Observations of magnetic fields in galaxies
&
confrontation with dynamo models

Rainer Beck (MPIfR Bonn)

&

Tigran Arshakian, Elly Berkhuijsen, Rene Gießübel, Uli Klein,
Marita Krause, Fatemeh Tabatabaei, Richard Wielebinski (Bonn)
Ralf-Jürgen Dettmar, Marek Wezgowiec (Bochum)
Volker Heesen (Hertfordshire)
Andrew Fletcher, Anvar Shukurov (Newcastle)
Chris Chyzy, Robert Drzazga, Marian Soida, Marek Urbanik (Krakow)
Dmitry Sokoloff (Moscow)
Peter Frick, Rodion Stepanov (Perm)
Michael Dumke (ESO)

Fundamental questions on 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 ?
- Is intergalactic space magnetic ?
- Do magnetic monopoles exist ?

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

Mean-field (large-scale) dynamo models

(see talks in Session 7)

- Generation of large-scale coherent fields (modes)
- Disks (galaxies):
  Quadrupolar fields of symmetric *(even)* parity (*S0*) are excited most easily
- Spherical objects (halos):
  Dipolar fields of antisymmetric *(odd)* parity (*A0*) are excited most easily
- Mixed parity fields are possible (see talk by David Moss)
- High star-formation rate or a fast galactic wind can suppress the dynamo

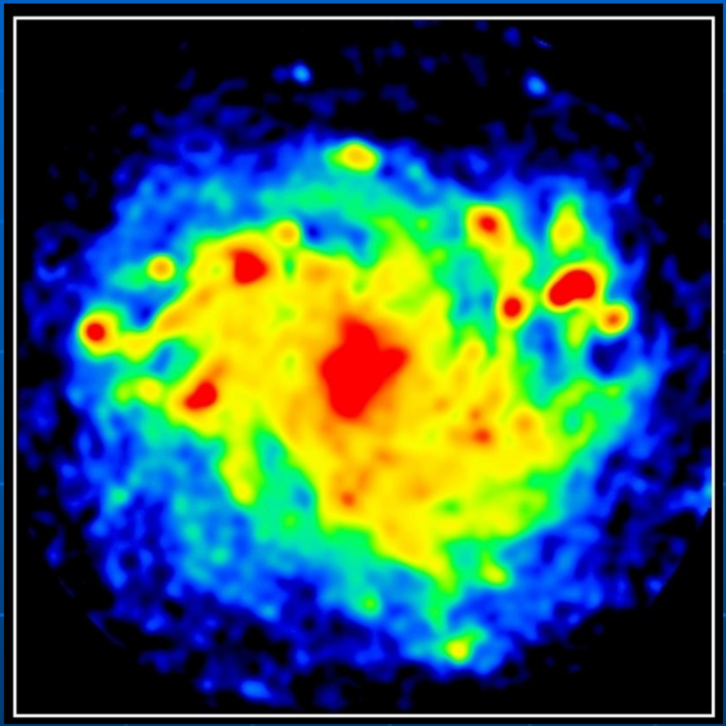
Problems with classical mean-field dynamos

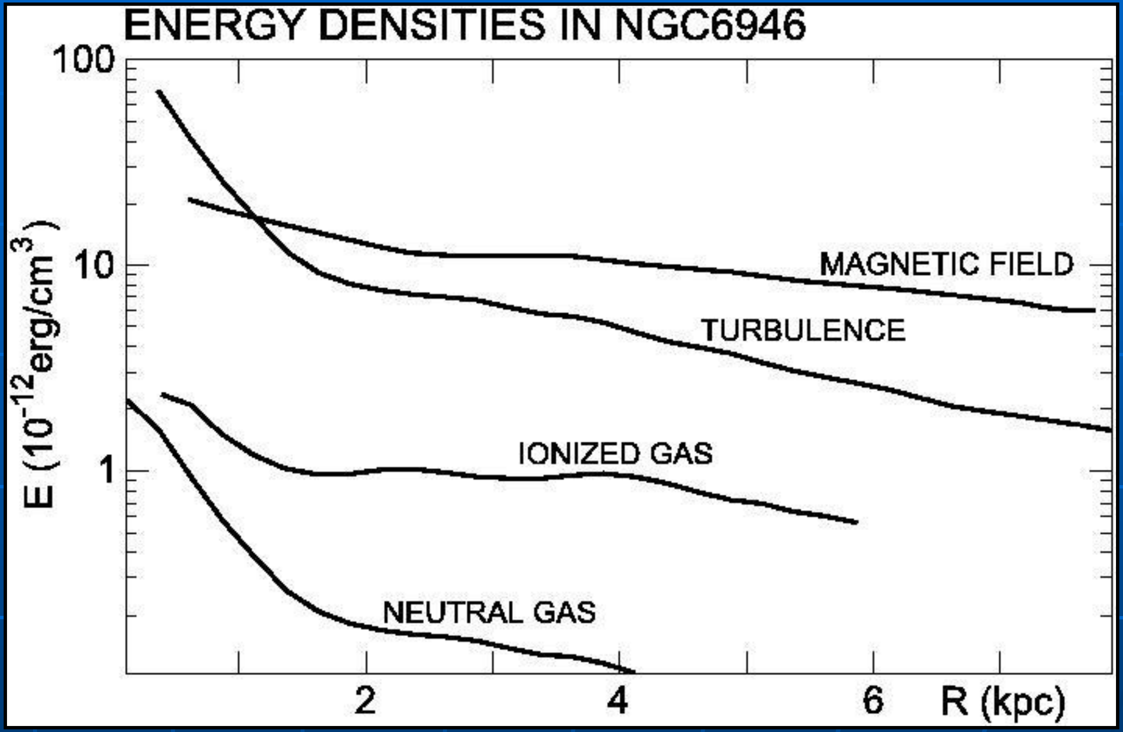
- Detailed physics not included
- Amplification of large-scale field is slow (several 10^8 years)
- No feedback: field amplification needs to be "quenched" when energy equipartition with turbulence is reached
- Helicity conservation in a closed system:
  small-scale helicity suppresses dynamo action
  $\longrightarrow$ Outflow needed
- Alpha effect assumed to be constant in time and space: evolution of fields in young galaxies neglected

Total synchrotron emission:
Tracer of total magnetic fields

Total synchrotron intensity: magnetic energy density

(assuming equipartition with cosmic rays)





Beck 2007

Magnetic energy density is similar to that of turbulent gas motions

Cold clouds:

V_{turb}=7 km/s, T=50 K, h=100 pc

Ionized gas:

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

Evidence no.1 for dynamo action:

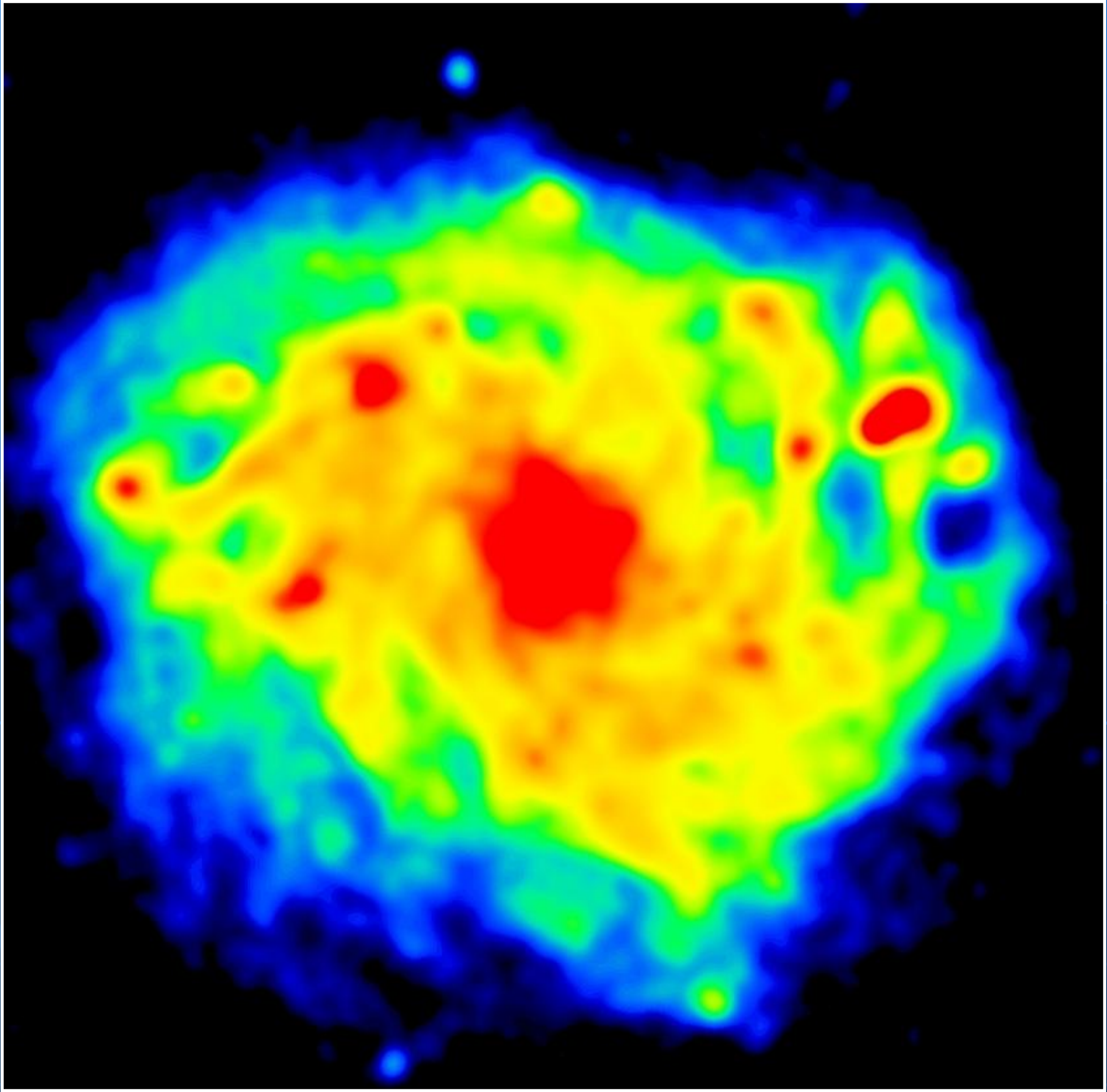
Magnetic energy density is similar to that of turbulent gas motions

Question no.1:

Does the total magnetic energy exceed the turbulent energy in the outer disk ?

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

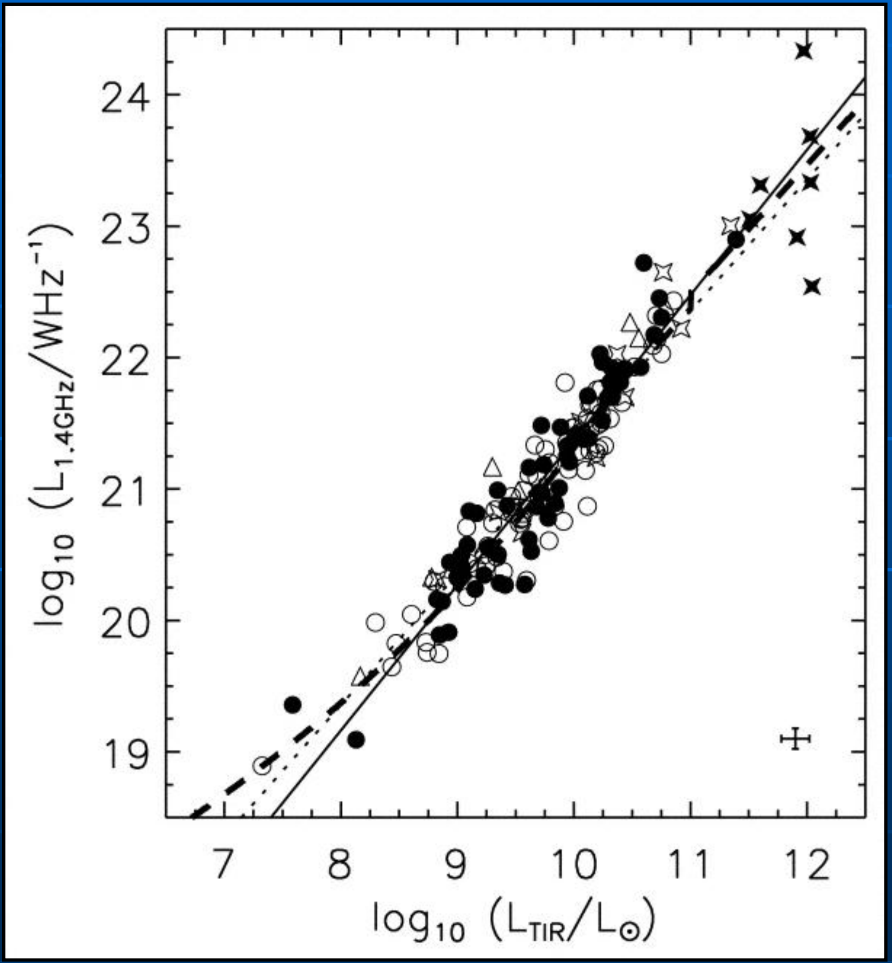
- Cold & warm gas: ≈ 4 kpc
- Synchrotron: ≈ 4 kpc
- Cosmic-ray electrons: ≤ 8 kpc
  (assuming equipartition, upper limit due to energy losses)
- Total magnetic field: ≥ 16 kpc

Question no.2:

What is the extent of magnetic fields in galaxies ?

The radio continuum - infrared luminosity correlation of star-forming galaxies

One of the tightest correlations in astronomy !



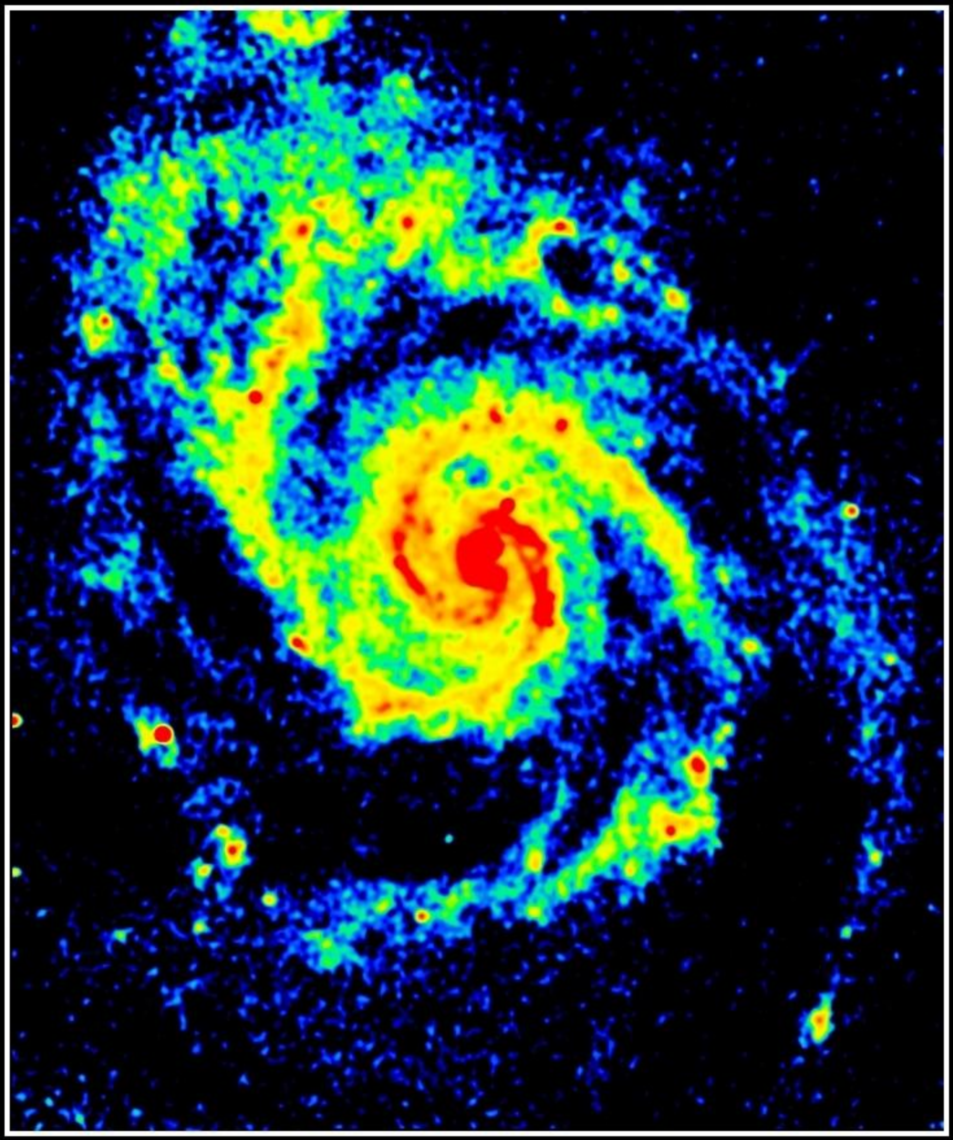
Bell 2003

Radio continuum intensity

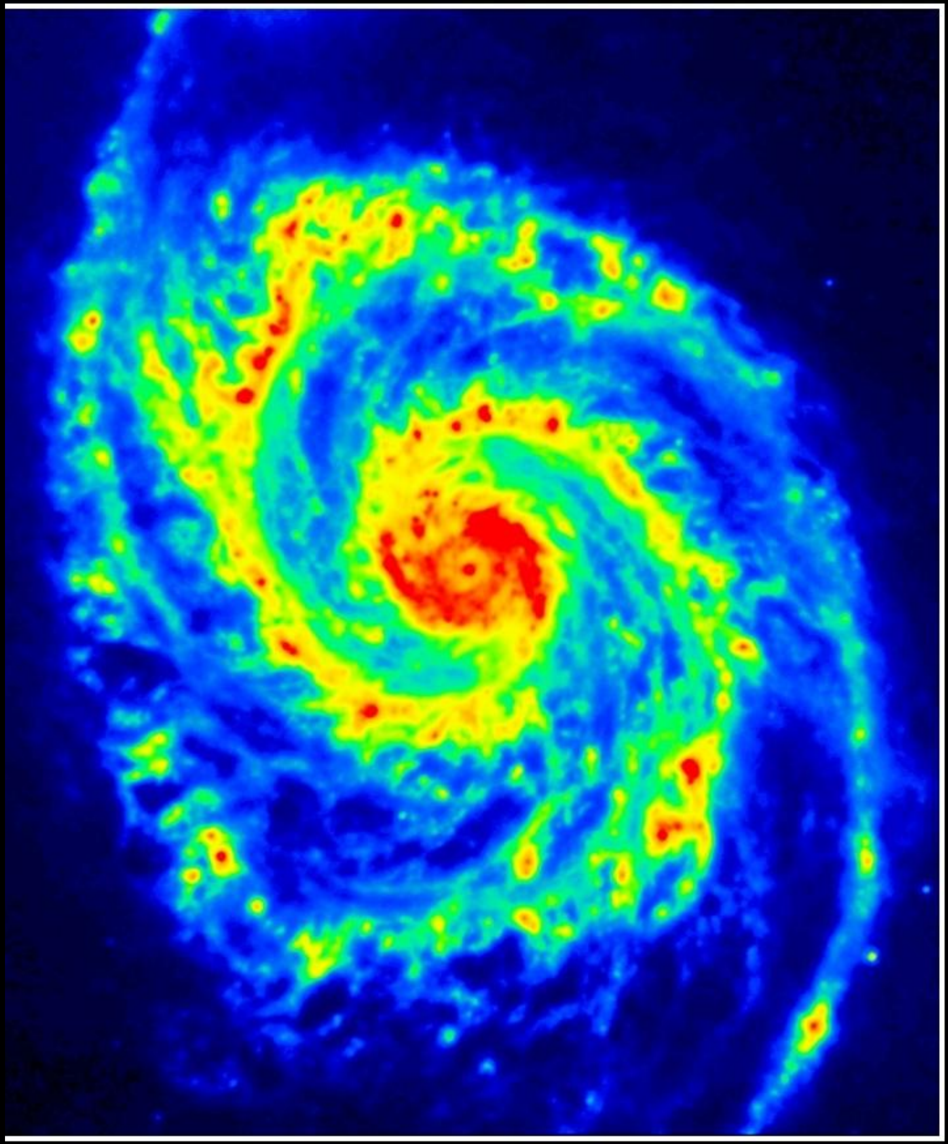
(VLA + Effelsberg 6cm)

Infrared intensity

(Spitzer 8μm)



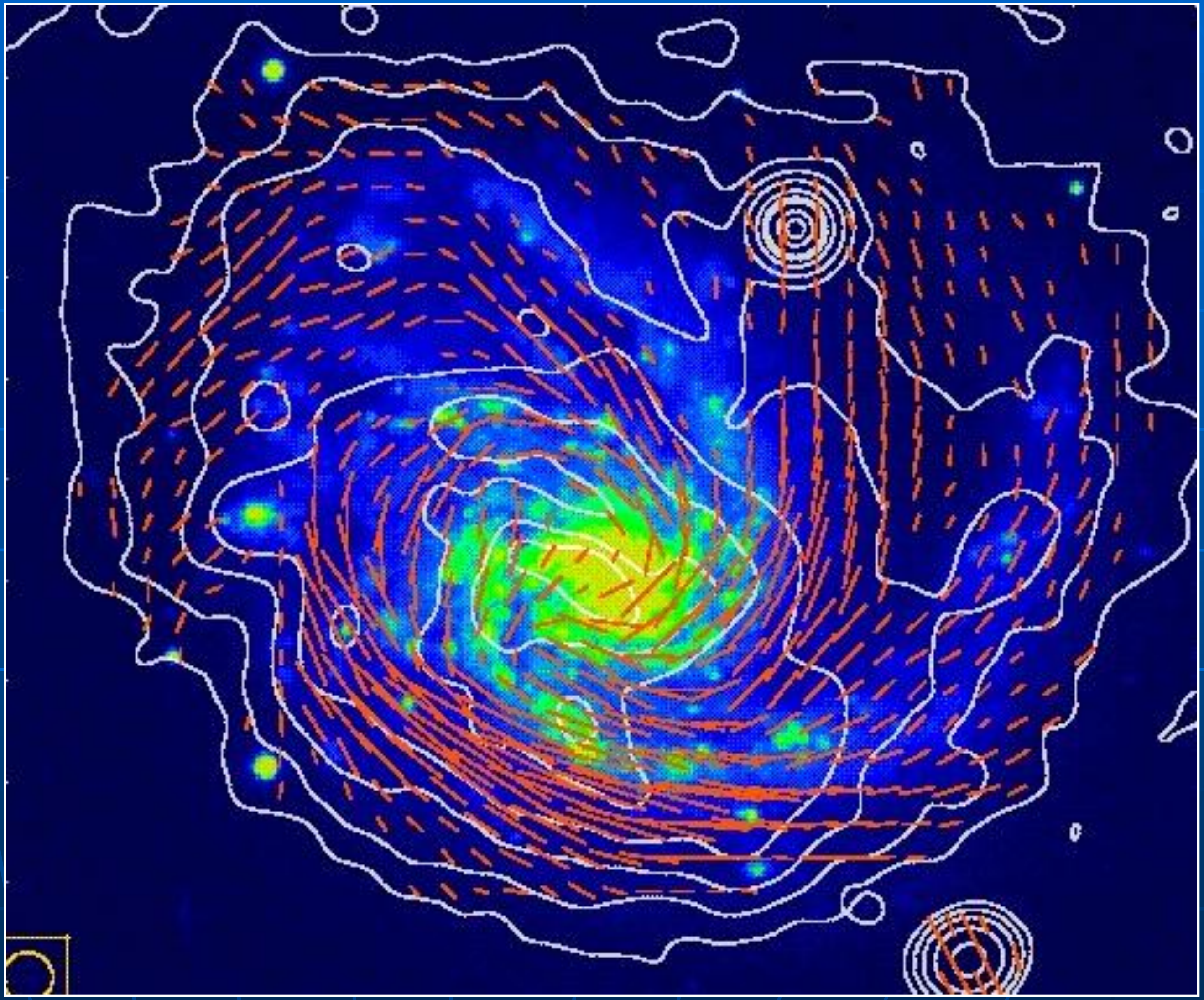
Fletcher et al. 2010



Schinnerer et al. 2006

NGC 4254

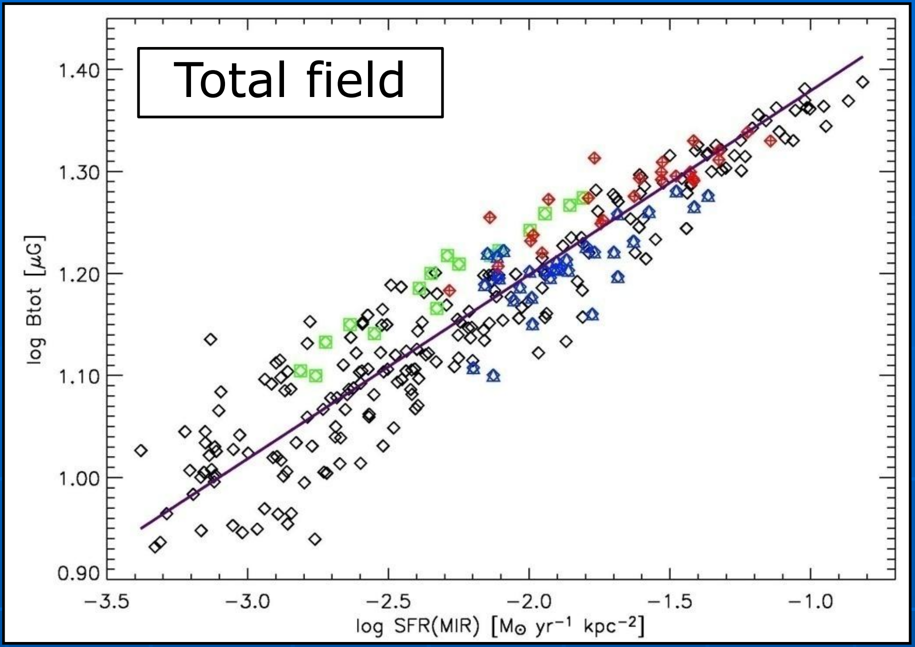
6cm VLA
Total intensity
+ B-vectors
(Chyzy et al. 2007)



