Observation of galactic magnetic fields and confrontation with dynamo models

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&

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Advantages of galaxies:

- Transparent
- Wide range of properties
- Gas flow can be measured
- Radio observations allow direct measurement of magnetic field patterns

Outline

- Models of field amplification
- Observations
- Confrontation:

  5 evidences, 11 problems and

  2 mysteries
- Future observations and modelling

Magnetic field generation and amplification

- *Stage 1*: Field seeding

  Primordial, Weibel instability, or ejection by supernovae, stellar winds or jets

- *Stage 2*: Field amplification

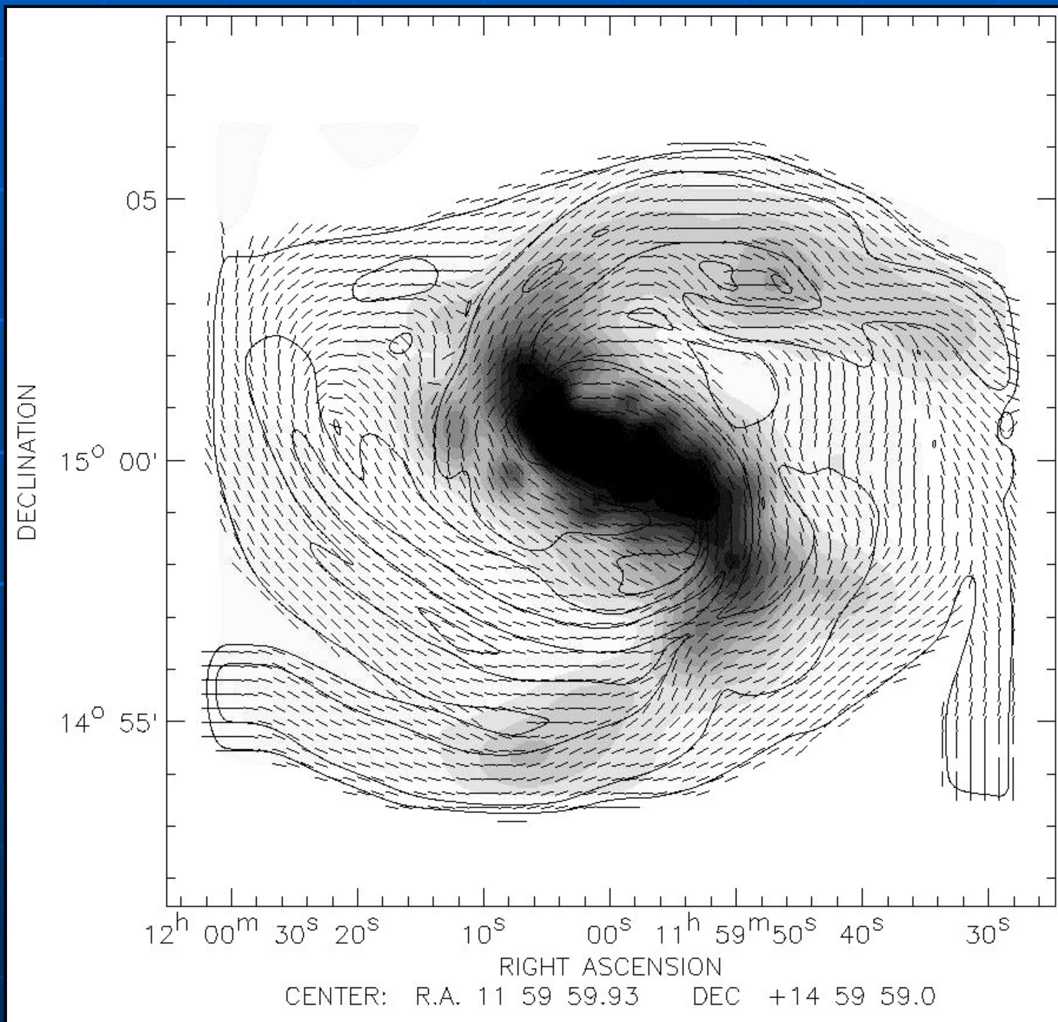
  MRI, compressing flows, shearing flows,

  turbulent flows, small-scale (turbulent) dynamo

- *Stage 3*: Coherent field ordering

  Large-scale (α-Ω, mean-field) dynamo

Kinematic galaxy models
(using model velocity fields)



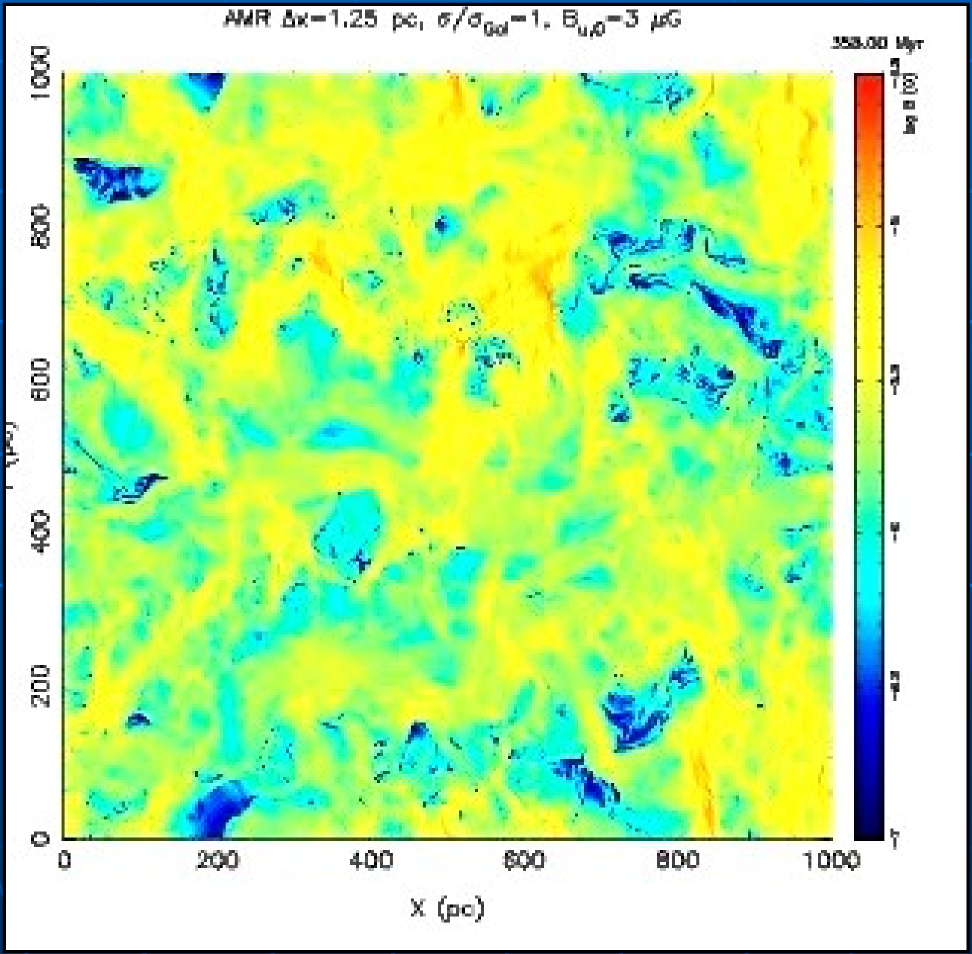
Otmianowska-Mazur, Elstner, Soida & Urbanik 2002

Generation of coherent fields by shear

Coherence length:

≈1 kpc

Dynamic MHD model of supernova-induced turbulence in the ISM



Magnetic field strength

de Avillez & Breitschwerdt 2005

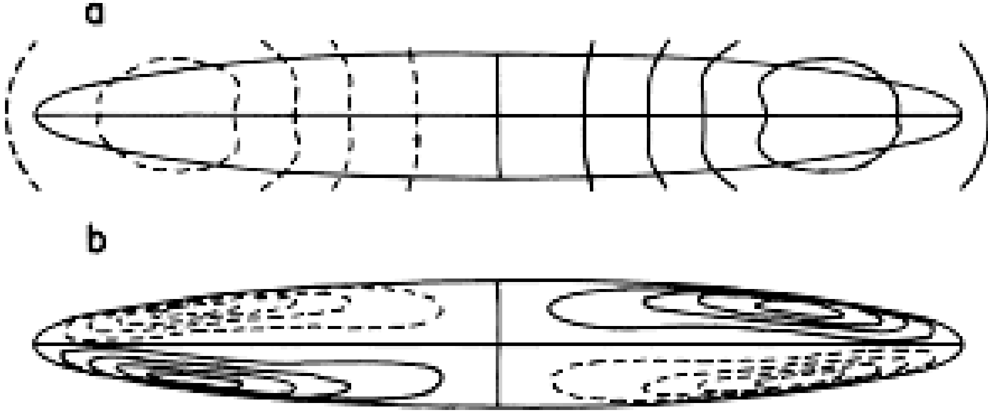
Generation of turbulent and anisotropic fields by compression and shear

Classical dynamo models

- Ideal galaxies: axisymmetric gas distribution + turbulence + differential rotation
- Generation of large-scale coherent fields (modes), described by a *toroidal* (r,Φ) and a *poloidal* (r,z) component
- Thin-disk galaxies:
  The lowest azimuthal mode with *quadrupolar* vertical symmetry (*S0*) is excited most easily,
  toroidal field is much stronger than the poloidal field
- Spherical (halo) or thick-disk galaxies:
  The lowest azimuthal mode with *dipolar* vertical symmetry (*A0*) is excited most easily
- Dynamo modes are stable (non-oscillating)
- Combination of modes possible, but hard to excite

Antisymmetric and symmetric dynamo modes

Stix 1975

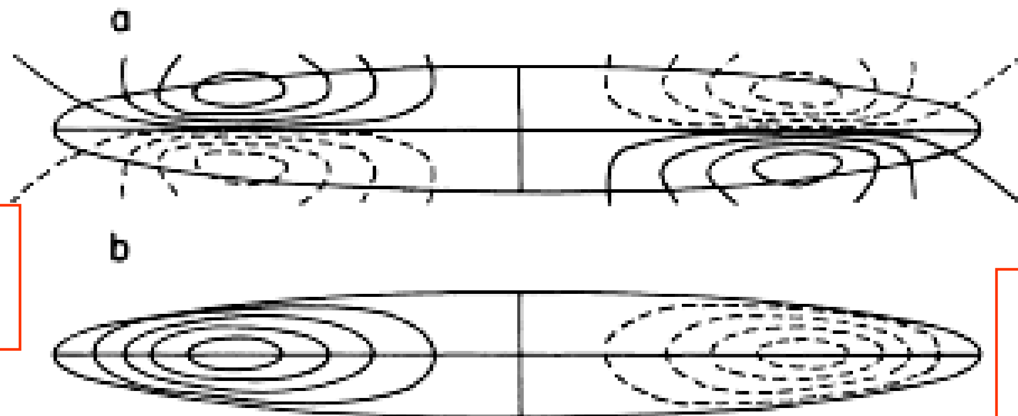


Dipolar poloidal field

A0 mode

Reversing toroidal field in the plane

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 $P = 1.1 \cdot 10^3$



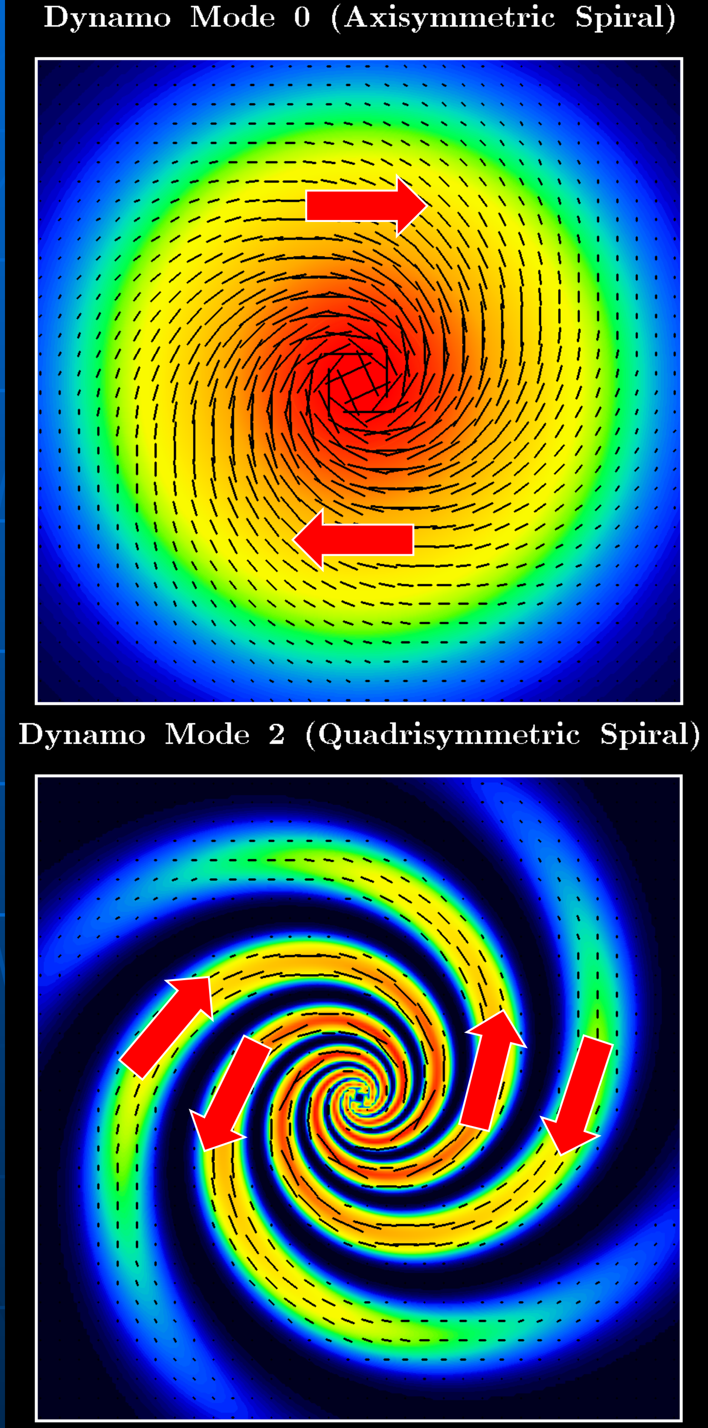
Quadrupolar poloidal field

S0 mode

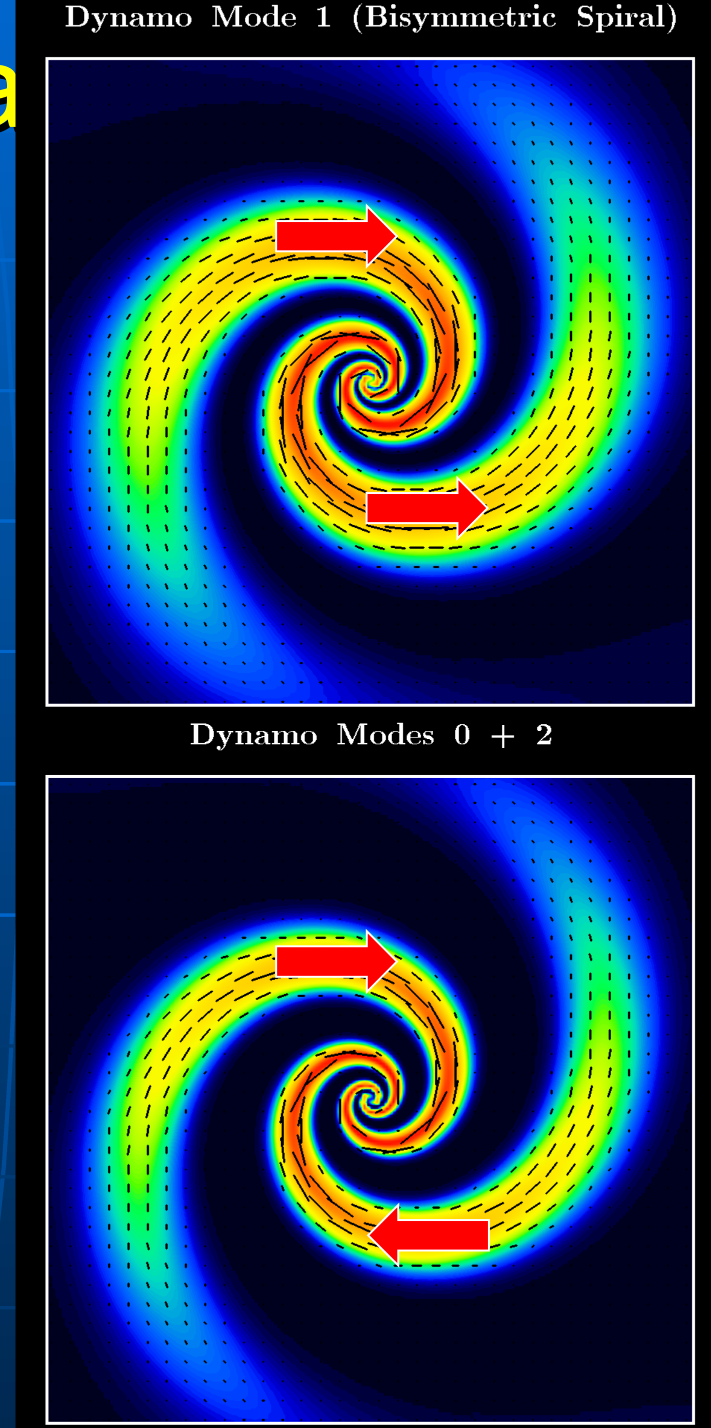
No reversing toroidal field

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 $P = -8.5 \cdot 10^3$

dyna



Dynamo Mode 0 (Axisymmetric Spiral)
Dynamo Mode 2 (Quadrisymmetric Spiral)



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

Atlas of dynamo models

Elstner et al. 1992

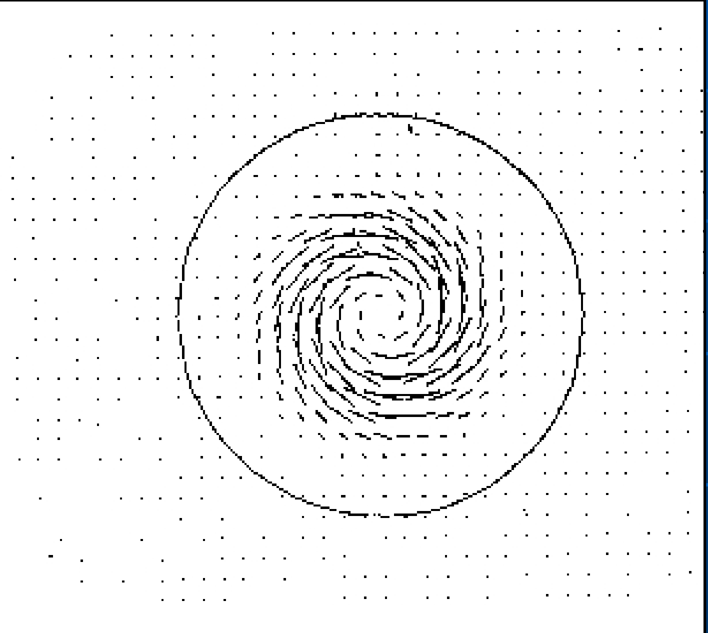


FIGURE 11. Model VIc, mode A0, $i = 0°$

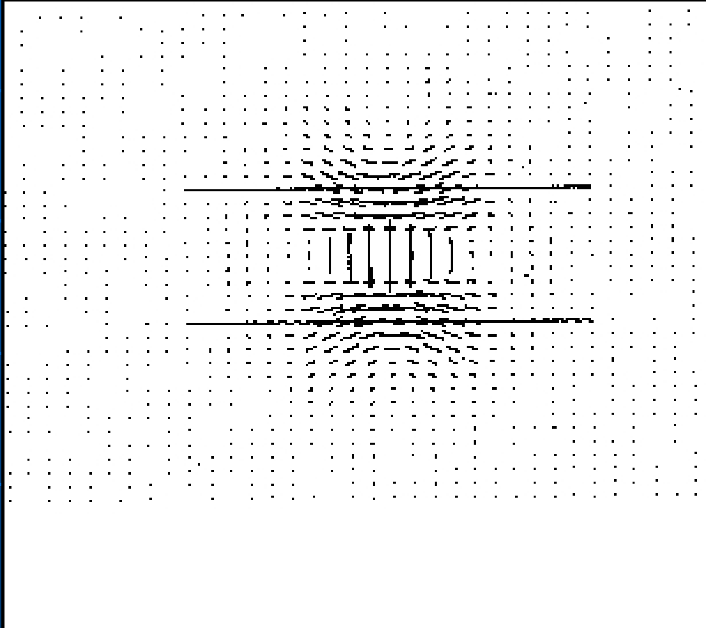


FIGURE 12. Model VIc, mode A0, $i = 90°$

A0 mode

X-shaped halo field

Atlas of dynamo modes

Elstner et al. 1992

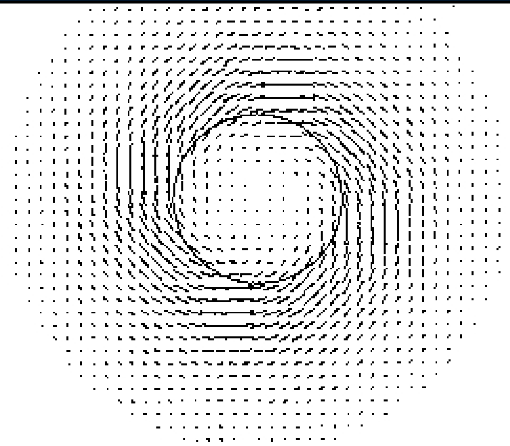


FIGURE 3. Model II, mode S0, $i = 0°$

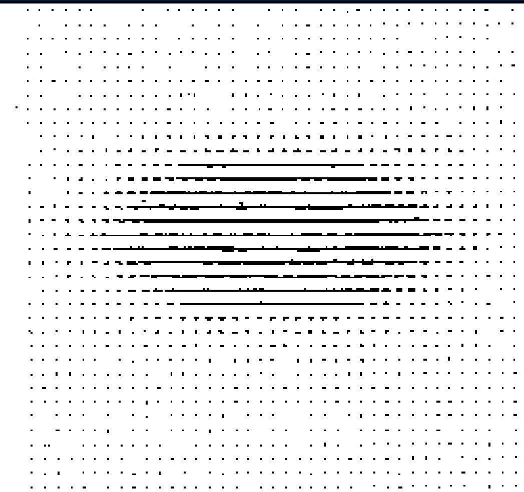


FIGURE 6. Model II, mode S0, $i = 90°$

S0 mode

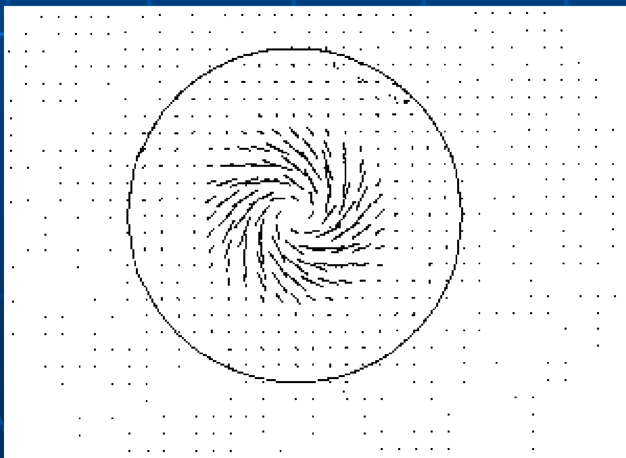


FIGURE 9. Model VIb, mode A0, $i = 0°$

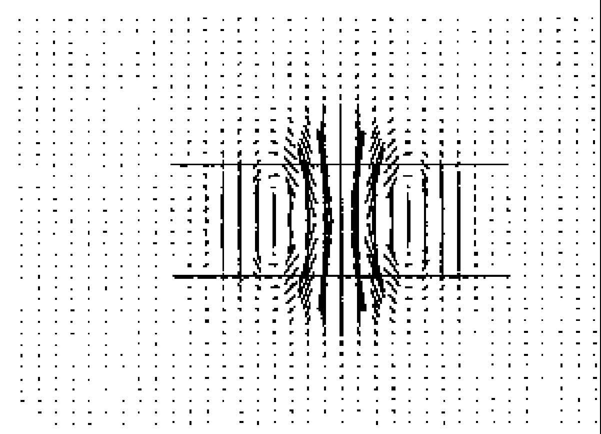


FIGURE 10. Model VIb, mode A0, $i = 90°$

A0 mode

Dynamo models with galactic winds

(Brandenburg et al. 1993)

Oscillating X-shaped modes with reversals

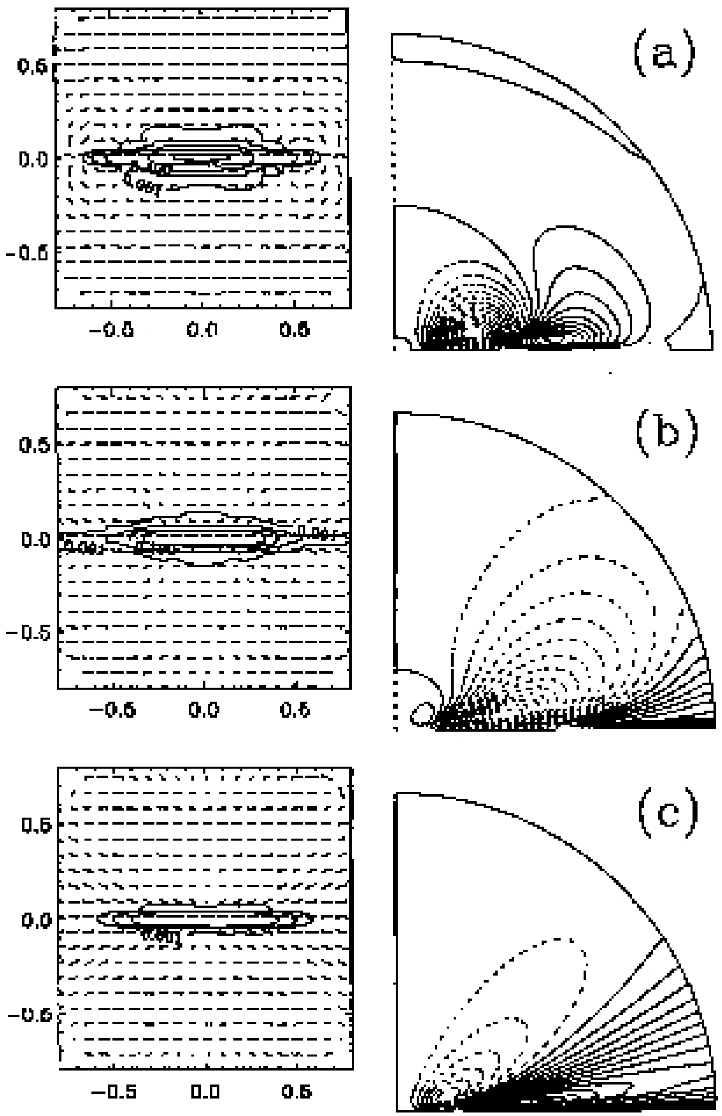


Fig. 9. Polarisation map and poloidal field geometry for a model using the rotation curve parameters of NGC 891 and different wind strengths, for $C_\Omega = 1040$, $\varpi_\Omega = 0.2$, $\xi = 0.02$, $\alpha_z = 0$, $W_z = 0$. (a) $W_r = 0$, (b) $W_r = 50$, (c) $W_r = 200$

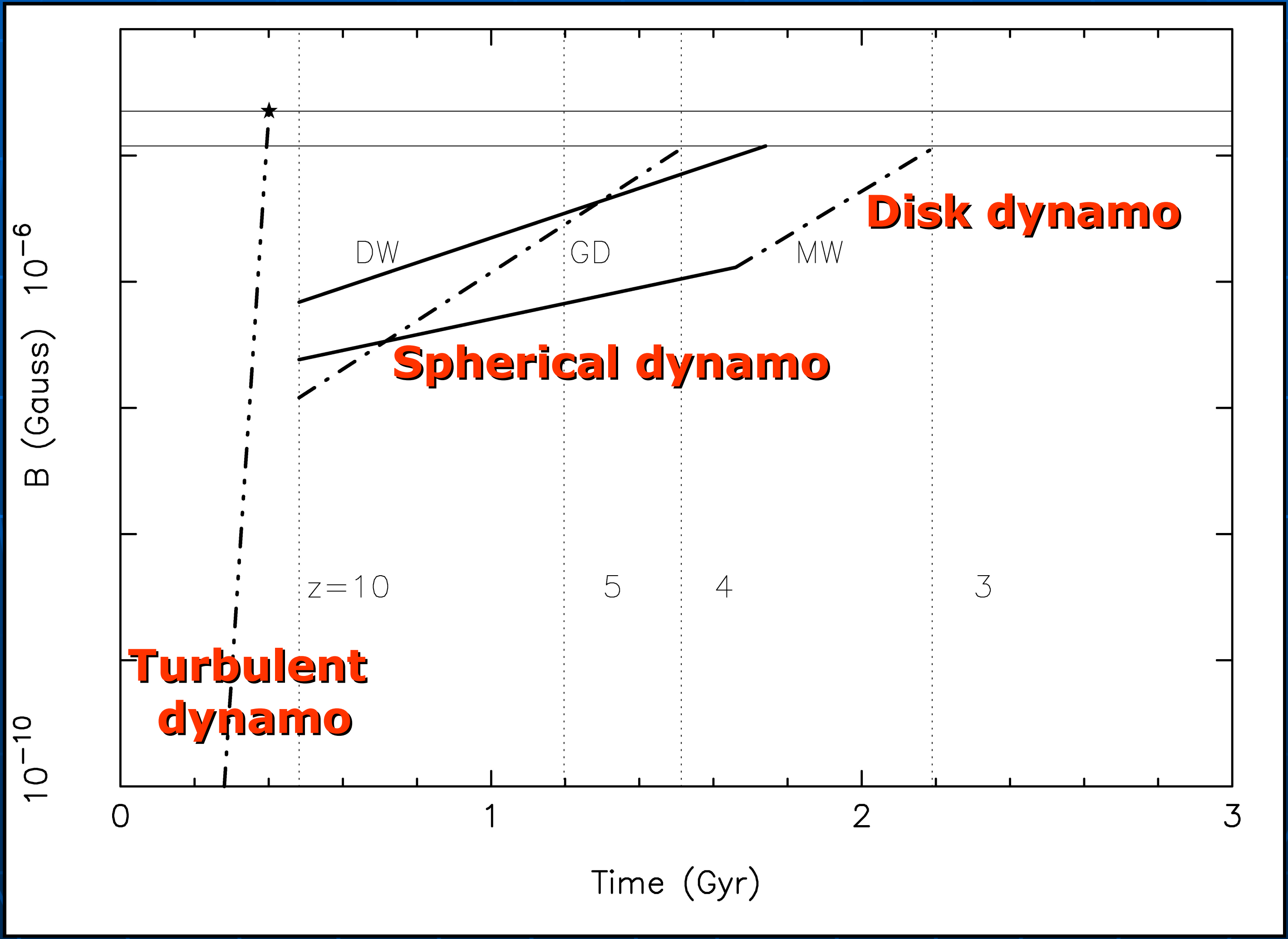
No wind

V_r=50 km/s

V_r=200 km/s

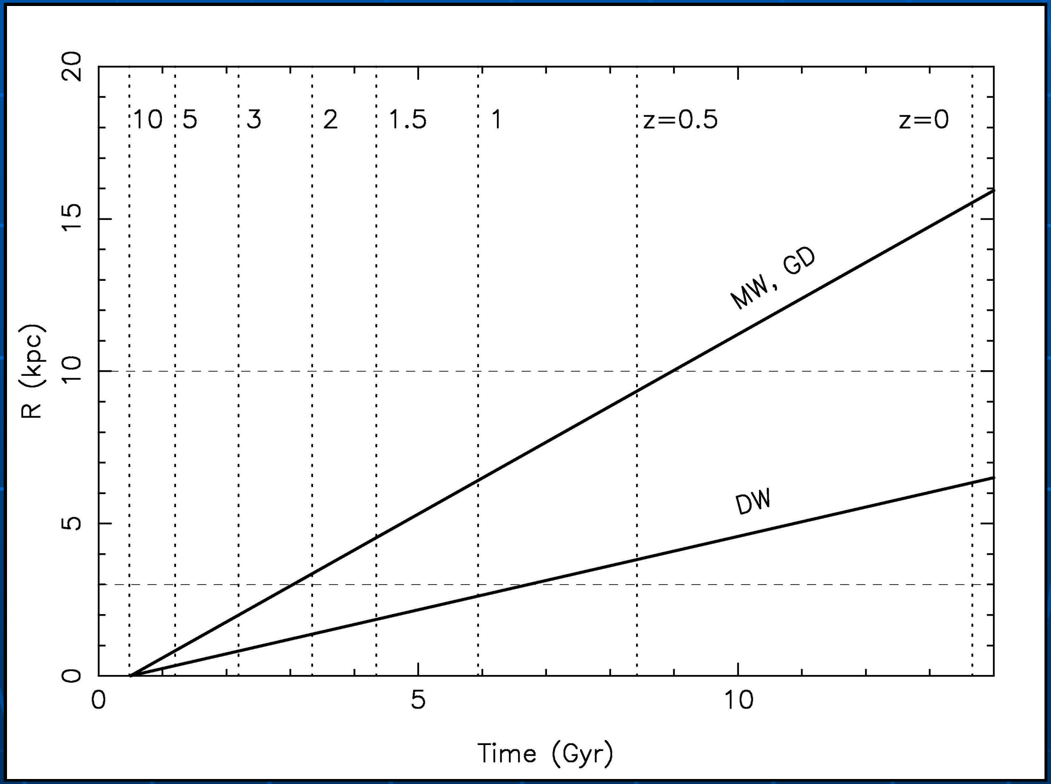
Dynamo action in young galaxies: field strength

Arshakian et al. 2008



Dynamo action in young galaxies: coherence lengths

Arshakian et al. 2008



Large galaxies need more than 10 Gyr to build up a fully coherent field

- Most (visible) cosmic objects are ionized:

  Magnetic fields are easy to generate

- No magnetic monopoles:

  Magnetic fields are hard to destroy

- But magnetic fields need illumination:

  They are difficult to observe

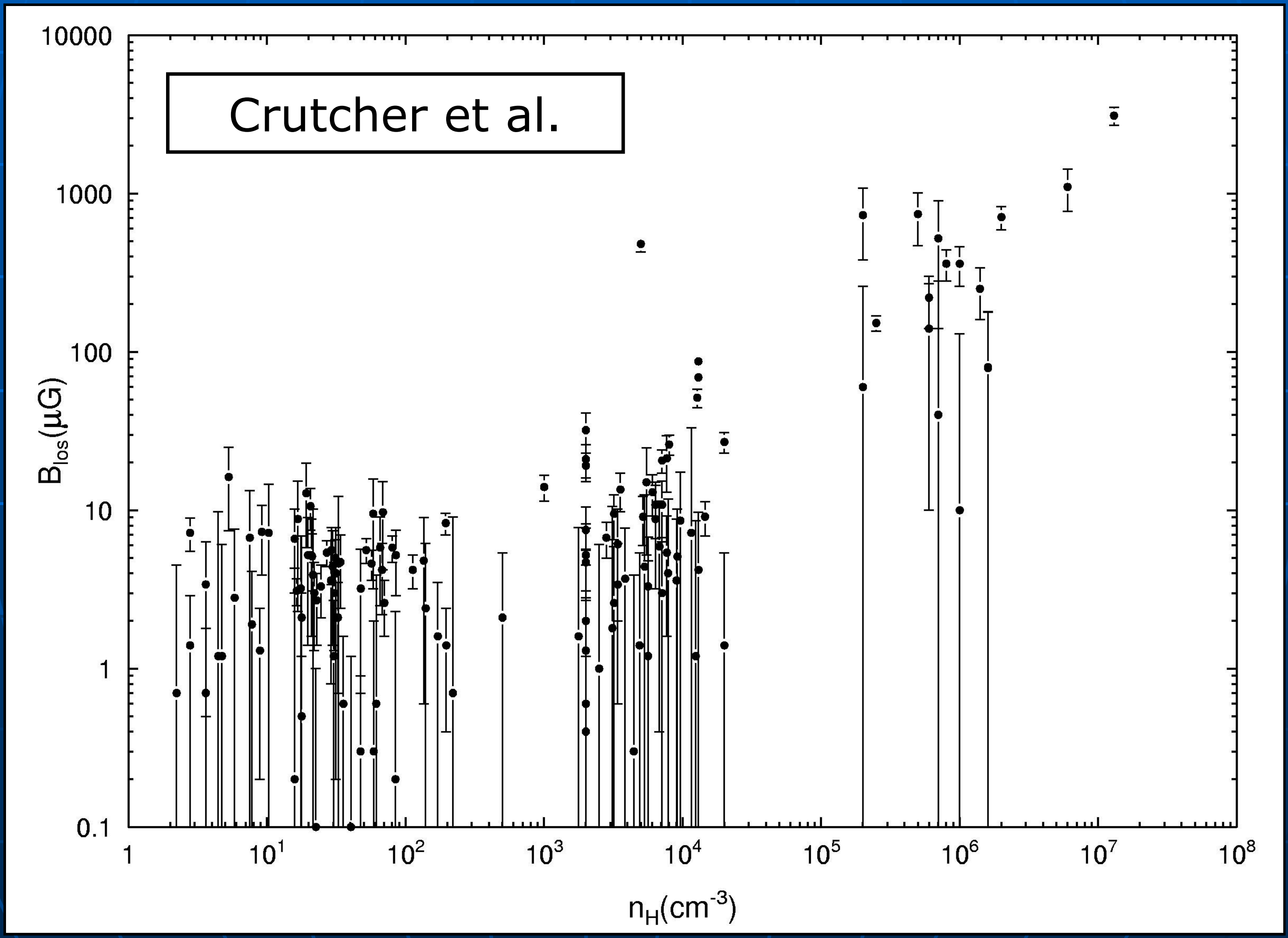
Observations and confrontation with models

1. Methods
2. Field strength
3. Field regularity
4. Field structure
5. Pitch angle
6. Coherent fields
7. Sign of radial component
8. Depolarization asymmetry
9. Halo fields
10. Milky Way and field reversals

Tools to study magnetic fields

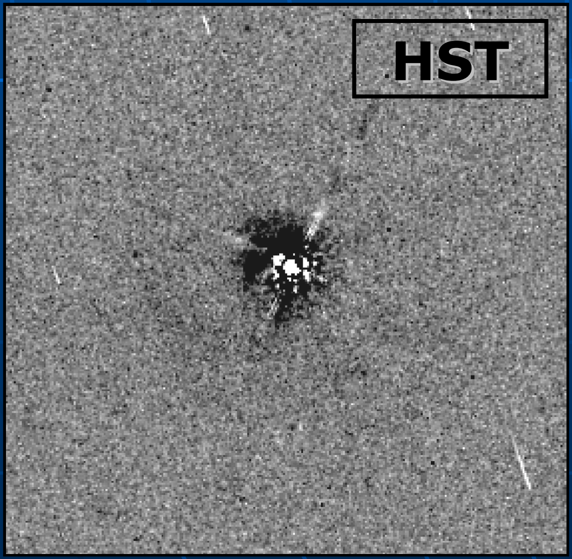
- Zeeman effect:
  Strength and sign of ordered $B_\parallel$
- Optical / infrared / submm polarization by dust grains:
  Structure of ordered $B_\perp$
- Total synchrotron intensity:
  Strength of total $B_\perp$
- Polarized synchrotron intensity:
  Strength and structure of ordered $B_\perp$
- Faraday rotation:
  Strength and sign of ordered $B_\parallel$
- Faraday depolarization:
  Strength and scale of turbulent fields

