# Magnetized turbulence, accretion and outflows.

Collaborators:

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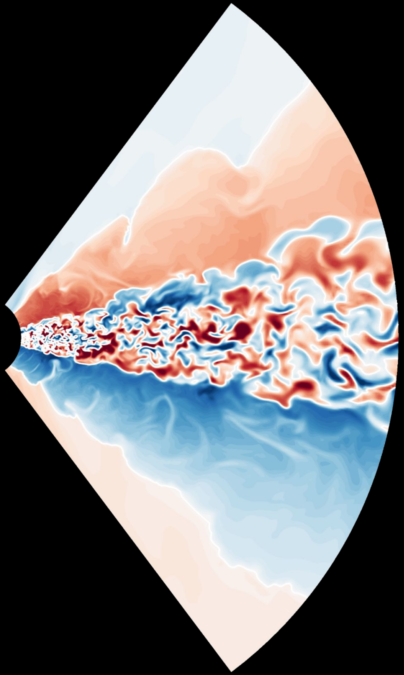

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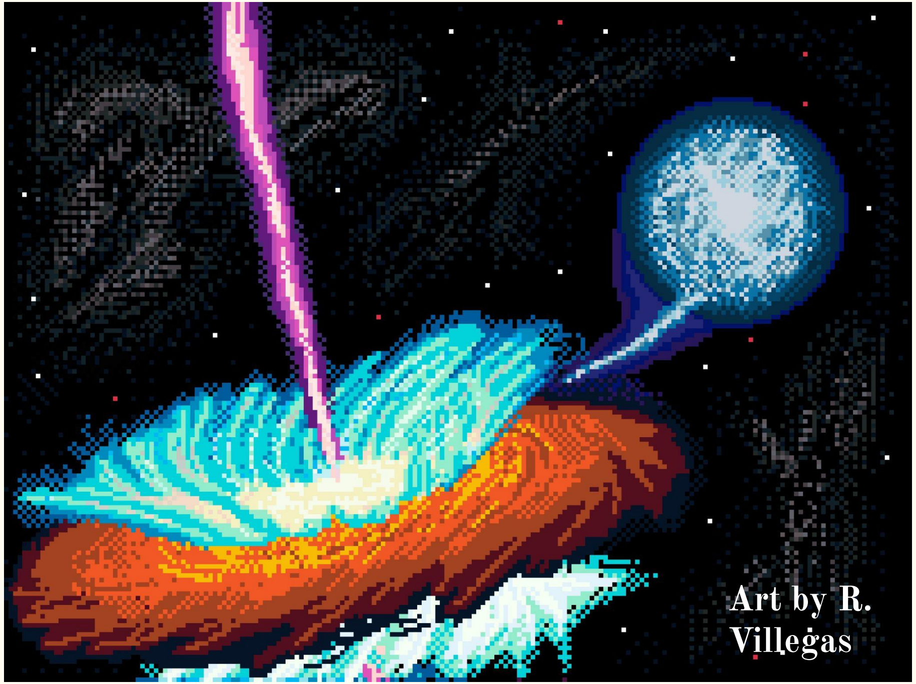
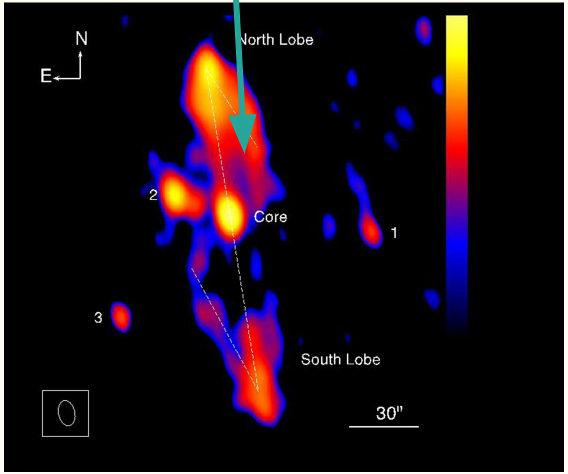
# Accretion and ejection signatures from X-ray Binaries



1. A binary system with a star and a compact object.
2. The compact object is surrounded by an accretion disk.
3. The inner regions of the accretion disk emit jets and winds.

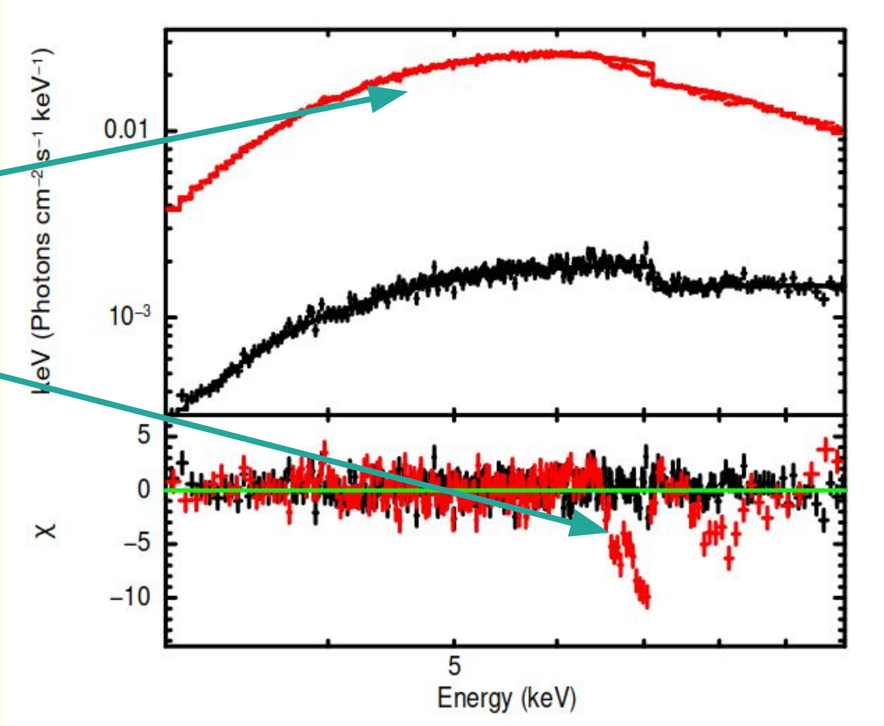
# Accretion and ejection signatures from X-ray Binaries


Art by R. Villegas



Marti et al. 2017

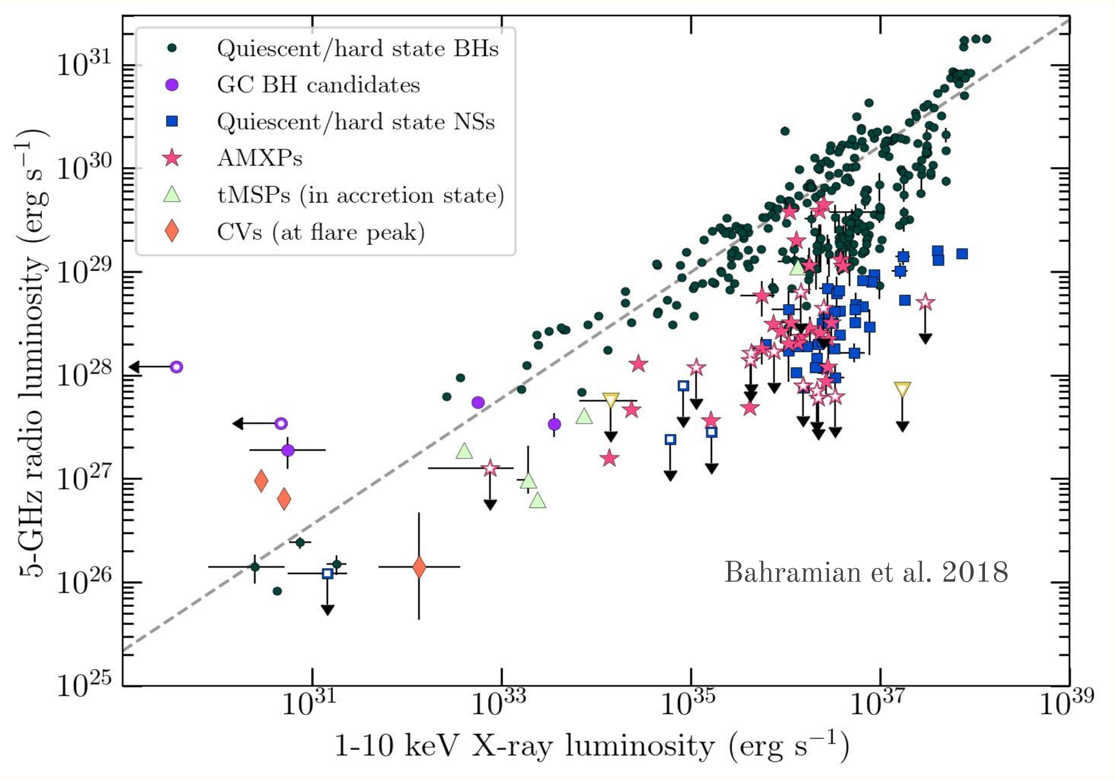
GRS 1758-258



Ponti et al. 2015

# Correlation between accretion and ejection

Jet emission

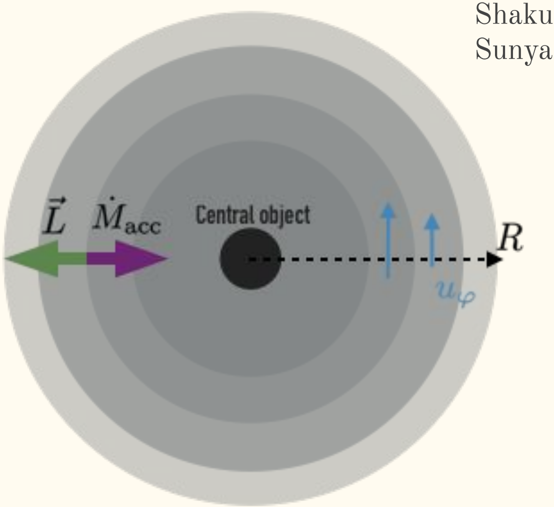


Disk emission

# Two torques

## Turbulent torque

Shakura & Sunyaev 1973

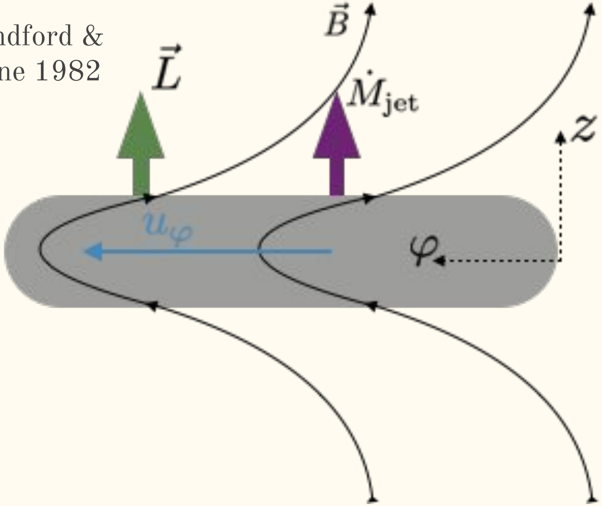


Driven by the Magneto Rotational Instability (MRI)

