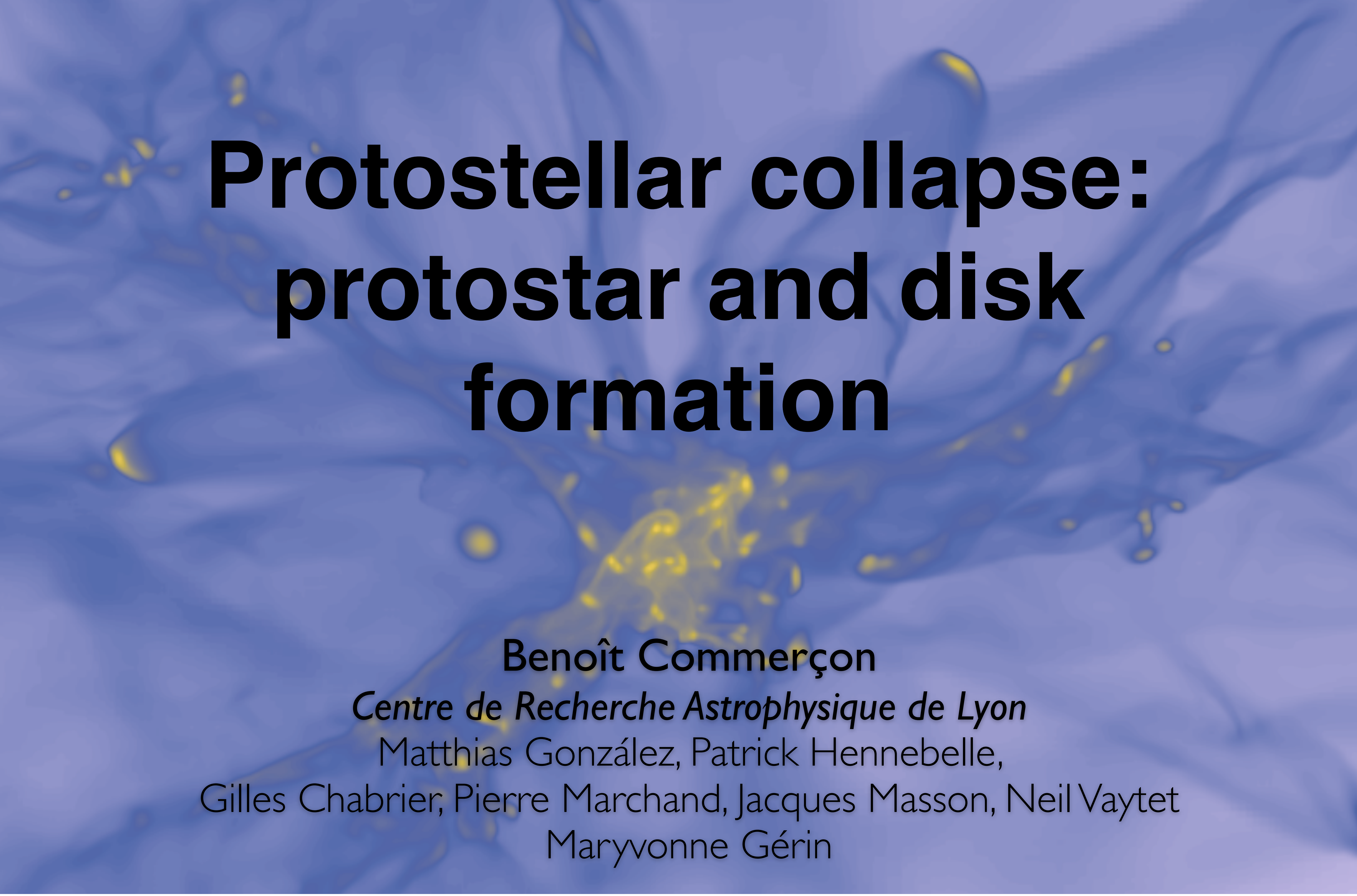

Protostellar collapse: protostar and disk formation

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Outline

1. Introduction

- Context
- What has changed since 2014?

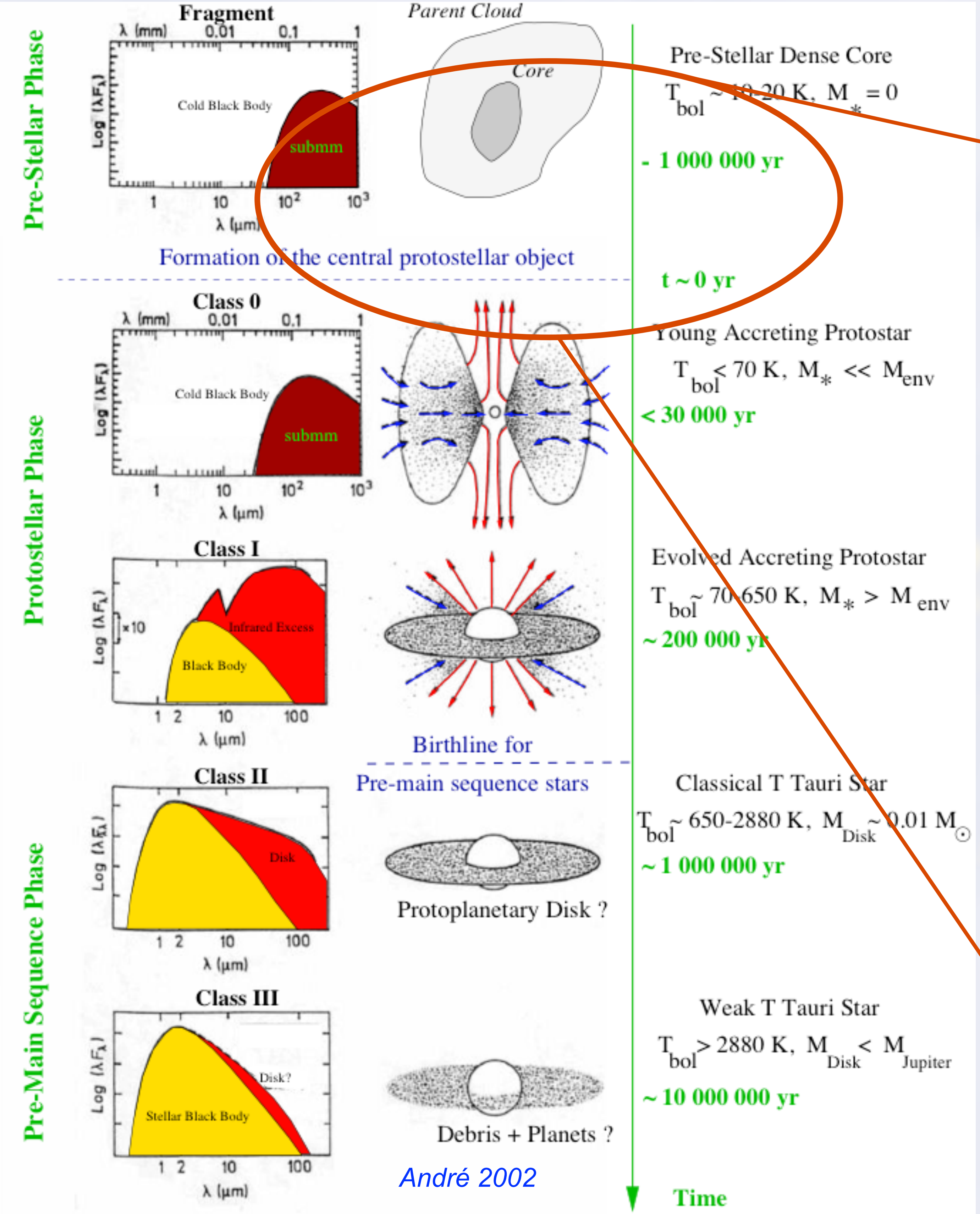
2. From dense core collapse….

- Disc formation
- Comparison with ALMA observations

3. To protostar and protoplanetary disc birth

- Early evolution
- Dust and gas mixture

Star formation evolutionary sequence



André 2002

Prestellar dense core collapse

First collapse

(10K, 10^{-20} g cm^{-3})

Isothermal ***$10^{4,5}$ yr***

First Larson core

(100K, 10^{-12} g cm^{-3}, 10 AU)

Adiabatic ***a few 10^{3} yr***

H_2 dissociation

Second collapse

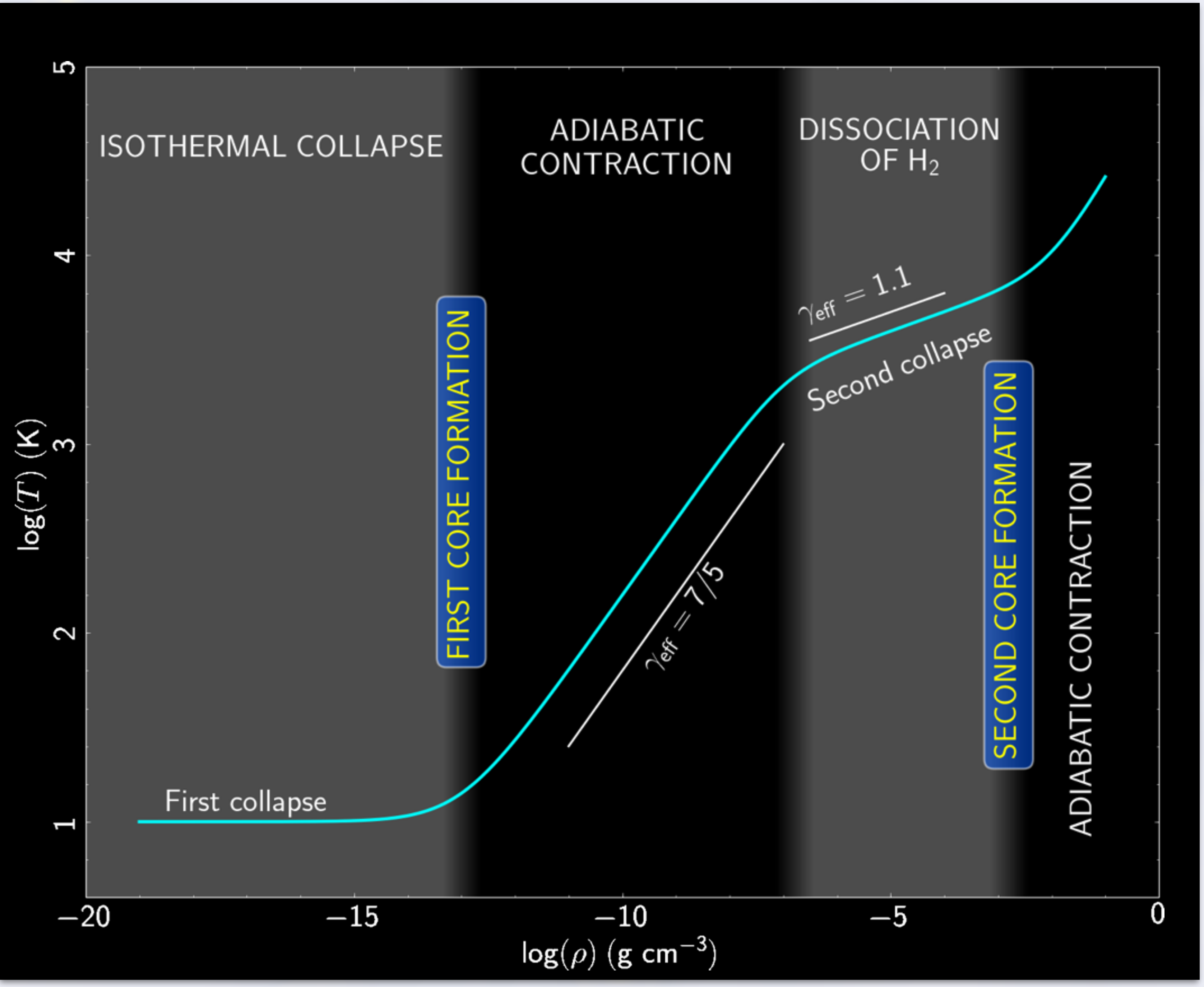
(2000K, 10^{-8} g cm^{-3})

Quasi - isothermal ***10^{2} yr***

Second Larson core

(10^{4}K, 10^{-4} g cm^{-3}, 10^{-2} AU)

Star formation evolutionary sequence



Vaytet et al. (2013)

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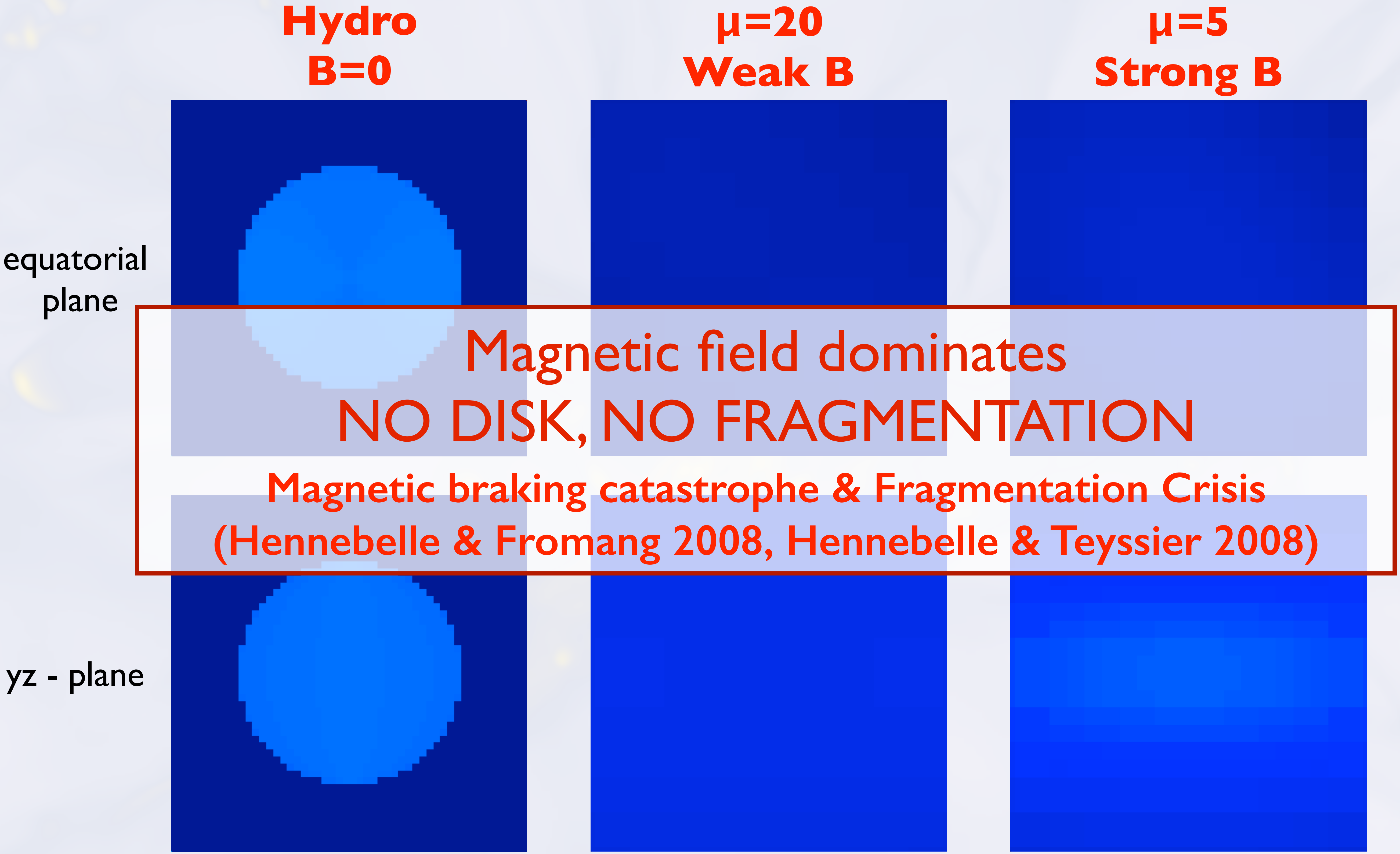
André 2002

