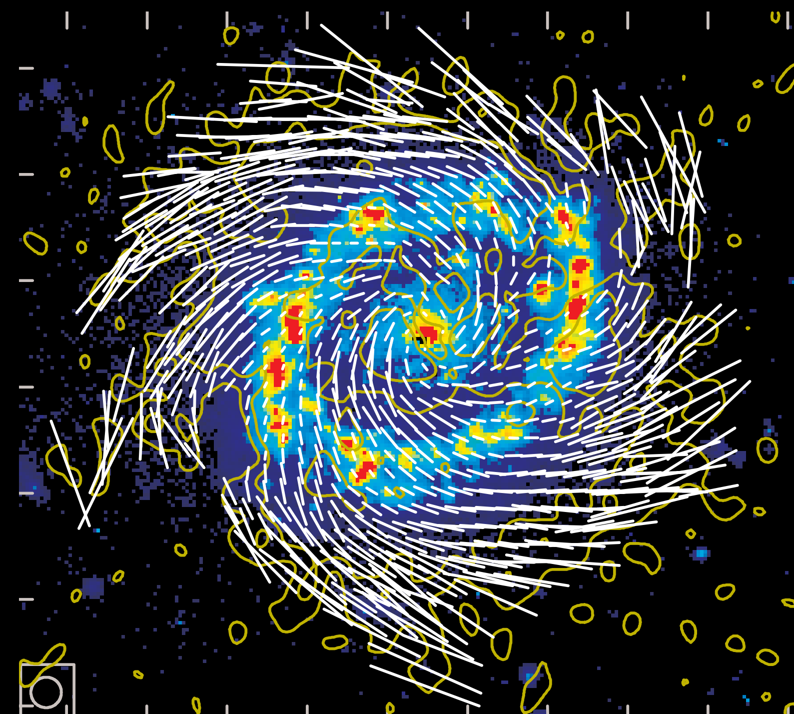
(What do we really know about the) magnetic fields of disc galaxies?

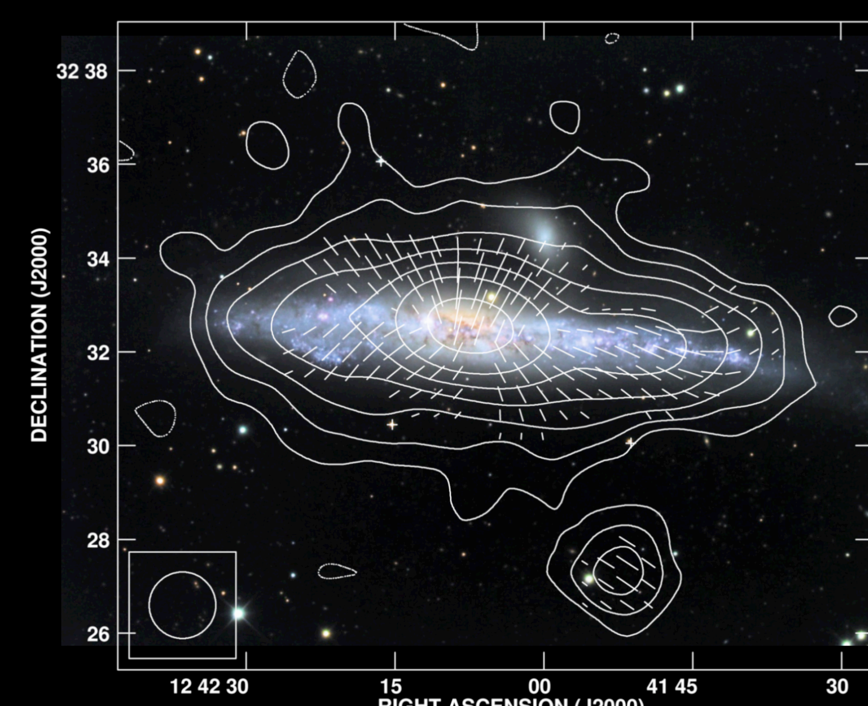
Andrew Fletcher
Newcastle University

Lots of observations:

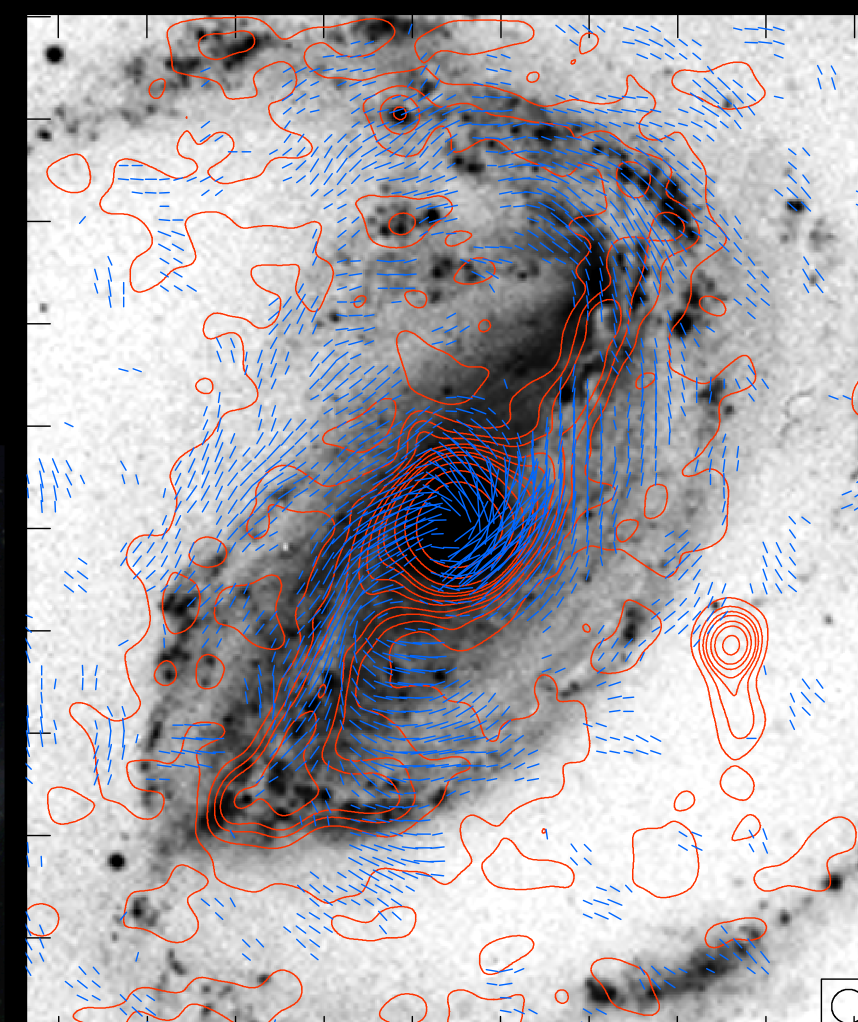
Fletcher et al. 2011



Chyzy & Buta 2007



Krause 2009



Beck et al. 2005

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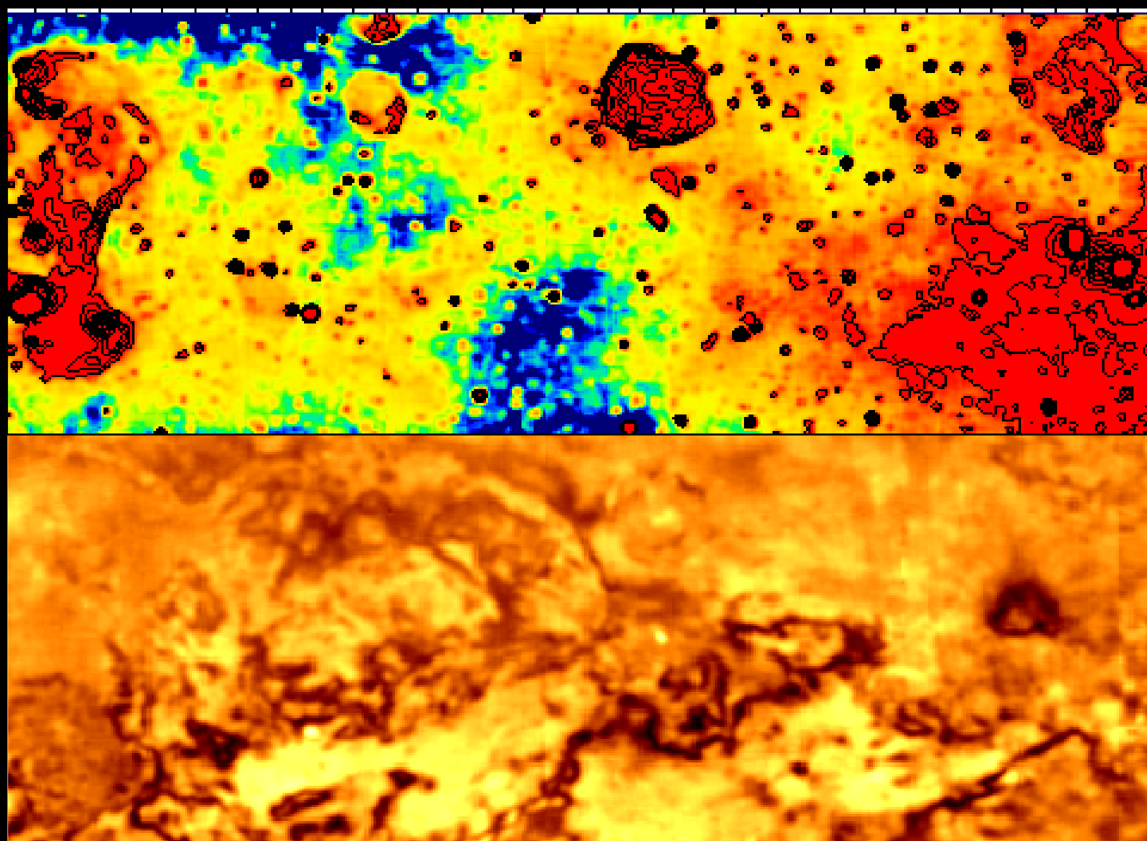
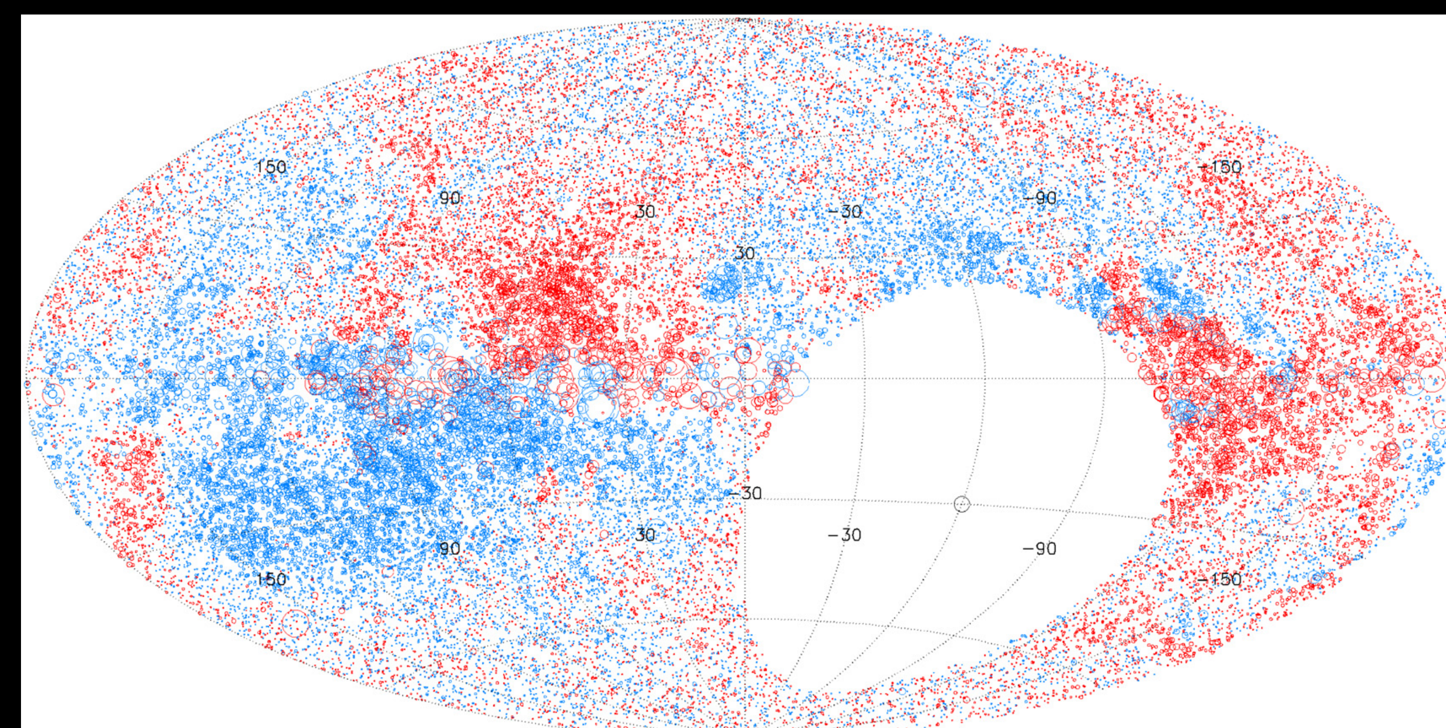
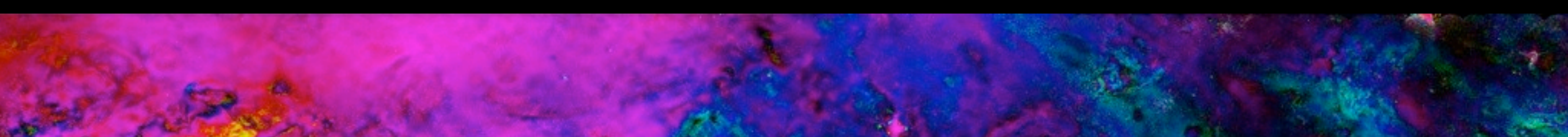


Taylor et al. 2009



Reich et al. 2004



Landecker et al. 2010

What are the magnetic properties of a typical disc galaxy?

