CRIME workshop

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The role of cosmic rays on magnetic field diffusion and the formation of protostellar discs

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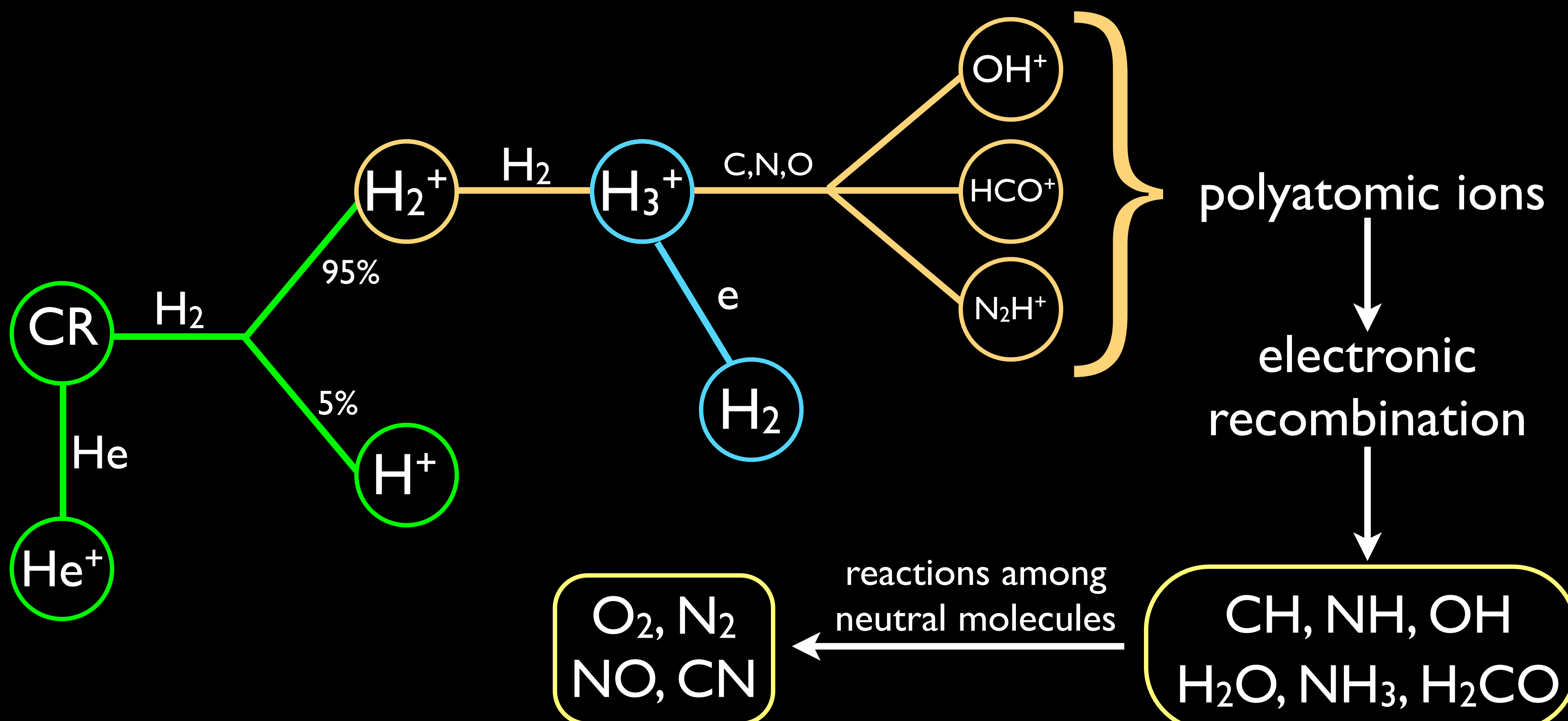
- Development of new telescopes with higher and higher resolution
- New observation techniques with consequent large data sets

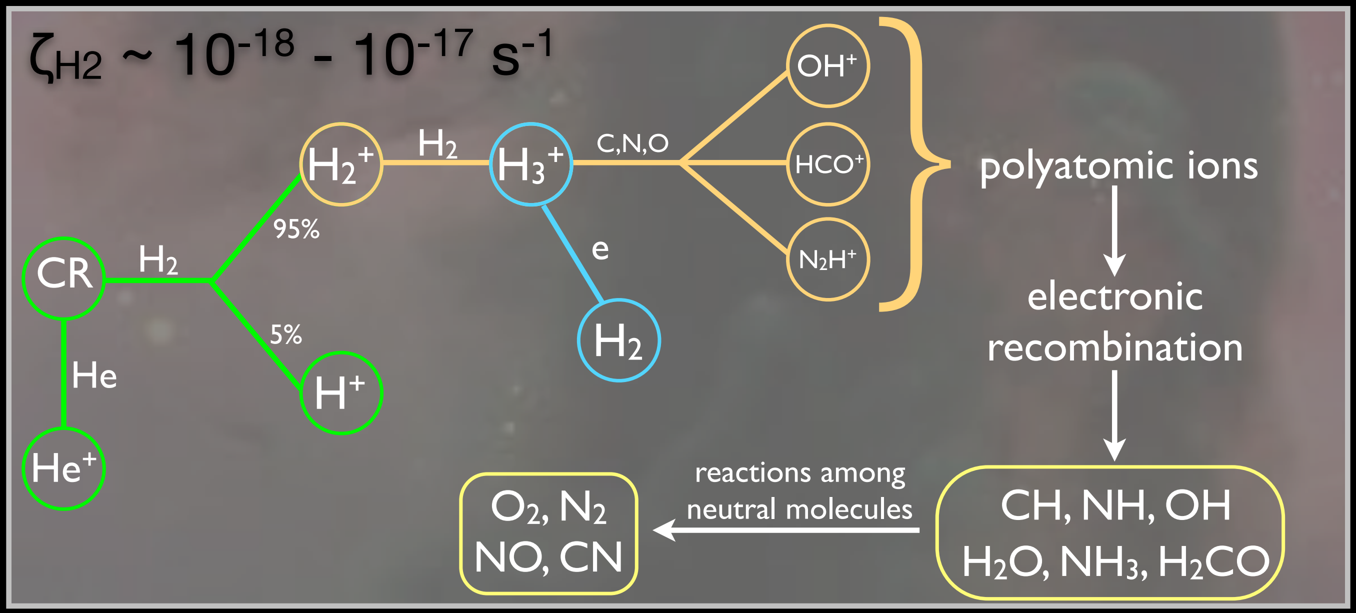
- H_3^+ : UKIRT, VLT-CRIRES — *Indriolo+ (2012)*
- OH^+, H_2O^+ : Herschel — *Neufeld+ (2010), Gerin+ (2010)*
- γ-ray emission : Fermi-LAT (CTA) — *Montmerle (2010)*
- magnetic field morphology : SMA, Planck (ALMA) — *Girart+ (2009)*

All these observations require a solid theoretical support. A detailed effort in the modelling of the CR spectrum, and more precisely of its low-energy tail, was missing as well as the integration of the models in chemical and numerical codes for interpreting observations.

- Diffuse clouds ($A_v \sim 1$ mag) → the UV radiation field is the principal ionising agent (photodissociation regions);

- Dense clouds ($A_v \gtrsim 5$ mag) → the ionisation is due to low-energy CRs ($E < 100$ MeV) and, if close to young stars, to soft X–rays ($E < 10$ keV).

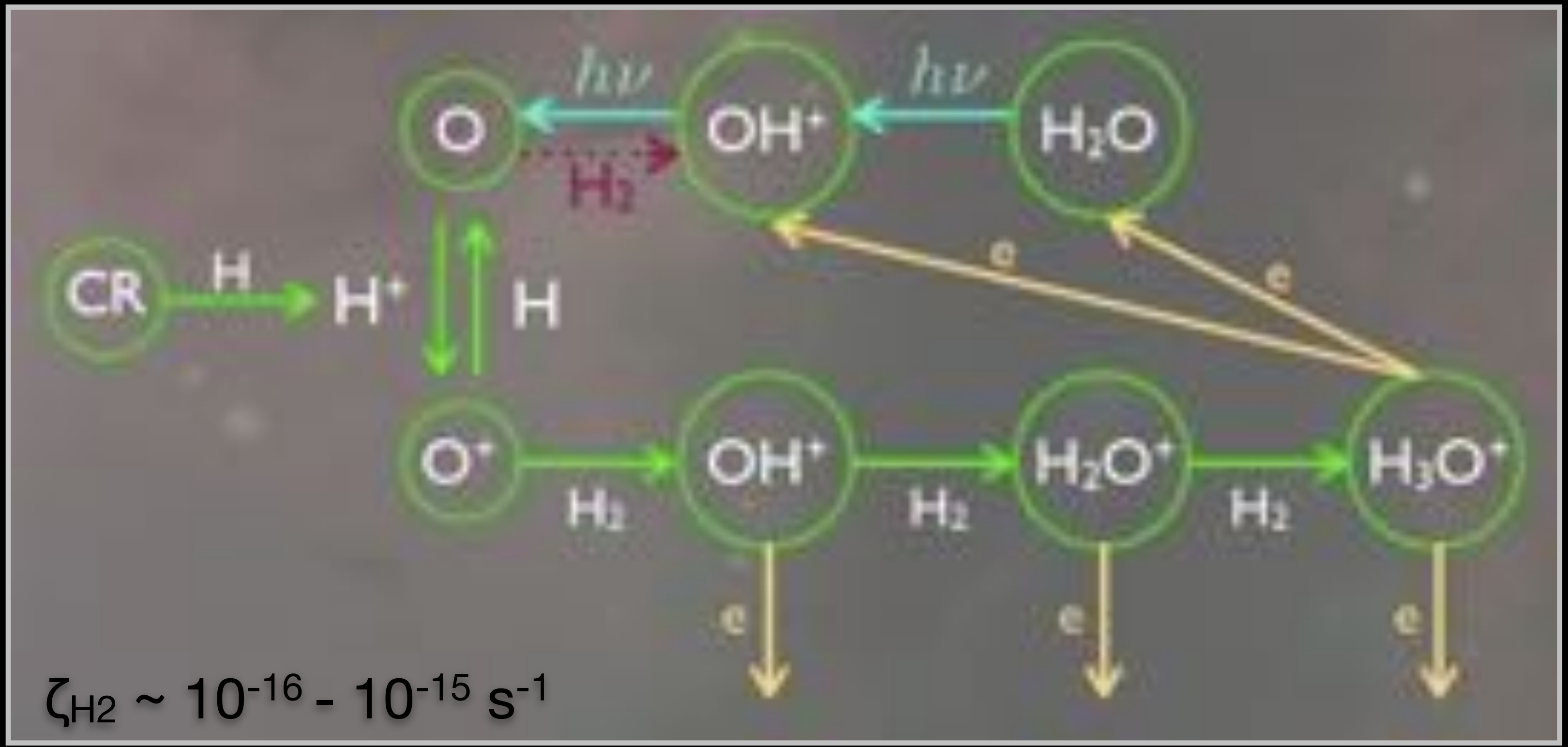




Dense cores

(HCO^+,DCO^+)

Caselli+ (1998)



Diffuse clouds

(OH, HD, NH)

Black & Dalgarno (1977), Hartquist+ (1978), Black+ (1978), van Dishoeck & Black (1986), Federman+ (1996)

(H_3^+)

McCall+ (1993), Geballe+ (1999)
McCall+ (2003), Indriolo+ (2009,2012)

(OH^+,H_2O^+)

Neufeld+ (2010), Gerin+ (2010)

Main questions:

- origin of the CR flux that generates such a high ionisation rate ($\zeta_{\rm CR}$) in diffuse regions;
- how to reconcile these values with those ones measured in denser regions;

Different strategies approaching these problems:

- effects of Alfvén waves on CR streaming

  Skilling & Strong (1976); Hartquist+ (1978); Padoan & Scalo (2005); Everett & Zweibel (2011); Rimmer+ (2012); Morlino & Gabici (2014);

- magnetic mirroring and focusing

  Cesarsky & Völk (1978); Chandran (2000); **PM & Galli (2011,2013)**;

- possible low-energy CR flux able to ionise diffuse but not dense clouds

  Takayanagi (1973); Umebayashi & Nakano (1981); McCall+ (2003); **PM, Galli & Glassgold (2009)**

The story so far...

