Disk formation during star formation in **non-ideal** MHD simulations

G. Chabrier, J. Masson, P. Marchand, B. Commerçon, P. Hennebelle, N. Vaytet, R. Teyssier

State-of-the-art

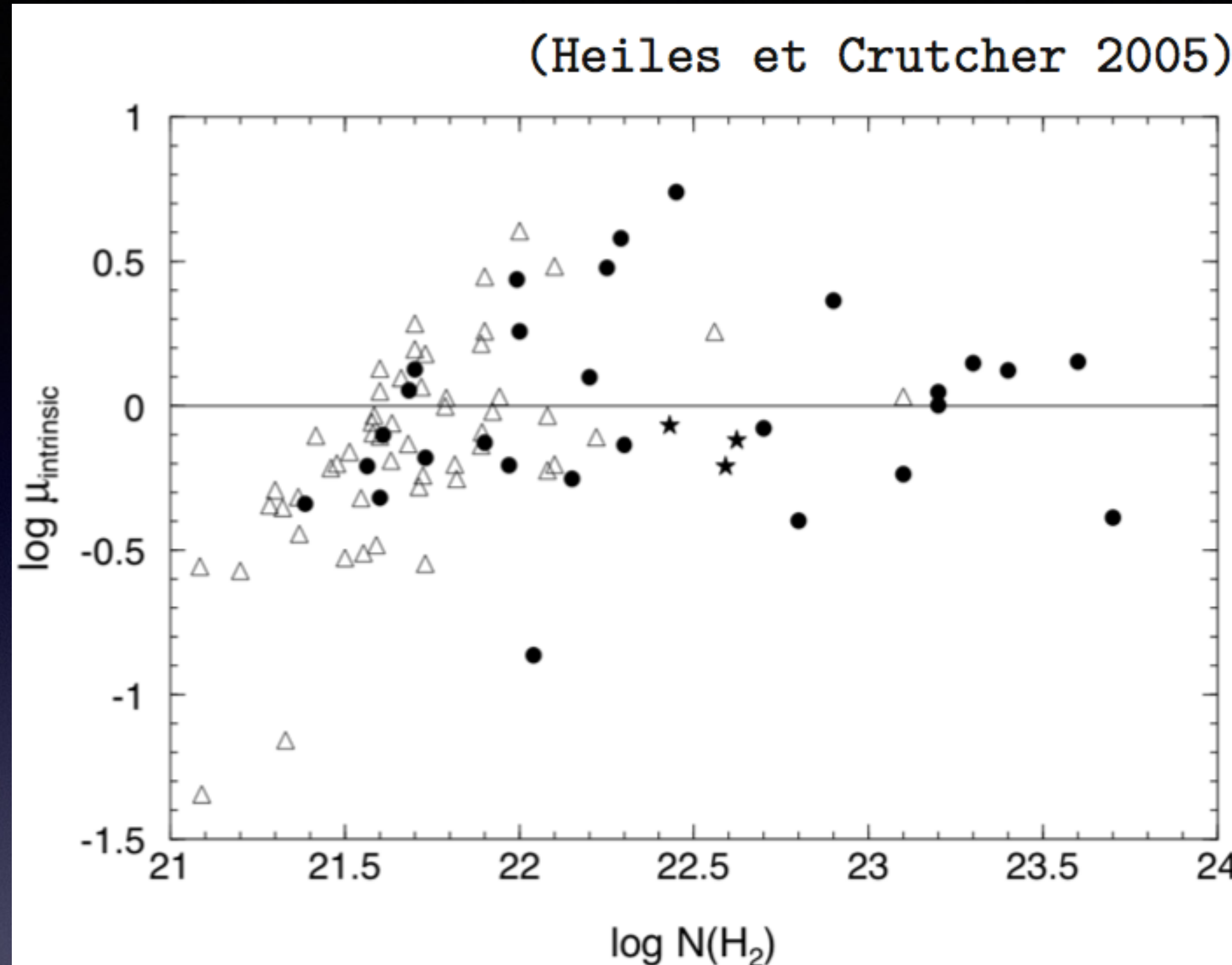
3D dynamical models make step-by-step necessary developments

- magnetic fields: ideal and non ideal MHD
- radiation hydrodynamics
- chemodynamics, but no retroaction
- cosmic rays
- inclusion of different feedback processes
- non-ideal EOS (Saumon, Chabrier, vanHorn 1995)

$$
\begin{cases}
\partial_t \rho + \nabla \cdot [\rho \mathbf{u}] = 0 \\
\partial_t \rho \mathbf{u} + \nabla \cdot [\rho \mathbf{u} \otimes \mathbf{u} + P\mathbb{I} - \mathbf{B} \otimes \mathbf{B}] = -\lambda \nabla E_{\mathrm{r}} \\
\partial_t E_{\mathrm{T}} + \nabla \cdot [\mathbf{u}\,(E_{\mathrm{T}} + P) + \mathbf{B}(\mathbf{B} \cdot \mathbf{u})] = -\mathbb{P}_{\mathrm{r}} \nabla : \mathbf{u} - \lambda \mathbf{u} \nabla E_{\mathrm{r}} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_{\mathrm{R}}} \nabla E_{\mathrm{r}} \right) \\
\partial_t E_{\mathrm{r}} + \nabla \cdot [\mathbf{u} E_{\mathrm{r}}] = -\mathbb{P}_{\mathrm{r}} \nabla : \mathbf{u} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_{\mathrm{R}}} \nabla E_{\mathrm{r}} \right) + \kappa_{\mathrm{P}} \rho c (a_{\mathrm{R}} T^4 - E_{\mathrm{r}}) \\
\partial_t \mathbf{B} + \nabla \times \left[\mathbf{u} \times \mathbf{B} - \frac{\mathbf{J} \times \mathbf{B}}{e n_e} + \frac{[(\nabla \times \mathbf{B}) \times \mathbf{B}] \times \mathbf{B}}{\gamma_{\mathrm{AD}} \rho \rho_{\mathrm{i}}} - \frac{\mathbf{J}}{\sigma_{\|}} \right] = 0
\end{cases}
$$

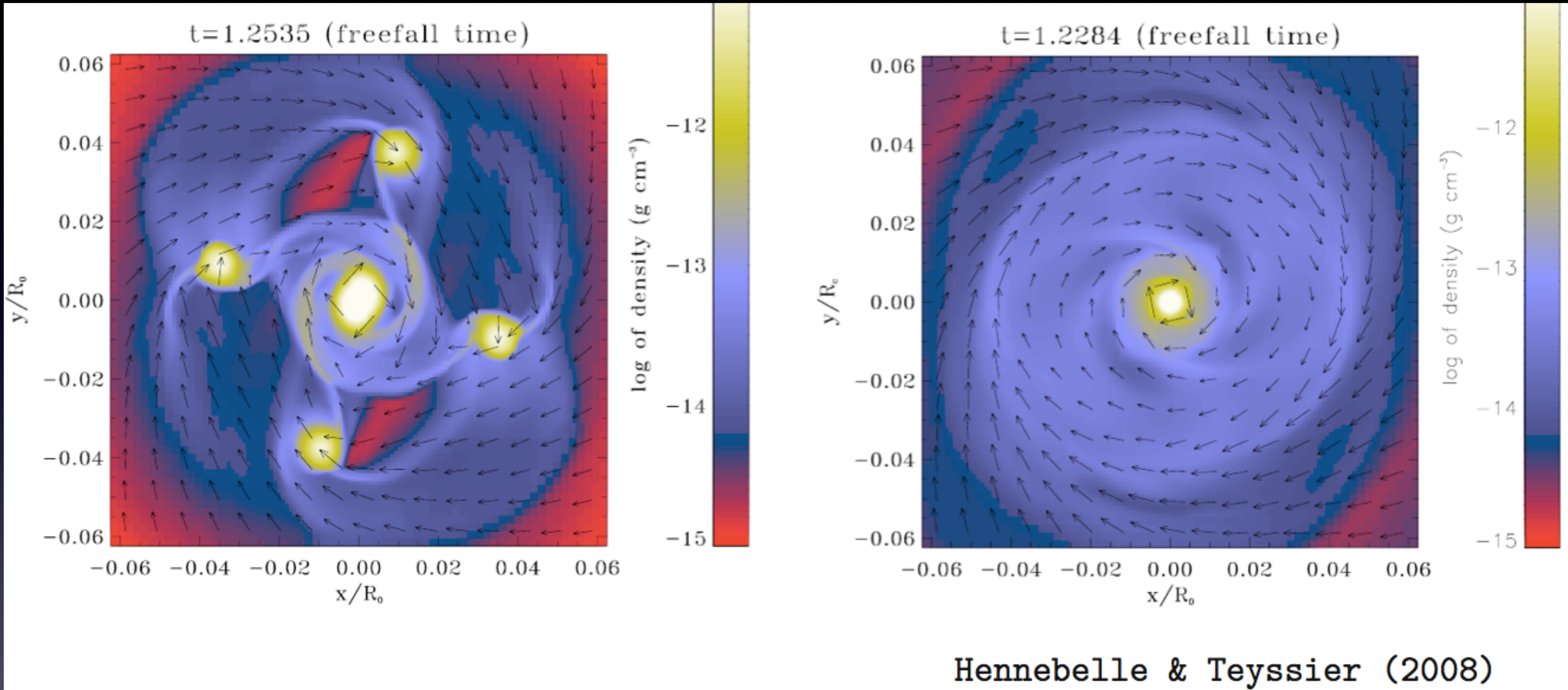
$$\mu = \frac{\left(\frac{M}{\Phi}\right)}{\left(\frac{M}{\Phi}\right)_{crit}} \approx 2$$

$(\phi_{cr} = B_{cr}\, \pi\, R^2 \sim G^{1/2} M)$



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

Hydro IMHD



too large and massive disks
too much frag'n

No disk !