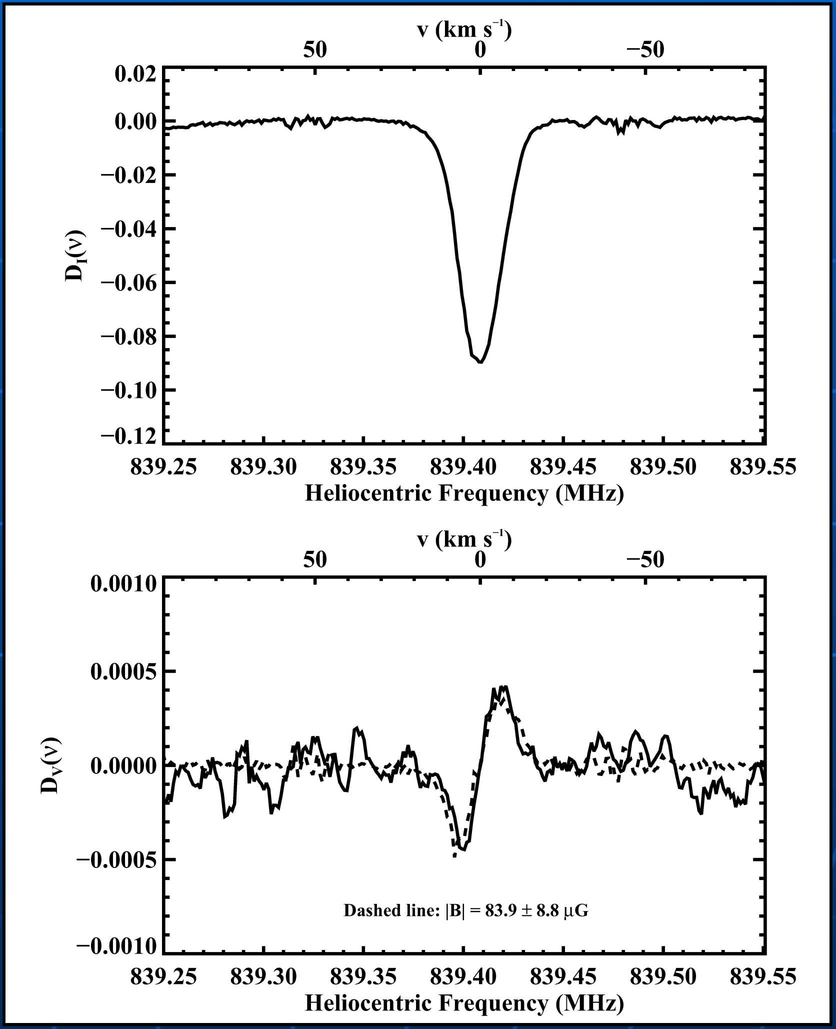
Zeeman field strengths ($B_{\parallel}$) in Milky Way clouds



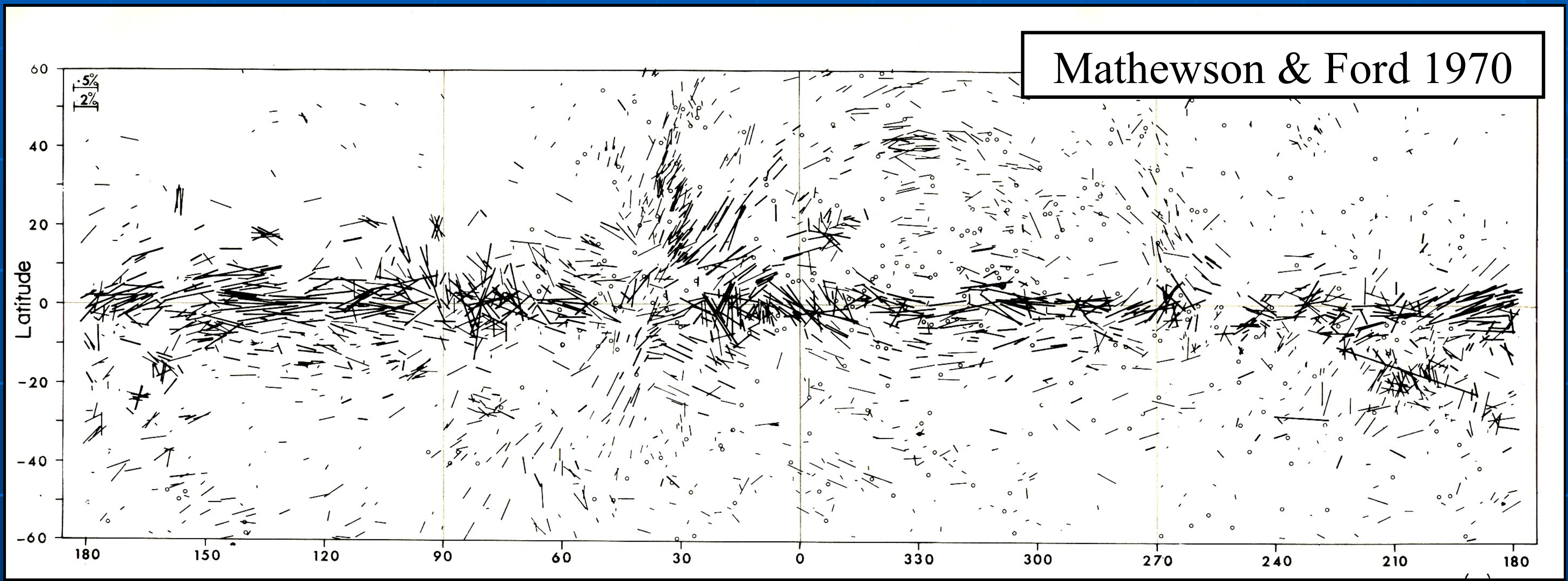
Zeeman effect in a distant galaxy

Zeeman effect in
the HI absorption line
of an intervening
galaxy at z=0.692
against a bright quasar:
$B_{\square} \approx 84\ \mu G$
(Wolfe et al. 2008)



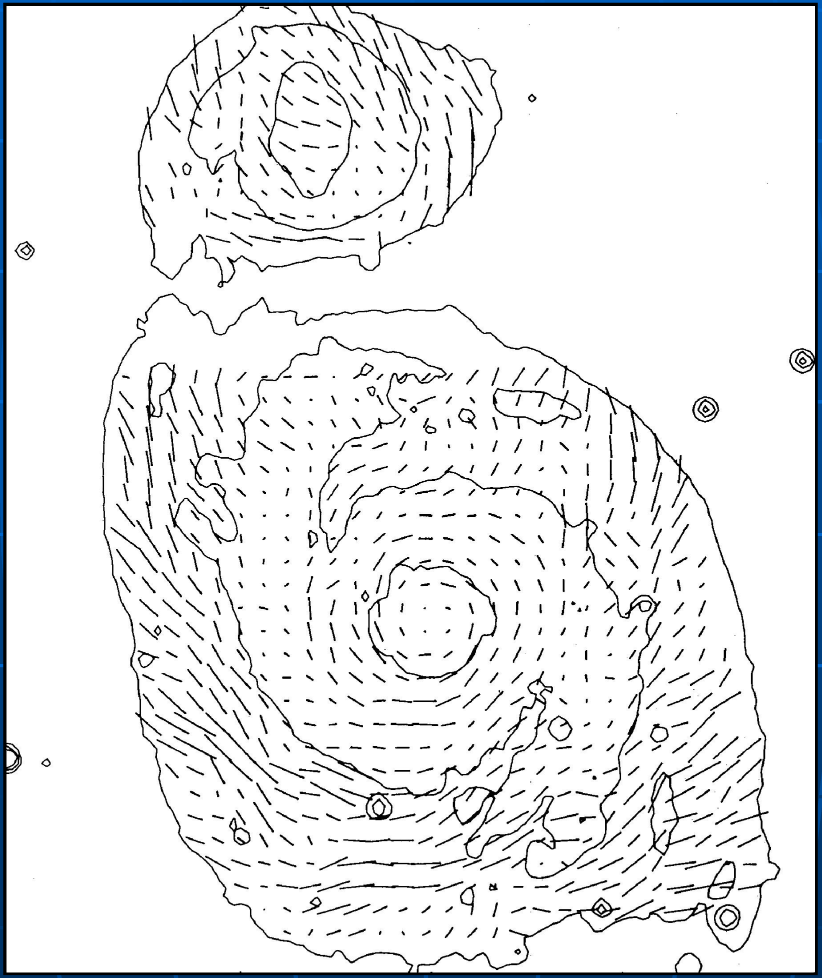


Starlight polarization



Large-scale ordered field in the Milky Way, directed towards *l* ≈77°, pitch angle ≈ 7° (Heiles 1996)

Starlight polarization in M 51



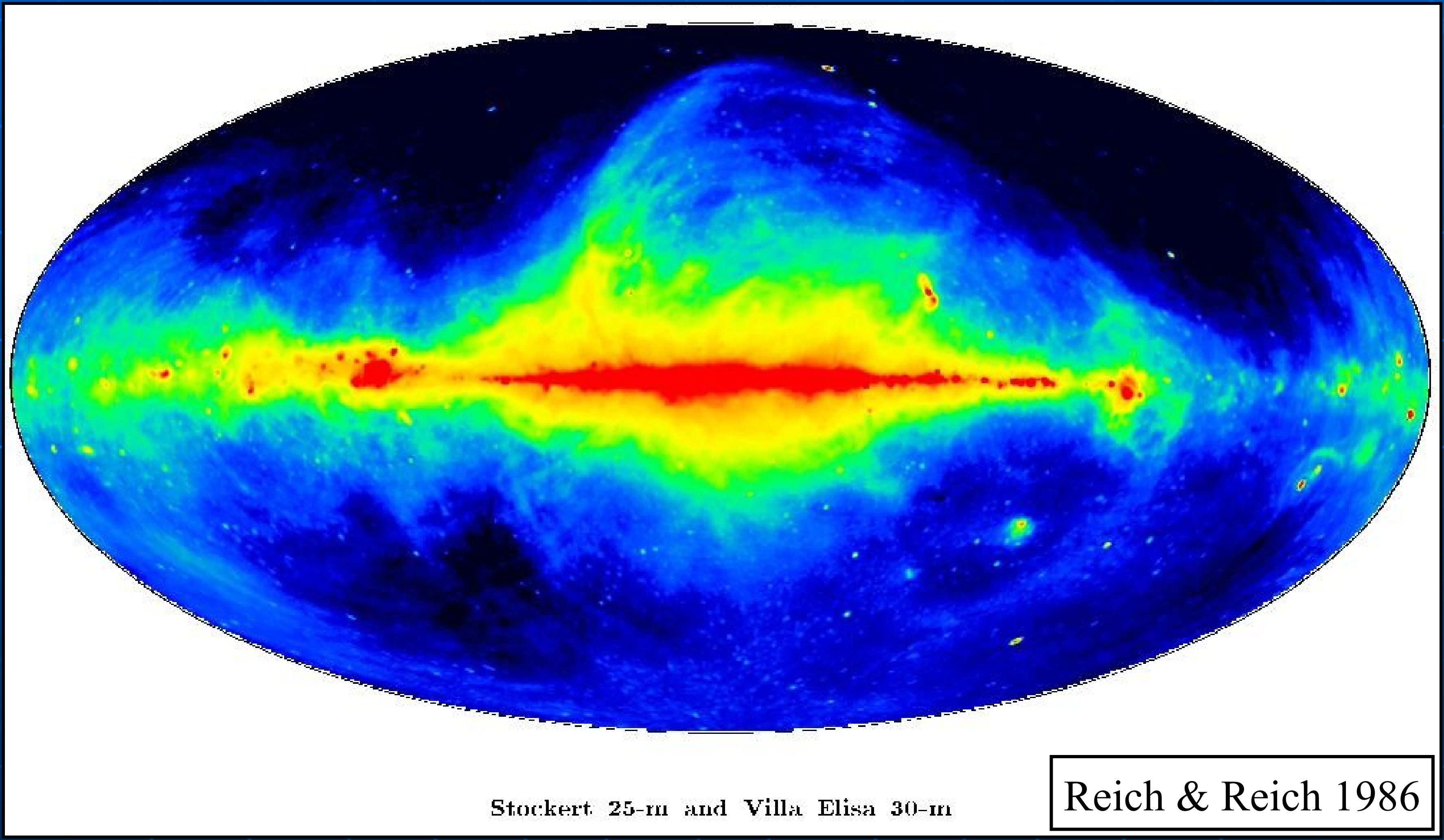
Scarrott et al. 1977

Large-scale spiral field or scattered light ?

Radio radio from the Milky Way:

Synchrotron emission

(K.G. Jansky 1931, K.O. Kiepenheuer 1950)



Reich & Reich 1986

Equipartition strength of the total field

(assuming equipartition between magnetic fields and cosmic rays)

Beck & Krause 2005

$$B_{eq,\square} \propto \left(I_{sync}\,(K+1) / L \right)^{1/(3+\alpha)}$$

I_{sync}: Synchrotron intensity

L: Pathlength through source

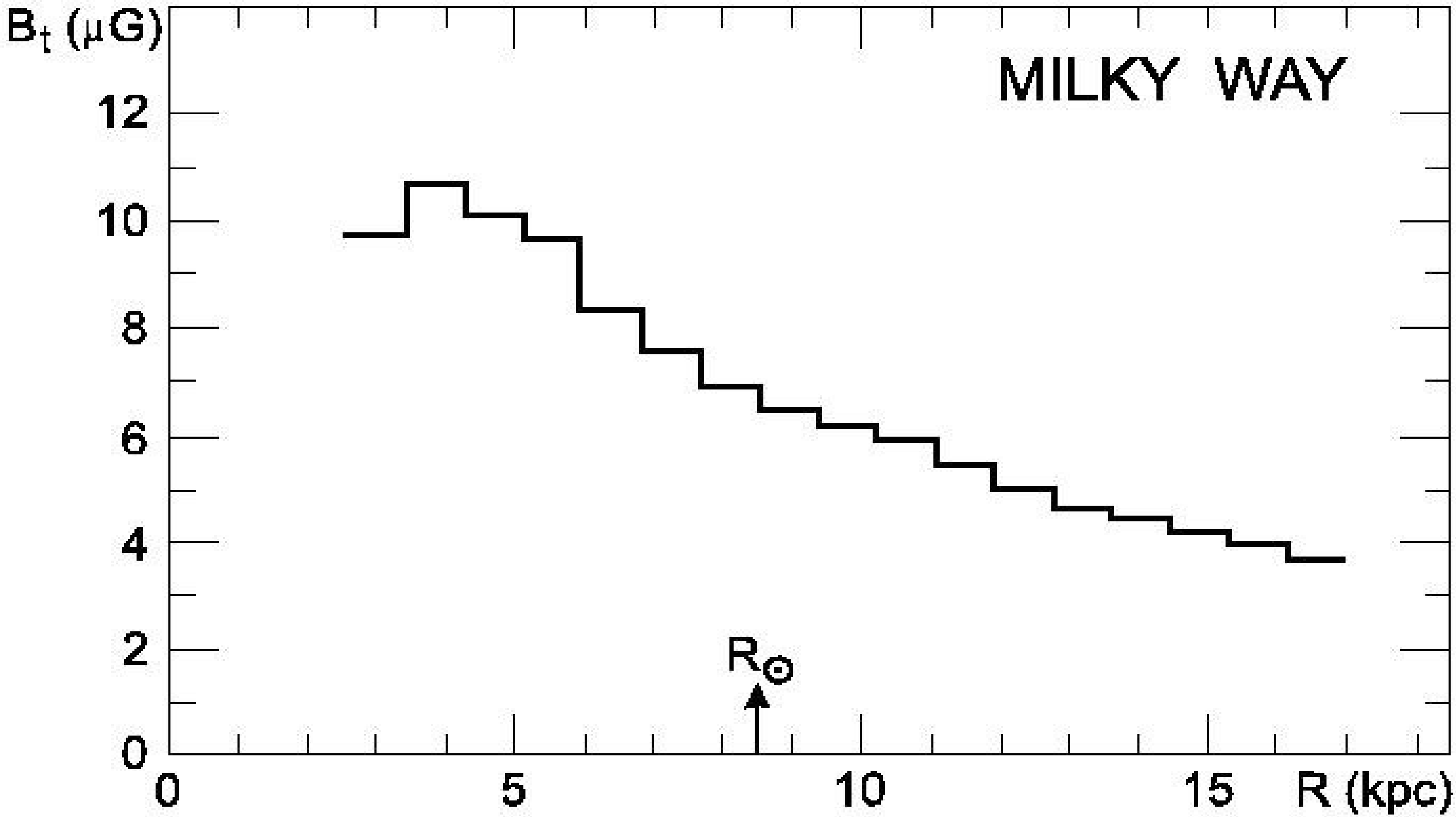
α: Synchrotron spectral index ($S \propto \nu^{-\alpha}$)

K: Ratio of cosmic-ray proton/electron number densities n_p/n_e

Usual assumption: K=100 (no energy losses of CR electrons)

Equipartition field in the Milky Way

(Berkhuijsen, in Wielebinski & Beck 2005)

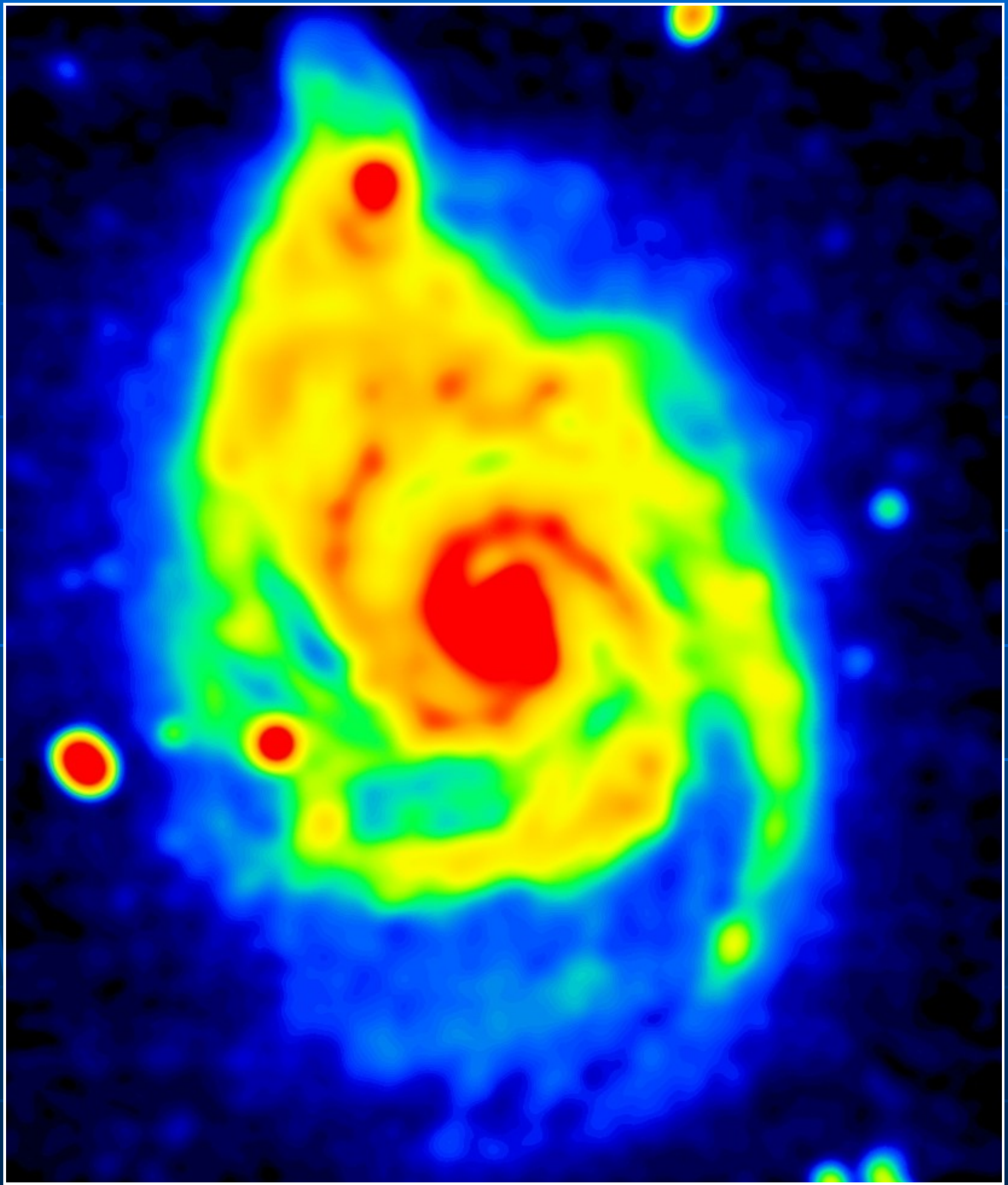


Consistent with estimates from γ rays

(Strong et al. 2000)

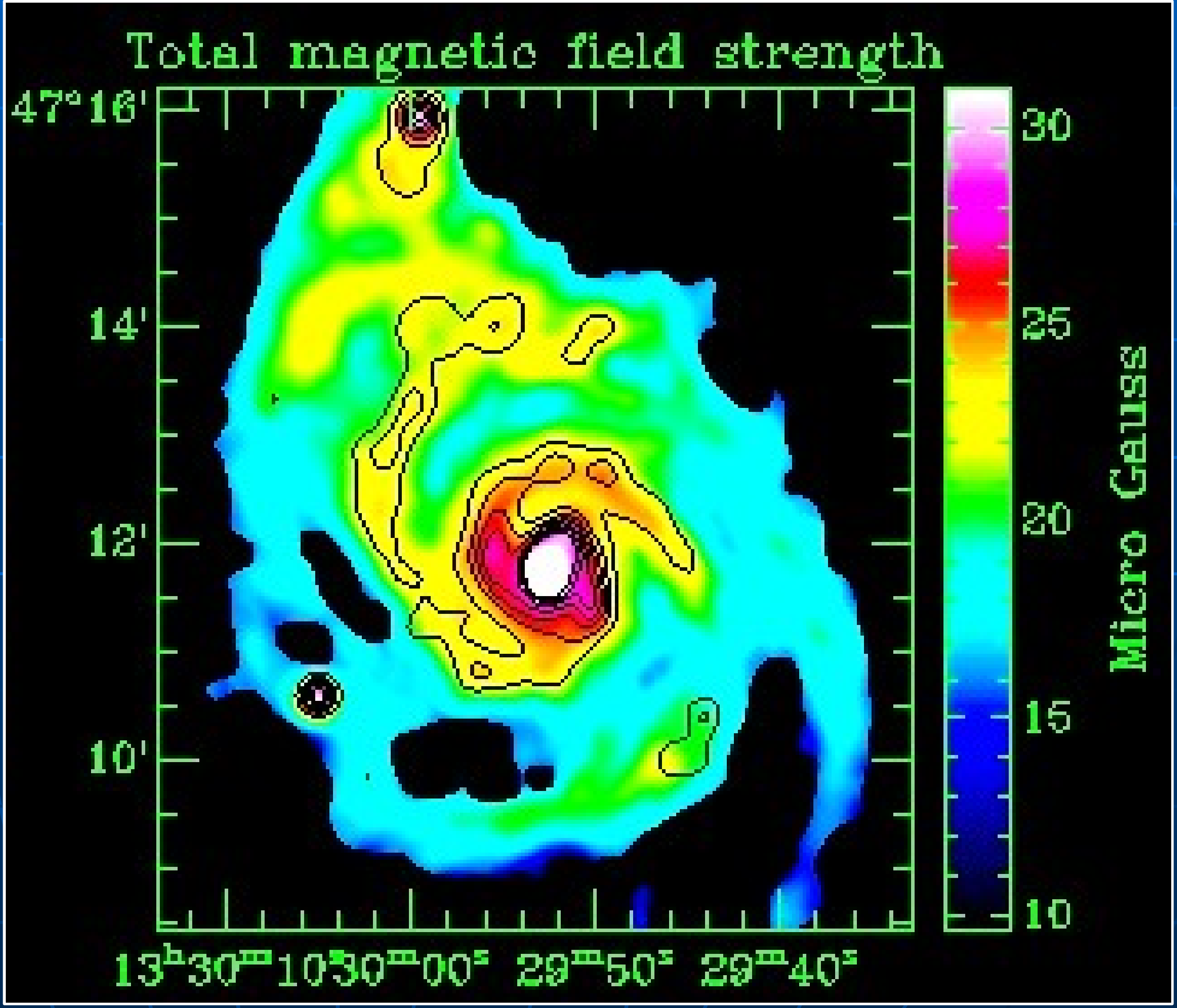
M 51

20cm VLA
Total intensity
(Fletcher et al. 2009)



Equipartition field strengths in M 51

Fletcher et al. 2009



Magnetic field strengths in spiral galaxies

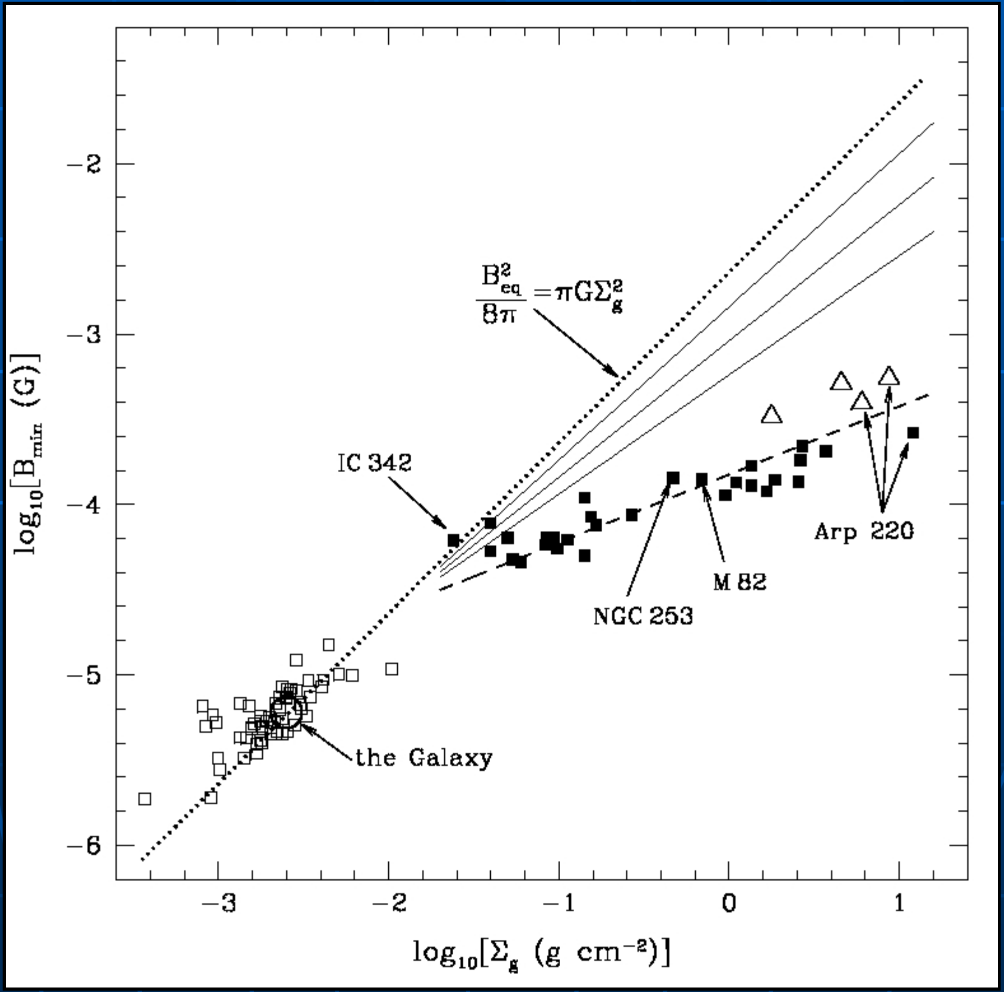
(from synchrotron intensity, assuming energy equipartition with cosmic rays)

Total field in spiral arms:	**20 - 30 μG**
Regular field in interarm regions:	**5 - 15 μG**
Total field in circum-nuclear rings:	**40 – 100 μG**
Total field in galaxy centre filaments:	**≈ 1 mG**

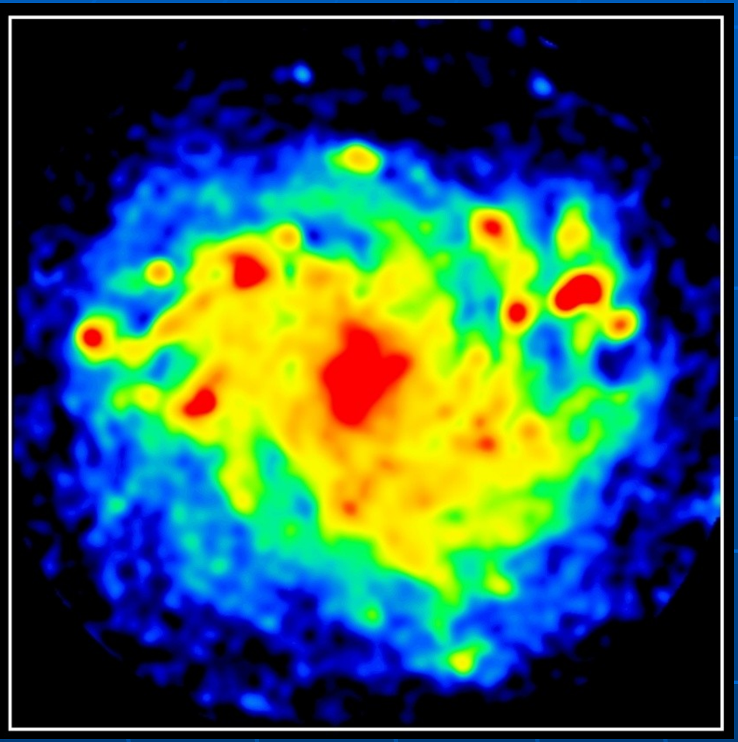
Magnetic fields and gas surface density

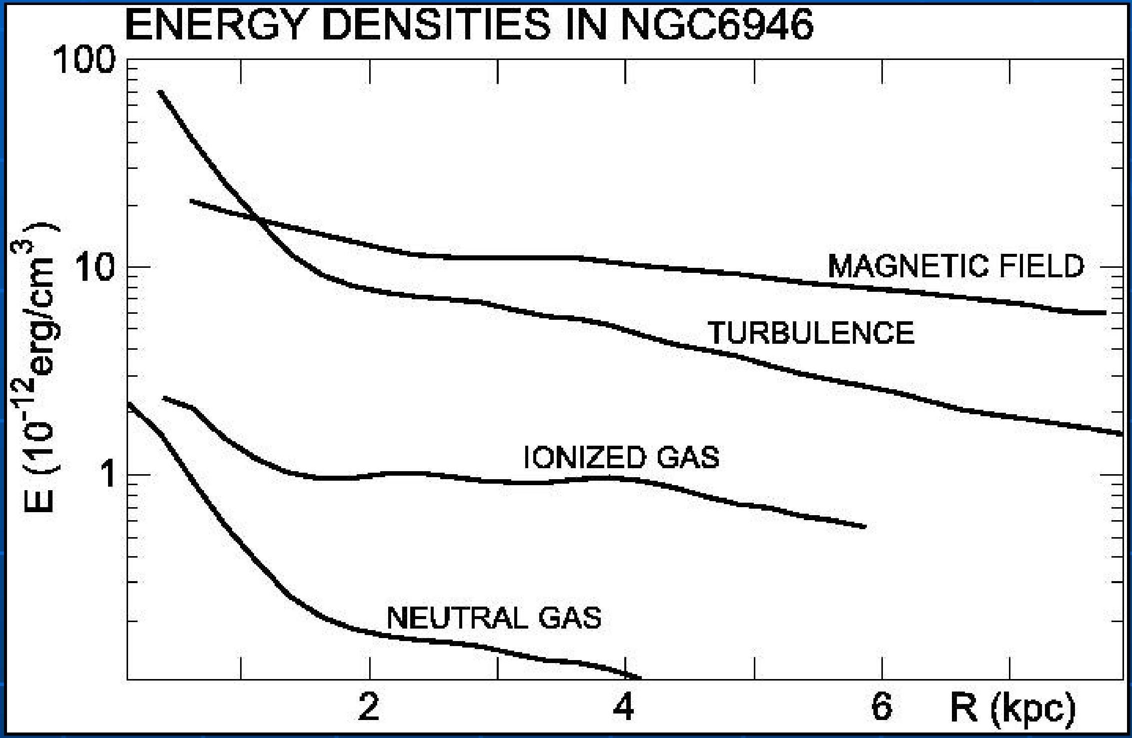
Thompson et al. (2006)

Equipartition magnetic field strengths in starburst galaxies are probably underestimates



Energy densities





Cold clouds:

V_{turb} = 7 km/s ≈ const (from SNRs),

T=50 K, h=100 pc

Beck 2007

Ionized gas:

T=10^4 K, f_v=0.05, h=1 kpc

Energy densities
(NGC 6946, M 33)

Beck 2007,
Tabatabaei et al. 2008

- $E_{magn} \approx E_{turb}$ (inner disk)

  (evidence for turbulent amplification)

- $E_{magn} > E_{turb}$ (outer disk)

  (turbulence underestimated ? MRI ?)

- $E_{magn} > E_{therm}$ (everywhere)

  (low-beta plasma)

Dynamo evidence no.1:

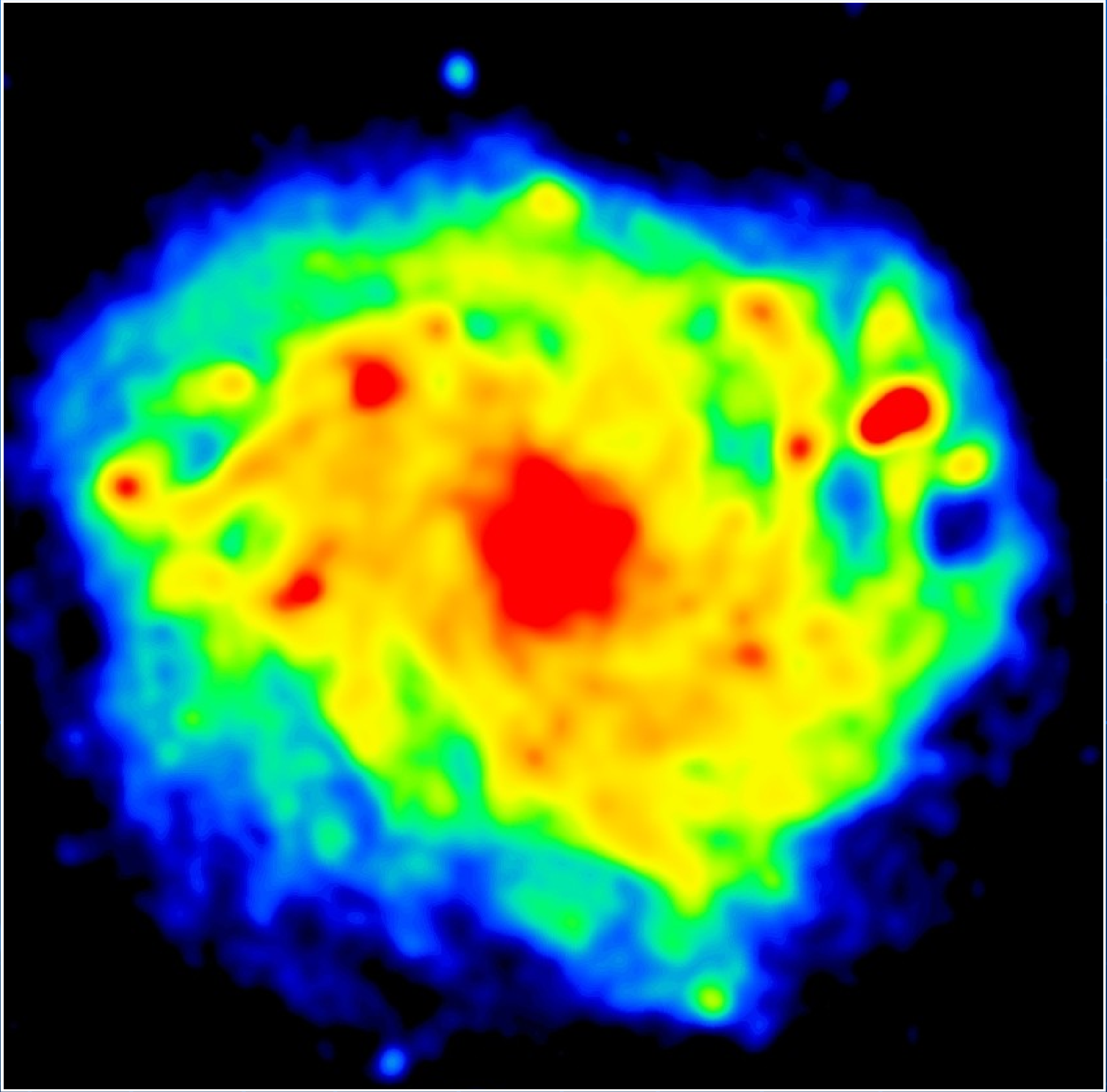
Magnetic energy density is similar to that of turbulent gas motions

Problem no.1:

The total magnetic energy seems to exceed the turbulent energy in the outer disk - how ?

NGC 6946

20cm VLA
Total intensity
(Beck 2007)



Exponential radio disk

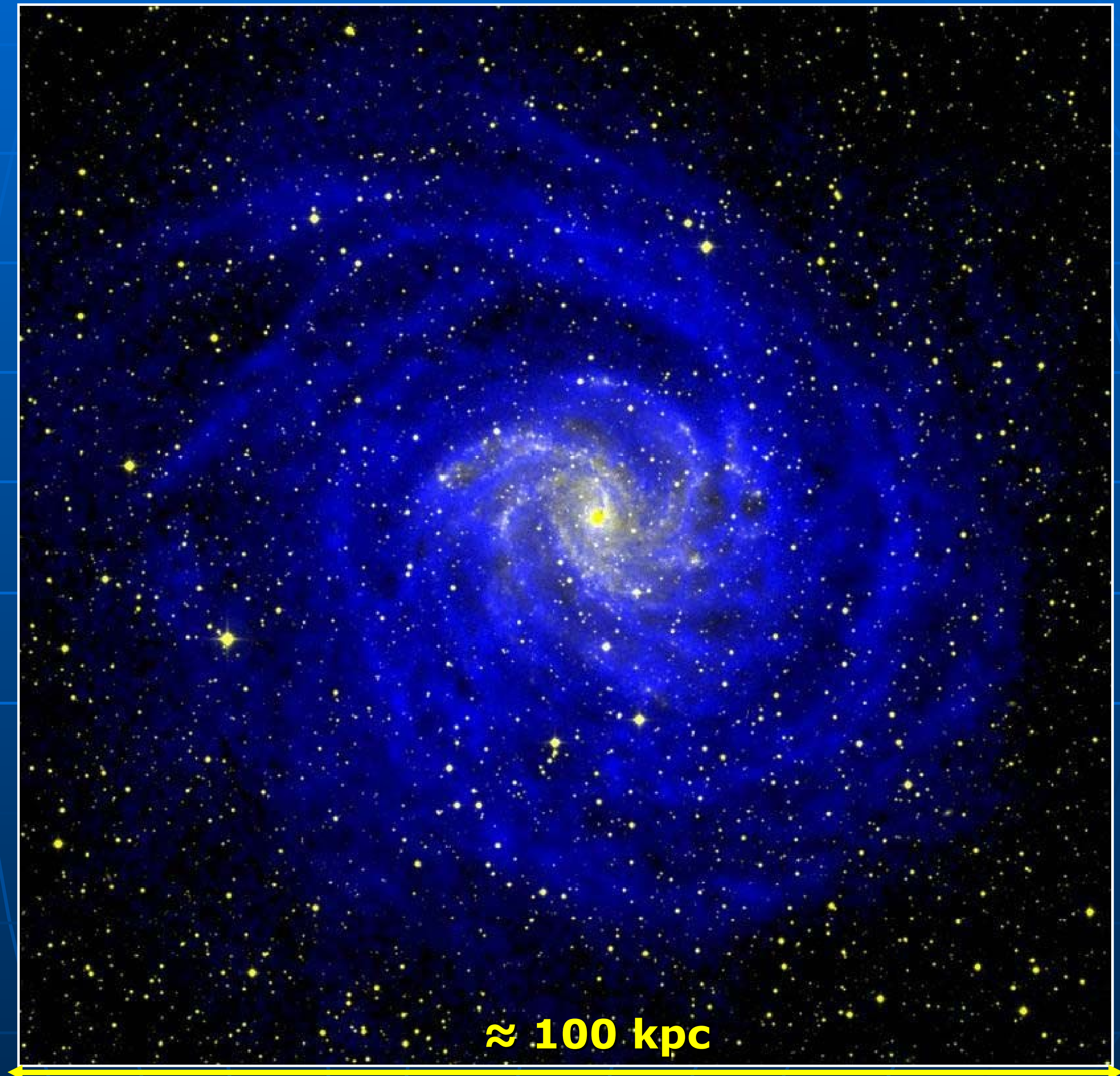
Extent is limited by energy losses of the cosmic-ray electrons

Typical scale lengths of radio disks of spiral galaxies

- Cold & warm gas: ≈4 kpc
- Synchrotron: ≈4 kpc
- Cosmic-ray electrons: ≤8 kpc
  (upper limit due to energy losses)
- Total magnetic field: ≥16 kpc

NGC 6946

WSRT HI
+ optical
(Boomsma et al. 2006)



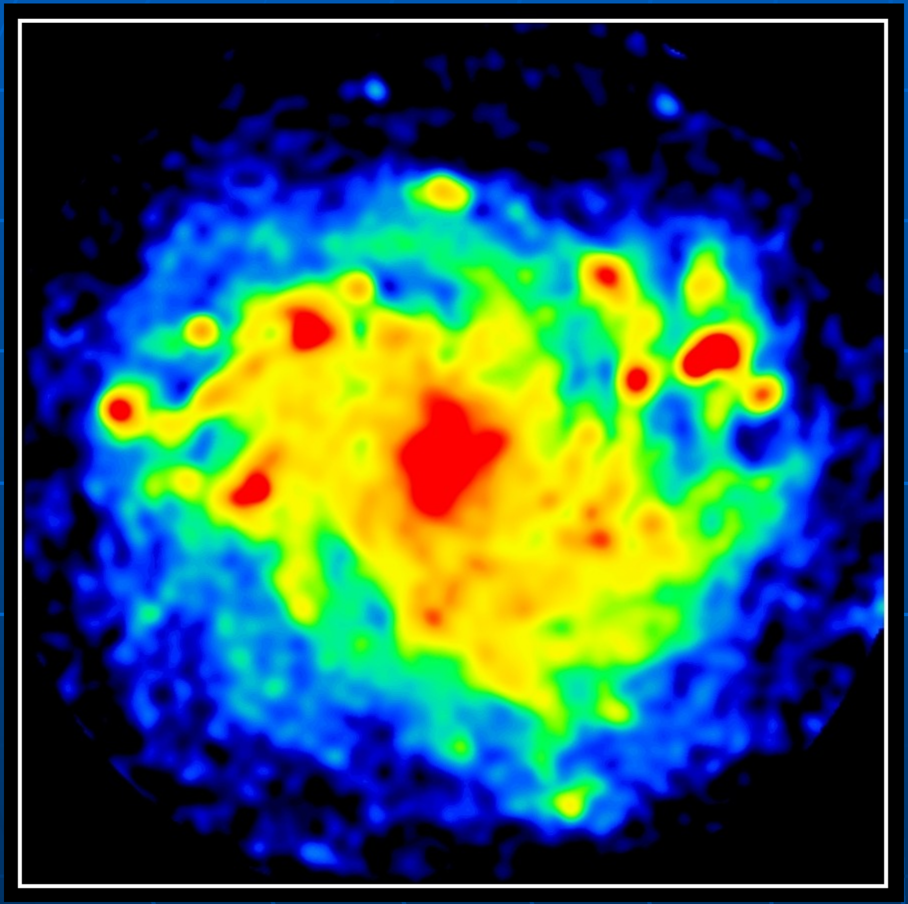
All magnetic ?

