The importance of cosmic rays in star and planet formation

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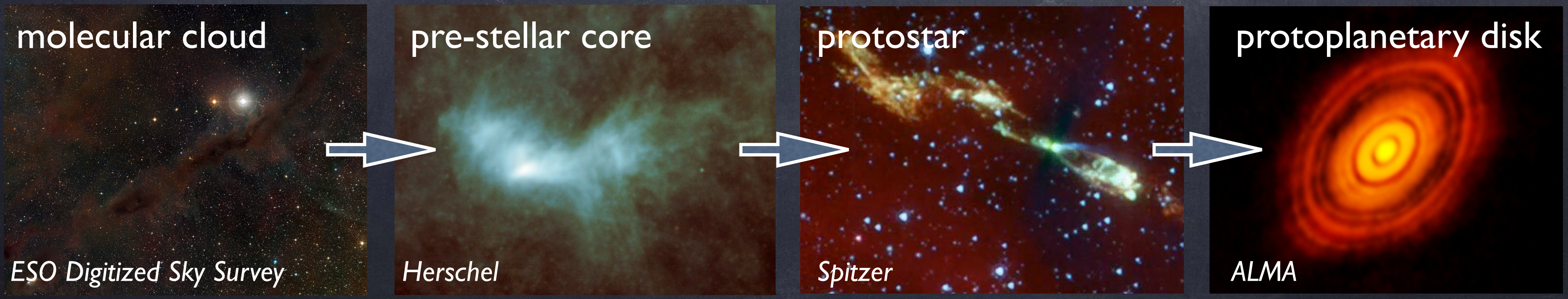


OUTLINE

- The start of astrochemistry
- D-fractionation and x(e)
- Dust charging
- Processing of icy mantles
- The formation of protoplanetary disks

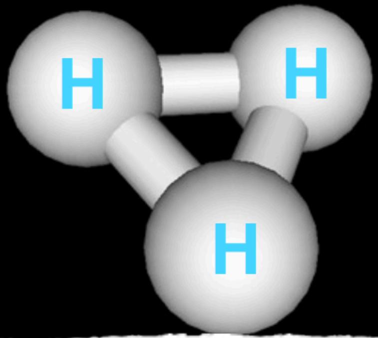
The start of astrochemistry

After the formation of molecular hydrogen, cosmic rays ionize H_2 initiating fast routes towards the formation of complex molecules in dark clouds:

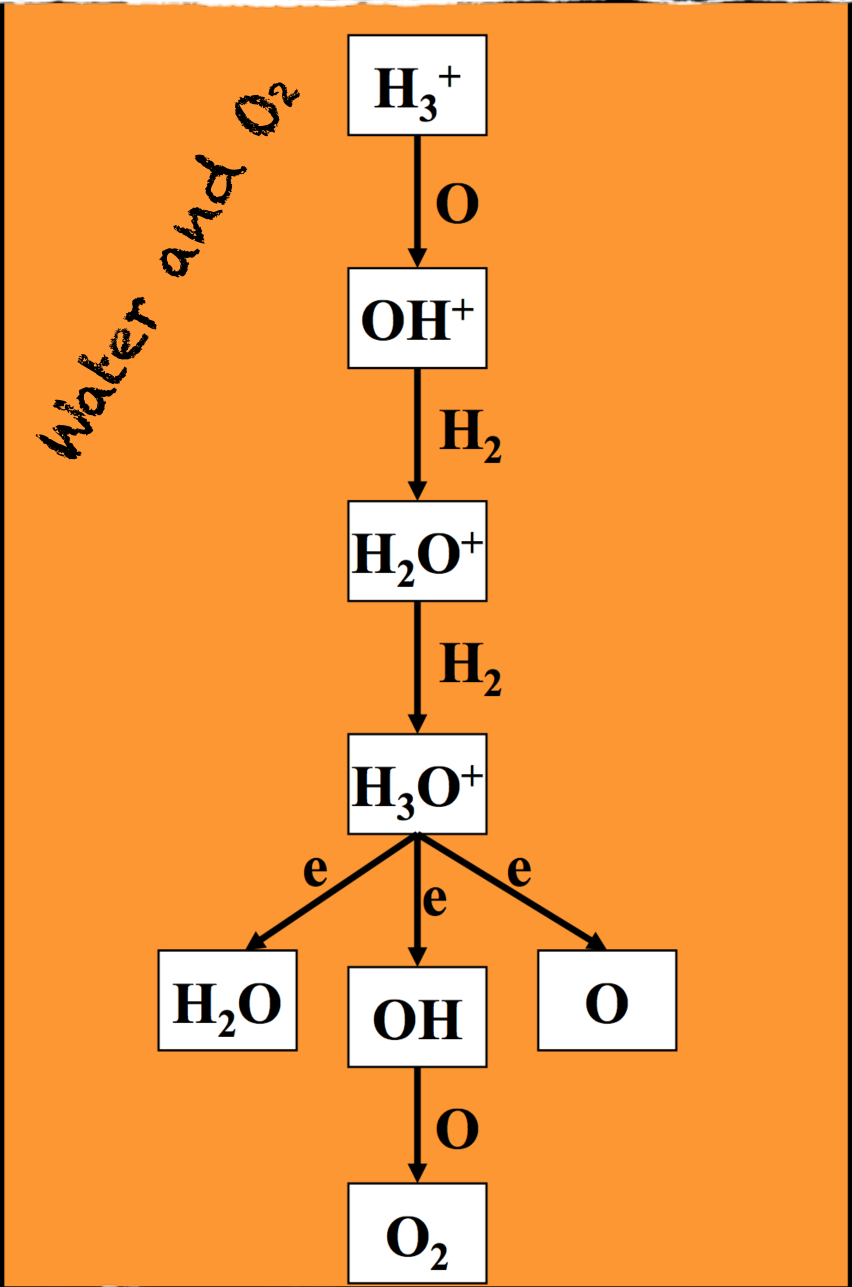
$$H_2 + \text{c.r.} \rightarrow H_2^+ + e^- + \text{c.r.}$$

Once H_2^+ is formed (97% of the times a c.r. hits H_2), it very quickly reacts with the abundant H_2 molecules to form H_3^+, the most important molecular ion in interstellar chemistry

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$



The start of astrochemistry



Water and O_2

H_3^+

O

OH^+

H_2

H_2O^+

H_2

H_3O^+

e

e

e

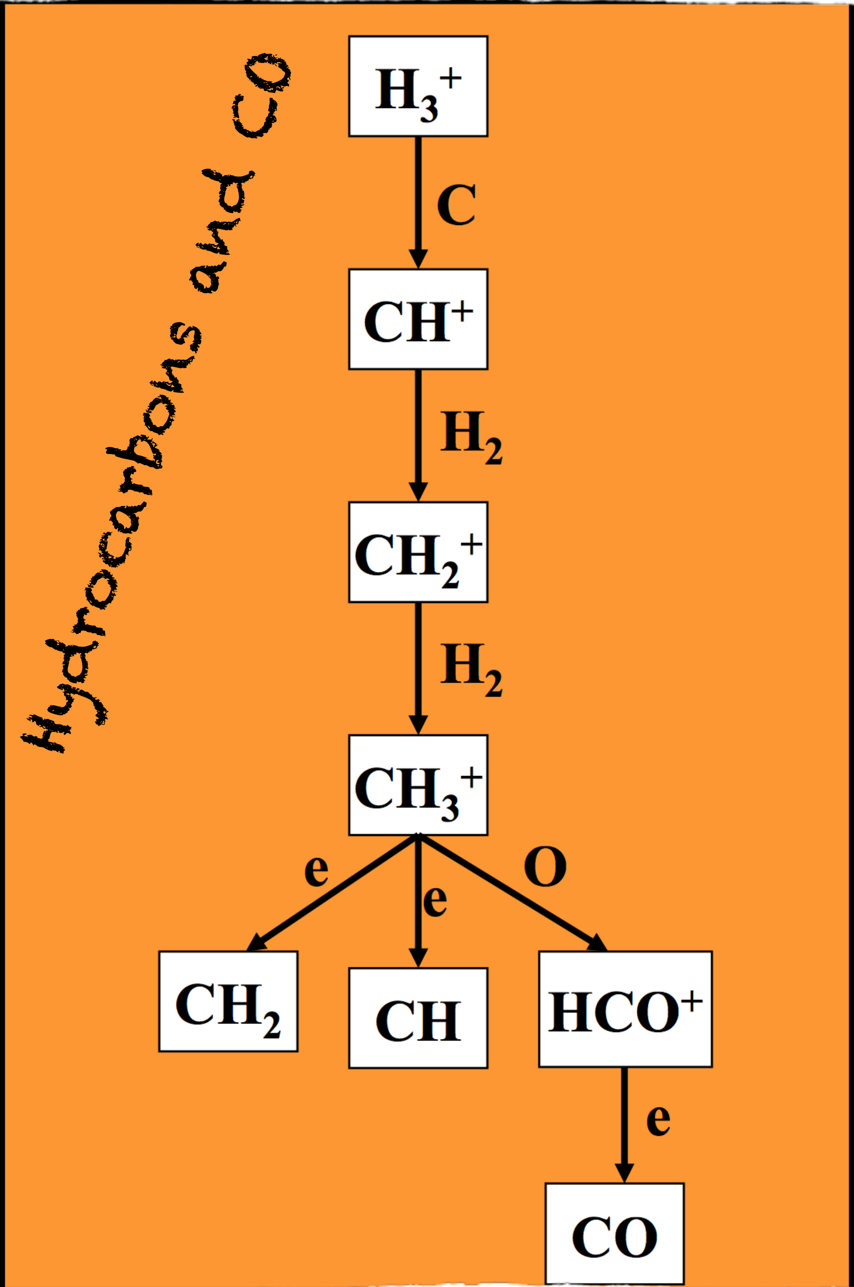
H_2O

OH

O

O

O_2



Hydrocarbons and CO

H_3^+

C

CH^+

H_2

CH_2^+

H_2

CH_3^+

e

e

O

CH_2

CH

HCO^+

e

CO

D-fractionation and x(e)

$H_3^+ + HD \Rightarrow H_2D^+ + H_2 + 230\ K$

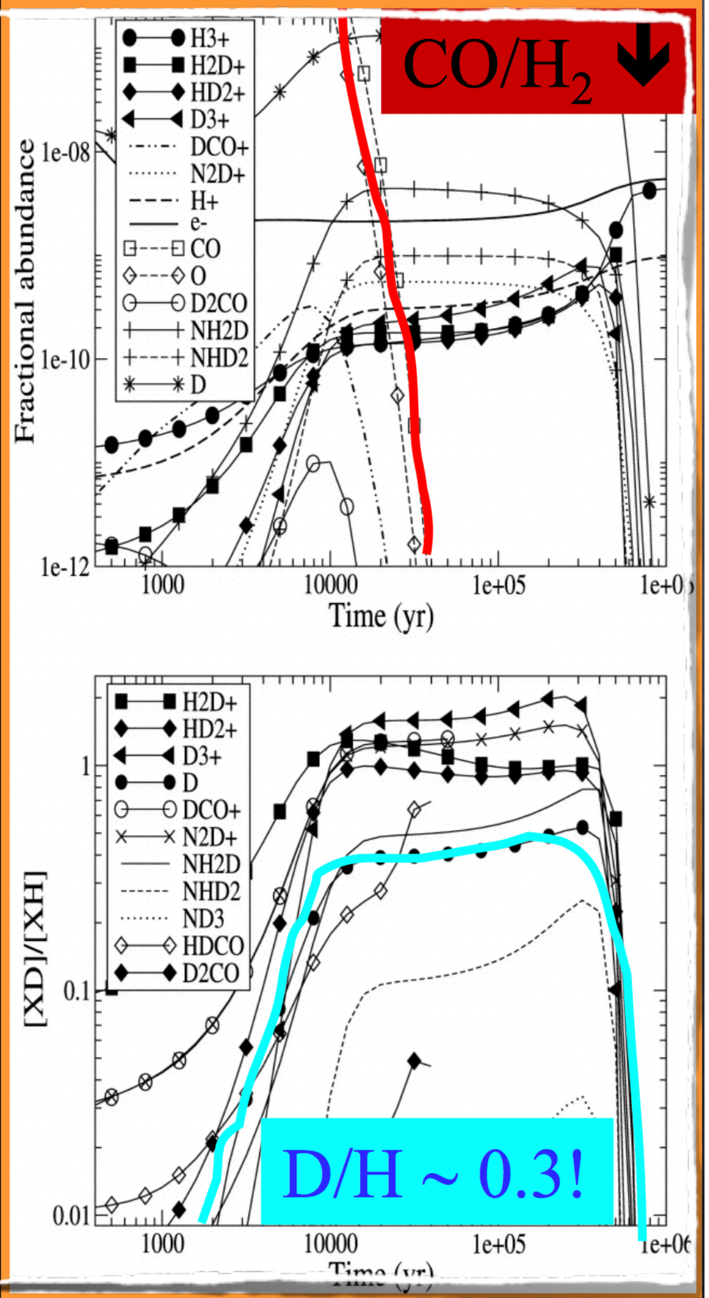
Watson 1974

$$H_2D^+ + \begin{cases} N_2 \rightarrow N_2D^+ + H_2 \\ CO \rightarrow DCO^+ + H_2 \end{cases}$$

