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

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in collaboration with

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

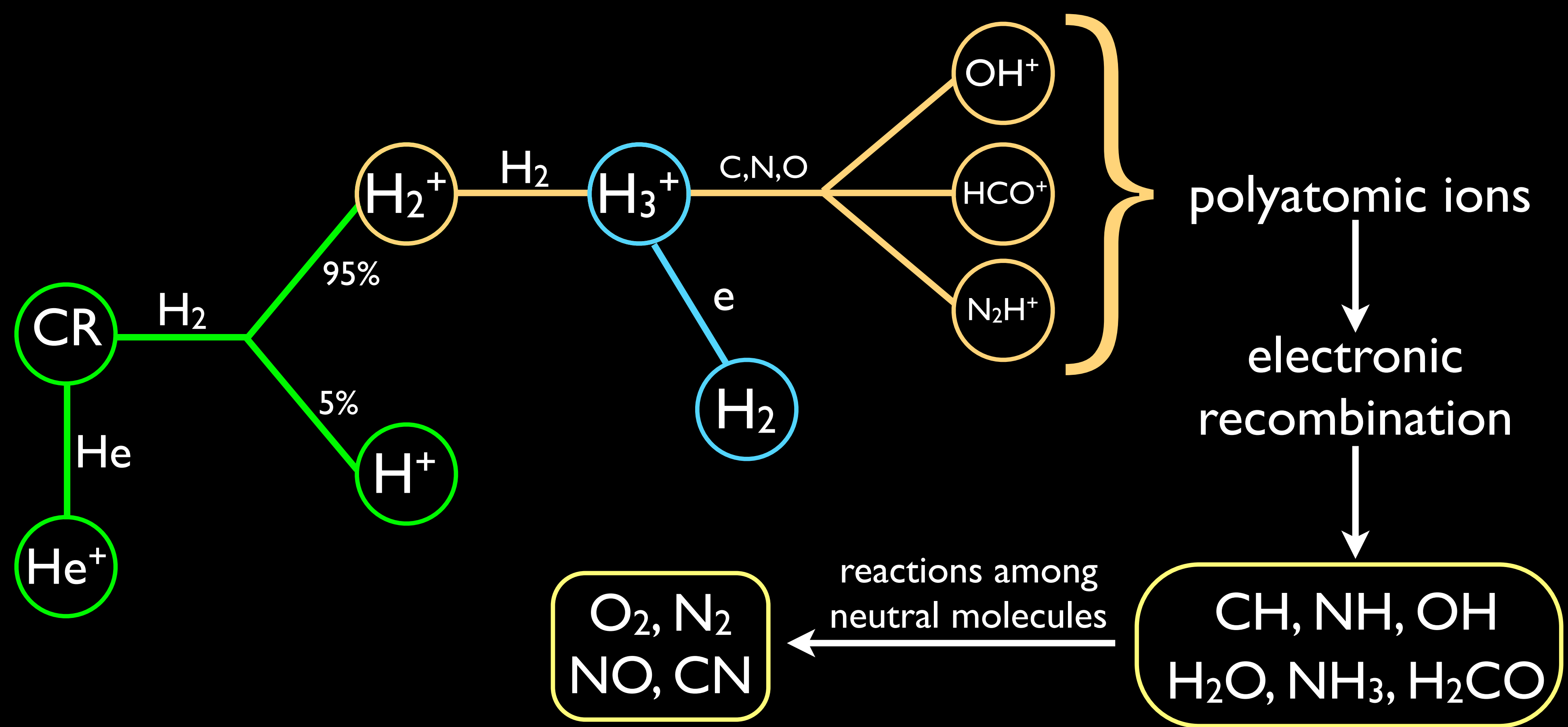
- H_3^+ : UKIRT, VLT-CRIRES — *Indriolo+ (2012)*
- OH^+, H_2O^+ : Herschel — *Neufeld+ (2010), Gerin+ (2010)*
- γ-ray emission : Fermi-LAT (CTA) — *Montmerle (2010)*
- magnetic field morphology : SMA, Planck (ALMA) — *Girart+ (2009)*

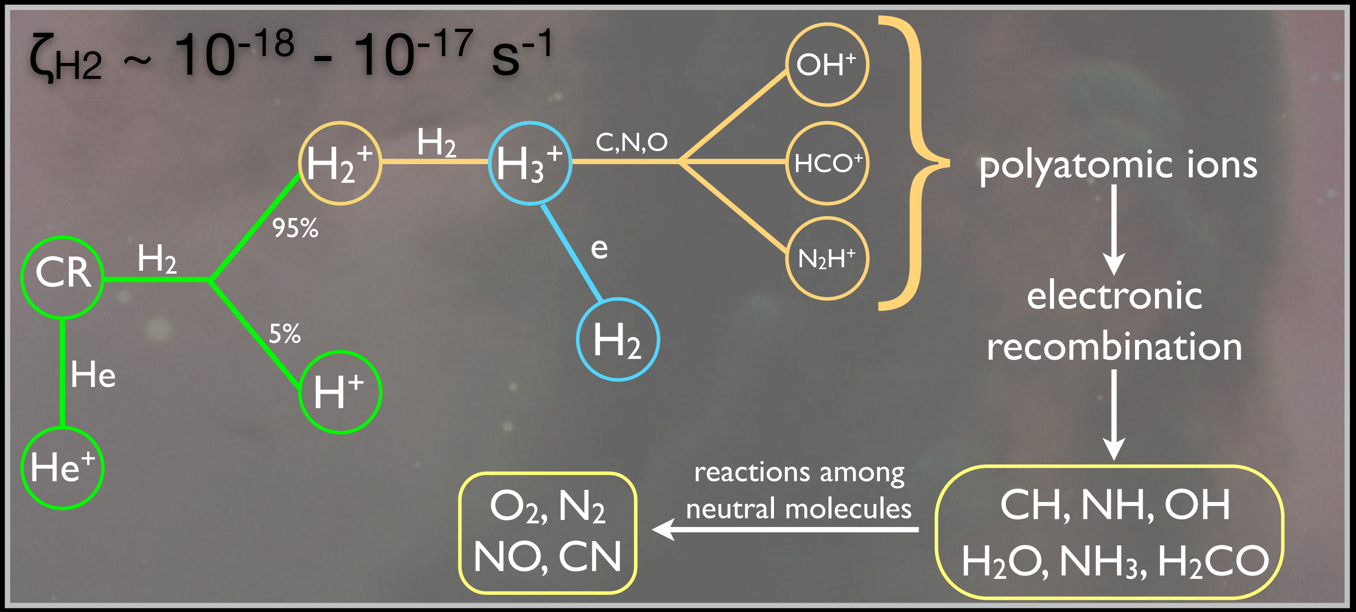
All these observations require a solid theoretical support. A detailed effort in the modelling of the CR spectrum, and more precisely of its low-energy tail, was missing as well as the integration of the models in chemical and numerical codes for interpreting observations.

Cosmic rays and molecular cloud chemistry

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

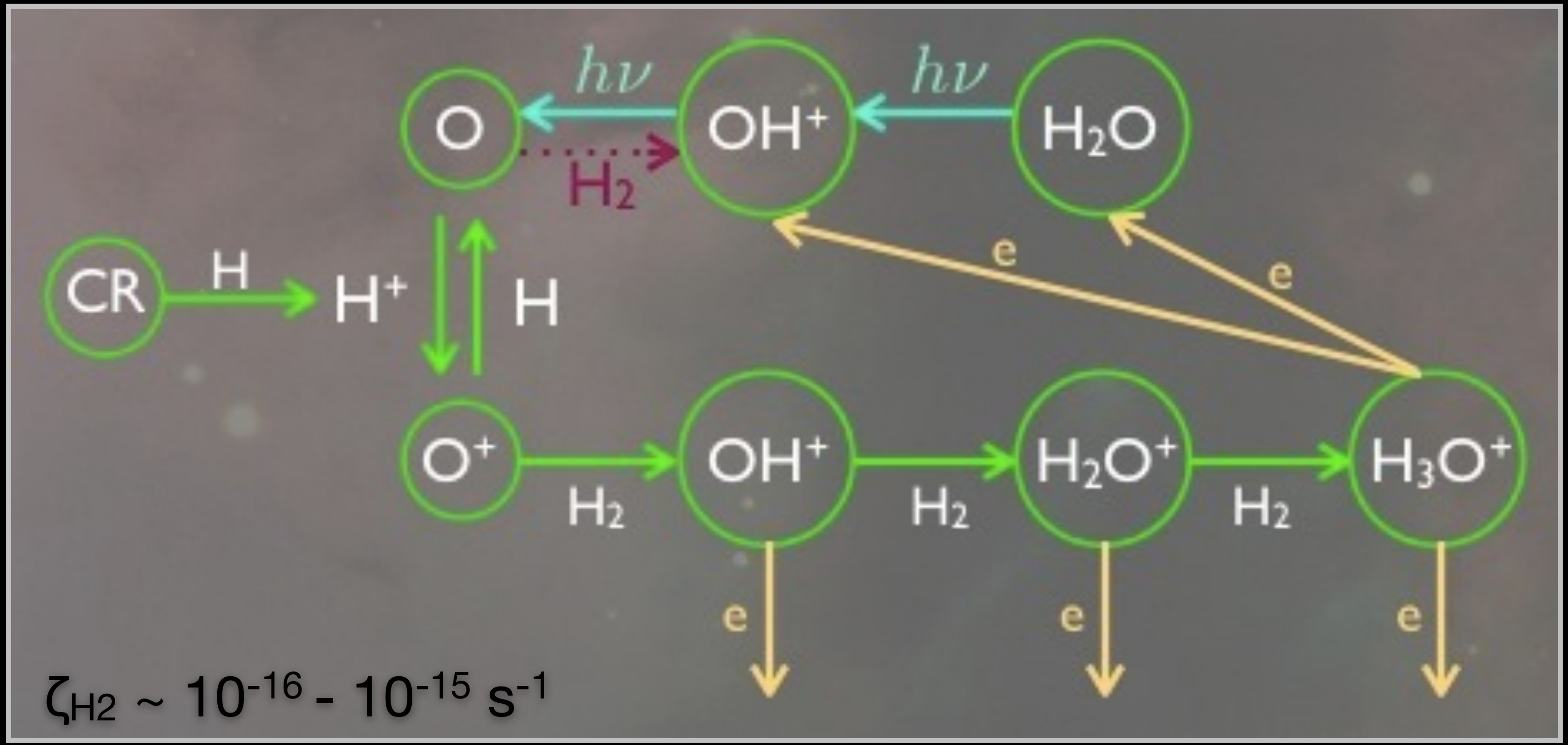
- **Dense clouds ($A_v \gtrsim 5$ mag) $\rightarrow$ the ionisation is due to low-energy CRs ($E < 100$ MeV) and, if close to young stars, to soft X–rays ($E < 10$ keV).**





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:

- possible low-energy CR flux able to ionise diffuse but not dense clouds
  Takayanagi (1973); Umebayashi & Nakano (1981); McCall+ (2003); **PM, Galli & Glassgold (2009)**
- magnetic mirroring and focusing
  Cesarsky & Völk (1978); Chandran (2000); **PM & Galli (2011)**;
- effects of Alfvén waves on CR streaming
  Skilling & Strong (1976); Hartquist+ (1978); Padoan & Scalo (2005); Rimmer+ (2012);

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.

