Modeling the evolution of regular fields in galaxies: tests with upcoming radio telescopes

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Outline

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

- Three-phase model of the evolution of regular fields in SFG.

- SKADS: simulations of total emission, polarization and Faraday rotation in SFG.

- Summary: perspectives for the SKA.

Importance of SF galaxies

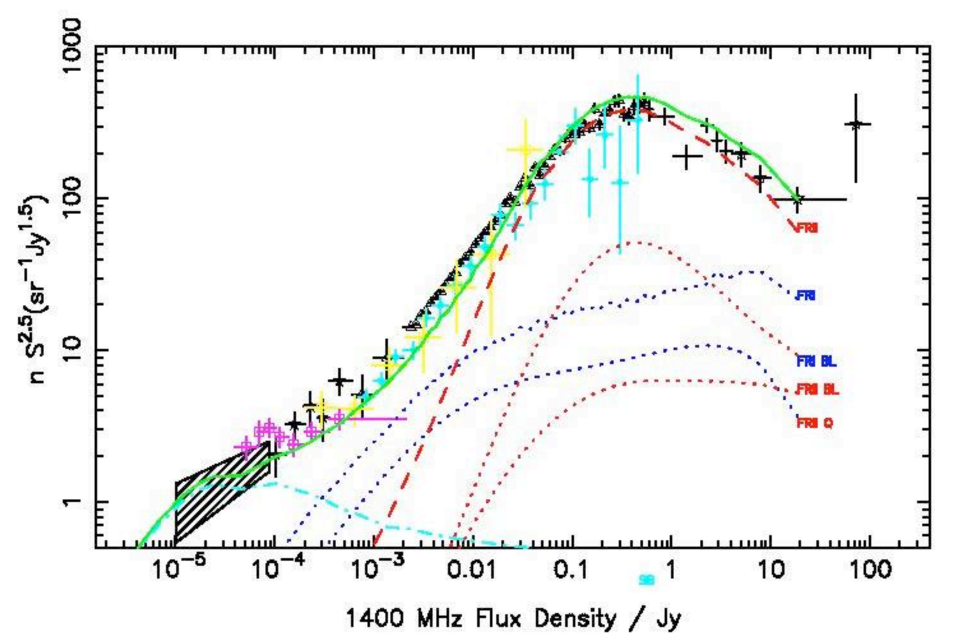
• Local SFG: magnetic-field structure and mechanism of generation.

• Distant SFG: main population of galaxies observed at 1.4 GHz with the **SKA** at flux densities <0.1 mJy (*Jackson 2004*).

• Origin and evolution of magnetic fields:
- The radio luminosity of SF galaxies is linked to the **star formation rate** (SFR) and **the magnetic field strength.**
- SFR in SFGs is high at large redshifts

• Models of the origin and evolution of magnetic fields are needed

(SKA, ASKAP, MeerKat, EVLA).



3-Phase model

(Arshakian et al. 2009)

First attempt to link the structure formation and evolution of magnetic fields in SFG.

- Cosmology: hierarchical structure formation

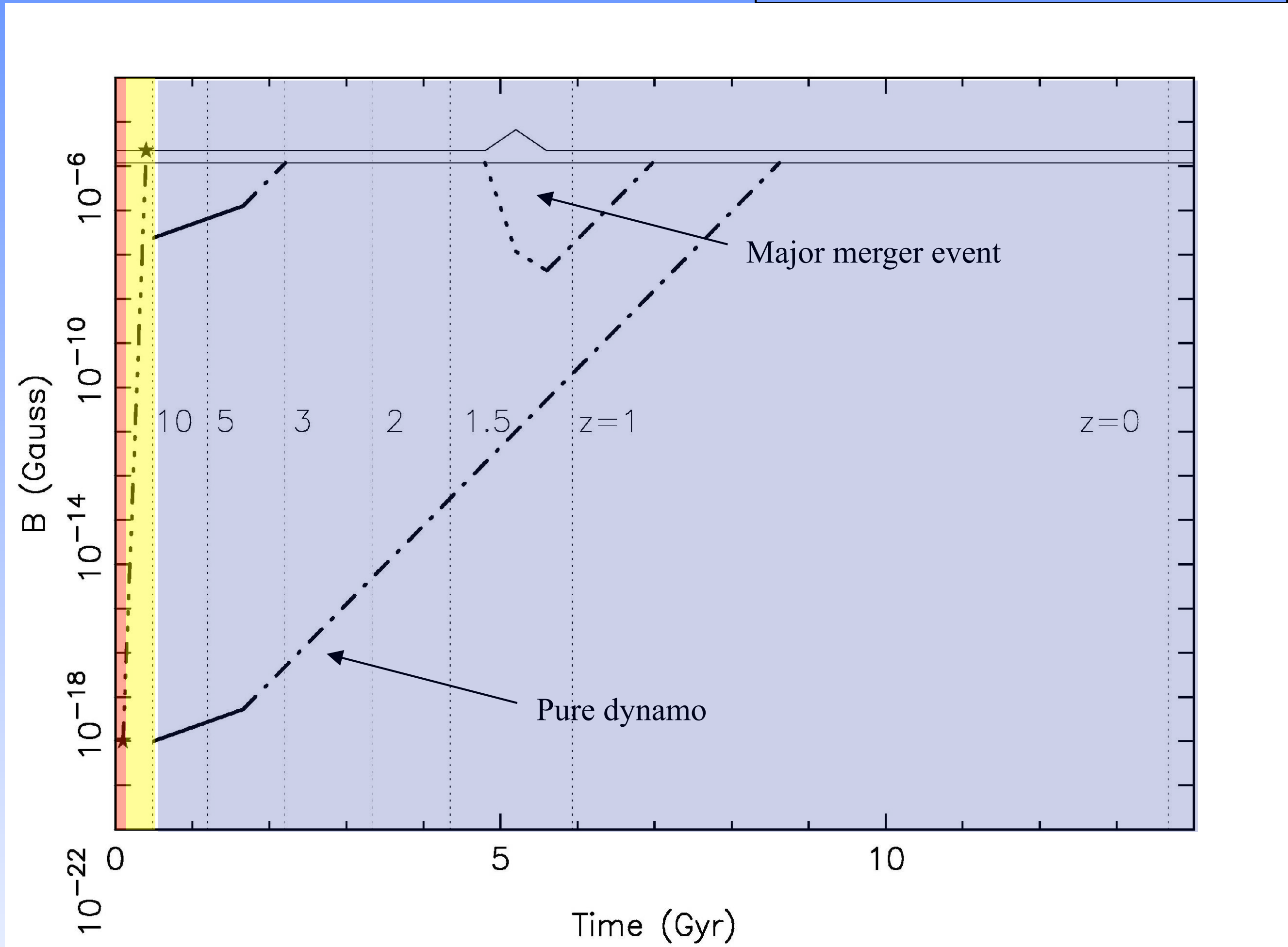
- Phase 1: primordial seed fields of 10^{-18} Gauss
  (before merging of dark matter halos: z<40).

