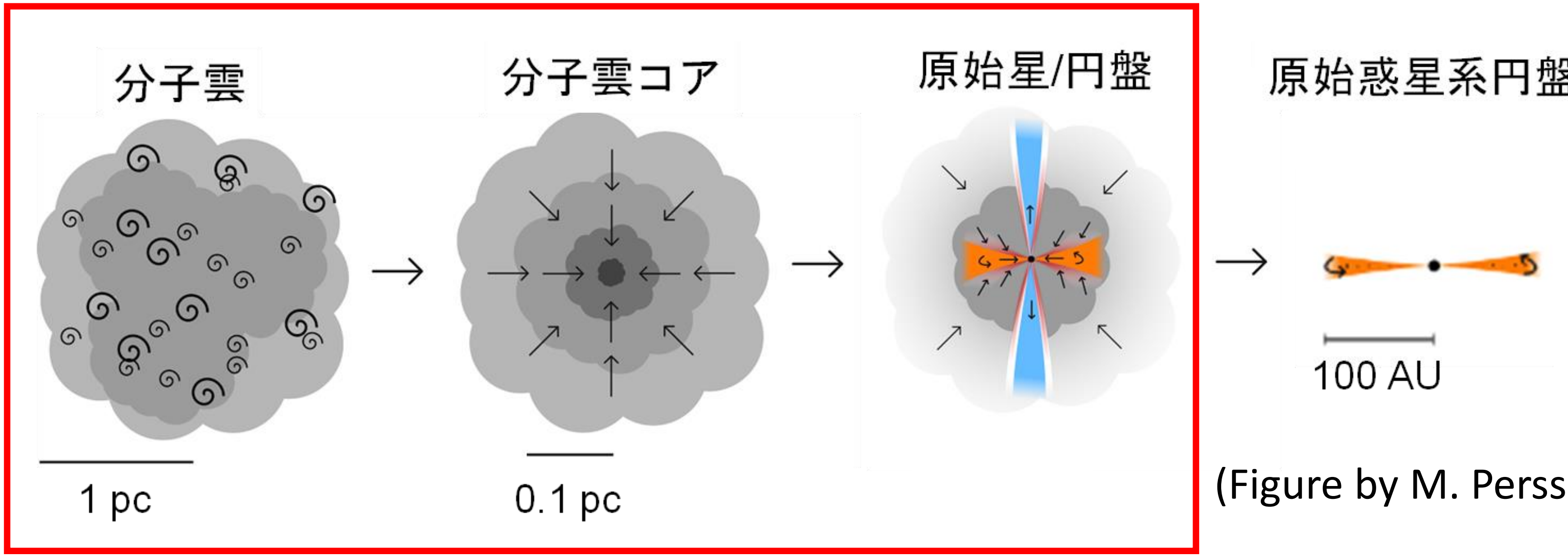
星･惑星系形成領域における
水の重水素比

古家健次
筑波大･計算科学研究センター

星・惑星形成過程

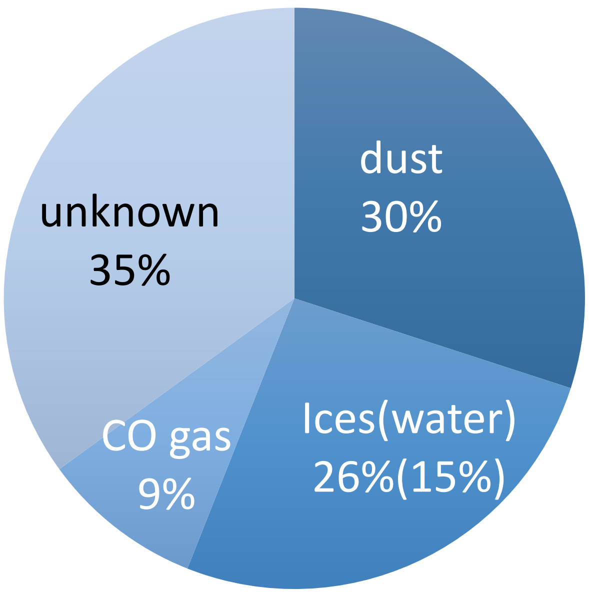


(Figure by M. Persson)

宇宙における水

- 分子雲に既にダストを覆う氷として豊富に存在 (Whittet+1983)
- 酸素の主要な形態 (~40 % of volatile oxygen)
- 星間氷・彗星氷の主成分
  → 惑星の材料物質
  地球の海・生命の起源

