Magnetic fields in galaxies and the Milky Way

Rainer Beck
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Magnetic fields are widely accepted as being important in most astrophysical processes

- Interest in magnetic fields is also rising thanks to UHECRs

Fundamental questions

- Structure
  - What is the magnetic field structure at small and large scales ?
- Dynamics
  - Do magnetic fields affect gas flows and galaxy evolution ?
- Origin
  - When and how were the first magnetic fields generated ?
- Evolution
  - How and how fast were galactic magnetic field amplified ?

Observing magnetic fields with radio waves

- Total synchrotron intensity:
  Strength of total $B_{\perp}$
- Polarized synchrotron intensity:
  Strength and structure of ordered $B_{\perp}$
- Faraday rotation:
  Strength and sign of regular $B_{\parallel}$
- Faraday depolarization:
  Strength and scale of regular + turbulent fields
- Zeeman effect:
  Strength and sign of regular $B_{\parallel}$

Outline

- Field origin
- Cosmic ray electrons
- Field strengths and structures
- Radio halos
- Faraday rotation
- Field reversals
- Milky Way
- Future observations

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Magnetic field generation and amplification

- **Field seeding**
  Primordial, Weibel instability,
  ejection by supernovae, stellar winds or jets

- **Field amplification**
  MRI, compressing / shearing flows,
  turbulent flows, small-scale dynamo

- **Coherent field ordering**
  Mean-field dynamo

Classical mean-field dynamo

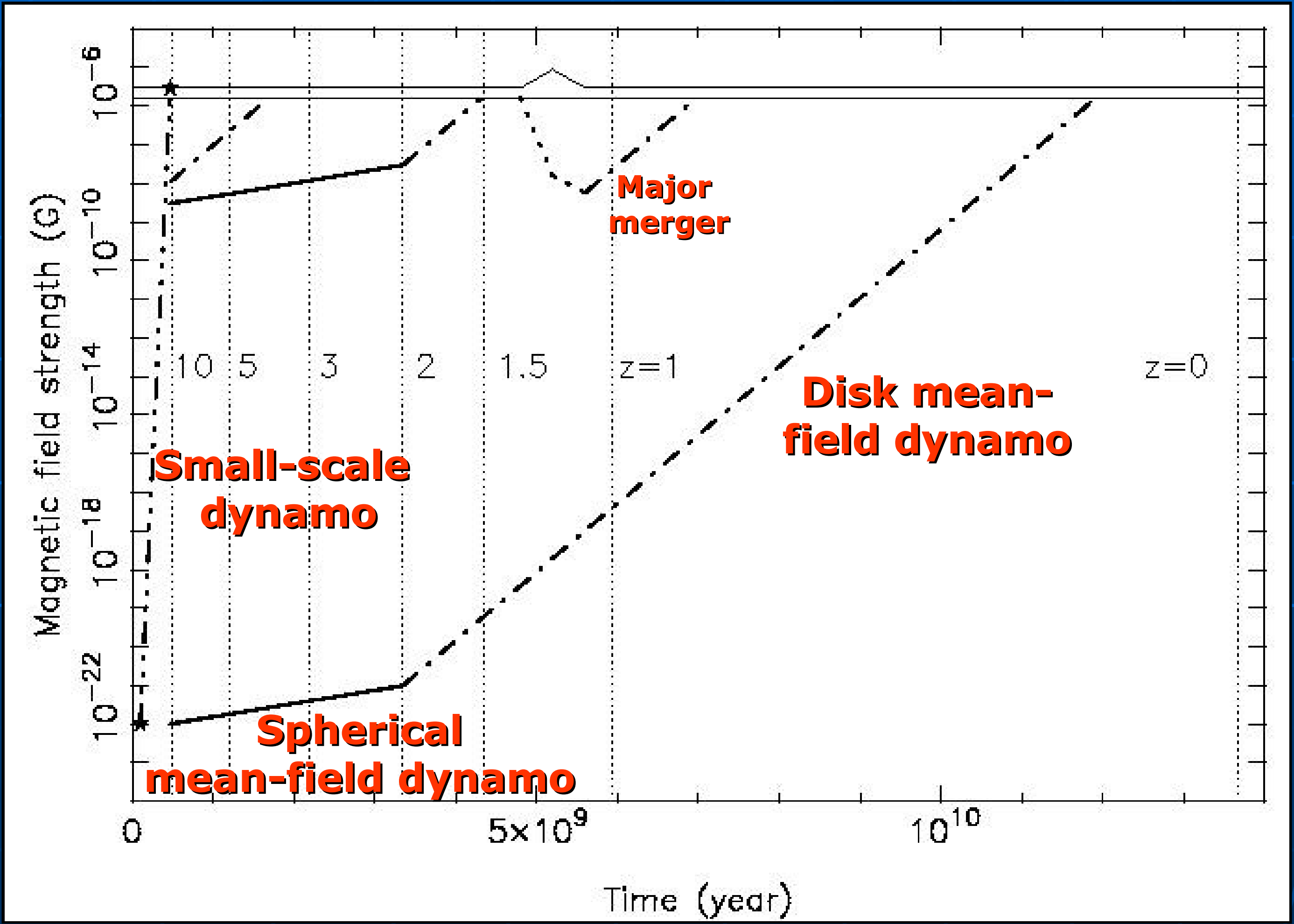
- Ingredients:
  Ionized gas + differential rotation
  + helical turbulence + magnetic diffusion

- Microphysics approximated by the average parameters
  "alpha-effect" and diffusivity

- Dynamo equation for the large-scale "mean" field

- Generation of large-scale modes

Dynamo action in evolving galaxies

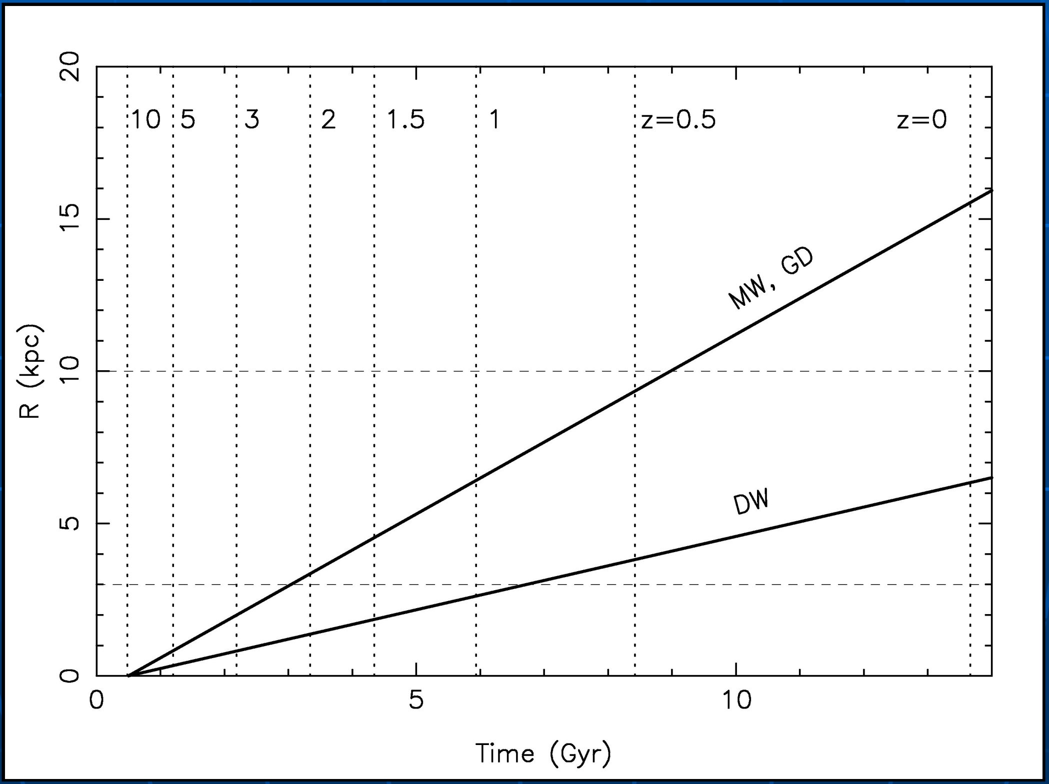


Arshakian et al. 2009

Turbulent magnetic fields can be expected after z≈10, large-scale (regular) fields after z≈4

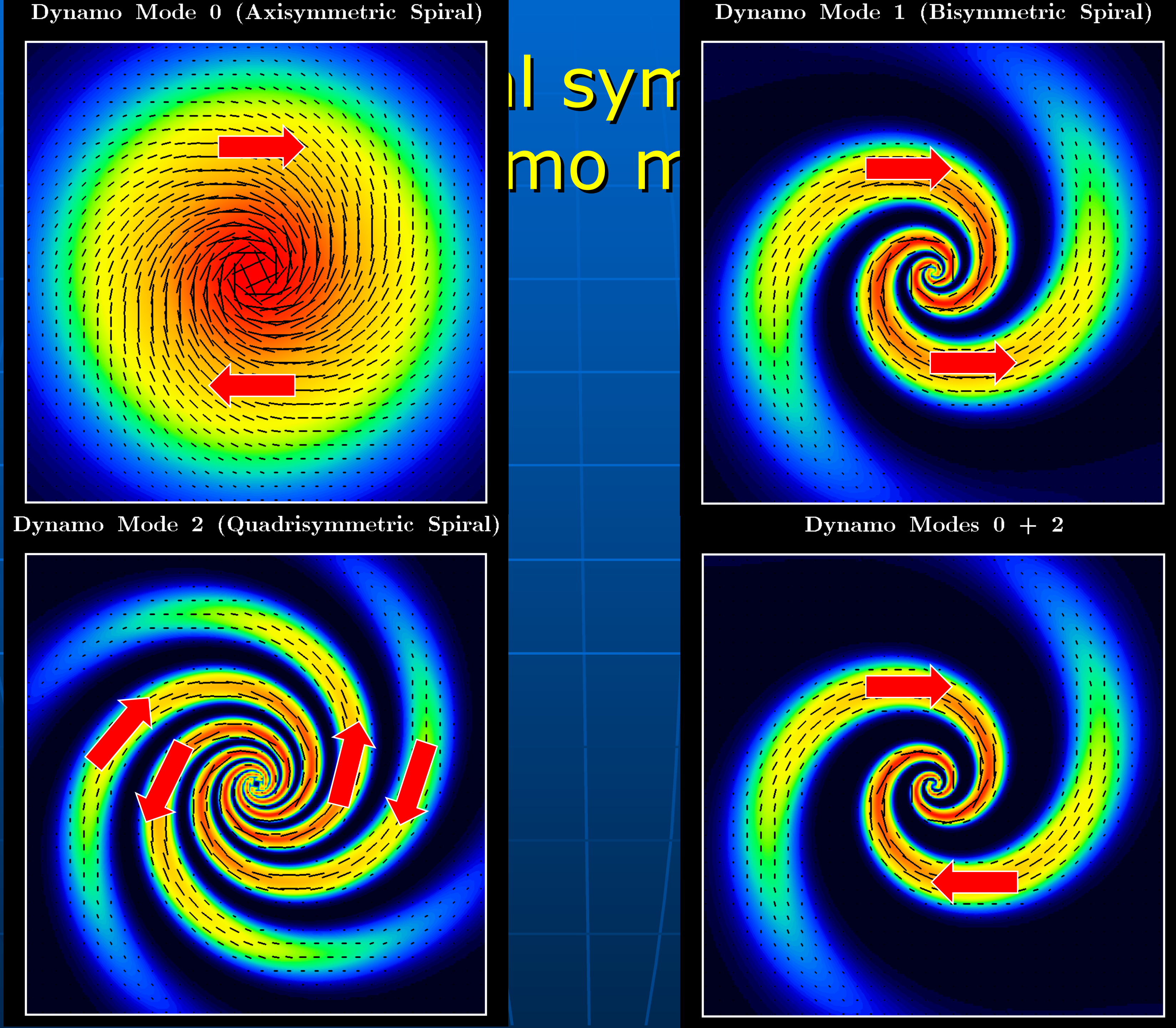
Dynamo action in evolving galaxies: coherence lengths

Arshakian et al. 2009

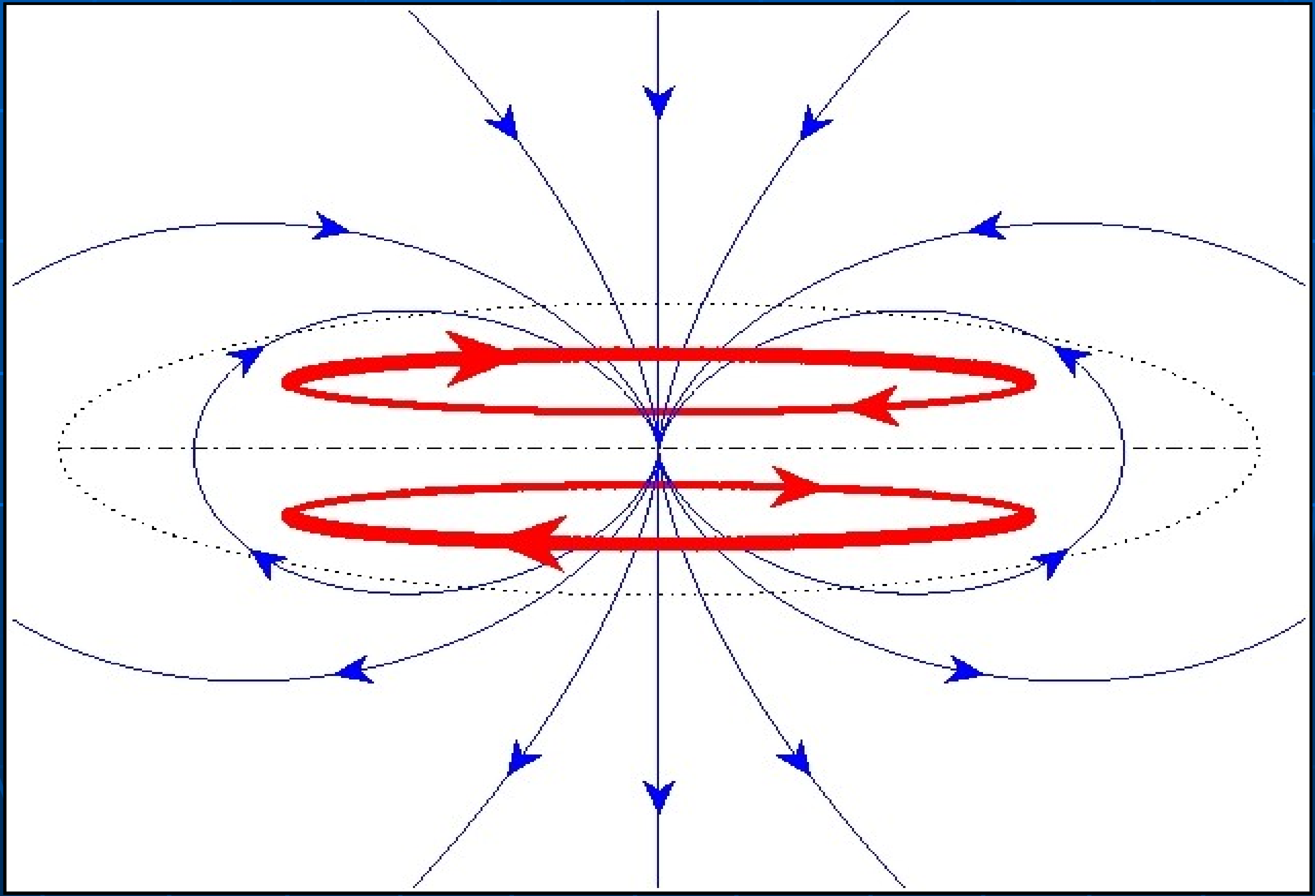


Large galaxies need more than 10 Gyr to build up a fully coherent field

l sym
mo m


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

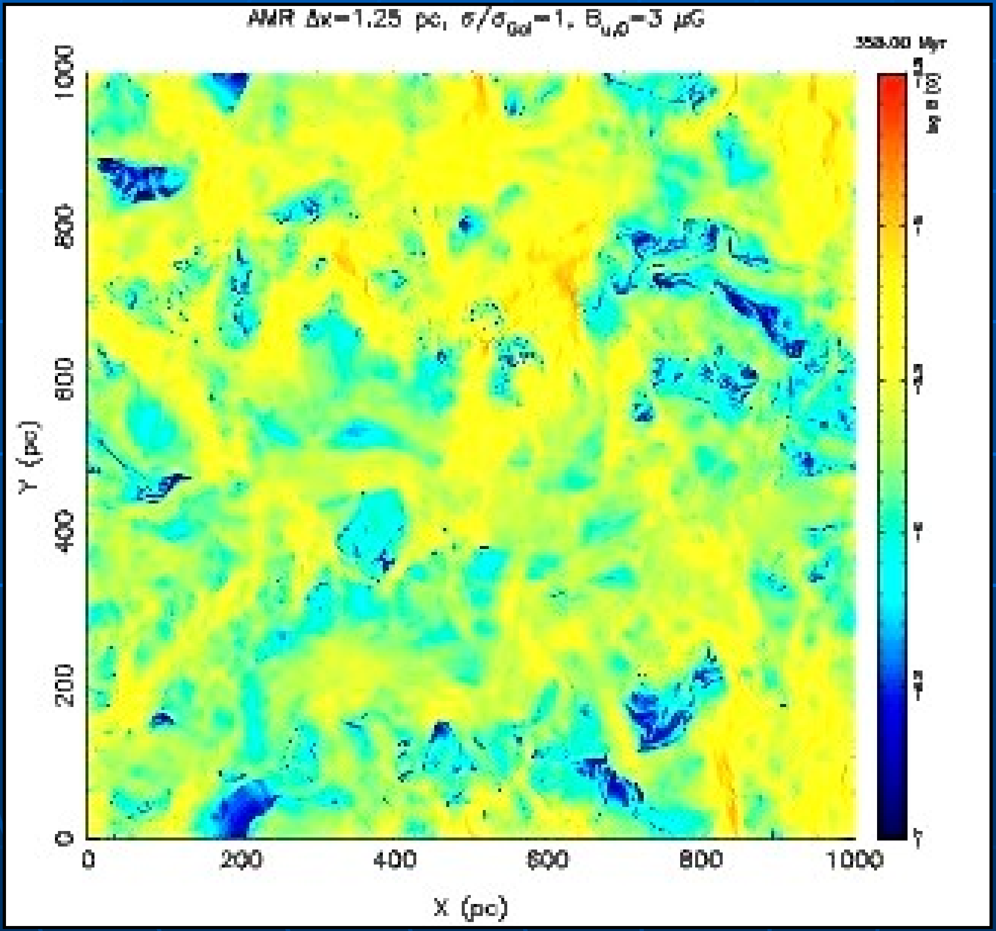
Antisymmetric (dipolar) dynamo mode



Realistic models

- MHD models: Include magnetic fields on all scales and back-reaction of the field onto gas turbulence and flows
- Include cosmic rays
- Global models of galaxies, including rotation and non-axisymmetric gas flows (e.g. spiral arms, bar and outflow)
- Include galaxy evolution

MHD model of supernova-induced turbulence in the ISM



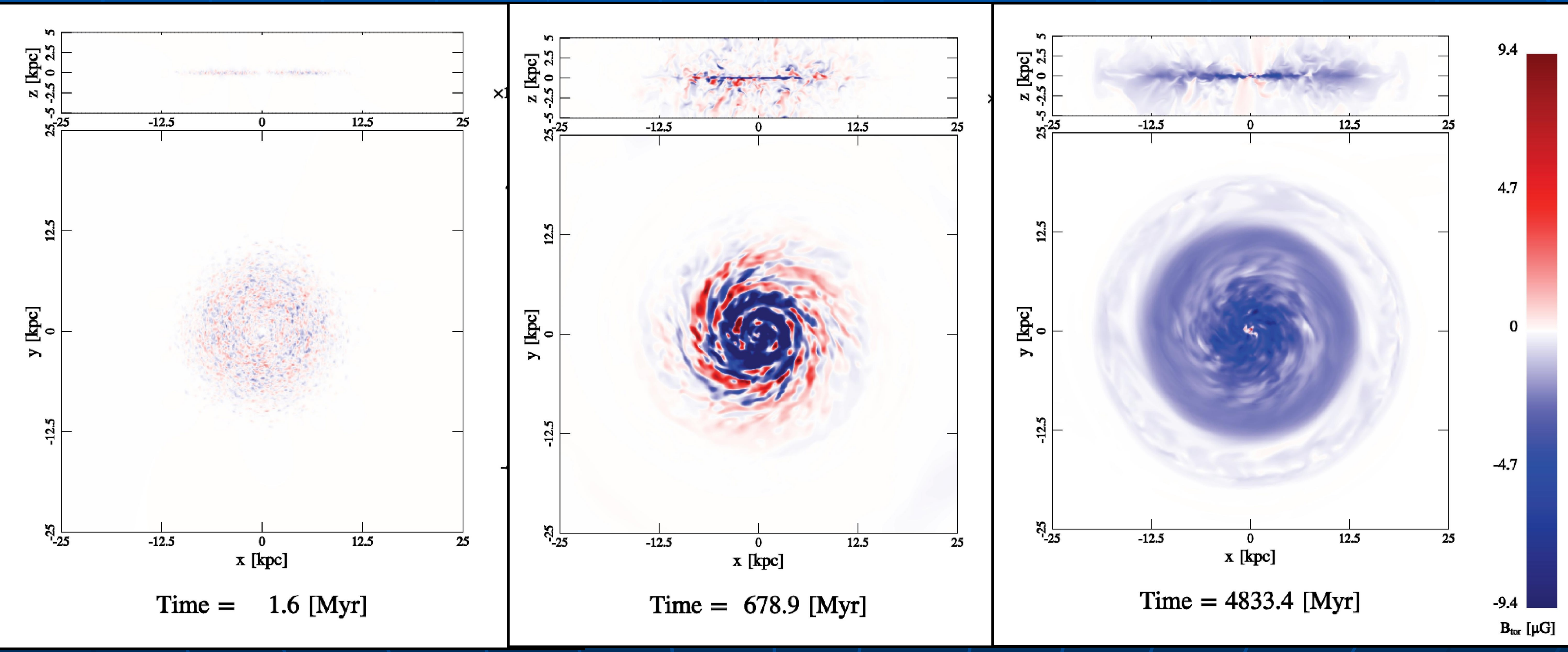
de Avillez & Breitschwerdt 2005

Generation of small-scale turbulent, filamentary fields by compression and shear

Magnetic field strength

Global cosmic-ray driven MHD model

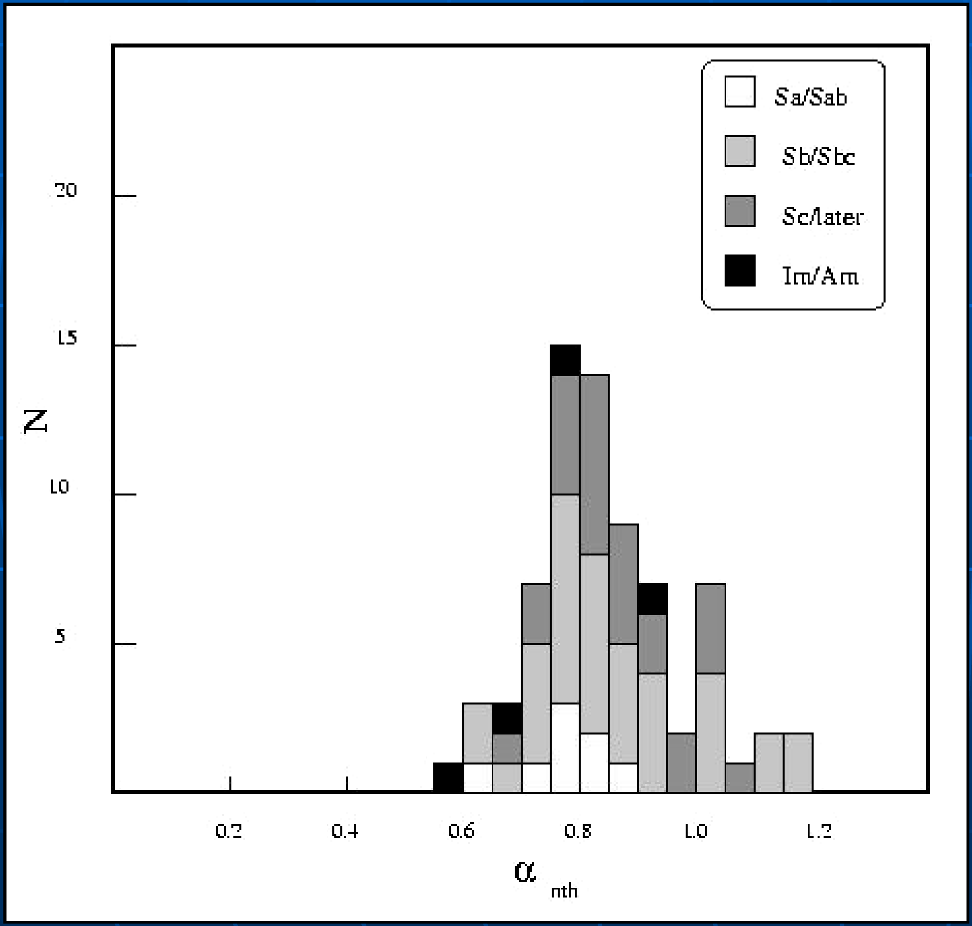
Hanasz et al., in prep.



