Water deuterium fractionation in the warm inner regions of solar-type protostars

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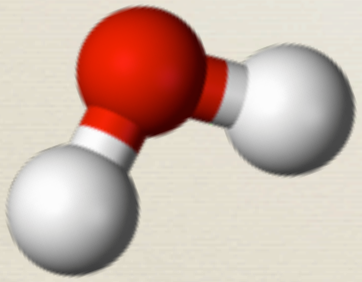
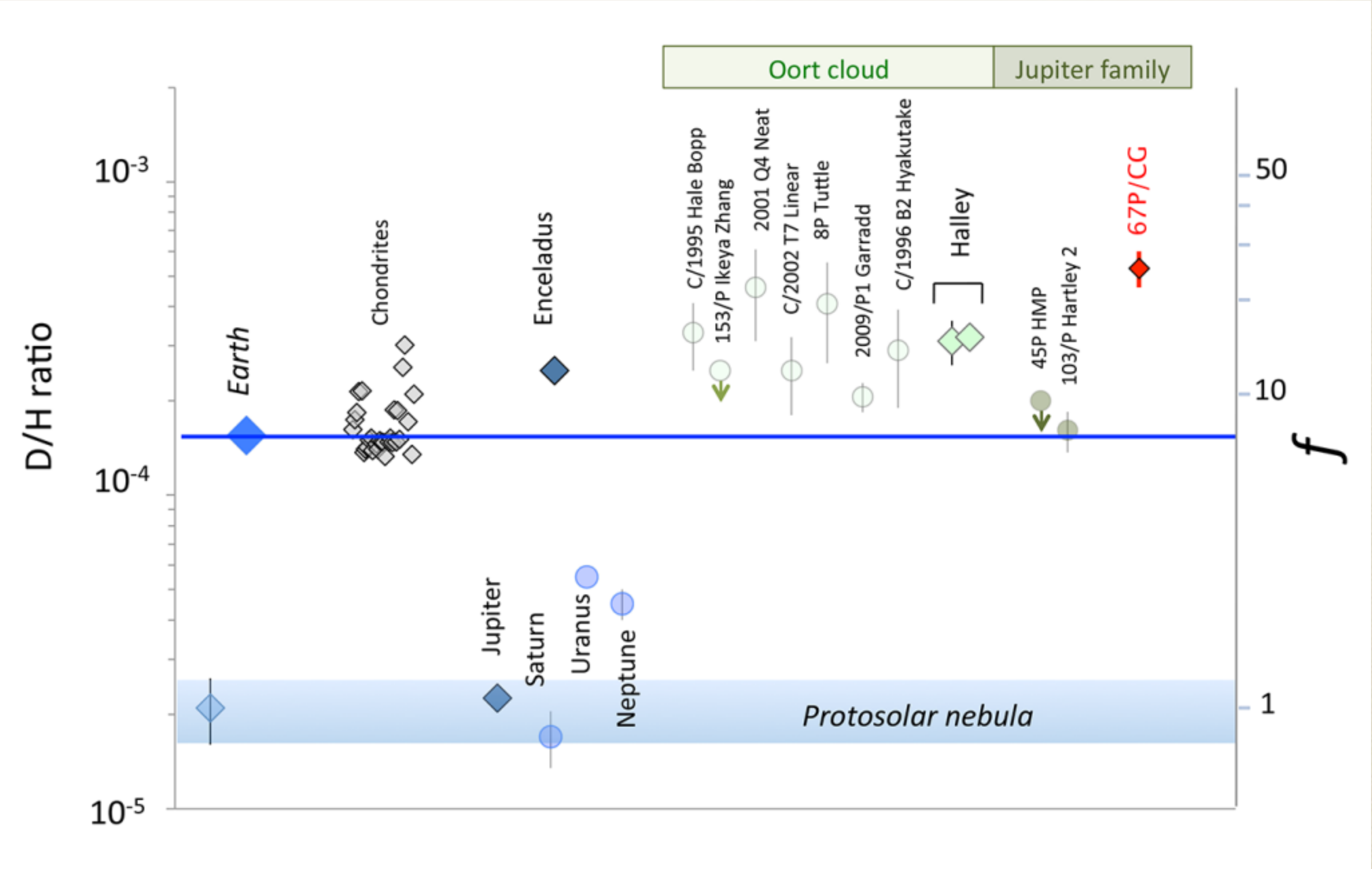
Introduction

- Water omnipresent in the interstellar medium (hot cores, low-mass protostars, shocks, prestellar cores, protoplanetary disks, ...)