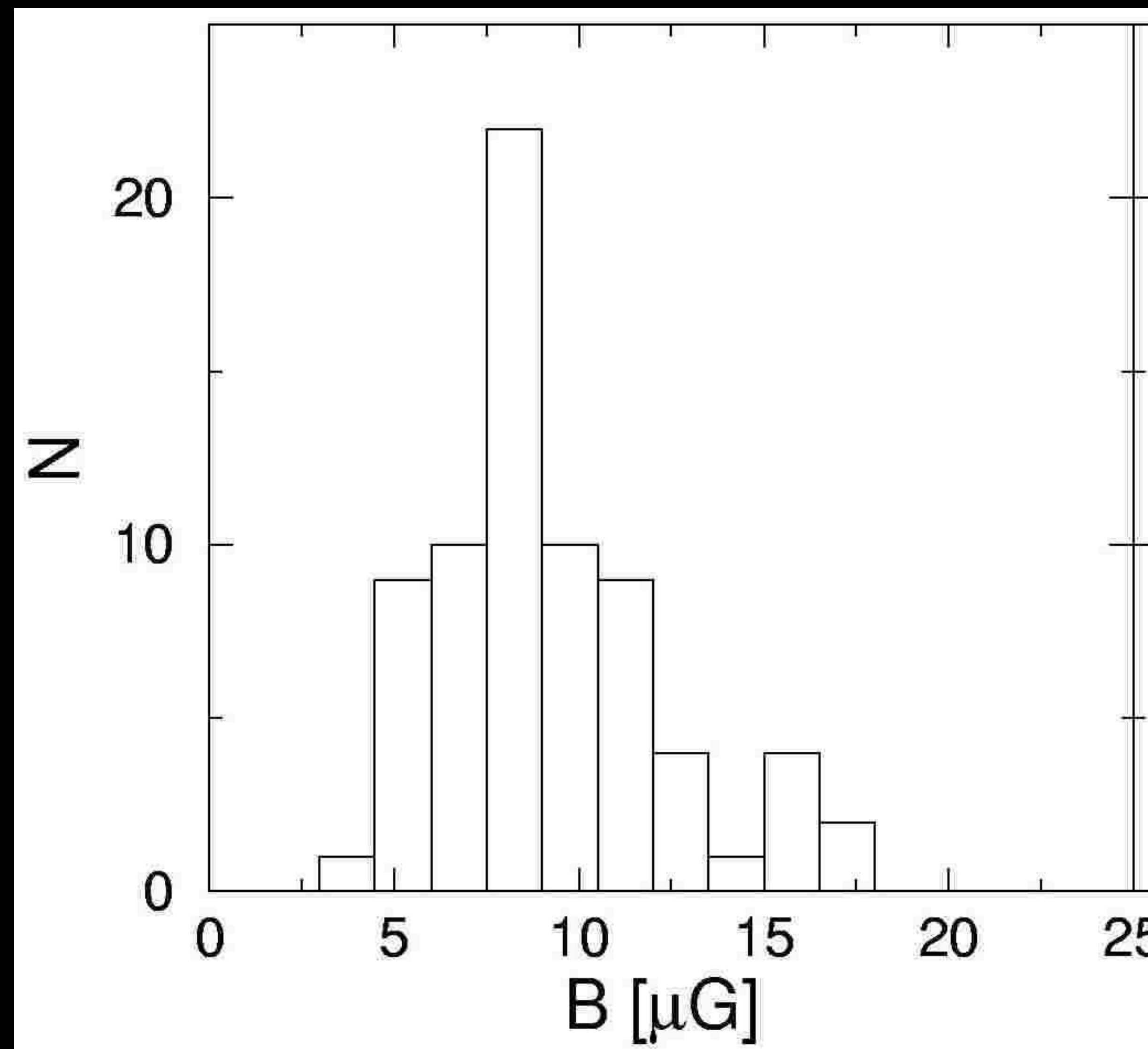
An overview with **numbers and tables**

(Magnetism of diffuse ISM i.e. *not* molecular clouds)

Synchrotron radiation

Total intensity	$I_{\rm syn} \propto B_{\perp}^{(1+\gamma)/2}$	observed
Degree of polarization	$p = p_0 \dfrac{\bar{B}^2}{(\bar{B}^2 + b^2)}$	observed
Polarization angle	$\psi \cdot \bar{B} = 0$	observed
Faraday rotation	$\mathrm{RM} = \dfrac{\Delta\psi}{\Delta(\lambda^2)}$	observed
$R = 0.81 \int_{\rm los} \dfrac{n_e}{\rm cm^{-3}} \dfrac{B_{\parallel}}{\mu \rm G} \dfrac{{\rm d}l}{\rm pc} \quad {\rm rad\, m^{-2}}$		theoretical

Magnetic field strength



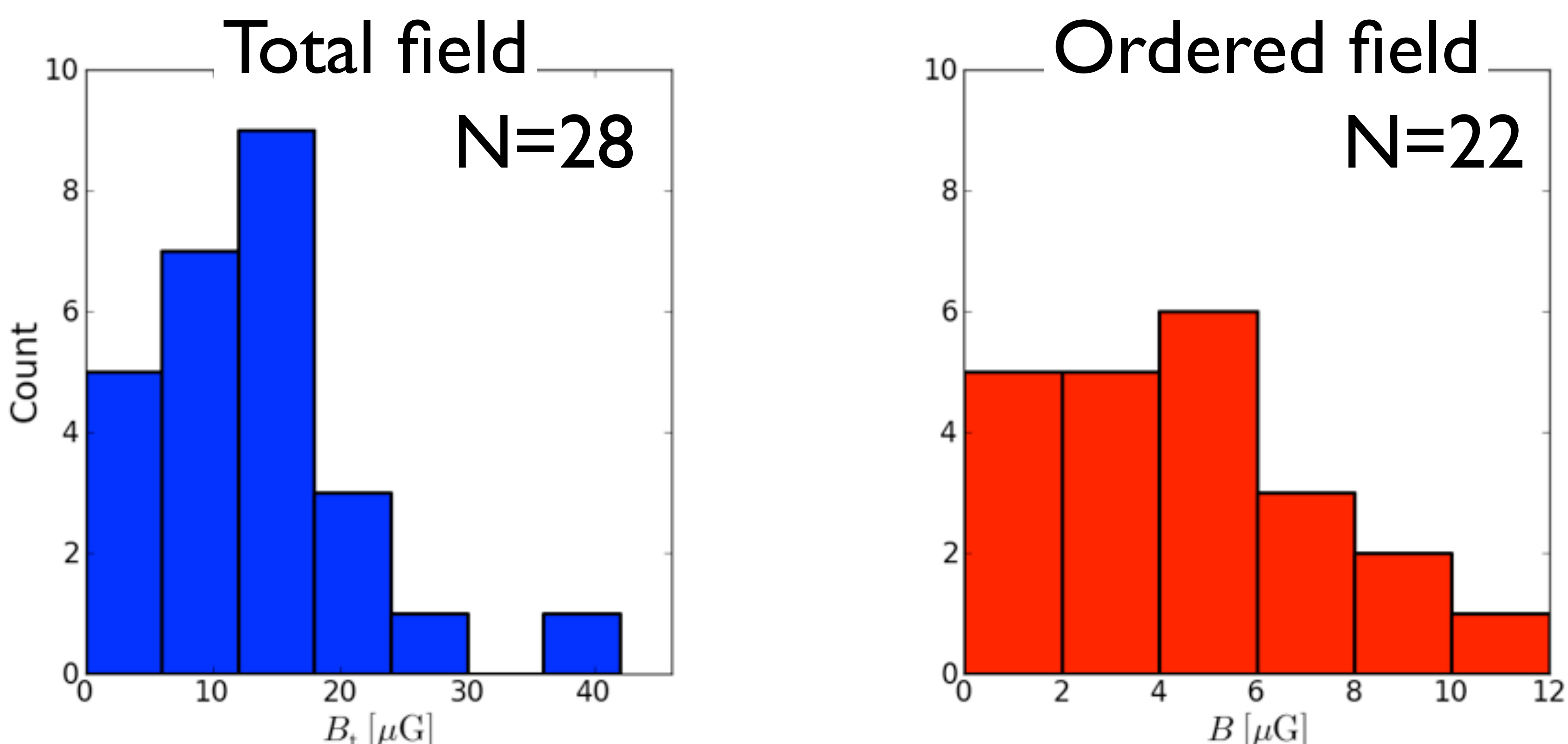
Niklas PhD thesis, Bonn 1995

Hummel's (1986) sample of 88 Sbc galaxies has a mean minimum-energy field of ≃ 8 µG, using $K = 100$. Using the same value of K for the sample of 146 late-type galaxies by Fitt & Alexander (1993), one obtains a mean total minimum-energy field strength of 10 ± 4 µG.