- Field origin
- Cosmic ray electrons (GeV only)
- Field strengths and structures
- Radio halos
- Faraday rotation
- Field reversals
- Milky Way
- Future observations

Synchrotron spectra of spiral galaxies

Niklas 1995



Synchrotron spectrum:
$\langle \alpha_{syn} \rangle = 0.85 \pm 0.05$

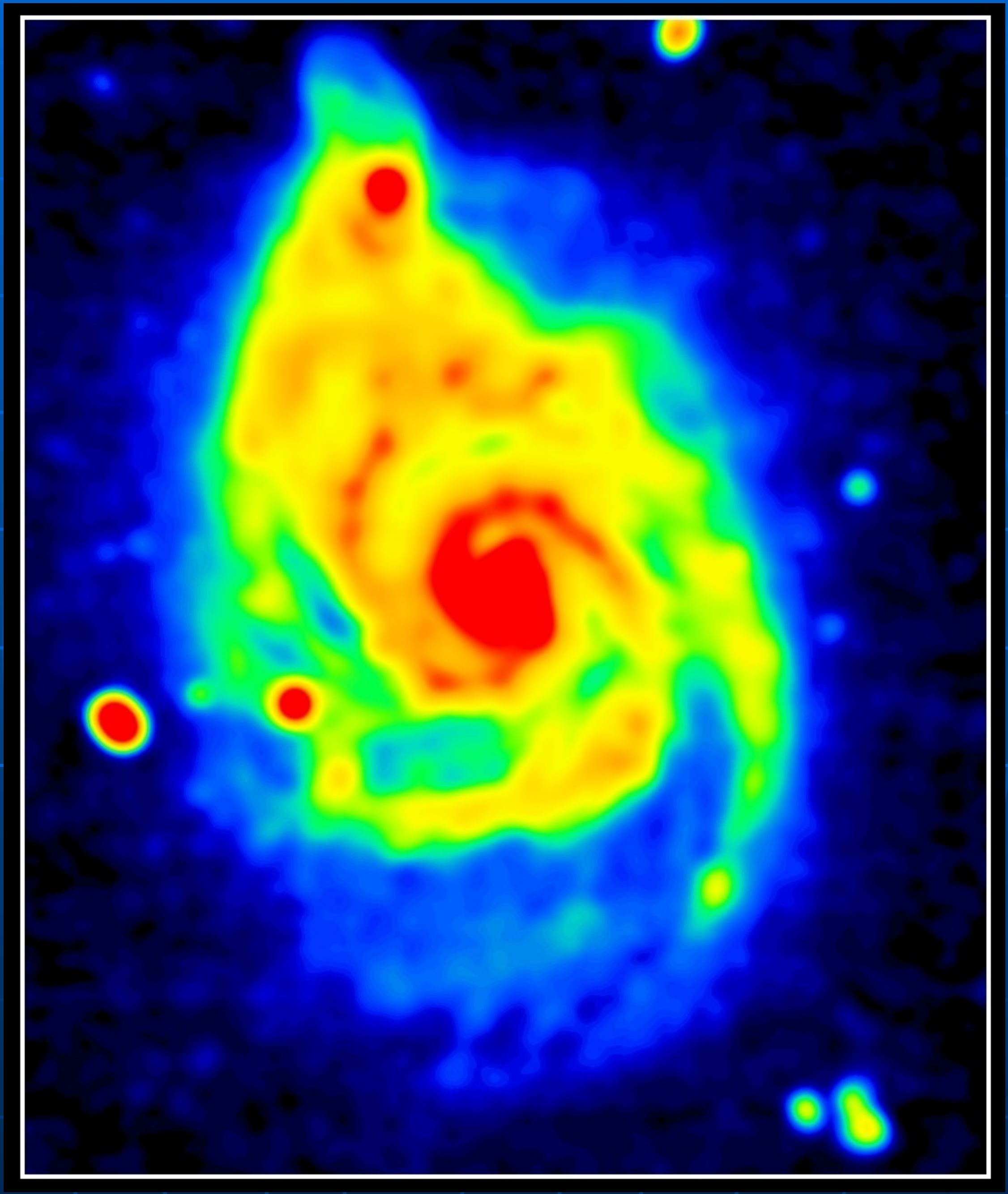
CR electron spectrum:
$\langle \varepsilon \rangle = 2.7 \pm 0.1$

Canonical value !

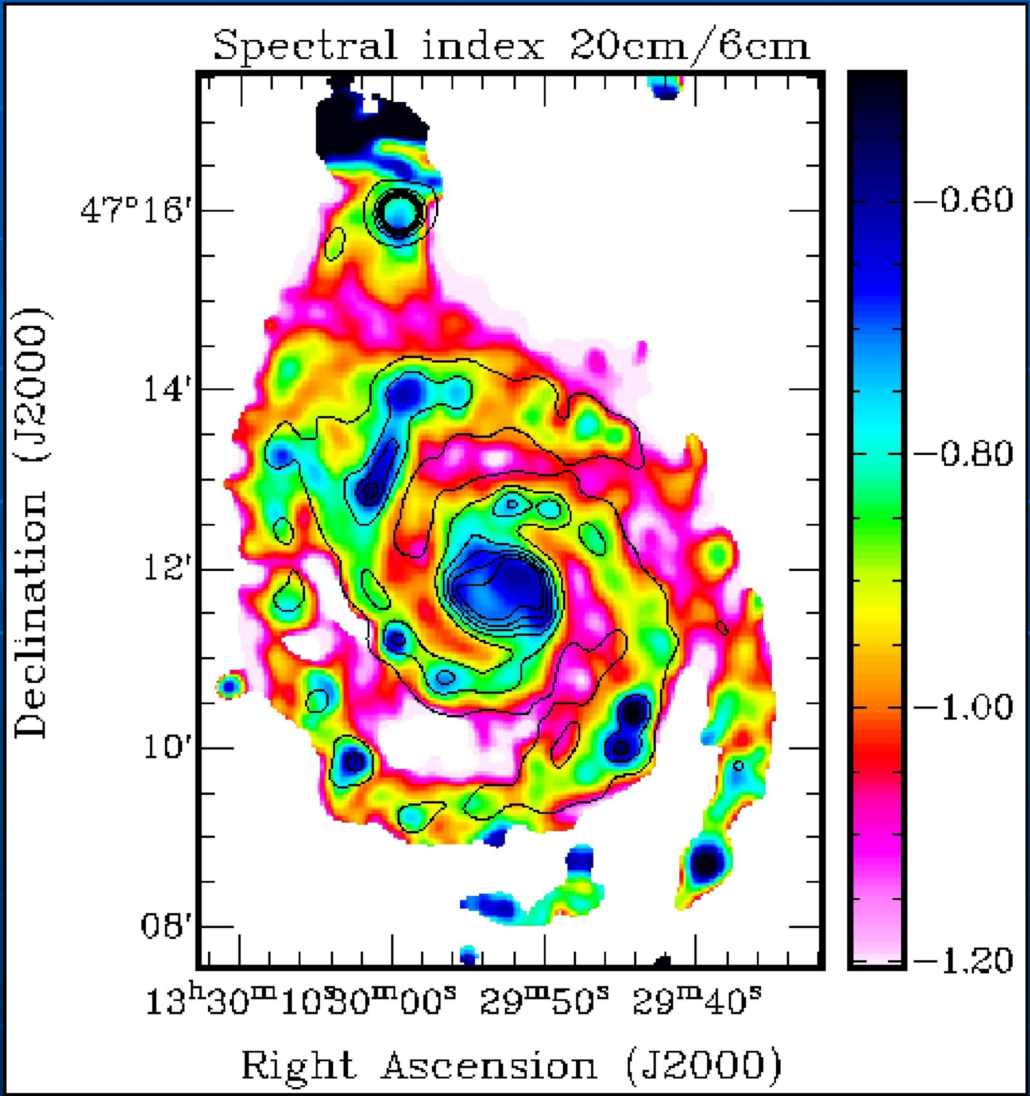
M 51

VLA 20cm

(Fletcher et al. 2009)



Radio spectral indices in M 51



Fletcher et al. 2009

Strong steepening from arm to interarm:

Synchrotron /IC losses of GeV CR electrons

Cosmic-ray electron spectra in spiral galaxies

1. Spiral arms:
   Injection by strong shocks in supernova remnants ($\varepsilon \approx 2.2$) + energy-dependent escape ($\delta \approx 0.5$)

4. Interarm regions:
   Mixture of young particles from SNR ($\varepsilon \approx 2.2$) and old particles with spectra steepened by synchrotron / IC losses ($\varepsilon \approx 3.2$)

Diffusion of cosmic-ray electrons in M51

Fletcher et al. 2009

- Lifetime of synchrotron-emitting electrons:

ν_{syn} = 5 GHz, $B_\perp$ = 15 μG: $t_{syn} \approx$ 8 Myr

- Propagation length: L ≈ 1 kpc
- Diffusion coefficient:

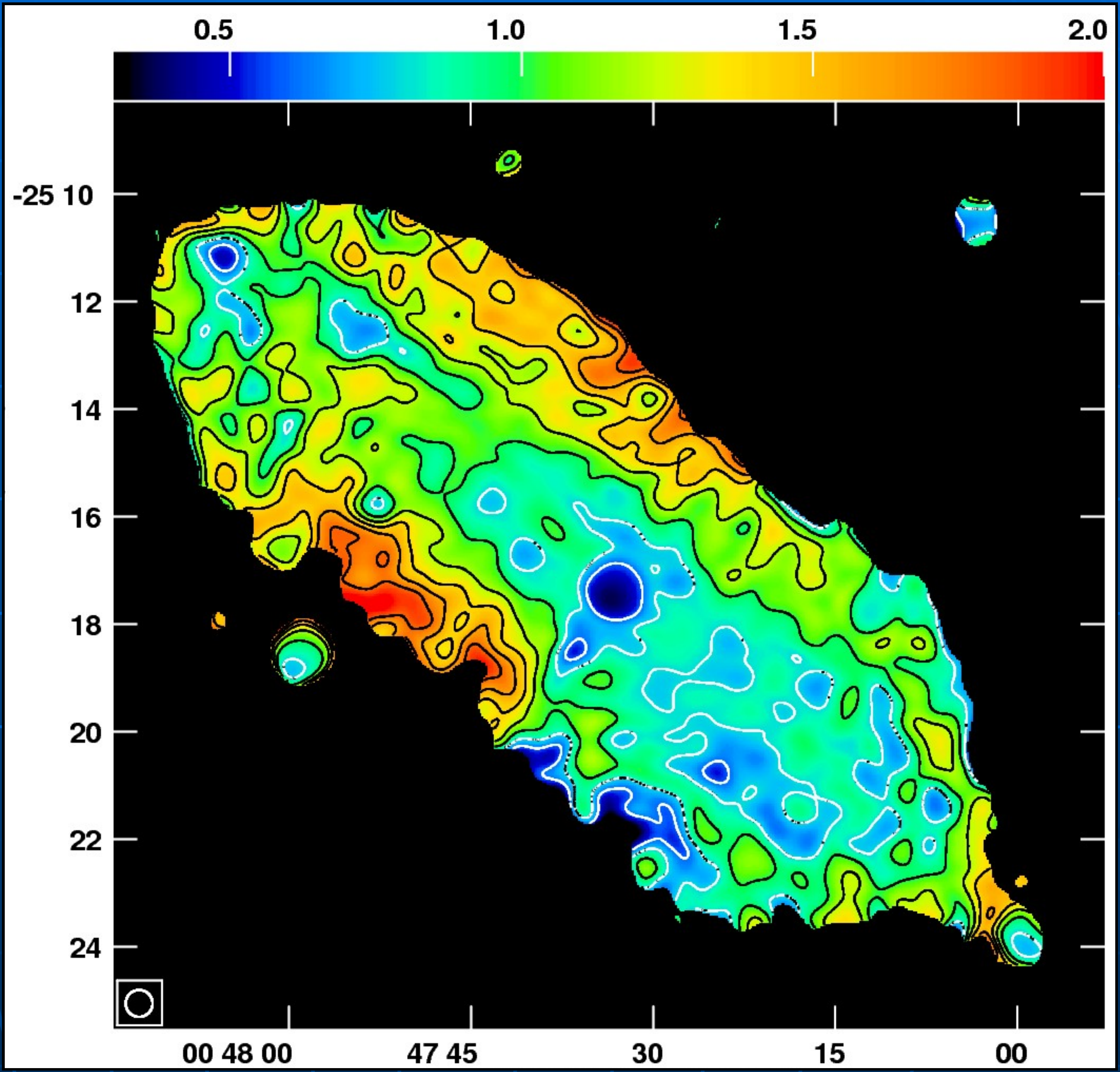
$$D = L^2 / t_{syn} \approx 4\ 10^{28}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$

NGC 253

Spectral index 6/20cm
(Heesen et al. 2009)

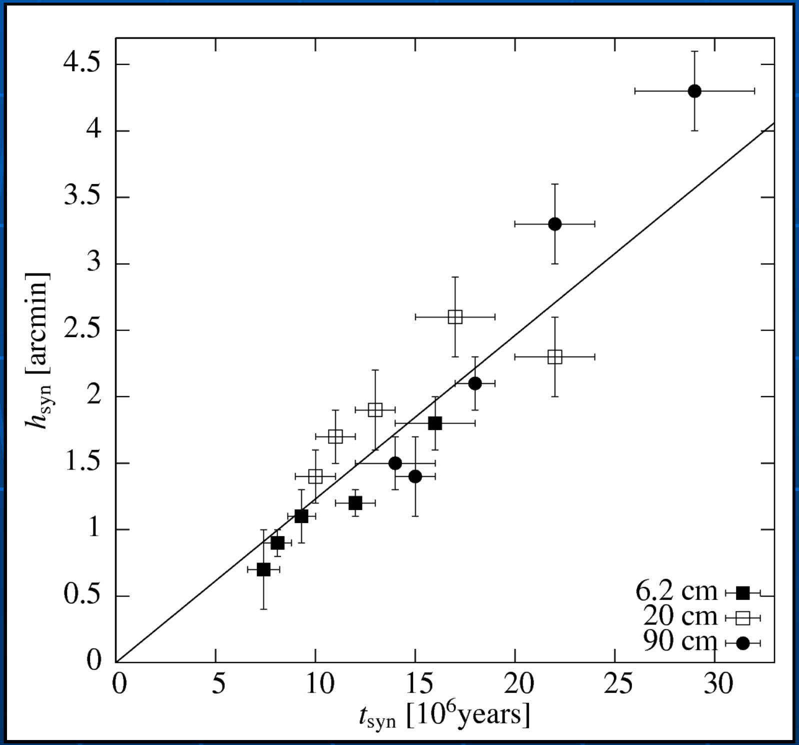
Spectral index steepens with height:

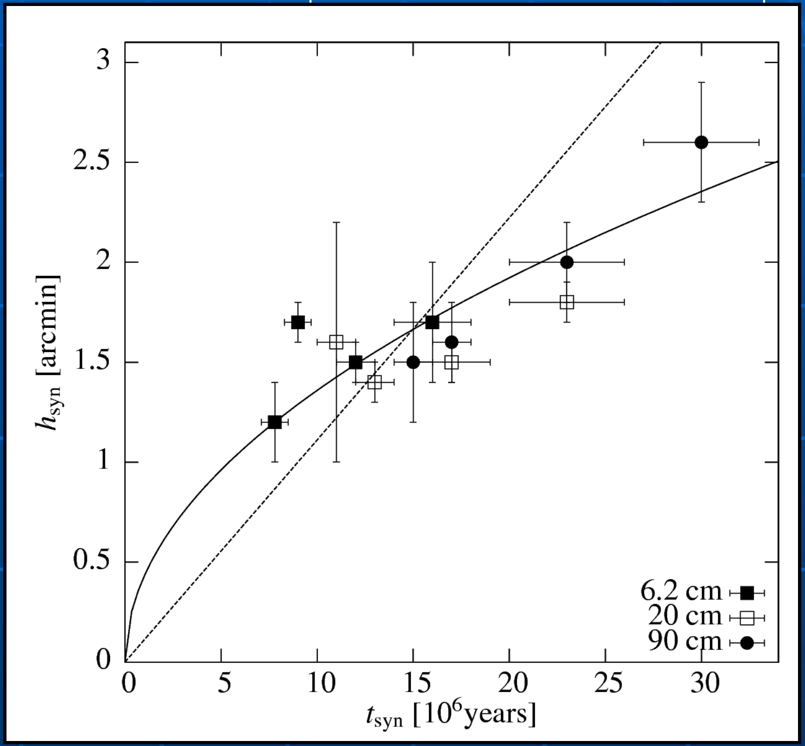
Synchrotron losses of GeV CREs



Scale heights of cosmic-ray electrons in NGC 253

Heesen et al. 2009





- North: Convection dominates, bulk speed $v_z = 300 \pm 30$ km/s
- South: Diffusion dominates, $D = (2 \pm 0.2)\ 10^{29}$ cm^2 s^{-1}

- Field origin
- Cosmic ray electrons
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- Radio halos
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Equipartition strength of the total field

(assuming equipartition between magnetic fields and total cosmic rays)

Beck & Krause 2005

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

I_{sync}: Synchrotron intensity

L: Pathlength through source

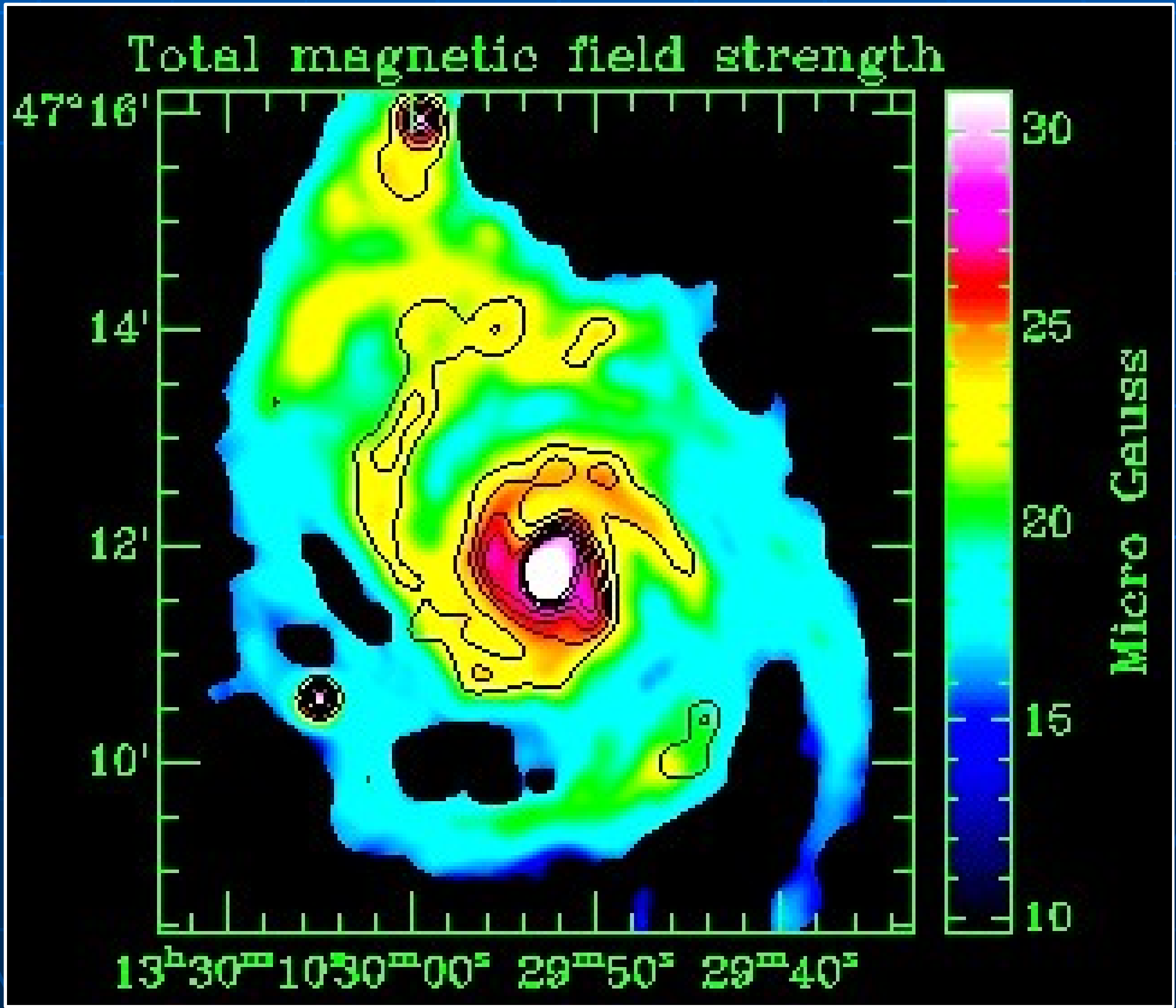
α: Synchrotron spectral index ($S \propto \nu^{-\alpha}$)

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

Usual assumption: K=100

Equipartition field strengths in M 51

Fletcher et al. 2009



Equipartition magnetic field strengths in spiral galaxies

Average total field in disks:	**5 – 15 μG**
Total field in spiral arms:	**20 - 30 μG**
Total field in interarm regions:	**10 - 15 μG**
Regular field in interarm regions:	**5 - 15 μG**
Total field in halos:	**≤ 10 μG**
Total field in starburst regions:	**40 – 100 μG**

Typical radial scale lengths of disks of spiral galaxies

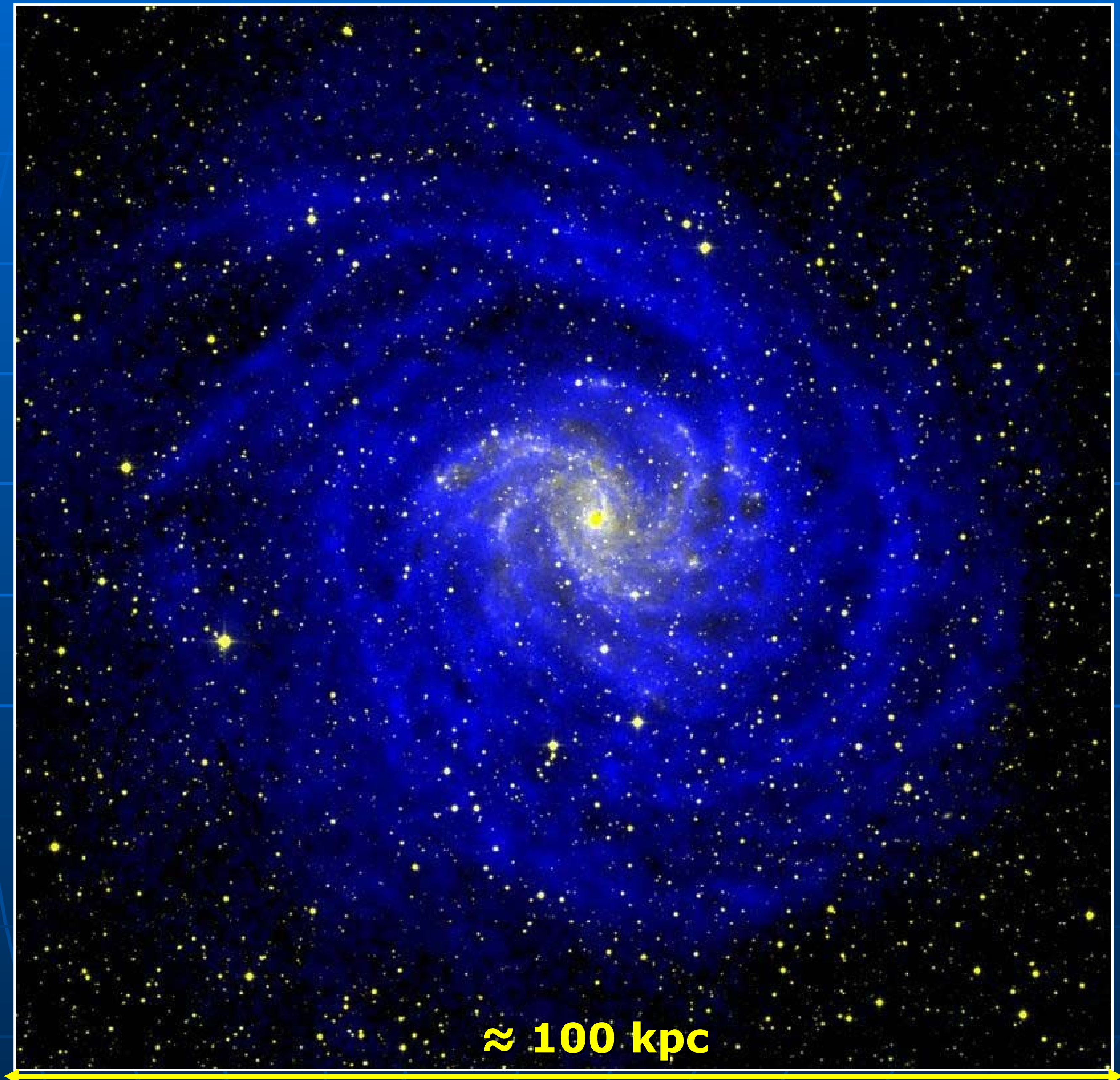
- Cold & warm gas: ≈4 kpc
- Synchrotron: ≈4 kpc
- Cosmic-ray electrons: ≤8 kpc
  (upper limit due to energy losses of CREs)
- Total magnetic field strength: **≥16 kpc**

The full extent of the magnetic field into intergalactic space is not yet known !

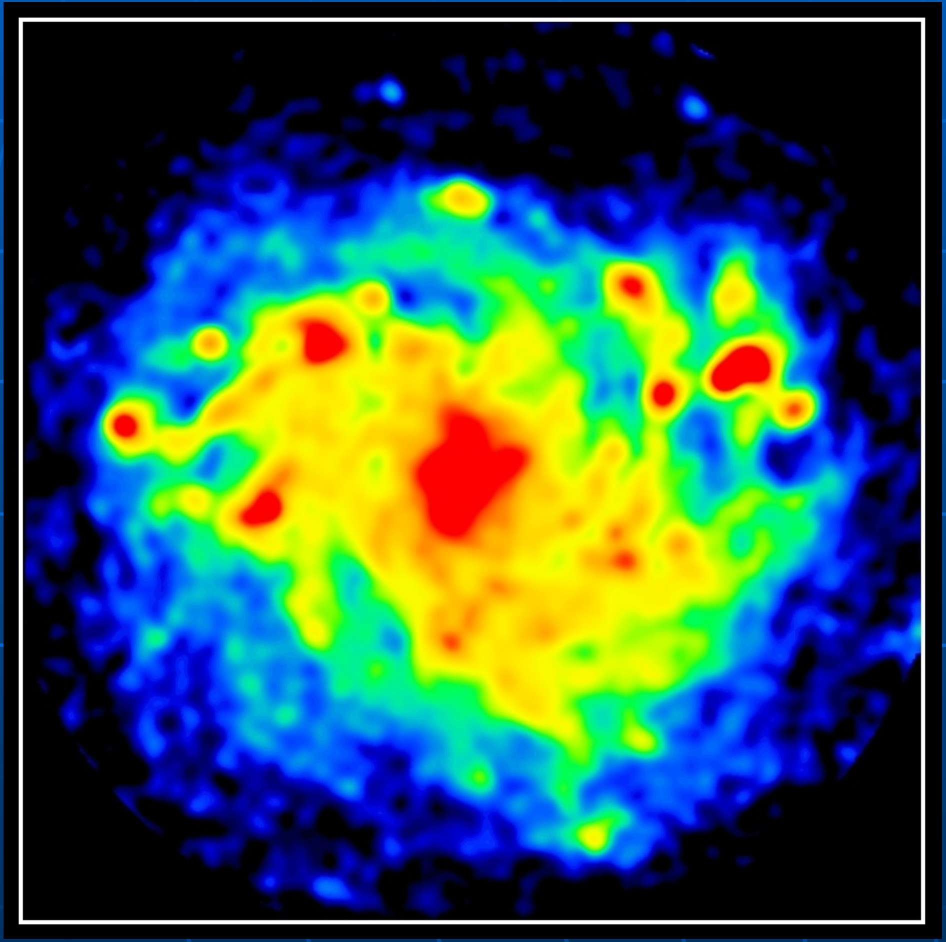
NGC 6946

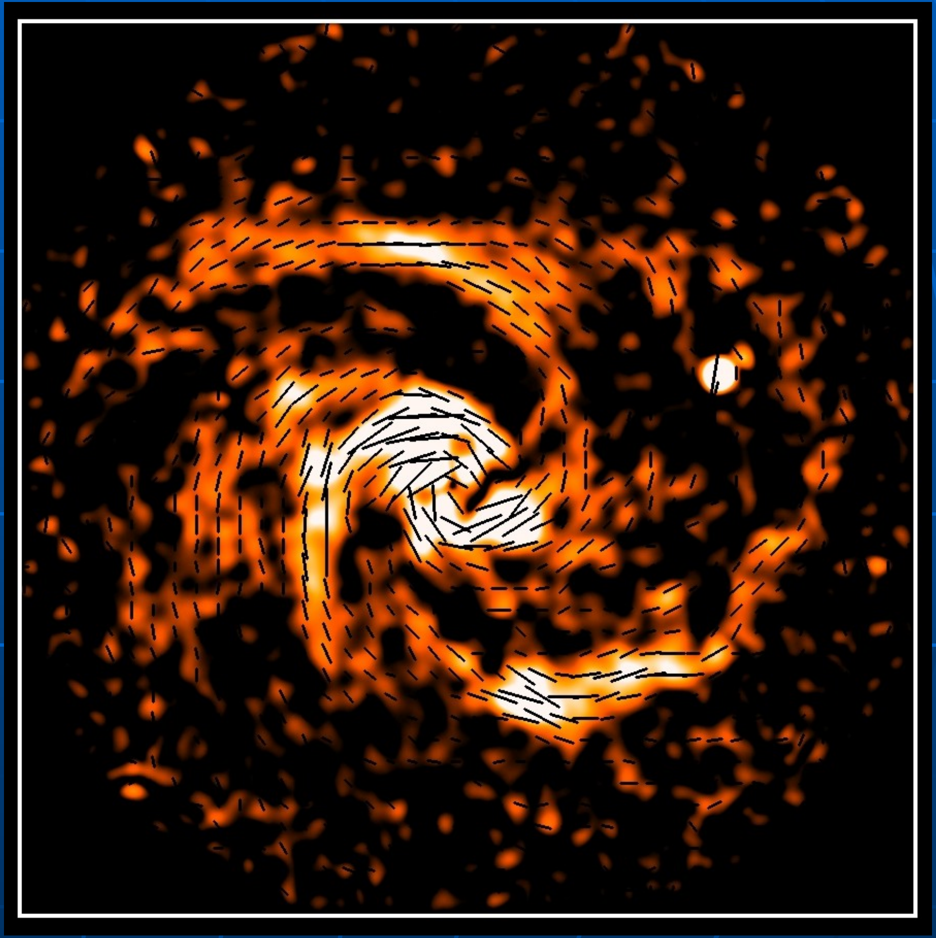
WSRT HI
+ optical
(Boomsma et al. 2006)

Where does
a galaxy end ?



