Max-Planck-Institut
für
Radioastronomie

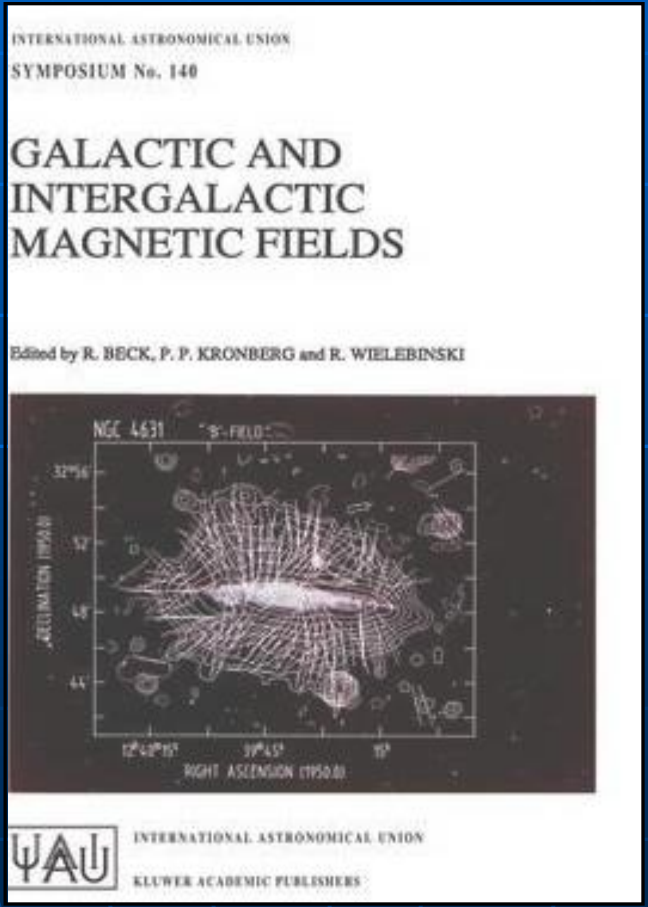
Magnetic Fields in the Central Regions of Spiral Galaxies

Rainer Beck, MPIfR Bonn

Elly Berkhuijsen, René Gießübel, Marita Krause, MPIfR
Björn Adebahr, Ralf-Jürgen Dettmar, Univ. Bochum
Chris Chyzy, Marian Soida, Marek Urbanik, Univ. Kraków
Volker Heesen, Univ. Hertfordshire
Andrew Fletcher, Anvar Shukurov, Univ. Newcastle
Matthias Ehle, ESA Villafranca
Dmitry Sokoloff, Moscow State University
Vladimir Shoutenkov, Astro Space Center Pushchino

The first IAU Symposium on galactic and extragalactic magnetic fields:

22 years ago in this conference center



Are magnetic fields in central regions dynamically important?

What can external galaxies tell us about magnetic fields in the central region of our Milky Way?

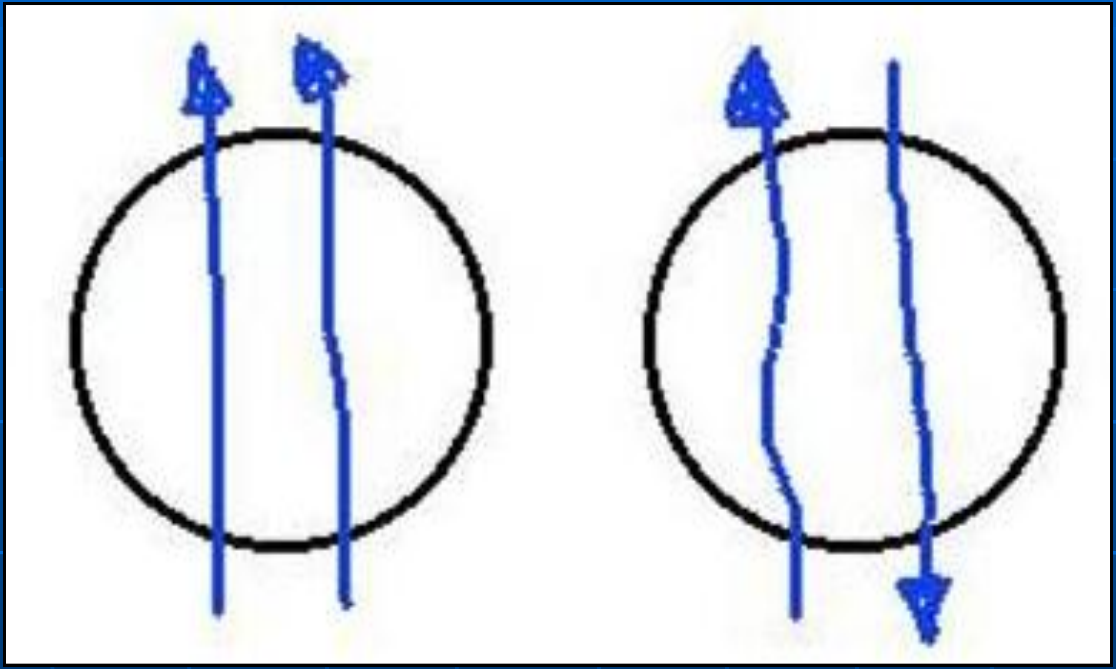
Radio synchrotron emission is a tracer of interstellar magnetic fields

- Total synchrotron intensity:
  Strength of **total** magnetic field $B_\perp$
- Polarized synchrotron intensity:
  Strength of **ordered** $B_\perp$ (regular or anisotropic)
- Polarization B vectors:
  Orientation (but not the sign) of **ordered** $B_\perp$
- Faraday rotation:
  Strength and direction of **regular** $B_\parallel$

Regular field

Anisotropic field

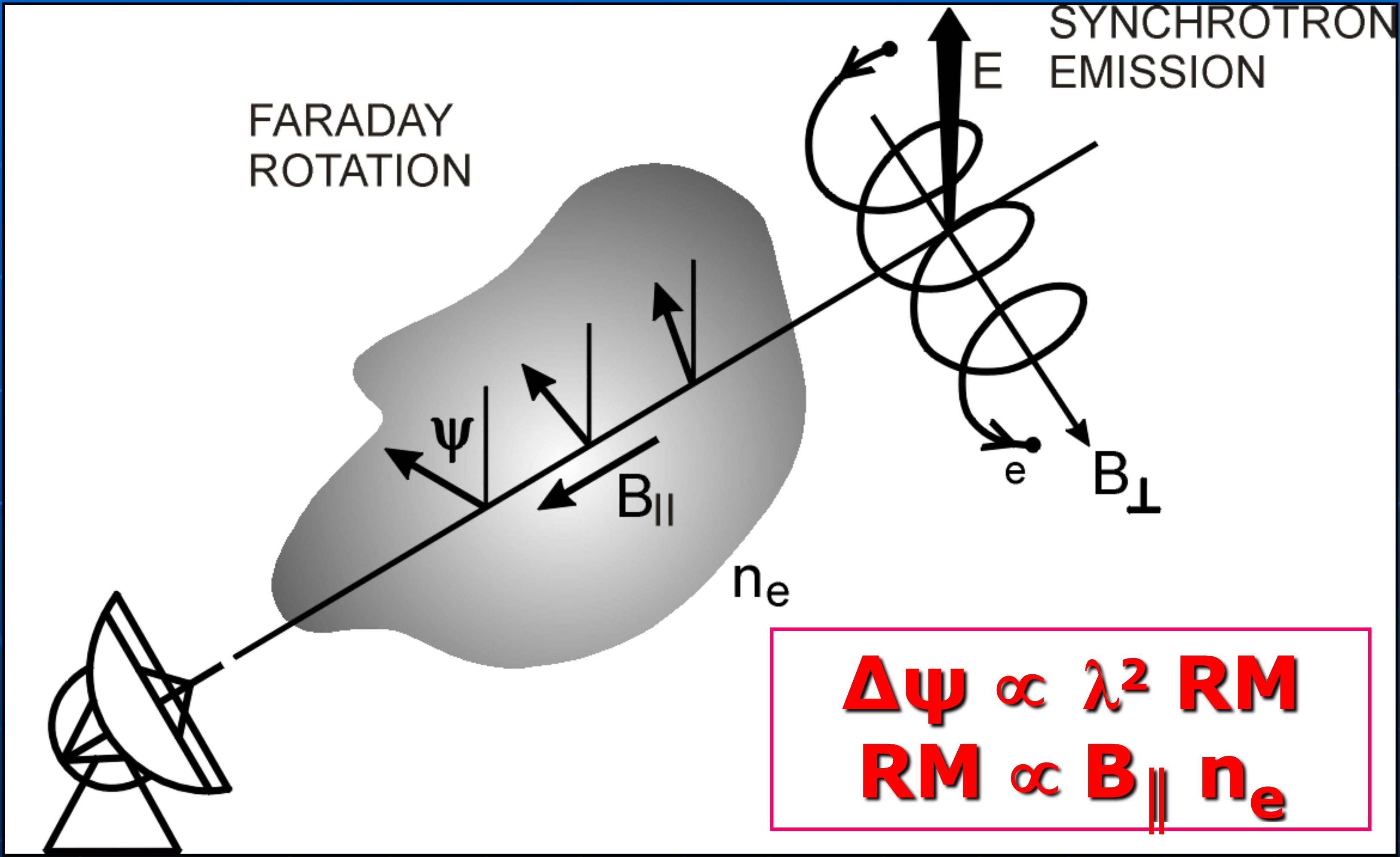
Fletcher 2004



Polarization : strong strong

Faraday rotation : **high** low

Faraday rotation:
crucial to detect regular fields



$$\Delta\psi \propto \lambda^2 \, RM$$
$$RM \propto B_{\parallel} \, n_e$$

1. Spiral galaxies with non-active nuclei

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**

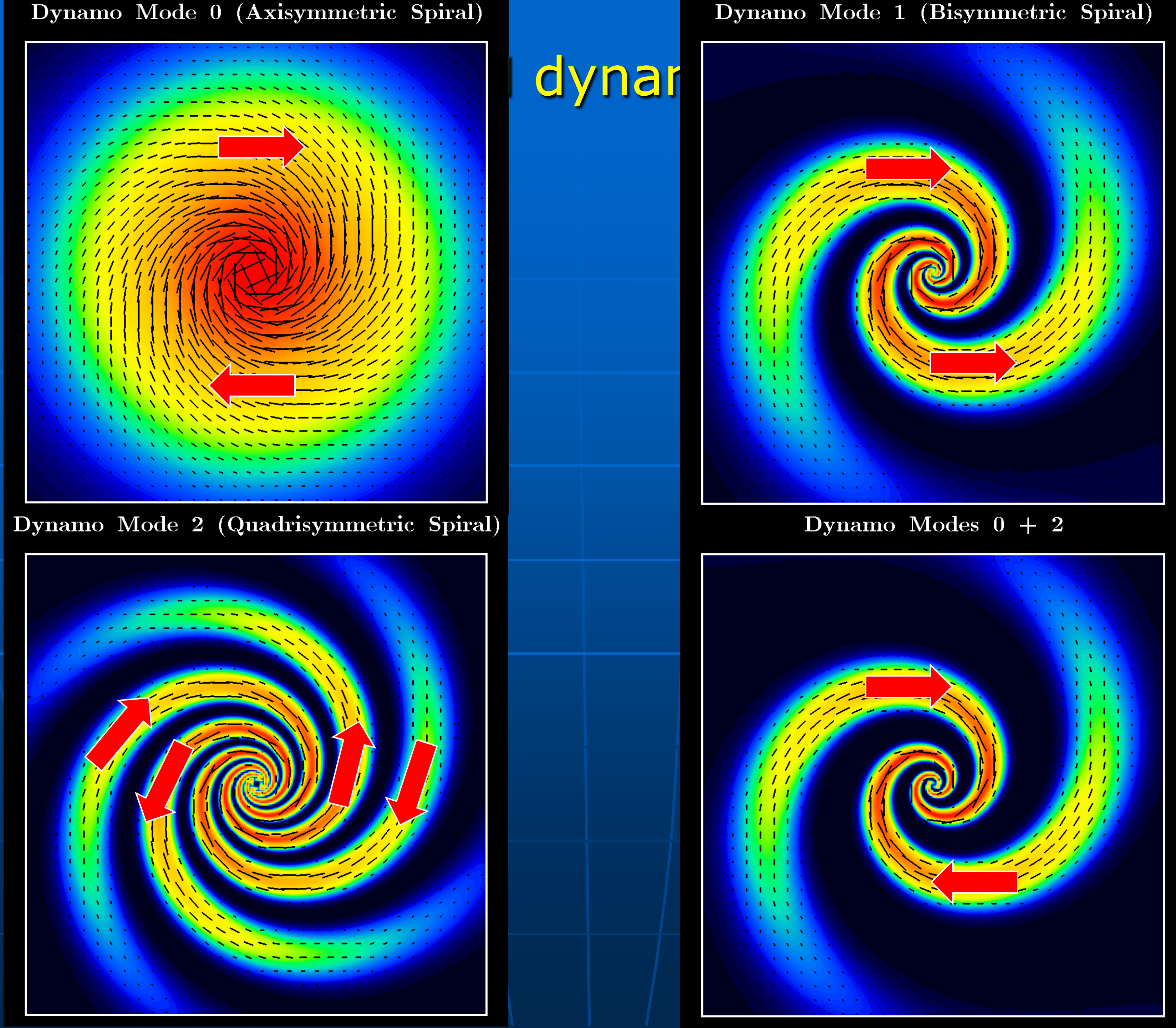
Stage 3: Coherent field ordering

Large-scale (mean-field) dynamo

Mean-field (large-scale) dynamo models

- Generation of large-scale regular fields (modes)
- Flat objects (e.g. galaxy disks):
  Symmetric (even-parity) fields
- Spherical objects (e.g. galaxy halos):
  Antisymmetric (odd-parity) fields

l dynar


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

Antisymmetric and symmetric dynamo modes

Stix 1975

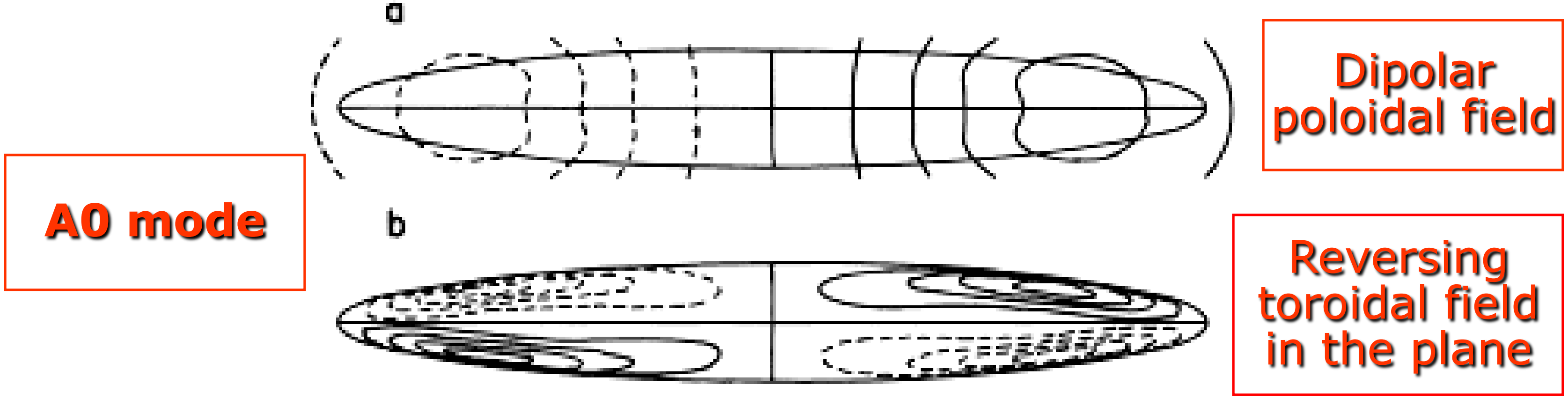


Fig. 1a and b. Poloidal field lines (a) and curves of constant toroidal field strength (b) for a dipole type field, with $R = 15$ kpc, $b = 2$ kpc, and $P = 1.1 \cdot 10^3$

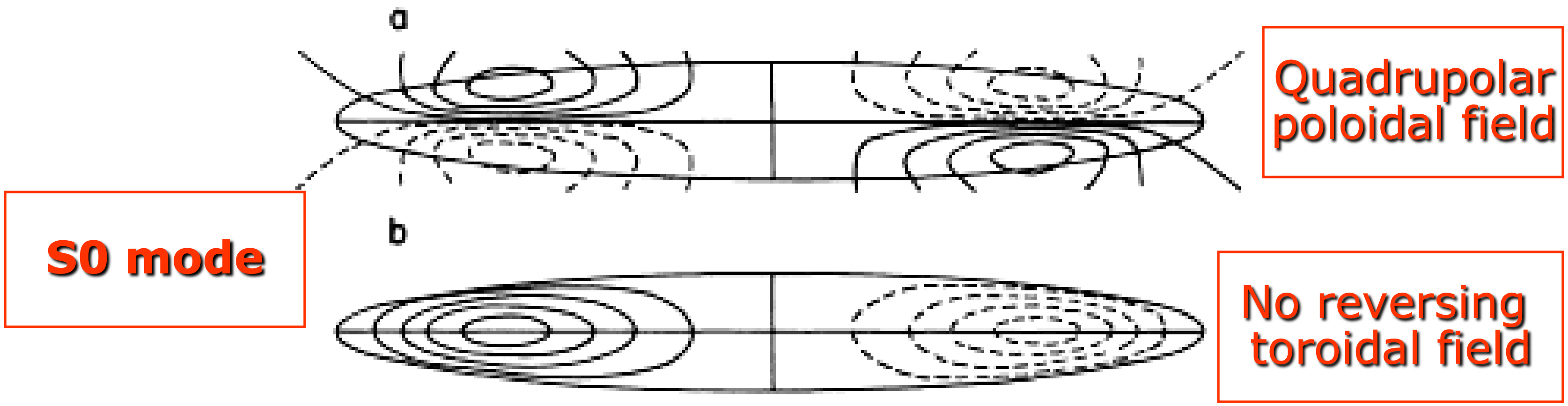


Fig. 2a and b. Poloidal field lines (a) and curves of constant toroidal field strength (b) for a quadrupole type field, with $R = 15$ kpc, $b = 2$ kpc, and $P = -8.5 \cdot 10^3$

Faraday rotation in antisymmetric (odd) and symmetric (even) dynamo modes
(i=78°)

Heesen et al. 2009

Odd mode

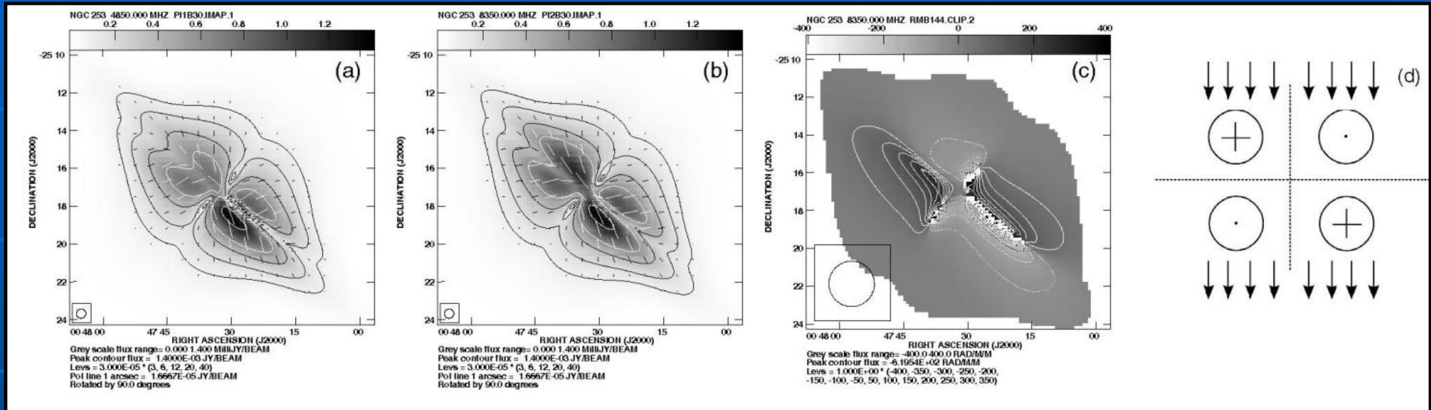


Fig. A.11. Odd disk magnetic field and odd halo magnetic field. The halo field points away from the disk in the southern halo.