Theoretical model (PM, Galli & Glassgold 2009)

computing the variation of the ionisation rate due to cosmic rays, $\zeta_{\rm CR}$ [s^{-1}], inside a molecular cloud, with the increasing of the column density, N [cm^{-2}], of the traversed interstellar matter.

$$\zeta^{\rm H_2}(N) = \eta_{\rm h}\boxed{\zeta_{\rm p}^{\rm H_2}(N)} + \boxed{\zeta_{\rm e}^{\rm H_2}(N)}$$

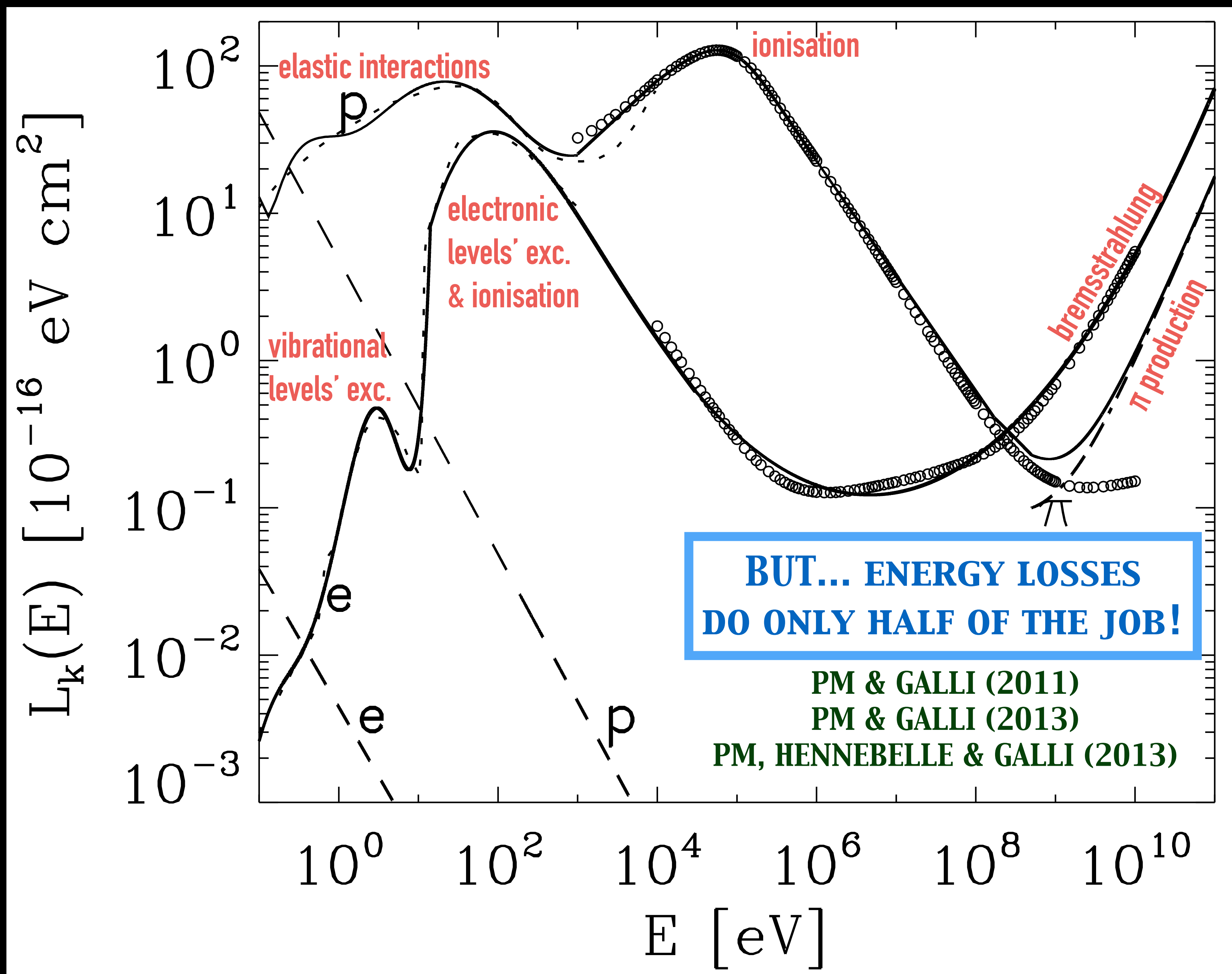
correction due to the presence of heavy nuclei among CRs

$$4\pi\int_0^\infty j_{\rm p}(E,N)\,\eta_{\rm p}^{\rm sec}(E)\,\sigma_{\rm p+H_2}(E)\,{\rm d}E$$

$$4\pi\int_0^\infty j_{\rm e}(E,N)\,\eta_{\rm e}^{\rm sec}(E)\,\sigma_{\rm e+H_2}(E)\,{\rm d}E$$

correction due to the ionisation of secondary electrons

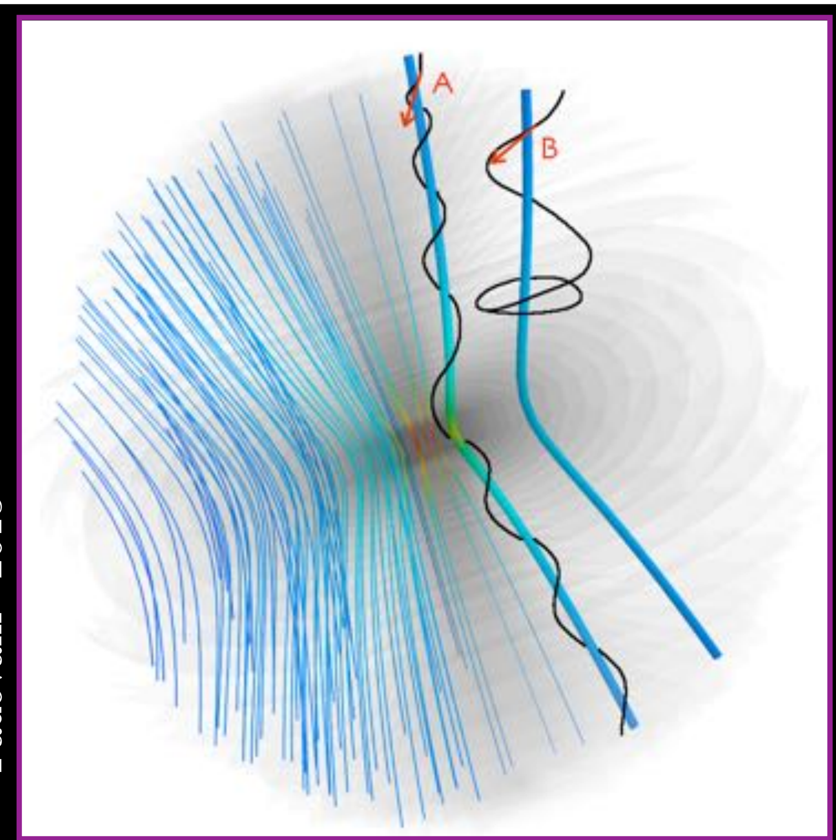
CR–proton and electron energy loss function



$\vec{B}$

magnetic mirroring
bounces many CRs out of the core

magnetic focusing
increases CR flux in the core



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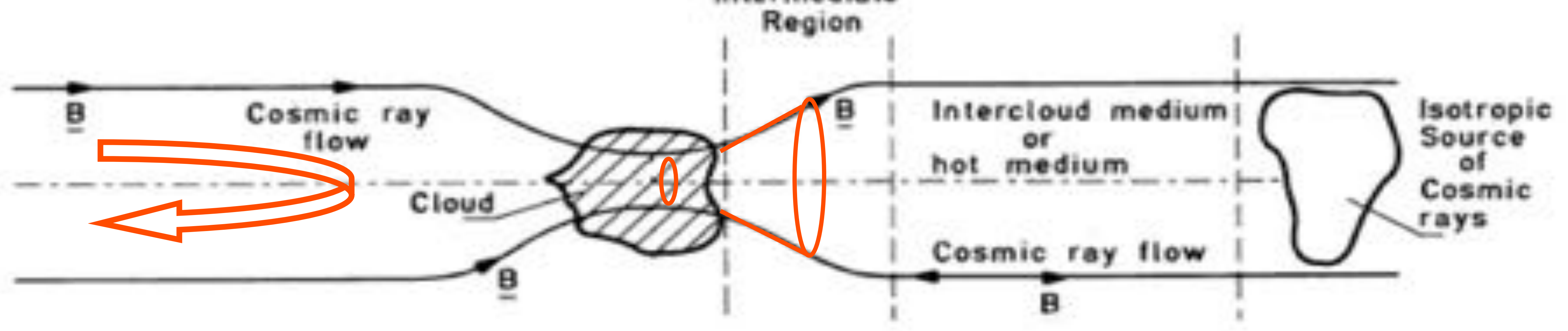
The Larmor radii of ionising CRs are smaller than typical sizes of Bok globules (~ 0.05 pc), dense cores (~ 1-5 pc), and GMC (~ 25 pc).

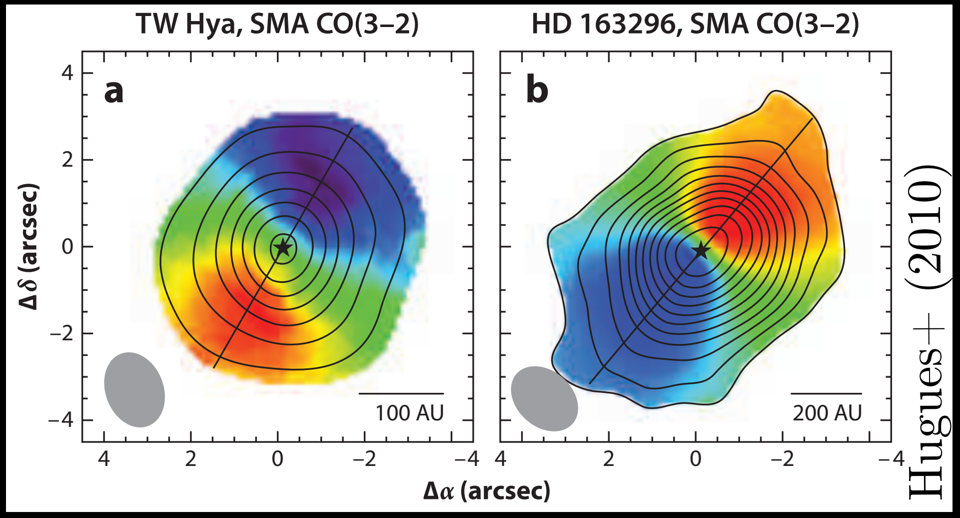
`non-uniformity of the magnetic field`

Césarsky & Völk, 1978

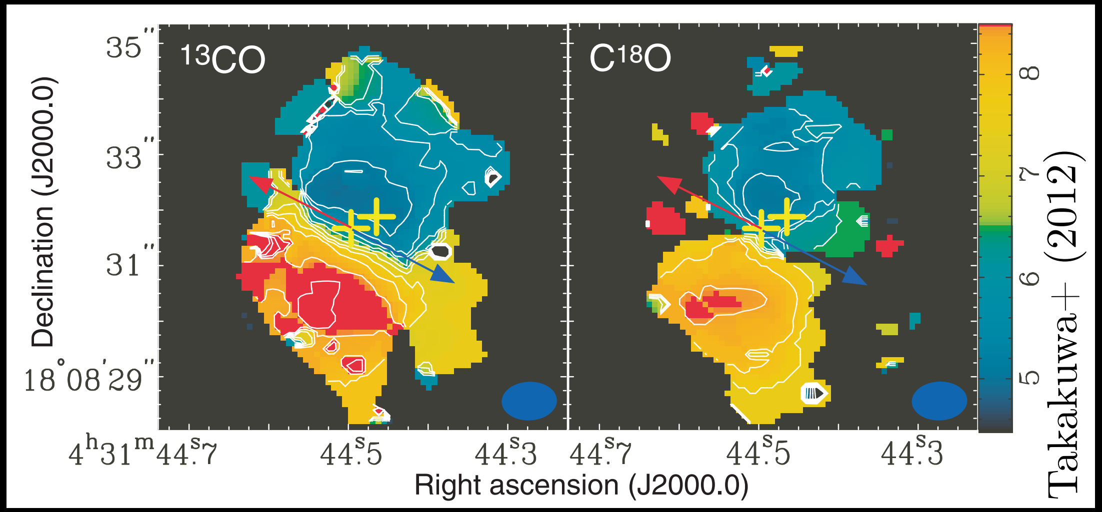


- Theoretical challenge: formation of protostellar discs.
- Magnetic fields entrained by collapsing cloud brake any rotational motion and prevents cloud's collapse (Galli+ 2006; Mellon & Li 2008; Hennebelle & Fromang 2008).

