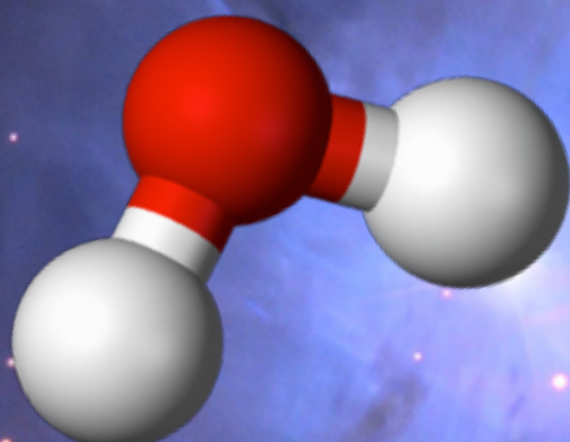
The HDO/H_2O and D_2O/HDO ratios in solar-type protostars



Audrey COUTENS
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Deuterium fractionation

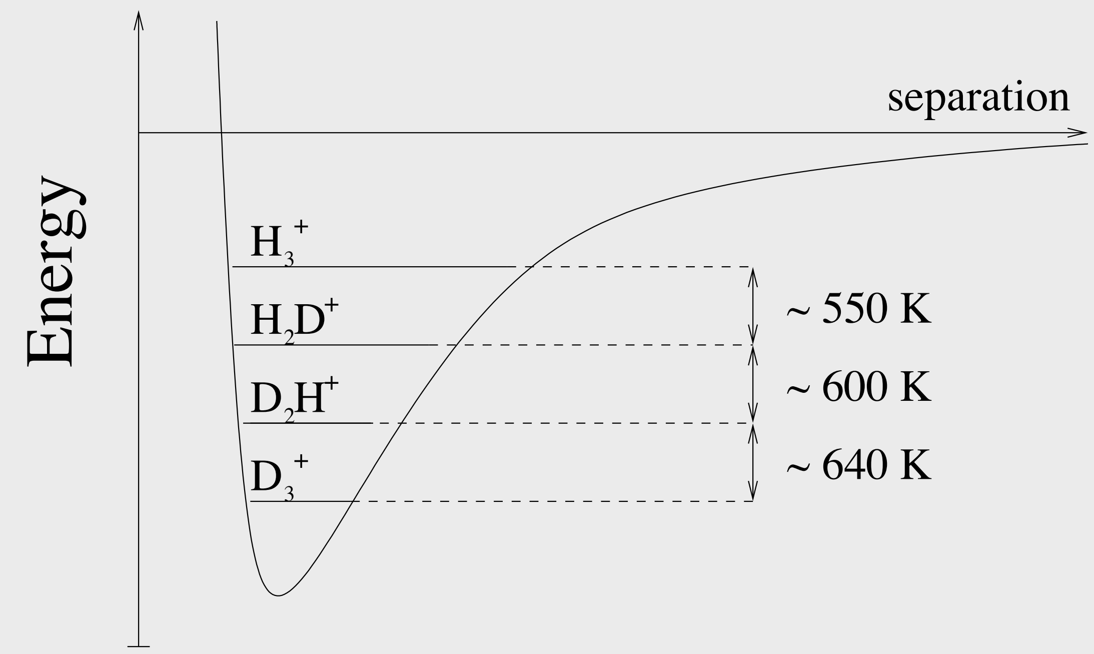
- High deuterium fractionation observed in low-mass protostars

- Main chemical reactions extracting D from HD (main D reservoir in dense regions):

$$\boxed{H_3^+ + HD \longrightarrow H_2D^+ + H_2 + \Delta E_3}$$

$$CH_3^+ + HD \longrightarrow CH_2D^+ + H_2 + \Delta E_4$$

$$C_2H_2^+ + HD \longrightarrow C_2HD^+ + H_2 + \Delta E_5$$



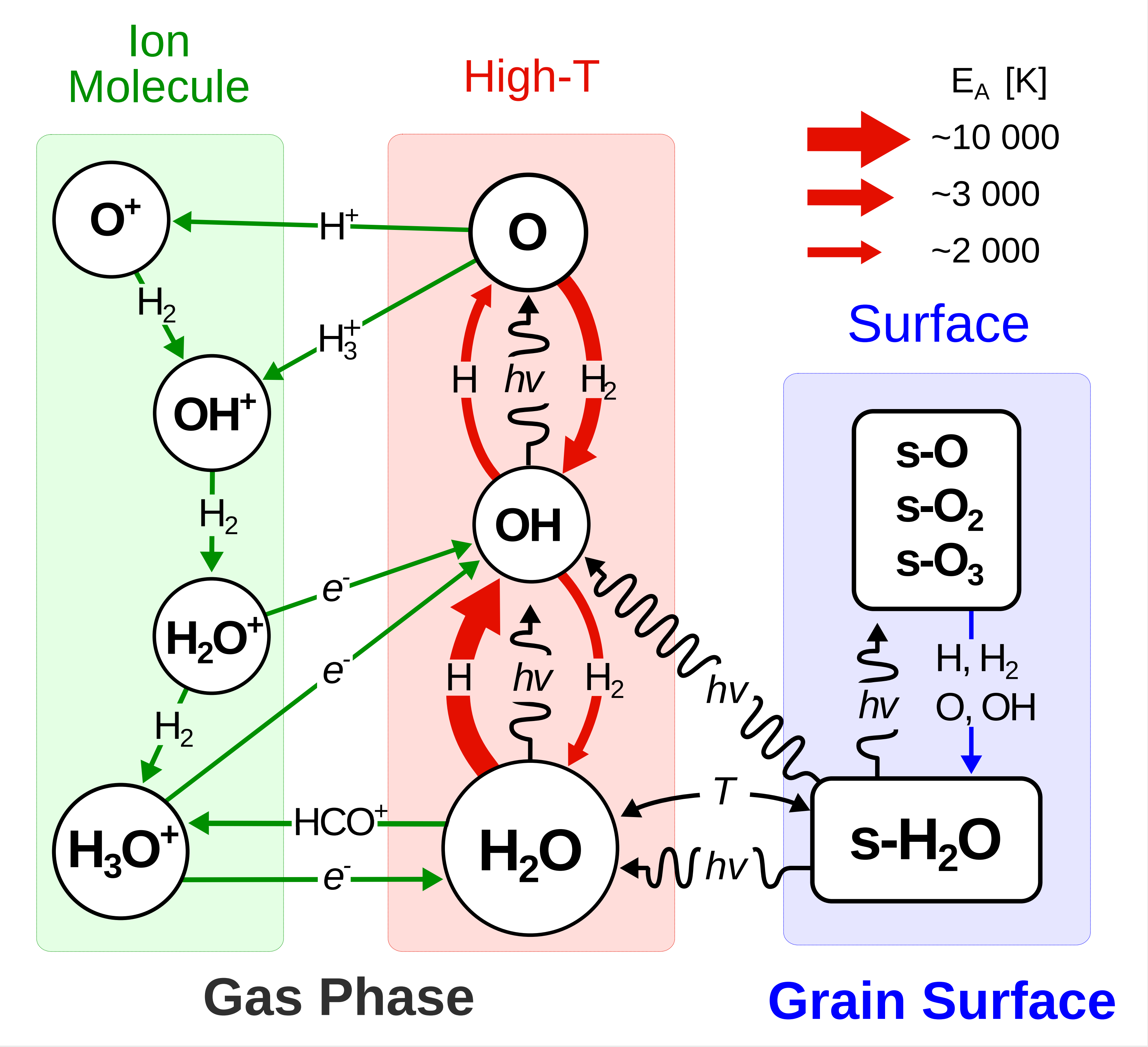
Cold regions (10-20 K) : backwards reactions not efficient despite the high H_2 abundance

- Subsequent reactions will deuterate more and more molecules.