Even mode

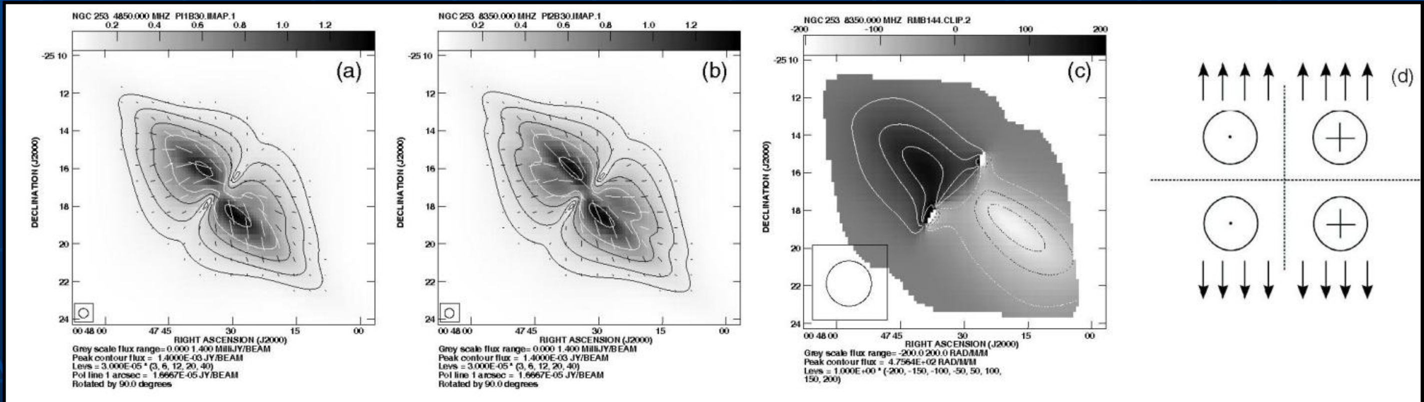
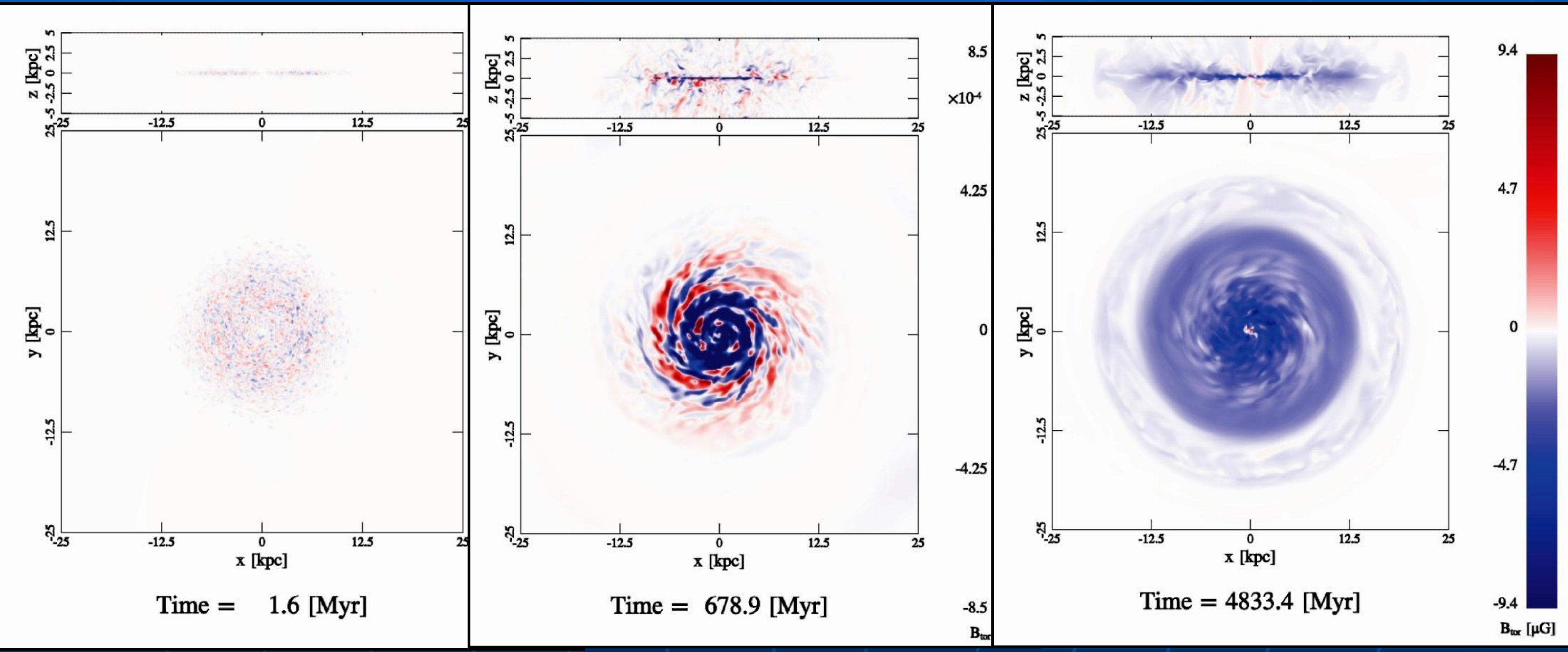


Fig. A.5. Even disk magnetic field and even halo magnetic field. The halo field points away from the disk.

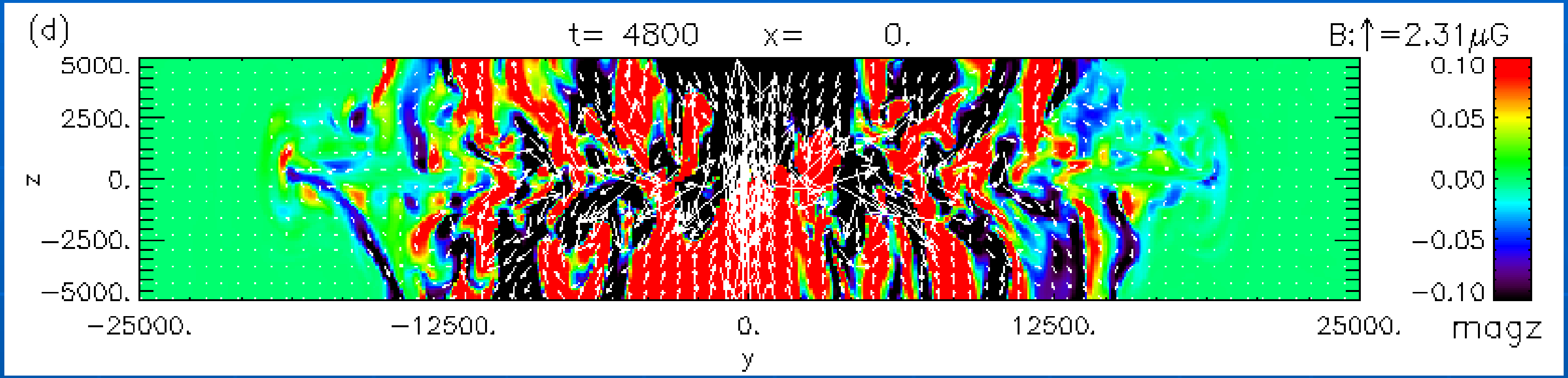
MHD model of a cosmic-ray driven dynamo

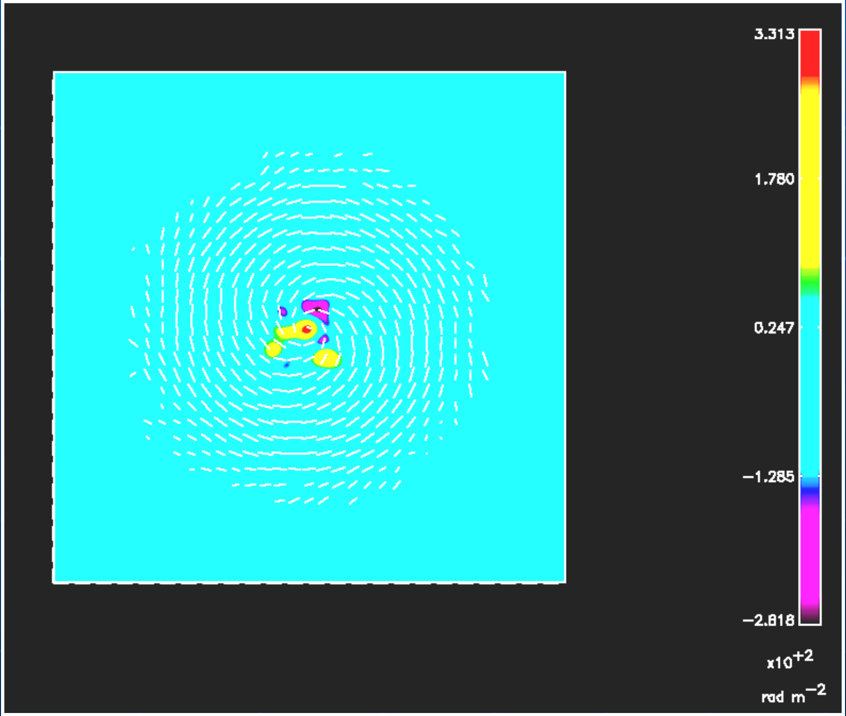
Hanasz et al. 2009



Regular fields with several μG strength generated within a few Gyrs

MHD model of a cosmic-ray driven dynamo



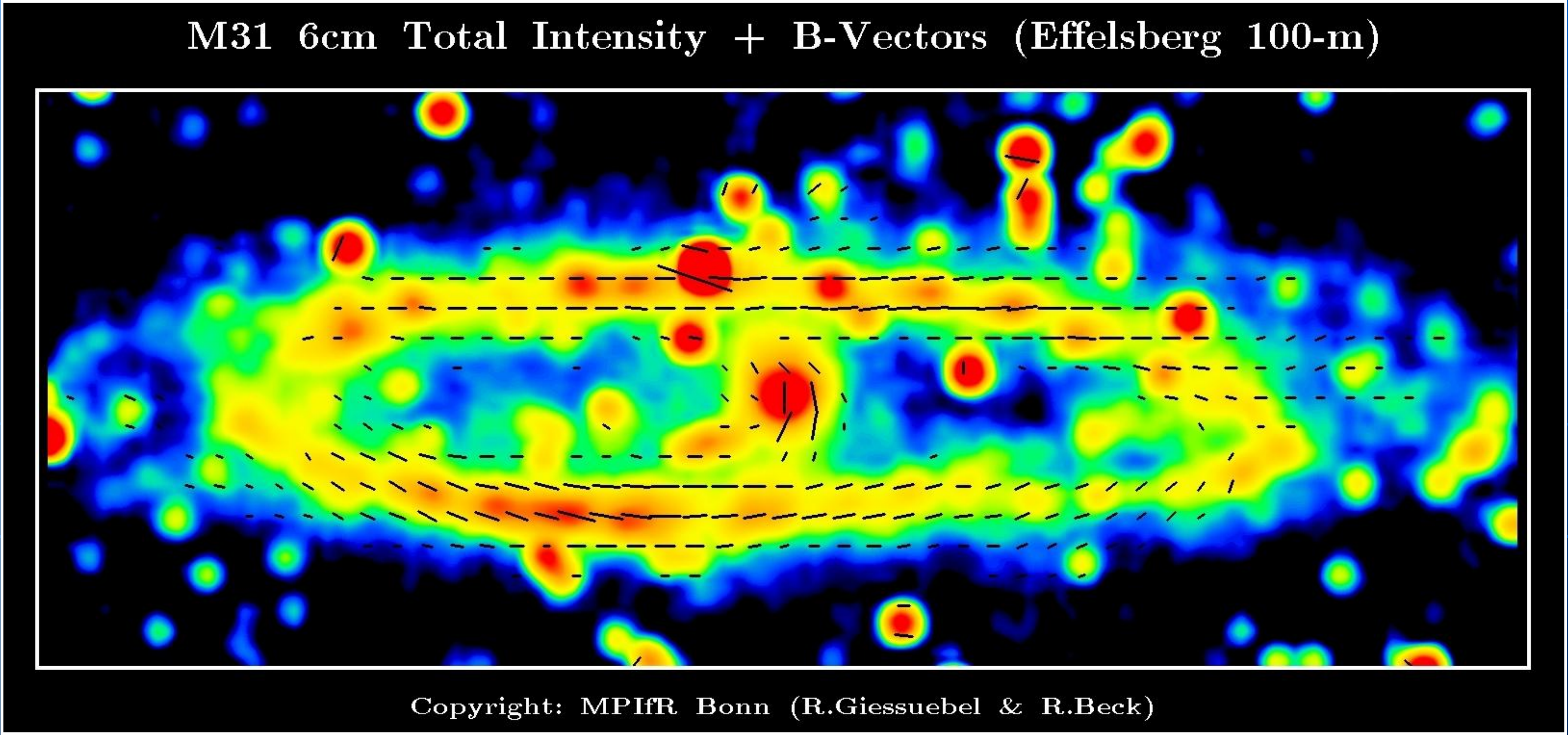


Regular vertical fields in central region

→ Strong Faraday rotation

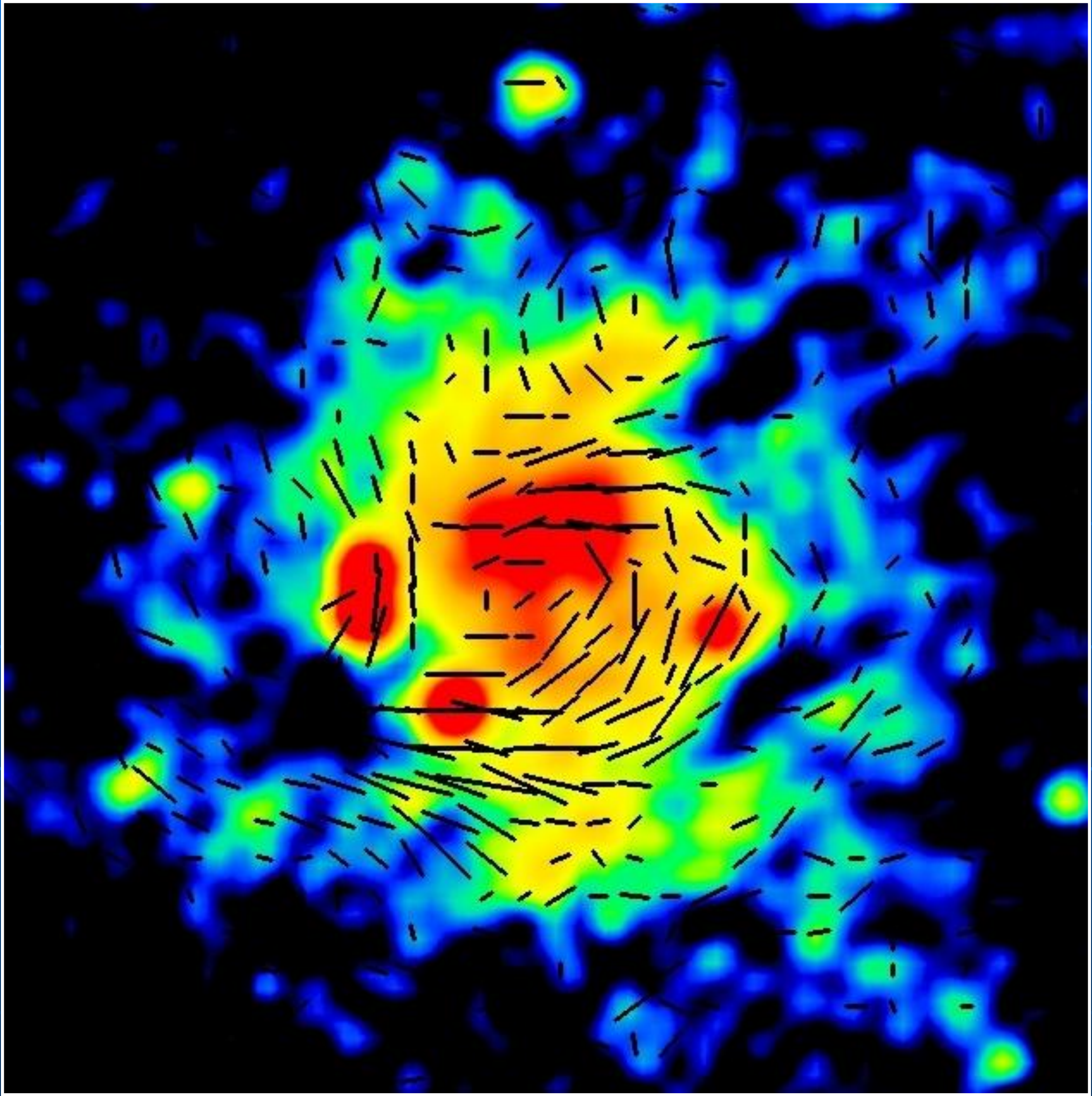
Hanasz et al. 2009

Effelsberg survey of M31



Axisymmetric regular field – the classical dynamo case

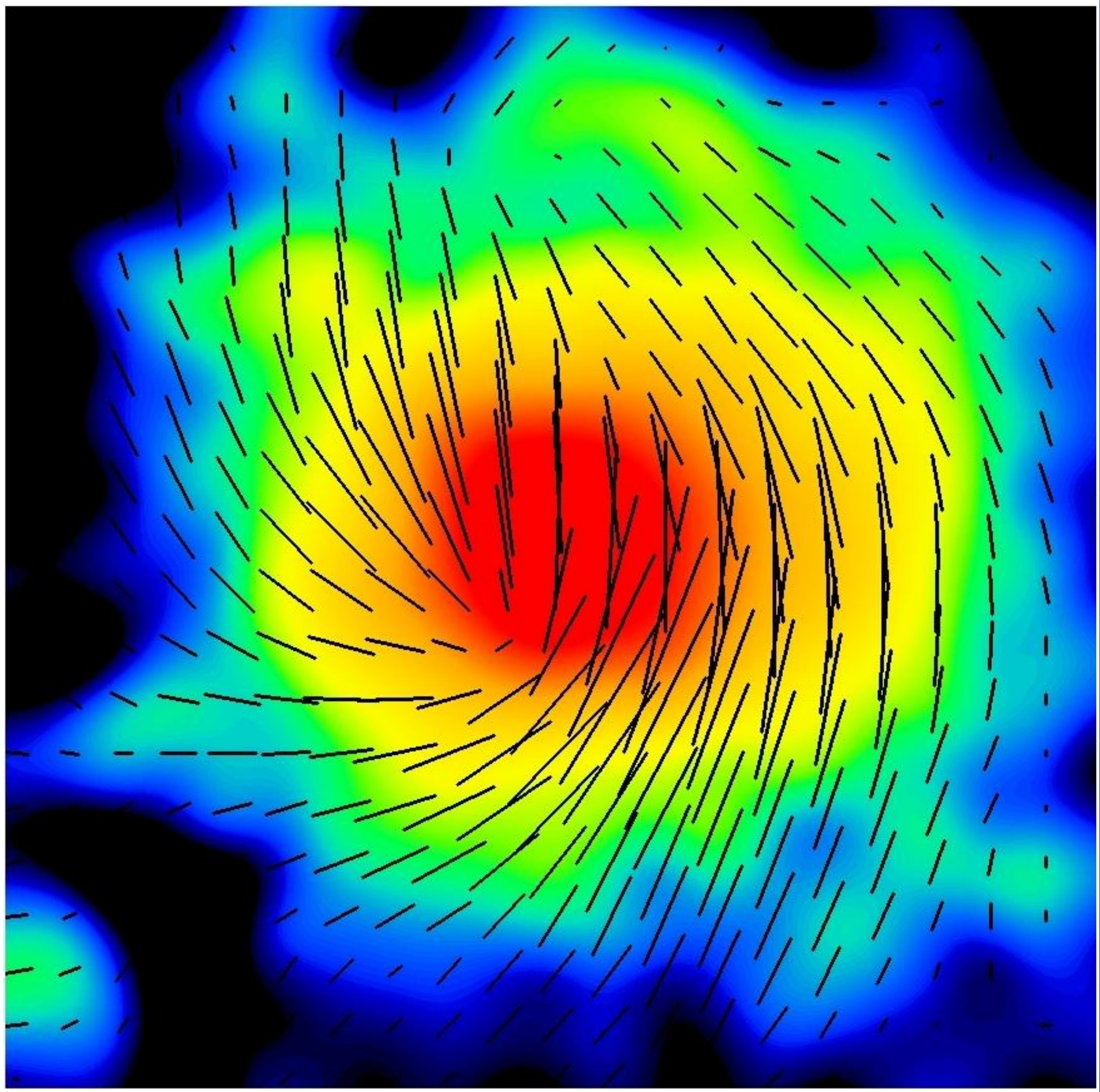
M31
Central region
6cm VLA
Total intensity
+ B-vectors
(Hoernes PhD 2006)