Balbus & Hawley 1991

## Laminar torque

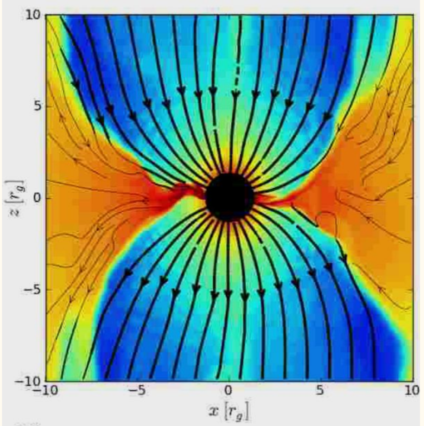
Blandford & Payne 1982



Requires a large scale magnetic field and a magnetic diffusivity

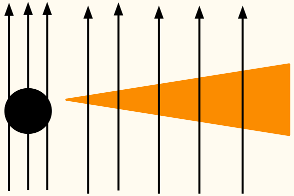
$$\dot{M}_{acc} \simeq \frac{4\pi}{\Omega_K}\left(\mathcal{T}_{tu} + \mathcal{T}_{la}\right)$$

# The large scale magnetic field



McKinney et al. 2012

A large scale magnetic field threading the **disk** is needed for producing **jet-like outflows**.

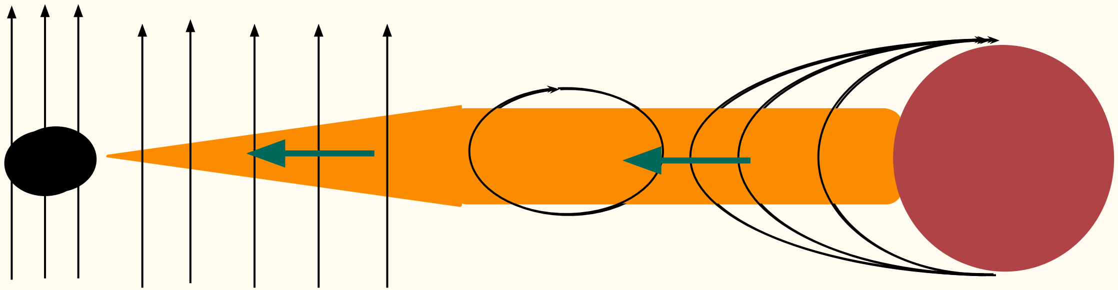


However, there is no reason why the magnetic field would be perpendicular to the plane of the **disk**.

1 The magnetic field is advected from the secondary into the accretion disk.

2 The magnetic field is generated within the accretion disk.

# Large scale field is advected from the secondary



Competition between **accretion** of the **field lines** and **diffusion** due to the **turbulence**

The **magnetic field** could be provided by the stellar dipole. The **overflow advection** is not **trivial**.

Once it reaches the disk, GRMHD simulations suggests that **advection** is a robust process.

Tchekhovskoy et al. 2011
Mckinney et al. 2012

Problems:

- What happens with a **weaker magnetic field**?
- What happens if the advected magnetic field is **toroidal**, **parallel** to the disk plane.

# Method and simulations for weak field

$\log \rho$

We solve ideal MHD equations using PLUTO

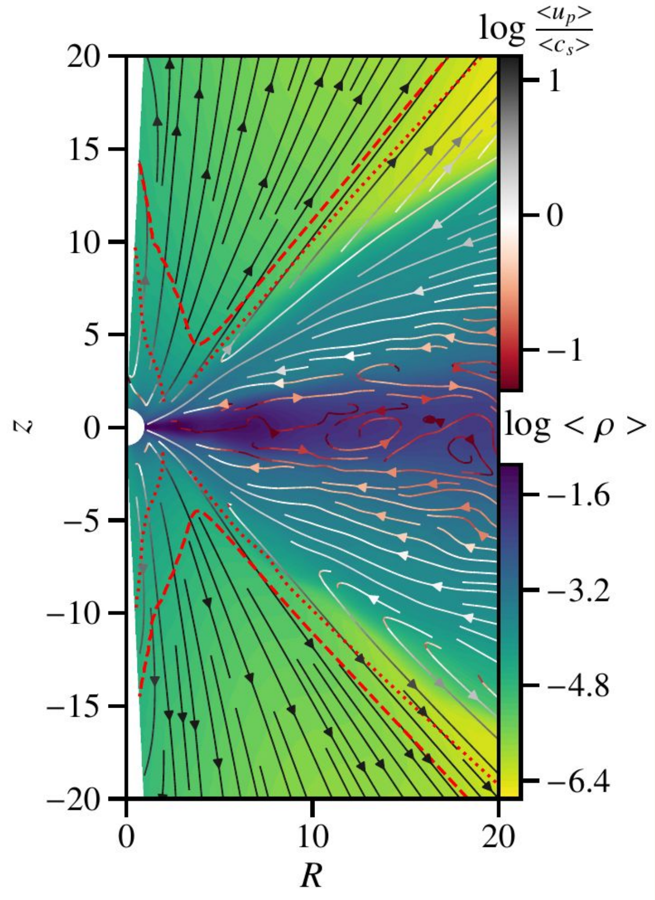
Mignone et al. 2007

Initial conditions

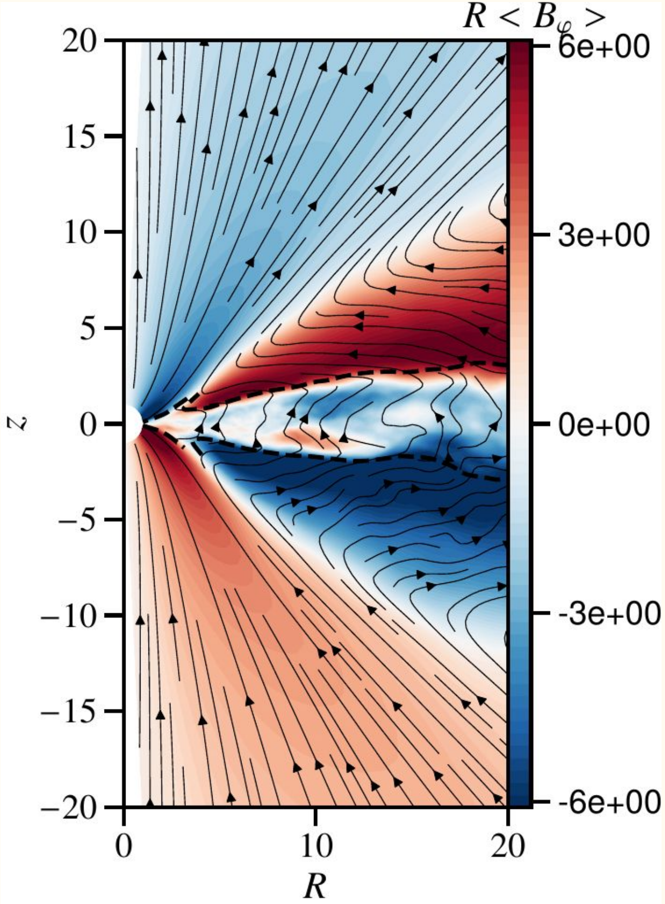
- Hydrostatic Keplerian disk
- Locally isothermal
- Large scale magnetic field threading the disk.
- We start with a weak magnetic field.

$$\beta = \frac{P_{gas}}{P_{mag}} = 10^3$$

# Vertical structure of weakly magnetized disk



$$\beta = 10^3$$



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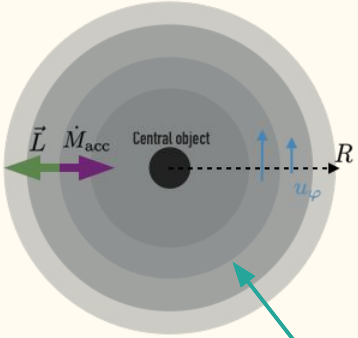
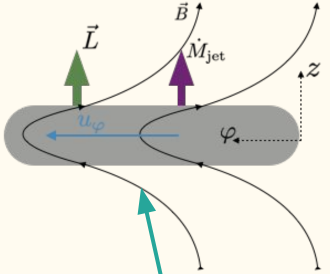
# Turbulent structure

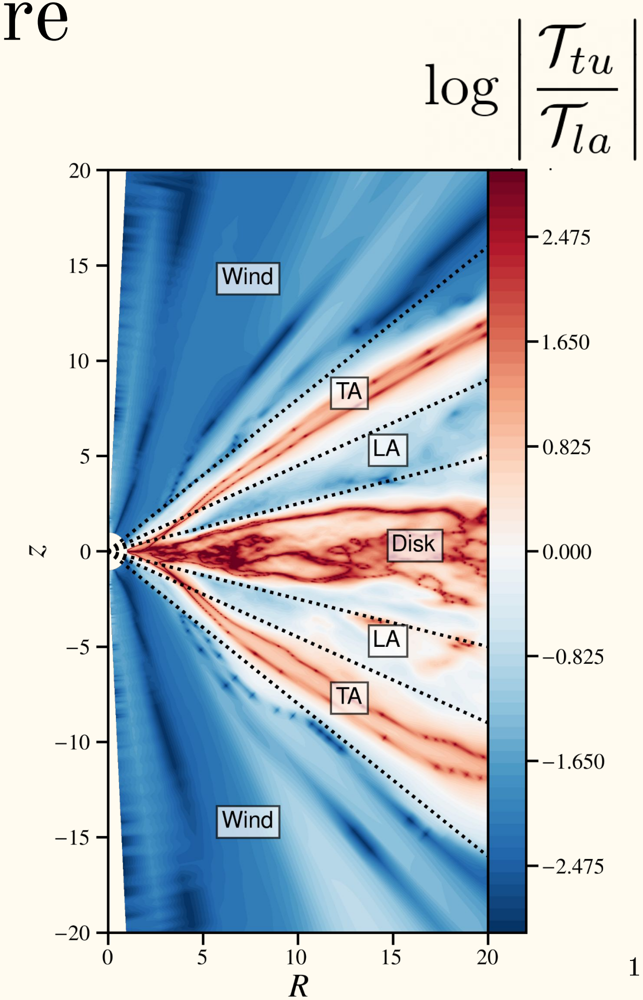
## Turbulent torque



## Laminar torque



$$\dot{M}_{acc} \simeq \frac{4\pi}{\Omega_K}\left(\mathcal{T}_{tu} + \mathcal{T}_{la}\right)$$