- Atomic D/H ratio increases in the gas phase and consequently the deuterium fractionation of molecules formed on the grain surfaces increases

Deuterium fractionation sensitive to formation conditions (*T*, *n*)

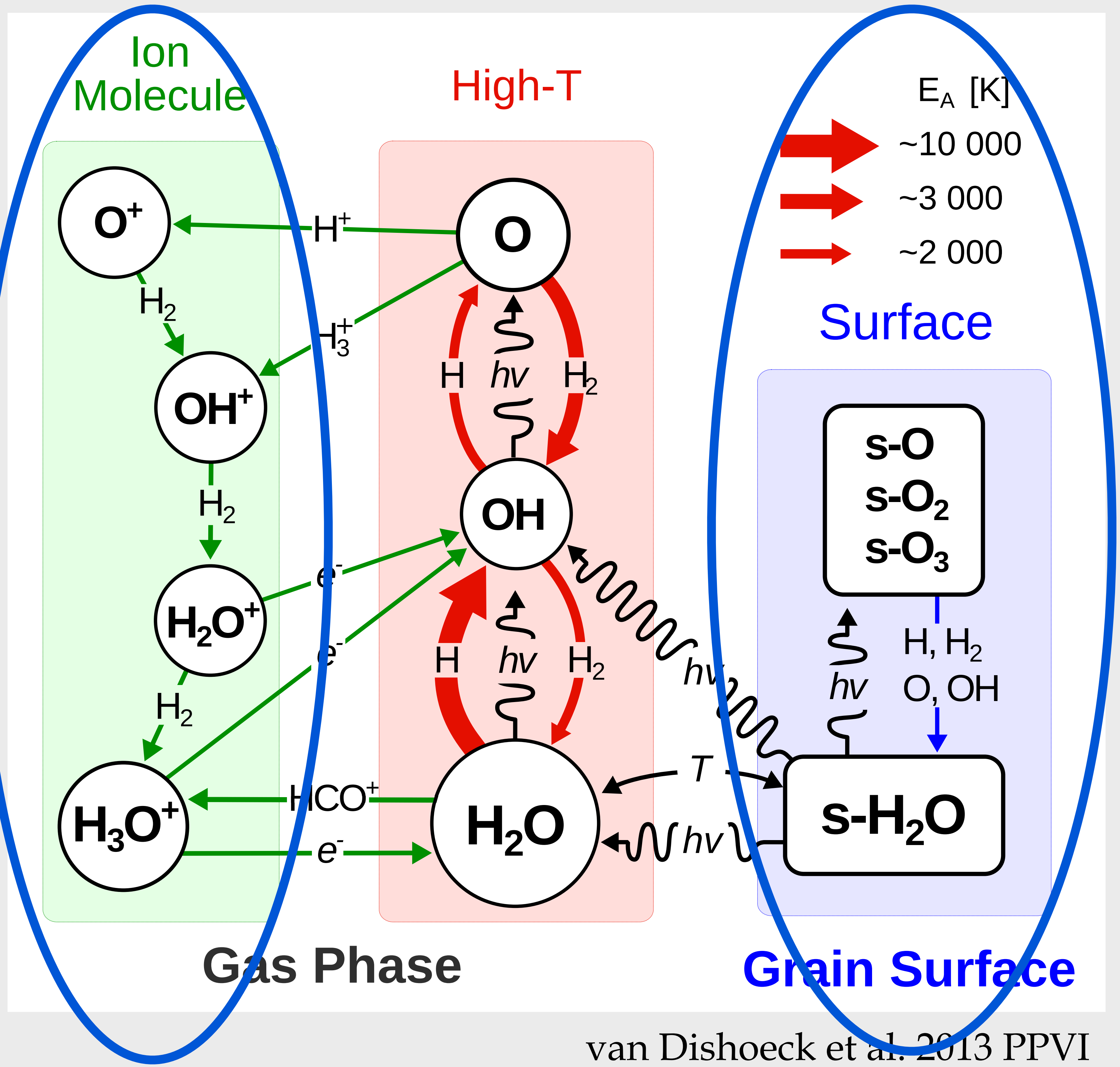
Water deuterium fractionation



van Dishoeck et al. 2013 PPVI

Water deuterium fractionation

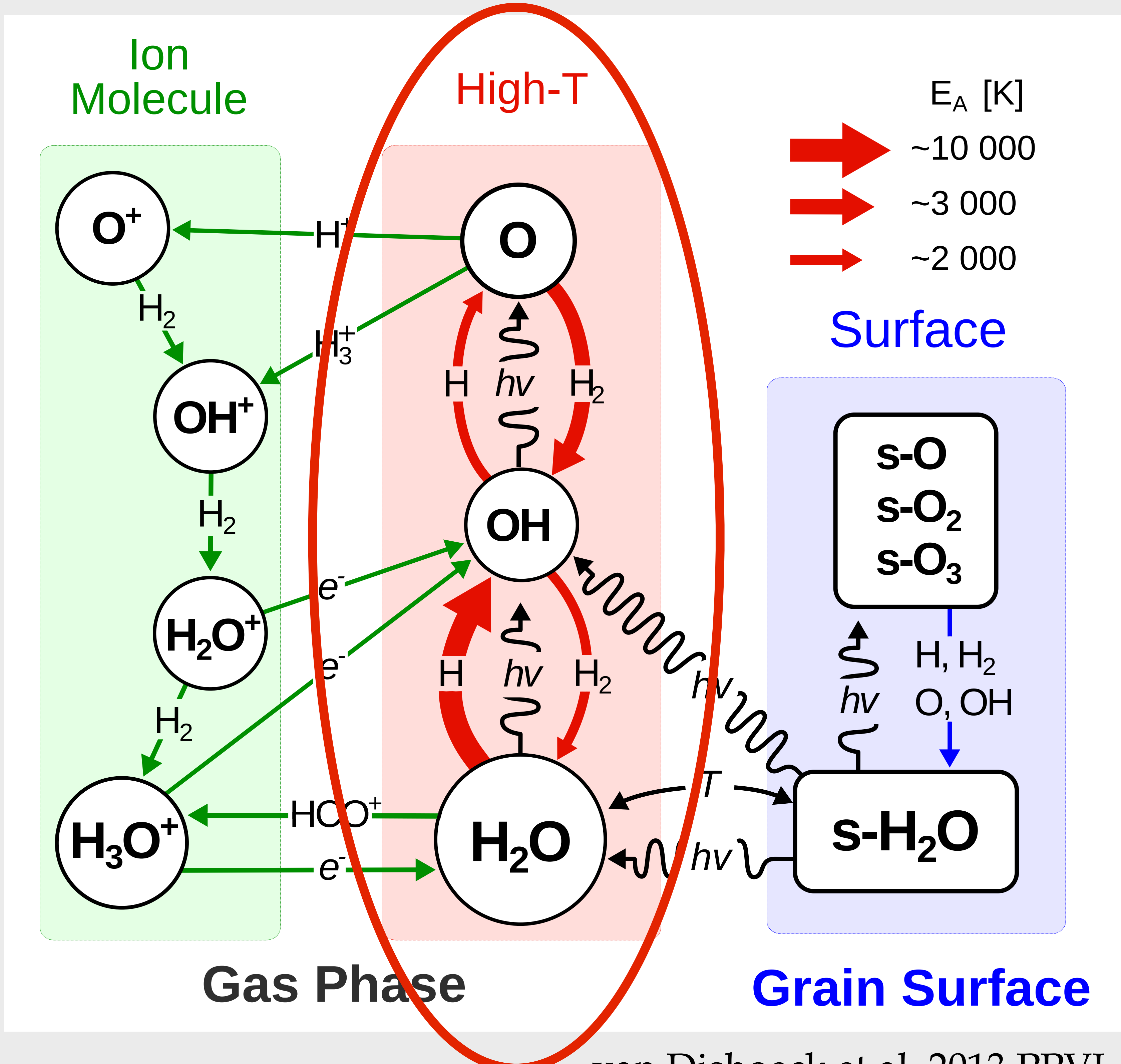
High water D/H ratios



High water D/H ratios

van Dishoeck et al. 2013 PPVI

Water deuterium fractionation



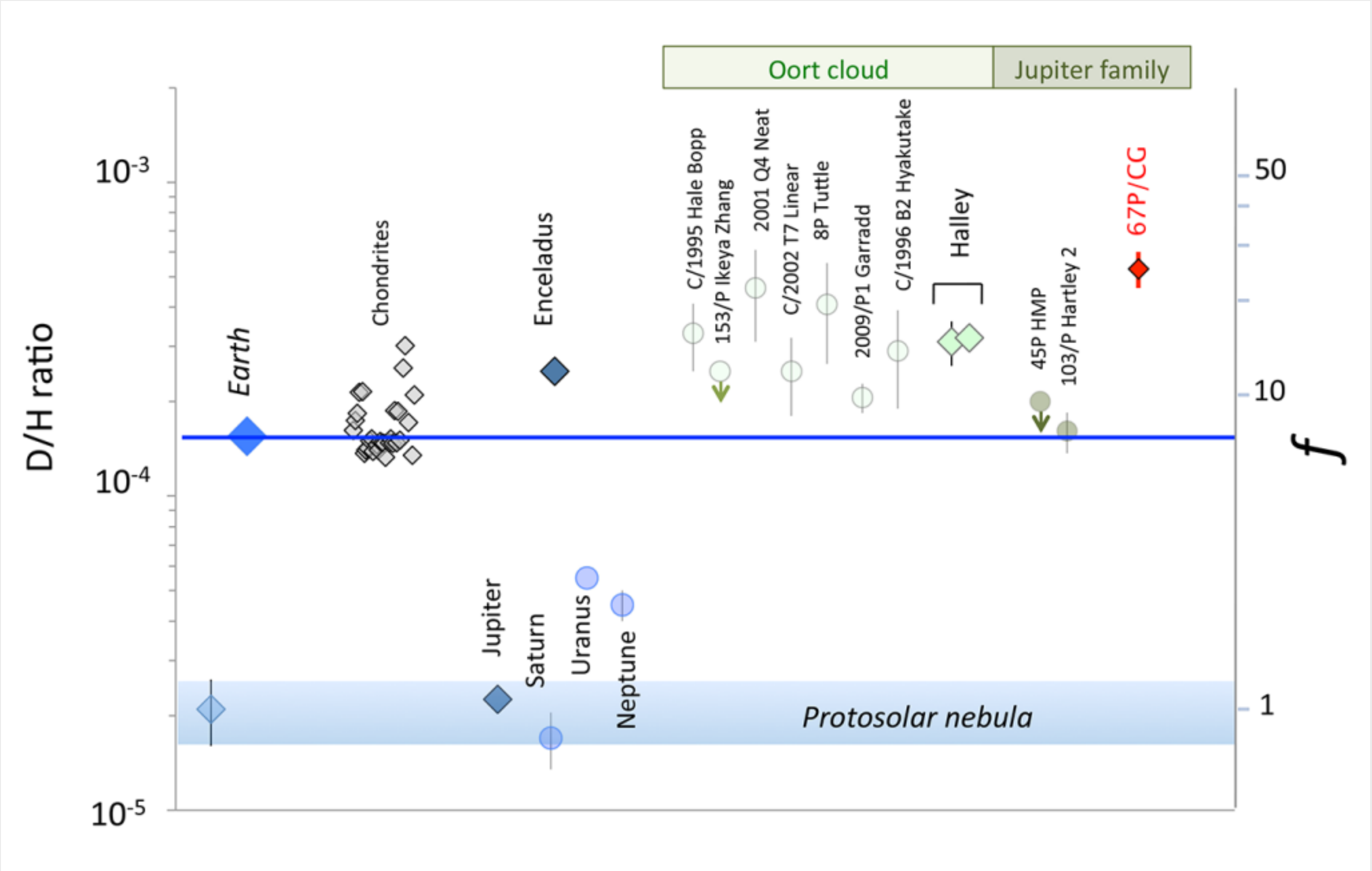