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

SOURCE — SINK

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

Induction — Hall — Ambipolaire — Ohm

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

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

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

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

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

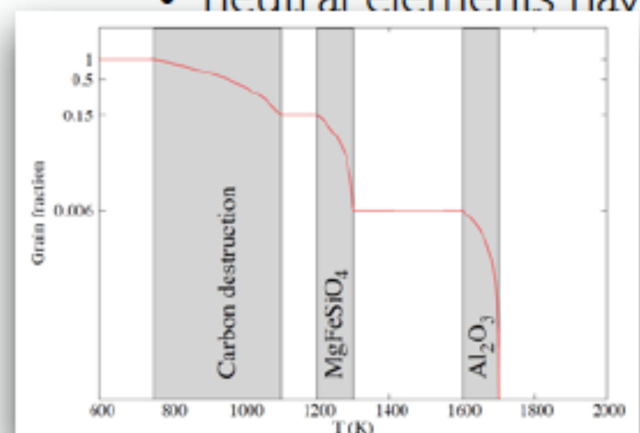
Soit, avec : $\gamma_{\mathrm{AD}} = \frac{<\sigma_{in} v_i>}{(m_i + m_n)}$ et $\sigma = \frac{n_e e^2}{n_n m_e < \sigma_{en} v_e >}$

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

Equilibrium chemistry for non-ideal MHD

✓ Reduced chemical network dedicated for ionisation (based on the work by *Umebayashi & Nakano 1990*)

- H, He, C, O, metallic elements (Fe, Na, Mg, etc..)
- H^+, H_3^+, He^+, C^+, molecular and metallic ions
- bins in the dust grains size distribution (G, G^+, G^-)
- dust evaporation at T>800 K
- thermal ionisation of potassium (T>1000 K)
- neutral elements have constant abundances



✓UMIST database for gas species (*McElroy et al. 2013*)

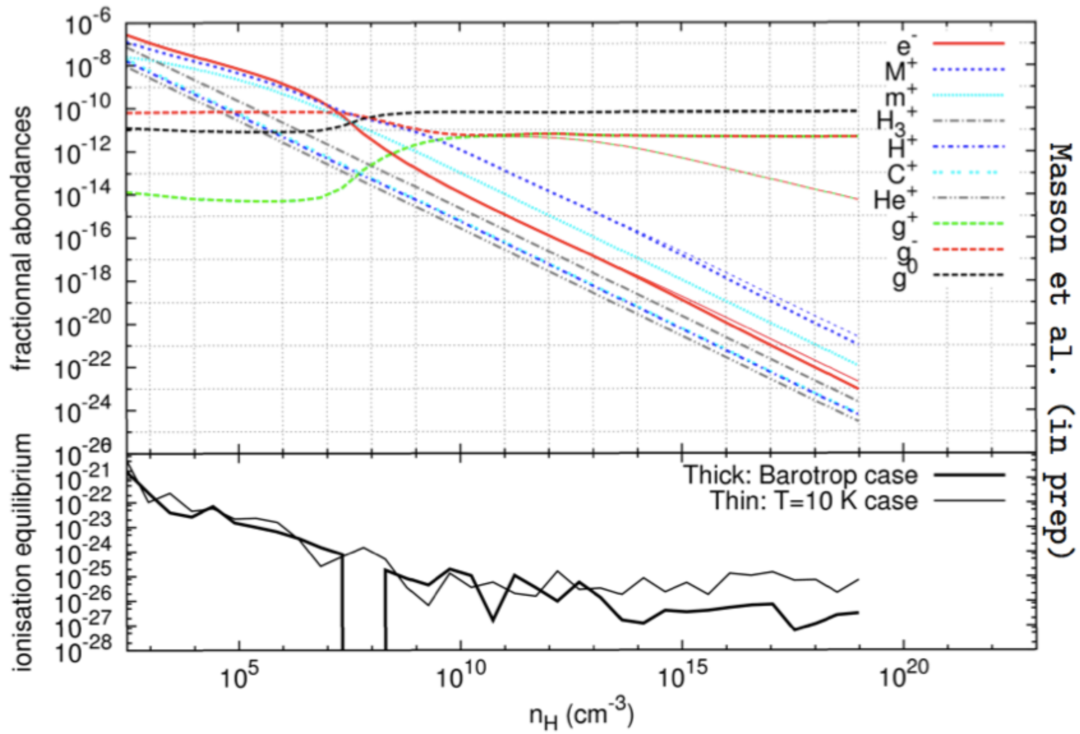
✓*Kunz & Mouschovias (2009)* for interactions with and between grains

Reaction	α	β	γ
$H^+ + O \rightarrow H + O^+$	6.86×10^{-10}	0.26	0
$H^+ + O_2 \rightarrow H + O_2^+$	2.00×10^{-9}	0.00	0
$H^+ + M \rightarrow H + M^+$	1.10×10^{-9}	0.00	0
$He^+ + H_2 \rightarrow He + H^+ + H$	3.70×10^{-14}	0.00	35
$He^+ + CO \rightarrow He + C^+ + O$	1.60×10^{-9}	0.00	0
$He^+ + O_2 \rightarrow He + O^+ + O$	1.10×10^{-9}	0.00	0
$H_3^+ + CO \rightarrow H_2 + HCO^+$	1.36×10^{-9}	−0.14	0
$H_3^+ + O \rightarrow H_2 + OH^+$	7.98×10^{-10}	−0.16	0
$H_3^+ + O_2 \rightarrow H_2 + O_2H^+$	9.30×10^{-10}	0.00	0
$H_3^+ + M \rightarrow H_2 + H + M^+$	1.10×10^{-9}	0.00	0
$C^+ + H_2 \rightarrow CH_2^+ + h\nu$	2.00×10^{-16}	0.00	0
$C^+ + O_2 \rightarrow CO^+ + O$	3.42×10^{-10}	0.00	0
$C^+ + O_2 \rightarrow CO + O^+$	4.54×10^{-10}	0.00	0
$C^+ + M \rightarrow C + M^+$	1.10×10^{-9}	0.00	0
$m^+ + M \rightarrow m + M^+$	2.90×10^{-9}	0.00	0
$H^+ + e^- \rightarrow H + h\nu$	3.50×10^{-12}	−0.75	0
$He^+ + e^- \rightarrow He + h\nu$	5.36×10^{-12}	−0.5	0
$H_3^+ + e^- \rightarrow H + H + H$; $\rightarrow H_2 + H$	2.34×10^{-8}	−0.52	0
$C^+ + e^- \rightarrow C + h\nu$	2.36×10^{-12}	−0.29	0
$m^+ + e^- \rightarrow m_1 + m_2$	2.40×10^{-7}	−0.69	0
$M^+ + e^- \rightarrow M + h\nu$	2.78×10^{-12}	−0.68	0
$H_2 \rightarrow H_2^+ + e^-$	1.2×10^{-17}		
$H_2 \rightarrow H^+ + H + e^-$	2.86×10^{-19}		
$He \rightarrow He^+ + e^-$	6.58×10^{-18}		

✓ **Goal: compute a 3D table of abundances:**

- depends on temperature, density and CR ionisation
- used on-the-fly in 3D calculations to compute resistivities

Marchand et al. (2016)



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

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

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

avec

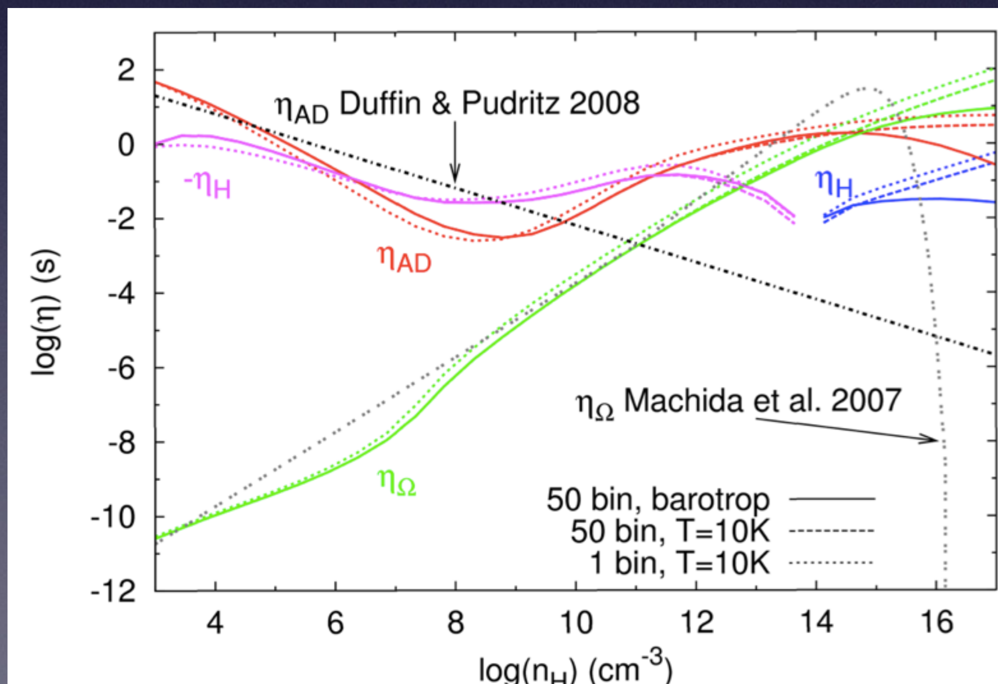
$$\sigma_s = \frac{n_s q_s^2 \tau_{sn}}{m_s}$$