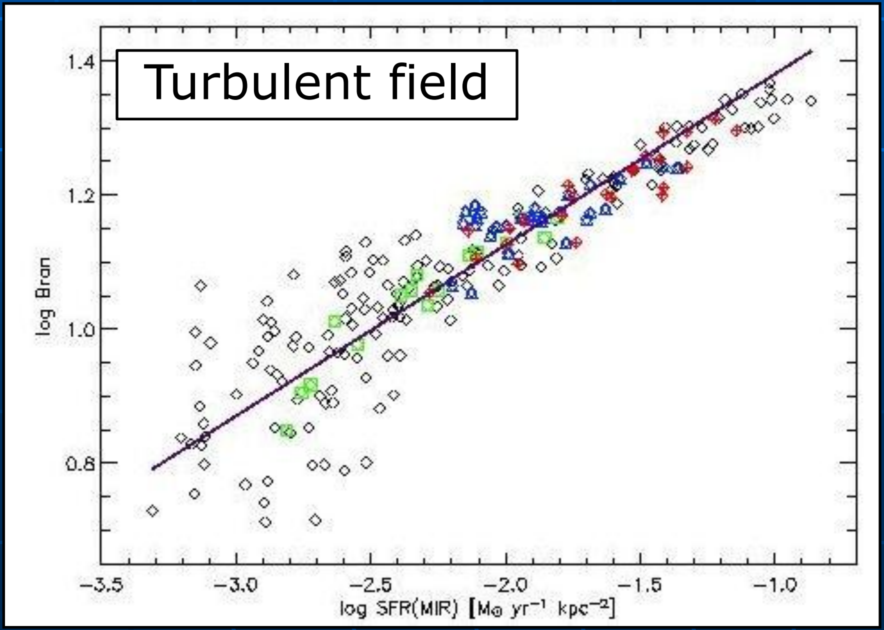
NGC 4254

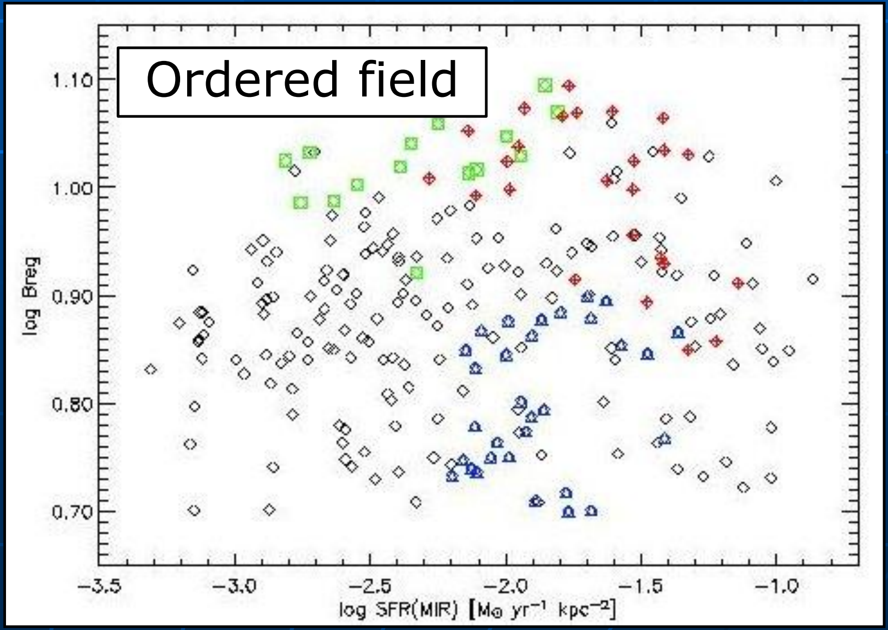
6cm VLA

(Chyzy 2008)



The radio-IR correlation is due to the **turbulent** field !





Radio-infrared correlation in star-forming galaxies

- The radio-IR correlation suggests a close interaction between star-formation activity and turbulent magnetic fields
- Strong magnetic field (calorimeter model):
  Cosmic-ray density and magnetic field strength increase with star-formation rate
- Weak magnetic field (equipartition model):
  Total field strength increases with gas density
- Modeling: Very complicated, many parameters (Lacki et al. 2010)

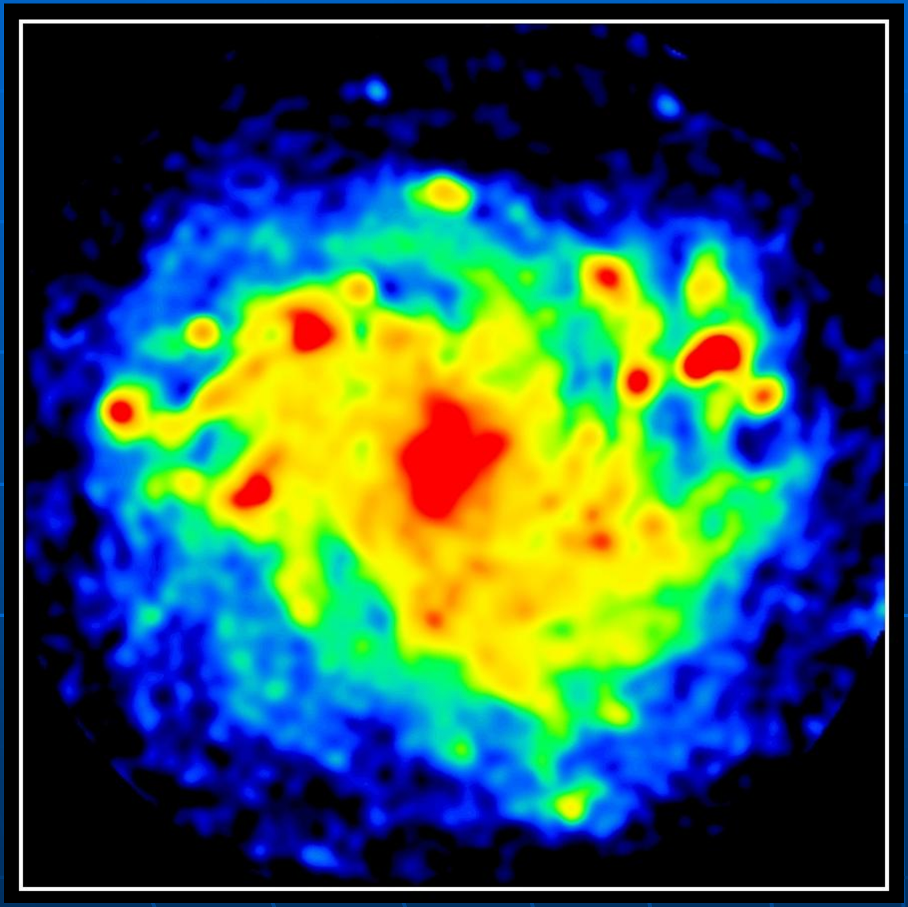
Question no.3:

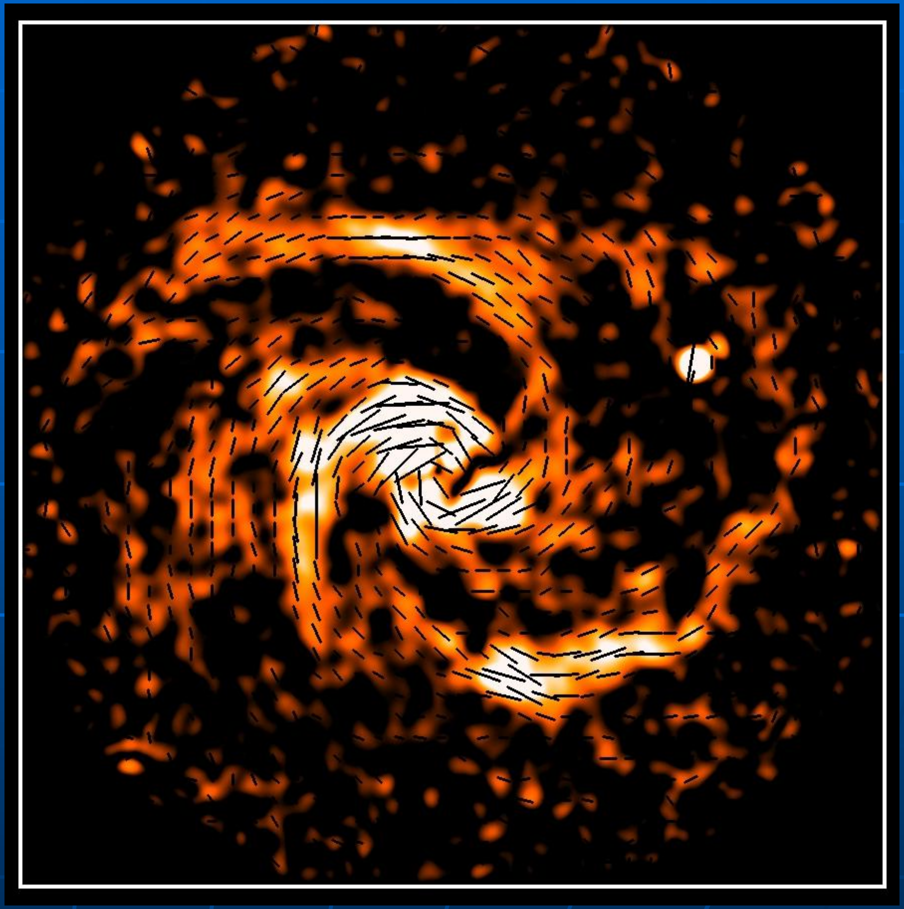
How does the self-regulation of the radio-IR correlation work ?

(via the magnetic field ?)

Synchrotron polarization

Beck & Hoernes 1996

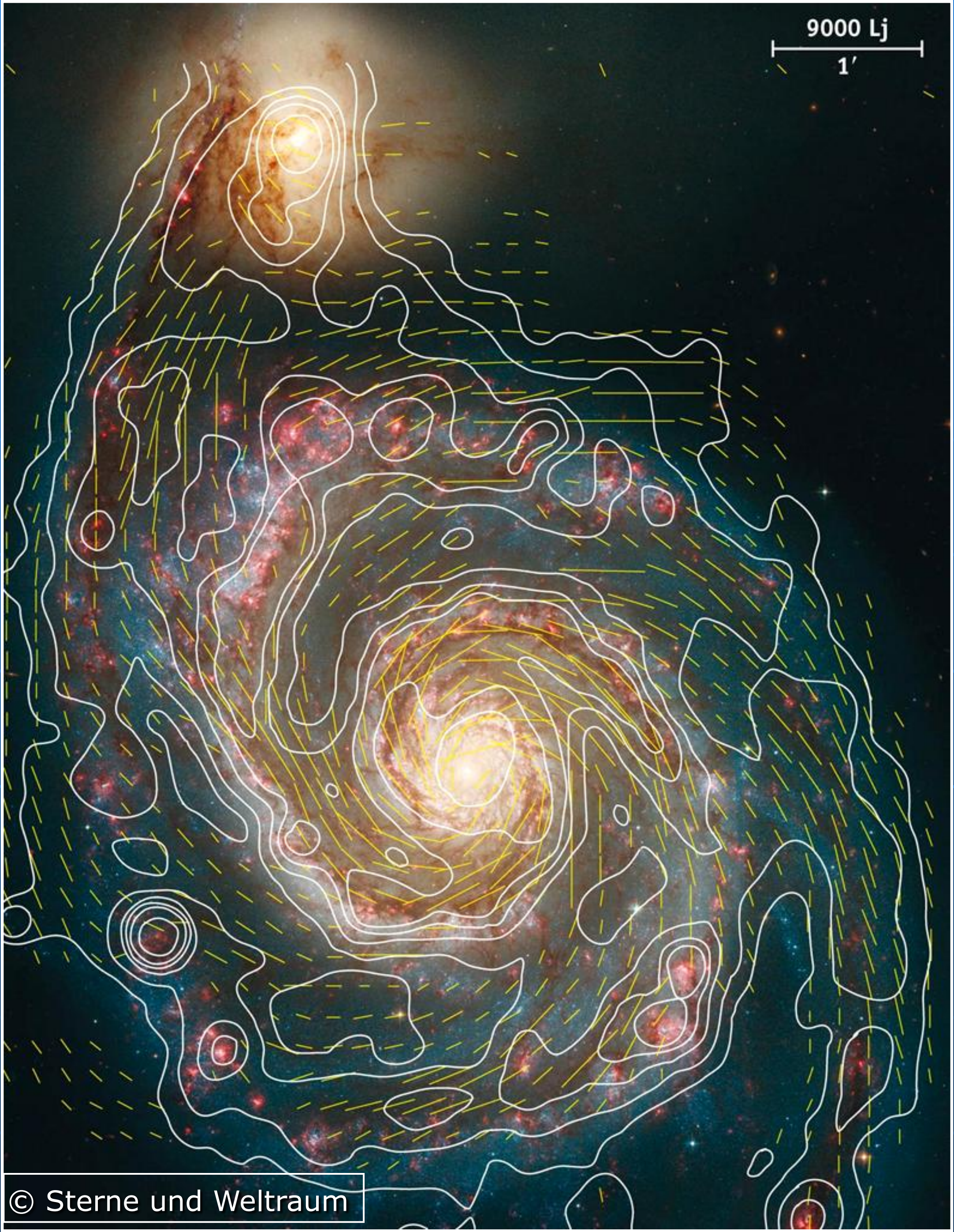




NGC 6946 Total and polarized intensity at 6cm

M 51

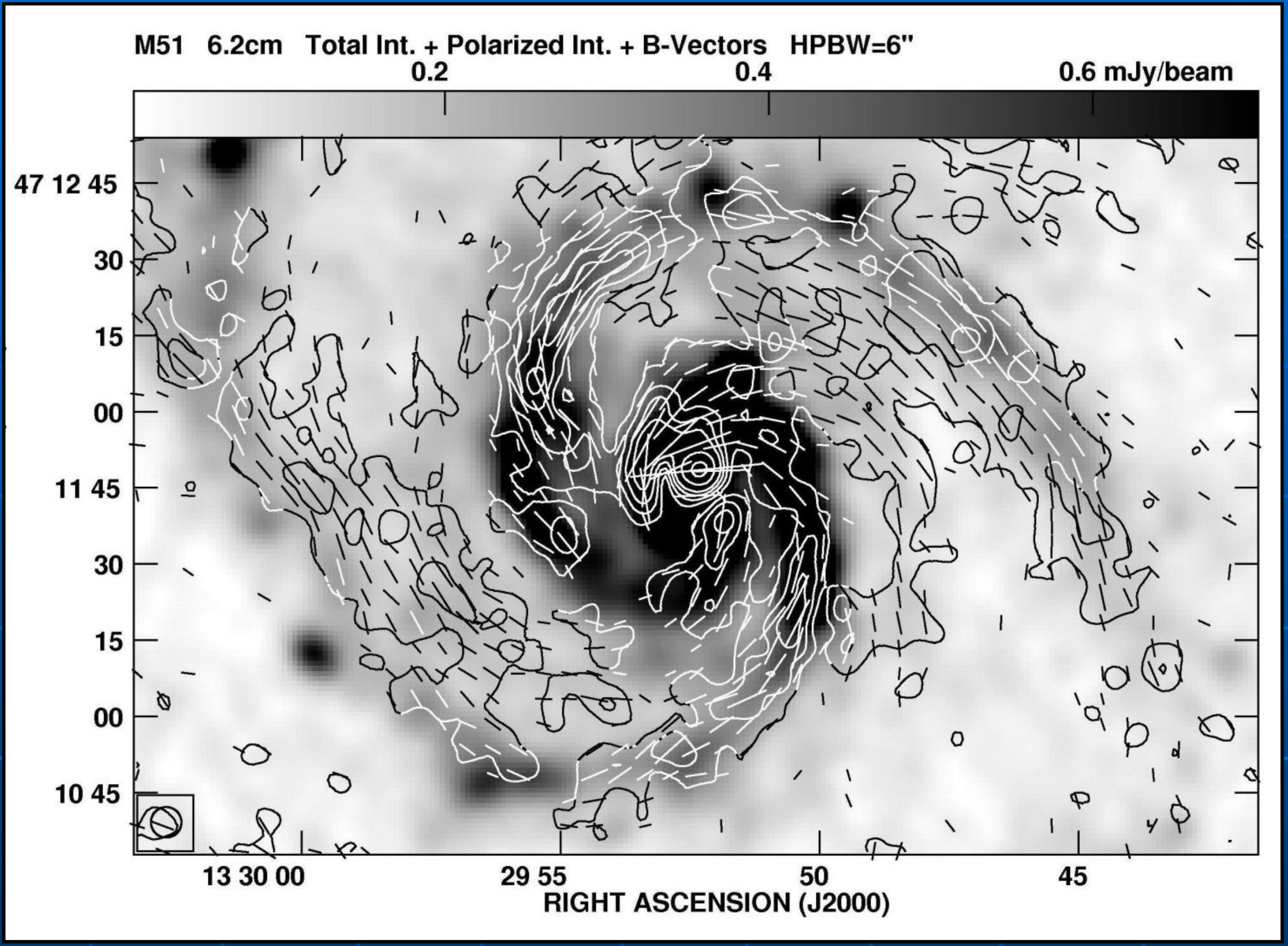
6cm VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2010)



Spiral fields
more or less
parallel to the
optical
spiral arms

M 51

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

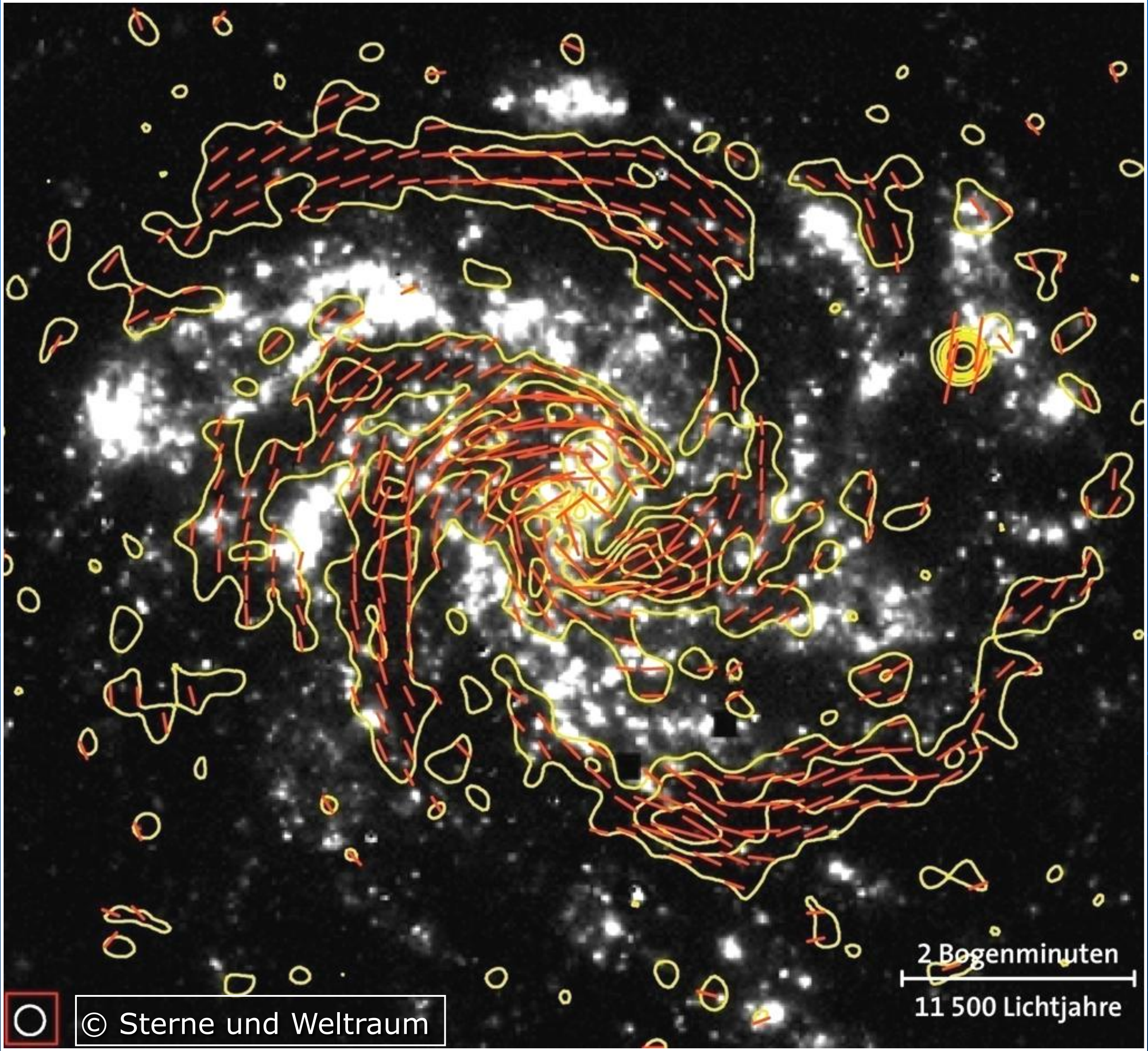


Spiral fields perfectly parallel to the inner spiral arms:

density-wave compression or shear

NGC 6946

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

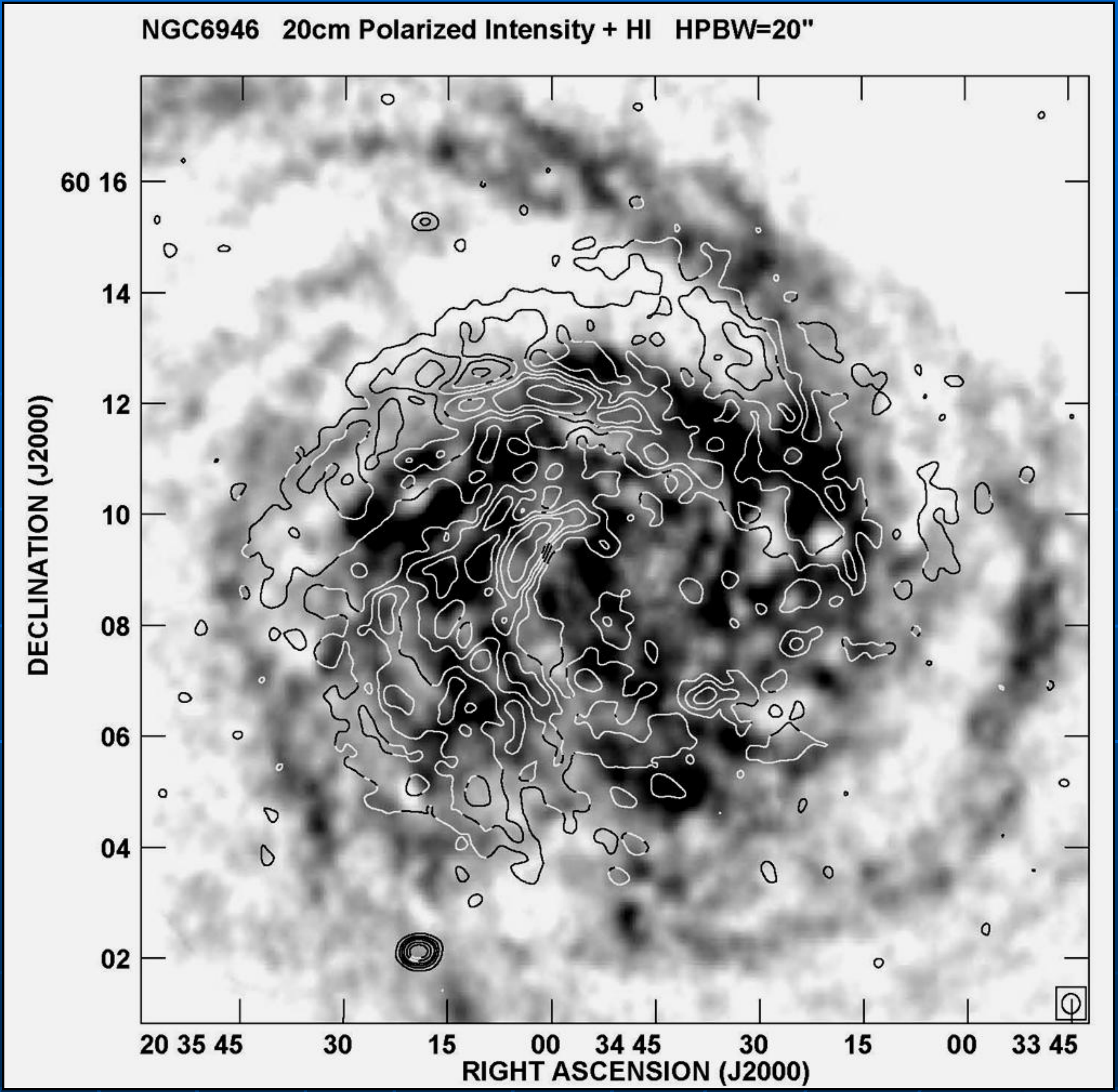


"Magnetic arms":

