Disk formation during star formation in (**non-ideal**) RMHD simulations

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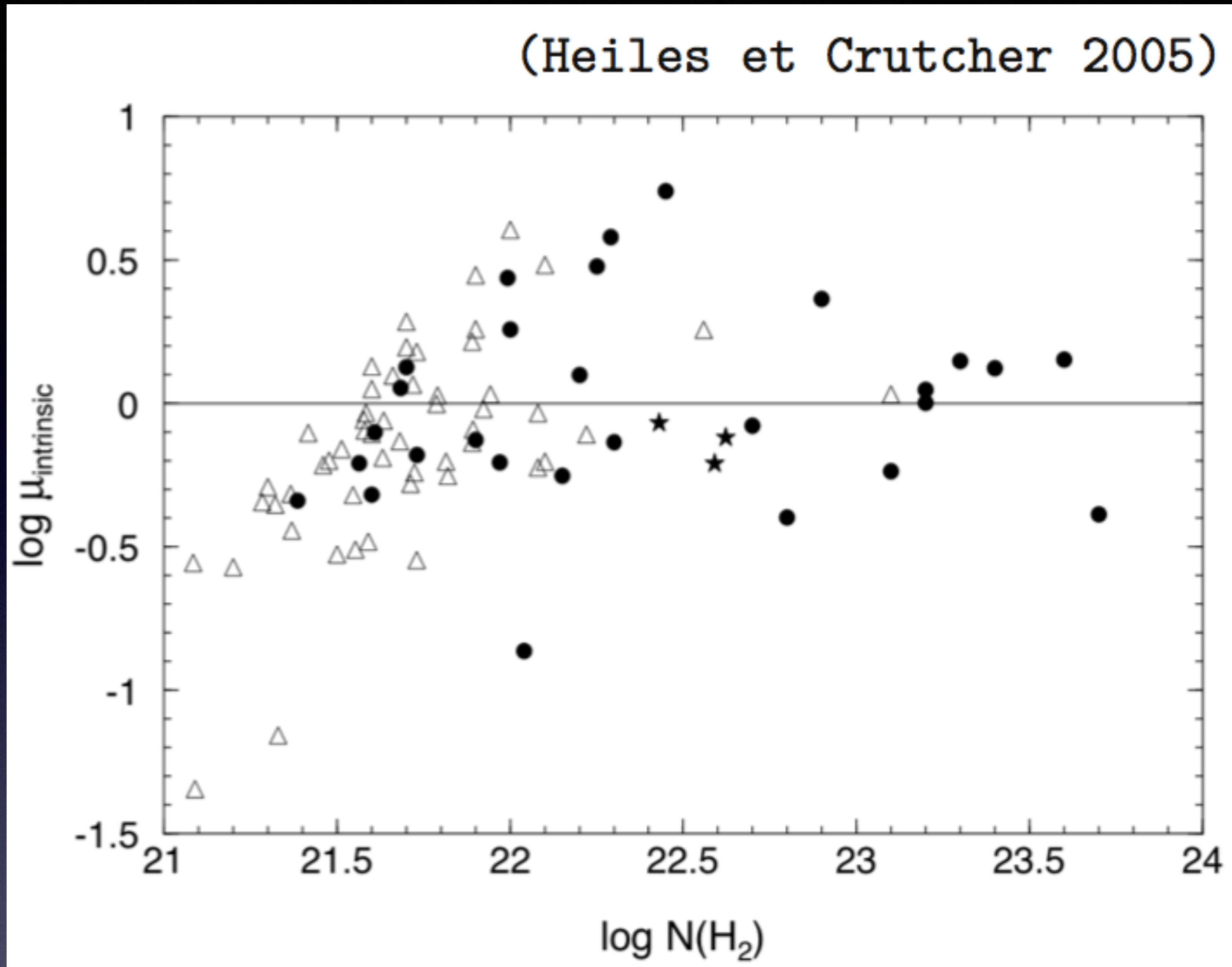
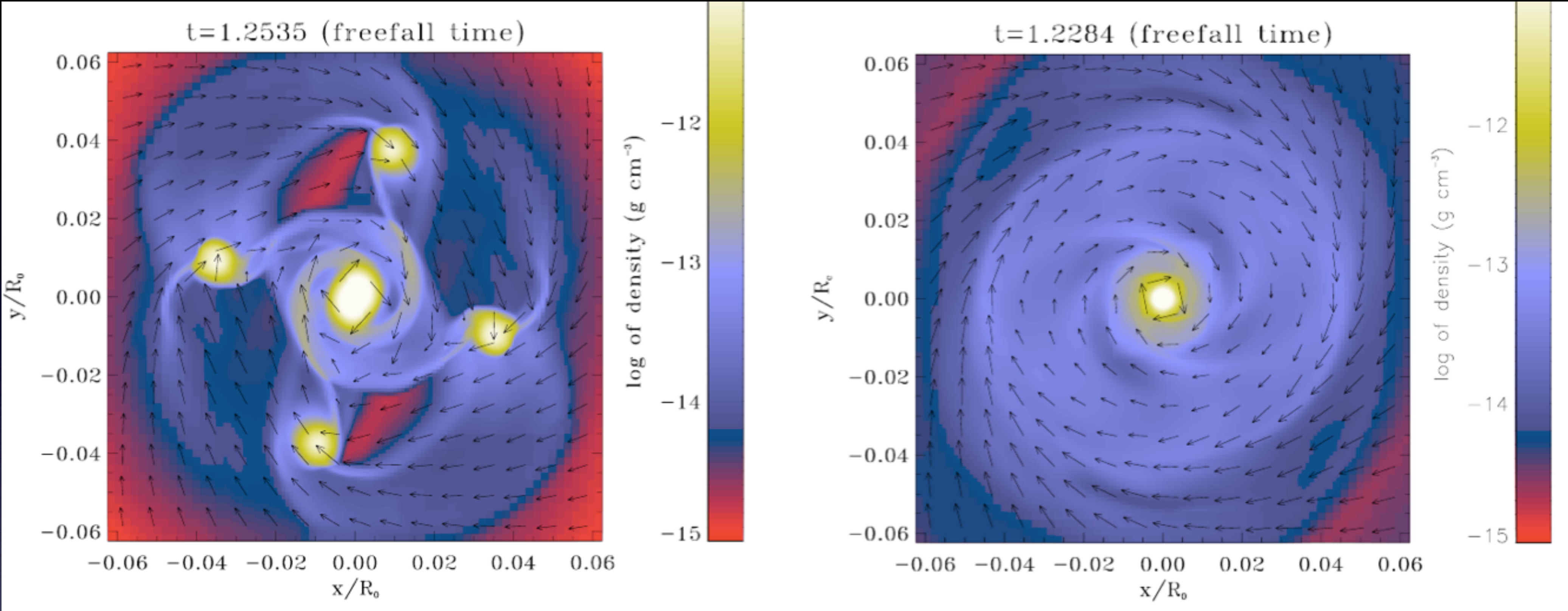
$$\mu = \frac{\left(\frac{M}{\Phi}\right)}{\left(\frac{M}{\Phi}\right)_{crit}} \approx 2$$



$$\rho \frac{D\boldsymbol{v}}{Dt} = -\boldsymbol{\nabla}\left(P + \boxed{\frac{B^2}{2\mu_0}}\right) - \rho \boldsymbol{\nabla}\Phi + \boxed{\left(\frac{\boldsymbol{B}}{\mu_0}\cdot\boldsymbol{\nabla}\right)\boldsymbol{B}}$$

Hydro | IMHD



Hennebelle & Teyssier (2008)

too large and massive disks
too much frag'n

No disk !