Observational evidence of the presence of discs

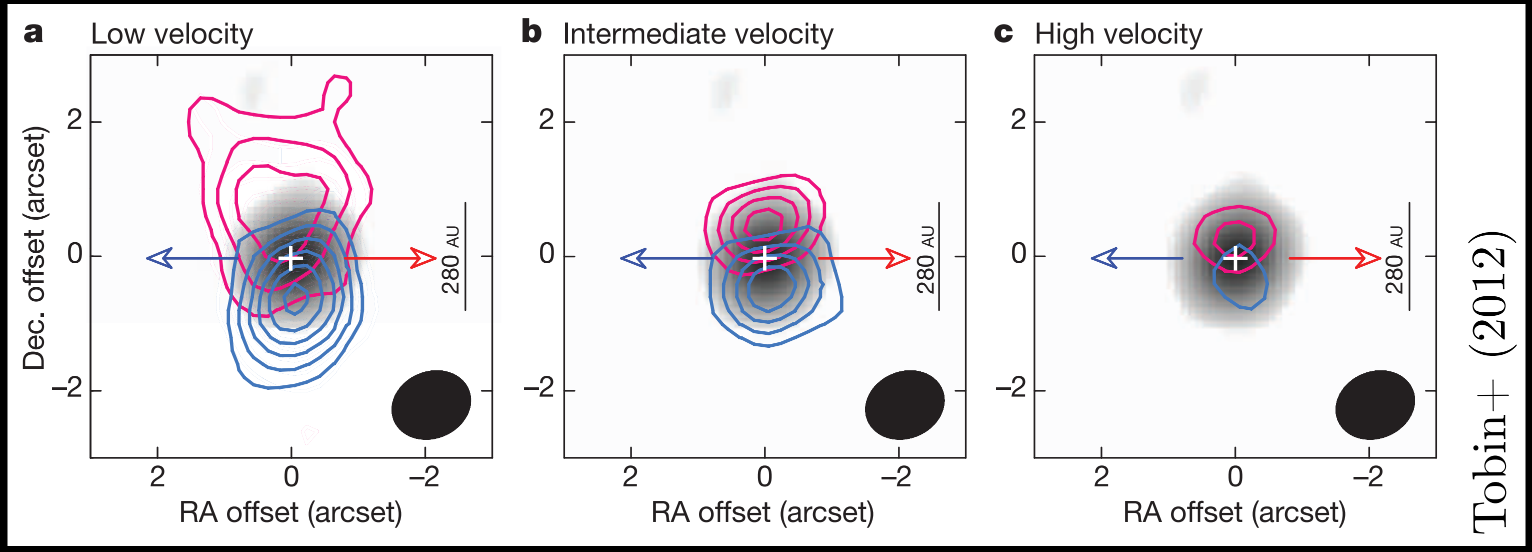


Class II YSO



Class I YSO

Class 0 YSO



- A number of possible solution to solve the magnetic braking

(i) non-ideal MHD effects (Shu+ 2006; Dapp & Basu 2010; Krasnopolsky+ 2011; Braiding & Wardle 2012)

(ii) misalignment between **B** and **J** (Hennebelle & Ciardi 2009; Joos+ 2012)

(iii) turbulent diffusion of **B** (Seifried+ 2012; Santos-Lima+ 2013; Joos+ 2013)

(iv) depletion of the infalling envelope anchoring **B** (Mellon & Li 2009; Machida+ 2011)

Numerical models : rotating collapsing core

Table 1. Parameters of the simulations described in the text (from Joos et al. 2012): mass-to-flux ratio, initial angle between the magnetic field direction and the rotation axis, time after the formation of the first Larson's core (core formed in the centre of the pseudo-disc with $n \gtrsim 10^{10}$ cm^{-3} and $r \sim 10-20$ AU), maximum mass of the protostellar core and of the disc. Last column gives information about the disc formation.

Case	λ	$\alpha_{\rm B,J}$ [rad]	t [kyr]	$M_\star$ [$M_\odot$]	$M_{\rm disc}$ [$M_\odot$]	Disc ? (Y^a / N^b / K^c)
A_1	5	0	0.824	–	–	N
A_2	5	0	11.025	0.26	0.05	N
B	5	$\pi/4$	7.949	0.23	0.15	Y
C	5	$\pi/2$	10.756	0.46	0.28	K
D	2	0	5.702	0.24	–	N
E	17	0	6.620	0.43	0.15	K

[a] A disc with flat rotation curve is formed (Fig. 15 in Joos et al. 2012).
[b] No significant disc is formed ($M_{\rm disc} < 5 \times 10^{-2}\ M_\odot$).
[c] A keplerian disc is formed (Fig. 14 in Joos et al. 2012).

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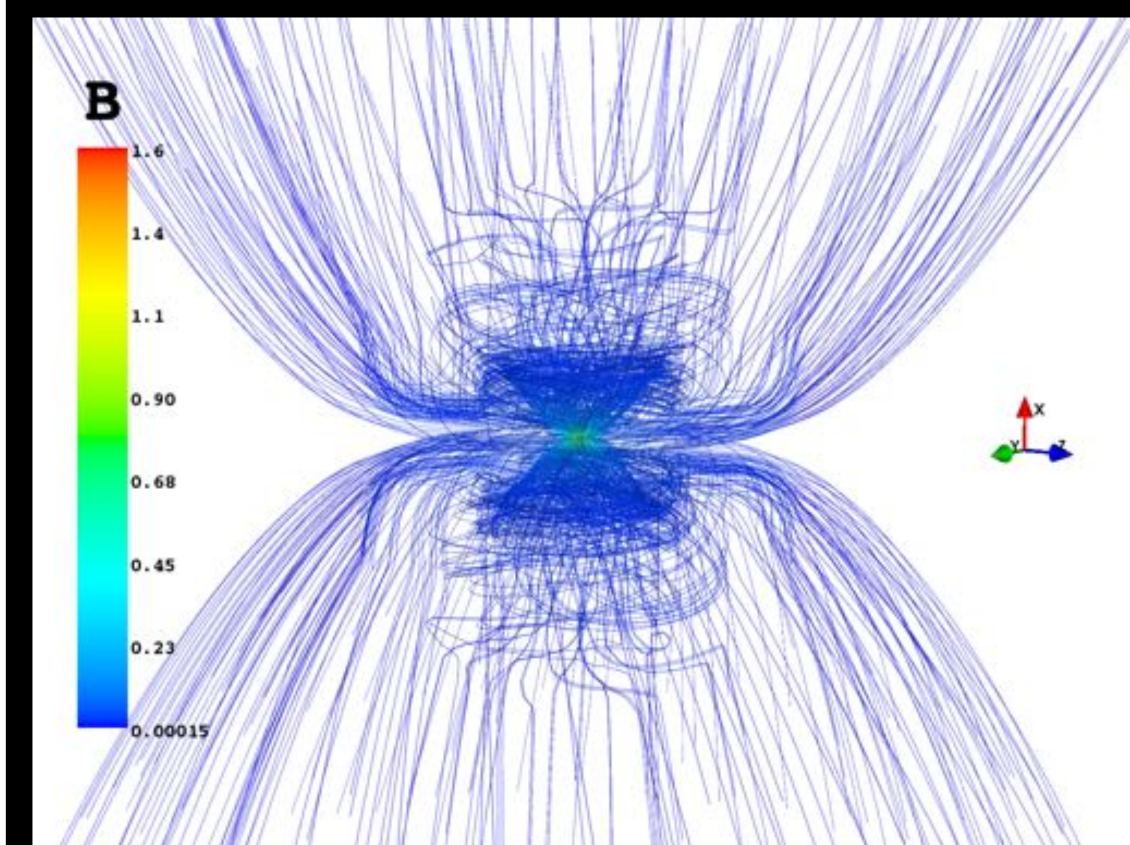
Numerical models : rotating collapsing core

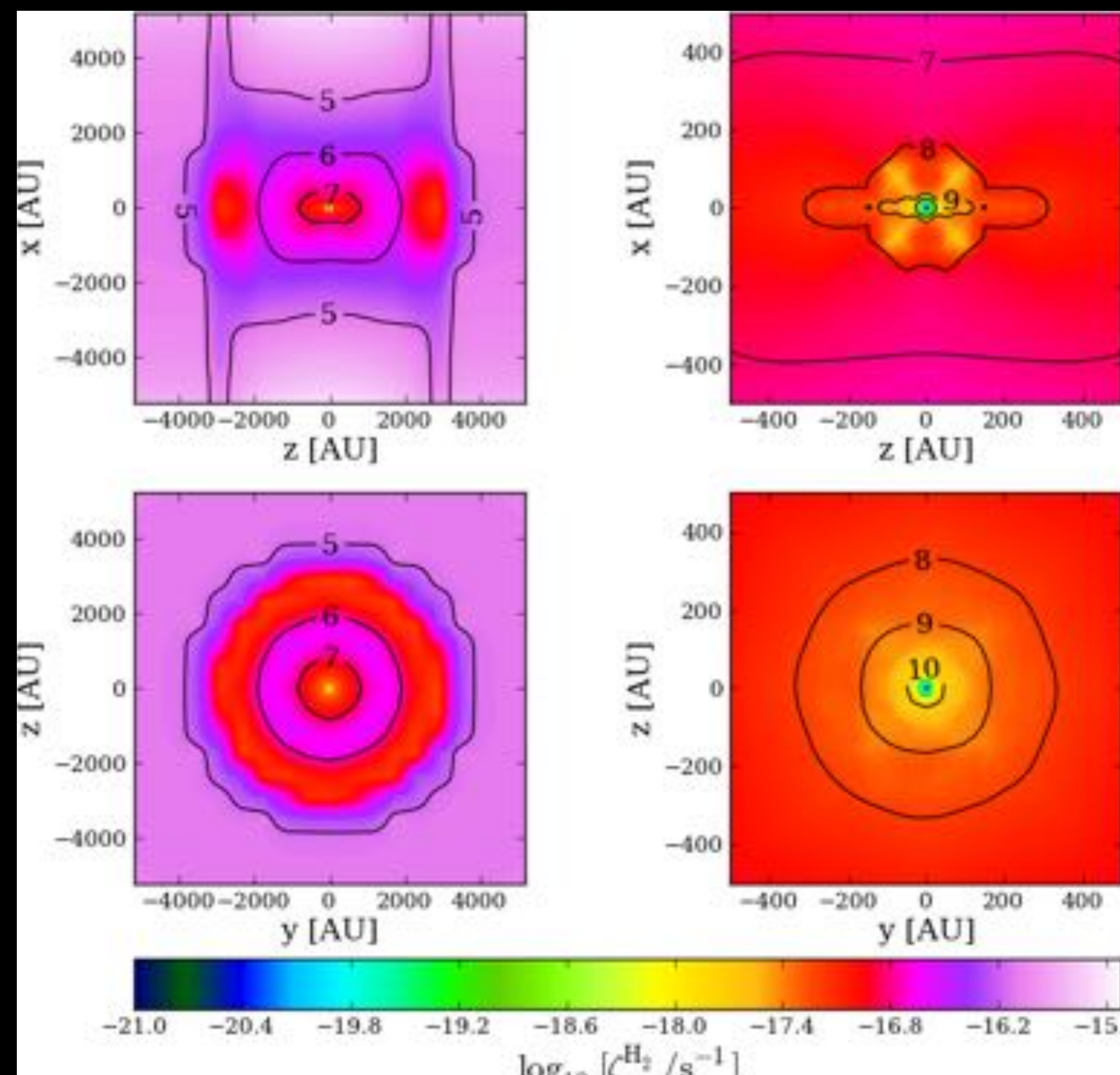
Intermediate magnetisation λ=5

Aligned rotator $(\mathbf{J},\mathbf{B})$=0

It is not possible to unravel magnetic from column-density effects, but both intervene on the decrease of $\zeta_{\rm CR}$. Deviations between iso-density contours and $\zeta_{\rm CR}$ maps can be interpreted as due to magnetic imprints

