Galactic dynamos with wind

Detlef Elstner
Abhijit Bendre
Udo Ziegler
Oliver Gressel
Harald Lesch
Frederico Stasyszyn
Hanna Kotarba
Klaus Dolag
Günther Rüdiger

AIP

Irsee 2010

Dynamo

Instability of the induction equation

$$\frac{\partial B}{\partial t} = curl\left(u \times B - \eta curl(B)\right)$$

Kinematic laminar dynamo

Turbulent dynamo: u is turbulent

Fast dynamo: solution converges for $\eta \Rightarrow 0$

Small scale dynamo: no mean field

Magnetic field amplification

Dynamos by SN-driven turbulence are numerically feasible

Box models:

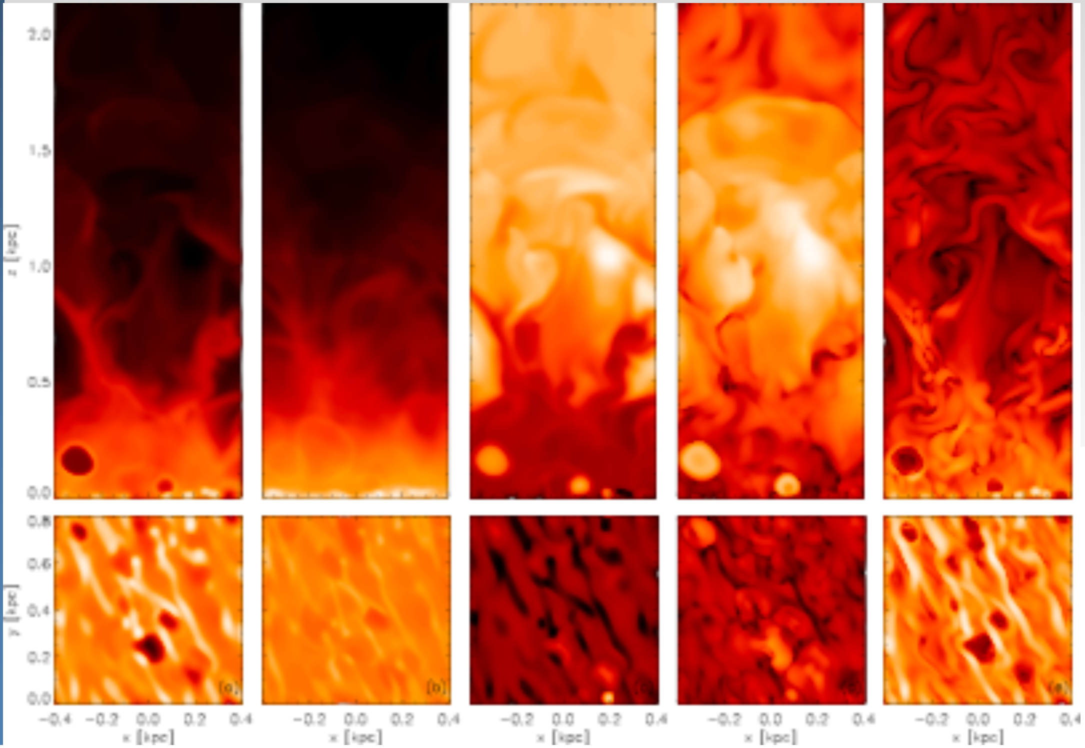
cosmic ray injection (Hanasz et al. 2004)
thermal energy input (Gressel et al. 2008)

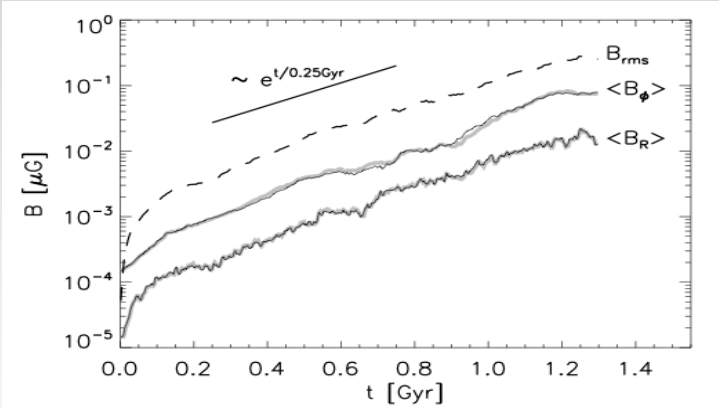
Global models:

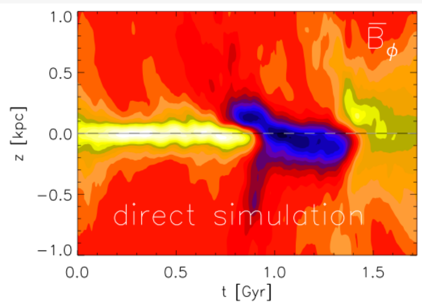
mean field models (.......... since 1960)
artificial velocities (Gissinger et al. 2008)
cosmic ray injection by SN (Hanasz et al.2009)

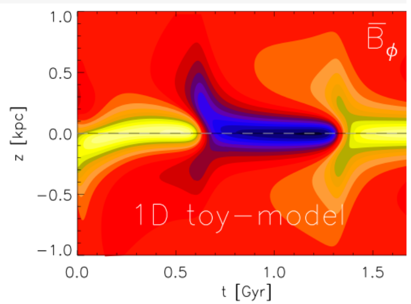
SN driven dynamo

- SN energy is injected by thermal energy explosions
- State of the art simulations of the ISM with heating, cooling
- Wind or fountain flow develops (essential for helicity transport)
- Clustering is essential









SN driven dynamo

Field regularity as IR based star formation rate for NGC 4254

(Chyzy 2008)

