Magnetic fields in nearby galaxies:

Prospects with future radio telescopes

Rainer Beck
MPIfR Bonn

Magnetic fields are widely accepted now as important in most astrophysical processes

Key Science Projects on *Cosmic Magnetism* for LOFAR and SKA

Fundamental questions

- Structure
  What is the magnetic power spectrum at small and large scales ?
- Dynamics
  Do magnetic fields affect gas flows and galaxy evolution ?
- Connection
  Are galaxies magnetically connected to intergalactic space ?
- Origin
  When and how were the first magnetic fields generated ?
- Evolution
  How and how fast were galactic magnetic field amplified ?
  (Important for the interpretation of the radio-IR correlation !)

Magnetic field generation and amplification

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

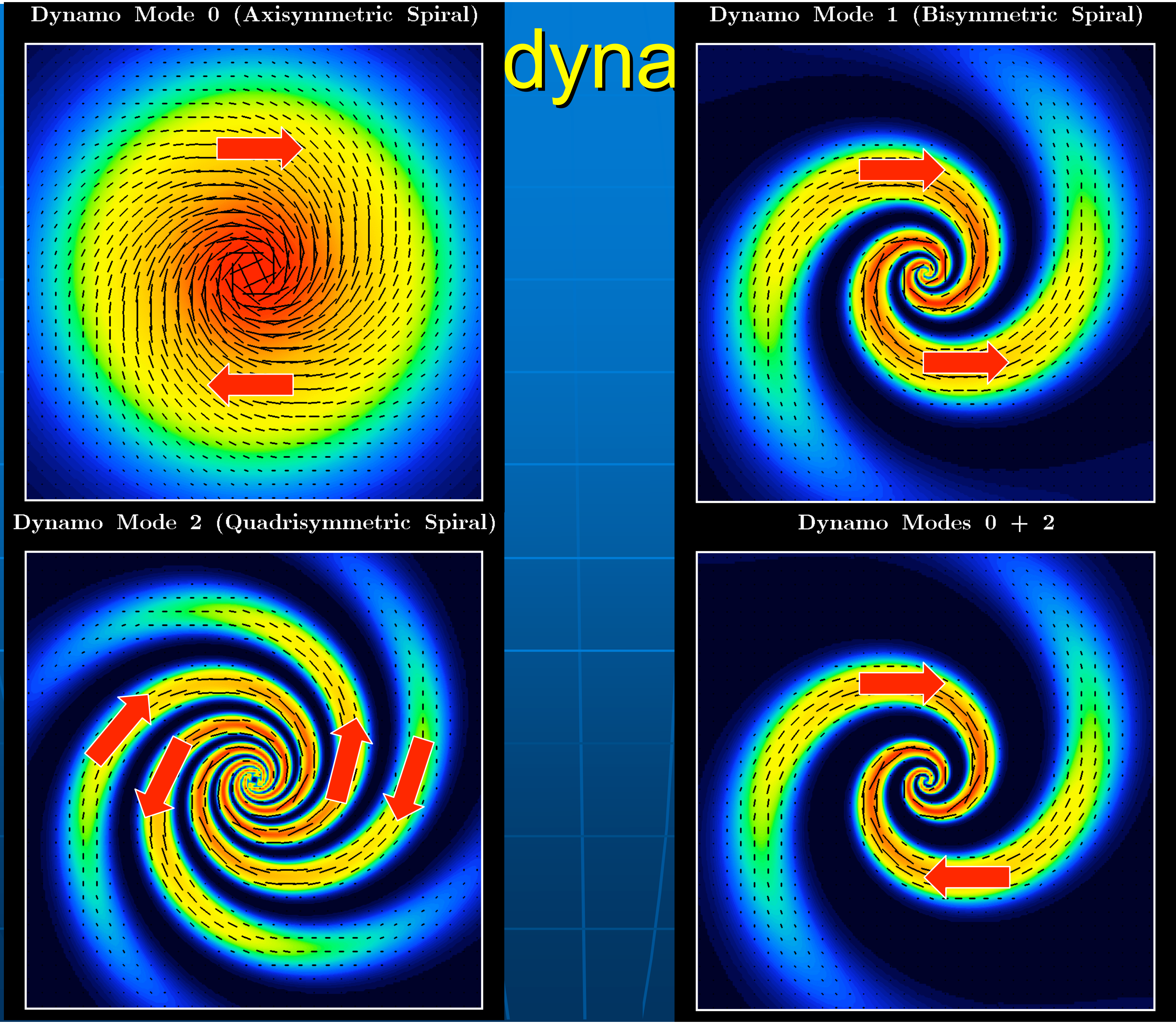
- **Field amplification**
  MRI, compressing / shearing flows,
  turbulent flows, small-scale dynamo

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

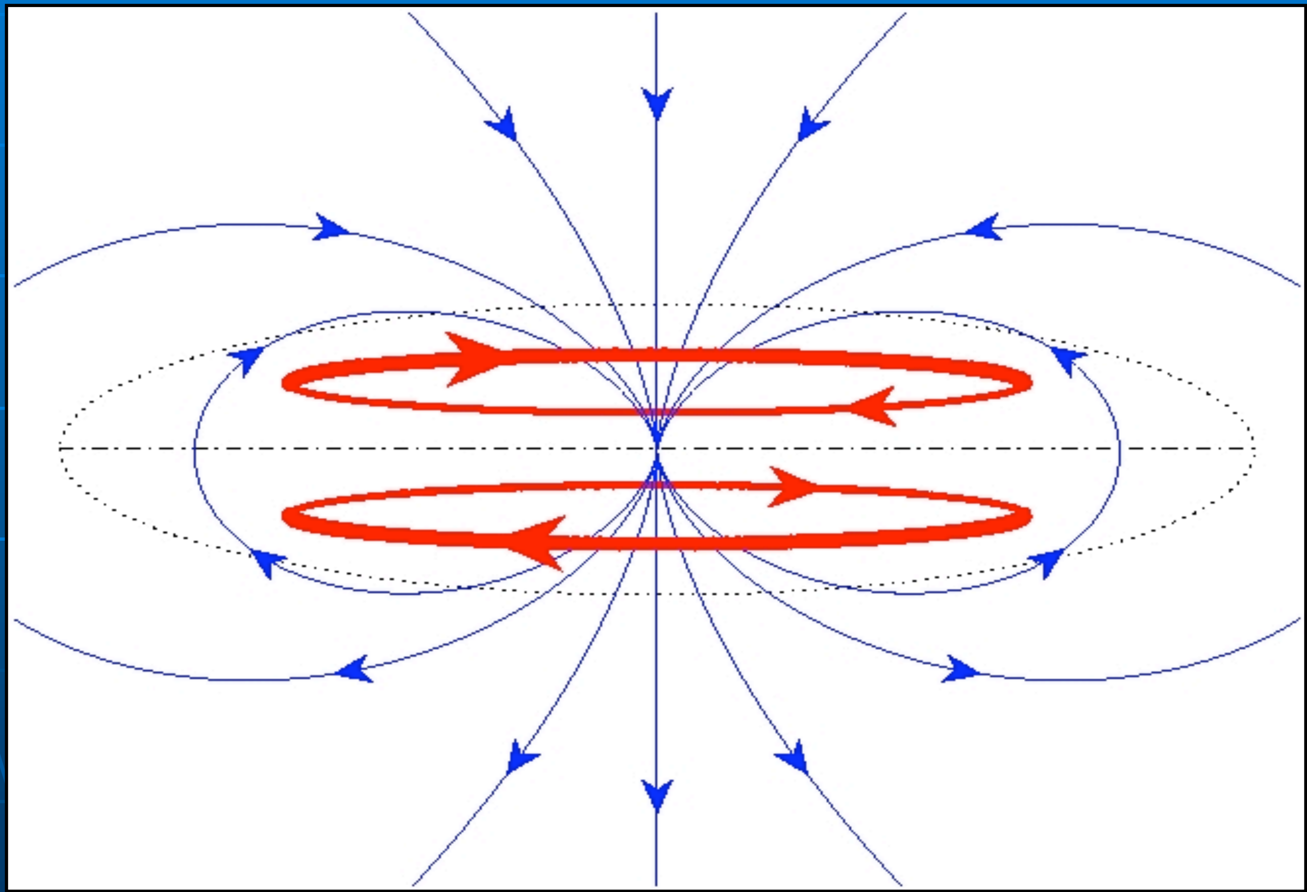
Classical mean-field dynamo

- Ionized gas + differential rotation
  + helical turbulence + magnetic diffusion
- Microphysics approximated by the average parameters
  "alpha-effect" and diffusivity
- → Dynamo equation for the large-scale field
- Generation of large-scale modes
- Field evolution: see talk by Tigran Arshakian

dyna


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

Antisymmetric (dipolar) dynamo mode



Need for realistic models

- MHD models: Back-reaction of the field onto turbulence and gas flow
- Global dynamo models of galaxies including rotation and gas flows (e.g. spiral arms, bar and galactic outflow)
- Dynamo action emerges automatically
- Include galaxy evolution

Limitation no 1:

Global 3-D MHD models
are limited by
huge computing time
on present-day computers

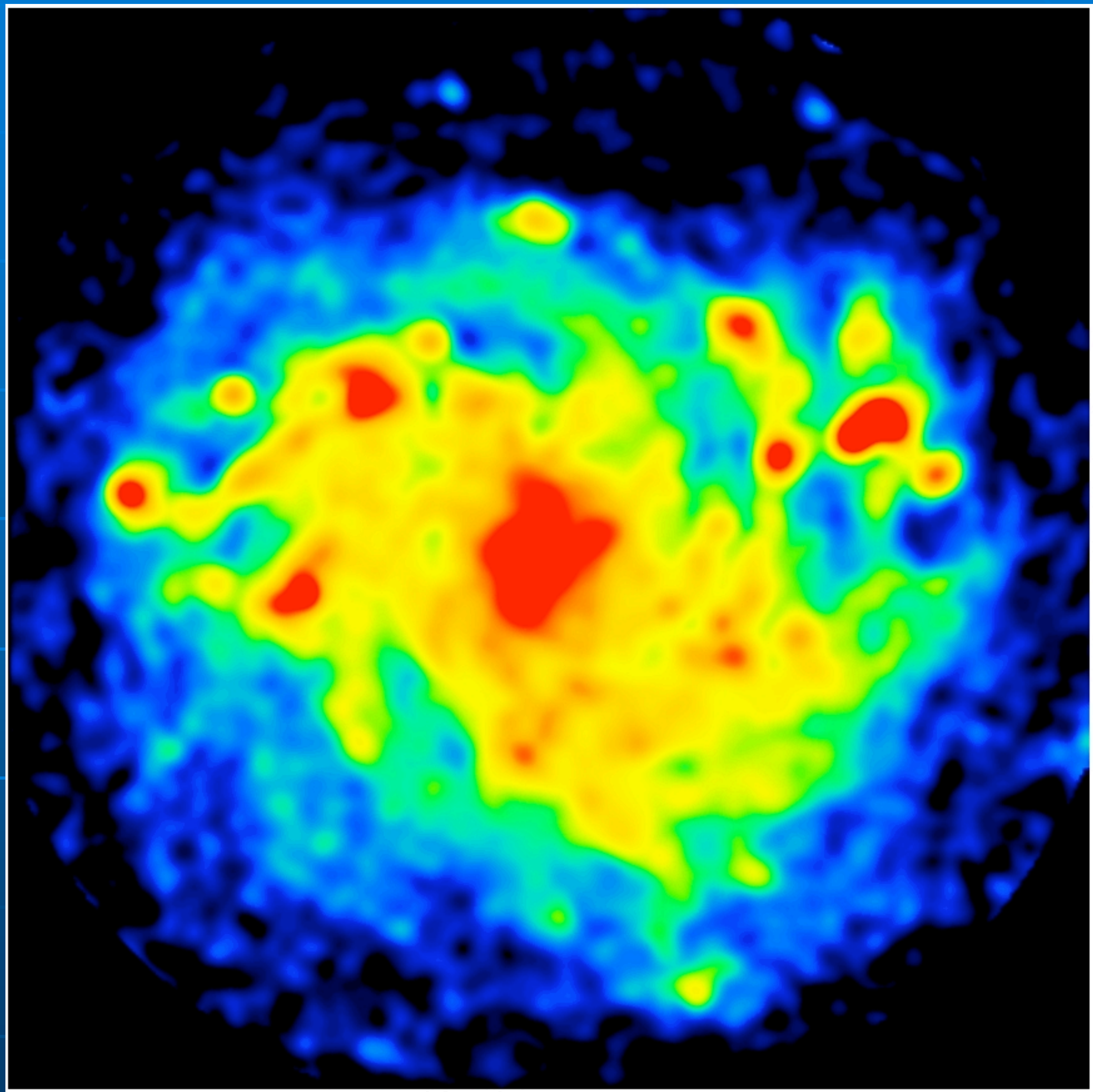
Observational tools

- Total and polarized synchrotron emission
- Faraday rotation
- Faraday depolarization
- Zeeman effect

