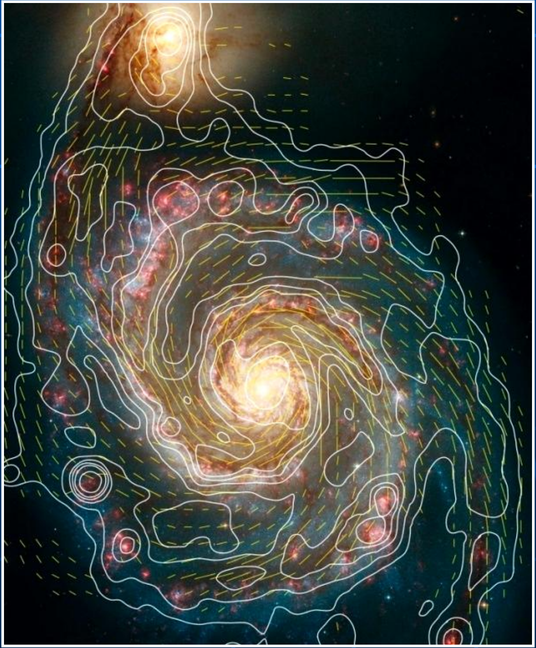
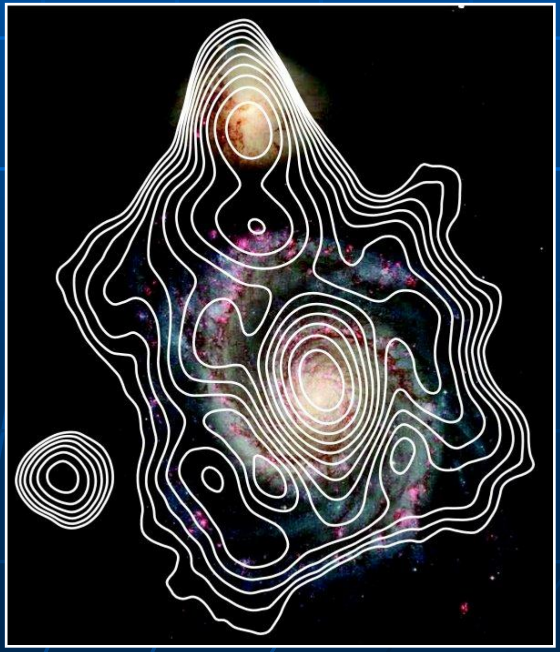
DFG Research Unit, Project A2:

# Magnetic fields in spiral galaxies

# Part I: Disks

David Mulcahy & Rainer Beck (MPIfR)





# Fundamental questions on galactic magnetic fields

- When and how were the first fields generated ?
- Did significant fields exist before galaxies formed ?
- How and how fast were fields amplified in galaxies ?
- Did fields affect the evolution of galaxies ?
- Do galaxies magnetize the intergalactic medium?

# Magnetic field generation and amplification

*Stage 1*: Field seeding

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

*Stage 2*: Field amplification

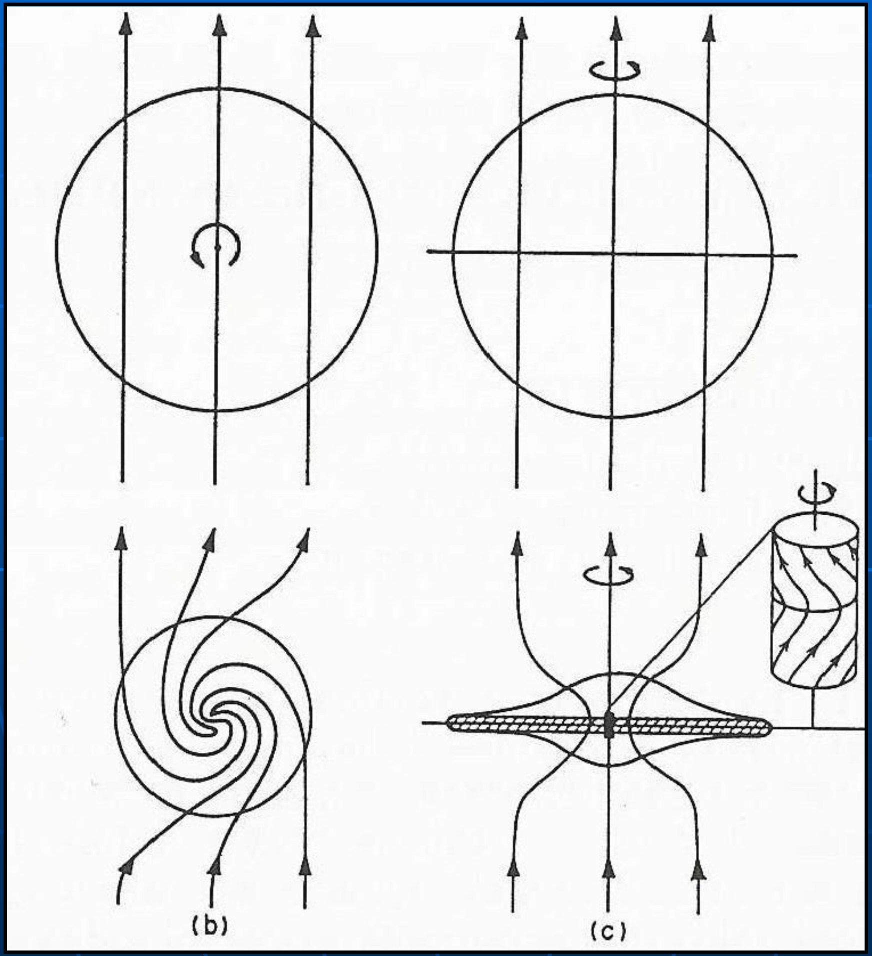
MRI, compressing flows, shearing flows,
turbulent flows, small-scale (turbulent) dynamo

*Stage 3*: Coherent field ordering

Large-scale (mean-field) dynamo

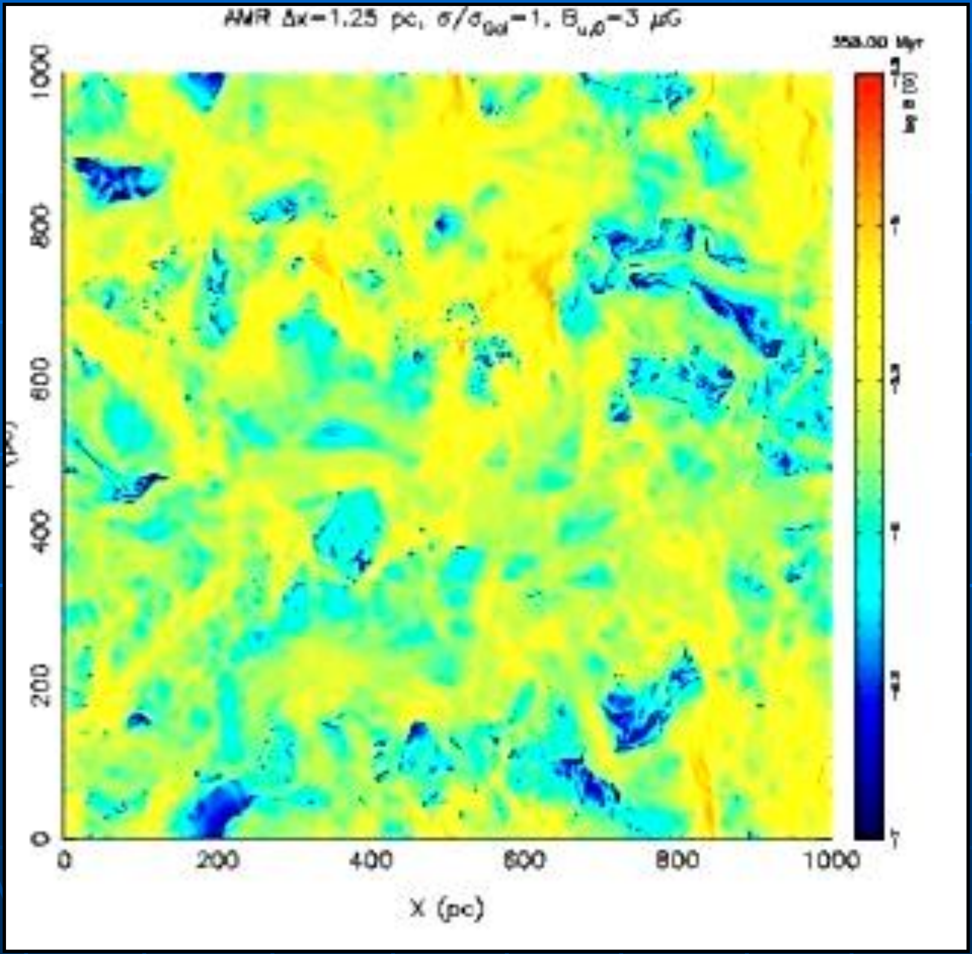
# “Primordial” models for galactic fields