Main achievements since 2014

- **Observations by ALMA & NOEMA**
  - down to a spatial resolution <50 AU in Class 0 protostars => the fragmentation and disk scales!
  - dust polarization => magnetic fields
- **New numerical tools:**
  - non-ideal MHD : ambipolar diffusion, Ohmic diffusion, and Hall effect
  - multifrequency radiation hydrodynamics
  - dust and gas mixture

State-of-the-art in 2010: ideal MHD



Magnetic field dominates

NO DISK, NO FRAGMENTATION

Magnetic braking catastrophe & Fragmentation Crisis
(Hennebelle & Fromang 2008, Hennebelle & Teyssier 2008)

Commerçon et al. (2010)

Disk formation in magnetised cores

- ✓ **Late formation**
  - ➢ end of class 0, $M_{env} << M_{env,0}$ (e.g., *Machida & Hosokawa 2013*)
- ✓ **Misalignment**
  - ➢ no reason for the rotation axis and the magnetic field to be aligned (e.g., *Hull et al. 2013*)
  - ➢ reduces magnetic braking efficiency (e.g., *Hennebelle & Ciardi 2009, Joos et al. 2012, Li et al. 2013*)
- ✓ **Turbulent diffusion**
  - ➢ reconnection events fast with Ohmic diffusion only, collective effect at larger scale (e.g., *Santos Lima et al. 2012, Joos et al. 2013, Seifried et al. 2013*)
- ✓ **Non-ideal MHD**
  - ➢ Ohm dissipation (*Tomida et al. 2013, 2015, Machida et al.*)
  - ➢ Hall effect (*Krasnopolsky et al. 2011, Tsukamota et al. 2015, Wurster et al. 2016*)
  - ➢ ambipolar diffusion (*Tsukamota et al. 2015, Masson et al. 2016*)

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Non-ideal MHD

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \left[\mathbf{u} \times \mathbf{B} - \eta_\Omega \mathbf{J} - \frac{\eta_\mathrm{H}}{||\mathbf{B}||} \mathbf{J} \times \mathbf{B} + \frac{\eta_\mathrm{AD}}{||\mathbf{B}||^2} \mathbf{J} \times \mathbf{B} \times \mathbf{B} \right] = 0$$

Non-ideal effects:

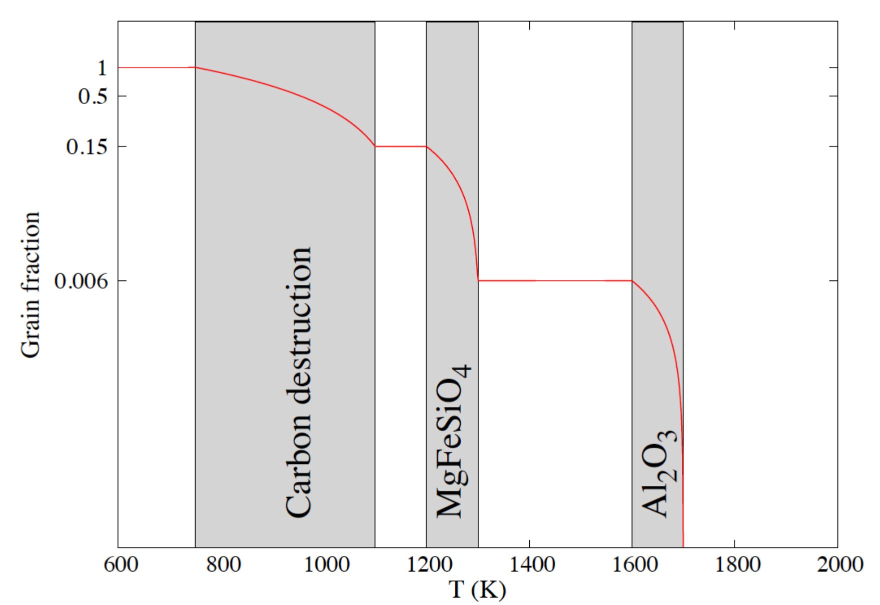
- rearrangement of magnetic field lines
- reconnection
- magnetic flux diffusion
- … needs gas-grain chemistry

✓ Non-ideal MHD

- Ohm dissipation (*Tomida et al. 2013, 2015, Machida et al.*)
- Hall effect (*Krasnopolsky et al. 2011, Tsukamota et al. 2015, Wurster et al. 2016*)
- ambipolar diffusion (*Tsukamota et al. 2015, Masson et al. 2016*)

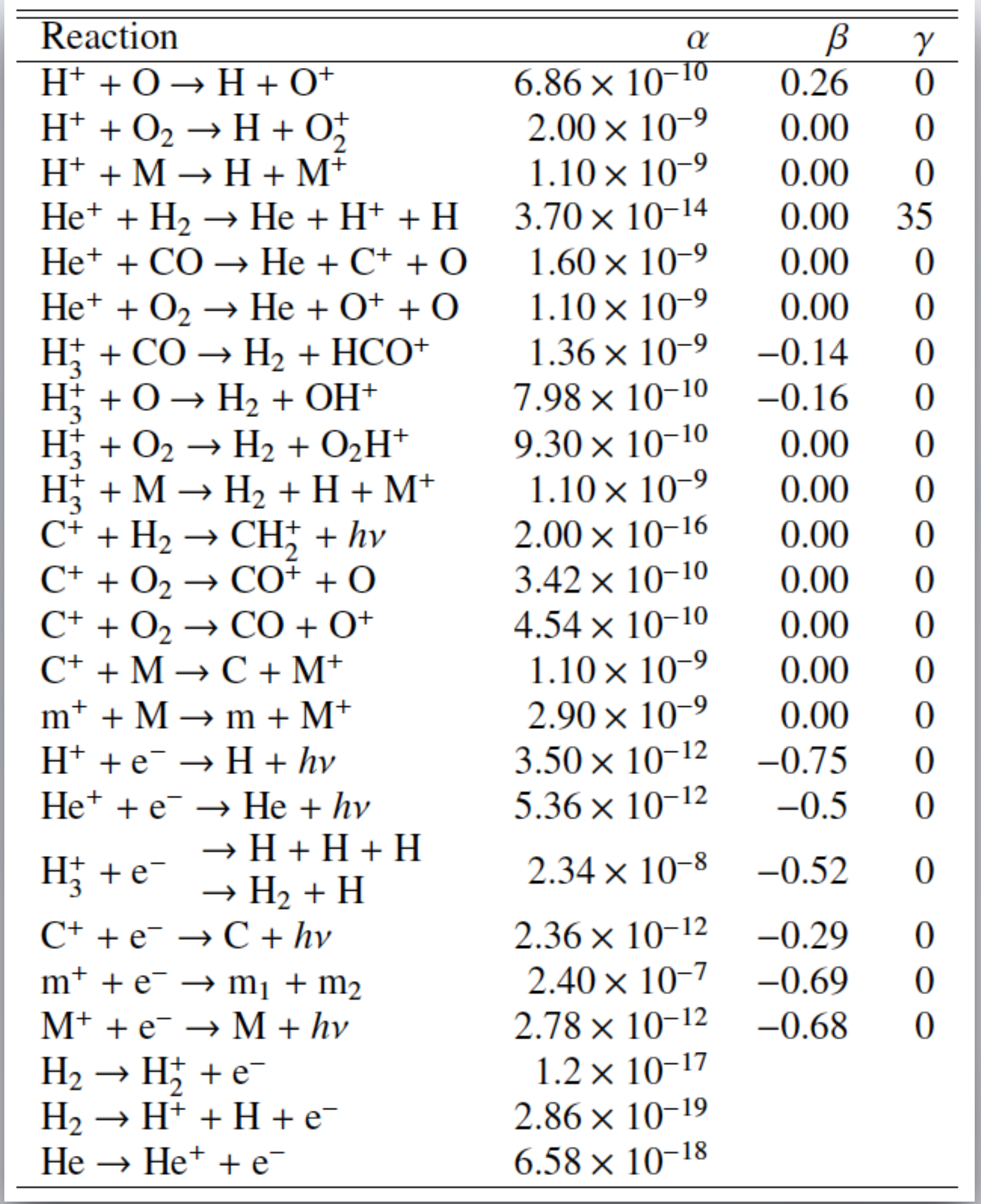
Equilibrium chemistry for non-ideal MHD

- ✓ **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



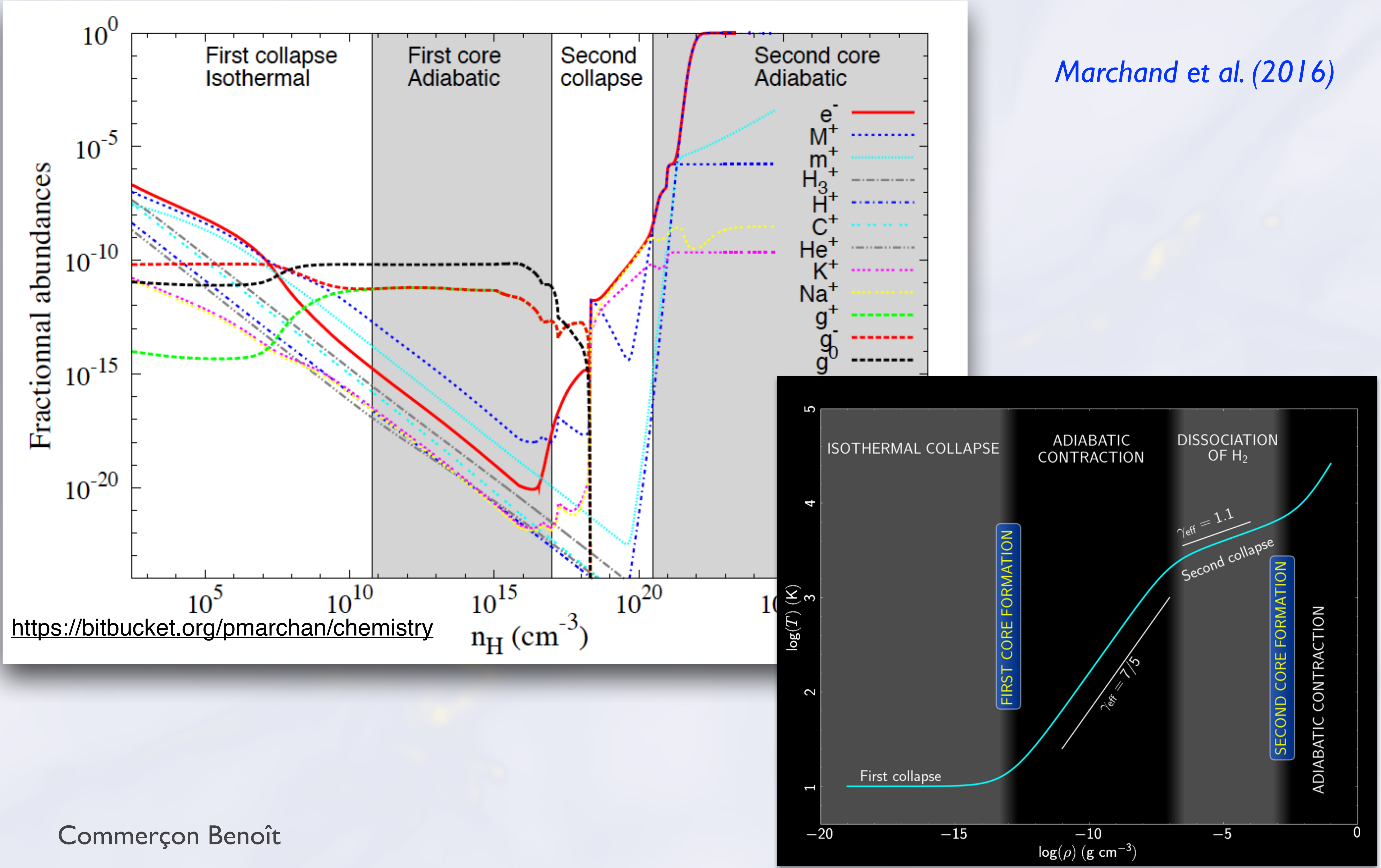
Reaction	α	β	γ
$H^+ + O \rightarrow H + O^+$	6.86×10^{-10}	0.26	0
$H^+ + O_2 \rightarrow H + O_2^+$	2.00×10^{-9}	0.00	0
$H^+ + M \rightarrow H + M^+$	1.10×10^{-9}	0.00	0
$He^+ + H_2 \rightarrow He + H^+ + H$	3.70×10^{-14}	0.00	35
$He^+ + CO \rightarrow He + C^+ + O$	1.60×10^{-9}	0.00	0
$He^+ + O_2 \rightarrow He + O^+ + O$	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)

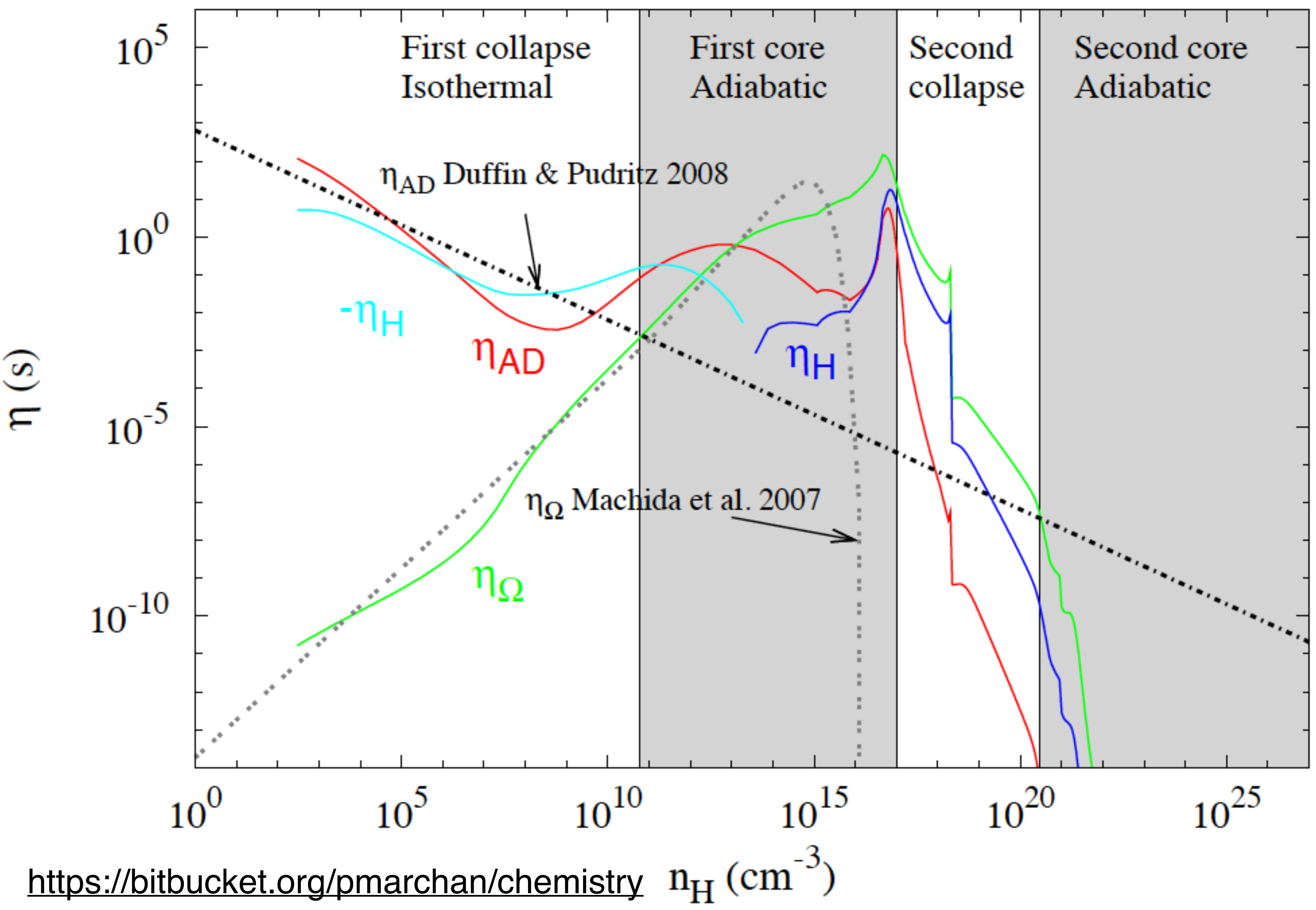
Equilibrium chemistry for non-ideal MHD: results

