Cosmological evolution of magnetic fields in galaxies: future tests with the SKA

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Outline

- Motivations to study the cosmological evolution of magnetic fields of star-forming galaxies (SFG).

- Model for the cosmological evolution of regular fields

- Evolution of strength and ordering scale of regular fields

- SKADS: simulations of total intensity and polarization intensity

- Summary and perspectives for the SKA

Evolution of regular magnetic fields in galaxies

Motivations to study the evolution of magnetic fields of SFG

- Magnetic fields can be studied via *synchrotron emission* (strength), *linear polarization* (ordering), *Faraday rotation* (weak fields and ordering).
- SKA with high-sensitivity will detect high-z SF galaxies (dominant population at low flux densities < 0.1 mJy !) ⟹ evolution of MFs.
- SKA: Radio-IR correlation ⟹ SF at high-z if B_{tot} is sufficiently strong.
- Magnetic fields origin at early cosmological epochs (z>40).
- Coupled with formation and evolution of galaxies (fundamental problem).

What is the mechanism of generation of regular mag. fields?

- *Dynamo theory* successfully reproduces the large-scale regular fields in the disks of nearby galaxies ⟹ can be used to model the evolution of magnetic fields at high-z.

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*

Magnetic fields in distant galaxies: perspectives for the SKA

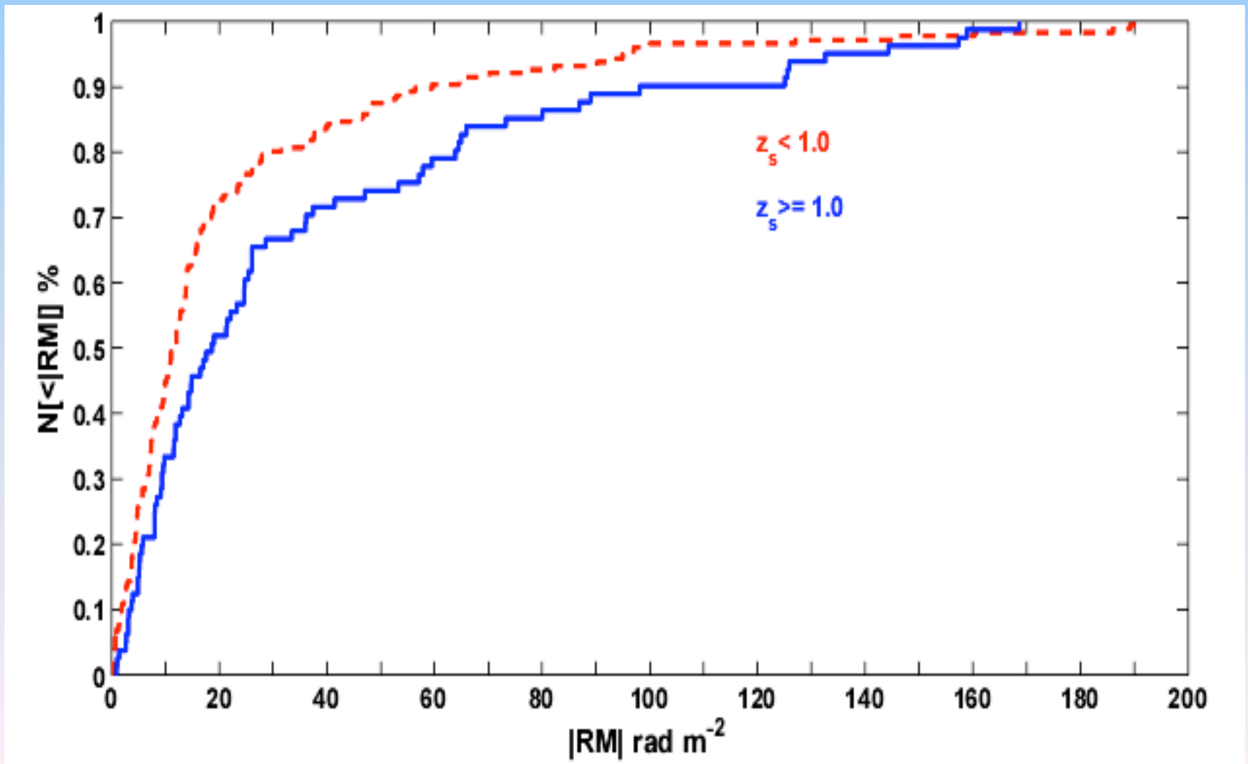
Evidence

- RM of distant background quasars.
- Radio FIR correlation is valid up to z~3.

