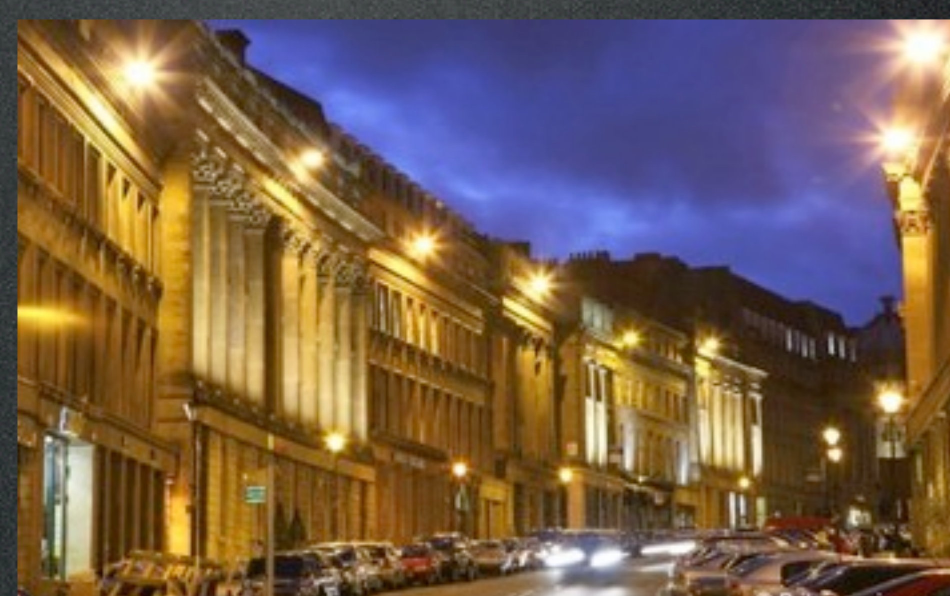
Magnetic fields in nearby galaxies

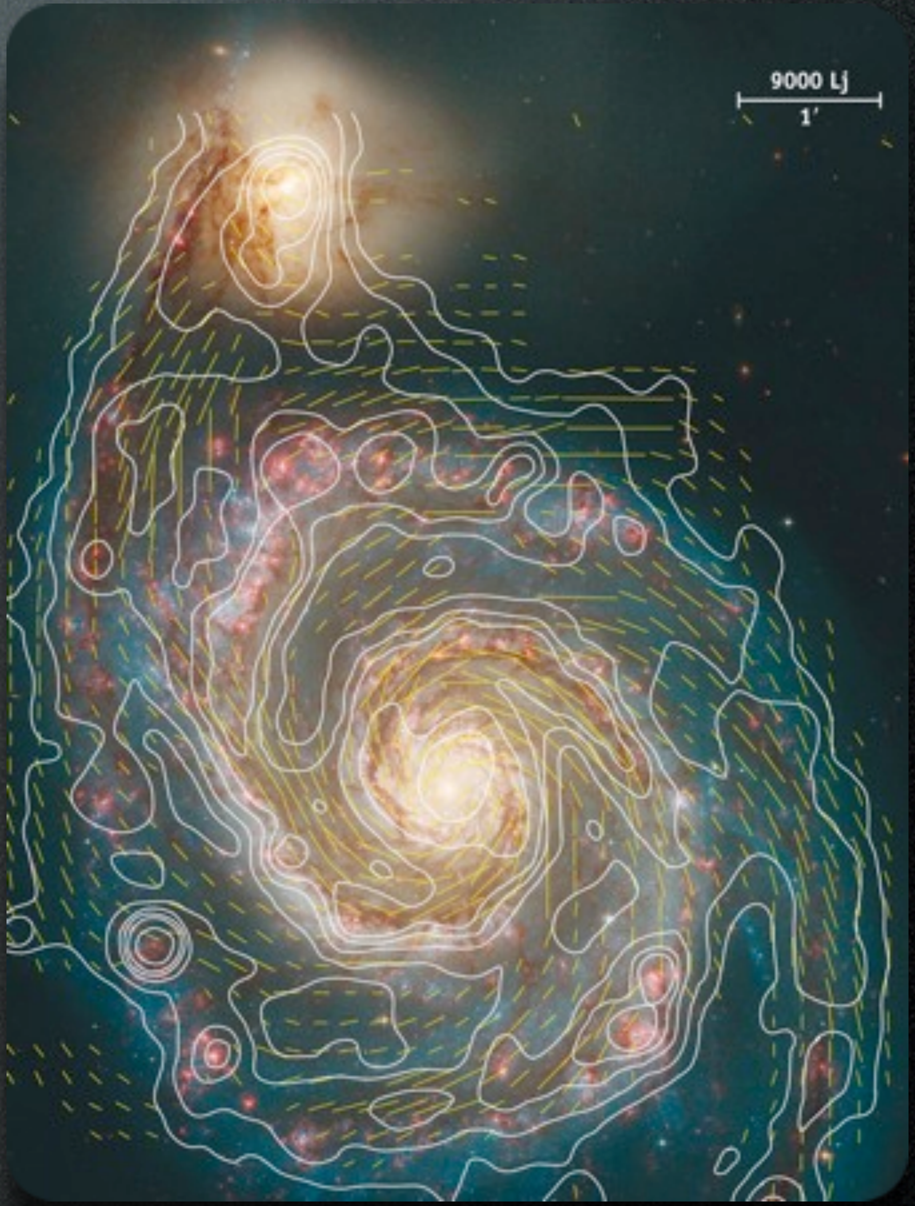
Andrew Fletcher, Newcastle University

with Anvar Shukurov, Rainer Beck, Elly Berkhuijsen
and many others



Content

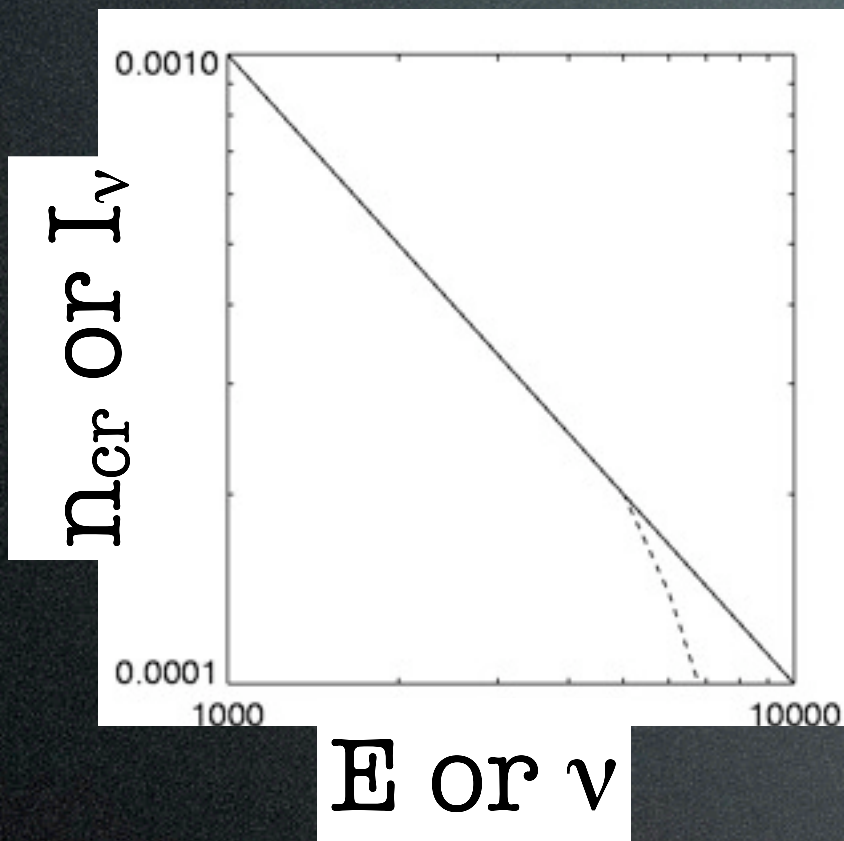
- Sources of information.
  - Synchrotron radiation ...
  - ... its polarization ...
  - ... Faraday rotation ...
  - and depolarization.
- Overview of observations.
- Some connection to theory.
- Concentrate on large-scale magnetic fields

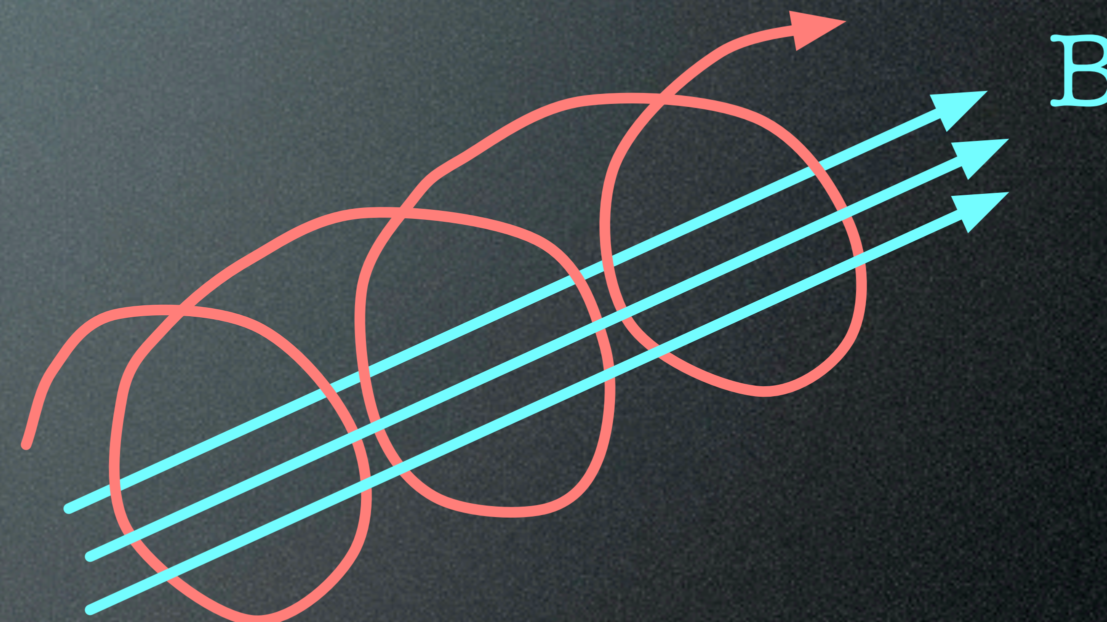


Fletcher et al. 2010 / SuW

Optical Image credit: NASA, ESA, S. Beckwith (STScI), and The Hubble Heritage Team (STScI/AURA)

Synchrotron intensity





$$n_{\rm cr}(E)\mathrm{d}E = n_0 \left(\frac{E}{E_0}\right)^{-s} \mathrm{d}E$$

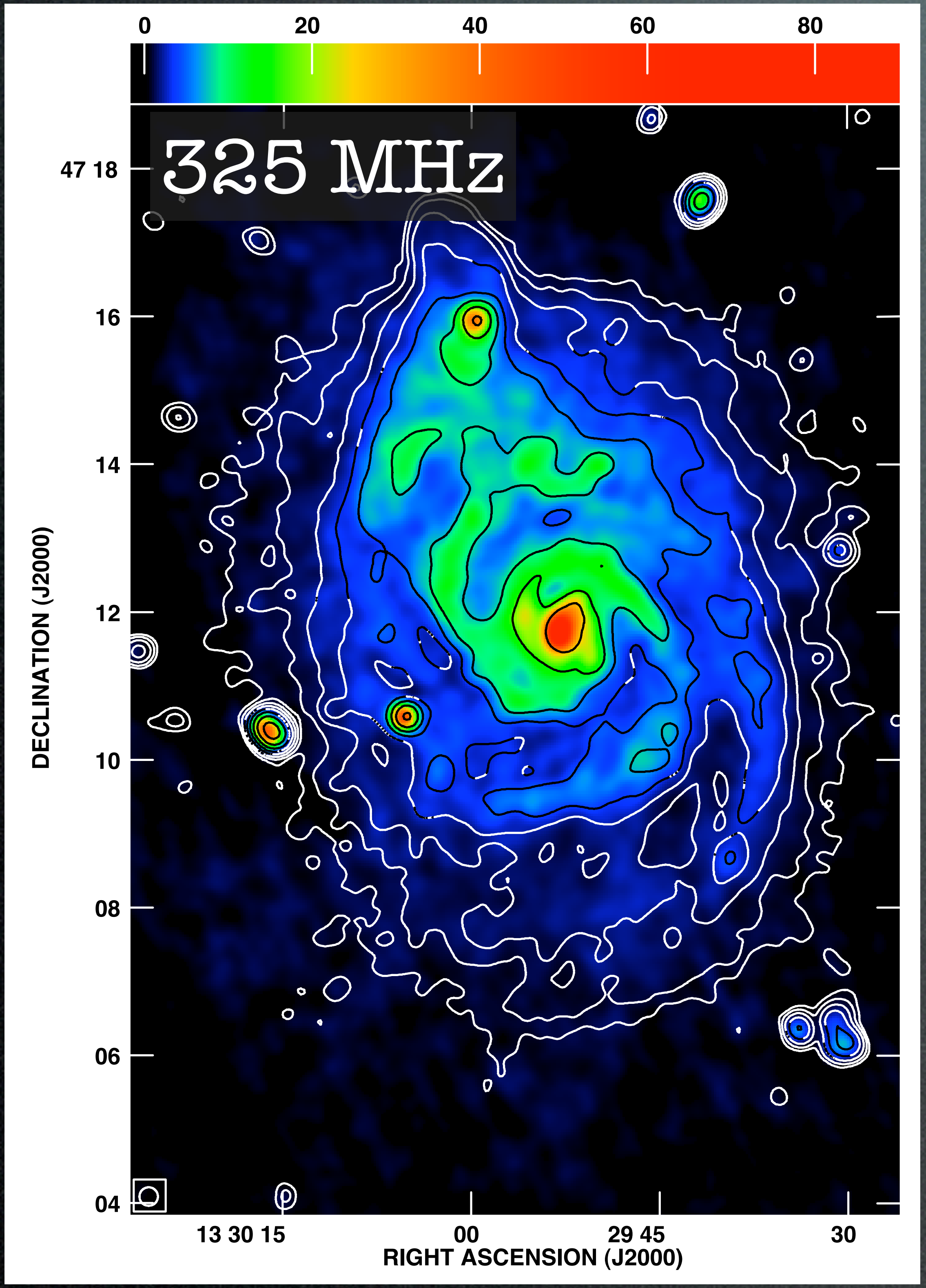
cosmic ray electrons,
s ≈ 2.5 to 3

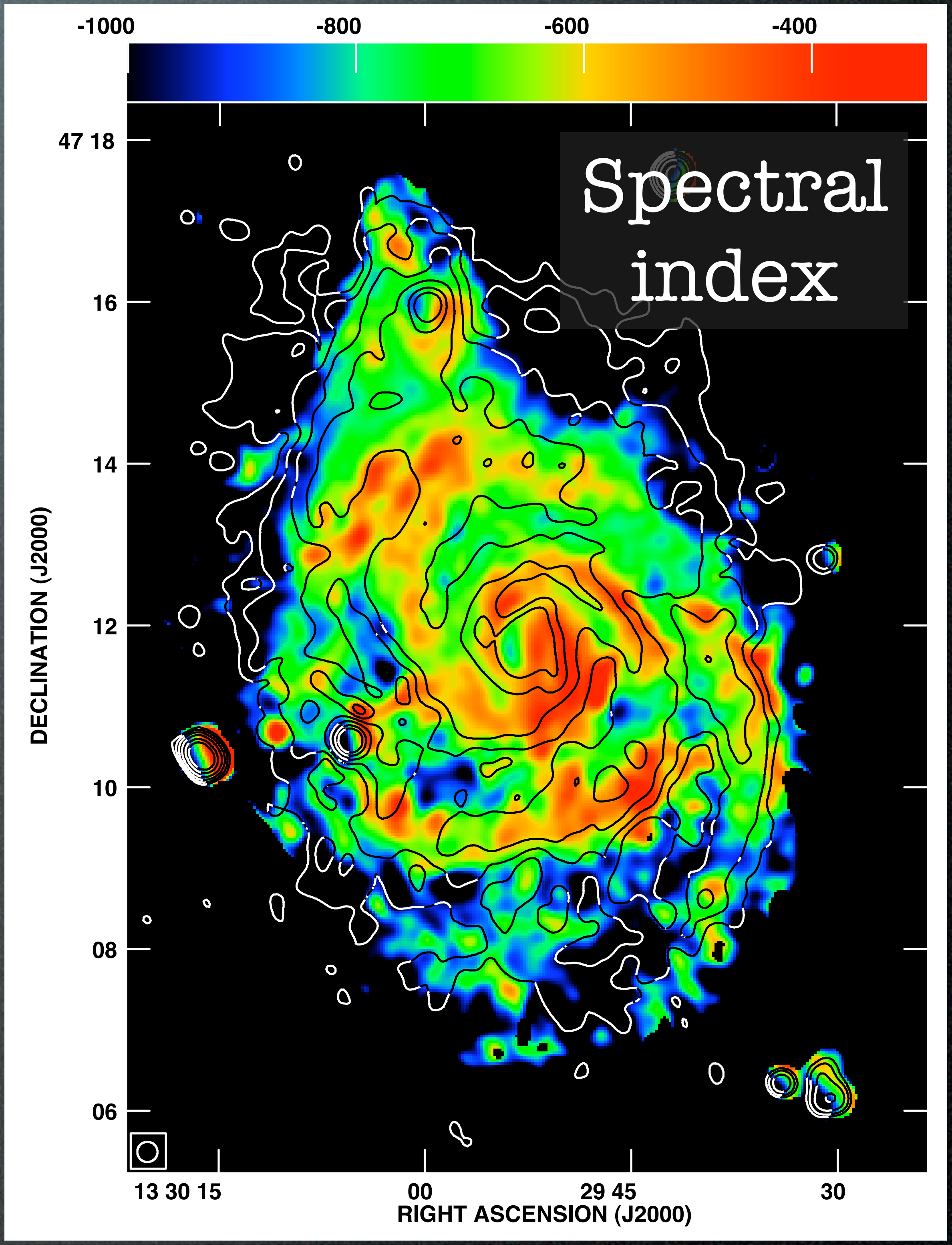
$$I_\nu \propto n_0\, B_\perp^{(1+s)/2}\, \nu^{(1-s)/2}$$

synchrotron emission

(+ thermal emission)