Sofue 1990




Generation of
large-scale fields
(bisymmetric
or dipolar),
hard to maintain

# Dynamic MHD model of supernova-induced turbulence in the ISM




Magnetic field strength

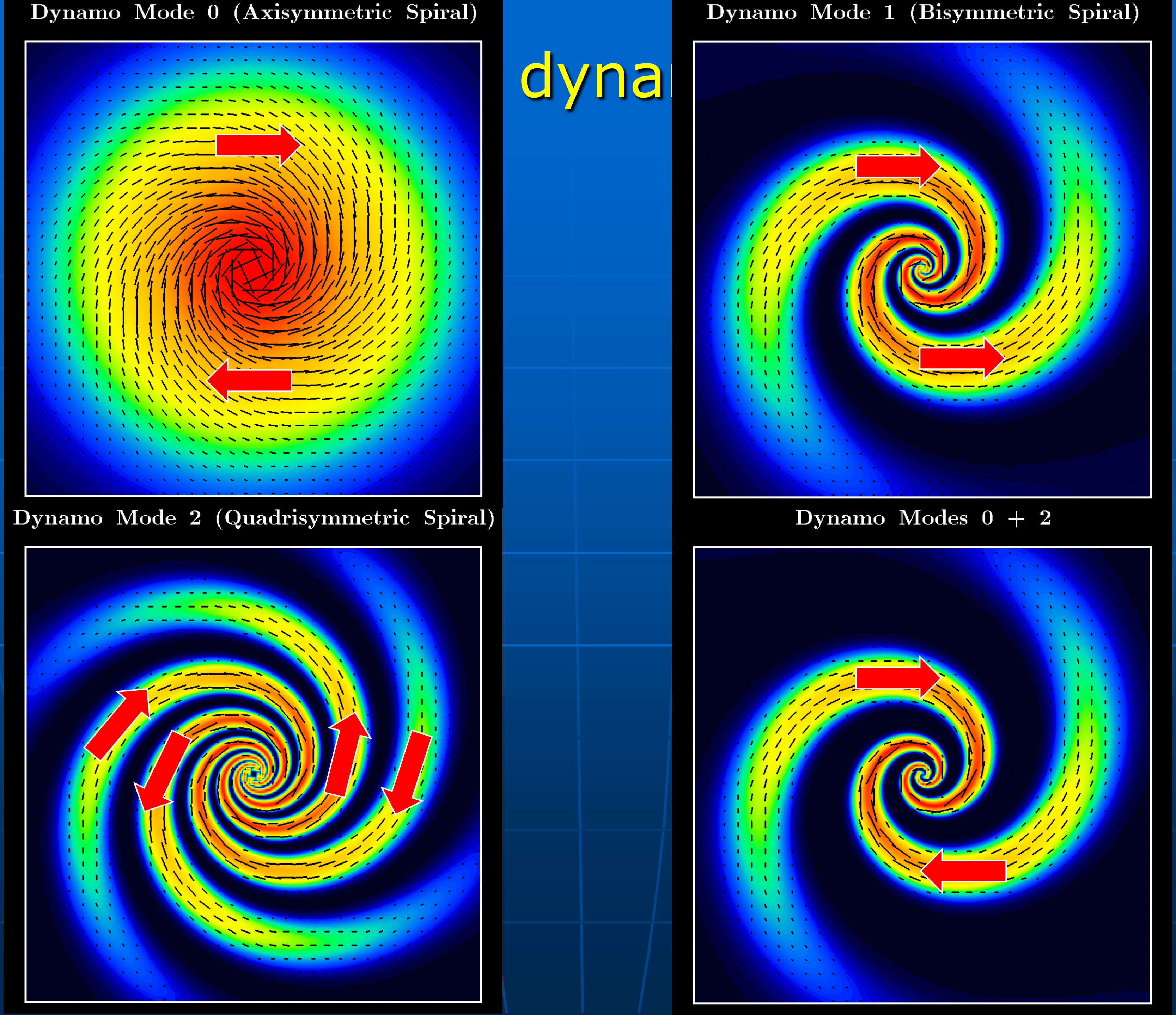
de Avillez & Breitschwerdt 2005

Generation of turbulent and anisotropic fields by compression and shear

# Mean-field (large-scale) dynamo models

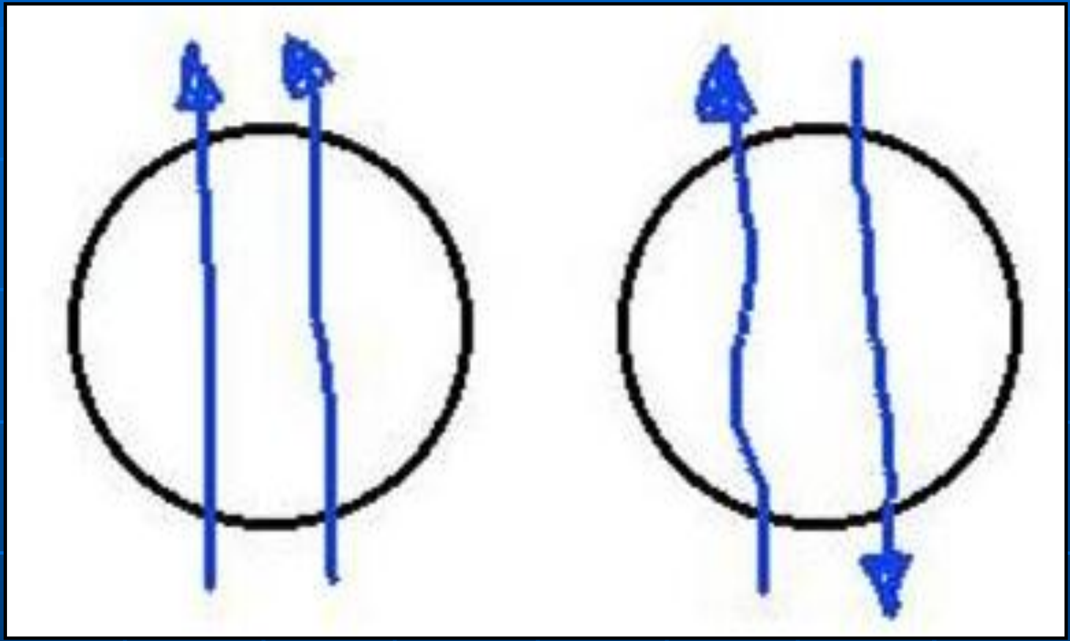
- Generation of large-scale coherent fields (modes)
- Flat objects (e.g. galaxy disks):
  *Quadrupolar* fields of symmetric *(even)* parity
- Spherical objects (e.g. galaxy halos):
  *Dipolar* fields of antisymmetric *(odd)* parity

# dyna


Dynamo Mode 0 (Axisymmetric Spiral)
Dynamo Mode 1 (Bisymmetric Spiral)
Dynamo Mode 2 (Quadrisymmetric Spiral)
Dynamo Modes 0 + 2

Regular (dynamo) field

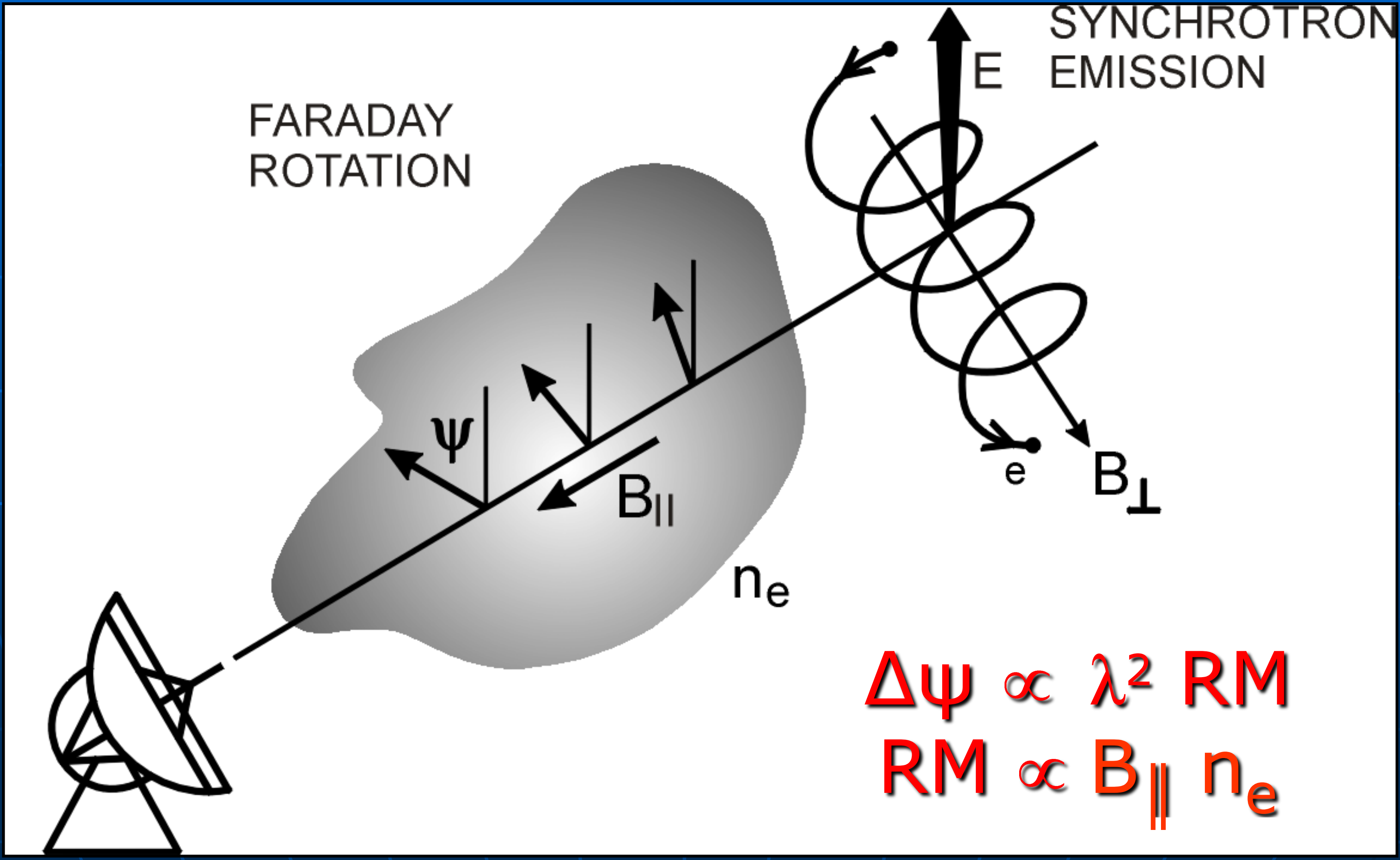
Ordered, but incoherent field



| | | |
|---|---|---|
| Polarization : | strong | strong |
| Faraday rotation : | **high** | low |