Beck et al. 1996

Magnetic field strength

Compilation: Fletcher 2010



Average: 16 ±15 μG
Excl. starburst: 12 ±6 μG

Average: 4 ±3 μG
B_{ord}/B_{ran} 0.4 ±0.2

Field strength summary

Source	Total B [μG]	N	Notes
Hummel 1986	8	88	Sbc galaxies
Fitt & Alexander 1993	10 ± 4	146	Late type galaxies
Niklas 1995	9	74	
Fletcher 2010	12 ± 6	28	Resolved, 1990+

Total field ≈ 10 μG
Ordered field ≈ 4 μG
Random field ≈ 10 μG

1. Total magnetic field: 8-12 ±6 μG
2. Regular magnetic field: 4 ±3 μG

Global distribution

Fletcher 2010

Exponential scale length of B
≈ 1.2 stellar radius

Krause 2014

Exponential scale height of B
≈ 0.6 & 3.6 kpc

Magnetic field everywhere

Vertical fields in disc are weak

Observed pitch angles

$$B_r \sim (0.2\text{–}0.4) B_\phi$$

Modelling of mean field in ~10 galaxies requires no B_z

Mao et al. 2010

Observed RM in Milky Way

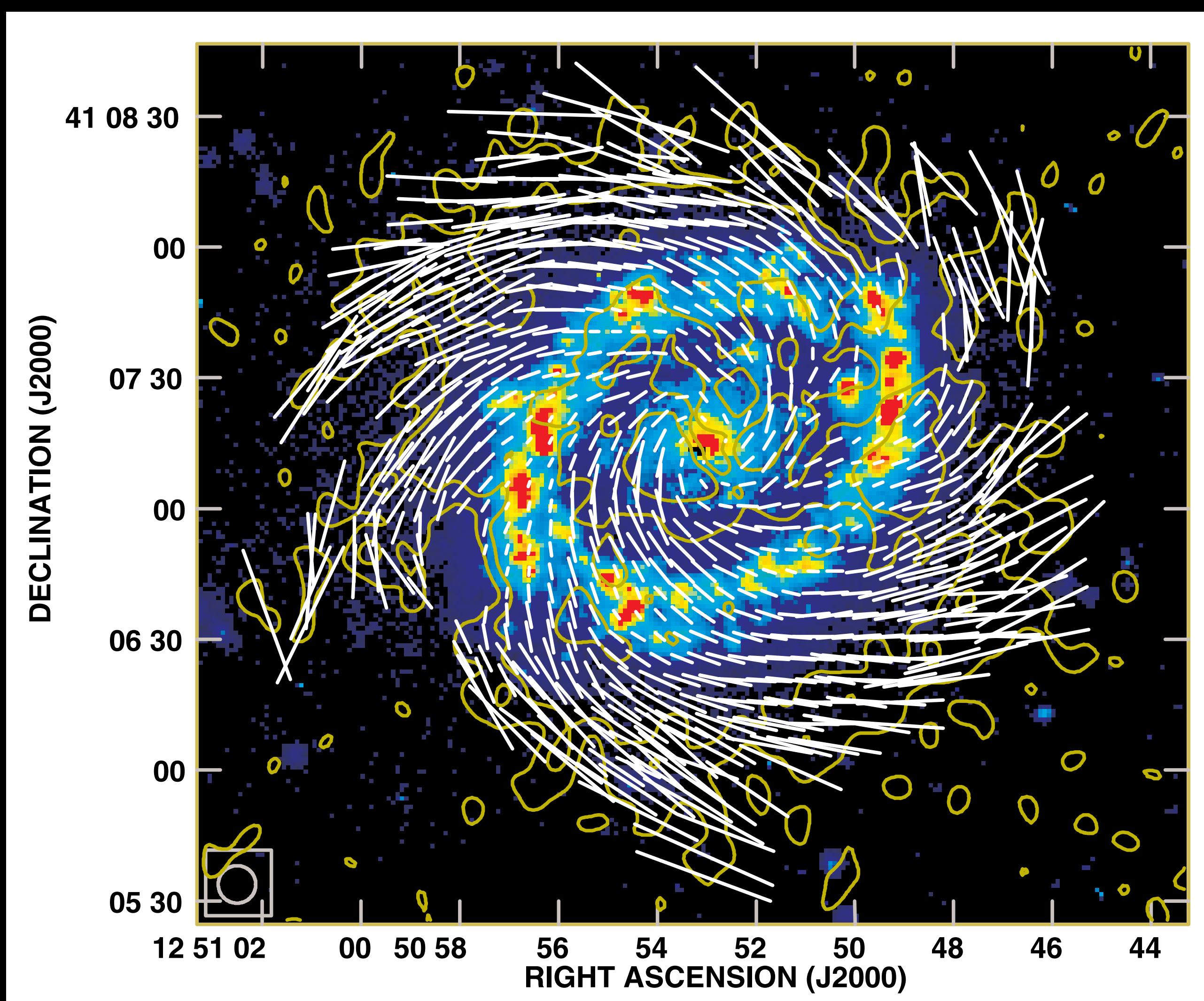
$$B_z \sim 0.1 B_r$$

Only consider B_r and B_φ initially.

1. Total magnetic field: 8-16 ±6 μG
2. Regular magnetic field: 4 ±3 μG
3. I_{syn} scale length ≈ 1/2 optical radius
4. I_{syn} scale height ≈ 2 kpc
5. No holes: field everywhere

Large-scale B lines spirals

$$\tan p = \frac{B_r}{B_\theta} \neq 0$$



Chyzy & Buta 2007

Fletcher et al. 2011

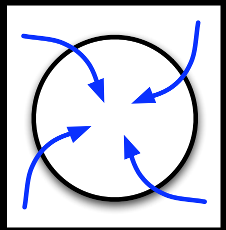
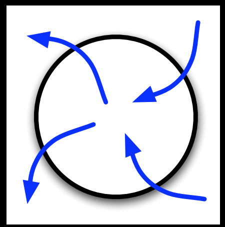
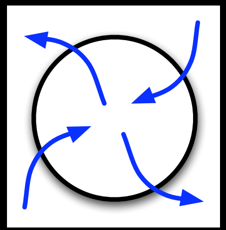
Pitch angles: B & spiral arms

	pitch angle			
Galaxy	B inner	B outer	spiral arm	B field Ref.
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	-26°±5	Tabatabaei et al. 2009
M51	-20°±1	-18°±1	-15°±8 → -10°±8	Fletcher et al. 2011
M81	-14°±7	-22°±5	-11° → -17°	Krause et al. 1989
NGC 6946	-38°±12		-36°±7	Frick et al. 2000
Milky Way	-11.5°	0°	-11.5° (n_e)	Van Eck et al. 2011

Pitch angles: not constant

Galaxy	amplitude of pitch angle variation	Ref.
IC 342	30°	Graeve & Beck 1988
M31	0°	Fletcher et al. 2004
M33	30°	Tabatabaei et al. 2008
M51	30°	Patrikeev, Fletcher et al. 2006
M81	50°	Beck et al. 1985
NGC 1566	0°	Ehle et al. 1996
NGC 6946	10°	Ehle & Beck 1993

