Probing the evolution of magnetic fields in young galaxies

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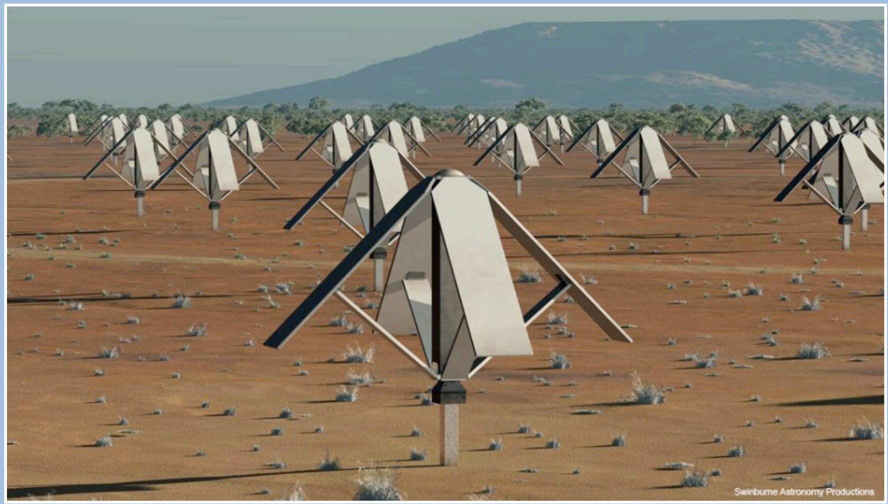
Square Kilometre Array (SKA)

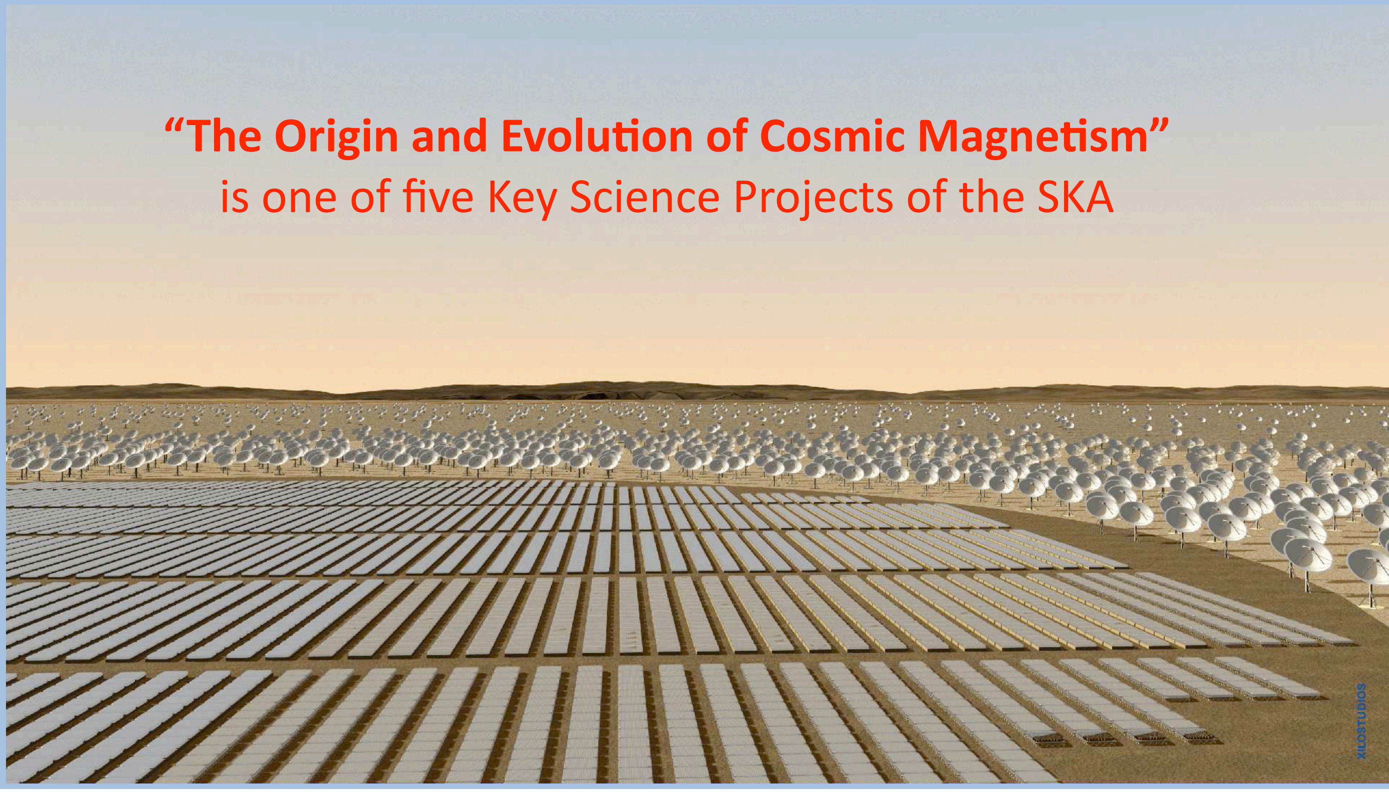


Three array concepts:

- Low (70 - 450 MHz)
- Mid (500 - 1000 MHz)
- High (450 - 3000 MHz)

Square Kilometre Array (SKA)

- Collecting area of 1 km^2
- Frequency range (700 MHz – 25 GHz)
- Angular resolution of 0.02 arcsec at 1.4 GHz
- Field of view of 20 sq. deg. --> incredible survey capability
- Operations start in around 2016



Cosmic magnetism with the Square Kilometre Array (SKA)

SKA polarisation pathfinders

- The Galactic Arecibo L-Band Feed Array Continuum Transit Survey (GALFACTS)
- The Low Frequency Array (LOFAR)
- The Allen Telescope Array (ATA)
- The Square Kilometre Array Molonglo Prototype (SKAMP)
- The Murchison Widefield Array (MWA)
- The Expanded Very Large Array (EVLA)
- The Karoo Array Telescope (MeerKAT)
- The Australian SKA Pathfinder (ASKAP)

New polarimetric experiments and Faraday rotation surveys

Outline

- Models for the evolution of magnetic fields in star-forming (SF) galaxies

- Tools to test the magnetic field evolution in distant SF galaxies:
    - FIR-Radio correlation
    - Polarimetry of unresoved galaxies
    - Faraday rotation towards background polarized quasars

Evolution of magnetic fields in SF galaxies

- Magnetic fields (turbulent and regular) in local SF galaxies.

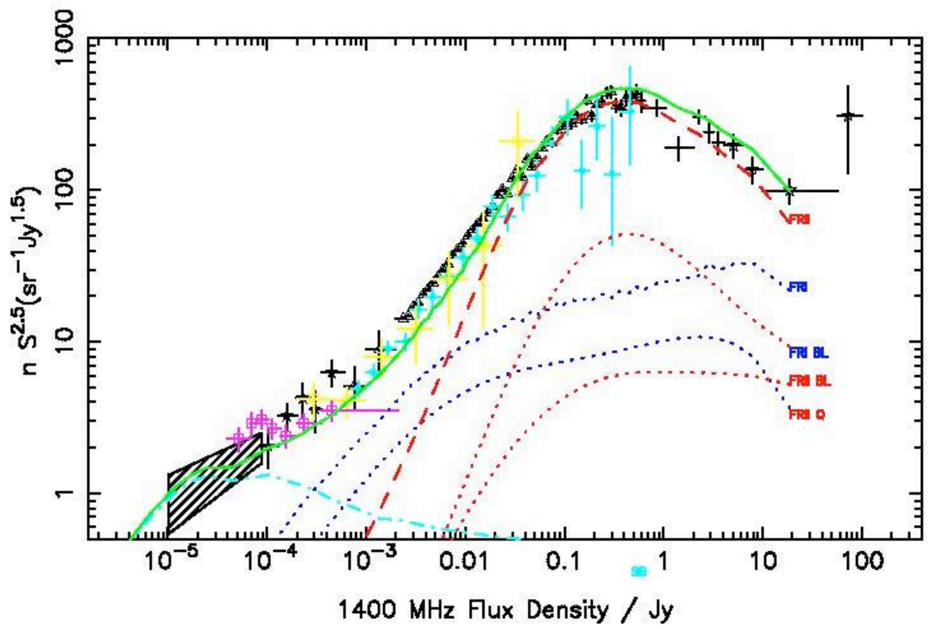
- Physical mechanism for the field amplification.

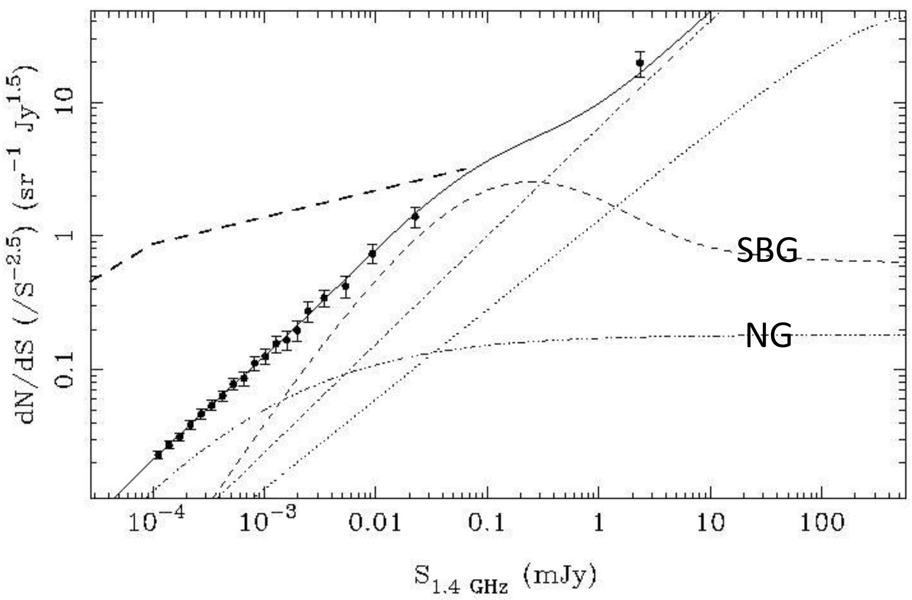
- Models of cosmological evolution of magnetic fields:

  - "Primordial" weak regular fields maintained by dynamo
  - Weak random (turbulent) seed fields amplified by dynamo

Why the population of SF galaxies is important ?

- "Normal" (NG) and starburst galaxies (SBG) will be the **main population of galaxies observed at 1.4 GHz with SKA** at flux densities <0.1 mJy (*Jackson 2004; Hopkins 2000*).





Motivations to study the evolution of magnetic fields in SF galaxies

- Magnetic fields can be studied via *synchrotron emission* (strength), *linear polarization* (ordering), *Faraday rotation* (weak fields and ordering).
- SKA: Radio-IR correlation – tracer of the SF and turbulent field.
- Magnetic fields origin at early cosmological epochs ($z>40$).
- Coupled with formation and evolution of galaxies (fundamental problem).

