H_2, H_3^+ and the age of molecular clouds

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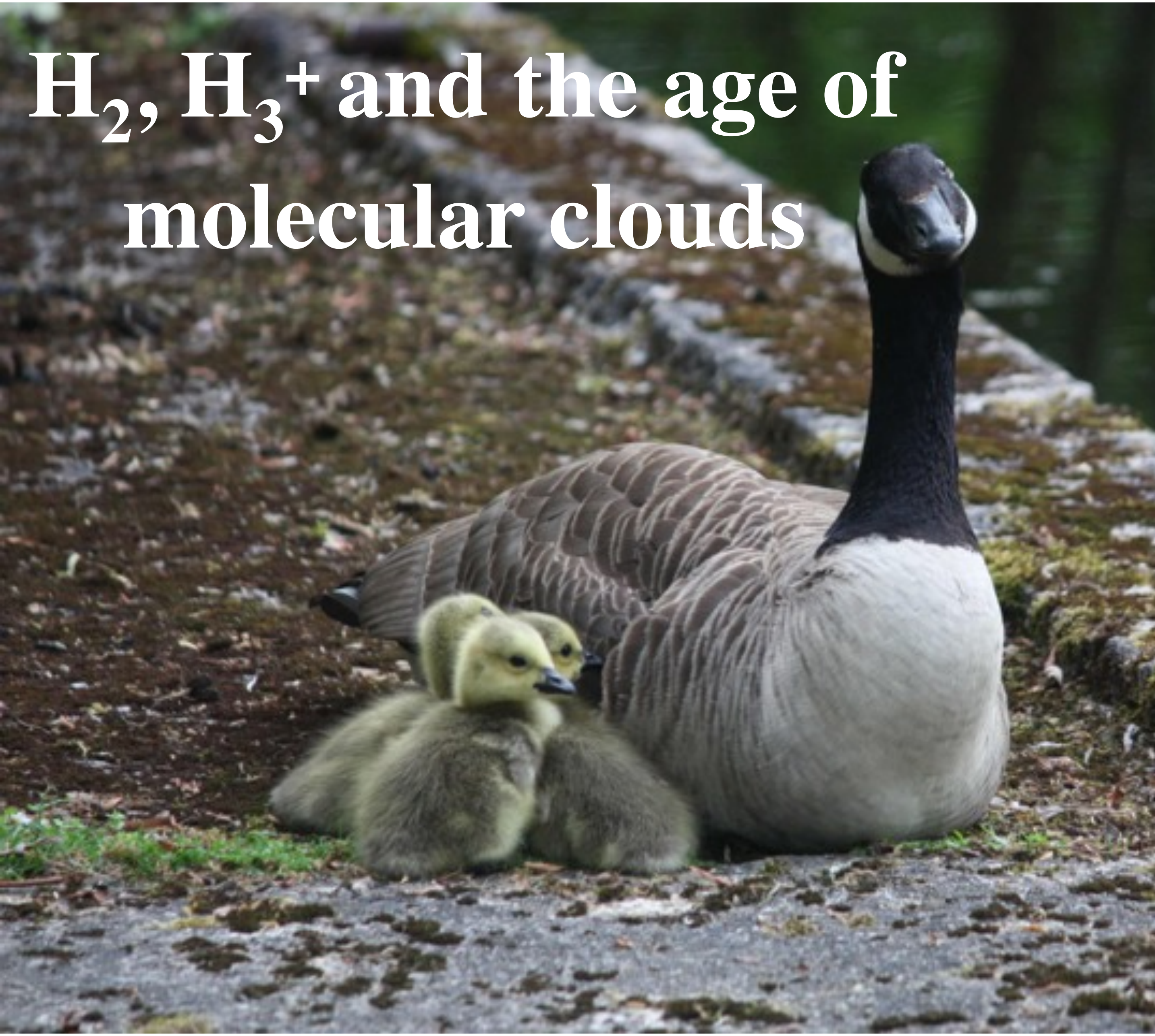


Pierre Lesaffre, Evelyne Roueff, Pascal Honvault, Mohamed Jorfi, T. Gonzalez-Lezana, Alex Faure

(1) Low mass star formation

(2) Deuteration & ortho-H_2 :

- ❖ its role in H_3^+ chemistry (deuteration control)
- ❖ formation and destruction

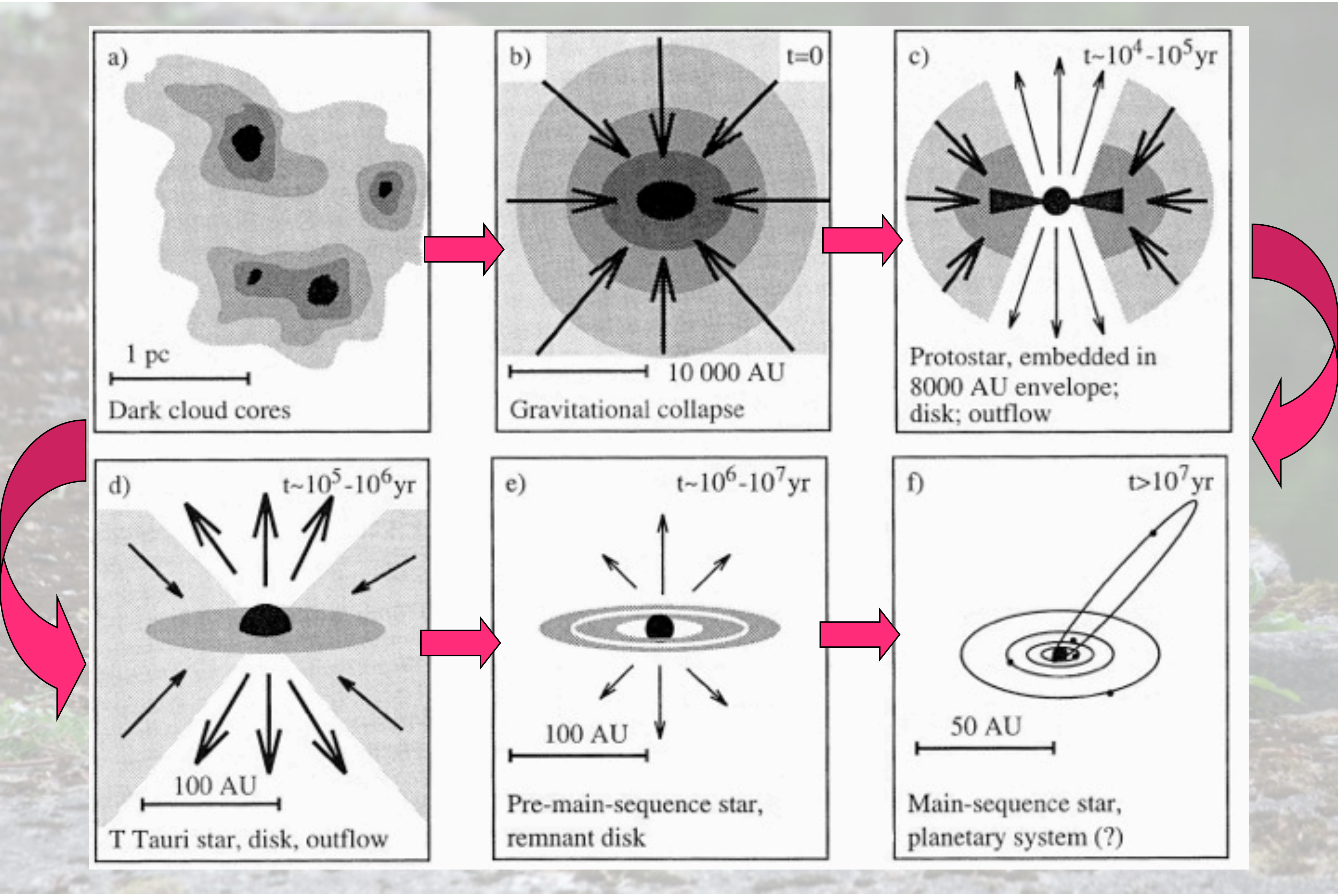
(3) Deuteration amplification needs CO depletion – is it always true?

(4) (2) + (3) ⇨ How old is a cold cloud ?

(5) Deuteration profile in prestellar cores

(6) (2) + (5) ⇨ How old is a prestellar core ?

Low mass star formation



Low mass star formation

- Prestellar cores form either slowly:
  - Turbulence dissipation (Nakano 1998)
  - Ambipolar diffusion (Mouschovias 1991, Ciolek & Basu 2000, 2006,...): depends on $\vec{\mathbf{B}}$
- or fast :
  - Supersonic turbulent flows -> local density enhancements (Klessen et al. 2000, Larson 2007, Hennebelle et al. 2007, 2008…)

Cloud formation: same problem

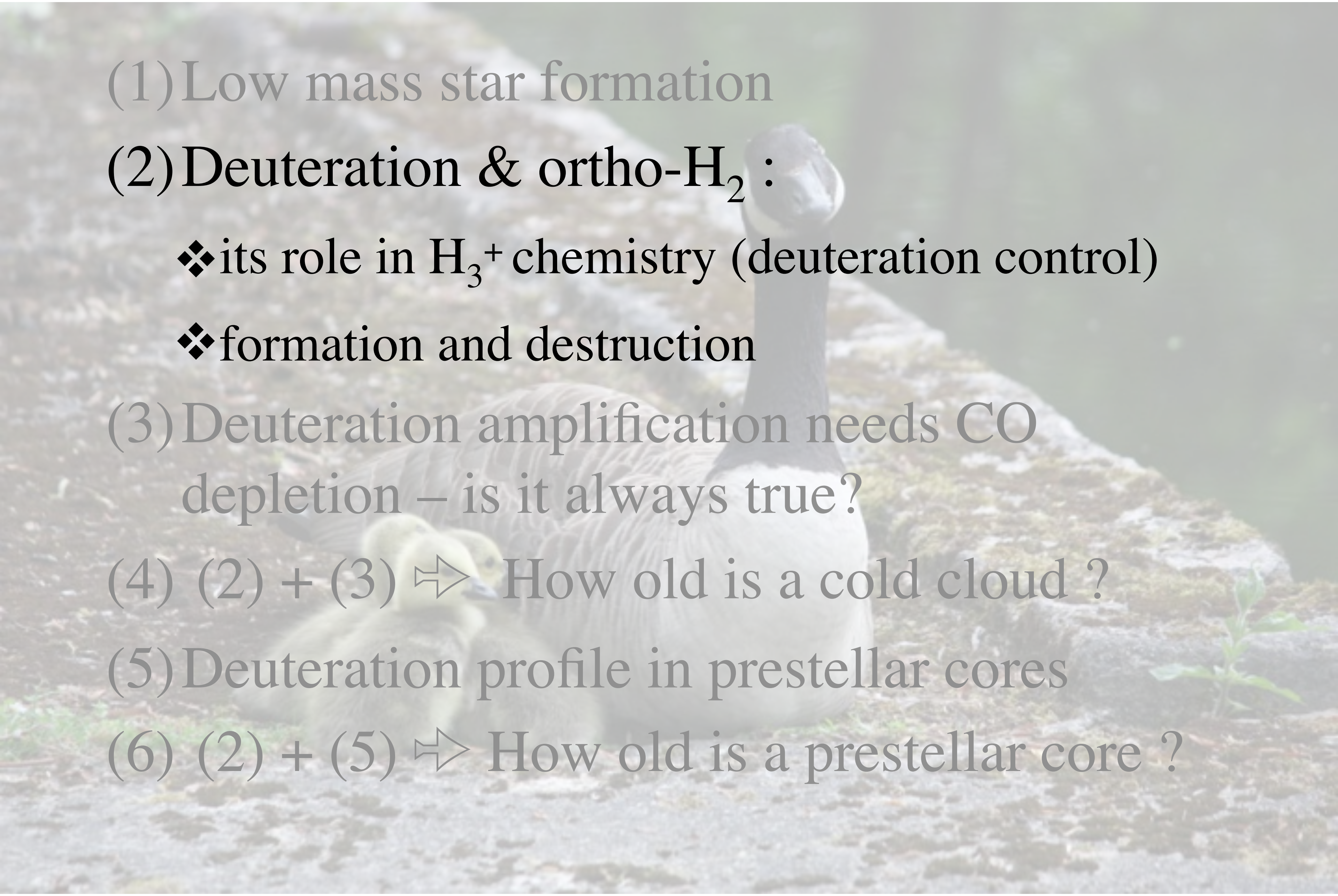
- Clouds form either fast :
  - From local cloud studies (Hartmann et al. 2001)

  „ star formation is highly dynamic, clouds are short-lived, no slowing down of collapse but low efficiency in star formation "

- or slowly:
  - Ambipolar diffusion (Tassis & Mouschovias 2004, Mouschovias et al, 2006)

  „ no evidence from statistics and models for fast action, clouds compatible with lifetimes of 10^7 years"

WHO IS RIGHT ?



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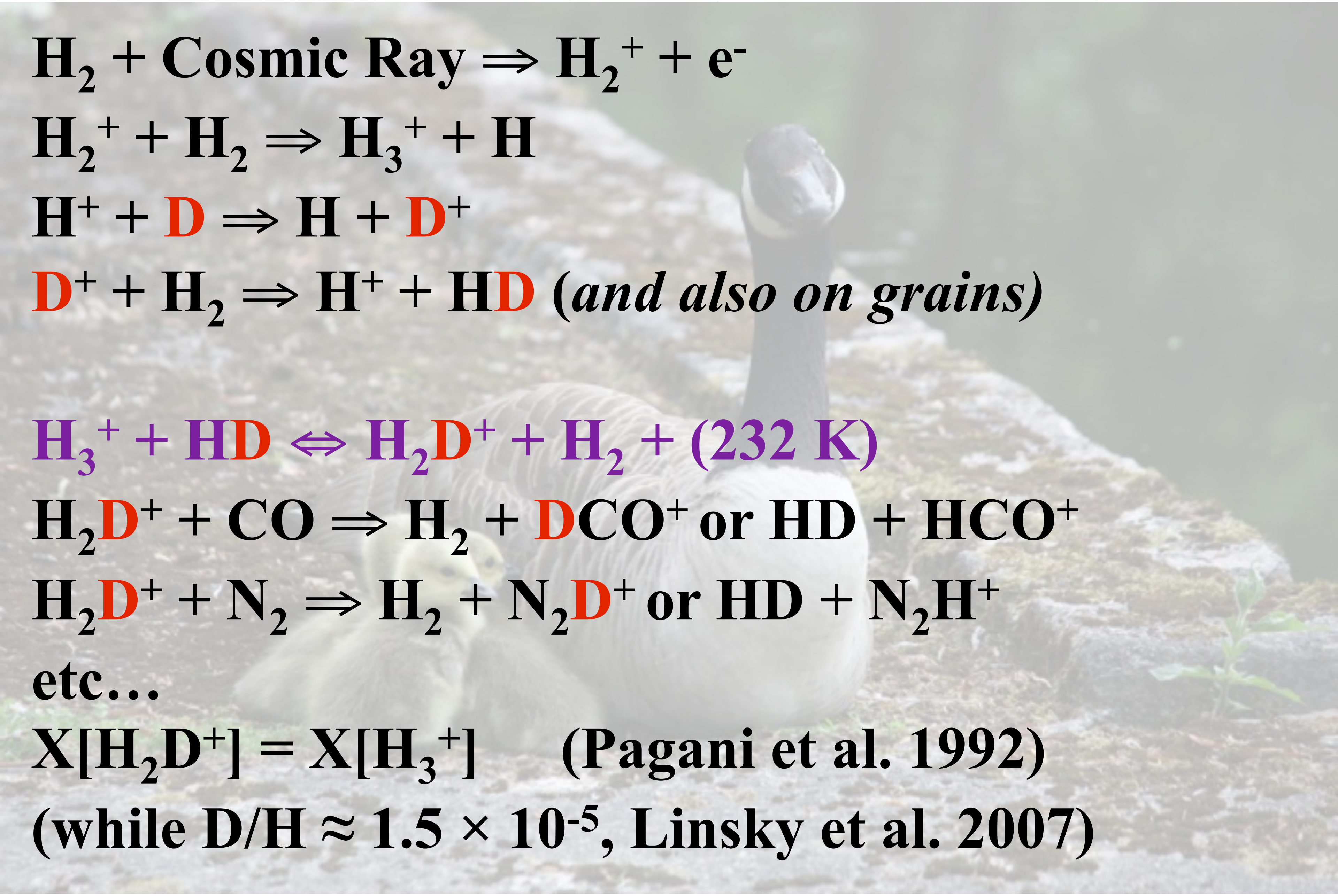
Deuterium chemistry in dense clouds