Field lines in the inner 600 AU





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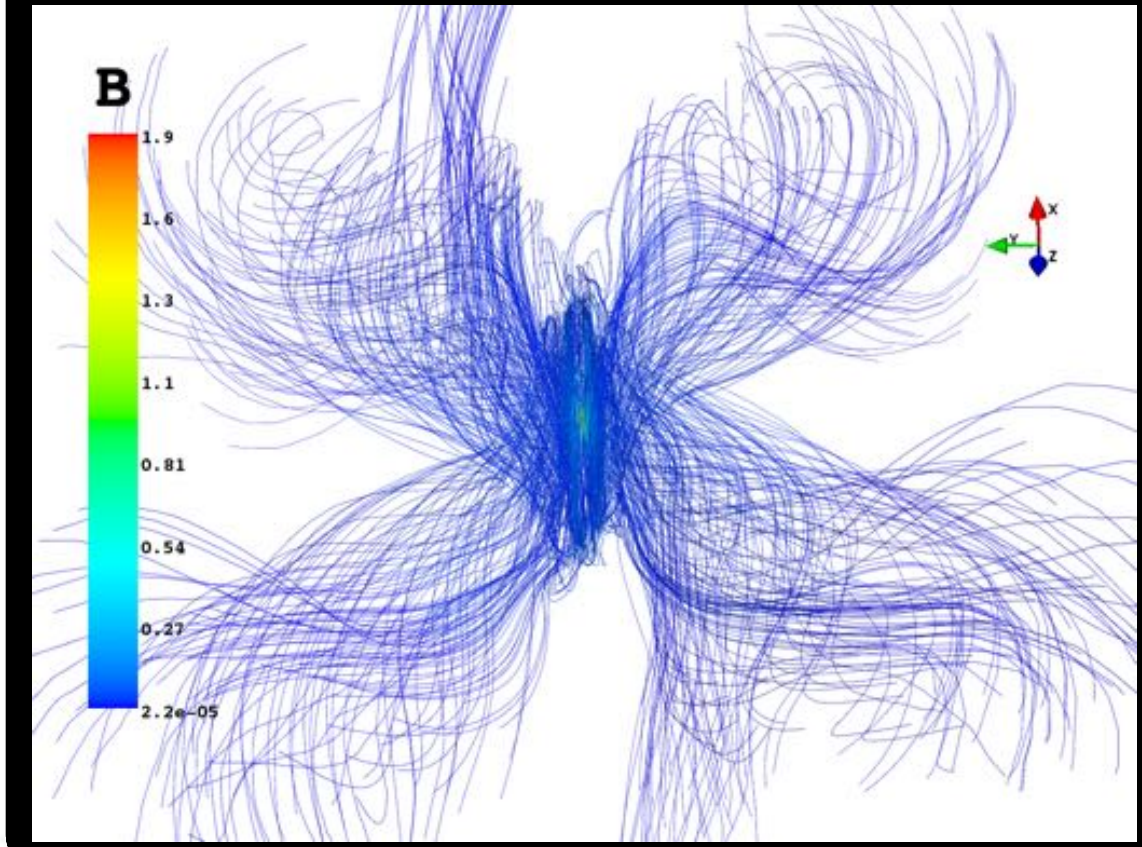
Numerical models : rotating collapsing core

Intermediate magnetisation λ=5

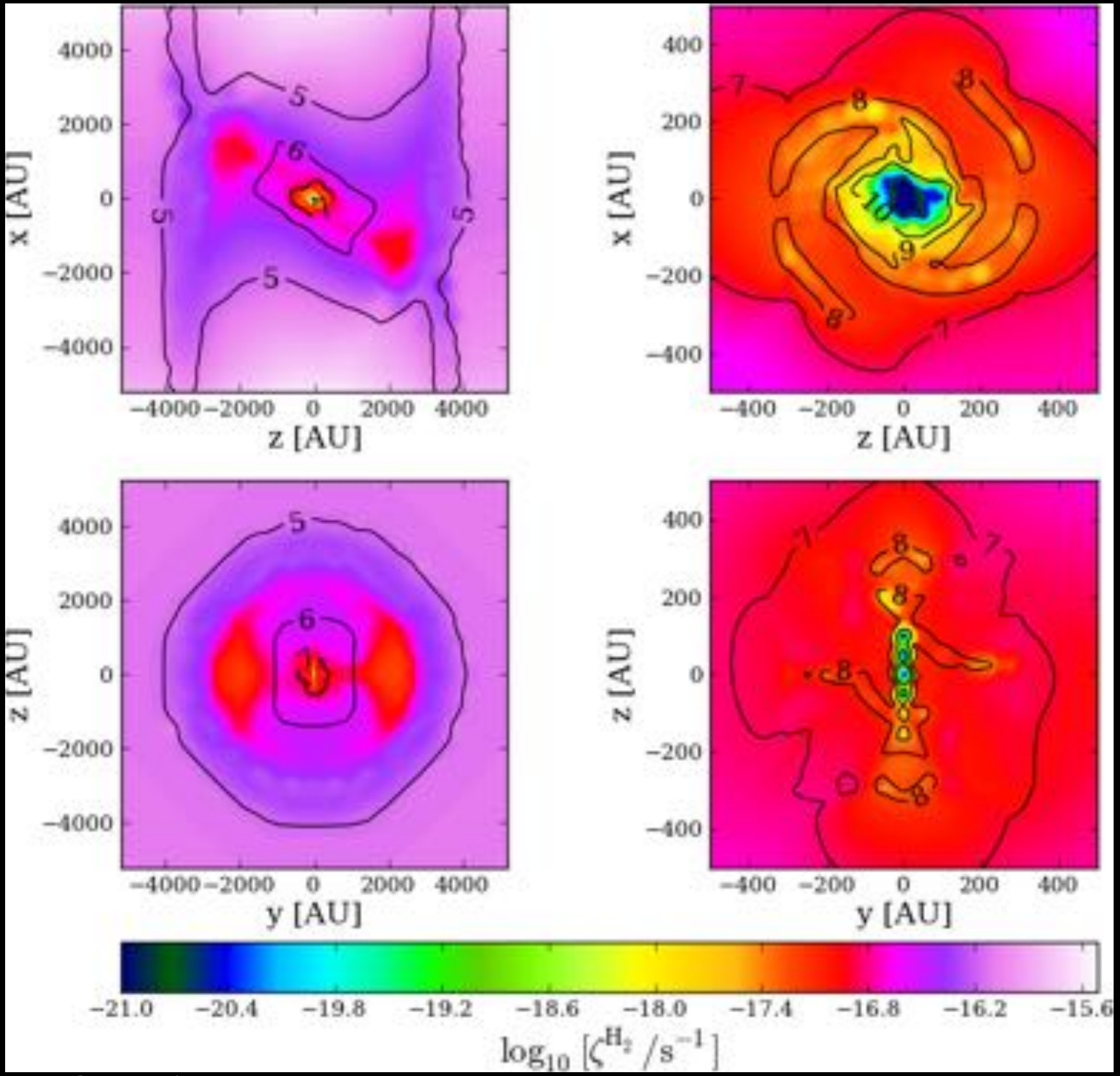
Perpendicular rotator (**J**,**B**)=π/2

$\zeta_{CR} < 10^{-18}$ s^{-1} down to 2×10^{-21} s^{-1} in the inner area with an extent of a few tenths of AU. We can assume that the gas is effectively decoupled with the magnetic field.