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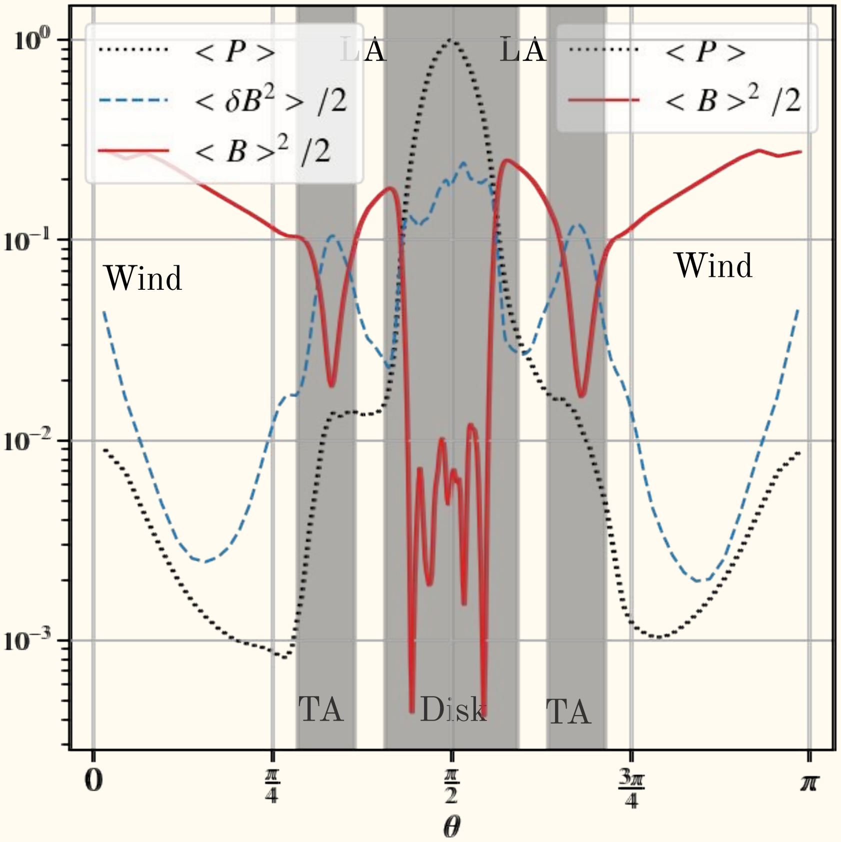
# The role of turbulent pressure



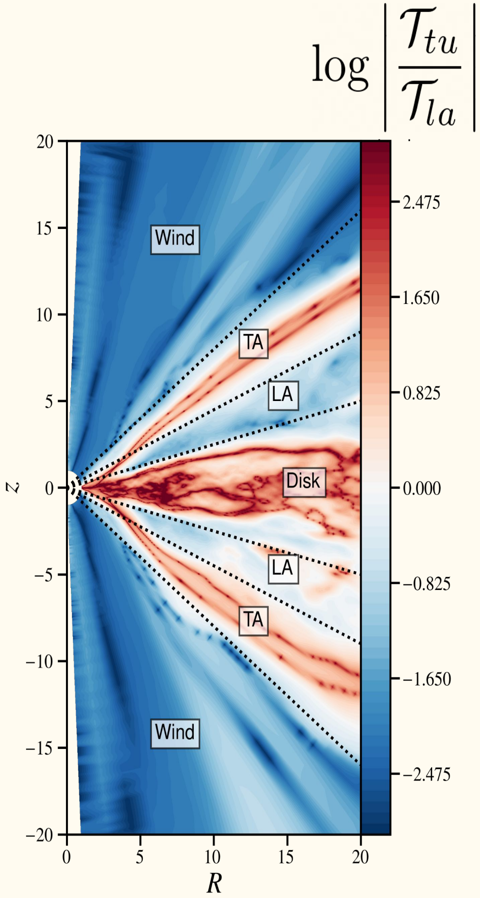
$$\langle B\rangle^2$$

Laminar magnetic pressure compresses the disk and supports the turbulent atmosphere

$$\langle \delta B^2\rangle$$

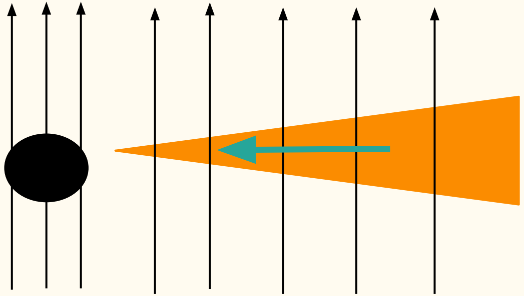
Supplementary turbulent magnetic pressure decompresses the disk and atmosphere.

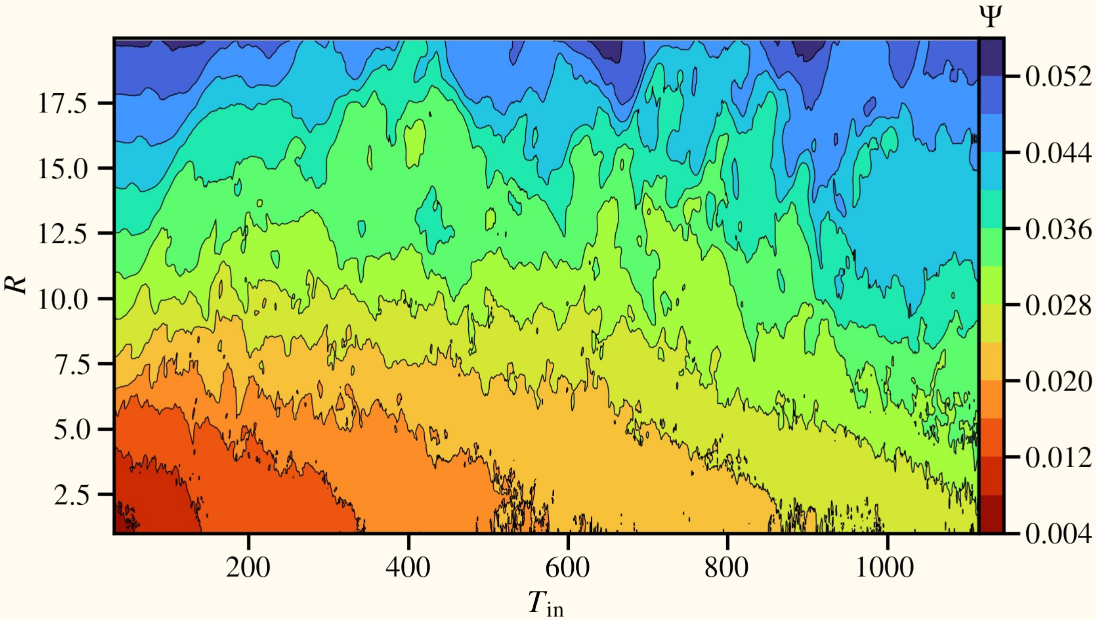
Usually not included in 2D effective models (see however Begelman et al 2015)



Jacquemin-Ide
et al. 2021

# Advection of magnetic flux





Every contour represents a **magnetic field line**

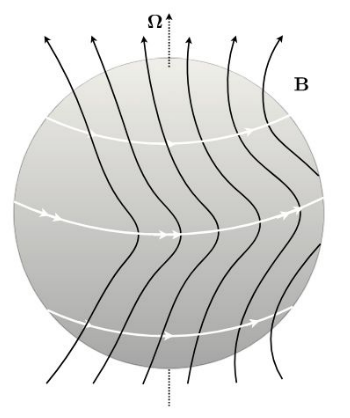
The **magnetic field** is **advected** even when it is **initially weak.**

The **inner regions** of this simulation will eventually become **MAD**

# A dynamo mechanism for accretion disks?

A dynamo is a **positive feedback loop** between the **radial and toroidal field**

## The classical dynamo:

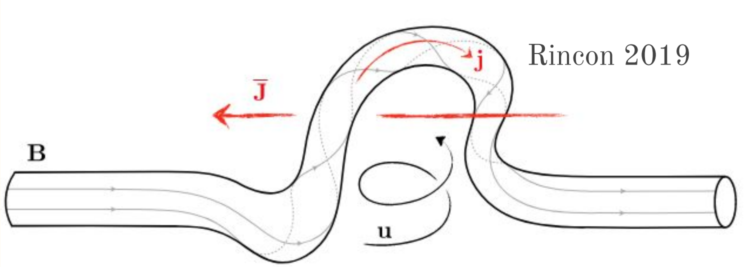


Rincon 2019

**Advection** leads to the **omega effect**

Poloidal becomes toroidal.

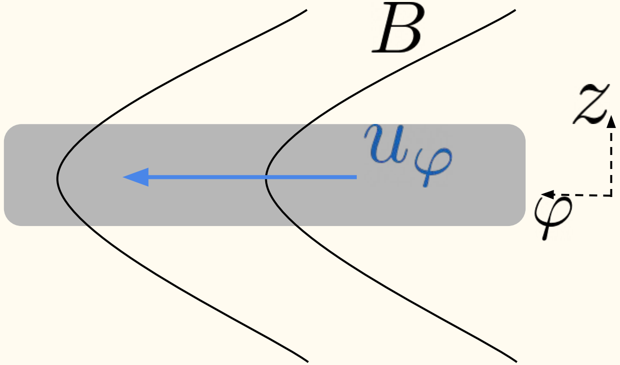
Toroidal becomes poloidal.



