Accretion disks viscous or turbulent?

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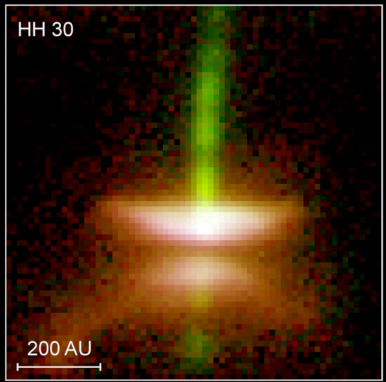
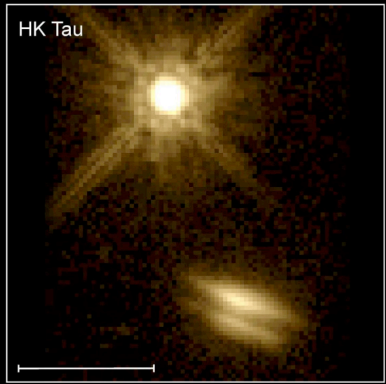
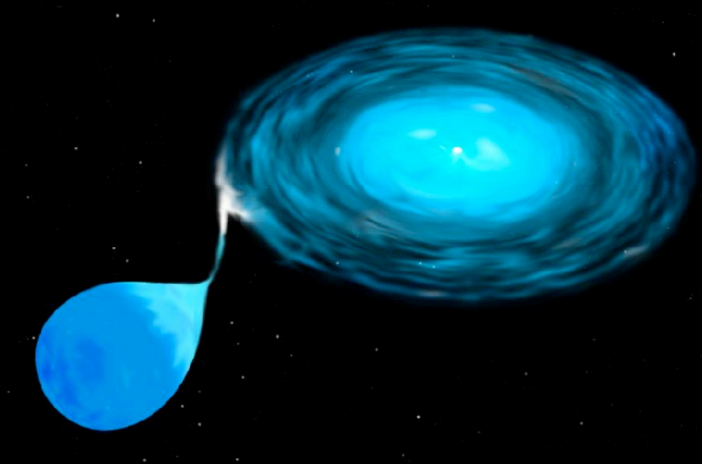
Introduction

Accretion disks

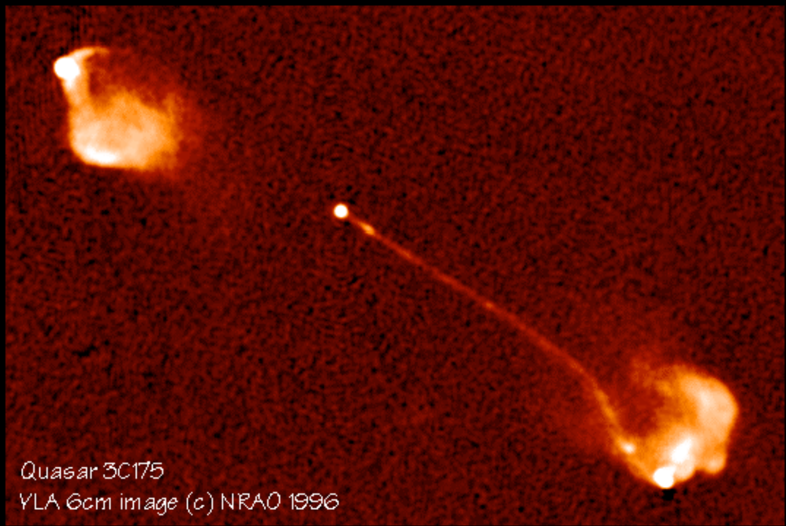




Orbiting young stars



In binary star system



In Active Galaxy Nuclei

Key question: radial transport of angular momentum…

Angular momentum transport

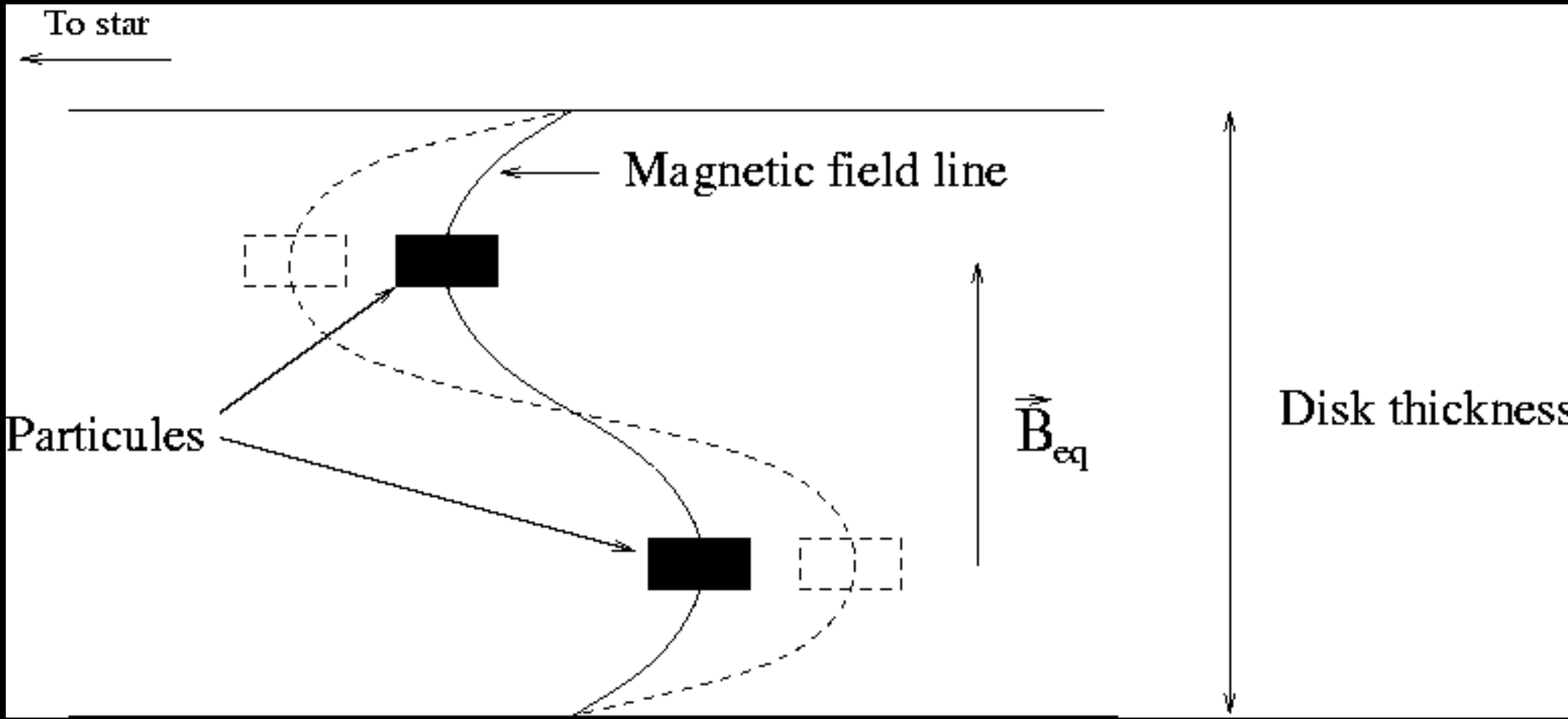
- **Molecular transport too small**
- **Disks are turbulent**