Field lines in the inner 600 AU



including magnetic effects



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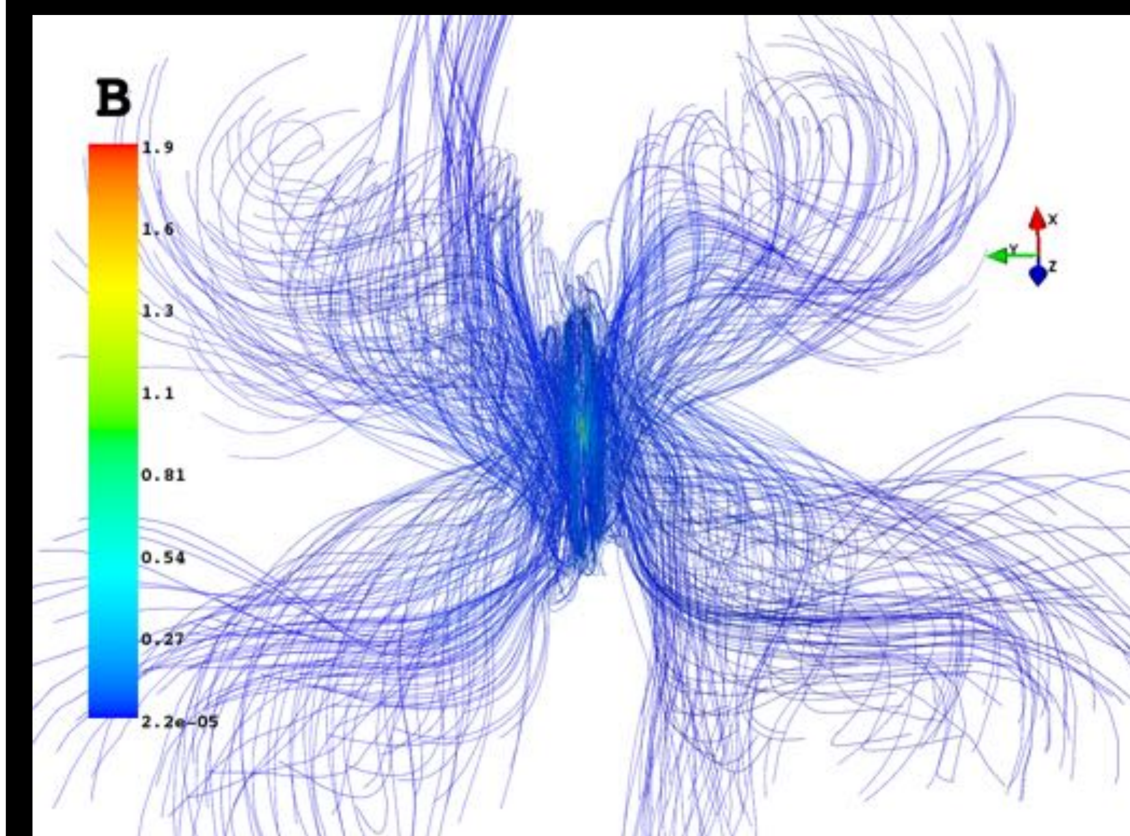
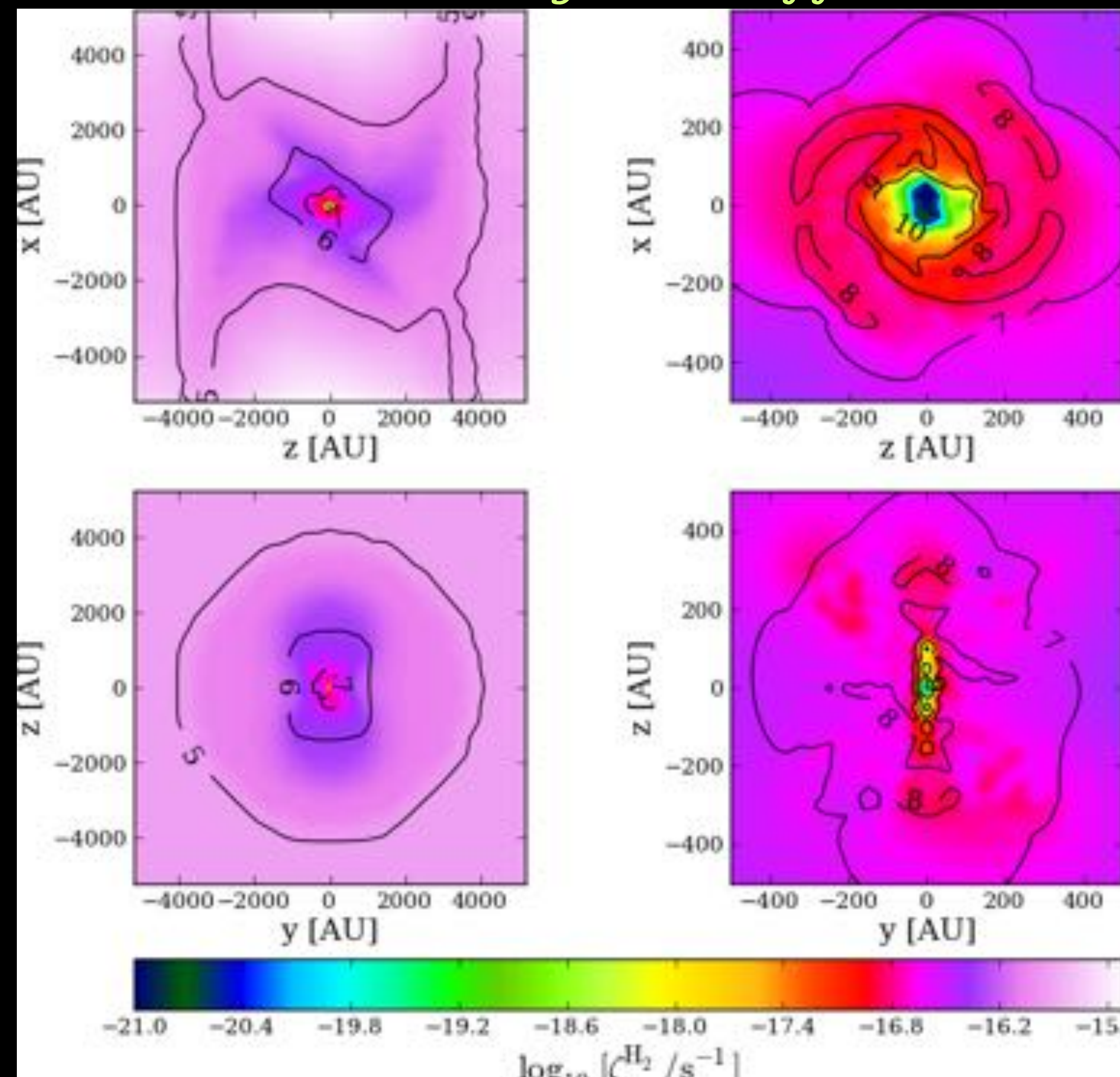


without magnetic effects



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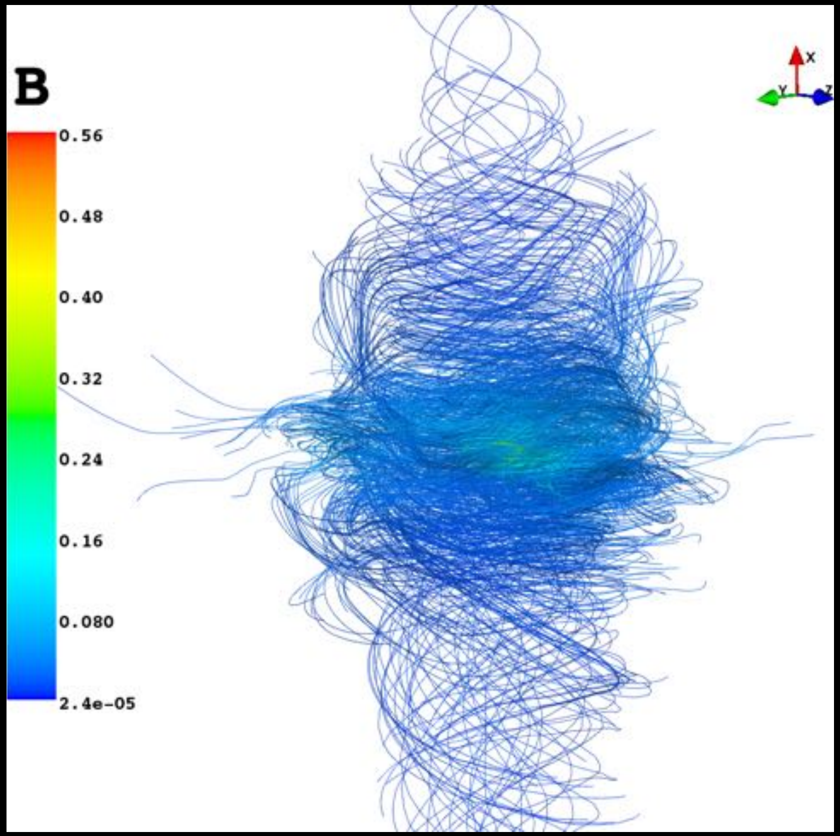
Numerical models : rotating collapsing core

Weak magnetisation λ=17

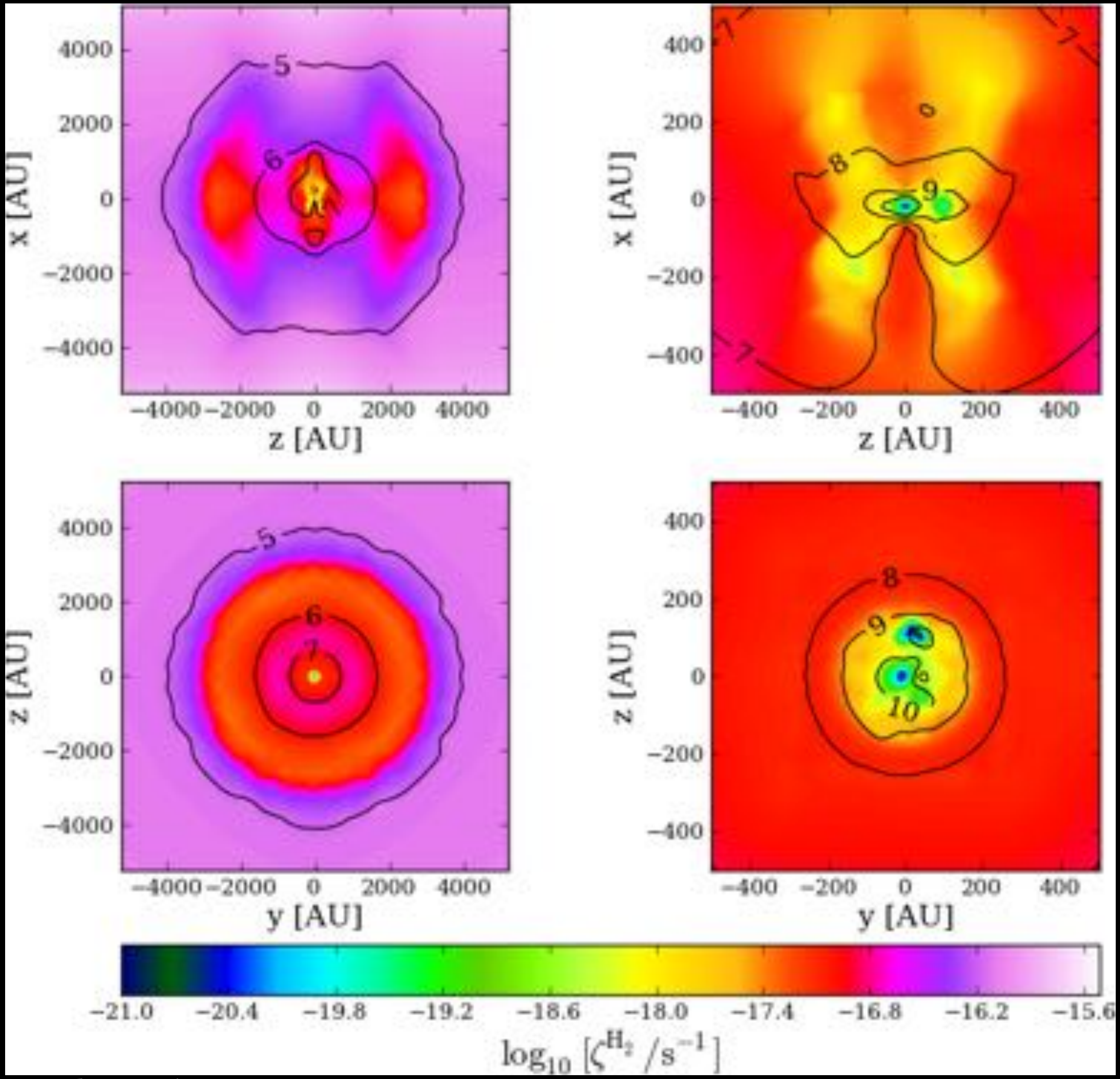
Aligned rotator (**J**,**B**)=0

The magnetic braking is very faint and the rotation acts in wrapping powerfully the field lines. The region with $\zeta_{CR} < 10^{-18}$ s^{-1} broadens out along the rotation axis where field line tangling up is very marked.