Ordered fields concentrated in interarm regions

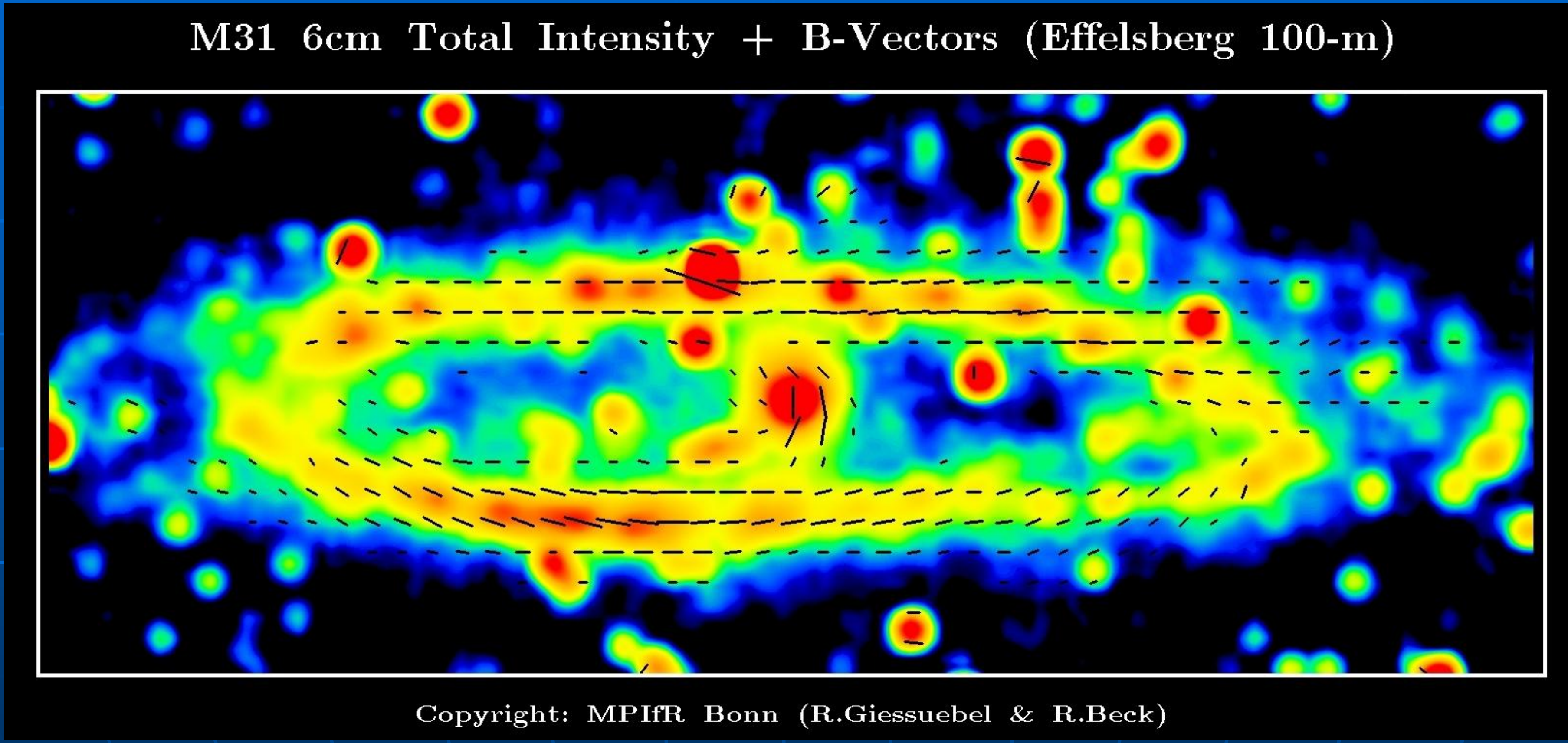
NGC6946

20cm VLA
Polarized intensity
+ B-vectors
(Beck 2007)



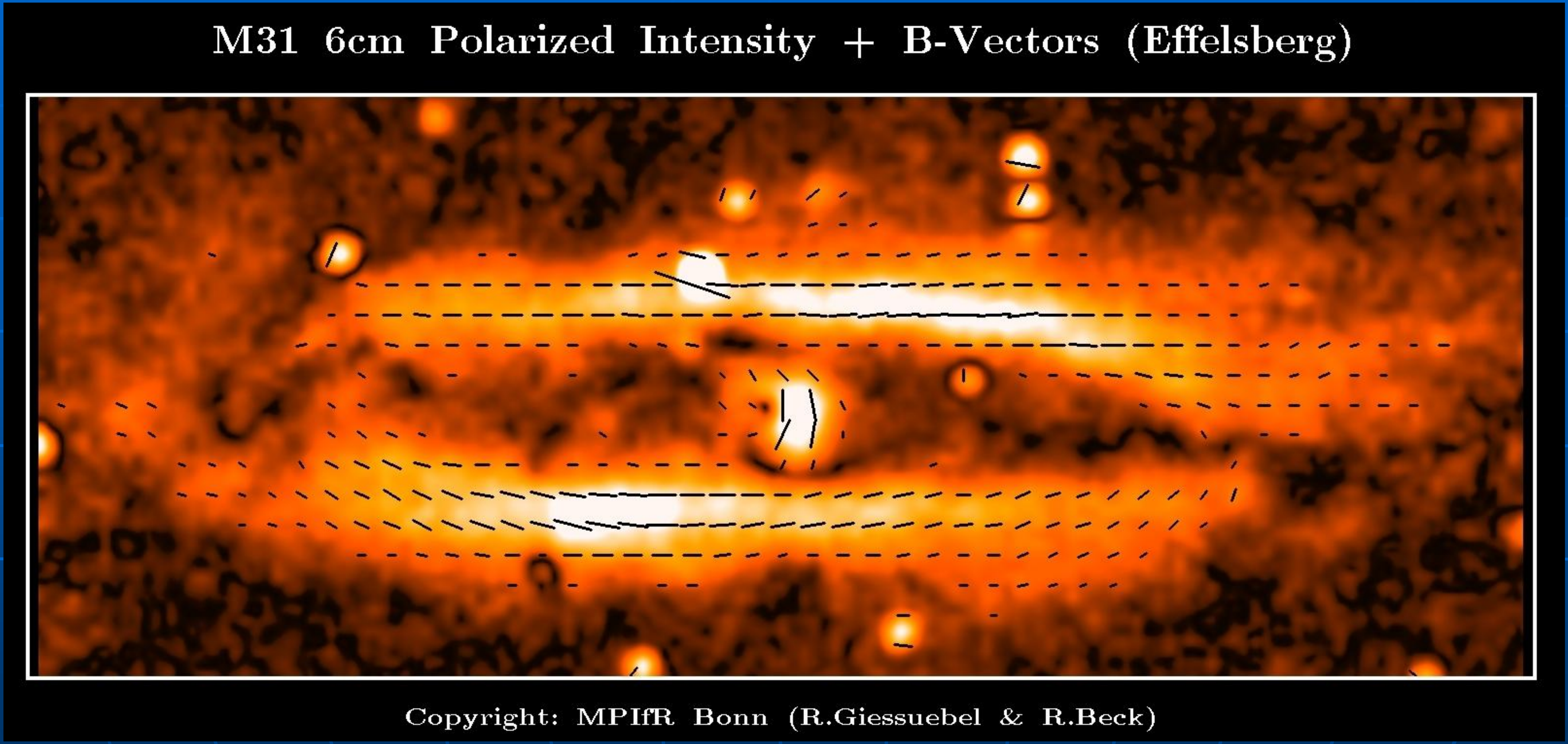
More magnetic arms in the outer galaxy, along HI arms

New deep survey of M31



(see poster by René Gießübel)

New deep survey of M31



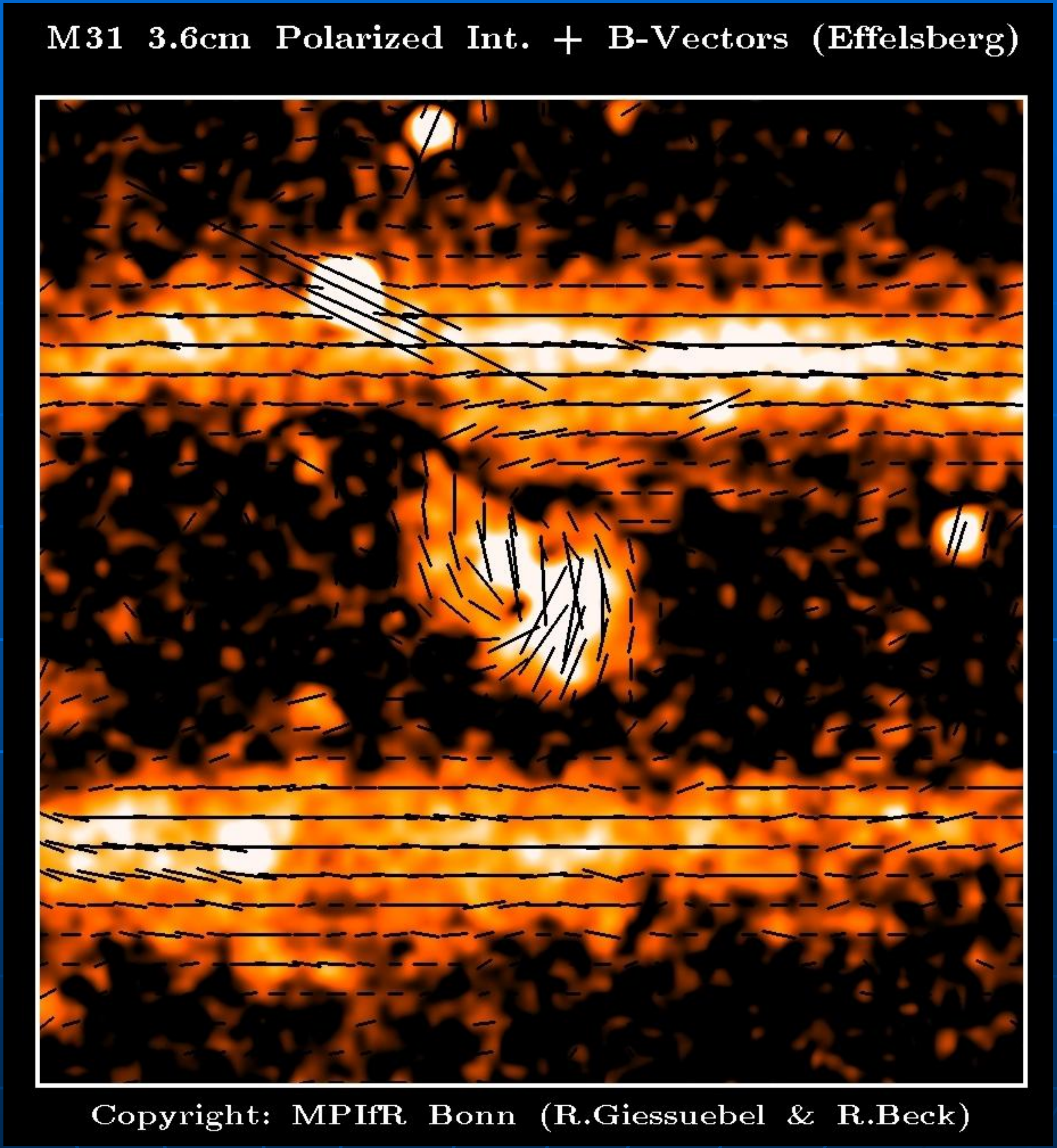
Ordered fields extend out to > 25 kpc

M 31

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

High resolution (300pc):

Highly ordered field in the "ring", spiral field in the central region

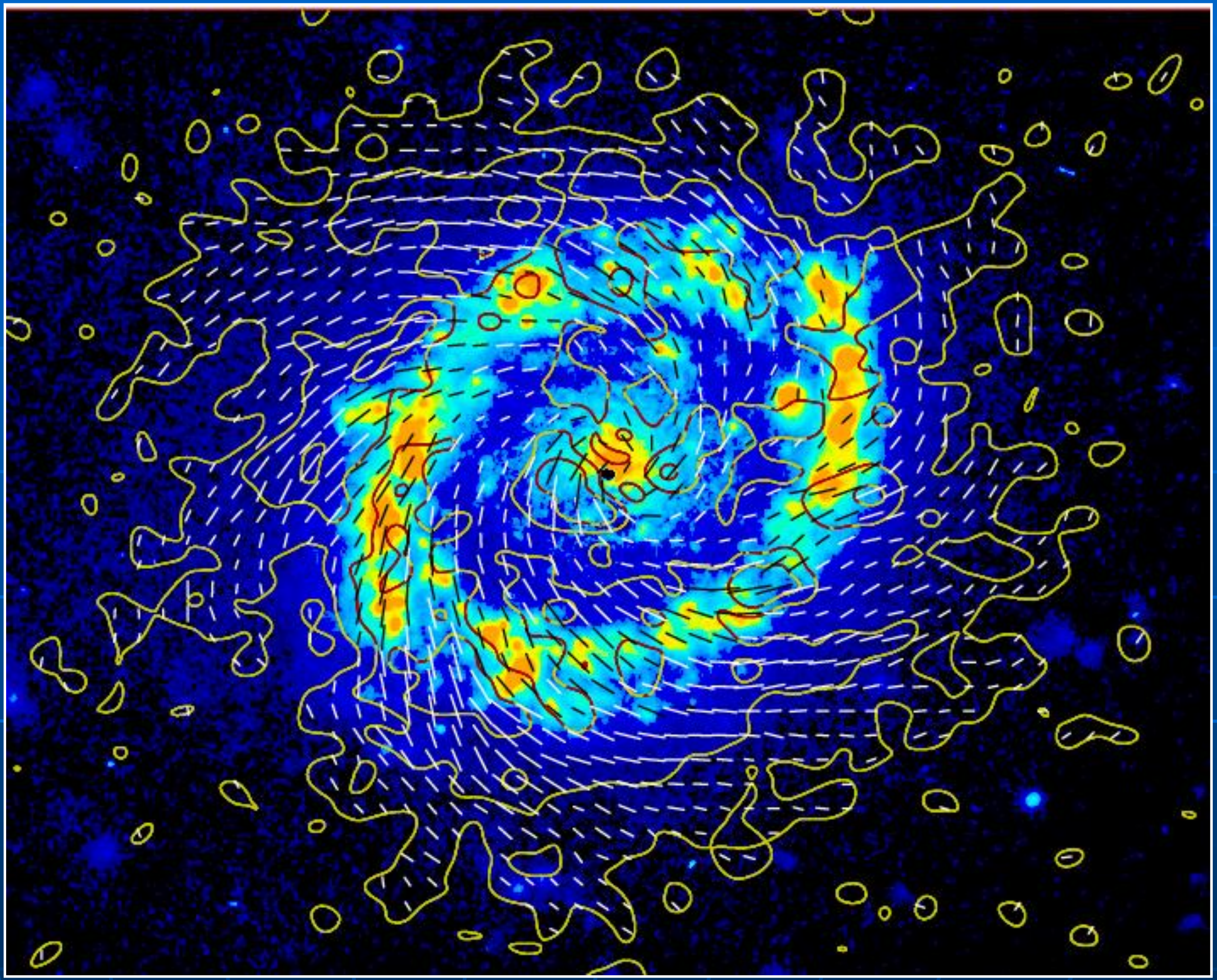


Question no.4:

How is the spiral field aligned with the gaseous spiral arms if density waves are weak ?

NGC 4736

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



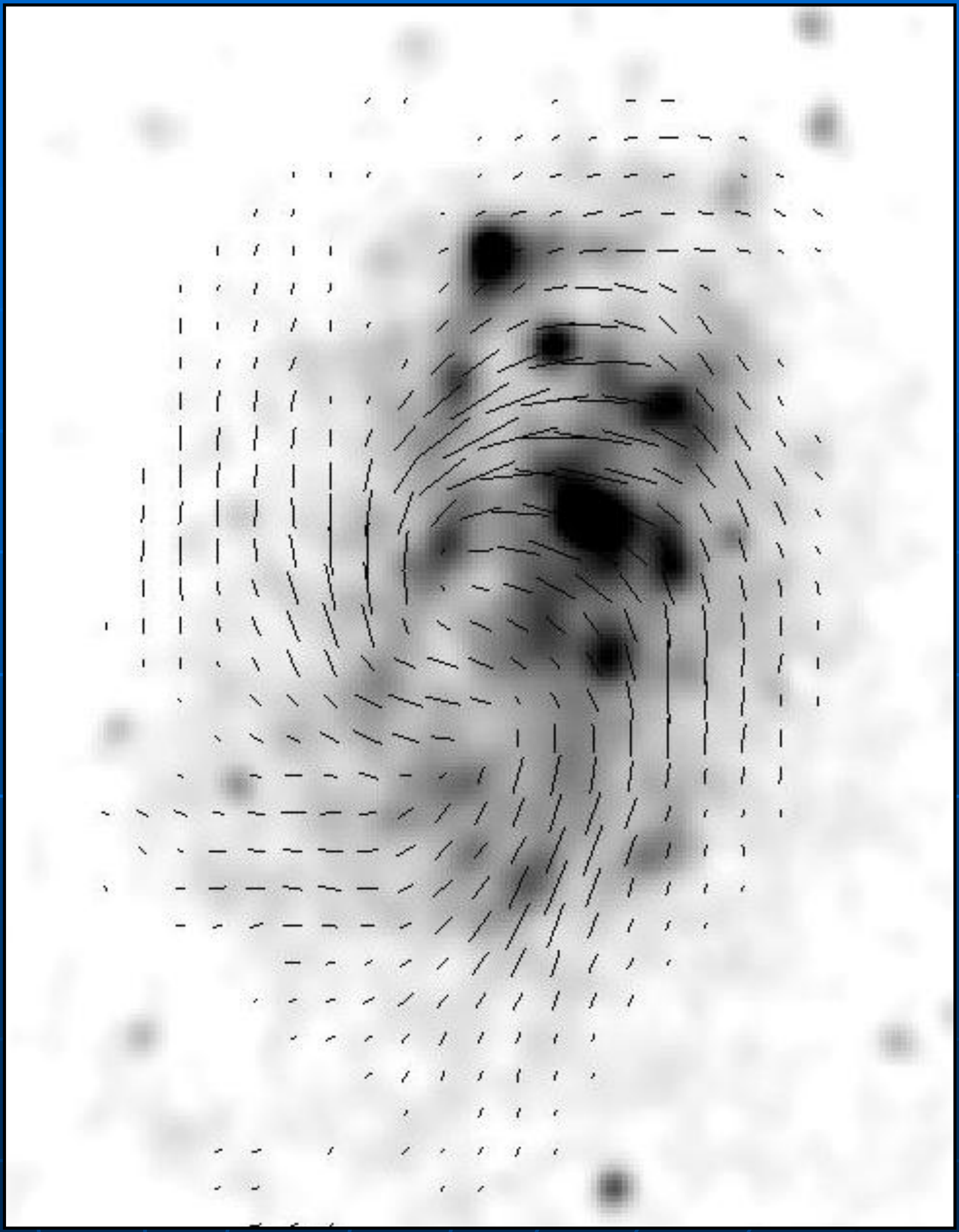
Spiral fields in a ring galaxy -

No alignment with the gas pattern !