H_2 + Cosmic Ray ⇒ $H_2^+ + e^-$

$H_2^+ + H_2$ ⇒ $H_3^+ + H$

$H^+ + D$ ⇒ $H + D^+$

$D^+ + H_2$ ⇒ $H^+ + HD$ *(and also on grains)*

$H_3^+ + HD$ ⇔ $H_2D^+ + H_2$ + (232 K)

$H_2D^+ + CO$ ⇒ $H_2 + DCO^+$ or $HD + HCO^+$

$H_2D^+ + N_2$ ⇒ $H_2 + N_2D^+$ or $HD + N_2H^+$

etc…

$X[H_2D^+] = X[H_3^+]$ (Pagani et al. 1992)

(while D/H ≈ 1.5×10^{-5}, Linsky et al. 2007)

Deute… …ouds

H_2 + Cosmic…

$H_2^+ + H_2 \Rightarrow$ …

$H^+ + D \Rightarrow H$…

$D^+ + H_2 \Rightarrow H$… …)

$H_3^+ + HD \Leftrightarrow$ …

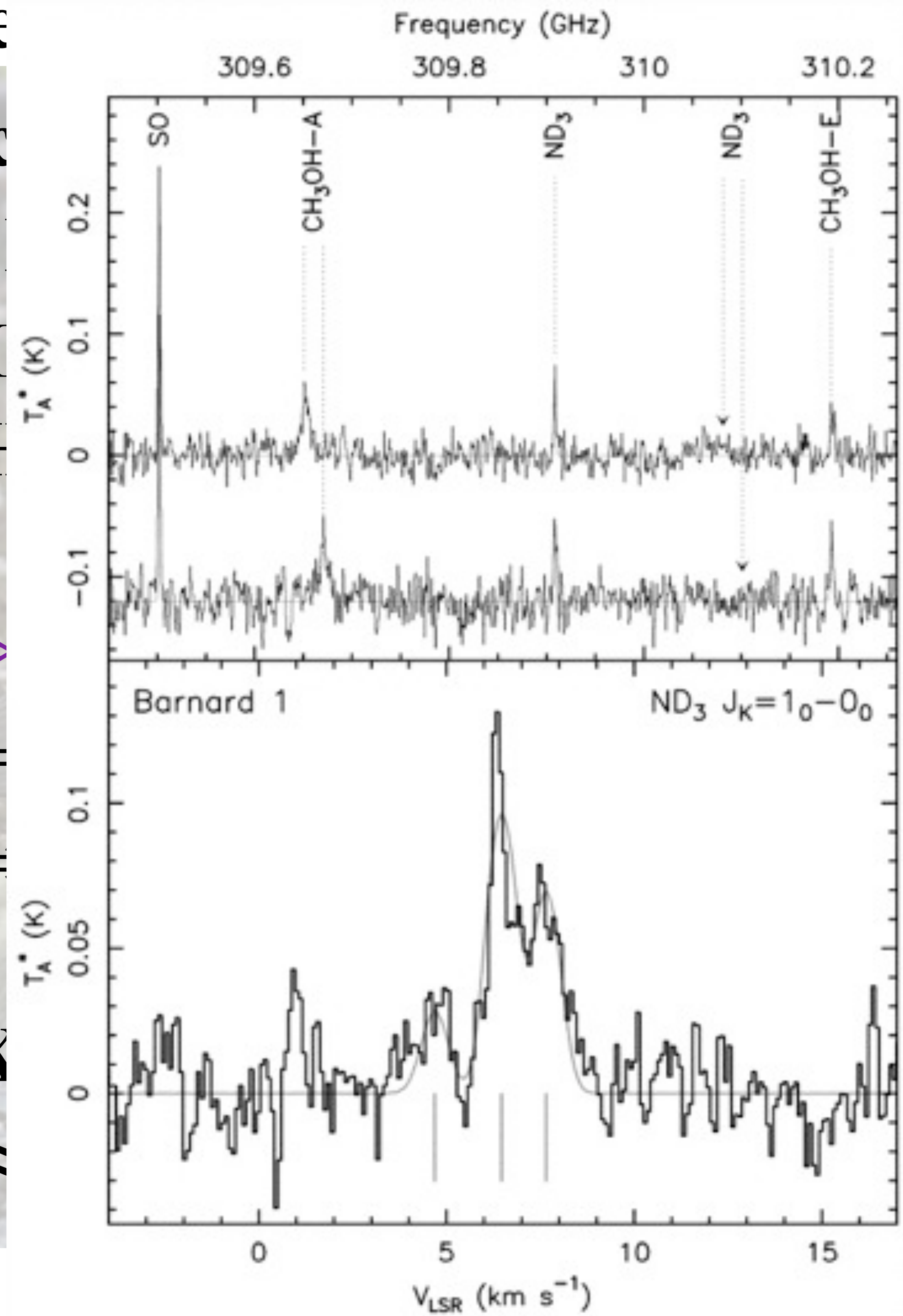
$H_2D^+ + CO =$ … …O^+

$H_2D^+ + N_2 =$ …

etc…

$X[H_2D^+] = X$… …)

(while D/H ≈ … …07)



Deuterium chemistry in dense clouds

H_2 + Cosmic Ray ⇒ $H_2^+ + e^-$

$H_2^+ + H_2$ ⇒ $H_3^+ + H$

$H^+ + D$ ⇒ $H + D^+$

$D^+ + H_2$ ⇒ $H^+ + HD$ (*et aussi sur les grains*)

$H_3^+ + HD$ ⇔ $H_2D^+ + H_2$ + (232 K)

$H_2D^+ + CO$ ⇒ $H_2 + DCO^+$ or $HD + HCO^+$

$H_2D^+ + N_2$ ⇒ $H_2 + N_2D^+$ or $HD + N_2H^+$

etc…

Detection of D_2CO, ND_2H, D_2O, CD_2OH,…

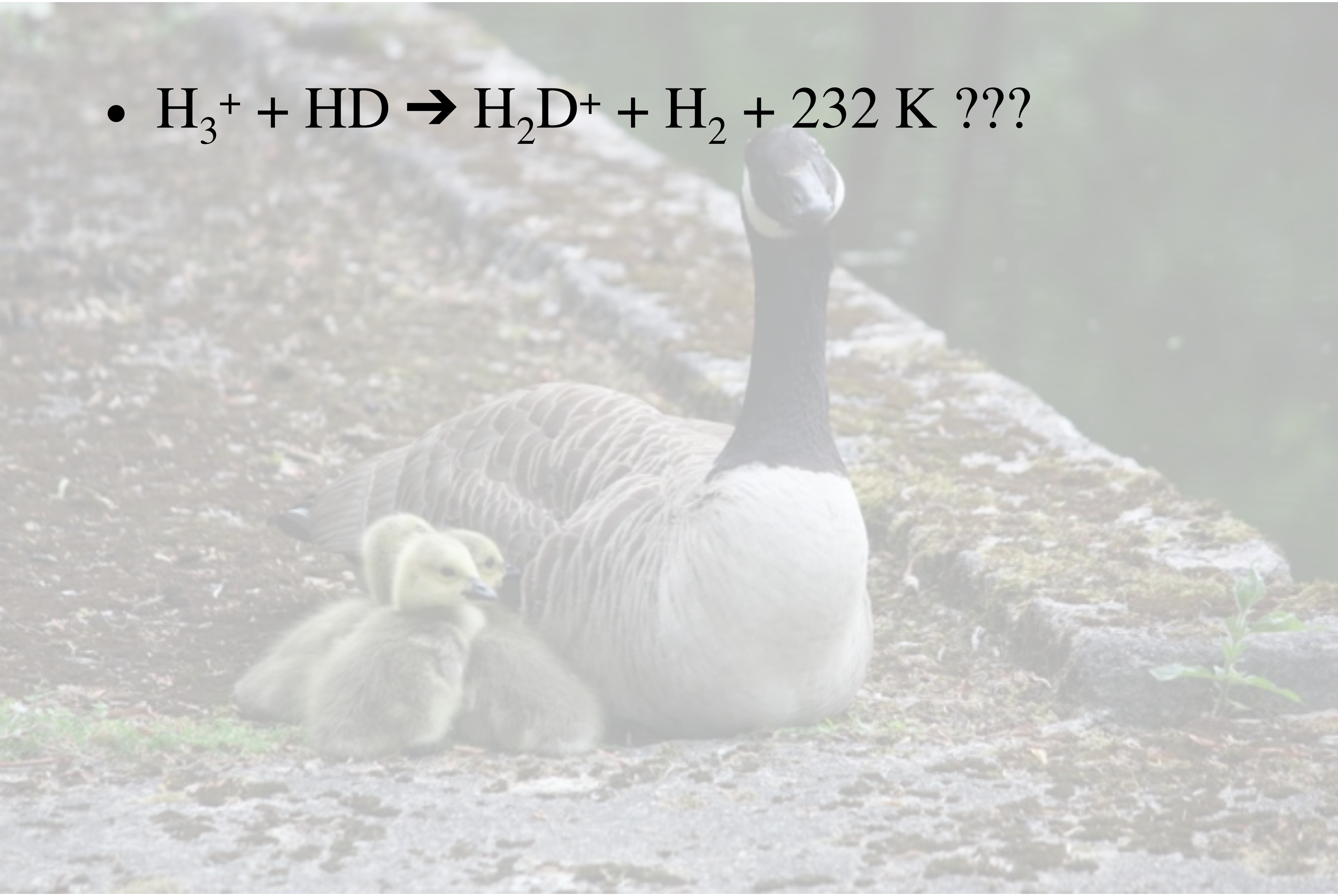
Detection of ND_3 and CD_3OH !

⇨ need for D_2H^+ and D_3^+

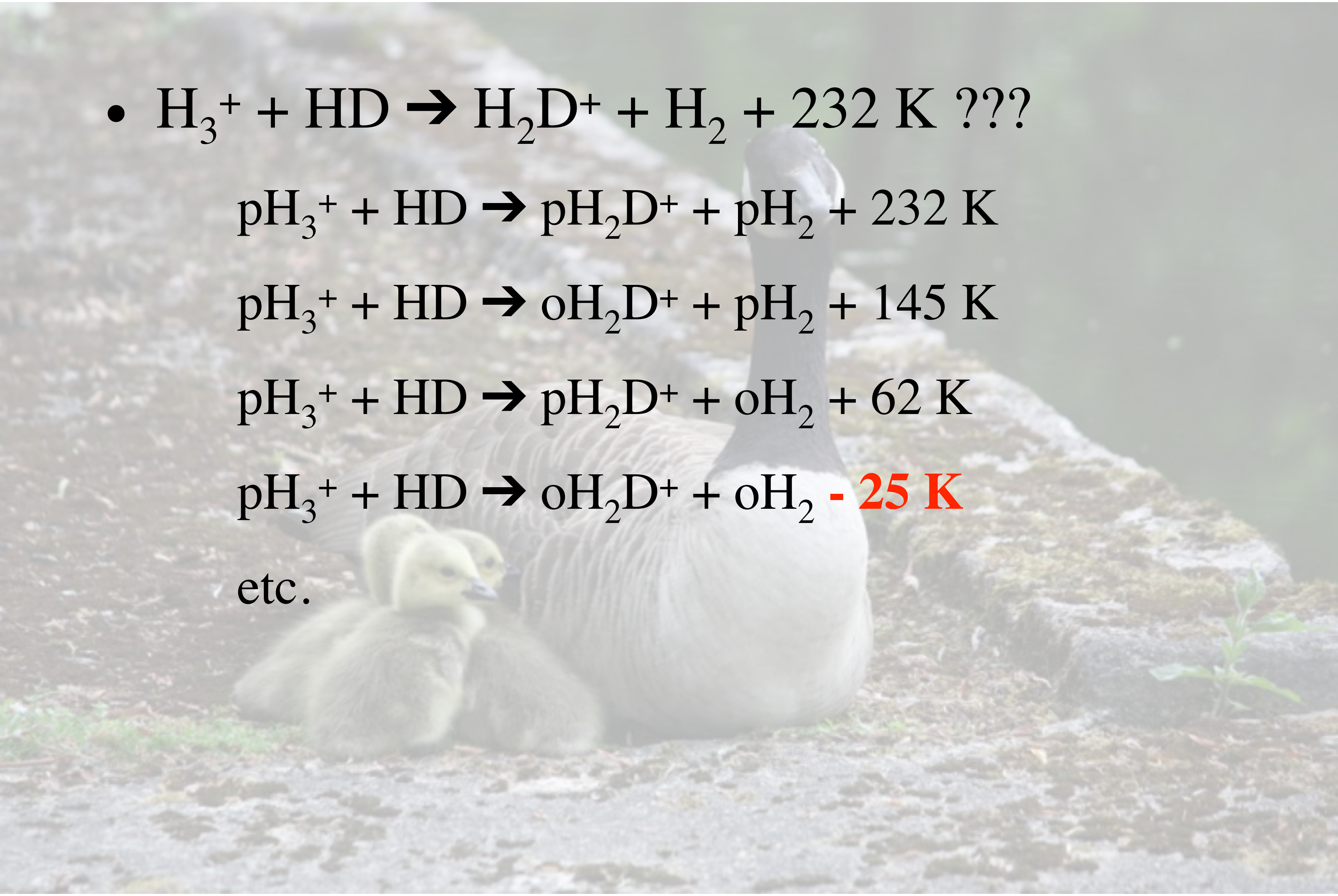
(Lis et al. 2002, Roberts et al. 2003)

Ortho H_2 : deuteration control

- $H_3^+ + HD \rightarrow H_2D^+ + H_2 + 232$ K ???



Ortho H_2 : deuteration control



- $H_3^+ + HD \rightarrow H_2D^+ + H_2 + 232\ K$???

  $pH_3^+ + HD \rightarrow pH_2D^+ + pH_2 + 232\ K$

  $pH_3^+ + HD \rightarrow oH_2D^+ + pH_2 + 145\ K$

  $pH_3^+ + HD \rightarrow pH_2D^+ + oH_2 + 62\ K$

  $pH_3^+ + HD \rightarrow oH_2D^+ + oH_2$ **- 25 K**

  etc.

Ortho H_2 : deuteration control

- $H_3^+ + HD \rightarrow H_2D^+ + H_2 + 232$ K ???

$$pH_3^+ + HD \rightarrow pH_2D^+ + pH_2 + 232\ \text{K}$$

$$pH_3^+ + HD \rightarrow oH_2D^+ + pH_2 + 145\ \text{K}$$

$$pH_3^+ + HD \rightarrow pH_2D^+ + oH_2 + 62\ \text{K}$$

$$pH_3^+ + HD \rightarrow oH_2D^+ + oH_2 - 25\ \text{K}$$

etc.

$$pH_2D^+ + oH_2 \rightarrow oH_2D^+ + pH_2 + 83\ \text{K}$$

ortho - $H_2 > 1$ % $\Leftrightarrow$ no H_2D^+

Pagani et al. 2009

Ortho H_2 : deuteration control

- $CH_3^+ + HD \rightarrow CH_2D^+ + pH_2 + 375$ K
- $CH_3^+ + HD \rightarrow CH_2D^+ + oH_2 + 205$ K
- $C_2H_2^+ + HD \rightarrow C_2HD^+ + pH_2 + 550$ K
- $C_2H_2^+ + HD \rightarrow C_2HD^+ + oH_2 + 380$ K
- etc.