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

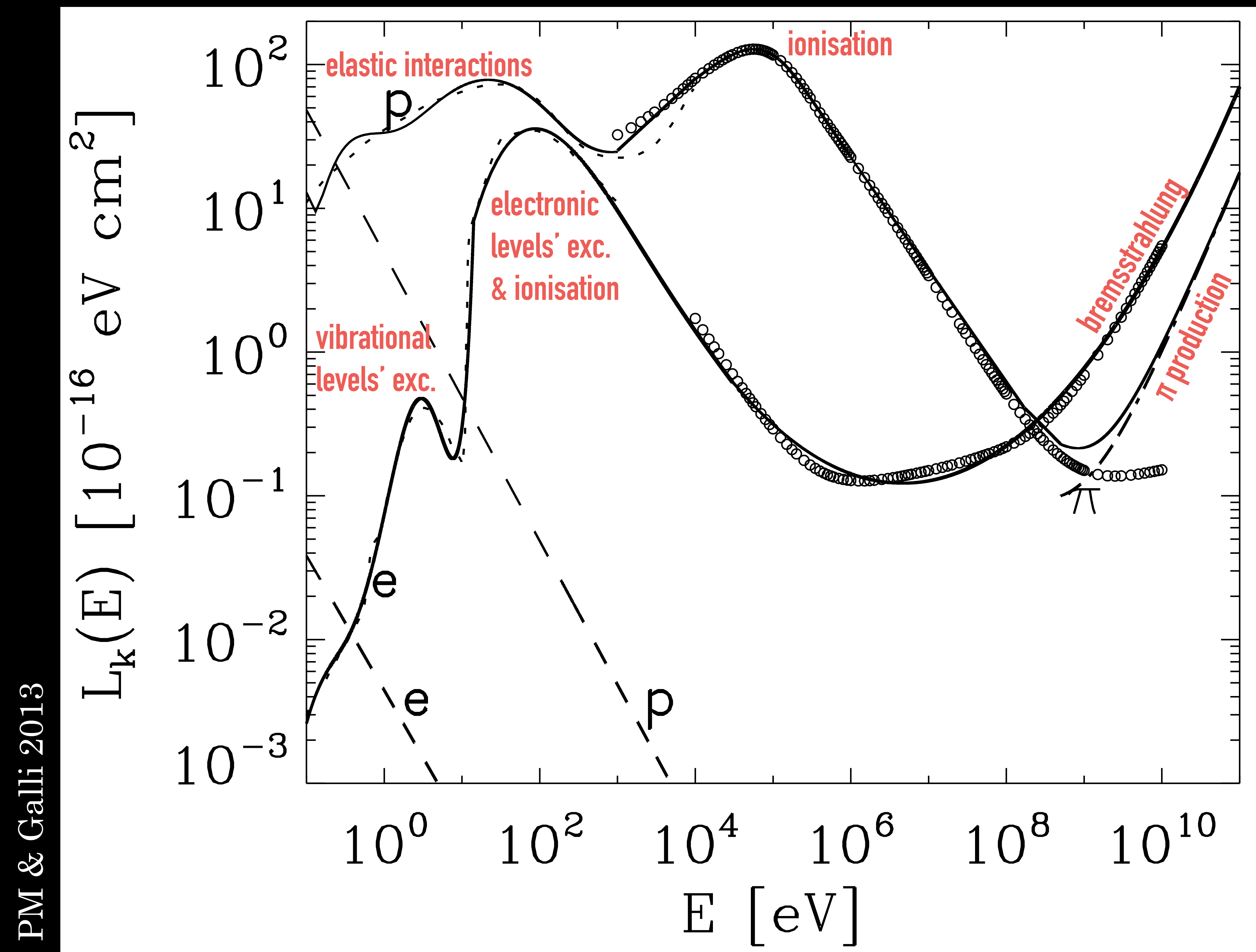
$\eta_{\rm h}$: correction due to the presence of heavy nuclei among CRs

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

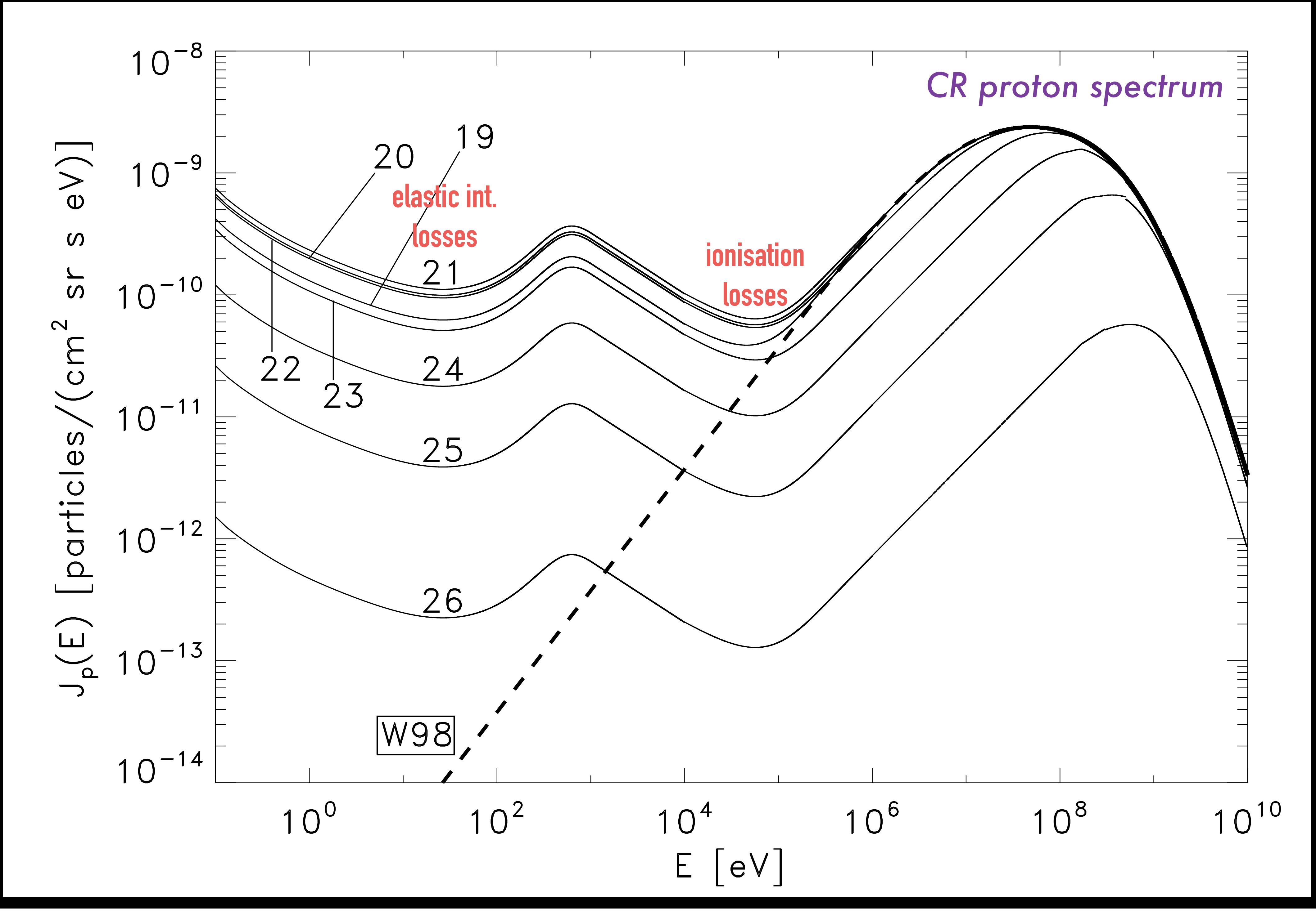
$$\zeta_{\rm e}^{\rm H_2}(N) = 4\pi\int_0^\infty j_{\rm e}(E,N)\,\eta_{\rm e}^{\rm sec}(E)\,\sigma_{\rm e+H_2}(E)\,{\rm d}E$$

$\eta_{\rm p}^{\rm sec}$, $\eta_{\rm e}^{\rm sec}$: correction due to the ionisation of secondary electrons

