The formation and early evolution of planet-forming disks

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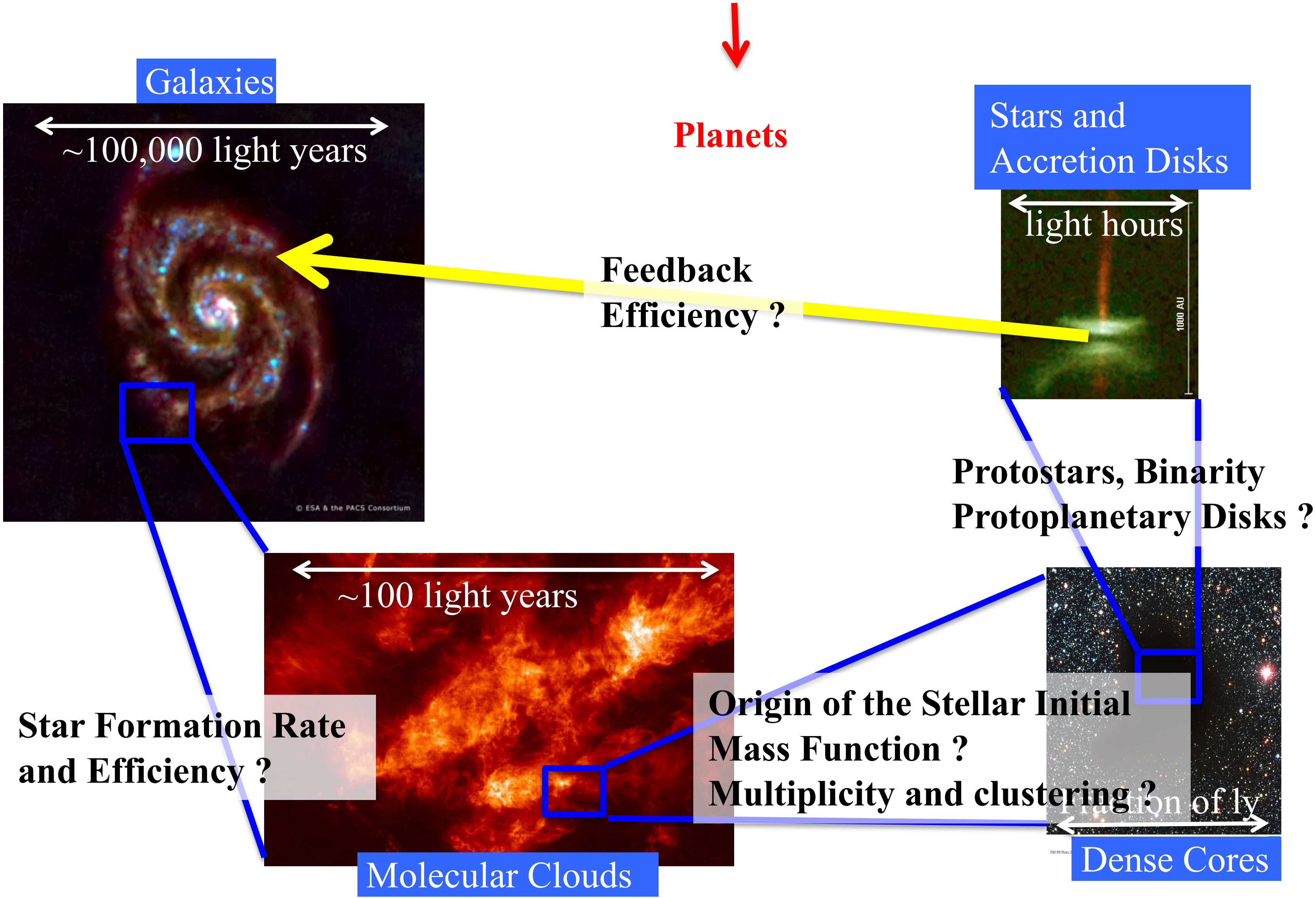
Large Scale Structures

Interstellar Cycle and Star Formation



I – What sets the “typical” size of early protoplanetary disks ?

II- Are late disks really “isolated” ?

I- The Physics of the collapse

- -hydro vs MHD: the magnetic "catastrophy"
- -a "catastrophy" really ? What observations say
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  - -misalignement
  - -turbulence
- -MHD is NOT ideal
  - -the uncontrolled nature of non-ideality
  - -ideal vs non-ideal

II- An analytical model to predict disk size: **magnetic self-regulation**

- -the model
- -comparisons between theory and simulations

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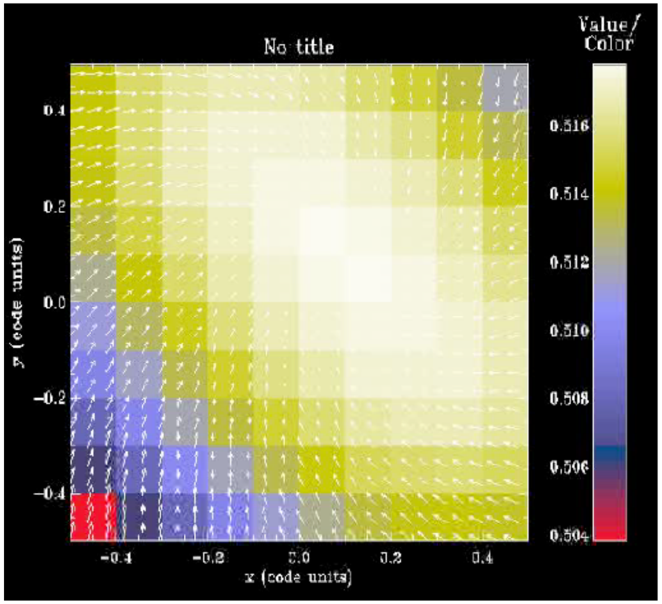
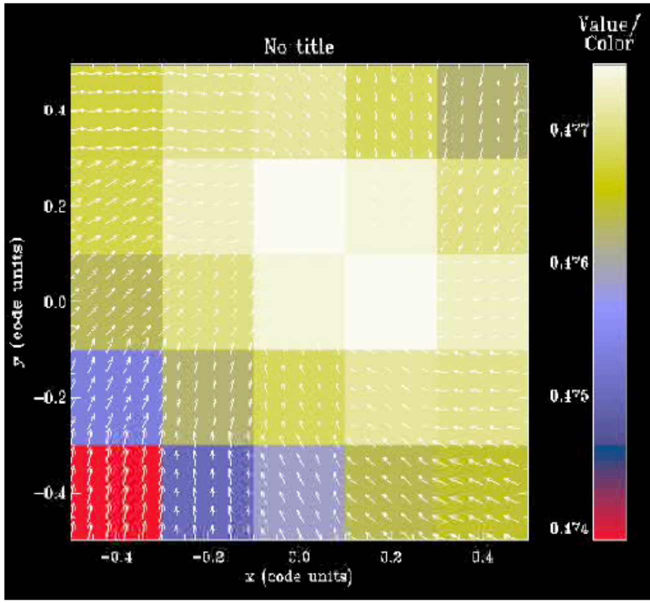
Zoom into the central part of a collapse calculation

~30 light hours

XY
hydro

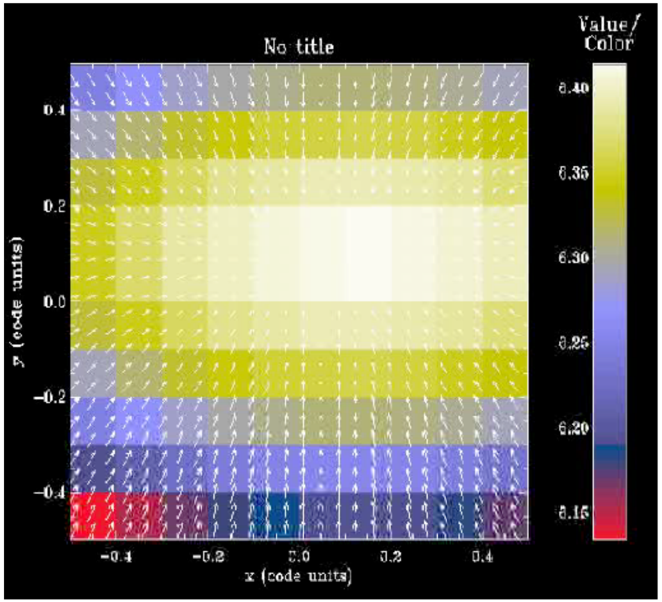


XY
MHD
μ=2

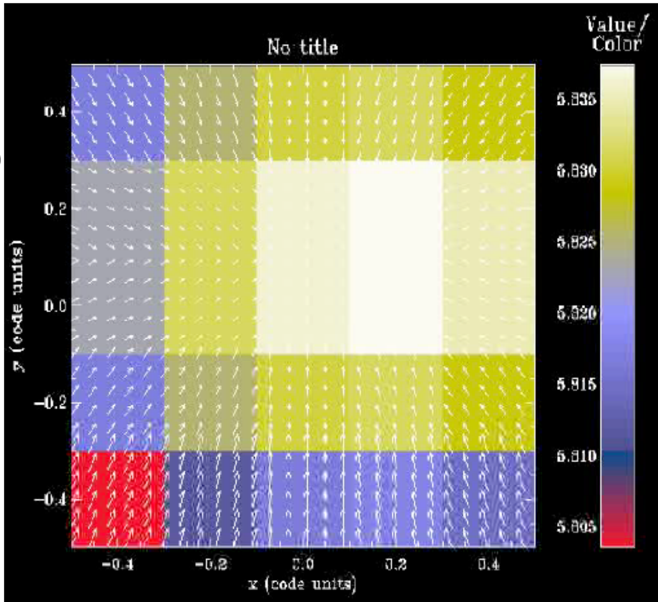


B, ω

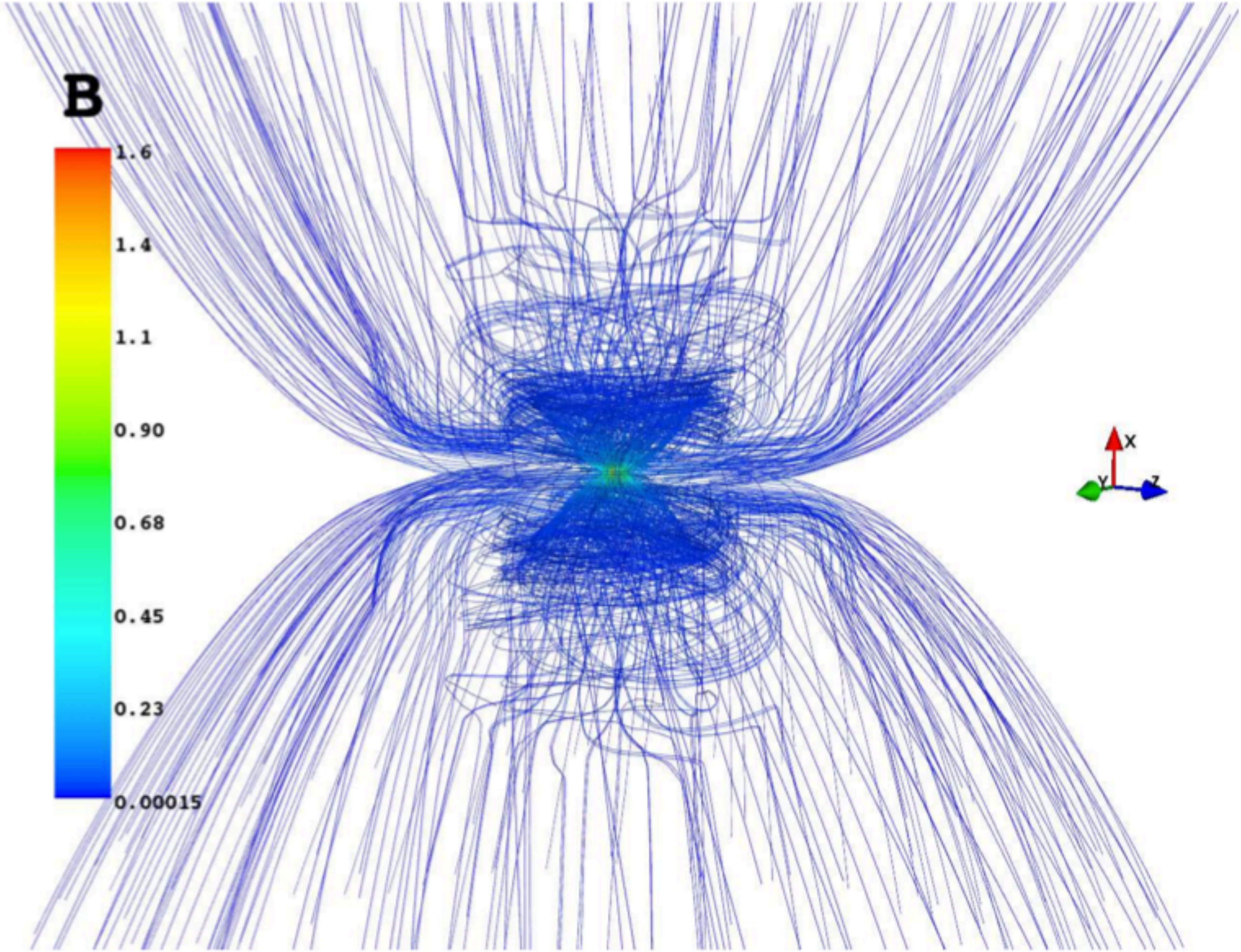
XZ
hydro



XZ
MHD
μ=2



B, ω

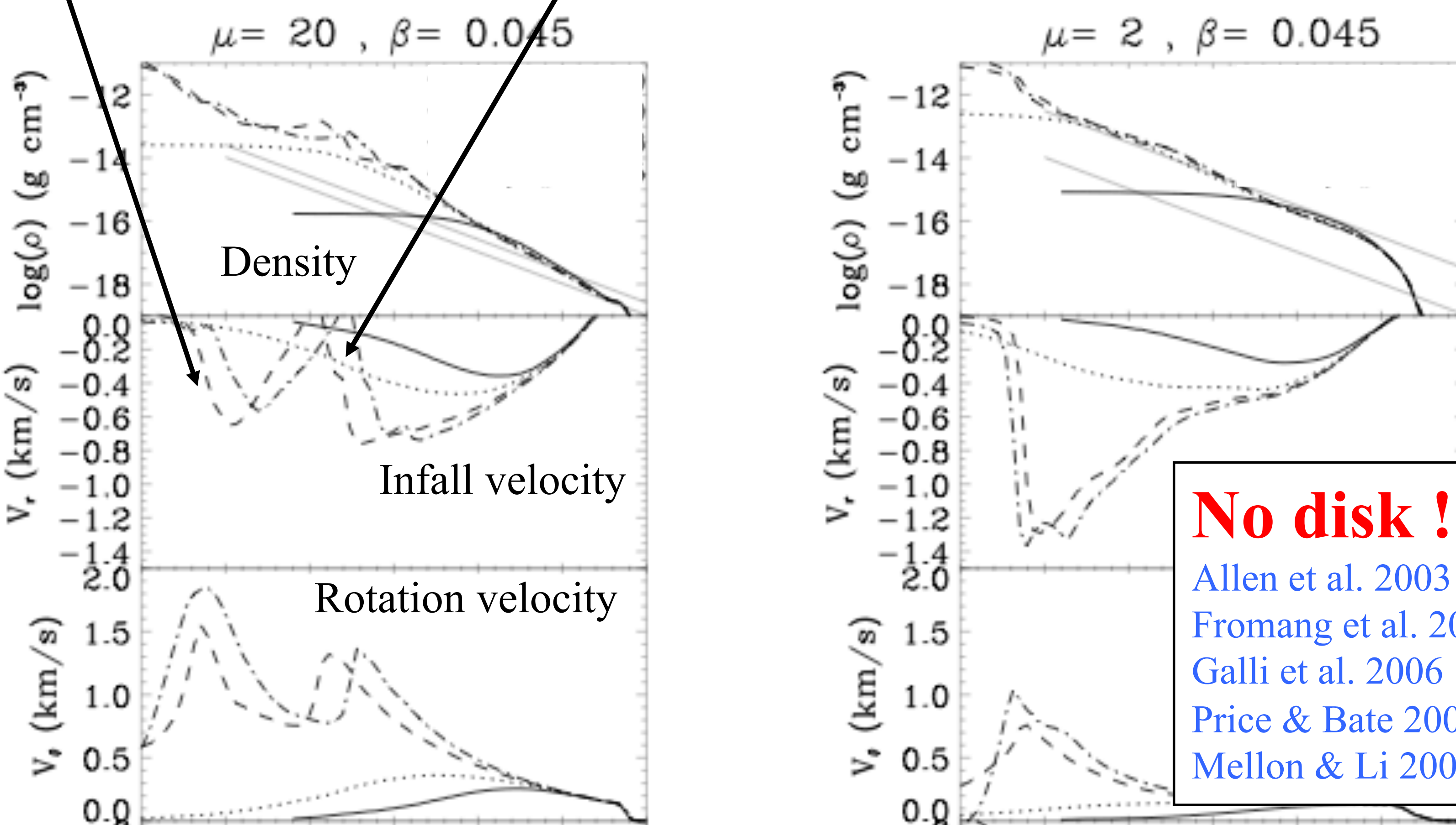


B
1.6
1.4
1.1
0.90
0.68
0.45
0.23
0.00015
x
y
z

Density, rotation and infall velocity profiles

Thermally supported core

Centrifugally supported disk



No disk !

Allen et al. 2003
Fromang et al. 2006
Galli et al. 2006
Price & Bate 2007
Mellon & Li 2008

H & Fromang 2008

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Magnetic field has solved the hydrodynamical catastrophy !

Comparison of the PdBI maps with simulations

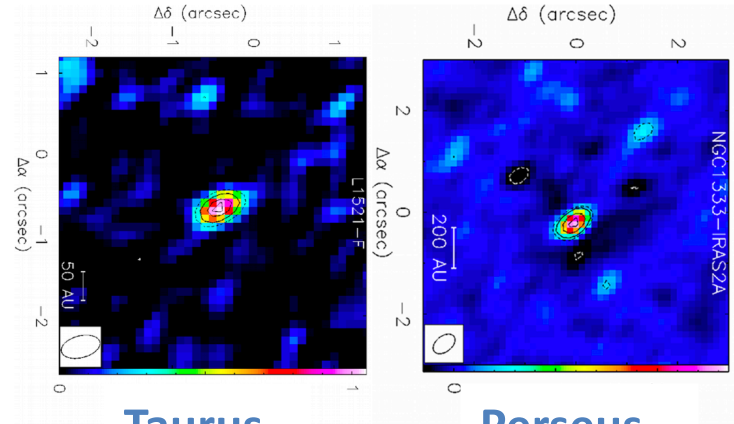
Hydrodynamical simulations produce too much extended (+ multiple) structures if compared to Maury et al. 2010 Observations. Tobin+2015 observe few big disks (but most are small).

