Observation of magnetic fields in galaxies

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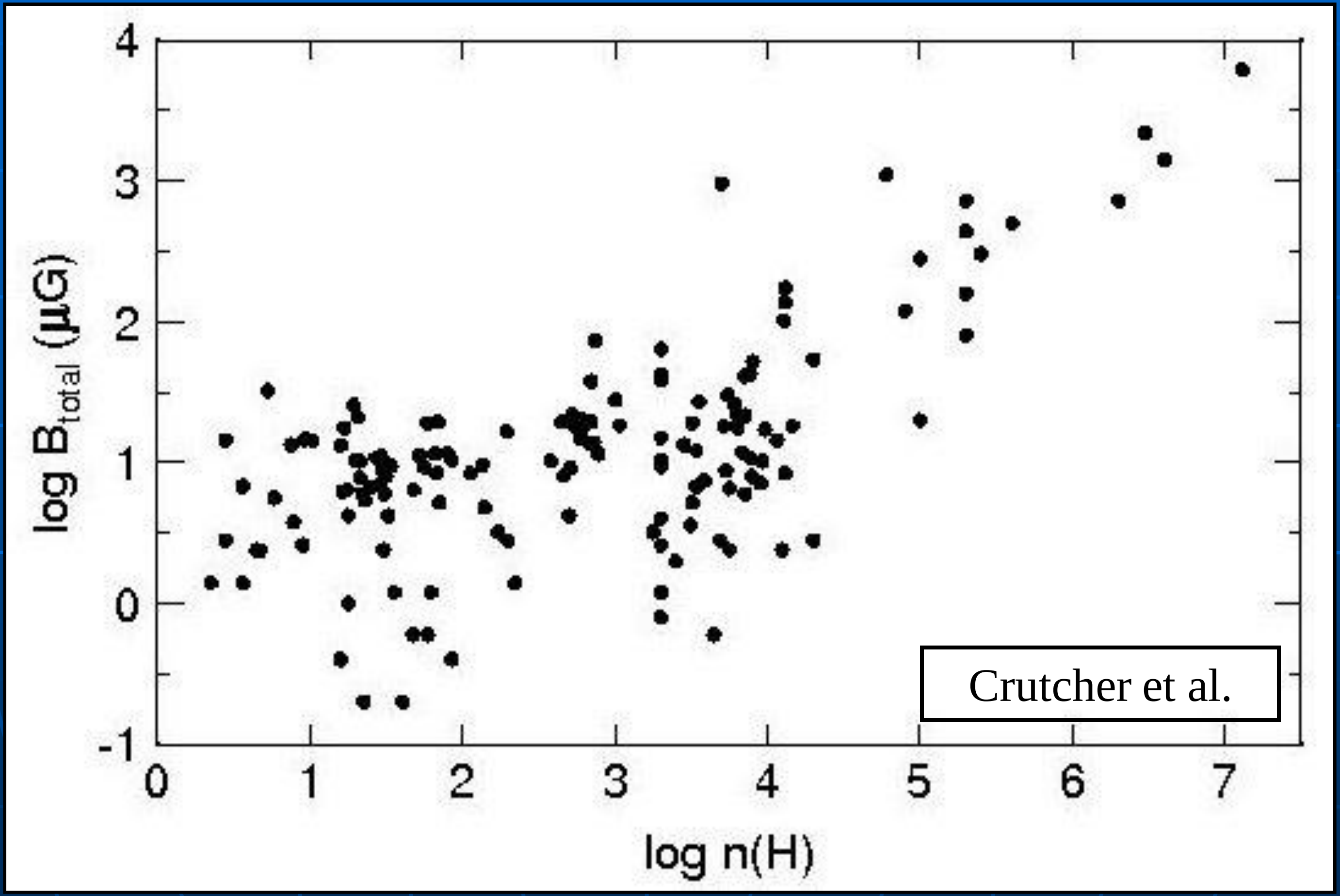
Tools to study magnetic fields

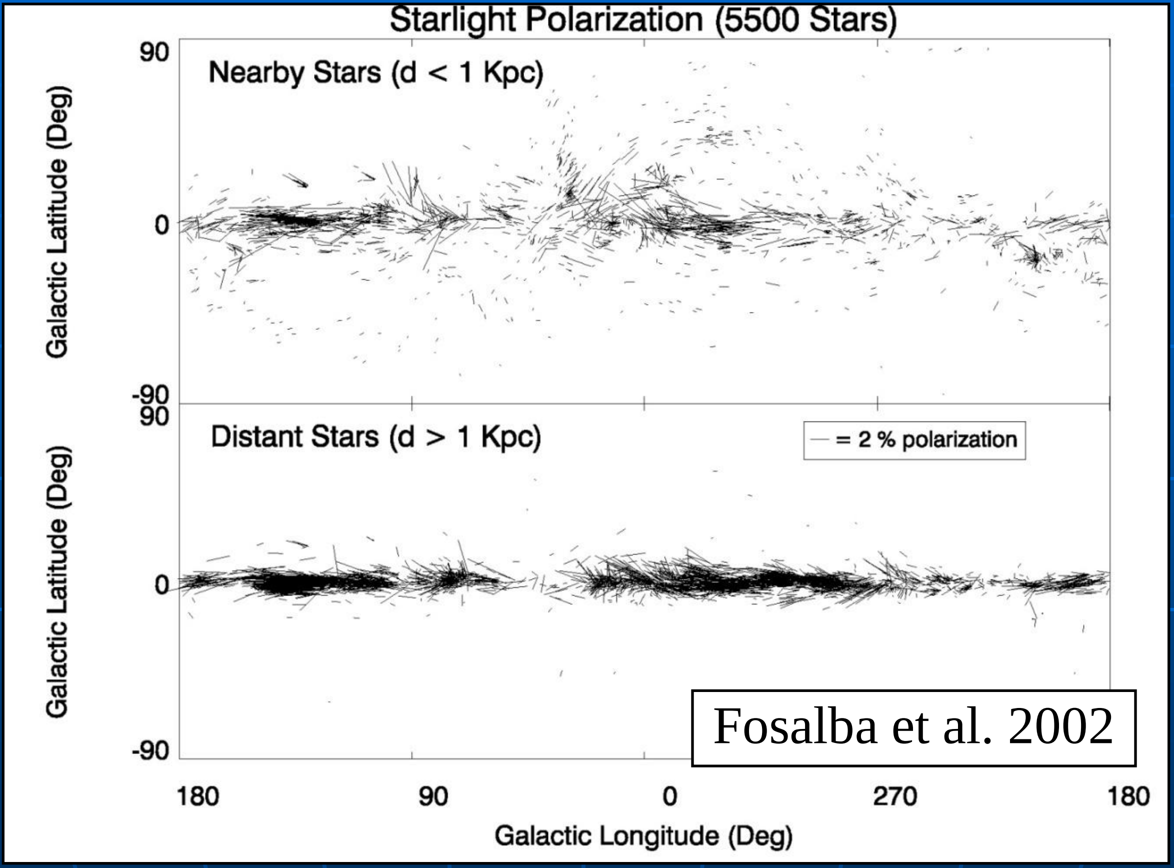
- Zeeman effect:
  Strength and sign of ordered $B_{\parallel}$
- Optical / infrared / submm polarization by dust grains:
  Structure of ordered $B_{\perp}$
- Total synchrotron intensity:
  Strength of total $B_{\perp}$
- Polarized synchrotron intensity:
  Strength and structure of ordered $B_{\perp}$
- Faraday rotation:
  Strength and sign of ordered $B_{\parallel}$
- Faraday depolarization:
  Strength and scale of turbulent fields

Zeeman effect:
Field strengths ($B_{\parallel}$) in Milky Way clouds



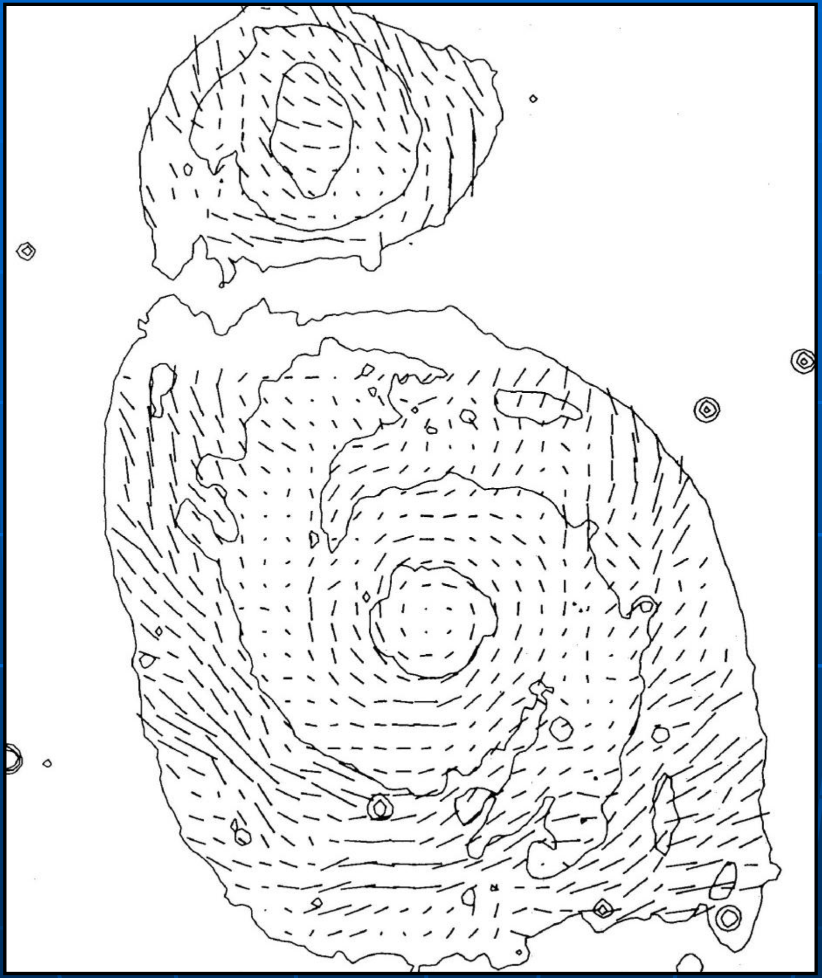
Average field strength ≈6 μG

Starlight polarization: Ordered fields ($B_\perp$)



Large-scale ordered field along the plane, directed towards $l \approx 77^\circ$

Starlight polarization in M 51

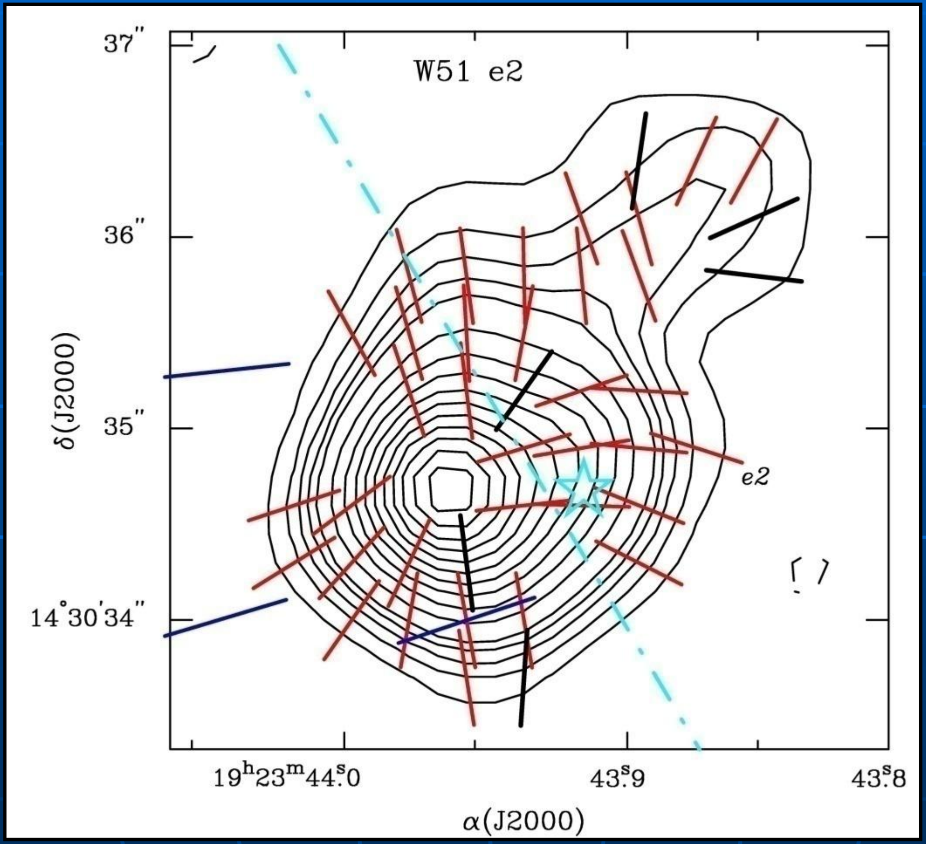


Scarrott et al. 1977

Large-scale spiral field or scattered light ?

Submm polarization:
Ordered magnetic fields in a molecular gas disk

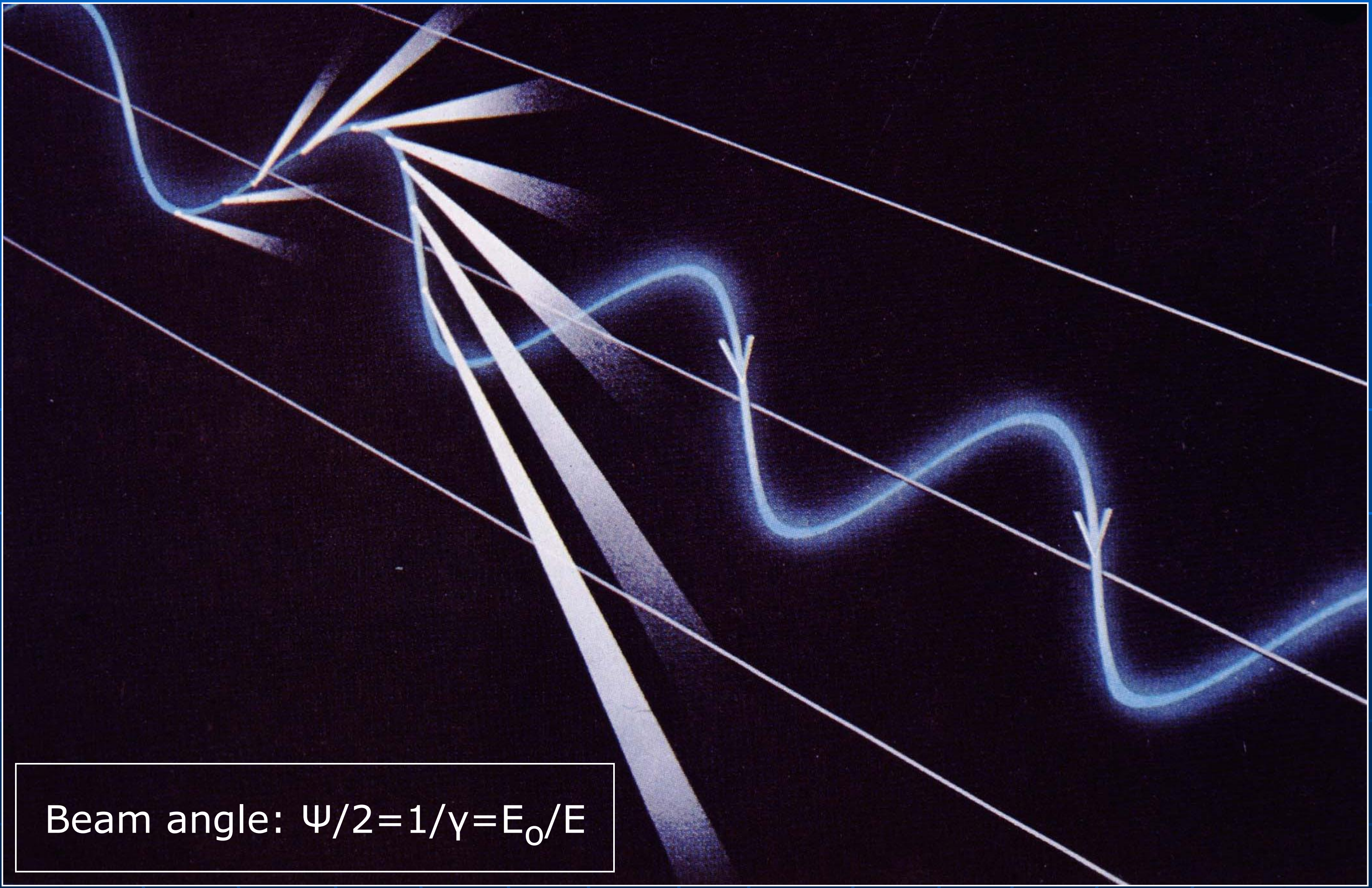
(SMA 870 μm, 0.02 pc resolution)



Tang et al. 2009

X-shaped field:
Ambipolar diffusion?

Synchrotron emission



Synchrotron emission

- Ensemble of cosmic-ray electrons:

  Power-law energy spectrum with spectral index ε:

  $N(E)\,dE = N_0\, E^{-\varepsilon}\, dE$

- Intensity of synchrotron spectrum:

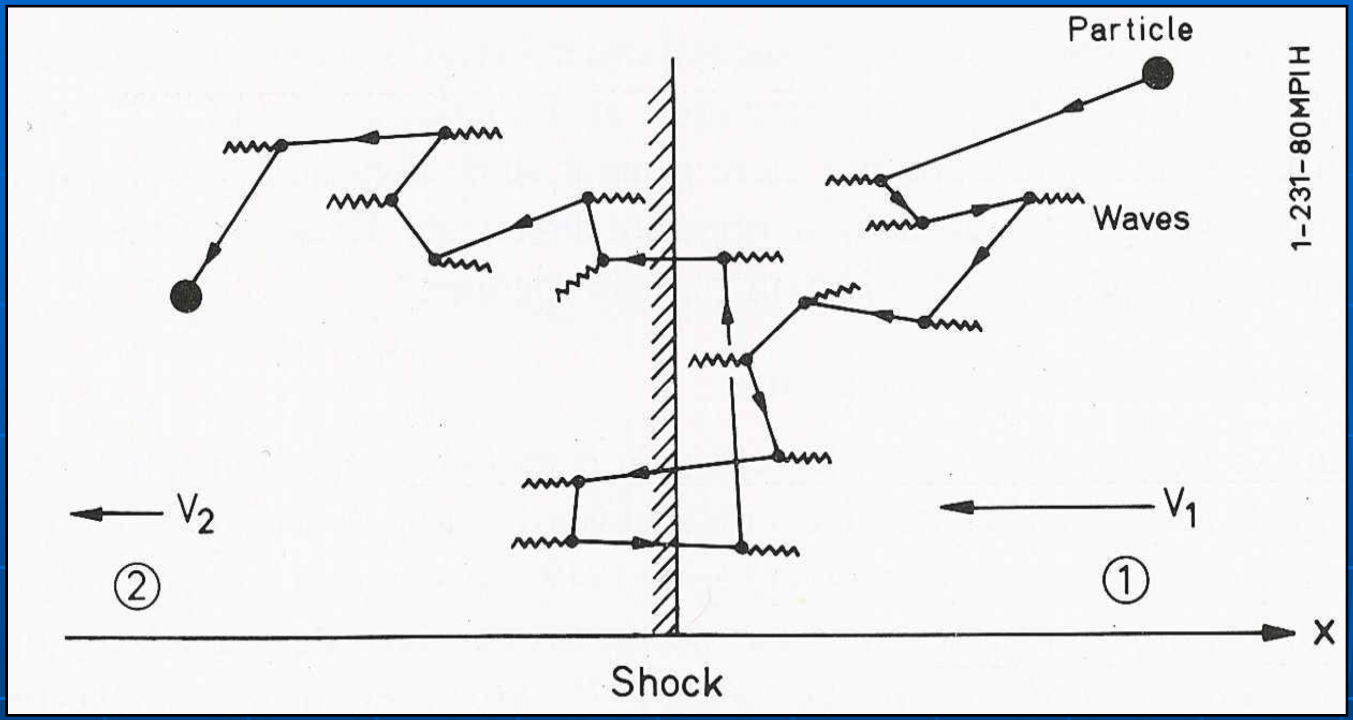
  $I_\nu = c_5(\varepsilon) \int N_0\, B_\perp^{(\varepsilon+1)/2}\, (\nu/2c_1)^{-(\varepsilon-1)/2}\, dL$

- Synchrotron spectral index:

  $\alpha = (\varepsilon-1)/2$

  Strong shocks: $\varepsilon=2$, $\alpha=0.5$

Diffusive shock acceleration



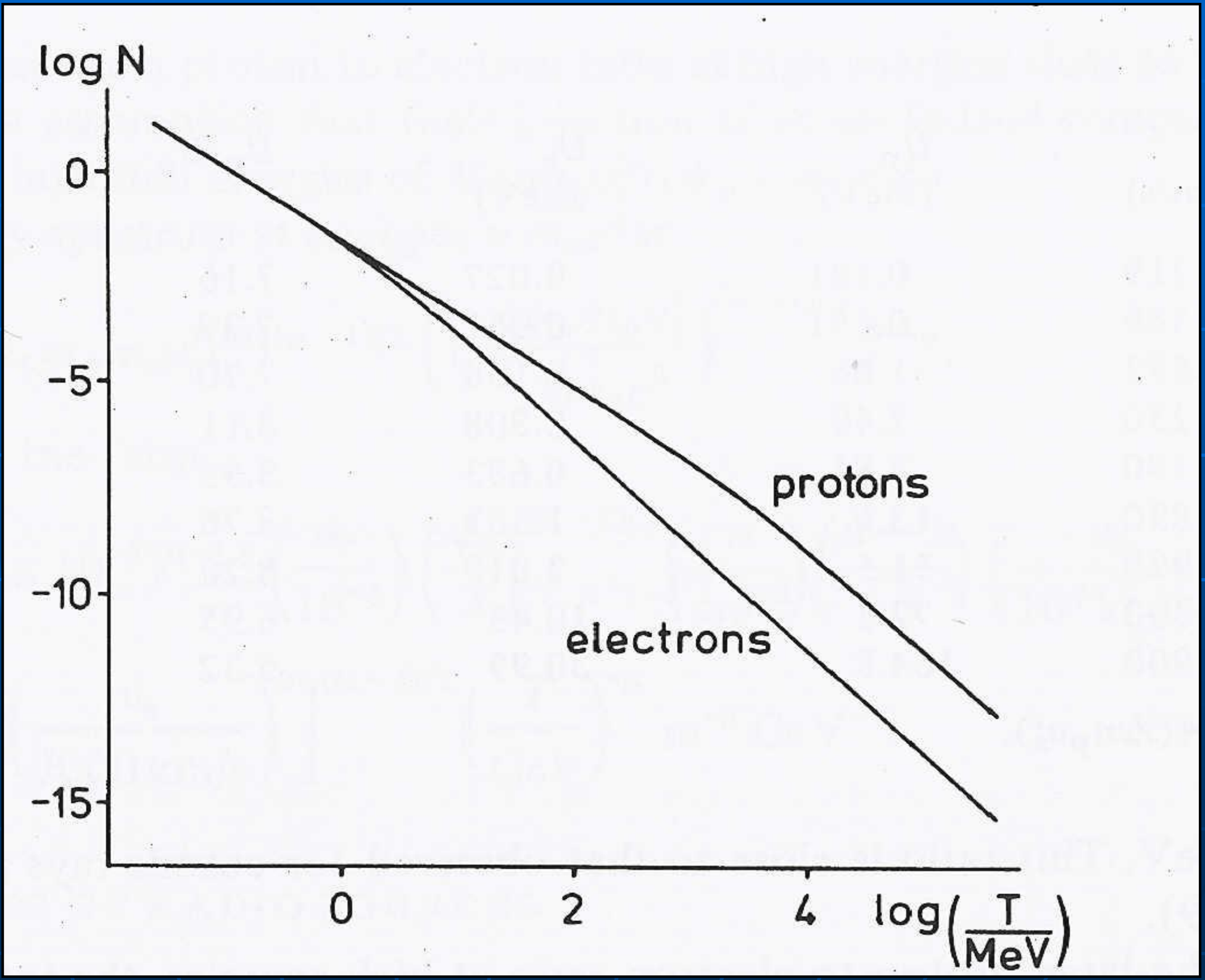
- Shock compression ratio: r
- Electron spectrum: $\varepsilon = (2+r)/(r-1)$
- Strong shocks (r=4): $\varepsilon=2$, $\alpha=0.5$

Energy spectra of cosmic rays

Bell 1978

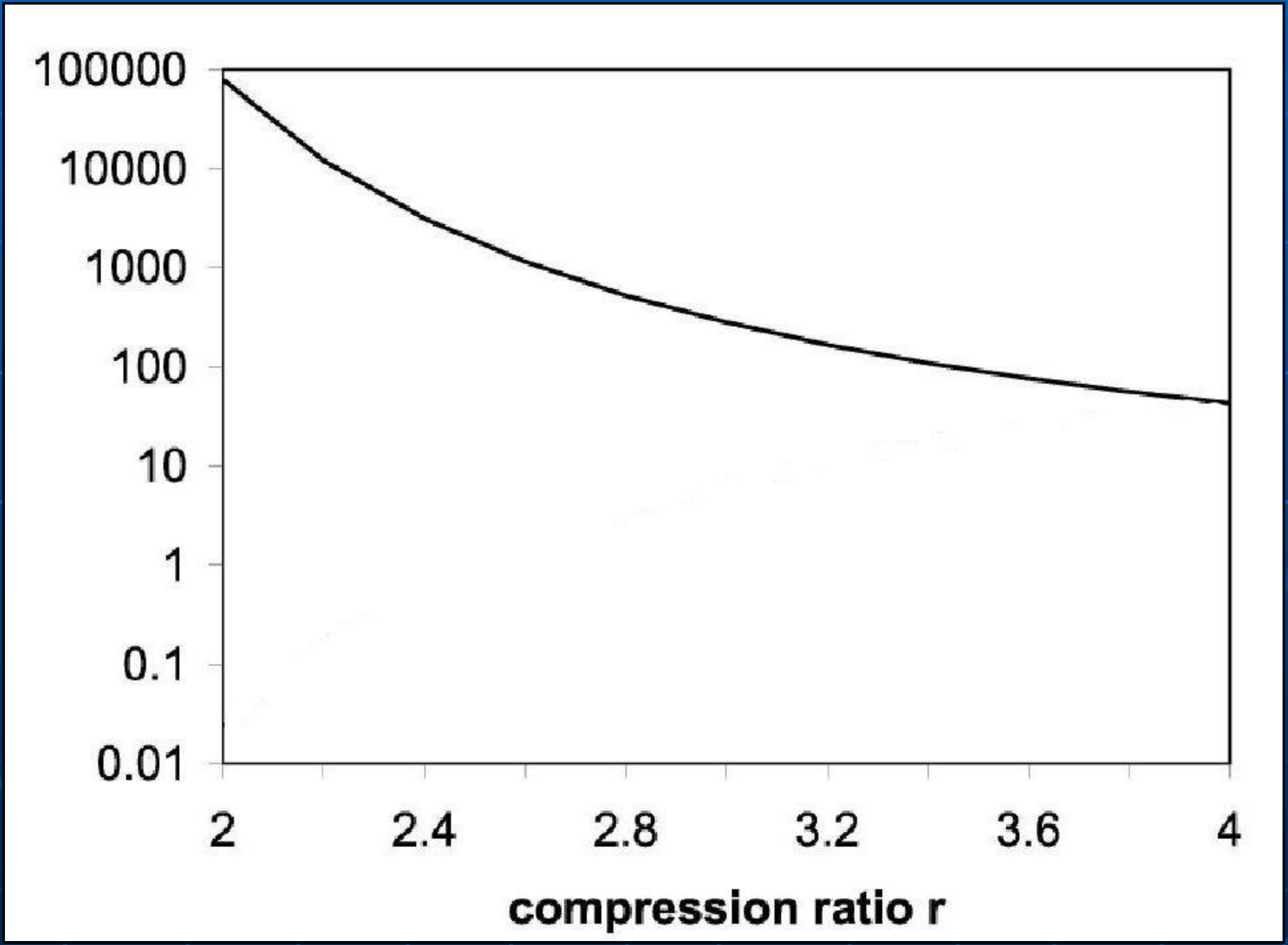
Diffusive shock acceleration: ε ≥ 2 (above rest Energy)

E > 1 GeV: K ≥ 100



Proton-electron ratio (K)