CR–proton and electron energy loss function

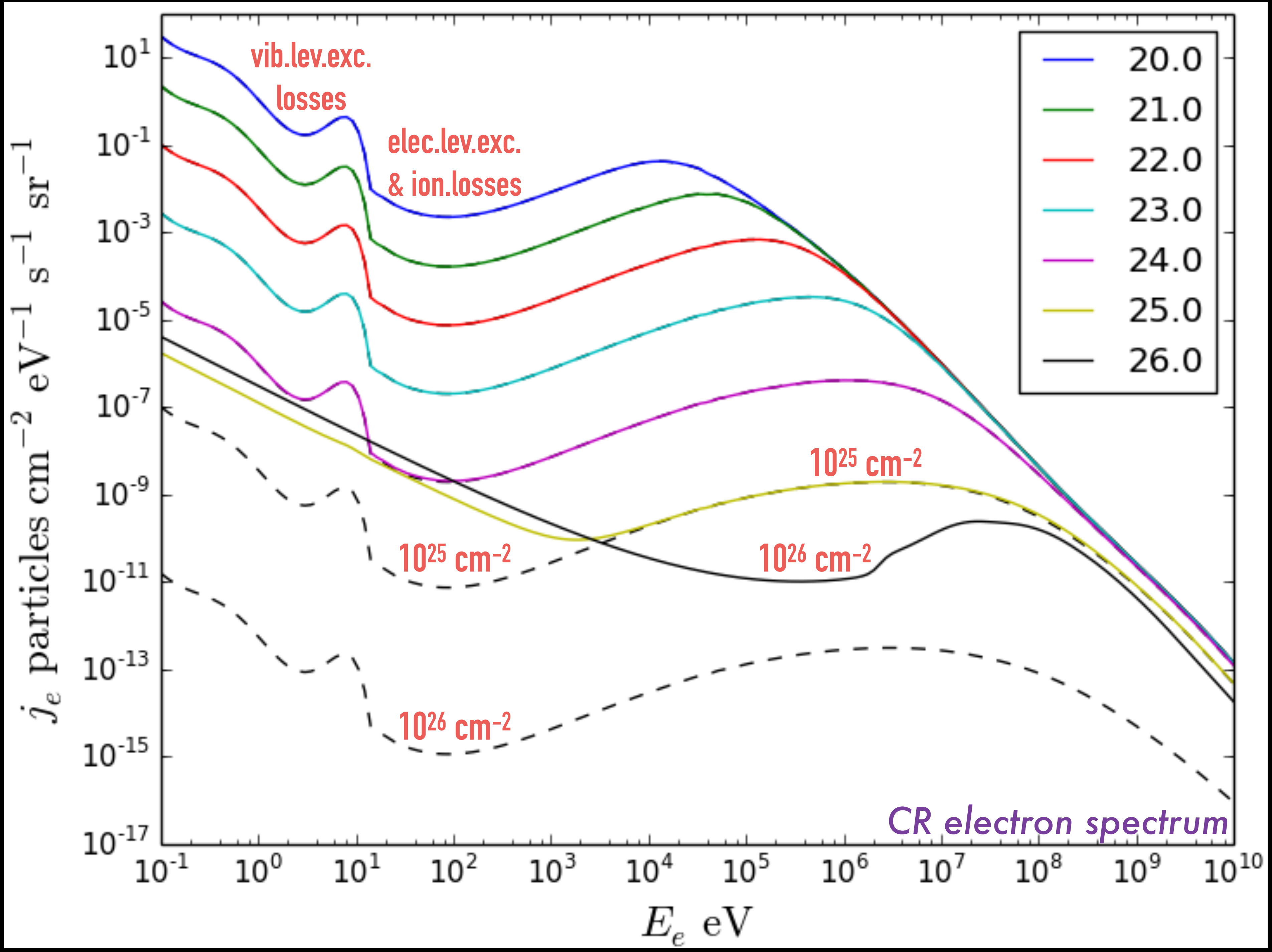


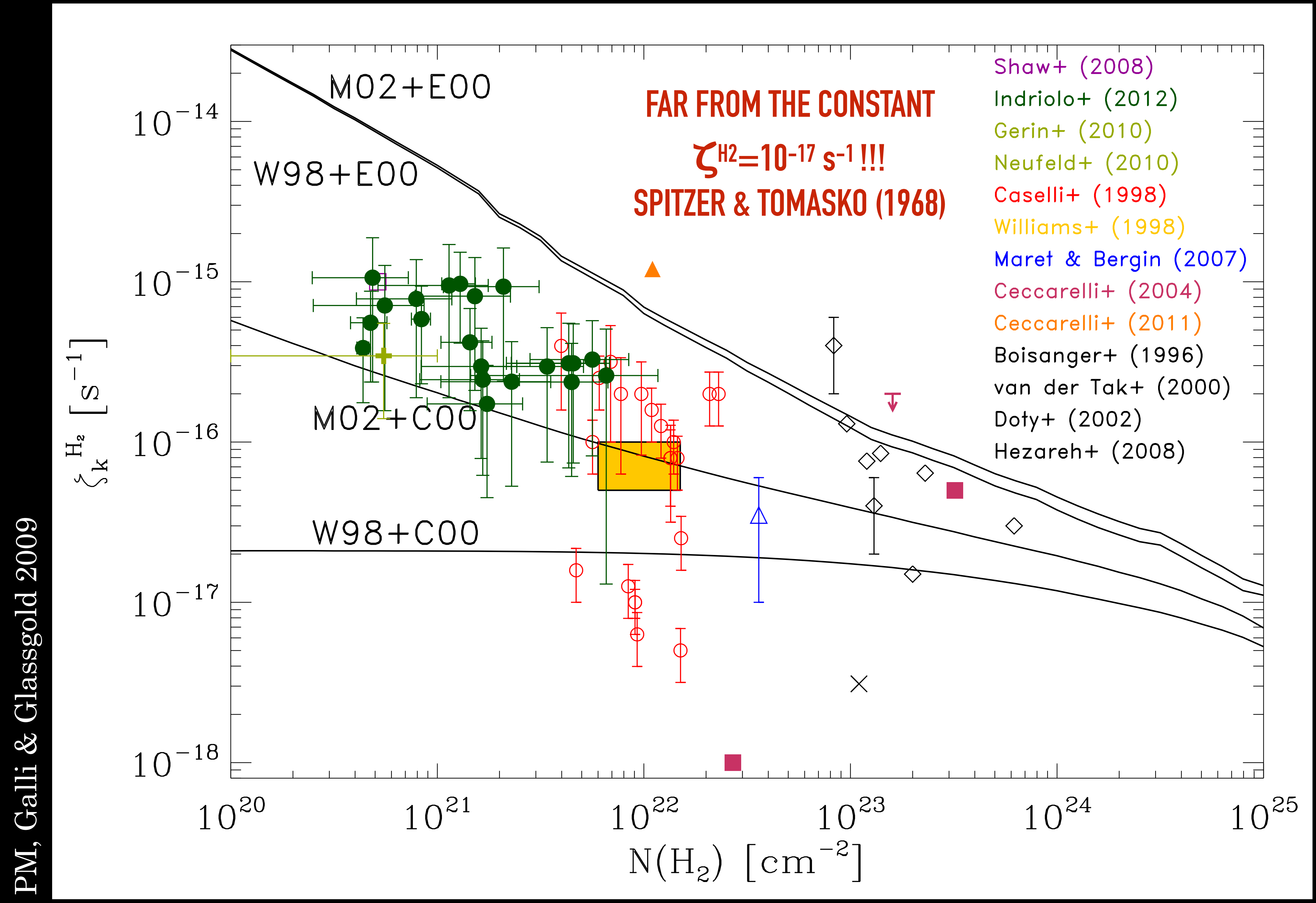
The low-energy tail in CR incident spectrum is produced during the propagation of CRs in the cloud EVEN when the incident spectrum is devoid of low-energy particles.



PM, Galli, Glassgold 2009

Accounting for secondary electrons produced by π^- decay (following Kamae+ 2006)

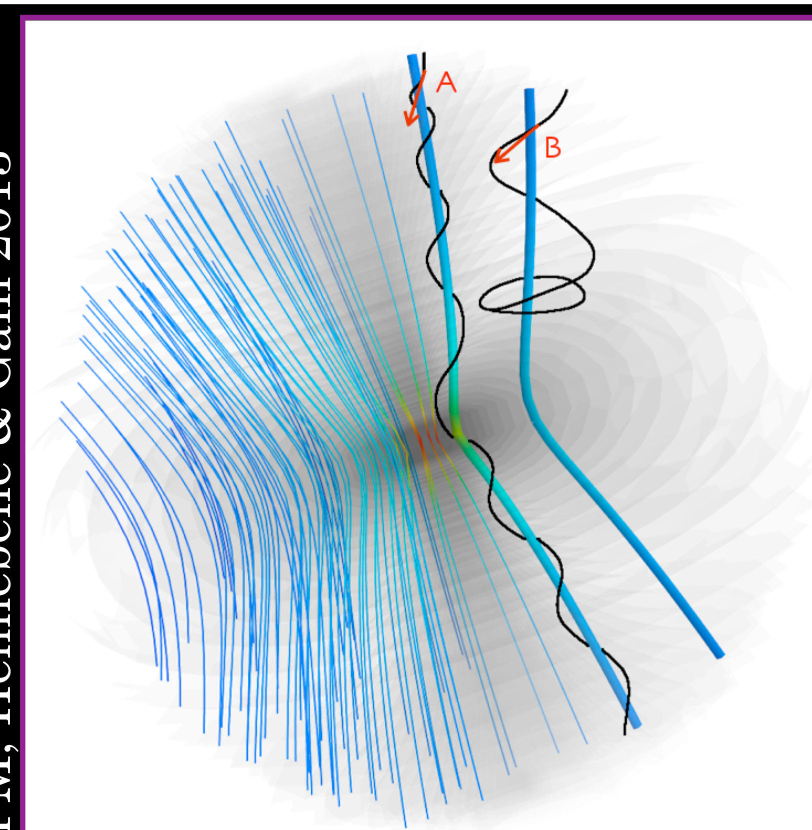



FAR FROM THE CONSTANT
ζH2=10-17 s-1 !!!
SPITZER & TOMASKO (1968)
M02+E00
W98+E00
M02+C00
W98+C00
Shaw+ (2008)
Indriolo+ (2012)
Gerin+ (2010)
Neufeld+ (2010)
Caselli+ (1998)
Williams+ (1998)
Maret & Bergin (2007)
Ceccarelli+ (2004)
Ceccarelli+ (2011)
Boisanger+ (1996)
van der Tak+ (2000)
Doty+ (2002)
Hezareh+ (2008)
$\zeta_k^{H_2}$ [s^{-1}]
N(H$_2$) [cm^{-2}]
PM, Galli & Glassgold 2009

$\vec{B}$

magnetic mirroring
bounces many CRs
out of the core

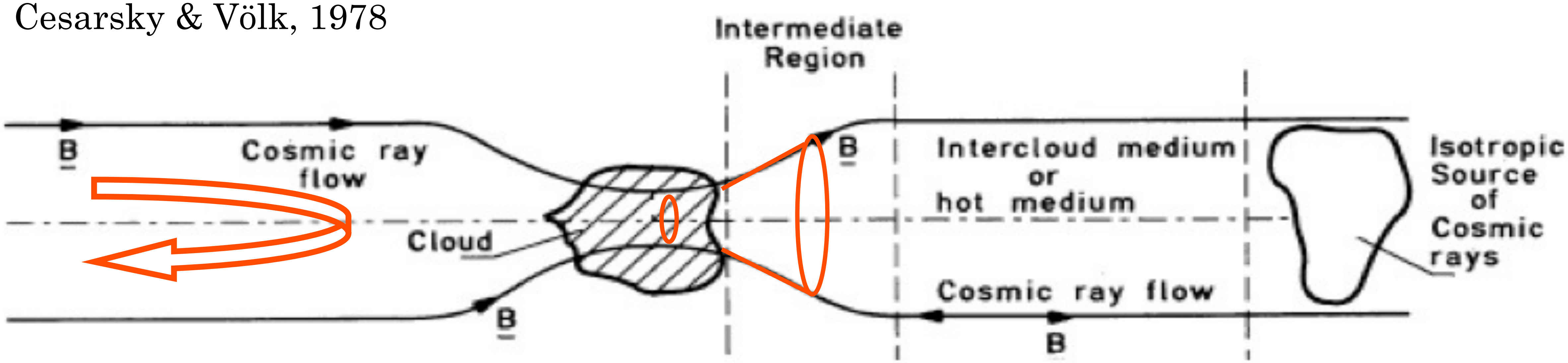
magnetic focusing
increases CR flux
in the core



PM, Hennebelle & Galli 2013

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).