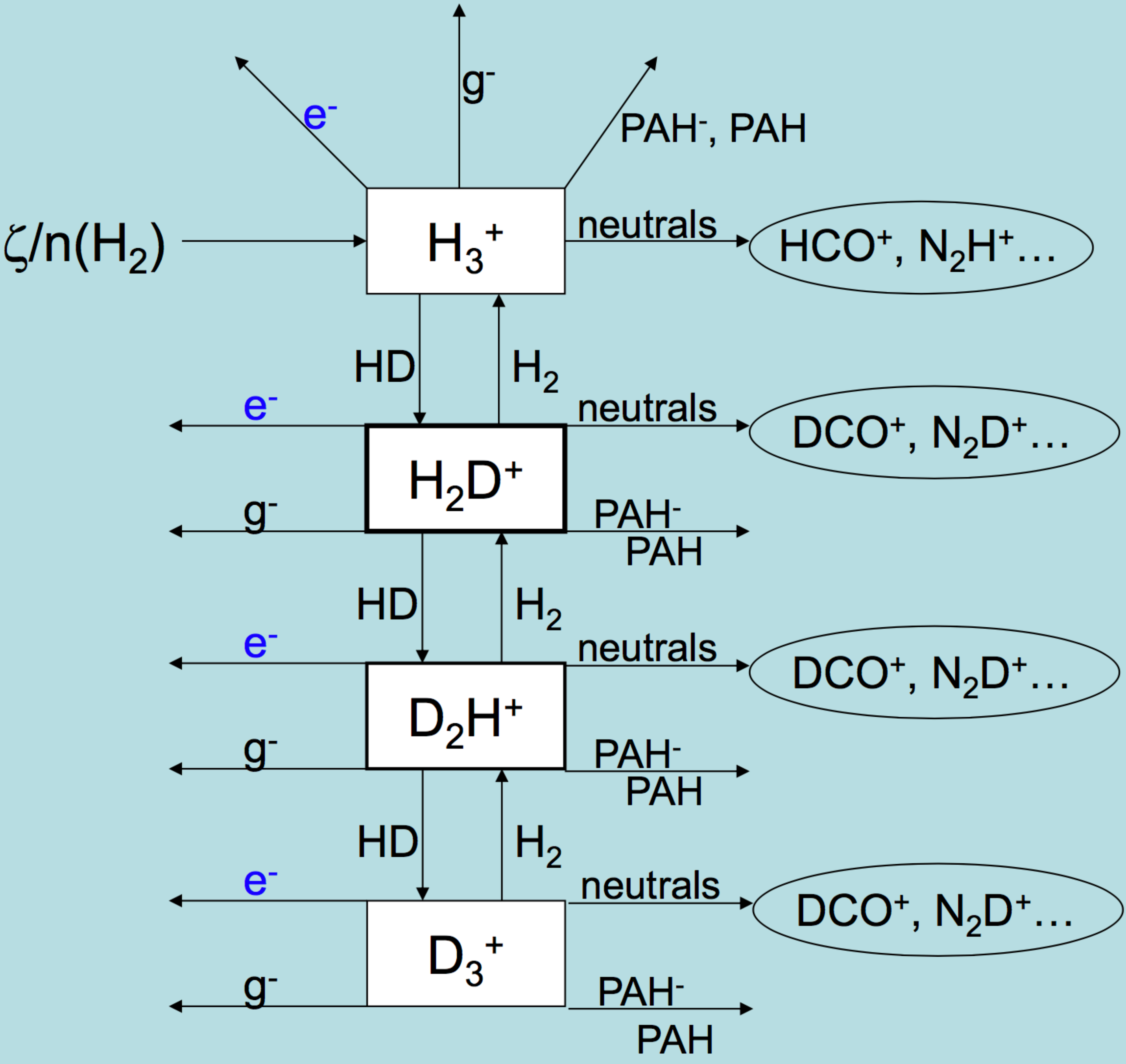
H_2D^+ / H_3^+ (and D/H) increases if the abundance of gas phase neutral species decreases *(Dalgarno & Lepp 1984).*

Roberts, Millar & Herbst 2003 →

(explaining CO and H_2D^+ observations of Caselli et al. 1999, 2003)



D-fractionation and x(e)



e$^-$

g$^-$

PAH$^-$, PAH

$\zeta/n(H_2)$

H_3^+

neutrals

HCO^+, N_2H^+…

HD

H_2

e$^-$

neutrals

H_2D^+

DCO^+, N_2D^+…

g$^-$

PAH$^-$

PAH

HD

H_2

e$^-$

neutrals

D_2H^+

DCO^+, N_2D^+…

g$^-$

PAH$^-$

PAH

HD

H_2

e$^-$

neutrals

D_3^+

DCO^+, N_2D^+…

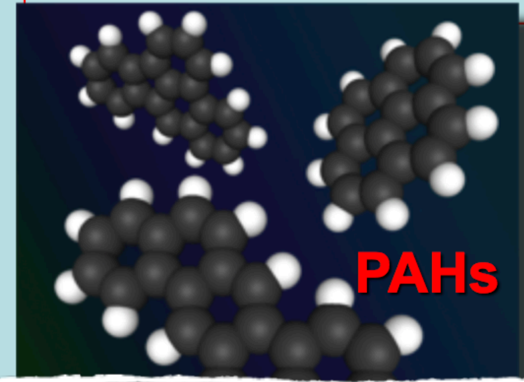
g$^-$

PAH$^-$

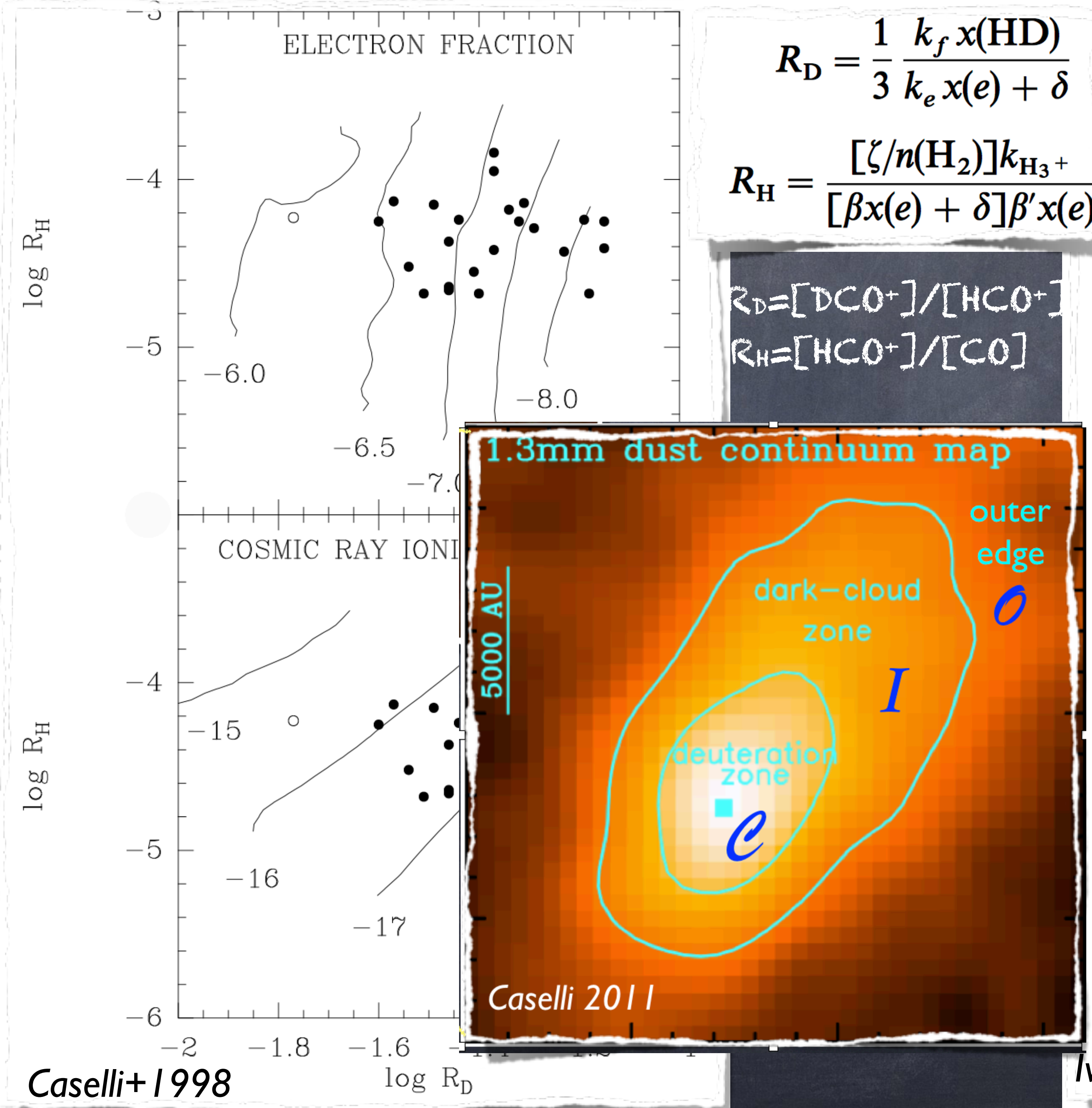
PAH

Guelin et al. 1977
Wootten et al. 1979
Guelin et al. 1982
Bergin et al. 1998
Caselli et al. 1998
Dalgarno 2006

Uncertainties:
*** grain charging**
*** neutrals (O)**
*** ortho:para H_2**
*** PAH**



D-fractionation and x(e)