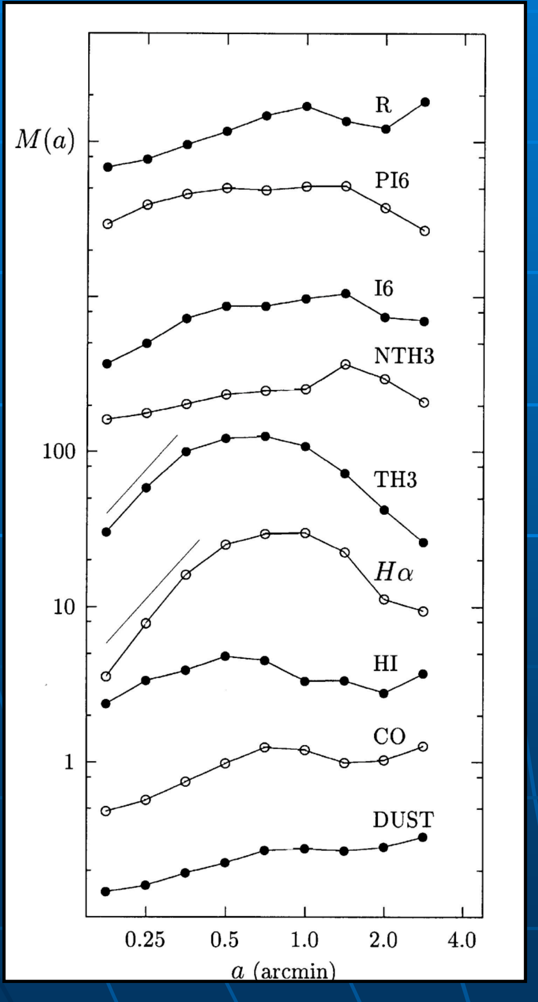
NGC 6946

VLA+Effelsberg 6cm
Total intensity
(Beck 2007)

Typical
radio synchrotron
disk



Structure analysis:
Wavelet spectra for NGC 6946
- using 2-D isotropic wavelet functions



Frick et al. 2001

Three different slopes:
Turbulence – spiral arms – extended disk

Advantages compared to power spectra:

- Wavelet function can be adapted to structures of interest
- Positional information is preserved

Equipartition magnetic field strengths in spiral galaxies

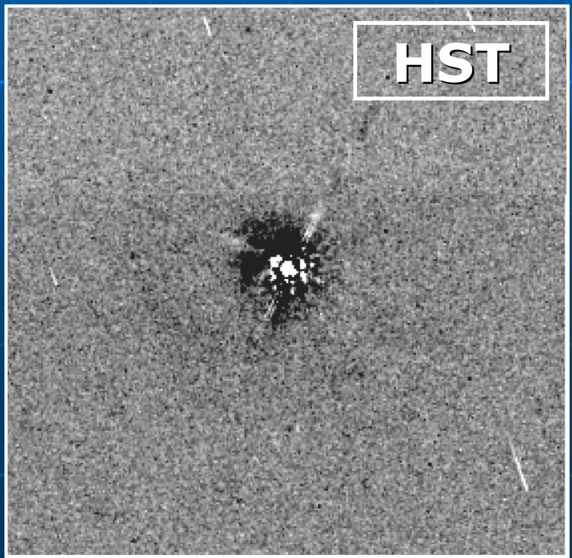
Total field in spiral arms:	**20 - 30 μG**
Regular field in interarm regions:	**5 - 15 μG**
Total field in circum-nuclear rings:	**40 – 100 μG**

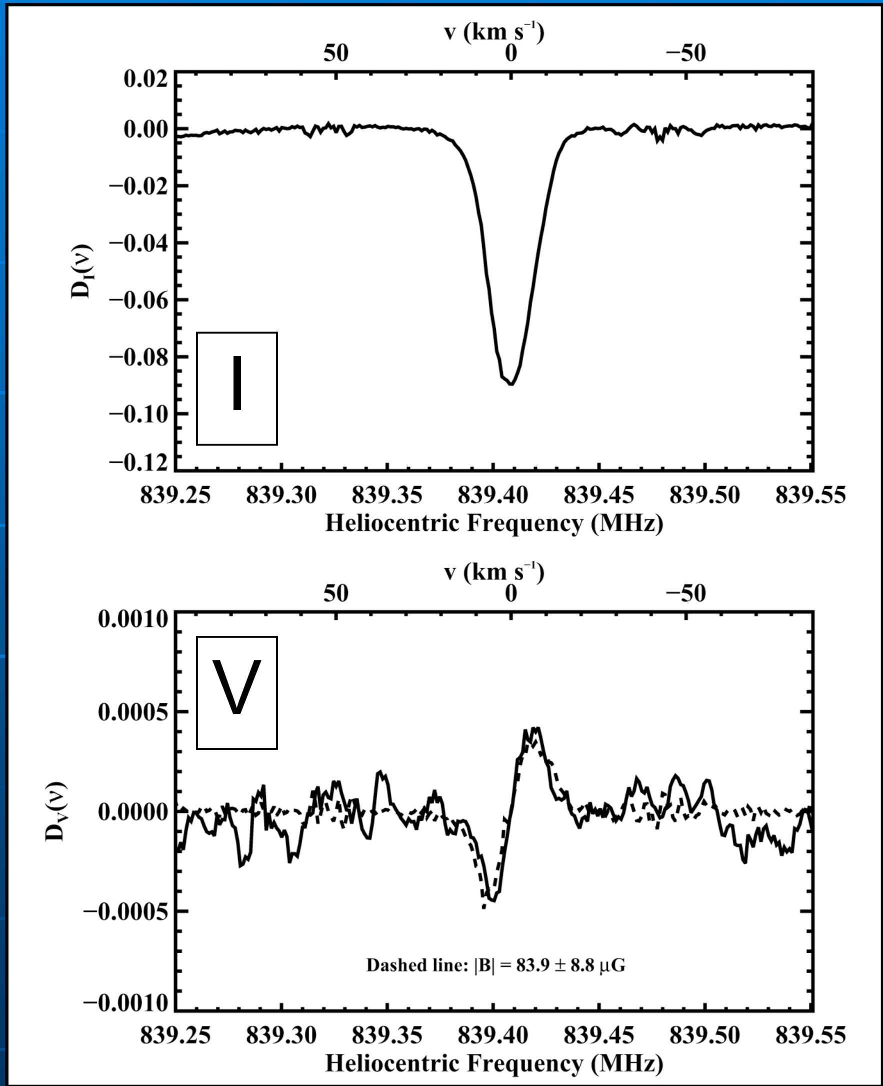
Zeeman effect in a distant galaxy

Zeeman effect in
the HI absorption line
of an intervening
galaxy at z=0.692
against a bright quasar:

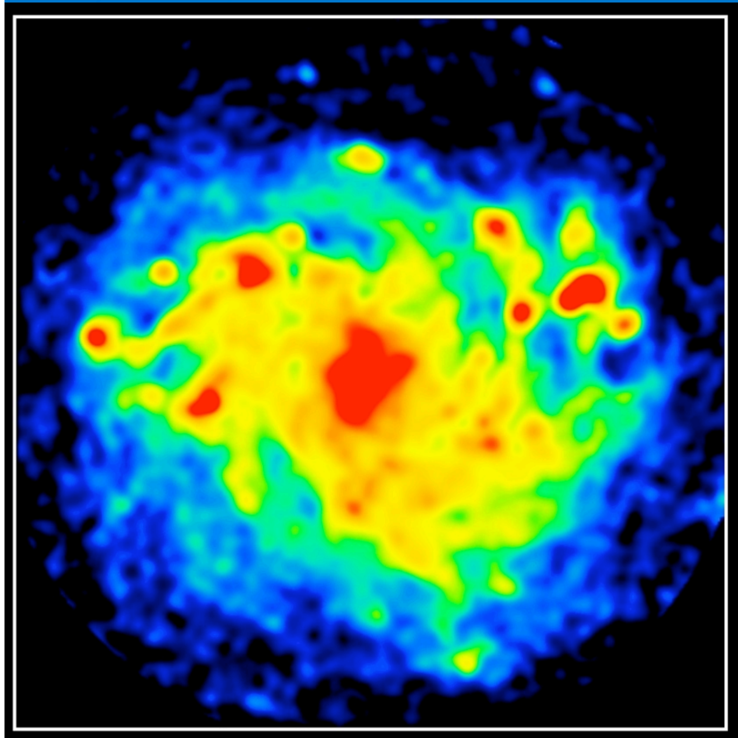
$B_{\parallel} \approx 84\ \mu G$

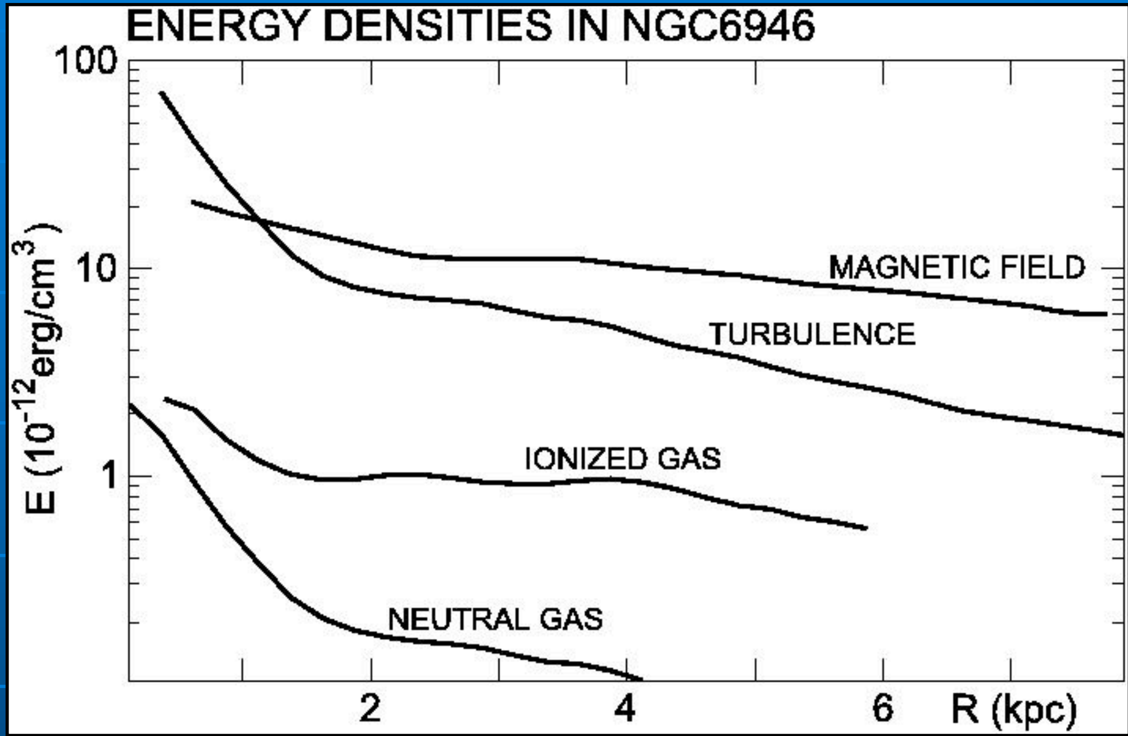
(Wolfe et al. 2008)





