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Magnetic field evolution in neutron stars

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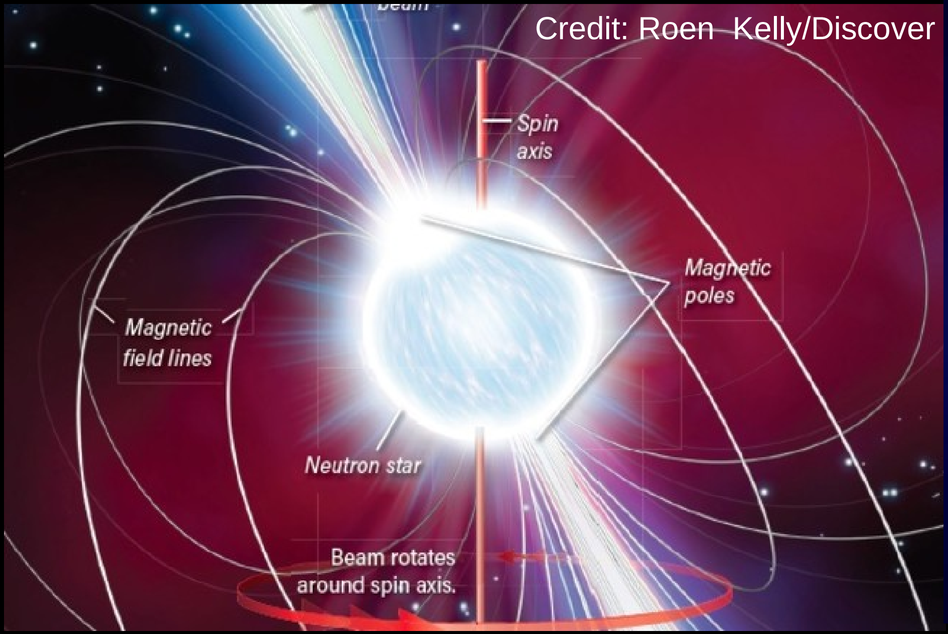
Outline

Magnetic field configurations in neutron stars from MHD simulation : (Volume 495, Issue 1, June 2020, Pages 1360–1371, MNRAS)

Current Projects:

- Magnetic field dissipation through Hall effect, Ohmic decay and Accretion.
- Building equilibrium models.
- Gravitational-Wave data analysis.

Introduction

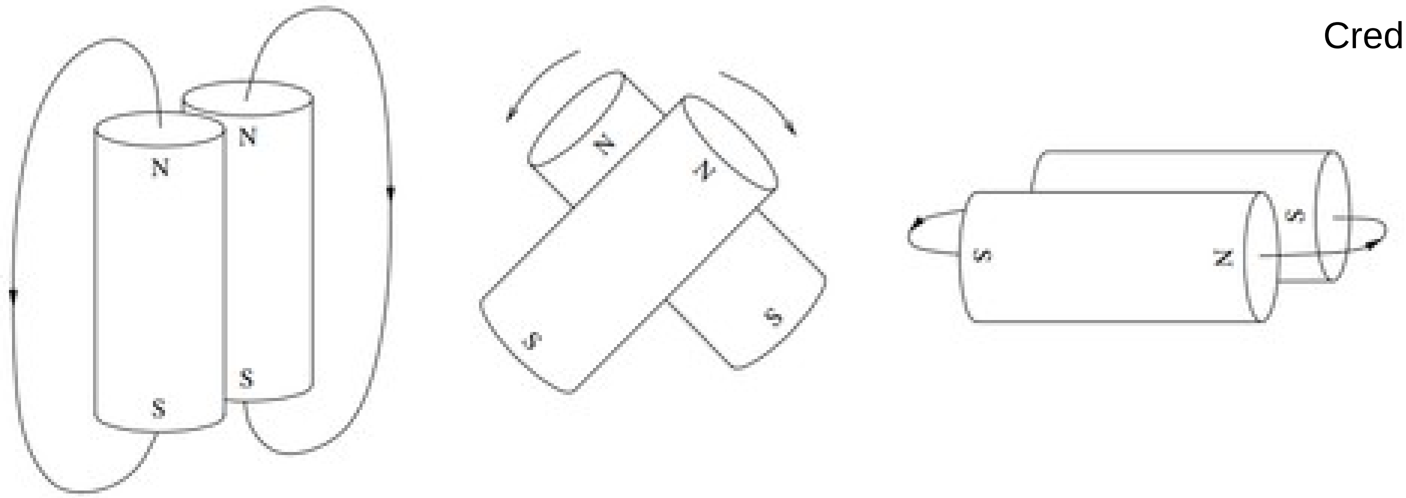


Credit: Roen Kelly/Discover

Credit: NICER/NASA Goddard

- The magnetic field structure is not completely known.
- Radio emission (Chung & Melatos, 2011) have been used to probe pulsar magnetosphere - Dipolar.
- X-ray analysis (A. V. Bilous et. al. 2019) shows there is no direct observational evidence that PSR J0030+0451’s magnetic field is a centered dipole. (see also SGR J1745-2900, de Lima et. al. 2020, ApJ)