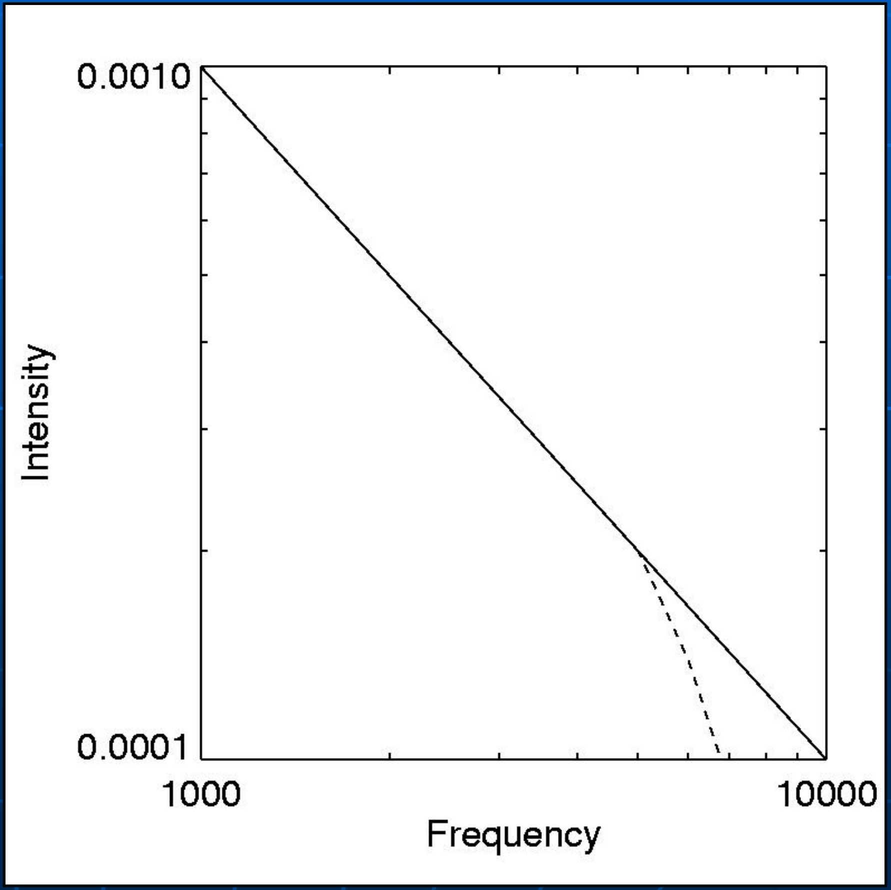
Beck & Krause 2005



Lifetime of synchrotron-emitting electrons

$t_{syn} \approx 1$ Gyr $B_{\perp}\,[\mu G]^{-1.5}$ $\nu_{syn}\,[GHz]^{-0.5}$

Synchrotron spectrum steepens above a critical frequency

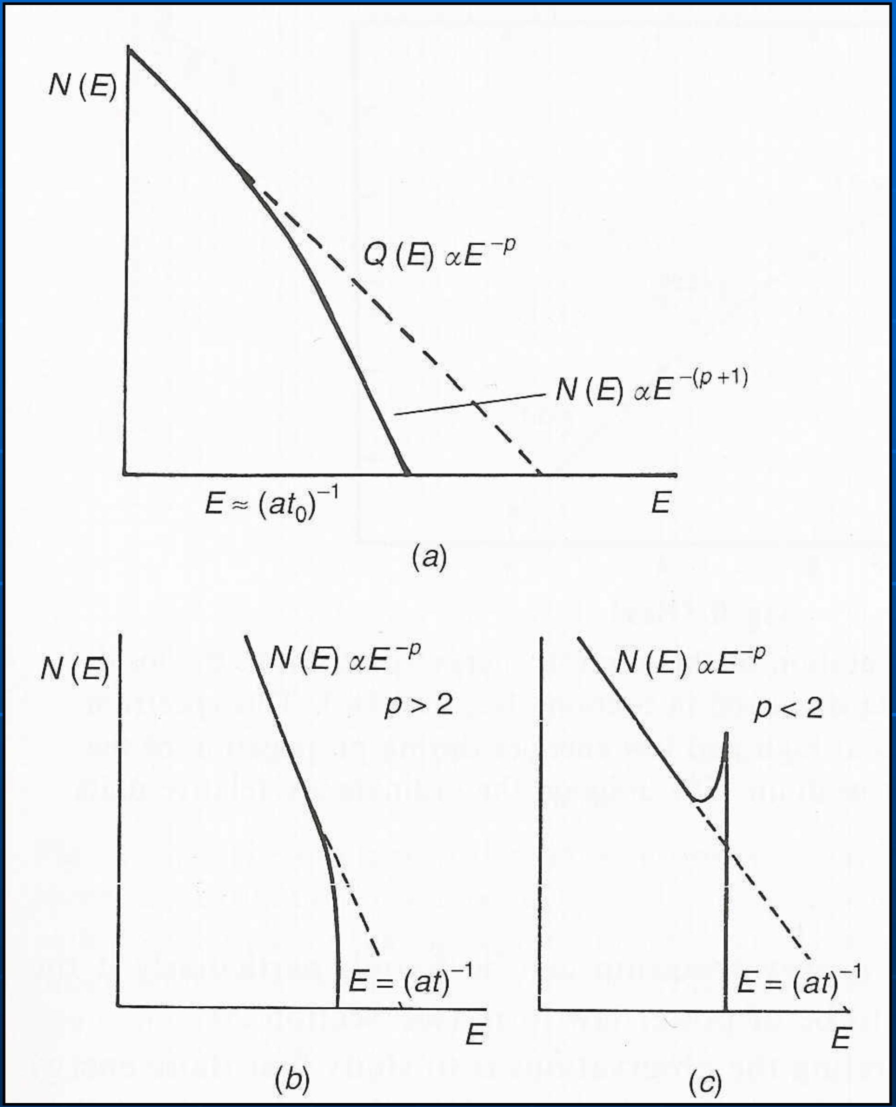


Cosmic ray electron spectra

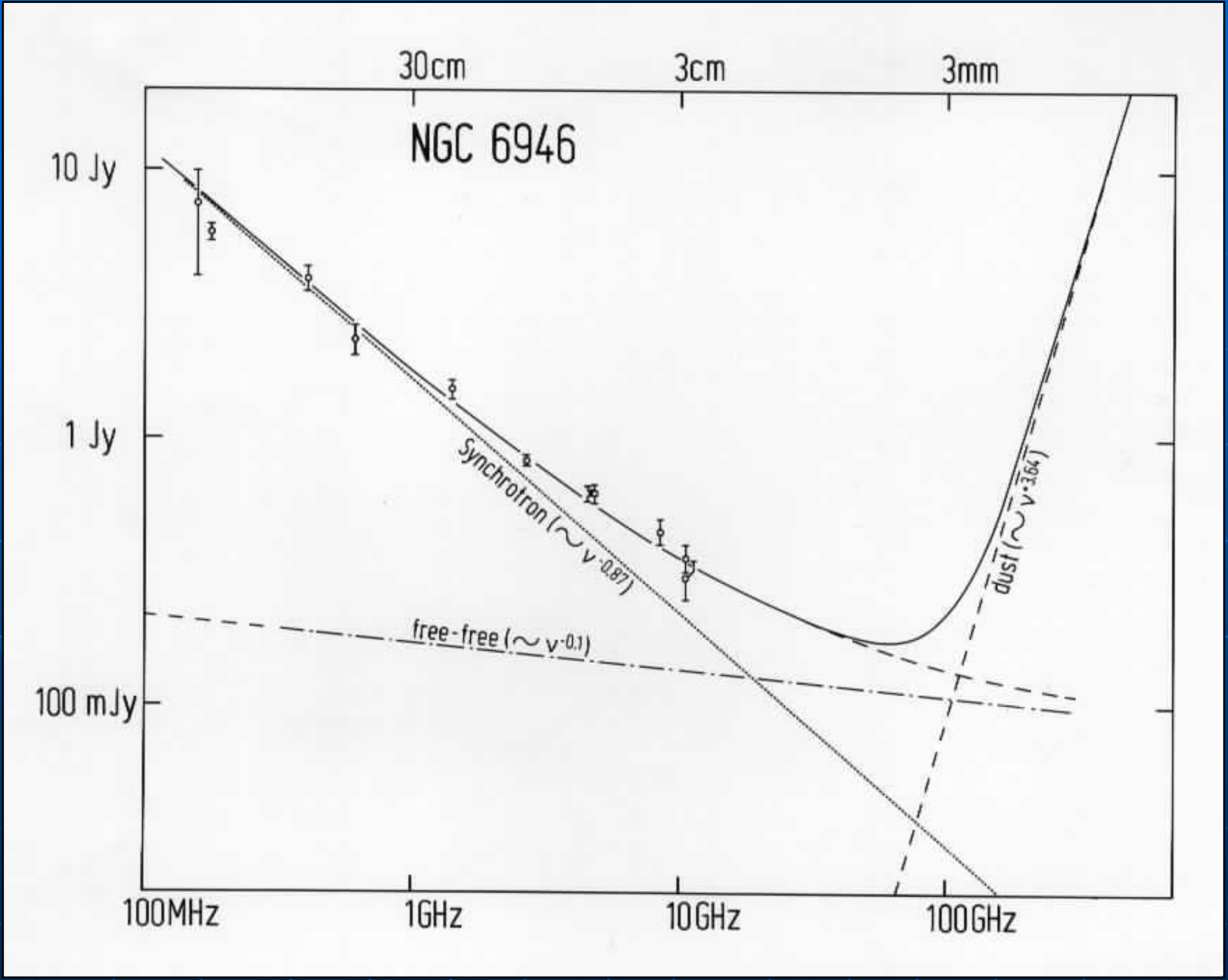
a) Continuous injection
+ energy loss:
Energy spectral index
steepens by 1

b) Injection at time t=0
with spectral index $\varepsilon_e > 2$
+ energy loss:
exponential steepening

c) same, but $\varepsilon_e < 2$:
pile-up peak

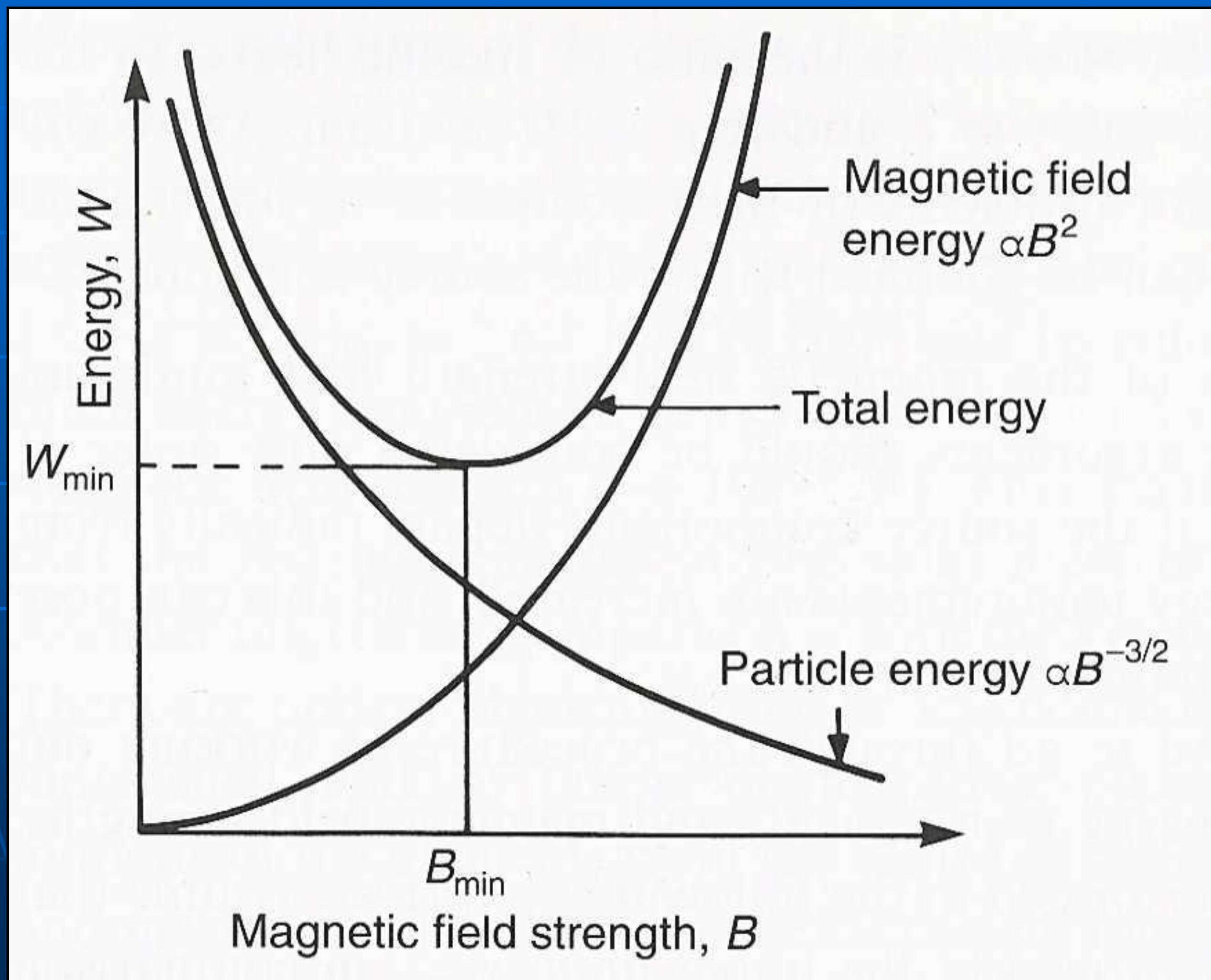


Longair, High Energy Astrophysics, 1994



NGC 6946
30cm
3cm
3mm
10 Jy
1 Jy
100 mJy
100MHz
1GHz
10GHz
100GHz
Synchrotron (∼ ν^-0.87)
free-free (∼ ν^-0.1)
dust (∼ ν^+3.64)

Equipartition field strengths



Longair, High Energy Astrophysics, 1994

Equipartition strength of the total field

(assuming equipartition between magnetic fields and cosmic rays)

Beck & Krause 2005

$$\mathbf{B}_{\mathbf{eq},\perp} \propto \left(\mathbf{I}_{\mathbf{sync}}\,(K+1)\,/\,L \right)^{1/(3+\alpha)}$$

$\mathbf{I}_{\mathbf{sync}}$: Synchrotron intensity

L: Pathlength through source

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

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

Usual assumption: K=100 (no energy losses of CR electrons)

Equipartition magnetic field strengths

Problem: Electrons suffer from energy losses
(synchrotron, Inverse Compton, bremsstrahlung, ionization)
which modify their spectral index (ε_e) and K

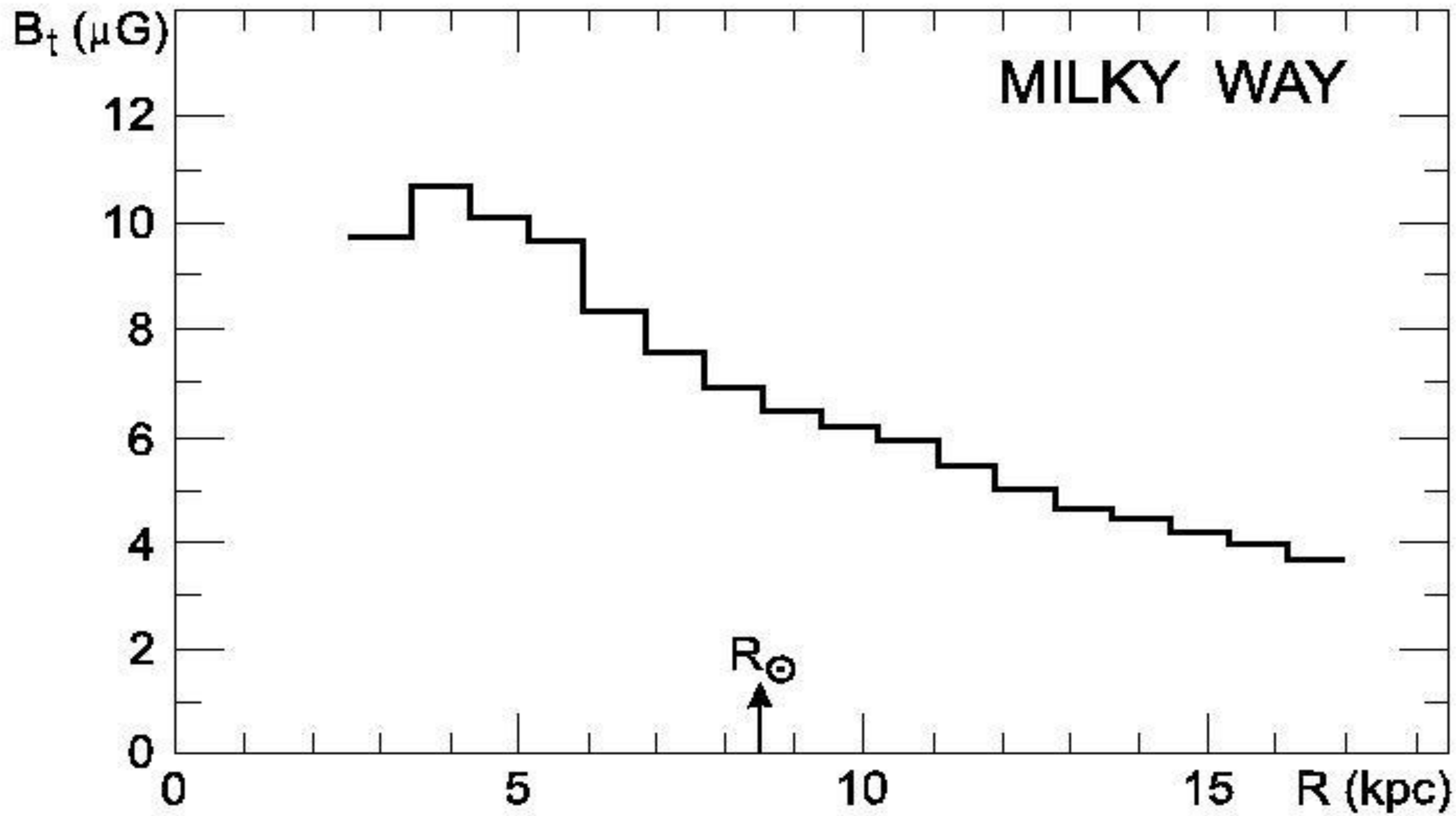
→ Electron spectrum cannot be used to extrapolate the proton spectrum

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

Needed: independent data on cosmic-ray proton spectrum (e.g. γ rays)

Equipartition field in the Milky Way

(Berkhuijsen, in Wielebinski & Beck 2005)

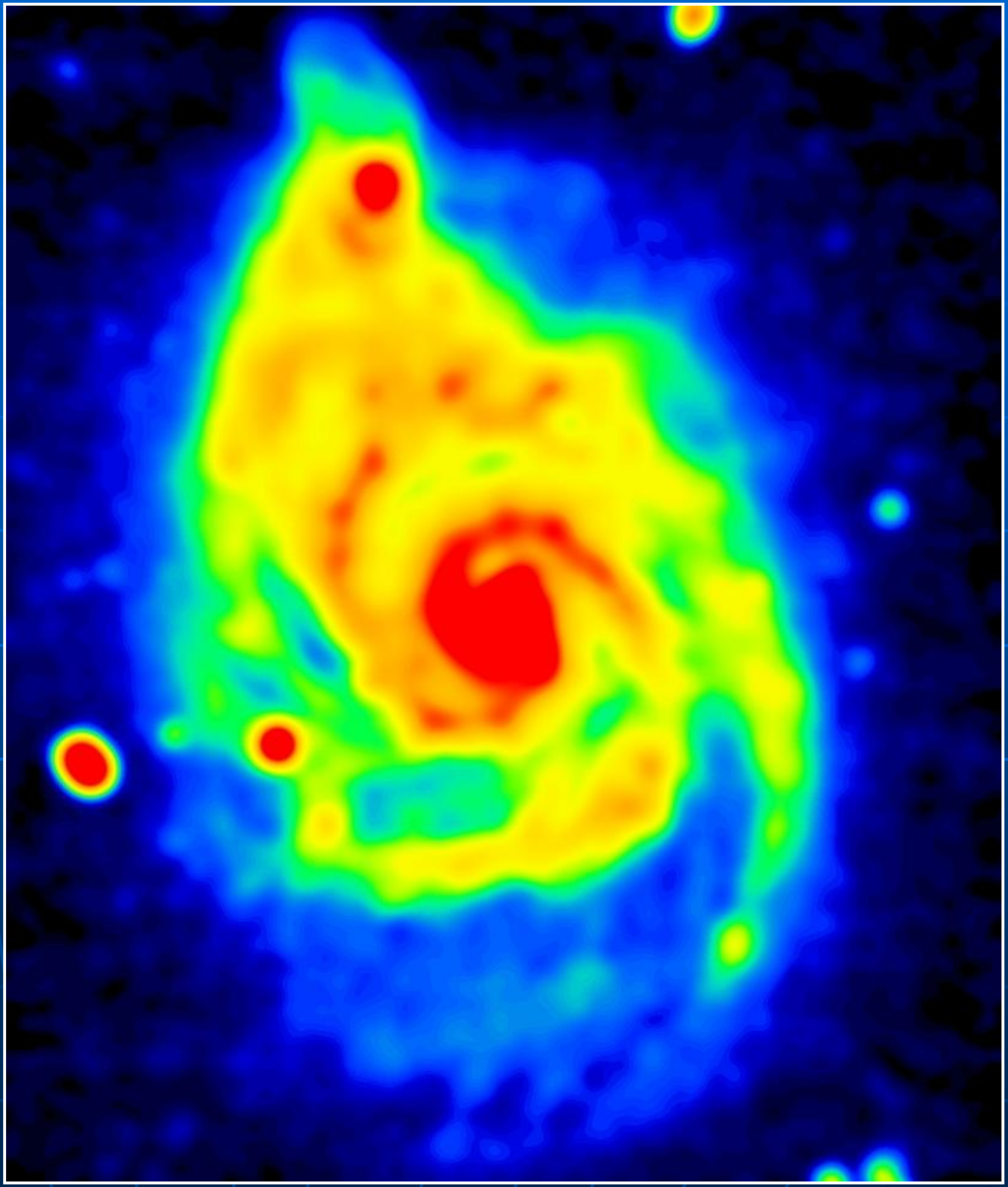


Consistent with estimates from γ rays

(Strong et al. 2000)

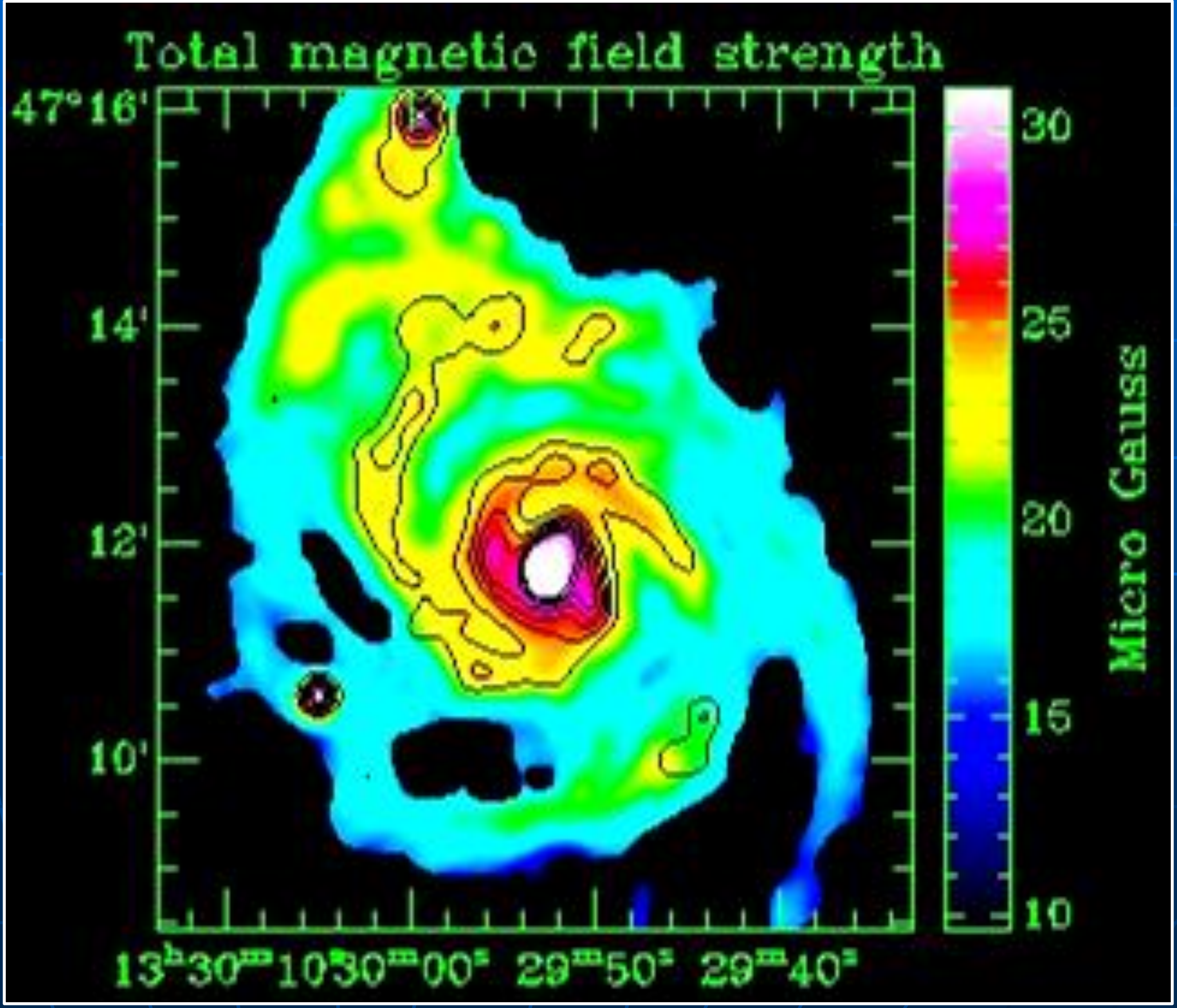
M 51

20cm VLA
Total intensity
(Fletcher et al. 2010)



Equipartition field strengths in M 51

Fletcher et al. 2010



Magnetic field strengths in spiral galaxies

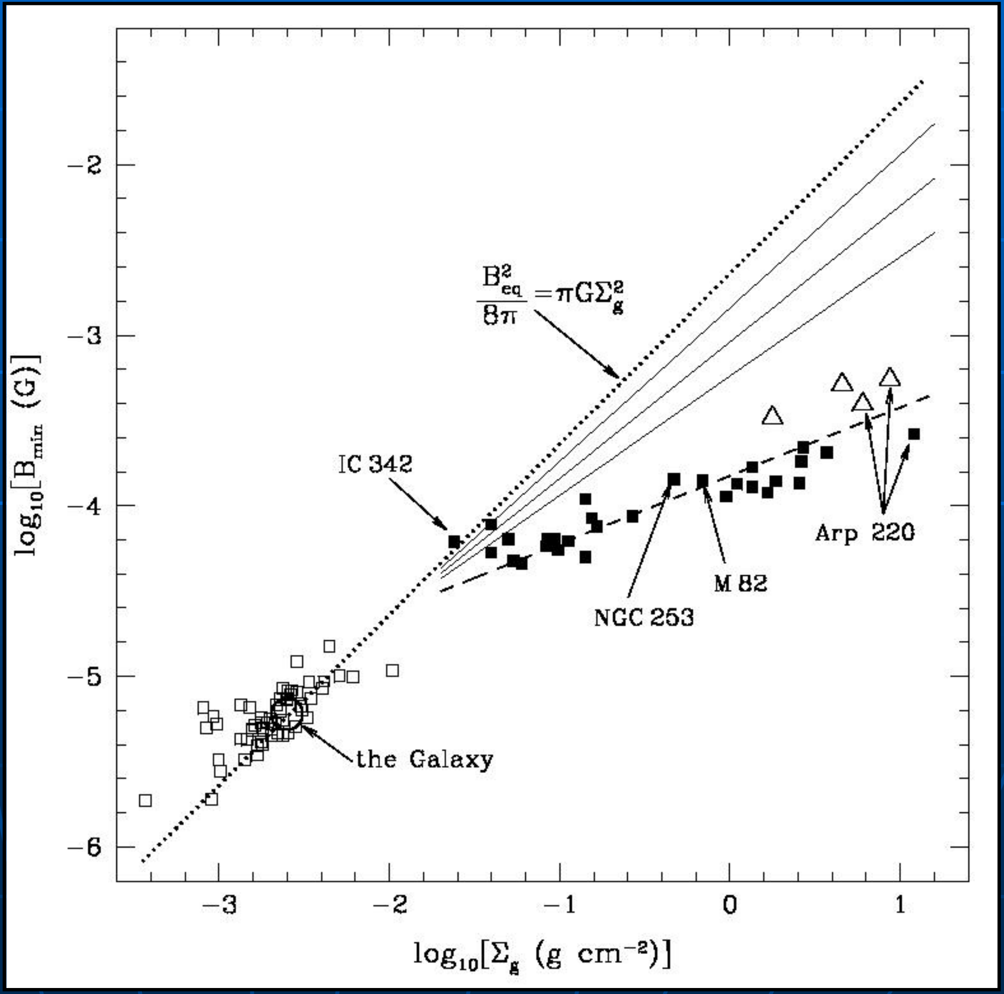
(from synchrotron intensity, assuming energy equipartition with cosmic rays)

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**
Total field in galaxy center filaments:	**≈ 1 mG**

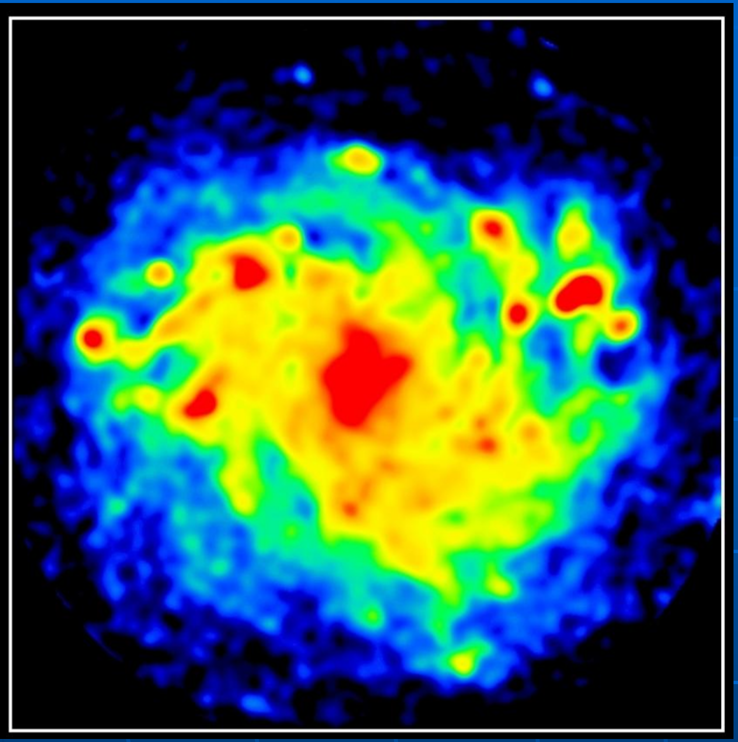
Magnetic fields and gas surface density

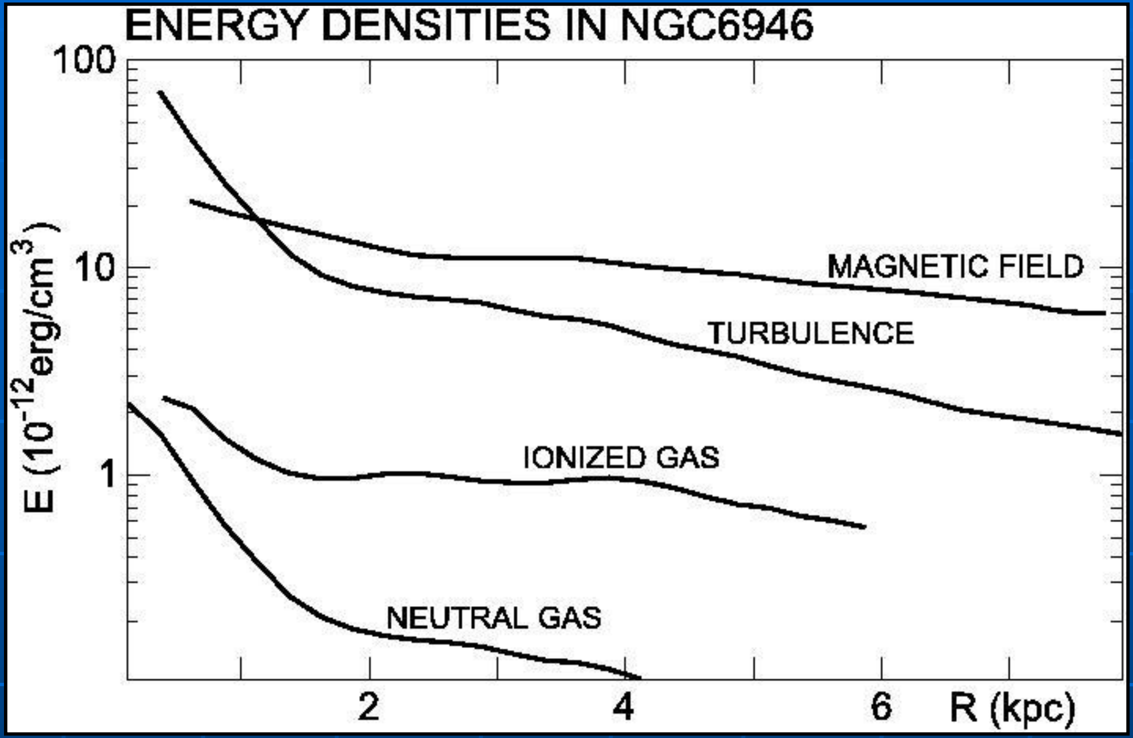
Thompson et al. (2006)