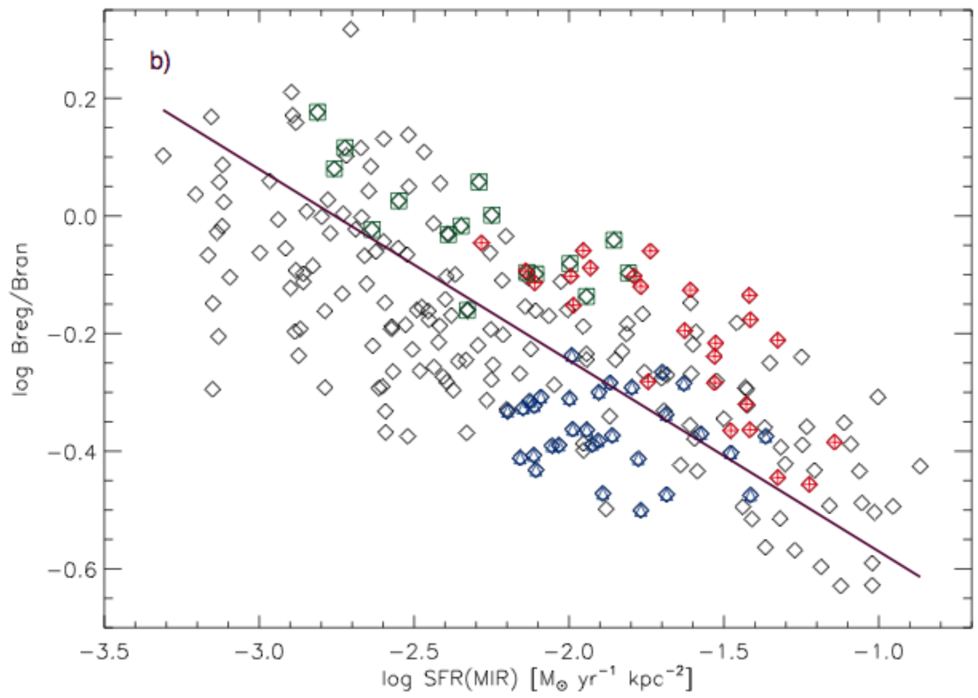
log (B_{reg}: B_{tur}) =

-0.32 ($\pm$0.01) log SFR

-0.90 ($\pm$0.03)

From simulations we get

-0.38 ($\pm$0.01)



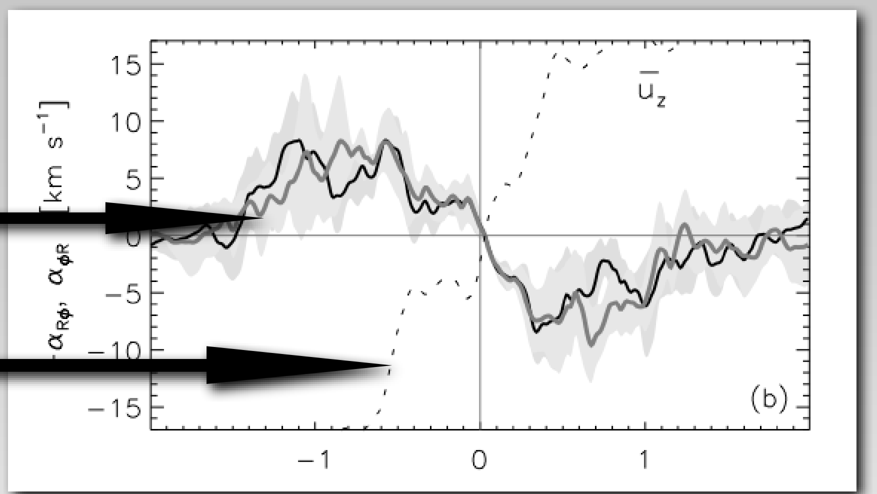
SN-driven dynamo

How it works:

downward pumping

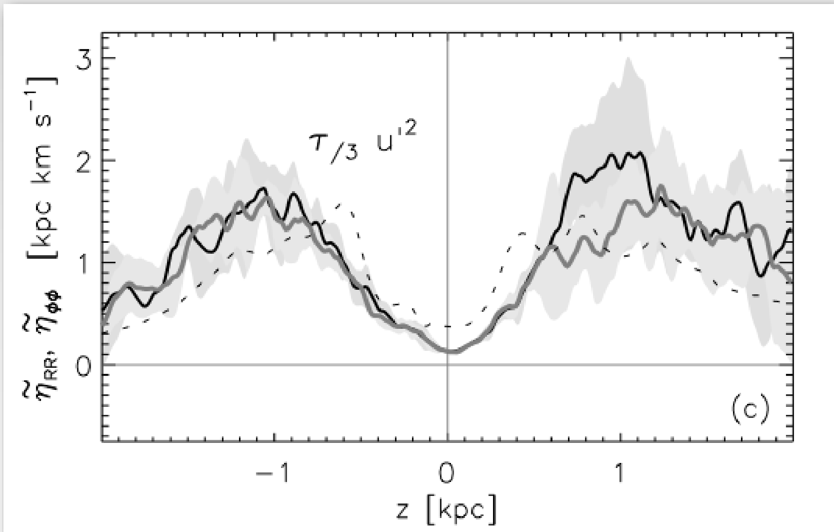
equal

upward fountain flow



pumping acts only on the mean field

fountain flow transports all the magnetic field



Cosmic ray dynamo

- Cosmic ray injection by SN
- Cosmic ray pressure drives more or less turbulent gas flows
- Cosmic rays propagate by anisotropic diffusion
- Missing small scales

How is the behaviour of cosmic ray dynamo in the turbulent ISM ?

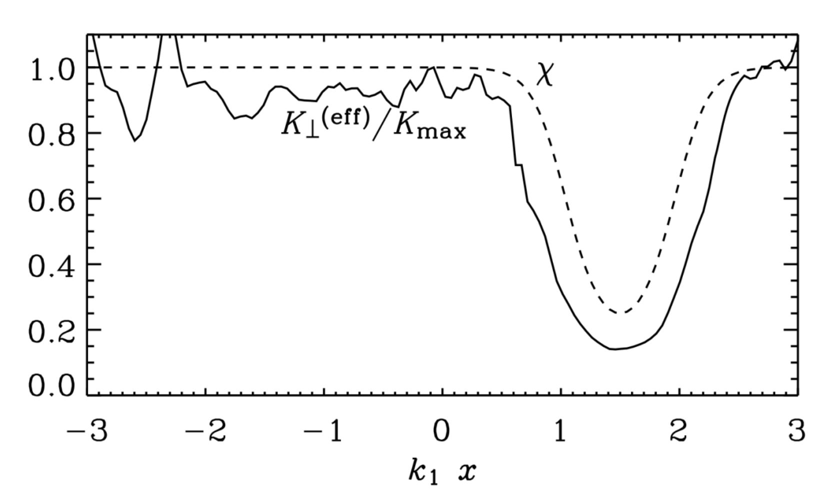
- fast diffusion of cosmic rays
- more isotropic for turbulent fields

