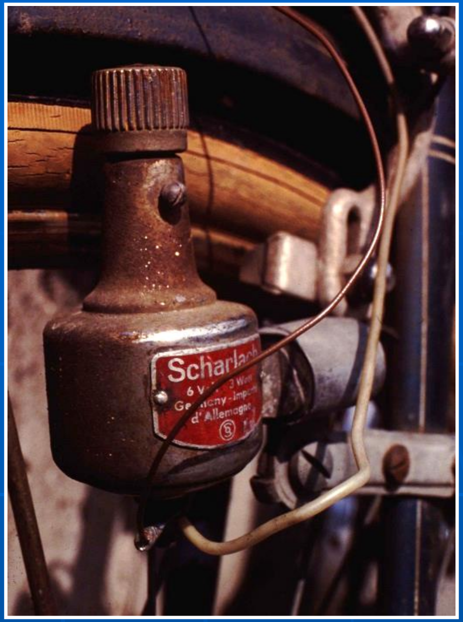


Lecture 4:

Origin of Magnetic Fields in Galaxies

Rainer Beck, MPIfR Bonn

Generation and amplification of cosmic magnetic fields

Stage 1: Field seeding

Stage 2: Field amplification

Stage 3: Coherent field ordering

Generation and amplification of cosmic magnetic fields

Stage 1: Field seeding

Primordial (intergalactic), Biermann battery, Weibel instability; ejection by supernovae, stellar winds or jets

Stage 2: Field amplification

Magneto-rotational instability (MRI), shock fronts, compressing flows, shearing flows, turbulent flows, small-scale (turbulent) dynamo

Stage 3: Coherent field ordering

Large-scale (mean-field) dynamo

Primordial seed fields
(more in the lecture by Fabio Finelli)

Caprini et al. 2009

- CMB power spectra:

  $B_{IGM} \leq 4$ nG on 1 Mpc scale

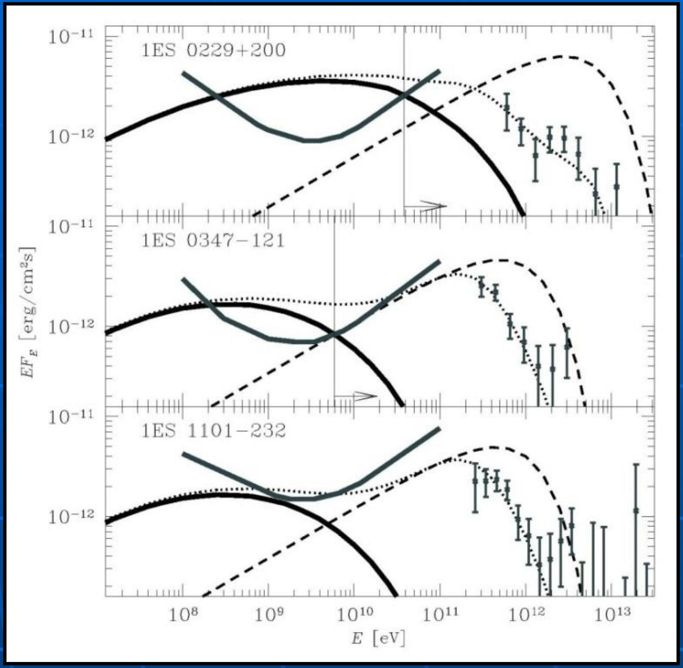
- Generation at inflation:

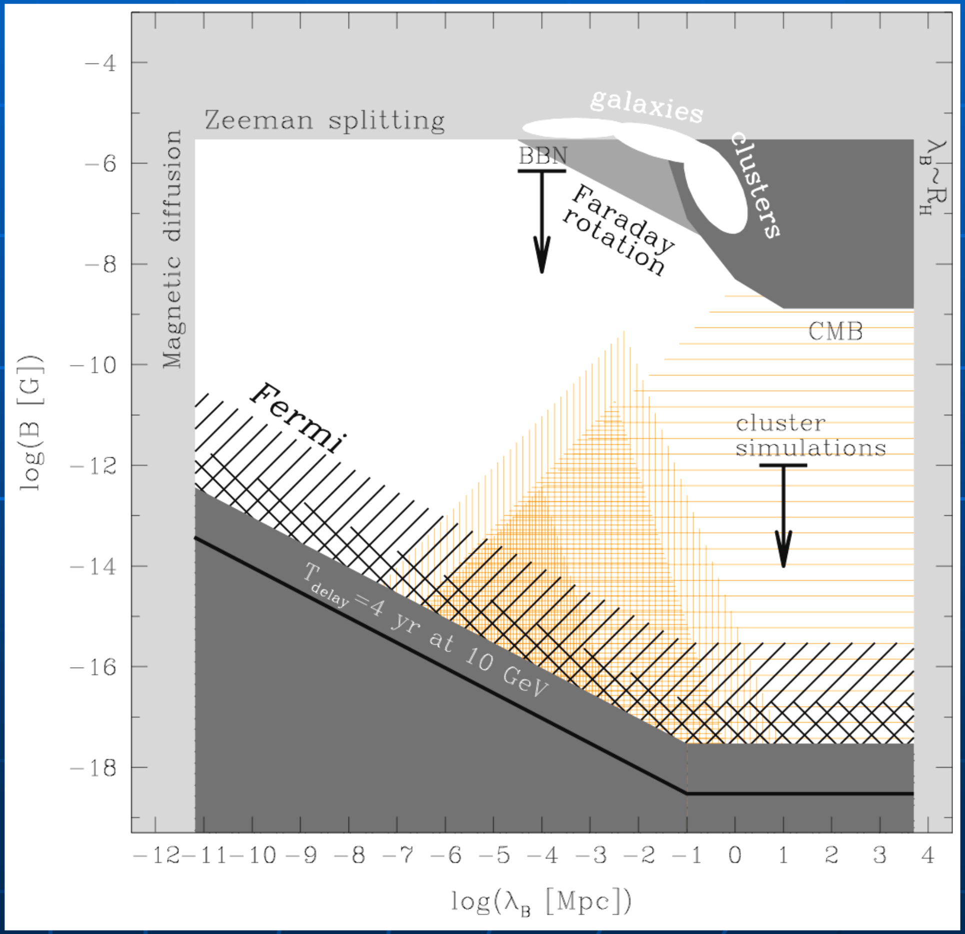
  $B_{IGM} \leq 10^{-9}$ G on 0.1 Mpc scale (non-helical fields)

  $B_{IGM} \leq 10^{-18}$ G on 0.1 Mpc scale (helical fields)

Intergalactic seed fields ?

Neronov & Vovk 2010



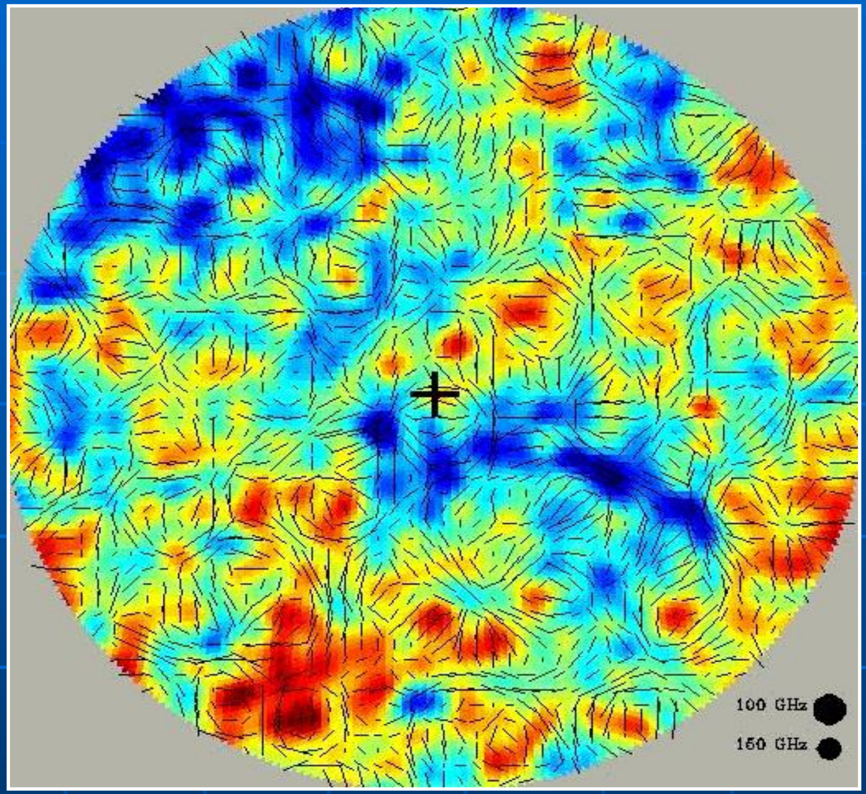


Non-detection of TeV blasars in the GeV range by FERMI:

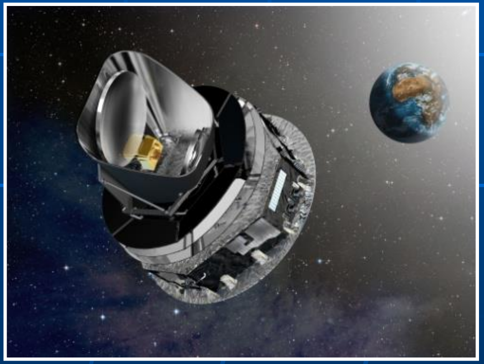
$B_{ISM} \approx 10^{-17 \ldots -15}$ G

Sufficient for seeding !

Primordial magnetic fields in the CMB era ?



BICEP CMB polarization (Caltech Observational Cosmology)

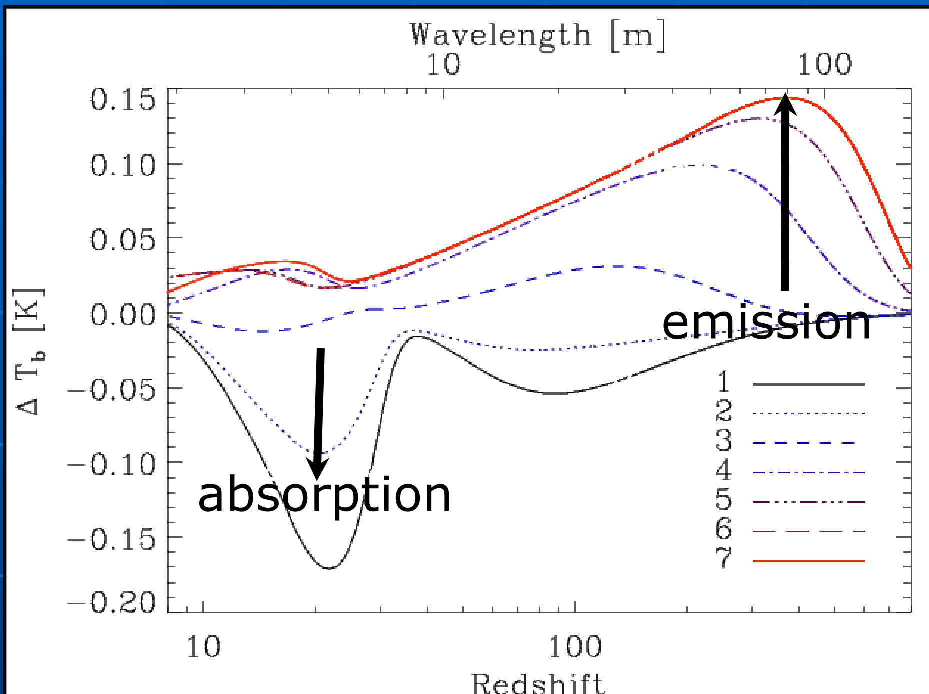


- CMB-era fields generate "B-modes" (correlated with E-modes) which may be detectable with PLANCK
- ≈nG fields may be detectable via its Faraday rotation (Kosowky & Loeb 1996)

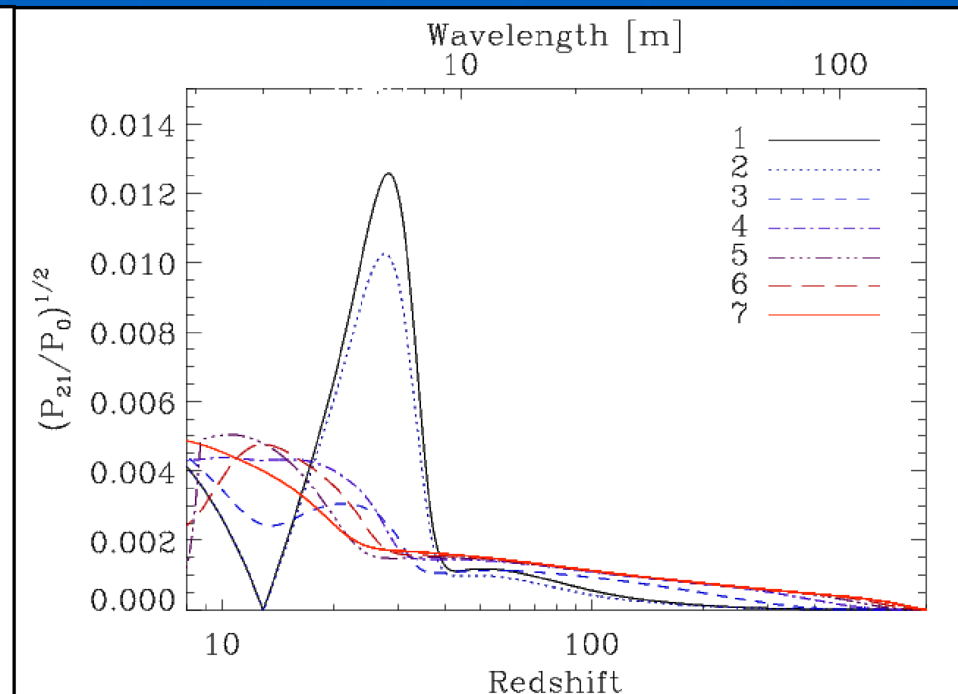
Primordial fields in the Epoch of Reionization ?