Equilibrium : Earlier Works



Credit: Braithwaite

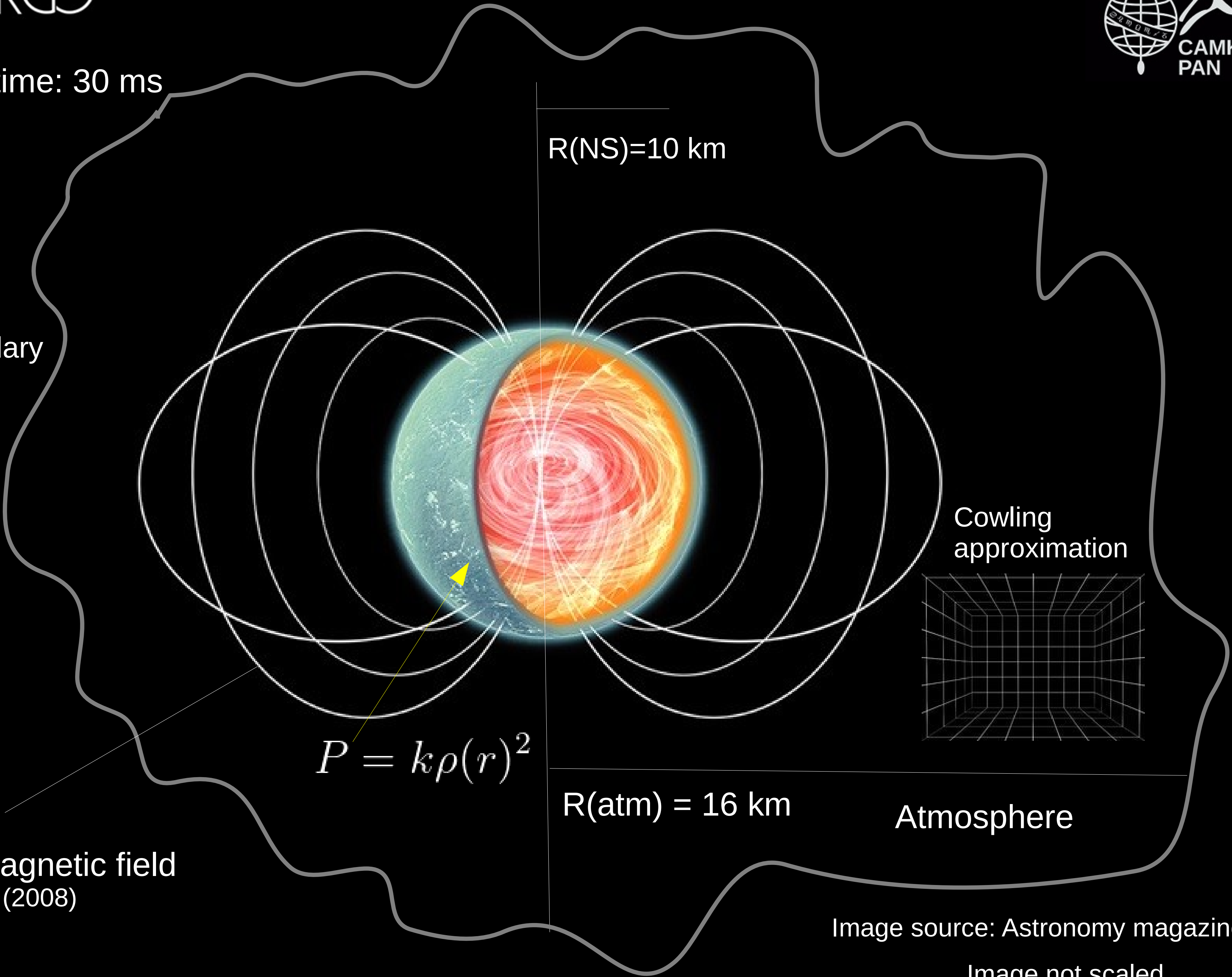
Fig. 2. Flowers-Ruderman argument for the instability of a star with a uniform interior magnetic field. Two bar magnets are free to rotate about a common axis. If pointing in the same direction, they are unstable and will rotate until pointing in opposite directions.

- A purely poloidal field undergoes the ‘Tayler’ instability (Tayler 1957,1973, Flowers & Ruderman 1977).

- Ap stars - random initial field to stable ‘twisted-torus’ (Braithwaite & Nordlund 2006).
- Poloidal field in neutron stars : twisted torus or complete decay of the field (Braithwaite & Spruit 2006).
- Axisymmetric and Non-axisymmetric linear perturbations of rotating magnetized NS (Lander&Jones (2009, 2010, 2011).

Numerical Simulations: MHD

Simulation time: 30 ms



R(NS)=10 km

Fixed Boundary Conditions

Cowling approximation

$$P = k\rho(r)^2$$

R(atm) = 16 km

Atmosphere

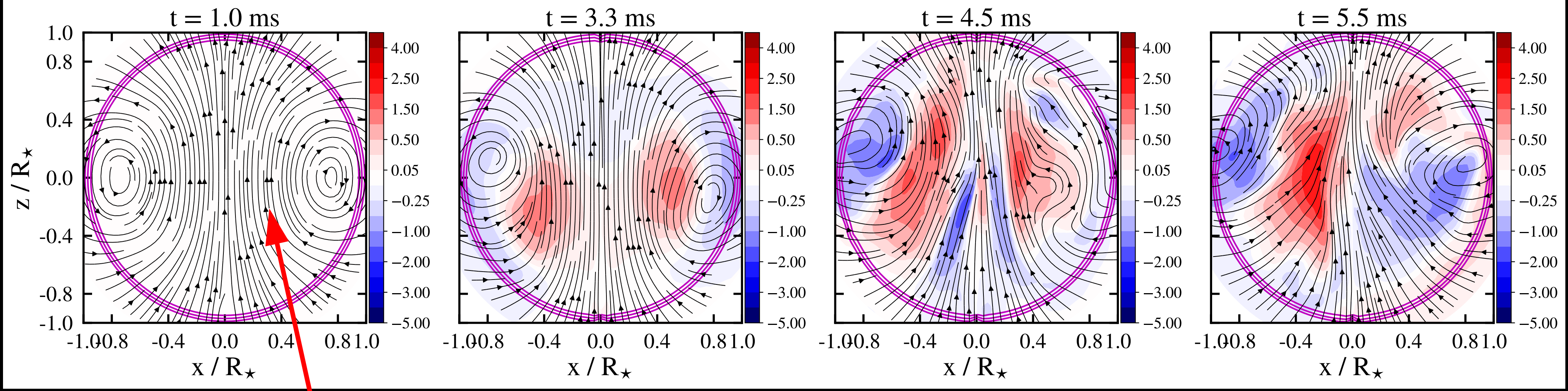
Poloidal magnetic field
(Haskell et.al (2008)