SN driven dynamo

Energy input	thermal energy	cosmic rays
Growth time	200 Myrs	200 Myrs
Large Rm	may work	no dynamo
Small Omega	no dynamo (C_Ω=25)	slower growth
B_{reg}/B_{tur}	scales with SN	up to 1
Mean field theory	good agreement	unclear (CR diffusion

Cosmic ray dynamo

Snodin et al. 2006



Dependence of diffusion from ratio of large scale to small scale

$$\chi = \frac{\overline{\delta B^2}}{B_0^2 + (1/3)\delta B^2} = 3\,\frac{\overline{B_x^2}}{\overline{B_y^2}}$$

Lorentz force versus cosmic ray pressure force

$$\frac{F_{\mathrm{c}}}{F_{\mathrm{m}}} \simeq \frac{\ell}{l_{\mathrm{c}}}\frac{E_{\mathrm{c}}}{E_{\mathrm{m}}} \simeq \frac{1}{30}\frac{E_{\mathrm{c}}}{E_{\mathrm{m}}}.$$

AIP

Task 1

Including cosmic rays into the ISM model

Testing the dynamo: Does the cosmic ray dynamo still operate?

Cosmic ray transport advection versus diffusion

Dynamical relevance of cosmic rays for the gas dynamics

Toward global galaxies
Mean field approach

Dynamo models:

global LES in the framework of MF-MHD predict field amplification and topology

rely on proper modelling of underlying turbulence

Mean-field approach: split into mean + fluctuation

U = <u> + u’ B= <B> + B’

MF induction equation

$$\partial_t \bar{\mathbf{B}} = \nabla \times (\bar{\mathbf{u}} \times \bar{\mathbf{B}}) + \nabla \times \mathcal{E} + \eta \nabla^2 \bar{\mathbf{B}}$$

Turbulent EMF $\mathcal{E} = \overline{\mathbf{u}' \times \mathbf{B}'}$

Mean field approach

General closure ansatz

turbulent EMF as functional of <u>, <B> and <f(u´)>

$$\mathcal{E}_i = \alpha_{ij}\bar{B}_j + \eta_{ijk}\partial_k\bar{B}_j \qquad = \alpha_{ij}\bar{B}_j - \tilde{\eta}_{ij}\,\varepsilon_{jkl}\partial_k\bar{B}_l$$

Determine α and η from direct simulations

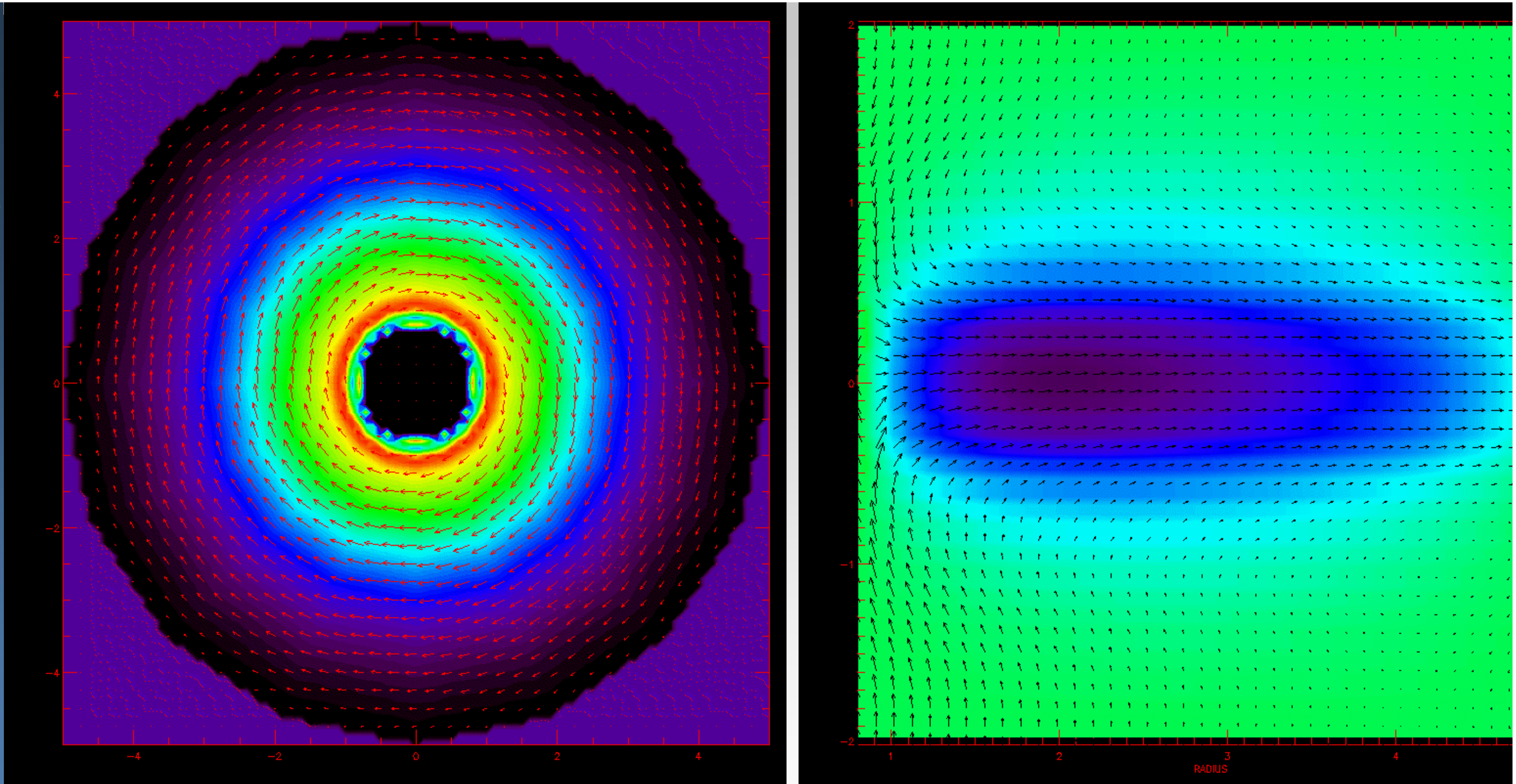
AIP

Test field method

Integrate the induction equation for special choices of B

$$\partial_t \mathcal{B}'_{(\nu)} = \nabla\times \quad [\,\bar{\mathbf{u}}\times\mathcal{B}'_{(\nu)} + \mathbf{u}'\times\mathcal{B}'_{(\nu)} \\ -\overline{\mathbf{u}'\times\mathcal{B}'_{(\nu)}} + \mathbf{u}'\times\bar{\mathcal{B}}_{(\nu)} - \eta\nabla\times\mathcal{B}'_{(\nu)}\,]$$