  ⇒ « enhanced » transport coefficients

- **Source for the turbulence?**
  - ✓ Nonlinear pure hydro instability unlikely
    Lesur & Longaretti 2005, Ji et al. 2006, but research ongoing…
  - ✓ Baroclinic instability *(Lesur & Papaloizou 2010, Lyra & Klahr 2011)*
    Transport properties unclear…
  - ✓ *The Magnetorotational instability (MRI, Balbus & Hawley 1991)*
    Most likely mechanism to date, but plenty of questions remains…

The magnetorotational instability

(Balbus & Hawley, 1991)



Criterions for instability criterion:

- Keplerian rotation

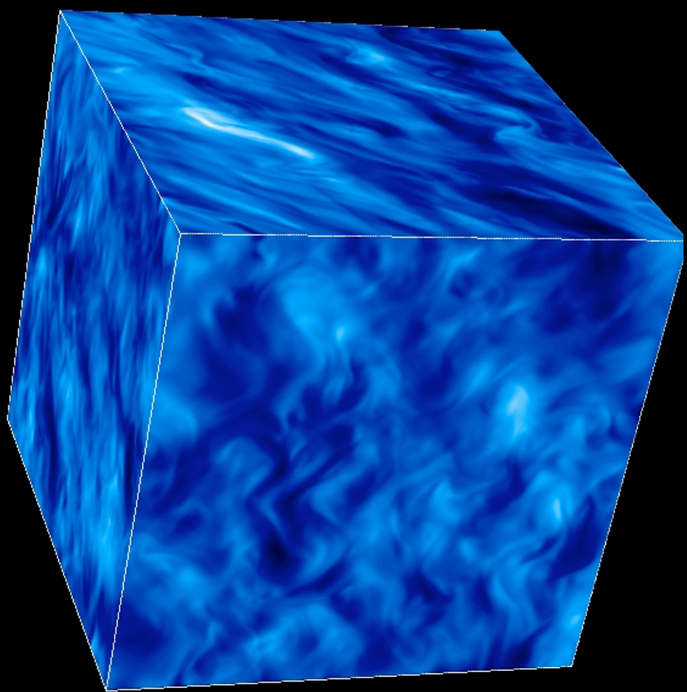
- A weak magnetic field

Nonlinear evolution ⇒ numerical simulations

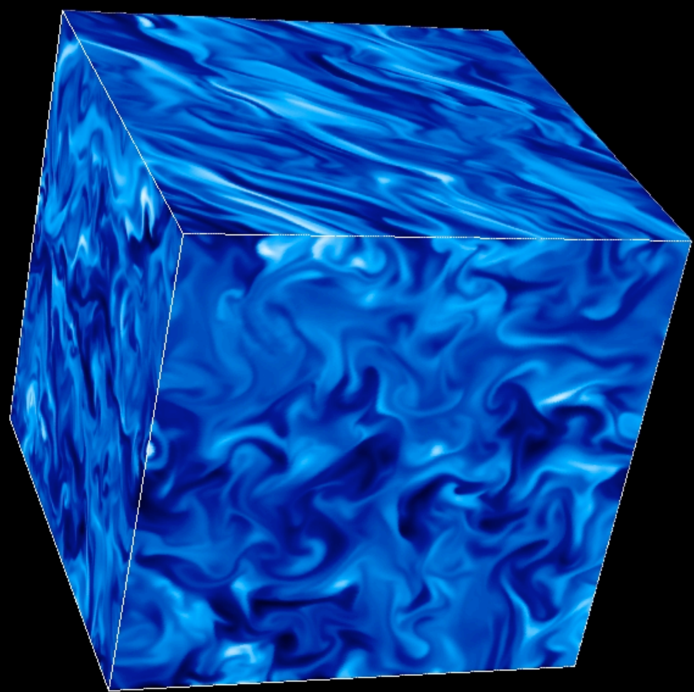
Nonlinear outcome

- **Breakdown into MHD turbulence (Hawley & Balbus 1992)**
- **Dynamo process (Gammie et al. 1995)**
- **Transport angular momentum outward: $<\alpha>\sim10^{-3}-10^{-1}$**
- **Many unsolved questions remain…**

Local high resolution numerical simulations



Vertical velocity



Azimuthal B-field

Fromang (2010)

α-disc model

(Shakura & Sunyaev 1973, Lynden-Bell & Pringle 1974)

A <u>large scale</u> model of turbulence

Interaction between large scale eddies ⇒ $\nu \sim l.v$

Typical size of the eddies $<H$

Typical amplitude of the velocity fluctuations $<c_s$

$\nu = \alpha c_s H$ with $\alpha < 1$ ($\alpha \sim 10^{-3}$ to 10^{-1})

Height averaged (Navier-Stokes) angular momentum conservation

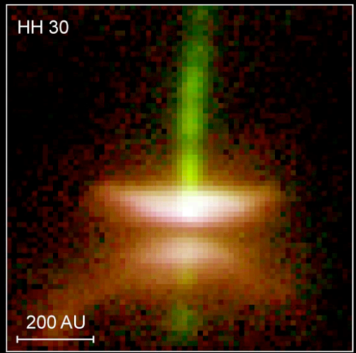
$$2\pi \bar{v}_R \frac{d}{dR}\left(R^2\Omega\right) = \frac{d}{dR}\left(R^3 \bar{\nu} \Sigma \frac{d\Omega}{dR}\right)$$

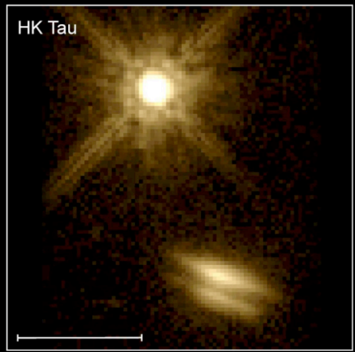
+ Energy is dissipated locally (ignored in this talk)

Question

Is the α-disk paradigm always an appropriate model for MHD turbulence?

This talk: two issues in PP disk theory

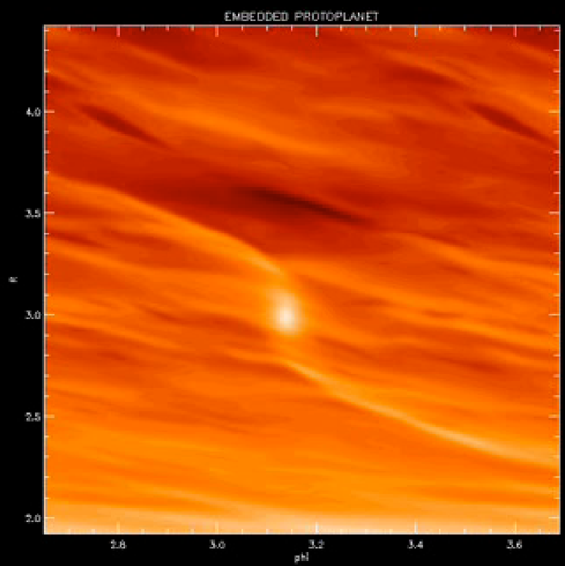




- **Size: R_d~100-500 AU**
- **Mass: M_d ~10^{-2} M_{sol}**
- **Lifetime: τ_d ~10^{-6-7} yr**
- **Accretion rate: M_{acc} ~10^{-7-8} $M_{sol}.yr^{-1}$**
- **Planet nurseries**

Planet-disk interaction

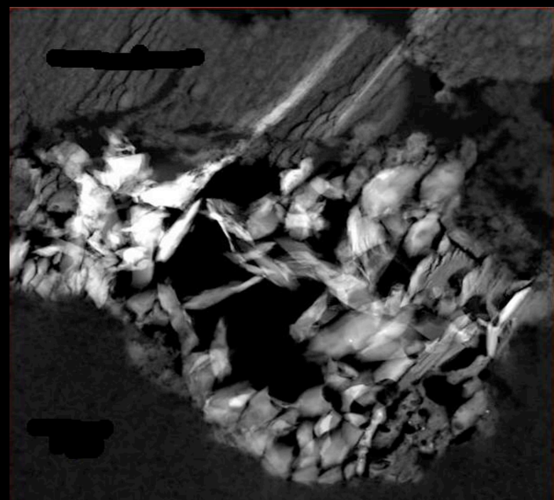
Is there a corotation torque in turbulent disk?



