COSMIC-RAY DRIVEN MAGNETIC FIELD DYNAMO IN GALAXIES

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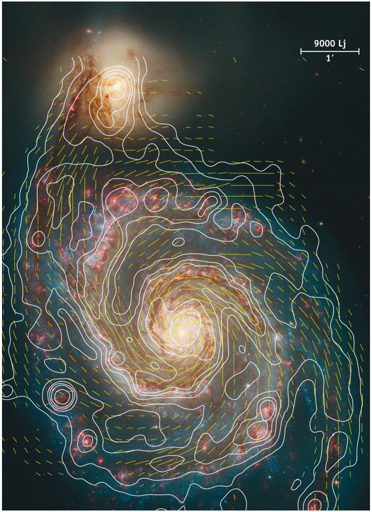
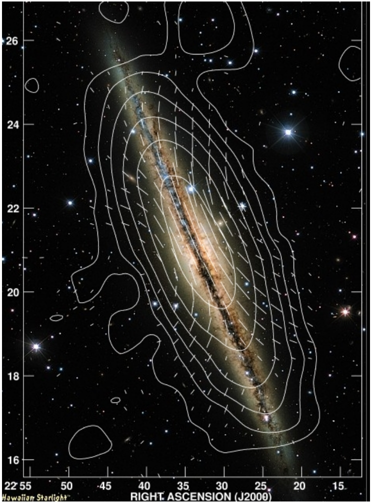
MAGNETIC FIELDS IN SPIRAL GALAXIES - RADIO OBSERVATIONS

M51



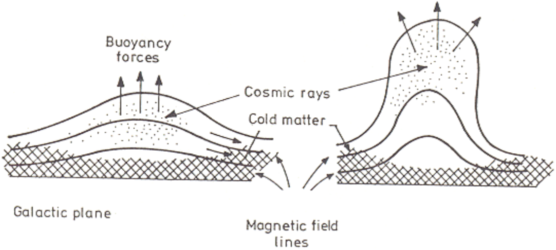
A. Fletcher et al. 2008

NGC891



M. Krause et al. 2008

Parker instability in the ISM (Parker 1966, 1967)



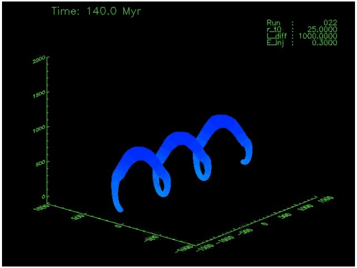
(from Longair 1994, *High Energy Astrophysics)*

- Cosmic ray gas: an important ingredient - continuously supplied by SN remnants (diffusive shock acceleration), lead to strong buoyancy effects.
- Kinetic energy of SN II explosion $\sim 10^{51}$erg $\Rightarrow$ 10 % of $E_{\rm SN}$ $\rightarrow$ acceleration of cosmic rays - charged particles (protons, electrons) accelerated in shocks to relativistic energies

TOY MODEL: THIN FLUX-TUBE APPROXIMATION

(Hanasz & Lesch 2000, ApJ, 543, 235)

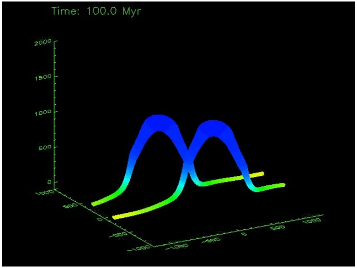
⇒ helical magnetic loops form on initially azimuthal magnetic field due to buoyancy of cosmic rays and the Coriolis force



⇒ small scale loops reconnect to form larger loops

⇒ generation of the large-scale radial m.f.

⇒ differential rotation: generation of the azimuthal m.f.



