Research of influence of regular magnetic fields on flows in outer rings of galaxies

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Introduction

- Several galaxies have magnetic field structures.
- Their existence is proved by Faraday rotation measurements, synchrotron emission spectra and cosmic rays detection.
- From the theoretical point of view, they are connected with dynamo mechanism (Beck 1996).

Galactic magnetic field

- Galactic magnetic field contains regular part and small-scale one.
- The small-scale part is connected with random effect and it is concentrated in relatively small cells.
- The large-scale part is generated by the mean field dynamo.

Mean field dynamo

- Mean field dynamo is based on joint action of alpha-effect (characterizes turbulent motions) and differential rotation.
- They compete with turbulent diffusion, which destroys regular field structures.
- The generation of the field is a threshold process: it can grow only for some values of the parameters.

Outer rings of galaxies

- Nowadays it is interesting to study not only the galaxy, but also the outer rings which are situated at some distance from the main part.
- The processes in the outer rings are quite similar, but there are some difficulties in studying the magnetic field
- Also the turbulent motions in the outer rings can be associated with the magnetic fields.

Magnetic field models

- Usually the magnetic fields of galaxies are studied using so-called no-z approximation.
- It was developed for thin galactic discs, where the half-thickness is much smaller than radius.
- As for the outer rings, the radial lengthscales are quite comparable with vertical ones, and it is necessary to take another approaches.

Torus dynamo model

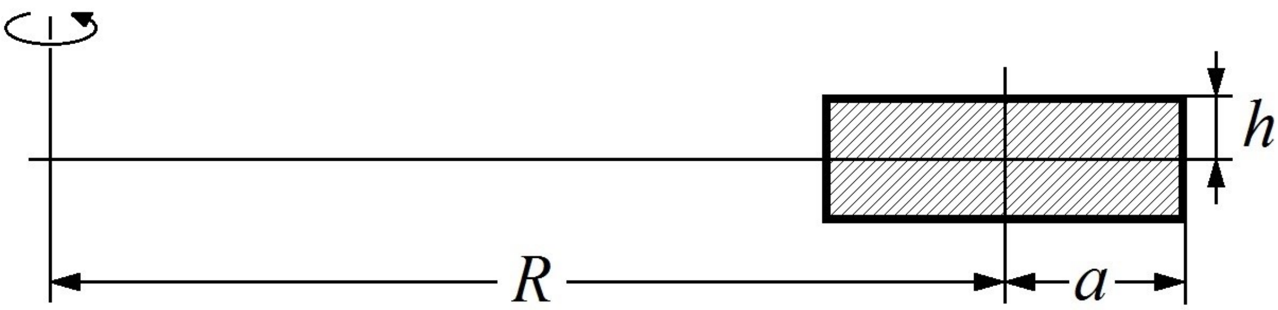
- In the axisymmetric case it is useful to take the torus dynamo approximation (Deinzer et al., 1993; Mikhailov, 2018).
- The magnetic field can be divided to toroidal component and poloidal one.
- The poloidal magnetic field can be described by toroidal component of the vector potential of the magnetic field.

Basic equations

- The magnetic field evolution is decribed by Steenbeck – Krauze – Raedler equation:

$$\frac{\partial \vec{B}}{\partial t} = \mathrm{rot}[\vec{V}, \vec{B}] + \mathrm{rot}(\alpha \vec{B}) + \eta \Delta \vec{B}$$

- V is the the large scale velocity, α is the alpha-effect and η is the turbulent diffusivity coefficient.



Models for the parameters

- The parameters for the field are the following:

$$\vec{V} = r\Omega\vec{e}_\phi$$

$$\alpha = \frac{\Omega l^2 \mathrm{z}}{\mathrm{h}^2}$$

- The magnetic field can be presented as:

$$\vec{B} = B\vec{e}_\phi + \mathrm{rot}\left(A\vec{e}_\phi\right)$$

Field equations

- For the magnetic field we can obtain the equations:

$$\frac{\partial A}{\partial t} = \frac{\Omega l^2 z}{\mathrm{h}^2} B + \eta \Delta A$$

$$\frac{\partial B}{\partial t} = \Omega \frac{\partial A}{\partial z} + \eta \Delta B$$

Dimensionless form

- It is convenient to measure the distances in R, and the time in $\frac{a^2}{\eta}$
- The equations will be the following:

$$\frac{\partial A}{\partial t} = R_\alpha \mathrm{zB} + \lambda^2 \Delta A$$

$$\frac{\partial B}{\partial t} = R_\omega \frac{\partial A}{\partial z} + \lambda^2 \Delta B$$

Dimensionless parameters

- Here we have introduced dimensionless values which describe alpha-effect, differential rotation and diffusion in the disc plane:

$$R_\alpha = \frac{\Omega l^2 a^2}{\eta h^2}$$

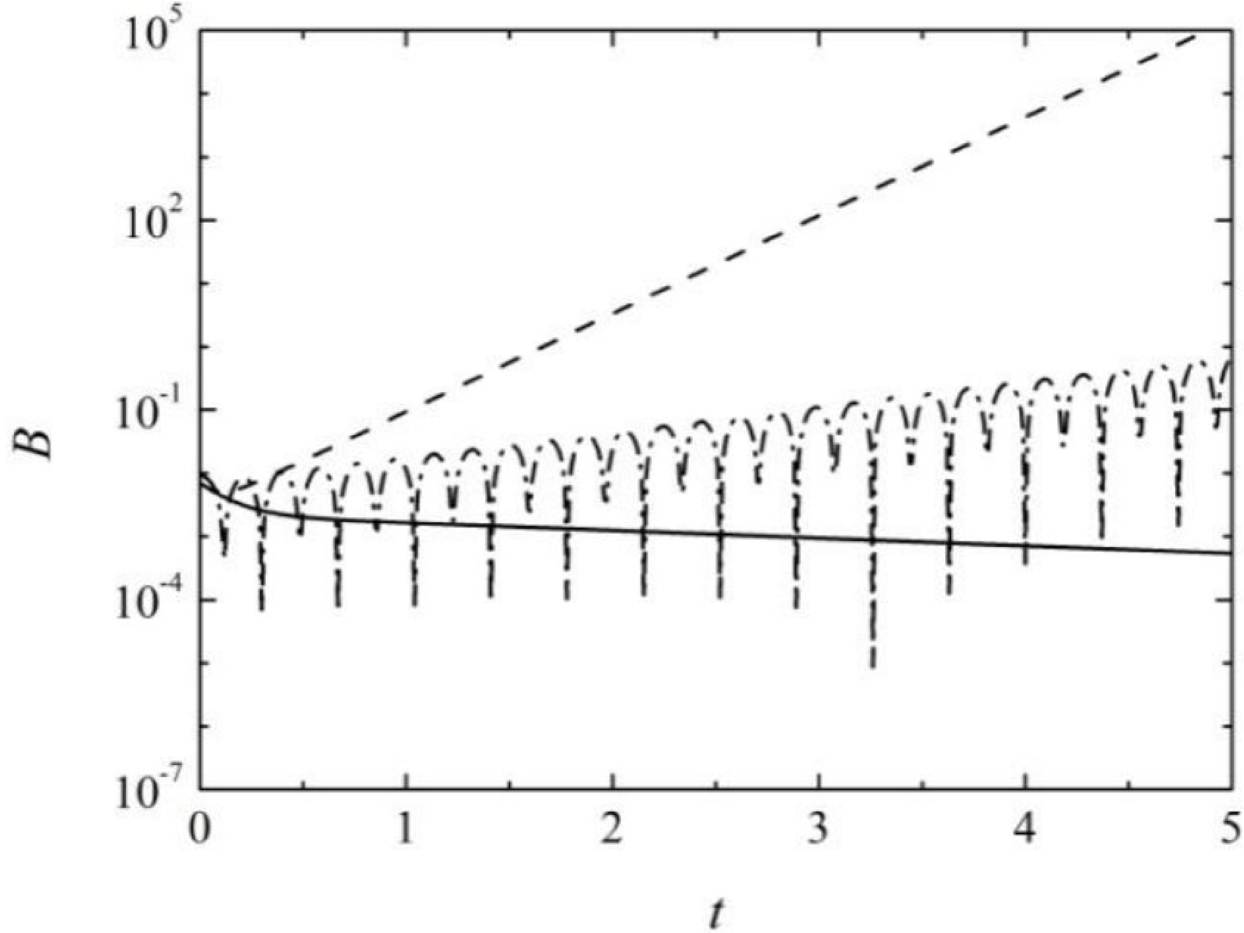
$$R_\omega = \frac{\Omega a^2}{\eta}$$

$$\lambda = \frac{a}{R}$$

- The field generation is described by dynamo number (Deinzer et al., 1993):

$$D = R_\alpha R_\omega$$

Field evolution



Nonlinear model

- If we assume that the magnetic field growth saturates if it becomes close to the equipartition value, the equations will be:

$$\frac{\partial A}{\partial t} = R_{\alpha} \mathrm{zB} \left(1 - \frac{B^2}{B_0^2} \right) + \lambda^2 \Delta A$$

$$\frac{\partial B}{\partial t} = R_{\omega} \frac{\partial A}{\partial z} + \lambda^2 \Delta B$$

Nonlinear model in dimensionless form

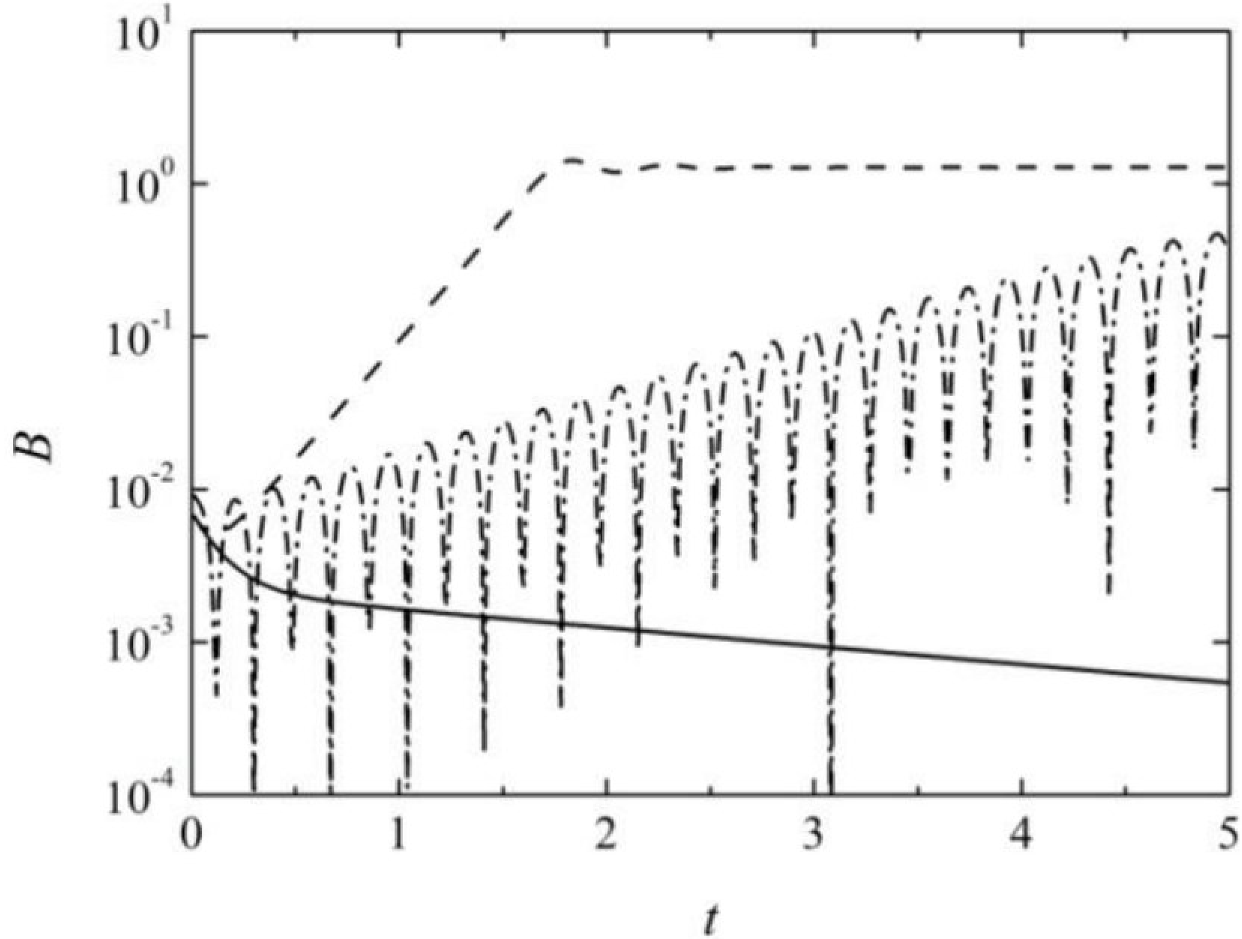
- If take dimensionless parameters, the equations for the magnetic field will be:

$$\frac{\partial A}{\partial t} = R_\alpha \mathrm{zB}(1 - B^2) + \lambda^2 \Delta A$$