Low water D/H ratios

van Dishoeck et al. 2013 PPVI

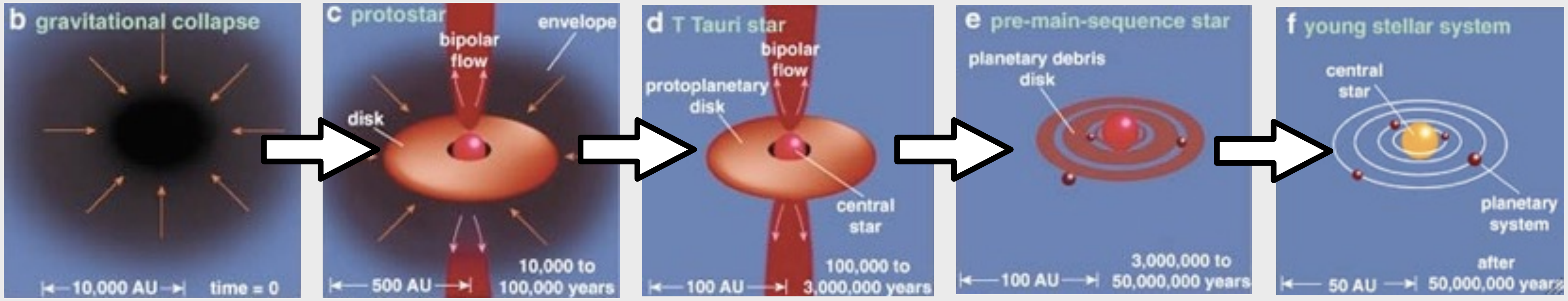
Origin of terrestrial water

Delivery of water on Earth by comets and/or asteroids through impacts

- **Where does the water contained in comets and asteroids come from?**
- **How and when did this water form?**

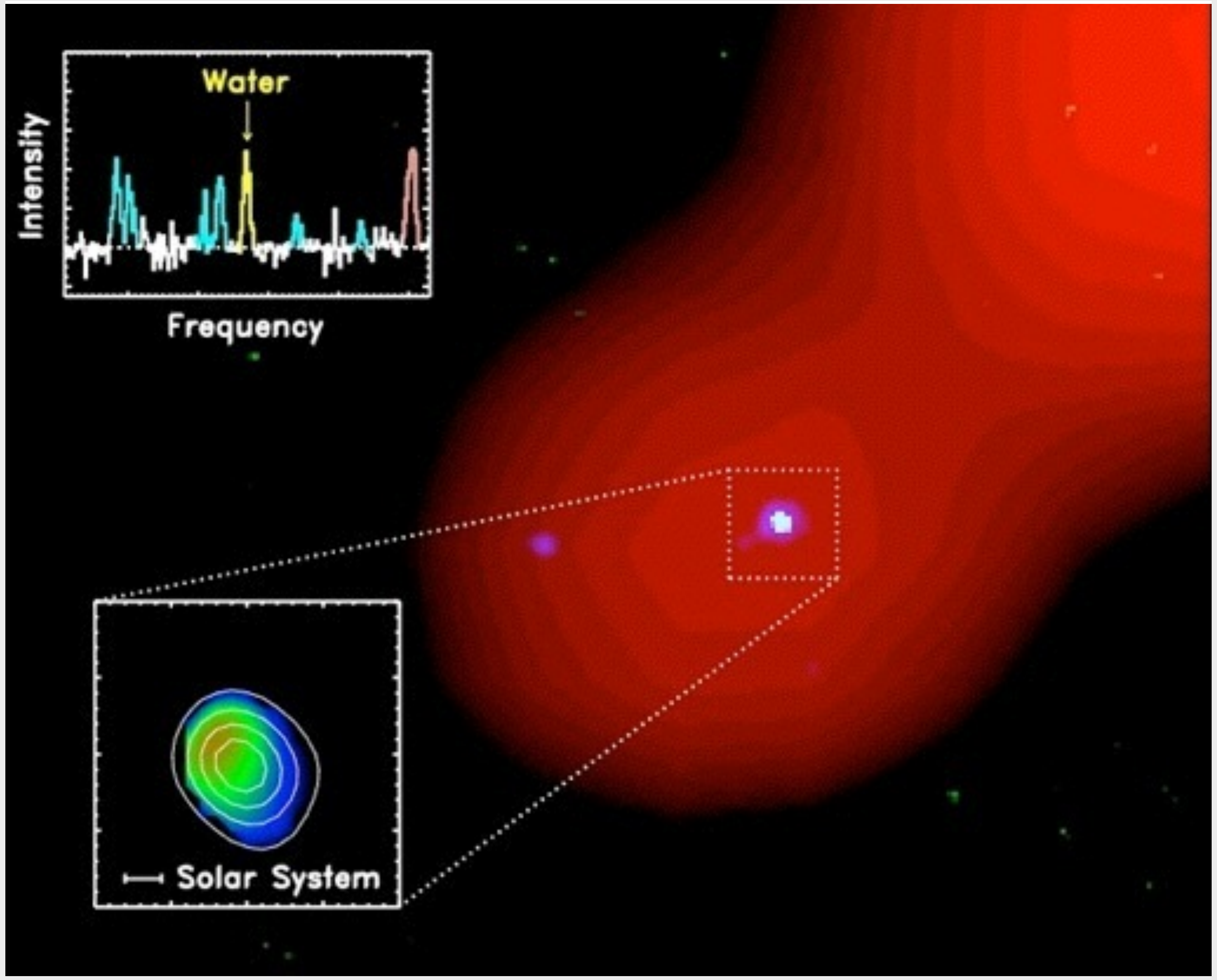


Altwegg et al. 2015



Spitzer Science Center IR Compendium

Detection of water in the inner regions of solar-type protostars



Jørgensen & van Dishoeck (2010)

