# Meridional circulation in PP disks

**S. Fromang** *(CEA Saclay, France)*

M. Gounelle *(Museum d'histoire naturelle, Paris, France)*

E. Jacquet *(Museum d'histoire naturelle, Paris, France -> CITA, Toronto, Canada)*

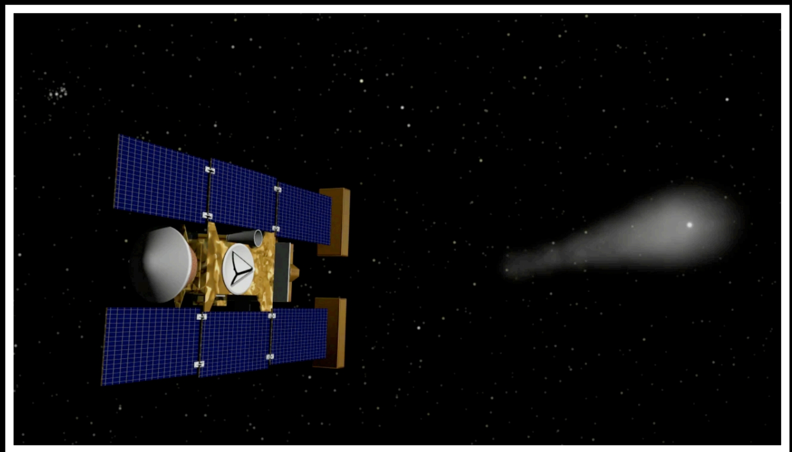
W. Lyra *(Museum of Natural History, New York, USA)*

F. Masset *(Instituto de Ciencias Fisicas, UNAM, Mexico)*

*Fromang, Lyra & Masset (2011), Jacquet, Fromang & Gounelle (2011)*

# CAIs

- CAI: Calcium- and Aluminium-rich Inclusions
- Size: ~1mm to 1cm
- Cristallized
- Found in meteorites
- Returned by the Stardust mission flyby over Wild 2



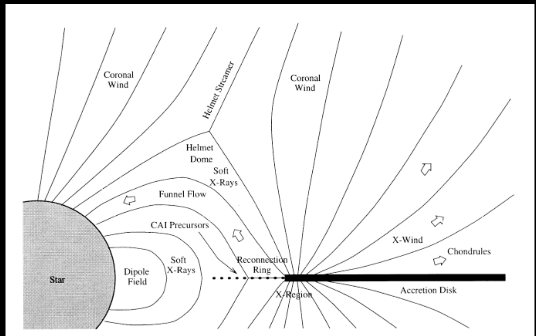
*Stardust encounter with comet Wild 2 (artist view)*