Caselli 2011

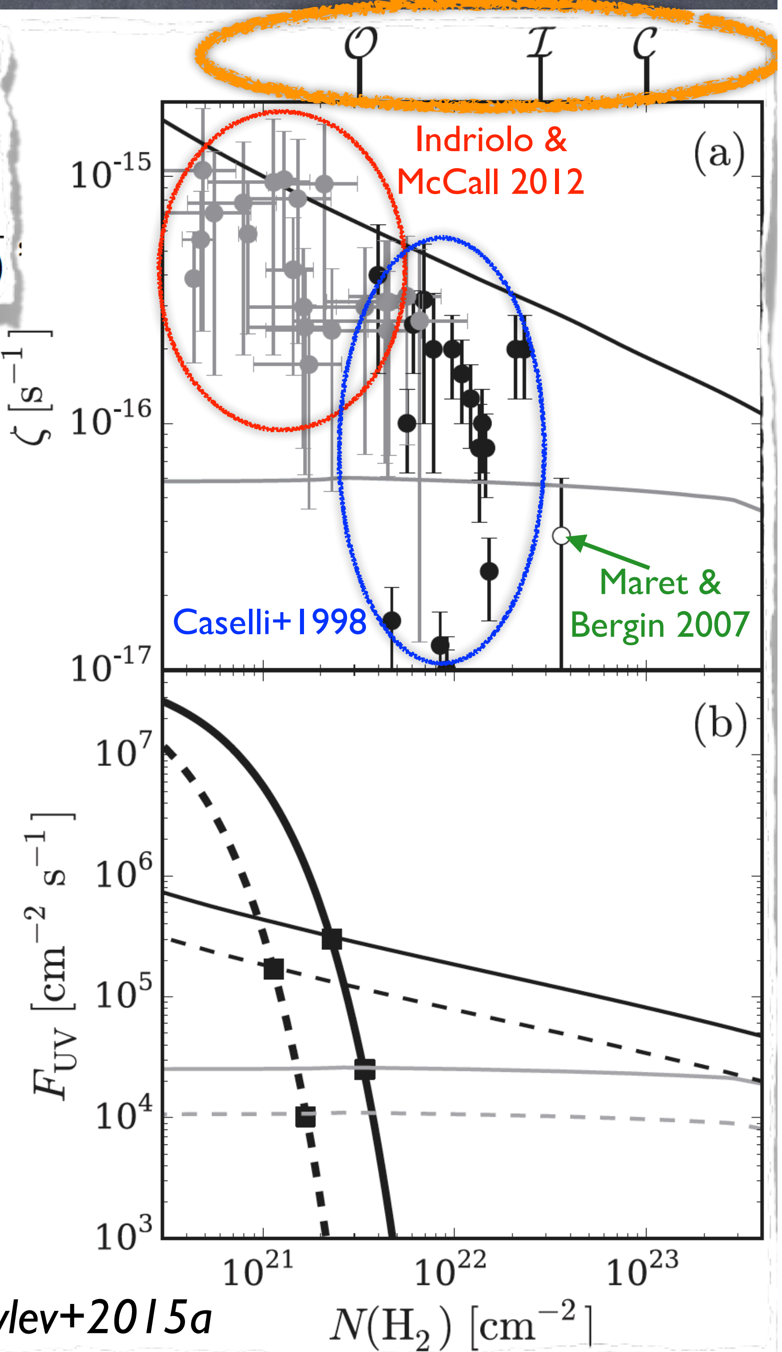
Caselli+1998

$$R_D = \frac{1}{3}\frac{k_f\, x(\mathrm{HD})}{k_e\, x(e) + \delta}$$

$$R_H = \frac{[\zeta/n(\mathrm{H_2})]k_{\mathrm{H_3^+}}}{[\beta x(e) + \delta]\beta' x(e)}$$