- Moment angulaire ωr^2
- Flux magnétique $\phi_B \propto B r^2$

$$\partial_t \mathbf{B} = \nabla \times \left[\boxed{\mathbf{v_n} \times \mathbf{B}} - \boxed{\frac{\mathbf{J} \times \mathbf{B}}{e n_e}} + \boxed{\frac{[(\nabla \times \mathbf{B}) \times \mathbf{B}] \times \mathbf{B}}{\gamma_{\mathrm{AD}} \rho \rho_i}} - \boxed{\frac{\mathbf{J}}{\sigma}} \right]$$

Induction Hall Ambipolaire Ohm

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\mathbf{v} \times \mathbf{B} \boxed{-\eta_\Omega} (\nabla \times \mathbf{B}) \boxed{-\eta_H} \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{B} \right\} \boxed{-\eta_{AD}} \frac{\mathbf{B}}{B} \times \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{B} \right\} \right]$$

$$Z e n_i (\mathbf{E} + \mathbf{v_i} \times \mathbf{B}) - \rho_i \sum_{j=e,n} \nu_{ij} (\mathbf{v_i} - \mathbf{v_j}) = 0$$

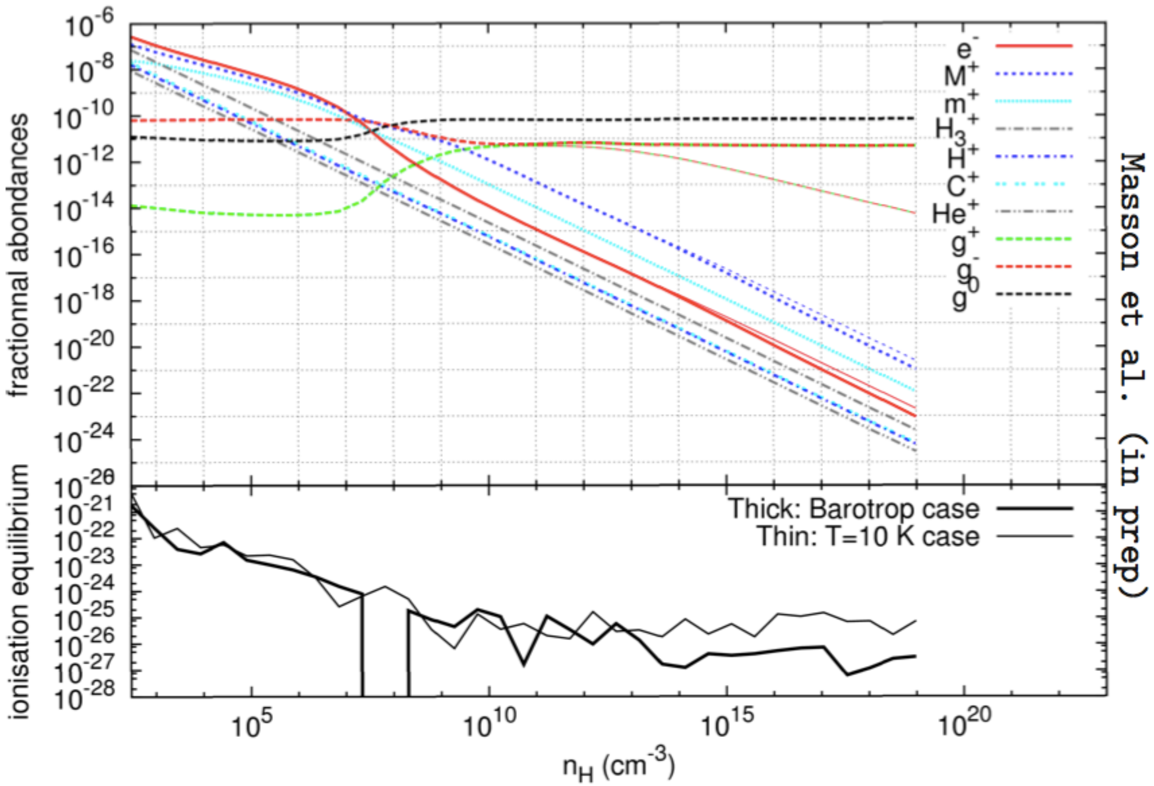
$$-e n_e (\mathbf{E} + \mathbf{v_e} \times \mathbf{B}) - \rho_e \sum_{j=i,n} \nu_{ej} (\mathbf{v_e} - \mathbf{v_j}) = 0$$

avec $\nu_{\mathbf{kj}} = \rho_j \gamma_{kj} = \rho_j < \sigma v >_{kj} (m_j + m_k)^{-1}$

$$\mathbf{E} + \left[\mathbf{v} + (\mathbf{v_e} - \mathbf{v_i}) + (\mathbf{v_i} - \mathbf{v}) \right] \times \mathbf{B} + \frac{n_n m_e < \sigma_{en} v_e >}{e} \left[(\mathbf{v_e} - \mathbf{v_i}) + (\mathbf{v_i} - \mathbf{v}) \right] = 0$$

Soit, avec : $\gamma_{\mathrm{AD}} = \frac{<\sigma_{in} v_i>}{(m_i + m_n)}$ et $\sigma = \frac{n_e e^2}{n_n m_e <\sigma_{en} v_e>}$

$$\begin{cases} \dots \\ \frac{dx_i}{\tilde{d}t} = \sum_{j=1}^N \left[\alpha_{ij} x_j + \frac{n_H}{2\zeta} \sum_{k=1}^N \beta_{ijk} x_j x_k - \frac{n_H}{\zeta} \gamma_{ij} x_j x_i \right] \\ \dots \end{cases}$$



$$\sigma_{\parallel} = \sum_s \sigma_s$$

$$\sigma_{\perp} = \sum_s \frac{\sigma_s}{1 + (\omega_s \tau_{sn})^2}$$

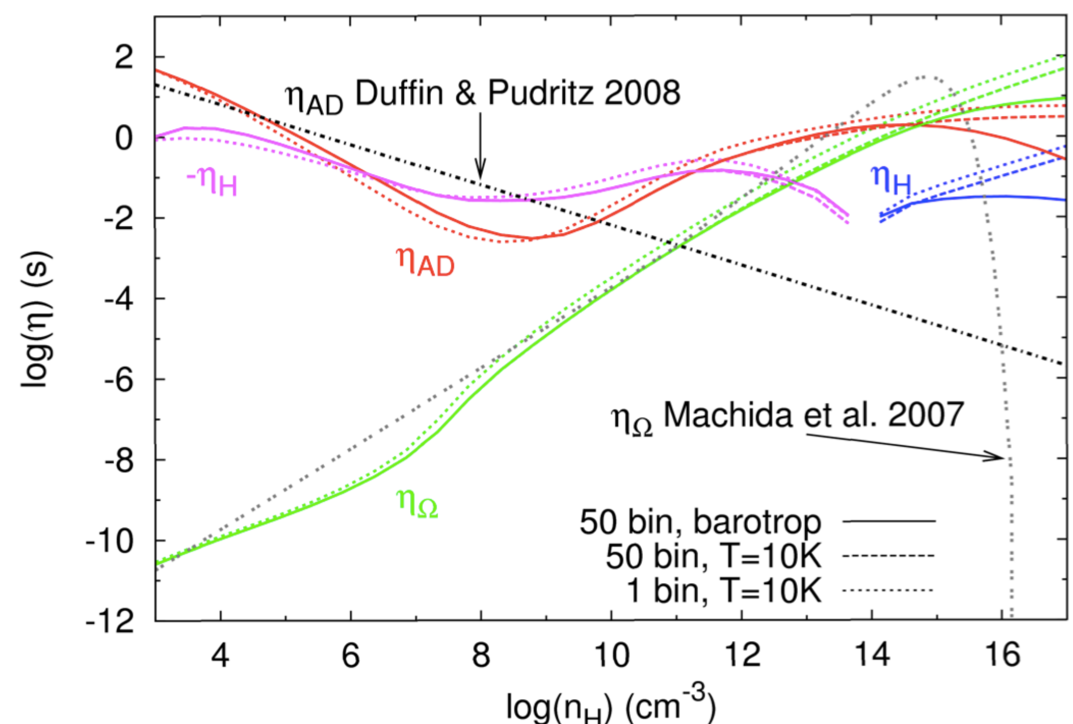
$$\sigma_H = -\sum_s \frac{\sigma_s \omega_s \tau_s n}{1 + (\omega_s \tau_{sn})^2}$$