*CAI returned by the Stardust mission*

# Different transport scenario

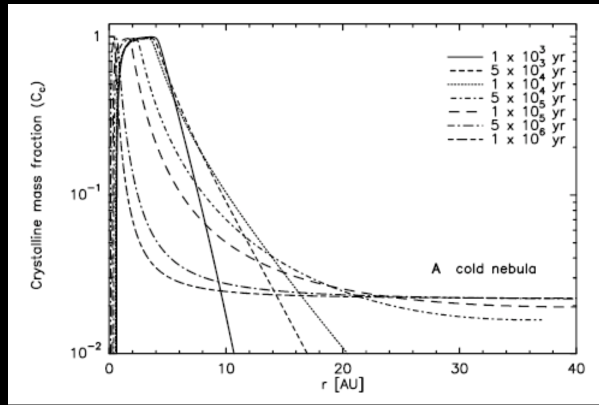
## The X-wind model

*Shu et al. (2001)*

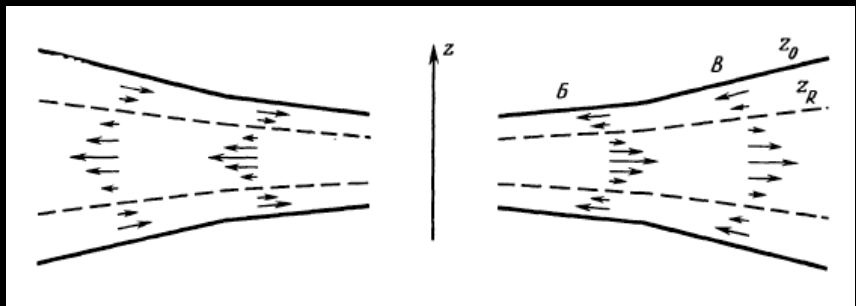



## Turbulent diffusion

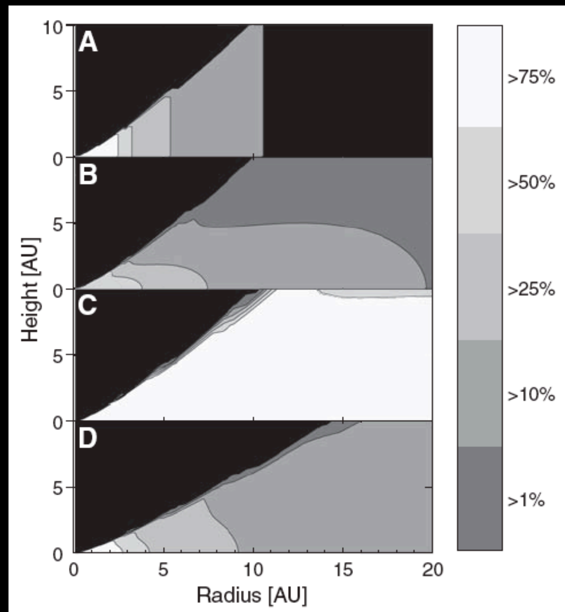
*Gail,H.P. (2001), Bekelée-Morvan et al. (2002)*




## Large scale flow *(Ciesla 2006)*




*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)
- $\alpha$ disc model: $\nu = \alpha c_s H$ ($\alpha$=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 $v_R(R,Z)$

