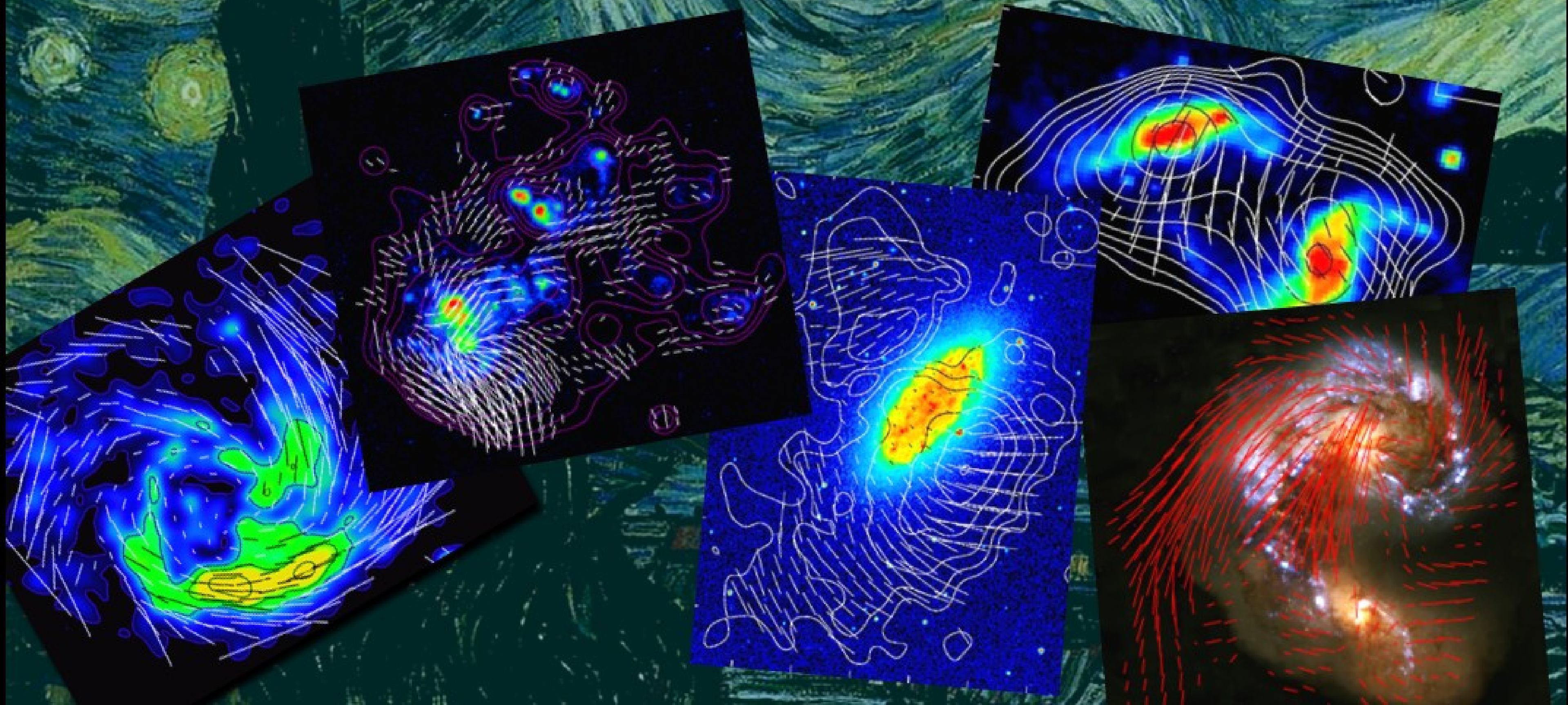
Magnetic properties of galaxies

From dwarf irregulars to mergers

Krzysztof T. Chyży
(Jagiellonian University, Kraków)



Outline

- Observational methods
- Magnetic fields and SF activity
- Structure and strength of MF in dIrrs
- Magnetisation of the IGM
- Magnetic field evolution in merging galaxies
- Conclusions and outlook

In collaboration with Rainer Beck, Marek Weżgowiec, Dominik Bomans, Robert Drzazga, George Heald, Wojciech Jurusik, Uli Klein, Marek Urbanik

Methods

Magnetic field components and strength

from synchrotron emission and Faraday rotation

Before (Beck 1996):

$$B^2_{total} = B^2_{regular} + B^2_{random}$$

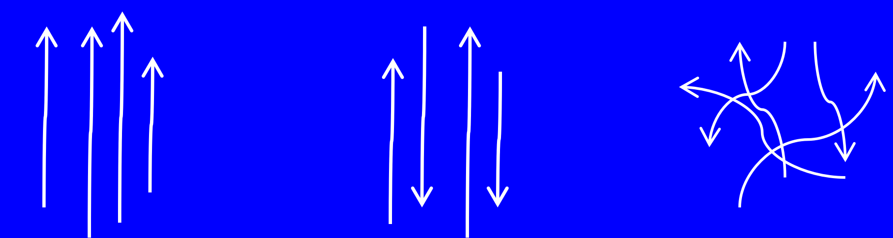
(uniform) (turbulent)

Now (Beck 2012):

compression, shear (anisotr. turb.)

$$B^2_{total} = B^2_{coherent} + B^2_{anisotropic} + B^2_{random}$$

(regular)



$RM \propto \int n_e B_{coh\parallel} dl$ ➔ $B_{coh\parallel}$

$$B^2_{total} = B^2_{ordered} + B^2_{random}$$

I_{synchr} ➔ B_{tot} PI ➔ $B_{ord\perp}$

Mean 74 gal. : 9μG 2 –5μG (Beck 2005)

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12.10.2012

New posibility – RM Synthesis

Presents polarized intensity as a function of Faraday depth

Faraday depth:

$$\phi(\mathbf{r}) = 0.81 \int_{\text{there}}^{\text{here}} n_{\text{e}} \boldsymbol{B} \cdot \, \mathrm{d}\mathbf{r} \ \text{rad m}^{-2},$$

Only for Faraday screen $\Phi = RM = d\chi / d\lambda^2$

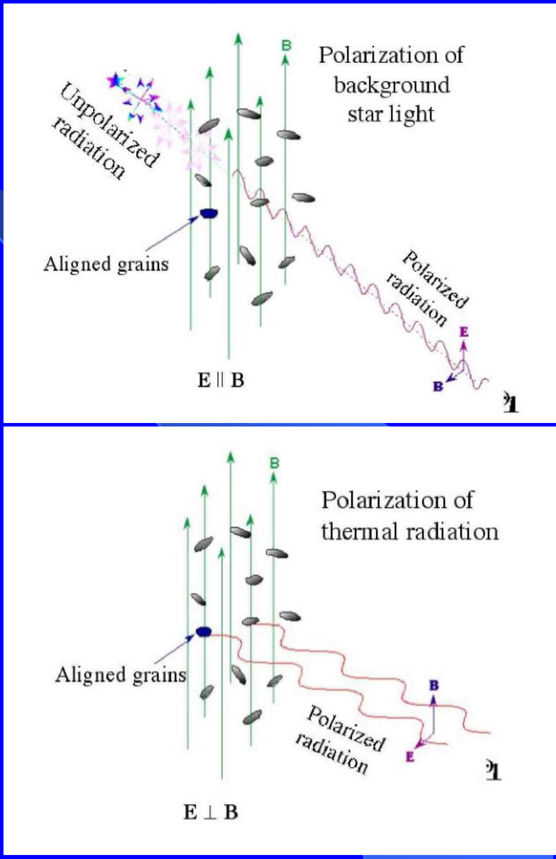
Multichannel radio observations of polarized signal are required – spectro-polarimetry

Burn 1966, Brentjens & de Bruyn 2005, Heald et al. 2009 (application for SINGS galaxies)

Other methods

Lazarian 2008

- Radio Zeeman effect => $B_{\|}$
- Optical (UV-NIR) polarization of background starlight (differential absorption by aligned, rotating, paramagnetic dust grains, diffuse ISM) $E \| B_{\perp}$
- Infrared (mm-submm) polarization (emission from aligned dust grains, dense ISM) $E \perp B_{\perp}$



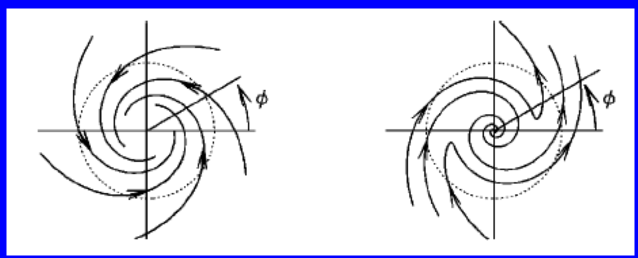
ALMA!

Heiles 2010, Heiles & Havercorn 2012

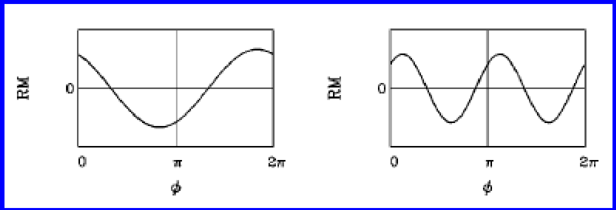
B structure and dynamo

- Random field – small-scale (turbul.) dynamo e.g. Brandenburg and Ferrière 2006
- Regular (coherent) field - large-scale, “mean-field” , αΩ dynamo review: Beck 1996, 2012, Widrow 2002; MHD simul.: Gressel et al. 2008, Hanasz et al. 2009, Moss et al. 2012
- Large-scale dynamo modes:

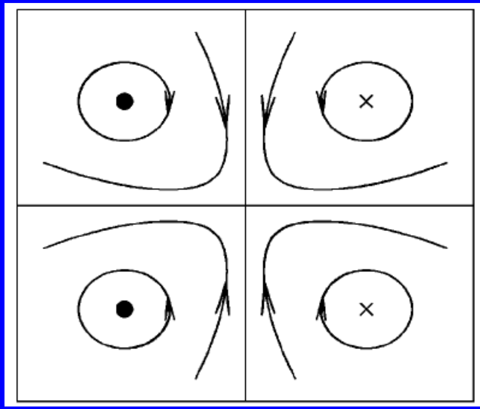
Disk (top view)



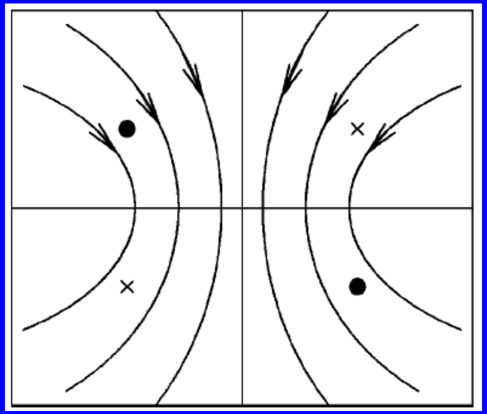
ASS BSS



Halo (weaker) (side view)



even (sym)
(quadrupolar)



odd (antisym)
(dipolar)

- Dynamo modes can be identified from the characteristic patterns of polarization angles and RMs (see Rainer’s talk)

Magnetic fields and SF activity

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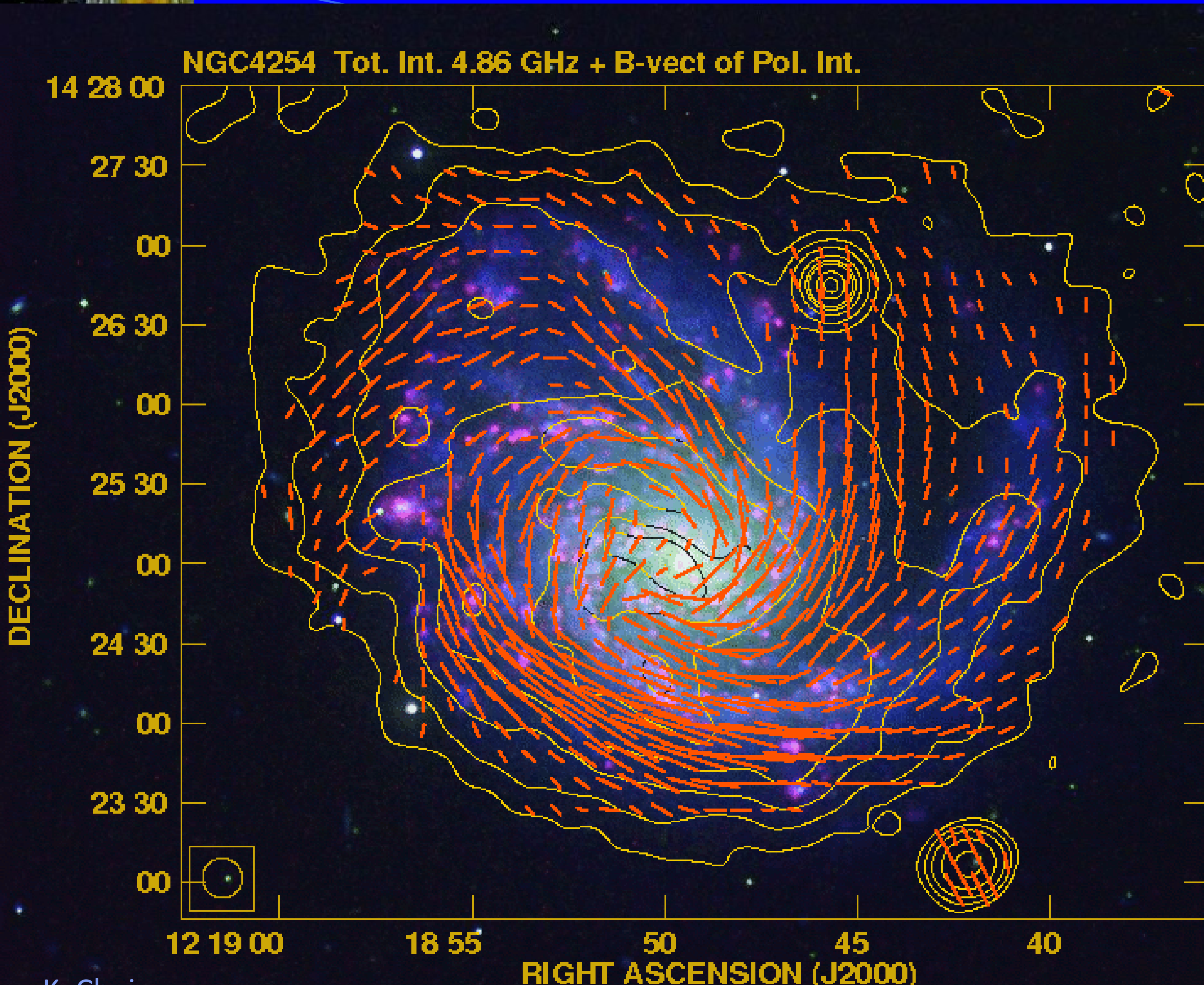