Fletcher 2004

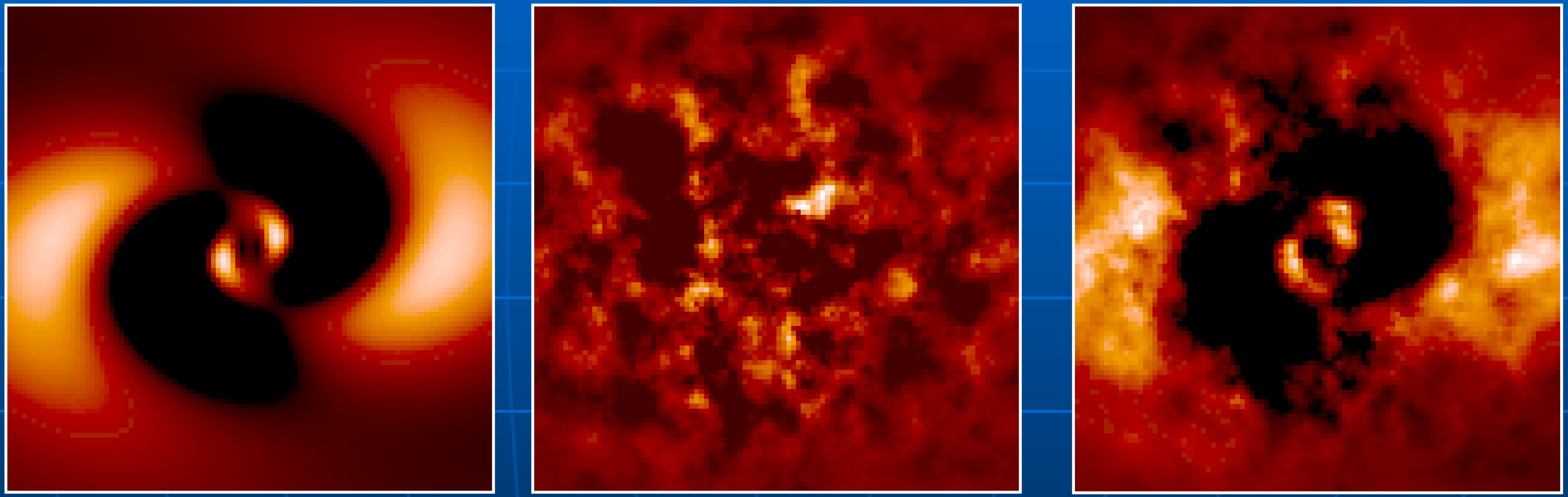
# Faraday rotation




$$\Delta\psi \propto \lambda^2 \, RM$$
$$RM \propto B_{\parallel} \, n_e$$

# Faraday RM of extragalactic sources behind spiral galaxies

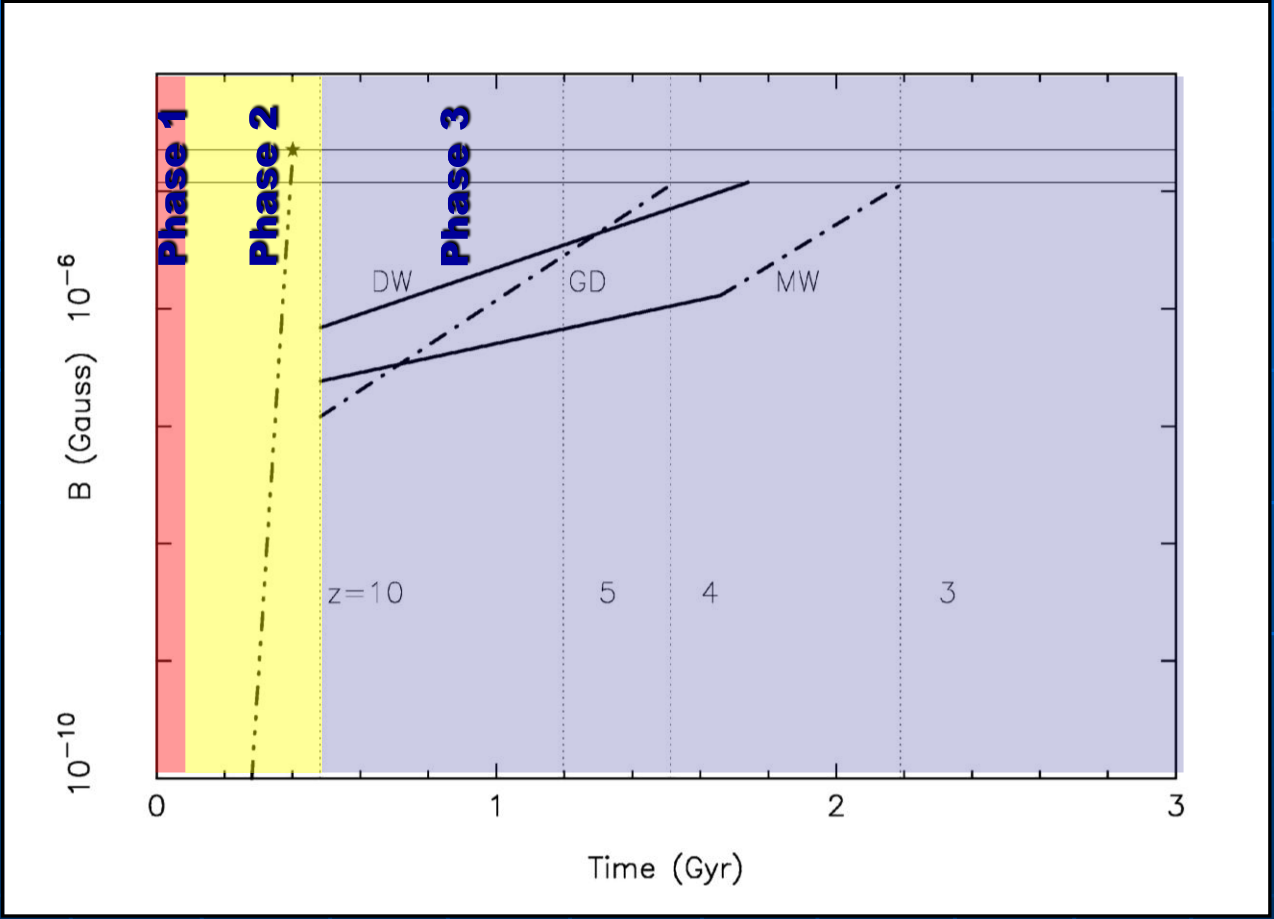
Stepanov et al. 2008



Bisymmetric regular field | Turbulent field | Sum

Recognition of large-scale field structures needs ≥ 10 RMs from background sources

# 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 of dynamo models

SKADS

Arshakian et al. 2009

- Strong turbulent magnetic fields at $z < 10$
  → Unpolarized synchrotron emission from starburst galaxies can be observed at **$z < 10$**

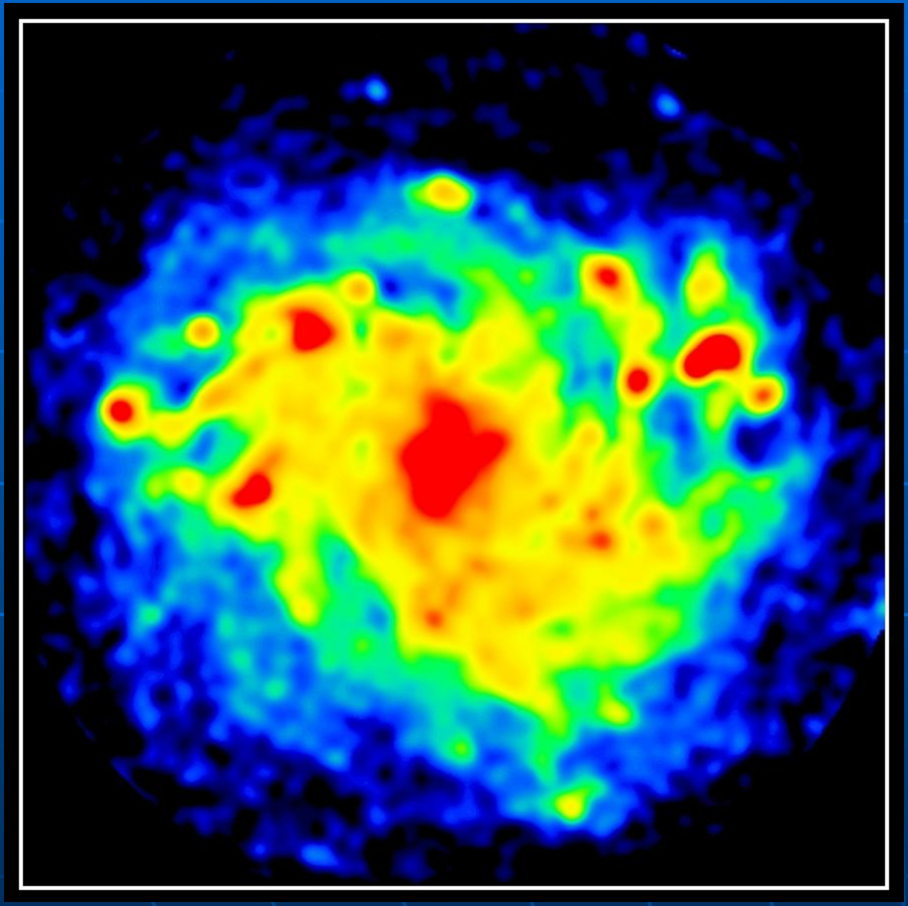
- Strong regular fields at $z < 3$
  → Polarized radio emission and Faraday rotation from normal and dwarf galaxies can be observed at **$z < 3$**

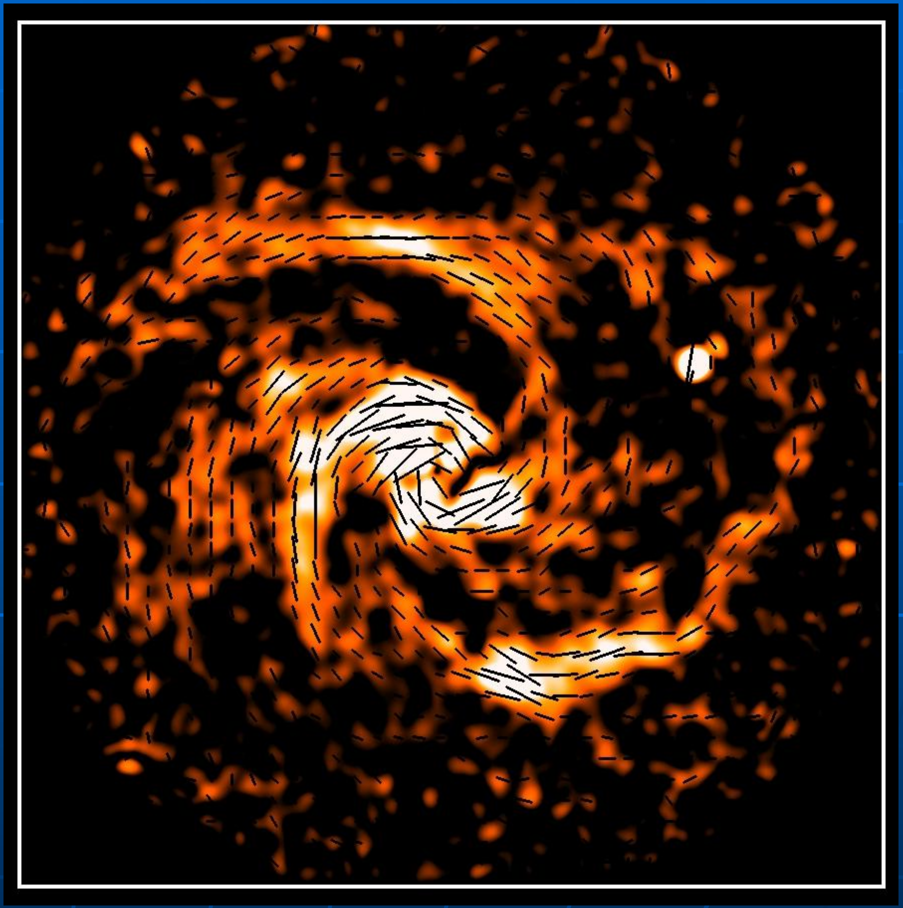
- Large-scale coherent regular magnetic fields in dwarf or Milky Way-type galaxies at $z < 1$
  → Large-scale patterns of Faraday rotation can be observed at **$z < 1$**

- Large galaxies (>15 kpc) may not yet have generated fully coherent fields

# Synchrotron polarization

Beck & Hoernes 1996

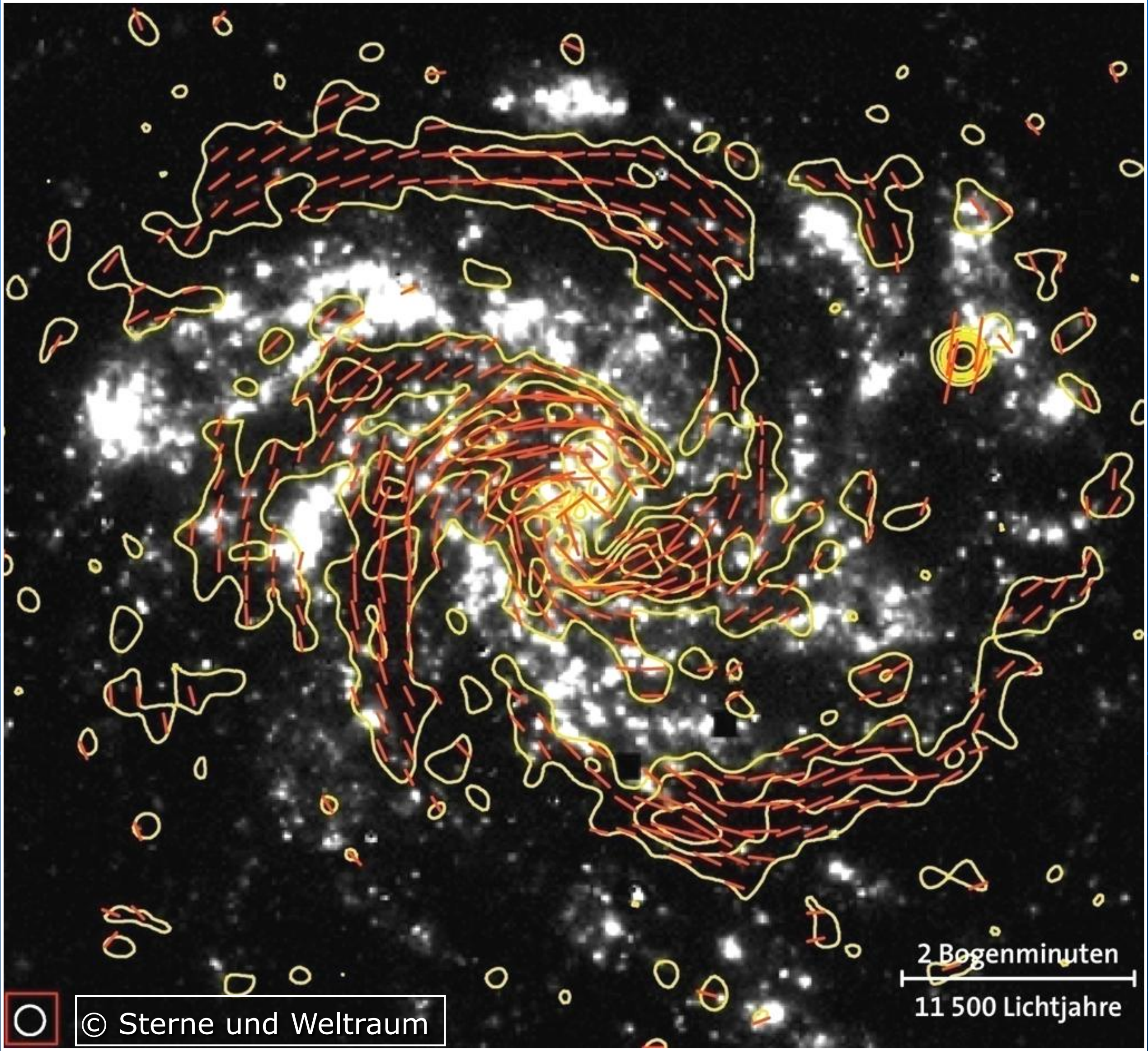




NGC 6946: Total and polarized intensity at 6cm

# NGC 6946

6cm VLA+Effelsberg
Polarized intensity
+ B-vectors
(Beck & Hoernes 1996)




"Magnetic arms":

Ordered fields concentrated in *interarm* regions !