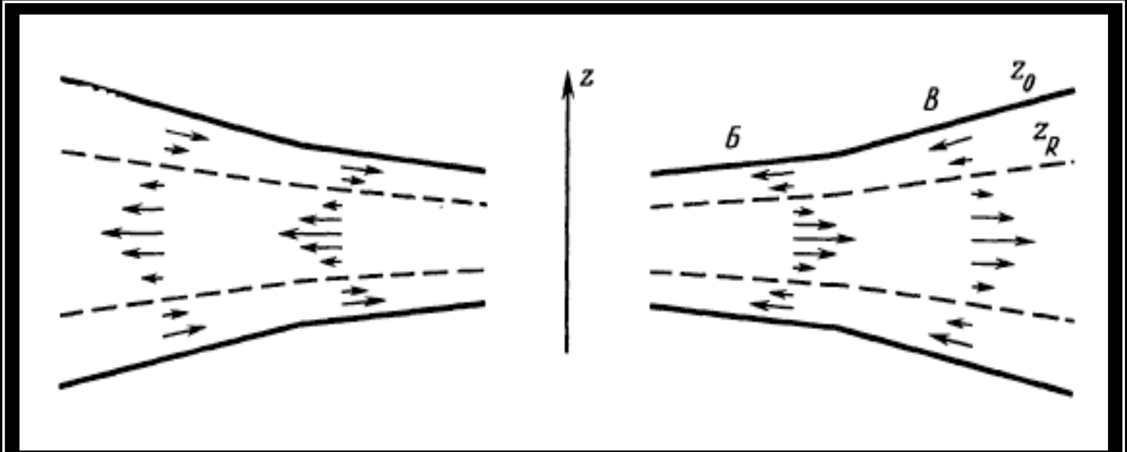
# Meridional circulation

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

negative

Usually negative
outflow in the equatorial plane

Usually positive
inflow in the disk corona

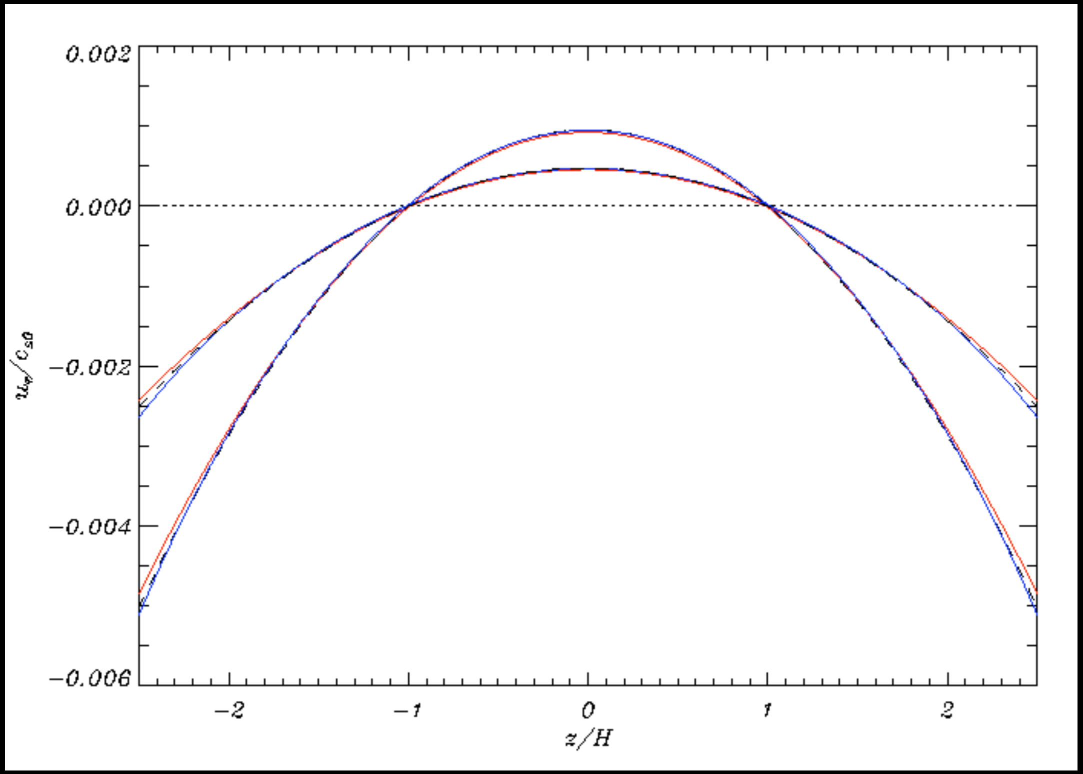



*Urpin (2004)*

**Physical origin**
pressure gradient changes with Z

# Hydro models

• Code: NIRVANA (finite difference, 6th order) & JUPITER (Finite volume Godunov method)
• No magnetic field
• Solve the 2D Navier-Stokes equations with α-prescription