First spatially and spectrally resolved image of water vapor around a **Class 0 protostar** (NGC 1333 IRAS 4B) through millimeter wavelength observations of the **$H_2{}^{18}O$ isotopologue** with the PdBI (Jørgensen & van Dishoeck 2010)

Compact emission
consistent with thermal desorption of the icy grain mantles
in the warm inner region of the protostar (T > 100 K)

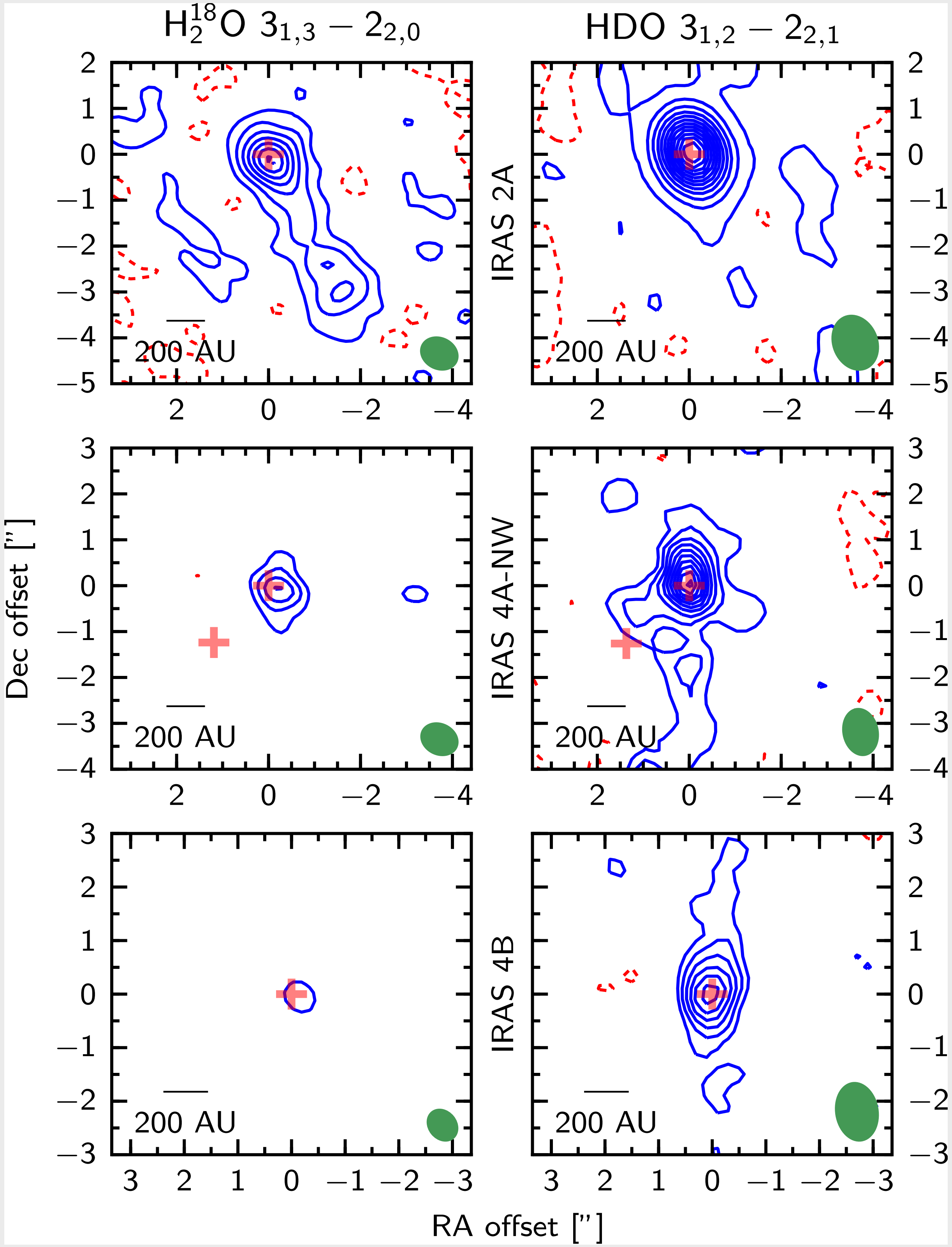
HDO in the inner regions of solar-type protostars

- HDO detected in the warm inner regions of Class 0 protostars (Codella et al. 2010, Persson et al. 2013, 2014, Taquet et al. 2013, Coutens et al. 2014) with interferometers

- Compact emission as seen for $H_2{}^{18}O$

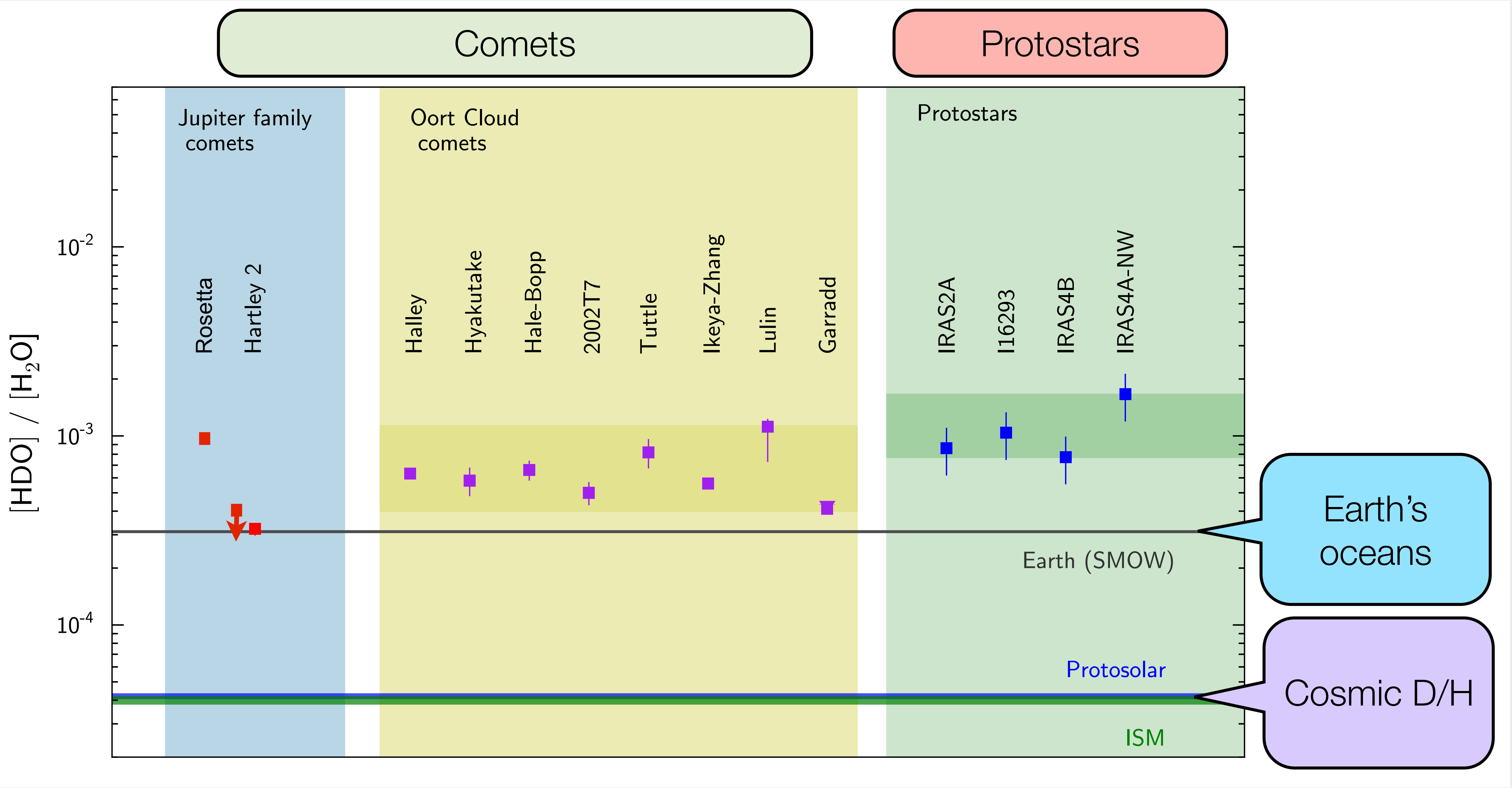
- Assuming $H_2{}^{16}O/H_2{}^{18}O \sim 500$ (Solar System value)