- **Phase 2:** turbulent dynamo in a protogalaxy – B_{turb} ~ 2×10^{-5} Gauss in about a few 10^8 yr (during the merging: z~20-10).

- Phase 3: mean-field dynamo in the disk of a new born galaxy – B_{reg}~10^{-5} G in a few 10^9 yr (z~10).

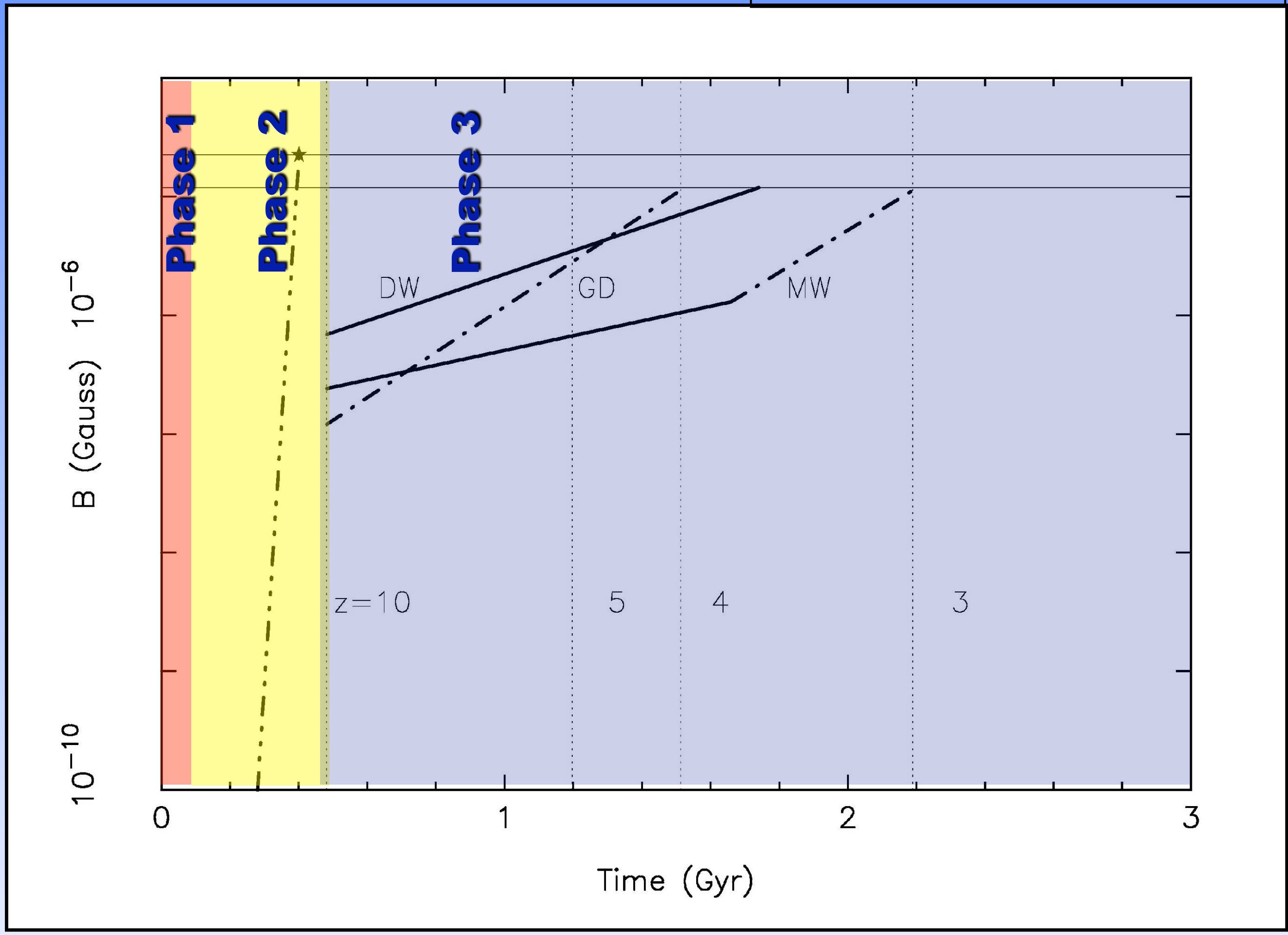
Magnetic field amplification

Arshakian et al. 2009



Magnetic field amplification

Arshakian et al. 2009



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

Phase 3: Toy model of evolving magnetic fields in disk galaxies

