - \vec{k}')\, f_{ij}(\vec{k})$$

statistical isotropy and solenoidality:

$$f_{ij}(\vec{k}) = \left(\delta_{ij} - \frac{k_i k_j}{k^2}\right) M_N(k) - i\, \epsilon_{ijk} \frac{k_k}{k}\, M_H(k)$$

Magnetic correlation tensor

in helicity basis

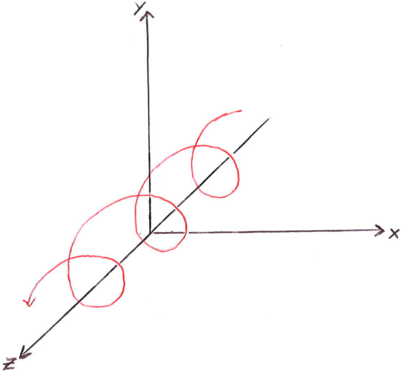
$$\hat{\mathrm{e}}_\pm = \frac{1}{\sqrt{2}}\left(i\hat{\mathrm{e}}_\theta \pm \hat{\mathrm{e}}_\phi\right)$$

$$\left\langle B_+(\vec{k})\, B_+^*(\vec{k}')\right\rangle = (2\pi)^3\,\delta^{(3)}(\vec{k}-\vec{k}')\,\left(M_N(k)+M_H(k)\right)$$

$$\left\langle B_-(\vec{k})\, B_-^*(\vec{k}')\right\rangle = (2\pi)^3\,\delta^{(3)}(\vec{k}-\vec{k}')\,\left(M_N(k)-M_H(k)\right)$$

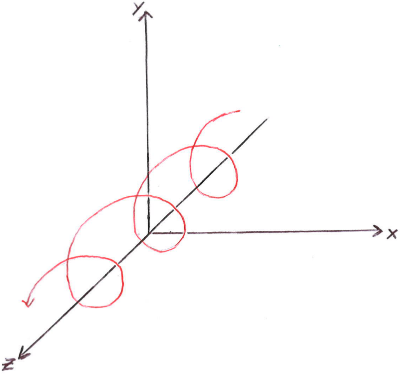
$$\left\langle B_+(\vec{k})\, B_-^*(\vec{k}')\right\rangle = 0$$

Magnetic helicity



left-handed vs. right-handed

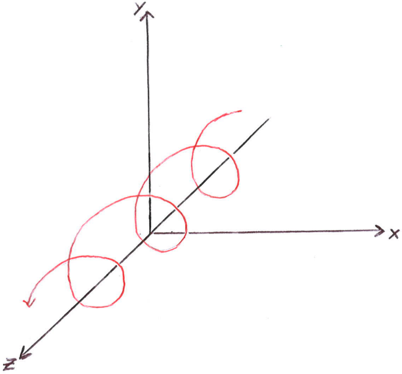
Magnetic helicity



left-handed vs. right-handed

Why bother?

Magnetic helicity

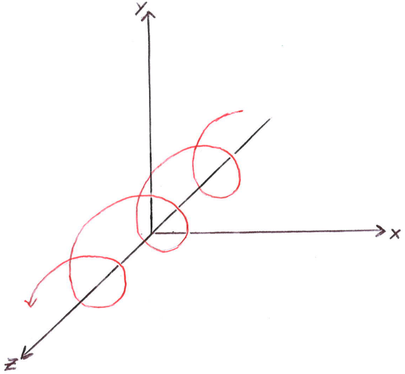


left-handed vs. right-handed

Why bother?

- Galactic magnetic field (probably) generated by dynamo

Magnetic helicity

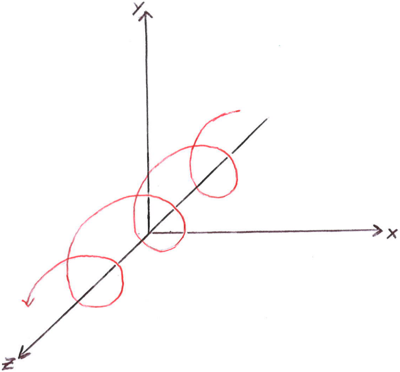


left-handed vs. right-handed

Why bother?