Rincon 2019

**Convection and/or turbulence** lead to the **alpha effect.**

## The accretion disk dynamo:



**MRI turbulence** could lead to some kind of **alpha effect**

# Method and simulations for dynamo

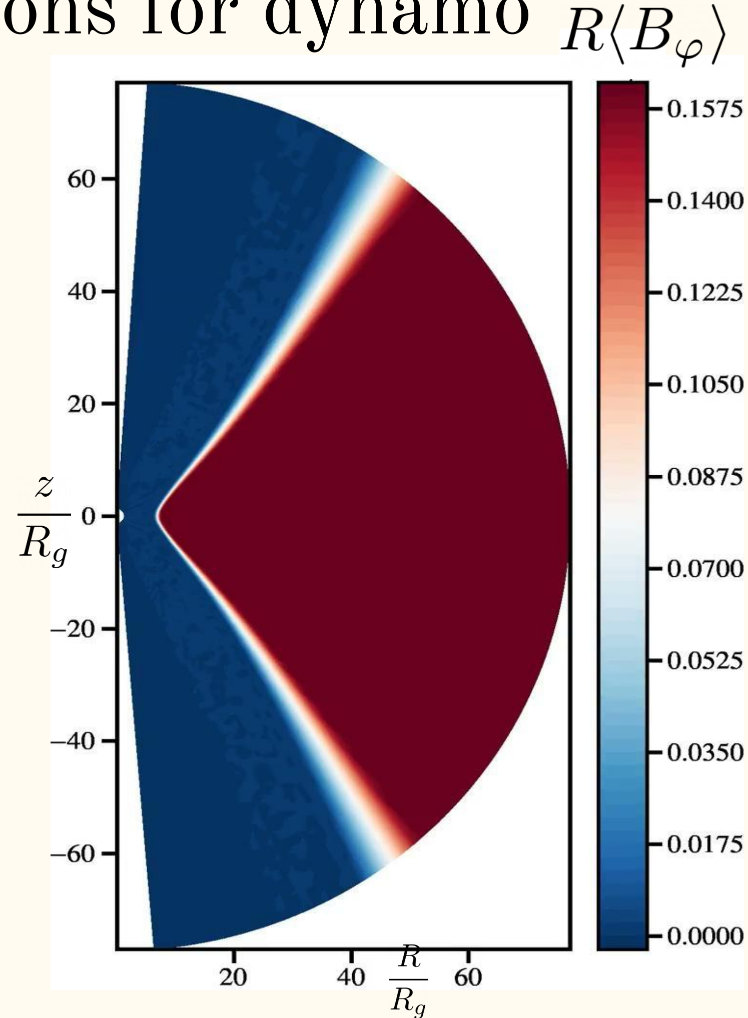
I re-analyzed the simulation from Liska et al. 2020. To try to better understand the dynamo-like mechanism.

We solve ideal GRMHD equations using H-AMR

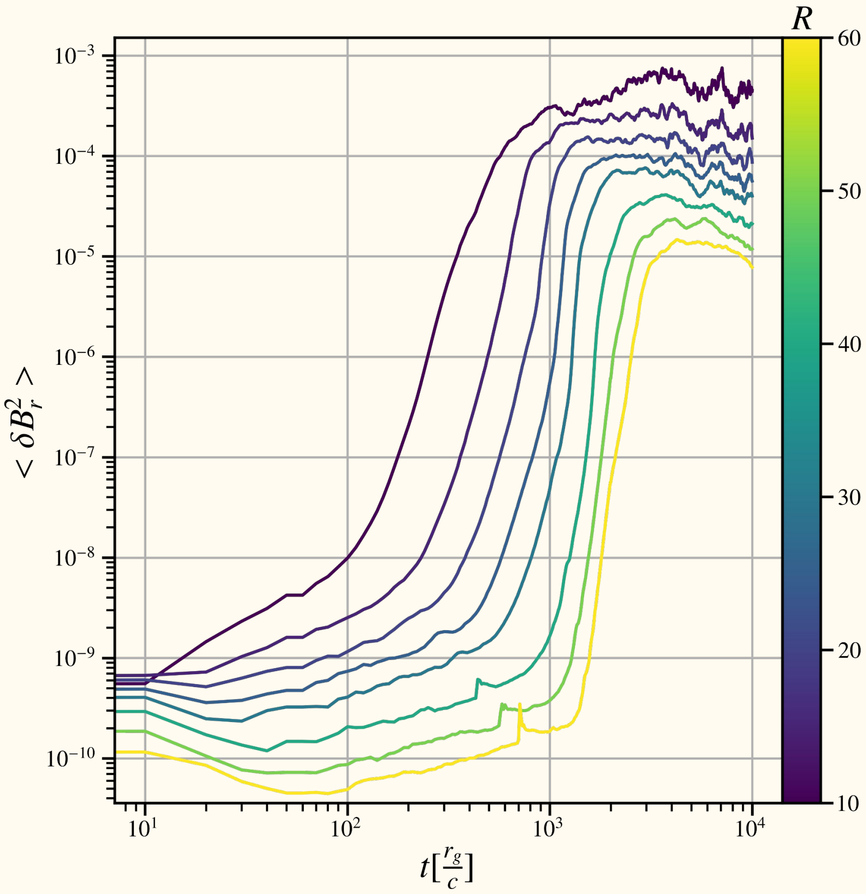
Liska et al. 2018

Initial conditions

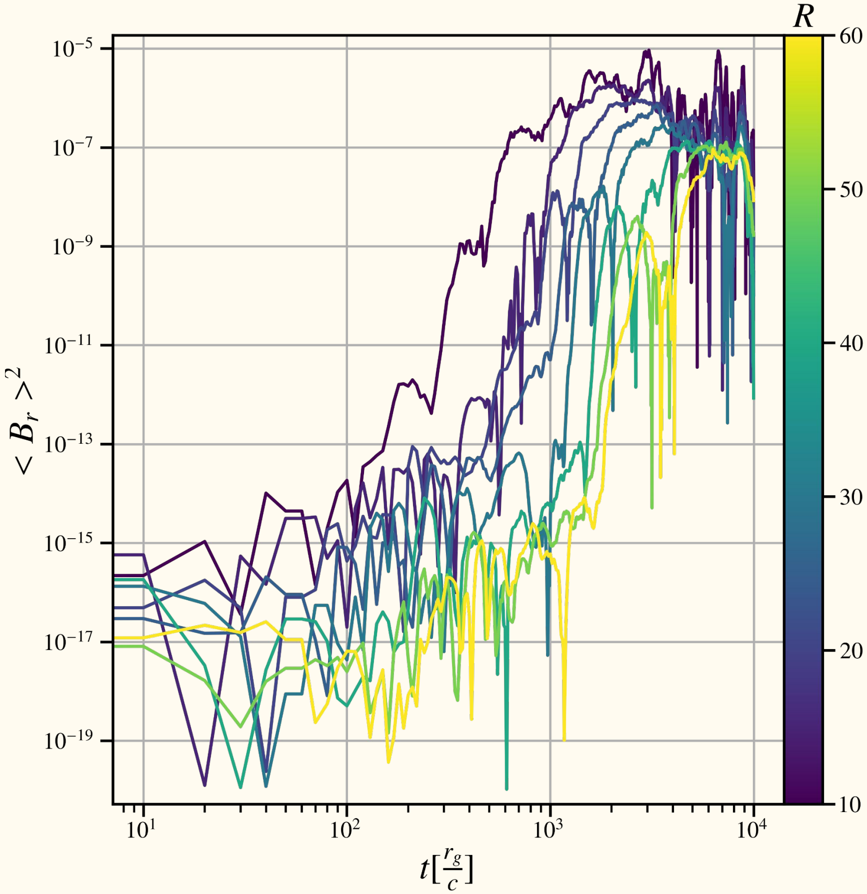
- Hydrostatic torus
- Adiabatic
- Large scale magnetic field that is purely toroidal