Image source: Astronomy magazine

Image not scaled

Results: Magnetic Fieldlines

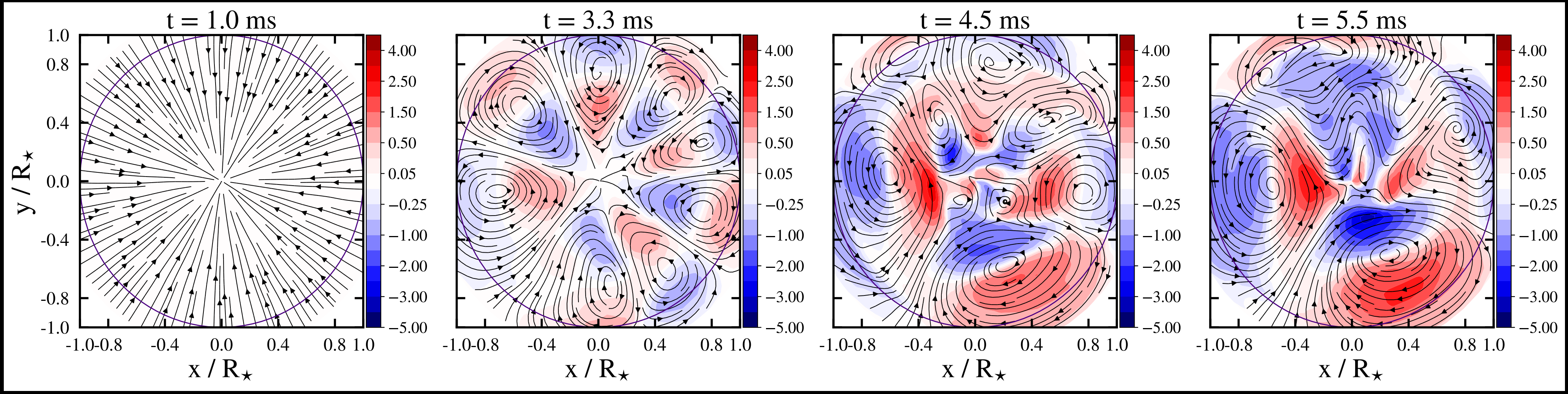
Side view



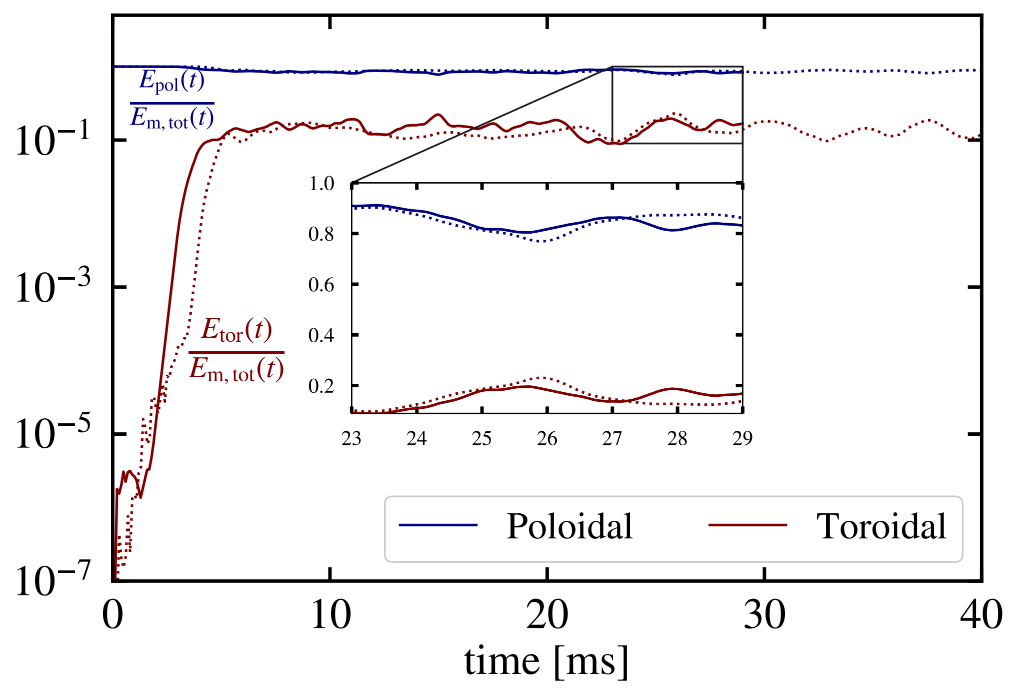
This field is initially unstable

Color scale: Toroidal field

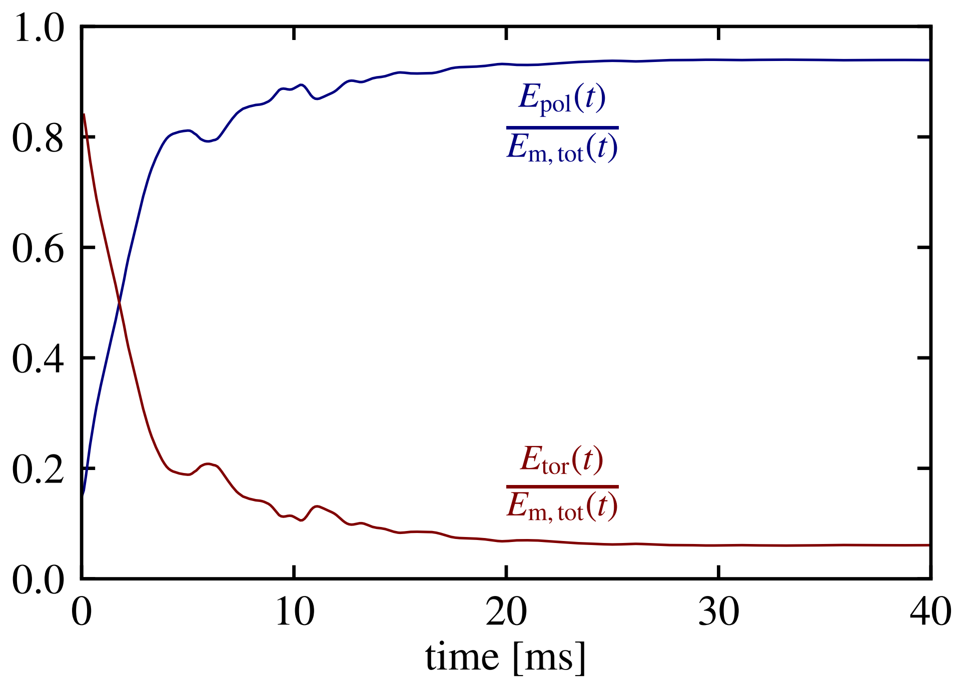
Top view



Results: Energies



Initially purely poloidal field.