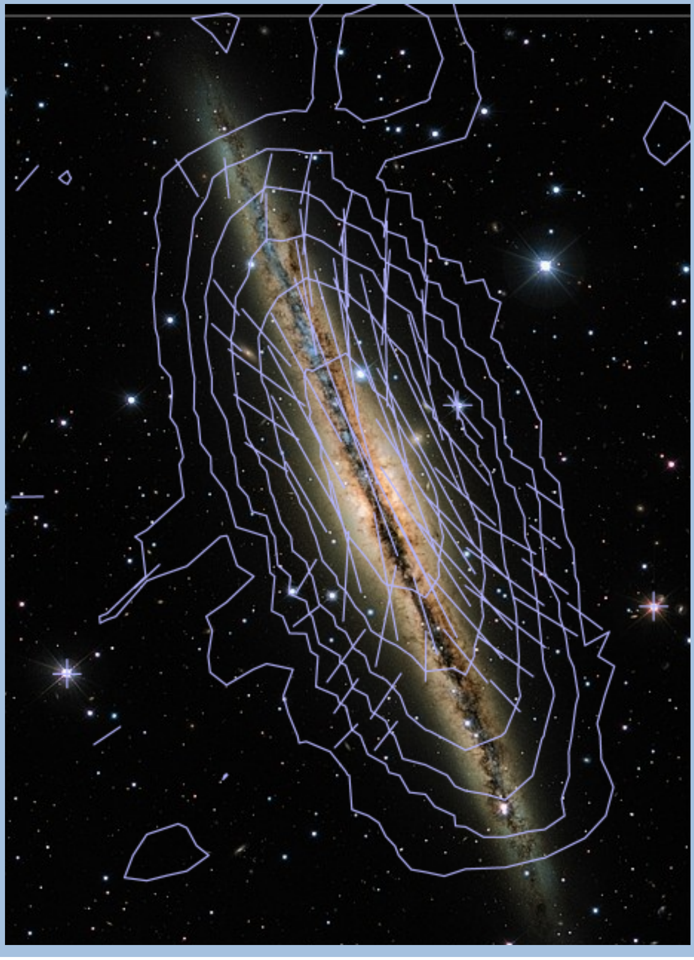
What we know about evolution of magnetic fields in galaxies?

- Very little from *polarization observations* of nearby galaxies.
- Strong magnetic fields are present in high redshift galaxies – from *Faraday Rotation* of background sources (Kronberg et al. 2008; Bernet et al. 2008).

Regular fields in the disk and halo

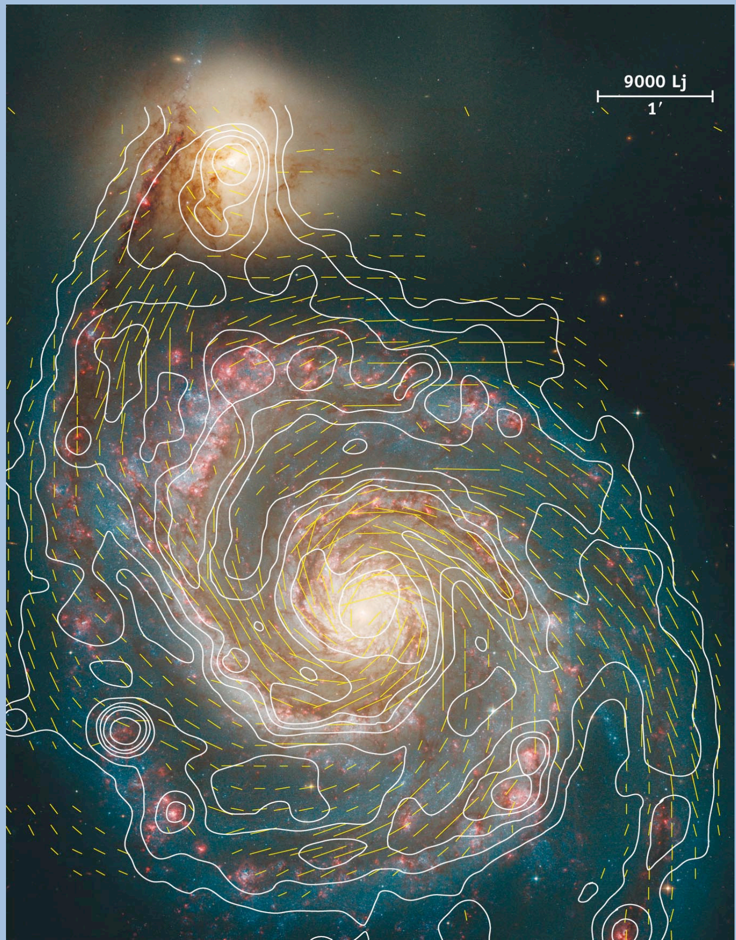
NGC 891 (Krause 2009)

M 51 VLA+Eff 6cm total
Intensity + B-vectors
(Fletcher & Beck)



X-shaped magnetic fields in the halo

Spiral fields along and between the optical spiral arms



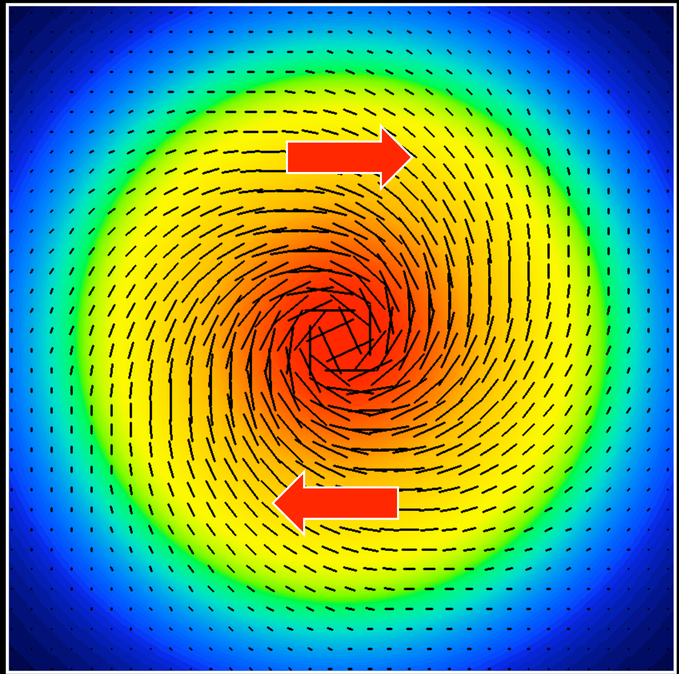
Magnetic properties of nearby galaxies

- Total field: ~15 μG
- Regular field: ~ 5 μG
- Turbulent field: ~13 μG
- Pitch angle: ~20 deg.
- B-field: axisymmetric
- Coherence: size of a galaxy

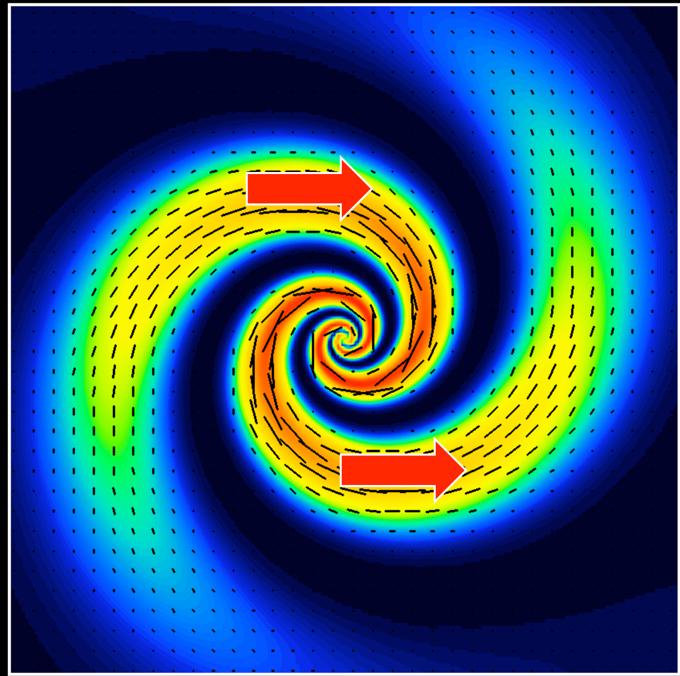
Classical "mean-field" dynamo

- Initial seed field
- Separation of large and small scales
- Ingredients:
  Ionized gas + differential rotation + turbulence
- Dynamo equation for the large-scale regular ("mean") field
- Solutions: large-scale modes

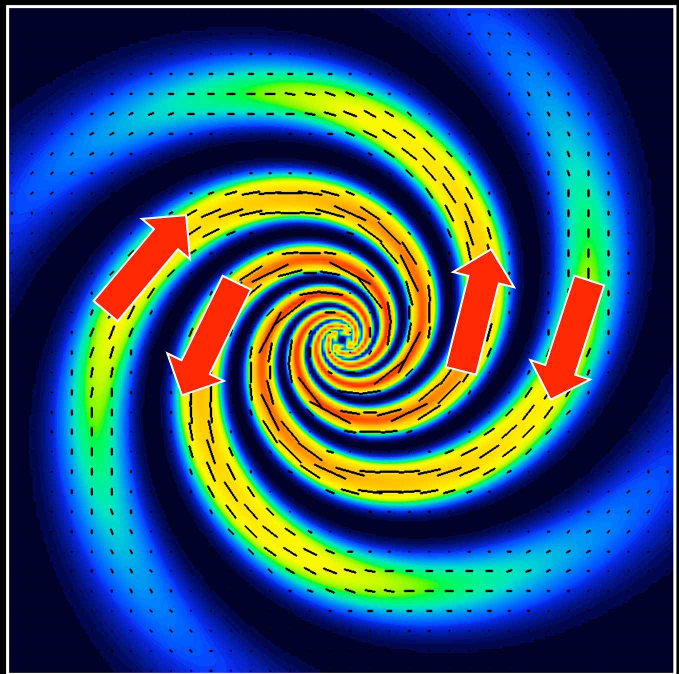
Dynamo Mode 0 (Axisymmetric Spiral)



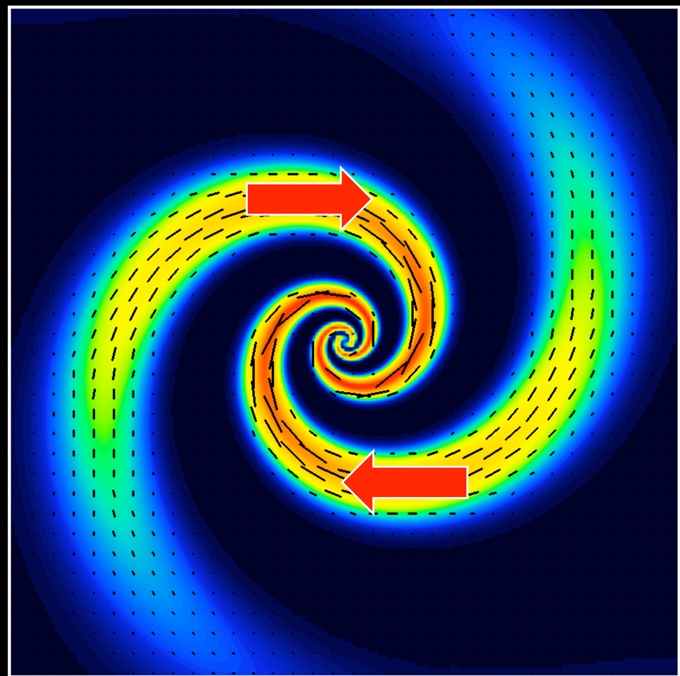
Dynamo Mode 1 (Bisymmetric Spiral)



Dynamo Mode 2 (Quadrisymmetric Spiral)