Central gas disk is inclined by ≈0° - 45° (main disk: 78°)

Resolution: ≈ 70 pc

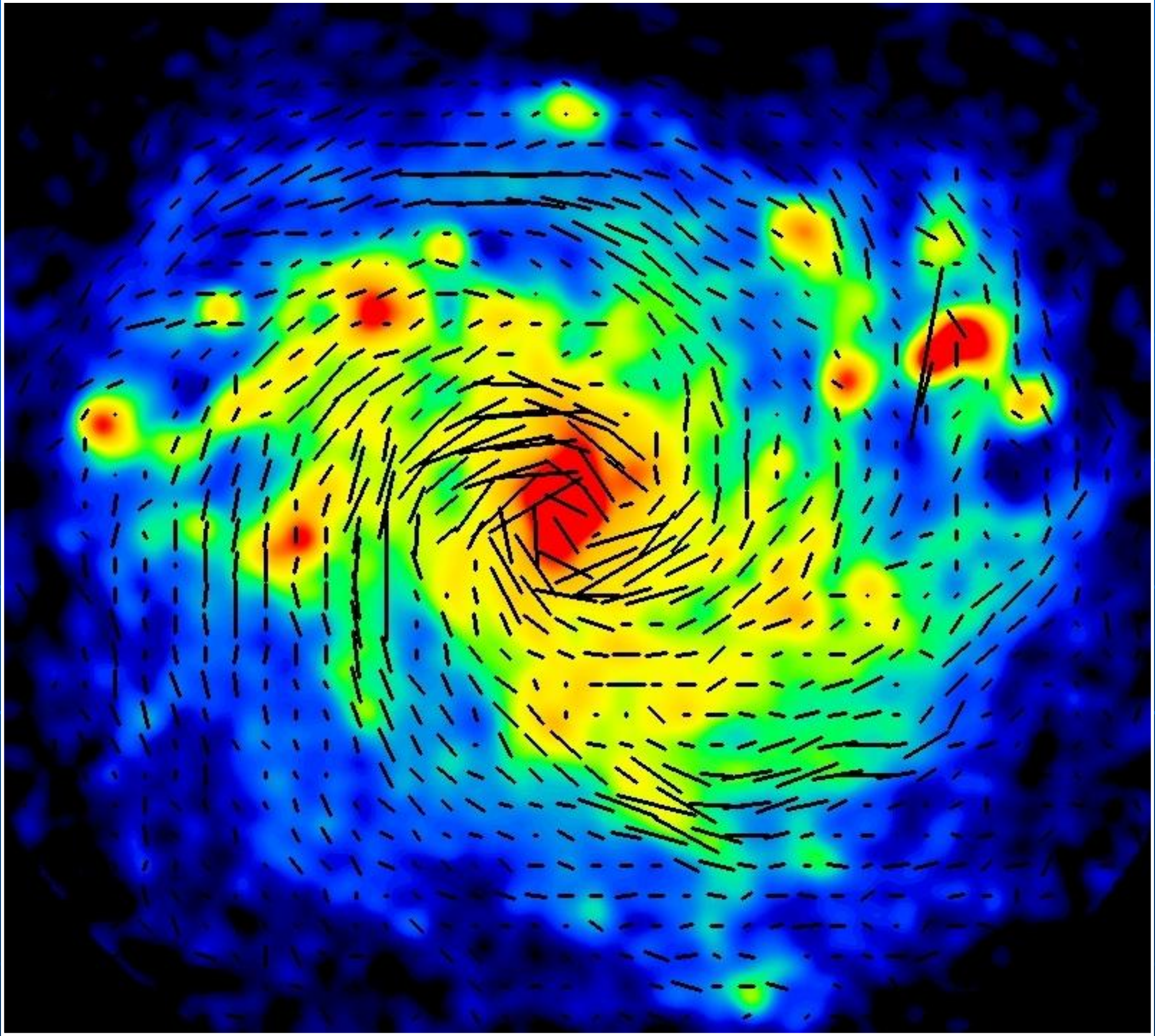
M31
Central region
3cm Effelsberg
Total intensity
+ B-vectors
(Gießübel PhD 2006)



Independent dynamo action in central region?

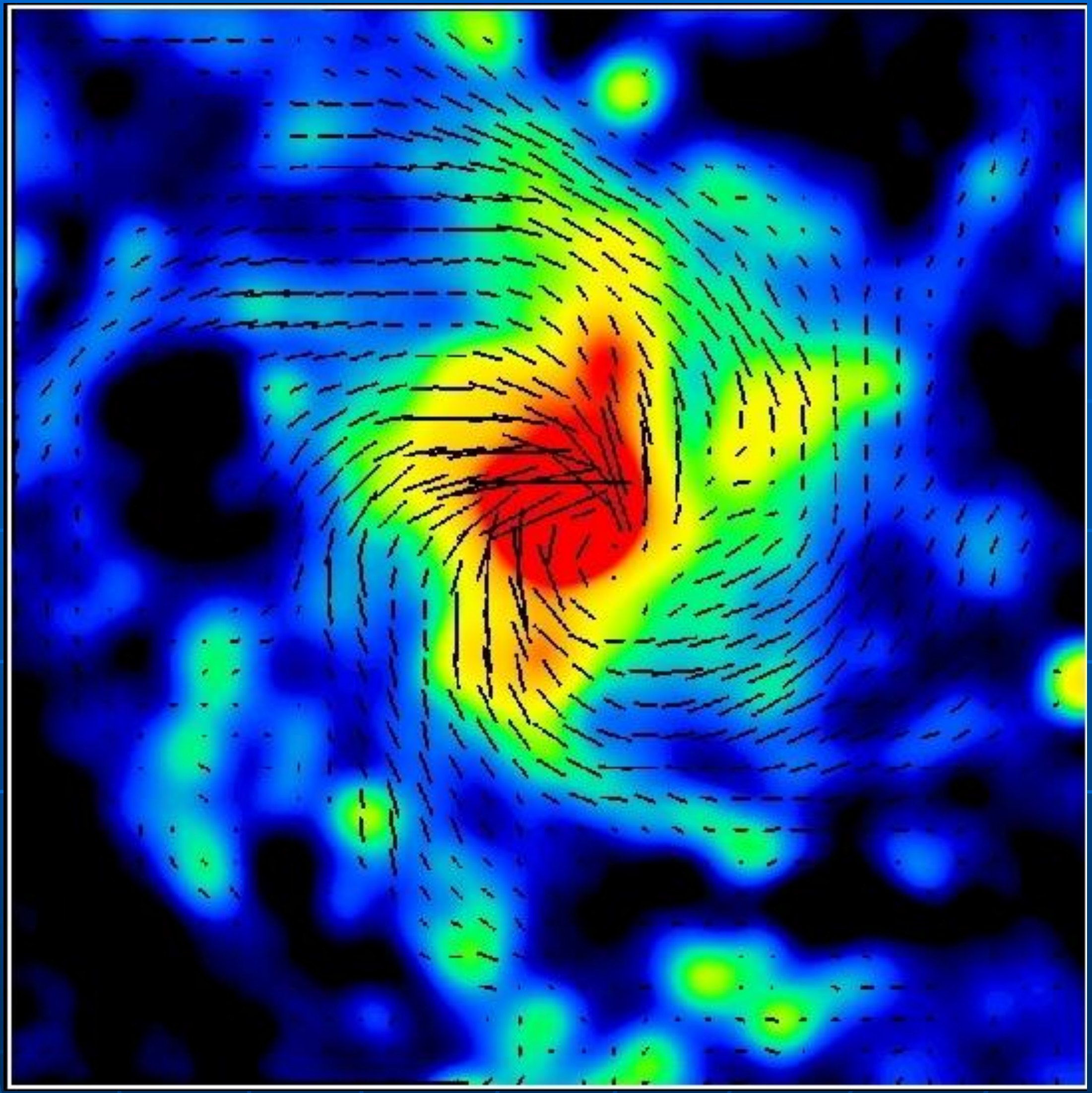
NGC 6946

6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Beck 2007)



NGC 6946
Central region
3cm VLA
Total intensity
+B-vectors
(Beck 2007)

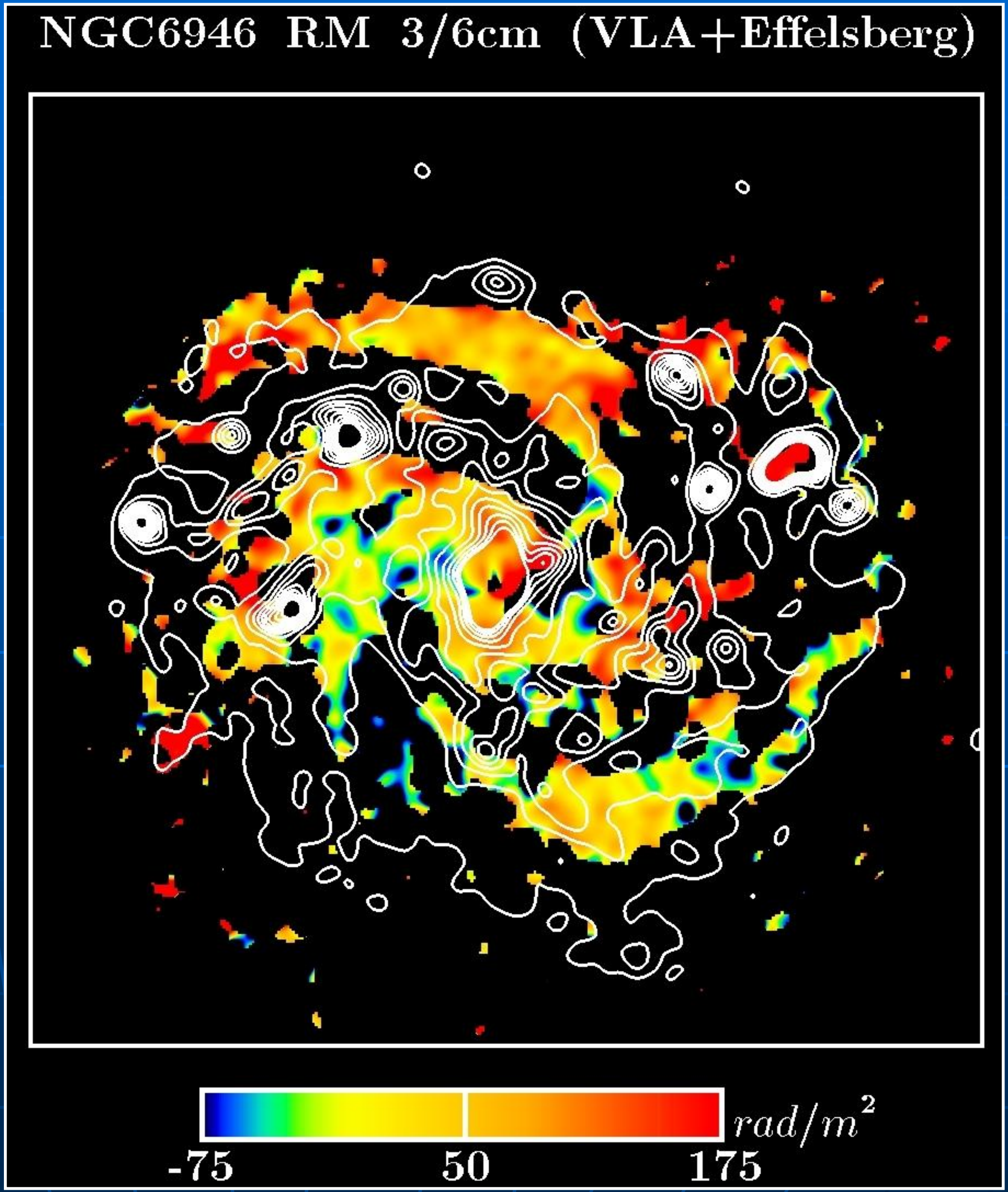
Spiral field continues into the central region



Resolution: ≈ 270 pc

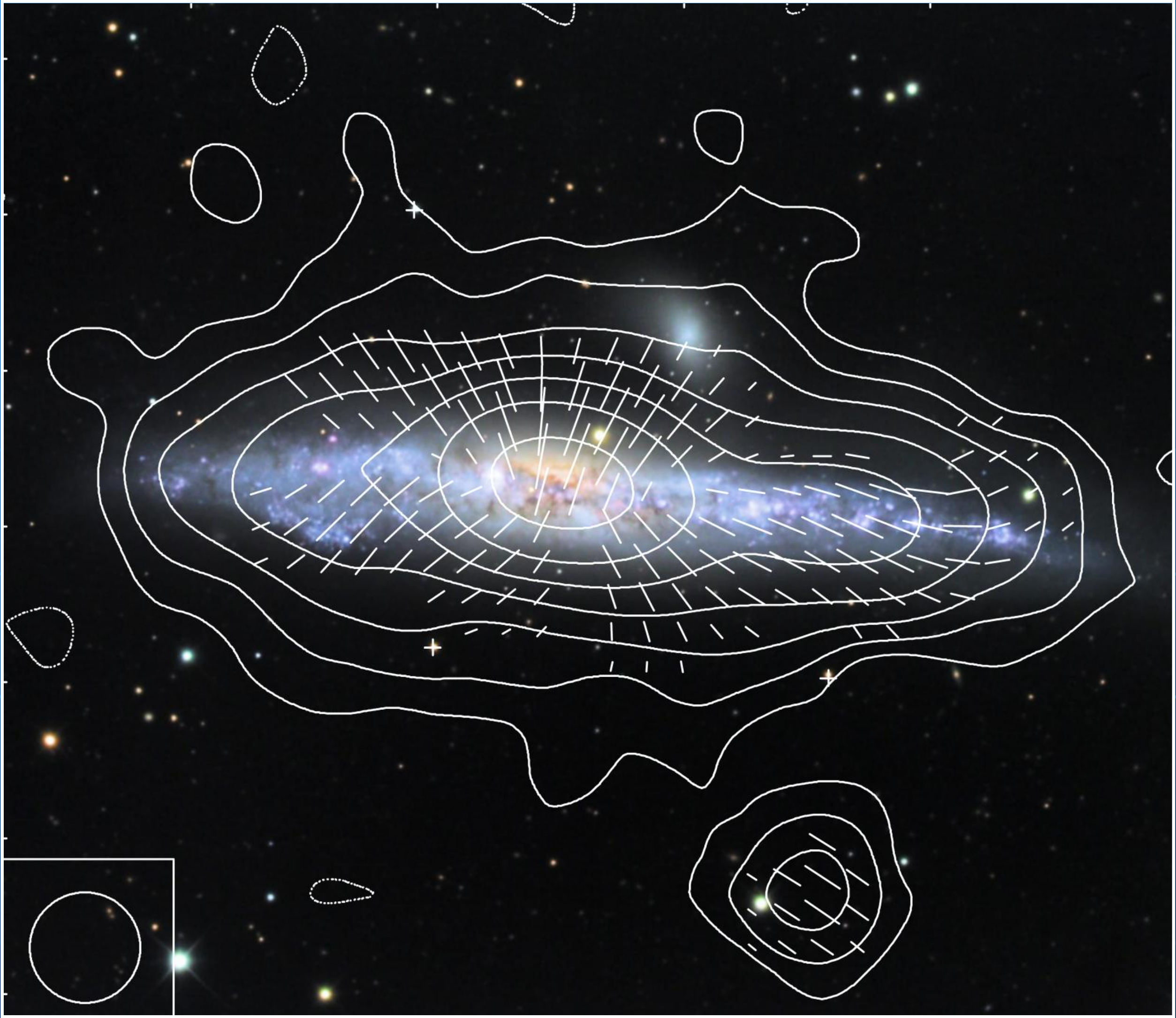
NGC 6946
Faraday RM 3/6cm
VLA+Effelsberg
(Beck 2007)

No enhanced Faraday rotation in the central region:
No regular vertical fields



NGC 4631

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

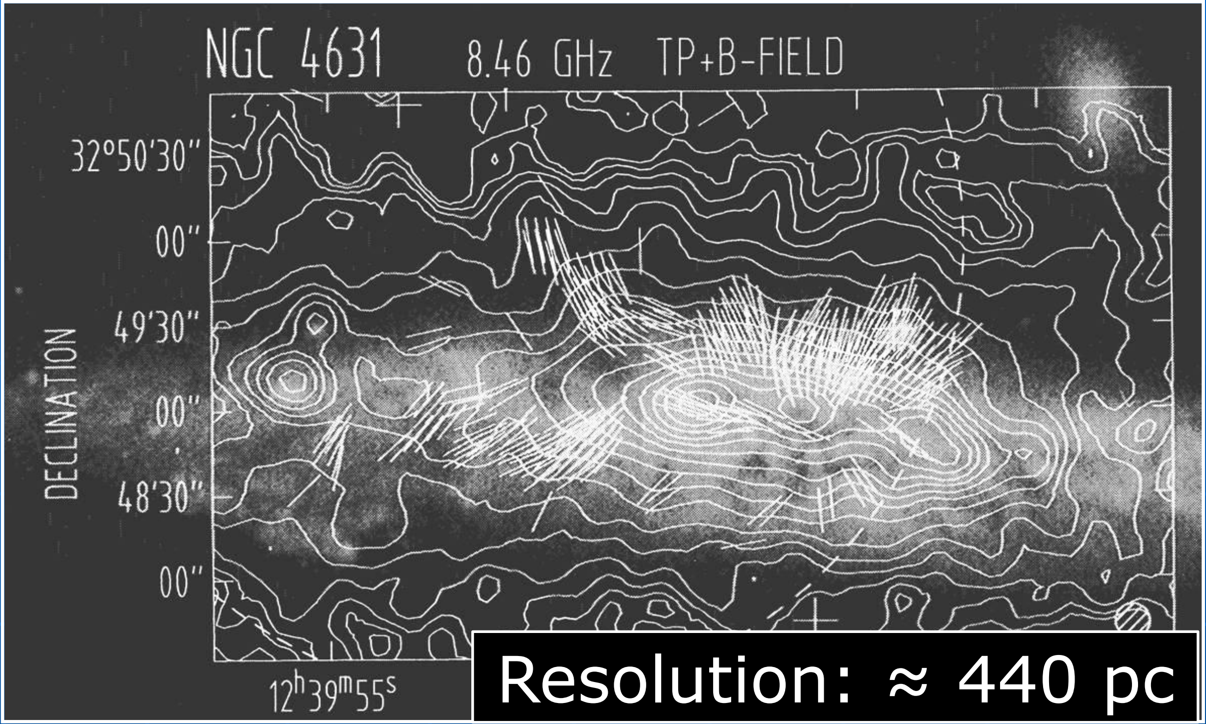


Huge halo:

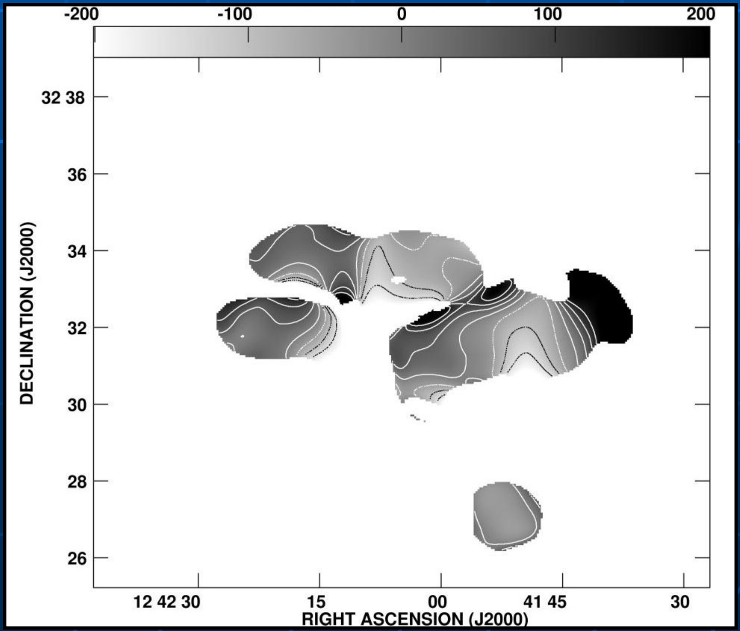
X-shaped halo field, driven by a wind

NGC 4631

3cm VLA
Total intensity
+ B-vectors
(Golla & Hummel 1994)



Vertical field lines emerging from star-forming regions



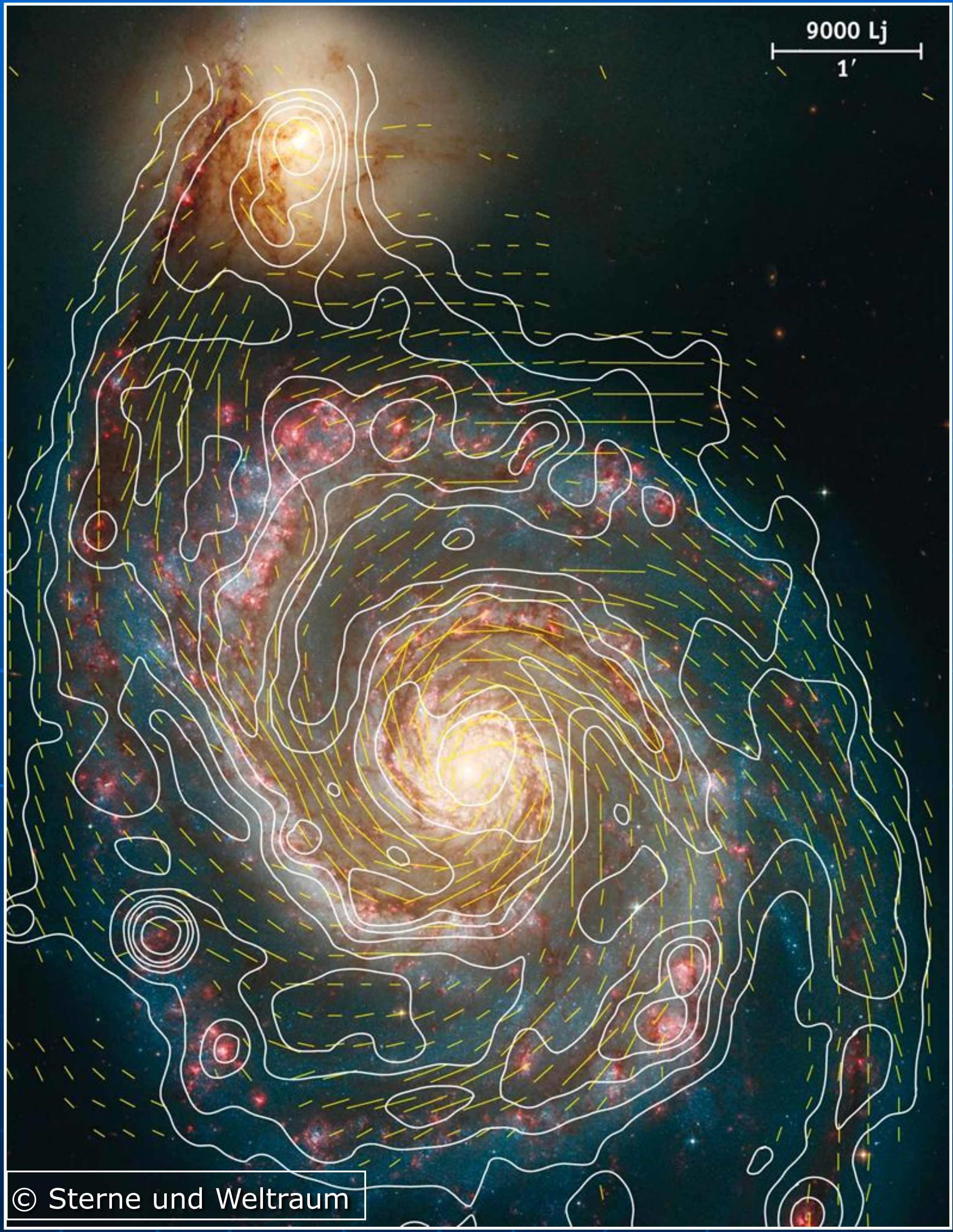
No systematic pattern of Faraday rotation: anisotropic fields (frequent field reversals)?

2. Spiral galaxies with mildly active nuclei

M51

6cm VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2011)

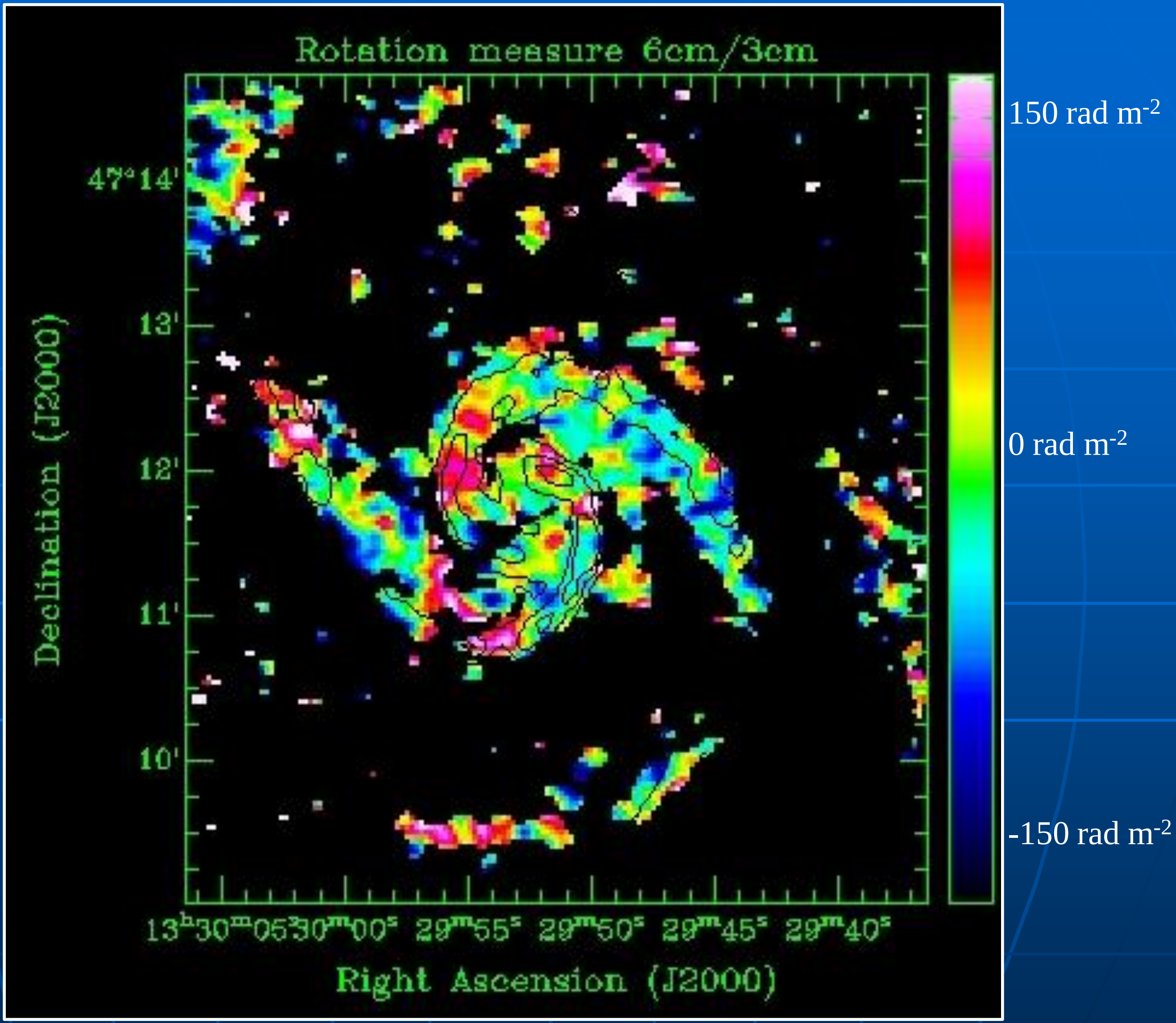
Spiral fields
more or less
parallel to the
optical
spiral arms



M51

Faraday RM 3/6cm

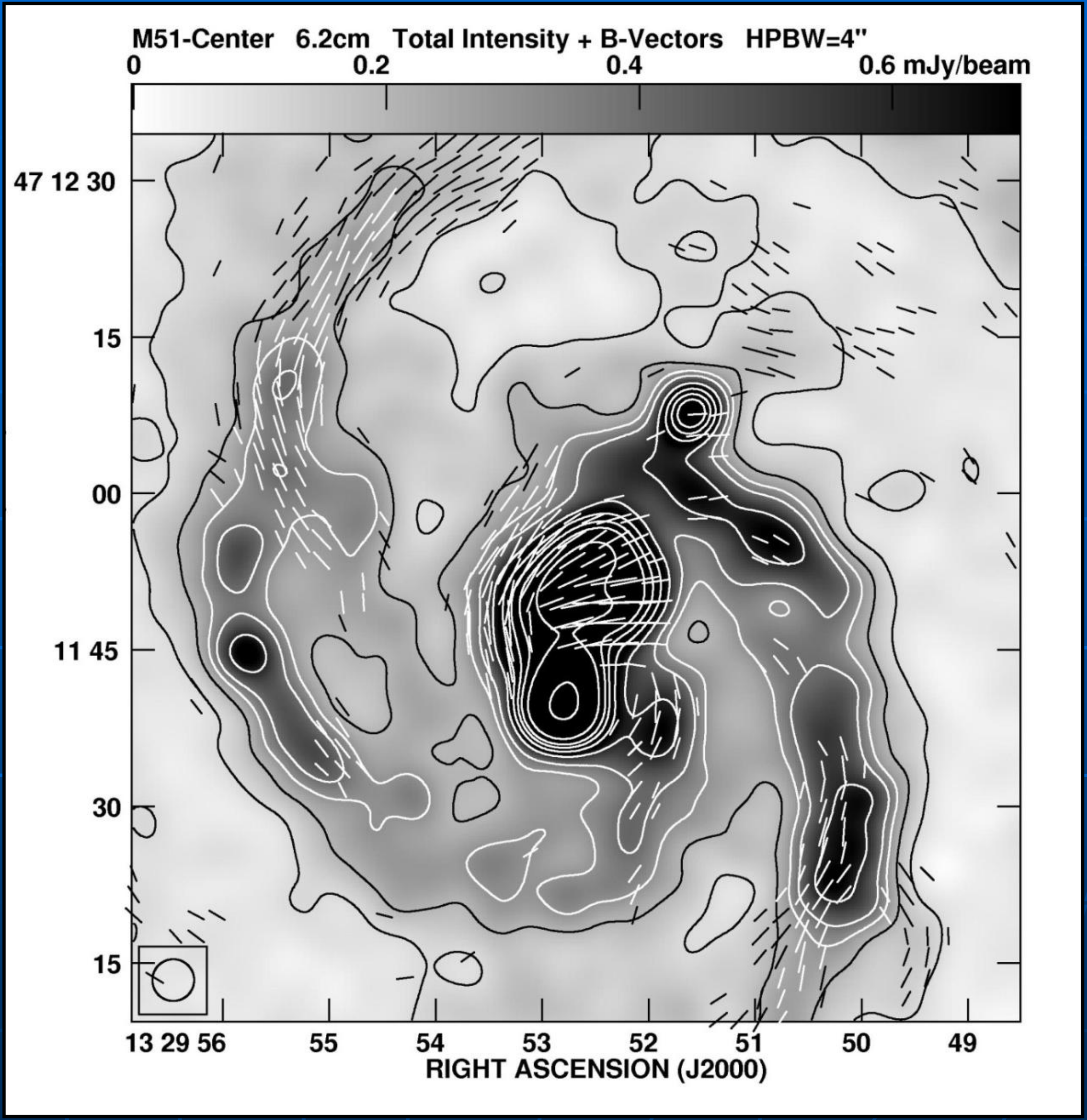
(Fletcher et al. 2011)



No enhanced Faraday rotation in the central region:
No regular vertical fields

M51

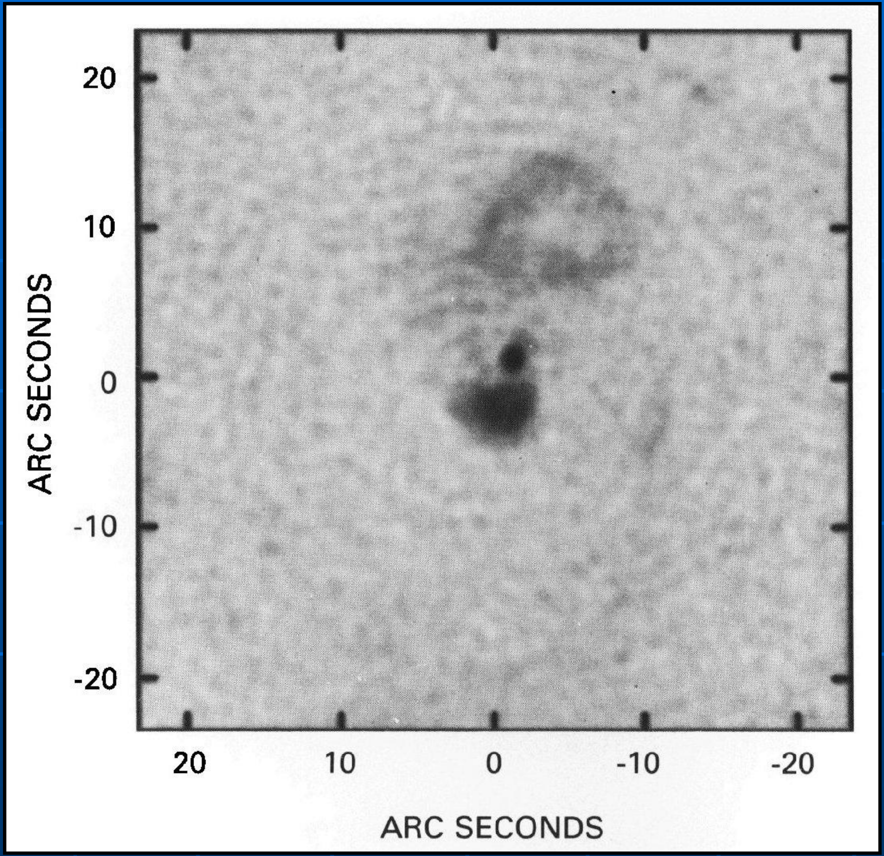
6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Fletcher et al. 2011)

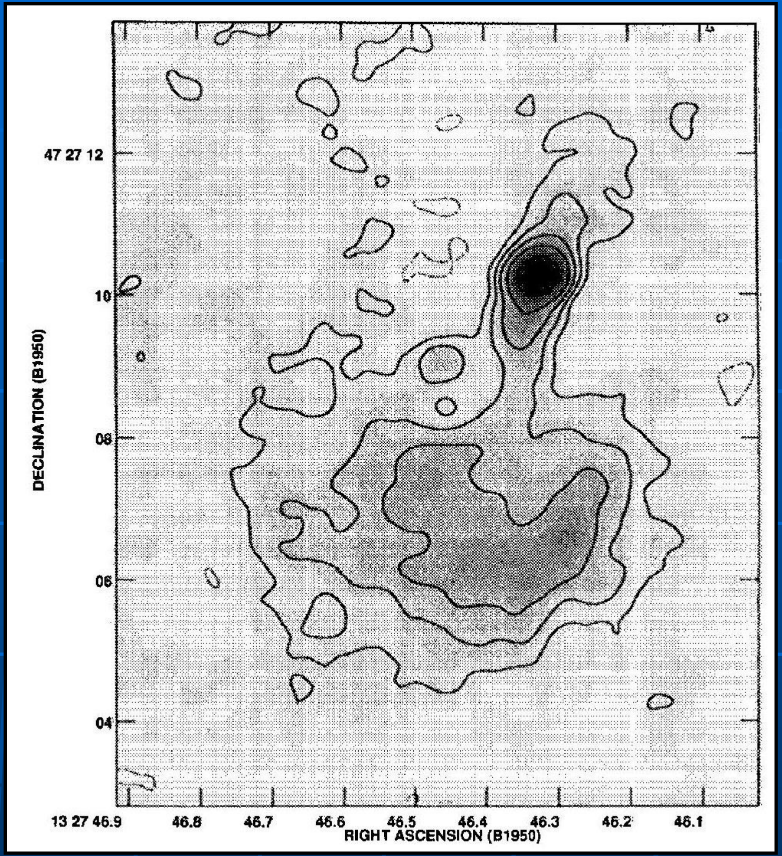


Highly polarized regions north and east of the nucleus

Resolution: ≈ 190 pc

High-resolution radio images of M51





VLA 20cm HPBW=1" (50 pc)
Lobes + bubble
(Ford et al. 1985)