Synchrotron polarization



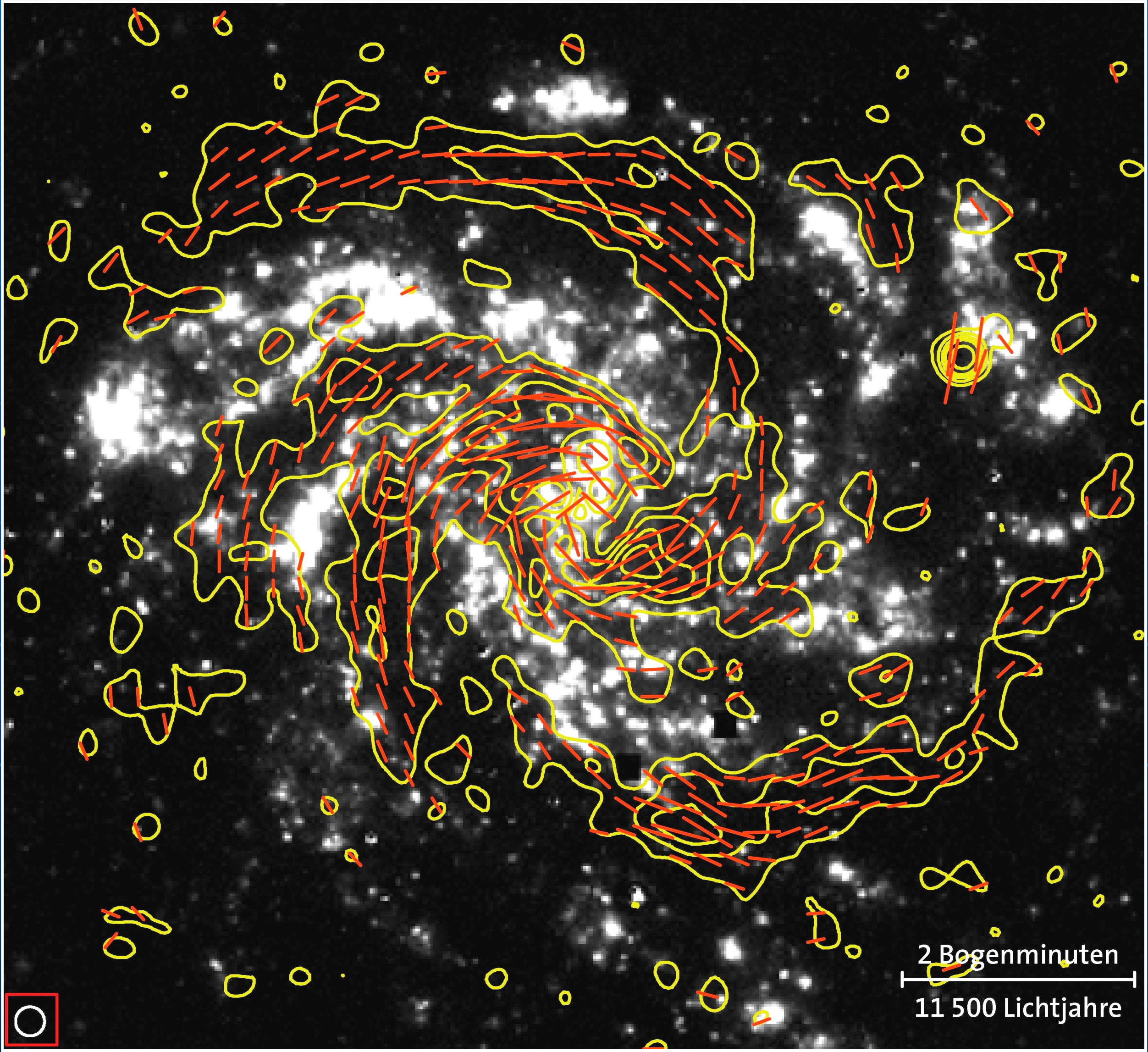


VLA + Effelsberg 6cm

Beck & Hoernes 1996

NGC 6946

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

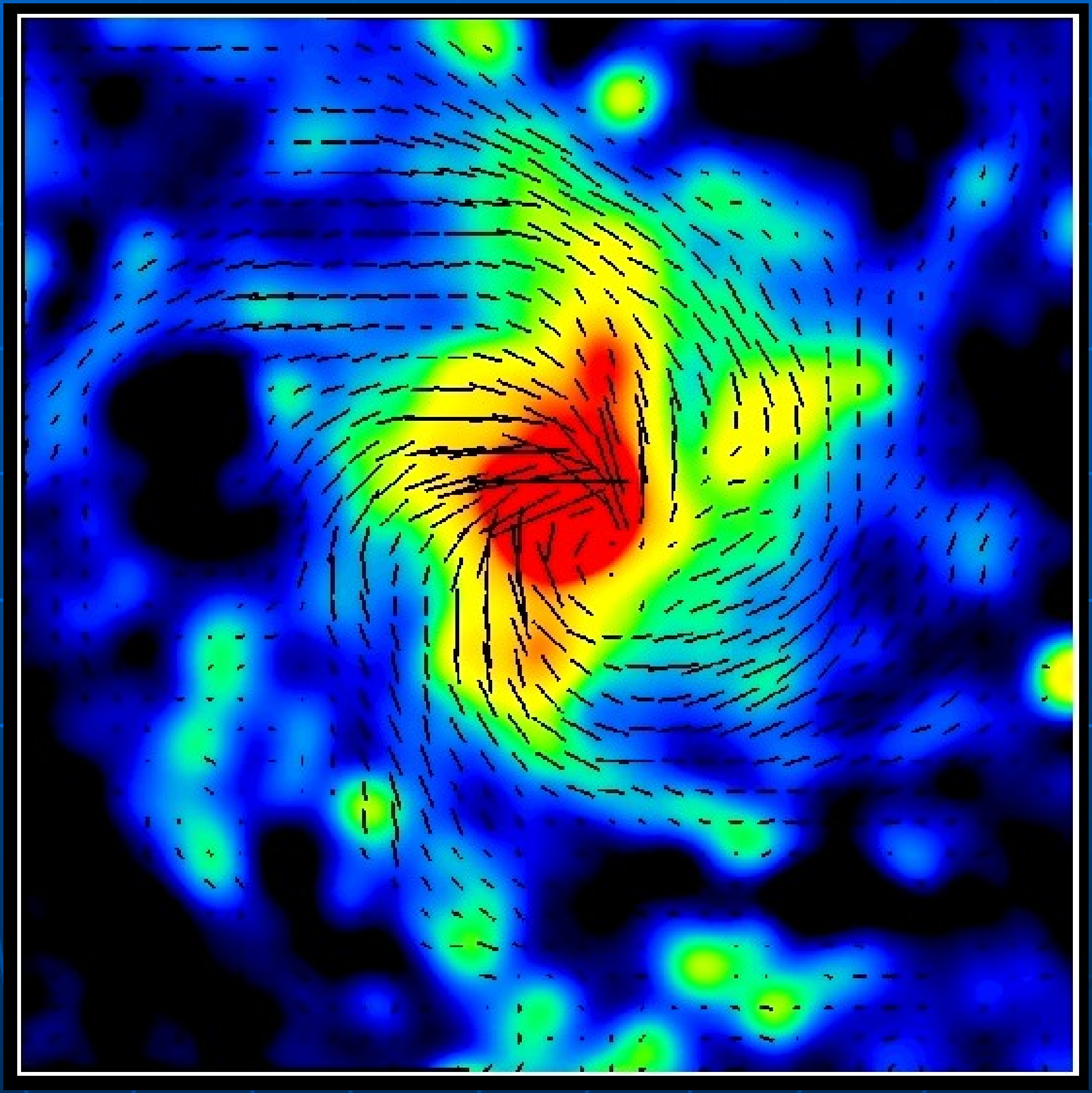


"Magnetic arms":

Ordered fields concentrated in interarm regions

NGC 6946 Center

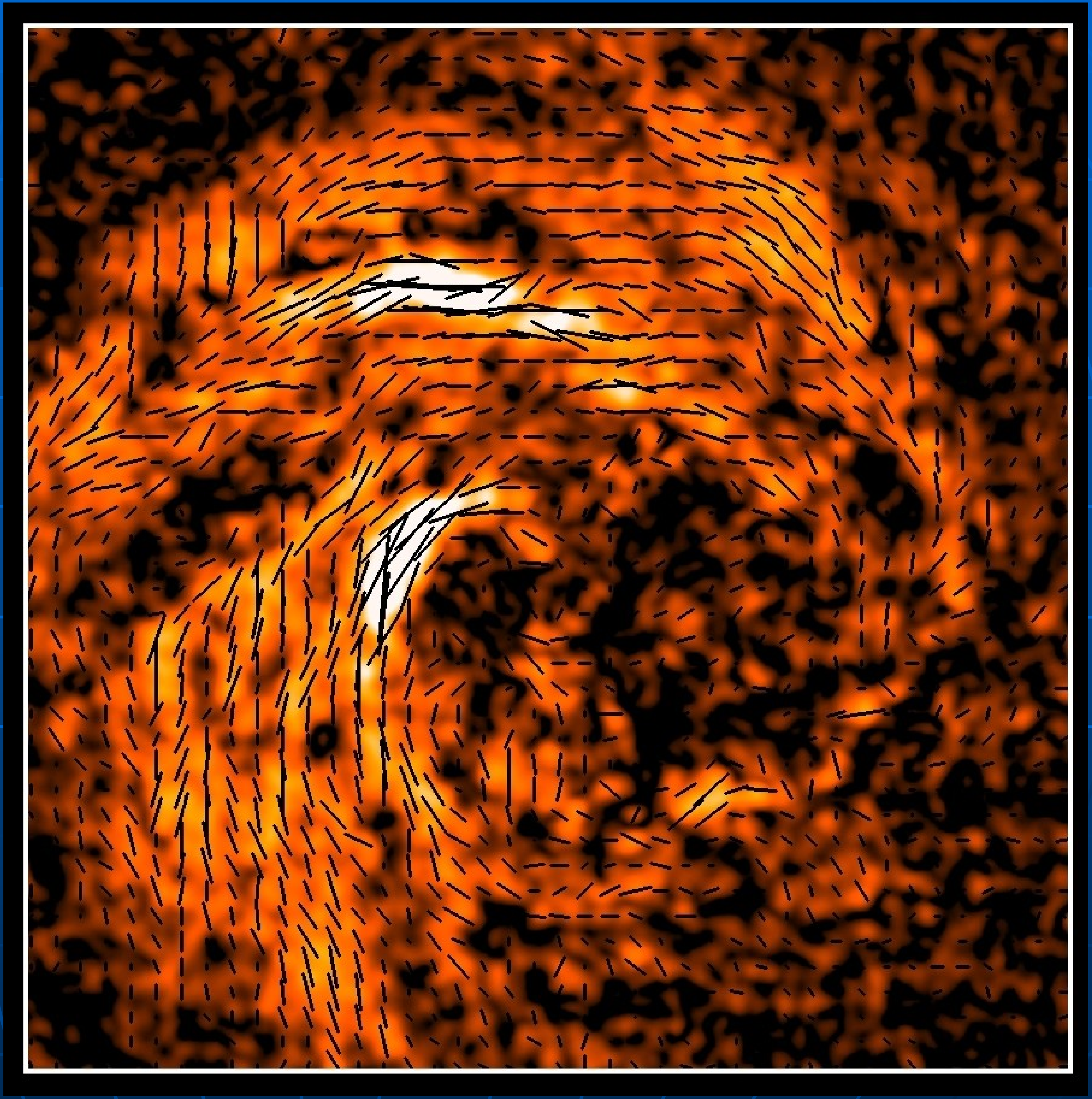
3cm VLA
Total intensity
+B-vectors
(Beck 2007)



The spiral field continues deep into the central region

NGC 6946

VLA Polarized Intensity + B (Beck 2006)



Deep mapping:

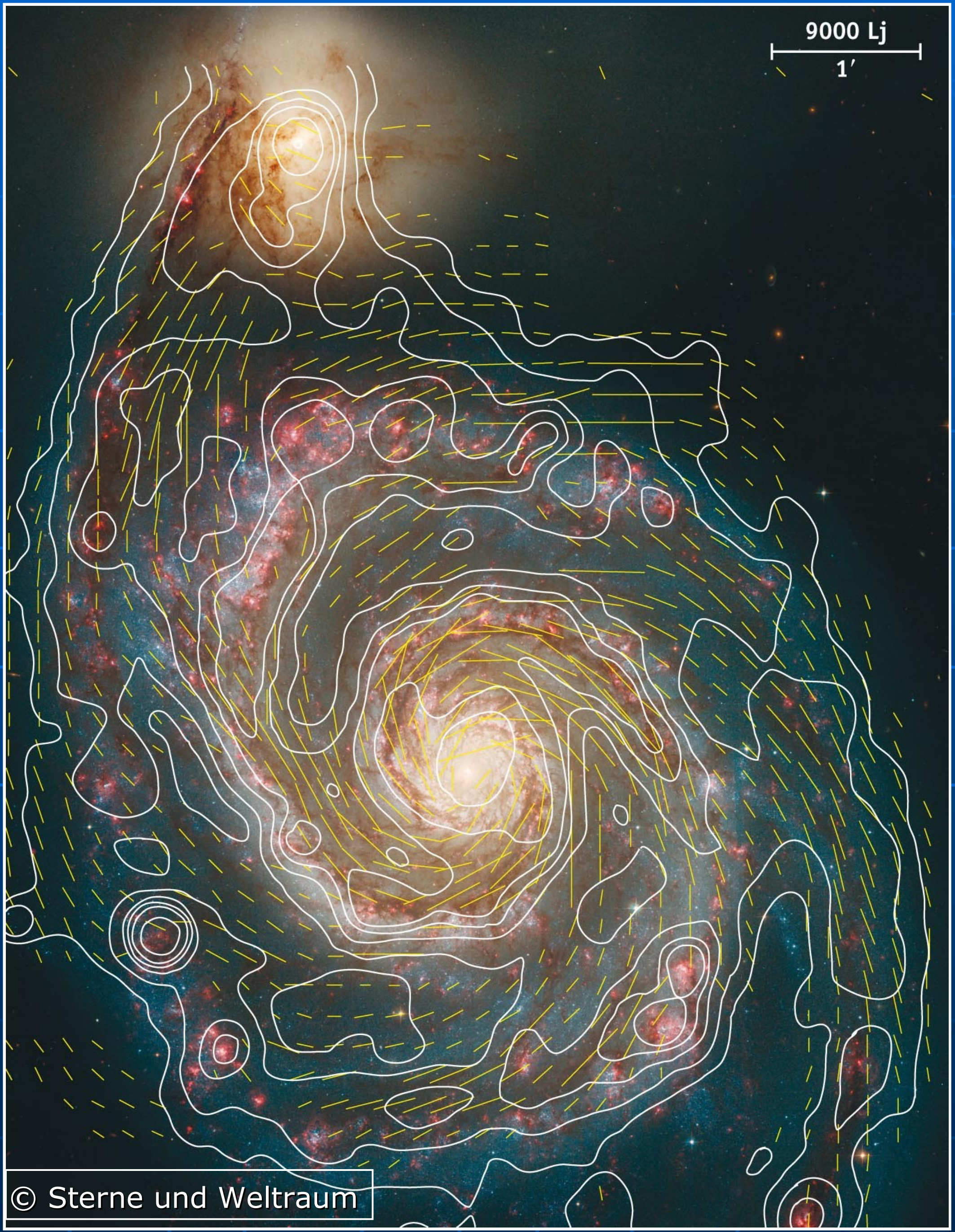
More magnetic spiral arms out to ≥ 25 kpc

M 51

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

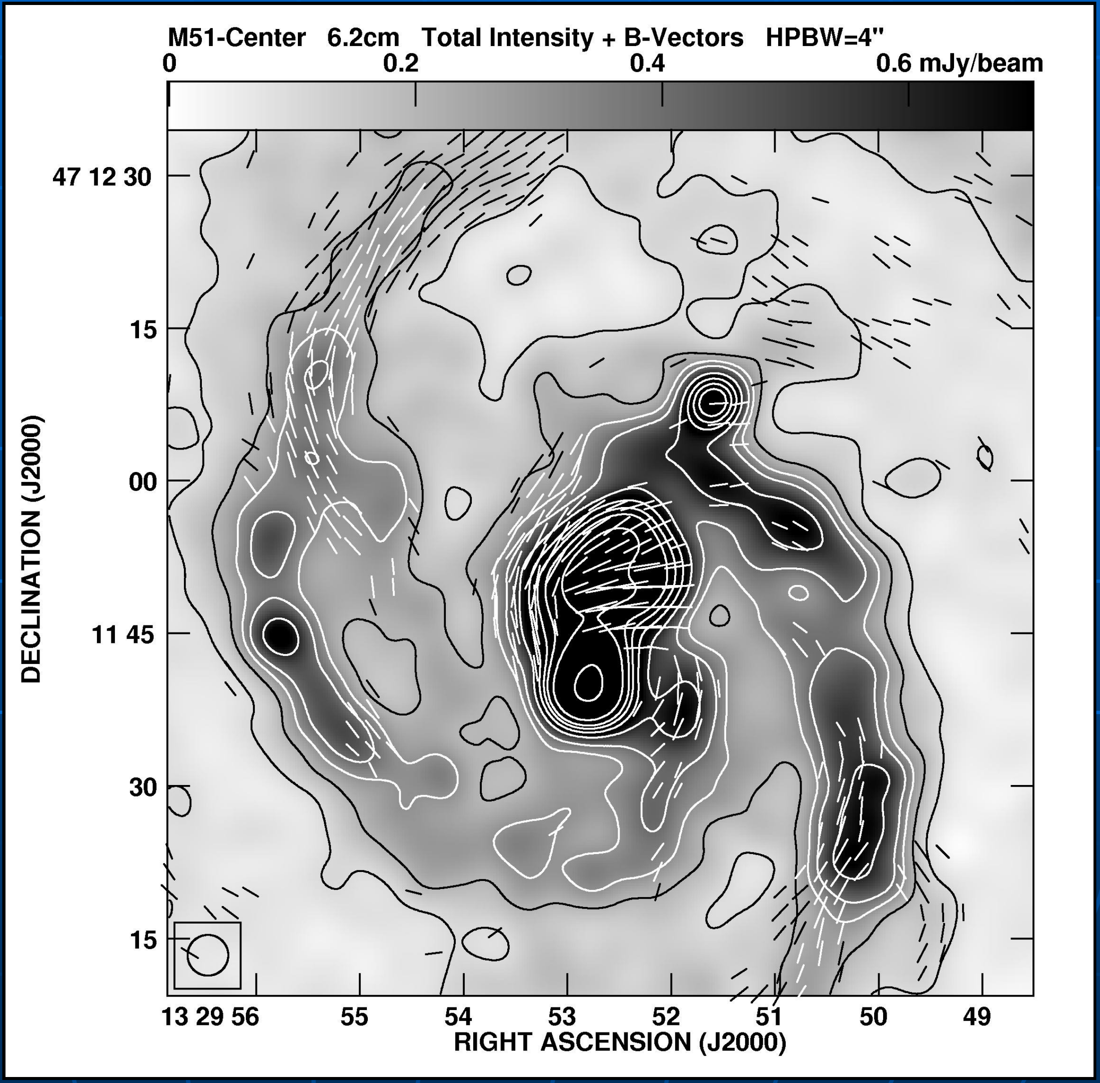
Prototypical
density-wave galaxy:

Spiral fields
along and between
the optical spiral arms



M 51

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

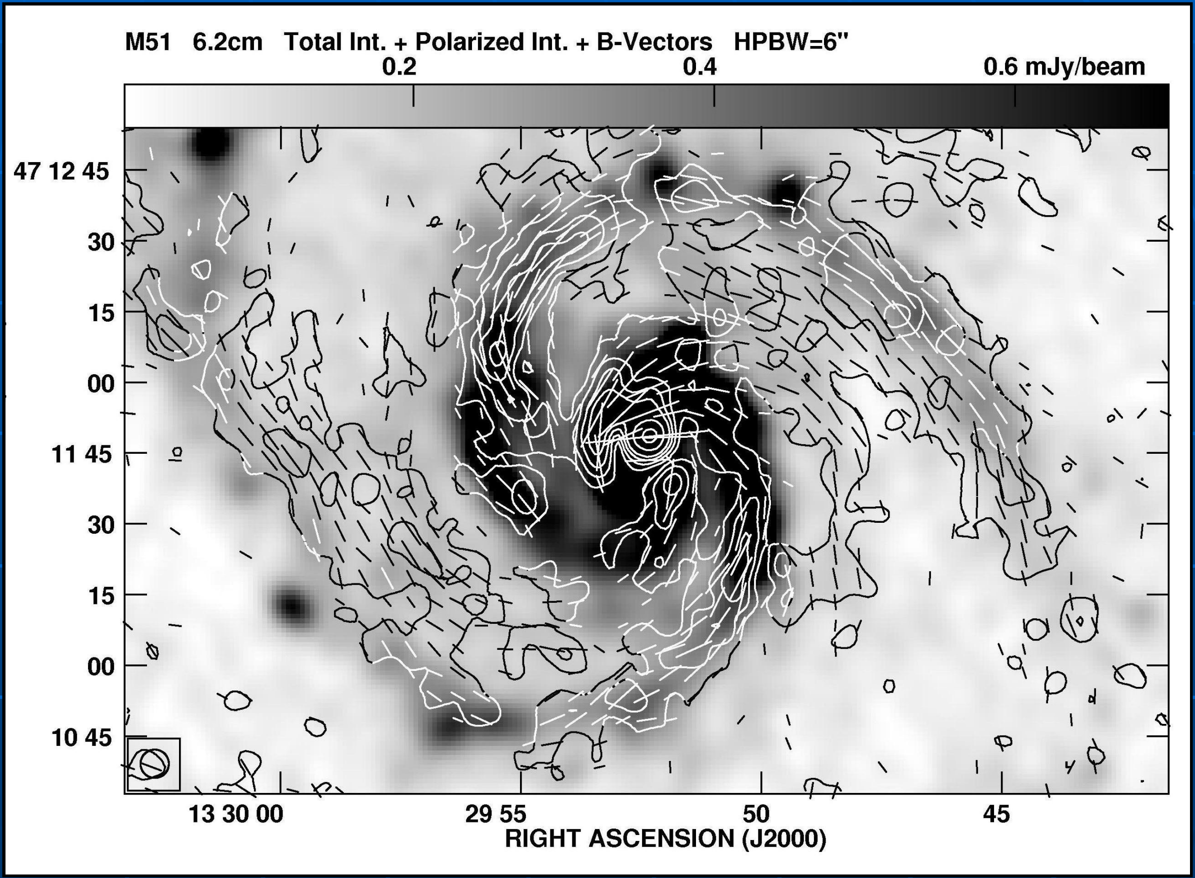


Spiral fields parallel to the inner spiral arms:

Strong density-wave compression

M 51

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

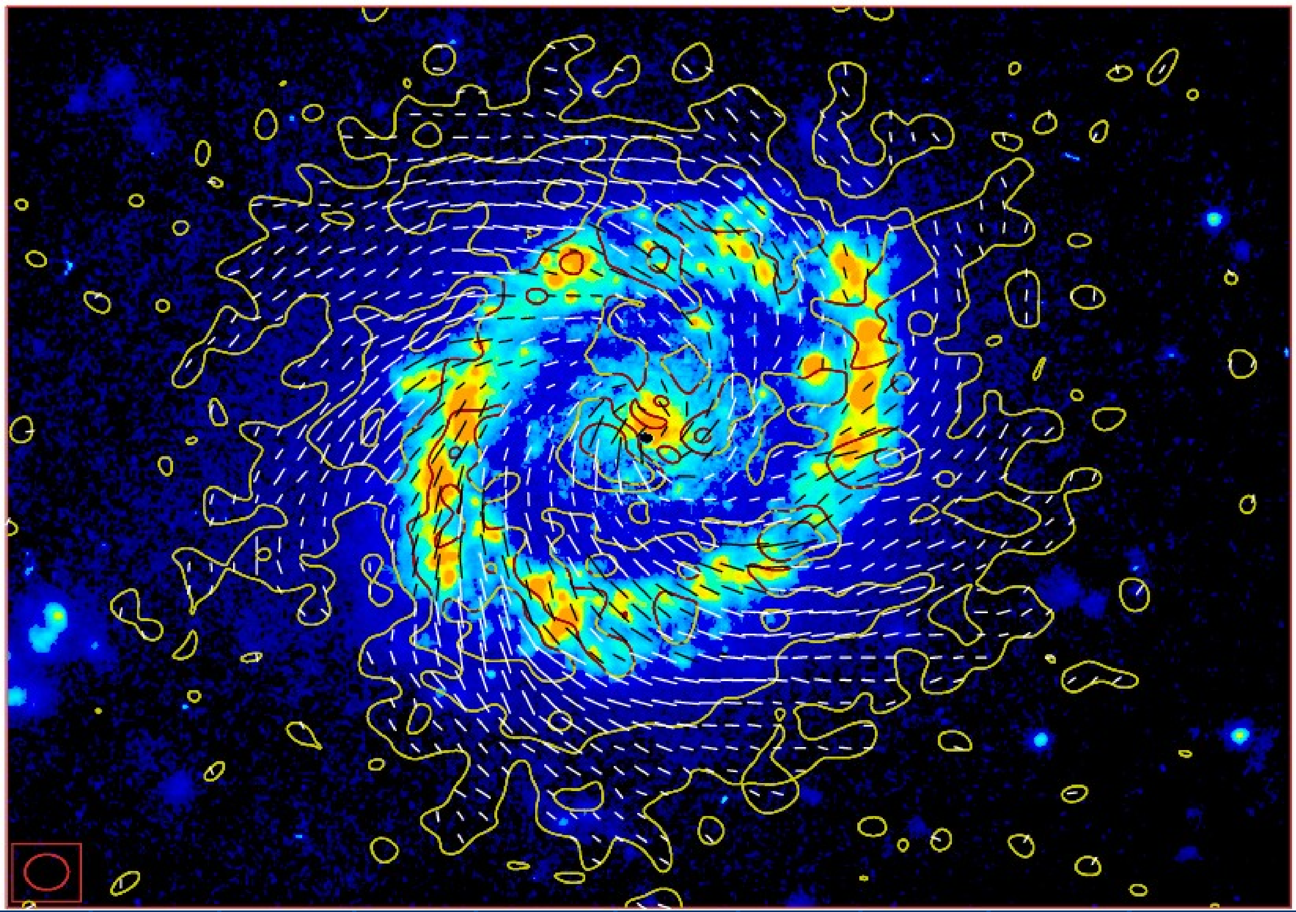


Spiral fields
between the
outer spiral arms
(weak density waves):

Dynamo action?
Shear?