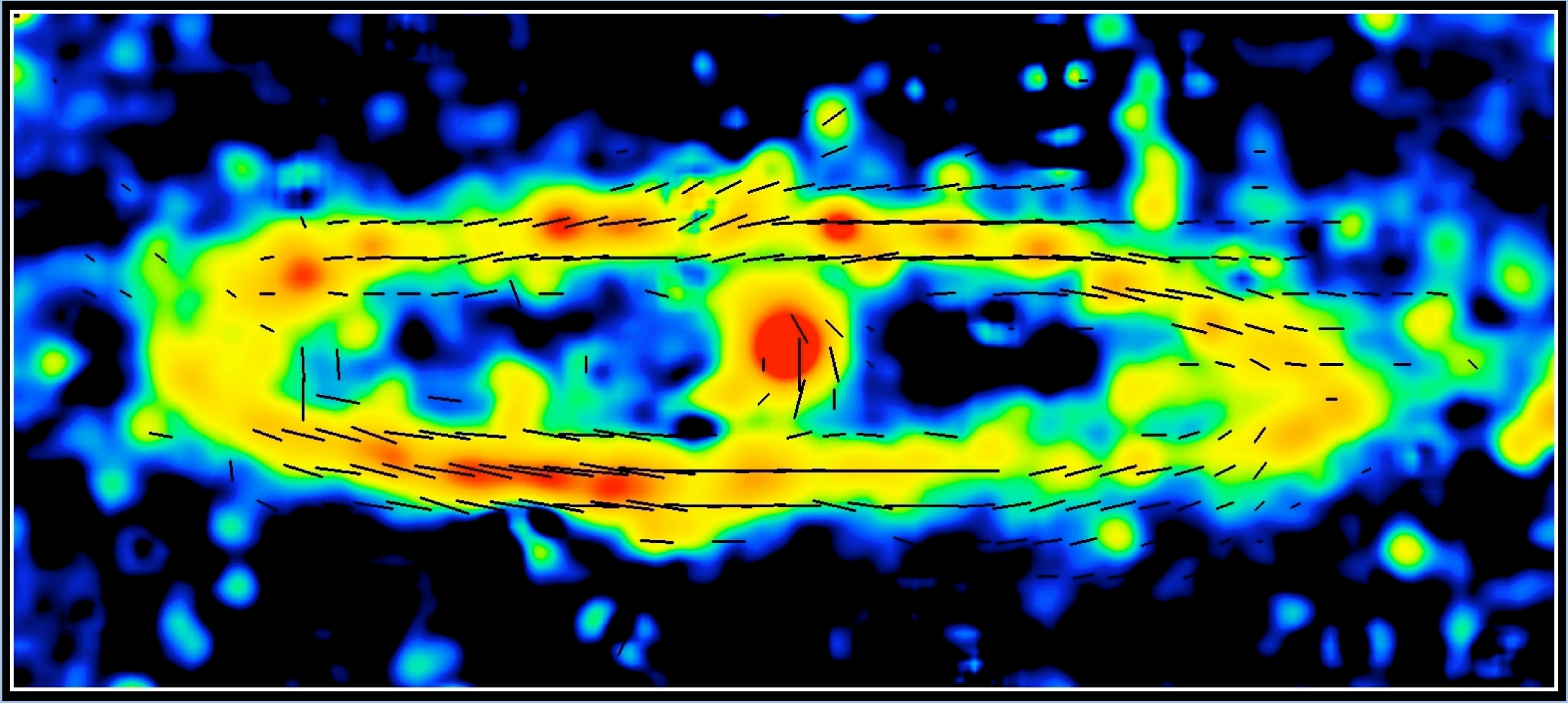


Dynamo Modes 0 + 2



M 31: The classical dynamo case

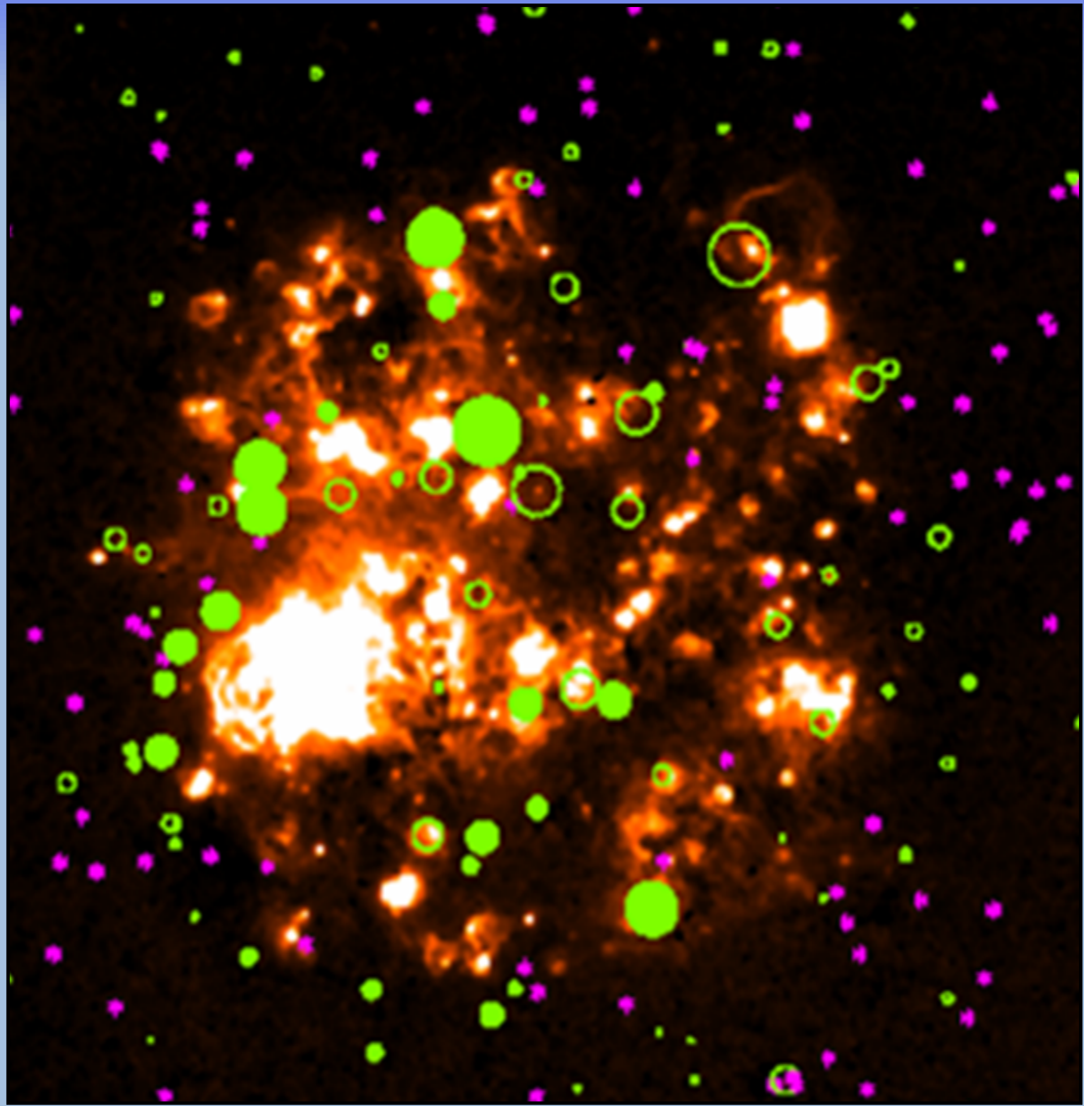
Fletcher et al. 2004



Large-scale Faraday RM pattern of the diffuse emission:
Axisymmetric (ASS) azimuthal mode

LMC

RM 20-22cm
ATCA
(Gaensler et al. 2005)



Large-scale Faraday RM pattern of polarized background sources:

Axisymmetric field with small pitch angle

Evidences for dynamo action

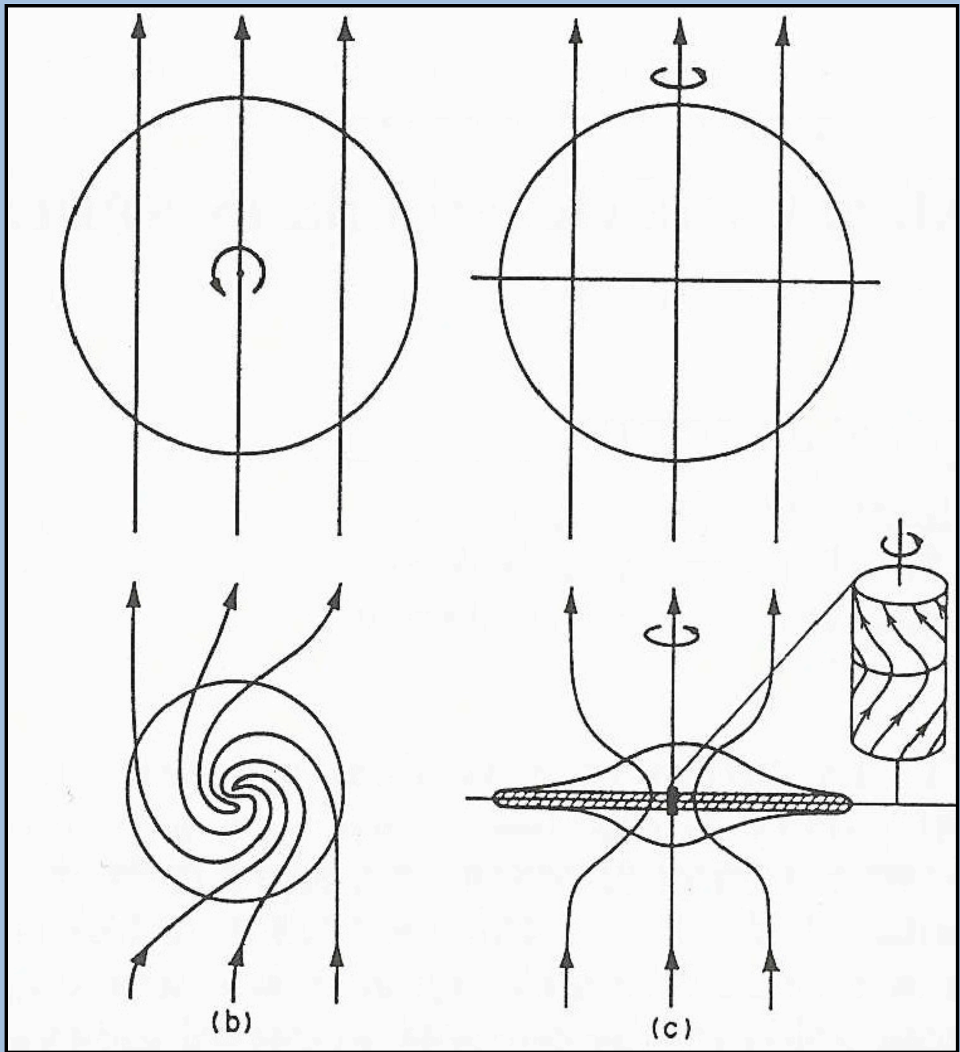
- Spiral field patterns exist in most galaxy disks
- Pitch angles are as large as predicted
- Faraday rotation reveals large-scale regular fields with a dominant azimuthal mode or a superposition of modes

The dynamo model successfully explains the basic properties of large-scale magnetic fields in present day galaxies

"Primordial" models

Disk field

Vertical field



Sofue 1990

Generation of large-scale fields (bisymmetric or dipolar only), but hard to maintain