Energy densities





Turbulence (cold clouds):
V_{turb} = 7 km/s

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

Beck 2007

Limitation no 2:

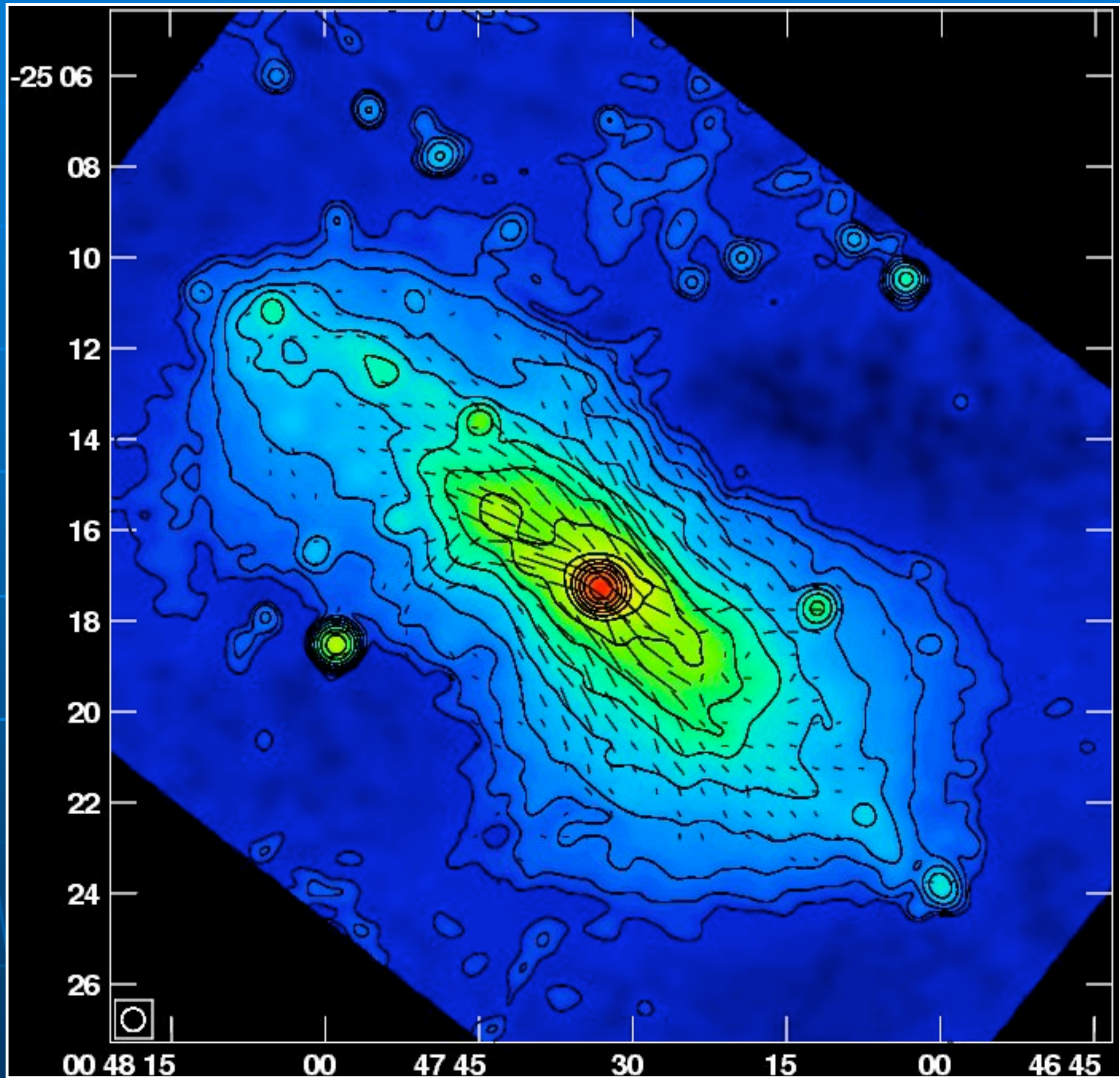
Understanding the dynamical effects
of magnetic fields in galaxies
is limited by
the insufficient resolution
of present-day radio telescopes

Typical scale lengths in 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 253

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

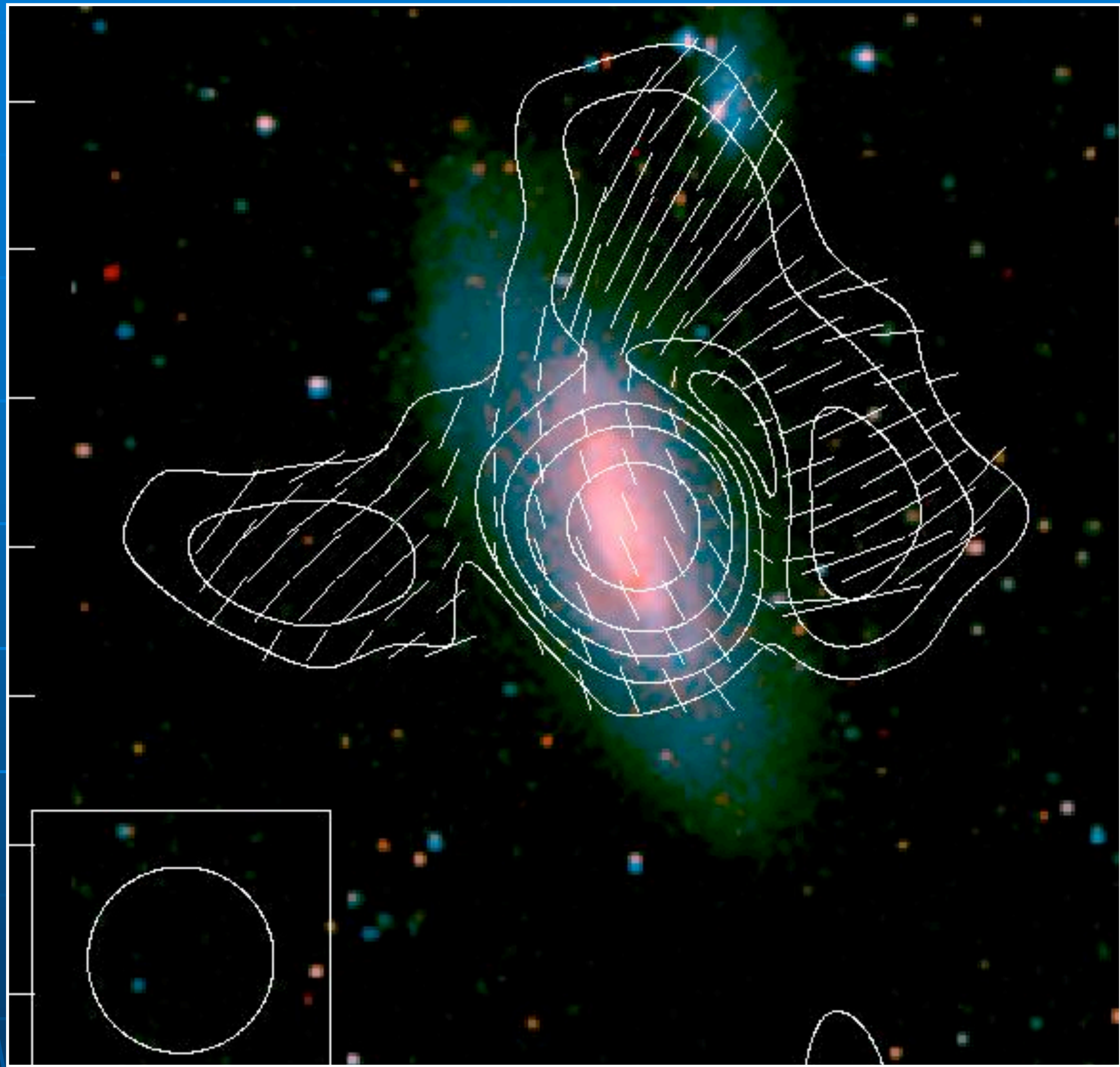


Exponential radio halo

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

NGC 4569

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



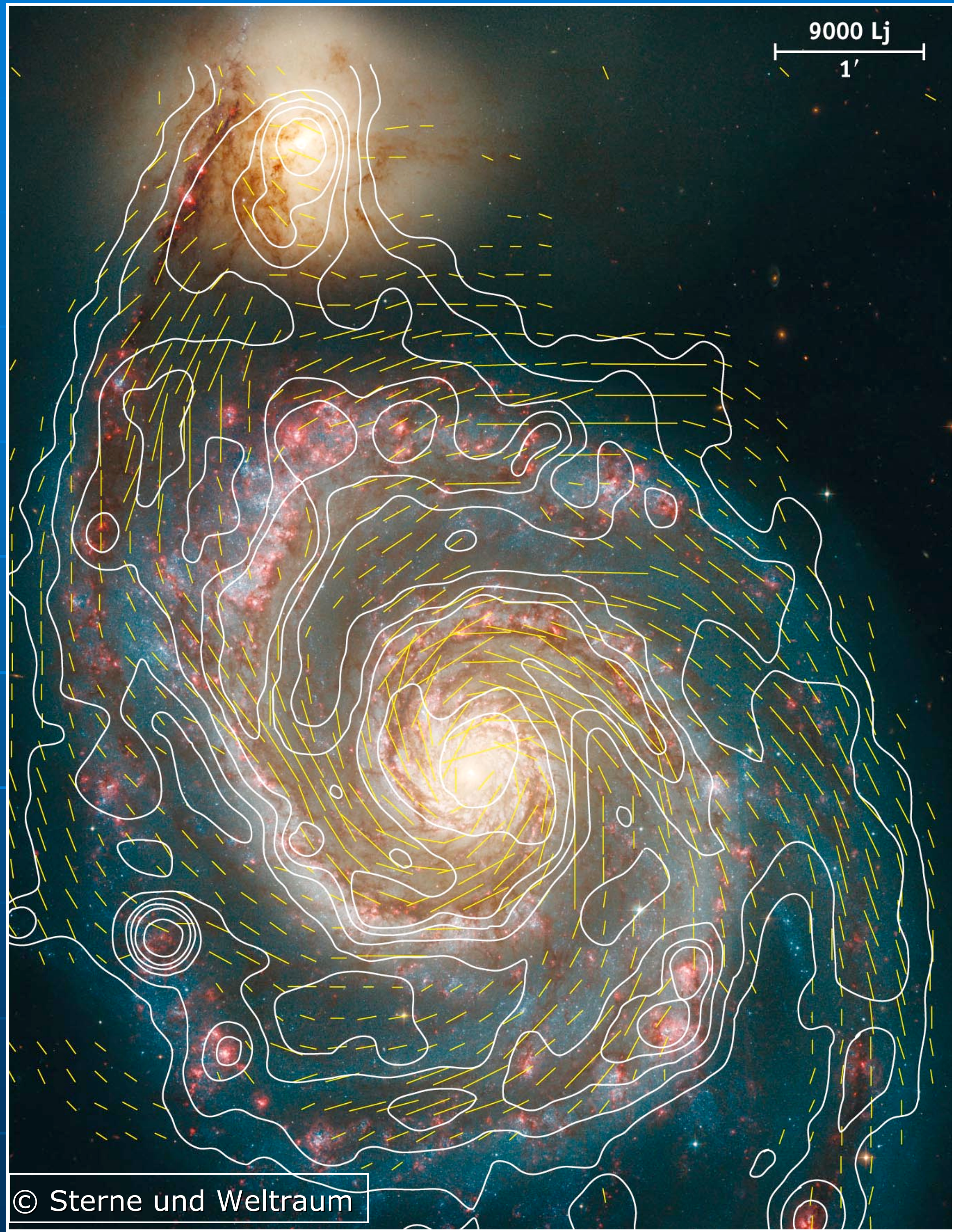
Past interactions are best visible in the magnetic field !