avec

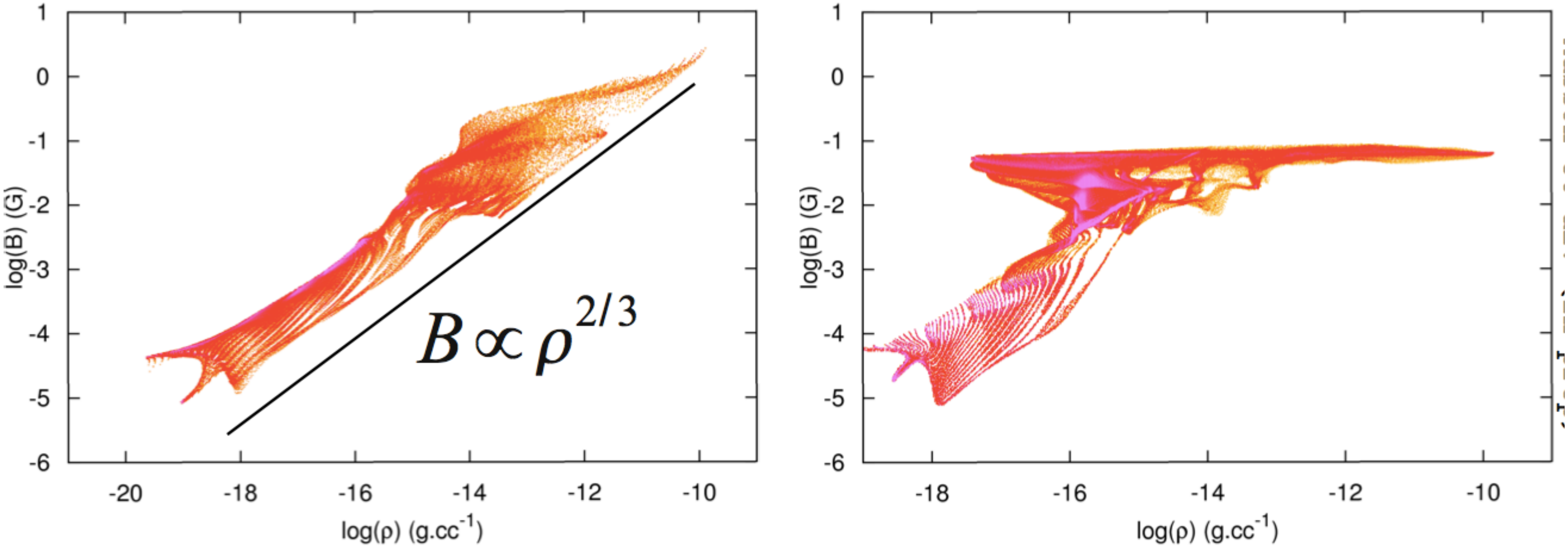
$$\sigma_s = \frac{n_s q_s^2 \tau_{sn}}{m_s}$$

$$w_s = \frac{q_s B}{m_s c}$$

$$\tau_{sn} = \frac{1}{a_{sH_e}} \frac{m_s + m_{H_2}}{m_{H_2}} \frac{1}{n_{H_2} < \sigma_{coll} w >_{sH_2}}$$



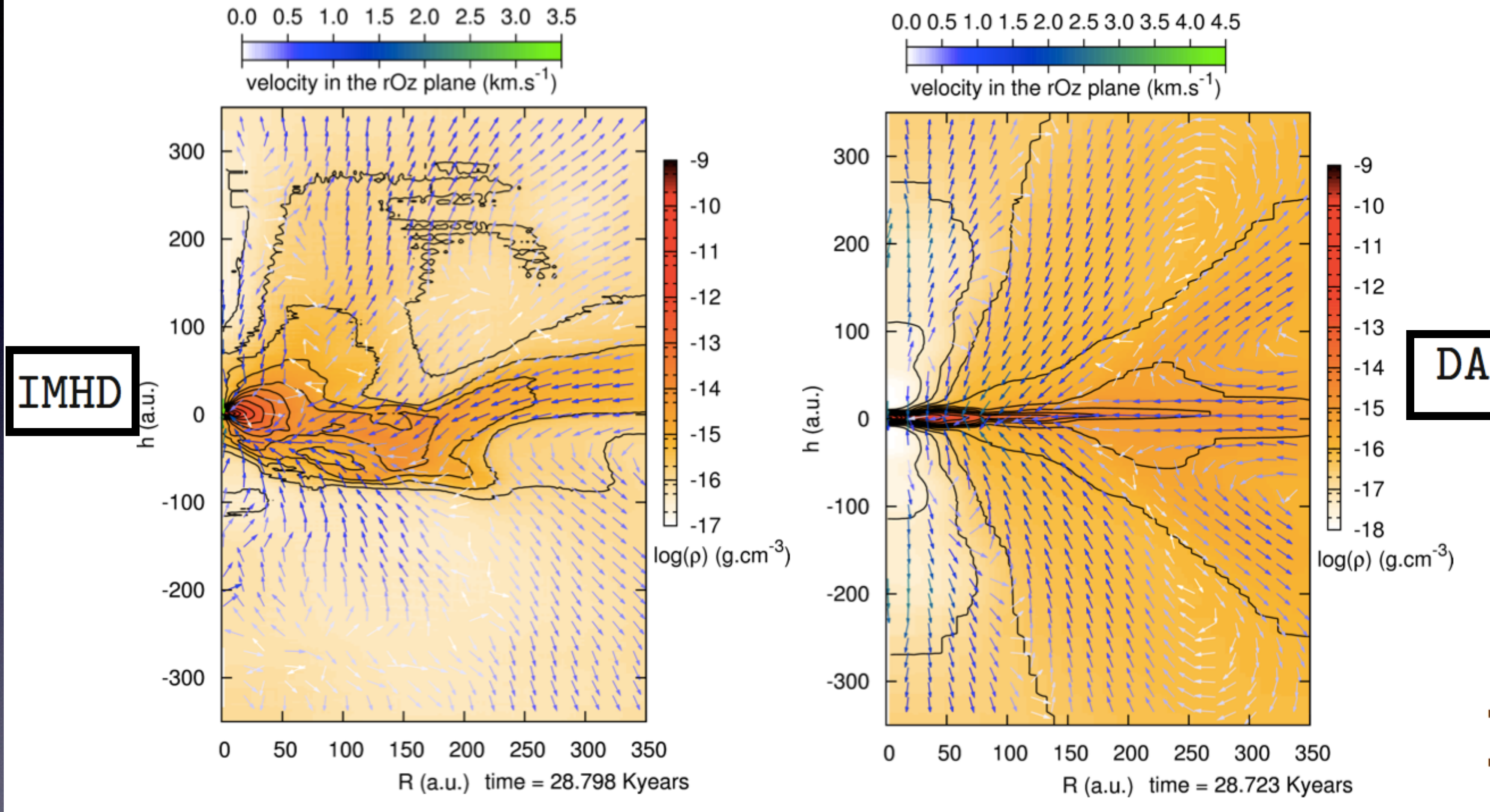
Masson et al., 2012, ApJS
Masson et al., 2014, in prep.