NGC 4736

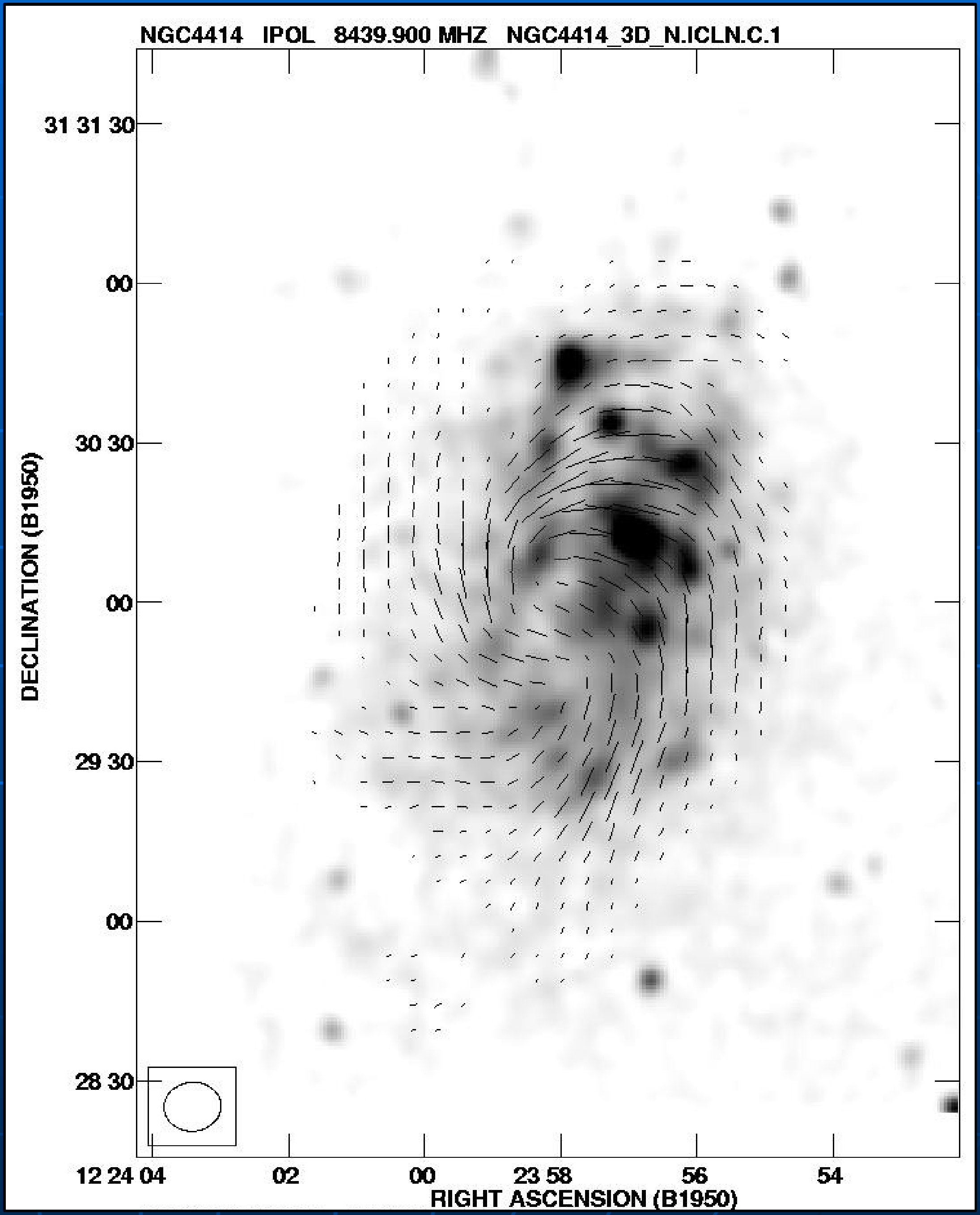
3cm VLA
Polarized intensity
+ B-vectors
(Chyzy & Buta 2007)



Spiral fields
in a ring galaxy

NGC 4414

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



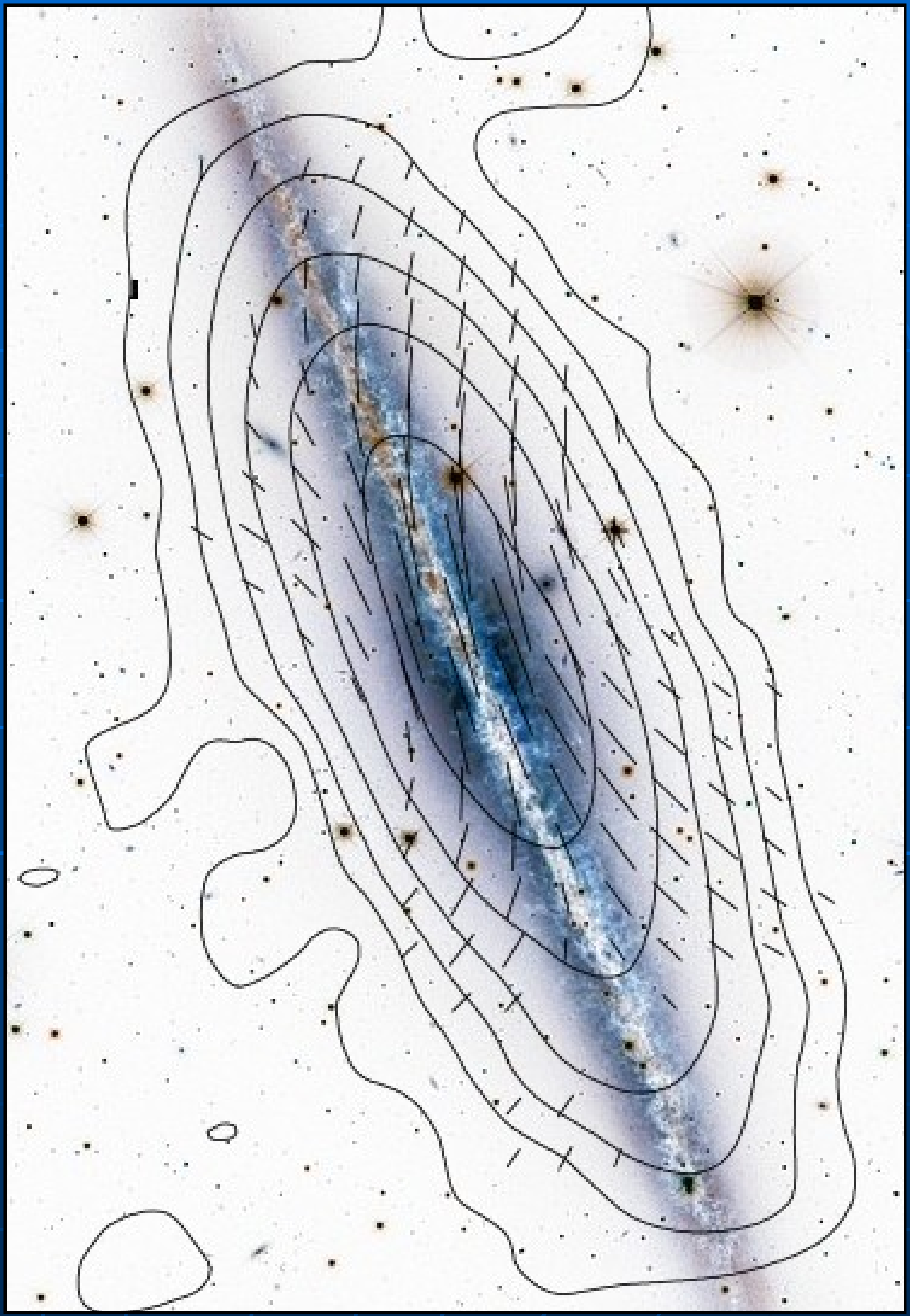
Flocculent galaxies:

Spiral field exists
even without spiral arms,
large pitch angles

- Field origin
- Cosmic ray electrons
- Field strengths and structures
- Radio halos
- Faraday rotation
- Field reversals
- Milky Way
- Future observations

NGC 891

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



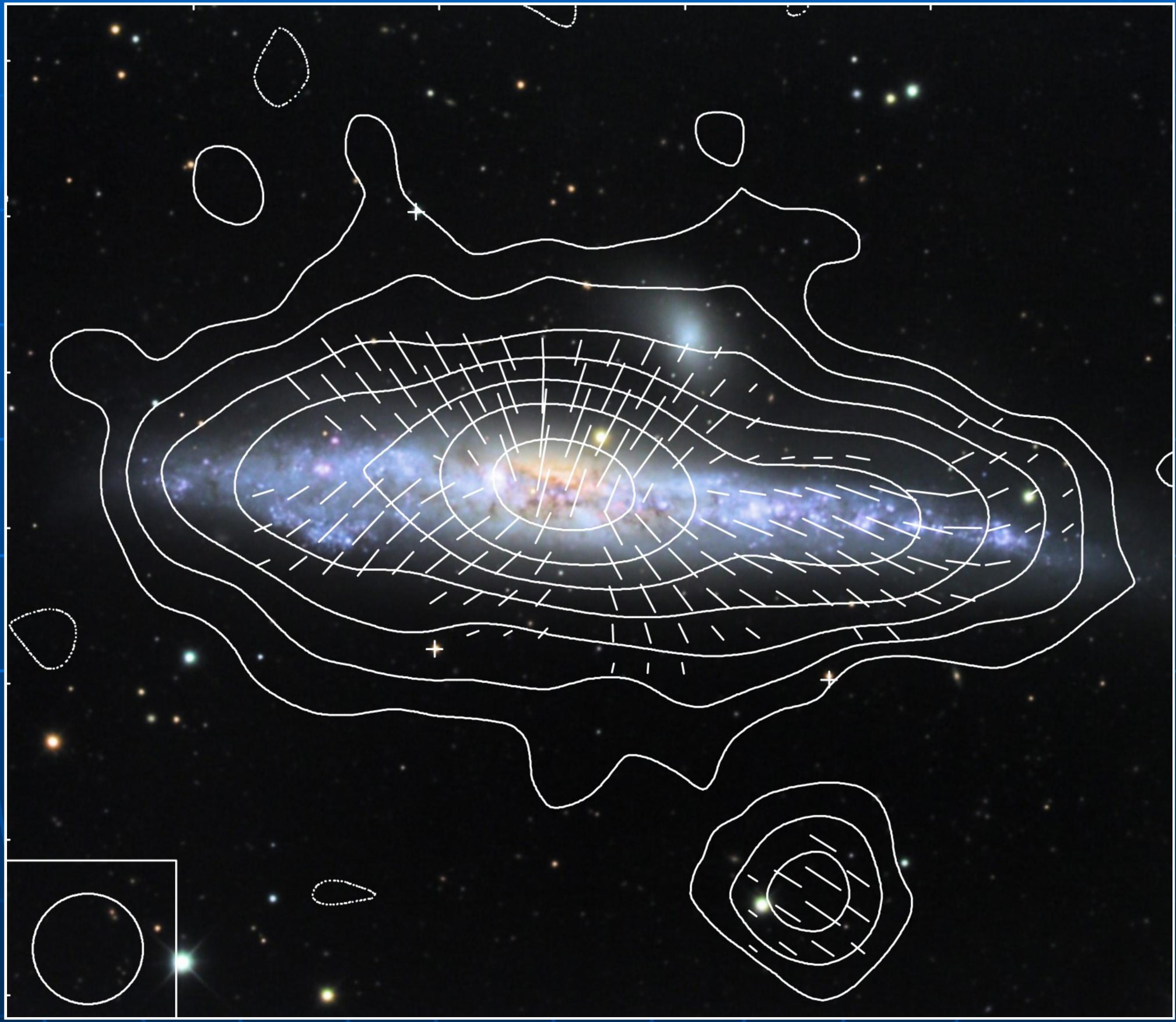
Similar to the Milky Way !

Bright radio halo with X-shaped field pattern:

Vertical field increases with increasing height

NGC 4631

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



Huge halo with exceptionally large scale height and strong vertical field

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

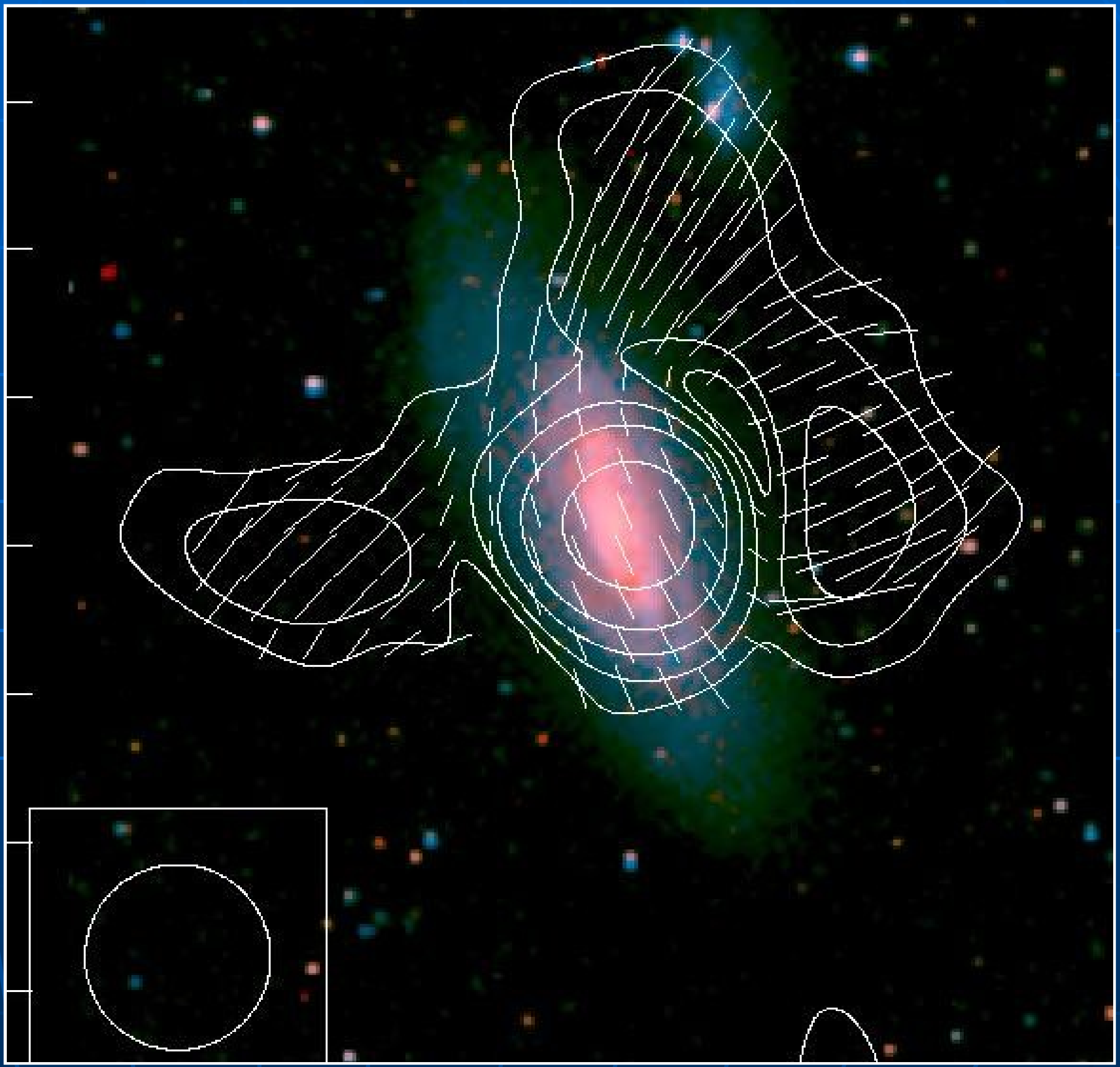
Typical scale heights of radio halos

- Cold gas: ≈0.1 kpc
- Warm gas: ≈2 kpc
- Synchrotron: ≈1.5-2 kpc
- Cosmic-ray electrons: ≤ 3-4 kpc

  (assuming equipartition, upper limit due to energy losses of GeV CREs)
- Total magnetic field strength: **≥ 7-8 kpc**

NGC 4569

6cm Effelsberg
Polarized intensity
+ B-vectors
(Chyzy et al. 2006)



Field pulled out
and ordered –

tracer of
past interactions

Results (1): Ordered magnetic fields

- Ordered magnetic fields prefer spiral patterns
- Ordered magnetic fields are hardly compressed in spiral arms and bars
- Ordered magnetic fields are concentrated in interarm regions
- Ordered fields in radio halos are X-shaped
- Ordered magnetic fields keep memory of past interactions

Random (turbulent) fields

- Ratio of random to ordered magnetic fields:
  - ≥ 4 in spiral arms, bars and starburst regions
  - 0.5 – 2 in magnetic arms
  - 1 - 3 in halos

- Random and ordered fields are anticorrelated

- Turbulence scale of random fields: 10-50 pc

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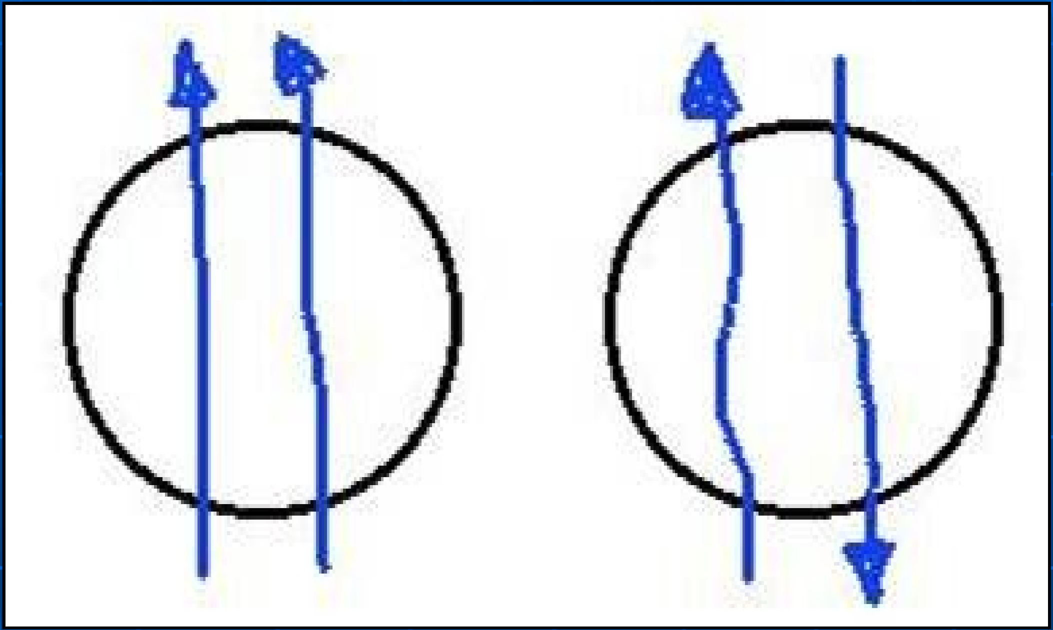
- Milky Way
- Future observations

Ordered fields:

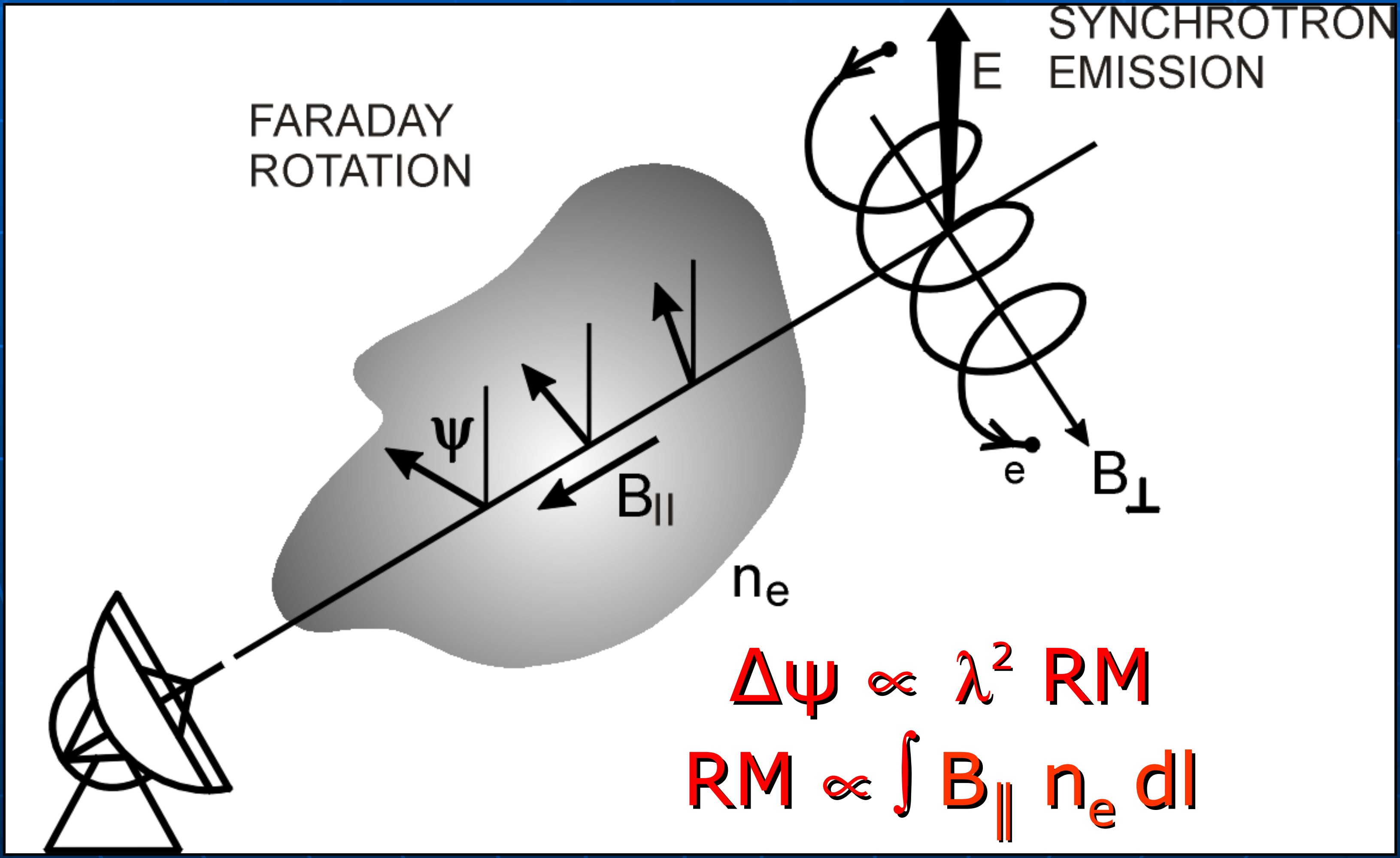
Coherent (dynamo)
or
incoherent (shear / compression)
?