SKA: high sensitivity and angular resolution
⟹ huge number of distant galaxies with the same resolution as in nearby galaxies
⟹ huge number of RM from point sources

RM of distant background sources

- Population of intervening galaxies towards distant quasars (~200) with strong regular fields detected (Kronberg et al. 2008; Bernet et al. 2008).
- The SKA All-sky Survey will provide a much larger sample of RMs

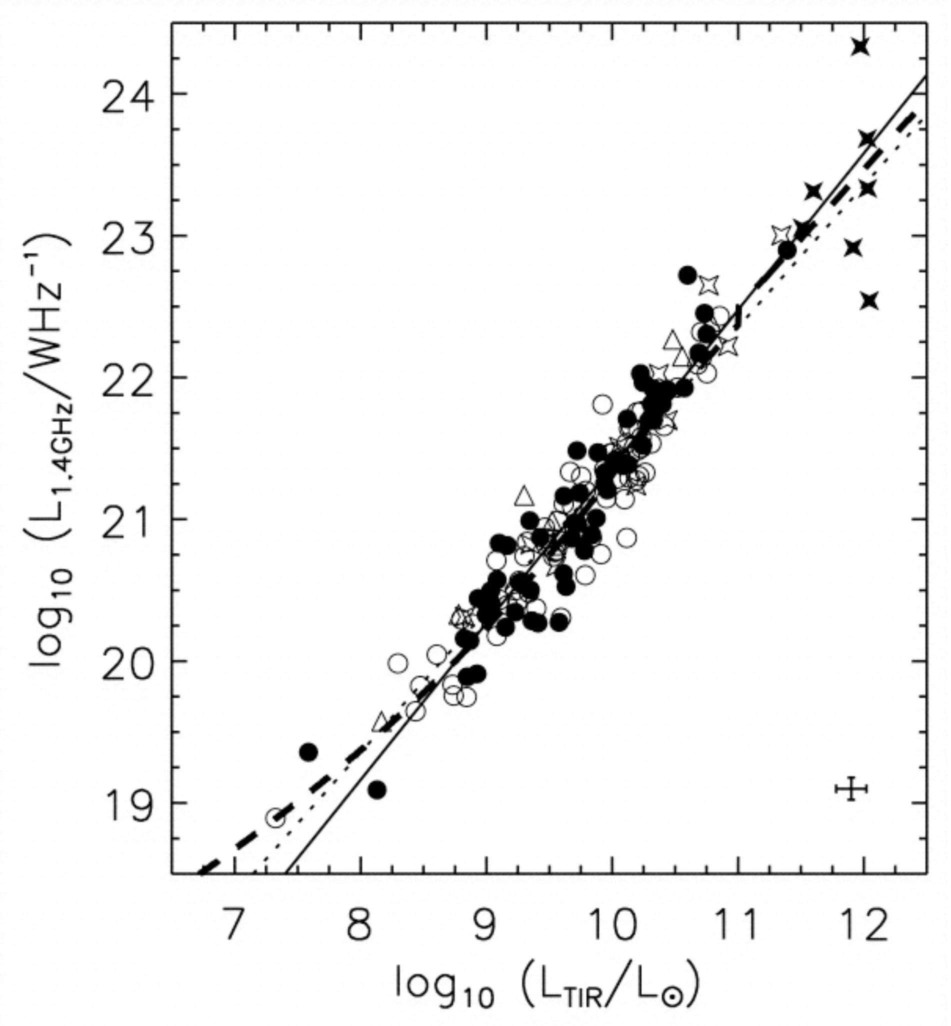


The radio continuum - FIR correlation of star-forming galaxies

• Holds over a factor of (at least) 10^5 in luminosity
(e.g., Bell 2003)

• Is valid out to (at least) z≈3
(e.g., Ivison et al. 2005, Seymour et al. 2008)

• Also holds within galaxies, down to ≈ 50pc scale
(Hughes et al. 2006, Tabatabaei et al. 2007)



Dynamo timescales

Dynamo theory: **timescales of amplification of magnetic field strength** (Arshakian et al. 2008):

- Turbulent dynamo (small-scale): $t_{TD} = \frac{l}{v}$
- Mean-field dynamo (large-scale) in disk galaxies (R/h>10):

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

- 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 timescale of regular fields: $t_{order} \approx \frac{R}{l} \left(\frac{h}{v\Omega} \right)^{1/2}$

Model for the evolution of magnetic fields

Measures of magnetic evolution

- **Angular rotation of a galaxy** (Ω)
- **Radial and vertical height (*R* and *h*)**
- **Turbulence velocity of the ionized gas (*v*)**
- **Turbulence length scale of the gas (*l*)**
- **Gas density (ρ)**

Evolution of magnetic fields is coupled with the formation and evolution of galaxies !