NGC 4414

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

Flocculent galaxies:
spiral field exists
even without
optical spiral arms



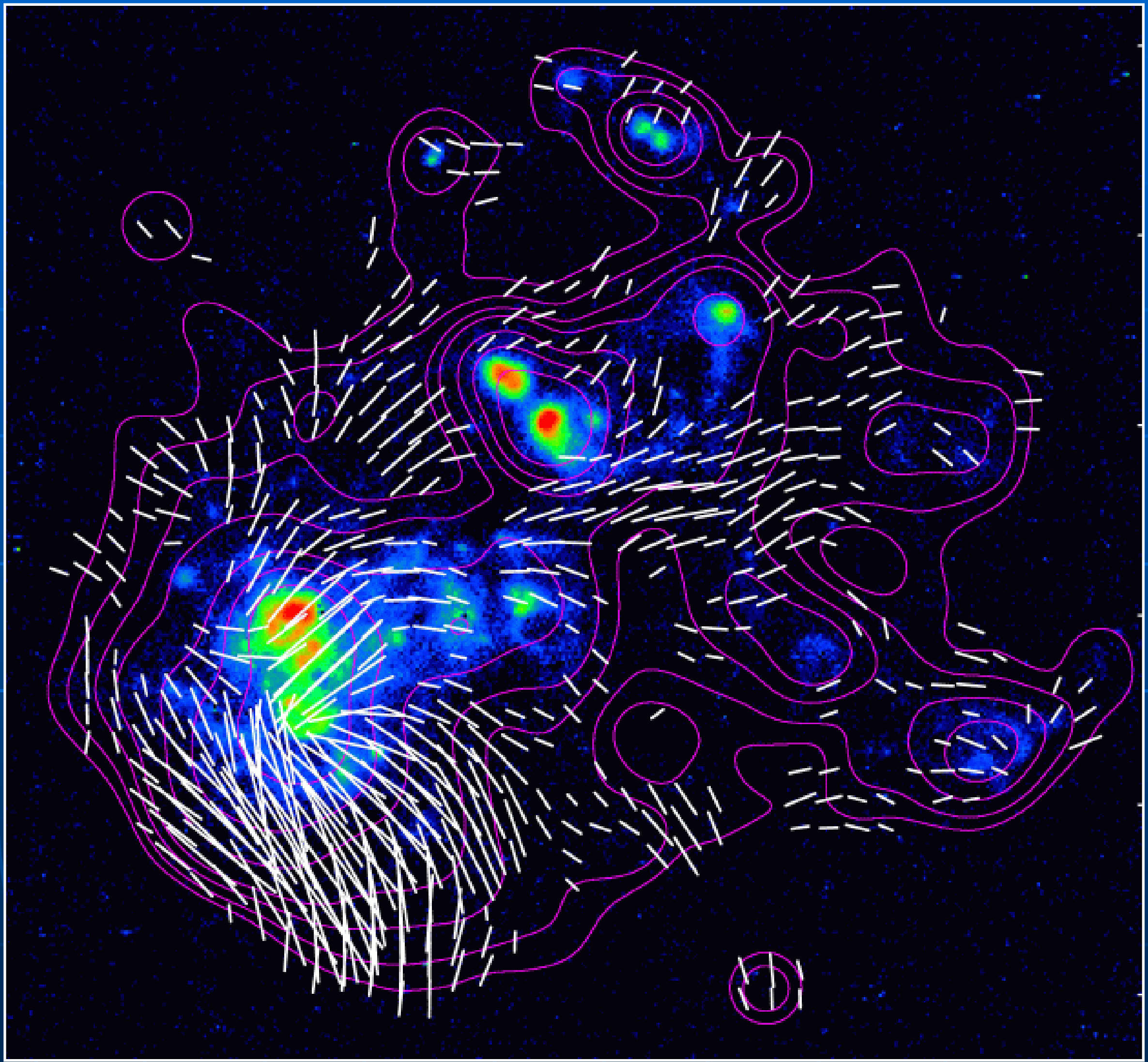
Evidence no.2 for dynamo action:

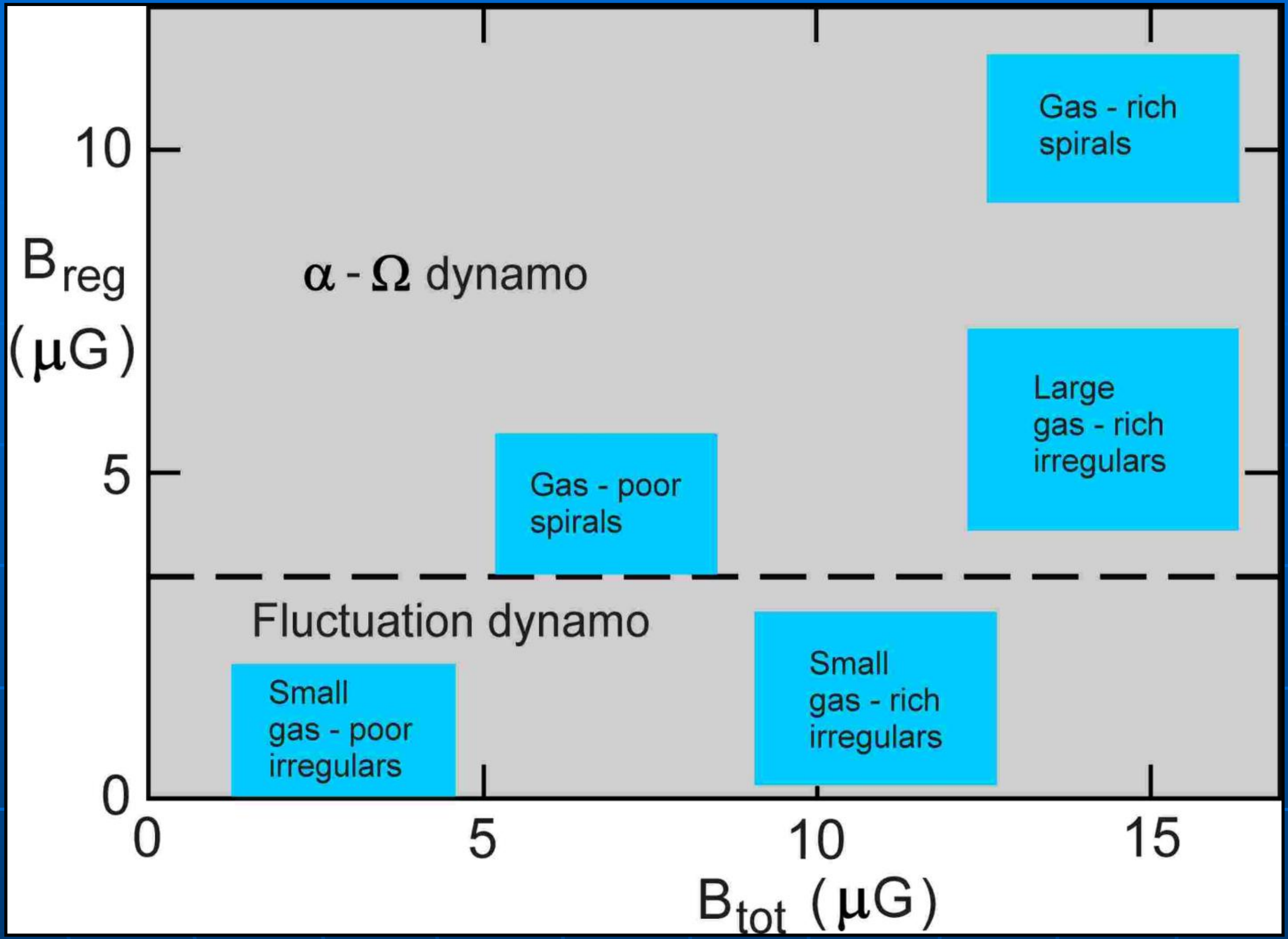
The magnetic field forms
spiral patterns in all galaxies
with fast rotation
and large gas mass

IC 10

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

No large-scale
ordered field





Question no. 5:

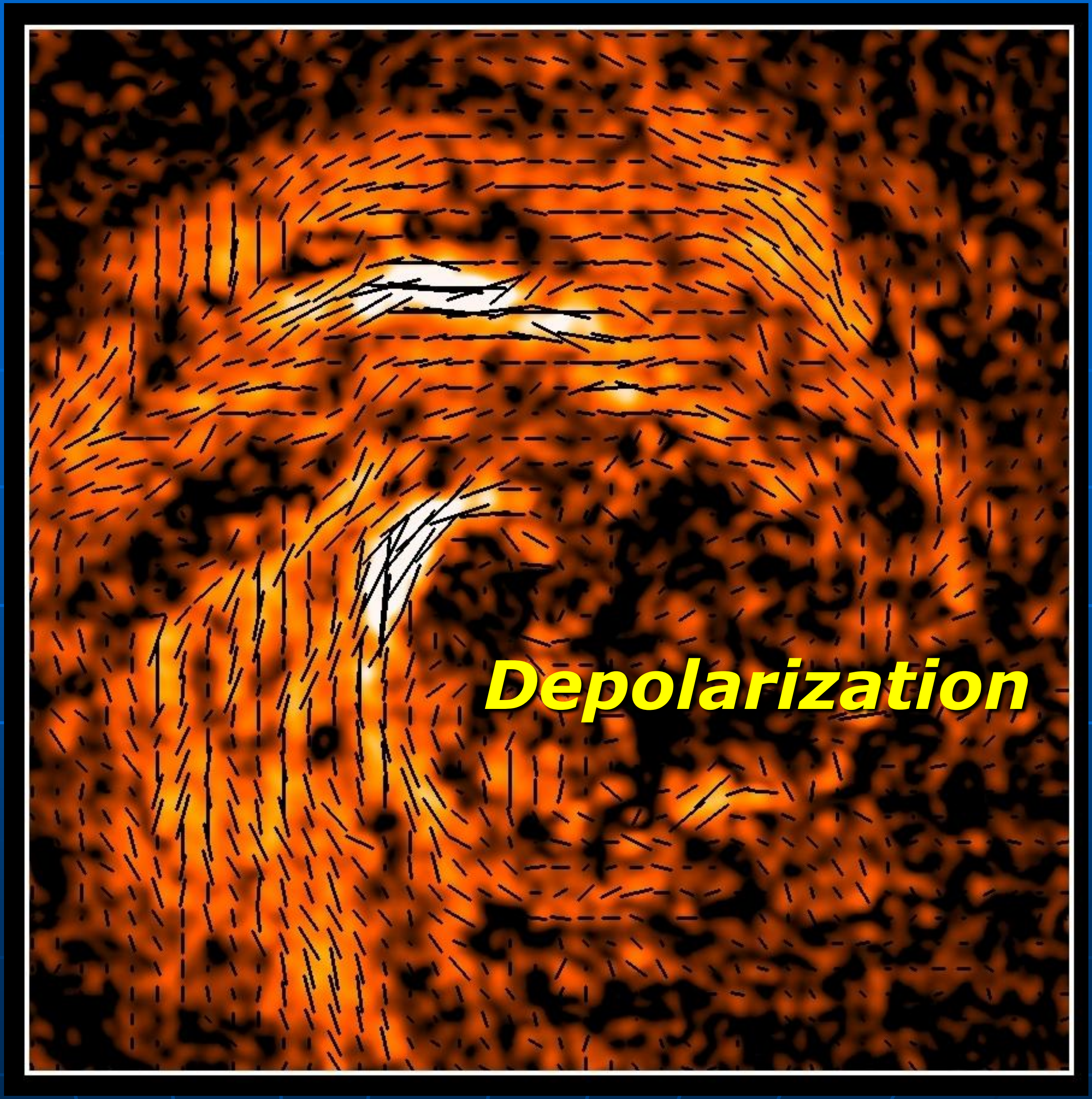
What determines threshold for the mean-field dynamo ?

Asymmetry in Faraday depolarization

(see talk by George Heald)

NGC6946

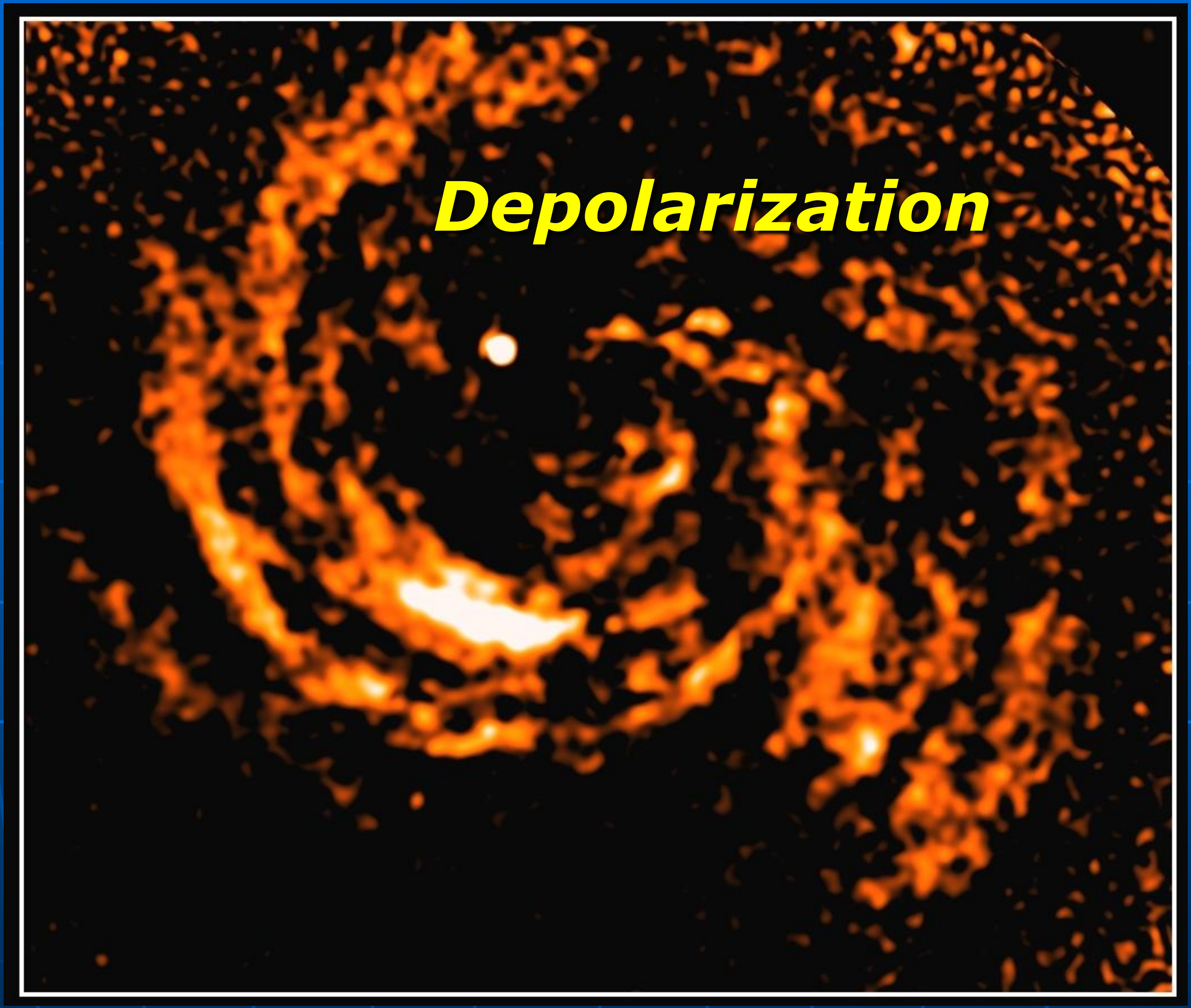
20cm VLA
Polarized intensity
+ B-vectors
(Beck 2007)



Stronger Faraday depolarization around the southwestern major axis

IC 342

20cm VLA Polarized intensity (Beck 2006)

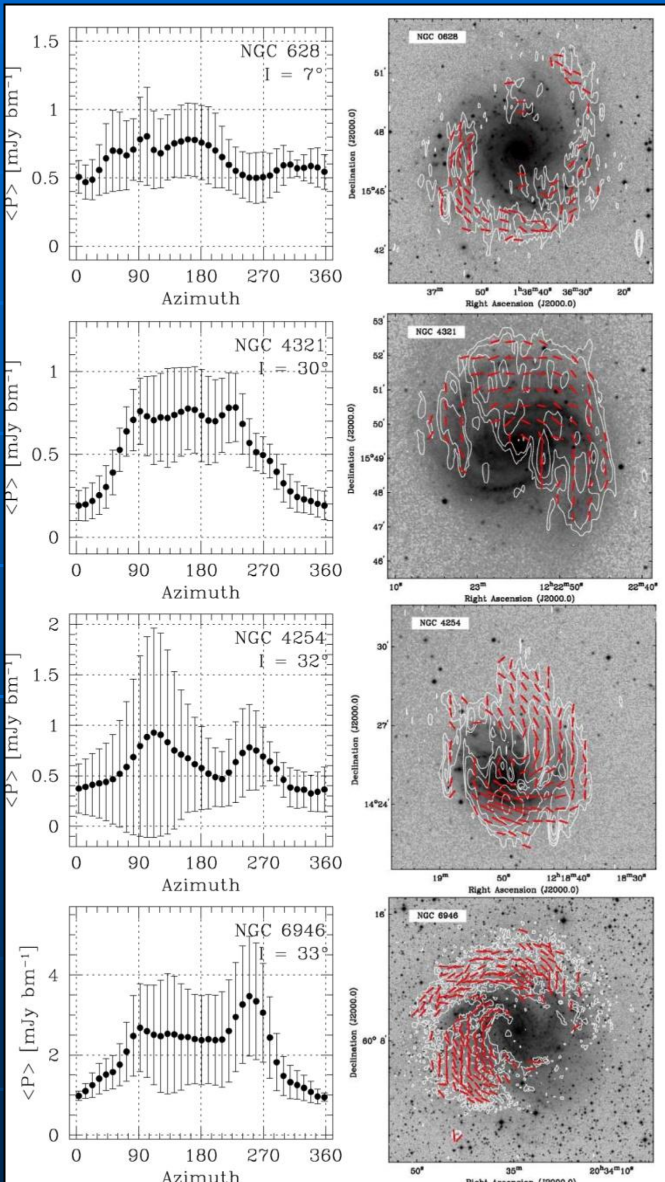


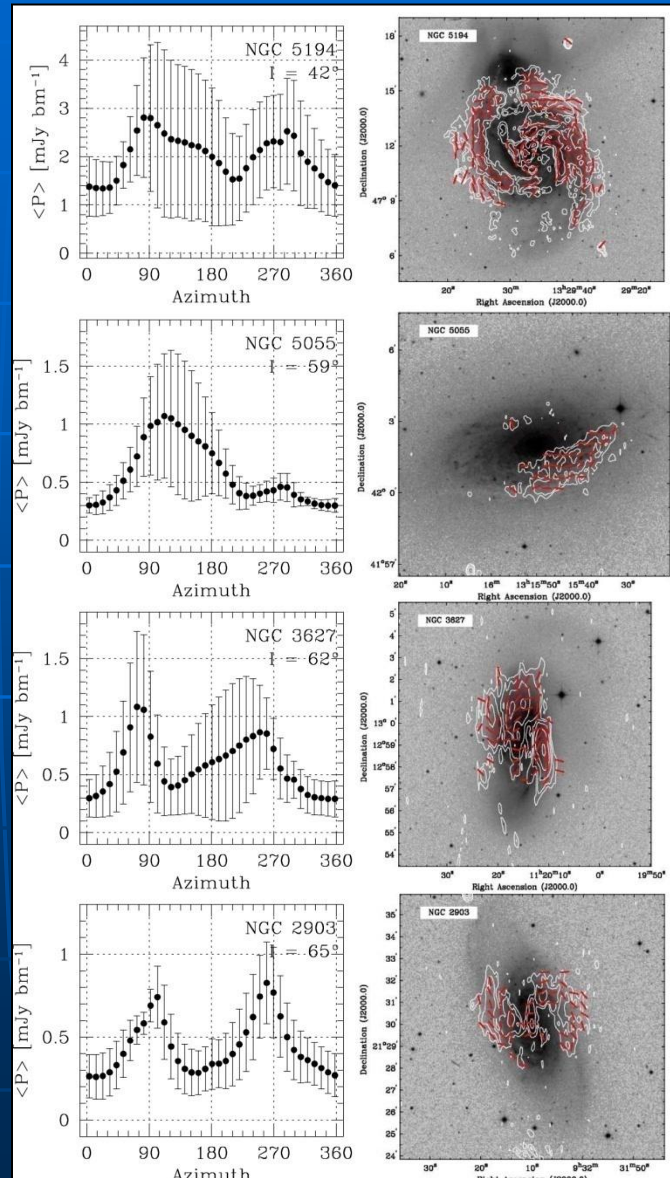
Stronger Faraday depolarization around the northern major axis

Polarization asymmetry

(see talk by George Heald)

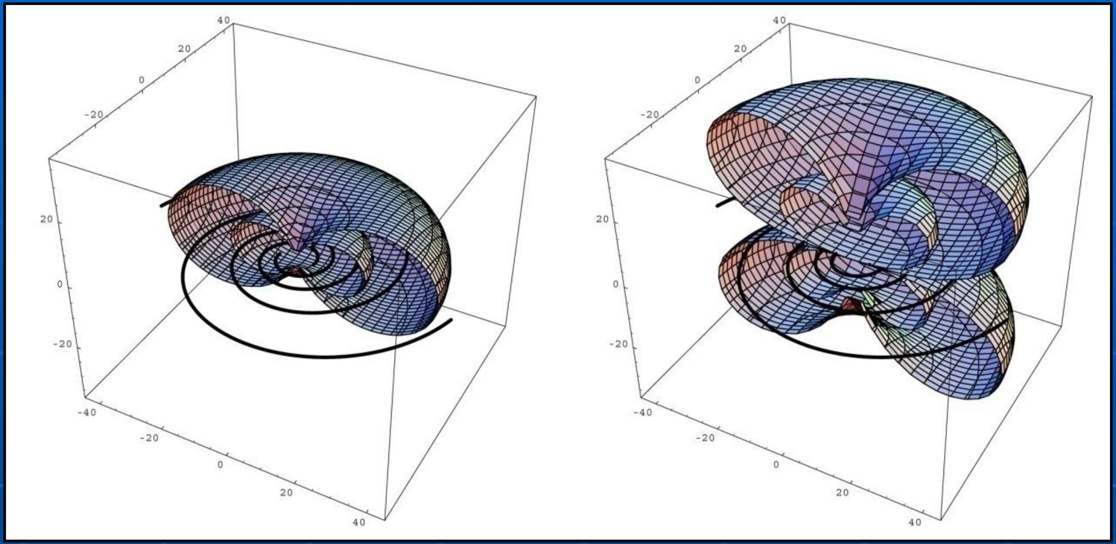
Braun et al. 2010



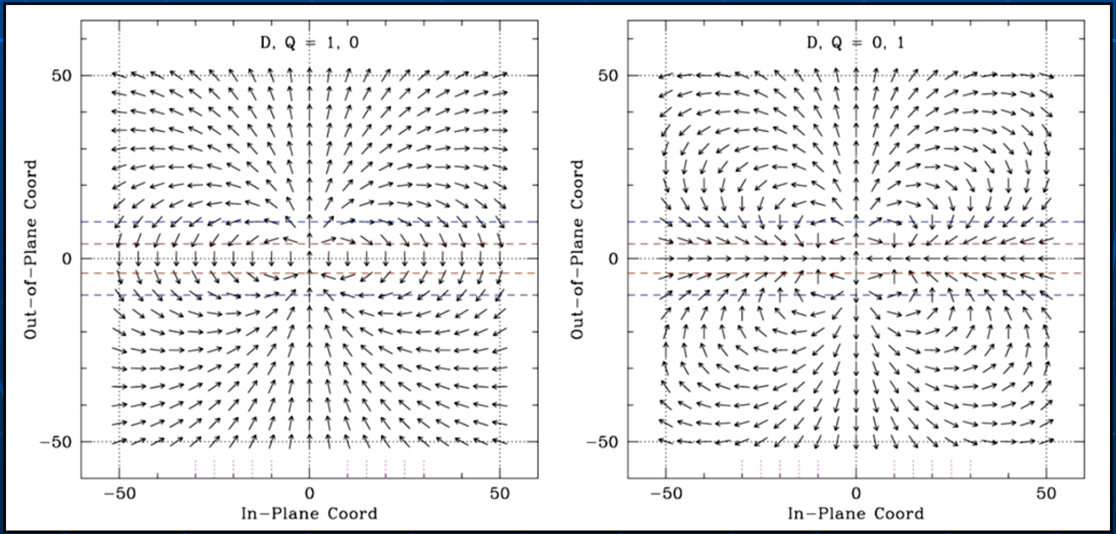


Dipolar and quadrupolar fields

Braun et al. 2010



Disk + halo fields



Halo field

Evidence no.3 for dynamo action:

Magnetic fields of mildly inclined galaxies are quadrupolar

Question no.6:

In which frequency range is the polarization asymmetry observable?

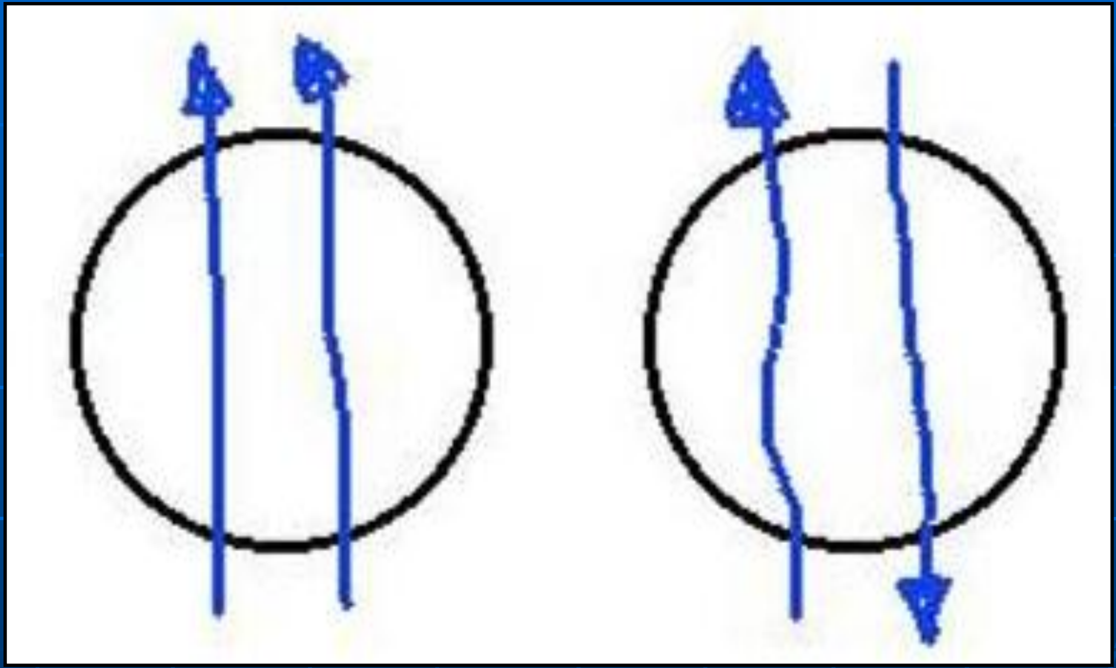
Spiral fields:

Coherent (dynamo modes) or incoherent (compression) ?