	Regular (coherent) field	Anisotropic (incoherent) field



Polarization :	strong	strong
Faraday rotation :	high	low
UHECR deflection :	high	low

Faraday rotation: crucial to detect regular fields

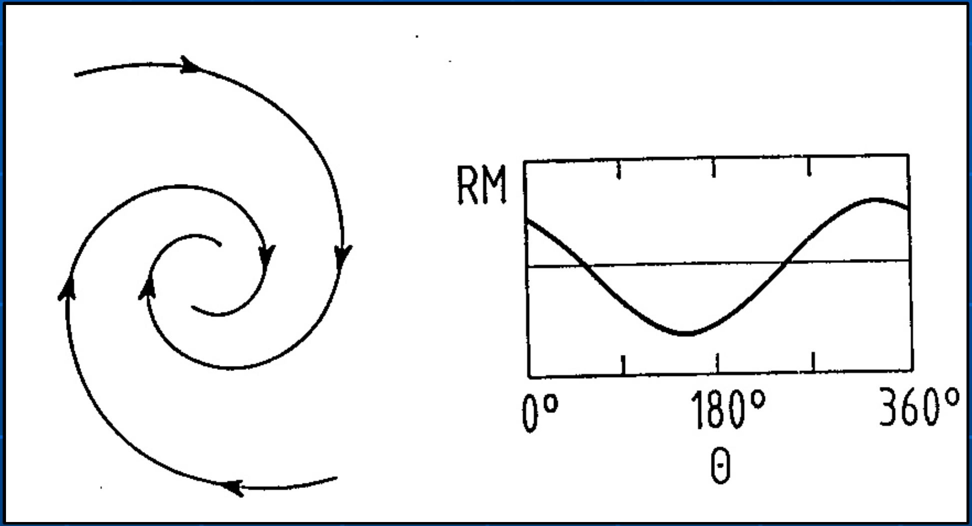


$$\Delta\psi \propto \lambda^2 \, RM$$

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

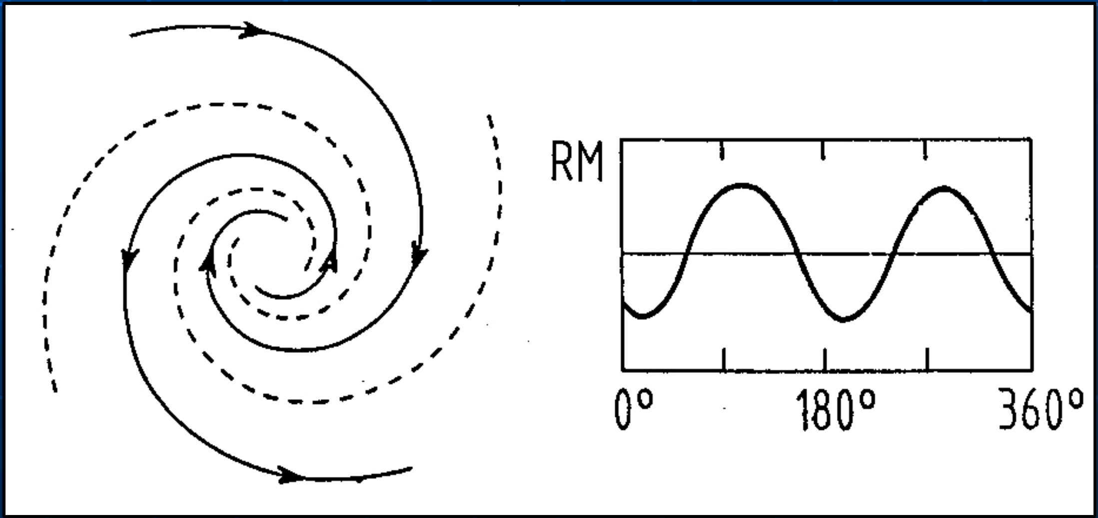
Searching for dynamo modes:
Azimuthal variation of Faraday rotation

Krause 1990



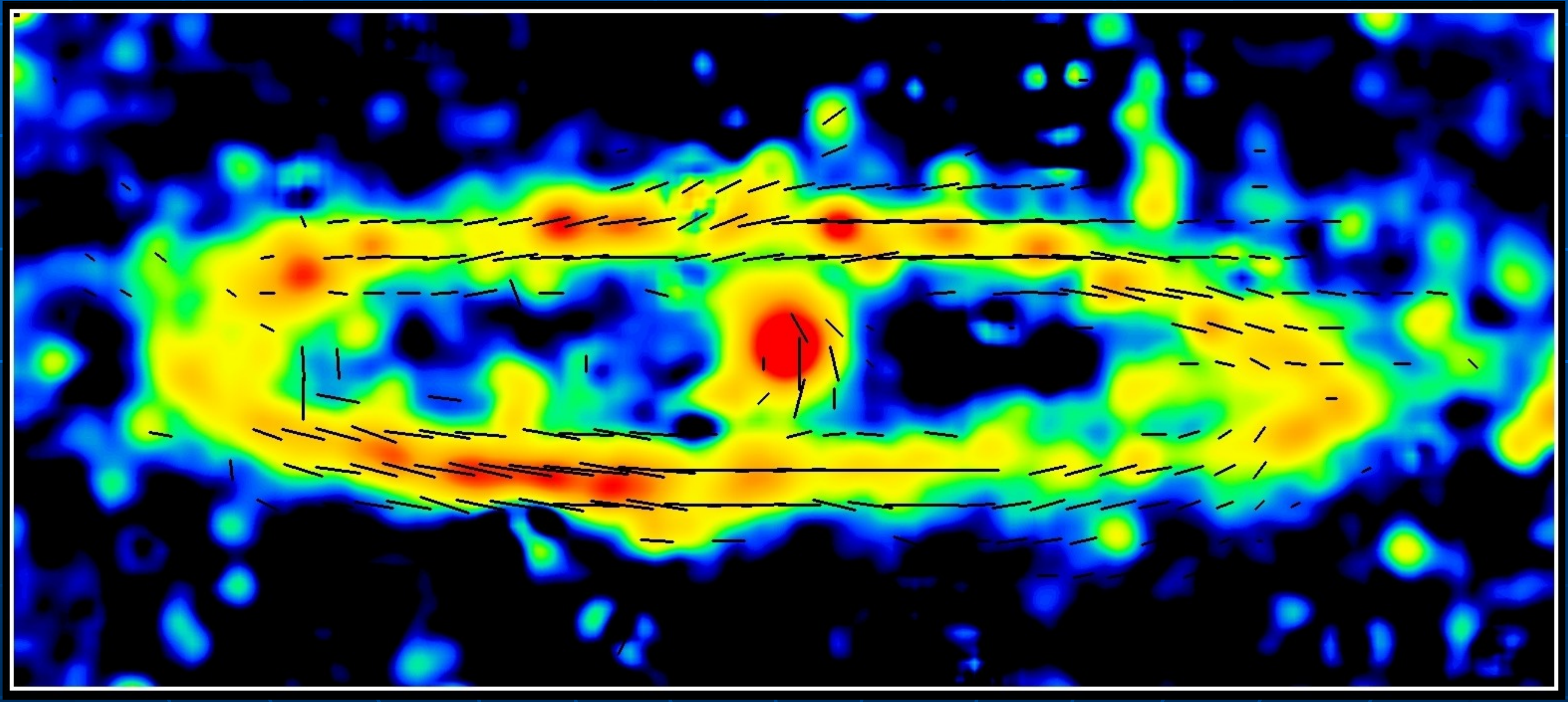
Axisymmetric spiral
(mode m=0)

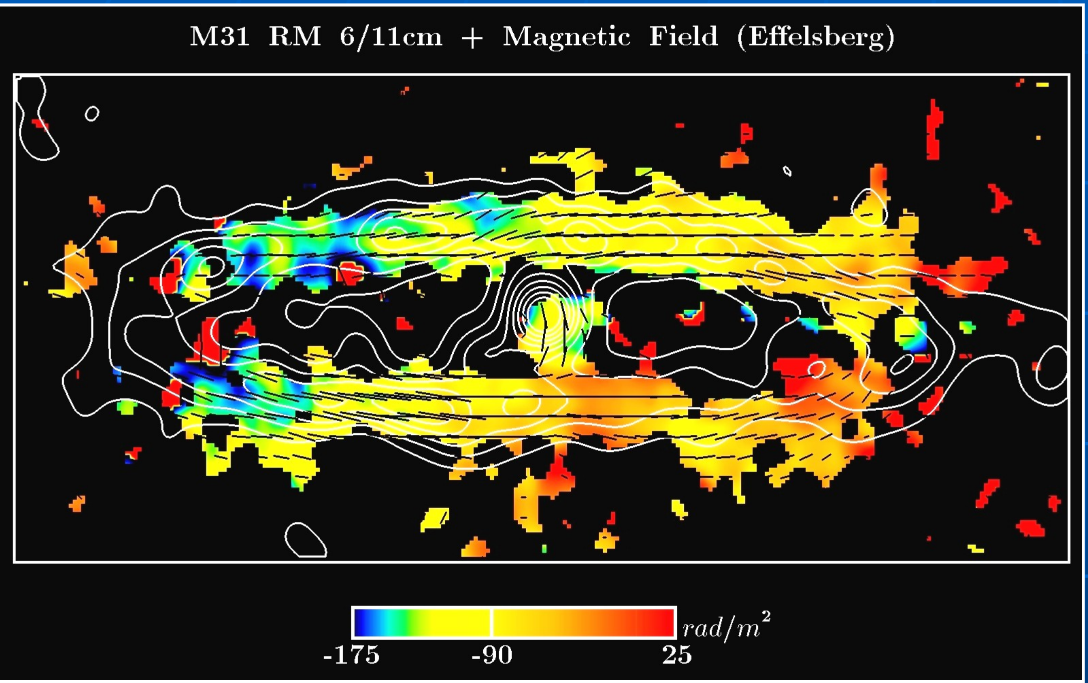
Bisymmetric spiral
(mode m=1)

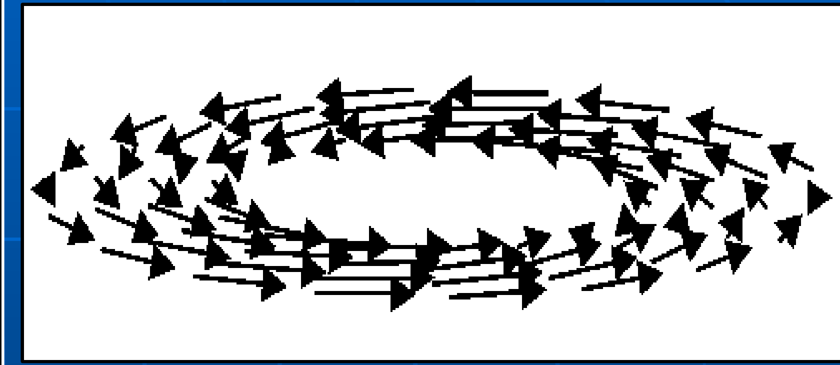


M 31: The classical dynamo field

Berkhuijsen et al. 2003







Fletcher et al. 2004

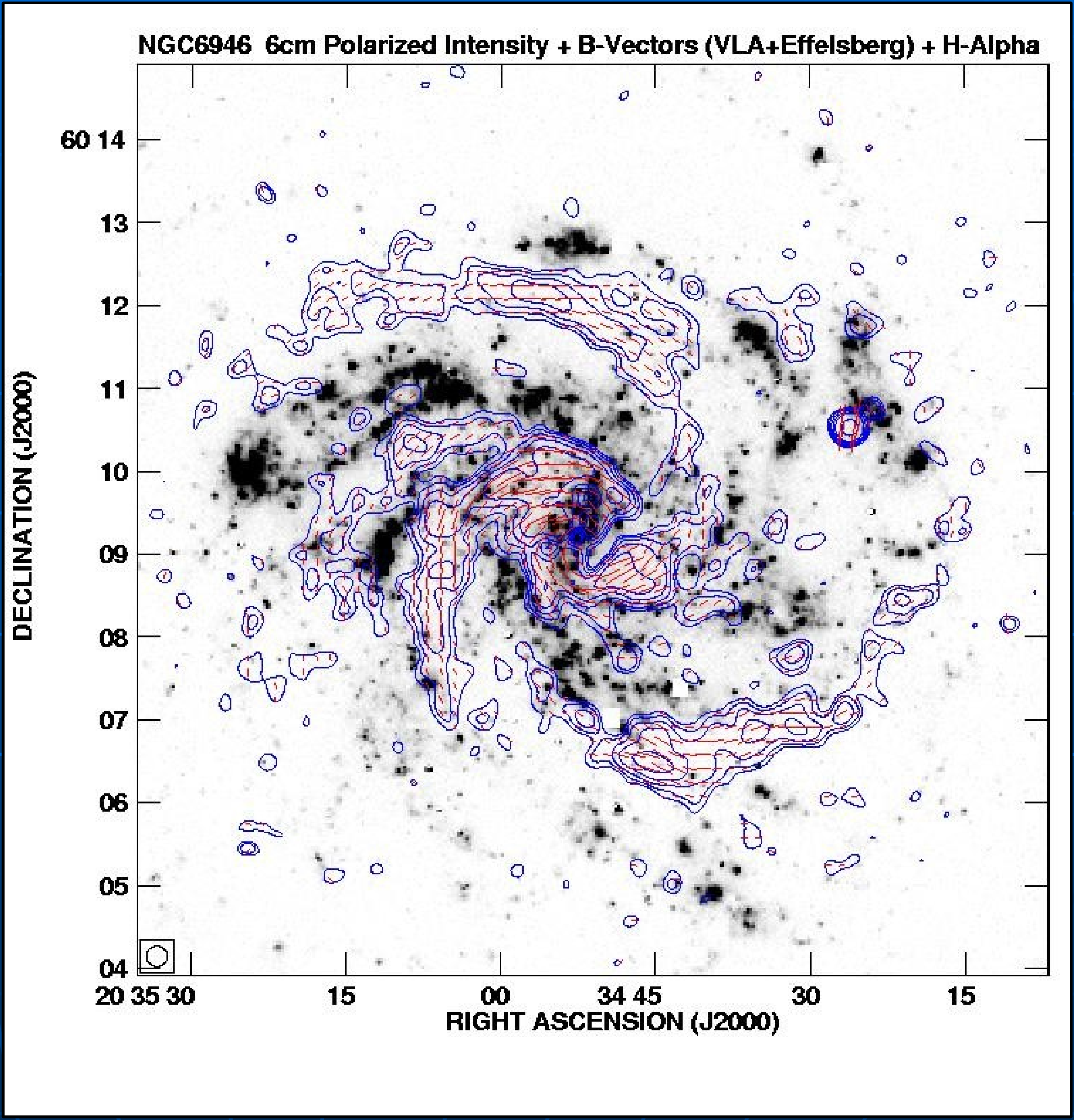
Berkhuijsen et al. 2003

Large-scale RM pattern of the diffuse emission:
Axisymmetric (m=0) dynamo field

NGC 6946

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

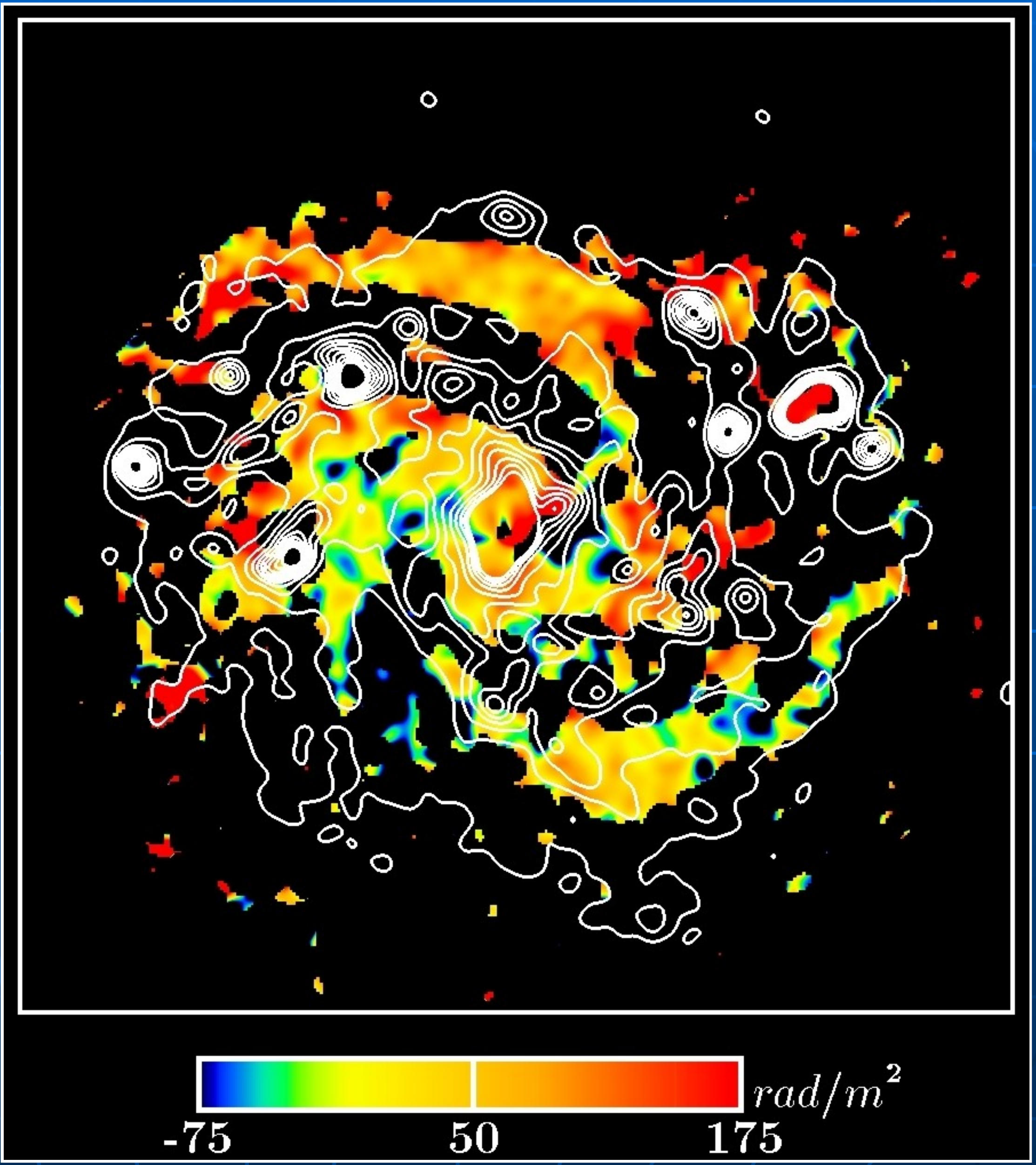
Magnetic arms



NGC 6946

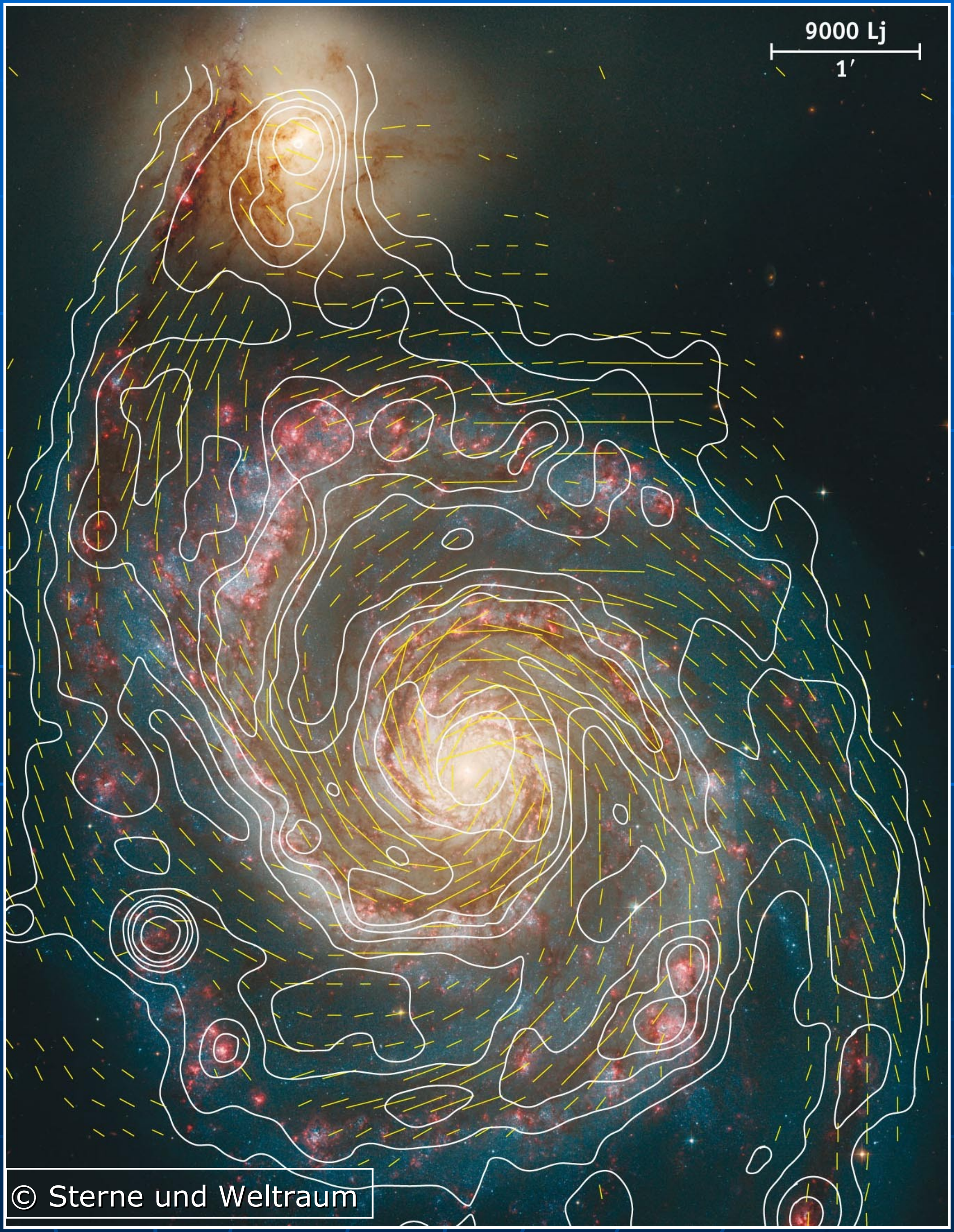
RM 3/6cm
VLA+Effelsberg
(Beck 2007)