IMHD

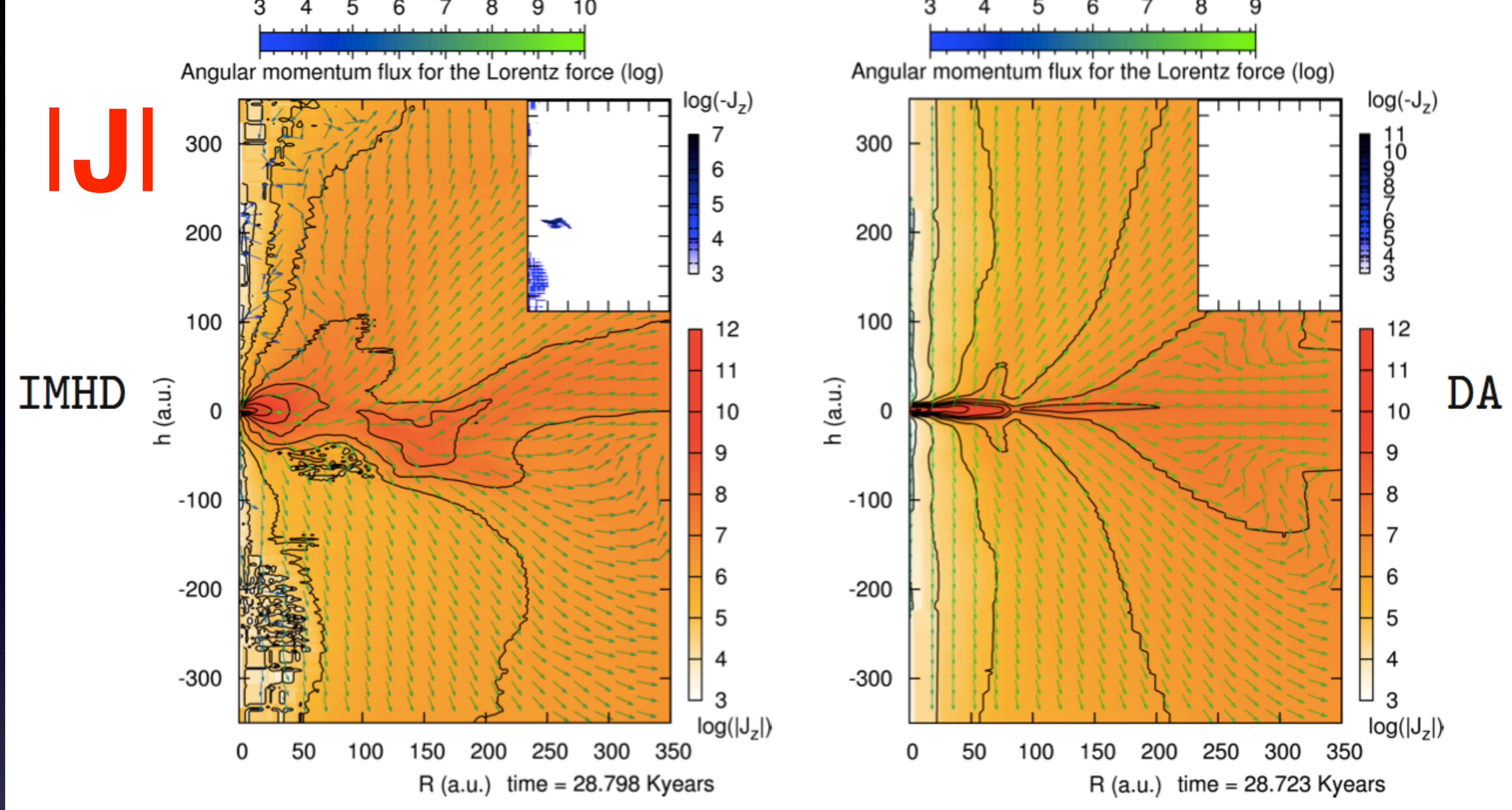
AD

- Rotation, Mach=0, $\mu=5$

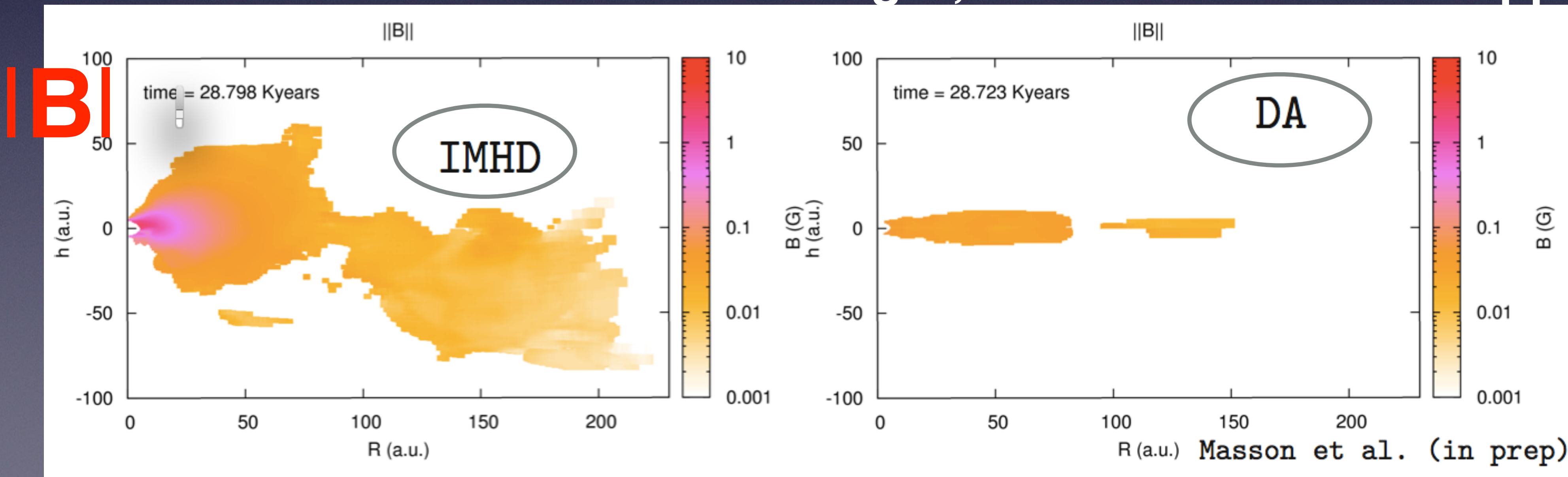


pile-up of B_ϕ
strong outflow
interchange instability

Disk formed within ~ 6 kyr after collapse

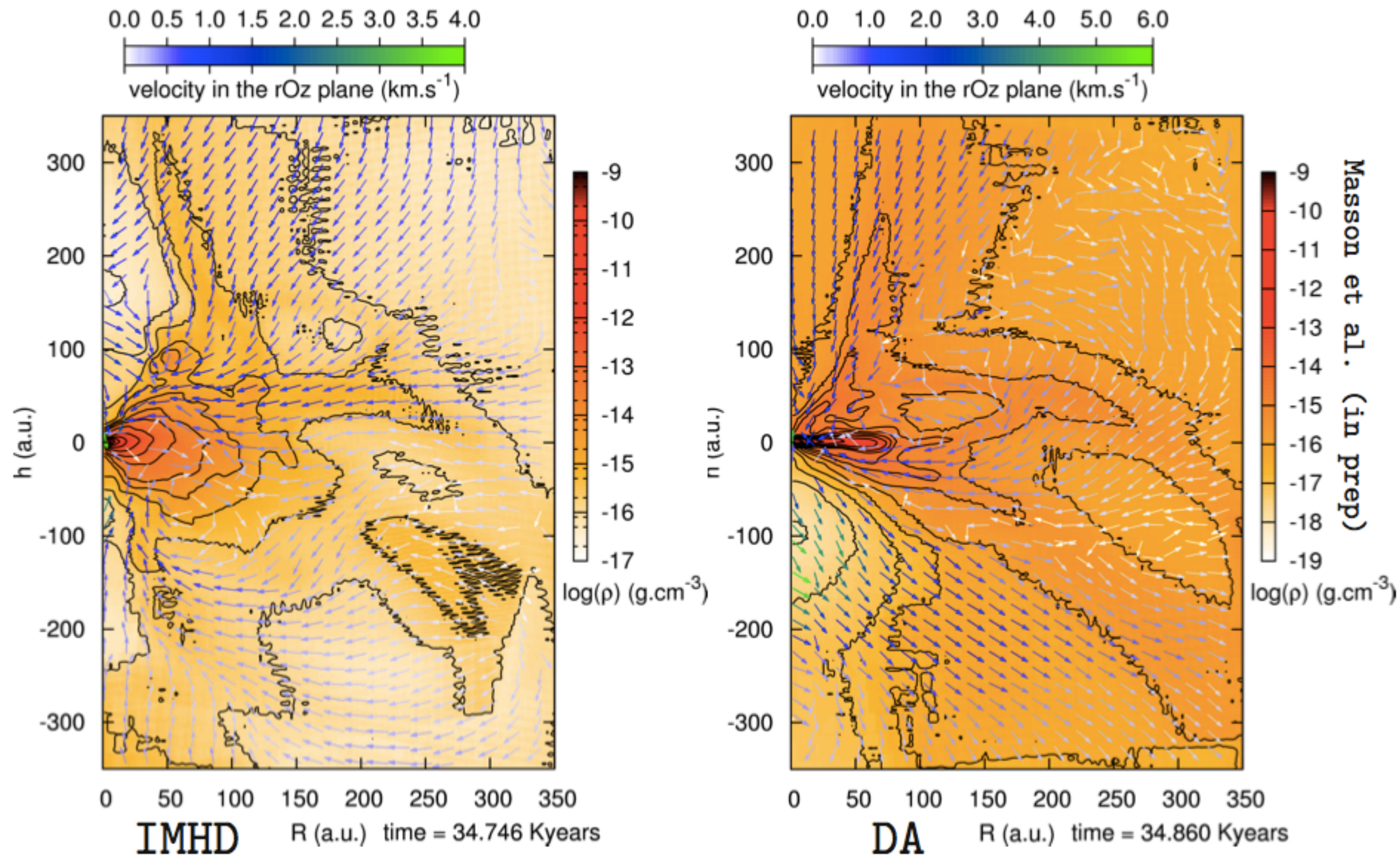


J~10x larger; increase rotational support



strong (toroidal) mag. support ~B/100; negligible mag. support; less B-bking