Fletcher 2004

Regular (coherent) field

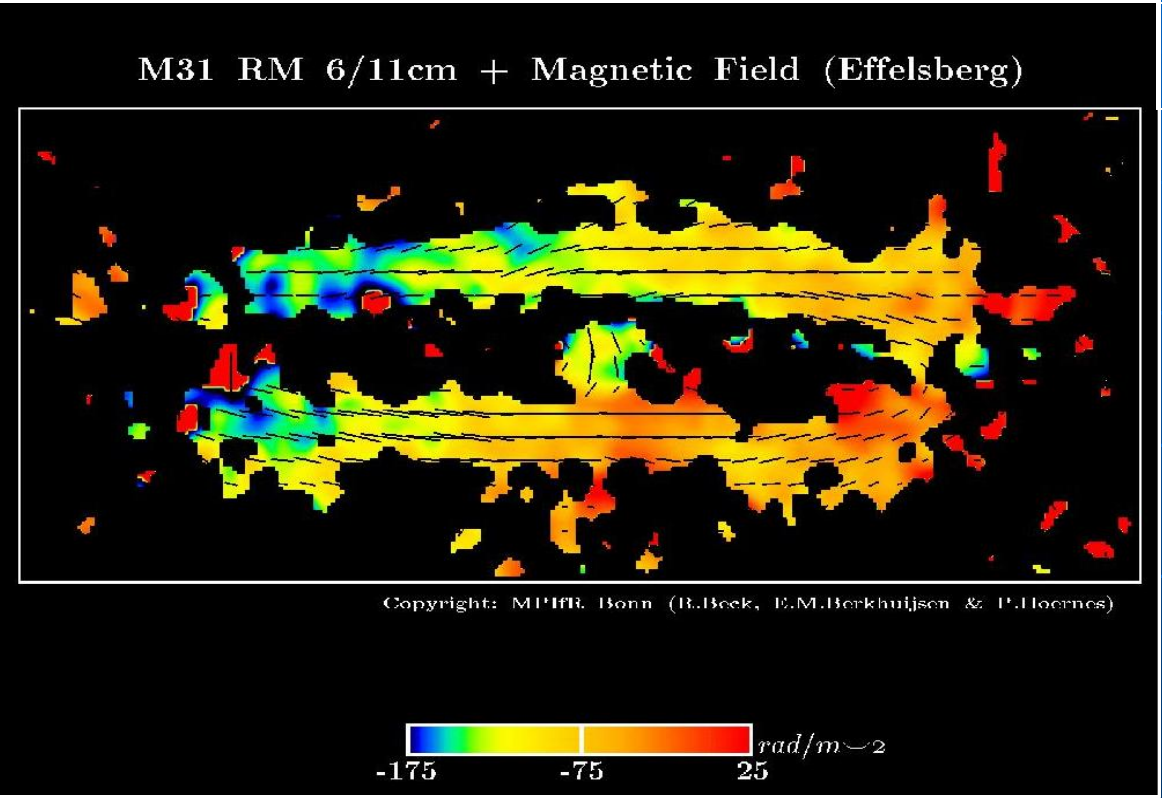
Anisotropic (incoherent) field



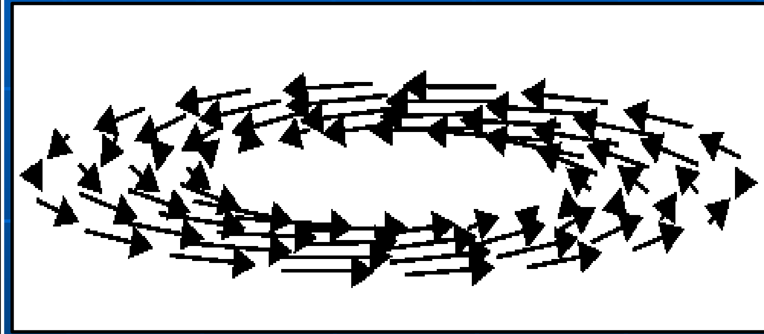
Polarization : strong strong

Faraday rotation : **high** low

M31: The dynamo **IS** working !



Berkhuijsen et al. 2003



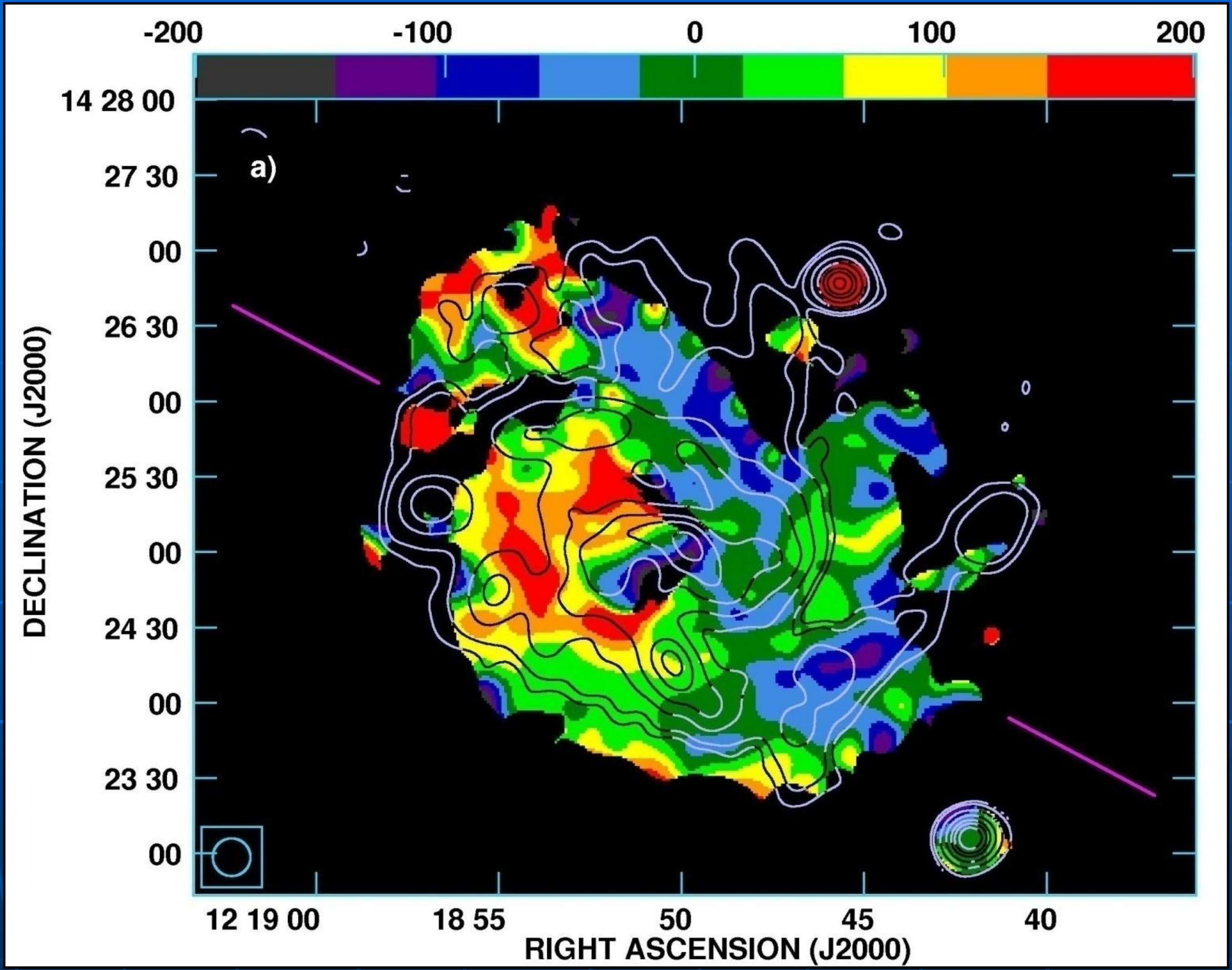
Fletcher et al. 2004

The spiral field of M31 is coherent and axisymmetric
(small spiral pitch angle, but no ring)

NGC 4254

RM (6/3cm)
VLA+Effelsberg
(Chyzy 2008)

Axisymmetric dynamo field

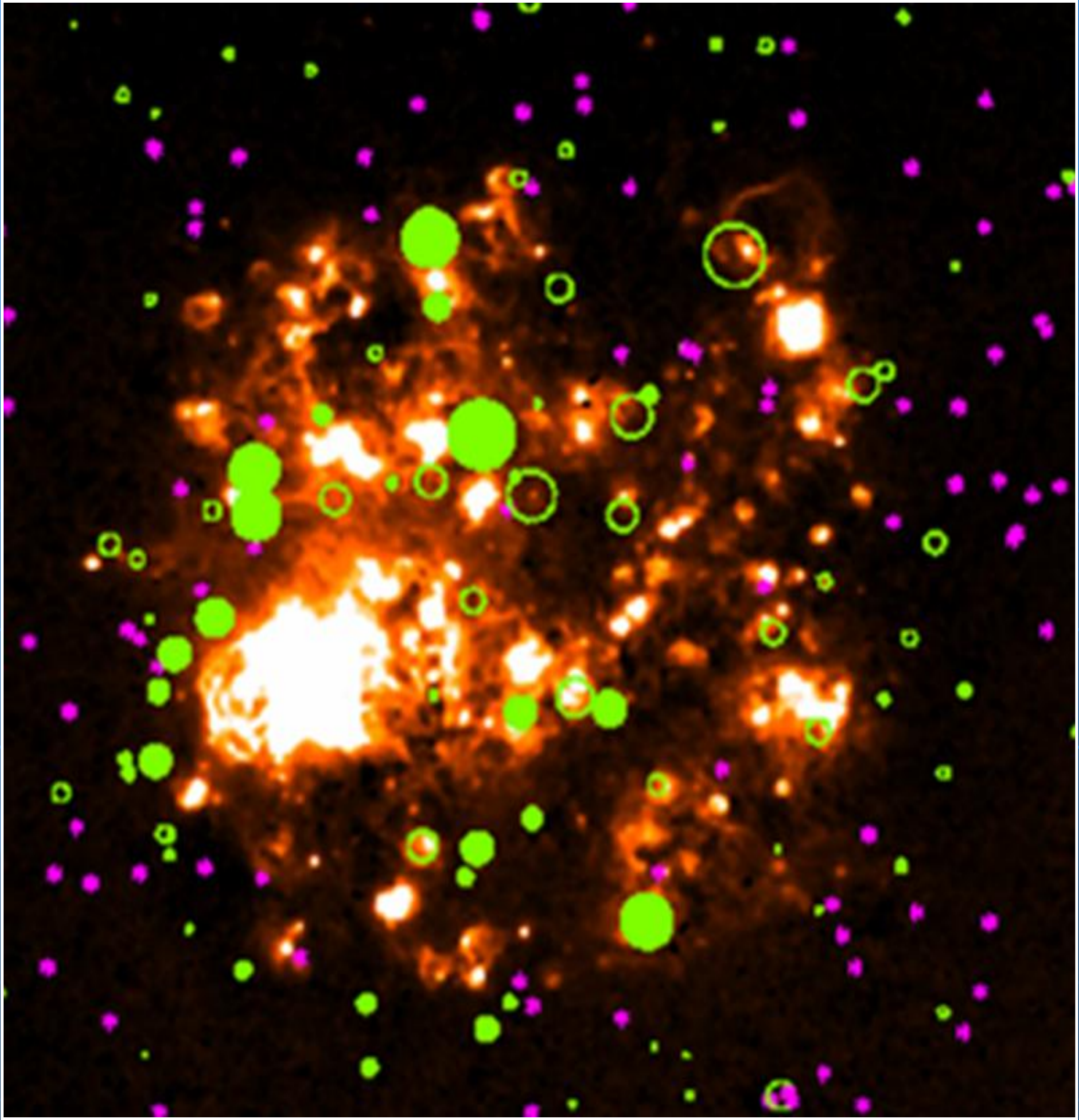


LMC

RM (18-20cm)
ATCA
(Gaensler et al. 2005)

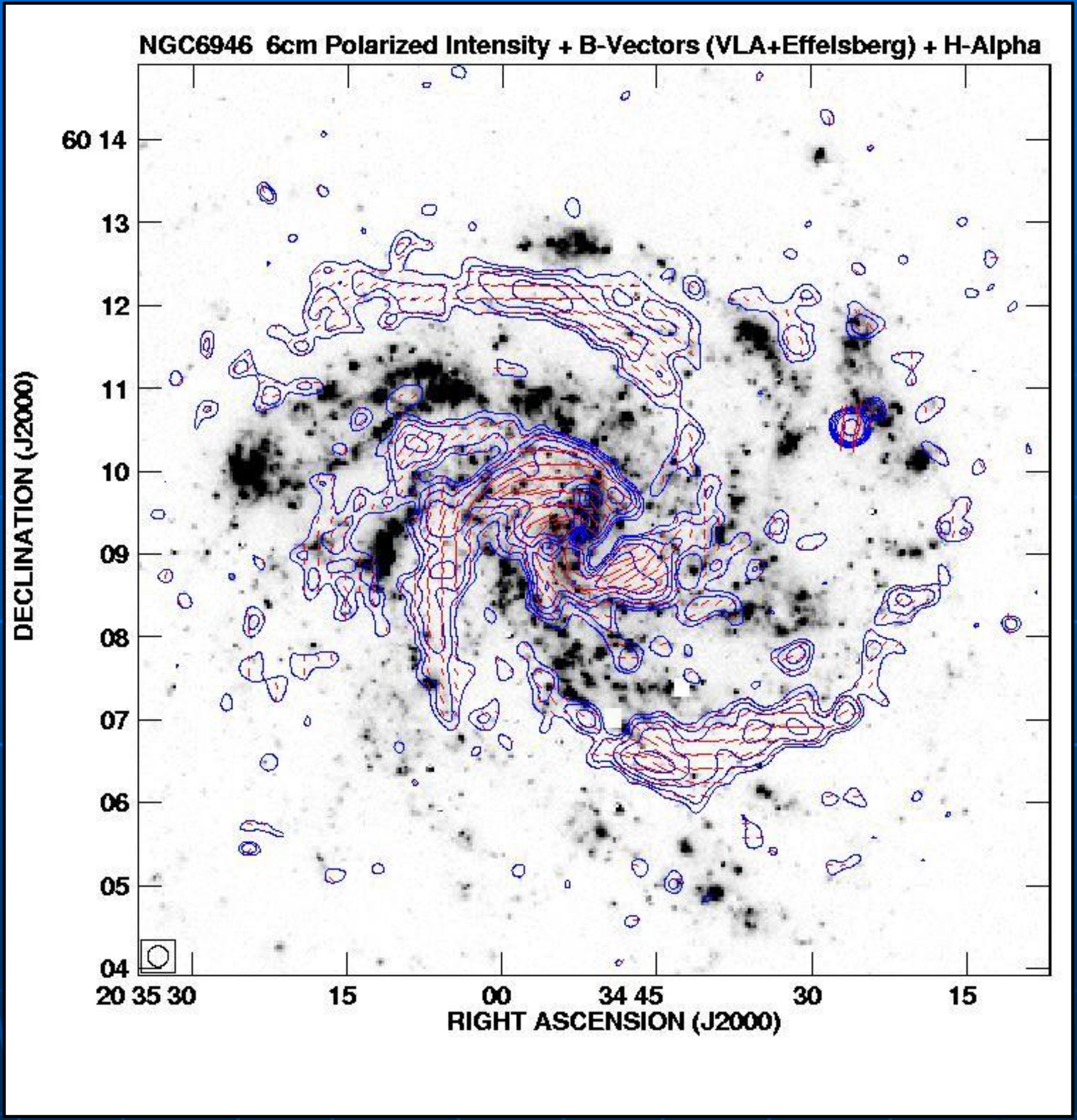
Large-scale pattern of the RMs towards polarized background sources:

Axisymmetric dynamo field (?)



NGC 6946

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



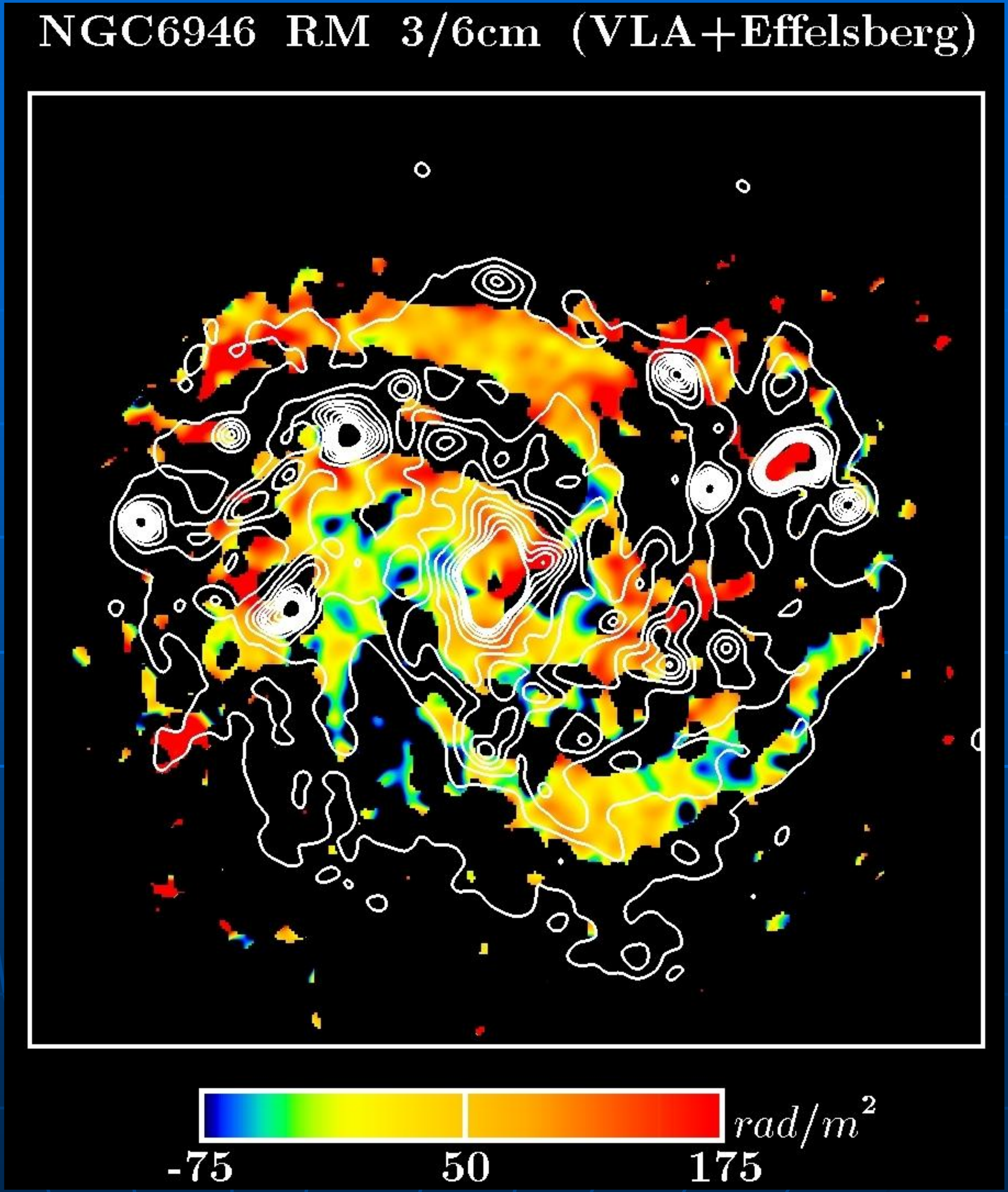
Magnetic arms:
generated
by a dynamo?

NGC 6946

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

Inward-directed field:

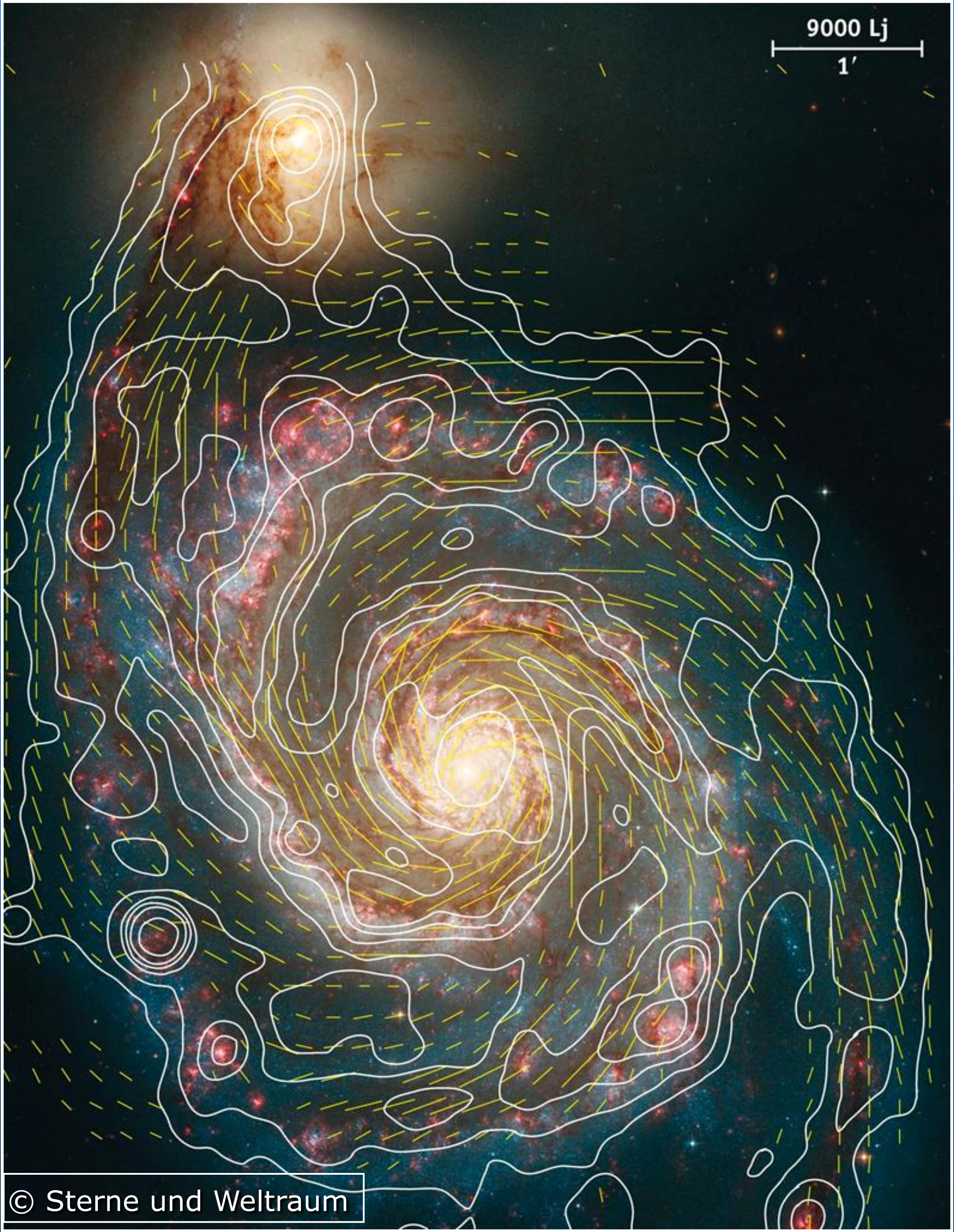
Superposition of two dynamo modes (m=0 + m=2) ?



