Radio Continuum:

Cosmic Rays
&
Magnetic Fields

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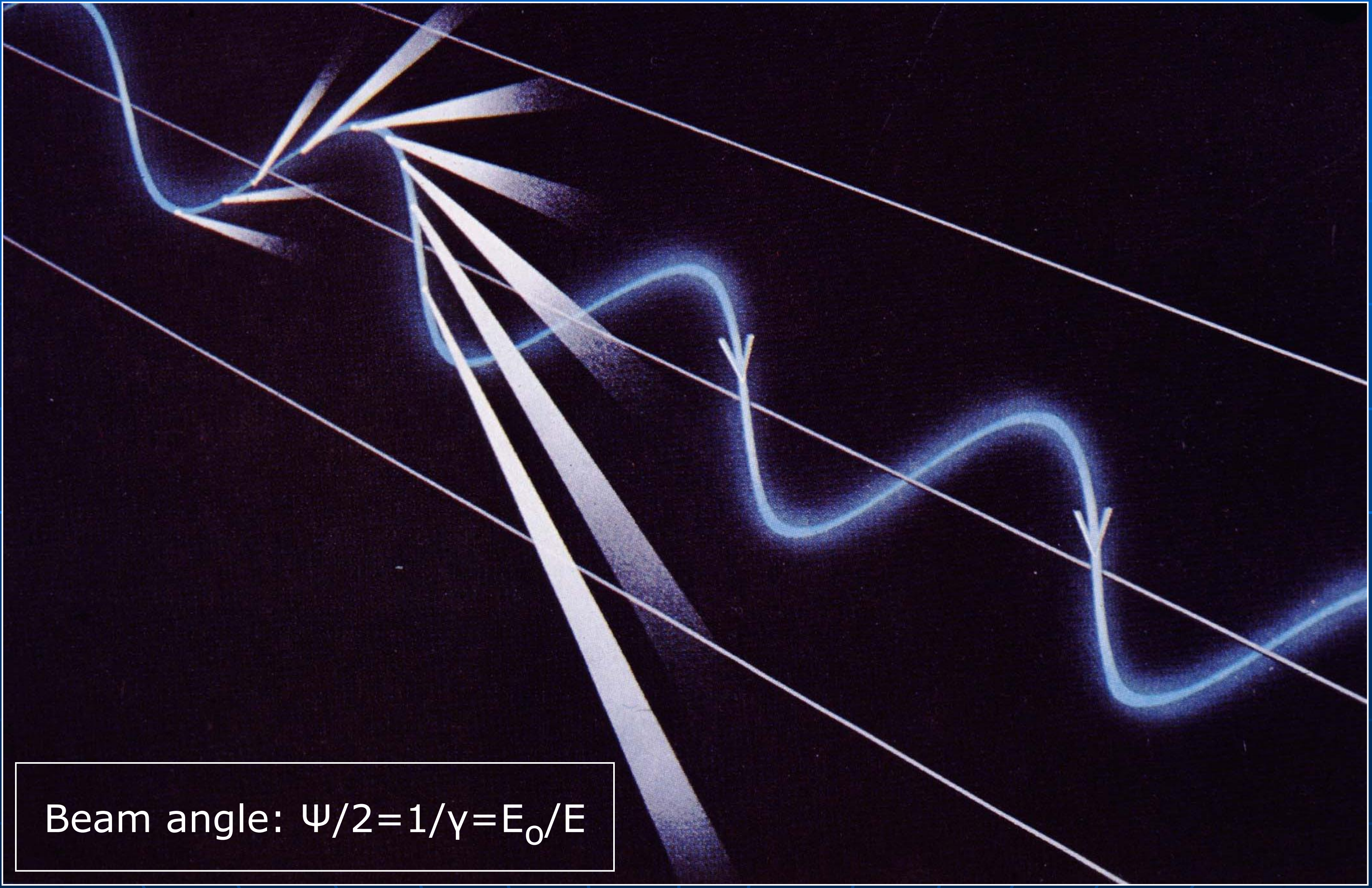
MPIfR Bonn

Synchrotron emission



Beam angle: $\Psi/2 = 1/\gamma = E_o/E$

Radio continuum tools to study
GeV Cosmic ray electrons (CRE)

- Synchrotron spectrum:
  Energy density, energy spectrum,
  energy losses of CRE
- Distribution of synchrotron spectral index:
  Propagation type and velocity of CRE
- Scale height/length of galaxy and cluster halos:
  Bulk outflow velocity, diffusion coefficient

Synchrotron emission

- Power-law energy spectrum of CRE (with spectral index ε):
  $N(E)\, dE = N_0\, E^{-\varepsilon}\, dE$
- Intensity of synchrotron spectrum:
  $I_\nu \sim \int N_0\, B_\perp^{(\varepsilon+1)/2}\ \nu^{-(\varepsilon-1)/2}\, dL$
- Synchrotron spectral index:
  $\alpha = (\varepsilon-1)/2$
  Strong shocks: $\varepsilon=2$, $\alpha=0.5$

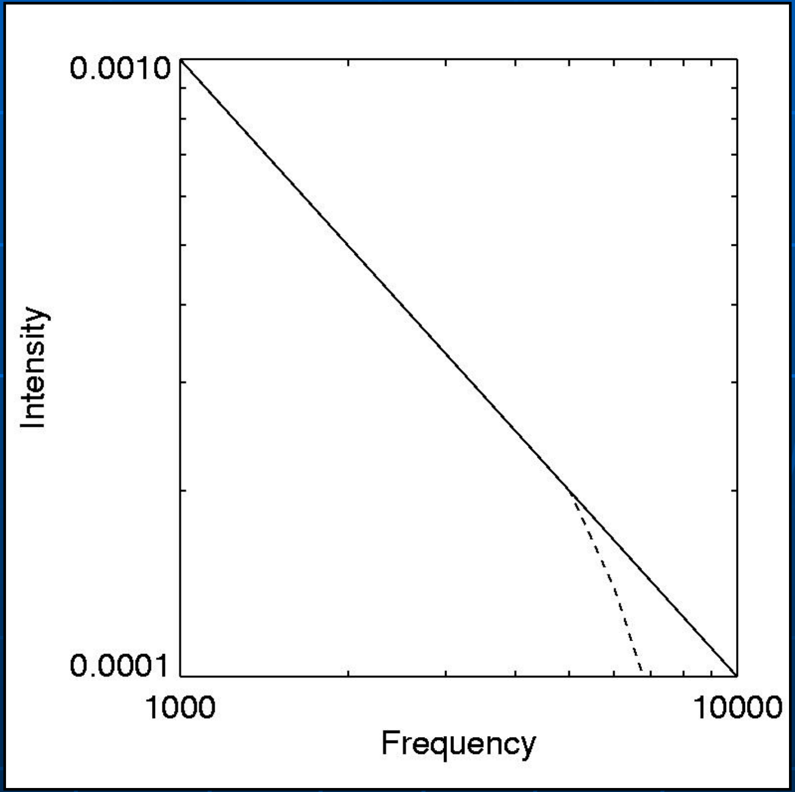
Energy loss mechanisms of CRE

Ionisation	$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{ion}} \propto \ln E \sim \text{constant}$
Bremsstrahlung	$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{brem}} \propto E$
Adiabatic cooling	$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{adiab}} \propto E$
Synchrotron	$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{syn}} \propto E^2$
Inverse Compton	$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{invC}} \propto E^2$
Escape into halo	diffusion coefficient $D \propto E^{\delta}$.

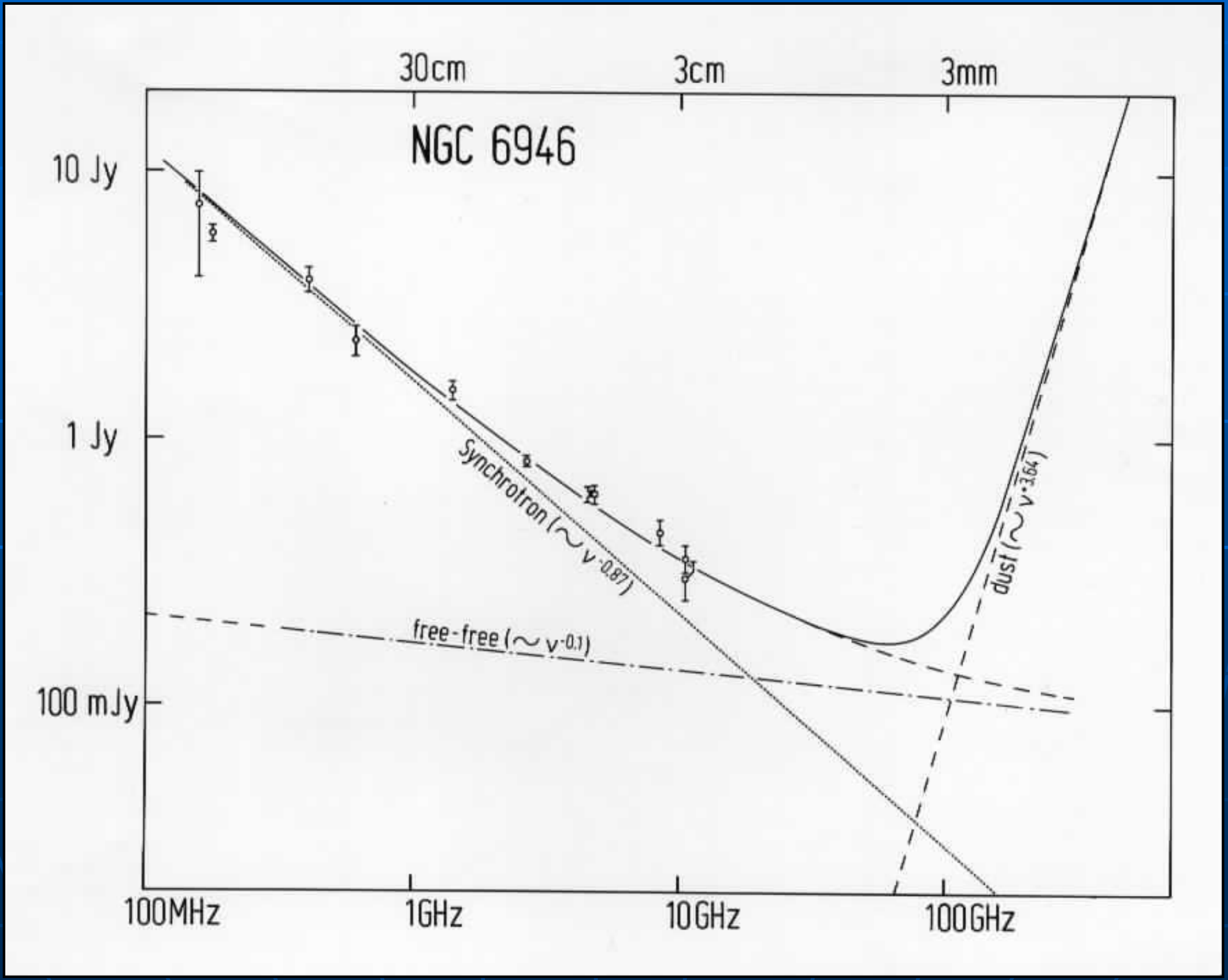
Synchrotron lifetime of GeV CRE

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

Continuous injection:
synchrotron spectrum
steepens by $\Delta\alpha = 0.5$
above a critical frequency



