Galactic dynamo action from small to large scales

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Outline

1. Large-scale magnetic structures in spiral galaxies
2. Meso-scale magnetic structures: reversals, magnetic arms, etc.
3. Small-scale magnetic structures in the ISM: intermittency, magnetic filaments and ribbons

1. Large-scale magnetic structures in spiral galaxies

- ❑ Azimuthal structure
- ❑ Vertical structure
- ❑ Radial structure

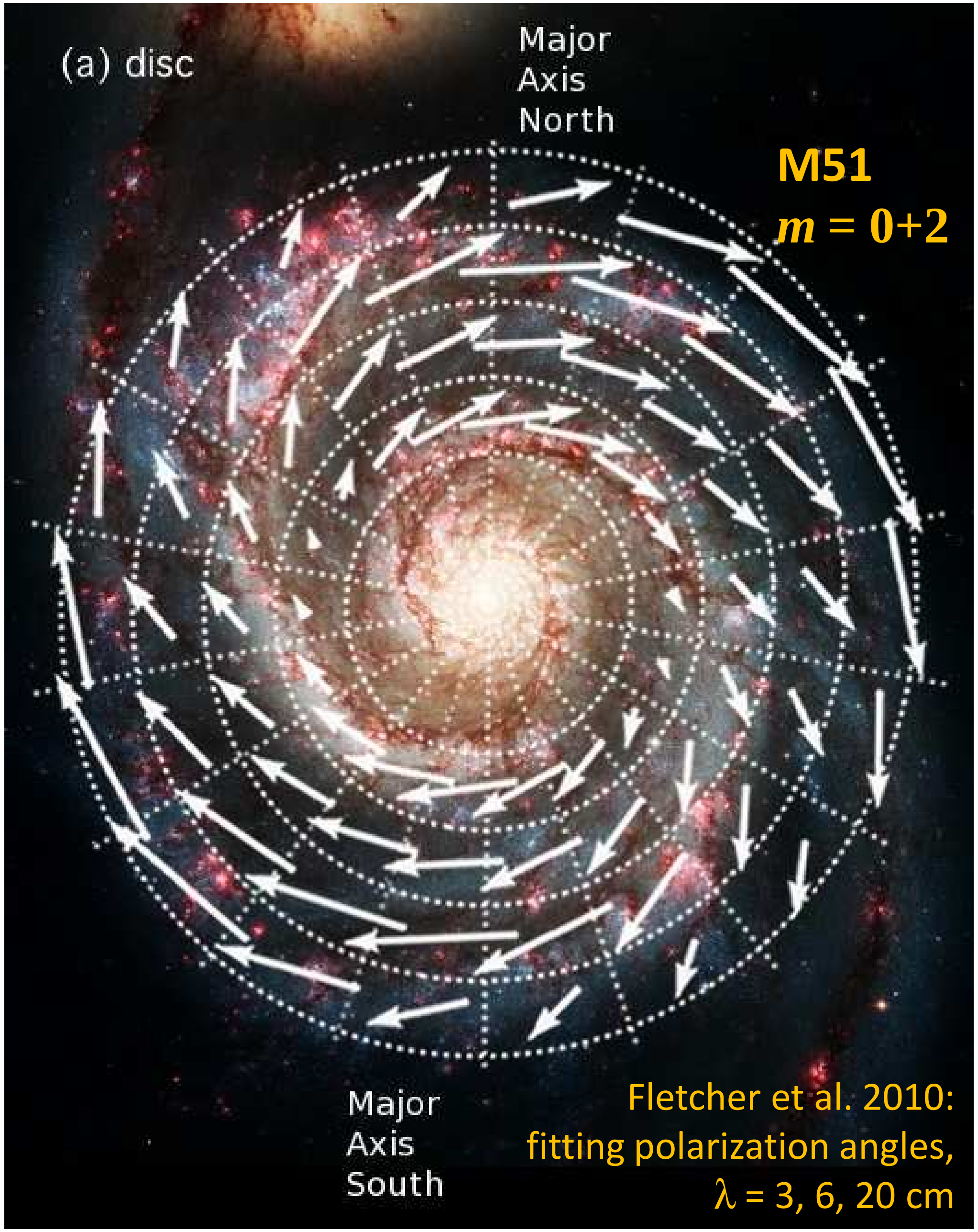
Further details in, e.g., A. Shukurov, Introduction to galactic dynamos. In: *Mathematical Aspects of Natural Dynamos*, eds E. Dormy & A. M. Soward, Chapman & Hall/CRC, 2007, pp. 313--359 (astro-ph/0411739).

1.1. Azimuthal structure

Observed: predominance of axisymmetric structures, azimuthal Fourier mode $m = 0$.

Prediction of dynamo theory: $m = 0$ dominates (strong differential rotation).

Distortions:
$m = 2$ (spiral arms),
$m = 1$ (overall asymmetries), … … …



This disc, $h/r \ll 1$, dynamo modes:

$$\frac{B_r}{B_\phi} \simeq -\frac{l}{h}\,|d\ln\Omega/d\ln r|^{1/2}.$$

Magnetic pitch angle:

$$p = \arctan\frac{B_r}{B_\phi} \simeq -(10\text{–}20^\circ), \text{ as observed.}$$

Vertical magnetic field:

$$\frac{B_z}{B_\phi} \simeq (h/r)^{1/2} \lesssim 0.3, \ \underline{\textbf{on average}}.$$

$B_z \simeq 0.3\,\mu$G near the Sun (Mao et al. 2010).

$B_z \simeq B_r, B_\phi$ near reversals and at $h \simeq r$.

$h \cong 0.5$–1 kpc, $r \cong 10$ kpc, $l \cong 0.1$ kpc (turbulent scale)

1.2. Vertical structure

Quadrupolar symmetry in the main part of the disc:

$B_\phi(z) = B_\phi(-z), \quad B_r(z) = B_r(-z),$

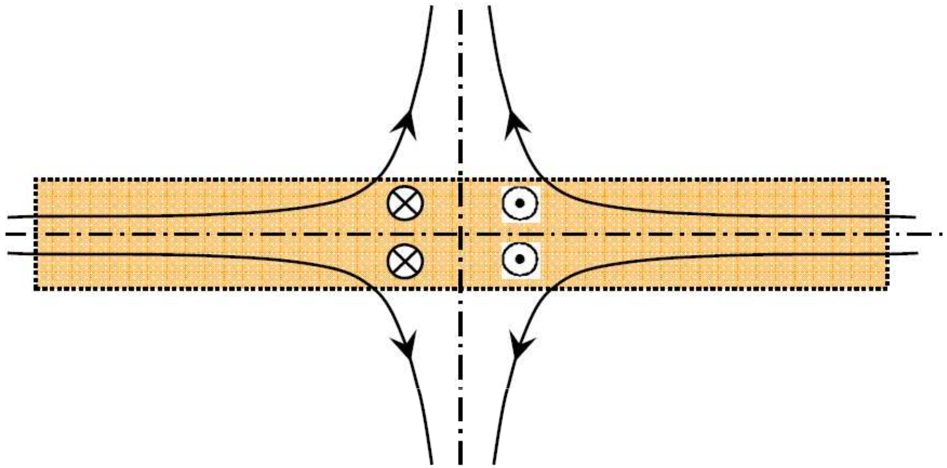
$B_z(z) = -B_z(-z)$.