M 51

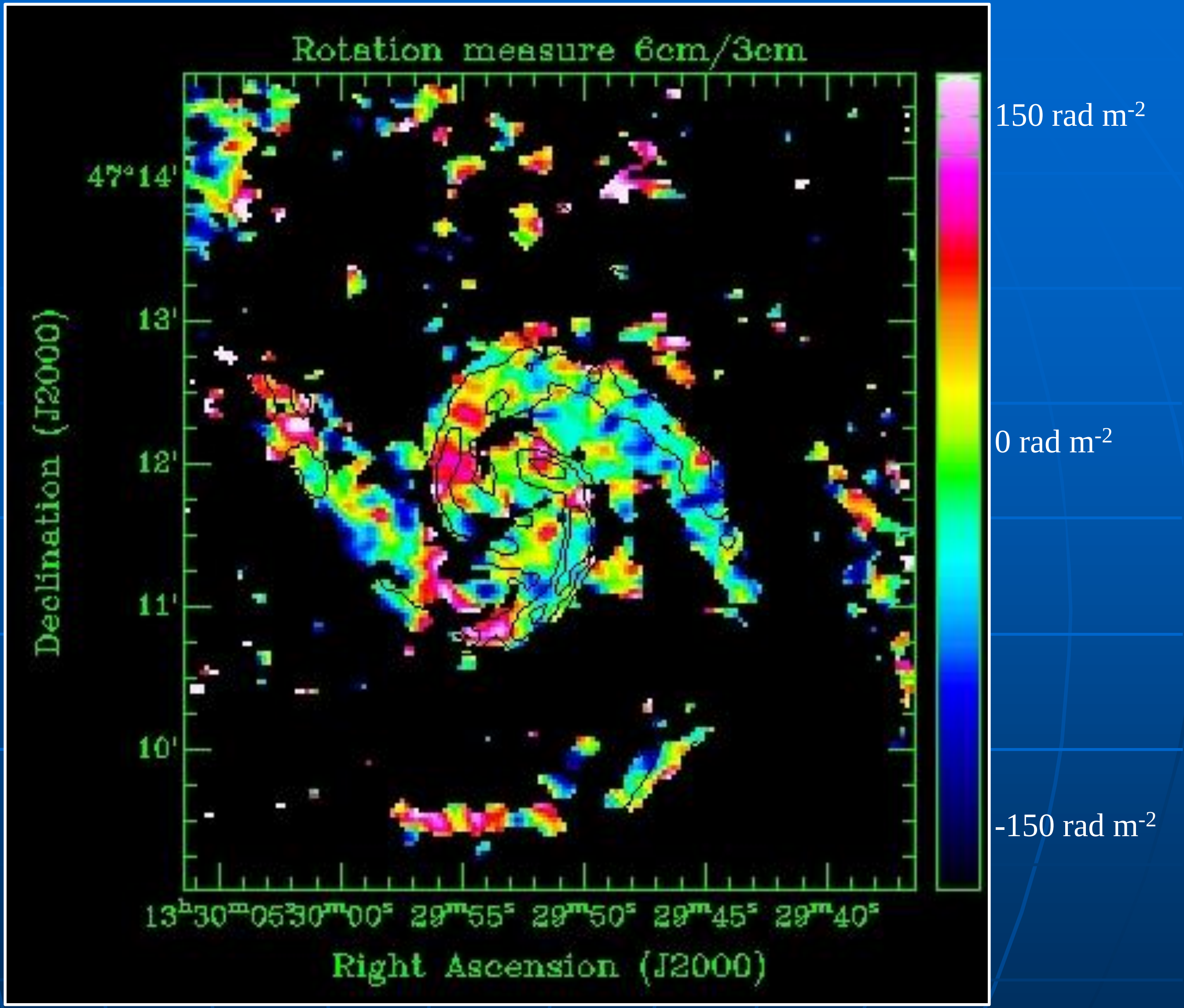
6cm VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2010)

Spiral fields
more or less
parallel to the
optical
spiral arms



M51

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



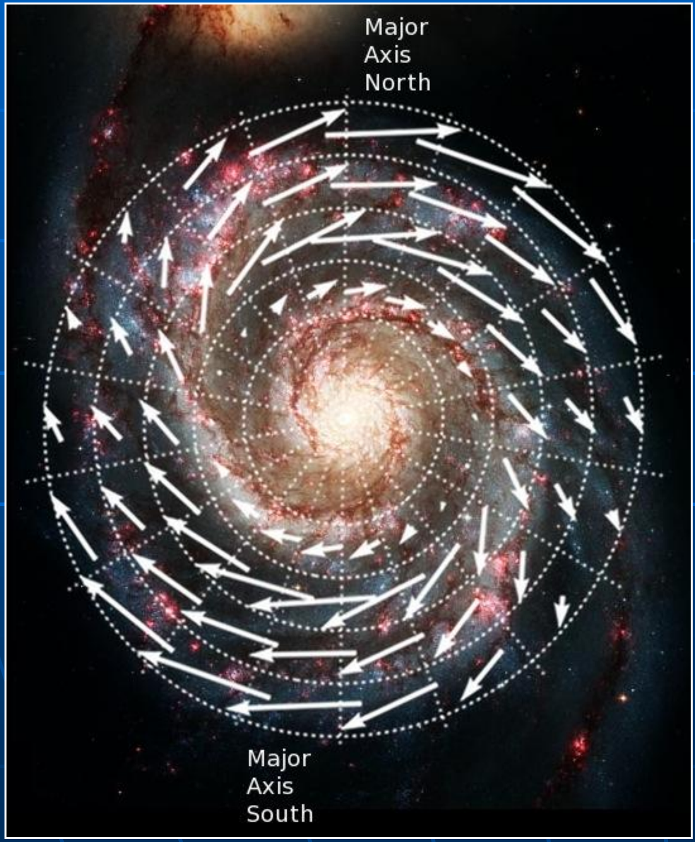
Complicated RM pattern:

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)

Evidence no.4 for dynamo action:

Large-scale coherent fields do exist

Large-scale dynamo modes

- Single dominant axisymmetric (m=0) mode are frequent (M31, NGC253, NGC4254, *NGC4736*, NGC5775, IC342, LMC)
- Dominating bisymmetric (m=1) modes are rare (*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 the field is not yet fully developed

Evidence no.5 for dynamo action:

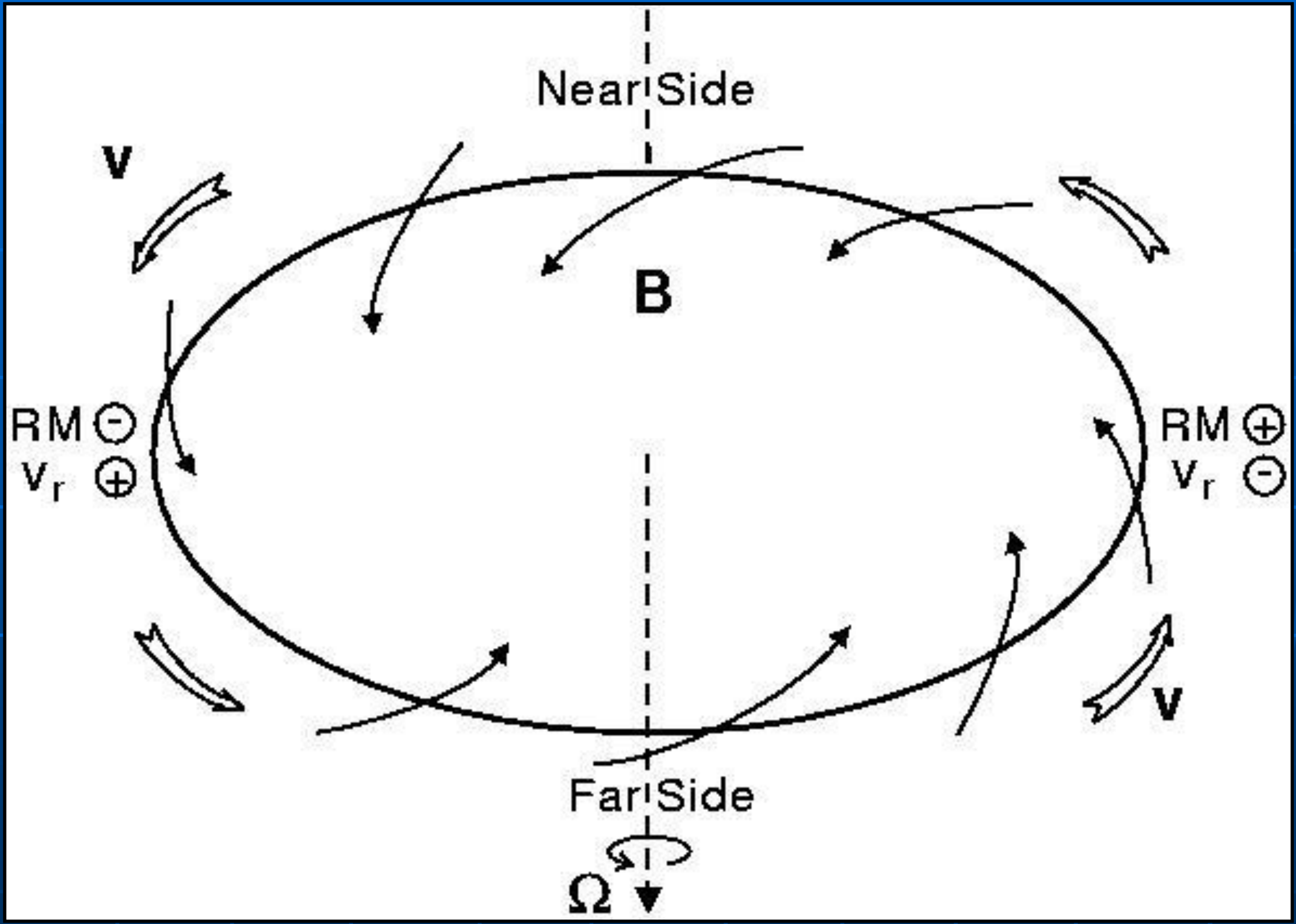
Axisymmetric spiral fields dominate

Question no.7:

What is the origin of the $m=2$ mode in the interarm regions of some galaxies ?

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

Inwards:

M31, IC342, NGC253, NGC1097, NGC6946

Outwards:

NGC4254, NGC 4736, NGC5775, M51 (disk)

Evidence no.7 for dynamo action:

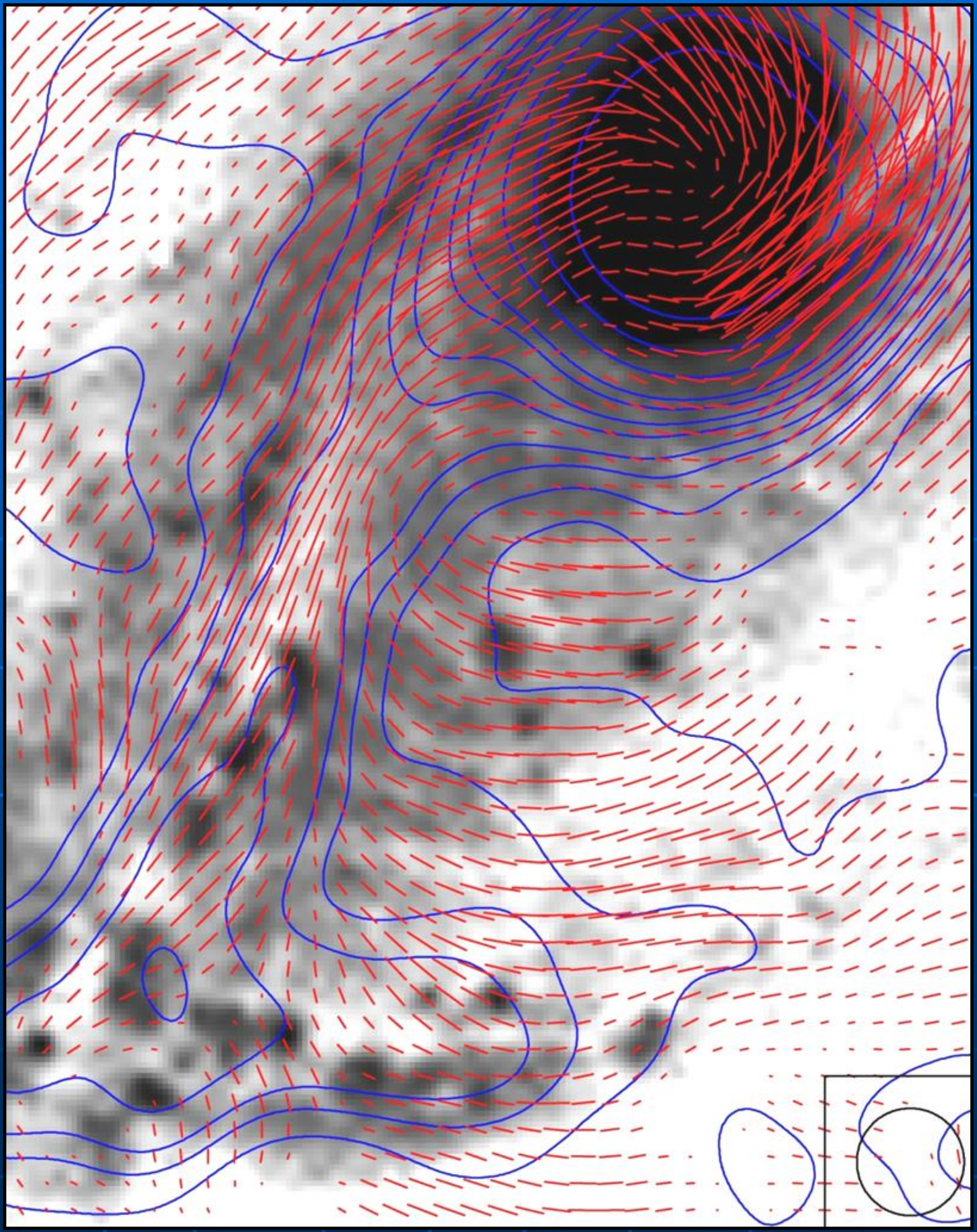
No preference of
one radial direction

Barred galaxies: Can they drive strong dynamos ?

Galaxy NGC 1097
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / The SINGS team (SSC/Caltech)
ssc2009-14a

NGC 1097

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



Little compression in shock:
The field is connected
to the warm diffuse gas

Strong ordered field
in front of the bar:
amplification by
shearing gas flows ?

Question no.8:

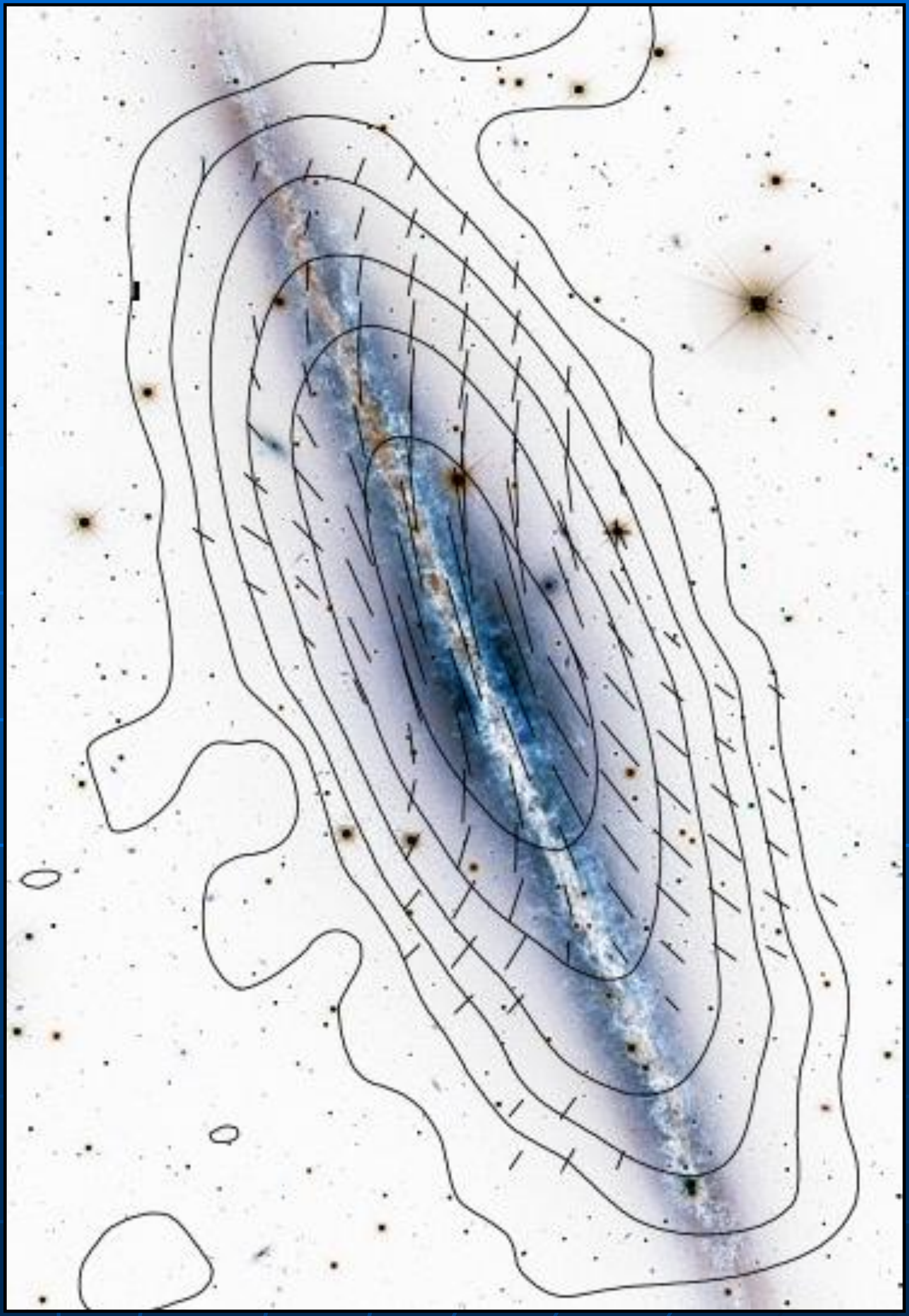
What is the origin of the ordered field in barred galaxies ?

Large-scale fields in edge-on galaxies

(see talks in Session 3)

NGC 891

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

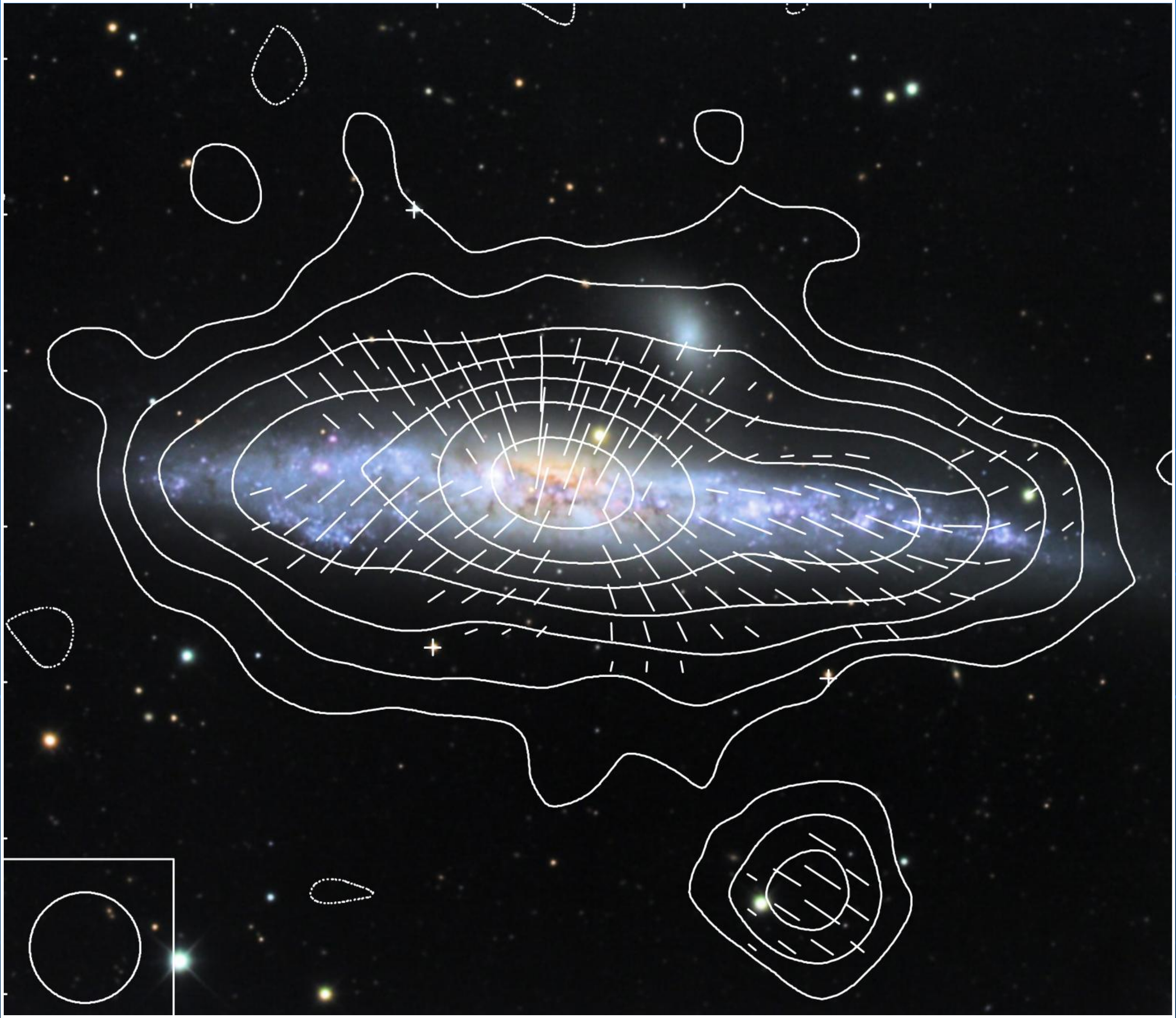


Bright radio halo with
X-shaped field pattern:

Quadrupolar halo field with
strong disk field?
+ galactic wind?

NGC 4631

Effelsberg 3.6cm
Total intensity
+ B-vectors
(Krause 2009)

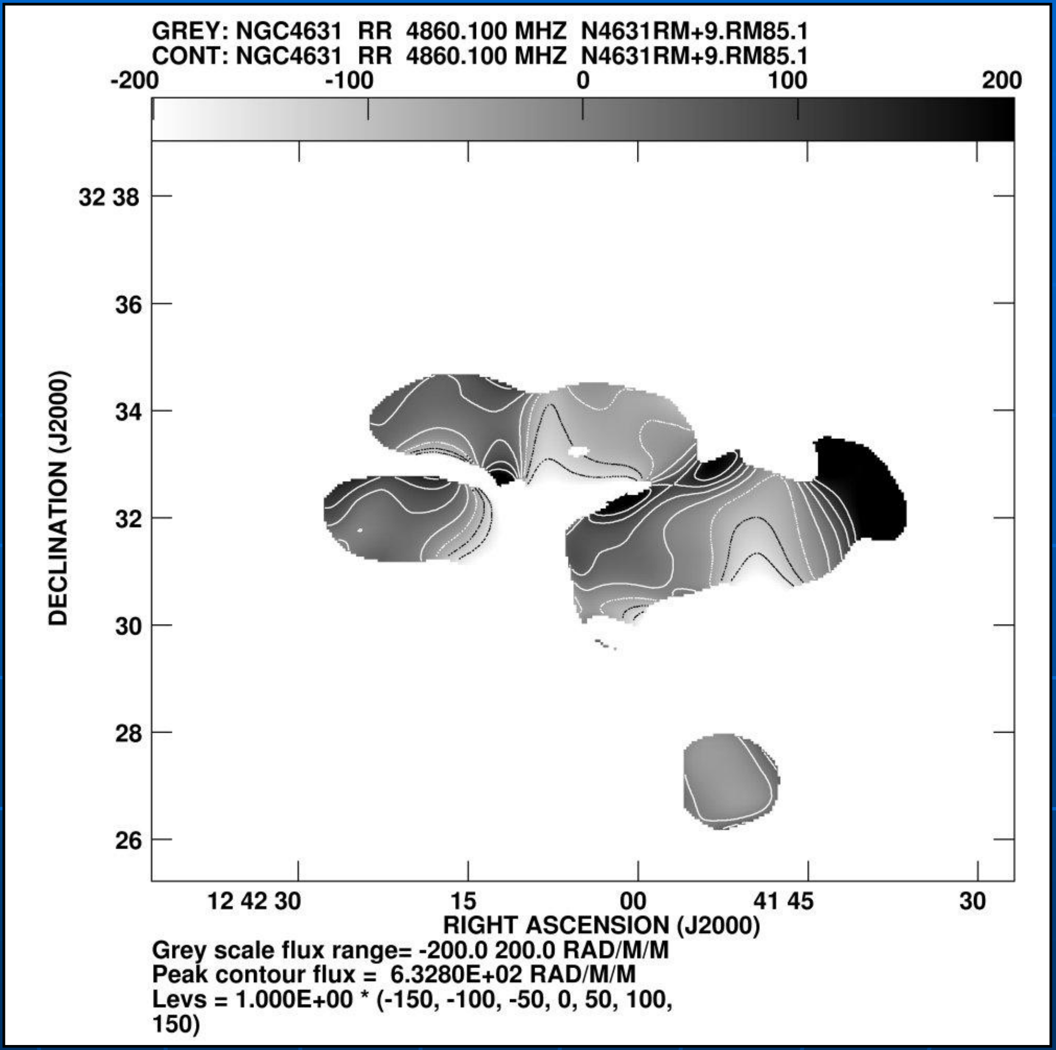


Huge halo:

X-shaped halo field
(quadrupole?)
with weak disk field,
driven by a wind?