NGC 4254 B and ISM

Virgo cluster spiral, weakly disturbed

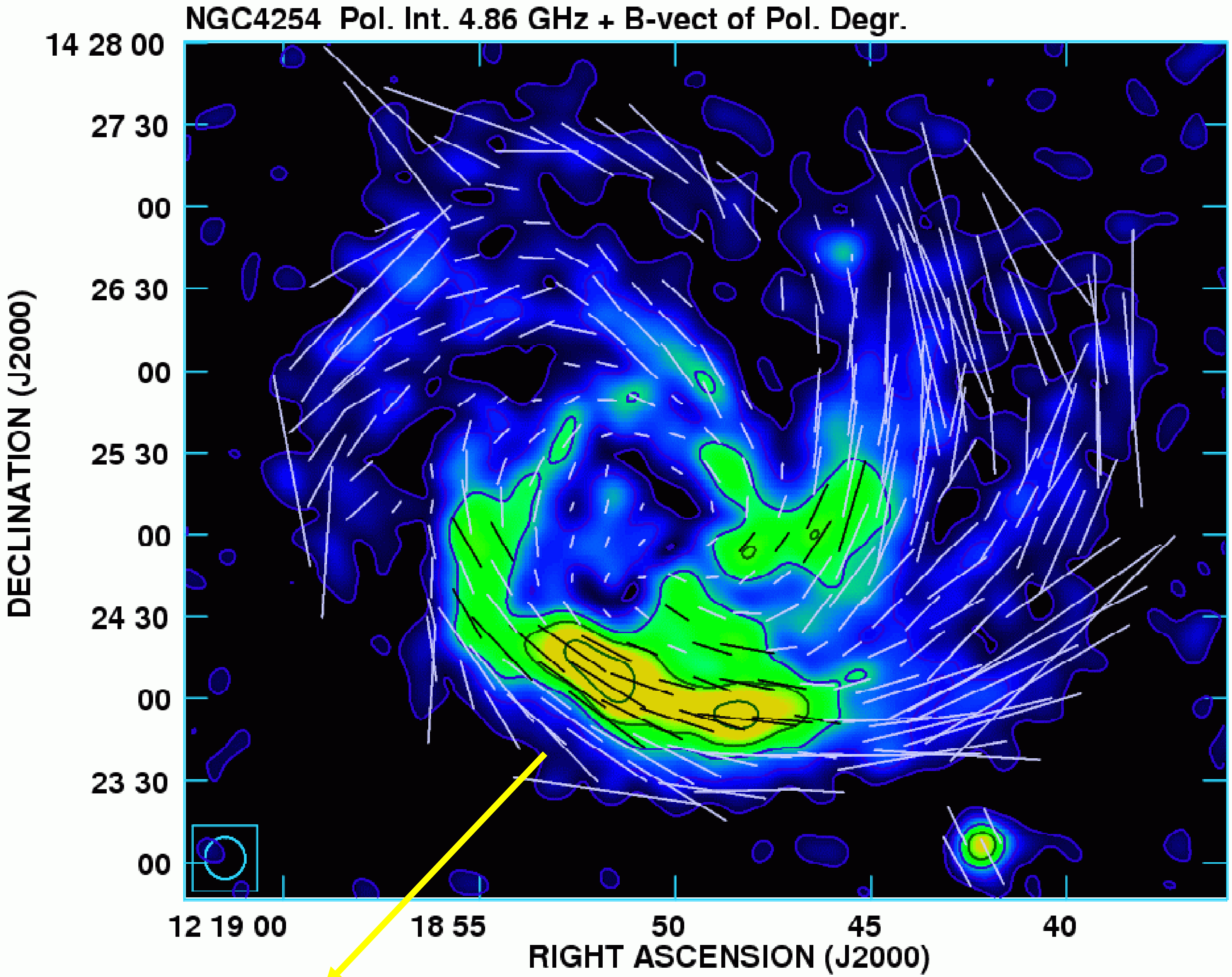
VLA+EFF 4.86 GHz (6.3cm)

B_{tot} =16μG
B_{ord} =7μG

Spiral manetic fields more or less parallel to the optical spiral arms

Chyży, Ehle & Beck 2007, A&A, 474, 415

NGC 4254



PI 4.86 GHz

There are coherent fields (large-scale dynamo, ASS mode) but a large part of PI comes from anisotropic random fields!

Vir A
1.2 Mpc

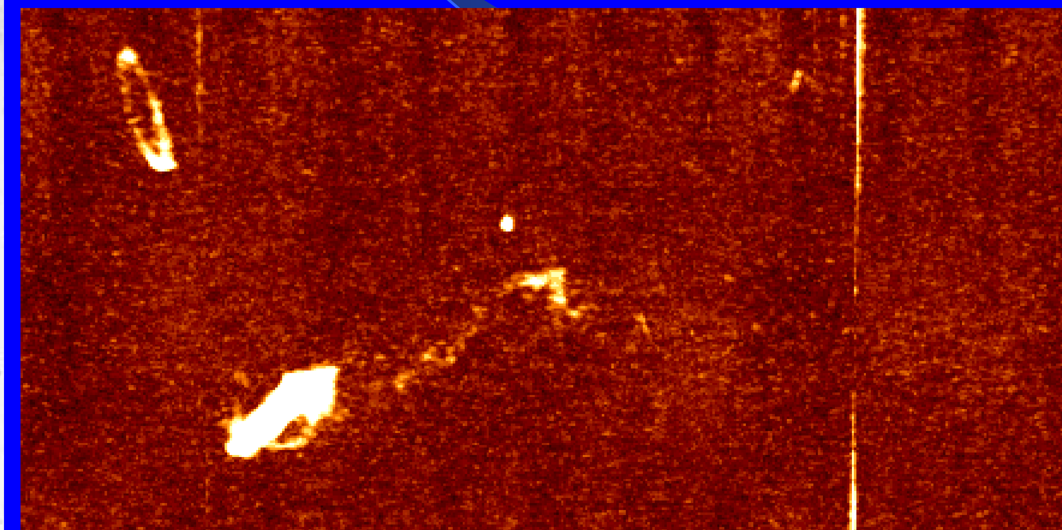
Compression - the ram-pressure of the cluster gas?
Stretching - by tidal forces?

Ram-pressure or tidal interaction?

HI (WSRT) - VIRGOHI 21 (Minchin et al. 2007)

Vir A

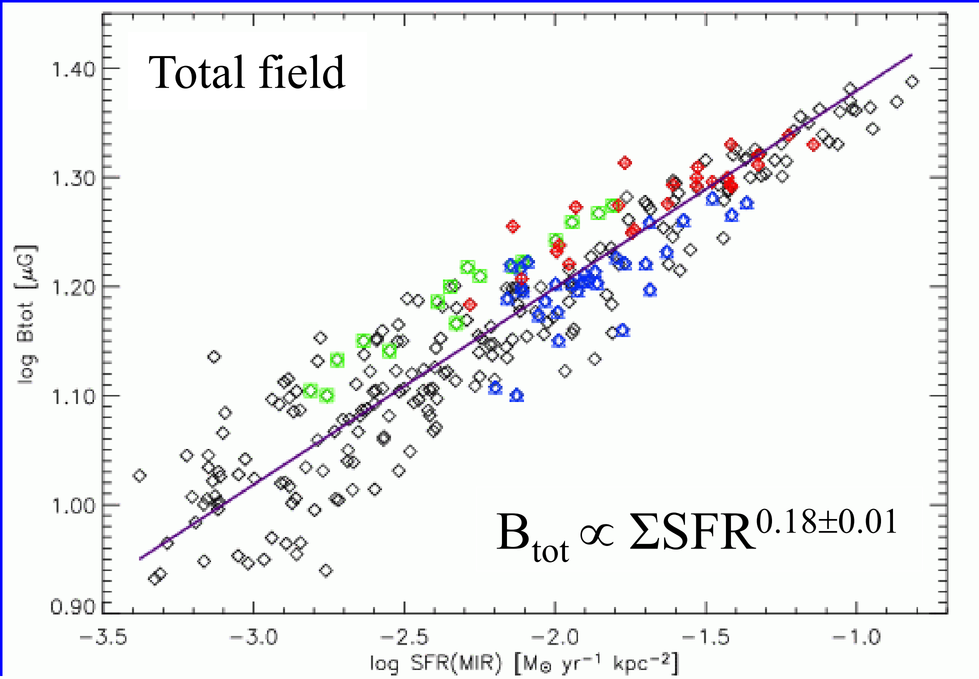
HI data cube (xyv)

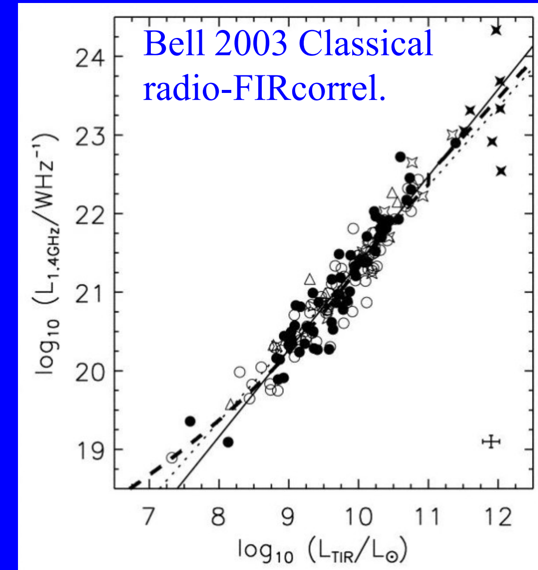


A range of HI blobs. The largest one: $M=10^8$

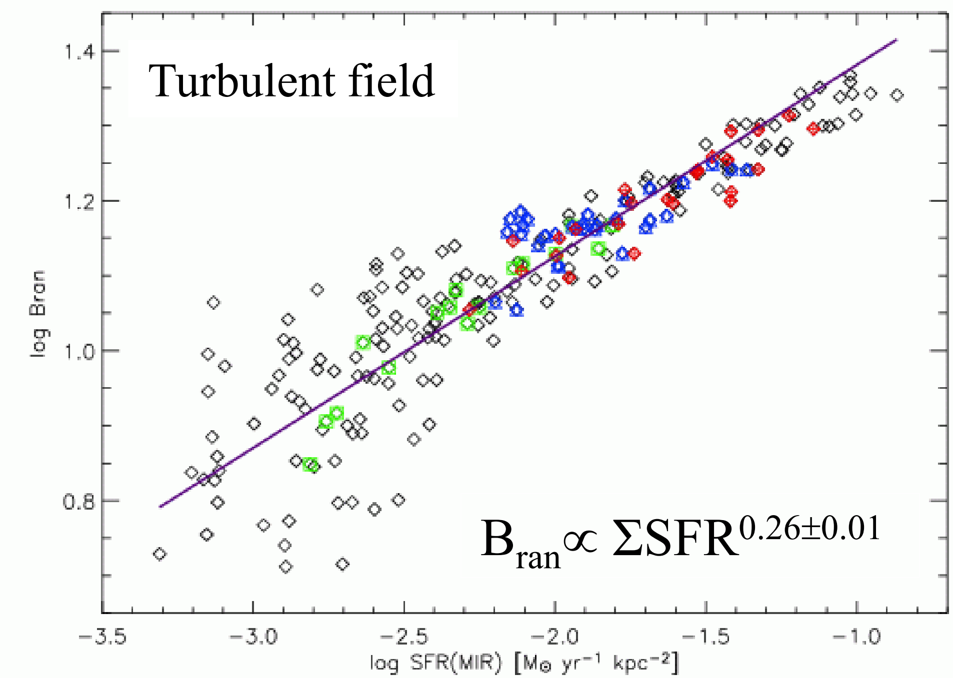
Distortion of spiral fields by past tidal interaction - stretching/shearing is the origin of strong anisotropic random field

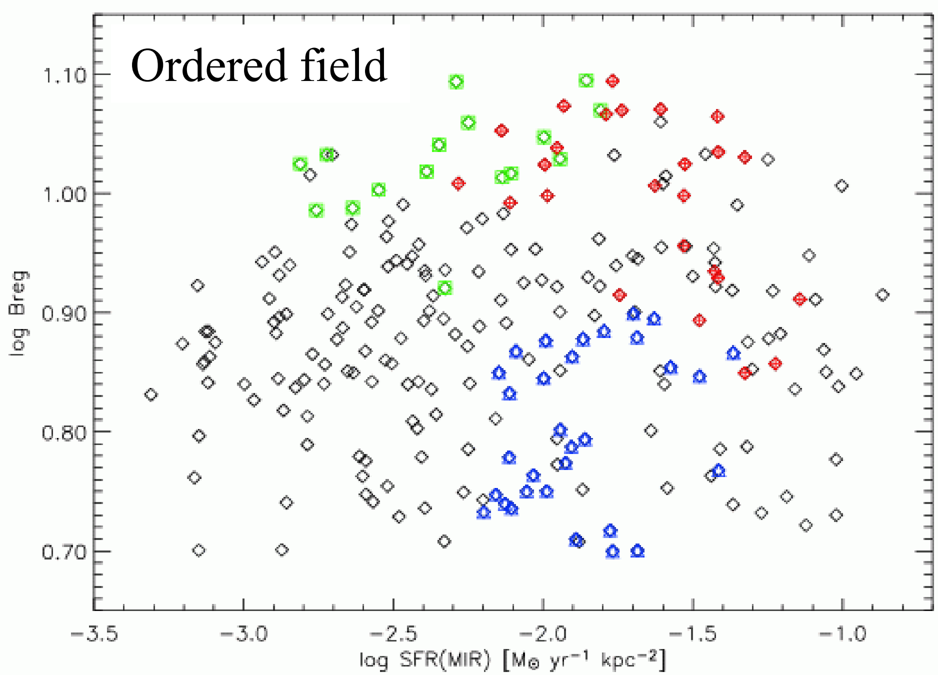
Magnetic field components - SFR





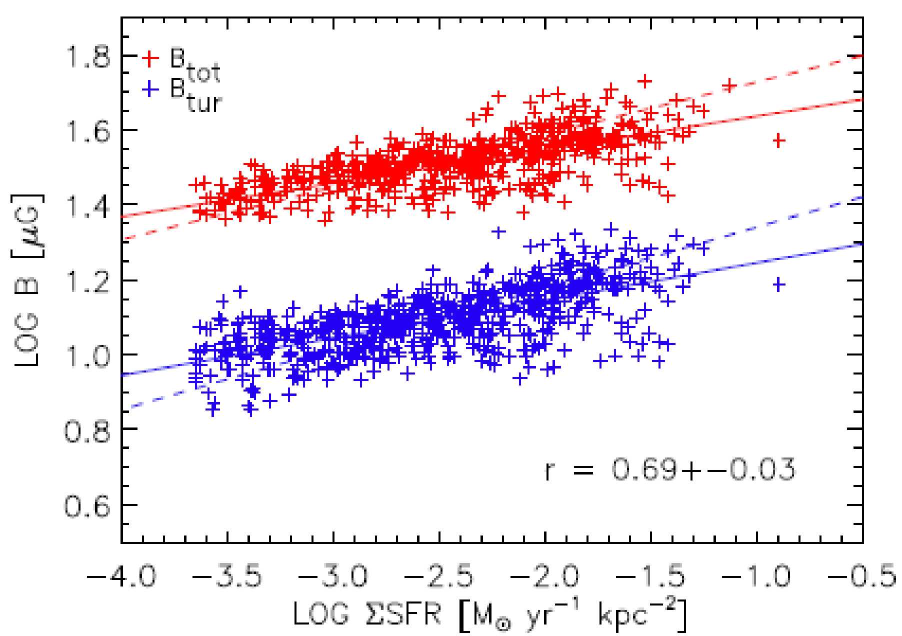
The radio-IR correlation is due to the turbulent field