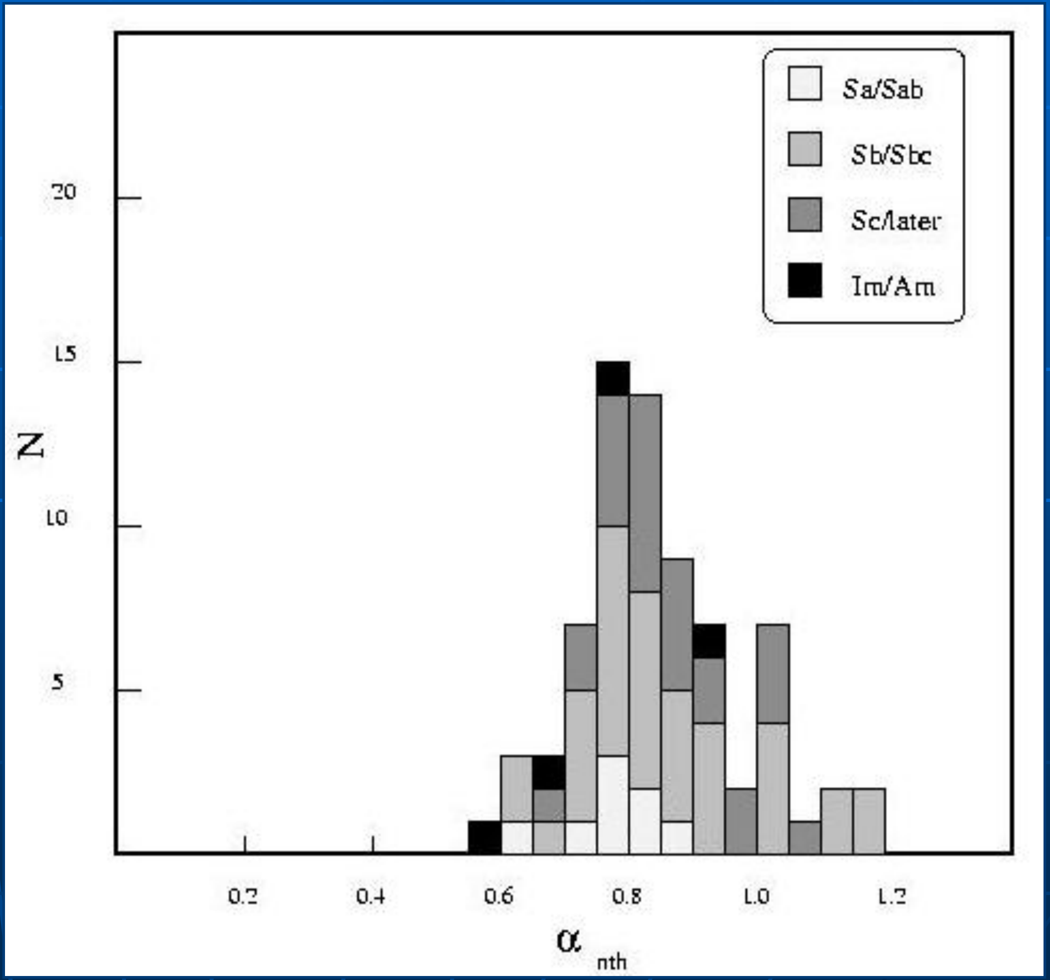
Typical radio continuum spectrum of a spiral galaxy



Thermal-nonthermal separation of total flux densities of galaxies

$\alpha_{sync} = 0.85 \pm 0.05$

$\varepsilon = 2.7 \pm 0.1$



Niklas 1997

Origin of GeV CRE spectra in galaxies

Observed: $\varepsilon \approx 2.7$ in most galaxies (and in the Milky Way)

- Injection by supernova remnants ($\varepsilon \approx 2.2$)
  + energy-dependent escape ($\rightarrow \varepsilon \approx 2.7$)

- Mixture of young CRE from SNRs ($\varepsilon \approx 2.2$) and old CRE steepened by synchrotron loss ($\varepsilon \approx 3.2$)

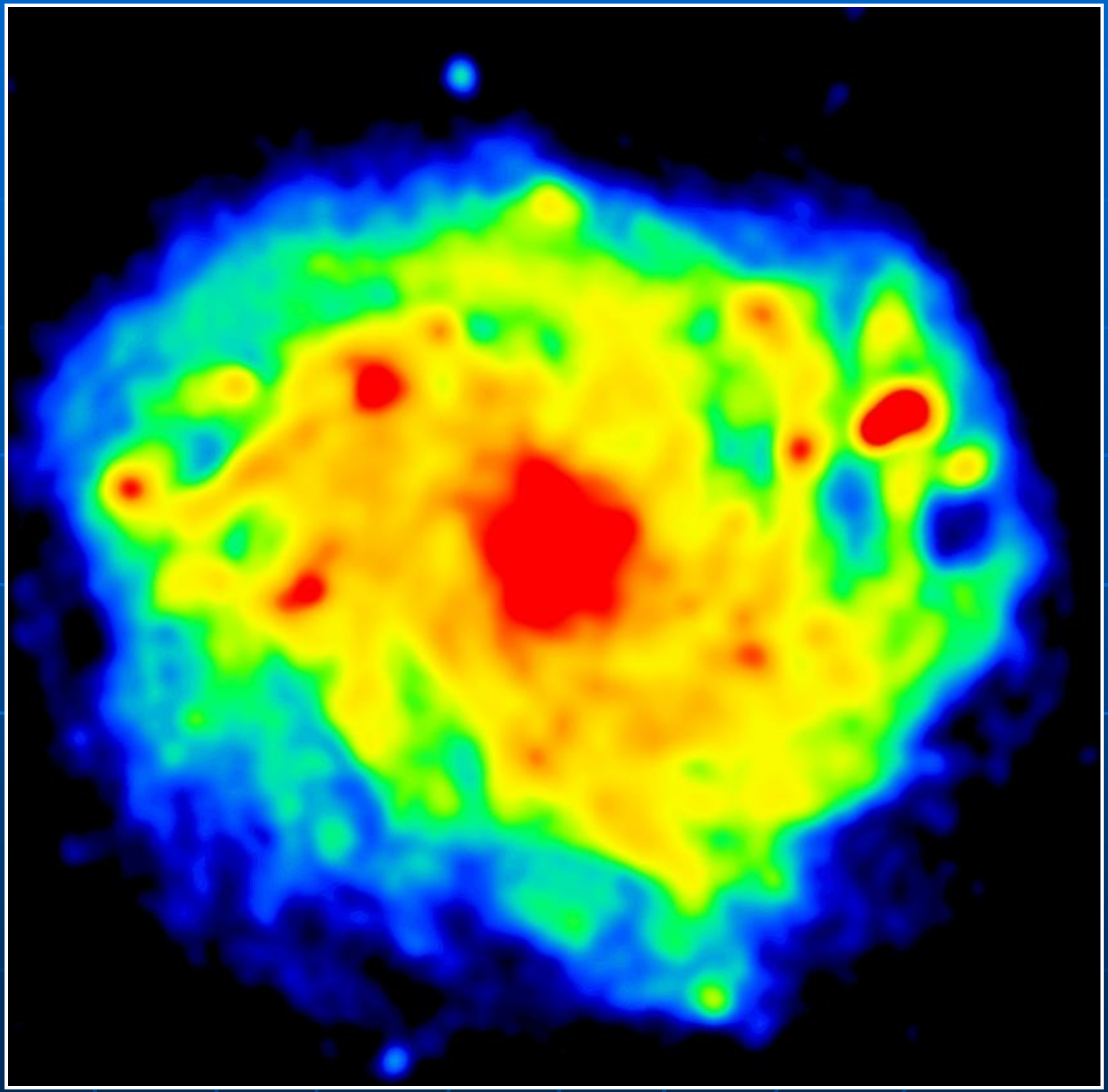
- Injection with $\varepsilon \approx 2.7$ (?)

NGC 6946

20cm VLA
Total intensity
(Beck 2007)