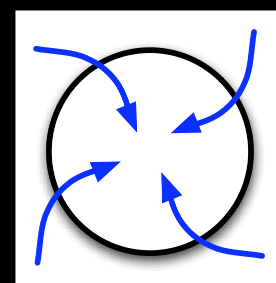
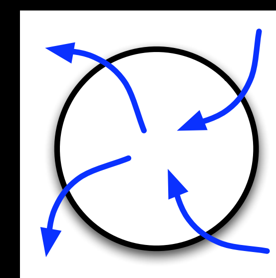
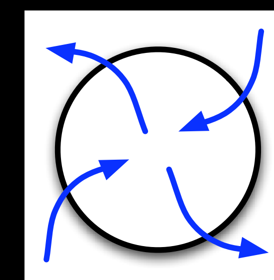
Mean B-field structure

Galaxy	m=0	m=1	m=2	Ref.
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. 2011
M81	-	1	-	Krause et al. 1989
M81	0.5	1	-	Sokoloff et al. 1992
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 $p \geq 10°$

Mean B-field structure

	m=0	m=1	m=2
			
mode present	12	6	5
mode dominant	8	1	0

no dominant mode: 3

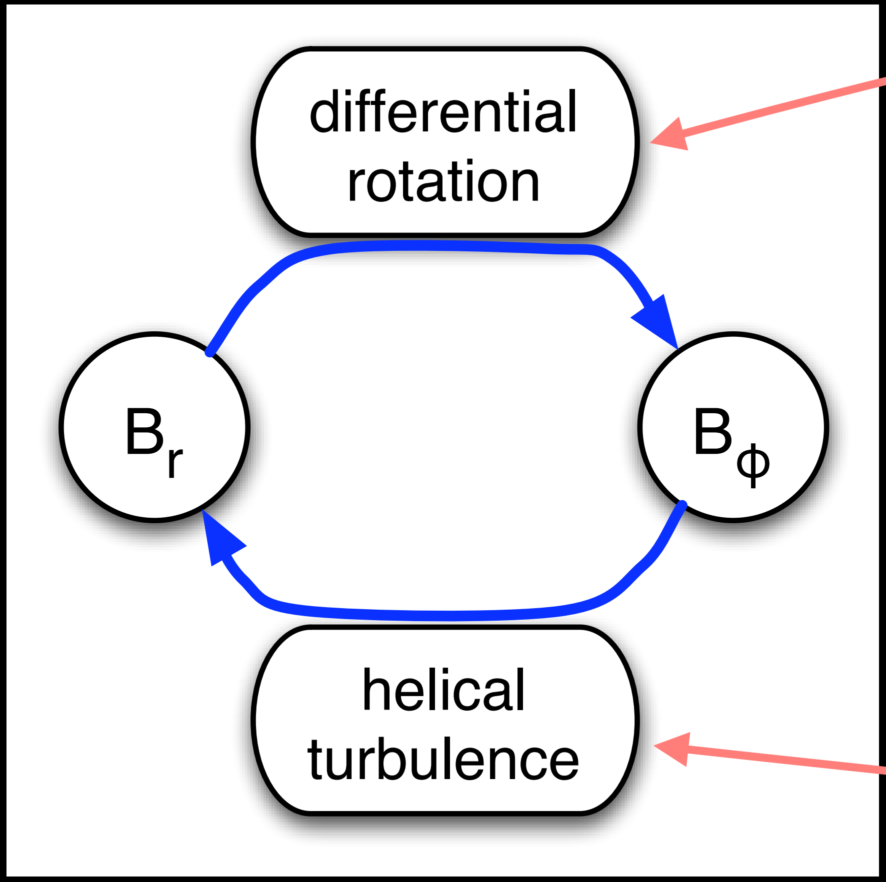
Simple mean-field dynamo I

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

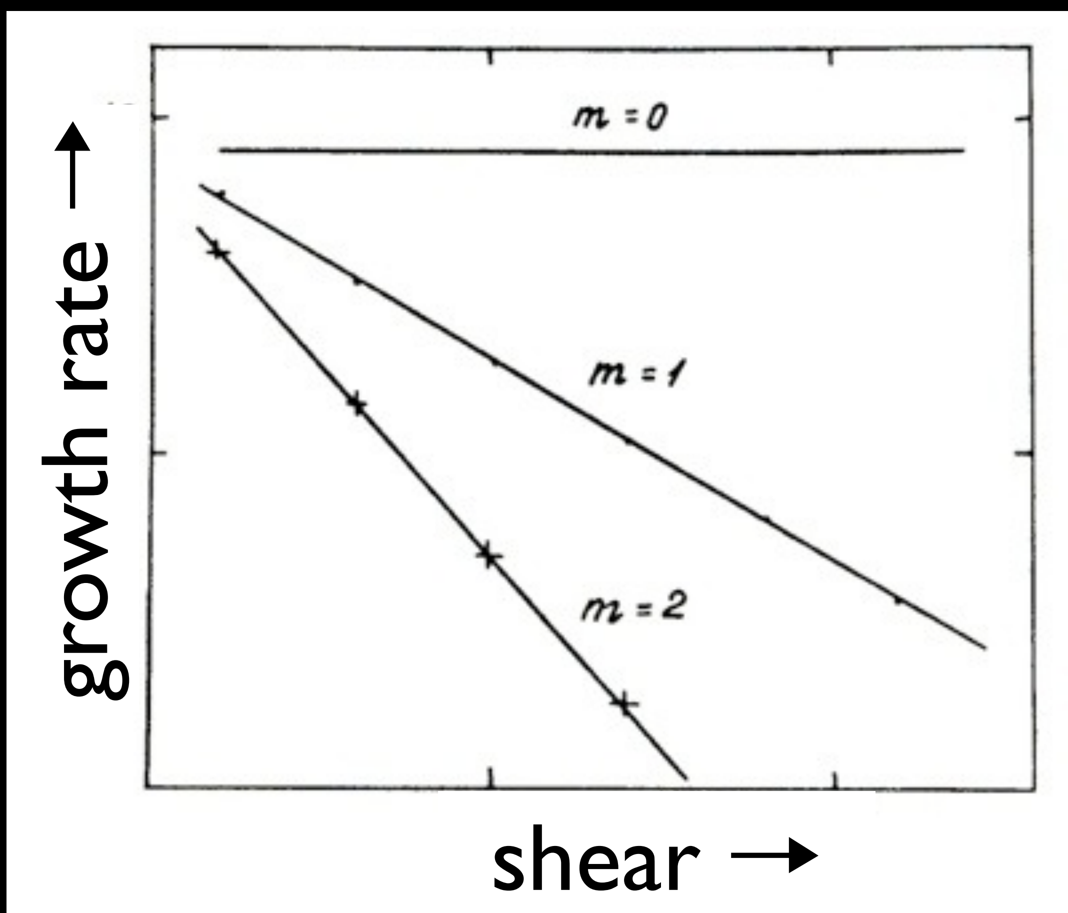


$$\frac{\partial B_\theta}{\partial t} = r \frac{\mathrm{d}\Omega}{\mathrm{d}r} B_r + \eta_\mathrm{T} \frac{\partial^2 B_\theta}{\partial z^2}$$

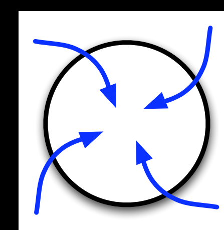
$$\frac{\partial B_r}{\partial t} = -\frac{\partial}{\partial z}(\alpha B_\theta) + \eta_\mathrm{T} \frac{\partial^2 B_r}{\partial z^2}$$