Evolution of magnetic fields

Two main cosmological epochs in the hierarchical formation scenario

- **Virialization and merging of dark matter halos (z~20)**
- **Formation of the extended large-scale disk (z~10)**

Evolution of magnetic fields

Three-phase model

1. ***z~40:*** **Formation of halos:** ***Generation of seed magnetic fields***

2. ***z~20:*** **Merging of halos and virialization:** ***amplification of turbulent magnetic fields (small-scale dynamo)***

3. ***z~10:*** **Formation of the large-scale disk:** ***origin and amplification of regular fields (large-scale dynamo).***

Main assumptions

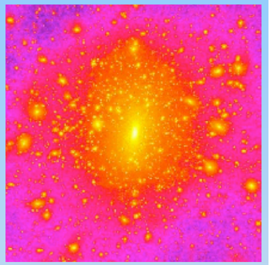
- **Phase 2:** *Turbulence is driven by merging and virialization of dark matter halos.*
- **Phase 3:** *Turbulence is driven by SN explosions in the disk.*

Recent results of simulations of the hierarchical structure formation are used to identify the mechanisms of MF generation

- **Formation of low density halos with $M \sim 10^7 M_{sun}$ (z~40-20)**

Phase 1: The origin of seed magnetic fields at $z \approx 40$
Mechanism of generation: Biermann battery or Weibel instability
Amplitude: ~10^{-18} Gauss

Governato & Mayer



- **Virialization and merging of dark matter halos (z~20-10)**
  - thermal virialization generated turbulence in the halo (Abel & Wise 2007)

Phase 2: Amplification of seed fields by turbulent (small-scale) dynamo
Timescale of amplification: ≈ 3×10^8 Gyr

- **First galaxies: Formation of the extended large-scale disk (z~10)**

Phase 3: Amplification and ordering by mean-field (large-scale) dynamo
Timescale of amplification: disk galaxy ≈ **2 Gyr**; dwarf galaxy ≈ **1 Gyr**
Timescale of ordering: disk galaxy ≈ **8 Gyr**; dwarf galaxy ≈ **6 Gyr**

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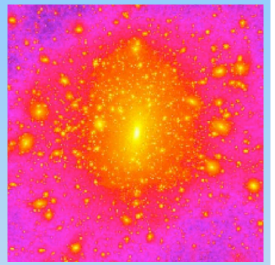

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Phase 2: The scale of **turbulent dynamo in HALOS** is driven by the largest size of the infaling matter:
$l \sim 200$ pc and $v \sim 20$ km s^{-1}

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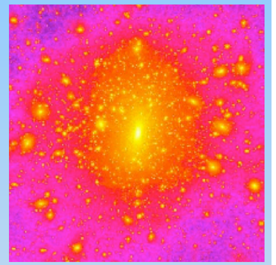

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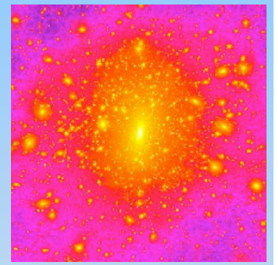

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o

- **First galaxies: Formation of the extended large-scale disk (z~10)**

Phase 3: The **dynamo in DISKS** is driven by SN explositions:

$l \sim 100$ pc and $v \sim 10$ km s^{-1}

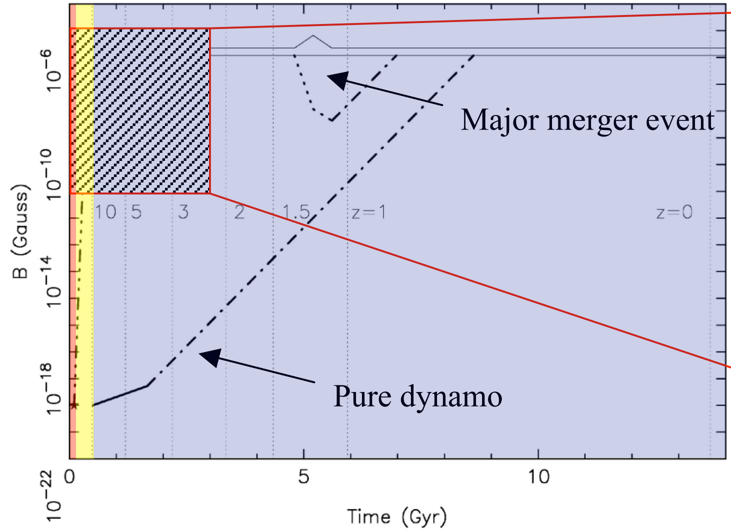
o

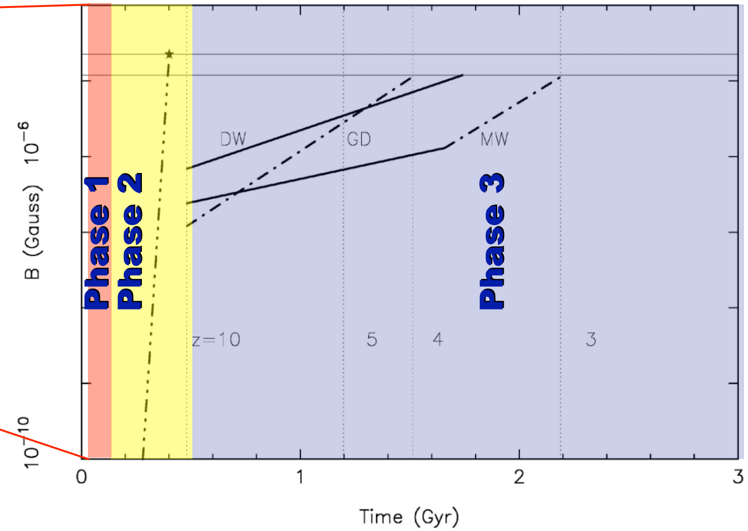
1 Gyr

Gyr

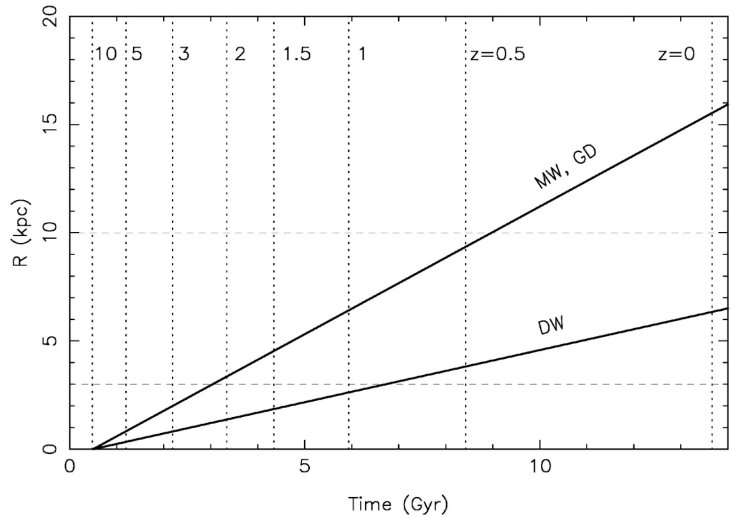
Evolution of regular magnetic fields

Amplification of the field

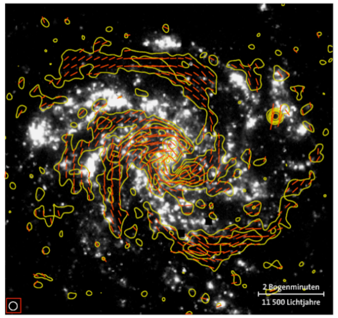




Ordering of the field



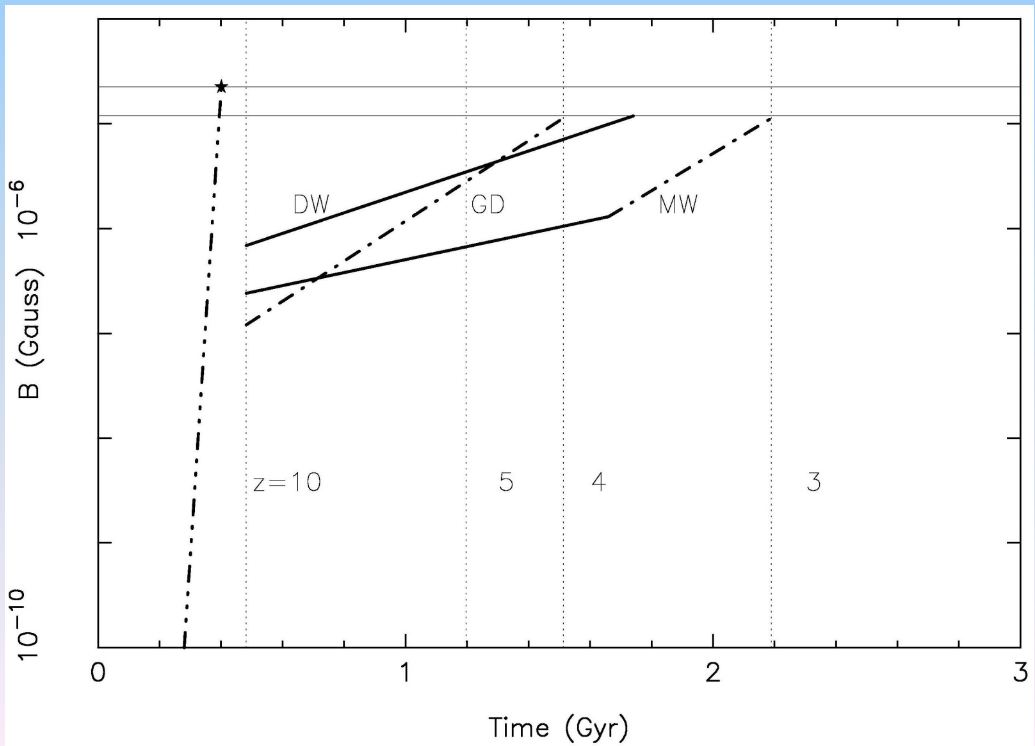
GD – giant disk galaxy (>15 kpc)
MW – Milky Way type galaxy (~10 kpc)
DW – dwarf galaxy (~ 4 kpc)



NGC 6946 (Beck & Hoernes 1996).