Limitation no 3:

The observable extent of magnetic fields in galaxies is limited by energy losses of the cosmic-ray electrons

M 51

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



Polarization vectors:

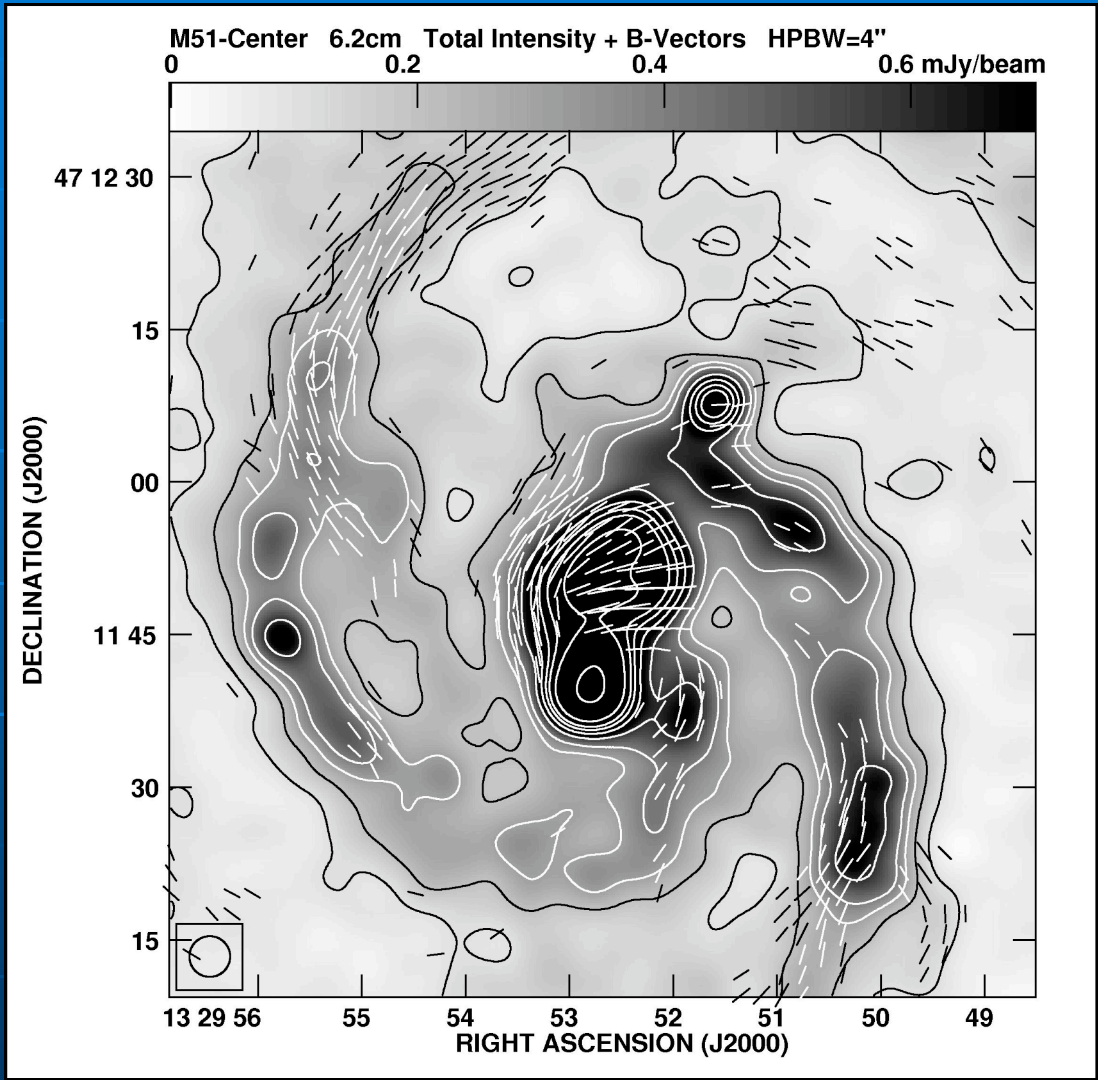
Spiral fields
more or less
parallel to the
optical
spiral arms

M 51

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

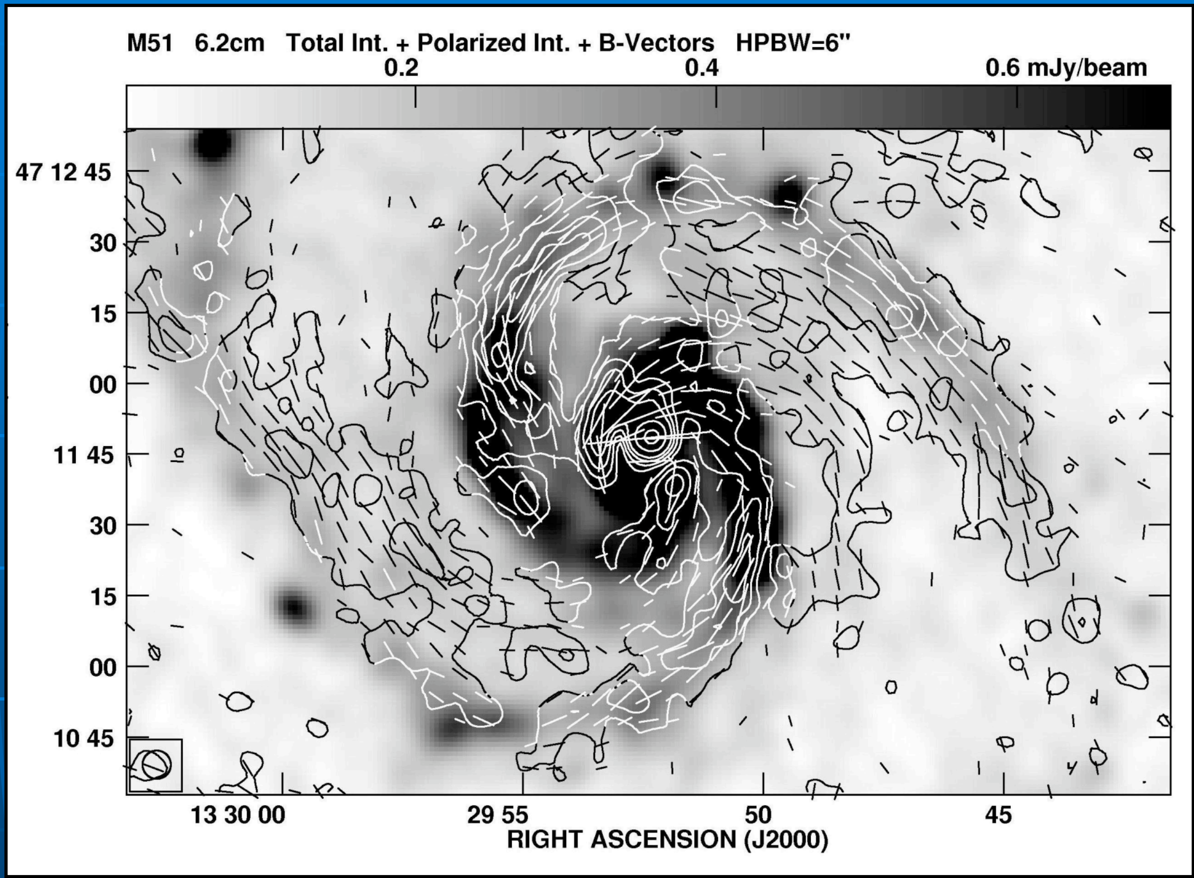
Spiral fields parallel to the inner spiral arms:

Density-wave compression



M 51

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



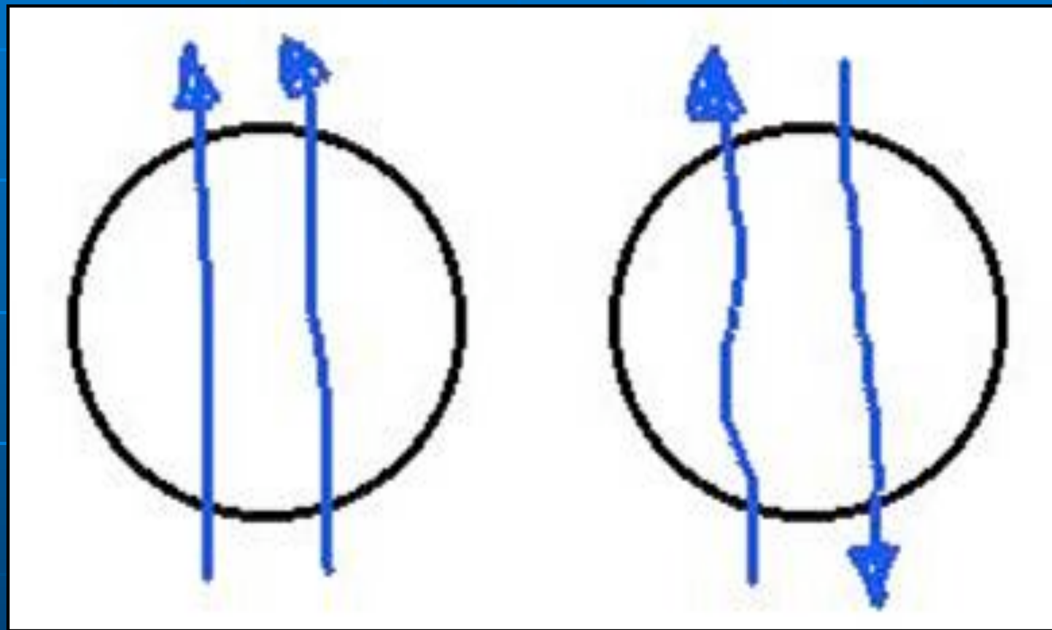
Spiral fields
between the
outer spiral arms
(weak density waves):

Dynamo action?
Shear?

Spiral fields: coherent or incoherent ?