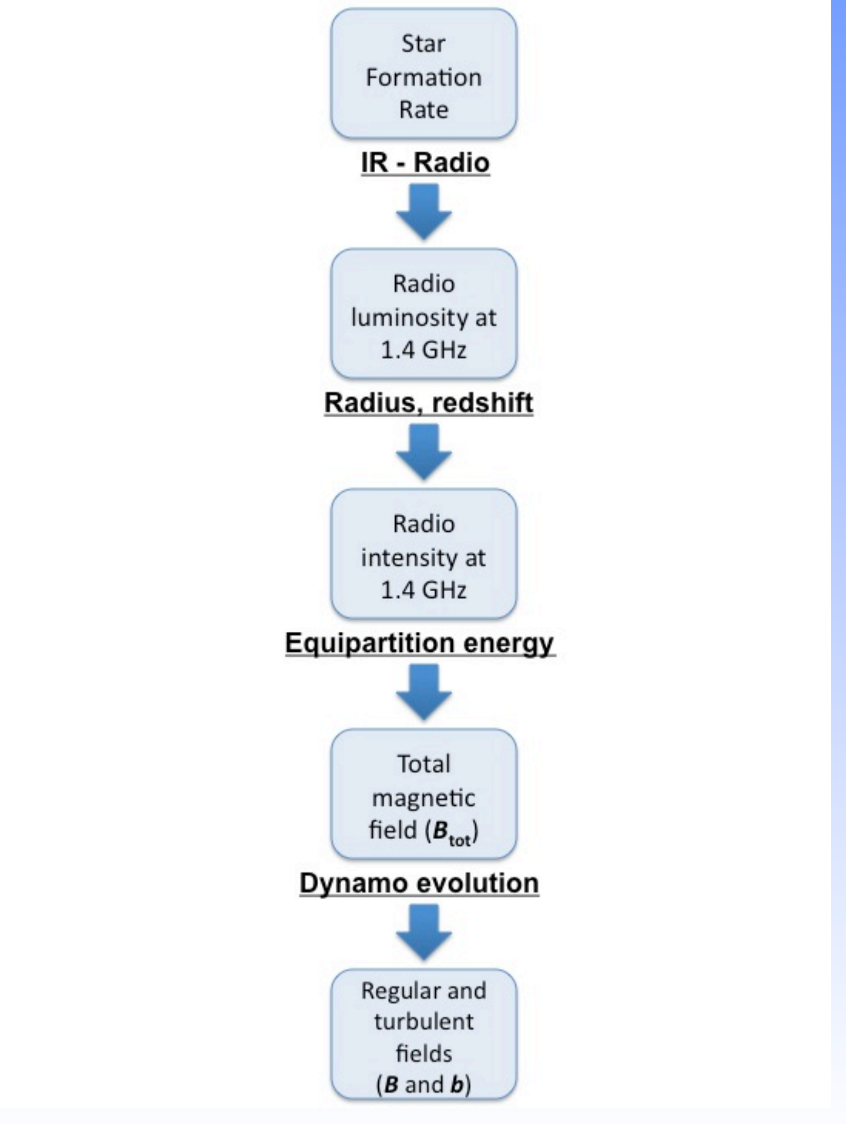
- Structure: thin disk (*h/R* < 0.1).

- Turbulence: SN-driven.

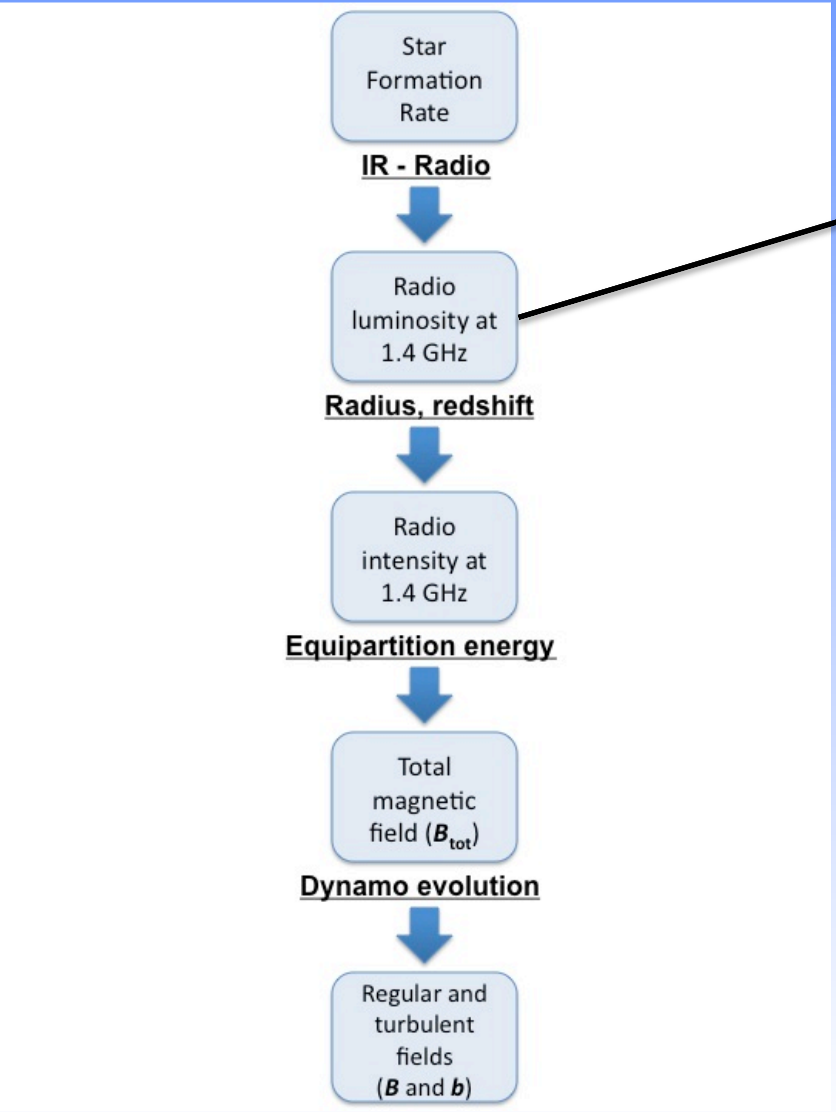
- Initial configuration of magnetic fields in the disk:
  - **Amplitude of initial seed fields**: rms of turbulent magnetic field of 20 microG.
  - **Structure of the field**: magnetic spots of size ~100 pc (N~75,000).
  - **Spots in action**: with pitch angles between 15 and 25 deg (N~20).
  - **Orientation** of the regular field in the spots: random.