Nelson & Papaloizou (2004)

CAIs radial transport

What is the nature of the disk large scale flow in PP disks?



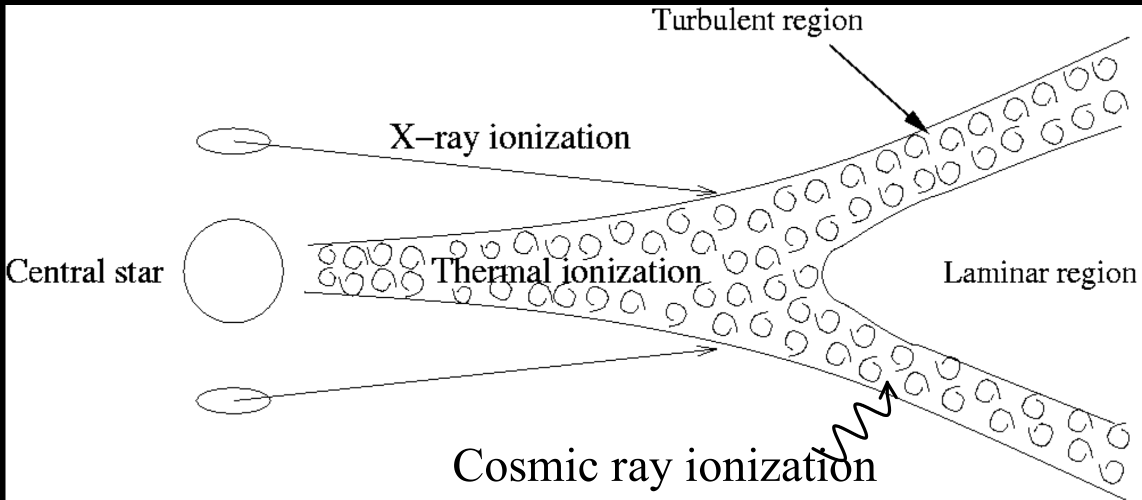
Warnings & issues (numerical, etc…)

Numerical issues:

- Small resolution (because global simulations…)
- Artifacts from the boundary conditions, finite time integration

Astrophysical issues:

- Idealized experiments (thermodynamics, cylindrical approximation,…)
- PP disks harbor Dead Zone



Gammie (1996)

In this talk: PP disk are fully turbulent, non-ideal MHD effects ignored!

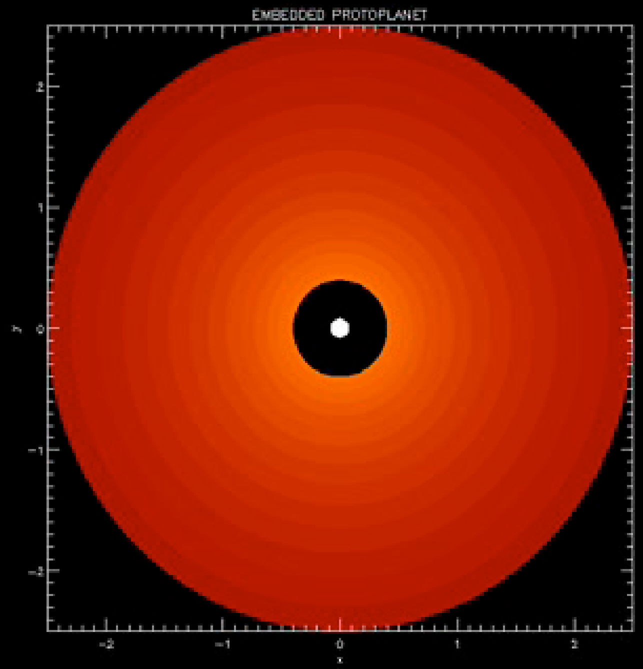
Corotation torque in turbulent PP disks

Baruteau, Fromang, Nelson & Masset (2011)

Planet/disk interaction in laminar disks

Type I migration

Low mass planets

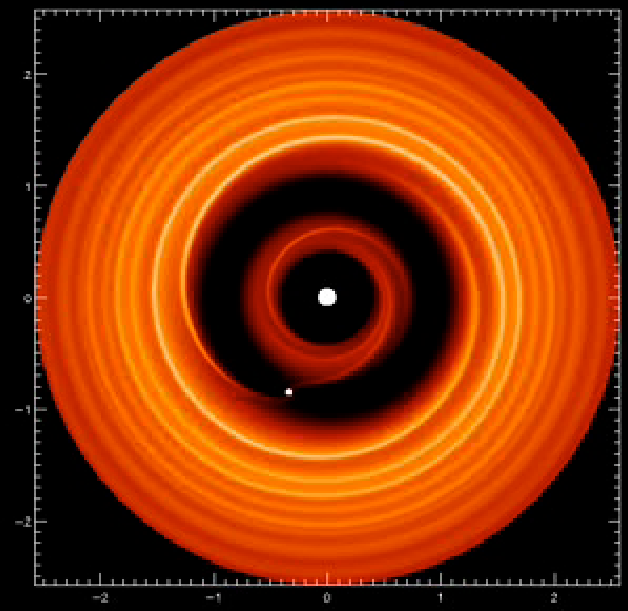


The planet migrates on top of the disk & fall on the star

⇒ **FOCUS of this talk**

Type II migration

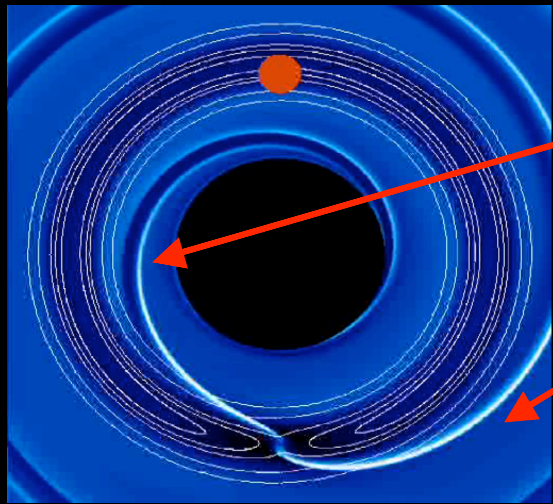
High mass planets



The planet migrates with the disk

Movies: courtesy R.Nelson (QMUL)

Disk torques on the planet (type I)



Courtesy F.Masset

T_{in}: Lindblad torque from inner disk (>0)

T_{out} : Lindblad torque from outer disk (<0)

$\Gamma_{Lindblad}$<0: planets migrate inward

Libration of particles around planet orbit
⇒ **Corotation torque**

Properties of the corotation torque

$$\Gamma_c \propto \frac{d(\Sigma/B)}{dr}$$

→ **Γ_c>0 for negative vortensity gradients** → **Can potentially stop migration…**

BUT…

- Γ_c vanishes on long terms in inviscid disks
- Γ_c>0 when viscosity nonzero in laminar disks

Corotation torque in turbulent disks

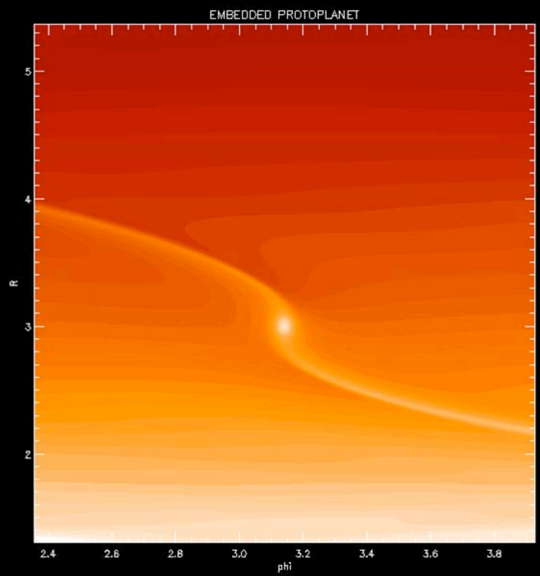
Why can we question a viscous modelling here?