- LTE modeling used to derive the HDO/H_2O ratio



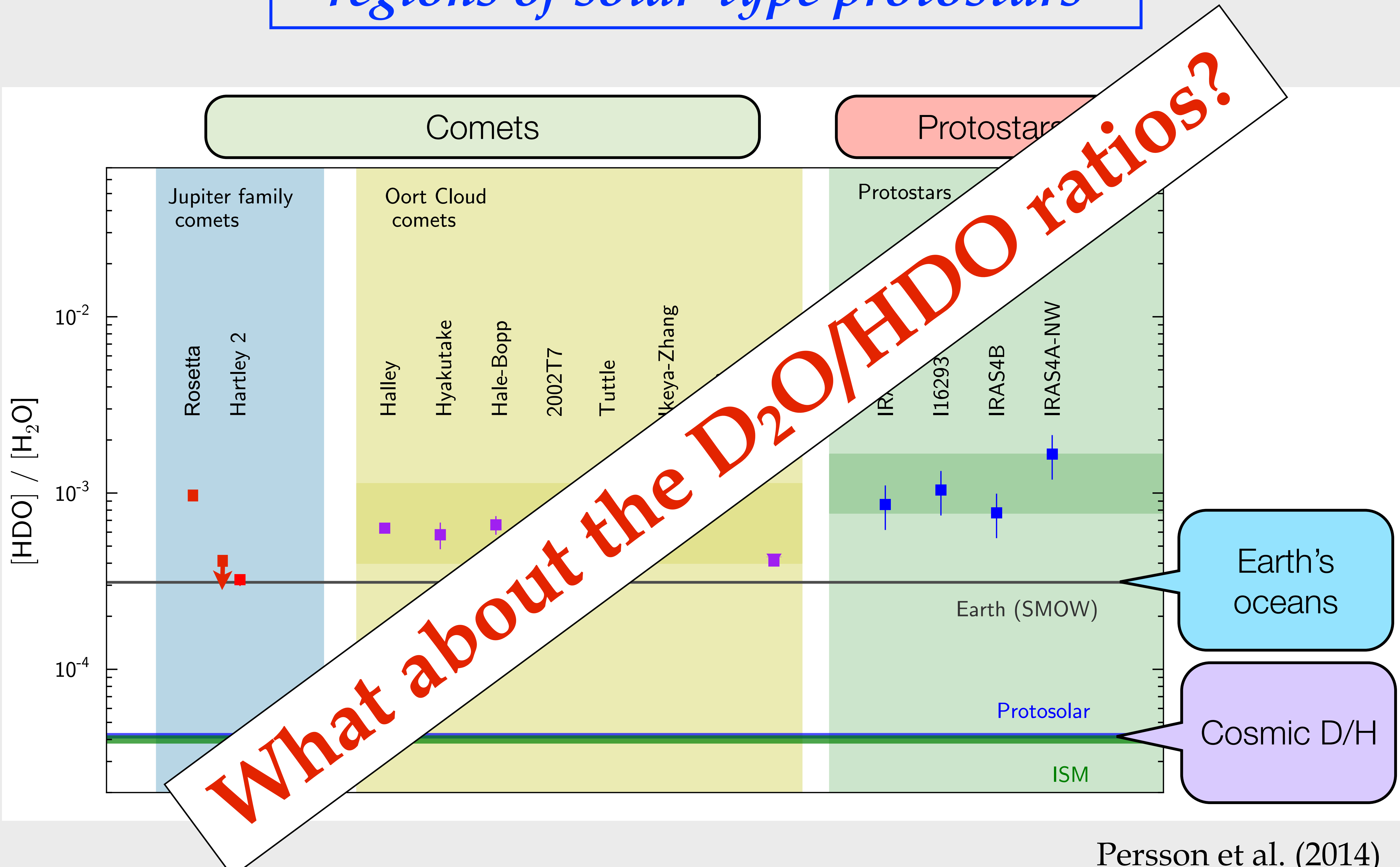
Persson et al. (2014)

The HDO/H_2O ratios in the inner regions of solar-type protostars



Persson et al. (2014)

The HDO/H_2O ratios in the inner regions of solar-type protostars



Persson et al. (2014)

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)

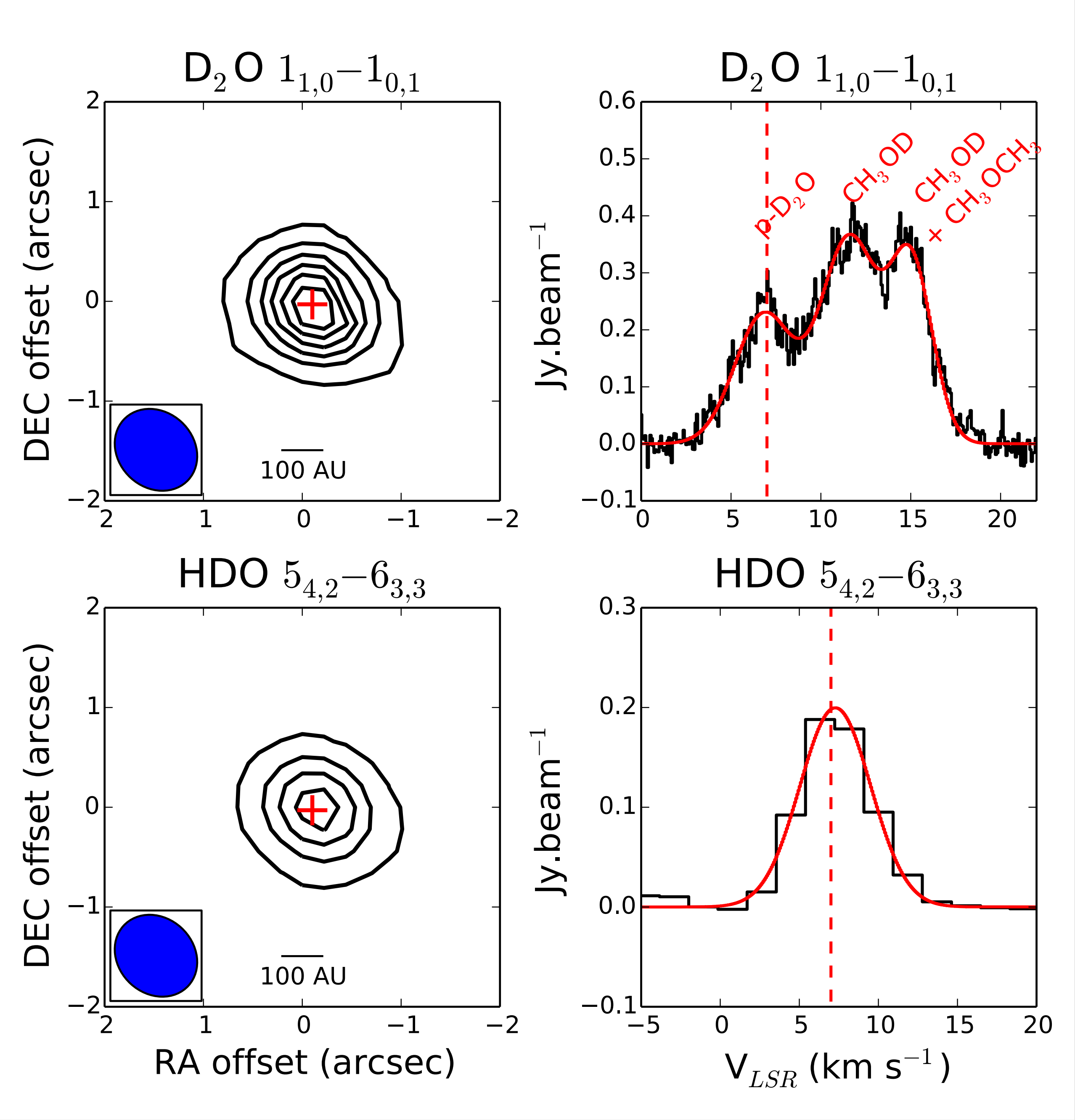
- LTE modeling (HDO, D_2O, $H_2^{18}O$)

- D_2O/HDO ~ 1.2×10^{-2}
- HDO/H_2O ~ 1.7×10^{-3}

D_2O/HDO ~ 7 × HDO/H_2O

<u>Expectations :</u>
- *Statistically*

D_2O/HDO ~ 1/4 × HDO/H_2O
- *Surface grain chemical models also predicted* D_2O/HDO ≲ HDO/H_2O



Coutens et al. (2014, ApJL)

Is $D_2O/HDO > HDO/H_2O$ common in low-mass protostars?