Amplification by dynamo

Coherence length of a regular field is of the size of a galaxy

Evolution of magnetic fields is coupled to the formation and evolution of galaxies

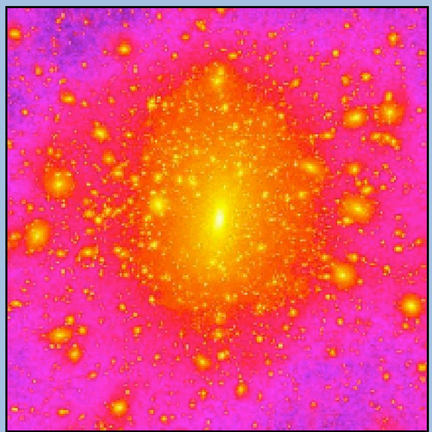
Formation of galaxies

Three main cosmological phases in simulations of hierarchical galaxy formation (Cold Dark Matter):

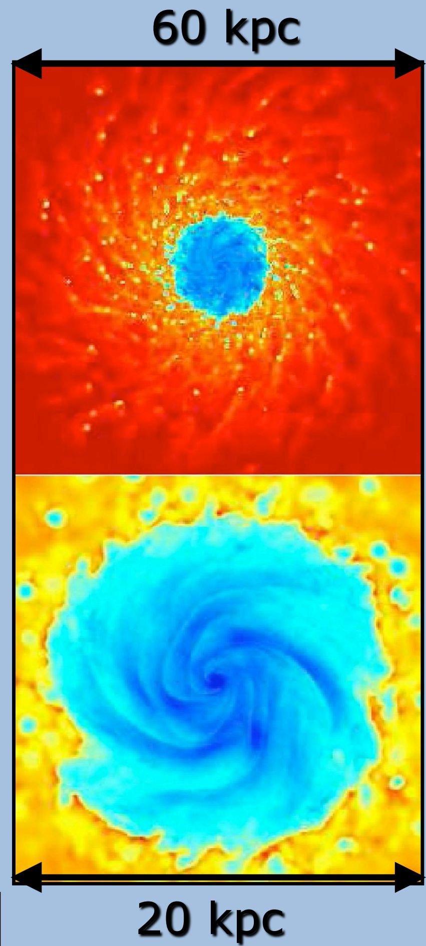
Phase 1 ($z \approx 40$-20): Formation of low-density dark halos with $M \approx 10^7\ M_{sun}$

Phase 2 ($z \approx 20$-10): Merging of sub-halos and thermal virialization (Wise & Abel 2007)

Phase 3 ($z \approx 10$-2): Formation of large-scale baryonic disks



Mayer & Governato 2008



Kaufmann et al. 2007

Evolution of magnetic fields

The evolution of magnetic fields is coupled to the evolution of galaxies

Phase 1 ($z \approx$ 40-20): Formation of halos

Generation of seed magnetic fields by the Biermann battery
in protogalactic clouds or by the
(counter-streaming) Weibel instability
in cosmological or protogalactic shocks

Amplitude: $\approx 10^{-18} - 10^{-6}$ (!) Gauss

Evolution of magnetic fields

Phase 2 ($z \approx 20$-10): Merging of halos and virialization:

Amplification of seed fields by the turbulent (small-scale) dynamo

Turbulence is driven by merging and thermal virialization of dark matter halos

Timescale of amplification: $\approx 3 \times 10^8$ yr

Amplitude: $\approx 10^{-5}$ Gauss

Evolution of magnetic fields

Phase 3 (z ≈ 10-2): Formation of large-scale disks:

Amplification of regular fields and ordering by the
"mean-field" (large-scale) dynamo

Turbulence is driven by SN explosions in the disk

Timescale of amplification:
disk galaxy ≈ 2 Gyr; dwarf galaxy ≈ 1 Gyr

Timescale of ordering:
disk galaxy ≈ 8 Gyr; dwarf galaxy ≈ 6 Gyr

Dynamo timescales

Arshakian et al. 2009

- Amplification of turbulent fields by small-scale dynamo:

$$t_{TD} = \frac{l}{v}$$

- Amplification of regular fields by mean-field dynamo (large-scale) in flat-disk galaxies (R/h>10):

$$t_{disk} = \frac{h}{\Omega l}$$

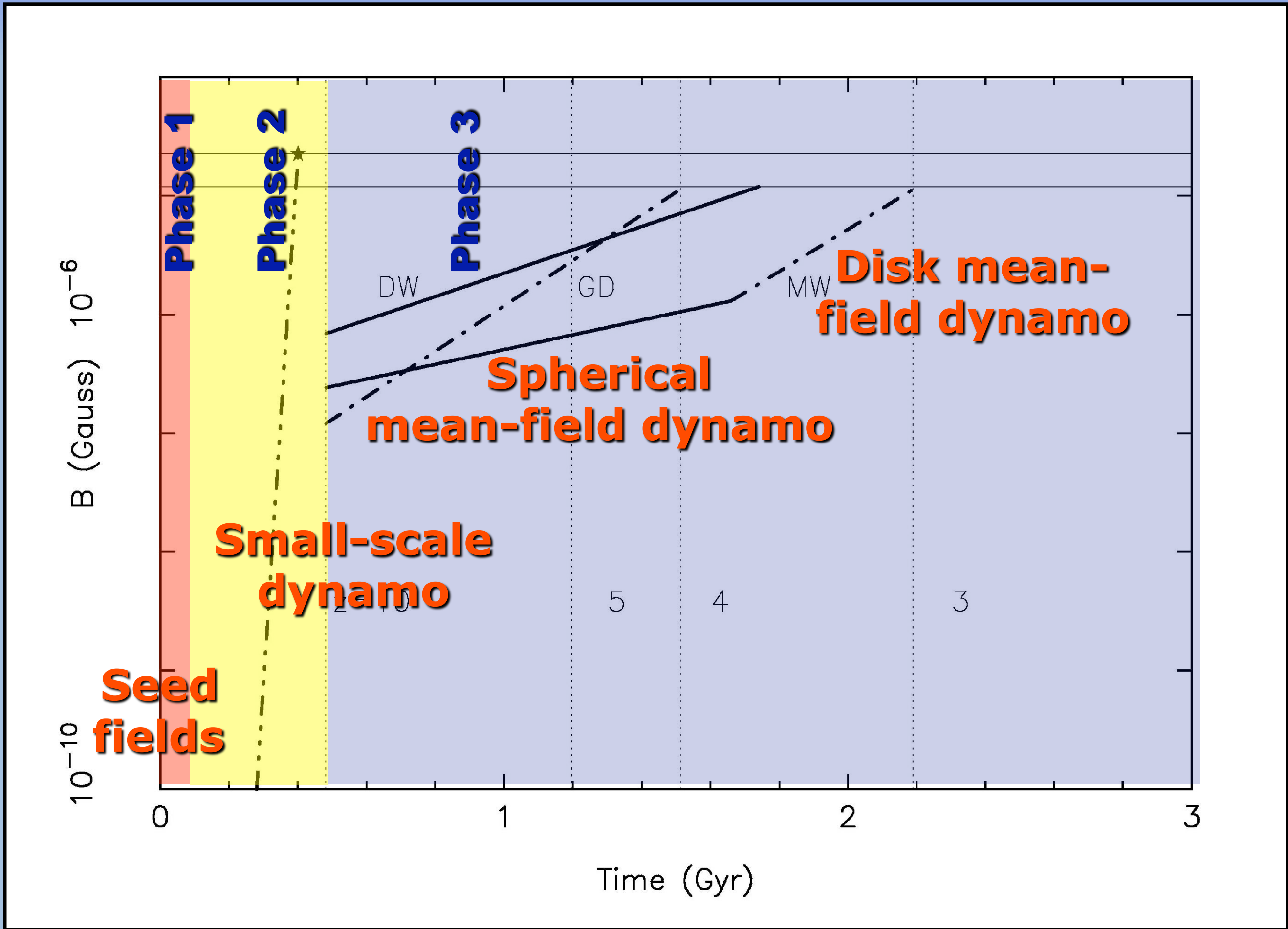
- Amplification of regular fields by mean-field dynamo in quasi-spherical objects (R/h<10):

$$t_{sph} = \frac{3}{9^{2/3}} \left(\frac{v}{R\Omega} \right)^{1/3} \frac{R}{\Omega l}$$

- Ordering of regular fields:

$$t_{order} \approx \frac{R}{l} \left(\frac{h}{v\Omega} \right)^{1/2}$$

Magnetic field amplification by galactic dynamos



Arshakian et al. 2009

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

Magnetic field amplification

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

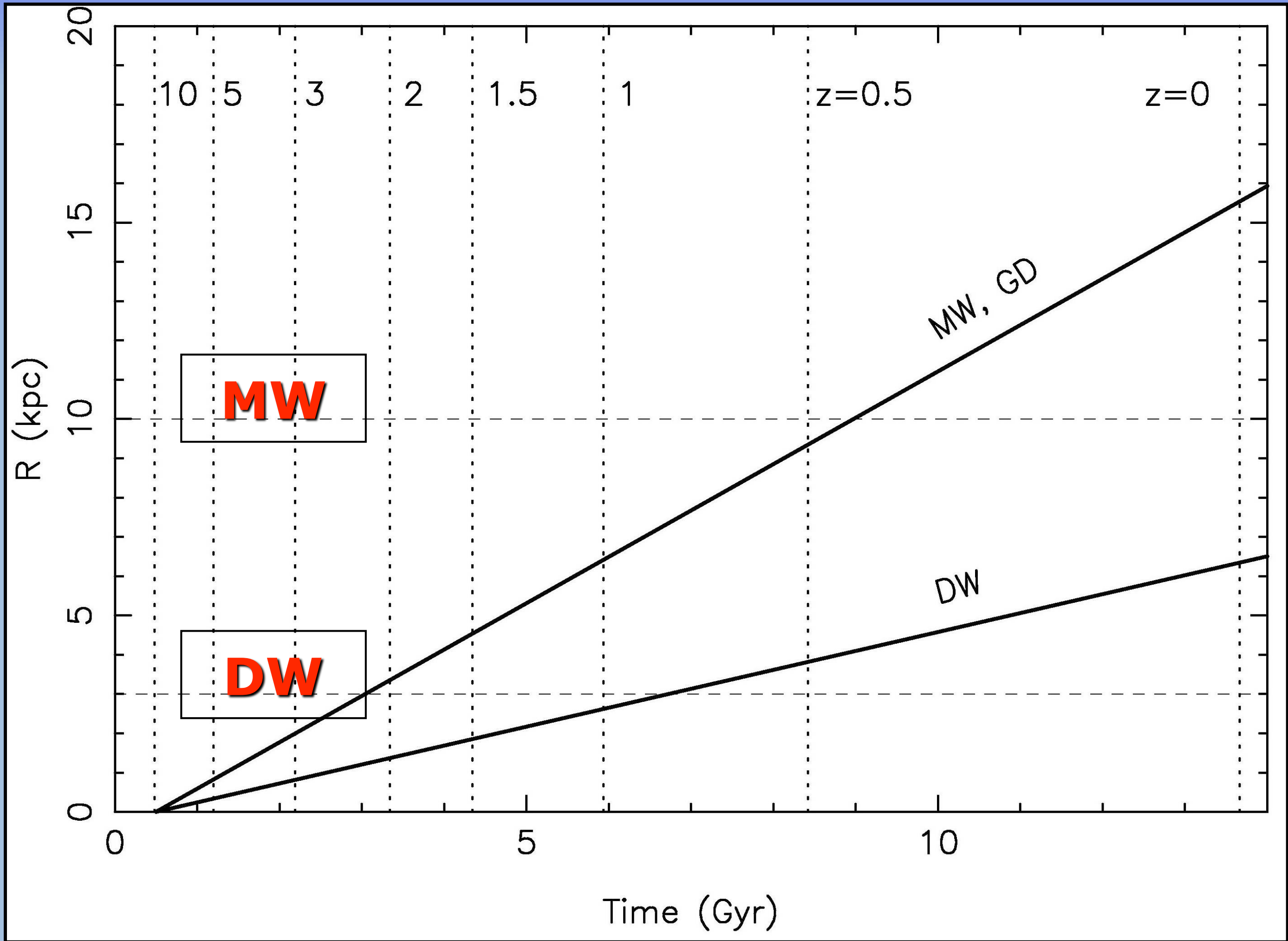
  → Strong radio synchrotron emission from starburst galaxies can be observed at $z < 10$