- Corotation torque operates on small scales
- Can turbulence be modeled as a viscous process on those small scales?

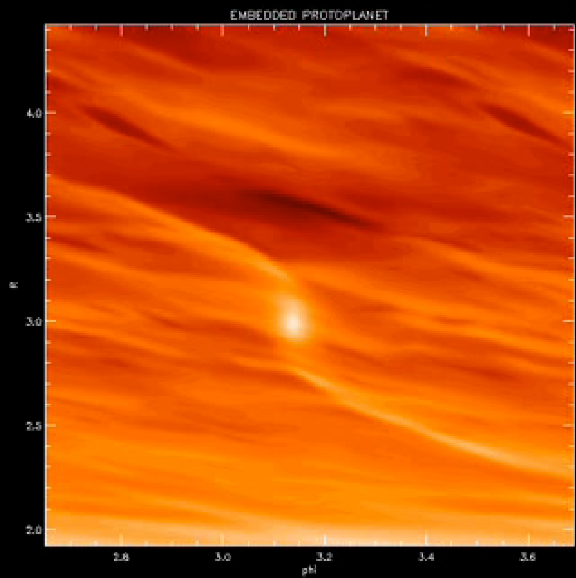
Numerical issues:

- Need to resolve the coorbital region as well as the large scale disk structure
- Need to integrate for long time to averaged the turbulent fluctuations out

Lindblad torque in turbulent disks
stochastic migration



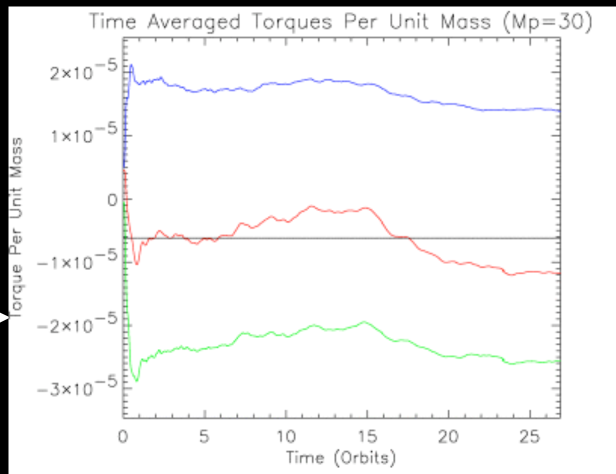
Laminar disk



Turbulent disk

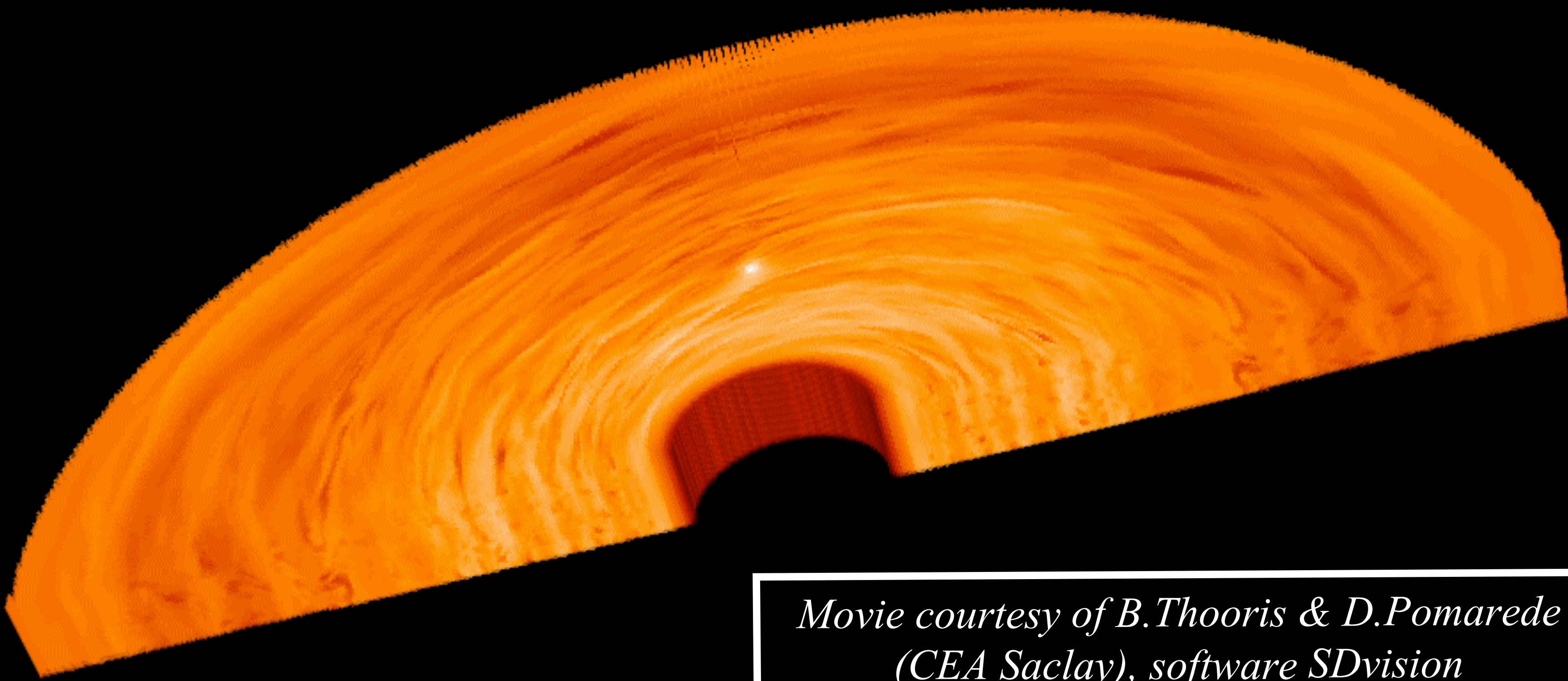
Nelson & Papaloizou (2004)

Stress exerted on the planet



Movie: courtesy R.Nelson (QMUL)