MHD EQUATIONS

$$\frac{\partial \boldsymbol{V}}{\partial t} + (\boldsymbol{V} \cdot \nabla)\boldsymbol{V} = -\frac{1}{\rho}\nabla(p + p_{CR}) + \boldsymbol{g} + \frac{1}{\rho}\nabla\left(\frac{B^2}{8\pi}\right) + \frac{\boldsymbol{B} \cdot \nabla \boldsymbol{B}}{4\pi\rho}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0$$

$$p = c_s^2 \rho \qquad \text{(isoth.approx)}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) + \eta \nabla^2 B$$

CR TRANSPORT EQUATION

Diffusion - advection approximation

(eg. Schlickeiser & Lerche 1985, A&A, 151, 151)

$$\frac{\partial e_{\rm cr}}{\partial t} + \nabla(e_{\rm cr}\boldsymbol{V}) = -p_{\rm cr}\nabla\boldsymbol{V} + \nabla(\hat{K}\nabla e_{\rm cr}) \qquad (1)$$

$$+ \text{ CR sources (SN remnants)}$$

$$p_{\rm cr} = (\gamma_{\rm cr} - 1)e_{\rm cr} \qquad (2)$$

Anisotropic diffusion of CRs

(Giaccalone & Jokipii 1998 , Jokipii 1999, Ryu et al. 2003)

$$K_{ij} = K_{\perp}\delta_{ij} + (K_{\parallel} - K_{\perp})n_i n_j, \quad n_i = B_i/B, \qquad (3)$$

$$K_{\parallel} = 3\cdot 10^{28}\mathrm{cm}^{2}\mathrm{s}^{-1}, \qquad K_{\perp} = (1-10)\%\,(K_{\parallel})$$

Original idea: Parker (1992)

Shearing box model:

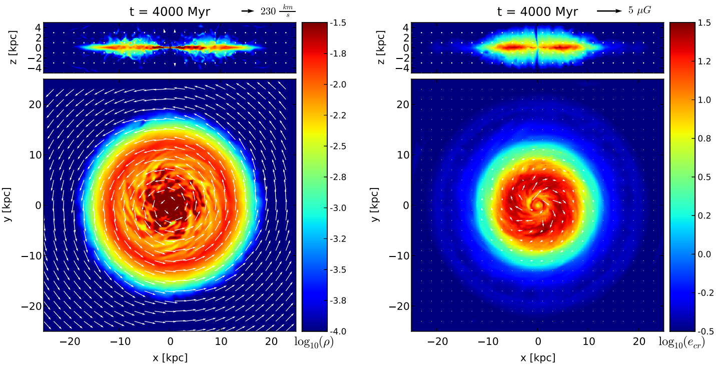
Hanasz, Kowal, Otmianowska-Mazur & Lesch, 2004, ApJL, 605, 33
Hanasz, Otmianowska-Mazur, Kowal & Lesch, 2009, A&A, 498, 335

- the cosmic ray component: anisotropic diffusion-advection transport (Hanasz and Lesch 2003 - numerical algorithm).
- localized sources of cosmic rays: supernova remnants, exploding randomly in the disk volume, SN shocks & thermal effects neglected
- resistivity of the ISM (see Hanasz, Otmianowska-Mazur and Lesch 2002, and Hanasz and Lesch 2003, Kowal, Hanasz & Otmianowska-Mazur 2003) $\Rightarrow$ magnetic reconnection.
- differential rotation (+ Coriolis and tidal forces in local simulations)
- realistic vertical disk gravity following the model of ISM in the Milky Way by Ferriere (1998)