Fletcher 2004

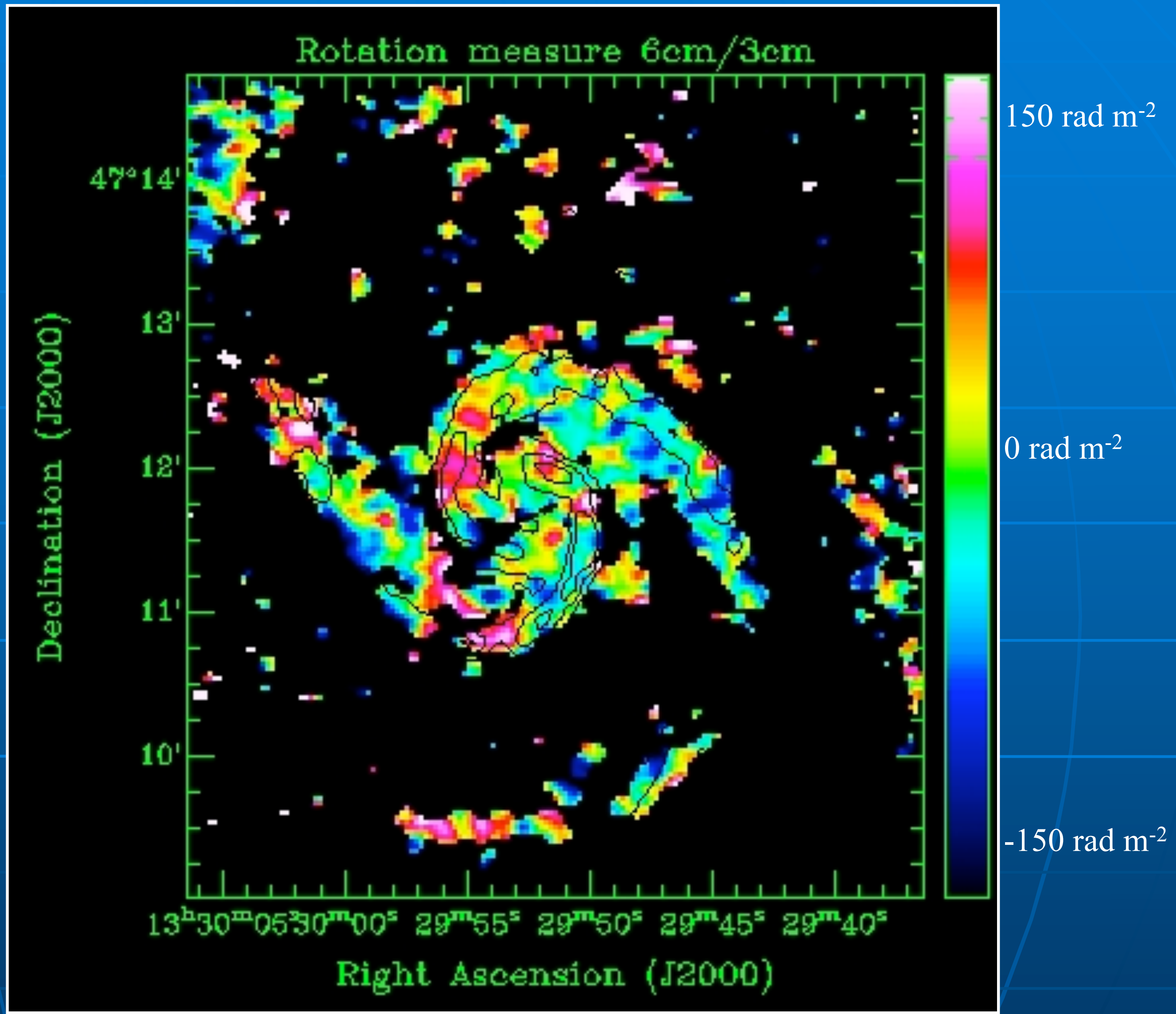
Regular field (coherent) | Anisotropic field (incoherent)



	Regular field (coherent)	Anisotropic field (incoherent)
Polarization :	strong	strong
Faraday rotation :	**high**	low

M51

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



Complicated & noisy RM pattern:

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

Limitation no 4:

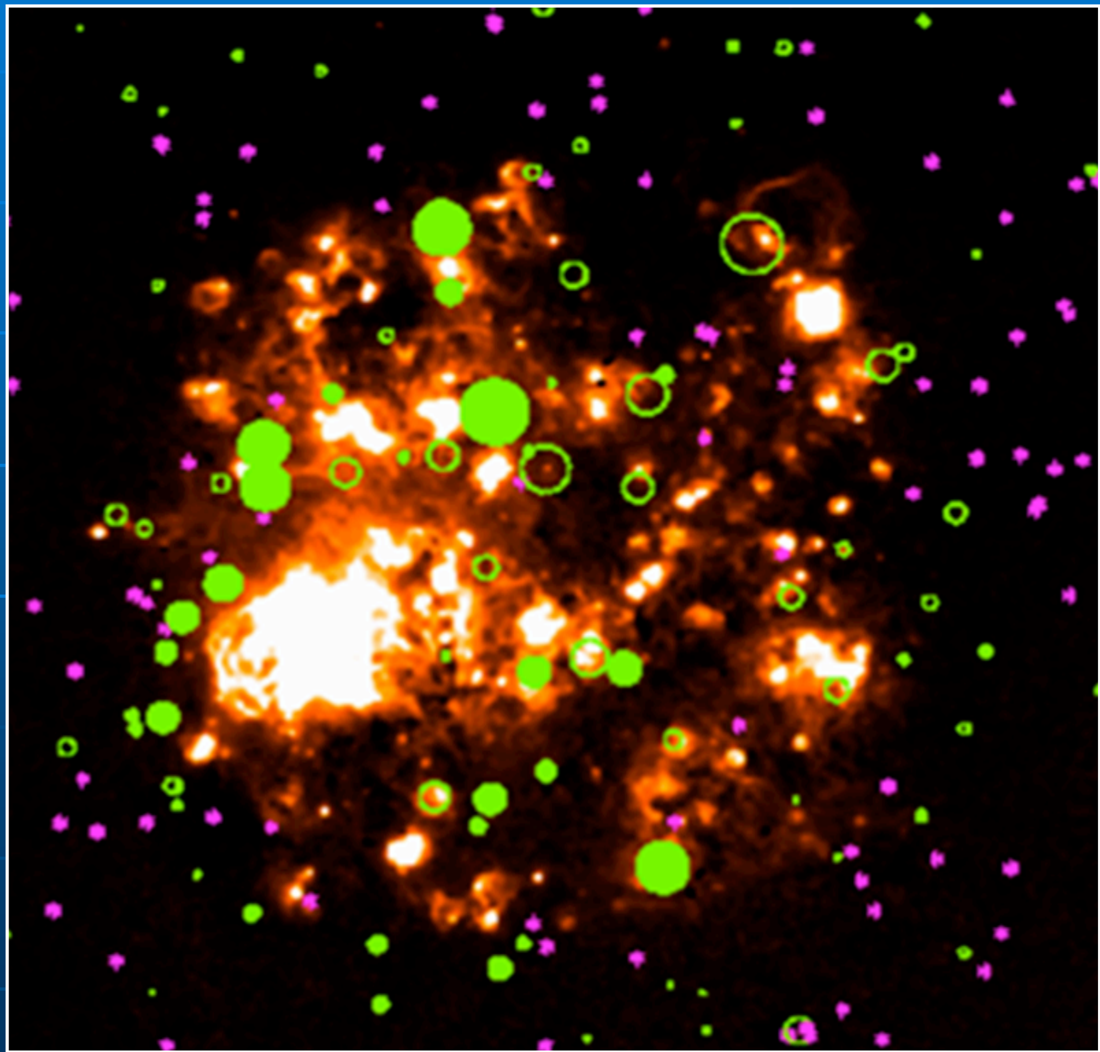
The distinction between
regular and anisotropic fields
is limited by
the low signal-to-noise and
the low resolution of present-day
polarization observations

High S/N:
RMs from background sources

LMC

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

Axisymmetric
dynamo field ?



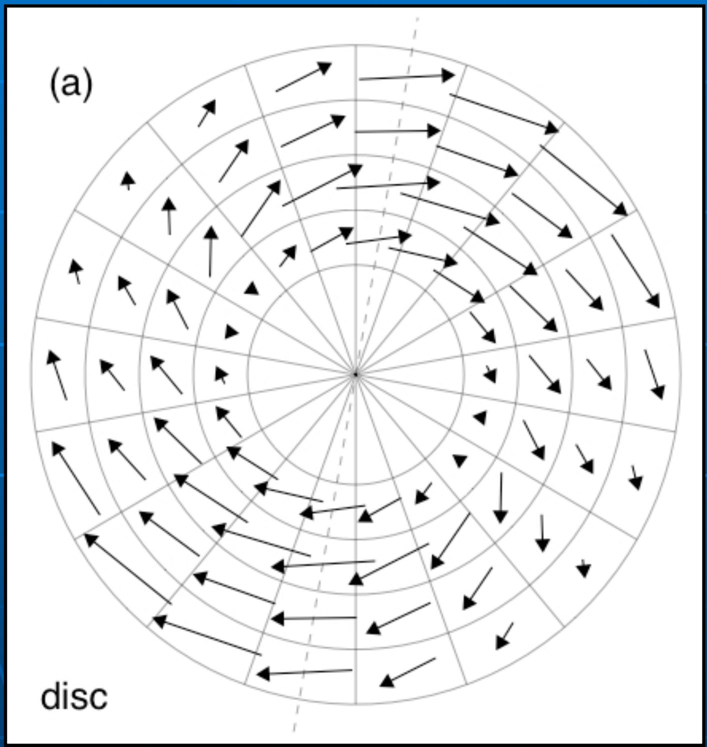
Limitation no 5:

Detection of
large-scale field structures
is limited by
the small number density of
polarized background sources

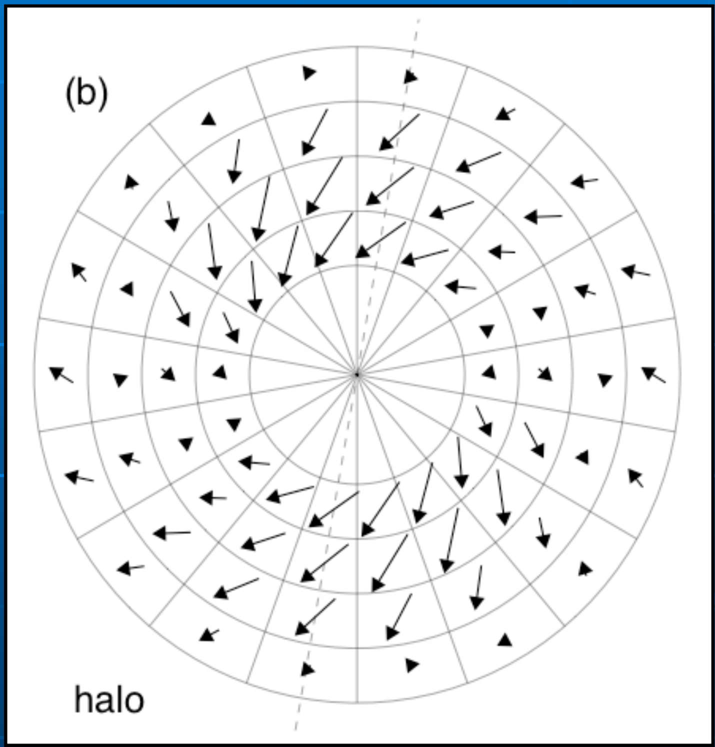
Four-frequency analysis in M51

Fletcher et al. 2009

Broadband RM 3/6cm
Disk: ASS (m=0) + m=2 modes



Broadband RM 18/20cm
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)

Limitation no 6:

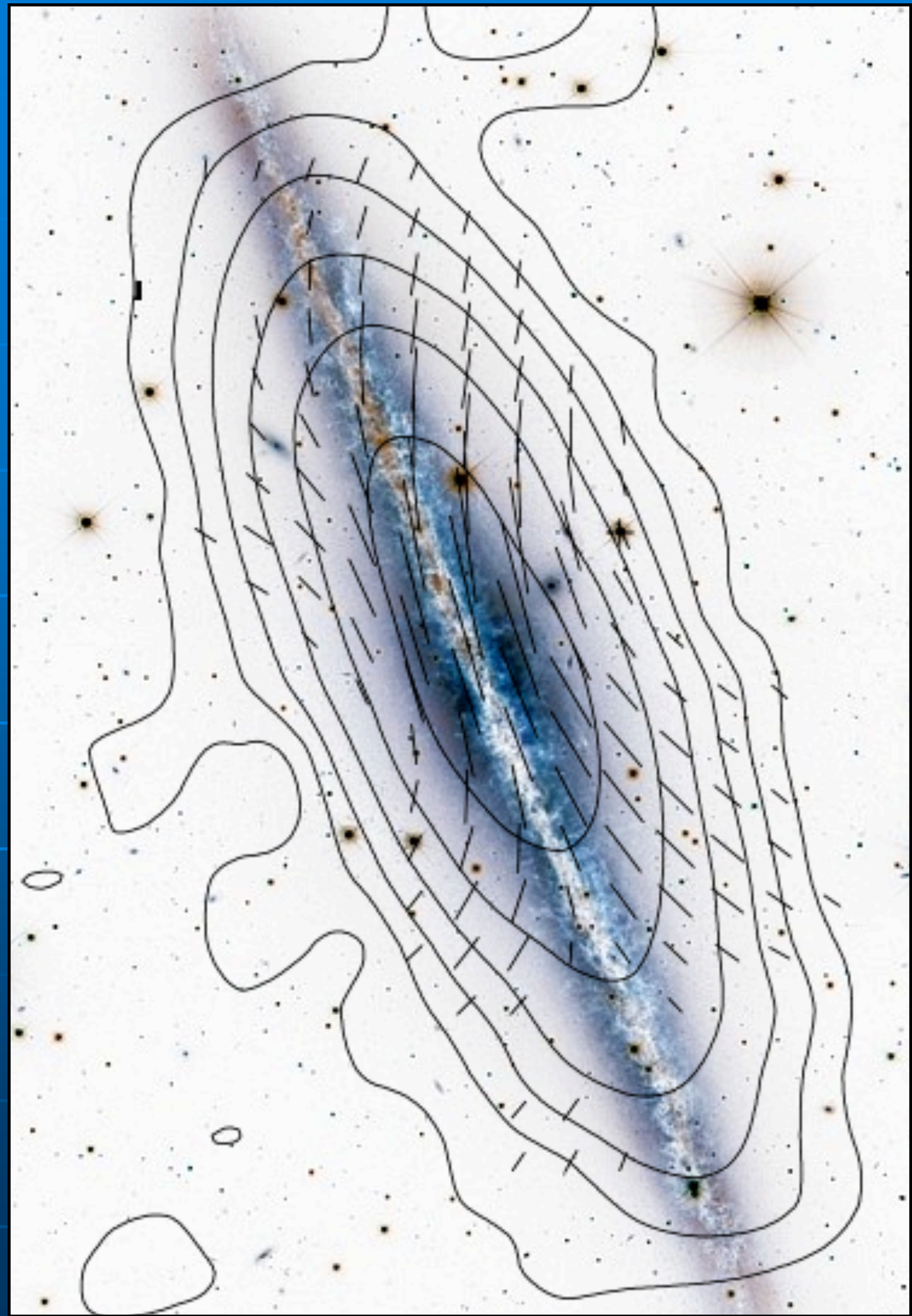
Field patterns
in the disk and the halo
are hard to distinguish
by broadband polarimetry

(but see next talk by George Heald)

Radio halos: Edge-on galaxies

NGC 891

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

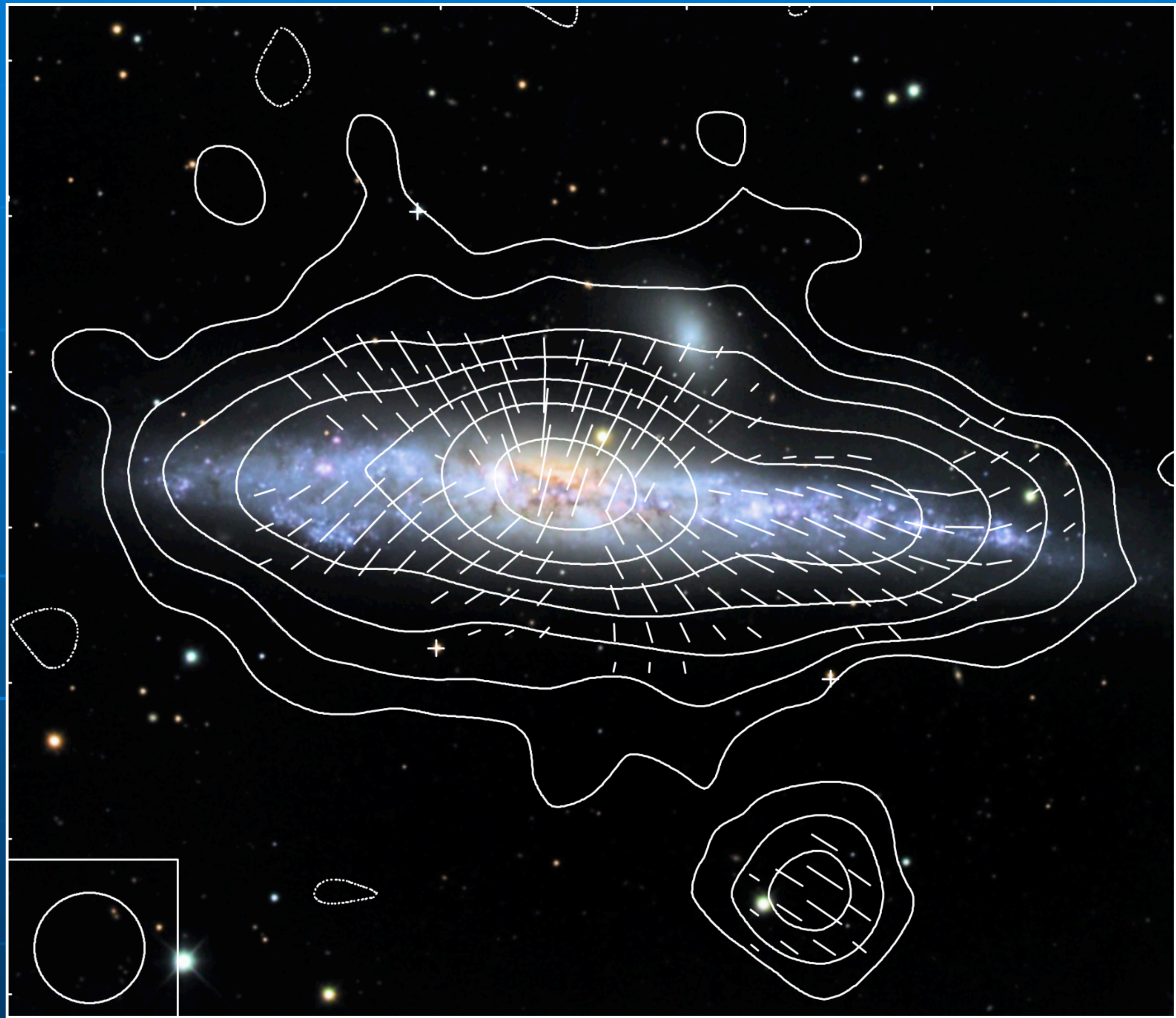


Bright radio halo with
vertical field components:

Driven by a disk wind?

NGC 4631

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



Huge halo:

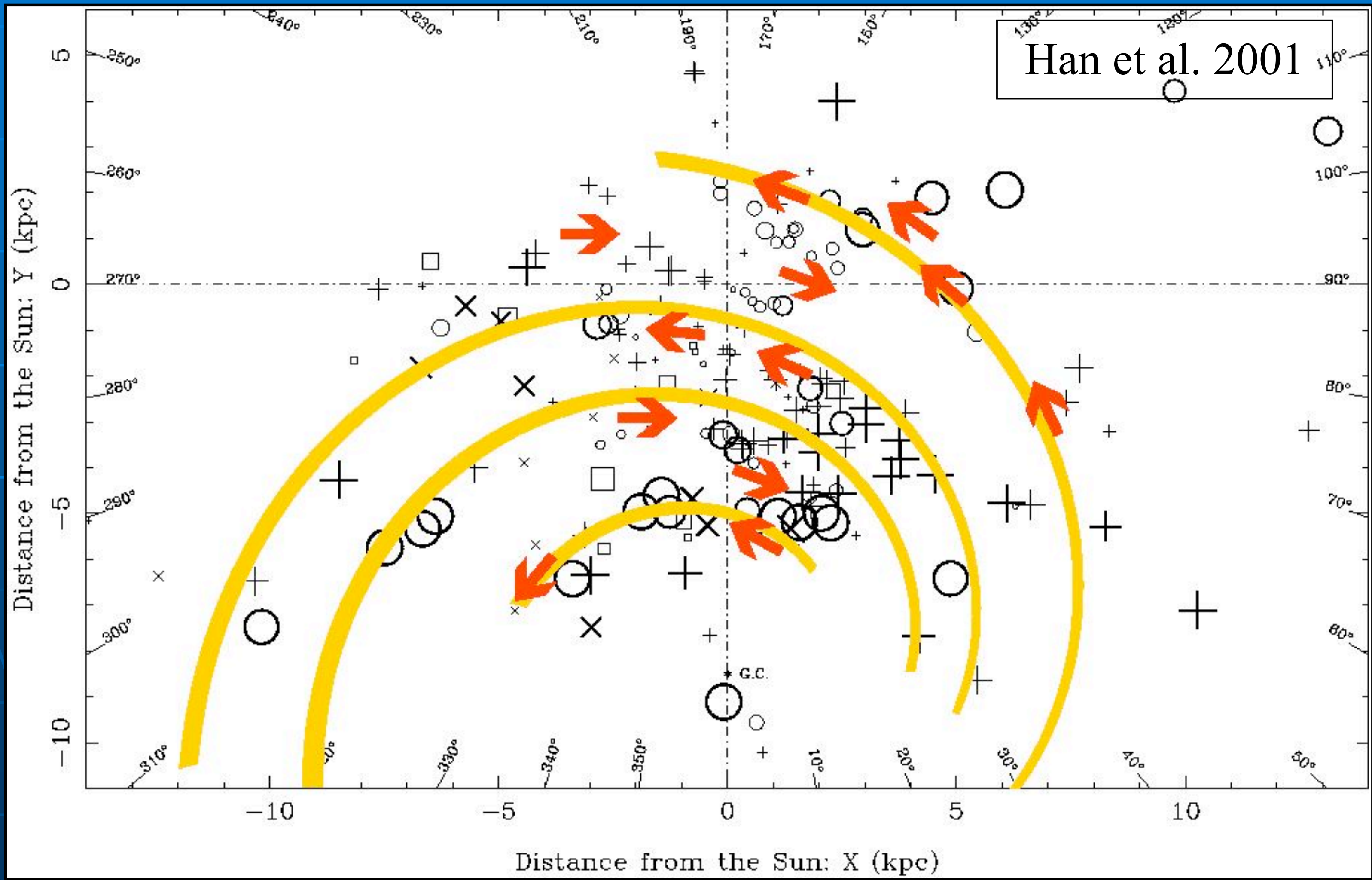
X-shaped field,
not consistent
with standard
dynamo modes

Noisy RM pattern

Limitation no 7:

Present-day radio telescopes do not allow to resolve the structure of radio halos

Pulsar RMs in the Milky Way:
Many reversals ?