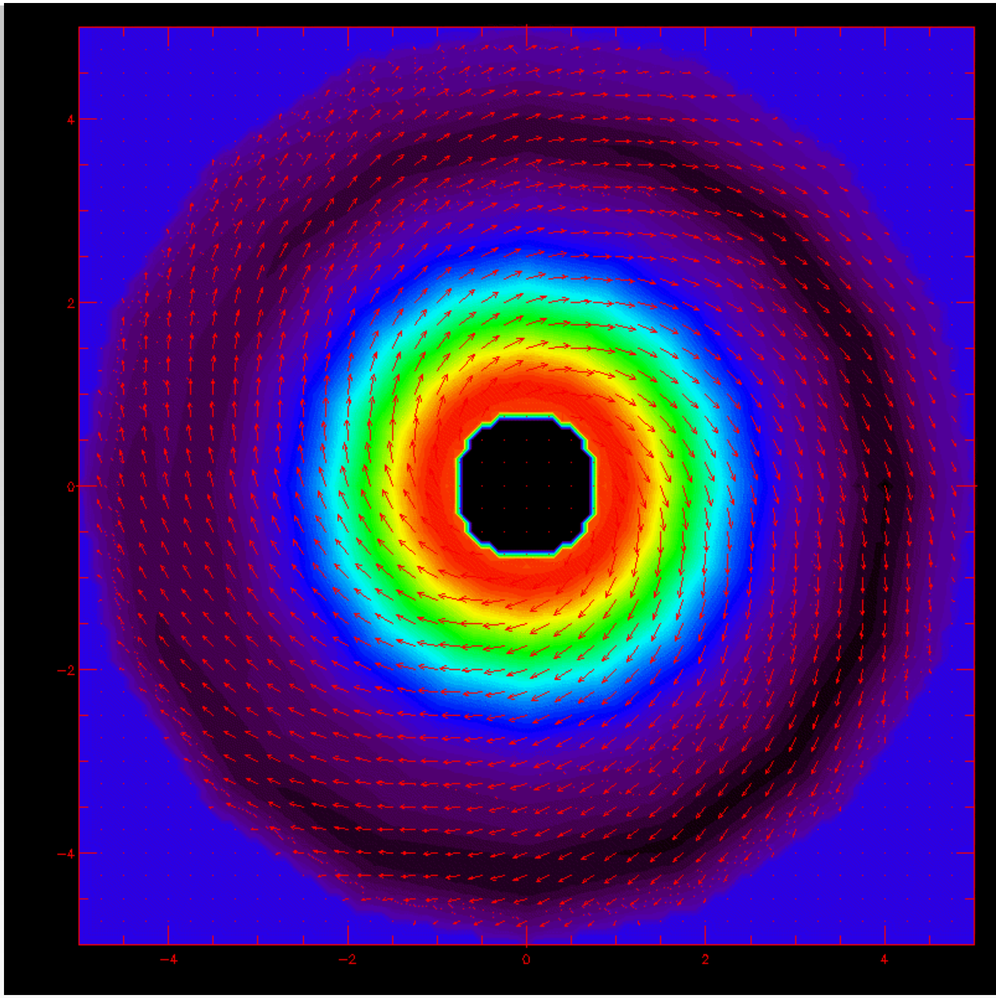
solve the linear system for α and η

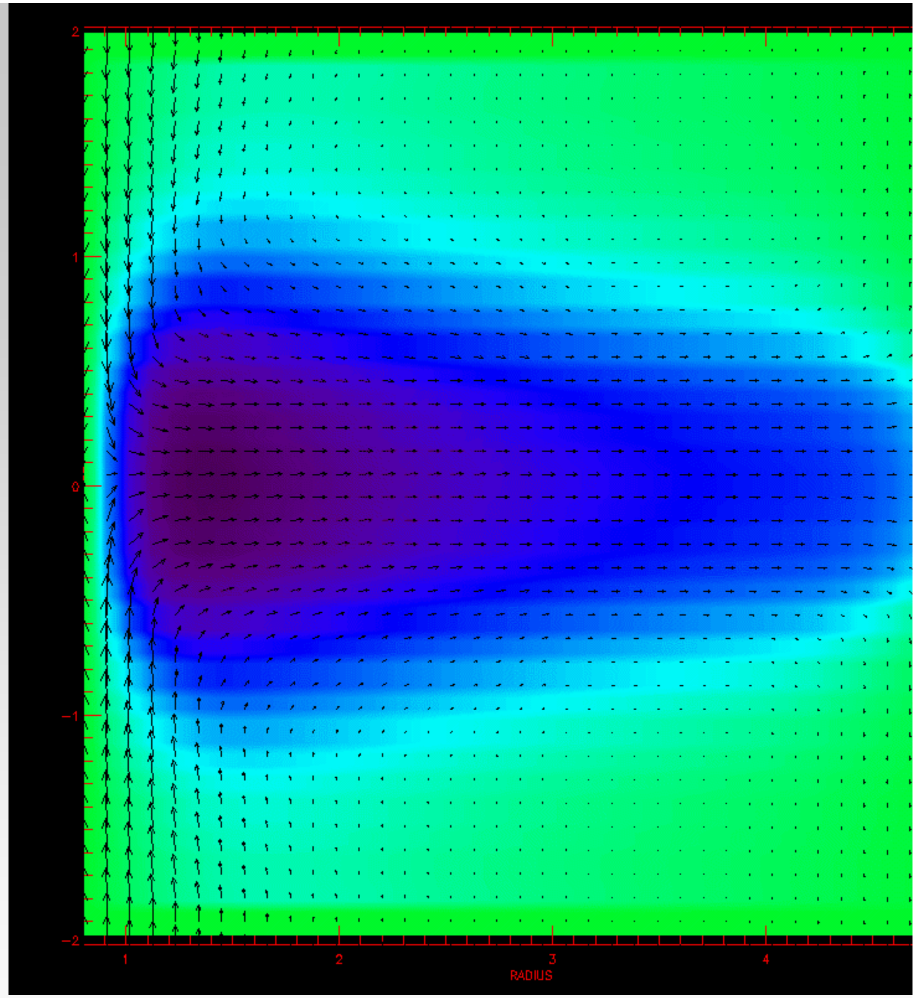


Pitch angle: 1^0

Dynamo saturation by α-quenching

Irsee 2010



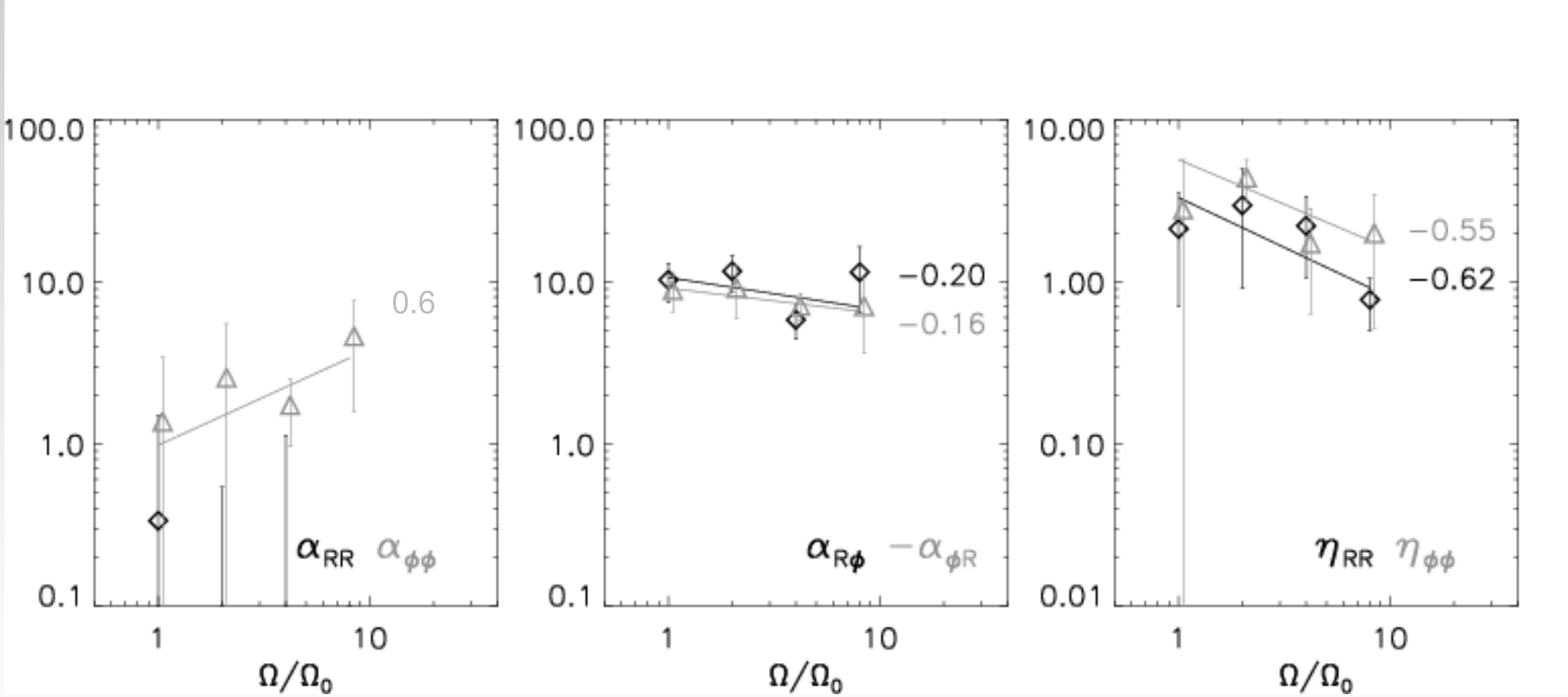


Pitch angle: 16^0

Dynamo saturation by wind

SN driven dynamo

Omega dependence



Dependence of turbulence on SN-rat

For $0.01 < \sigma/\sigma_0 < 1$

$\alpha_{\varphi\varphi} \sim 3(\sigma/\sigma_0)^{1/2}$

$\eta \sim 2(\sigma/\sigma_0)^{1/2}$

$\alpha_{r\varphi} \sim 6(\sigma/\sigma_0)^{1/2}$

$u_z \sim 15\,(\sigma/\sigma_0)^{0.4}\, z$

AIP

Dependence of turbulence on SN-rat

$C_\alpha \sim \Omega H$ $C_\Omega \sim \Omega^{3/2} H^2 \sigma^{-1/2}$ $C_{pum} \sim \Omega^{-1/2} H$ $C_w \sim \Omega^{-1}$