GALACTIC DISK MODEL

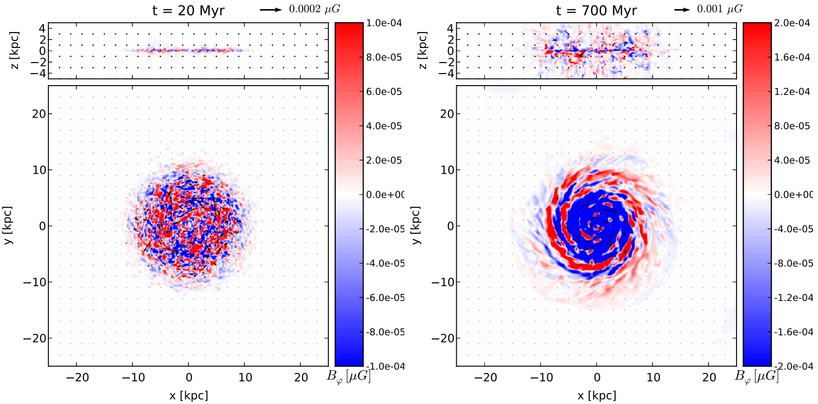
- Galactic gravitational potential: halo+bulge+disk (Allen & Santillan 1991)
- Interstellar gas: Global model of ISM for the Milky Way (Ferriere 1998)
- **No magnetic field at** $t = 0$
- SN rate $\propto$ star formation rate $\propto$ to gas column density: maximum of SN activity at $R_G = 4.5\text{kpc}$, Gaussian distribution of SNe in z-coordinate ($H = 200\text{pc}$)
- 10% of of SN energy output is converted to CR energy.
- **weak ($10^{-4}\mu$G) dipolar, small scale ($r \sim 50\text{pc}$) randomly oriented magnetic field is supplied locally with every SN explosion for** $t \leq 1$**Gyr**
- resistive dissipation of small-scale magnetic fields.

Multifluid, parallel (MPI) magnetohydrodynamical code PIERNIK (Hanasz et al. 2008): http://piernik.astri.uni.torun.pl, GALERA, TASK Gdańsk, resol. 500x500x200 up to 1000x1000x200 grid cells, $\simeq$ 100k-250k CPU h per experiment, 400-1600 CPU cores.



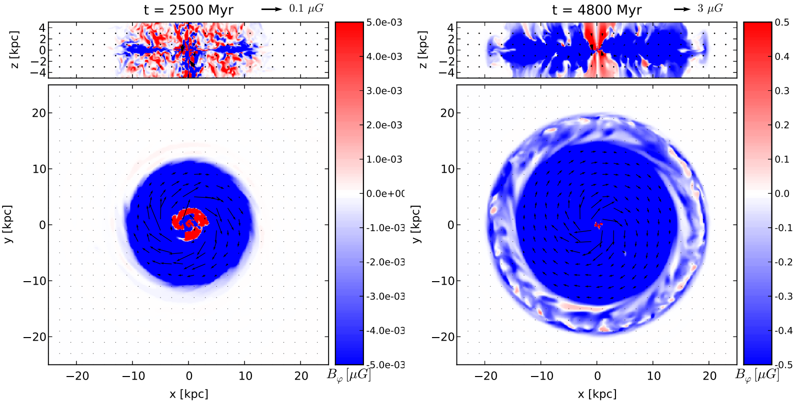
Gas density + wectors of gas velocity (left), a and cosmic ray energy density + vectors of magnetic field at $t = 4$Gyr .

Hanasz, Woltański, Kowalik 2009, ApJ Letter 706L, 155



Colours: – azimuthal (toroidal) magnetic field component blue: $B_\varphi < 0$, red: $B_\varphi > 0$

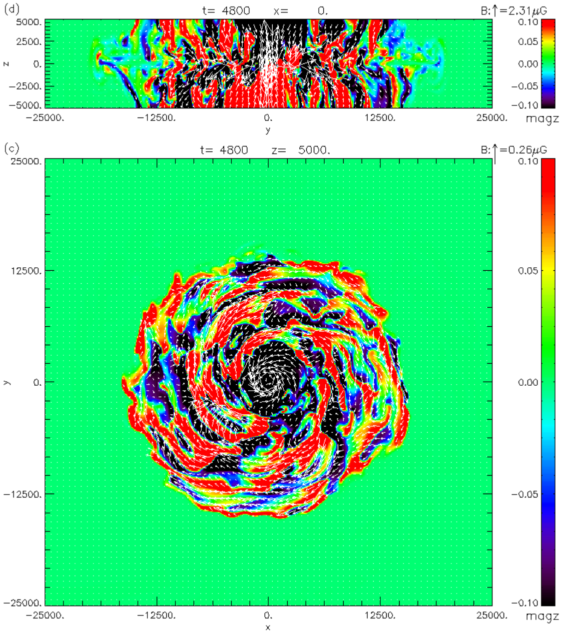
Exploding magnetized stars spread weak irregular magnetic fields in the interstellar medium