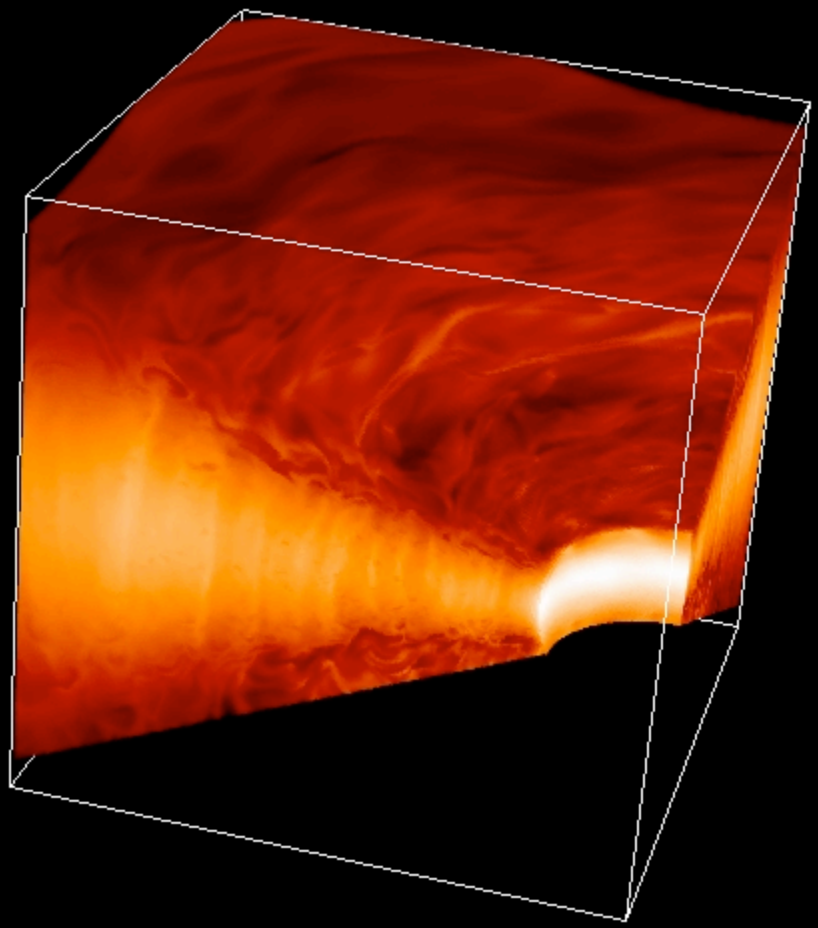



**Conclusion**: Meridional circulation easily recovered, amplitude very small

# Numerical simulations

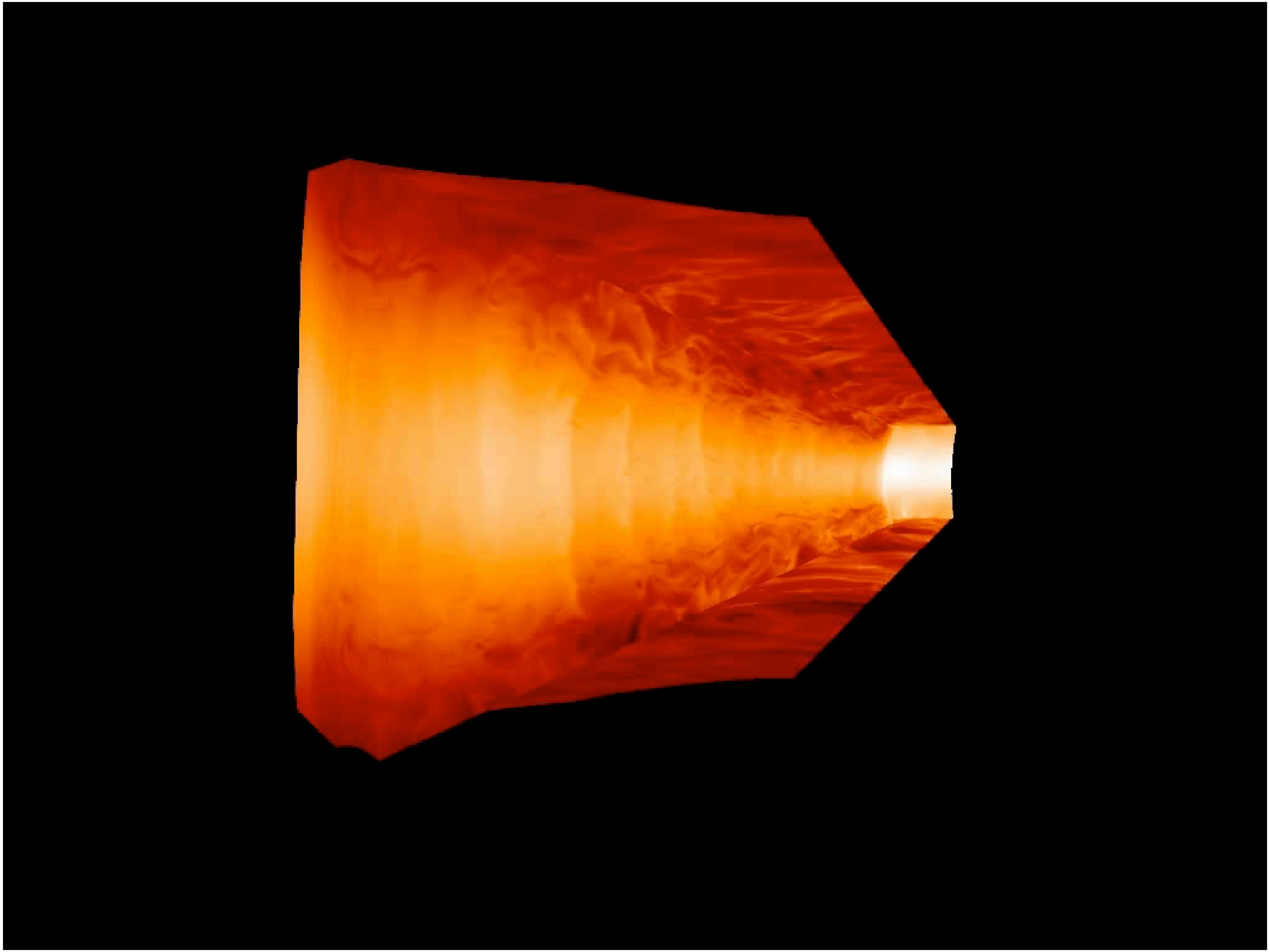
# Global turbulent disk model

*Fromang & Nelson (2006)*



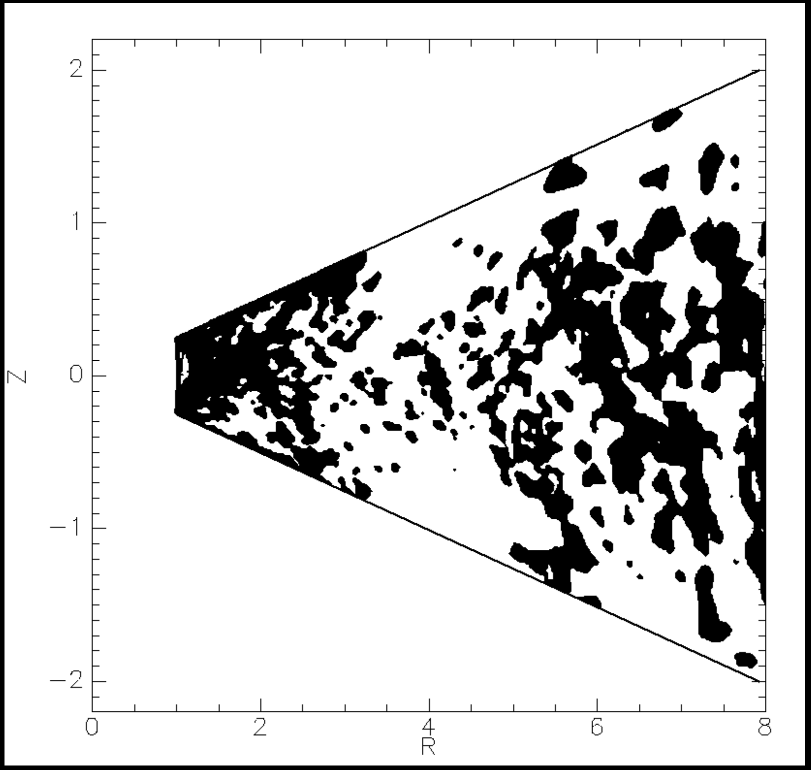
- Code: ZEUS (MHD code)
- Spherical coordinates