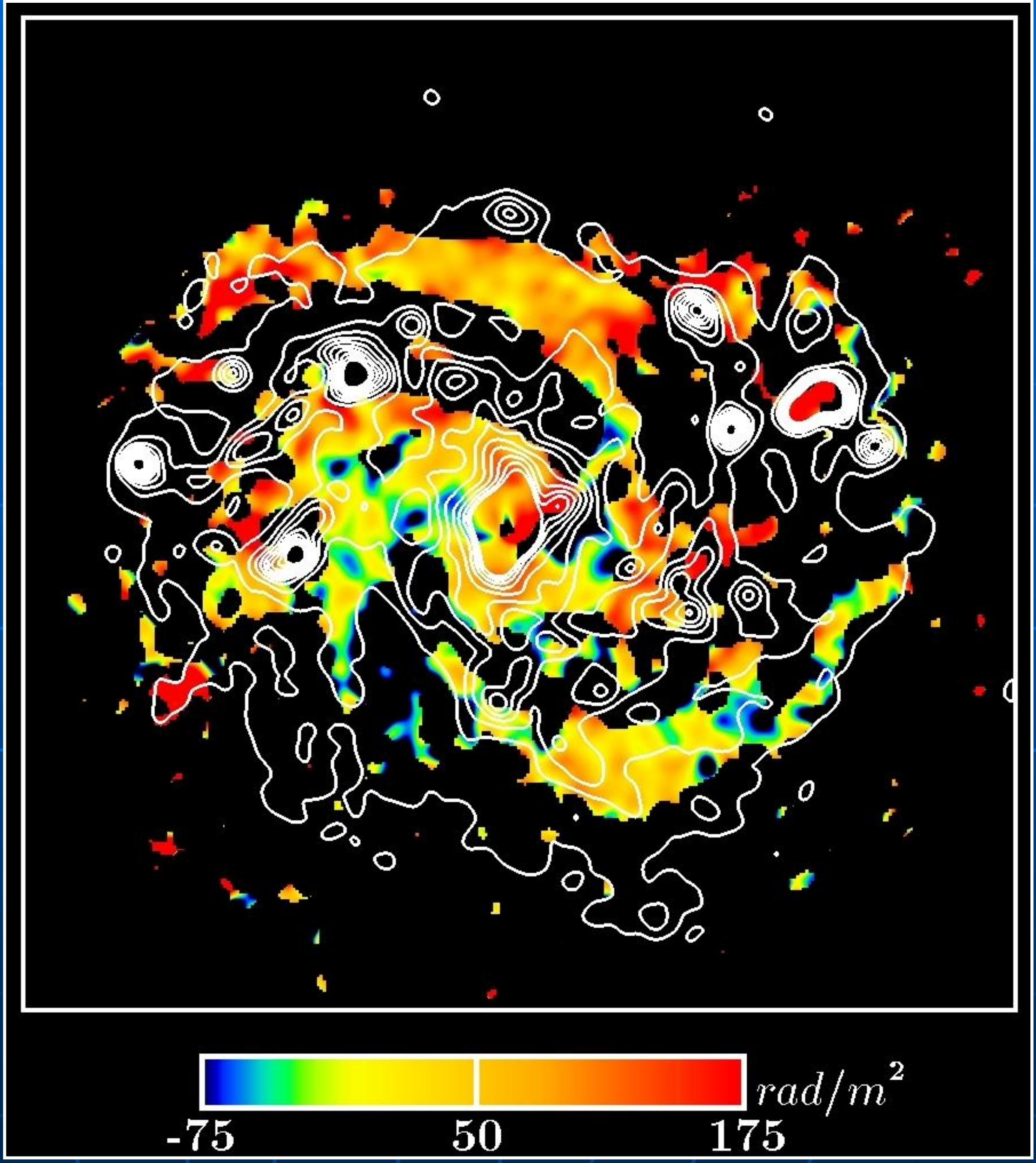
# Origin of "magnetic arms"

- High mode of the mean-field dynamo? (Rohde et al. 1999)
- Slow MHD waves? (Lou & Fan 1998, Lou & Bai 2006)
- Drifting of magnetic arms away from the gas arms? (Otmianowska-Mazur et al.)

# NGC 6946

RM 3/6cm
VLA+Effelsberg
(Beck 2007)

Faraday RM pattern:
Superposition of two dynamo modes



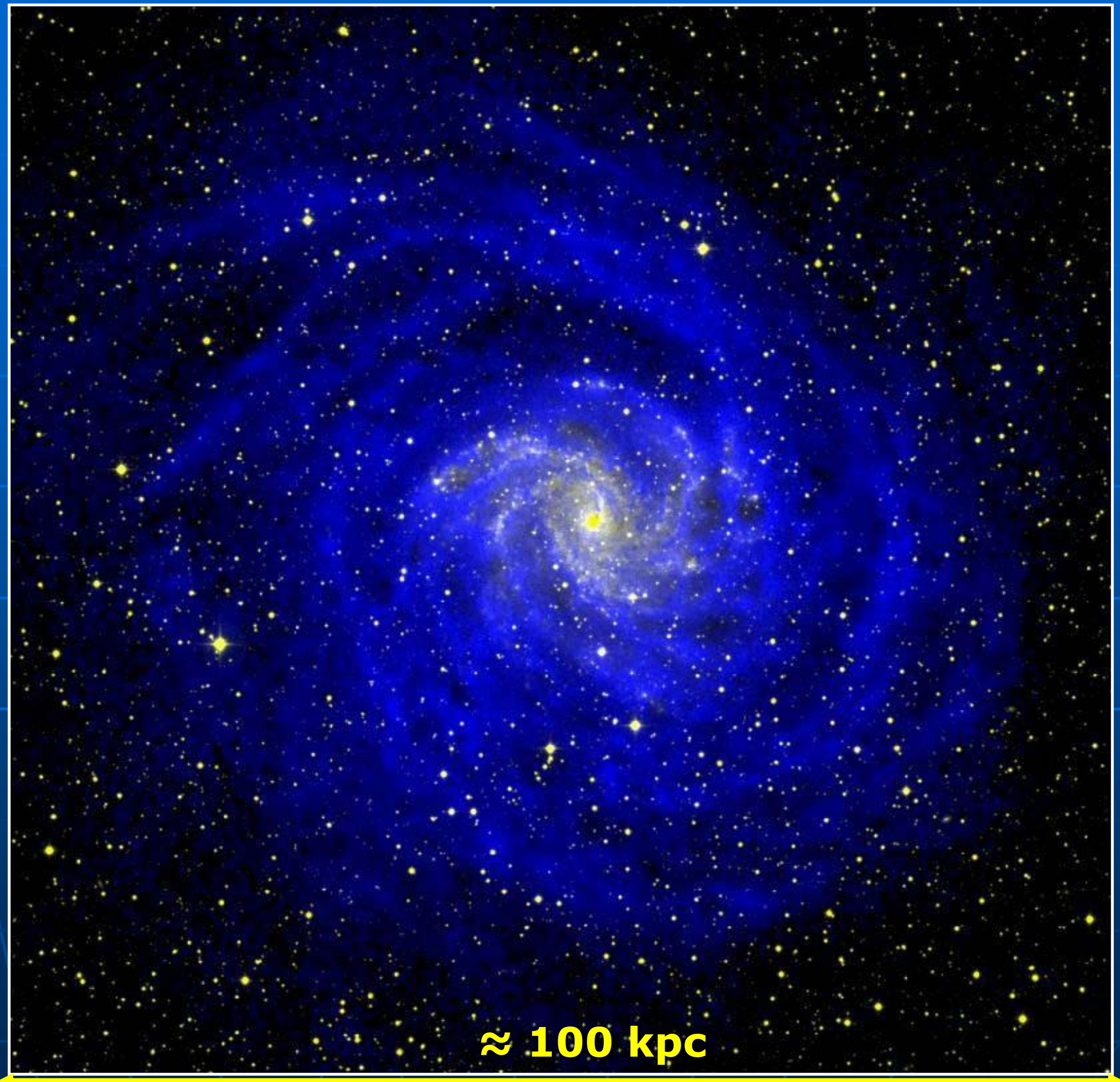
# NGC 6946

WSRT HI

+ optical

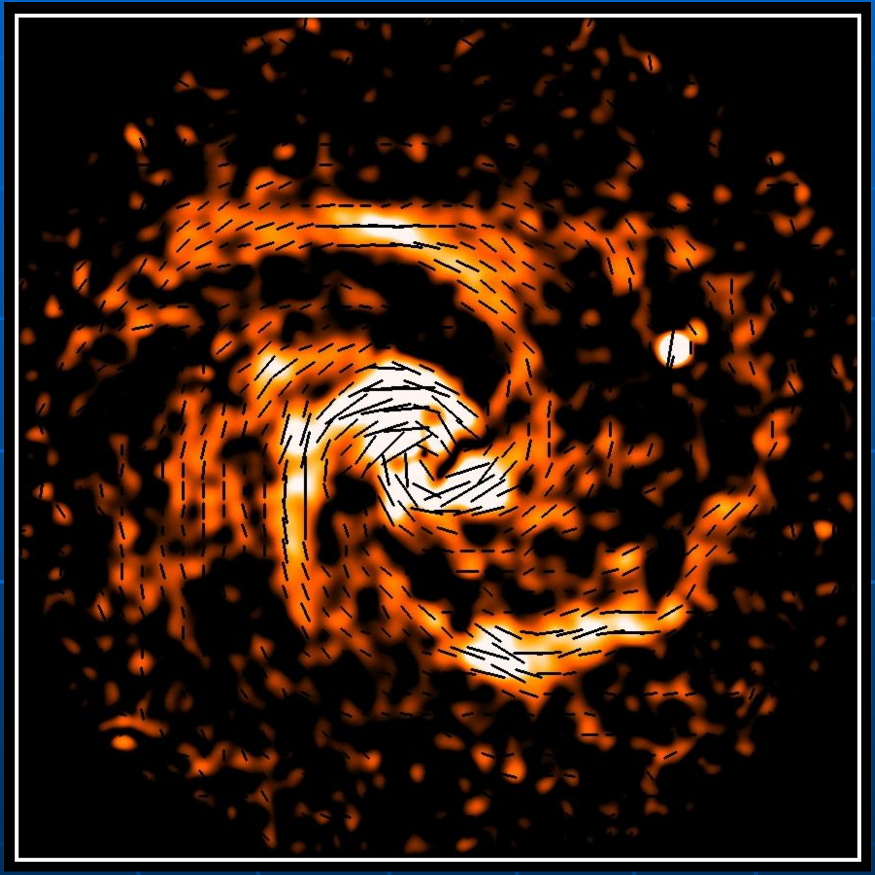
(Boomsma et al. 2006)