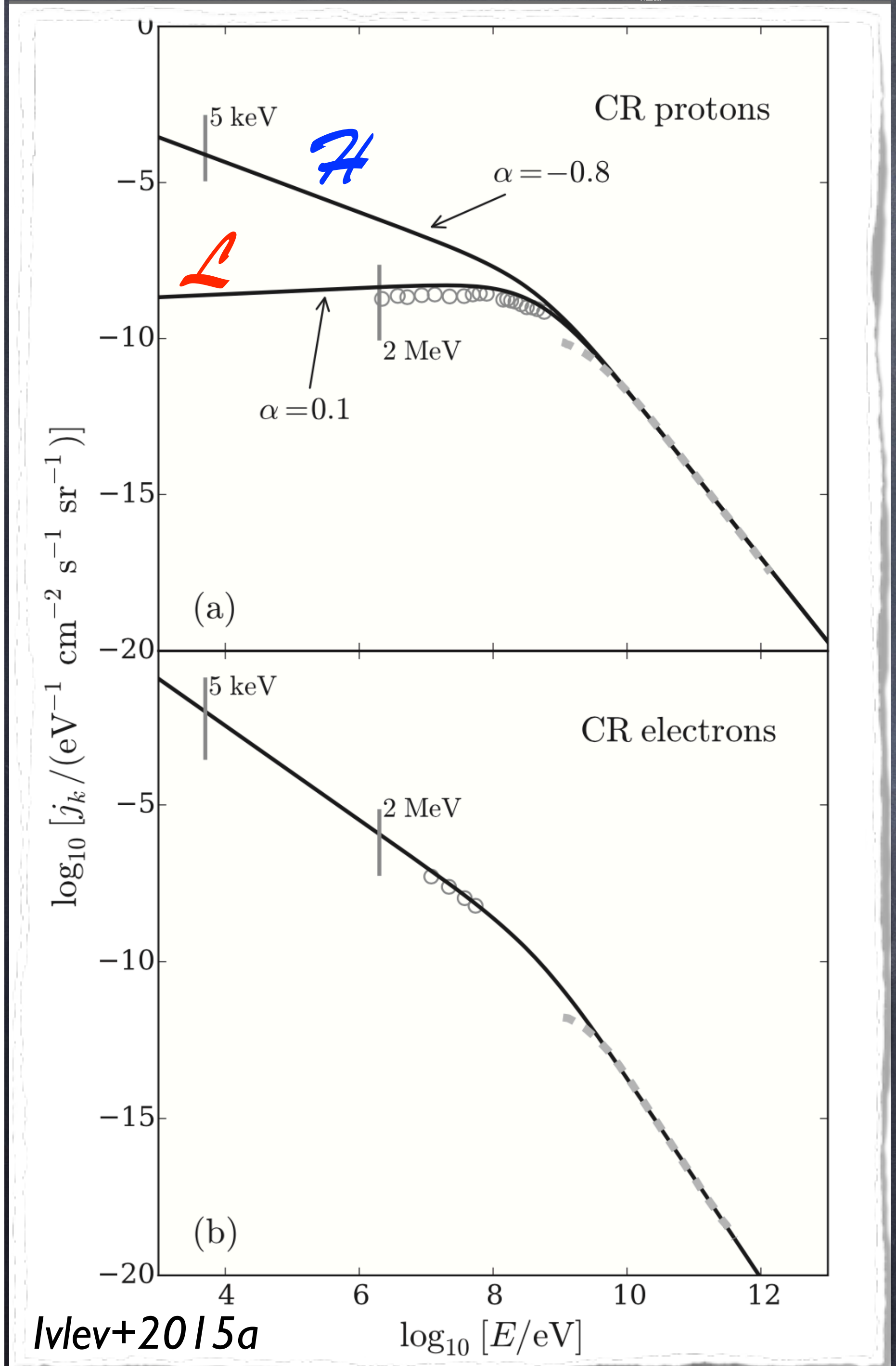
$R_D=[DCO^+]/[HCO^+]$

$R_H=[HCO^+]/[CO]$

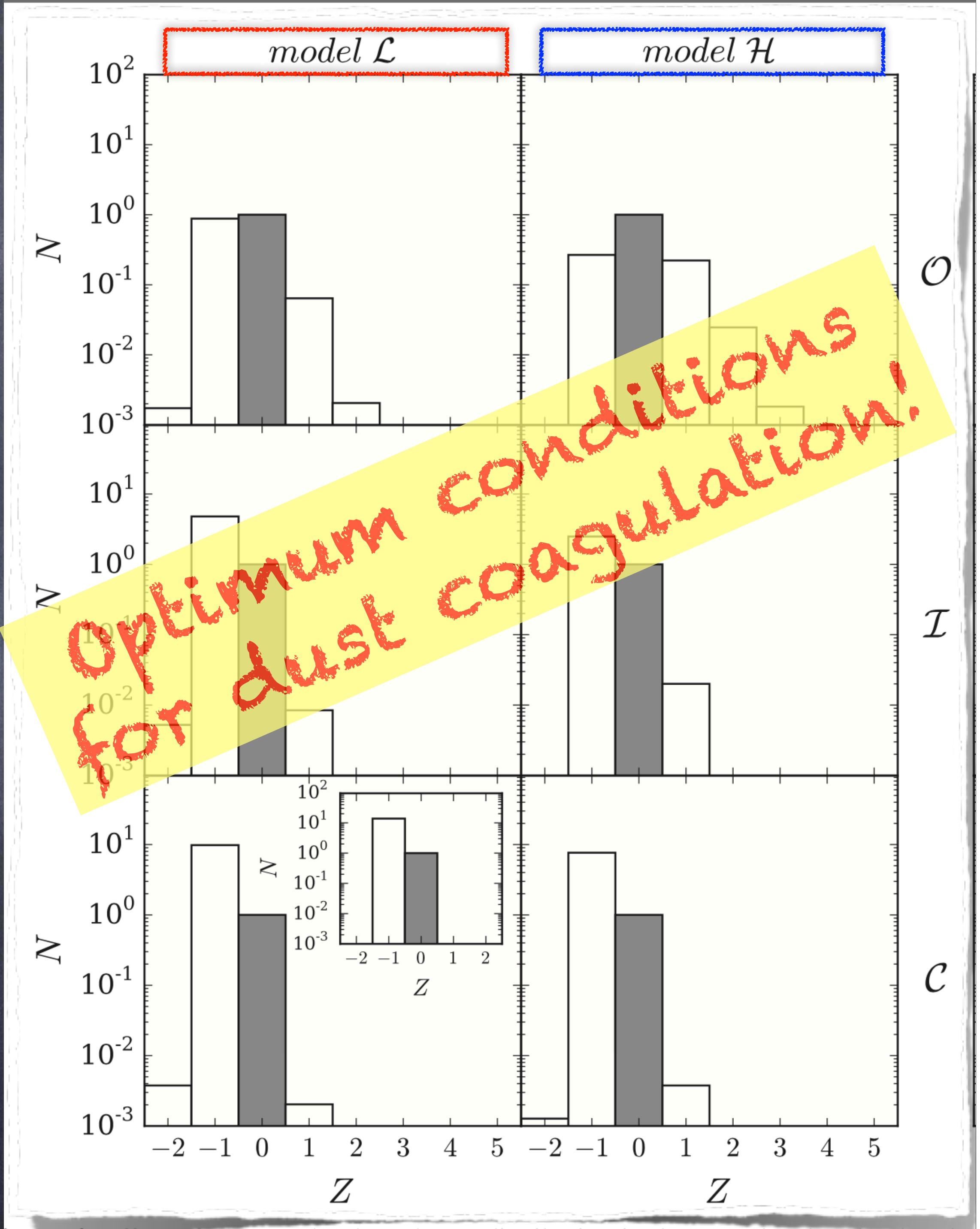


Ivlev+2015a

Cosmic-ray effects on dust charging

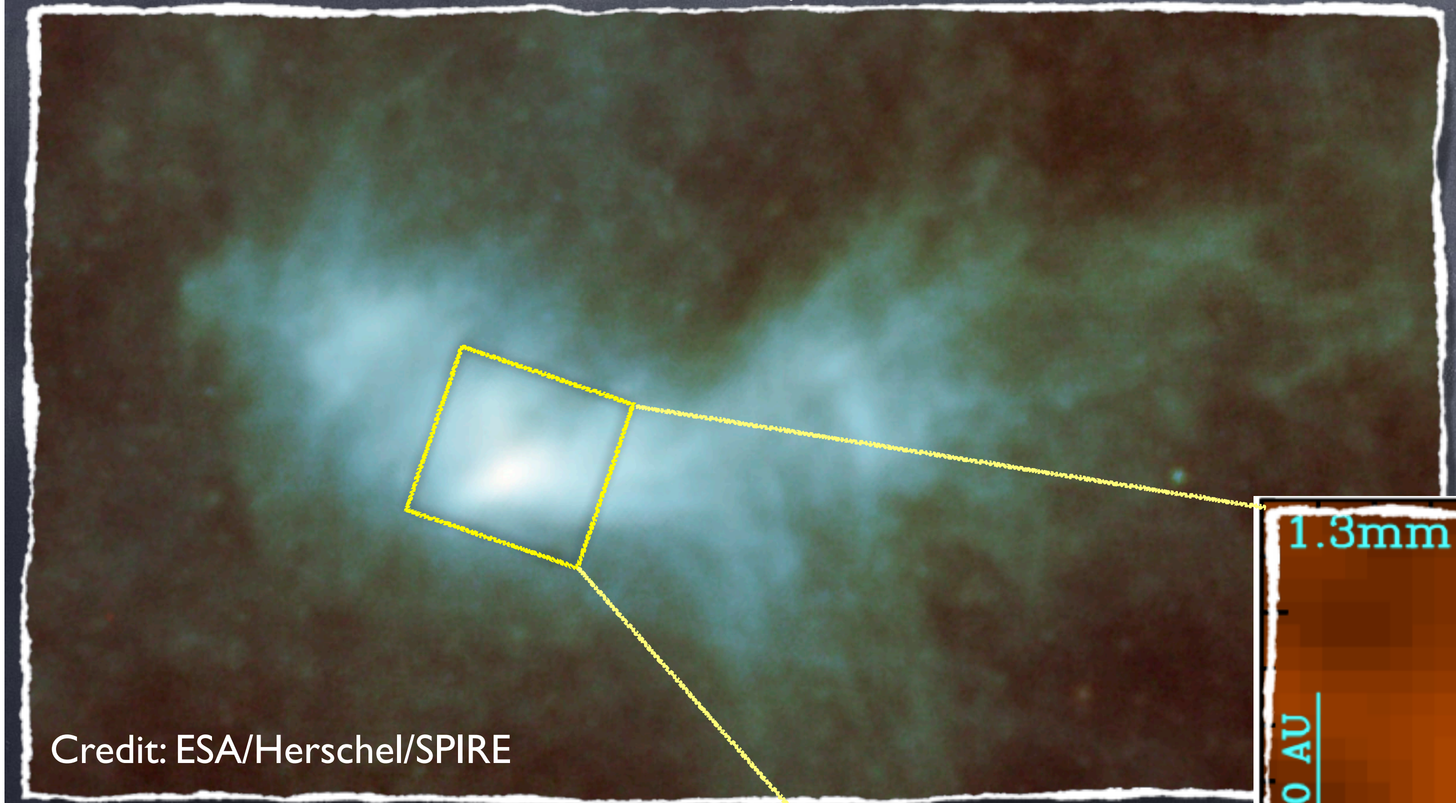


Ivlev+2015a

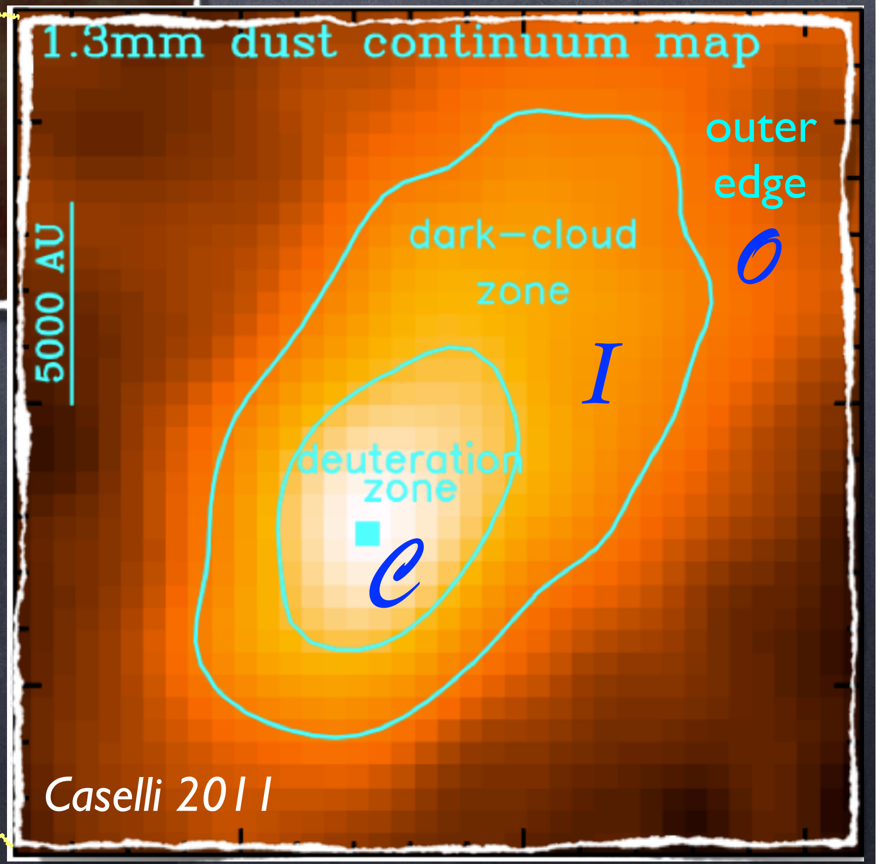


Optimum conditions for dust coagulation!

The importance of x(e)



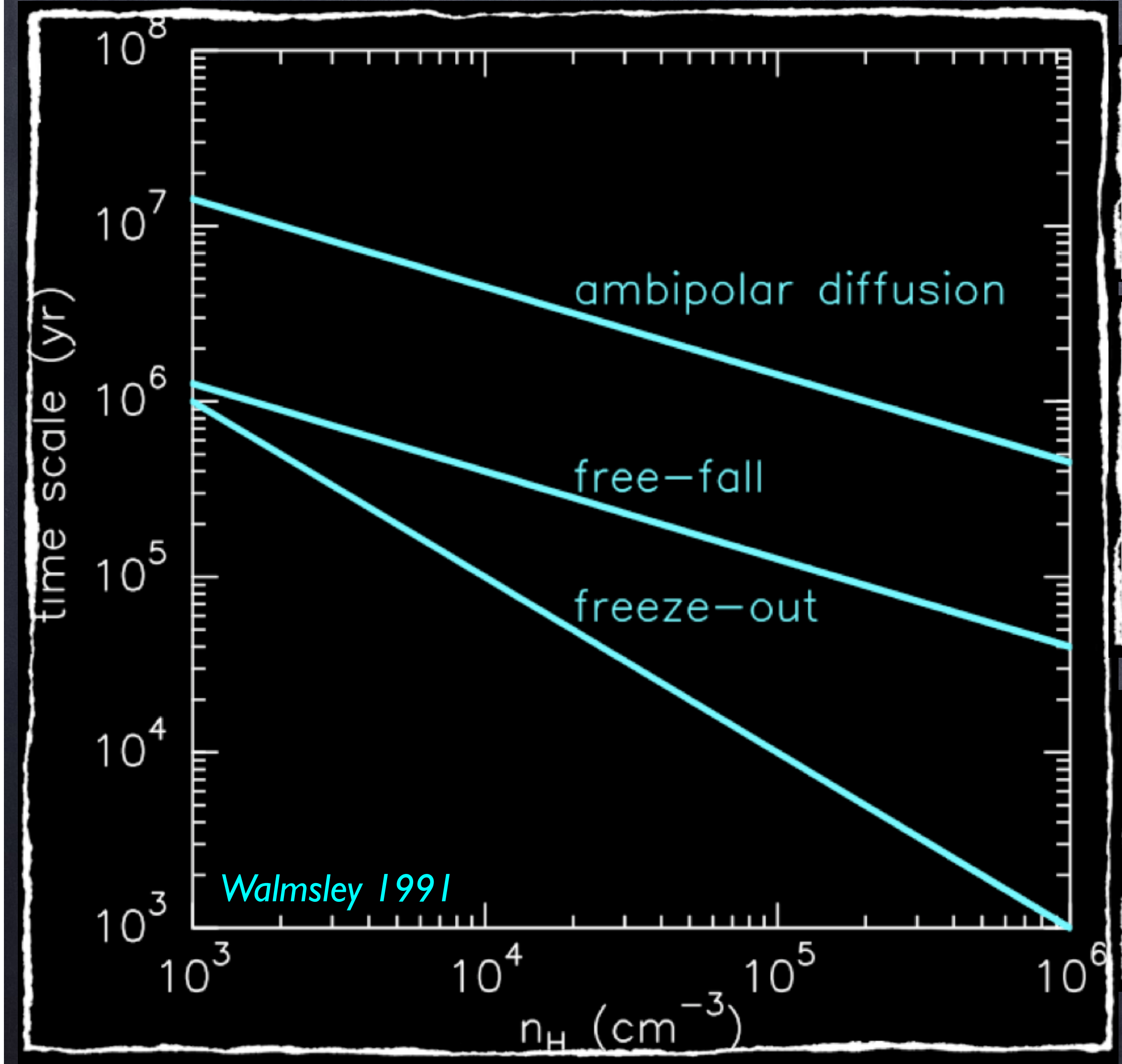
Credit: ESA/Herschel/SPIRE



Caselli 2011

x(e) regulates the dynamical evolution of molecular clouds and star formation (e.g. McKee 1989)

The importance of x(e)



Walmsley 1991

$$t_{ambipolar} \approx 2.5 \times 10^{13}\, x(e)\ \mathrm{yr}$$

$$\approx 4.5 \times 10^{8} / \sqrt{n_H}\ \mathrm{yr}$$

$$t_{free-fall} = \sqrt{\frac{3\pi}{32 G \rho}}$$

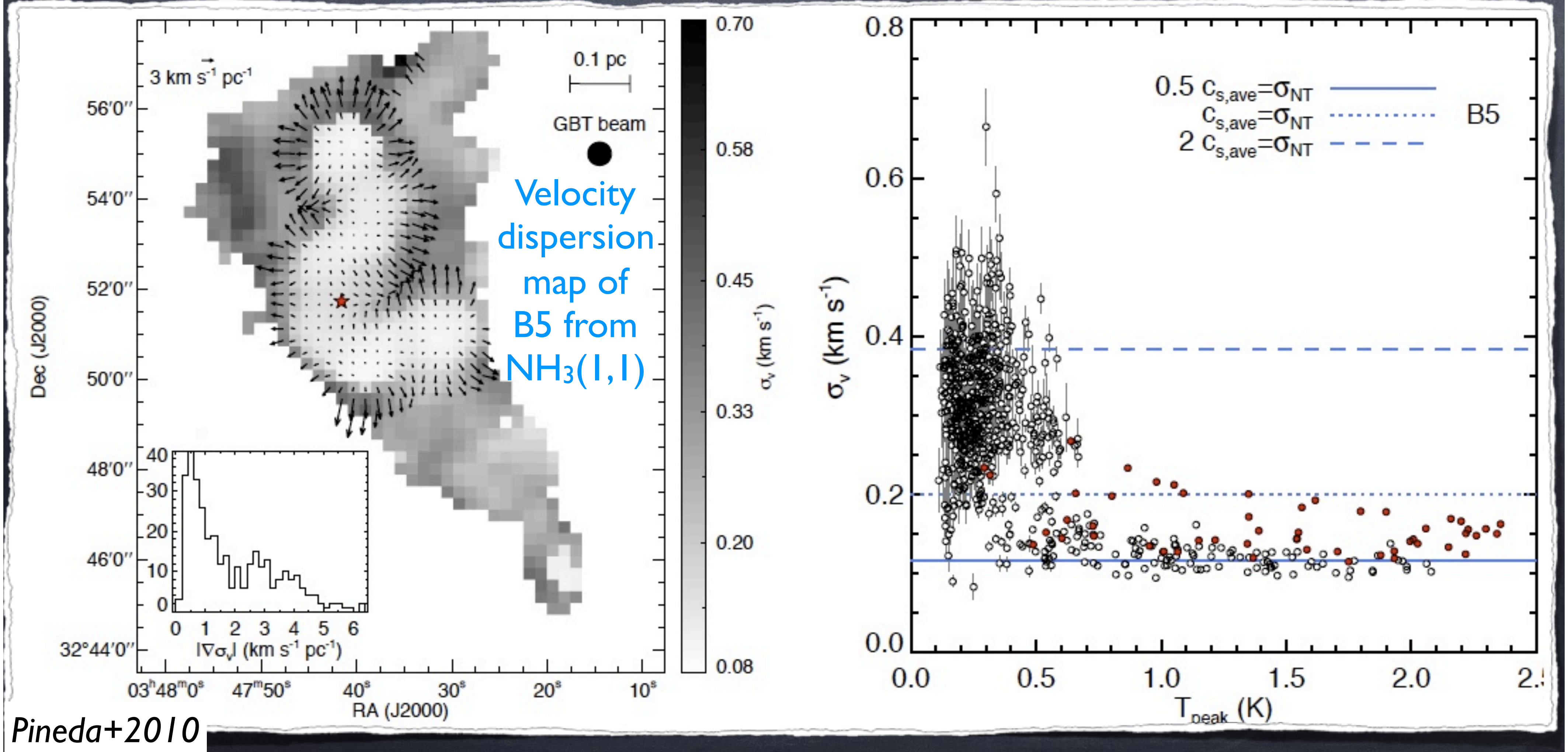
$$\approx 4 \times 10^{7} / \sqrt{n_H}\ \mathrm{yr}$$

$$t_{freeze-out} = \frac{1}{\alpha n_d \pi a_d^2 \mathrm{v}_t}$$

$$\approx 10^{9} / n_H\ \mathrm{yr}$$

The transition to coherence in dense cores ...