- Evolution of the spotty configuration:
  - **Amplification** of the regular field and **growth** of the ordering scale in a radial direction (Arshakian et al. 2009).
  - **Azimuthal ordering scale**: ~1.5 faster than in radial direction.

The link between SFR and total magnetic field



The link between SFR and total magnetic field

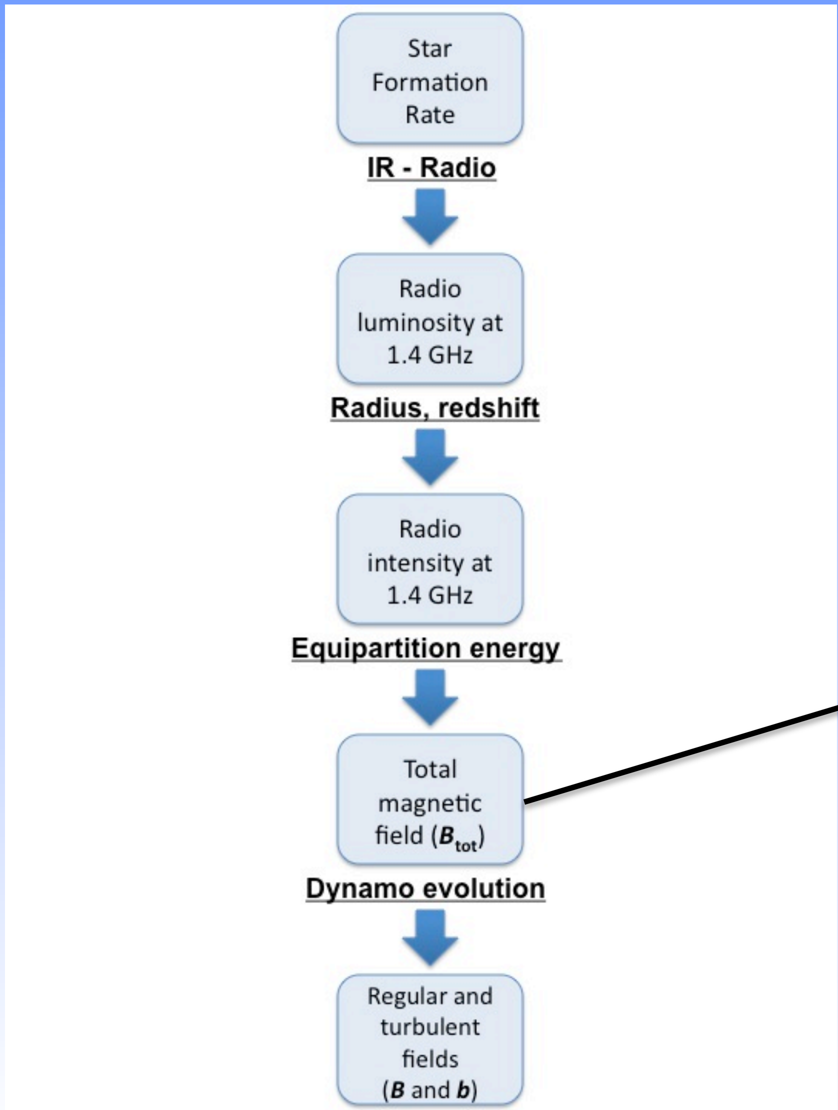


$$\mathrm{SFR(radio)} = \begin{cases} 5.52 \times 10^{-22} L_{1.4}, & \text{if } L_{1.4} > L_c \\ \dfrac{5.52 \times 10^{-22} L_{1.4}}{0.1 + 0.9 (L_{1.4}/L_c)^{0.3}}, & \text{if } L_{1.4} \leq L_c, \end{cases}$$

where $L_c = 6.4 \times 10^{21}$ W Hz^{-1}.

