Properties of Interstellar Magnetic Fields Derived from Radio Polarization Observations -

Open questions and prospects with future radio telescopes

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Outline

Some open questions:

- Energy equipartition ?
- Origin of the radio-infrared correlation
- Do magnetic fields affect gas flows?
- Origin of field structures
- Field reversals

Next generation radio telescopes:

- LOFAR
- SKA

Estimating magnetic field strengths

Needed :

- Equipartition between magnetic fields and cosmic rays
- Energy spectral index of protons (ε_p)
- Ratio *K* of proton/electron number densities

  (*K*≈100 for diffusive shock acceleration)

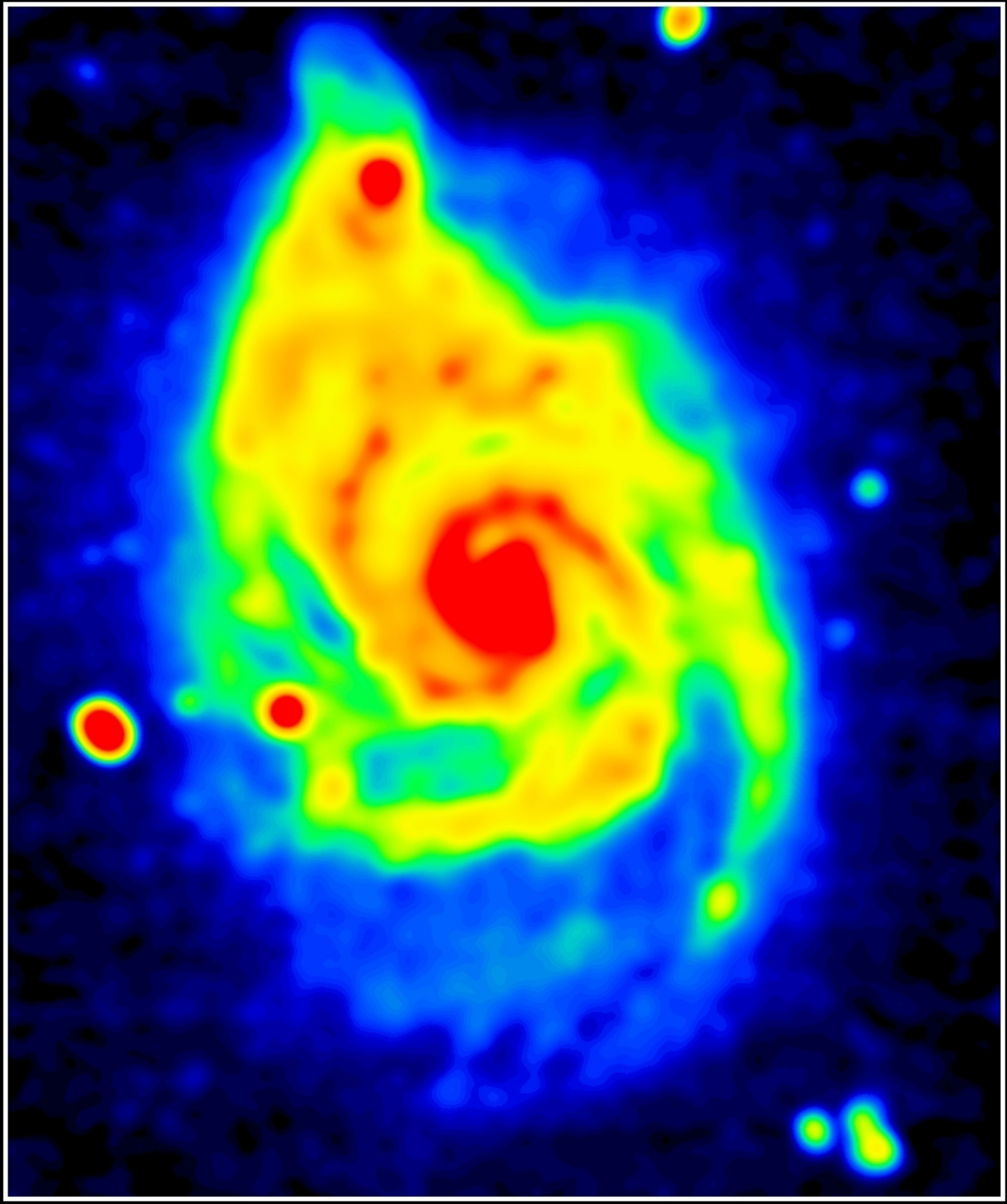
Problems:

- ISM is dynamic, not static
- Electrons suffer from energy losses which modify their spectral index (ε_e) and *K*

  → Equipartition formula cannot be applied if energy losses are strong (Beck & Krause 2005)

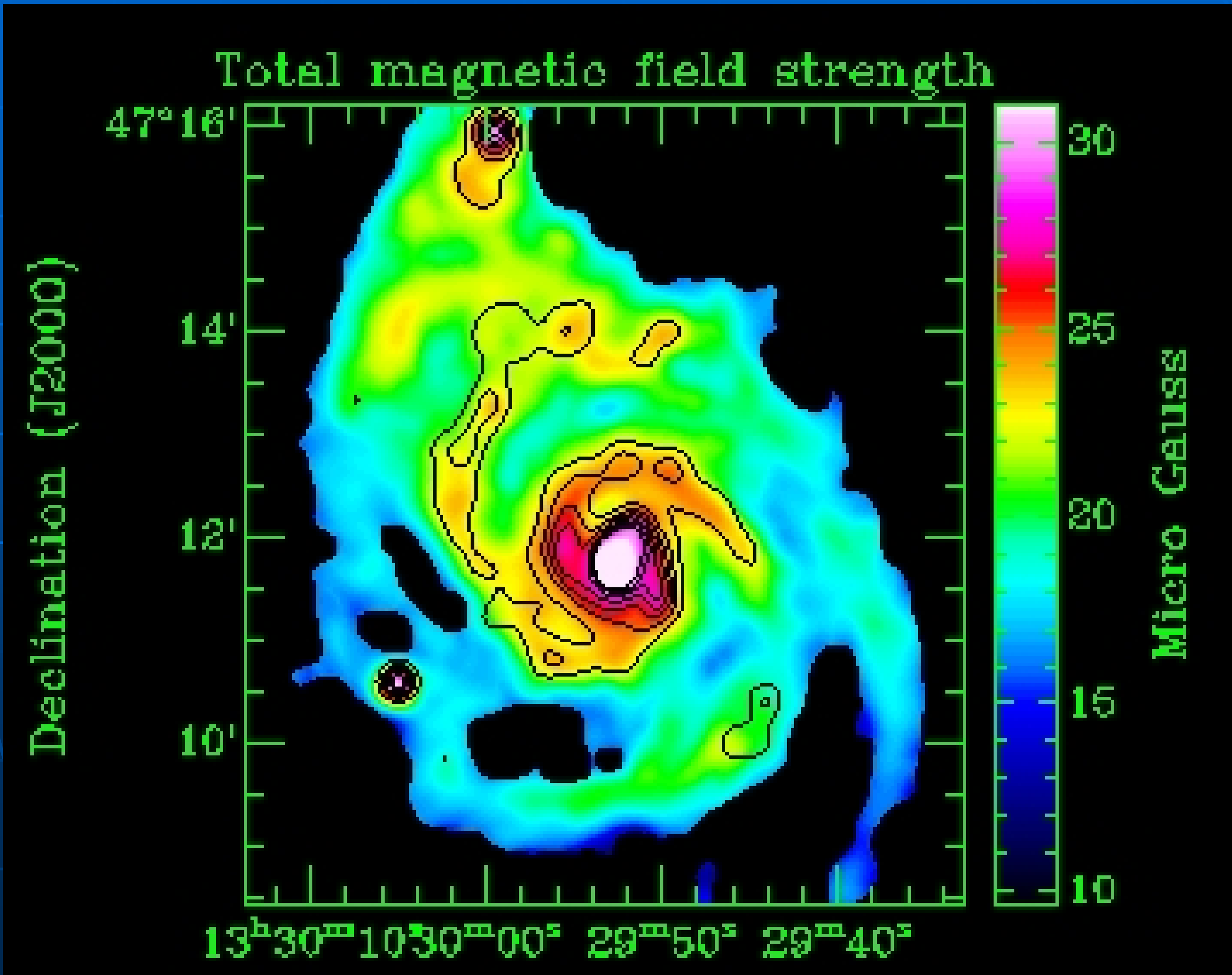
M51

(Fletcher, Beck et al. 2006)



Equipartition magnetic field strengths in M51

Fletcher, Beck et al. (2005)



Equipartition field strengths in massive spiral galaxies

	Spiral arm	Inter-arm
Total intensity:	≈ 20 μG	≈ 15 μG
Polarized intensity:	5-10 μG	≈ 10 μG

Turbulent fields are strongest in the spiral arms, regular fields are strongest in interarm regions.

However: Field strengths may be underestimated due to synchrotron losses.

Understanding equipartition

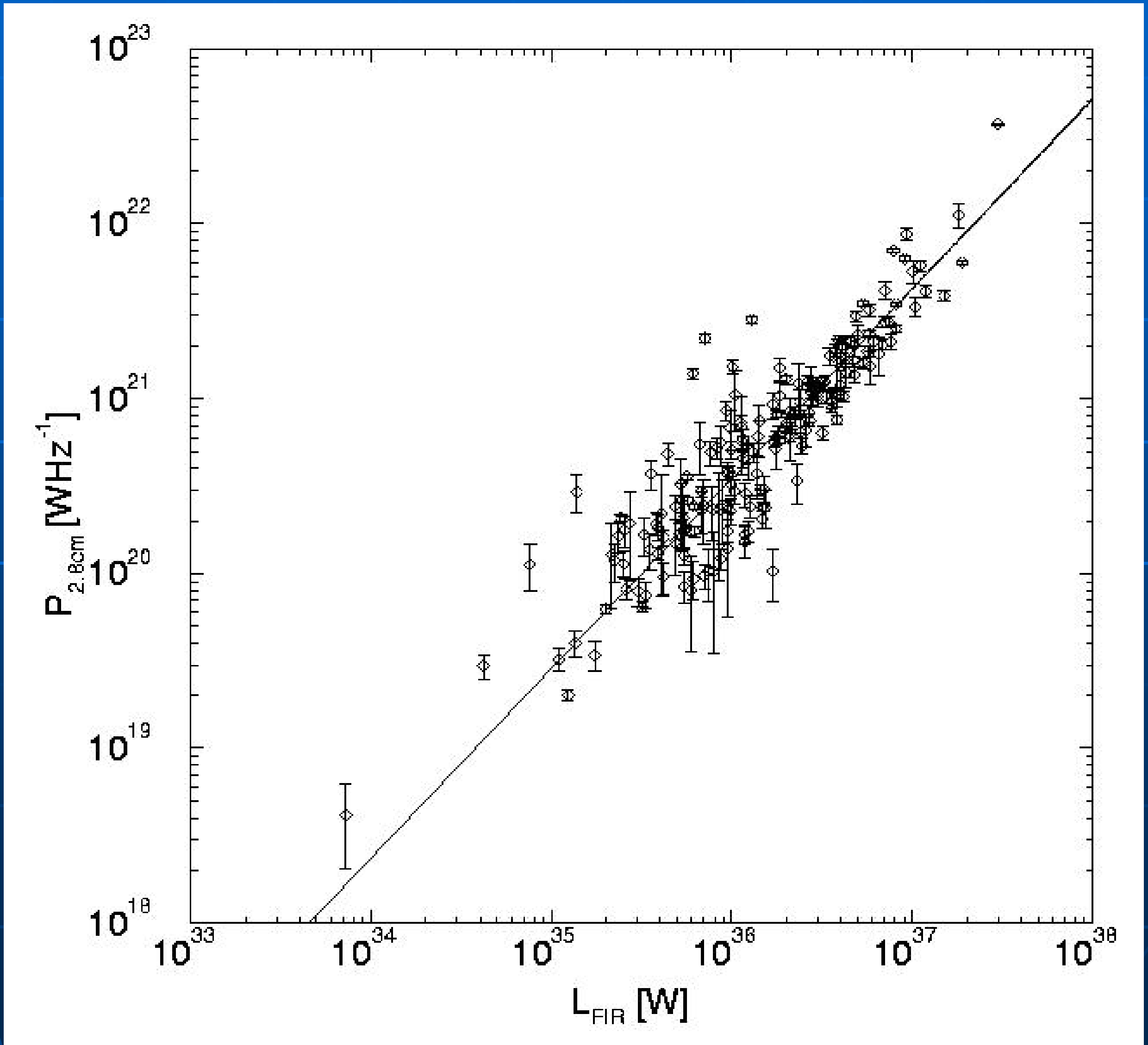
Needed:

- High-resolution radio observations in galaxies over a wide frequency range to measure energy losses of cosmic-ray electrons
- Independent information about field strengths (e.g. from Faraday rotation)
- Independent information about the cosmic-ray electron density and spectrum in galaxies (e.g. from γ-ray bremsstrahlung or X-ray Inverse Compton emission)

The radio – infrared correlation: evidence for equipartition ?

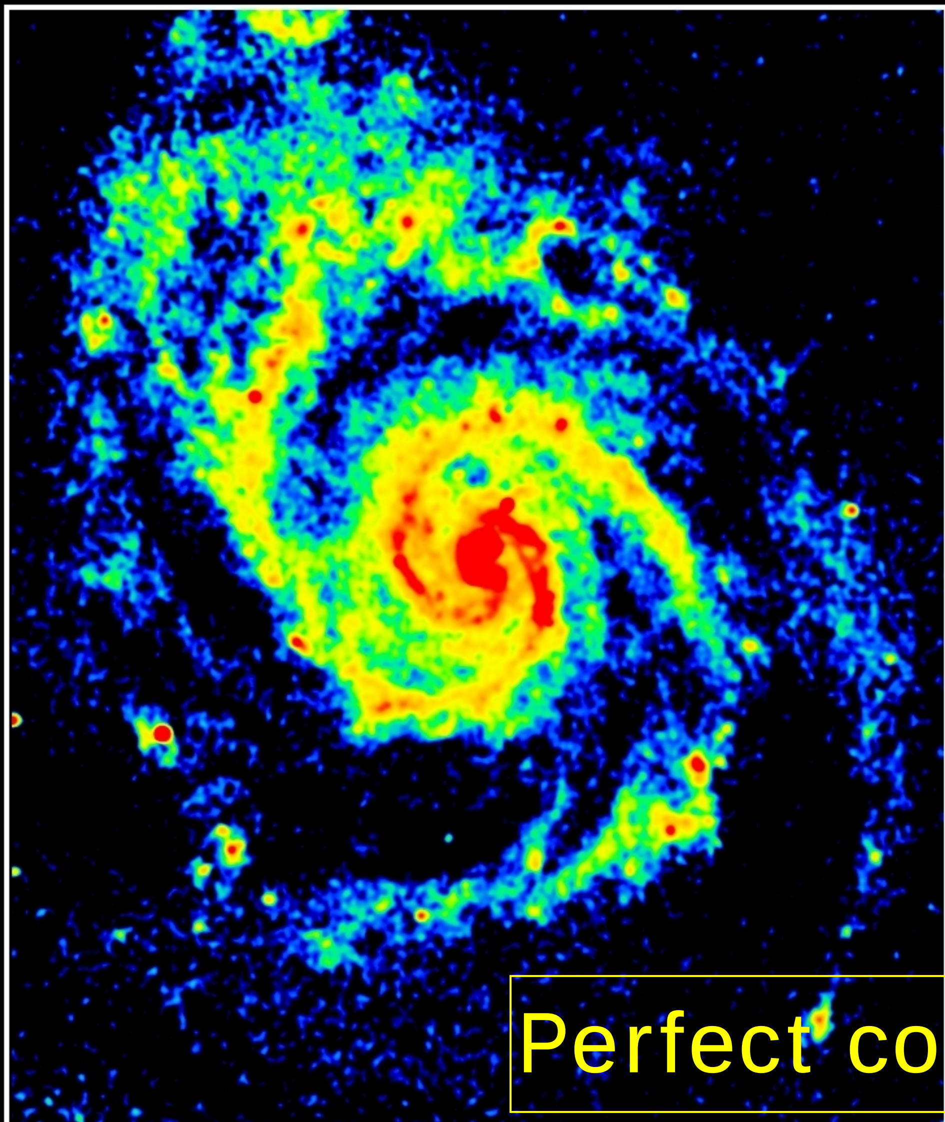
The global radio - FIR correlation for normal galaxies