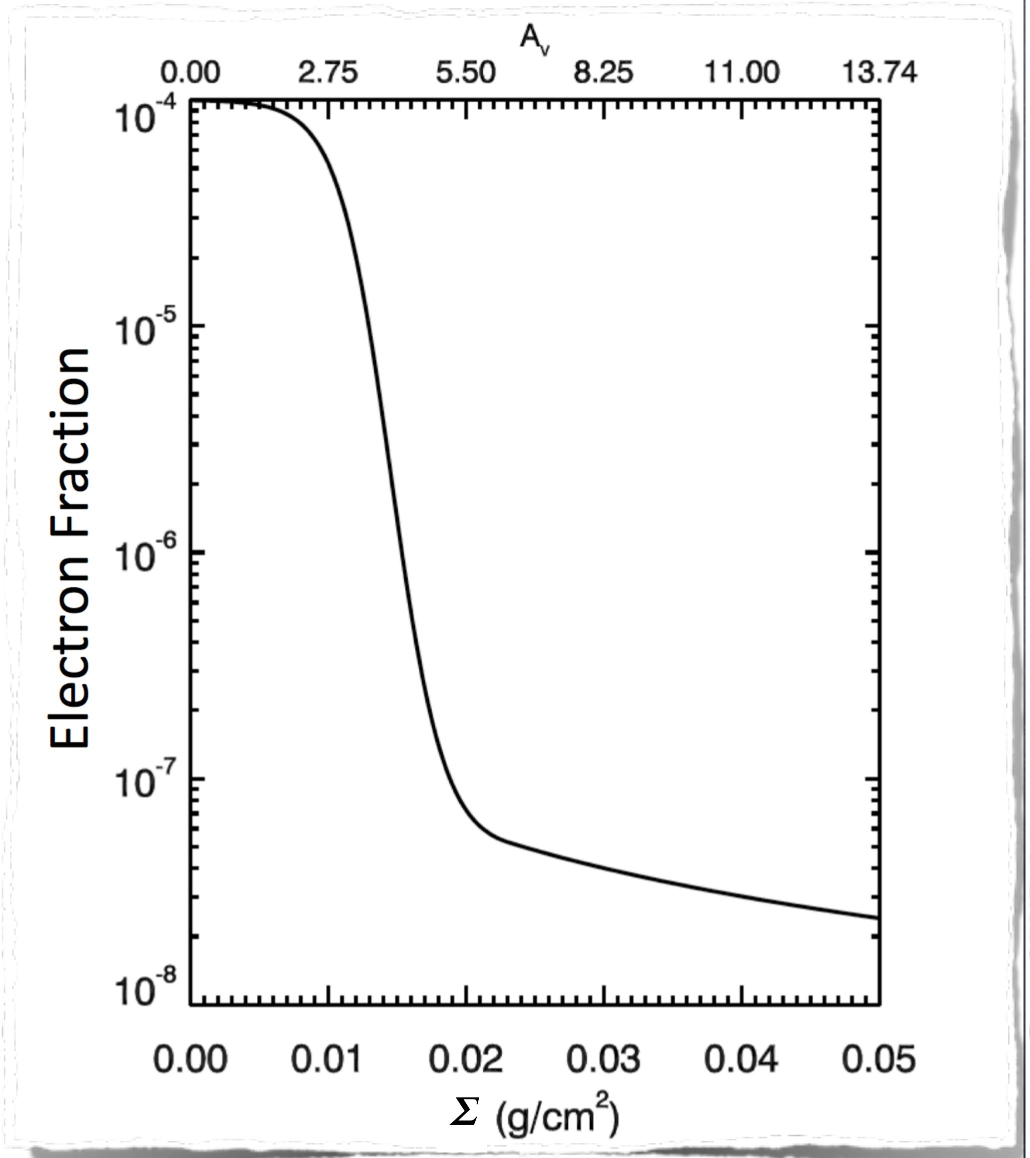
The velocity dispersion changes abruptly between the dense core and the surrounding cloud, increasing by a factor of 2 in less than 0.03 pc.