# Turbulent vs average radial magnetic energy

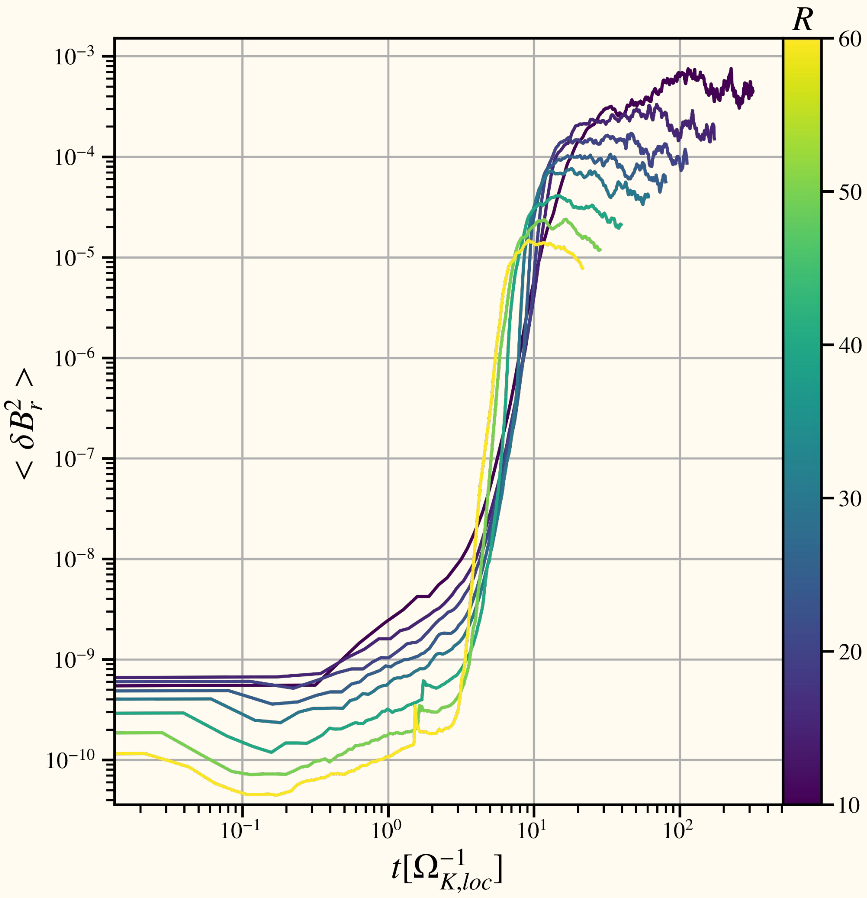


Different growth rates at different radii is a signature of MRI

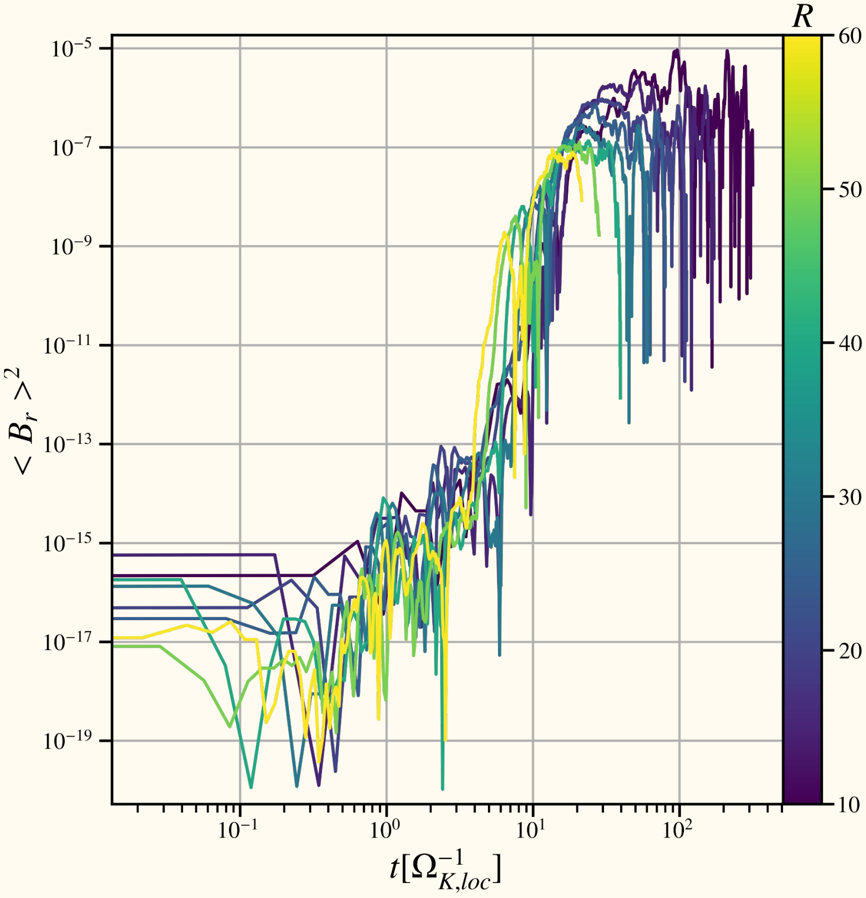


Growth but has non-linear features

# Turbulent vs average radial magnetic energy

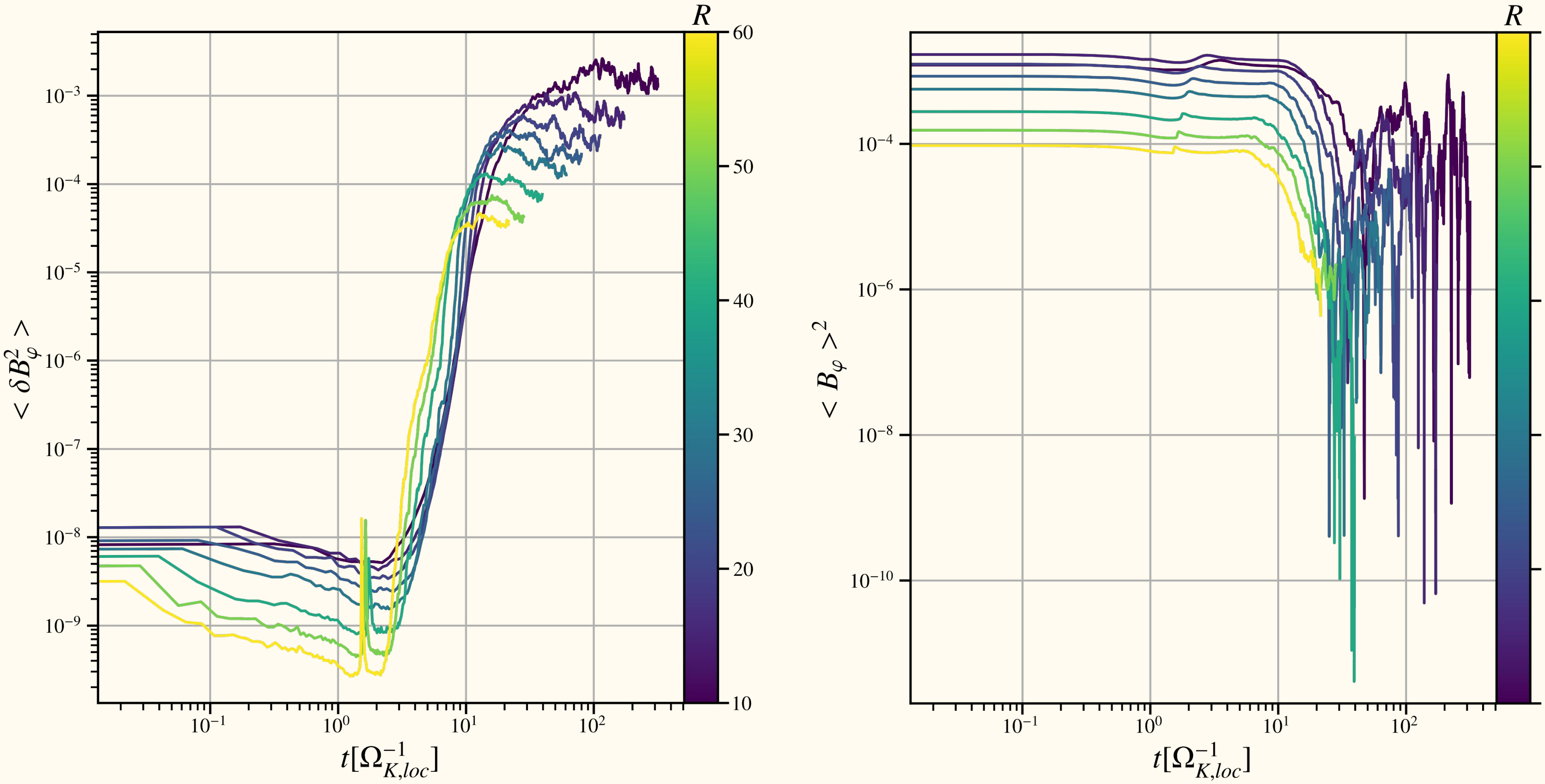


We recover the MRI timescale



Same time-scale as the MRI, Non-linear dynamo growth is driven by the MRI.

# Turbulent vs average toroidal magnetic energy



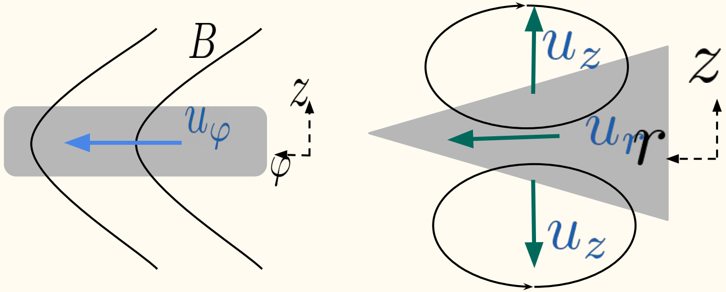
Energy now decreases instead of increasing.
Non-linear dissipation of the toroidal field.

# Energy through advection or turbulence

$$\frac{1}{2}\partial_t\langle B_r\rangle^2 = \textbf{Advection} + \textbf{Turbulent}$$

$$\frac{1}{2}\partial_t\langle B_\varphi\rangle^2 = \textbf{Advection} + \textbf{Turbulent}$$

## Advection



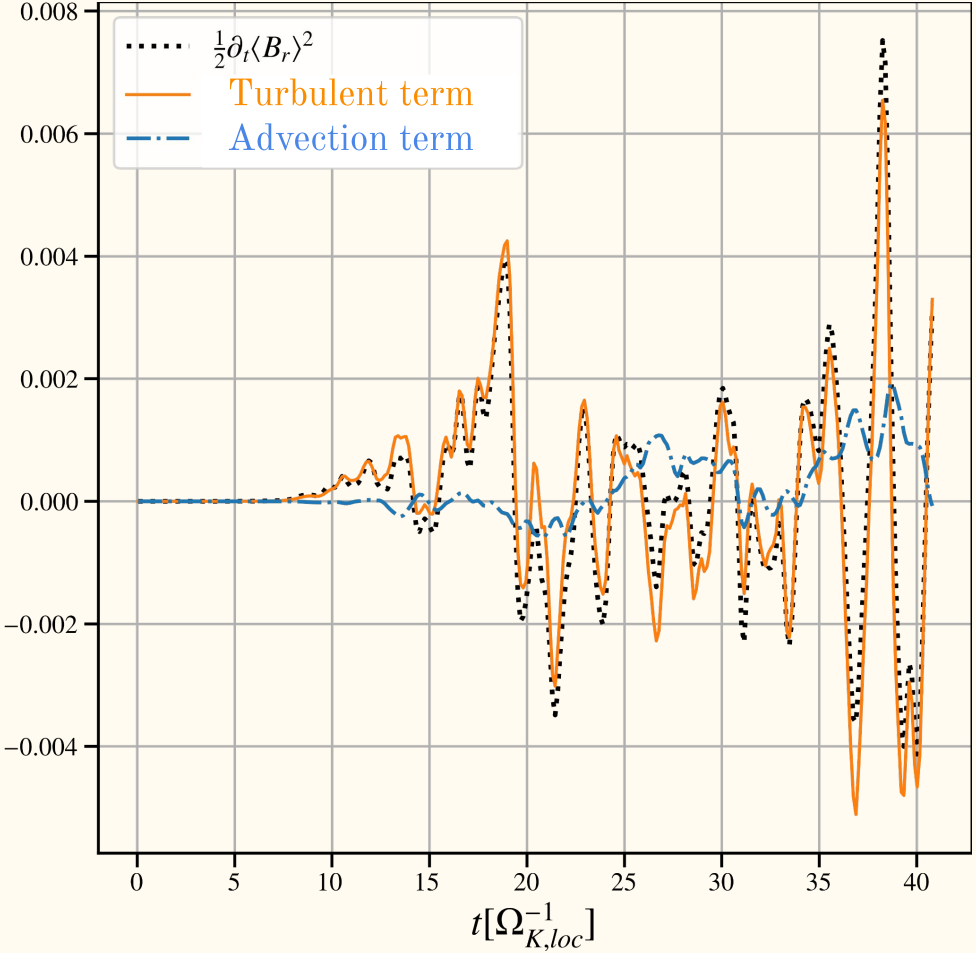
**Advection** is not limited to the **omega effect.**