Dynamo theory:
faster decay of dipolar modes $\rightarrow$ predominance of quadrupolar symmetry.

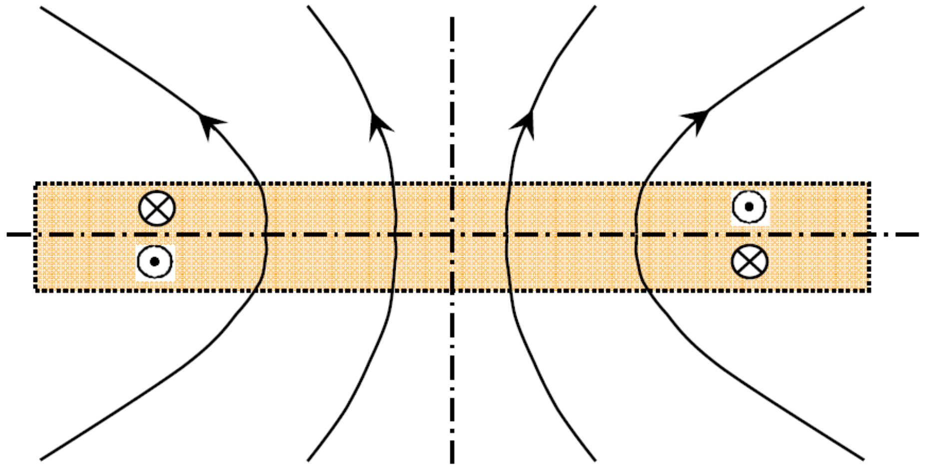
Distortions (e.g., north-south asymmetry in the Milky Way).

Confirmed observationally for the Solar vicinity of the Milky Way.

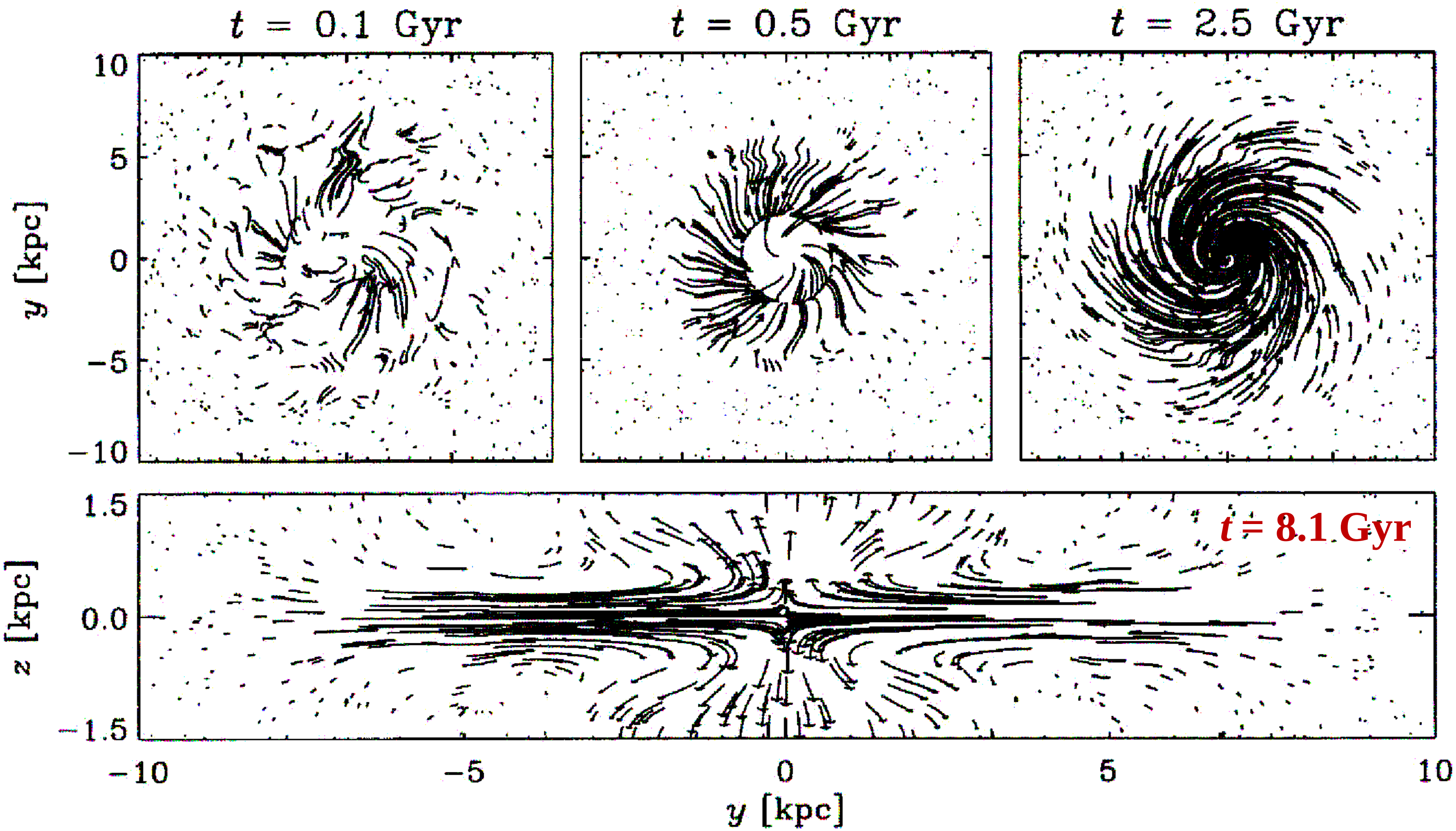
Quadrupolar symmetry



Dipolar symmetry



αω-dynamo in a thin disc embedded in a poorly conducting halo, with random seed field (A. Brandenburg, from Beck et al., *Ann. Rev. Astron. Astrophys*. 1996)