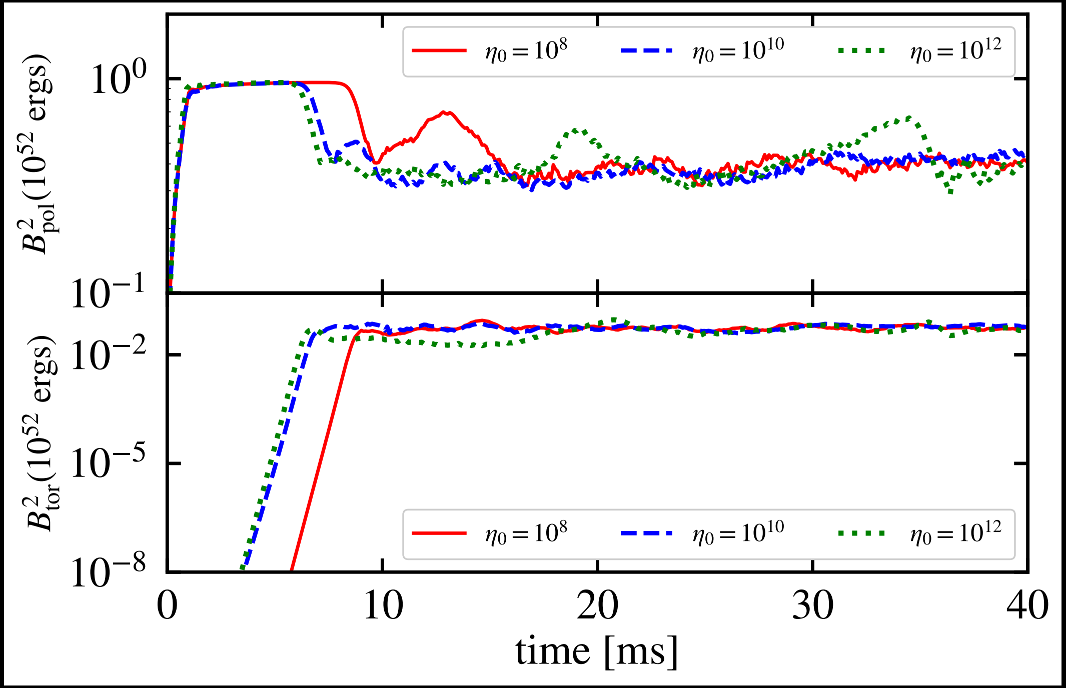
Mixed field with stronger toroidal field.

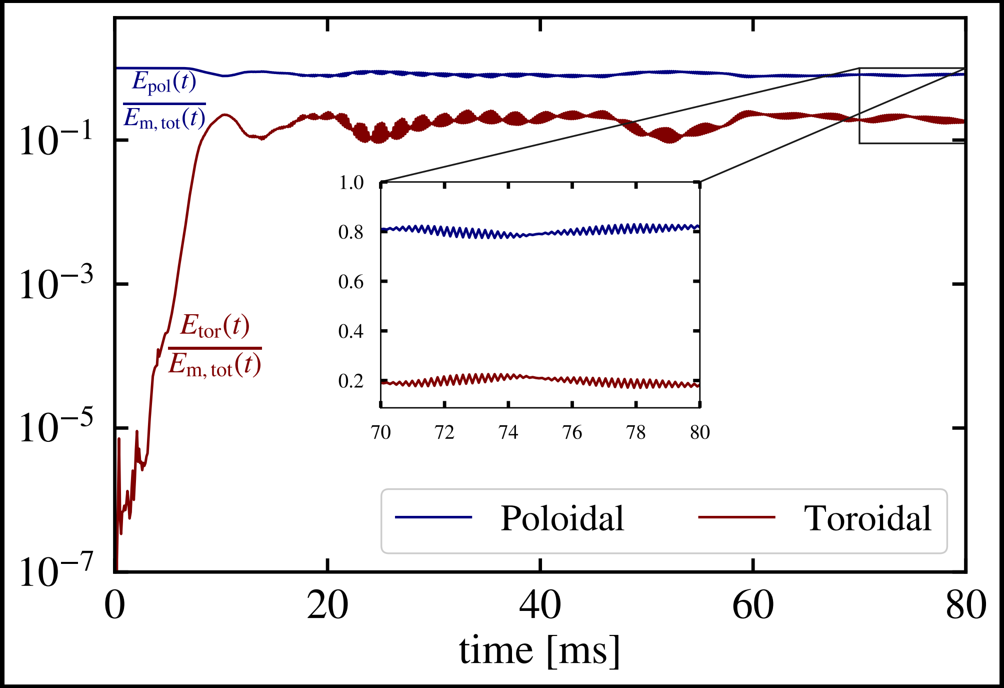
This instability gives rise to the development of the toroidal component to attend pseudo-equilibrium. Alfven crossing timescale is 1 ms.

The poloidal field ~ 80 % of the total magnetic energy
while the toroidal remains less than 20%.