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

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

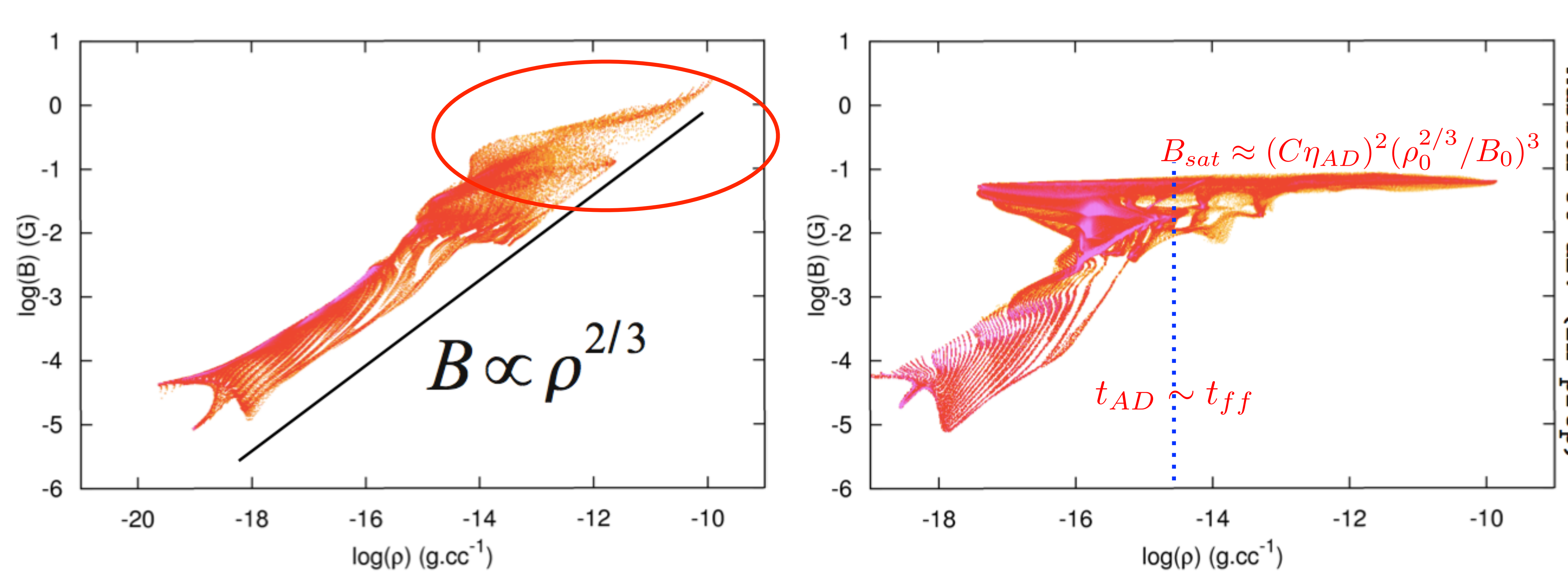
Molecules + grains w/ size distribution

non-ideal MHD resistivities



★ Code publicly available (see Marchand et al. 2016)

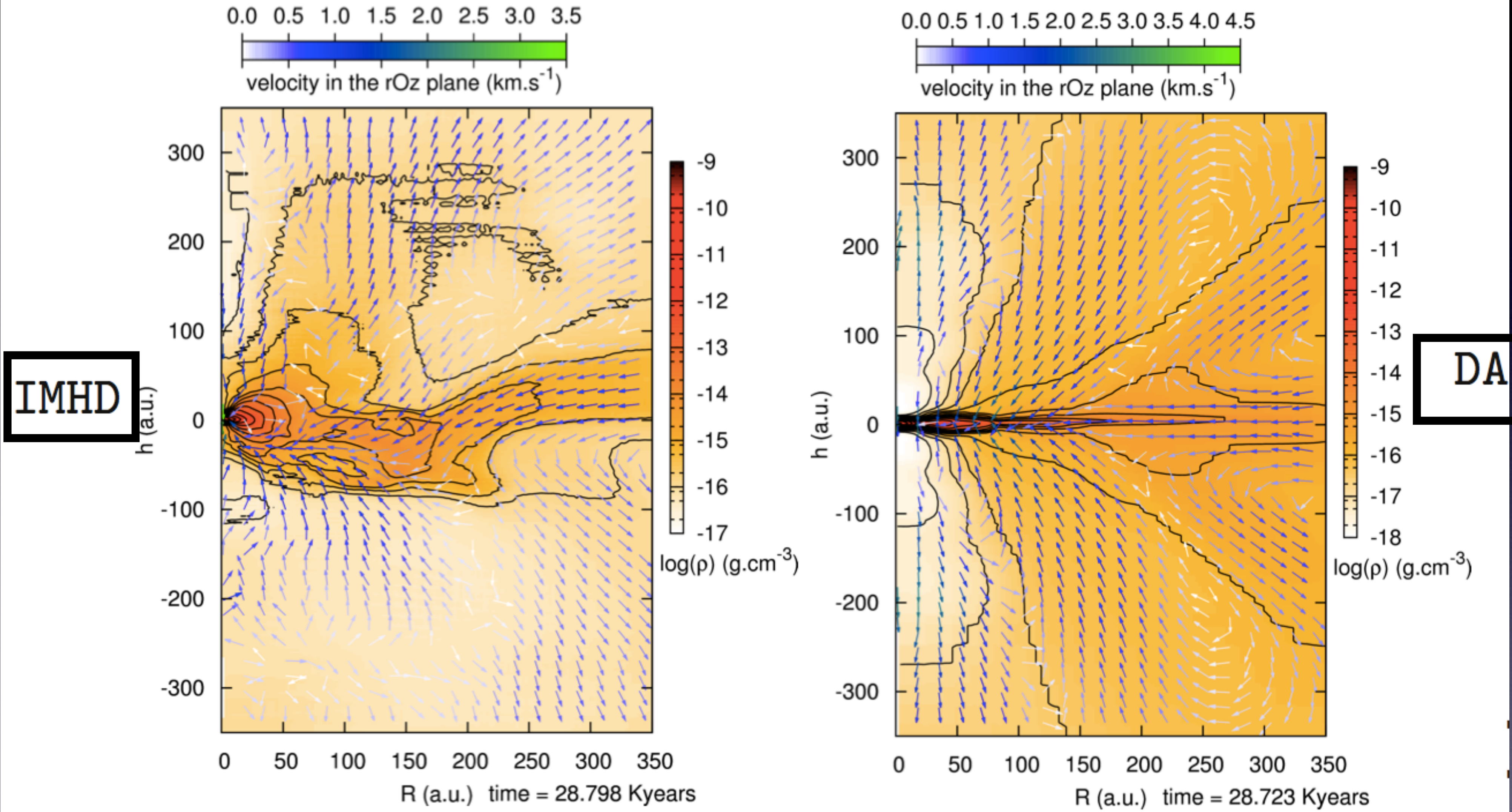
Masson et al., A&A 2016
Marchand et al., A&A 2016



IMHD Masson et al. 2016 **AD**

See also:
Desch & Mouschovias 2001, Krasnoplosky et al. 2012, Li et al. 2014, Machida et al. 2014, Tomida et al. 2015, Tsukamoto et al. 2015, Wurster et al. 2016