Extent of disc

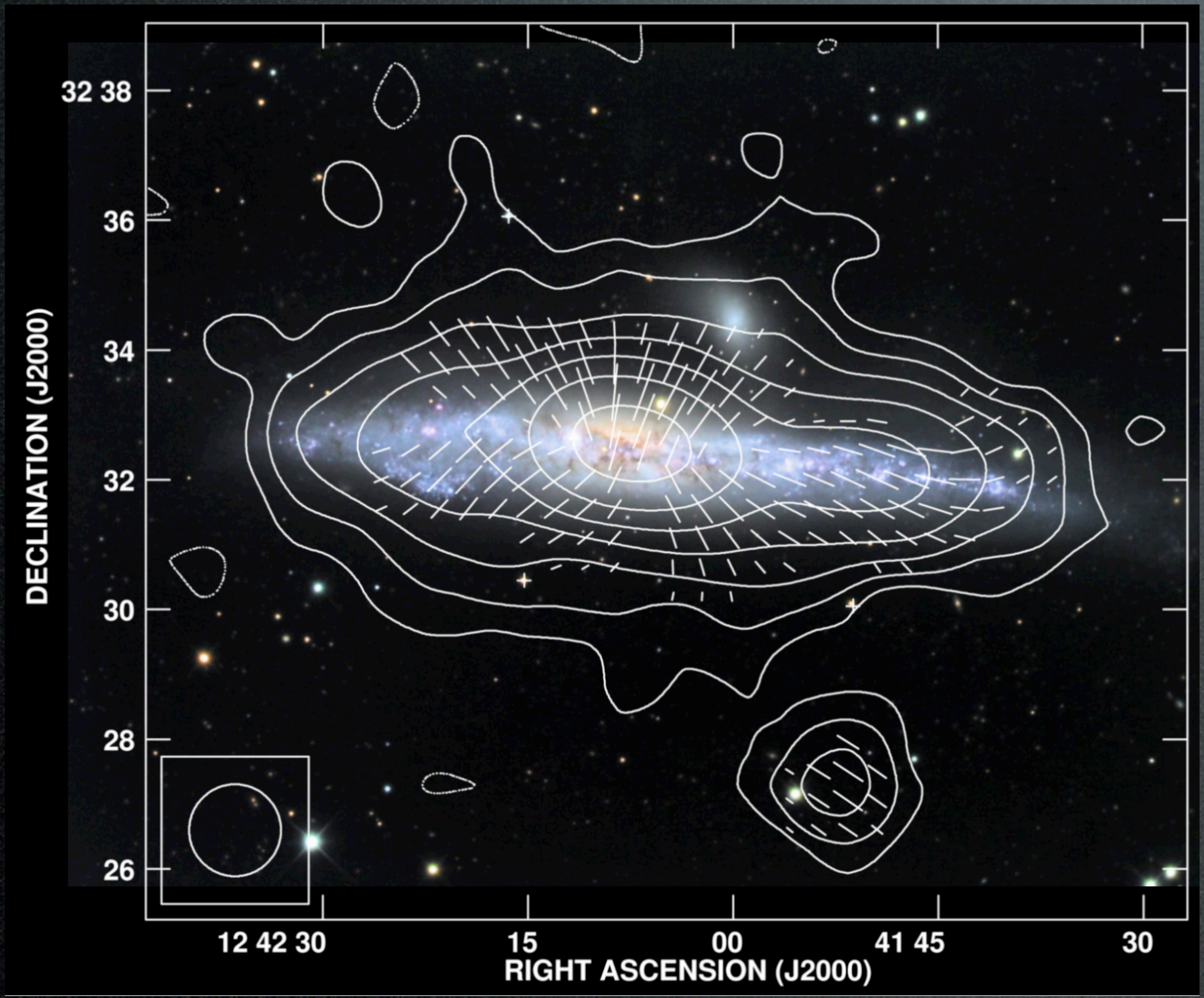




Mitra, Fletcher et al. in prep.