- Important species :
  - in the process of star formation through the cooling of warm gas
  - chemistry of O-bearing species both in the gas phase and on the grain surfaces
  - crucial ingredient for the emergence of Life

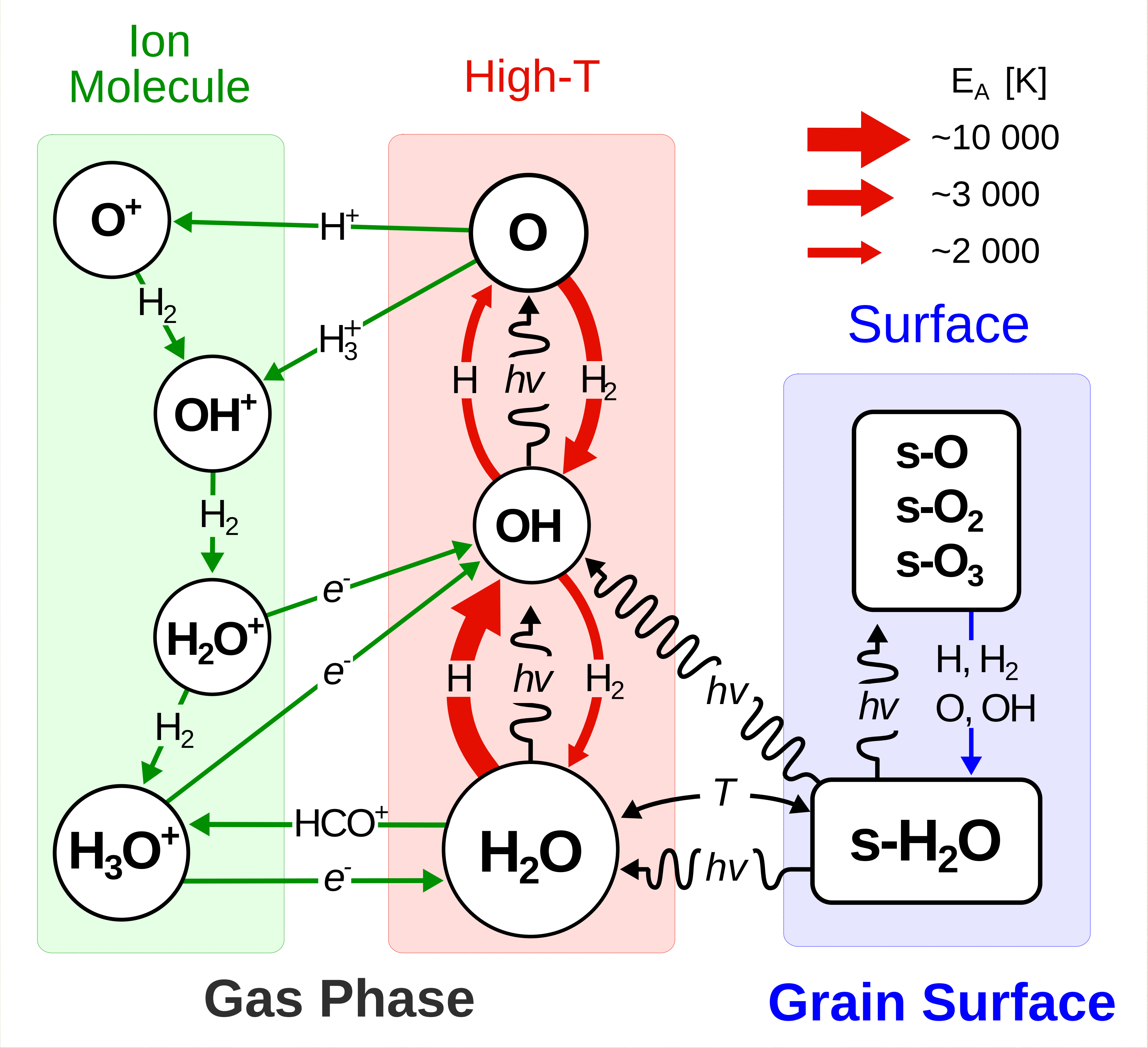
- Delivery of water on Earth by comets and/or asteroids through impacts





Altwegg et al. (2015)