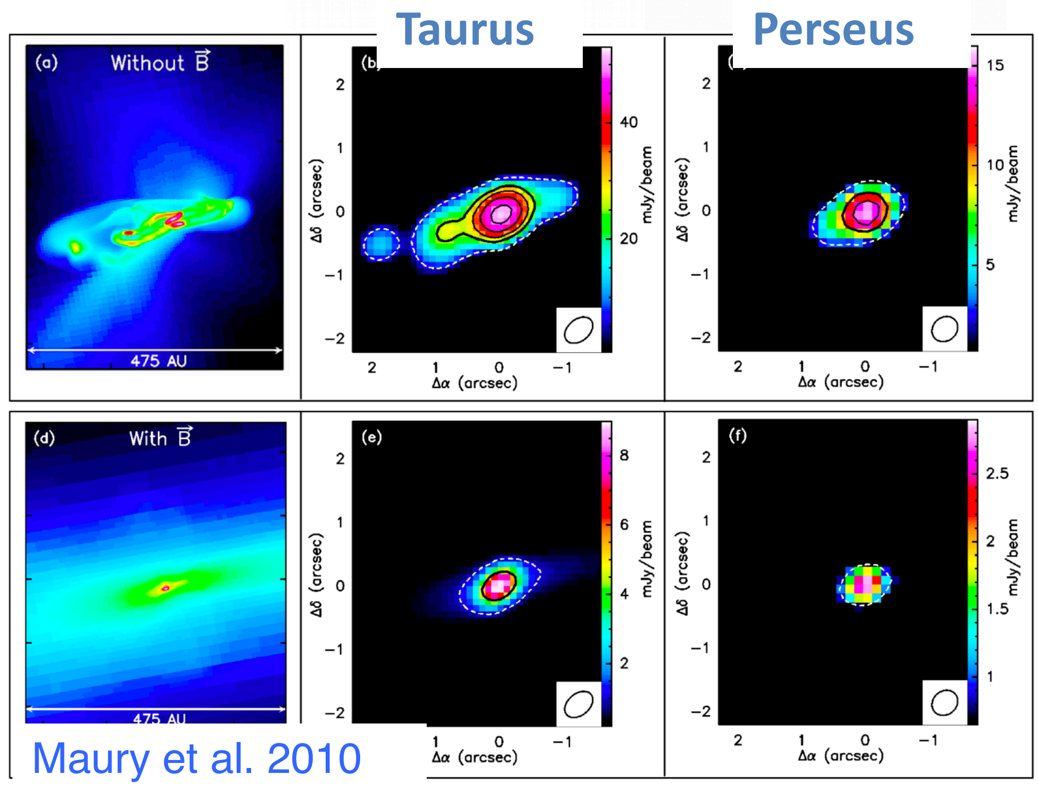
MHD simulations : produce PdB-A synthetic images with **typical FWHM ~ 0.2" - 0.6"**

Similar to Class 0 PdB-A sources observed !

need B to produce compact, single PdB-A sources.

Taurus : L1521-F **Perseus : N1333-IRS2A**





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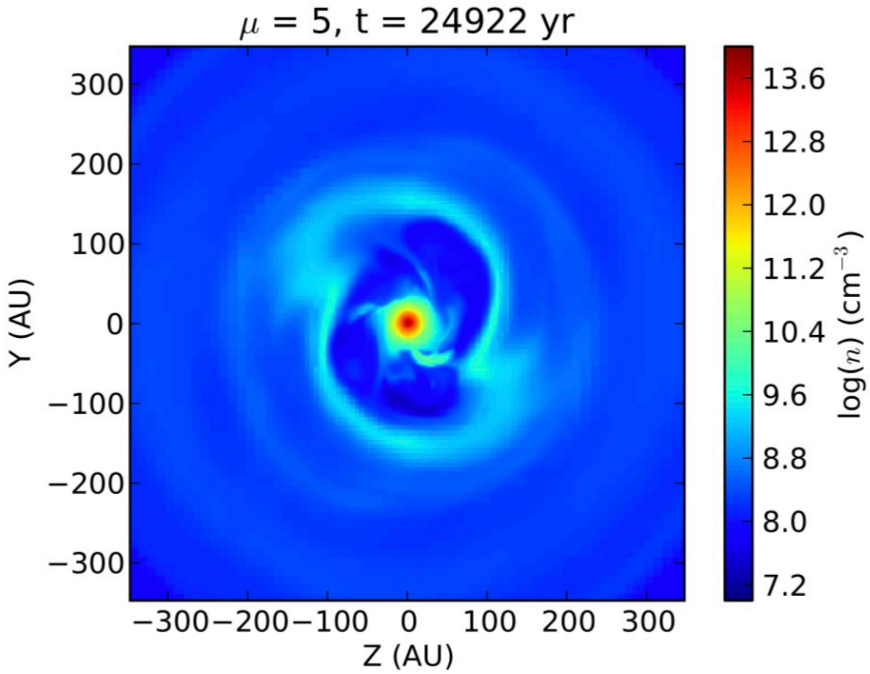
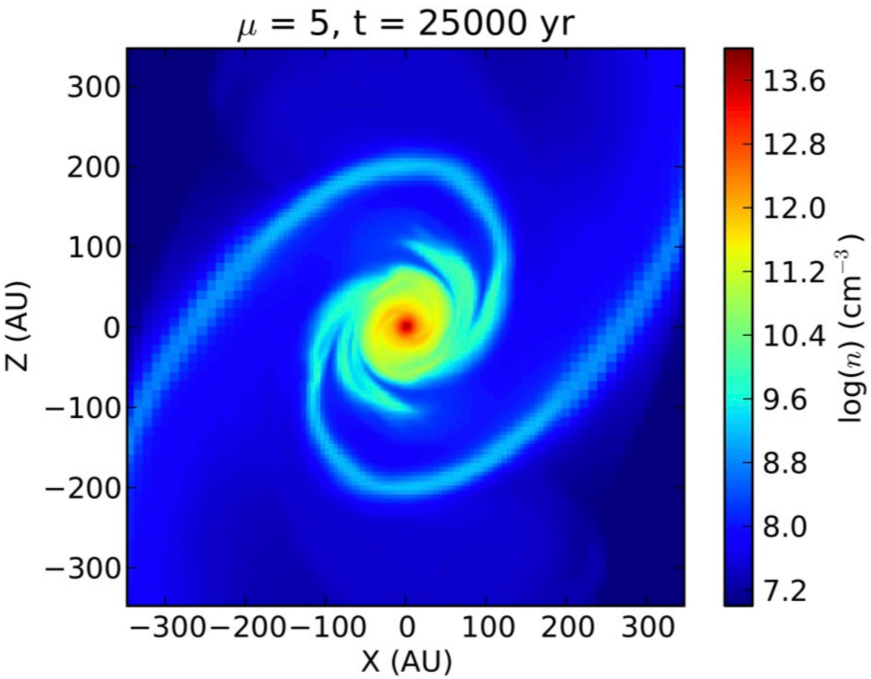
B//J initially



B perp to J initially



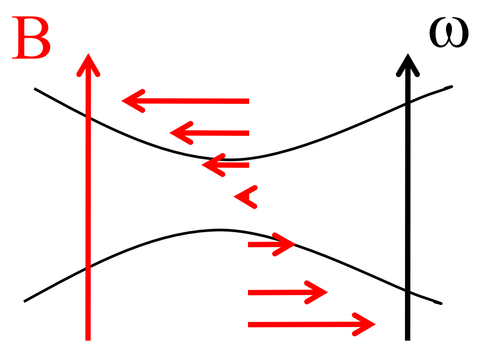
Joos+2012

Why (and is) Magnetic braking so efficient ?

(H+Ciardi 2009, Joos+2012, Li+2013, Gray+2017)

$$\left.\begin{aligned} \frac{\rho V_\theta}{\tau_{br}} &\propto B_z \frac{B_\theta}{4\pi h} \\ \frac{B_\theta}{\tau_{br}} &\propto B_z \frac{V_\theta}{h} \end{aligned}\right\} \Rightarrow \tau_{br} \propto \frac{\sqrt{4\pi h^2 \rho}}{B_z}$$

Aligned case



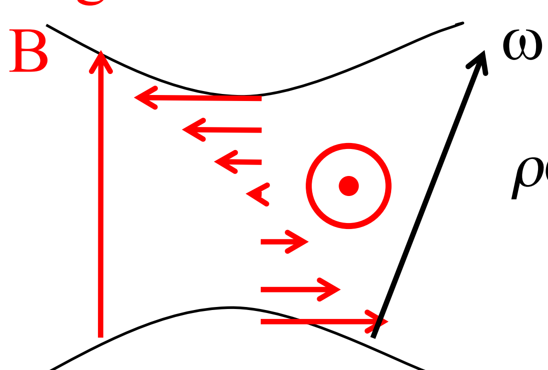
$$\rho C_s^2 = (\partial_z \phi)^2 + \frac{B_r^2}{8\pi}$$

Radial magnetic *field vanishes in the equatorial plan* and compresses the cloud

=> Creates a thin pseudo-disk

=> Magnetic braking very efficient

Misaligned case

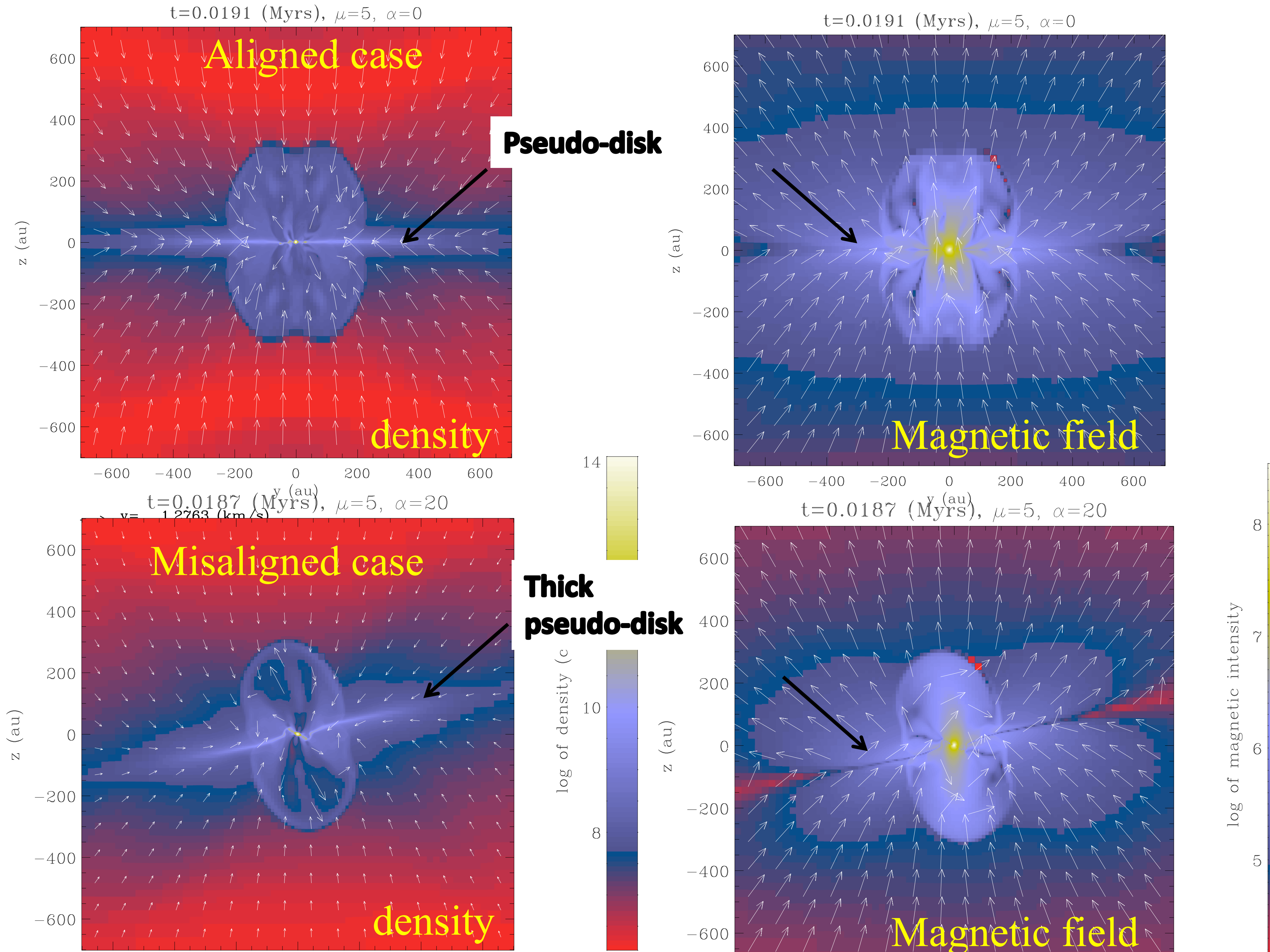


$$\rho C_s^2 + \frac{B_y^2}{8\pi} = (\partial_z \phi)^2 + \frac{B_r^2}{8\pi}$$

Rotation generates a new magnetic component which *does not vanish in the equatorial plan*

⇒Thicker pseudo-disk

⇒Magnetic braking less efficient


t=0.0191 (Myrs), μ=5, α=0
Aligned case
Pseudo-disk
density
z (au)
y (au)
t=0.0191 (Myrs), μ=5, α=0
Magnetic field
z (au)
y (au)
t=0.0187 (Myrs), μ=5, α=20
Misaligned case
Thick pseudo-disk
density
z (au)
log of density
t=0.0187 (Myrs), μ=5, α=20
Magnetic field
z (au)
log of magnetic intensity

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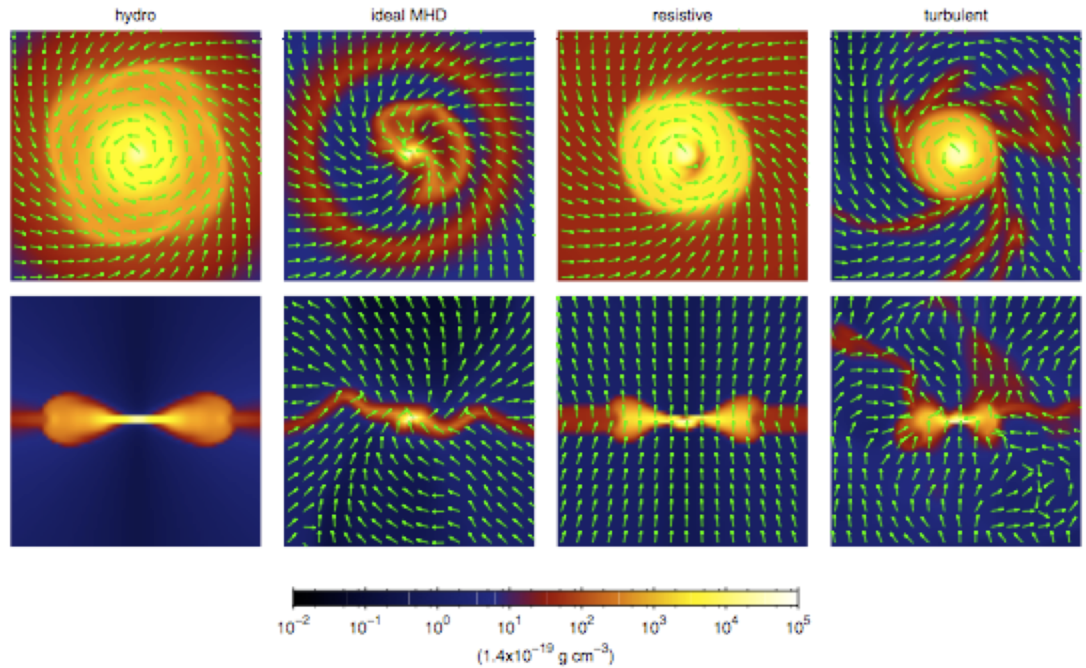
So-called « magnetic braking catastrophy » is a consequence of over-simplifying the collapse by setting B and J parallel

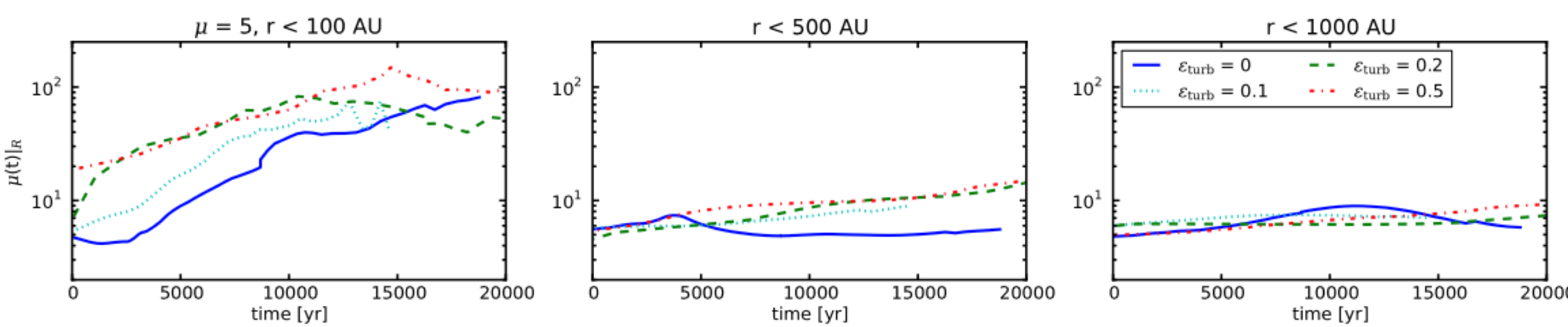
=>small angle between J and B leads to disk formation

=> weak turbulence also leads to disk formation (Seifried+2011, Santos-Lima+2012, Joos+2013)

Santos-Lima+2012



Mass-to-flux ratio as a function of times for 3 radius and 4 levels of turbulence



Joos et al. 2013

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MHD is (likely) highly non-ideal as the collapse proceeds

(Nishi & Nakano 1991, Nakano+2002, Kunz & Mouschovias2009, Krasnopolsky+2010,Dapp+2012, Tsukamoto+2015,Marchand+2016, Wurster+2016, Zhao+2016)

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = -\frac{c^2}{4\pi} \nabla \times \left[\eta_\Omega (\nabla \times \mathbf{B}) \right.$$

← Ohmic

$$- \eta_{\mathrm{H}} \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{||\mathbf{B}||} \right\}$$

← Hall

$$\left. - \eta_{\mathrm{AD}} \frac{\mathbf{B}}{||\mathbf{B}||} \times \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{||\mathbf{B}||} \right\} \right],$$