Schleicher et al. 2009

Brightness temperature



Power spectrum



Strong field: no absorption

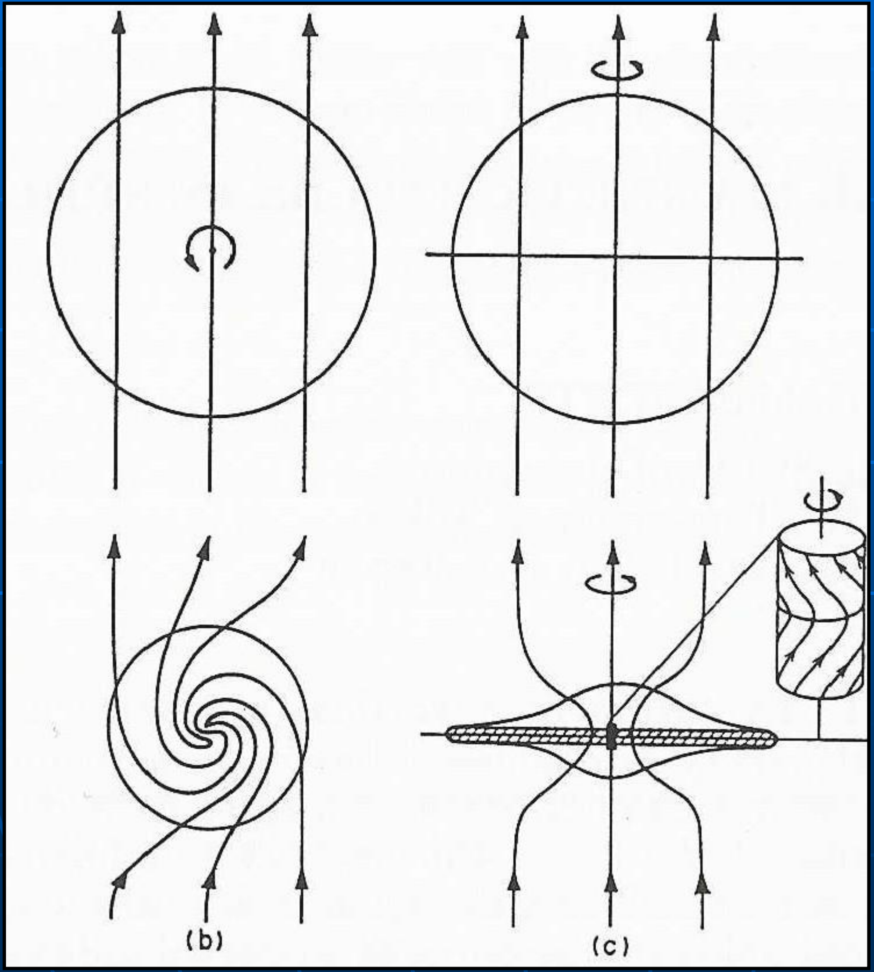
Strong field: more power at low z

Model	B_0 [nG]	f_*
1	0	0.1%
2	0.02	0.1%
3	0.05	0.1%
4	0.2	0.1%
5	0.5	0.1%
6	0.8	0.1%
7	0.8	1%

Strong impact on predicted HI spectra

Requested: Observations at $z \geq 50$ (≤ 30 MHz)

Large-scale primordial seed fields ?



Generation of
large-scale
bisymmetric
or dipolar fields

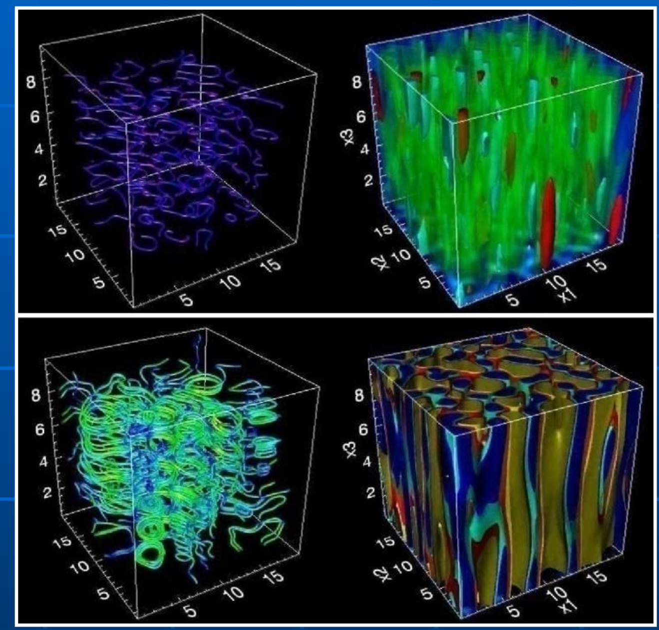
Problem:
Winding up of
field lines

Sofue 1990

Protogalactic seed fields ?

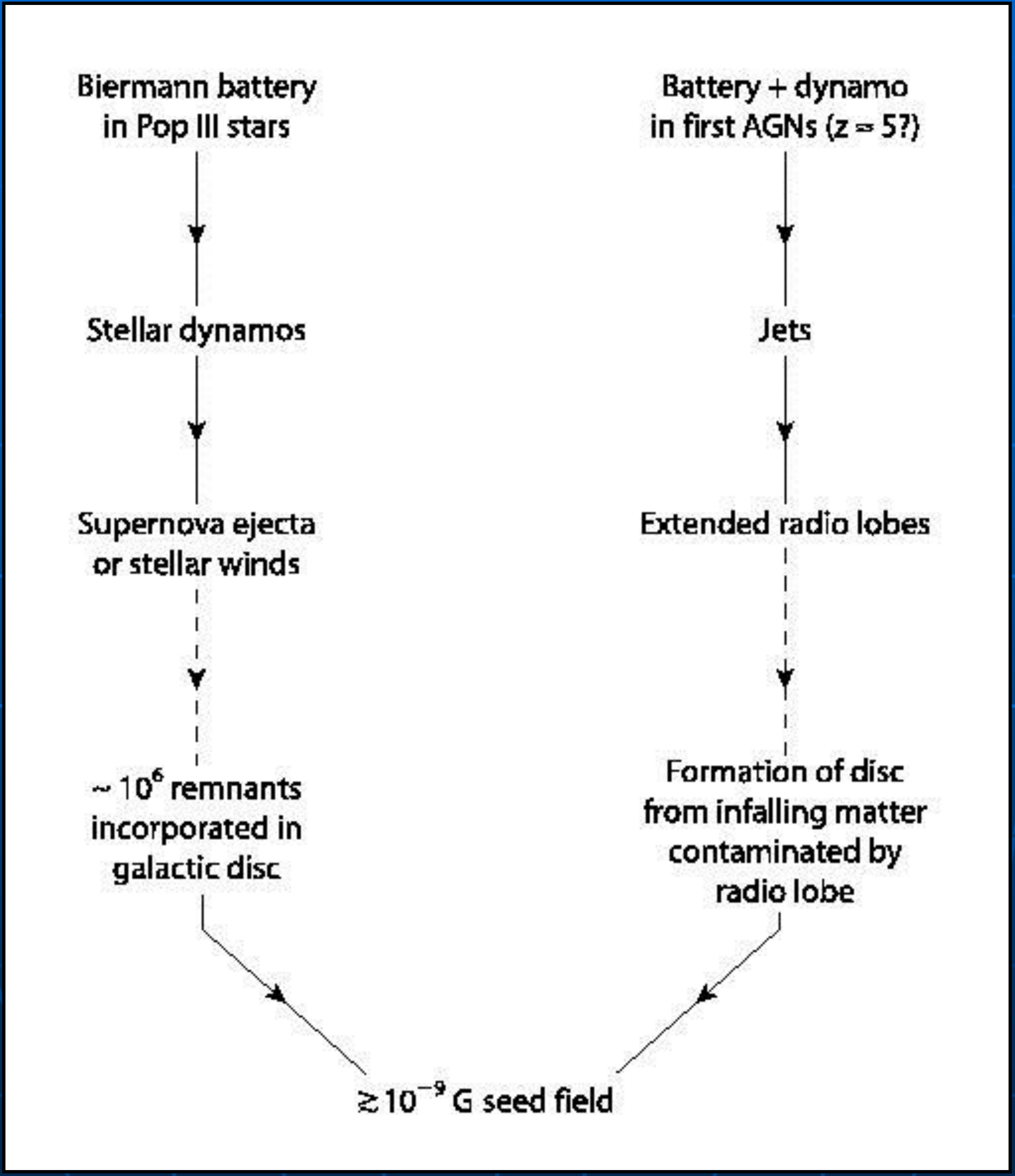
z ≈ 40-20: Formation of protogalactic halos

- Generation of seed magnetic fields in shock fronts (Weibel instability)
Amplitude: ≈ 10^{-18} - 10^{-6} Gauss
(Medvedev et al. 2004)



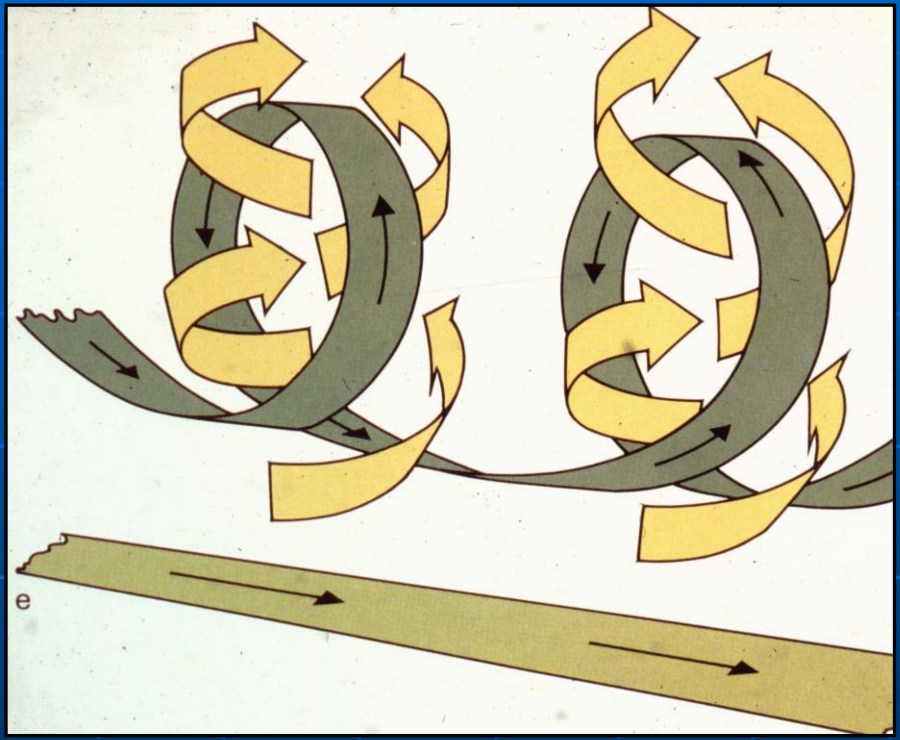
- Generation of seed magnetic fields by plasma fluctuations
Amplitude: ≈ 10^{-21} - 10^{-12} Gauss
(Schlickeiser 2012)