- Turbulence, Mach=0.9, $\mu=2$



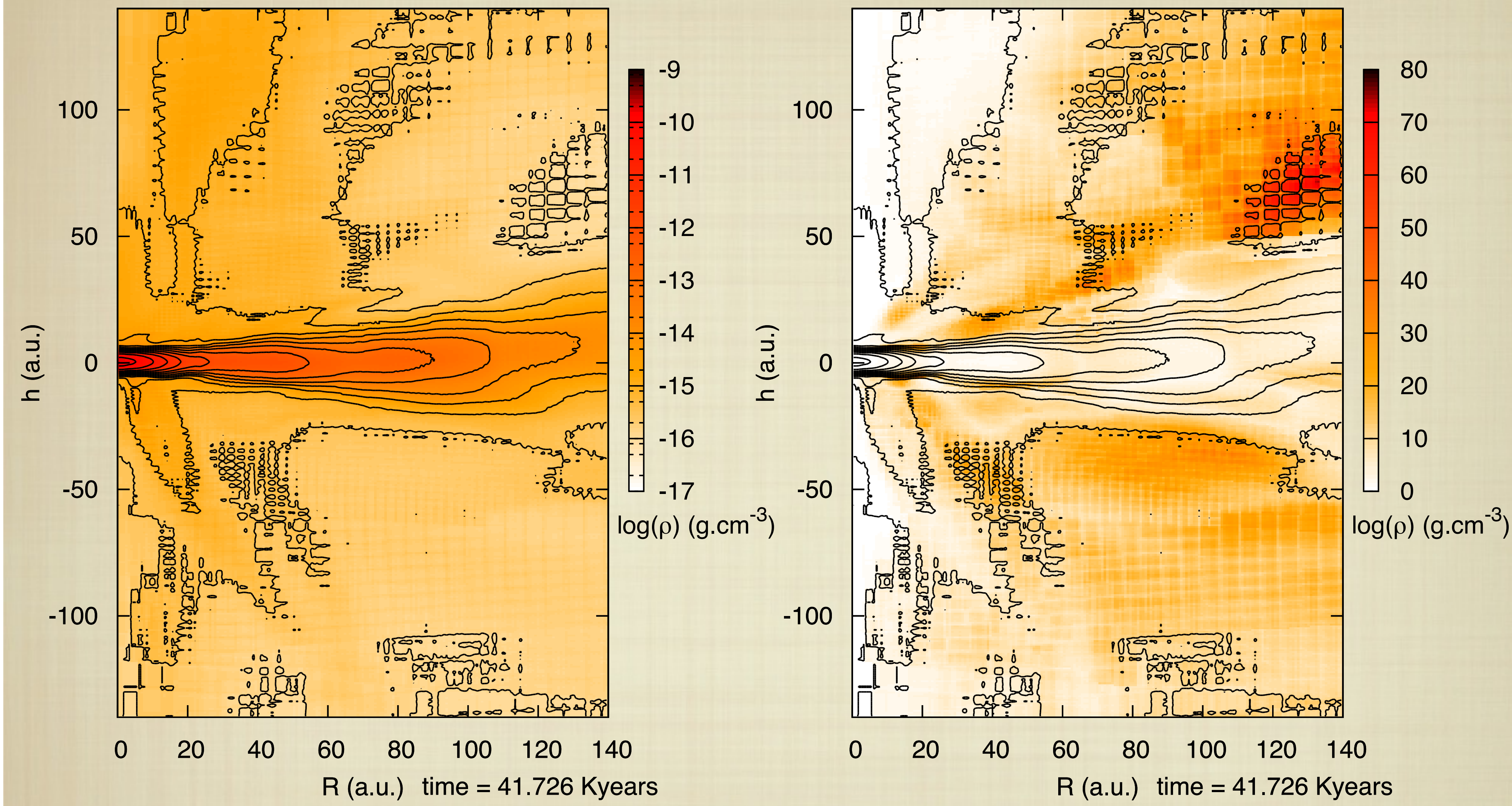
decreases growth of B_ϕ ; induces magnetic reconnection

=> **decreases further magnetic breaking**

less small-scale org'n in J; generates large scale ordered flows : turbulence diffusivity

affects the accretion history

Is the disk stable ?