← Ambipolar diffusion

$$\eta_\Omega = \frac{1}{\sigma_{||}},$$

$$\eta_{\mathrm{H}} = \frac{\sigma_{\mathrm{H}}}{\sigma_\perp^2 + \sigma_{\mathrm{H}}^2},$$

$$\eta_{\mathrm{AD}} = \frac{\sigma_\perp}{\sigma_\perp^2 + \sigma_{\mathrm{H}}^2} - \frac{1}{\sigma_{||}},$$

$$\sigma_{||} = \sum_i \sigma_i,$$

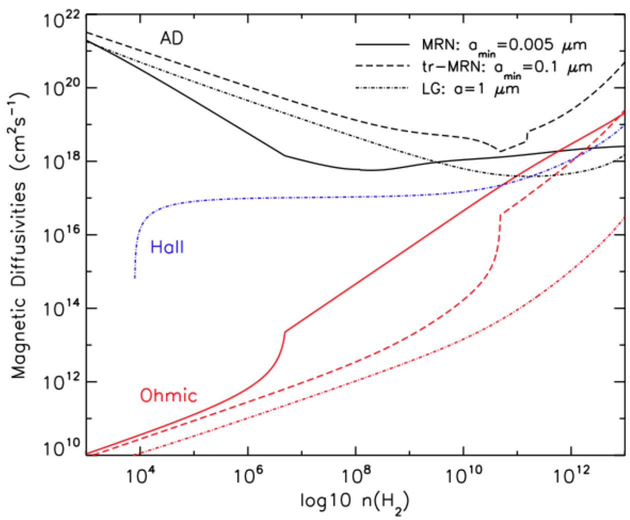
$$\sigma_\perp = \sum_i \frac{\sigma_i}{1 + (\omega_i \tau_{in})^2},$$

$$\sigma_{\mathrm{H}} = -\sum_i \frac{\sigma_i \omega_i \tau_{in}}{1 + (\omega_i \tau_{in})^2}.$$

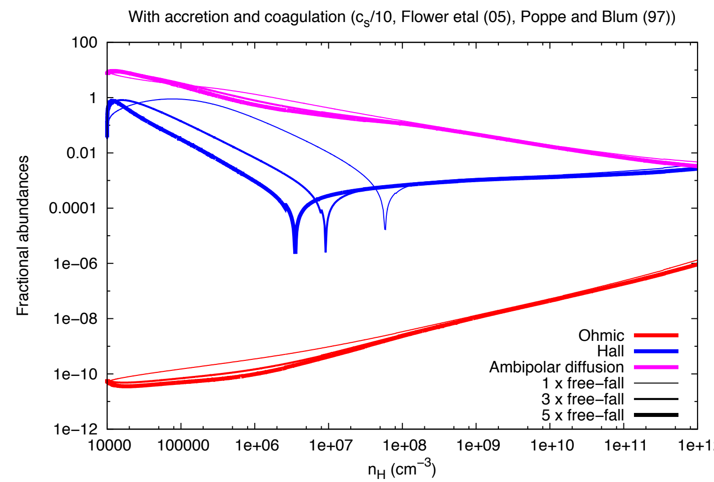
Need to consider a chemical network, a grain distribution and a cosmic rate ionisation rate **(and remember: none of them has been tested…)**

Resistivities for different assumptions

(Nishi & Nakano 1991, Nakano+2002, Kunz & Mouschovias2009, Krasnopolsky+2010 , Dapp+2012, Marchand+2016, Wurster+2016, Zhao+2016)

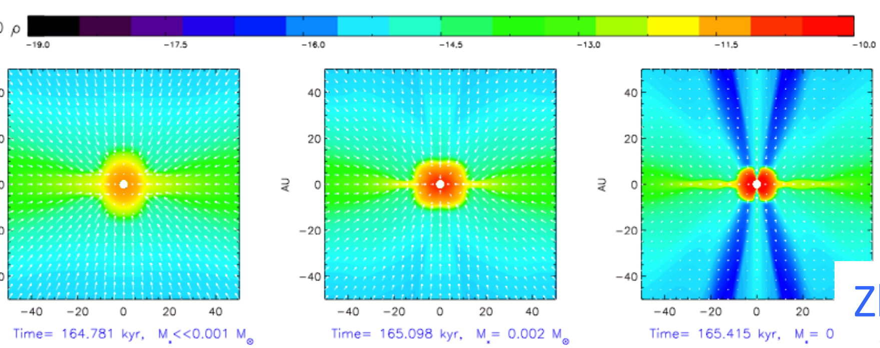


Zhao+2016

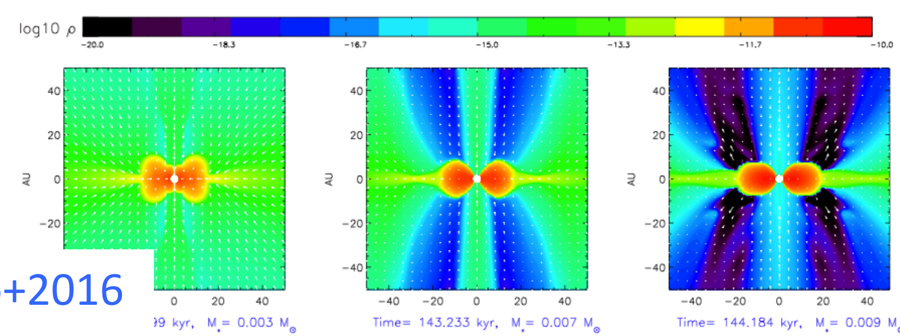


Guillet+ in prep

2D simulation of disk formation for MRN distribution



2D simulation of disk formation for truncated MRN distribution



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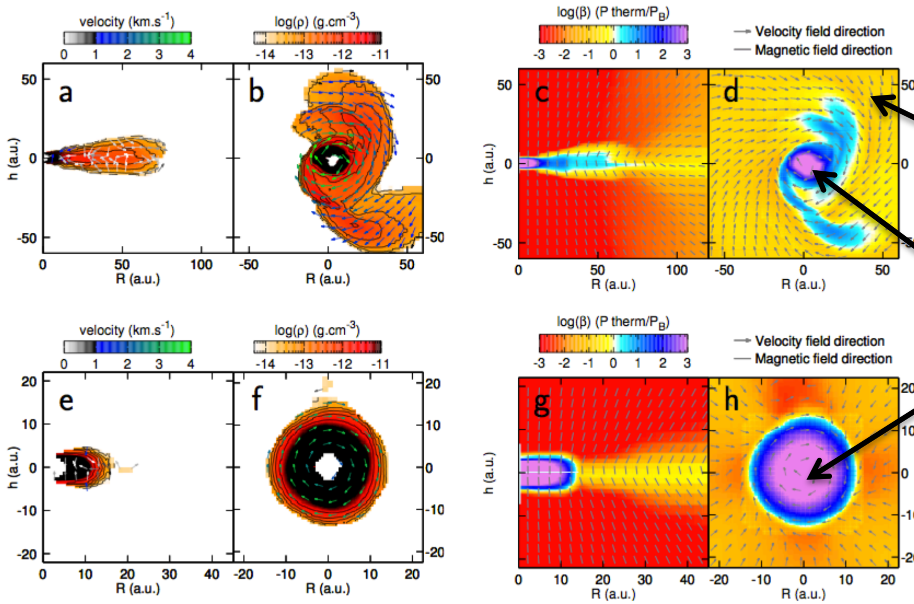
Non-ideal MHD: more regular and leads to the formation of small disks

(Machida+2006,2010, Krasnopolsky+2011, Li+2014, Tomida+2015,2017,Masson+2016,H+2016)

Weak B (μ=5)
15 AU disk
+spirals

Strong B (μ=2)
15 AU disk



Ptherm/Pmag <1

Ptherm/Pmag ~1000

Masson+2016

200 AU

800 AU

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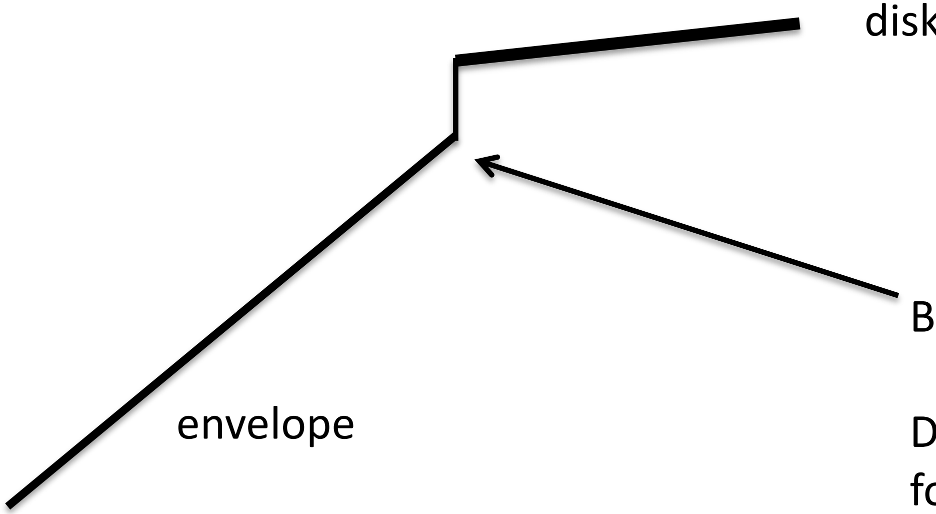
Can we predict, even qualitatively, the typical size of the disks ?

H+2016 propose a model based on simple timescales estimated at the outer disk edge



Braking time=rotation time

Diffusion time=generation time
for B toroidal component

=> Need B, density, rotation

Comparing time scales

-generation of toroidal field

$$\tau_{\rm far} \simeq \frac{B_\phi h}{B_z v_\phi},$$

-diffusion of toroidal field

$$\tau_{\rm diff} \simeq \frac{4\pi h^2}{c^2 \eta_{\rm AD}} \frac{B_z^2 + B_\phi^2}{B_z^2} \simeq \frac{4\pi h^2}{c^2 \eta_{\rm AD}},$$

-magnetic braking

$$\tau_{\rm br} \simeq \frac{\rho v_\phi 4\pi h}{B_z B_\phi},$$

-rotation within the disk outer part

$$\tau_{\rm rot} \simeq \frac{2\pi r}{v_\phi},$$

-radial equilibrium

$$v_\phi \simeq \sqrt{\frac{G\,(M_* + M_{\rm d})}{r}},$$

-vertical equilibrium

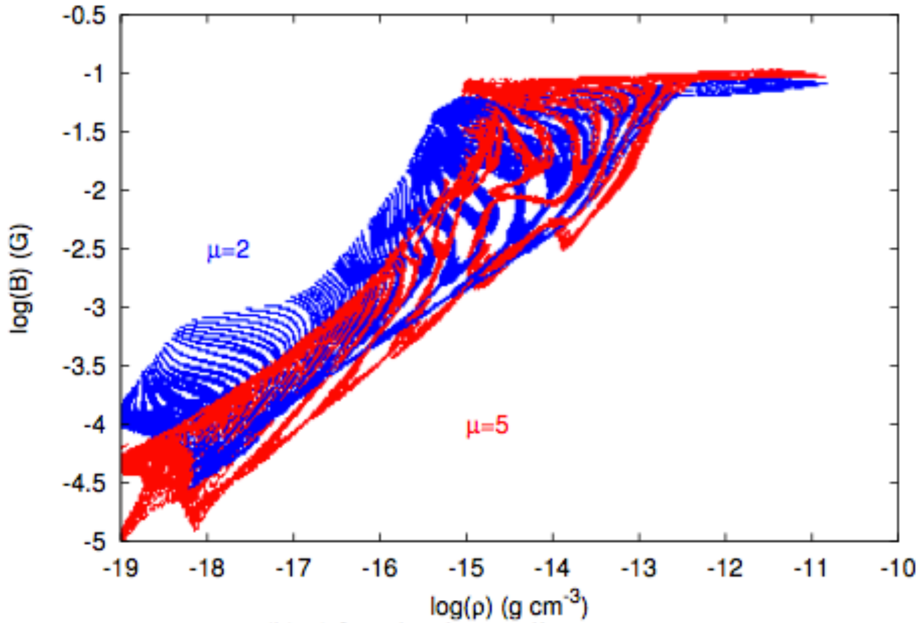
$$h \simeq \frac{C_{\rm s}}{\sqrt{4\pi G\,(\rho + \rho_*)}},$$

Inner magnetic field weakly depends weakly on initial conditions

-magnetic field in the envelope/disk edge

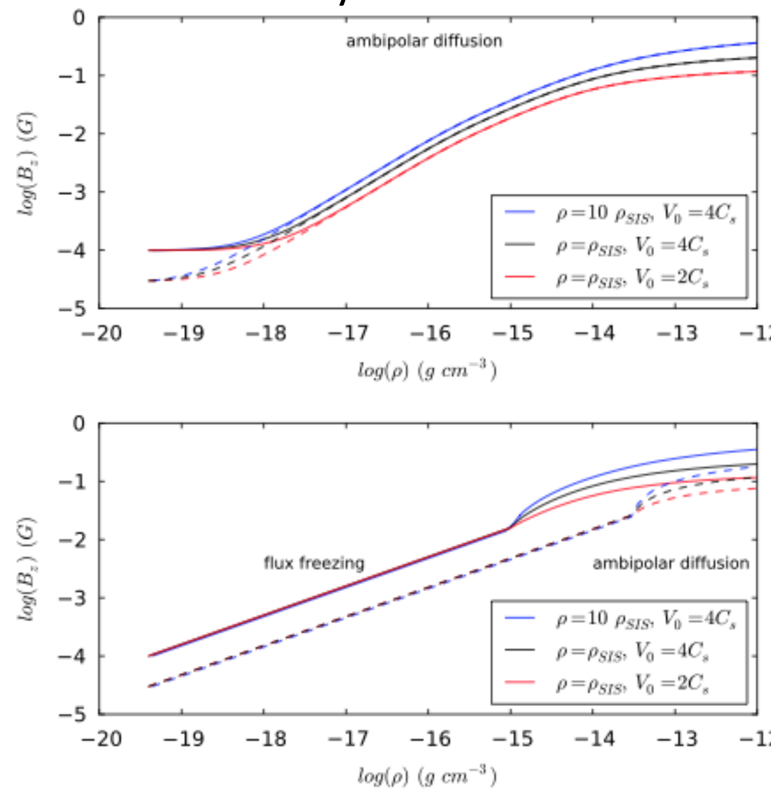
$$v_r B_z \simeq \frac{c^2 \eta_{\rm AD} \partial_r B_z}{4\pi},$$

Numerical simulations



(b) After the decoupling stage.

Analytical models



Masson+2016

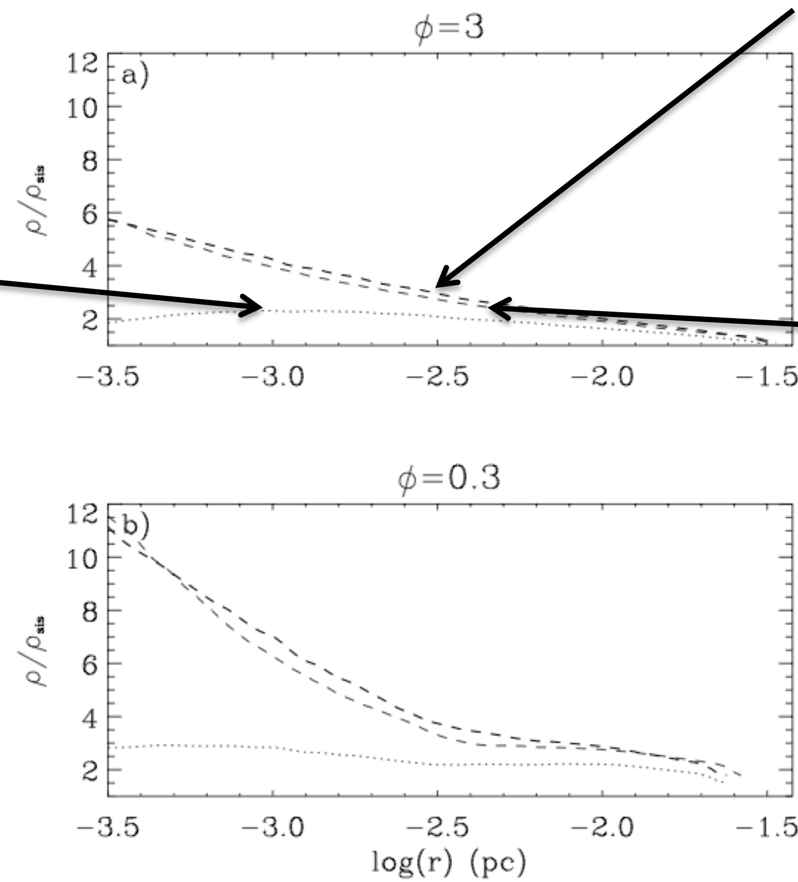
H+2016

Density profile within the core close to the disk edge

-density in the envelope/disk edge

$$\rho(r) = \delta \frac{C_s^2}{2\pi G r^2}\left(1 + \frac{1}{2}\left(\frac{v_\phi(r)}{C_s}\right)^2\right).$$

Singular isothermal sphere density



density within the simulation

H+2004

Hydrodynamical collapse with rotation

Disk Radius dependence

Typical radius is:

$$r_{\rm d,AD} \simeq 18\,{\rm AU}\,\times$$
$$\delta^{2/9}\left(\frac{\eta_{\rm AD}}{0.1\,{\rm s}}\right)^{2/9}\left(\frac{B_z}{0.1\,{\rm G}}\right)^{-4/9}\left(\frac{M_{\rm d}+M_*}{0.1\,{\rm M}_\odot}\right)^{1/3}.$$

By contrast hydro would lead to:

$$r_{\rm d,hydro} \simeq 106\,{\rm AU}\,\frac{\beta}{0.02}\left(\frac{M}{0.1\,{\rm M}_\odot}\right)^{1/3}\left(\frac{\rho_0}{10^{-18}{\rm g\,cm^{-3}}}\right)^{-1/3}$$

=> Early disk formation is magnetically *self-regulated* !

Their characteristics weakly depend (in some reasonable range) on the initial conditions such as magnetization and rotation.