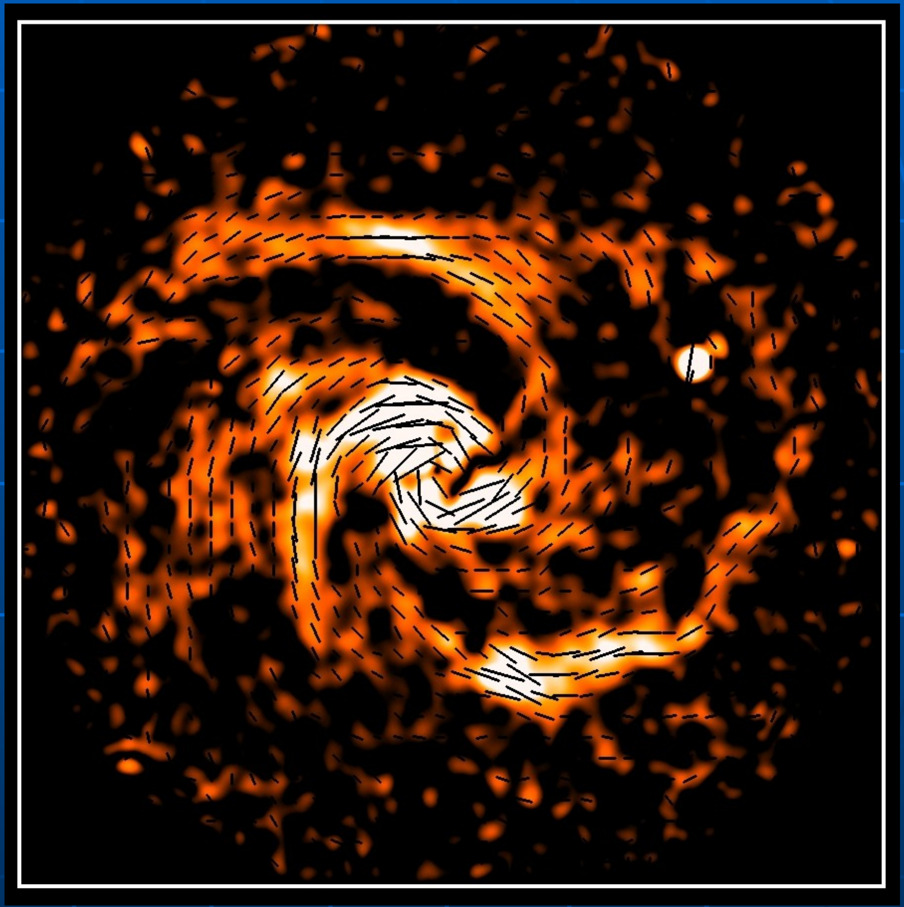
Problem no.2:

The true extent of magnetic fields is unknown

Synchrotron polarization

Beck & Hoernes 1996

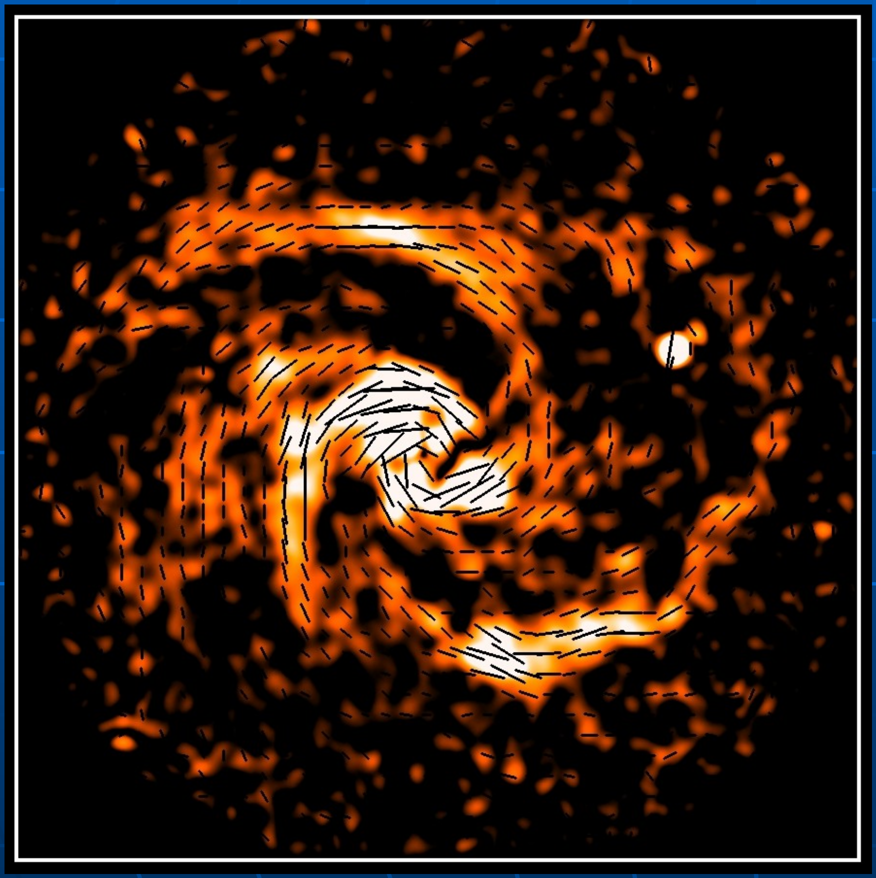


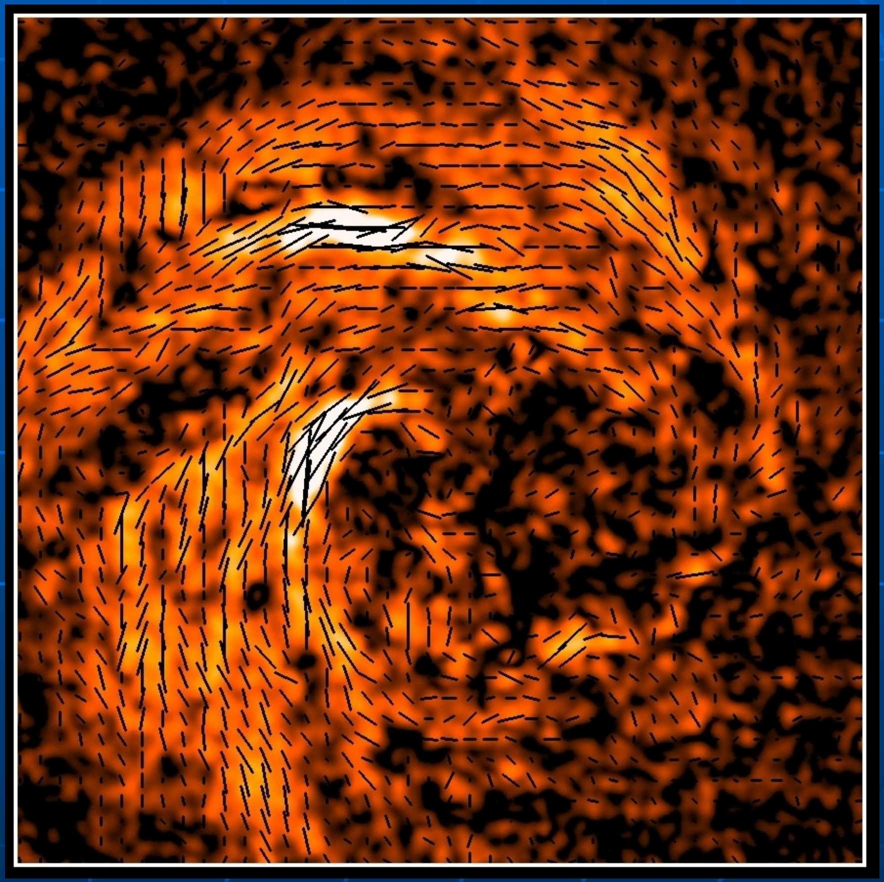


NGC 6946 Total and polarized intensity at 6cm

Faraday depolarization

Beck 2007





NGC 6946 Polarized intensity at 6cm and 20.5cm

Degree of polarization:

≤ 5% in spiral arms

20 - 60% in magnetic arms

Ratio of random to regular magnetic fields:

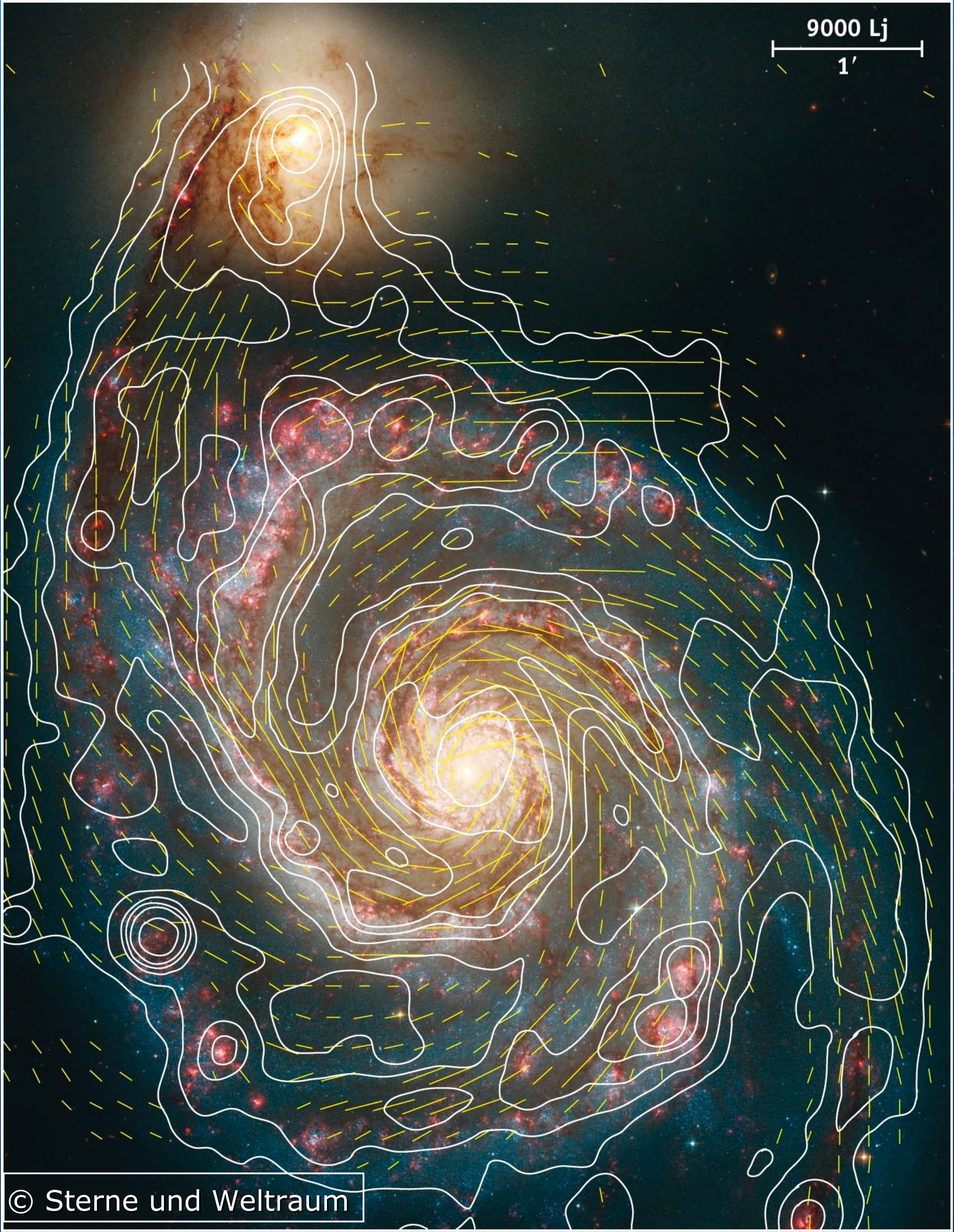
≥ 4 in spiral arms and starburst regions

0.5 – 2 in magnetic arms

M 51

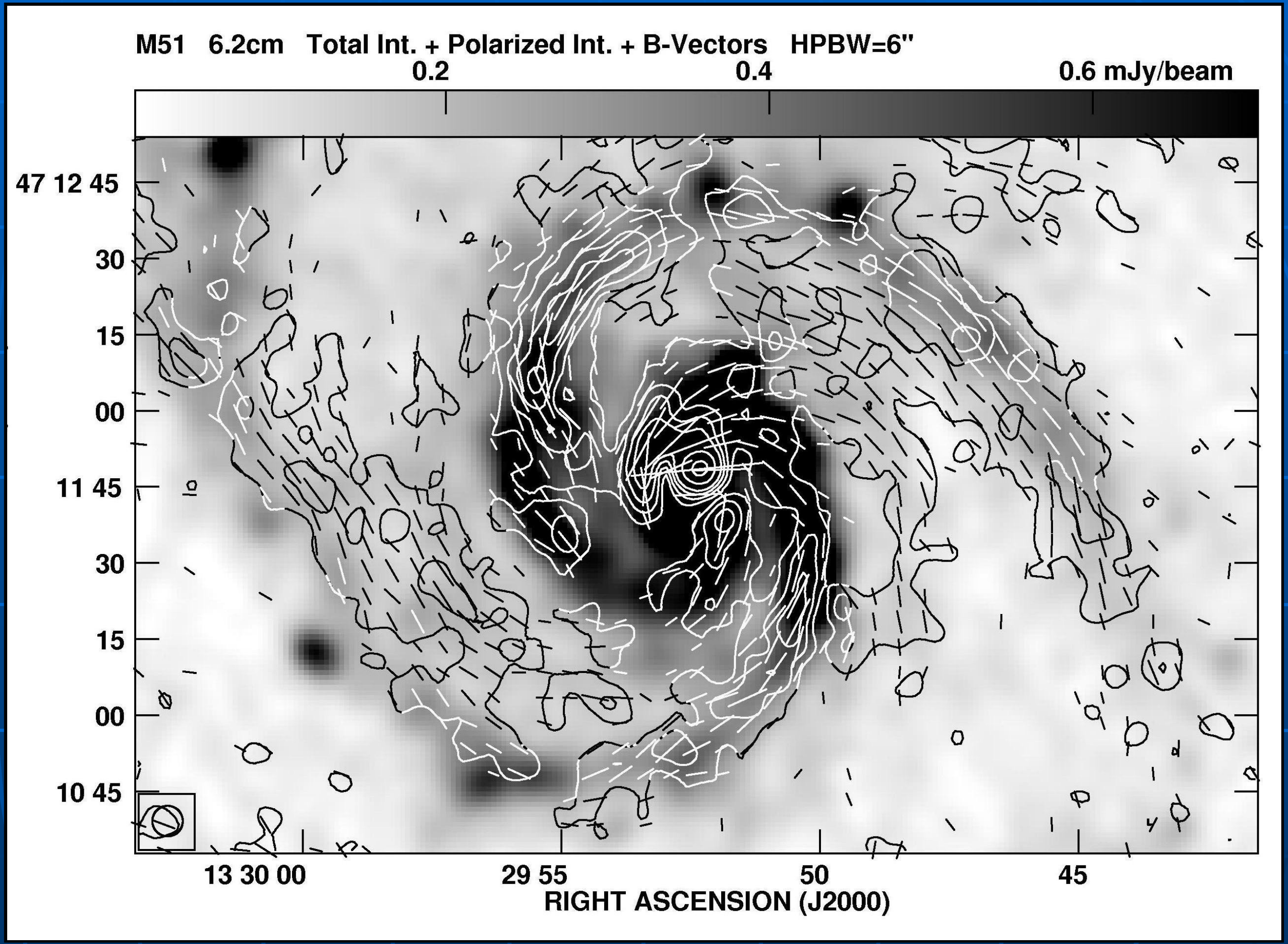
6cm VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2009)

Spiral fields more or less parallel to the optical spiral arms



M 51

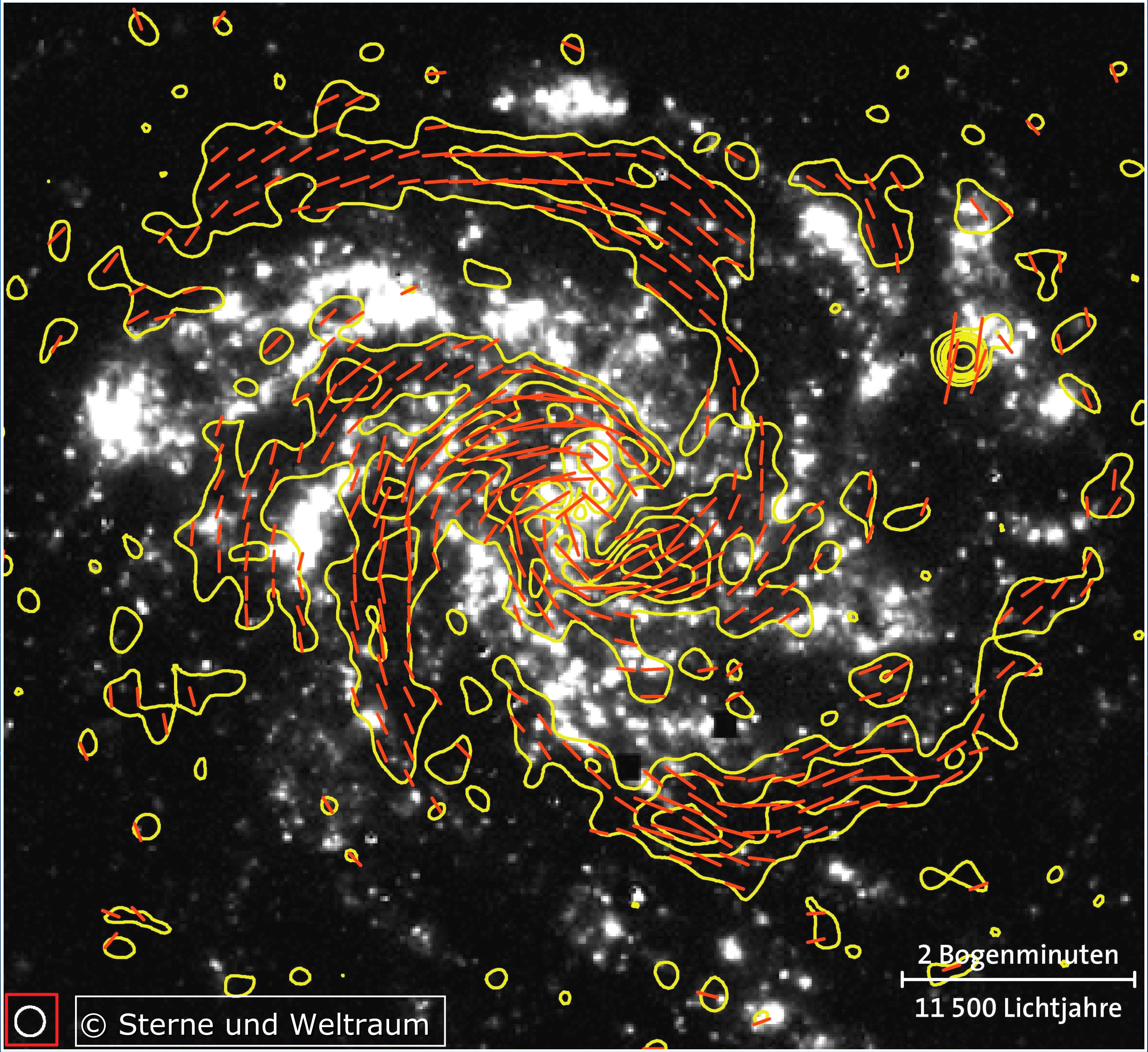
6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2009)



Spiral fields perfectly parallel to the inner spiral arms - by density-wave compression

NGC 6946

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



"Magnetic arms":

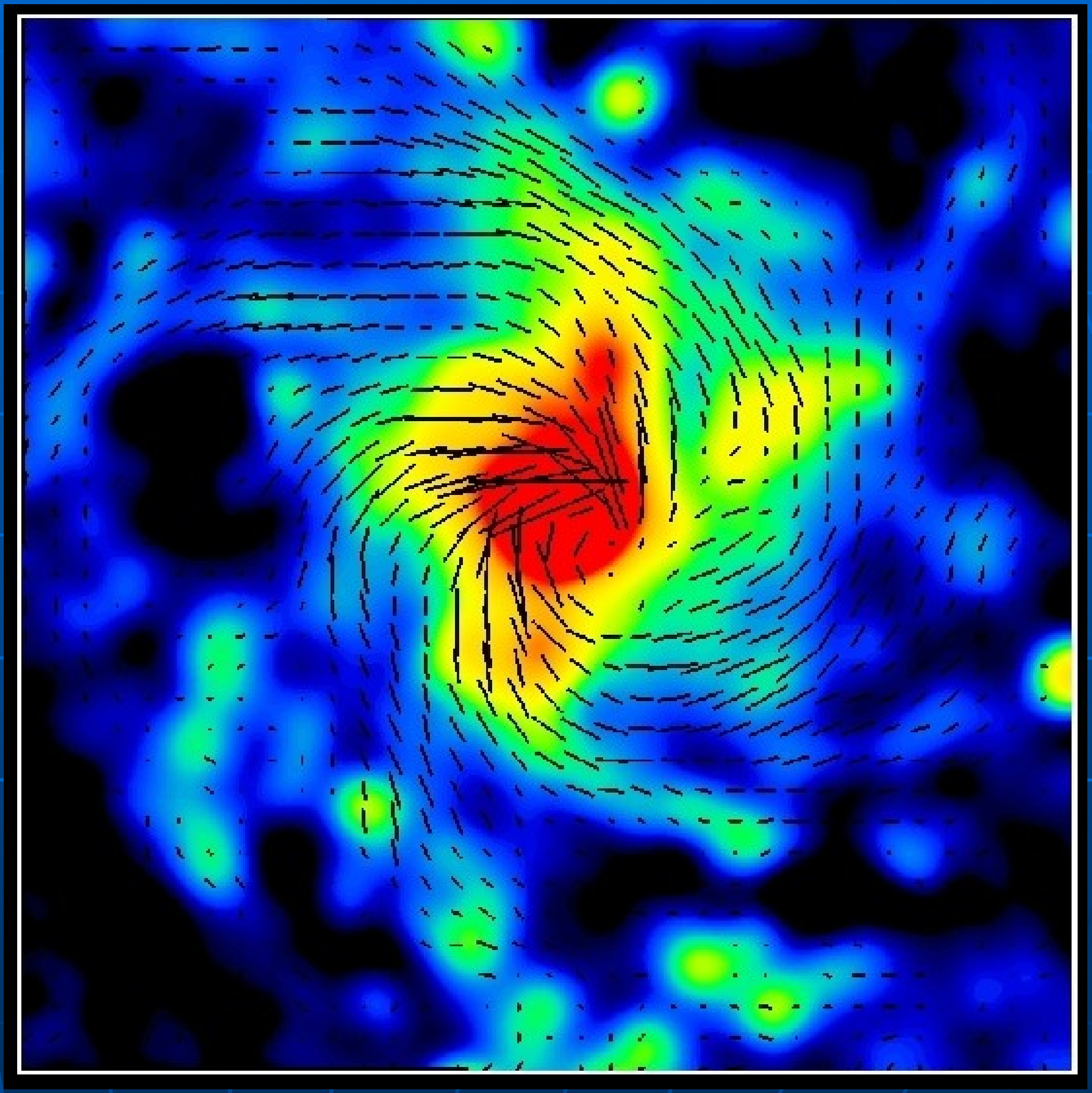
Ordered fields concentrated in interarm regions

Problem no.3:

How can the spiral field be so closely aligned with the spiral arms in galaxies with only weak density waves ?

NGC 6946

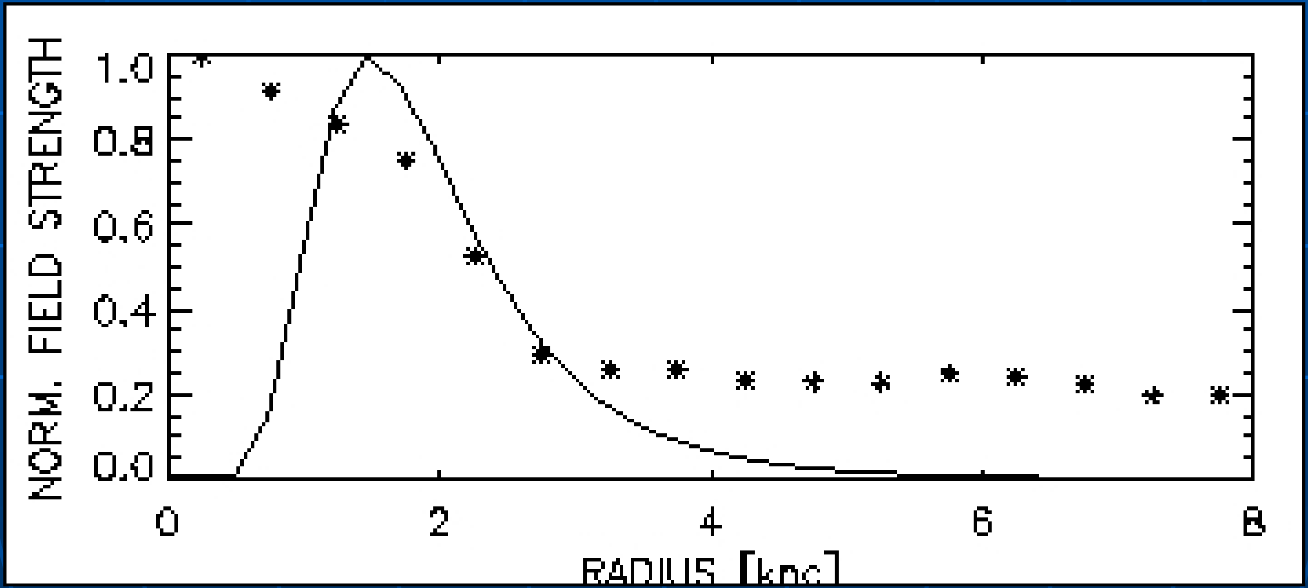
3cm VLA
Total intensity
+B-vectors
(Beck 2007)



Spiral field continues into the central region

Strength of the regular field in NGC 6946

Rohde et al. 1999



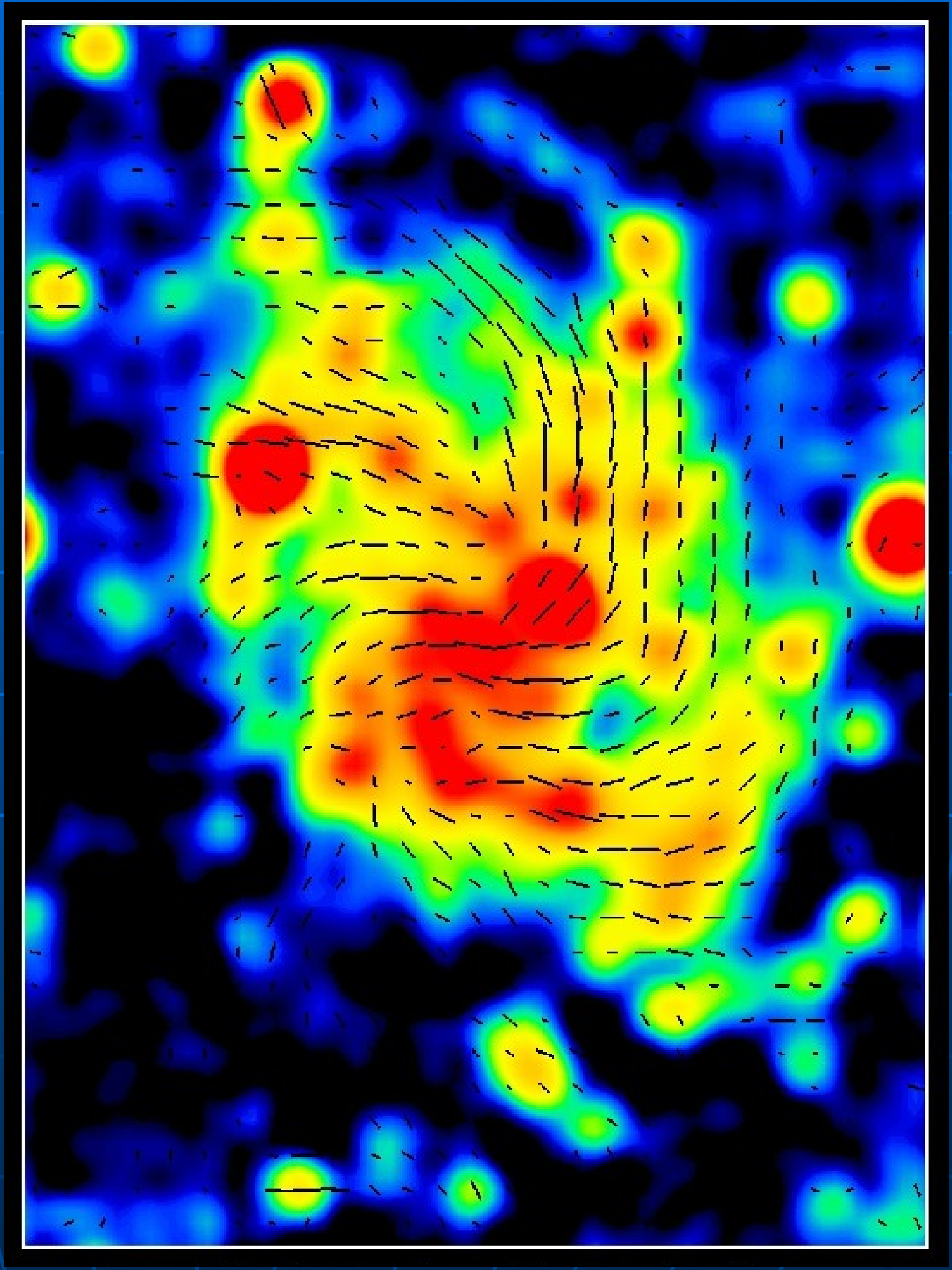
Poor agreement !

Problem no.4:

Classical dynamo models cannot explain the strong spiral fields near galaxy centers

M 33

3cm Effelsberg
Total intensity
+ B-vectors
(Tabatabaei et al. 2007)

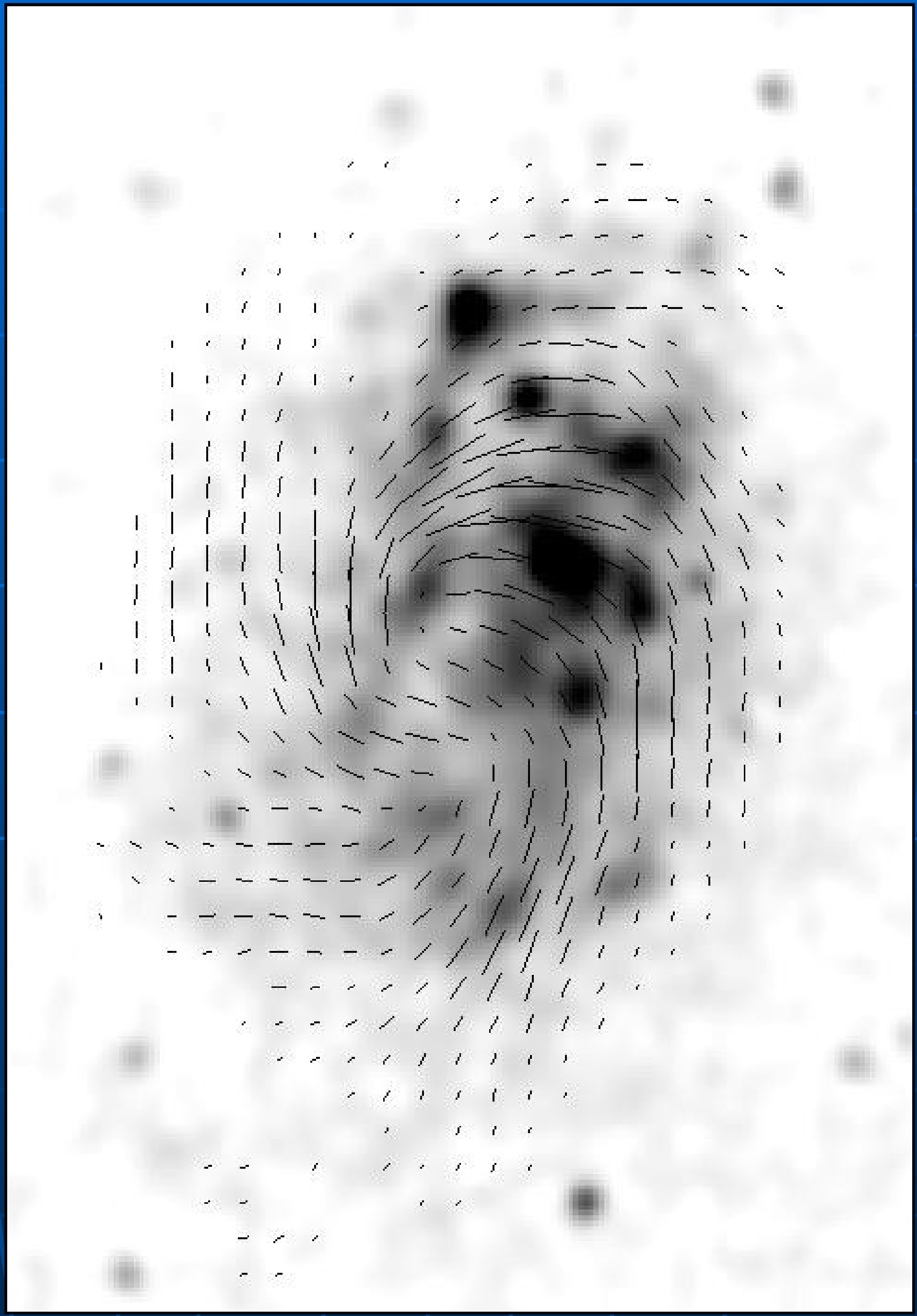


Spiral field pattern with a large pitch angle

NGC 4414

3cm VLA
H-alpha
+ B-vectors
(Soida et al. 2002)

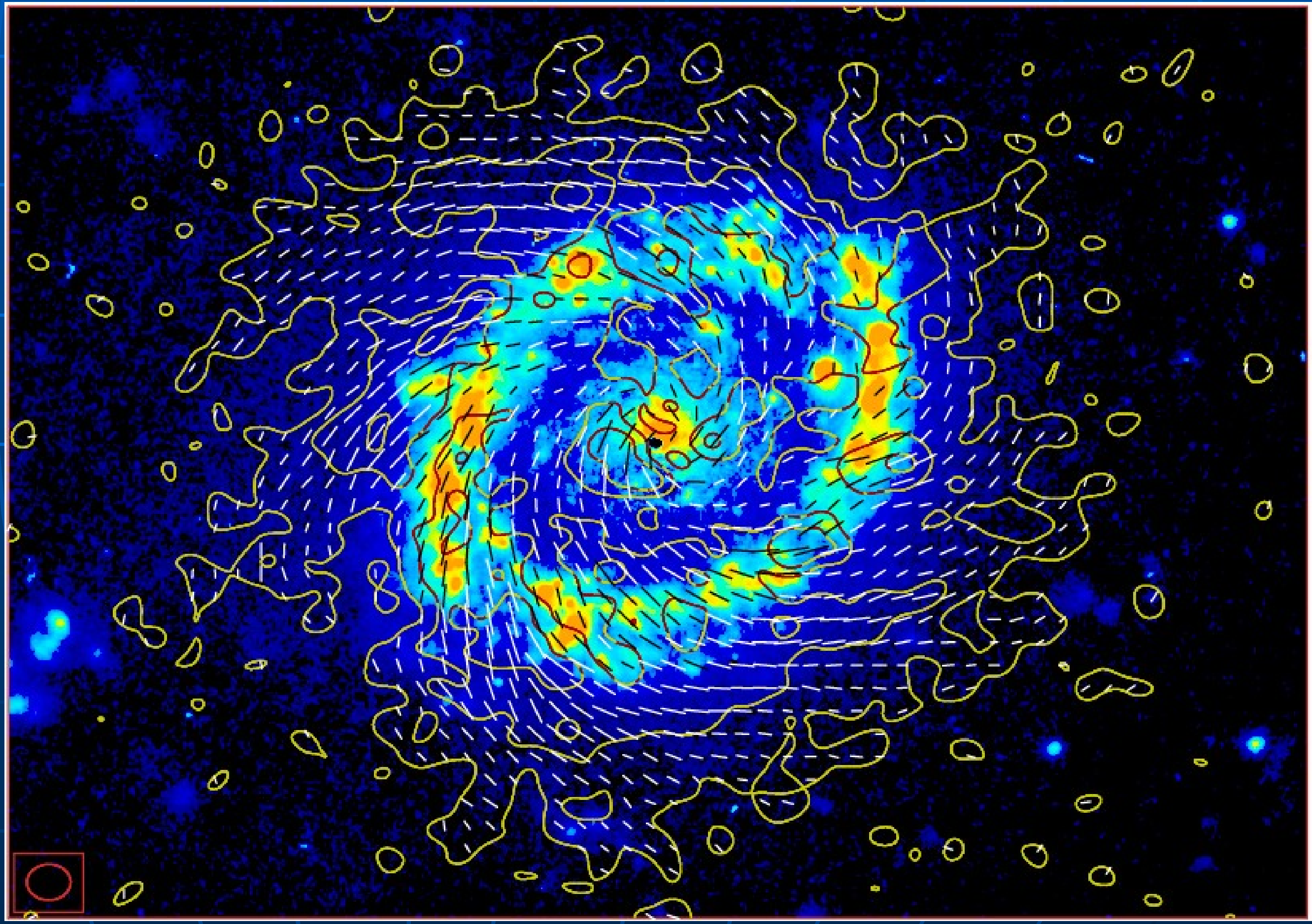
Flocculent galaxies:
spiral field exists
even without
Spiral arms