Limitation no 8:

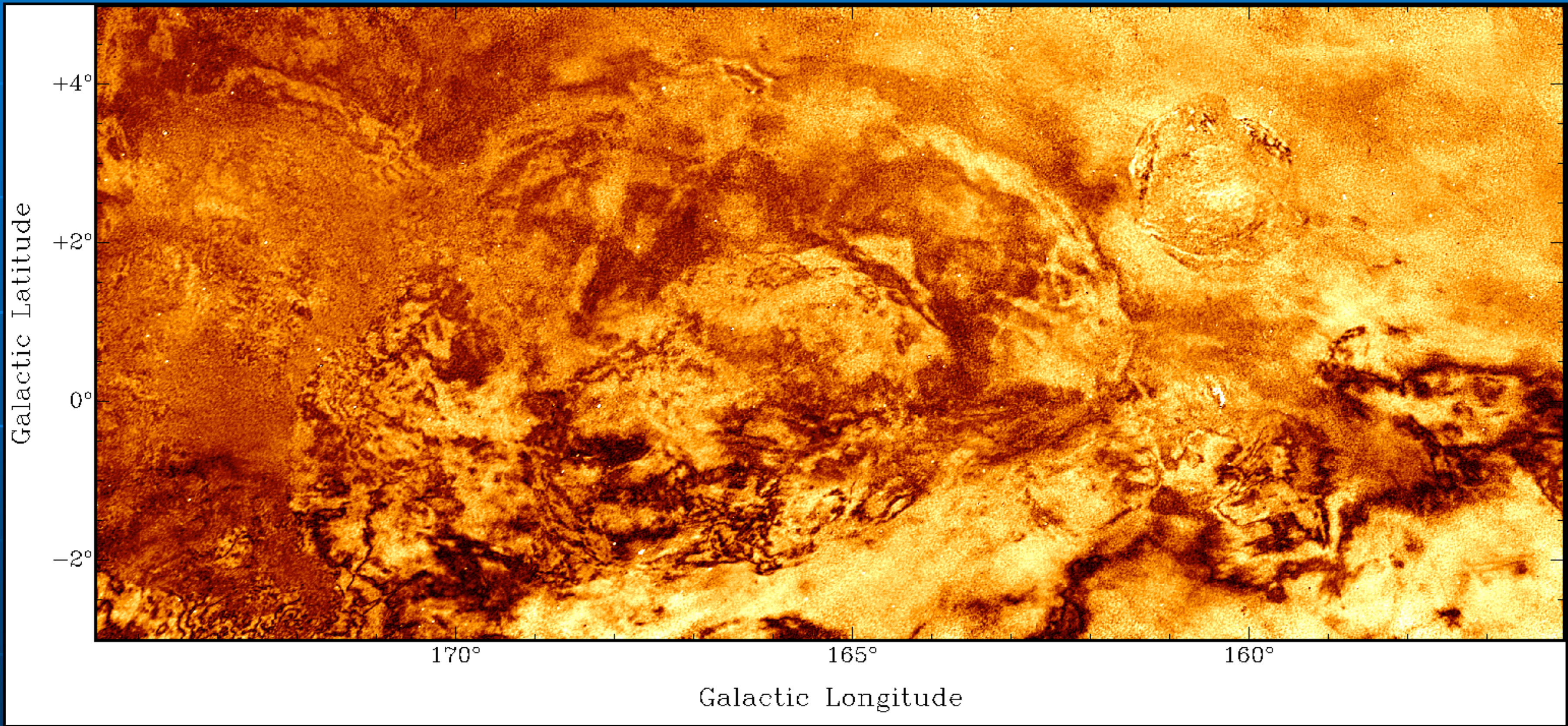
Detection of
large-scale field structures
in the Milky Way
is limited by
the small number of
pulsar RMs

Polarization in the Milky Way

Canadian Galactic Plane Survey (CGPS)

(21cm, DRAO+Effelsberg)

Landecker, Kothes, Reich, et al.



Magnetic filaments or Faraday screens?

Limitation no 9:

Observation of the
small-scale field structure
in the Milky Way
is limited by
Faraday depolarization

Breaking the limits

- **Higher resolution** (resolving gas-field interaction, resolving dynamo modes, less depolarization)
- **Larger sensitivity (A_{eff}/T_{sys})** (high S/N at high resolution, more polarized background sources, more pulsars, more Zeeman sources)
- **Low frequencies** (extended halos, interactions, IGM fields, detection of very low RMs)
- **Spectro-polarimetry** (resolve RM structures along the line-of-sight, reduce Faraday depolarization)
- **Global 3-D MHD models** (understand dynamo action)

Polarization Pathfinders

NAIC

← GALFACTS
(Arecibo, 2008)

LOFAR →
(Europe, 2009)

MPIfR

RAL Berkeley

← ATA
(Hat Creek, 2008)

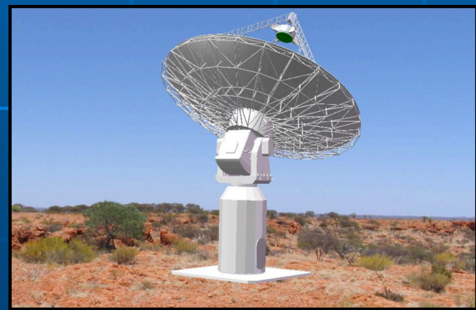
SKAMP →
(Bungendore, 2009)

ATNF

NRAO

← EVLA
(New Mexico, 2012)

ASKAP →
(Boolardy, 2012)



ATNF

← MeerKAT
(Karoo, 2012)

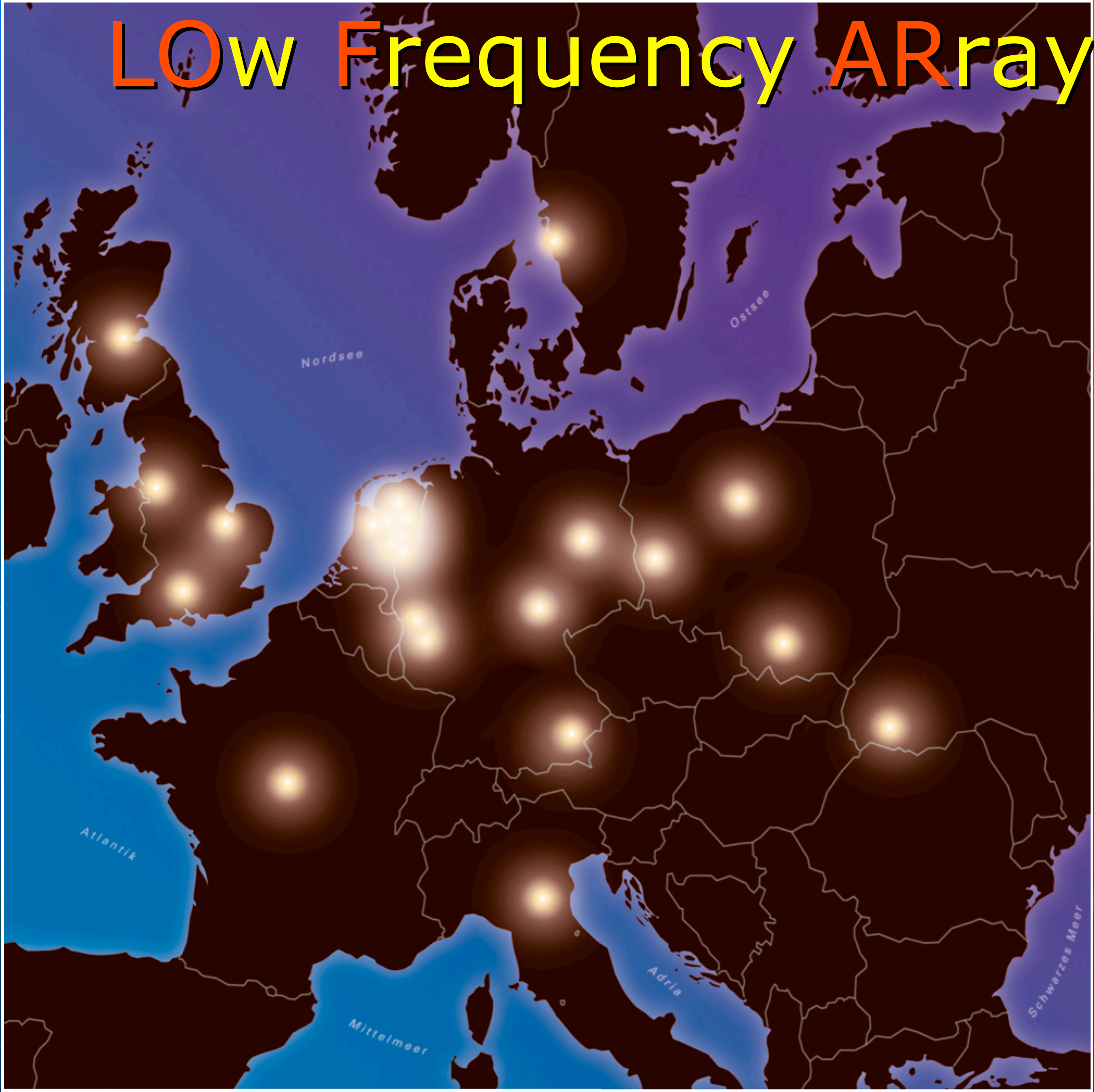
APERTIF →
(Westerbork, 2012)

The future I:

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

LOw Frequency ARray

30-80 MHz
110-240 MHz



© Spektrum der Wissenschaft/Emde-Grafik

Low-frequency radio observations

LOFAR

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

$\longrightarrow$ low frequencies trace cosmic-ray electrons in weak magnetic fields

- Lifetime of electrons due to synchrotron loss:

$t \sim \upsilon^{-0.5} B^{-1.5}$

$\longrightarrow$ low frequencies trace old cosmic-ray electrons

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

$\longrightarrow$ low frequencies allow to measure small rotation measures

Faraday rotation errors

Detection of low RM needs:

- high signal-to-noise in polarization (S_p/σ_p) and/or
- wide frequency span ($\Delta\lambda^2$):

$$\Delta RM \approx \sqrt{3}\ \left((S_p/\sigma_p)\ \Delta\lambda^2 \right)^{-1}$$

Increasing $\Delta\lambda^2$ is less expensive than increasing S_p/σ_p !

Polarization surveys with LOFAR

LOFAR

Plans:

- All-sky shallow surveys at 30, 60, 120, 200 MHz: Search for polarized sources, determine RMs
- Deeper survey of ≈ 60 nearby galaxies: RM grid
- Very deep survey of ≈ 20 nearby galaxies: Diffuse pol + RM maps, RM grid

Issues:

- Instrumental & ionospheric calibration
- Accuracy of Galactic foreground subtraction
- Intrinsic depolarization within background sources: Background source density may be low

The future II:

Recognition of
large-scale field structures
via RM grids

Faraday rotation grids at ≈1.4 GHz with SKA pathfinders

- **ATA:** $A/T \approx 25$, $\Delta\nu \approx 0.2$ GHz,
  $\sigma \approx 20$ μJy/beam at 1.4 GHz in 12h
  → ≈ 30 sources per deg^2

- **ASKAP, APERTIF:** $A/T \approx 80$, $\Delta\nu \approx 0.3$ GHz,
  $\sigma \approx 10$ μJy/beam at 1.4 GHz in 12h
  → ≈ 50 sources per deg^2

- **MeerKAT:** $A/T \approx 200$, $\Delta\nu \approx 0.5$ GHz,
  $\sigma \approx 2$ μJy/beam at 1.4 GHz in 12h
  → ≈ 200 sources per deg^2

- **EVLA:** $A/T \approx 400$, $\Delta\nu \approx 1$ GHz,
  $\sigma \approx 1$ μJy/beam at 1.4 GHz in 12h
  → ≈ 400 sources per deg^2

ASKAP

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

- POSSUM wide (all sky): ≈ 50 sources per deg^2
  - can recognize large-scale fields in LMC+SMC
- POSSUM deep (one field): ≈ 400 sources per deg^2
  - can measure integrated pol from distant galaxies

  (see talk by Jeroen Stil)