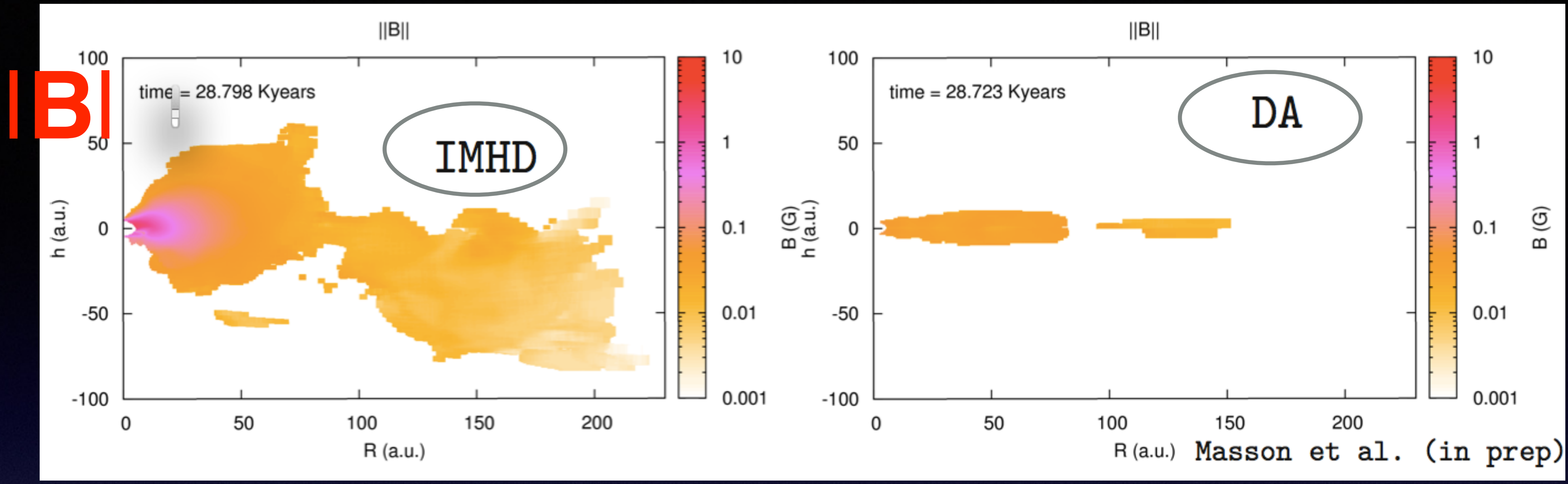
- Rotation, Mach=0, $\mu=5$



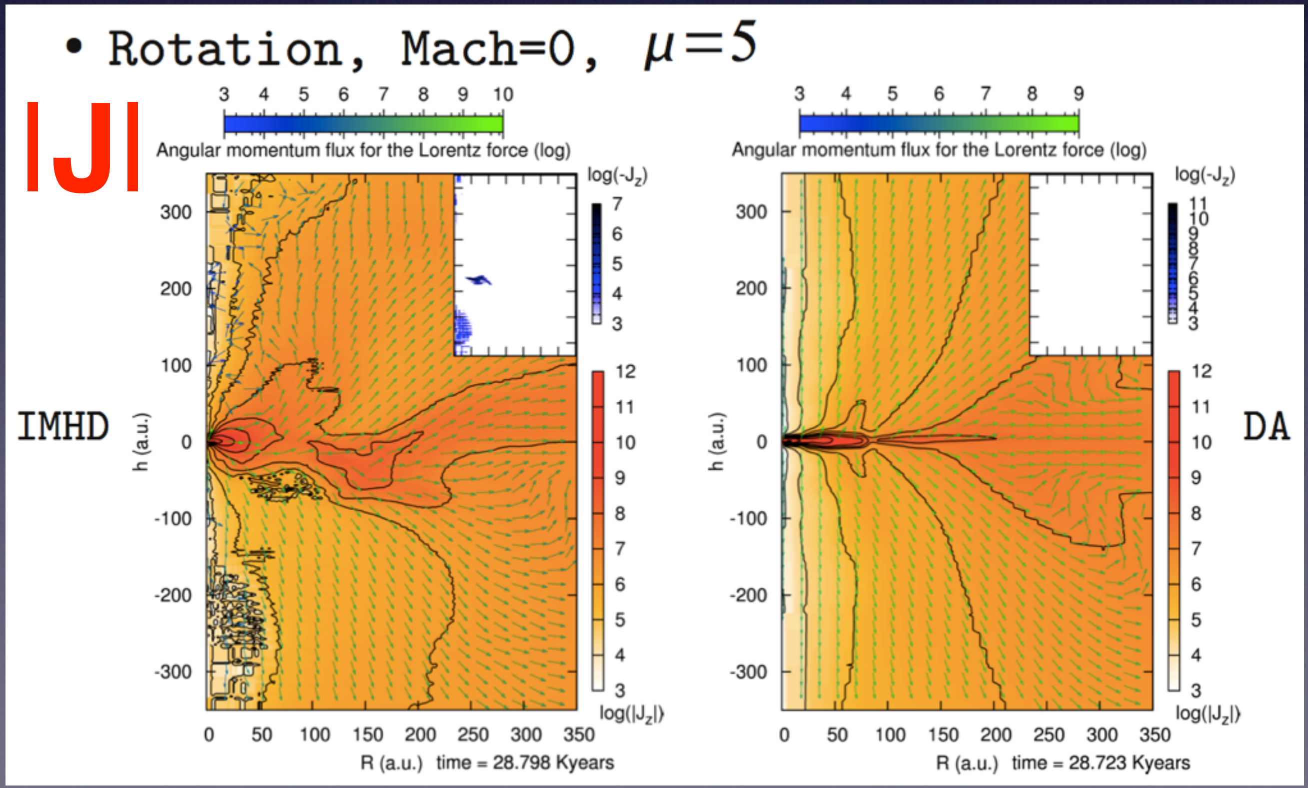
pile-up of B_ϕ
strong outflow
interchange instability !