VLA 6cm HPBW=0.5" (25 pc)
Lobe + jet?
(Crane & van der Hulst 1992)

3. Barred galaxies with circumnuclear rings

Radio continuum survey of barred galaxies

(Beck et al. 2002, 2005a,b)

VLA + Effelsberg:

NGC 1097, 1300, 1365, 2336, 3359, 3953, 3992, 4535, 5068, 7479

Wavelengths: 3.5, 6.2, 18.0, 22.0cm (VLA), 2.8cm (Effelsberg)

ATCA:

NGC 986, 1313, 1433, 1493, 1559, 1672, 2442, 3059, 5643, 7552

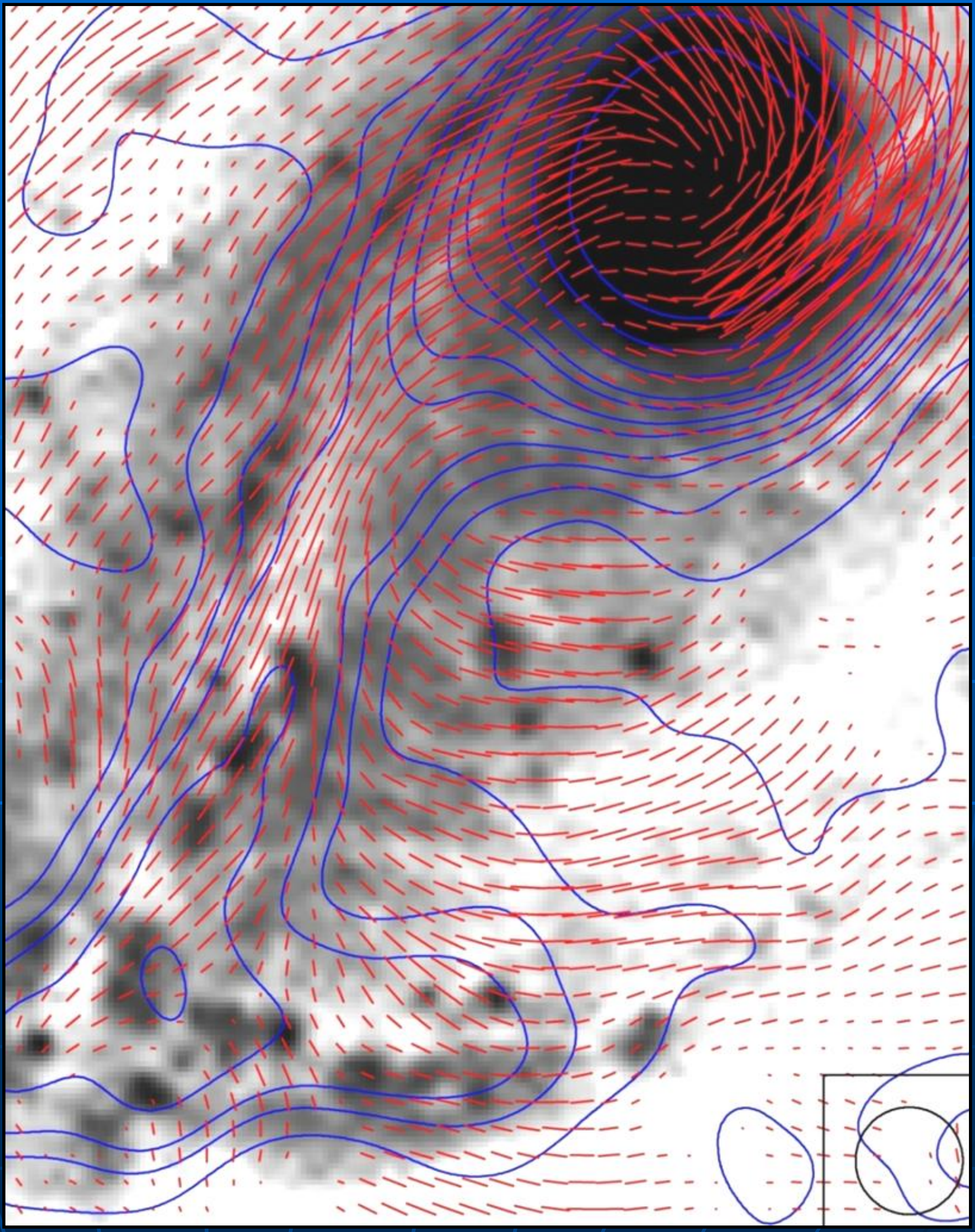
Wavelengths: 5.4+6.2, 13.1, 21.7cm

NGC 1097
SPITZER
(Henning et al. 2009)

NGC 1097

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

The magnetic field traces the flow of the warm diffuse gas



NGC 1097

Circumnuclear ring

3.6cm VLA

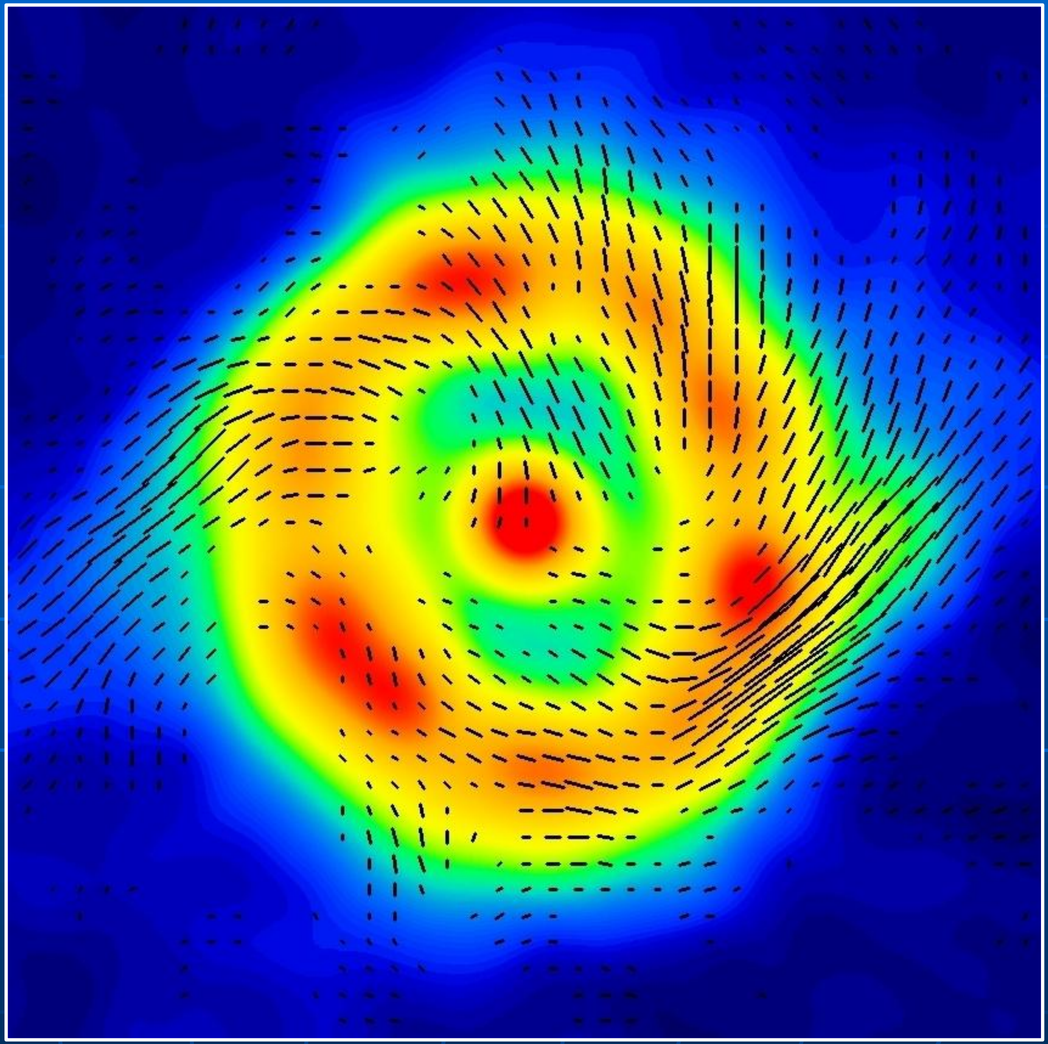
Total intensity + B-vectors

(Beck et al. 2005a)

Diameter ≈ 1.5 kpc

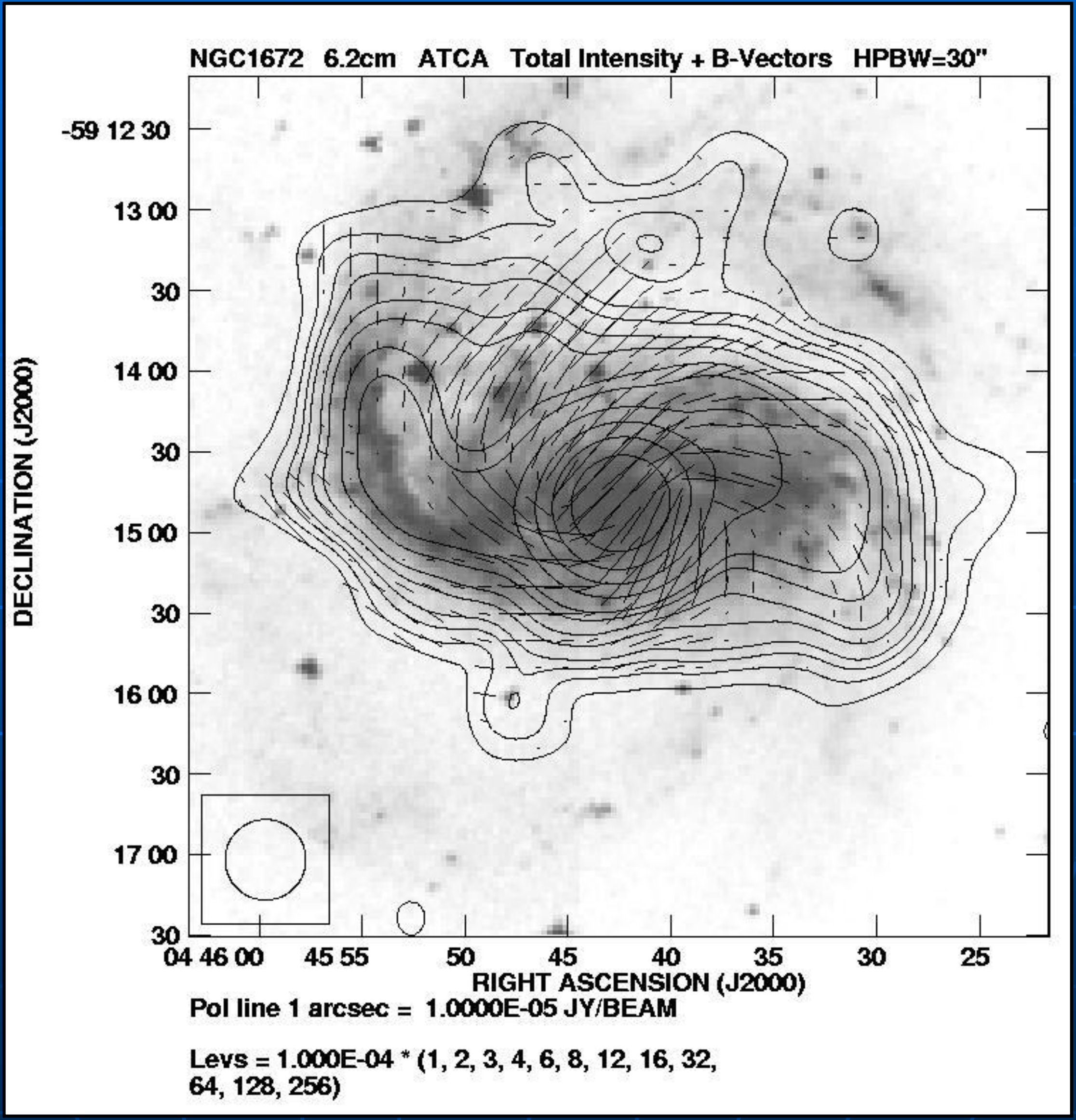
Bright radio ring
(turbulent field)
+ weak spiral field

Periodic peaks:
Magnetic instability ?



NGC 1672

6cm ATCA
Total intensity
(Harnett, Beck , et al., unpublished)



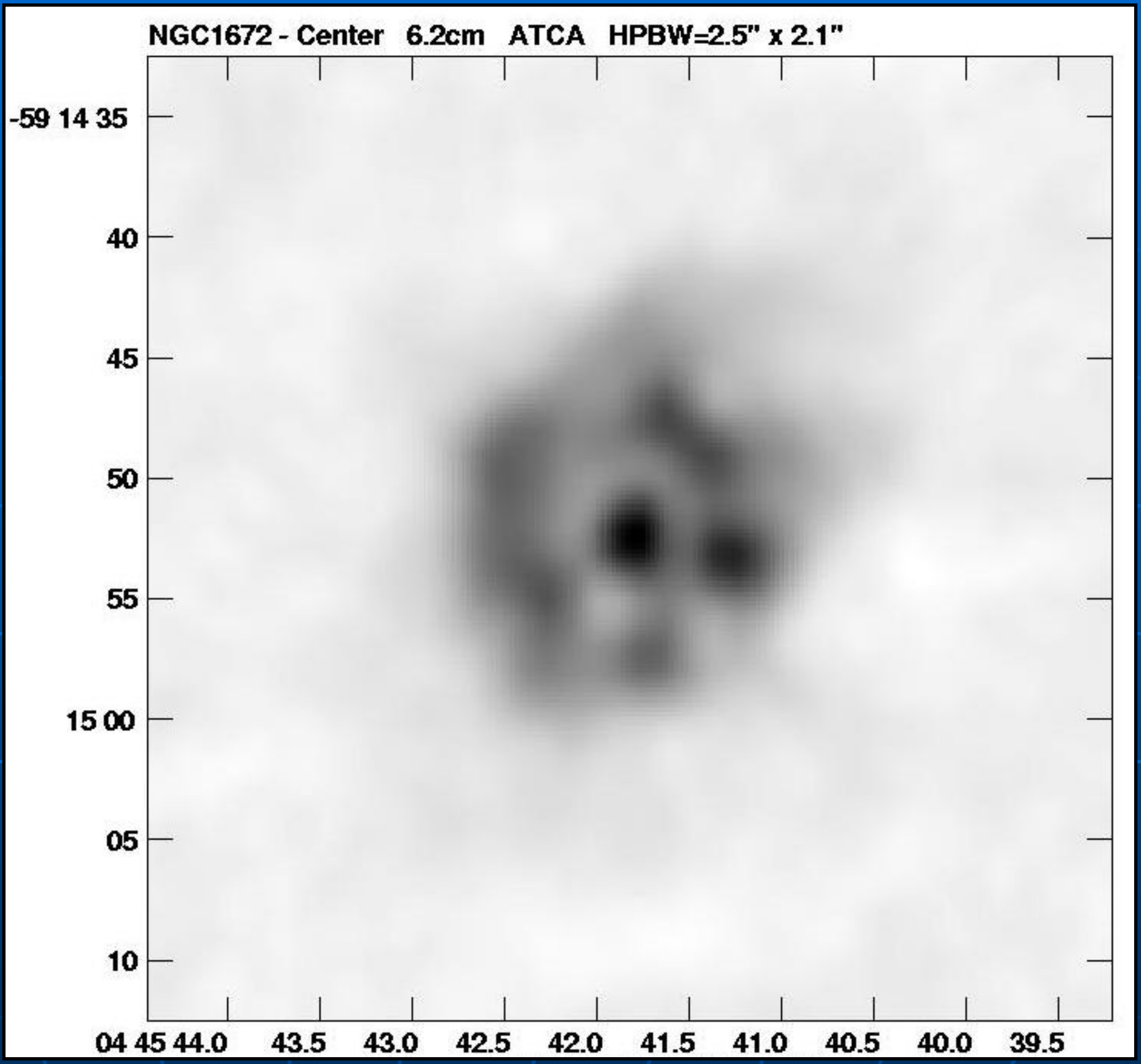
NGC 1672

Circumnuclear ring

6cm ATCA

Total intensity

(Beck et al. 2005b)

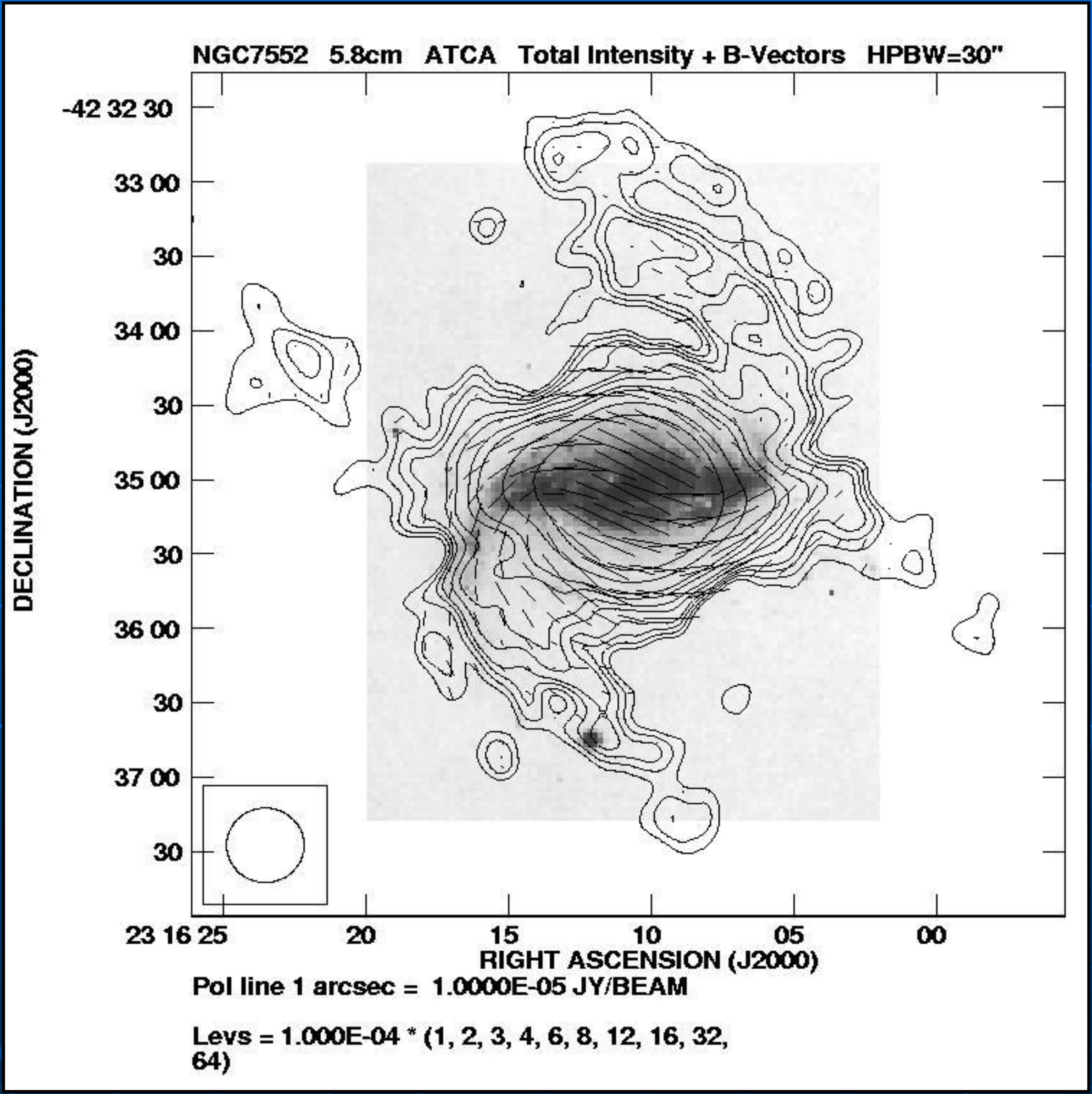


d ≈ 0.7 kpc

Bright radio ring (no polarization detected)