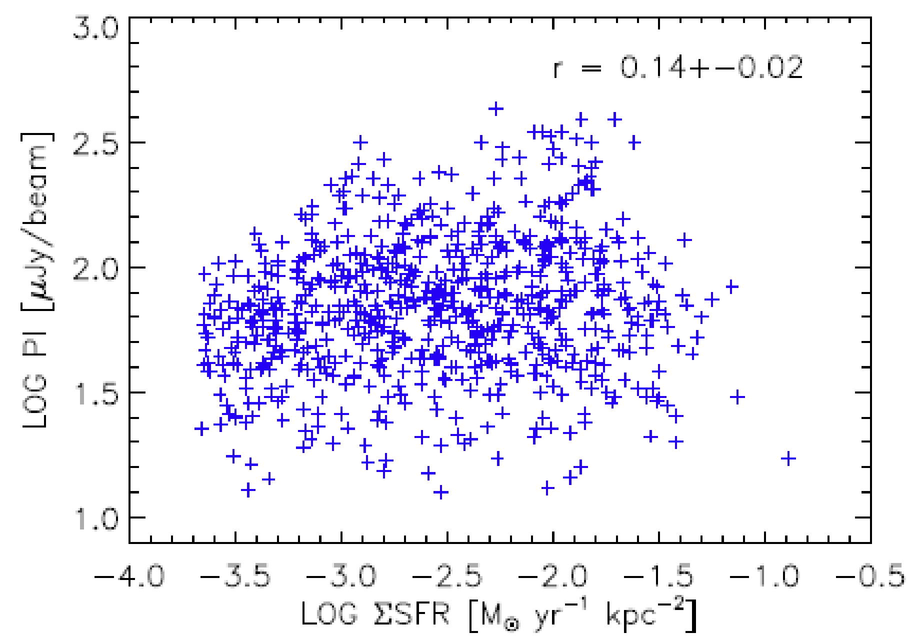


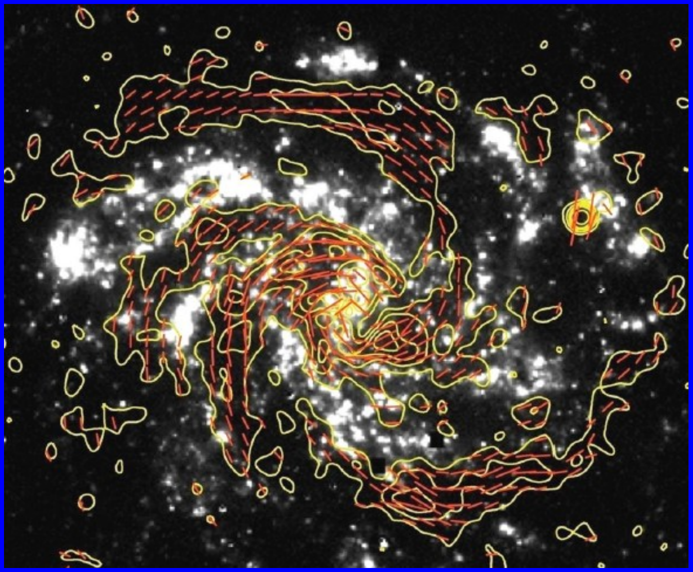


Similar relations NGC 6946

Tabatabaei et al. (2012 subm.)





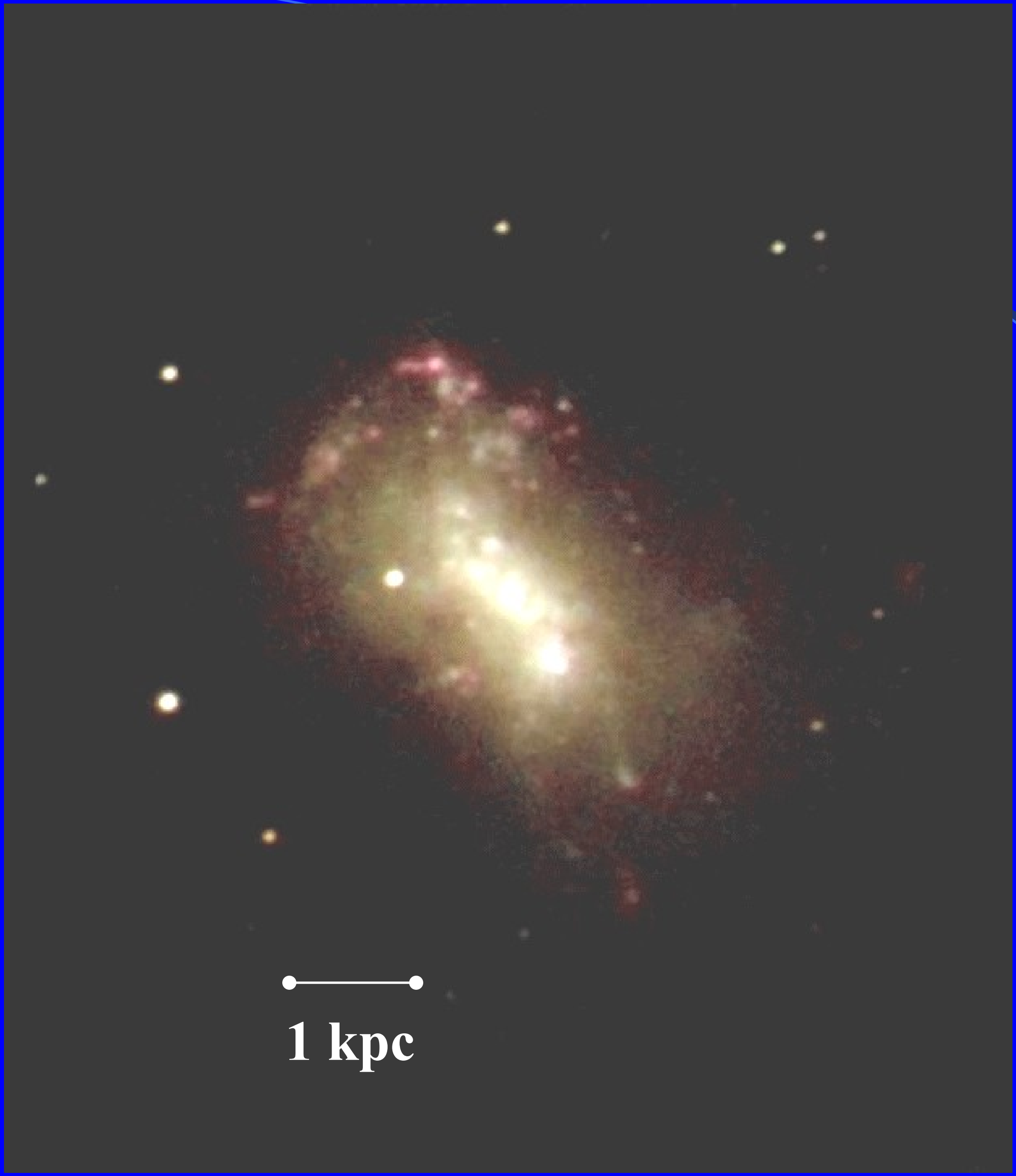


The origin of the ordered magnetic field can be linked to the dynamo effect on galactic scales (e.g. Beck et al. 1990, 1996) and is not easily connected to SFR (e.g. Chyży 2008; Krause 2009; Fletcher et al. 2011).

See Frick et al. 2001 (anticor. of PI and Hα on interm. scales).

Beck 2007

Are dwarf galaxies different?



NGC 4449

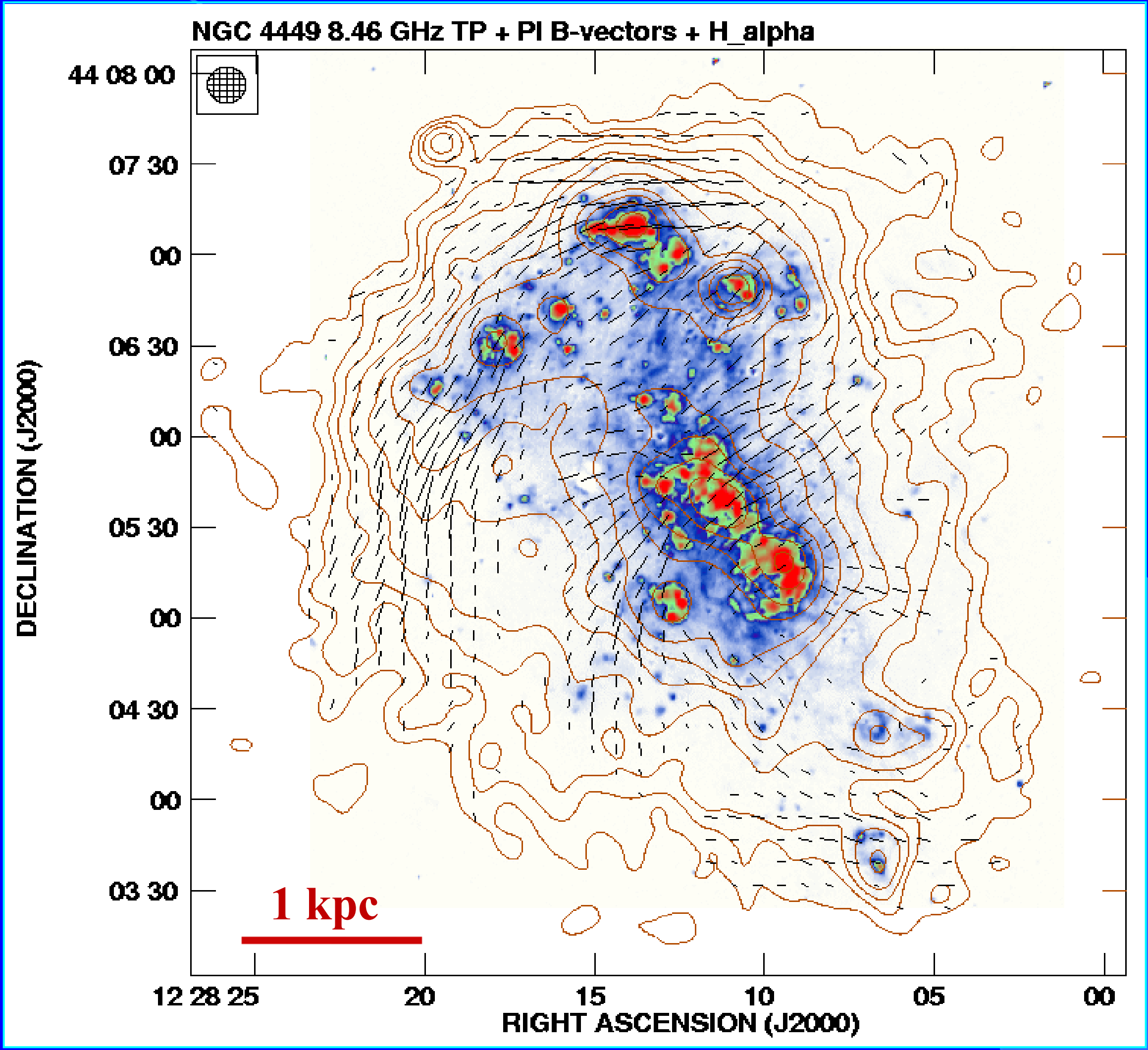
5x smaller, 8x less massive than the Milky Way
No spiral arms, slow rotation (30-50 km/s)

These conditions are difficult for efficient large-scale dynamo process.

$$D = \frac{\alpha \, \Omega \, H^3}{\beta^2}$$

Dwarf irregular galaxy NGC 4449

- B_{tot}=14μG !
  B_{ord}=7μG !
- Partly spiral with magnetic fans in the centre
- Efficient large-scale dynamo can explain that (e.g. supernova-driven Gressel et al. 2008 or CR-driven – Hanasz et al. 2009, Otmianowska-Mazur et al. 2002)



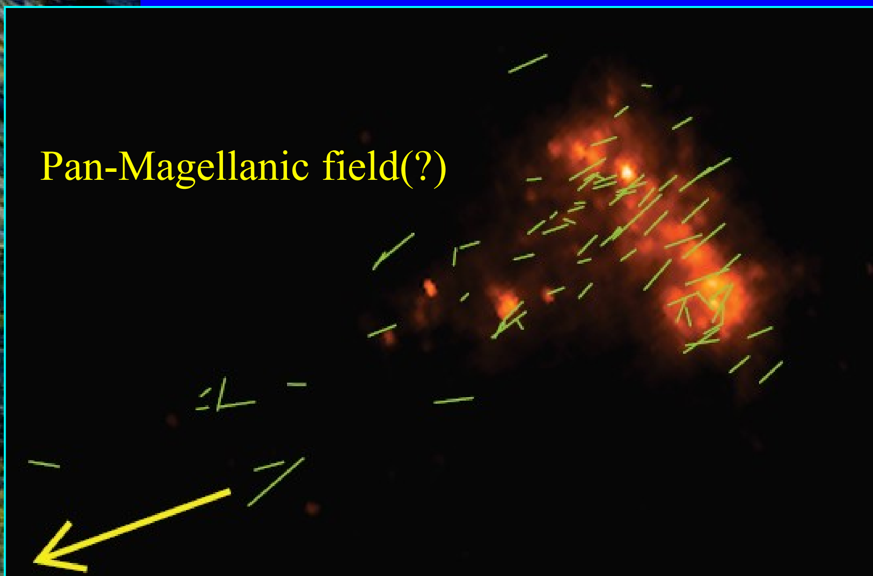
VLA + Effelsberg 8.46 GHz, Chyży et al. 2000

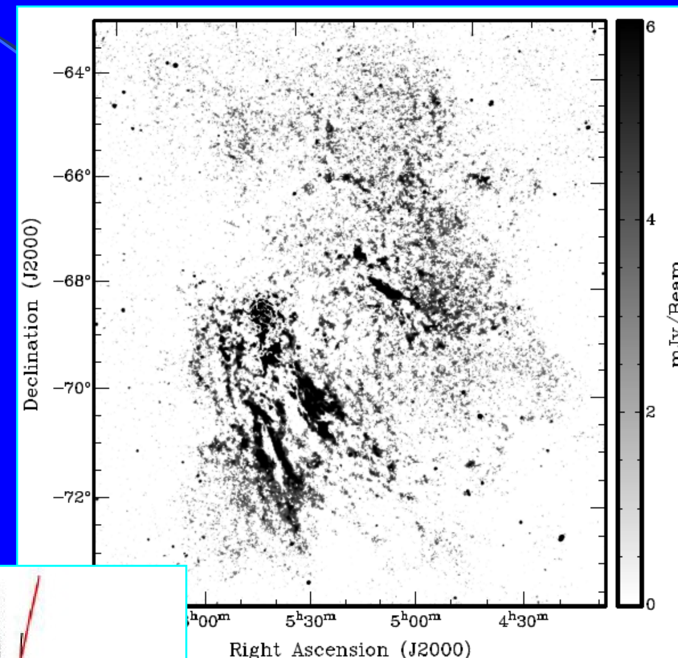
Is NGC 4449 a rule or an exception?