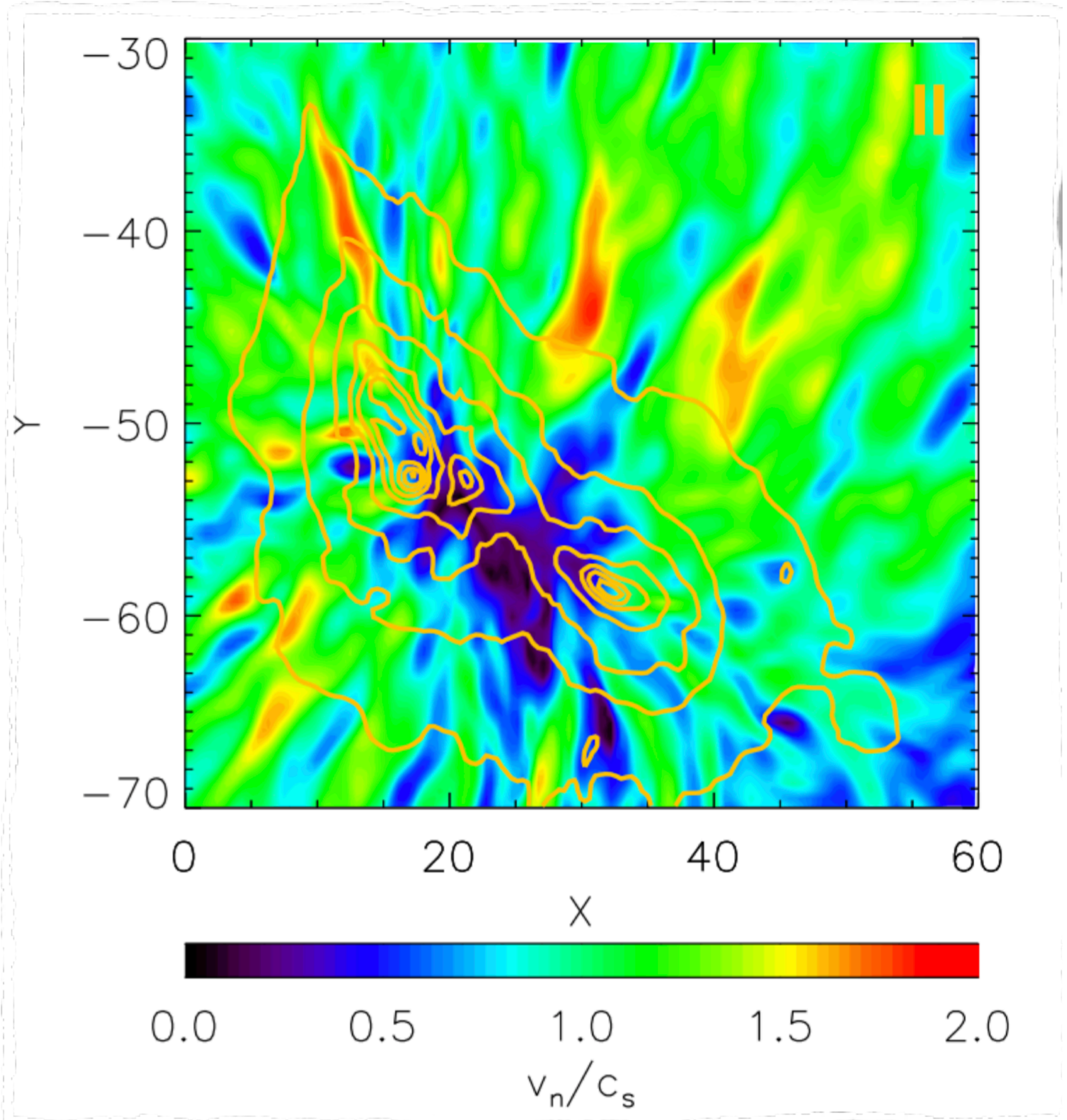


Velocity dispersion map of B5 from $NH_3(1,1)$

Pineda+2010

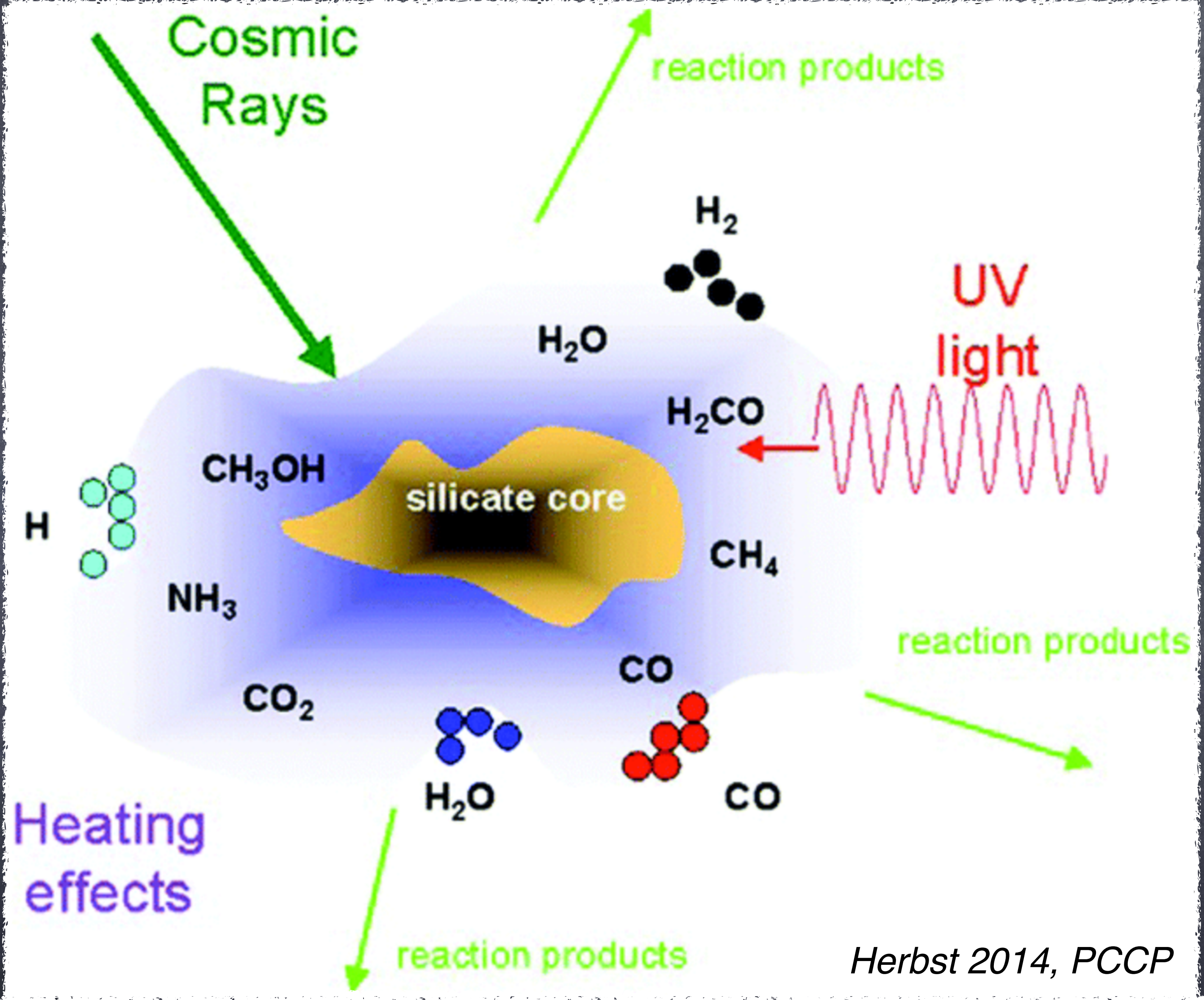
…may be explained by non-ideal MHD





Bailey et al. 2014

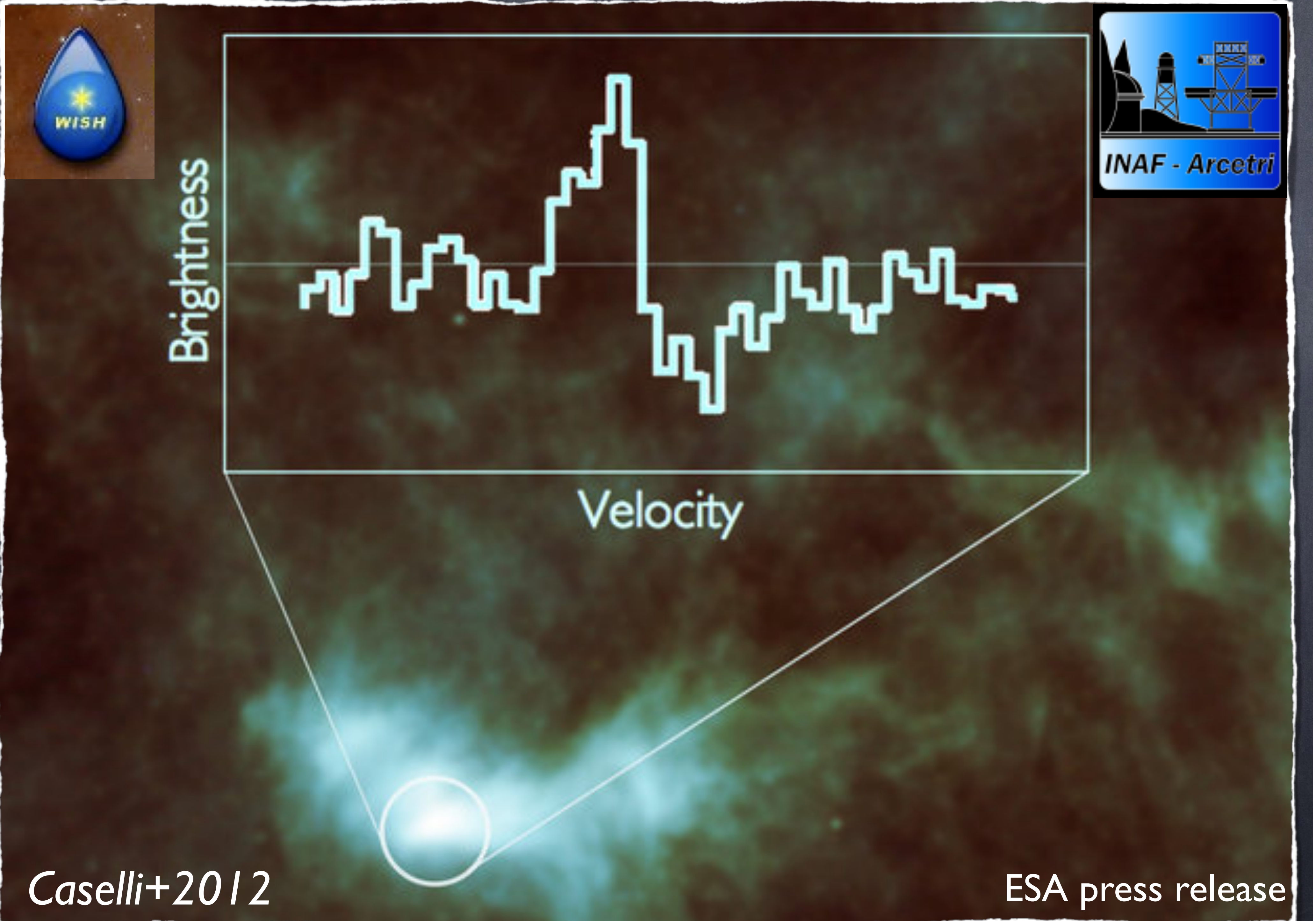
Cosmic-ray effects on chemistry



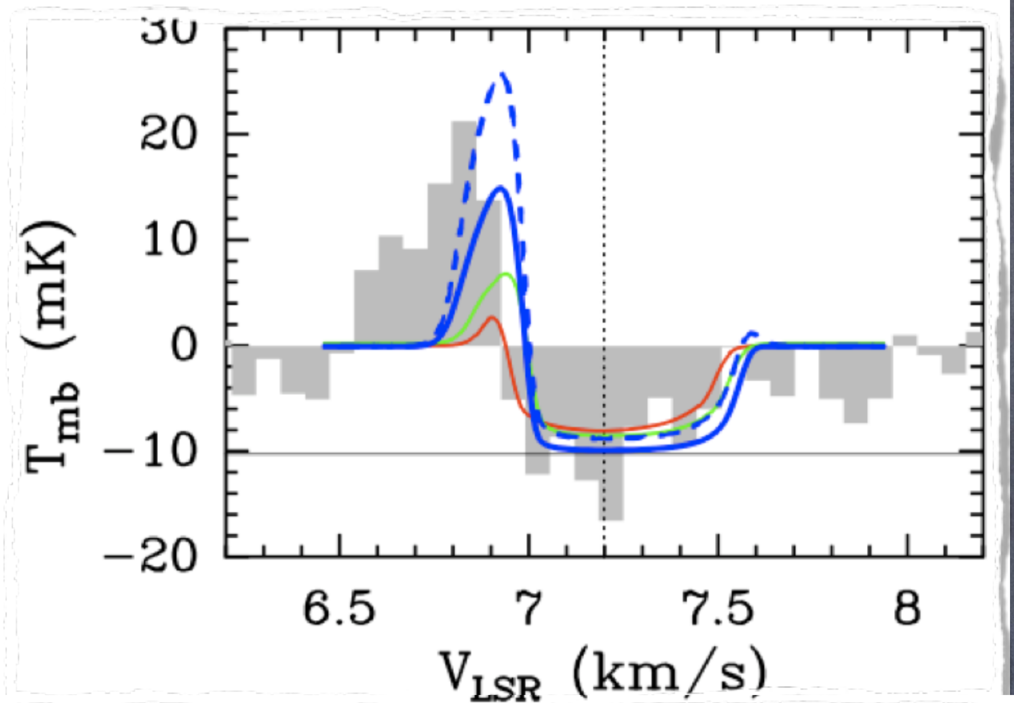
Herbst 2014, PCCP

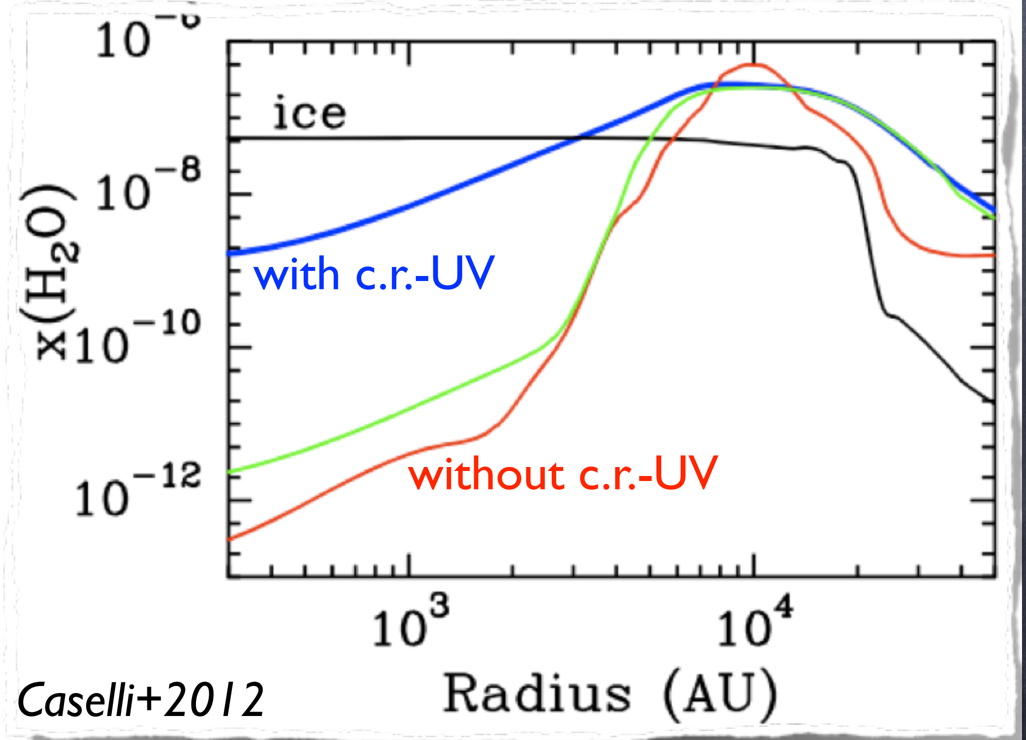
see talks of Session 2b and
poster by Chris Shingledecker

First detection of water vapour in a pre-stellar core



The importance of FUV photons produced by c.r.