Dynamo number: $D \sim \Omega^{5/2} H^3 \sigma^{-1/2}$

Pitch angle: $P \sim \Omega^{-1/2} H^{-1} \sigma^{1/2}$

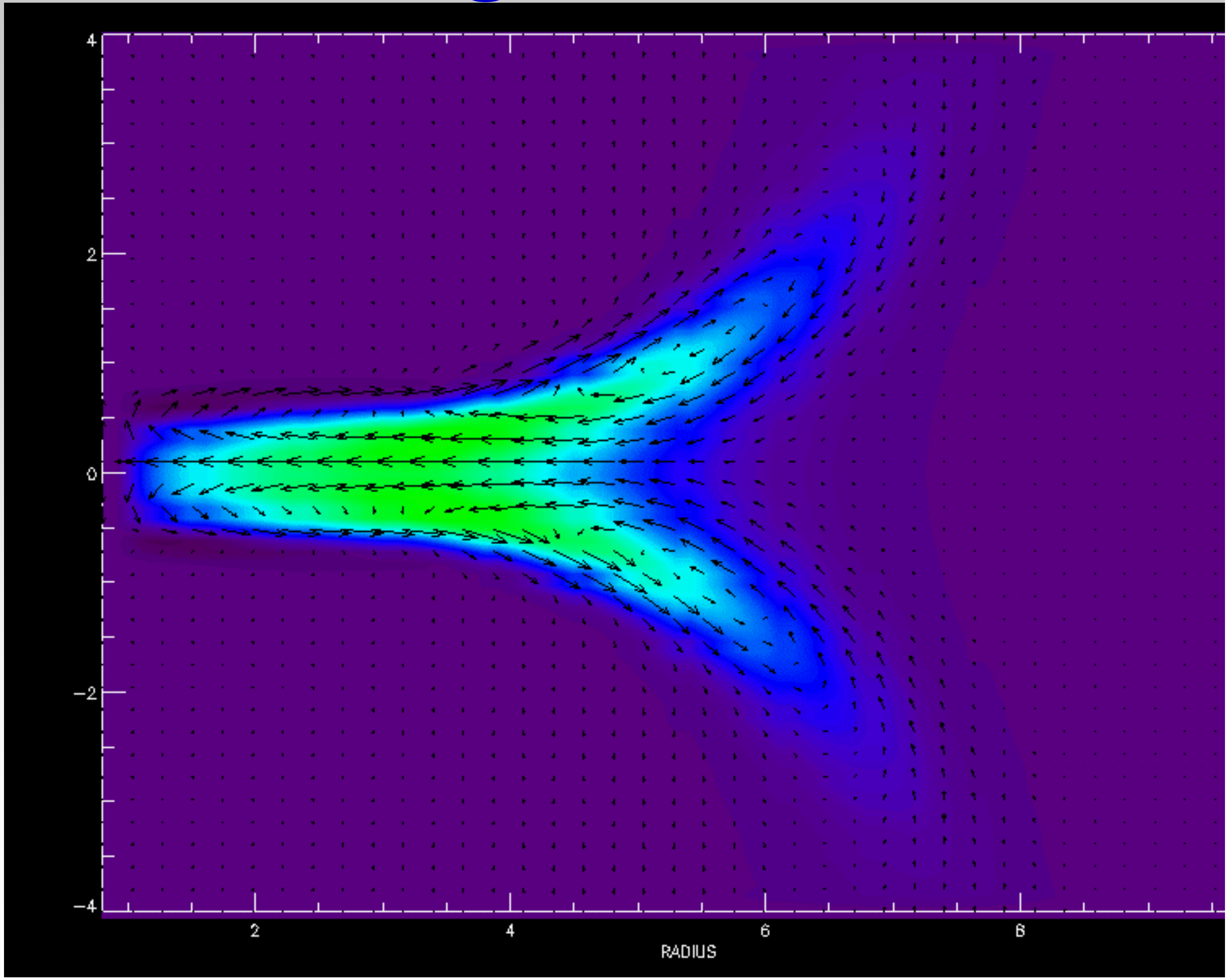
Regular field decreases with increasing SF

Pitch angle increases

Increasing scale-height

$D \sim \Omega^{5/2} H^3 \sigma^{-1/2}$

$P \sim \Omega^{-1/2} H^{-1} \sigma^{1/2}$



Irsee 2010

Task 2

Doing parameter studies for different envirotments

Star formation rate

Density

Gravitational potential

Rotation law

Investigating the non-linear saturation process

Is the dynamo helicity quenched? Or does the wind switch off the dynamo process?

Magneto-rotational instability

Limits for MRI by other sources of turbulence:

Kitchatinov et al. (2004)

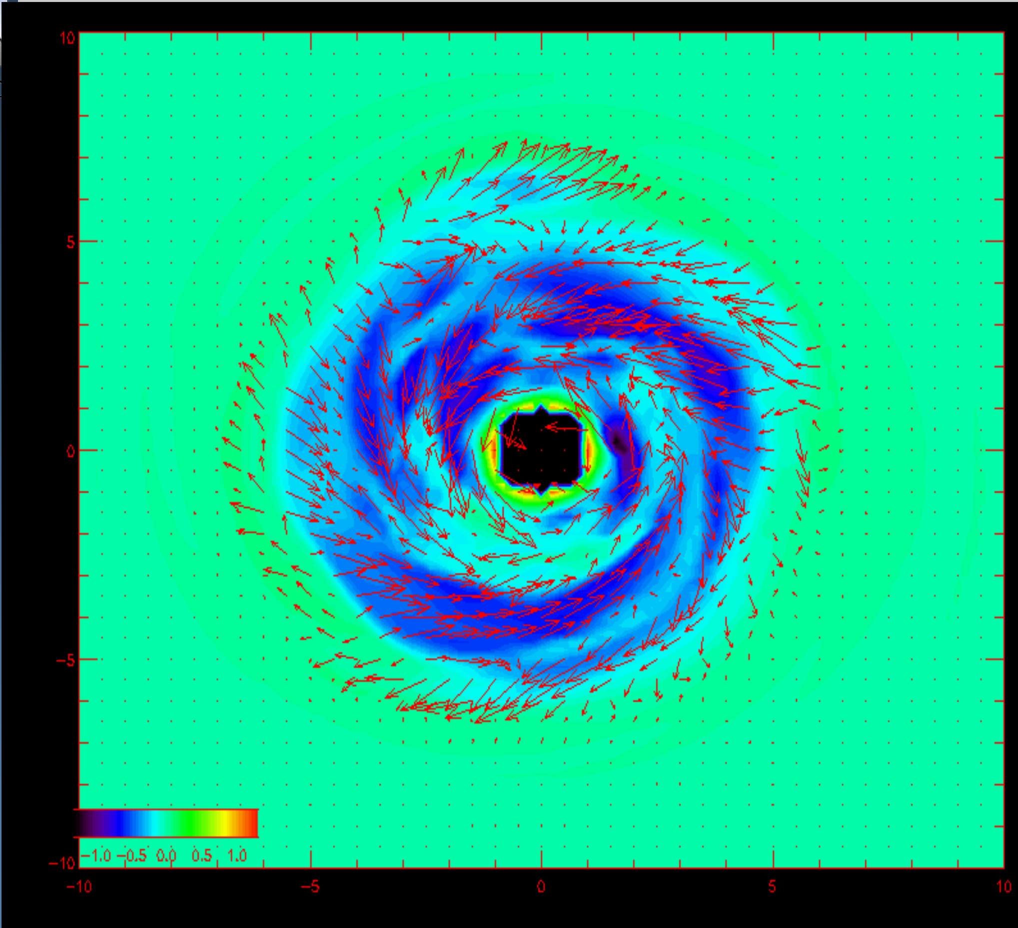
$0.7\ \eta/H < v_a < \Omega_0 H$ ----> $0.7 < C_\Omega = \Omega_0 H^2/\eta$