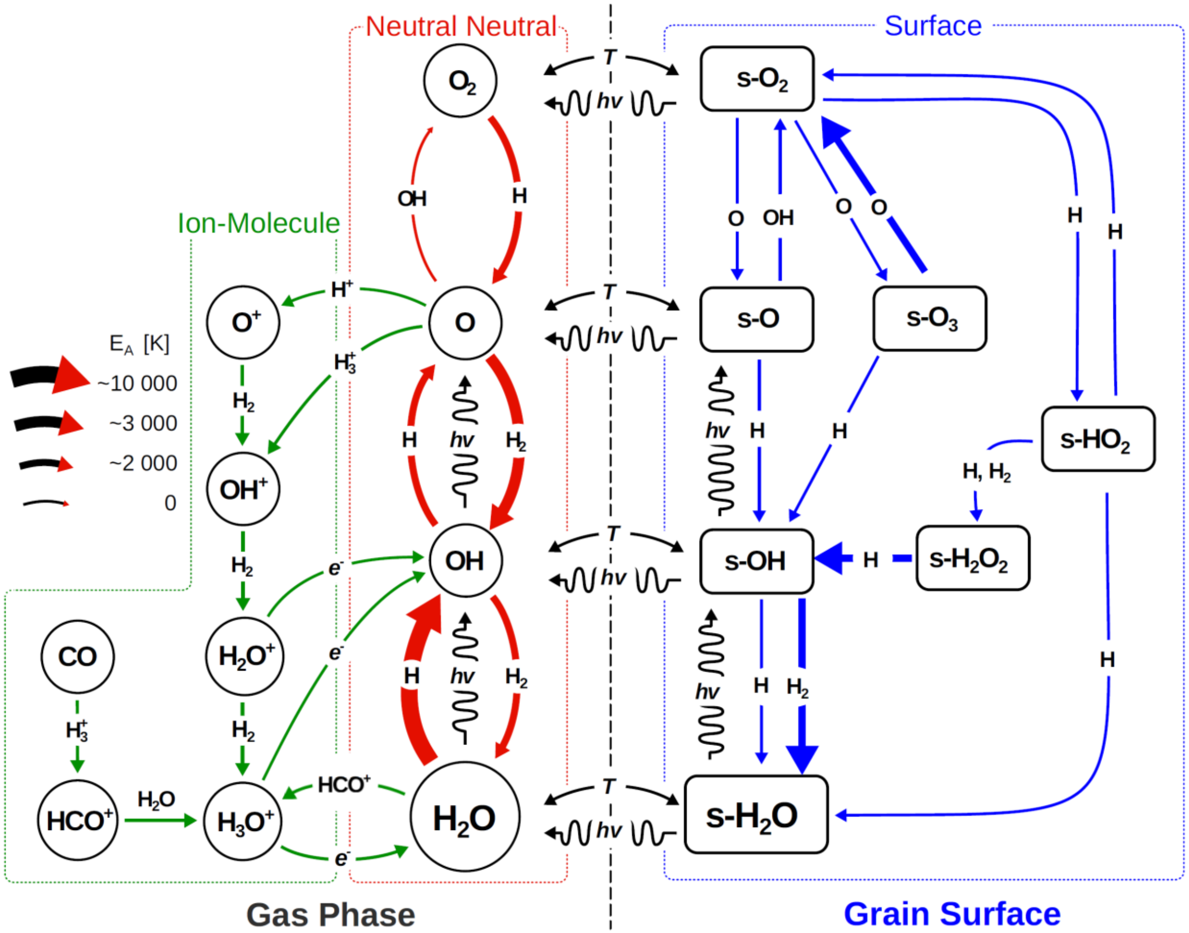
100% = 宇宙存在度[O/H]~10^{-3}



分子雲(コア)における
酸素の存在形態

(Whittet+ 2007)

Water chemistry: well studied



(van Dishoeck et al. 2013)

(Original ref. Jensen+2000; Miyauchi+2008; Ioppolo+2008; Oba+2012 and many others)

The formation of water on interstellar dust particles

prof. Ewine F. van Dishoeck, PhD, A.L.M. “Thanja” Lamberts, MSc

Universiteit Leiden
The Netherlands

Deuterium fractionation

➡ Probe of formation environments of molecules

- The [D/H] elemental ratio in the local ISM ~ 10^{-5} (Linsky 2003)

- Molecules formed at low temperatures, XD/XH >> 10^{-5}

(e.g., Watson+1976; Tielens 1983)