- Strong **regular** fields expected at $z < 3$

  → Polarized radio emission and *some* Faraday rotation can be observed at $z < 3$

  (if no major mergers occured)

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)

Coherence length of regular fields

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

→ Large-scale pattern of Faraday rotation can be observed at $z < 1$

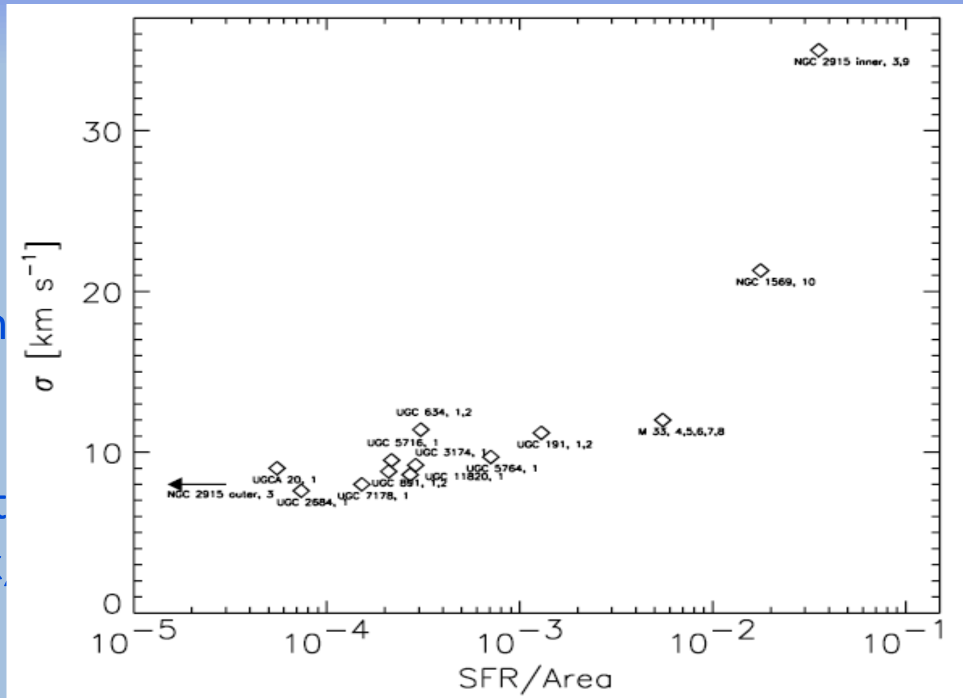
(if no major mergers occured)

- Anticorrelation expected between galaxy size and the ratio between coherence scale and galaxy size

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

Influence of star formation and mergers on evolution of MF

Star formation



- Can be trigged by grav. in … and interactions of diffuse clouds.
- High SFR – high velocity t … -scale dynamo if $D < D_c \approx 7$ (for the thin disk …
- Positive correlation between v and SFR (Dib et al. 2006).

The action of the large-scale dynamo is possible if

SFR < 20 M_{sun} yr $^{-1}$ (in case of no outflow)

Influence of star formation and mergers on evolution of MF

Arshakian et al. 2009

Mergers

- Major mergers are rare:
  - Can alter or destroy the *gas-disk*.
  - Regular field is destroyed, turbulent field is increased.
  - If the disk recovers: ~ 1.5 Gyr to amplify the regular field to the equip. level, ~ 8 Gyr to generate a fully ordered magnetic field.

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

- Minor mergers are more frequent:
  - May alter the *morphology* (spiral into elliptical, spiral to spheroidal), *size* and *thickness* of the disk, and control the *SFR* (gas density, turbulence).
  - Increase the disk height and radius –> large dynamo and ordering timescales.

Influence of star formation and mergers on evolution of MF

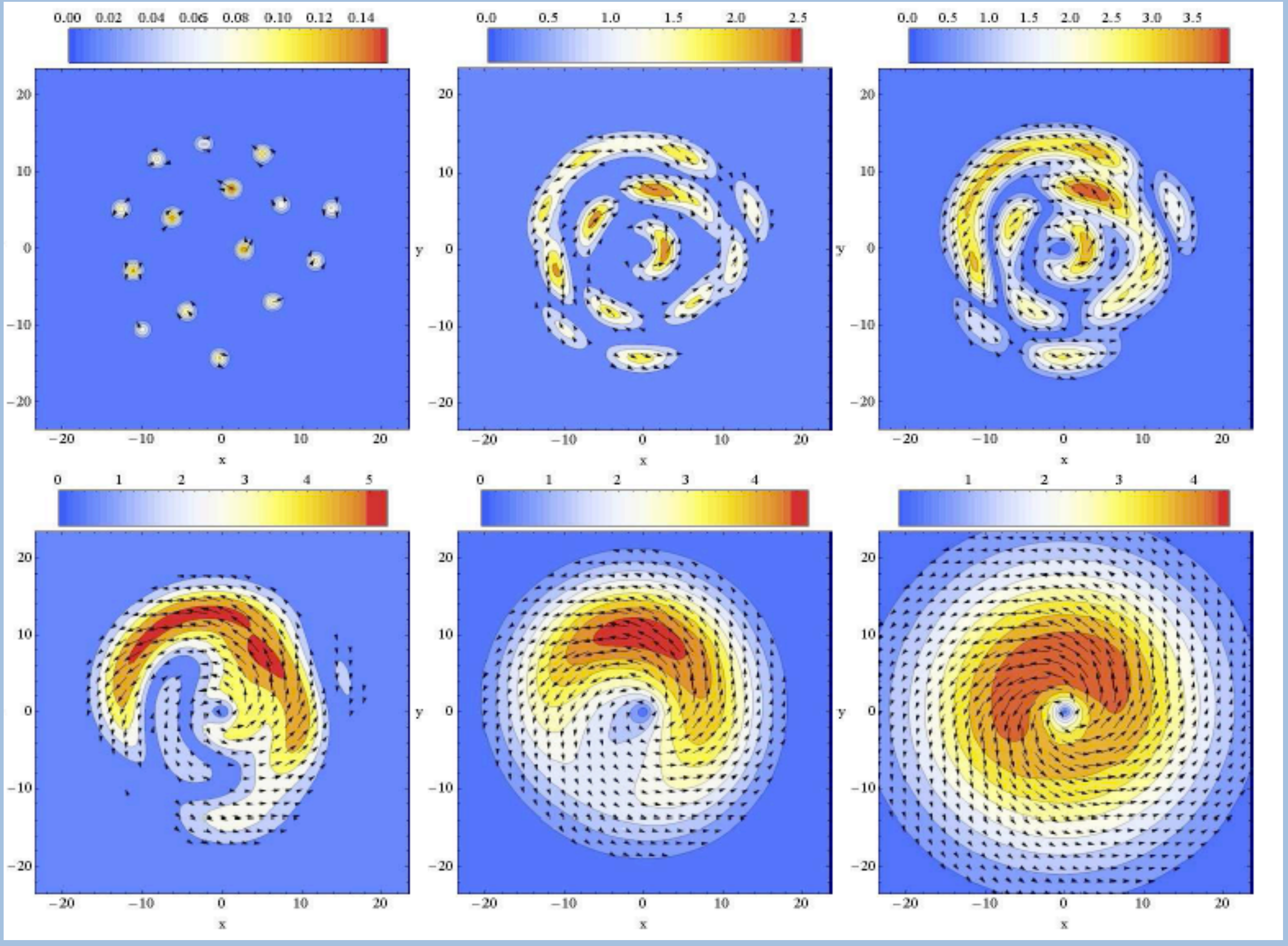
The increase of SFR and mergers events lead to the shift of the formation of regular magnetic fields to later epochs

Summary: Dynamo model

- Protogalaxies: Efficient generation of equipartition turbulent fields until $z \approx 10$
- Giant disk galaxies: formed at $z > 10$; efficient generation of equipartition regular fields until $z \approx 4$; fully ordered fields are not developed in galaxies with sizes >15 kpc
- MW-type galaxies: formed at $z \leq 10$; equipartition regular fields reached at $z \approx 3$, full ordering at $z \approx 0.5$
- Dwarf galaxies: generated regular fields earlier; full ordering at $z \approx 1$
- Major mergers can disrupt or delay the evolution of regular magnetic fields
- Present-day data are consistent with the dynamo model

Simulations of the evolution of the regular magnetic fields (SKADS project)

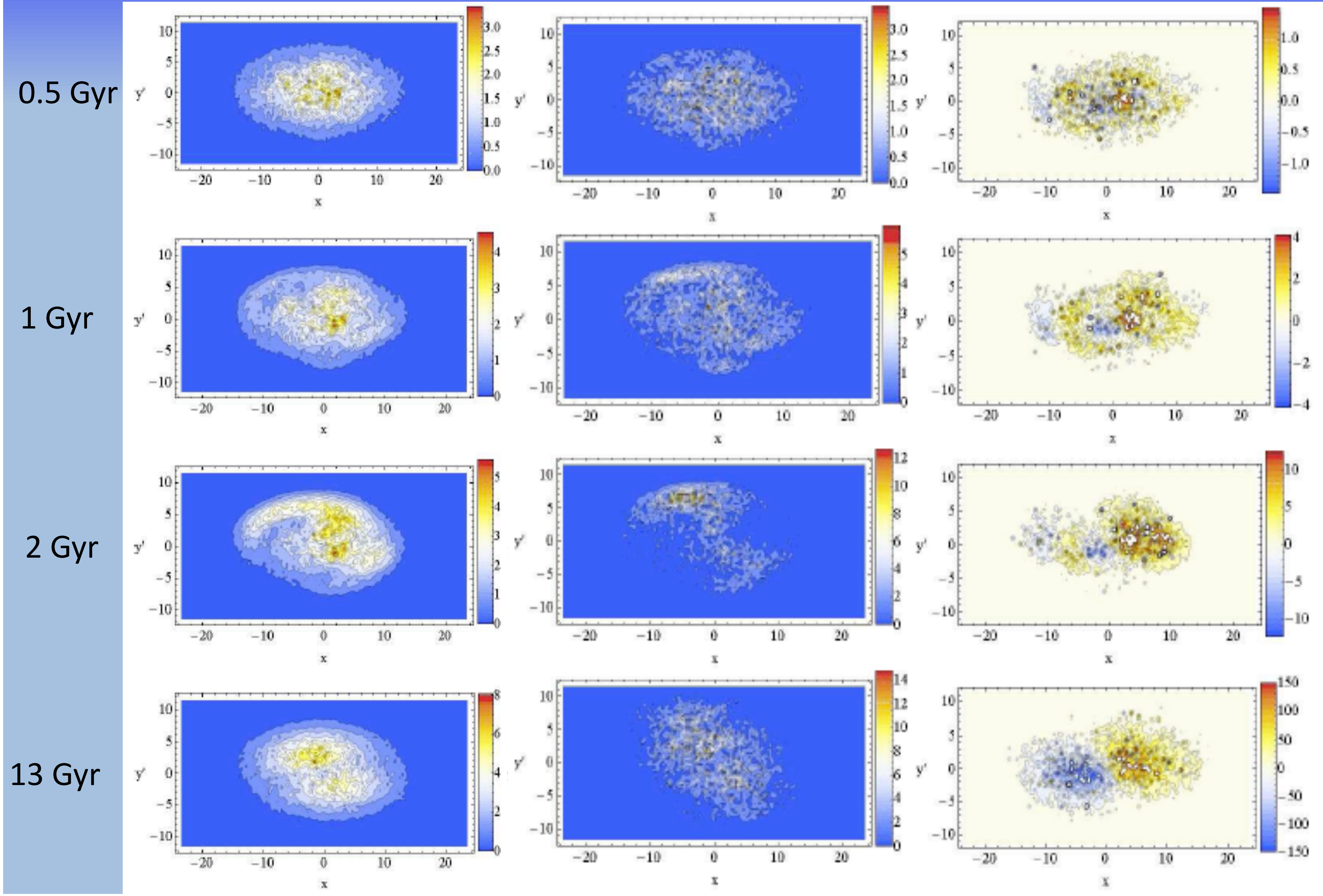
0 Gyr (1 kpc) | 0.5 Gyr (1.6 kpc) | 1 Gyr (2.2 kpc)