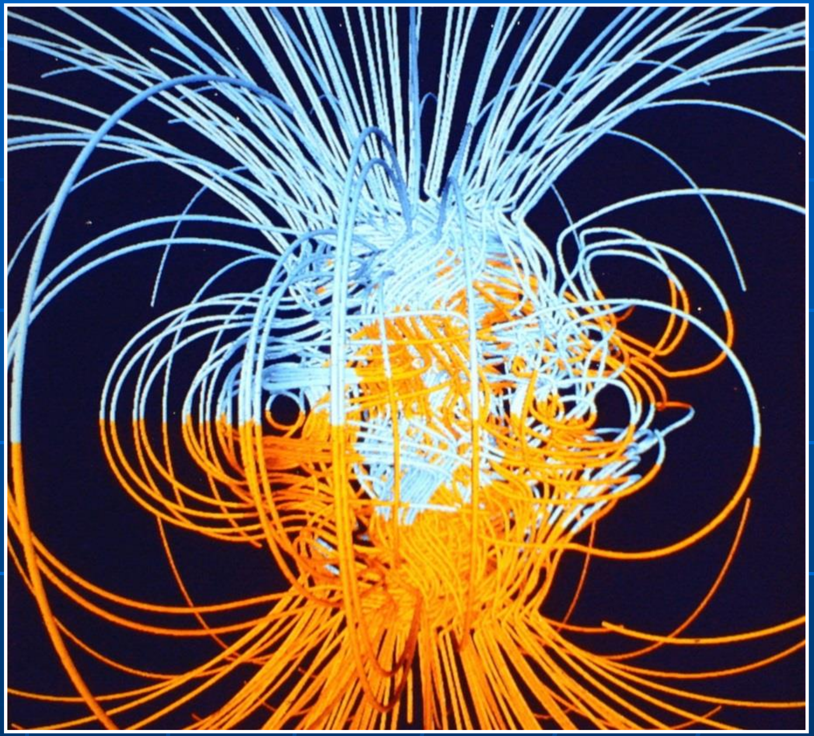
Seed fields from the first stars or AGNs?



Rees 2005

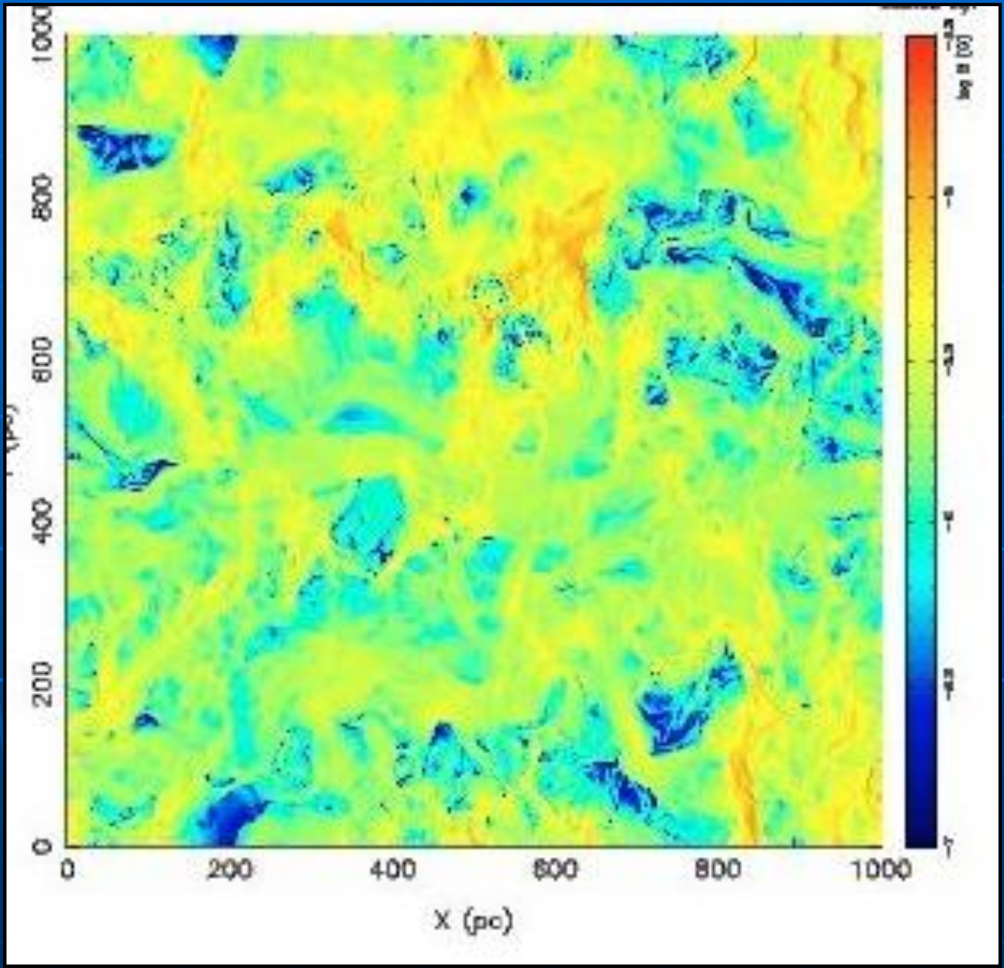
Field amplification: The dynamo
(see also the lecture by Fausto Cattaneo)





“Stretch, twist & fold”

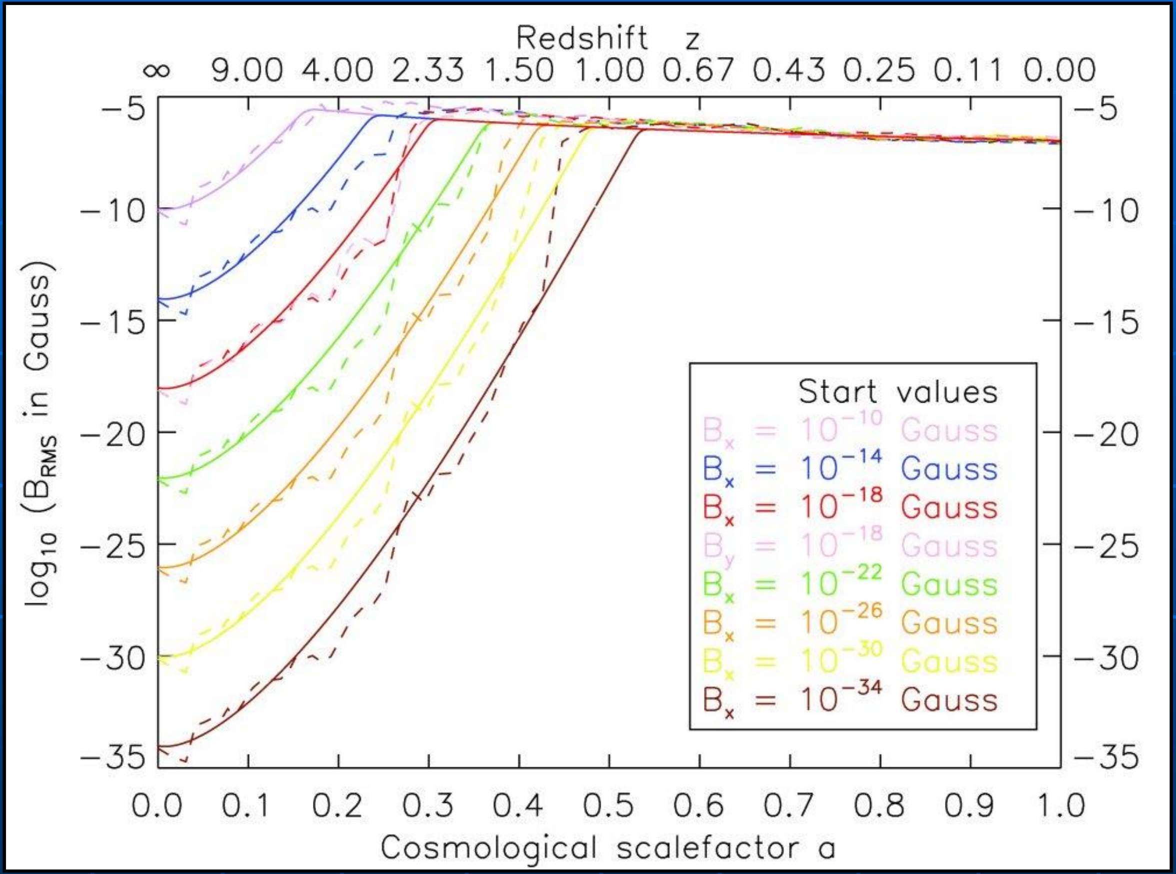
Turbulence: small-scale dynamo



de Avillez & Breitschwerdt 2005

Magnetic fields in the interstellar medium

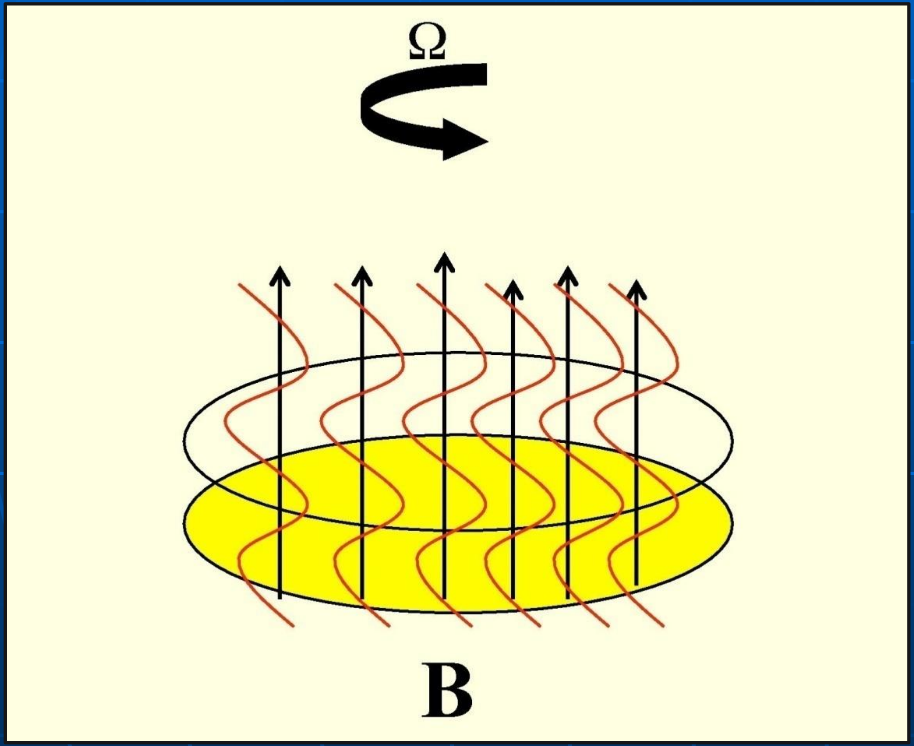
Simulation of a small-scale dynamo in young galaxies