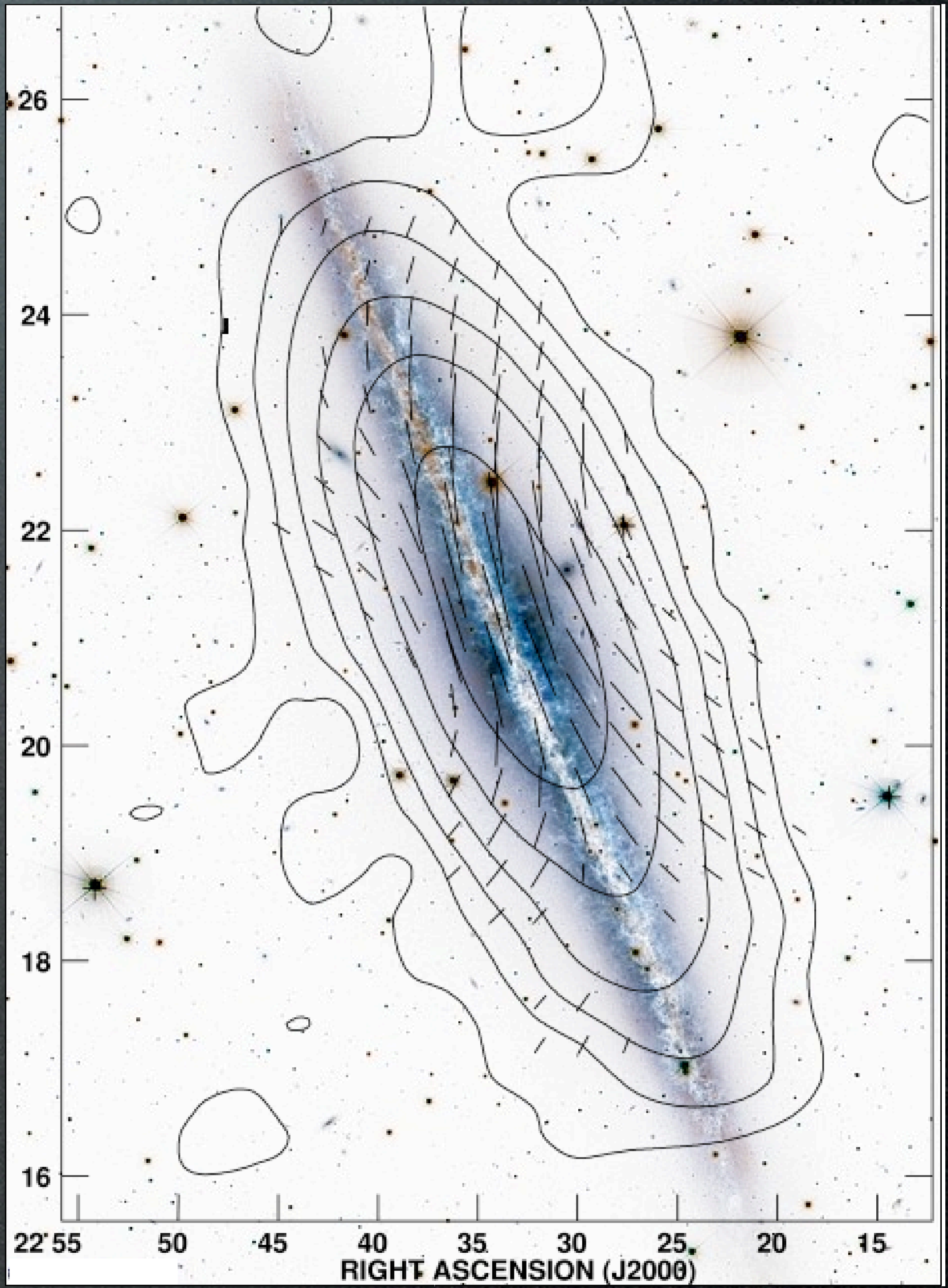
Extent of halo

NGC 4631



Krause 2009

NGC 891



Krause 2009

Synchrotron polarization

Linear polarization perpendicular to $B_\perp$

$$p_0 = \frac{s+1}{1+7/3} \simeq 0.7$$

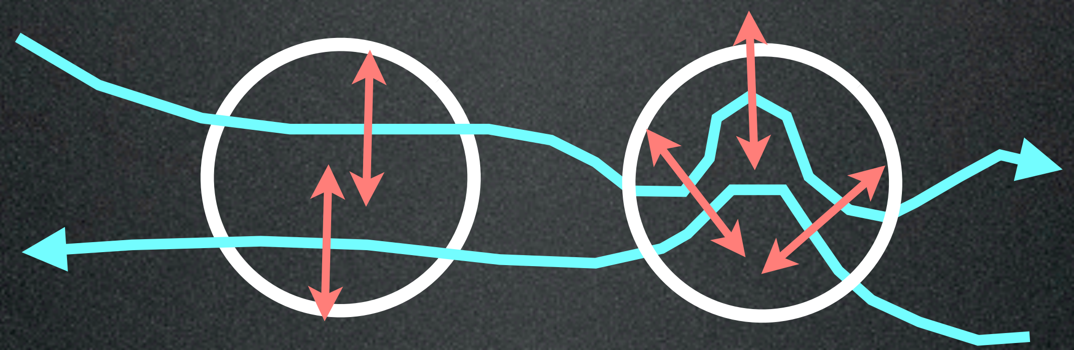
for purely ordered B

$$p = p_0 \frac{\bar{B}^2}{(\bar{B}^2 + b^2)}$$

degree of B order

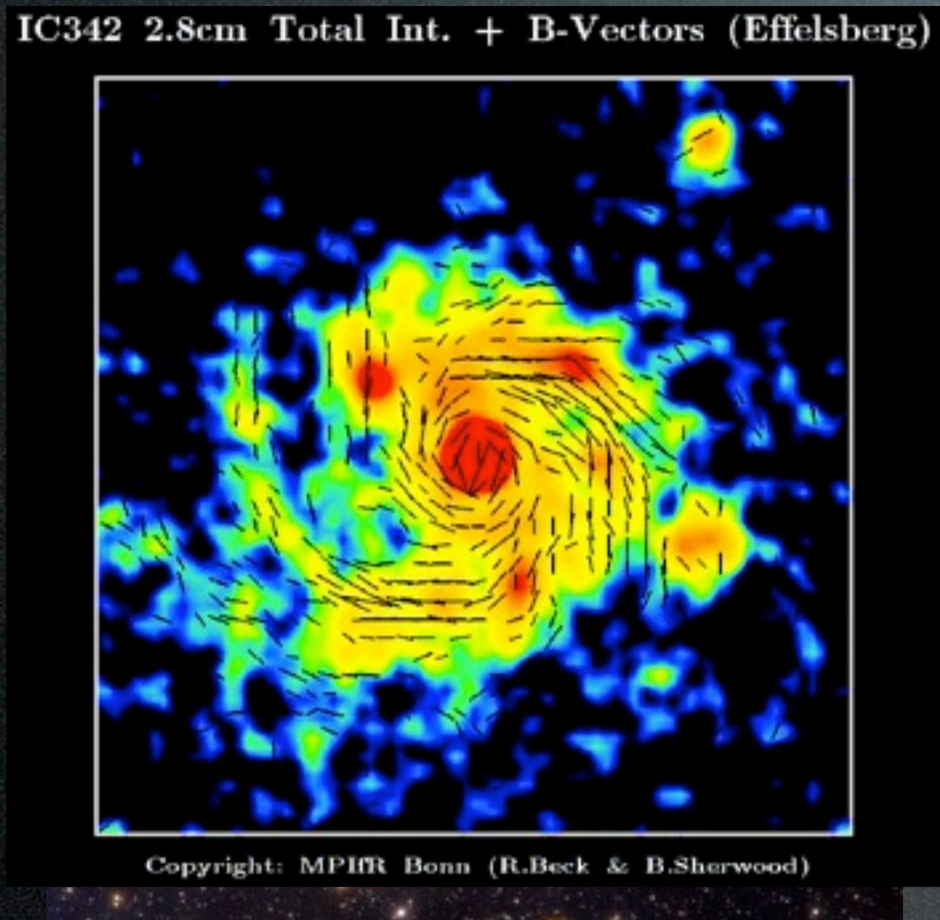
Burn 1966

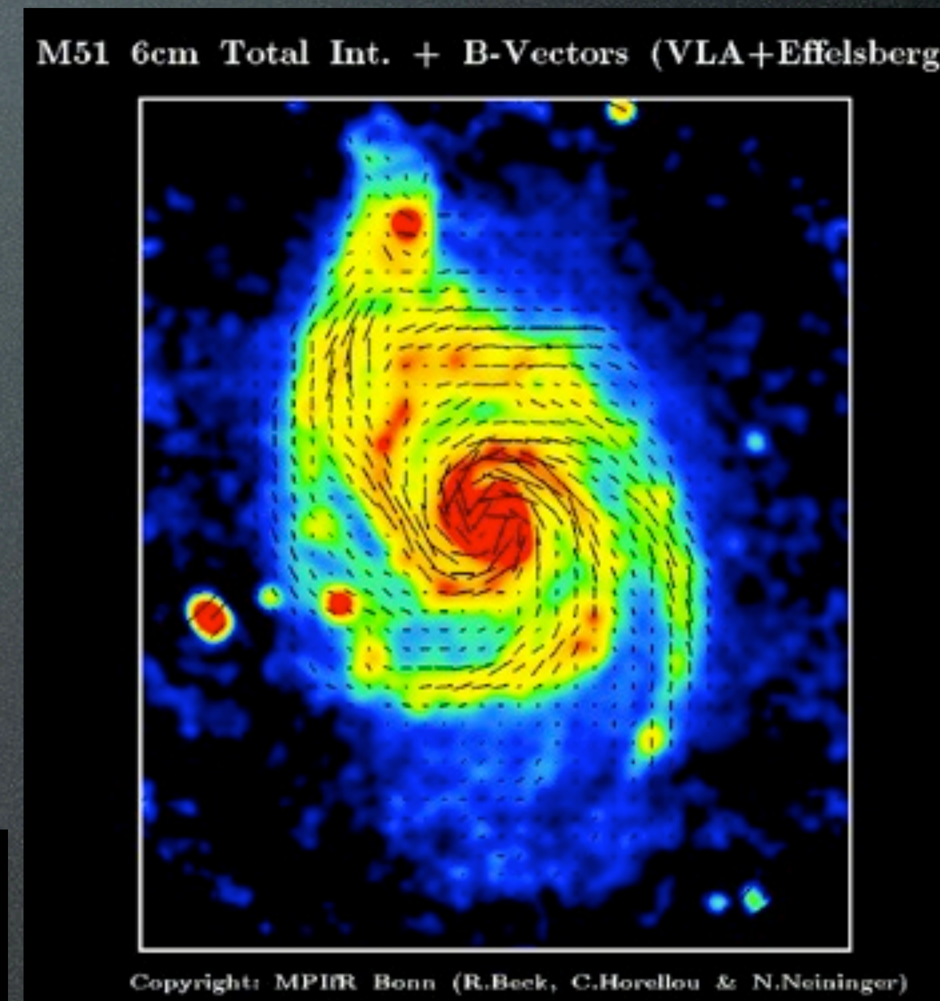
high p

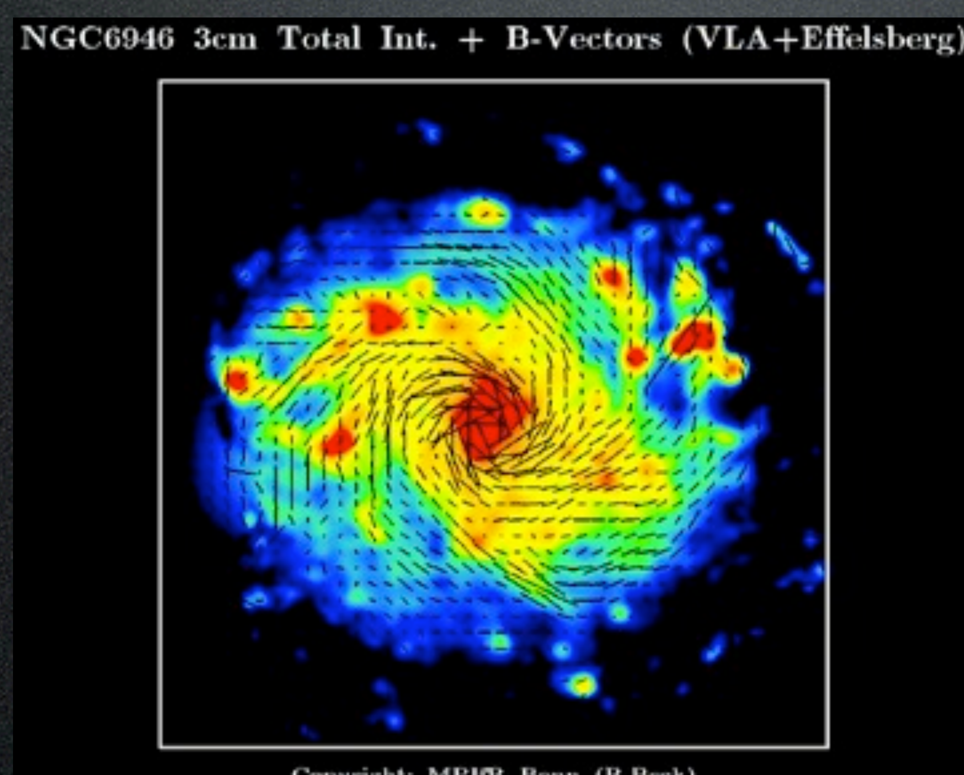


low p

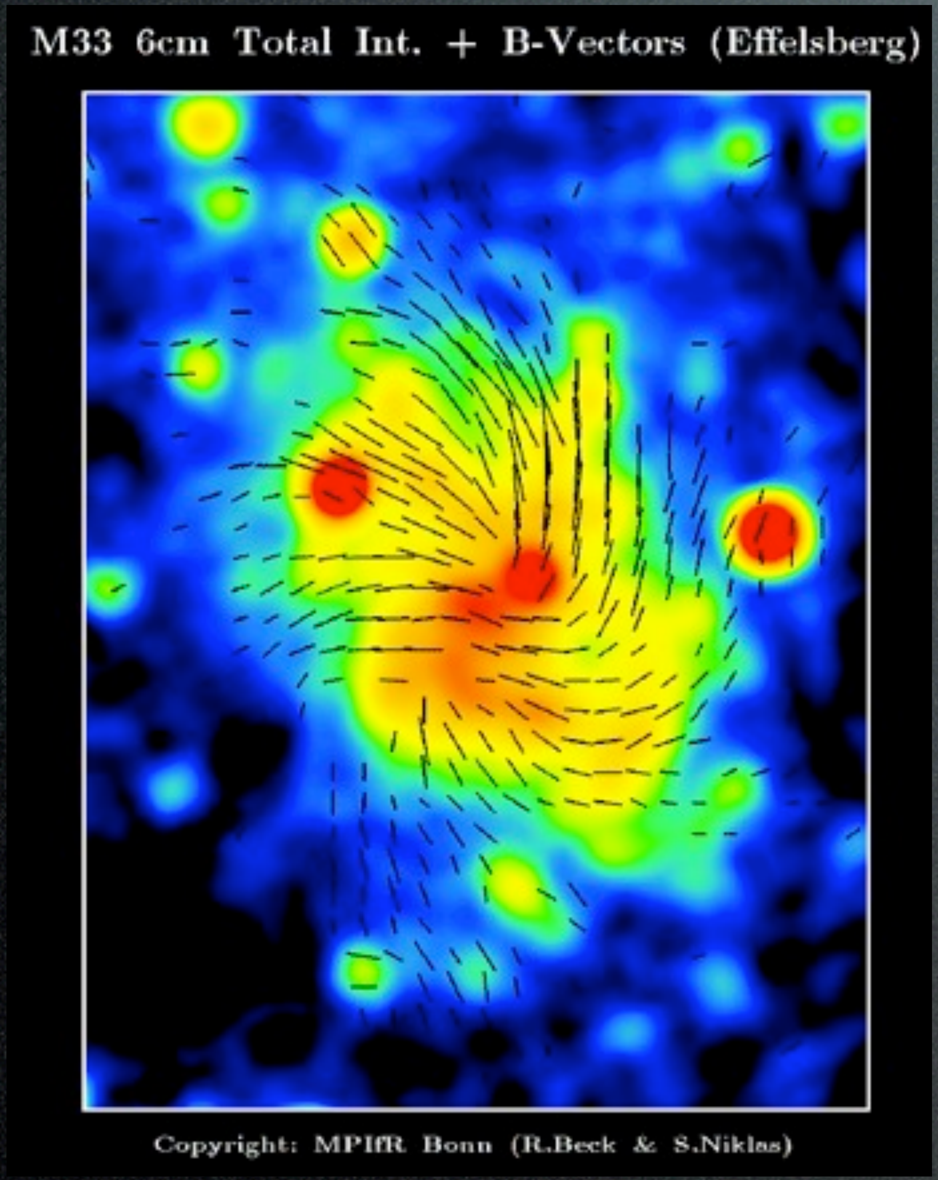
Spiral galaxies

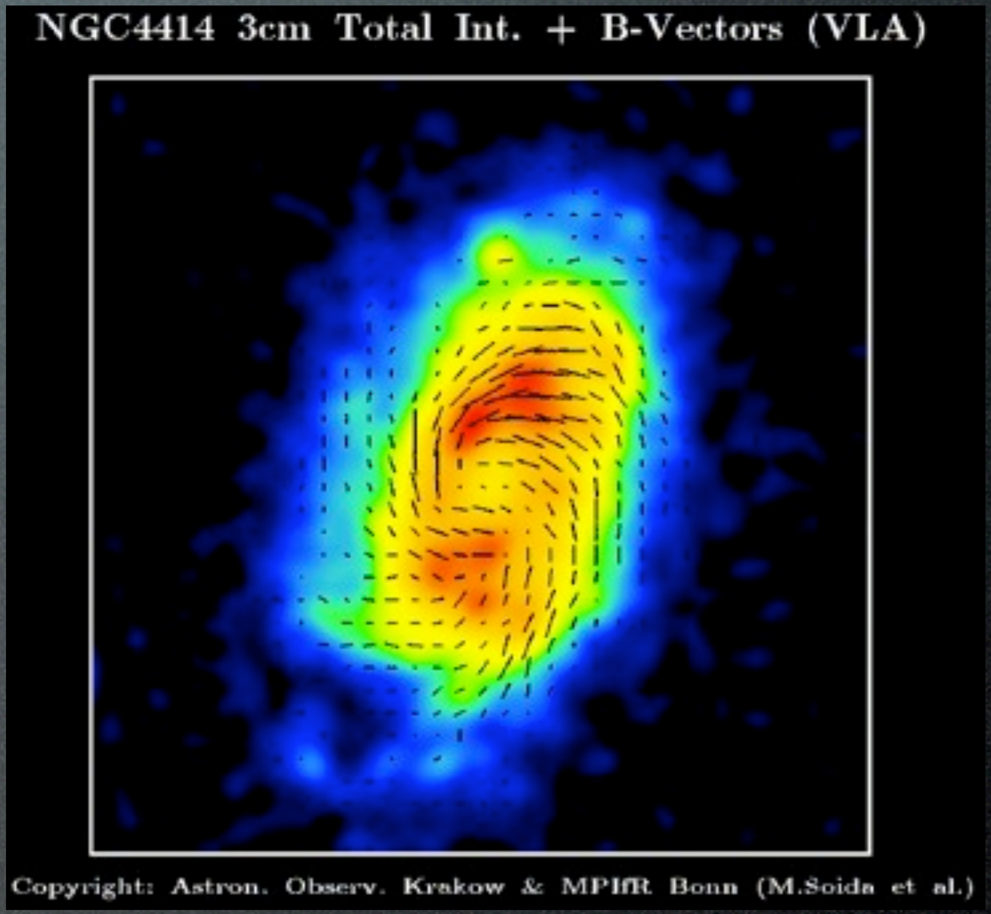






Flocculent galaxies

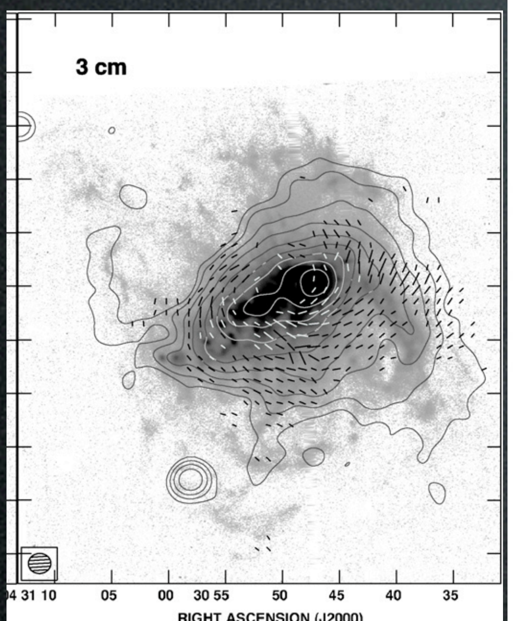


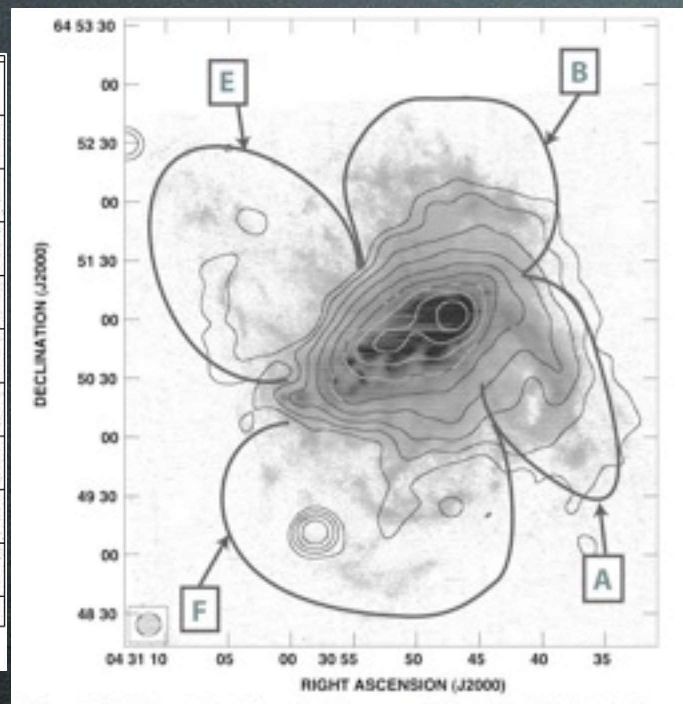


Dwarf & irregular galaxies

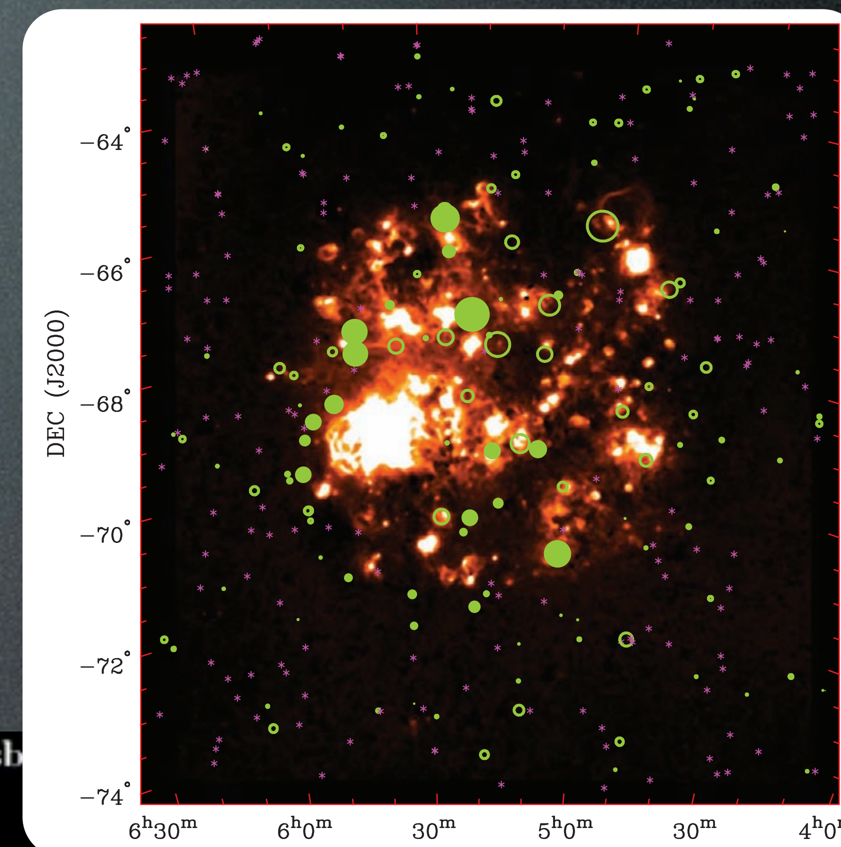
NGC 1569

Kepley et al. 2010



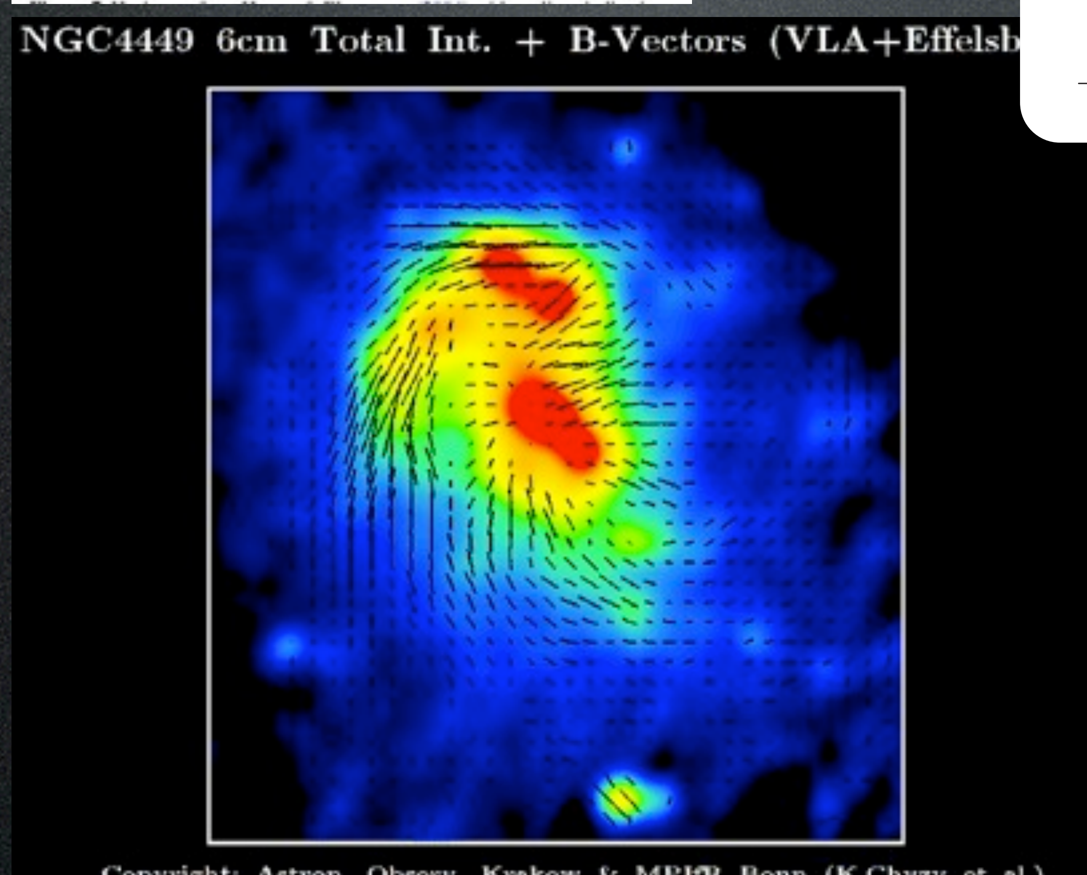


LMC



Gaensler et al. 2005

NGC 4449

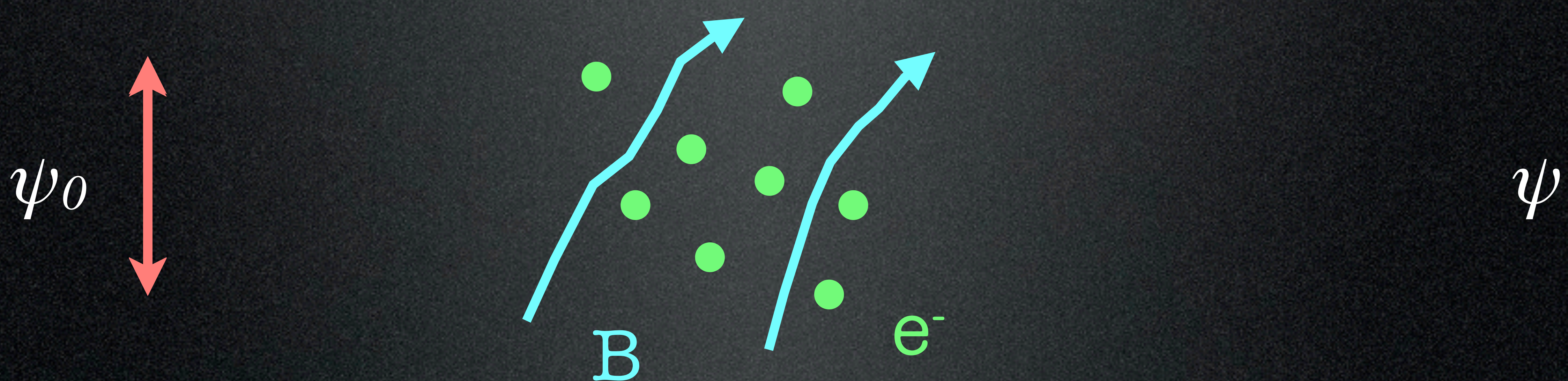


Chyzy et al. 2000

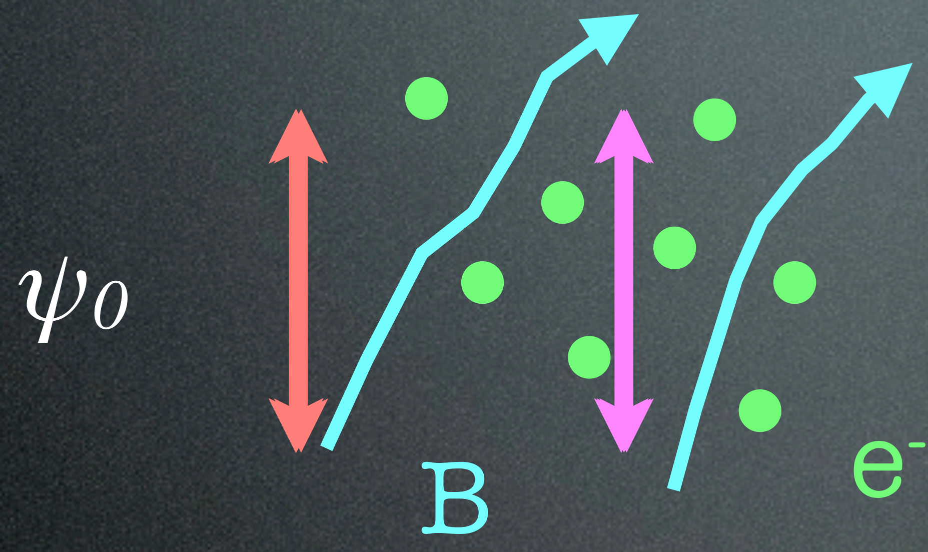
Faraday rotation