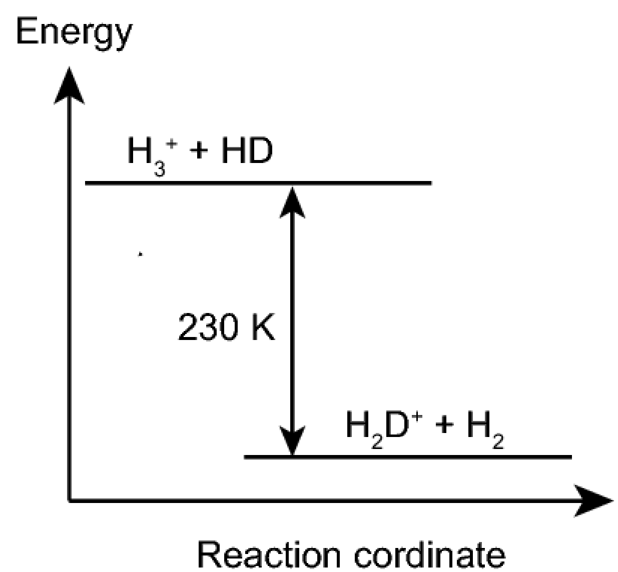
$$H_3^+ + HD \underset{\cancel{\longleftarrow}}{\longrightarrow} H_2D^+ + H_2 + 230\ \mathrm{K}$$

➡ $H_2D^+/H_3^+ >> 10^{-5}$

$$H_2D^+ + e \rightarrow D + H_2$$

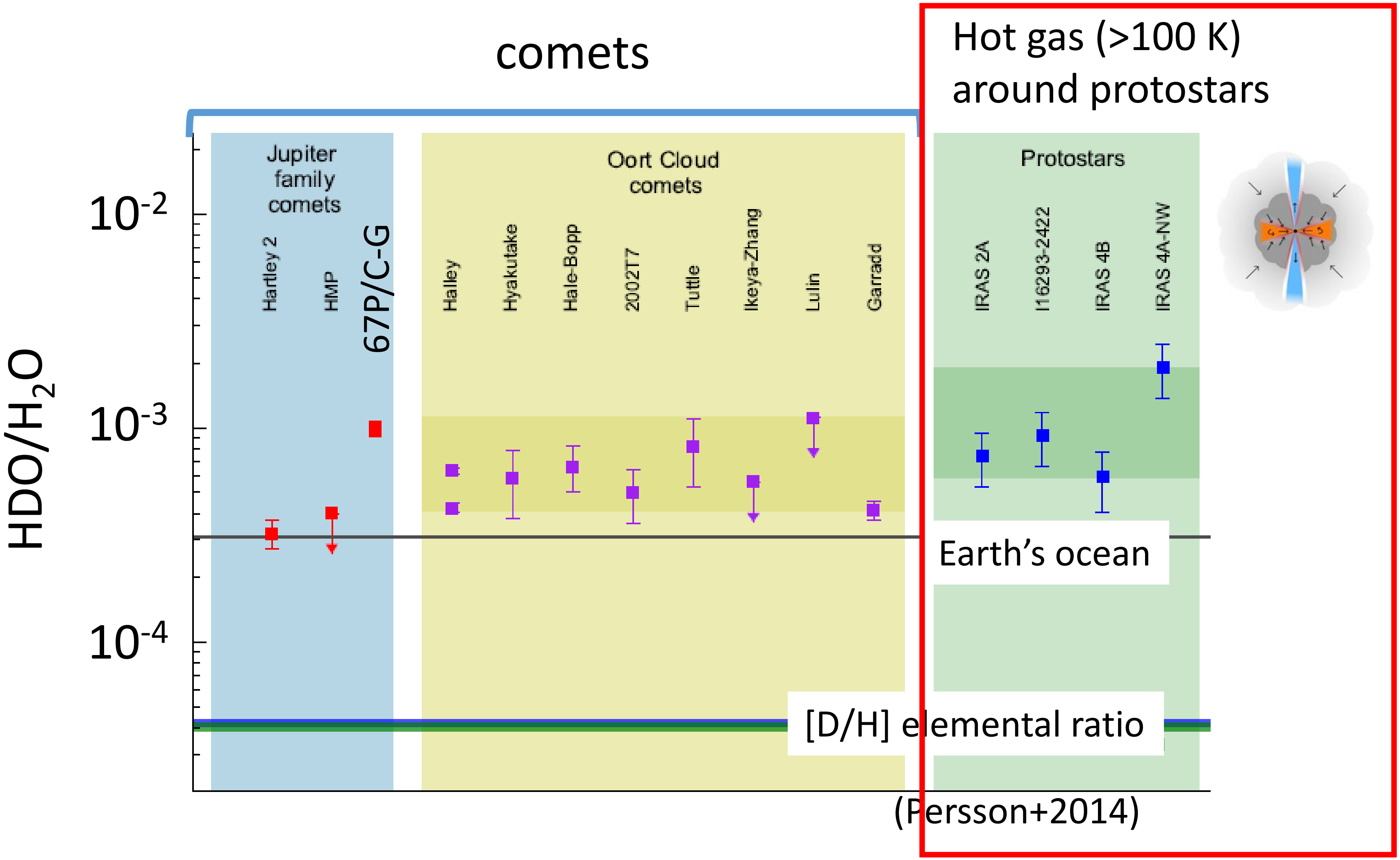
➡ High atomic D/H

➡ High D/H in Icy molecules



- CO freeze-out, higher density, lower H_2 o/p
  → enhanced deuterium fractionation