SMC & LMC

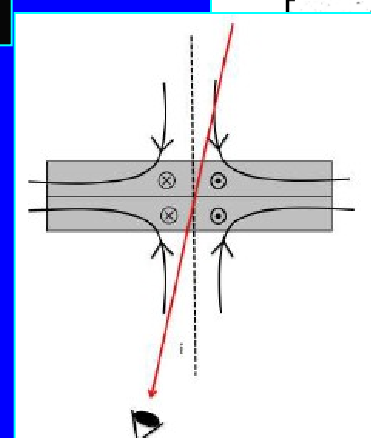
SMC – optical starlight polarization + RM, Mao et al. 2008, 2012

LMC – 1.4 GHz PI + RM (Parkes ATCA), Mao et al. 2012





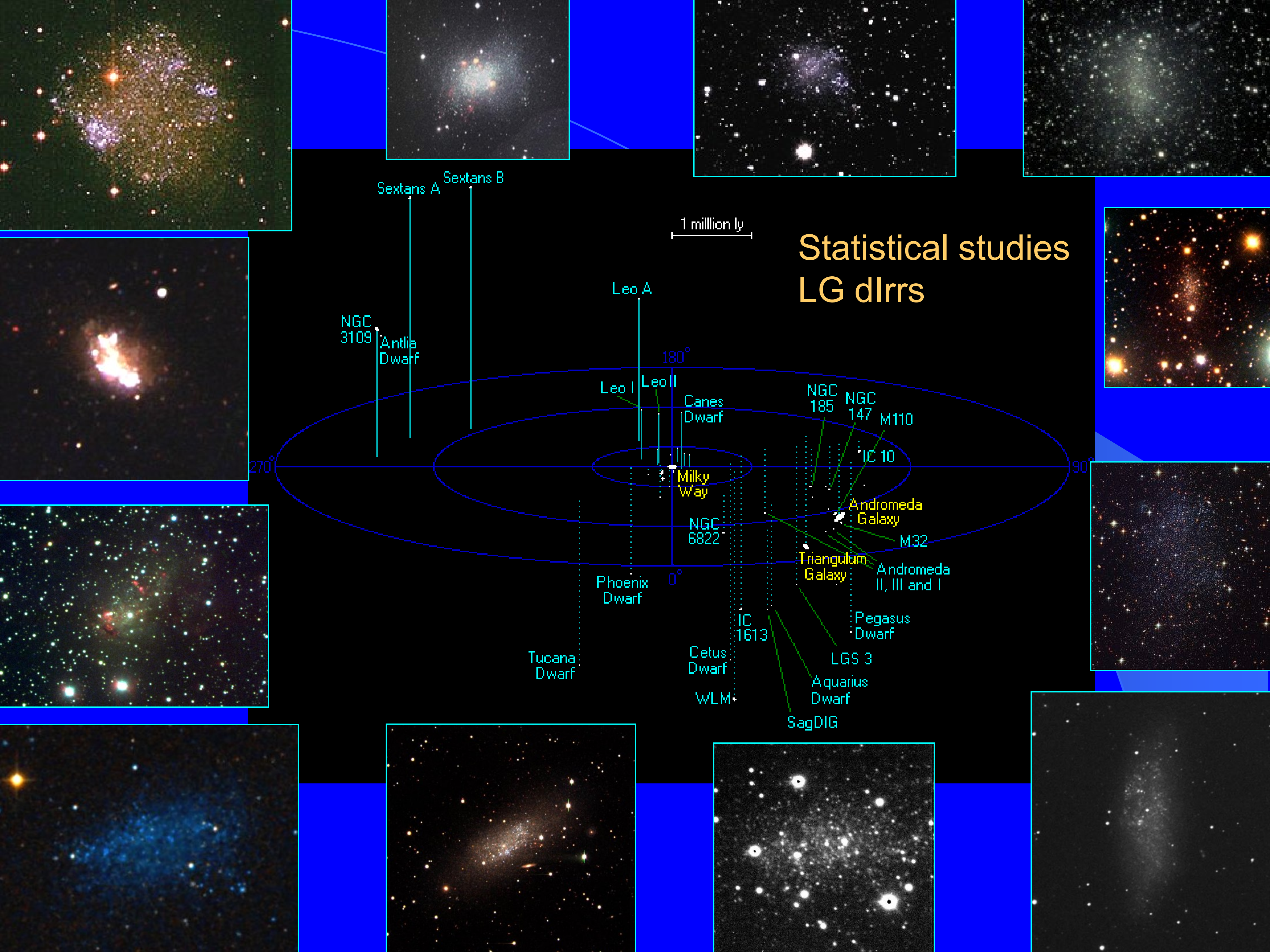
Starlight pol.: $B_{\perp}$=1.6 μG
RM: $Bc_{\parallel}$ =-0.16 μG
B_{tot}=~3 μG



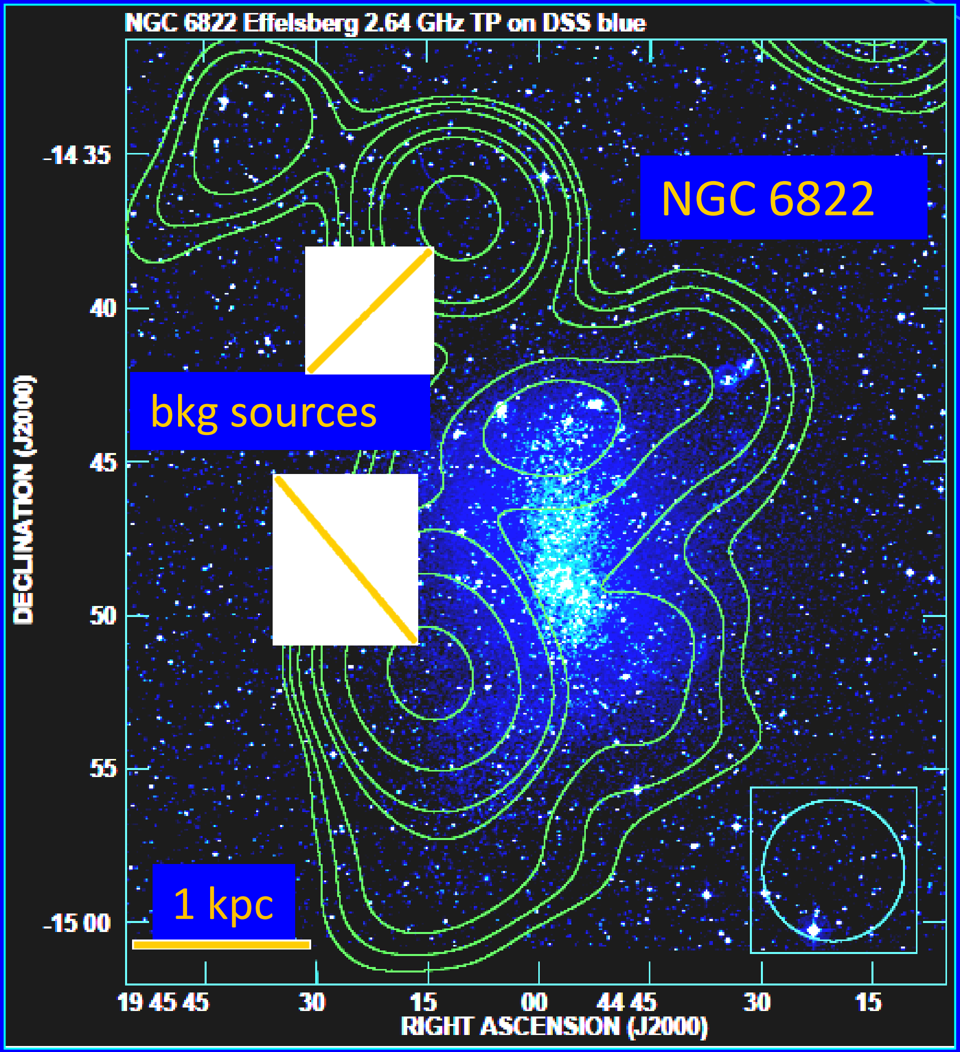
Quadrupole-type field (from RM of background sources after subtraction of the Galactic foreground)

Equipartition method B_{tot}~4 μG

Statistical studies LG dIrrs



Radio Detections



Mateo (1998), Salvadori & Ferrara (2009)

S	Irr	dwarfs			
		dIrr	dE	dSph	UF dSph
3	**7**	**14**	2	15	~20

21 dIrrs

12 attainable from Effelsberg

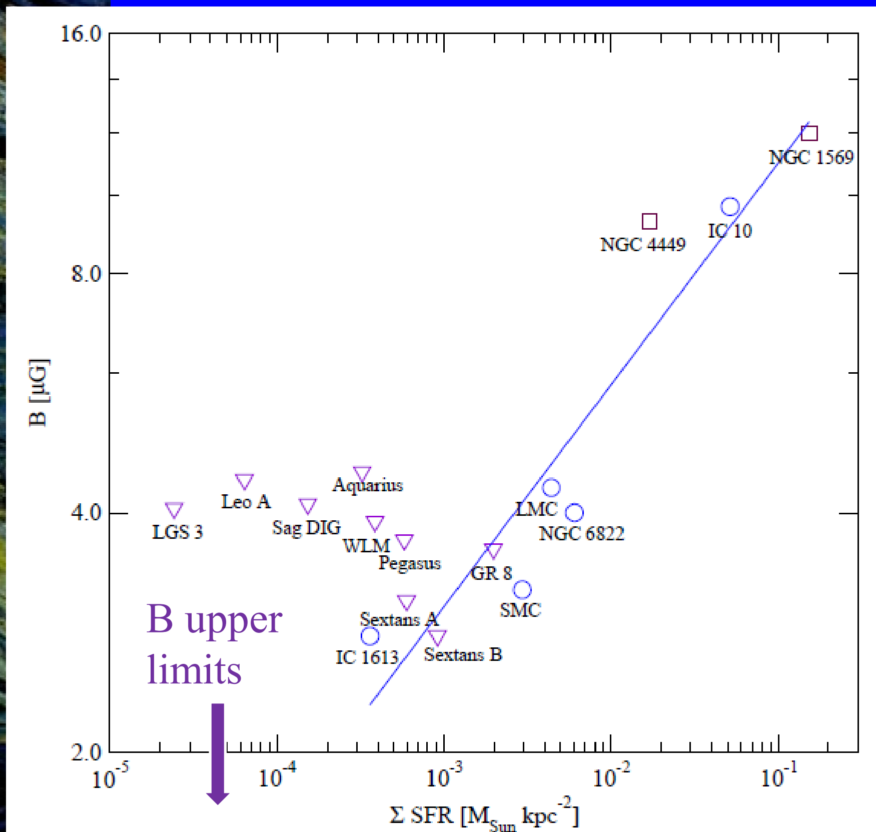
- 3 out of 12 dIrrs are radio detected at 2.64 GHz (IC 10, NGC 6822, IC1613)
- Undetected: give upper limits of B

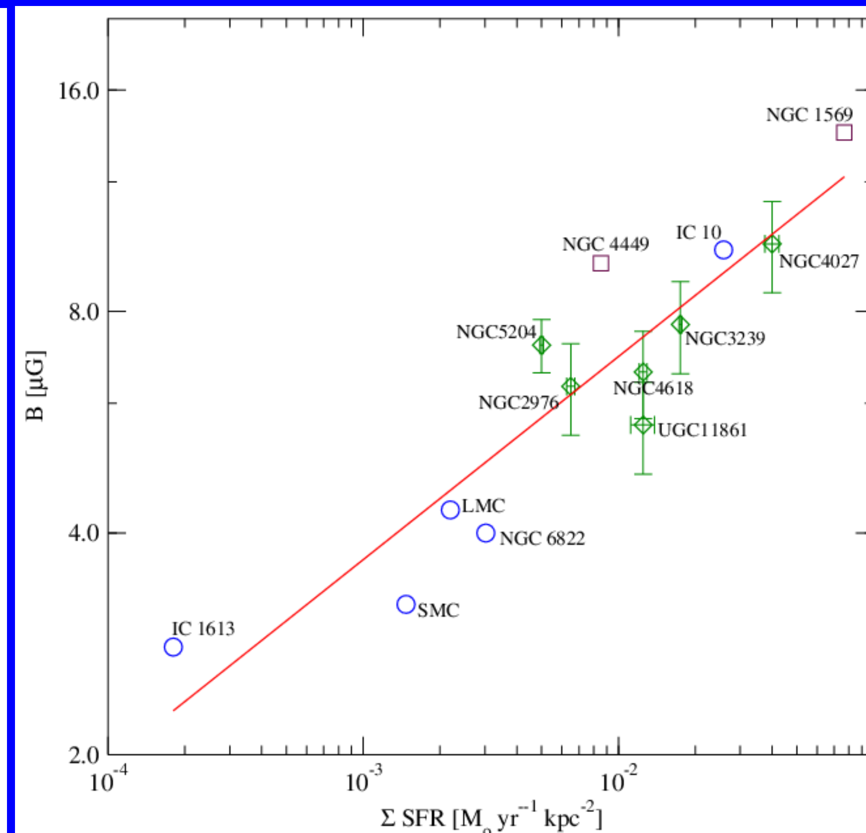
- Weak fields: typical B≤4μG
- IC10 – 10μG exceptionally strong

Dwarfs of the Local Group

B correlates mainly with ΣSFR or Σρ

- +6 more massive galaxies
- Mean B_{tot} 6-10 μG , B_{ord} 1-2 μG





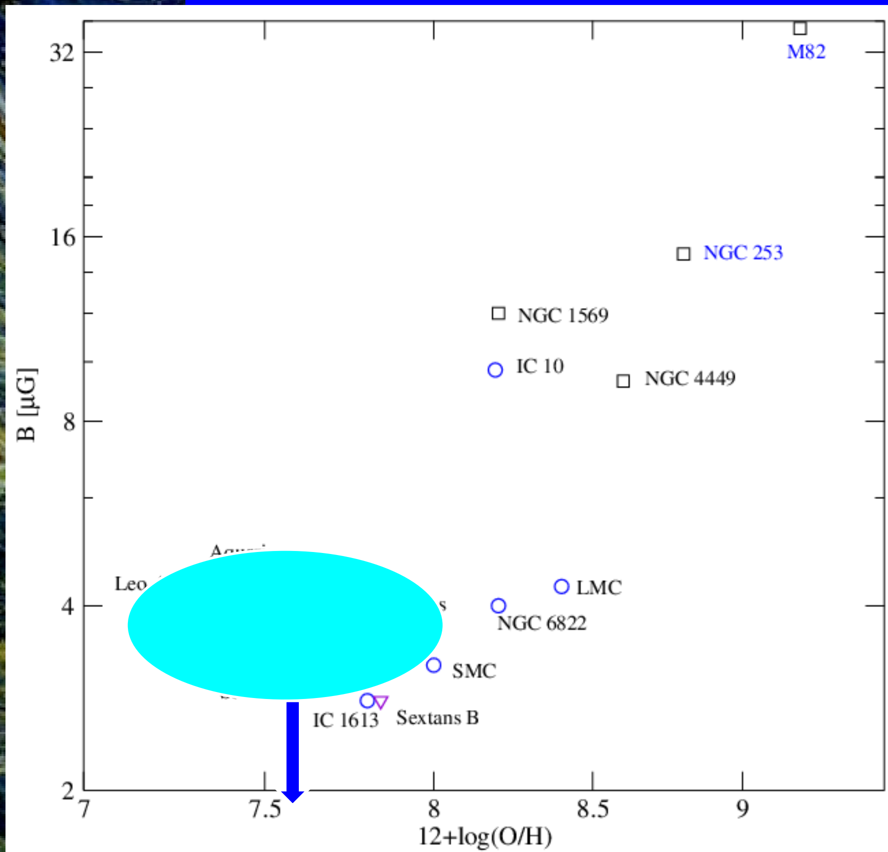
$B \propto \Sigma SFR^{0.24\pm0.05}$ $\propto \Sigma\rho^{0.47\pm0.09}$ $B \propto \Sigma SFR^{0.28\pm0.04}$