- ALMA program accepted to study water deuteration in the low-mass protostar IRAS 16293-2422 (binary source, A and B)

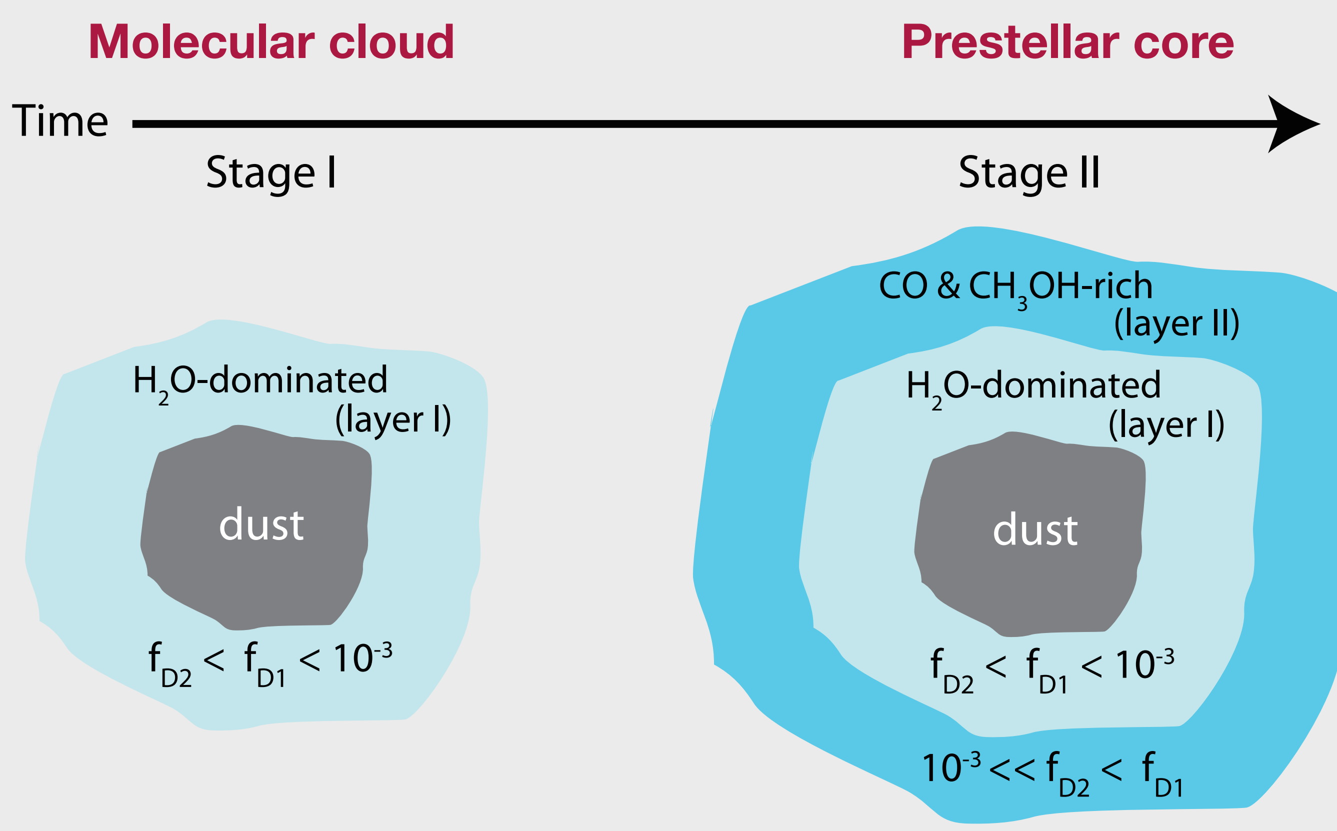
→ observations of several HDO, D_2O and $H_2{}^{18}O$ transitions

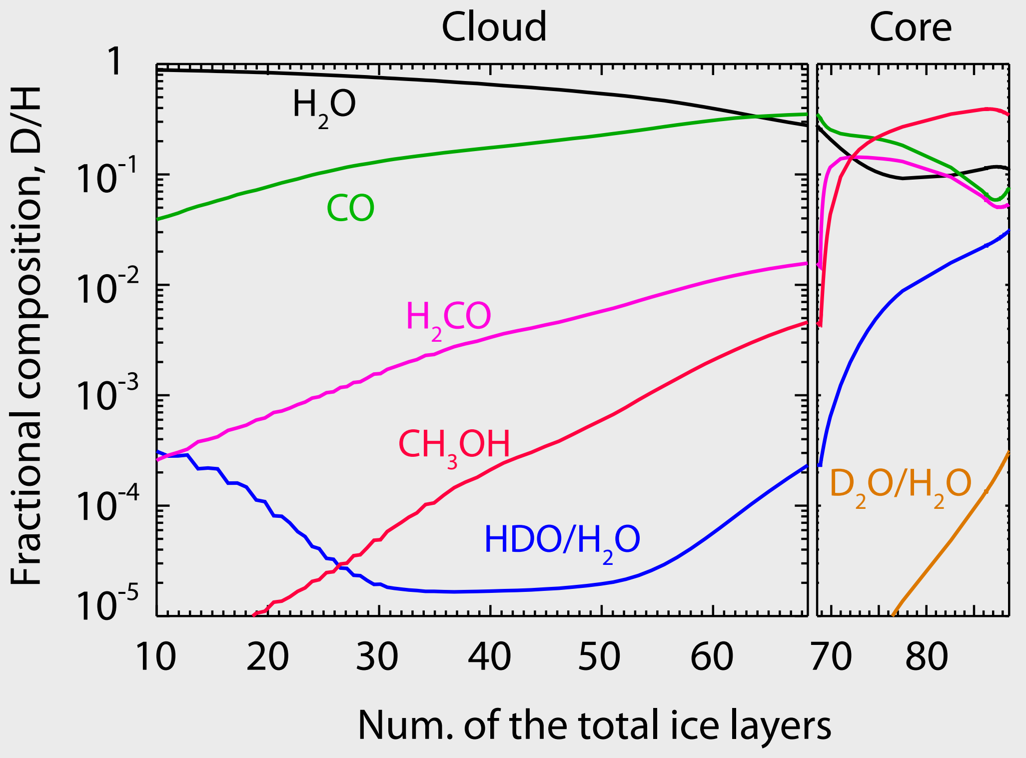
- Partly observed

- Resolution of 0.3″ (~35 AU): possible to study the dynamics with spatially resolved lines

How to explain $D_2O/HDO > HDO/H_2O$ in the inner region of a solar-type protostar?

Natural consequence of the evolution in the early cold stages of low-mass star formation (Furuya et al. 2016)