Evolution of regular fields

***Amplification* in dwarf (DW), MW type and giant disk (GD) galaxies**

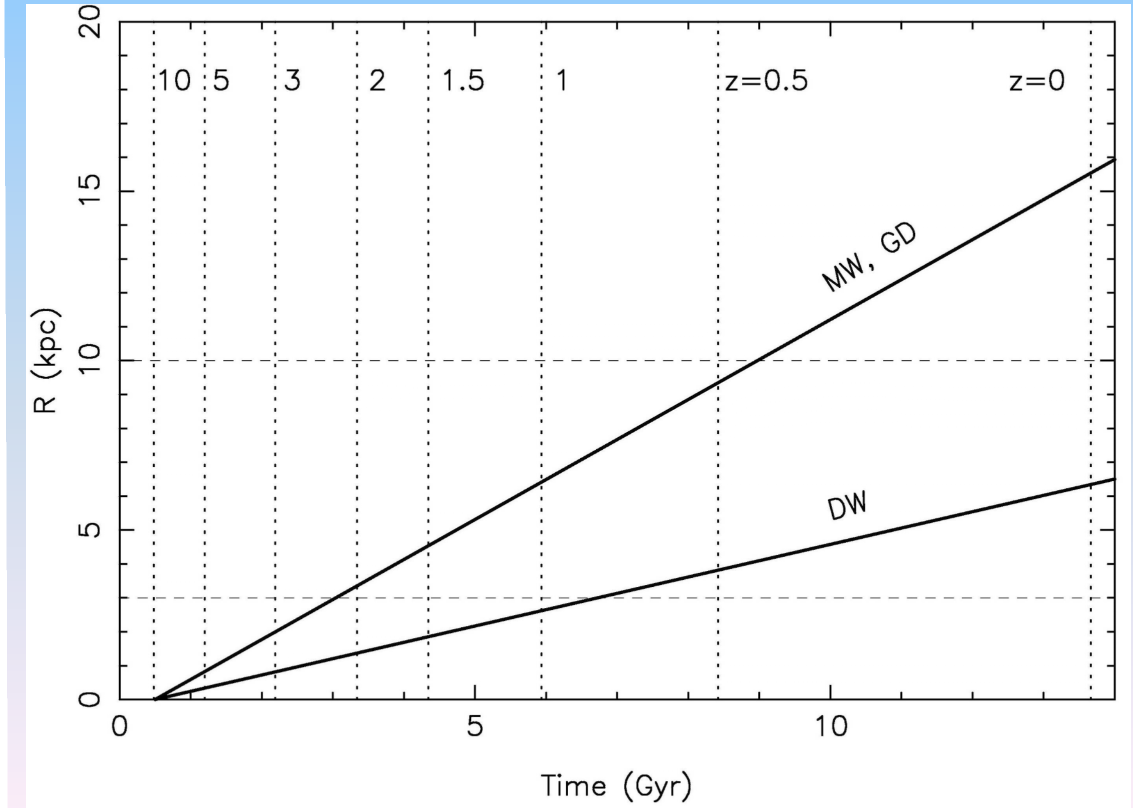


Strong magnetic field at $z \sim 10 \rightarrow$ strong radio continuum $\rightarrow$ SF can be traced to $z<10$ with the SKA.

Polarized radio disks are expected at $z<3$ in all galaxies.

Evolution of regular fields

Field ordering **in DW, MW type and GD galaxies**



Faraday rotatation is expected at z<3 in DW, MW and GD galaxies.

Anticorrelation between galaxy size and ratio between coherence scale and size.