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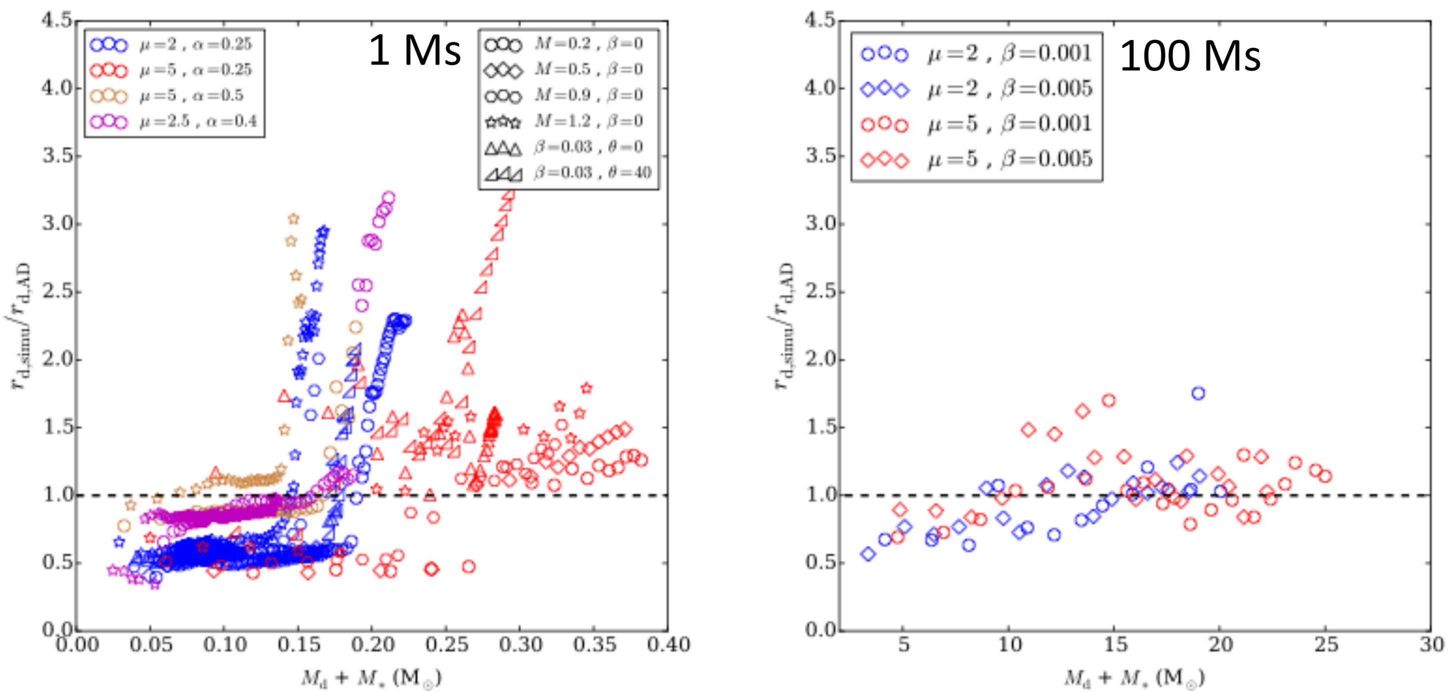
Comparison between analytical models and several simulations

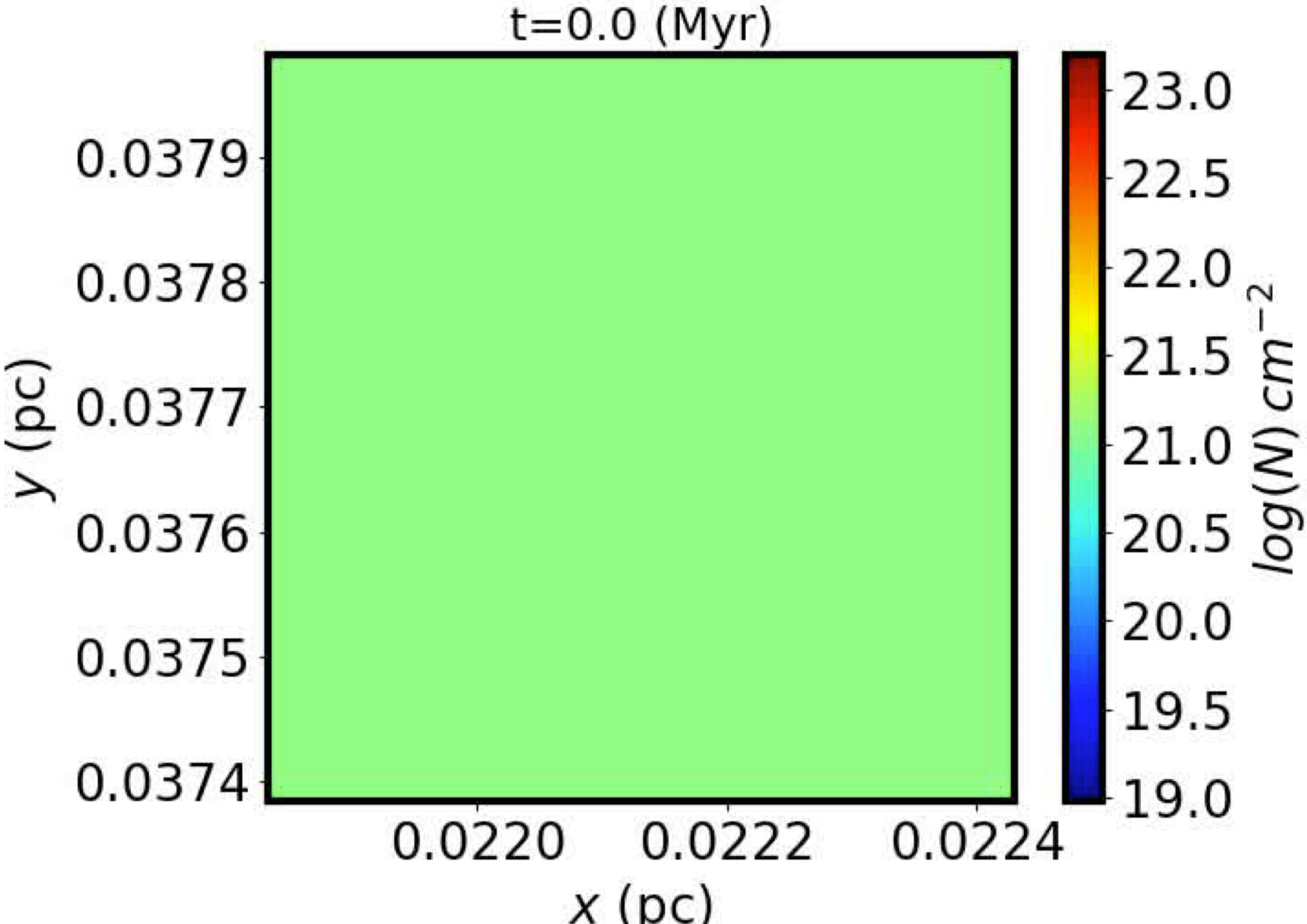
$$r_{\mathrm{d,AD}} \simeq 18\,\mathrm{AU} \times \delta^{2/9} \left(\frac{\eta_{\mathrm{AD}}}{0.1\,\mathrm{s}}\right)^{2/9} \left(\frac{B_z}{0.1\,\mathrm{G}}\right)^{-4/9} \left(\frac{M_{\mathrm{d}} + M_*}{0.1\,\mathrm{M}_\odot}\right)^{1/3}.$$

Comparison between analytical model and simulations for a wide range of parameters
Turbulence and rotation are varied by a factor 5, mass by a factor 100, B by a factor 2

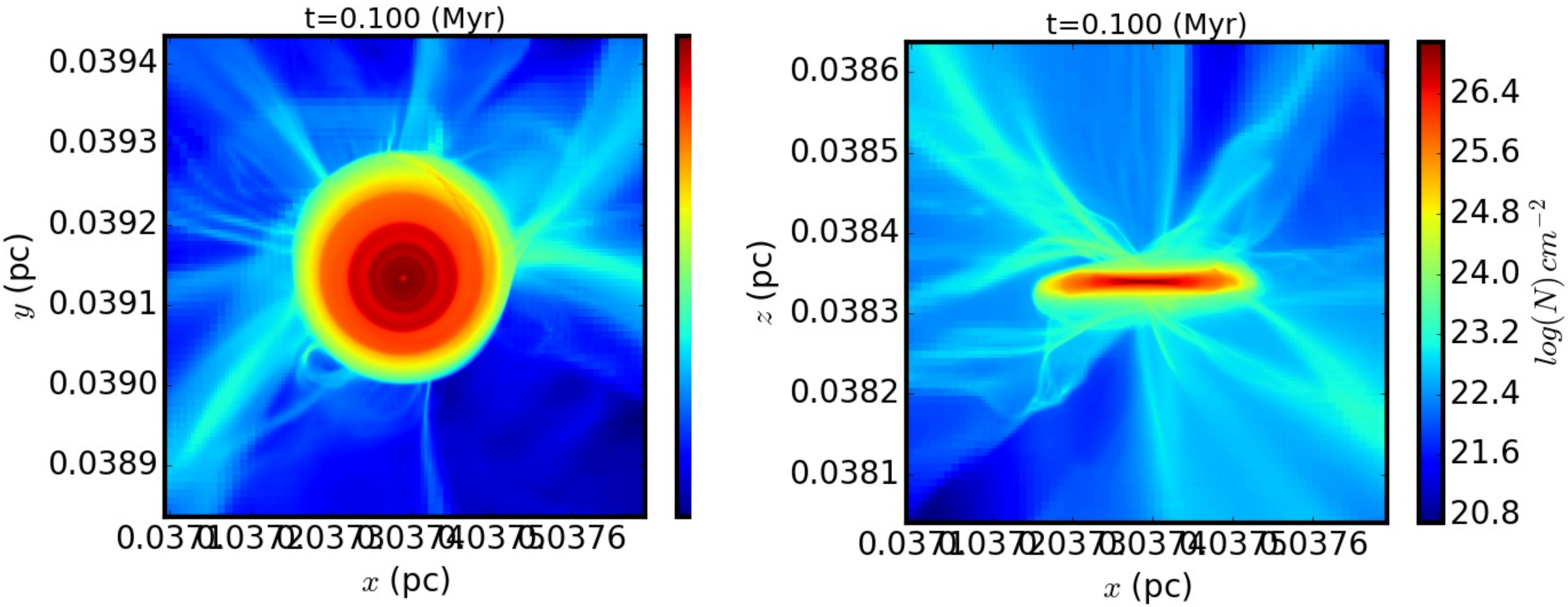


H+2016

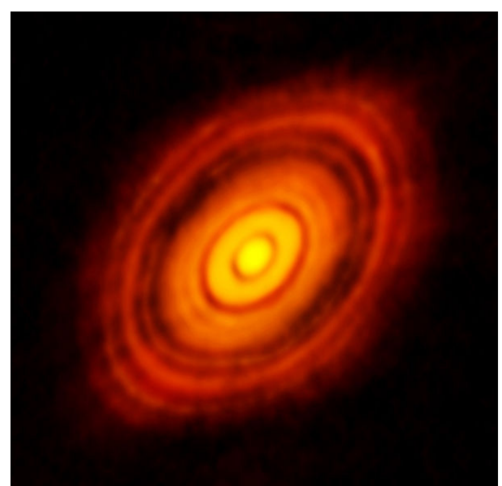
Long term evolution



8 times more resolution



Magnetic field origin as proposed by Bethune et al. 2017



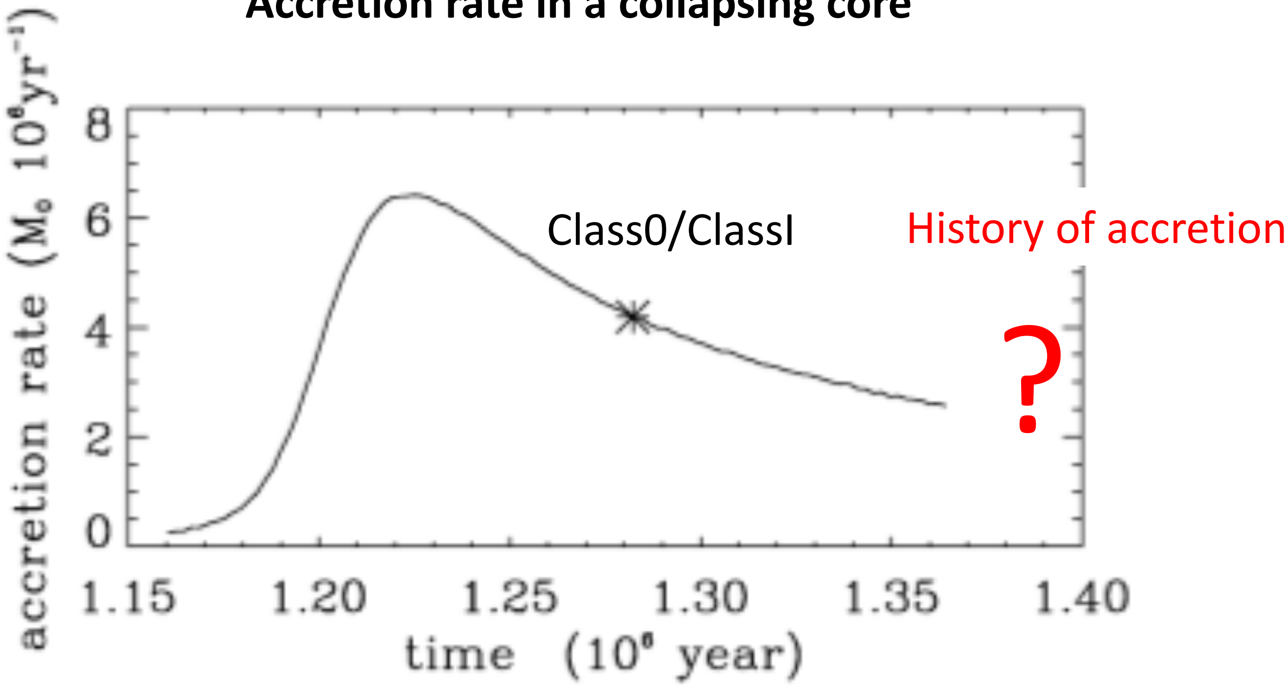
An explanation for observed rings ?

I – What sets the “typical” size of early protoplanetary disks ?

II- Are late disks really “isolated” ?

Are late disks completely isolated ?

Accretion rate in a collapsing core



H+03

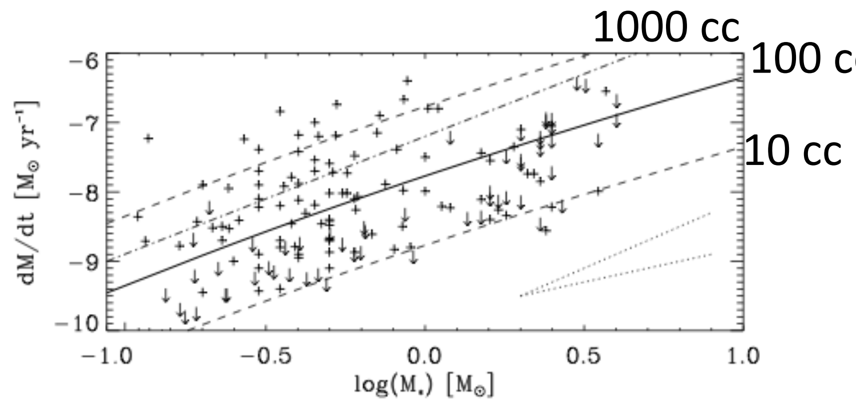
Correlation between accretion rate and star mass

accretion laws dM/dt vs M_* seems to be *“naturally”* explained by Bondi-Hoyle accretion onto the disk
(Padoan et al. 2005, Klessen & H 2010, Padoan et al. 2014)

Link between external and internal accretion ?

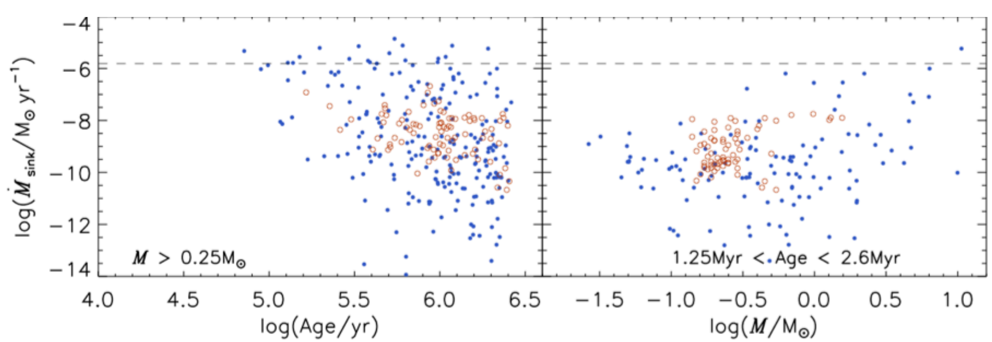
Expected accretion as a function of star mass for various mean density (100 cc standard)
Comparison with observed rates

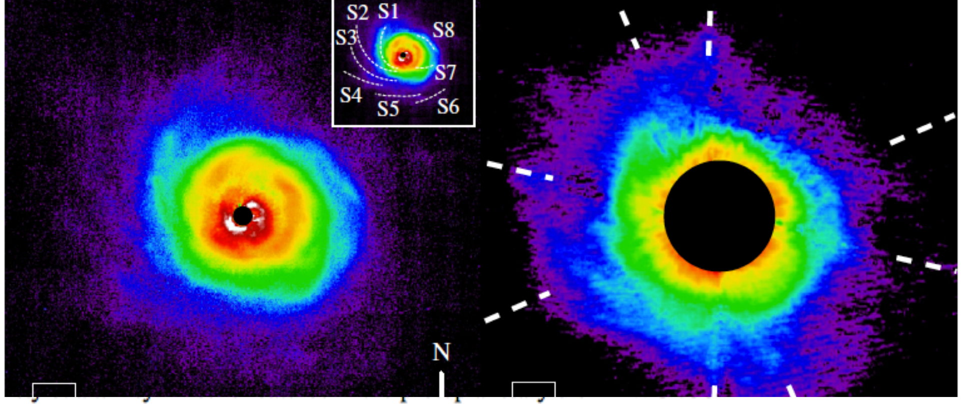
Klessen & H 2010



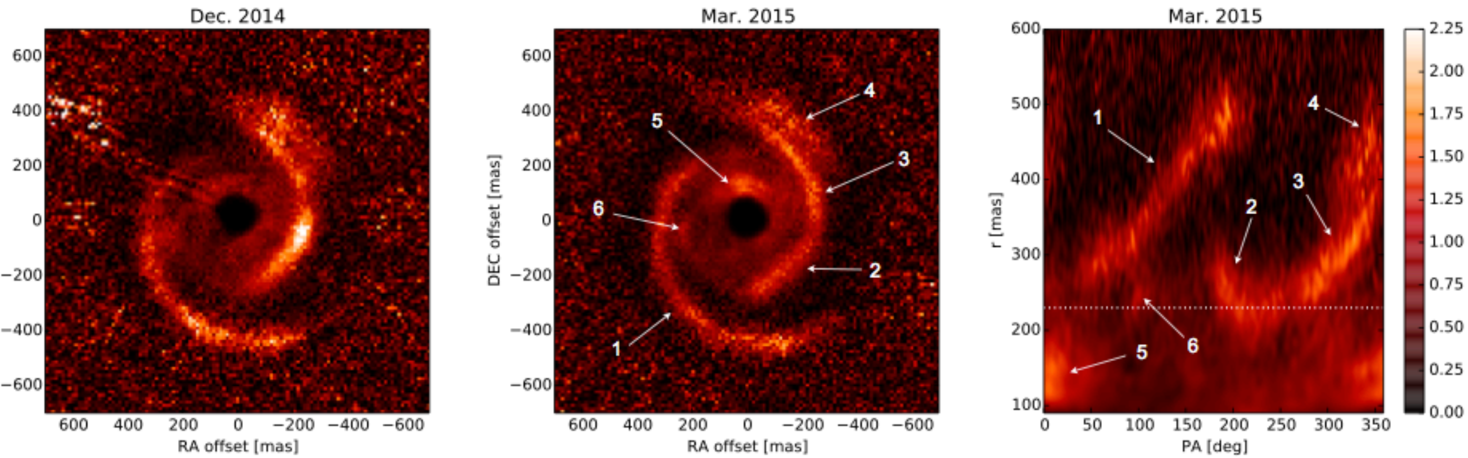
Result from very large MHD simulations (self-gravity and sink particles included)

Padoan+ 2014

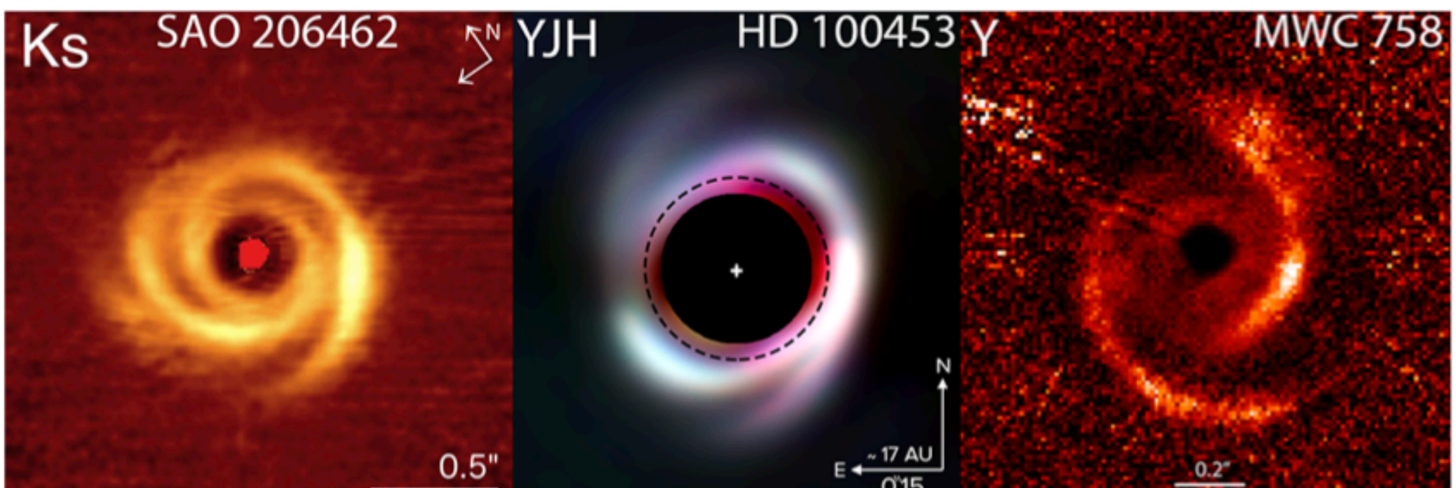




Hashimoto et al. 2011



Benisty et al. 2015



Wagner et al. 2016

Approach and possible impact

To probe the influence accretion may have, we consider the simplest configuration ignoring explicitly magnetic field and self-gravity

Accretion is not symmetric => source of non-axisymmetric perturbations, which may transport angular momentum

Other processes: flux of angular momentum, instabilities at the accretion shock

MAJOR QUESTION:

Is the perturbation induced at the edge of the disk propagating deep inside the disk ?