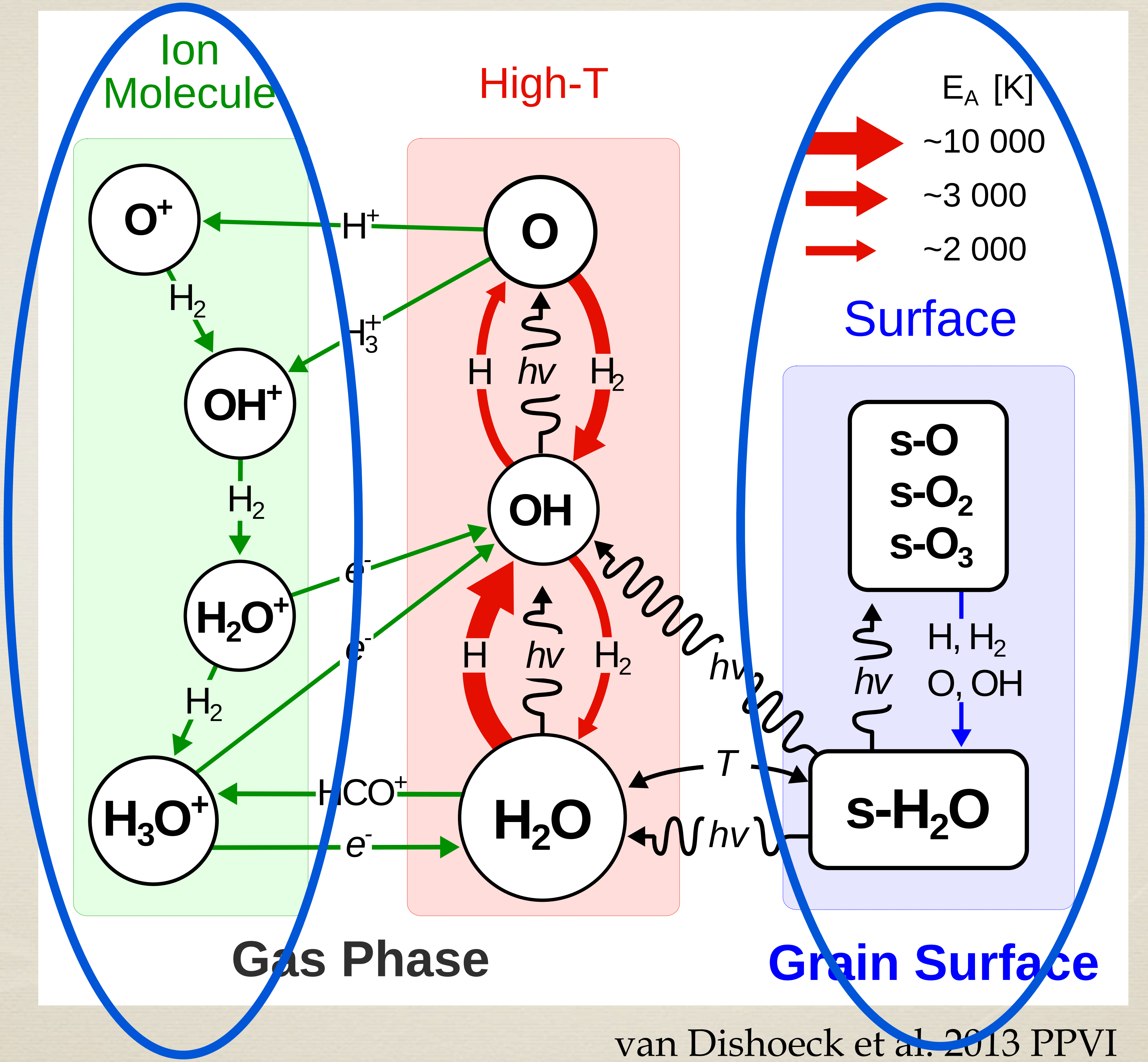
Water chemistry in the interstellar medium