NGC 4736

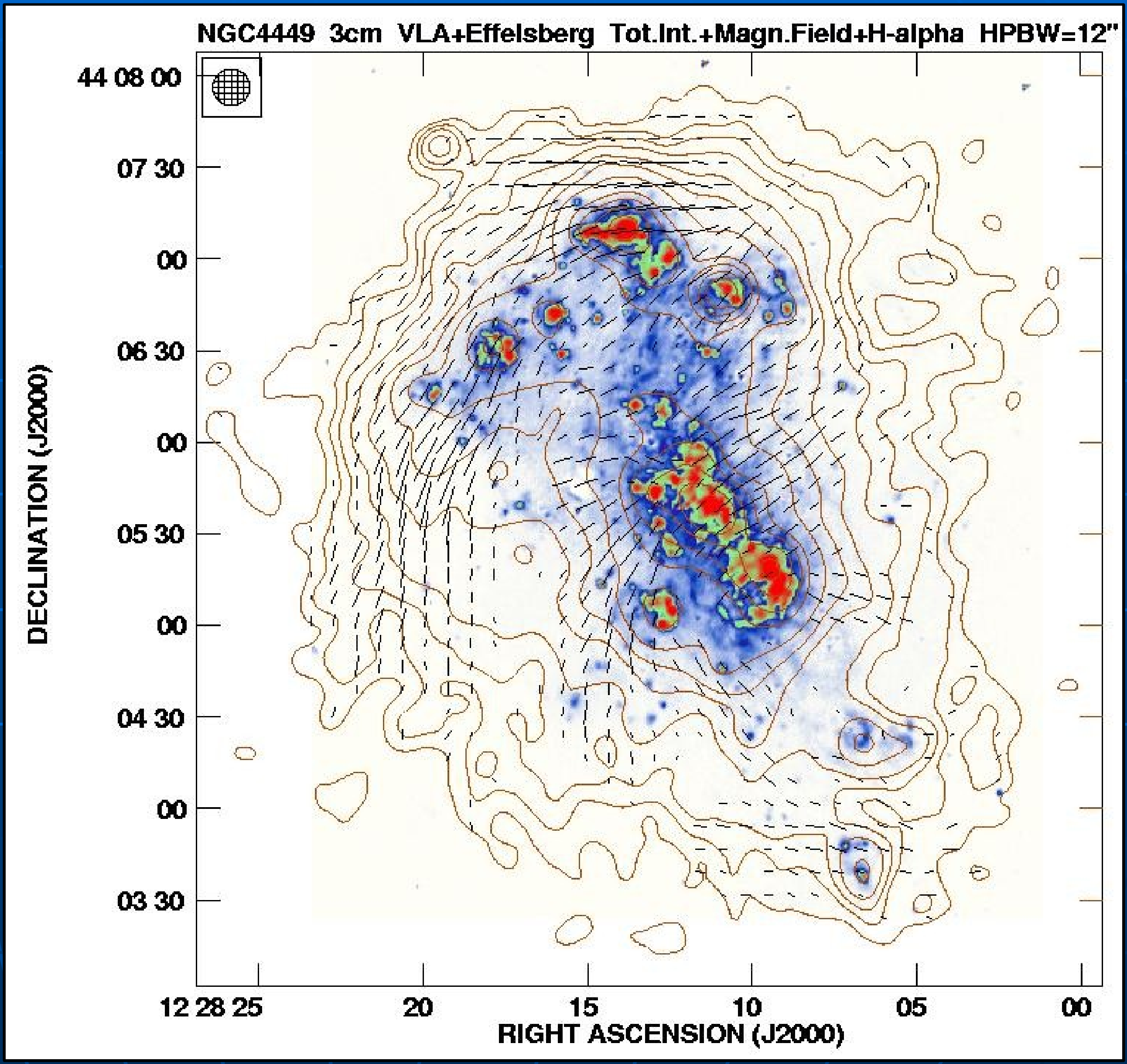
3cm VLA
Polarized intensity
+ B-vectors
(Chyzy & Buta 2007)

Spiral fields
in a
ring galaxy



NGC 4449

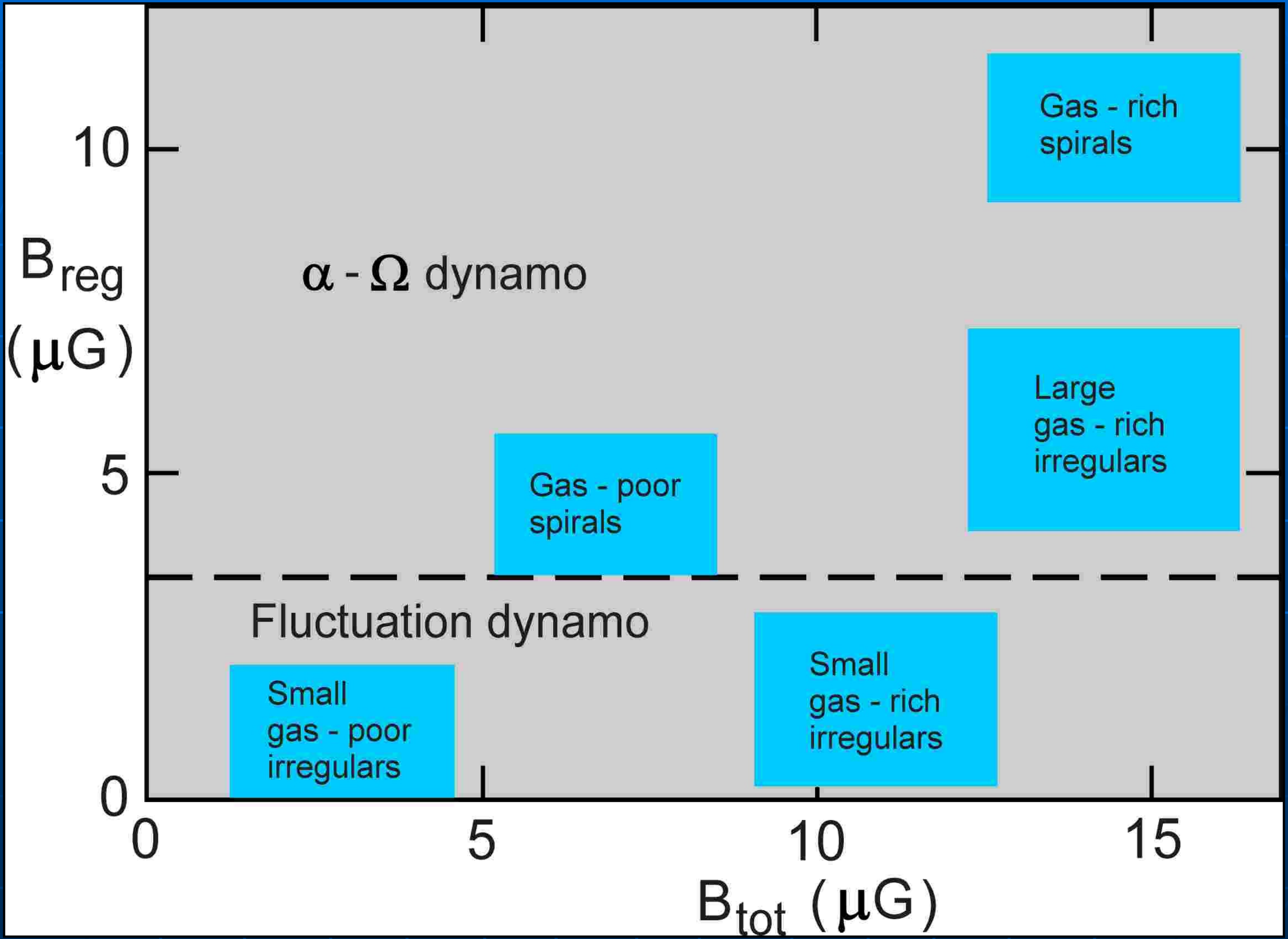
3cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Chyzy et al. 2000)



Asymmetric regular field in irregular galaxy

Dynamo evidence no.2:

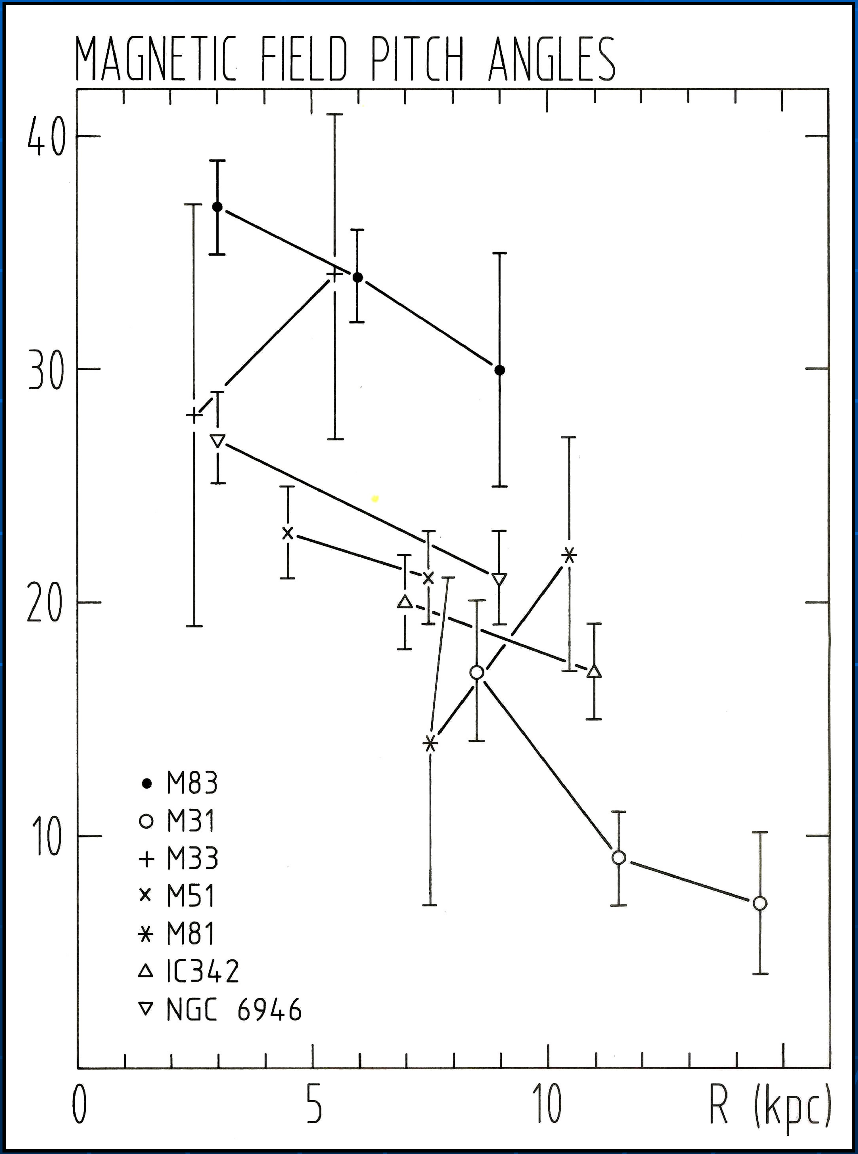
Magnetic field patterns are spiral in large galaxies with fast rotation and large gas mass



10
B reg
(μG)
5
0
α - Ω dynamo
Gas - rich spirals
Large gas - rich irregulars
Gas - poor spirals
Fluctuation dynamo
Small gas - poor irregulars
Small gas - rich irregulars
0
5
10
15
B tot (μG)

Magnetic field pitch angles

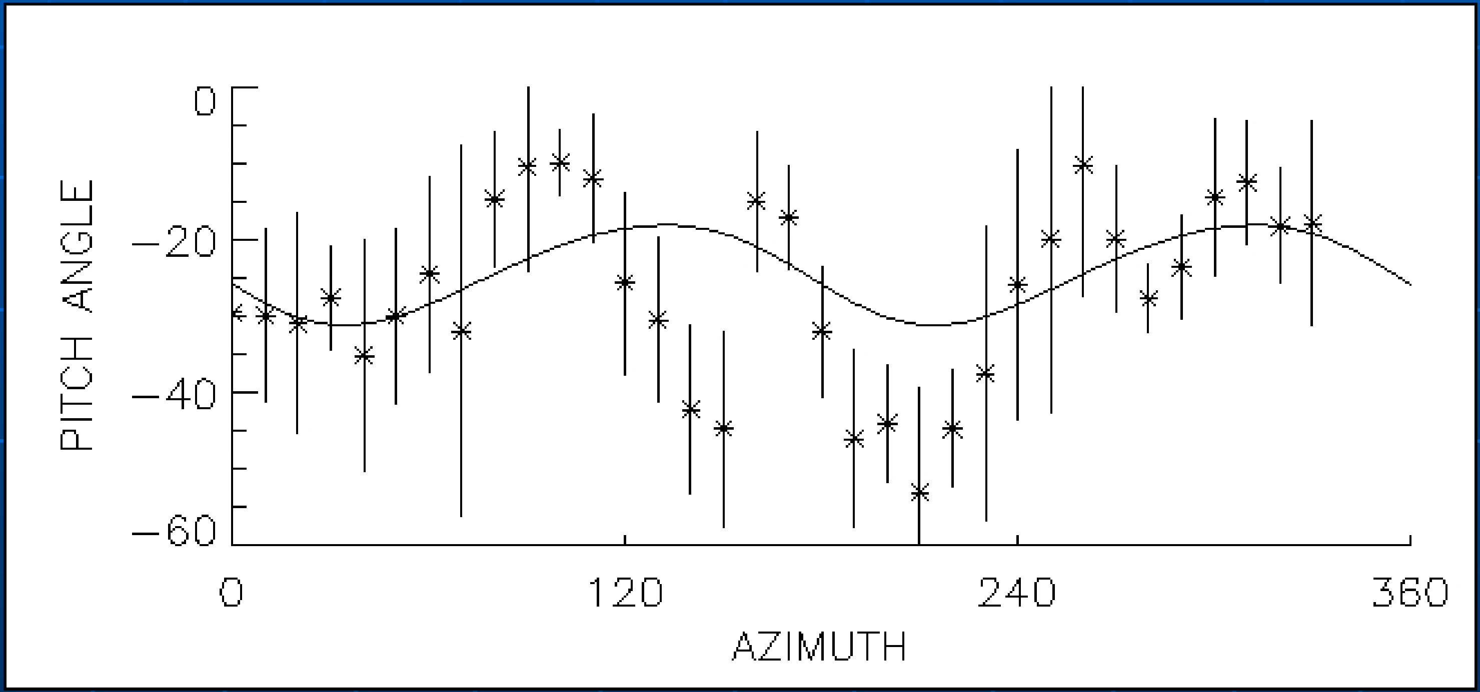
Beck 1995



The observed pitch angles of spiral fields decrease with increasing radius

Magnetic field pitch angles in NGC 6946

Rohde et al. 1999



Pitch angles smaller in the magnetic arms: explained by the dynamo model

Dynamo evidence no.3:

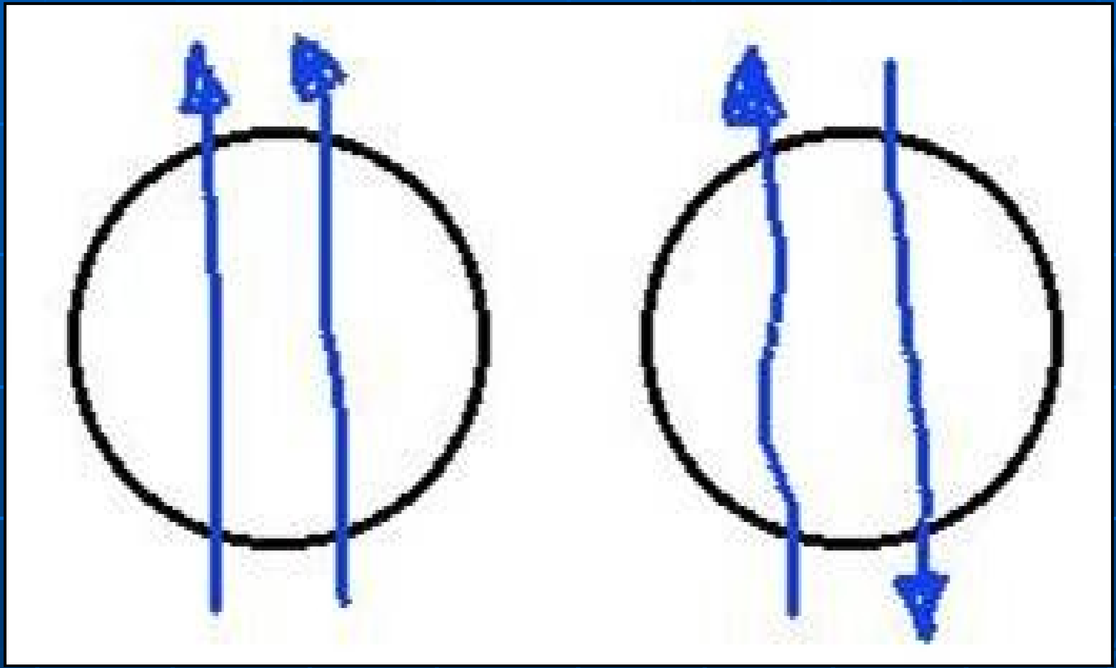
Pitch angles
of spiral field patterns
decrease with
decreasing
star-formation rate

Spiral fields:

Coherent (dynamo modes) or incoherent (compression) ?

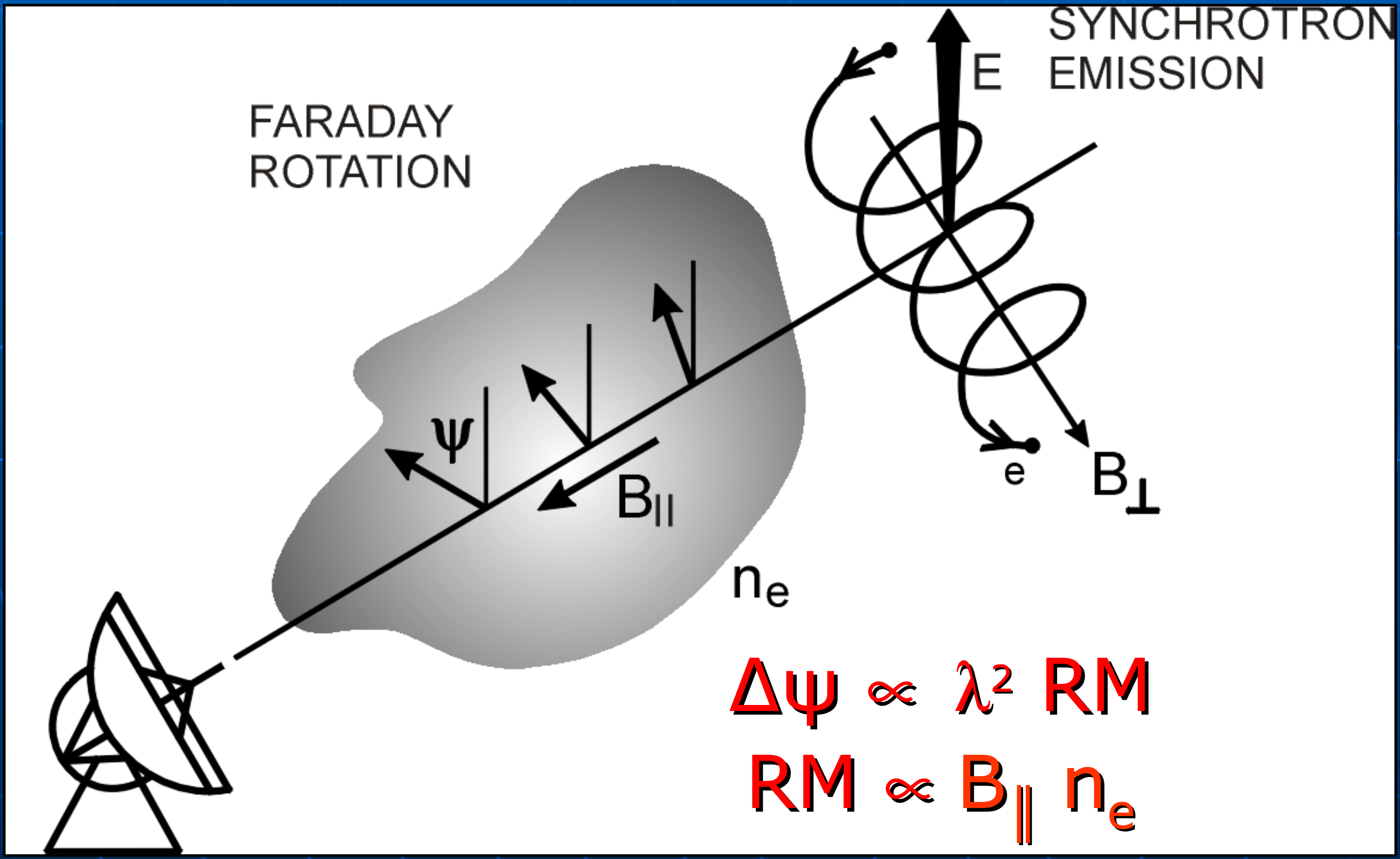
Fletcher 2004

	Regular (coherent) field	Anisotropic (incoherent) field



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

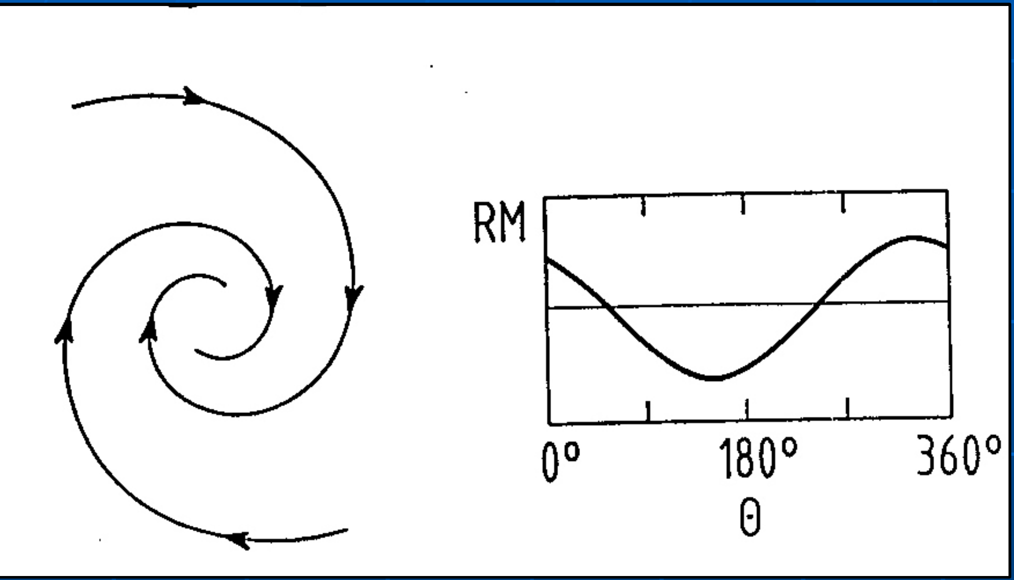
Faraday rotation:
crucial to detect regular fields !



$$\Delta\psi \propto \lambda^2\, RM$$

$$RM \propto B_{\parallel}\, n_e$$

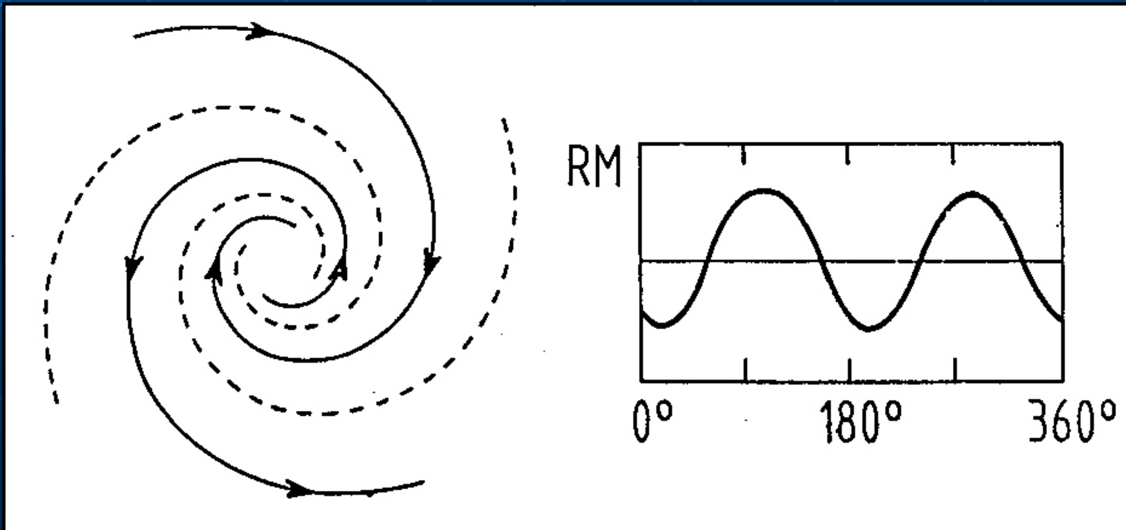
Finding dynamo modes:
Azimuthal variation of Faraday rotation



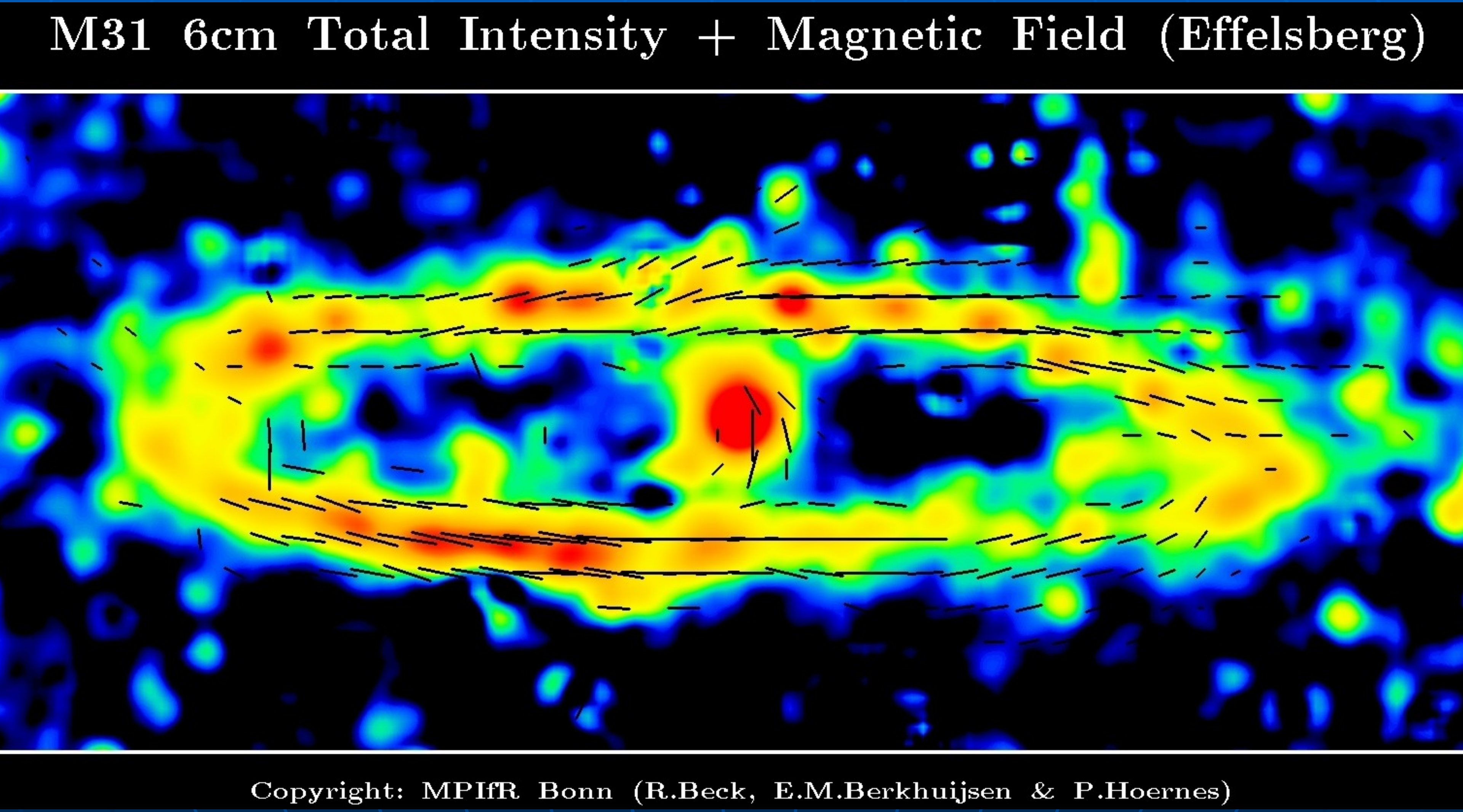
Krause 1990

Axisymmetric spiral
(m=0)

Bisymmetric spiral
(m=1)



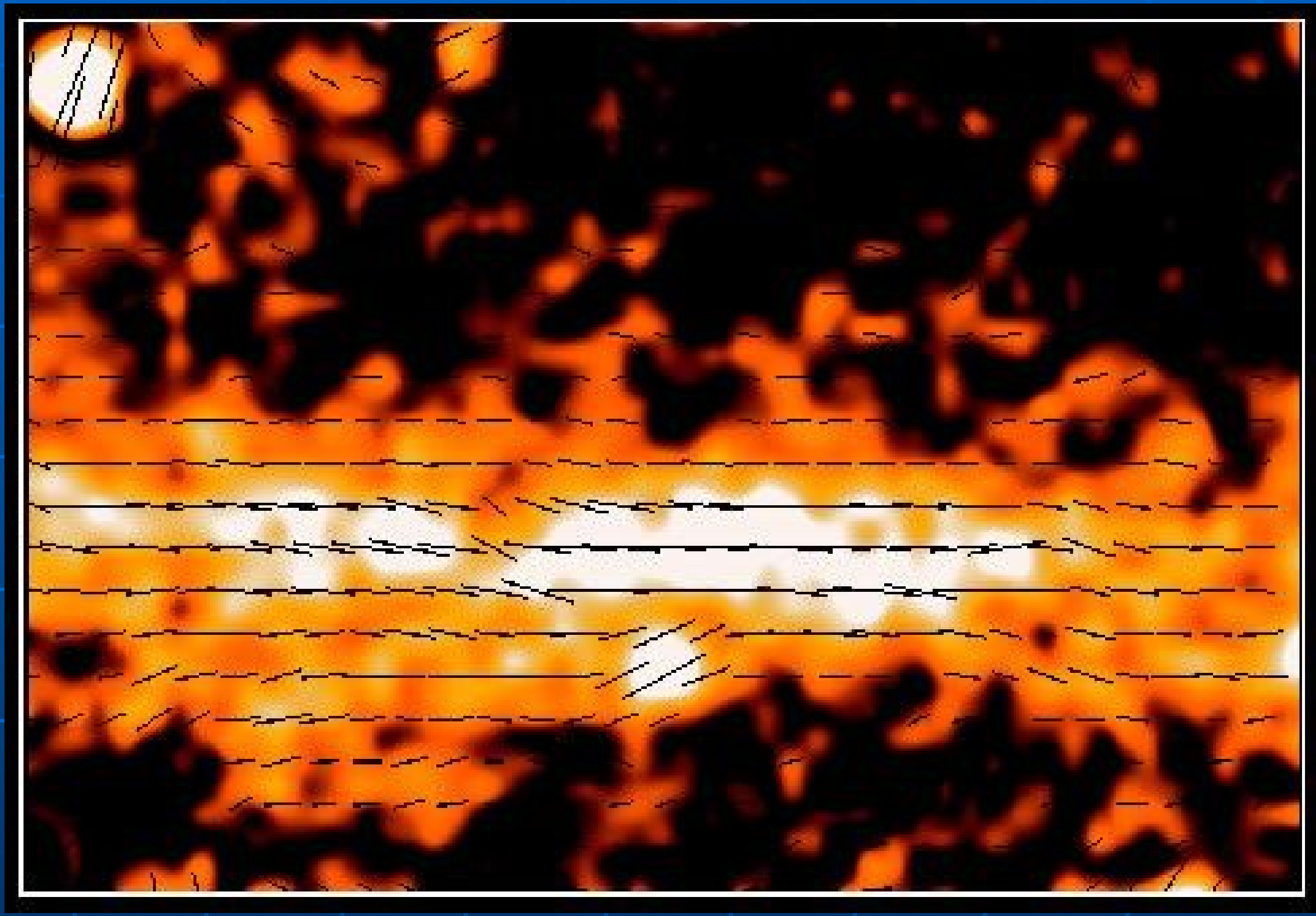
M31: The classical dynamo case



M 31

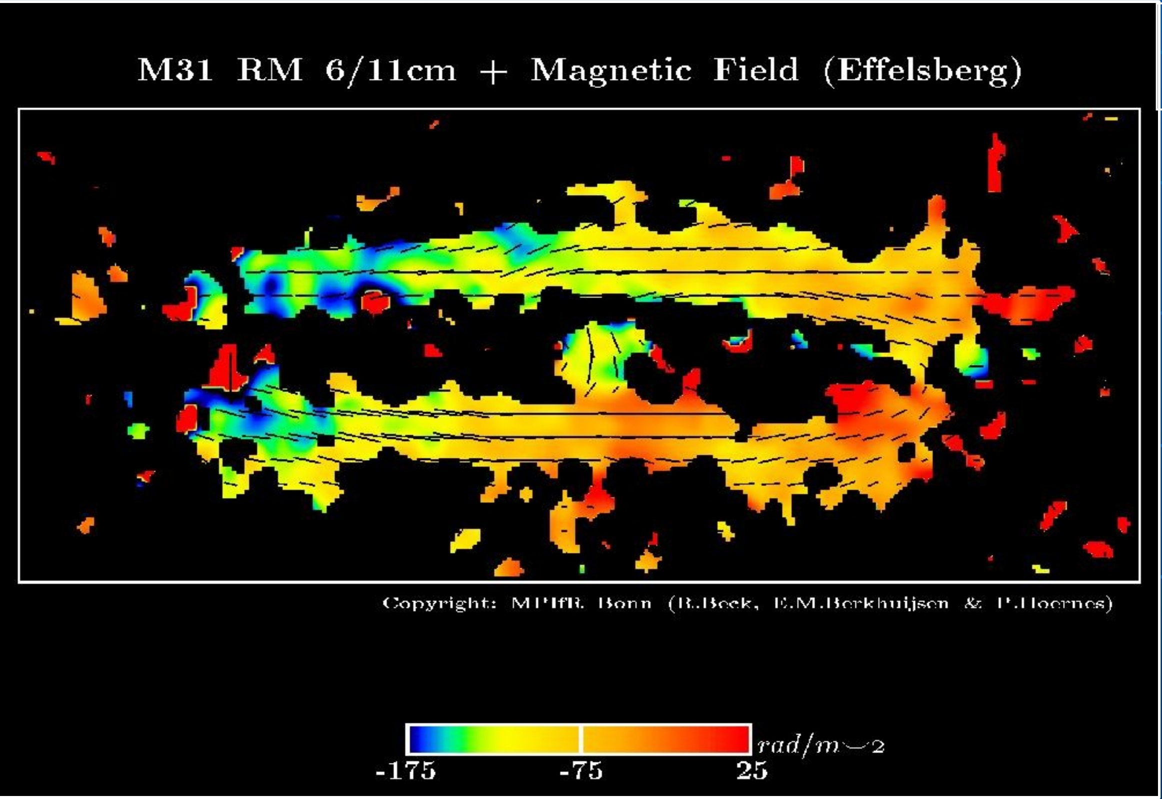
Northern arm

3cm Effelsberg
Polarized intensity
+ B-vectors
(Beck et al.)

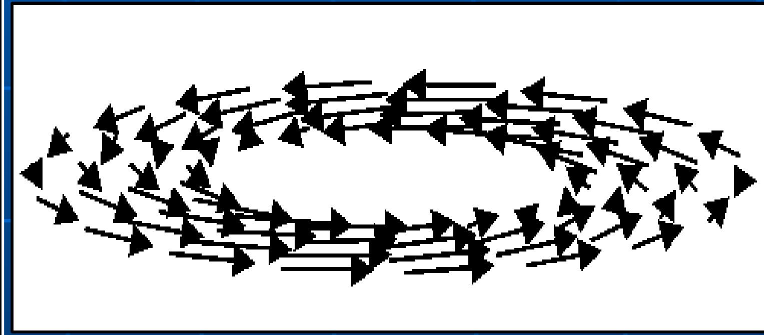


High resolution:
Highly regular
field

M31: The dynamo **IS** working !



Berkhuijsen et al. 2003



Fletcher et al. 2004

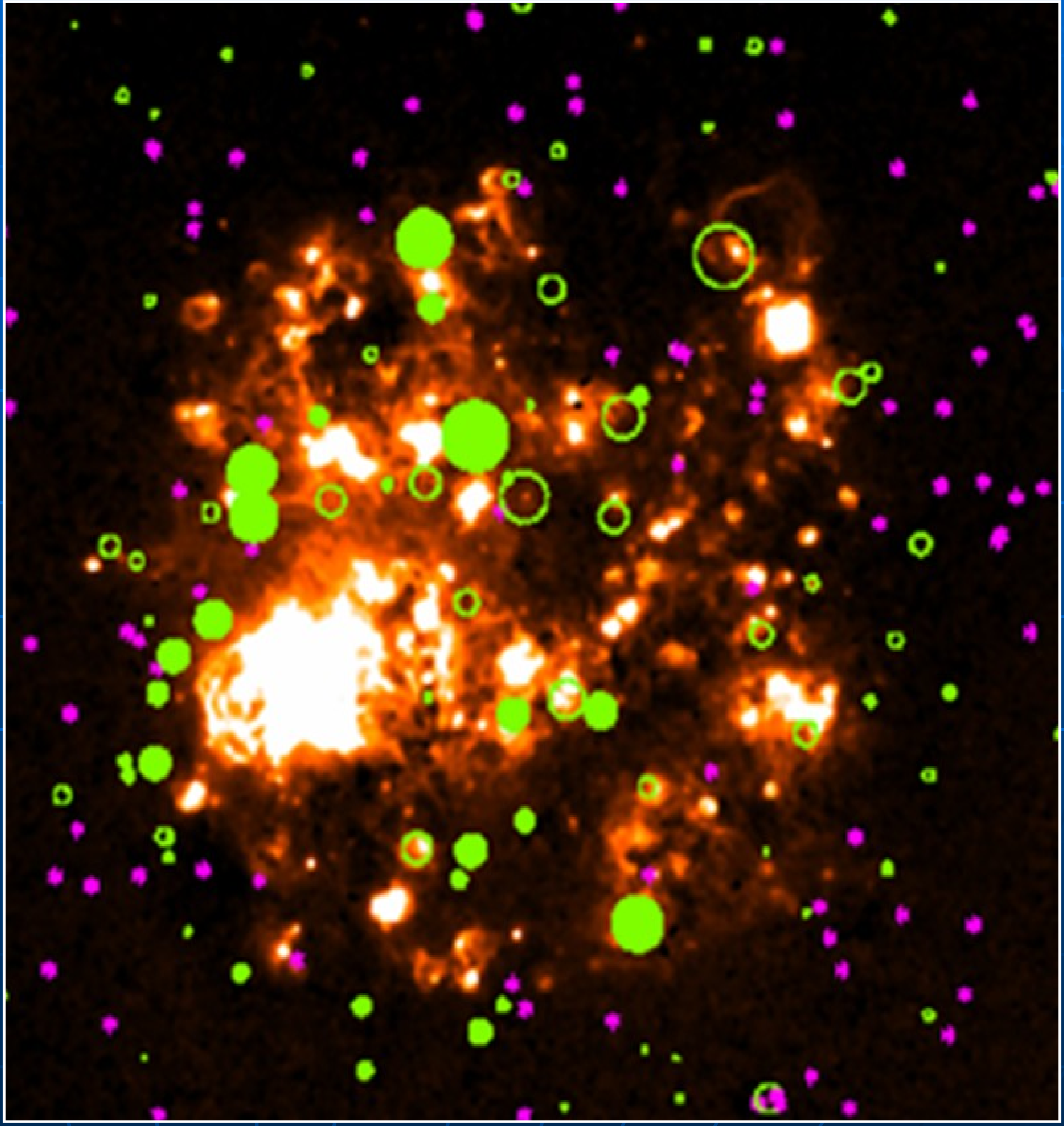
The spiral field of M31 is coherent and axisymmetric

LMC

20cm ATCA
RM
(Gaensler et al. 2005)

Large-scale pattern of the RM of polarized emission from background sources:

Axisymmetric dynamo field (?)