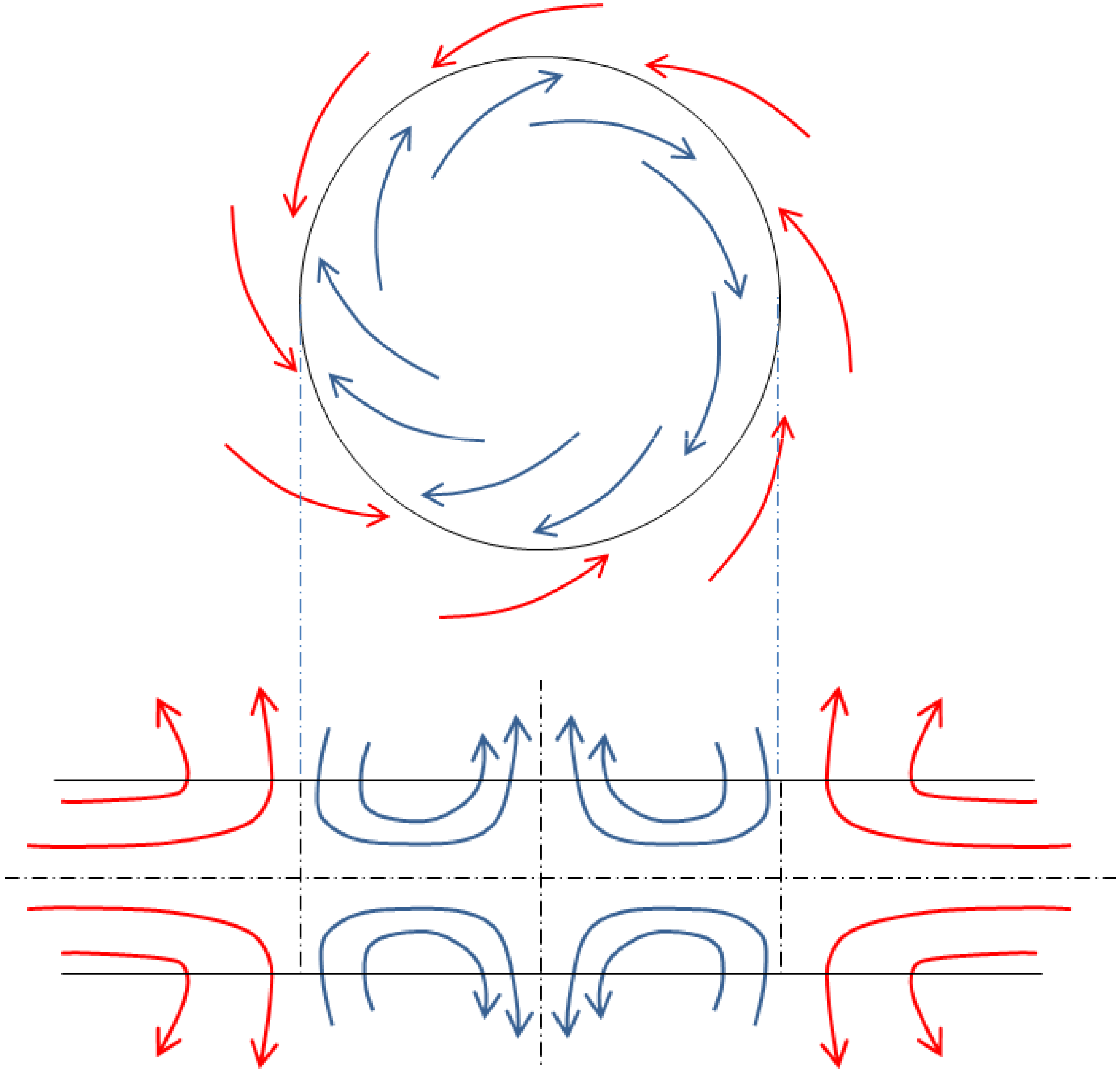


Axisymmetric field structure near a reversal

$B_r \ll B_z < B_\phi$

or

$B_r , B_\phi \ll B_z$



Simple analytical solution for αω-dynamo in a thin disc in vacuum

(Shukurov & Sokoloff 2008, Dynamos, Elsevier, p. 251)

$$B_r \approx R_\alpha C_0 \left[\cos\frac{\pi z}{2} + \frac{3}{4\pi^{3/2}}\sqrt{-D}\cos\frac{3\pi z}{2}\right],$$

$$B_\phi \approx -2C_0\sqrt{-\frac{D}{\pi}}\cos\frac{\pi z}{2}, \qquad B_z \approx 0.$$

Accuracy better than 10% in galactic discs

$+$ radial dependence: $\vec{\mathcal{B}} = Q(r)\vec{B}(z;r)$ (flared disc)

$$R_\alpha \simeq 3\frac{l\Omega}{v}, \quad R_\omega \simeq 3\frac{h^2}{lv} r\frac{d\Omega}{dr}, \quad D = R_\alpha R_\omega \simeq 9r\Omega\frac{d\Omega}{dr}\,\frac{h^2}{v^2}.$$

$v \cong 10$ km/s (turbulent velocity), C_0 = arbitrary constant

Further details in: Anvar Shukurov and Dmitry Sokoloff, Astrophysical dynamos. In: Ph. Cardin, L.F. Cugliandolo, editors, *Les Houches, Session LXXXVIII, 2007, Dynamos*. Elsevier, 2008, p. 251—299.

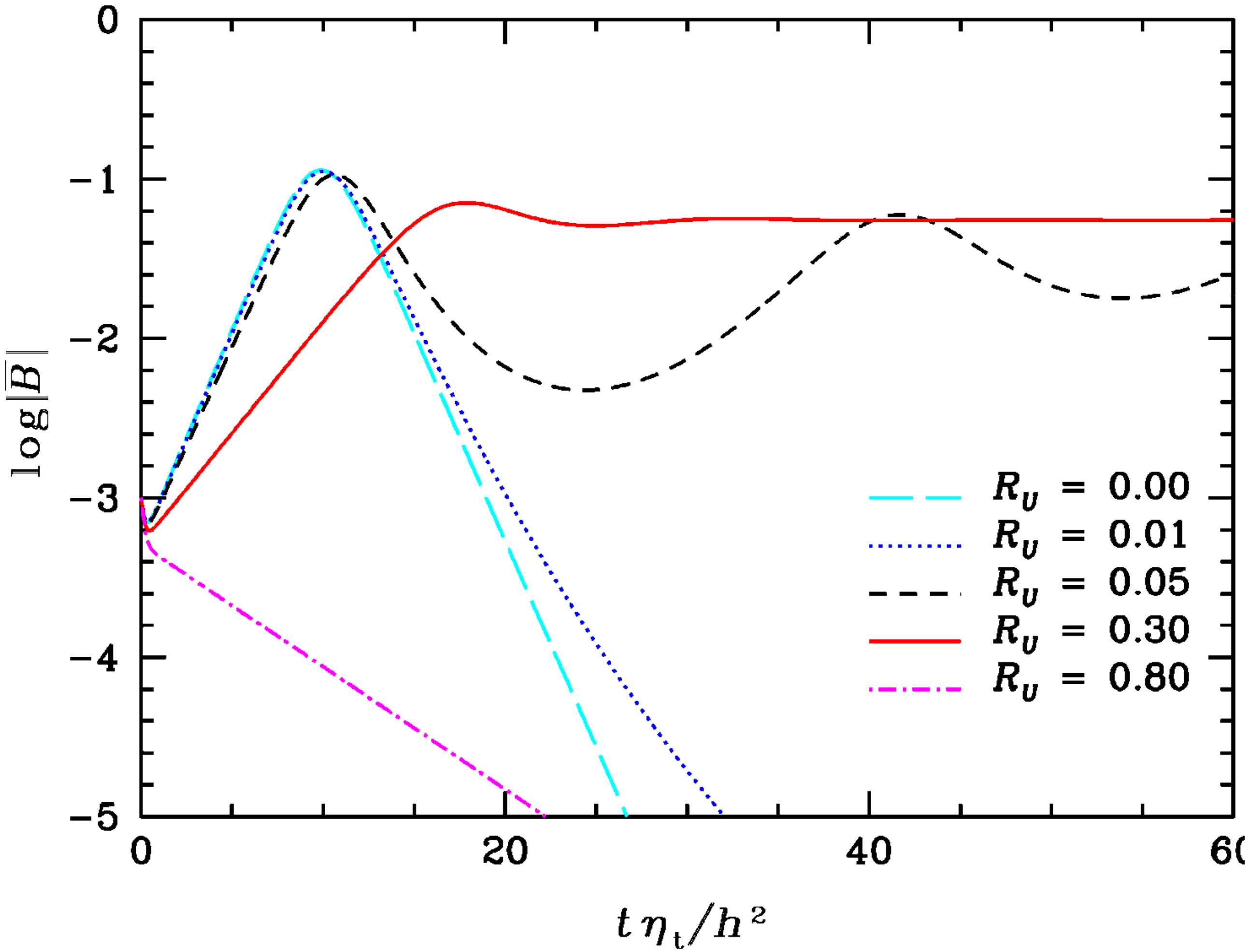
1.3. Radial structure

Large-scale dynamo controlled by magnetic helicity conservation (Shukurov et al., MNRAS, 2006):