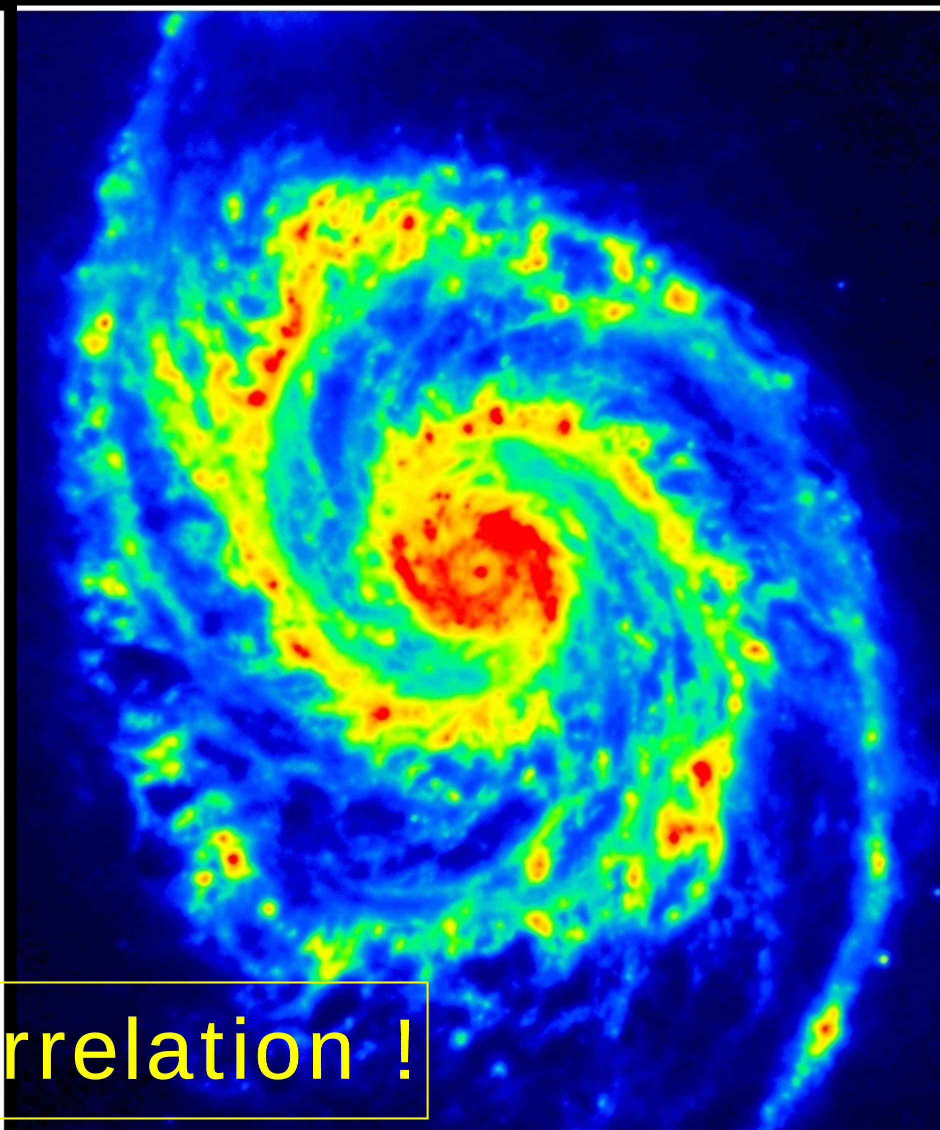
Niklas 1997



Radio continuum
(Effelsberg + VLA 6cm)

Infrared
(Spitzer 8μm)

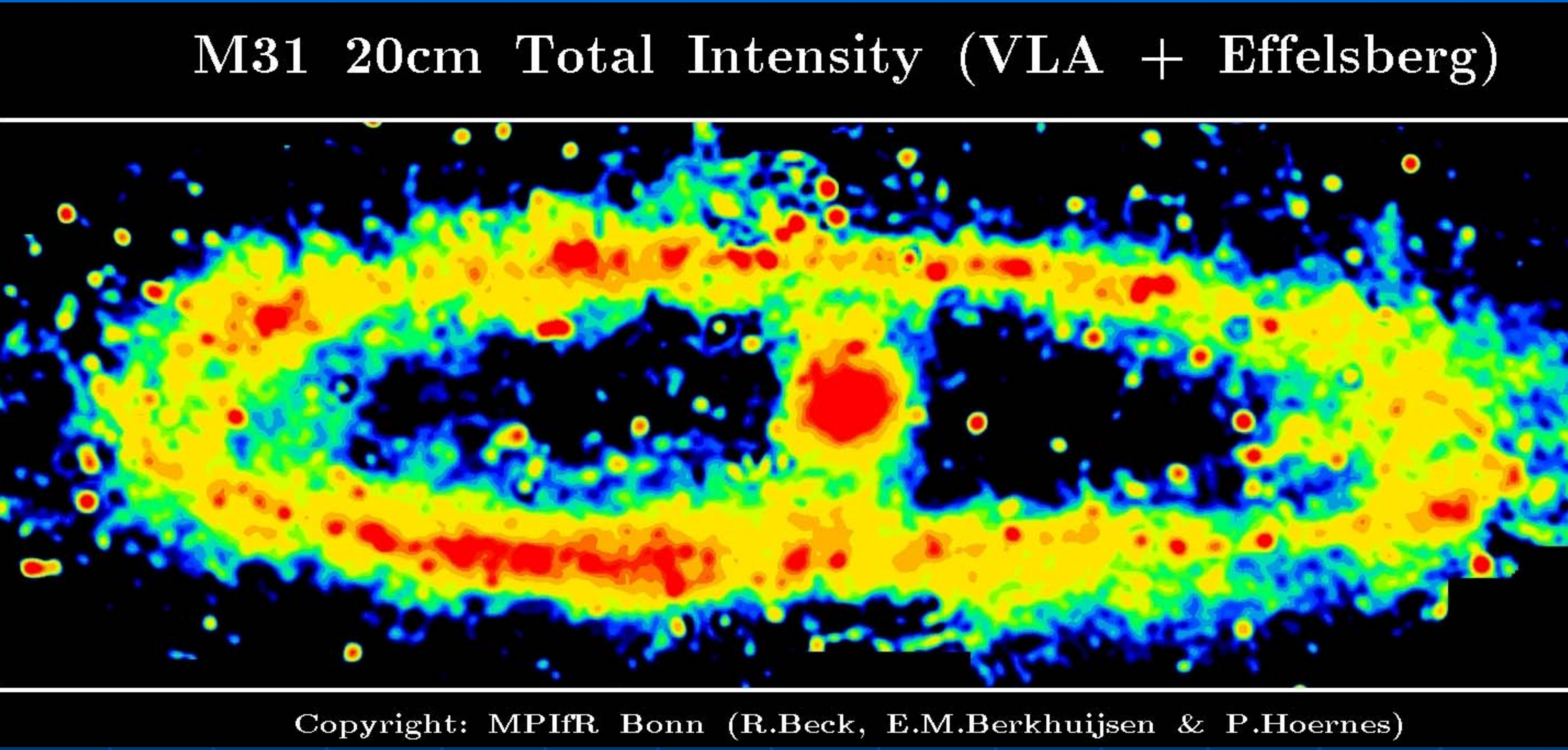




Perfect correlation !

Fletcher et al. 2006

Schinnerer et al. 2006



Faraday rotation measures show that the regular magnetic field inside and outside the “ring” is similarly strong as in the ring

→ equipartition is NOT valid outside the “ring”

The radio – FIR correlation

Global correlation:

- Extends over more than 10^5 in luminosity scale
- Holds for early galaxies to redshifts of at least z=2
- Radio deficit for galaxies with very young starbursts

Local correlation:

- Holds for thermal *and* nonthermal radio emission
- Holds down to ~50pc scale
  → no strong energy losses of electrons
- Breaks down at < 50 pc from star-forming regions
  → ??
- Breaks down far away from star-forming regions
  → electron diffusion or convection

Equipartition model

(Niklas & Beck 1997, Hoernes et al. 1998)

- Energy equipartition between magnetic field and turbulent gas motion: $B_{tot}^2 \propto \rho$
- Energy equipartition between magnetic field and cosmic rays: $B_{tot}^2 \propto n_{CR}$
- Star-formation rate depends on gas density (*Schmidt law*, $SFR \propto \rho^b$, $b \approx 1.4$)
- Predicted slope of the radio-FIR correlation:

≈1.3 (optically thick gas), 0.8-1.0 (optically thin gas)

Equipartition model
(Niklas & Beck 1997, Hoernes et al. 1998)

- Energy equipartition between magnetic field and turbulent gas motion: $B_{tot}^2 \propto \rho$
- Energy equipartition between magnetic field and cosmic rays: $B_{tot}^2 \propto n_{CR}$
- Predicts correct slope of the radio-FIR correlation for the *nonthermal* radio emission

Understanding the radio-FIR correlation

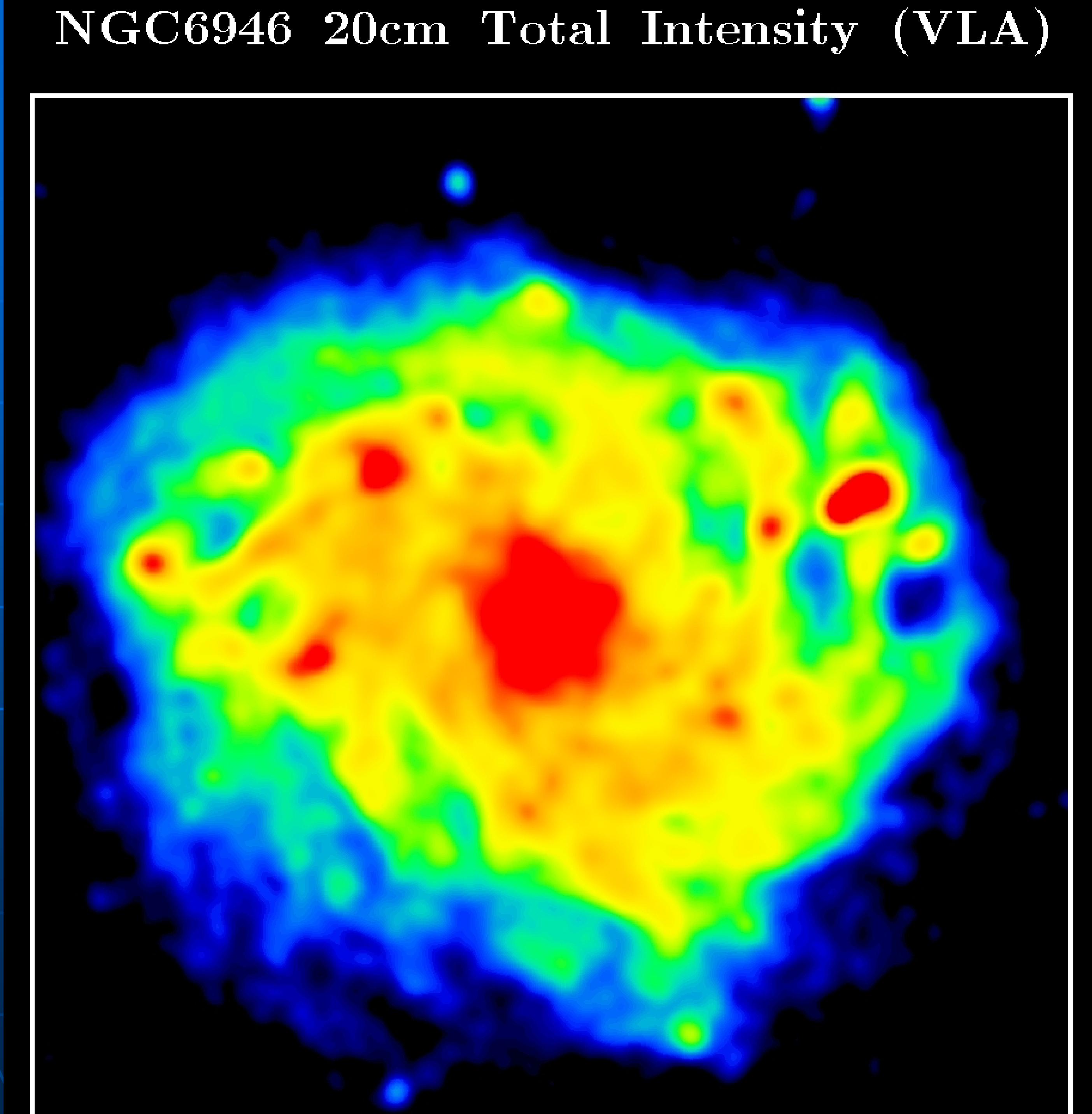
Needed:

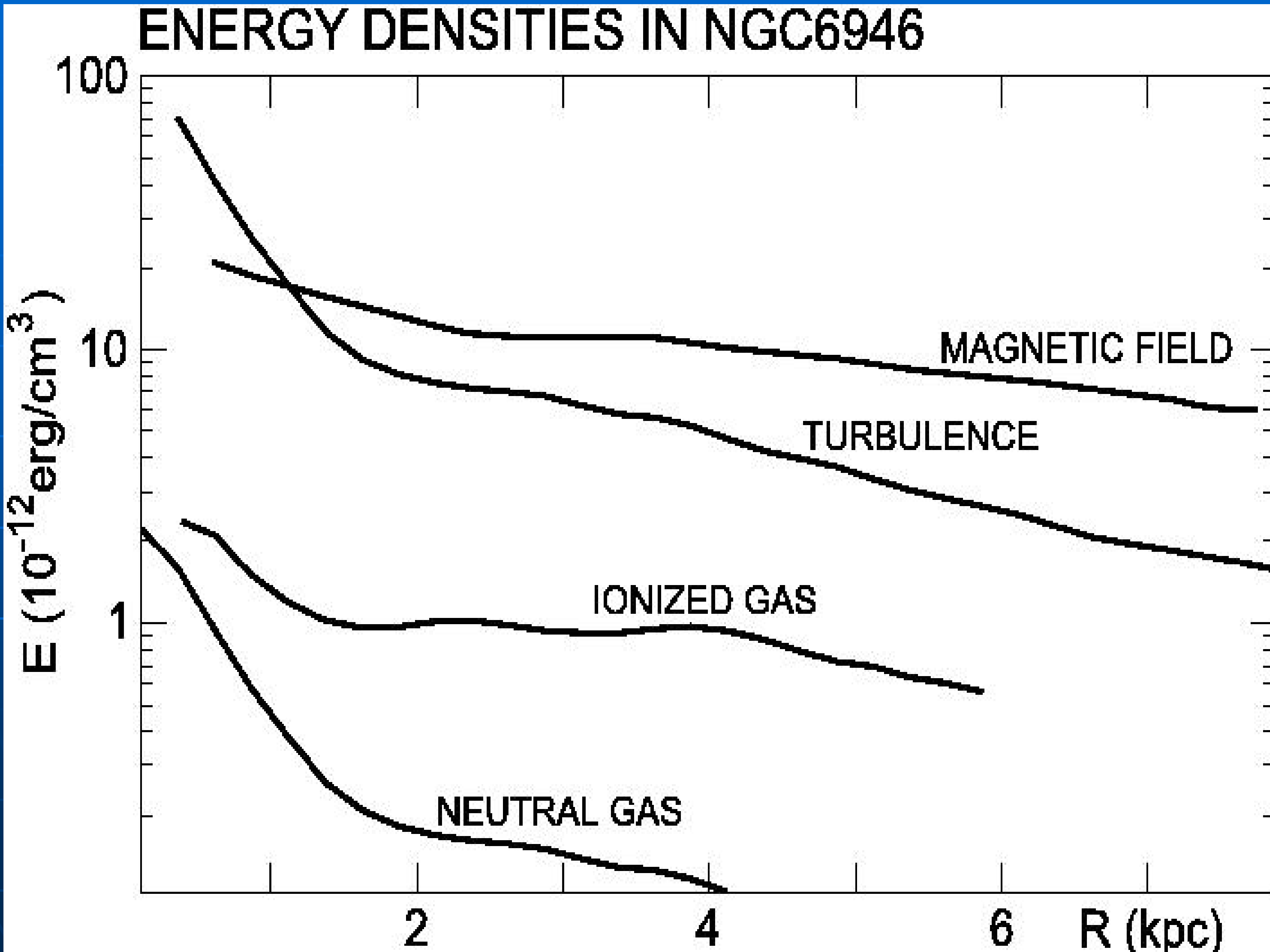
- Radio and FIR data for galaxies in different evolutionary stages
- Separation of thermal and nonthermal radio emission (see talk by Fatemeh Tabatabaei)
- Models for the evolution of magnetic fields in galaxies
- High-resolution observations in the Milky Way of magnetic fields around molecular clouds and in star-forming regions

Can magnetic fields affect gas flows ?

NGC6946

(Beck, in prep.)




ENERGY DENSITIES IN NGC6946
100
10
1
E (10^-12 erg/cm^3)
MAGNETIC FIELD
TURBULENCE
IONIZED GAS
NEUTRAL GAS
2
4
6
R (kpc)

Energy densities in NGC6946

(Beck 2004)

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

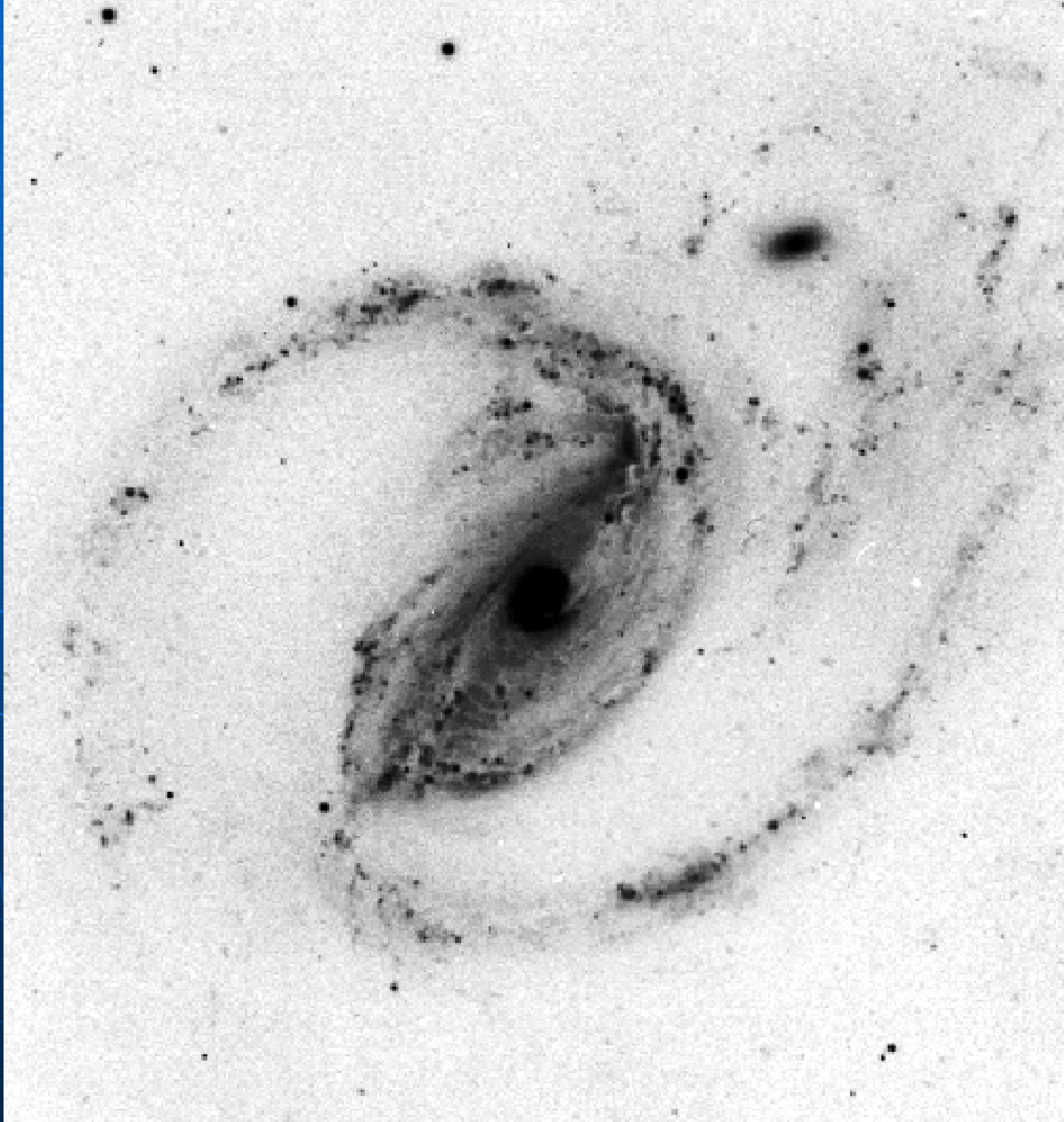
→ magnetic fields affect the flow of cold gas