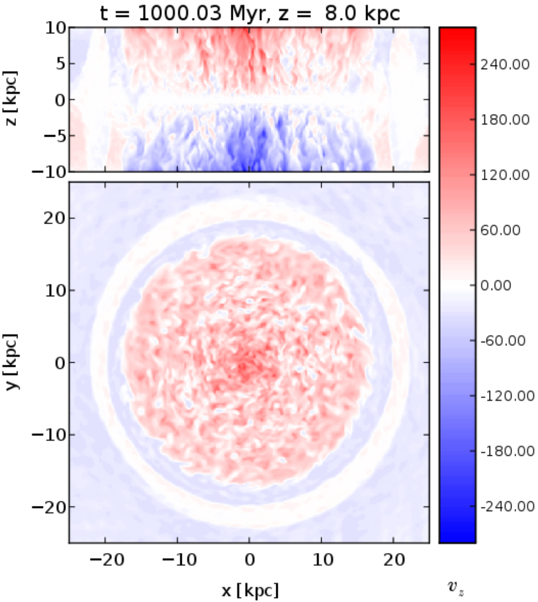
Colours: – azimuthal (toroidal) magnetic field component blue: $B_\varphi < 0$, red: $B_\varphi > 0$

Cosmic rays resulting from Supernova Explosions, and disk rotation cause amplification and ordering of magnetic field in the interstellar medium