Ortho H_2 : deuteration control

- $CH_3^+ + HD \rightarrow CH_2D^+ + pH_2 + 375$ K
- $CH_3^+ + HD \rightarrow CH_2D^+ + oH_2 + 205$ K
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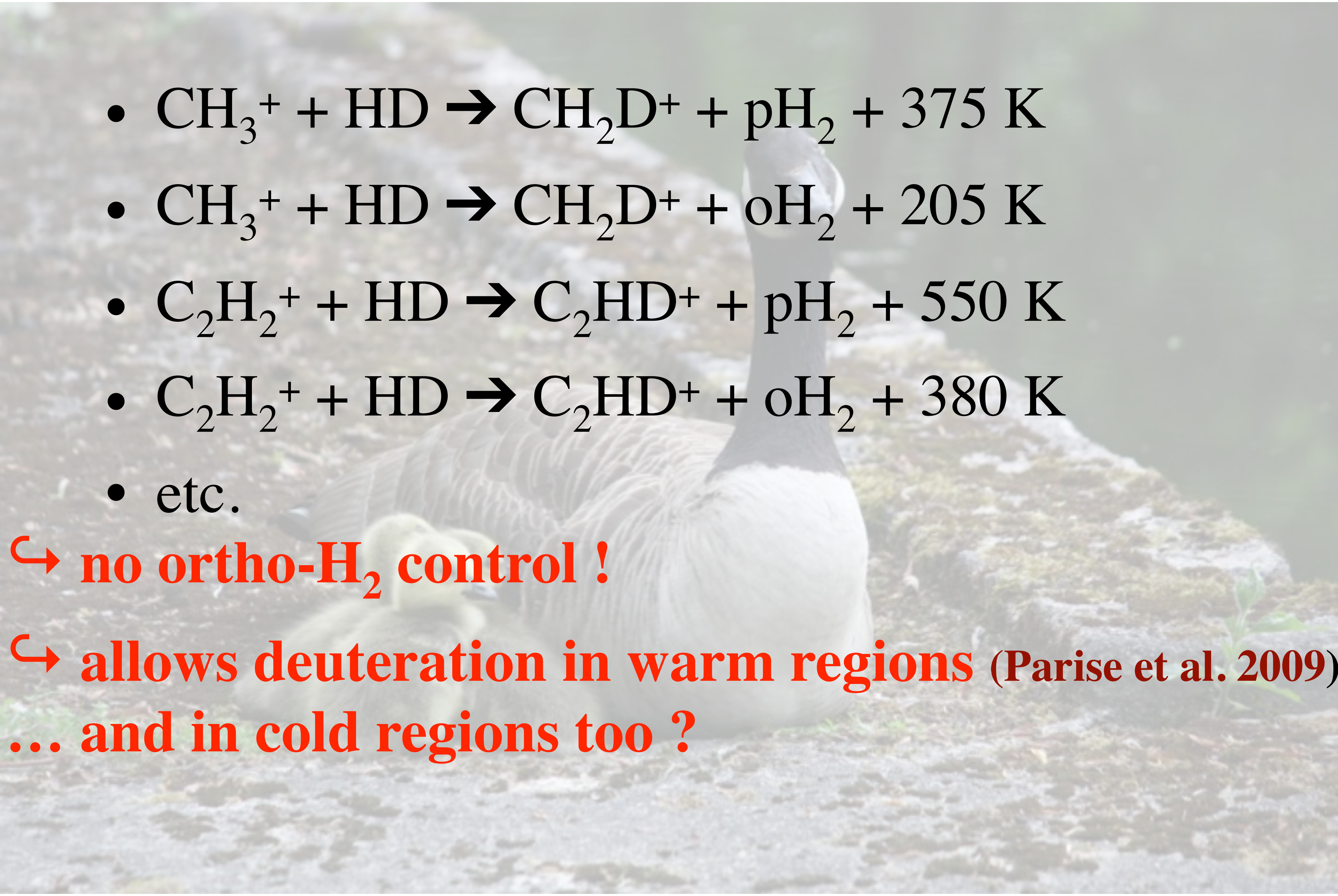
- etc.

↪ **no ortho-H_2 control !**

Ortho H_2 : deuteration control



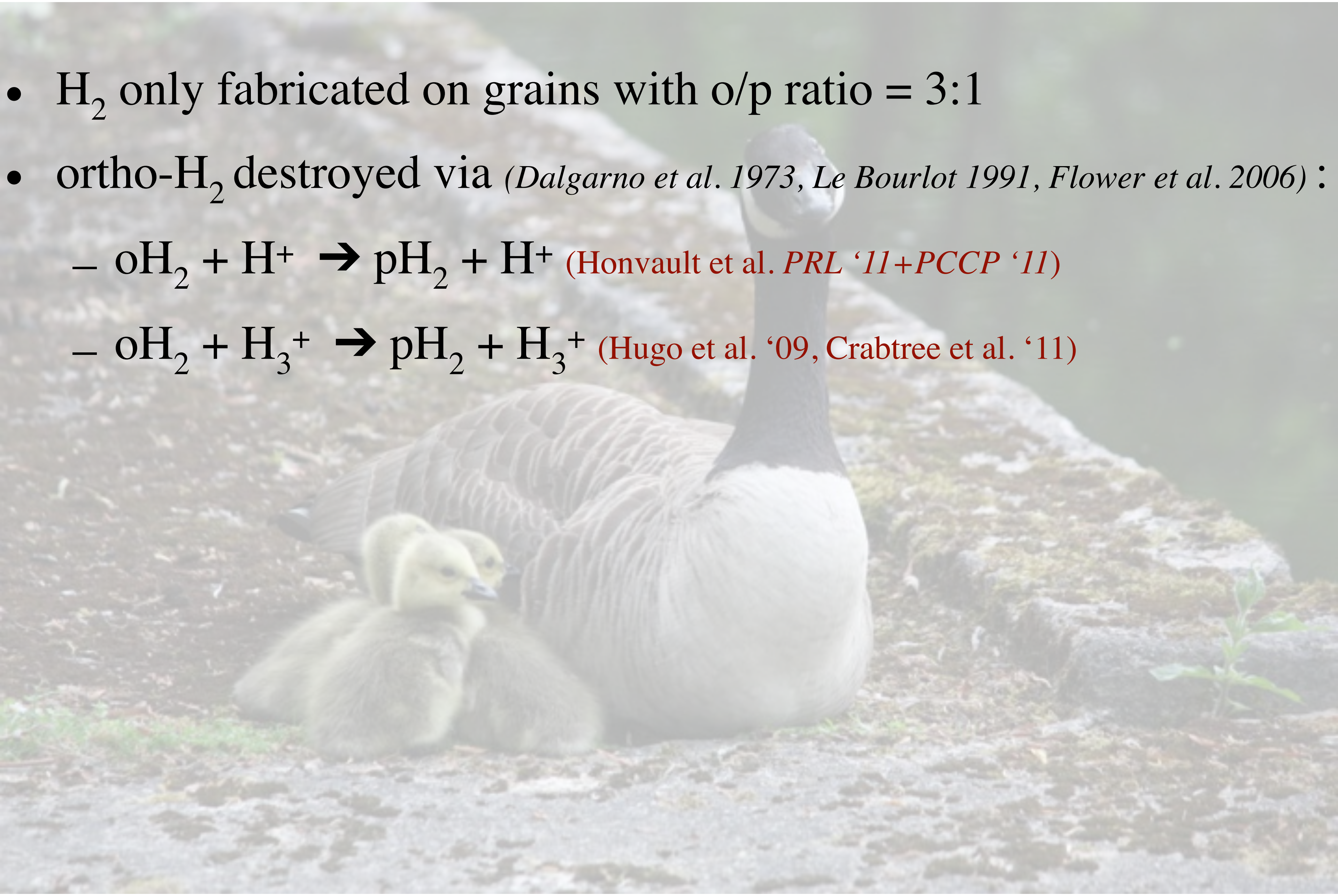
- $CH_3^+ + HD \rightarrow CH_2D^+ + pH_2 + 375\ K$
- $CH_3^+ + HD \rightarrow CH_2D^+ + oH_2 + 205\ K$
- $C_2H_2^+ + HD \rightarrow C_2HD^+ + pH_2 + 550\ K$
- $C_2H_2^+ + HD \rightarrow C_2HD^+ + oH_2 + 380\ K$
- etc.

↪ **no ortho-H_2 control !**

↪ **allows deuteration in warm regions (Parise et al. 2009)**

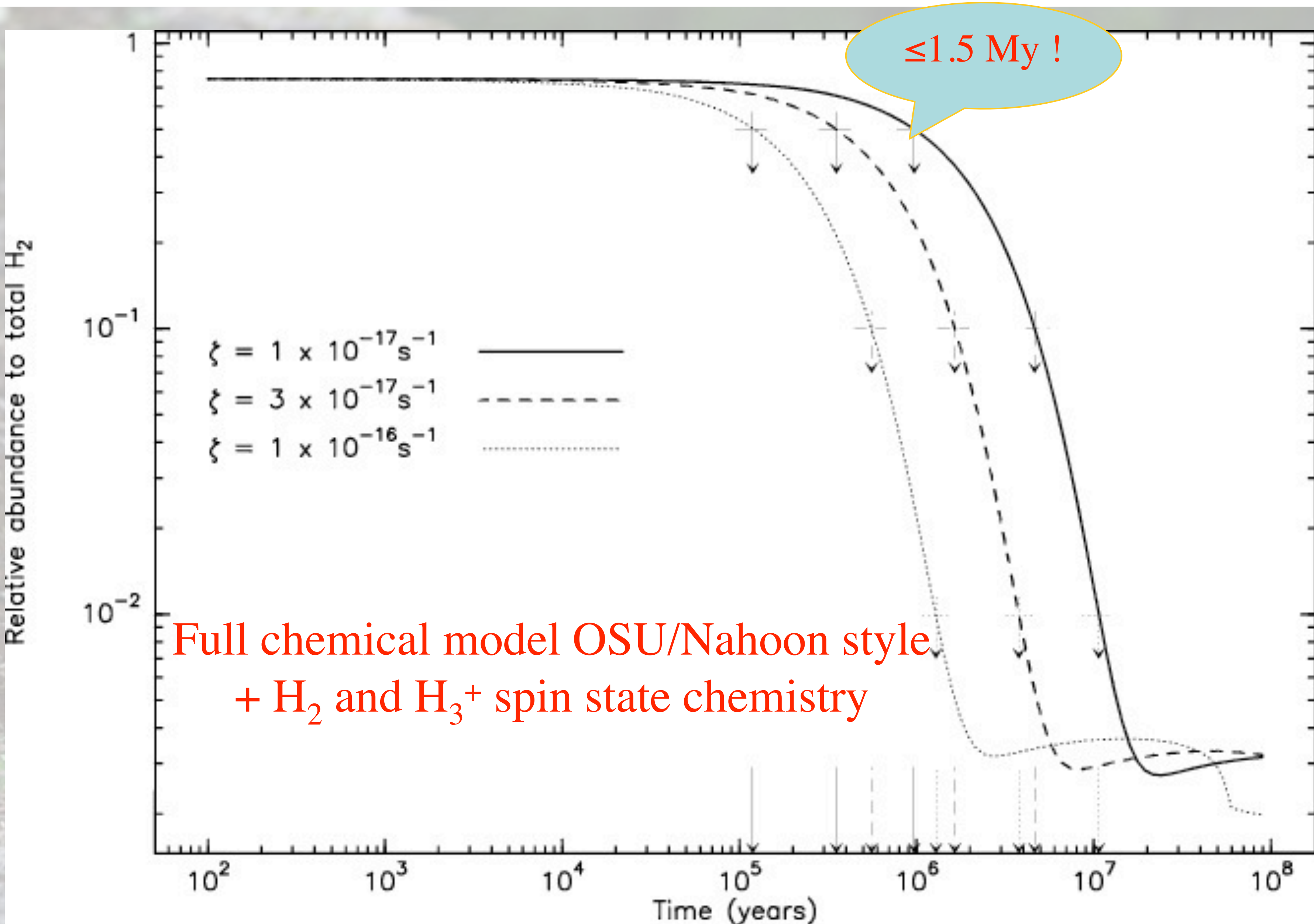
… and in cold regions too ?

Ortho H_2 : fabrication/destruction



- H_2 only fabricated on grains with o/p ratio = 3:1
- ortho-H_2 destroyed via *(Dalgarno et al. 1973, Le Bourlot 1991, Flower et al. 2006)* :
  - $oH_2 + H^+ \rightarrow pH_2 + H^+$ (Honvault et al. *PRL '11+PCCP '11*)
  - $oH_2 + H_3^+ \rightarrow pH_2 + H_3^+$ (Hugo et al. '09, Crabtree et al. '11)

Ortho H_2 : fabrication/destruction



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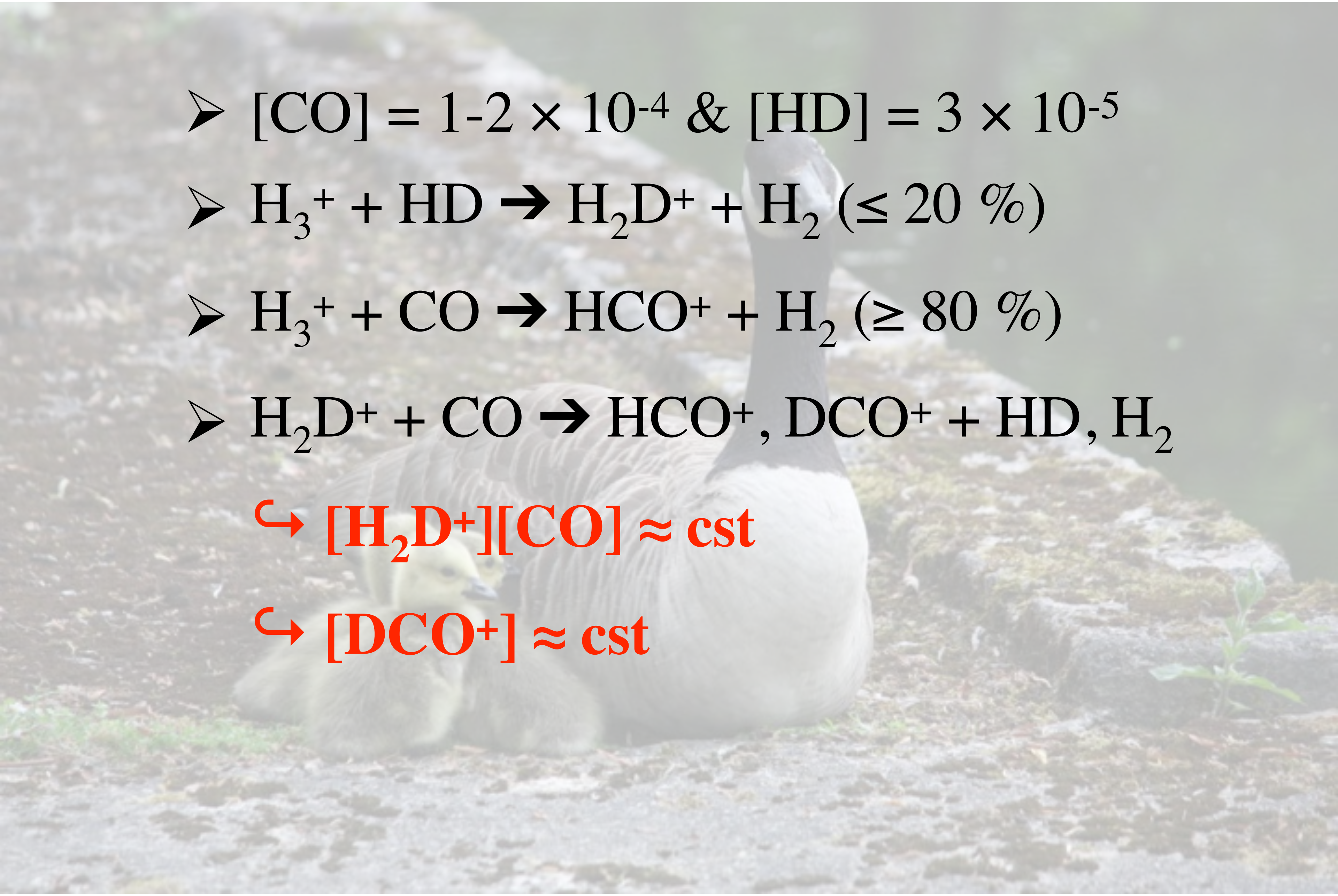
Do we need CO depletion to deuterate ?