Field lines in the inner 600 AU



including magnetic effects



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Numerical models : rotating collapsing core

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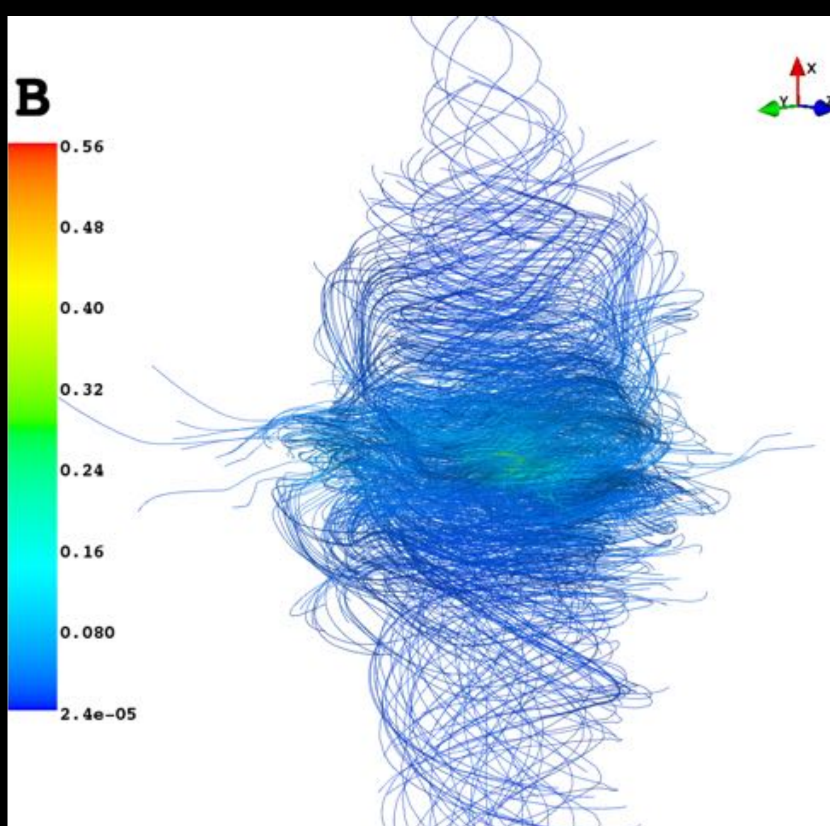
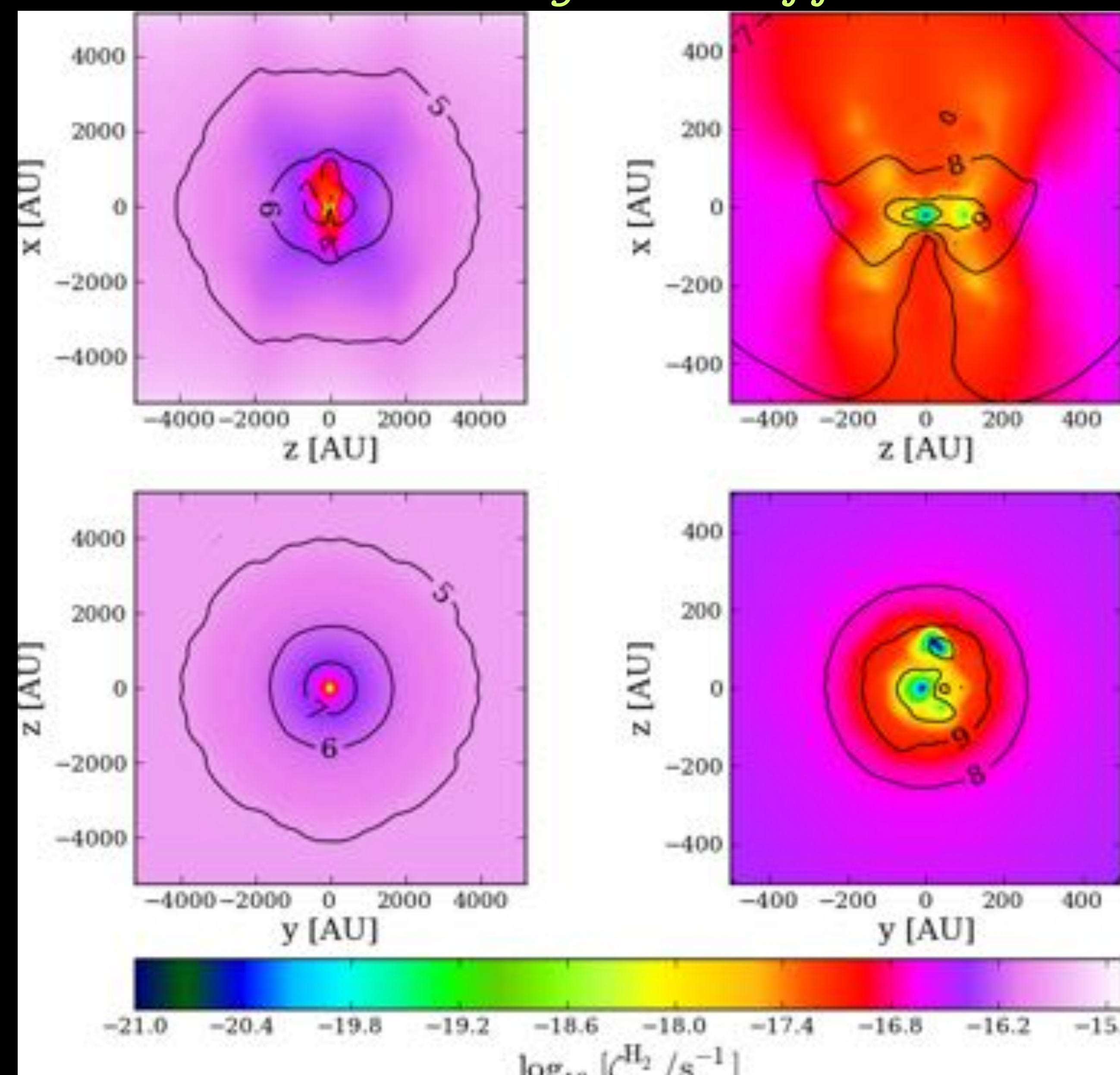


without magnetic effects



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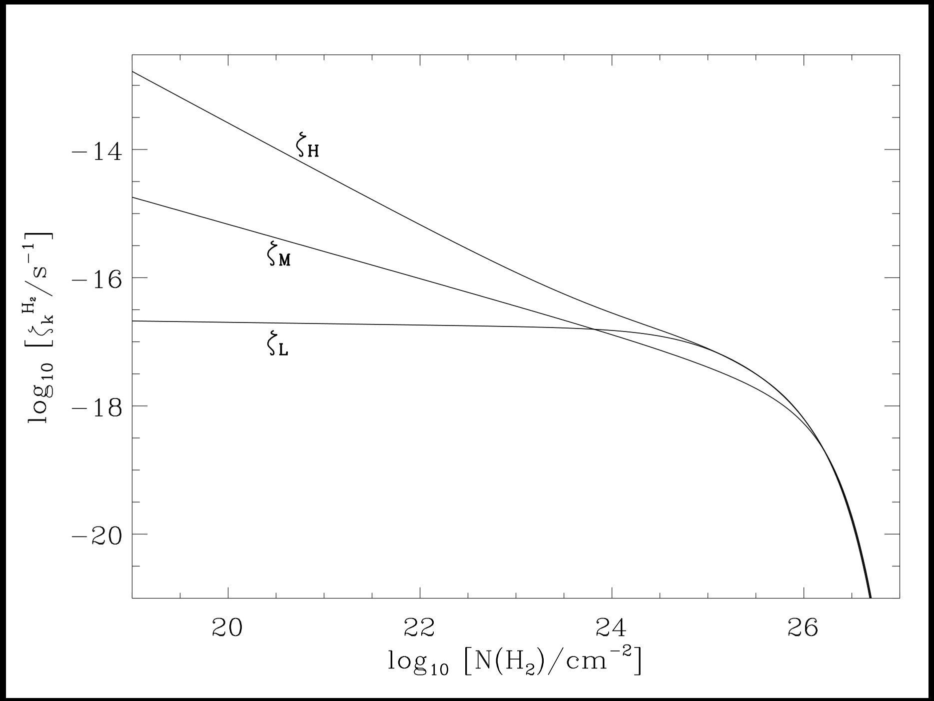
A useful fitting formula

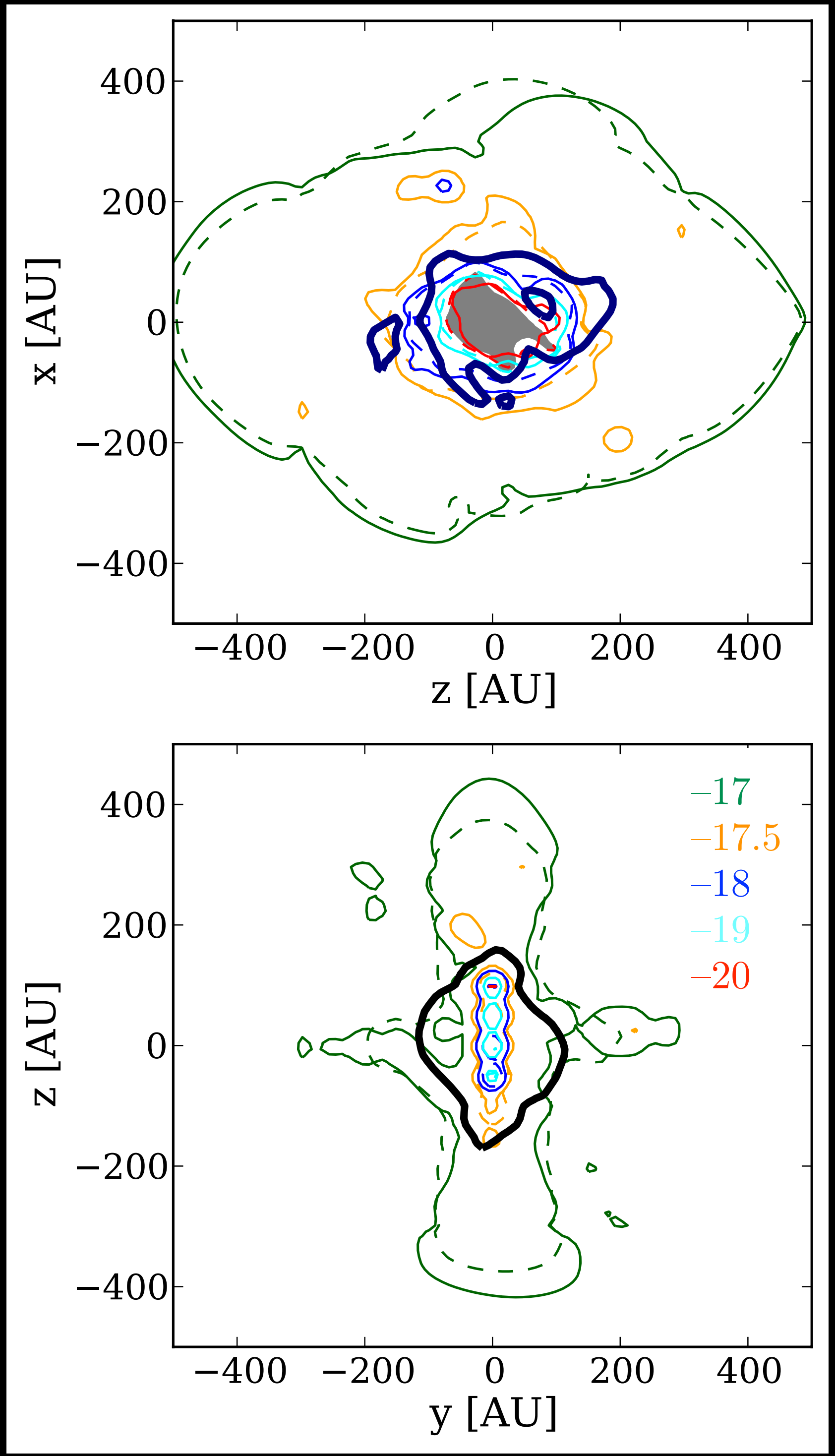
When in presence of a magnetic field, the effective column density, $N_{\rm eff}$, seen by a CR can be much larger than that obtained through a rectilinear propagation.

$N(H_2)$ = average column density seen by an isotropic flux of CRs

$$N_{\rm eff} = (1 + 2\pi\mathcal{F}^s)\ N(\mathrm{H}_2)$$
$$\mathcal{F} = \mathcal{F}(|\mathbf{B}|, |B_\phi/B_p|)\,,\ s = s(n)$$

$$\zeta^{\mathrm{H}_2}_{\rm eff} \propto \zeta^{\mathrm{H}_2}(N_{\rm eff})$$





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Cosmic rays and magnetic diffusion

(PM, Galli, Hennebelle, Commerçon & Joos 2014)

Drifts of charged species with respect to neutrals determines different regimes of magnetic diffusivity.

$$\frac{\partial \vec{B}}{\partial t} + \nabla \times (\vec{B} \times \vec{U}) = \nabla \times \left\{ \eta_{\rm O} \nabla \times \vec{B} + \eta_{\rm H} (\nabla \times \vec{B}) \times \frac{\vec{B}}{|B|} + \eta_{\rm AD} \left[(\nabla \times \vec{B}) \times \frac{\vec{B}}{|B|} \right] \times \frac{\vec{B}}{|B|} \right\}$$

Resistivities

$$\left\{ \begin{aligned} \eta_{\rm AD} &= \frac{c^2}{4\pi}\left(\frac{\sigma_{\rm P}}{\sigma_{\rm P}^2+\sigma_{\rm H}^2} - \frac{1}{\sigma_\parallel}\right) \\ \eta_{\rm H} &= \frac{c^2}{4\pi}\left(\frac{\sigma_{\rm H}}{\sigma_{\rm P}^2+\sigma_{\rm H}^2}\right) \\ \eta_{\rm O} &= \frac{c^2}{4\pi\sigma_\parallel} \end{aligned} \right.$$

Conductivities

$$\sigma_\parallel = \frac{ecn({\rm H_2})}{B}\sum_i Z_i x_i \; \beta_{i,{\rm H_2}}$$

$$\sigma_{\rm P} = \frac{ecn({\rm H_2})}{B}\sum_i \frac{Z_i x_i \beta_{i,{\rm H_2}}}{1+\beta_{i,{\rm H_2}}^2}$$

$$\sigma_{\rm H} = \frac{ecn({\rm H_2})}{B}\sum_i \frac{Z_i x_i}{1+\beta_{i,{\rm H_2}}^2}$$

The degree of diffusion is determined by the ionisation fractions that, in turn, are determined by $\zeta^{\rm H2}$.