Results: Effect of Resistivity

(Non-ideal MHD)





The resistivity only affects the timescale of the simulation and does not influence the overall conclusion to which the field settles down to.

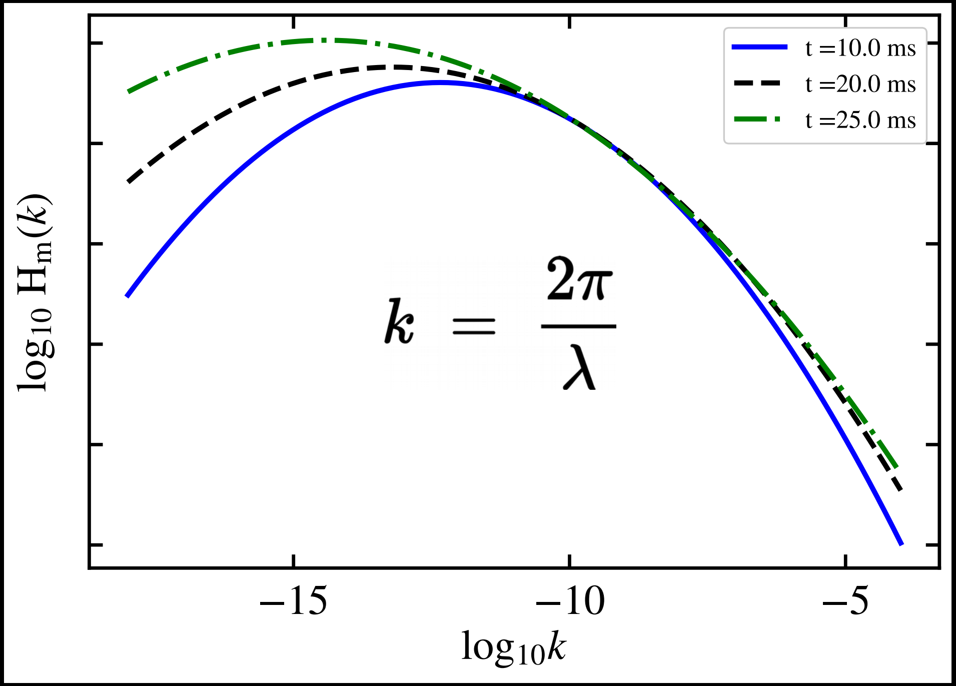
Results: Turbulence

$$H = \int_V A \cdot B \, dV$$

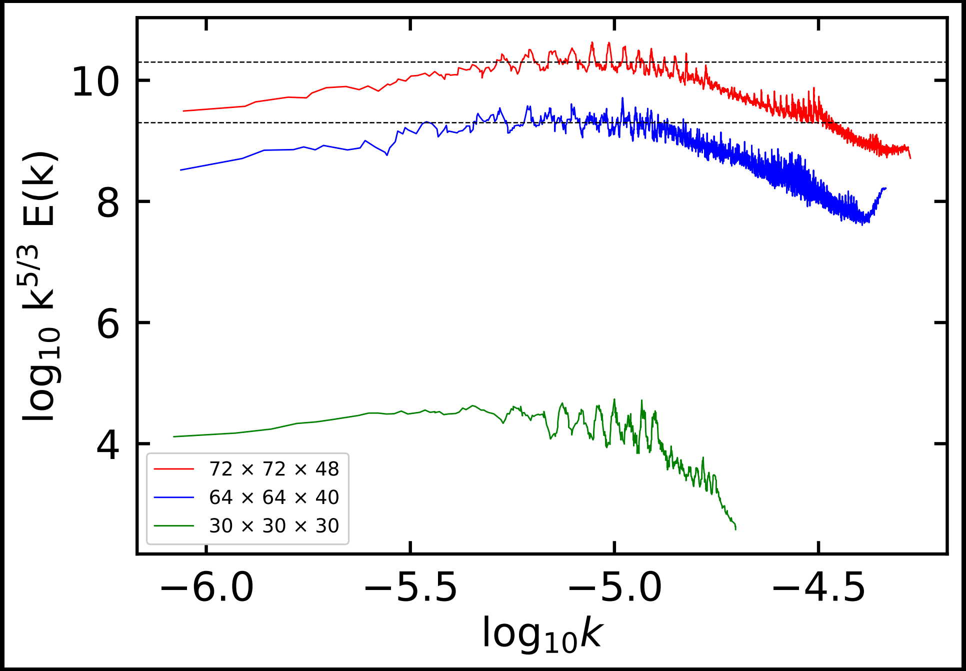
Instabilities

Helicity (H) is scattered to different length scales : transfer proceeds from larger to smaller wavenumbers showing an inverse cascade (Frisch et al. 1975).

The system attempts to conserve by moving it to scales much larger than the resistive scale.