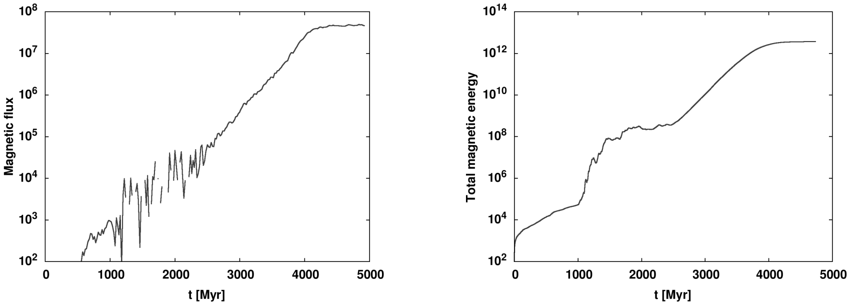
VERTICAL FIELDS



CR-DRIVEN WIND



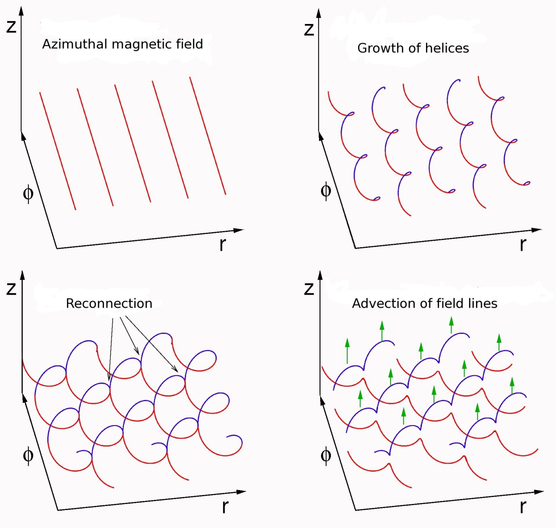
GROWTH OF MAGNETIC FLUX AND ENERGY IN THE GLOBAL DISK



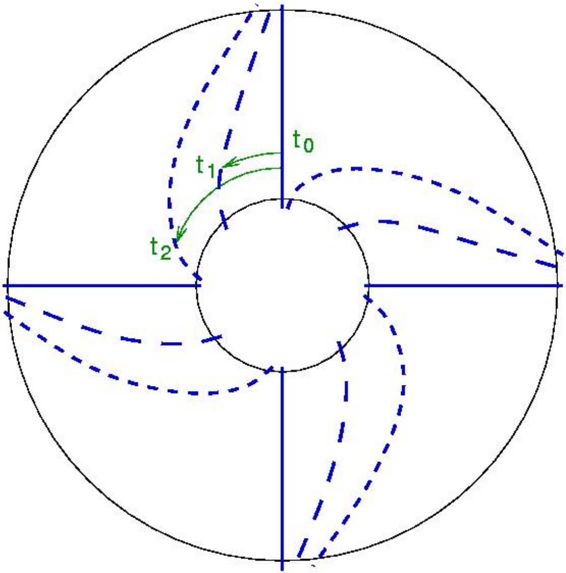
Amplification timescale of the large-scale magnetic field component:

$$T_{\langle B \rangle} = 270\mathrm{Myr} \simeq T_{rot}$$

Parker instability + resistivity

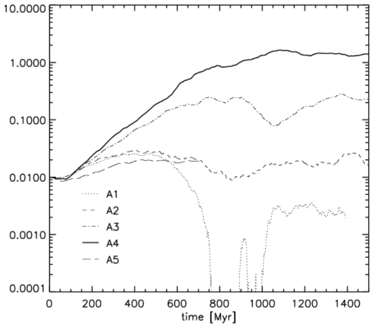


Hanasz & Lesch (1998)

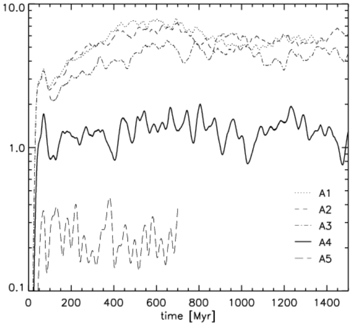


Differential rotation

Azimuthal magnetic flux



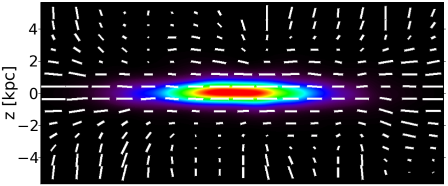
B^2_{vert} / B^2_{azim}

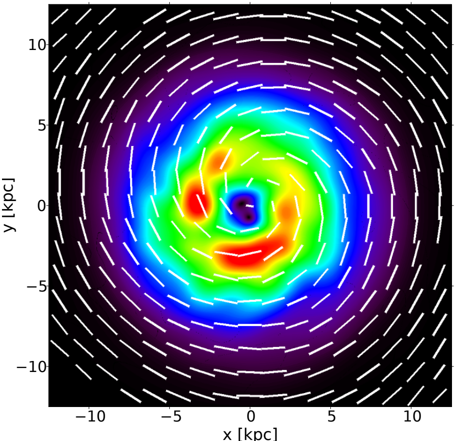


Runs: A1: $\eta = 0$, A2: $\eta = 1$, A3: $\eta = 10$, A4: $\eta = 100$, A5: $\eta = 1000$
Units: $1\text{pc}^2\text{Myr}^{-1} = 3 \cdot 10^{23}\text{cm}^2\text{s}^{-1}$

The fastest magnetic field amplification for magn. diffusivity

$$\eta \simeq 3 \cdot 10^{25}\text{cm}^2\text{s}^{-1}$$



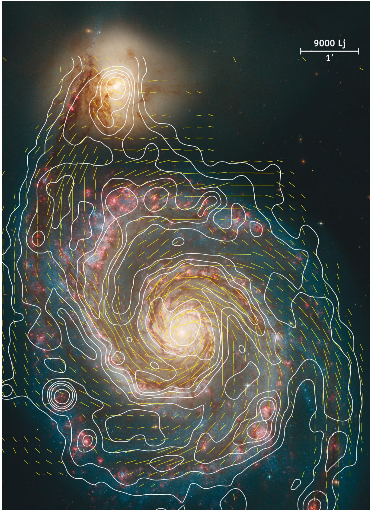


X-type structure in edge-on view

Synthetic radio-maps of the simulated galaxy reproduce the main features observed in real galaxies