Equipartition magnetic field strengths in starburst galaxies are probably underestimates



Energy densities





Cold clouds:
V_{turb} = 7 km/s ≈ const (from SNRs),
T=50 K, h=100 pc

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

Beck 2007

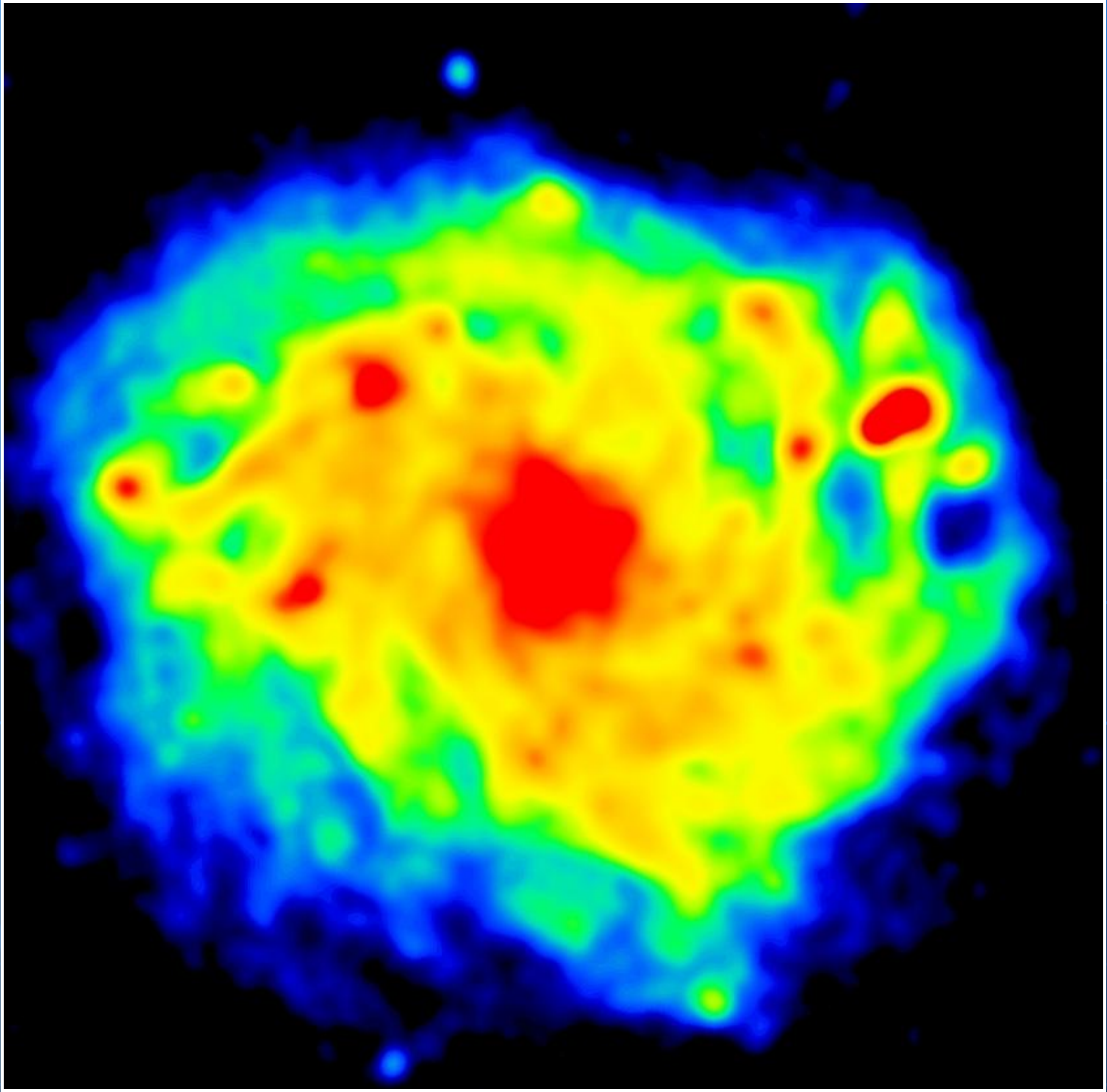
Energy densities
(NGC 6946, M 33)

Beck 2007,
Tabatabaei et al. 2008

- $E_{magn} \approx E_{turb}$ (inner disk)
  (evidence for turbulent amplification)
- $E_{magn} > E_{turb}$ (outer disk)
  (turbulence underestimated ? MRI ?)
- $E_{magn} > E_{therm}$ (everywhere)
  (low-beta plasma – hard to maintain over large scales !)

NGC 6946

20cm VLA
Total intensity
(Beck 2007)



Exponential radio disk

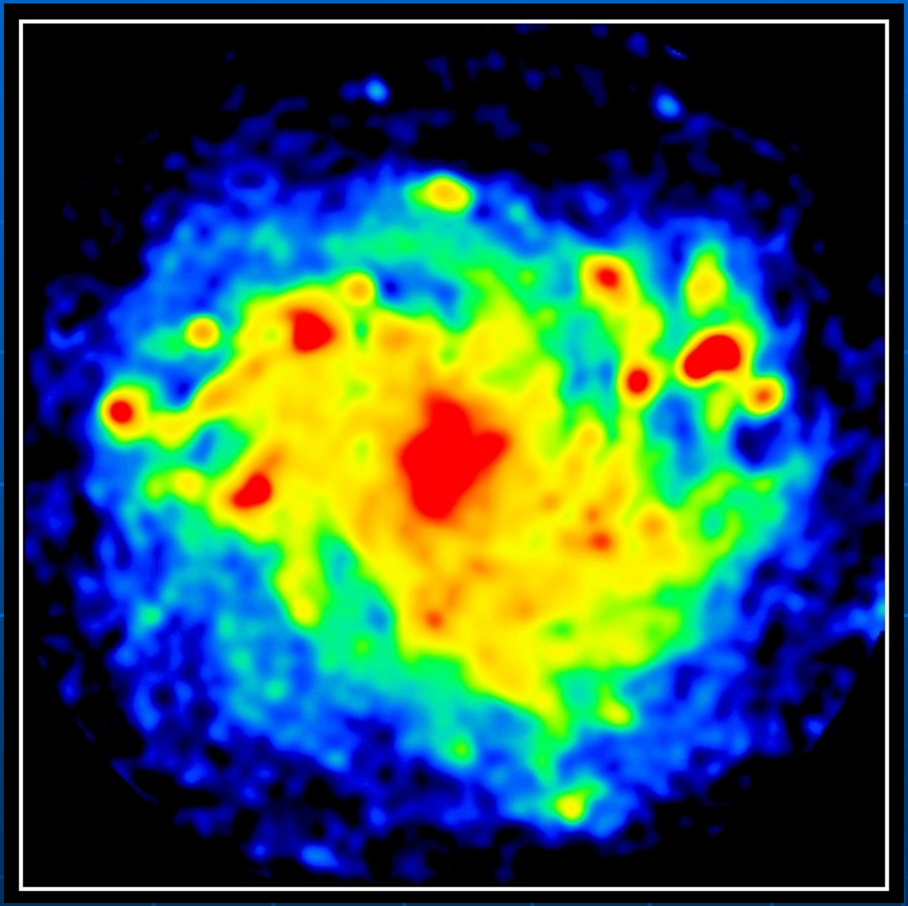
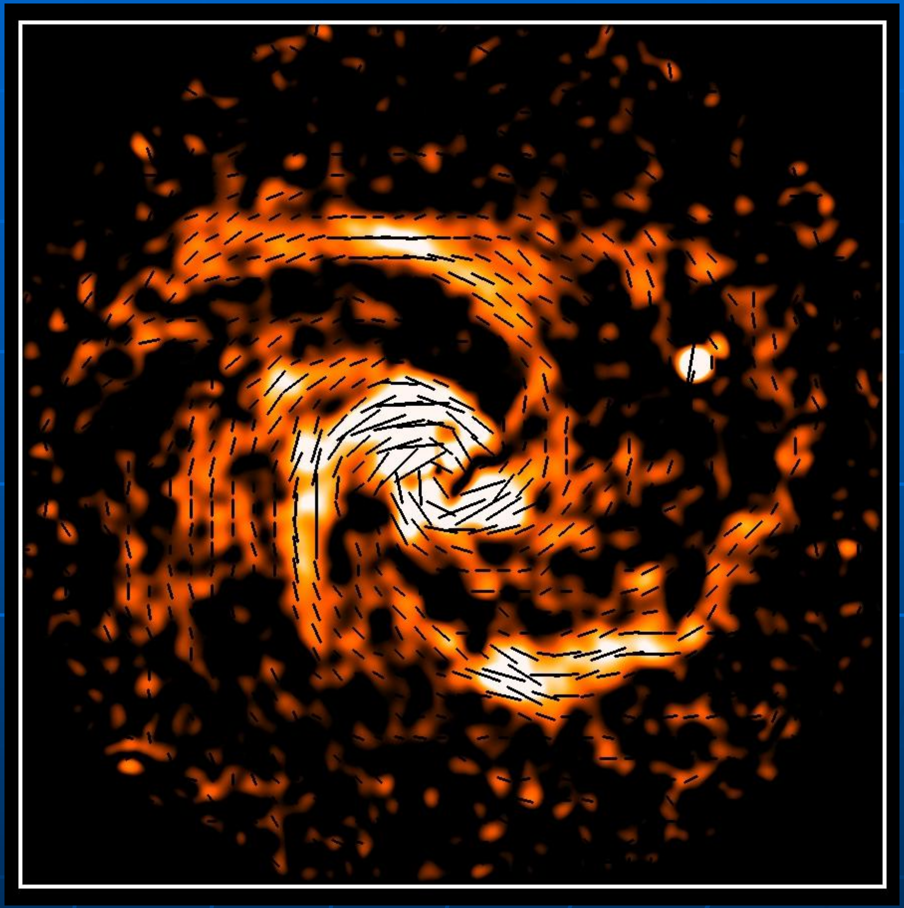
Extent is limited by energy losses of the cosmic-ray electrons

Typical scale lengths of radio disks of spiral galaxies

- Cold & warm gas: $\approx$ 4 kpc
- Synchrotron: $\approx$ 4 kpc
- Cosmic-ray electrons: $\leq$ 8 kpc
  (upper limit due to energy losses)
- Total magnetic field: $\geq$ 16 kpc

Synchrotron polarization

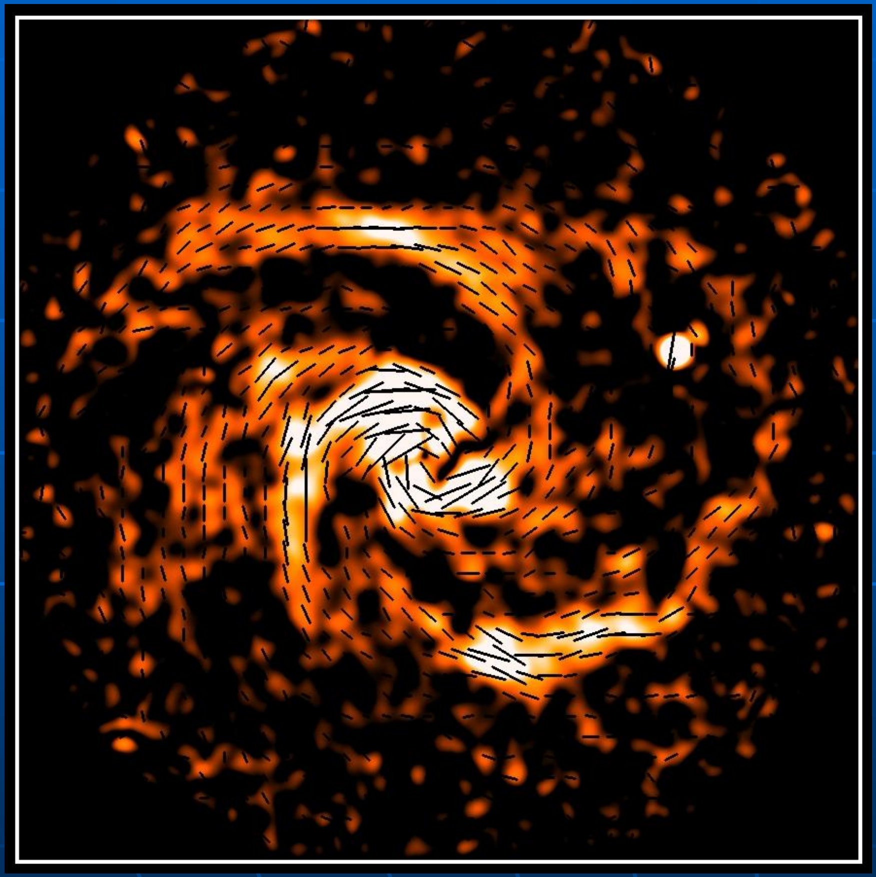
Beck & Hoernes 1996

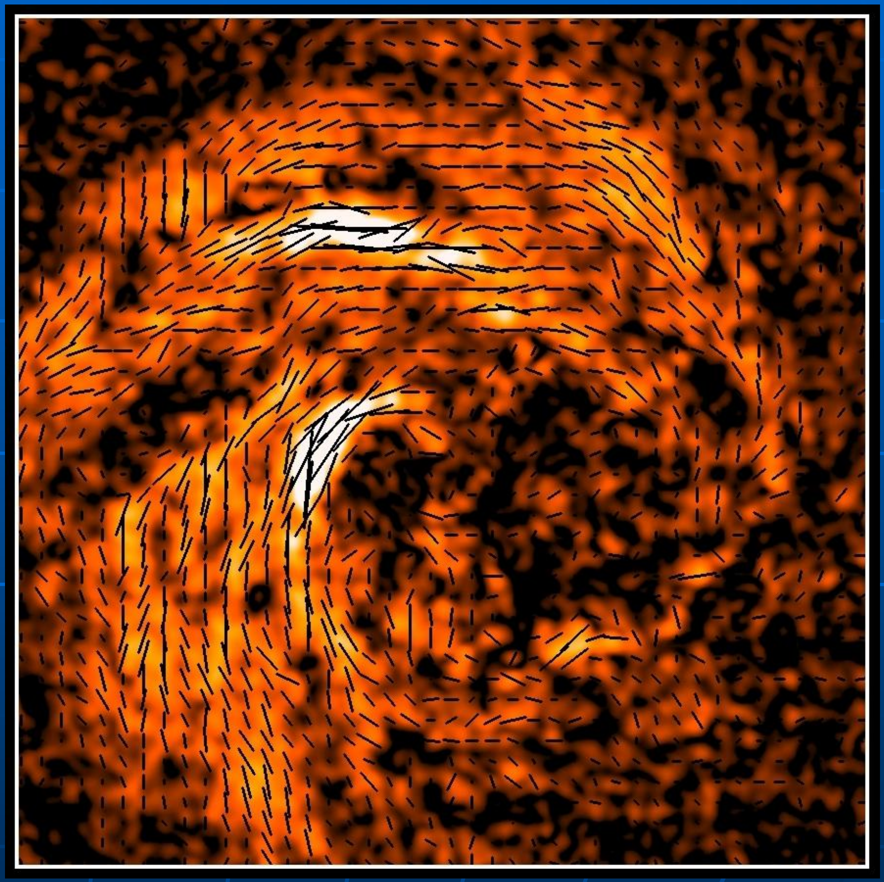



NGC 6946 Total and polarized intensity at 6cm

Faraday depolarization

Beck 2007





NGC 6946 Polarized intensity at 6cm and 20.5cm

Synchrotron polarization

for a power-law electron spectrum

Intrinsic degree of linear polarization:

$$p_o = (\varepsilon+1) / (\varepsilon+7/3)$$
$$= (\alpha+1) / (\alpha+5/3)$$

Typical value: $\alpha=1.0$, $p_o=75\%$

Note: circular polarization is generally negligible

Degree of polarization:

≤ 5% in spiral arms

20 - 60% in magnetic arms at ≥5 GHz,

≤10% at ≤1.4 GHz

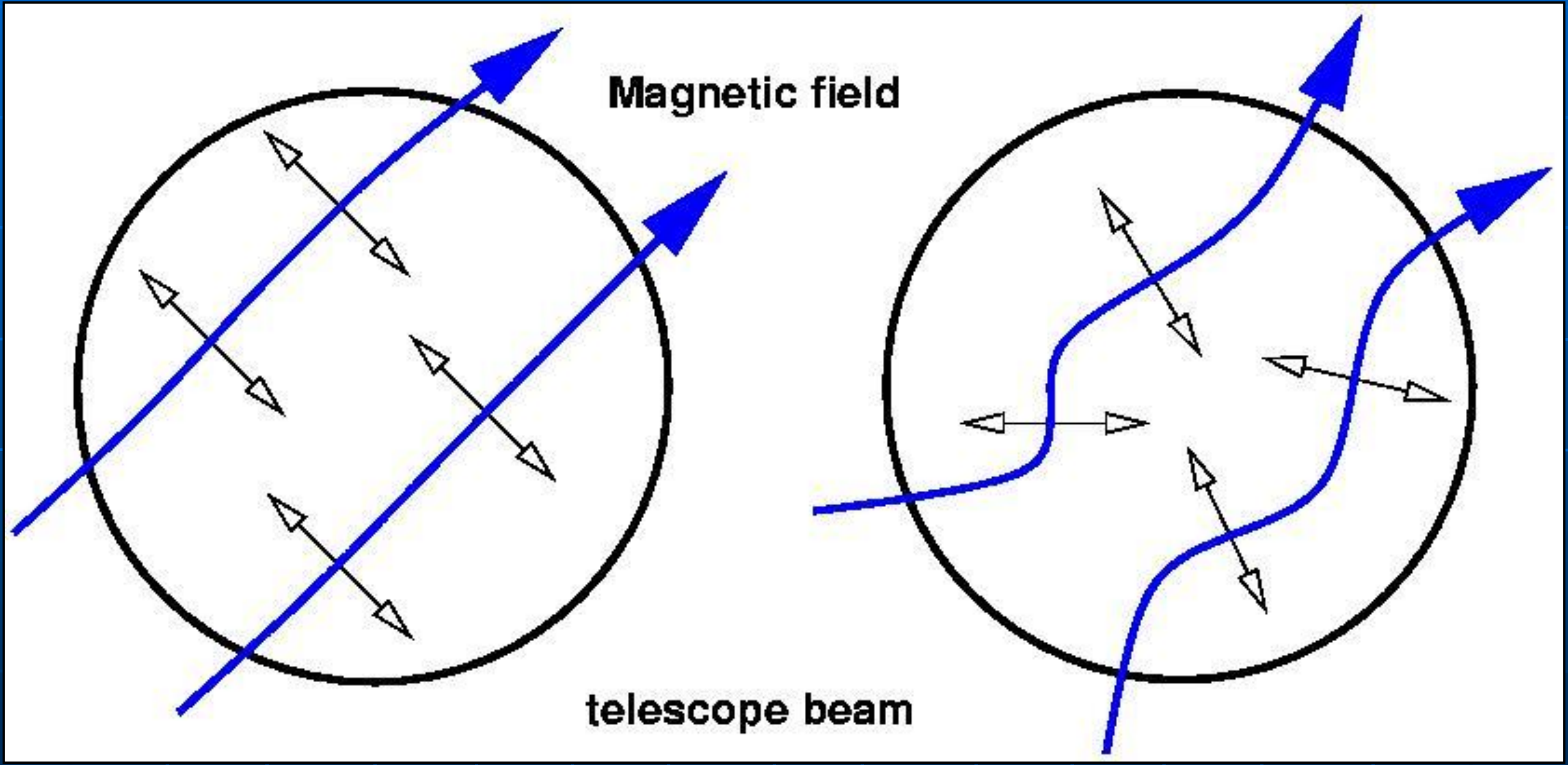
Ratio of random to regular magnetic fields:

≥ 4 in spiral arms and starburst regions,

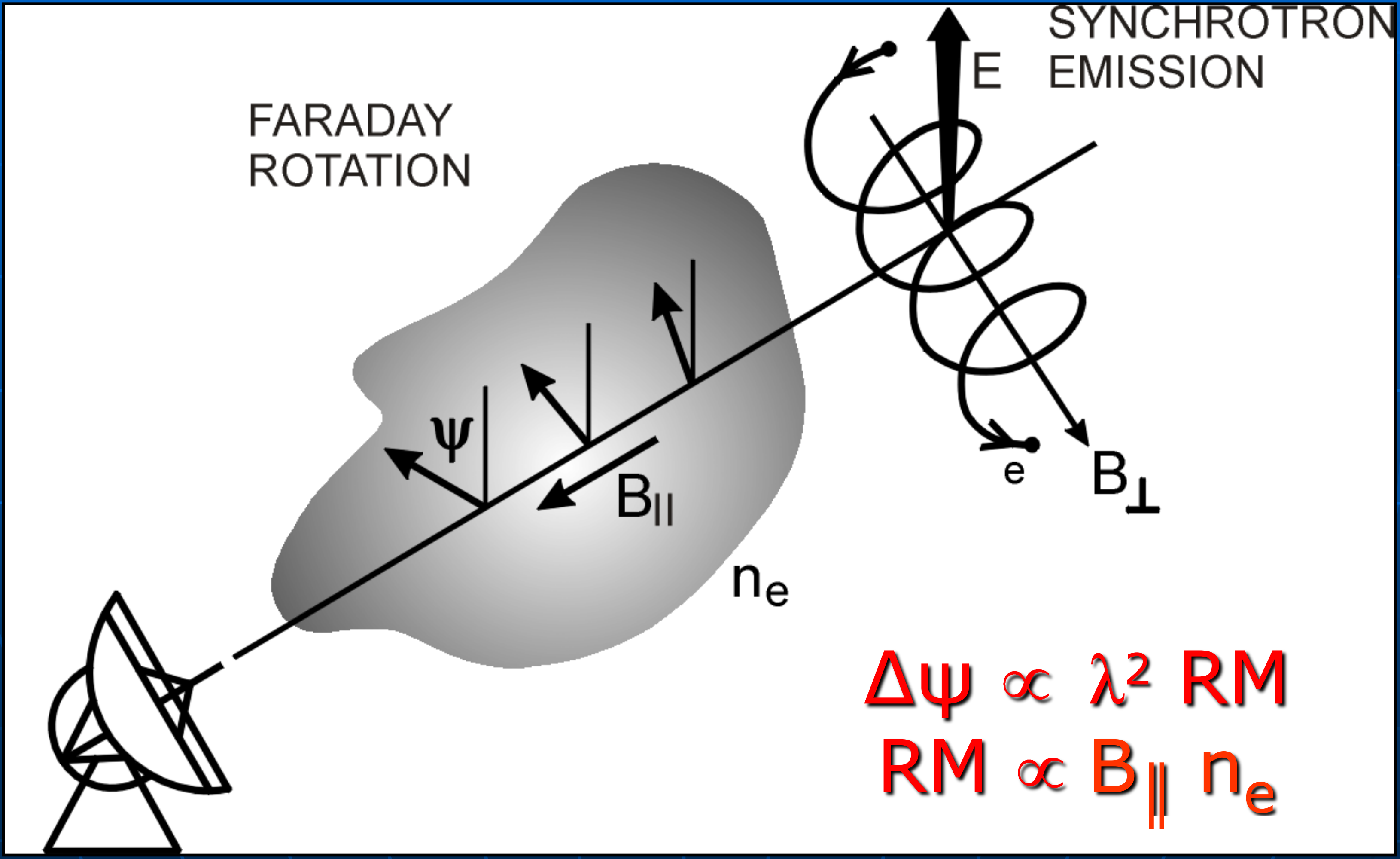
0.5 – 2 in magnetic arms

Beam depolarization
(wavelength-independent)

Fletcher et al. 2004



Faraday rotation

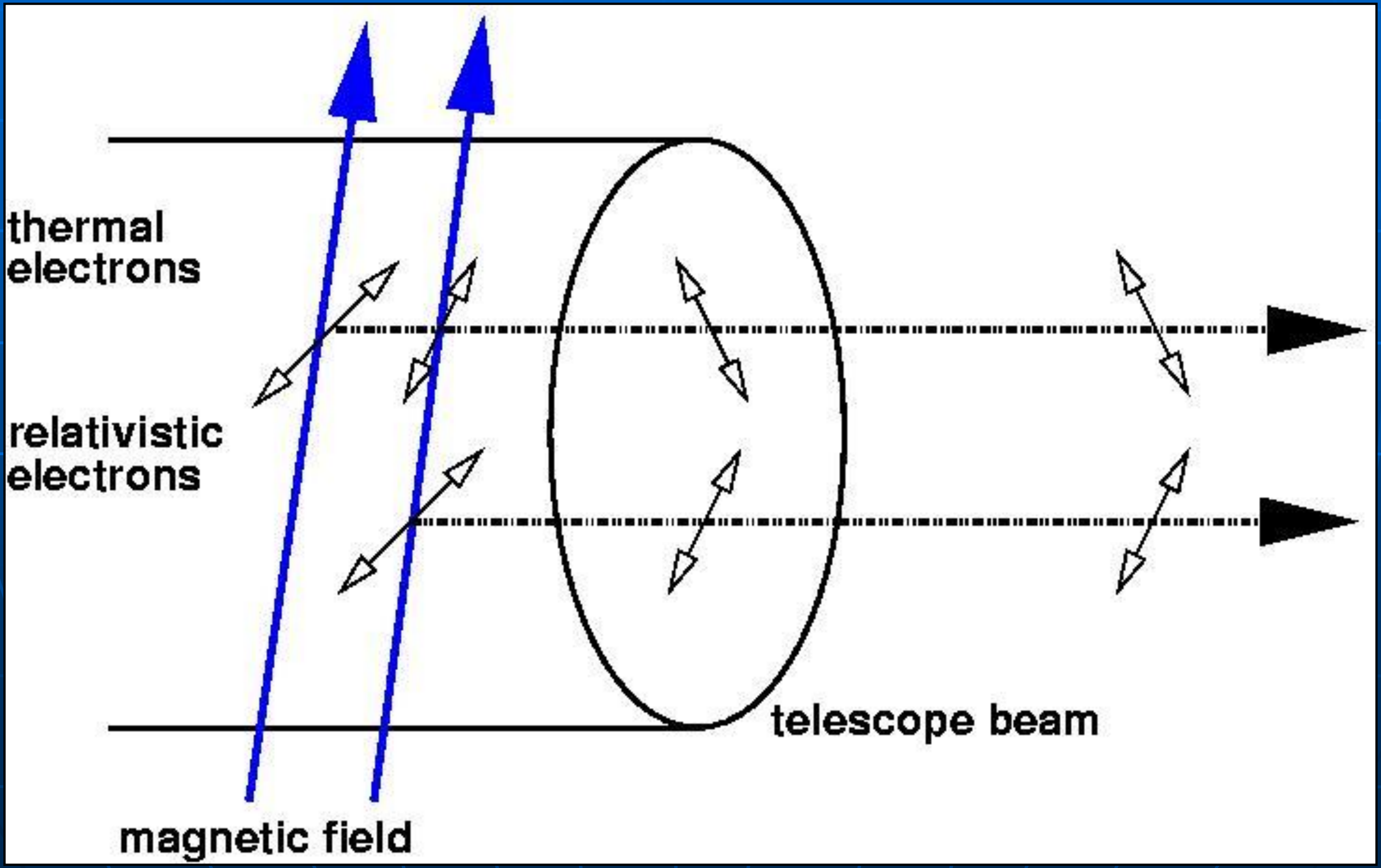


$$\Delta\psi \propto \lambda^2 \, RM$$

$$RM \propto B_{\|} \, n_e$$

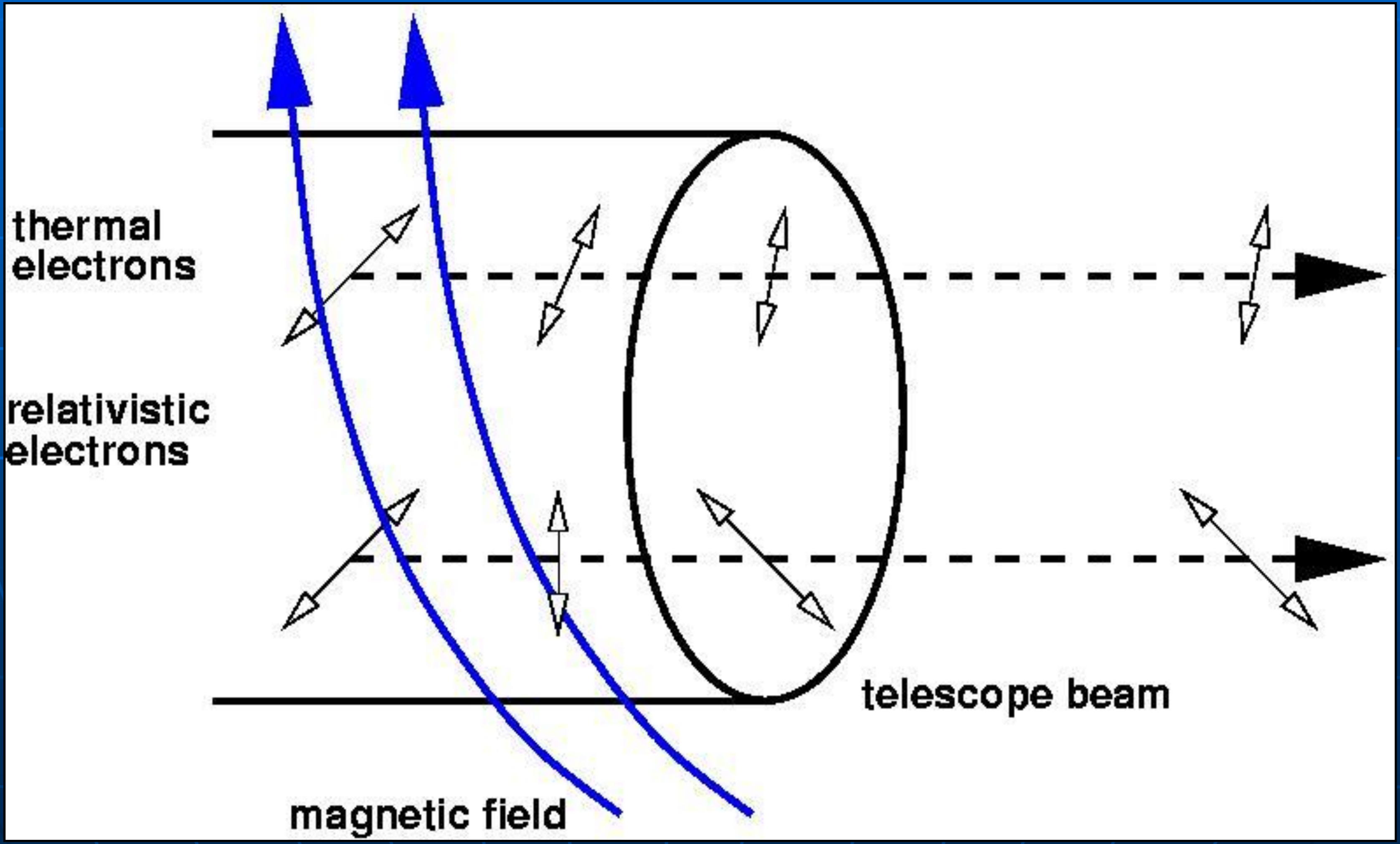
Differential Faraday rotation
(wavelength-dependent)