Marchand et al. (2016)



https://bitbucket.org/pmarchan/chemistry

Equilibrium chemistry for non-ideal MHD: results



https://bitbucket.org/pmarchan/chemistry

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

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

1/ **Grain evaporation** is the most important effect
2/ Needs at least 10 bins in dust grain size distribution to converge…

Marchand et al. (2016)

Radiation-magneto-hydrodynamics in RAMSES

- ✓ **Adaptive-mesh-refinement** code **RAMSES** (*Teyssier 2002*)
- ✓ **Non-ideal MHD** solver using Constrained Transport (*Teyssier et al. 2006, Fromang et al. 2006, **Masson et al. 2012,2016***). Resistivity from steady-state gas-grain chemistry (***Marchand et al. 2016***)
- ✓ **Multifrequency Radiation-HD** solver using the Flux Limited Diffusion approximation (***Commerçon et al. 2011b, 2014, González et al. 2015***). In this work, just **grey**
- ✓ See *Lesur et al. (2014)* for a full niMHD implementation in the **PLUTO** code.

$$
\begin{aligned}
\partial_t \rho &+ \nabla \cdot [\rho \mathbf{u}] &&= 0 \\
\partial_t \rho \mathbf{u} &+ \nabla \cdot [\rho \mathbf{u} \otimes \mathbf{u} + P\mathbb{I}] &&= -\rho \nabla \Phi - \lambda \nabla E_{\mathrm{r}} + (\nabla \times \mathbf{B}) \times \mathbf{B} \\
\partial_t E_{\mathrm{T}} &+ \nabla \cdot [\mathbf{u}(E_{\mathrm{T}} + P_{\mathrm{T}}) - \mathbf{B}(\mathbf{B} \cdot \mathbf{u}) + \mathbf{E}_{\mathrm{NIMHD}} \times \mathbf{B}] &&= -\rho \mathbf{u} \cdot \nabla \Phi - \mathbb{P}_{\mathrm{r}} \nabla : \mathbf{u} - \lambda \mathbf{u} \nabla E_{\mathrm{r}} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_{\mathrm{R}}} \nabla E_{\mathrm{r}} \right) \\
\partial_t E_{\mathrm{r}} &+ \nabla \cdot [\mathbf{u} E_{\mathrm{r}}] &&= -\mathbb{P}_{\mathrm{r}} \nabla : \mathbf{u} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_{\mathrm{R}}} \nabla E_{\mathrm{r}} \right) + \kappa_{\mathrm{P}} \rho c (a_{\mathrm{R}} T^4 - E_{\mathrm{r}}) \\
\partial_t B &- \nabla \times (\mathbf{u} \times \mathbf{B}) - \nabla \times \mathbf{E}_{\mathrm{NIMHD}} &&= 0
\end{aligned}
$$

Gravitational force

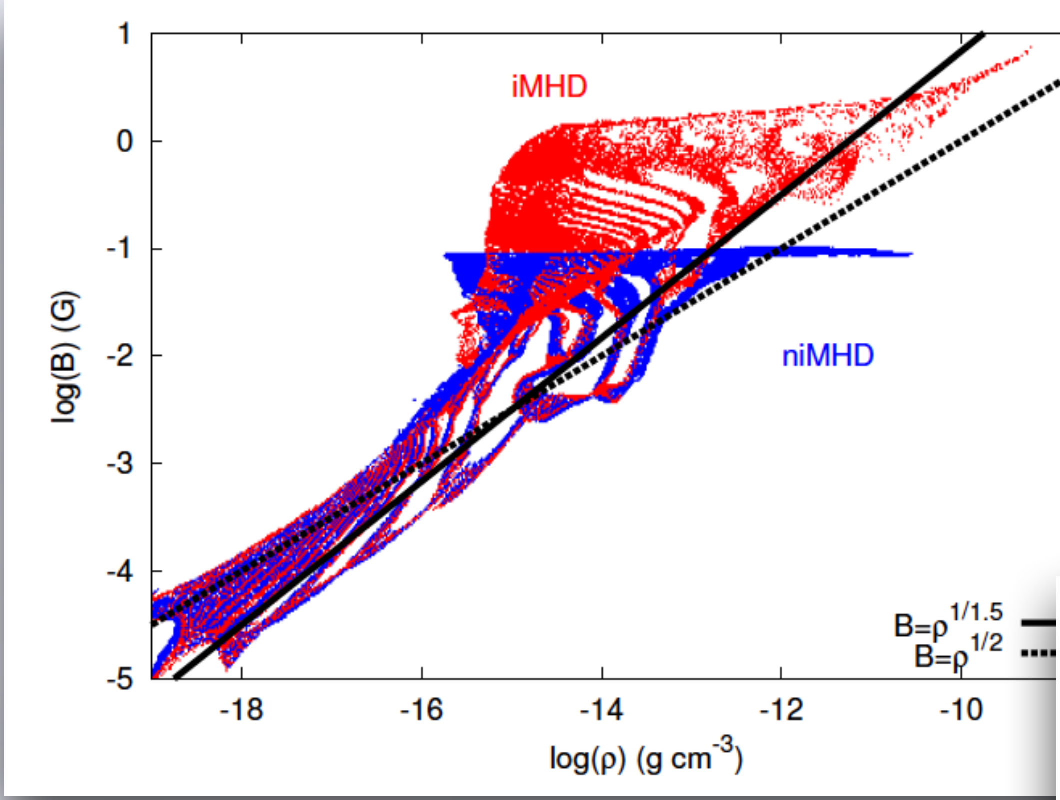
Radiative force

Lorentz force

Resisitive EMF

$$\mathbf{E}_{\mathrm{NIMHD}} = +\eta_{\Omega} \mathbf{J} + \frac{\eta_{\mathrm{H}}}{||\mathbf{B}||} \mathbf{J} \times \mathbf{B} - \frac{\eta_{\mathrm{AD}}}{||\mathbf{B}||^2} \mathbf{J} \times \mathbf{B} \times \mathbf{B}$$

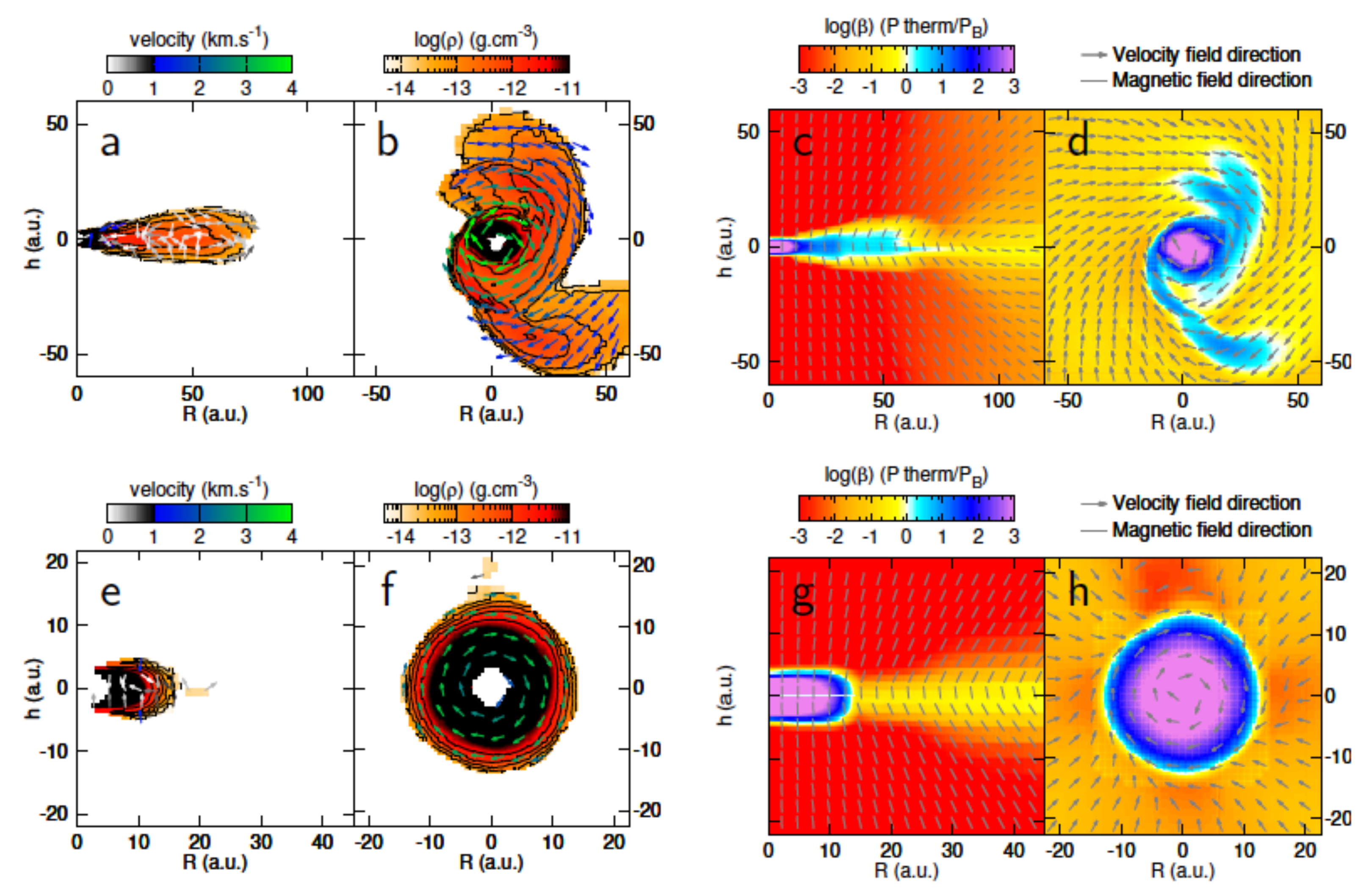
Misalignment & ambipolar diffusion



- formation of a **plateau** at B~0.1G
- **reorganisation** of magnetic field lines (essentially **poloidal**)

=> **reduced magnetic braking**

- mass and radius of first core do not change
- **weaker outflows** compared to ideal MHD

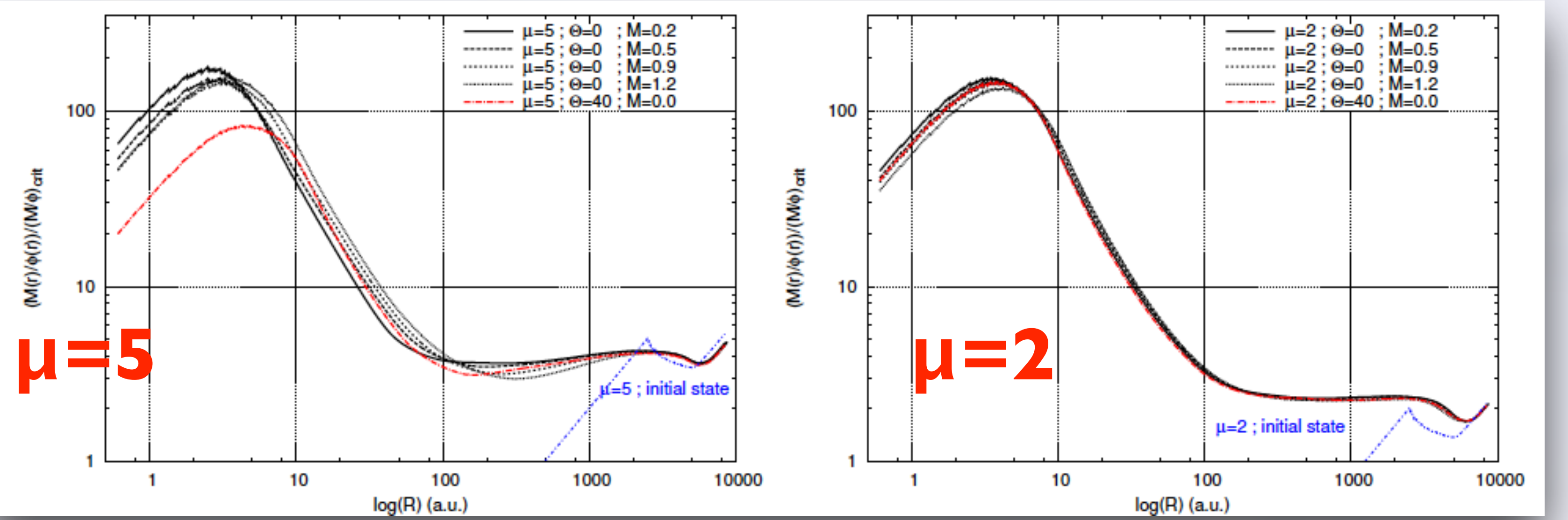


- Rotationally supported disk formation (**R ~ 50 AU**) - consistent with obs.
- **P_{therm}/P_{mag}>1** within disks
- **poloidal** magnetic field

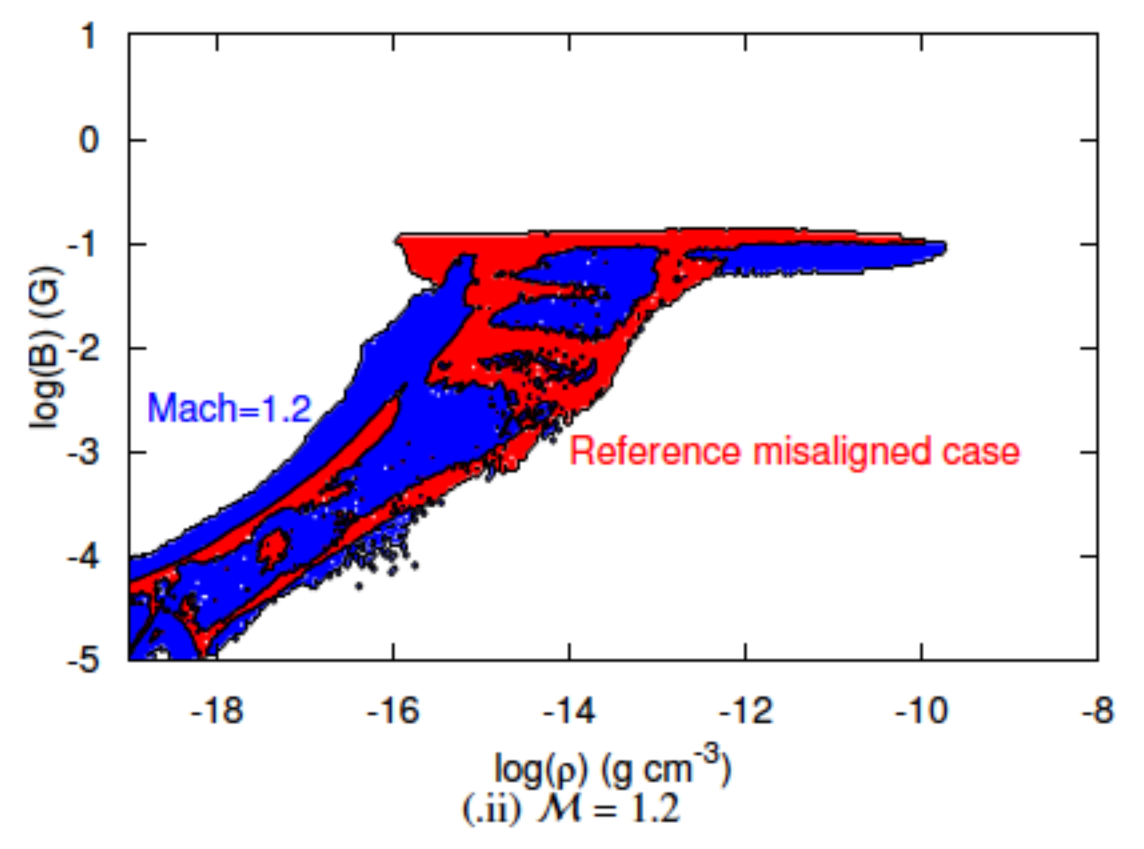
=> initial conditions for protoplanetary disks studies