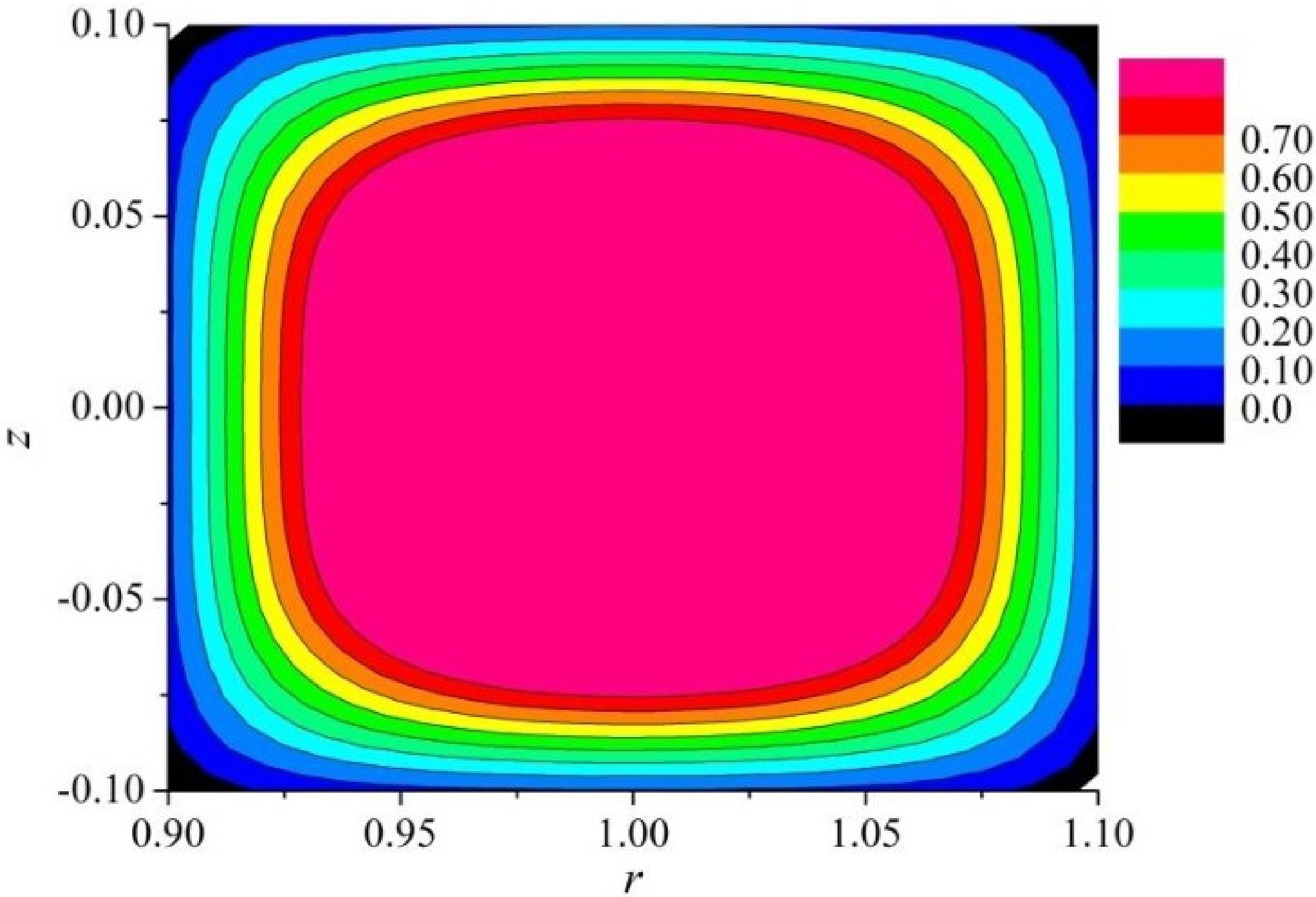
$$\frac{\partial B}{\partial t} = R_\omega \frac{\partial A}{\partial z} + \lambda^2 \Delta B$$

- The magnetic field is measured in equipartition value B_0.