2 Gyr (3.4 kpc) | 5 Gyr (7 kpc) | 13 Gyr (10 kpc)

Arshakian et al., in prep.

Simulations of I, PI, and RM at 150 MHz



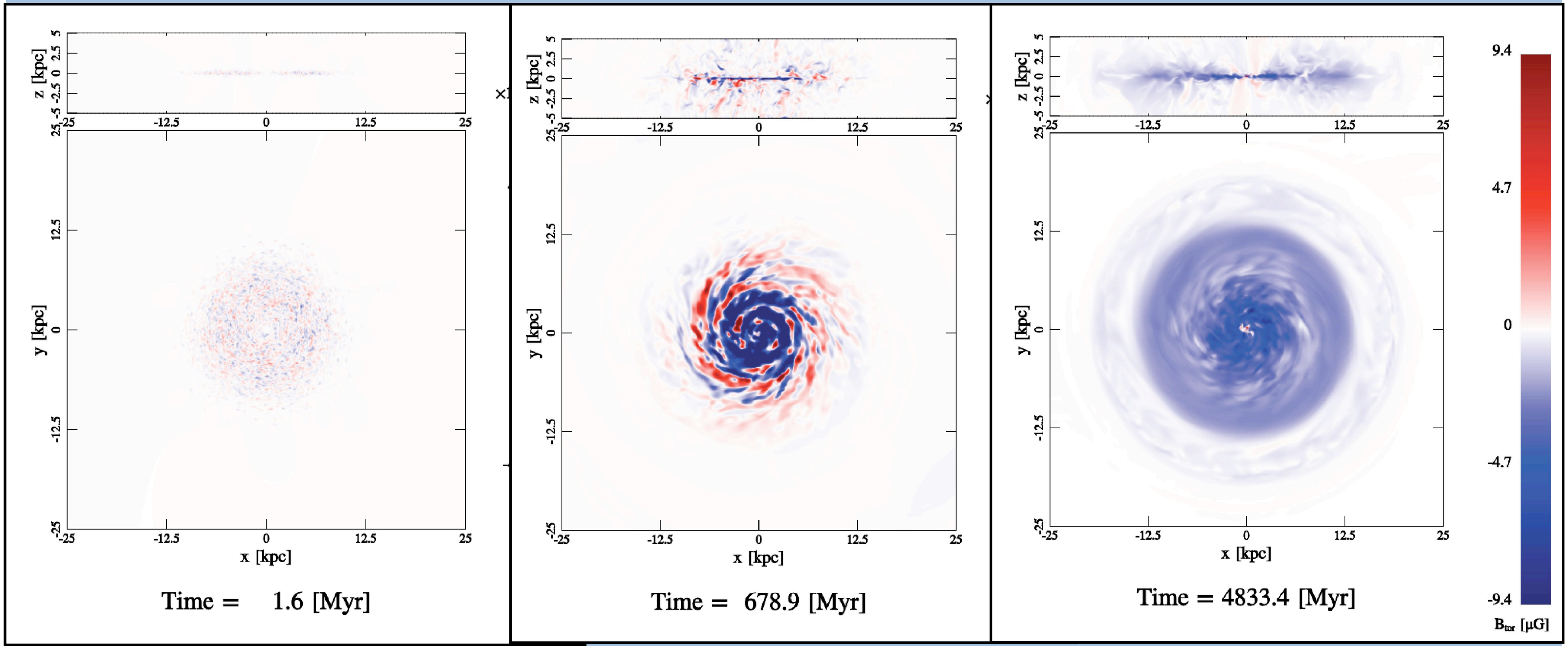
More realistic dynamo models

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

Global cosmic-ray driven MHD model

Global galactic-scale CR-MHD simulations.

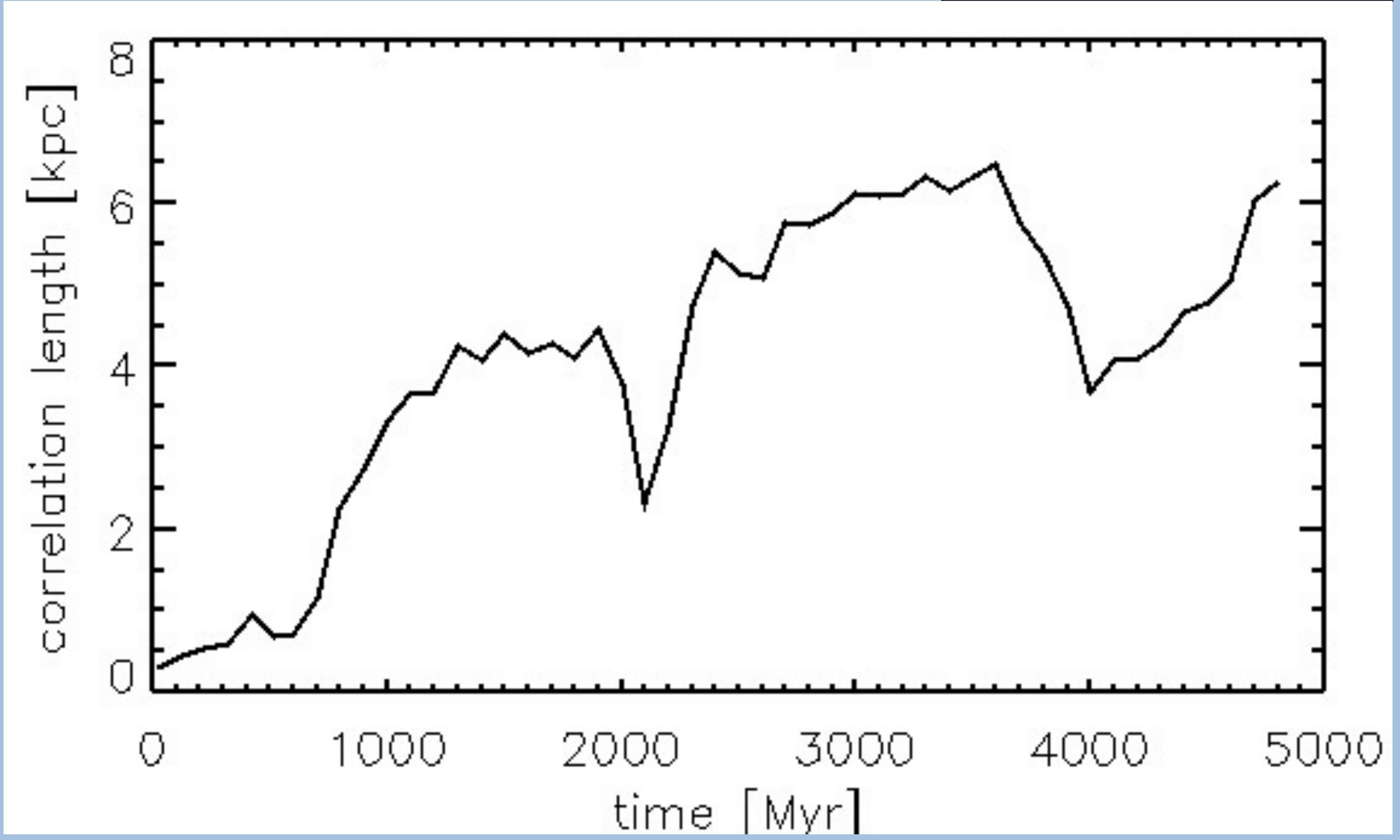
Hanasz et al. (2009)



Global cosmic-ray driven MHD model

Evolution of the coherence length

Hanasz, private comm.



Total synchrotron emission:

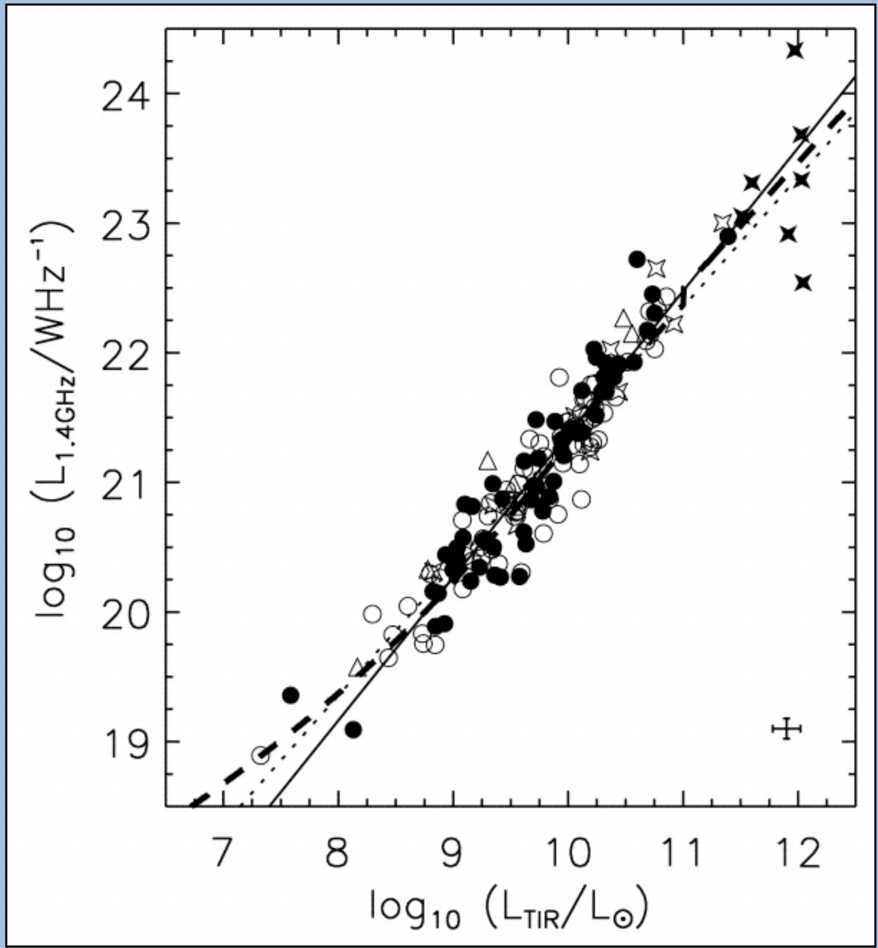
Tracer of total magnetic fields

The radio continuum - FIR correlation for star-forming galaxies

- One of the tightest correlations in astronomy !