Numerical setup



Movie courtesy of B.Thooris & D.Pomarede (CEA Saclay), software SDvision

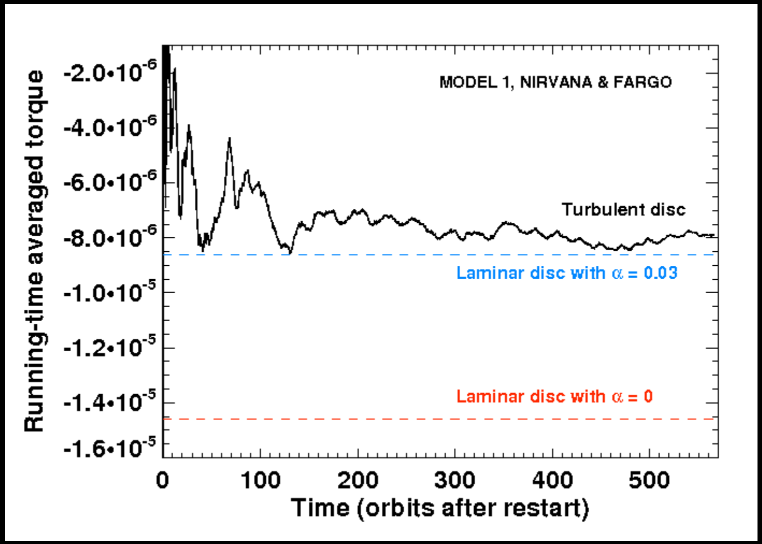
- NIRVANA *(Ziegler & Yorke 1997)* and RAMSES *(Teyssier 2002, Fromang et al. 2006)*
- Cylindrical coordinates, no vertical gravity, $(N_R,N_\phi,N_Z)=(320,480,40)$
- « Ideal MHD », Initial B field toroidal
- Radial extent: [1,8], Azimuthal extent: $[0,\pi]$
- Planet location & mass: $R_{pl}=3$, $\Phi_{pl}=\pi/2$, $M_{pl}=3.10^{-4}\ M_{sun}$
- $\rho=\rho_0(R/R_0)^p$, $T=T_0(R/R_0)^q$, density profile relaxes toward initial state

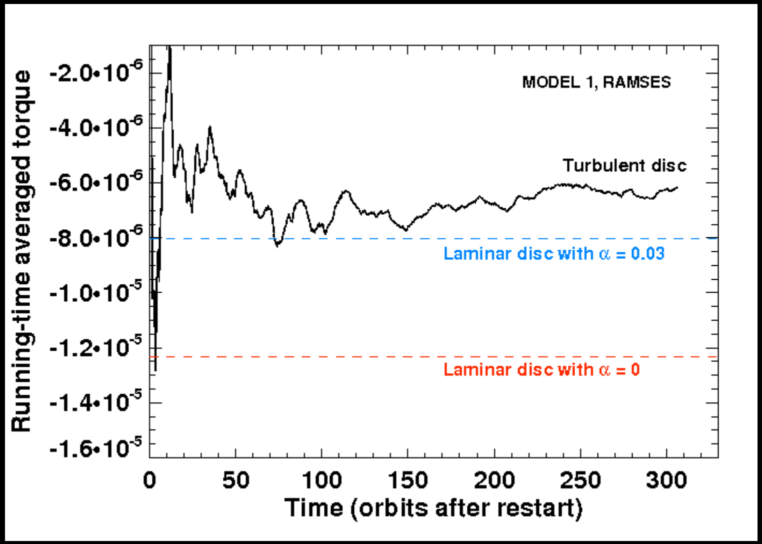
[redacted]

[redacted]

Power-law disk

$$\rho=\rho_0(R/R_0)^{-1/2},\ T=T_0(R/R_0)^{-1}$$



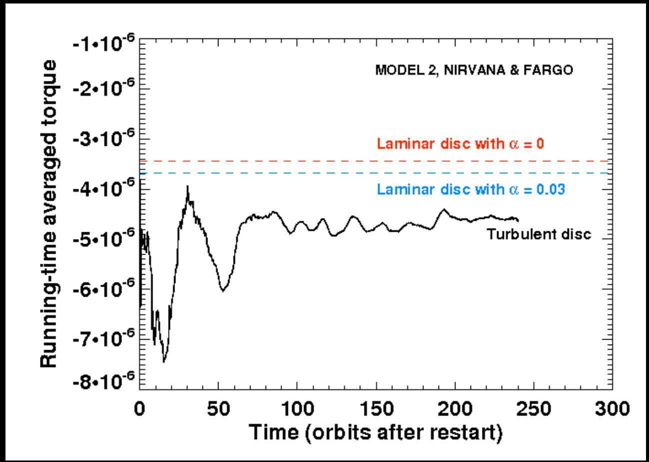


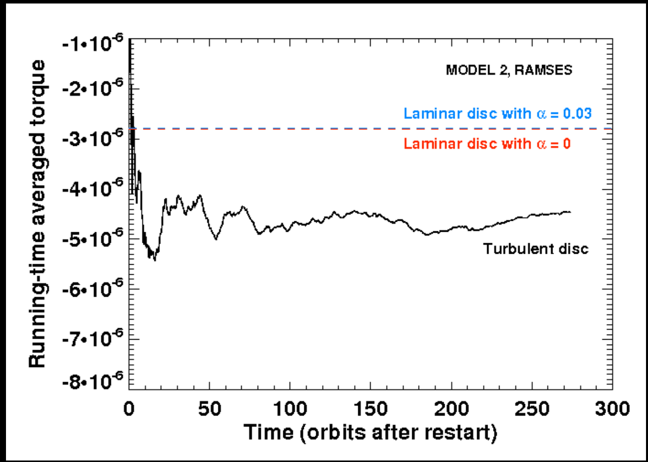
- **Total torque:** good agreement between viscous and turbulent disk model

$\Gamma_c \neq 0$ in turbulent disks

A disk model w/o vortensity gradient

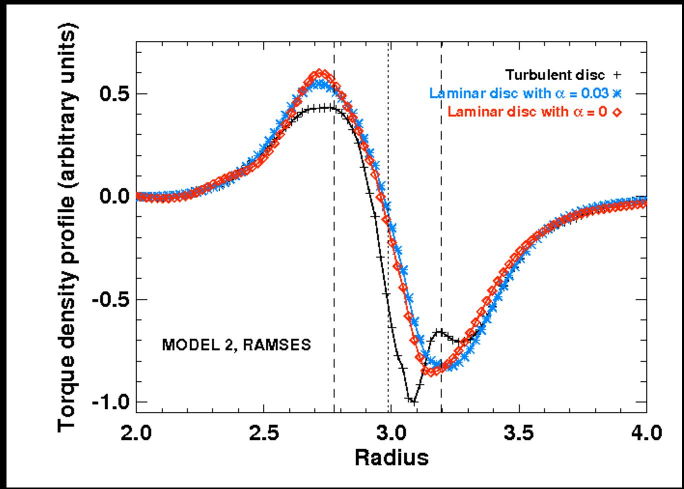
$\rho = \rho_0 (R/R_0)^{-3/2}$, $T = T_0$
⇒ No vortensity gradient
⇒ No corotation torque expected





• **Total torque:** differences between viscous and turbulent disk model

•**Torque density:**
- Good agreement between Lindblad torques
- Possible additional corotation torque in turbulent case



Conclusions (for part I)

- **Corotation torque in turbulent PP disks** ***(Baruteau et al. 2011)*****:**

  $\Gamma c \neq 0$ in turbulent disks

  Viscous modeling gives reasonable agreement…

  …but possible additional torque due to (MHD) turbulence

Large scale flow in turbulent PP disks

Fromang, Lyra & Masset (2011)