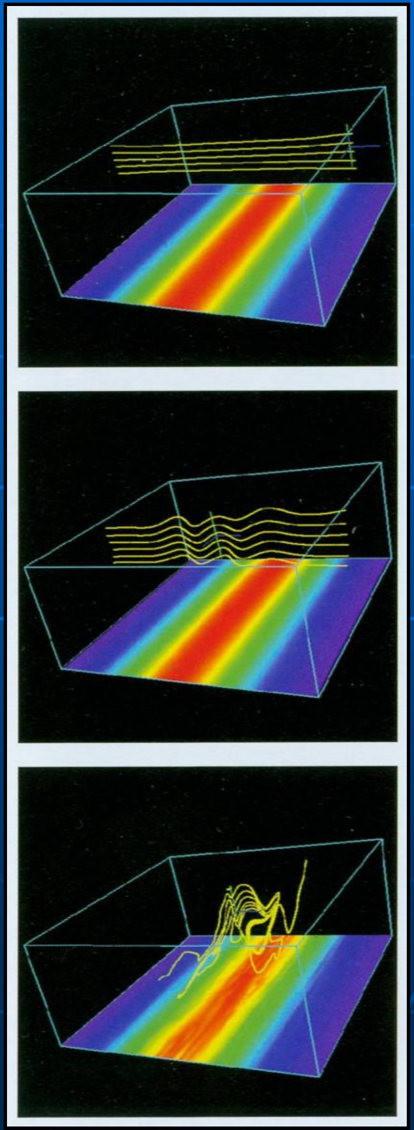


A. Beck et al. 2012

Equipartition with turbulent energy is reached within $\approx 10^8$ yr, almost independent of the seed field

Magneto-rotational instability (MRI): source of turbulence in outer galaxies





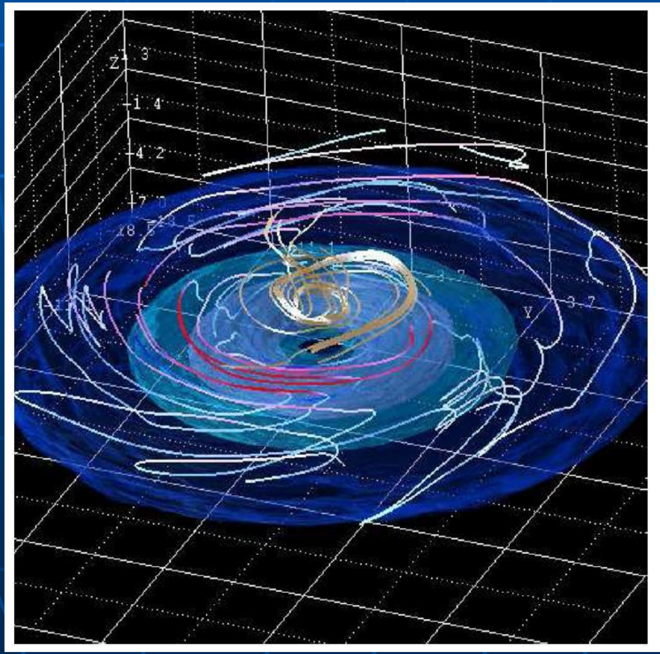
Balbus & Hawley 1998

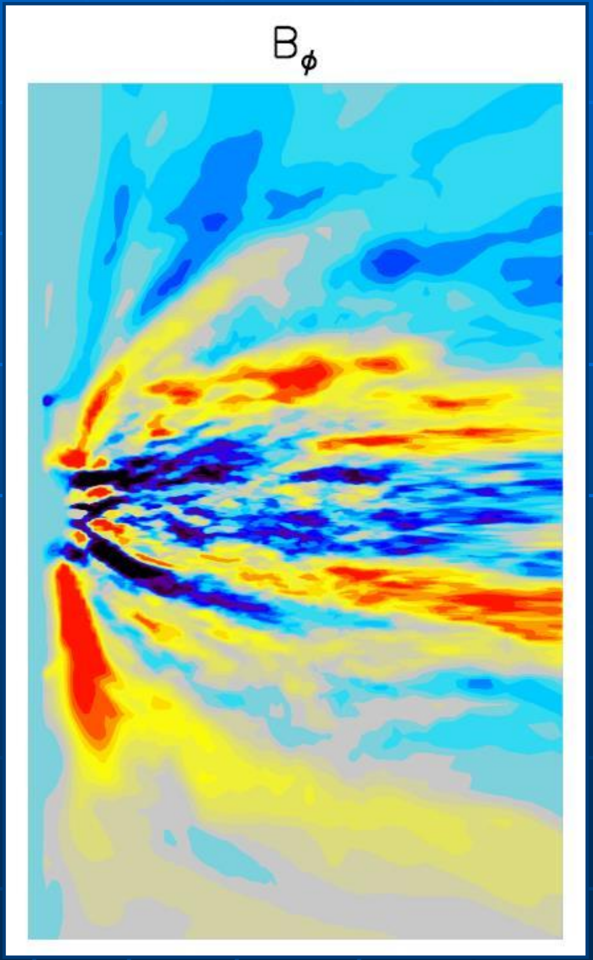
Jim Stone, Princeton

MHD-MRI model of spiral galaxies (1)

- Magnetic fields are dynamically unimportant ($\beta > 1$)
- Many large-scale field reversals along radius and height
- No large-scale field

Machida et al. 2013

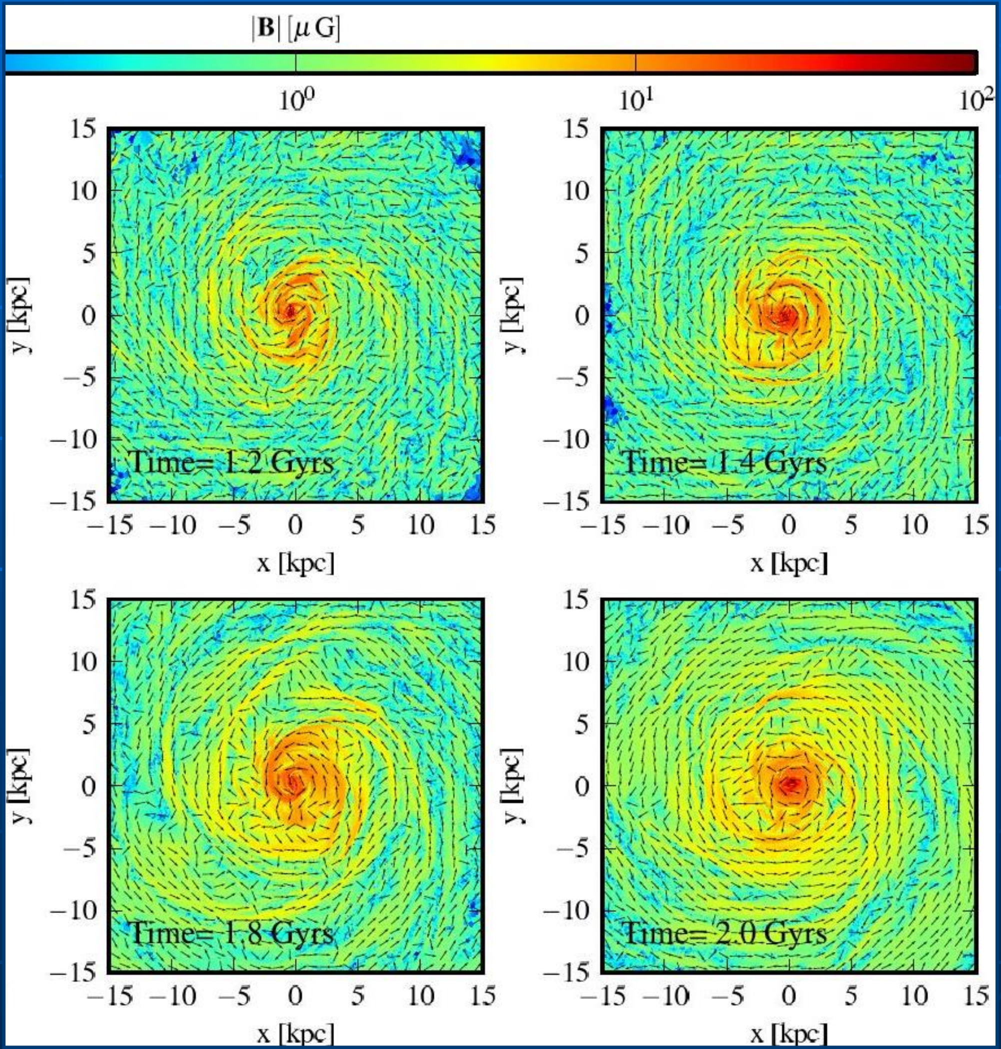




MHD-MRI model of spiral galaxies (2)

Pakmor & Springel 2013

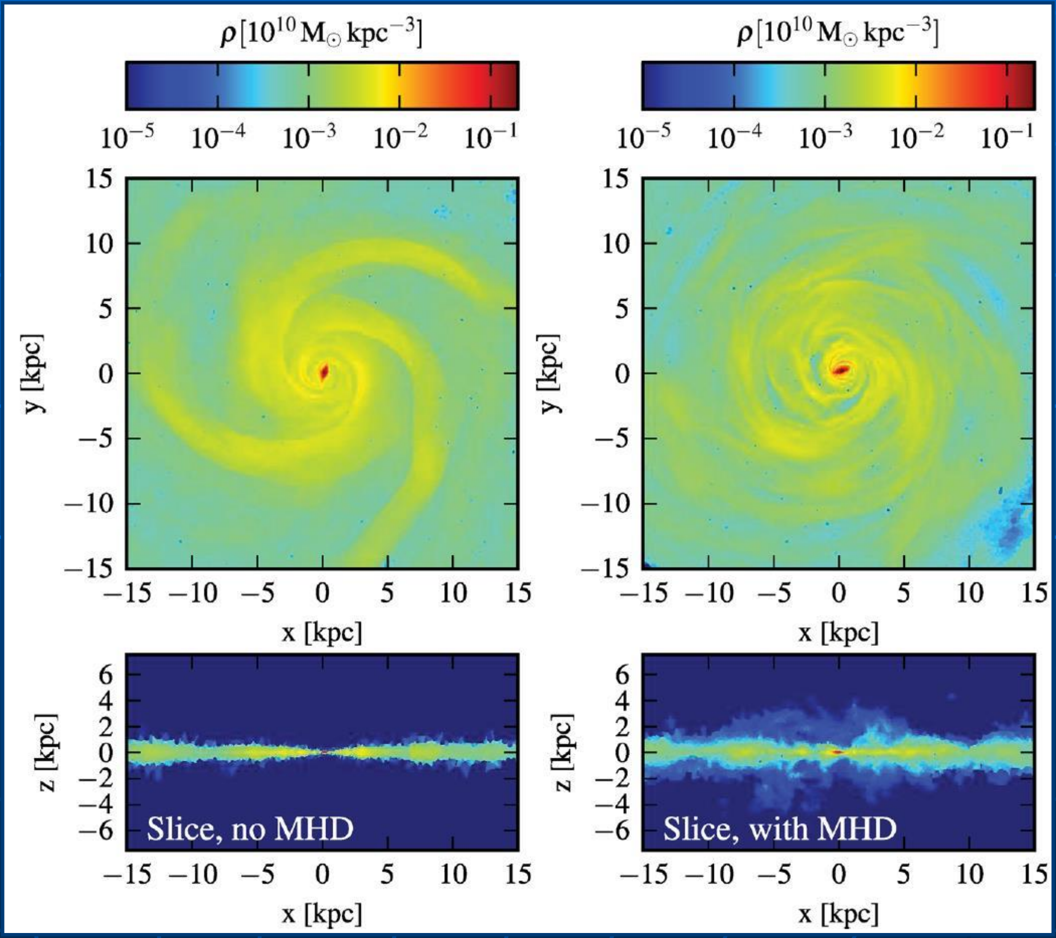
- Magnetic fields are dynamically important ($\beta \approx 1$)
- Many large-scale field reversals along radius and height
- No large-scale field



MHD-MRI model of spiral galaxies (2)

Pakmor & Springel 2013

- Spiral arms are more patchy in MHD case after 2 Gyr
- Star-formation rate is ≈30% lower in MHD case
- Vertical outflows only in MHD case



Large-scale (mean-field) dynamo

$$\partial \underline{\mathbf{B}} / \partial t = \underline{\nabla} \times (\underline{\mathbf{v}} \times \underline{\mathbf{B}}) - \eta \underline{\nabla}^2 \underline{\mathbf{B}}$$