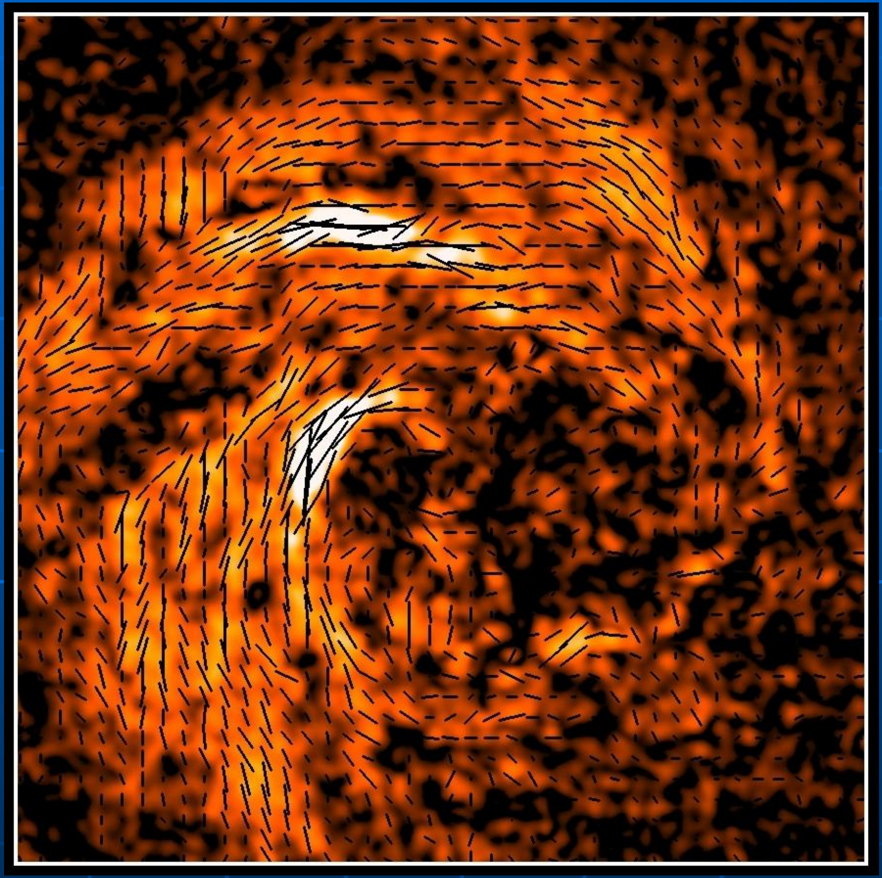
All magnetic ?



# Faraday depolarization

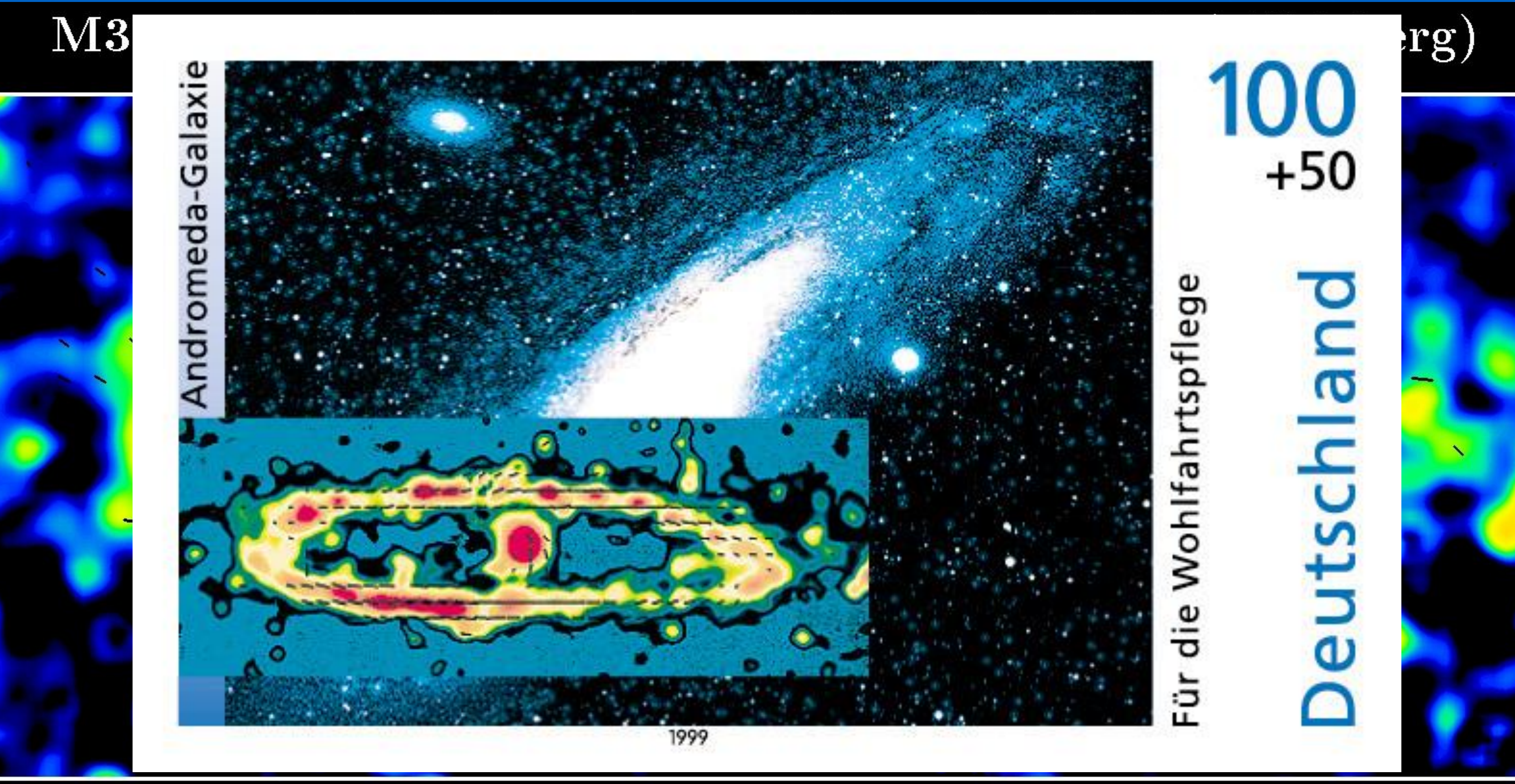
Beck 2007





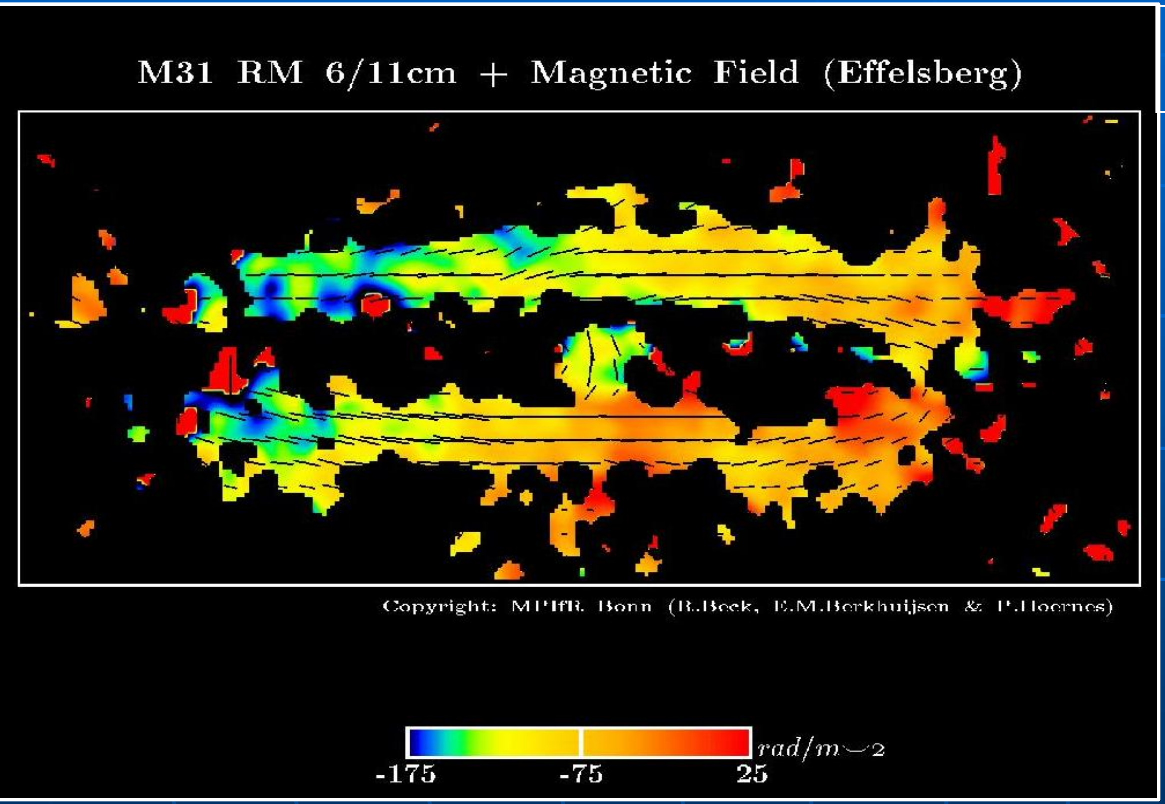
NGC 6946 Polarized intensity at 6cm and 20.5cm

# M31: The classical dynamo case

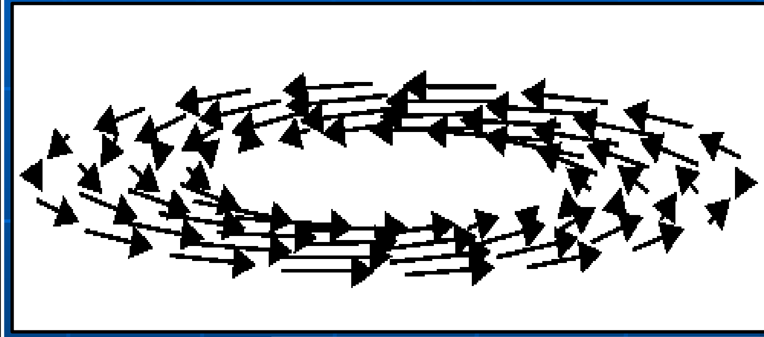



Copyright: MPIfR Bonn (R.Beck, E.M.Berkhuijsen & P.Hoernes)