$0.7 < S < C_\Omega$

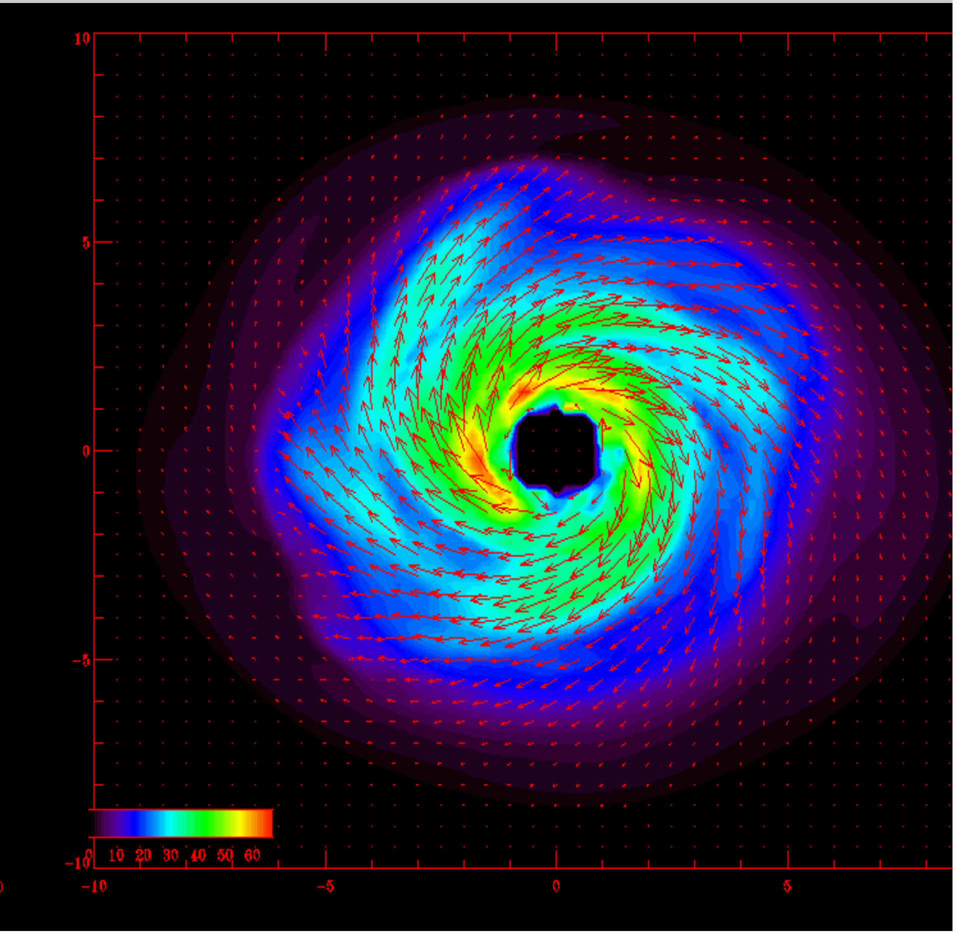
for turbulent η:

$100 - 3\ \mu G > B > 0.5\ \mu G$ (observed above the disk)

MRI



Disk field at 1.6 Gys



Polarisation at 1.6 Gys

Irsee 2010

Task 3

Comparison to MRI

Also the magneto-rotational instability is excited in the box model, because we have sheared periodic boundary conditions in the horizontal direction. Here one has to inves- tigate also models without SN explosions.

Influence of vertical flux

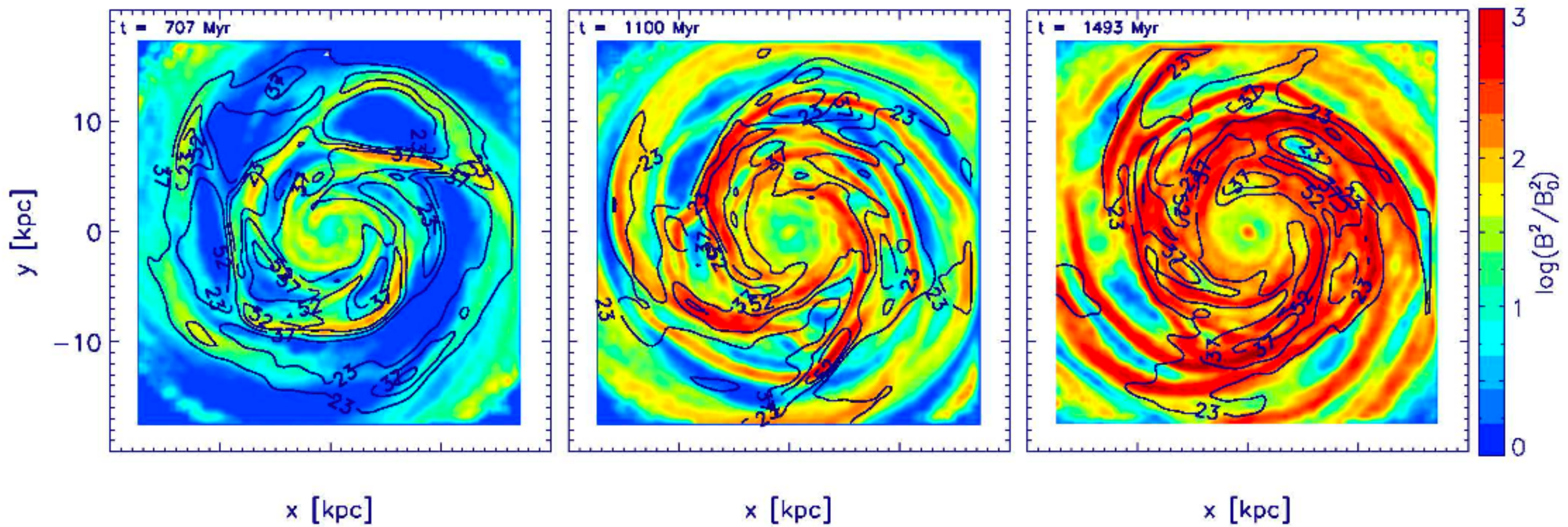
In the box calculations with periodic boundaries the vertical magnetic flux is a conserved quantity. The influence of the vertical flux has to be studied. This is be essential for the excitation of the magneto-rotational instability. Also the outflow into the halo could depend on a mean vertical flux.