NGC 4631

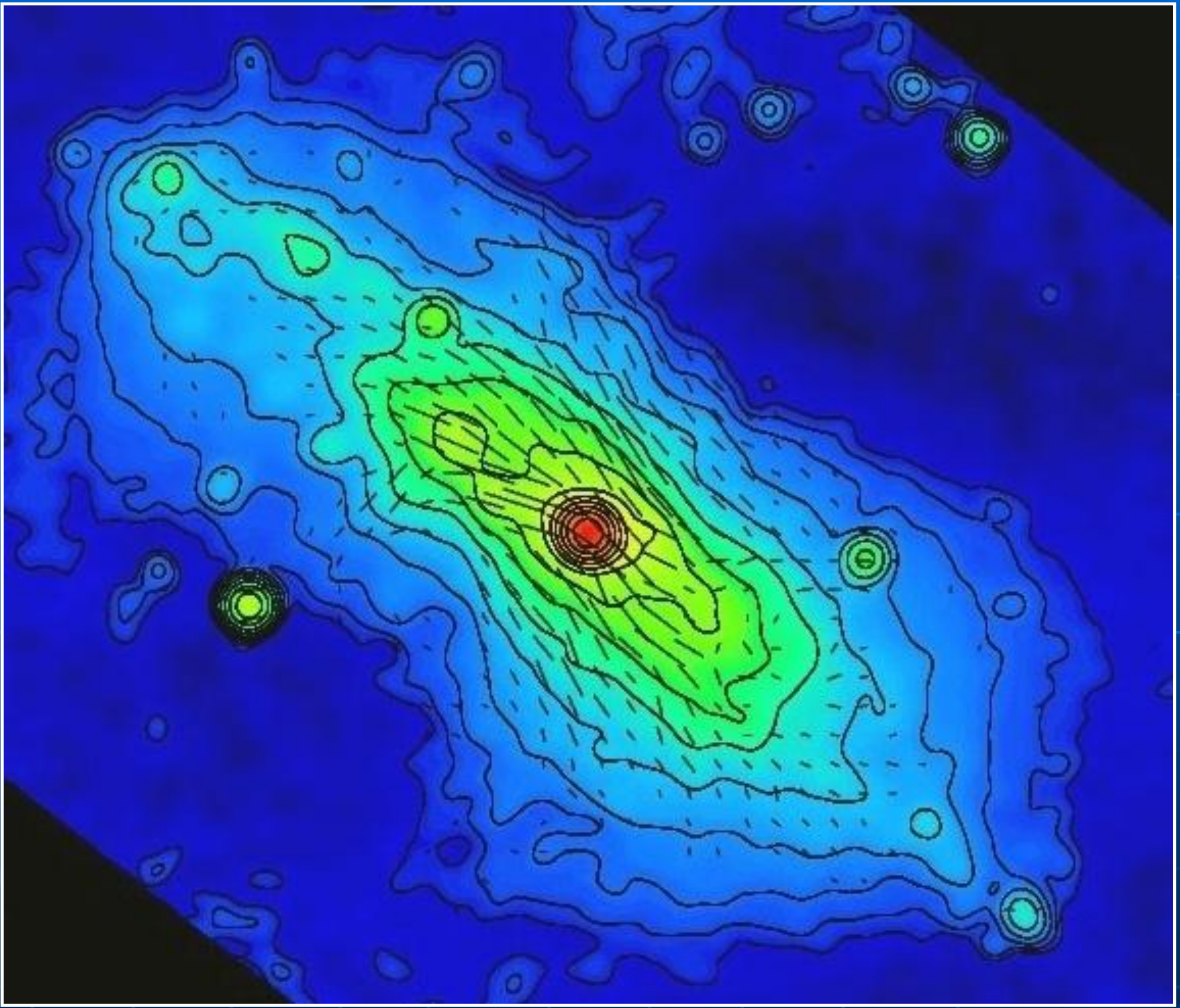
RM (6/3cm)
Effelsberg+VLA
(Krause, unpubl.)



No large-scale pattern in RM:
no quadrupole dynamo field!

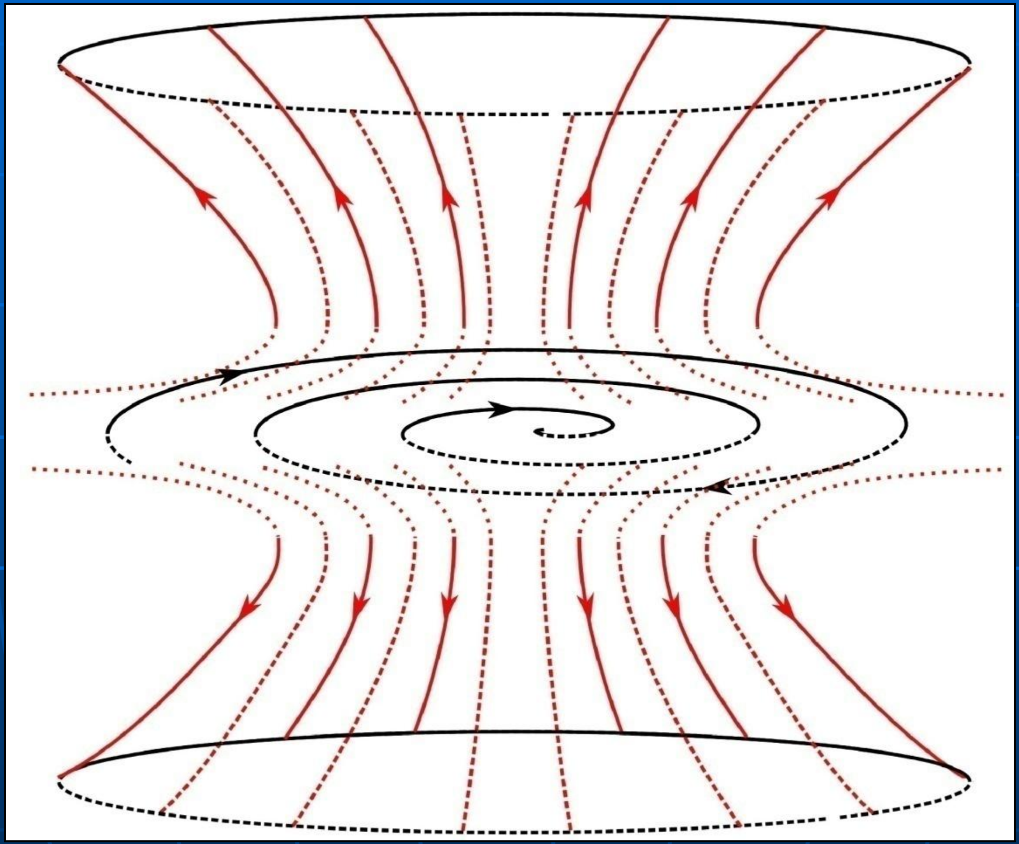
NGC 253

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



Magnetic field model for NGC 253

Heesen et al. 2009



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

Evidence no.7 for dynamo action:

Large-scale quadrupolar field in the halo of NGC253

Question no.9:

How strong are galactic outflows and how are they related to star formation?

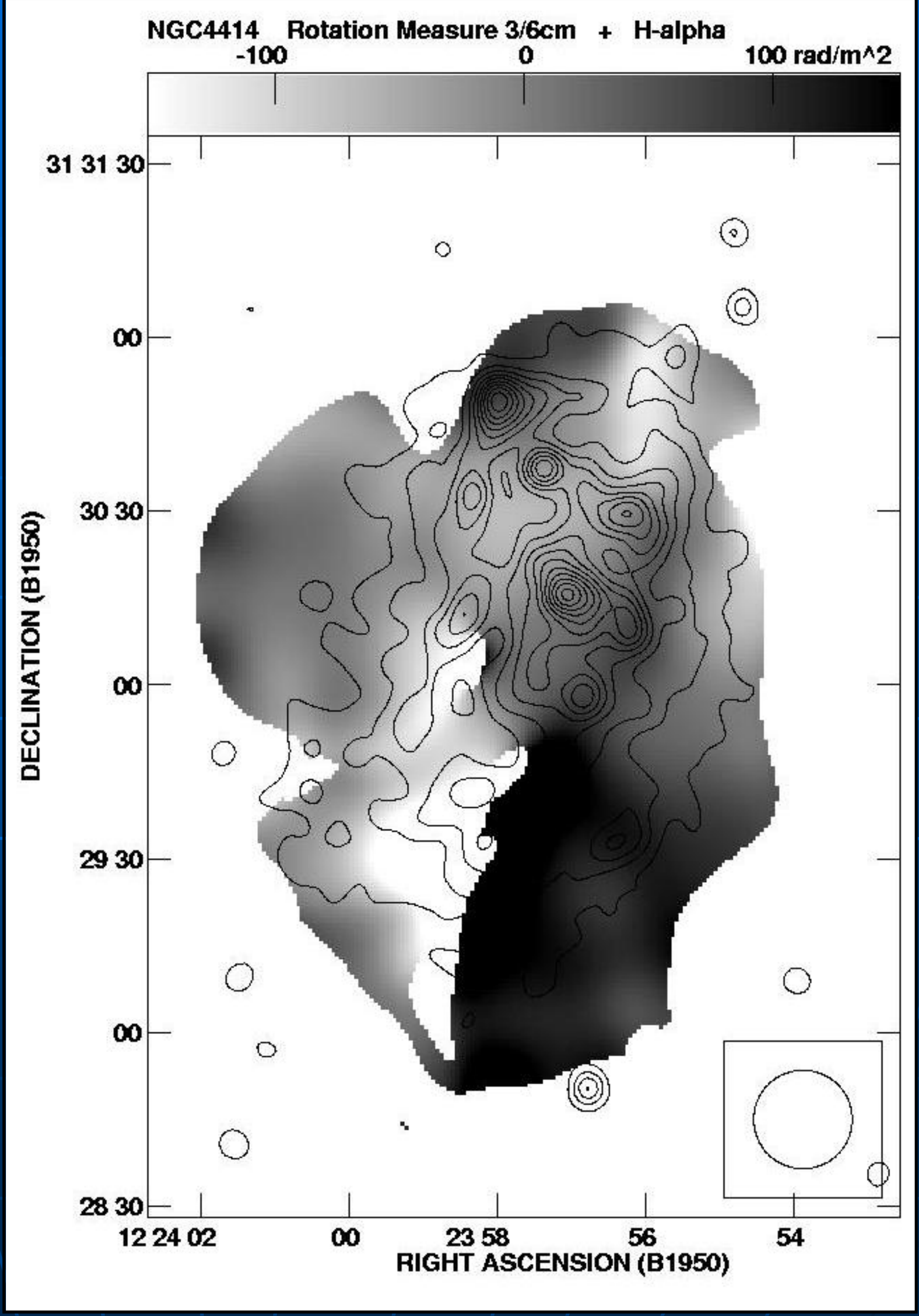
Reversals

NGC 4414

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

One large-scale field reversal??

RM Synthesis needed!

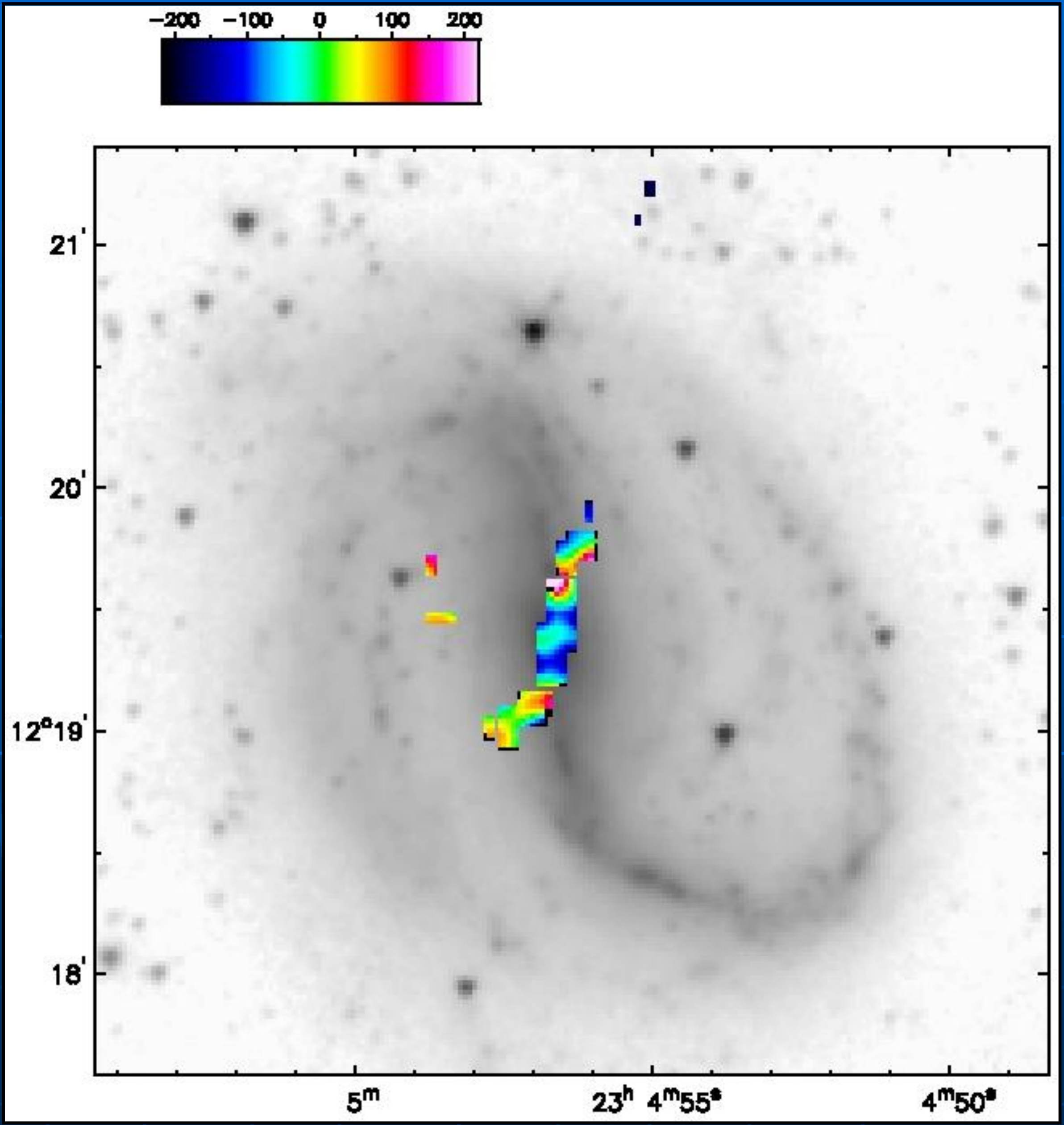


NGC 7479

VLA

RM 3/6cm

(Laine & Beck 2007)



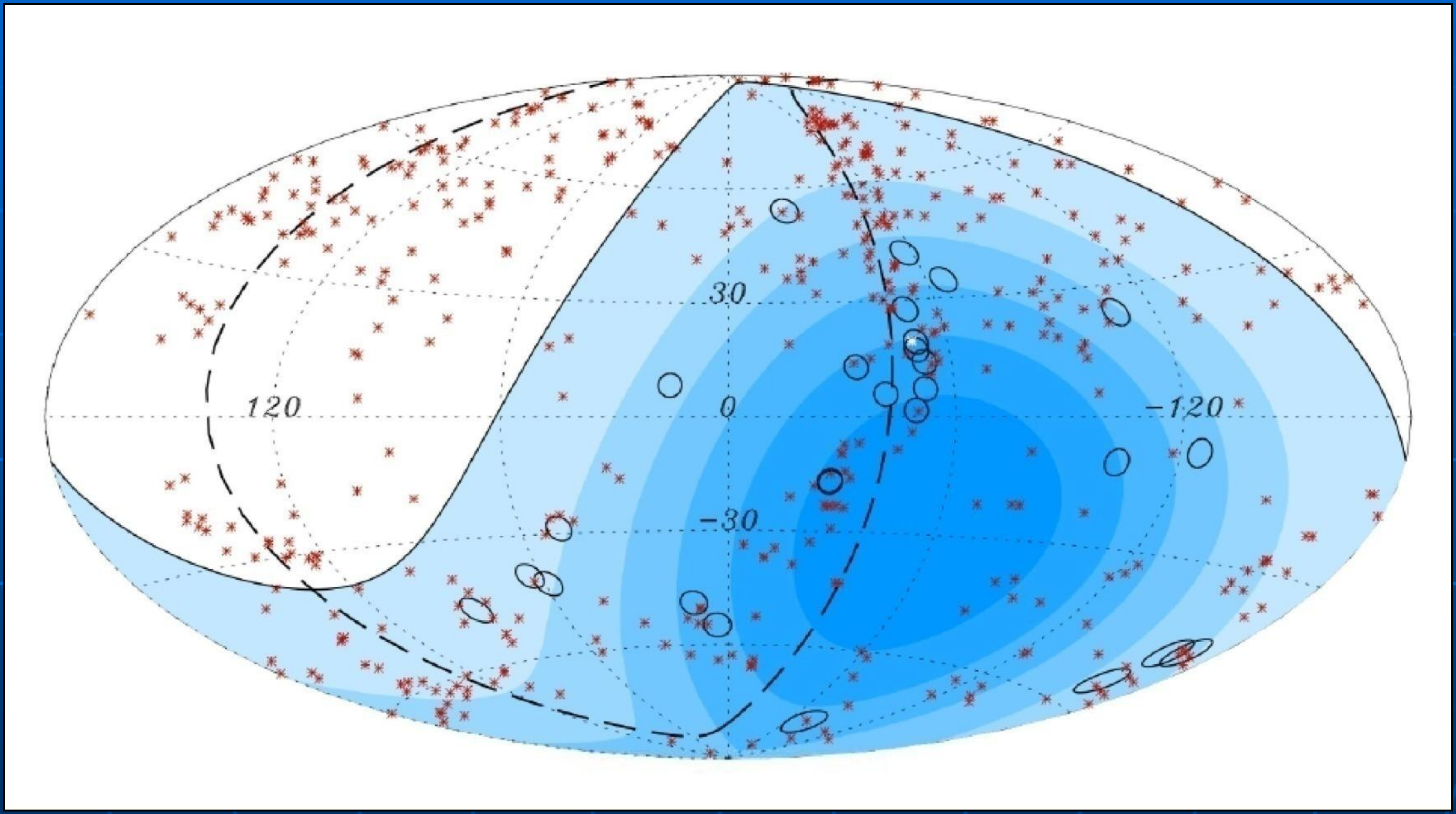
Multiple reversals on ≈1 kpc scale: anisotropic fields !

Results (1):
Magnetic fields in nearby galaxies

- Turbulent fields are closely related to star-formation
- Ordered fields in large galaxies are spiral
- Ordered fields are compressed by strong density waves
- Ordered fields are concentrated in interarm regions in galaxies with weak density waves
- Ordered fields in barred galaxies map the shearing flow of the diffuse gas
- Ordered fields in galaxy halos are X-shaped
- Large-scale RM patterns indicate coherent fields and hence dynamo action
- Strong anisotropic fields exist
- No large-scale reversals were found so far

Milky Way
(an outsider's view)

AUGER UHECR events (> 5 10^{19} eV)

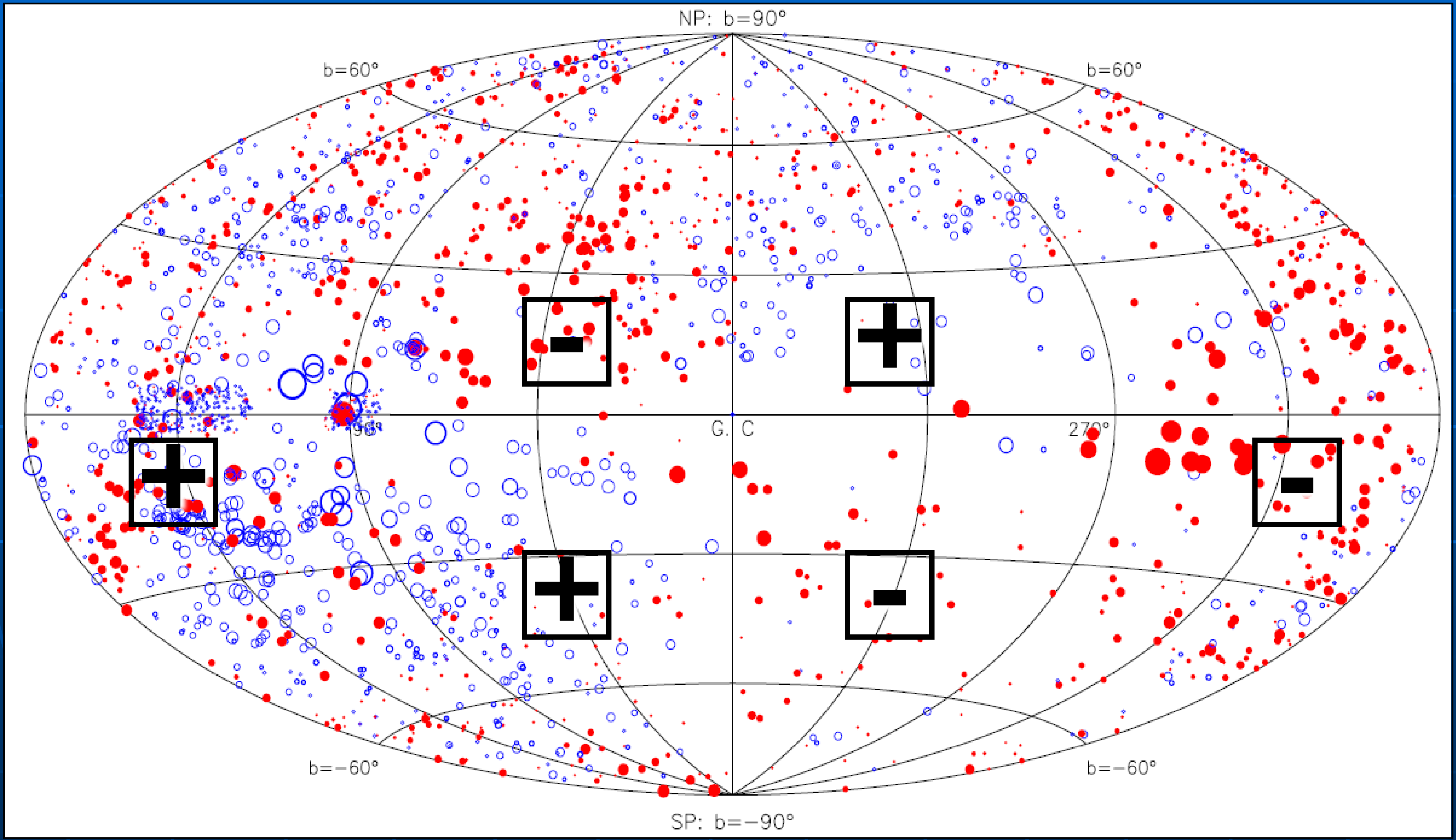


Knowledge about the Milky Way´s magnetic field
is essential to localize the UHECR sources

RMs from extragalactic sources

≈2000 sources (≈0.05 sources per deg^2)

Han et al. 2007

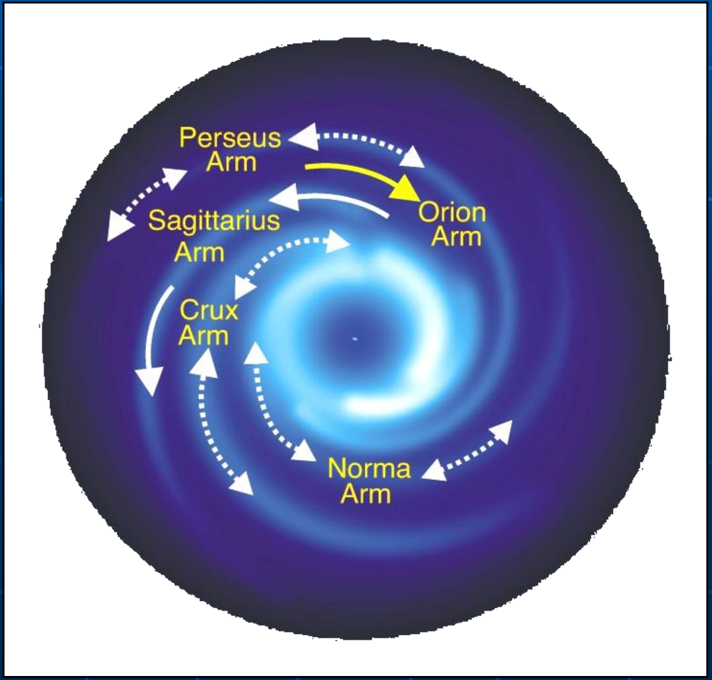


Evidence for an antisymmetric (dipolar) halo field ?