- « Ideal MHD »
- Initial B field toroidal
- Resolution:
  $(N_r,N_\phi,N_\theta)=(512,256,256)$
  $\Rightarrow$ ~25 cells per scaleheight
- Computing cost:
  $\Rightarrow$~100 000 CPU hours/run

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



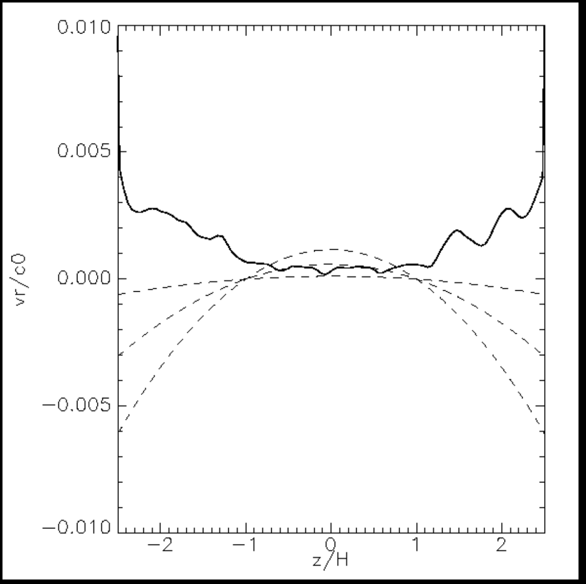
# $\Sigma=\Sigma_0(R/R_0)^{-1/2}$ and $T=T_0(R/R_0)^{-1}$