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



M 51

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

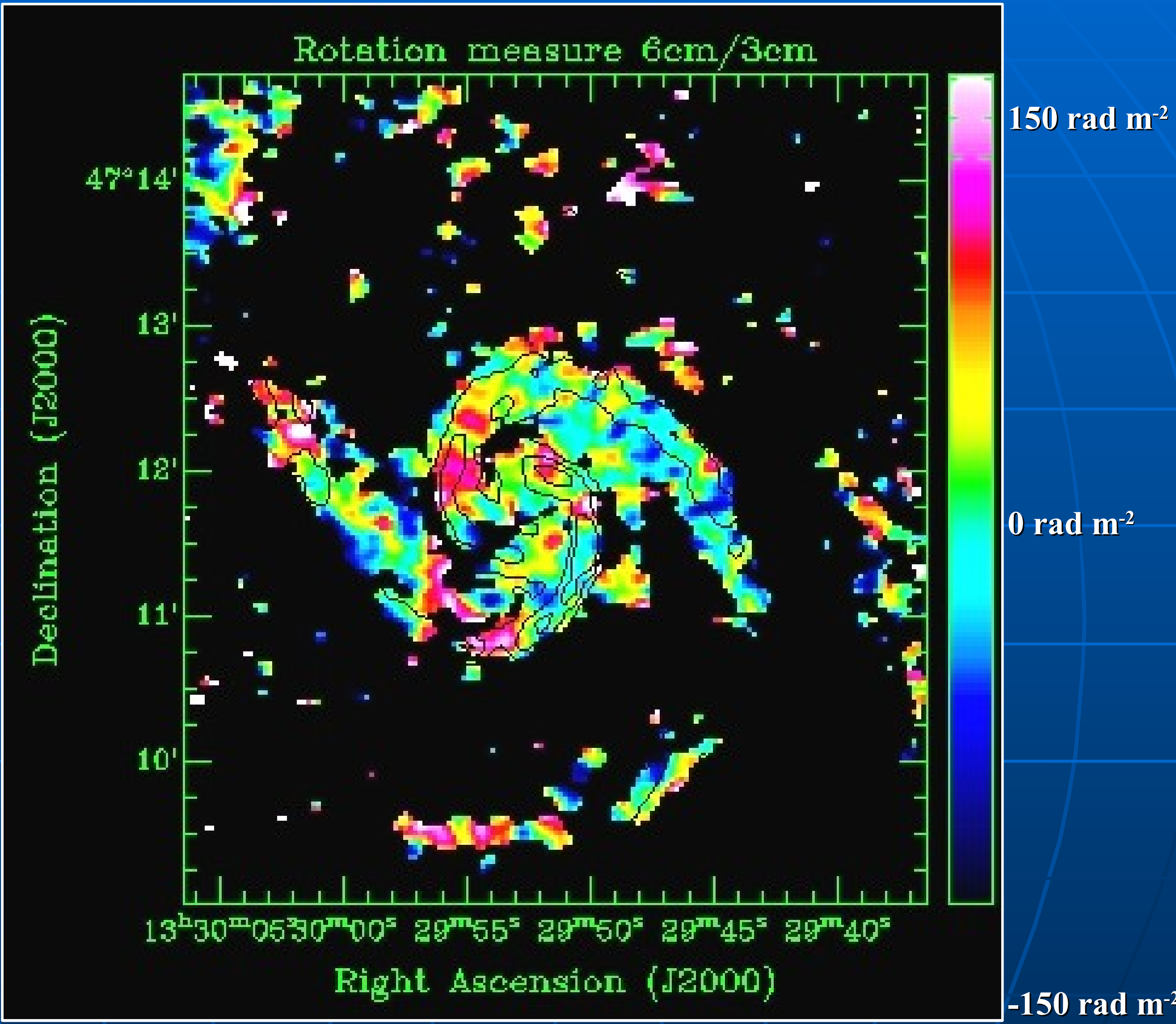


Prime candidate
for strong
dynamo action

but …

M 51

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

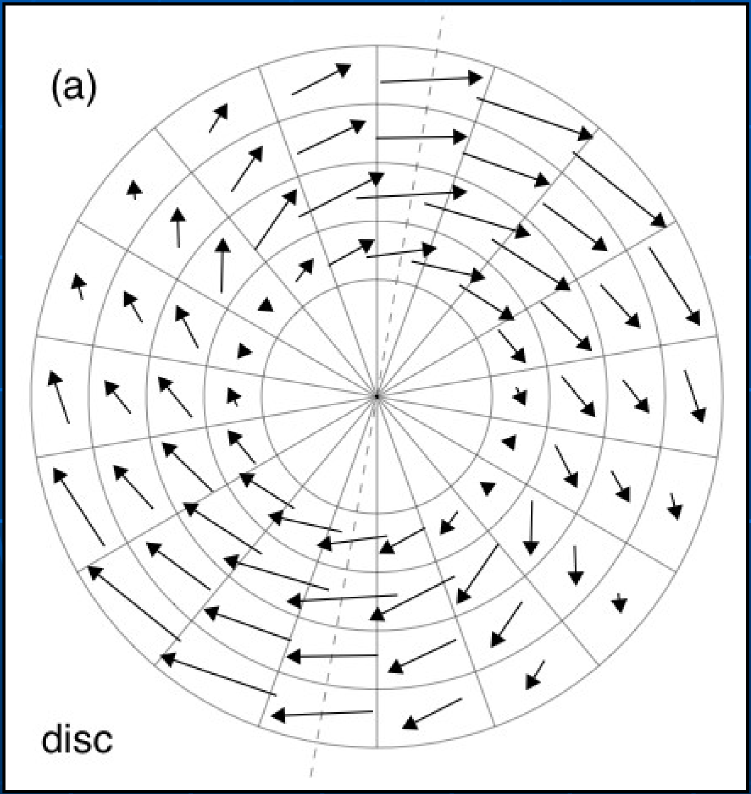


Two *weak* dynamo modes (m=0+2) + strong anisotropic fields

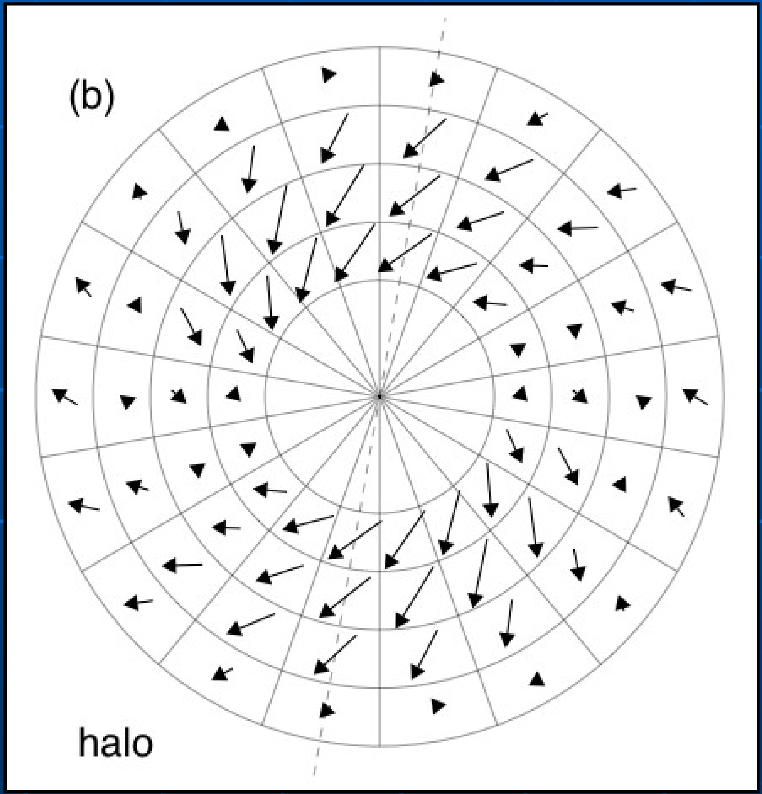
Large-scale magnetic fields in M51

Fletcher et al. 2009

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



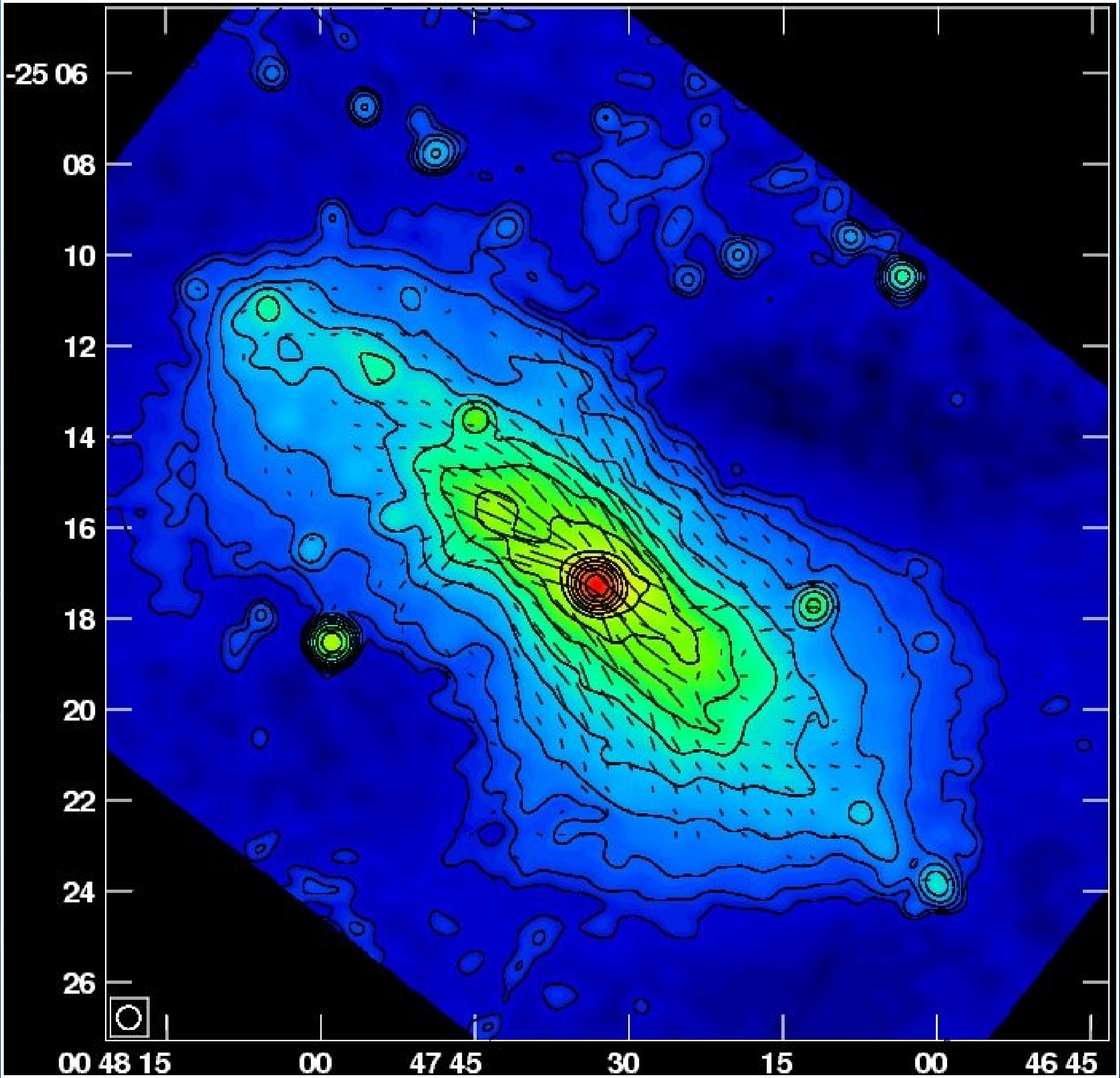
Upper layer: BSS (m=1) mode



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

NGC 253

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

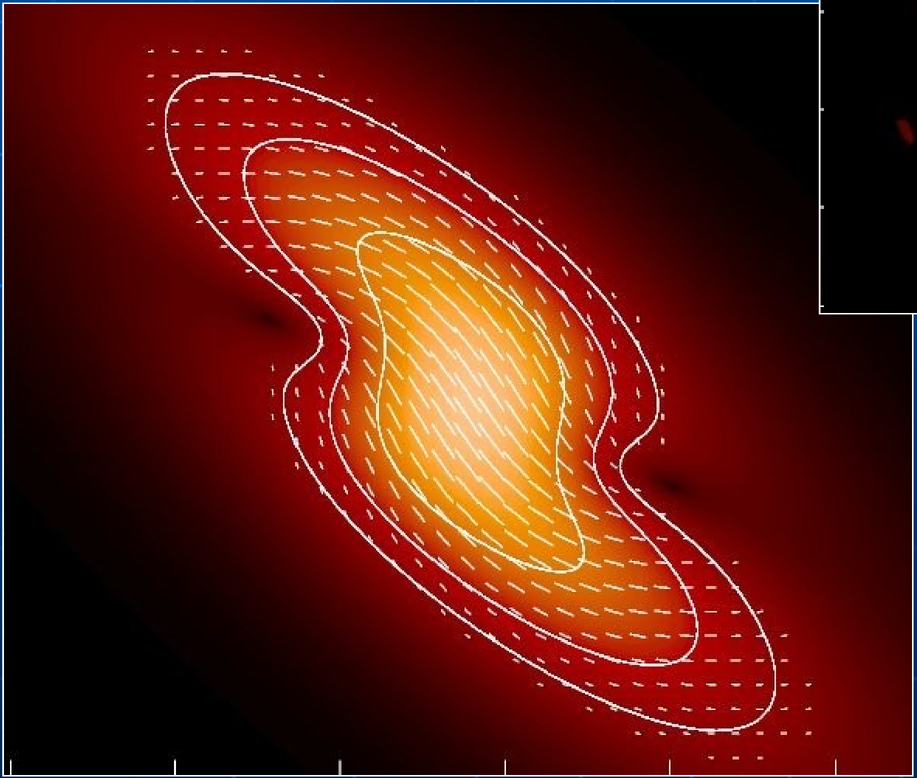


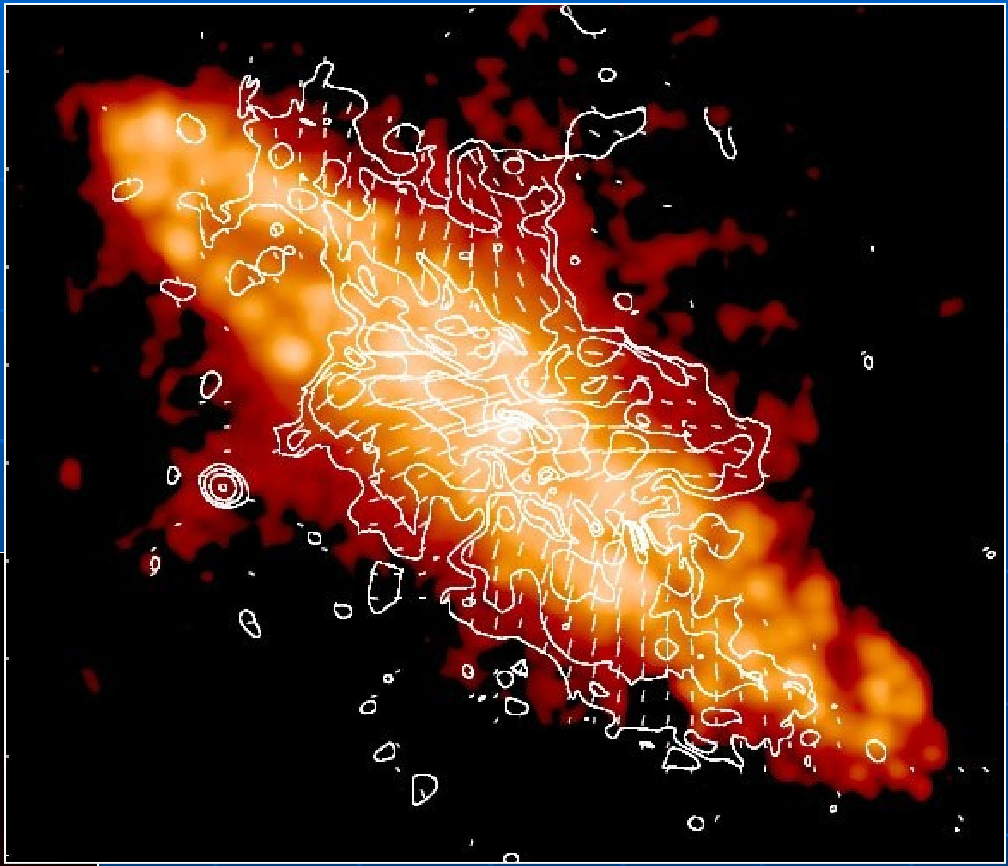
Exponential radio halo

NGC 253

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

Disk:
Axisymmetric spiral field





Halo:
X-shaped field,
probably symmetric
(quadrupolar)

Results (2): Dynamo action

- Preference of spiral field patterns indicates dynamo action
- Dominating single modes are rare among disk fields
- In most cases the disk field is a superposition of several unresolved modes, or the field is mostly anisotropic
- Is the time scale for generation of coherent disk fields larger than galaxy age ? (Arshakian et al. 2008)
- The symmetry of poloidal (halo) fields is hard to measure (only in the halo of NGC 253 so far)

- Field origin
- Cosmic ray electrons
- Field strengths and structures
- Radio halos
- Faraday rotation
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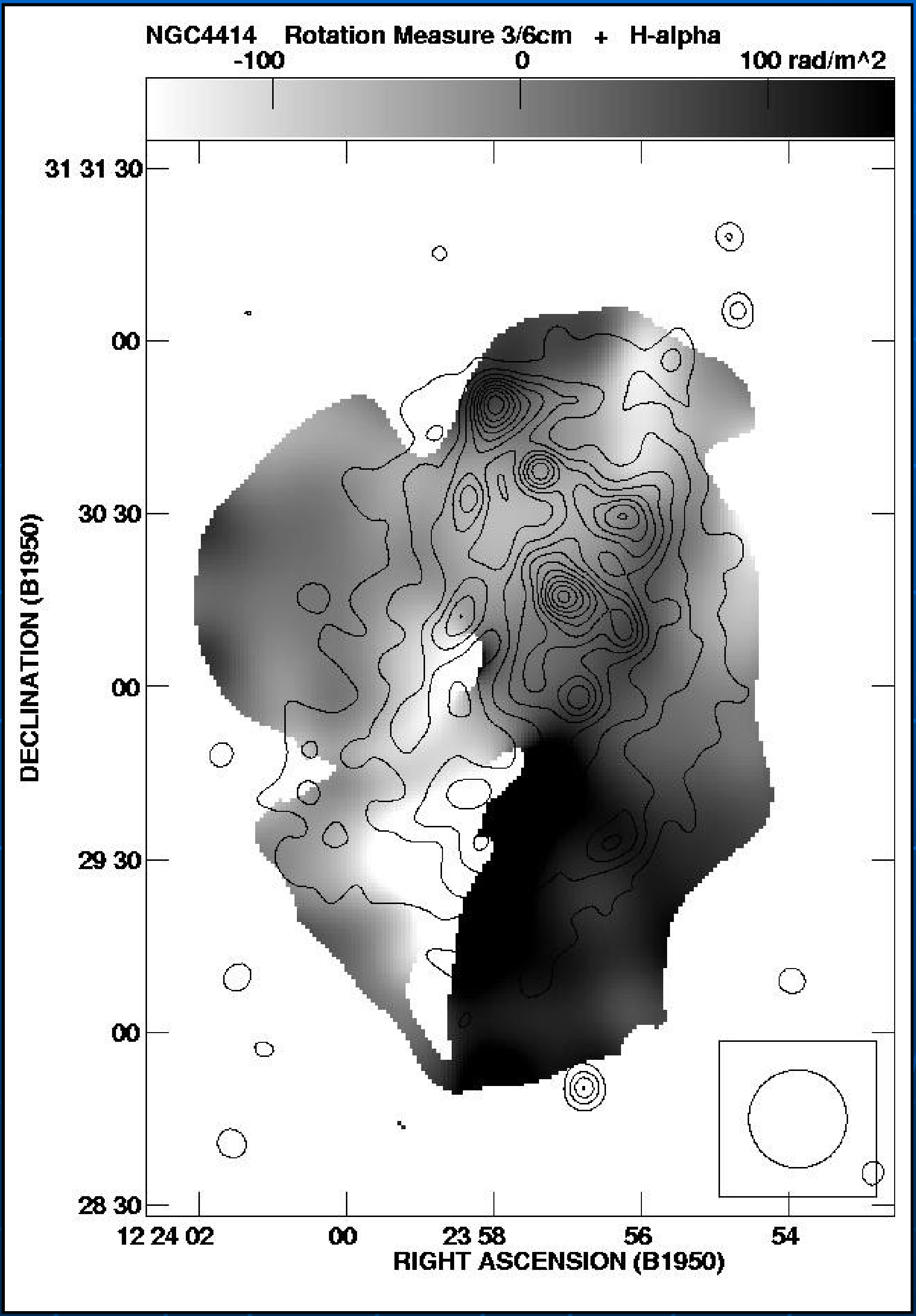
- Milky Way
- Future observations

NGC 4414

VLA

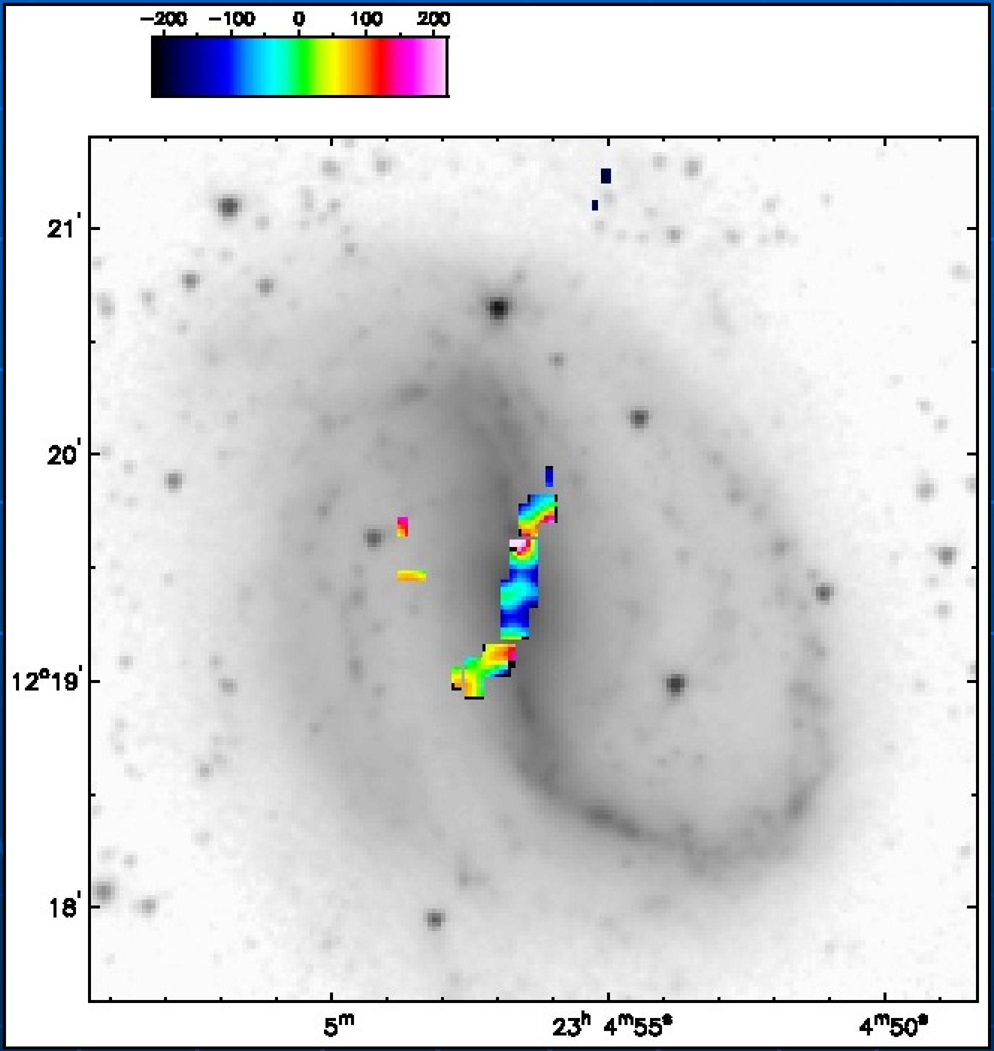
RM 3/6cm

(Soida et al. 2002)



One large-scale field reversal along radius

RM 3/6cm in the jet of NGC 7479



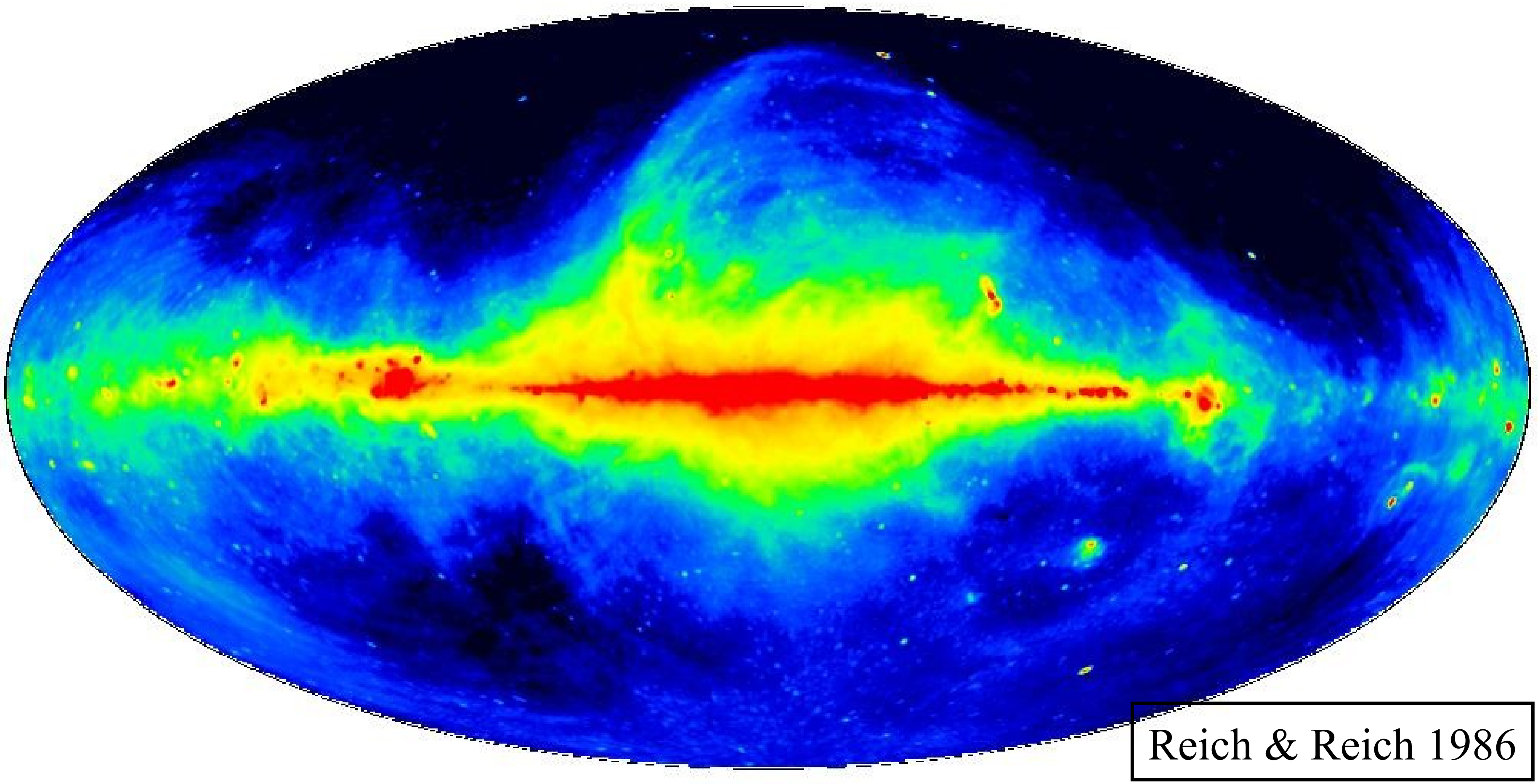
Laine & Beck 2007

Multiple reversals on ~1 kpc scale

- Field origin
- Cosmic ray electrons
- Field strengths and structures
- Radio halos
- Faraday rotation
- Field reversals
- Cosmic ray electrons
- Milky Way
- Future observations

All-sky radio continuum survey

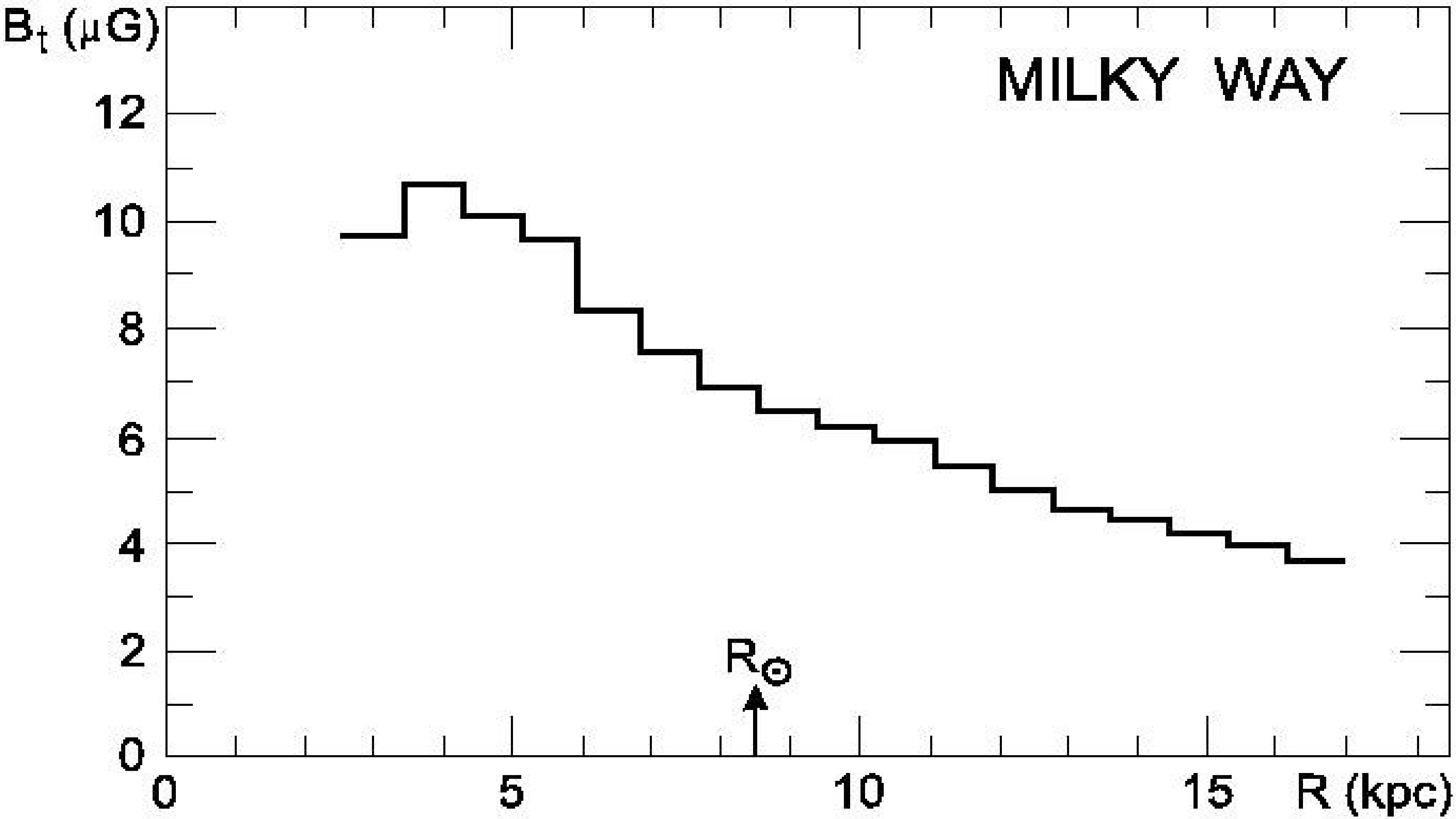
(Stockert + Villa Elisa 1.4 GHz)



Reich & Reich 1986

Equipartition field in the Milky Way

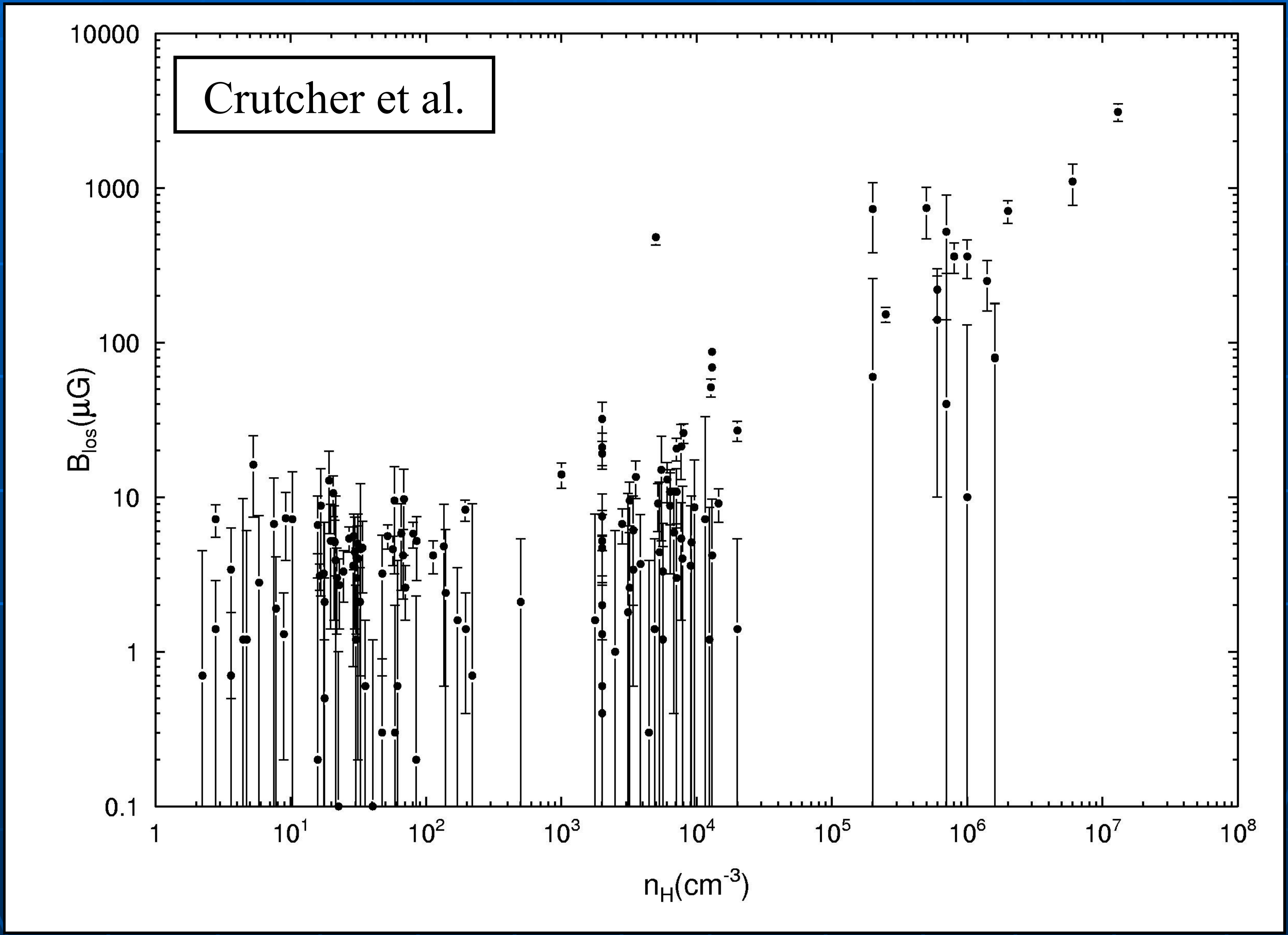
(Berkhuijsen, in Wielebinski & Beck 2005)