Spiral structure of magnetic field in the disk plane

M51



A. Fletcher et al. 2008

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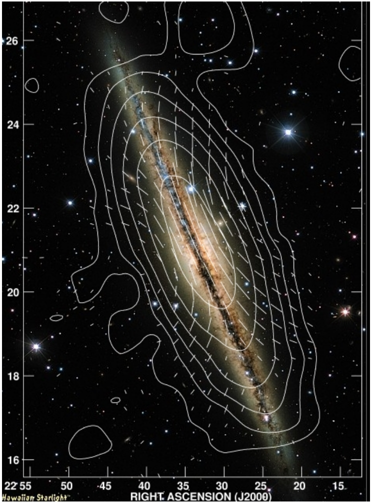
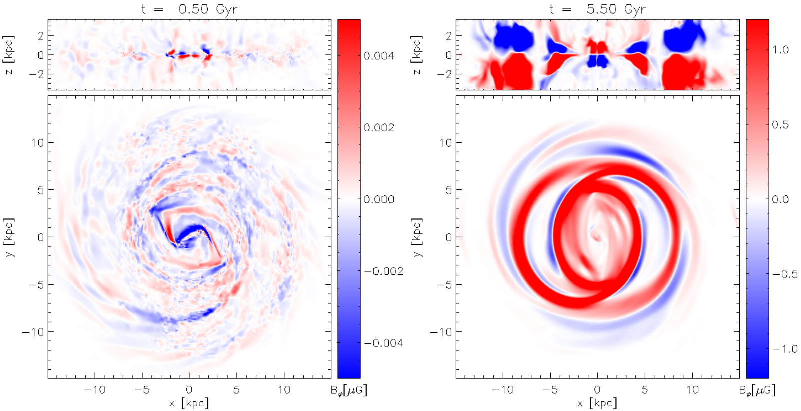


M. Krause et al. 2008

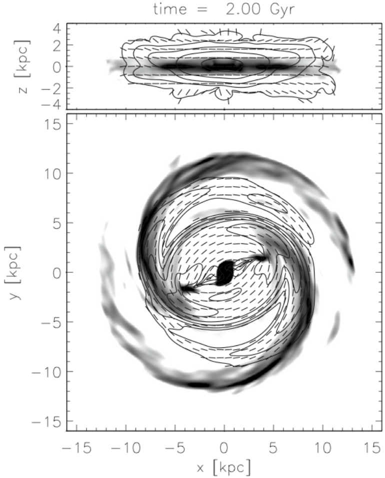
Axisymmetric gravitational potential + elliptical bar



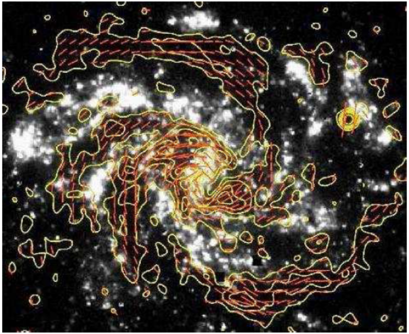
Colours: – azimuthal magnetic field component blue: $B_\varphi < 0$, red: $B_\varphi > 0$
– antisymmetry of the azimuthal m.f with respect to galactic midplane.