HDO/H_2O observations



- Water is enriched in deuterium

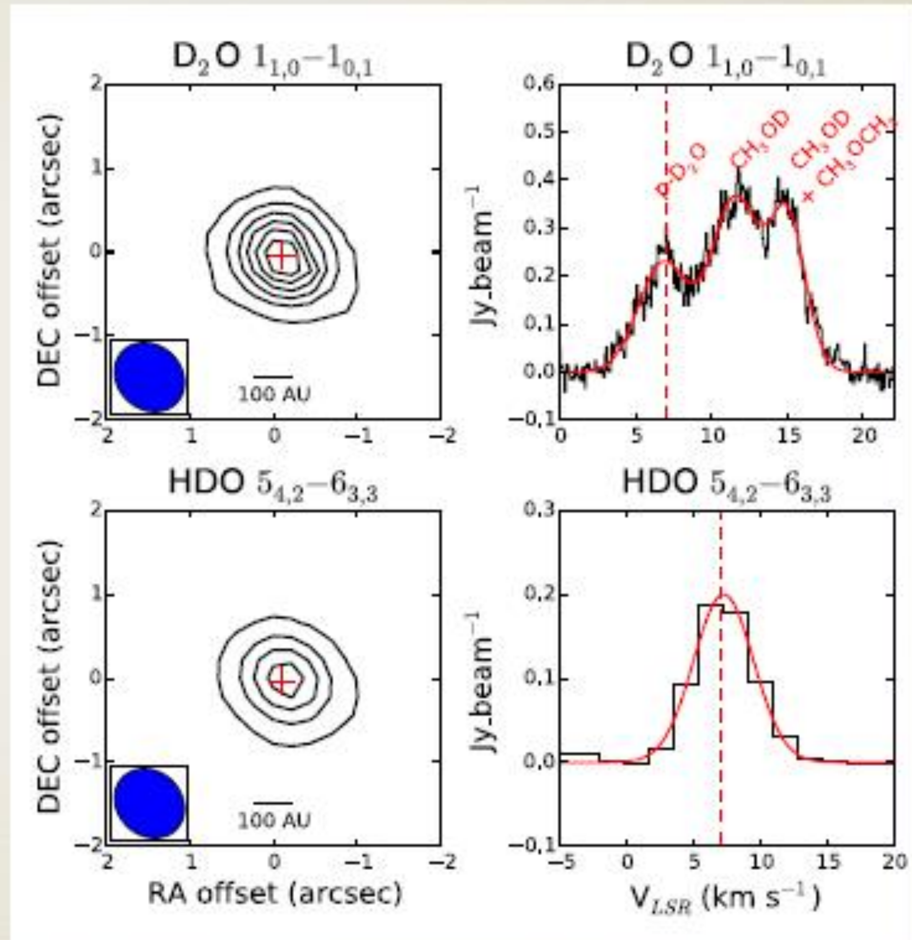
Detection of D_2O in the inner region of a solar-type protostar

- First interferometric detection of D_2O towards the Class 0 protostar NGC1333 IRAS2A with the PdBI (Coutens et al. 2014)

- LTE modeling (HDO, D_2O, $H_2{}^{18}O$)

- $D_2O/HDO \sim 1.2 \times 10^{-2}$
- $HDO/H_2O \sim 1.7 \times 10^{-3}$

$\boxed{D_2O/HDO \sim 7 \times HDO/H_2O}$



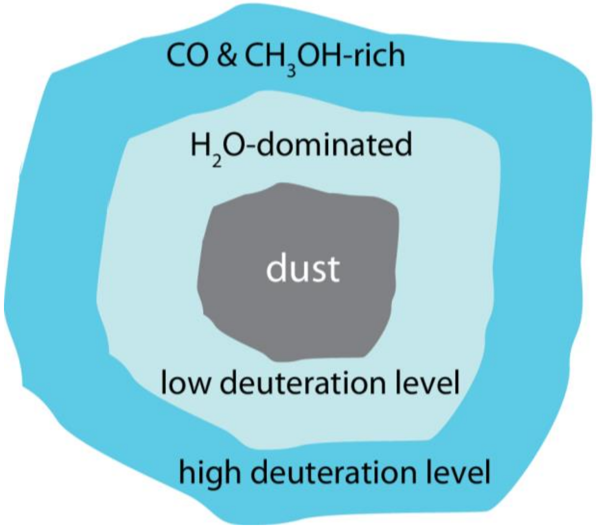
(別の1天体も同様な傾向)

Coutens et al. (2014, ApJL)