# M31: The dynamo is working




Berkhuijsen et al. 2003



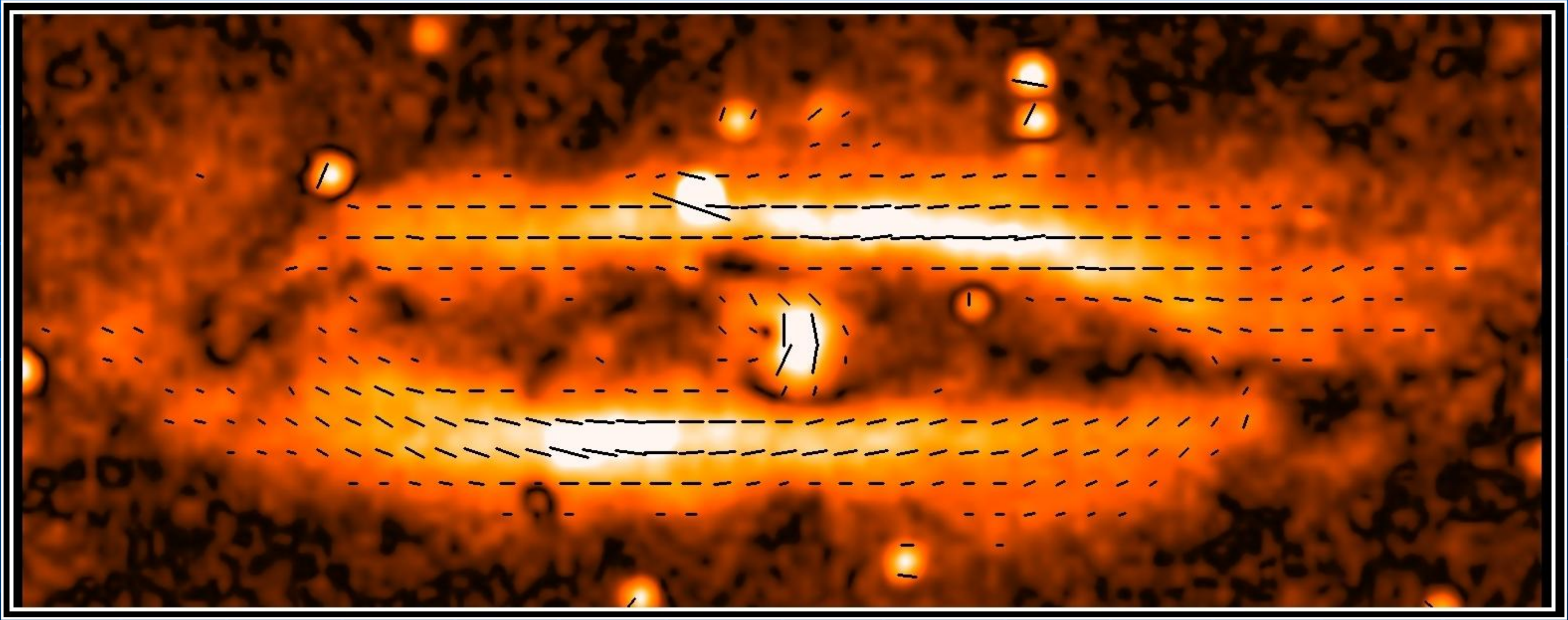
Fletcher et al. 2004

The spiral field of M31 is coherent and axisymmetric
(small spiral pitch angle)

# Deep Effelsberg polarization survey of M31 at 6cm

One of the deepest images ever made in Effelsberg

Gießübel et al., in prep.

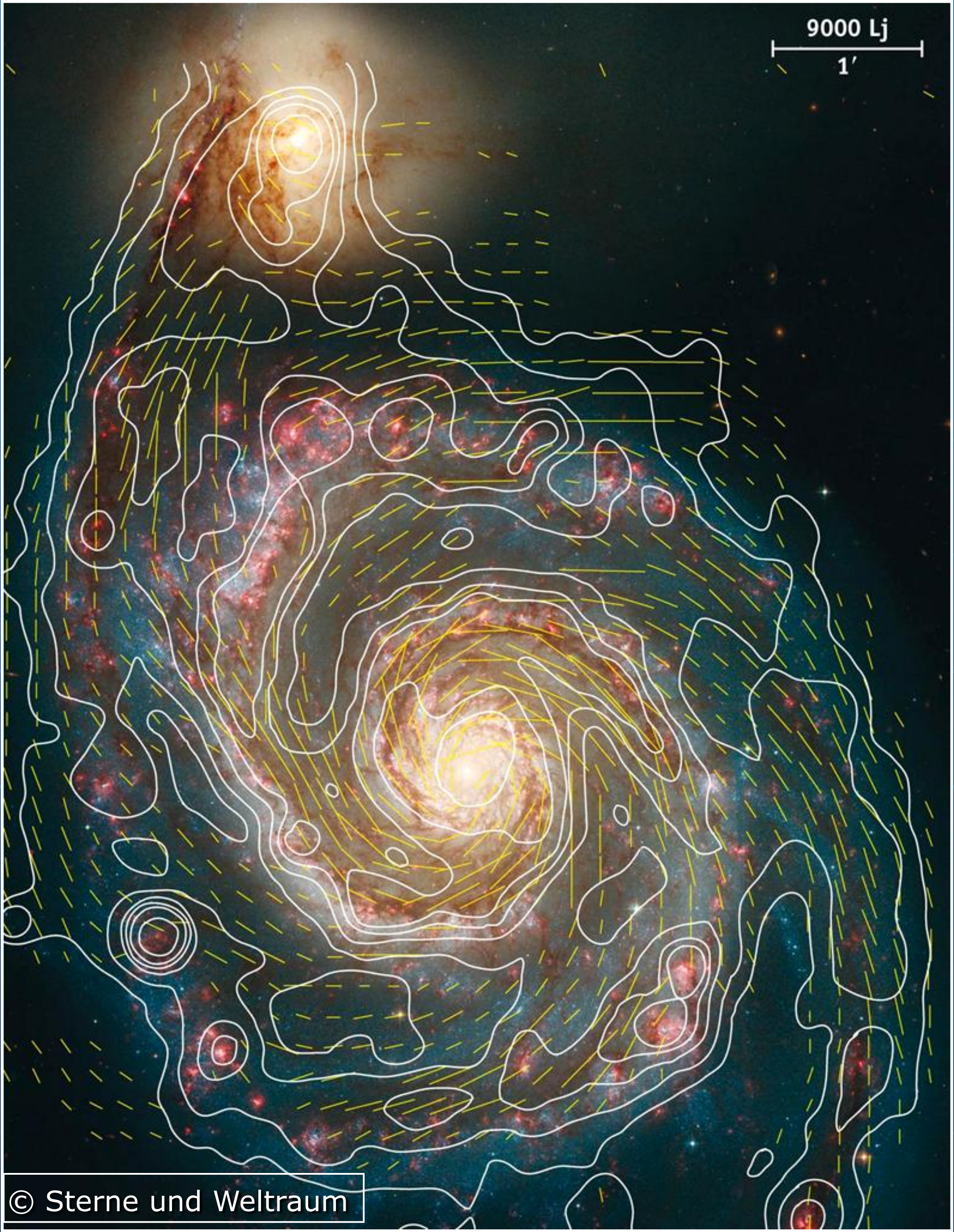


Classical dynamo: axisymmetric field
Ordered fields extend out to > 25 kpc

# M 51

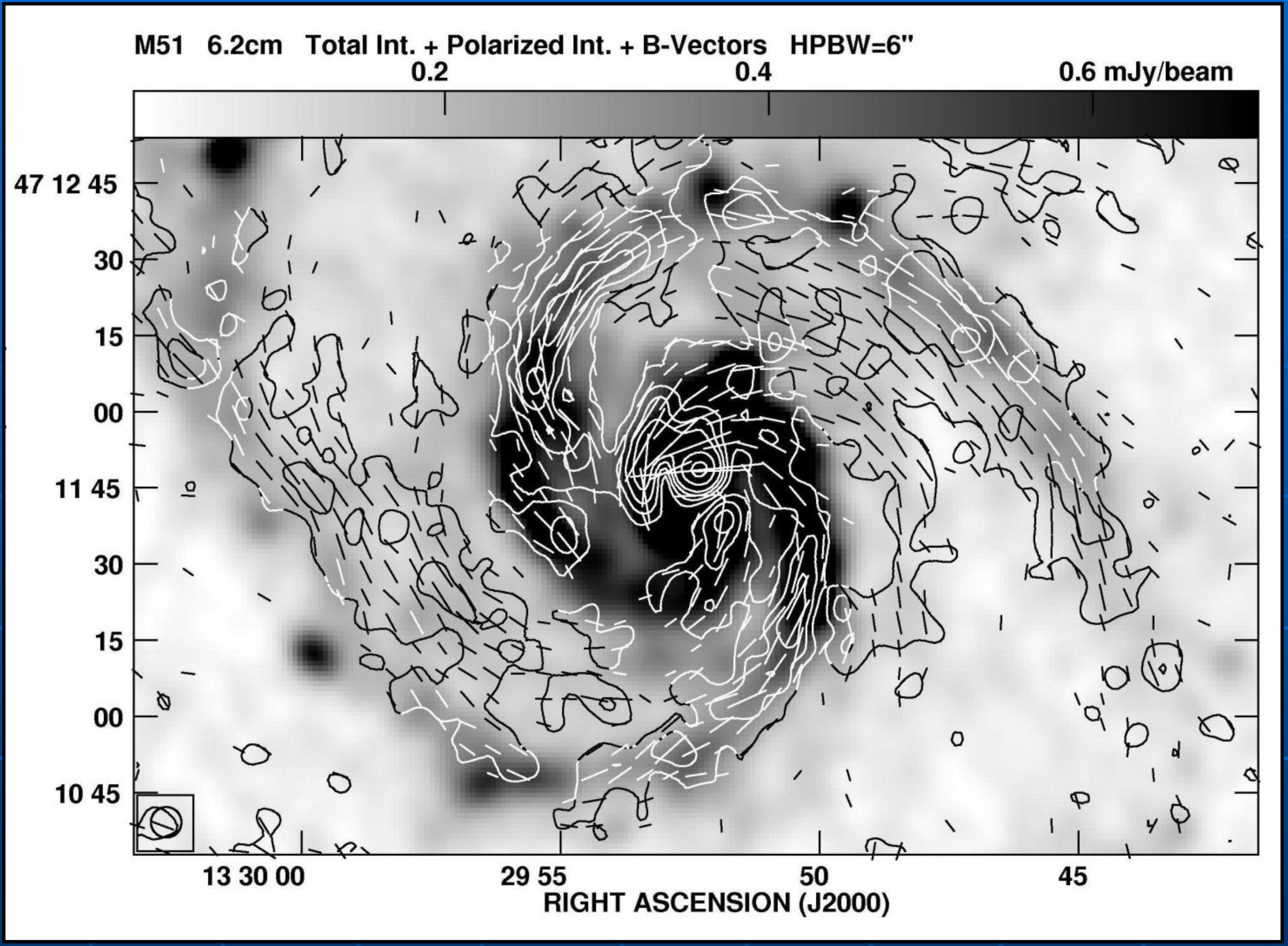
6cm VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2010)

Ordered spiral fields, mostly parallel to the optical spiral arms



# M 51

6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2010)