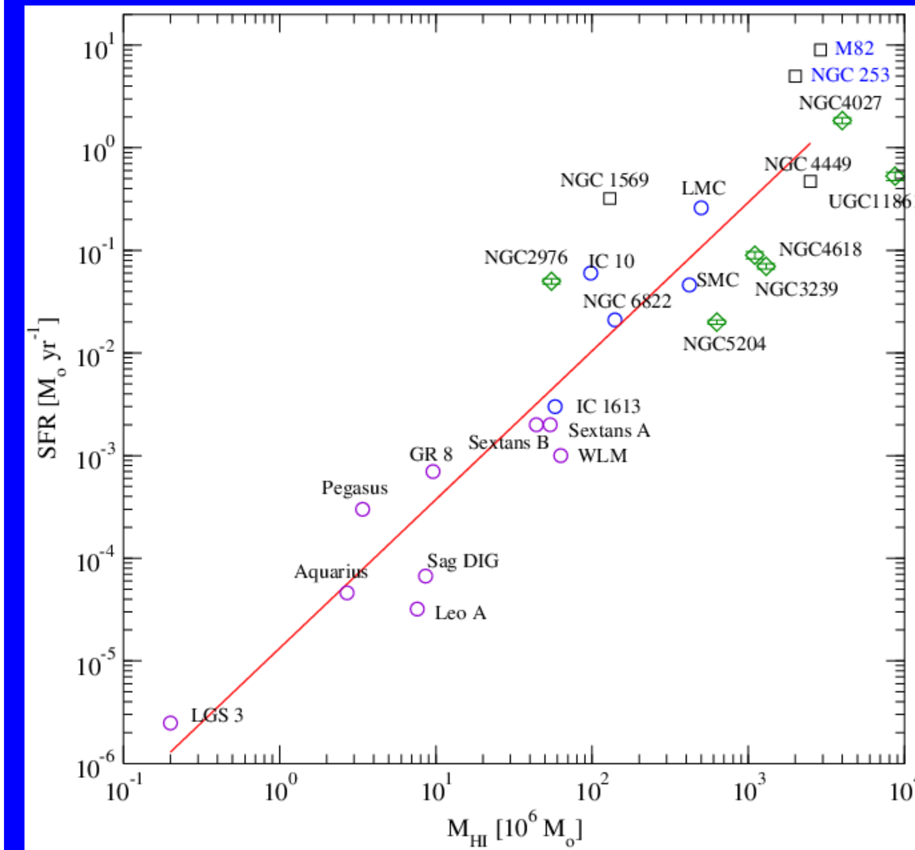
Effelsberg 2.6, 4.8 GHz, Chyży et al. 2011 in prep.

Agrees well with equipartition model (Niklas & Beck 1997)

K. Chyży
Göttingen
12.10.2012

B – metallicity

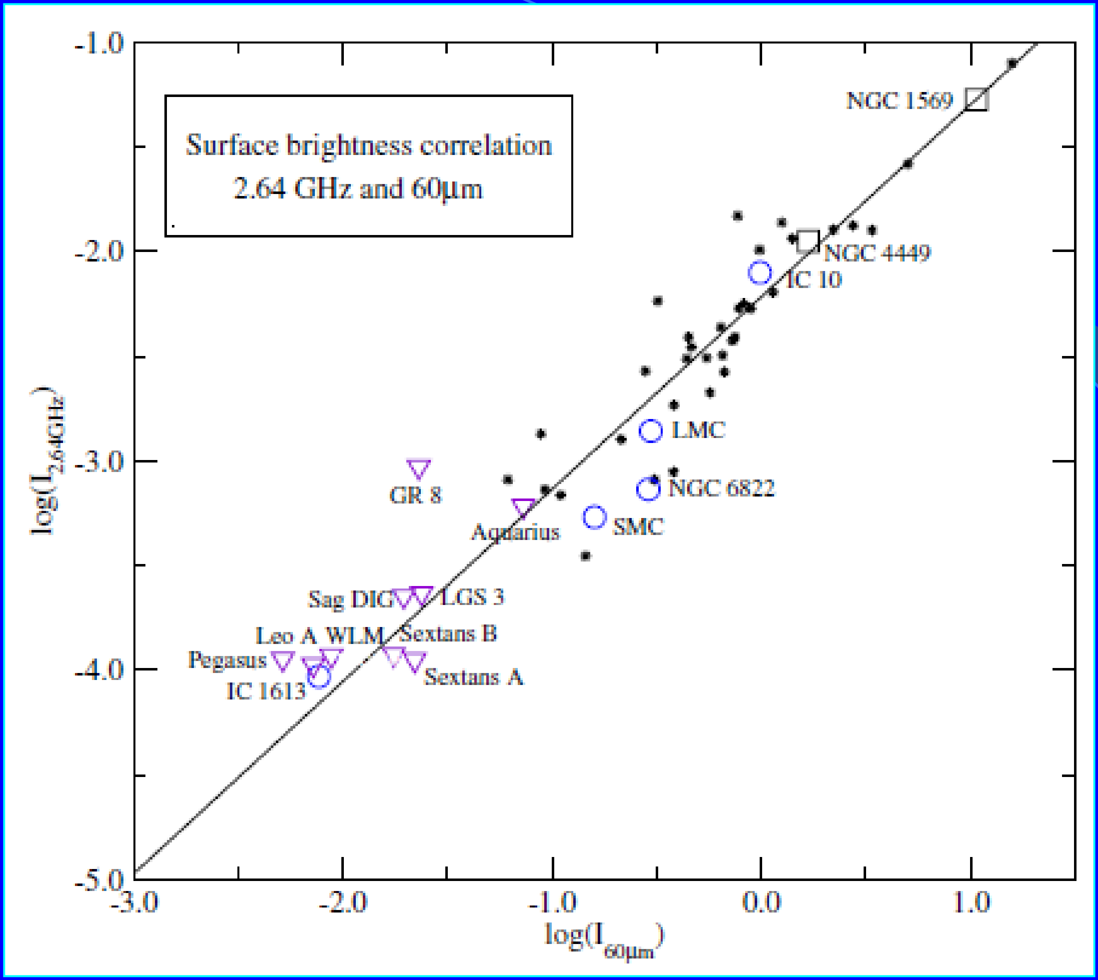




M82, NGC 253 are local starbursts, Heesen et al. 2009
NGC 1569 is a starbursting dwarf, Kepley et al. 2010

- Only dwarfs have low metallicity
- Because SFR – M_{HI} relation, B also correlates with global SFR, mass,
- metallicity

LG dIrrs – radio-FIR



Effelsberg 2.6, 4.8 GHz, Chyży et al. 2011

Low-mass dwarf galaxies follow a trend determined for high surface brightness spirals

Both quantities suppressed by approximately by the same amount („a conspiracy", Bell 2003)

Similar results: NVSS stacking - Roychowdhury & Chengalu (2012)

Magnetisation of the IGM

K. Chyży
Göttingen
12.10.2012

Magnetisation of the IGM

M82

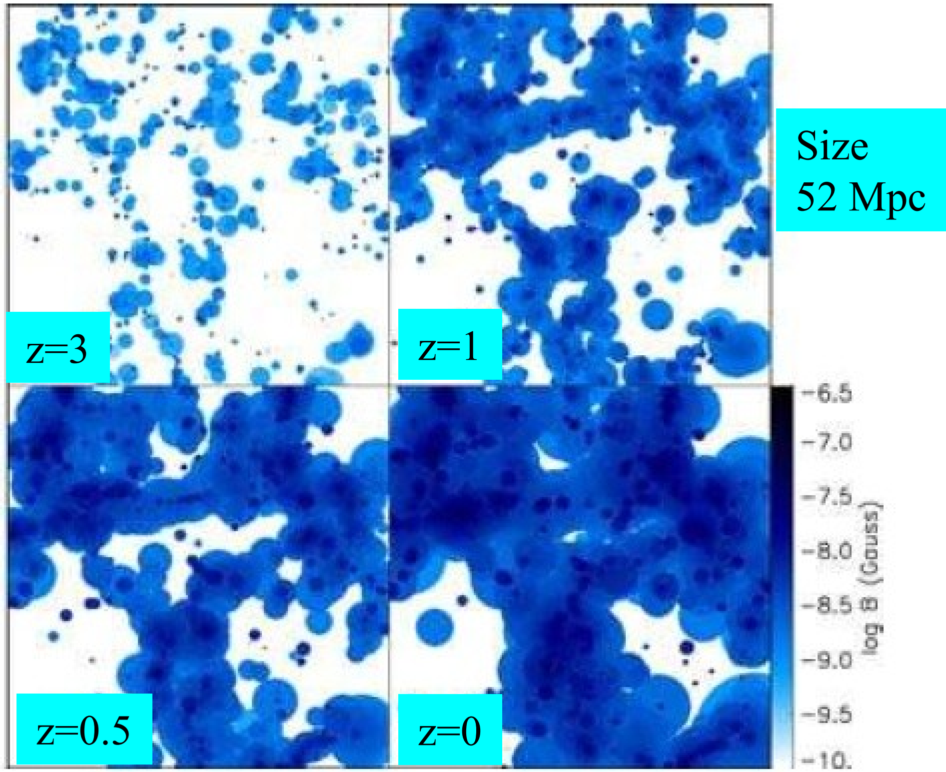
- Primordial, battery, dynamo (turbulence), first stars
- Outflows from protogalaxies
- AGNs lobes and jets
- Interacting galaxies, tidal tails, bridges

Kronberg et al. 1999, 2001, 2006

Galactic outflows are easier in low grvitational potential of dwarfs

- Huge numbers of M82 analogues present at early epochs, injection scale 8kpc, then 5 nG at Mpc scale

Dwarfs and magnetisation of the IGM



Bertone et al. 2006
Donnert et al. 2009, Samui et al. 2009

We find that the magnetic fields ejected by galaxies with stellar masses $M_\star \gtrsim 10^8\ M_\odot$ can fill a substantial fraction of our simulated volume, producing a mean (seed) magnetization of the order of 10^{-12} to 10^{-8} G in the conservative models and of the order of 10^{-9} to 10^{-7} G in the optimistic models. Magnetic field are not uniformly distributed in space, but rather seem to roughly follow the large-scale distribution of the underlying dark matter density field.

Typical LG dwarfs have lower stellar masses

Spreading out B (based on LG dIrrs)

1. Meiksin (2009), Veilleux (2005) approach (metal enrichment) :

$$P_b = \frac{2}{3} E_b / V_b = \frac{E_b}{2\pi R_b^3}$$

pressure of the expanding bubble

$$P_{IGM} \propto T_{IGM} (1+z)^3$$

equilibrium with the IGM

$$R_s \propto \left(\frac{\varepsilon E_w}{T_{IGM}} \right)^{1/3} (1+z)^{-1}$$

stall radius

2. Assume

$$B_b \propto \rho^{2/3}$$

random magnetic field

$$E_w$$

mechanical energy injected by supernovae and stellar winds
Stel. Pop. Synthesis Code Starburst 99 (Leitherer 1999, Vazquez & Leitherer 2005)
- star-forming mass, Geneva tracks, Z=0.004, Salpeter IMF, $E_b = \varepsilon E_w \cong 0.01\, E_w$

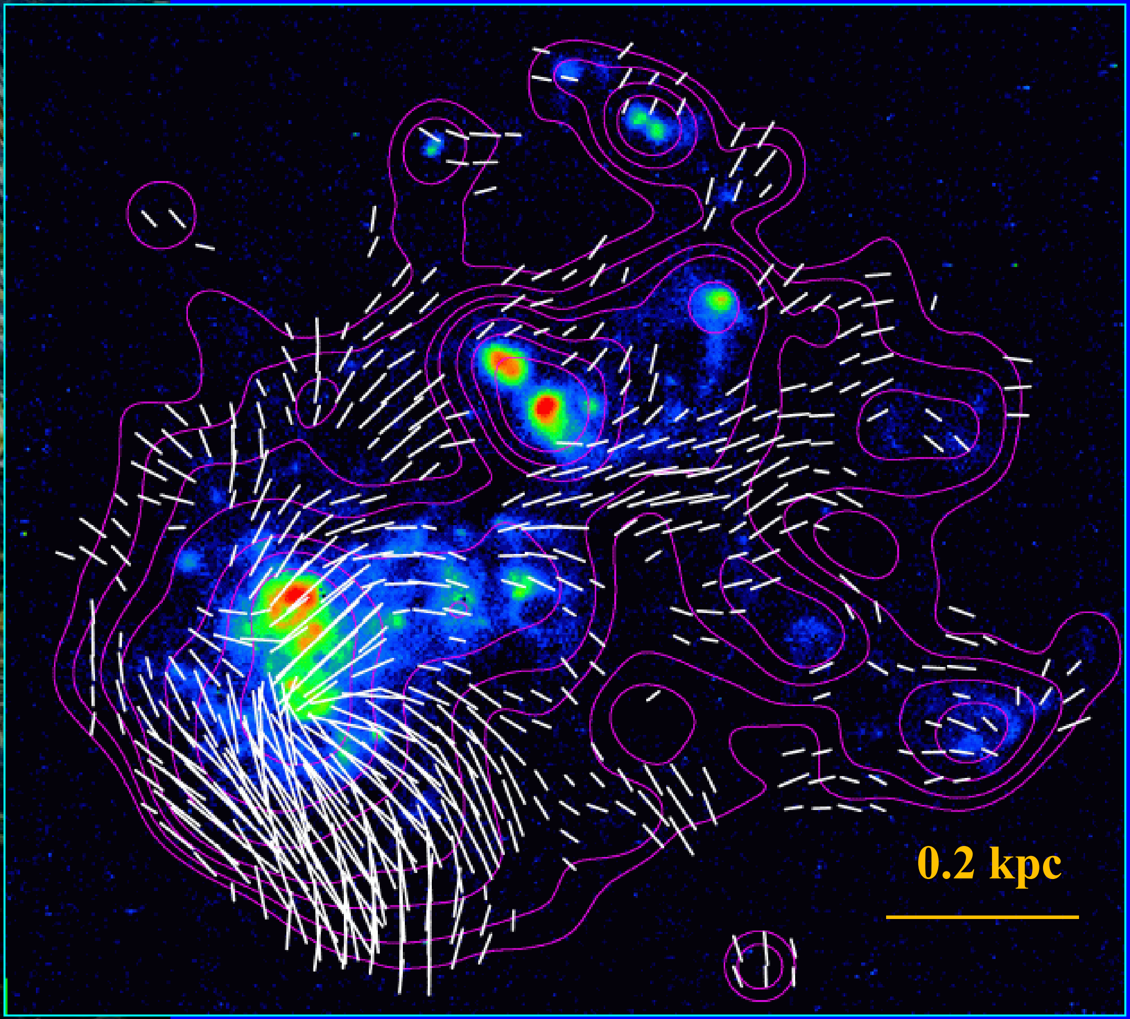
Could dIrrs magnetise the Universe?