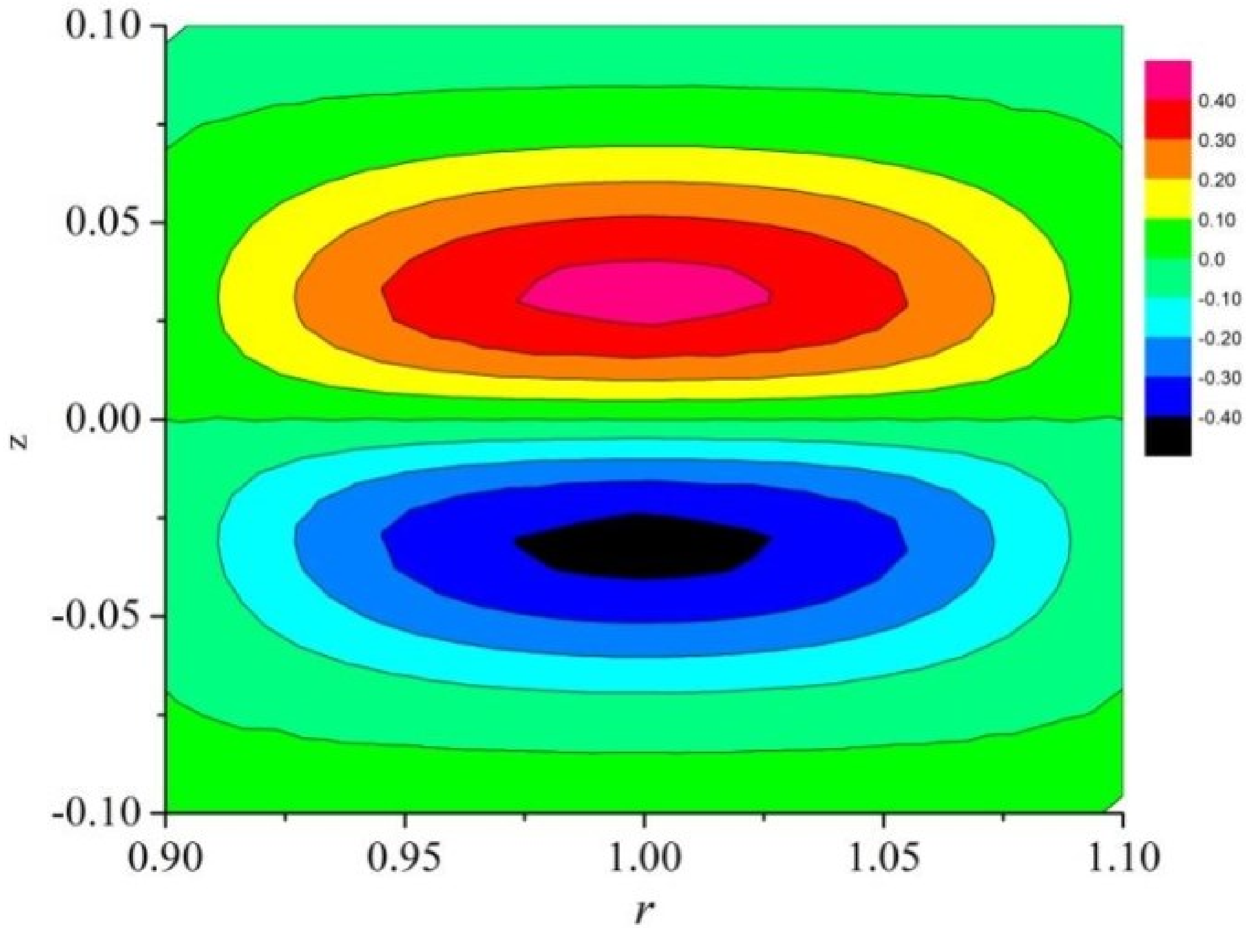
Field evolution in the nonlinear case



Spatial field structure for D=150



Field structure for D=900



Quadrupolar and dipolar magnetic field

- We can obtain magnetic field of quadrupolar symmetry:

$$B(z)=B(-z)$$

- For higher values ($D \sim 10^3$) we can have dipolar magnetic field:

$$B(z)=-B(-z)$$

- For most cases we can take the magnetic field of quadrupolar symmetry, which can be approximated as:

$$B = B_0 \cos\left(\frac{\pi z k}{2\lambda}\right) \cos\left(\frac{\pi(r-R)}{2\lambda}\right)$$

$$k = \frac{a}{h}$$

Turbulent motions

- We can study the influence of the magnetic field on turbulent motions using Navier – Stokes equation:

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}, \vec{\nabla})\vec{v} = -\frac{1}{\rho}\vec{\nabla}p + \vec{g} - \vec{f}_{\mathrm{Cor}} + \vec{f}_L + \beta \Delta \vec{v}$$

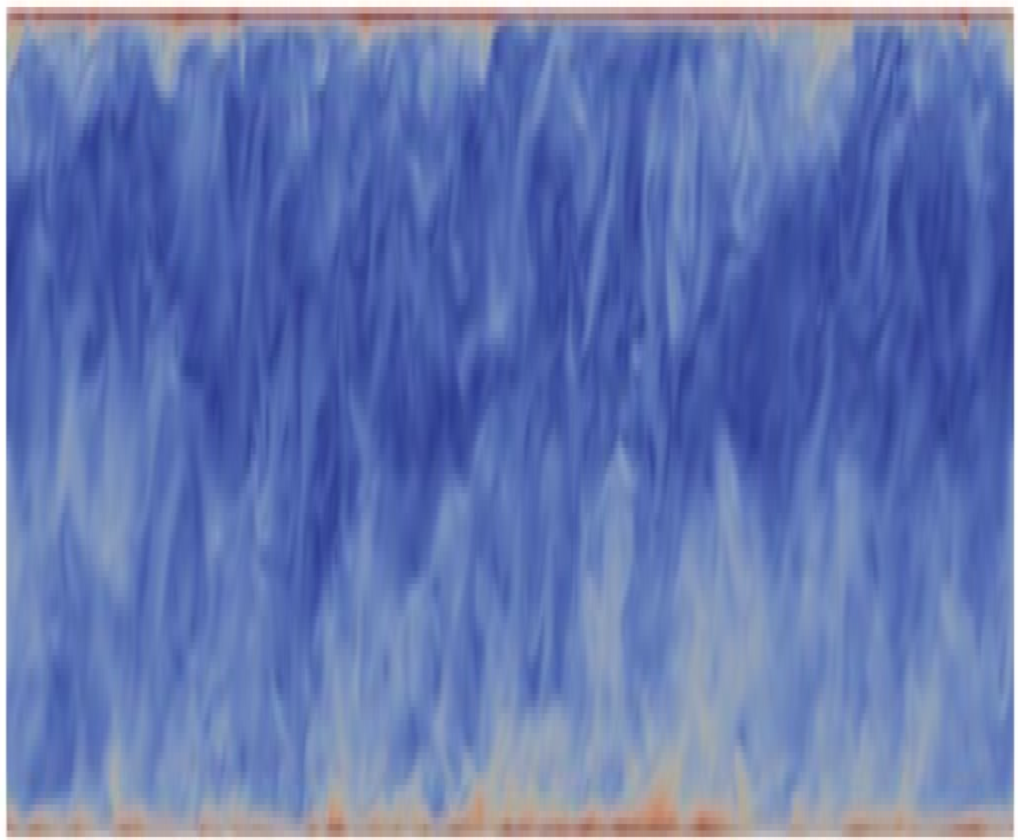
- The Lorentz force will be:

$$\vec{f}_L = \frac{1}{4\pi\rho}[\vec{B}, \mathrm{rot}\,\vec{B}]$$

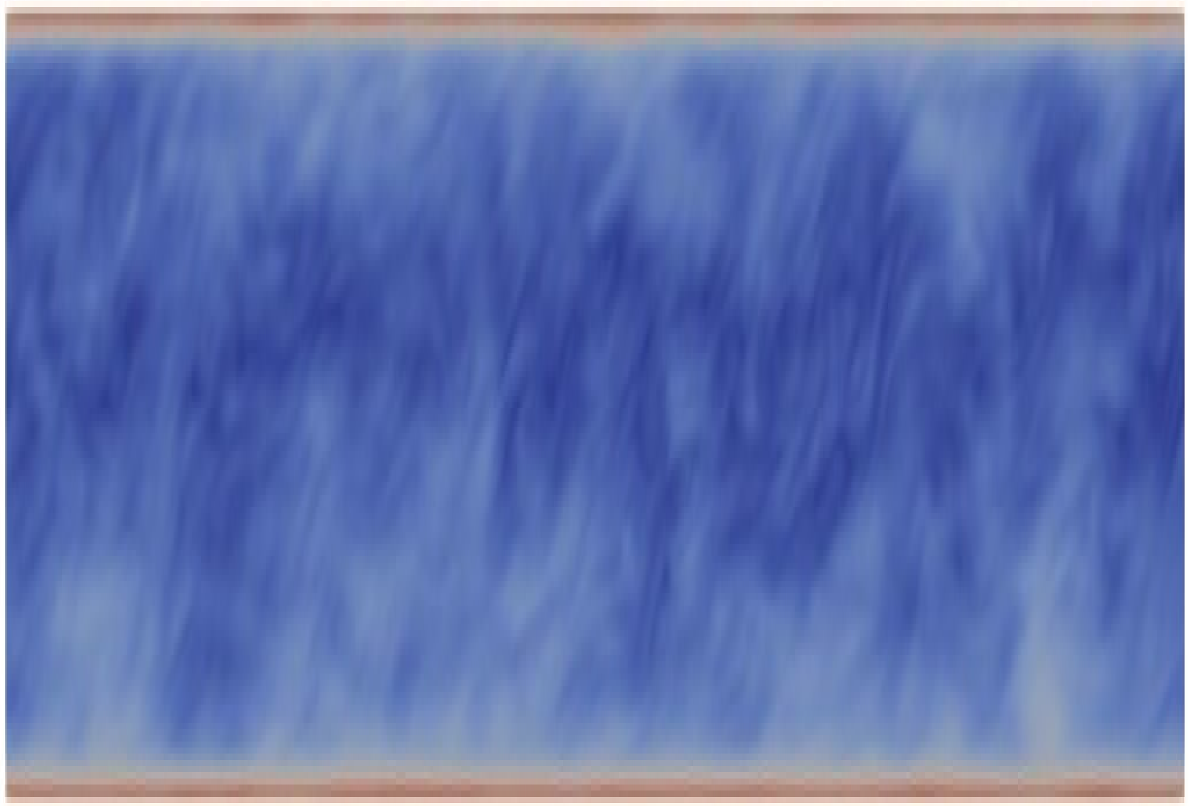
Modeling the turbulent motions

- To model the turbulent motions, we apply spectral elements approach.
- Intensity of shear flow in the disk is set by Re~10^4-10^5.
- The initial condition of the flow is turbulent shear flow. To initiate turbulence finite amplitude perturbations are imposed which may correspond to suernovae explosions.