Slide of Audrey Coutens

小質量原始星周りの
高温ガス(>100 K)の観測

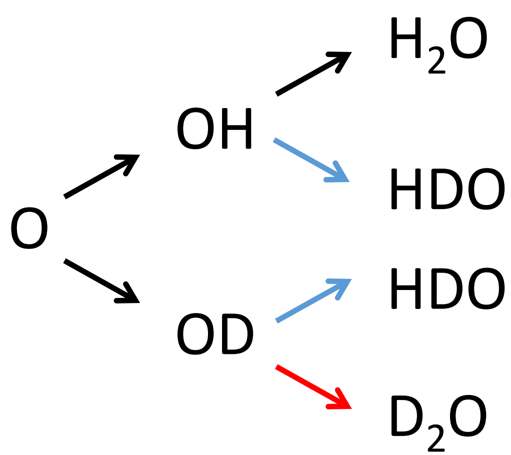
$$\frac{D_2O}{HDO} \sim 7\frac{HDO}{H_2O}$$



原始星周りのガス組成から
星形成前に生成された氷の層構造の推定が可能

Constant atomic D/H case

i.e., assumes quasi-steady state



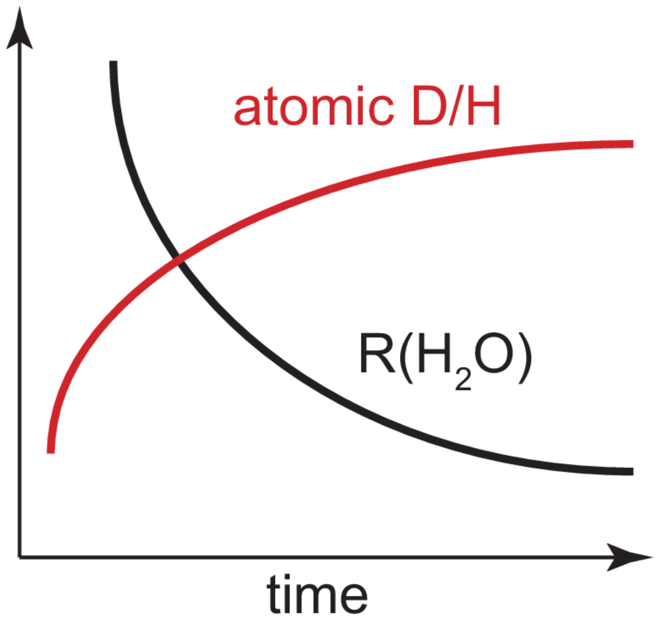
$$\frac{D_2O}{HDO} \leqq \frac{1}{4}\frac{HDO}{H_2O}$$

(e.g., Roberts&Charnley 2002; Oba+2012,2014)

contradicts with the observational relation $\frac{D_2O}{HDO} \sim 7\frac{HDO}{H_2O}$

→ time-dependency of the atomic D/H

Let's consider chemical evolution



$R(HDO) \propto R(H_2O)*(\text{atomic D/H})$

$R(D_2O) \propto R(H_2O)*(\text{atomic D/H})^2$

→Production rates of HDO and D_2O do not necessarily follow that of H_2O

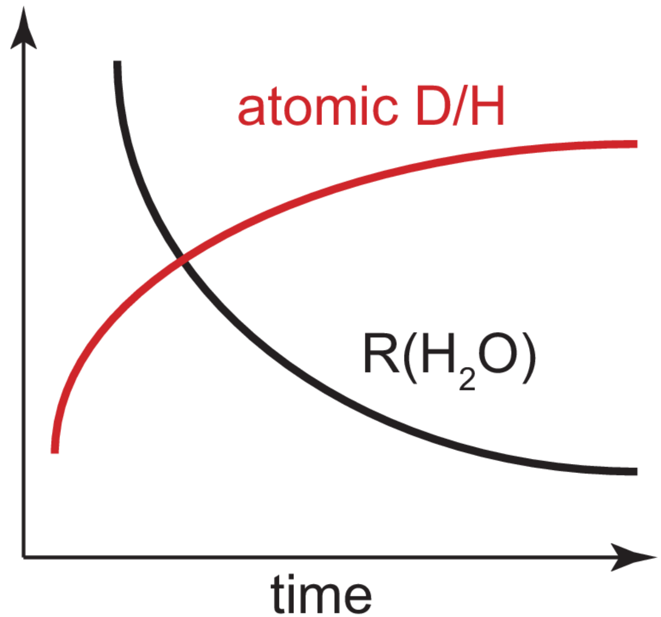
If the production of HDO and D_2O are dominated in late times