- $E_{magn} \gg E_{therm}$ (everywhere)

→ magnetic fields affect the flow of warm and hot gas

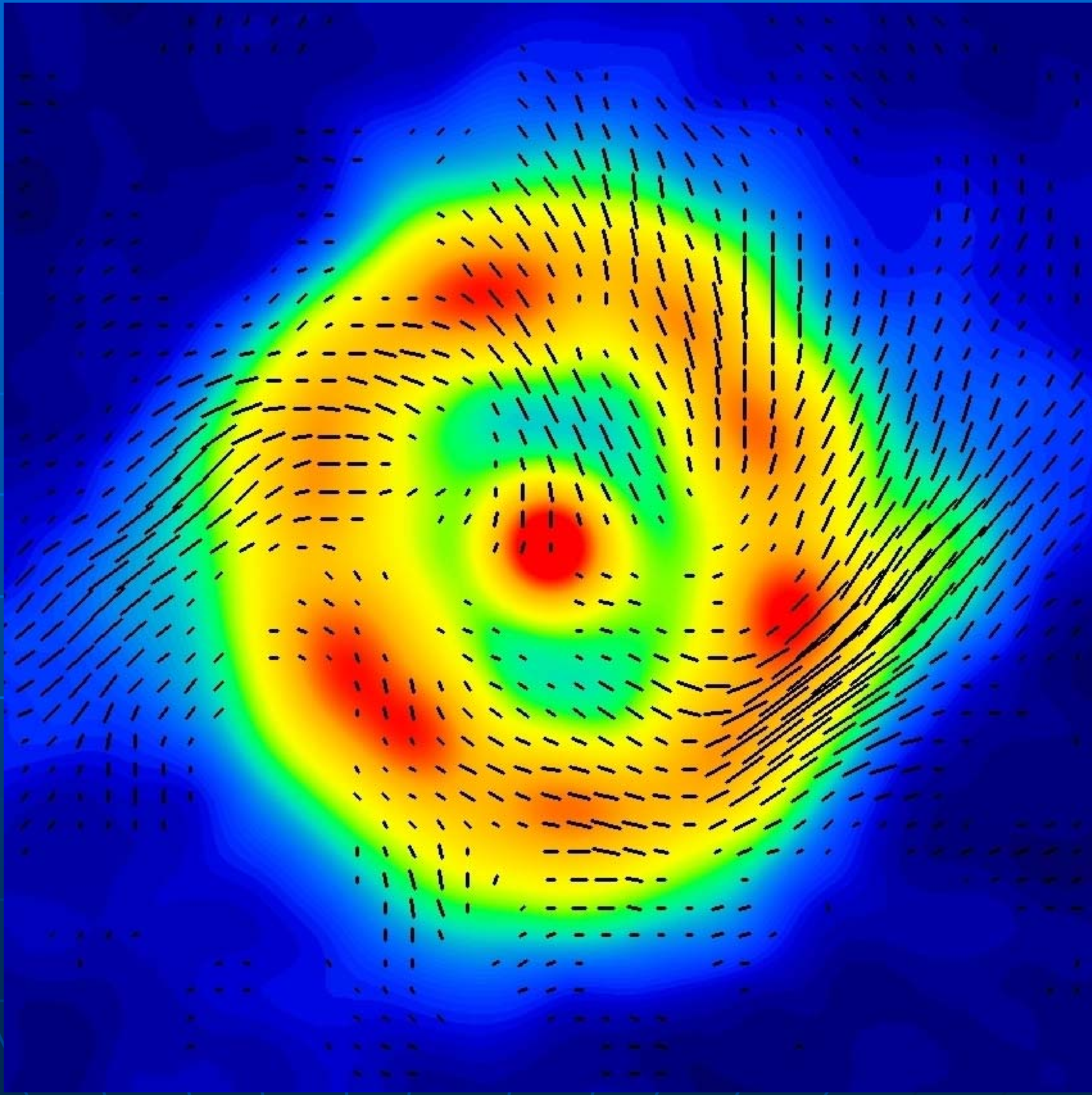
NGC1097

(Cerro Tololo, by Halton Arp)



NGC1097 Center

(Beck et al. 2005)



Magnetic field strengths in barred galaxies

(assuming equipartition with cosmic rays)

- NGC 1097 (bar): ≈20μG
- NGC 1097 (central ring): ≈60μG
- NGC 7552 (central ring): ≈**100μG**

The strongest extended fields detected so far in spiral galaxies

Mass inflow into the center by magnetic stress

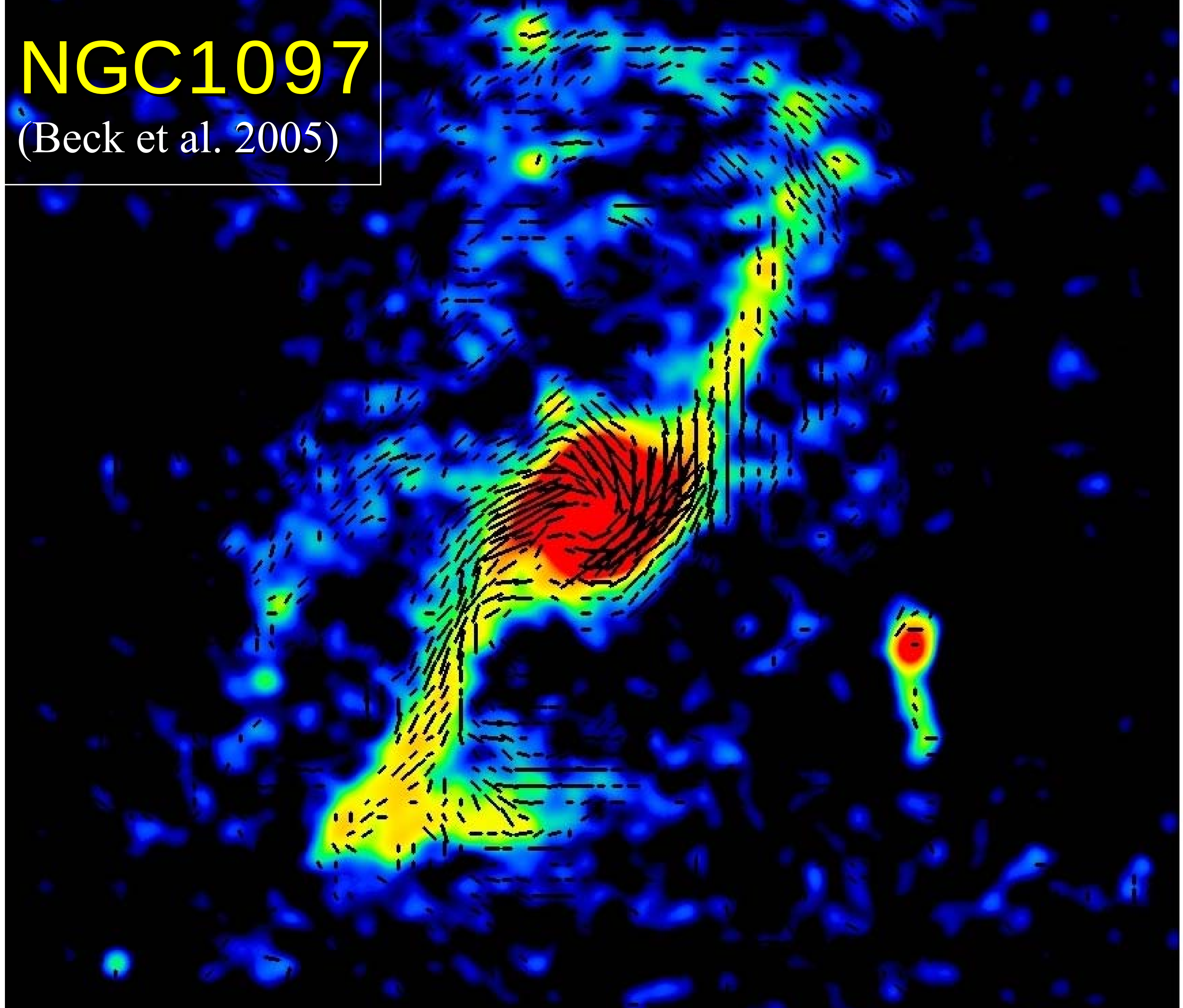
$$dM/dt = - h/\Omega\ (<b_r\ b_\Phi> + B_r\ B_\Phi)$$

(Balbus & Hawley 1998)

NGC1097:

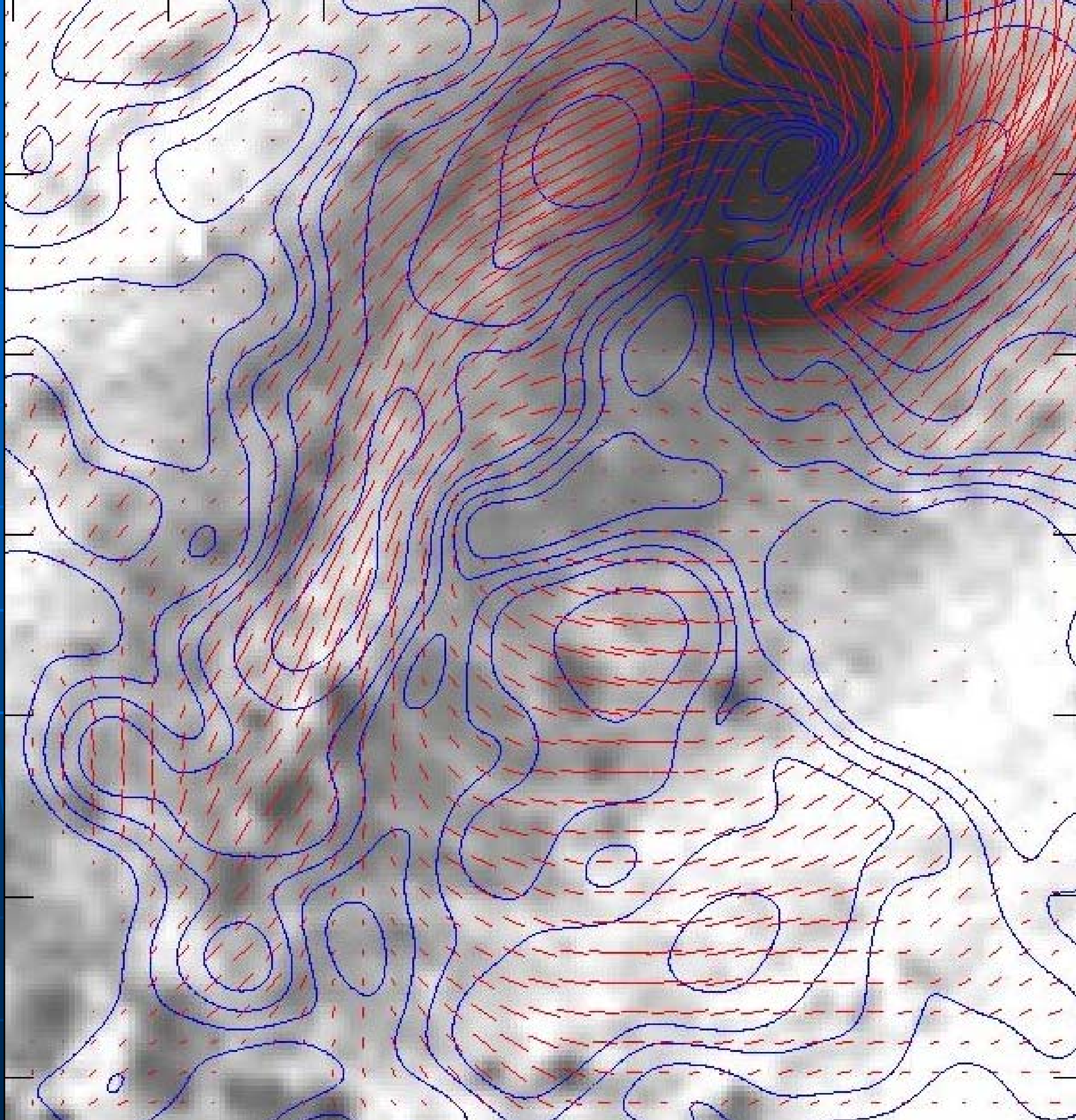
h=100pc, v=450km/s, $b_r \approx b_\Phi \approx 60\mu G$:

$dM/dt \approx 1\ M_o\ /\ yr$


NGC1097
(Beck et al. 2005)

NGC1097

(Beck et al. 2005)



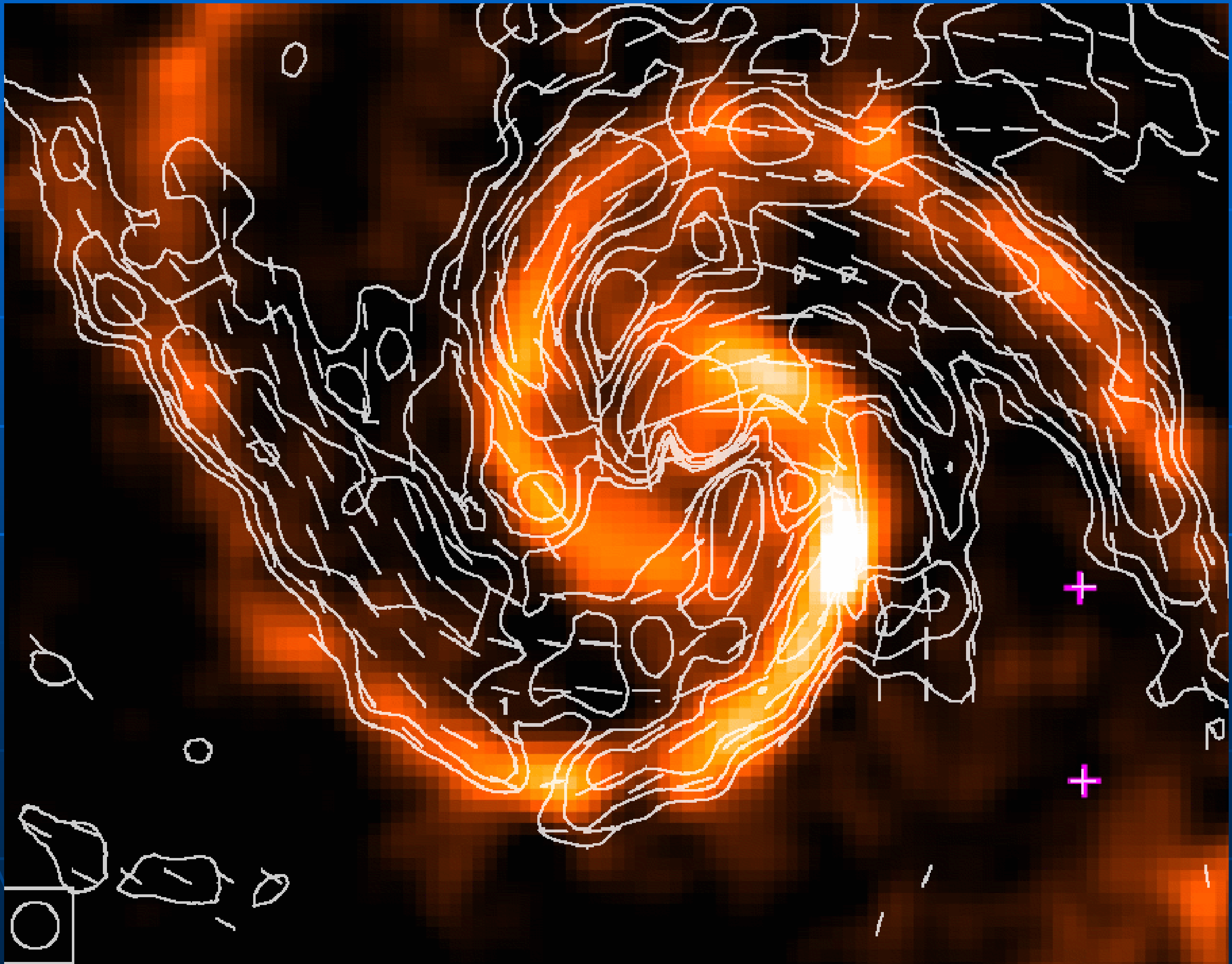
NGC1097

- The turbulent field is compressed in the bar shock
- The regular field is *not* compressed
- The regular field is strong *outside* the bar
- The regular field decouples from the cold gas
- The regular field is sufficiently strong to affect the flow of the diffuse gas

Magnetic field and molecular gas

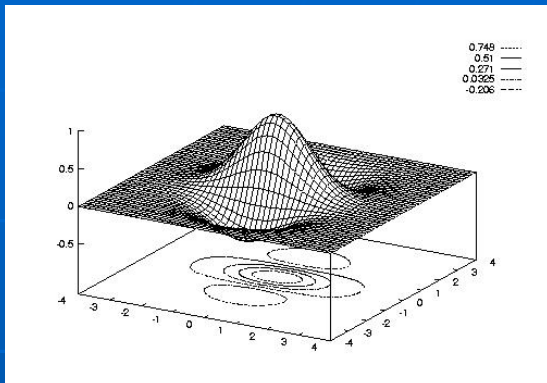
Polarized intensity (Effelsberg+VLA) and BIMA CO data (Regan et al. 2001)