Mean-field dynamo II

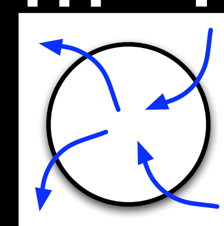
Ruzmaikin, Sokoloff & Shukurov 1988



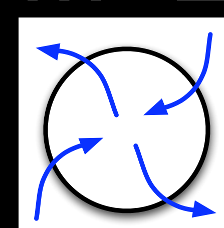
m=0

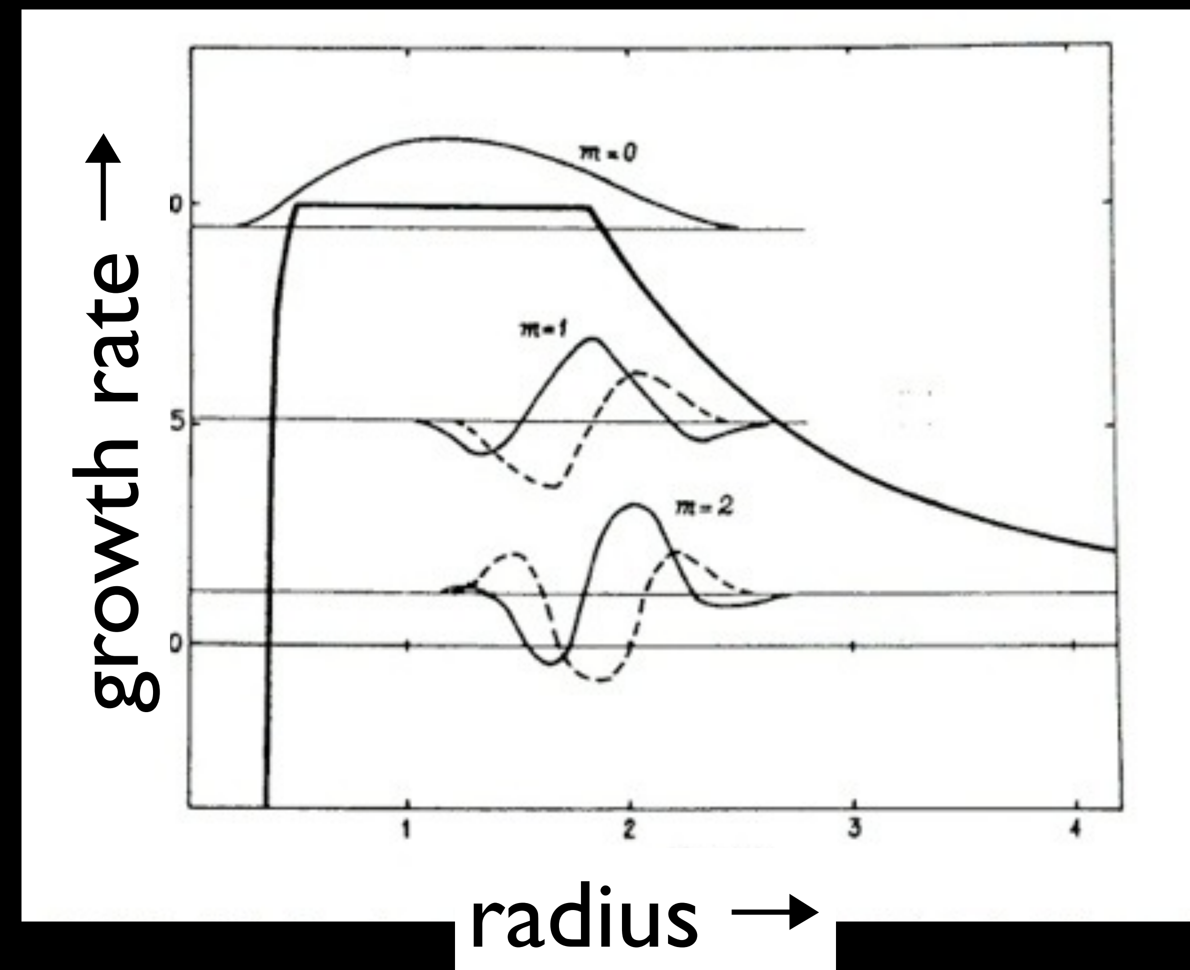


m=1



m=2



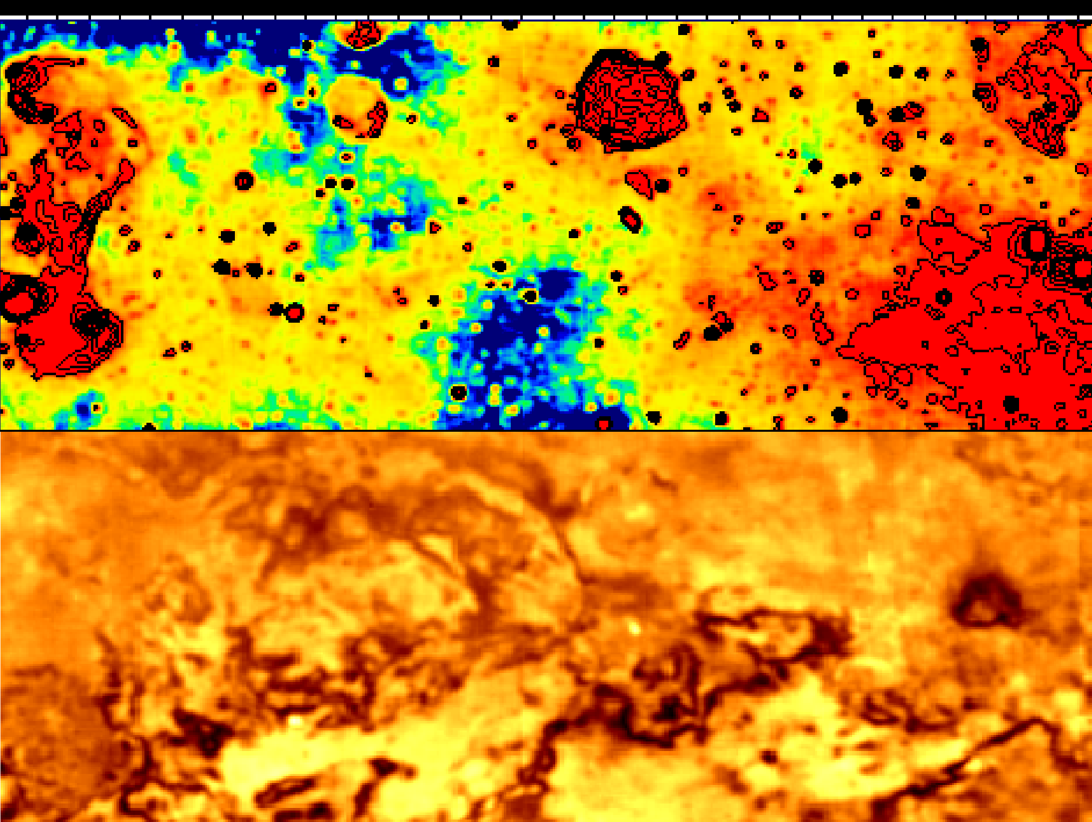


m=0 mode by far easiest to produce

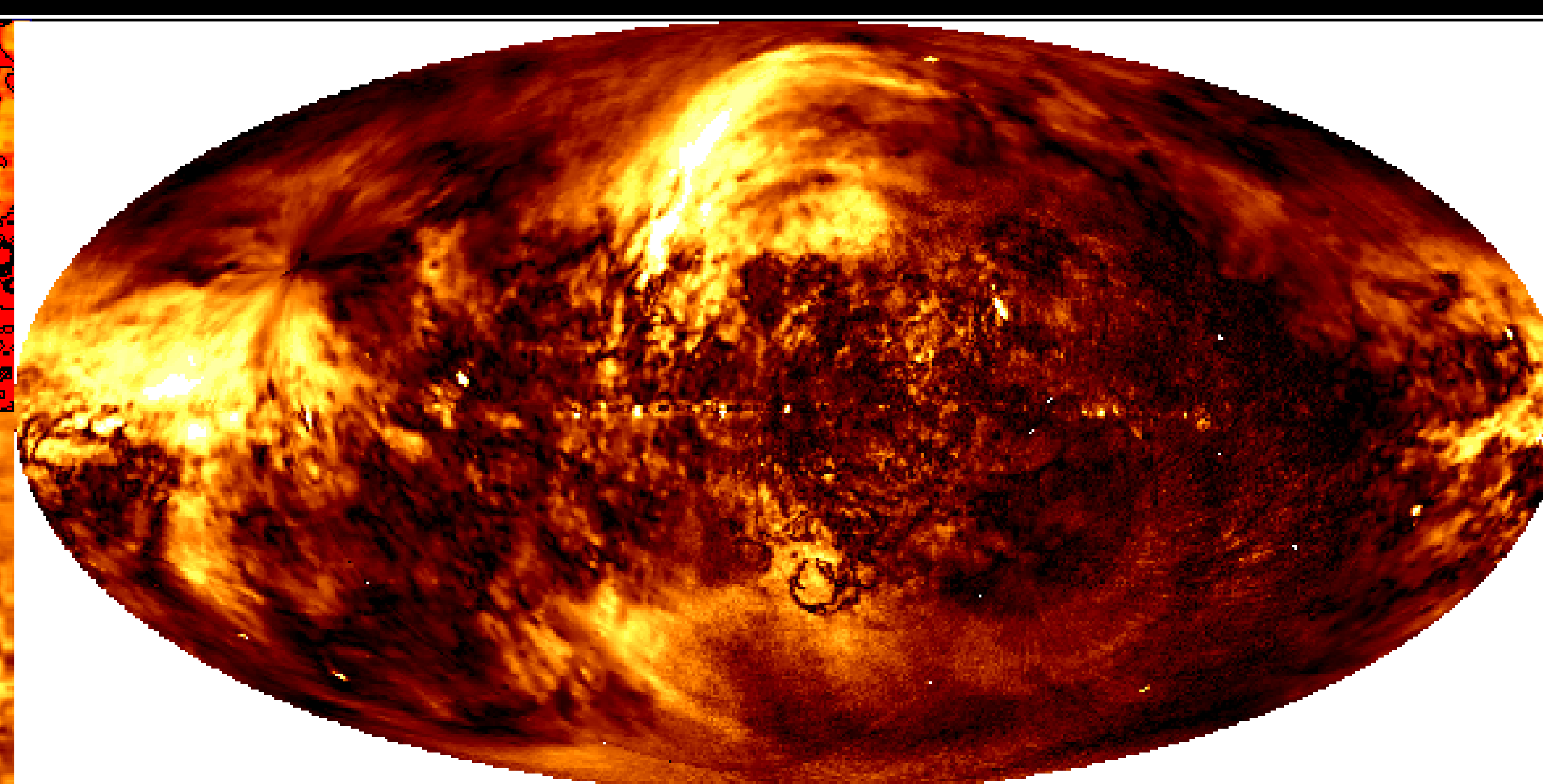
1. Total magnetic field: 8-16 ±6 μG
2. Regular magnetic field: 4 ±3 μG
3. I_{syn} scale length ≈ 1/2 optical radius
4. I_{syn} scale height ≈ 2 kpc
5. No holes: field everywhere
6. Regular field lines are spiral $p \geq 10°$
7. Axisymmetry (m=0) in disc fields
8. B pitch angles decrease with radius
9. B pitch angles can vary strongly in azimuth

The small-scale, random magnetic field

Ordered field ≈ 4 μG
Random field ≈ 10 μG