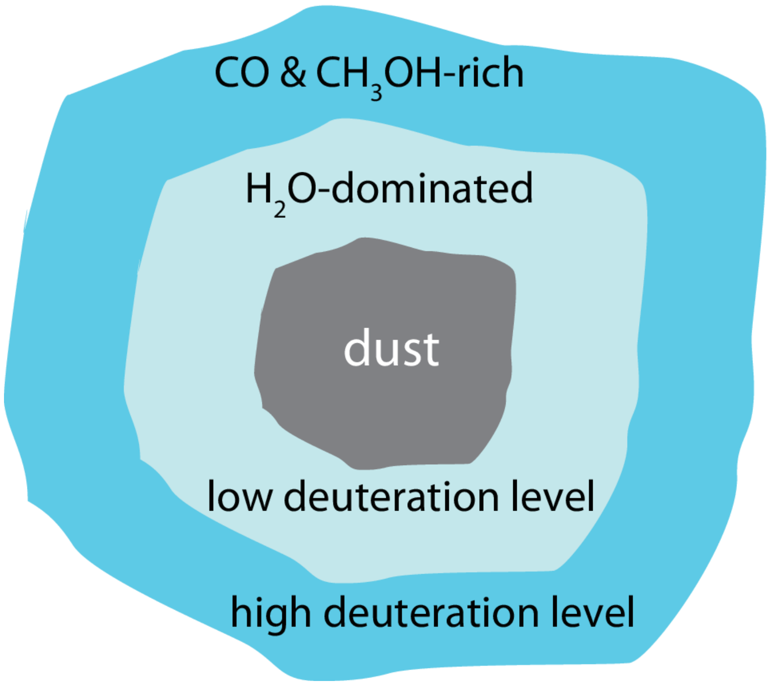
D_2O/HDO in the whole ice ~ atomic D/H in late times

HDO/H_2O in the whole ice << atomic D/H in late times

$$\frac{D_2O}{HDO} \gg \frac{HDO}{H_2O}$$

Let's consider chemical evolution





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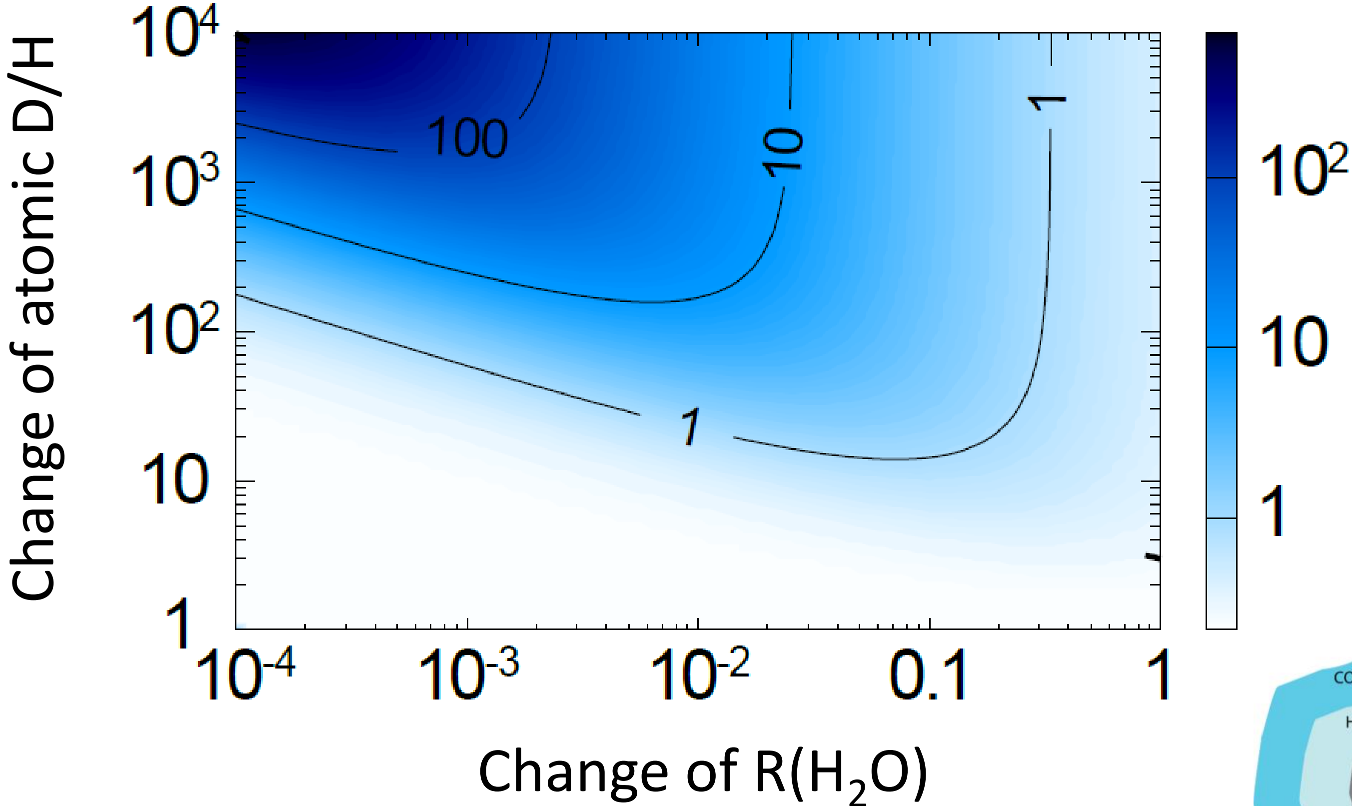
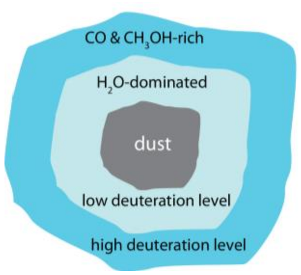
Required conditions for reproducing the observations