Patrikeev et al. 2006



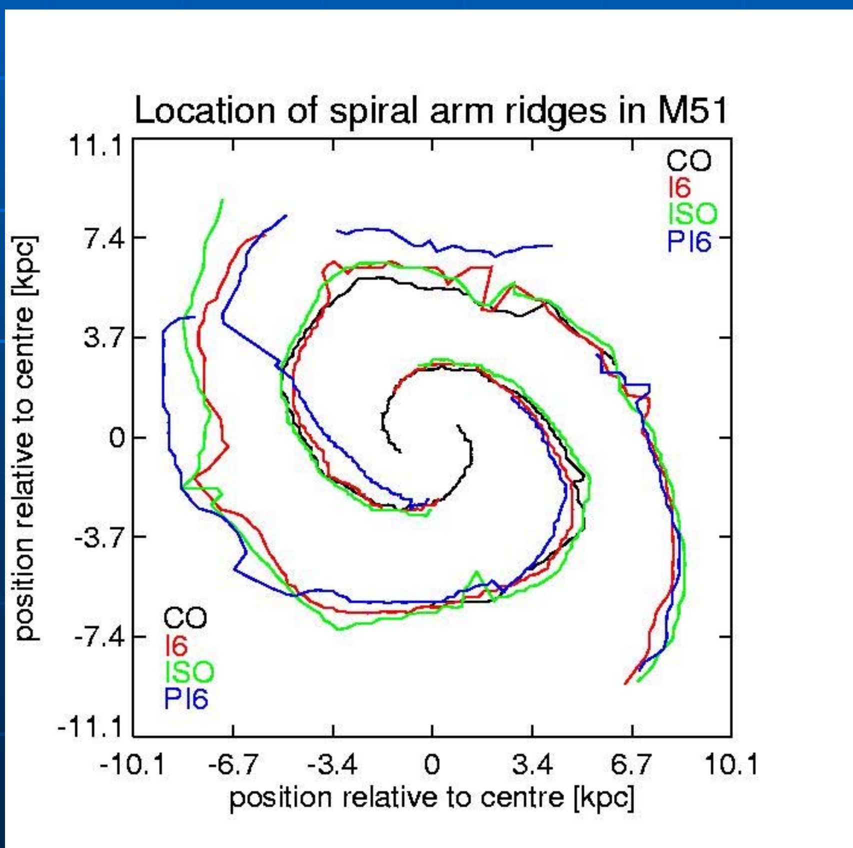
Spiral arms in M51

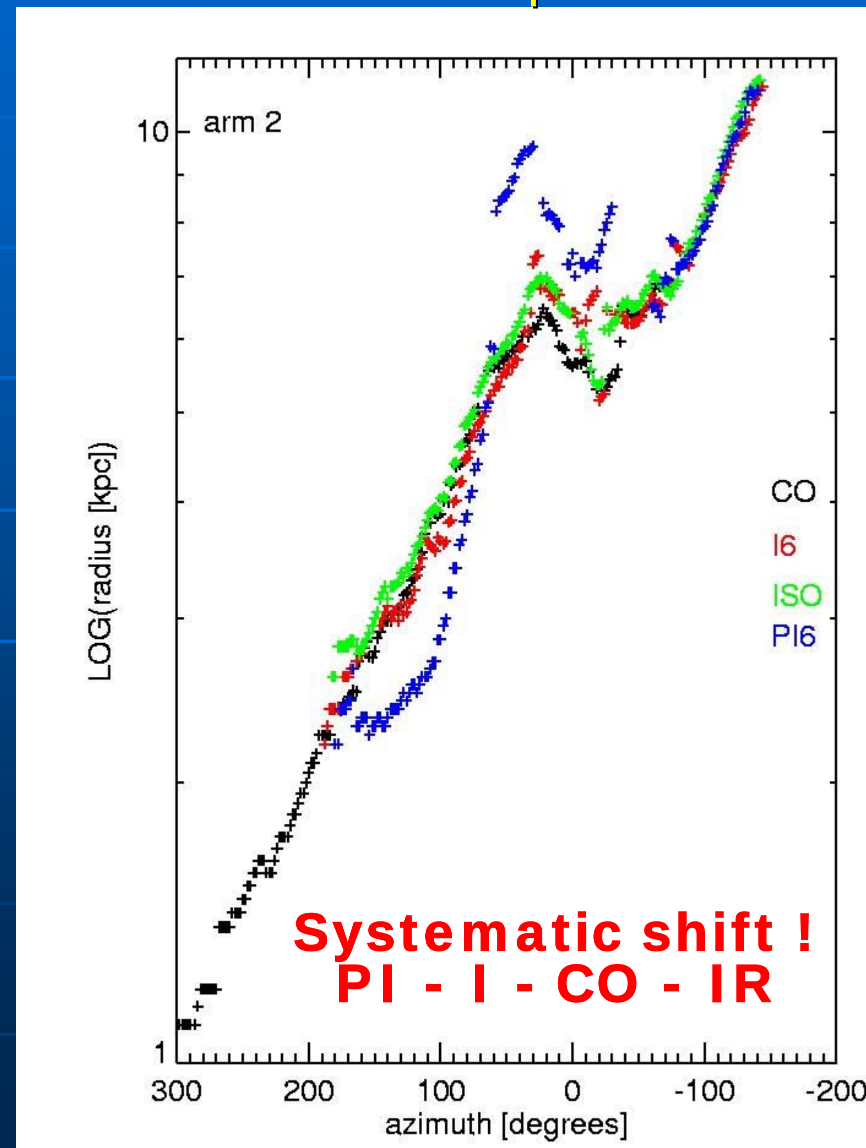
Patrikeev et al. 2006



Anisotropic wavelet function

Polar plot





Systematic shift !
PI - I - CO - IR

M51

- The turbulent field is compressed in the spiral arm shock
- The regular field is *weakly* compressed at the inner edge of the spiral arm
- The regular field is strong also in the interarm regions
- The regular field decouples from the cold gas
- The regular field may affect the flow of the diffuse gas

Understanding the interaction between magnetic fields and gas flows

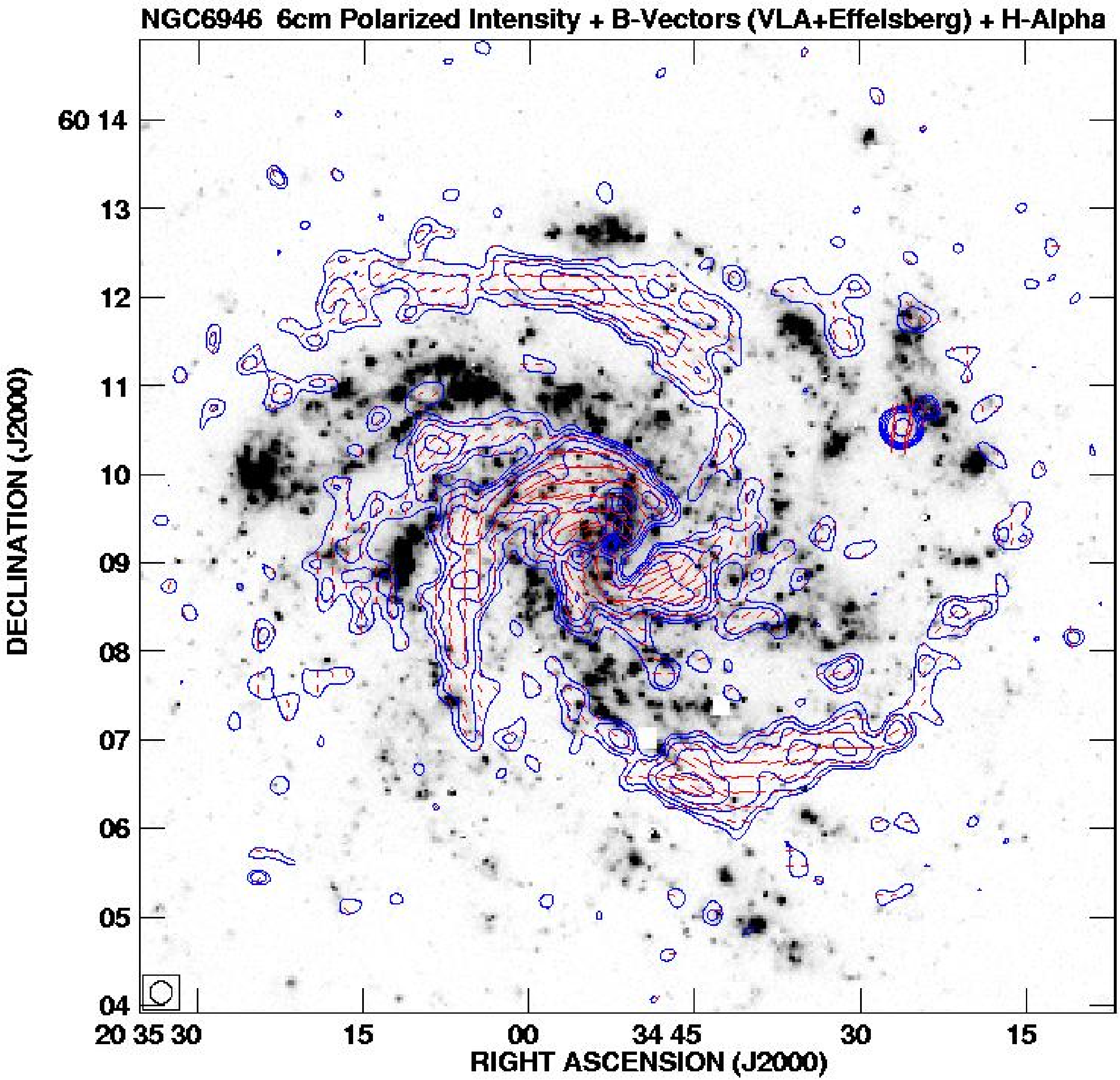
Needed:

- High-resolution radio polarization and gas velocity data (from HI, CO or Hα)
- High-resolution RM data (to detect coherent fields)
- Estimates of energy densities

Magnetic fields prefer spiral patterns

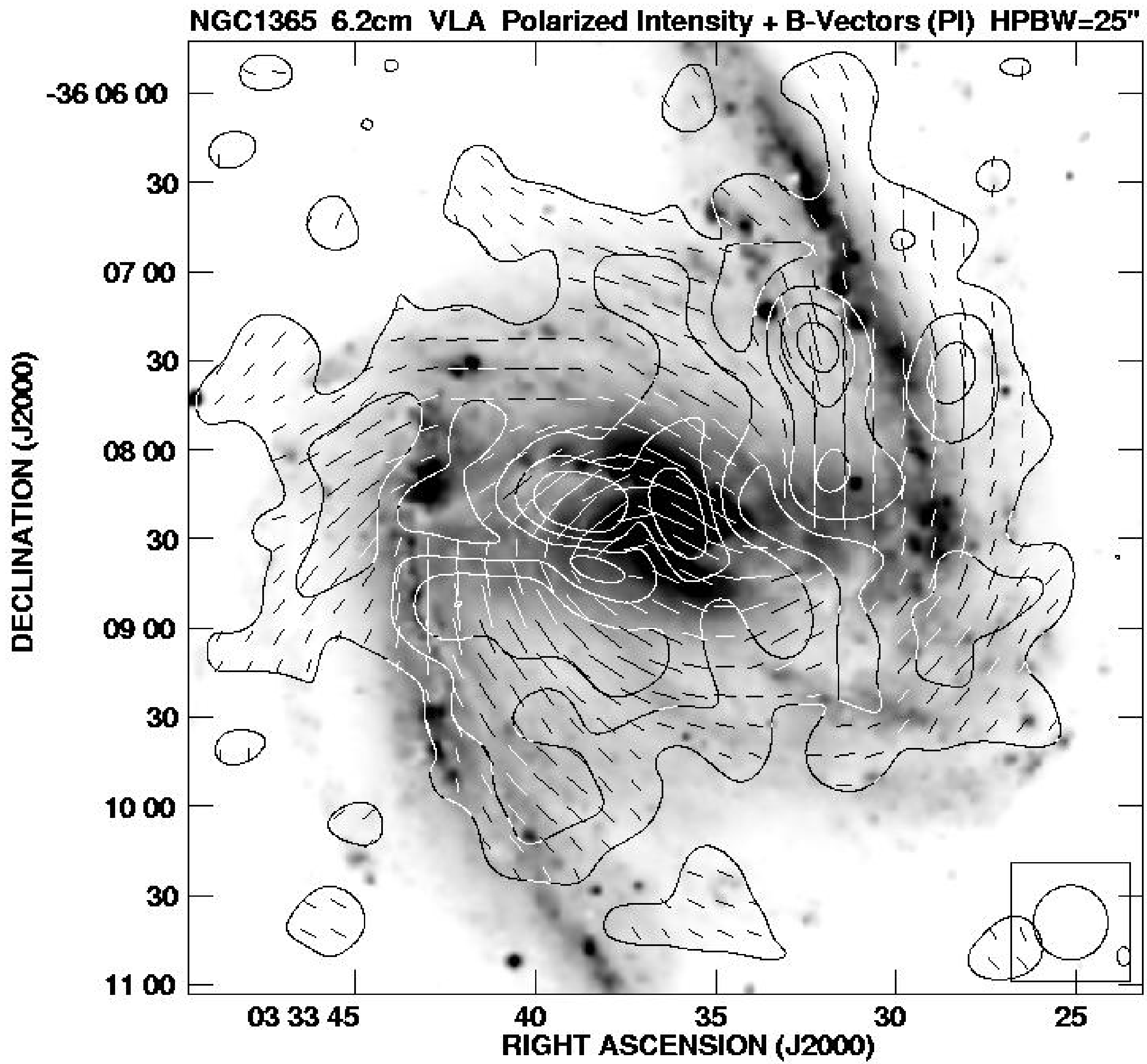
NGC6946

(Beck & Hoernes 1996)



NGC1365

(Beck et al. 2005)



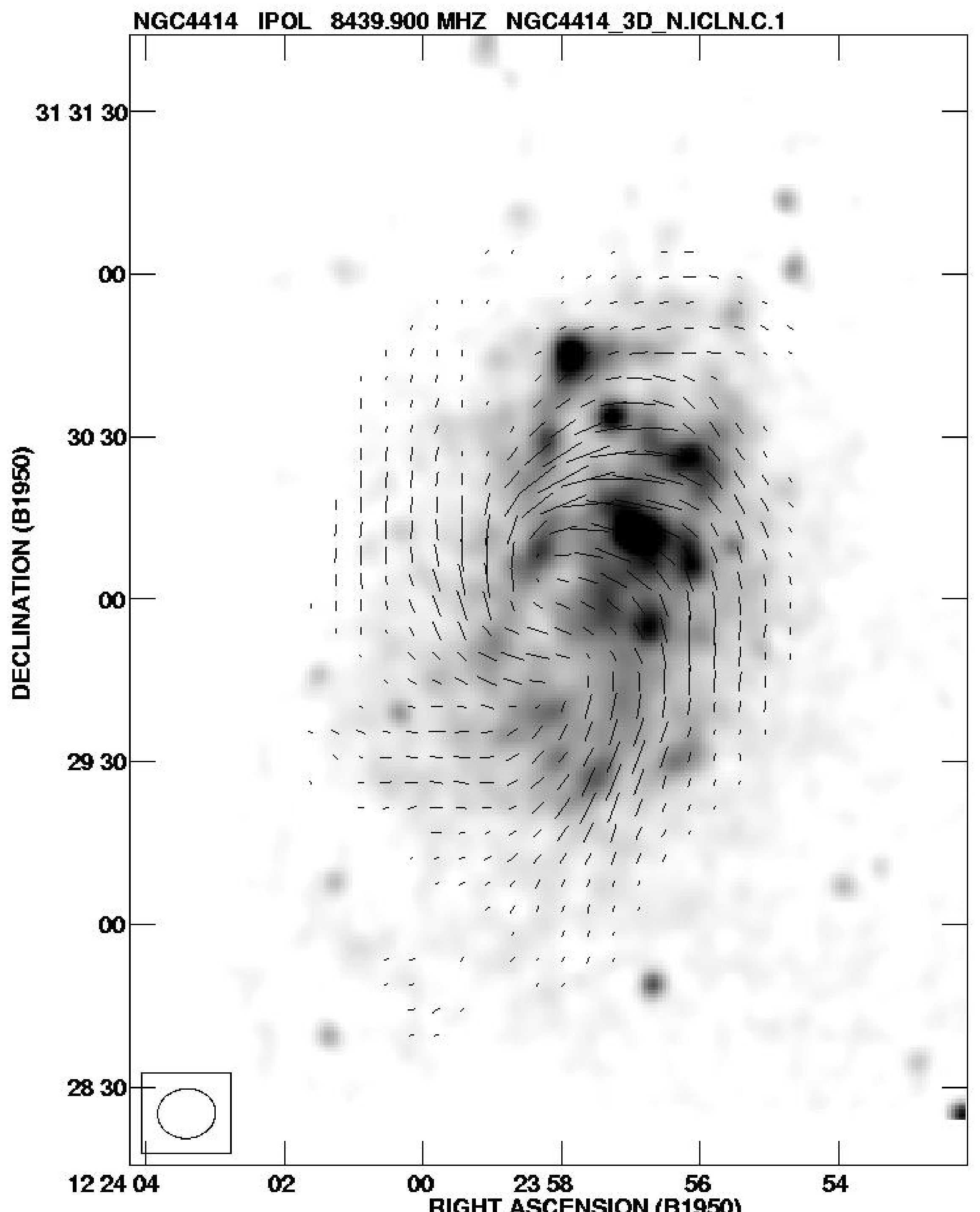
NGC4414

(Soida et al. 2002)