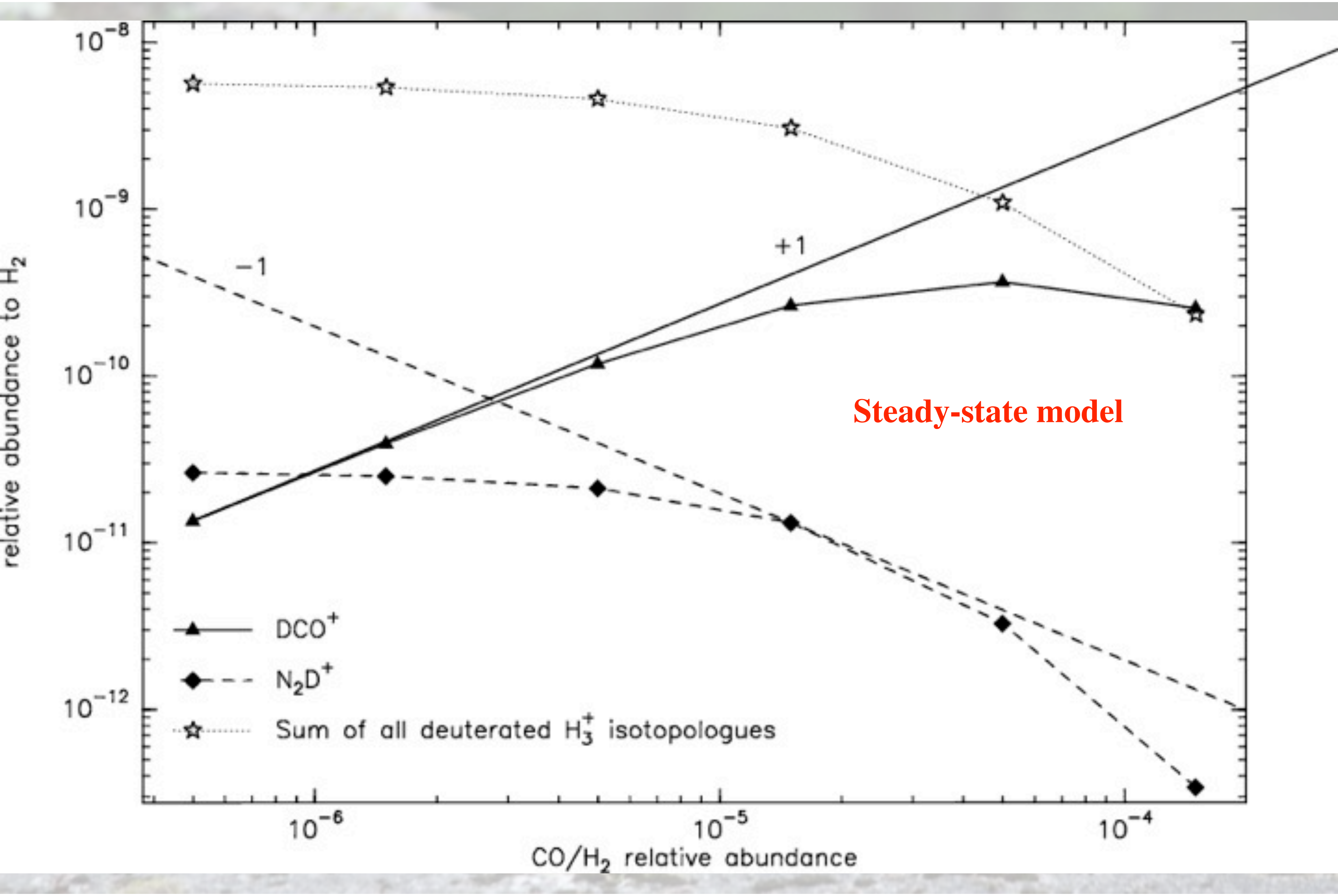


- $[CO] = 1\text{-}2 \times 10^{-4}$ & $[HD] = 3 \times 10^{-5}$
- $H_3^+ + HD \rightarrow H_2D^+ + H_2$ (≤ 20 %)
- $H_3^+ + CO \rightarrow HCO^+ + H_2$ (≥ 80 %)
- $H_2D^+ + CO \rightarrow HCO^+, DCO^+ + HD, H_2$

↪ **$[H_2D^+][CO] \approx cst$**

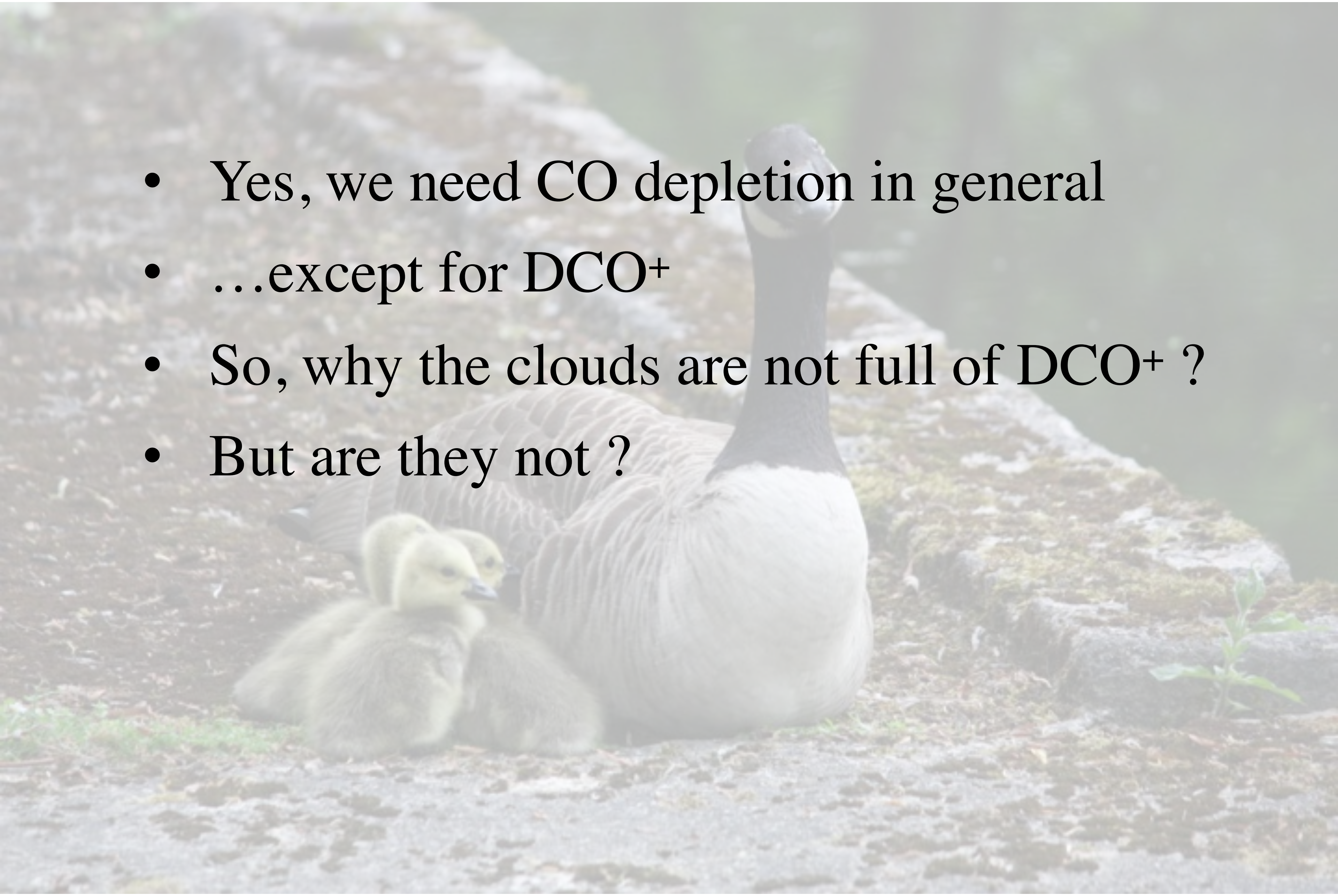
↪ **$[DCO^+] \approx cst$**

Do we need CO depletion to deuterate ?



Do we need CO depletion to deuterate ?

Do we need CO depletion to deuterate ?



- Yes, we need CO depletion in general
- …except for DCO^+
- So, why the clouds are not full of DCO^+ ?
- But are they not ?

Do we need CO depletion to deuterate ?

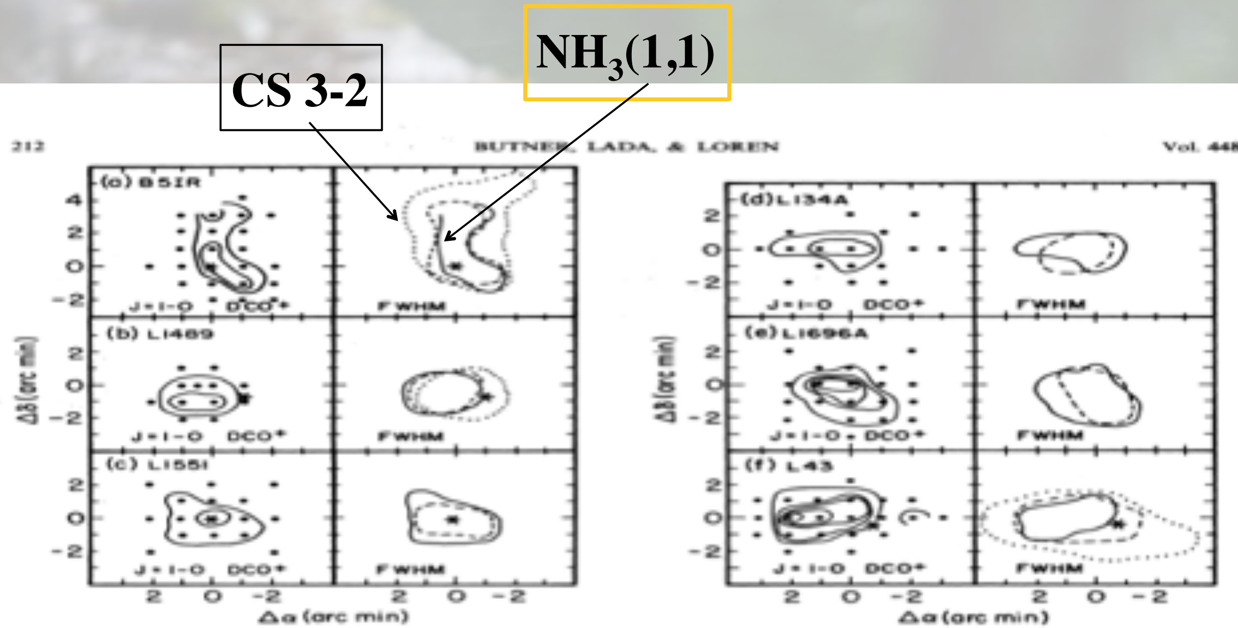


FIG. 2.—(a) The left-hand panel is the contour plot of the DCO^+ map for B5-IR. The lowest contour is 1.2, the steps are 0.5 K. Units are T_R. The right-hand panel is a comparison of the full width half-maximum (FWHM) maps of NH_3 (1,1) (*dashed line*), DCO^+ ($J = 1 \rightarrow 0$) (*solid line*), and CS ($J = 3 \rightarrow 2$) (*dotted line*). The NH_3 map is taken from Benson & Myers (1989), the CS map is taken from Zhou et al. (1989). (b) Same as (a), for L1489. The lowest contour is 2.3 K, steps of 0.7 K. (c) Same as (a), for L1551-IR. The lowest contour is 1.3 K, steps of 0.6 K. (d) Same as (a) for L134A. The lowest contour is 0.9 K, steps of 0.4 K. (e) Same as (a), for L1696A. The lowest contour is 1.4 K, steps of 0.4 K. (f) Same as (a), for L43. The lowest contour is 1.7 K, steps of 0.5 K. (g) Same as (a), for L234A. The lowest contour is 1.5 K, steps of 0.5 K. (h) Same as (a), for L234E. The lowest contour is 1.5 K, steps of 0.5 K. (i) Same as (a), for L1262. The lowest contour is 1.4 K, steps of 0.4 K.

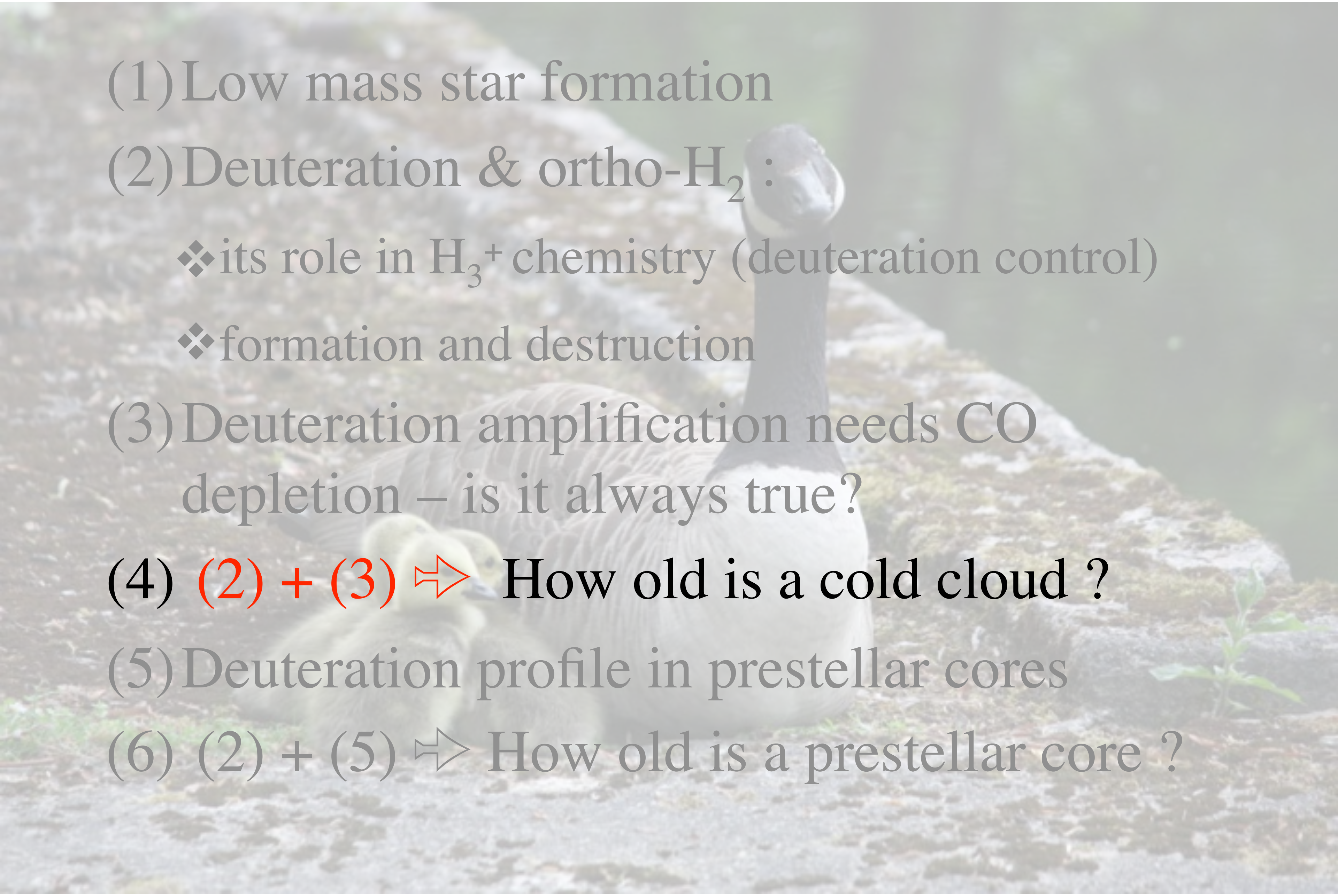
DCO^+ abundance. They found good agreement with the temperature/abundance predictions of Herbst.

Additional reactions suggested by Dalgarno & Lepp (1984) and revised H_3^+ recombination rates (Smith & Adams 1984) have complicated the simple picture developed by Herbst (1982). In addition, our knowledge about possible reaction networks has increased dramatically in the past 10 years. There has also been increased interest in the possible time-dependent variations of molecular abundances (Millar et al. 1988). However, there have been few attempts to incorporate deuterium chemistry in the new reaction models. For this reason, Millar et al. (1989) calculated the expected relative abundance for a number of deuterated molecules over a range of physical conditions, including those found in TMC-1 (cold, $T_K \sim 10$ K; dense, $n \sim 10^4$–10^5 cm^{-3}). They used a reaction network based on the models of Millar, Leung, & Herbst (1987), which describes the chemistry of dense molecular clouds using a pseudo–time-dependent model. In cores with physical conditions similar to TMC-1, Millar et al. (1989) predicted that the DCO^+/HCO^+ ratio should be between 0.02 and 0.05.