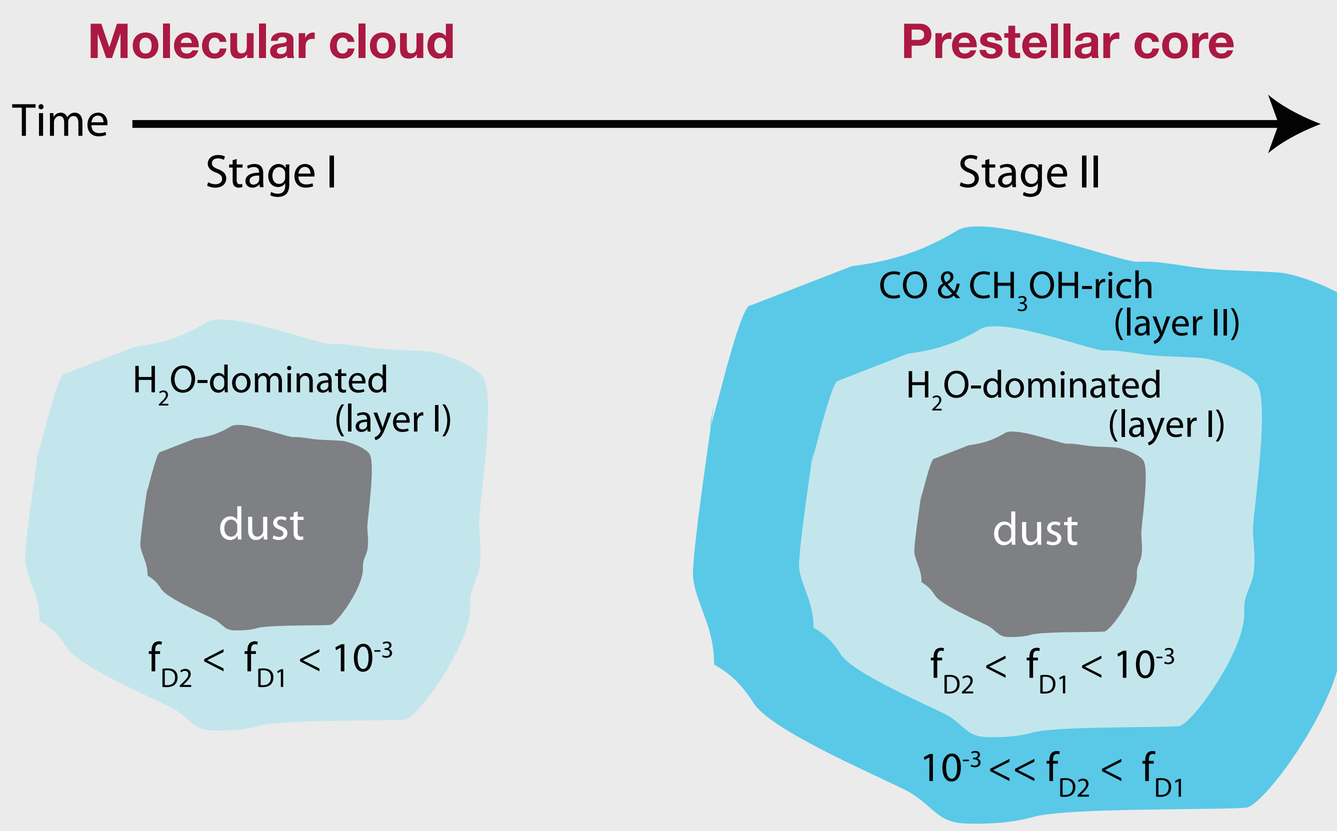


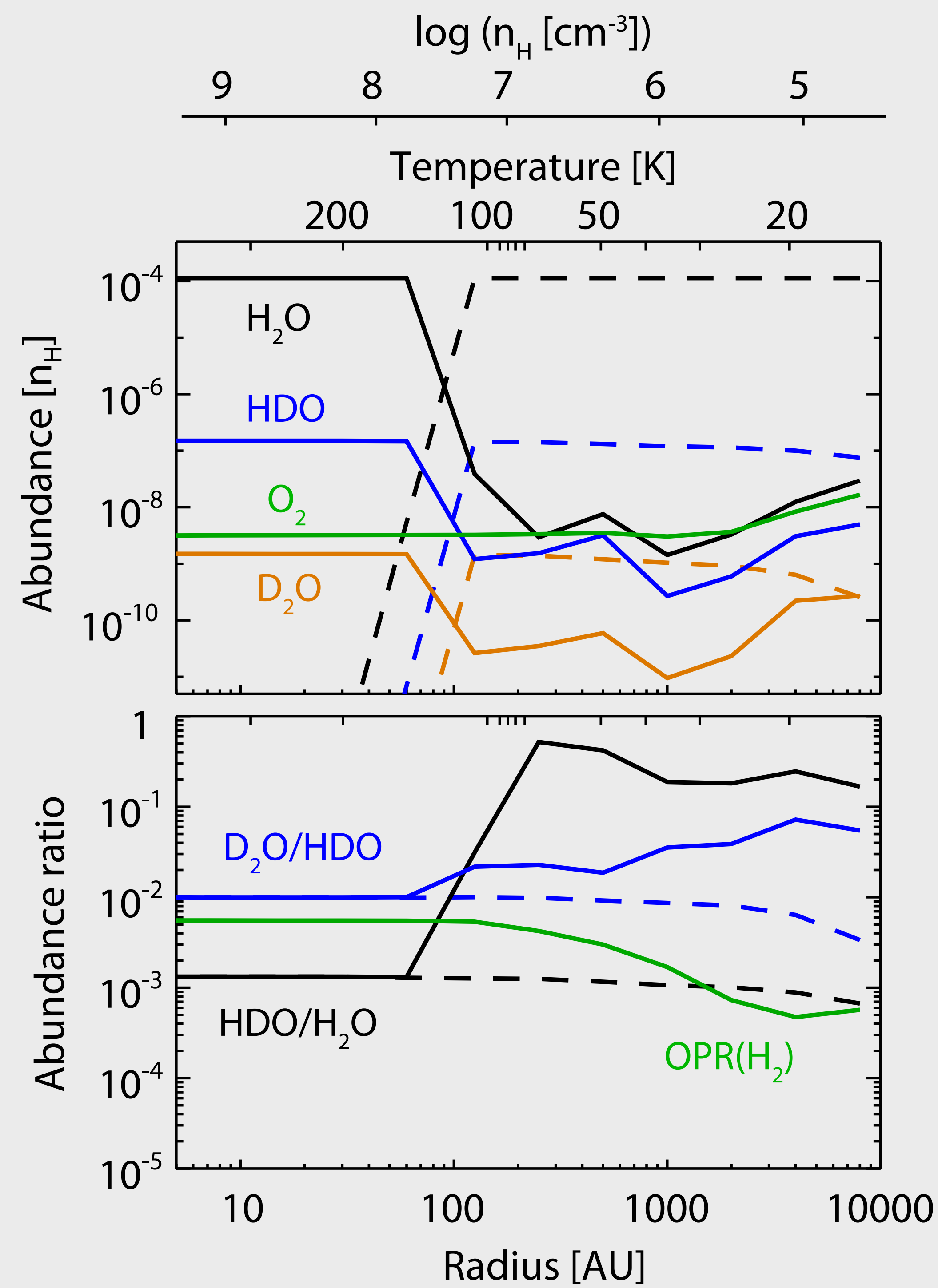


Furuya et al. 2016

How to explain $D_2O/HDO > HDO/H_2O$ in the inner region of a solar-type protostar

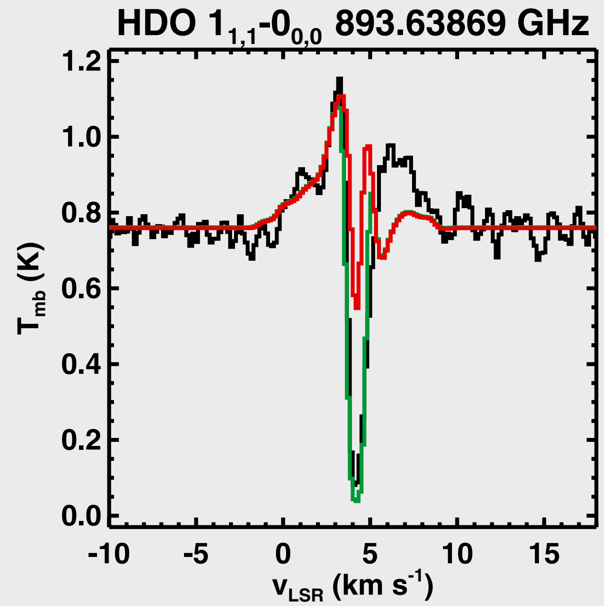
Natural consequence of the evolution in the early cold stages of low-mass star formation (Furuya et al. 2016)