Disk formed within ~ 6 kyr after collapse

Masson et al. 2016

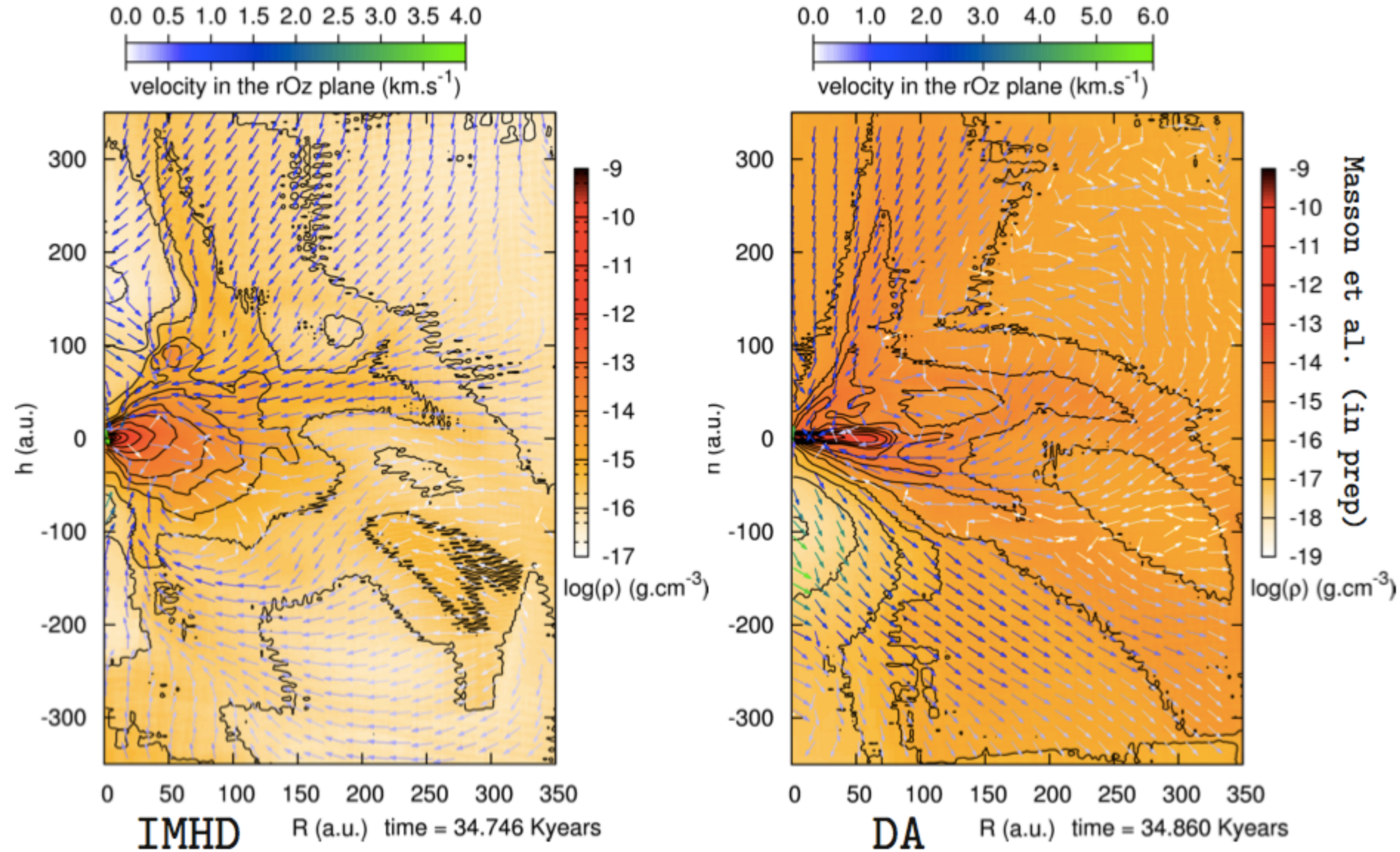


strong (toroidal) mag. support **~B/100; negligible mag. support; less B-bking**



J~10x larger; increases rotational support

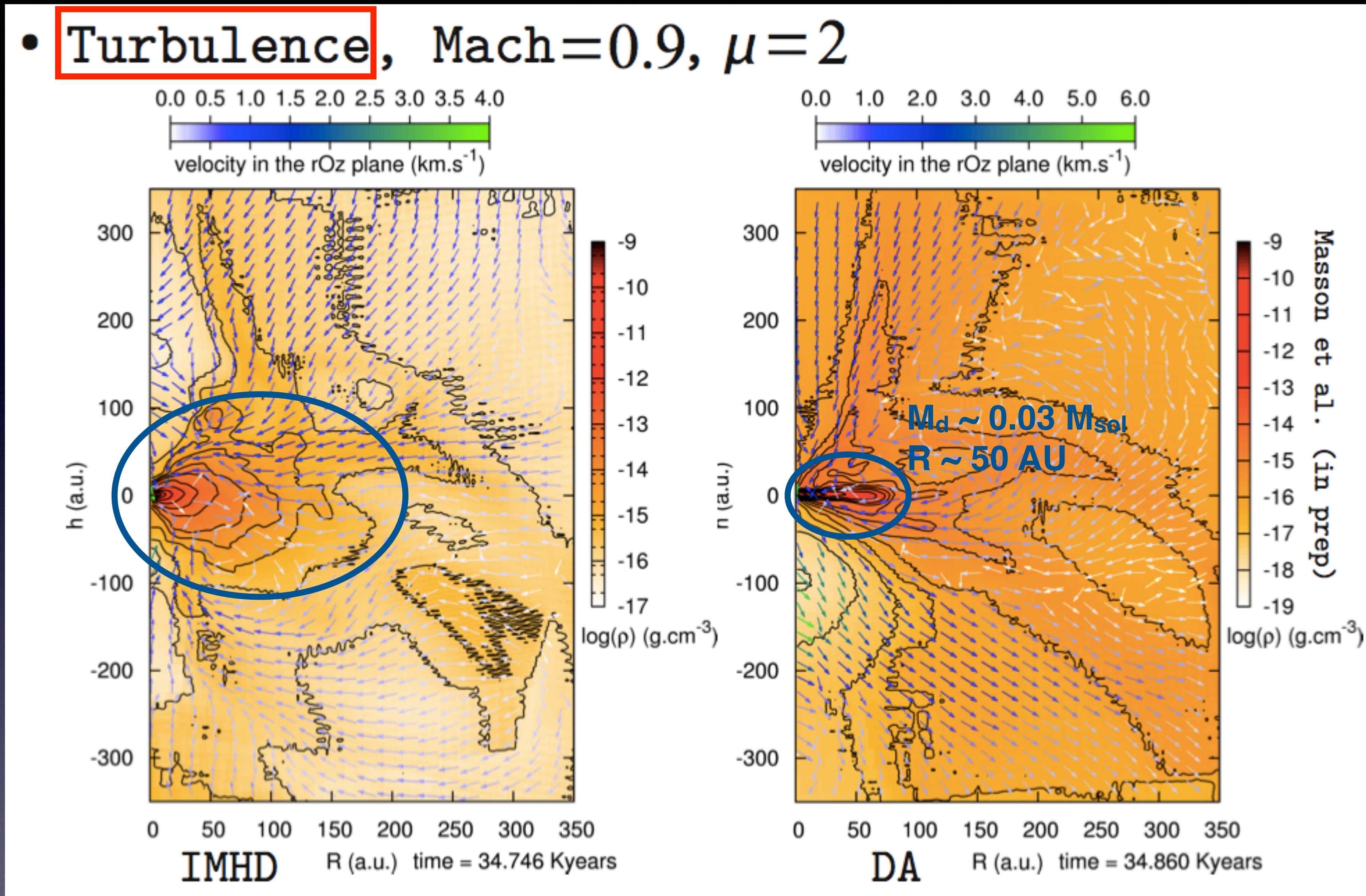
• Turbulence, Mach=0.9, $\mu=2$



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



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ANALYTICAL ESTIMATE

Hennebelle, Commerçon, Chabrier, Marchand, ApJL 2016

$$\tau_{Far} \simeq \frac{B_\phi h}{B_z v_\phi} \quad \approx \quad \tau_{diff} \simeq \frac{4\pi h^2}{c^2 \eta_{AD}}$$

$$\tau_{bk} \simeq \frac{4\pi \rho h v_\phi}{B_z B_\phi} \quad \approx \quad \tau_{rot} \simeq \frac{2\pi r}{v_\phi}$$

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

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$$R_{hydro} \simeq 106\,\mathrm{AU} \times (\frac{\beta}{0.02}) (\frac{\rho_0}{10^{-18}\,\mathrm{g\,cm^{-3}}})^{-1/3} (\frac{M_d + M_\star}{0.1\,\mathrm{M_\odot}})^{1/3}$$

$$(\beta = \frac{R_0^4 \Omega_0^2}{4\pi/3\, \rho_0 R_0^3 G})$$

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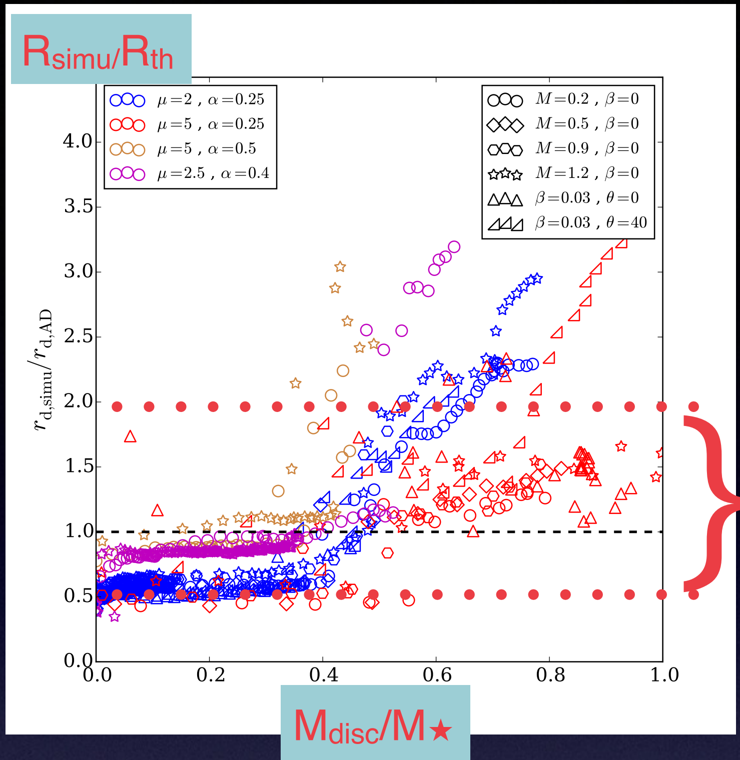
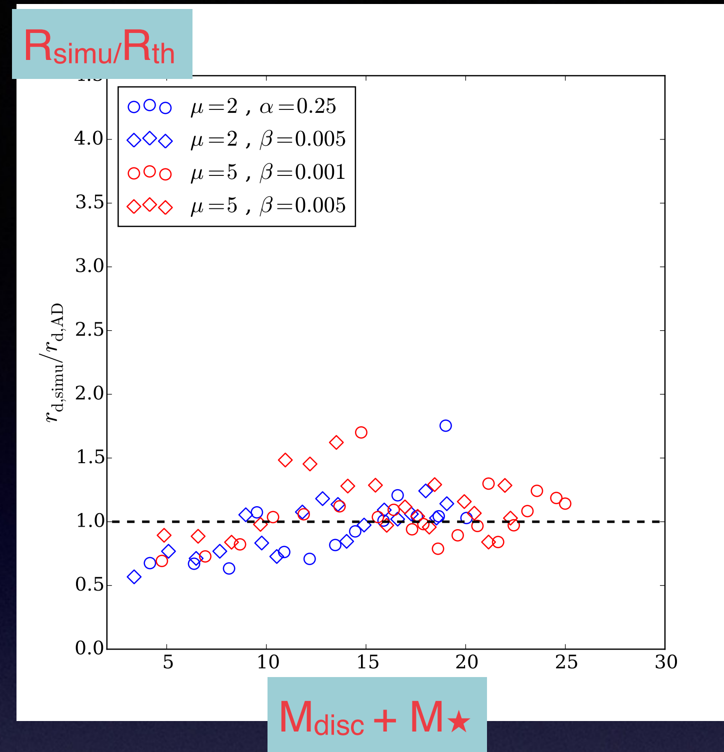
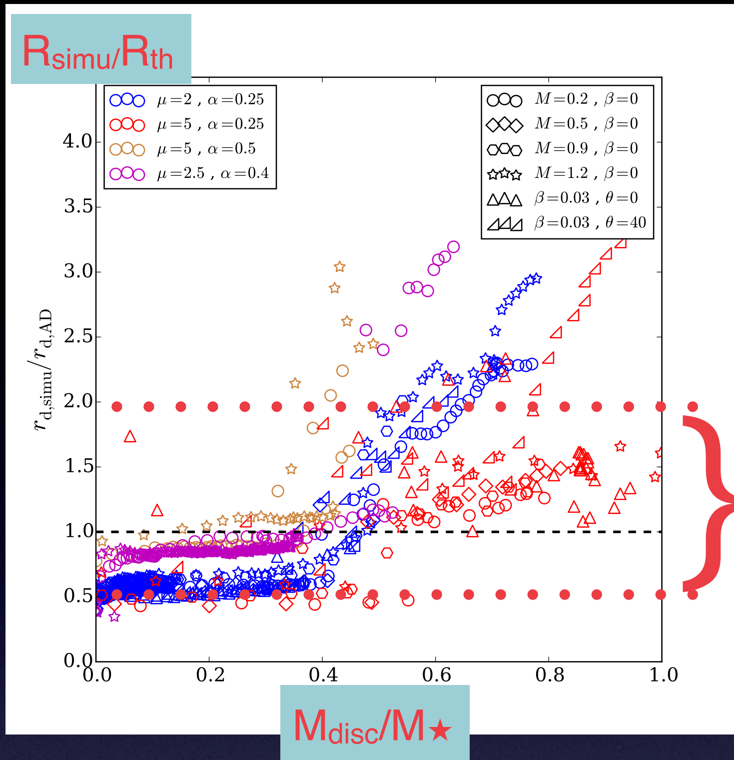
$$\left(\beta = \frac{R_0^4 \Omega_0^2}{4\pi/3\,\rho_0 R_0^3 G}\right)$$

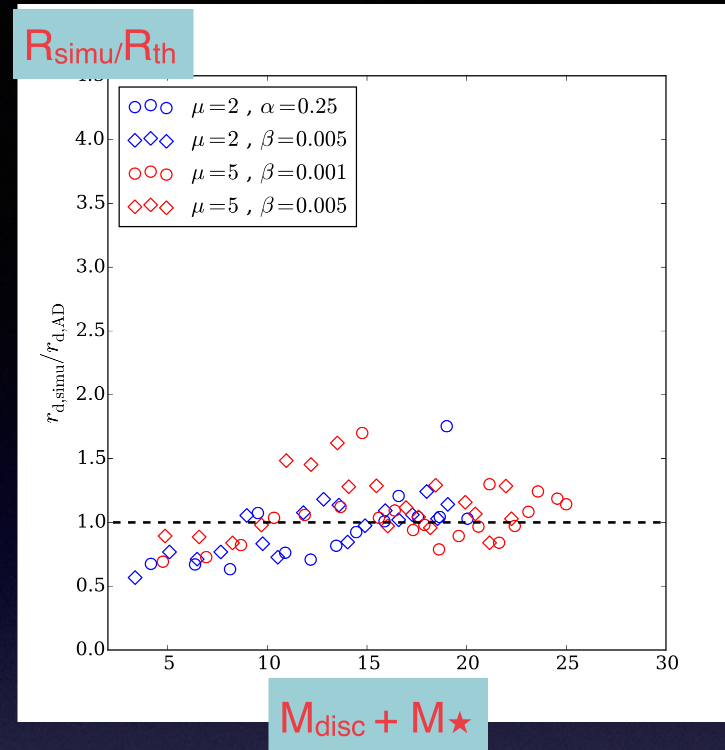
A. Maury's in prep. : ~25% **at most** of Class-0 disks have R $\gtrsim$ 60 AU