van Dishoeck et al. 2013 PPVI

Water deuterium fractionation

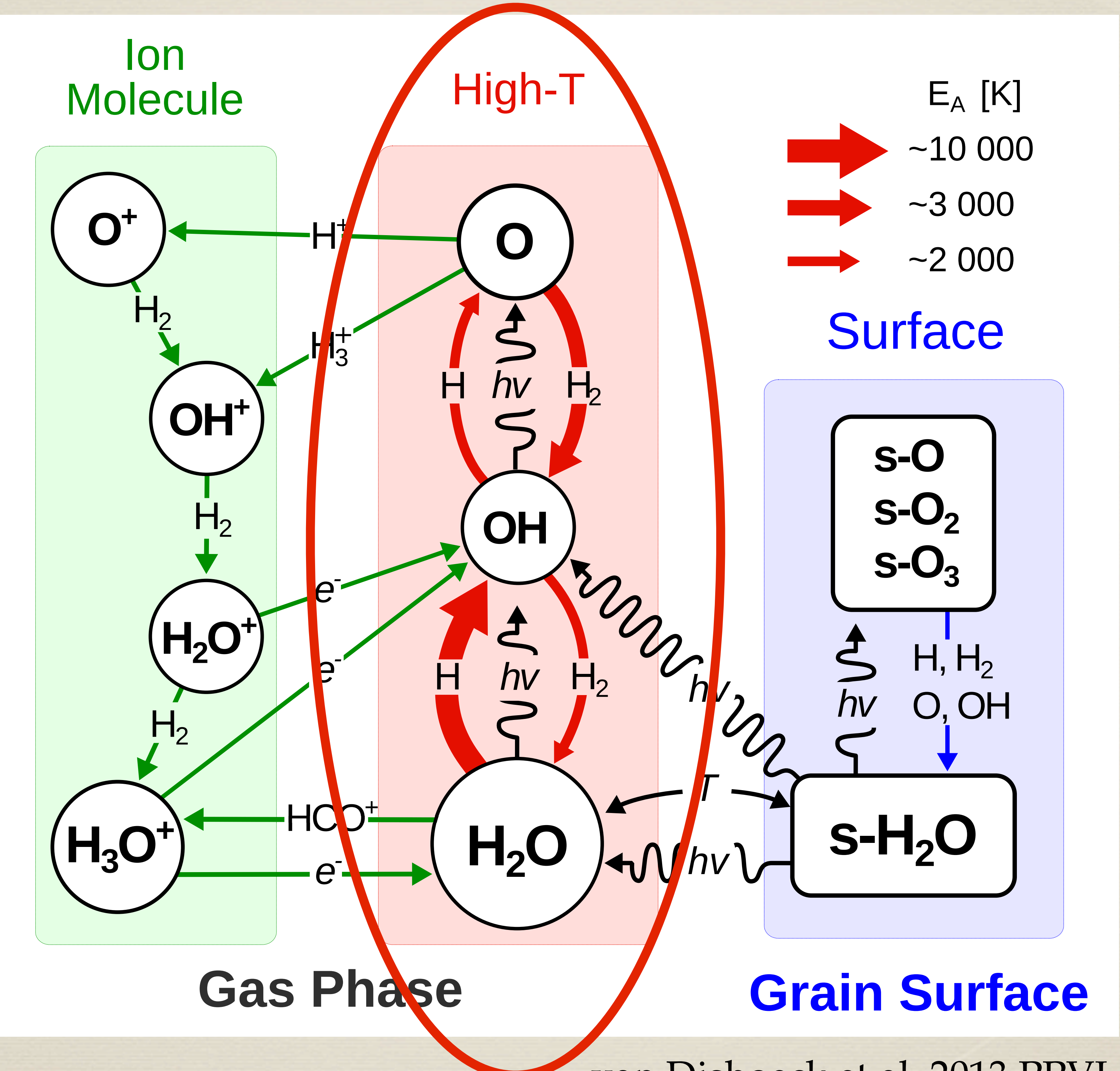
High water D/H ratios



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

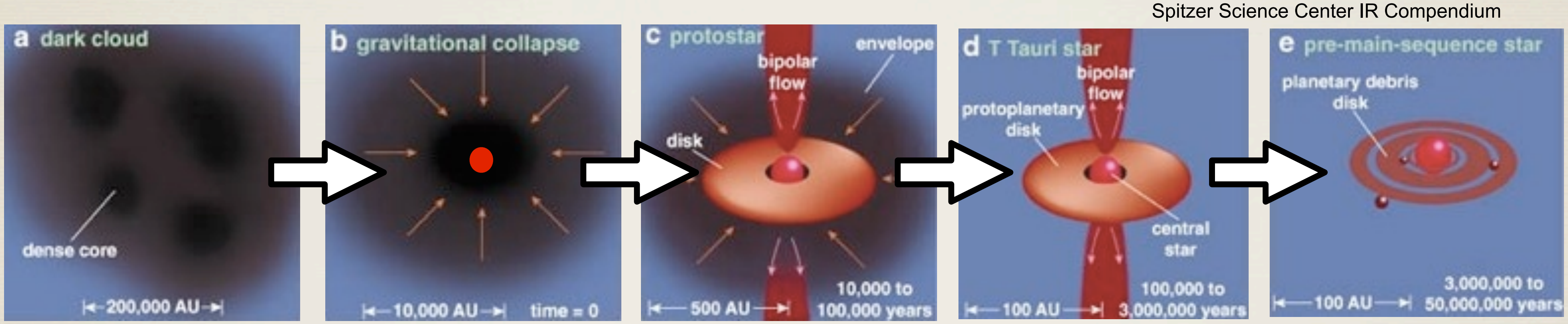
Origin of water in Solar System objects

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

→ *Use of water deuterium fractionation (HDO/H_2O, D_2O/HDO, D_2O/H_2O)*

Star formation

Spitzer Science Center IR Compendium



Prestellar core | **Class 0 protostar** | **Class I protostar** | **Class II protostar** | **Protoplanetary disk**

Formation in the protoplanetary disk (ion-molecule reactions) ?
OR
Earlier formation in the molecular cloud or in the protostellar envelope?