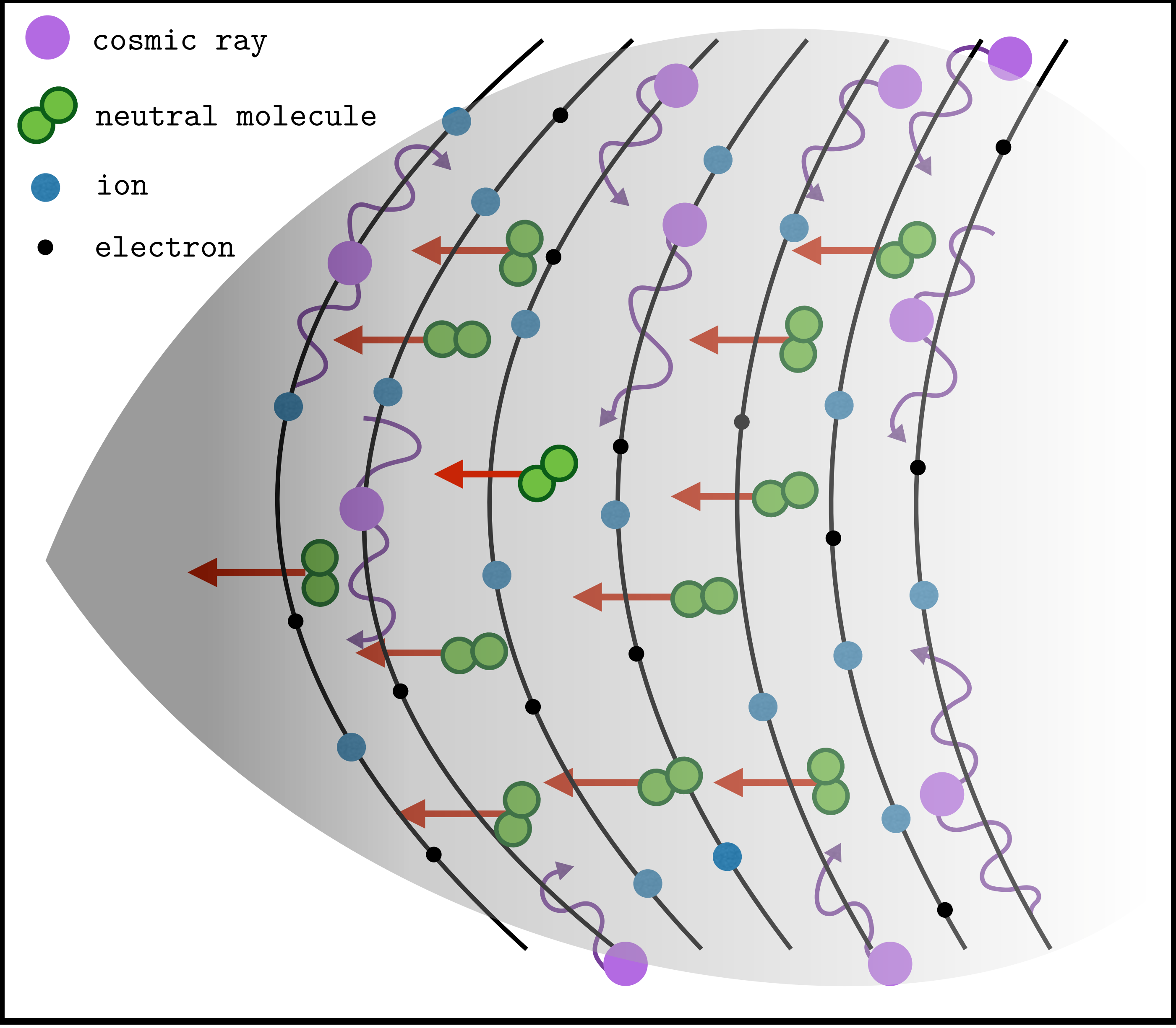
`non-uniformity of the magnetic field`



Cesarsky & Völk, 1978

Cosmic rays and the magnetic braking problem

- Theoretical challenge: protostellar discs could not form because of magnetic braking.
- Magnetic fields entrained by collapsing cloud brake any rotational motion preventing disc formation (Galli+ 2006; Mellon & Li 2008; Hennebelle & Fromang 2008).



- ions and electrons are frozen into magnetic field;
- neutrals drift reaching the central part of the core.

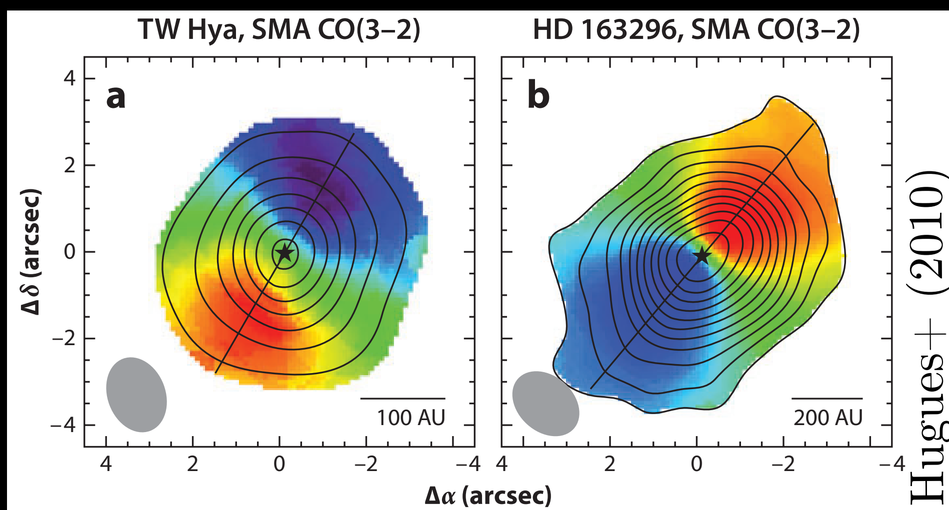
A frictional force couples charged particles and neutrals

CRs regulate the ionisation degree

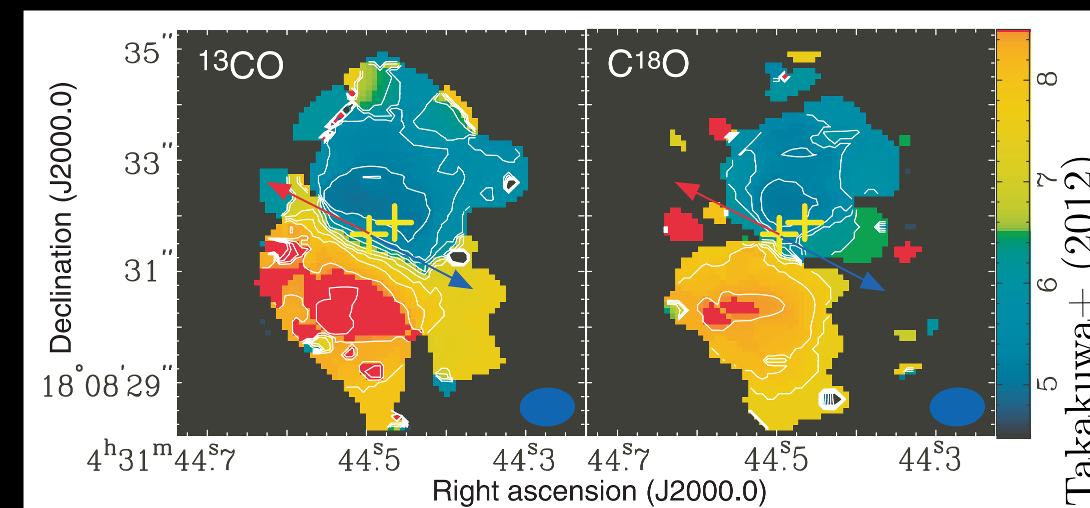
⇓

limit on the coupling between gas and magnetic field

Observational evidence of the presence of discs

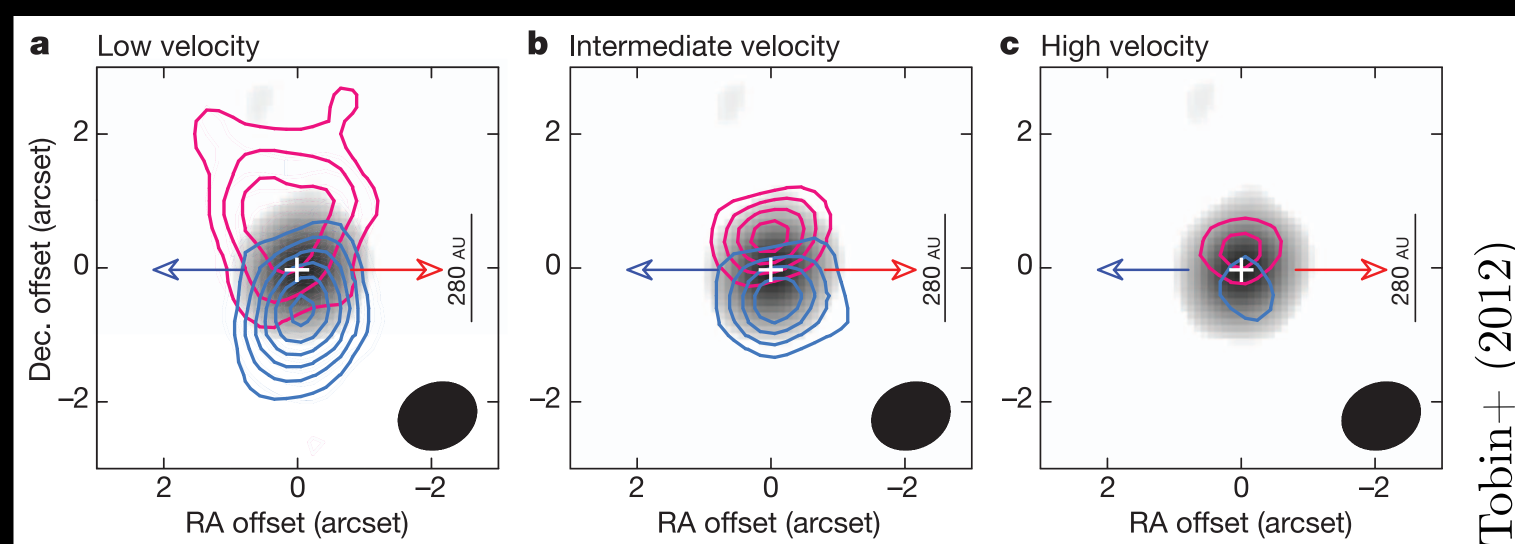


Class II YSO



Class I YSO

Class 0 YSO



Can CRs alleviate the magnetic braking favouring cloud collapse and protostellar formation?