Work approach

1- Exact self-similar solutions

2- 2D numerical simulations

3- 3D numerical simulations

Work approach

1- Exact self-similar solutions

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Self-similar variables

Stationary 2D equations

$$\rho\left(u_r\partial_r u_r + \frac{u_\phi}{r}\partial_\phi u_r - \frac{u_\phi^2}{r}\right) = -\partial_r P + \rho g_r,$$
$$\rho\left(u_r\partial_r u_\phi + \frac{u_\phi}{r}\partial_\phi u_\phi + \frac{u_r u_\phi}{r}\right) = -\frac{1}{r}\partial_\phi P,$$
$$\frac{1}{r}\partial_r(rh\rho u_r) + \frac{1}{r}\partial_\phi(h\rho u_\phi) = 0,$$
$$g_r = -\frac{GM}{r^2} = -\Omega^2 r,$$
$$h \simeq \frac{C_s}{\Omega}$$

$$\begin{aligned} r &= r_0 x, \\ h &= h_0 \tilde{h}, \\ u_r &= r_0\Omega_0\tilde{u}_r, \\ u_\phi &= r_0\Omega_0(x^{-1/2} + \tilde{u}_1), \\ \rho &= \rho_0\tilde{\rho}, \\ P &= \rho_0 r_0^2\Omega_0^2\tilde{T}\tilde{\rho}, \end{aligned}$$

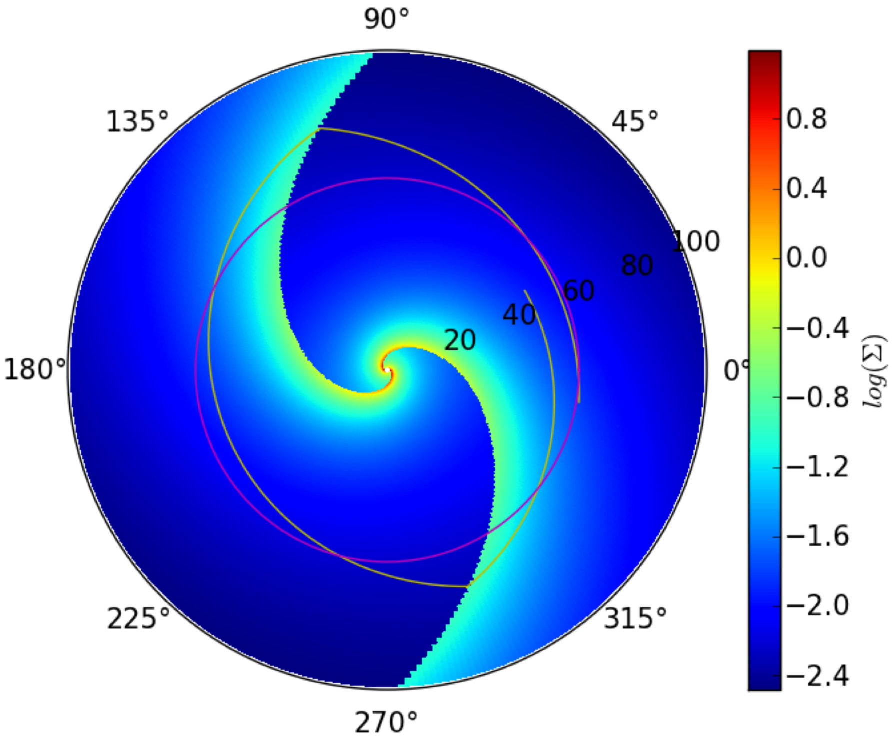
$$\begin{aligned} \tilde{u}_r &= x^{-1/2}U(\psi), \\ \tilde{u}_1 &= x^{-1/2}V(\psi), \\ \tilde{\rho} &= x^{-n}R(\psi), \\ \tilde{T} &= x^{-1}T_0, \\ \beta' &= Bx^{-1}. \end{aligned}$$

Ordinary self-similar equations

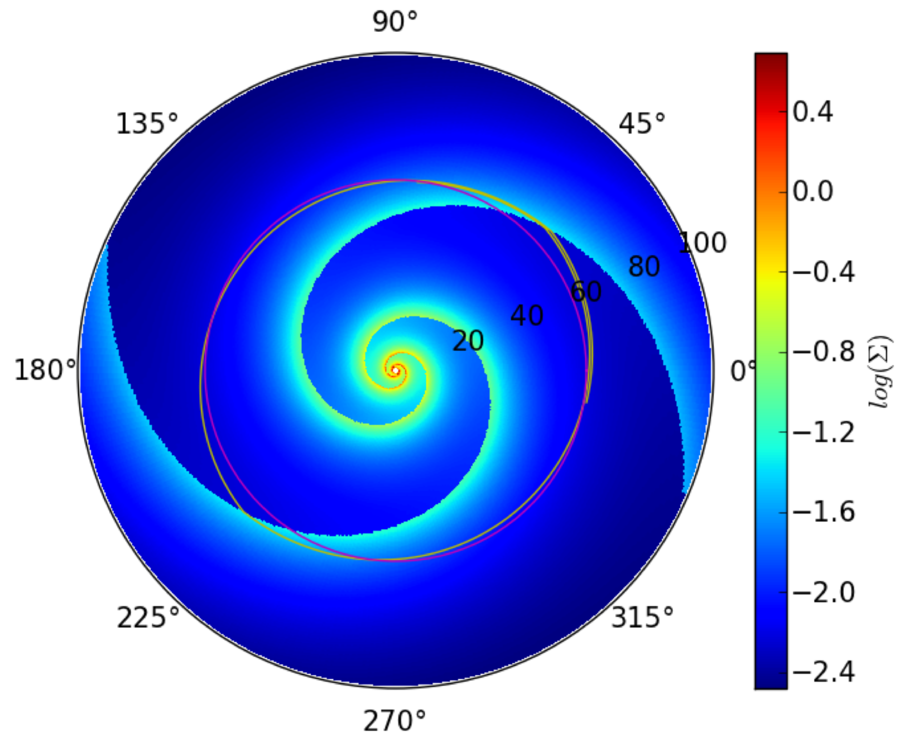
$$(BU + 1 + V)U' + BT_0\frac{R'}{R}$$
$$= (n+1)T_0 + \frac{1}{2}U^2 + V^2 + 2V,$$
$$(BU + 1 + V)V' + T_0\frac{R'}{R} = -\frac{1}{2}U(V+1),$$
$$(-n + 3/2)RU + (R(BU + 1 + V))' = 0.$$

+shock condition to match left and right part through RK conditions
=> Shocks provide the dissipation in the system

Spruit 1987
H+ 2016



h/r ~0.4

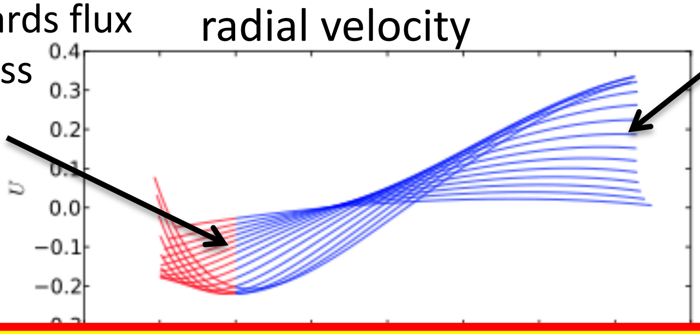


h/r ~0.2

$\tan\theta \sim V_{\phi}/C_s \sim r/h$

Self-similar solutions for various temperatures

Indwards flux of mass

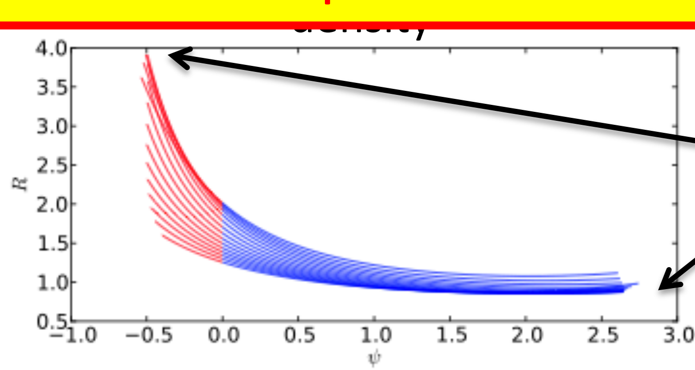


Outwards flux of mass carrying away momentum

alpha vs temperature for various "m"

Suggest: outer perturbations do propagate far into the disk and provide transport of momentum through spiral patterns with 2 opposite fluxes of mass.

The question as to whether it is robust to temperature and density profiles is still open.



$$\alpha = \frac{< \rho \delta u_r \delta u_\phi >}{< P >}$$

Shock, Rankine-Hugoniot conditions

Work approach

1- Exact self-similar solutions

2- 2D numerical simulations

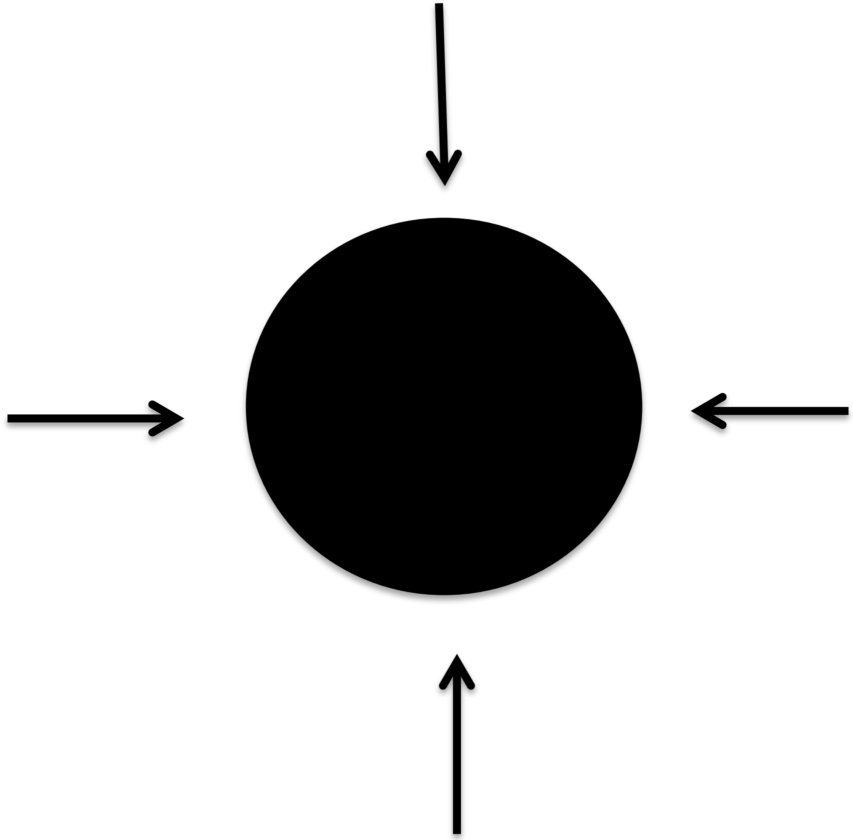
3- 3D numerical simulations

Setup:

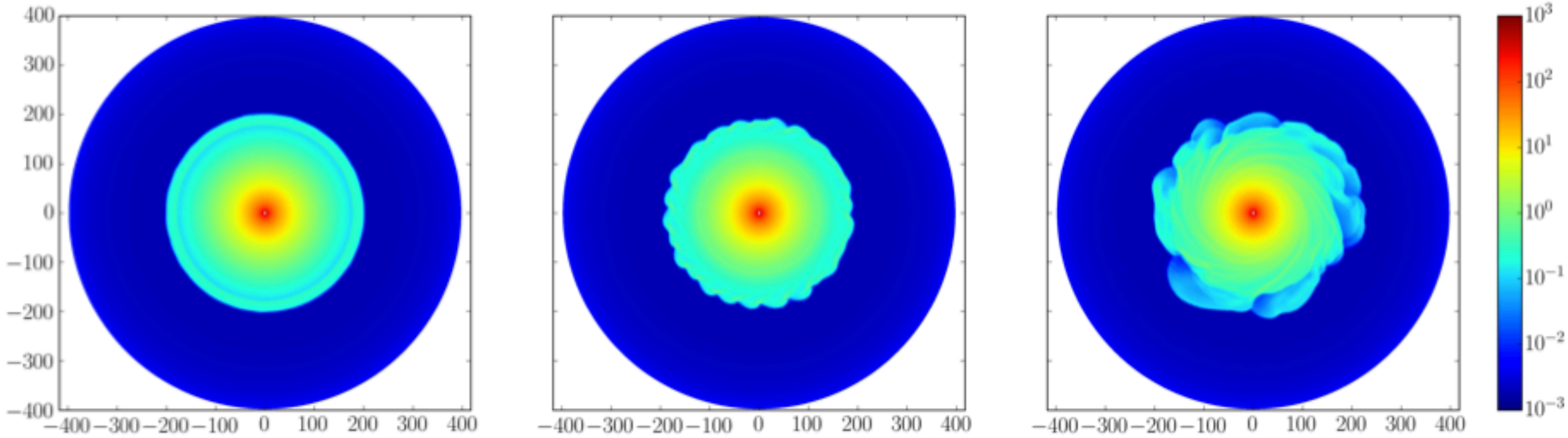
Simulations done with PLUTO
Cylindrical mesh, resolution of 512^2
Absorbing inner boundary
No effective viscosity

Parameters:

Accretion rate (range around 10^{-7} M yr^{-1})
Symmetry of accretion
Angular momentum

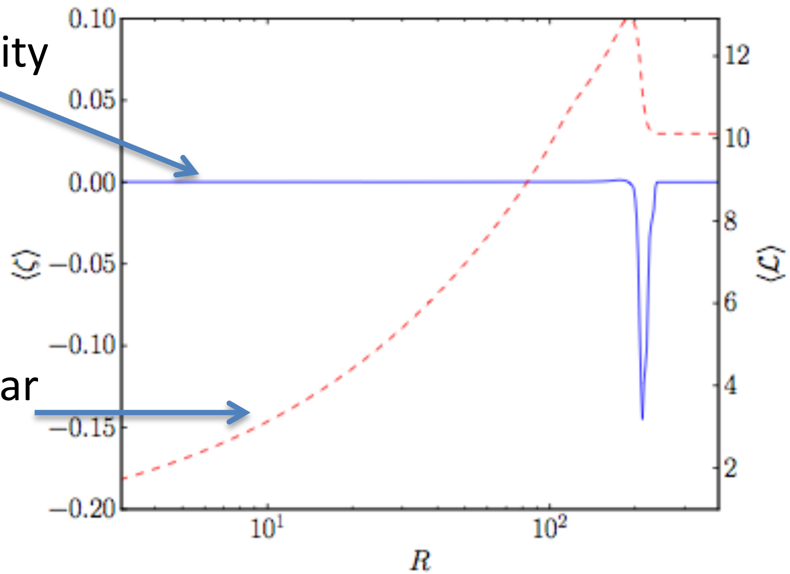


Axisymmetric accretion



Potential vorticity

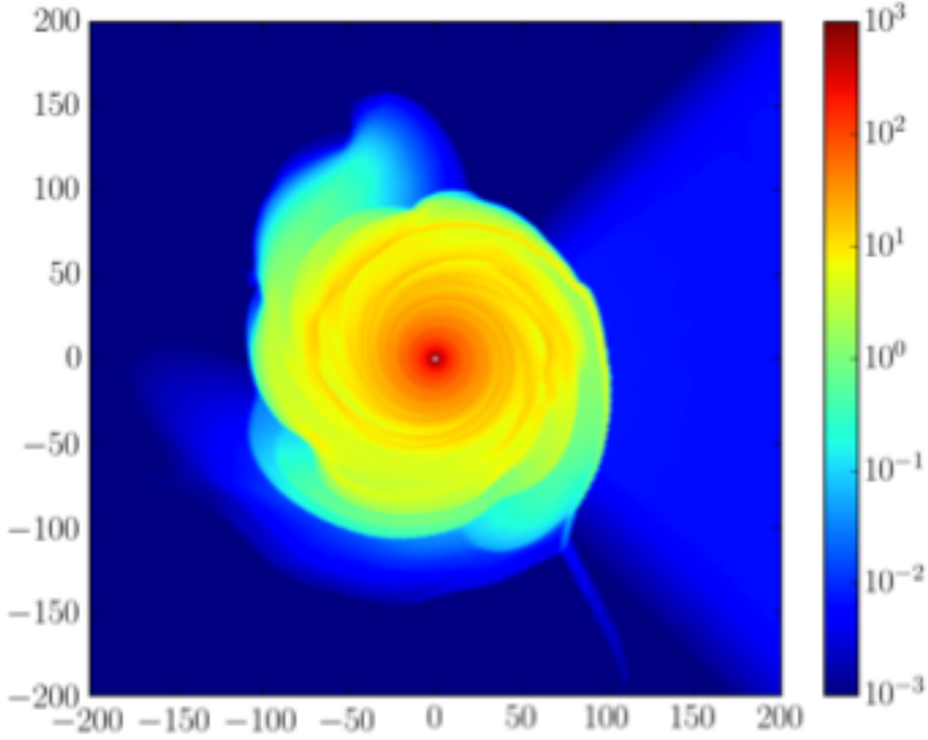
Steep vorticity layer at the edge of the disk