1. Theoretical models
2. Observations

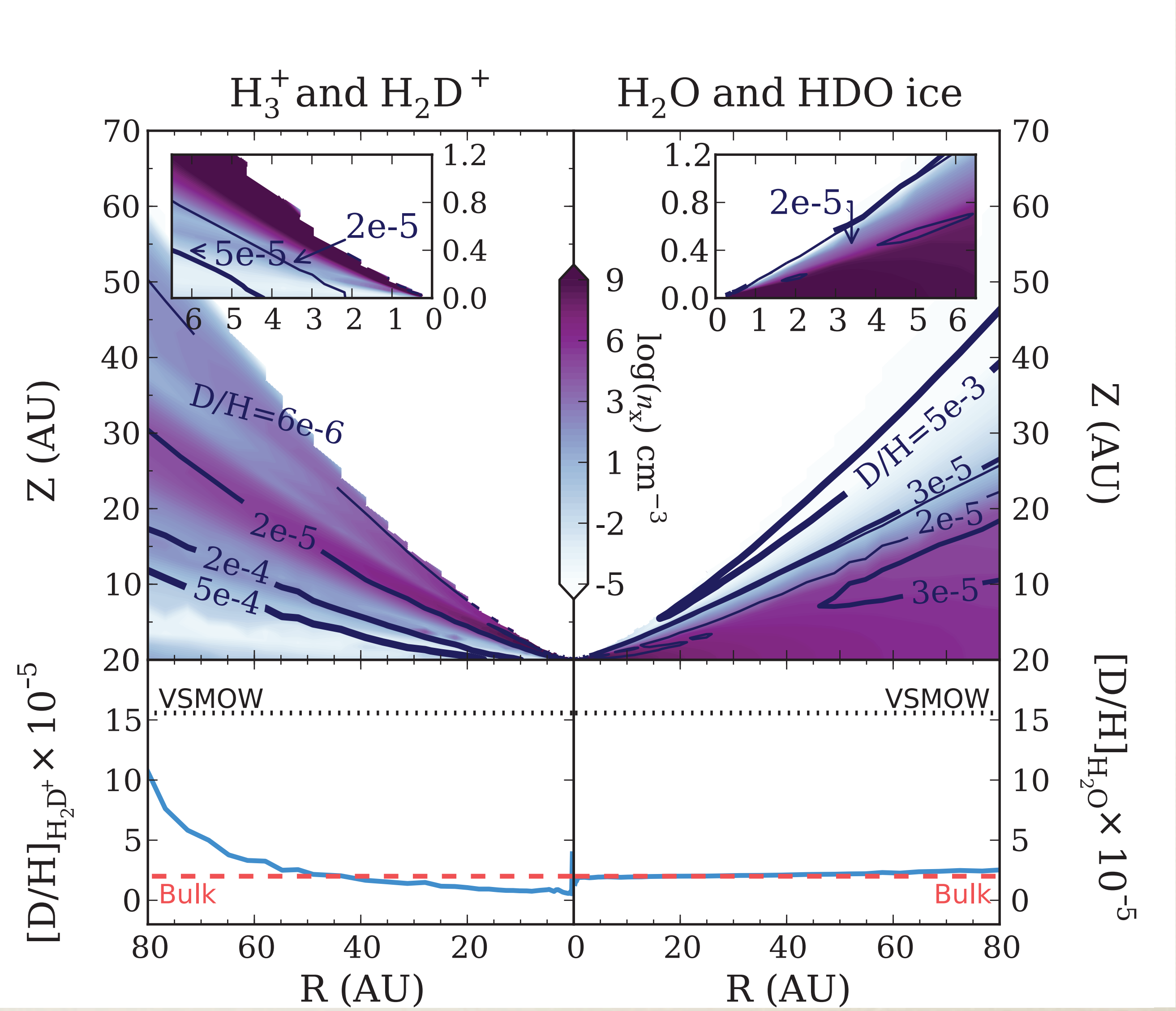
Origin of water in Solar System objects

Theoretical study: Cleeves et al. 2014

- Aim: Identifying the source of Earth's (and other solar system objects) water

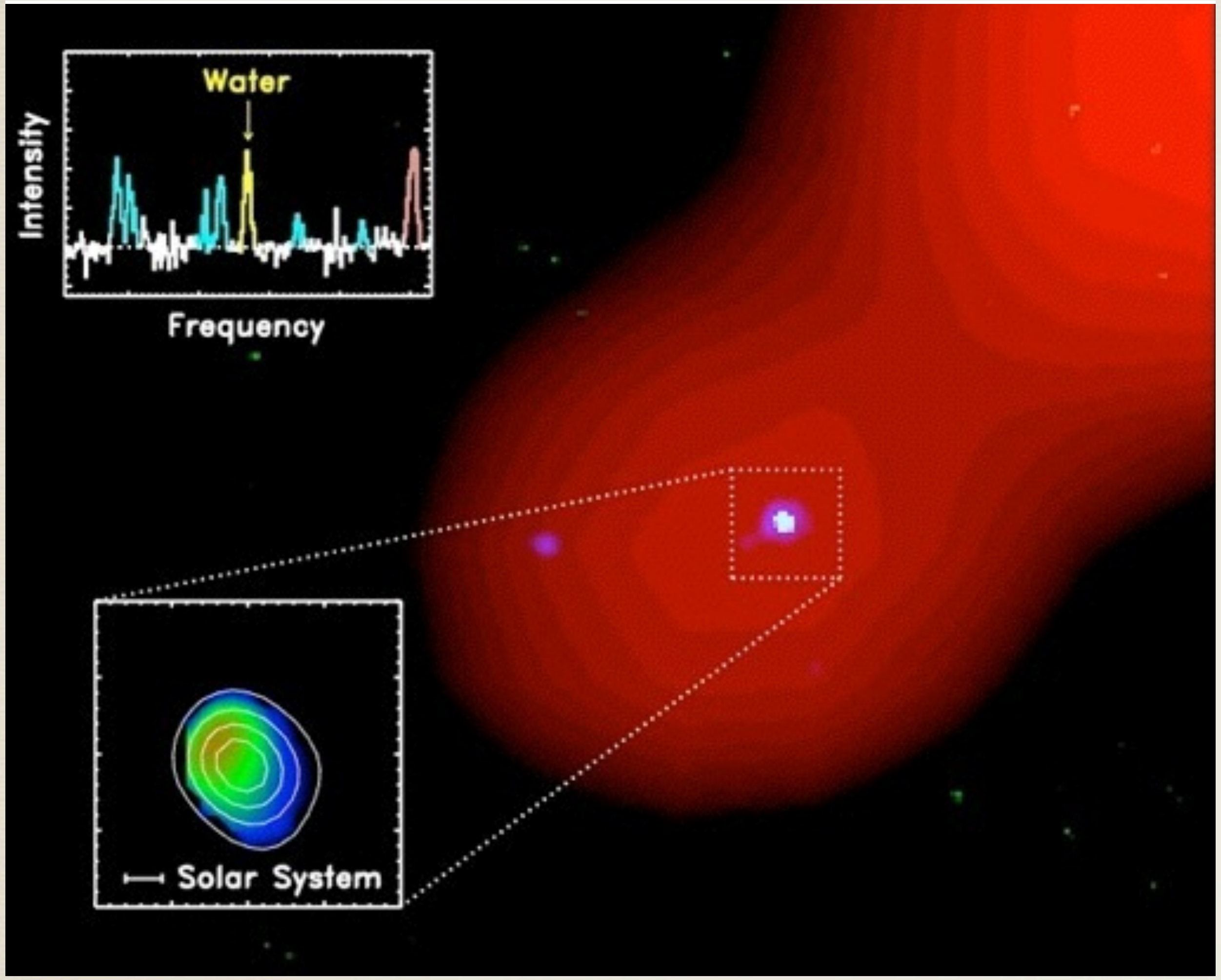
- Test with a chemical network if it is possible to reach the terrestrial HDO/H_2O ratio in a disk using an initial $(D/H)_{H2} = 2 \times 10^{-5}$ (solar nebula value)