Kulpa-Dybel et al. 2011, ApJL, 733,L18

Synthetic radio maps

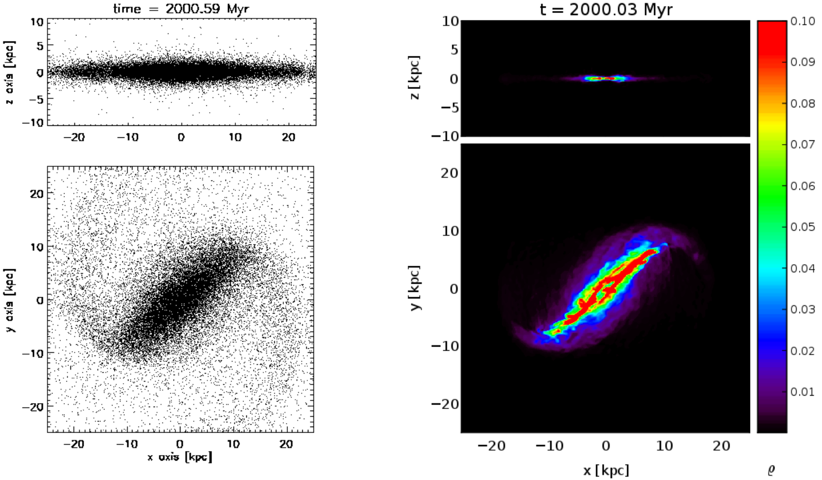


Kulpa-Dybel et al. 2011, ApJL, 733,L18

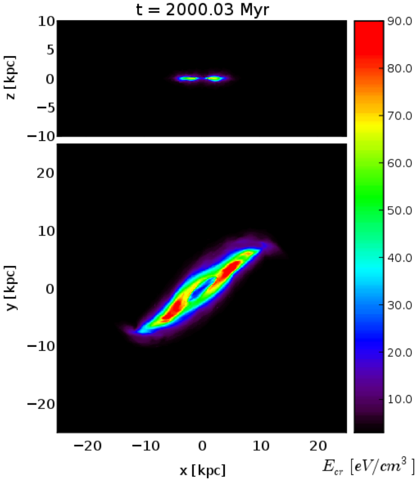


Beck & Hoernes 1996, Beck 2011

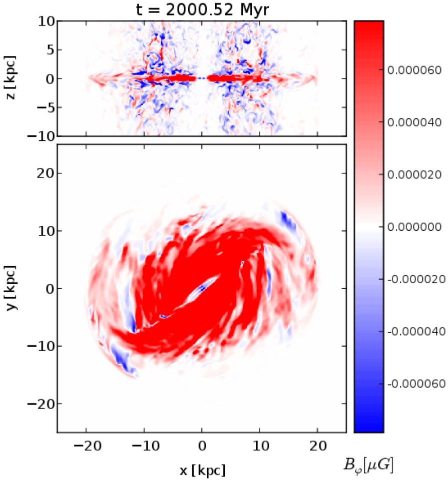
LIVE DISKS: STARS + GAS



STARS + GAS

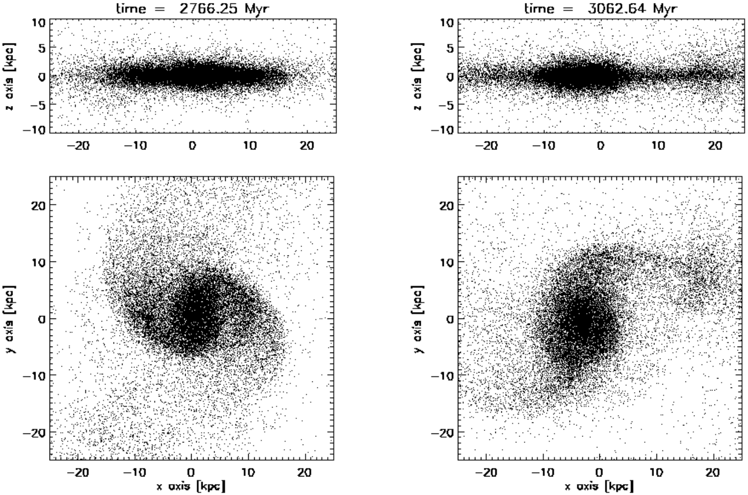


t = 2000.03 Myr
z [kpc]
y [kpc]
x [kpc]
E_{cr} $[eV/cm^3]$
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0