Specific angular momentum

Lesur+2015

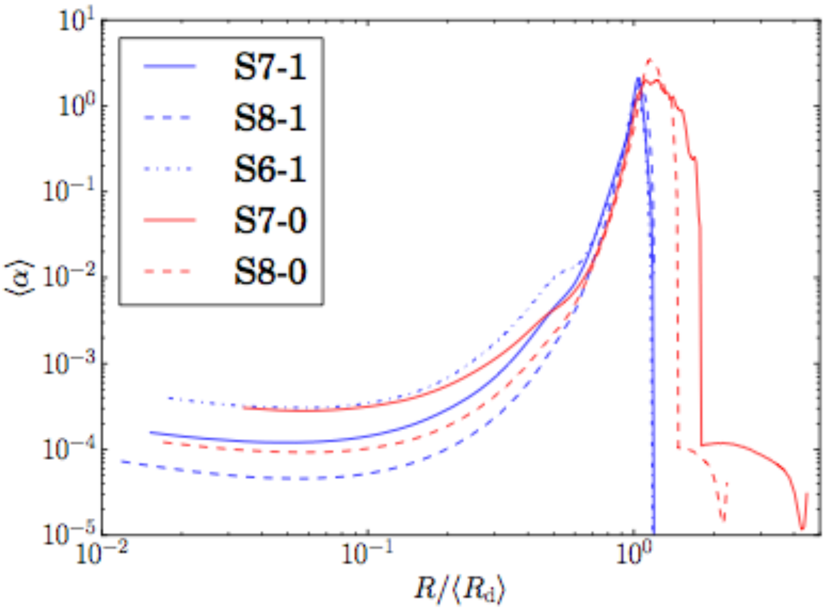
Non-axisymmetric accretion



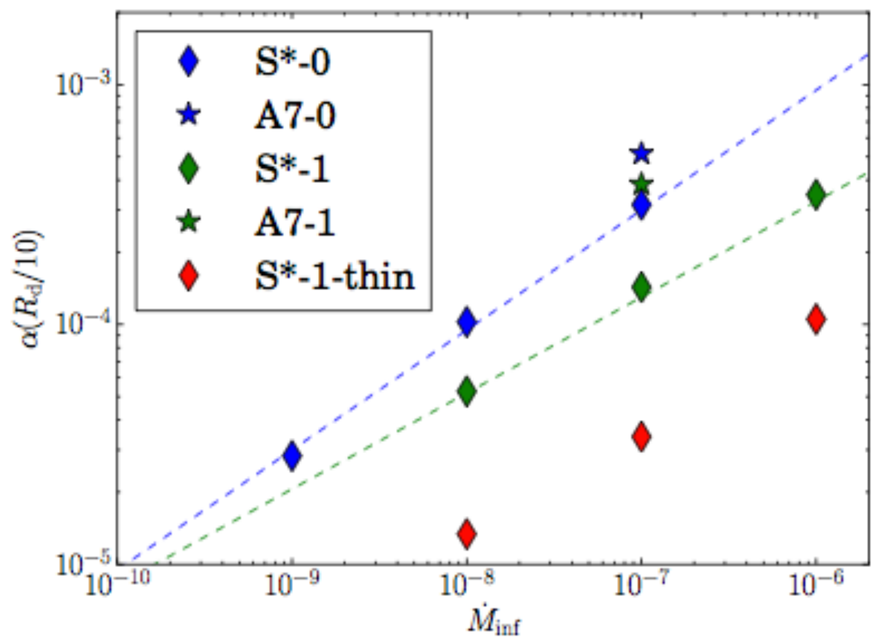
Stronger spiral patterns than in the axisymmetric case

Lesur+2015

alpha vs radius



alpha vs accretion rate



$$\alpha = \frac{< \rho \delta u_r \delta u_\phi >}{< P >}$$

alpha – dM/dt relations “inside” the disk

$$\alpha(R_d/10, \mathcal{L}_{out} = 1) \simeq 1.3 \times 10^{-4} \left(\frac{\dot{M}_{inf}}{10^{-7}\, M_\odot \cdot yr^{-1}} \right)^{0.4}$$

$$\alpha(R_d/10, \mathcal{L}_{out} = 0) \simeq 3 \times 10^{-4} \left(\frac{\dot{M}_{inf}}{10^{-7}\, M_\odot \cdot yr^{-1}} \right)^{0.5}$$

Lesur+2015

Work approach

1- Exact self-similar solutions

2- 2D numerical simulations

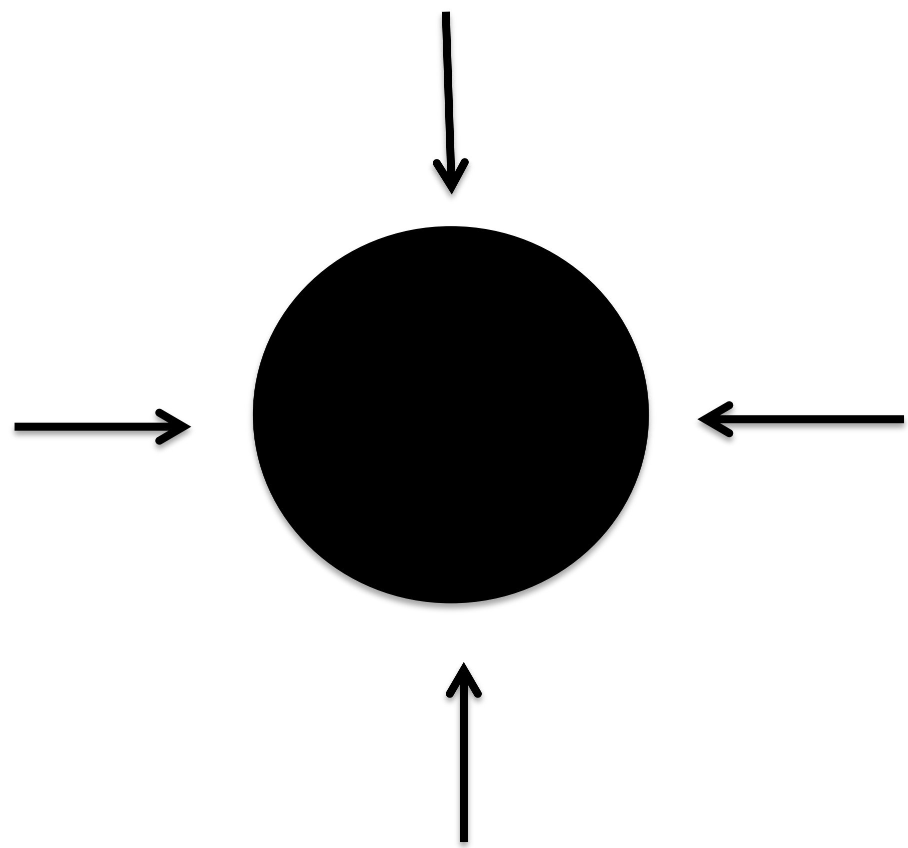
3- 3D numerical simulations

Setup:

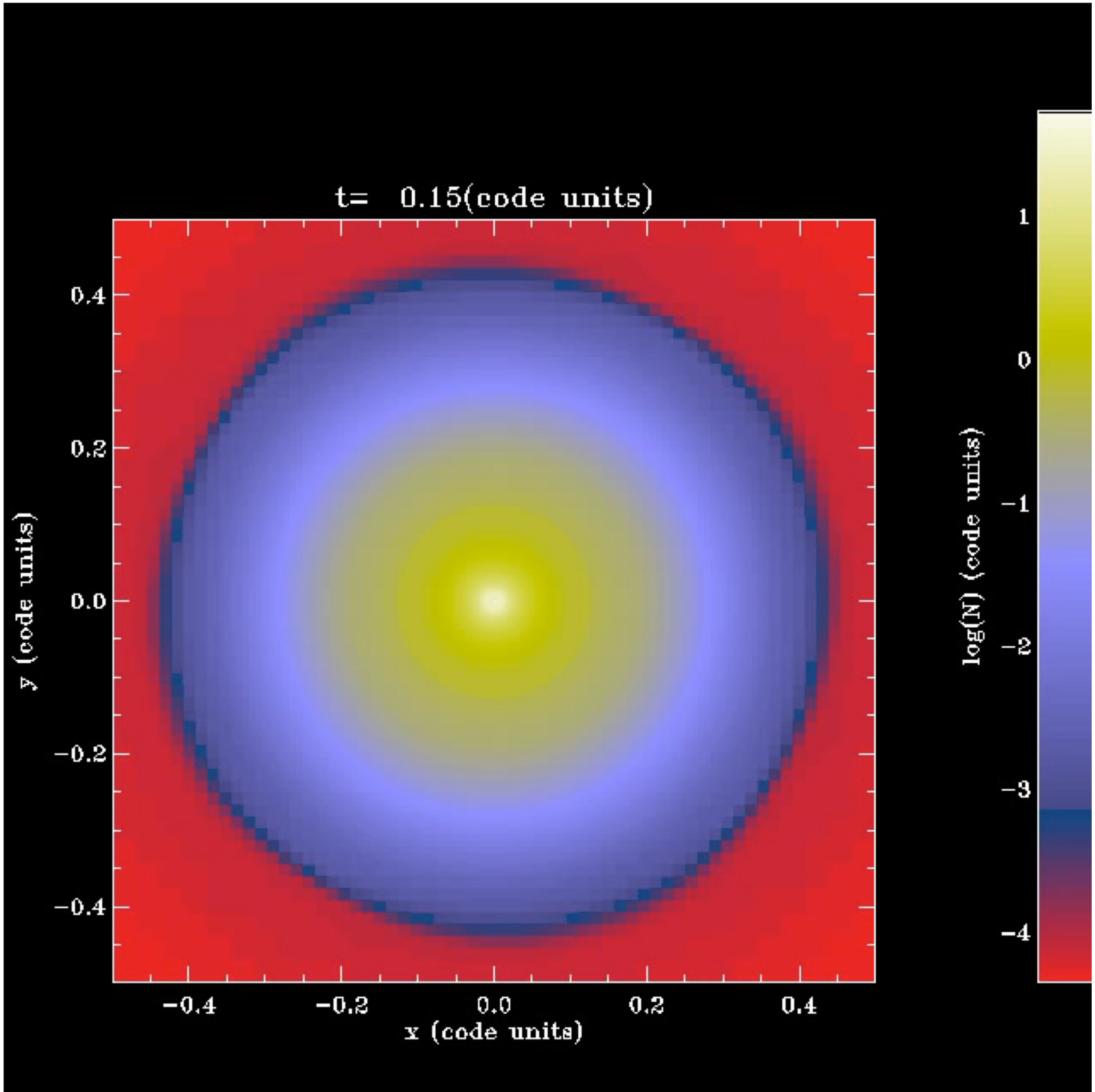
Simulations done with RAMSES (used in nested grid mode)
Cartesian mesh, resolution more tricky (up to h/r ~8 at rd/10)
No "inner" boundary
No explicit viscosity

Parameters:

Accretion rate ($4\ 10^{-7}$ M yr^{-1})
Symmetry of accretion
Angular momentum

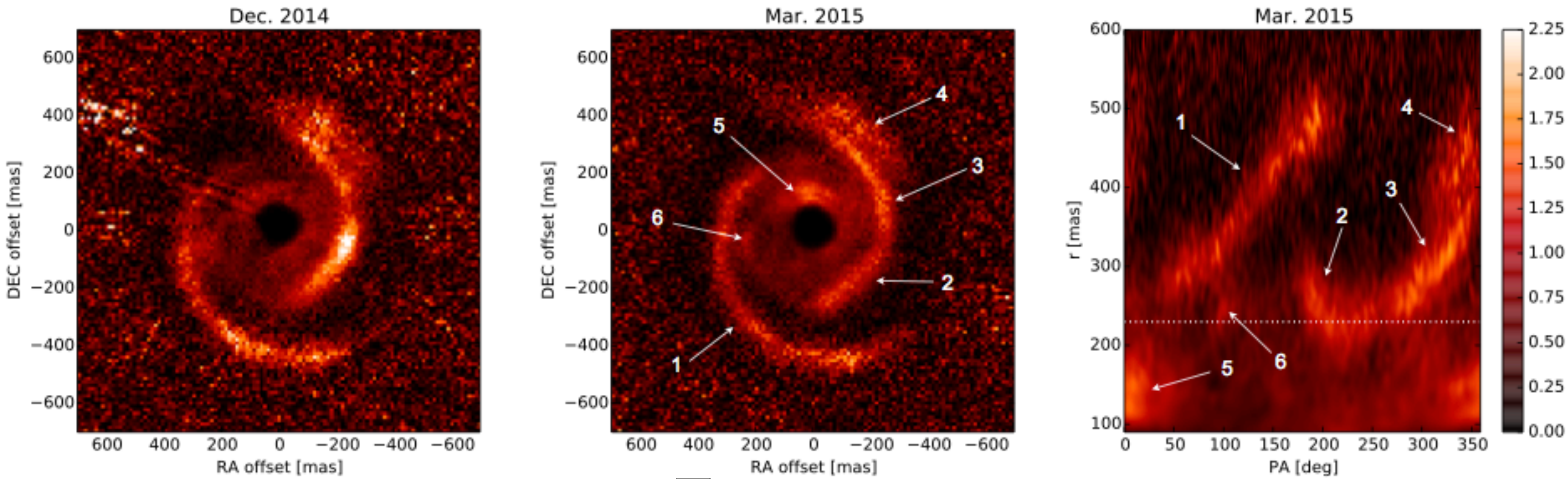


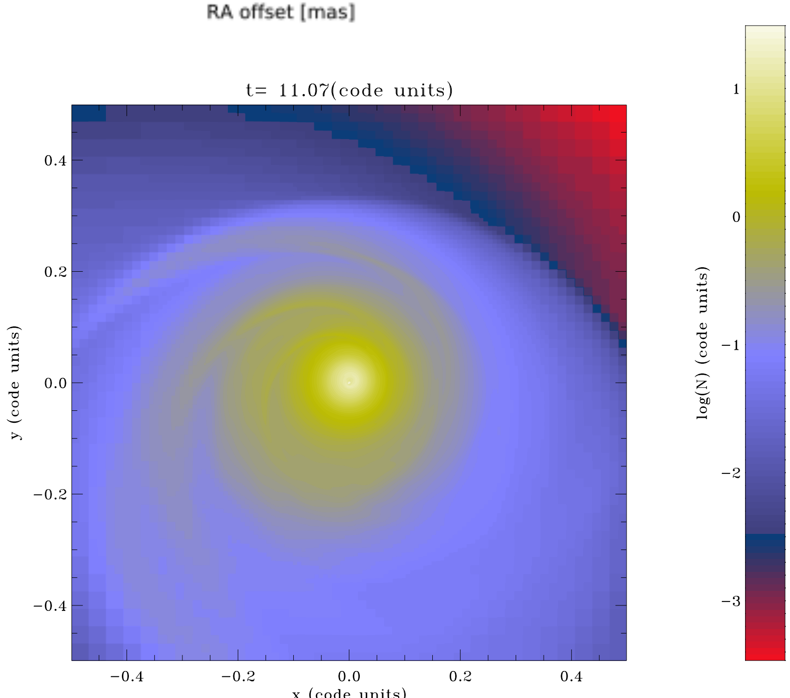
Non-axisymmetric accretion (~4 10^{-7} M yr^{-1} , 10^{-2} solar mass disk)

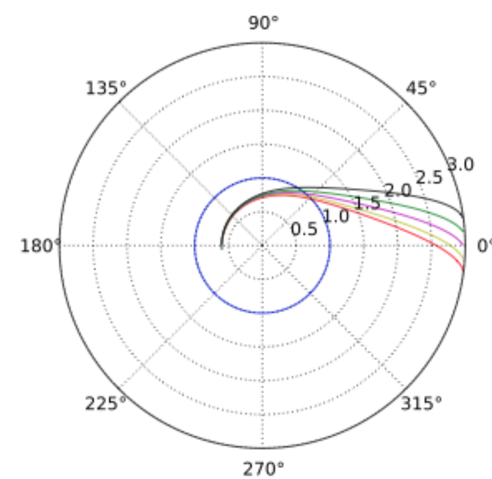


Are these spirals kinematic spirals ?