- Results: The ion-driven deuterium pathways are inefficient in the disk. A part of interstellar ice survived the formation of solar system and was incorporated into planetesimal bodies.



"If the solar system's formation was typical, abundant interstellar ices are available to all nascent planetary systems."

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 in the hot corino (T > 100 K)

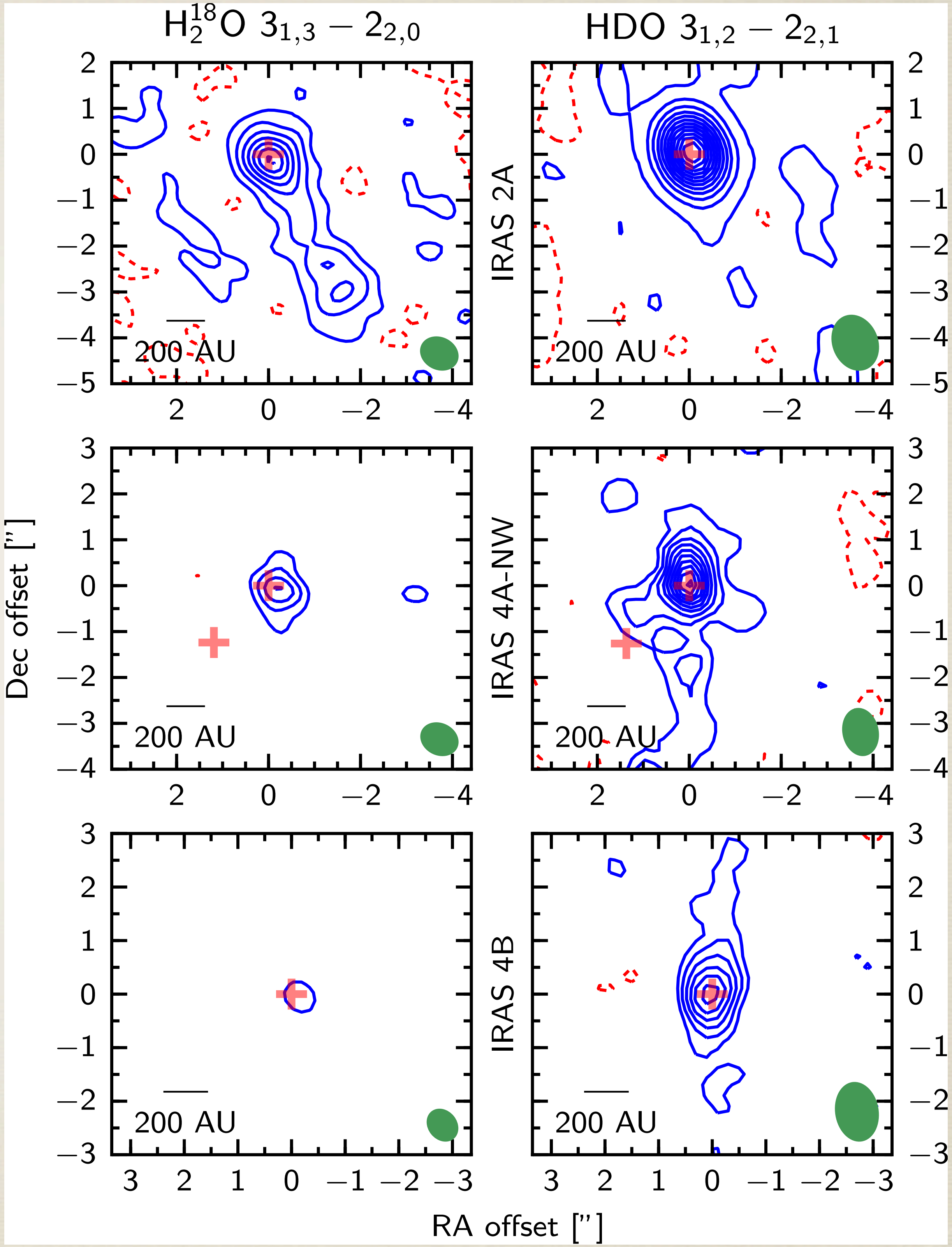
HDO in the inner regions of solar-type protostars