Exponential radio disk: mostly synchrotron

Extent is limited by energy losses of the CRE

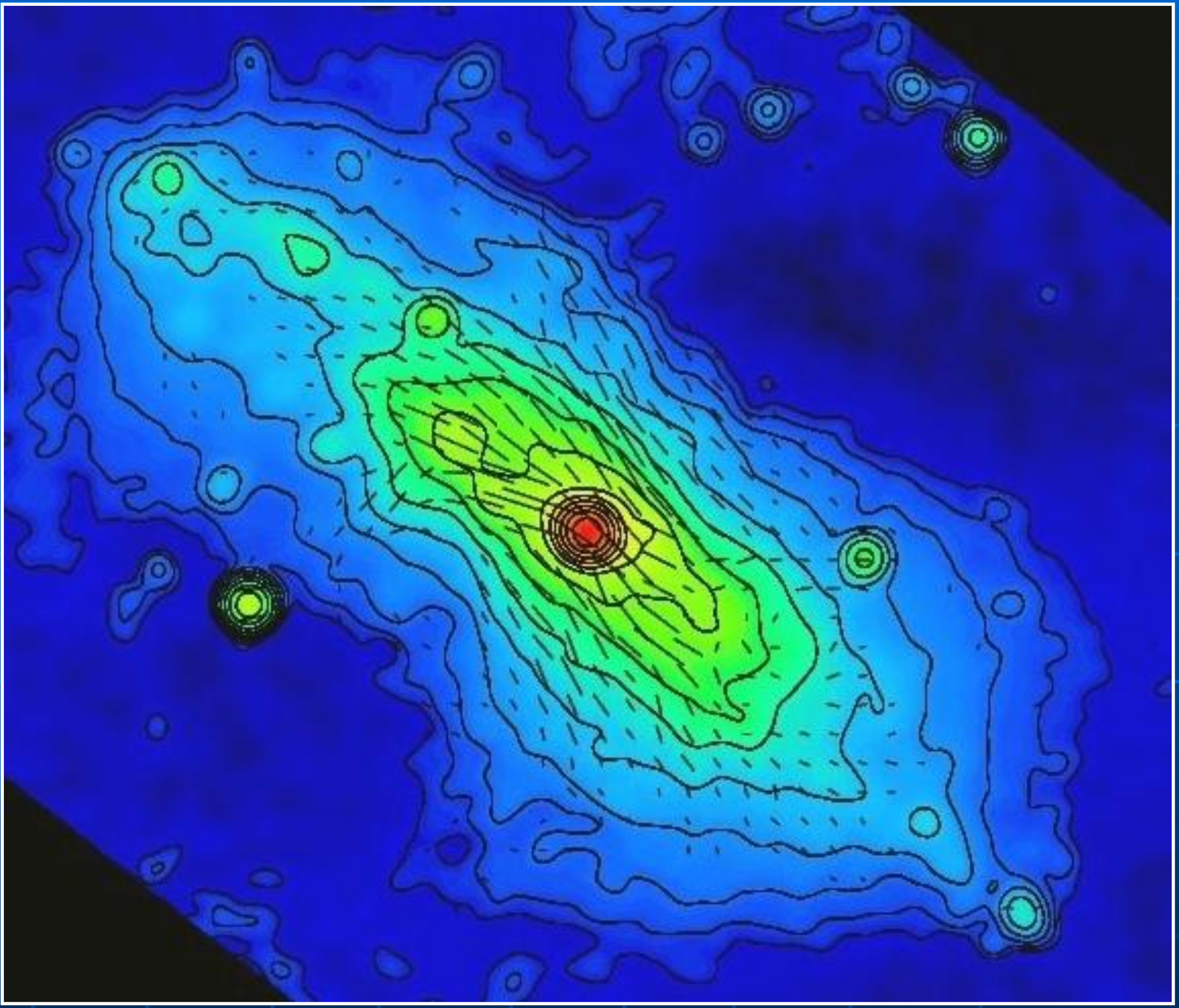


Typical exponential scale lengths of radio disks of spiral galaxies

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

Typical exponential scale heights of radio halos

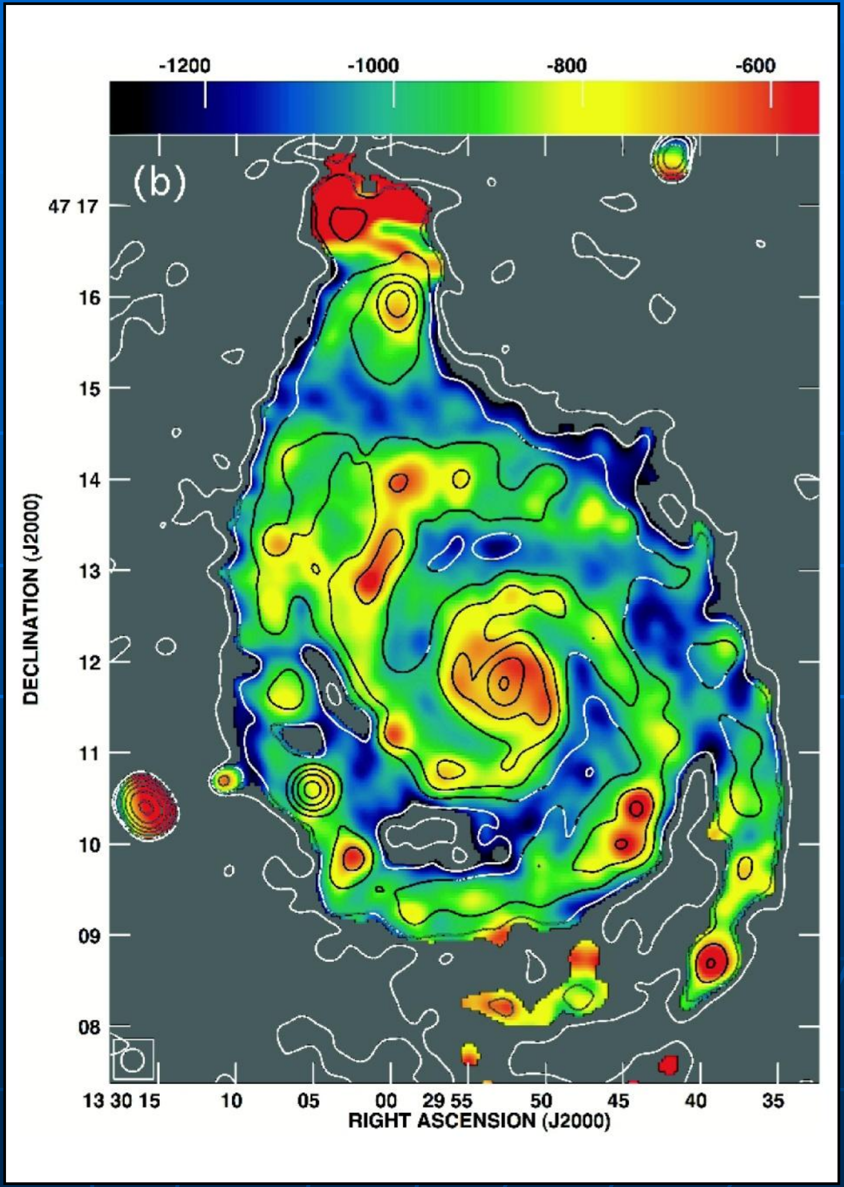
- Cold gas: ≈0.1 kpc
- Warm gas: ≈1 kpc
- Synchrotron: ≈2 kpc
- Cosmic-ray electrons: ≤4 kpc

  (assuming equipartition, upper limit due to energy losses)
- Total magnetic field: ≥8 kpc

Spectral index in M51

Spectral index is flat
in the spiral arms and
steep in interarm regions:

Synchrotron & IC
losses of CRE

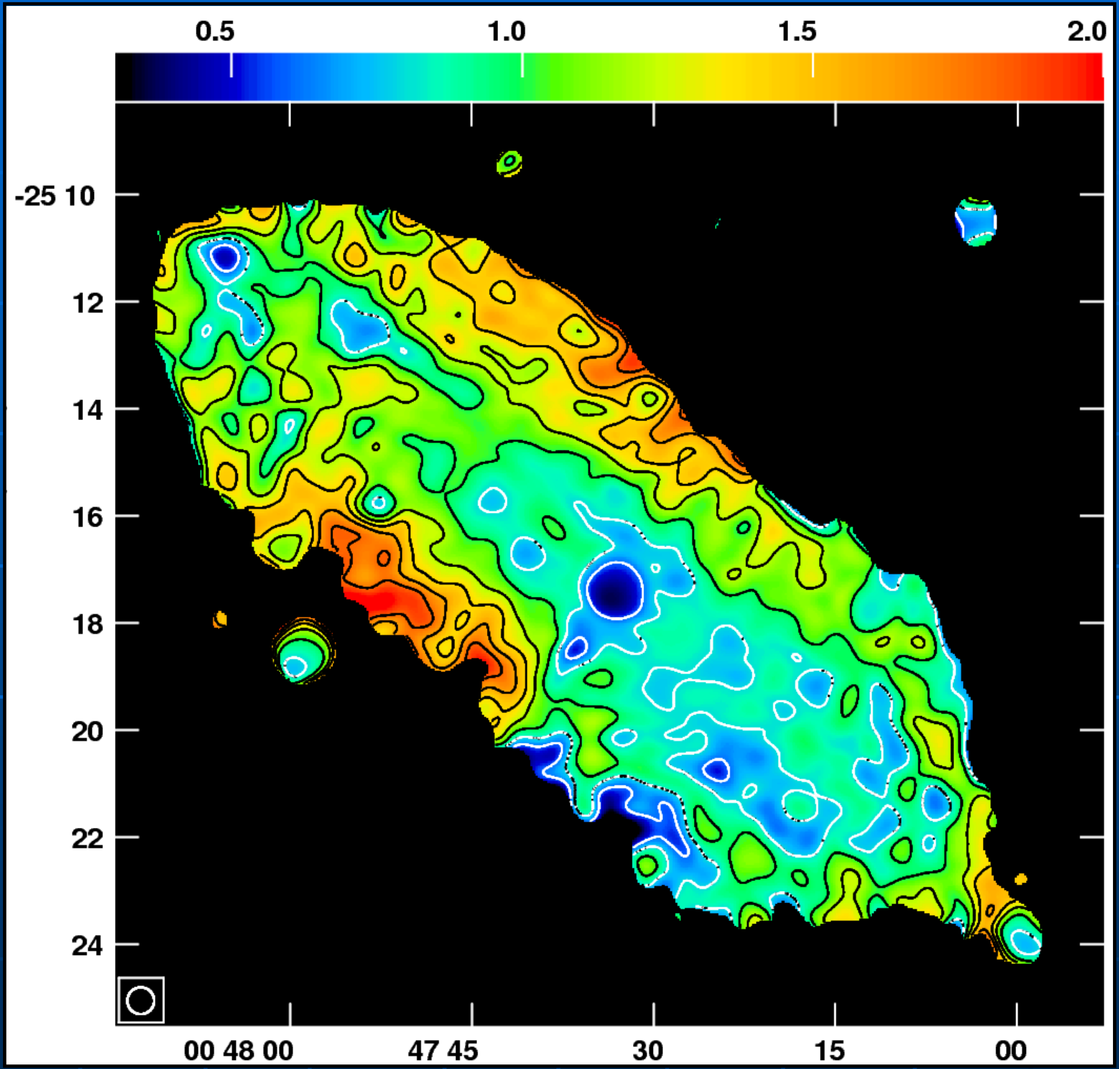


NGC 253

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

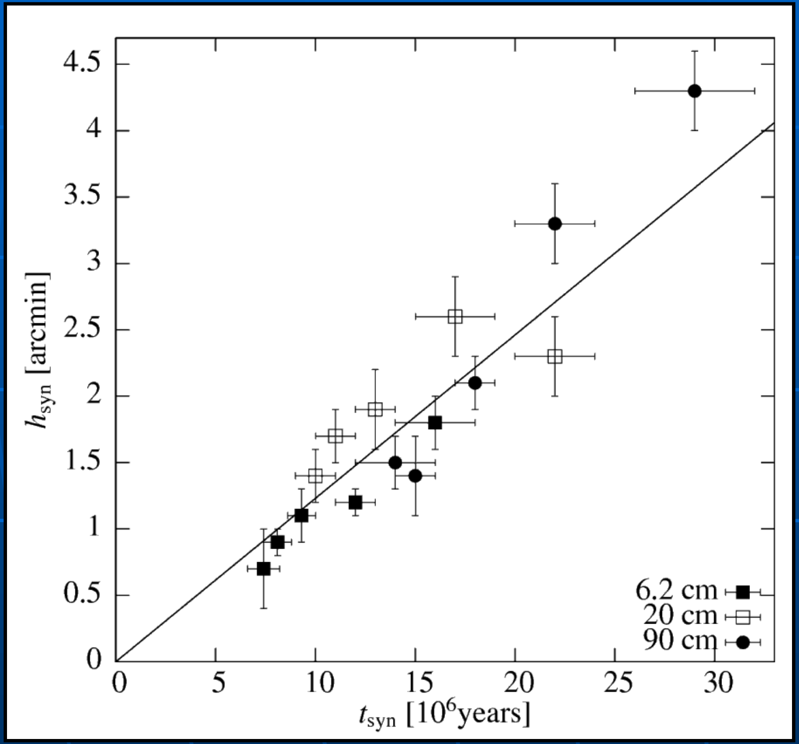
Spectral index steepens with height:

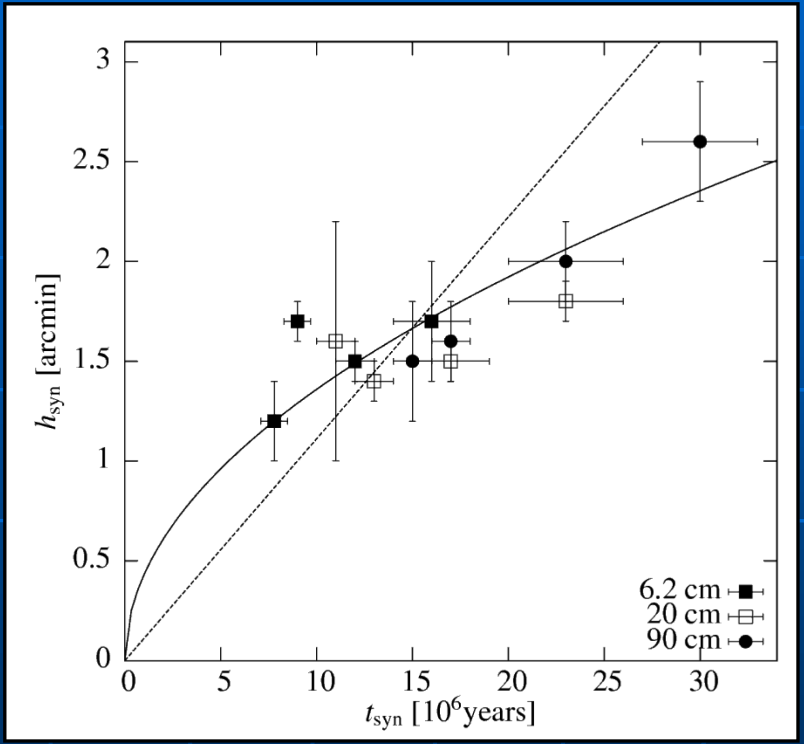
Synchrotron & IC losses of CREs



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}

Radio continuum tools to study

Magnetic fields

- 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

Equipartition strength of the total field

(assuming equipartition between magnetic fields and cosmic rays)