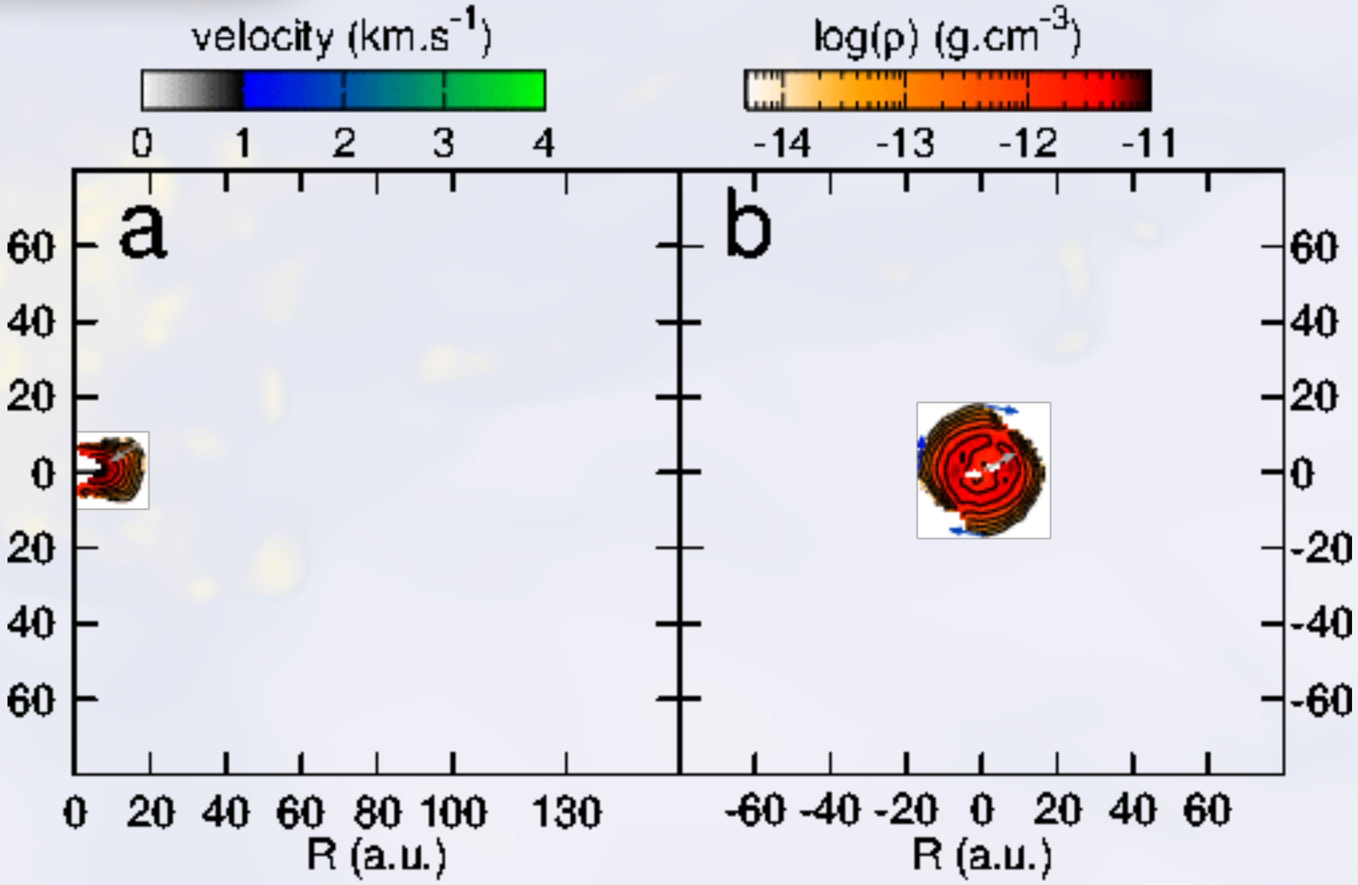
Masson et al. 2016

Turbulence and ambipolar diffusion



- magnetisation & disc size **does not depend** on turbulence level, nor on the initial magnetic field amplitude





Commerçon et al. in prep.

Magnetically regulated disc size with AD

Hennebelle et al. (2016)

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

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

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

- disc size **does not depend** on turbulence level
- weak dependance on the mass

VS.

$$r_{\rm d,hydro} \simeq \frac{\Omega_0^2 R_0^4}{4\pi/3\rho_0 R_0^3 G} = 3\beta R_0 = 106\ {\rm AU}\ \frac{\beta}{0.02} \left(\frac{M}{0.1\ {\rm M}_\odot}\right)^{1/3} \left(\frac{\rho_0}{10^{-18} {\rm g\ cm}^{-3}}\right)^{-1/3}$$

Magnetically regulated disc size with AD

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

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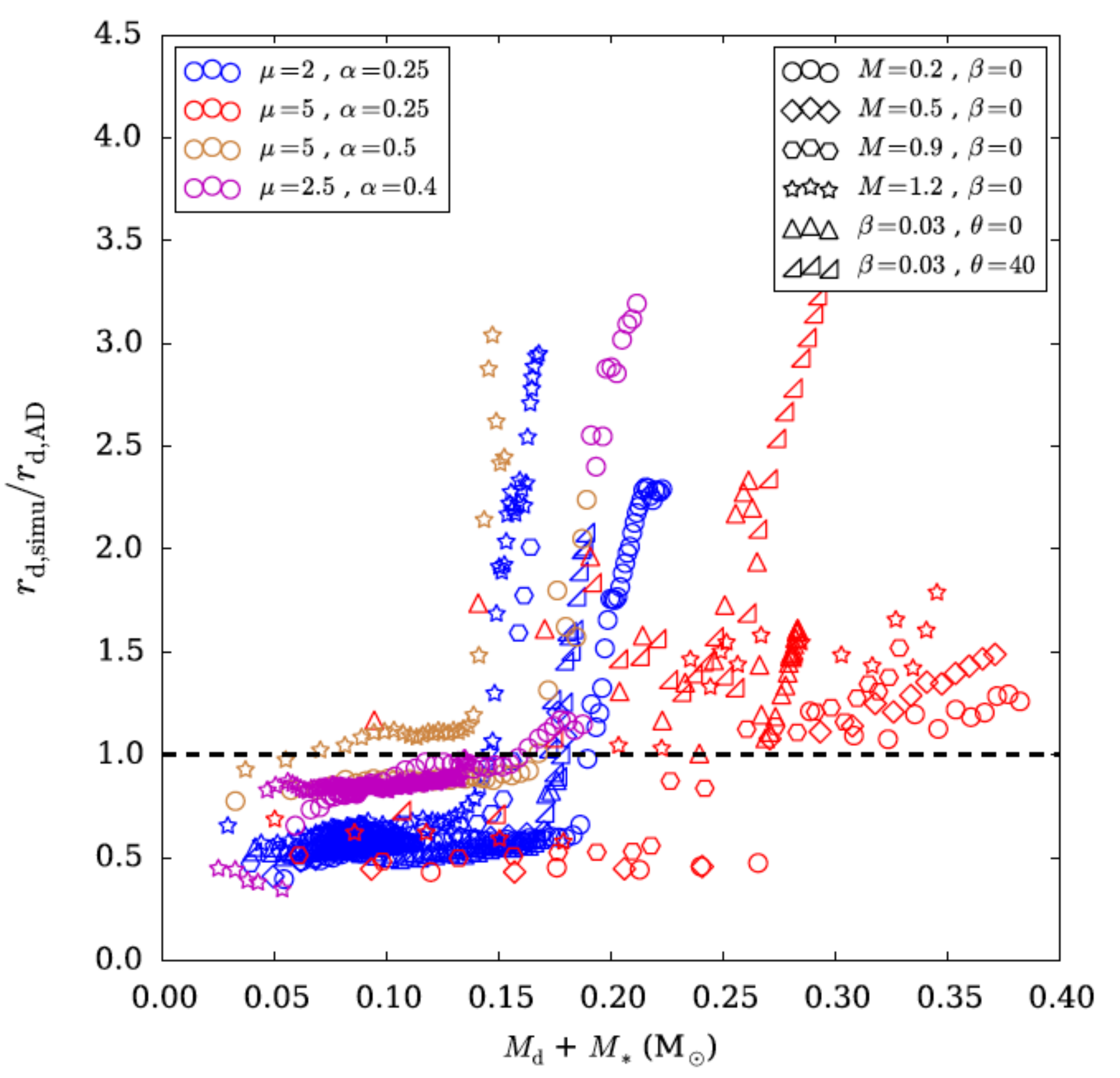
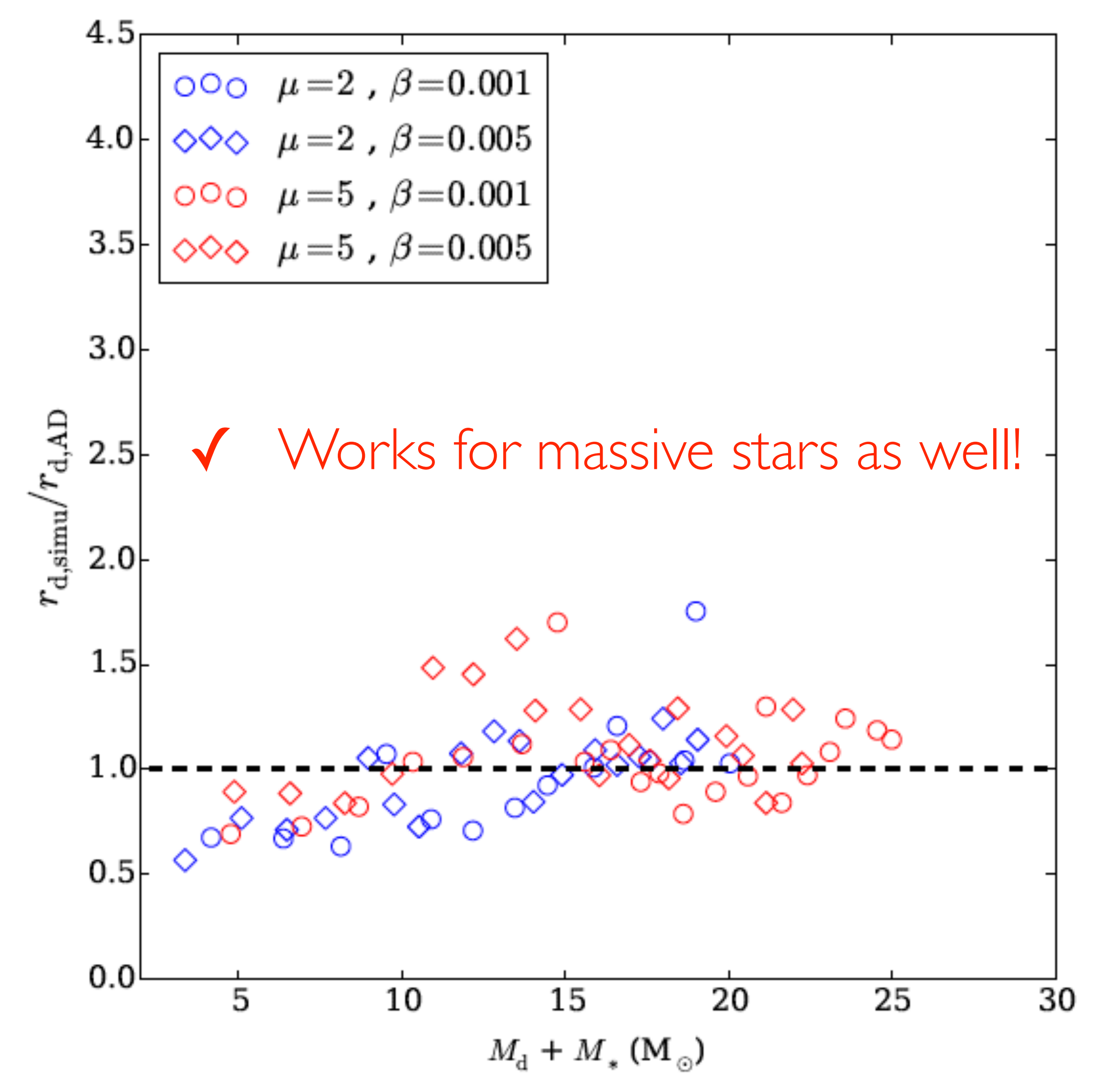
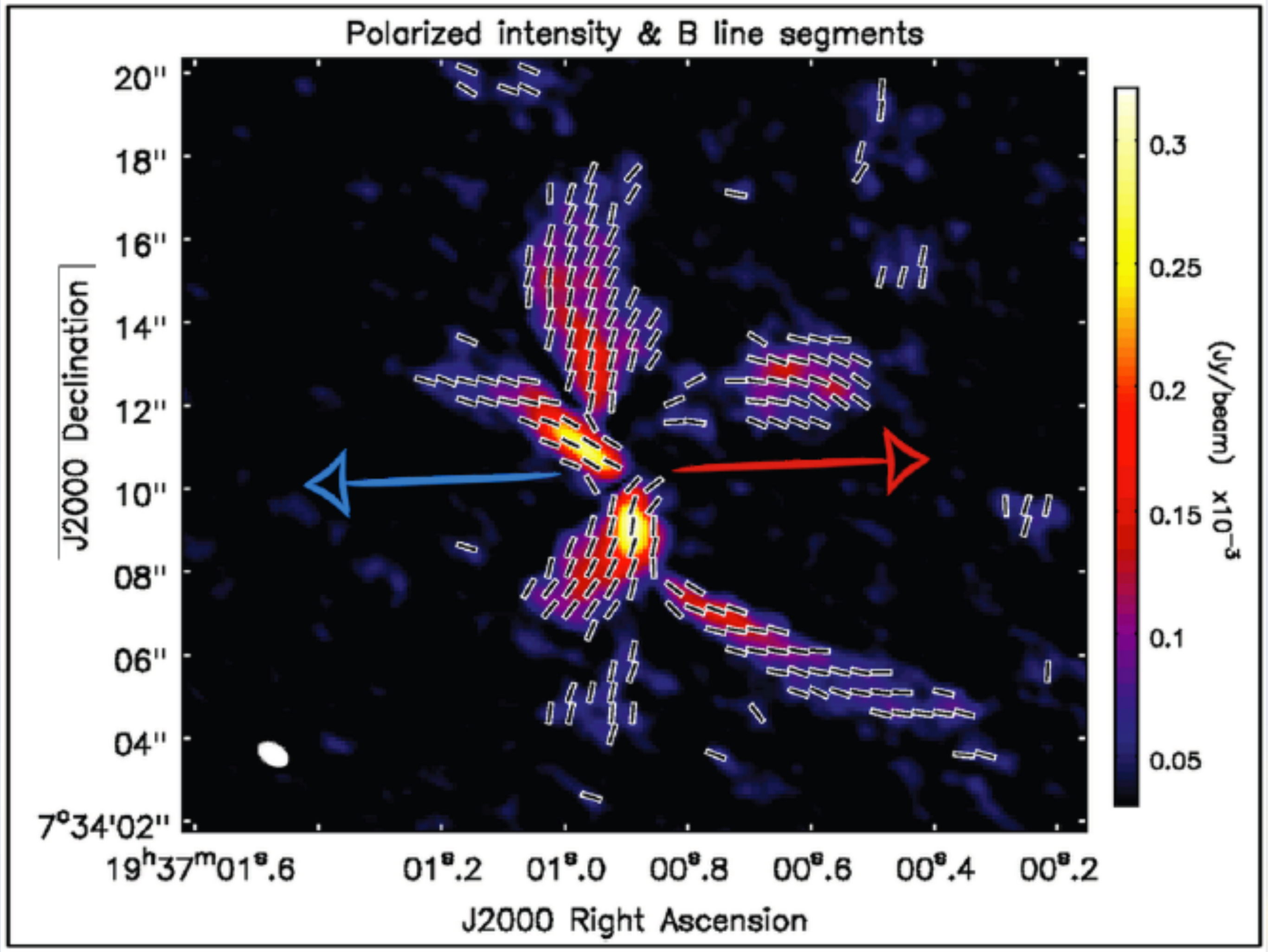




✓ Works for massive stars as well!