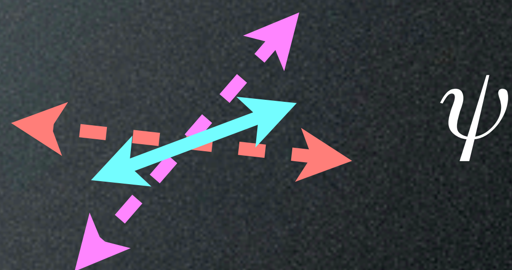
$$\psi = \psi_0 + R\,\lambda^2 \qquad \mathrm{RM} = \frac{\Delta\psi}{\Delta(\lambda^2)}$$ observed

$$R = 0.81 \int_{\mathrm{los}} \frac{n_e}{\mathrm{cm}^{-3}} \frac{B_{\|}}{\mu\mathrm{G}} \frac{\mathrm{d}l}{\mathrm{pc}} \quad \mathrm{rad\,m}^{-2}$$ intrinsic



Faraday Depolarization





Differential Faraday rotation

$$p = p_0 \left| \frac{\sin\left(R\,\lambda^2\right)}{R\,\lambda^2} \right| .$$

Faraday dispersion

$$p = p_0 \frac{1 - \exp\left(-2\,\sigma_R\,\lambda^4\right)}{2\,\sigma_R\,\lambda^4}$$

Burn 1966, Sokoloff et al. 1998

Field strength I

$$I_\nu \propto n_0\, B_\perp^{(1+s)/2}\, \nu^{(1-s)/2}$$

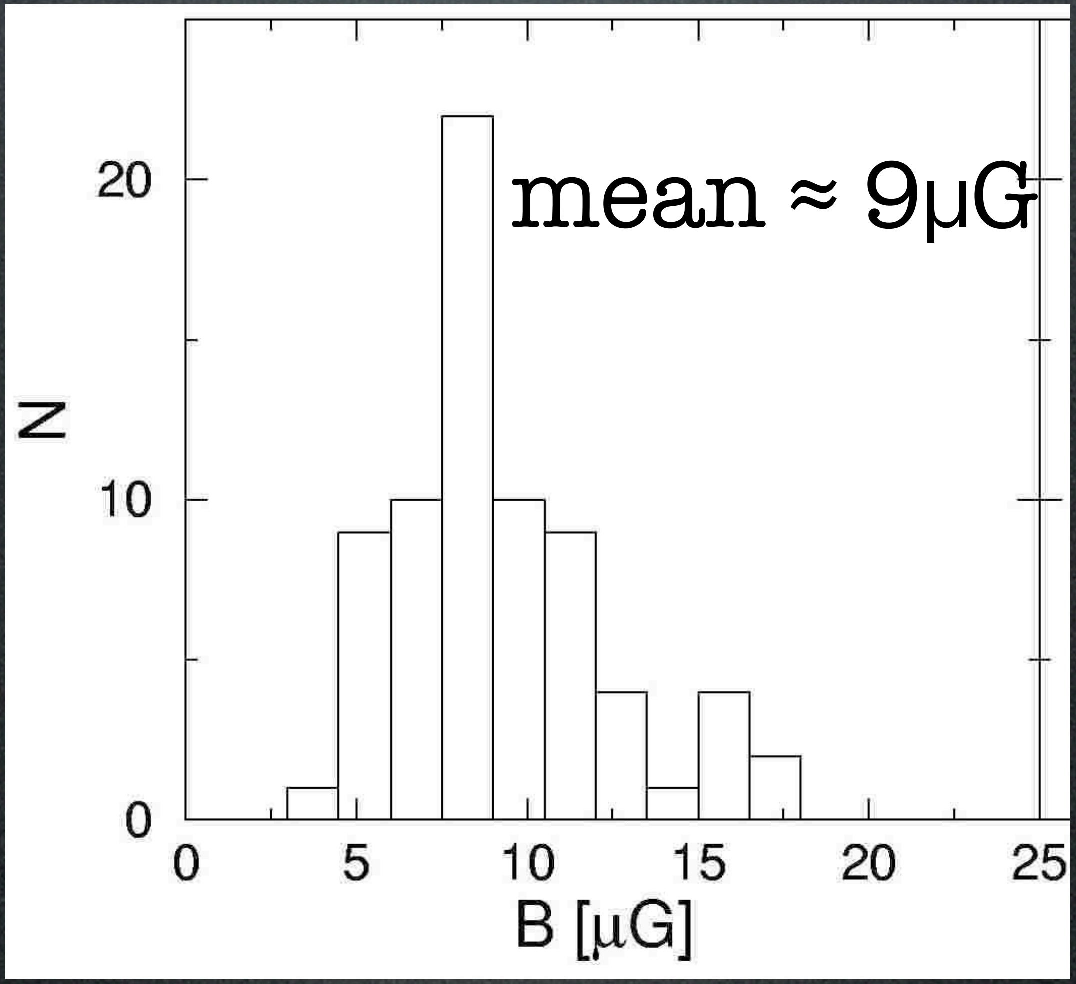
synchrotron emission

$$B_{\rm eq} \propto I^{\,2/(\gamma+5)}$$

assume equipartition cosmic rays and B

Total magnetic field

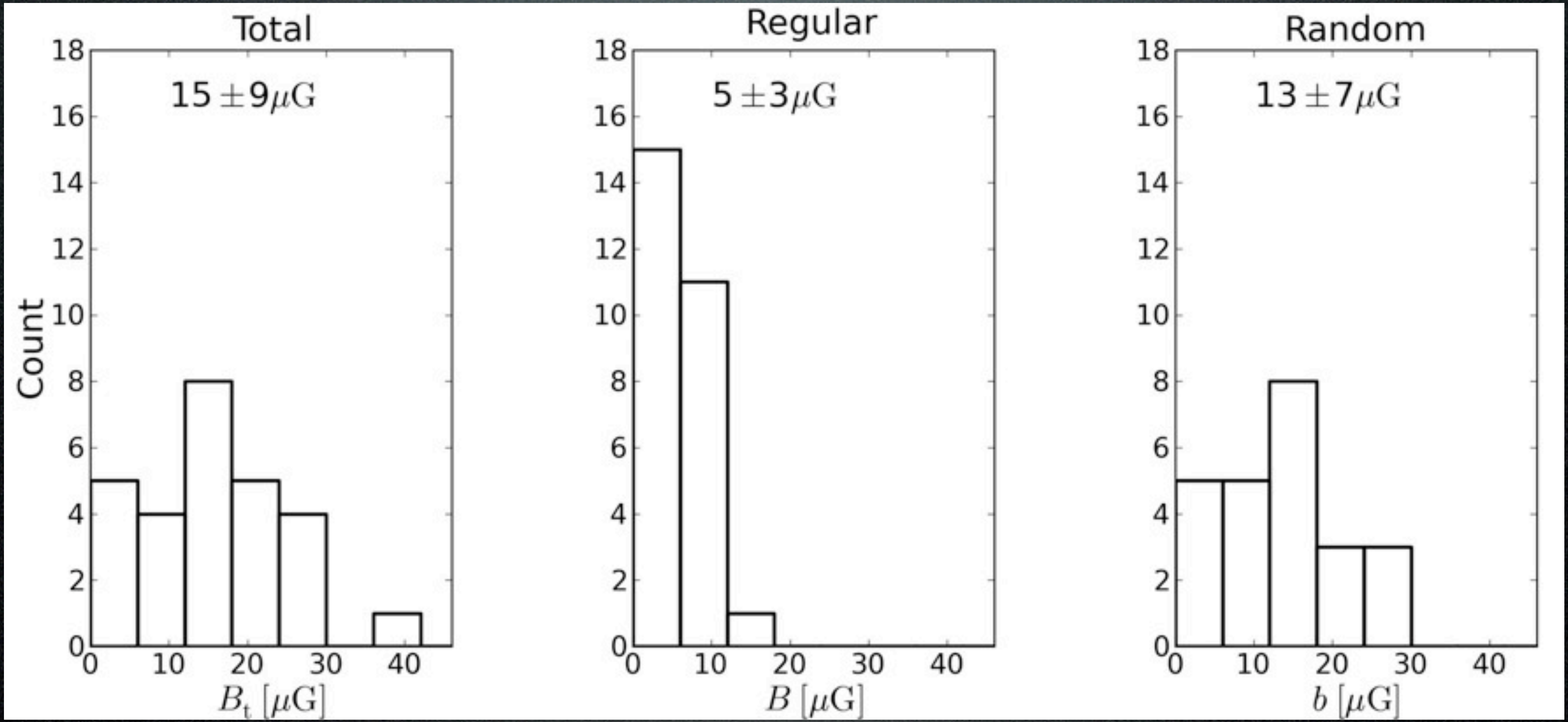
Integrated fluxes of 74 galaxies



Niklas 1995

Field strength II

"Typical" equipartition field strengths, 27 galaxies observed since 2000.