- 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 $H_2{}^{18}O$

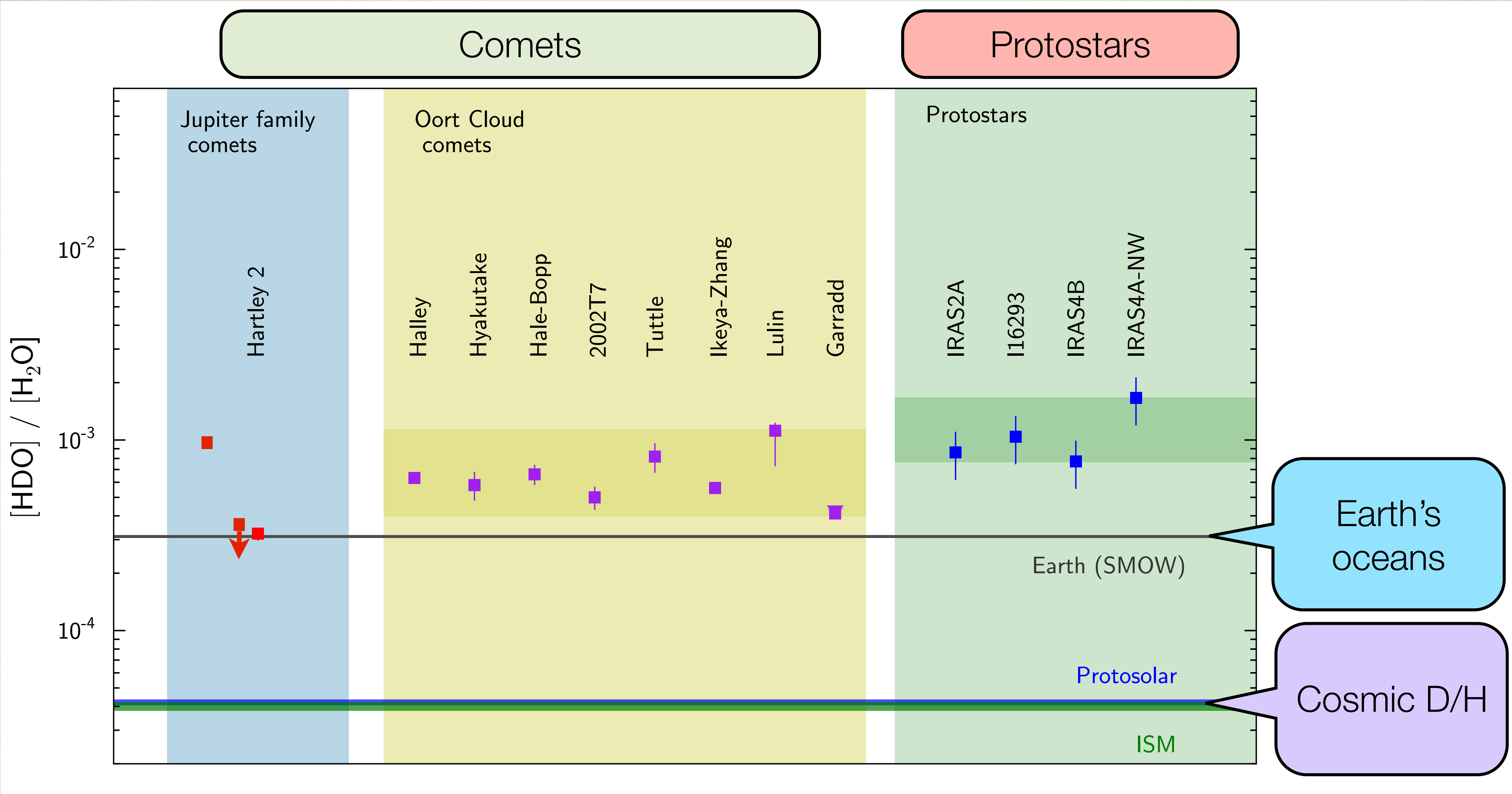
- Assuming $H_2{}^{16}O/H_2{}^{18}O \sim 500$ (Solar System value)