- differential rotation, $\Omega(r, z)$,
- helicity of interstellar turbulence, $\alpha \simeq l^2\Omega/h \cong 0.5$ km/s,
- gas outflow from the disc, $R_U = U_z h/\beta \cong 0.2\text{–}2$.

U_z = mass-averaged outflow velocity, $U_z = V_z\rho_{\rm hot}/\langle\rho\rangle \cong 0.1\text{–}1$ km/s,
$\beta \cong \tfrac{1}{3} l\boldsymbol{v} \cong 10^{26}$ cm^2/s turbulent magnetic diffusivity.

Sur, Shukurov & Subramanian, MNRAS, 2007:
Magnetic field evolution in a galactic disc with helicity advection by the galactic fountain or wind



Steady-state large-scale magnetic field (Sur et al., MNRAS 2007) due to helicity advection:

$$B^2 \approx \frac{8\pi}{C} R_U (D/D_{\rm crit} - 1)\rho v^2 \simeq (1\mu{\rm G})^2,$$

$C = 2(h/l)^2 \simeq 50,$

$D \simeq (\Omega h/v)^2 \approx 10,$ the dynamo number near the Sun,

$D_{\rm crit} \approx 8$, critical dynamo number

Dependence of B on SFR, disc-halo connection, winds, galactic evolution, etc.

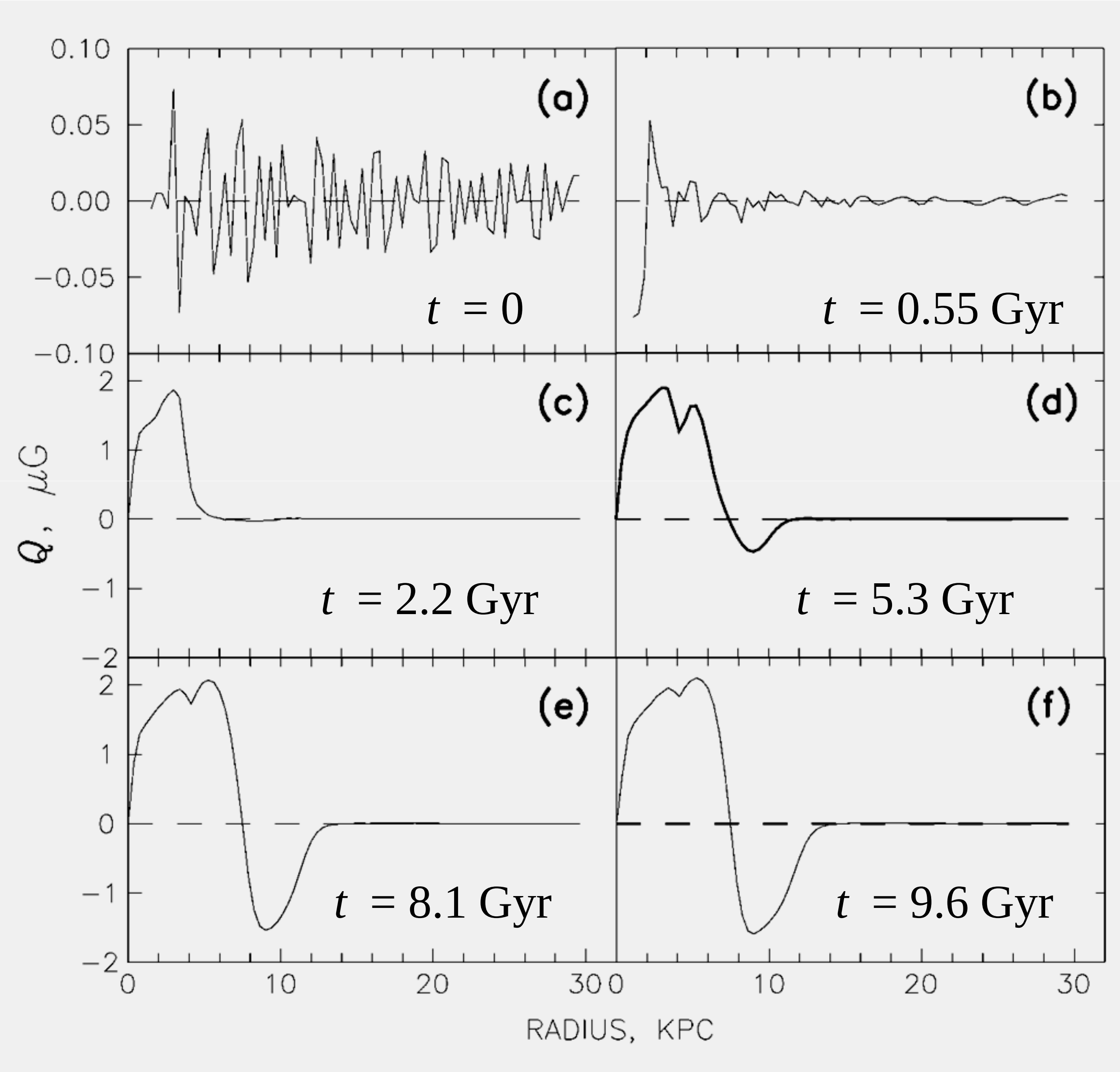
$$\rho_{\rm hot} V_z^2 = \xi S, \quad S = {\rm SFR} \quad \Rightarrow \quad B \propto S^{1/4}$$

(IF all other relevant parameters are independent of SFR)

2. Meso-scale magnetic structures

Further details in: A. Shukurov, Mesoscale Magnetic Structures in Spiral Galaxies, in: *Cosmic Magnetic Fields*, eds. R. Wielebinski & R. Beck, Lect. Notes Phys. 664, Springer, 2005, pp. 113-135.