Abundance of charged species

We adopted a simplified chemical network that computes the steady-state abundance of $\mathbf{H^+}$, $\mathbf{H_3^+}$, a typical molecular ion $\boldsymbol{mH^+}$ (e.g. HCO^+), a typical metal ion $\boldsymbol{M^+}$ (e.g. Mg^+), $\boldsymbol{e^-}$ and ***dust grains*** ($\boldsymbol{g^0}$, $\boldsymbol{g^-}$) as a function of:

— H_2 density ;
— Temperature ;
— *Cosmic-ray ionisation rate.*

} computed at each spatial position in our models.

Table 1. Parameters of the simulations described in the text: non-dimensional mass-to-flux ratio λ, initial angle between the magnetic field direction and the rotation axis $\alpha_{B,J}$, time after the formation of the first Larson's core t (core formed in the centre of the pseudo-disc with $n \geq 10^{10}$ cm^{-3} and $r \sim 10-20$ AU), initial mass M_{in}, mass of the protostellar core $M_\bigstar$ and of the disc M_{disc}.

Case	λ	$\alpha_{B,J}$ [rad]	t [kyr]	M_{in} [$M_\odot$]	$M_\bigstar$ [$M_\odot$]	M_{disc} [$M_\odot$]
L_1	5	0	0.824	1	–	–
L_2	5	$\pi/2$	10.756	1	0.46	0.28
H	~ 2	no initial rotation	6.000	100	1.24[a]	0.87[a]

[a] This value refers to the densest fragment formed.

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Effects of the grain size distribution

Grains play a decisive role in determining the degree of coupling between gas and B.

<u>Three grain size distribution</u>

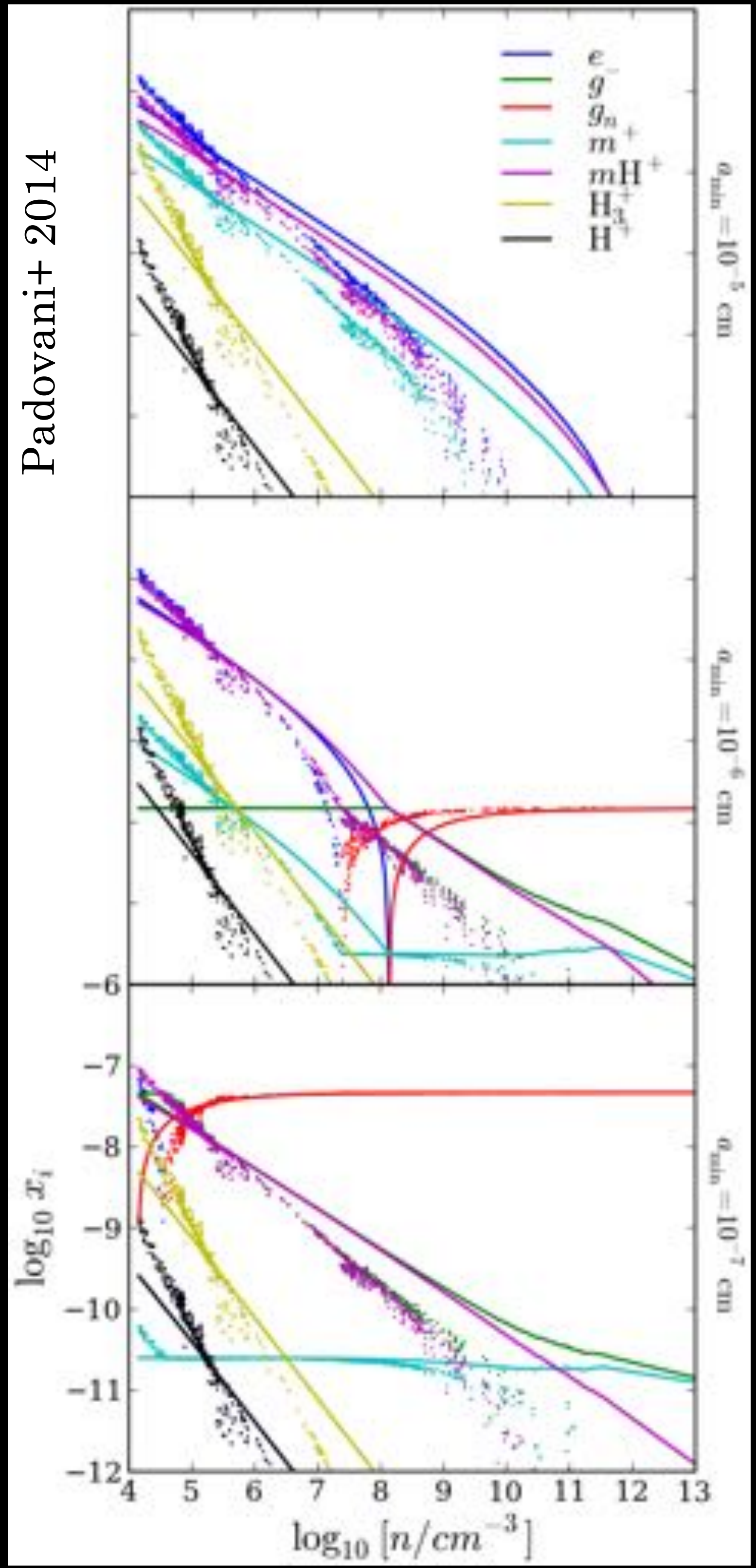
$a_{\min} = 10^{-5}$ cm (representative of large grains formed by compression and coagulation during collapse; Flower et al. 2005)

$a_{\min} = 10^{-6}$ cm (the minimum grain radius of a MRN size distribution Mathis et al. 1977 that gives the same grain opacity found by Flower et al. 2005)

$a_{\min} = 10^{-7}$ cm (typical size of very small grains)

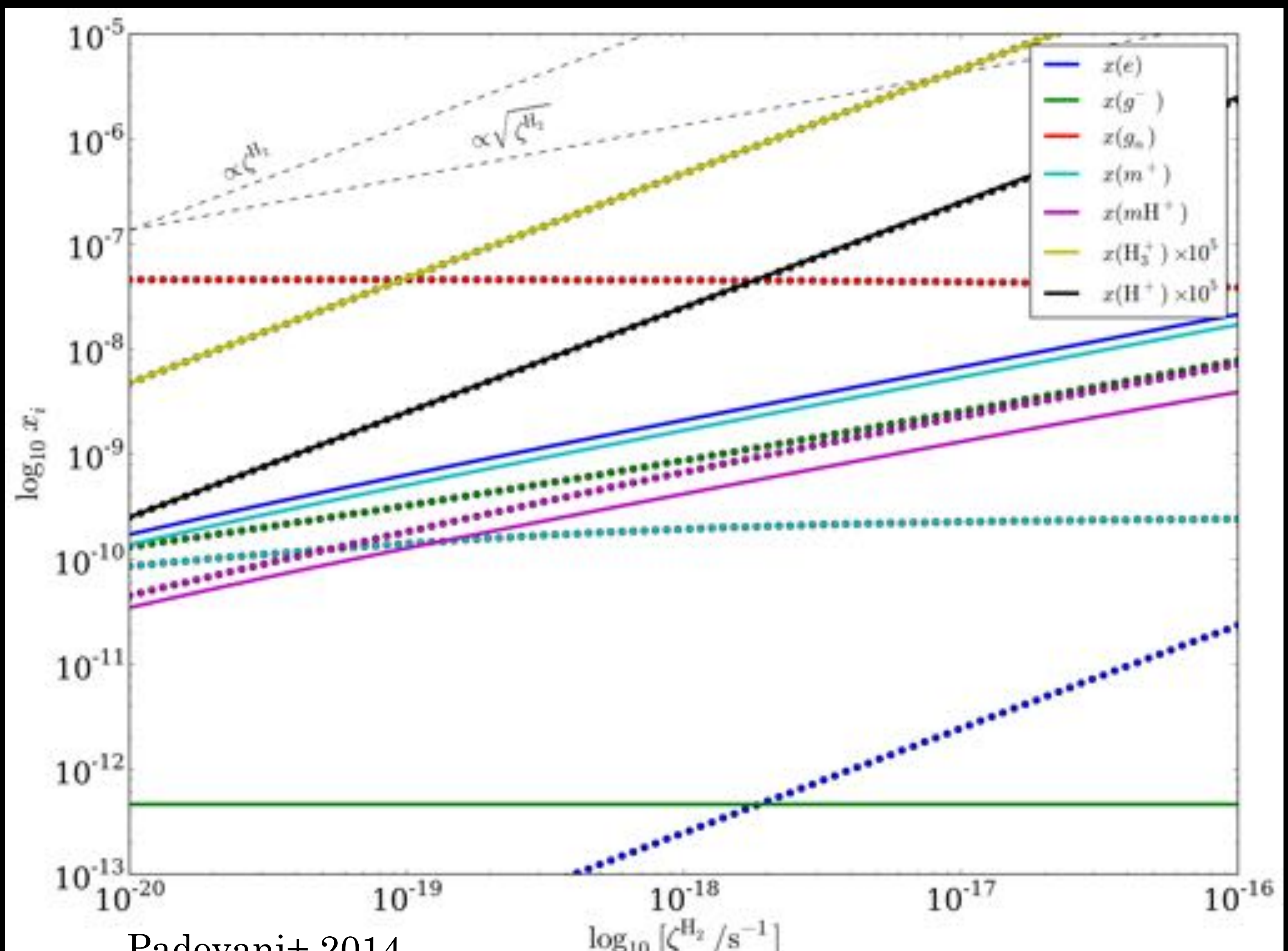
$a_{\max} = 3{\times}10^{-5}$ cm (Nakano et al. 2002)

larger grains → less number of grains
→ more free electrons (one electron per grain)



Dependence of chemical abundances on ζ^{H2}

Density of charged species usually parameterised as $n(i) \propto \left(\zeta^{\mathrm{H}_2}\right)^{k'}$ with $k' \approx 1/2$ (e.g. Ciolek & Mouschovias 1994, 1995), but… it depends on the grain size!



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$n(H_2)=10^6$ cm^{-3}
$a_{\min} = 10^{-5}$ cm (solid lines)
$a_{\min} = 10^{-7}$ cm (dotted lines)

k'	10^{-5}	10^{-7}
e^-	**1/2**	**1**
M^+	**1/2**	**0**
g^-	**0**	**1/2**
H_3^+, H^+, mH^+	**1/2**	**1/2**

ζ_{H2} and the gas-magnetic field decoupling

Drift velocity of magnetic field $\mathbf{U_B}$: it can be represented by the velocity of the charged species (frozen with the field lines) with respect to neutrals.

By comparing $\mathbf{U_B}$ with the fluid velocity, it is possible:

— to assess the degree of diffusion of the field;
— to estimate the size of the region where gas and B are decoupled.