The dense cores identified in the Myers & Benson (1983) NH_3 survey provide an excellent laboratory to measure the amount of deuterium fractionation and thereby to better constrain the chemical models. The cores all have similar density and temperature ($n \sim 10^4$–10^5 cm^{-3}, $T_K \sim 10$–15 K) to TMC-1.

To estimate the DCO^+/HCO^+ ratio, we use the column density derived from the DCO^+ and the $H^{13}CO^+$ $J = 1 \rightarrow 0$ observations with the assumption that $T_{ex} = T_K$. The simple LTE excitation calculation is used instead of more sophisticated multitransitional line transfer models since only one $H^{13}CO^+$ transition was observed. [Using a multiple transition line analysis, however, we find good agreement with the LTE estimates for $N(DCO^+)$ and $\tau_{J=1\rightarrow 0}$ (§ 6)]. $H^{13}CO^+$ was observed instead of the more abundant HCO^+ because the HCO^+ $J = 1 \rightarrow 0$ transition is expected to be optically thick in most cases. The $H^{13}CO^+$ abundance is converted to an HCO^+ abundance by assuming that the $HCO^+/H^{13}CO^+$ ratio equaled the $^{12}C/^{13}C$ ratio [$^{12}C/^{13}C = 76 \pm 7(1\ \sigma)$ in the local interstellar medium; see Wilson & Rood 1994 and references therein]. Since the typical optical depth of the $H^{13}CO^+$ $J = 1 \rightarrow 0$ line is ~ 0.2, the corresponding typical HCO^+ $J = 1 \rightarrow 0$ line would have optical depths in excess of 10, justifying our choice of $H^{13}CO^+$. The DCO^+ and $H^{13}CO^+$

(Butner et al. 1995)



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(5) Deuteration profile in prestellar cores

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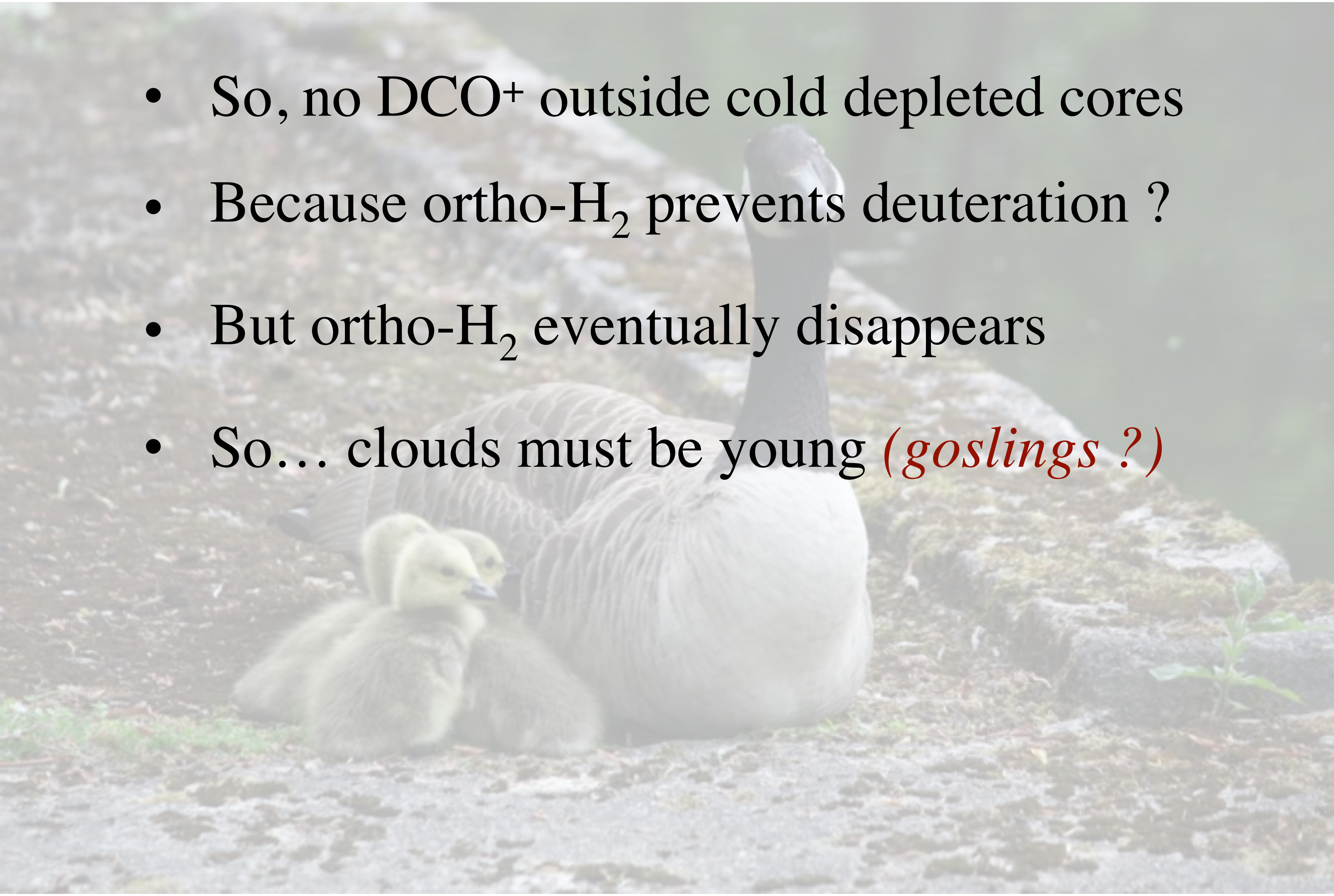
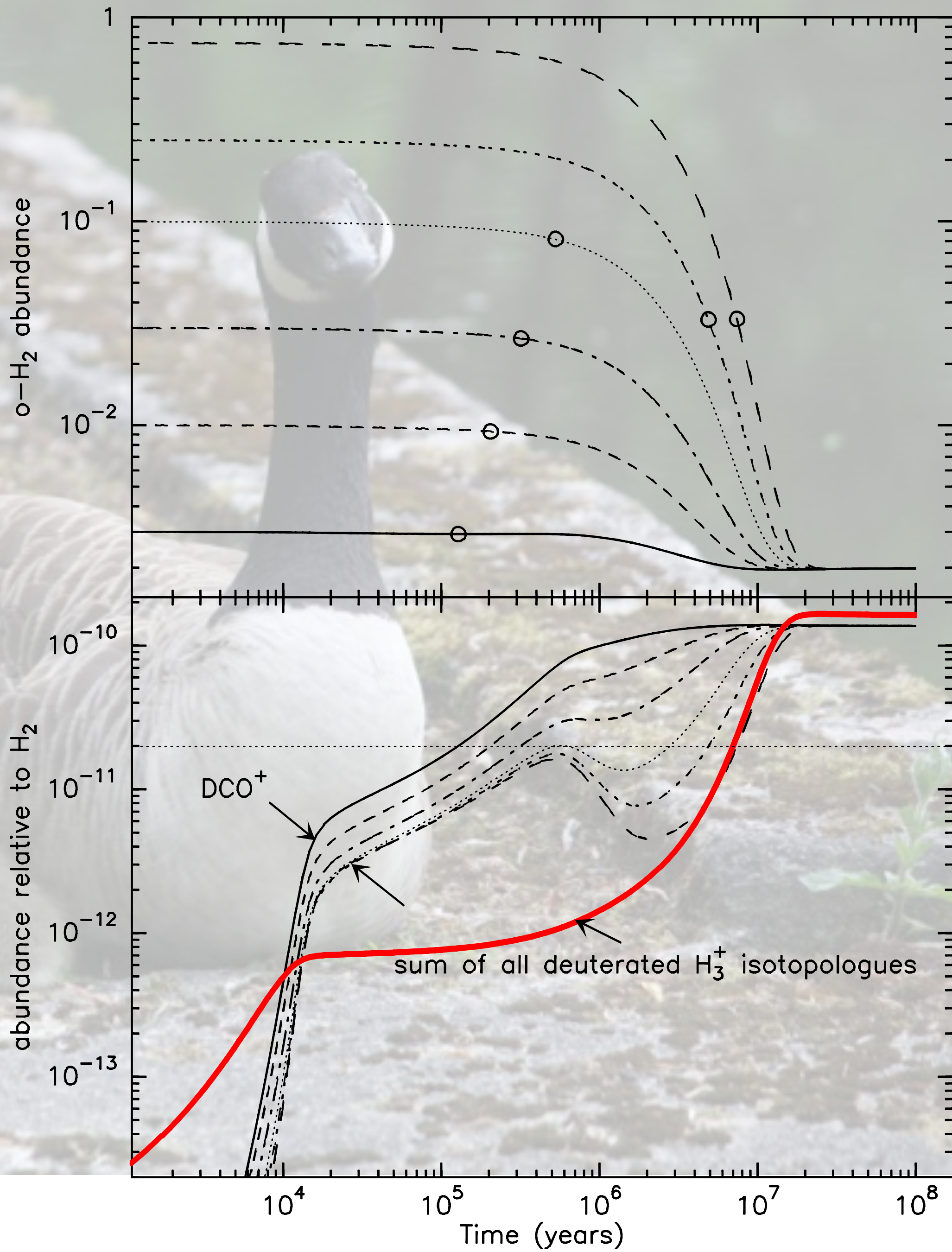
How old is a cold cloud ?

- So, no DCO^+ outside cold depleted cores
- Because ortho-H_2 prevents deuteration ?
- But ortho-H_2 eventually disappears
- So… clouds must be young *(goslings ?)*



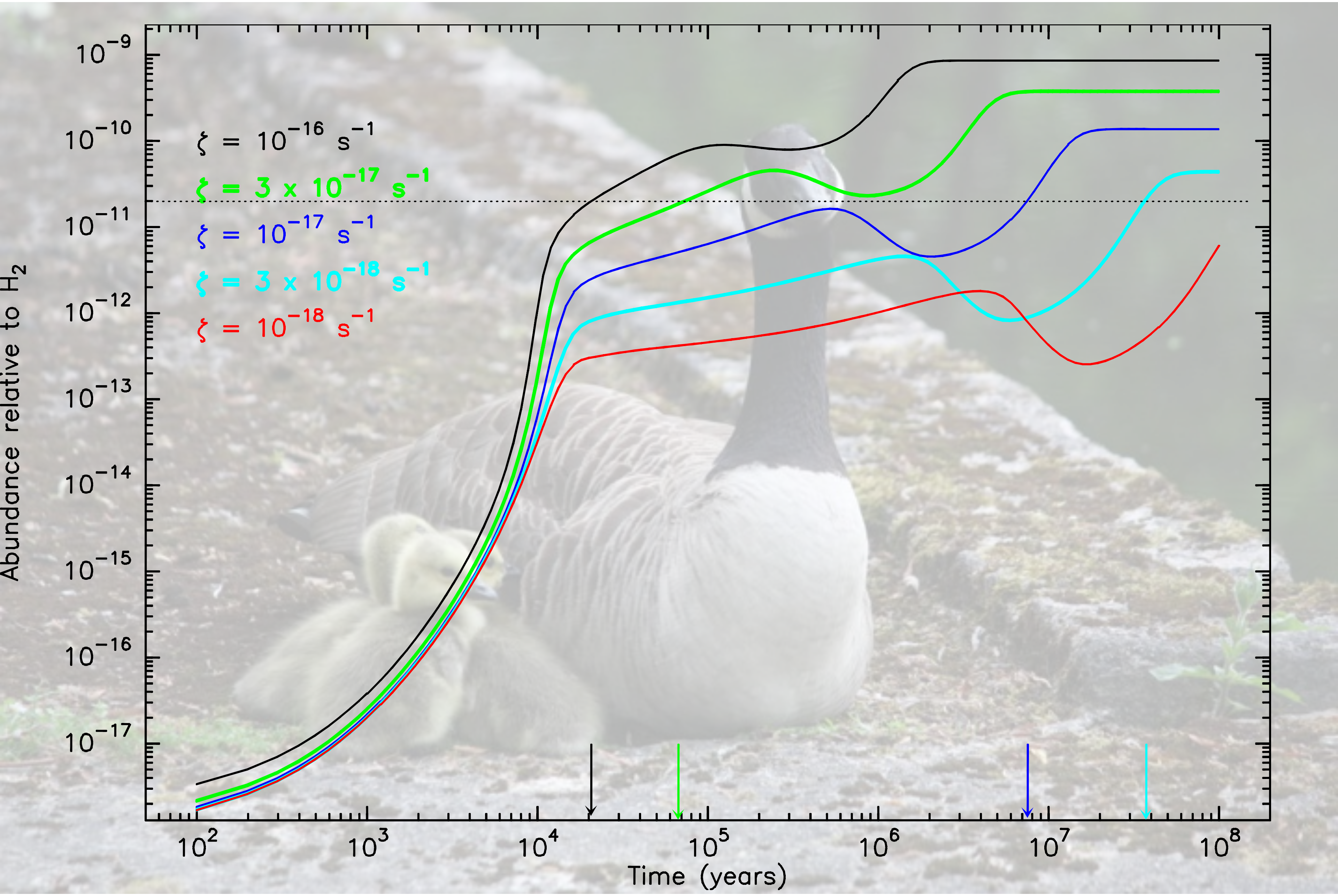
How old is a cold cloud ?

- ❖ Deuteration network (Roueff et al. 2005)
- ◆ + ortho/para spin state H_3^+ chemistry (Hugo et al. 2009)
- ◆ + DR rates (Pagani et al. 2009)
- ◆ + corrections (CD + oH_2,…)
- ✧ Undepleted
- ✧ □= 10^{-17} s^{-1}
- ✧ metals = 3.4 × 10^{-8}
- ✧ T_{kin} = 10 K
- ✧ n_H = 2 × 10^4 cm^{-3}

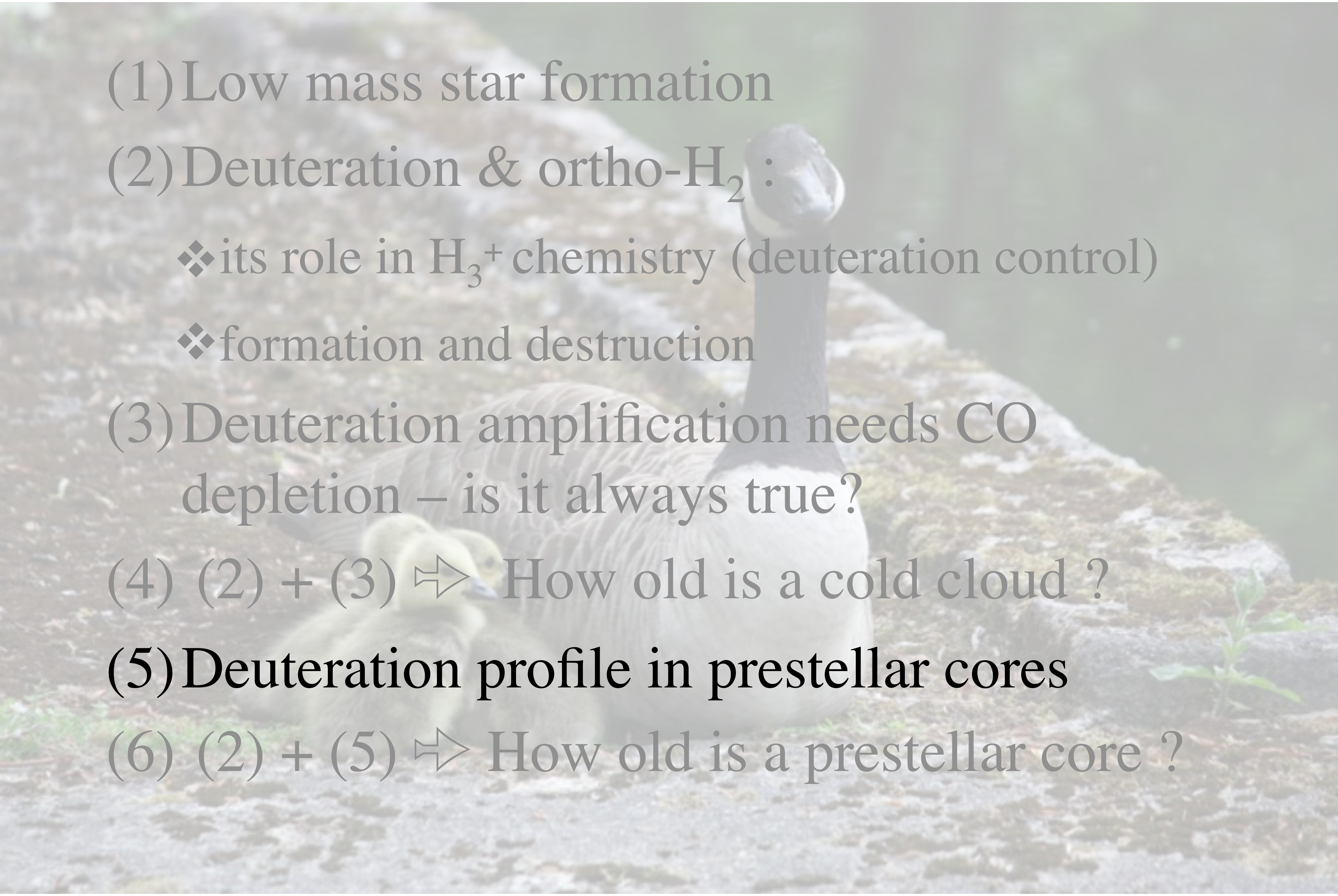


- ❖ Detection limit : 0.1 K in 0.5 km/s (DCO^+ J:1-0)
- ❖ Column density : 10^{22} H_2 cm^{-2}

How old is a cold cloud ?