2.1. Axisymmetric reversals

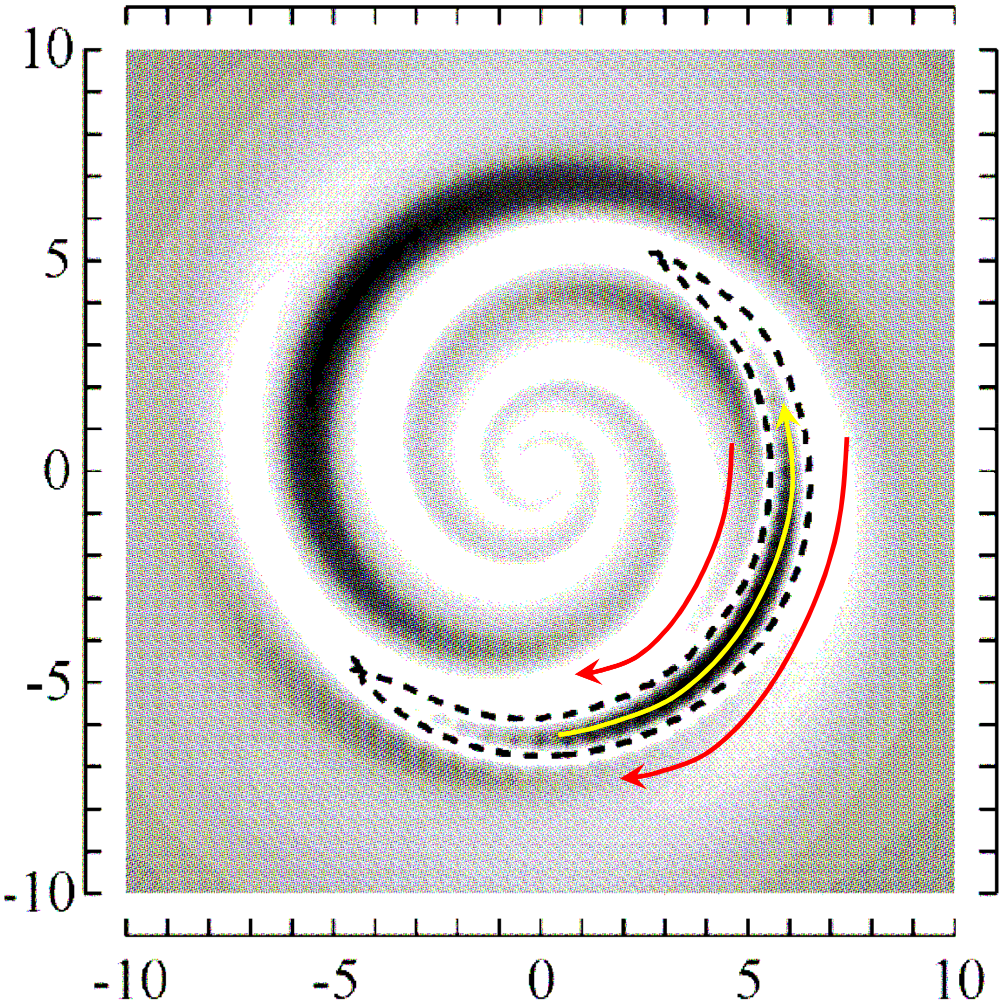


Poezd at al. (1993): thin-disc dynamo, random seed field: numerous reversals, nonlinear effects can preserve some of them for a long time in the Milky Way, but not in M31.

Positions of reversals:

$$r^2\gamma\left(\frac{1}{r}+2\,\frac{B_0'}{B_0}\right)+\frac{1}{2}\,r^2\gamma' = 0$$

Localised reversals?



Bykov et al . (1997): long-lived region of reversed magnetic field near the corotation radius.

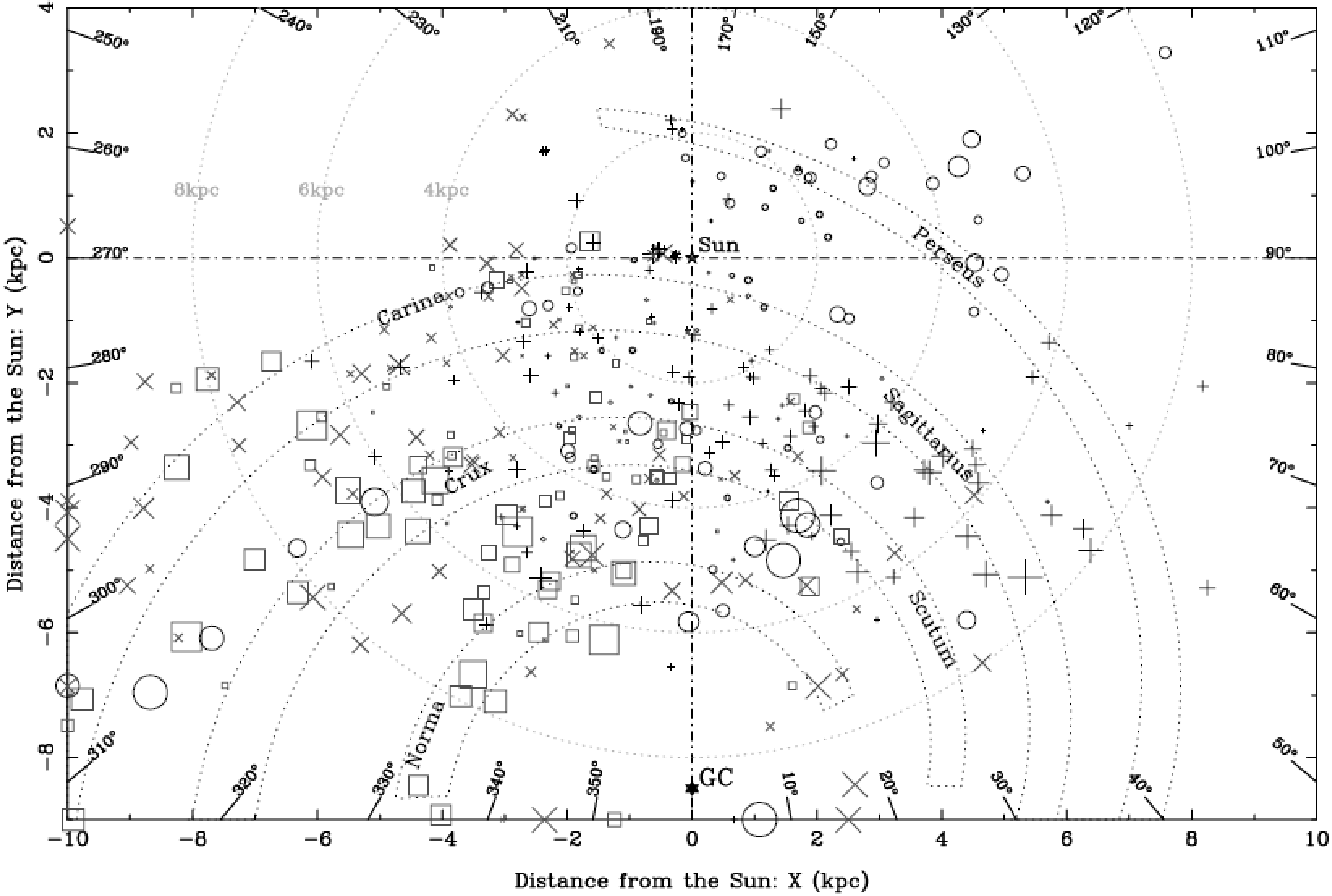
Rotation curve and spiral structure of M51

Observational picture

- The only firmly established reversal of the large-scale magnetic field is the Sagittarius-arm one (Simard-Normandin & Kronberg, Nature 1979).