Radial transport of CAIs

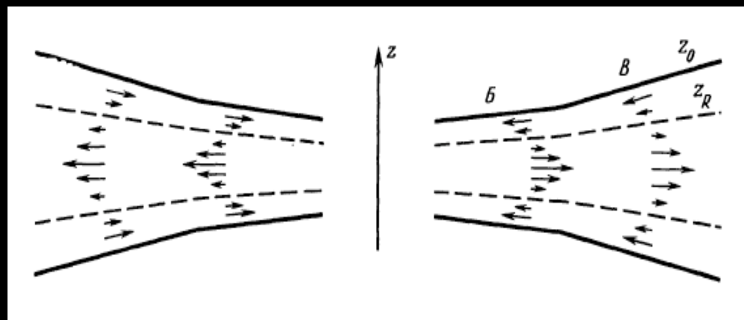
- CAI: Calcium- and Aluminium-rich Inclusions
- Size: ~1mm to 1cm
- Cristallized, very old
- Found in cold regions (meteorites, comets)
- Formed in warm regions (close to the sun)

CAI returned by the Stardust mission

Different transport scenario

Large scale flow

Ciesla (2006,2009,2010), Gail. (2001)



Urpin (2004)

Theoretical background

Urpin (1984), Siemiginowska (1988), Kley & Lin (1992), Rozyczka et al. (1994), Kluzniak & Kita (2000), Regev & Gitelman (2002), Takeuchi & Lin (2002), Keller & Gail (2004), Tscharnuter & Gail (2007), Ciesla (2007)

Disk model:
- Axisymmetric disk, 2D (R and z)
- α disc model: $\nu=\alpha c_s H$ (α=cte)
- Sound speed and midplane density are power laws

$$c^2 = c_0^2 \left(\frac{R}{R_0}\right)^q$$

$$\rho(R,Z=0) = \rho_0 \left(\frac{R}{R_0}\right)^p$$

- Force balance in vertical direction ⇒ density vertical profile
- Force balance in radial direction ⇒ angular velocity
- Angular momentum conservation:

$$R\rho v_R \frac{\partial}{\partial R}(R^2\Omega) = \frac{\partial}{\partial R}\left(R^2 T_{R\phi}^{visc}\right) + \frac{\partial}{\partial Z}\left(R^2 T_{Z\phi}^{visc}\right)$$

$$T_{R\phi}^{visc} = R\rho\nu \frac{\partial\Omega}{\partial R} \qquad T_{Z\phi}^{visc} = R\rho\nu \frac{\partial\Omega}{\partial Z}$$

⇒ Radial velocity $v_R(R,Z)$

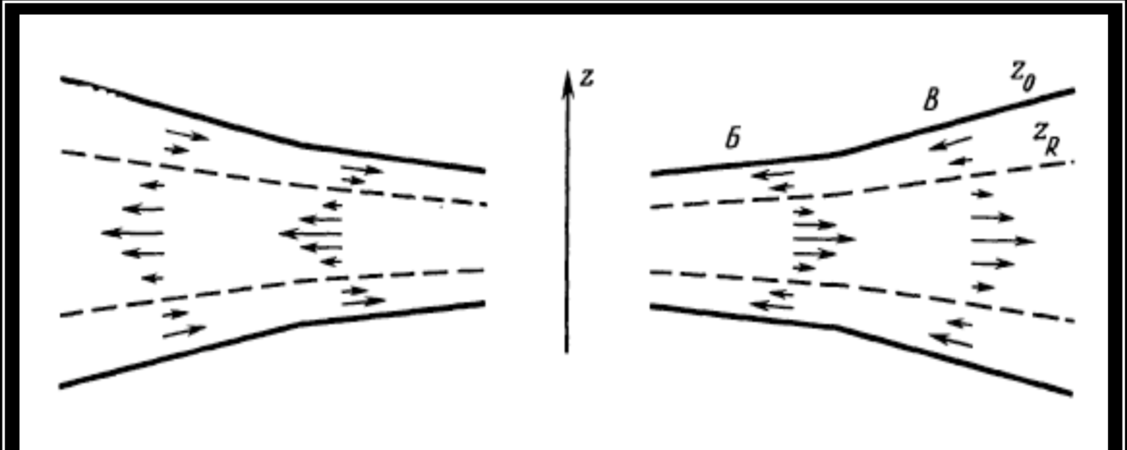
Meridional circulation

$$\frac{v_R}{c_0} = -\alpha \left(\frac{H_0}{R_0}\right)\left(\frac{R}{R_0}\right)^{q+1/2}\left[3p + 2q + 6 + \frac{5q+9}{2}\left(\frac{Z}{H}\right)^2\right]$$

negative

Usually negative
outflow in the equatorial plane

Usually positive
inflow in the disk corona



Urpin (2004)

Physical origin
pressure gradient changes with Z

Meridional circulation in turbulent disks

Why can we question a viscous modelling here?

• Meridional structure established on scale <H

• α-disk model assumes spatial averaging over spatial scales larger than the eddy size (~H)

Numerical issues:

• Meridional circulation amplitude is very small

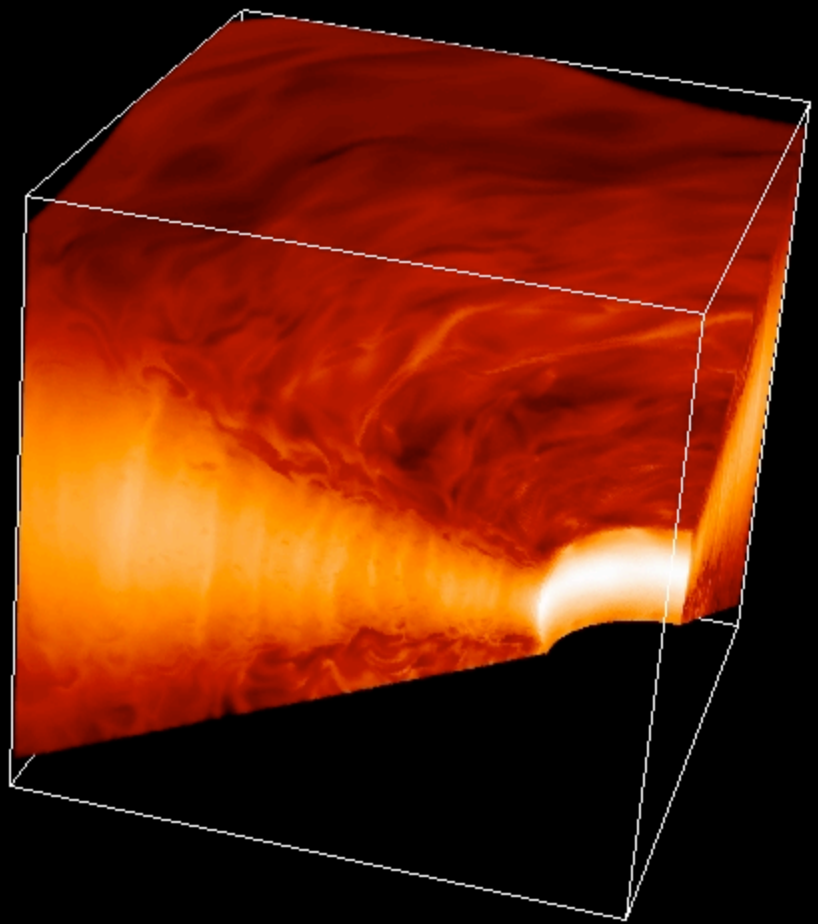
$v_R/c_0 \sim 0.2\ \% \ll \delta v_R/c_0 \sim 5\text{-}10\ \%$

• Need to integrate for long time to averaged the turbulent fluctuations out

• Effect requires a proper treatment of disk density stratification

Global turbulent disk model

Fromang & Nelson (2006)