Type	Pri dSph	Pri dIrr	LBG	LBG
	instantaneous star formation			
SF Mass	1.0e6	1.0e7	1.0e8	1.0e9
Redshift z	8	7	5	3
Wind energy E_b [erg]	2.0e55	2.0e56	2.0e57	2.0e58
SF size R_0 [kpc]	0.5	1.0	2.0	3.0
Stall radius R_s [kpc]	15	36	103	333
B_0 [G]	1.0e-7	1.0e-6	1.0e-5	5.0e-5
B_s [G]	1.1e-10	7.8e-10	3.8e-9	4.1e-9
Type	Local Group dIrrs continuous SF			
SFR	0.00001	0.0003	0.01	0.1
Redshift z	0	0	0	0
Wind energy E_b [erg]	3.0e50	1.5e52	3.0e53	3.0e54
SF size R_0 [kpc]	0.05	0.2	0.4	0.7
Stall radius R_s [kpc]	0.2	0.9	2.3	5.0
B_0 [G]	5.0e-7	1.0e-6	3.0e-6	8.0e-6
B_s [G]	2.3e-8	5.5e-8	8.8e-8	1.5e-7

- LBG – Verma et al. 2007, Samui 2008
- Pri dSph – Strigari 2008, Ricotti 2010
- Massive (LBG) galaxies can efficiently magnetise the IGM
- Typical LG dIrrs could magnetise the local space

Chyży et al. 2011

How far do magnetic fields extend out of local dwarfs ?



IC10

10x less massive than NGC 4449

No spiral arms, probably infalling HI gas from SE

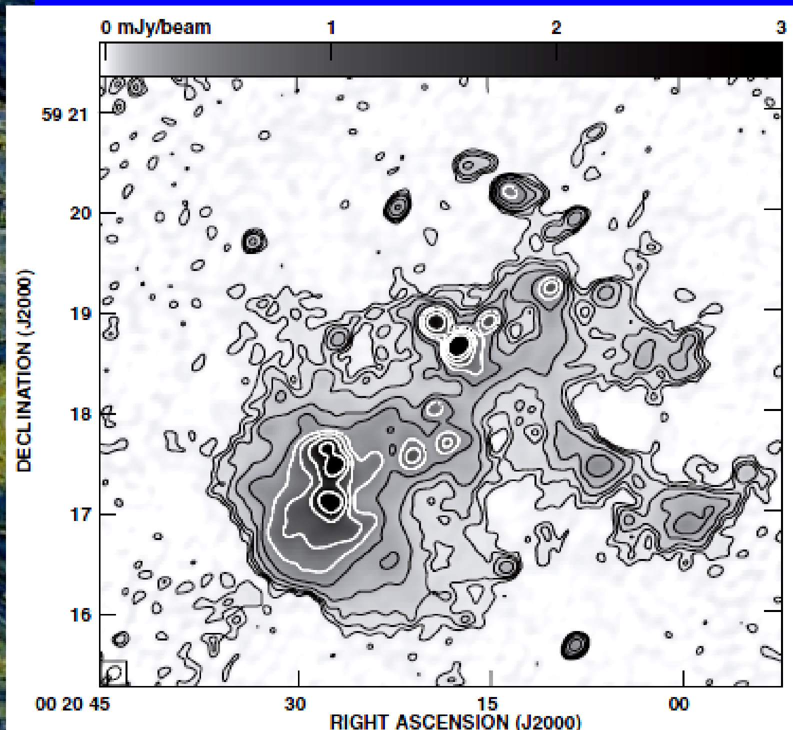
Local equivalent of BCG

B_{tot}~10μG

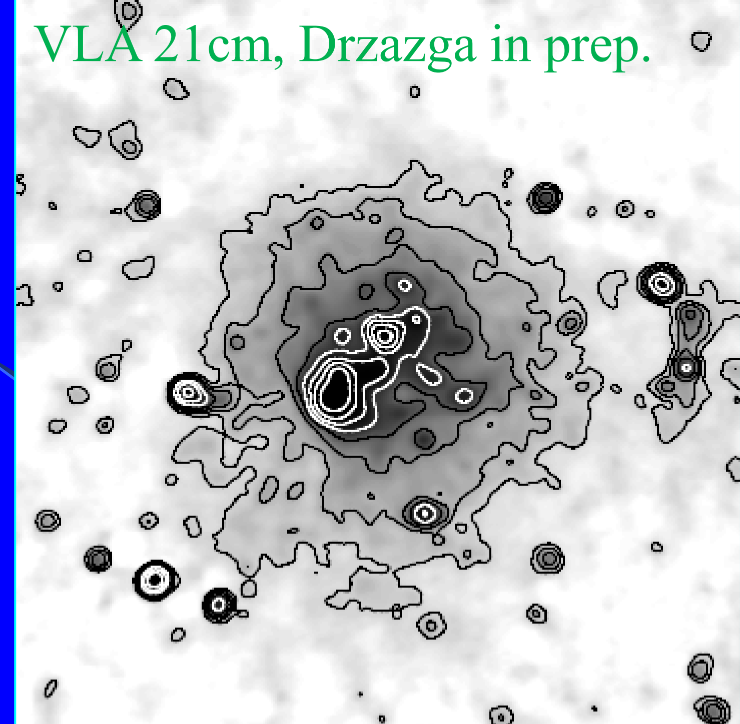
Only small-scale dynamo

VLA 4.6 GHz + Halpha, Chyży et al. 2005

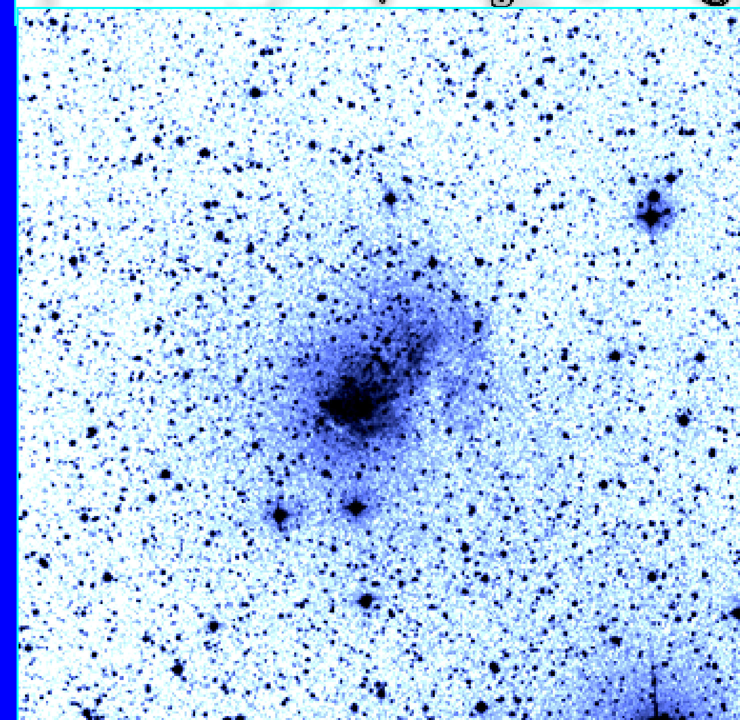
Synchrotron envelopes IC10 – VLA observations



6cm, EVLA, Heesen et al. 2012



VLA 21cm, Drzazga in prep.



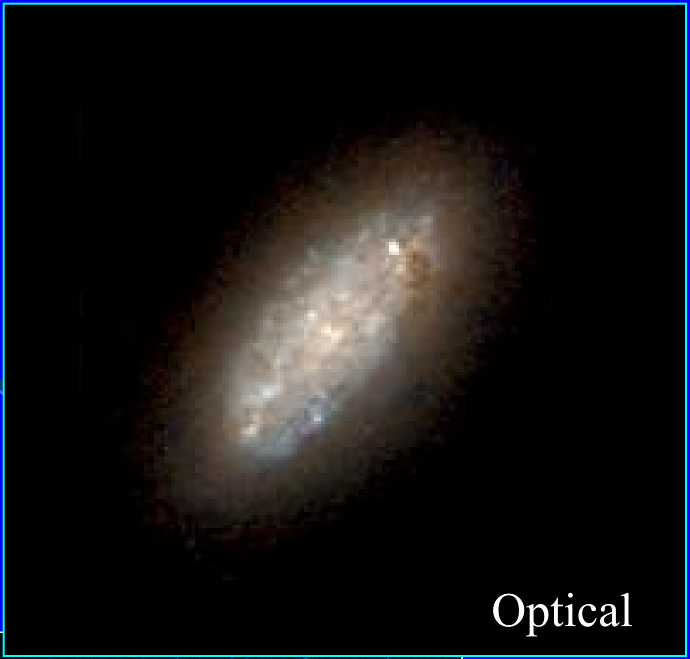
Can LOFAR or WSRT detect larger synchrotron envelope at lower frequencies?

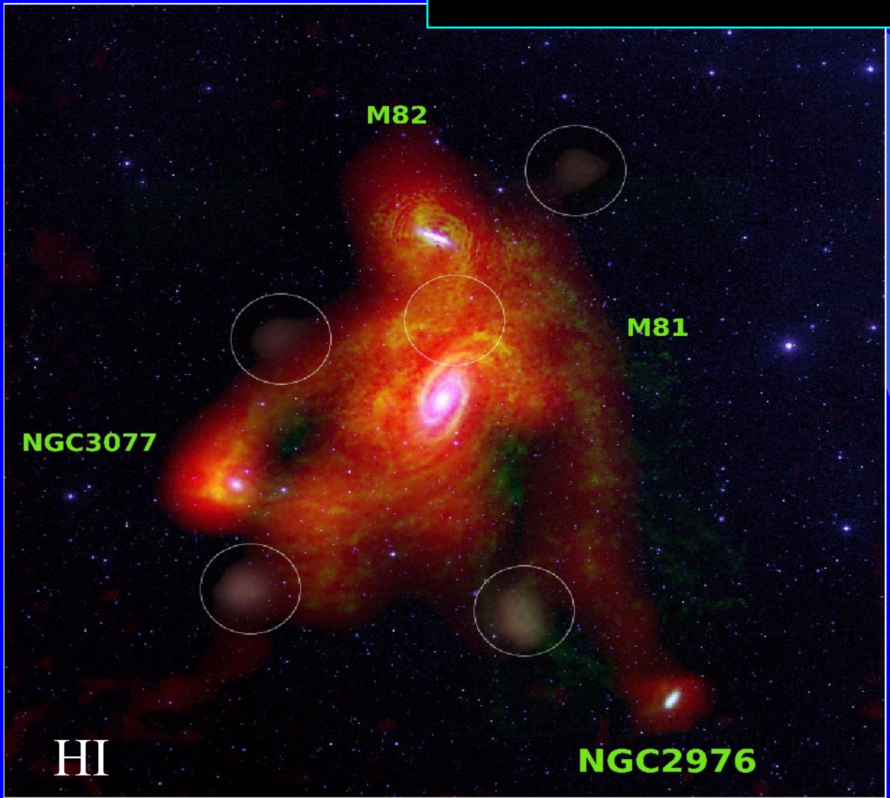
K. Chyży
Göttingen
12.10.2012

NGC 2976

- Dynamically simple, bulgeless pure-disk object (Simon et al. 2003)
- Disk - 6kpc
- Low HI mass (1.5 10^8 Ms)
- In the periphery of M81/M82 group

Below large-scale dynamo threshold?

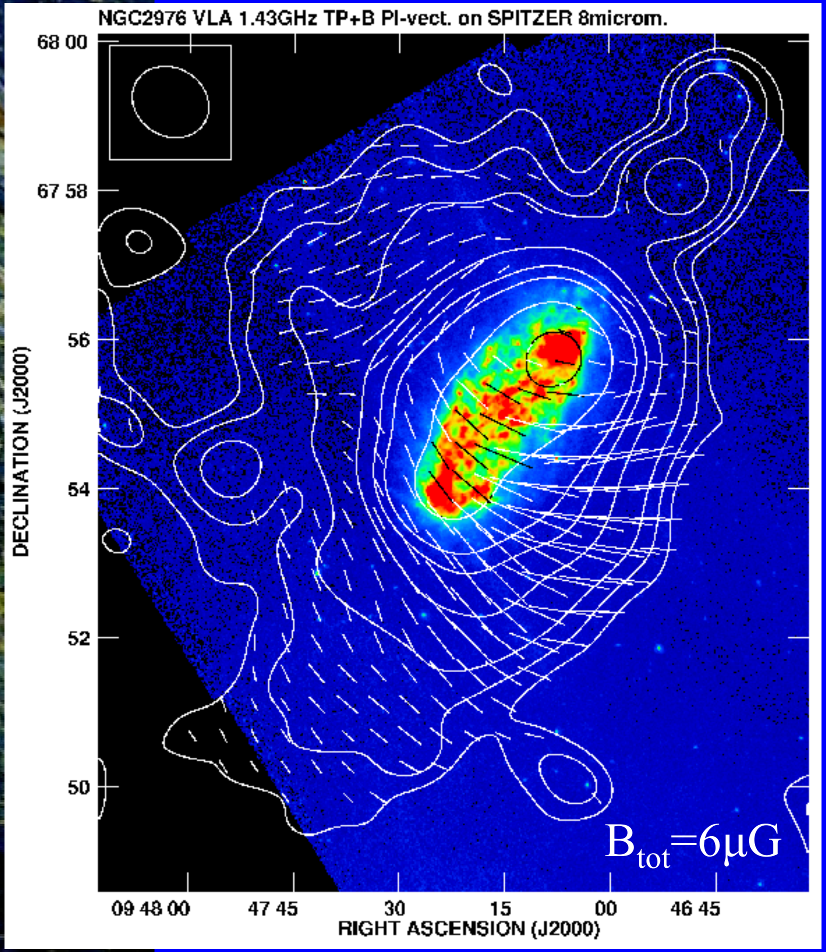




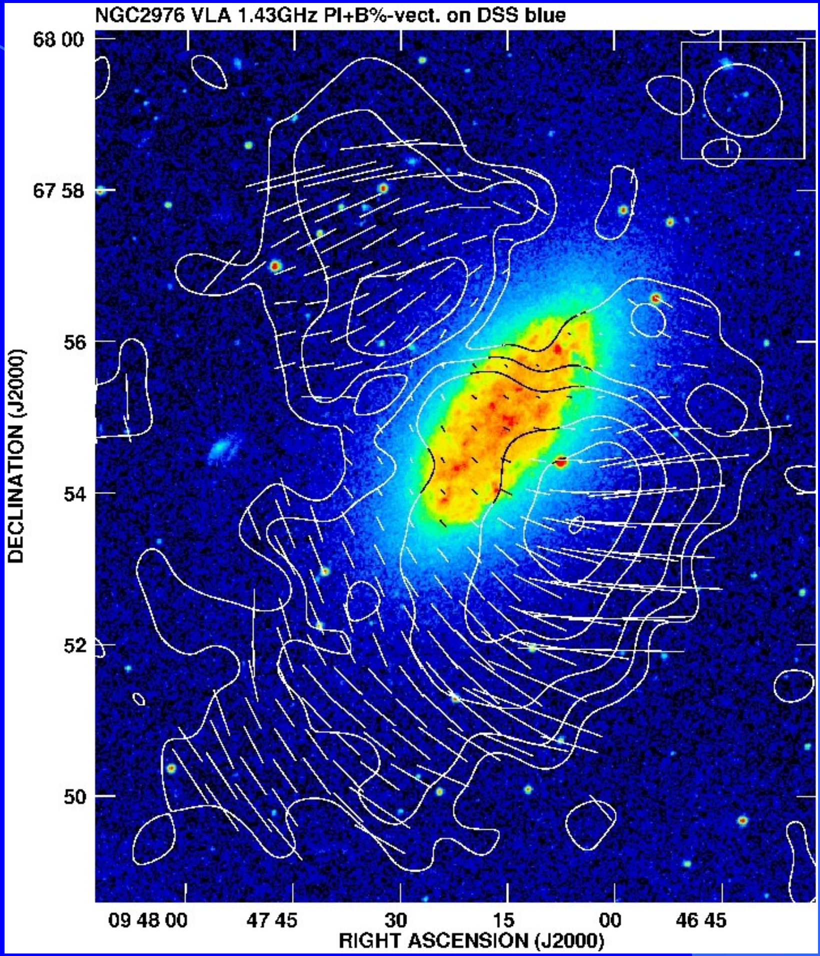
Chynoweth 2008

M81/M82 group magnetizer?