Bell (2003)

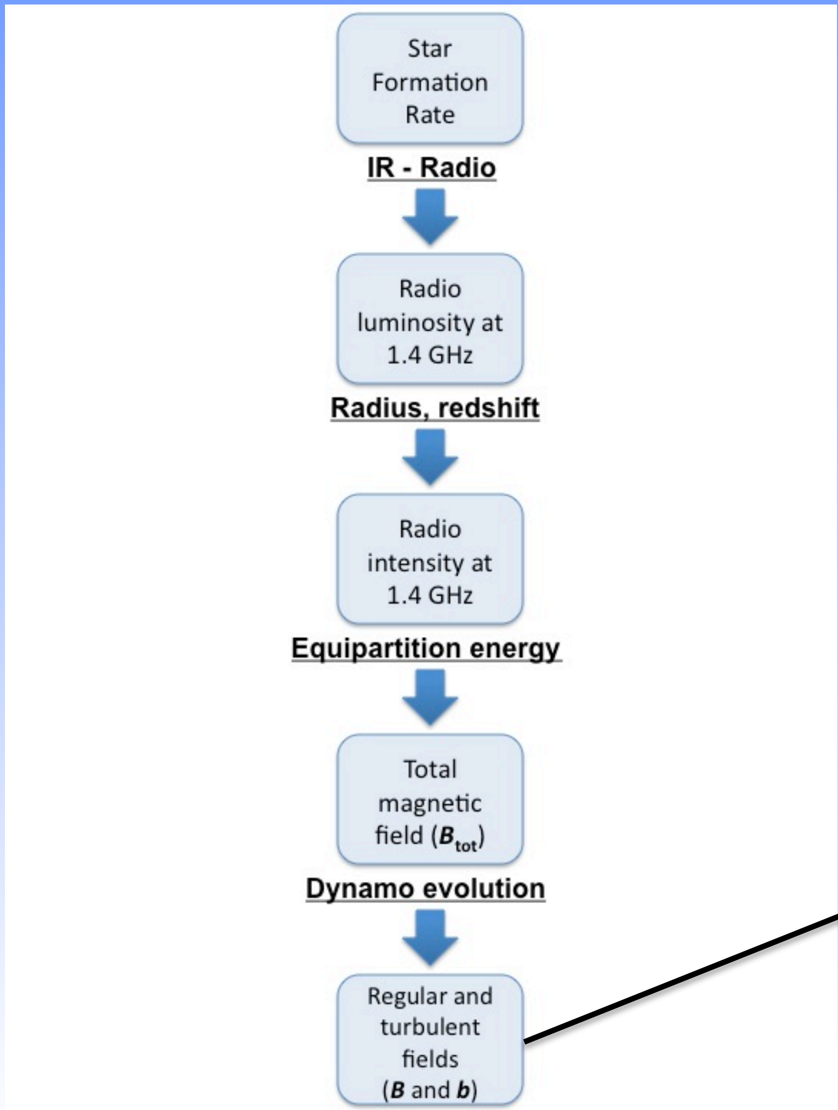
The link between SFR and total magnetic field



$$B_{\mathrm{eq}} = \left\{ 4\pi(2\alpha+1)\,(\mathbf{K_0}+1)\,I_\nu\ E_{\mathrm{p}}^{1-2\alpha}\ (\nu/2c_1)^{\alpha} \ / \ \left[(2\alpha-1)\,c_2(\alpha)\,l\,c_4(i)\right]\right\}^{1/(\alpha+3)} .$$

Beck & Krause (2005)

The link between SFR and total magnetic field



Arshakian et al. (2009)

$$b = B_{\rm tot}(t)\left[1 + \left(\frac{e^{t/t^*}}{\sqrt{N}}\right)^2\right]^{-\frac{1}{2}},$$

and

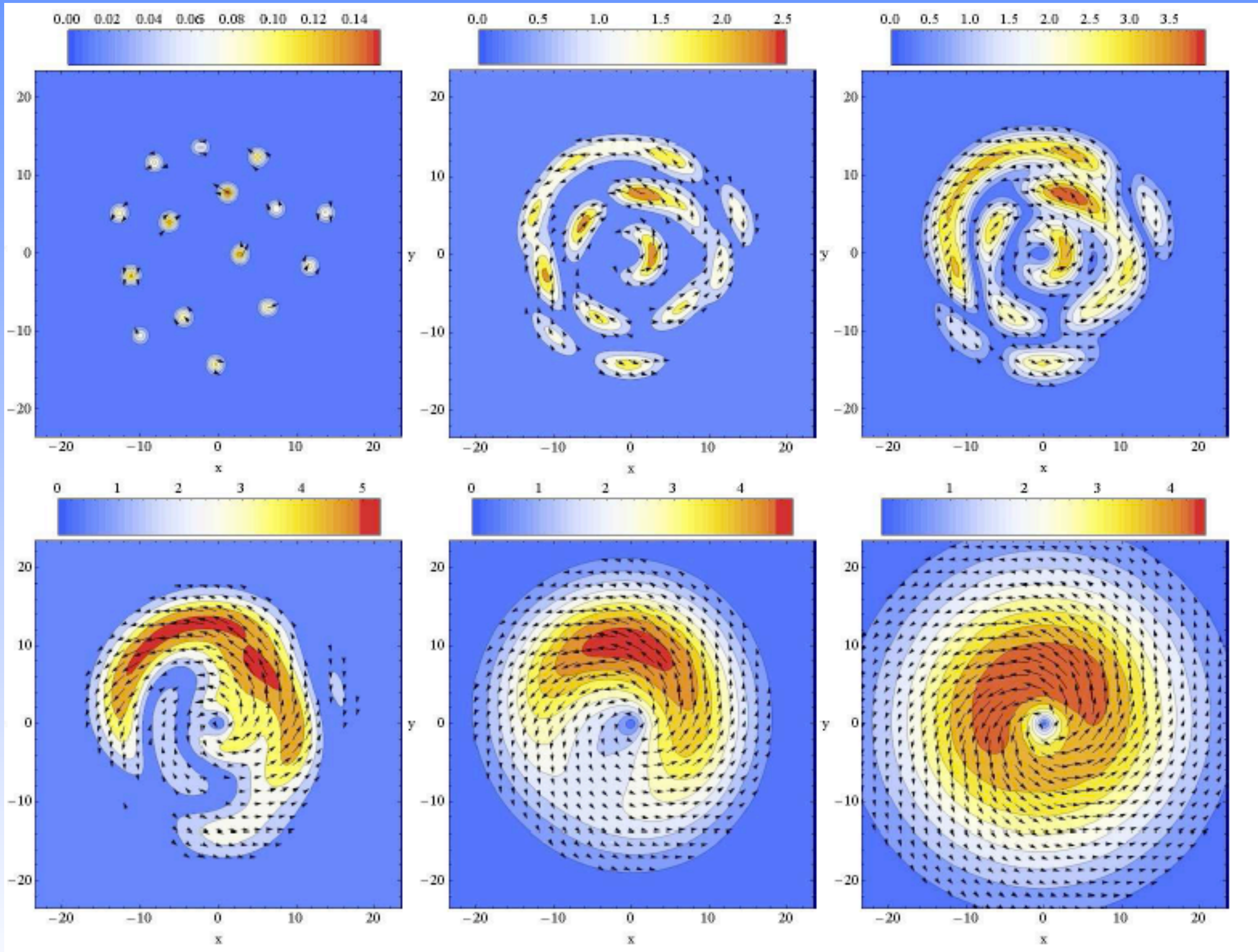
$$B(t) = B_{\rm tot}(t)\frac{e^{t/t^*}}{\sqrt{N}}\left[1 + \left(\frac{e^{t/t^*}}{\sqrt{N}}\right)^2\right]^{-\frac{1}{2}}$$