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




Vertical profile

*($3<R_{avg}<6$)*




$v_R/c_0$

Z/H

Simulation

Model: $\alpha=10^{-3}$, $5\times10^{-3}$, $10^{-2}$

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

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

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

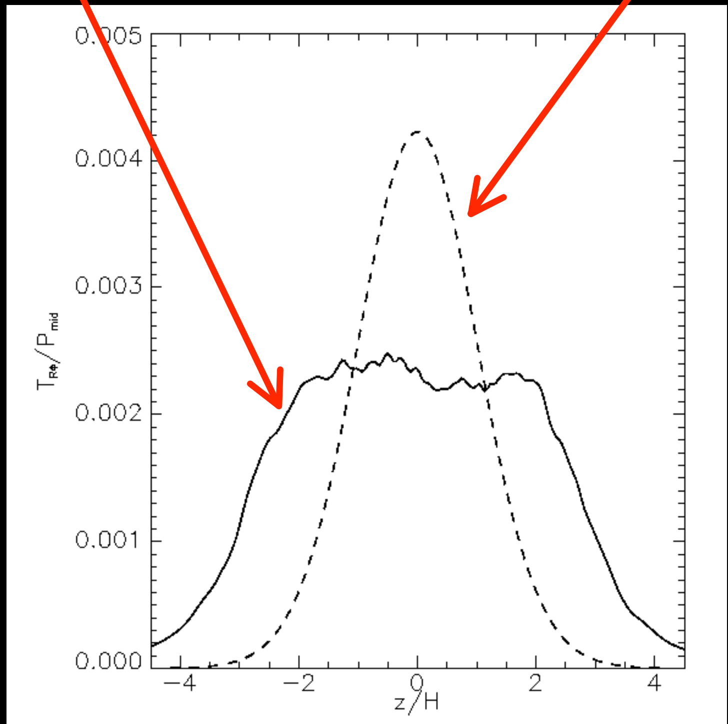
# Turbulent vs. viscous stress

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

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

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

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




Different vertical structures

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

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

# A simple model

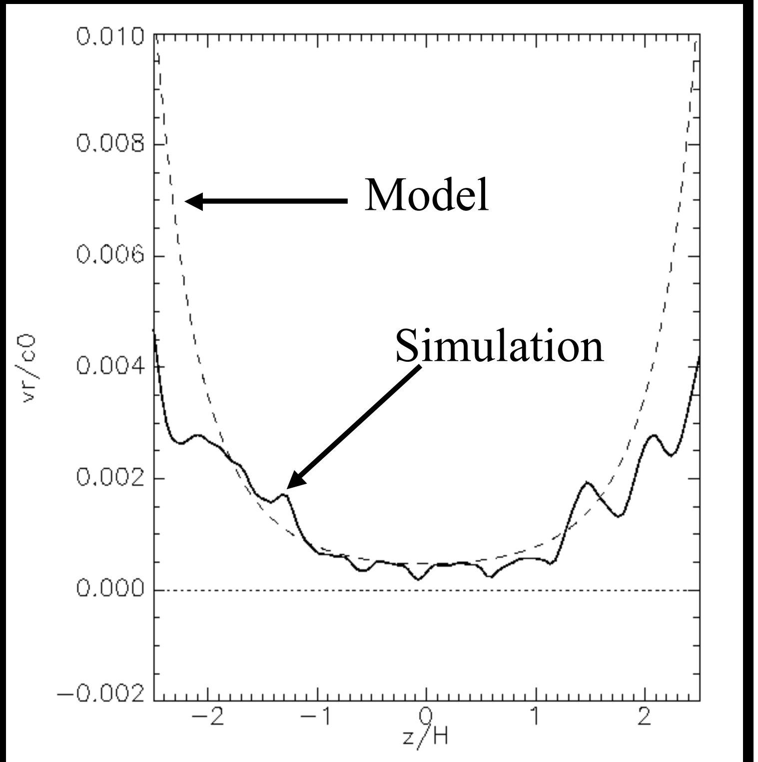
$$R\rho v_R \frac{\partial}{\partial R}(R^2\Omega) = \frac{\partial}{\partial R}\left(R^2 T_{R\phi}^{turb}\right) + \frac{\partial}{\partial Z}\left(R^2 T_{Z\phi}^{turb}\right)$$

**Two prescriptions:**

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

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

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




Good agreement!