Dependence on Cosmic Ray Ionization rate



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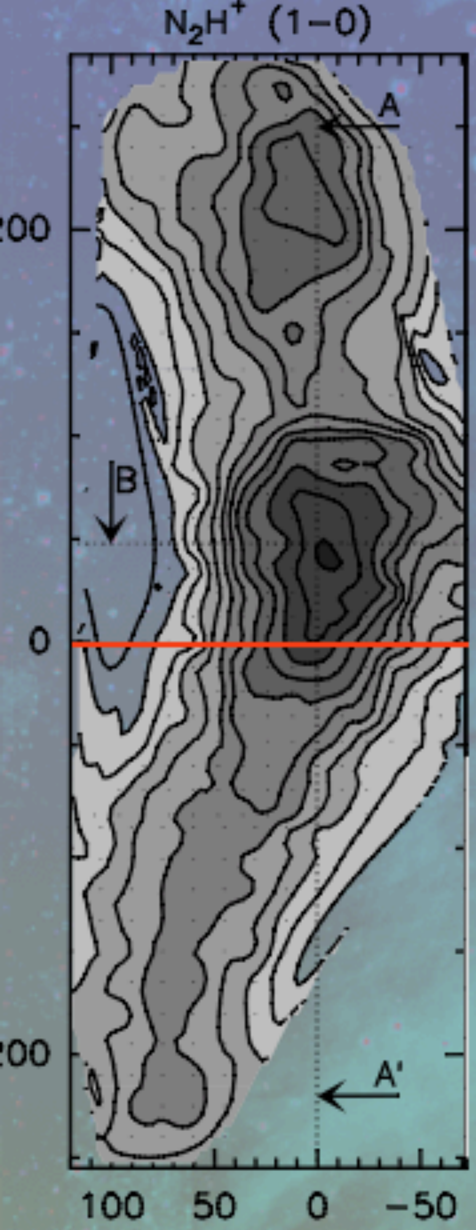
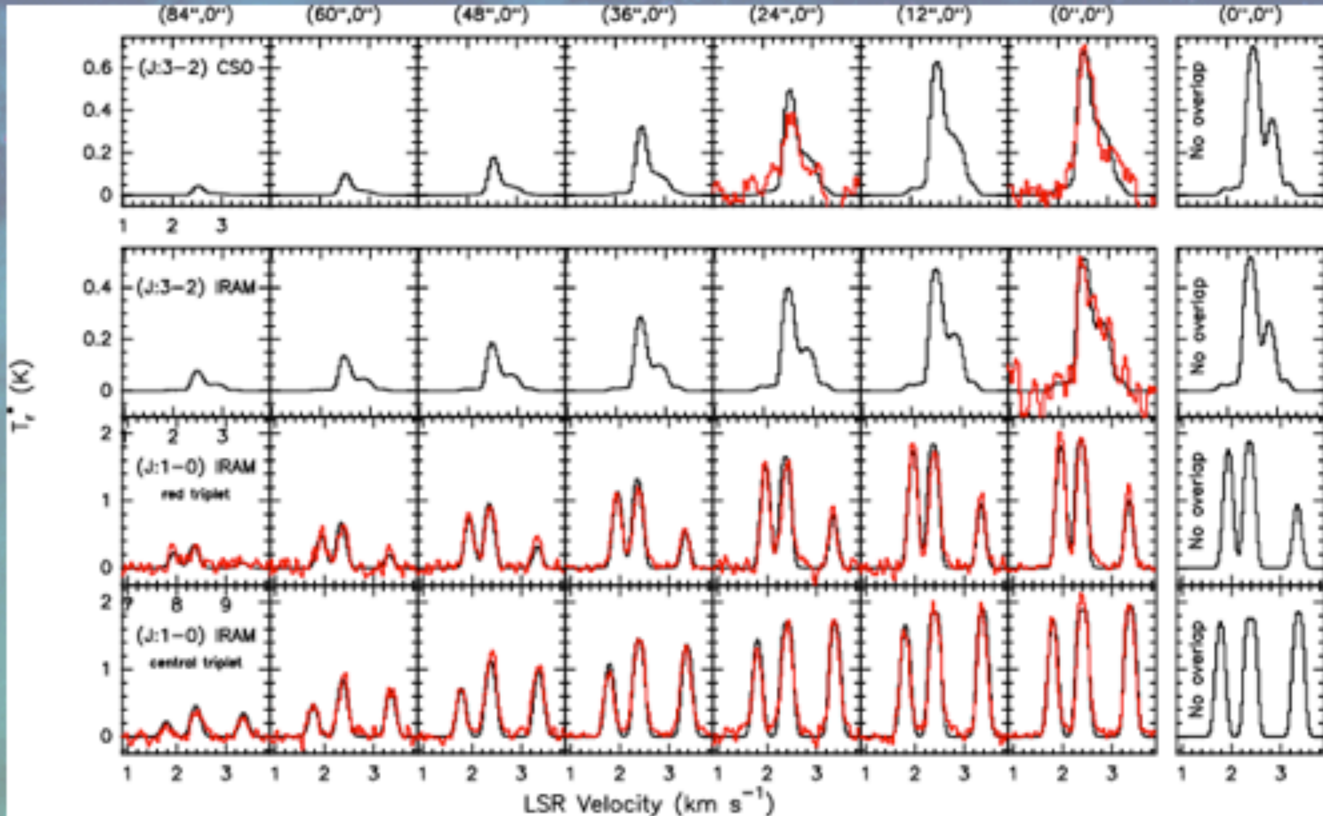
L183 N_2H^+ cut and fit