Rsimu/Rth
μ=2 , α=0.25
μ=5 , α=0.25
μ=5 , α=0.5
μ=2.5 , α=0.4
M=0.2 , β=0
M=0.5 , β=0
M=0.9 , β=0
M=1.2 , β=0
β=0.03 , θ=0
β=0.03 , θ=40
r_d,simu/r_d,AD
Mdisc/M★

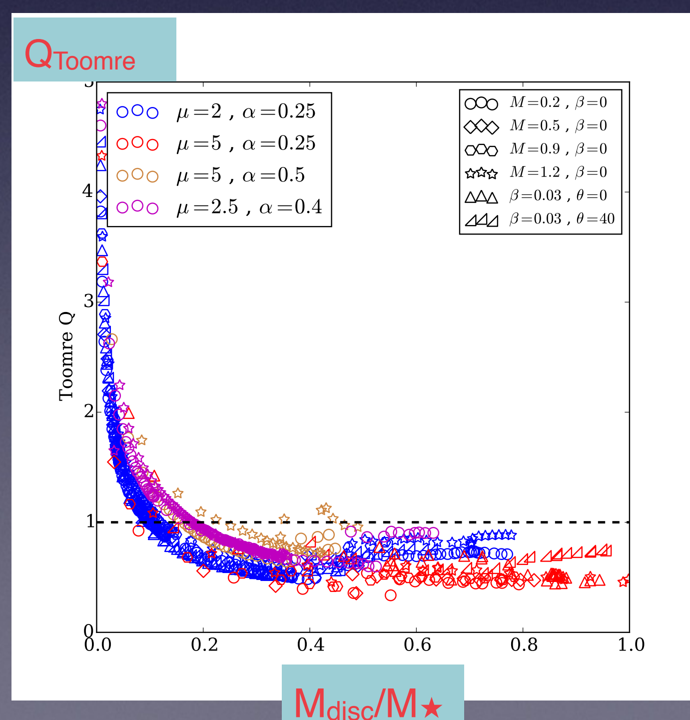

Rsimu/Rth
μ=2 , α=0.25
μ=2 , β=0.005
μ=5 , β=0.001
μ=5 , β=0.005
r_d,simu/r_d,AD
Mdisc + M★



Rsimu/Rth
$\mu=2$, $\alpha=0.25$
$\mu=5$, $\alpha=0.25$
$\mu=5$, $\alpha=0.5$
$\mu=2.5$, $\alpha=0.4$
$M=0.2$, $\beta=0$
$M=0.5$, $\beta=0$
$M=0.9$, $\beta=0$
$M=1.2$, $\beta=0$
$\beta=0.03$, $\theta=0$
$\beta=0.03$, $\theta=40$
$r_{\rm d,simu}/r_{\rm d,AD}$
Mdisc/M★



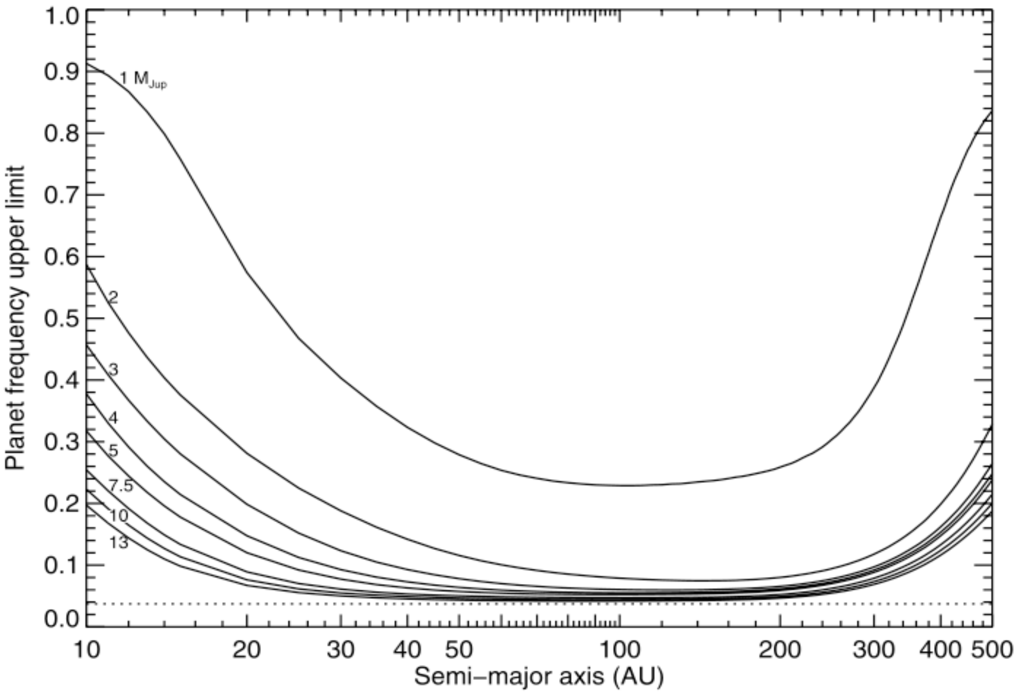
Rsimu/Rth
$\mu=2$, $\alpha=0.25$
$\mu=2$, $\beta=0.005$
$\mu=5$, $\beta=0.001$
$\mu=5$, $\beta=0.005$
$r_{\rm d,simu}/r_{\rm d,AD}$
Mdisc + M★



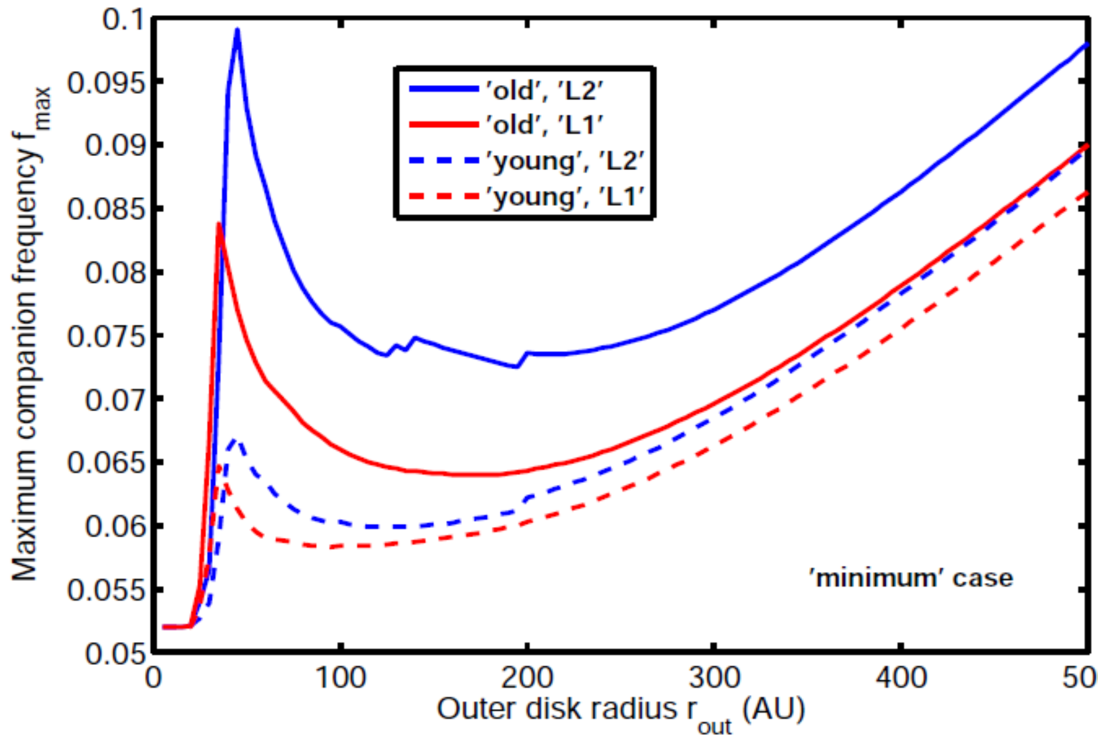
QToomre
$\mu=2$, $\alpha=0.25$
$\mu=5$, $\alpha=0.25$
$\mu=5$, $\alpha=0.5$
$\mu=2.5$, $\alpha=0.4$
$M=0.2$, $\beta=0$
$M=0.5$, $\beta=0$
$M=0.9$, $\beta=0$
$M=1.2$, $\beta=0$
$\beta=0.03$, $\theta=0$
$\beta=0.03$, $\theta=40$
Toomre Q
Mdisc/M★

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

apply both to BD's and planets !