Fletcher et al. 2004



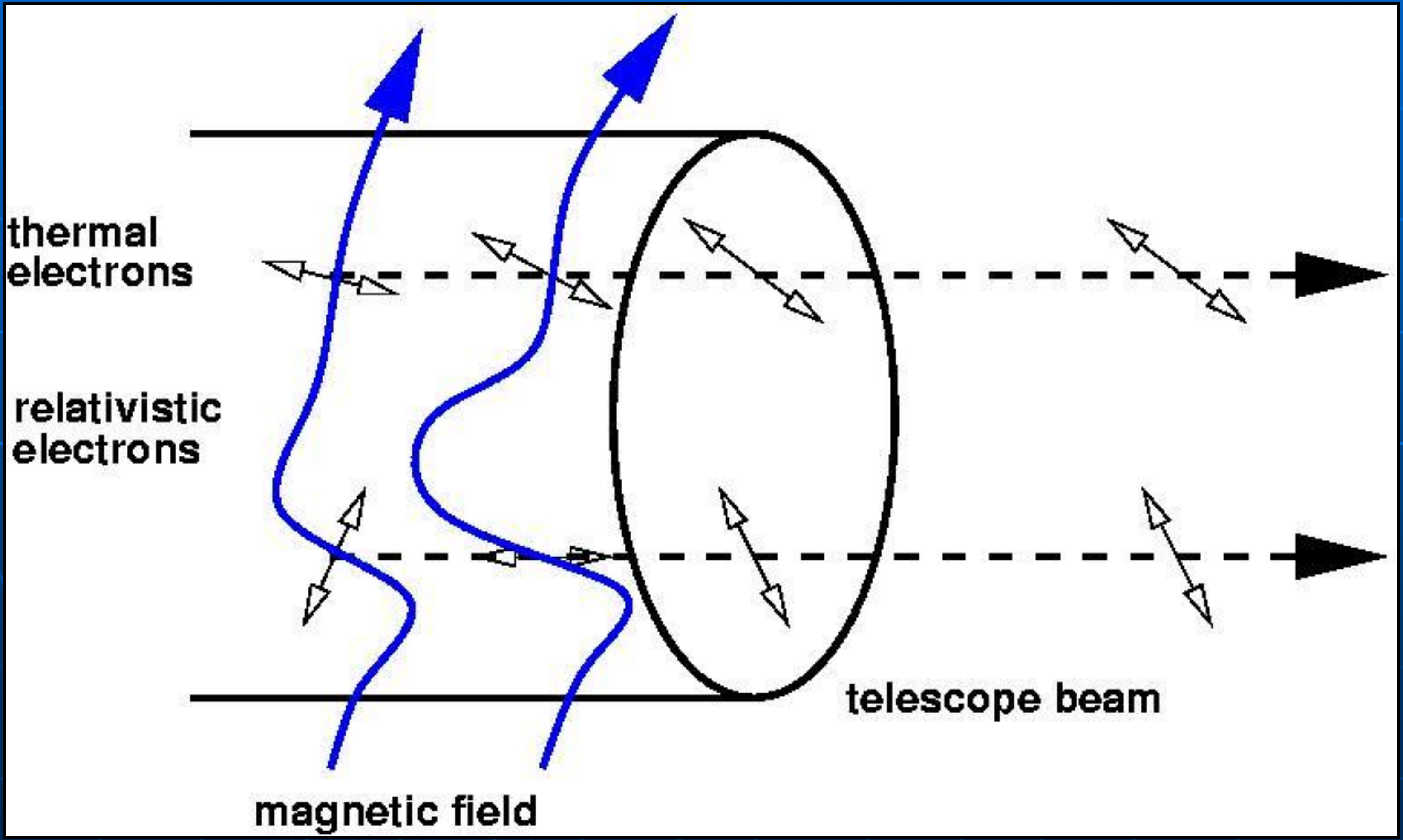
Rotation measure gradient
(wavelength-dependent)

Fletcher et al. 2004



Internal Faraday dispersion
(wavelength-dependent)

Fletcher et al. 2004



Depolarization effects

- Turbulent fields (wavelength-independent):

  $$p = p_o / N^{1/2}$$

  (where *N* is the number of turbulent field cells)

- Differential Faraday rotation (wavelength-dep.):

  $$p = p_o \left|\sin (2\, RM\, \lambda^2)\right| / (2\, RM\, \lambda^2)$$

- Internal Faraday dispersion (wavelength-dep.):

  $$p = p_o (1 - \exp (-2\, \sigma_{RM}{}^2\, \lambda^4) / (2\, \sigma_{RM}{}^2\, \lambda^4)$$

- External Faraday dispersion (wavelength-dep.):

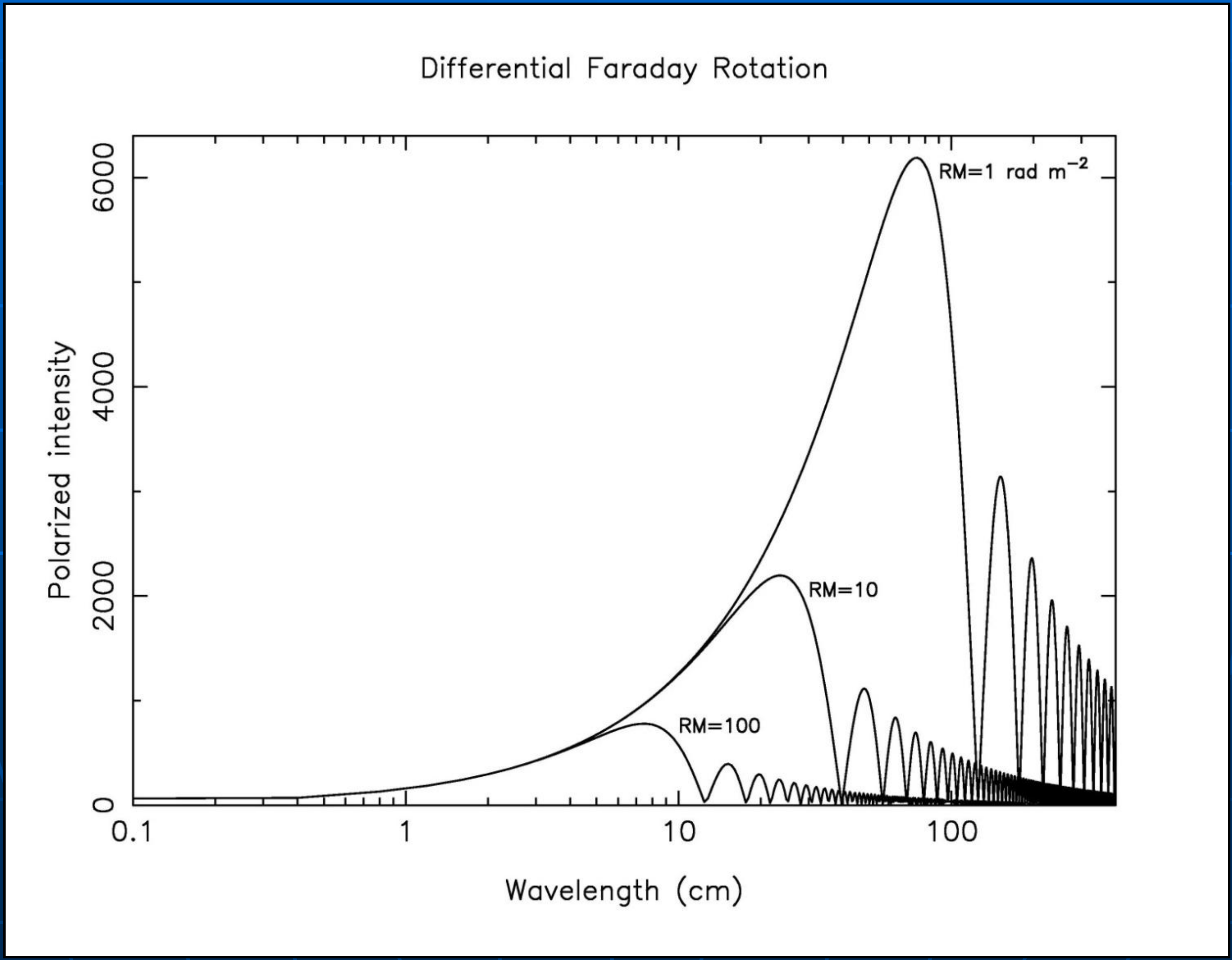
  $$p = p_o \exp(-2\, \sigma_{RM}{}^2\, \lambda^4)$$

- Faraday dispersion:

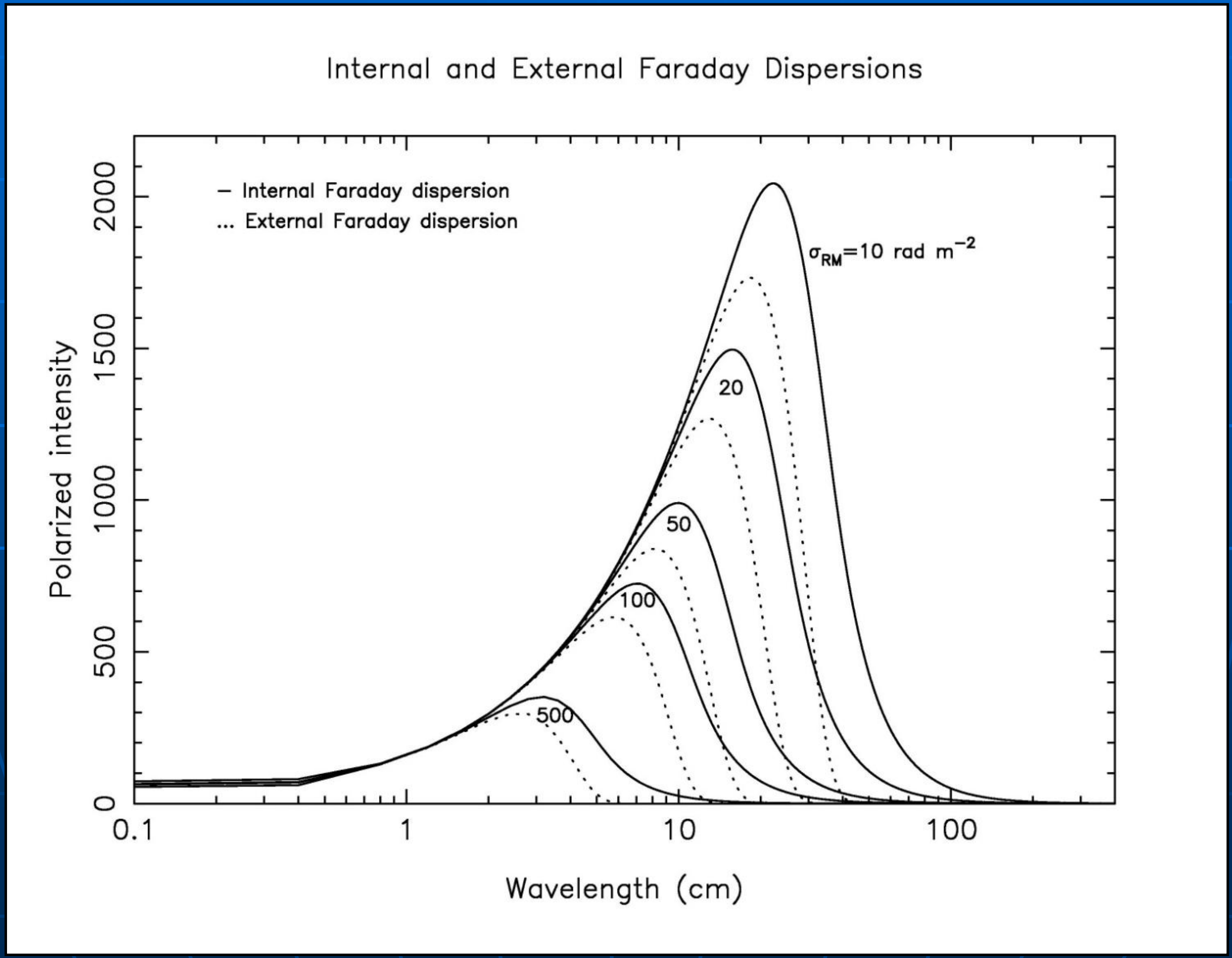
  $$\sigma_{RM}{}^2 = (0.81\, n_e\, B_r)^2\, L\, d\, f_v$$

  (B_r is the turbulent field strength, *d* the size of the turbulent cells)

Maximum polarization

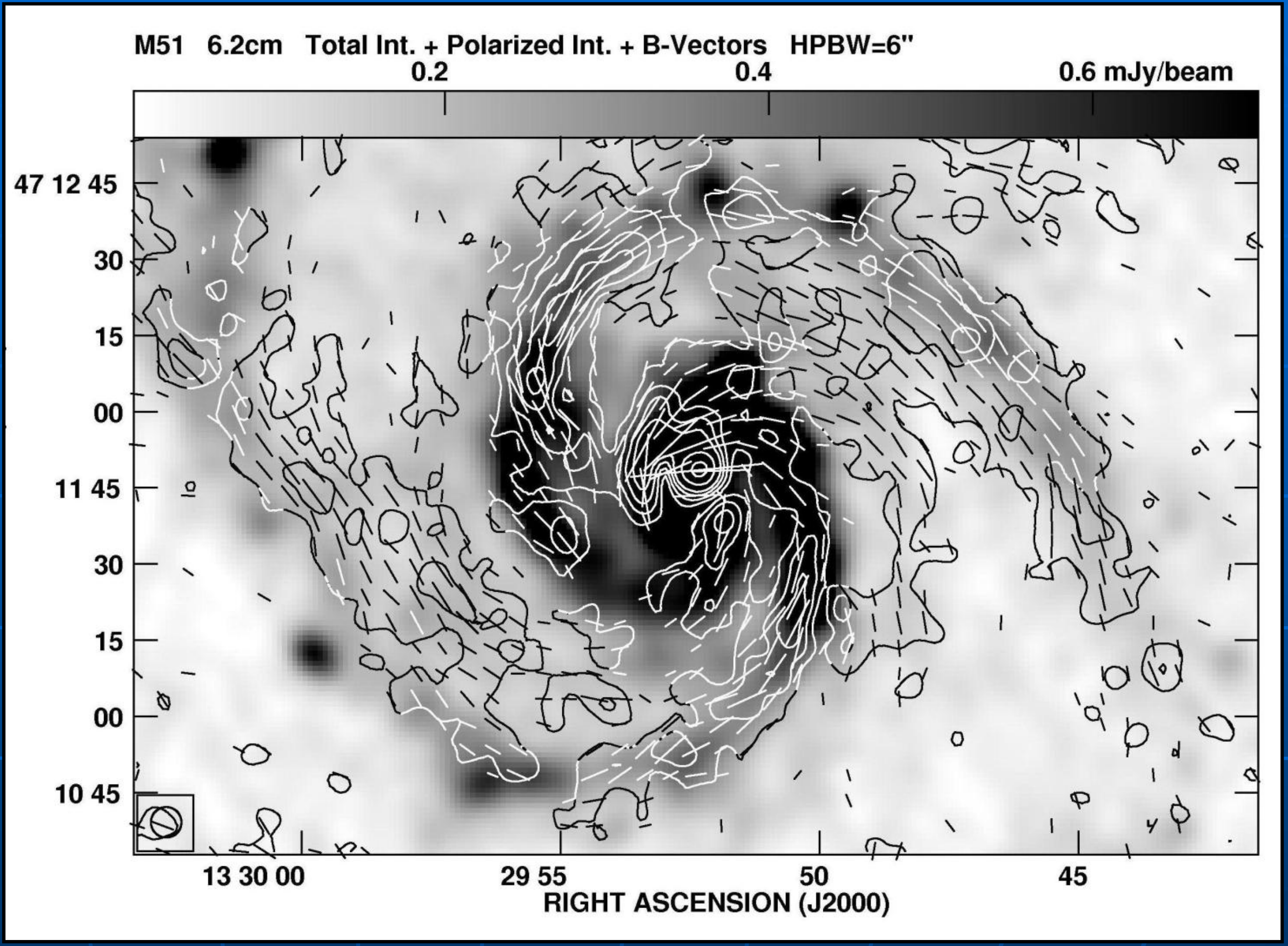


Maximum polarization



M 51

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

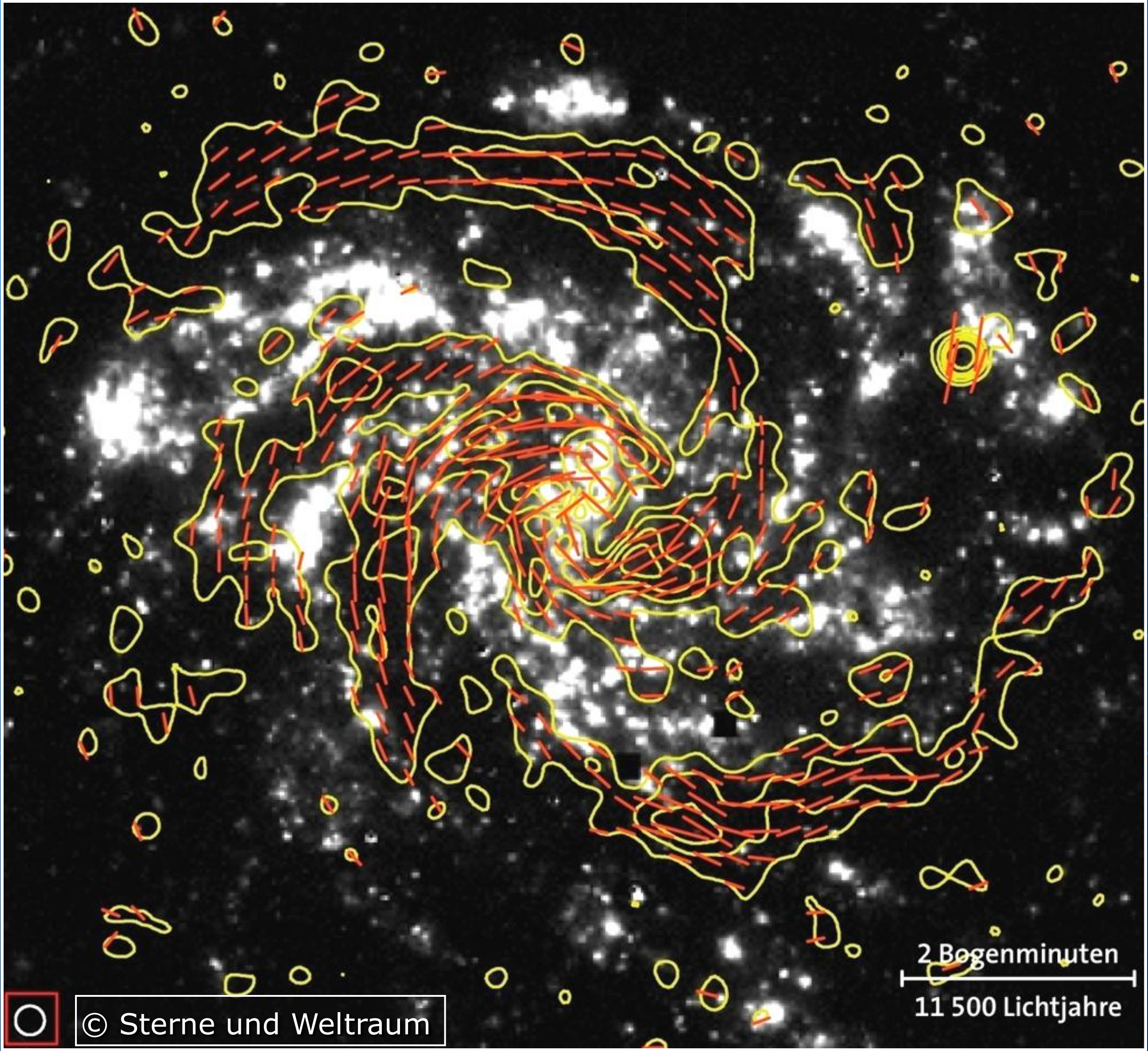


Spiral fields perfectly parallel to the inner spiral arms

(density-wave compression or shear)

NGC 6946

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



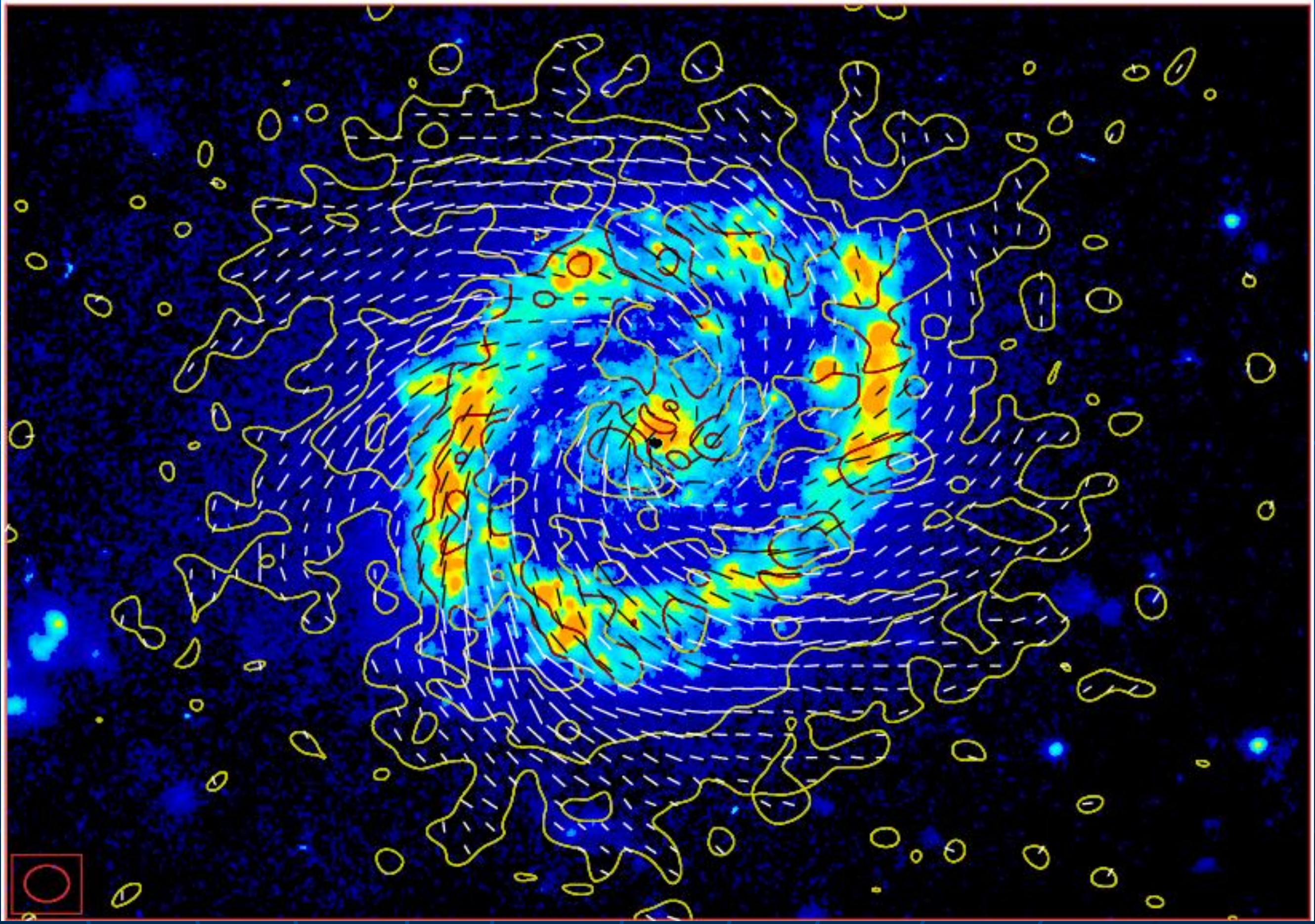
"Magnetic arms":

Ordered fields concentrated in interarm regions

NGC 4736

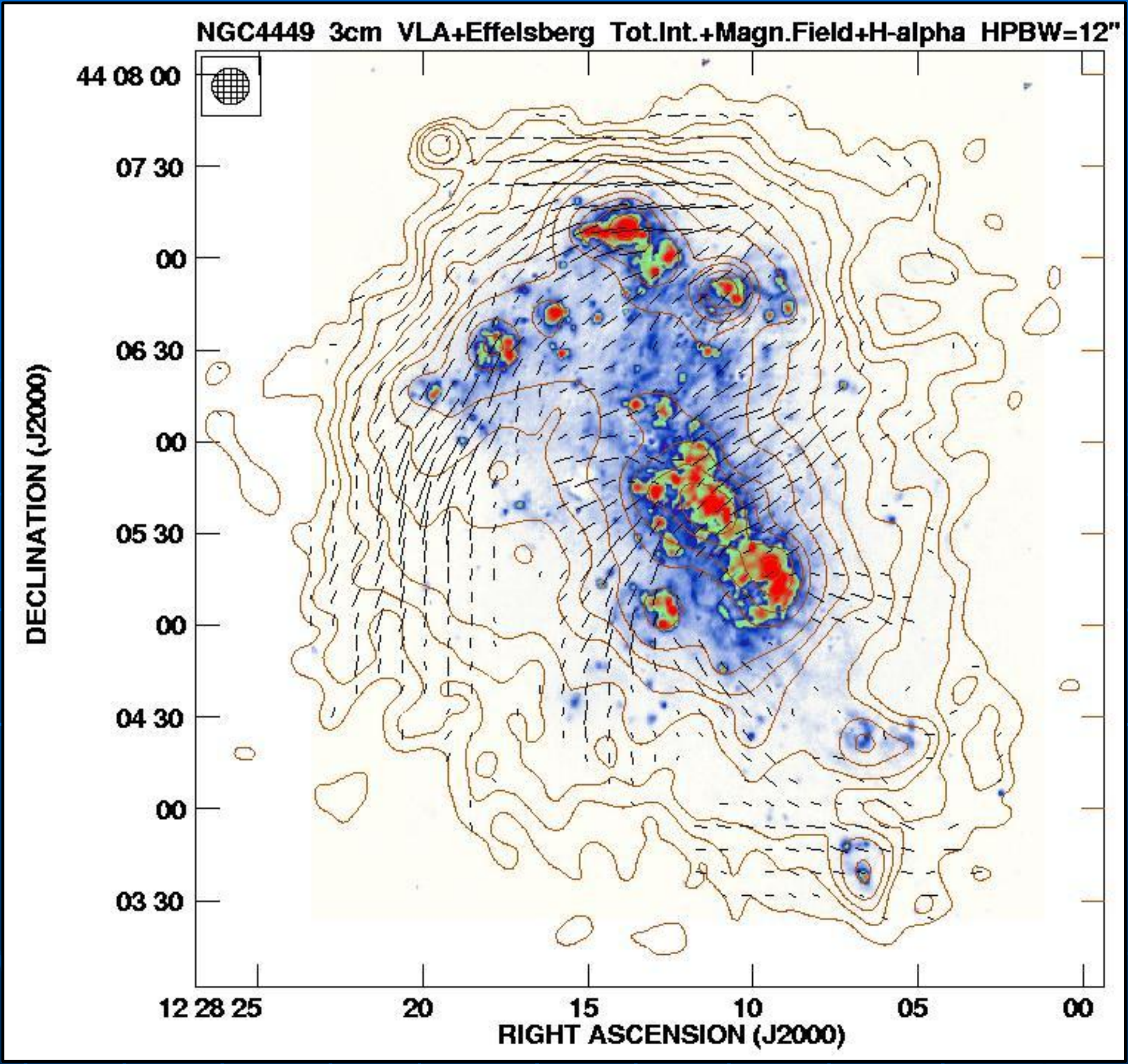
3cm VLA
Polarized intensity
+ B-vectors
(Chyzy & Buta 2007)

Spiral fields
in a
ring galaxy



NGC 4449

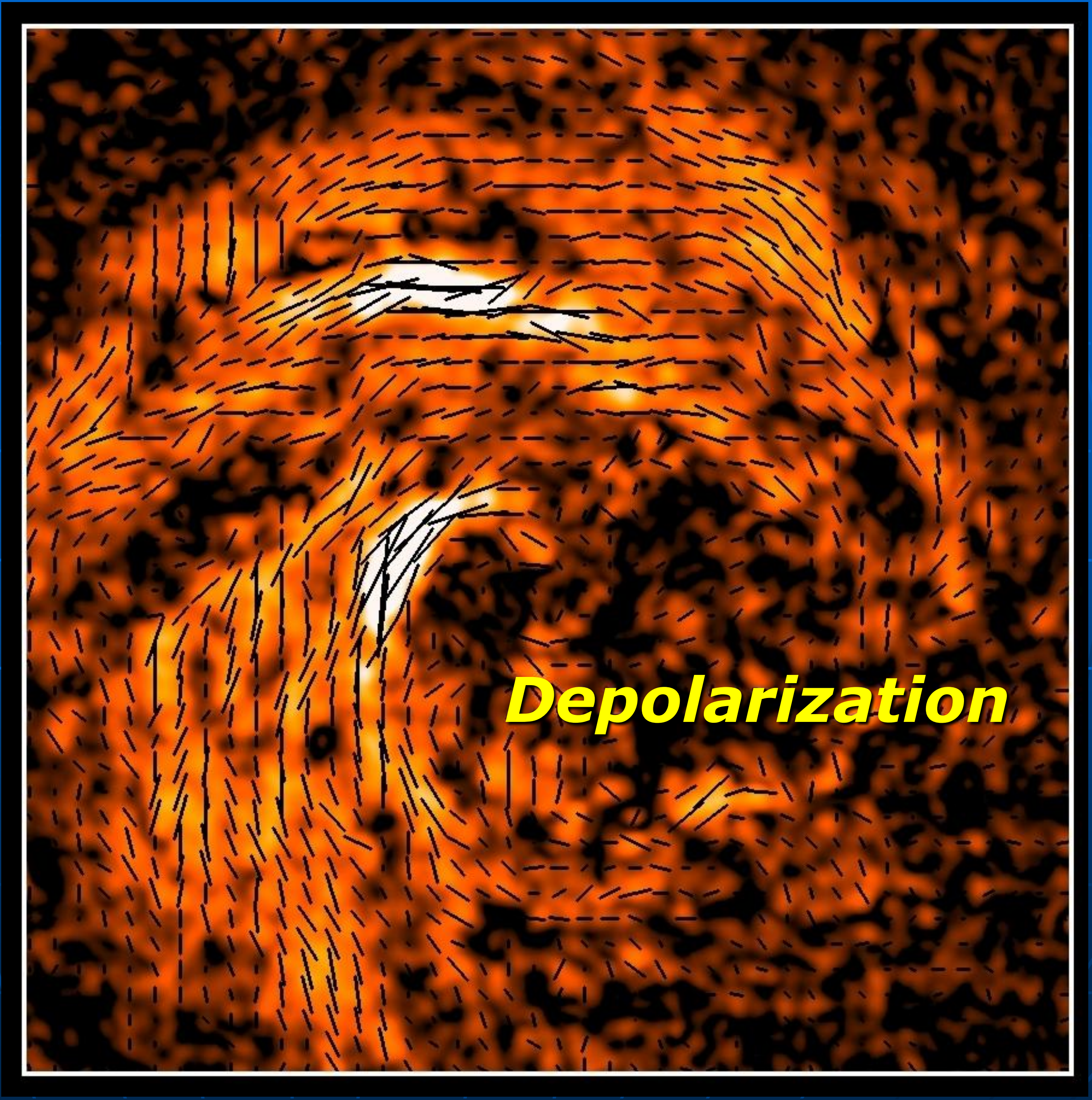
3cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Chyzy et al. 2000)