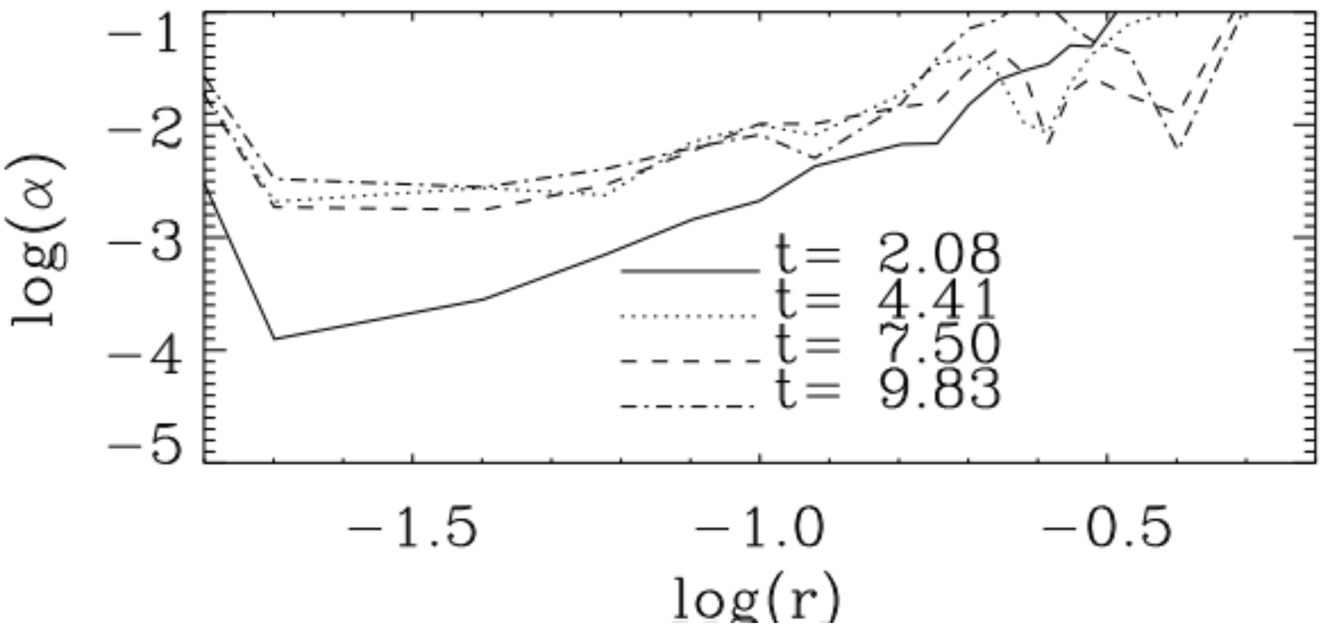
Benisty et al. 2015

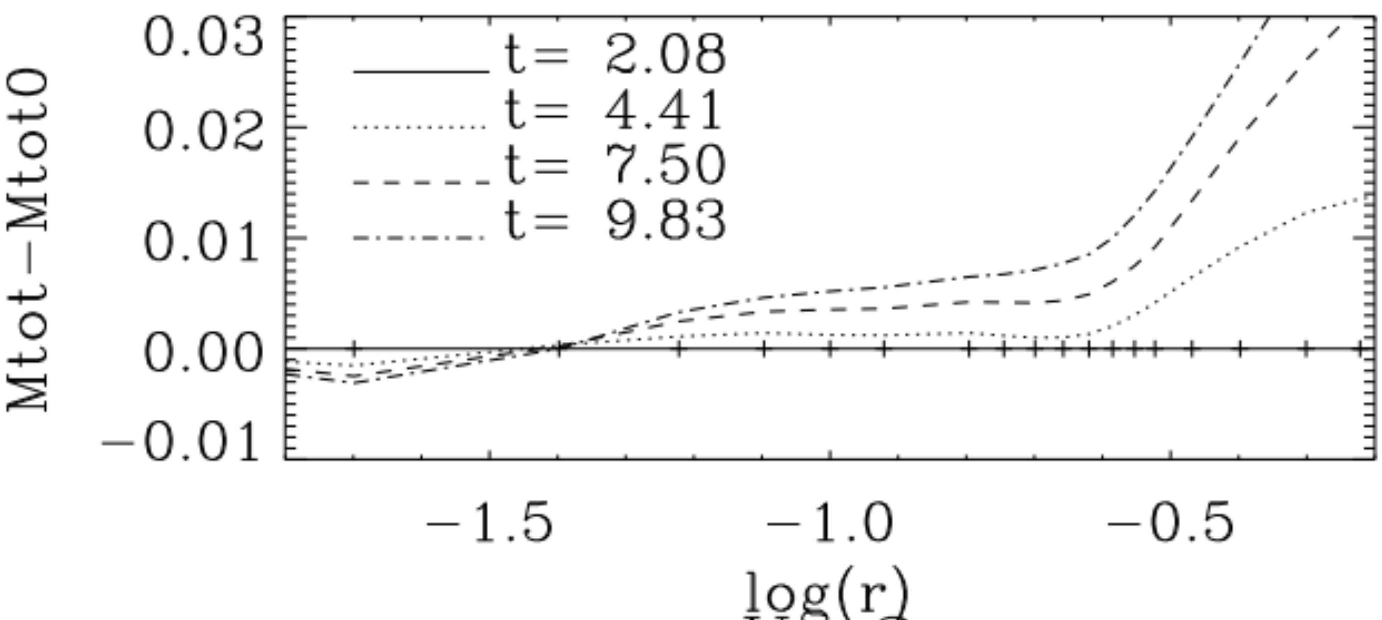




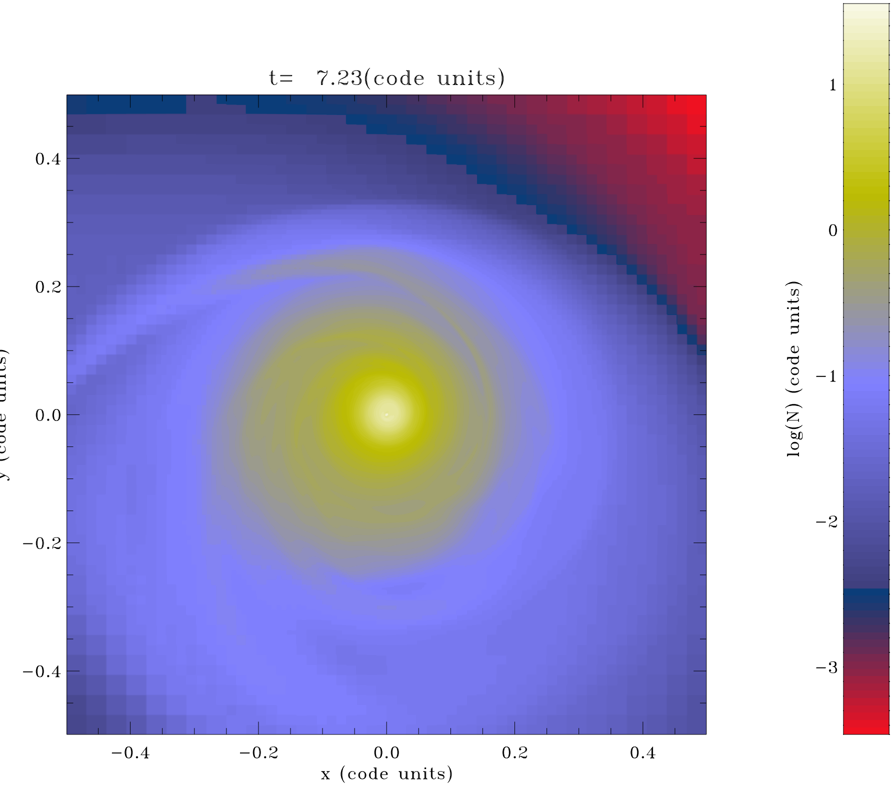


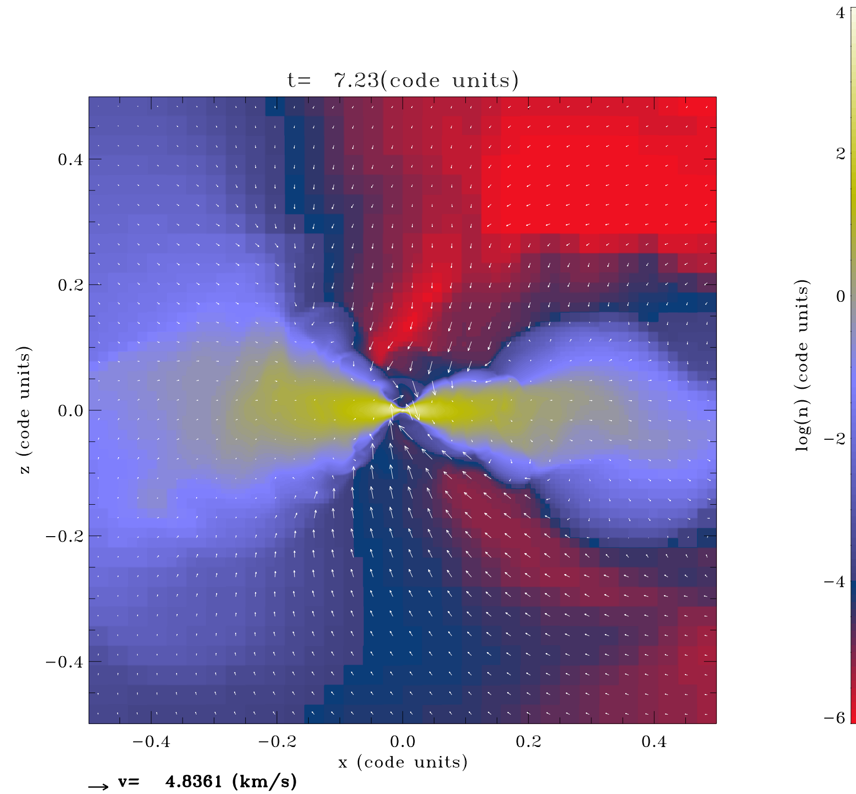
alpha and mass evolution



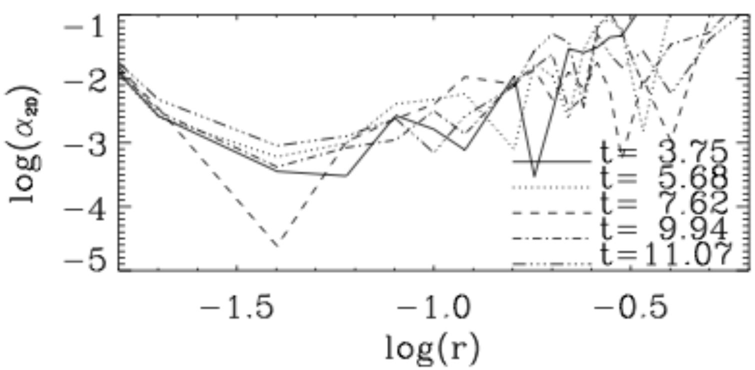


Influence of the z-fluctuations is comparable to the radial ones

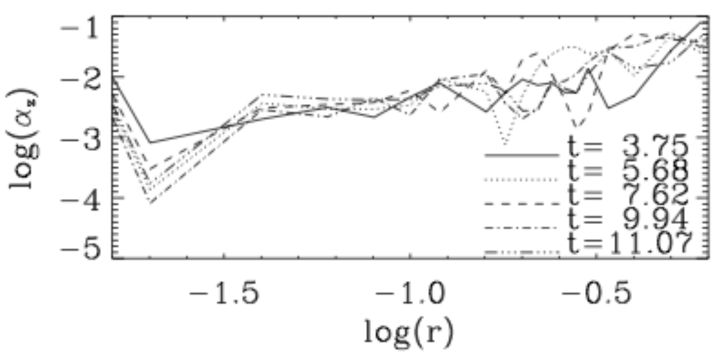




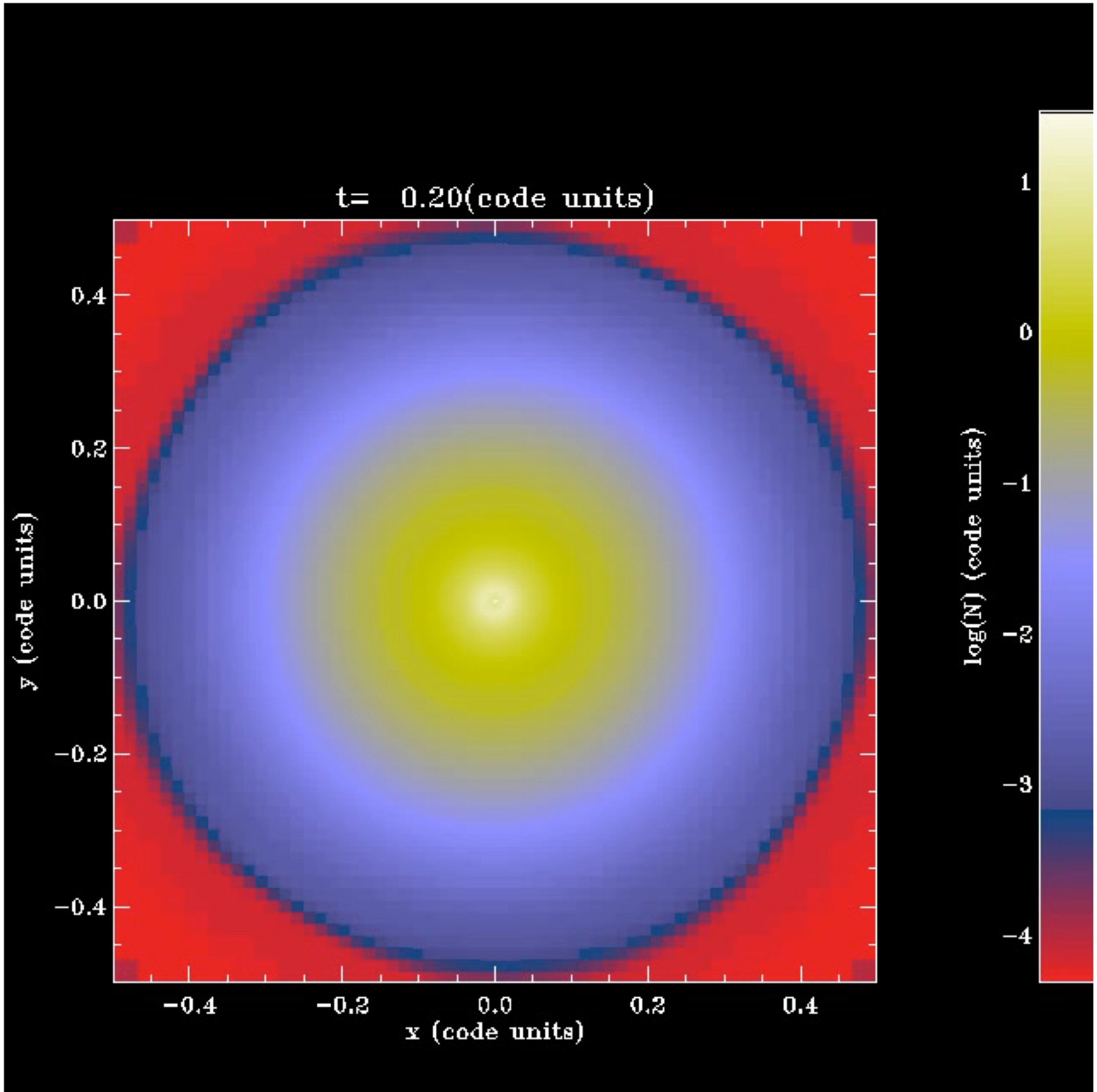
Radial fluctuations



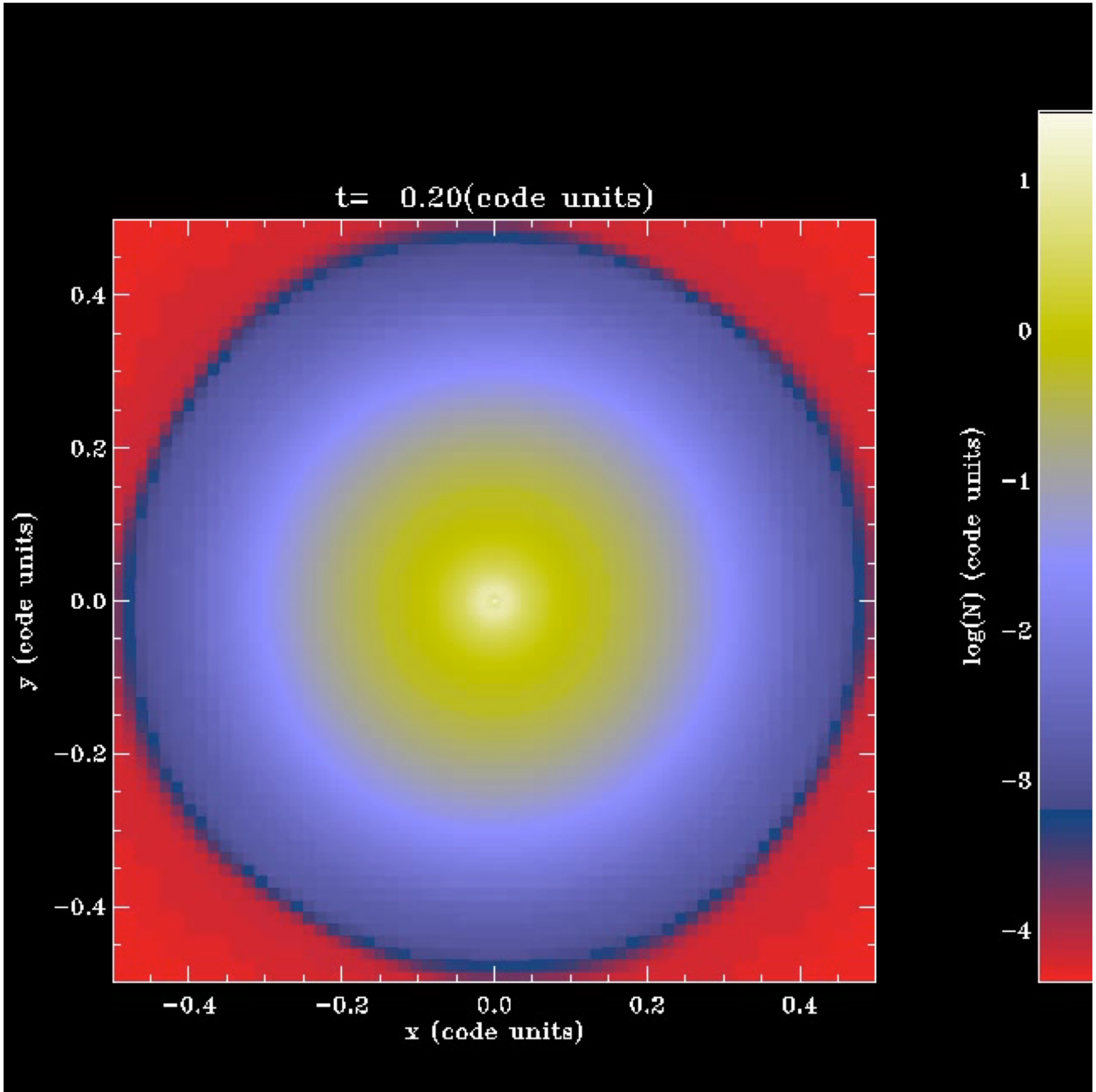
Axial fluctuations



Axisymmetric accretion (~4 10^{-7} M yr^{-1} , 10^{-2} solar mass disk)



Non-axisymmetric accretion (~4 10^{-7} M yr^{-1} , 10^{-2} solar mass disk)
No angular momentum in the accreted gas



Conclusions

Long road ahead to understand disk formation physics
=> need strong synergy between obs and theory and be ready for surprise

Alma observations are on the way. Statistical approach is the way to go.

Magnetic field seems to play a critical role in disk formation, possibly regulating their formation. Non-ideal MHD is important and not well controlled.

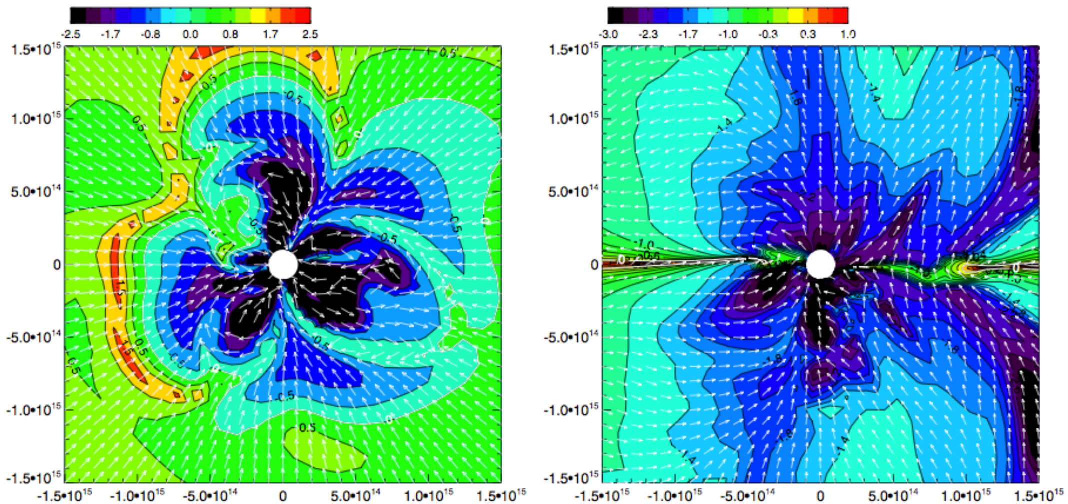
Are late protoplanetary disks accreting and at which rate ?
(we know it is the case at early stage, class-0, and I)

Are the structures (such as spiral arms) seen by observers related to accretion ?
How accretion will couple to other processes (gravity and magnetic field) ?