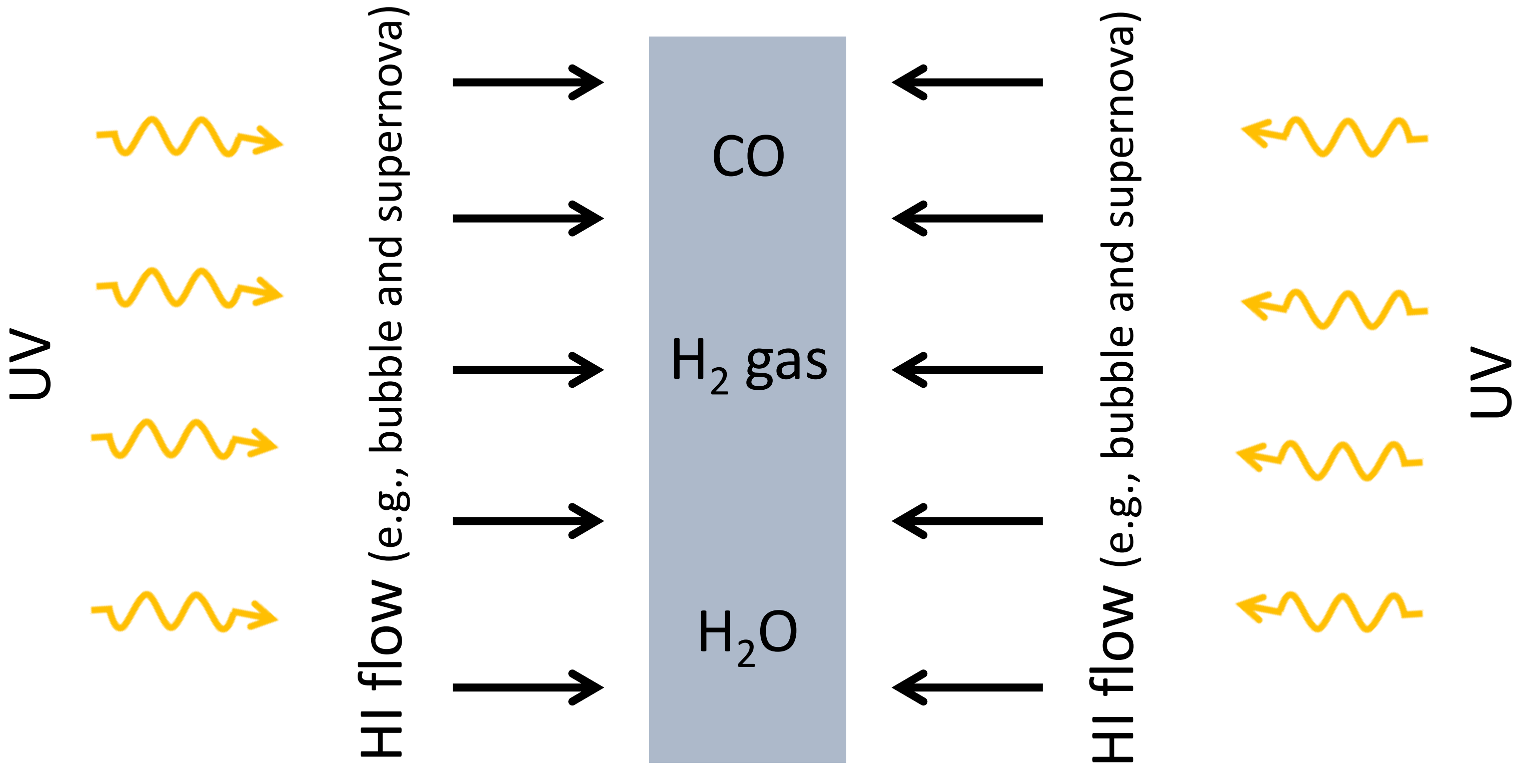


(i) drop of $R(H_2O)$ by a factor of >10

(ii) enhancement of the atomic D/H by a factor of >100

→ very inhomogeneous

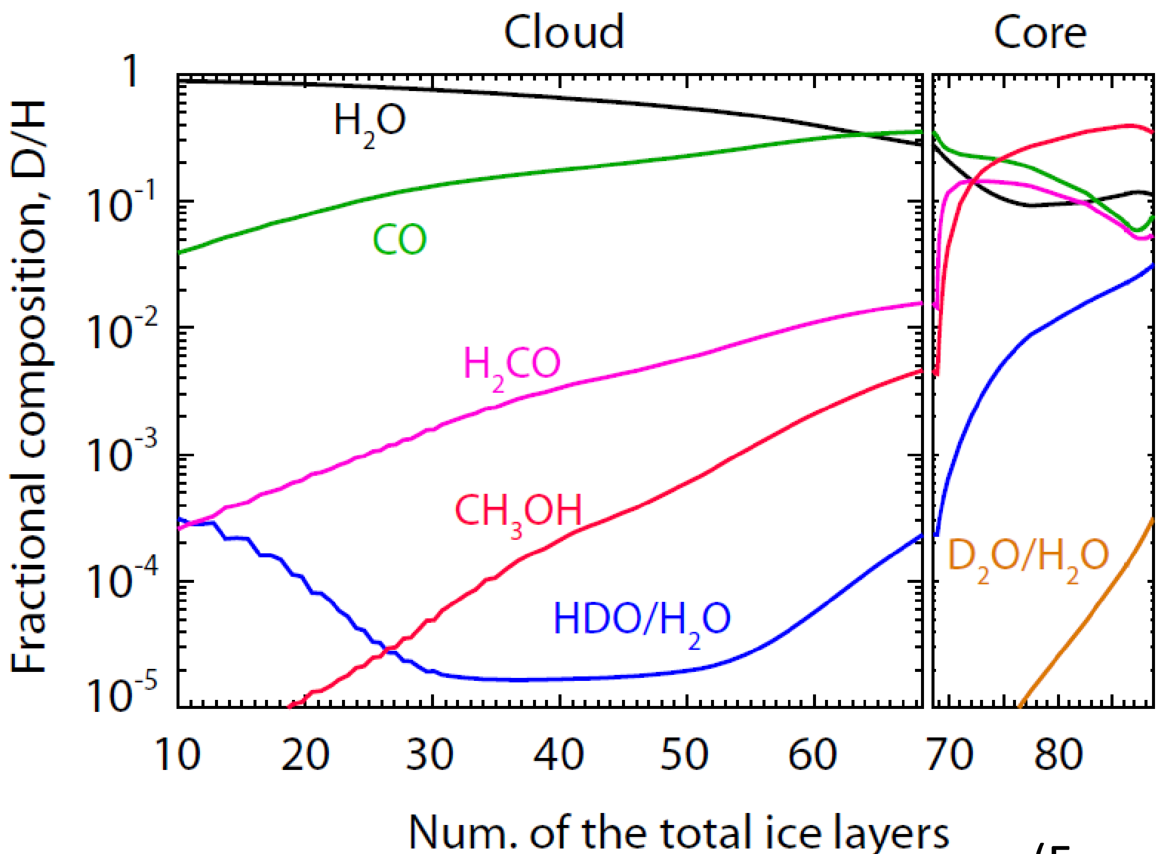
Molecular cloud formation



Accumulation of HI gas by accretion flows