NGC 7552

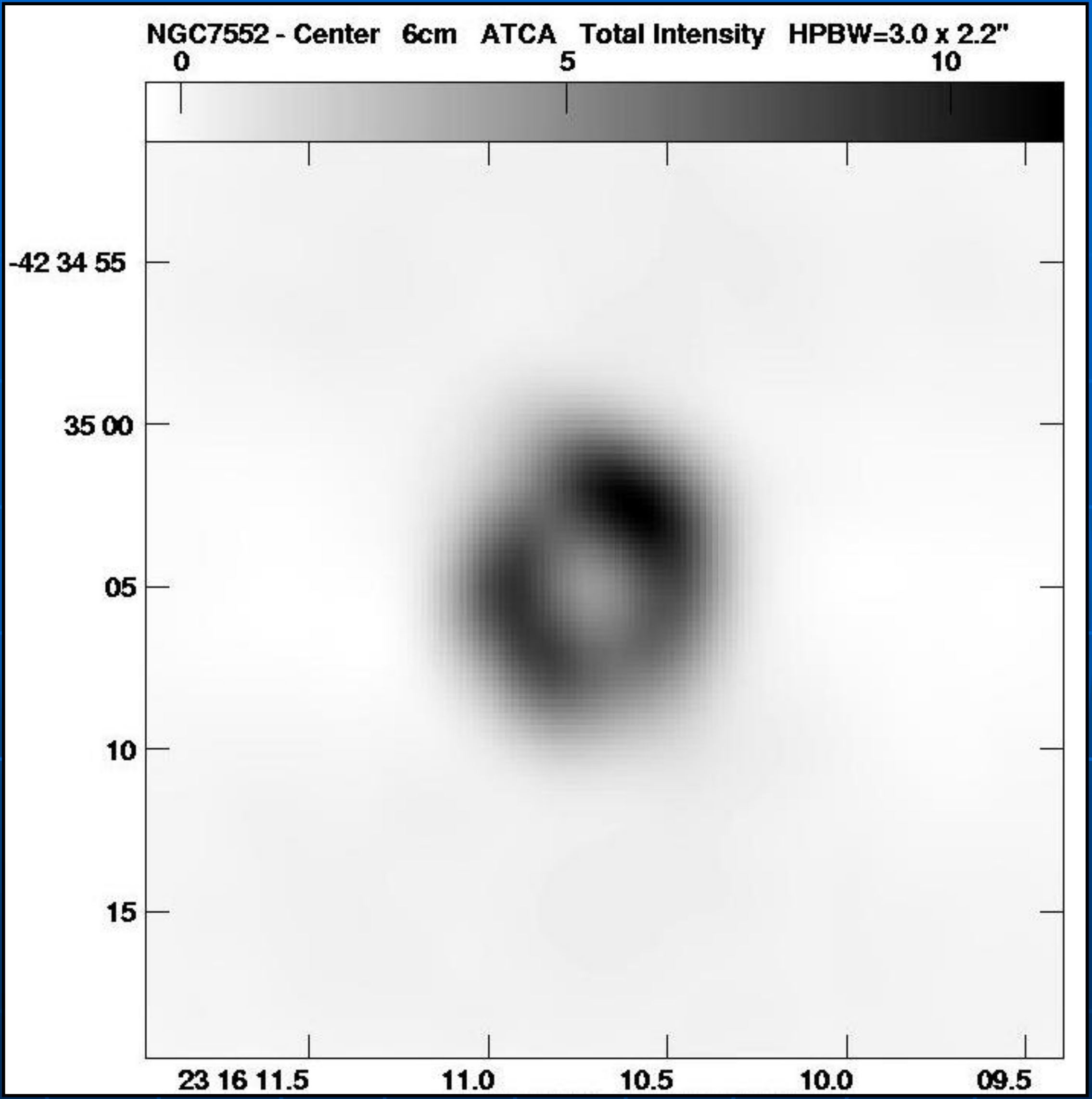
6cm ATCA
Total intensity
(Harnett, Beck et al., unpublished)



NGC 7552

Circumnuclear ring

6cm ATCA
Total intensity
(Beck et al. 2005b)

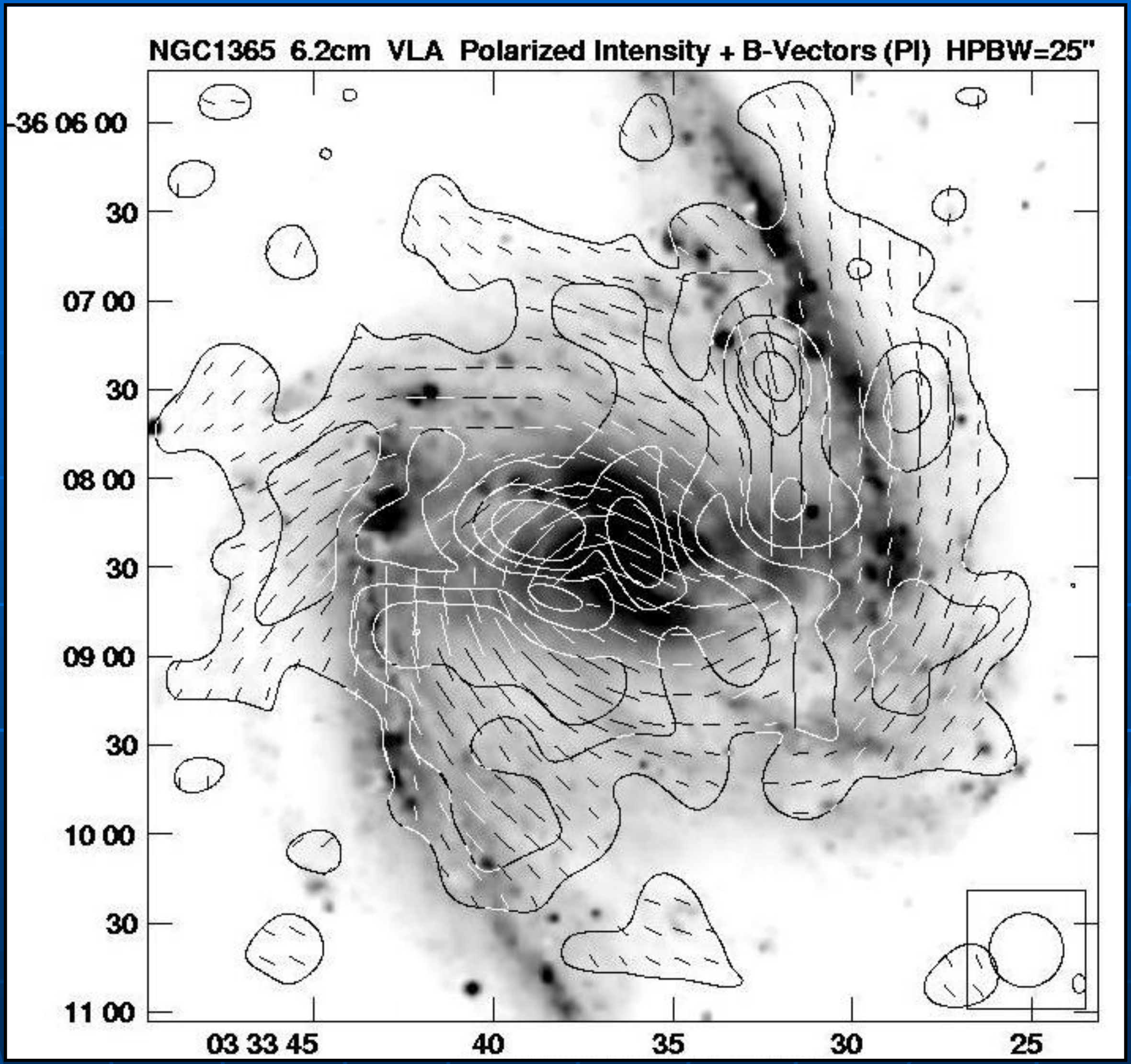


d ≈ 0.5 kpc

Bright radio ring (no polarization detected)

NGC 1365

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



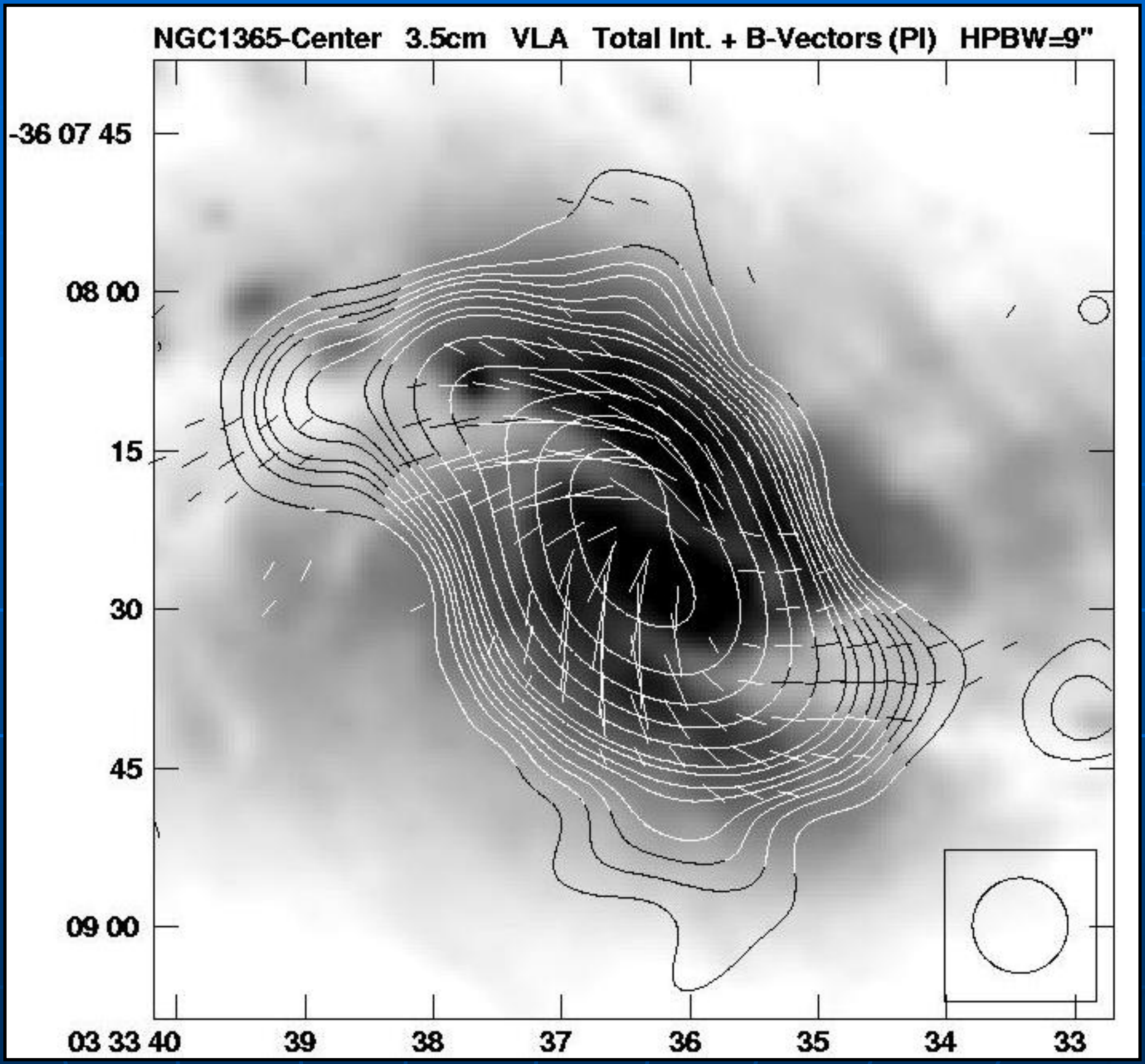
Smooth spiral field

NGC 1365

Circumnuclear region

3.6cm VLA Total intensity + B

(Beck et al. 2005a)



No radio ring, spiral field

Total magnetic field strengths in central starburst regions

(assuming energy equipartition with total cosmic rays
with proton/electron ratio of 100 -
give *lower limits* in case of energy losses –
see talk by David Jones)

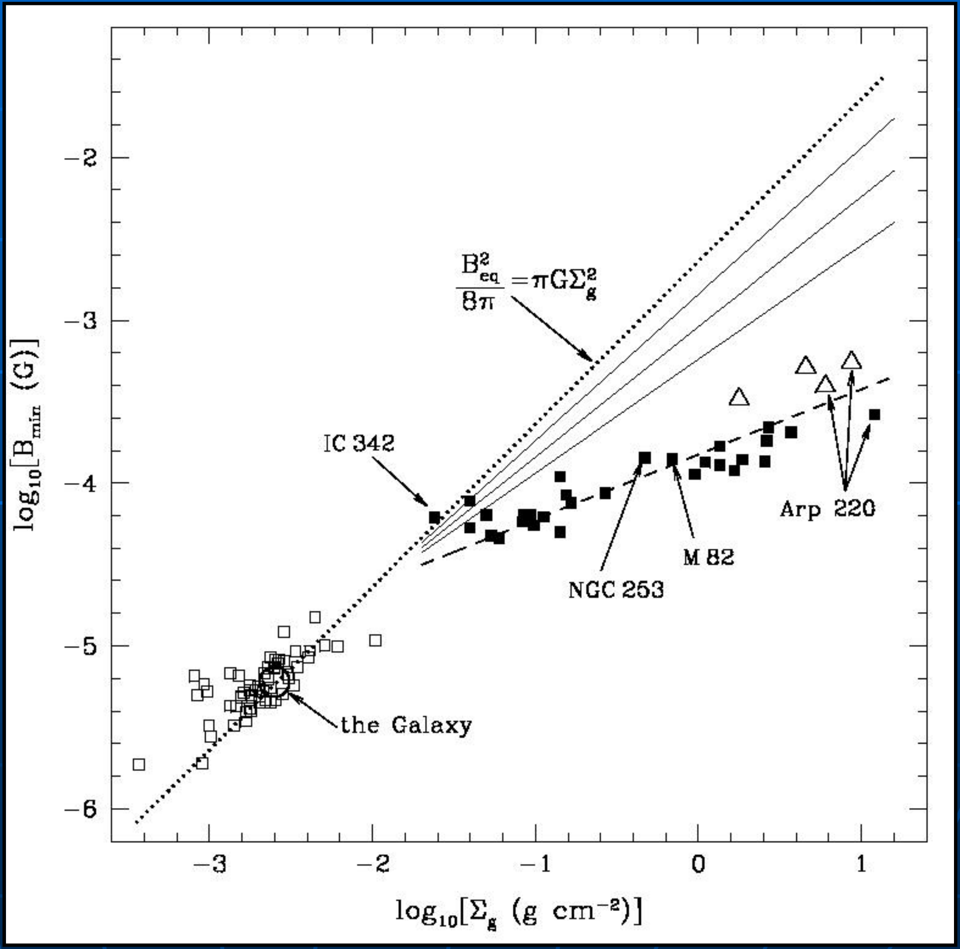
- NGC 1097 (ring knots): ≈60μG
- NGC 1365 (dust lanes): ≈60μG
- NGC 1672 (ring knots): ≈70μG
- NGC 7552 (ring knots): ≈105μG

Dynamically important

Magnetic fields and gas surface density

Thompson et al. (2006)

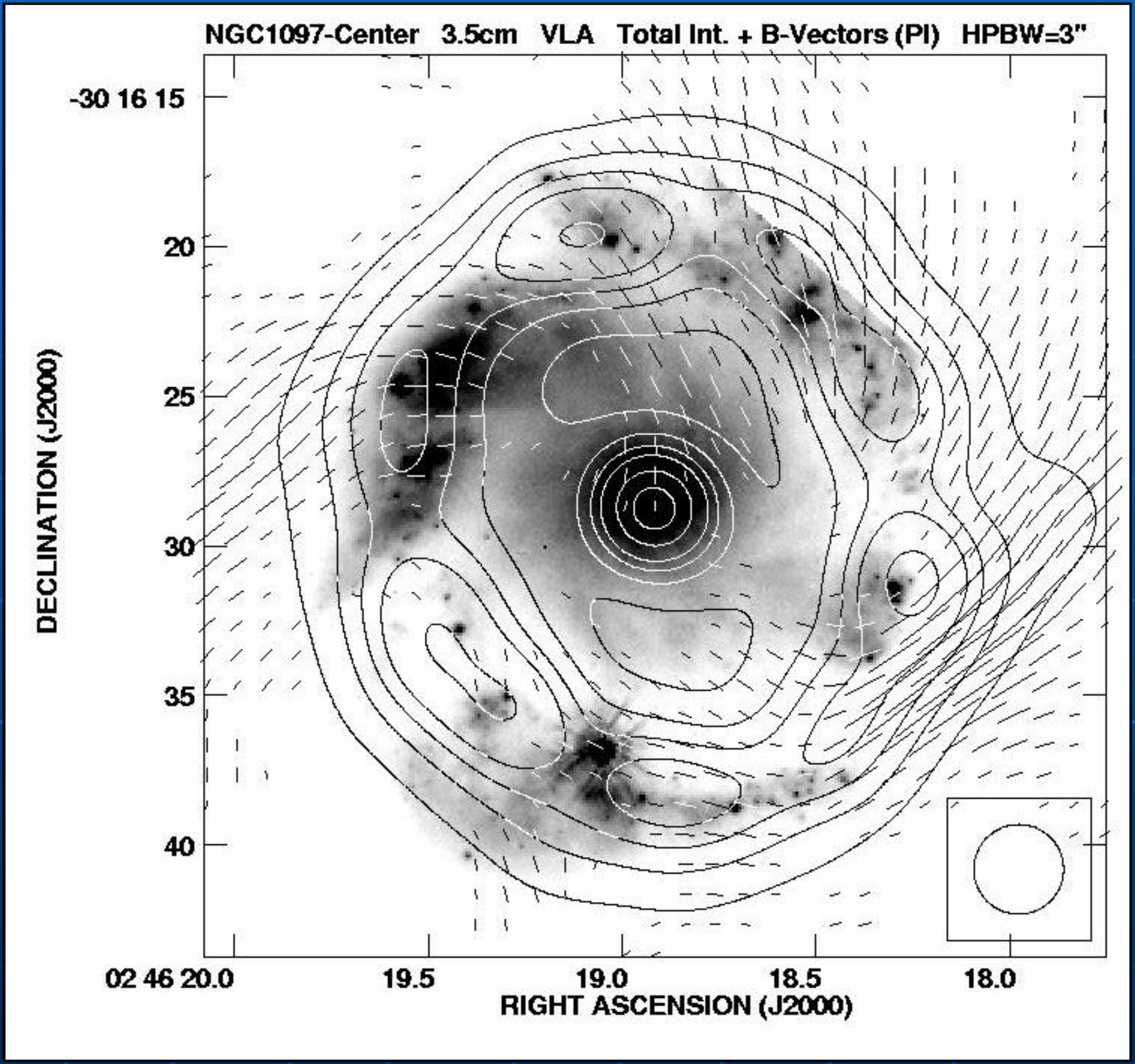
Equipartition magnetic field strengths in starburst galaxies are probably **underestimates**



NGC 1097
Circumnuclear ring

3.6cm VLA Total intensity + B

(Beck et al. 2005)



Inflow by magnetic stress

Basic MHD theory of a Keplerian magnetized gas disk:

(Balbus & Hawley, Rev. Mod. Phys. 1998)

Gas inflow:

$dM/dt = 2 \pi \sigma T_{r\Phi} / \Omega$ $(\sigma = 2 h \rho)$

Dominant component of the stress tensor:

$T_{r\Phi} = - < v_{A,r} v_{A,\Phi} >$ (V_A : Alfvén velocity)

$$dM/dt \approx -h/\Omega \, (< B_{turb,r} B_{turb,\Phi} > + < B_{reg,r} B_{reg,\Phi} >)$$

The correlation between $B_{turb,r}$ and $B_{turb,\Phi}$ is generated by shear from differential rotation.