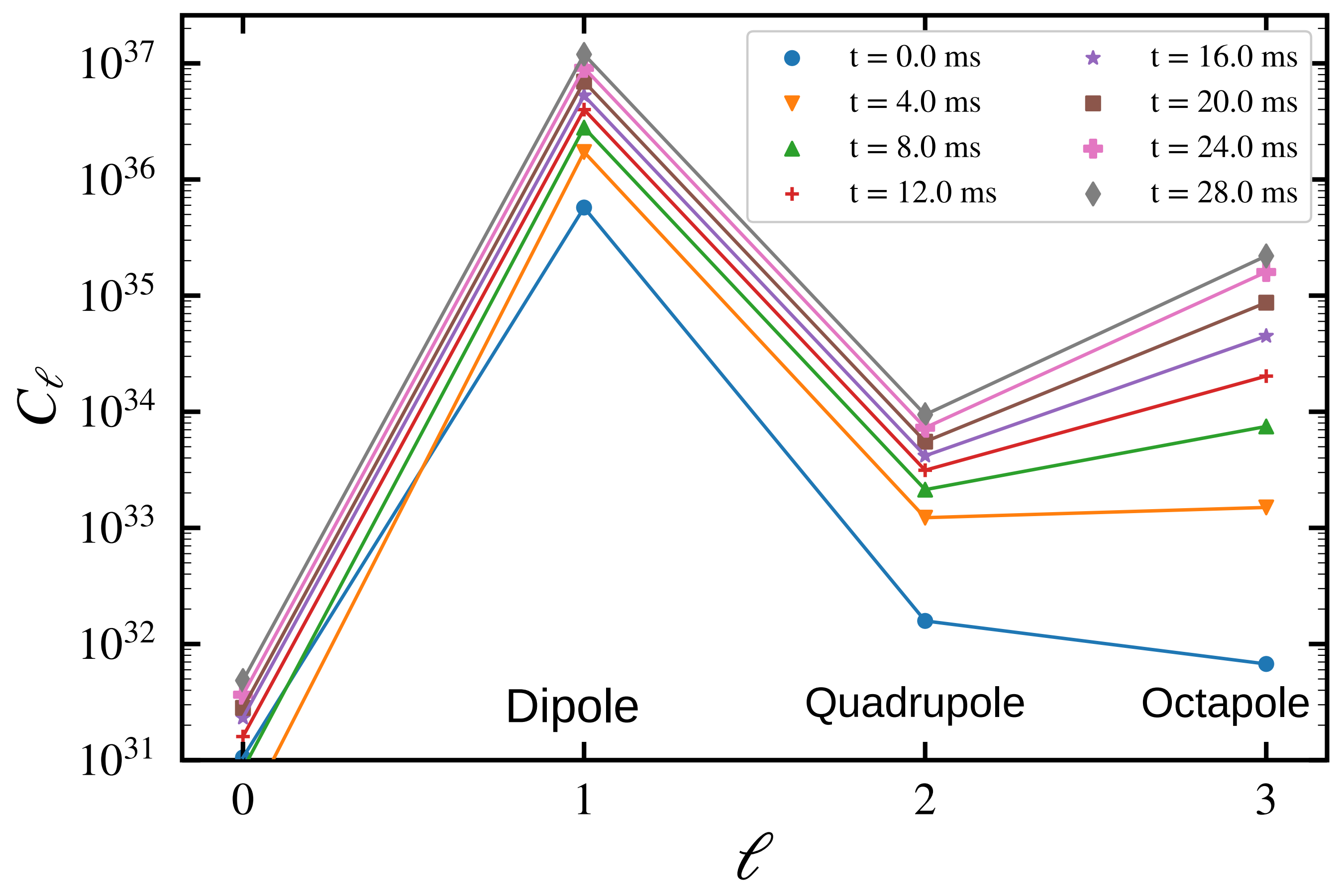


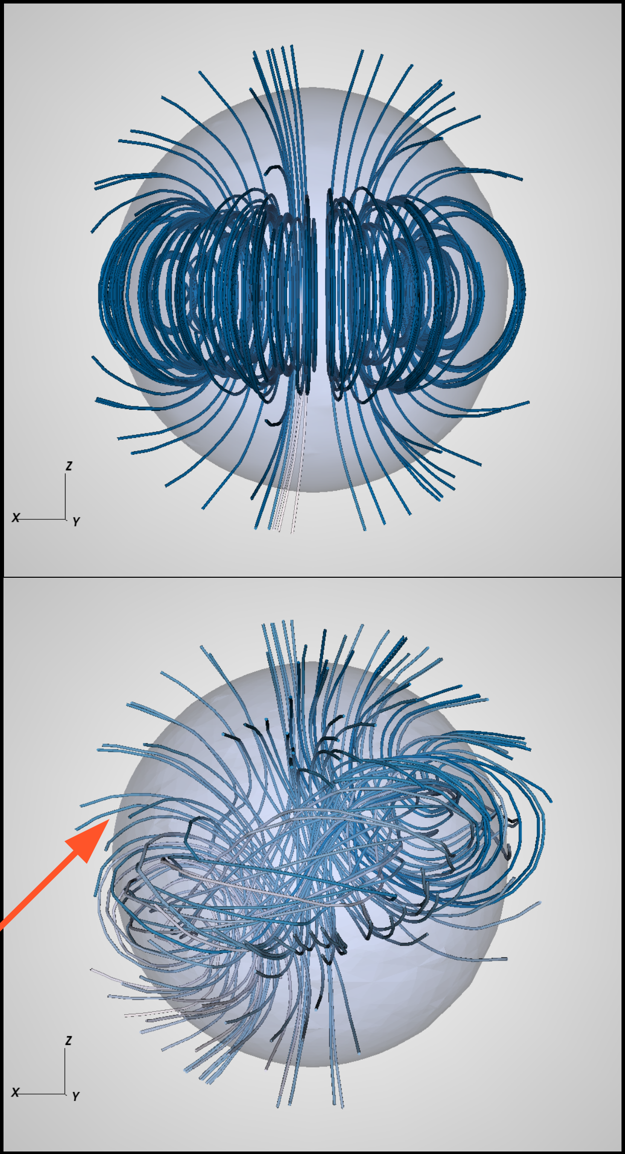
Inverse cascade



Kolmogorov Spectrum

Results: Field Structure





Snapshots: simulations

Initially dipole, higher order multipoles grow in magnitude later

Complex multipolar structure

Magnetic field dissipation

The induction equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B} \right) - \nabla \times \left(\eta \nabla \times \vec{B} \right)$$

electrical resistivity

The hall velocity is

$$\vec{v} = \vec{v}_{Hall} = -\frac{c}{4\pi n e} [\nabla \times \vec{B}]$$

n = electron density

The evolution equation becomes

$$\frac{\partial \vec{B}}{\partial t} = \underbrace{-\nabla \times \left(\frac{c}{4\pi n e} [\nabla \times \vec{B}] \times \vec{B} \right)}_{\text{Hall term}} \underbrace{- \nabla \times \left(\eta \nabla \times \vec{B} \right)}_{\text{Ohmic}}$$

Magnetic field dissipation

The induction equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B}\right) - \nabla \times \left(\eta \nabla \times \vec{B}\right)$$