Hennebelle et al. (2016)

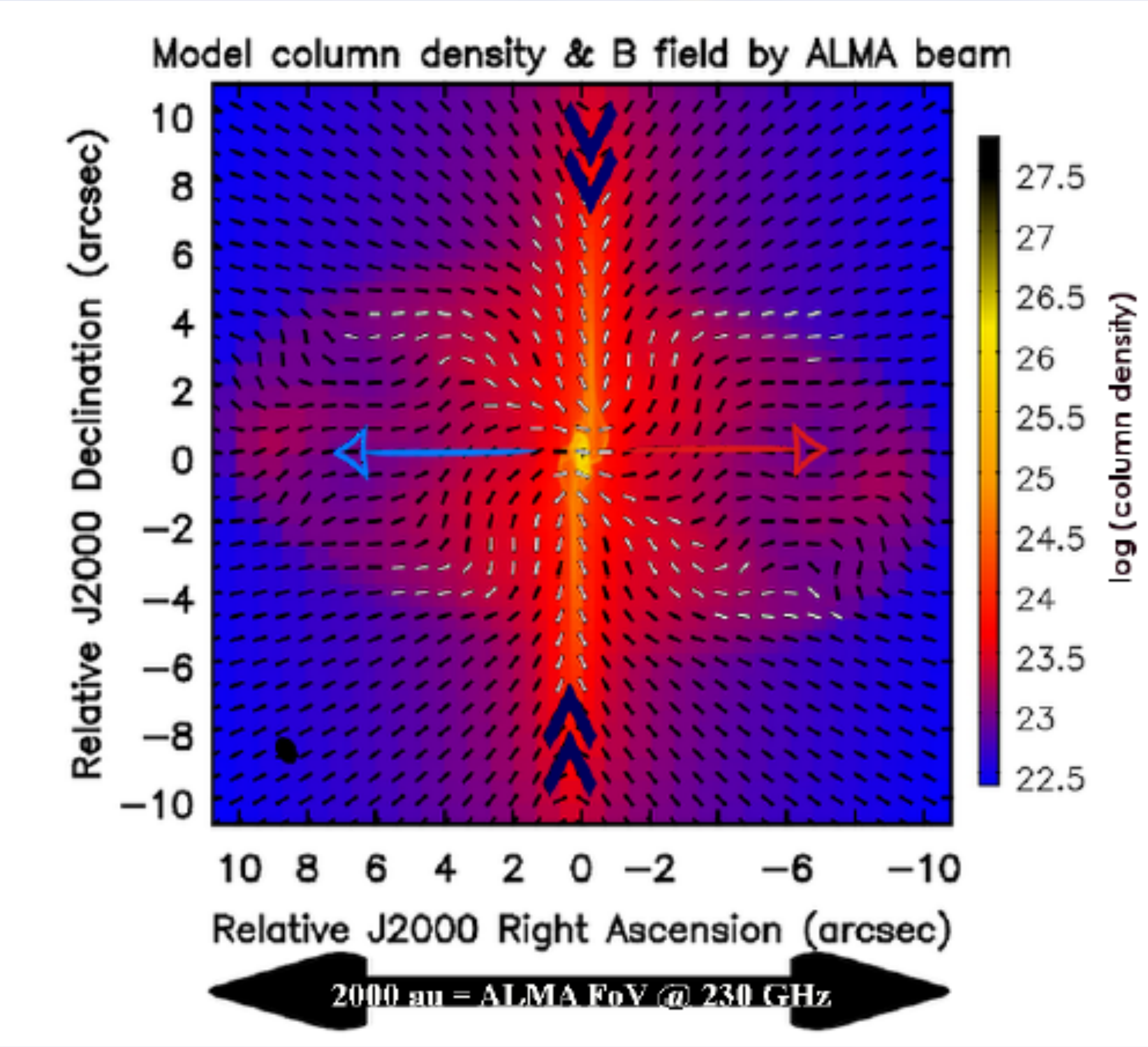
Magnetically regulated collapse?



Yen et al. (2015): No Keplerian disk with R>10 AU
=> Magnetic braking or young age?

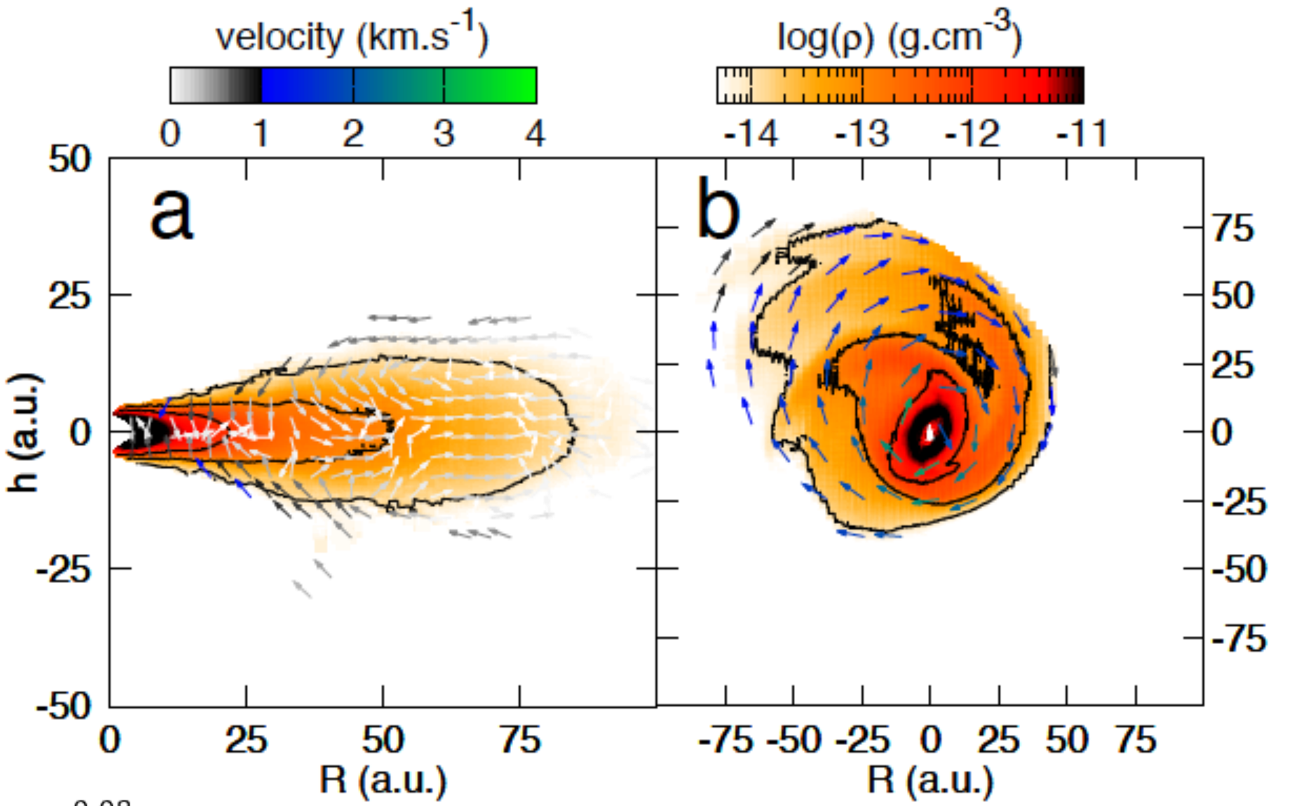
Maury et al. (2018)

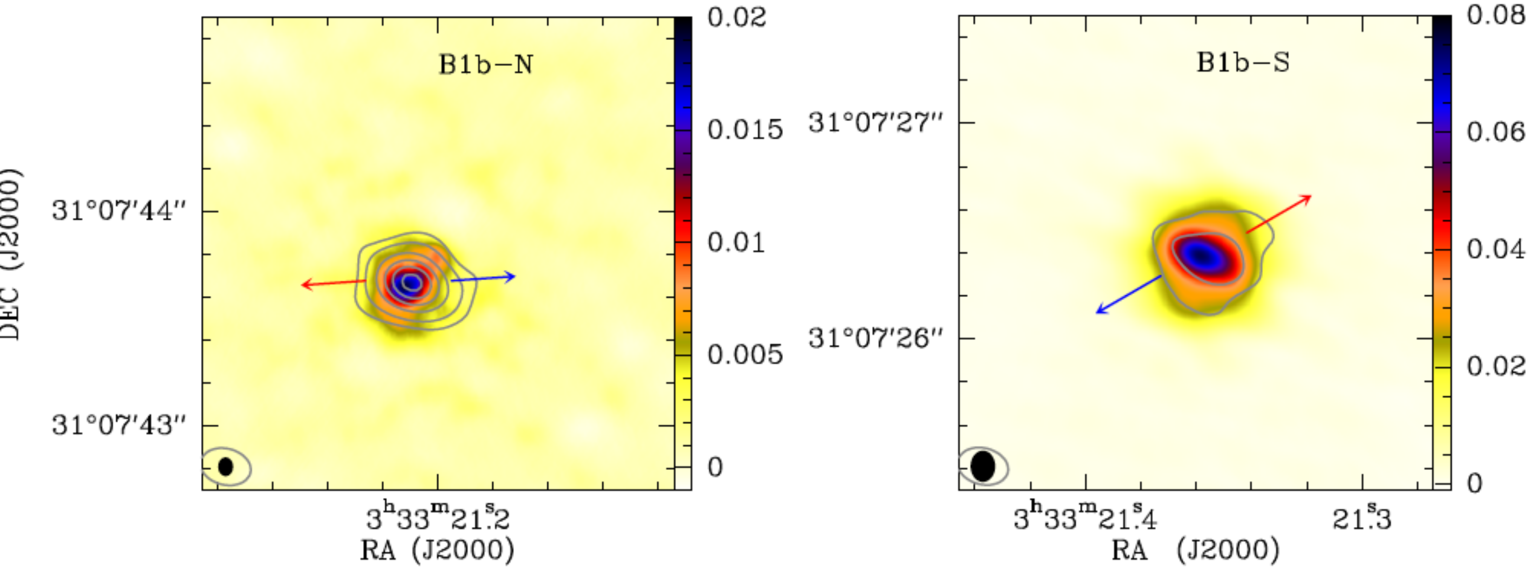
- Source B335 Class 0
- ALMA 0.8'' @ 233 GHz (~60 AU)
- data "consistent" with magnetised collapse model (2.5$M_\odot$; μ=6 ; low rotation)

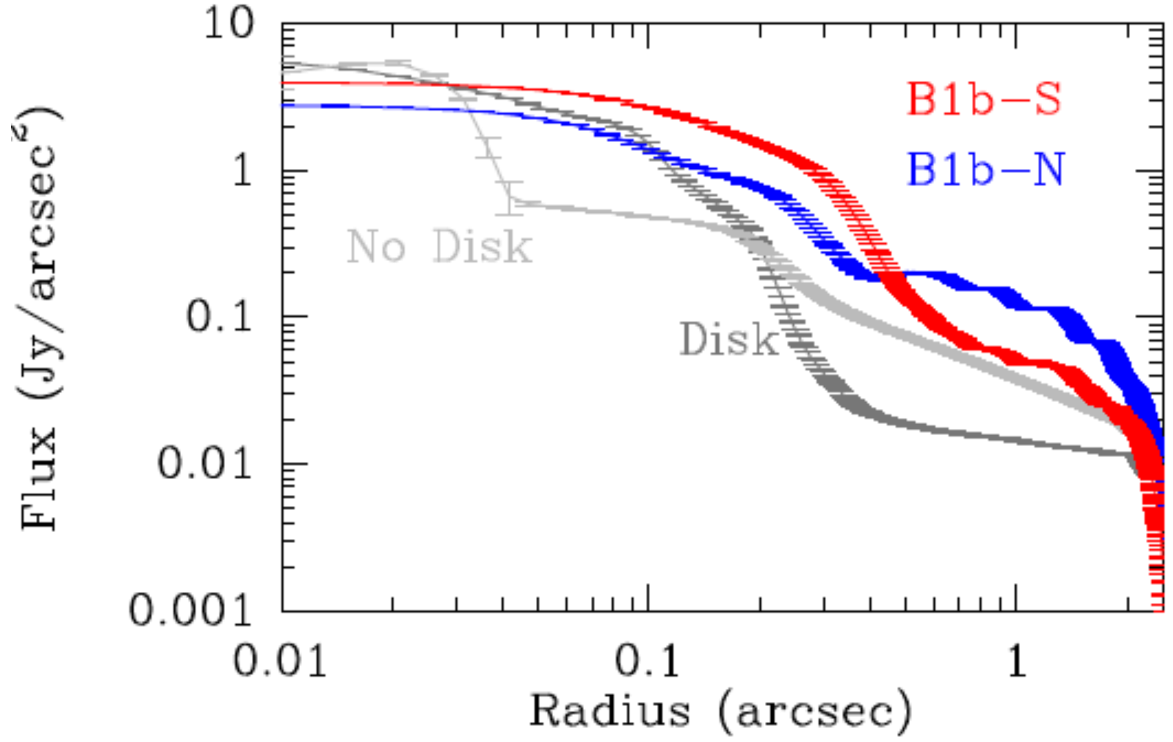


Comparison with ALMA observations

- Source Barnard 1b-N: first core candidate
- ALMA 0.06'' @ 350 GHz (~15 AU)
- data "consistent" with collapse model $(1M_\odot ; \mathcal{M}=1.2 ; \mu=2)$
- data compatible with disc growth with time