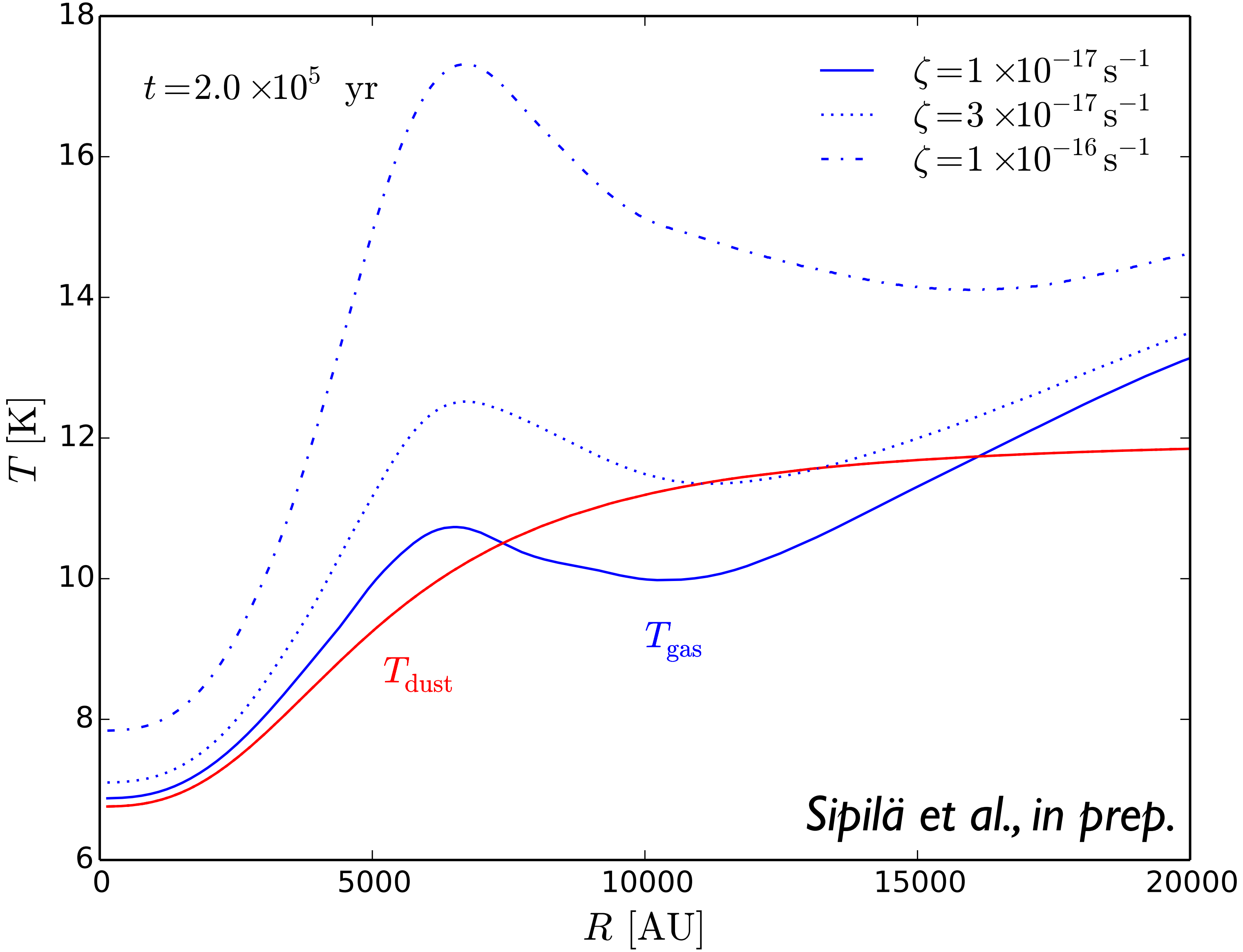
Caselli+2012

- $x(H_2O) \sim 10^{-9}$ - maintained by FUV photons produced by c.r. (total mass of water vapor: ~0.5 Earth masses; total mass of water ice: ~2.6 Jupiter masses).

- $n_H \geq 10^6$ cm^{-3}, to explain H_2O emission.

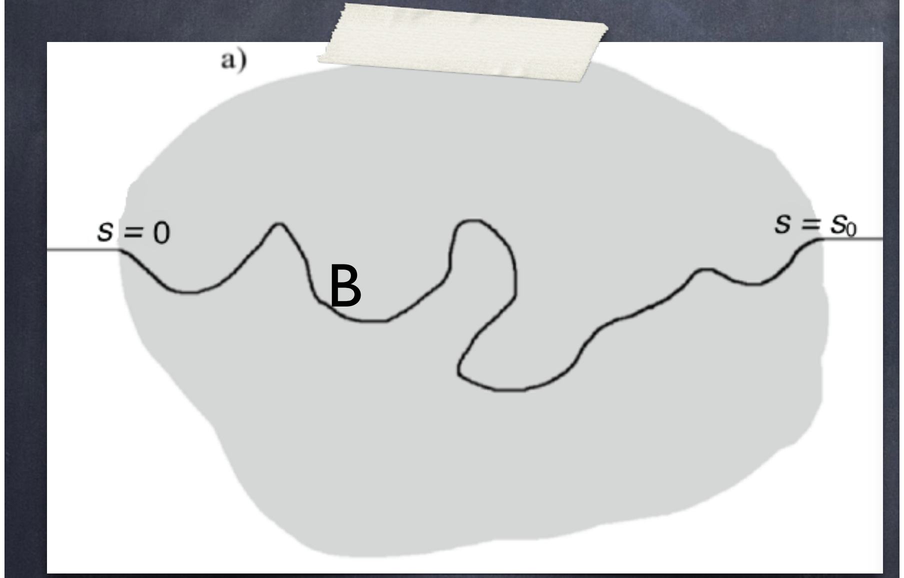
- Gravitational contraction to see blue wing in emission.

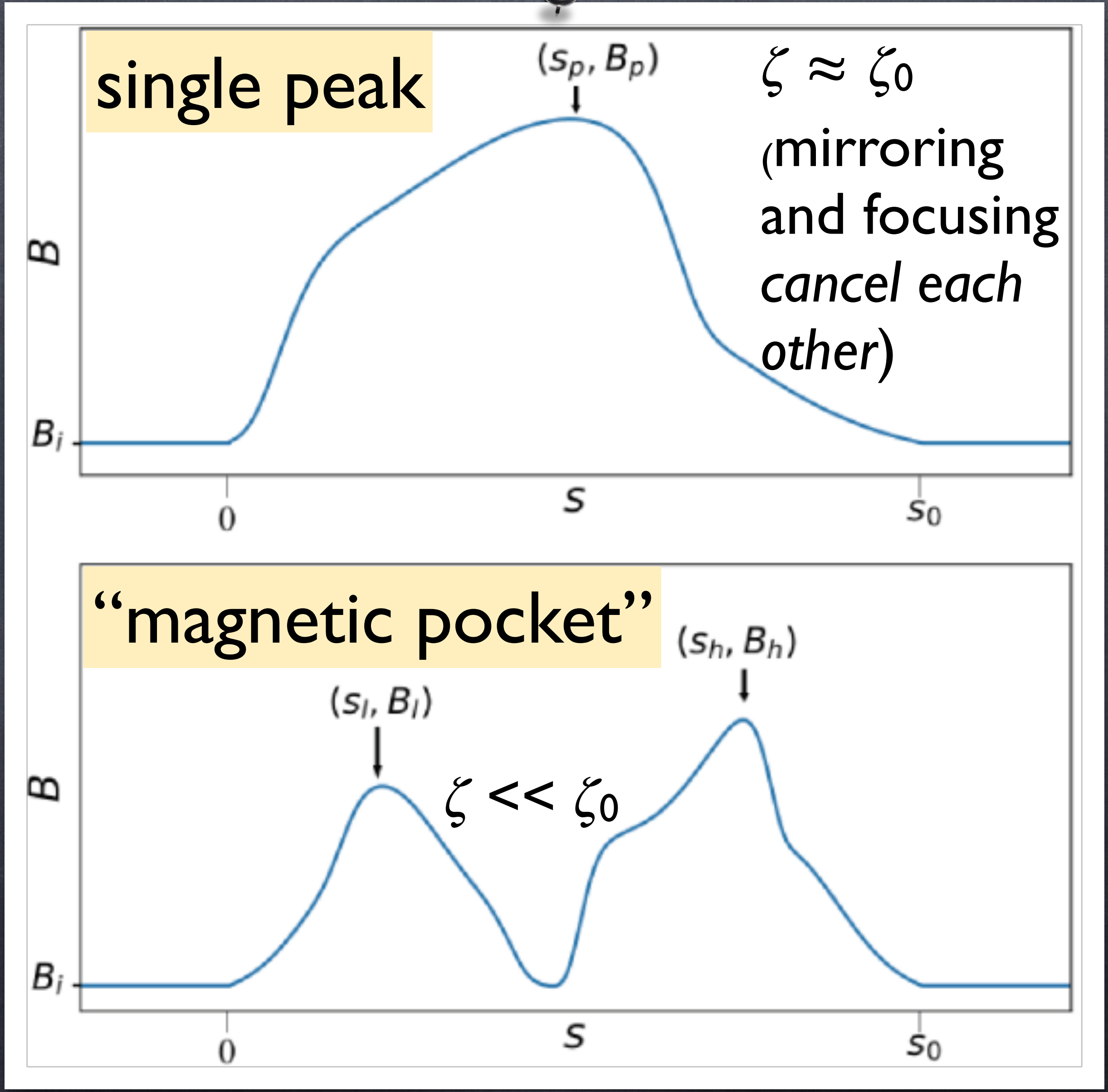
Effects of ζ on the thermal structure of pre-stellar cores



Sipilä et al., in prep.

Magnetic mirroring and focusing of cosmic rays





single peak

$\zeta \approx \zeta_0$

(mirroring and focusing *cancel each other*)

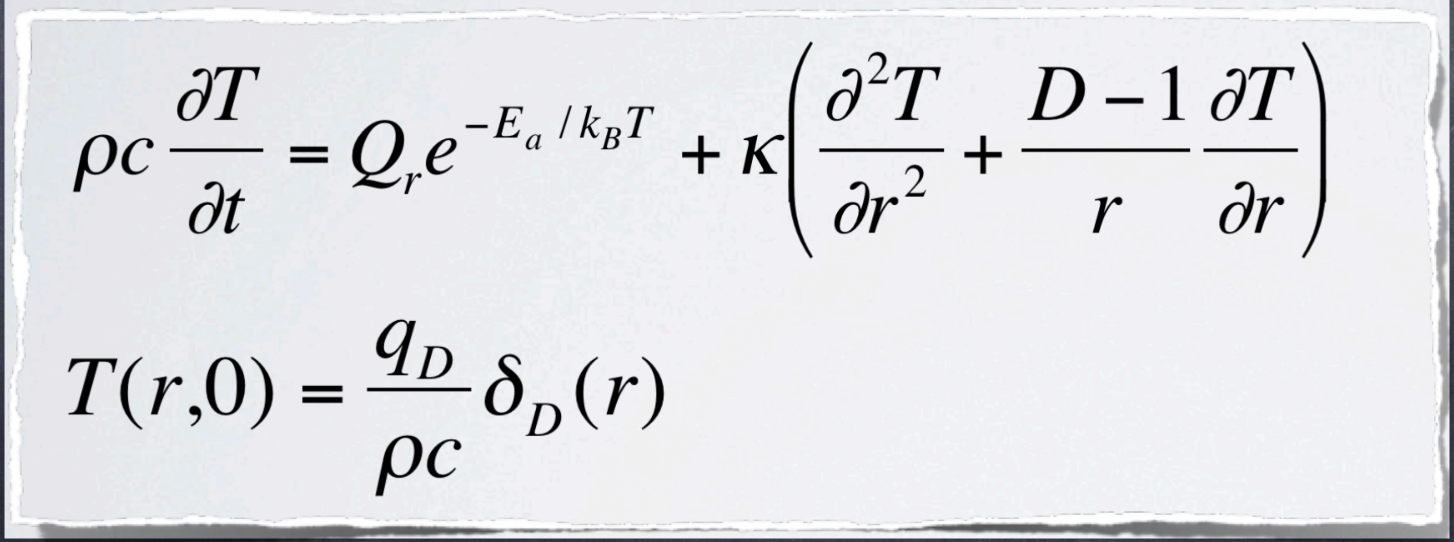
“magnetic pocket”

$\zeta << \zeta_0$

Silsbee+, in prep.