VLA 1.43 GHz TP



VLA 1.43 GHz PI



Drzazga et al. in prep.

Magnetic fields are escaping into IGM, far away from the group centre

Interacting galaxies

K. Chyży
Göttingen
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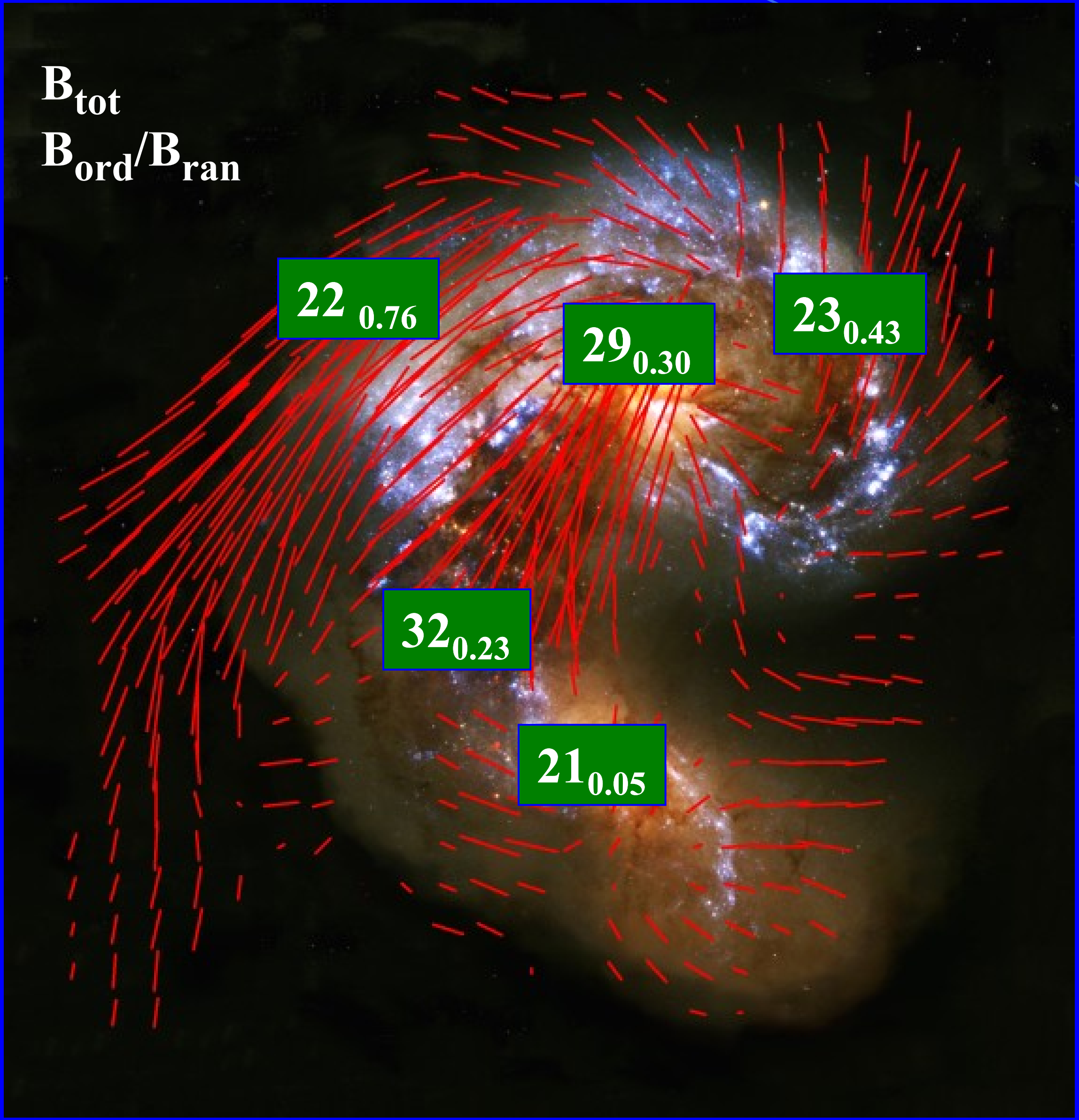
Interacting galaxies – the Antennae

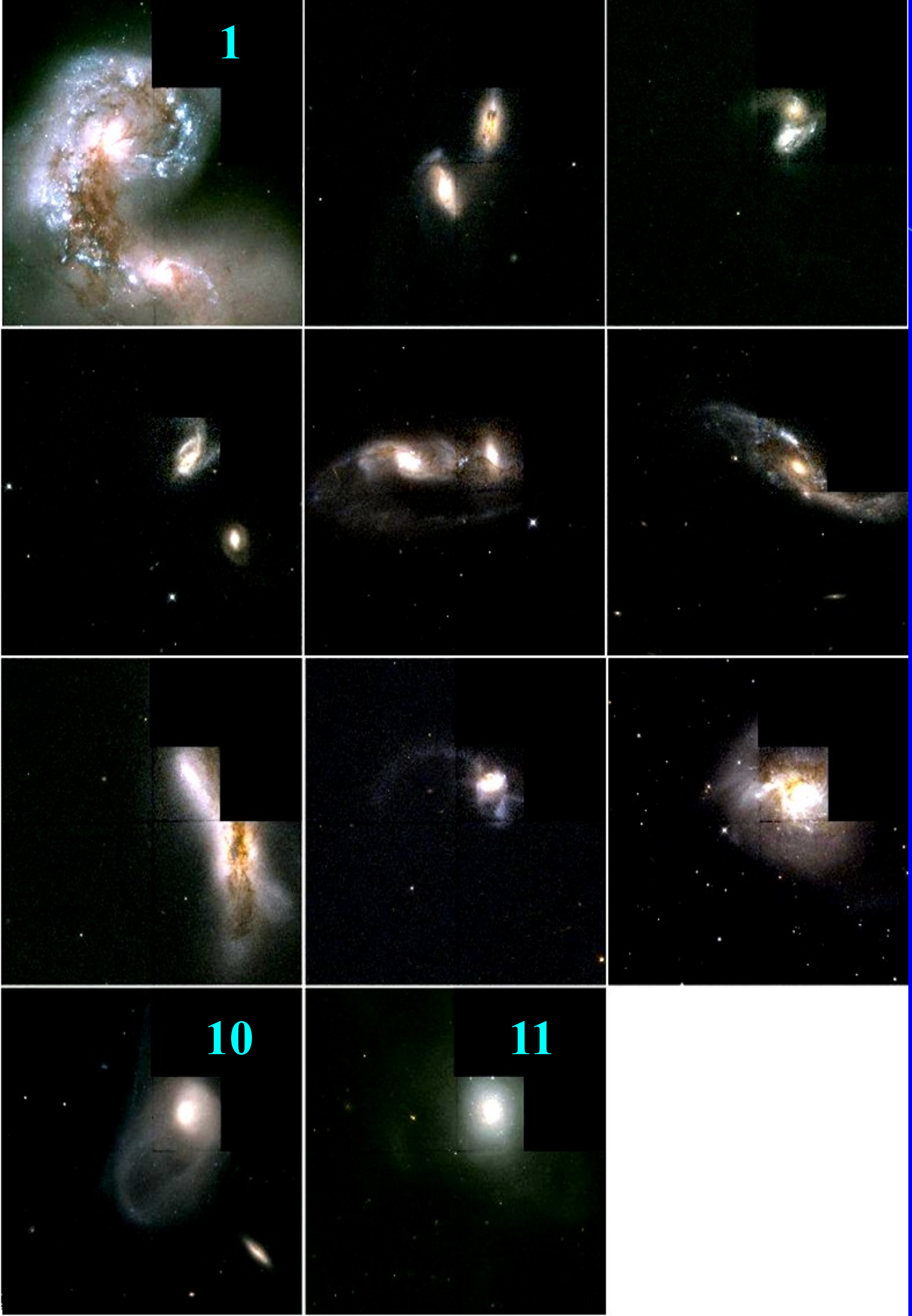


VLA 4.86 GHz, 17”x14” + HST, Chyży & Beck 2004

So far magnetic fields were fully studied only in one merging system (the Antennae)

MF is highly coherent in NE ridge with a strong ordered component of 10 μG tracing gas shearing motions along the tidal tail

MF 2x stronger than in normal spirals but of less regularity.



The Toomre sequence (Toomre 1977)

11 pairs of interacting galaxies arranged from early to late stages of merging.

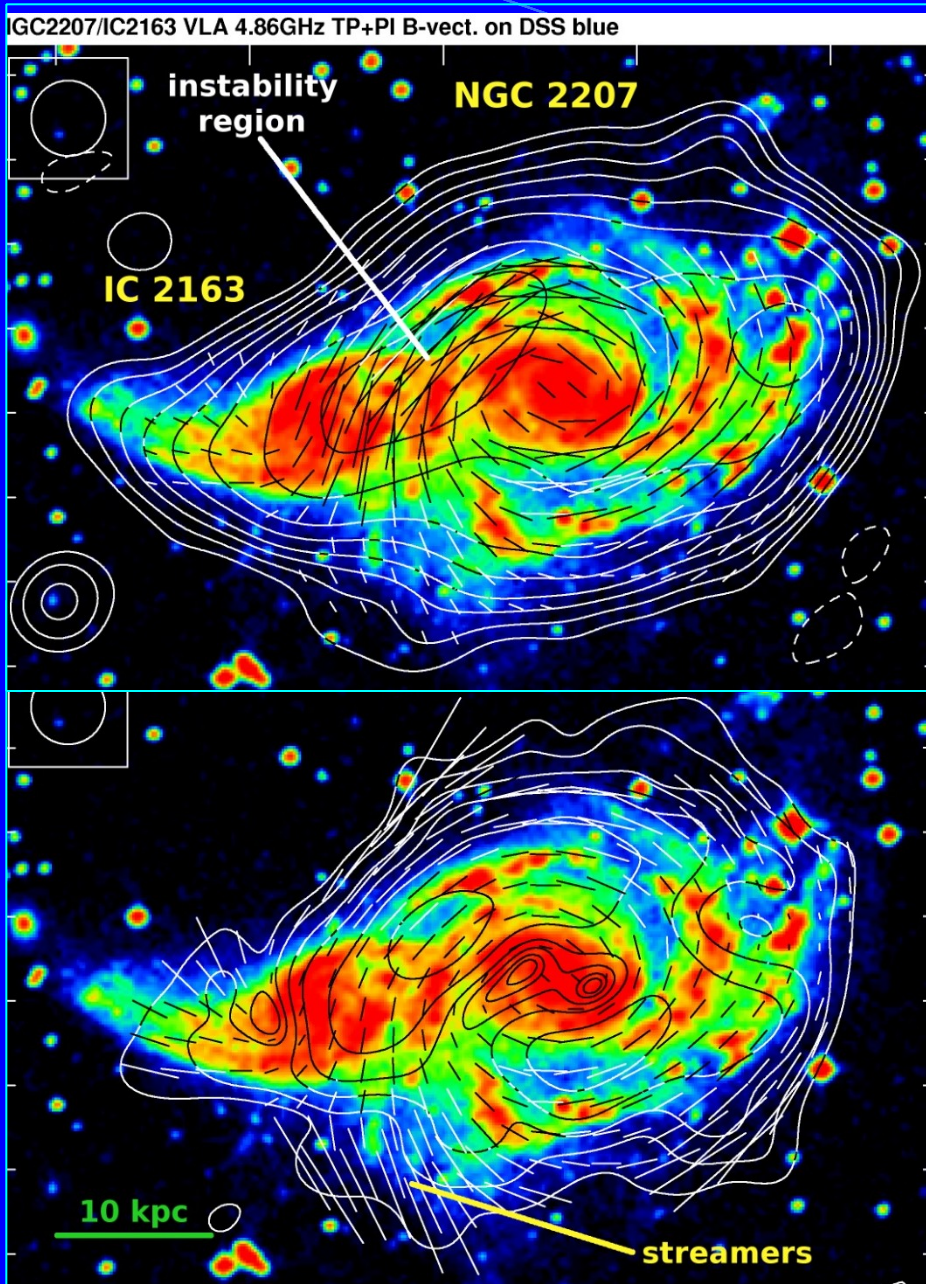
For each pair a number is assigned from 1 to 11 (Interaction Stage, IS)

1 - after 1st encounter
10 - nuclear coalescence
11 - merger remnant.

Extension : Brassington et al. 2007 + object available from VLA archive . In total 24 galaxies (16 interacting systems)

Drzazga, Chyży, Jurusik , Wiórkiewicz 2011

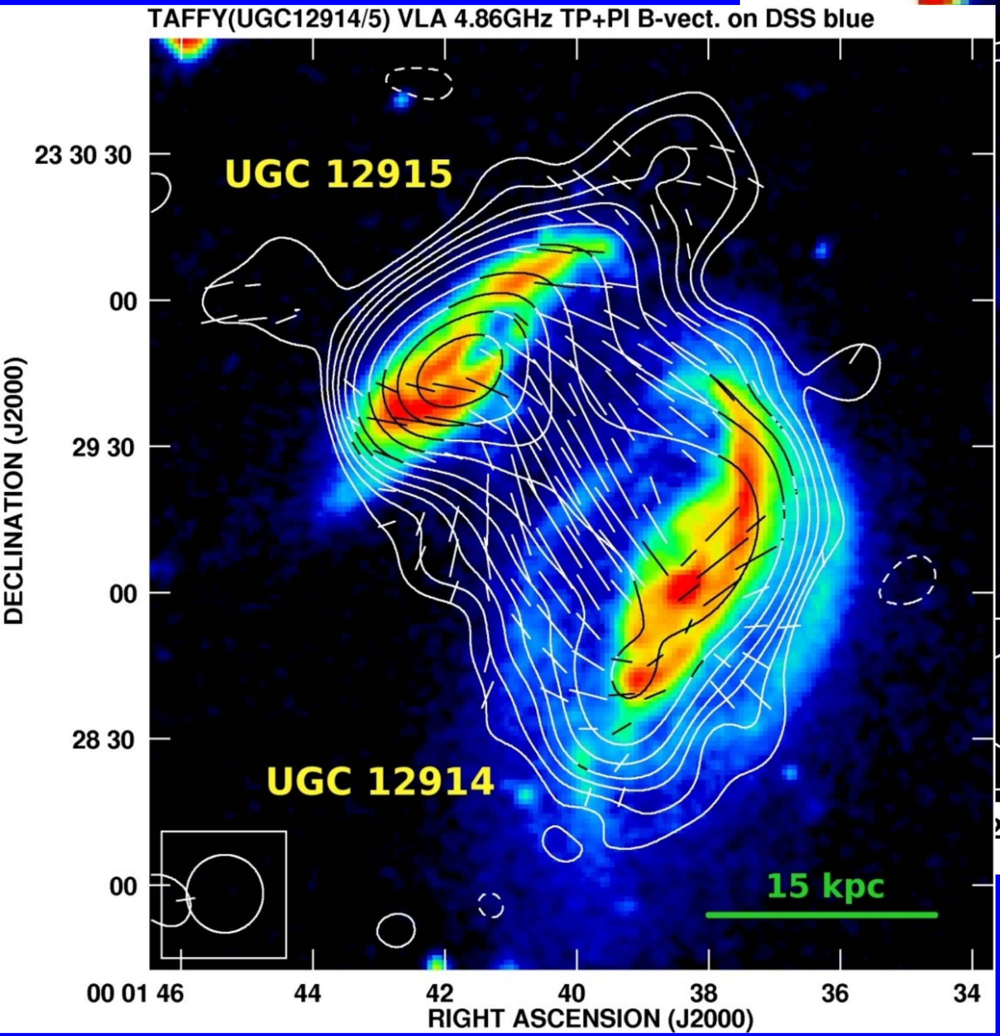
NGC2207/IC2163 – mysterious radio structure