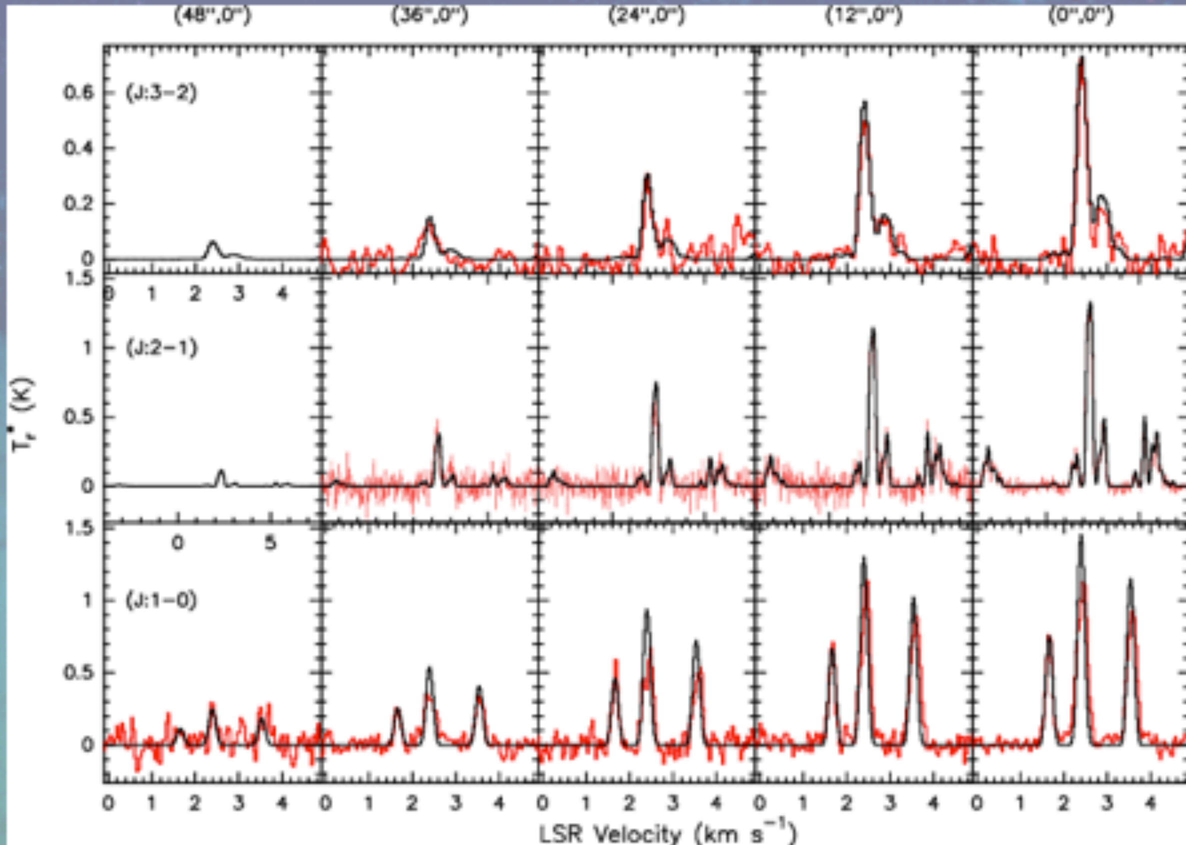


Pagani et al. 2007

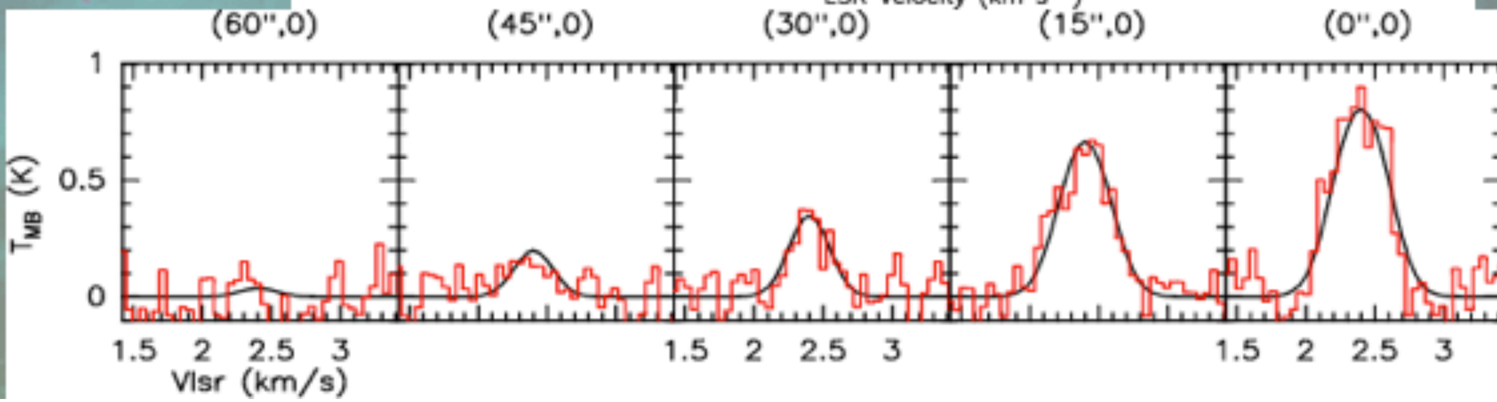
N_2D^+ and H_2D^+ cut and fit

CORE

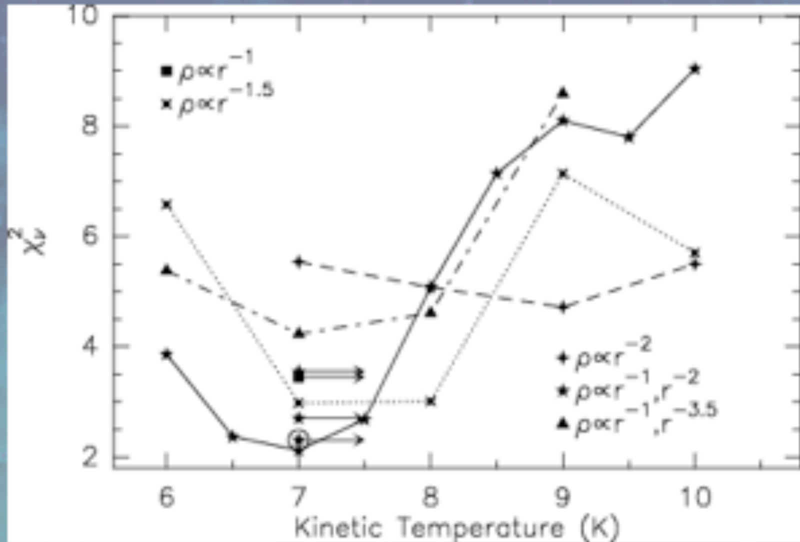
N_2D^+



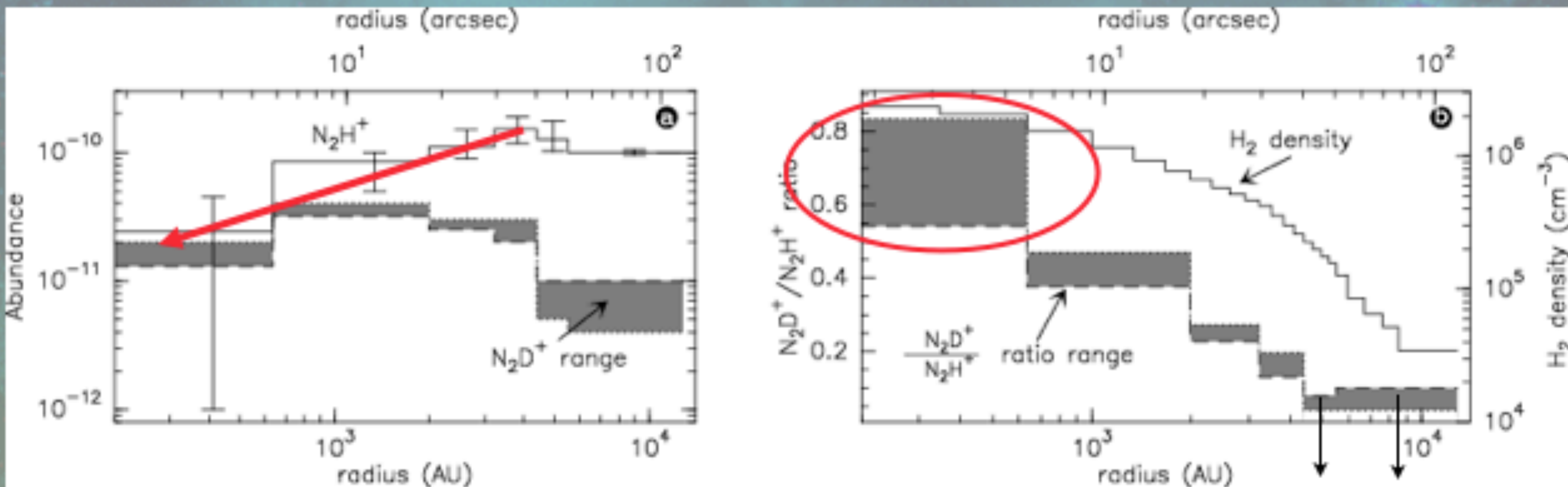
H_2D^+



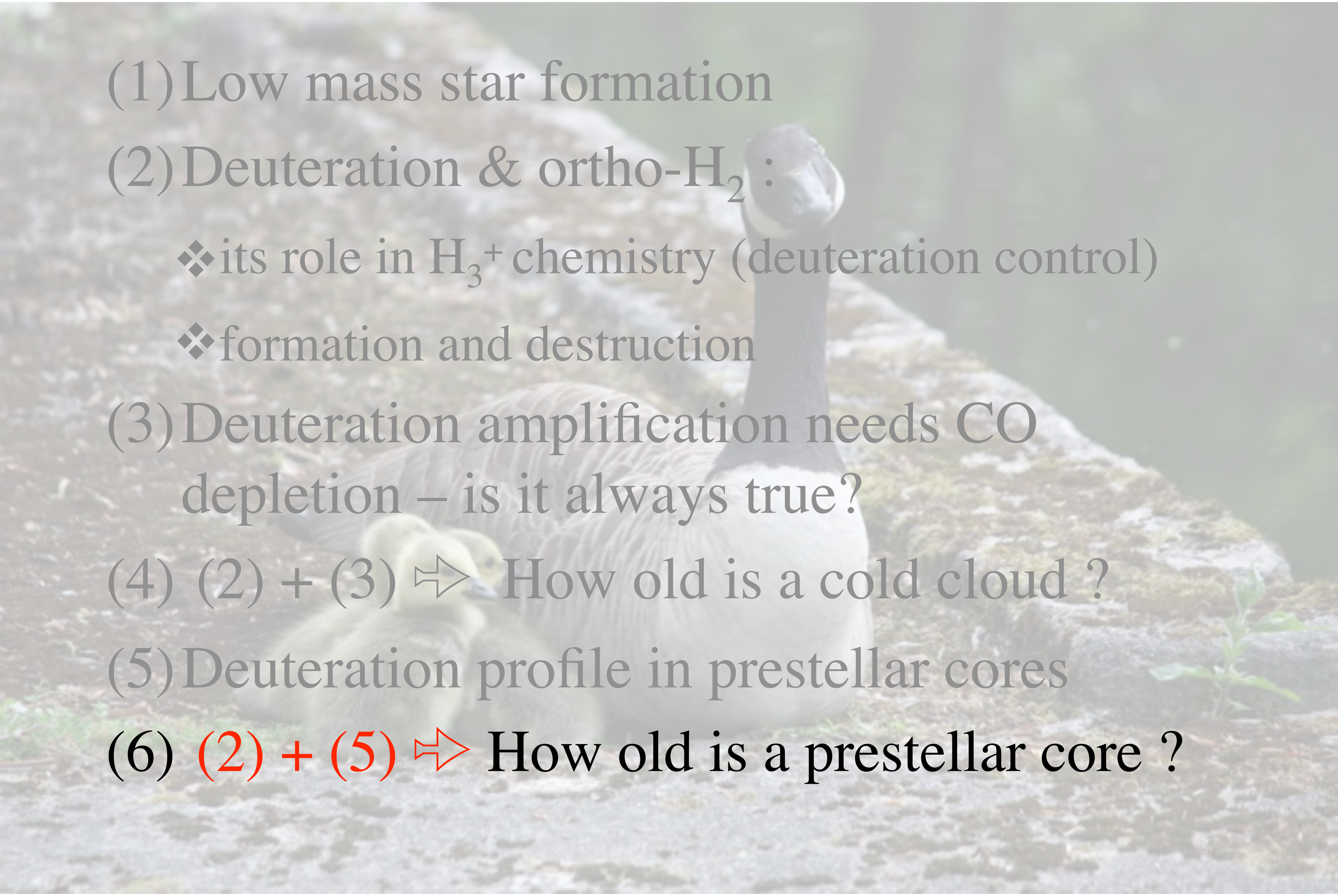
Low gas temperature and N_2H^+/N_2D^+ profile, ratio and depletion



Pagani et al. 2007



vendredi 17 février 12



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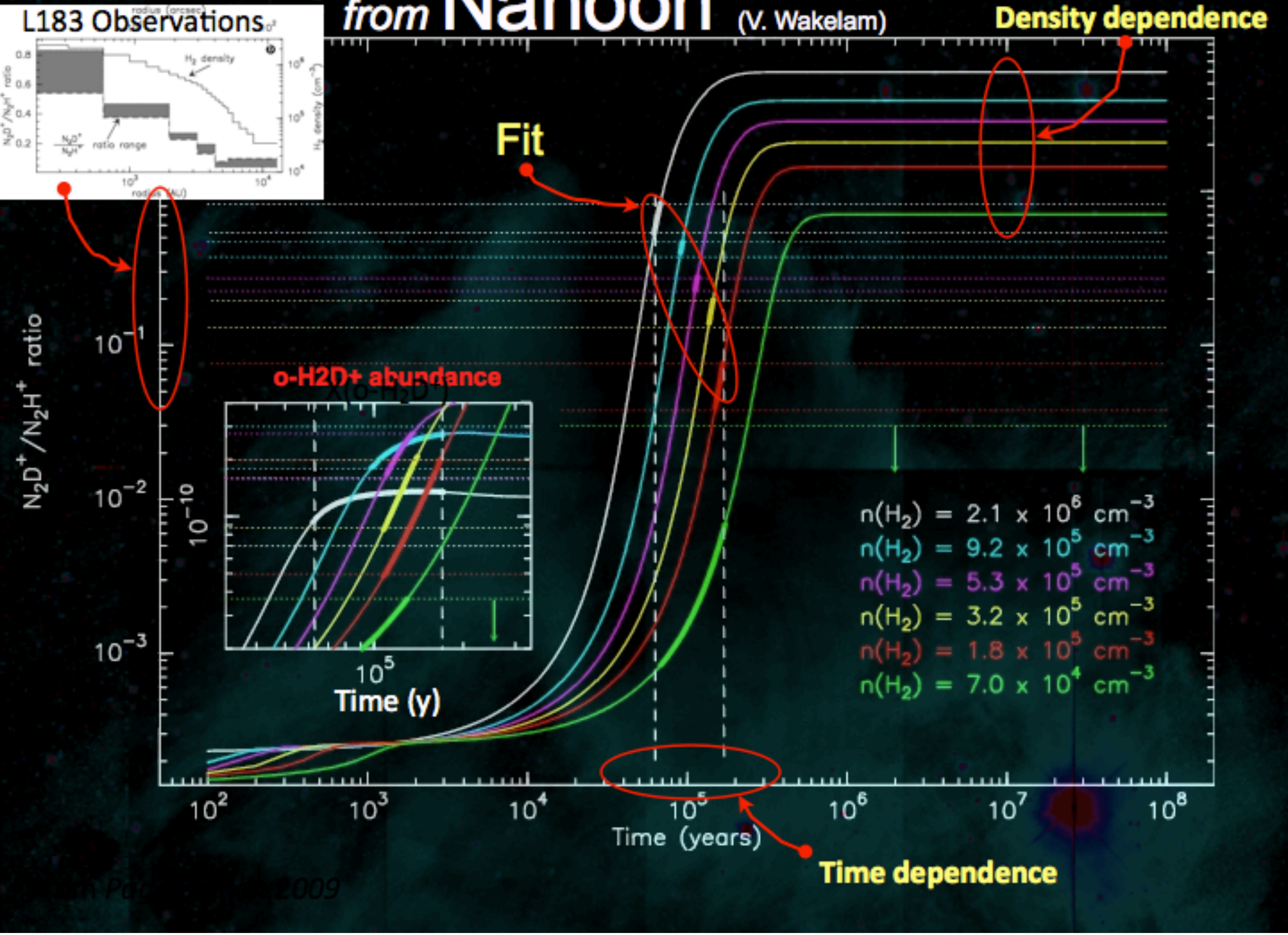
from Nahoon (V. Wakelam)



Low mass star formation

Pagani et al. *subm*.

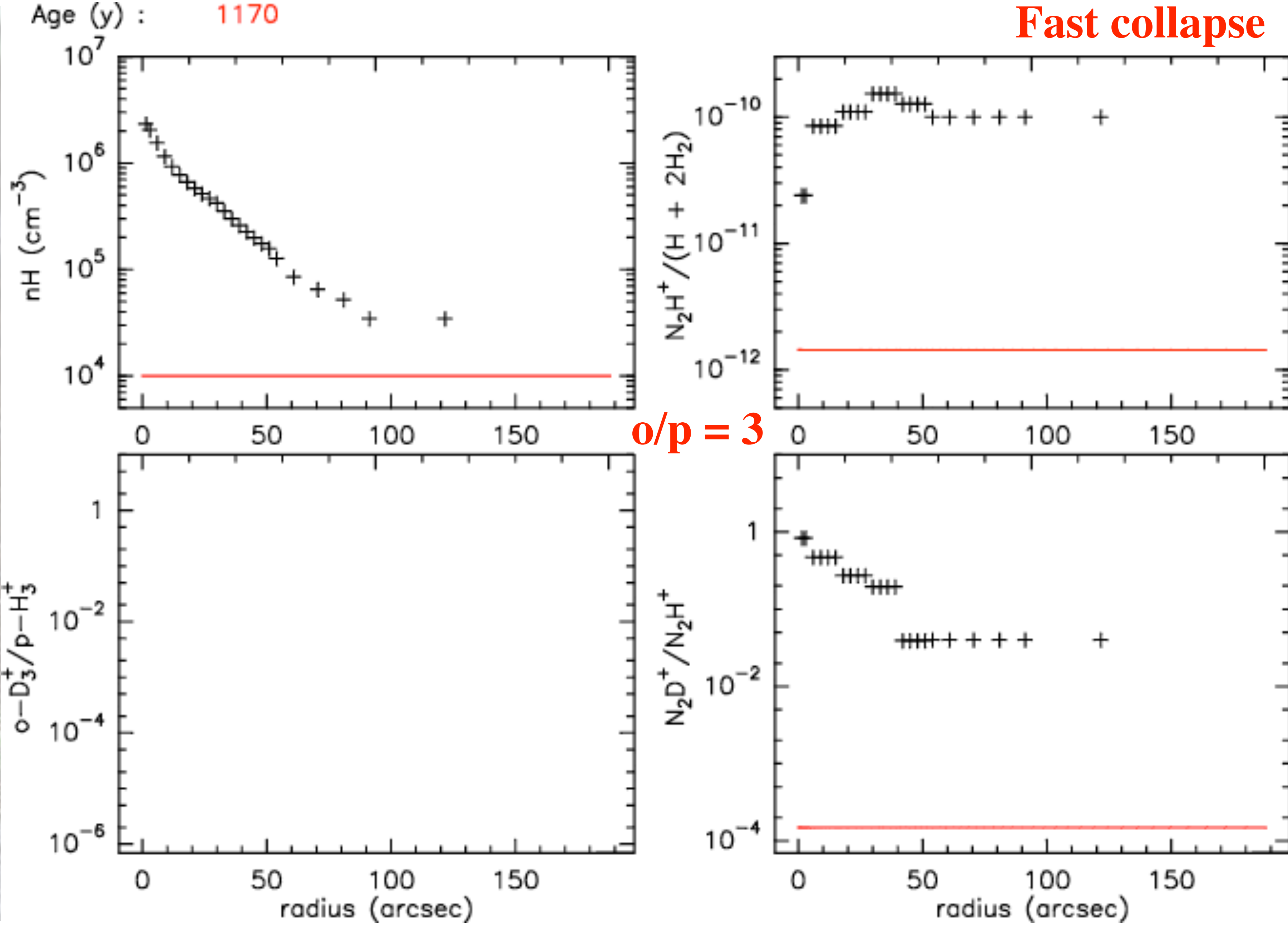
Fast collapse

o/p = 3

Low mass star formation

Pagani et al. *subm*.

Fast collapse



Low mass star formation

Pagani et al. *subm*.

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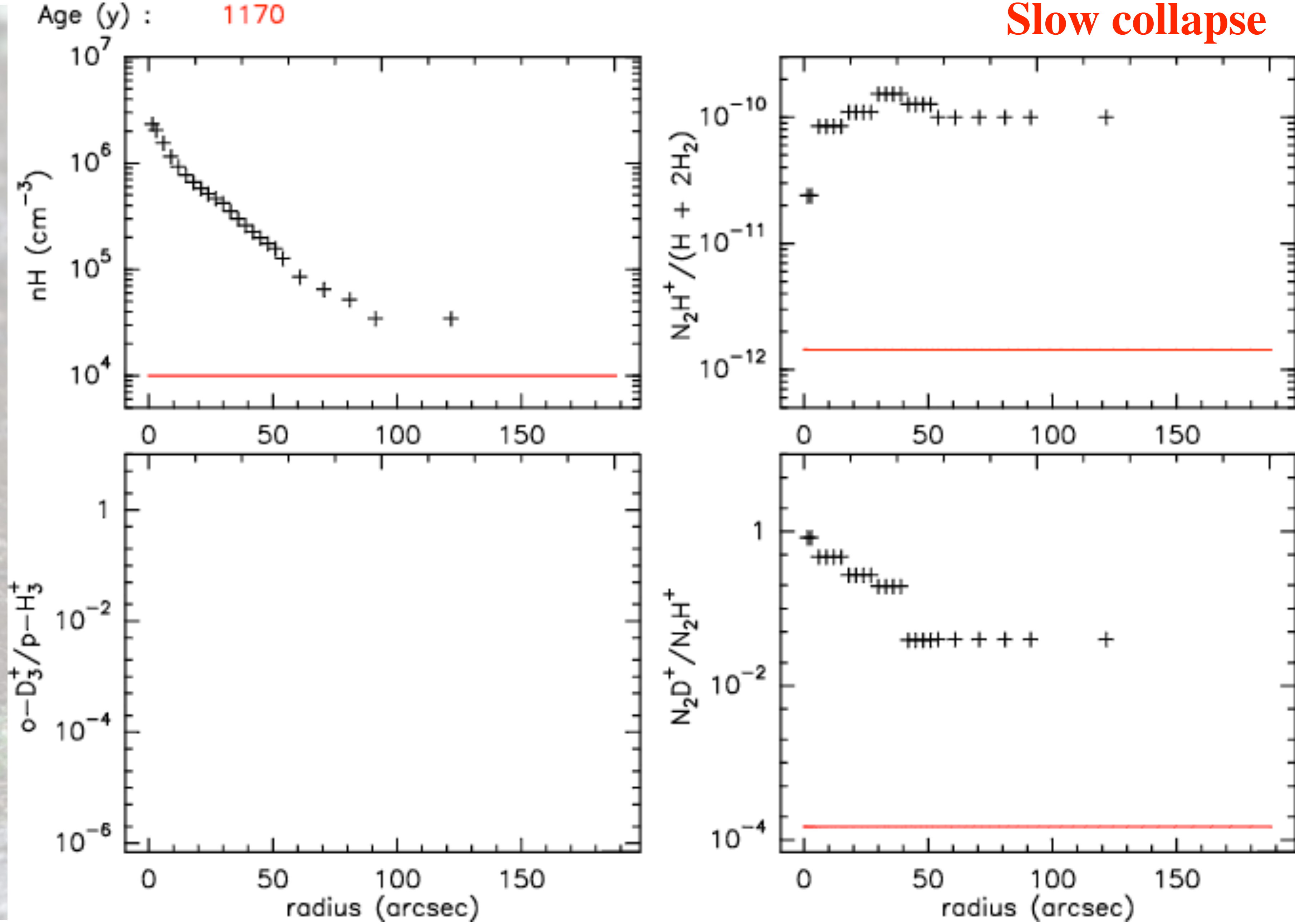
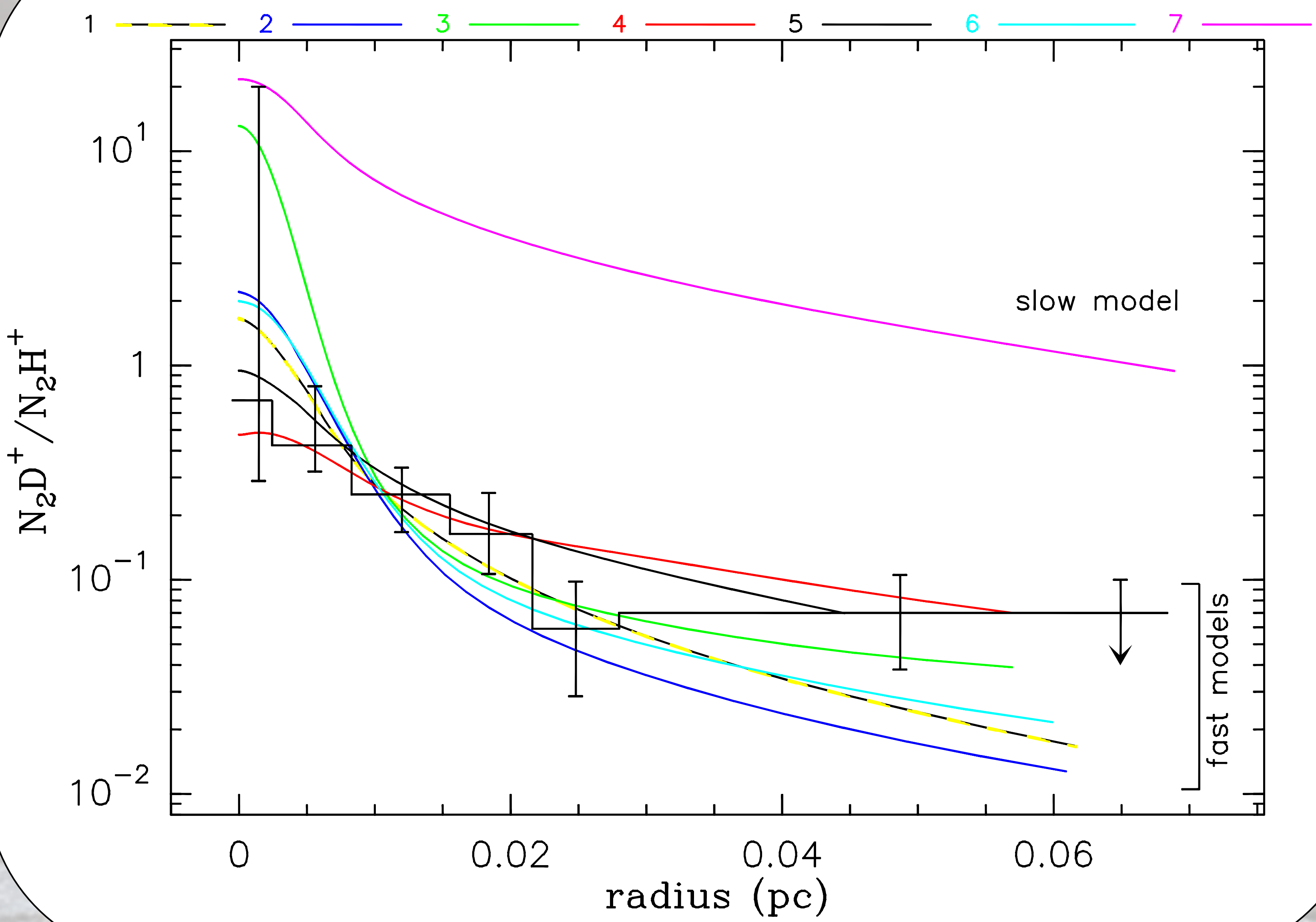
Low mass star formation