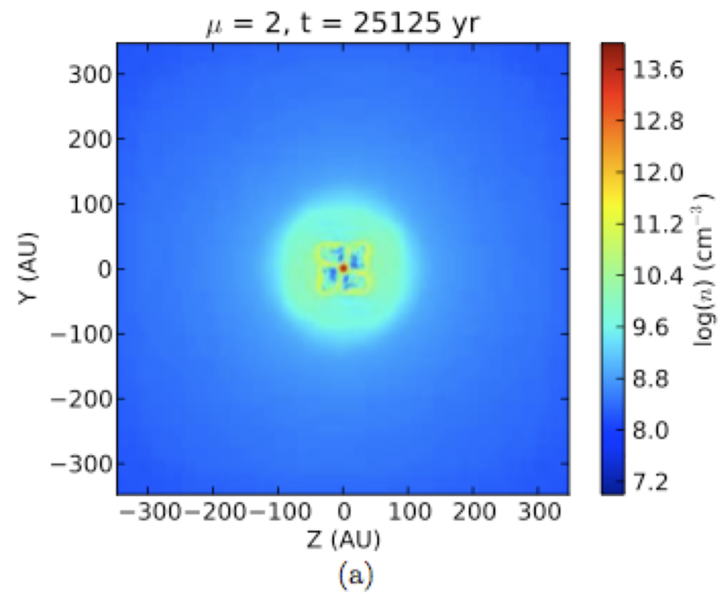
Ideal MHD: undergo the magnetic interchange instability (due to flux pilling in the center)

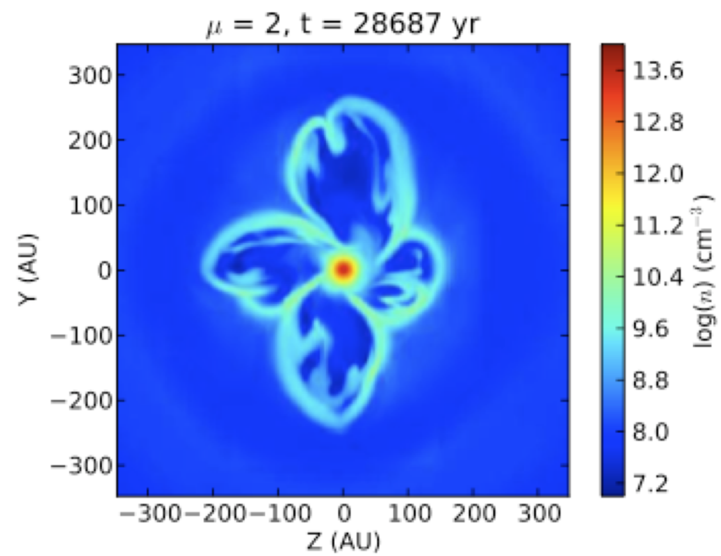
(Fromang+2006, Banerjee&Pudritz+2007, Joos+2012, Krasnopolsky+2014, Li+2014)

Krasnopolsky+2014



200 AU





Joos et al. 2012

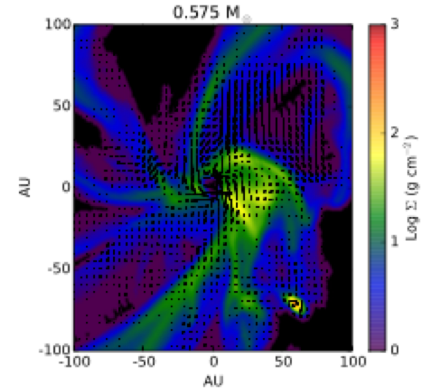
Turbulence induces both diffusion and misalignment.

Which one is dominant ?

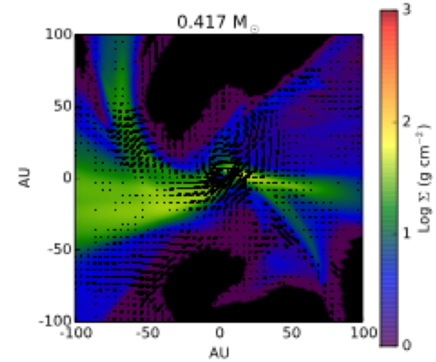
Gray+2017 run simulations with turbulence but manage to impose the angle between B and J (adjusting the mean J in concentric shells)

They concluded that:

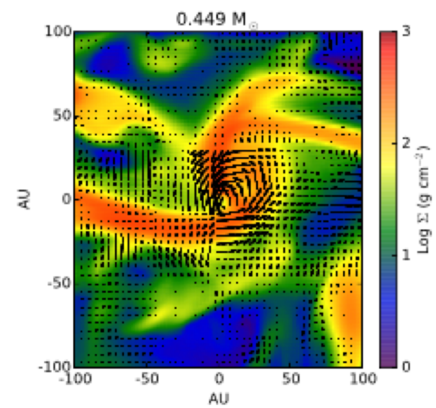
the dominant effect is the misalignment



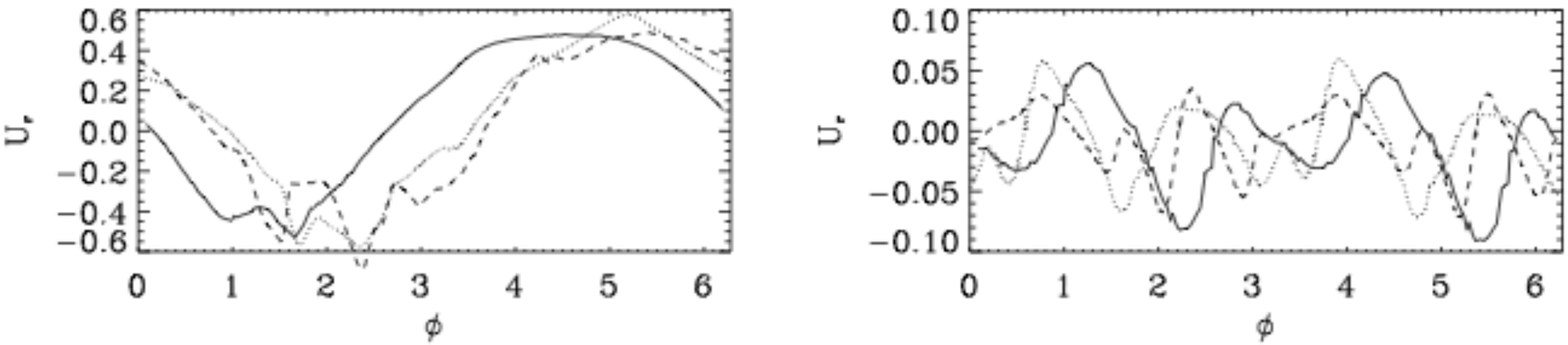
J//B



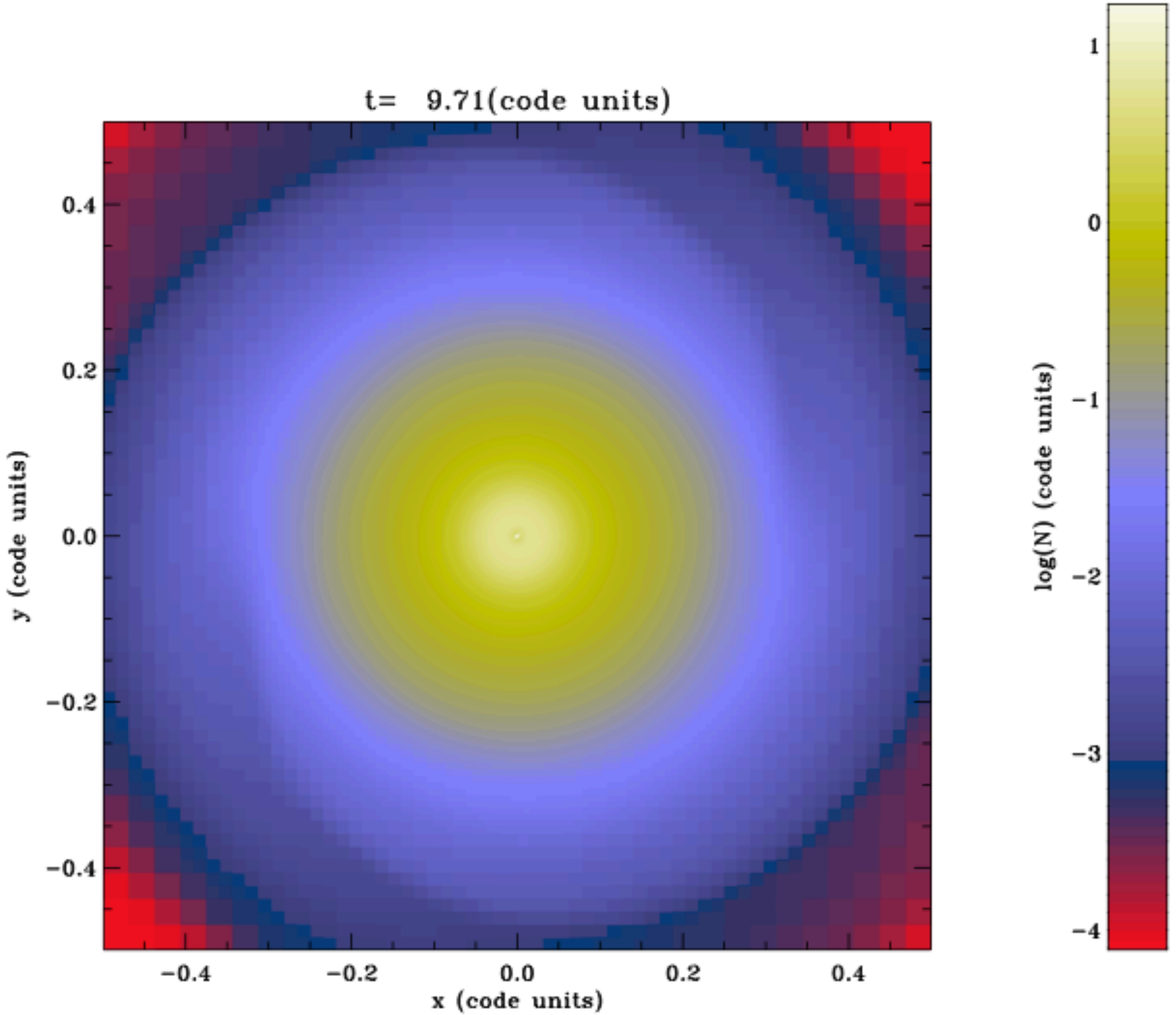
random
J and B

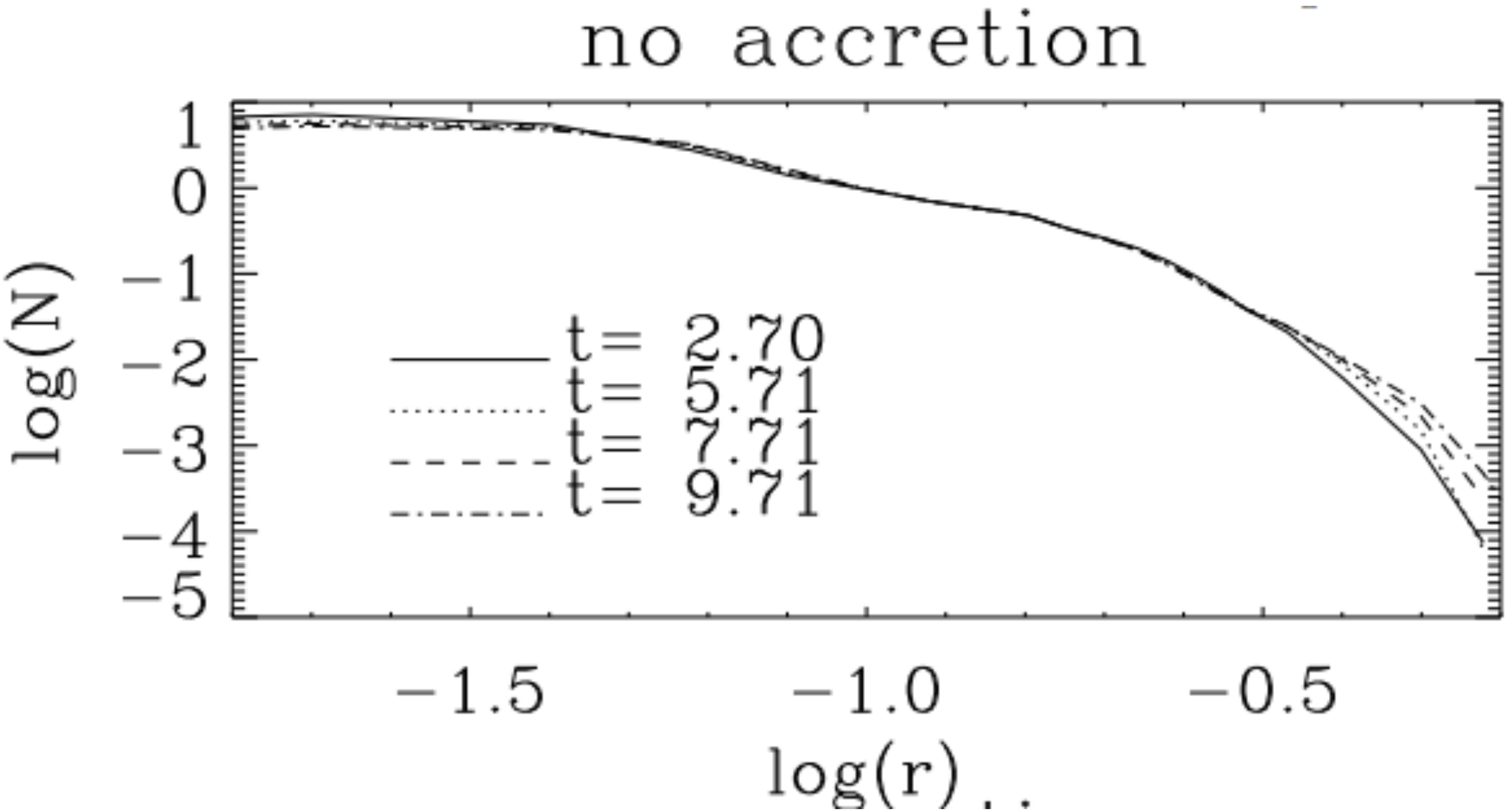


J.B=35 degree

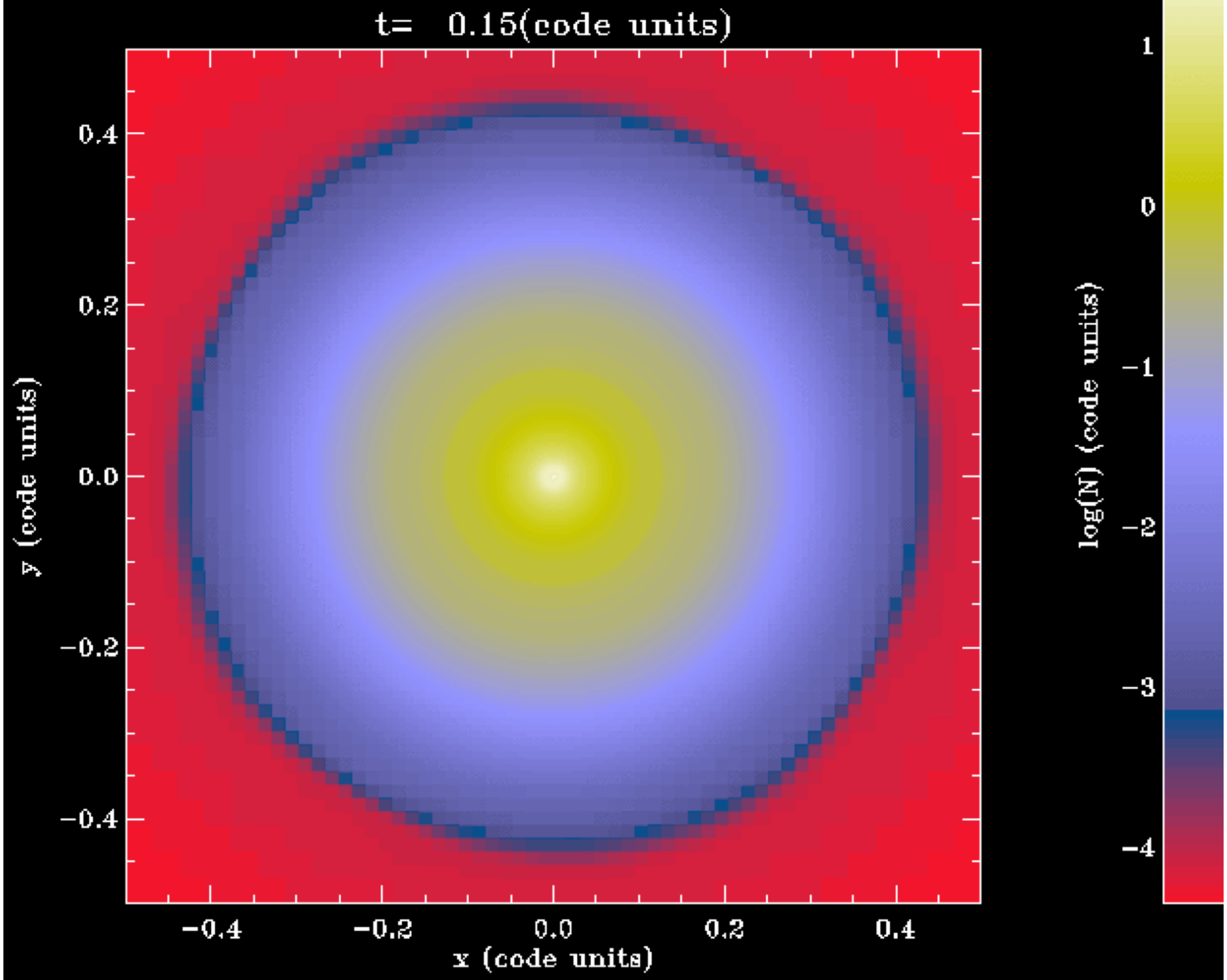


0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
U r
0
1
2
3
4
5
6
ϕ
0.10
0.05
0.00
−0.05
−0.10
U r
0
1
2
3
4
5
6
ϕ


t= 9.71(code units)
y (code units)
x (code units)
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
log(N) (code units)
1
0
−1
−2
−3
−4



no accretion
log(N)
1
0
−1
−2
−3
−4
−5
t= 2.70
t= 5.71
t= 7.71
t= 9.71
−1.5
−1.0
−0.5
log(r)


t= 0.15(code units)
0.4
0.2
0.0
−0.2
−0.4
y (code units)
−0.4
−0.2
0.0
0.2
0.4
x (code units)
1
0
−1
−2
−3
−4
log(N) (code units)

Conclusions

Magnetic field controls disk formation, hydro models not realistic enough

Magnetic braking “catastrophe”: a product of theoretical oversimplification.

Non-ideal MHD is crucial for disc formation but uncertainties

Analytical models and simulations suggest weak dependence on rotation, turbulence and magnetic field
=> Magnetically self-regulated disk formation

Alma observations are on the way. Statistical approach is the way to go.