Consistent with estimates from γ rays

(Strong et al. 2000)

Zeeman field strengths ($B_\parallel$) in gas clouds

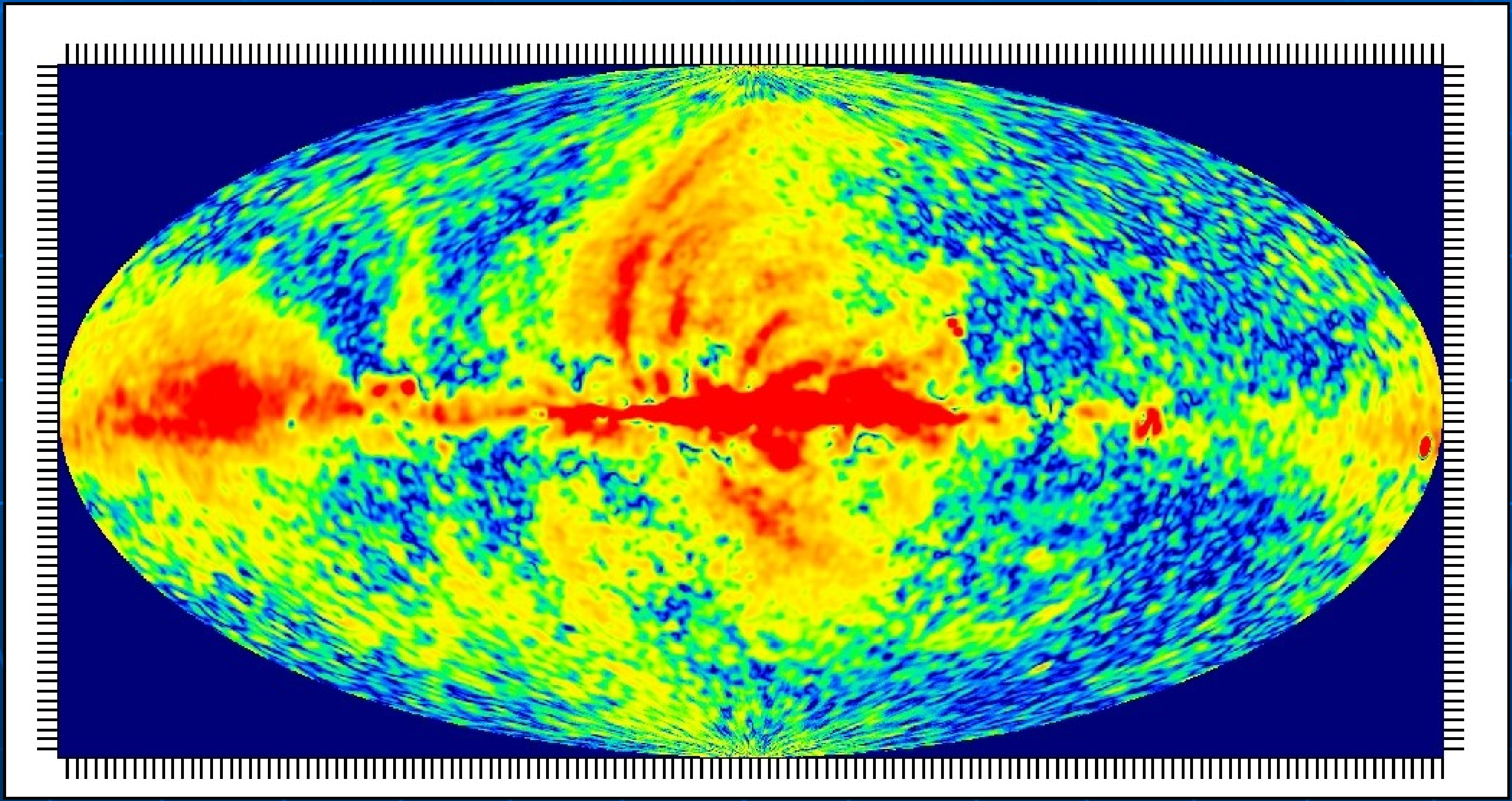


Average total field strength in the diffuse ISM: ≈ 6 μG

All-sky polarization survey

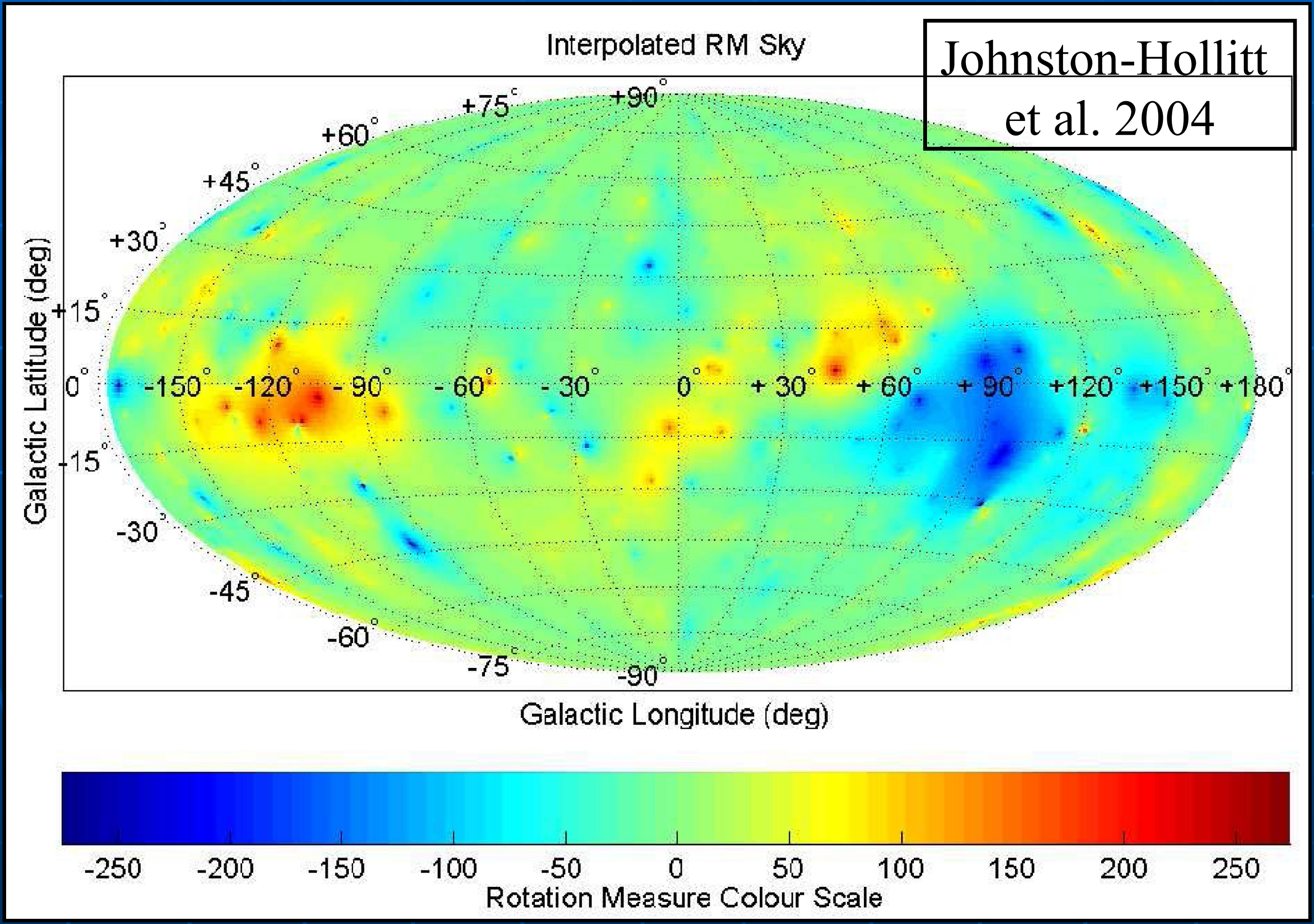
(WMAP 22.8 GHz)

Page et al. 2006



Strong north-south asymmetry !

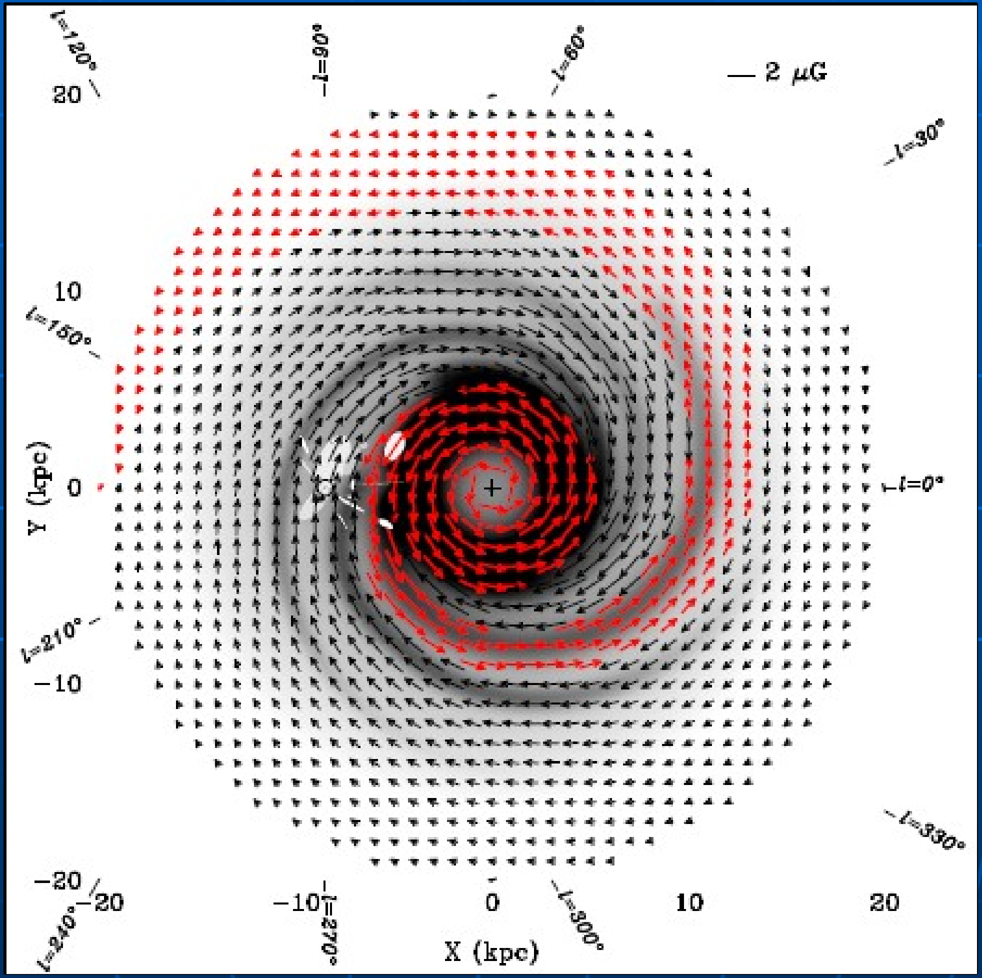
Rotation Measures (RMs) of polarized extragalactic background sources



Symmetric local field + antisymmetric (dipolar) halo field ?

Magnetic field model of the Milky Way

(from Galactic synchrotron emission and extragalactic RMs)



Sun et al. 2008

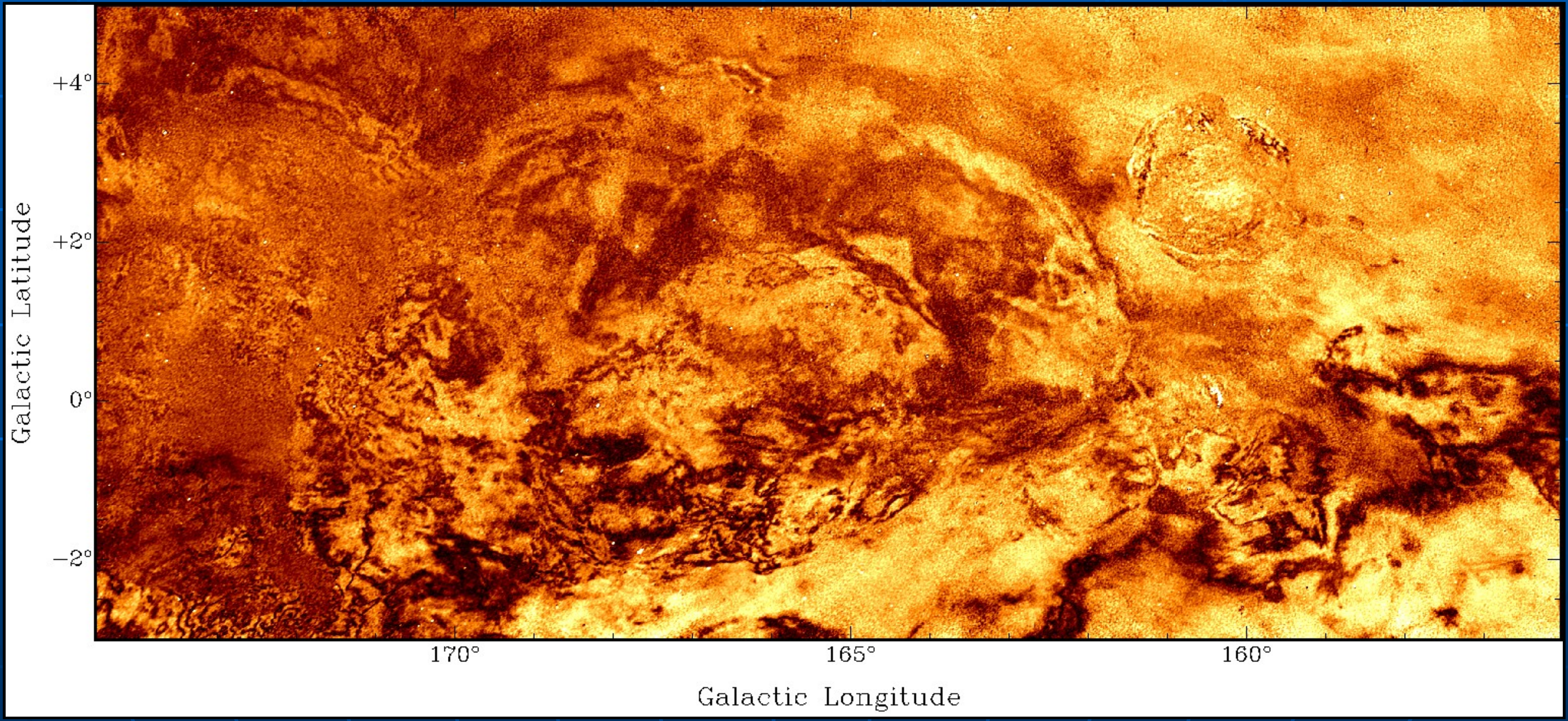
Axisymmetric spiral field (ASS)

+ one reversal in disk + antisymmetric halo field

Canadian Galactic Plane Survey

(21cm polarization, DRAO+Effelsberg)

Landecker, Kothes, Reich, et al.



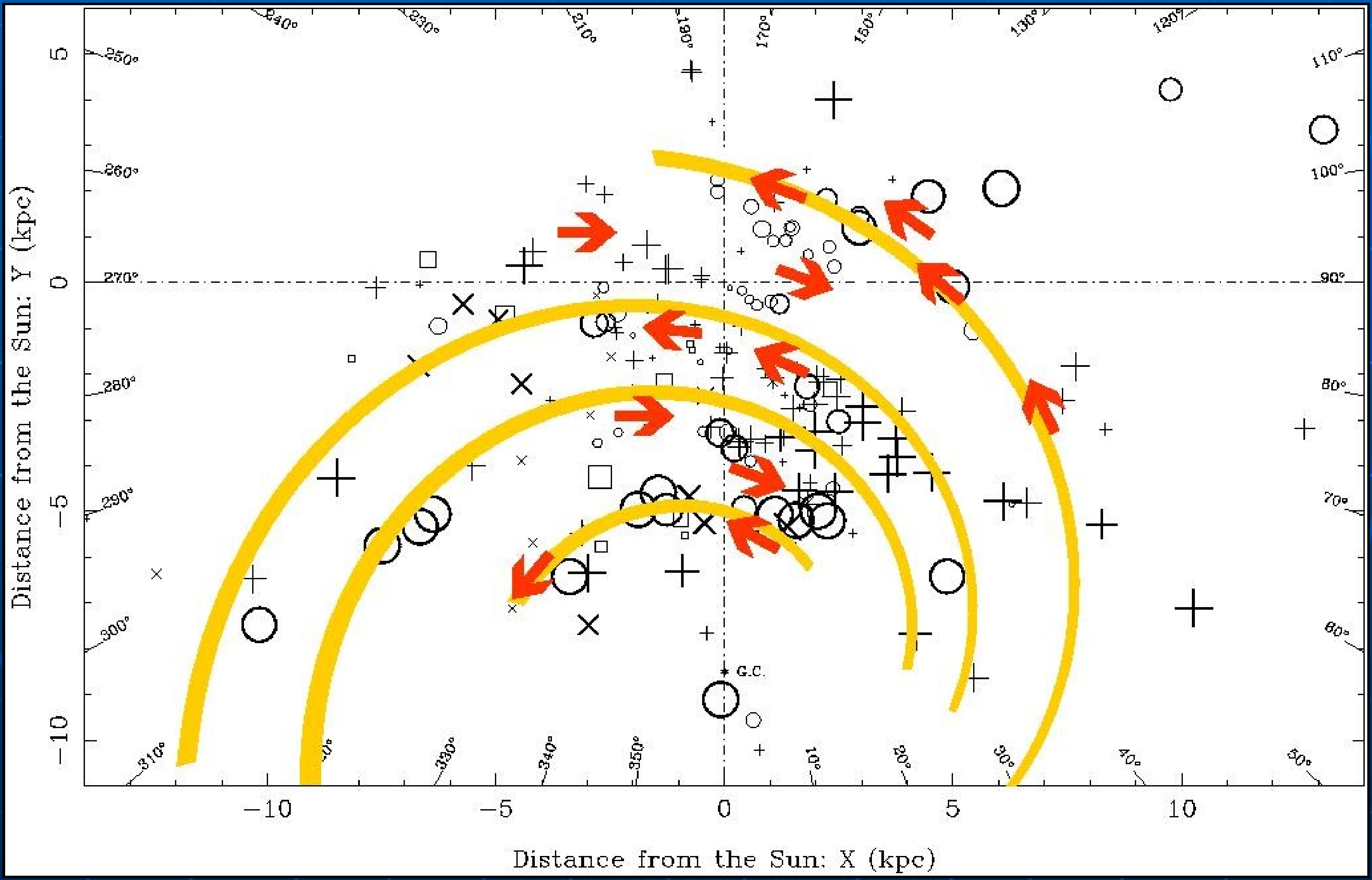
Depolarization canals : Signatures of MHD turbulence

(Fletcher & Shukurov 2006)

Pulsar RMs in the Milky Way:

Bisymmetric spiral (BSS) with many reversals ?

(Han et al. 2001, 2005, …)

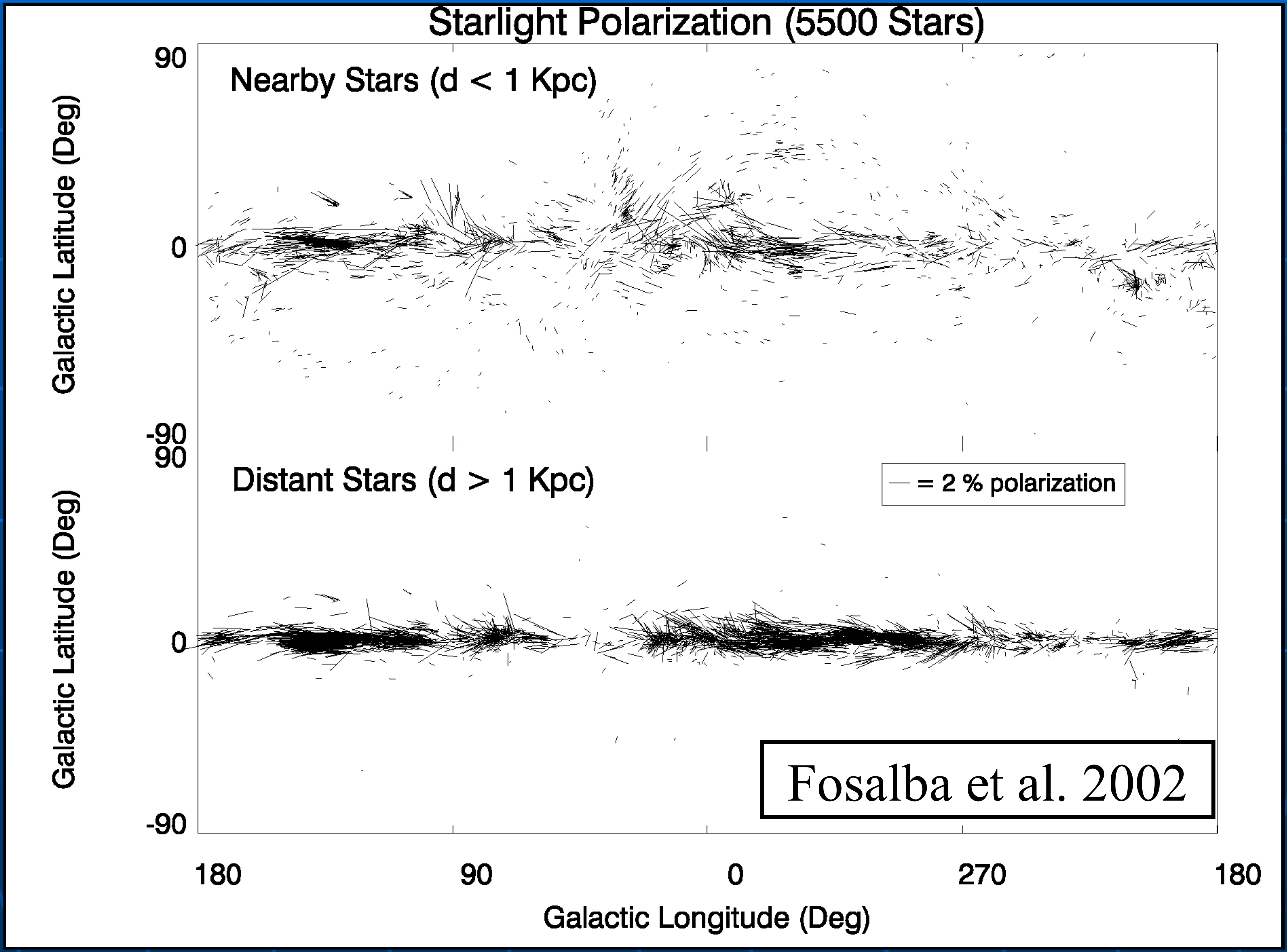


Large-scale field reversals are rare in spiral galaxies:

Is our Milky Way special ?

What is the structure of the local field ?

Starlight polarization



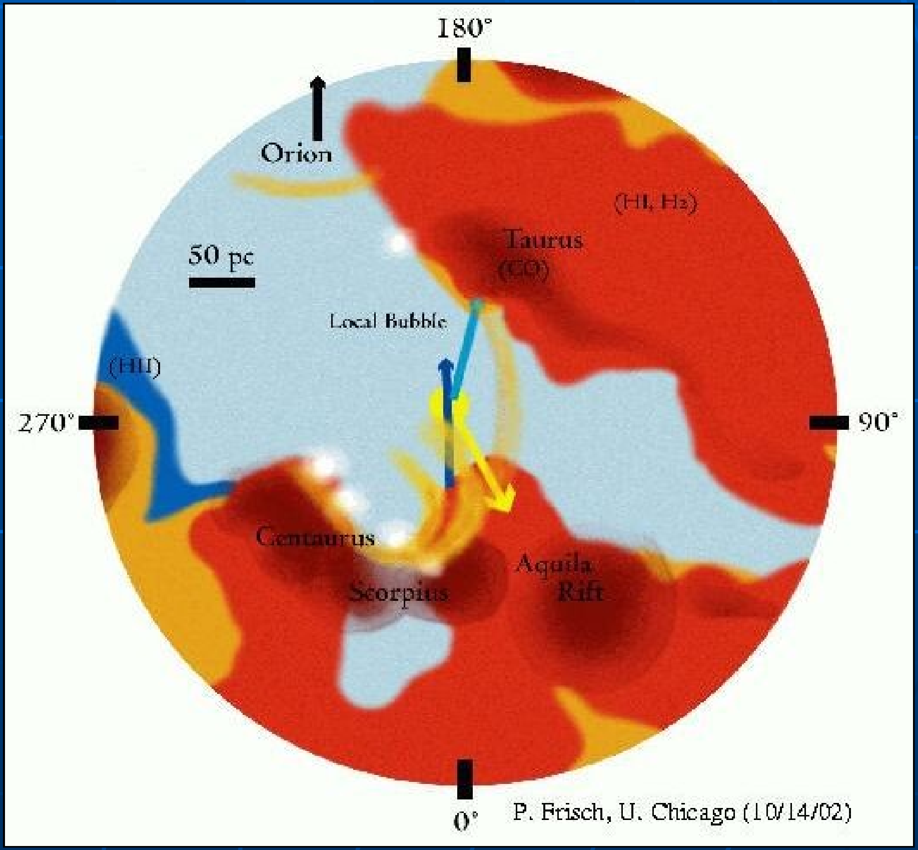
Local field is distorted !

The local environment

- Since 5-10 Myr the solar system passes through a low-density region generated by SNs, the Local Bubble

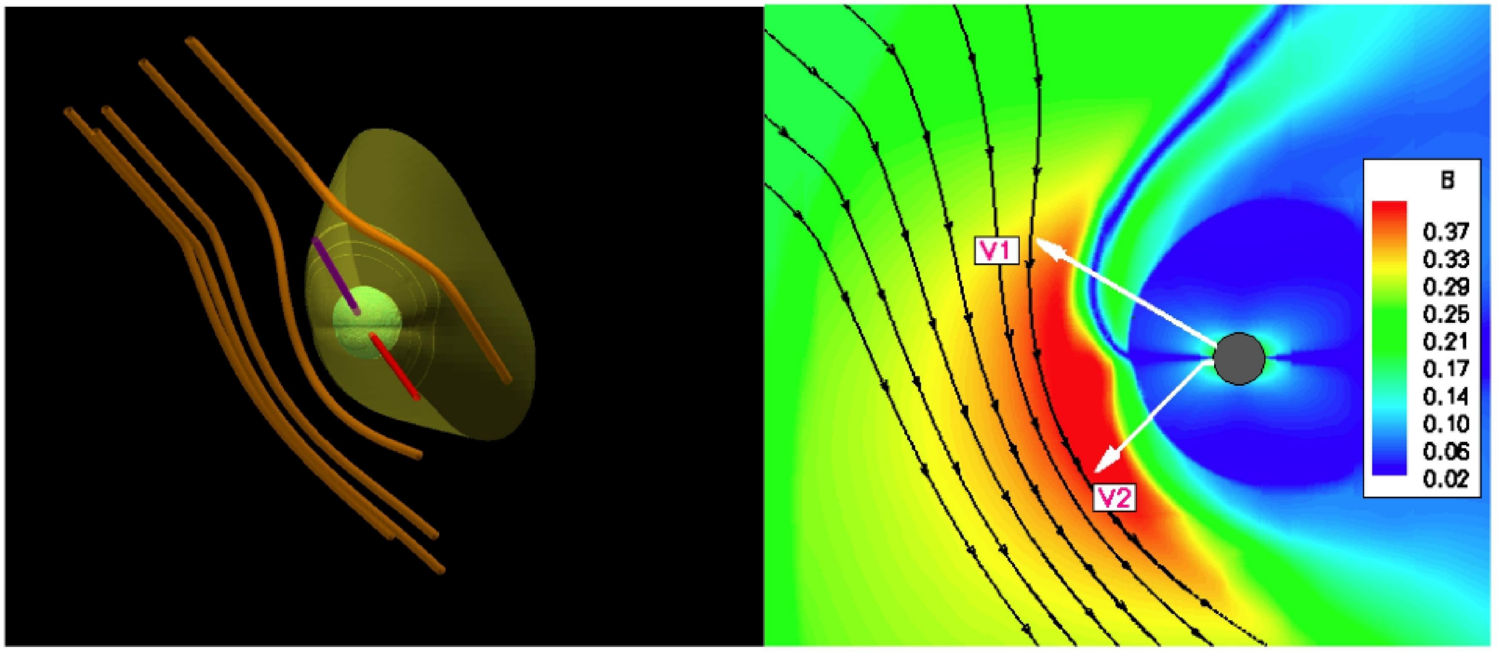
- A region of moderate density, the Local Interstellar Cloud, will be reached in ≈ 0.1 Myr

- Almost nothing is known about the local field !