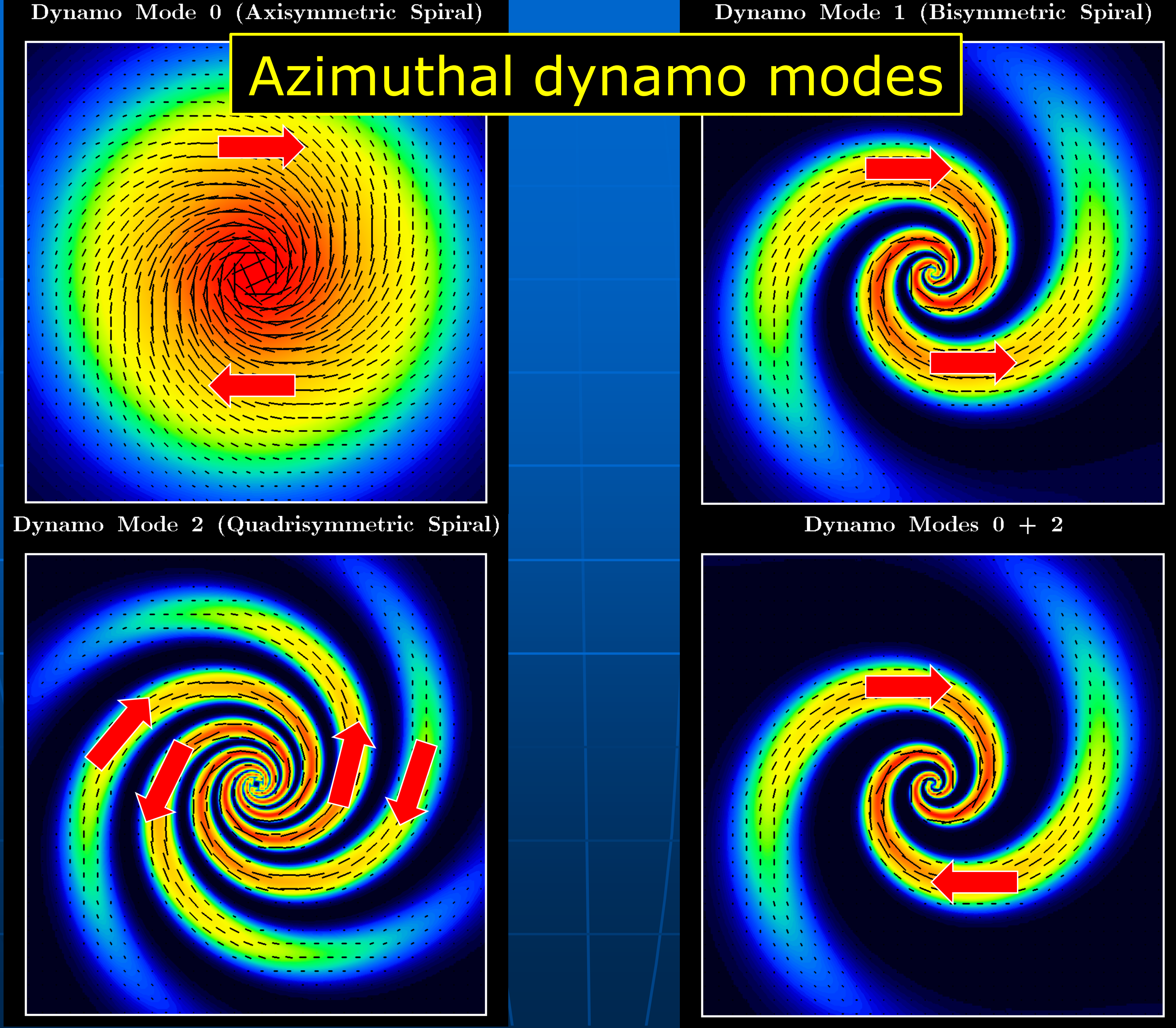
$$\partial \langle \underline{\mathbf{B}} \rangle / \partial t = \underline{\nabla} \times (\langle \underline{\mathbf{v}} \rangle \times \langle \underline{\mathbf{B}} \rangle + \alpha \langle \underline{\mathbf{B}} \rangle) - \eta \underline{\nabla}^2 \langle \underline{\mathbf{B}} \rangle$$

- Analytic solutions possible if small and large (< >) scales are separated
- Microphysics approximated by the average parameters:
  "alpha-effect" (α tensor) and magnetic diffusivity (η tensor)
- Needed:
  Ionized gas + differential rotation + turbulence + **seed field**
- Solutions for large scales: large-scale modes

Solutions of the mean-field dynamo equation

- Generation of large-scale coherent fields (modes)
- Flat objects (e.g. galaxy disks):
  Quadrupolar-type fields of symmetric *(even)* parity
- Spherical objects (e.g. stars, galaxy halos):
  Dipolar-type fields of antisymmetric *(odd)* parity

Azimuthal dynamo modes



Antisymmetric and symmetric dynamo modes

Stix 1975

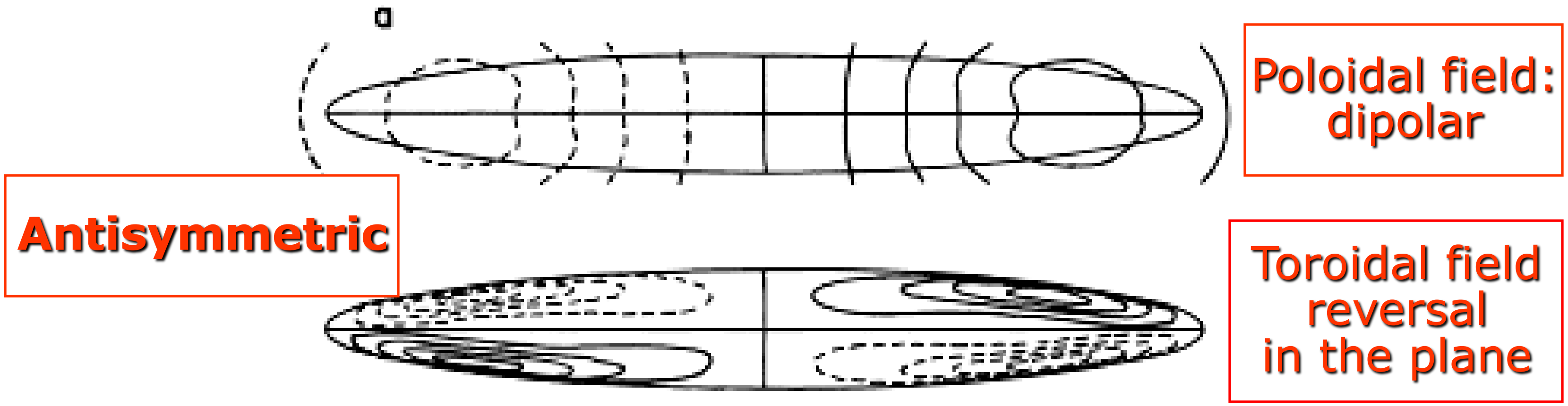


Fig. 1a and b. Poloidal field lines (a) and curves of constant toroidal field strength (b) for a dipole type field, with $R = 15$ kpc, $b = 2$ kpc, and $P = 1.1 \cdot 10^3$

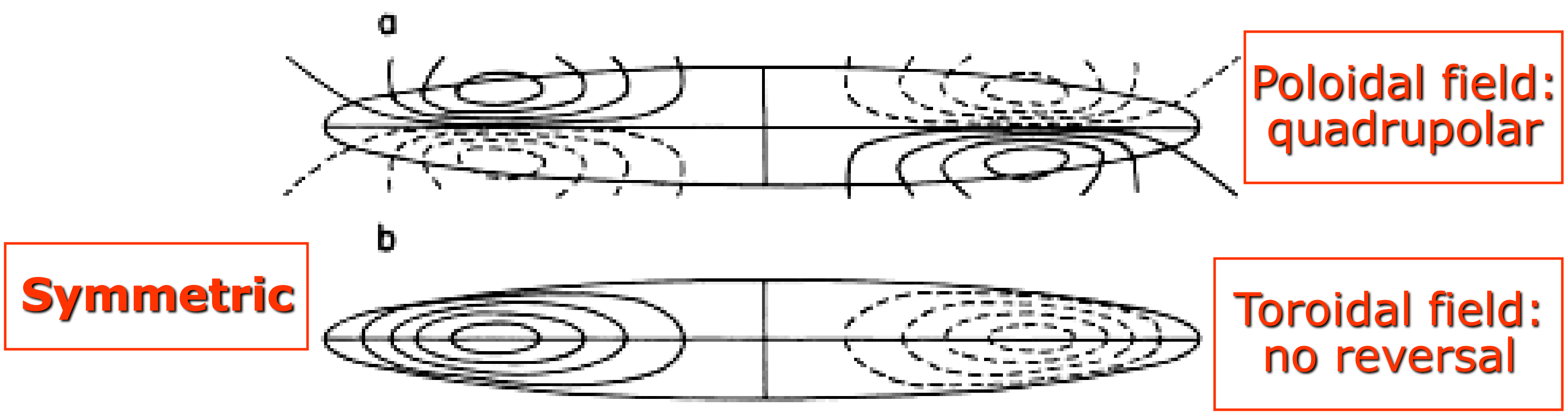
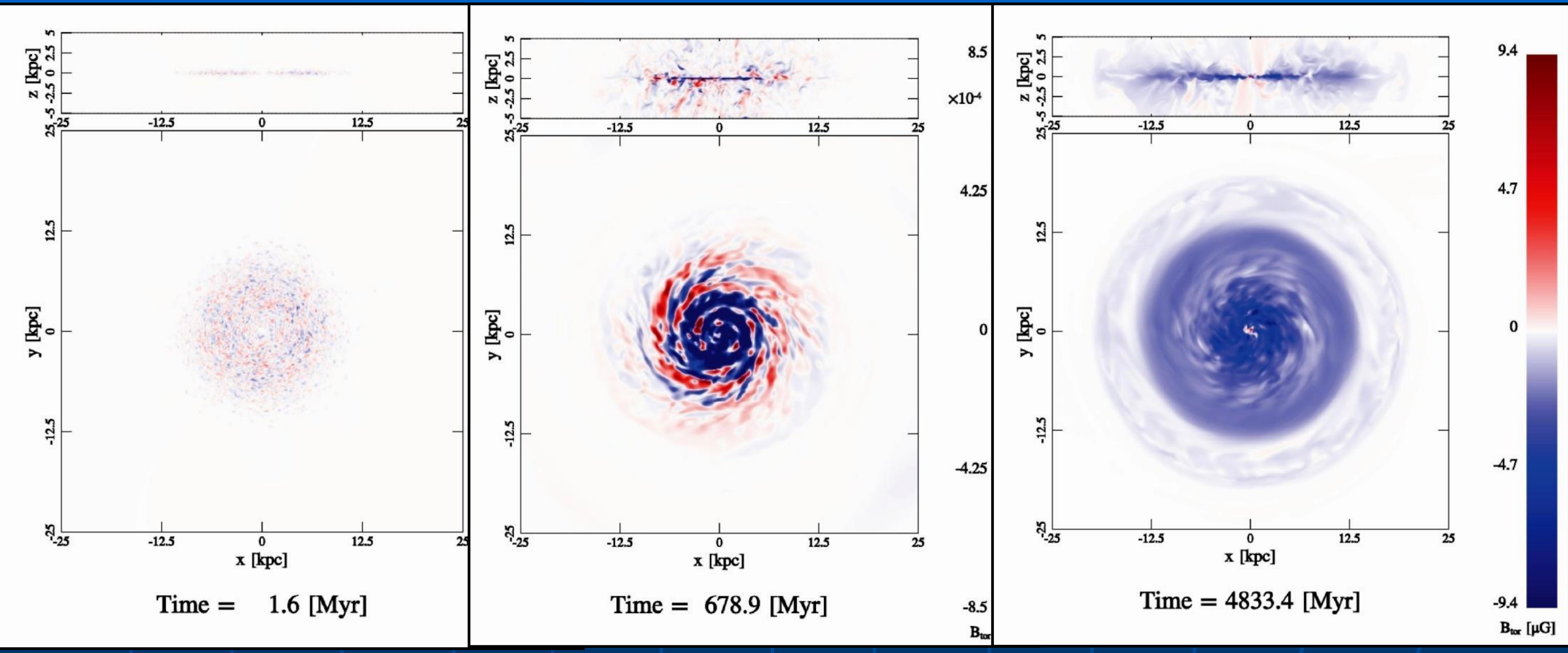


Fig. 2a and b. Poloidal field lines (a) and curves of constant toroidal field strength (b) for a quadrupole type field, with $R = 15$ kpc, $b = 2$ kpc, and $P = -8.5 \cdot 10^3$