Accretion:

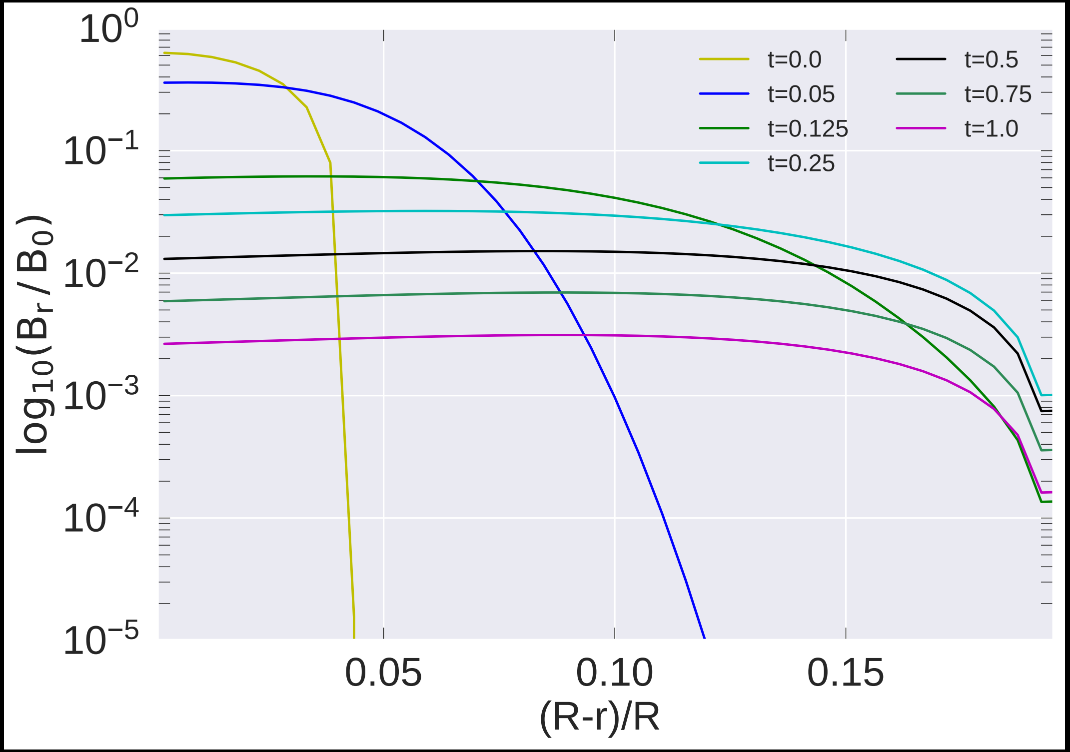
$$\vec{v}_{acc} = -\frac{\dot{M}}{4\pi r^2 \rho(r)} \hat{r}$$