## Turbulent

The turbulent term can have different kinds of behavior:

- It can **dissipate magnetic energy**. It acts as a **turbulent resistivity**.
- It can **transfer/create magnetic energy**. In this case it acts as an **alpha term** (in the simplest case)

# Radial energy transfer



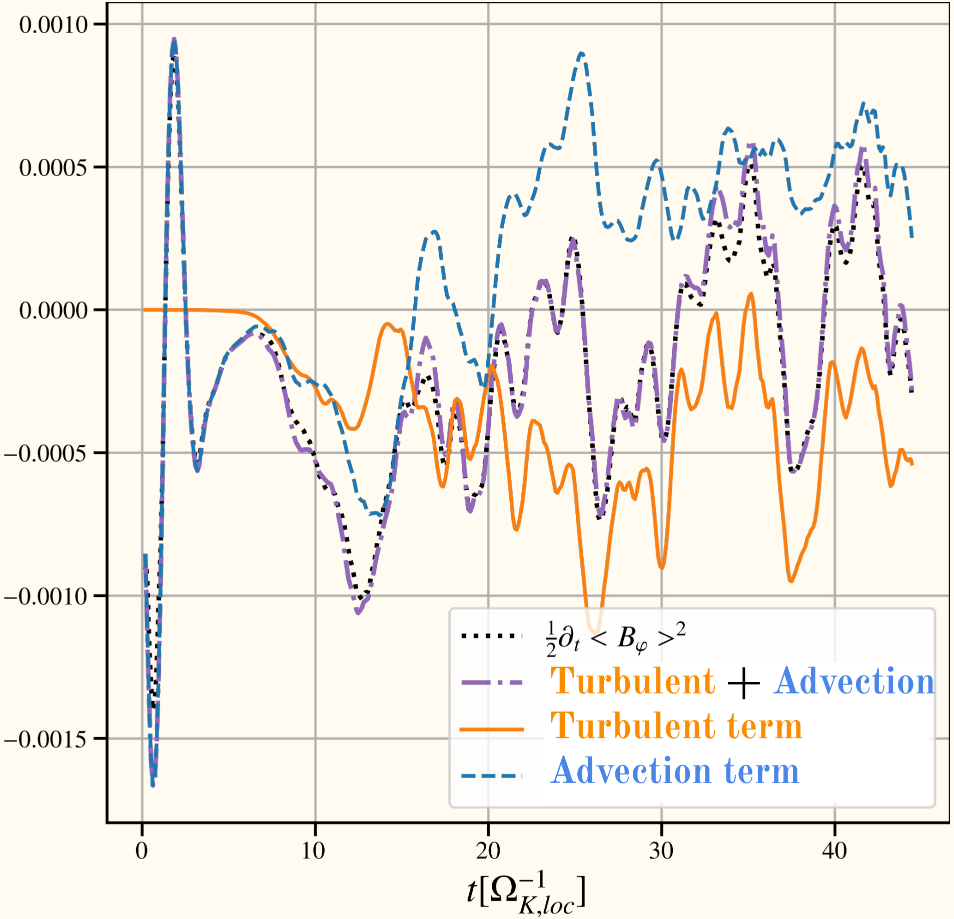
This energy transfer is fully dominated by the **turbulent term.** The **advective term** is negligible

We see it grow linearly until it dominates the energy exchange.

This **turbulent term generates** and **dissipates** radial magnetic energy! It performs both jobs!

This means that the turbulent EMF is complex and consist of multiple terms.

# Toroidal energy transfer



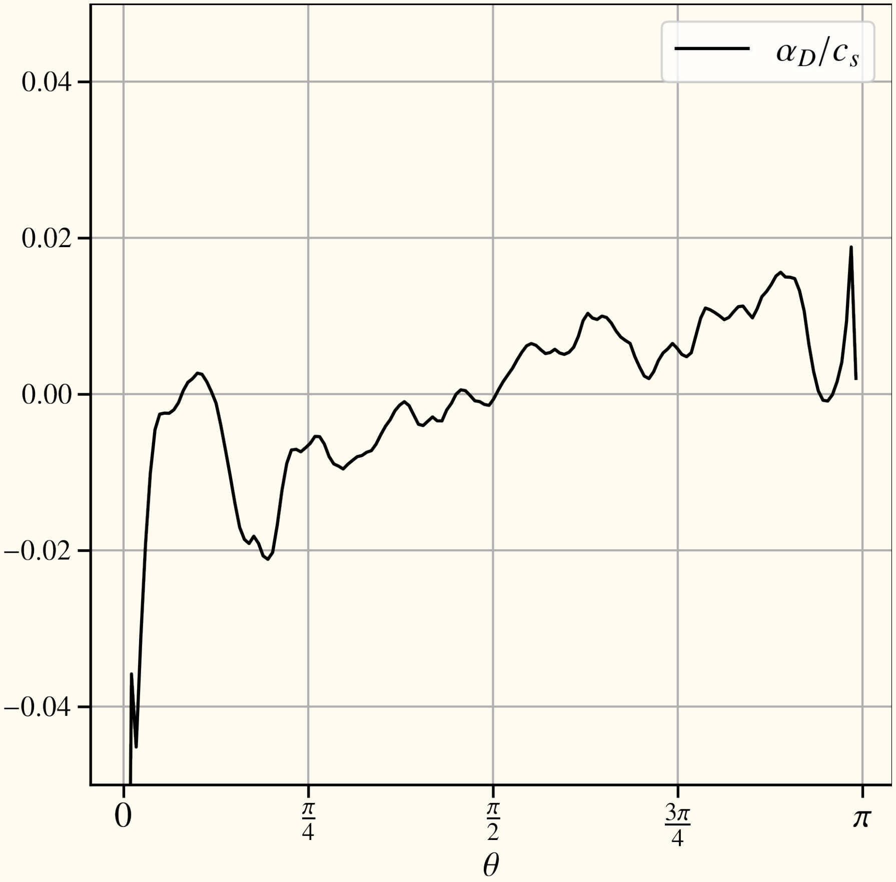
The turbulent term dissipates **magnetic energy**. While the advective term generates **magnetic energy**.

We also notice the linear growth of the turbulent term.

The advective term is dominated by the omega effect

This means that this EMF could be modeled as a simple resistivity!

# First signs of an alpha omega dynamo



An dynamo **alpha model** seems to capture the behavior of the system.

Our computation is consistent with shearing box simulations.
Brandenburg 1995, Davis et al. 2010,
Hogg and Reynolds 2018

First measurement of **alpha** in **fully global GRMHD** simulations.

However, this is still work in progress as we are ignoring the **dissipation** terms and other kinds of terms. Gressel and Pessah 2016

$$\mathcal{E}_\varphi = \alpha_{\varphi\varphi}\langle B_\varphi \rangle + \ldots$$

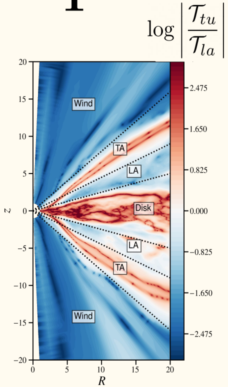
# Conclusions & perspectives

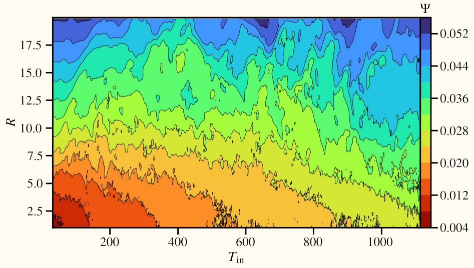
1. The structure of **weakly magnetized** accretion disk is linked to **MRI turbulence** and to the role of the **turbulent magnetic pressure**.

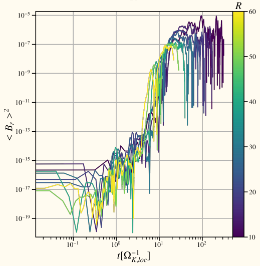
2. **Weakly magnetized** disk also **advect** their **poloidal magnetic field.**

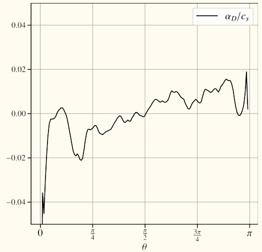
3. A **dynamo-like MRI-driven** mechanism can flip the **magnetic field** direction and lead to a **poloidal field.** It appears consistent with an **alpha omega dynamo**

4. The existence of a **poloidal field** in X-ray binaries seems to be more robust than what was once thought.









1. Do thin disk **transport magnetic flux** as efficiently?

2. Does the **dynamo-like** mechanism depend strongly on initial conditions?

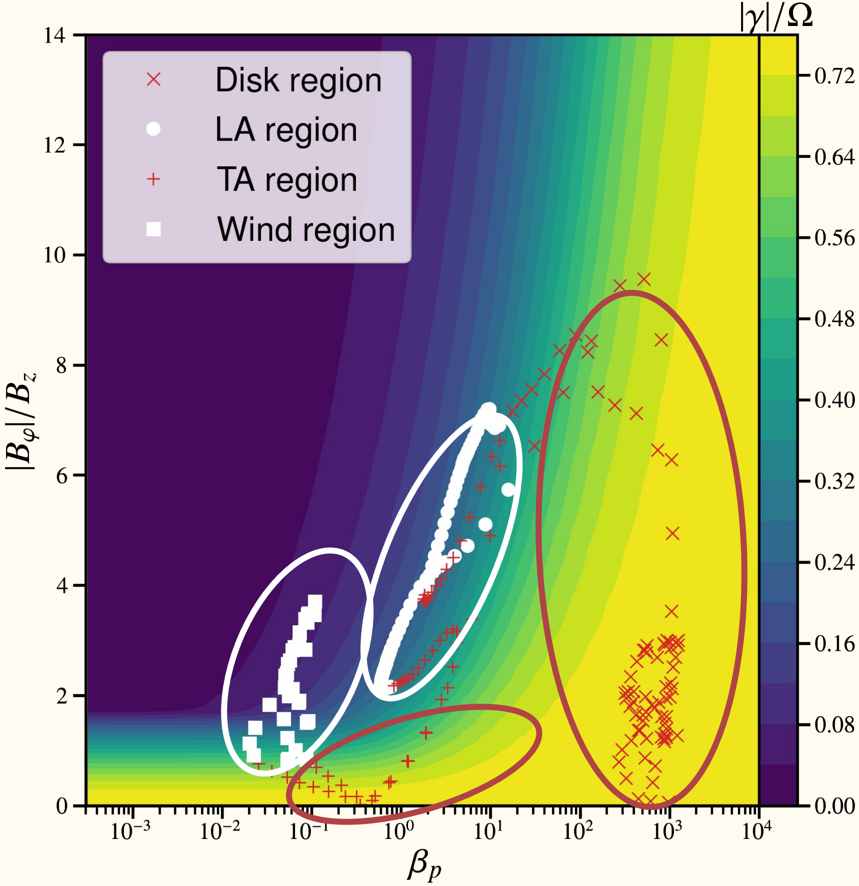
# The disappearance of MRI turbulence

MRI exists for all values of $\beta_p$ as long as the wavelength is large enough.