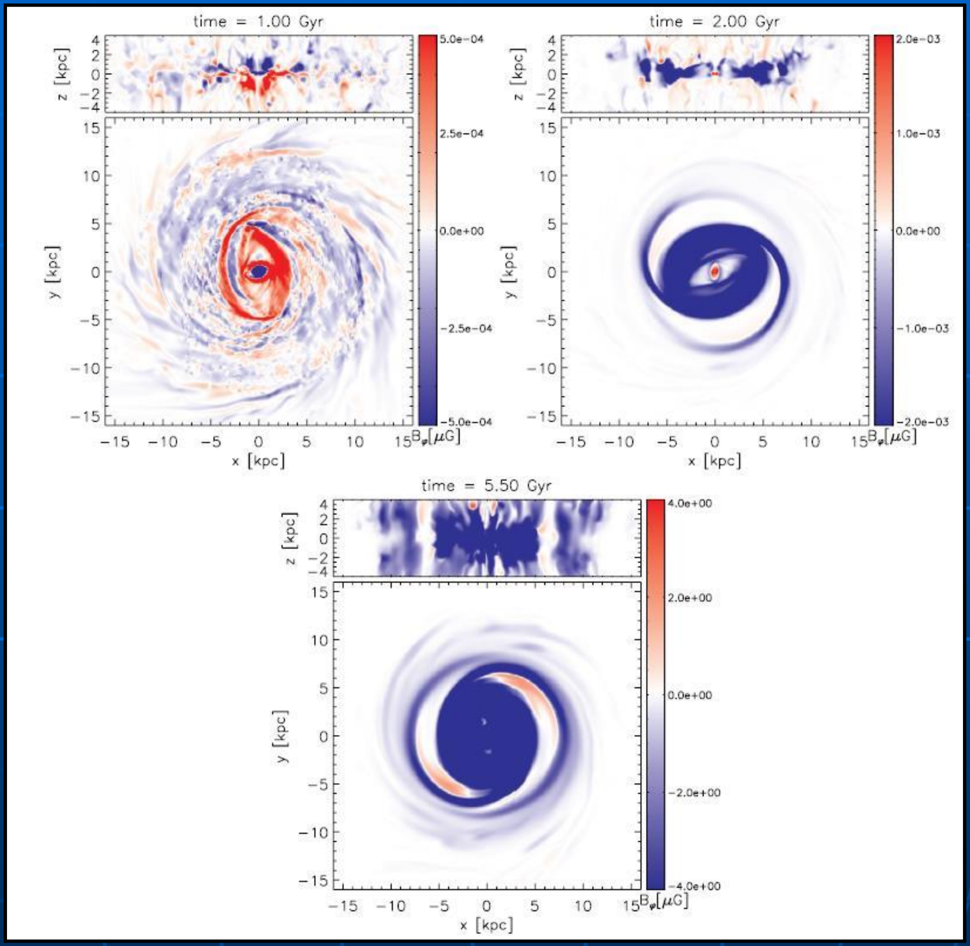
Global cosmic-ray driven MHD model (spiral galaxy)



Hanasz et al. 2009

Regular fields with several μG strength generated within a few Gyrs

Global cosmic-ray driven MHD model (barred galaxy)



Kulpa-Dybel et al. 2011

Regular fields with several μG strength generated within a few Gyrs

High-resolution dynamo simulation
(box of 1x1x2 kpc^3)

Gent et al. 2012

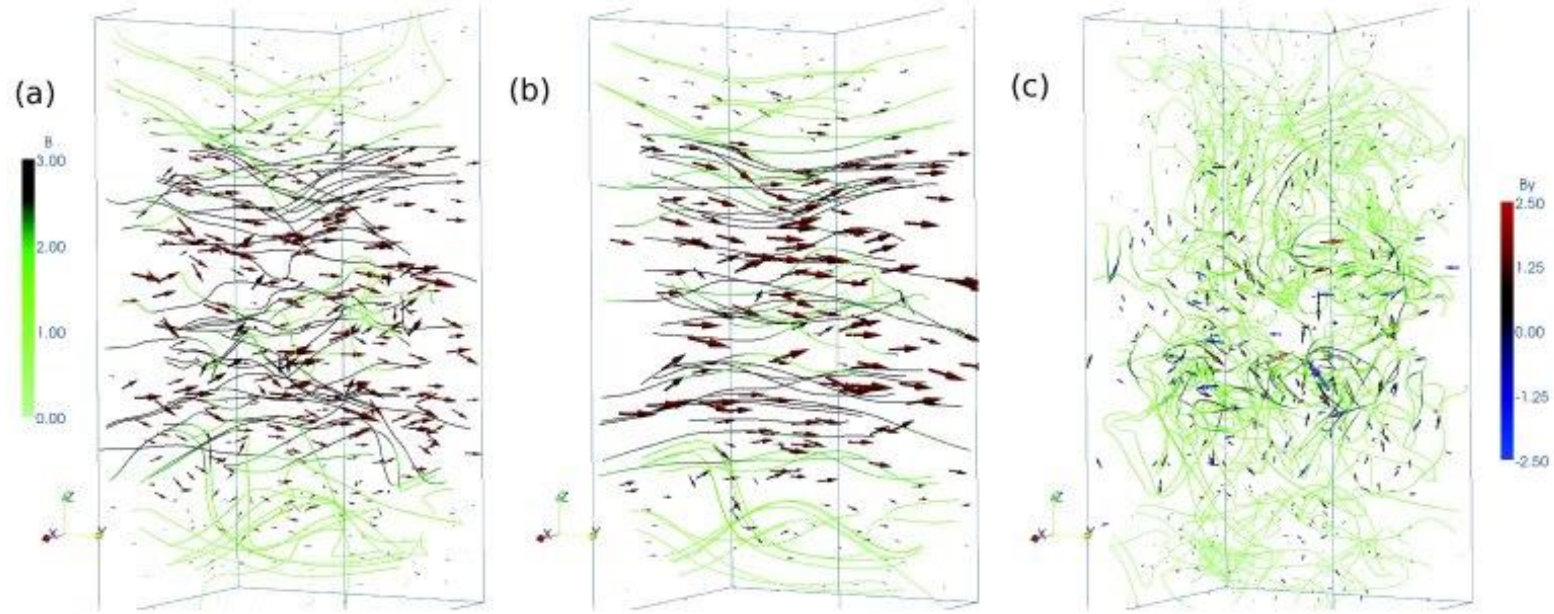
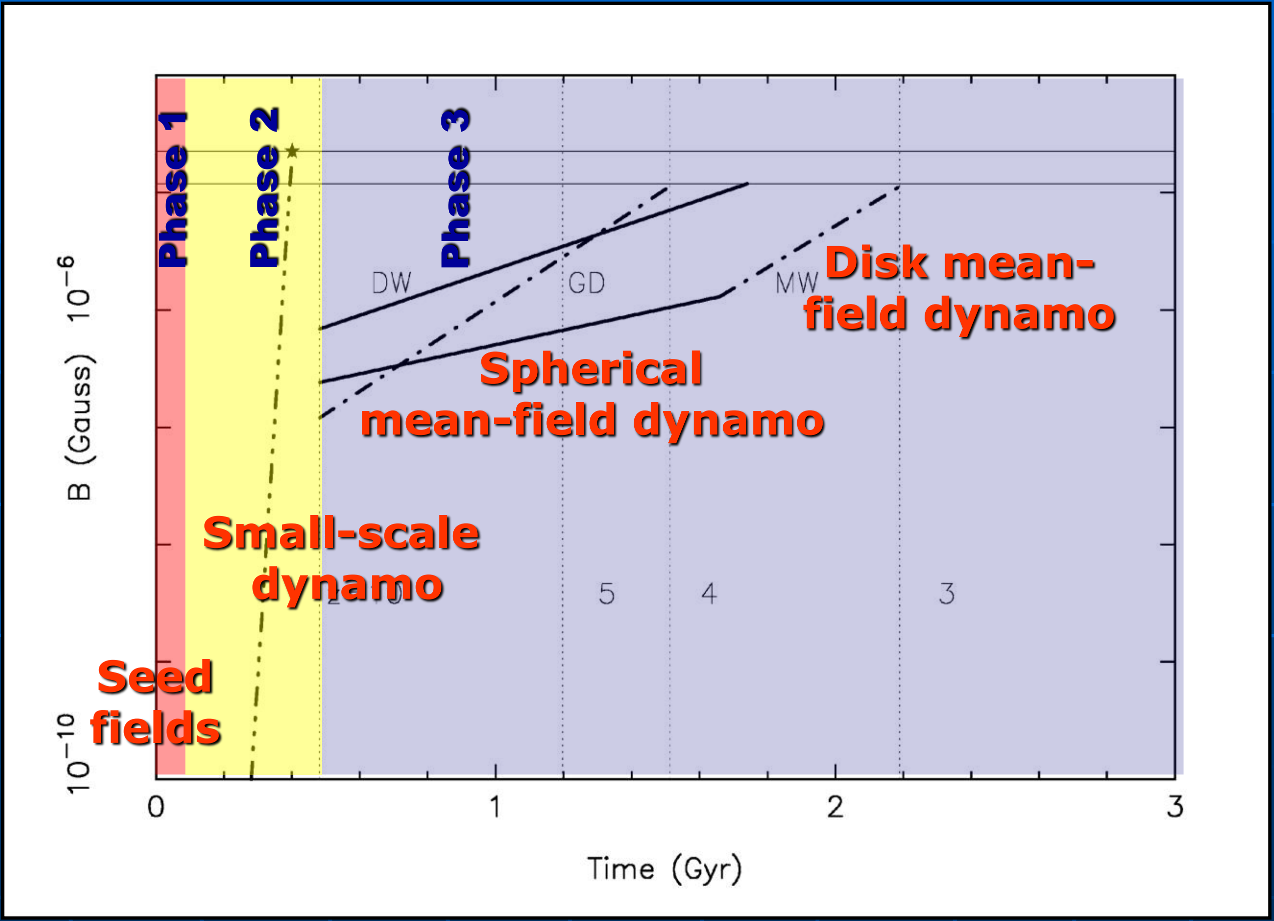


Figure 3. Field lines of (a) the total magnetic field $\boldsymbol{B}$, (b) its averaged part $\boldsymbol{B}_\ell$, (c) the fluctuations $\boldsymbol{b}$, obtained by averaging with $\ell = 50$ pc, for $t = 1.625$ Gyr. Field directions are indicated by arrows. The colour of the field lines indicates the field strength (colour bar on the left), whereas the vectors are coloured according to the strength of the azimuthal (y) component (colour bar on the right).

Total field | Regular field | Turbulent field

Time scales of magnetic field amplification by galactic dynamos

Arshakian et al. 2009



GD – giant disk galaxy (>15 kpc)
MW – Milky Way type galaxy (≈ 10 kpc)
DW – dwarf galaxy (≈ 3 kpc)