- Holds over a factor of (at least) 10^5 in luminosity (Bell 2003)

- Holds from dwarf to starburst galaxies
(Lisenfeld et al. 1996, Chyzy et al. 2006)

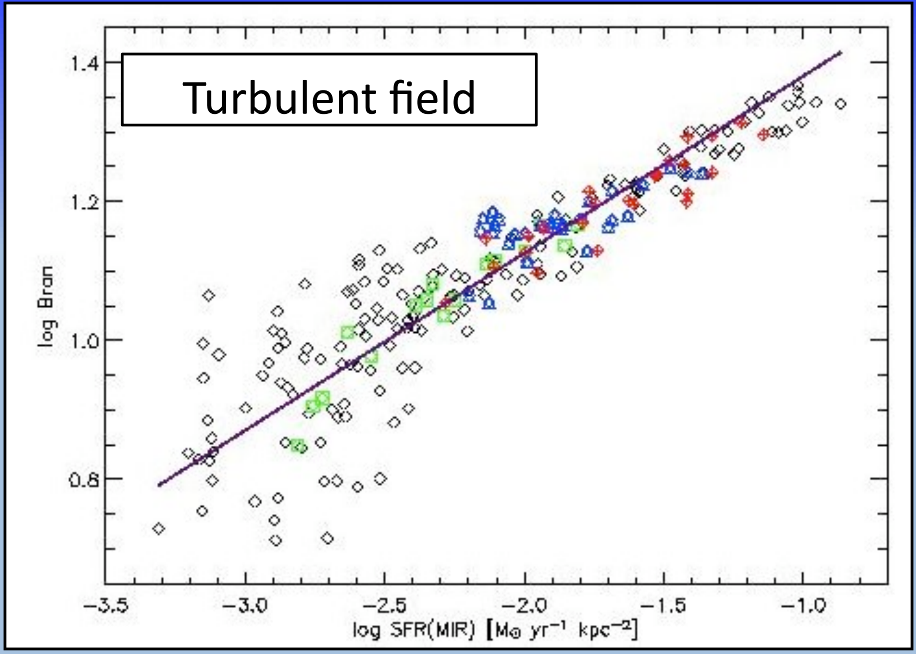


Bell 2003

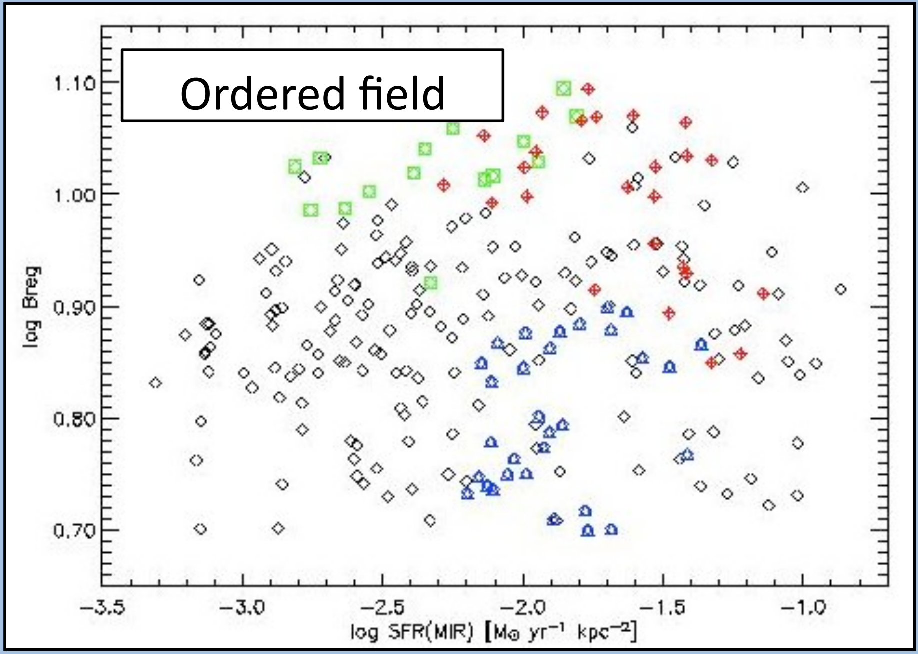
NGC 4254

6cm VLA + Hα

(Chyzy 2008)



The radio-IR correlation is due to the **turbulent field** generated in star-forming regions

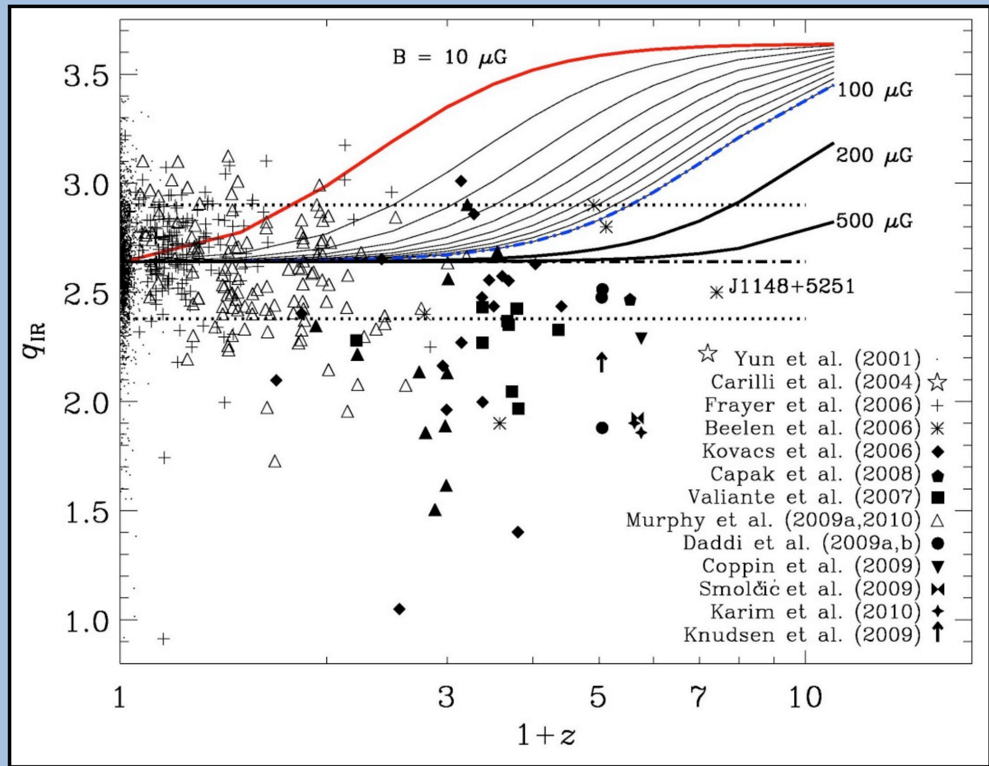


The radio continuum - FIR correlation for distant galaxies

- 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 **starburst** galaxies:
  $B > B_{CMB} = 3.25\ \mu G\ (1+z)^2$

Needs better data at high z (Herschel, SKA & pathfinders)

Murphy 2009



IR/radio luminosity

The radio continuum - FIR correlation for distant galaxies

- Radio continuum dominated by synchrotron emission:
  Strong dependence on magnetic field strength

- Correlation holds until at least $z \approx 3$:
  (Ivison et al. 2005, Seymour et al. 2008)
  Magnetic fields existed already in young galaxies

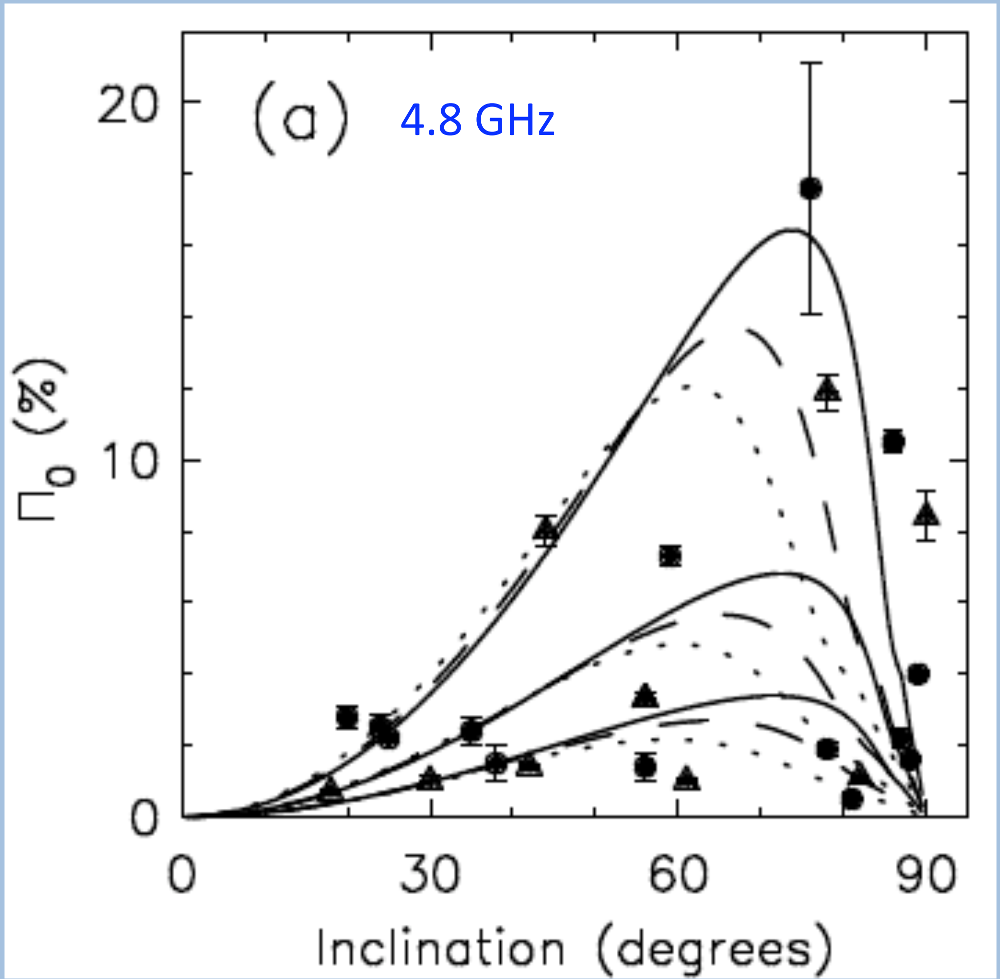
- Radio synchrotron emission was strong:
  Magnetic fields must have been stronger than
  the CMB-equivalent field of $\approx 3.25\ \mu G\ (1+z)^2$
  in order to compete with Inverse Compton losses
  ($z=3$: $\approx$ **50 μG** !)