However, for small values of $\beta_p$ the MRI disappears no matter the wavelength.

$$\beta_p \to 0$$

$$\frac{\langle B_\varphi \rangle^2}{\langle B_z \rangle^2} > \frac{3}{4} \to \text{stability.}$$



Kim & Ostriker 2000

# Energy transfer from the induction equation

$$\frac{\partial\langle\mathbf{B}\rangle}{\partial t} = \nabla\times\left(\langle\mathbf{u}\rangle\times\langle\mathbf{B}\rangle + \mathcal{E}\right)$$

$$\mathcal{E} = \langle\delta\mathbf{u}\times\delta\mathbf{B}\rangle$$

Advection term

The omega-effect is contained within it.

Turbulent EMF

Can be modeled in very different forms.

$$\frac{1}{2}\frac{\partial\langle B_r\rangle^2}{\partial t} = \langle B_r\rangle\nabla\times\left(\langle\mathbf{u}\rangle\times\langle\mathbf{B}\rangle + \mathcal{E}\right)_\mathbf{r}$$

$$\frac{1}{2}\frac{\partial\langle B_\varphi\rangle^2}{\partial t} = \langle B_\varphi\rangle\nabla\times\left(\langle\mathbf{u}\rangle\times\langle\mathbf{B}\rangle + \mathcal{E}\right)_\varphi$$

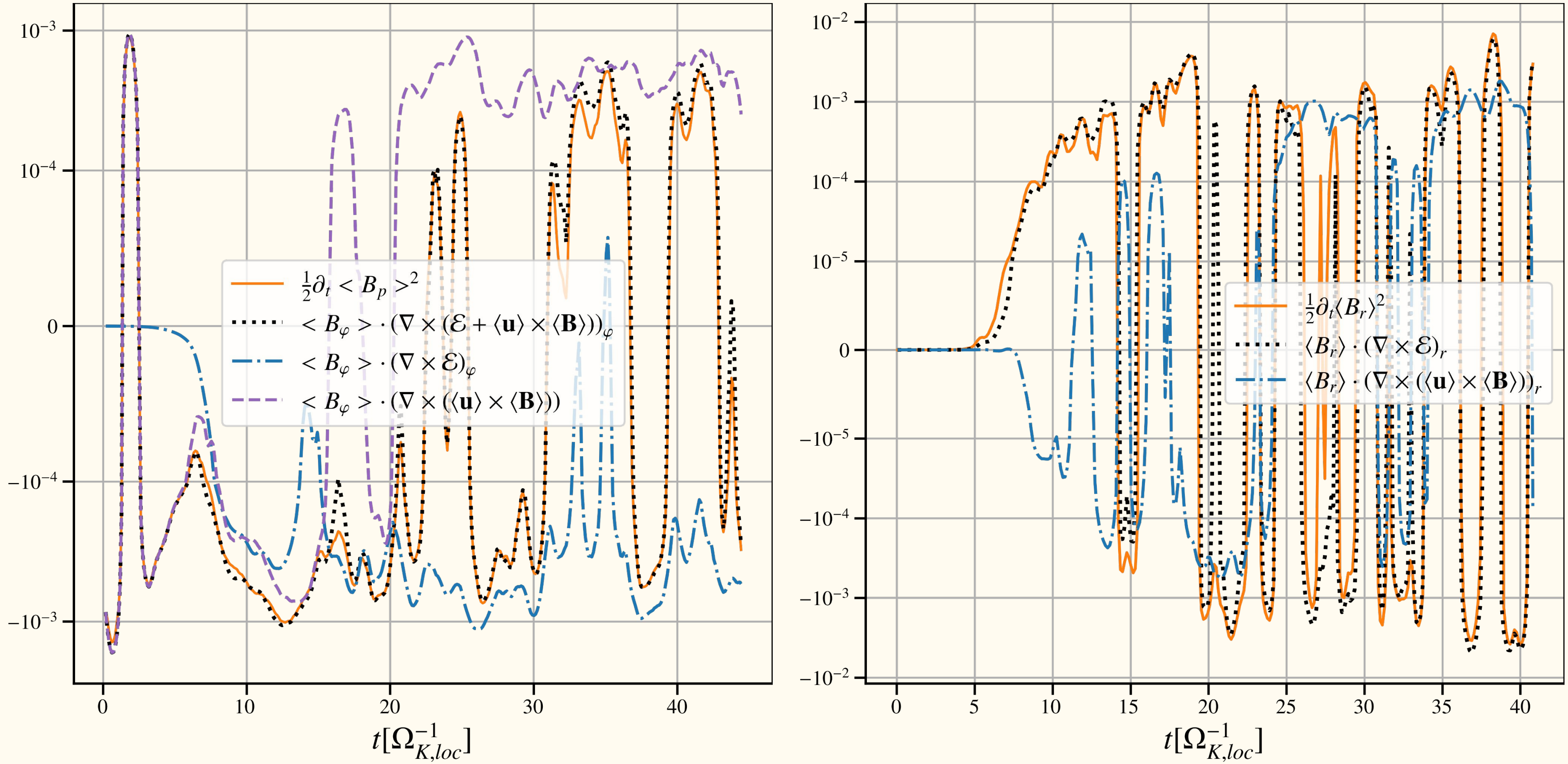
Turbulent source term

Net energy change

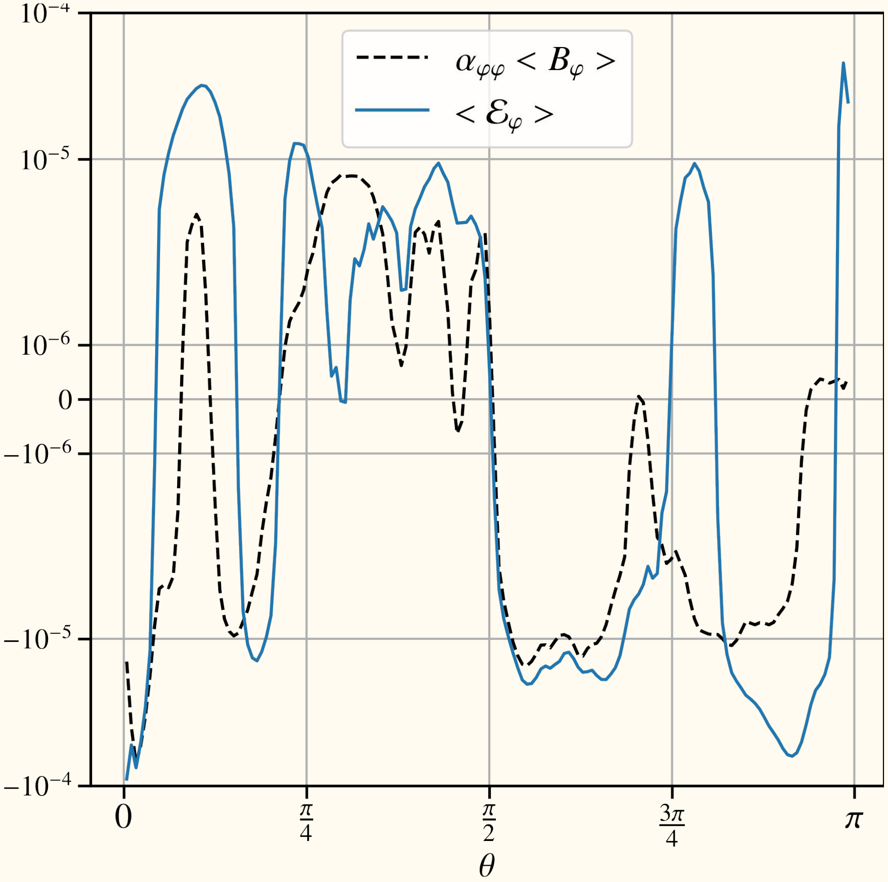
Advection term

Energy can be advected from one component to another. Omega effect transforms the radial field into toroidal field.

# Log for energy transfer



# First signs of an alpha omega dynamo



Model

$$\mathcal{E}_\varphi \simeq \alpha_{\varphi\varphi}\langle B_\varphi \rangle$$

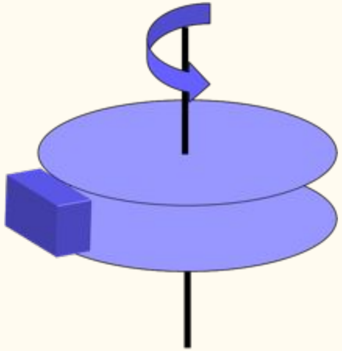
An dynamo alpha model seems to capture the turbulent EMF.