Flocculent galaxies:

spiral field without

spiral arms

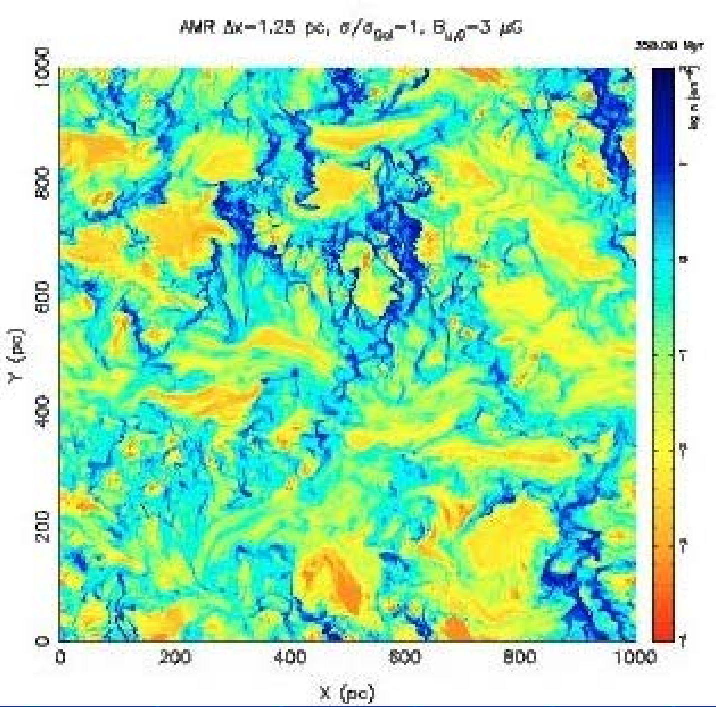


Incoherent spiral fields
(by shear or compression along the spiral arms)

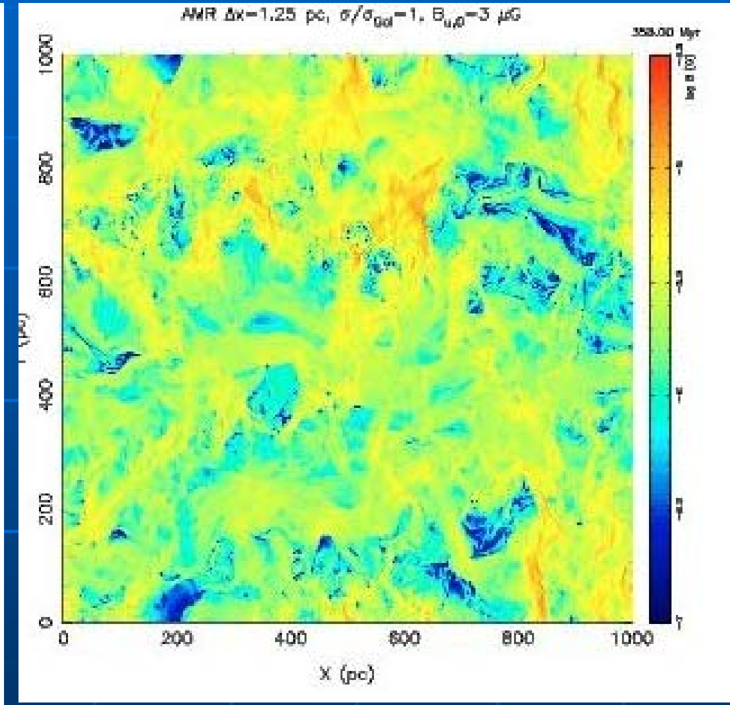
or coherent spiral fields
(by dynamo action)

?