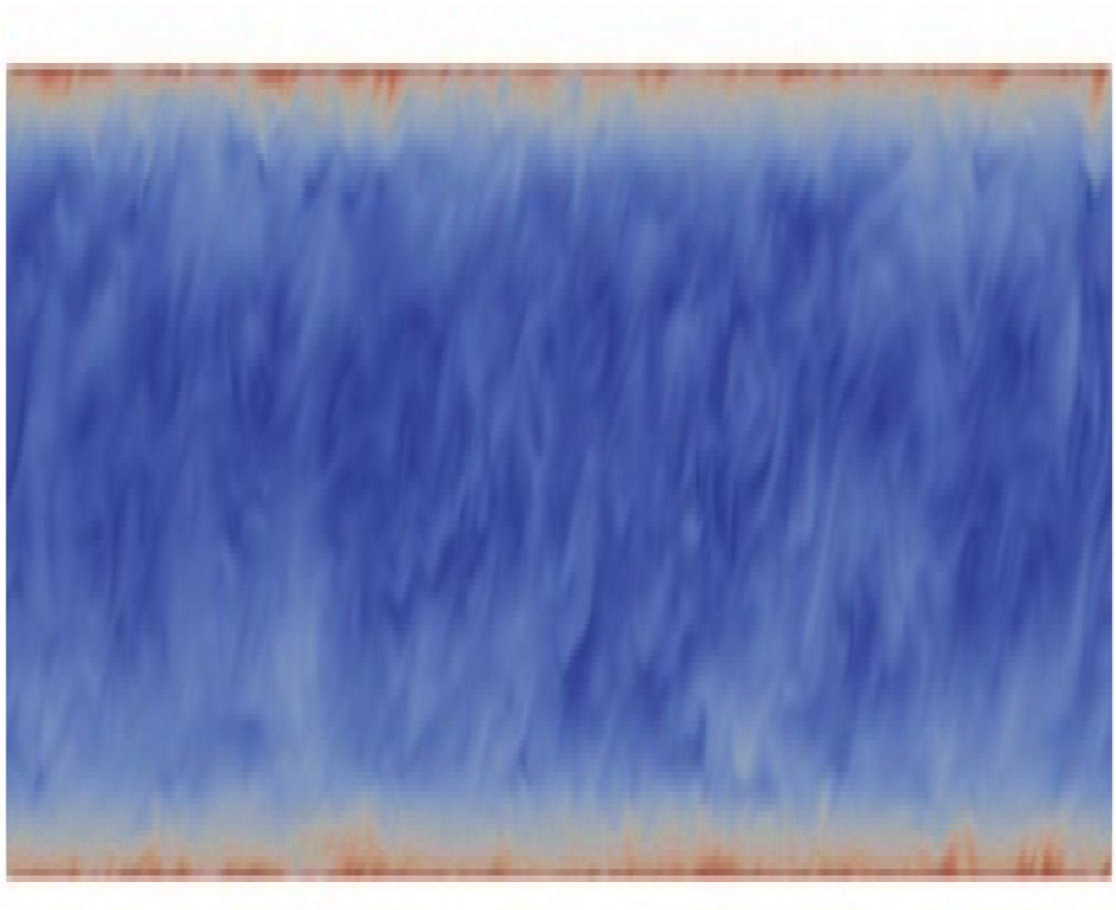
Magnetic field without magnetic field



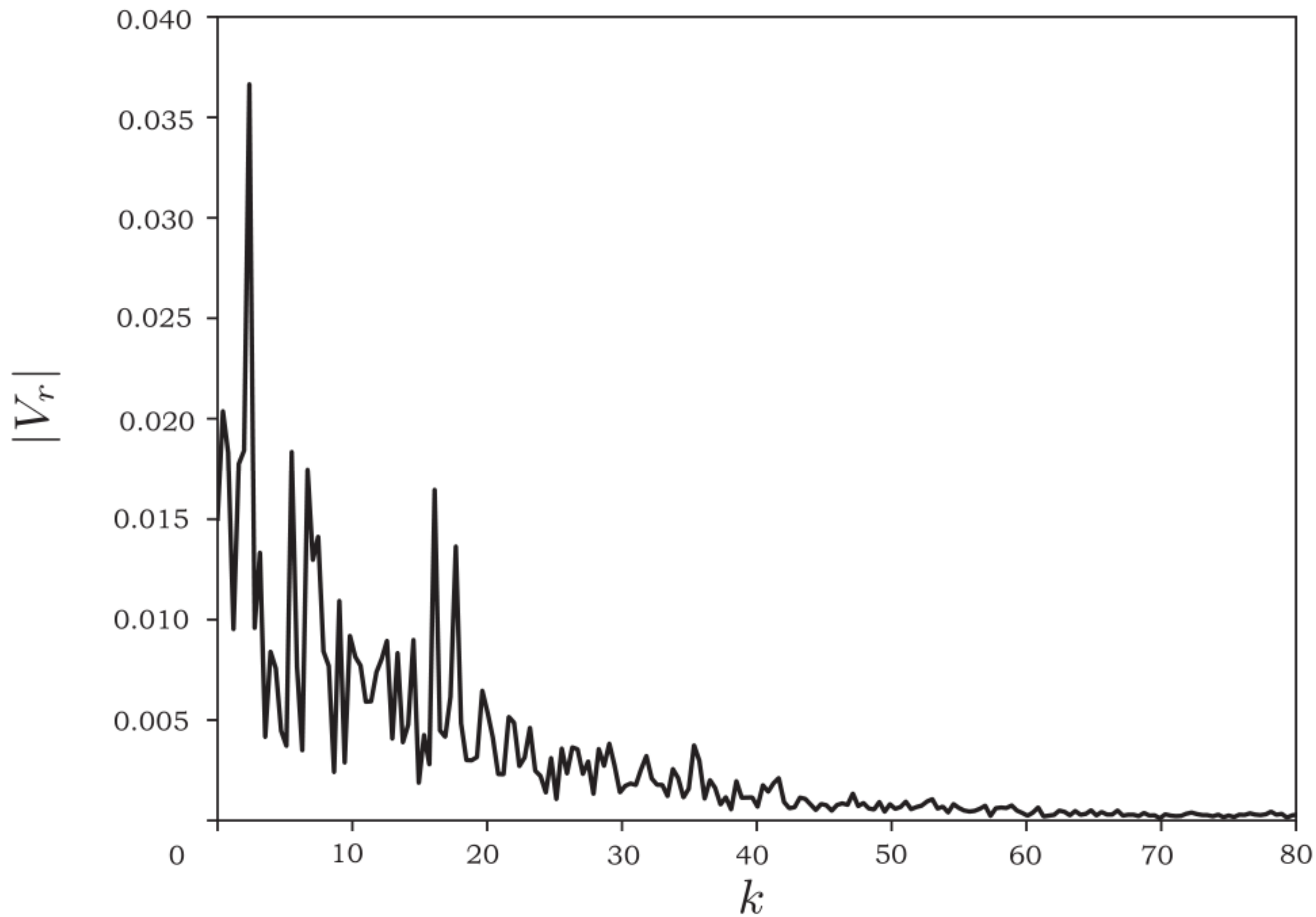
Magnetic field with dipolar magnetic field



Magnetic field with quadrupolar field



Spectrum without magnetic field and Coriolis force



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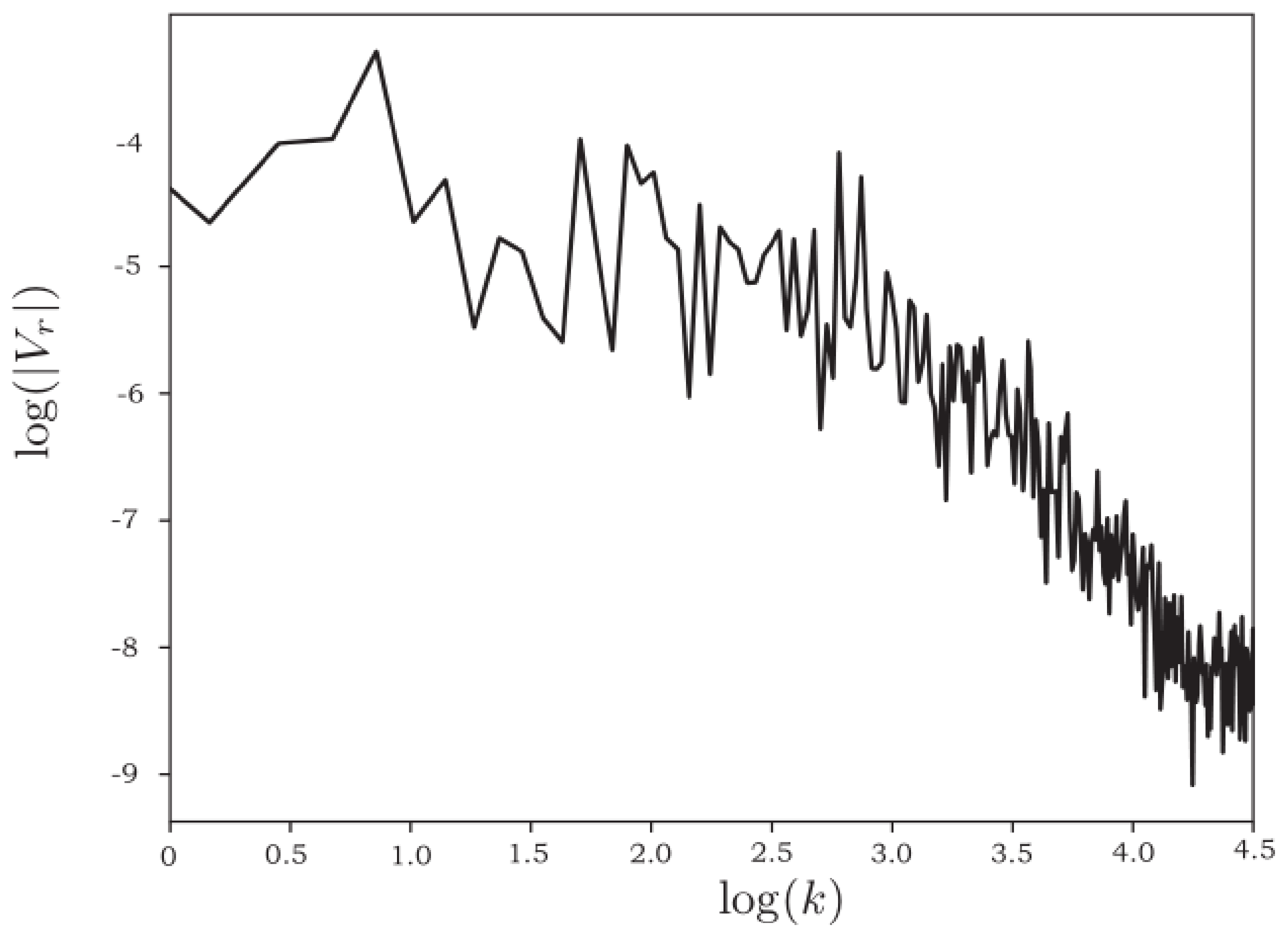
Spectrum without magnetic field and Coriolis force (logarithmic scale)