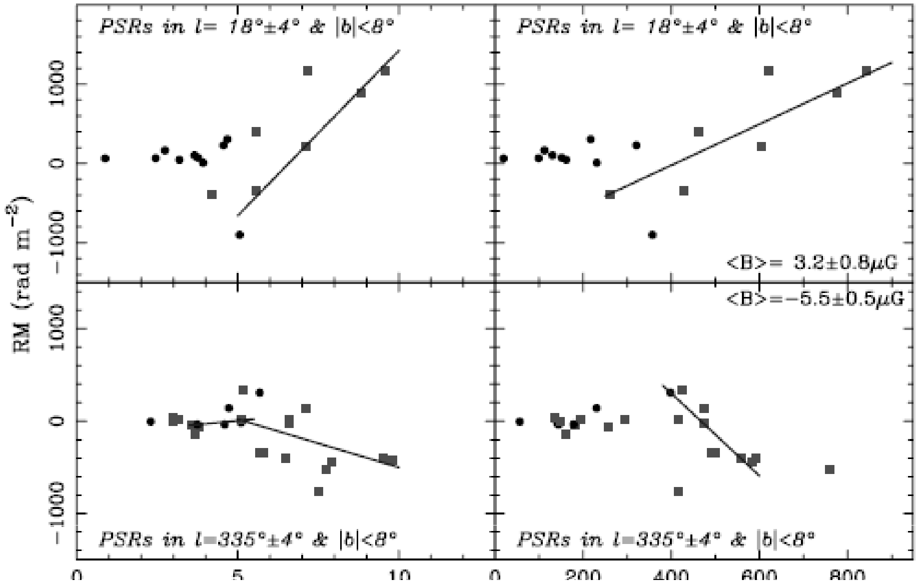
- All models with more reversals do not meet even basic statstical criteria. Likewise, it is not possible to decide what is the global azimuthal symmetry (ASS vs BSS) (Men et al. A&A, 819, 2008; Farrar et al. 2009).

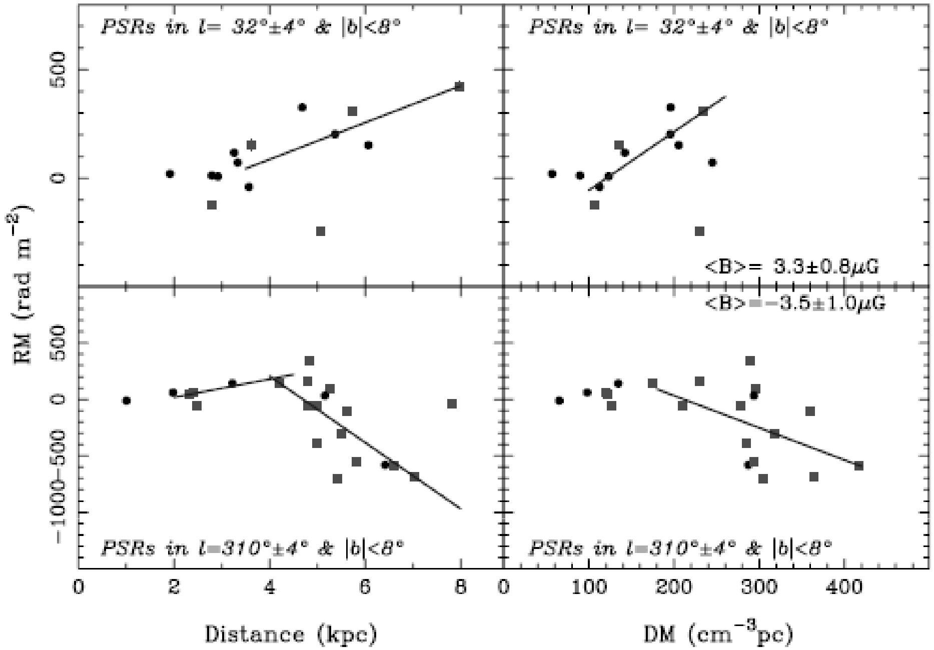
- Nature of the problems: deriving B from $\int_0^L n_e B_{//}\, \mathrm{d}s$, need for a **VERY** careful statistical treatment

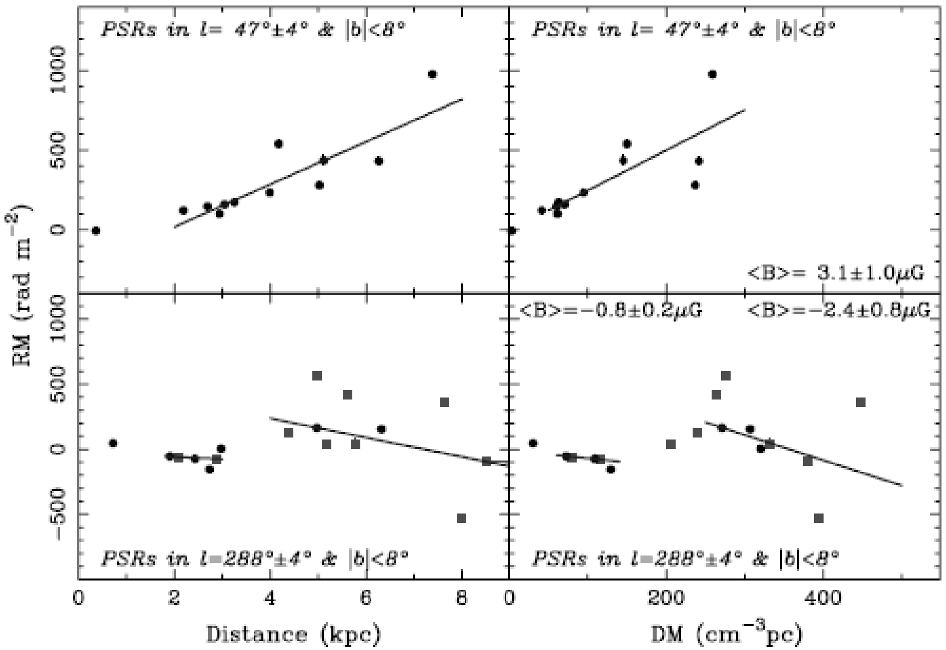


Deducing the global structure from noisy data

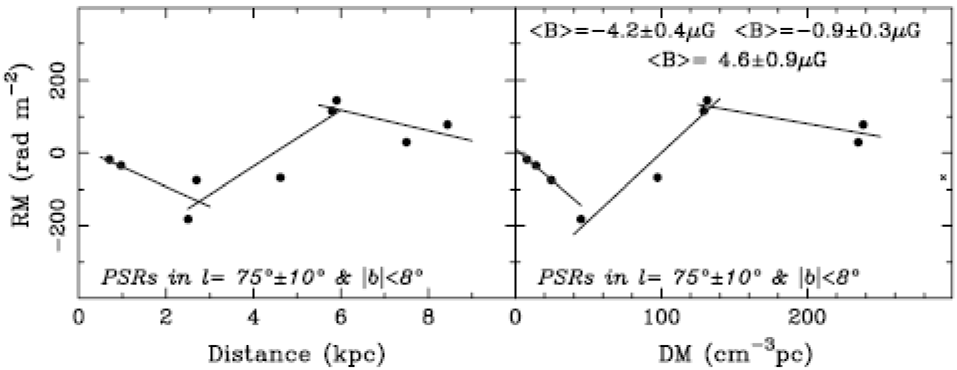
Multiple reversals?