Relaxing the horizontal periodic boundary condition (embedding in a non-explosive medium)

Realistic galaxies

The Gadget code is successful in modelling 3D formation and evolution of galaxies.

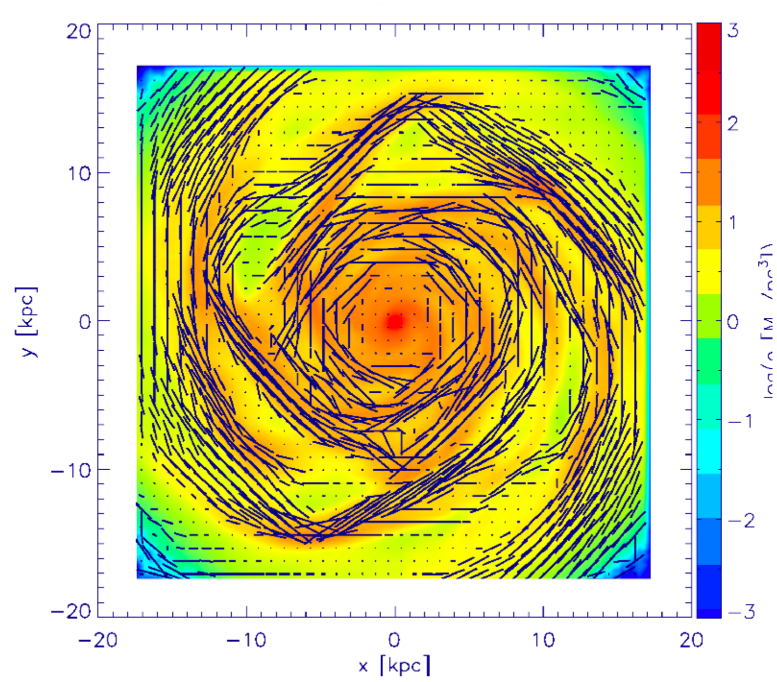
Global, self-consistent **N-body / SPH** simulations of galactic disks with gas and magnetic fields



Realistic galaxies

Our galaxies consist of an exponential stellar disc and an extended gas disc, a stellar bulge and a dark matter halo of collisionless particles. Also star formation can be turned on in these simulations. We have found that by differential rotation and self-consistent spiral structure formation of the disc the field is amplified by one order of magnitude within five rotation periods.

Given the very good performance of the code and the elaborate implementation of different physics, **Gadget** poses a viable tool for self-consistent numerical simulations of galactic systems. **In combination with new sub-grid models for the αΩ-dynamo process and related physics derived from high-resolution grid-based simulations Gadget allows a detailed investigation of the formation and evolution of magnetised galaxies.**



Task 4 Munich

Extension of Gadget with mean-field turbulence

A complete inclusion of the full α-tensor and the turbulent diffusivity tensor into the induction equation has to be done.

Extensive testing of the code

The analytically known solution for an α2 dynamo in disk geometry will be the first test for a correct implementation. Using anisotropies of the α-tensor different numerically known solutions have to be verified.

Comparison with simple grid based models

Simple setups of a galactic rotation law allow the comparison to different types of αΩ dynamos in disks and haloes of galaxies under appropriate assumptions on the turbulence. For the haloes a vertical dependence of the angular velocity should be studied in more detail. The models have to be compared with a grid scheme preserving divergence-free fields on number precision.

Task 5 Munich

Inclusion of cosmic rays.

Extending and refining of cosmic ray treatment in general and including transport coupled to the magnetic field will be incorporated.

Running models in a kinematic way for different types of galaxies

How does the presence of cosmic rays influence the global structure of the magnetic field and how does this depend on the properties of the host galaxy? How much do minor mergers affect the globa magnetic field structure? How much do merger processes contribute to the transport of magnetised gas into the halo?

Coupling cosmic-ray injection to star formation

How do the cosmic rays get distributed within the galaxy if they are treated more real- istically and injected by the star formation process ? How do star forming regions then shape the global magnetic field configuration ?

Coupling magnetic field injection to star formation

How does the magnetic field in a galaxy look like if it is only injected by stellar evolution?Can we still get a dynamo working?

Task 5 Munich

Evolutionary effects, SN II vs. SN Ia, IMF

How much does the final cosmic-ray distribution and the magnetic field structure depend on our detailed understanding of the star formation process? How much magnetic field can be transported into the halo?

Task 6 Munich

Full inclusion of sub-grid physics from box simulations

Extending the mean-field turbulence model by using the results from the box simulations as a description for the sub-grid turbulence model. Developing the code towards sub-grid models used in so-called large eddy simulations.

Dynamic models with inclusion of magnetic force

Simulating the formation, evolution and interaction of galaxies within realistic configurations, including the dynamical back-reaction of magnetic fields.

Modelling magnetic instabilities like MRI and Parker

Simulating global models by studying the role of instabilities in driving dynamo actions, saturation of magnetic field configurations and global and local galactic outflows. Do such processes contribute to the creation or removal of coherent patterns in the halo magnetic field ?

GOALS

- Magnetic field scaling with density
- Magnetic energy loss into the halo in dependence on the properties of the ISM
- Influence of cosmic rays onto the dynamo process
- The role of outflow for the dynamo saturation process
- Structure of halo fields in global models for different types of galaxies
- Synthetic polarisation and RM maps for local and global models
- Connection between magnetic fields and star formation history
- The role of starburst driven winds