where $t^* = h/(\Omega l)$

N is the number of turbulent cells in the disk of a galaxy at $t = 0$

Simulations of regular magnetic fields

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)

Simulations of I, PI, and RM at 5 GHz (rest frame)

- R = 10 kpc
- Inclination = 60 deg
- SFR = 10 M_{sun} yr^{-1}
- B_{turb} = 20 microG
- B_{reg} = (0.06 – 10) microG
- Age: 0.5, 1, 2, and 13 Gyr

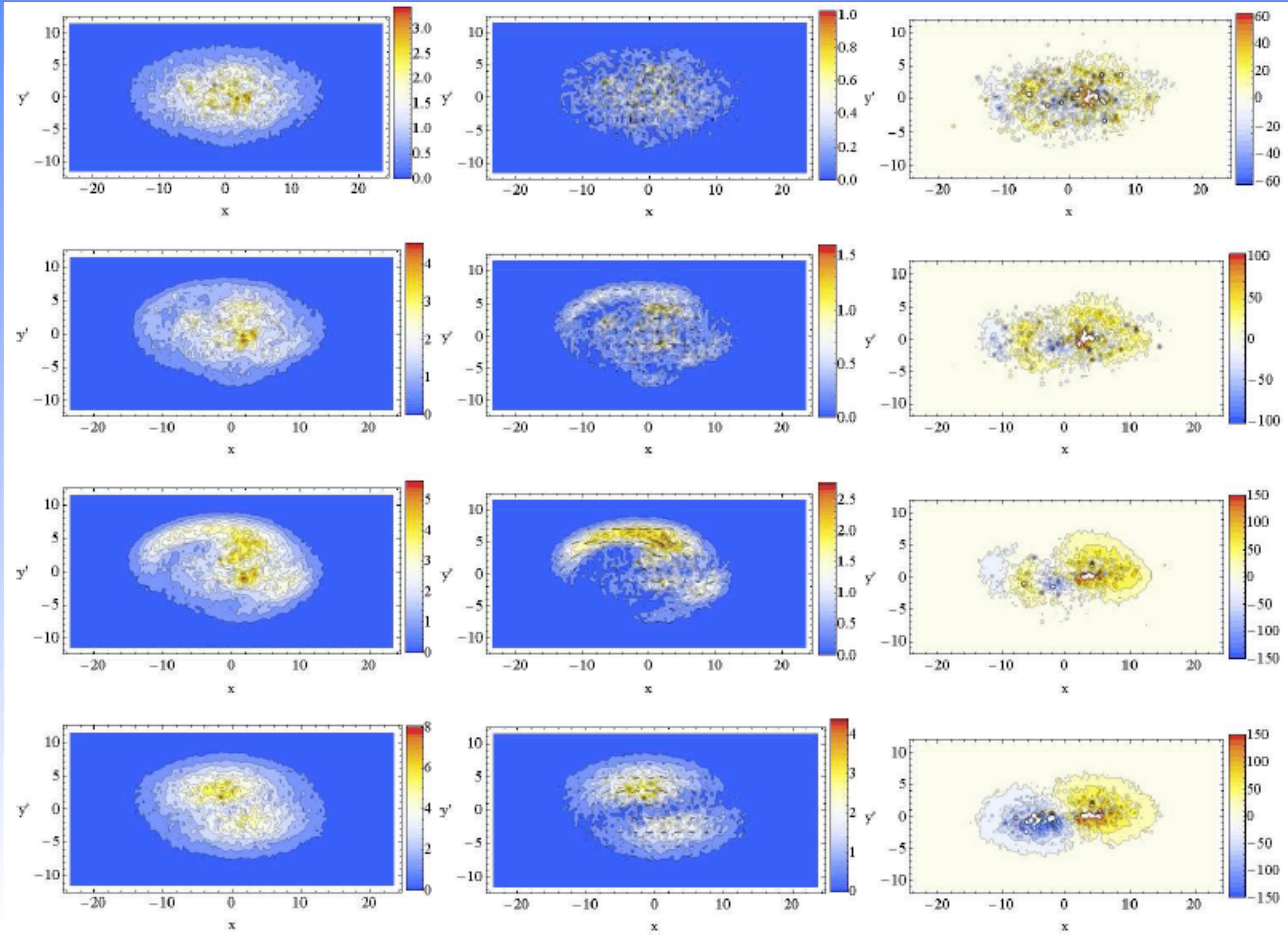
Simulations of I, PI, and RM at 5 GHz

0.5 Gyr

1 Gyr

2 Gyr

13 Gyr



Simulations of PI and RM at 150 MHz

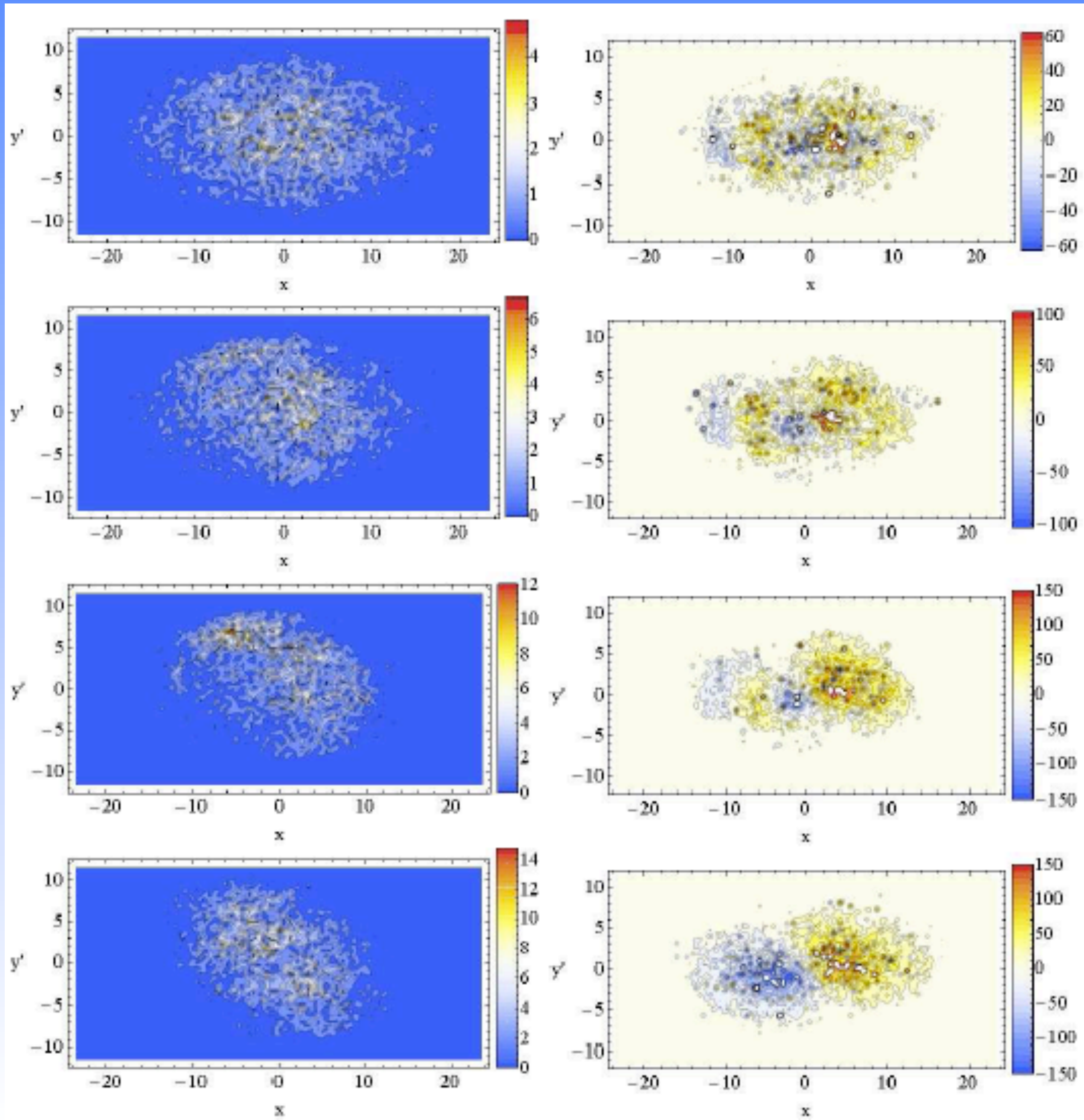
Rest frame

0.5 Gyr

1 Gyr

2 Gyr

13 Gyr



Simulations of PI and RM at 150 MHz