Regular field
in an irregular
galaxy

NGC6946

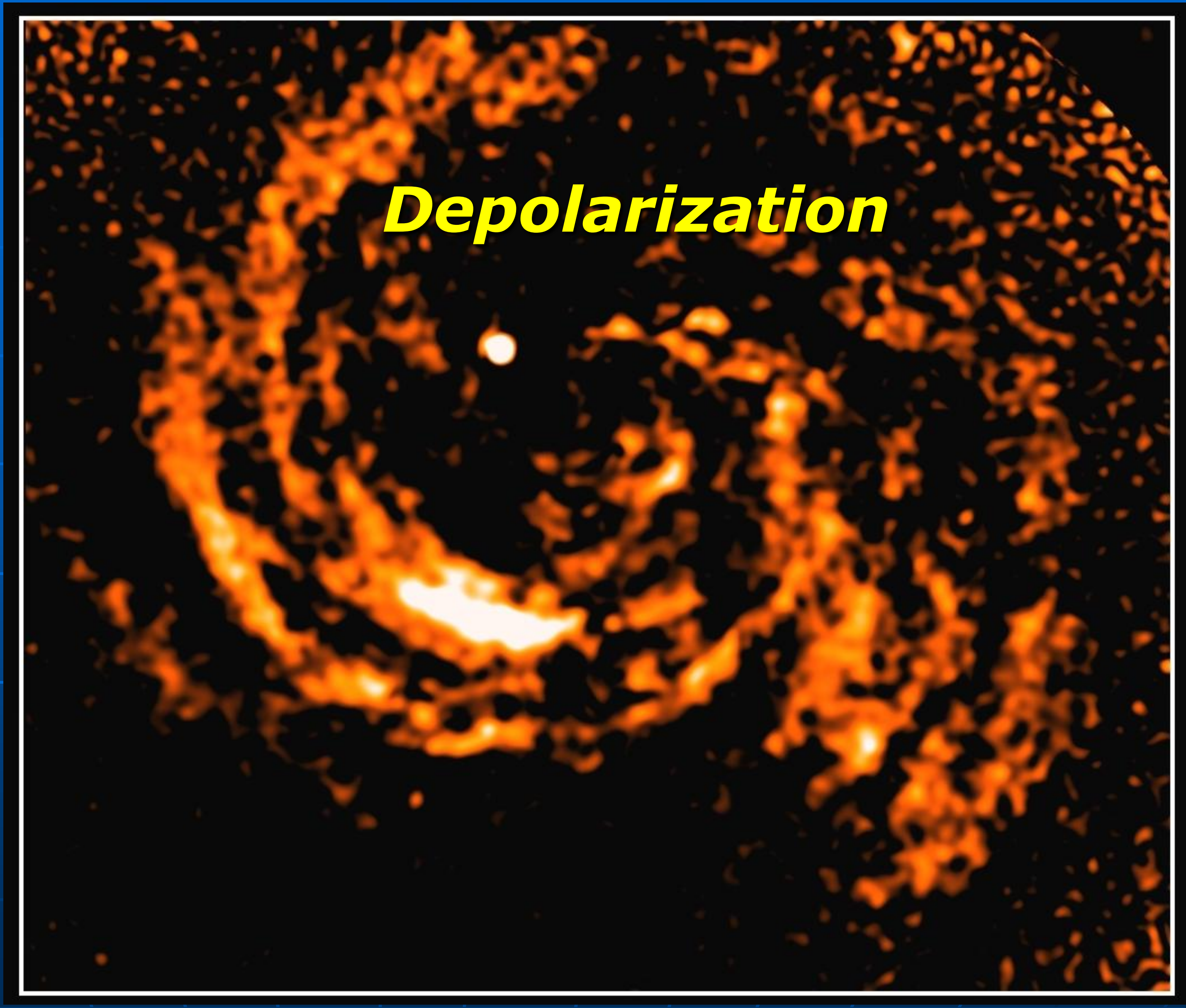
20cm VLA
Polarized intensity
+ B-vectors
(Beck 2007)



Stronger
Faraday
depolarization
around the
southwestern
major axis

IC 342

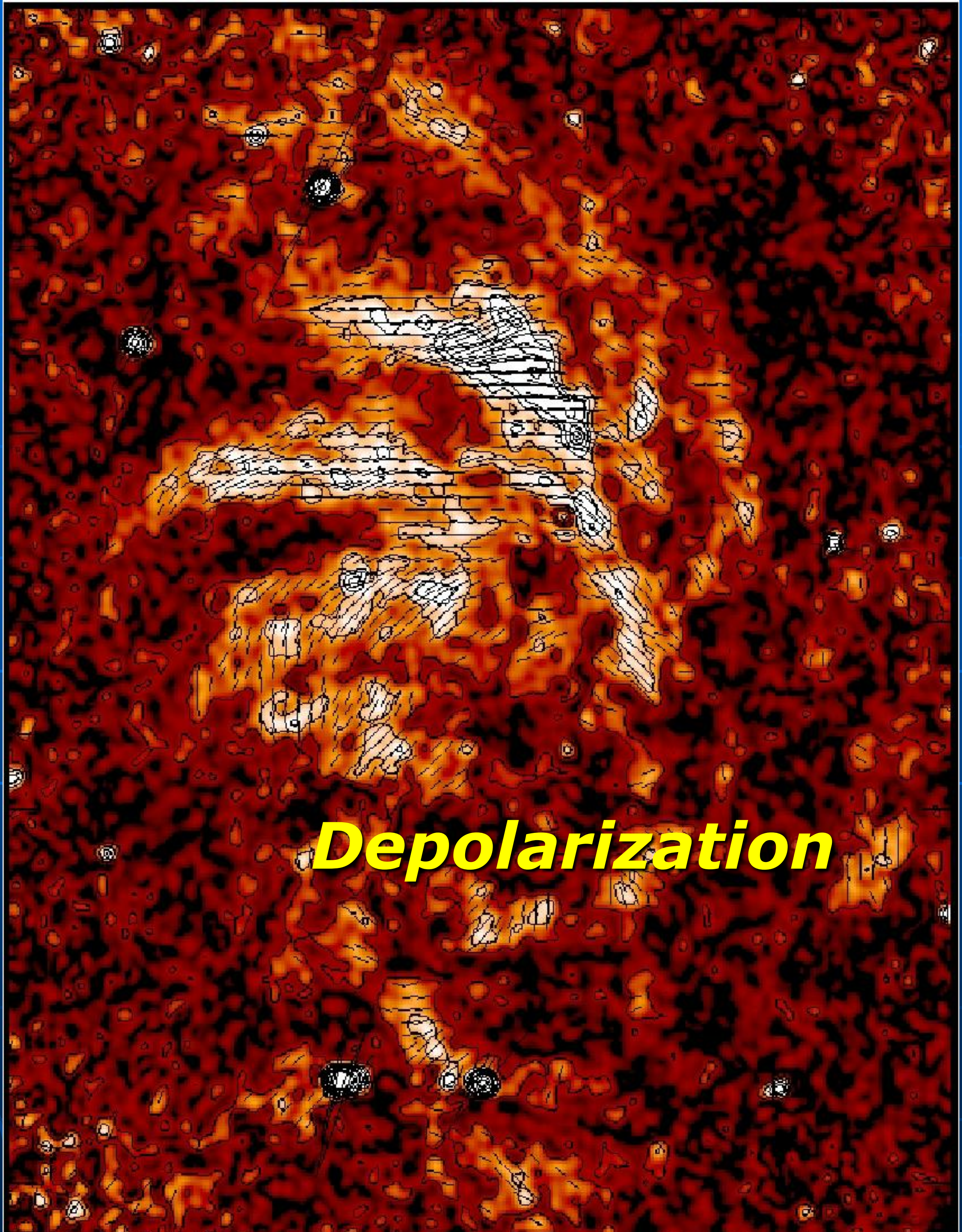
20cm VLA Polarized intensity (Beck 2006)



Stronger Faraday depolarization around the northern major axis

M33

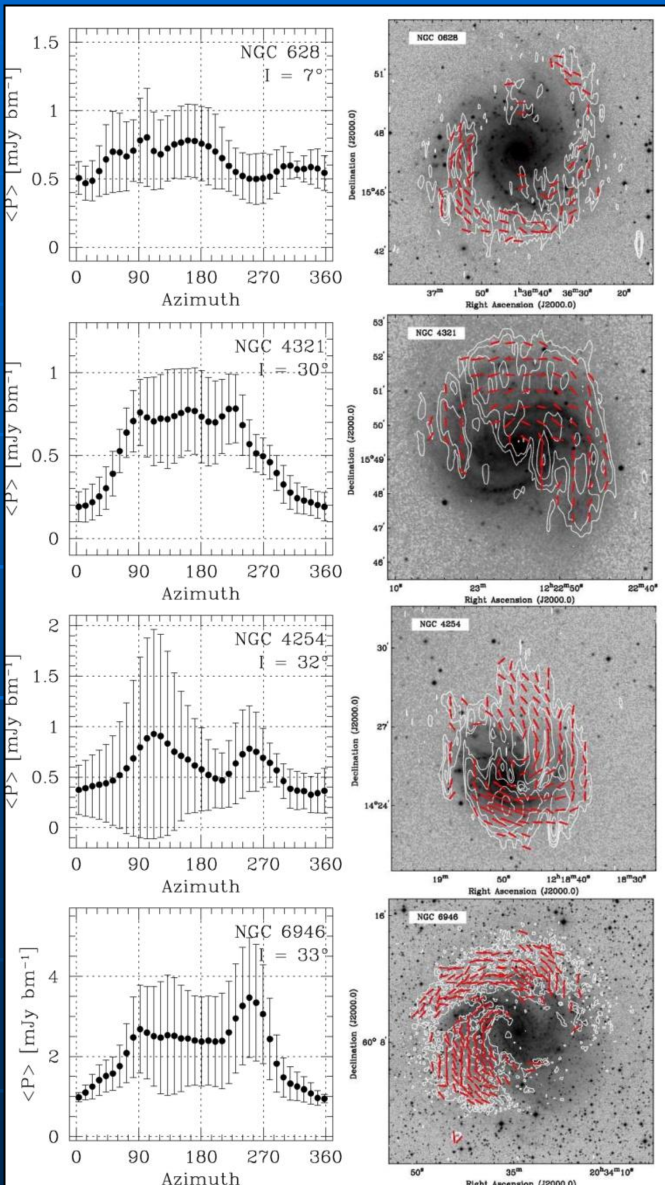
20cm
VLA+Effelsberg
Polarized intensity
(Tabatabaei et al. 2007)

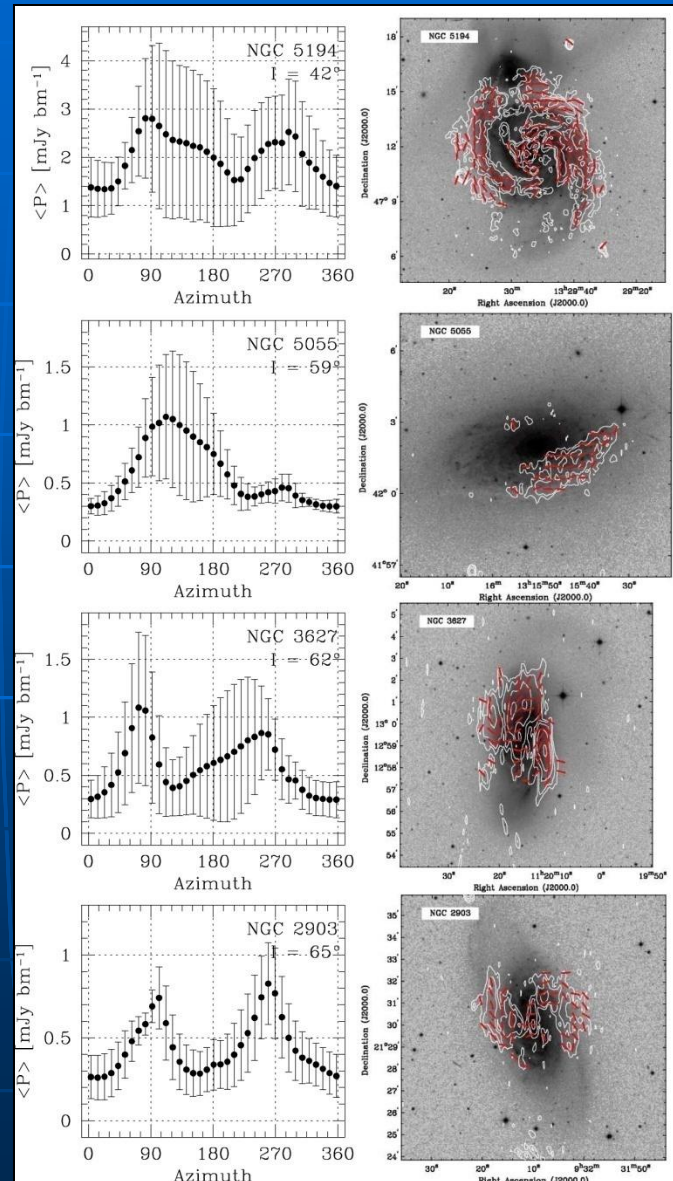


Stronger Faraday depolarization around the southern major axis

Polarization asymmetry

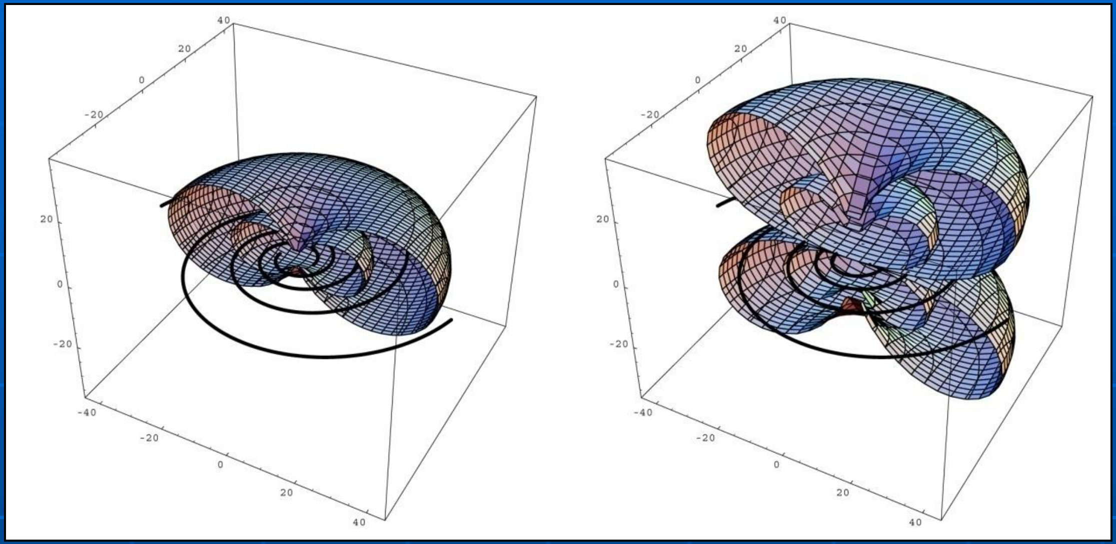
Braun et al. 2010

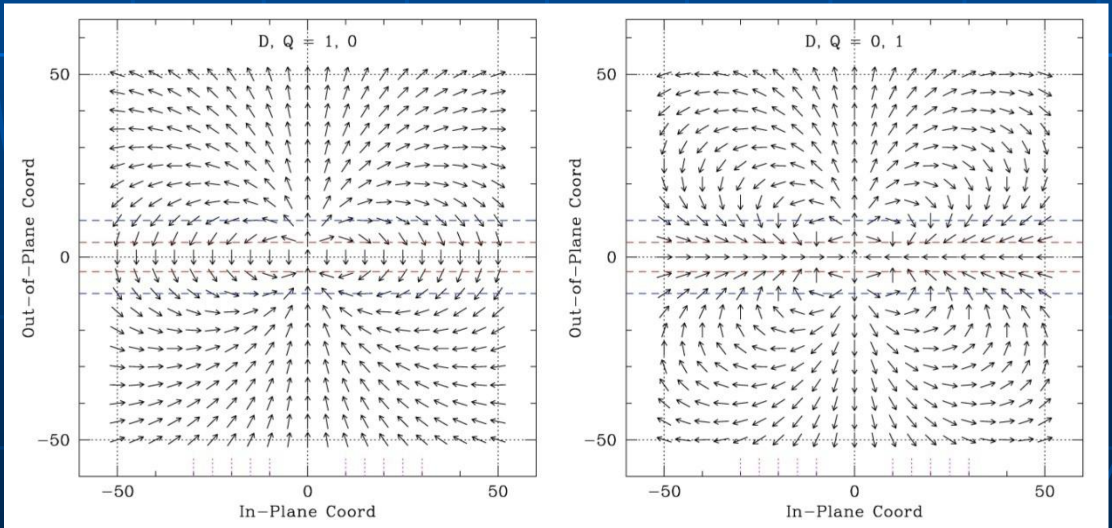




Polarization asymmetry: Dipole and quadrupole models

Braun et al. 2010



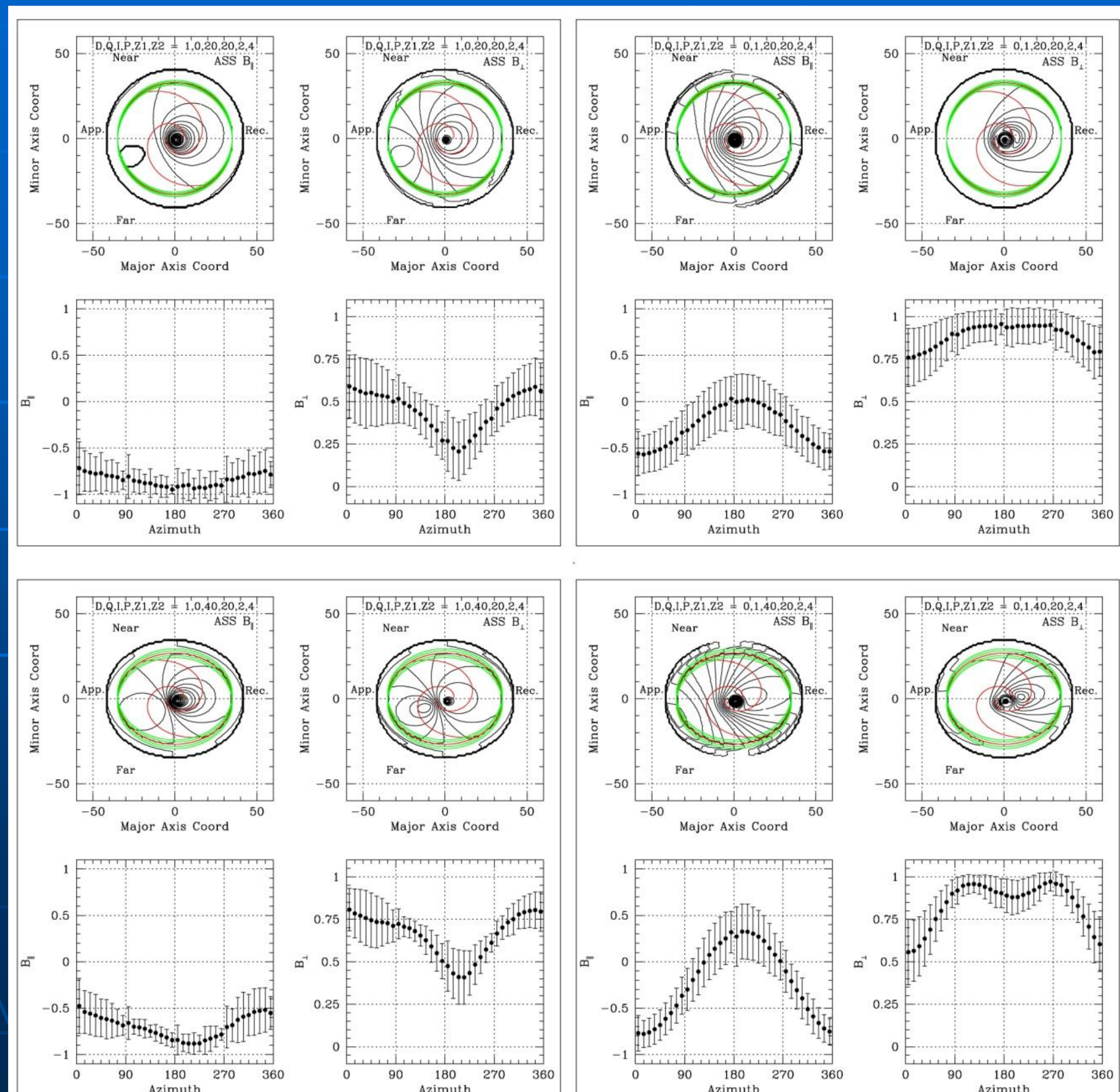


Polarization asymmetry: Dipole and quadrupole models

Braun et al. 2010

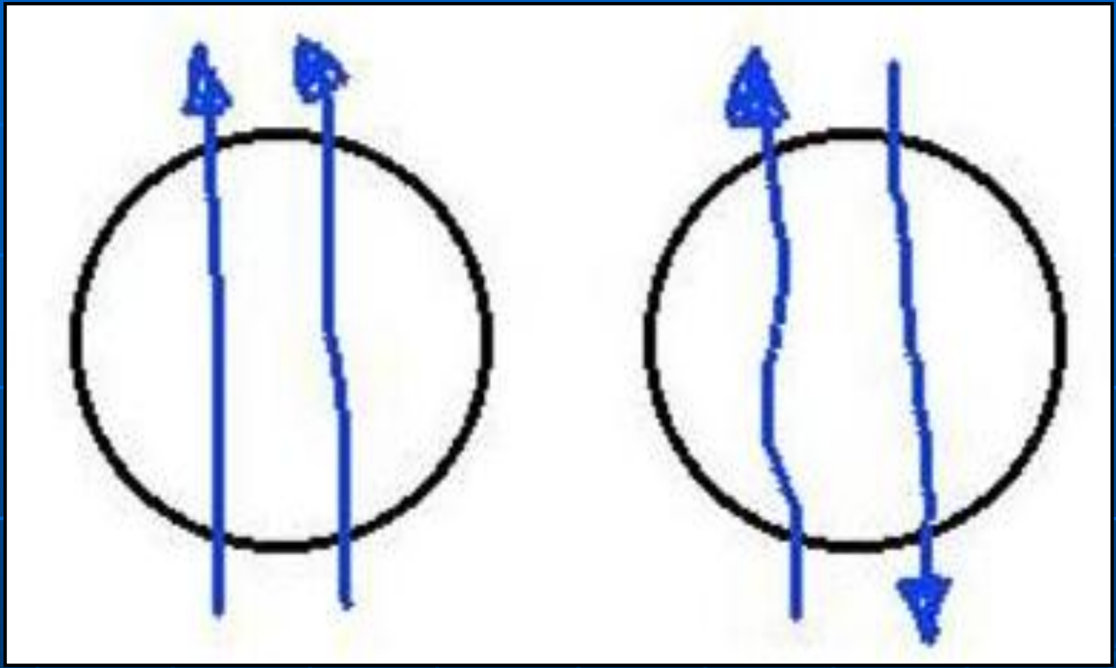
i = 20°

i = 40°



Fletcher et al. 2004

	Regular (coherent) field	Anisotropic (incoherent) field



Polarization :	strong	strong
Faraday rotation :	**high**	low

"Mean-field" dynamo theory for galactic fields

- Ingredients:
  Ionized gas + differential rotation + turbulence
- Dynamical separation between large scales and small scales
- Microphysics approximated by the average parameters
  "alpha-effect" (helicity) and magnetic diffusivity
- Fast reconnection needed to obtain the large-scale field
- Dynamo equation for the large-scale "mean" field
- Solutions: large-scale modes

Mean-field dynamo models

- Generation of large-scale coherent fields (modes) described by a *toroidal* (r,Φ) and a *poloidal* (r,z) component
- Thin-disk galaxies:
  The lowest azimuthal mode with *quadrupolar* fields of *even* parity (*S0*) is excited most easily,
  toroidal field is much stronger than the poloidal field
- Spherical (halo) or thick-disk galaxies:
  The lowest azimuthal mode with *dipolar* fields of *odd* parity (*A0*) is excited most easily
- Dynamo modes in thin disks are stable (non-oscillating)
- Excitation of several modes possible

Antisymmetric and symmetric dynamo modes

Stix 1975

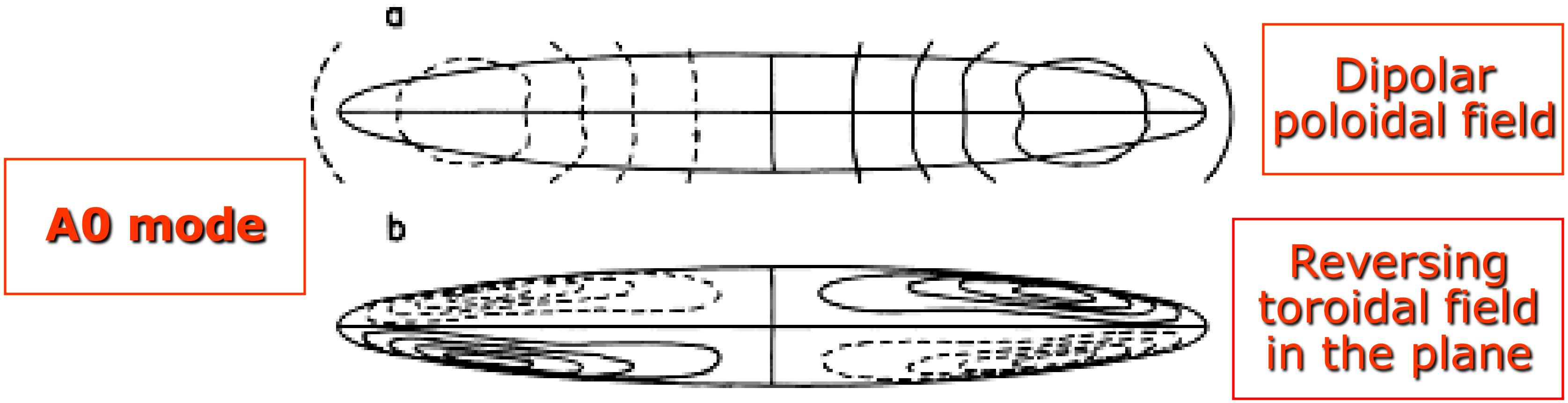


Fig. 1a and b. Poloidal field lines (a) and curves of constant toroidal field strength (b) for a dipole type field, with $R = 15$ kpc, $h = 2$ kpc, and $P = 1.1 \cdot 10^3$