MHD model of the ISM by SN-induced turbulence



Gas density

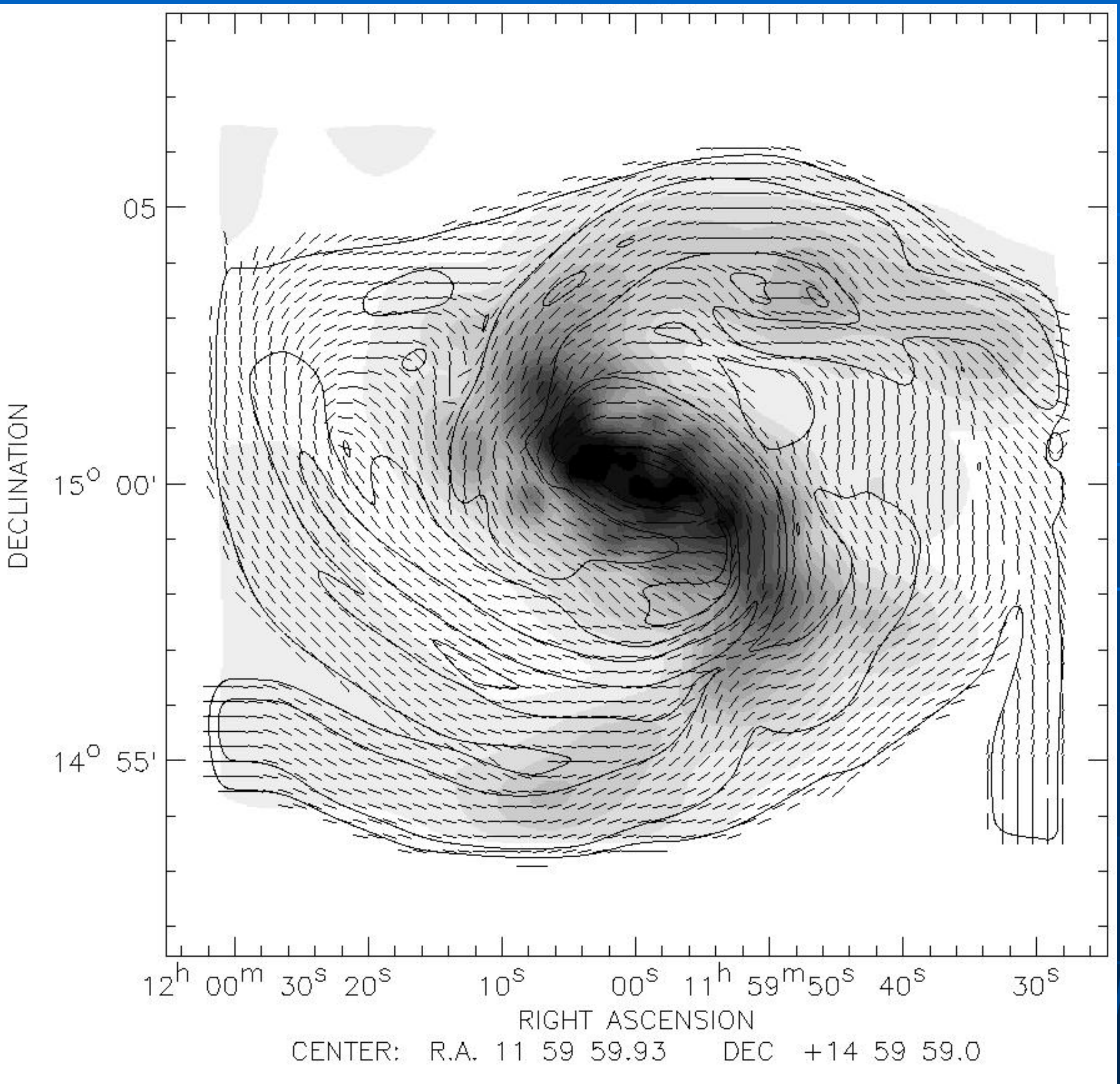


Magnetic field strength

de Avillez & Breitschwerdt 2005

Amplification of incoherent fields

MHD model of a barred galaxy

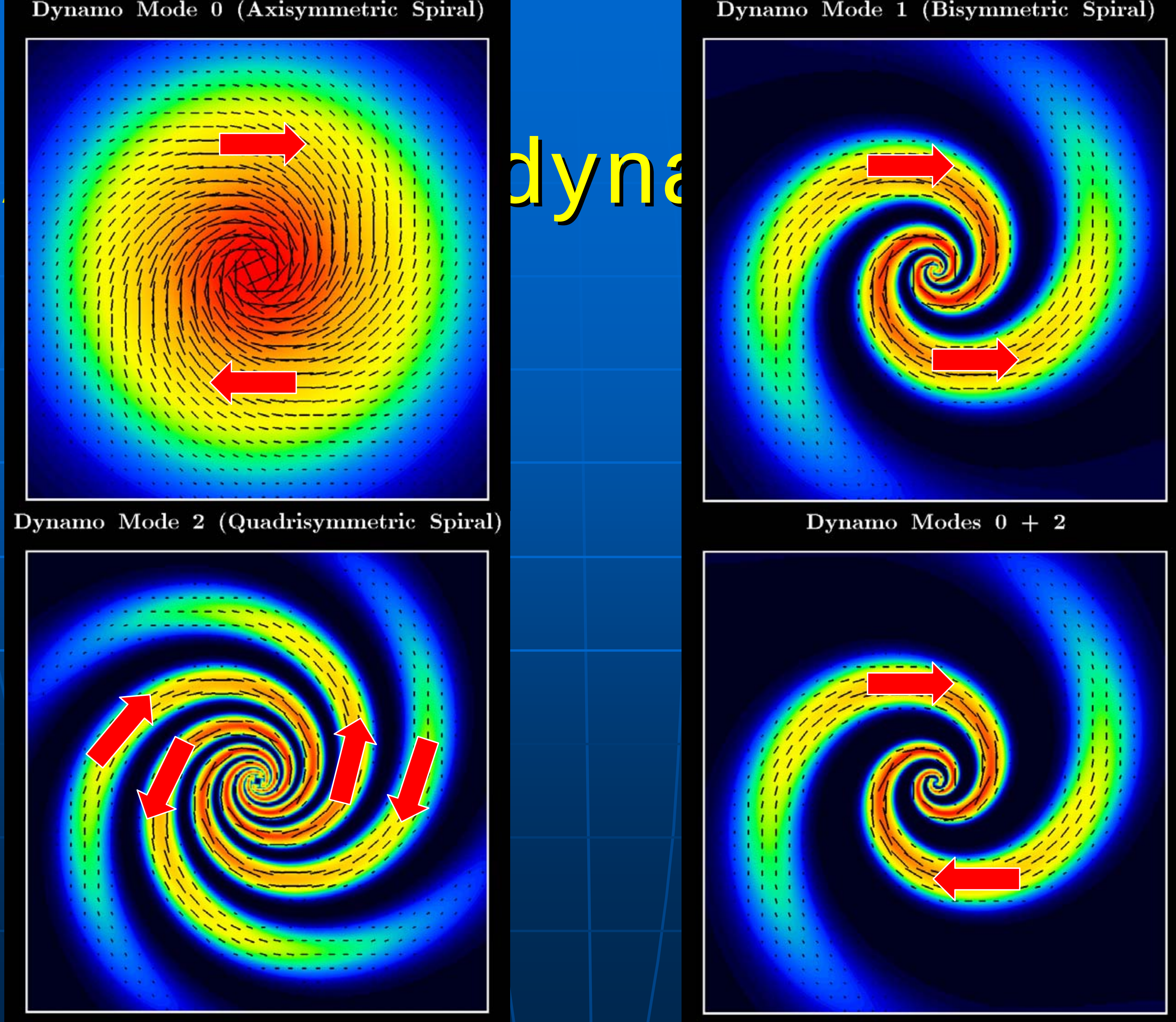


Otmianowska-Mazur, Elstner, Soida & Urbanik 2002

Generation of spiral fields by shear

Coherence length: ≈1 kpc

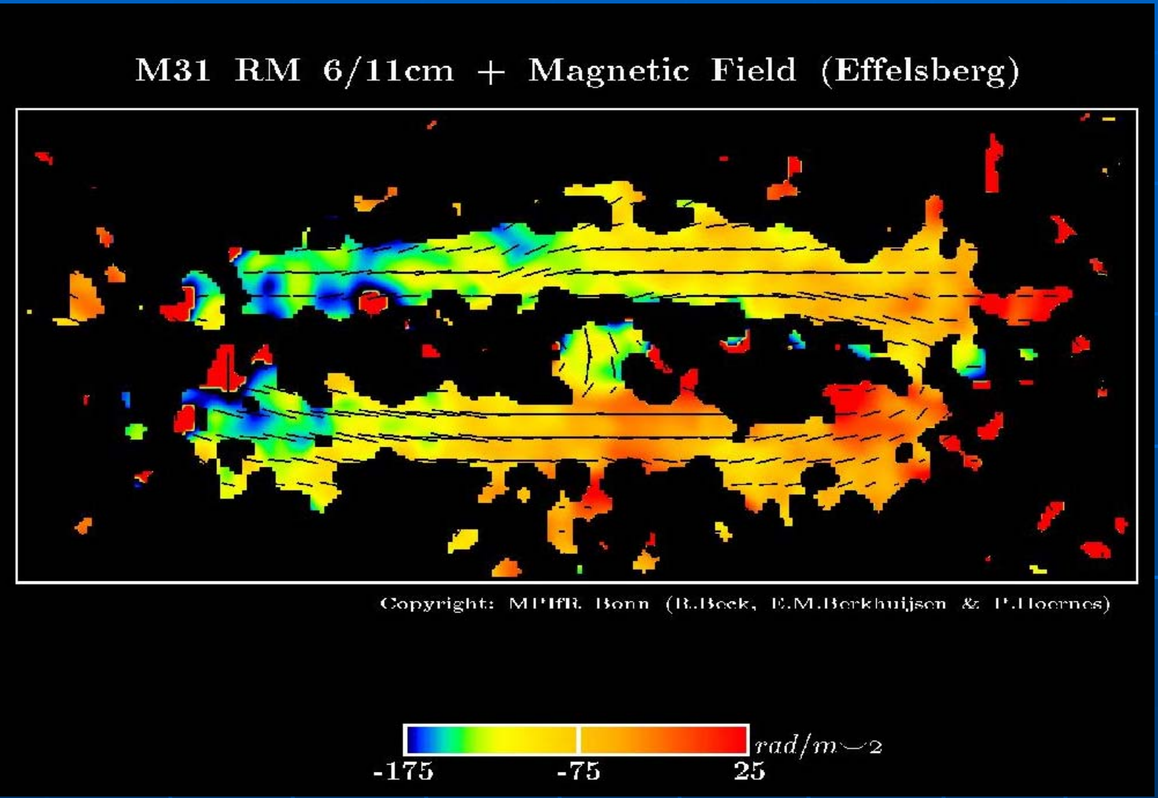
dyna


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

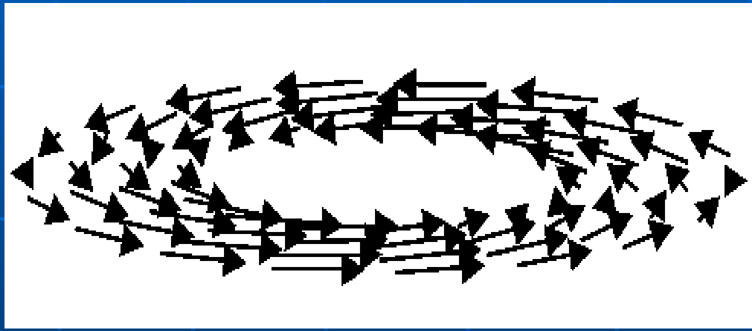
Faraday rotation

is the key to detect
coherent fields
and hence to test
large-scale dynamo action

M31: The classical dynamo case



Berkhuijsen et al. 2003



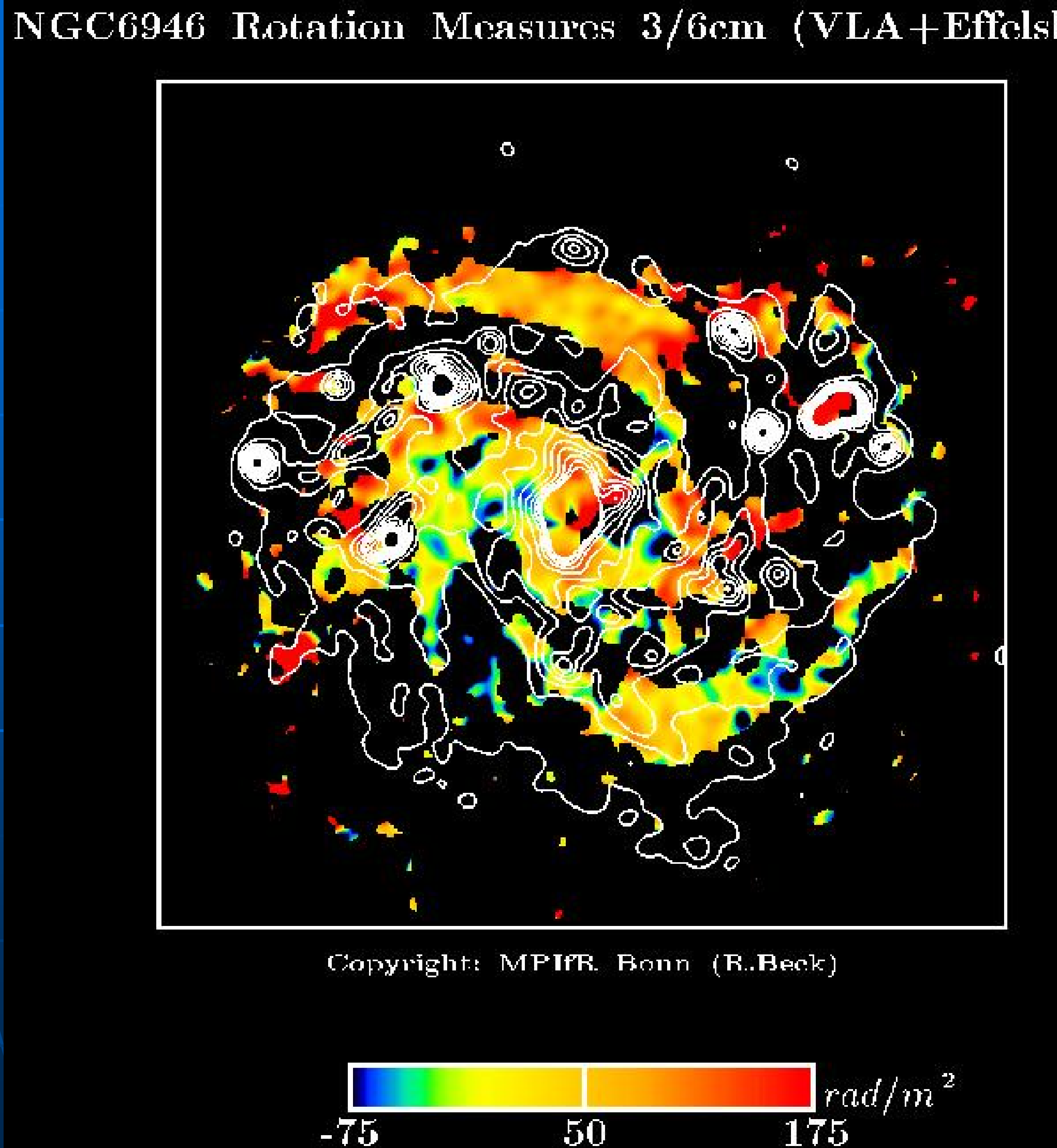
Fletcher et al. 2004

The spiral field of M31 is mostly coherent and an axisymmetric spiral

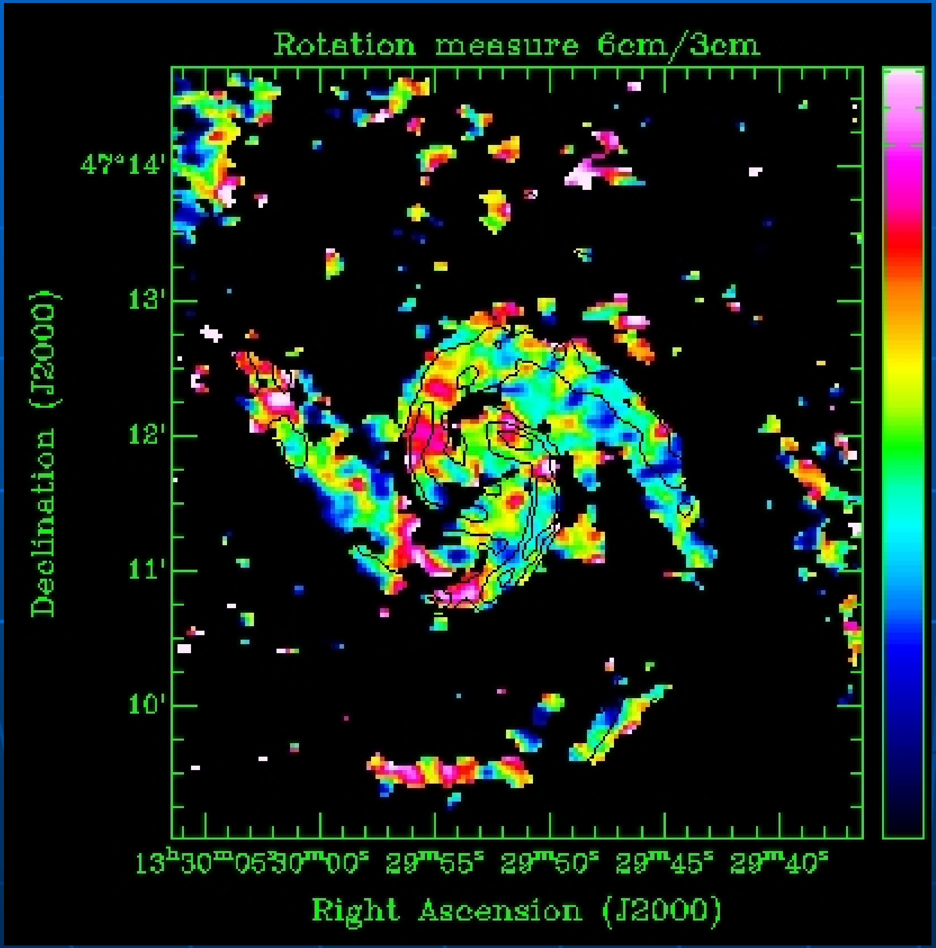
NGC6946

(F.Krause & Beck 1998)

The spiral field of NGC6946 is a mixture of coherent ($m=0$ + $m=2$) and incoherent fields



M51: chaotic rotation measures



Fletcher et al. 2005

Resolution ≈ 400pc

The spiral field of M51 seems mostly anisotropic

Understanding the origin of galactic magnetic fields

Needed:

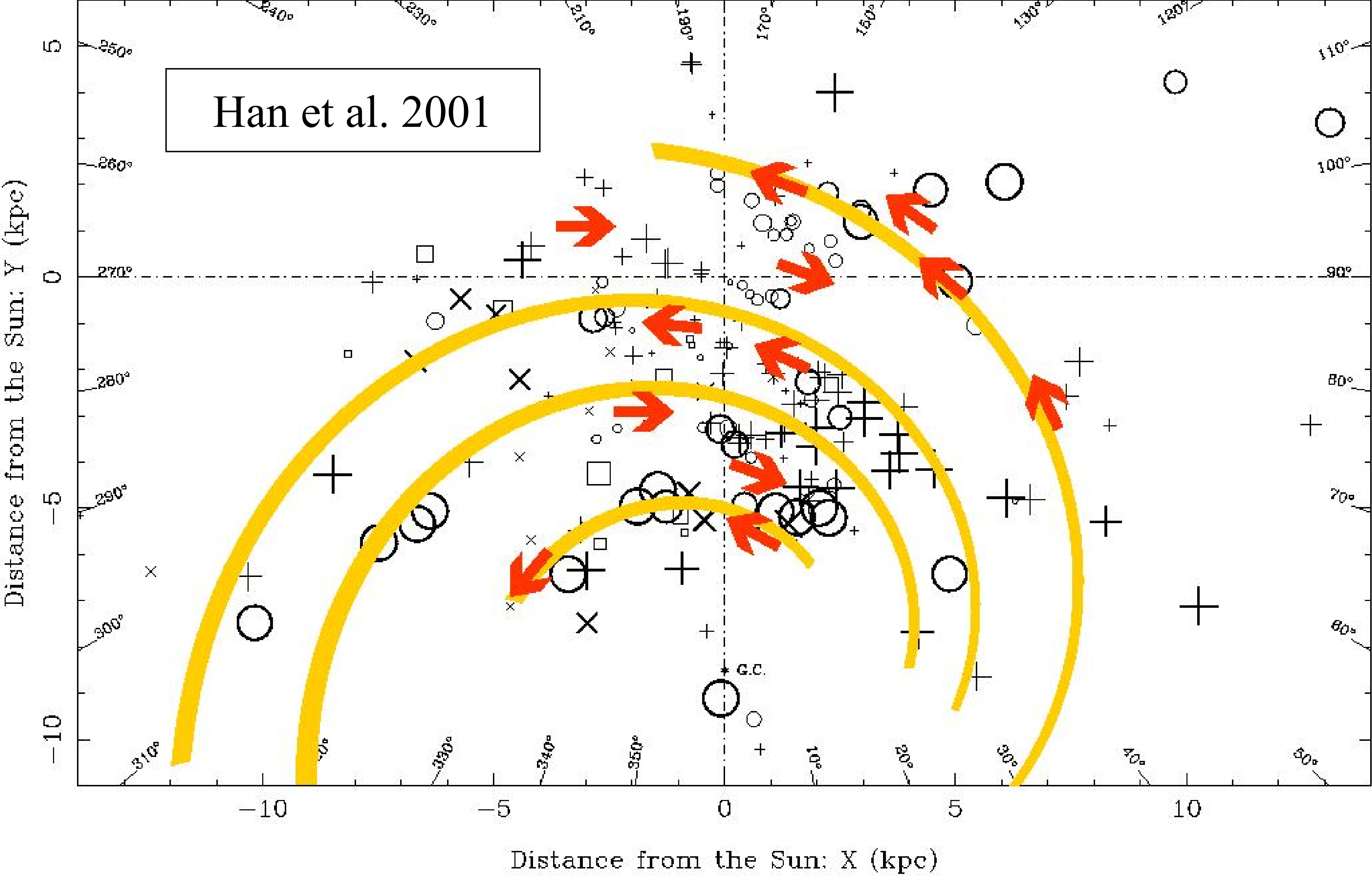
- High-resolution, high-frequency RM data to distinguish coherent from incoherent fields
- High-resolution, high-frequency RM data resolve the spectrum of dynamo modes
- High-sensitivity RM data to search for intergalactic (seed) fields
- Low-frequency polarization data to search for magnetic arms in the outer parts of galaxies
- Realistic dynamo models including turbulent flows *and* differential rotation

Resolving dynamo modes

- Mode *m* has *2m* field reversals and can be resolved if $\approx 10\,(m+1)$ independent sectors are observed in the disk
- To resolve $m \leq 4$ in a galaxy with R=10kpc and i=45° at D=100 Mpc, an angular resolution of $\theta \approx 1''$ is needed

Galactic field reversals:

Is our Galaxy special?

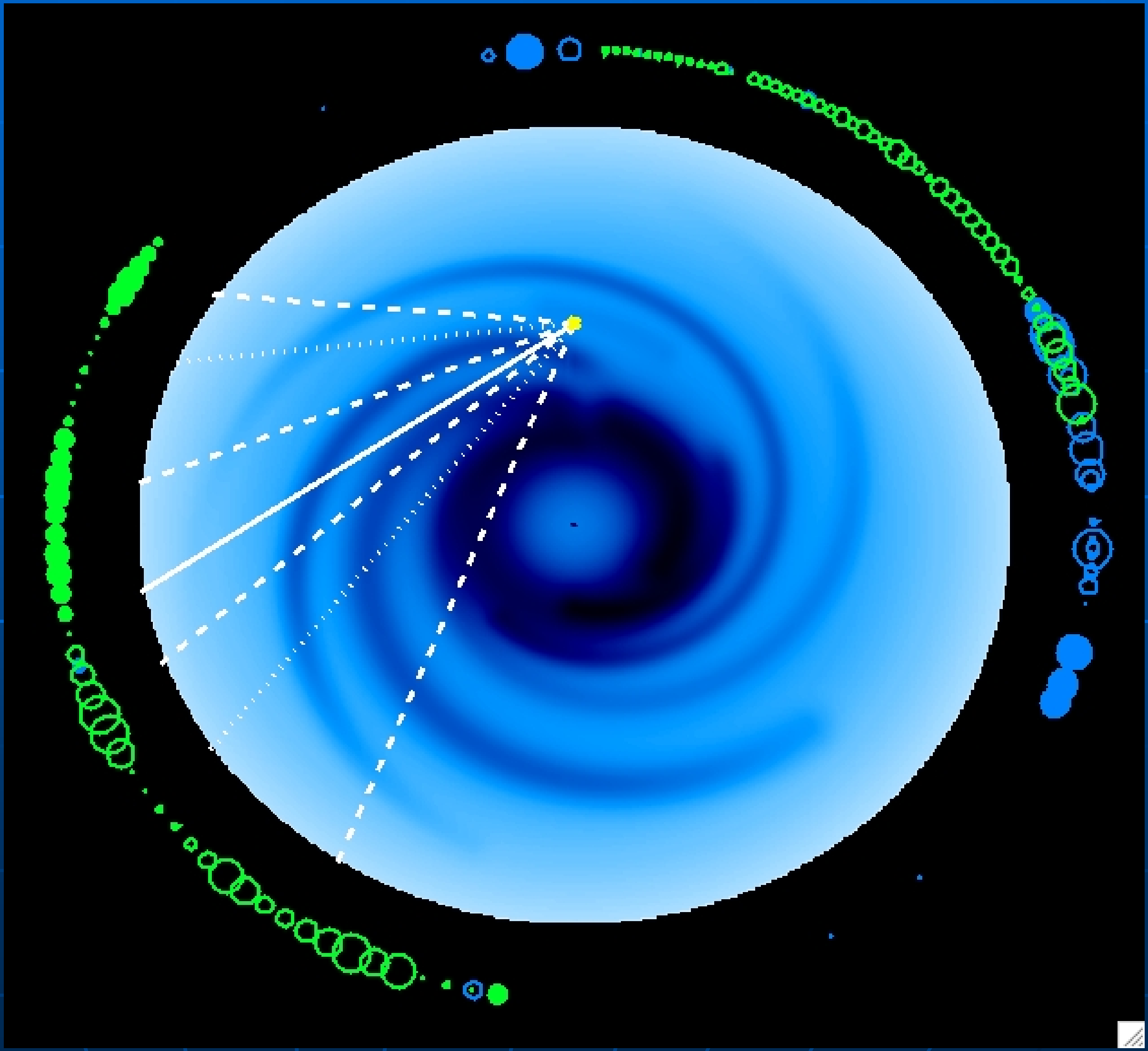


Bisymmetric spiral with 8˚ pitch angle and multiple reversals with radius - ???

RM Modulation by Spiral Arms

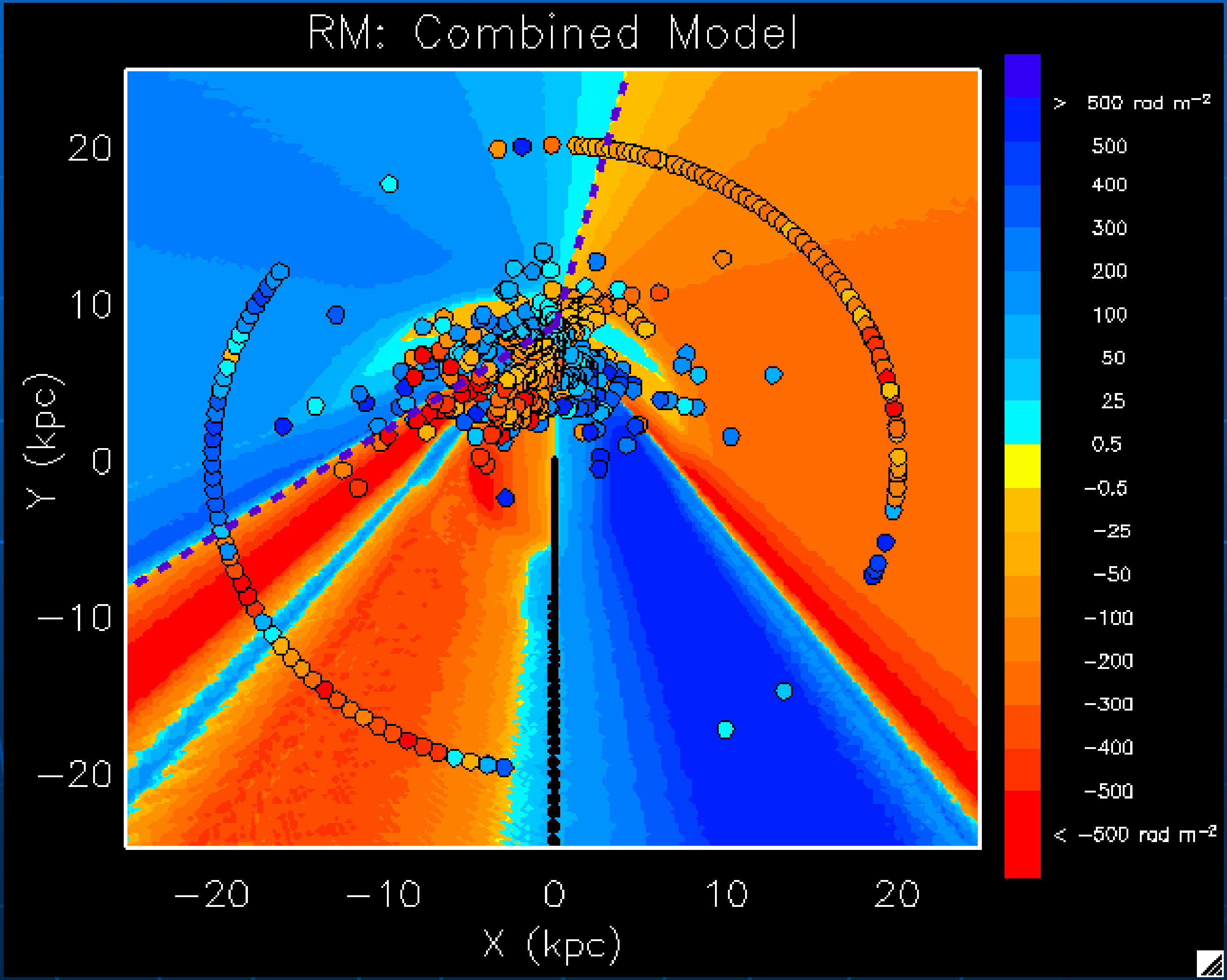
Brown et al. 2006

Only one reversal
is required



RM maps (one reversal)

Brown et al. 2006



Understanding field reversals in the Milky Way

Needed:

- Dense grid of extragalactic RM data points
- Dense 3-D grid of pulsar RM data points
- Reliable reconstruction techniques

  (using wavelets, see talk by Rodion Stepanov)

Future needs

- Higher sensitivity
- Higher resolution
  (as usual...)