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	$\alpha_{B,J}$ [rad]	t [kyr]	$M_\star$ [$M_\odot$]	M_{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 ($M_{disc} < 5 \times 10^{-2}\ M_\odot$).
[c] A keplerian disc is formed (Fig. 14 in Joos et al. 2012).

PM, Hennebelle & Galli 2013

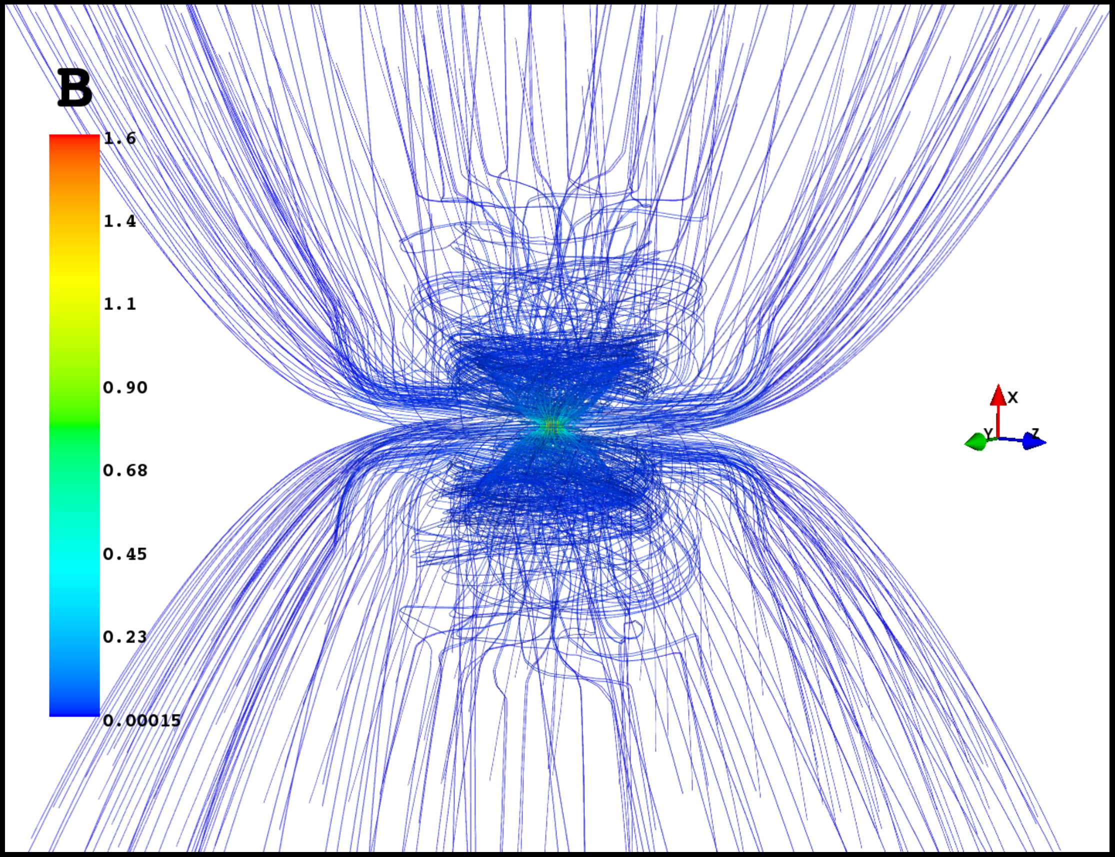
Numerical models : rotating collapsing core

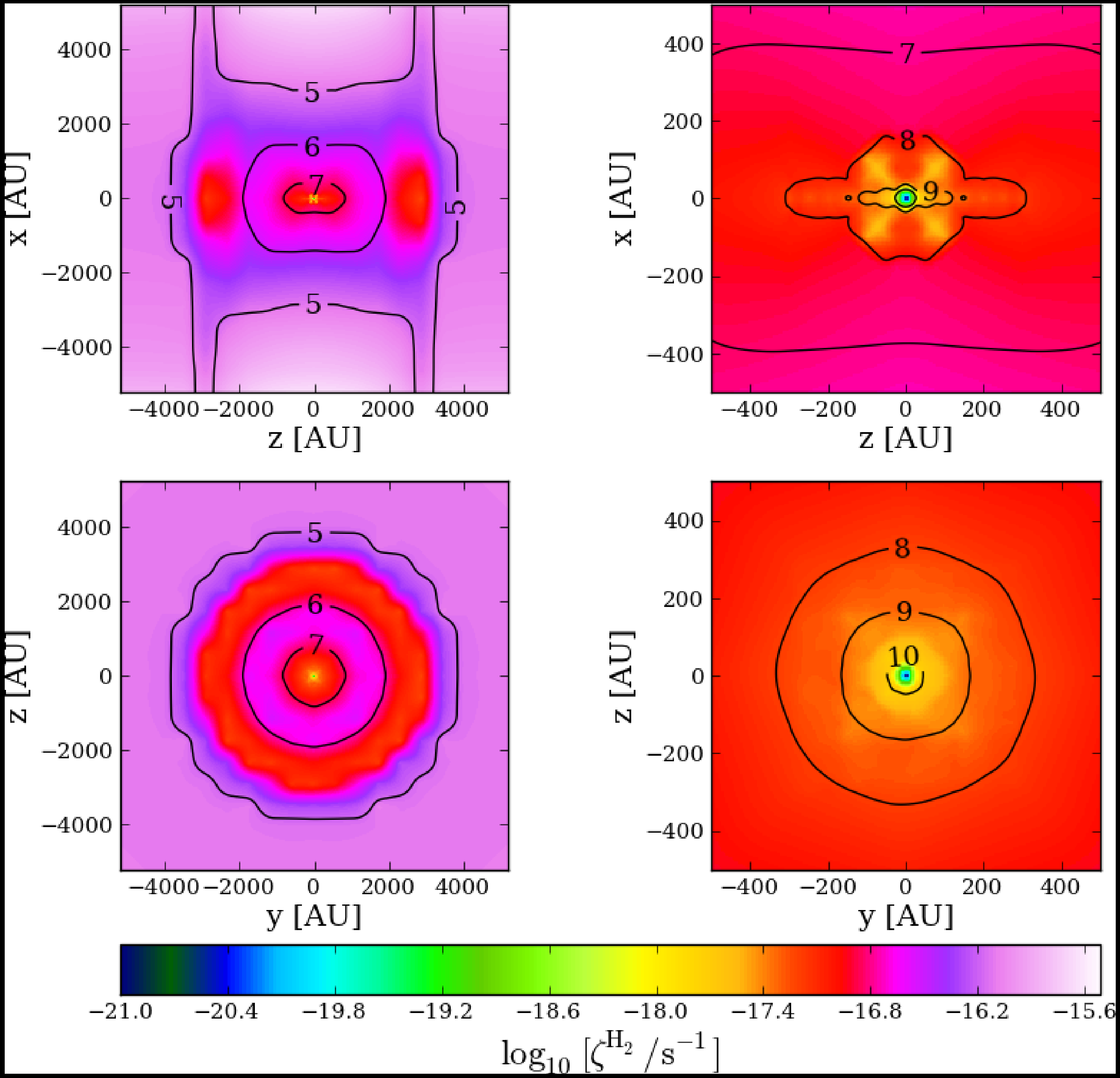
Intermediate magnetisation λ=5

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 ζ_{CR}. Deviations between iso-density contours and ζ_{CR} maps can be interpreted as due to magnetic imprints

Field lines in the inner 600 AU





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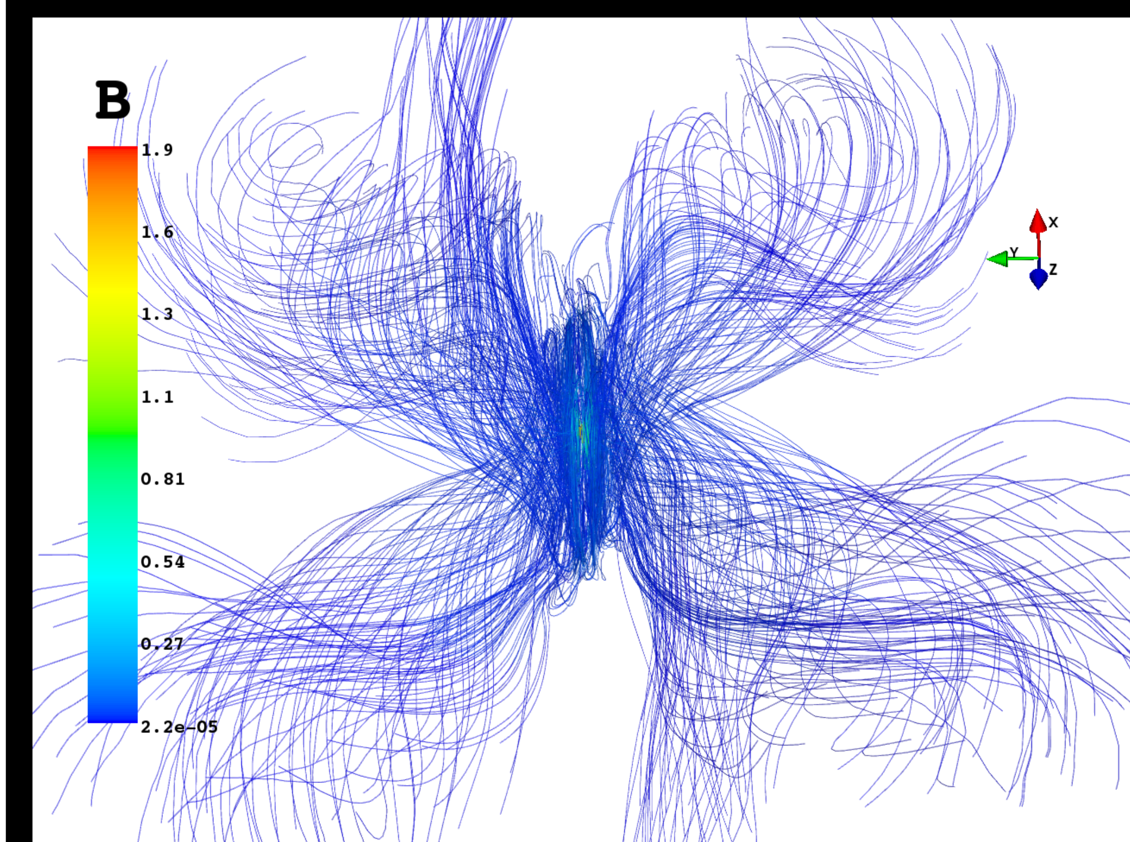
Numerical models : rotating collapsing core