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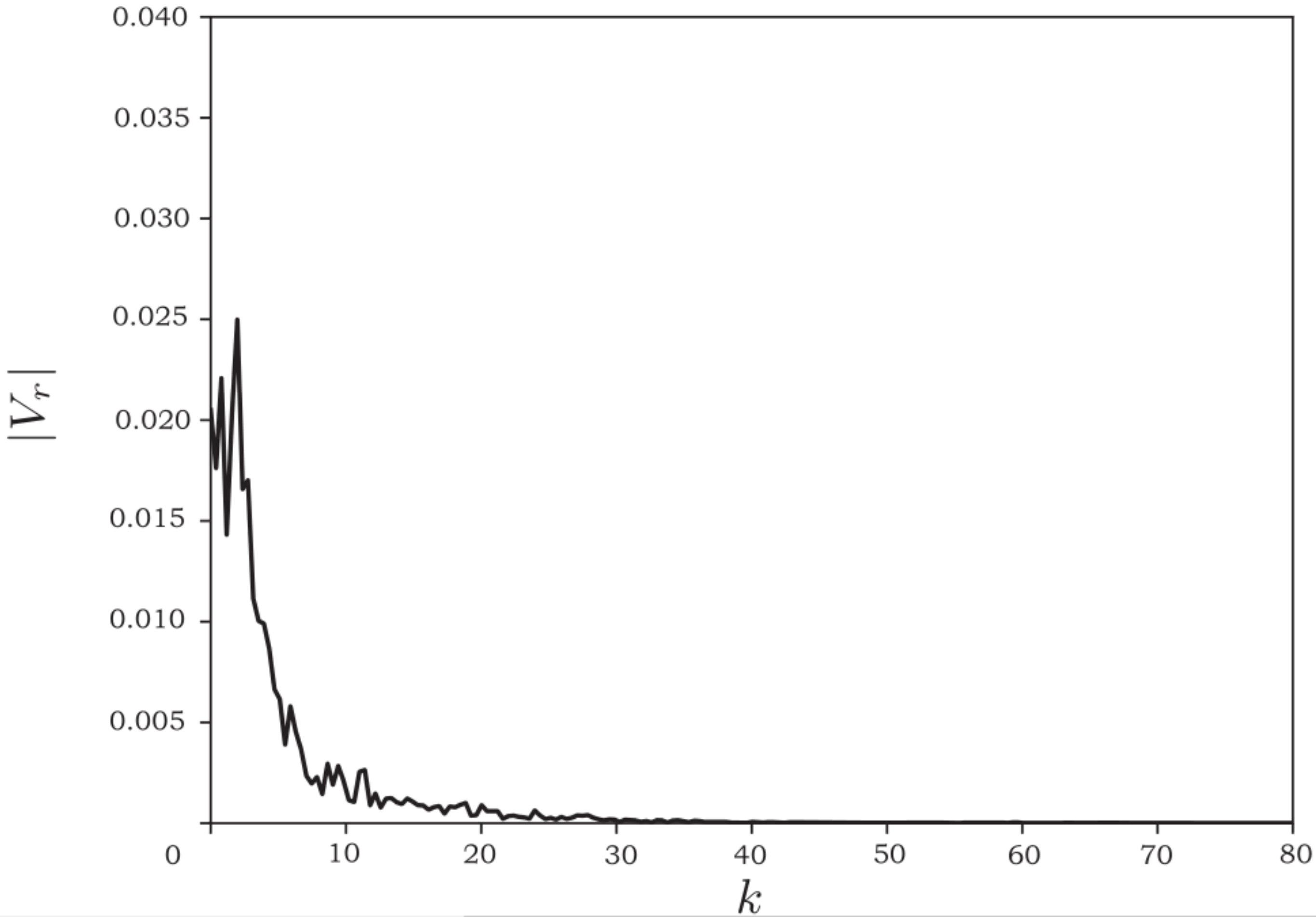
Spectrum for quadrupolar field