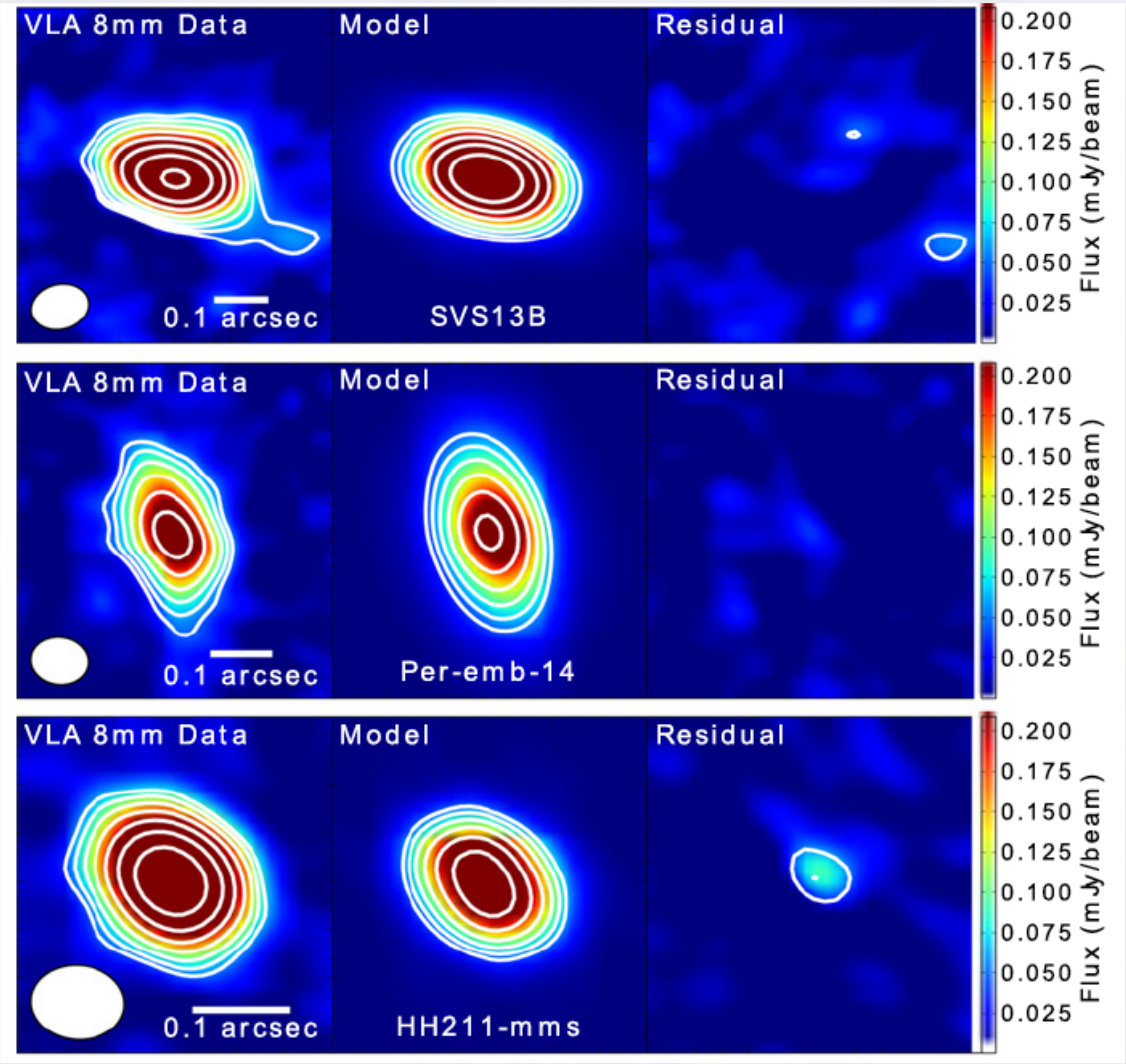






Gerin et al. A&A (2017)

Evidence of disks at class 0 & I stages



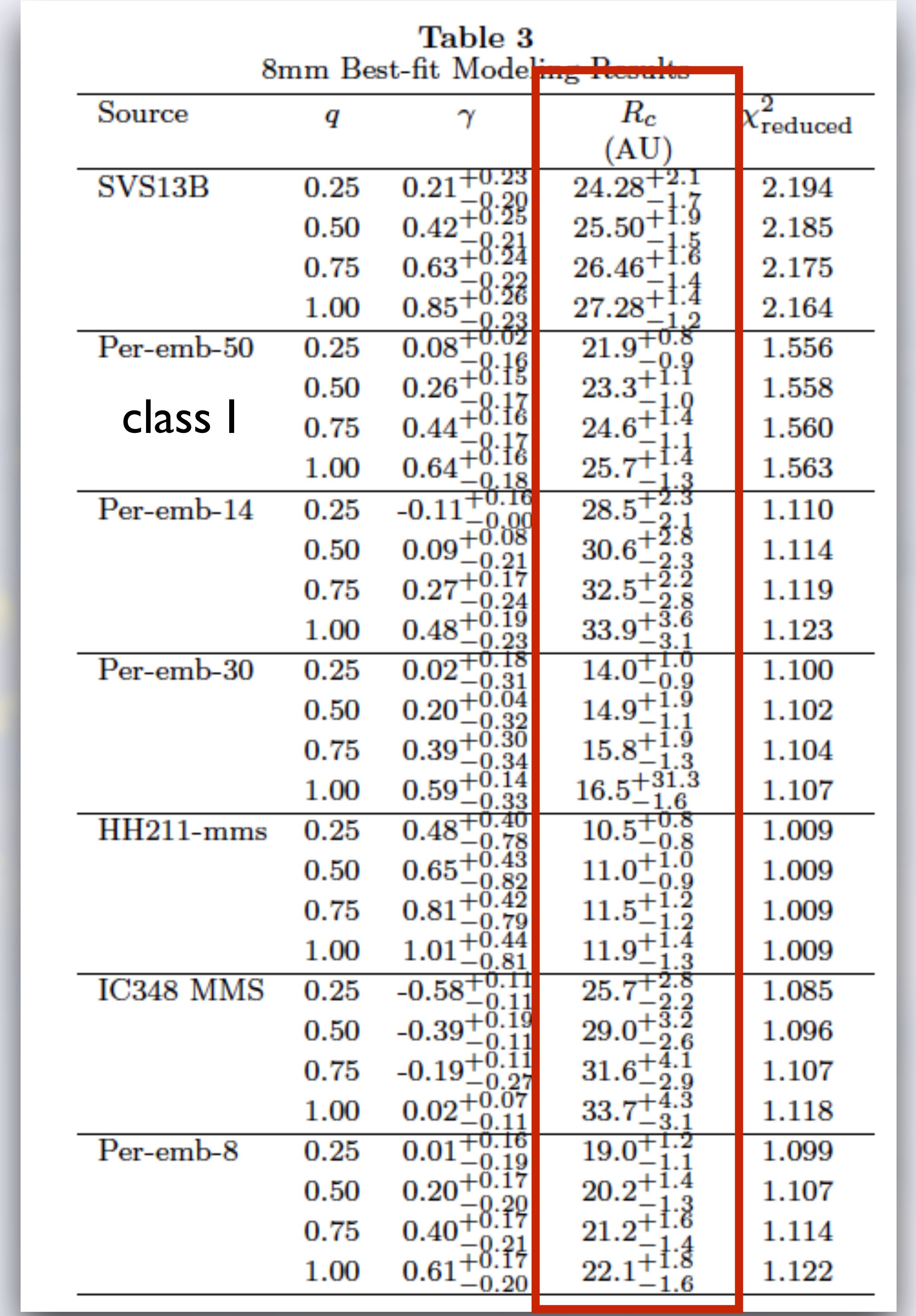


Table 3
8mm Best-fit Modeling Results

Source	q	γ	R_c (AU)	$\chi^2_{\mathrm{reduced}}$
SVS13B	0.25	$0.21^{+0.23}_{-0.20}$	$24.28^{+2.1}_{-1.7}$	2.194
	0.50	$0.42^{+0.25}_{-0.21}$	$25.50^{+1.9}_{-1.5}$	2.185
	0.75	$0.63^{+0.24}_{-0.22}$	$26.46^{+1.6}_{-1.4}$	2.175
	1.00	$0.85^{+0.26}_{-0.23}$	$27.28^{+1.4}_{-1.2}$	2.164
Per-emb-50	0.25	$0.08^{+0.02}_{-0.16}$	$21.9^{+0.8}_{-0.9}$	1.556
	0.50	$0.26^{+0.15}_{-0.17}$	$23.3^{+1.1}_{-1.0}$	1.558
	0.75	$0.44^{+0.16}_{-0.17}$	$24.6^{+1.4}_{-1.1}$	1.560
	1.00	$0.64^{+0.16}_{-0.18}$	$25.7^{+1.4}_{-1.3}$	1.563
Per-emb-14	0.25	$-0.11^{+0.16}_{-0.00}$	$28.5^{+2.3}_{-2.1}$	1.110
	0.50	$0.09^{+0.08}_{-0.21}$	$30.6^{+2.8}_{-2.3}$	1.114
	0.75	$0.27^{+0.17}_{-0.24}$	$32.5^{+2.2}_{-2.8}$	1.119
	1.00	$0.48^{+0.19}_{-0.23}$	$33.9^{+3.6}_{-3.1}$	1.123
Per-emb-30	0.25	$0.02^{+0.18}_{-0.31}$	$14.0^{+1.0}_{-0.9}$	1.100
	0.50	$0.20^{+0.04}_{-0.32}$	$14.9^{+1.9}_{-1.1}$	1.102
	0.75	$0.39^{+0.30}_{-0.34}$	$15.8^{+1.9}_{-1.3}$	1.104
	1.00	$0.59^{+0.14}_{-0.33}$	$16.5^{+31.3}_{-1.6}$	1.107
HH211-mms	0.25	$0.48^{+0.40}_{-0.78}$	$10.5^{+0.8}_{-0.8}$	1.009
	0.50	$0.65^{+0.43}_{-0.82}$	$11.0^{+1.0}_{-0.9}$	1.009
	0.75	$0.81^{+0.42}_{-0.79}$	$11.5^{+1.2}_{-1.2}$	1.009
	1.00	$1.01^{+0.44}_{-0.81}$	$11.9^{+1.4}_{-1.3}$	1.009
IC348 MMS	0.25	$-0.58^{+0.11}_{-0.11}$	$25.7^{+2.8}_{-2.2}$	1.085
	0.50	$-0.39^{+0.19}_{-0.11}$	$29.0^{+3.2}_{-2.6}$	1.096
	0.75	$-0.19^{+0.11}_{-0.27}$	$31.6^{+4.1}_{-2.9}$	1.107
	1.00	$0.02^{+0.07}_{-0.11}$	$33.7^{+4.3}_{-3.1}$	1.118
Per-emb-8	0.25	$0.01^{+0.16}_{-0.19}$	$19.0^{+1.2}_{-1.1}$	1.099
	0.50	$0.20^{+0.17}_{-0.20}$	$20.2^{+1.4}_{-1.3}$	1.107
	0.75	$0.40^{+0.17}_{-0.21}$	$21.2^{+1.6}_{-1.4}$	1.114
	1.00	$0.61^{+0.17}_{-0.20}$	$22.1^{+1.8}_{-1.6}$	1.122

class I

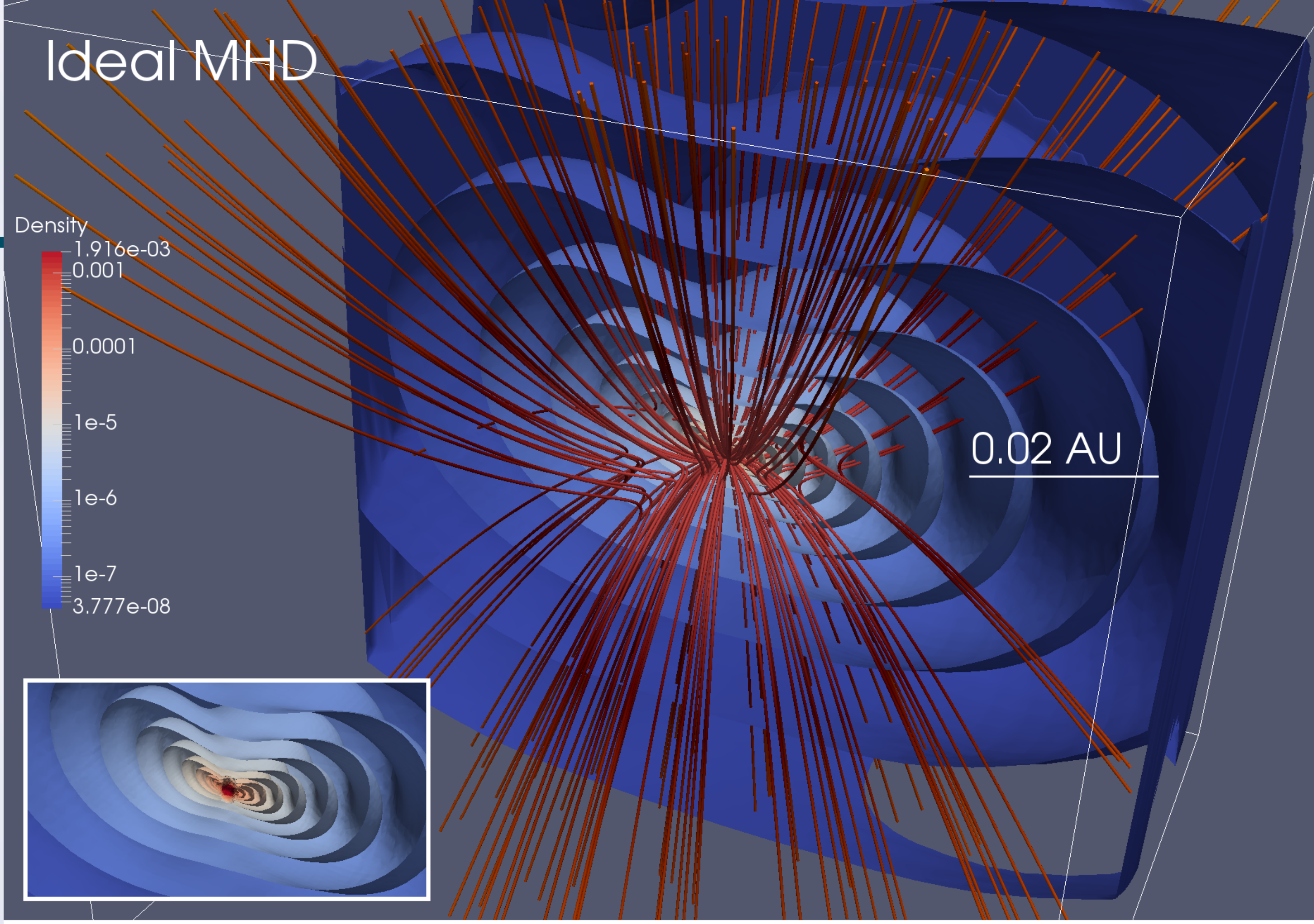
Segura-Cox et al. (2016)

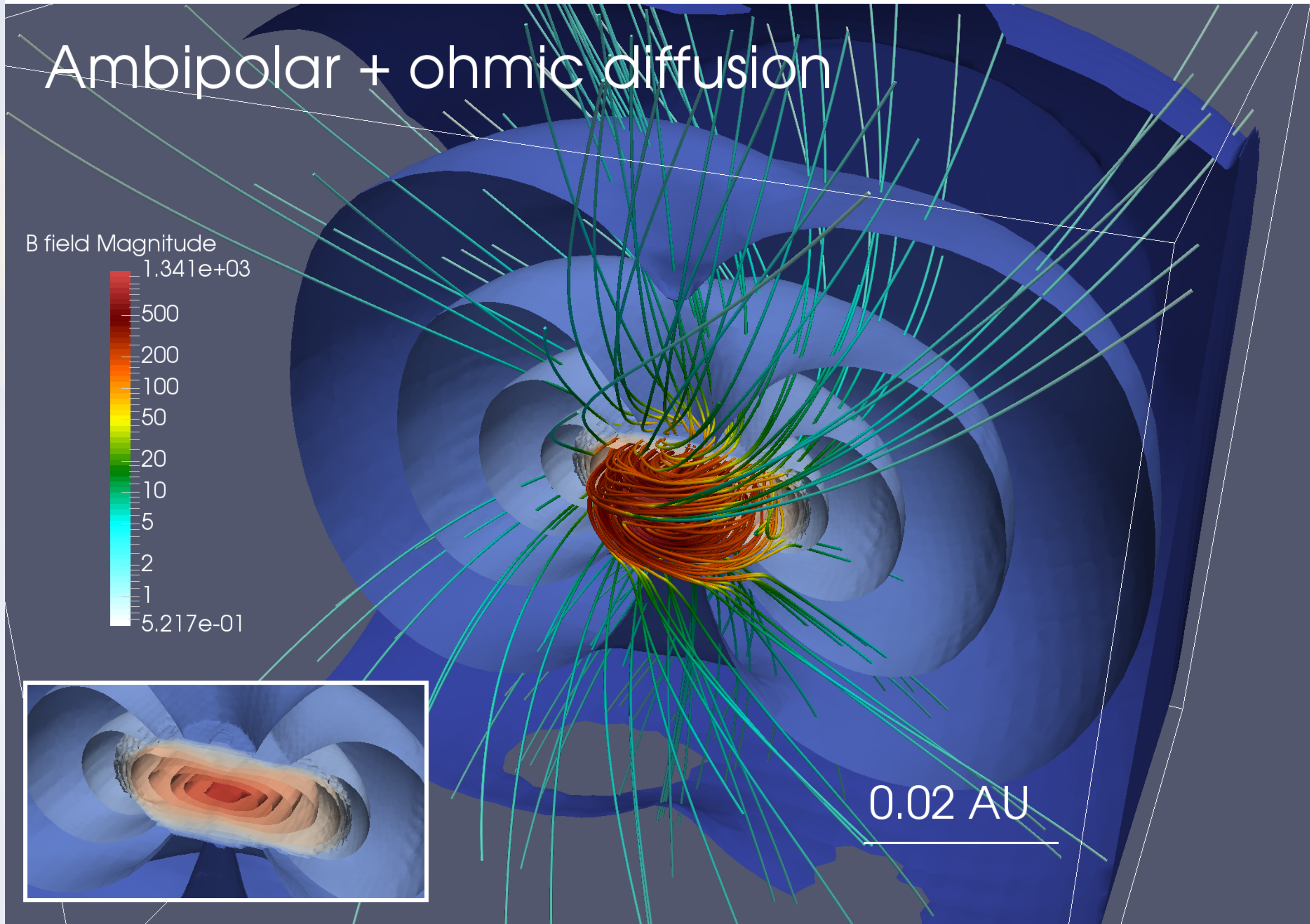
Second collapse

- Ohmic + ambipolar diffusion
- non-ideal gas EOS

Saumon, Chabrier & Von Horn (1995)