Intermediate magnetisation λ=5

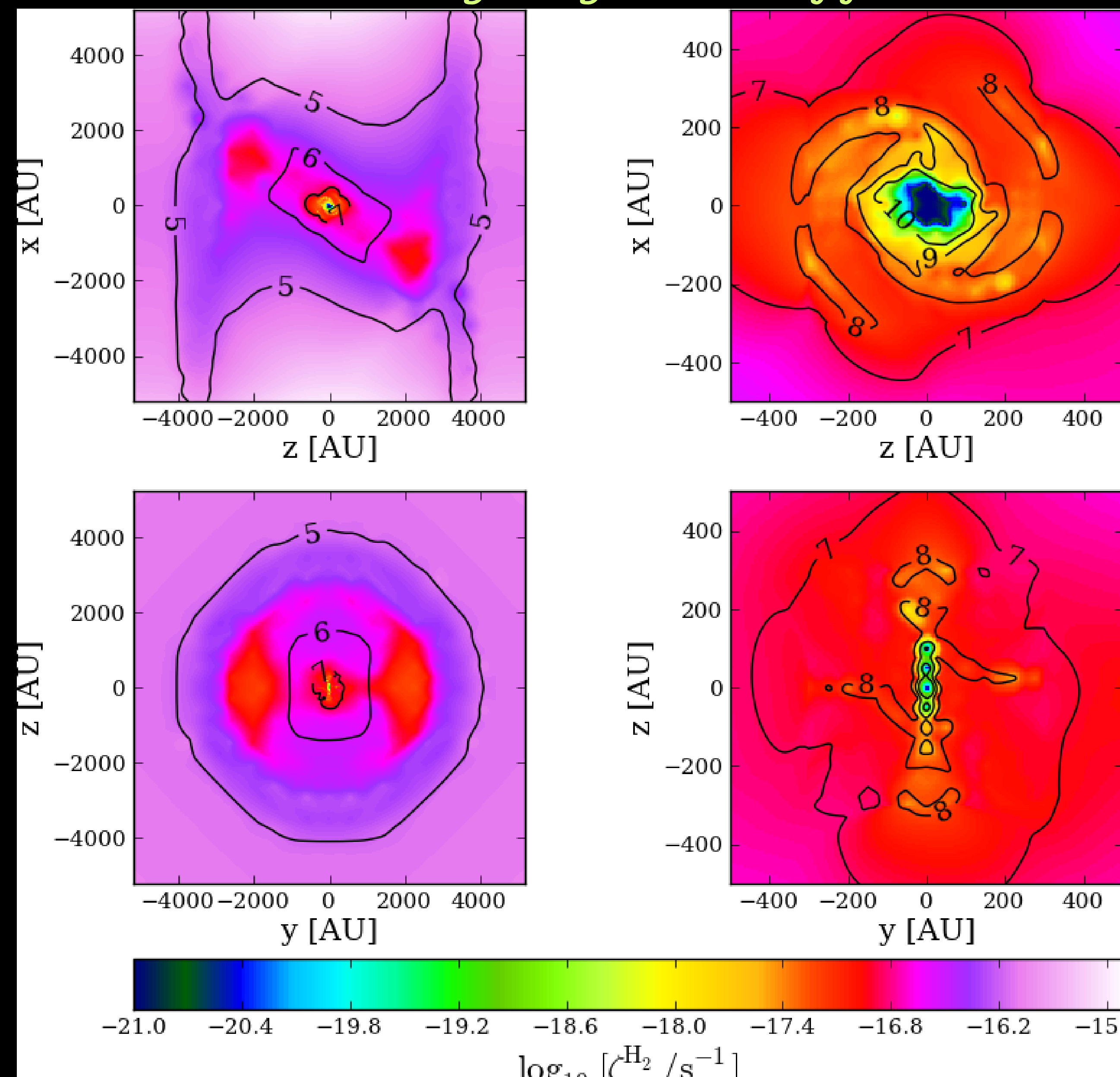
Perpendicular rotator (J,B)=π/2

$\zeta_{CR} < 10^{-18}$ s^{-1} down $\approx 10^{-20}$ s^{-1} (limit set by radionuclide decay, Umebayashi & Nakano 1981; Cleeves+ 2013) 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



PM, Hennebelle & Galli 2013

Numerical models : rotating collapsing core

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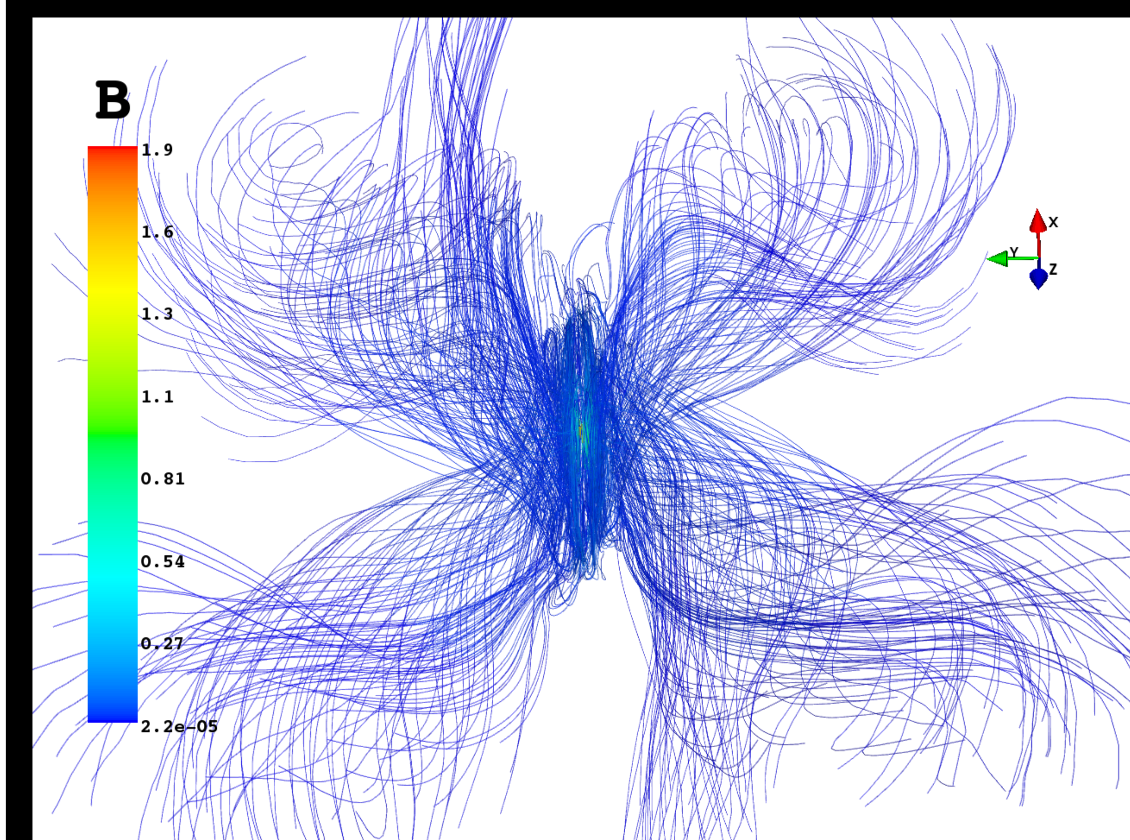
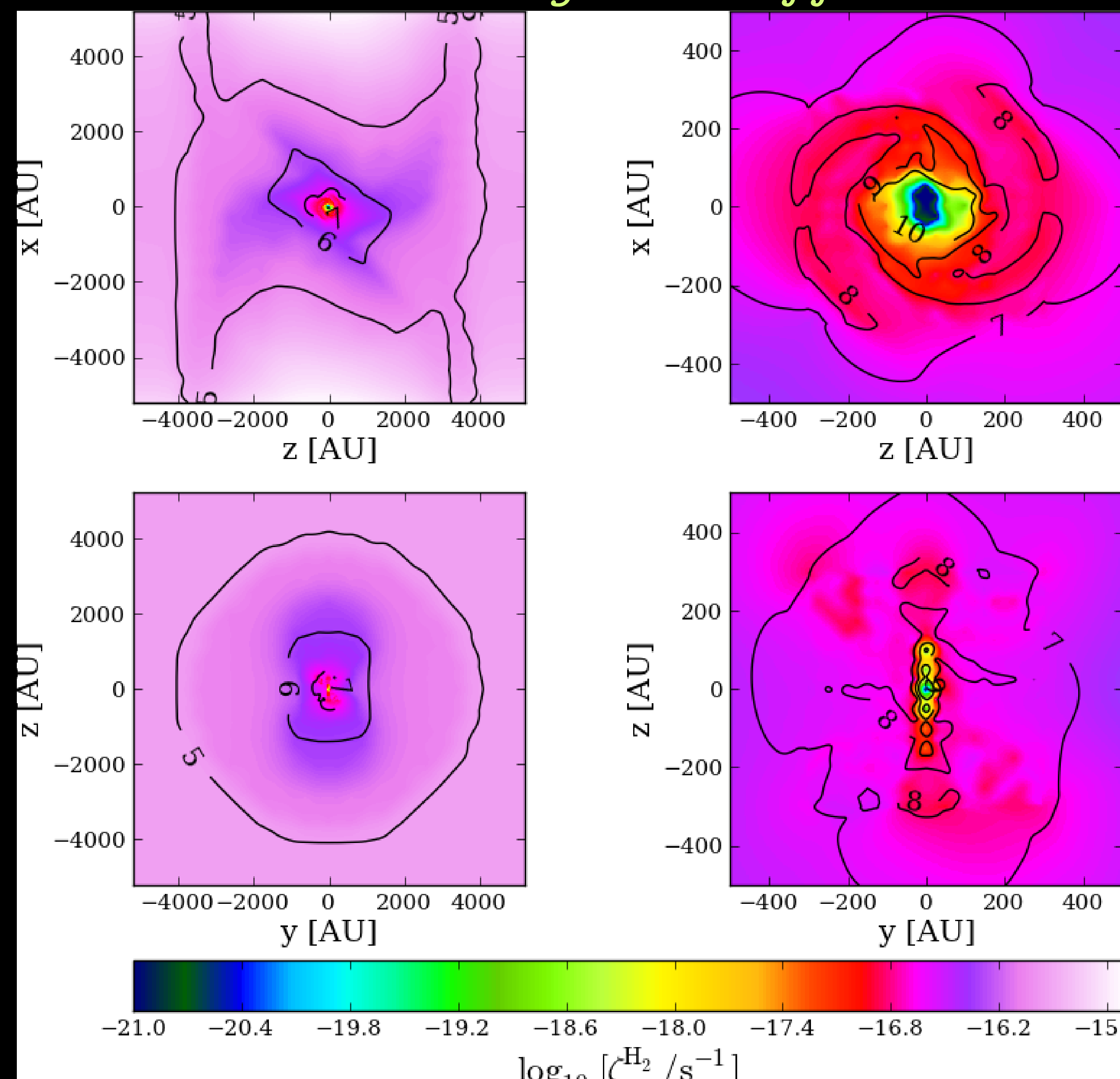