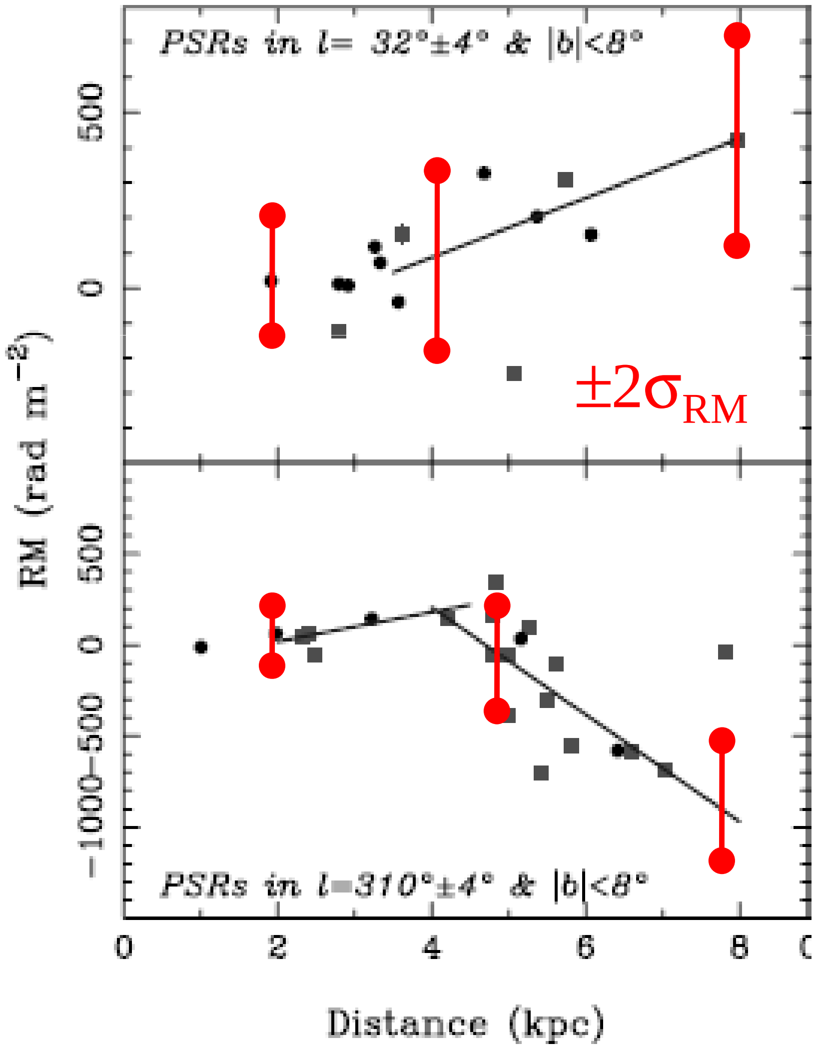


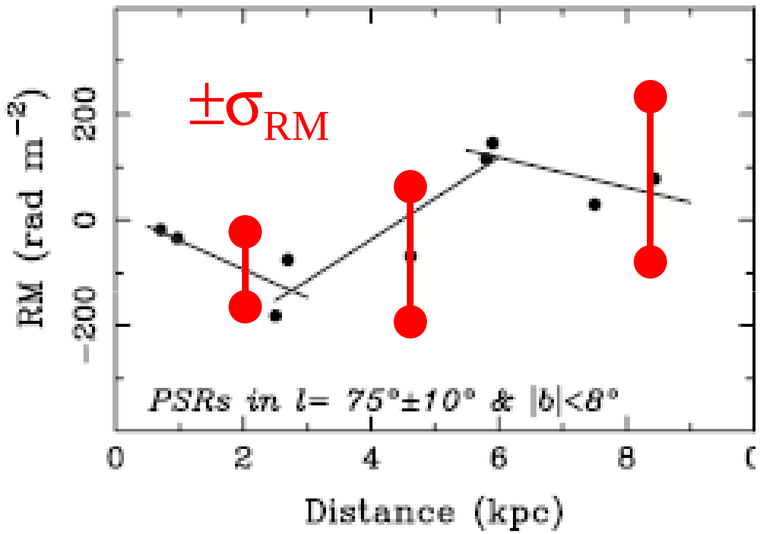
$$\mathrm{RM}(L) = \int_0^L n_e B_\parallel \, \mathrm{d}l$$



Random magnetic field:

$$\sigma_{\rm RM} = K n_{\rm e} b (2dL)^{1/2} \simeq 55\,{\rm rad\,m^{-2}} \frac{n_{\rm e}}{0.03\,{\rm cm^{-3}}} \frac{b}{5\,\mu{\rm G}} \left(\frac{d}{100\,{\rm pc}}\right)^{1/2} \left(\frac{L}{1\,{\rm kpc}}\right)^{1/2}$$





3. Small-scale magnetic structures in the multi-phase ISM

- Interstellar magnetic field ≠ a quasi-homogeneous Gaussian random vector field.
- Interstellar shocks, multi-phase structure, …
- A quasi-homogeneous, weaker magnetic background from the tangling of the large-scale magnetic field by turbulence.

Further details in:

A. Shukurov & D. Sokoloff, Astrophysical dynamos. In: Ph. Cardin, L.F. Cugliandolo, editors, *Les Houches, Session LXXXVIII, 2007, Dynamos*. Elsevier, 2008, p. 251—299.

A. Shukurov, Introduction to galactic dynamos. In: *Mathematical Aspects of Natural Dynamos*, eds E. Dormy & A. M. Soward, Chapman & Hall/CRC, 2007, pp. 313--359 (astro-ph/0411739).

- More importantly: **fluctuation dynamo** produces intermittent magnetic fields even in a homogeneous medium