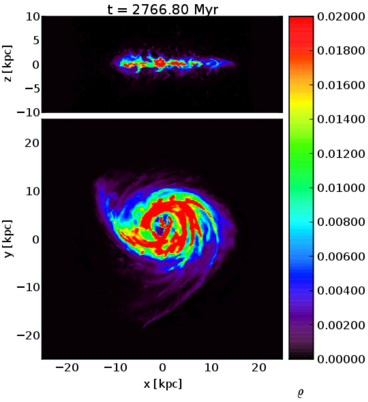


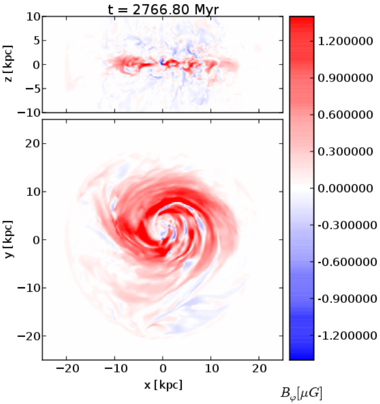
t = 2000.52 Myr
z [kpc]
y [kpc]
x [kpc]
$B_\varphi [\mu G]$
0.000060
0.000040
0.000020
0.000000
-0.000020
-0.000040
-0.000060

N-body simulations: VINE code (Wetzstein et al 2008)



Evolution of gas density and toroidal magnetic field in the gravitational field of N-body system





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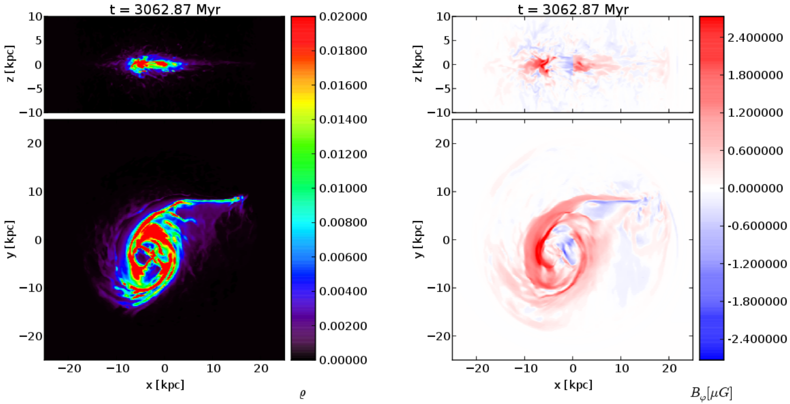
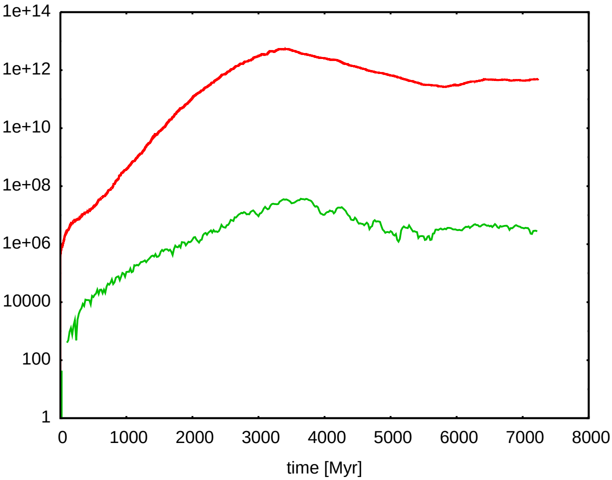


MAGNETIC FIELD AMPLIFICATION IN THE LIVE DISK



Amplification of magnetic energy (red) and azim. magnetic flux (green)

- COSMIC RAY DYNAMICS LEADS TO A VERY EFFICIENT MAGNETIC FIELD AMPLIFICATION IN GALACTIC DISKS
- Amplification timescale $\sim t_{rot} \Rightarrow$ growth of the large-scale magnetic field by several orders of magnitude, fast enough to expect $\sim 1\mu$G magnetic field in galaxies at $z \sim 1 \div 2$
- Dipolar small-scale magnetic fields supplied by exploding stars build up a large scale magnetic field $\Rightarrow$ no need for seed fields of cosmological origin.
- Efficient regularization of the random magnetic field component.
- Growth of magnetic field, driven by SNe, far outside the star forming ring.
- Synthetic radio-maps resemble magnetic field structures in real galaxies.
- Magnetic field in models based on N-body simulations tend to converge to real galaxies.