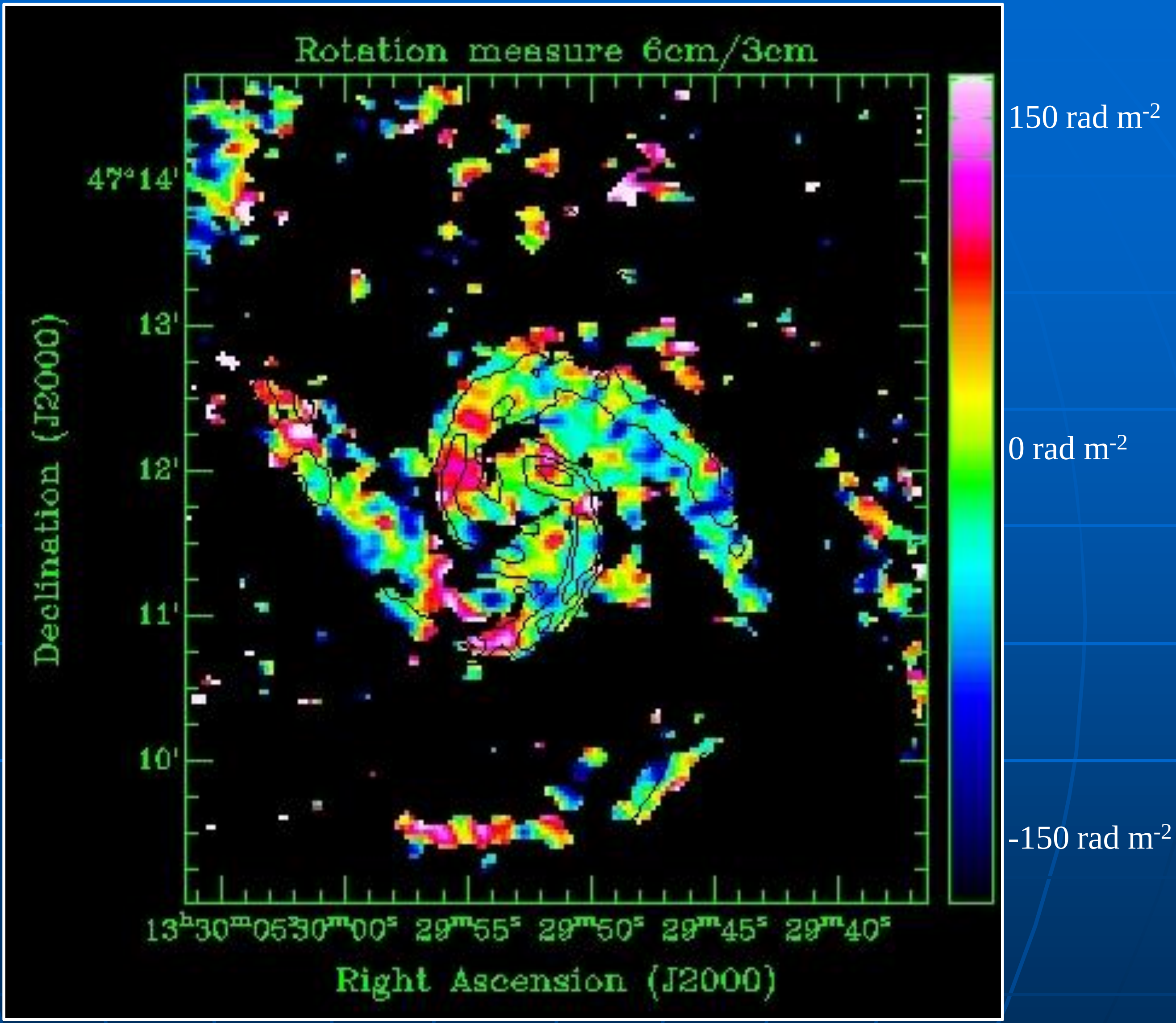



Field lines parallel to the inner spiral arms:

density-wave compression or shear

# M51

VLA+Effelsberg
RM 3/6cm
(Fletcher et al. 2010)



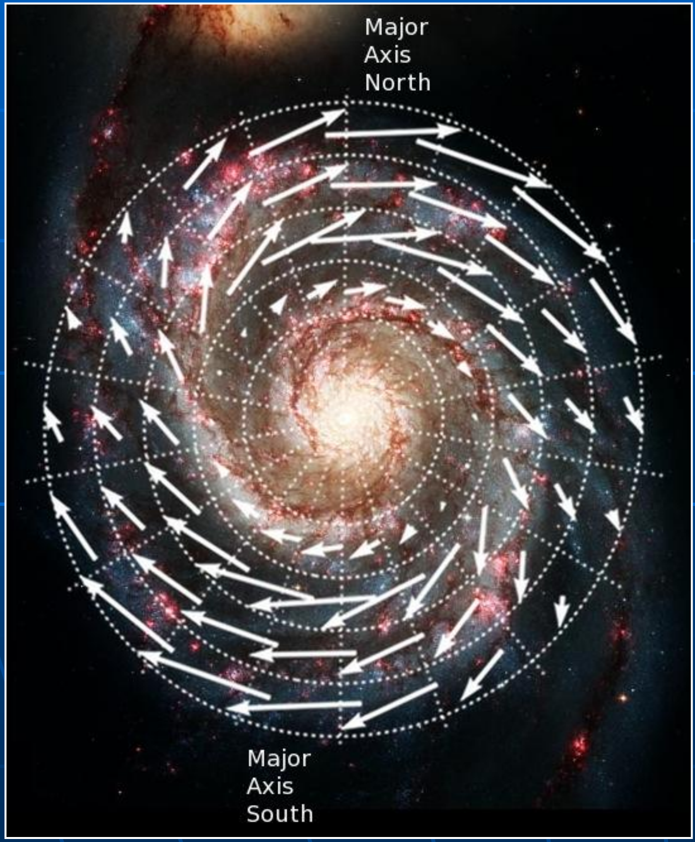

Complicated RM pattern:

Two *weak* dynamo modes (m=0+2), plus strong anisotropic fields

# Large-scale magnetic fields in M51

Fletcher et al. 2010

Disk: ASS (m=0) + m=2 modes




Upper layer: BSS (m=1) mode

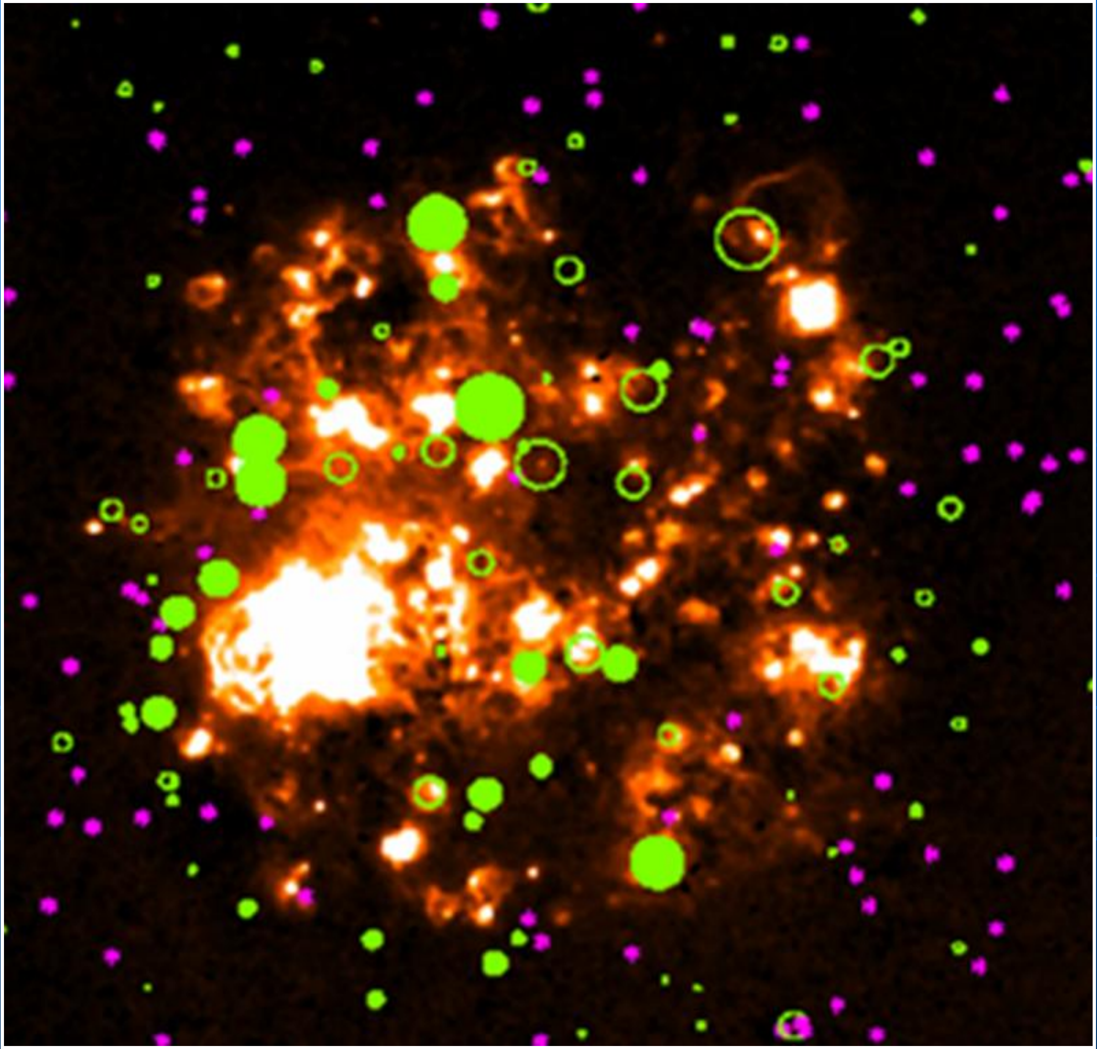

Field reversal between northern disk to inner halo – similar to that found for the Milky Way (Sun et al. 2008)

# LMC

RM 18-20cm ATCA

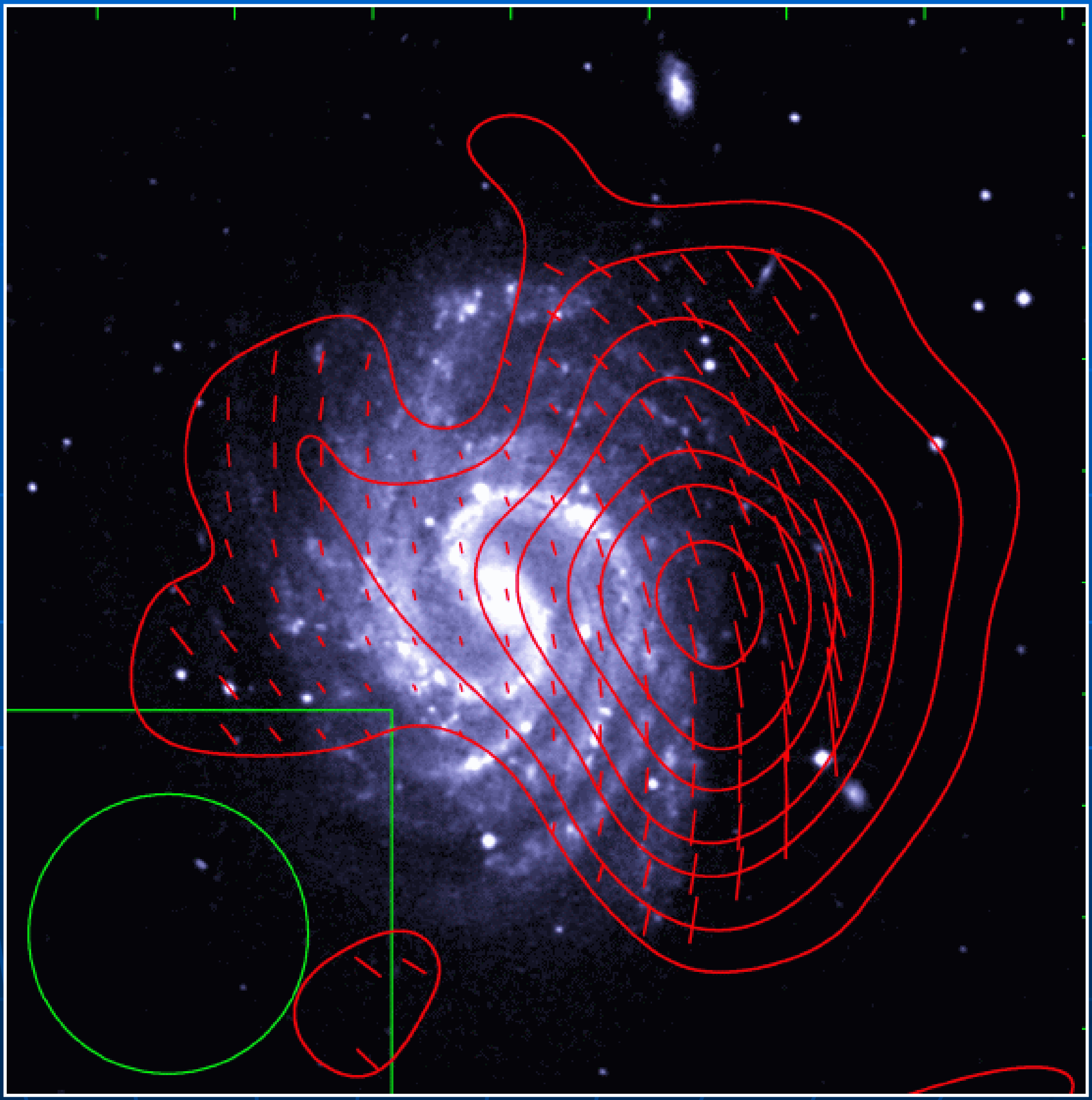
(Gaensler et al. 2005)