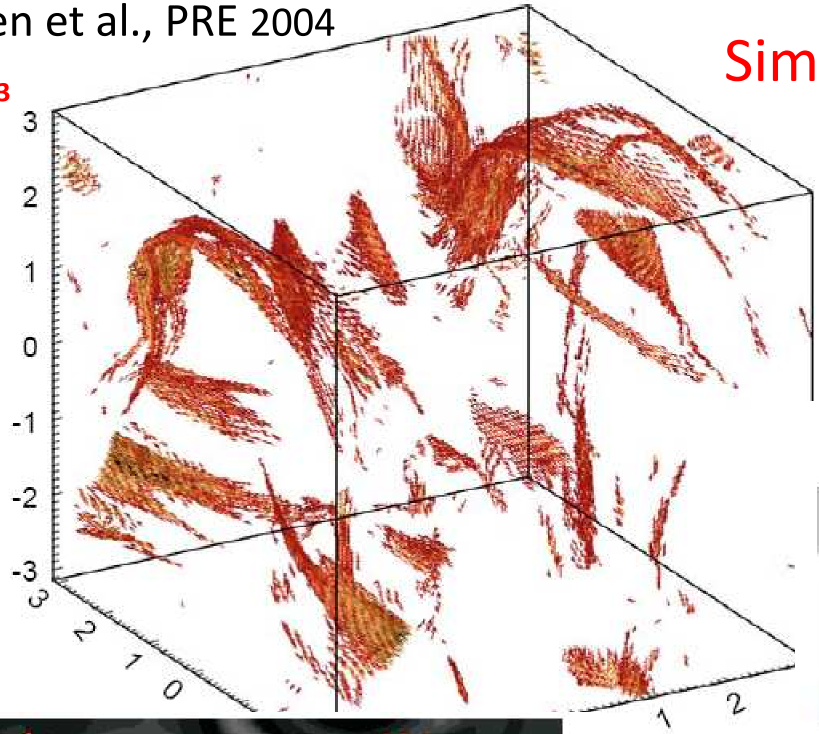
- Magnetic filaments (+ ribbons & sheets?), $\langle \boldsymbol{B} \rangle = 0$

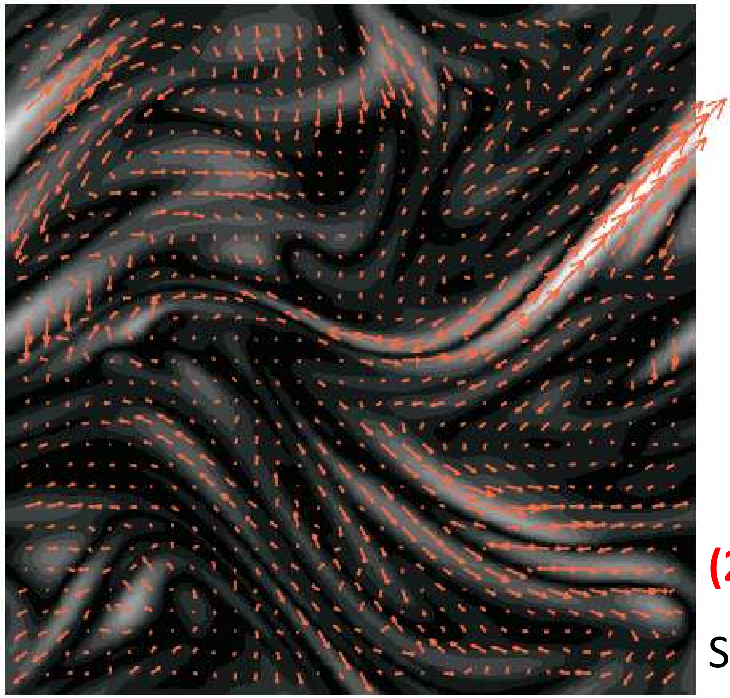
  - $B_{\max} \cong B_{\mathrm{eq}} = (4\pi\rho)^{1/2} \boldsymbol{v} \cong 5\ \mu\mathrm{G}$.
  - Length $\cong l \cong$ 50–100 pc.
  - Low volume filling factor, $\langle B^2 \rangle \cong 0.1\, B^2_{\max}$.
  - Kinematic stage: magnetic energy max at $l_\eta = l\, R_{\mathrm{m}}^{-1/2}$.
  - Nonlinear, statistically steady state: controversial
    - folds at $l_\eta = l\, R_{\mathrm{m}}^{-1/2} \cong 10^{-7}$ pc (???) (Schekochihin et al. 2004) or
    - thicker structures $l_{\eta,\mathrm{cr}} = l\, R_{\mathrm{m,cr}}^{-1/2} \cong 10$ pc (Subramanian 1999).

Simulations of the fluctuation dynamo: magnetic isosurfaces, $B^2 = \text{const}$

Haugen et al., PRE 2004

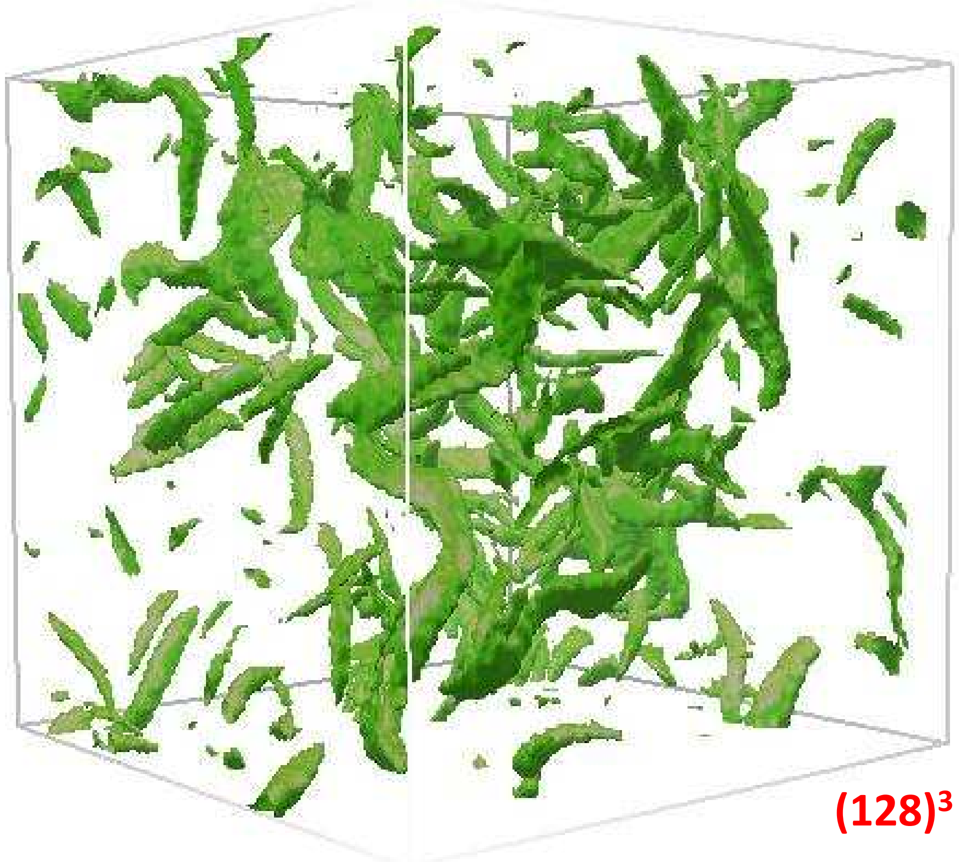
$(1024)^3$





$(256)^3$

Schekochihin et al., ApJ 2004



$(128)^3$

Wilkin et al., PRL 2007

Implications

- Power spectrum & structure/correlation function are not suitable tools to describe intermittent magnetic fields

  (intense flux ropes separated by extended regions with relatively weak magnetic field).

- Magnetic field estimates from synchrotron intensity can be strongly affected (underestimated random magnetic field).

- Cosmic ray propagation can be strongly affected by magnetic intermittency. No models available of cosmic ray propagation in such magnetic fields.

- Locally anisotropic magnetic fields are less efficient in cosmic ray scattering (> 10^2–10^3 GeV) (Chandran 2000).