Following Nakano et al. (2002), $\mathbf{U_B}$ can be written as a function of the resistivities.

$$\vec{U}_B = \vec{U}_{\mathrm{AD}} + \vec{U}_{\mathrm{H}} + \vec{U}_{\mathrm{O}} = \frac{4\pi}{cB^2}\left[(\eta_{\mathrm{AD}}+\eta_{\mathrm{O}})\,\vec{j}\times\vec{B} + \eta_{\mathrm{H}}\left(\vec{j}\times\vec{B}\right)\times\frac{\vec{B}}{B}\right]$$

$$\frac{1}{t_B} = \frac{1}{t_{\mathrm{AD}}} + \frac{1}{t_{\mathrm{H}}} + \frac{1}{t_{\mathrm{O}}}$$

$$t_k = R/U_k\,,\ \ (k = \mathrm{AD}, \mathrm{H}, \mathrm{O})$$

R is the typical length scale of the region (assumed as the distance from the density peak)

ζ_{H2} and the gas-magnetic field decoupling

$$\frac{1}{t_B} = \frac{1}{t_{\mathrm{AD}}} + \frac{1}{t_{\mathrm{H}}} + \frac{1}{t_{\mathrm{O}}}$$

$$t_k = R/U_k\,,\ (k = \mathrm{AD}, \mathrm{H}, \mathrm{O})$$

R is the typical length scale of the region (assumed as the distance from the density peak)

Nakano et al. (2002): comparison between t_B and the free-fall time scale.
Here we compare t_B with the $t_{\mathrm{dyn}} = R/U$ (U = fluid velocity including infall and rotation).

In regions where:

— $t_{\mathrm{B}}<t_{\mathrm{dyn}}$: B is partially decoupled and it has less influence on gas dynamics;
— $t_{\mathrm{B}}>t_{\mathrm{dyn}}$: diffusion is not efficient and B remains well coupled to the gas.

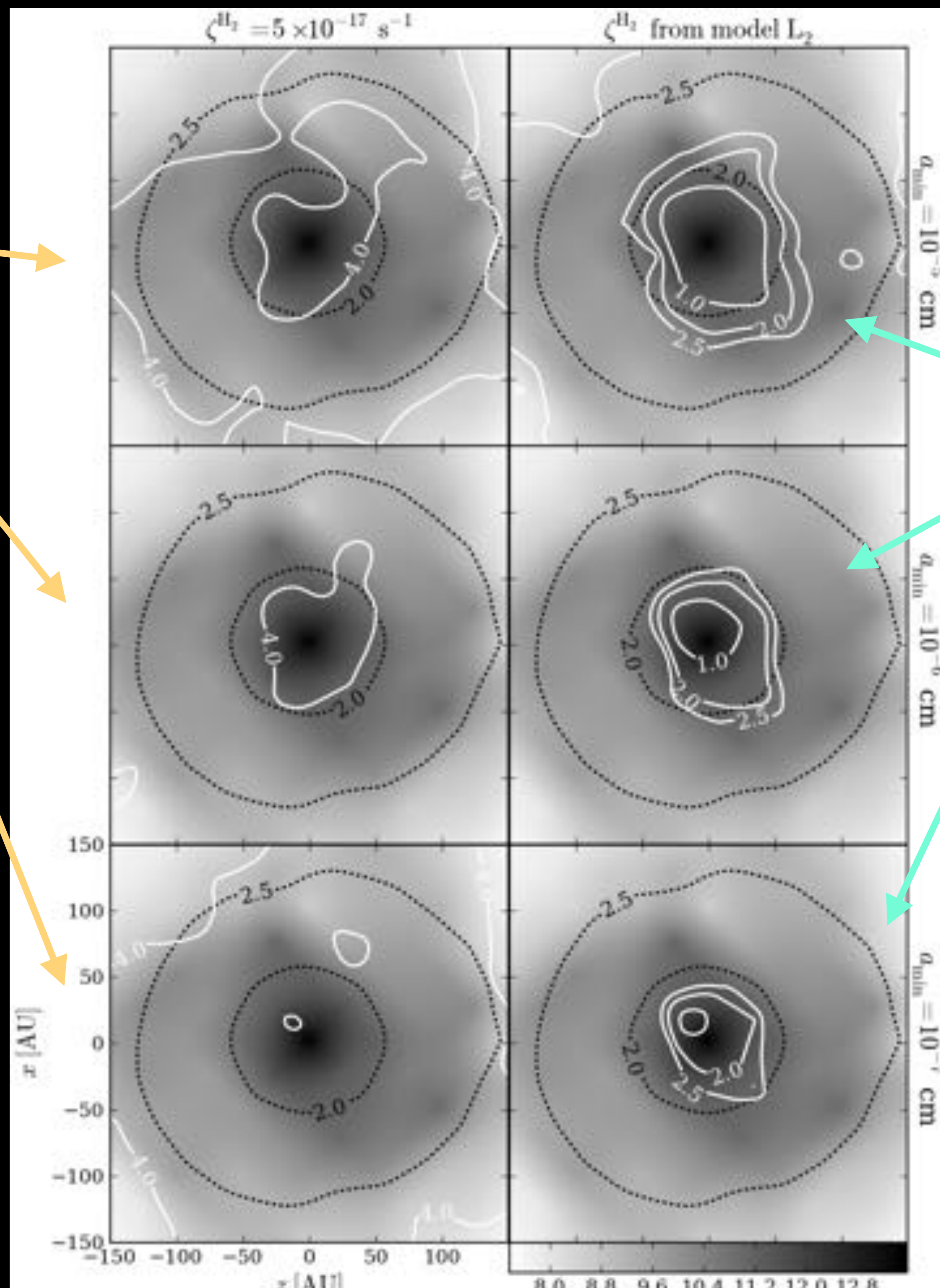
Is there a relevant variation in t_{B} using a constant $\zeta^{\mathrm{H2}} \approx 10^{-17}$ s^{-1} or accounting correctly for the dependence of ζ^{H2} on $N(H_2)$ and B?

YES!

Cosmic-ray ionisation rate and diffusion time scale

LOW-MASS CASE

$t_B > t_{dyn}$



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$t_B < t_{dyn}$

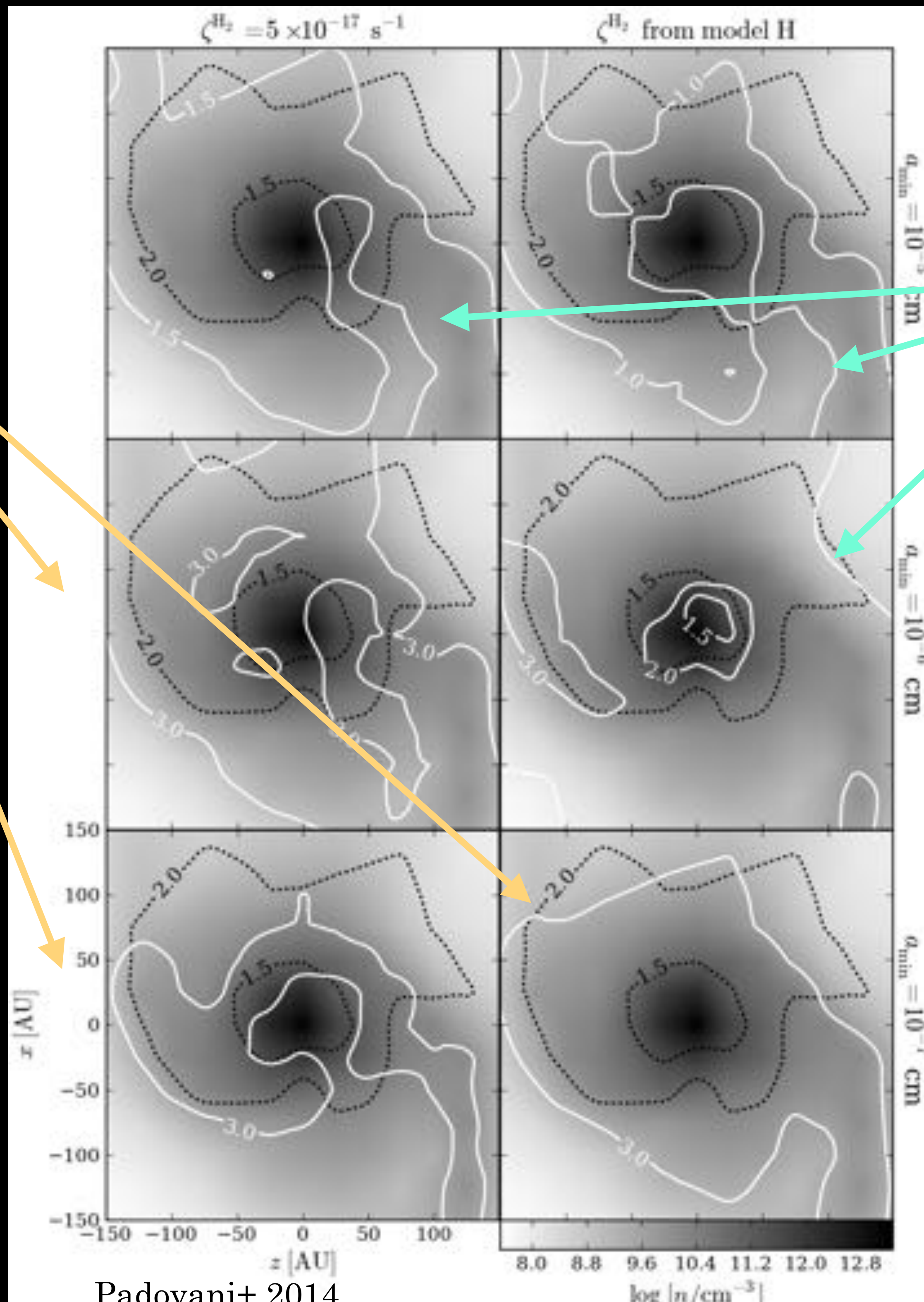
The region of decoupling decreases with decreasing a_{min} (from ≈50 AU to ≈20 AU of radius), but it is still present.

The correct evaluation of the CR ionisation rate as a function of density and magnetic field allows the diffusion time to decrease up to three order of magnitudes.

Cosmic-ray ionisation rate and diffusion time scale

HIGH-MASS CASE

$t_B > t_{dyn}$



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$t_B < t_{dyn}$

For $a_{min}=10^{-5}$ cm the decoupling region has a radius of ≈100 AU, but for $a_{min}=10^{-7}$ cm it vanishes.

Different behaviour wrt low-mass case: the field diffuses faster in the HM case (turbulent nature of the flow). Problems with limited resolution? Numerical diffusion (Hennebelle+ 2013; Joos+ 2013).

The turbulent diffusion present in the HM model reduces the field strength making the microscopic resistivities smaller (no decoupling).

Conclusions

- The study of **low energy** ($E < 1$ GeV) cosmic rays is fundamental for correctly dealing with **chemical modelling** and **non-ideal MHD simulations**;

- In order to study the cosmic-ray propagation we accounted for **energy losses** and **magnetic field effects**: an increment of the toroidal component, and in general a **more tangled magnetic field**, corresponds to a **decrease of ζ_{H2}** because of the growing preponderance of the **mirroring effect**;

- The extent to which density and magnetic effects make ζ_{H2} decrease can be ascribed to the degree of magnetisation; **$\zeta_{H2} < 10^{-18}$ s^{-1}** is attained in the central **300-400 AU**, where **n$>10^9$ cm^{-3}**, for toroidal fields larger than about **40%** of the total field in the cases of intermediate and low magnetisation (**λ=5 and 17**, respectively);

- We found an increase in η in the innermost region of a cloud after the collapse onset: (1) field has to be considerably twisted; (2) dust grains had time to grow by coagulation.

A correct treatment of CR propagation can explain the occurrence of a decoupling region between gas and magnetic field that in turn affects the disc formation.