Faraday RMs from background sources: Axisymmetric dynamo field



# NGC 4535

6cm Effelsberg
Polarized intensity
+ B-vectors
(Wezgowiecz et al. 2007)



Field compressed
by ram pressure

# Stephan's Quintet

6cm VLA
Total intensity
+ B-vectors
(Soida et al., in prep)

Ordered intergalactic fields

# Low-frequency radio observations

- Frequency of synchrotron emission: $\upsilon \sim E^2 B$

$\longrightarrow$ Observing at low frequencies traces cosmic-ray electrons in weak magnetic fields

- Lifetime of electrons due to synchrotron loss: $t \sim \upsilon^{-0.5} B^{-1.5}$

$\longrightarrow$ Observing at low frequencies traces old electrons

- Faraday rotation: $\Delta\psi \sim \upsilon^{-2}$ RM

$\longrightarrow$ Observing at low frequencies allows to measure small rotation measures

# Propagation lengths of cosmic-ray electrons

- Propagation of outflows with Alfvén speed in halos ($10^{-3}$ $cm^{-3}$):
  $V \approx 70$ km/s · B (μG)

- B > 3.25 $(z+1)^2$ μG: Synchrotron loss dominates
  Propagation length of electrons emitting at 50 MHz:
  $L \approx 330$ kpc / $(B\ (\mu G))^{0.5}$

- B < 3.25 $(z+1)^2$ μG: Inverse Compton loss dominates
  Propagation length of electrons emitting at 50 MHz:
  $L \approx 30$ kpc $(B\ (\mu G))^{1.5}$

- Maximum propagation length: ≈ 200 kpc

- Regular fields: propagation speed can be higher !

# Faraday rotation with LOFAR

- LOFAR can in measure very low Faraday rotation measures of polarized background sources and hence detect very weak magnetic fields:

- Galaxy halos, clusters, relics:

  $n_e = 10^{-3}$ $cm^{-3}$, $B_{||} = 1\ \mu G$, L=1 kpc: RM~1 rad $m^{-2}$

- Intergalactic magnetic fields:

  $n_e = 10^{-5}$ $cm^{-3}$, $B_{||} = 0.1\ \mu G$, L=100 kpc: RM~0.1 rad $m^{-2}$

# Faraday rotation angles

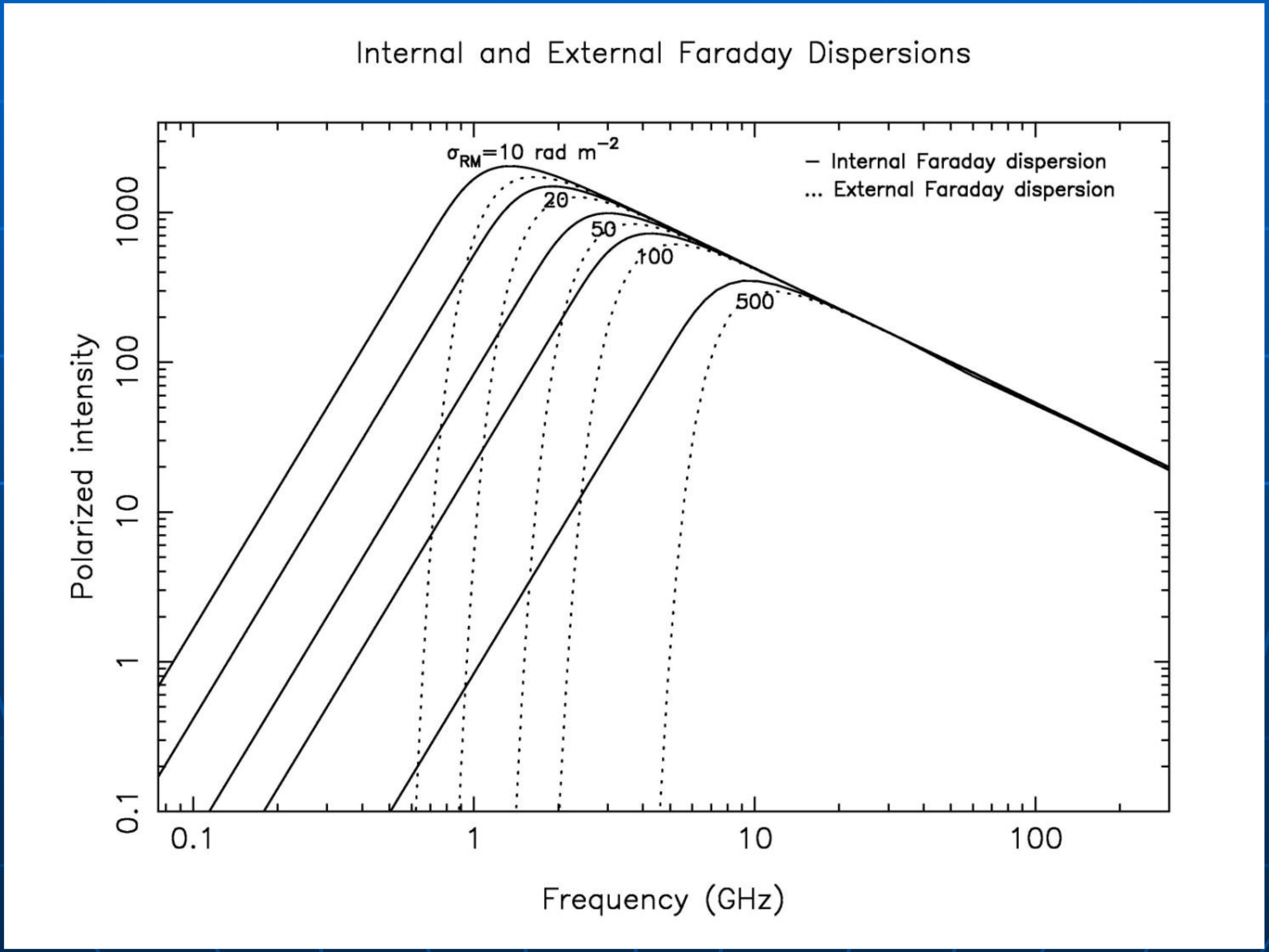
| | | | | |
|---|---|---|---|---|
| | **\|RM\|** = | 10 | 1 | 0.1 rad $m^{-2}$ |
| 1400 MHz | $\Delta\chi$ = | 30° | 3° | 0.3° |
| 200 MHz | $\Delta\chi$ = | 1300° | 130° | 13° |
| 120 MHz | $\Delta\chi$ = | 3600° | 360° | 36° |

Detection of ≈ 0.1 rad $m^{-2}$ is challenging but possible:

- Ionospheric Faraday rotation has to be accurately corrected (let's hope for a low solar activity cycle …)
- Foreground RM components have to be separated with help of RM Synthesis

# Maximum polarization due to Faraday dispersion

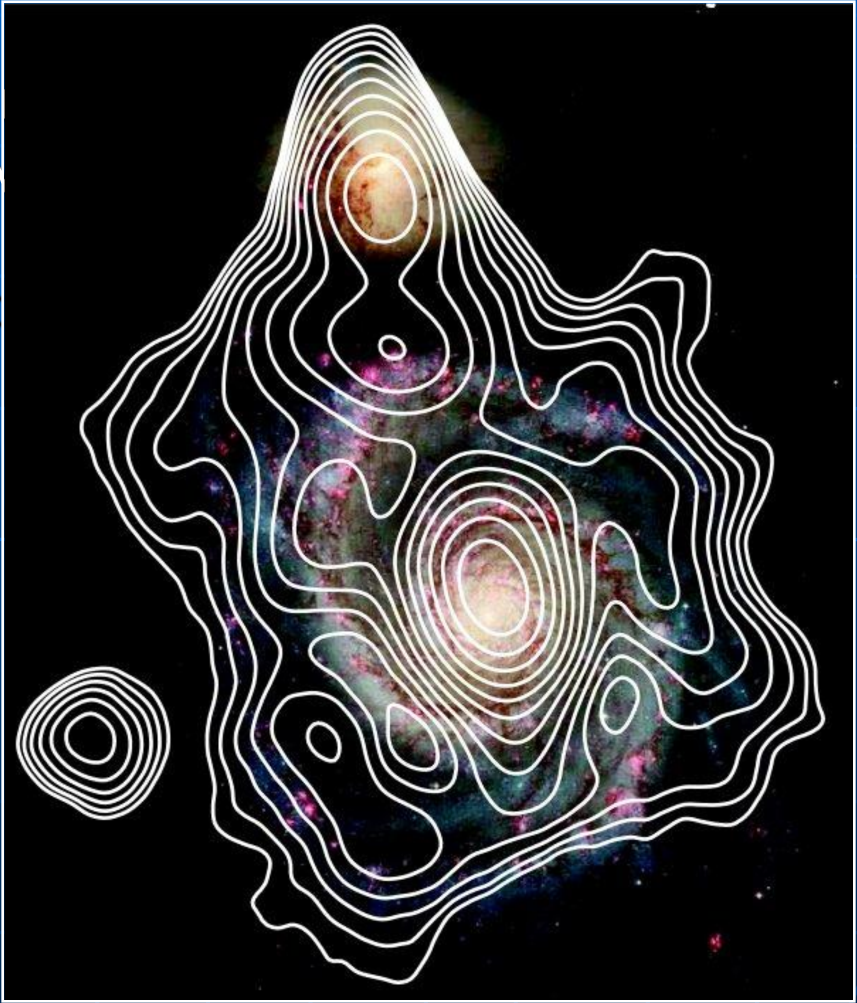
Arshakian & Beck 2010



# LOFAR:
## Extent of galactic halos: First results !

G. Heald et al.

- 6h observatio
- 10 MHz bandw
- Calibration on (no self-cal)
- Robust weight



# Summary:
# Key problems of galactic magnetic fields

- Physics of the galactic dynamo
- Origin of the "magnetic arms“
- Origin of anisotropic fields
- Origin of X-shaped halo fields
- Origin and velocity of magnetized outflows
- Origin of the large-scale reversal(s) in the Milky Way