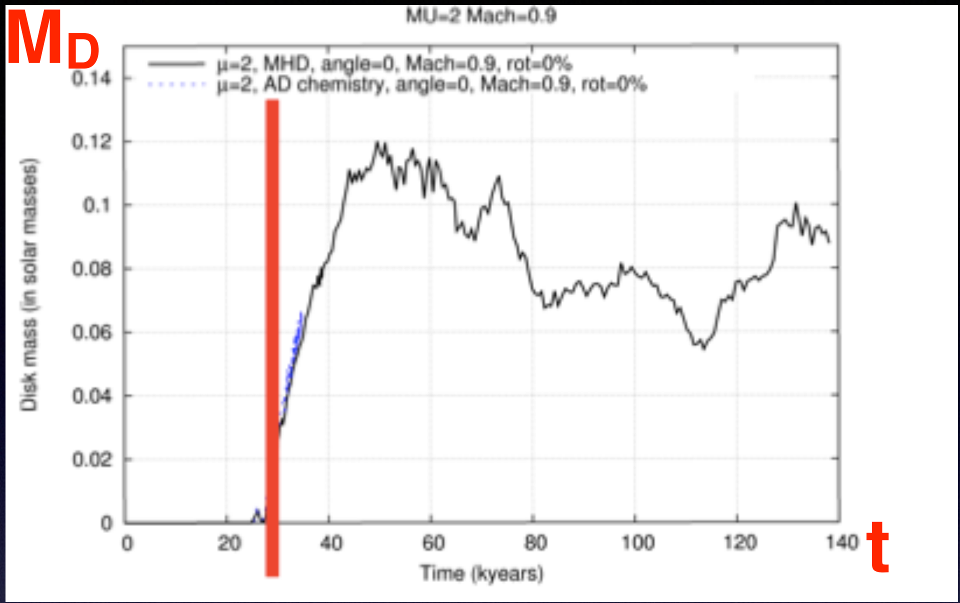


μ=2

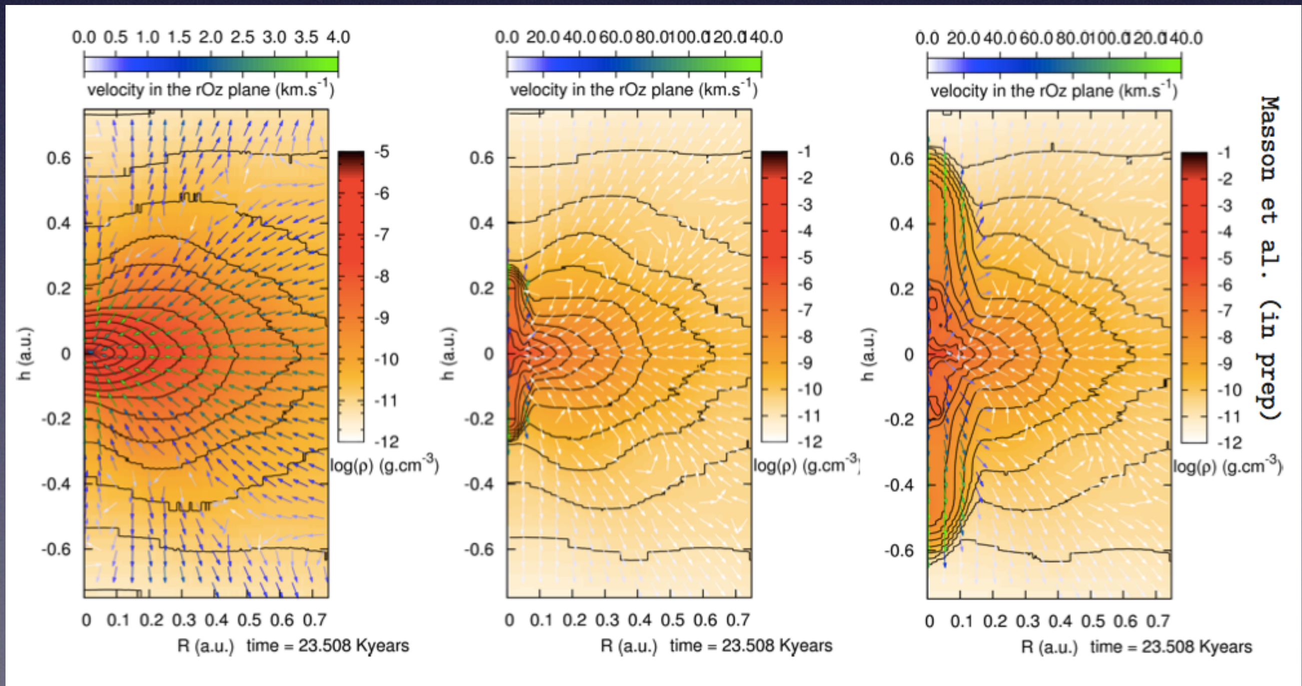
$$M_{disk} \sim 0.08\, M_{\odot}$$

$$R_{disk} \sim 100\, a.u.$$

Why don't we see (many) extended disks ?



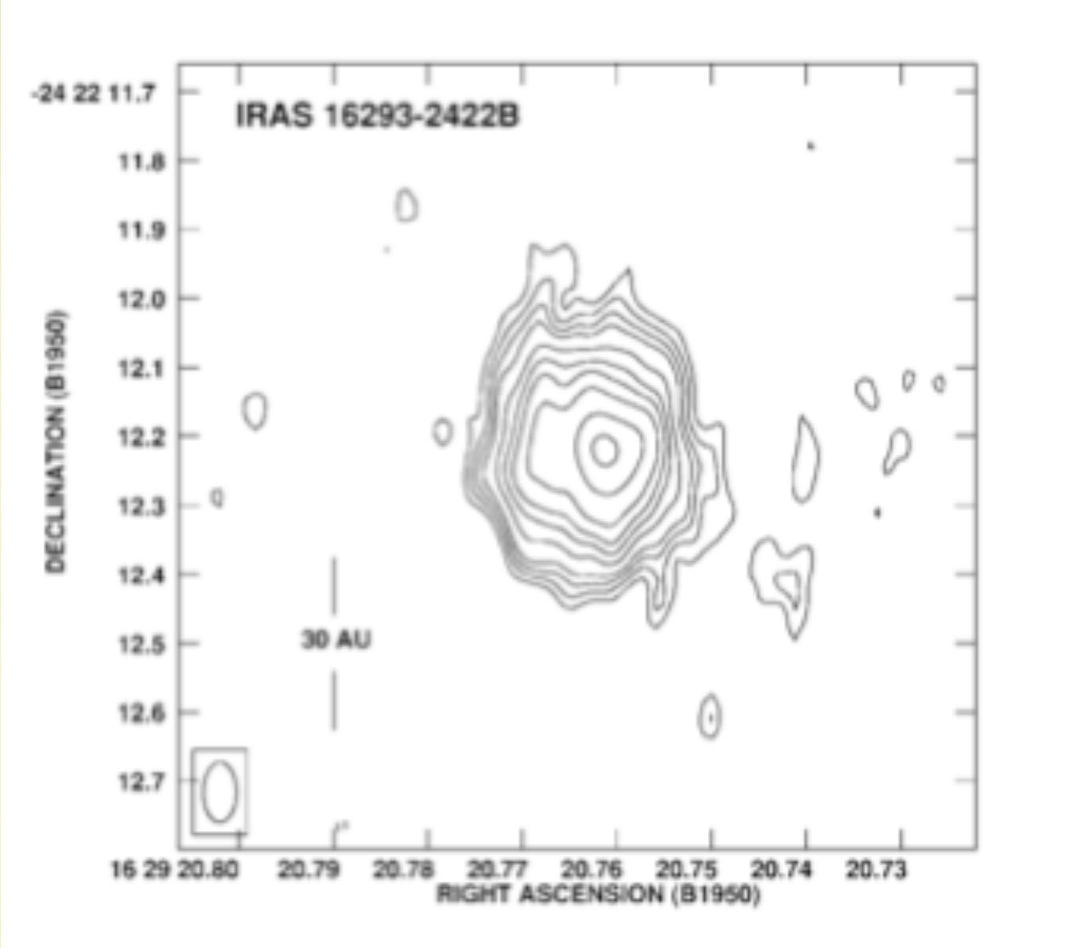
2nd core forms in ~100 yr when disk ~ 20 a.u.



powerful jet

V_{jet} ~ 38 a.u./yr : reaches the 1st core accretion shock in <1 yr

Rodriguez et al. '05



<u>Isolated</u>, massive, <u>compact</u> (R_{out}~20 AU) disk around class 0 consistent w/ MHD disks !

- AD (1st core) + Ohm (2nd core) : help diffusing the flux (B< ~0.1 G).
-Affects angular momentum evolution => decreases B-breaking => increases rotational support => *helps forming rotationally supported disks*
-Affects mass loss / accretion history : decreases pile-up of toroidal B at small scales (< 10 a.u.) => lower magnetic tower near the central objects => *smaller outflows*

- AD smoothes out density gradients => *suppresses interchange instability and counter-rotation*

- occurs very quickly after the 1st core f'n => **determines the I.C. for 2nd collapse**

- **turbulence** + AD :
- increases further the effect of AD (diffusivity, reconnection)
- yields less organized structures => affects accretion history

- M_{disk} ~ 0.1 $M_{central}$ « stability » depends on magnetization

- disks probably **truncated at ~20 a.u. at the <u>1st core stage</u>** by f'n of the 2nd core
- might be **more extended** (but NOT necessarily massive !) **at the <u>2nd core stage</u>** (and definitely grow with time !) and might get « clumpy » (=> episodic acc'n) because most of the flux has been lost at 1st core stage

Gravitational Instability does NOT imply existence of bound fragments !

Fragmentation + GI

High T needed for short cooling:

$$c_s^6 > \frac{\Sigma\Omega}{3\sigma}\left(\frac{k}{\mu}\right)^4$$

Fragmentation condition $\Omega t_c < 3$ then sets a lower limit on c_s:

$$\boxed{\left[\frac{\Sigma\Omega}{3\sigma}\left(\frac{k}{\mu}\right)^4\right]^{1/6} < c_s}$$

Instability requires

$$Q = \frac{\Omega c_s}{\pi G \Sigma} < 1$$

This sets an upper limit on c_s:

$$\boxed{c_s < \frac{\pi G \Sigma}{\Omega}}$$

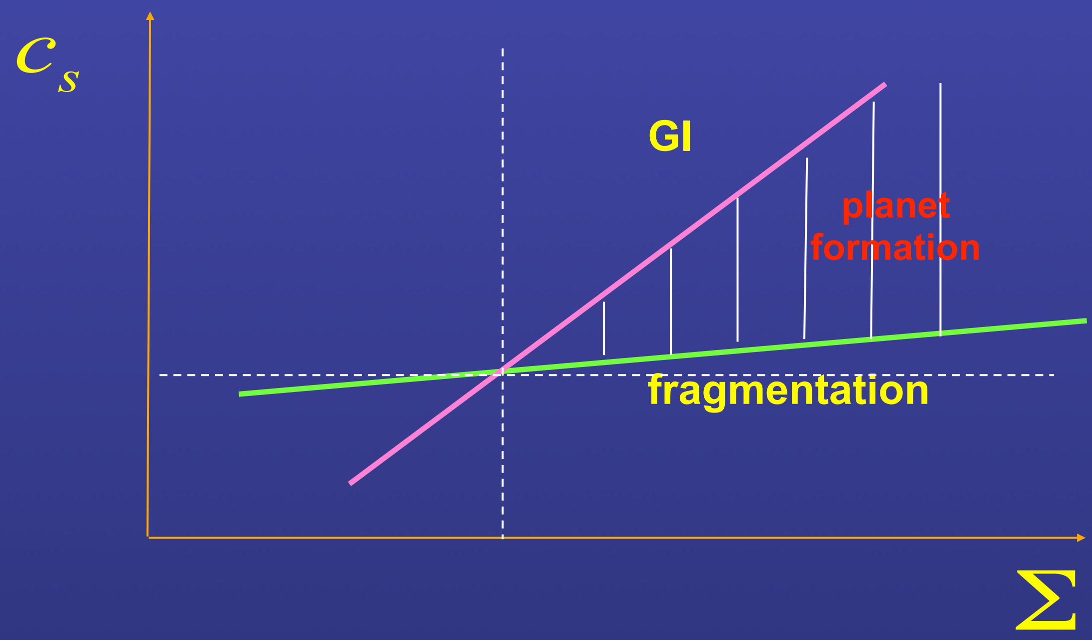
+

$$\boxed{\left[\frac{\Sigma\Omega}{3\sigma}\left(\frac{k}{\mu}\right)^4\right]^{1/6} < c_s < \frac{\pi G \Sigma}{\Omega}}$$

Rafikov 2005

Thermodynamical constraints

Rafikov 2005



As a result, giant planet formation by GI requires

$$\Sigma > \left[\frac{\Omega^7}{3\sigma(\pi G)^6} \left(\frac{k}{\mu} \right)^4 \right]^{1/5} = 3\times10^5\, g\ cm^{-2} a_{AU}^{-21/10}$$ (~ 100 MMSN) !

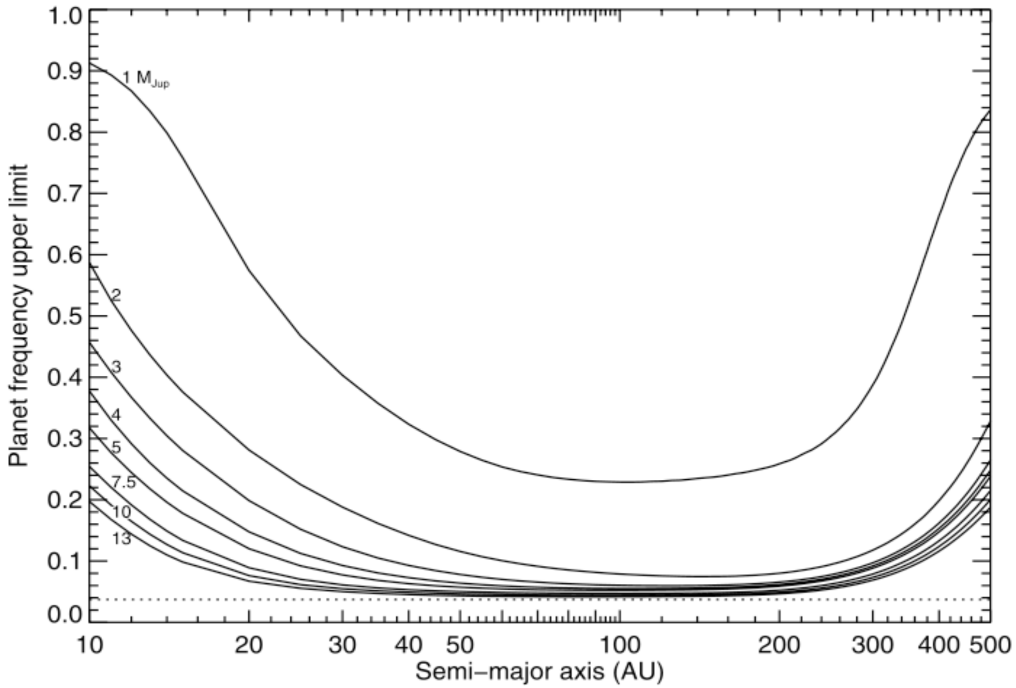
$$T > \left[\frac{\Omega^2}{3\pi\sigma G} \left(\frac{k}{\mu} \right)^{3/2} \right]^{2/5} = 2200\ K\ a_{AU}^{-6/5}$$ $\left(\sim T_{Sun} \right)$!!!

Requires rather extreme disk conditions

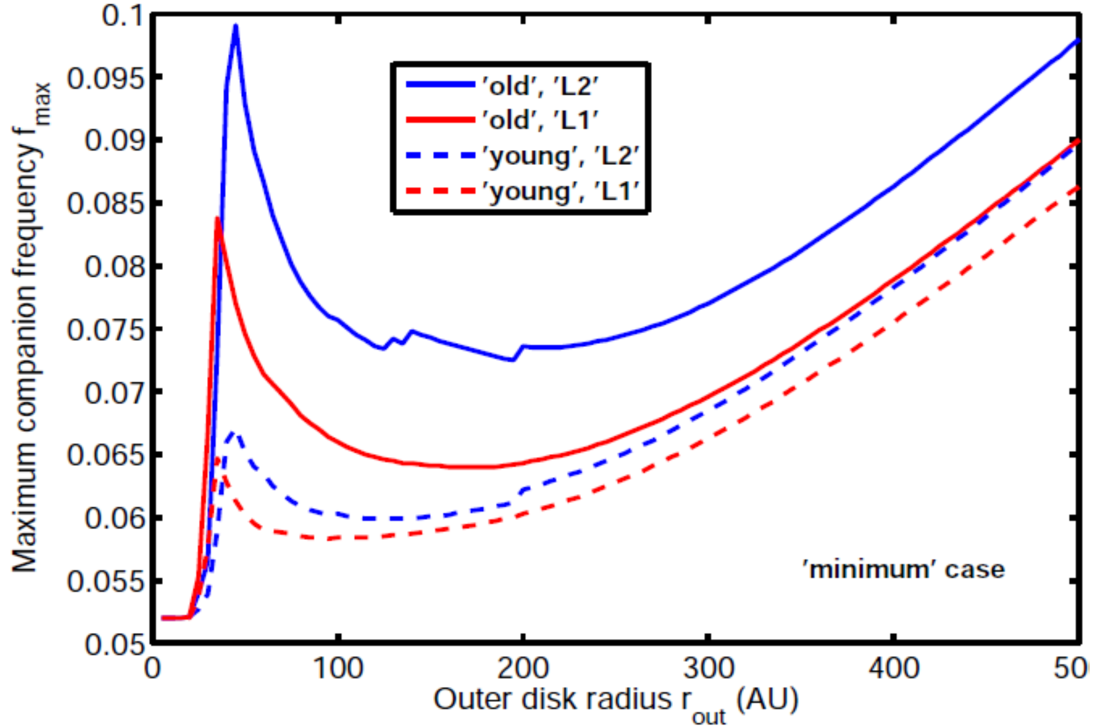
•Gravitational coupling to the massive disk quickly migrates them into the star
(Vorobyov & Basu 2005, Machida 2011, Baruteau et al. 2013)

Statistical constraints from D.I. (with caveats!)

apply both to BD's and planets !