As the universe expands more and more, we need a larger telescope …

LOw Frequency ARray

30-80 MHz
110-240 MHz

LOFAR

A revolution in radio telescope design:

- Pure software telescope: no moving parts, no mirrors, simultaneous multi-beaming, low costs

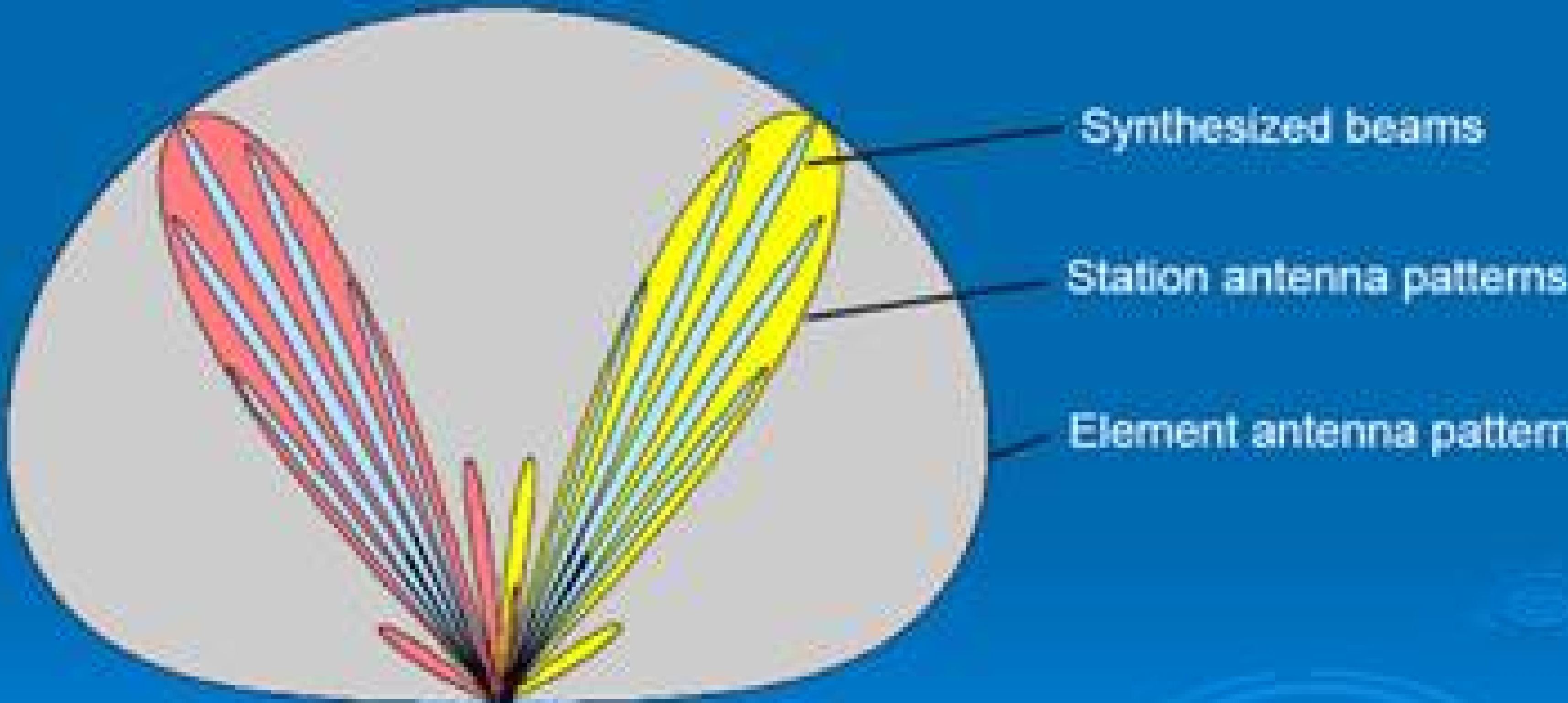
- Technological challenge in computing power, data transfer and data storage

LOFAR Antennas

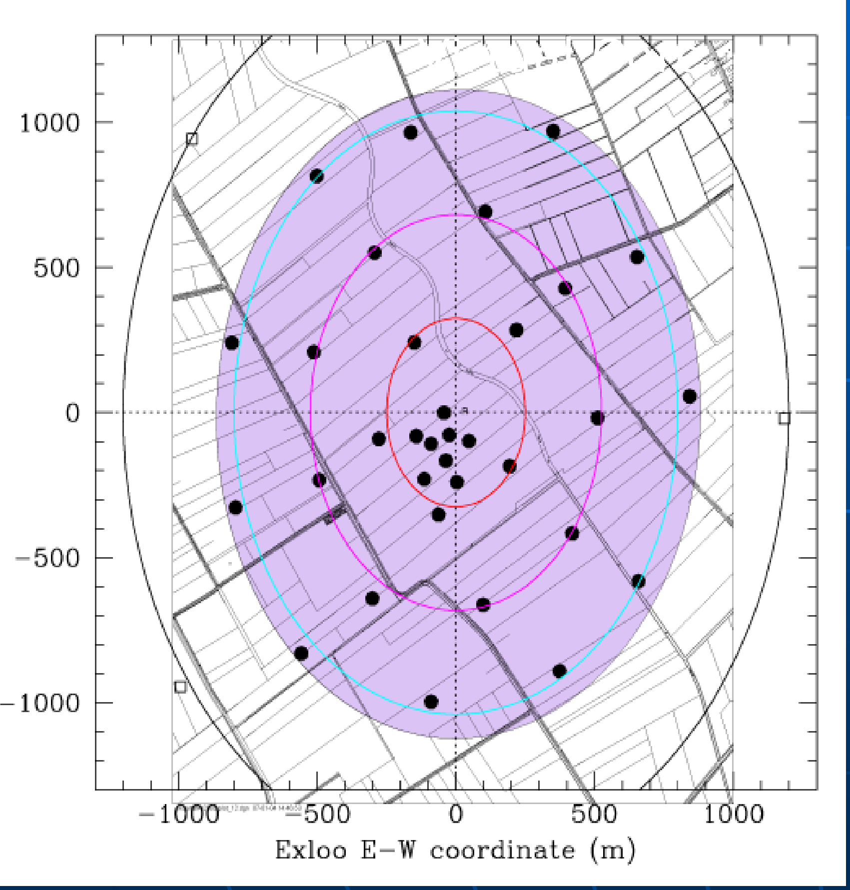
- 96 low-band dipoles per station
- optimized for 30-80 MHz

- 96 high-band antennas per station
- optimized for 110-240 MHz

Aperture Array



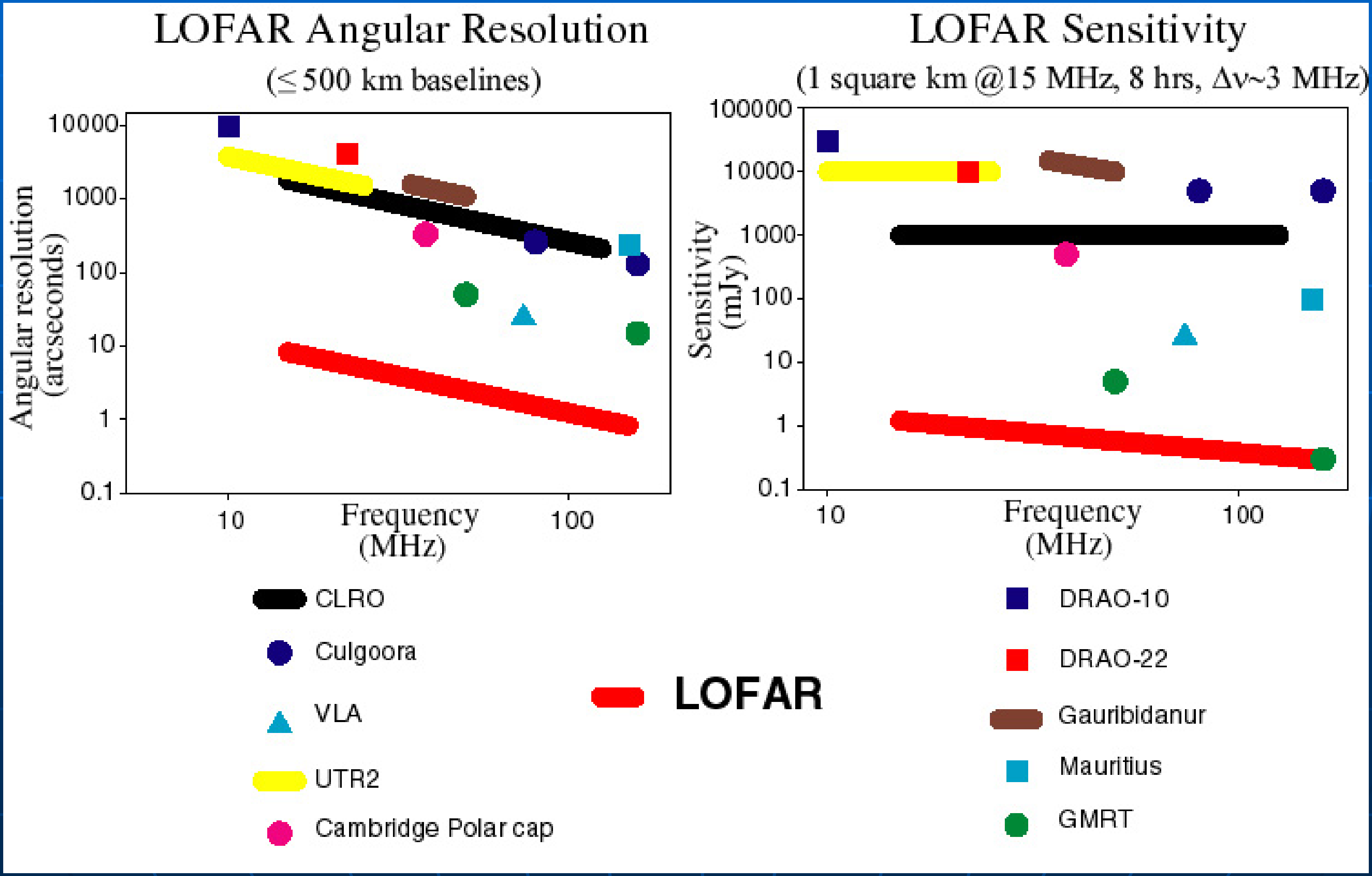
LOFAR Stations (Phase 1)



32 core stations (2007)

77 stations of full array (2009)

LOFAR performance



Key Science Projects

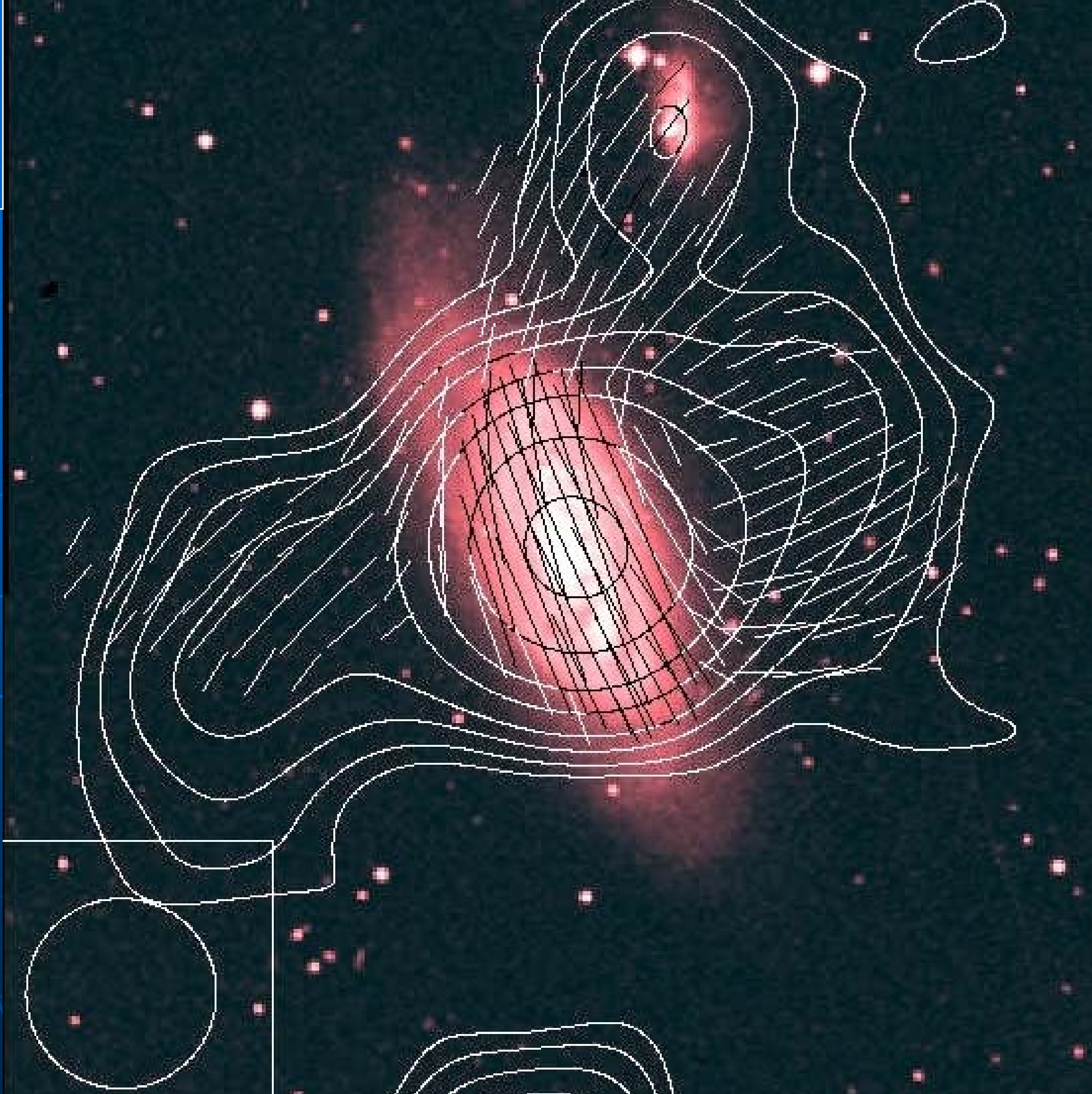
- Epoch of re-ionization – Groningen
- Extragalactic surveys – Leiden
- Transients and pulsars - Amsterdam
- Cosmic rays - Nijmegen
- Solar radio emission – Potsdam
- Cosmic magnetic fields – Bonn (?)

LOFAR:

Observing *weak* magnetic fields illuminated by *old* electrons

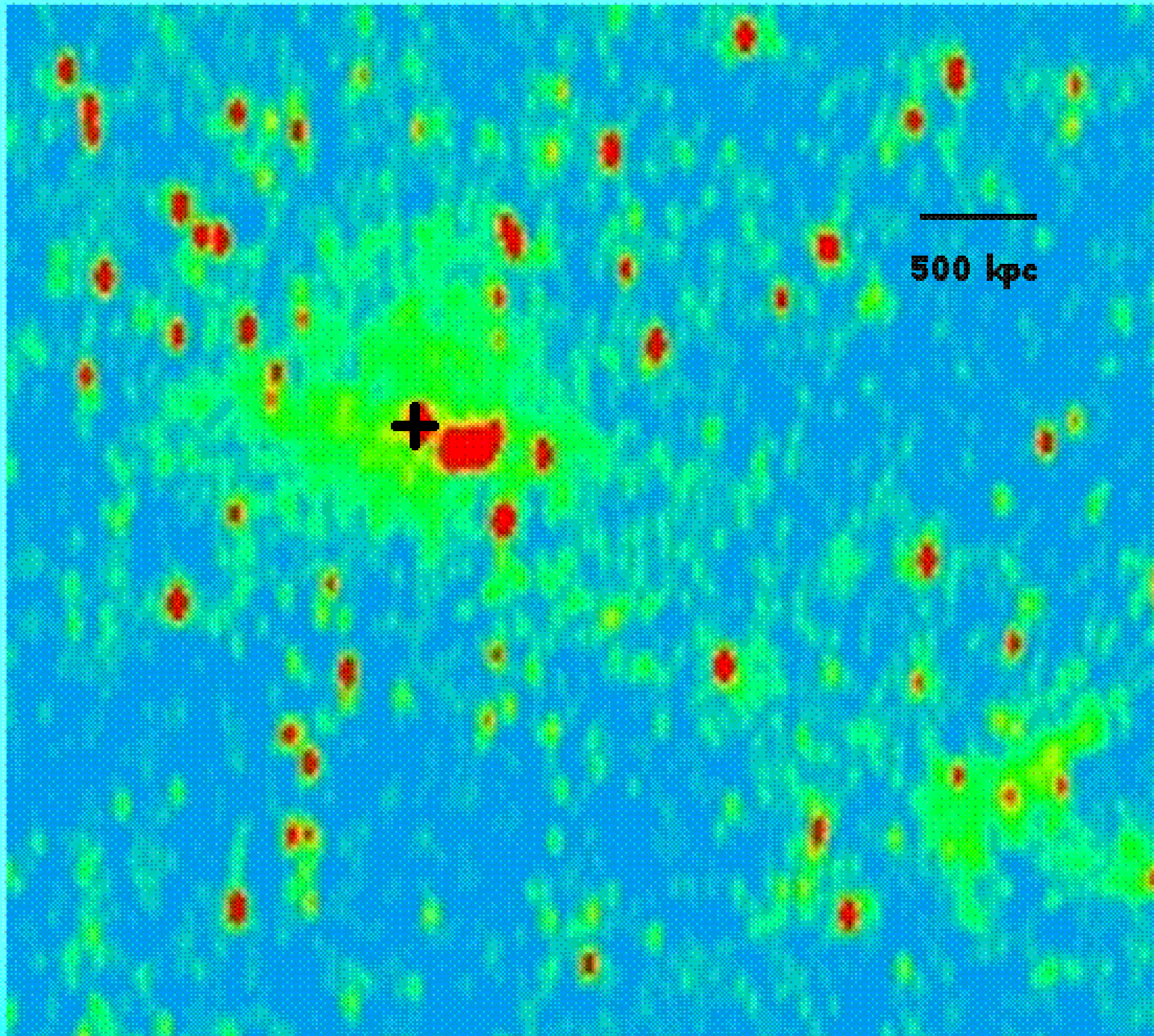
NGC4569

(Chyzy, Beck, et al.)