- Galactic magnetic field (probably) generated by dynamo
- seed field tiny $\Rightarrow$ negligible helicity

Magnetic helicity

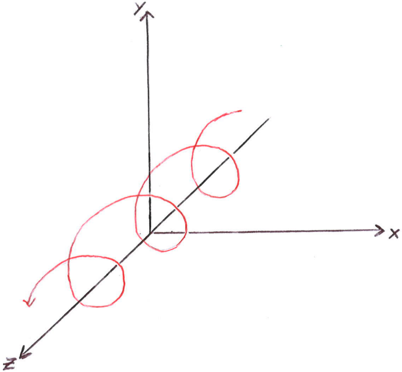


left-handed vs. right-handed

Why bother?

- Galactic magnetic field (probably) generated by dynamo
- seed field tiny $\Rightarrow$ negligible helicity
- helicity conserved

Magnetic helicity

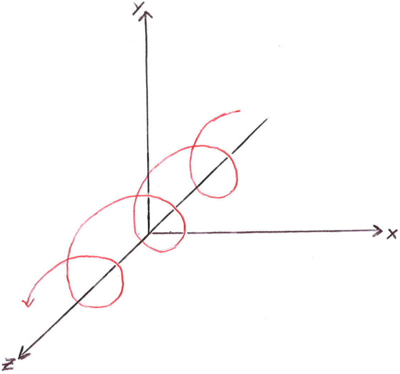


left-handed vs. right-handed

Why bother?

- Galactic magnetic field (probably) generated by dynamo
- seed field tiny $\Rightarrow$ negligible helicity
- helicity conserved
- large-scale helicity observed

Magnetic helicity



left-handed vs. right-handed

Why bother?

- Galactic magnetic field (probably) generated by dynamo
- seed field tiny $\Rightarrow$ negligible helicity
- helicity conserved
- large-scale helicity observed
- small-scale helicity (of opposite sign) predicted

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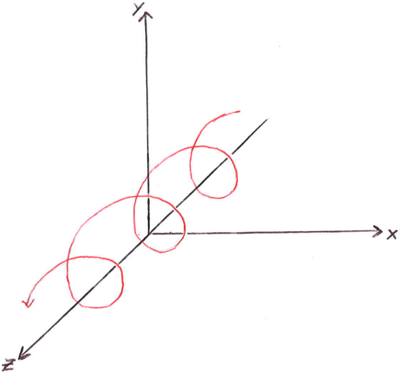
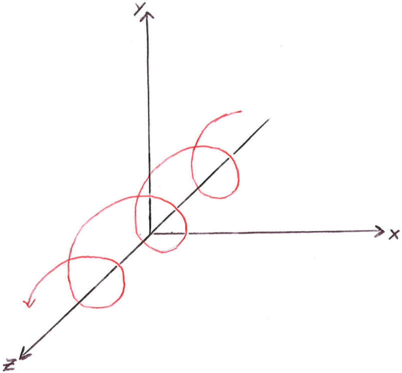
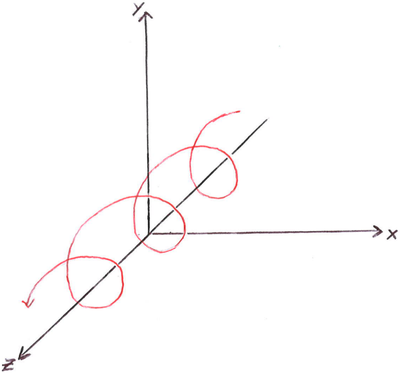


left-handed vs. right-handed



left-handed vs. right-handed

- $\left\langle \frac{\mathrm{d}\chi}{\mathrm{d}z} B_z(z) \right\rangle \lessgtr 0$