Influence of star formation and mergers on evolution of MF

Star formation

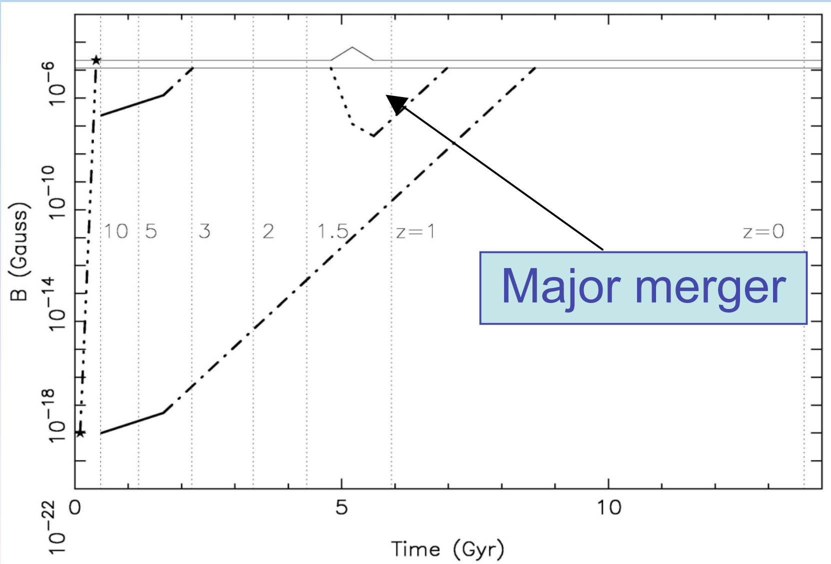
- Fundamental parameter for models of disk formation.
- Can be trigged by grav. instability, minor and major mergers, tidal forces and interactions of diffuse clouds.
- High SFR – high velocity turbulence of the gas – suppression of the large-scale dynamo if $D < D_c \approx 7$ (for the thin disk, R/h>10) or $v \geq 11\ km\ s^{-1}$.
- 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 $^{-1}$.

Influence of star formation and mergers on evolution of MF

Mergers

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



Weak regular fields (small Faraday rotation) in galaxies at $z < 3$, are signatures of major mergers.

Influence of star formation and mergers on evolution of MF

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  - 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.
- 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

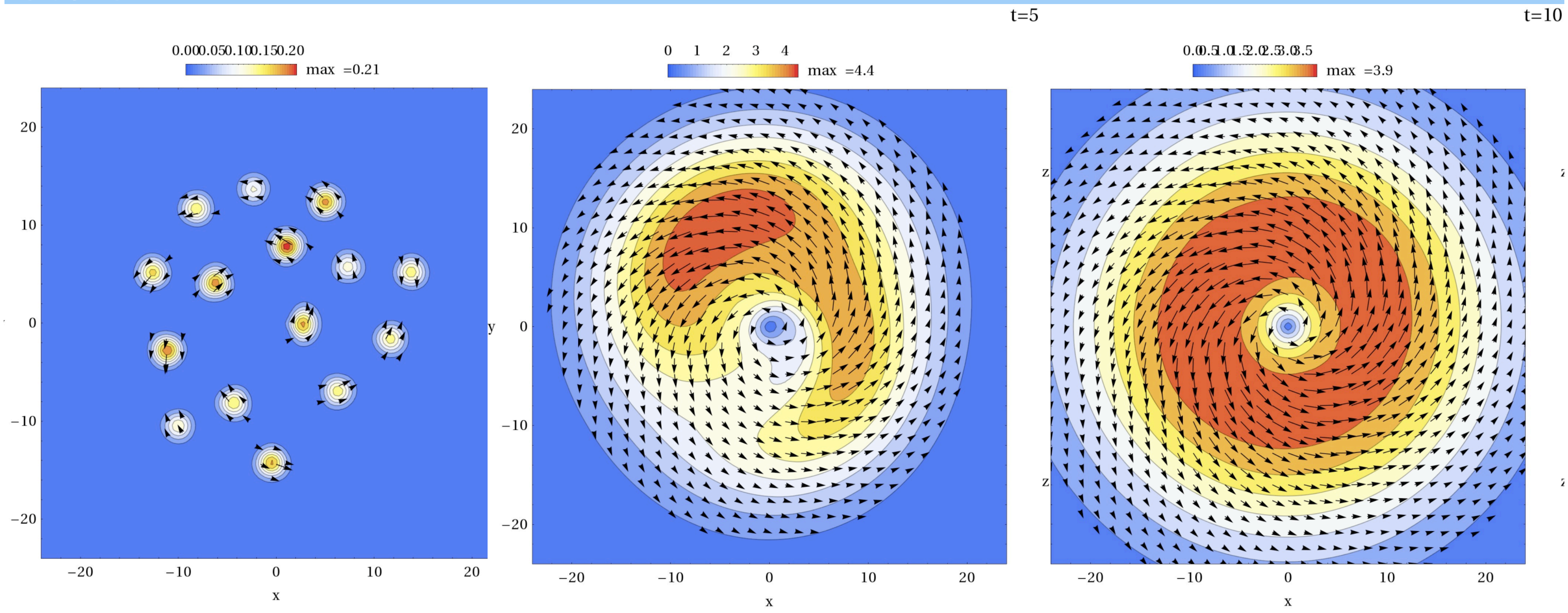
SKADS project: simulations of I, Q and U Stokes for SF galaxies

MW-type galaxy: simulation of MF evolution (age: 0, 5, 10 Gyr) for two frequencies (5 GHz and 150 MHz).