COMA Cluster

Center



RADIO: WSRT, 90 cm (Feretti et al.1998)

LOFAR RM Survey

- LOFAR can in measure very low Faraday rotation measures and hence very weak magnetic fields:

- Galaxy halos, cluster halos, relics

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

- Intergalactic magnetic fields

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

LOFAR stations in Germany

Planned:
7 stations

Goal:
12 stations

International Station *Germany 1* at Effelsberg

European Expansion

Current discussion:

Germany: ~12 stations

UK: ~5 stations

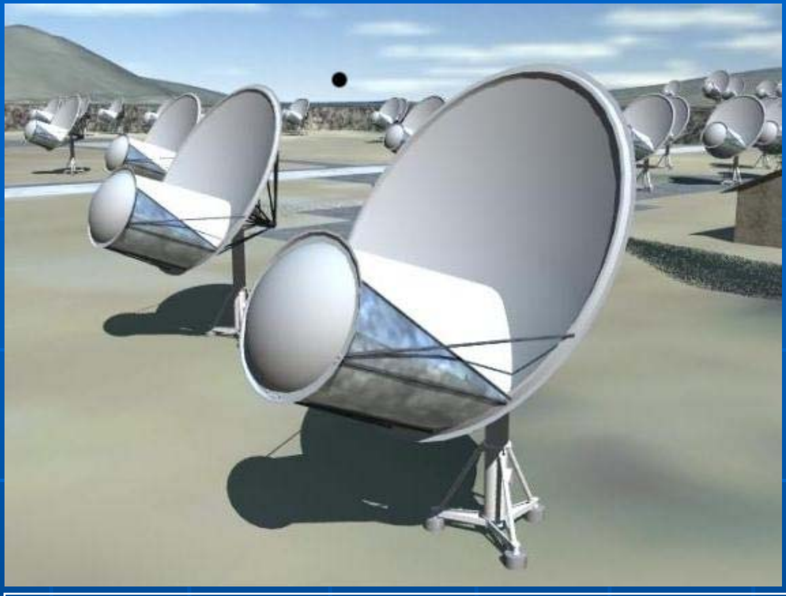
Italy: ~2 stations

France: ~1 station

Next step:

The Square Kilometre Array (SKA)

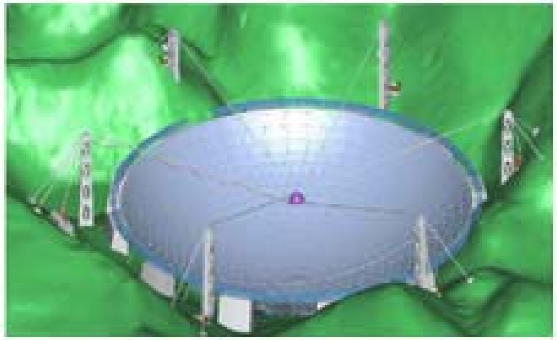
SKA Concepts



USA: Small parabolic reflectors

Australia: Focal plane arrays

Europe: Phased Array



FAST - 3D image (Courtesy of Dr. Cao Yang)

China: Large spherical mirrors

SKA Key Science

- Testing theories of gravitation
- Galaxy evolution & large-scale structures
- The Dark Ages
- The Cradle of Life
- Cosmic magnetism

SKA Key Science Project: All-Sky RM Survey

(Gaensler, Feretti & Beck)

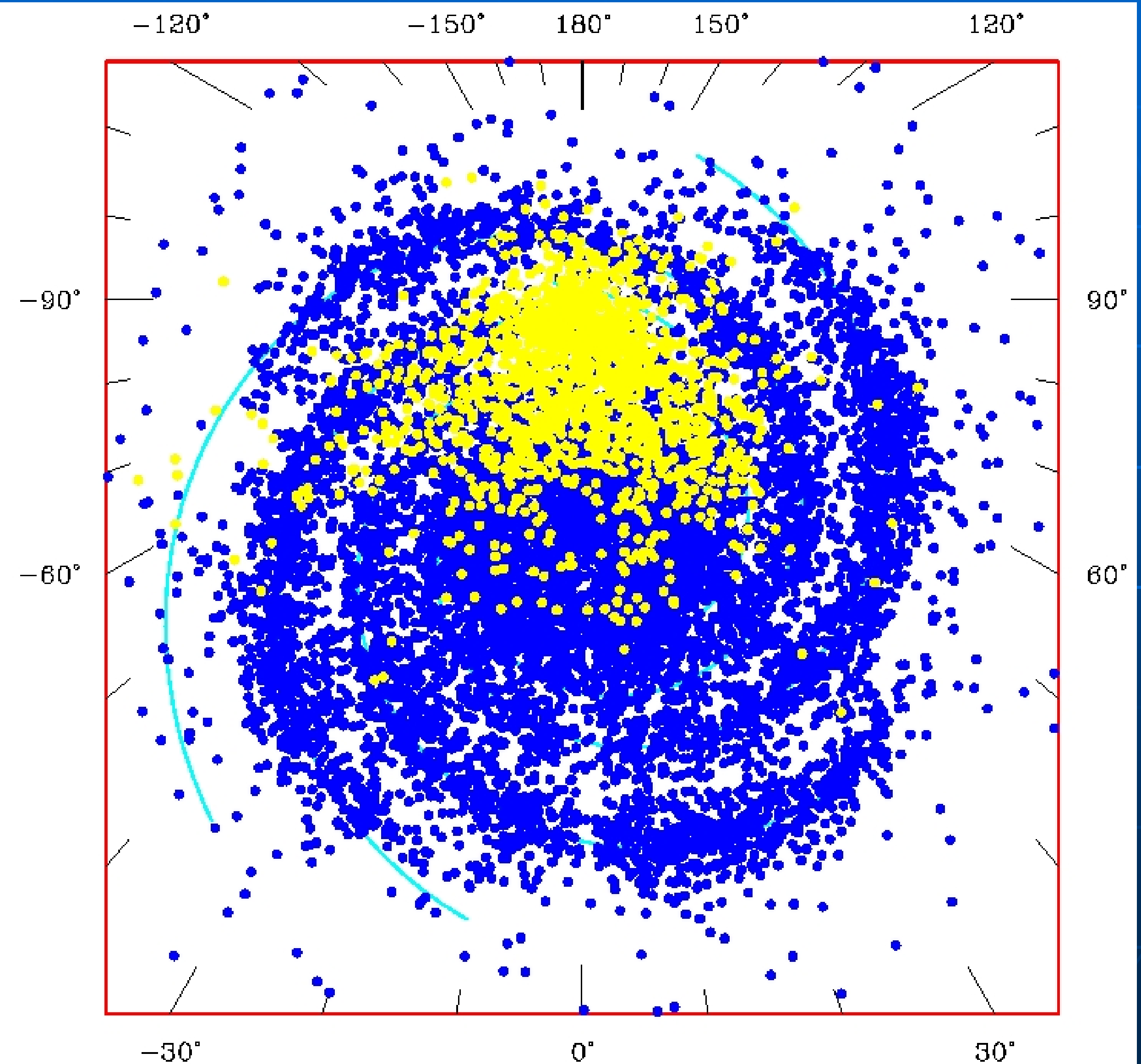
RMs for ~ **(1–5) x 10^8** polarized extragalactic sources, spaced by ~ 30"–50" on the sky

- High-resolution RM mapping of the Milky Way, nearby galaxies & clusters
- RM mapping of distant intervening galaxies
- Search for coherent magnetic fields in the first galaxies and clusters
- Search for coherent magnetic fields in the intergalactic medium

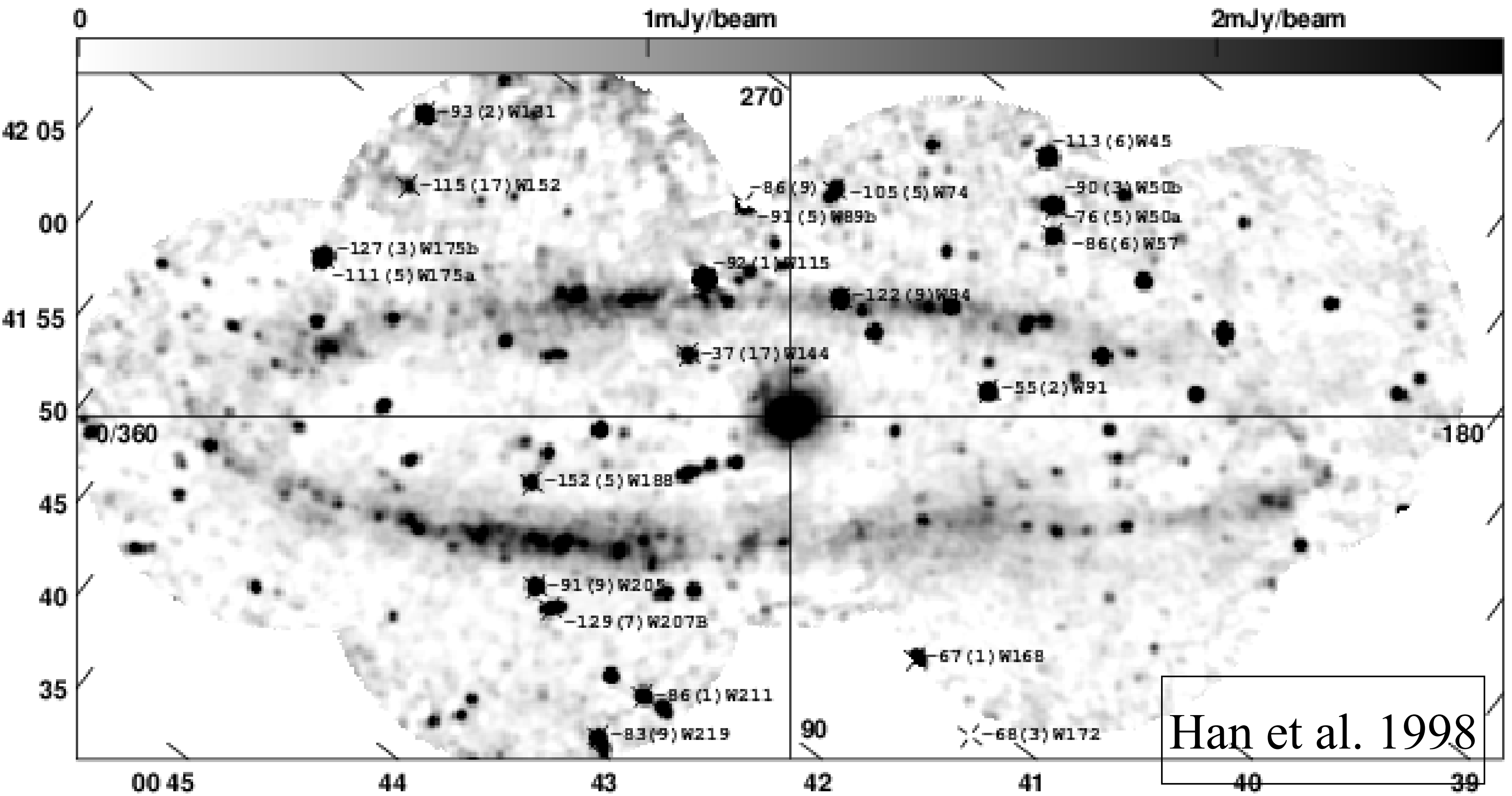
Future rotation measures in the Milky Way

Known pulsars and pulsars to be detected with the SKA

Cordes 2001

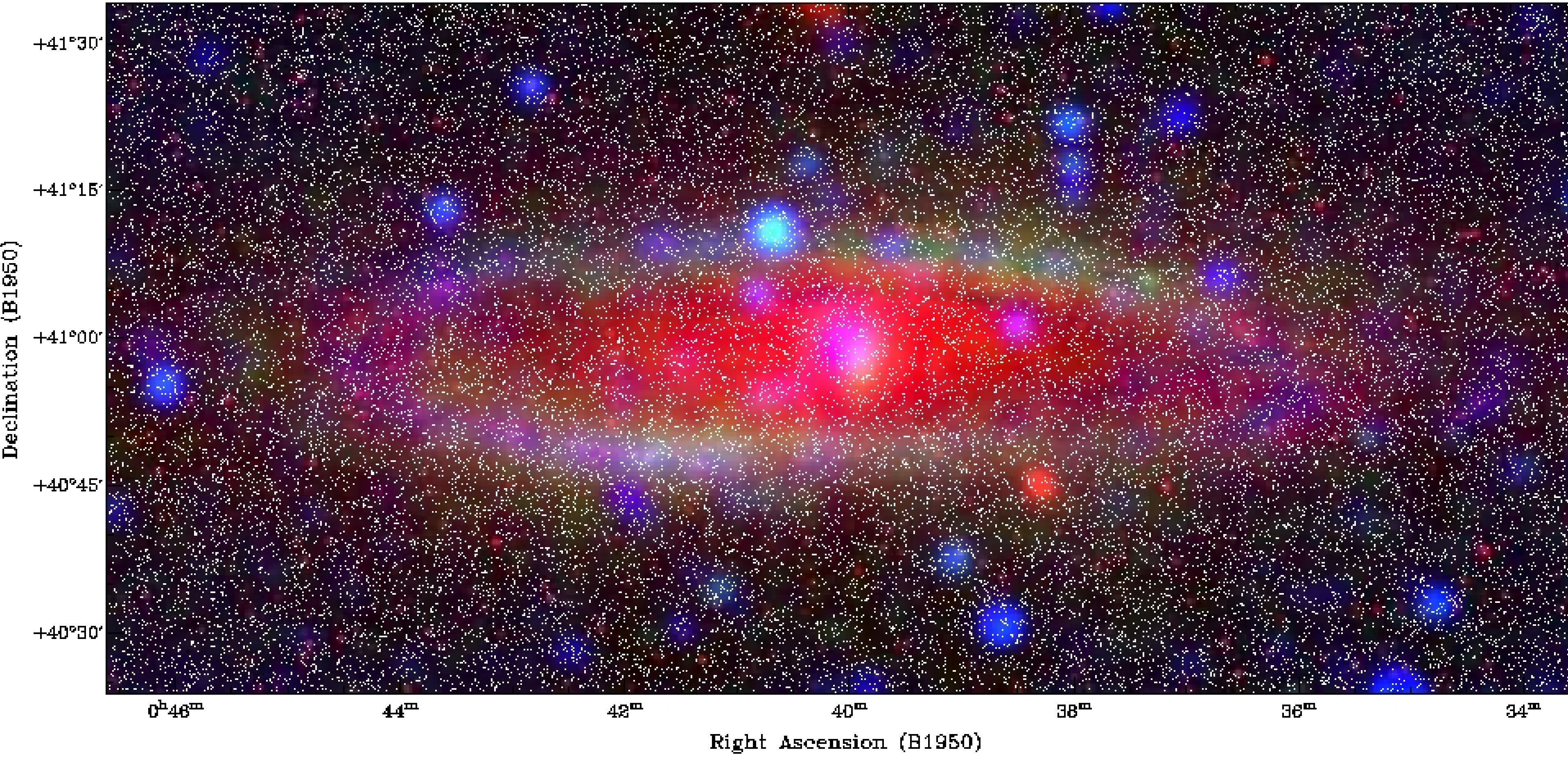


RMs Through Galaxies



RMs of 21 polarized sources shining through M31

Future RMs through M31 with the SKA



~10000 polarized sources shining through M31

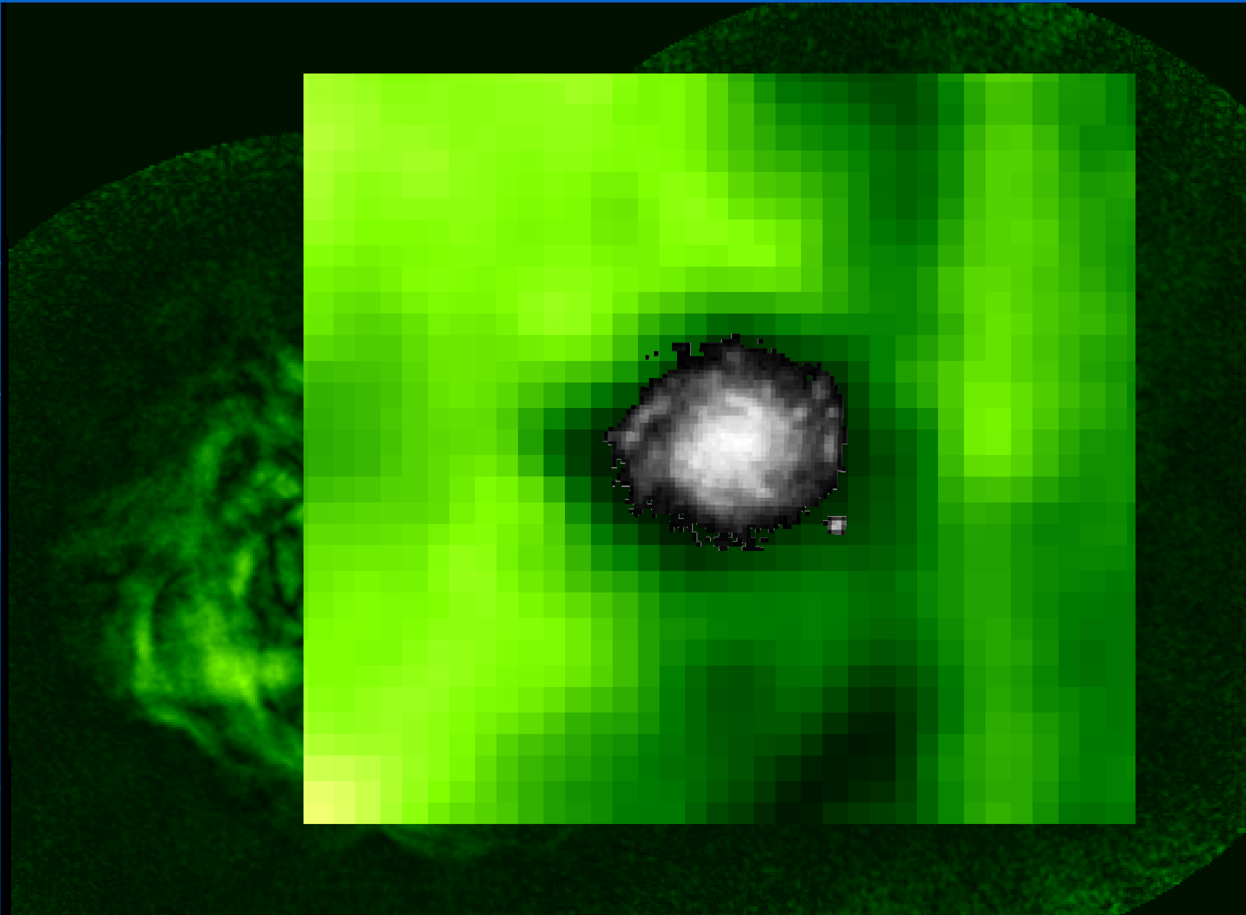
Polarization silhouettes

- Modification of extended foreground (Galactic) or background emission by Faraday effects:

  Powerful probes of galactic magnetism in distant galaxies

NGC 1310 against Fornax A:

Faraday depolarization of polarized background emission
(Fomalont et al. 1989)



SKA Design Study - Simulations

(SKADS *DS2-T1-WP3*, with Cavendish Lab. Cambridge/UK)

Preparing for future projects on magnetism by simulating the polarized sky:

- diffuse Galactic emission
- polarized background sources
- RM grid

Workshop planned in 2007

Polarized emission

(SKADS DS2-T1-WP3)

- Degree of magnetic field alignment and its evolution with galaxy age
- Faraday rotation and depolarization within the Milky Way, galaxies and the intergalactic medium
- Evolution of dynamo modes in galaxies

Final goal:

- Density of polarized sources on sky
- Density of RM grid required to observe magnetic fields in the Milky Way, in galaxies and in the IGM

Future radio telescopes: excellent prospects for magnetic field observations- cooperations are welcome