Beck & Krause 2005

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

I_{sync}: Synchrotron intensity

L: Pathlength through source

α: Synchrotron spectral index

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

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

Energy spectra of cosmic rays

Diffusive shock acceleration:

$\varepsilon \geq 2$

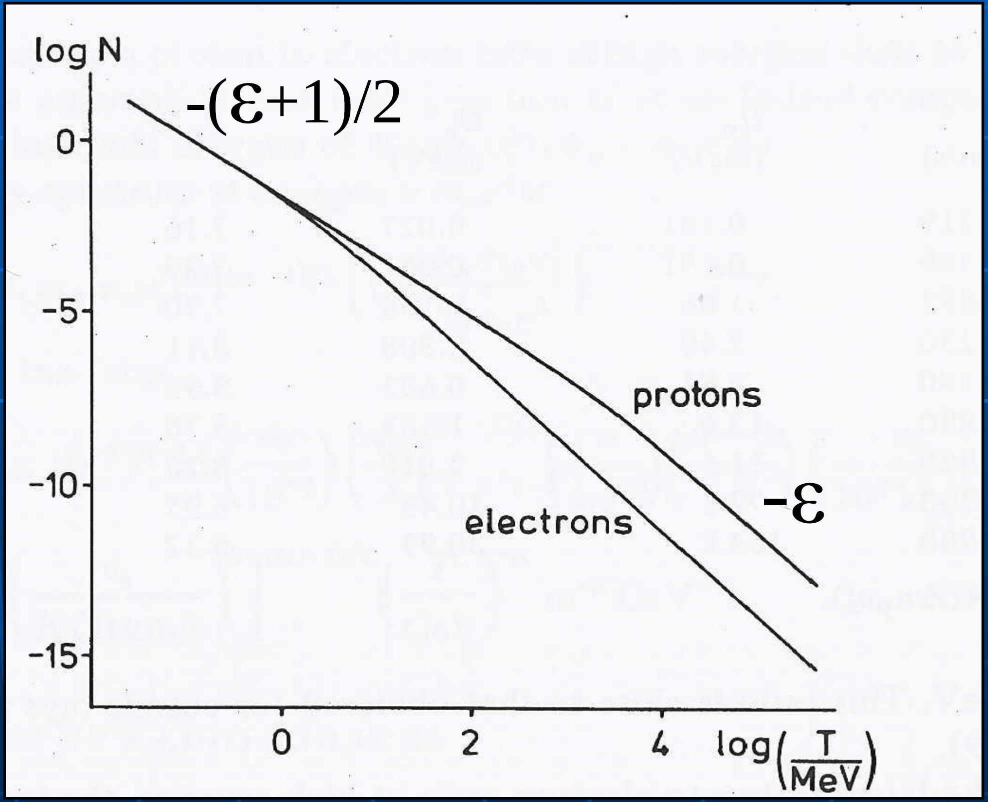
$\alpha \geq 0.5$

E > 1 GeV:

$K=(m_p/m_e)^{(\varepsilon-1)/2}$

$\varepsilon \approx 2.2$: $K \approx 90$

Bell 1978



Equipartition magnetic field strengths

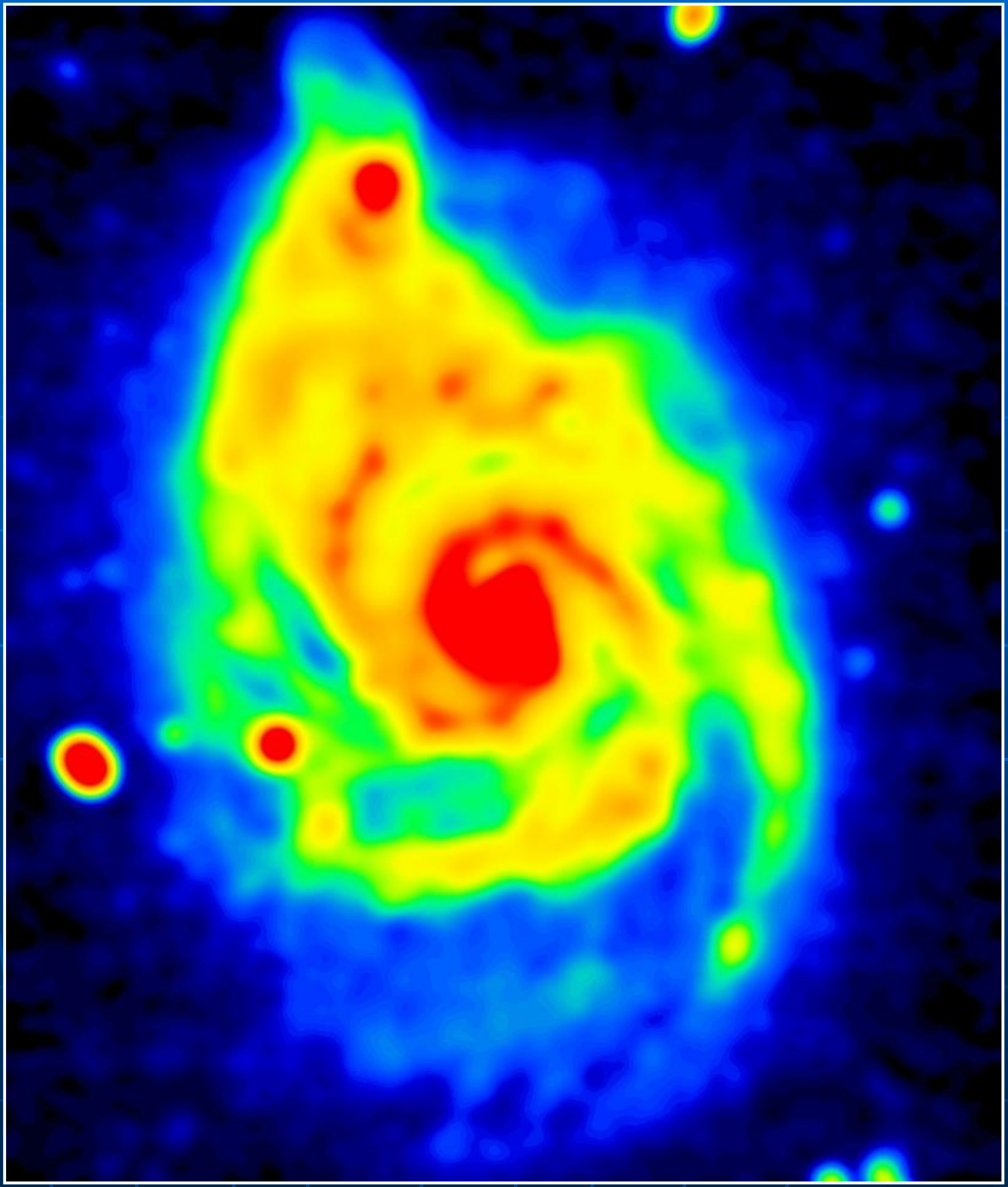
CRE energy losses:

- Spectral index (ε_e) is modified
- Proton/electron ratio is larger than 100
- Equipartition field estimate is too small
  (Beck & Krause 2005)

Needed: independent data on CR proton spectrum (e.g. from γ rays) or CR electron spectrum (from X-rays)