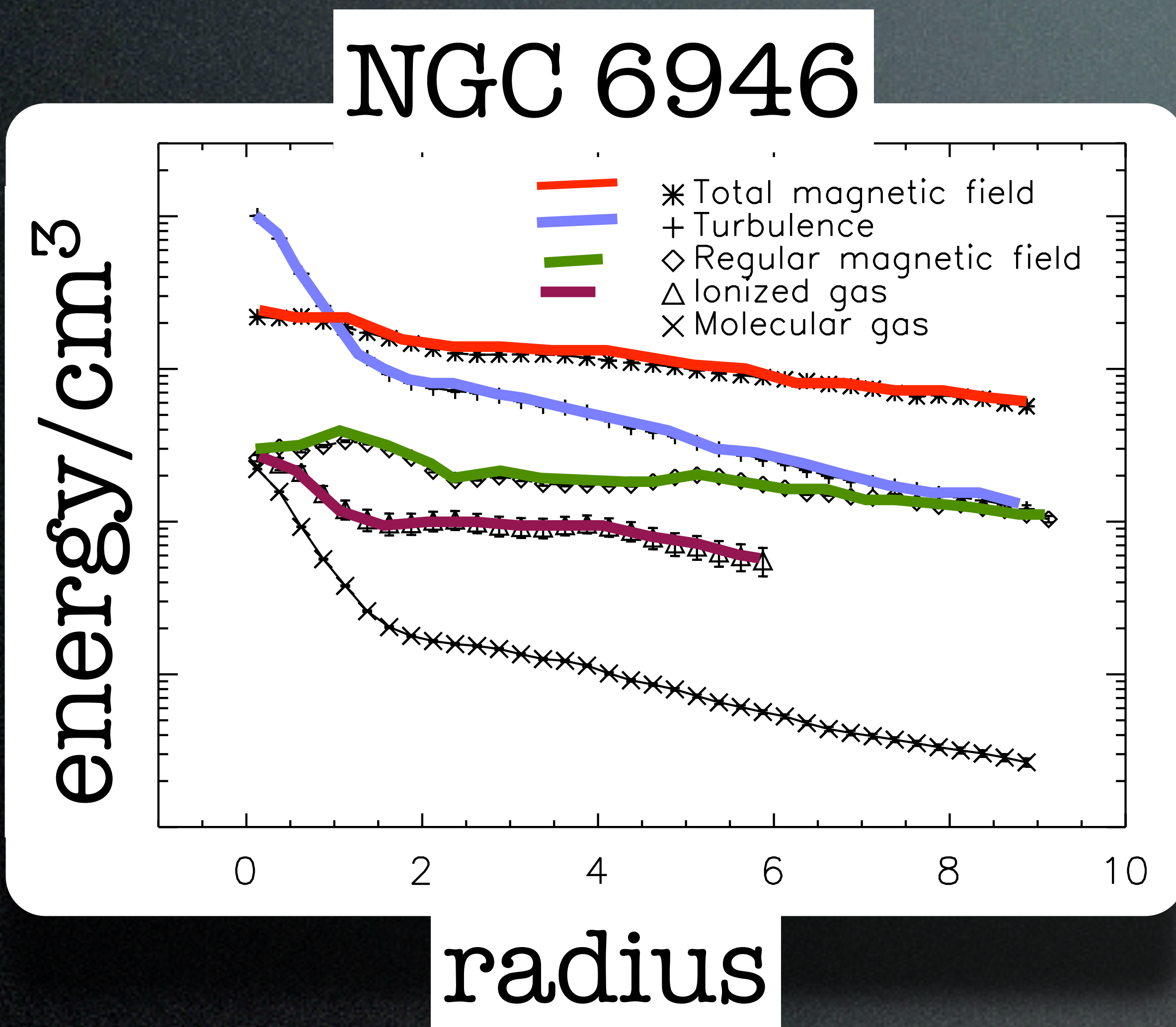
Fletcher unpublished

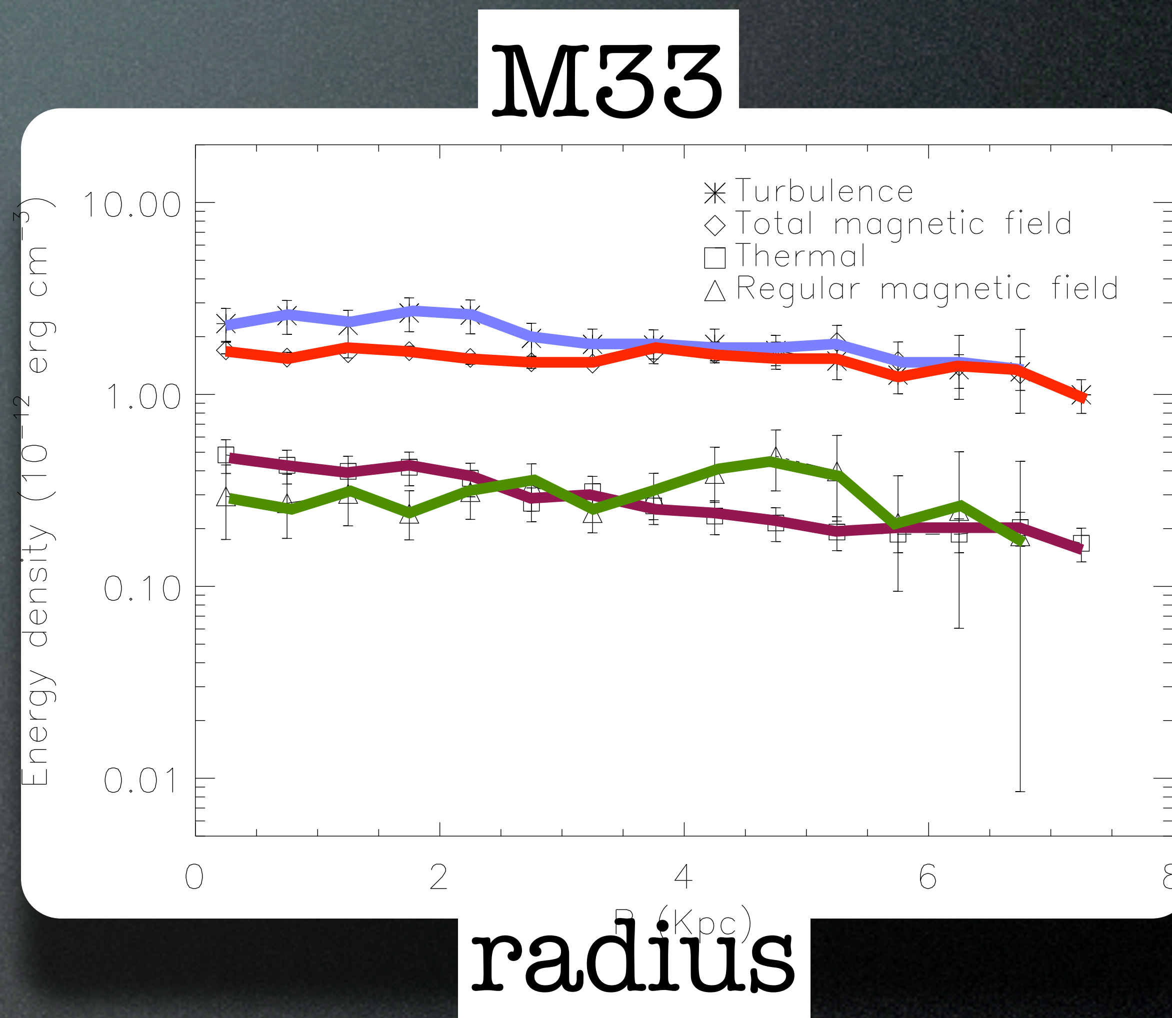
Scale lengths

	Scale length [kpc]		Galaxy size	
	I_{syn}	B	[kpc]	
NGC 6946	4	16	18	Beck 2007
NGC 253 (polarization)	3 & 7	13 & 26	28	Heesen et al. 2009
M51	5 to 7	10 to 14	27	Fletcher unpublished
M33	6	24	12	Tabatabaei et al. 2007

Field strength & scale-length

Beck 2007





Tabatabaei et al. 2008

Milky Way

$P_B \sim P_{th} \sim P_{tur} \sim P_{cr}$

Boulares & Cox, 1990

Scale-heights

For unpublished data on the scale-height of the synchrotron emission in six nearby, edge-on galaxies contact:

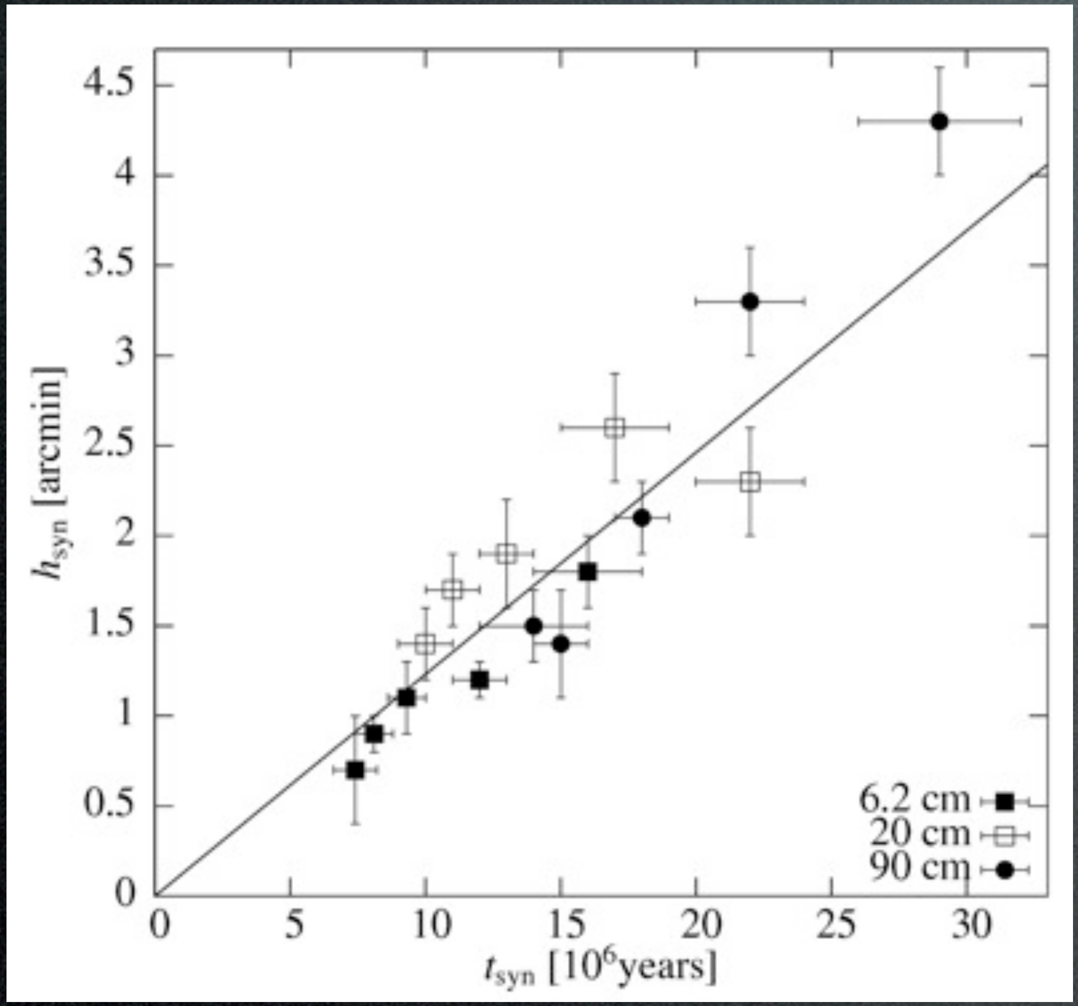
Marita Krause at the MPIfR, Bonn, Germany.

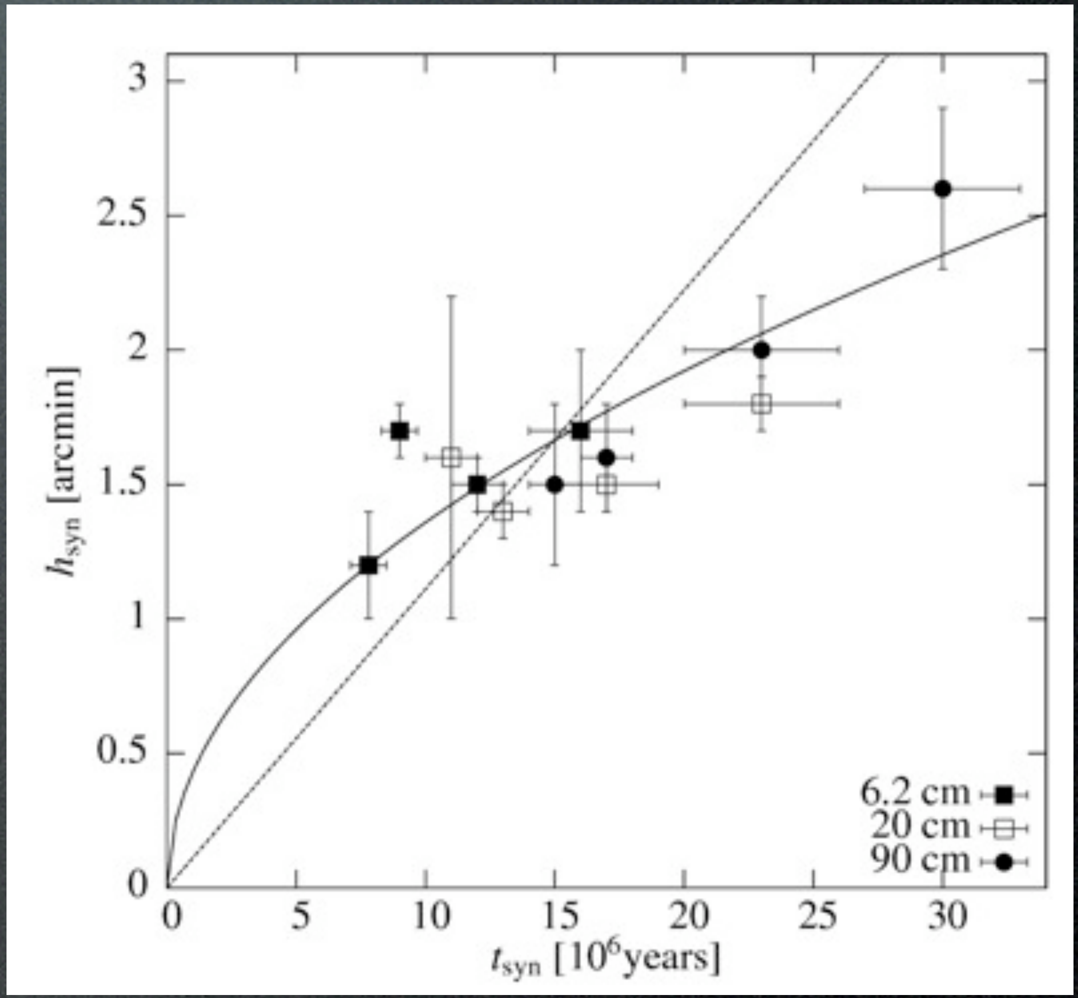
Transport of cosmic rays & magnetic field in NGC 253

North halo: advection

South halo: diffusion?

scale height





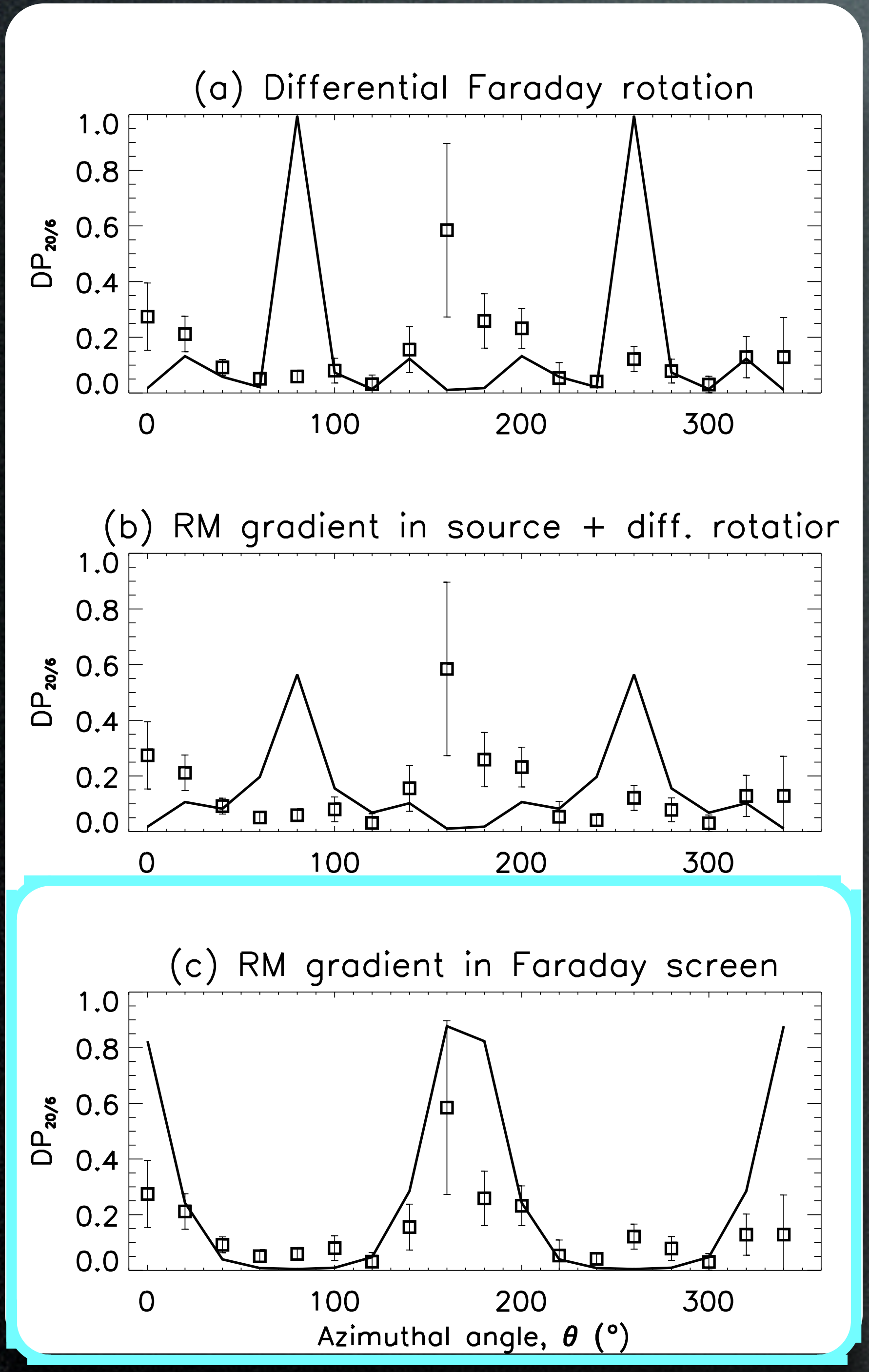
Heesen et al. 2009

synchrotron lifetime

Depolarization 20cm/6cm

M31

Fletcher et al. 2004



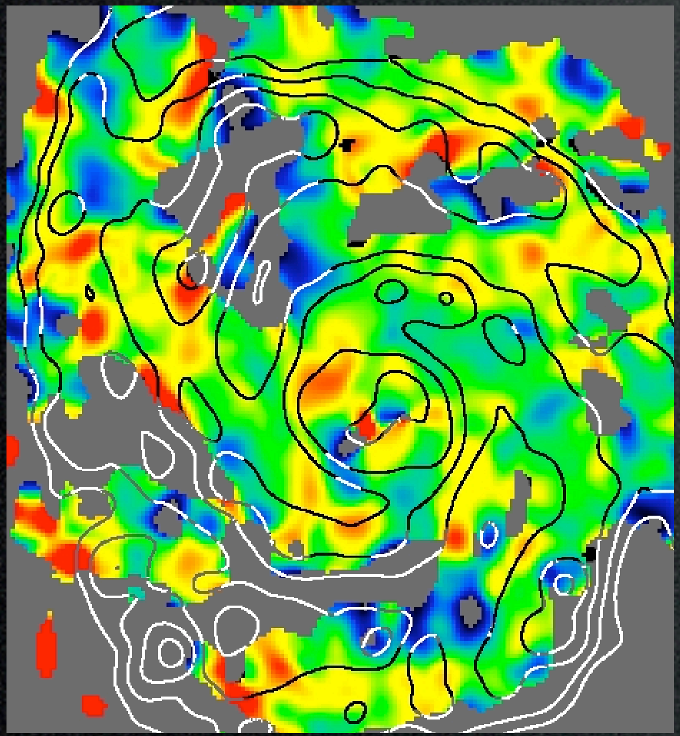
Differential Faraday rotation

Differential rotation + RM gradient in source

RM gradient in Faraday screen

$h_{th} = 3\ h_{syn}$

Small-scale fields in M51



Fletcher et al. 2010

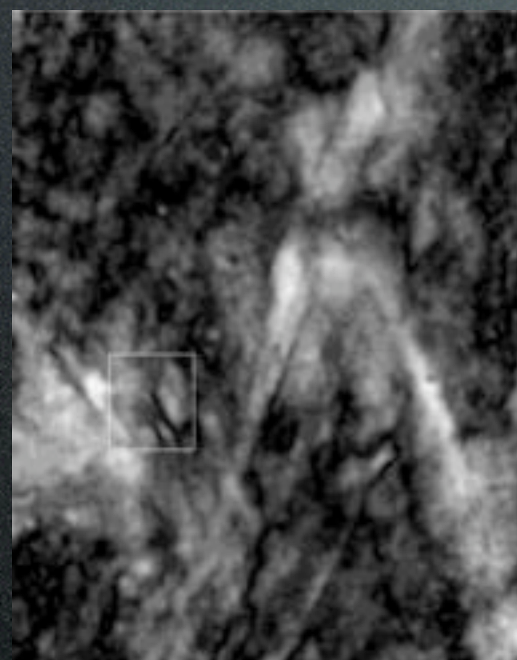
Anisotropic b ≈ 12 μG
Isotropic b ≈ 18 μG
Mean B ≈ 2 μG