The very local field

Opher et al. 2007



- Voyager 1+2: The very local field is strongly tilted with respect to the Galactic plane

→ The orientation of the very local field differs strongly from that of the large-scale Galactic magnetic field

No surprise !

Results (3): Milky Way

- The total field strength in the disk of the Milky Way is 5-10 μG, similar to that in other spiral galaxies
- The detailed field structure is very inhomogeneous
- 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 Milky Way probably has an extended magnetic halo, but nothing is known yet about its structure
- External galaxies show us how our Milky Way may looks like

UHECR propagation

Beck 2009

UHECR propagation in magnetic fields

Deflection of protons by a regular field at 50 EeV:
$\approx 1°\ (L/kpc)\ (B_\perp/\mu G)$

Deflection of protons (random walk) by a turbulent field at 50 EeV:
$\approx 1°\ (L/kpc)^{0.5}\ (D/kpc)^{0.5}\ (B_\perp/\mu G)$

Region of deflection	**Field structure**	**Field strength B**	**Scale height H**	**Path-length D**	**Correlation length L**	**Deflection angle at 50 EeV**
Milky Way disk	Regular toroidal: symmetric ASS	2 μG	2 kpc	10 kpc	3 kpc ?	**6°** (near plane)
	Turbulent	5 μG	2 kpc	10 kpc	50 pc	**4°** (near plane)
Milky Way halo	Regular toroidal: antisymmetric ?	1...3 μG	8 kpc	8 kpc	<3 kpc ?	<3...9° (near plane)
	Regular poloidal: X-shaped ?	1 μG ?	8 kpc ?	8 kpc	<3 kpc ?	<3°
	Turbulent	1...5 μG	8 kpc ?	8 kpc	100 pc ?	**1...4°**
IGM filaments	Turbulent	0.001...0.03 μG	-	1 Mpc ?	1 Mpc ?	**1...30°**

UHECR deflection in the Milky Way

- Strong deflection near the Galactic plane by regular and turbulent fields
- Significant deflection by turbulent fields in the Galactic halo
- Deflection by regular halo fields unknown because their structure and coherence length are unknown
- Asymmetries in field strength and structure between the northern and southern sky
- IGM fields of 30 nG and 1 Mpc coherence scale (Lee et al. 2009) would not allow UHECR astronomy !

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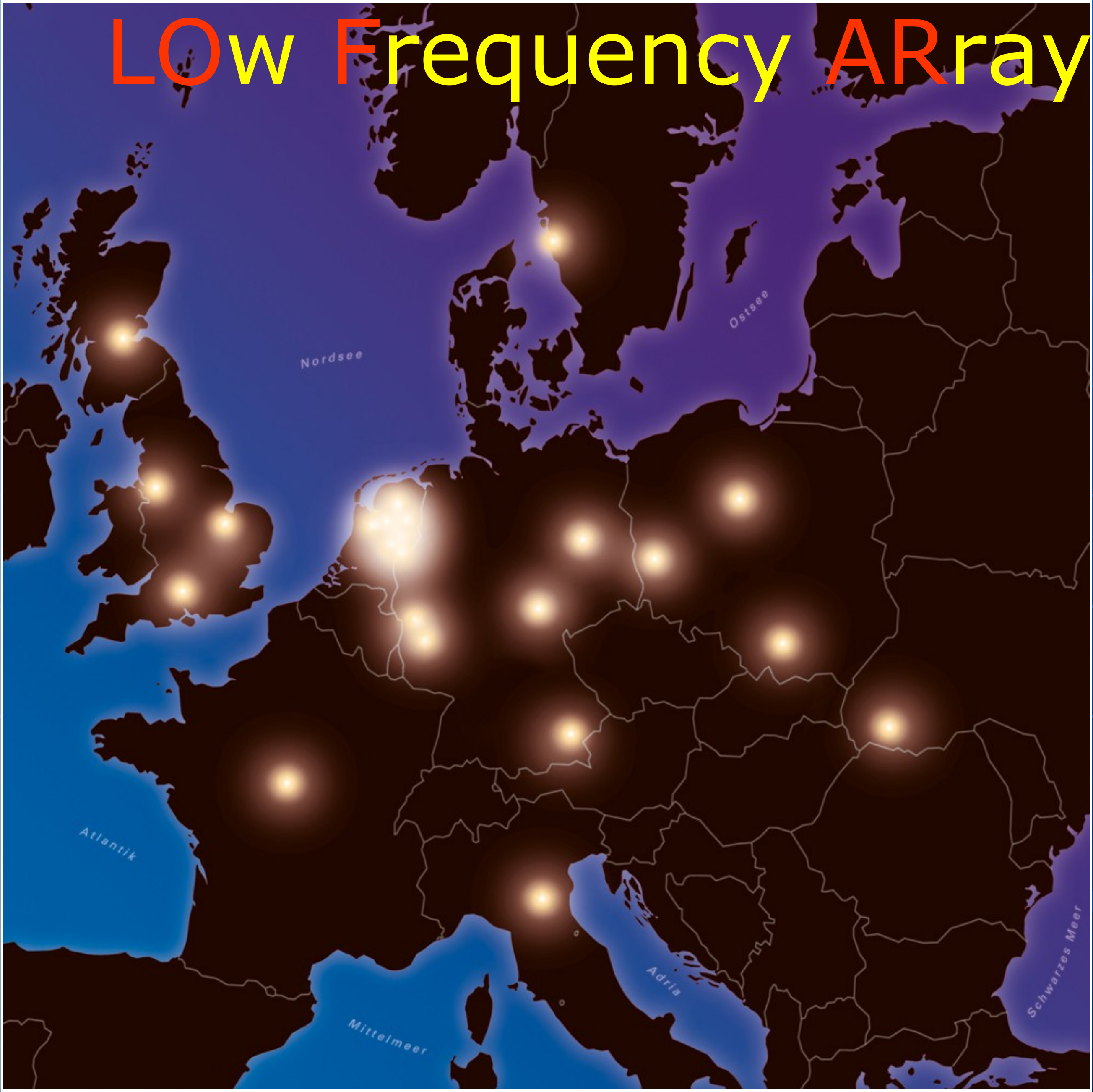
LOFAR

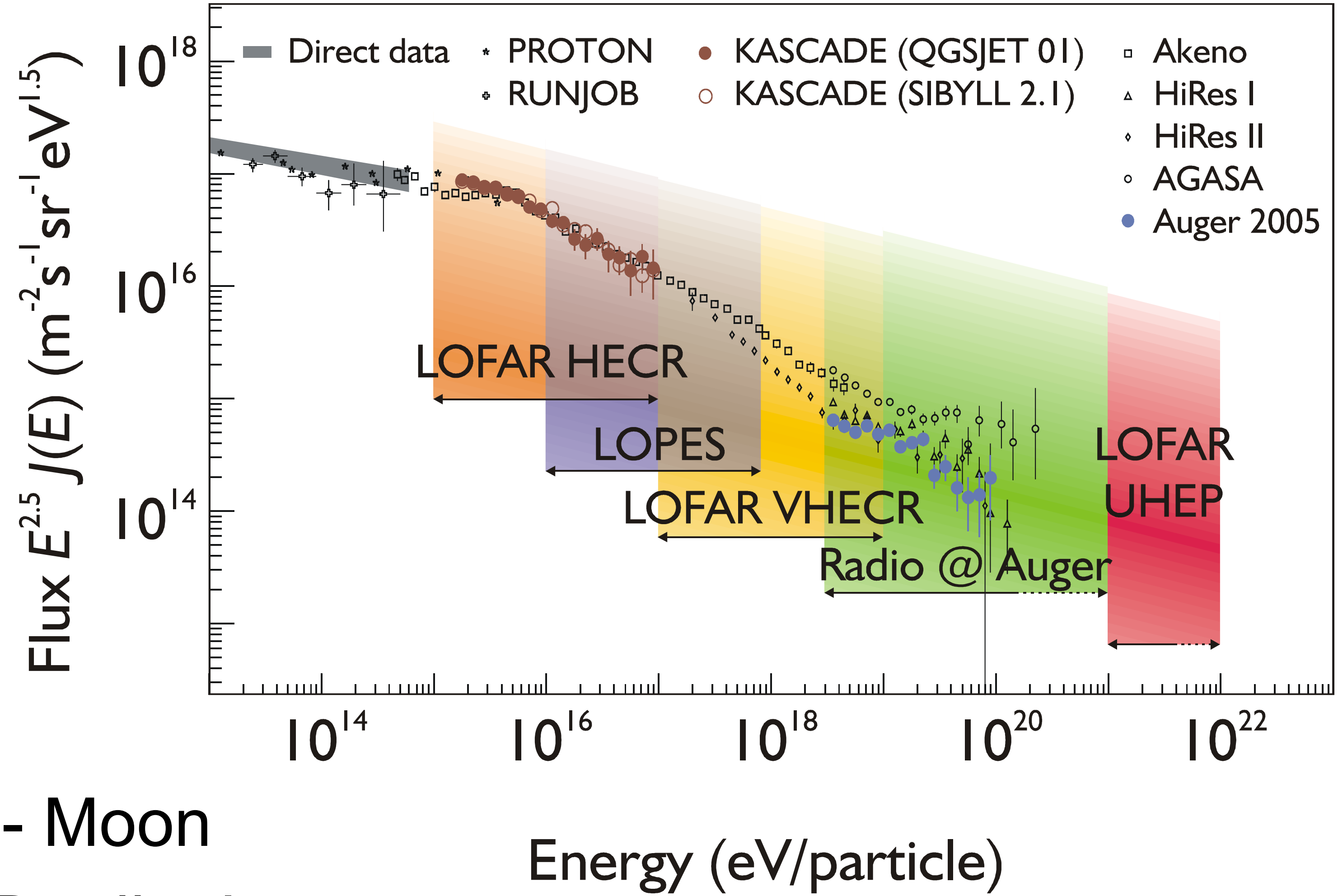
LOw Frequency ARray



30-80 MHz
110-240 MHz

Station 302

Cosmic Rays with LOFAR



- UHEP - Moon
- VHECR - dipole
- HECR - tied-array beam

H. Falcke

LOFAR

- Rotation measure (RM) errors are much lower at low frequencies
- LOFAR can detect very weak magnetic fields via RMs towards polarized background sources:

- Extended galaxy halos:

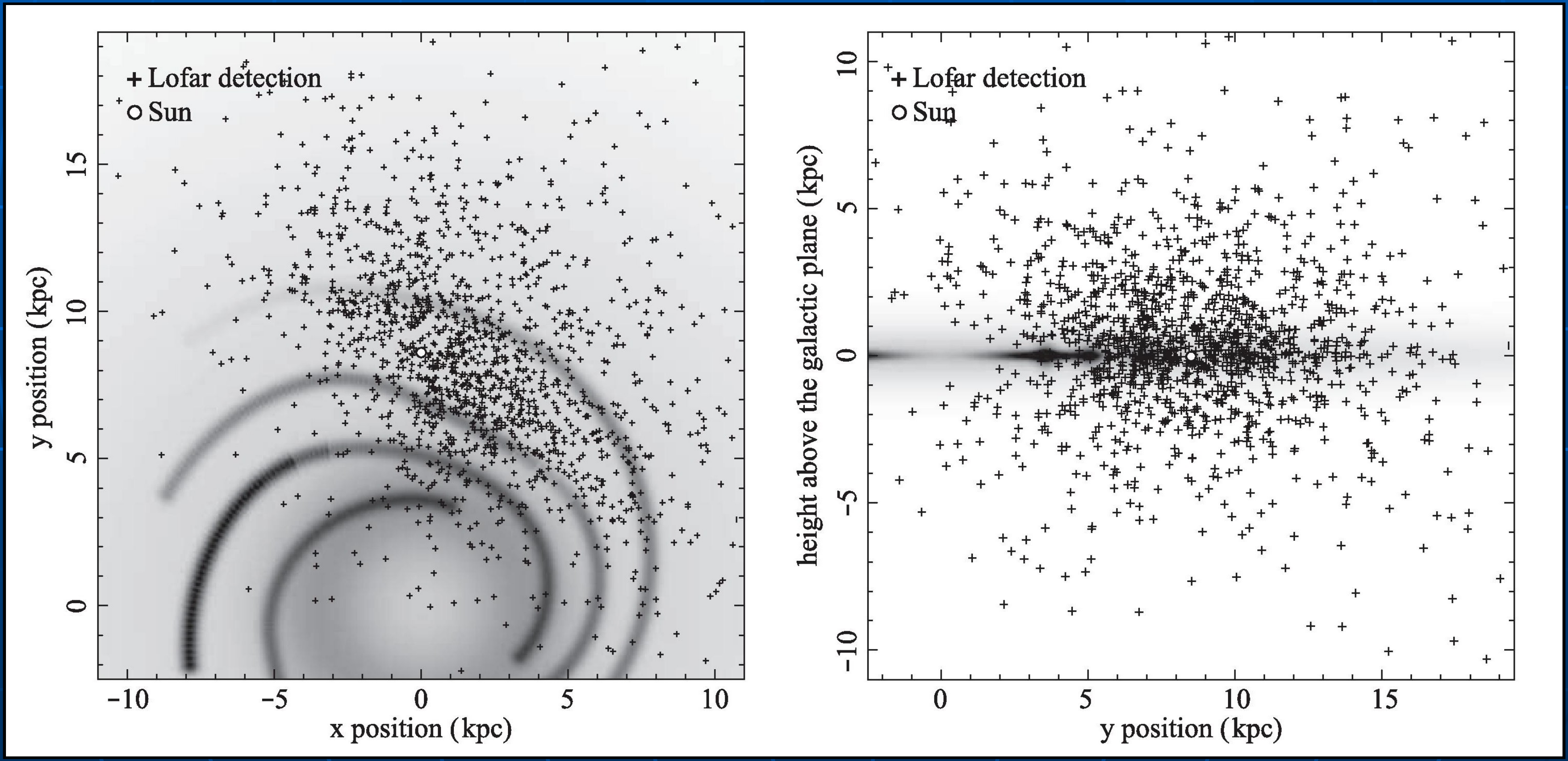
  $n_e = 10^{-3}$ cm^{-3}, $B_{||} = 1\ \mu G$, L=1 kpc: RM~1 rad m^{-2}
- Intergalactic magnetic fields:

  $n_e = 10^{-3}$ cm^{-3}, $B_{||} = 0.1\ \mu G$, L=1 kpc: RM~0.1 rad m^{-2}

- Nearby pulsars in the Milky Way and their RMs

Future rotation measures of pulsars in the Milky Way with LOFAR

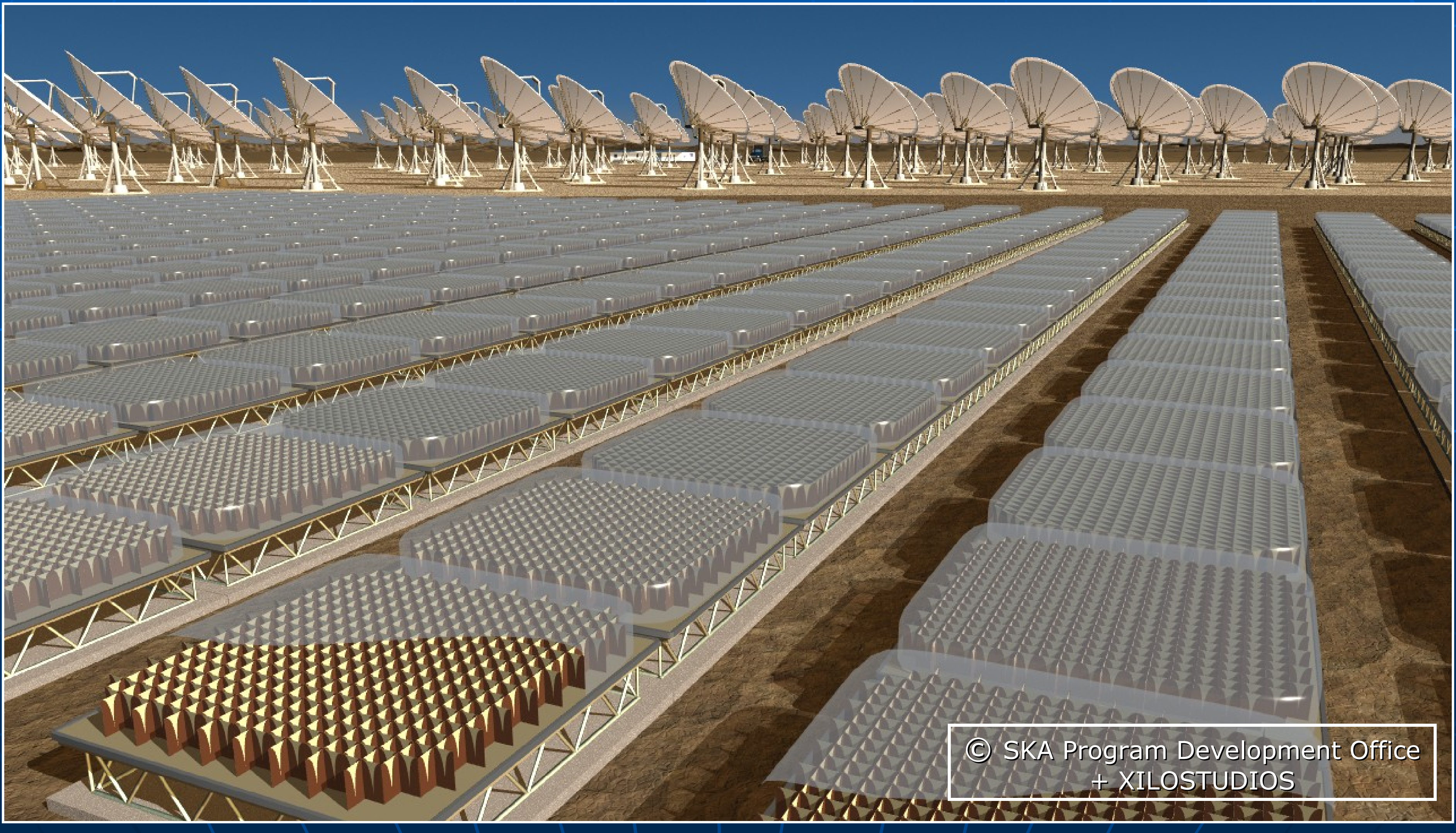
Leuwwen & Stappers



≈ 1000 pulsars within 2 kpc from the sun expected

Square Kilometre Array (SKA)
(Reference Design)

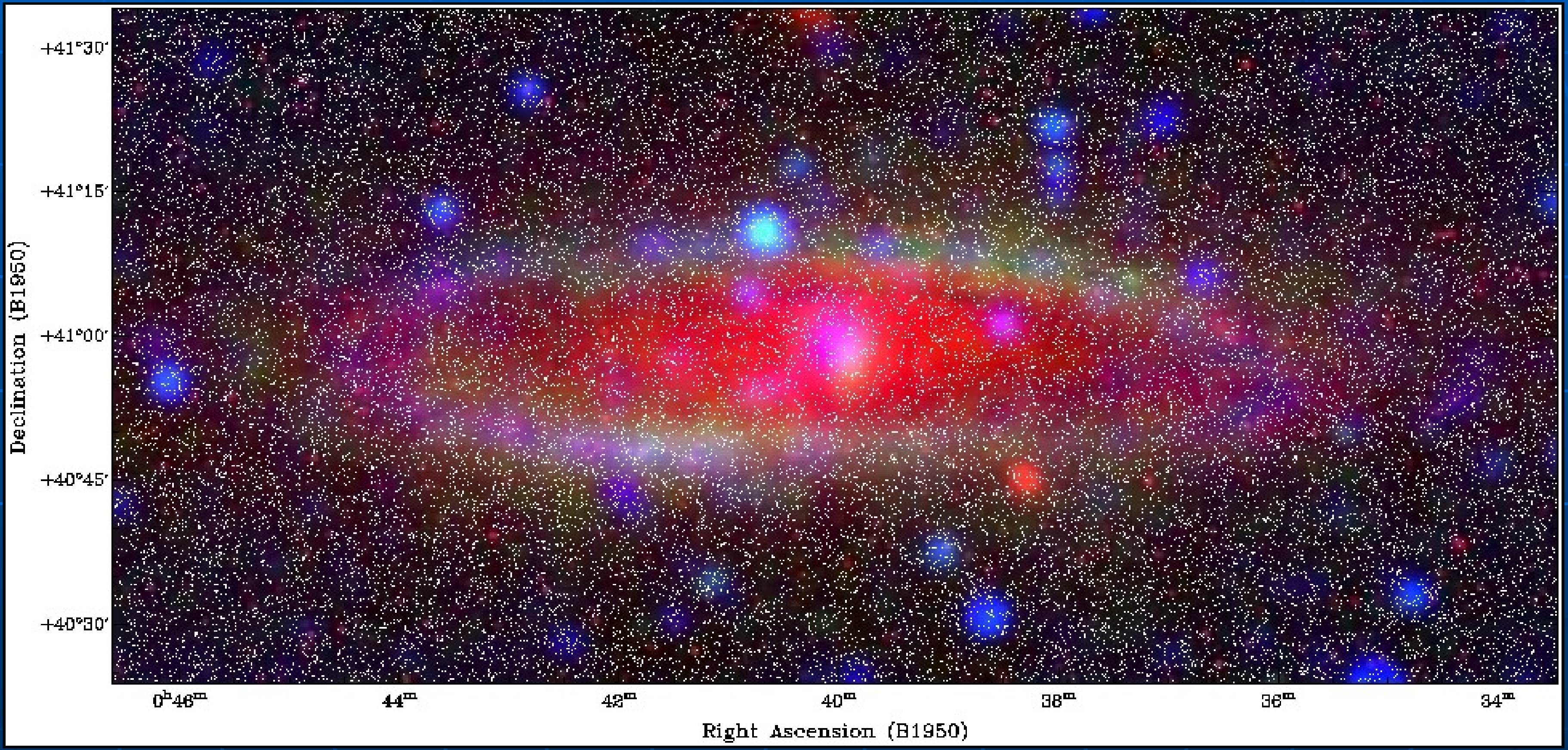
70 MHz - 10/35 GHz




SKA core station
© SKA Program Development Office
+ XILOSTUDIOS

M31 RM survey of M31

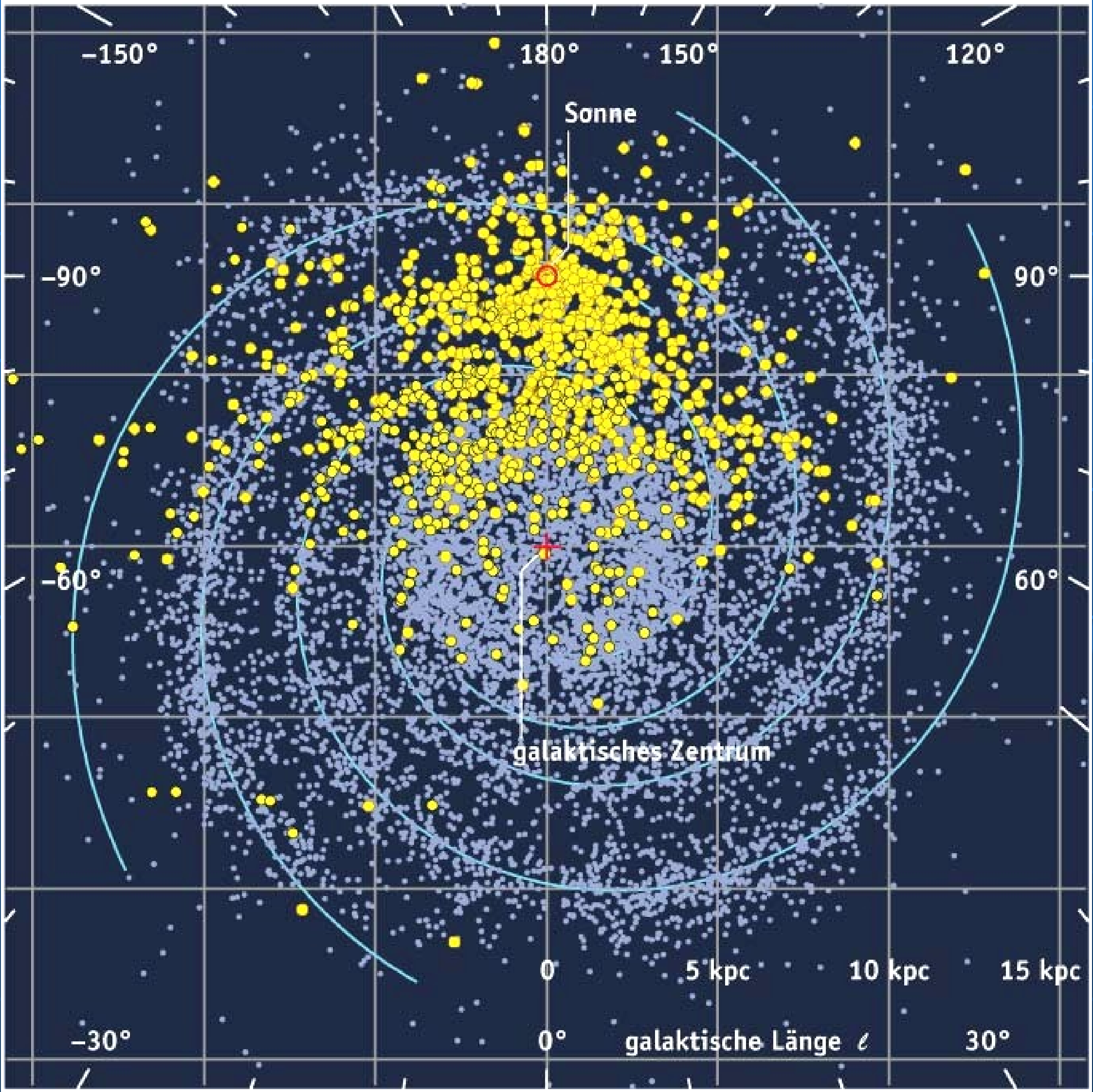
(simulation by Bryan Gaensler)



≈10000 polarized sources shining through M31

Future rotation measures of pulsars in the Milky Way with the SKA

≈ 20000 pulsars to be detected with the SKA



Cordes 2001

Key Science Projects on Cosmic Magnetism for most future radio telescopes