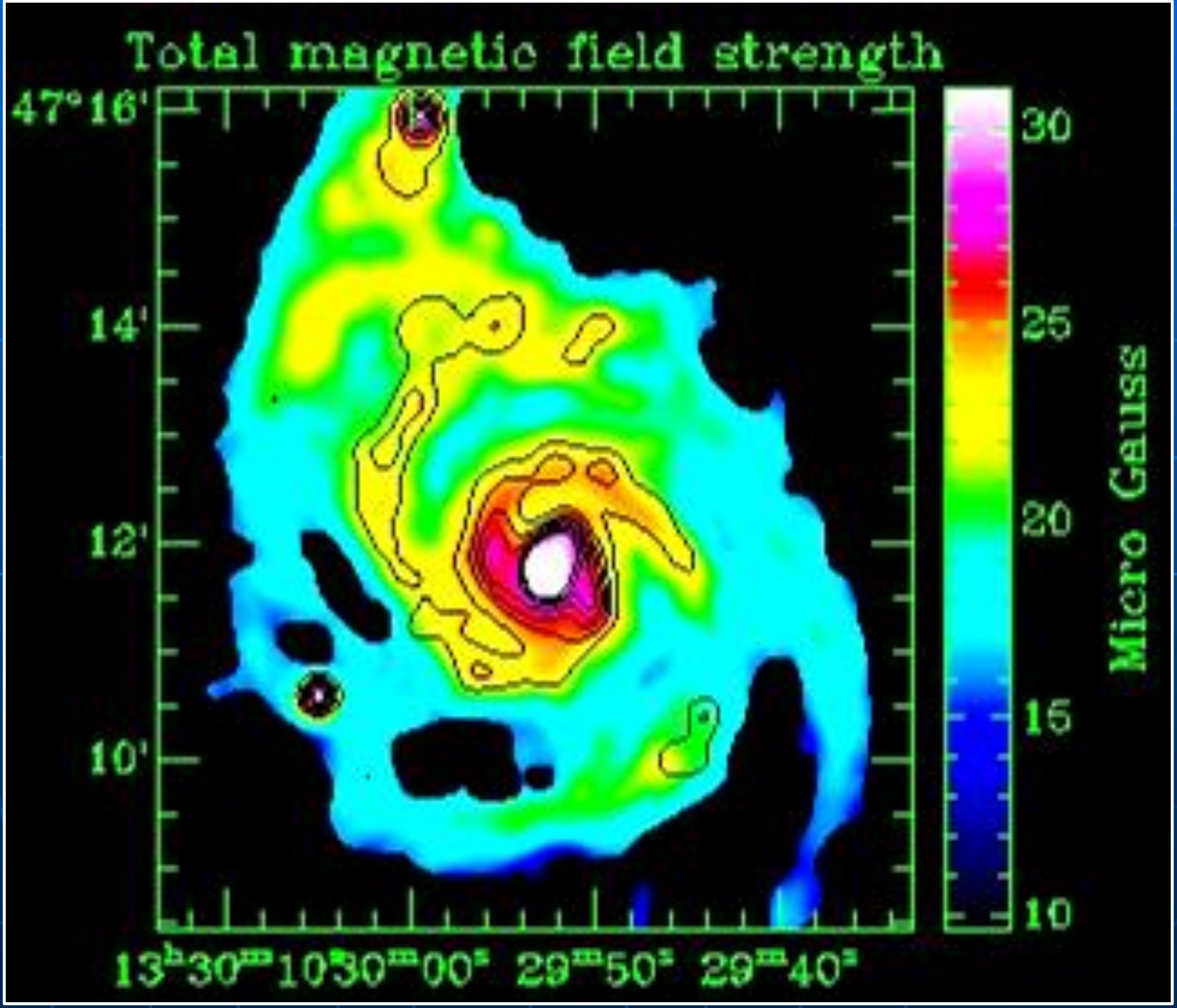
M 51

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



Equipartition field strengths in M 51

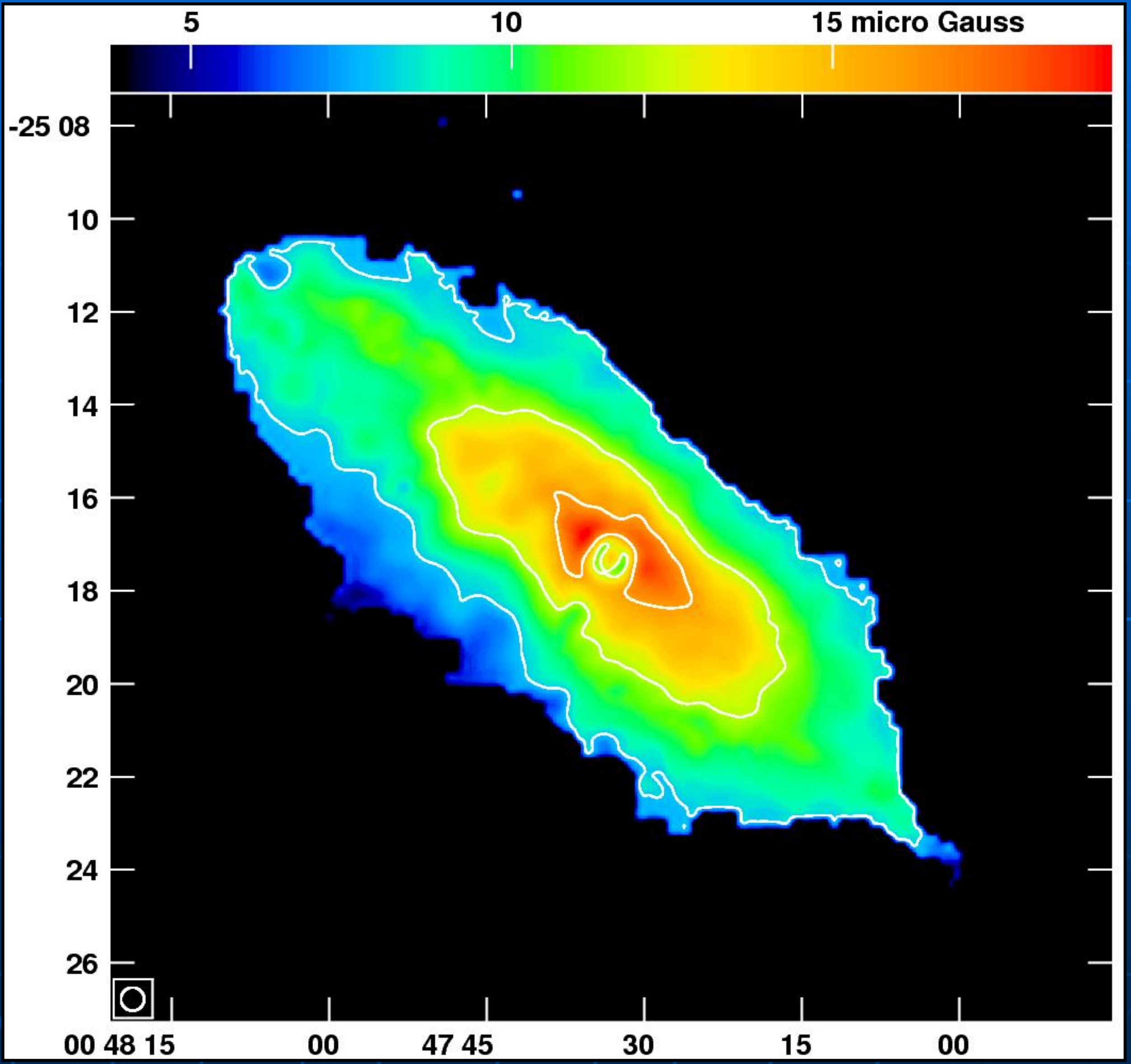
Equipartition underestimates the field in the outer galaxy due to energy losses of CRE



Fletcher et al. 2010

Equipartition field strengths in NGC 253

Equipartition underestimates the halo field due to energy losses of CR electrons



Heesen et al. 2009

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

Synchrotron polarization
for a power-law electron spectrum

Intrinsic degree of linear polarization:

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

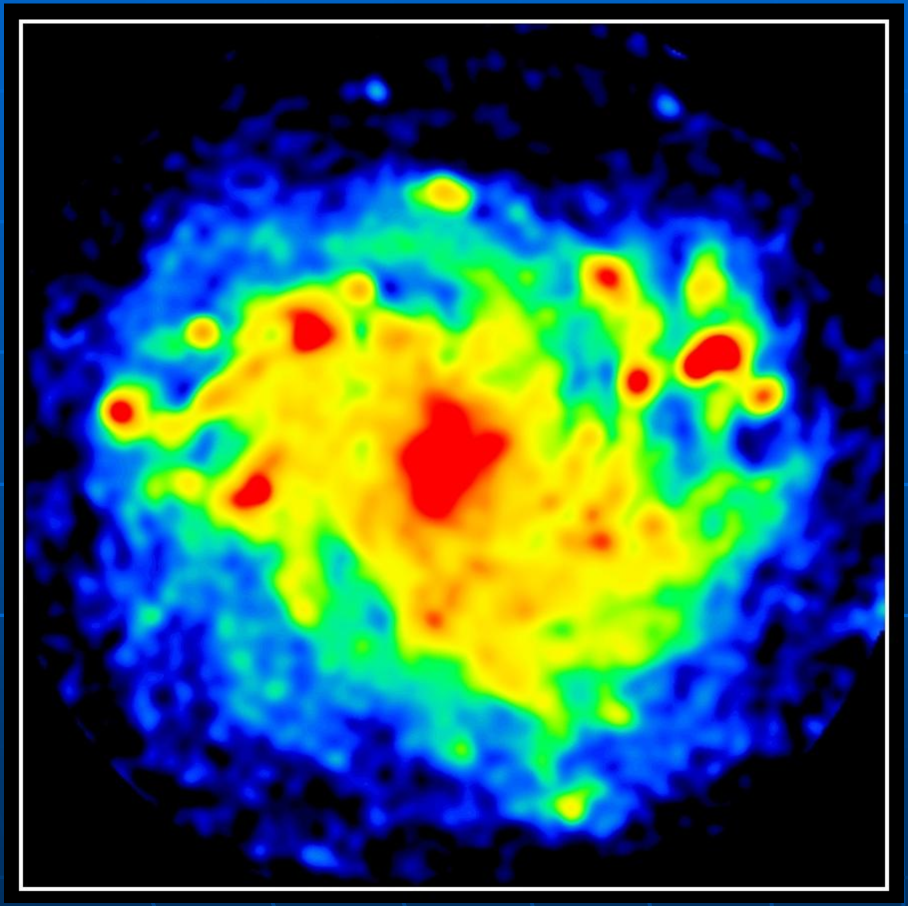
$$= (\alpha+1) / (\alpha+5/3)$$

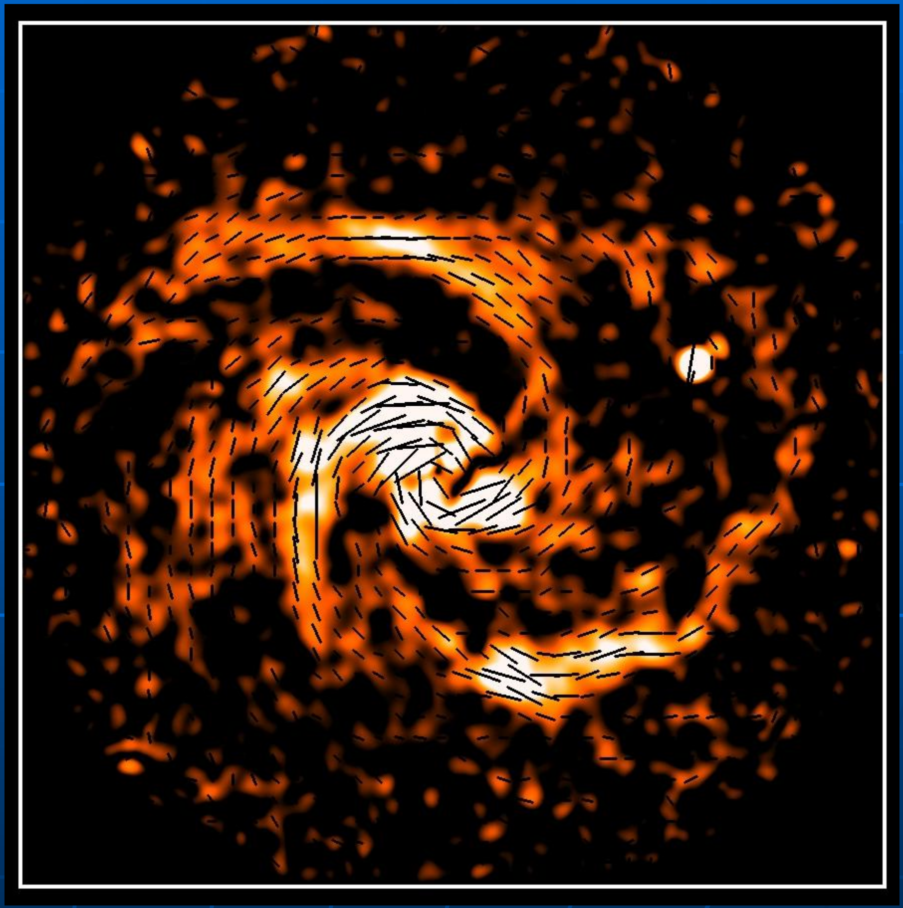
Typical value: $\alpha=0.85$, $p_o=74\%$