Mass Accretion rate

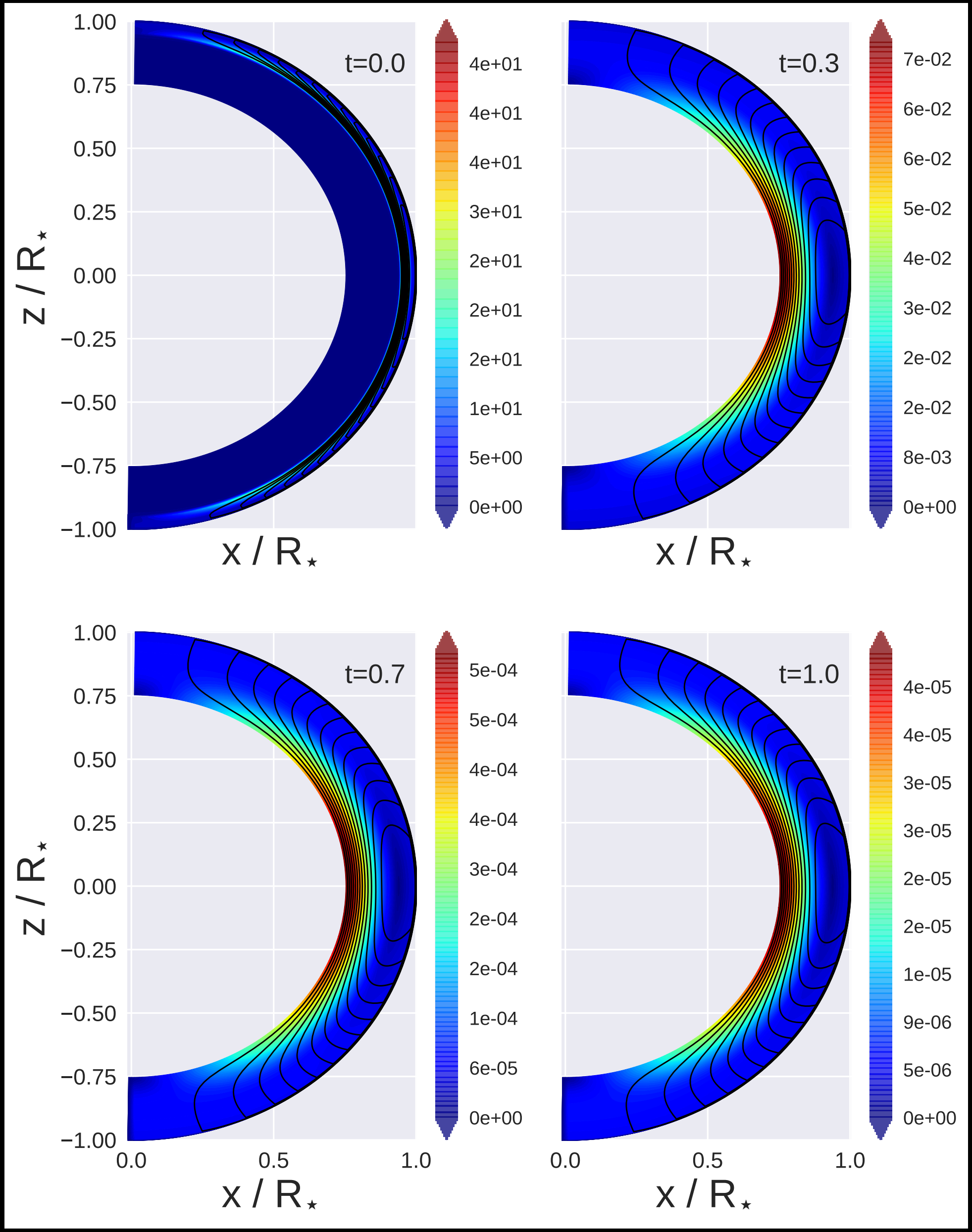
The final evolution equation becomes

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \left(\underbrace{\frac{c}{4\pi n e} [\nabla \times \vec{B}] \times \vec{B}}_{\text{Hall term}} + \underbrace{\frac{\dot{M}}{4\pi r^2 \rho(r)} \hat{r} \times \vec{B}}_{\text{Accretion}} \right) \underbrace{- \nabla \times \left(\eta \nabla \times \vec{B}\right)}_{\text{Ohmic}}$$

Preliminary results



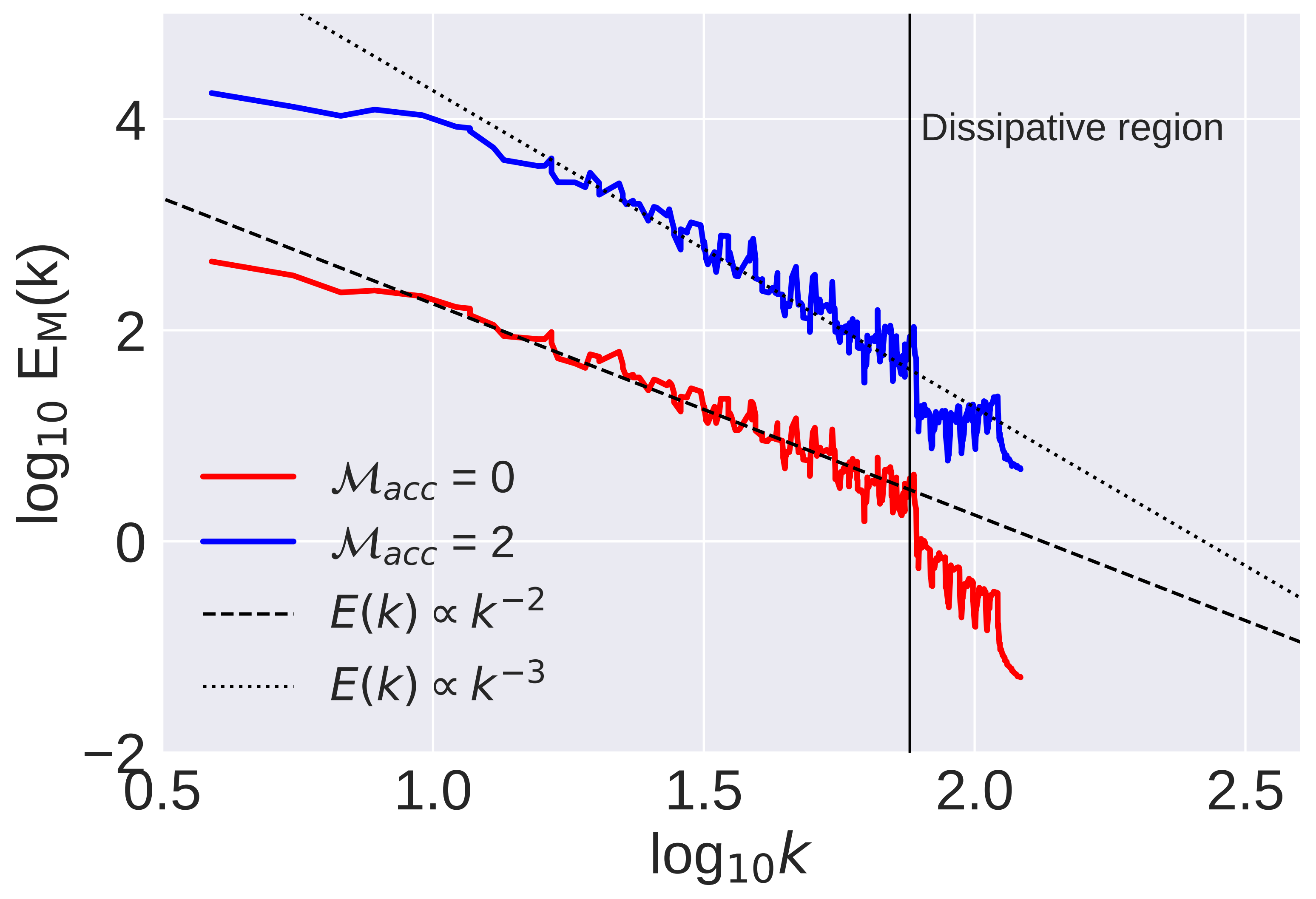
$$t_{\mathrm{Hall}} = 10^6 \text{ years}$$



The fieldlines are pushed inwards.

The magnitude decreases by several orders of magnitude.

Turbulence



Hall effect + Ohmic: Theoretically predicted slope = -2

Plus Accretion : slope=-3

Gravitational Waves

Isolated neutron stars can emit gravitational waves:

- Strong magnetic fields could deform the star
- Magnetic mountains

Data Analysis: with Prof. Michal Bejger and Prof. Haskell

- POLGRAW pipeline – All sky search code
- Modifying the code to incorporate astrophysics

Future

Study various magnetic field models and their decay, turbulence and structure. Make simulations and interpret results.

Build equilibrium models for the magnetic field (not from time evolution) : Solve Grad-Shafranov equation numerically.

Make use of the Polgraw pipeline to analyze O3 data.