Degree of anisotropy ≈ 2

Scaling of fluctuations in Faraday rotation give l_{turb} ≈ 25 pc

Milky Way polarization

λ92 cm

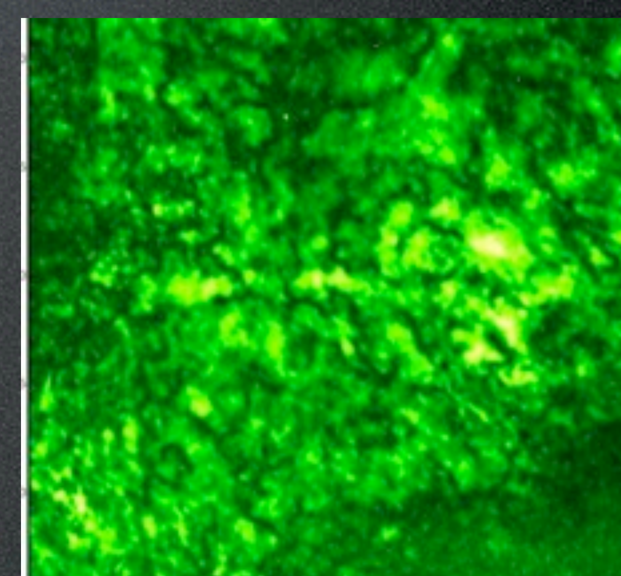


Haverkorn et al. 2000

λ21 cm

Wolleben et al. 2006

λ21 cm



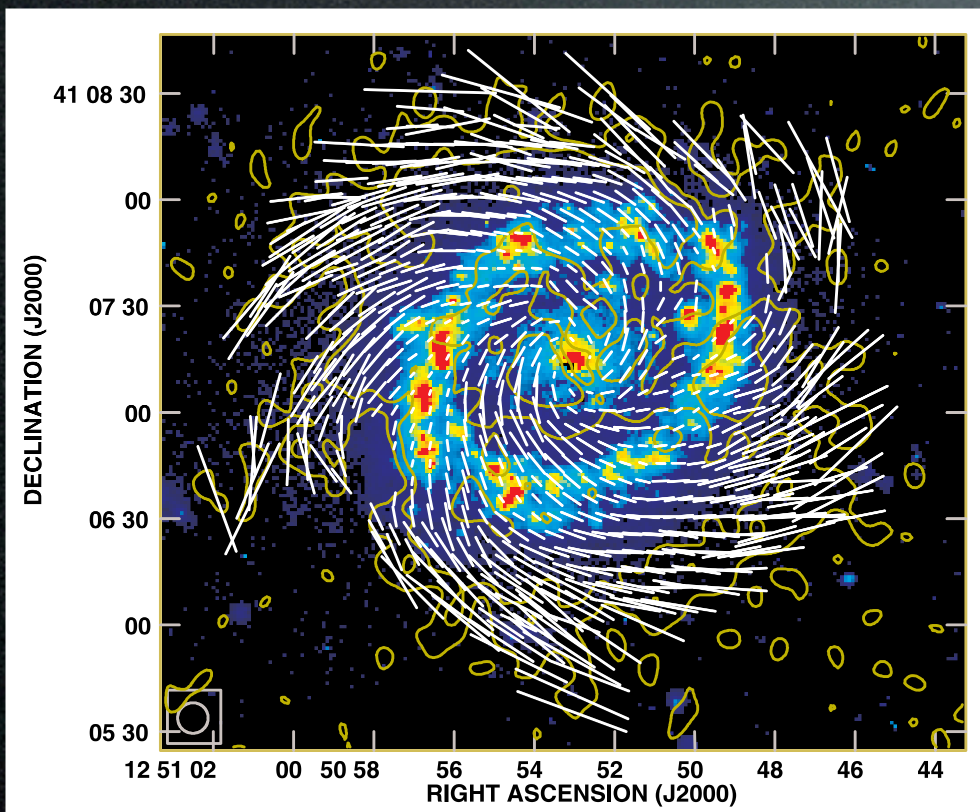
Gaensler et al. 2001

λ13 cm

Duncan et al. 1997

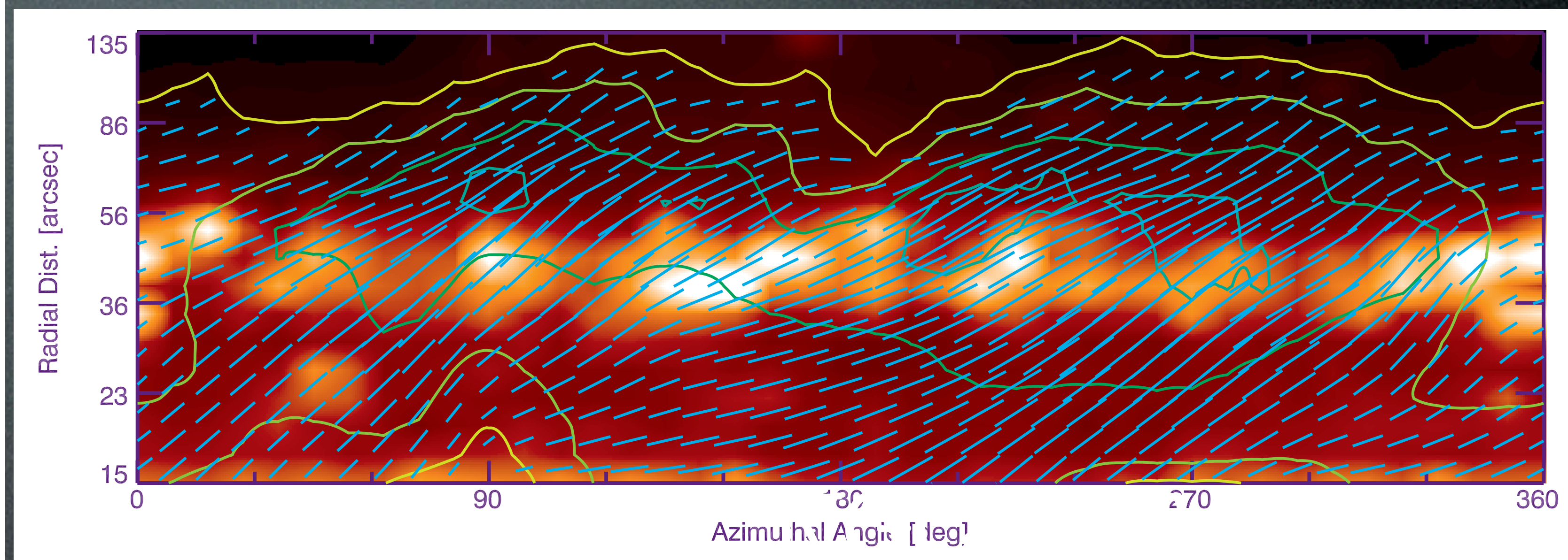
B-Field lines are spirals

NGC 4736 / M94

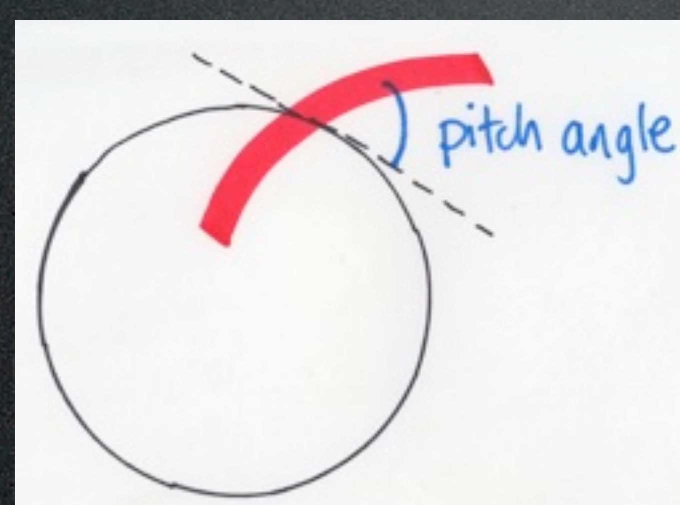


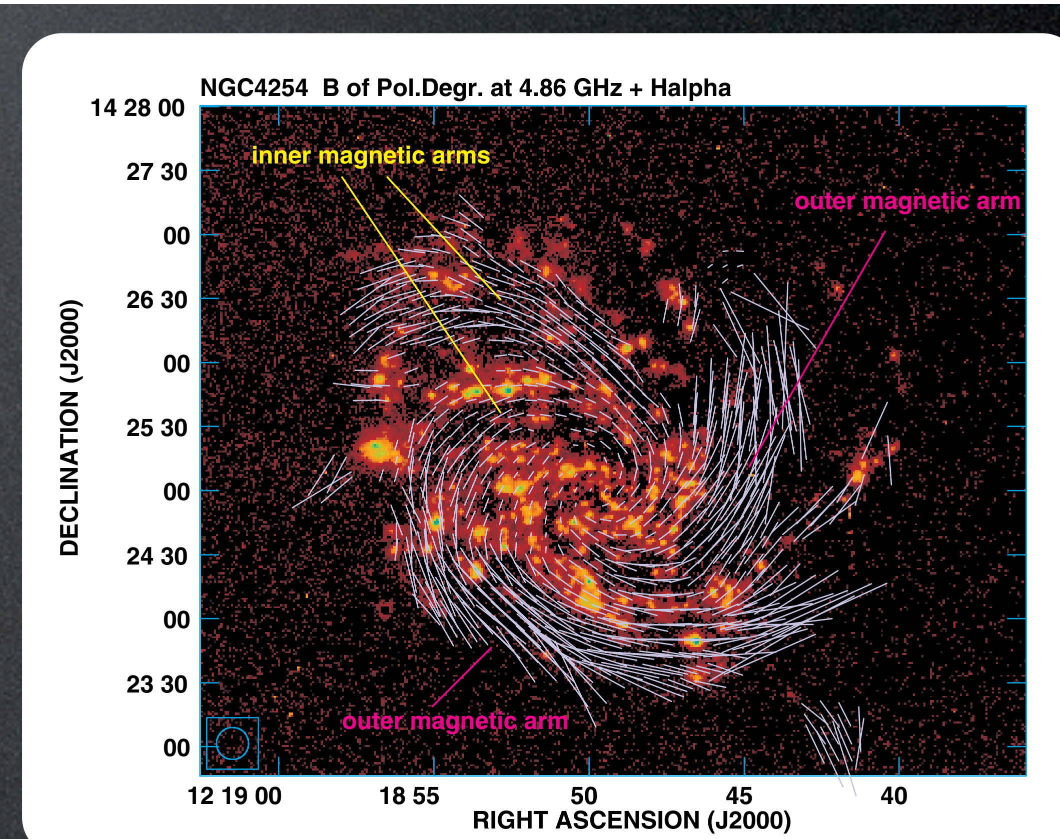
Chyzy & Buta 2007

NGC 4736 / M94



$$tan(p) = \frac{B_r}{B_\phi}$$





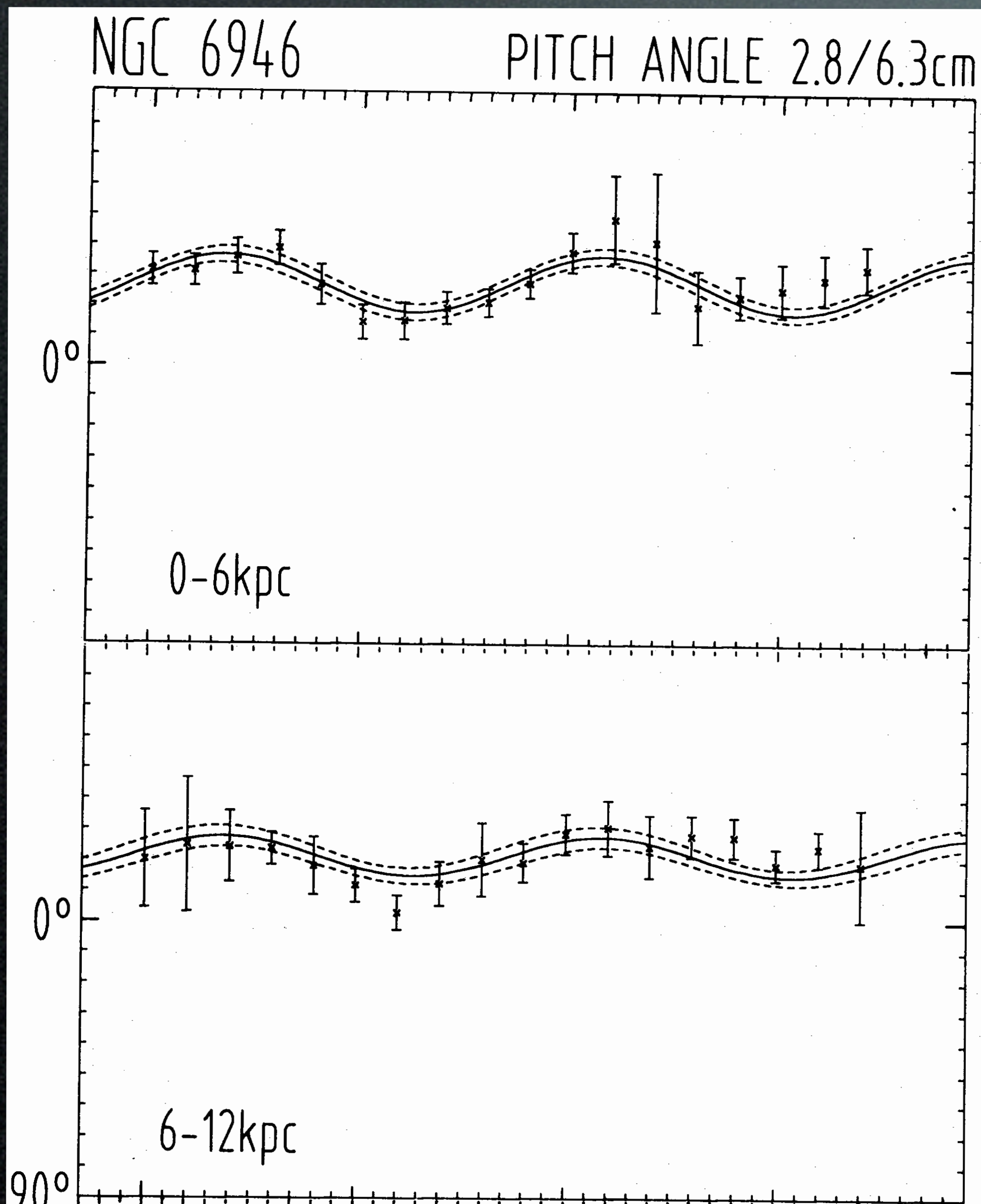
Chyzy 2008

B-Field lines are spirals

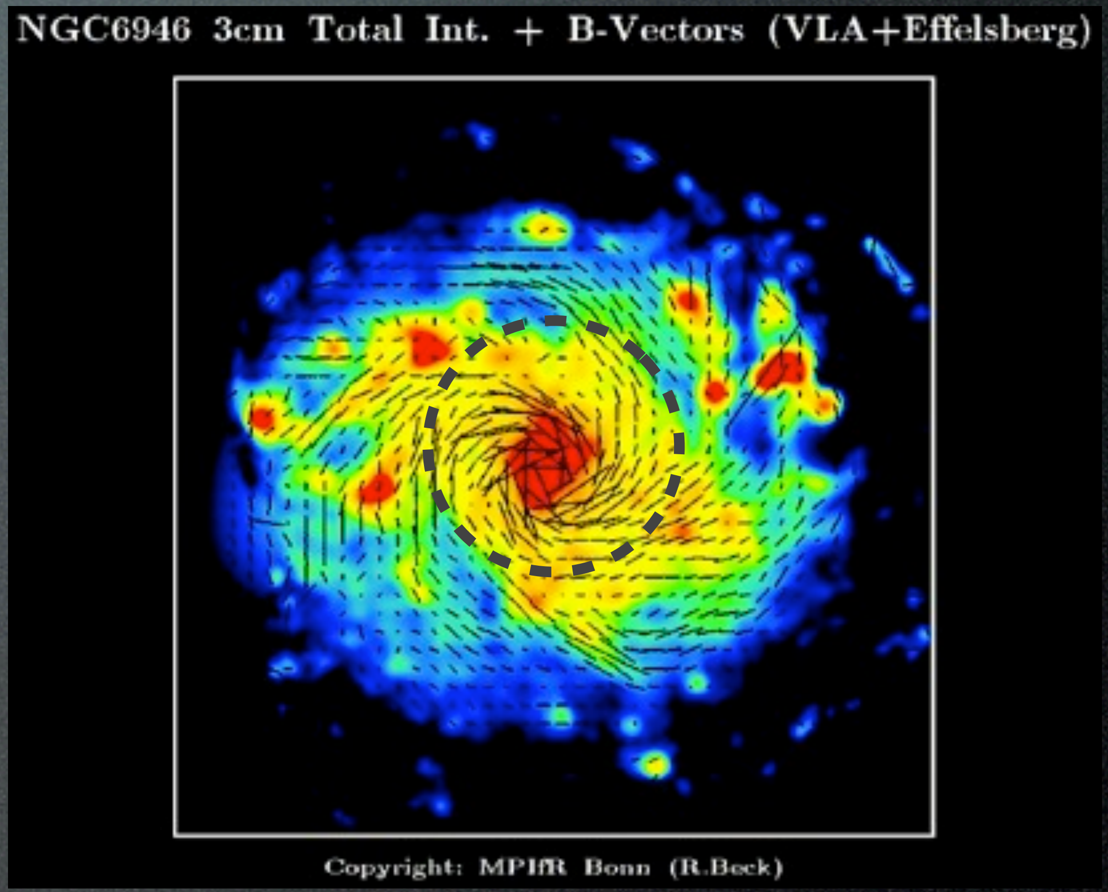
	pitch angle			
	inner	outer	optical	
IC 342	-20°±2	-16°±2	-19°±5	Krause et al. 1989
M31	-17°±4	-8°±3	-7°	Fletcher et al. 2004