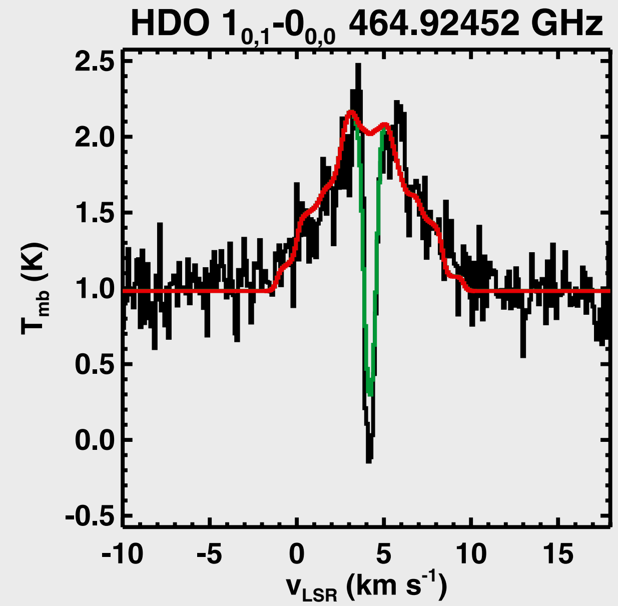




Furuya et al. 2016

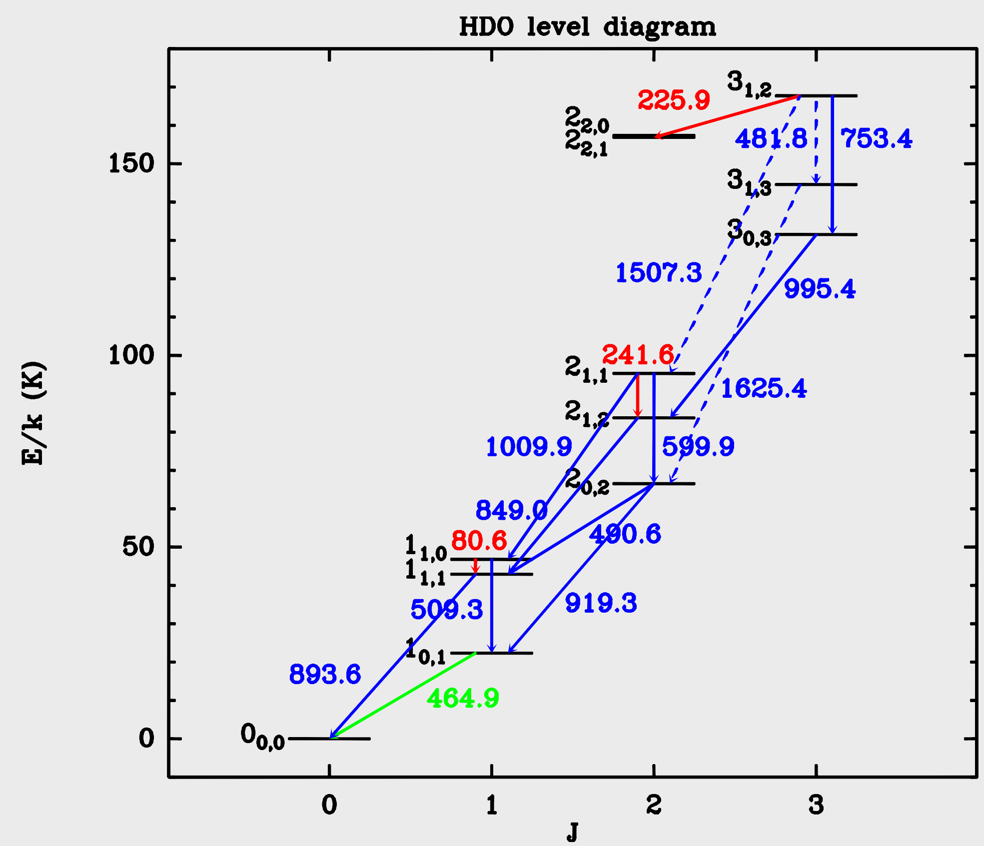
Water deuterium fractionation in the cold outer regions of protostars





- Deep absorptions for the fundamental HDO lines at 894 GHz and 465 GHz detected with *Herschel*/HIFI and the JCMT/APEX observed towards low-mass protostars

- 3 fundamental D_2O lines detected in absorption towards IRAS 16293-2422 with Herschel/HIFI (Vastel et al. 2010, Coutens et al. 2013) and the JCMT (Butner et al. 2007)



Coutens et al. (2012)

➡ Probe of the cold regions

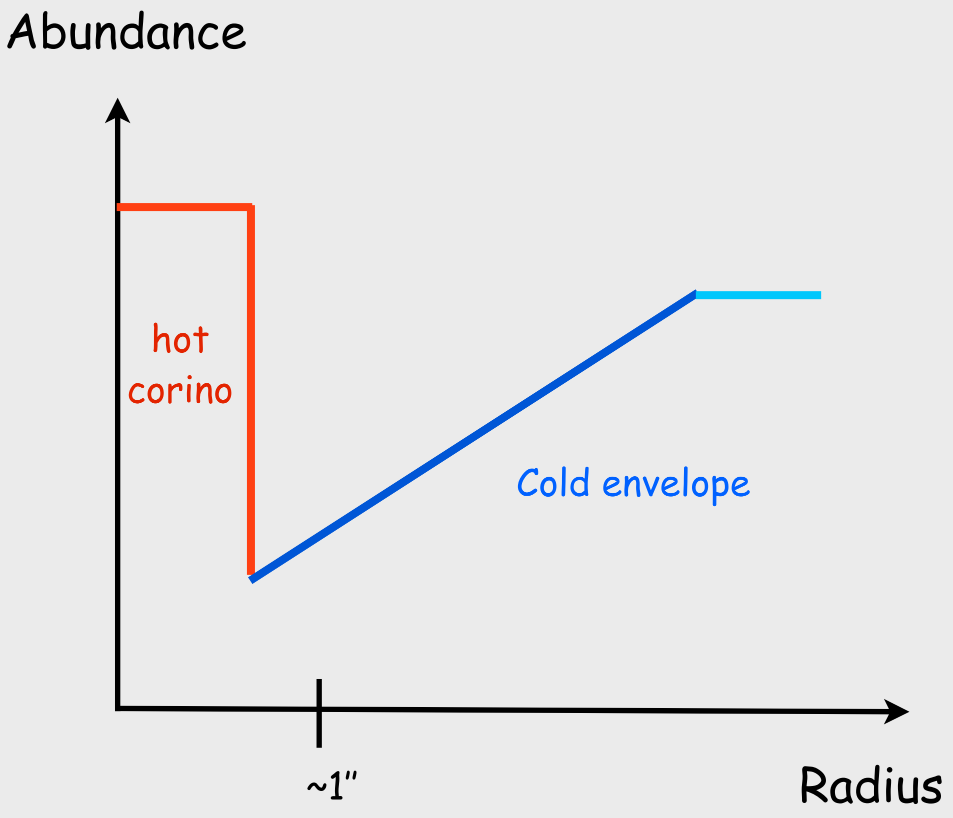
Water deuterium fractionation in the cold outer regions of protostars

- Spherical non-LTE modeling of the HDO lines

- Presence of a water rich layer surrounding the low-mass protostars (Coutens et al. 2012, 2013)

- Probably formed by photodesorption by the external/cosmic ray induced UV field or chemical desorption

- High HDO/H_2O ratio ~ 5% and D_2O/HDO ~ 11% for the outermost regions of the protostar IRAS 16293



Decrease of the water D/H ratio from the cold outer regions to the warm inner regions

In agreement with chemical models including layered structure of the icy grain mantles (Taquet et al. 2014, Furuya et al. 2016)

Summary

- Water deuteration helpful to constrain the water formation mechanisms in the interstellar medium and to follow the evolution of water during the star formation process

- Combination of the D_2O/HDO and HDO/H_2O ratios is a useful tool to reveal the past history of water formation

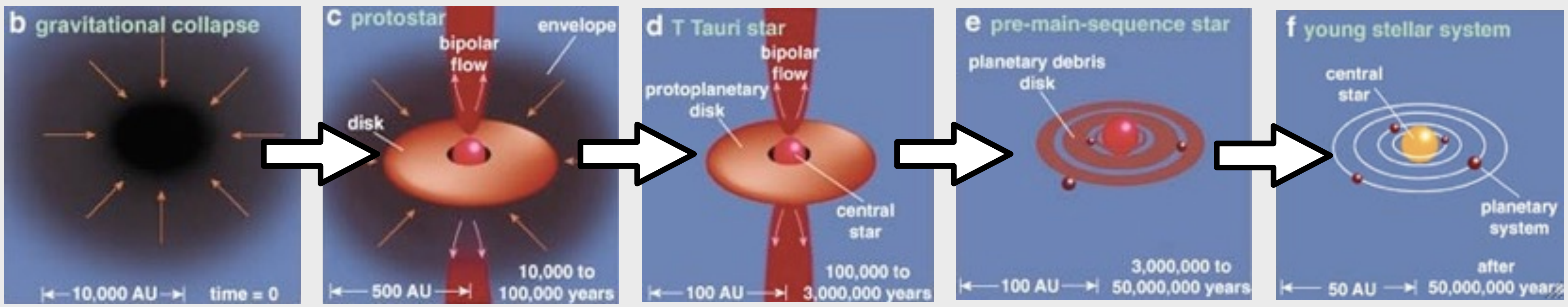
- Inner HDO/H_2O ratios consistent in some cases with cometary values

- Inner regions of the protostar NGC1333 IRAS2A : **D_2O/HDO > HDO/H_2O**
- Decrease of the water deuterium fractionation from the cold outer regions to the warm inner regions

➡ Result of the evolution of water formation during the early cold stages of low-mass star formation (molecular cloud + prestellar core, Furuya et al. 2016)

Future

Measurements of the HDO/H_2O ratios at different stages (Class I, Class II) would help us to understand the evolution of water during the star formation process.



Spitzer Science Center IR Compendium

Prestellar core

Class 0 protostar

?

Comets

See poster P17 on the detectability of deuterated water in prestellar cores (Quénard et al. 2016)