without magnetic effects



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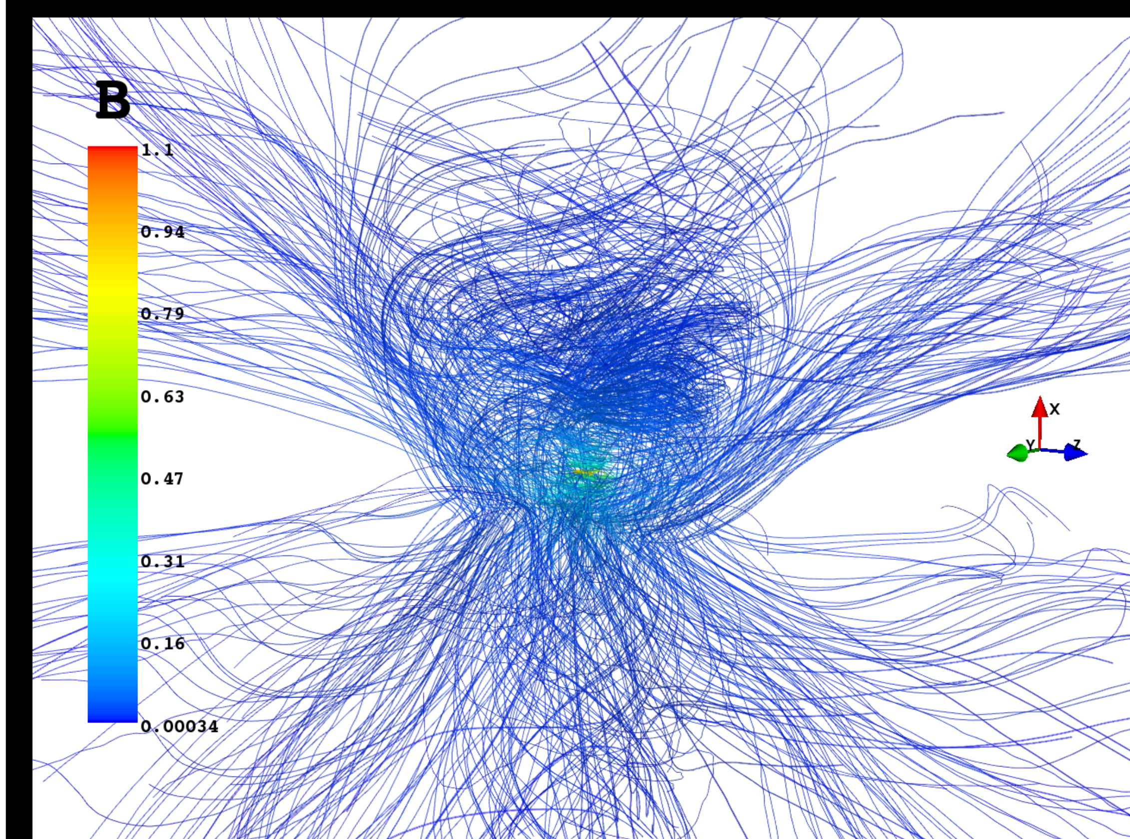
Numerical models : rotating collapsing core

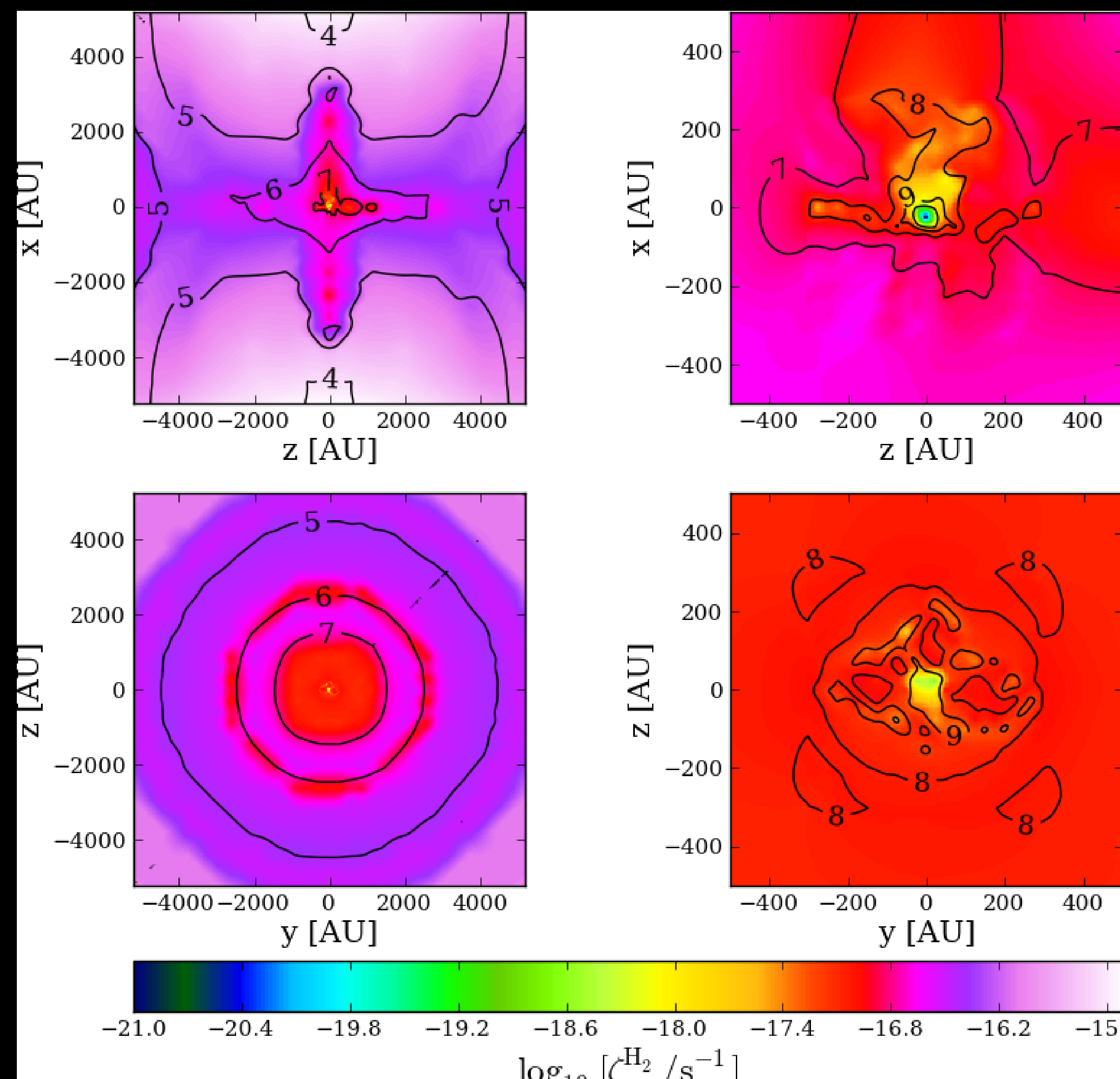
Strong magnetisation λ=2

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

A strong field is more resistant to line twisting caused by rotation. The poloidal configuration can be still identified due to a remarkable magnetic braking. No disc formation.

Field lines in the inner 600 AU





PM, Hennebelle & Galli 2013

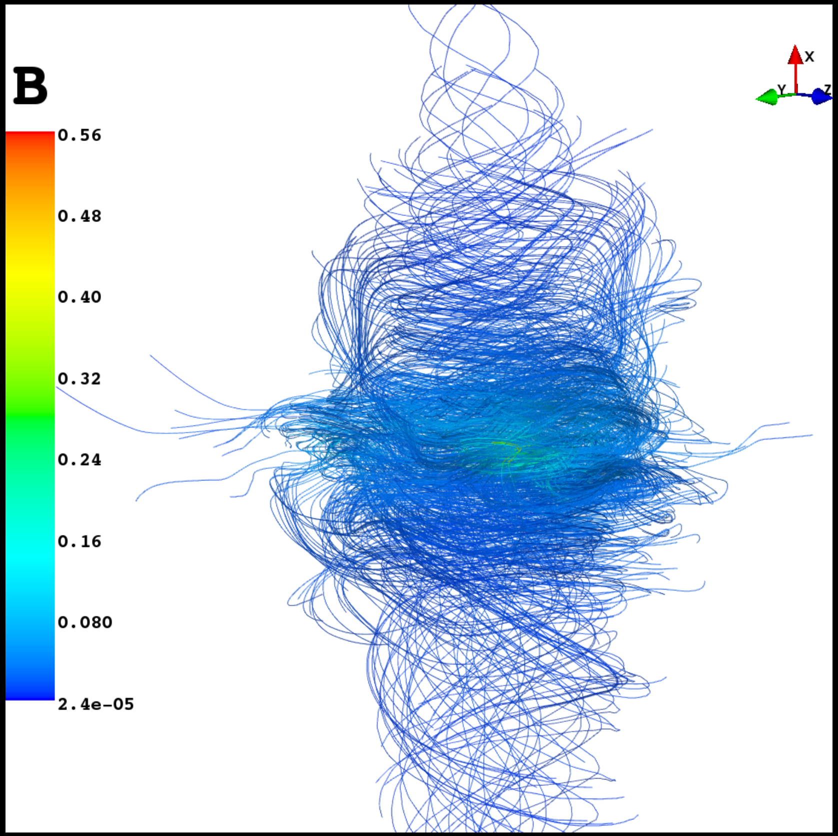
Numerical models : rotating collapsing core