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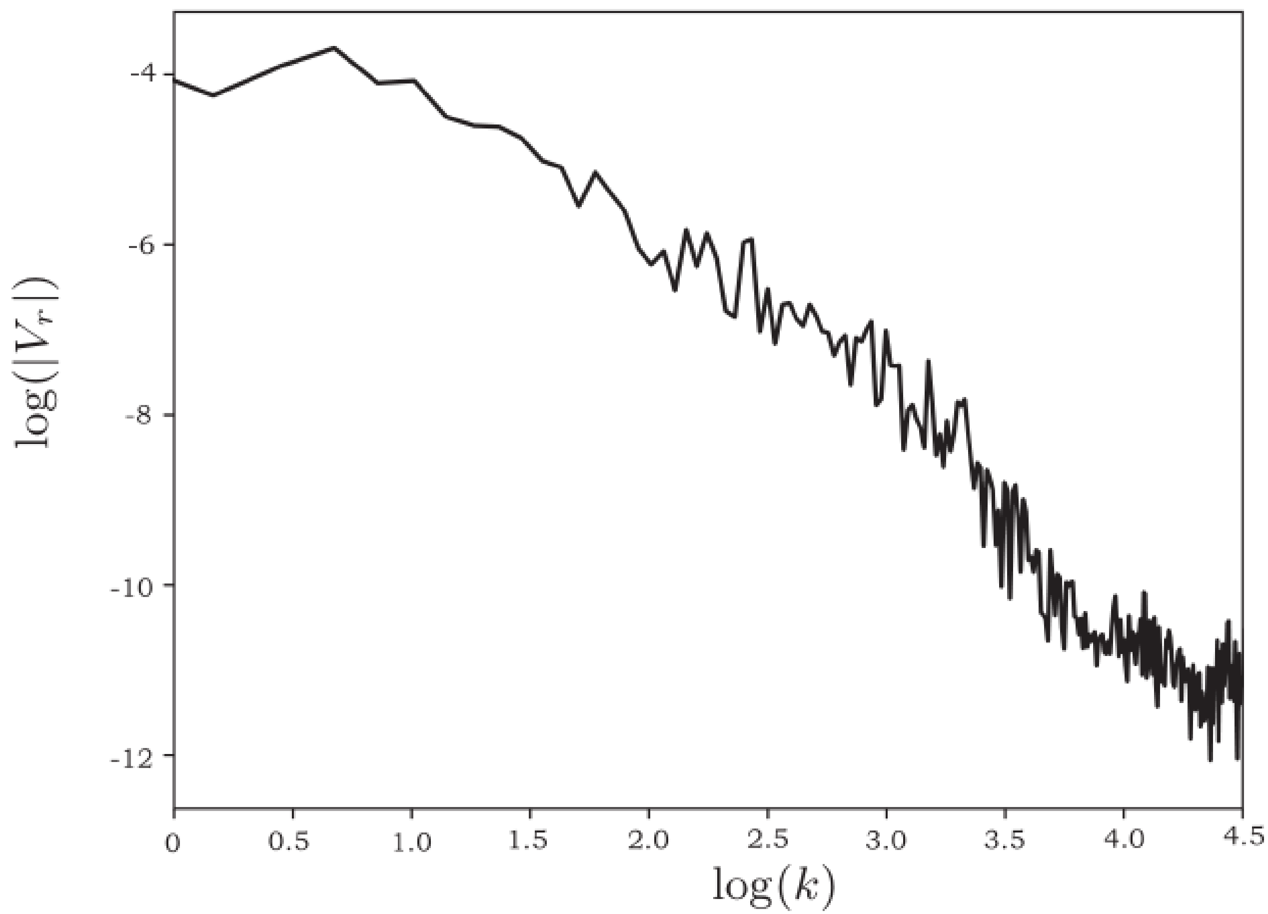
Spectrum for quadrupolar field (logarithmic scale)



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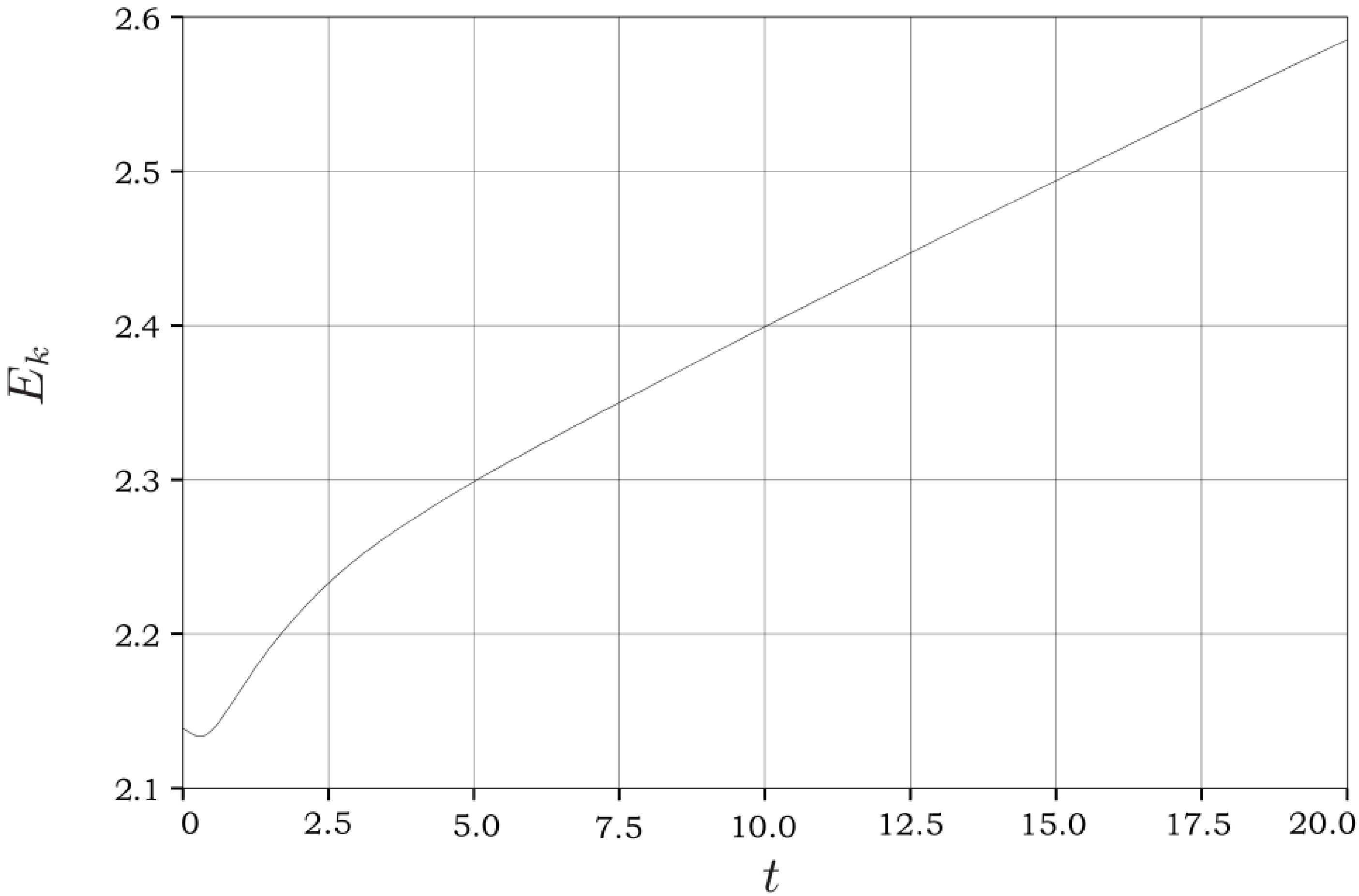
Kinetic energy evolution



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Conclusion

- We have studied the magnetic field evolution in the outer rings, and the connected turbulent motions.
- The structure of the motions is different for magnetic field and without them.
- These approaches can be also interesting for modeling the motions in accretion discs.

References

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THANKS FOR ATTENTION!