- maximum resolution : **Δ**x~8x10^{-5} AU (21 AMR levels)
- Comparaison ideal MHD (80 000 hCPU) vs. non ideal MHD(180 000 hCPU)

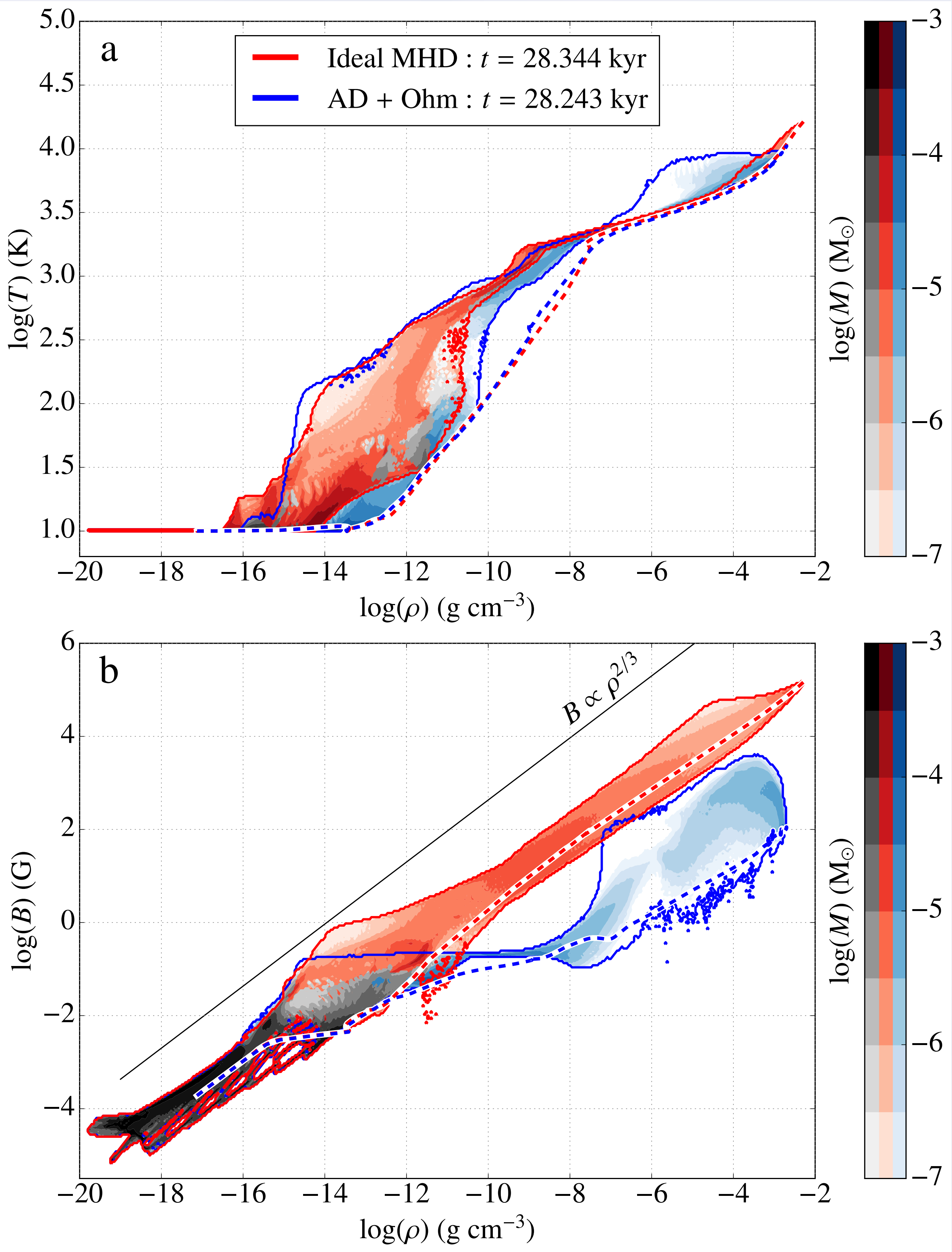




Vaytet et al. (2018)

Second collapse

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

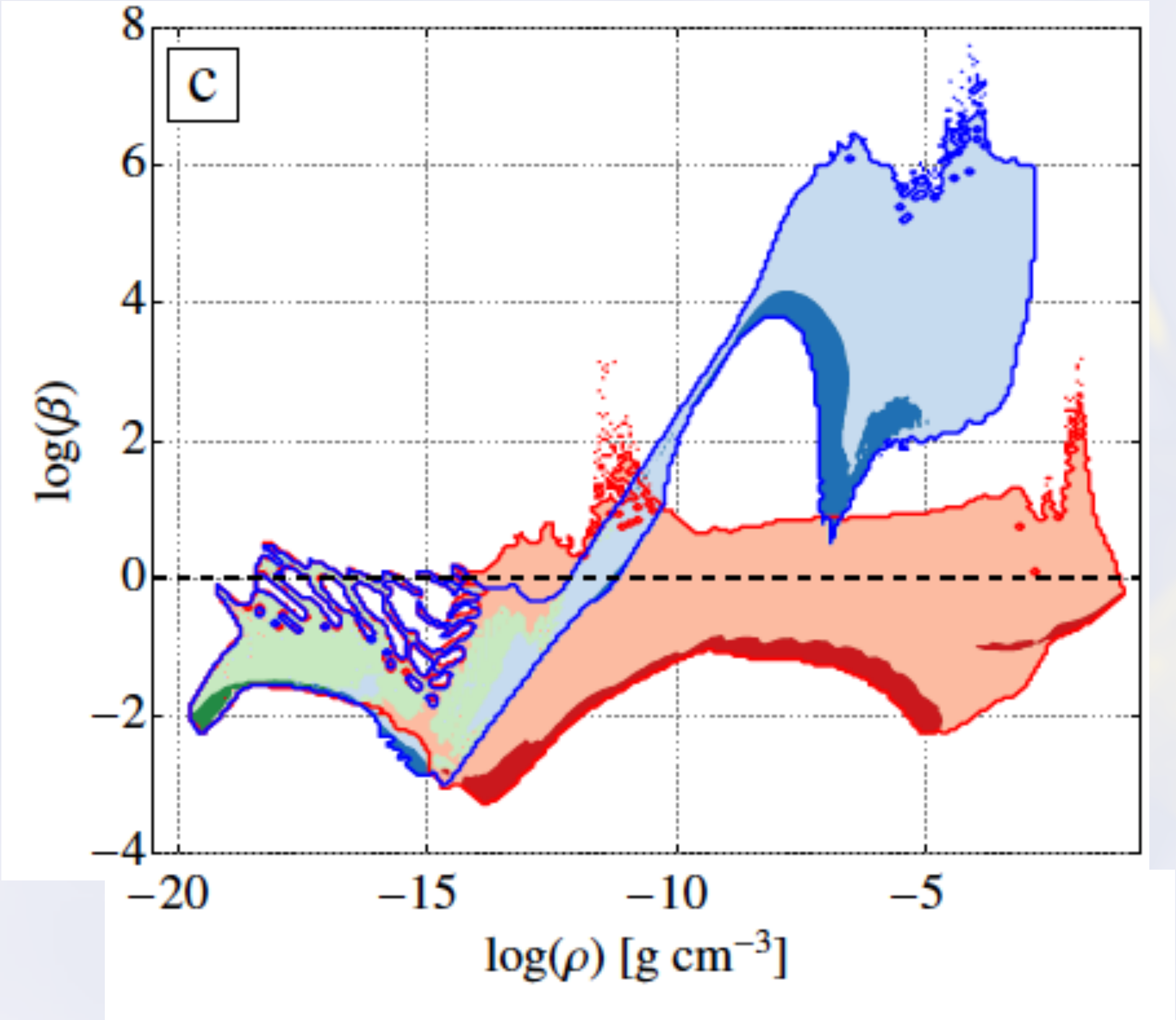


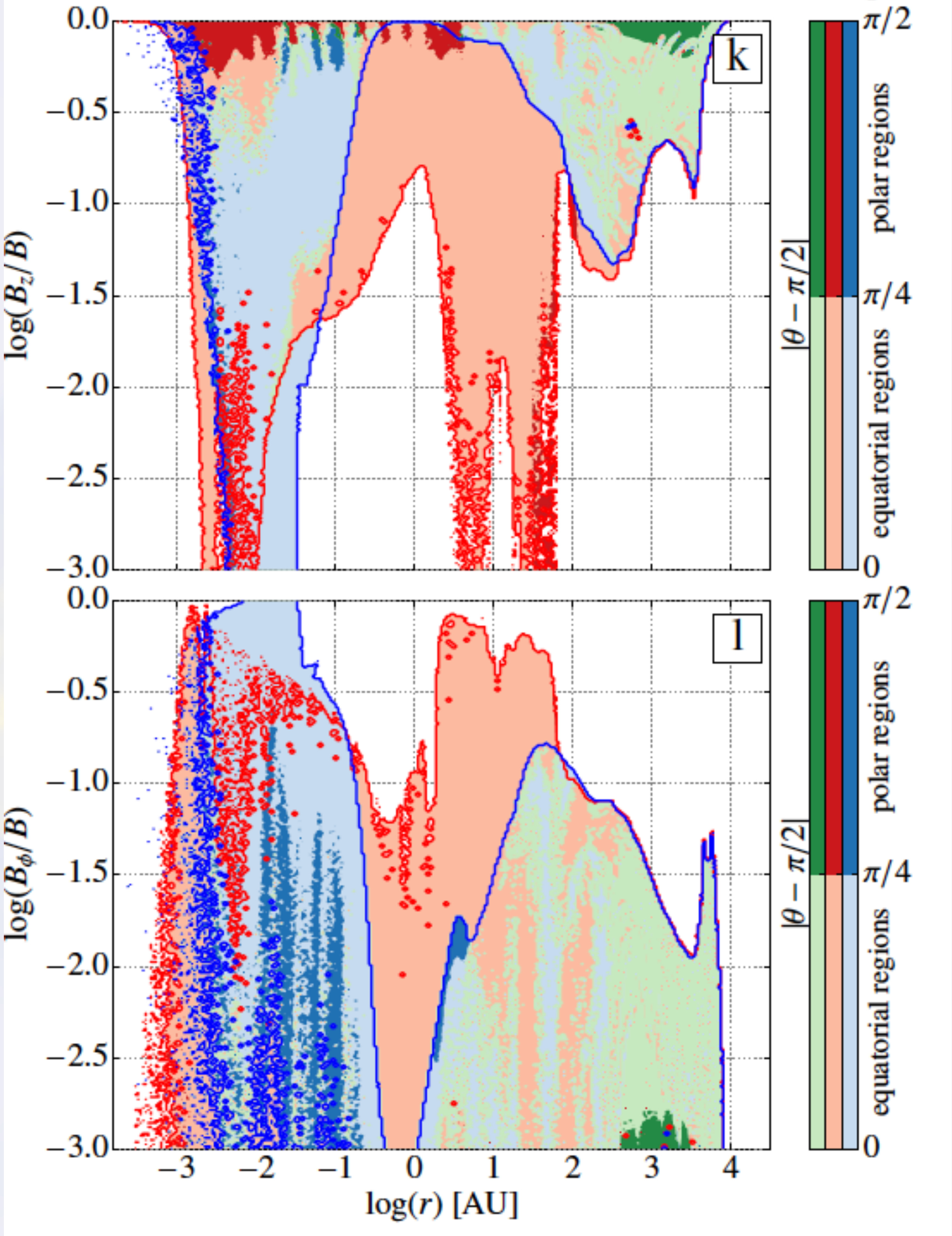
Vaytet et al. (2018)

Second collapse

— ideal MHD

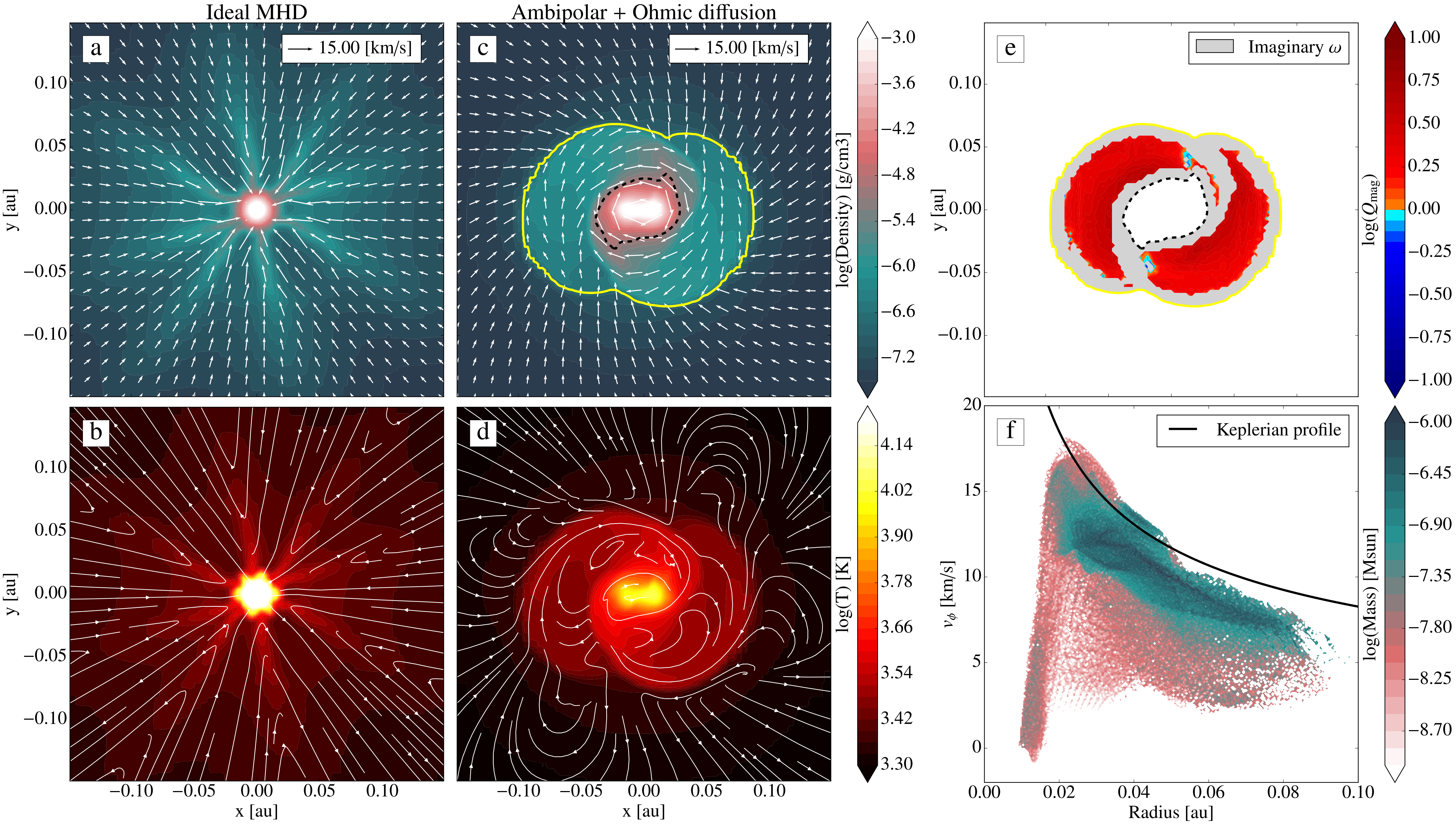
— non-ideal MHD





Vaytet et al. (2018)