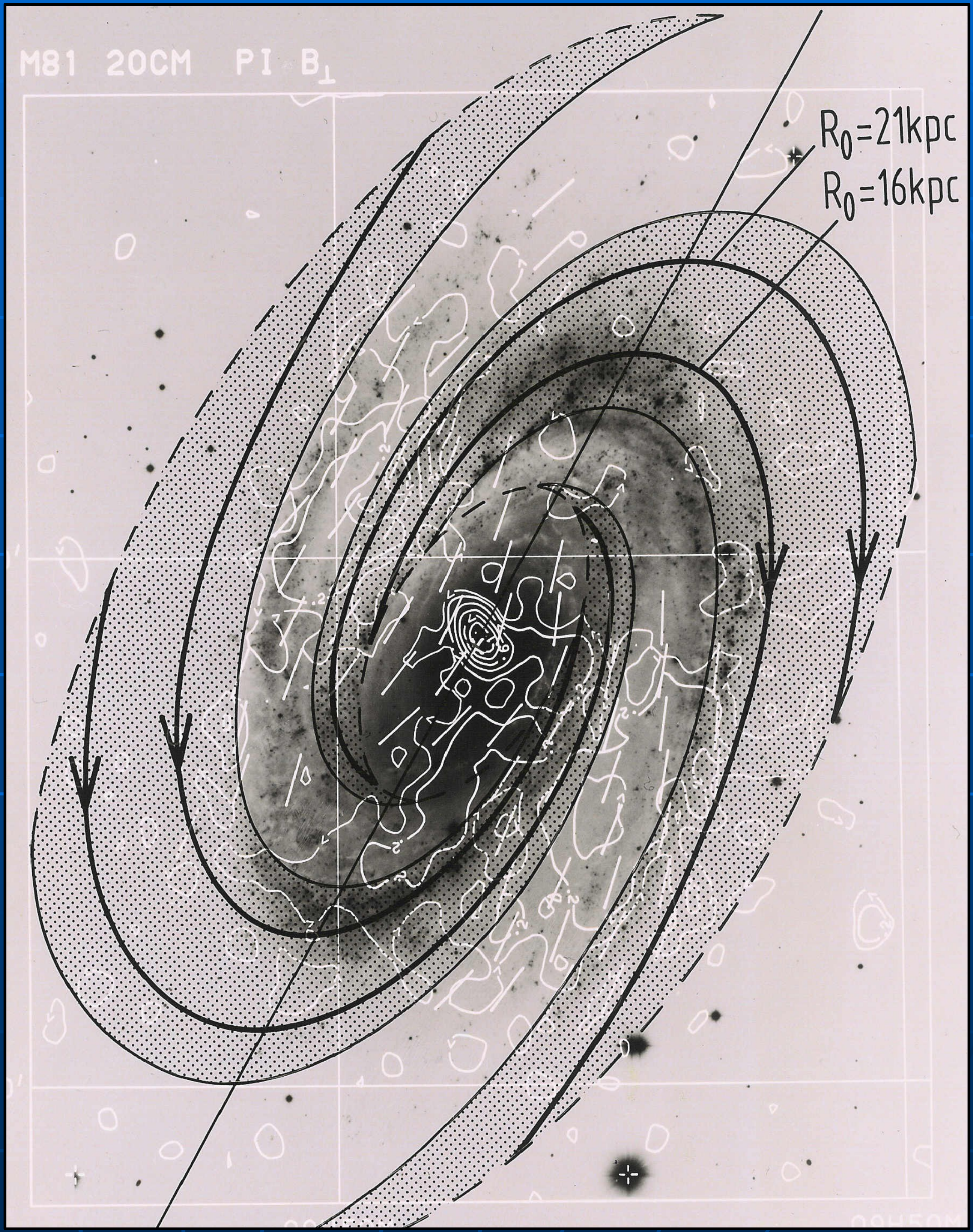


M 81

(M.Krause et al. 1989)

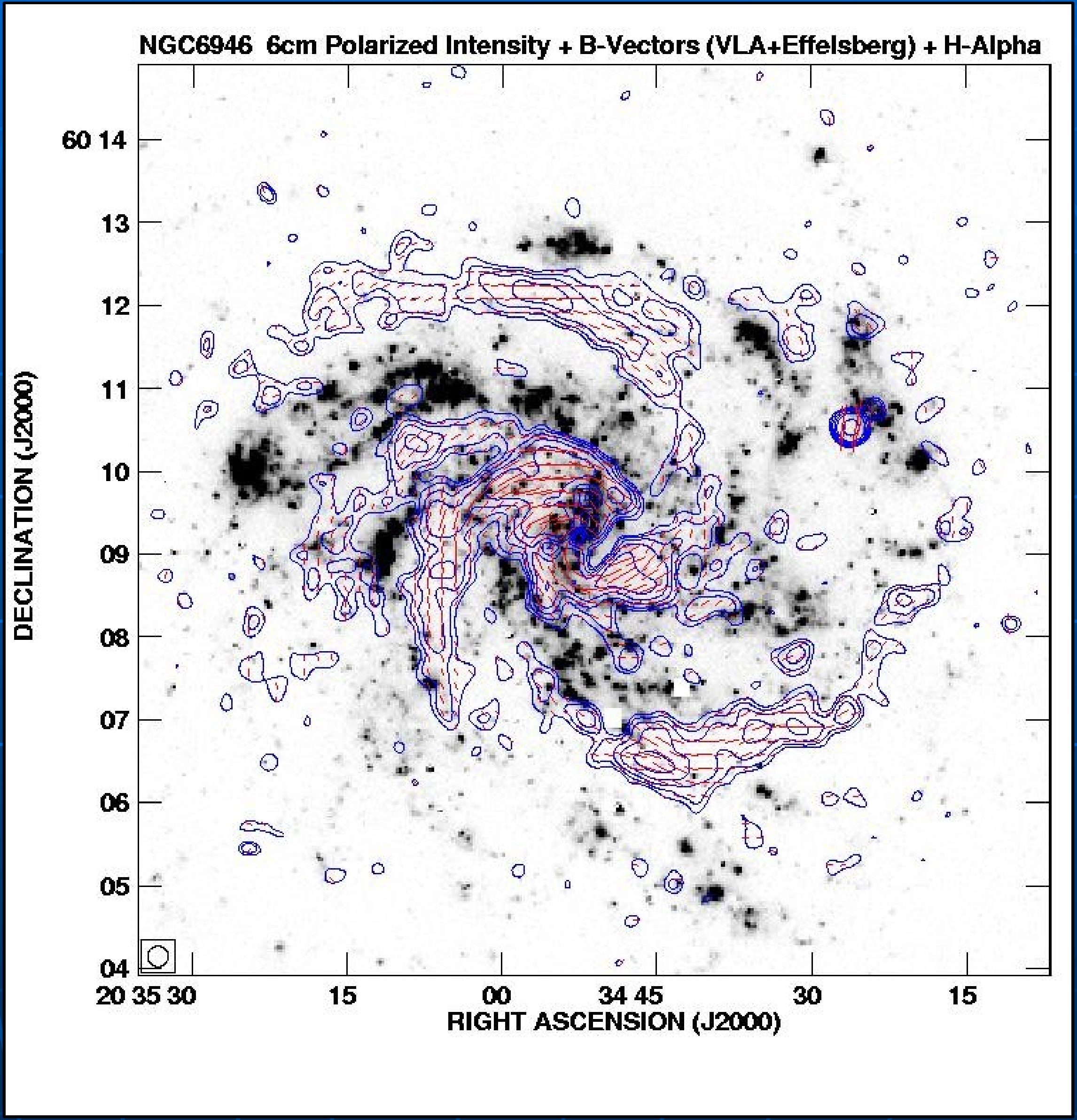
Two field reversals:

Bisymmetric dynamo field (m=1) ?



NGC 6946

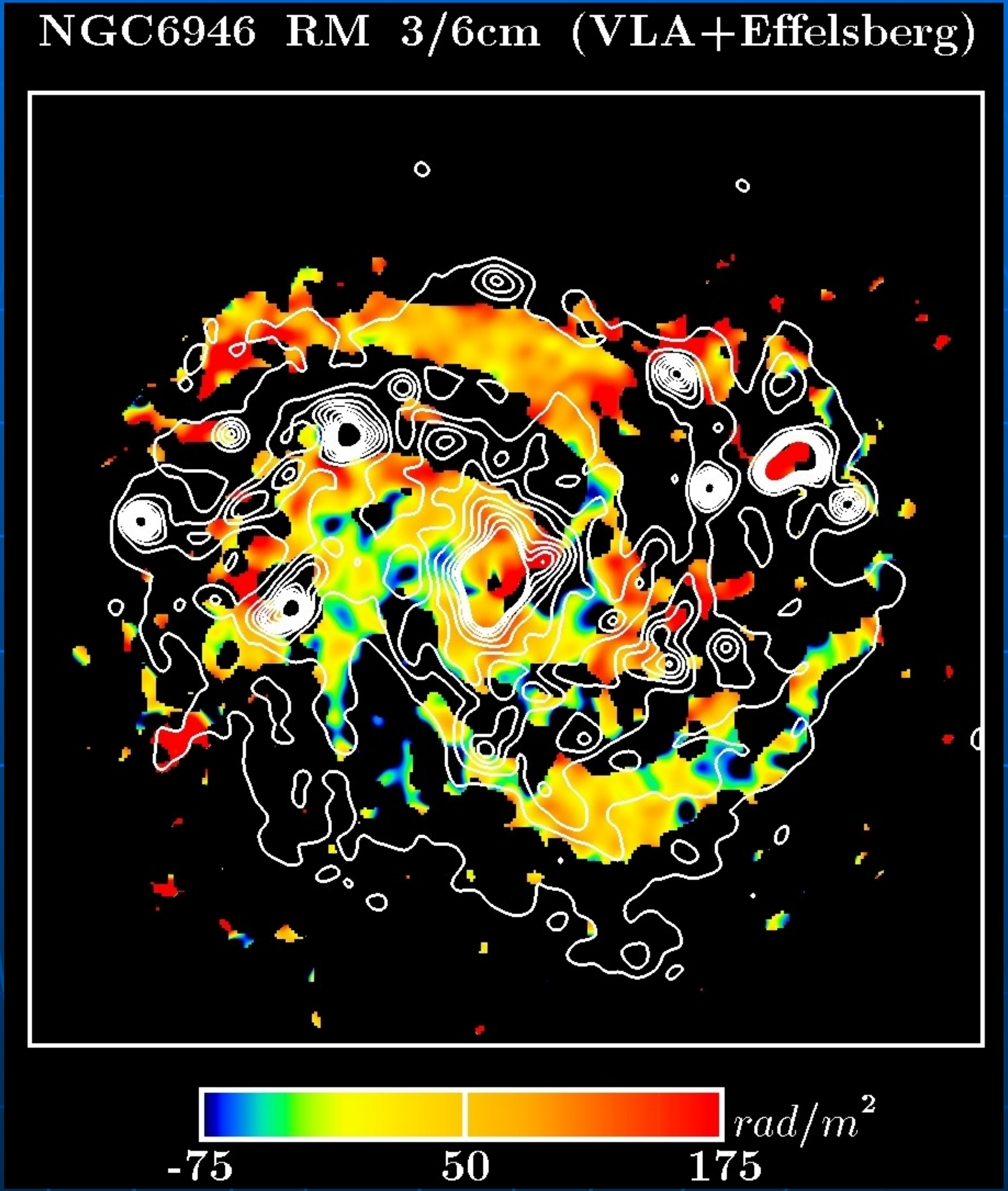
6cm
VLA+Effelsberg
Polarized intensity
+ B-vectors
(Beck & Hoernes 1996)



Magnetic arms

NGC 6946

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



Inward-directed field:

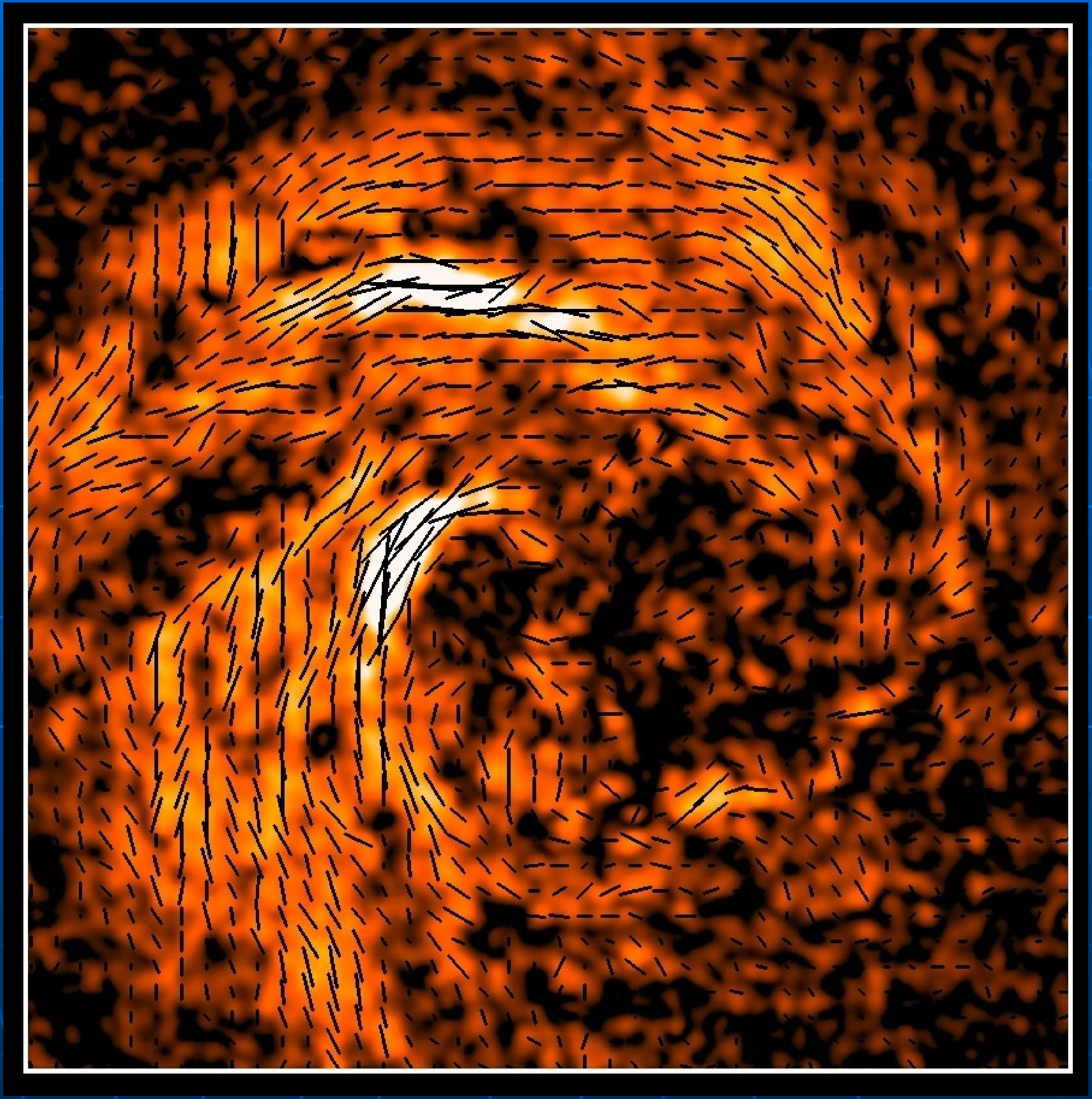
Superposition of two dynamo modes (m=0 + m=2) ?

NGC6946

VLA Polarized Intensity + B (Beck 2006)

However:
More magnetic spiral arms extending to ≥ 25 kpc

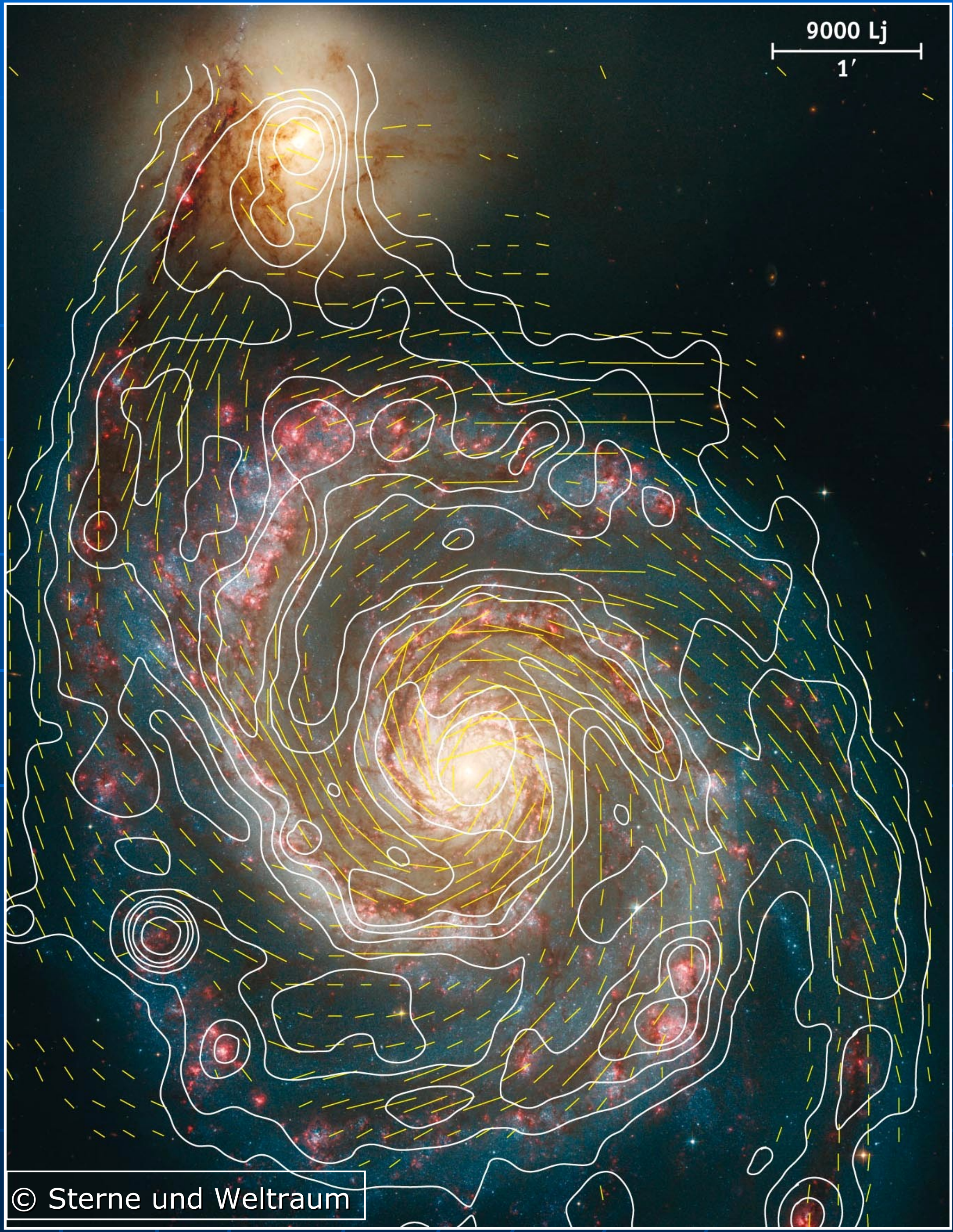
More modes needed ?



M 51

6cm VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2009)

Spiral fields
more or less
parallel to the
optical
spiral arms

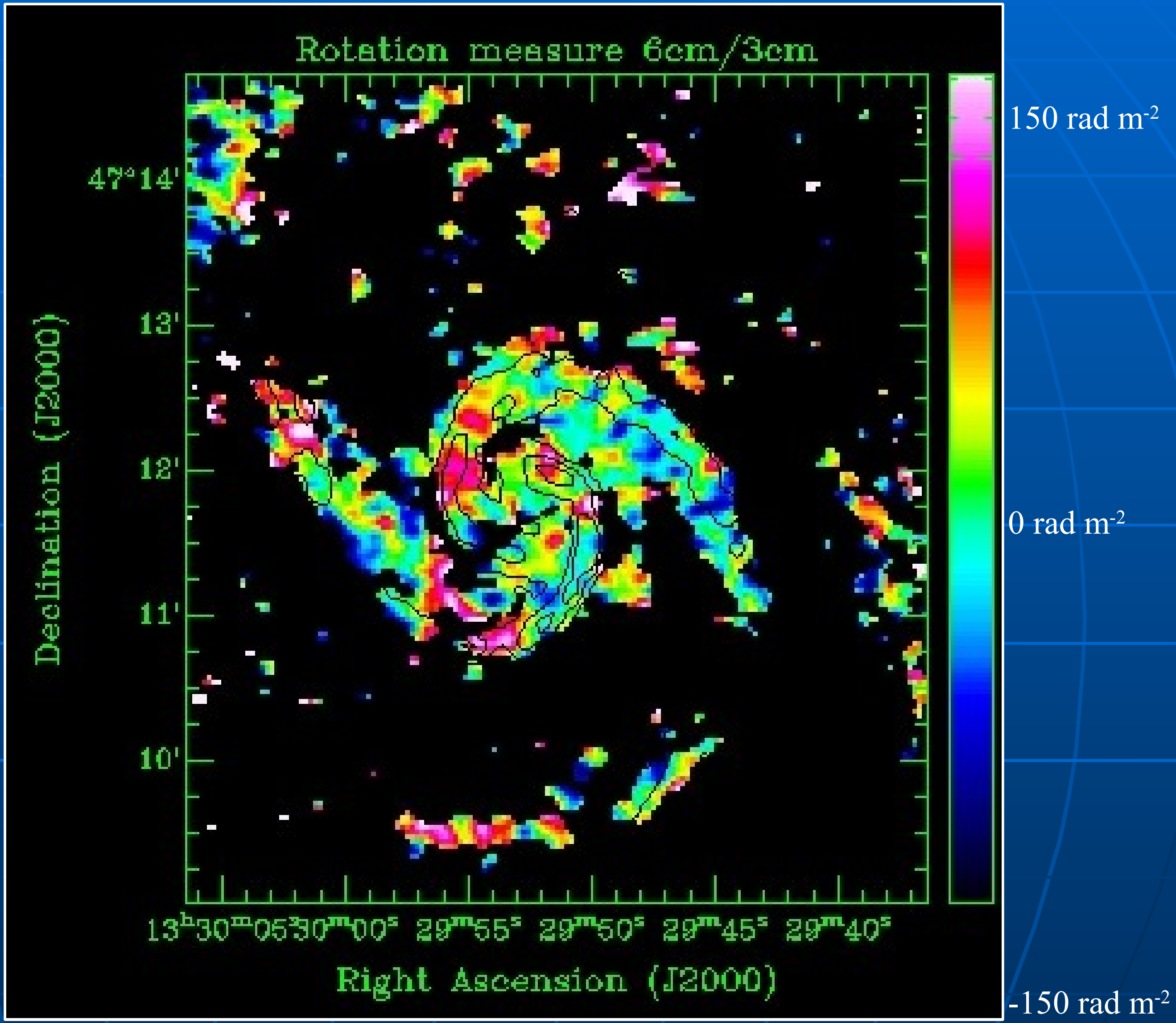


M51

VLA+Effelsberg
RM 3/6cm
(Fletcher et al. 2009)

Complicated RM pattern:

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

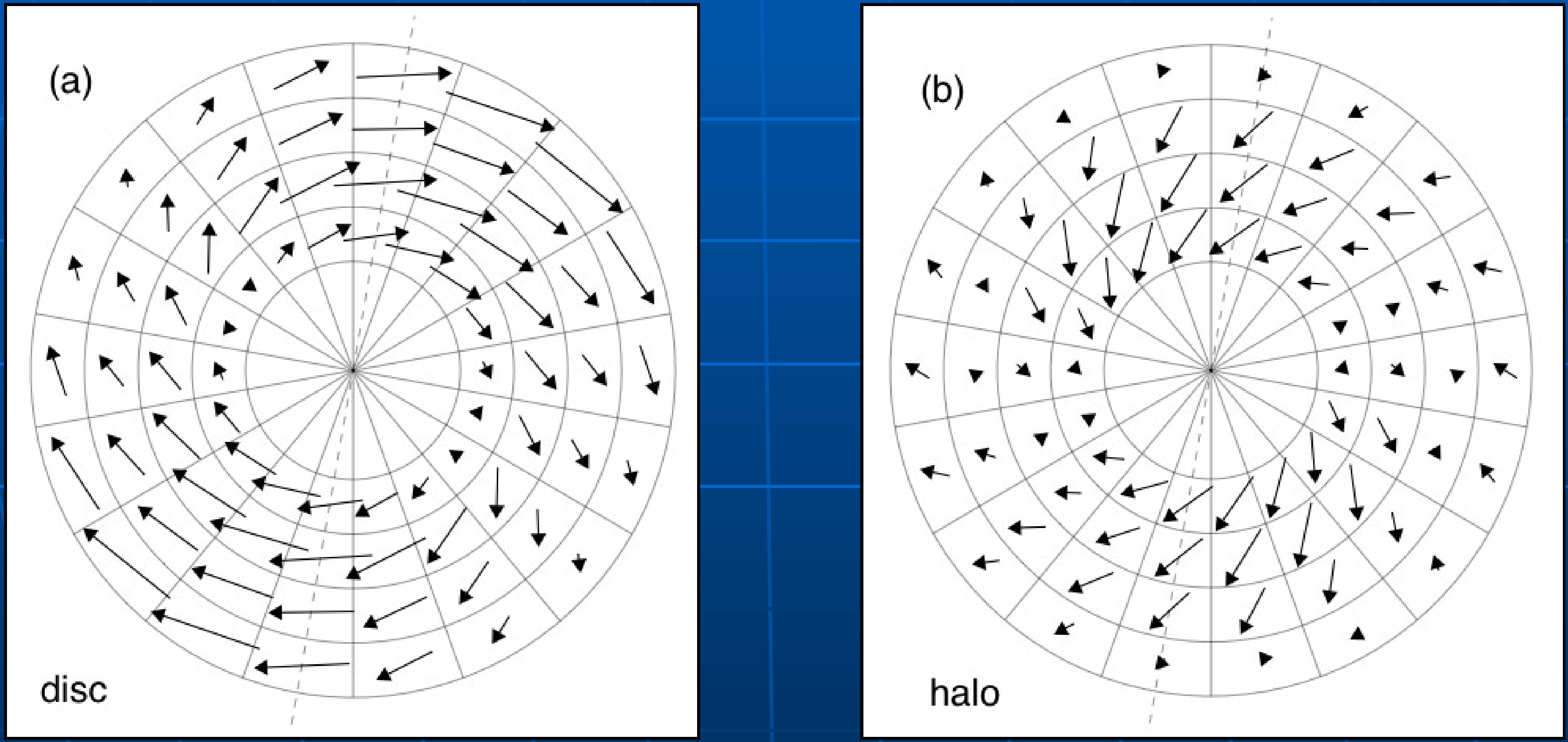


Large-scale magnetic fields in M51

Fletcher et al. 2009

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)

Large-scale dynamo modes

- Single dominant axisymmetric (m=0) mode are rare (M31, NGC253, NGC5775, IC342, LMC ?)
- Dominating bisymmetric (m=1) modes are even rarer (M81 ?, M51 halo)
- Two magnetic arms (M83, NGC2997, NGC6946) can be described by a superposition of m=0 and m=2 modes
- In *most* cases the field is a superposition of more than two modes (still unresolved), or the field is mostly anisotropic, or it is not yet fully developed

Dynamo evidence no.4:

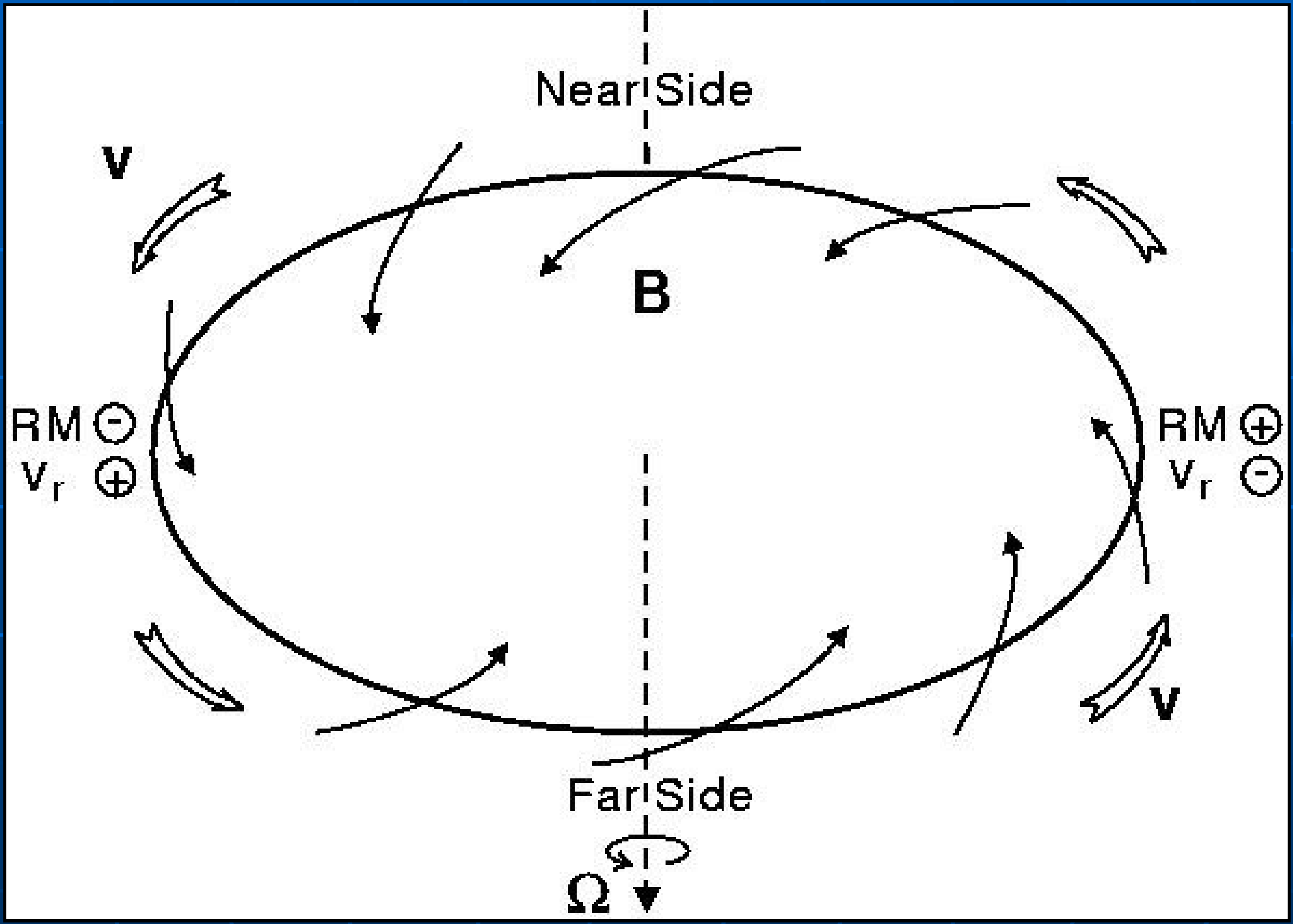
Large-scale coherent fields do exist !

Problem no.5:

What determines the spectrum of dynamo modes ?

Radial component of spiral fields

F.Krause & Beck 1998



Opposite signs of v_r and RM: inward field direction

Preference of inward-directed radial field components ?

Direction of the radial component of axisymmetric spiral fields

- Inwards:
  M31, IC342, NGC253, NGC1097, NGC6946
  (F.Krause & Beck 1998)

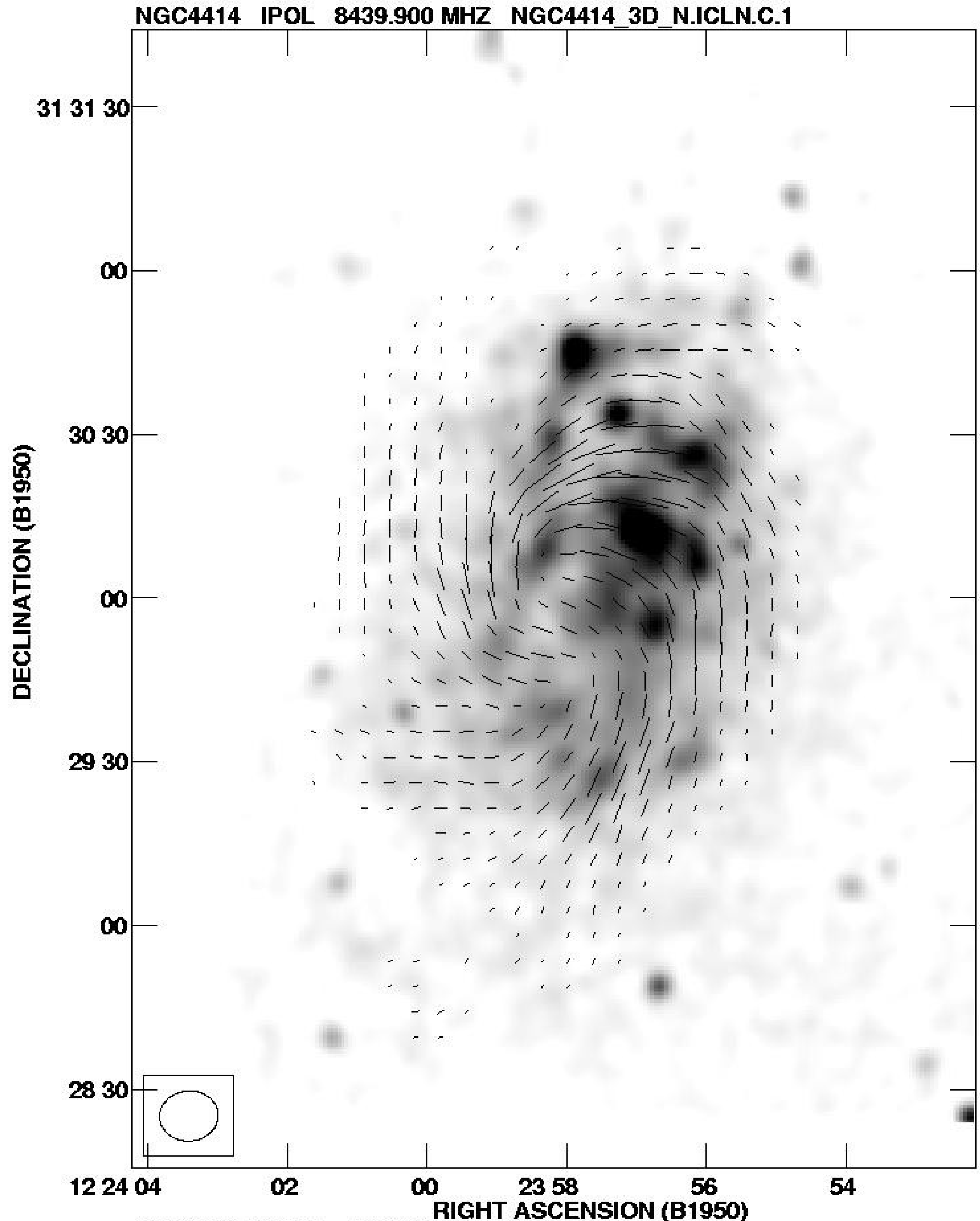
- Outwards:
  NGC4254, NGC 4736, NGC5775, M51
  (Chyzy, Soida, M.Krause et al. 2008/9)

No preference for inward direction (as expected from dynamo models)

NGC4414

VLA
RM 3/6cm
(Soida et al. 2002)

Flocculent galaxy with a smooth spiral pattern



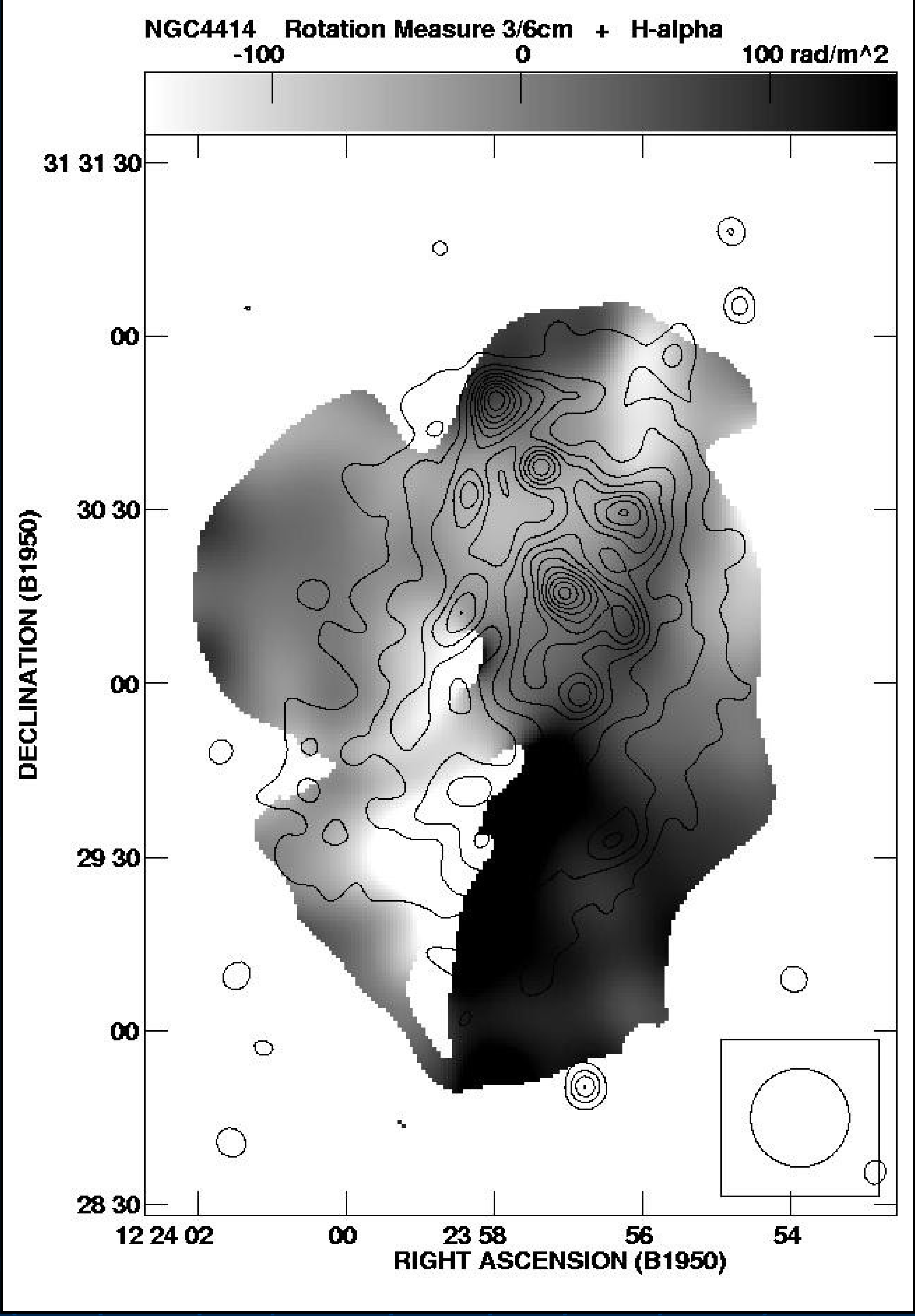
NGC4414

VLA

RM 3/6cm

(Soida et al. 2002)