Impulsive heating and thermal explosion of interstellar grains

Starting from the heat equation, describing the temperature T(r,t) in a reactive medium (Landau & Lifshitz 1987):



$$\rho c \frac{\partial T}{\partial t} = Q_r e^{-E_a / k_B T} + \kappa \left(\frac{\partial^2 T}{\partial r^2} + \frac{D-1}{r} \frac{\partial T}{\partial r} \right)$$

$$T(r,0) = \frac{q_D}{\rho c} \delta_D(r)$$

Ivlev et al. 2015b

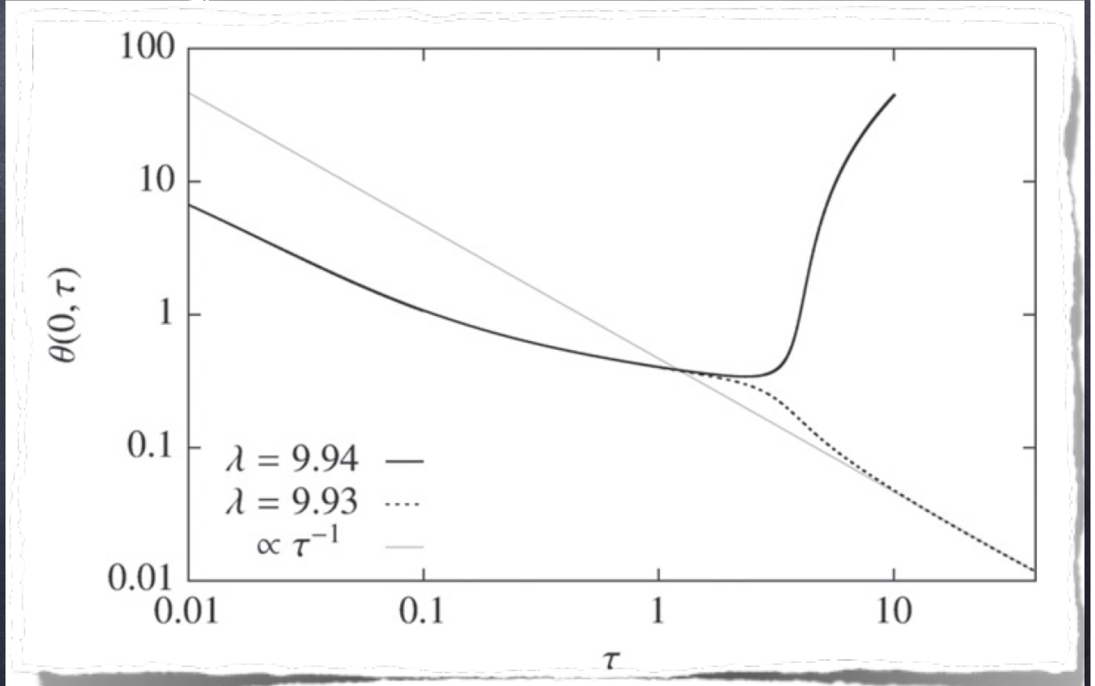
In dimensionless form:

$$\frac{\partial\theta}{\partial\tau} = \lambda e^{-1/\theta} + \frac{\partial^2\theta}{\partial\xi^2} + \frac{D-1}{\xi}\frac{\partial\theta}{\partial\xi}$$

$$\theta = k_B T / E_a ; \xi = r / r_* ; \tau = t / t_*$$

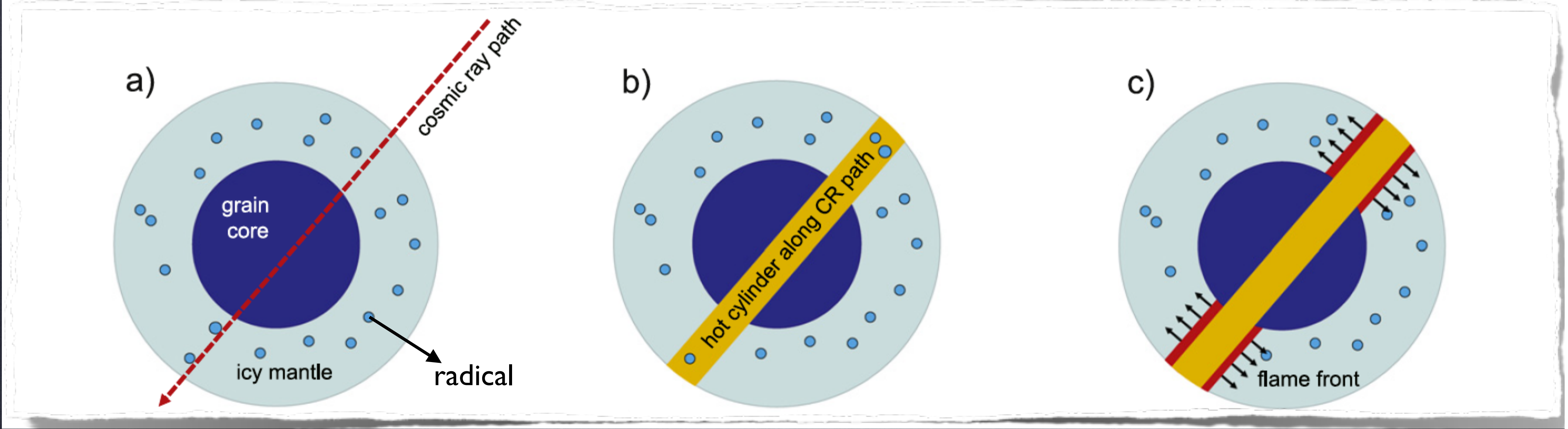
the problem is characterised by a single number:

$$\lambda = \frac{Q_r}{\kappa E_a}\left(\frac{q_D}{\rho c E_a}\right)^{2/D}$$



Ivlev et al. 2015b

Schematic representation of the thermal (chemical) explosion of an icy mantle due to cosmic-ray impact:



If $\lambda < \lambda_{cr}$, the deposited energy is redistributed over the grain's volume (the whole-grain-heating scenario);

If $\lambda > \lambda_{cr}$, the thermal explosion is triggered and runaway exothermic reactions generate a cylindrical flame front in the mantle, leading to its disruption.

SUMMARY on impulsive heating and thermal explosion

Considering the proton spectrum in dense clouds of Padovani et al. (2009), $\phi_{Fe} \sim 10^{-4}$ and fraction of radicals in bulk ice from chemical model:

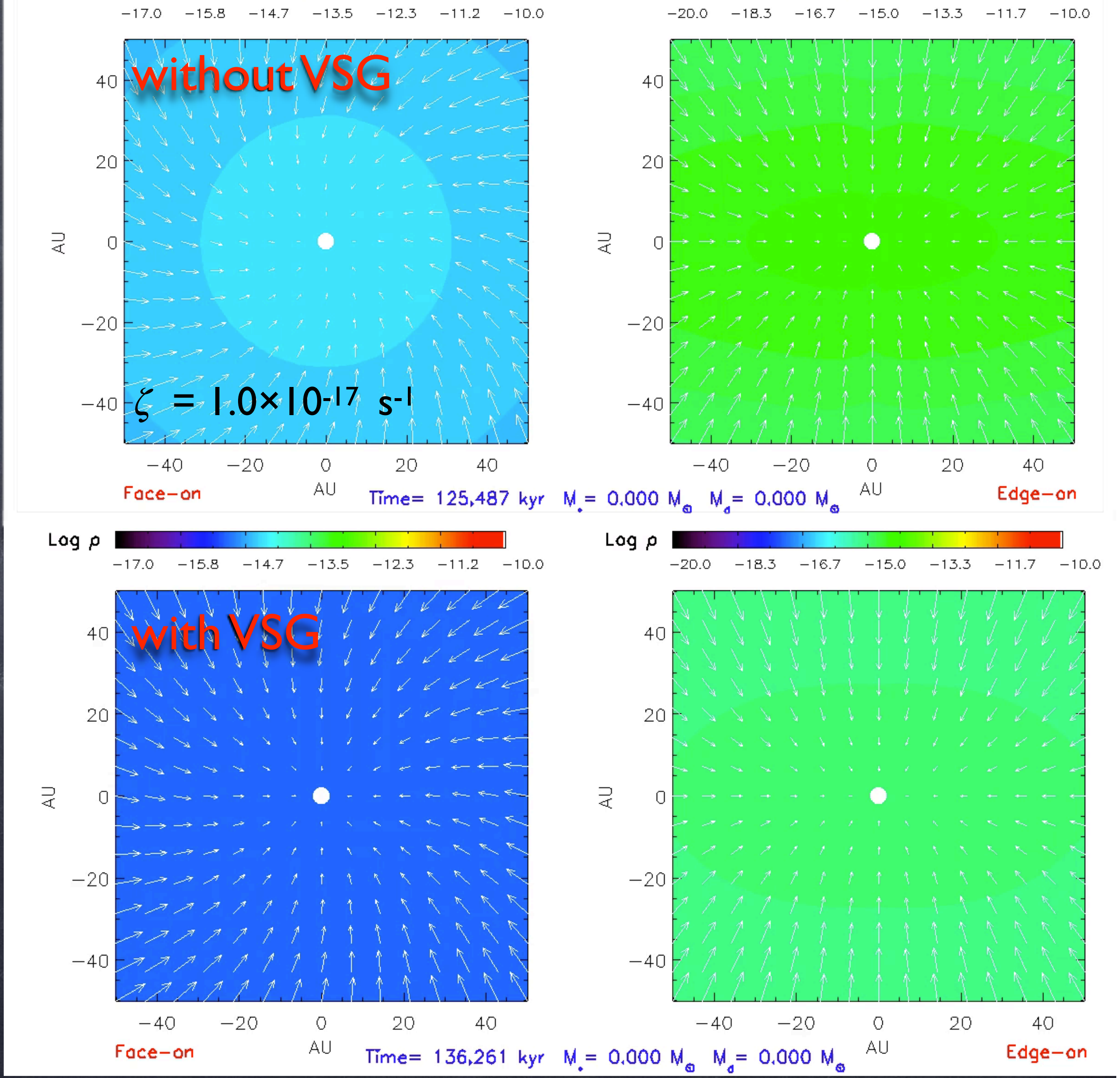
1. Fe nuclei can lead to explosion, with desorption rates (3×10^{-7} mol grain^{-1} s^{-1}), comparable to whole-grain and spot heating.
2. $\phi_A \phi_B < 10^{-3}$ (A,B pair of radicals that dominates the heat release) to avoid unrealistically large desorption rates.
3. Cosmic ray protons can heat up the dust grain, thus activating new surface chemistry (work in progress).

Ivlev et al. 2015b

Protostellar disk formation enabled by removal of very small dust grains

VSG removal enhances ambipolar diffusion, reducing magnetic breaking.

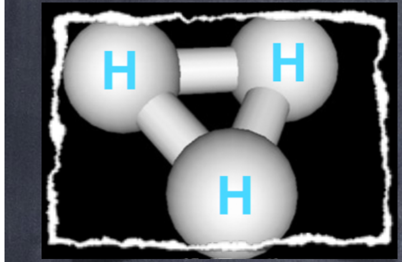
Different ζ values result in different disk structures. Values of ζ much larger than 10^{-17} s^{-1} can suppress disk formation.

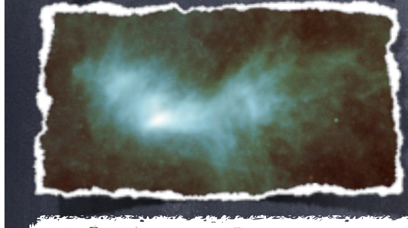


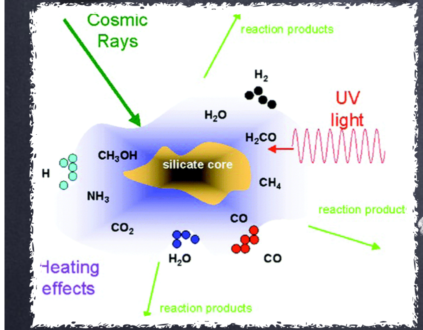
Zhao+2016, 2018

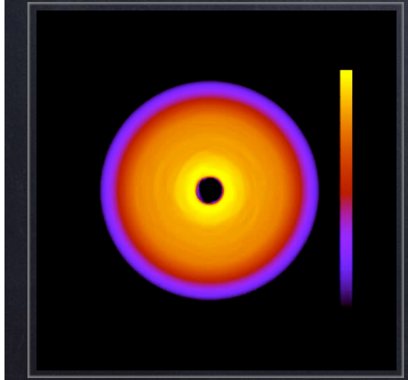
CONCLUSIONS

Cosmic rays are crucial ingredients for star and planet formation because they:









- start astrochemistry;
- determine x(e) and the dynamical evolution of molecular clouds;
- provide efficient non-thermal desorption mechanisms in cold clouds (and avoid complete freeze-out?);
- process icy mantles and modify the ice composition;
- influence the formation and evolution of protoplanetary disks.

It is very important to understand cosmic-ray propagation in molecular clouds and disks!

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