M33	-48°±12	-42°±5	-65°±5	Tabatabaei et al. 2009
M51	-20°±1	-18°±1	-20°	Fletcher et al. 2010
M81	-14°±7	-22°±5	-11° → -14°	Krause et al. 1989
NGC 6946	-27°±2	-21°±2		Ehle & Beck 1993

B-field pitch angles vary

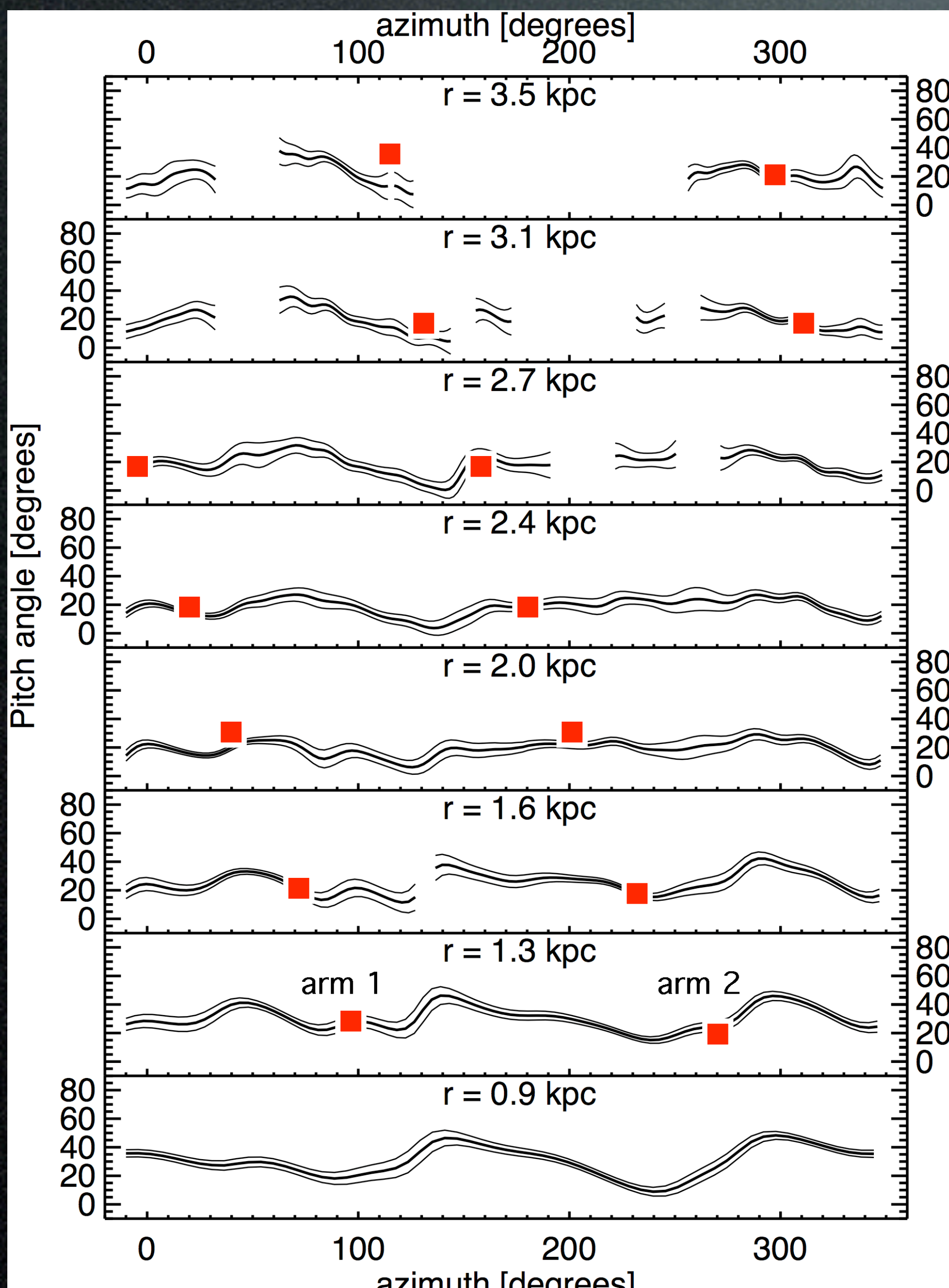
NGC 6946



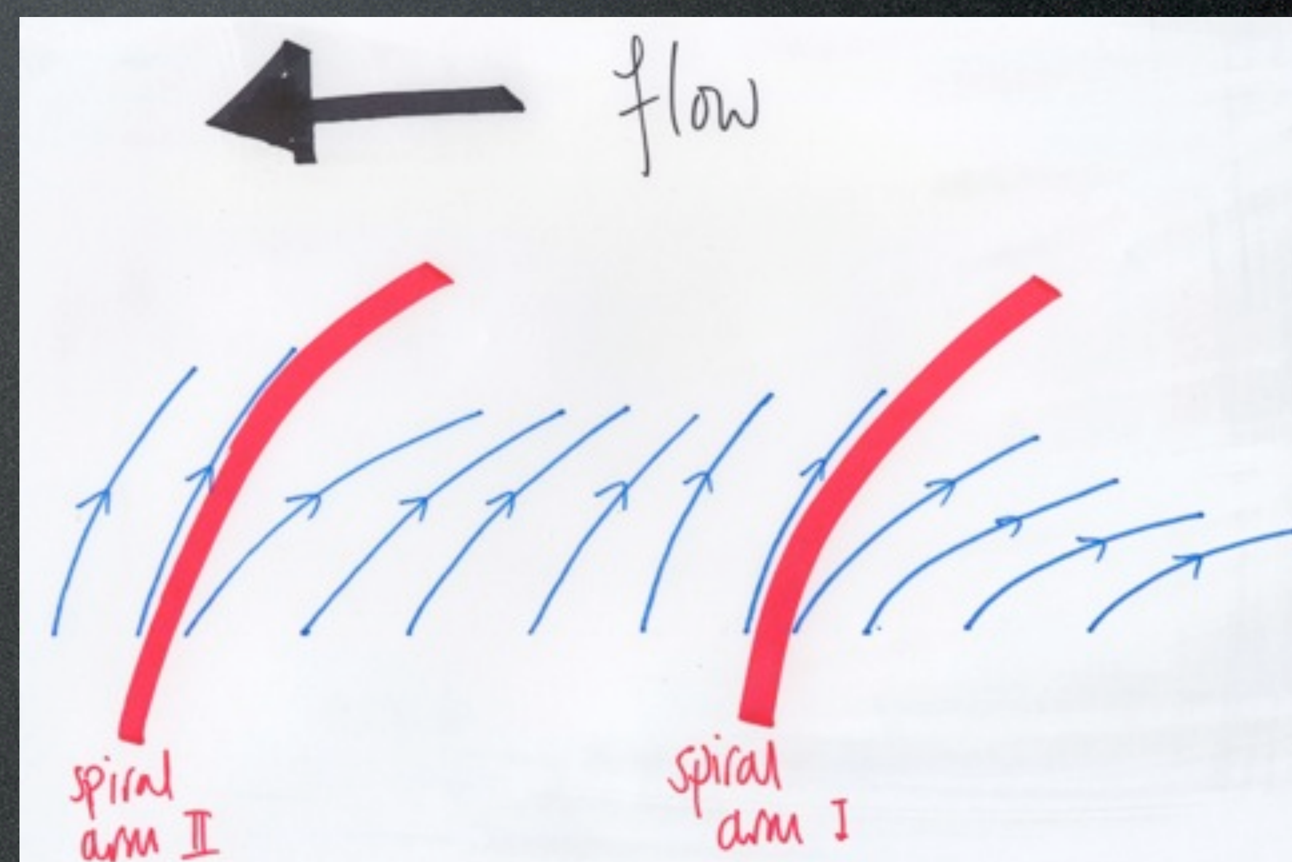
Ehle & Beck 1993



B-field aligned with CO arm at the arm

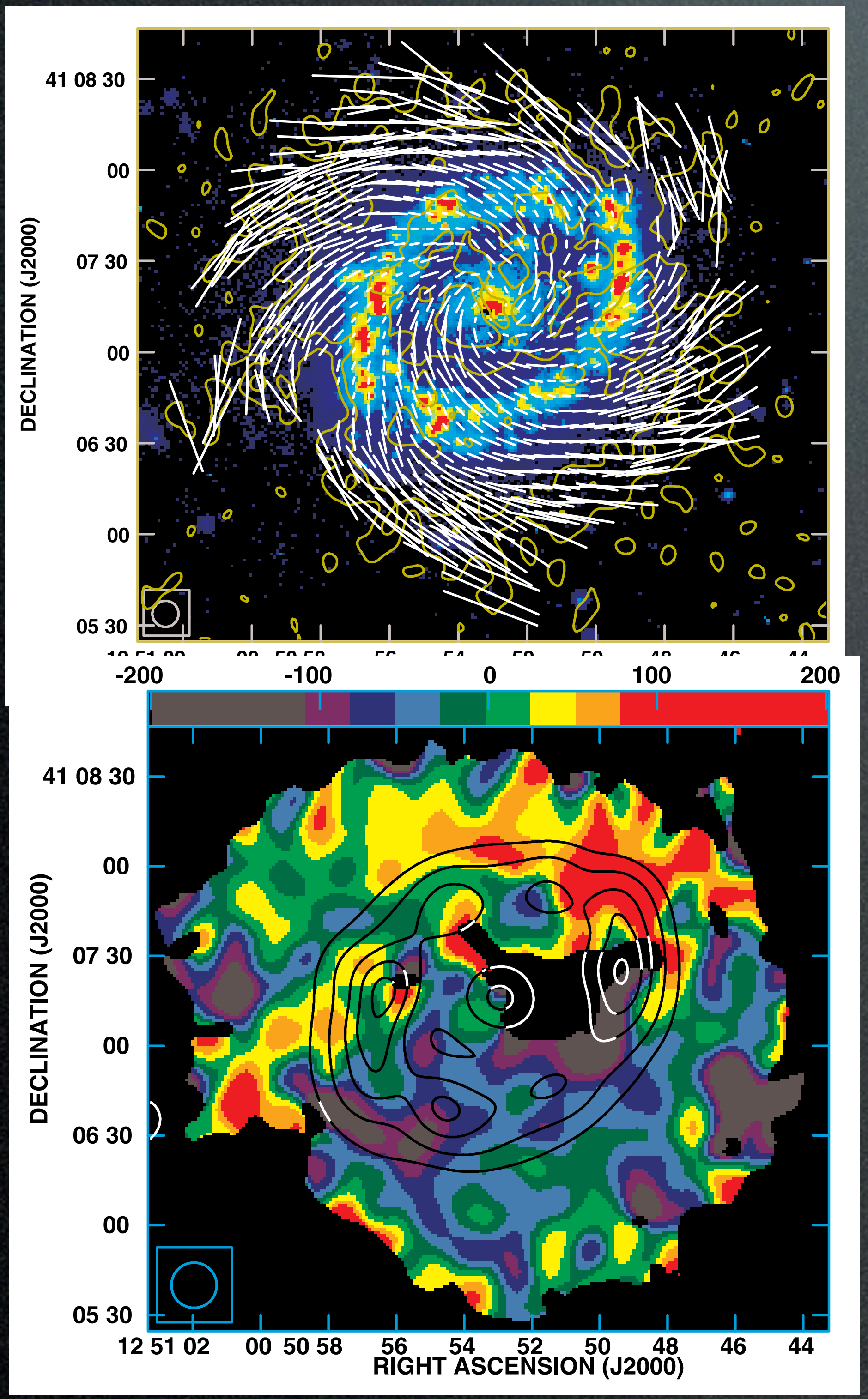


Patrikeev et al. 2006



Structure of regular field

NGC 4736 / M94



Chyzy & Buta 2007

Polarization angle:

$$B_\perp(r,\phi)$$

Faraday rotation:

$$B_\parallel(r,\phi)$$

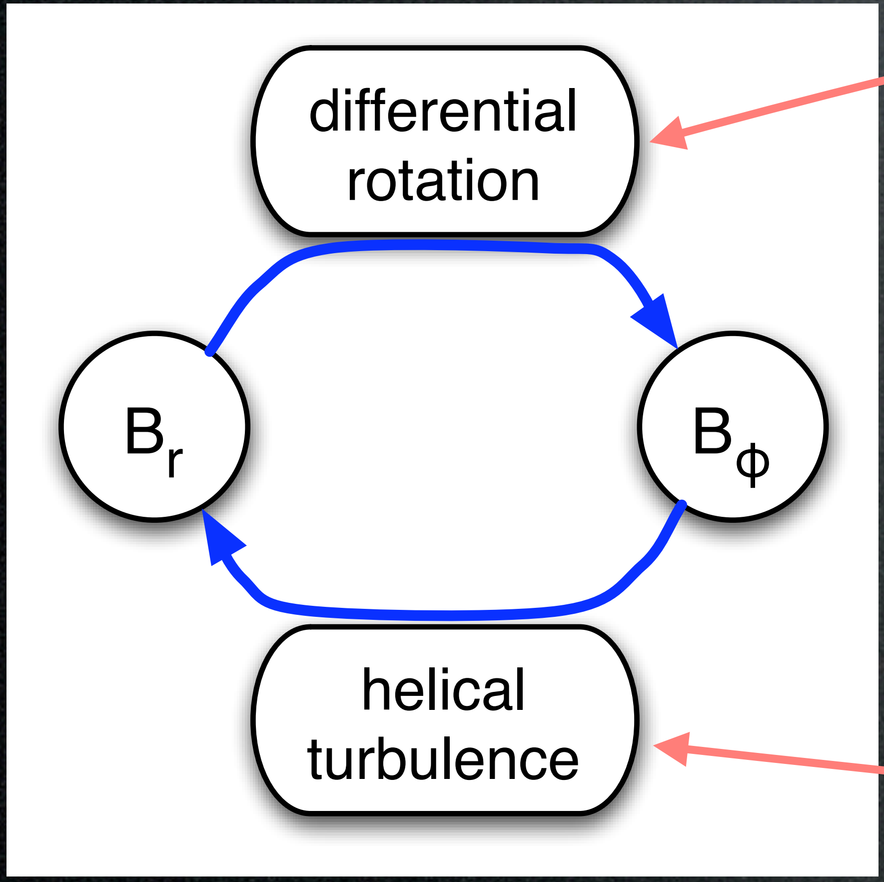
Mean-field dynamo I

Induction Equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\mathbf{B} = \bar{\mathbf{B}} + \mathbf{b}, \;\; \mathbf{V} = \bar{\mathbf{V}} + \mathbf{v}$$