Polarized synchrotron emission:

Tracer of ordered magnetic fields

Polarimetry of unresoved disk galaxies

Stil et al. (2008)



- Integrated polarization of nearby 27 resolved disk galaxies.

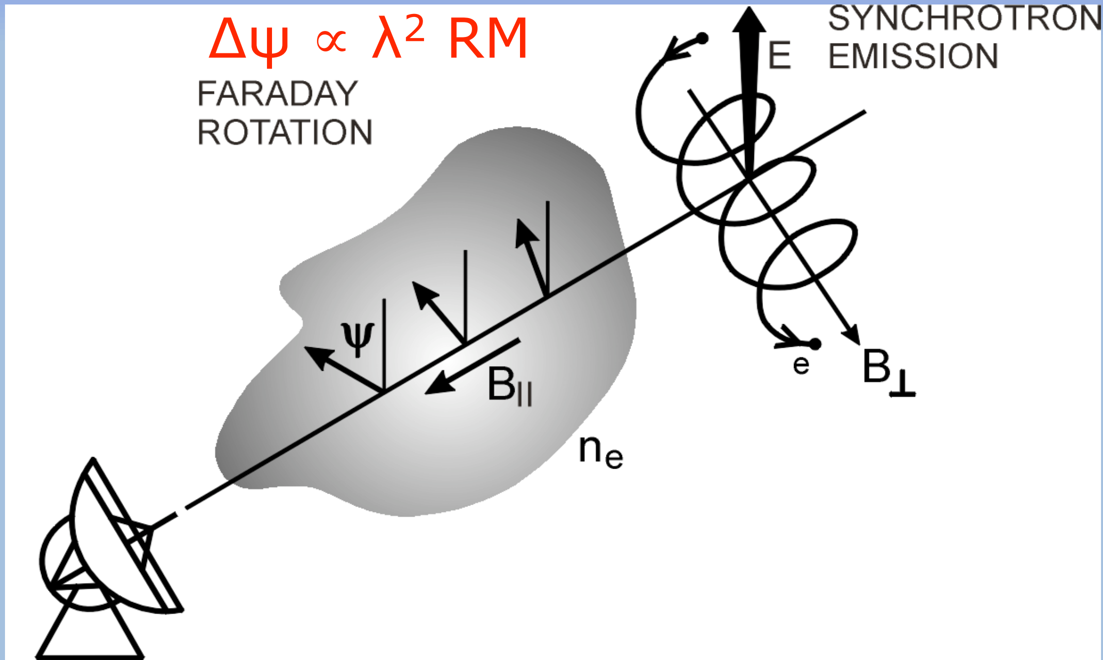
- Opens the possibility to study magnetic field properties and Faraday rotation in large samples of spiral galaxies, and in distant unresolved disk galaxies.

- A deep 1 - 2 GHz survey with the SKA could detect normal spiral galaxies at z>1.

Faraday rotation:

Tracer of ordered magnetic fields and its direction

Components of Faraday rotation



$$RM \propto \int_0^l n_e B_{||} dl$$

$$RM = RM_{IGM} + RM_{cl} + RM_{gal} + RM_{MW} + RM_{ion}$$

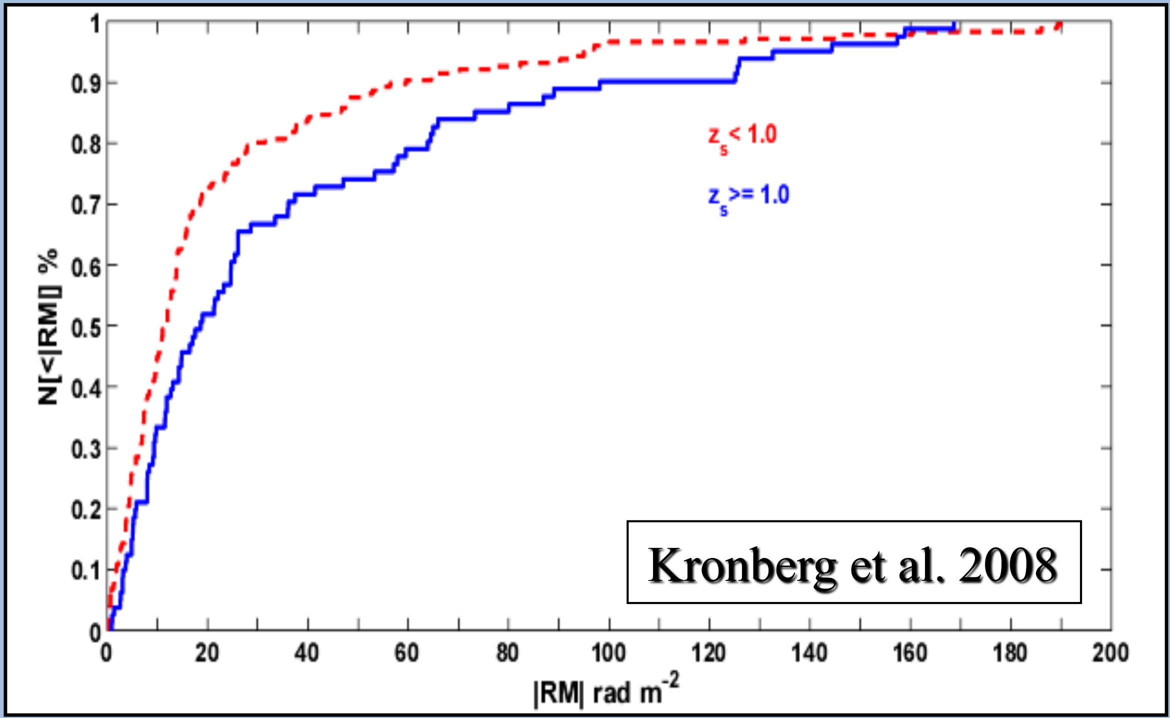
$<1 \quad \leq 10000 \quad \leq 1000 \quad \leq 1000 \quad \leq 10$

rad m^{-2}

RM towards distant background quasars

Probe for regular magnetic fields in distant intervening clouds

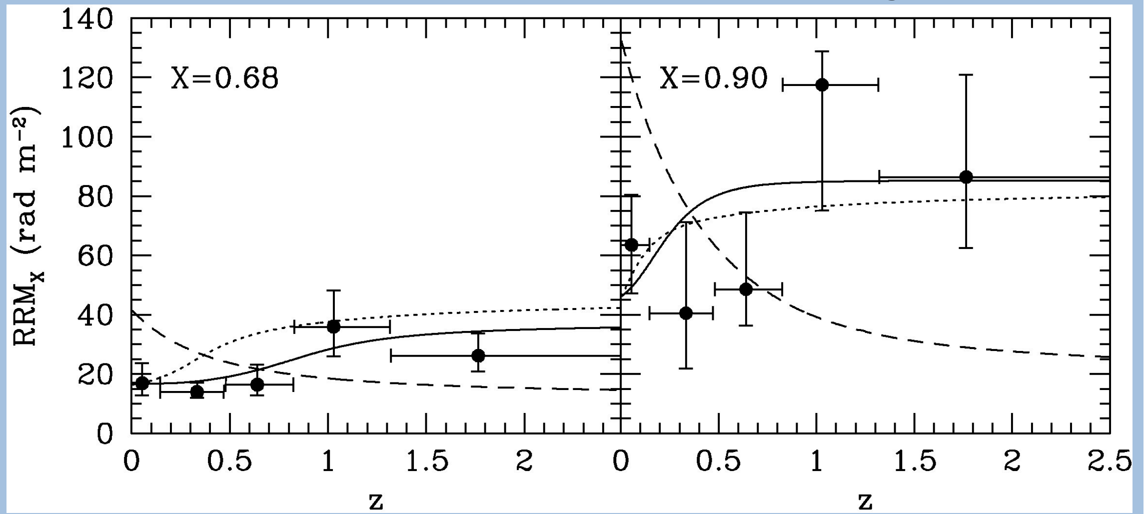
- Faraday rotation is stronger for more distant quasars
- Disk galaxies: Mg II absorption lines originate in intervening disk galaxies (Kronberg et al. 2008, Bernet et al. 2008)



RM towards distant background quasars

Probability of $P(RM,z_s) = F(P_{noise},P_{interv},P_{int})$, $P_{n,interv}(RRM, z_s) = f(z, n_e, B, l_c, R)$

Kronberg et al. 2008



RM intrinsic to the source:

$$RM(z) \propto (1+z)^{-2}$$

Toy model:

non-evolving magnetic field reproduce the data well: strong field at z<2.

Perspectives with the SKA and pathfinders:

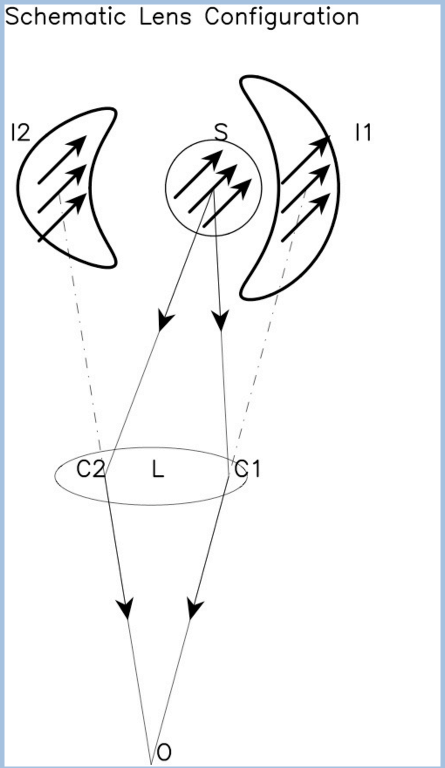
Deep RM-survey with SKA: large data set up to z~5 -> smaller z-bins

Detailed model of galaxy evolution (Arshakian 2010):

- Evolving magnetic-field amplitude: *B(z).*
- Evolving coherence length: $l_{c,}(z)$.
- Downsizing of interveners: *R(z).*

RM towards gravitational lens systems

Can effectively probe the large-scale mag. fields in distant SF galaxies



- Multiple components with separations from milliarcs to arcs

- Difference between RM from multiple components is due to lens itself:

$$< B_{||} > \propto RM(1+z)^2/N_e, \text{ where } N_e = \int n_e(z) dl(z)$$

- Regular fields are measured for few elliptical and disk galaxies at z~(0.3-1): $B_{ell} \approx B_{spir} \sim (1-10)\,\mu\mathrm{G}$

- Free from the contribution of:
  - RM intrinsic to the source
  - RM of IGM
  - RM of the Milky Way.

Perspectives for the SKA: a few thousands of lens systems will be detected per sq. deg. (Koopmans et al. 2004) -> probe for the evolution of mag. fields beyond z>1.

Observation of magnetic fields in distant galaxies with the SKA

SKA and pathfinders: high sensitivity and angular resolution

Deep SKA observations:

- Total synchrotron emission ($z < 3\text{-}5$)
- Polarized synchrotron emission ($z < 3$)
- Faraday rotation against background quasars ($z < 5$)

Perspectives for the SKA

Predictions of the dynamo model:

- Axisymmetric and quadrupolar modes preferred
- Anticorrelation between galaxy size and coherence scale
- Undisturbed dwarf galaxies host fully coherent fields at $z < 1$
- Large spiral galaxies host fully coherent fields at $z < 0.5$
- Weak regular fields in galaxies at $z < 0.5$ are signatures of mergers

Primordial models:

- Bisymmetric and dipolar modes preferred
- Fully ordered fields already in young galaxies