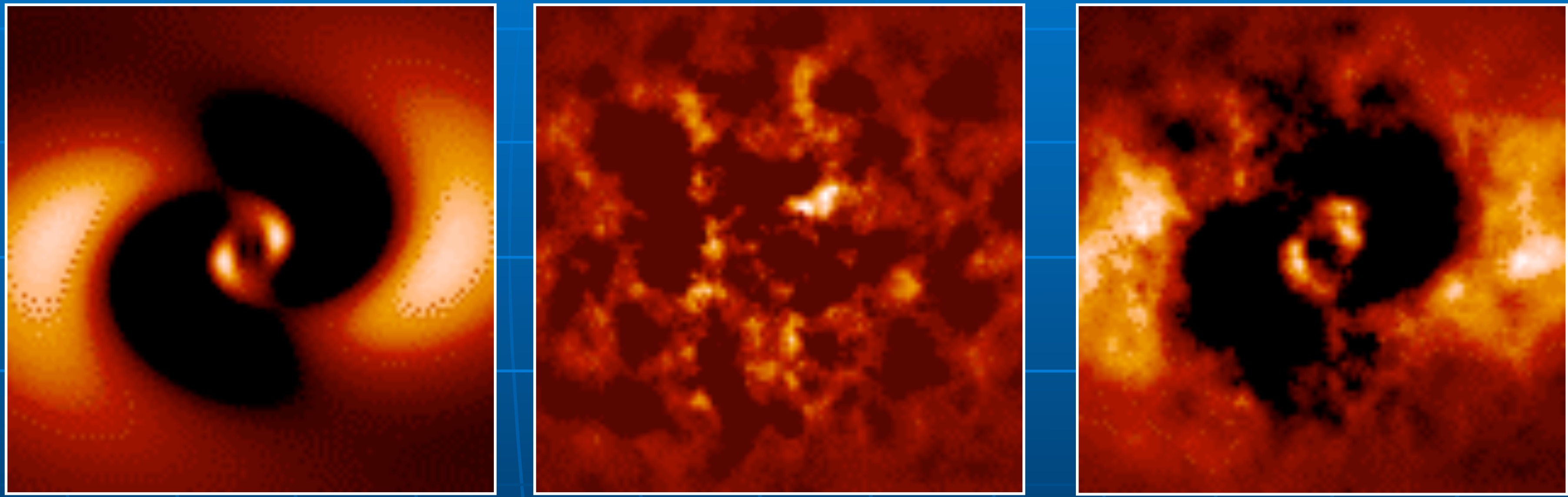
BROLGA: *Broadband Radio Observations of Local Groups with ASKAP*

(including RM grids)

(see talk by Tobias Westmeier)

Faraday rotation through spiral galaxies

Stepanov et al. 2008

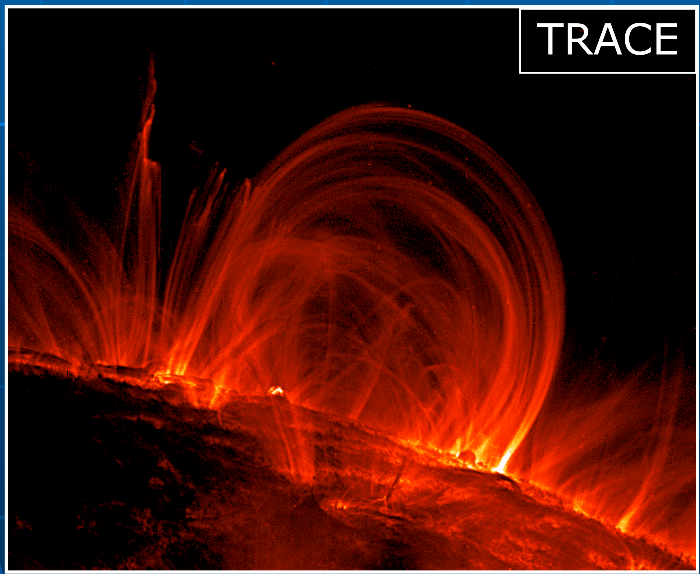


Bisymmetric regular field | Turbulent field | Sum

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

The future III:

Resolving magnetic field details with the SKA



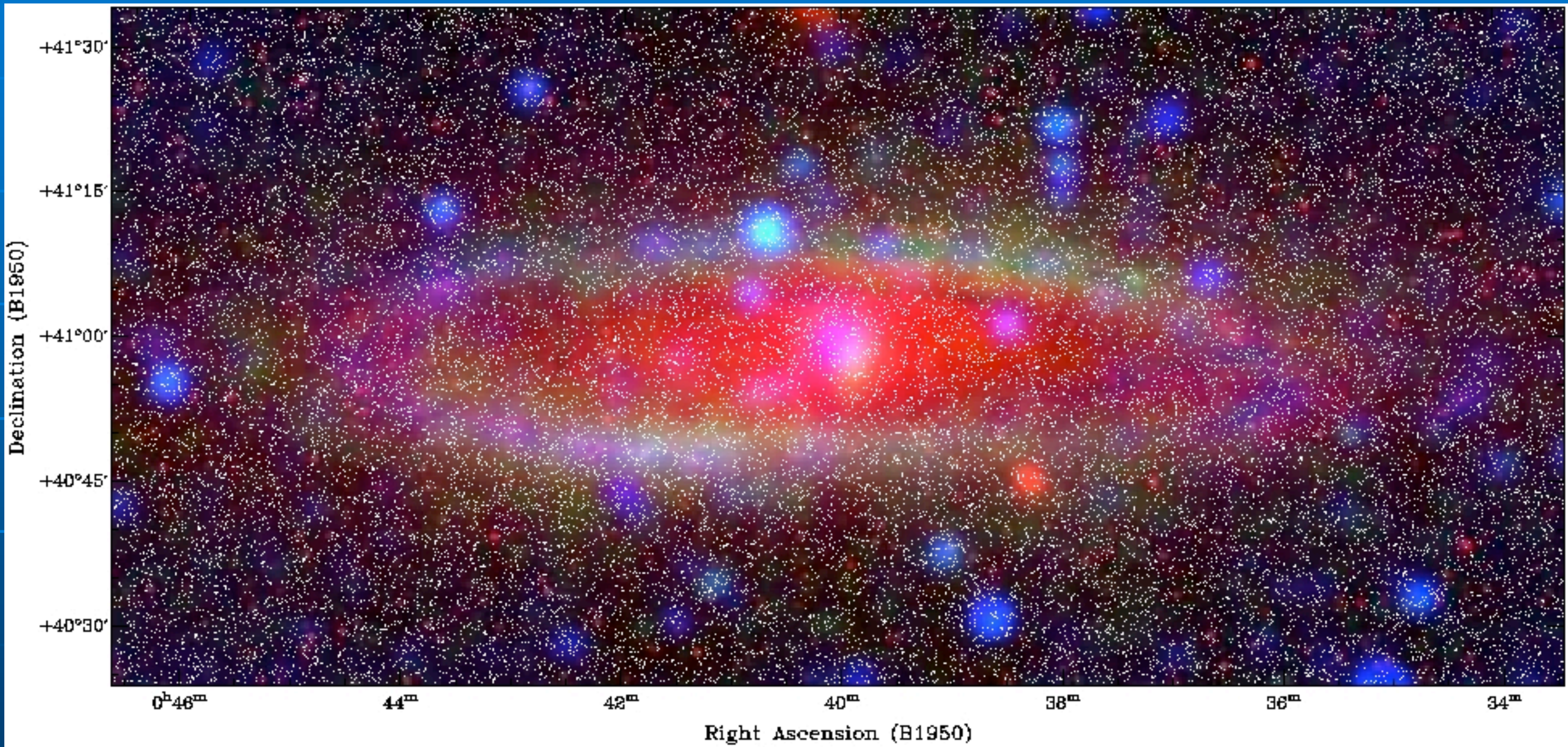
SKA core station

Faraday rotation grids with the SKA

- A/T ≈ 2000, $\Delta\nu \approx 0.5$ GHz
- $\sigma \approx 20$ nJy/beam at 1.4 GHz in 12h
- → ≈ 5000 sources per $\deg^2$

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 simple field patterns:

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

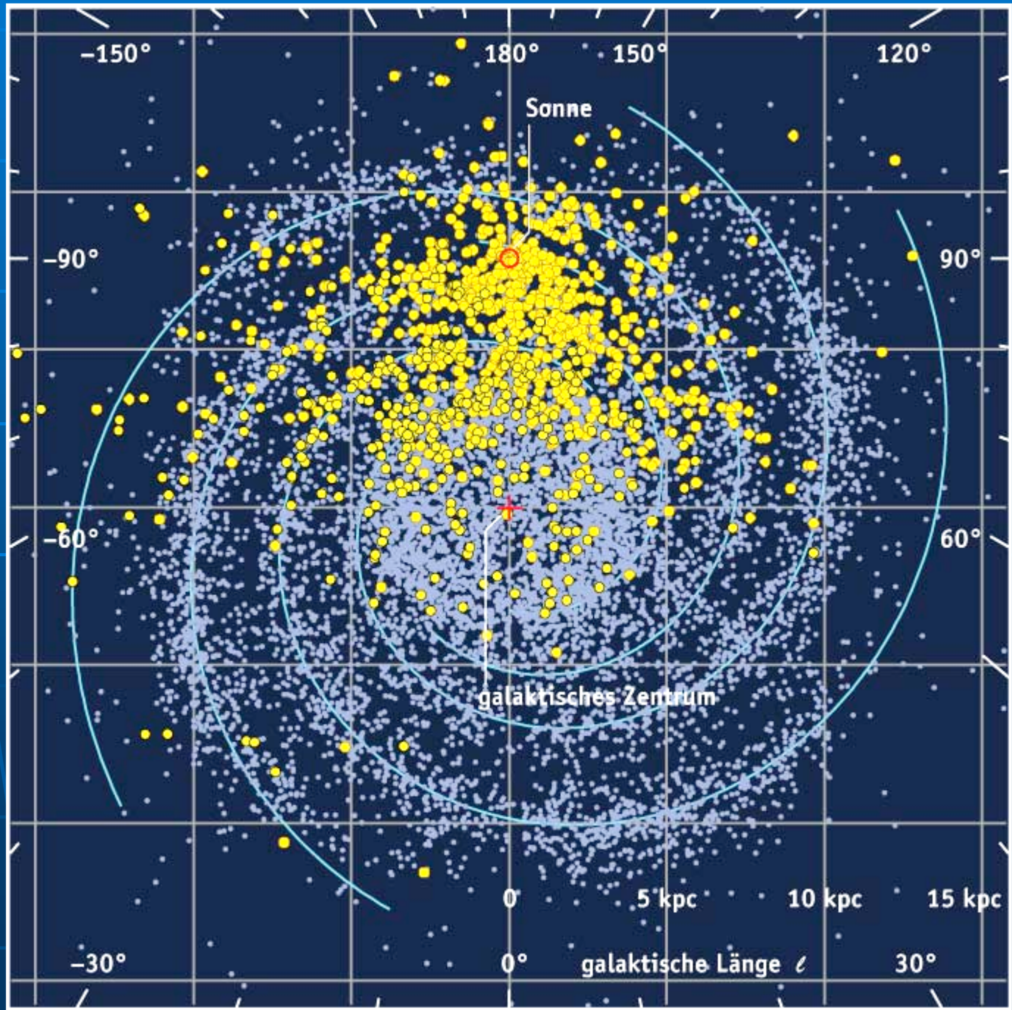
3-D reconstruction of field patterns:

- 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



Resolving diffuse emission with the SKA

- Intensity of diffuse emission scales as $(\text{beamsize})^2$
- Observation time scales as $(S/N)^2 \times (\text{beamsize})^{-4}$

→ Resolving diffuse polarized emission requires very high sensitivity and hence the SKA

- *Note: Short antenna spacings needed to detect the largest scales*

Summary: Future observations

Diffuse radio polarization:

- Polarization survey of distant galaxies: Effelsberg, GALFACTS, ASKAP, APERTIF
- Magnetic fields in outer disks and halos, intergalactic fields: LOFAR
- Detailed magnetic field structure in nearby galaxies: EVLA, SKA

RM grids of background sources:

- Field patterns in nearby galaxies & Milky Way: EVLA, ASKAP, APERTIF
- Field patterns in distant galaxies: EVLA, MeerKAT, SKA
- Evolution of galactic magnetic fields: SKA

Pulsar RMs:

- Detailed structure of the Milky Way's field: ASKAP, APERTIF, SKA