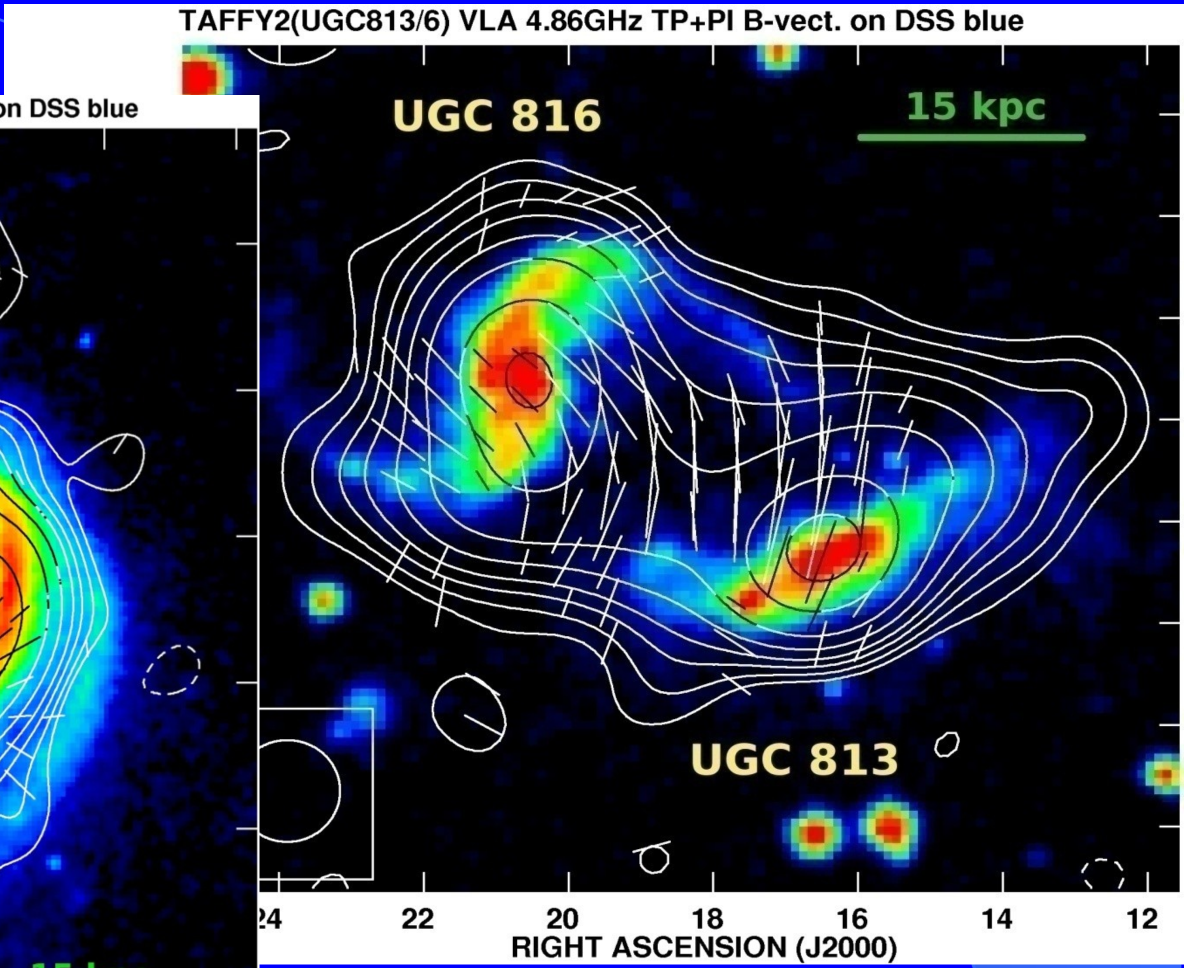


- Magnetic fields have a spiral structure, only weakly perturbed B_{tot} =16μG, B_{ord} =6μG
- In the southern part of NGC2207 and in the eastern part of IC 2163 magnetic fields are probably tidally stretched
- In the NE of NGC2207 total power and polarized intensity are brighter - Elmegreen et al. (1995) - compression of magnetic field and/or supply of CR from IC 2163.

The Taffy and The Taffy2

In the bridge: B_{tot} =16μG, B_{ord} =10μG

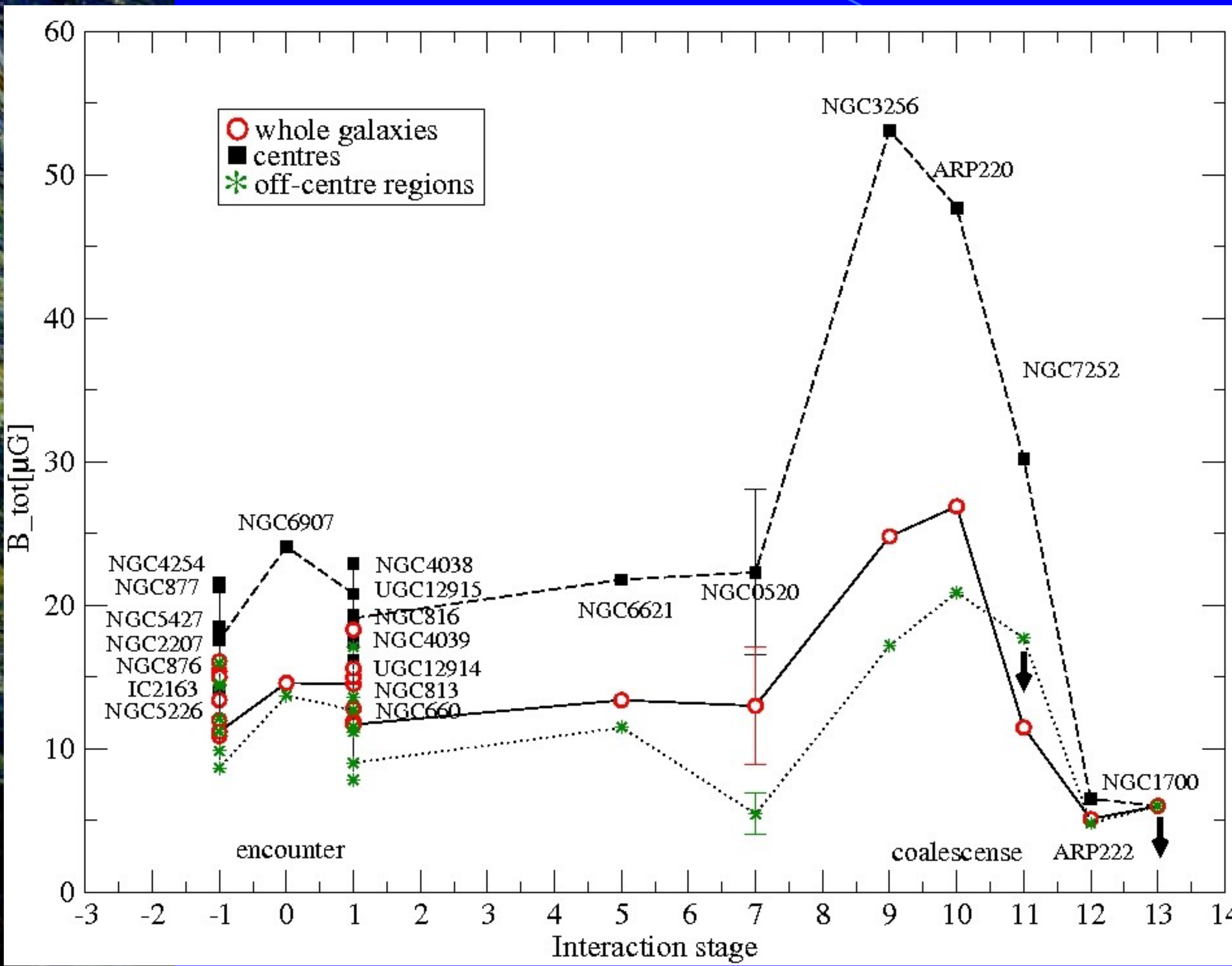




Nearly head-on collision occurred about 10^7 years ago in the Taffy and $5x10^7$ years ago in the Taffy2

- Radio bridges discovered by Condon et al. 2002
- Star forming regions have similar ages! Schmidt-Kennicutt relation without dispersion (Komugi et al. 2012)

Evolution of magnetic fields in interacting galaxies



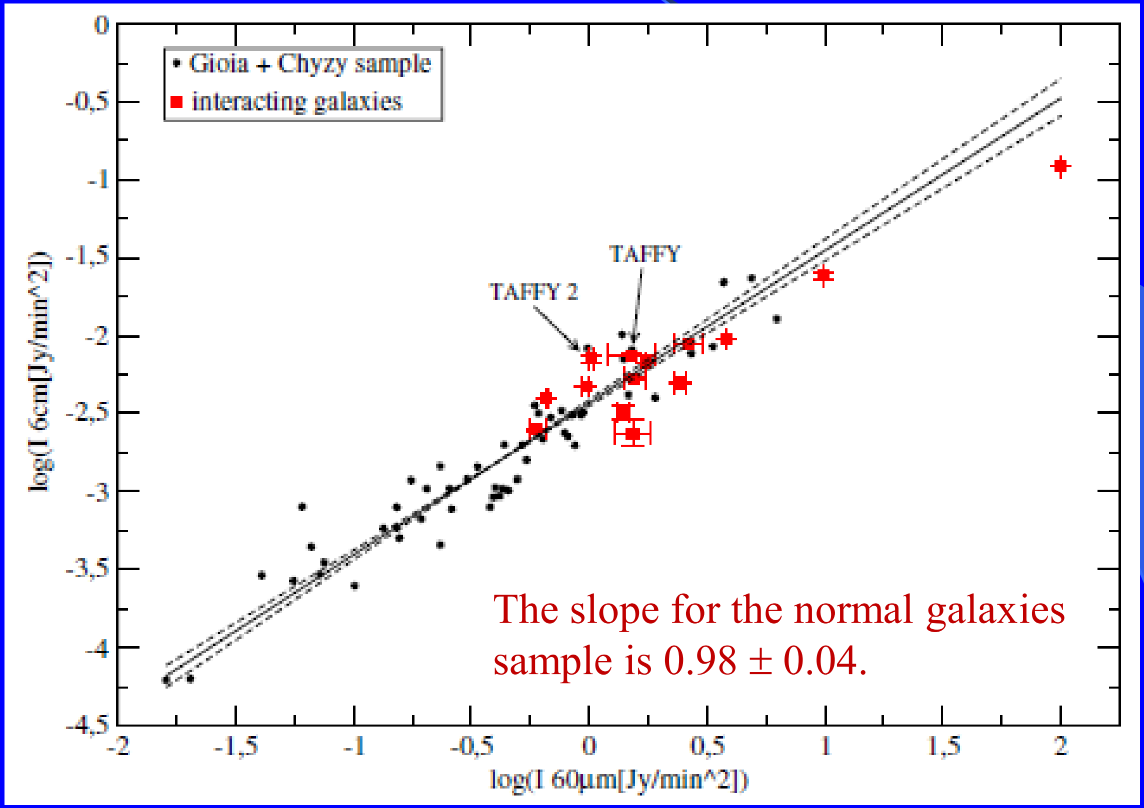
Major enhancement of SF and magnetic energy occurs at the stage of nuclear coalescence.

After that the process of generation of magnetic fields is terminated.

Agreement with the evolution of the SFE (Georgakakis et al. 2000)

The strongest evolution is observed for nuclear regions

Radio (6cm) – FIR(60μm) for interacting galaxies



K. Chyży
Göttingen
12.10.2012

MF around mergers

B-random			B-regular	
L_{BC} kpc	L_B kpc	B_{ran} μG	L_B kpc	B_{reg} μG
galactic disk				
0.05	10	15	3	10
$\delta = 3.4°$			$\delta = 16°$	
bridge, tidal tail				
0.1	10	15	5	10
$\delta = 4.9°$			$\delta = 23°$	
merger's halo				
2	200	0.1	200	0.01
$\delta = 0.7°$			$\delta = 1.0°$	

Mergers can be considered as sources of deflecting UHECRs. We use approach of Neronov & Semikoz (2009).

The largest deflection angle δ due to magnetic fields related to interacting objects is ~23 degrees.

In high-z Universe merging galaxies could efficiently spread out magnetic fields and magnetize the merger ssurroundings (likely up to about 100 kpc), exerting a similar impact as supernova explosions and galactic winds of M82 analogues.

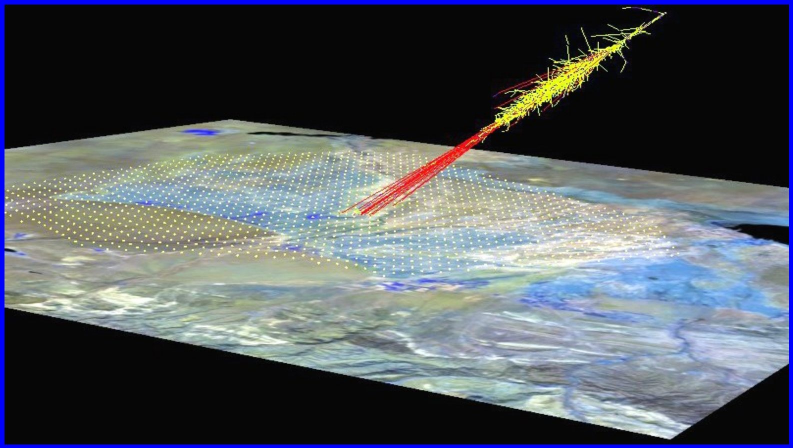


Photo by Cosmus at Univ. of Chicago: R. Landsberg, D. Surendran, and M. SubbaRao

Conclusions

Some dwarfs

- Show very strong and even spiral B (NGC 4449, NGV1569)
- Some dIrrs have strong and coherent fields – large-scale dynamo (NGC 4449, LMC)

Unbiased sample of LG Dwarfs

- Typical dwarf galaxies show **weak** magnetic fields ($\leq 4\mu$G), without spiral patterns, turbulent dynamo, similar B-ΣSFR correlation as for NGC4254 and NGC6946, follow radio-FIR correlation
- B scales with metallicity

Magnetisation

- IC10 - dwarf with a large synchrotron envelope (also NGC 1569). NGC2976 - magnetised outflows at the periphery of M81/M82 group. LOFAR - what is the full extent of synchrotron halos around dwarf galaxies? Are they consistent with modelling?

Evolution in interacting systems

- B evolve in merging galaxies: 3x stronger fields in the stage of nuclear coalescence.
- B correlates with SFR, radio-FIR valid in large scales.
- Tidal interactions can fill IGM with magnetic fields but of small volume filling factor. UHERCs - deflected up to 23°