Inflow by magnetic stress

(Beck et al. Nature 1999, A&A 2005)

NGC 1097:

h=100 pc, v=450 km/s,

$B_{tot,r} \approx B_{tot,\Phi} \approx 50\mu G$, $B_{reg,r} \approx B_{reg,\Phi} \approx 10\mu G$:

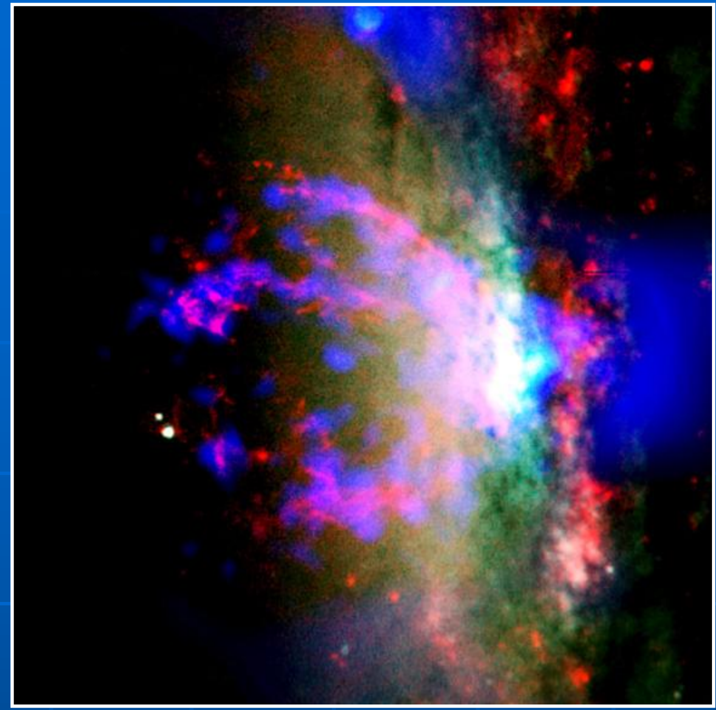
$dM/dt \approx 1\ M_o/yr$

Magnetic fields are able to drive sufficient inflow to feed the AGN

4. Spiral galaxies with starburst nuclei

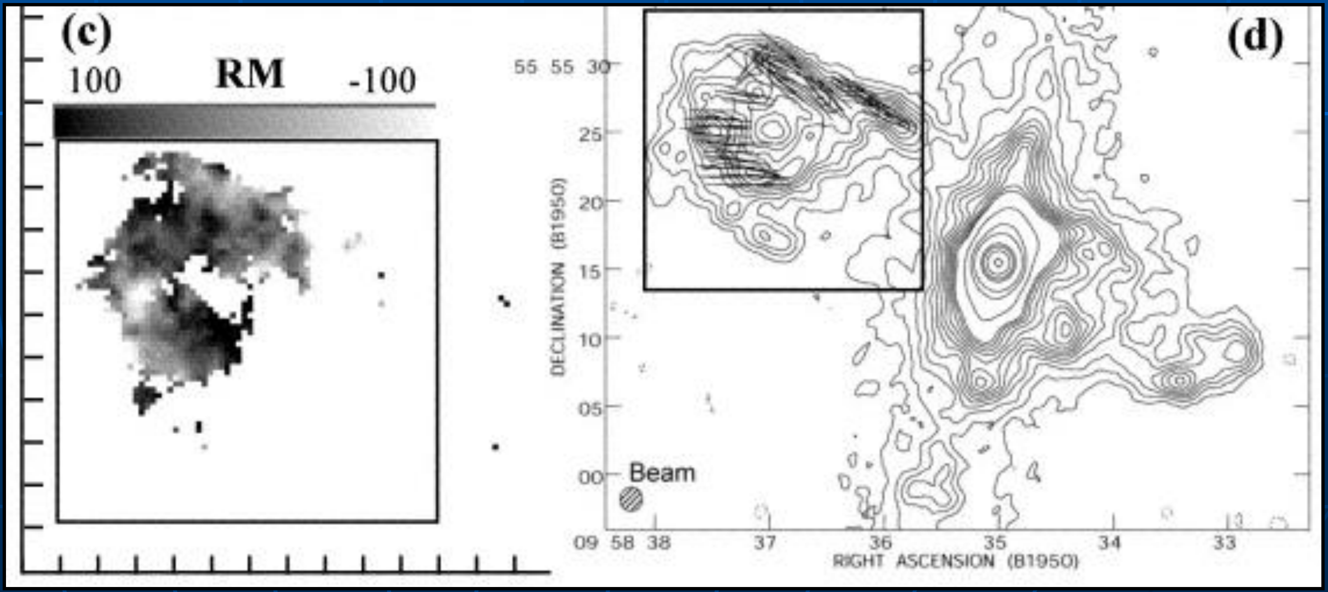
NGC 3079

Faraday RM
3/6cm VLA
Total intensity
+ B-vectors
(Cecil et al. 2001)



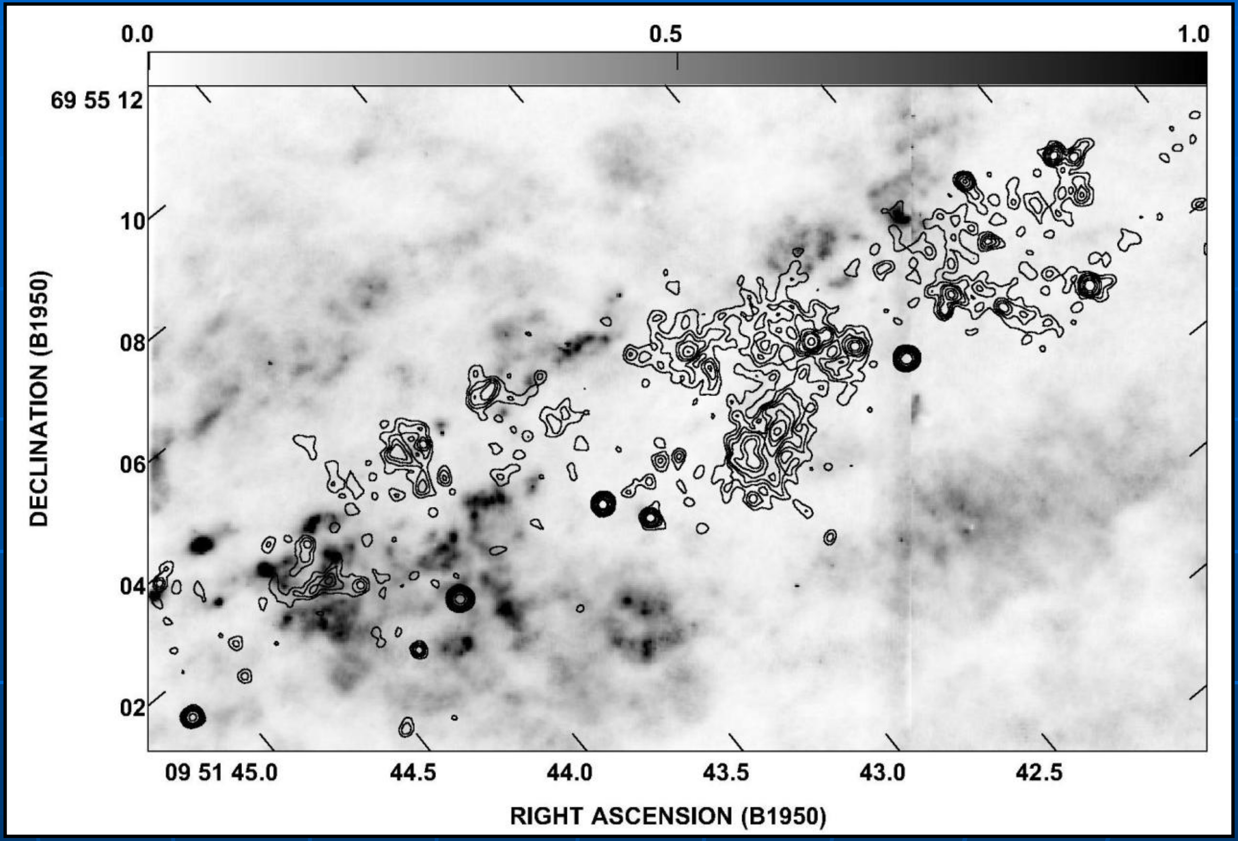
HST+
CHANDRA

Radio lobes
up to 3 kpc height
with highly
ordered fields
($p \leq 50\%$)



M82

20cm VLA
Total intensity
0.25" resolution
+ HST
(Golla et al. 1996)

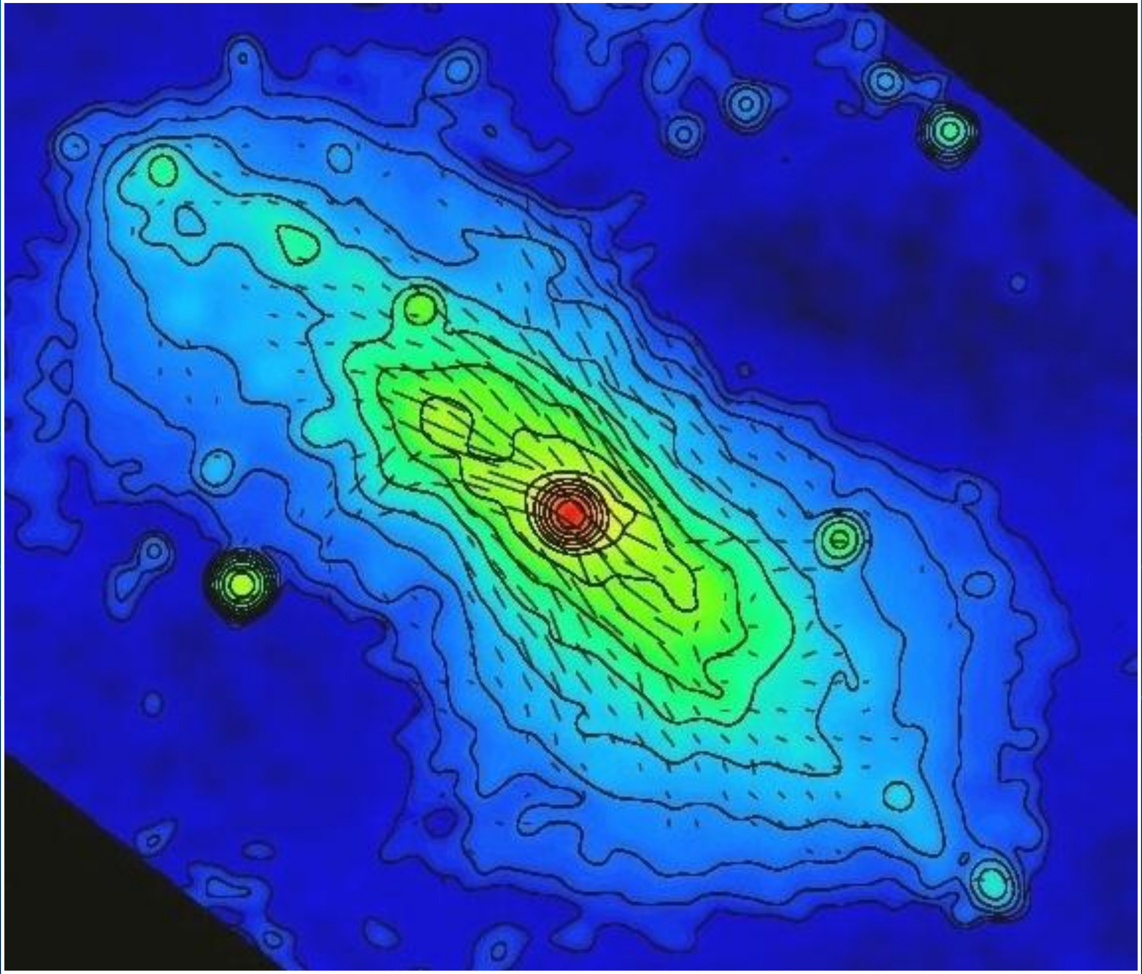


Mostly SNRs

Resolution: ≈ 5 pc

NGC 253

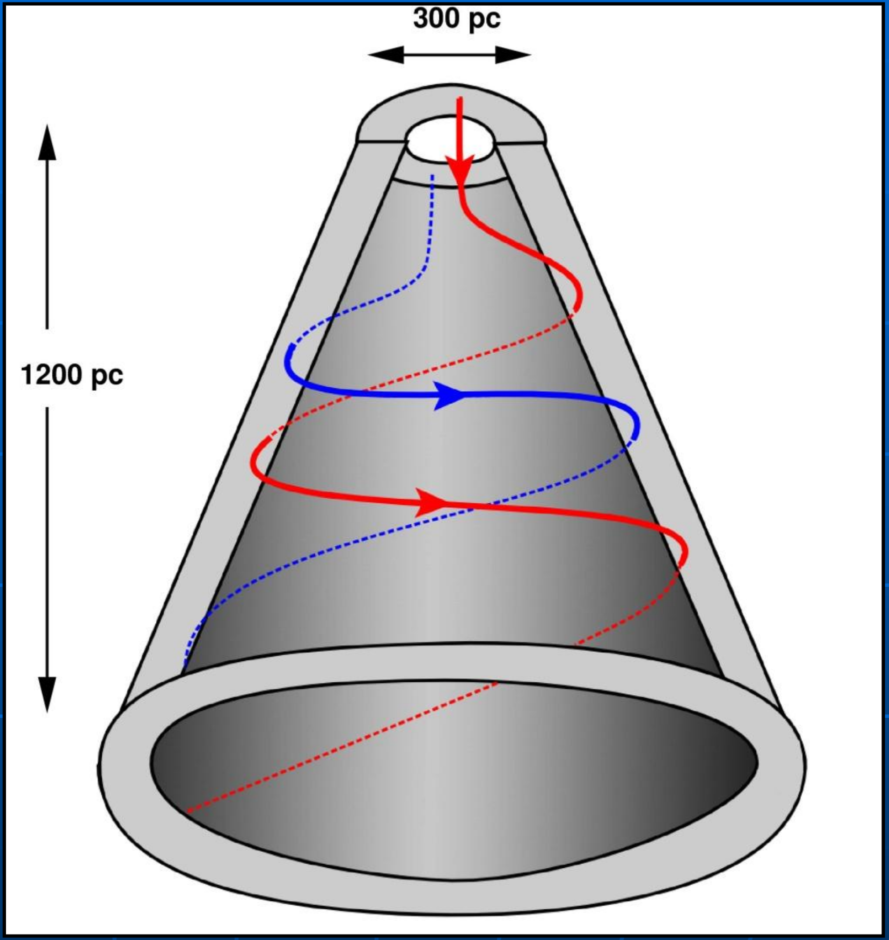
6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Heesen et al. 2009)



See next talk
by Volker Heesen

NGC 253
Central region
Heesen et al. 2011, arXiv:1109.0255

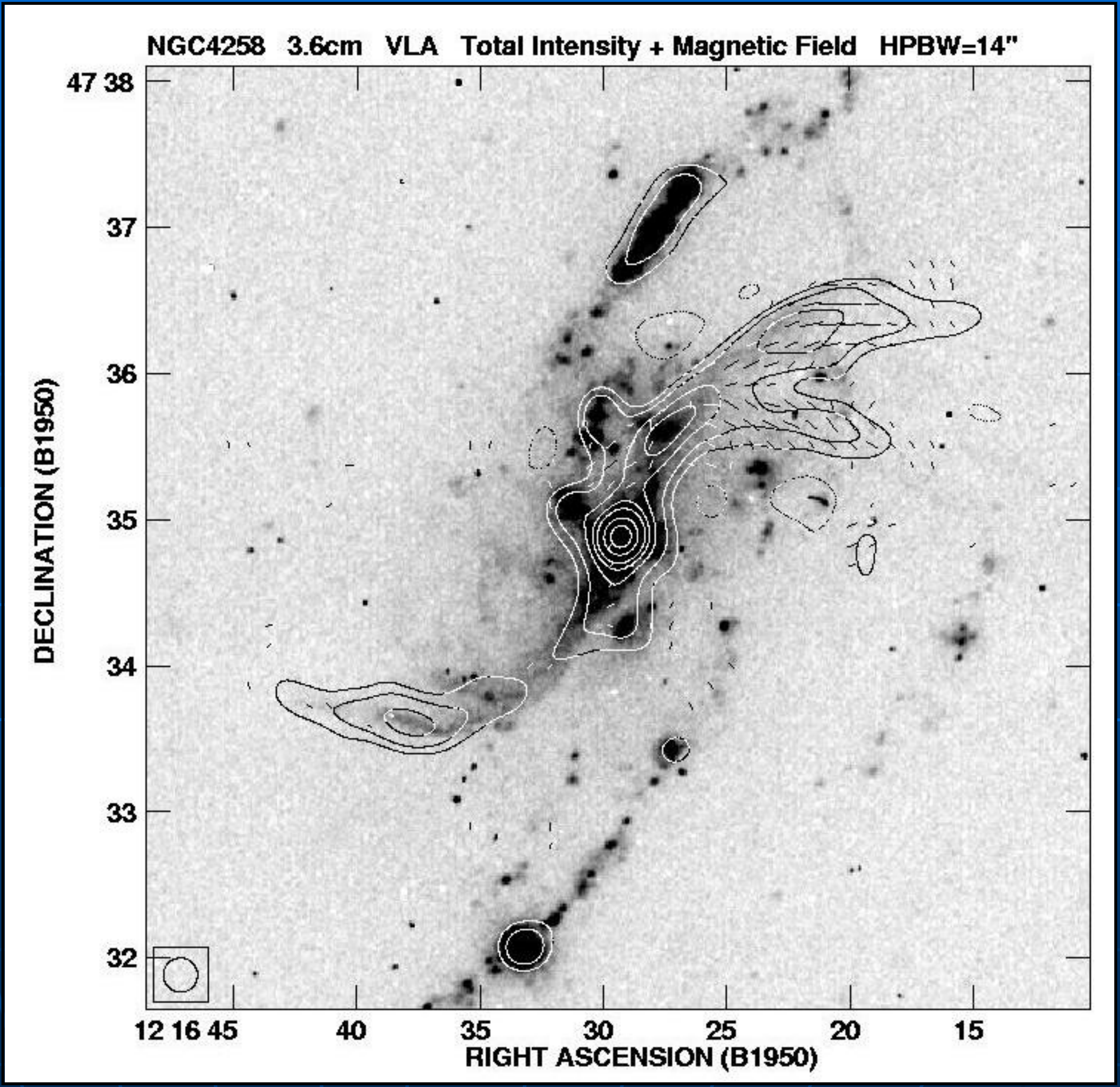
First detection of a regular magnetic field in a nuclear outflow