Lafreniere et al. (2007)



Janson et al. (2012)

<23% of stars have >2 M_J planets at 25-450 AU
<9% of stars have >5 M_J planets at 25-450 AU

<10% of stars host ~Jupiter-mass objects formed by disk instability

Janson et al. '12, '13

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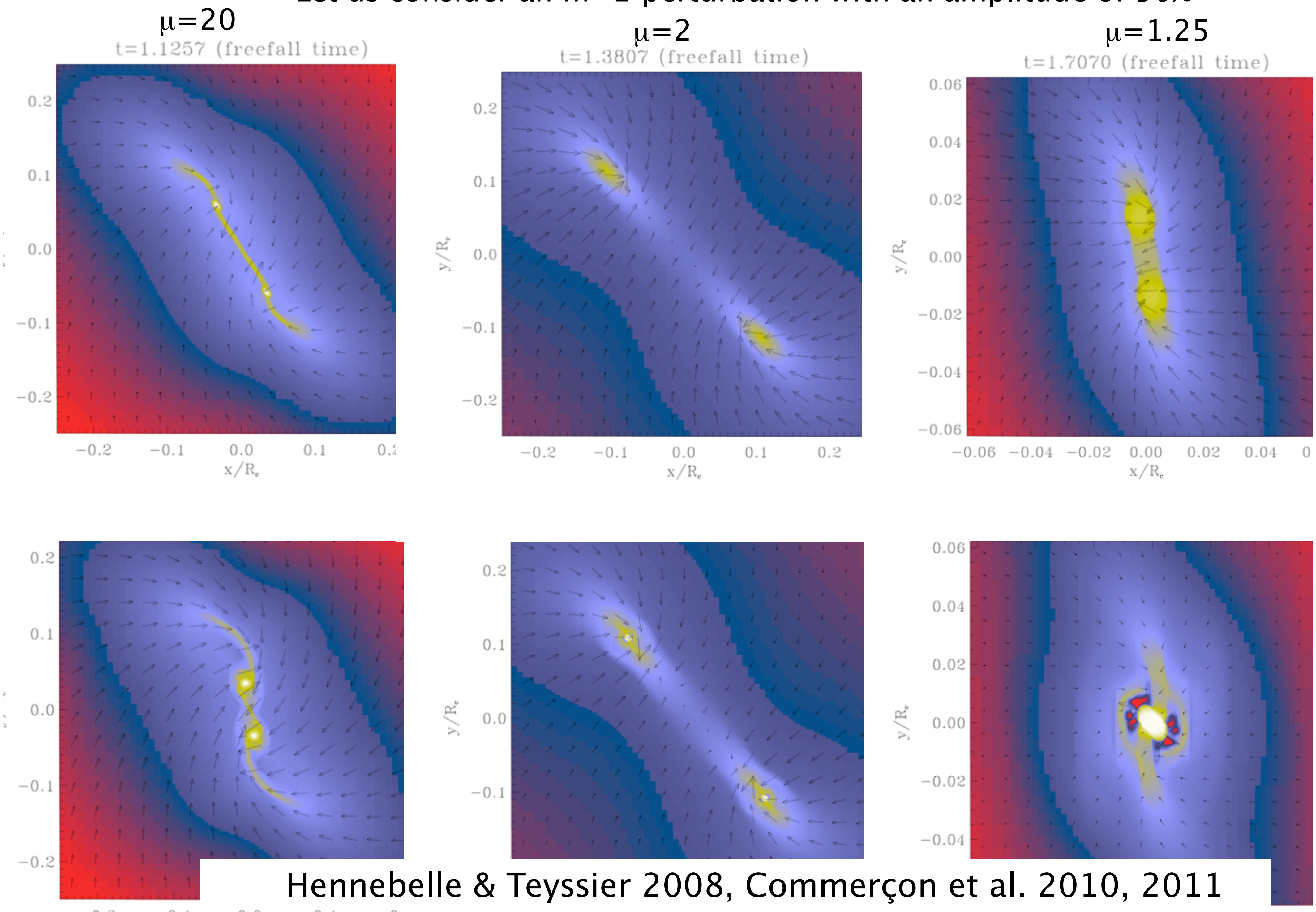
- **But… (1) G.I. does not last long ($<10^4$ yr, *Machida et al. '11*); (2) G.I. ~~=>~~ imply bound structures. And (3) if so, bound structures do not necessarily survive !**
  Need « very fined tuned » cond'ns *(Chabrier, Johansen, Janson & Rafikov, PPVI)*

How to produce binaries ?

Let us consider an m=2 perturbation with an amplitude of 50%



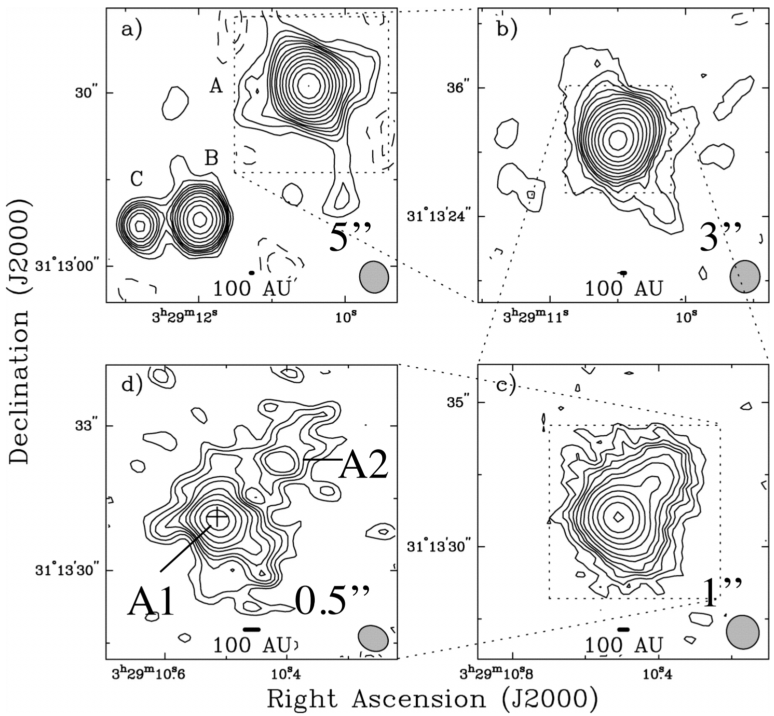
Hennebelle & Teyssier 2008, Commerçon et al. 2010, 2011

Observations and statistical properties of multiple Systems

About 50% of the stars are binaries (Duquenoy & Mayor 91)
There are evidences that the fragmentation occurs very early when the star is still accreting.

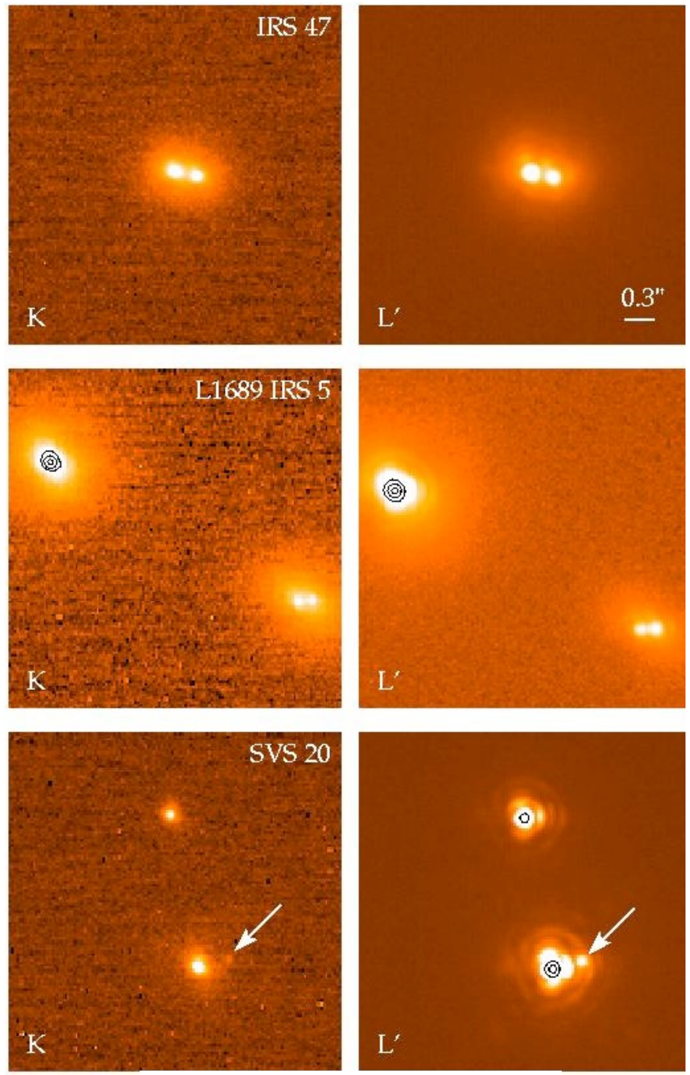
Evidences for fragmentation in the Class0 objects IRAS4A (Observations realised with the BIMA interferometer)

NGC1333 IRAS4 - BIMA - 2.7 mm



Looney, Mundy, Welch (2000)

Multiple embedded Young stellar objects in ρOph and Serpens



Duchêne et al. 2003