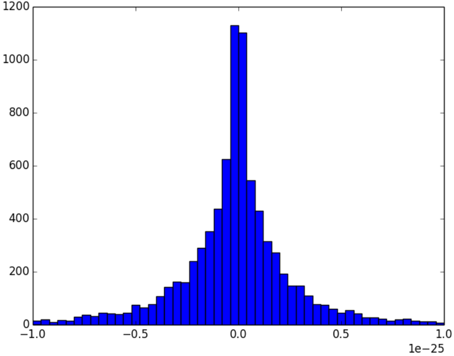
left-handed vs. right-handed

- $\left\langle \frac{\mathrm{d}\chi}{\mathrm{d}z} B_z(z) \right\rangle \lessgtr 0$
- $\left\langle \frac{\mathrm{d}\chi}{\mathrm{d}\phi} \phi \right\rangle \lessgtr 0$

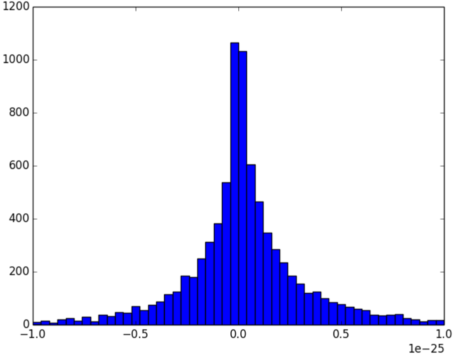
Test for random magnetic field in a box with

- $M_N(k) \propto \left(1 + \left(\frac{k}{k_0}\right)^2\right)^{-\alpha/2}$
- $M_H(k) = \pm M_N(k)$

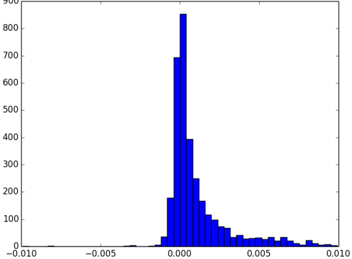
for each line of sight: product of $\int \mathrm{d}\phi \, \frac{\mathrm{d}\chi}{\mathrm{d}\phi} \, |P|$ and $\int \mathrm{d}\phi \, \phi \, |P|$



$$M_H(k) = +M_N(k)$$



$$M_H(k) = -M_N(k)$$



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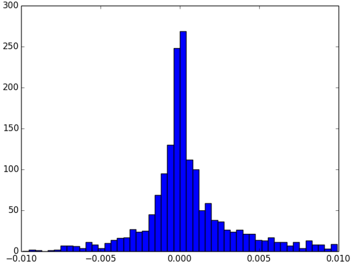

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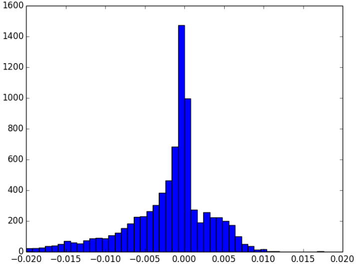

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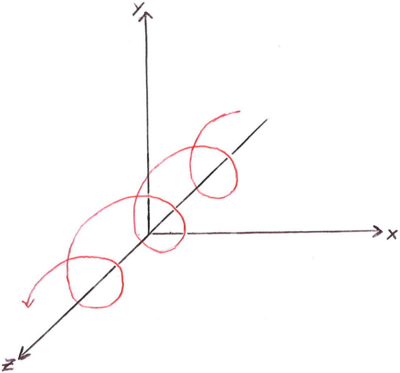

left-handed vs. right-handed

aternatively:

- $\langle E(\phi)\, B(\phi + \mathrm{d}\phi)\, \phi \rangle \lessgtr 0$

more sophisticated:

$$\mathcal{P}(M_N, M_H|P) = \int \mathcal{D}\vec{B}\ \mathcal{P}(P|\vec{B})\ \mathcal{P}(\vec{B}|M_N, M_H)\ \mathcal{P}(M_N, M_H)$$

Summary

- Foreground emission sensitive to all three B-field components
- Problems for statistical analysis:
  - no radial localization (only in ϕ-space)
  - distribution of electrons not known
  - non-isotropic magnetic fields