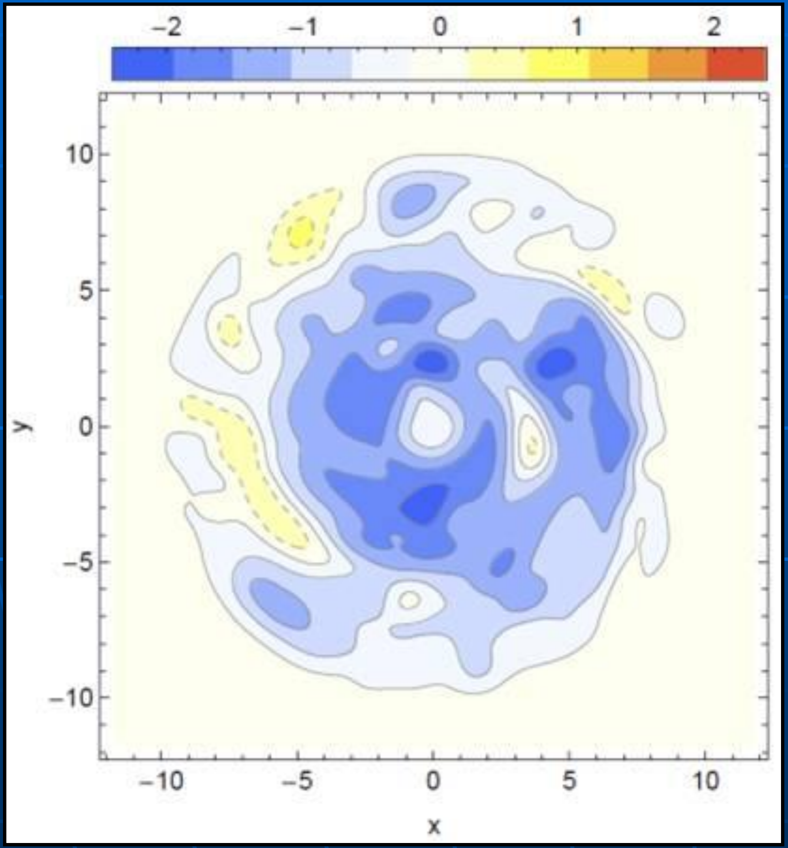
Predictions from dynamo theory

Arshakian et al. 2009

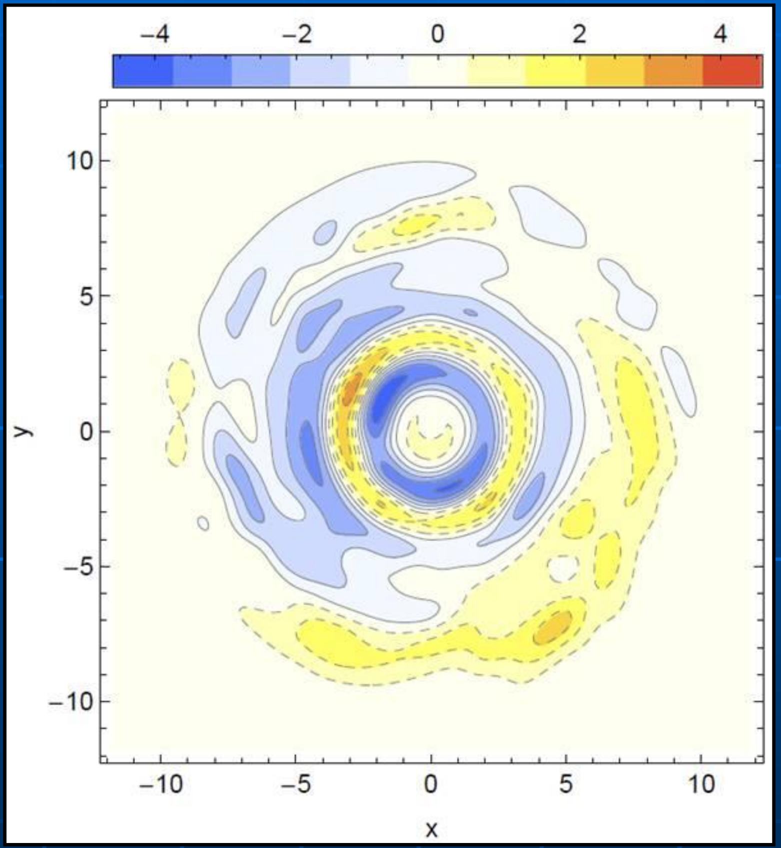
- Strong turbulent magnetic fields at $z < 10$
  → Unpolarized synchrotron emission from starburst galaxies: **$z < 10$**
- Strong regular fields at $z < 3$
  → Polarized radio emission and Faraday rotation from normal and dwarf galaxies: **$z < 3$**
- Large-scale regular magnetic fields in dwarf or Milky Way-type galaxies at $z < 1$
  → Large-scale patterns of Faraday rotation: **$z < 1$**
- Large galaxies (>15 kpc) may not yet have generated fully coherent fields

Model with injection of random seed fields
(moderate / high differential rotation)

Moss et al. 2012



Axisymmetric spiral field



Spiral field with large-scale reversals

Observational test:

Regular fields generated by dynamos should give rise to Faraday rotation

Discovery of the magnetic ring in M31
(Beck et al. 1980)

LETTERS

Distribution of polarised radio emission in M31

Rainer Beck, Elly M. Berkhuijsen & Richard Wielebinski

Max-Planck-Institut für Radioastronomie, Bonn, FRG

Observations yielding the distribution of large-scale magnetic fields in nearby spiral galaxies are still extremely scarce. Optical polarisation of starlight has been observed in the disks of M31, M51, M81 and some other spiral galaxies[1–3], but these measurements are too few to reveal the general distribution and direction of the magnetic fields. Segalovitz *et al.*[4] observed the distribution of the polarised radio emission in M51 at λ21 cm and λ6 cm with sufficient linear resolution (2.6×3.6 kpc) and sensitivity to conclude that the magnetic field in M51 is predominantly directed along the spiral arms. The first results of detailed polarisation measurements of the emission of M31 at λ11 cm (ref. 5) indicated that in the southern part of the bright ring of radio emission the magnetic field is generally aligned along the ring. We show here that this early conclusion seems to hold for the whole of the ring.

The observations were carried out with the 100-m telescope of the Max-Planck-Institut für Radioastronomie at Effelsberg between 1977 and 1978. The dual-channel correlation polarimeter in the secondary focus operated at 2,700 MHz (system temperature, 100 K; bandwidth, 80 MHz; observed half-power beamwidth, 4.4 arc min). The flux densities and polarisation characteristics of the calibration sources 3C48, 3C138 and 3C147 were taken from Baars *et al.*[6] and Wardle and Kronberg[7]. The ratio of main beam brightness temperature T_b(K) to the flux density S(Jy) was found to be 2.3 ± 0.1. 3C147 was used to determine the spurious instrumental polarisation, which was found to be highest at 2 arc min distance from the source with ~0.5% of the total emission.

Figure 1 shows the λ11.1 cm polarisation map of M31 superimposed on an optical picture. The map covers the area $-81<\lambda_A<+81$ arc min, $-45<\beta_A<+45$ arc min, where the coordinates λ_A and β_A lie along the major and minor axis, respectively. The area was observed in three parts, each overlapping by 10 arc min in λ_A. The northern part and the central part were scanned both in λ_A and β_A (~10 times each), while the southern part was scanned only in β_A (~20 times). For the northern and the central parts the averages of the maps in λ_A and of the maps in β_A were combined using a technique for optimising the base levels developed by C. J. Salter. By applying this technique to the maps in Stokes parameters Q and U separately, any polarised foreground emission varying linearly across the map is eliminated. (Faraday rotation in the foreground is not affected by this procedure.)

The polarisation temperatures derived from $(Q^2+U^2)^{1/2}$ suffer from a systematic positive bias due to noise. All values in Fig. 1 have, therefore, been corrected as proposed by Wardle and Kronberg[7]. The r.m.s. noise σ in the final map is 3 mK in main beam polarisation brightness temperature T_b^p.

A map of the total intensity of the area at λ11.1 cm was obtained from the total power channels of the same observations (Fig. 2); the r.m.s. noise is 5 mK in main beam brightness temperature T_b. This new total power map does not differ significantly from the map published by Berkhuijsen and Wielebinski[8], but it has a slightly better angular resolution and lower r.m.s. noise. The new map extends further in β_A so that the

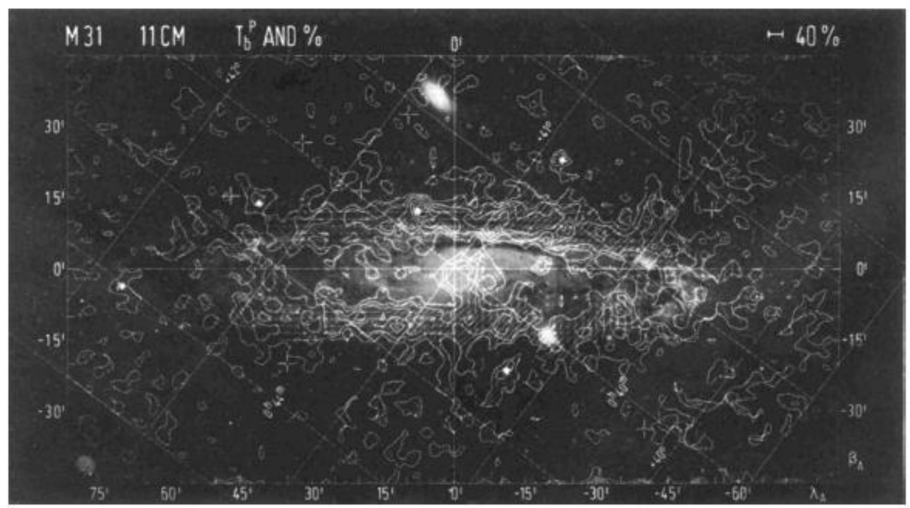
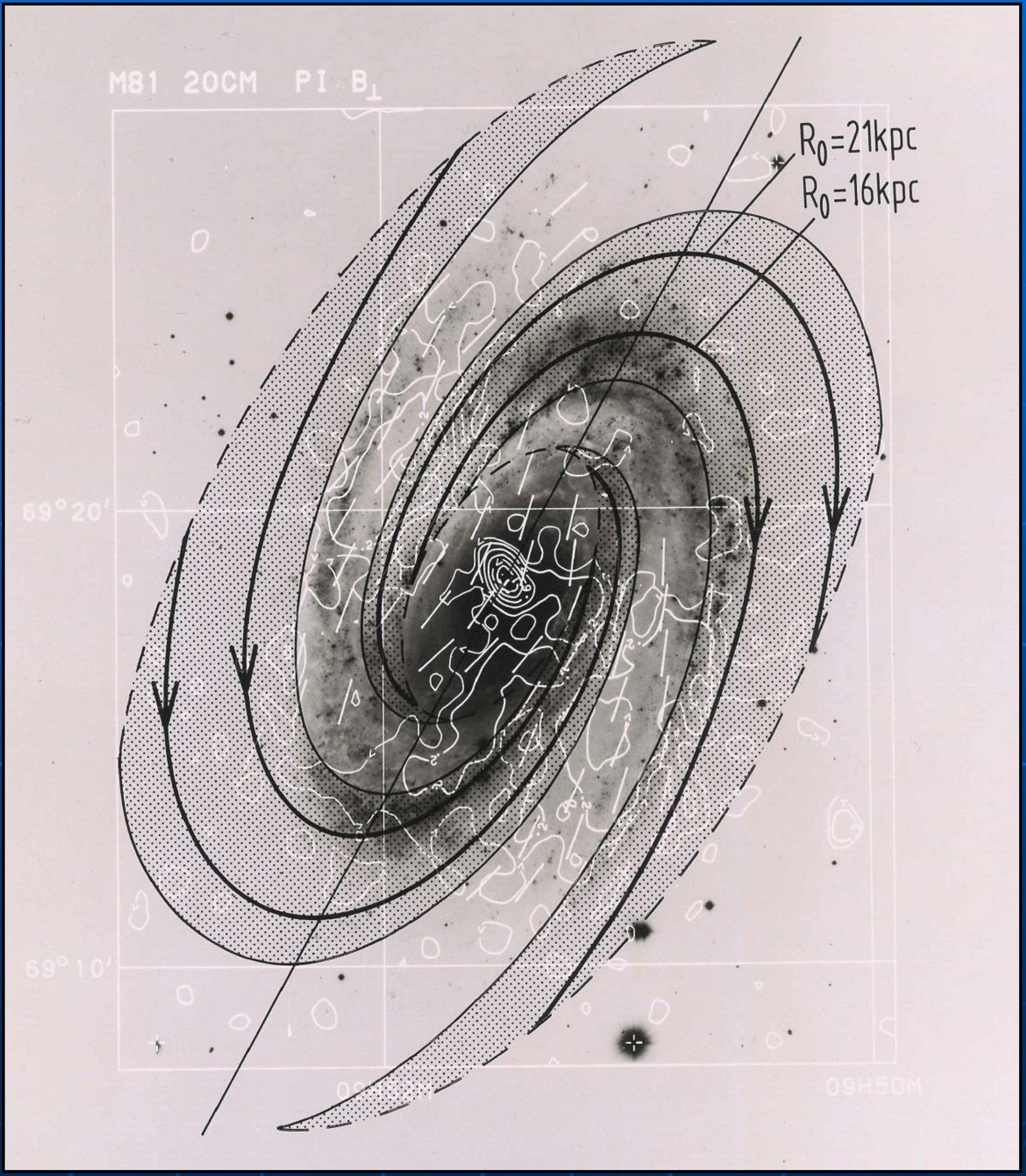


Fig. 1 Contour map of main beam polarisation brightness temperature T_b^p at λ11.1 cm superimposed on an optical picture of M31 (photograph from Hale Observatories). The first contour level is 4 mK ($=1.3\sigma$) in T_b^p; the contour interval is 4 mK. The length of the vectors is proportional to the percentage polarisation p which was only computed if $T_b^p>3$ mK and $T_b>15$ mK. Asterisks show the position of polarised point sources 5C3.73, 107, 120, 126 and 163.