5. Spiral galaxies with jets

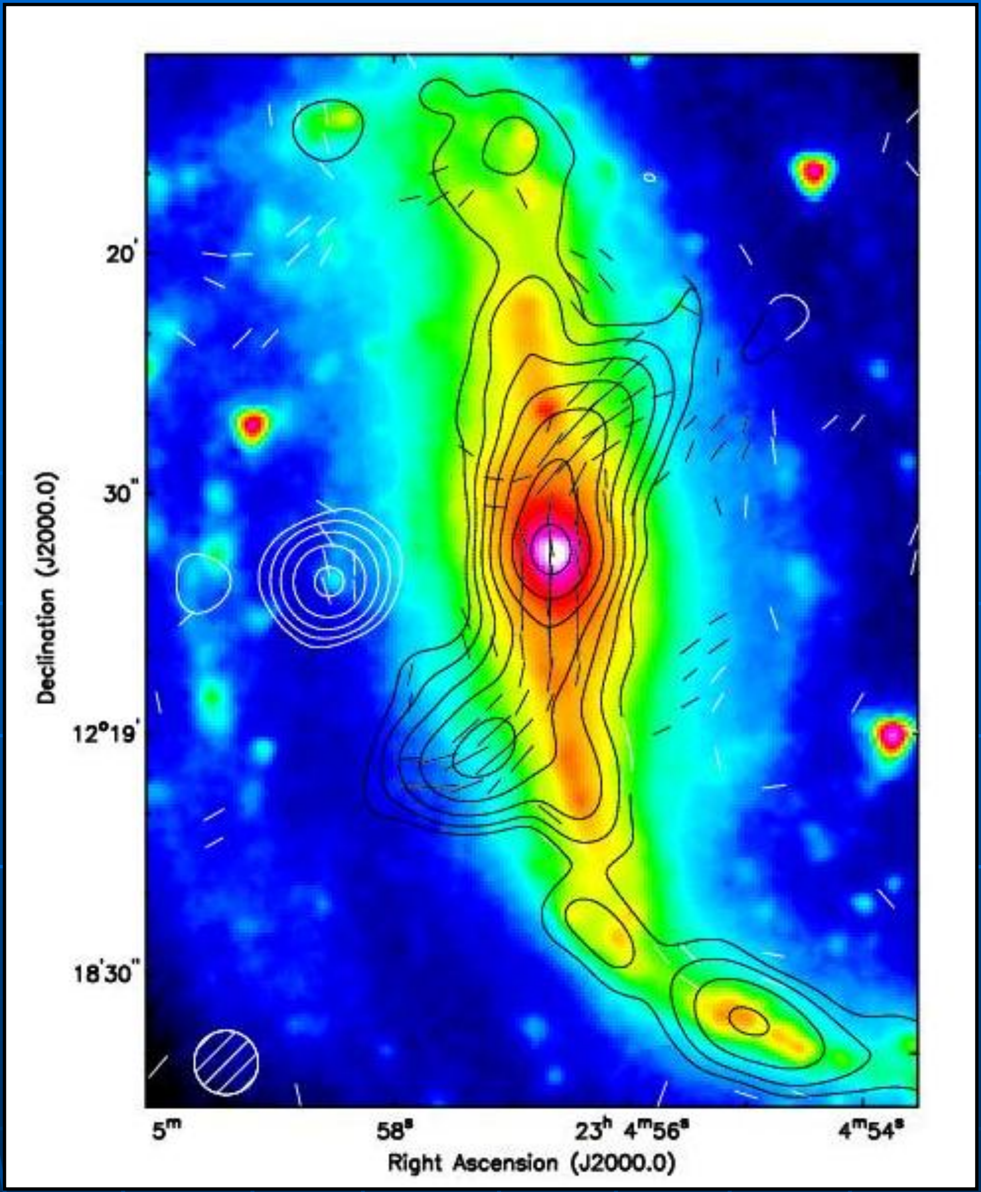
NGC 4258

6cm VLA
Total intensity
+ B-vectors
+ Hα
(Krause & Löhr 2004)



NGC 7479

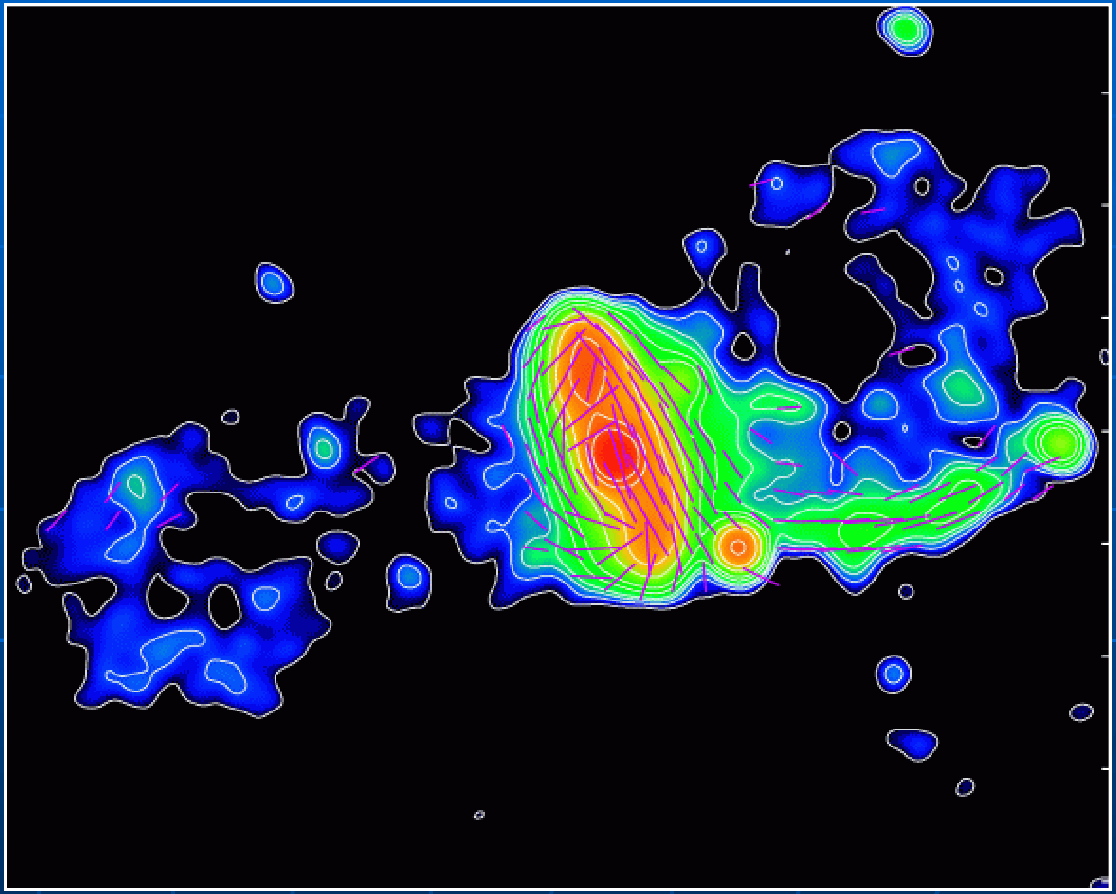
3cm VLA
+Spitzer 3.6μm
Total intensity
+ B-vectors
(Laine & Beck 2008)



Resolution: ≈ 1.2 kpc

NGC 4569

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



Radio lobes (jets?)
up to 20 kpc height
with highly ordered fields
($p \leq 50\%$)

No present nuclear
activity:
relics from a past
AGN phase?

Upscaled version of the
Galactic Fermi Bubbles?

Conclusions

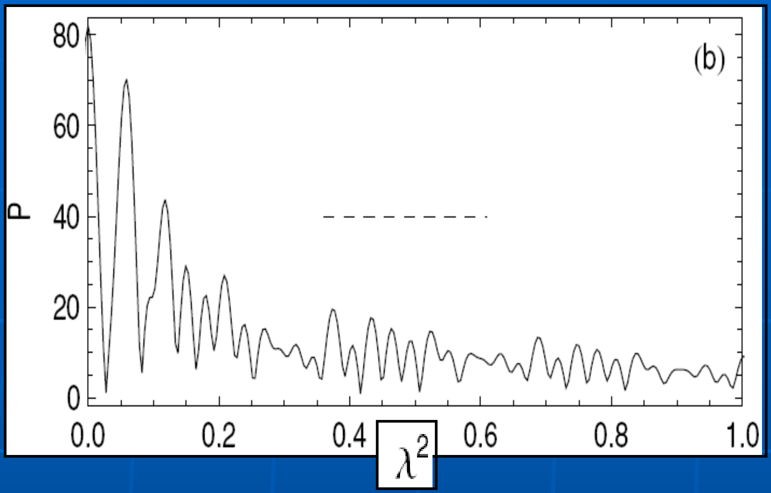
- Magnetic fields in the central regions of spiral galaxies have spiral patterns
- There are no indications for regular vertical fields
- Anisotropic vertical fields emerge from star-forming regions
- Magnetic stress in a rotating nuclear ring can drive inflow of gas and magnetic field, sufficient to feed the nuclear activity
- Faraday rotation in the central region of the starburst galaxy NGC253 indicates a helical field in the outflow cone
- Jets in spiral galaxies are rare (rarely observable?)
- Very little is known about the magnetic fields around AGNs

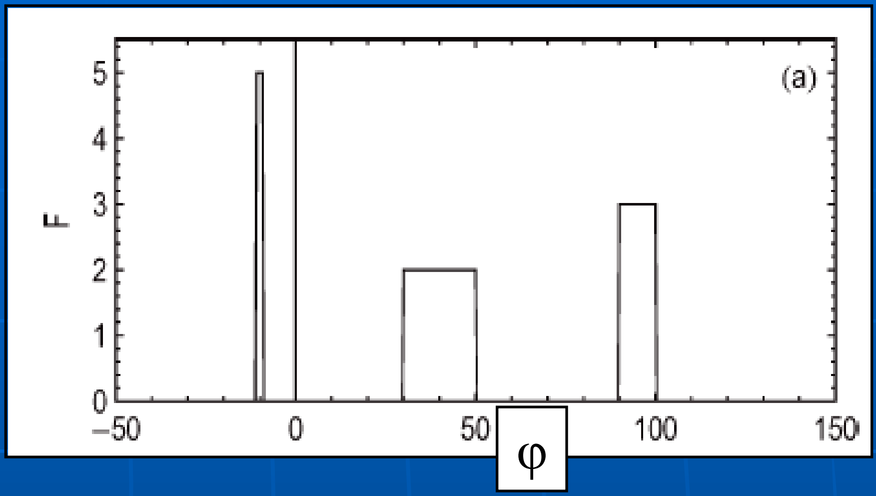
Needs

- MHD simulations of circumnuclear rings and nuclear outflows
- MHD dynamo simulations
- New method: Radio continuum spectropolarimetry (RM Synthesis)
- High-resolution radio polarization observations (EVLA, SKA)

SKA
SQUARE KILOMETRE ARRAY
www.skatelescope.org

RM Synthesis

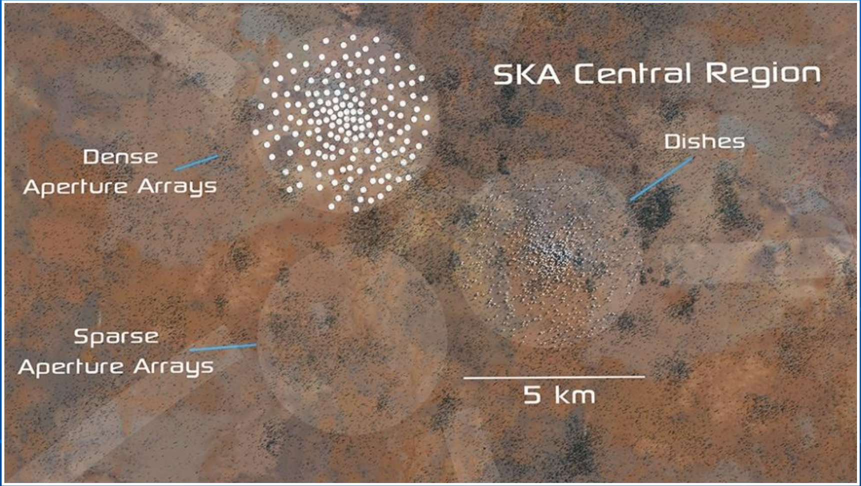




- The observed complex polarized intensity *P* is the Fourier transform of the complex Faraday spectrum $F(\varphi)$ (the source distribution in Faraday space)
- The Faraday spectrum is calculated by RM Synthesis
- Faraday depth ($\varphi \propto \int B_{\parallel}\, n_e\, dl$) is different from classical rotation measure

RM Synthesis
is going to revolutionize
radio polarization observations

SKA


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


Swinburne Astronomy Productions


Swinburne Astronomy Productions


Swinburne Astronomy Productions

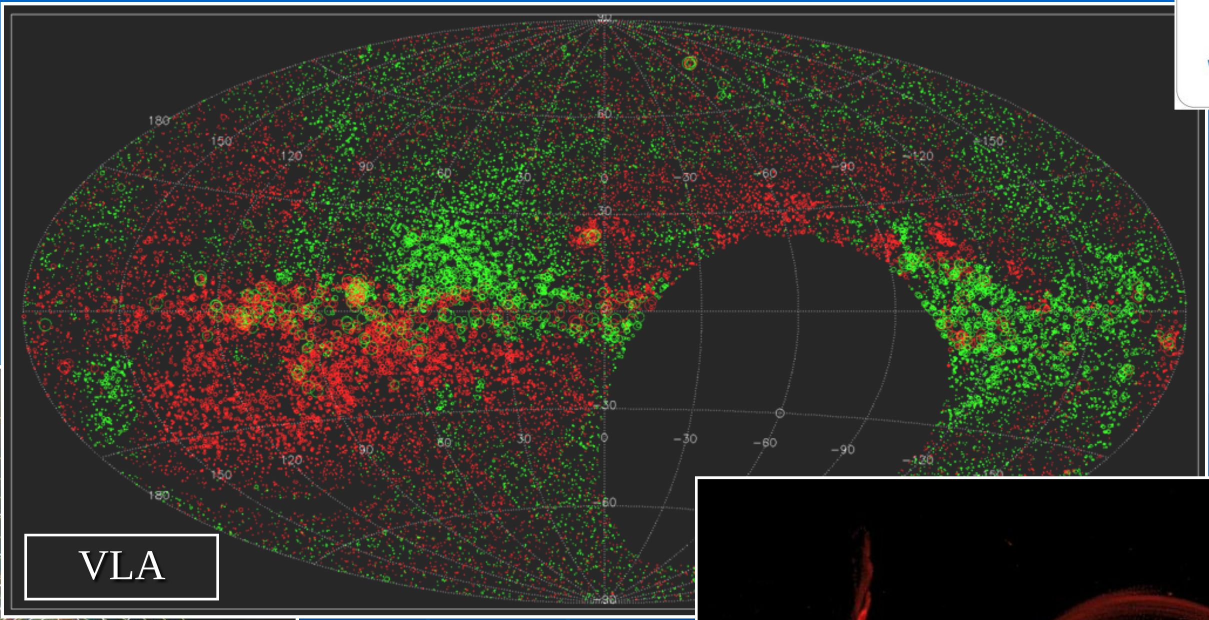
SKA timeline

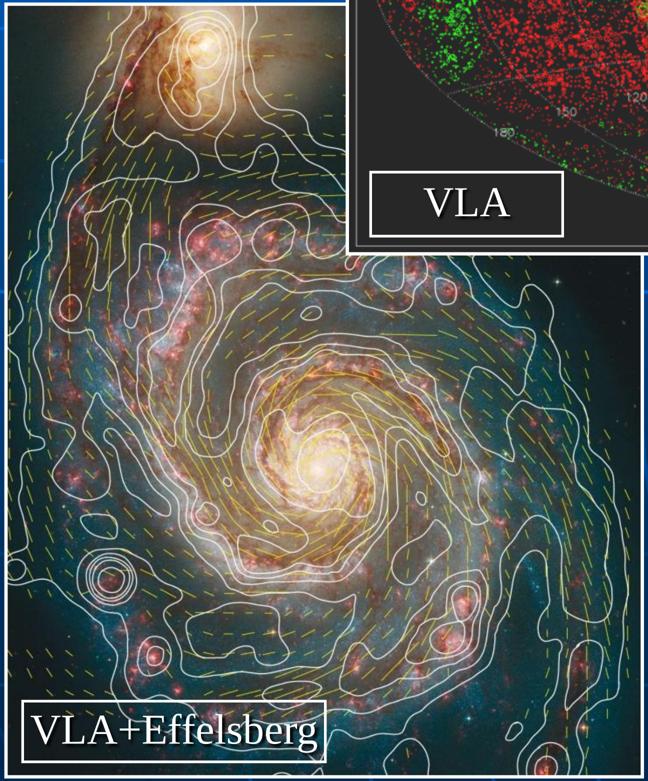
SQUARE KILOMETRE ARRAY
www.skatelescope.org

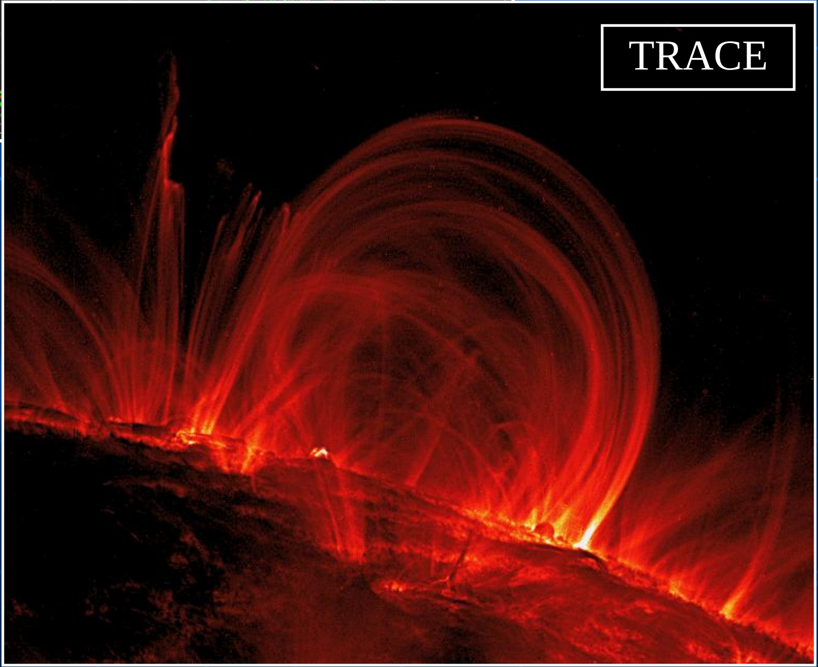
SKA Preparatory Phase	Phase 1 Pre-Construction Phase	Phase 1 Construction, Verification, Commissioning, Acceptance, Integration & First Science	Phase 2 Construction , Commissioning, Acceptance, Integration & First Science	SKA Operations
2008 - 2012	2013 - 2015	2016 - 2019	2018 - 2023	2020 onwards

Site decision: 29 Feb. 2012
(by Board of Directors)

SKA Key Science Project:
Origin and evolution of magnetic fields







SKA Key Science Project:
Faraday rotation in the foreground medium towards polarized background sources

All-sky survey (1h per field):

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

Deep fields (12h integration):

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

Ideal to measure central regions !

We are entering a Golden Age of cosmic magnetism observations