- Initial (age=0) ordering scale of randomly oriented magnetic spots: 1 kpc
- Initial number of magnetic spots: 15
- SFR: 10 M_{sun} yr^{-1} (B_{total} = 7 μG)
- Scale radius of a regular magnetic field: 10 kpc
- Inclination angle: 45 deg
- Resolution: 0.4 kpc

SKADS project: evolution of regular fields in SF galaxies

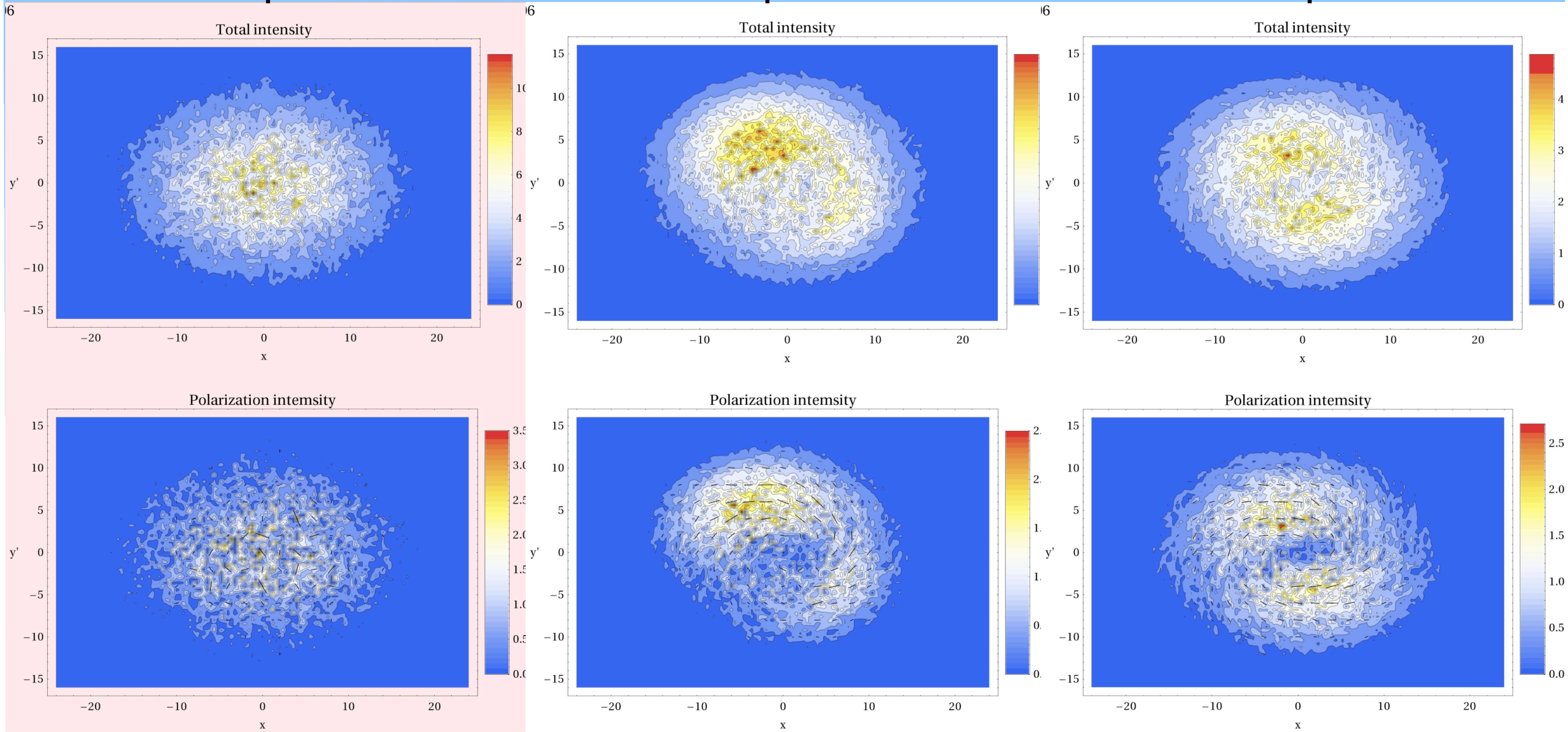
Age:	0 Gyr	5 Gyr	10 Gyr
Order.: scale	1 kpc	6 kpc	12 kpc