However, this is still work in progress as we are ignoring the dissipation terms.

$$\mathcal{E}_\varphi = \alpha_{\varphi\varphi}\langle B_\varphi \rangle + \ldots$$

# Three methods

## Shearing box simulations



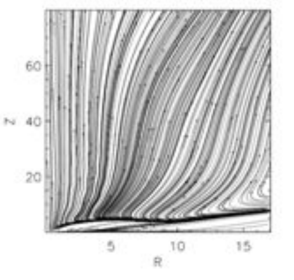
### No outflow torque

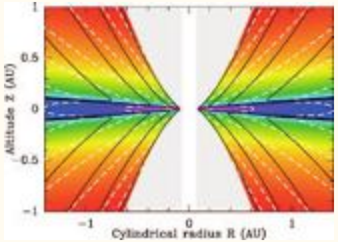
Hawley et al. 1995

### Outflow torque

Suzuki and Inutsuka 2009
Ogilvie 2012
Lesur et al. 2013
Salvesen et al. 2016

## Global 2D effective models





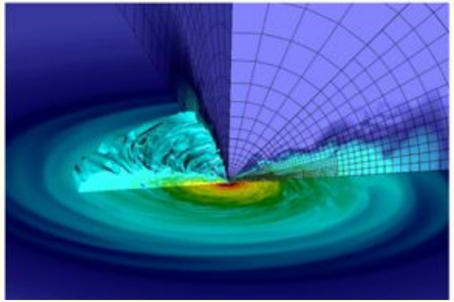
### Semi-analytical

Ferreira & Pelletier 1995
Ferreira 1997

### 2.5D simulations

Ferreira & Pelletier 1995
Ferreira 1997

## 3D global simulations



### General Relativistic MHD

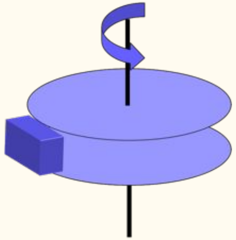
Tchekhovskoy et al. 2011
Mckinney et al. 2012

### MHD

Zhu & Stone 2018
Mishra et al. 2020

# Three methods

## Shearing box simulations



No outflow torque

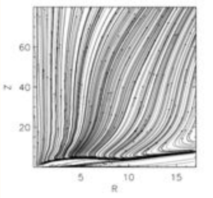
Hawley et al. 1995

Outflow torque

Suzuki and Inutsuka 2009
Ogilvie 2012
Lesur et al. 2013
Salvesen et al. 2016

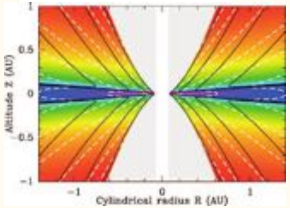
- Accurately model the MRI-driven turbulence and its structure.
- Radial shear boundary conditions are well understood
- The computed outflows are subject to several numerical biases

## Global 2D effective models



Semi-analytical

Ferreira & Pelletier 1995
Ferreira 1997

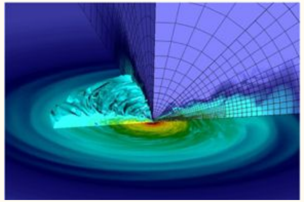


2.5D simulations

Ferreira & Pelletier 1995
Ferreira 1997

- Numerically cheap
- Captures the properties of the outflow
- Depend of ad-hoc closure of the turbulent structure

## 3D global simulations



General Relativistic MHD

Tchekhovskoy et al. 2011
Mckinney et al. 2012

MHD

Zhu & Stone 2018
Mishra et al. 2020

- Accurately model MRI-driven turbulence and its structure.
- Capture properties of the outflow
- Highly expensive

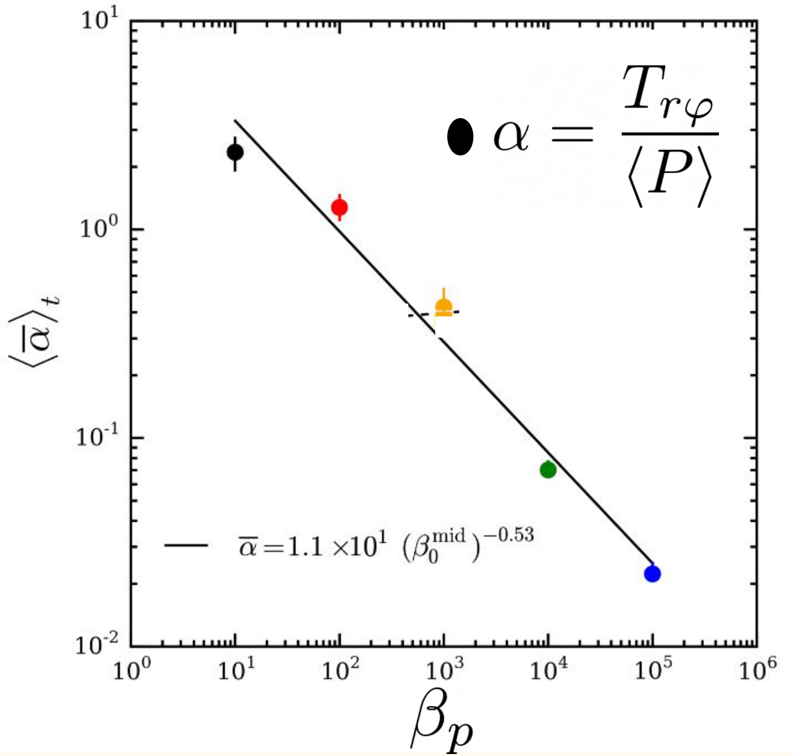
# Correlation of torque and magnetic field

Salvesen et al. 2016

The strength of the turbulent torque depends on the plasma beta

$$\beta_p = 8\pi \frac{\langle P \rangle}{\langle B \rangle^2}$$

$$\nu_t = \alpha_v c_s h$$



However, the strength of the magnetic field is very hard to measure in observations.

# Better models to compare with observations

beta is unknown
$\beta_p$

Expensive 3D global simulations are hard to compare with observations.

Simple or ad-hoc models are still predominant when comparing with observations.

Shakura & Sunyaev 1973

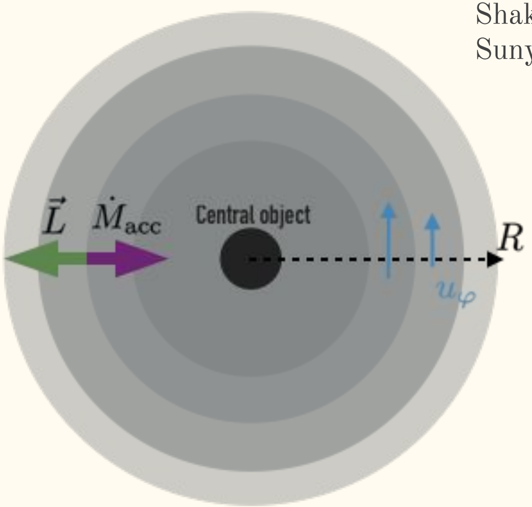
There is a need for better accretion disk models:

- Numerically cheap.
- It needs to capture the properties of the outflows.
- The turbulent structure is coherent with 3D models.

First we need to understand the effects of turbulence on the large scale structure.

# Two torques

## Turbulent torque



Shakura & Sunyaev 1973

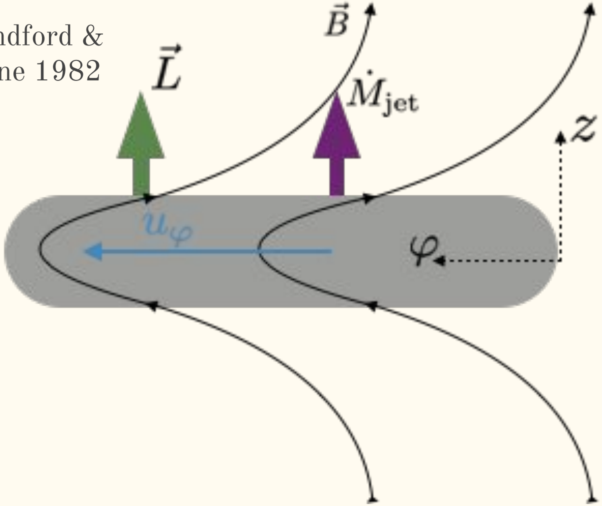
Driven by the Magneto Rotational Instability (MRI)

Balbus & Hawley 1991

$$\nu_t = \alpha_v c_s h$$

## Laminar torque

Blandford & Payne 1982



Requires a large scale magnetic field and a magnetic diffusivity

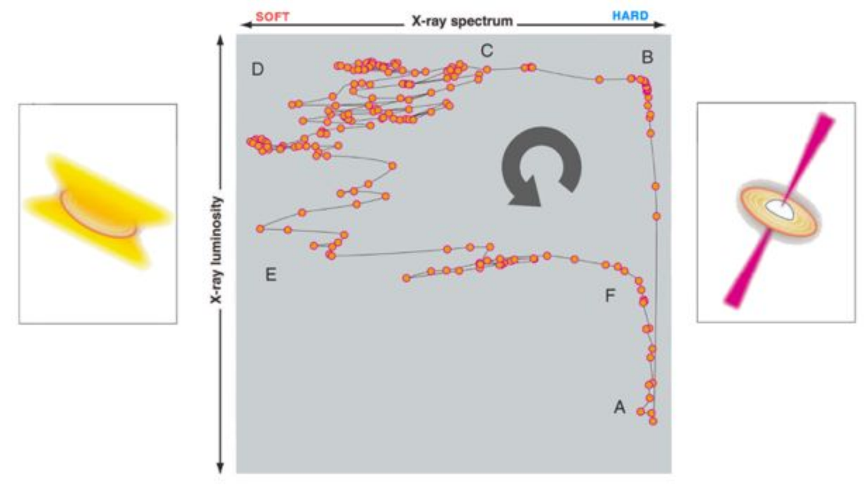
This magnetic diffusivity could be driven by the MRI or a molecular non ideal effect

Ferreira & Pelletier 1993

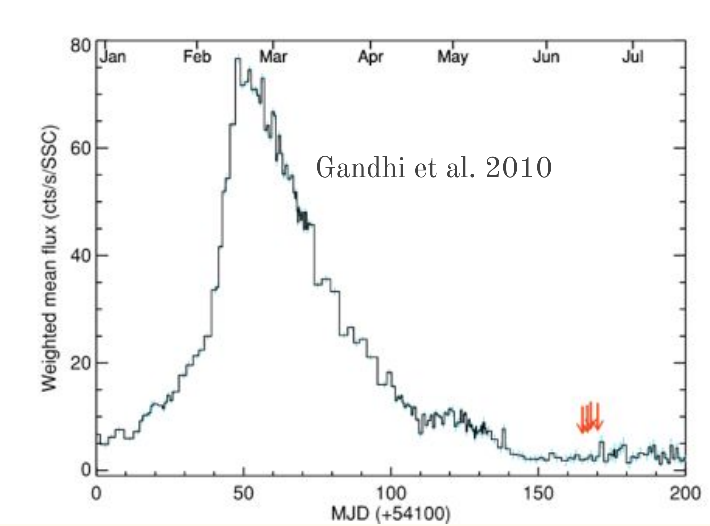
Wardle & Koenigl 1993

# X-ray binary outburst

Incredible outburst were their luminosity changes by several orders of magnitude.



From G. Marcel thesis, adapted from Zhang 2013



Gandhi et al. 2010

During this outburst the spectrum changes significantly. This happens on very long time scales.