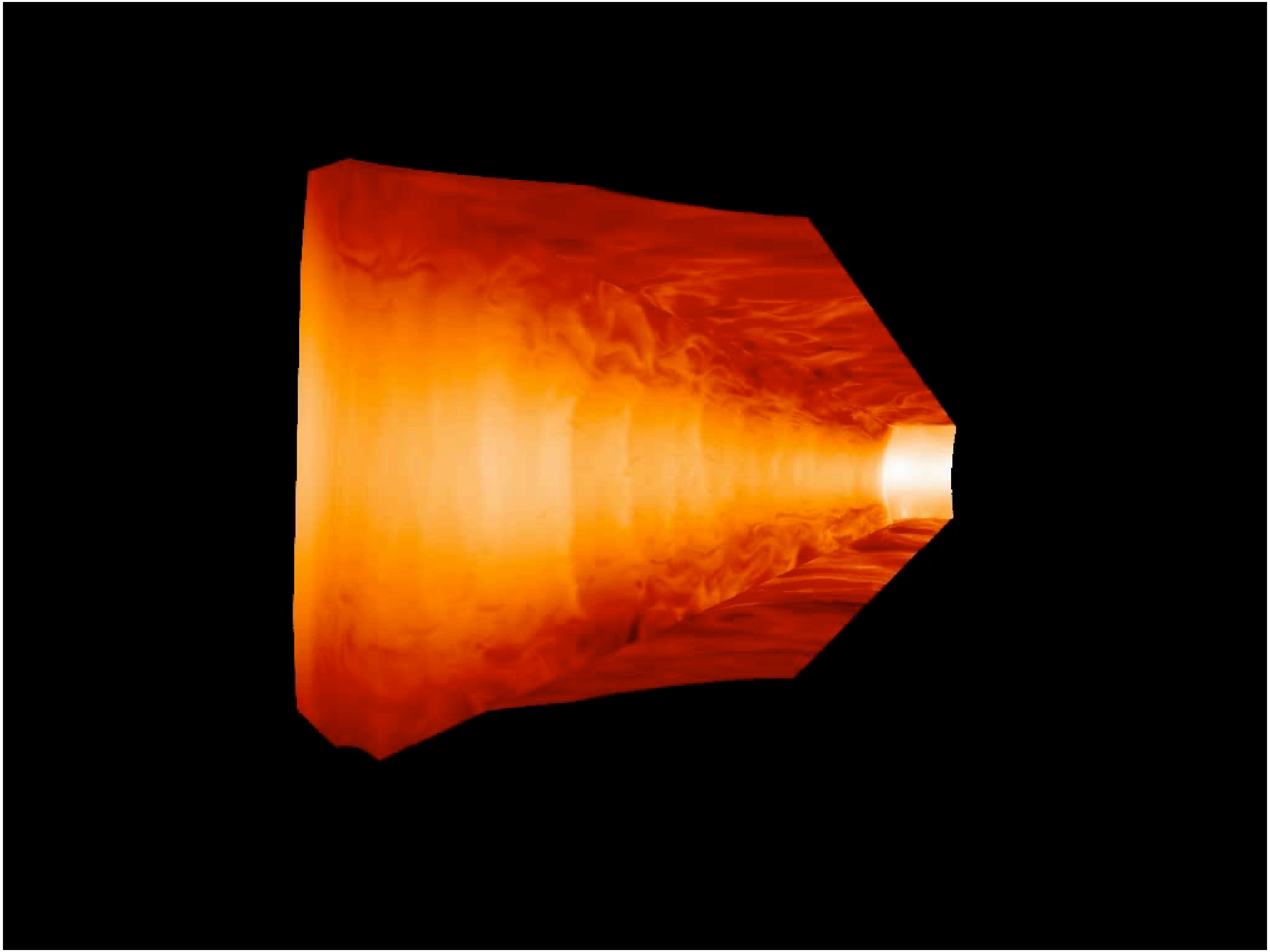
- Code: ZEUS (MHD code)
- Spherical coordinates
- « Ideal MHD »
- Initial B field toroidal
- Resolution:

  $(N_r,N_\phi,N_\theta)=(512,256,256)$

  ⇒ ~25 cells per scaleheight
- Computing cost:

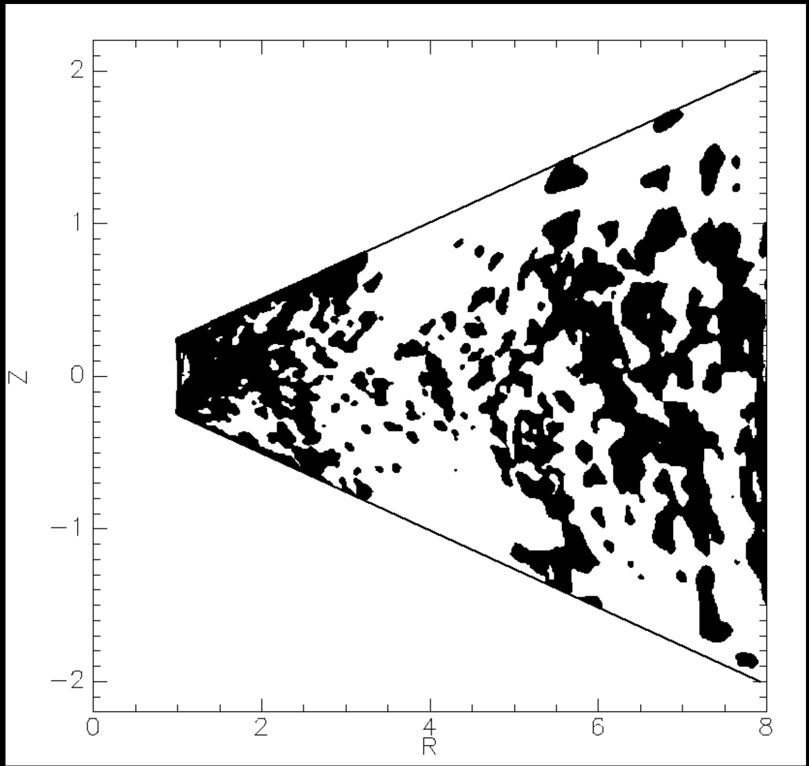
  ⇒~100 000 CPU hours/run

Movie courtesy of Y.Fidali (CEA Saclay)
Software: SDvision



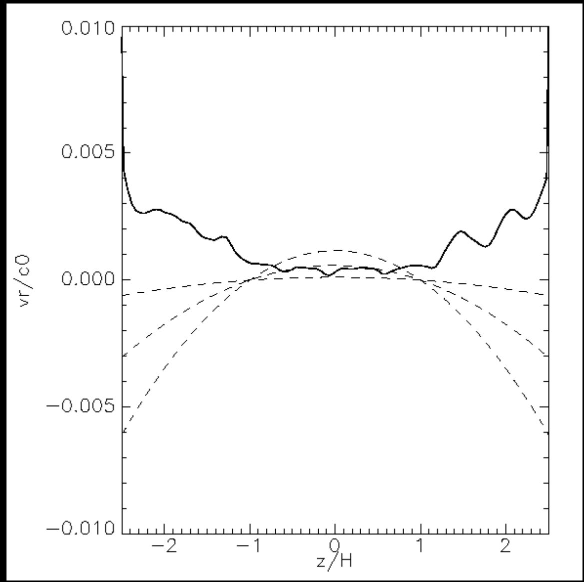
$\Sigma=\Sigma_0(R/R_0)^{-1/2}$ and $T=T_0(R/R_0)^{-1}$

2D disk structure (t_{avg}~200 orbits!)