Note: circular polarization is generally negligible

Synchrotron polarization

Beck & Hoernes 1996

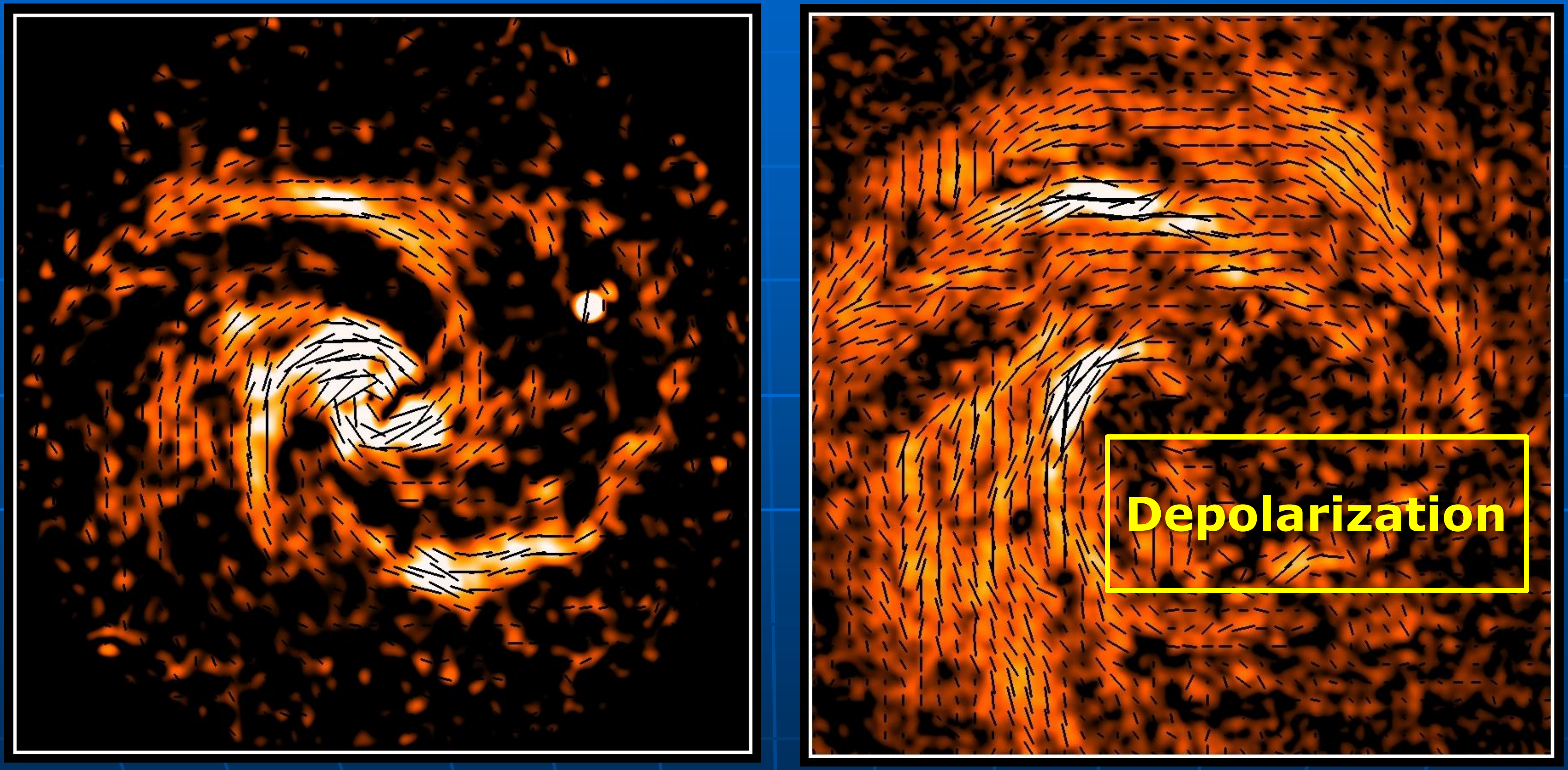




NGC 6946 Total and polarized intensity at 6cm

Faraday depolarization

Beck 2007



NGC 6946 Polarized intensity at 6cm and 20.5cm

Degree of polarization in galaxies:

≤ 5% in spiral arms

20 - 60% in magnetic arms at ≥5 GHz,

≤10% at ≤1.4 GHz

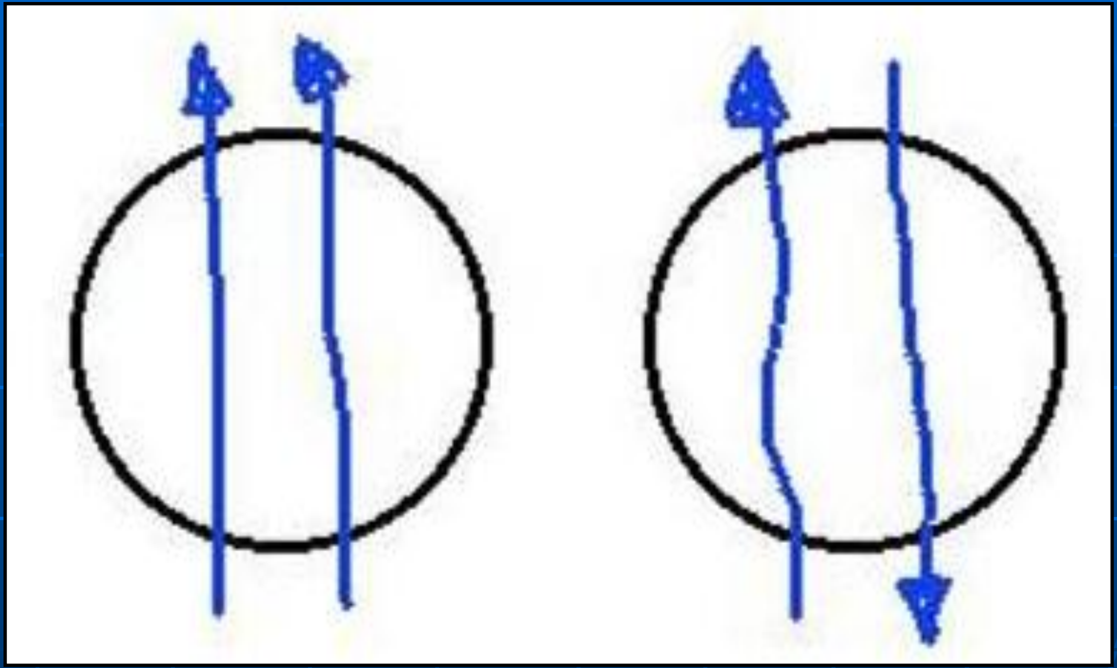
Ratio of random to regular magnetic fields:

≥ 4 in spiral arms and starburst regions,

0.5 – 2 in magnetic arms

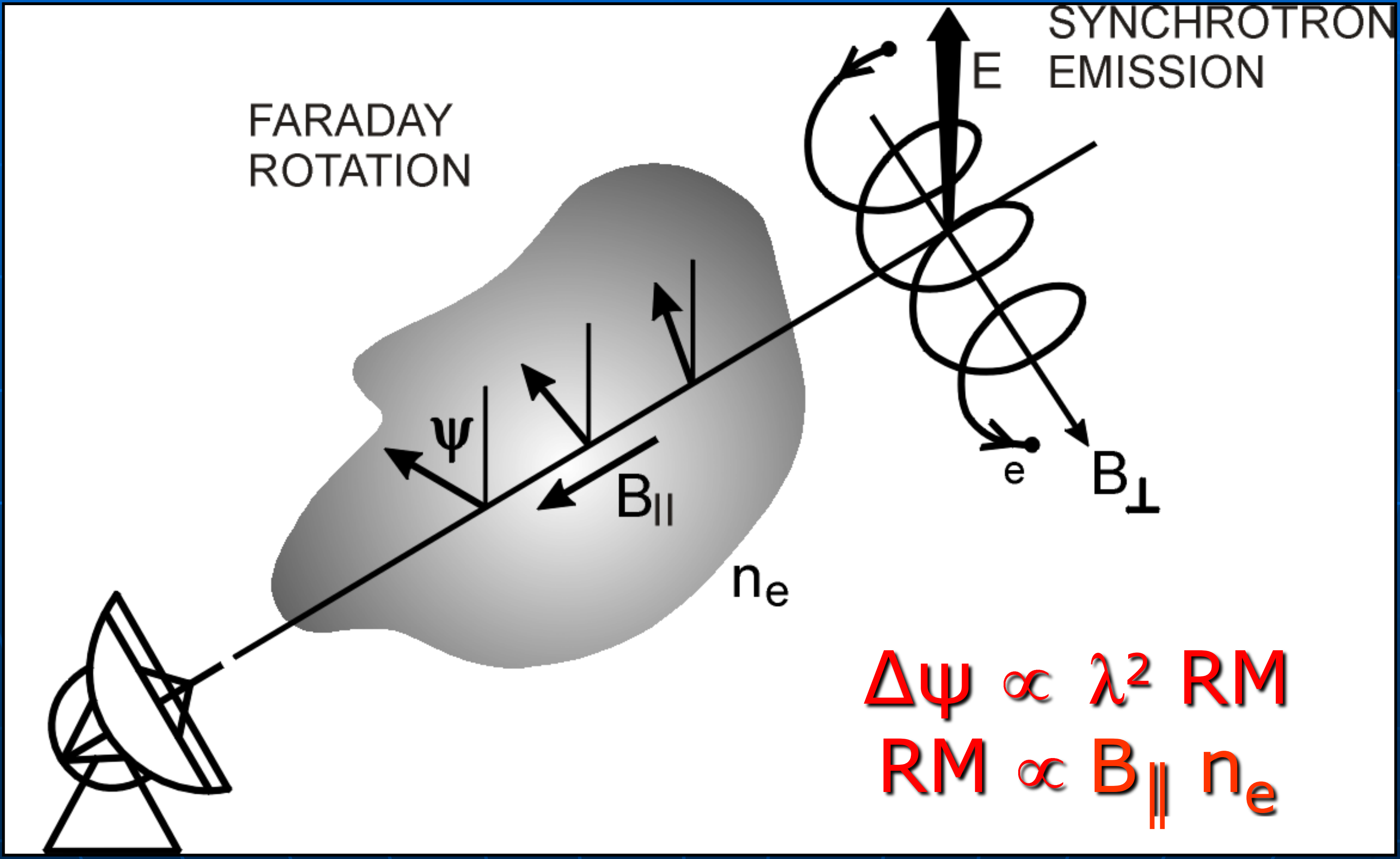
Fletcher et al. 2004

	Regular (coherent) field	Anisotropic (incoherent) field



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

Faraday rotation



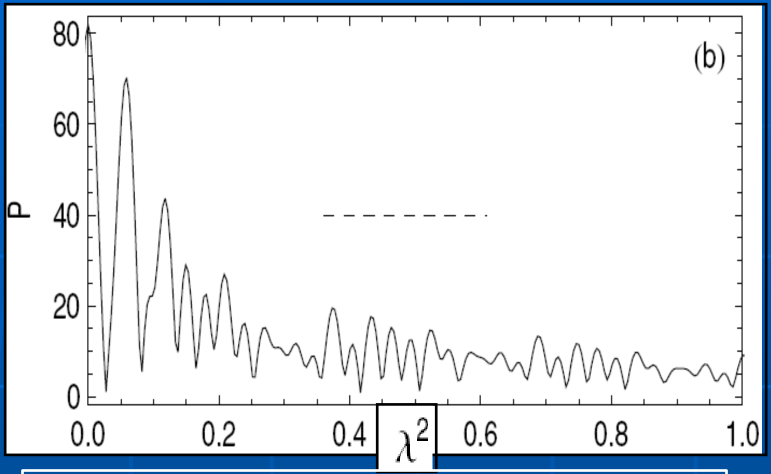
$$\Delta\psi \propto \lambda^2 \, RM$$

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

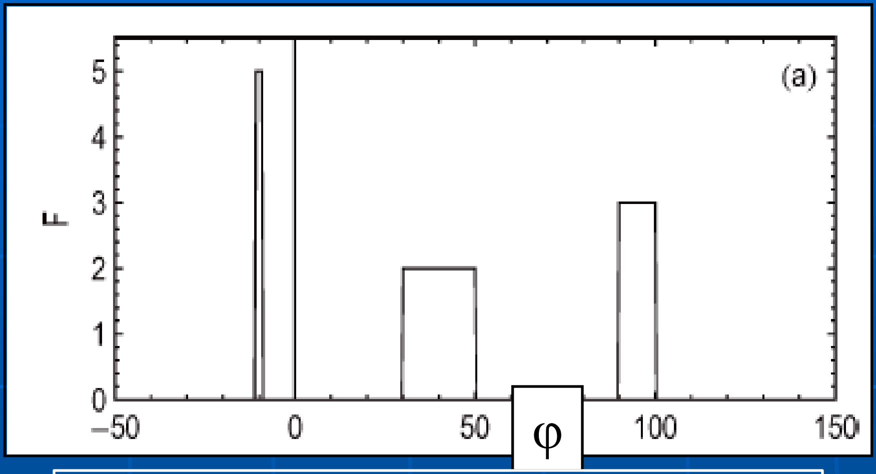
Faraday rotation angles

	|RM| =	10	1	0.1 rad m^{-2}
1400 MHz	$\Delta\chi$ =	30°	3°	0.3°
200 MHz	$\Delta\chi$ =	1300°	130°	13°
120 MHz	$\Delta\chi$ =	3600°	360°	36°

RM Synthesis



Frequency spectrum of complex polarized intensity



Faraday spectrum of Faraday depth components

The observed complex polarization *P* is the Fourier transform of the complex Faraday spectrum *F*(*φ*) (the "source distribution" in Faraday depth *φ*)