The large-scale Galactic magnetic field from pulsar RM data

(Han et al. 2006, Brown et al. 2007, Noutsos et al. 2008)

- Local field is clockwise
- Field in Sagittarius arm is counter-clockwise
- → ***Reversal*** between arms



Results (2): Milky Way

- The large-scale disk field has a spiral pattern with a pitch angle similar to that of the optical arms
- The large-scale disk field has at least one large-scale reversal at 0.5-1 kpc inside the solar radius
- The is no evidence for a large-scale vertical field
- The overall structure of the magnetic field in the Milky Way is not known yet

Question no.10:

Why are no large-scale field reversals observed in spiral galaxies?

Is our Milky Way special ?

Summary: 7 evidences for dynamo action

- Energy densities
- Spiral patterns
- Asymmetries in polarized intensity
- Large-scale coherent fields
- Dominance of axisymmetric fields
- Directions of radial fields
- Halo of NGC253

Summary: 10 open questions

- Dominating turbulent fields in outer galaxies?
- Extent of galactic fields?
- Origin of radio-IR correlation?
- Alignment of fields in galaxies with weak density waves?
- Dynamo threshold?
- Polarization asymmetry at low frequencies?
- Origin of "magnetic arms‟?
- Origin of ordered fields in barred galaxies?
- Outflows and star-formation?
- Origin of the reversals in the Milky Way?

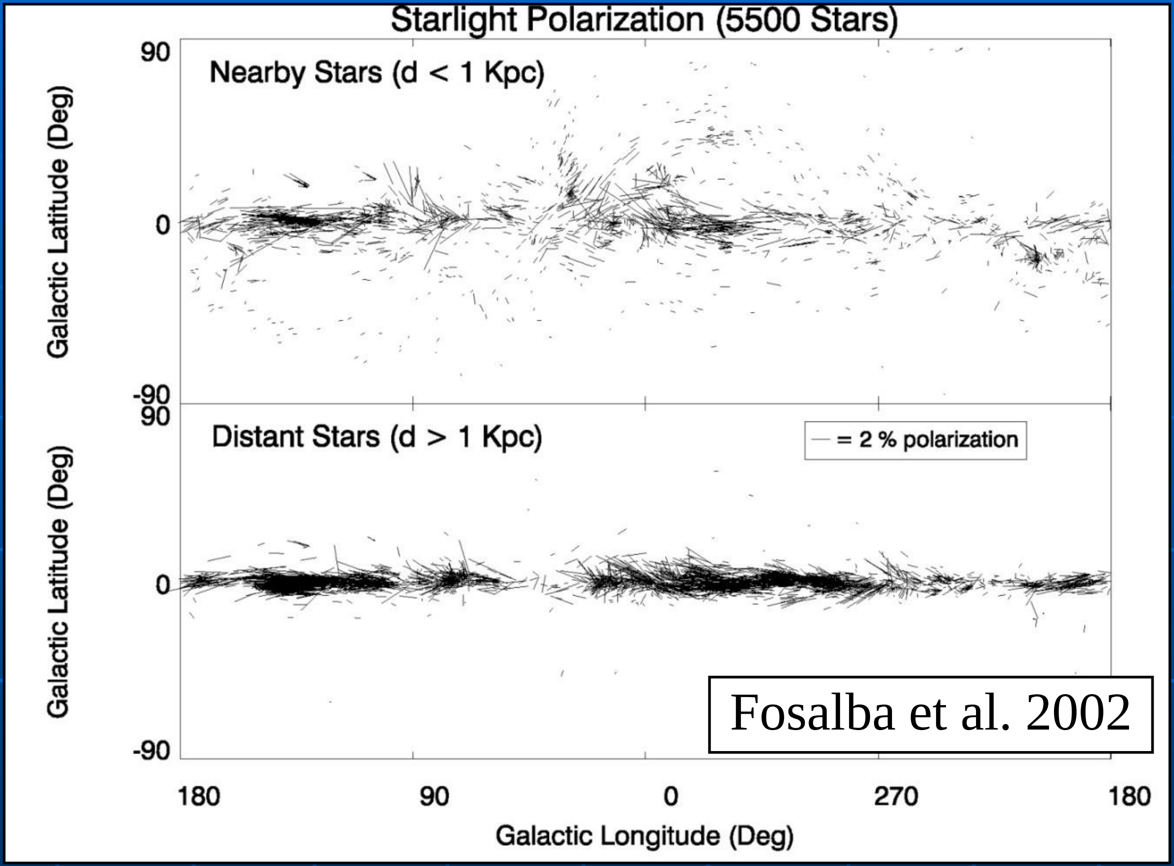
The future

- Optical/NIR: ??? (starlight pol)
- Submillimeter: ALMA (molecular clouds)

Radio:

- Higher resolution: EVLA, SKA
- Larger sensitivity: EVLA, MeerKAT, SKA
- Lower frequencies: LOFAR, SKA
- Higher survey speed: LOFAR, ASKAP, SKA
- Spectro-polarimetry

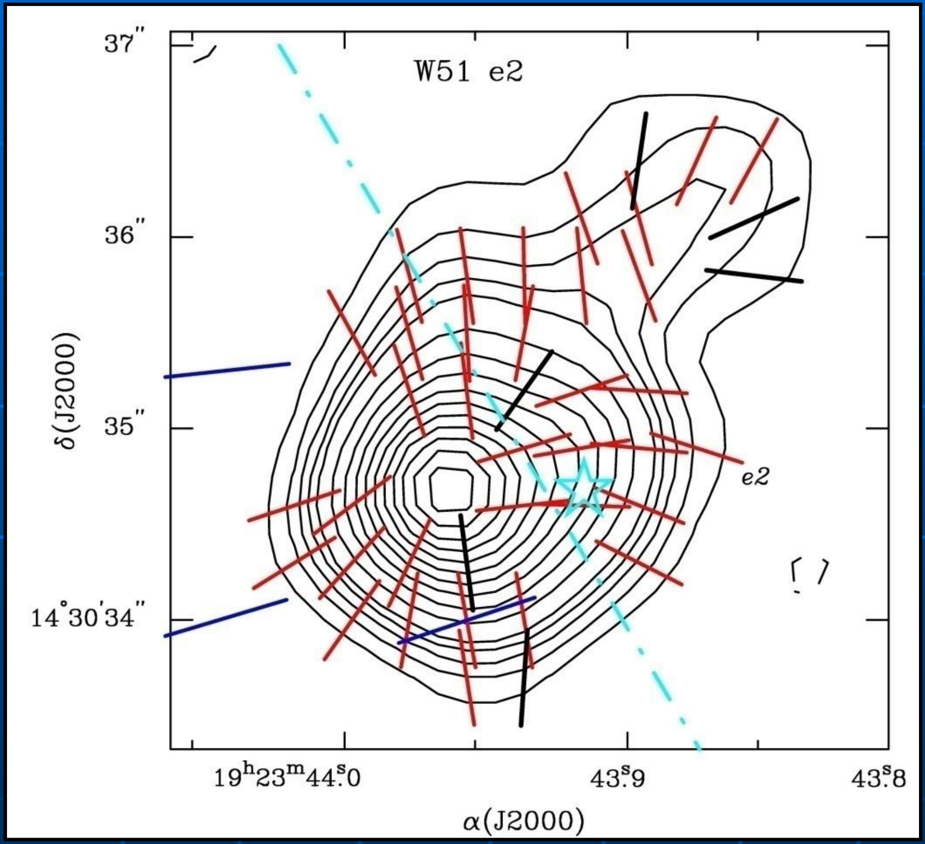
Starlight polarization ($B_\perp$)



Distance measurements of stars:
3-D field reconstruction possible !

Submm polarization in W51: Magnetic field in a rotating molecular gas disk

(SMA, 870 μm wavelength, 0.02 pc resolution)



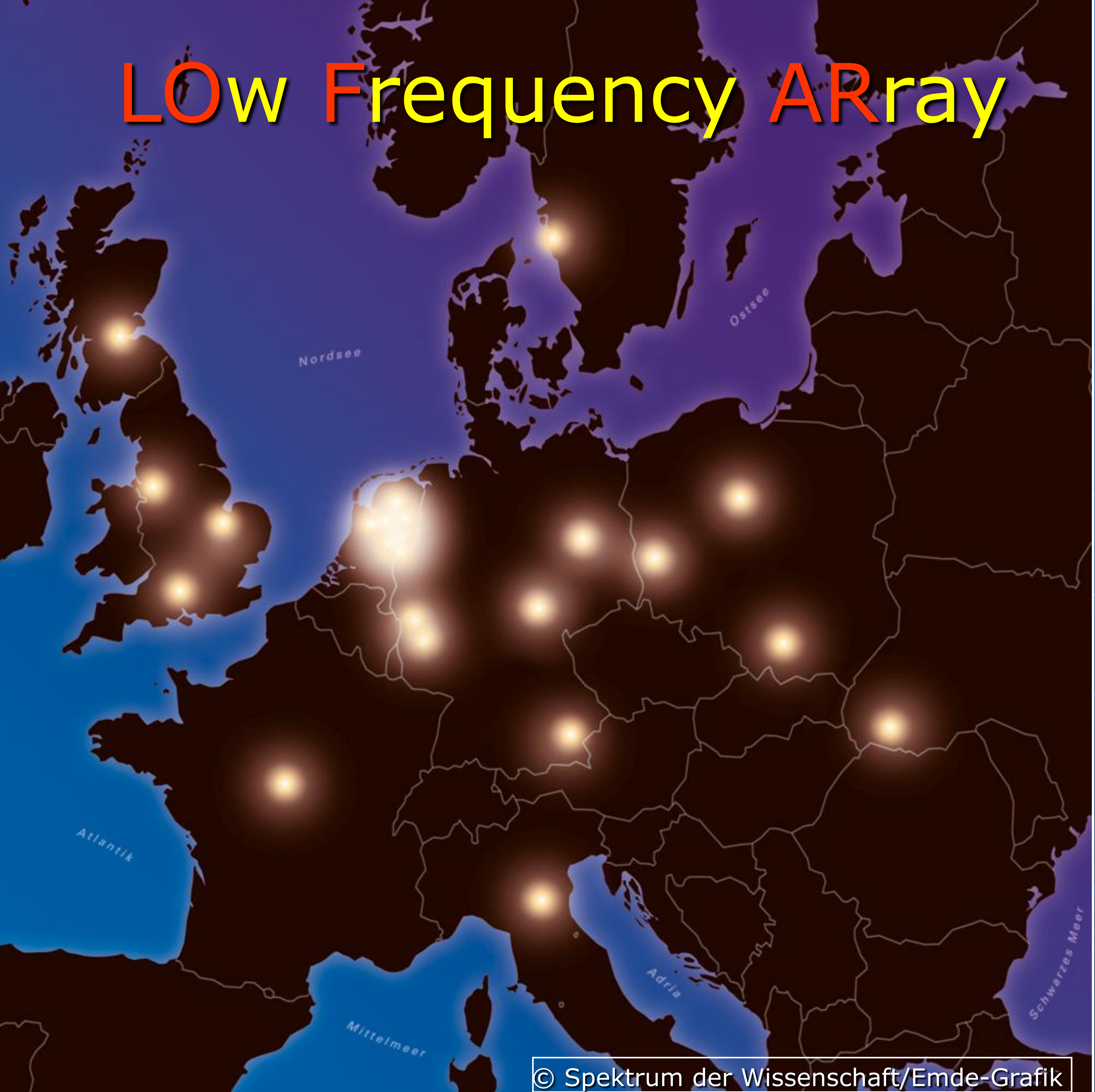
Tang et al. 2009

X-shaped field:
Ambipolar diffusion, or dynamo action?

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

LOw Frequency ARray

LOFAR



10-80 MHz
110-240 MHz

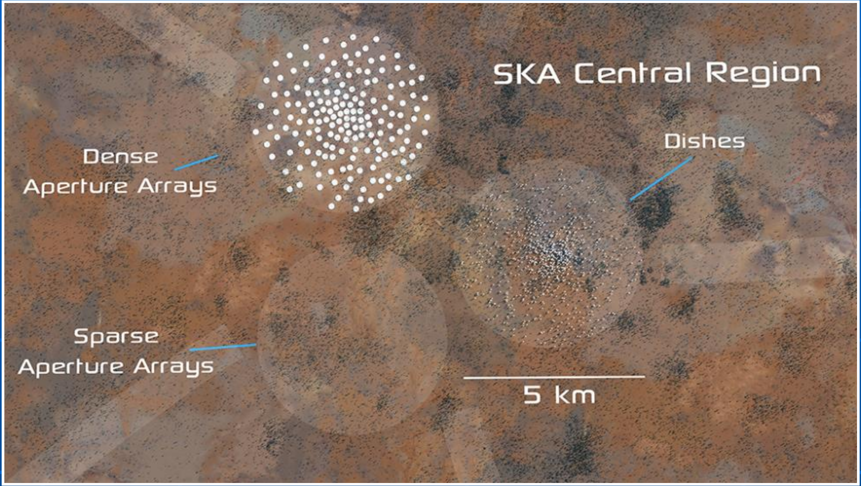
First international station *IS-DE1* in Effelsberg

International station *IS-DE3* in Tautenburg

Michael Pluto, TLS

The SKA will allow to observe detailed structures of magnetic fields

SKA


SKA Central Region
Dishes
Dense
Aperture Arrays
Sparse
Aperture Arrays
5 km


Swinburne Astronomy Productions


Swinburne Astronomy Productions


Swinburne Astronomy Productions

SKA Timeline

- Start of Phase 1 construction: 2016
- Start of observations: 2018
- Start of Phase 2 construction: 2020
- Start of Phase 3 design studies: 2023
- Phase 1: Only two science drivers (EoR/redshifted HI and pulsars)
- *Magnetism remains Key Science for Phase 2 and "demonstration science" for Phase 1*

Faraday rotation grids with the SKA

All-sky survey (1h per field):

- ≈ 2000 10-σ polarized sources per deg^2
  (≈ 0.5 RMs per $arcmin^2$)
- **Total number of RMs: ≈ 8 10^7 !**

Deep fields (12h integration):

- ≈ 8000 10-σ polarized sources per deg^2
  (≈ 2 RMs per $arcmin^2$)

- ASKAP: ≈ 80 RM per deg^2 within 12h (large field of view)
- MeerKAT: ≈ 400 RM per deg^2 (small field of view)
- Phase-1 SKA: ≈ 800 RM per deg^2 (large field of view)

ASKAP
(Australian SKA Pathfinder)

36 antennas of 12m diameter, max. baseline 6km, frequency range 0.7 - 1.8 GHz

POSSUM: *POlarization Survey of the Universe´s Magnetism*

- All-sky polarized continuum at 1.4 GHz
- Rotation measures for ≈ 1.5 million sources (≈ 50 RMs/deg^2)
- Recognize large-scale fields in Milky Way, nearby galaxies and clusters

MeerKAT

80 antennas of 12m diameter, max. baseline 60km, frequency range 0.6 - 14.5 GHz

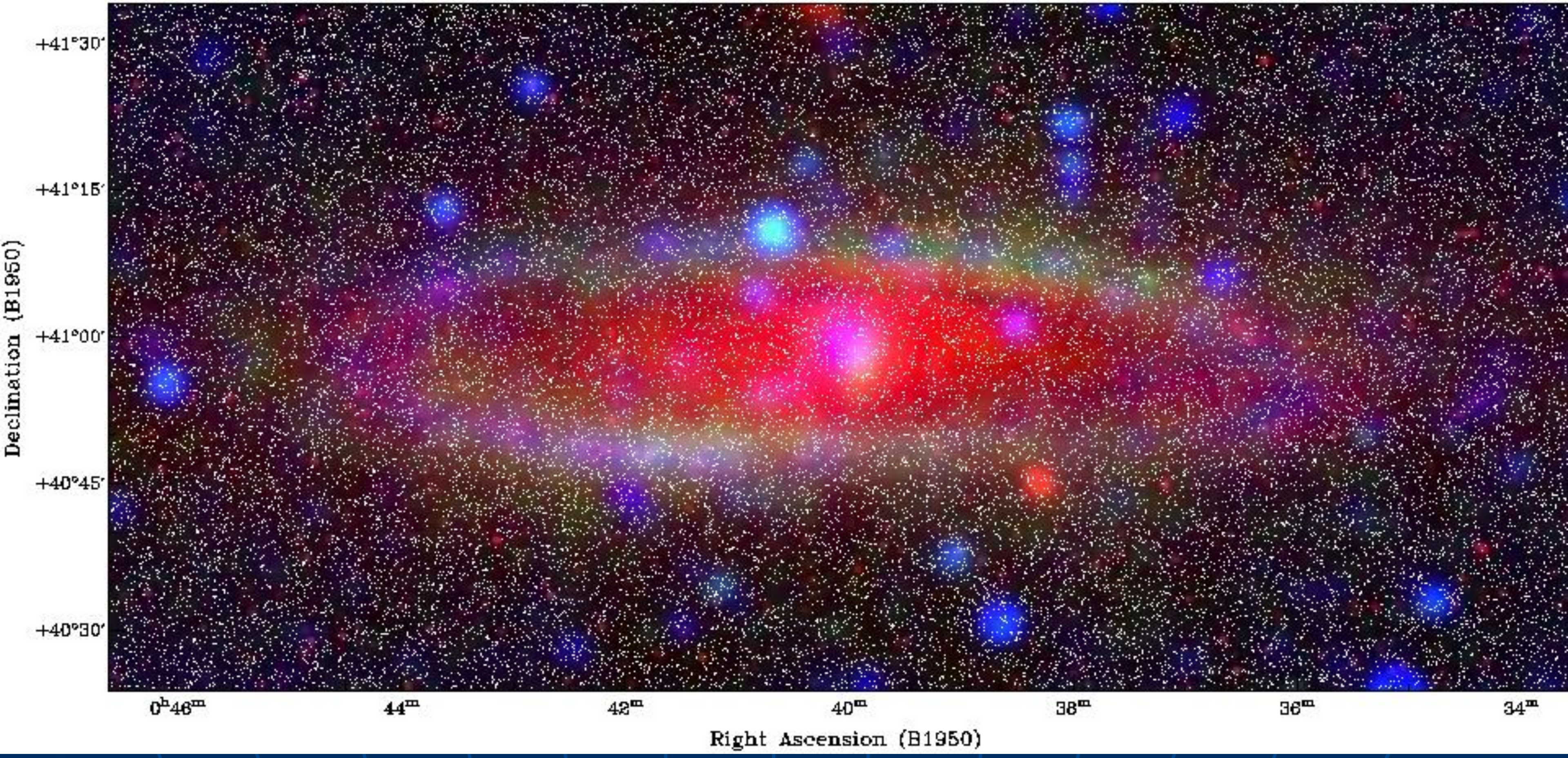
MeerQUITTENS (proposal):

MeerKAT QU Investigation To Trace Extragalactic Nonthermal Sources

- Deep imaging of synchrotron pol & RM grid of nearby spiral and dwarf galaxies, galaxy groups and clusters
- 900-1750 MHz and 8-10 GHz
- Ideal complement to LOFAR and POSSUM

SKA RM survey

(simulation by Bryan Gaensler)



≈10000 polarized sources shining through M31

Deep RM grids with the SKA

Stepanov et al. 2008

Recognition of field patterns:

- At least 10 RM values needed
- Can be applied to galaxies out to ≈ 100 Mpc distance (≈ 60000 galaxies)

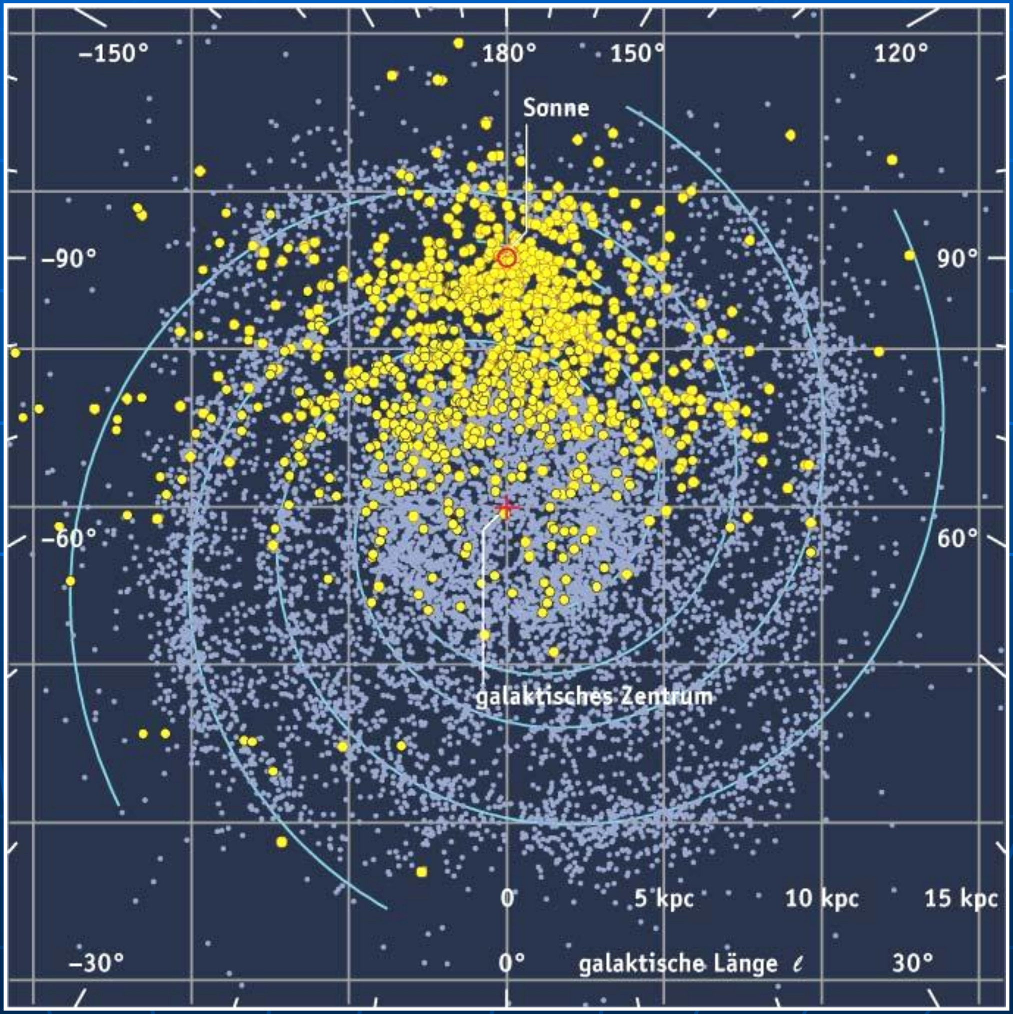
Reconstruction of field patterns:

- A few 1000 RM values needed
- 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 (≈30000)



Future radio observations

- Polarization of diffuse emission:
- Higher sensitivity and resolution (EVLA, SKA):
  Detailed field structure, spectrum of dynamo modes, 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 nearby galaxies (ASKAP, MeerKAT, SKA)
- Field patterns in distant galaxies (SKA)
- Evolution of galactic magnetic fields (SKA)

- Pulsar RMs:
  Detailed structure of the Milky Way's field (ASKAP, SKA)