Simulations of total and polarized fluxes at 5 GHz

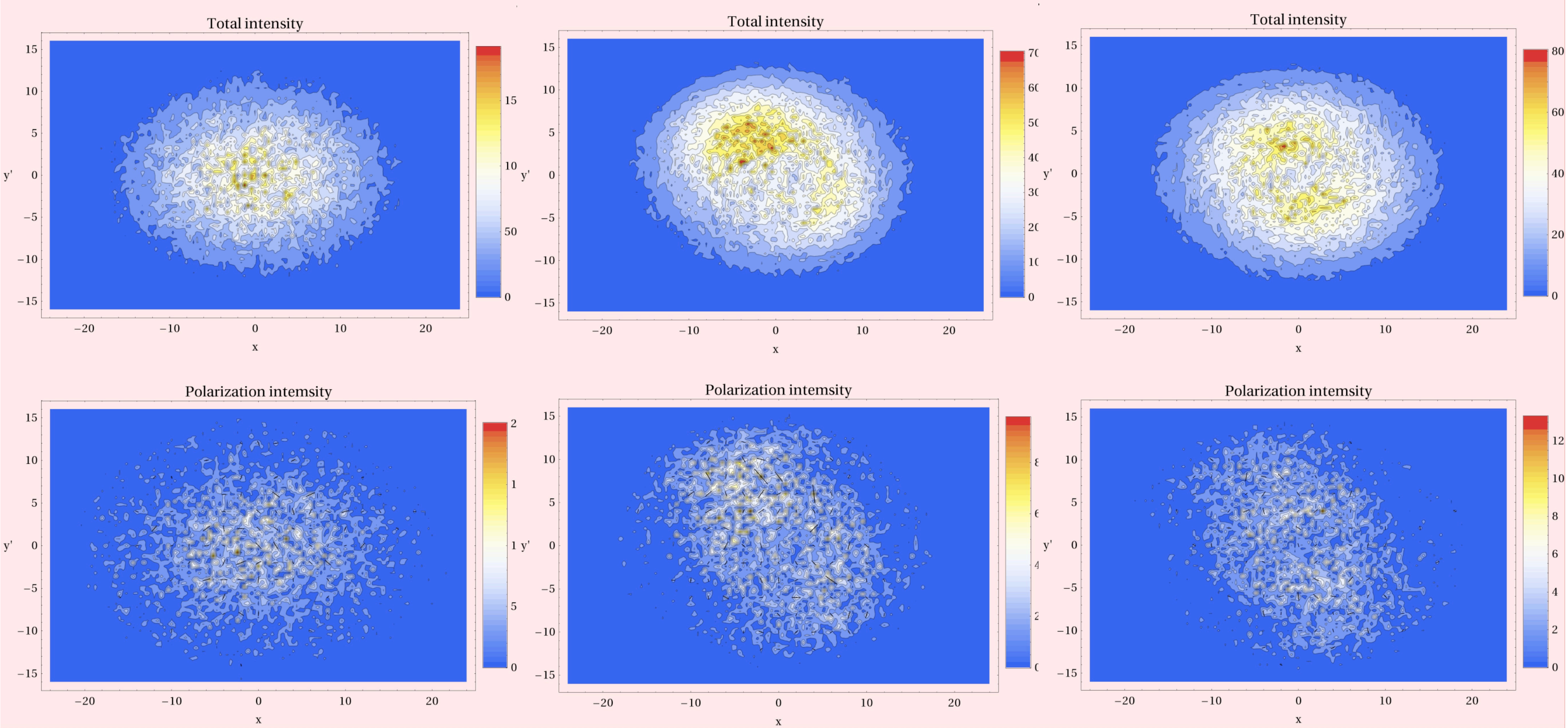
Age: 0 Gyr 5 Gyr 10 Gyr

Order.: 1 kpc 6 kpc 12 kpc



Simulations of total and polarized fluxes at 150 MHz

Age:	0 Gyr	5 Gyr	10 Gyr
Order.:	1 kpc	6 kpc	12 kpc



Summary

- **Evolutionary model** of magnetic fields coupled with formation and evolution of galaxies is developed for disk and puffy galaxies.

- **Giant disk galaxies:** formed at z > 10; efficient generation of equipartition regular fields until z ~ 4; fully ordered fields are not developed in galaxies with size >15 kpc.

- **MW-type galaxies:** formed at z ≤ 10; $\boldsymbol{B}_{\text{reg, equip}}$ is reached at z ~ 3, full ordering at z ~ 0.5.

- **Dwarf galaxies:** generated $\boldsymbol{B}_{\text{reg, equip}}$ even earlier; full ordering at z ~ 1.

- **Major mergers** and **star-formation** triggered by mergers can disrupt or delay the evolution of regular magnetic fields.

Perspectives for the SKA

- **Predictions** of the model:
  - anticorrelation between galaxy size and ratio between coherence scale and size.
  - undisturbed dwarf galaxies should host fully coherent field.
  - weak regular fields (small Faraday rotation) in galaxies at $z < 3$, are signatures of major mergers.

- **Test** of magnetic evolution (dynamo models) is possible with the polarized synchrotron emission (up to z~3) and Faraday rotation (z~5) with the SKA and its pathfinders.

Evolution of regular magnetic fields