diffusion

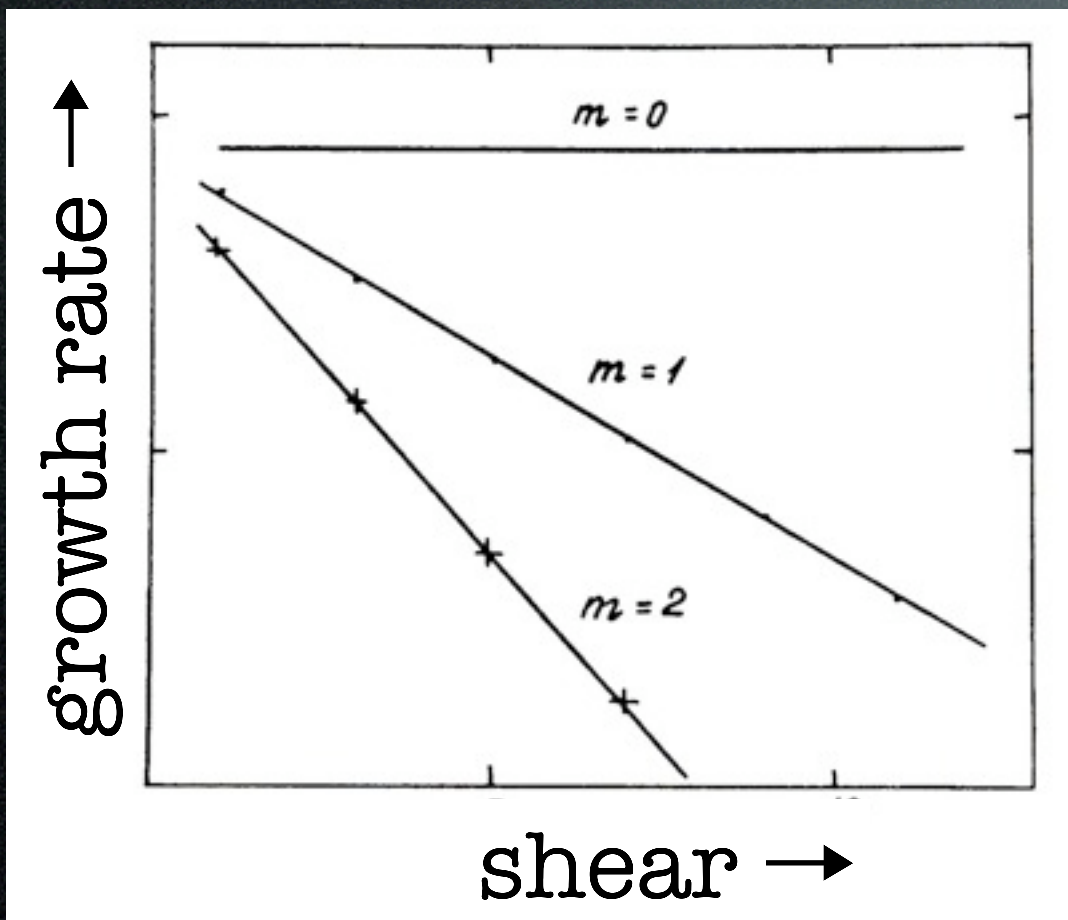


$$\frac{\partial B_\theta}{\partial t} = r \frac{\mathrm{d}\Omega}{\mathrm{d}r} B_r + \eta_\mathrm{T} \frac{\partial^2 B_\theta}{\partial z^2}$$

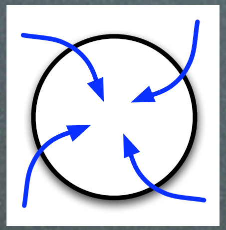
$$\frac{\partial B_r}{\partial t} = -\frac{\partial}{\partial z}(\alpha B_\theta) + \eta_\mathrm{T} \frac{\partial^2 B_r}{\partial z^2}$$

Mean-field dynamo II

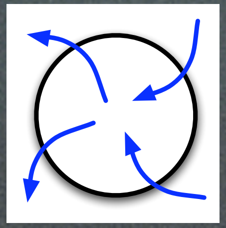
Ruzmaikin, Sokoloff & Shukurov 1988



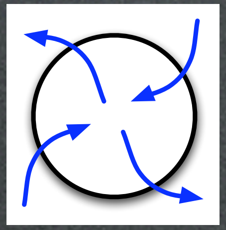
m=0

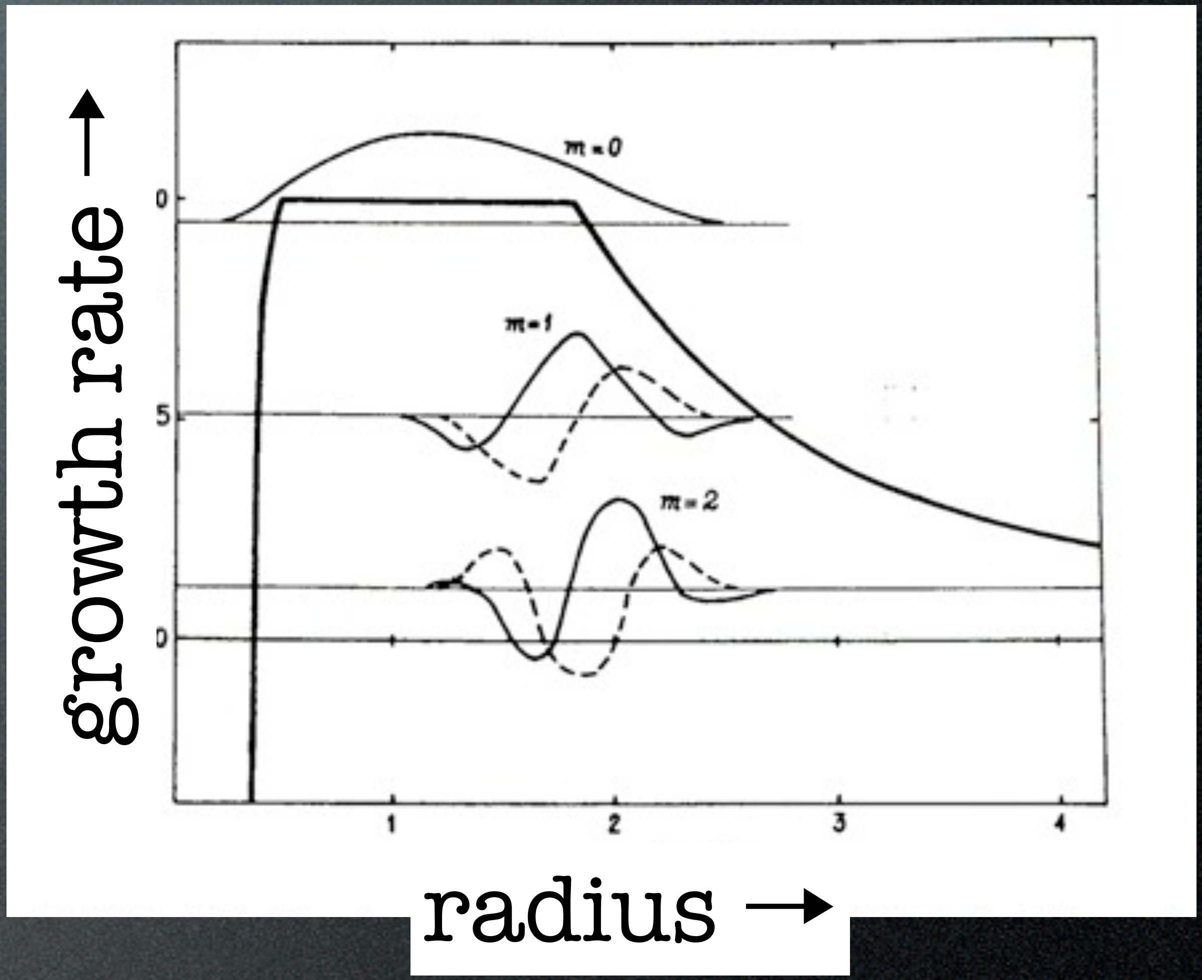


m=1



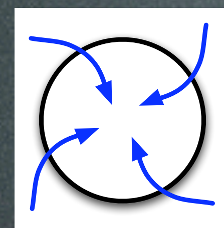
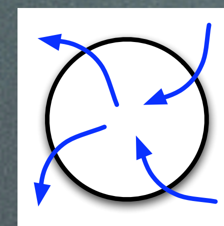
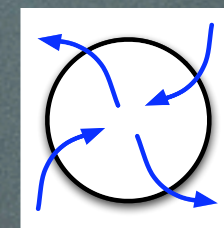
m=2





m=0 mode by far easiest to produce

Regular B-field structure

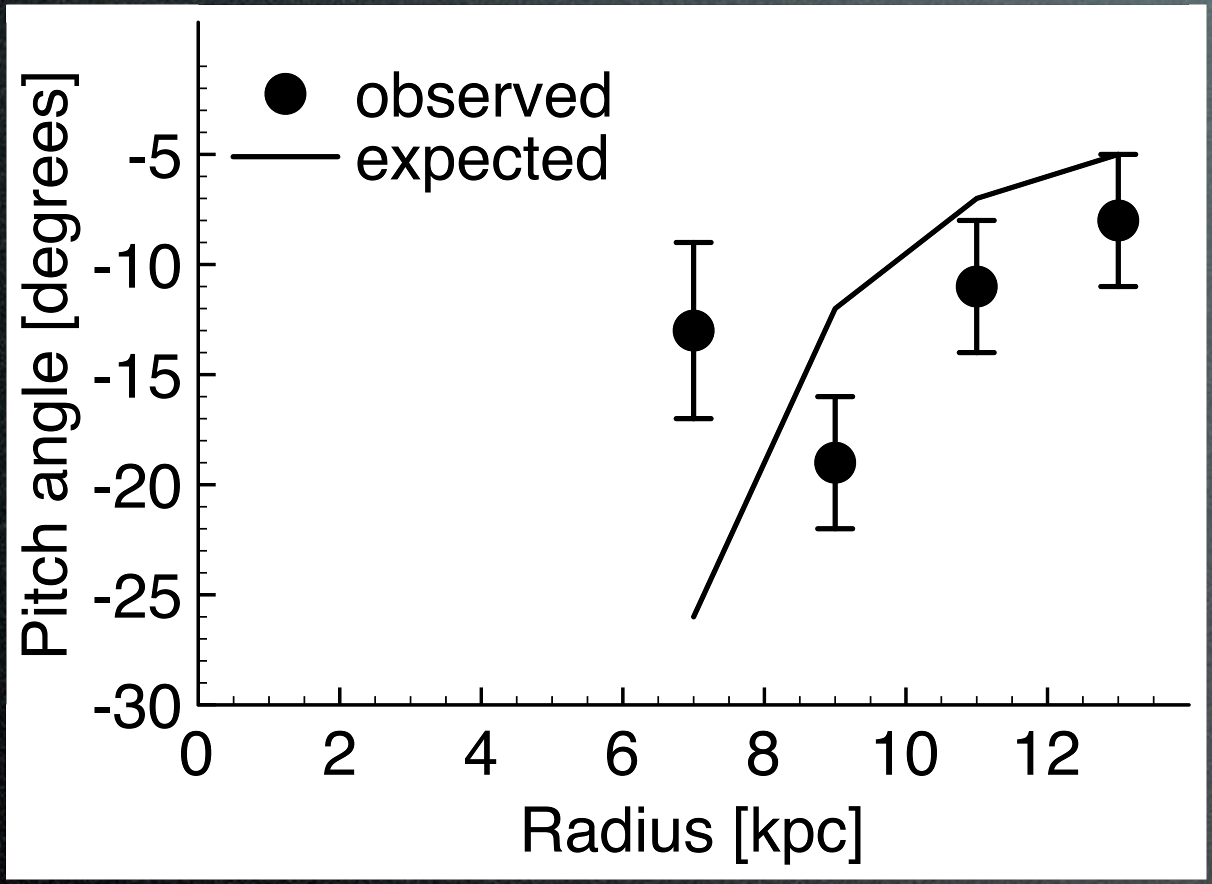
  

Galaxy	m=0	m=1	m=2	
IC 342	1	–	–	Krause et al. 1989
LMC	1	–	–	Gaensler et al. 2005
M31	1	0	0	Fletcher et al. 2004
M33	1	1	0.5	Tabatabaei et al. 2008
M51	1	0	0.5	Fletcher et al. 2010
M81	–	1	–	Krause et al. 1989
NGC 253	1	–	–	Heesen et al. 2009
NGC 1097	1	1	1	Beck et al. 2005
NGC 1365	1	1	1	Beck et al. 2005
NGC 4254	1	0.5	–	Chyży 2005
NGC 4414	1	0.5	0.5	Soida et al. 2002
NGC 6946	1	–	–	Ehle & Beck 1993

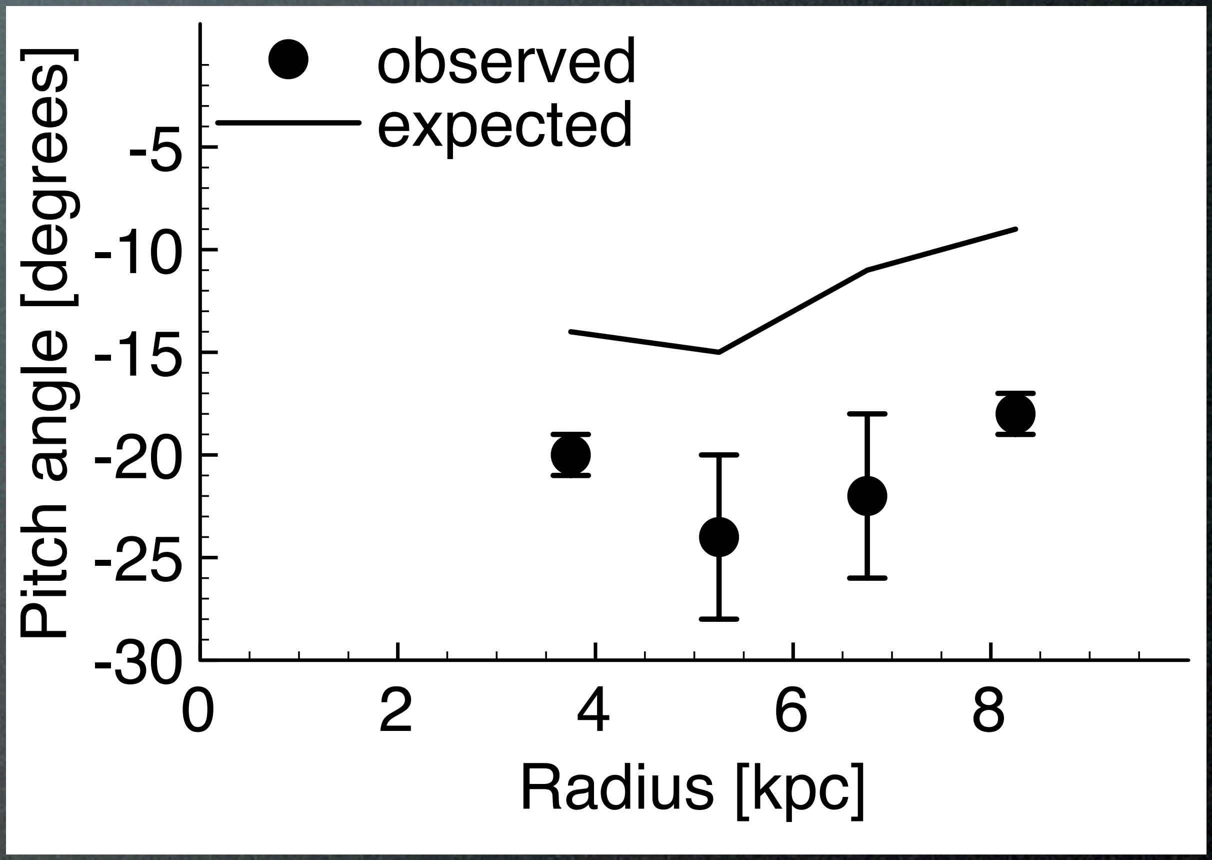
all spiral $p \geq 10°$

Pitch angles

M31



M51



$$\tan p = \frac{B_r}{B_\theta} \approx -\frac{1}{2}\sqrt{\frac{\pi\alpha}{hG}}$$

$G = r\frac{\mathrm{d}\Omega}{\mathrm{d}r}$ shear

$\alpha \sim 1$ km/s turbulence

h gas disc scale height

Summary

1. Lot of galaxies observed, information needs to be systematically collated.

2. $B_{tot} \approx 15\ \mu G$, $B_{reg} \approx 5\ \mu G$, $b_{ran} \approx 13\ \mu G$.

3. With careful (statistical) analysis can measure B-field properties directly related to theory.

Theory works!

4. New radio telescopes will open new possibilities, related to e.g. weak B-fields.