Lafreniere et al. (2007)



Janson et al. (2012)

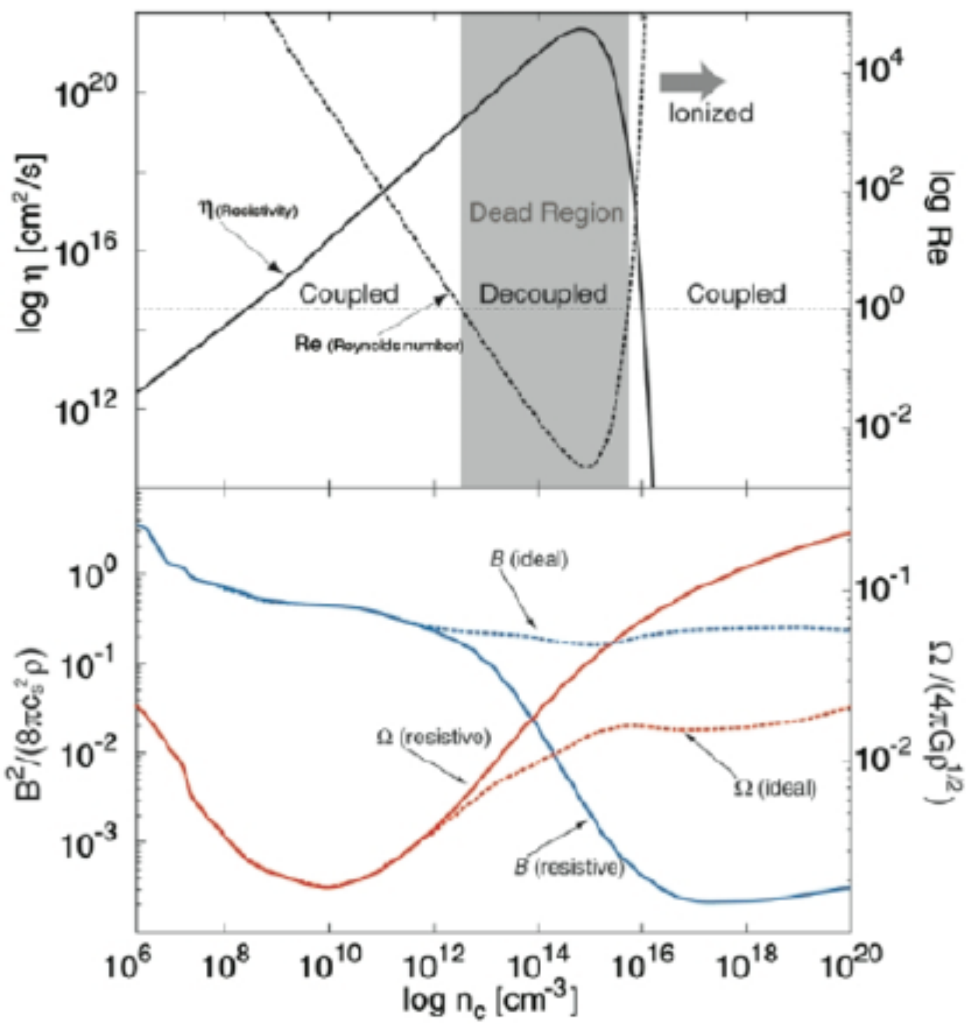
<23% of stars have >2 M_J planets at 25-450 AU
<9% of stars have >5 M_J planets at 25-450 AU

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

Janson et al. '12, '13

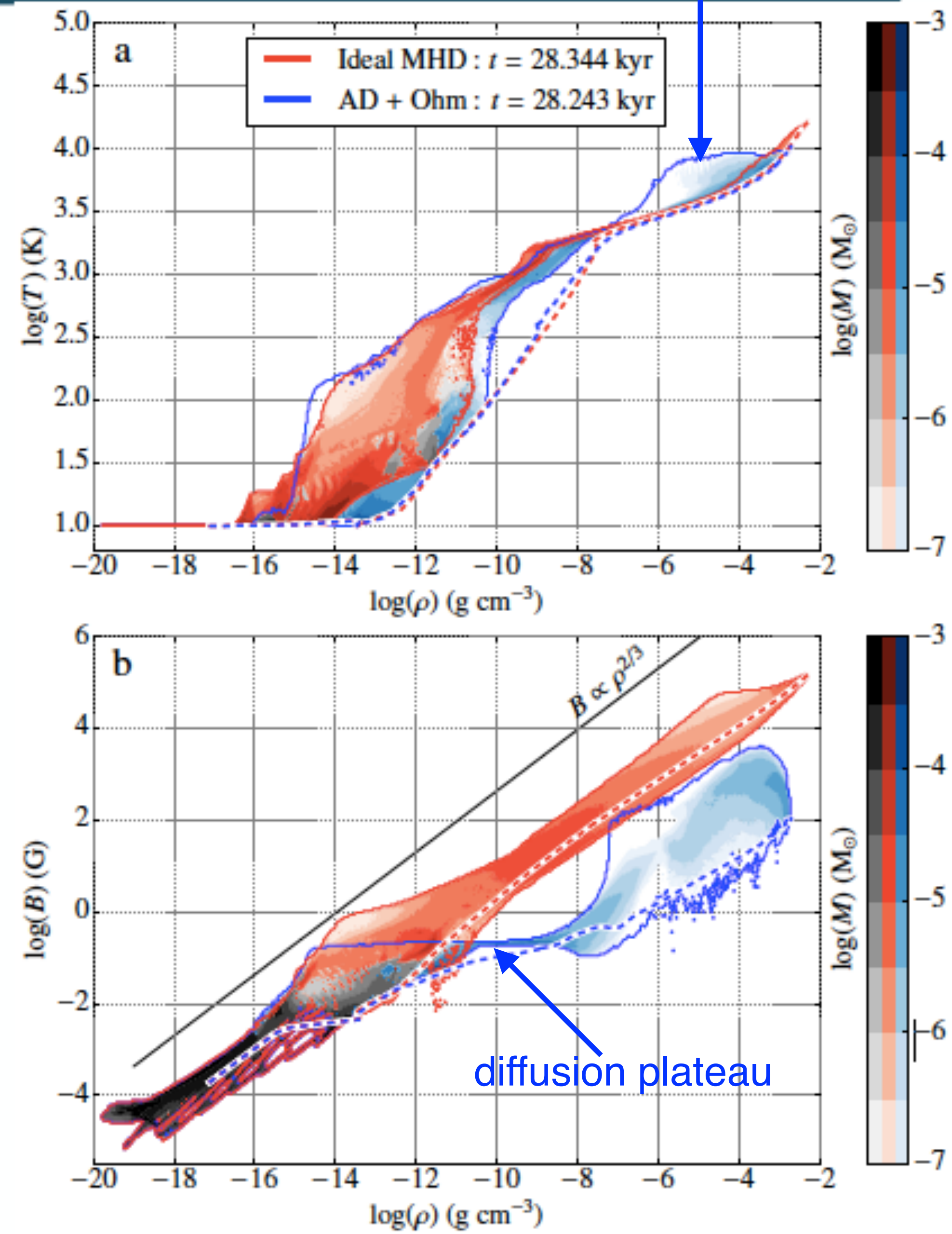
2nd collapse

Magnetic flux reduced by ~3 orders of magnitude only with ambipolar diffusion and Ohmic diffusion



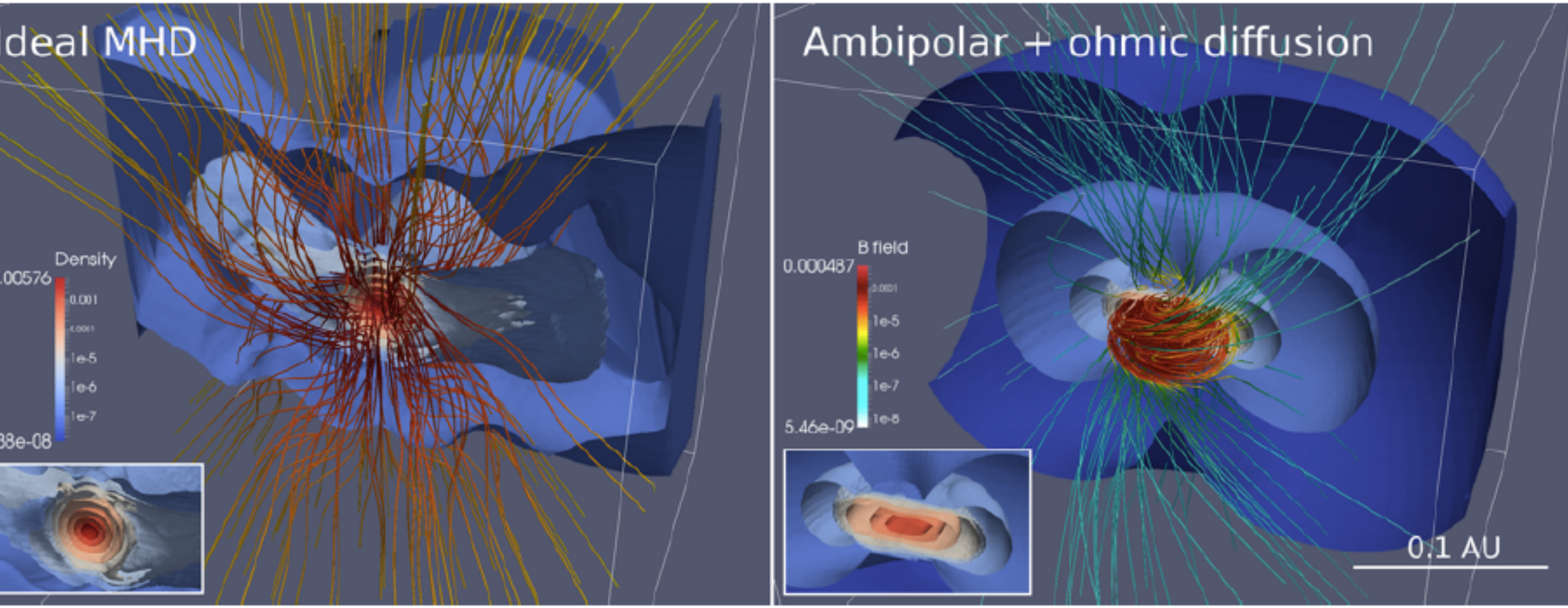
Machida et al (2008)

additional heating from magnetic diffusion



Vaytet et al (in prep.)