Brentjens & de Bruyn 2005

RM Synthesis
(radio spectro-polarimetry)

- The observed spectrum of complex polarization in frequency is Fourier-transformed into the Faraday spectrum in Faraday depth

- Faraday depth ($\varphi \propto \int B_{\|}\, n_e\, dl$) is a physical quantity, different from the classical (observable) rotation measure

- The Faraday spectrum allows to model different layers of magneto-ionic gas along the line of sight
  (Faraday tomography)

"Mean-field" dynamo theory for galactic magnetic fields

- Ingredients:
  Ionized gas + differential rotation + turbulence

- Dynamical separation between large scales and small scales

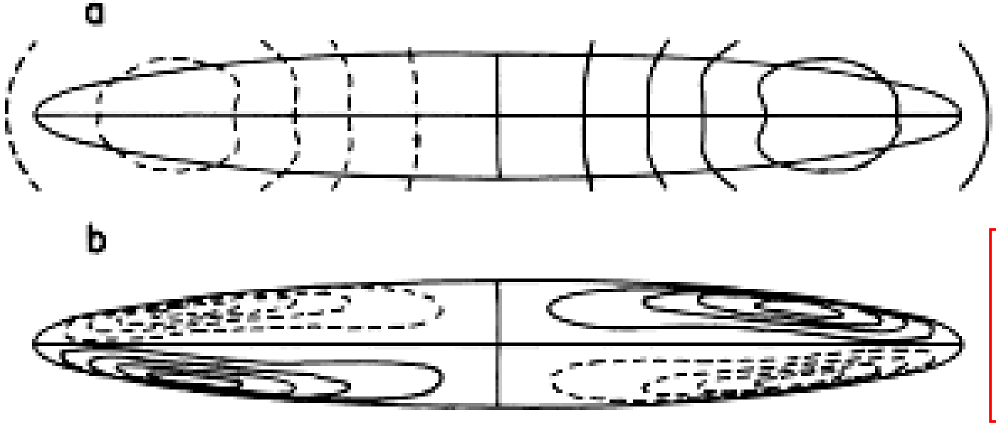
- Microphysics approximated by the average parameters
  "alpha-effect" (helicity) and magnetic diffusivity

- Solutions: large-scale modes

Antisymmetric and symmetric dynamo modes

Stix 1975

A0 mode

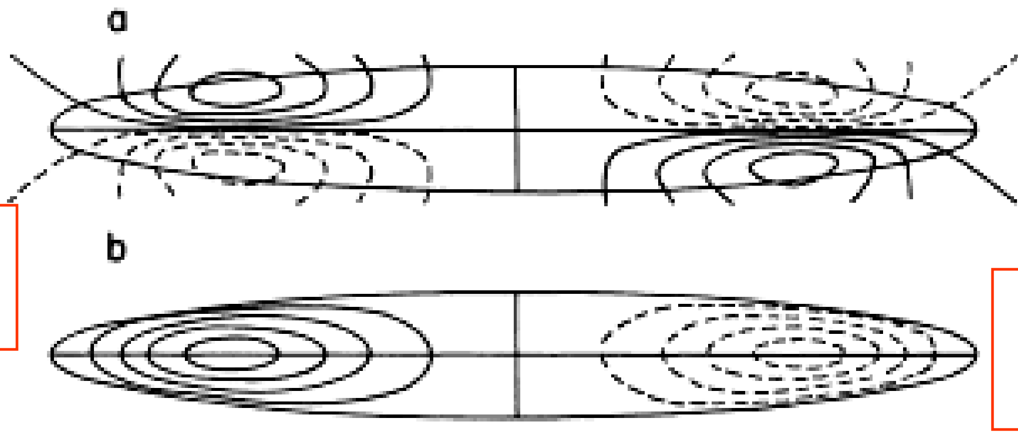


Dipolar poloidal field

Reversing toroidal field in the plane

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 $P = 1.1 \cdot 10^3$

S0 mode

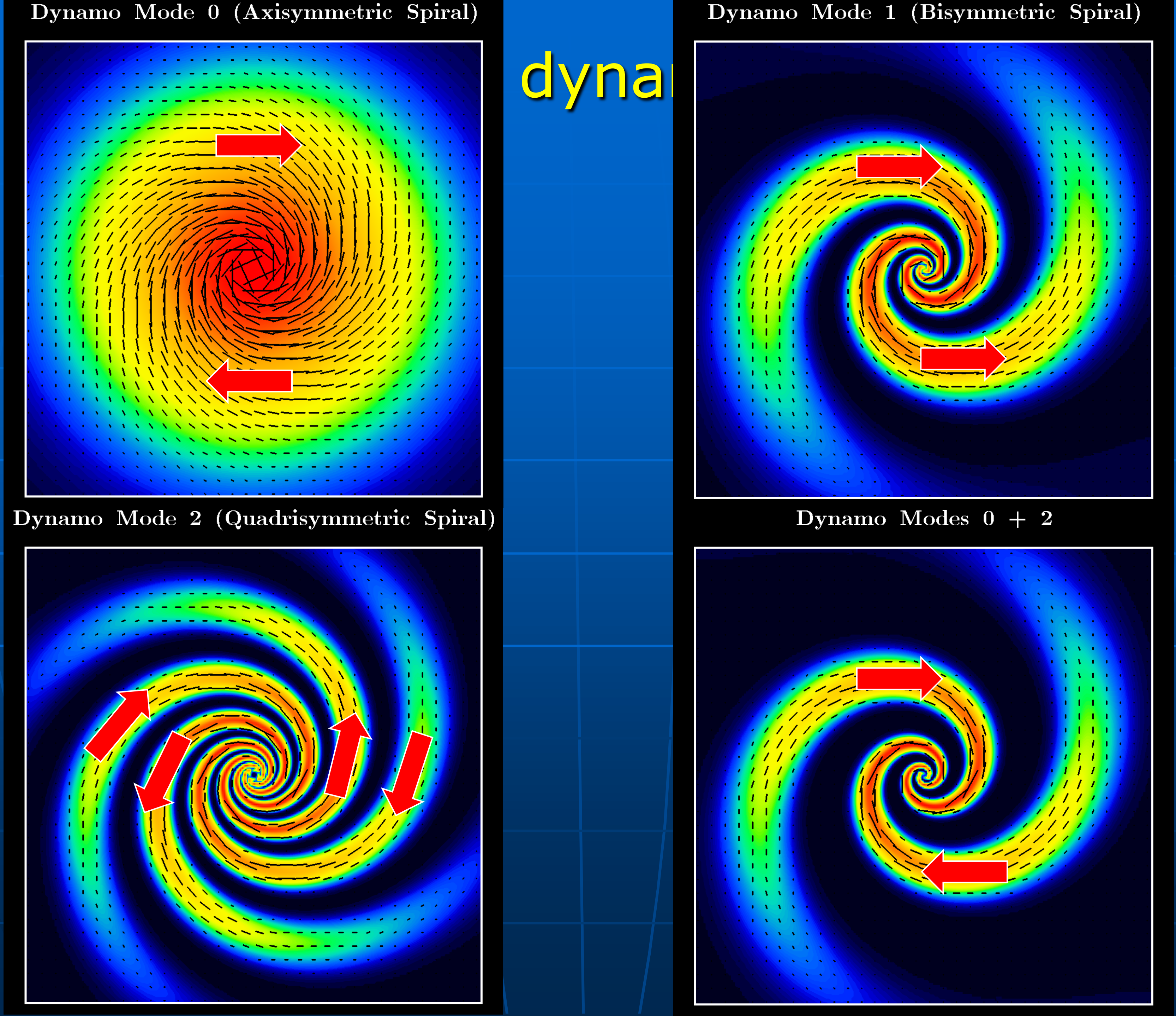


Quadrupolar poloidal field

No reversing toroidal field

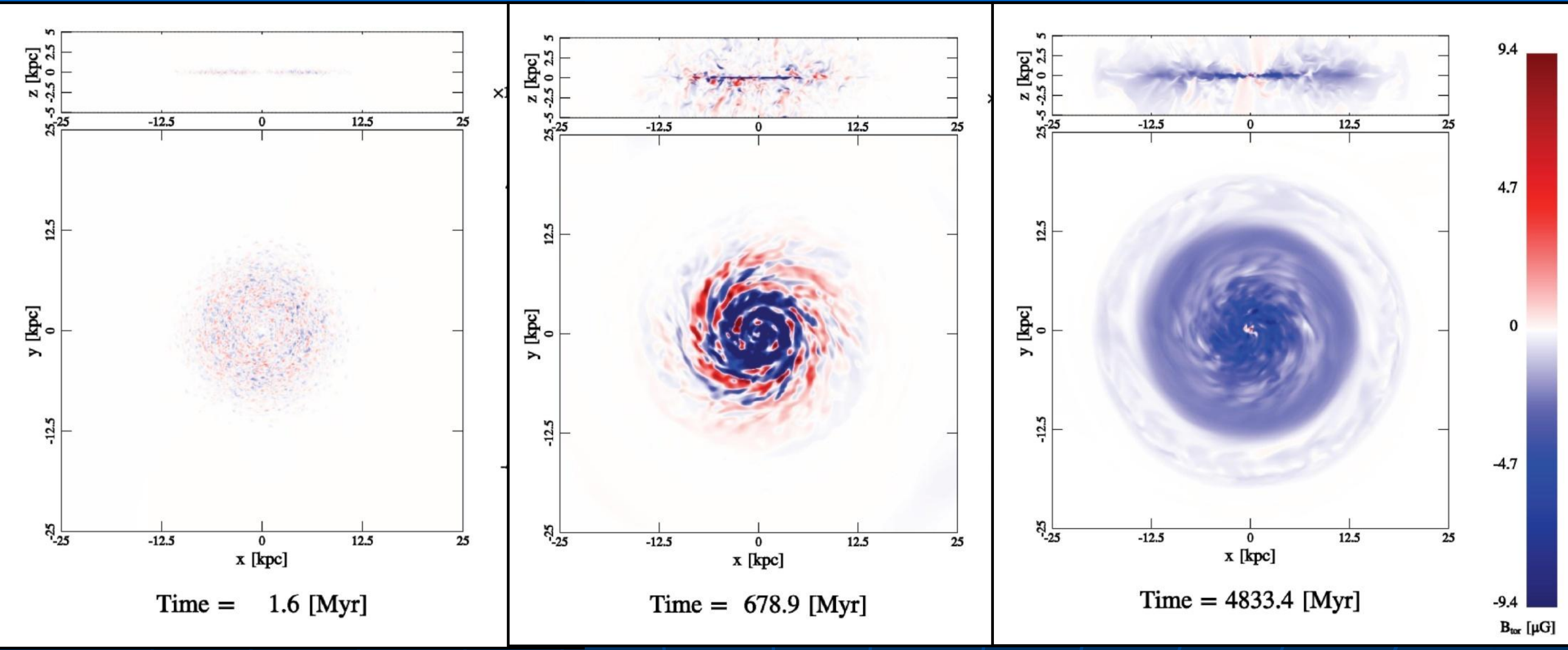
Fig. 2a and b. Poloidal field lines (a) and curves of constant toroidal field strength (b) for a quadrupole type field, with $R = 15$ kpc, $b = 2$ kpc, and $P = -8.5 \cdot 10^3$