No smooth pattern: Large-scale reversal



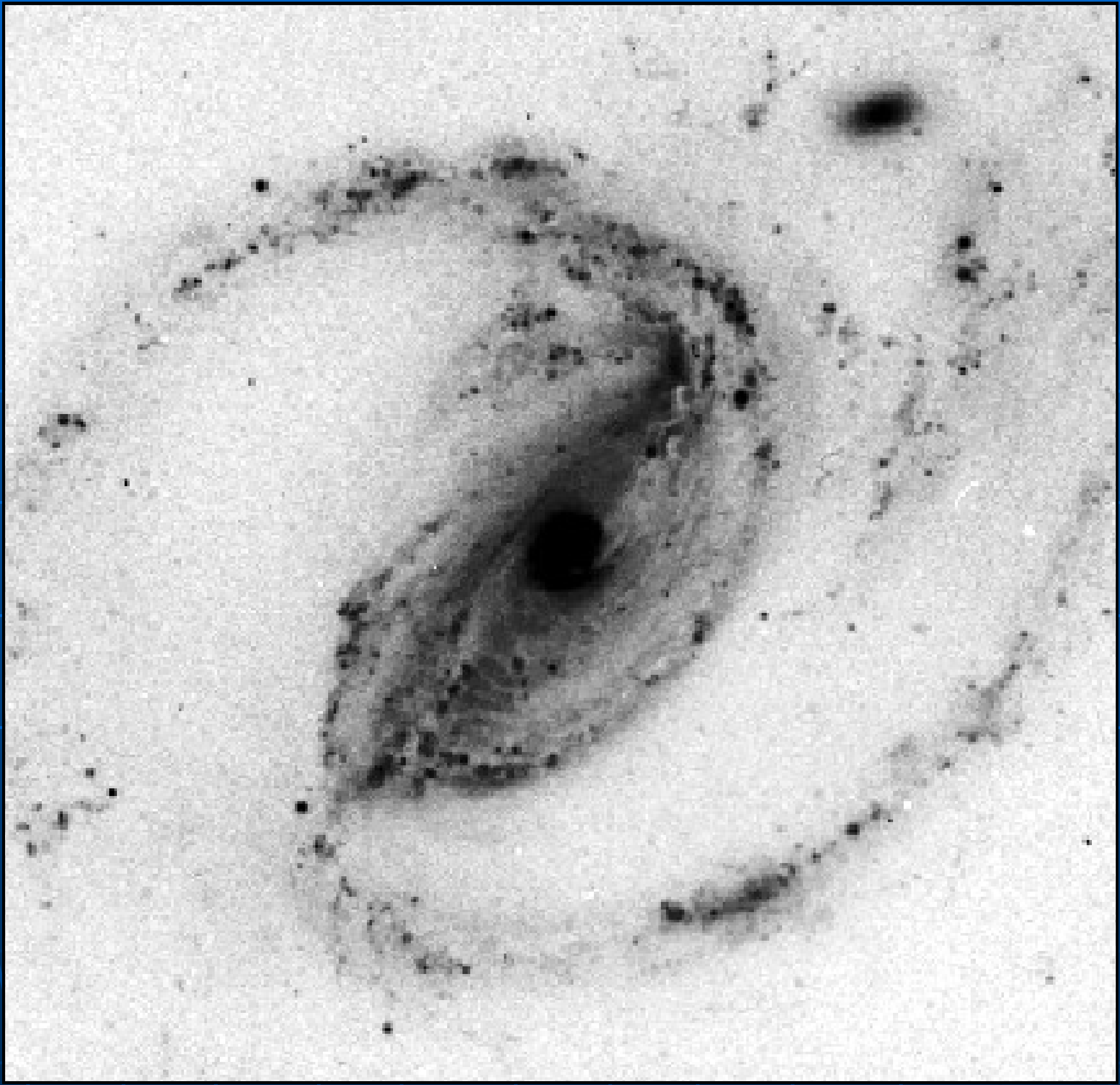
Problem no.6:

Field structure seen in Faraday rotation are often inconsistent with patterns seen in B-vectors

The fascinating world of barred galaxies

NGC 1097

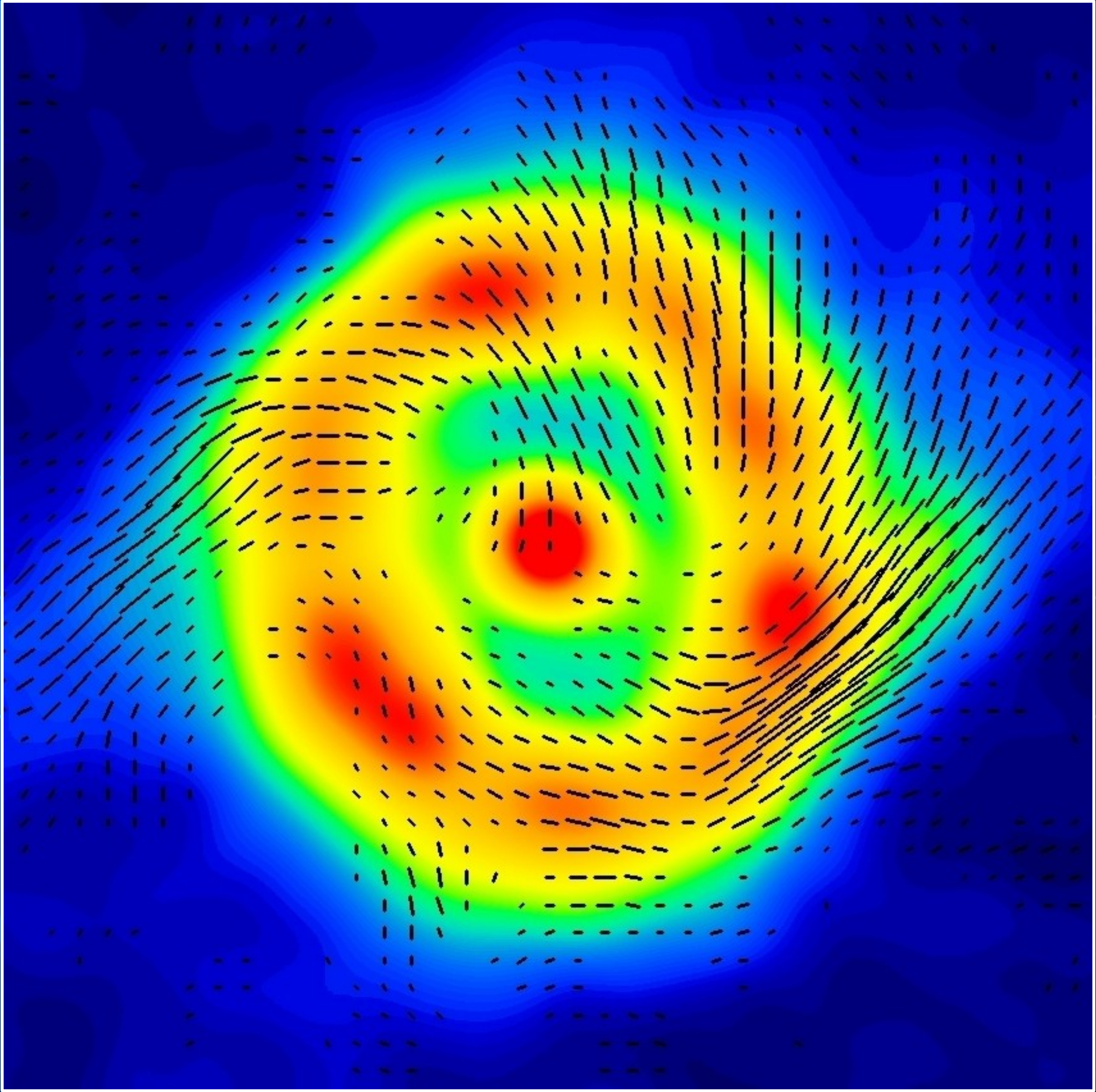
(Cerro Tololo, by Halton Arp)



NGC 1097
Circumnuclear ring

3.6cm VLA Total intensity + B

(Beck et al. 2005)



Strong field in the circumnuclear ring

Gas inflow into the center by magnetic stress

$$dM/dt = - h/\Omega\ (<b_r\ b_\Phi> + B_r\ B_\Phi)$$

(Balbus & Hawley 1998)

NGC 1097:

h=100 pc, v=450 km/s, $b_r \approx b_\Phi \approx 60\mu G$:

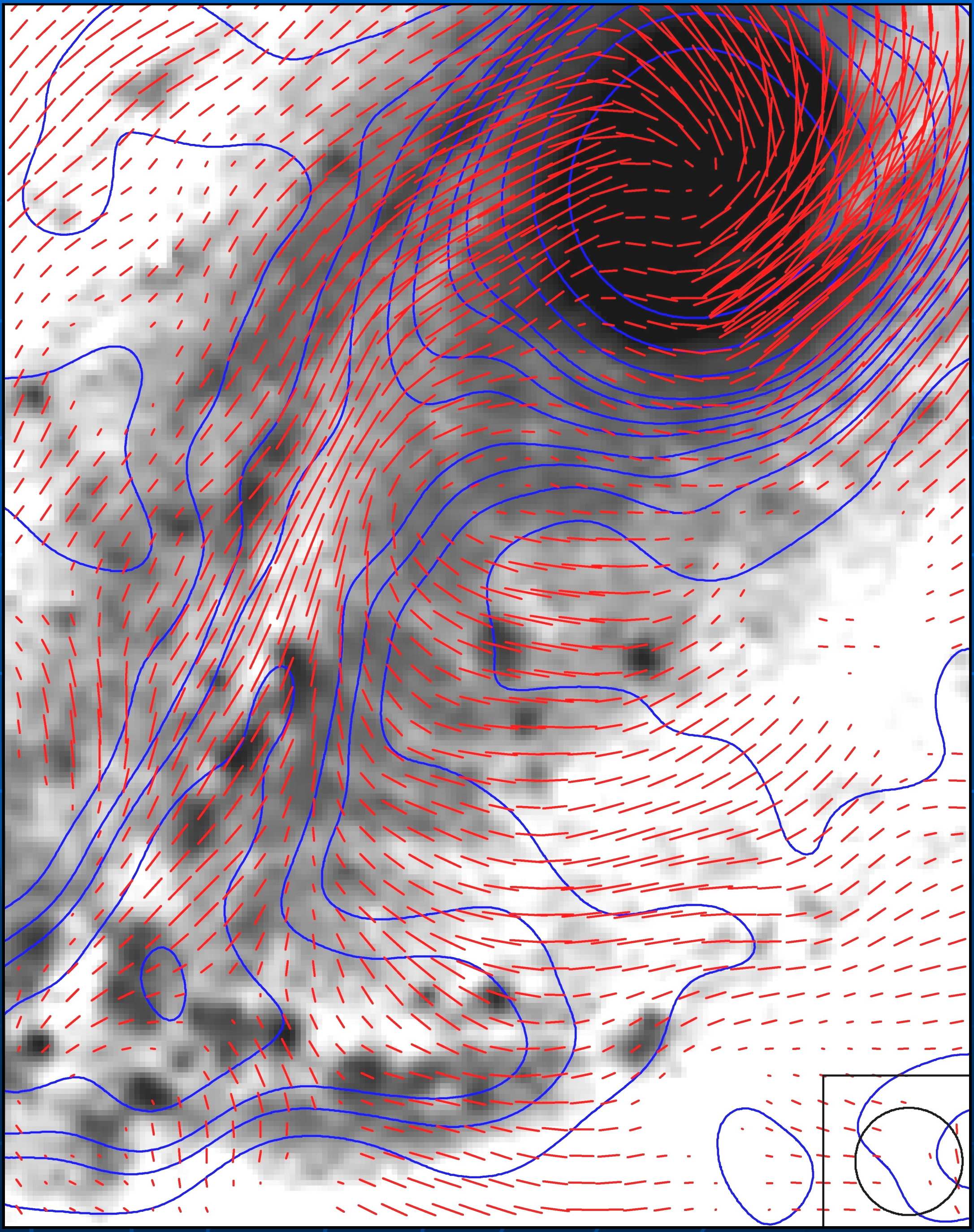
dM/dt ≈ 1 M_o / yr - just as required !

NGC 1097

6cm VLA
Total intensity
+ B-vectors
(Beck et al. 2005)

No shock,
strong shear in front
of the bar

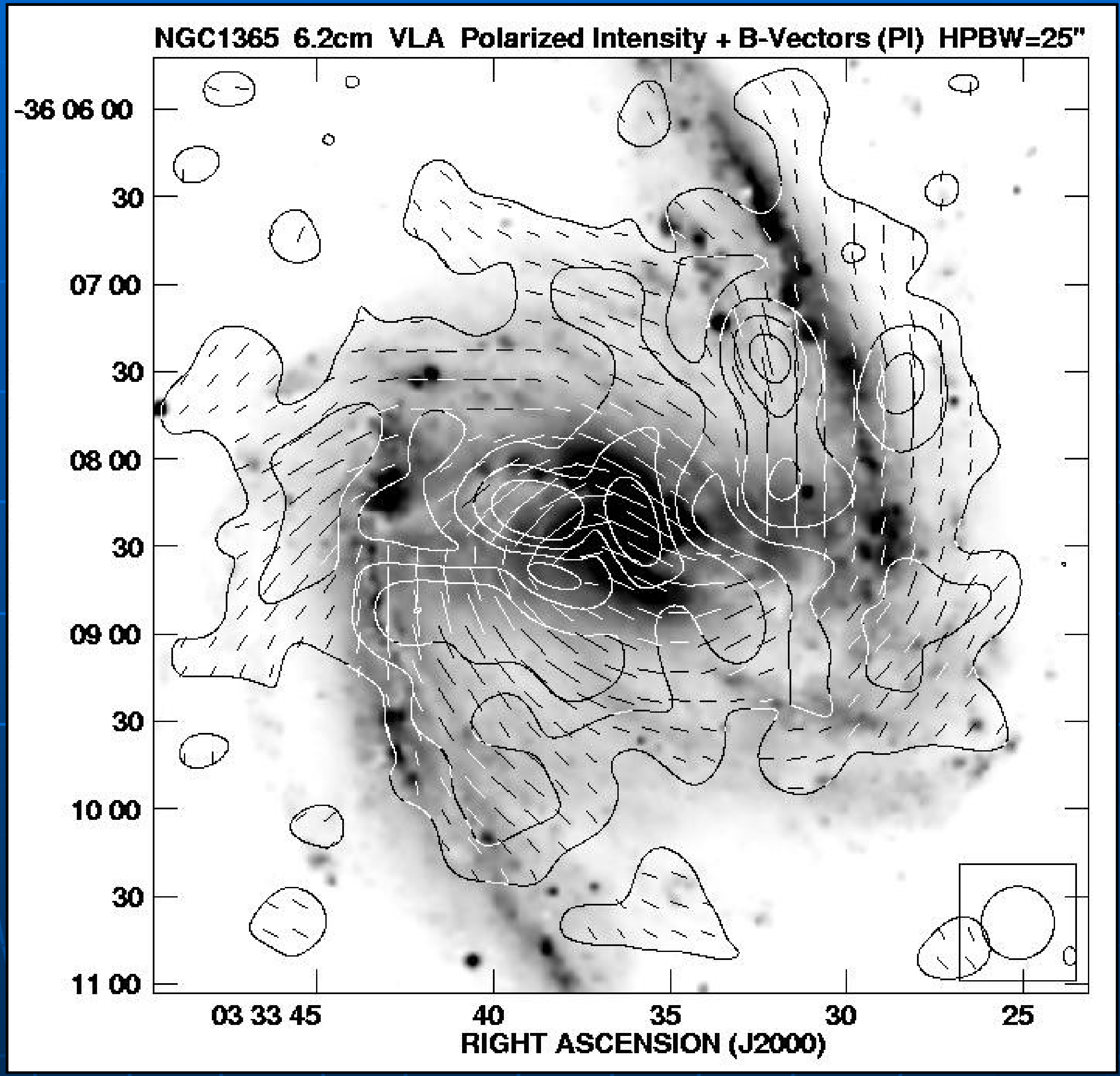
The field seems
to be connected
to the warm
diffuse gas



NGC1365

(Beck et al. 2005, Moss et al. 2007)

Smooth spiral field, ignores the bar !



Problem no.7:

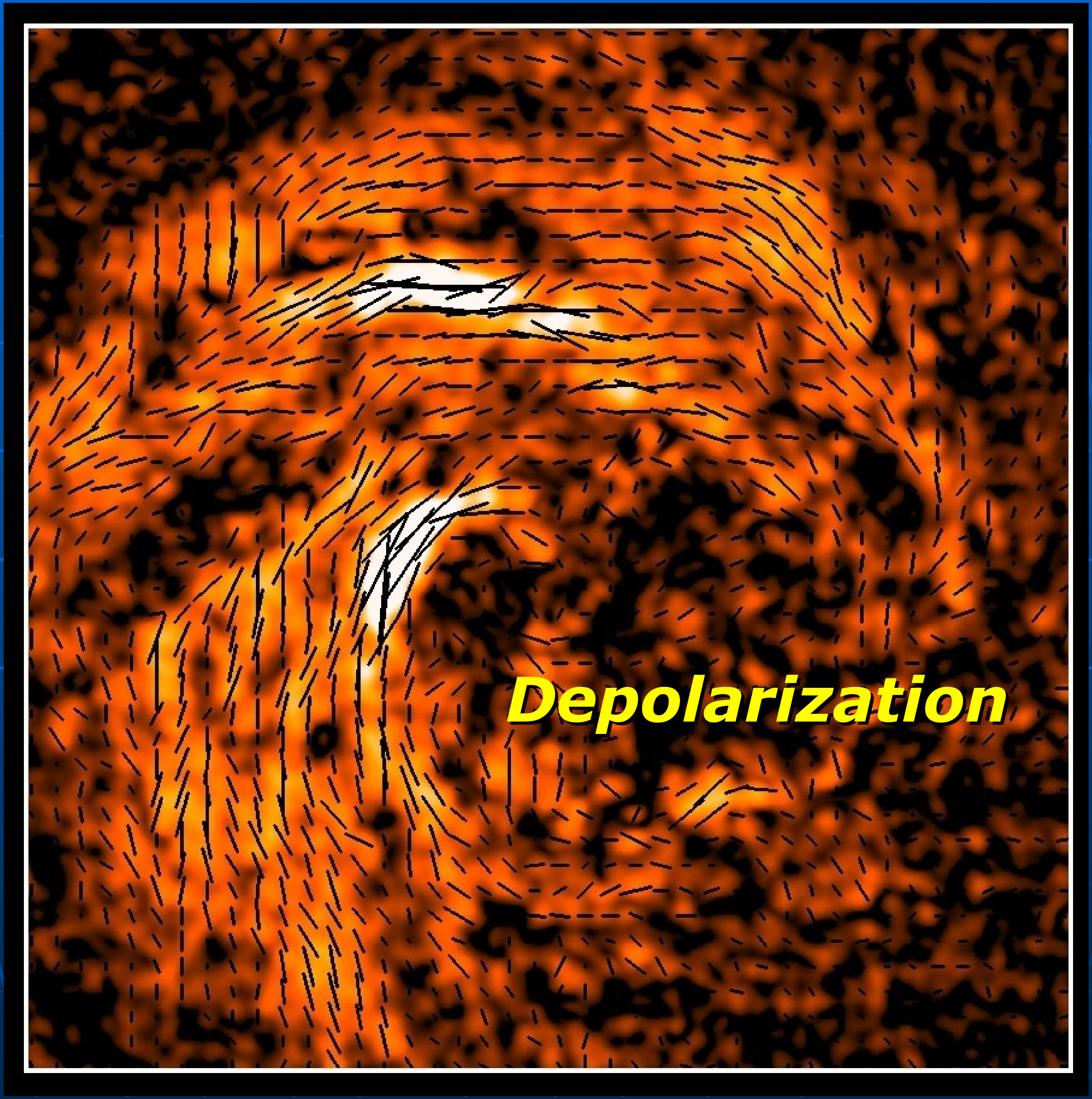
The field structure observed in barred galaxies cannot be explained by present-day dynamo models

The mystery of the asymmetry in Faraday depolarization

NGC6946

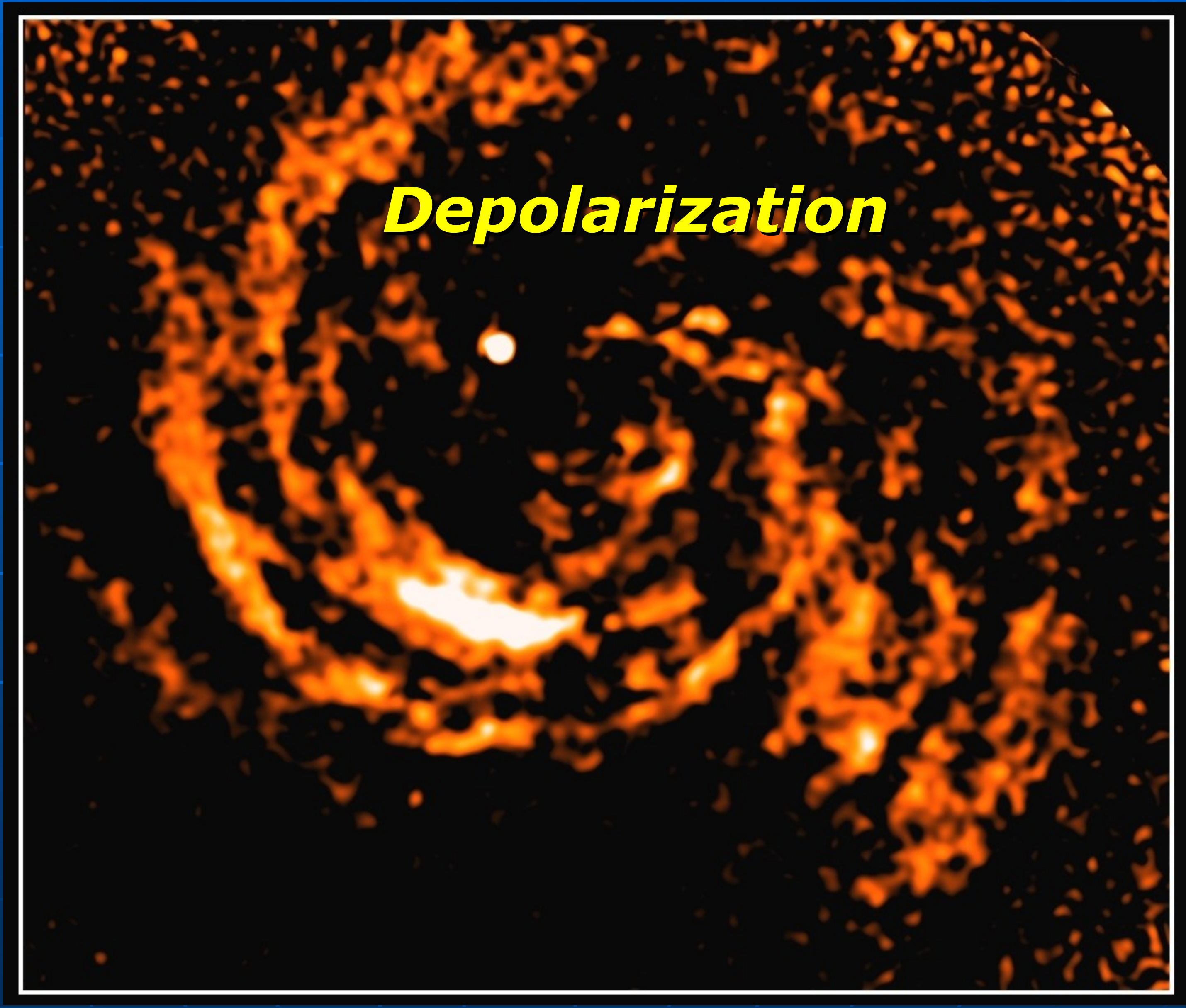
VLA Polarized Intensity + B (Beck 2006)

Stronger Faraday depolarization around the southern major axis



IC 342

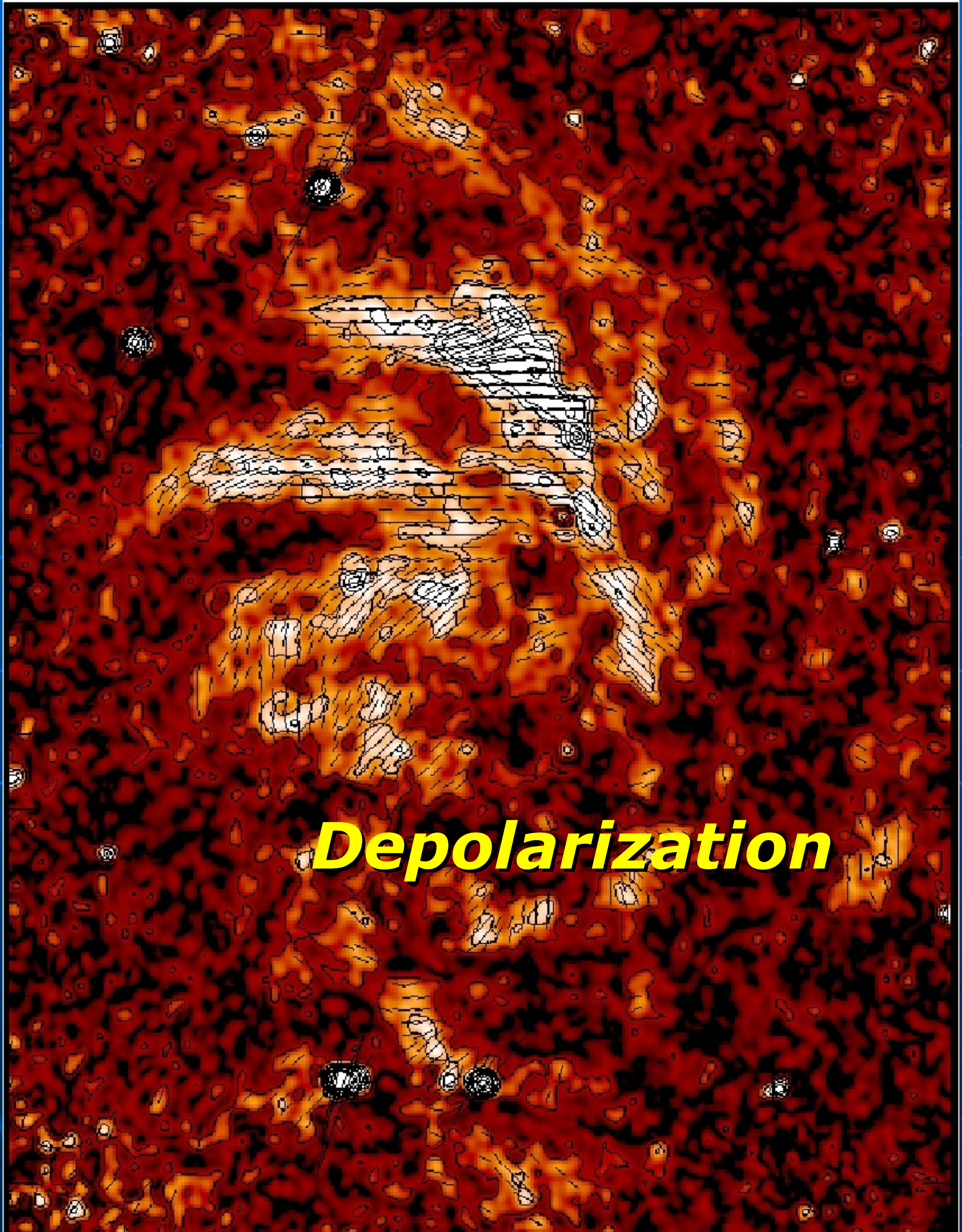
20cm VLA Polarized intensity (Beck 2006)



Stronger Faraday depolarization around the northern major axis

M33

20cm
VLA+Effelsberg
Polarized intensity
(Tabatabaei et al. 2007)



Stronger Faraday depolarization around the southern major axis

Asymmetry of Faraday depolarization

- DP on northern major axis:
  M81, IC342, NGC4254
- DP on southern major axis:
  M33, M83, NGC6946
- No asymmetry:
  M31, M51, N253

Geometrical asymmetry due to the pitch angle of the spiral field for moderate inclinations ?

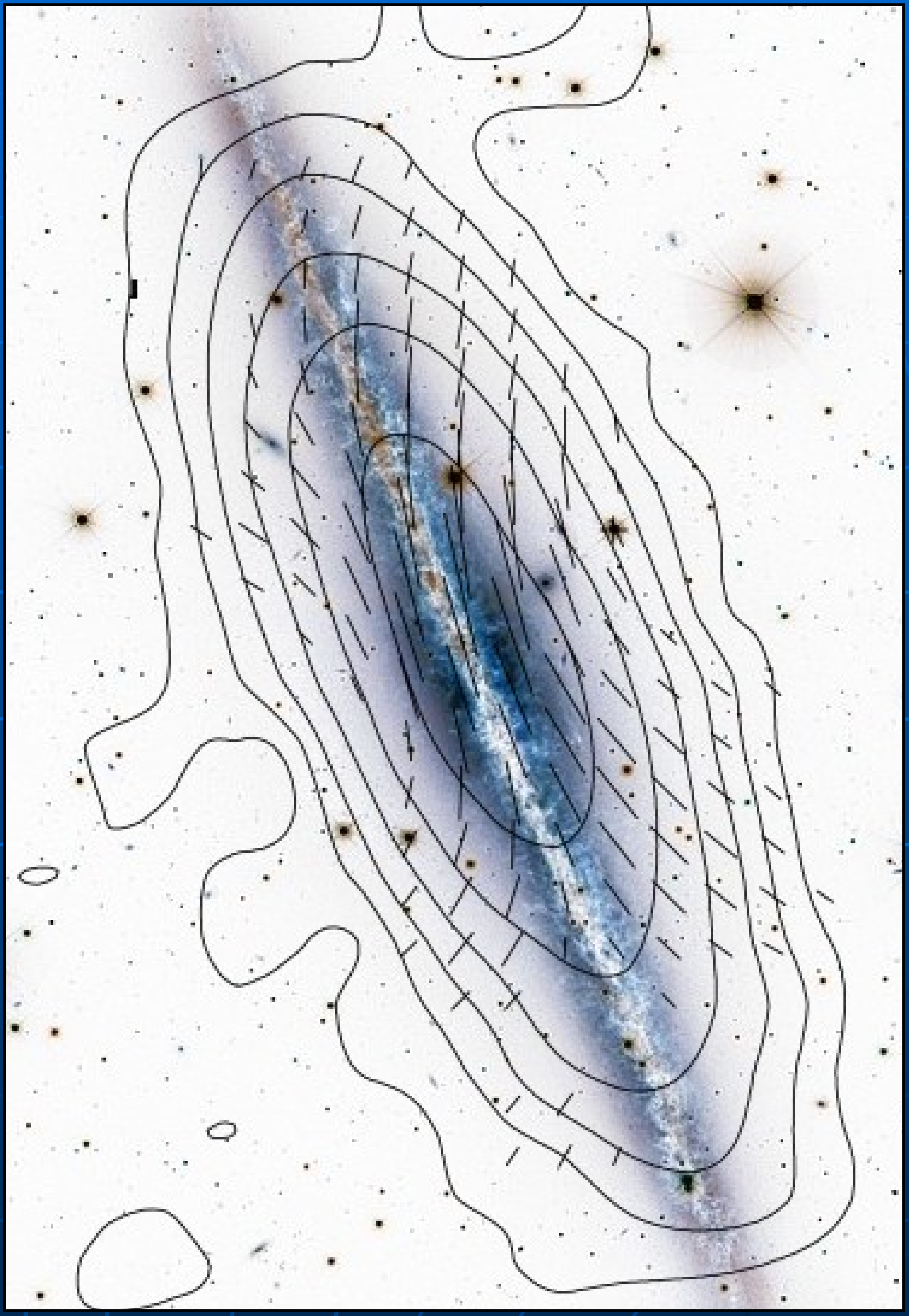
Problem no.8:

Field structures in halos of galaxies are not be symmetric

Edge-on galaxies

NGC 891

3cm Effelsberg
Total intensity
+ B-vectors
(Krause 2007)



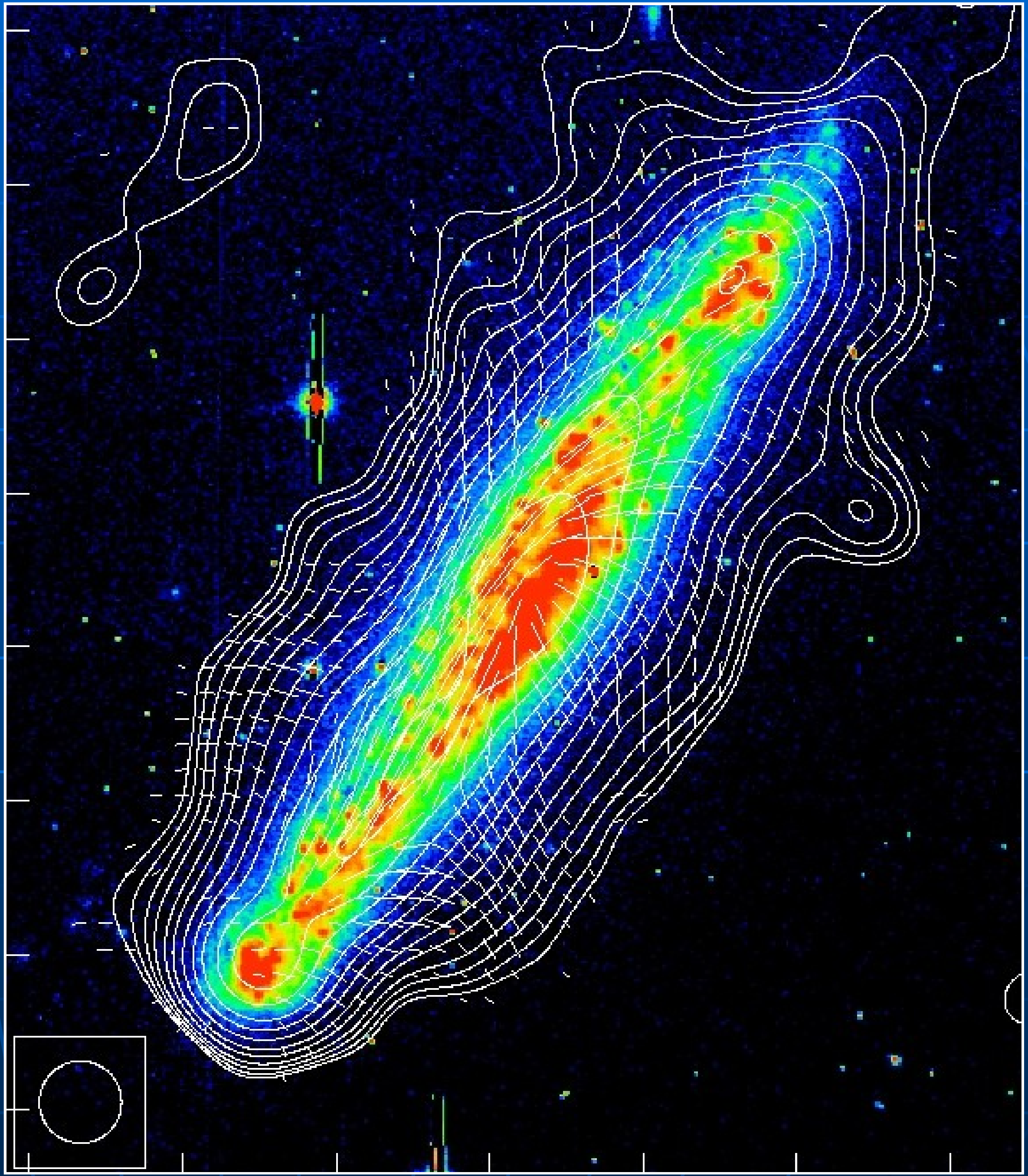
Bright radio halo with X-shaped field pattern:

Driven by a disk wind with radial components

NGC 5775

3cm VLA+Effelsberg total intensity
+ B-vectors
(Soida et al., in prep)

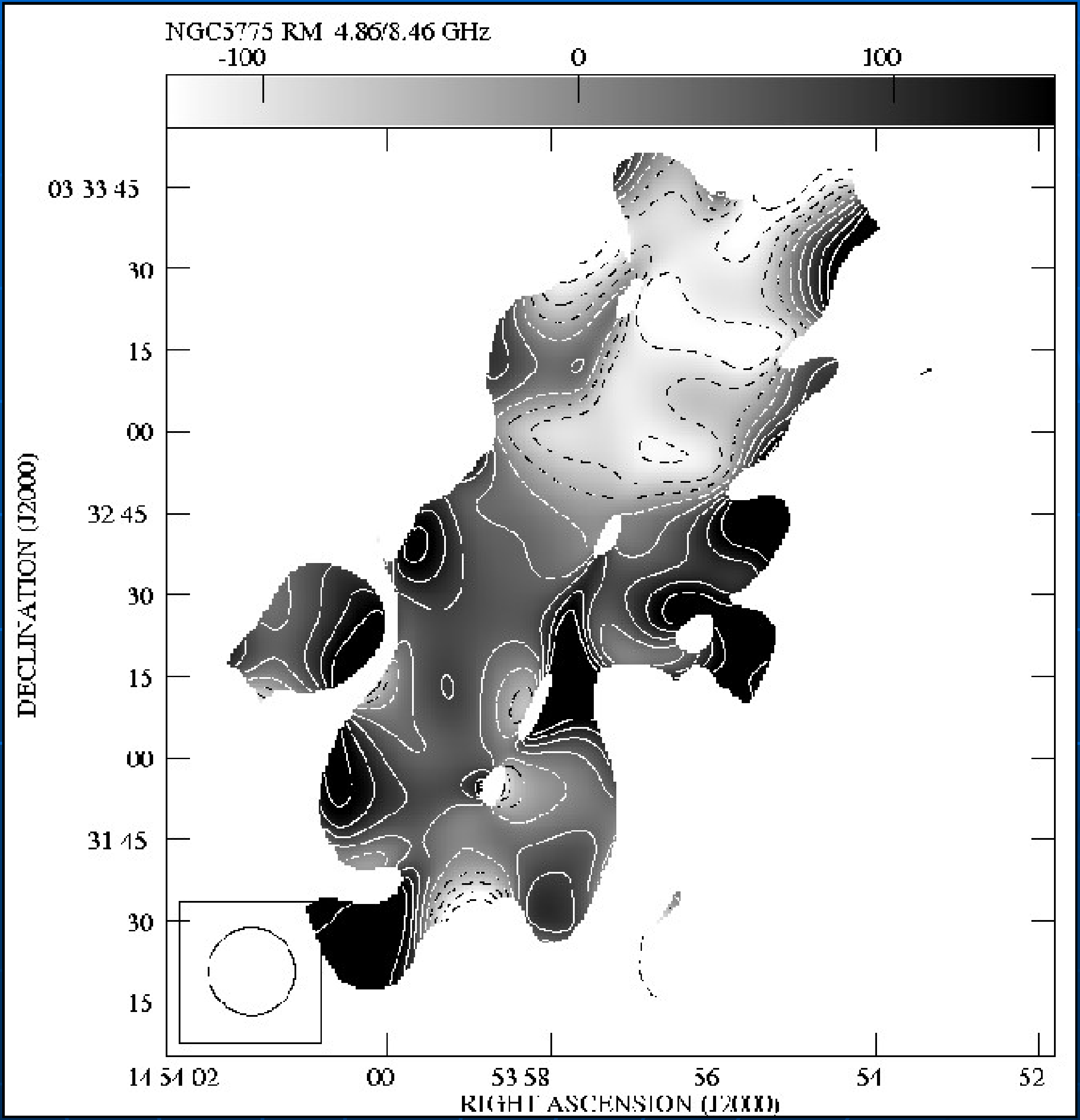
X-shaped halo field



NGC 5775

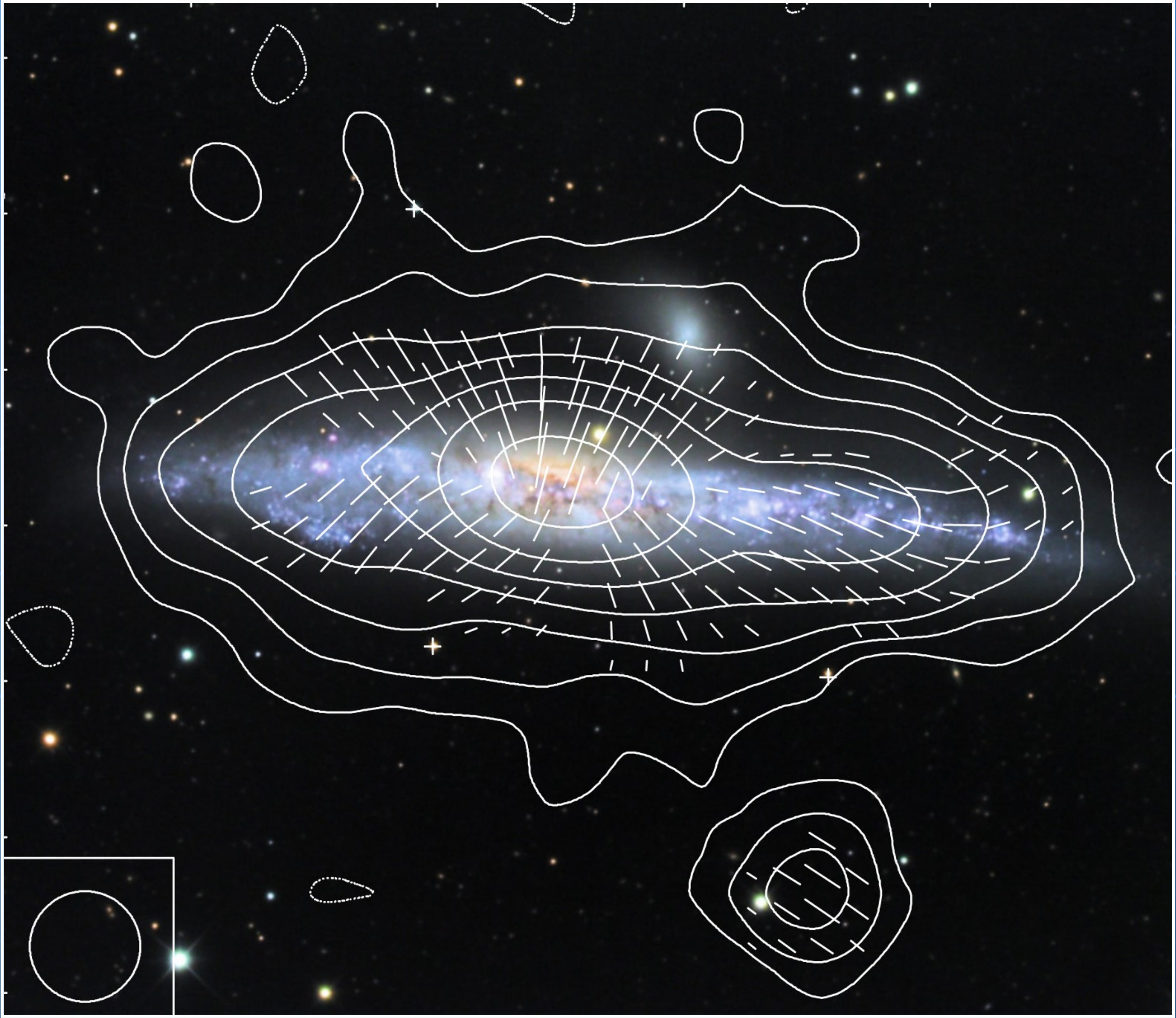
VLA+Effelsberg
RM 3/6cm
(Soida et al., in prep)