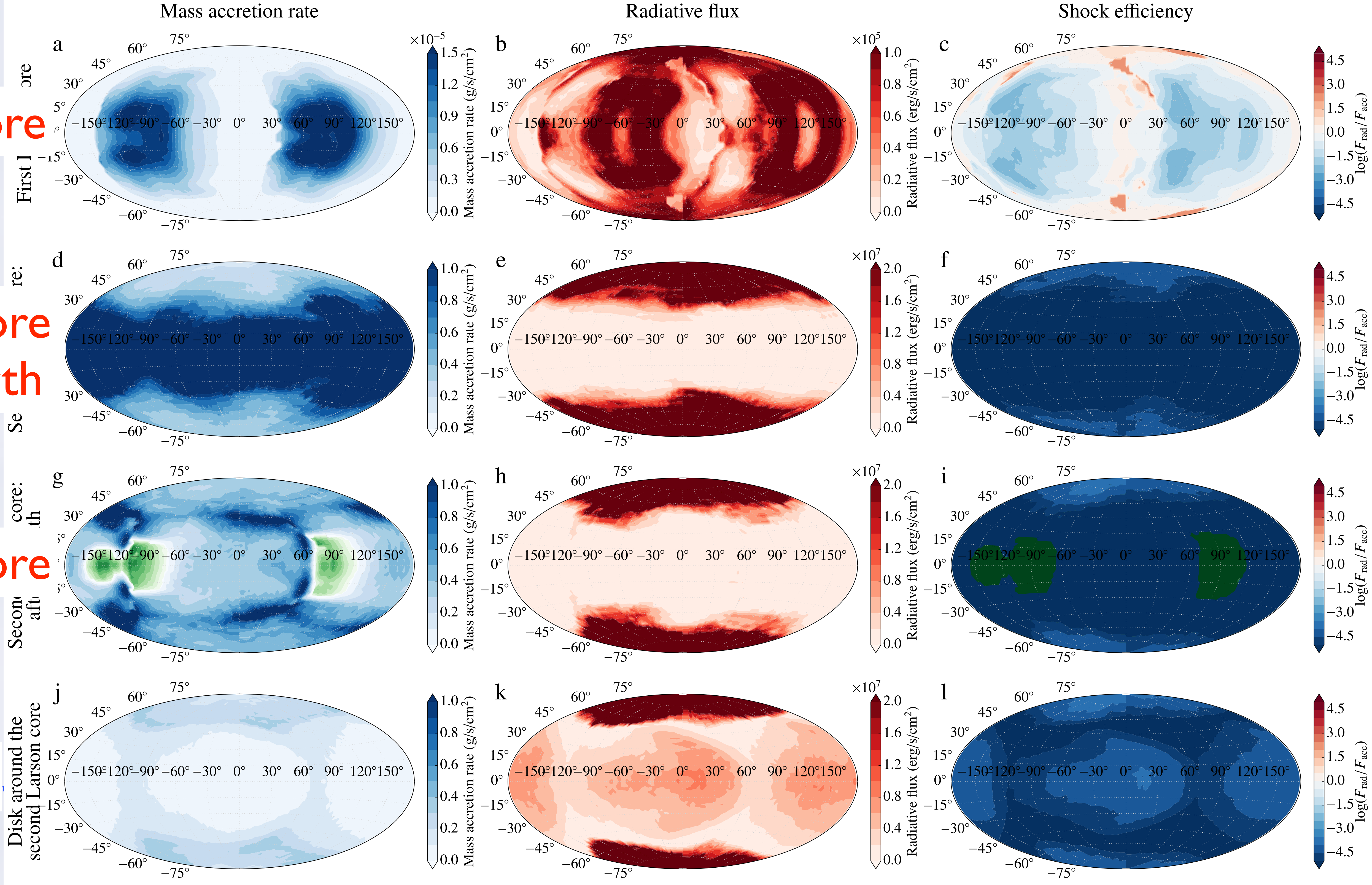
Disc birth



Vaytet et al. (2018)

Properties of the radiative accretion shock

Vaytet et al. (2018)



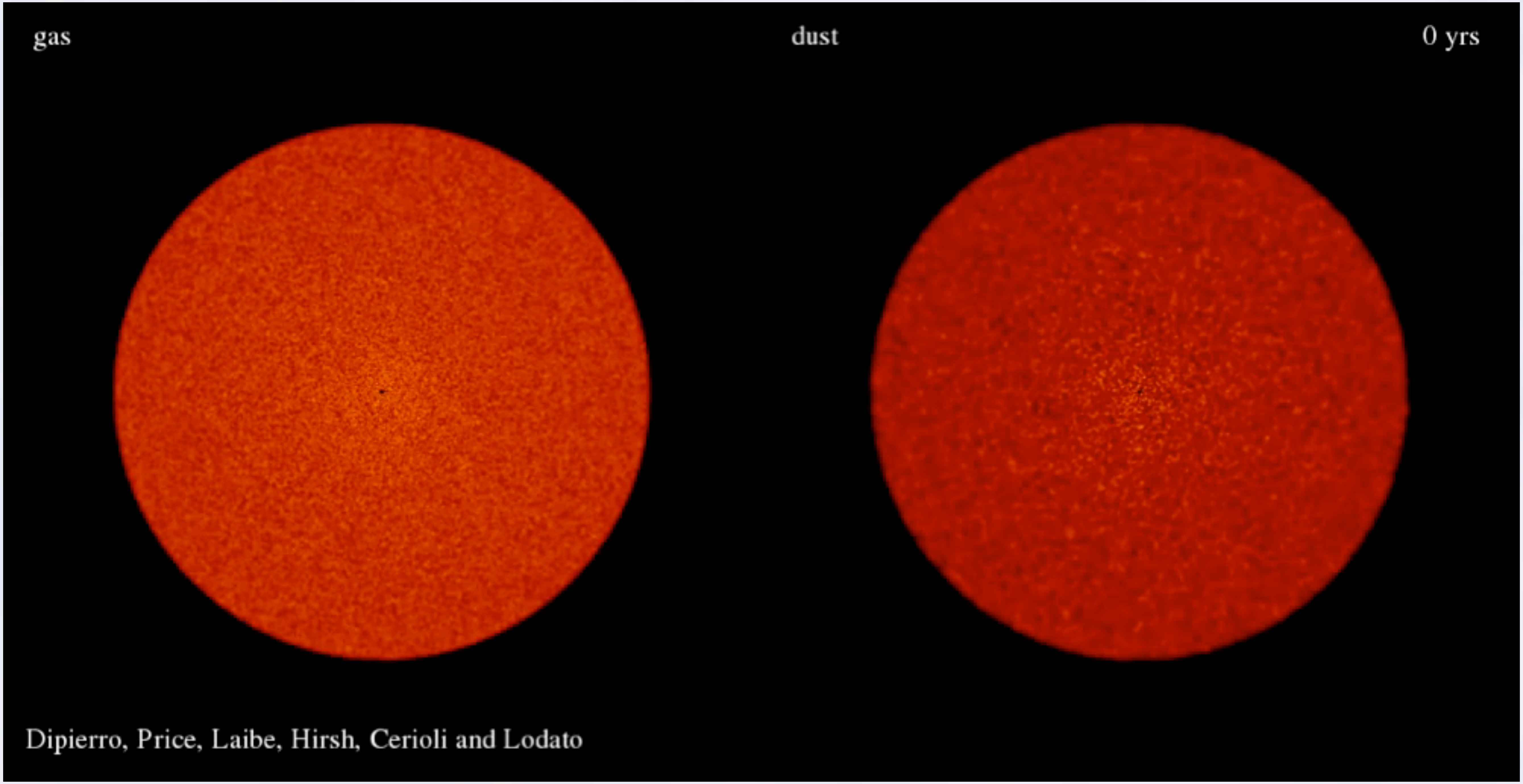
1st core

2nd core @birth

2nd core

Disc

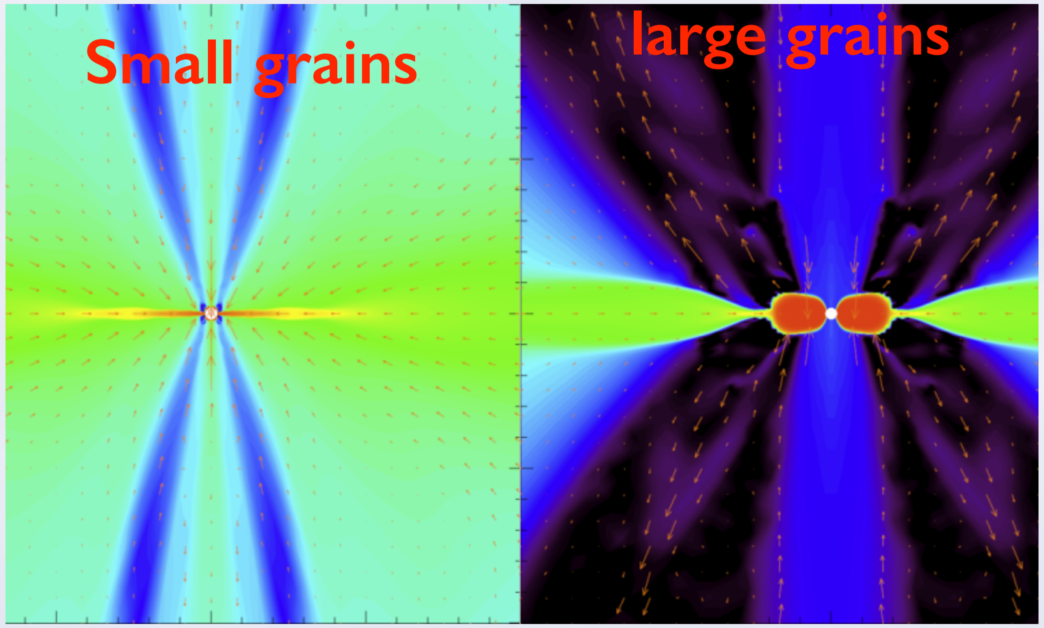
What is next?



Dipierro et al. (2015)

What is next?

- **Follow the dust dynamics at all scales**
  - dust growth
  - dust charge
  - gas-to-dust ratio



Zhao et al (2016)

- **Couple the processes**
  - magneto hydrodynamics: chemistry + dust + magnetic resistivities
  - radiation hydrodynamics: chemistry + dust + opacities
  - track cosmic rays ionisation

- **Couple the scales**
  - galaxy evolution to molecular clouds (e.g., Renaud et al. 2013)
  - self-regulated ISM, from diffuse ISM to collapsing dense cores (Hennebelle et al.)
  - protoplanetary disc evolution with accreting envelop

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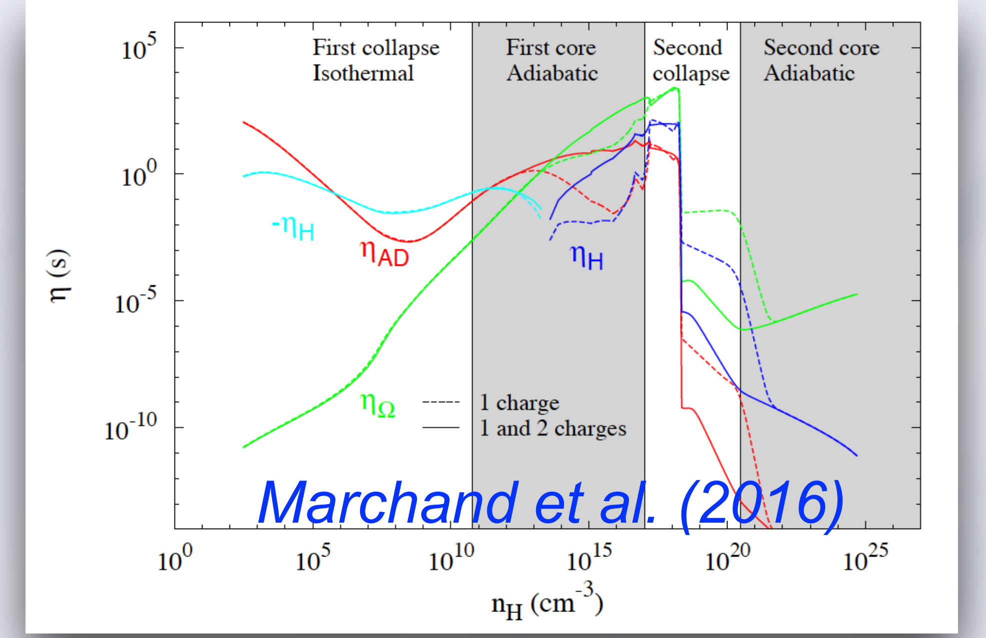

Marchand et al. (2016)

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Conclusion

☑ Discs are back! Disc size regulated by ambipolar diffusion

☑ Magnetic fields cannot be neglected. Non-ideal MHD as well…

☑ Magnetised models compare well with observations

➡ Dust evolution

➡ Second collapse - parameter study

➡ Massive stars

Astrosim Conf, 8-11 octobre 2018, Lyon

Highlights and prospects for numerical astrophysics in France

8-11 Oct 2018 Lyon (France)

Rational

High Performance Computing (HPC) has become an essential tool of all fields of astronomy and astrophysics. In particular, numerical simulations have become the tool of choice to carry out quantitative theoretical investigations, which take into acount the full complexity of astrophysical objects and their contexts, and reach a level of precision which matches the ever more demanding level of detail reached with observations. Today, numerical simulations of astrophysical objects have become the principal vector of the dialog between observations and theory, and they have reached a quality which allows us to use them for a direct interpretation of observations (from large-scale cosmological surveys to observations of atmospheric phenomena on the surface of giant planets).

As observations, simulations require high-performance instruments: super-computers. In less than 10 years, there has been a spectacular increase of the gigantic computing power that is now available to researchers, both at the national (through GENCI) and european level (trough PRACE). This is accompanied by profound evolutions of the methods used by specialists of numerical simulations. More and more research projects are now performed in close collaborations with software engineers. With exascale computers coming soon, such a professionalism of high performance computing (HPC) is expected to become more and more frequent. Like the other communities in France, astrophysicists must prepare to that transition.

The aim of this workshop is to bring together researchers working in France in all fields of numerical astrophysics, along with representatives of the HPC infrastructure at the regional, national, and European level, and key players in the forthcoming ExaScale HPC. Invited presentations from astronomers will both highlight astrophysical results and propose a reflexion on the evolutions of their work. Other invited presentations will present the expected evolution of the HPC landscape in France and Europe, both in terms of organisation and of technologies. A large number of contributed talks will complement the program.

Confirmed Speakers

Dominique **Aubert** (ObAS), Edouard **Audit** (MdS), Frédéric **Bournaud** (CEA), Allan Sacha **Brun** (CEA), Fabien **Casse** (APC), Benoît **Cerutti** (IPAG), Boris **Dintrans** (CINES), Yohan **Dubois** (IAP), François **Forget** (LMD), Philippe **Grandclément** (LUTh), Oliver **Hahn** (OCA), Patrcik **Hennebelle** (CEA), Laurène **Jouve** (IRAP), Guillaume **Laibe** (CRAL), Geoffroy **Lesur** (IPAG), Sophie **Masson** (LESIA), Stephane **Mazevet** (LUTh), Patrick **Michel** (OCA), Michel **Rieutord** (IRAP), Roch **Smets** (UPMC), Pascal **Tremblin** (CEA)