2nd collapse

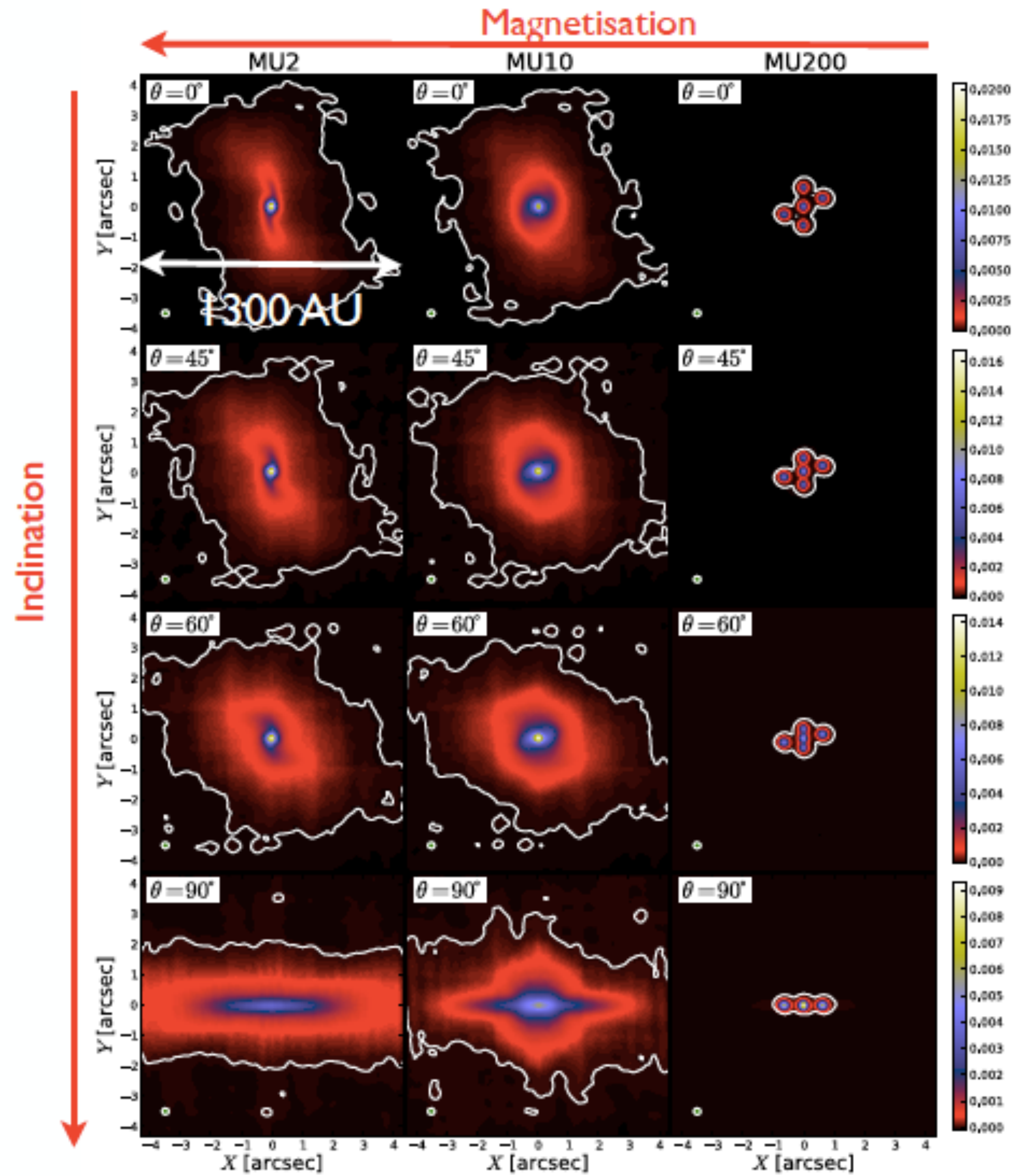


Vaytet et al (in prep.)

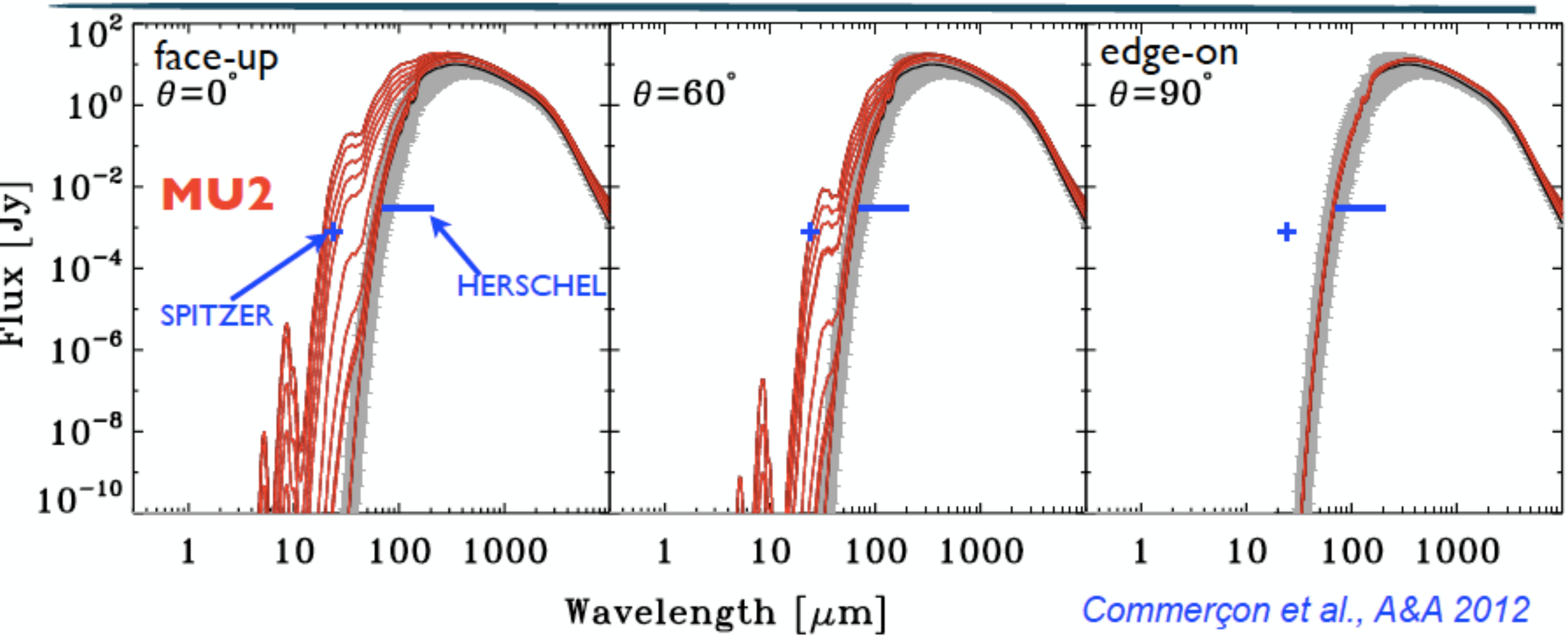
Synthetic ALMA dust emission maps

ALMA Band 3 Config 20 @150 pc

Commerçon, Levrier et al. A&A, 2012



SED - Do we see a first core signature?

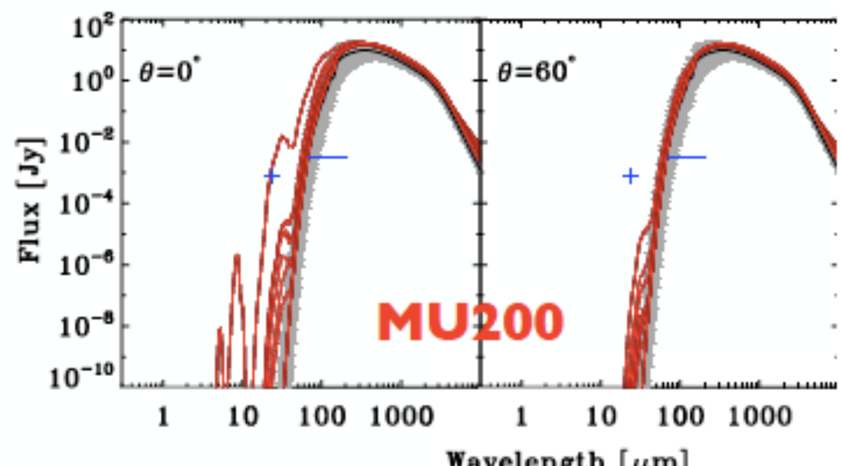


Commerçon et al., A&A 2012

- *Objects at 150 pc, 3000 AU x 3000 AU region*
- *Prestellar core = initial conditions (black line)*
- Emission in the FIR => HERSCHEL, SPITZER
- But similar SEDs in the MU200 model, i.e. with a disc!

=> Issues in SED-fitting models for early Class 0?

Help to select first core candidates & to distinguish starless cores and first cores



CONCLUSIONS & PERSPECTIVE

- Formation of magnetized disks is a **very complicated task** (see Li et al. 2014, PPVI review): need **non-ideal MHD**, **turbulence**, **rotation**, **outflows**, **chemistry… + numerical issues** (diffusivity, reconnection,…)

  Calculations w/o B (or ideal MHD), accreting envelope (J), (chemistry) meaningless always VERY cautious/ skeptical about numerical simulations !!!

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- **Ambipolar Diffusion / Ohmic dissp'n** (1st / 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*
- *Turbulence:*
  - increases further the effect of AD (diffusivity, reconnection)
  - yields less organized structures => affects accretion history

  strongly affect properties of the second core and surrounding disk

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    - increases further the effect of AD (diffusivity, reconnection)
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    strongly affect properties of the second core and surrounding disk

- Magnetized disks at the Class 0 stage should exhibit weak variations ($R_d \sim$ 20 AU $\propto B^{-1/2} M_\star^{1/3}$)
  Self-regulation between B-braking and AD
  (consistent with observations *(A. Maury)*)

CONCLUSIONS & PERSPECTIVE

- Formation of magnetized disks is a **very complicated task** (see Li et al. 2014, PPVI review): need **non-ideal MHD**, **turbulence**, **rotation**, **outflows**, **chemistry… + numerical issues** (diffusivity, reconnection,…)
  Calculations w/o B (or ideal MHD), accreting envelope (J), (chemistry) meaningless always VERY cautious/ skeptical about numerical simulations !!!

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- Perspective: need more (good) physics + need more observations (ALMA, SCUBA2, Artemis, SPHERE, GPI,…)