Discovery of the bisymmetric field in M81

(M. Krause et al. 1989)

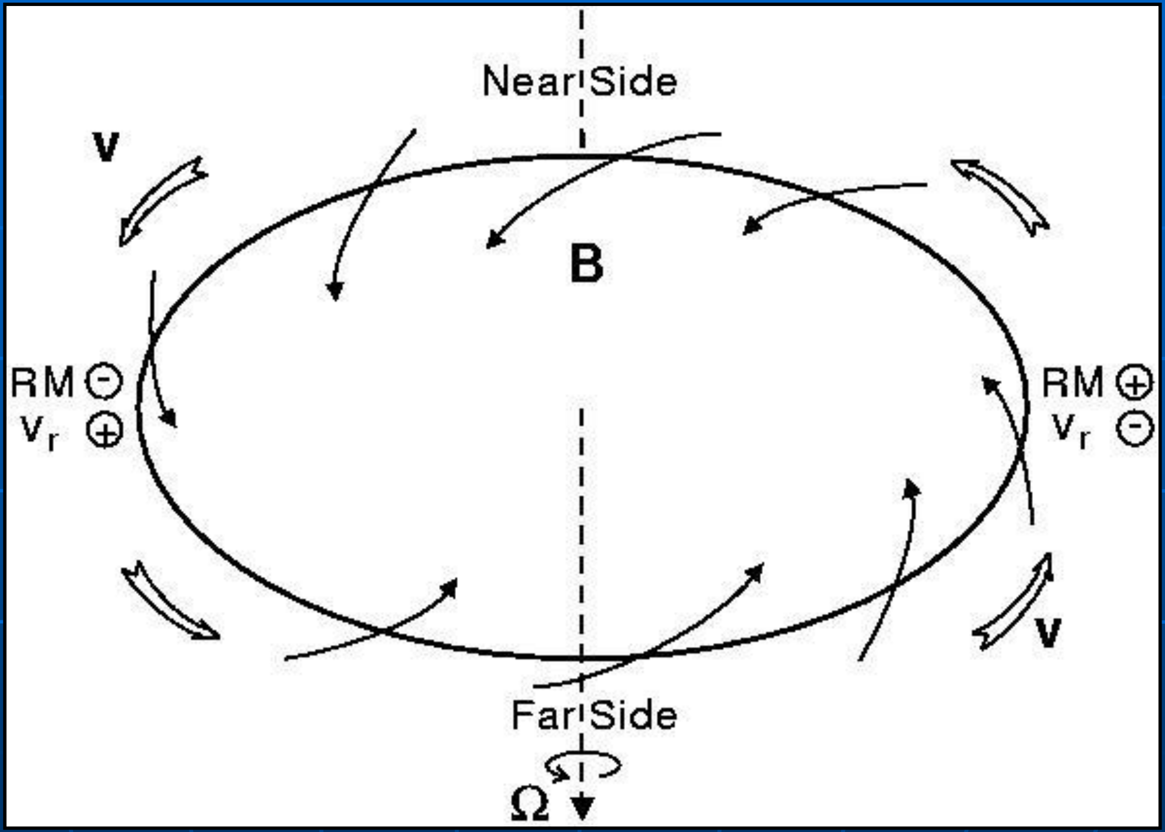


Observation of large-scale dynamo modes

- Single dominant axisymmetric (m=0) modes are frequent, as predicted
- Dominating bisymmetric (m=1) modes are rare, as predicted
- Superpositions of m=0 and m=2 modes are frequent
- In many cases the field is more complicated

Radial component of spiral fields

F. Krause & Beck 1998



Opposite signs of v_r and RM:
inward field direction

Direction of the radial component of axisymmetric spiral fields

(from the signs of RM and v_r)

Inwards:

M31, IC342, N253, N1097, N4192, N4302, N6946

Outwards:

N4254, N4535, N4736, N5775, M51 (disk)

Evidences for large-scale dynamos in galaxies
(see also Lecture 6)

- Magnetic and turbulent energy densities are similar
- Spiral patterns exist in almost all galaxies
- Large-scale coherent fields exist in the disks of many galaxies
- Axisymmetric coherent fields dominate
- Coherent fields exist in the halos of (some) edge-on galaxies

Problems with mean-field dynamo models

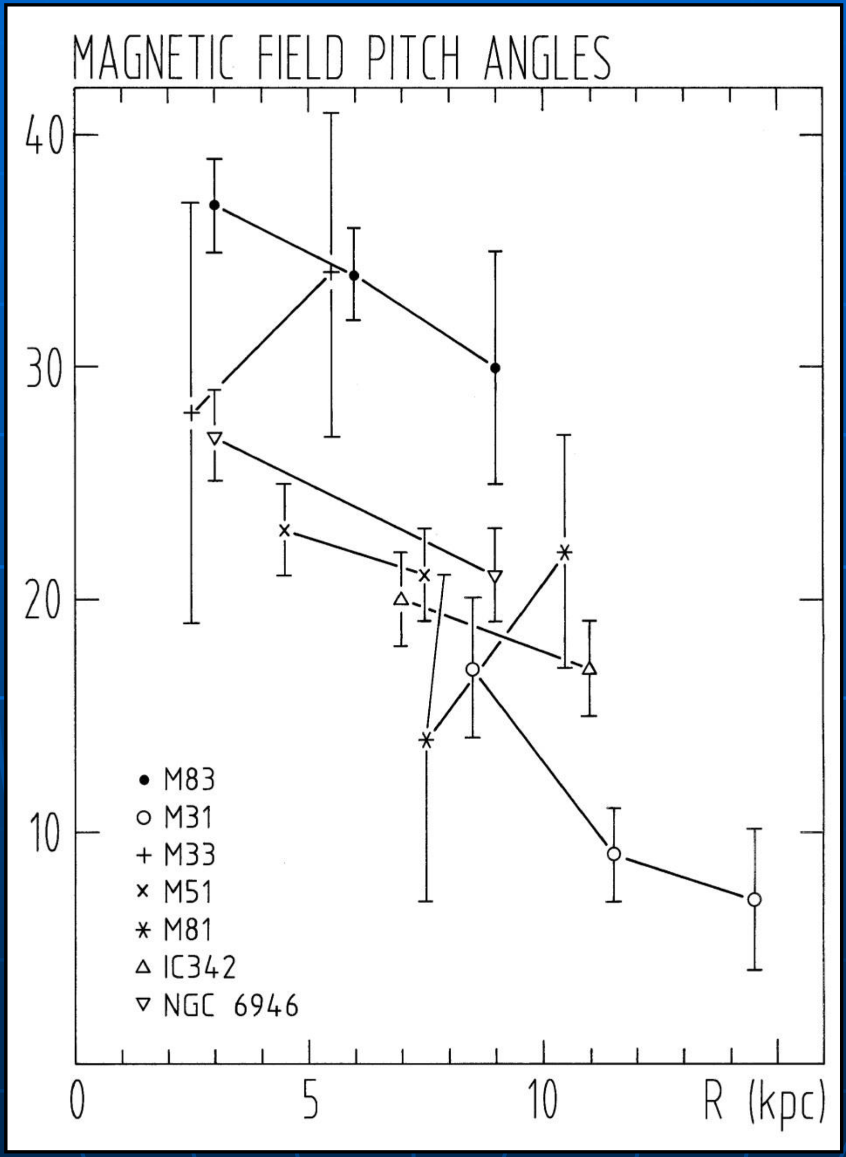
- Physics of α effect not understood
- Physics of reconnection not understood (see talk by Alex Lazarian)
- Field amplification is slow (several 10^8 years)
- Helicity is conserved in a closed system: generation of small-scale helicity suppresses dynamo action
- High star-formation rate or fast outflow can suppress the dynamo
- Observed similarity of magnetic and optical pitch angles
- Observed magnetic pitch angle decreases with radius

Magnetic pitch angles

Fletcher 2011

	pitch angle			
Galaxy	inner	outer	optical	Ref.
IC 342	-20°±2	-16°±2	-19°±5	Krause et al. 1989
M31	-17°±4	-8°±3	-7°	Fletcher et al. 2004
M33	-48°±12	-42°±5	-65°±5	Tabatabaei et al. 2009
M51	-20°±1	-18°±1	-20°	Fletcher et al. 2011
M81	-14°±7	-22°±5	-11° → -14°	Krause et al. 1989
NGC 6946	-27°±2	-21°±2	-43° → -22°	Ehle & Beck 1993
Milky Way	-11.5°	0°	-11.5° (n_e)	Van Eck et al. 2011

Radial variation of magnetic pitch angles



Beck 1993

Dynamos in outer disks
(assuming flat rotation curves)

- Dynamo number (efficiency):

  $D = (h / r)^2 \ (v_{rot} / v_{turb})^2$

  Outer disk: weaker dynamo (not observed)

- Magnetic pitch angle:

  $\tan p \sim (r / h)^{0.5} \ (\alpha / v_{rot})^{0.5} \sim L_{turb} / h$

  Outer disk: constant pitch angle (not observed)

Solution: flaring disks?

Future dynamo models

- Magnetic helicity is conserved in a closed system:
  models with outflows needed (to remove small-scale helicity)

  However: High star-formation rate / fast outflow can also suppress the dynamo

- Explain the observed similarity of pitch angles of the field spiral arms (interaction between dynamo and density wave ?)

- Explain the observed large-scale field reversals

- Higher resolution of MHD models:
  Include physics of α effect and reconnection

Seminal review paper: ARAA 1996

Annu. Rev. Astron. Astrophys. 1996. 34:155–206

GALACTIC MAGNETISM: Recent Developments and Perspectives

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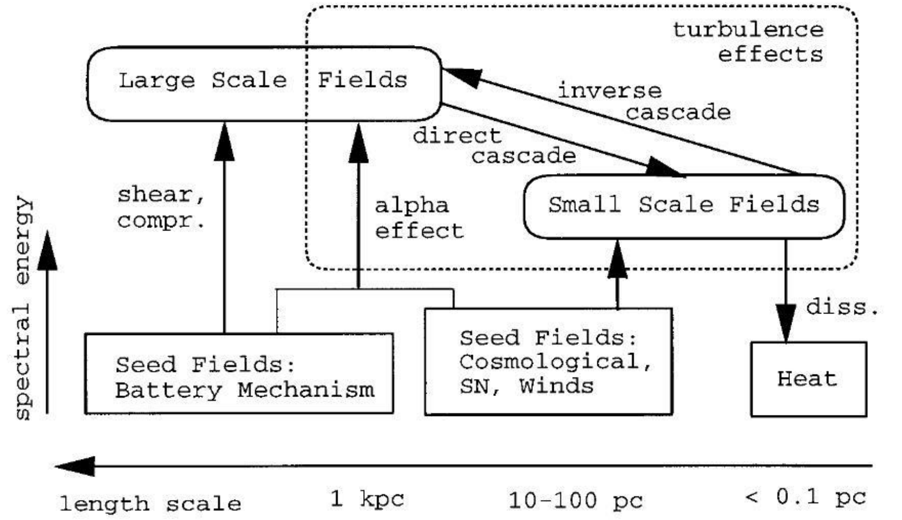

Figure 6 Sketch illustrating the various routes by which large-scale magnetic fields can arise. Turbulence effects (inverse cascade and α-effect) combined with shear and compression (differential rotation) amplify weak magnetic fields to produce strong large-scale fields.

We have attempted to draw together various strands contributing to our current understanding of galactic magnetism. We feel that neither dynamo nor fossil theory is at present in a satisfactory state. Nonetheless, we believe that, while the problems with the primordial theory are quite fundamental, ways of resolving the difficulties of the dynamo theory exist, in principle at least.

Future observational tests

- New telescopes at low frequencies (LOFAR, LWA, MWA, SKA): Weak magnetic field structure in outer disks and halos

- Upgraded and new telescopes at high frequencies (EVLA, ALMA, SKA): Dynamo modes in disks and halos, interaction with shearing and compressing gas flows

- Faraday spectra (RM Synthesis) with SKA & Precursors (ASKAP, MeerKAT, APERTIF): Field reversals, turbulent fields