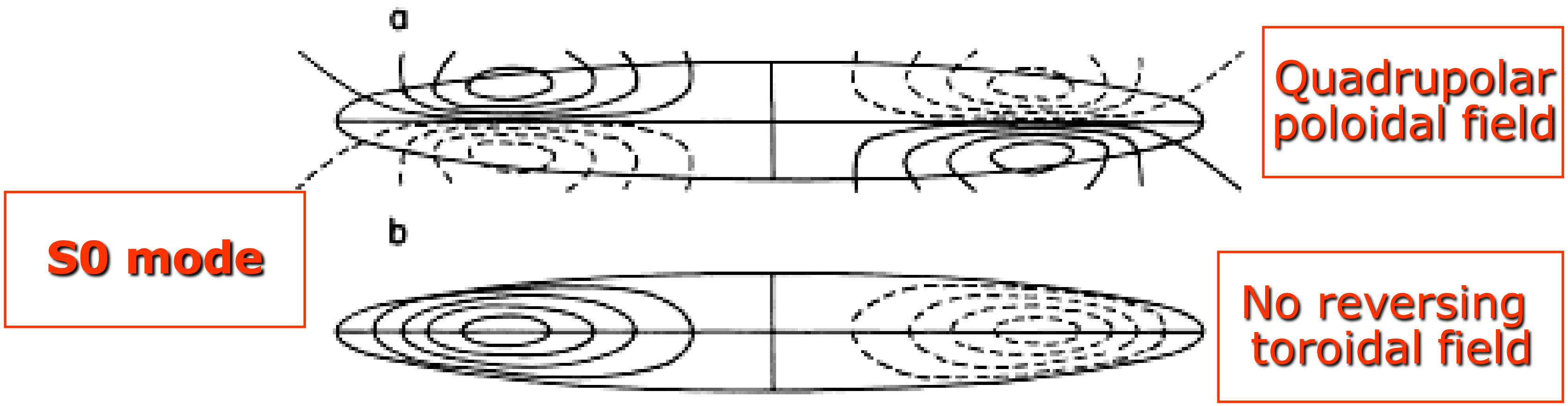
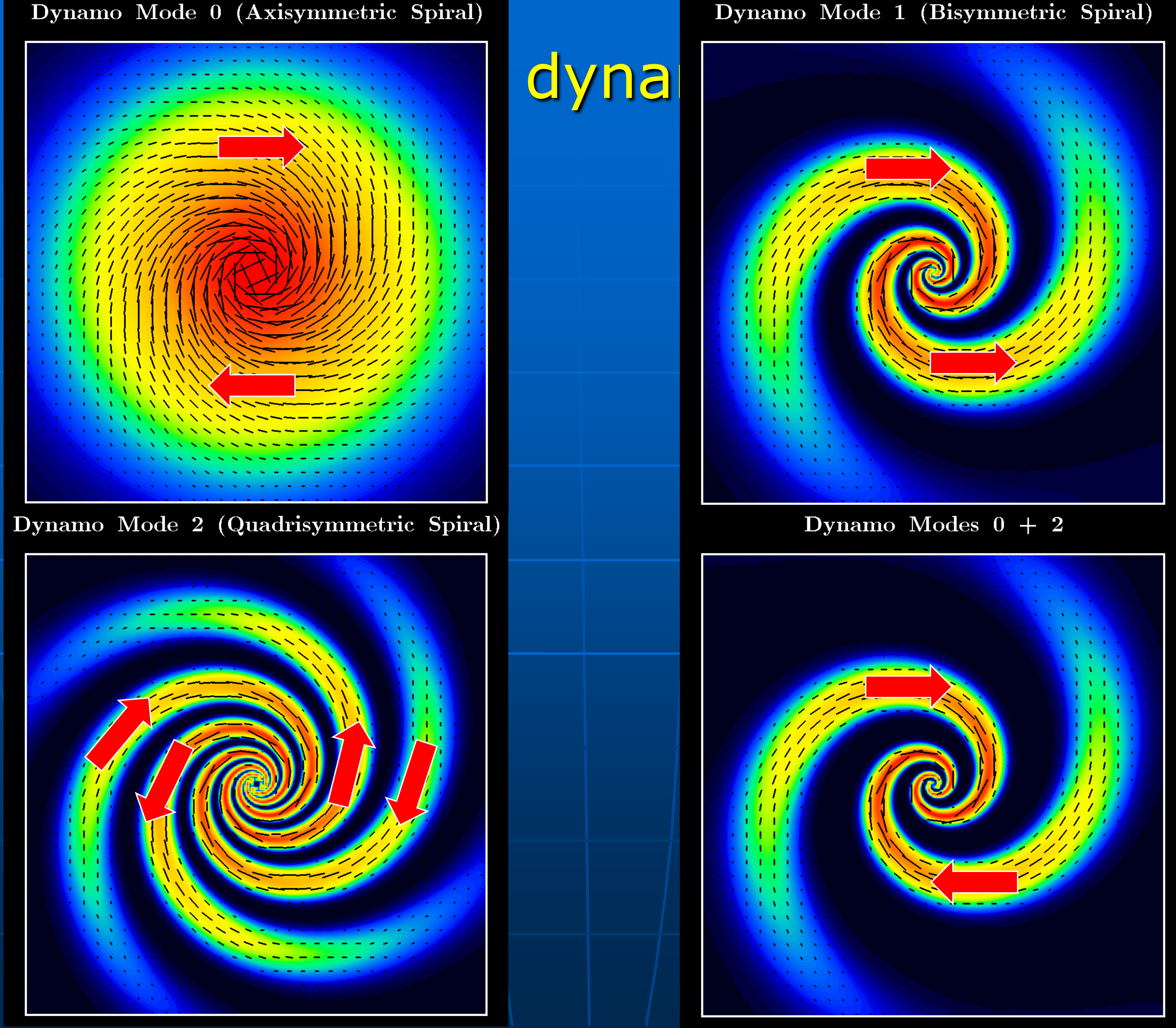


Fig. 2a and b. Poloidal field lines (a) and curves of constant toroidal field strength (b) for a quadrupole type field, with $R = 15$ kpc, $h = 2$ kpc, and $P = -8.5 \cdot 10^3$

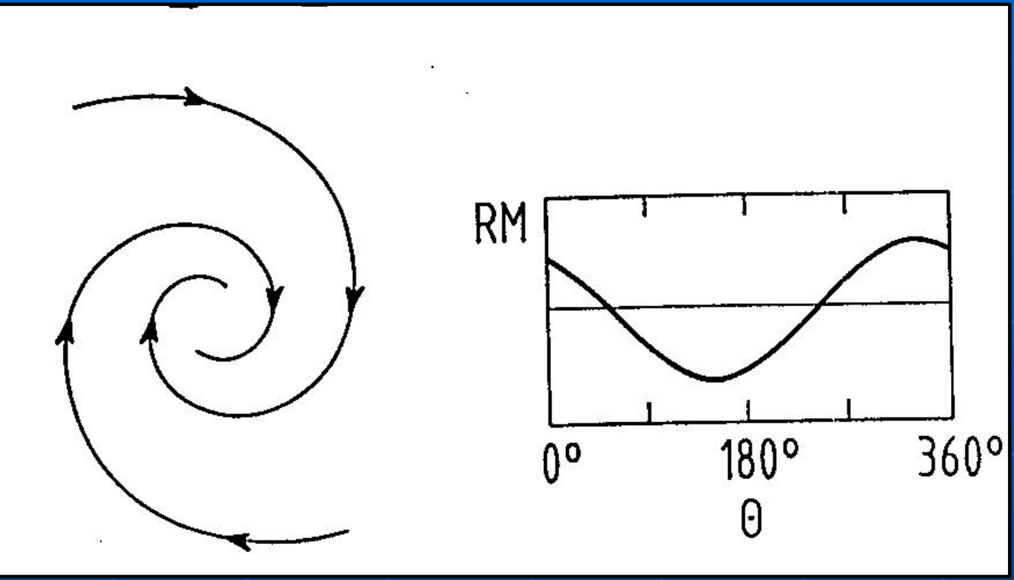
dyna



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

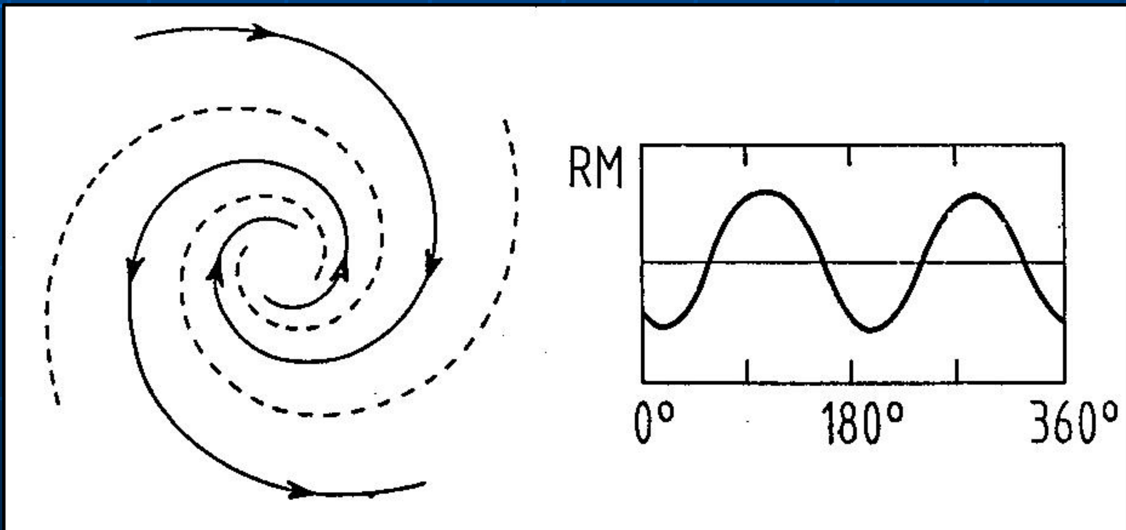
Finding dynamo modes:
Azimuthal variation of Faraday rotation

Krause 1990

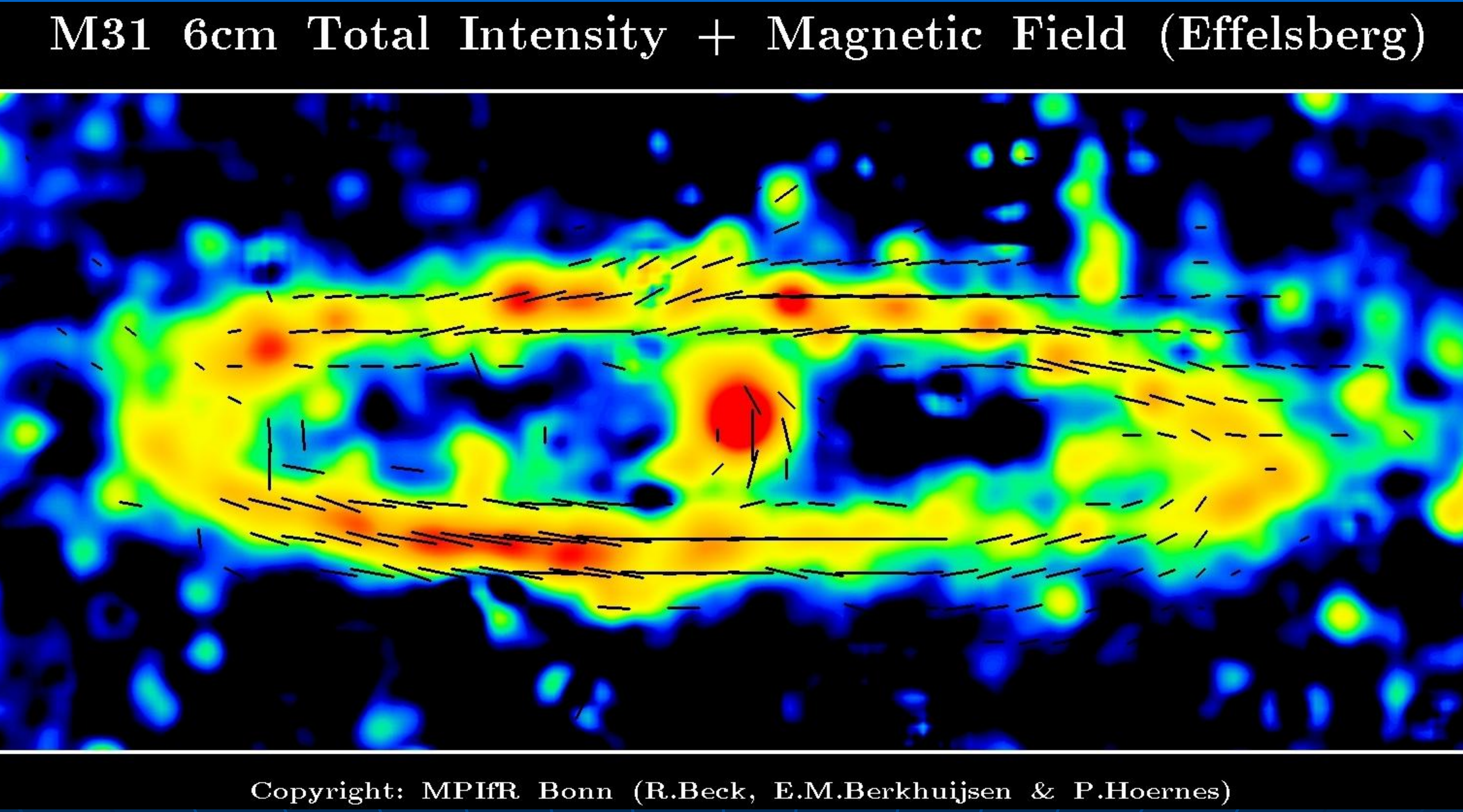


Axisymmetric spiral
(m=0)

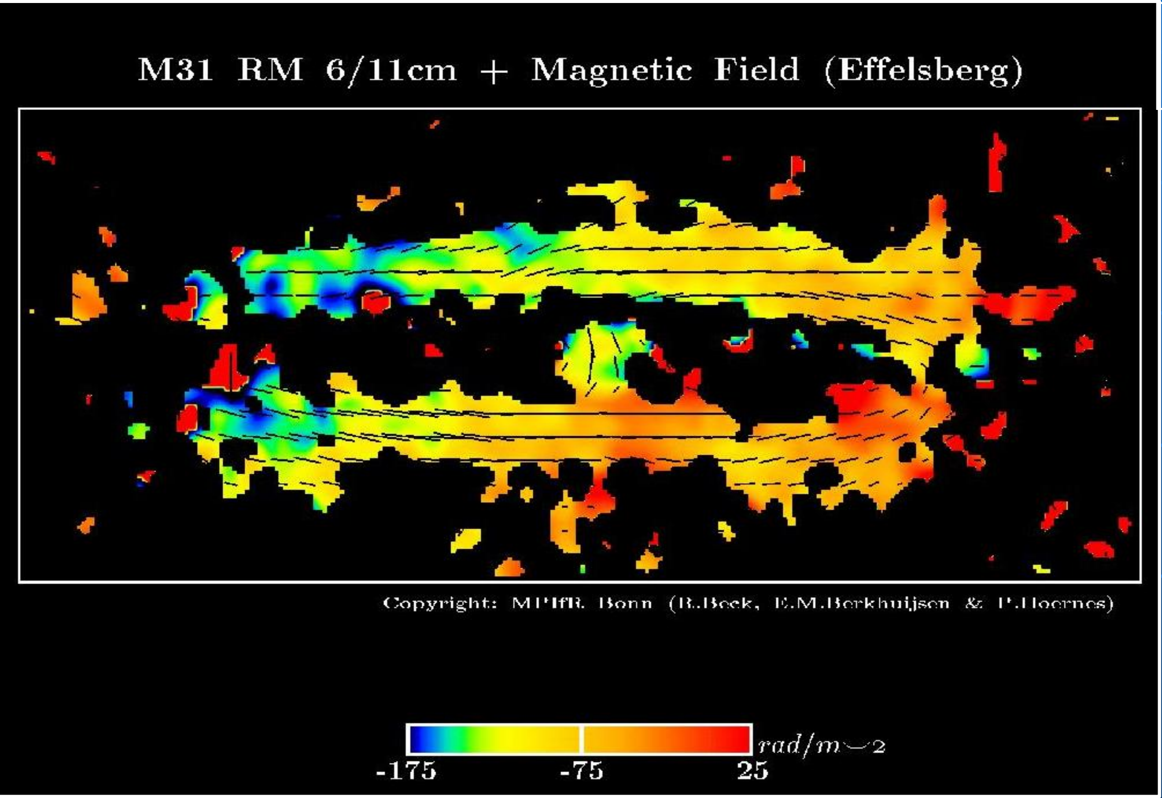
Bisymmetric spiral
(m=1)



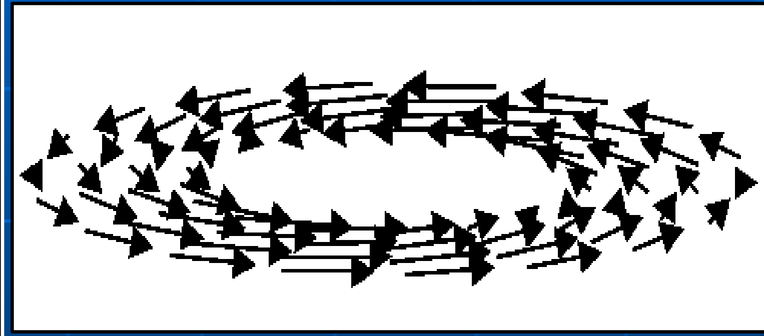
M31: The classical dynamo case



M31: The dynamo **IS** working !



Berkhuijsen et al. 2003



Fletcher et al. 2004

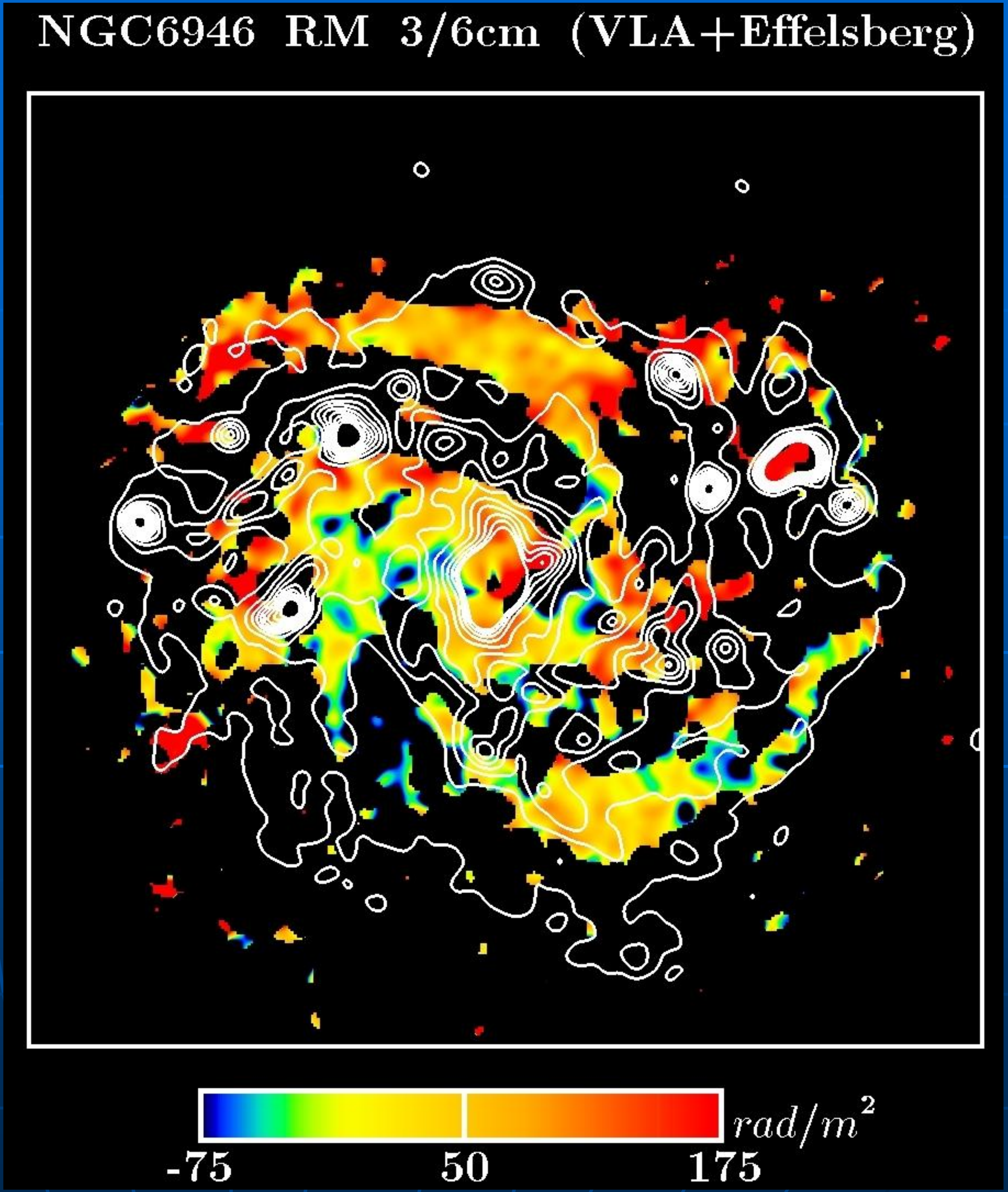
The spiral field of M31 is coherent and axisymmetric
(small spiral pitch angle, but no ring)

NGC 6946

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

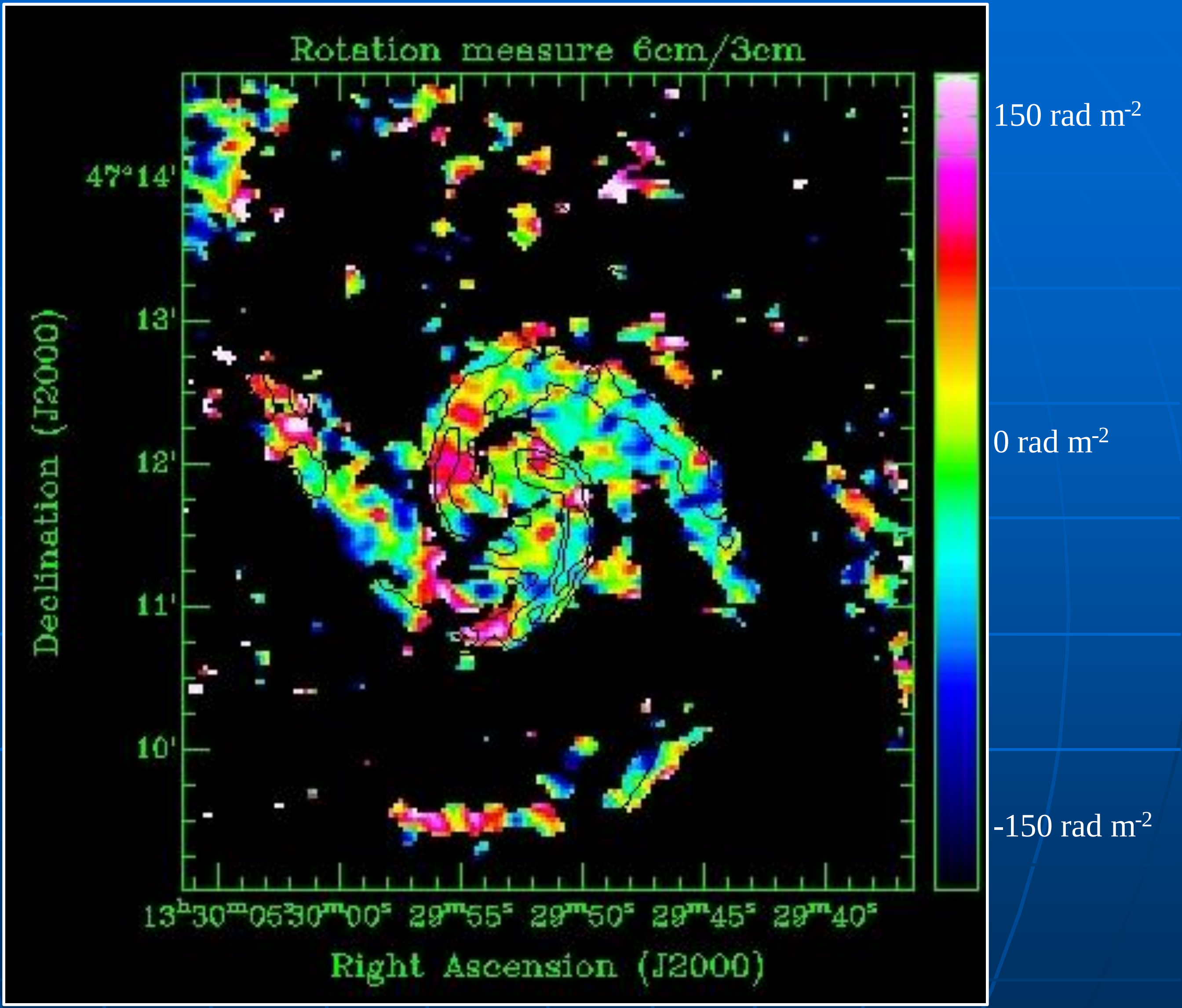
Inward-directed field:

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



M51

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



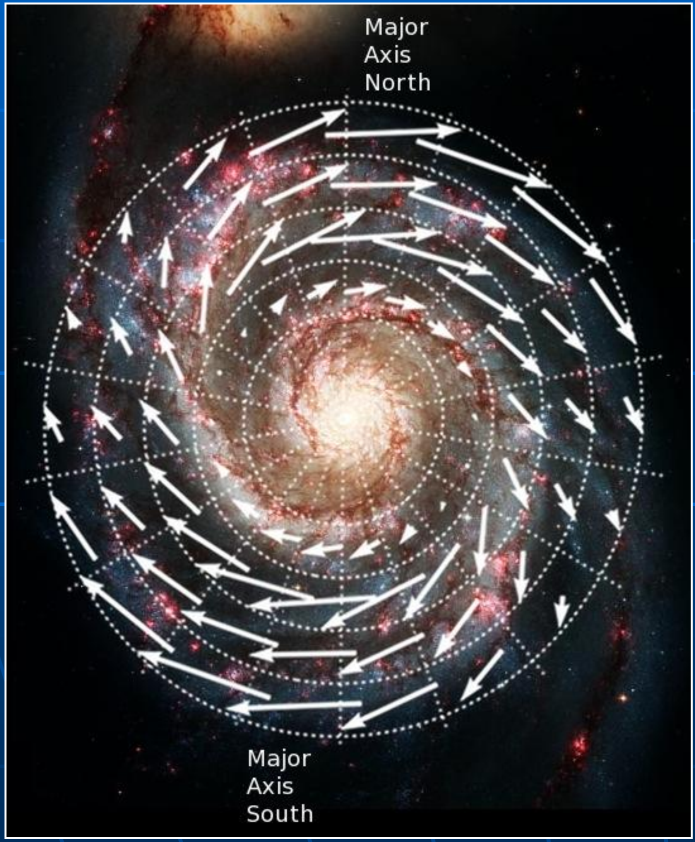
Complicated RM pattern:

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

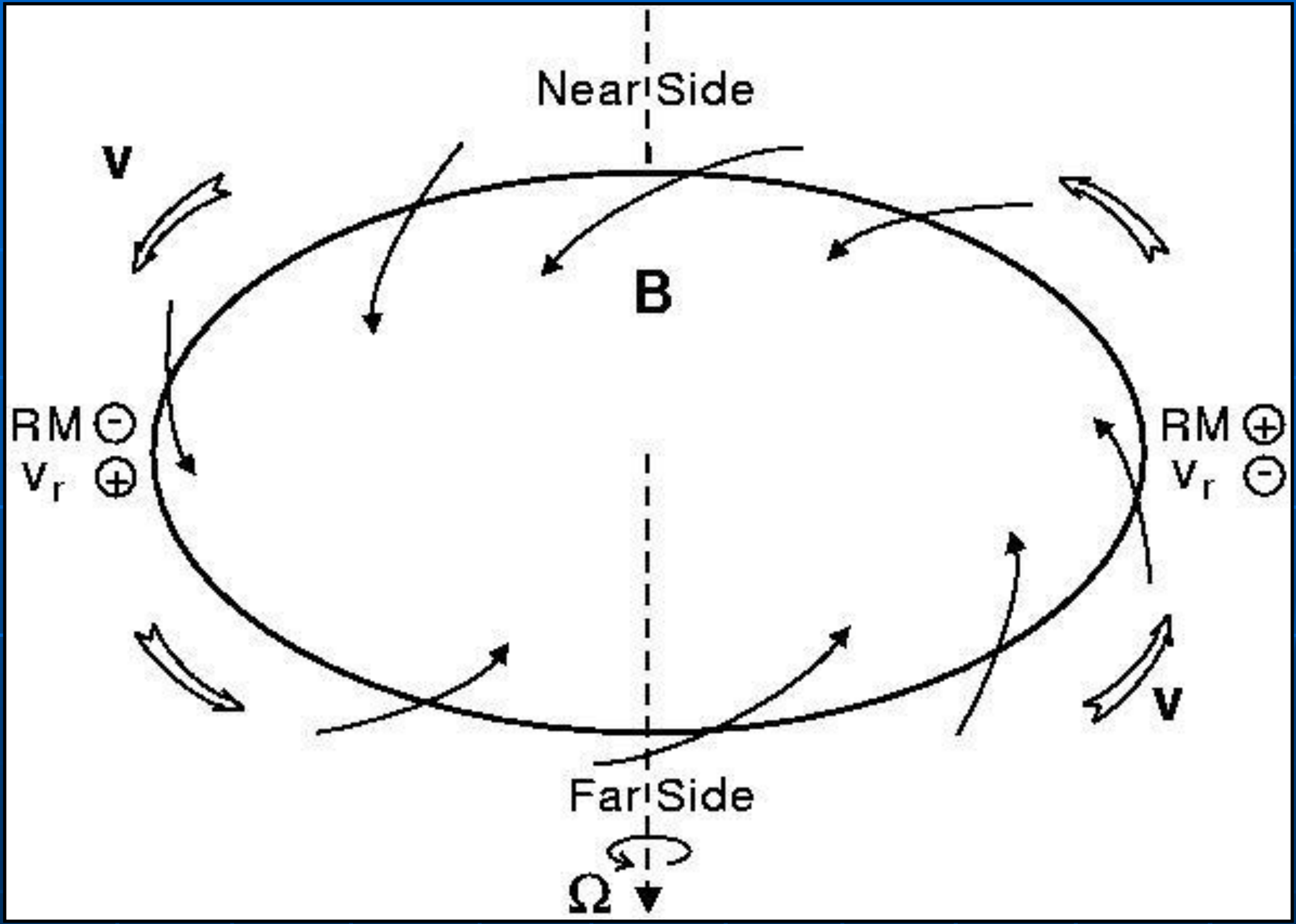
Field reversal between northern disk to inner halo – similar to that found for the Milky Way (Sun et al. 2008)

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 it is not yet fully developed

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:

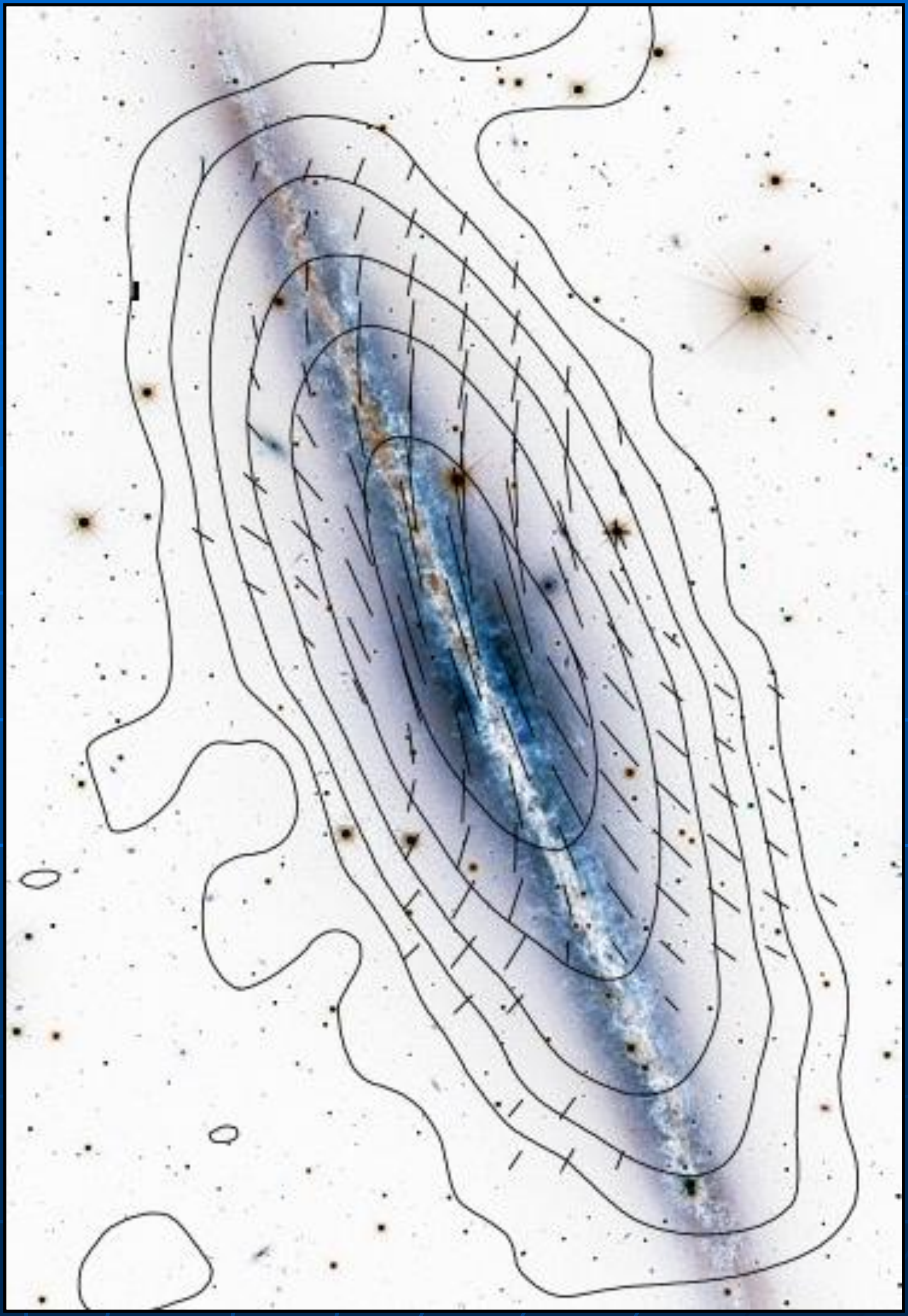
M31, IC342, NGC253, NGC1097, NGC6946

Outwards:

NGC4254, NGC 4736, NGC5775, M51 (disk)

NGC 891

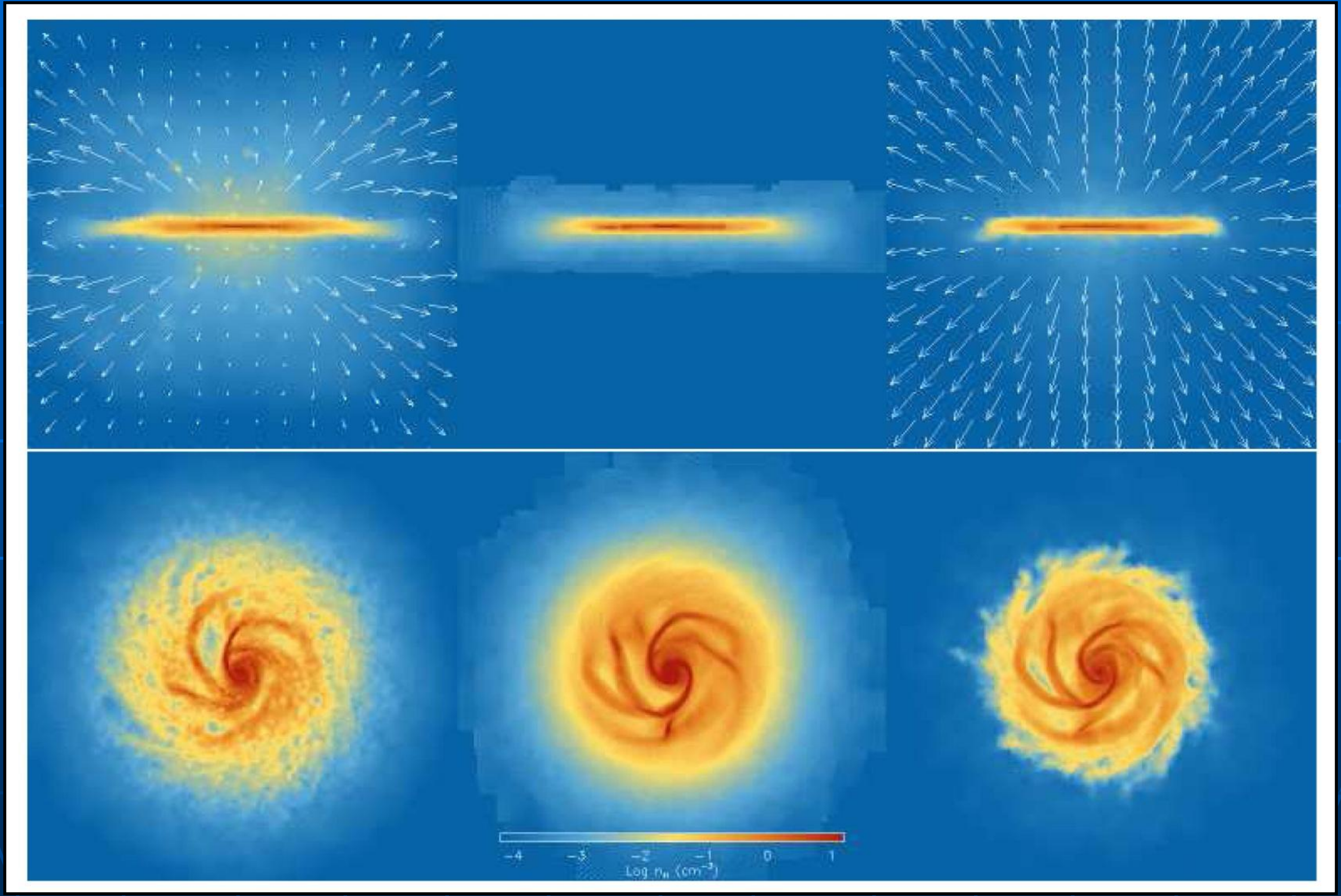
3cm Effelsberg
Total intensity
+ B-vectors
(Krause 2007)



Bright radio halo with
X-shaped field pattern:
quadrupolar pattern
or driven by a disk wind?

SN-driven outflow

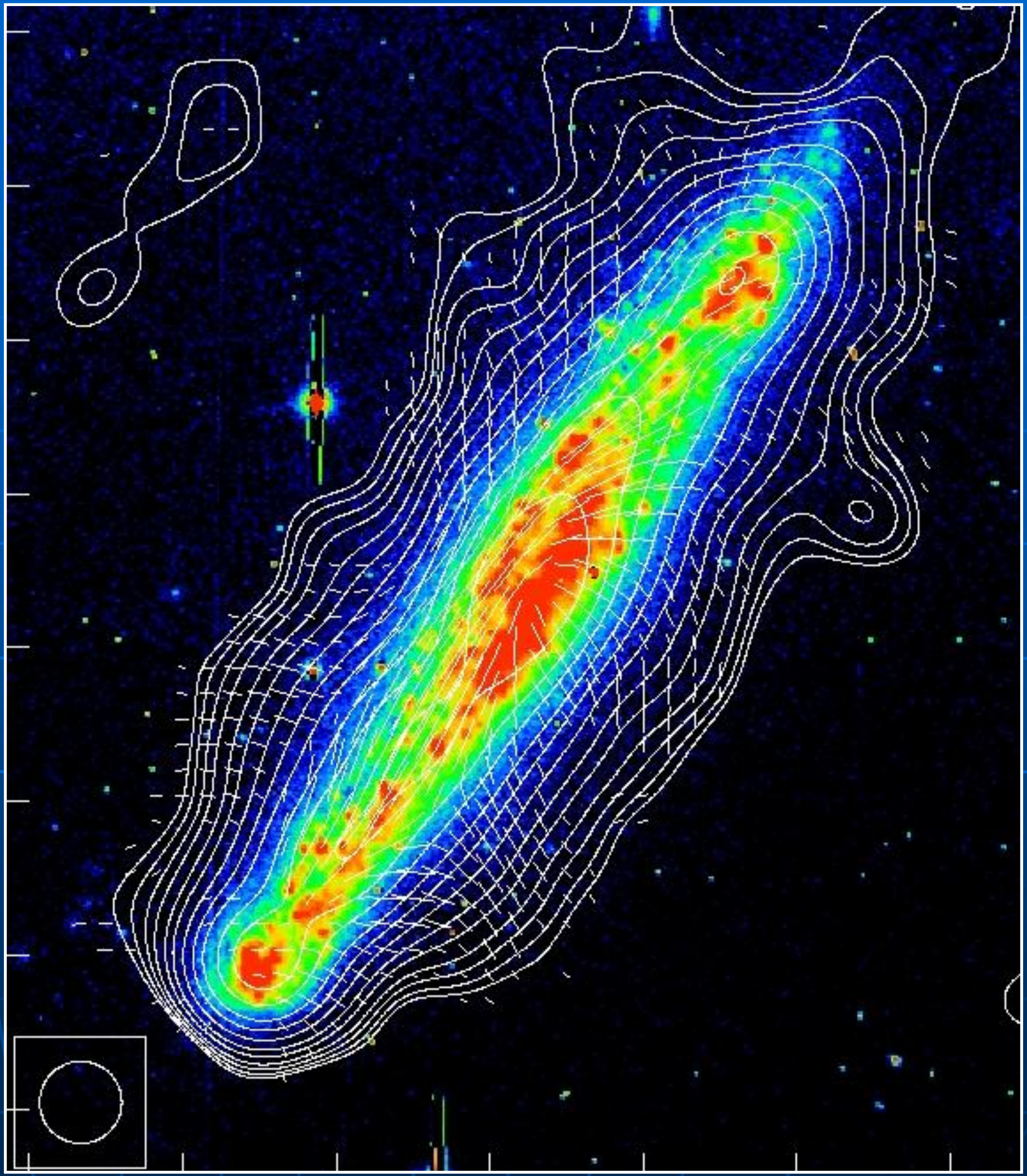
(HD model by Dalla Vecchia & Schaye 2008)



Interacting wind No wind Non-interacting wind

NGC 5775

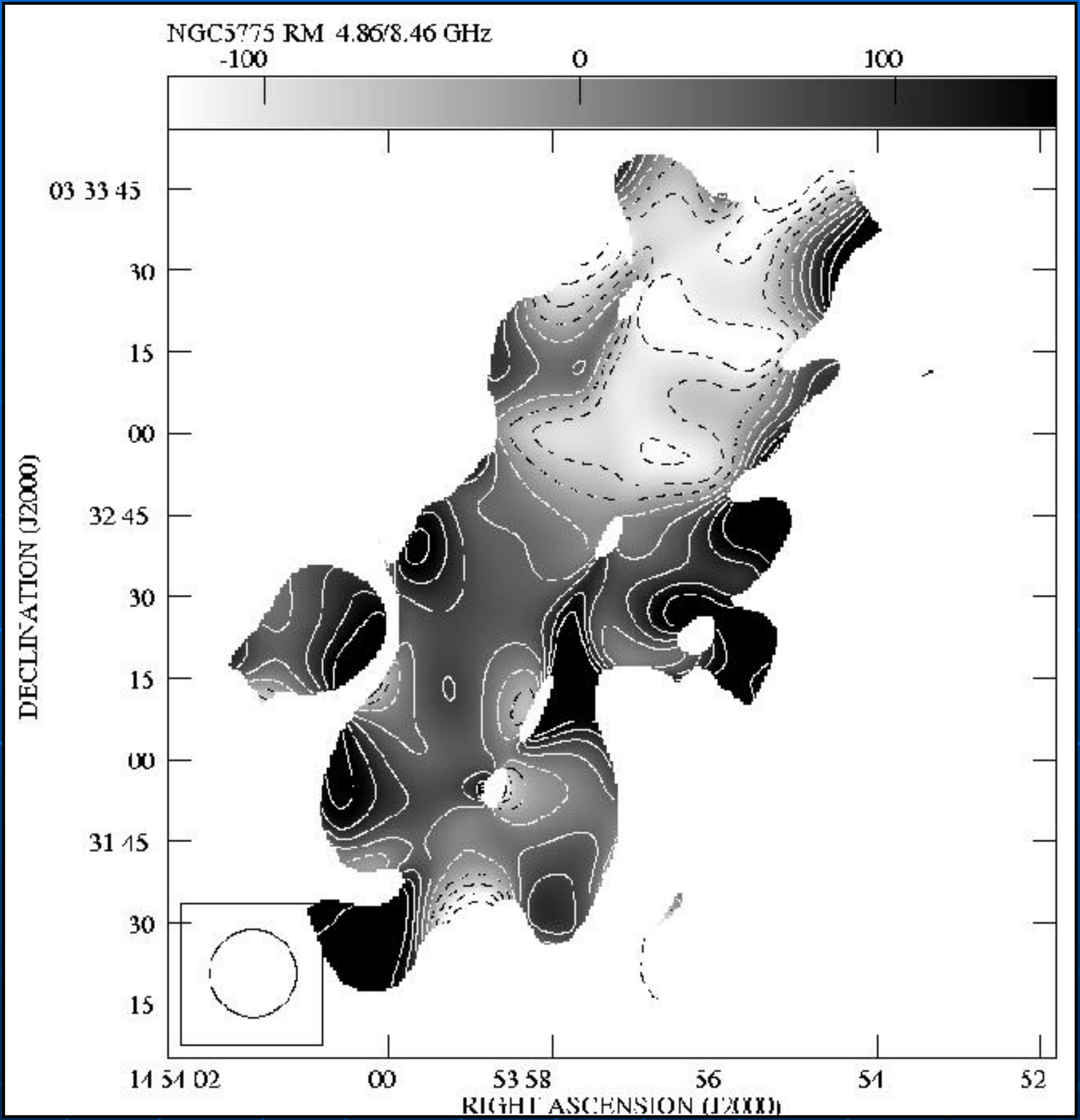
3cm VLA+Effelsberg
Total intensity
+ B-vectors
(Soida et al., in prep)



X-shaped
halo field

NGC 5775

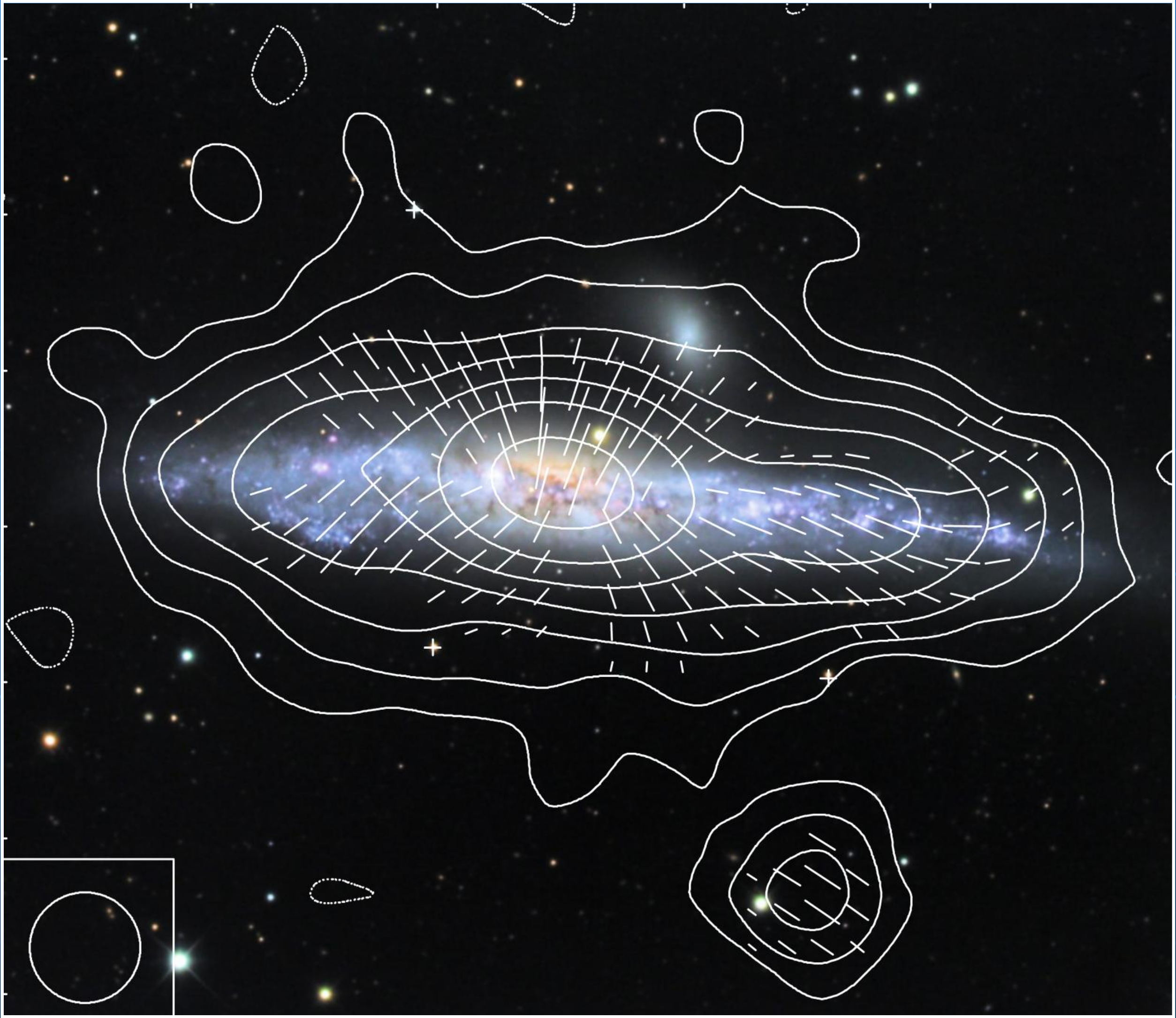
VLA+Effelsberg
RM 3/6cm
(Soida et al., in prep)



Axisymmetric dynamo mode in the disk

NGC 4631

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



Huge halo:

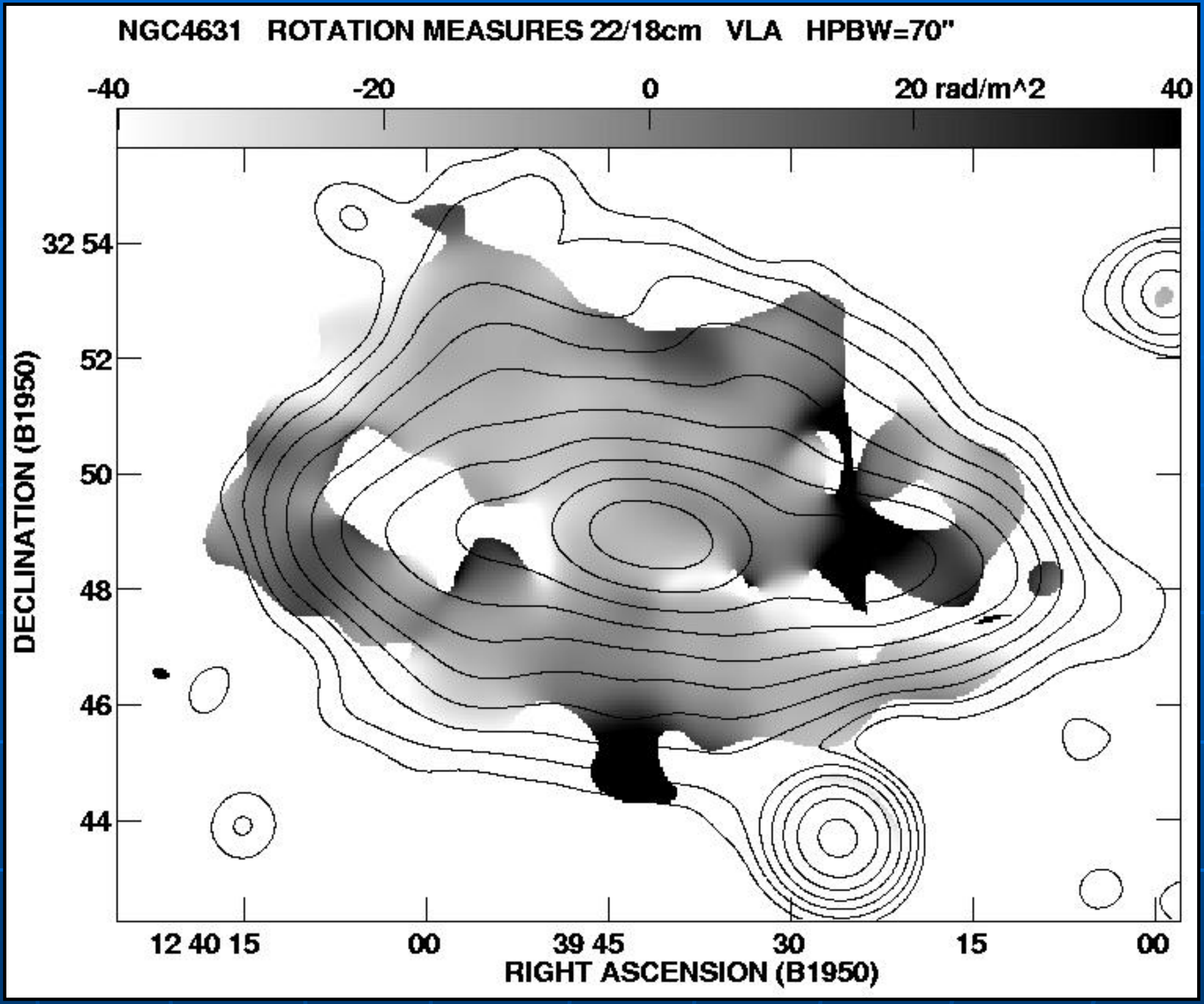
X-shaped field, consistent with quadrupolar pattern

NGC 4631

VLA

RM(18/22cm)

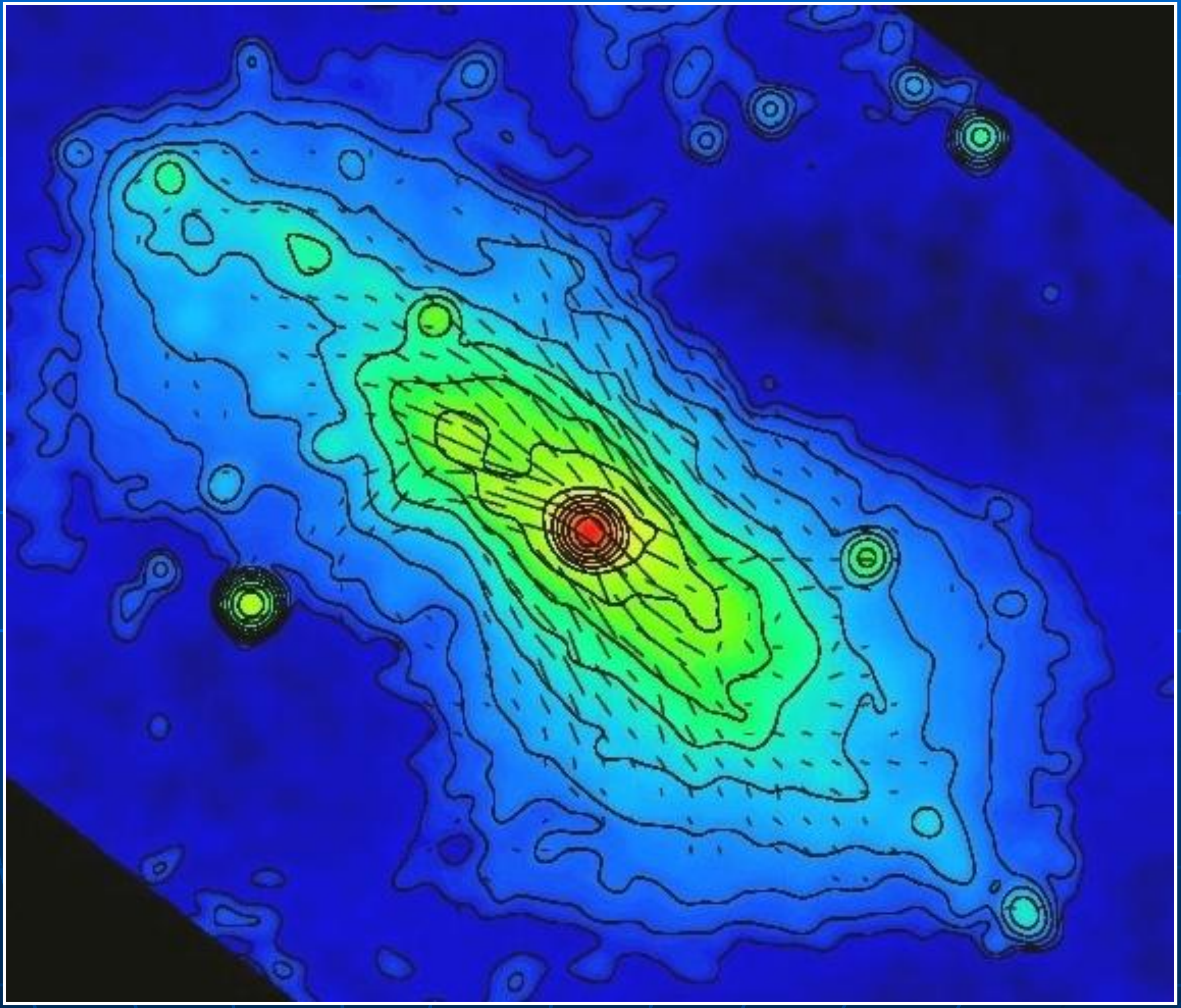
(Krause et al., in prep.)



- Expected RM of >100 rad/m^2 : not observed
- No large-scale pattern in RM: *hidden* quadrupole dynamo field?

NGC 253

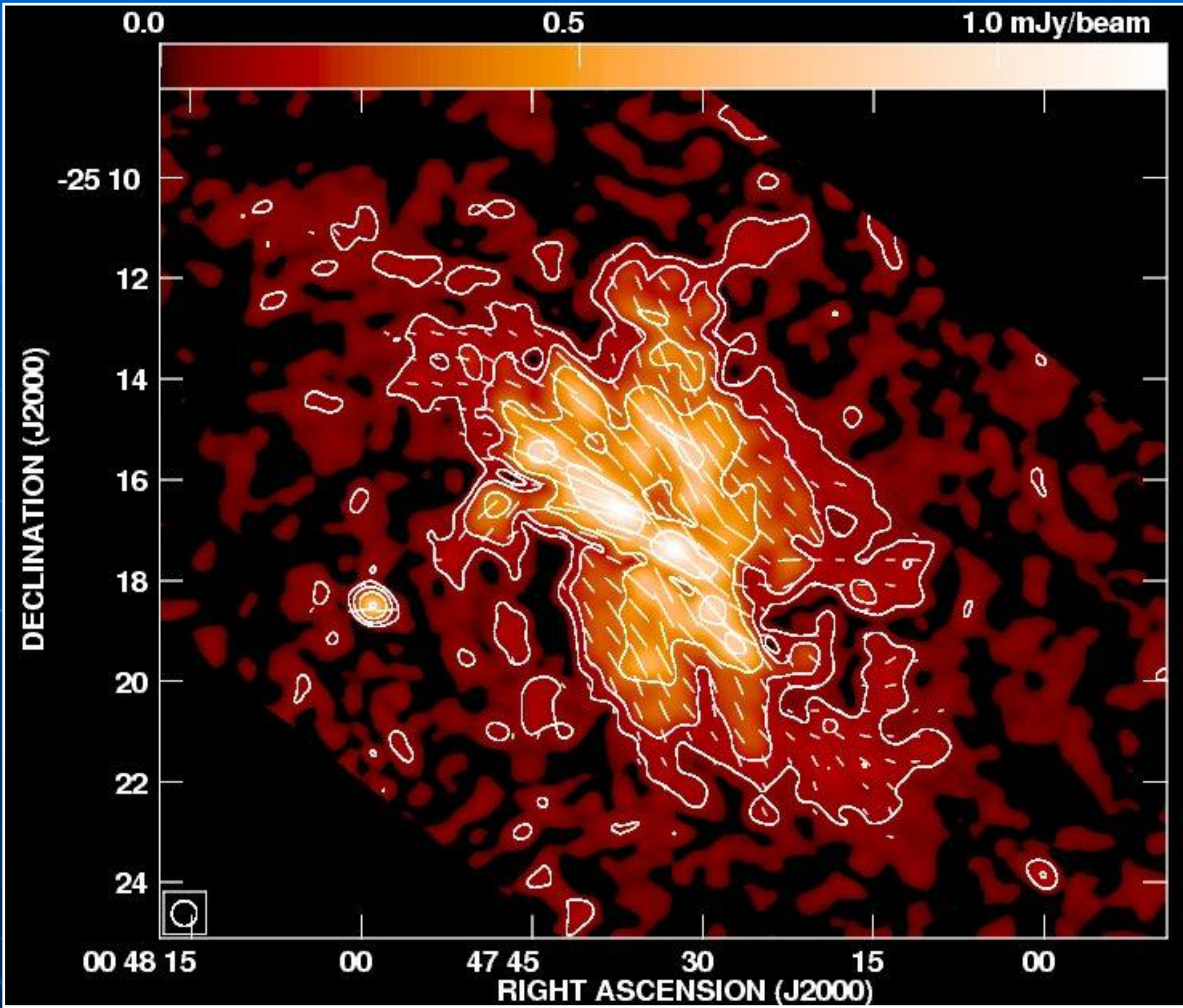
6cm
VLA+Effelsberg
Total intensity
+ B-vectors
(Heesen et al. 2009)