1
2
3
4
5
6
7
slow model
fast models
N_2D^+/N_2H^+
radius (pc)
0
0.02
0.04
0.06
10^{-2}
10^{-1}
1
10^1

Conclusions

- Ortho-H_2 is the key species in H_3^+-carried Deuterium chemistry
- D Chemistry must treat all spin states separately
- Ortho-H_2 is abundant outside prestellar cores (> 10%) and drops inside (< 1%)
- Deuterium chemistry seems to say that prestellar cores and clouds are young :
  - clouds < 6-7 My (for normal CR rates and Metallicity)
  - clouds + prestellar core < 1.5 My (at least for the L183 case)
- Role of C-carried Deuterium chemistry needs clarification
- Watson scheme is too simplistic : $DCO^+ \not\Leftrightarrow [e^-]$
- high Cosmic rays ionization rates impossible in dark clouds ?

Conclusions (2nd)

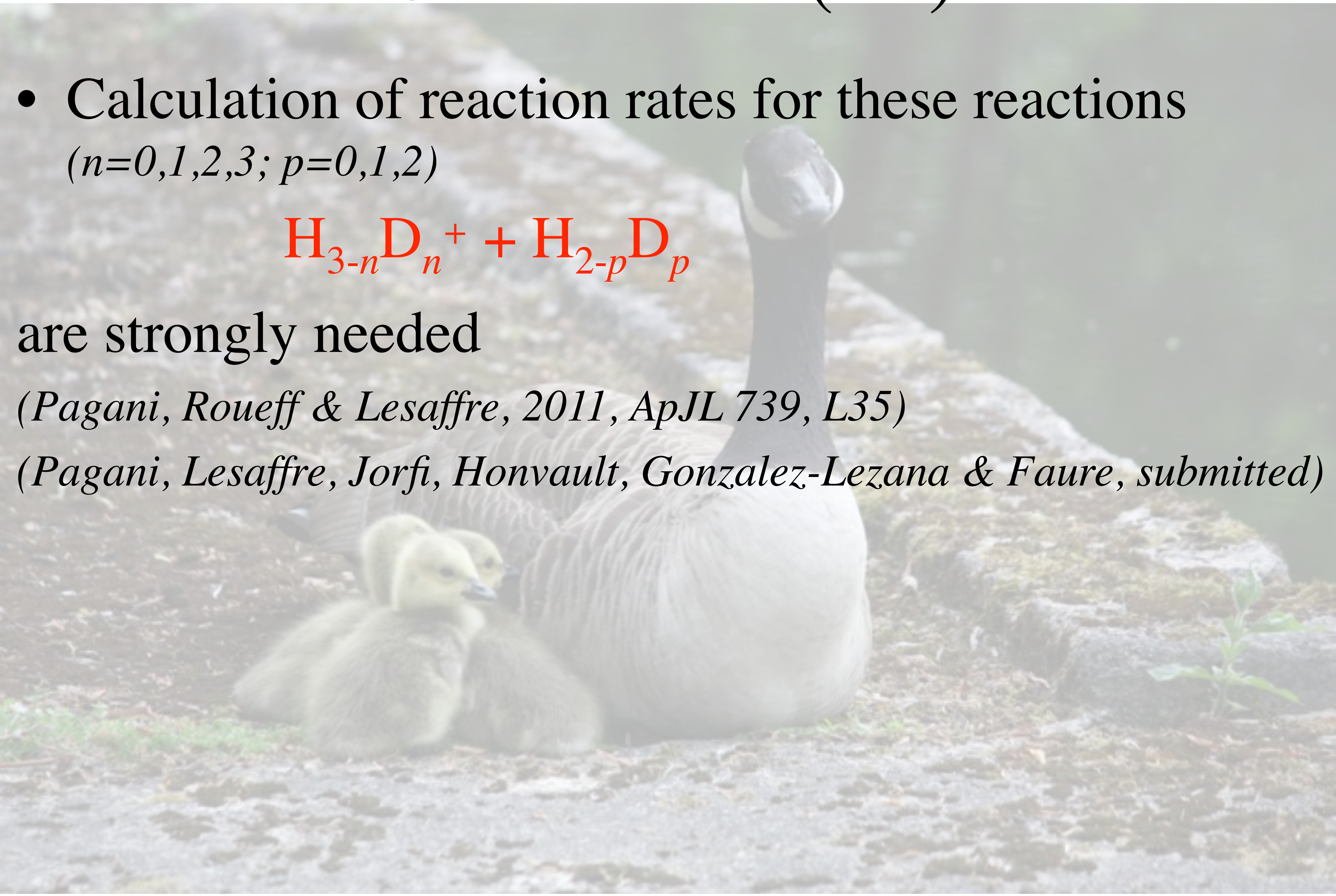
- Calculation of reaction rates for these reactions *(n=0,1,2,3; p=0,1,2)*

$$H_{3-n}D_n^+ + H_{2-p}D_p$$

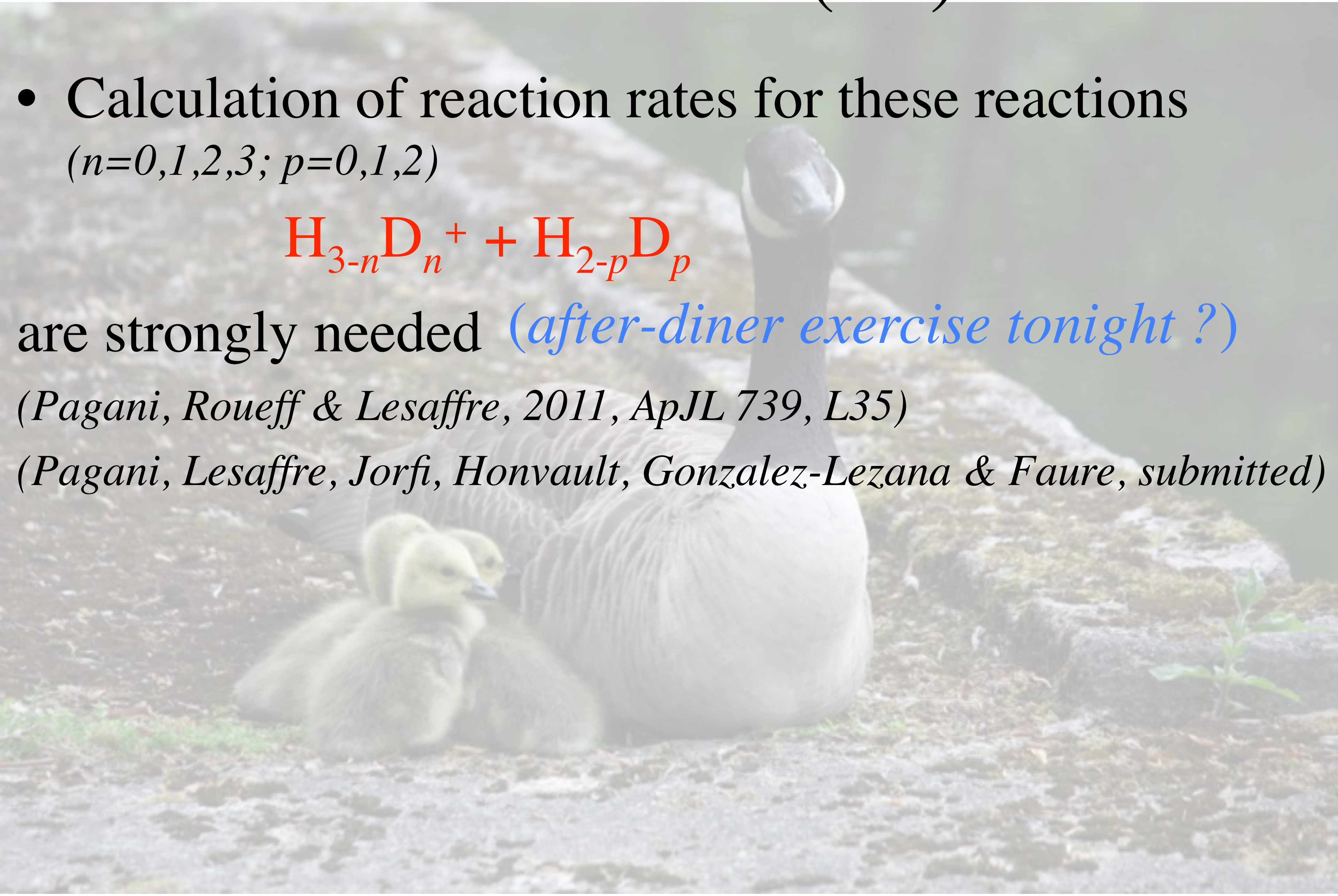
are strongly needed

(Pagani, Roueff & Lesaffre, 2011, ApJL 739, L35)

(Pagani, Lesaffre, Jorfi, Honvault, Gonzalez-Lezana & Faure, submitted)



Conclusions (2nd)



- Calculation of reaction rates for these reactions

  (n=0,1,2,3; p=0,1,2)

$$H_{3-n}D_n^+ + H_{2-p}D_p$$

are strongly needed *(after-diner exercise tonight ?)*

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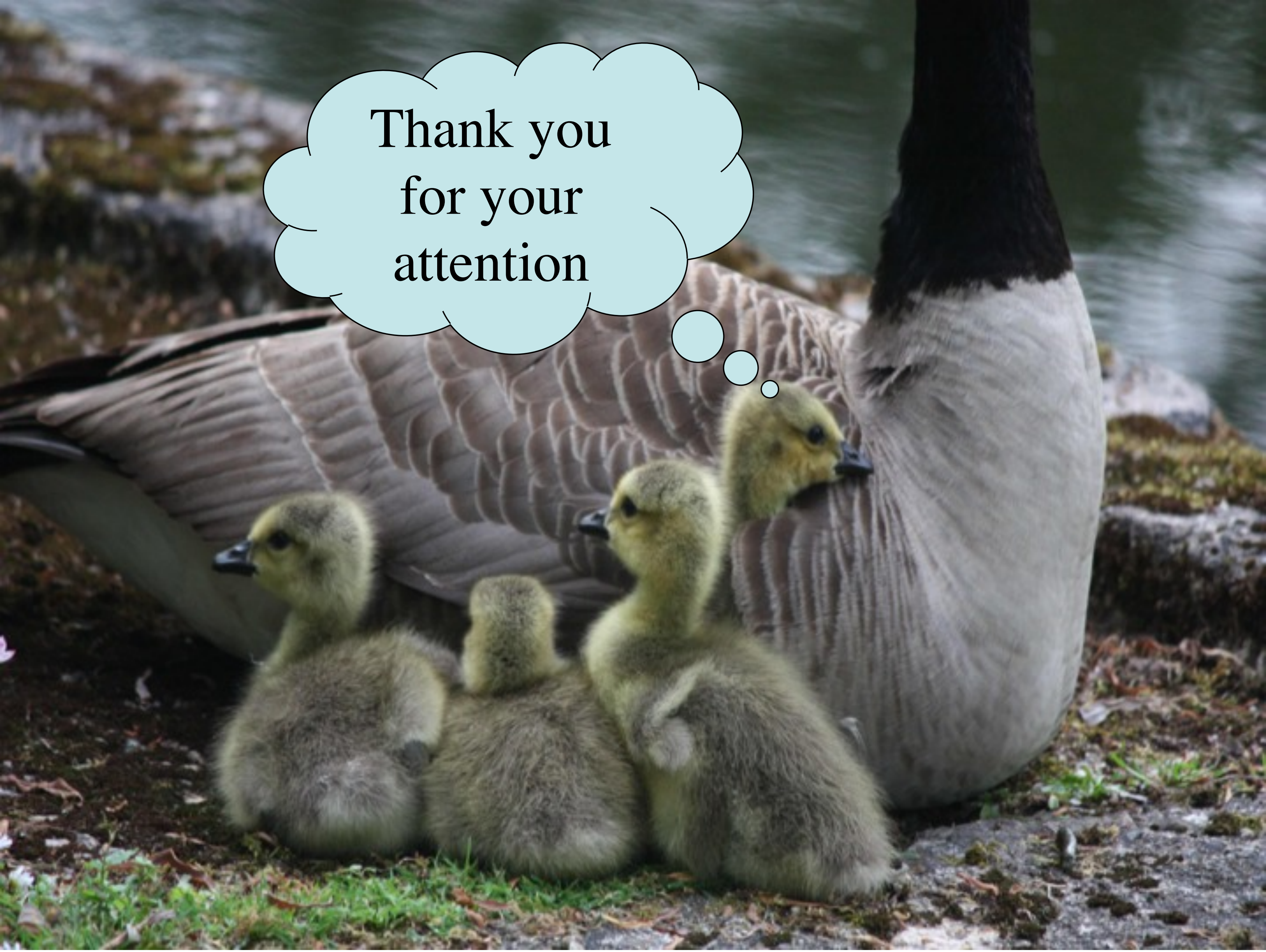
Thank you
for your
attention