dyna


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

Global cosmic-ray driven MHD model

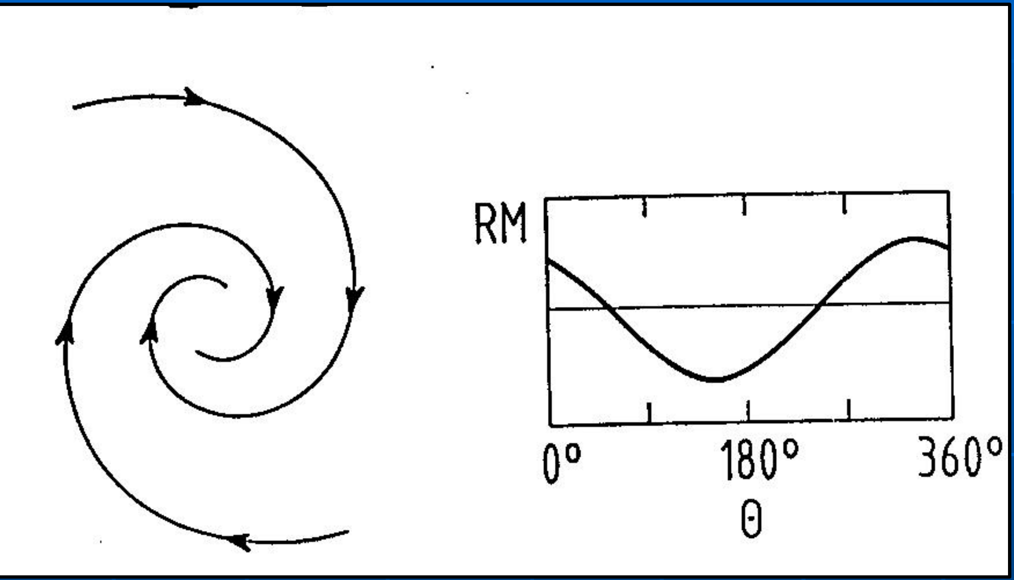
Hanasz et al. 2009



Generation of a dominant axisymmetric mode:
Confirmation of the mean-field model

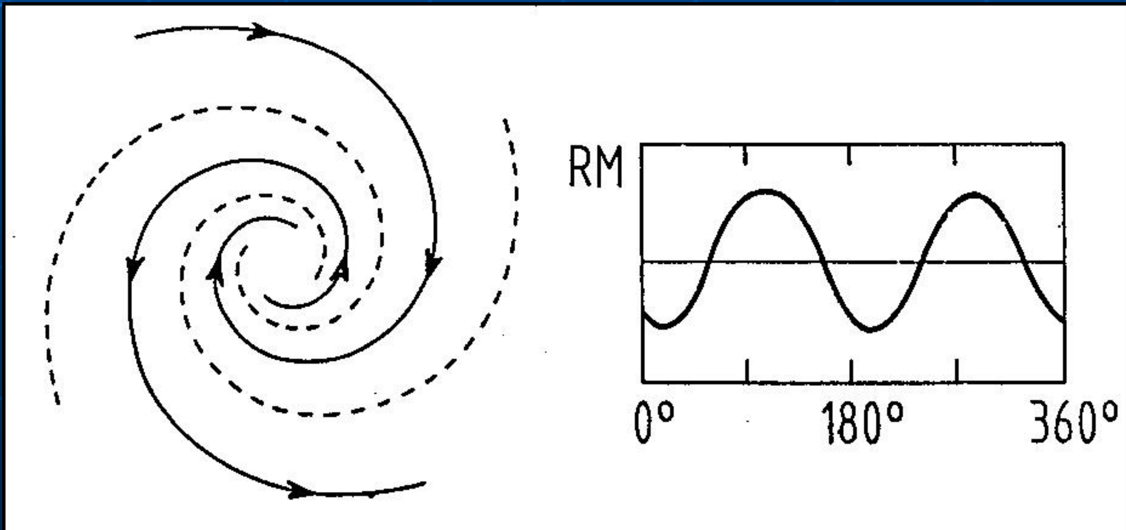
Finding dynamo modes:
Azimuthal variation of Faraday rotation

Krause 1990



Axisymmetric spiral
(m=0)

Bisymmetric spiral
(m=1)



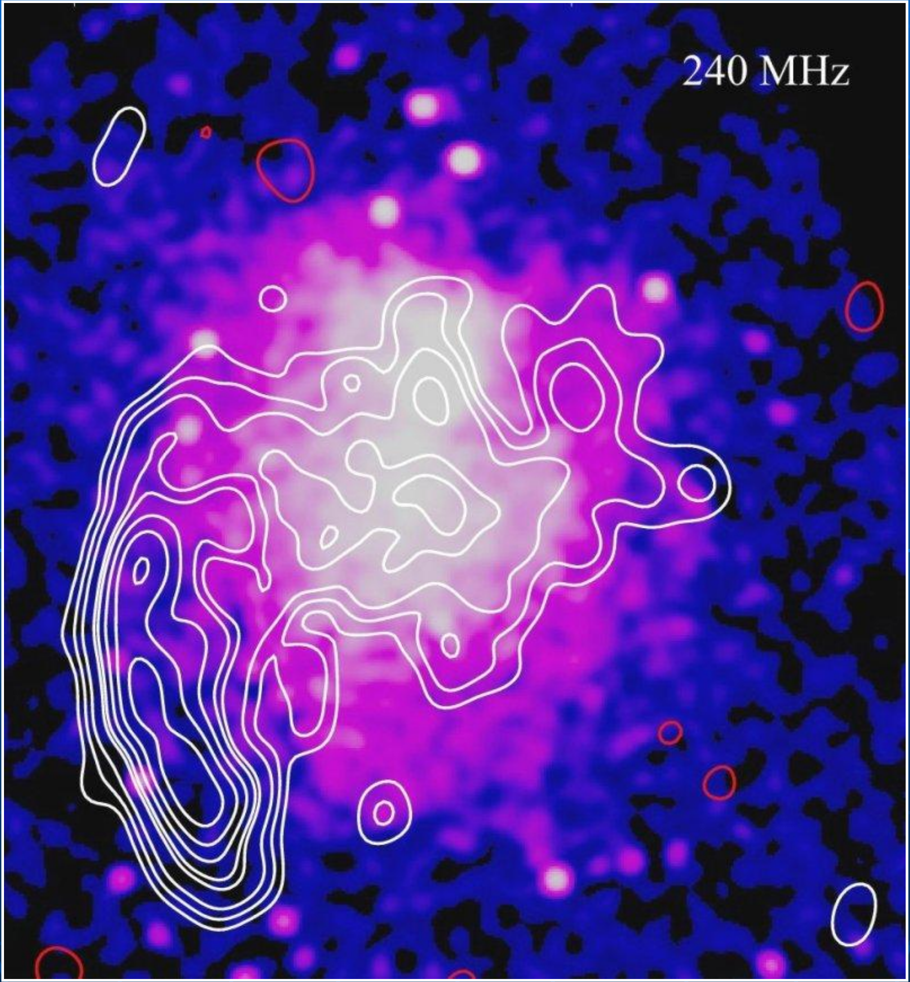
Future radio telescopes

- Higher resolution: EVLA, SKA
- Larger sensitivity: EVLA, MeerKAT, SKA
- Higher frequencies: ALMA
- Lower frequencies: LOFAR, SKA
- Higher survey speed: LOFAR, ASKAP, APERTIF, SKA

The advantages of low-frequency radio observations

- Low frequency synchrotron emission traces cosmic-ray electrons in weak magnetic fields
- Low frequencies trace old cosmic-ray electrons far away from their acceleration sites
- Low frequencies measure small rotation measures from weak magnetic fields

Halo and relic emission from Abell521
(GMRT 240MHz)



Brunetti et al.
2008

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:

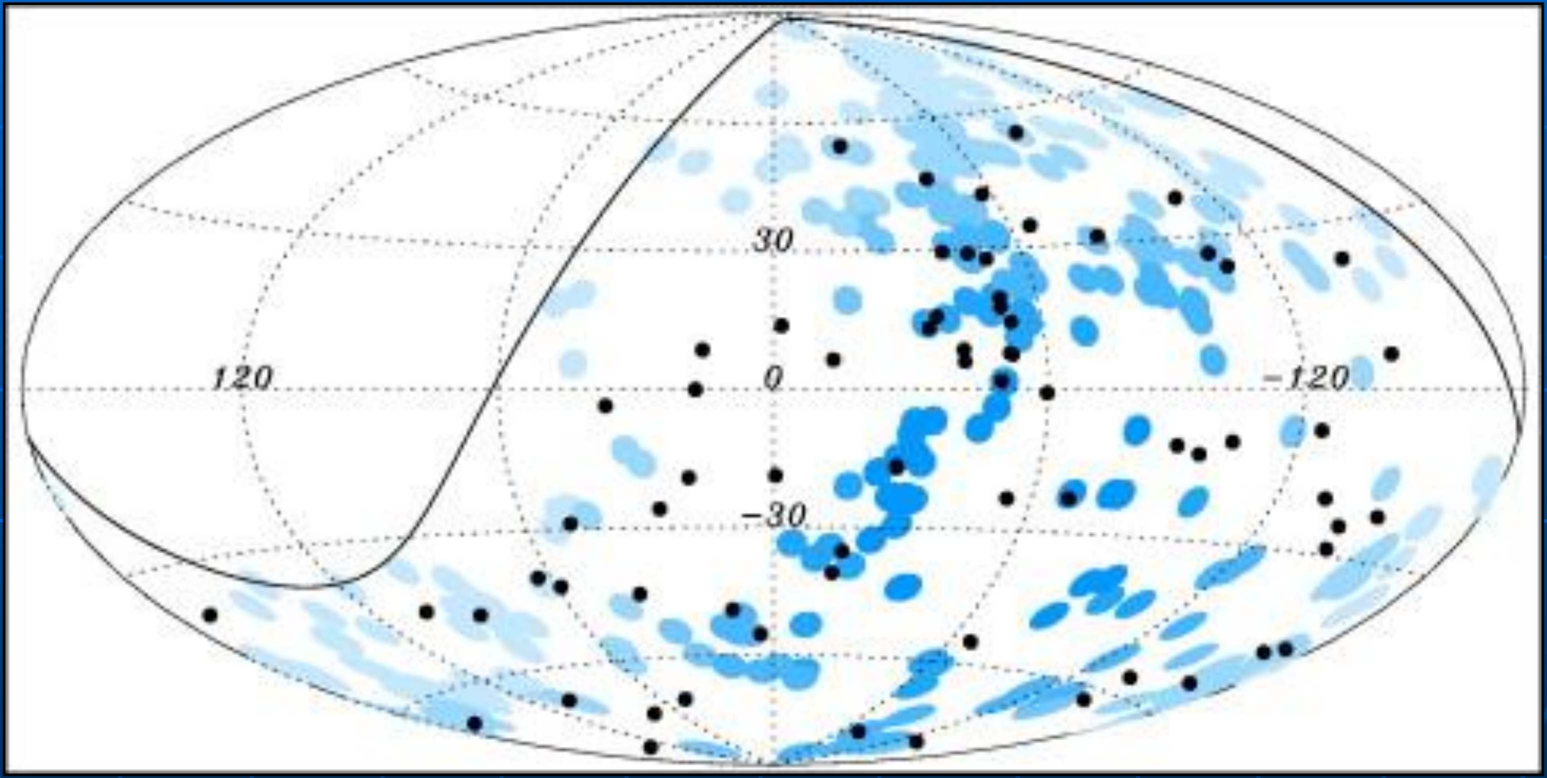
  n_e=10^{-3} cm^{-3}, $B_{||}$ =1 μG, L=1 kpc: RM~1 rad m^{-2}

- Intergalactic magnetic fields:

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

AUGER UHECR events (> 5 10^{19} eV)

AUGER 2010



Localizing the UHECR sources requires knowledge about the Milky Way's magnetic field