Vertical profile
($3<R_{avg}<6$)

v_R/c_0



Z/H

Simulation

Model: $\alpha=10^{-3}$, 5×10^{-3}, 10^{-2}

No meridional circulation similar to that of Ciesla (2007)!

Angular momentum transport in turbulent disk

Angular momentum conservation in turbulent disks

$$R\rho v_R \frac{\partial}{\partial R}(R^2\Omega) = \frac{\partial}{\partial R}\left(R^2 T_{R\phi}^{turb}\right) + \frac{\partial}{\partial Z}\left(R^2 T_{Z\phi}^{turb}\right)$$

$$T_{R\phi}^{turb} = < -B_R B_\phi + \rho v_R v_\phi >$$

$$T_{Z\phi}^{turb} = < -B_Z B_\phi + \rho v_Z v_\phi >$$

Angular momentum conservation in viscous disks…

$$R\rho v_R \frac{\partial}{\partial R}(R^2\Omega) = \frac{\partial}{\partial R}\left(R^2 T_{R\phi}^{visc}\right) + \frac{\partial}{\partial Z}\left(R^2 T_{Z\phi}^{visc}\right)$$

Viscous vs. Turbulent stress tensors

$$T_{R\phi}^{turb} \equiv T_{R\phi}^{visc} \; ???$$

$$T_{Z\phi}^{turb} \equiv T_{Z\phi}^{visc} \; ???$$

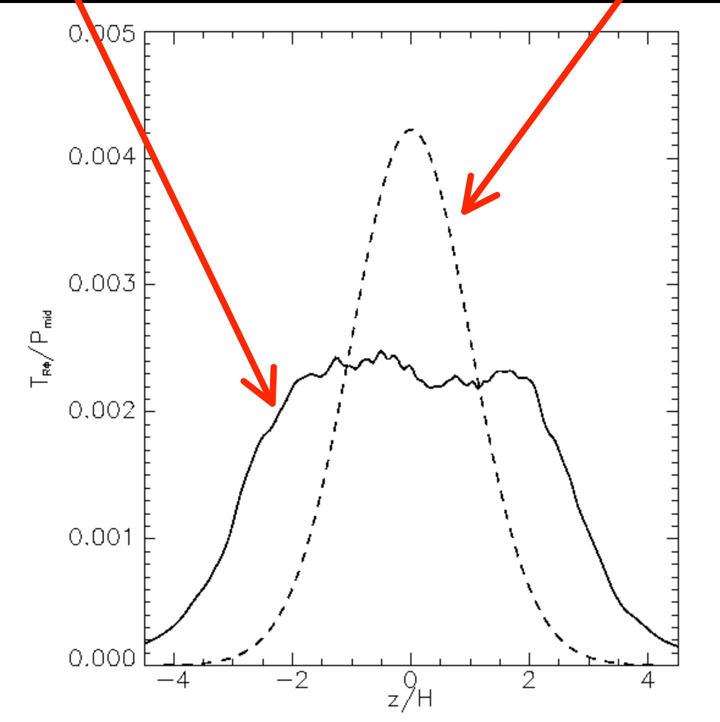
Turbulent vs. viscous stress

$$R\rho v_R \frac{\partial}{\partial R}(R^2\Omega) = \frac{\partial}{\partial R}\left(R^2 T_{R\phi}\right) + \frac{\partial}{\partial Z}\left(R^2 T_{Z\phi}\right)$$

$T_{R\phi}^{turb} / P_{mid}$

$T_{R\phi}^{visc} / P_{mid}$

$T_{Z\phi}^{turb}, T_{Z\phi}^{visc} << T_{R\phi}^{turb}, T_{R\phi}^{visc}$



Different vertical structures

$$T_{R\phi}^{visc} = R\rho\nu \frac{\partial\Omega}{\partial R}$$

$$T_{R\phi}^{turb} = < -B_R B_\phi + \rho v_R v_\phi >$$

A simple model

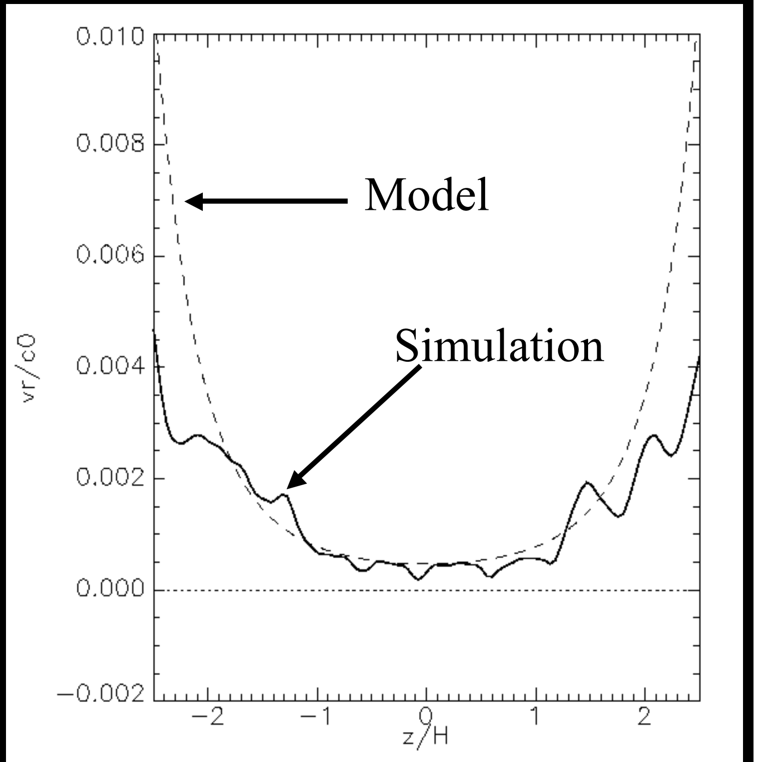
$$R\rho v_R \frac{\partial}{\partial R}(R^2\Omega) = \frac{\partial}{\partial R}\left(R^2 T_{R\phi}^{turb}\right) + \frac{\partial}{\partial Z}\left(R^2 T_{Z\phi}^{turb}\right)$$

Two prescriptions:

$$T_{Z\phi}^{turb} = <-B_Z B_\phi + \rho v_Z v_\phi> = 0$$

$$T_{R\phi}^{turb} = <-B_R B_\phi + \rho v_R v_\phi> = \begin{cases} -\alpha_t \rho_0 c_0^2 \left(\frac{R}{R_0}\right)^\delta & \text{for } |Z|<2.5H \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{v_R}{c_0} = -2\alpha_t(\delta+2)\left(\frac{H_0}{R_0}\right)\left(\frac{R}{R_0}\right)^{\delta-p+1/2} \exp\left(\frac{Z^2}{2H^2}\right)$$



Good agreement!

Conclusions (for part II)

- **Corotation torque in turbulent PP disks** ***(Baruteau et al. 2011)*****:**

  $\Gamma c \neq 0$ in turbulent disks

  Viscous modeling gives reasonable agreement…

  …but possible additional torque due to (MHD) turbulence

- **Meridional circulation in turbulent PP disks** ***(Fromang et al. 2011)*****:**

  No meridional circulation in turbulent disks

  Difference due to vertical structure of the turbulent stress

  Large disagreement with viscous modeling

Summary & Conclusions

Conclusions

- **Corotation torque in turbulent PP disks** ***(Baruteau et al. 2011)*:**

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Accretion disks: ~~viscous~~ or turbulent?

How to model it depends on the problem!