Reich et al. 2004



Wolleben et al. 2006, Testori et al. 2008, Sun et al. 2008

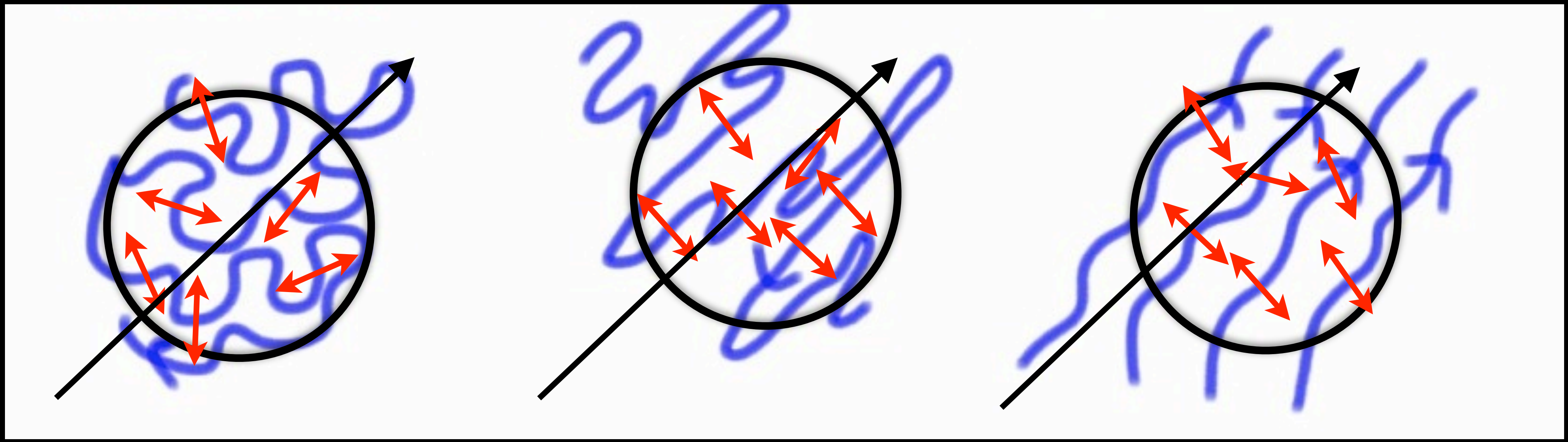
Correlation scale of b

Galaxy	Analysis	scale [pc]	Ref.
Milky Way	autocorrelation $I_{\rm syn}$	90	Lazaryan & Shutenkov 1990
LMC	RM structure function	90	Gaensler et al. 2005
Milky Way	RM structure function	arm < 10 interarm 100	Haverkorn et al. 2006
M51	depolarization by $\sigma_{\rm RM}$	50	Fletcher et al. 2011
M51	dispersion of pol. angles	65	Houde, Fletcher et al. 2013
Milky Way	power spectrum $I_{\rm syn}$	< 20	Iacobelli et al. 2013

Classification

random ordered

isotropic anisotropic mean



Synchrotron	$I > 0$	$I > 0$	$I > 0$
Polarization	$p \approx 0$	$p > 0$	$p > 0$
Faraday rotation	$RM \approx 0$	$RM \approx 0$	$\|RM\| > 0$