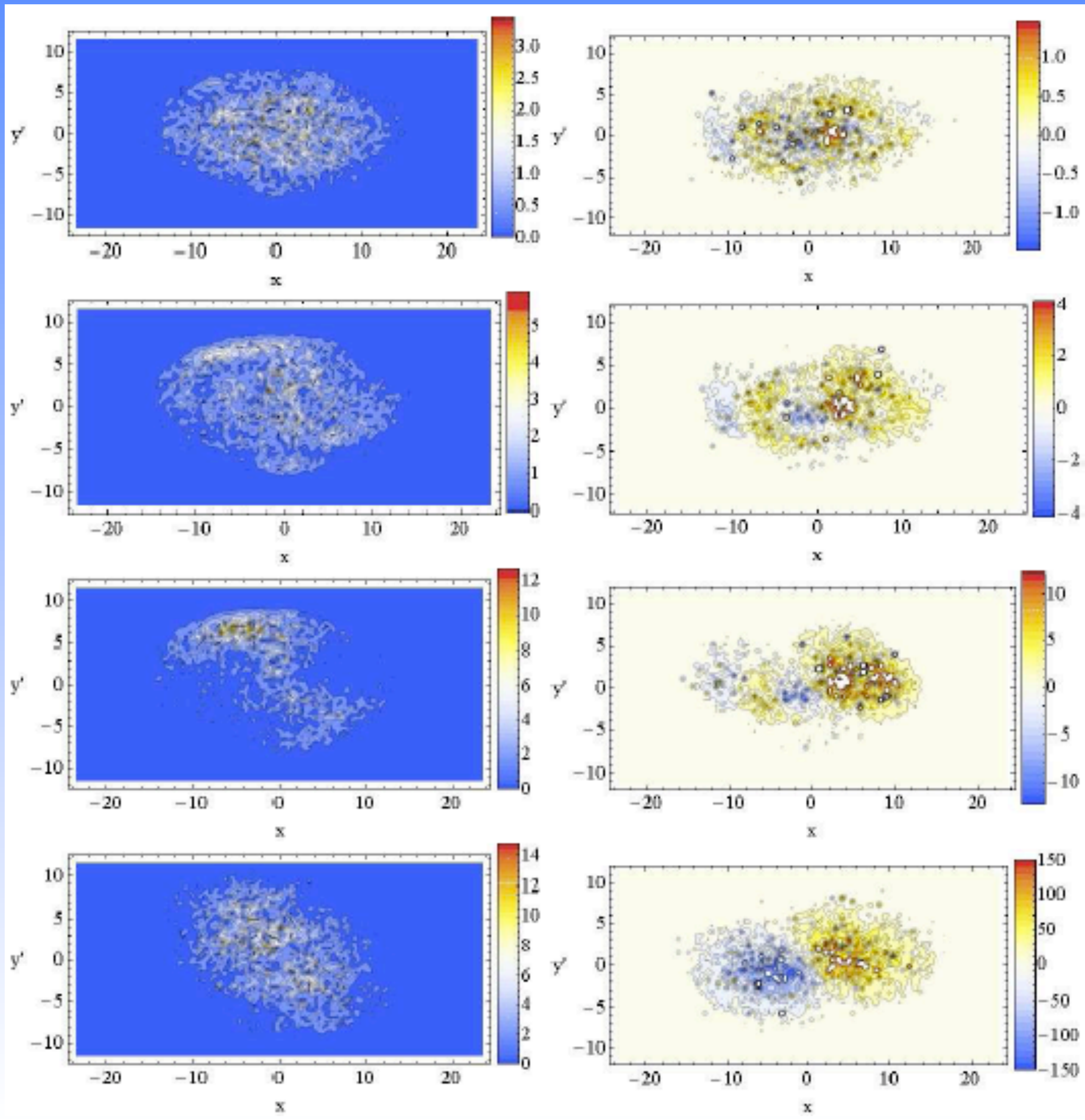
Observer frame

0.5 Gyr
(z~5.2)

1 Gyr
(z~4.5)

2 Gyr
(z~2.7)

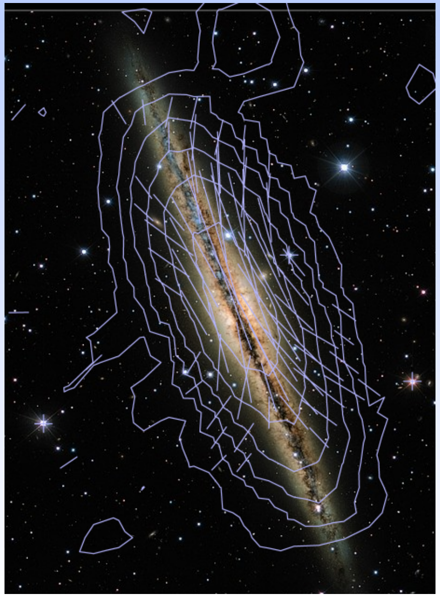
13 Gyr
(z~0)



Limitations of the present model

- Simulations are valid for thin-disk galaxies.
- IC losses off the CMB at z>3 are strong and not taken into accont -> Simulations should be realistic for SFG up to z~3.
- Simulations are valid for disk galaxies with SFR < 20 M_{sun} yr^{-1}.
- Simulations assume that the field structure in the halo is the same as in the disk and do not take into account the X-shaped halo fields.
- Realistic MHD and dynamo models are needed (Hanasz 2009, Elstner,Moss) for young galaxies.

NGC 891 (Krause 2009)



Perspectives for the SKA

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

Predictions of the simple dynamo model:

- Reversals of the regular field at intermediate age (~2 Gyr).
- MW-type galaxies: formed at $z \leq 10$; $\boldsymbol{B}_{reg,\ equip}$ is reached at $z \sim 3$, full ordering at $z \sim 0.5$.
- Large spiral galaxies host fully coherent fields at $z < 0.5$.
- Symmetric structures in polarization at earlier epochs, Axisymmetric at later epochs ().
- Interacting and merging of galaxies should reveal complicated field structures.
- Fully ordered fields indicates that a galaxy did not suffer any major merger since 9 Gyr.