Axisymmetric dynamo mode in the disk



NGC 4631

Effelsberg 3.6cm
Total intensity
+ B-vectors
(Krause & Dumke)



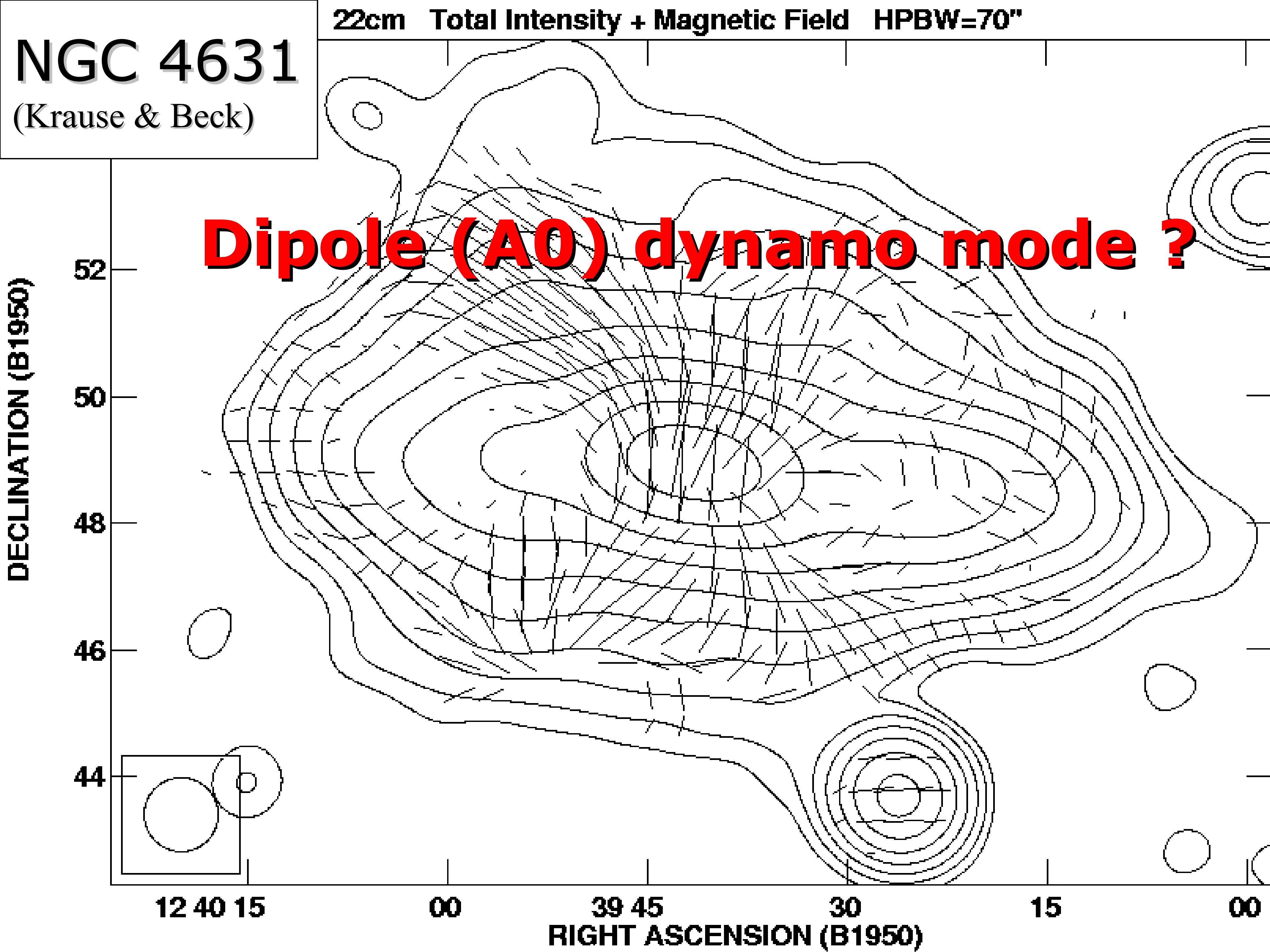
Huge halo:

X-shaped field, *not* consistent with standard dynamo modes

NGC 4631

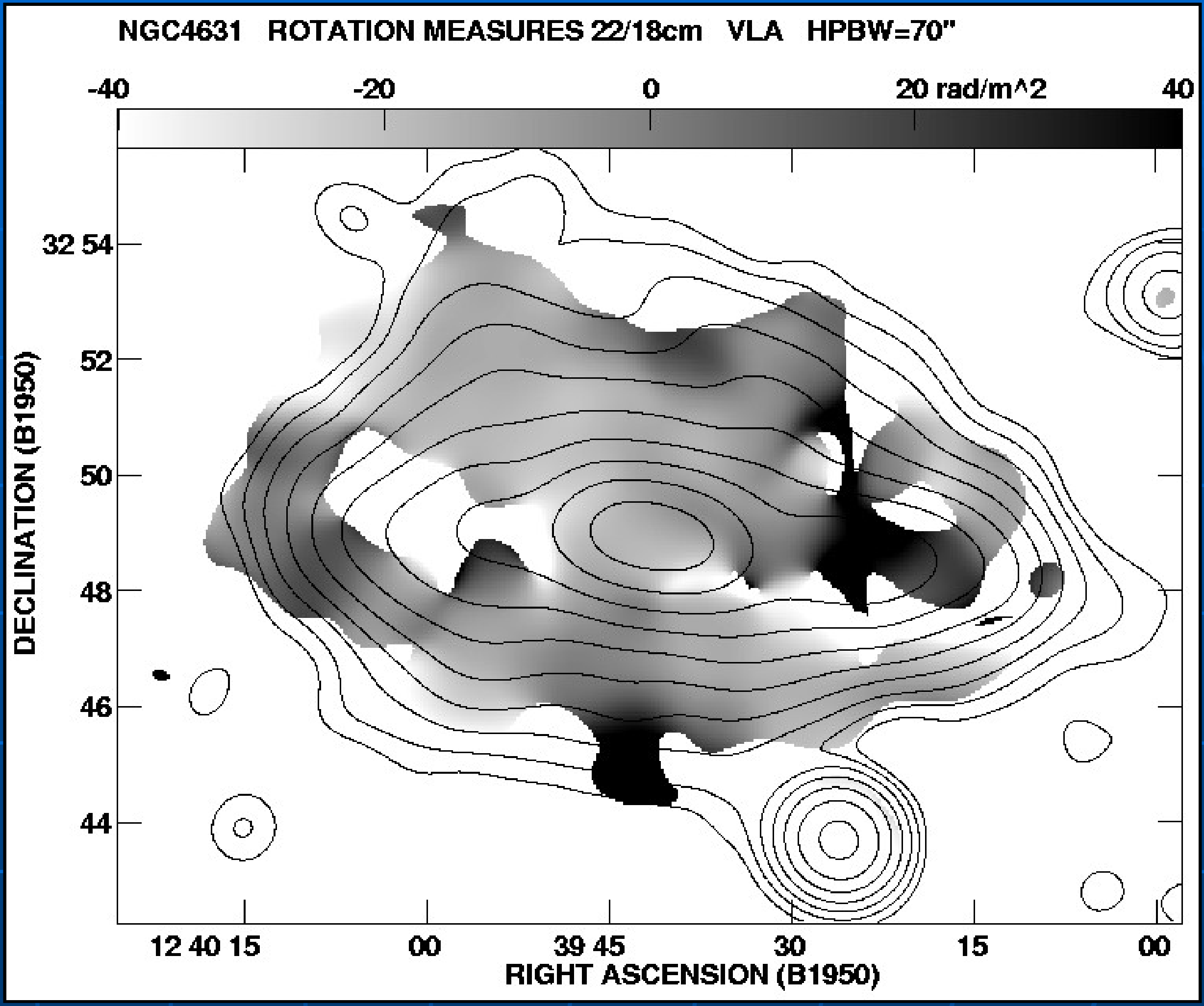
(Krause & Beck)

Dipole (A0) dynamo mode ?



NGC 4631

(Krause & Beck)



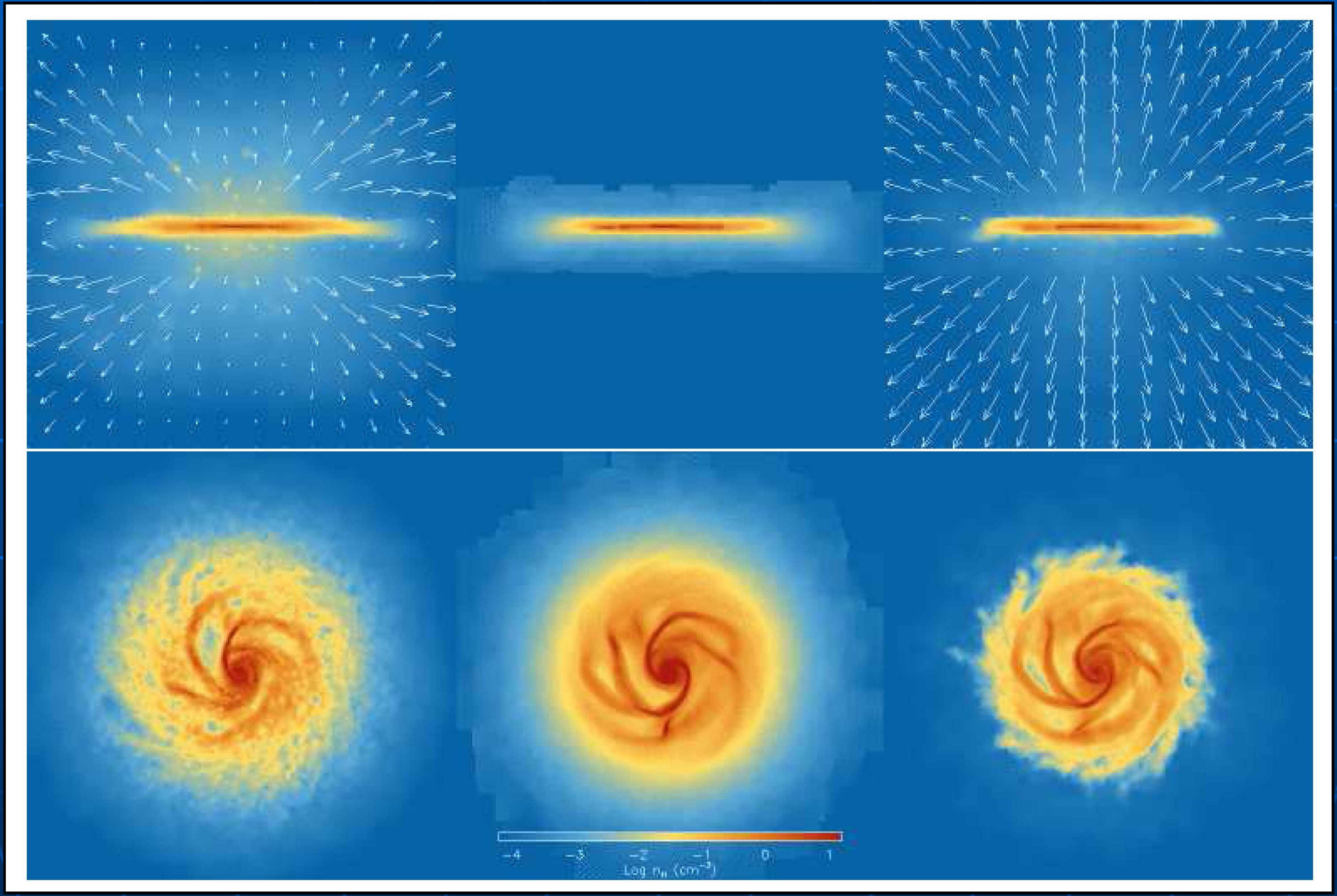
- Expected RM of >100 rad/m^2 : not observed !
- No large-scale pattern in RM: no dipole dynamo field

Problem no.9:

Large-scale fields in halos are neither dipolar nor quadrupolar, but X-shaped

SN-driven outflow

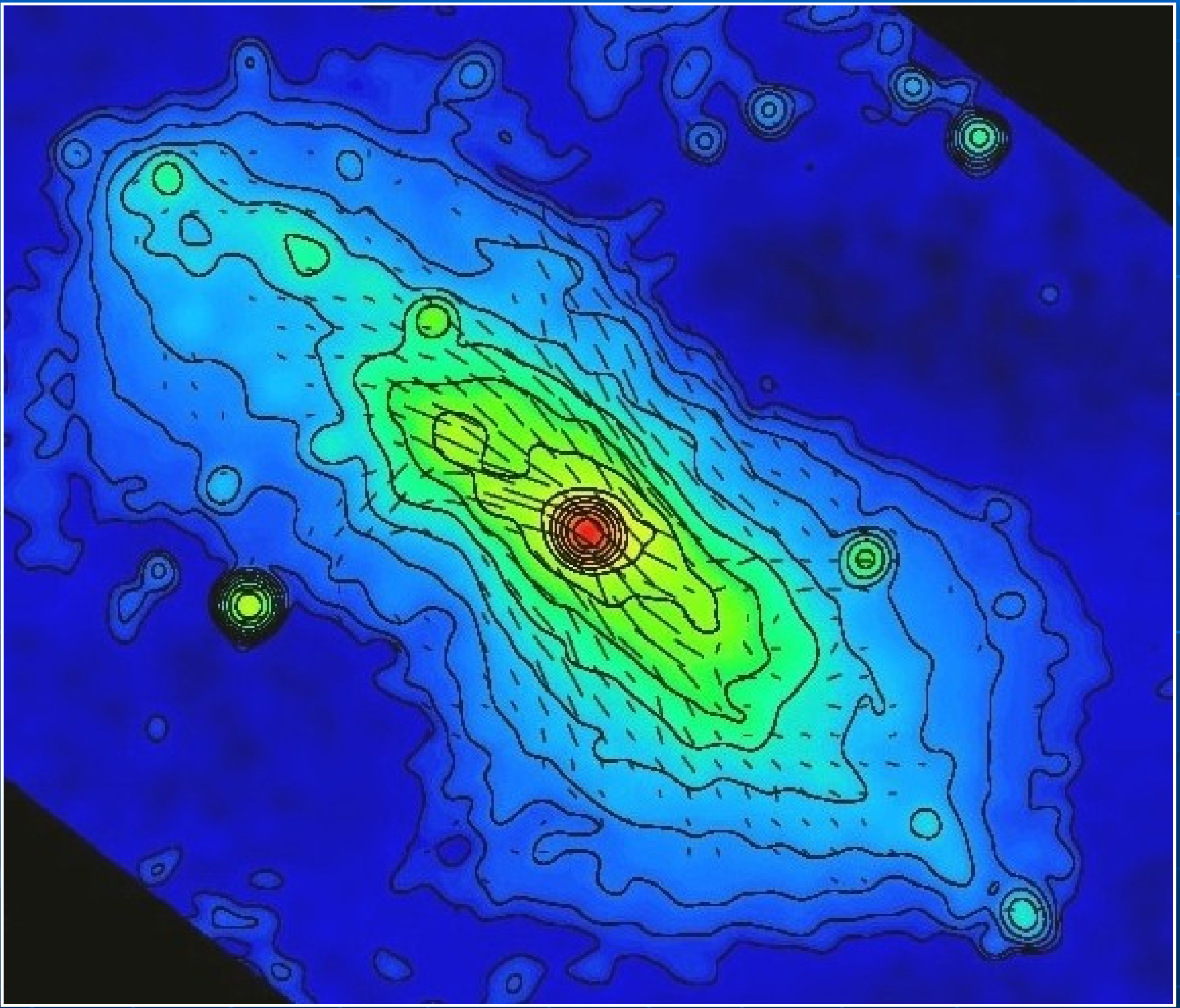
(HD model by Dalla Vecchia & Schaye 2008)



Interacting wind　　No wind　　Non-interacting wind

NGC 253

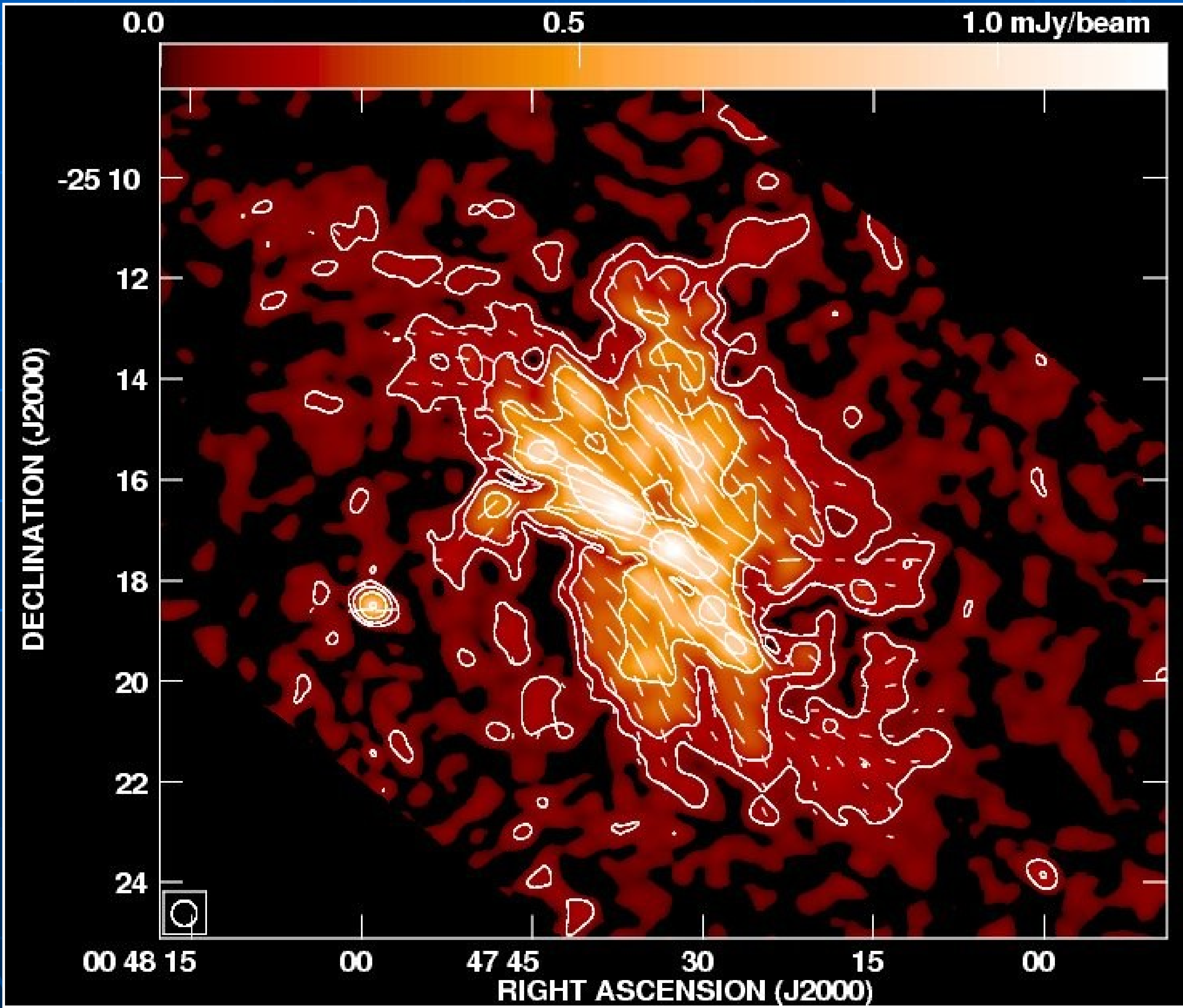
6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Heesen et al. 2009)



NGC 253

6cm
VLA+Effelsberg
Polarized intensity
+ B-vectors
(Heesen et al. 2009)

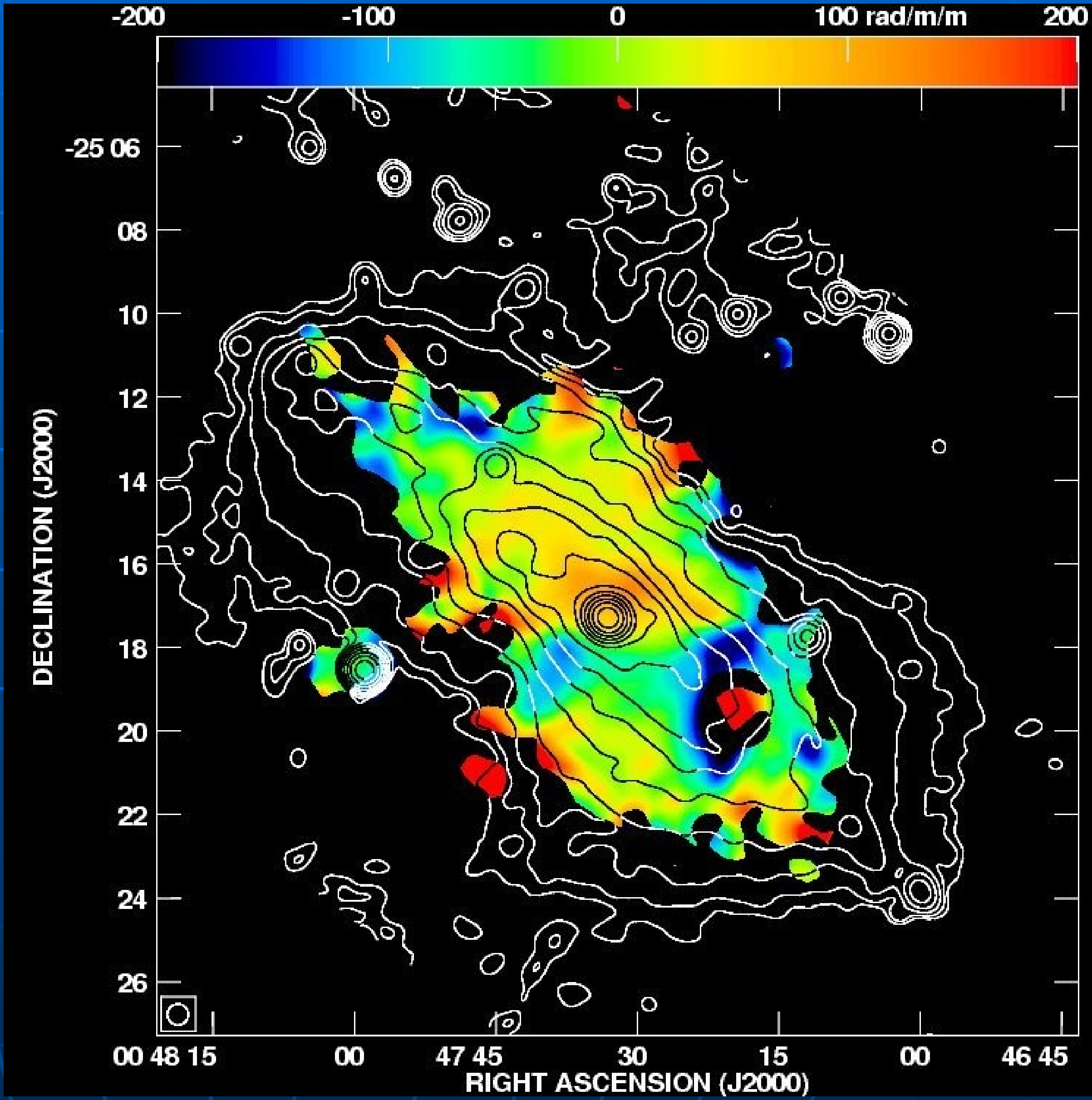
Disk + halo field



NGC 253

RM 3/6cm
(Heesen et al. 2009)

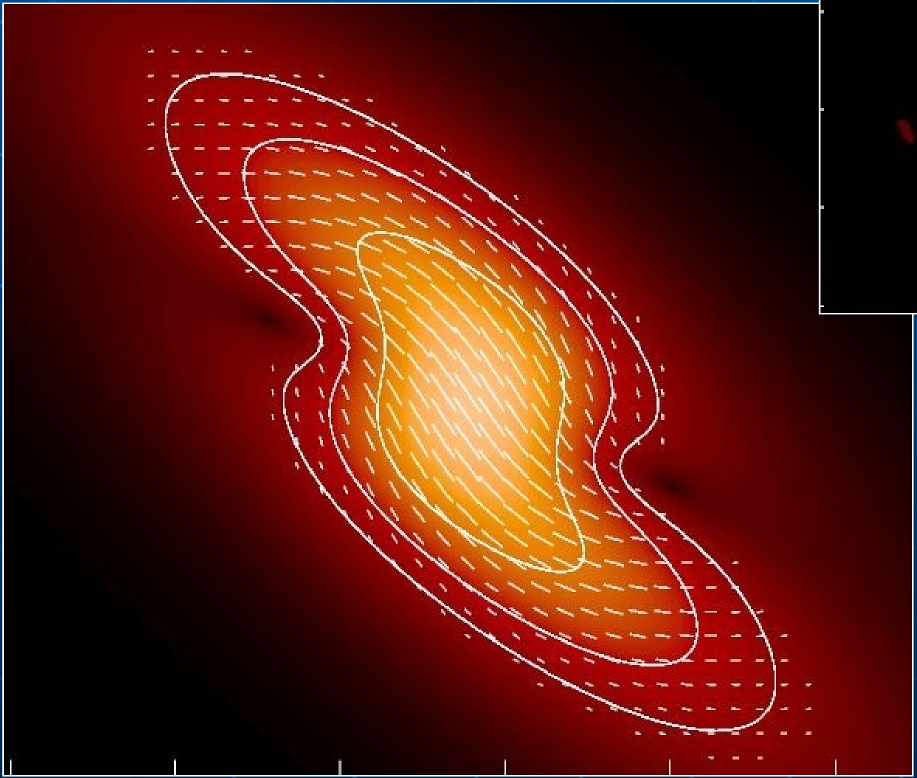
Axisymmetric dynamo mode in the disk

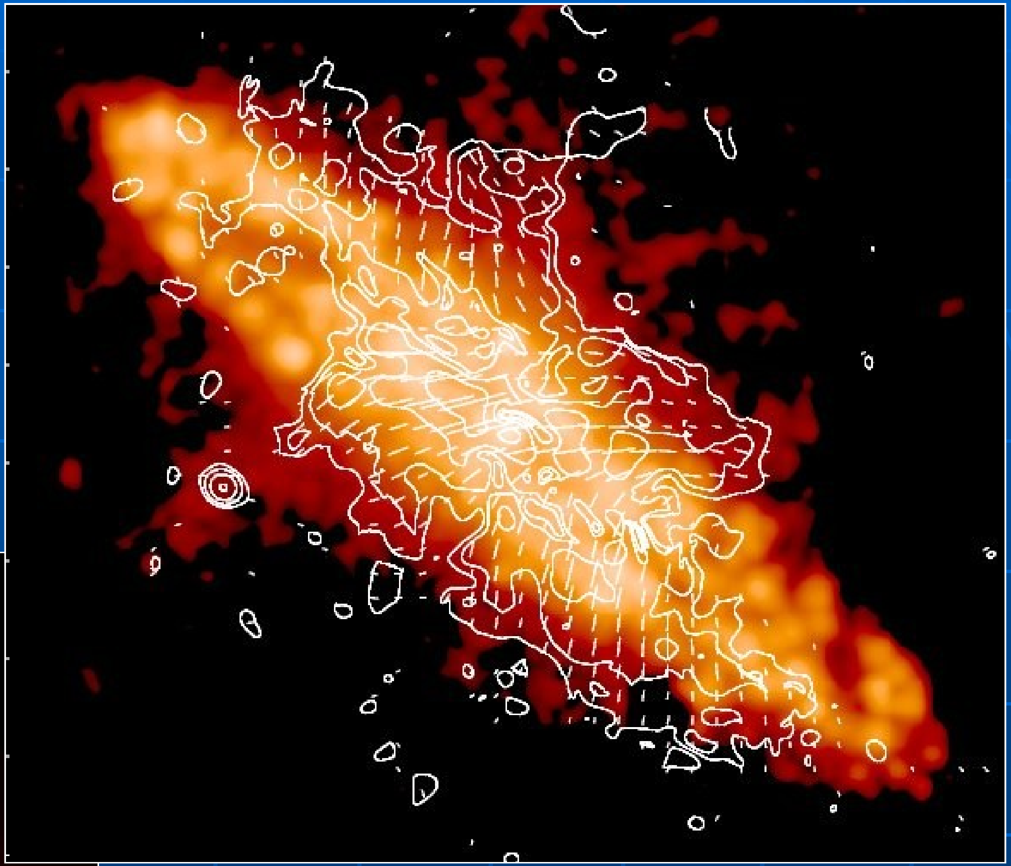


NGC 253

6cm VLA+Effelsberg
Polarized intensity
+ B-vectors
(Heesen et al. 2009)

Disk:
Axisymmetric spiral field

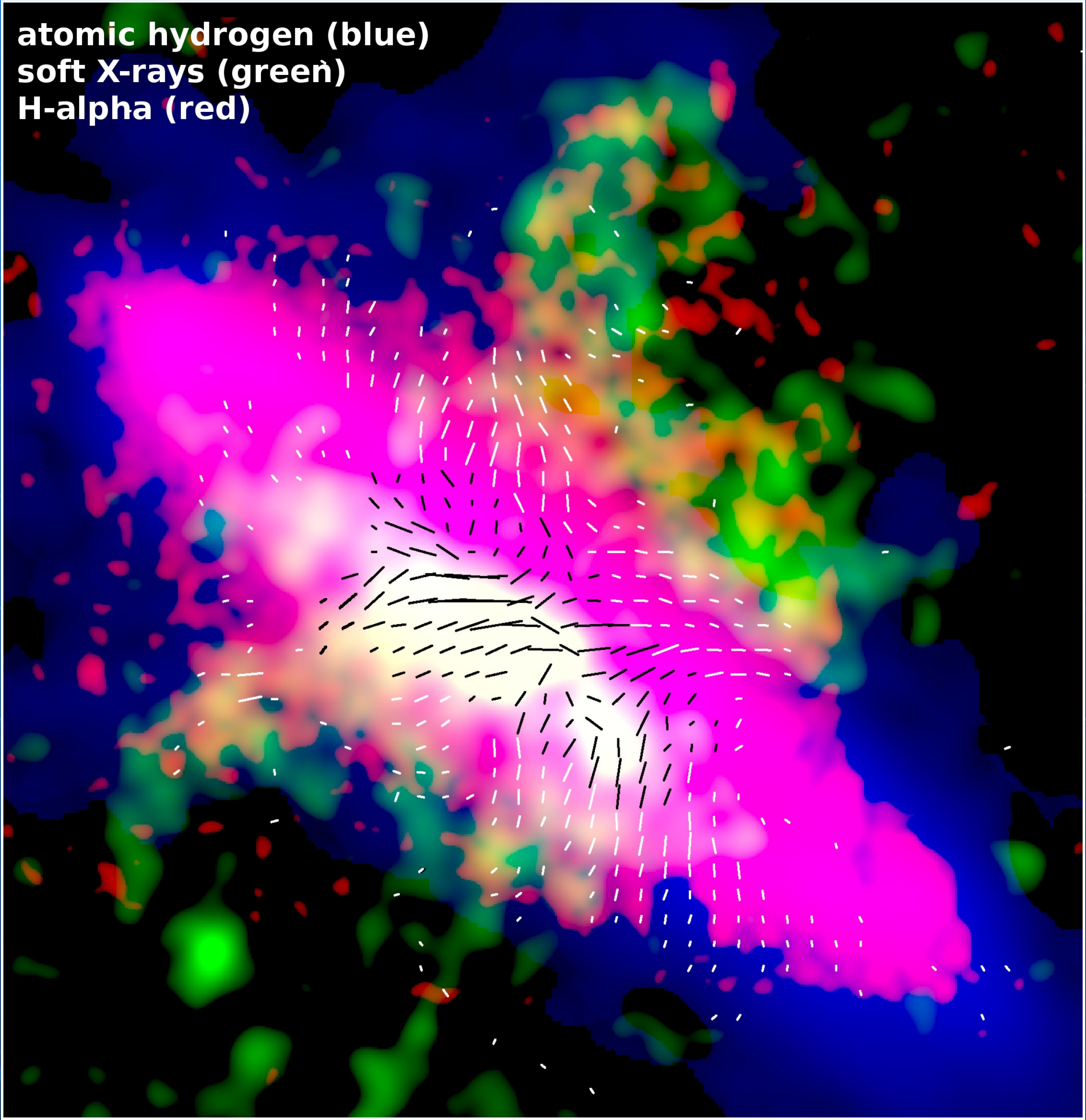




Halo:
X-shaped field

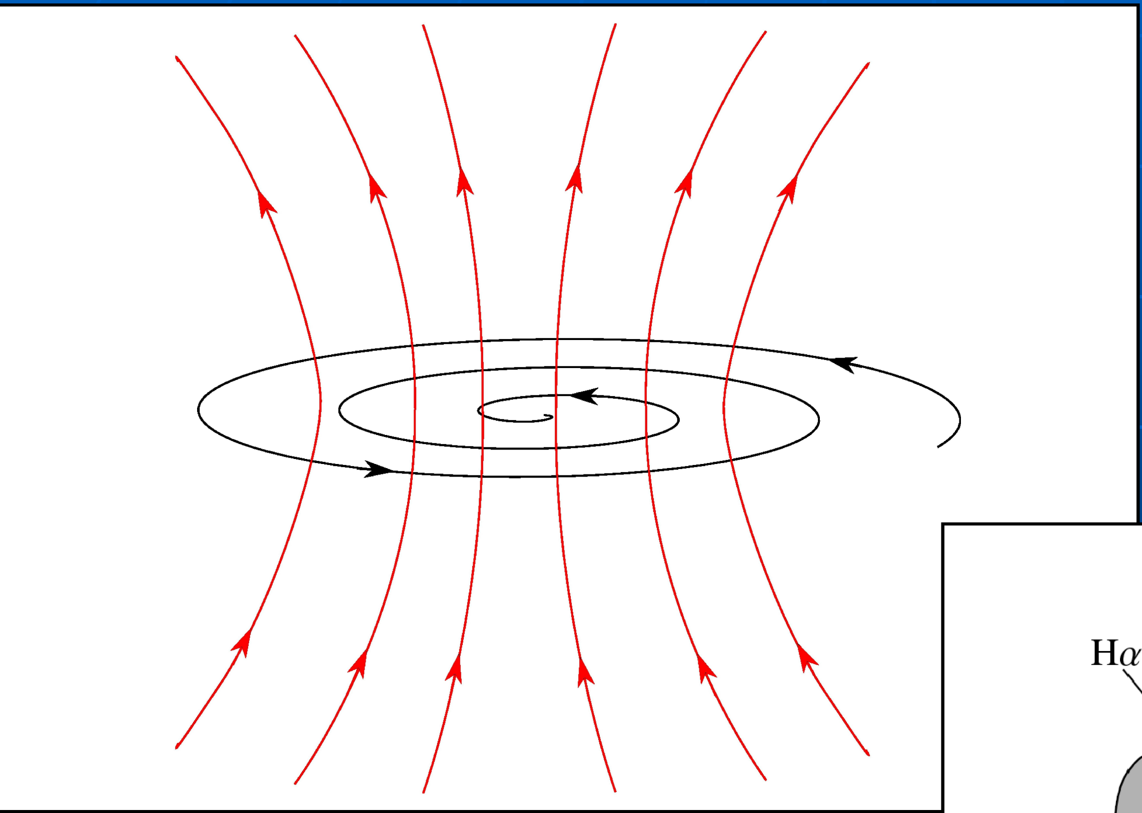
NGC 253

6cm B-vectors
+ Hα + X-rays + HI
(Heesen et al. 2009)



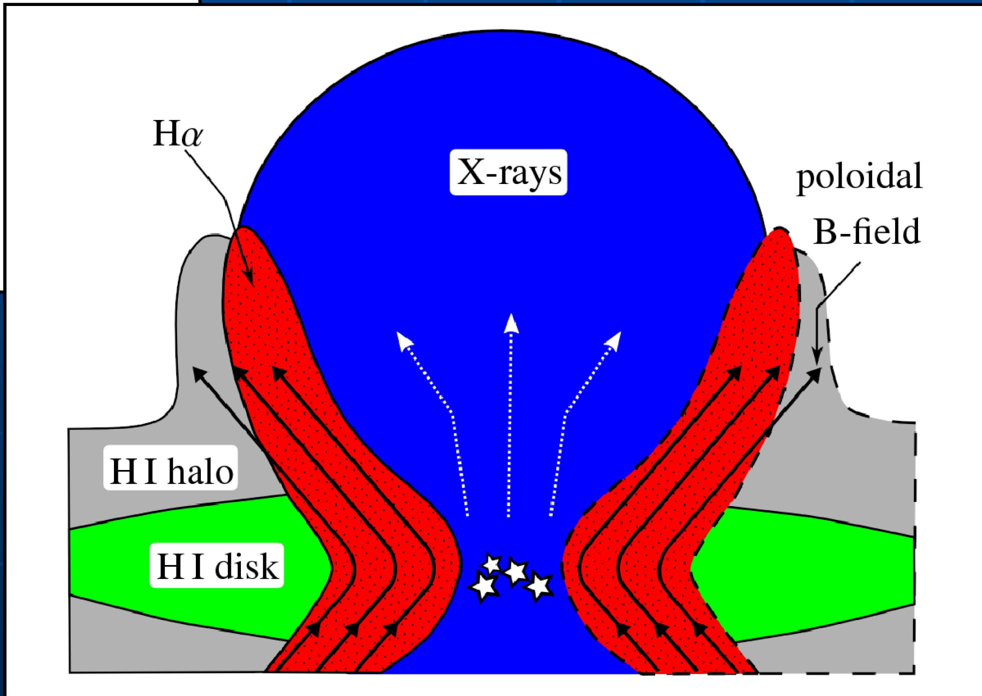
Interaction between warm & hot gas and ordered magnetic fields

Magnetic field model for NGC 253



Heesen et al. 2009

Axisymmetric (ASS) disk field +
antisymmetric (cone) halo field



Dynamo evidence no.5:

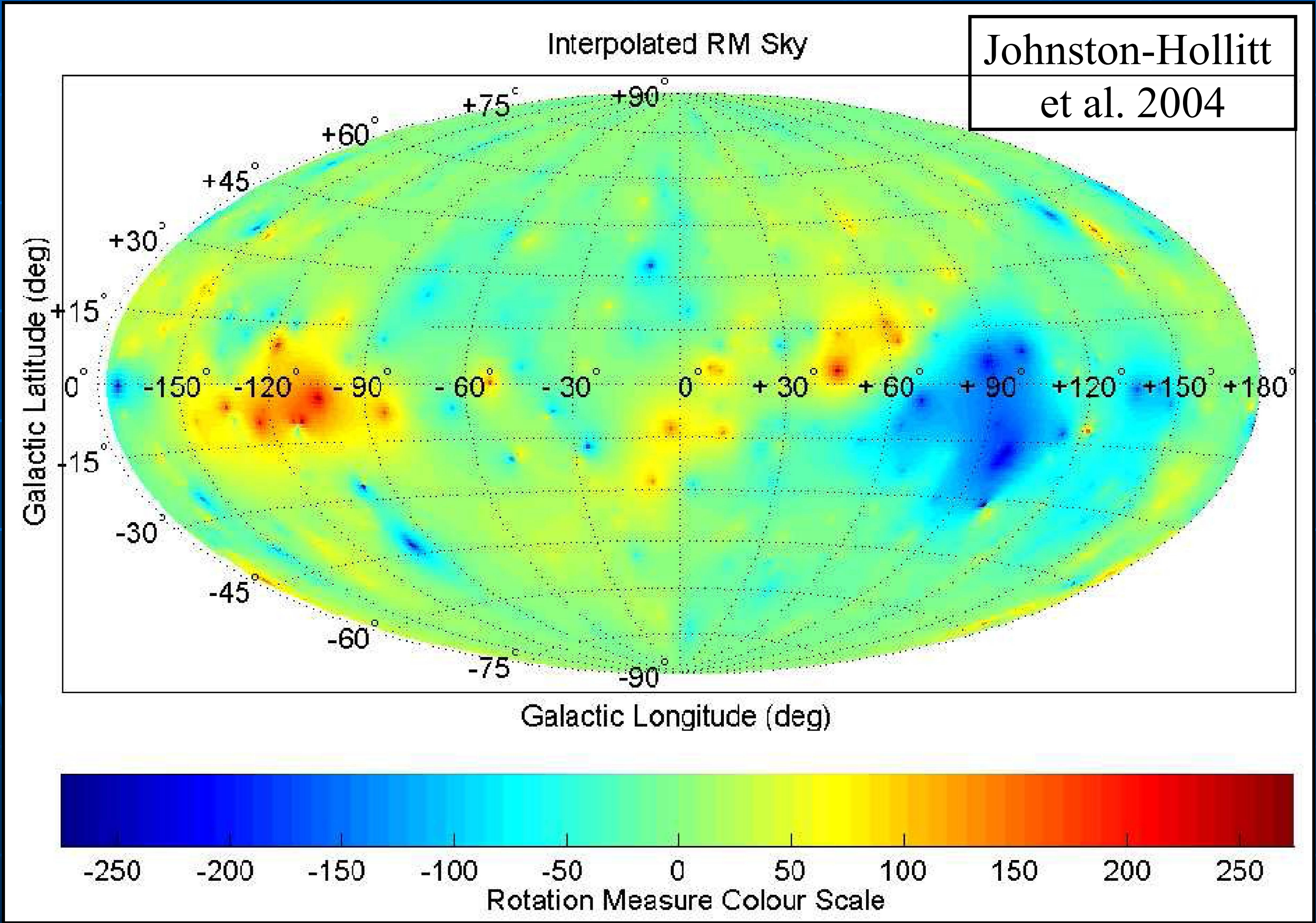
Large-scale poloidal fields exist !