→ molecular cloud formation

(e.g., Hartmann+2001; Inoue&inutsuka 2012)

Ice layered structure



(Furuya+2015,2016)

- 1D shock model + gas-ice chemical model

まとめ

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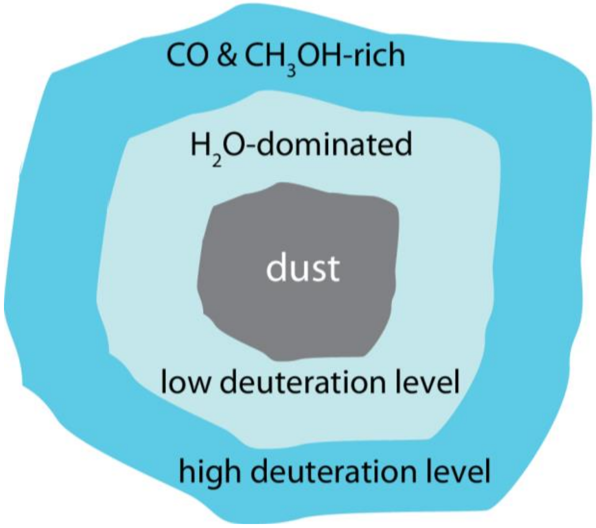

原始星周りのガス組成から
星形成前に生成された氷の層構造の推定が可能