NGC 253

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

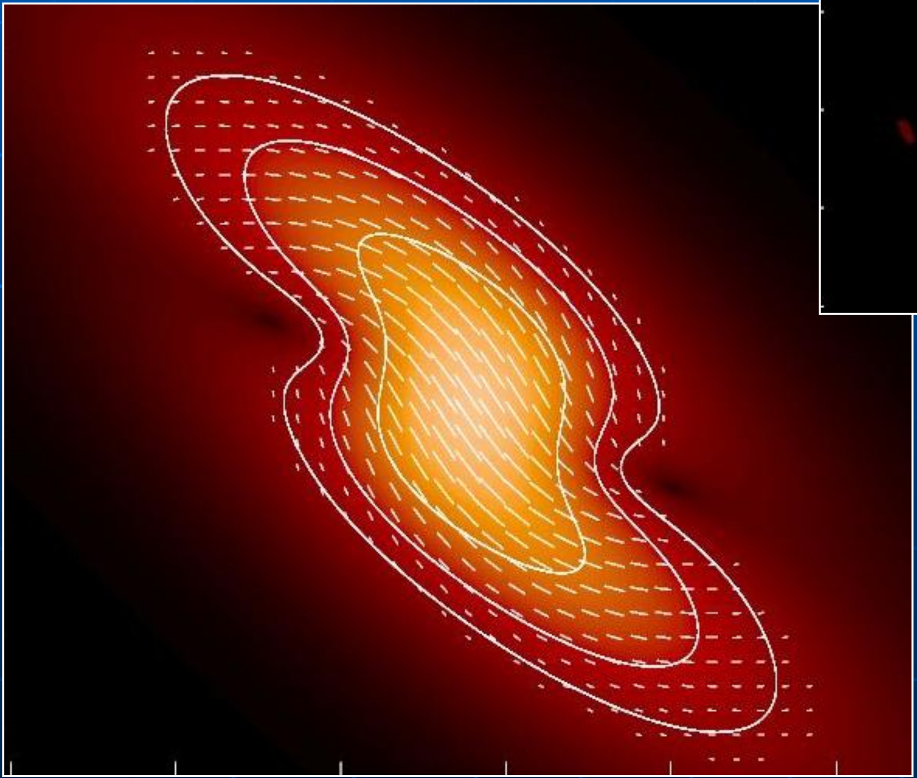
Disk + halo field

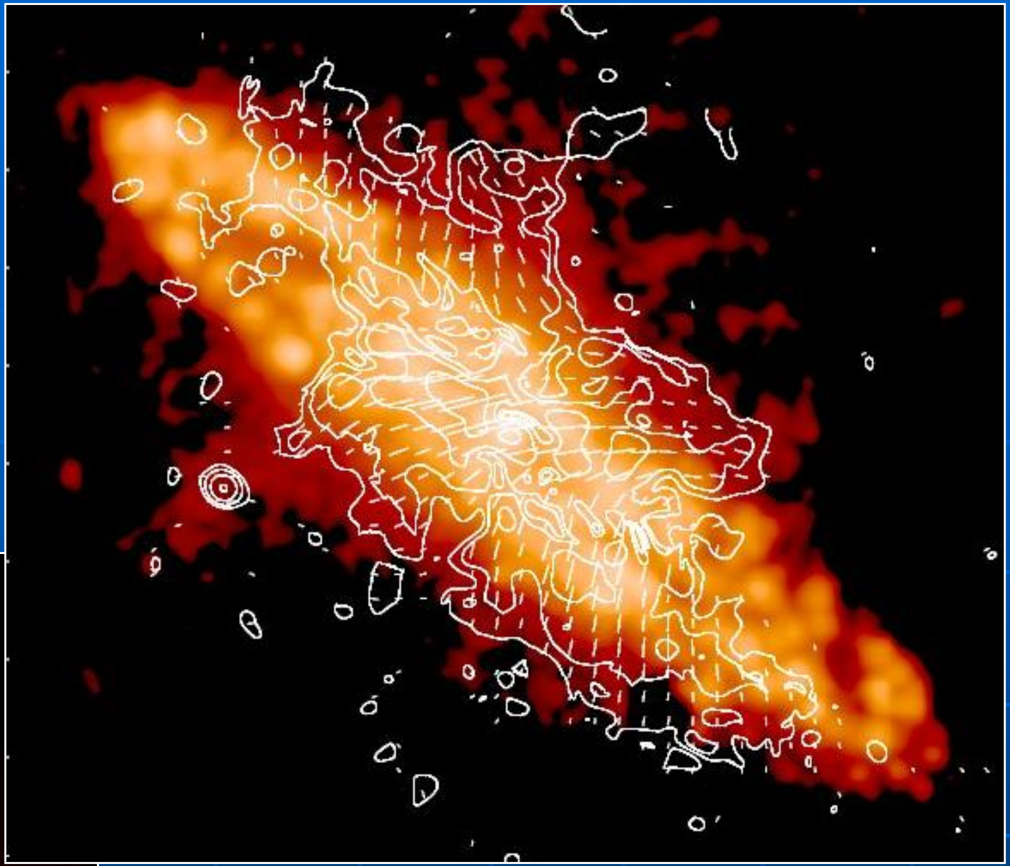


NGC 253

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

Disk:
Axisymmetric spiral field

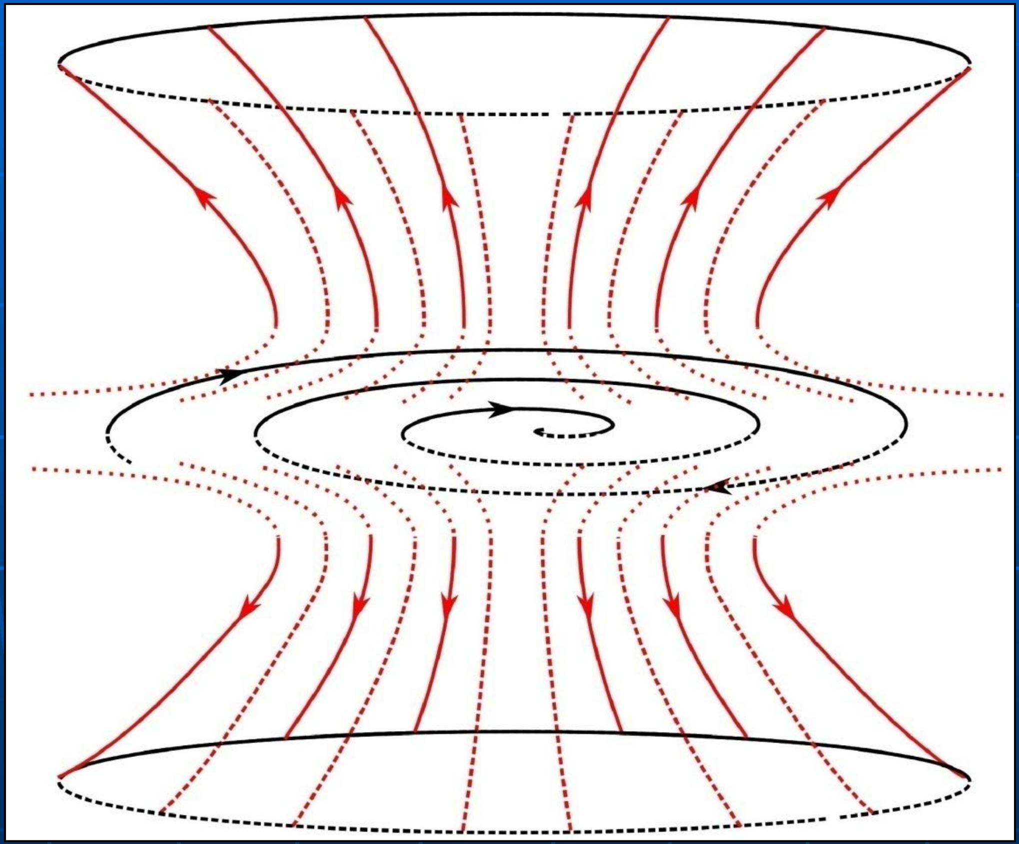




Halo:
X-shaped field

Magnetic field model for NGC 253

Heesen et al. 2009



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

Low-frequency radio observations

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

→ Observing at low frequencies traces cosmic-ray electrons in weak magnetic fields

- Lifetime of electrons due to synchrotron loss:

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

→ Observing at low frequencies traces old electrons

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

→ Observing at low frequencies allows to measure small rotation measures

Faraday rotation with LOFAR

- LOFAR can in measure very low Faraday rotation measures of polarized background sources and hence detect very weak magnetic fields:

- Galaxy halos, clusters, relics:

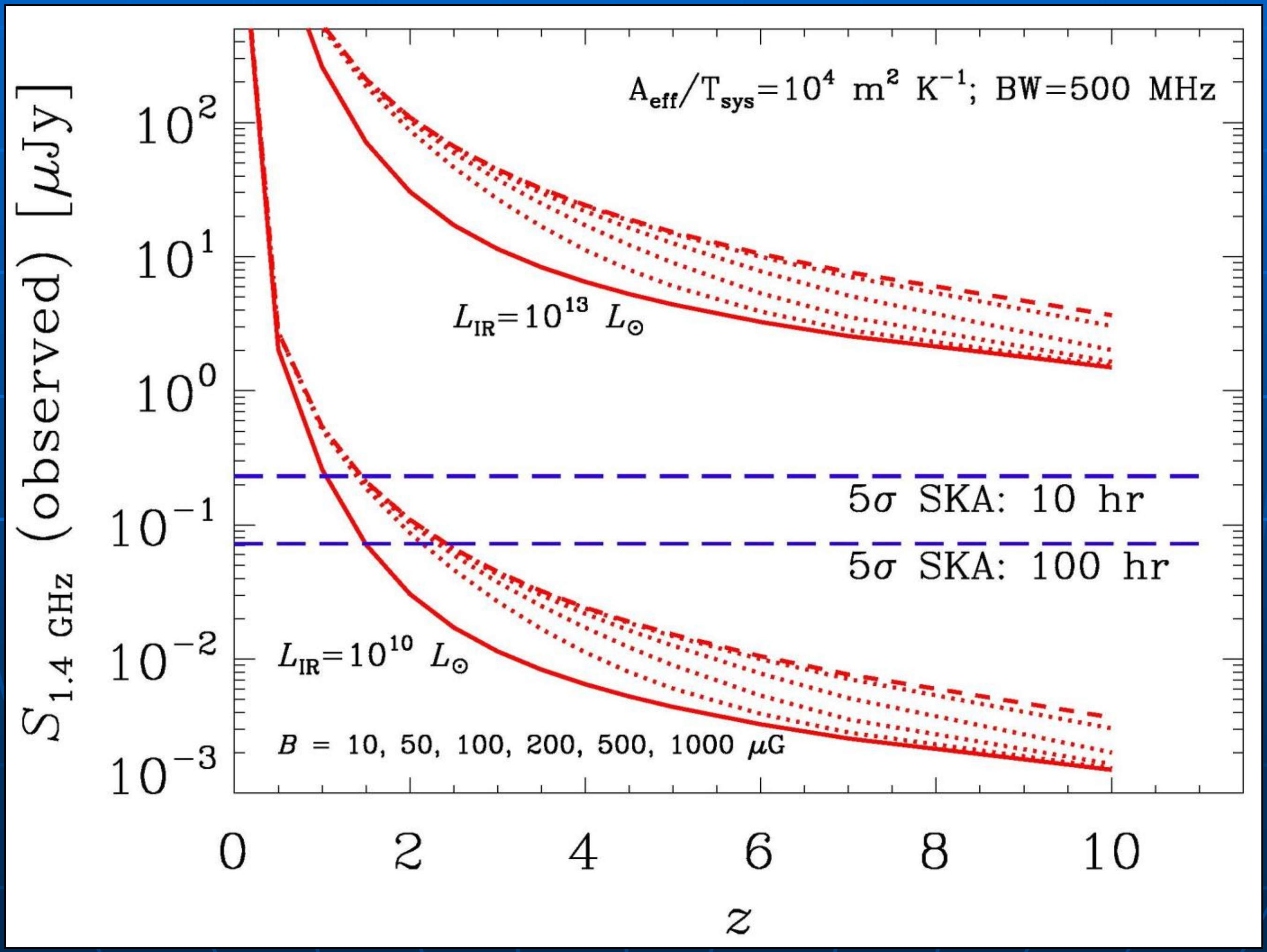
  $n_e=10^{-3}$ cm^{-3}, $B_{||}=1$ μG, L=1 kpc: RM~1 rad m^{-2}

- Intergalactic magnetic fields:

  $n_e=10^{-5}$ cm^{-3}, $B_{||}=0.1$ μG, L=100 kpc: RM~0.1 rad m^{-2}

Observation of distant galaxies with the SKA

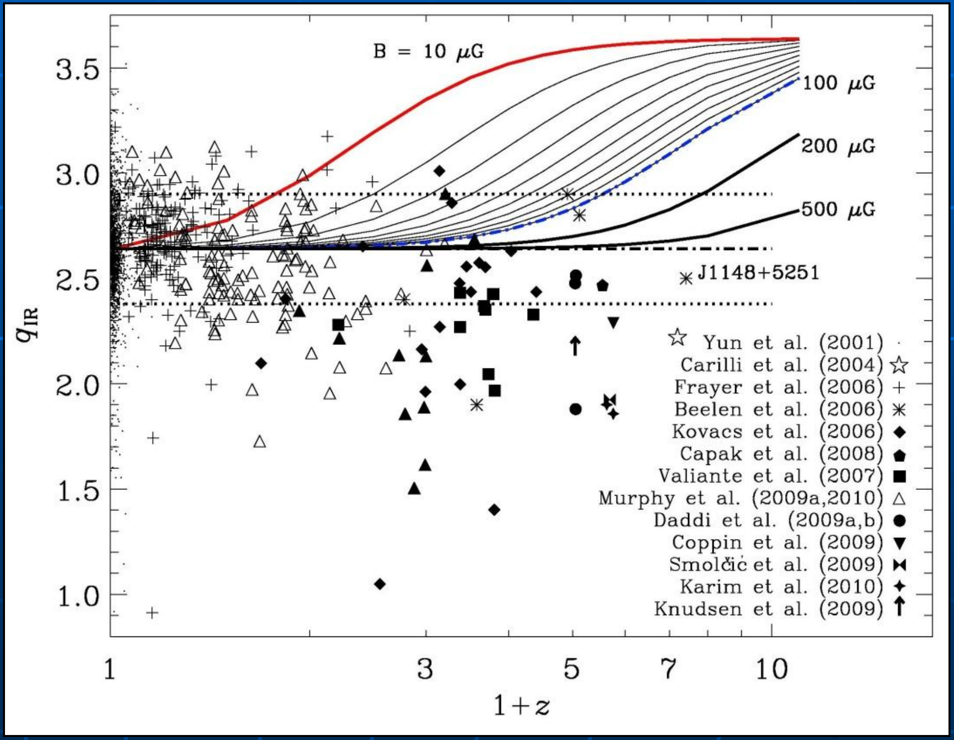
Murphy 2009



Radio-IR correlation at high z

Murphy 2009

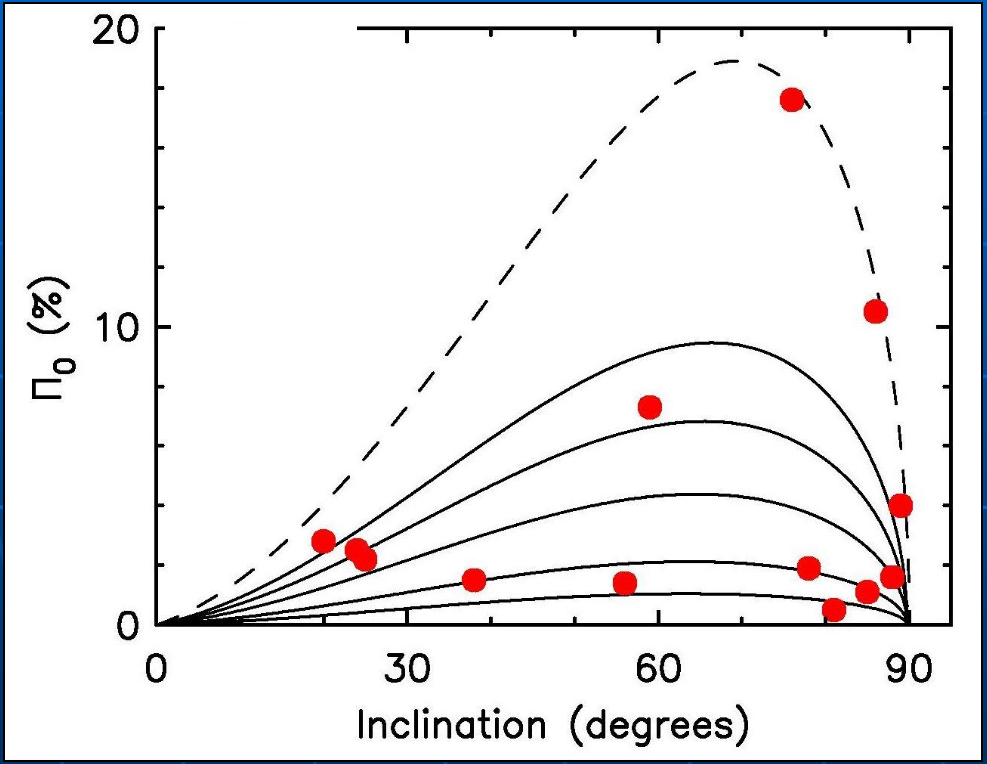
- Radio synchrotron emission should break down at large z due to IC loss
- IR/radio ratio should increase
- This is *not* observed:
  Magnetic fields are strong in distant galaxies !
  $B > B_{CMB} = 3.25\ \mu G\ (1+z)^2$



IR/radio luminosity

Polarization of the integrated emission from distant spiral galaxies

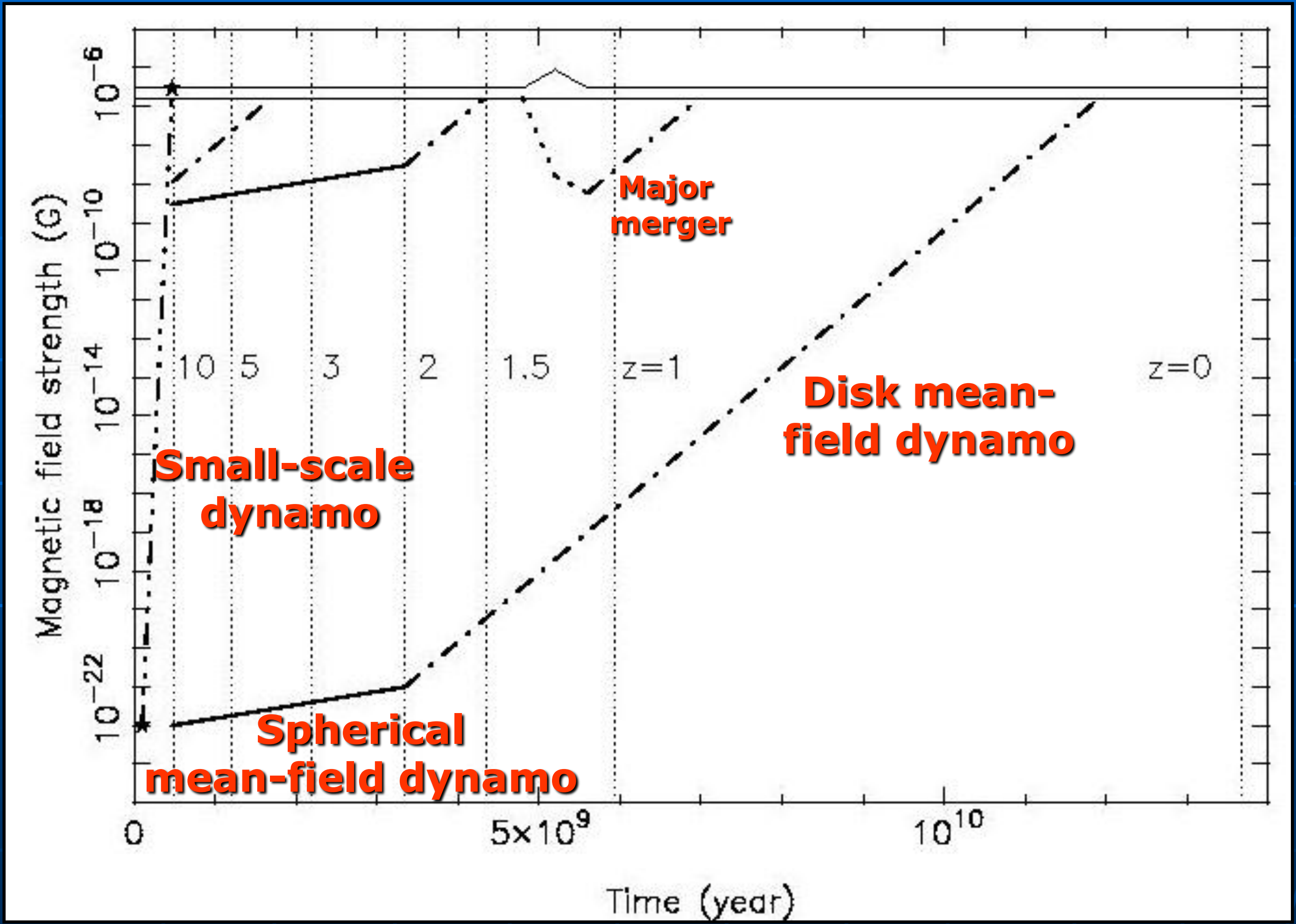
Stil et al. 2009



Model confirmed by observations:

Significant polarized emission for unresolved galaxies

Dynamo action in evolving galaxies



Arshakian et al. 2009

Influence of star formation on the evolution of magnetic fields

- Star formation can be trigged by gravitational instabilities, mergers or tidal forces

- High SF rate (SFR)
  → high velocity turbulence of the gas
  → suppression of the large-scale dynamo

Action of the large-scale dynamo is possible only if:

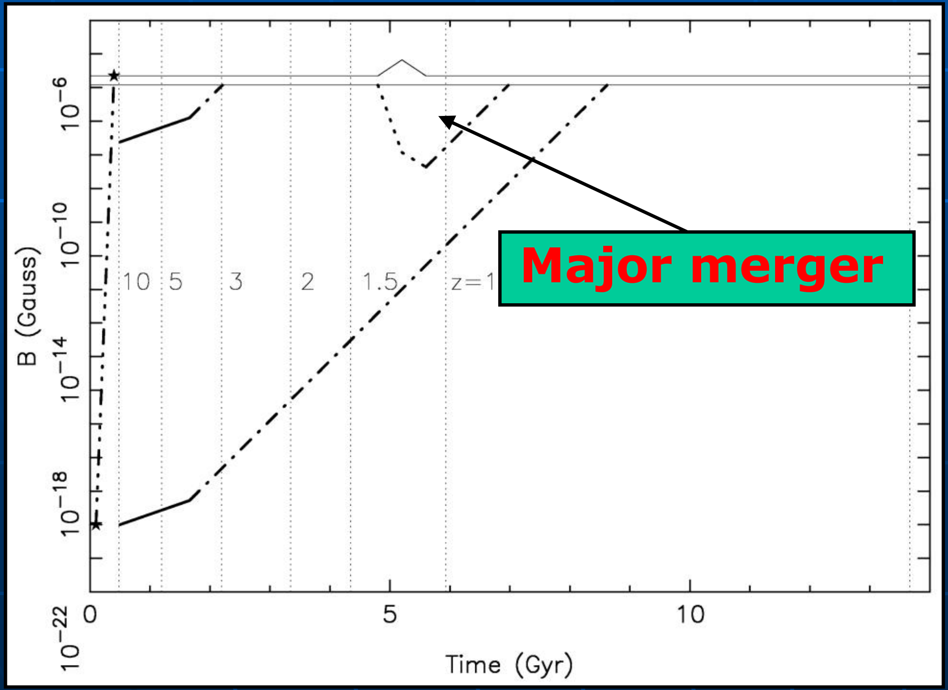
SFR < 20 M_{sun} yr^{-1}

Influence of major mergers on the evolution of magnetic fields

Arshakian et al. 2009

Major mergers:

- Can alter or destroy the gas disk
- Turbulent field is increased, but regular field is destroyed
- Disk and regular field may recover



Weak regular fields (small Faraday rotation) in galaxies at z < 3 can be signatures of major mergers

Predictions from dynamo theory (1)

- Strong turbulent magnetic fields expected at $z \approx 10$

  $\longrightarrow$ Strong radio synchrotron emission

  (if other losses of CR electrons are negligible)

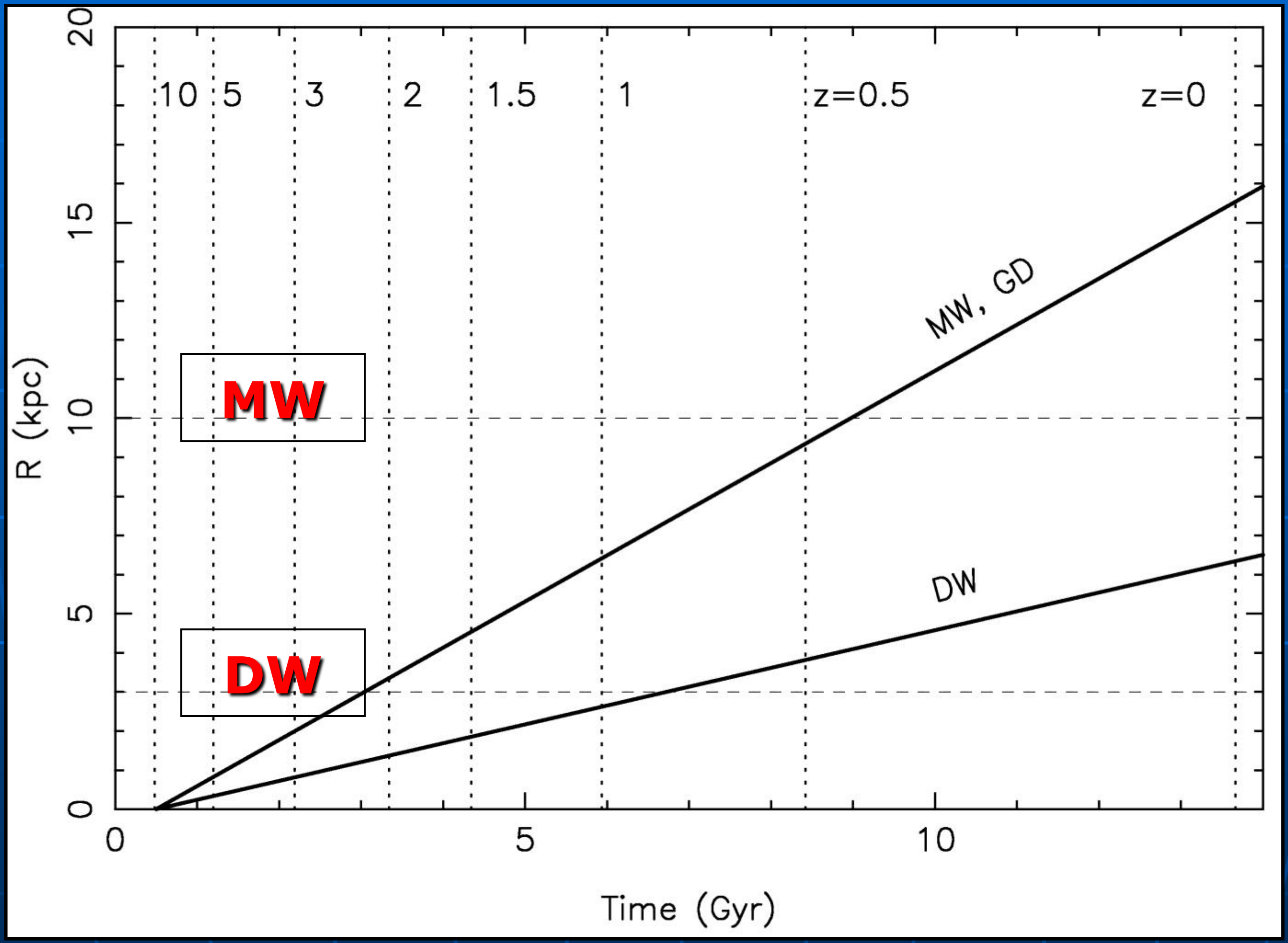
- Strong regular fields expected at $z<3$

  $\longrightarrow$ Polarized radio emission and *some* Faraday rotation

  (if no major mergers occured)

- Starburst galaxies: Strong turbulent, but no regular fields
- Major mergers can destroy the regular field
- Minor mergers slow down the development of regular fields

Coherence length of regular fields



Arshakian et al. 2009

GD – giant disk galaxy (>15 kpc)
MW – Milky Way-type galaxy (≈ 10 kpc)
DW – dwarf galaxy (≈ 3 kpc)

Predictions from dynamo theory (2)

- Large-scale coherent regular magnetic fields are expected not before $z \approx 1$ in dwarf and Milky Way-type galaxies

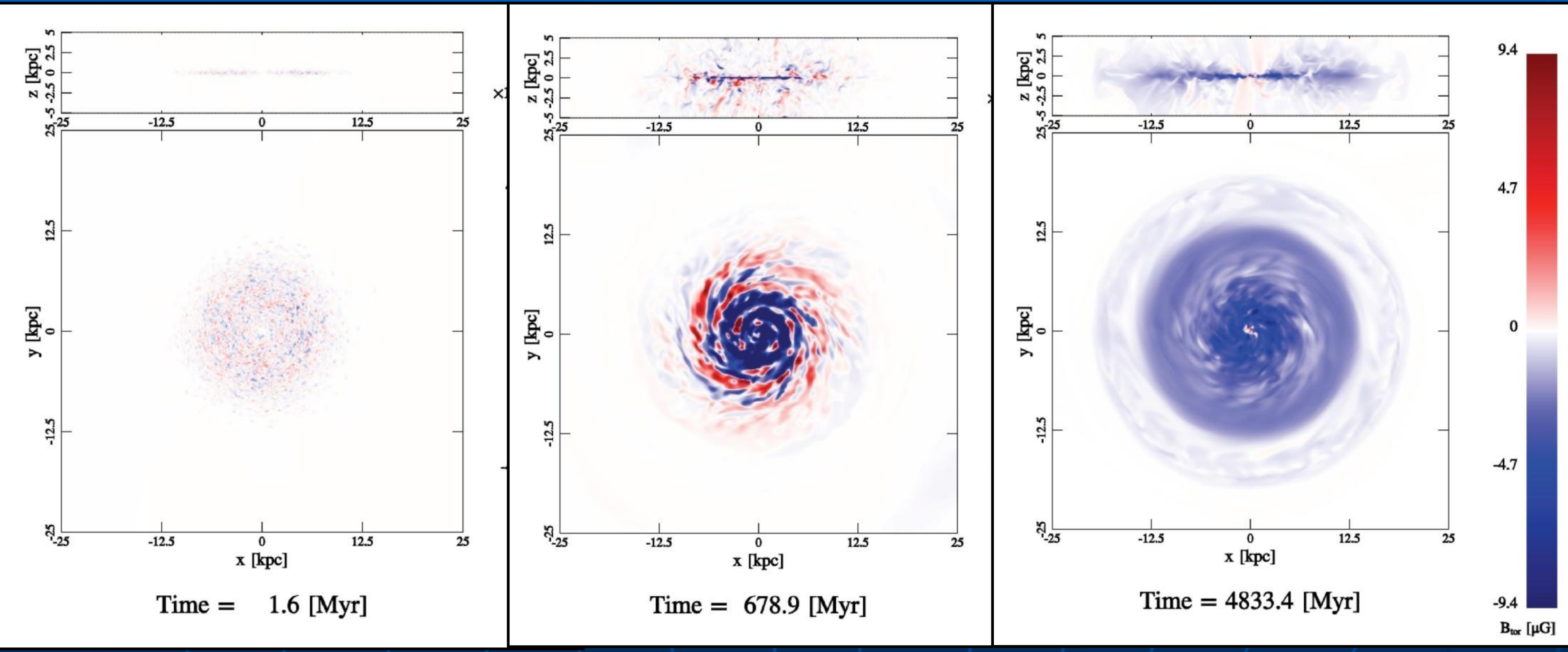
  $\rightarrow$ Large-scale pattern of Faraday rotation can be observed only at $z<1$

  (if no major mergers occured)

- Some very large galaxies (>15 kpc) may not yet host fully coherent fields

Global cosmic-ray driven MHD model

Hanasz et al. (2009)



Classical mean-field dynamo

Problems:

- Field amplification is slow (several 10^8 years)
- Kinematical model (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

Improved dynamo models

- MHD model: Include magnetic fields on all scales and back-reaction of the field onto gas turbulence and flows
- Cosmic-ray driven α-effect (faster!)
- Global model of a galaxy, including rotation and non-axisymmetric gas flows
  (e.g. spiral arms, bar and outflow)
- Include galaxy evolution