Weak magnetisation λ=17

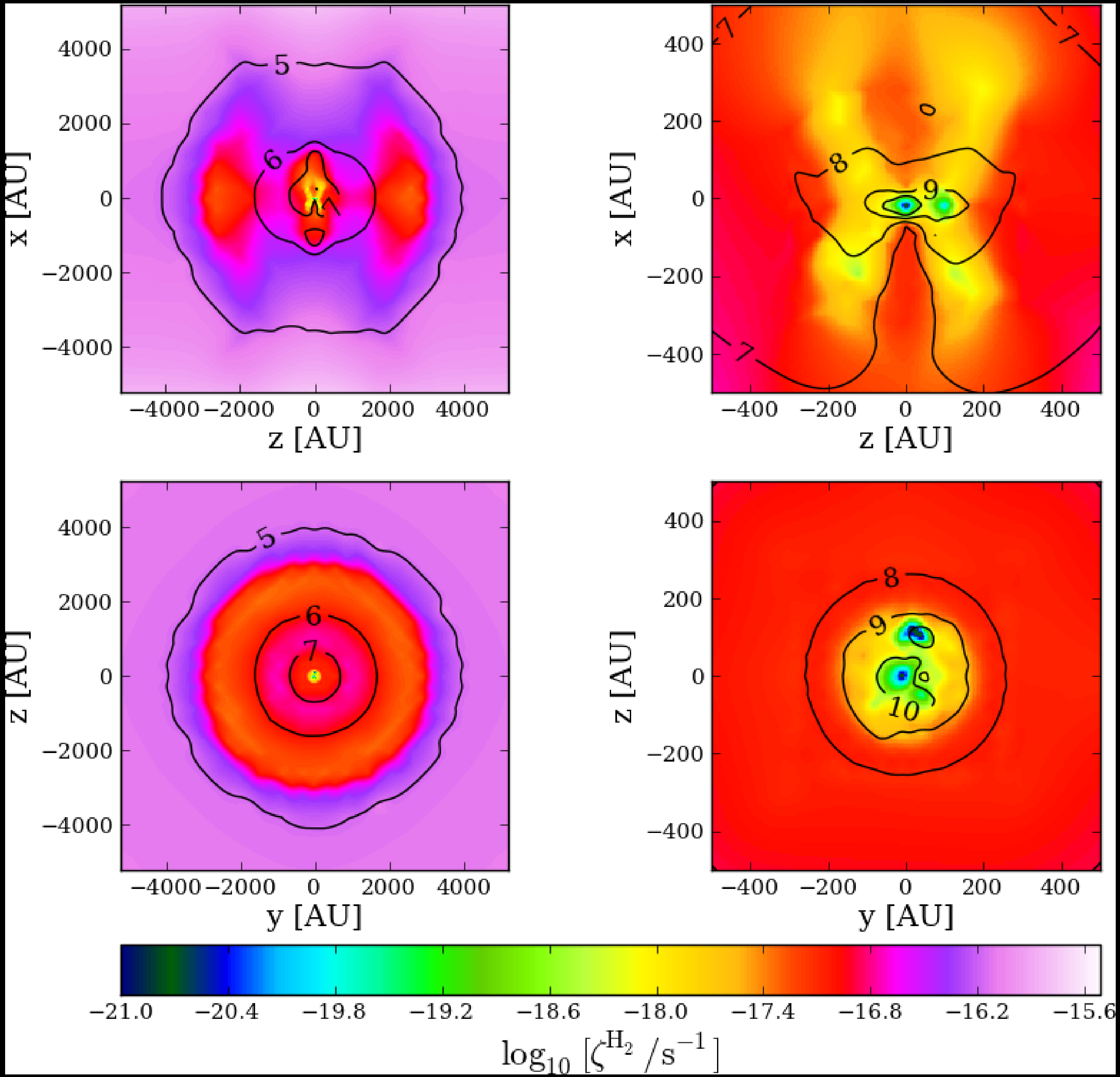
Aligned rotator (**J**,**B**)=0

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



PM, Hennebelle & Galli 2013

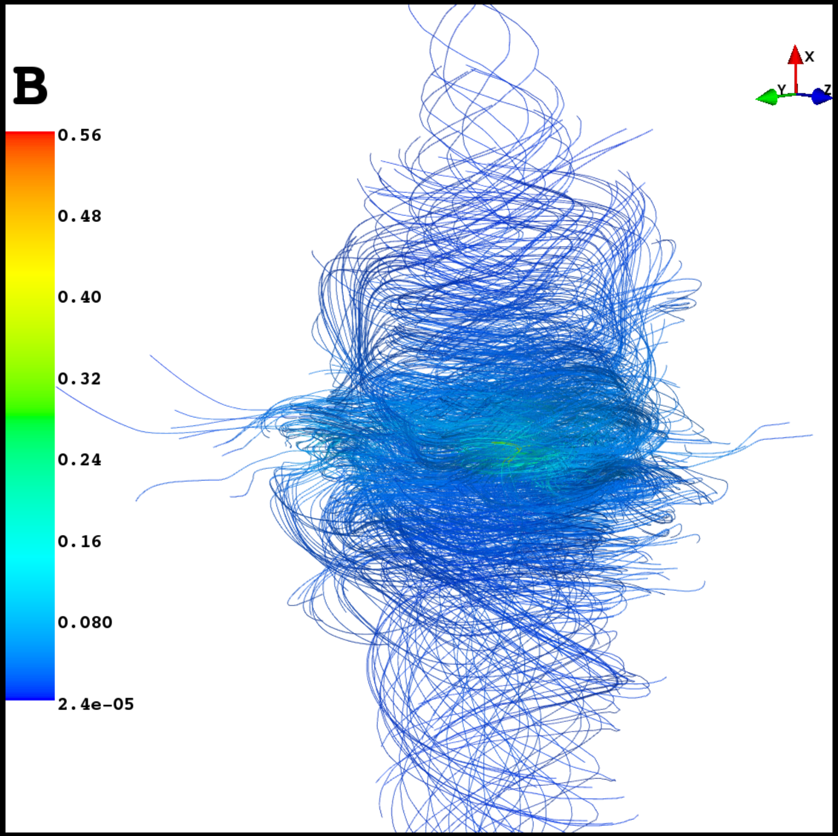
Numerical models : rotating collapsing core

Weak magnetisation λ=17

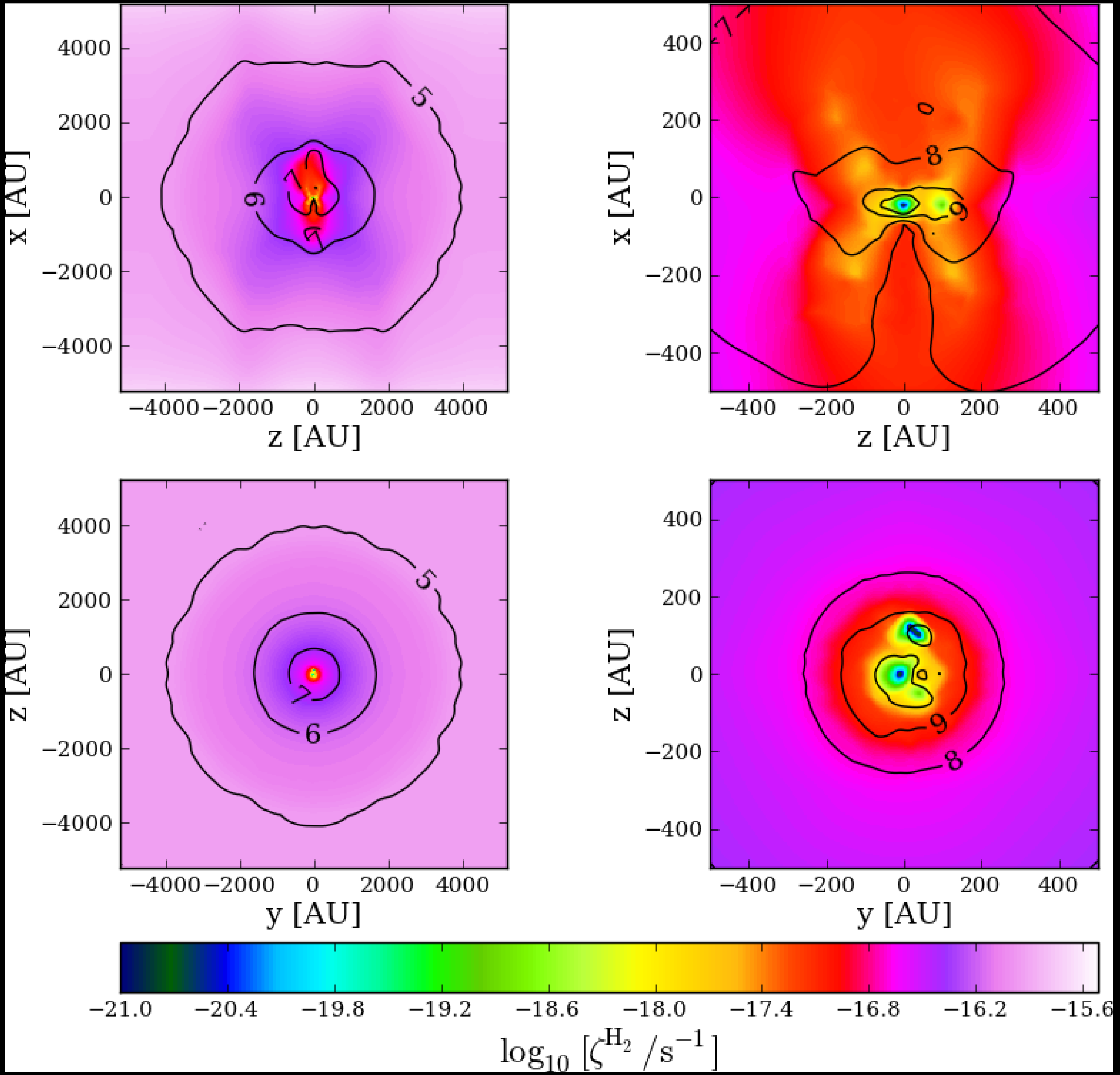
Aligned rotator (J,B)=0

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



without magnetic effects



PM, Hennebelle & Galli 2013

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 larger column density "seen" by CRs;

- 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);

- 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.