Problem no.10:

Are galactic outflows strong enough to remove small-scale helicity ?

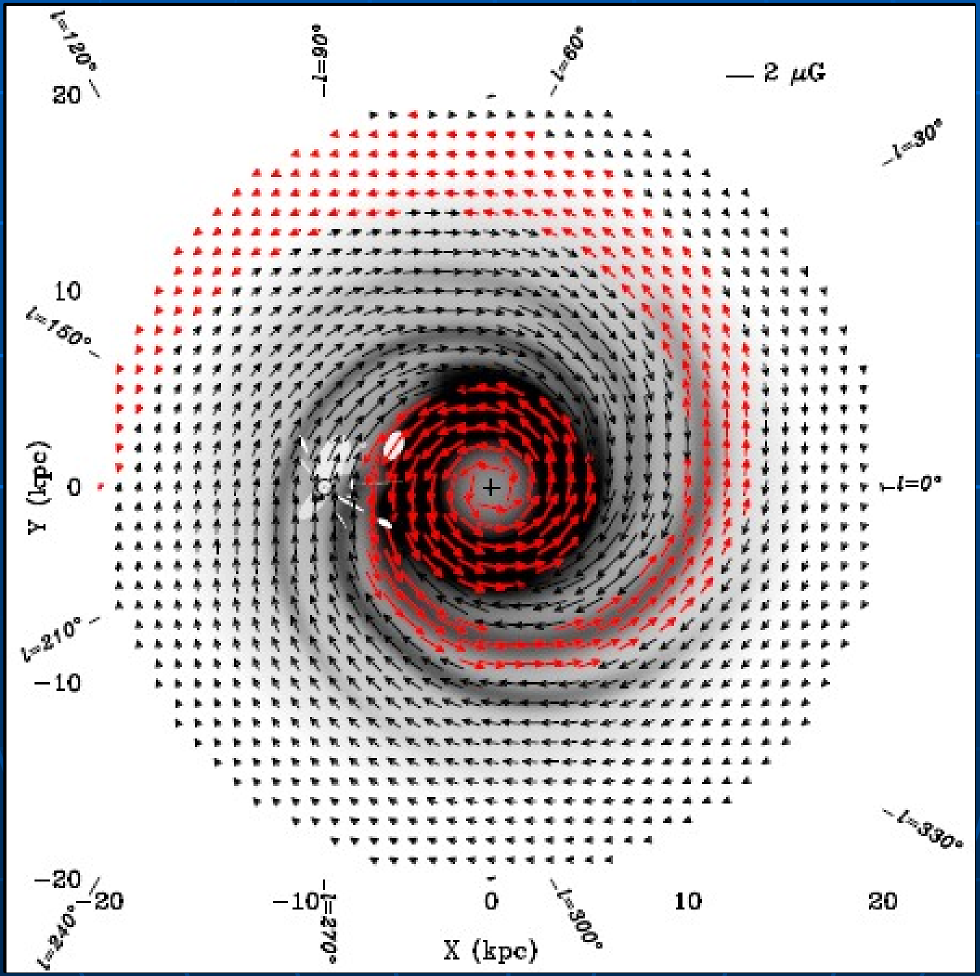
The mystery of the field reversals in the Milky Way

RMs of all-sky extragalactic sources



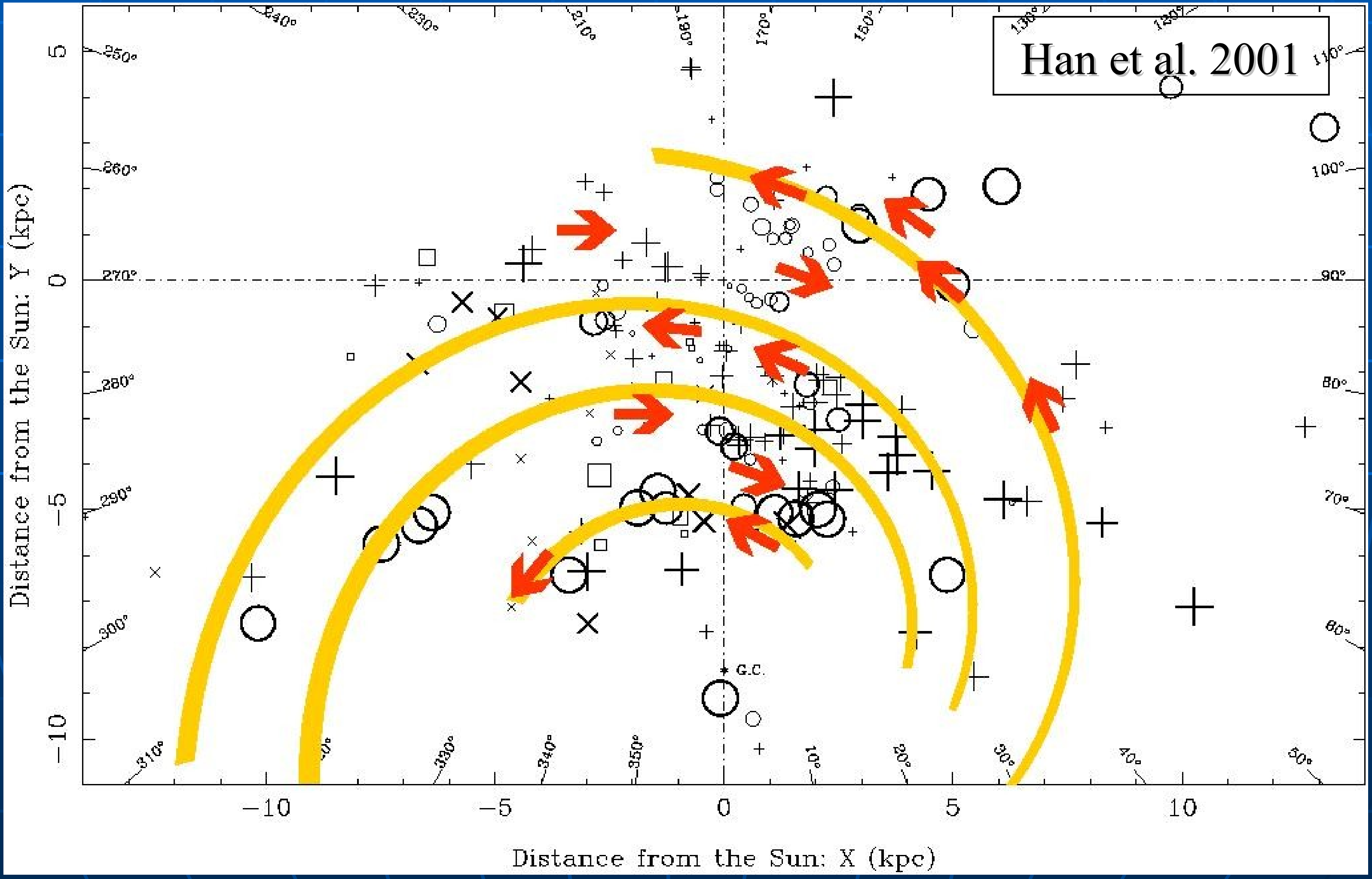
Synchrotron emission and extragalactic RMs:

Axisymmetric spiral (ASS)
+ one reversal along radius
+ antisymmetric halo field with reversal across the plane



Sun et al. 2008

Pulsar RMs in the Milky Way:
Many reversals (?)



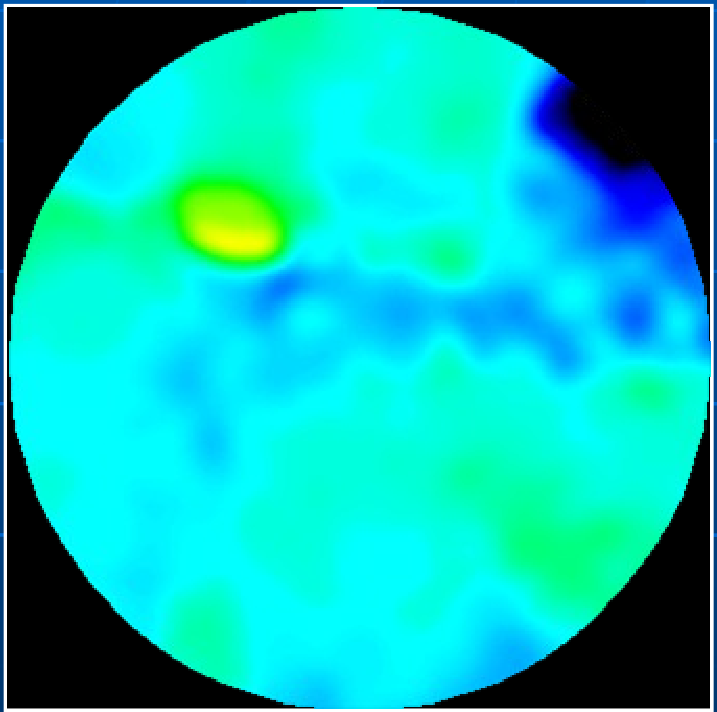
Problem no.11:

Large-scale field reversals are very rare in spiral galaxies:

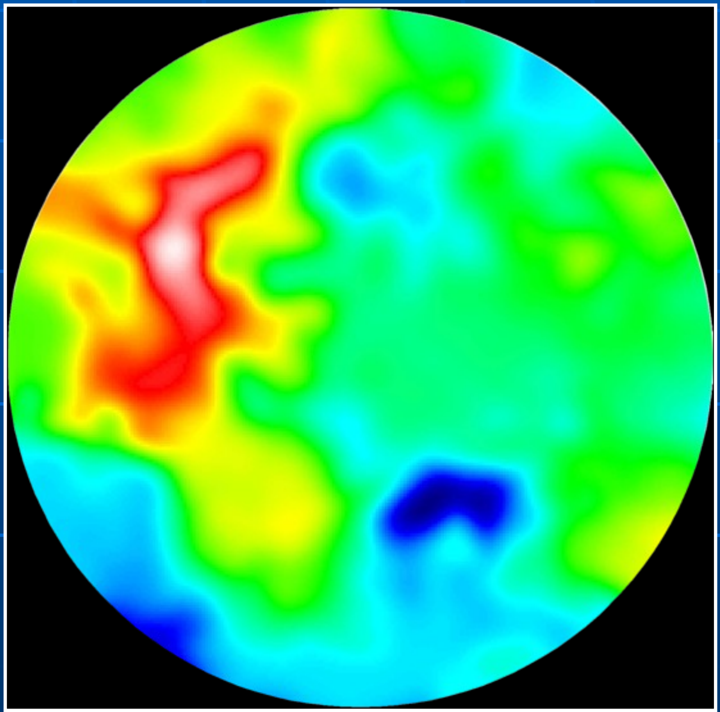
Is our Milky Way special ?

RMs of extragalactic sources

Mao et al., in prep.



North Galactic Pole



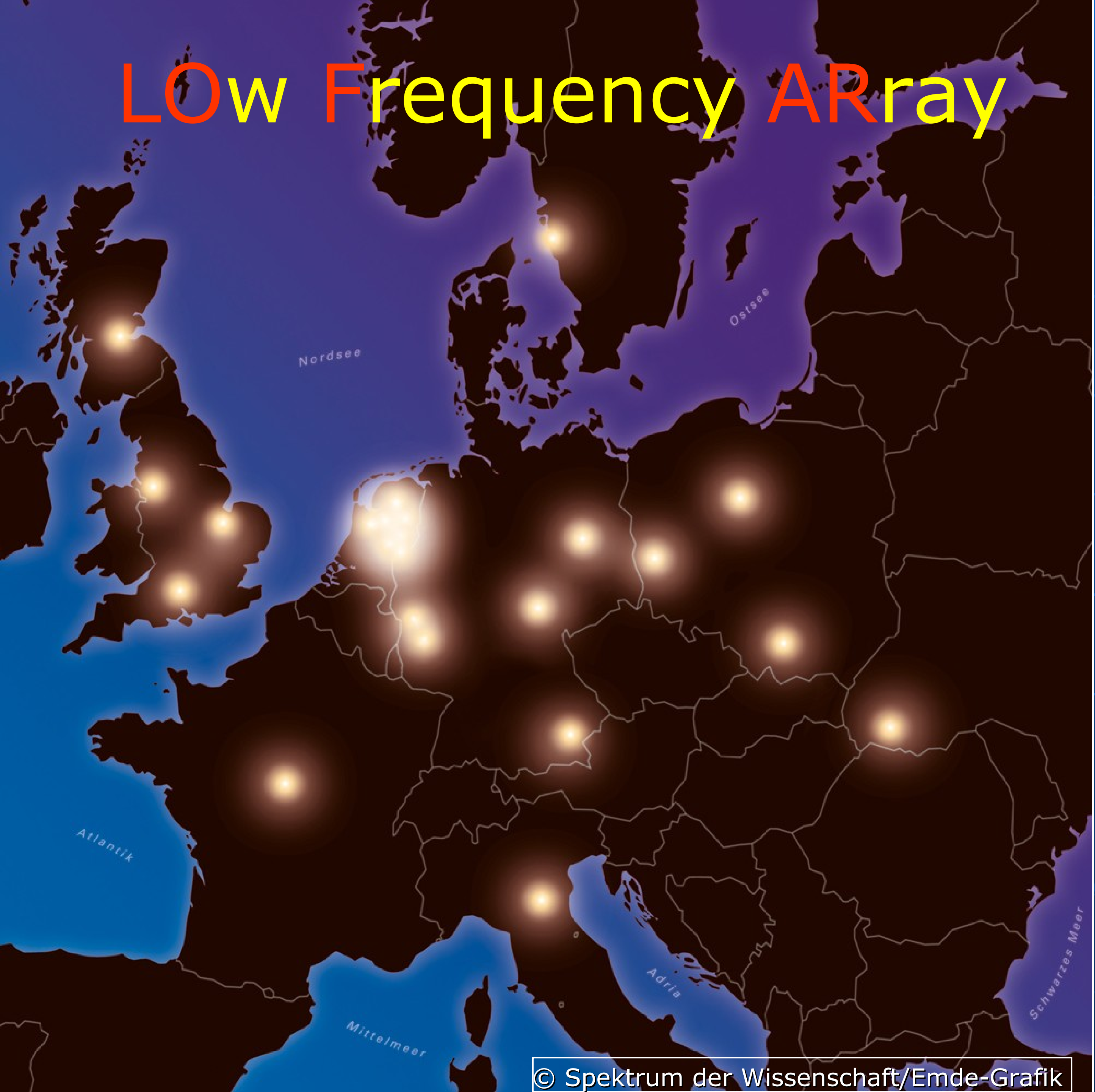
South Galactic Pole

Weak large-scale vertical field (≈0.2μG)

The future I:

Low-frequency radio emission will allow to observe weak magnetic fields

LOw Frequency ARray



LOFAR

30-80 MHz
110-240 MHz

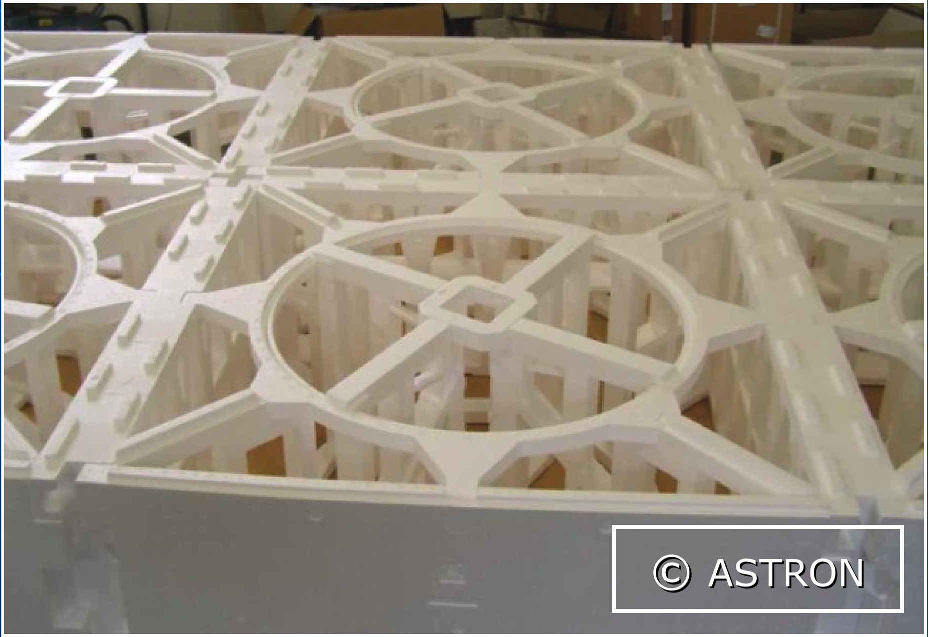

LOFAR core station
(Exloo, Netherlands)
© ASTRON

First international station in Effelsberg

LOFAR antenna design

Lowband:
30 – 80 MHz (10m – 4m),
96 antennae per station

Highband:
110 – 240 MHz (3m – 1.2m),
48-96 elements per station



Low-frequency radio observations

LOFAR

- 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

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:

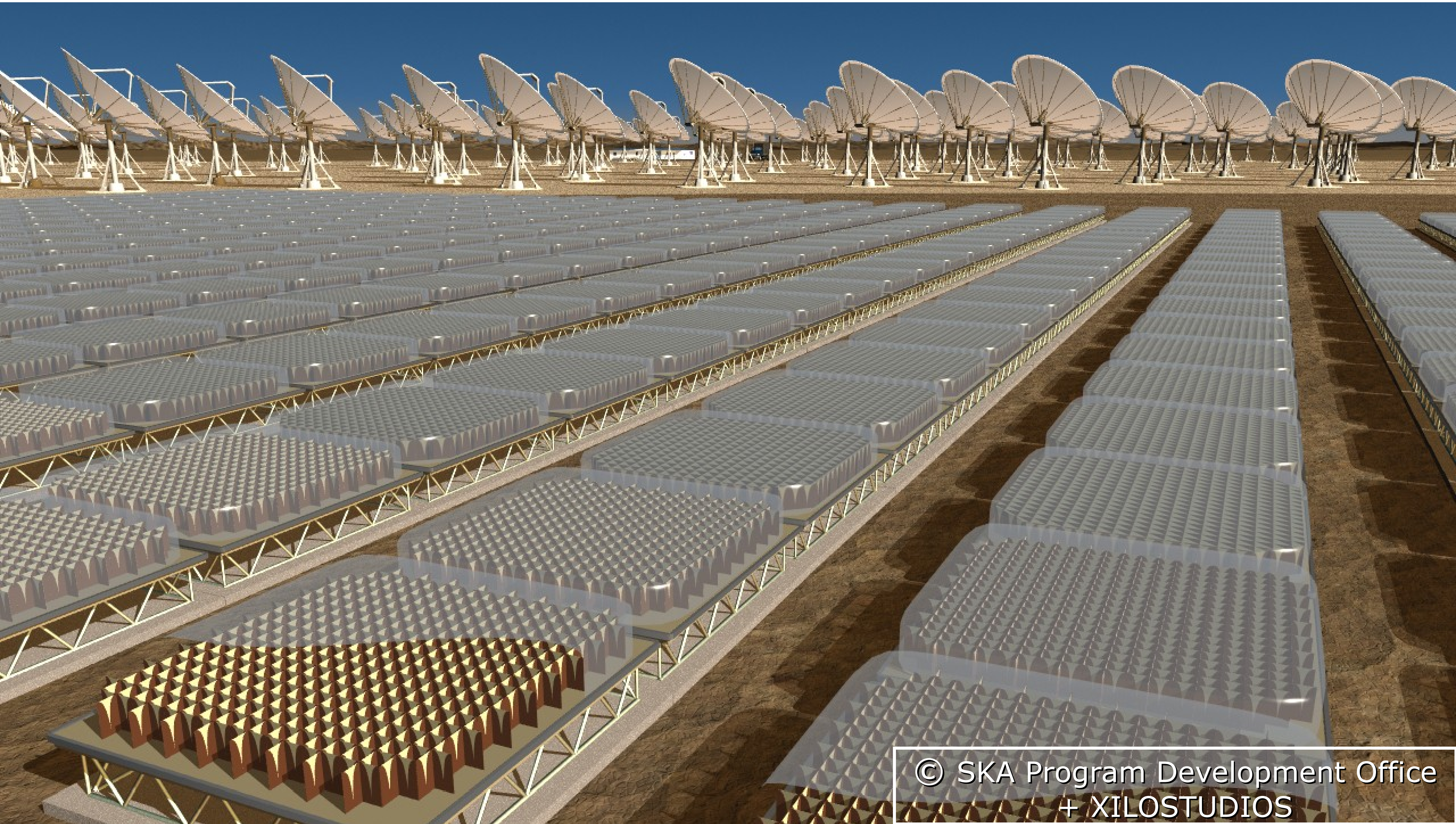
  $n_e=10^{-5}$ cm^{-3}, $B_{||}=0.1\ \mu G$, L=100 kpc: RM~0.1 rad m^{-2}

The future II:

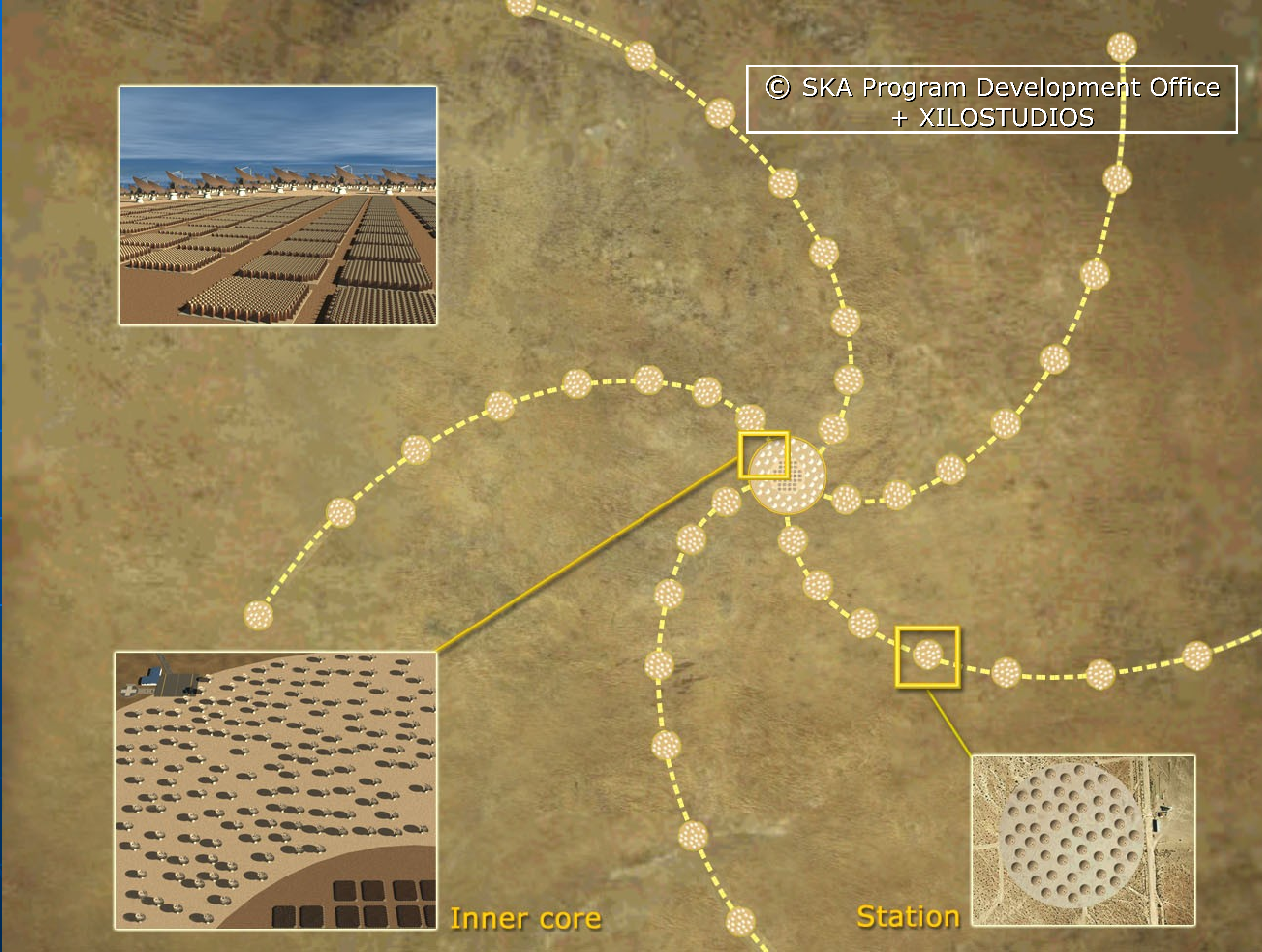
The SKA will allow
to observe
detailed structures
of magnetic fields

Square Kilometre Array (SKA)

70 MHz - 10/35 GHz




SKA core station
© SKA Program Development Office
+ XILOSTUDIOS


© SKA Program Development Office
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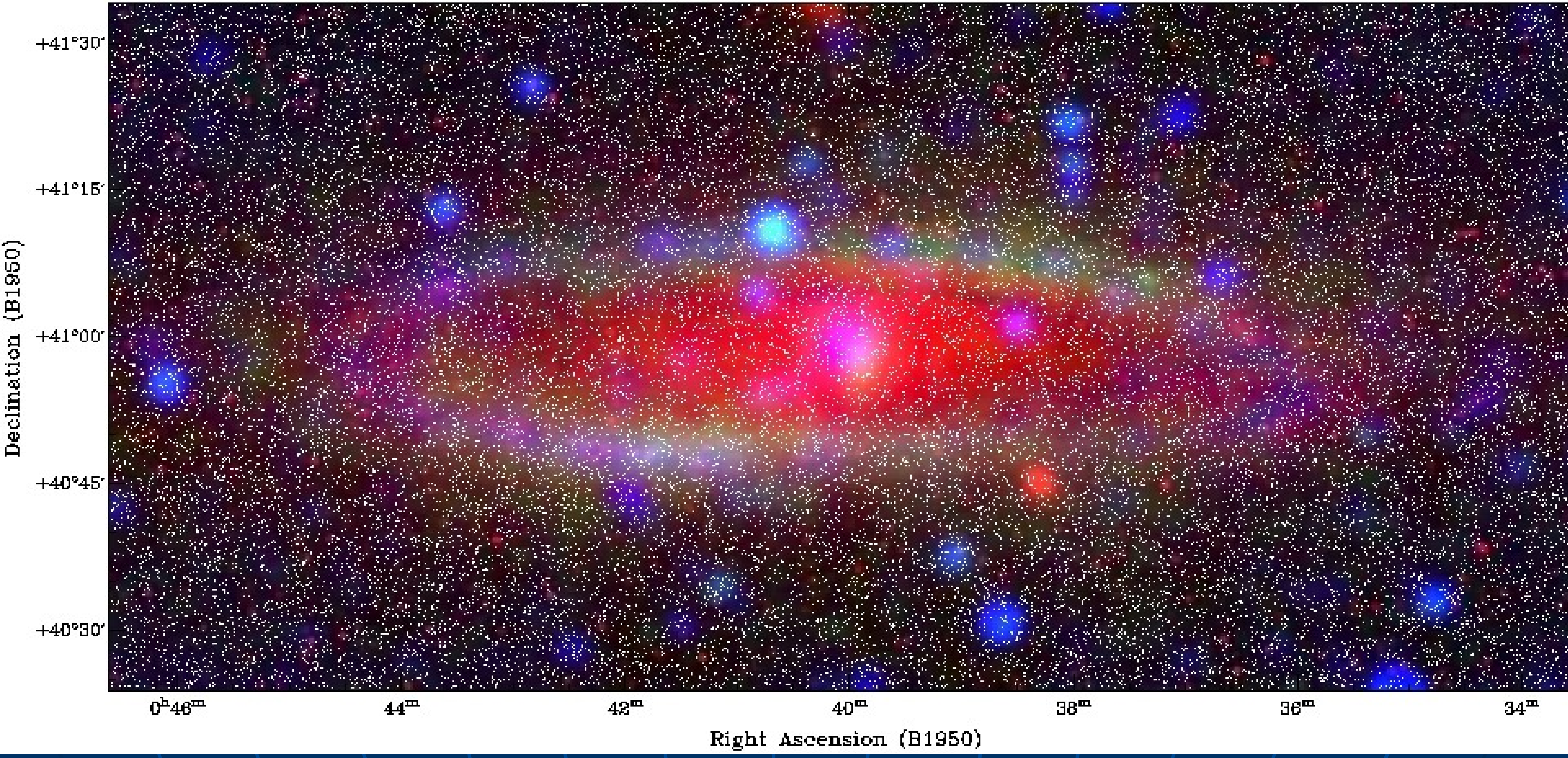
Inner core
Station

LOFAR and SKA:

Key Science Projects on Cosmic Magnetism

SKA RM survey

(simulation by Bryan Gaensler)

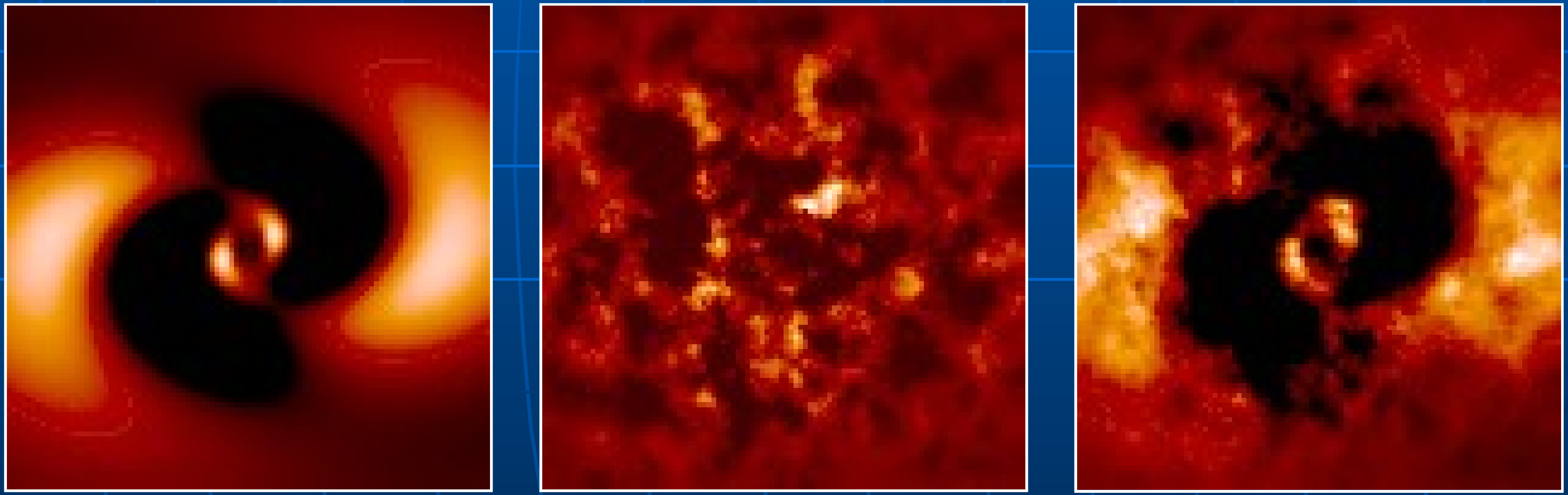


≈10000 polarized sources shining through M31

Faraday rotation through spiral galaxies

(SKADS science simulation)

Stepanov et al. 2008



Bisymmetric regular field | Turbulent field | Realistic field

Deep RM grids with the SKA

Stepanov et al. 2008

Recognition of field patterns:

- Can be applied to galaxies out to ≈ 100 Mpc distance (≈ 60000 galaxies)

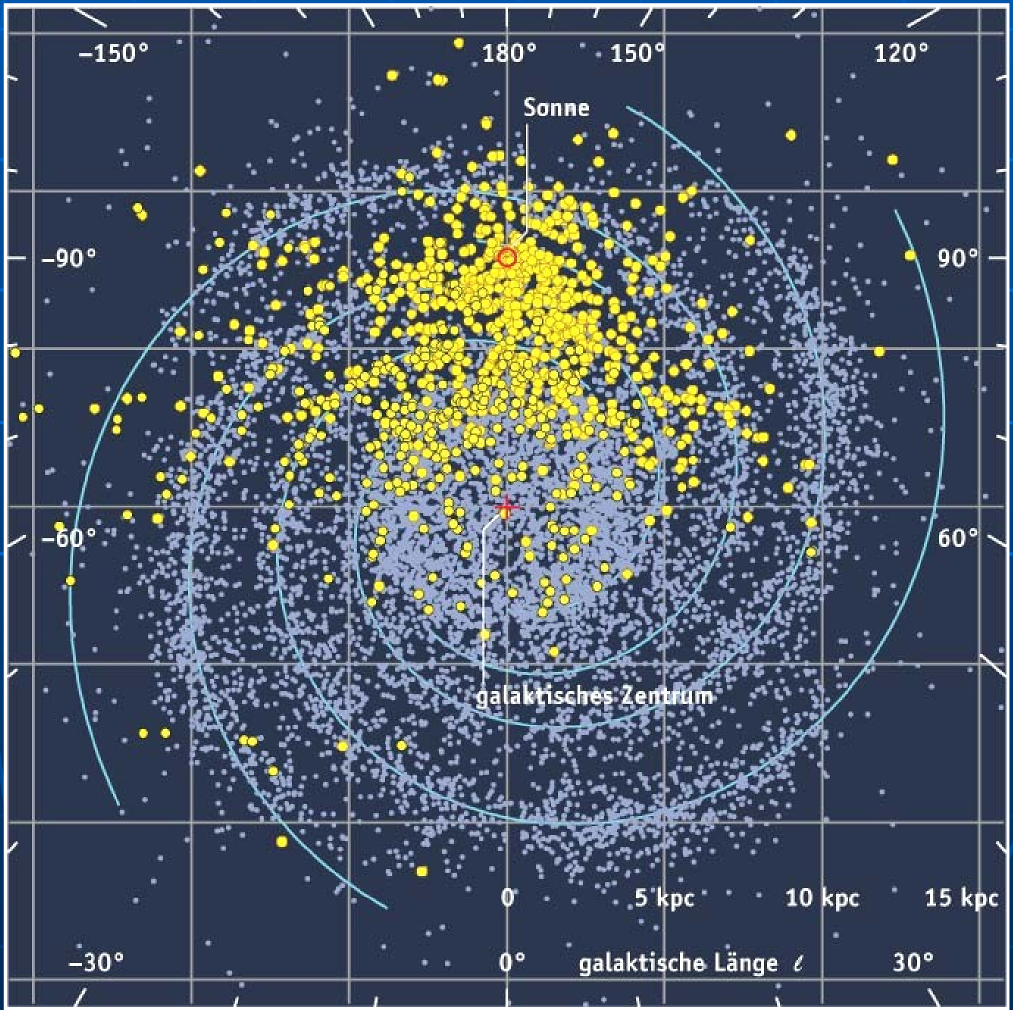
Reconstruction of field patterns:

- Can be applied to galaxies out to ≈ 10 Mpc distance (≈ 50 galaxies)

Future rotation measures of pulsars in the Milky Way

Cordes 2001

Known pulsars and pulsars to be detected with the SKA



Future observations

- Radio polarization:
  - Survey of unresolved spiral galaxies (Effelsberg, SKA)
  - Higher sensitivity and resolution (EVLA, SKA):
    detailed field structure, spectrum of dynamo modes,
    importance of anisotropic fields
  - Lower frequencies (LOFAR, SKA):
    extension of fields in outer disks and halos, intergalactic fields

- Dense RM grid of polarized background sources:
  - field patterns in distant galaxies (SKA)
  - evolution of galactic magnetic fields (SKA)

- Pulsar RMs:
  measure the detailed structure of the Milky Way field (SKA)

Need for realistic dynamo models

- Global dynamo models of galaxies including models of the 3D gas flow (spiral arms, bar and galactic outflow)
- Dynamical models: Back-reaction of the field onto turbulence and gas flow
- New *Atlas of dynamo modes* for typical galaxies needed
- Models including galaxy evolution needed

Any help is welcome