“Observed” anisotropy of small-scale magnetic field

Galaxy	Source	Ref.
Milky Way	$\sigma_{\mathrm{RM}} \propto \overline{\mathrm{RM}}$	Brown & Taylor 2001
NGCs 1097 & 1365	I and PI pre- & post-shock	Beck et al. 2005
Milky Way	I, PI & RM in Galactic plane	Jaffe et al. 2008
M51	$B_{\mathrm{ord}}\ [\mathrm{PI}] >> \overline{B}\ [\mathrm{RM}]$	Fletcher et al. 2011
Milky Way	I, PI & RM whole sky	Jansson & Farrar 2012
M51	Dispersion of pol. angles	Houde et al. 2013
M33	$B_{\mathrm{ord}}\ [\mathrm{PI}] >> \overline{B}\ [\mathrm{RM}]$	Stepanov et al. 2013
M51	Depolarization modelling	Shneider et al. 2014

I : total intensity

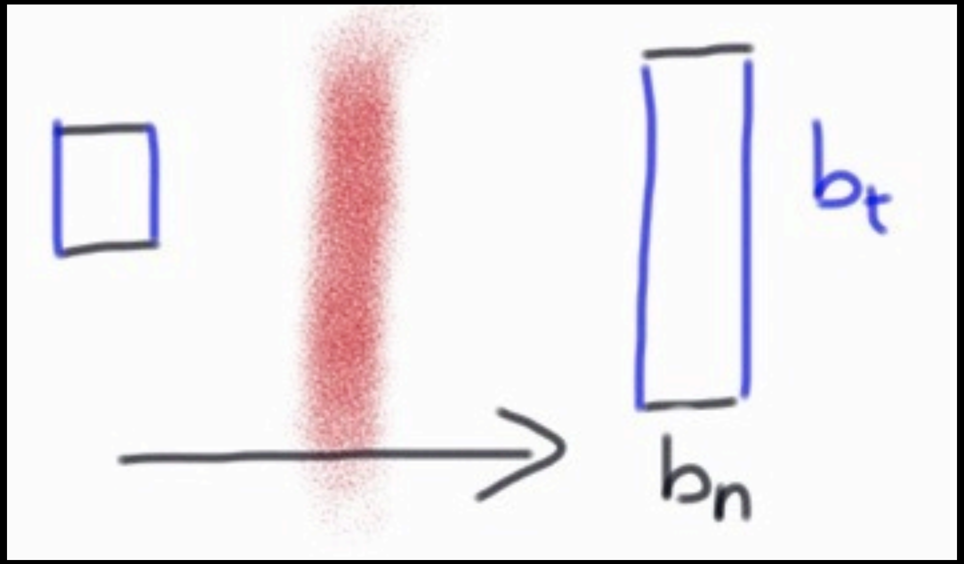
PI : polarized intensity

σ_{RM} : RM standard dviation

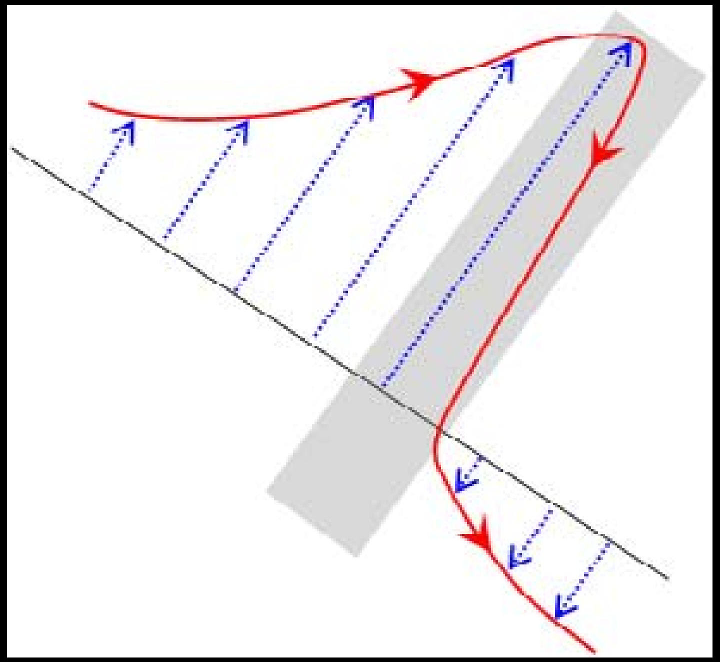
$\overline{\mathrm{RM}}$: mean rotation measure

Origin of anisotropy?

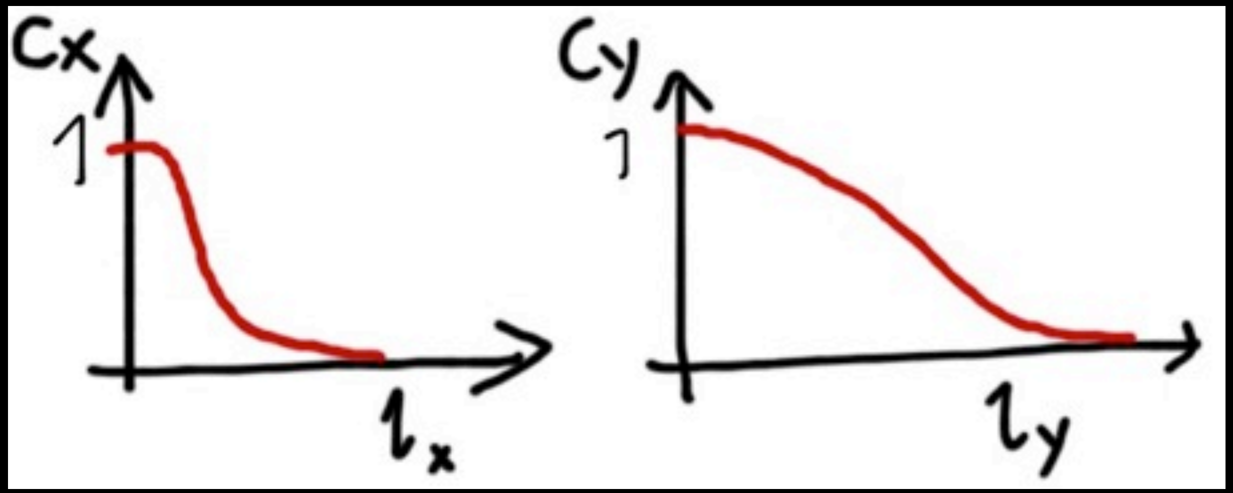
Compression (shocks, large & small)



Shear (differential rotation, streaming)



MHD turbulence ($k_\perp > k_{||}$)



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10. Correlation scale b: 10pc to 100pc
11. Anisotropic b can be important

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Unknown for typical disc galaxy

arm-interarm contrast in I, PI, B, b, etc. ?
(known for M51, NGC1097, NGC1365, NGC6946)

magnetic arms and spiral arms; streaming, corotation, alignment, ... ?
("magnetic arms" in NGCs6946, 4254, 2997, M51, ...)

Unknown for typical disc galaxy

Galaxies evolve [rotation(t), SFR(t), spiral pattern(t), scale-height(t), ...]:

how does B evolve?

What happens at large radius and height?

What is the relation (if any) between magnetic fields and star formation?

Unknown for typical disc galaxy

Most properties of small-scale magnetic field:

- power spectrum?
- turbulence and/or ‘structure’ (SNR, winds, ...)?
- volume filling or intermittent?
- origin: tangling or fluctuation dynamo?
- helicity?

What is the relation (if any) between magnetic fields and star formation?

Unknown for typical disc galaxy

Connection of magnetic field to ISM:

- which phase (cold, warm, hot)?
- spiral arms and spiral field lines?
- relative distributions of B, gas, cosmic rays?
- connection to velocity field?

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