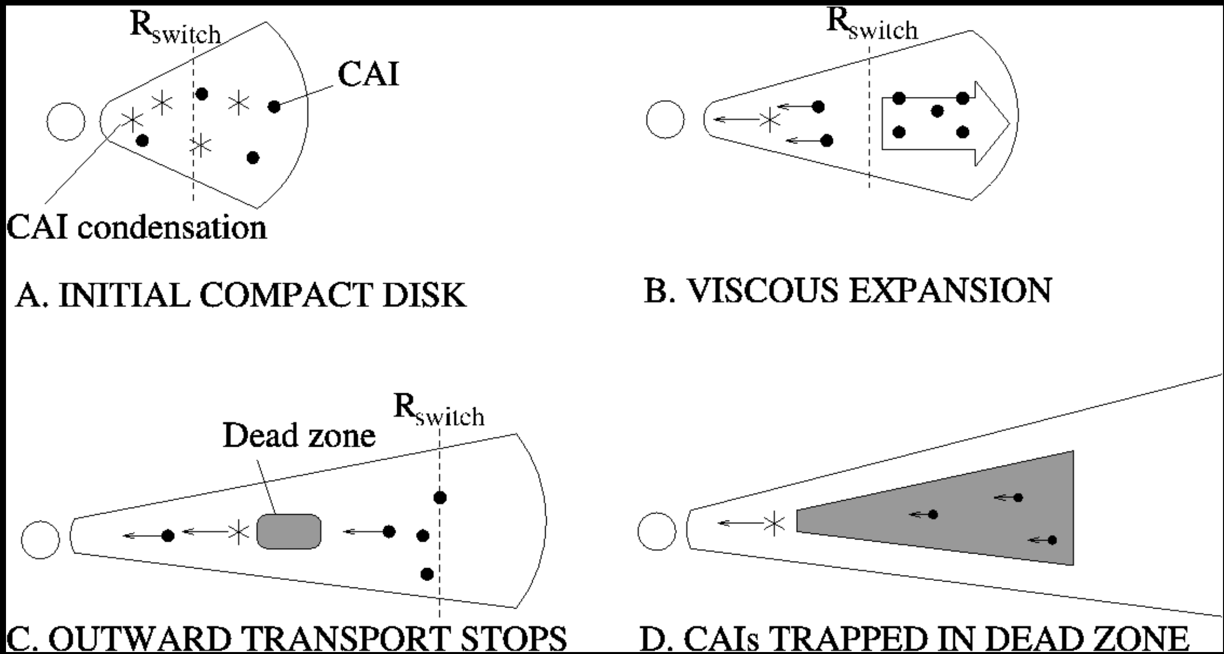
# An alternative scenario (yet another…)

# What about CAIs transport?

*(Jacquet, Fromang & Gounelle 2011)*

## Meteoretical constraints:

- $T_{cond}$ ~1400-1800K from a gas of solar composition
- Age ~4568 Myr *(Bouvier et al. 2007)*
- Formation interval restricted to a few $10^4$ yr *(Bizarro et al. 2004)*
- Need to survive in the disk for ~2 Myr *(Villeneuve et al. 2009)*



# Conclusions

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

  *No meridional circulation in turbulent disks*

  $\Rightarrow$ *also found by Flock et al. (2011)*

  *Difference due to vertical structure of the turbulent stress*

  *Large disagreement with viscous modeling*

- **CAIs transport scenario (Jacquet et al. 2011):**

  *Early CAIs formation (during class 0/I phase)*

  *CAIs advected during the disk outward spreading*

  *Detailed checks needed!*