- 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



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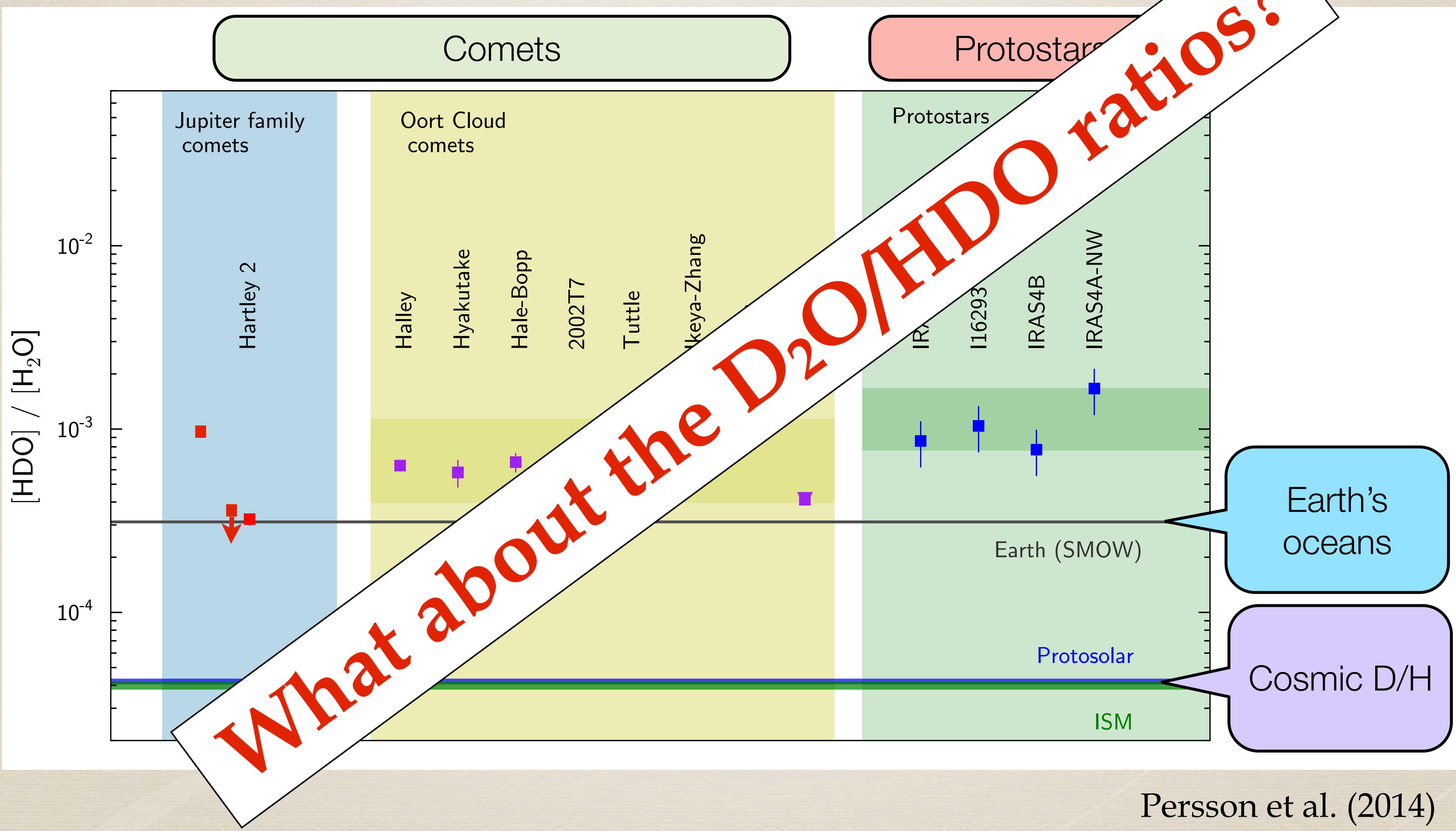


Persson et al. (2014)

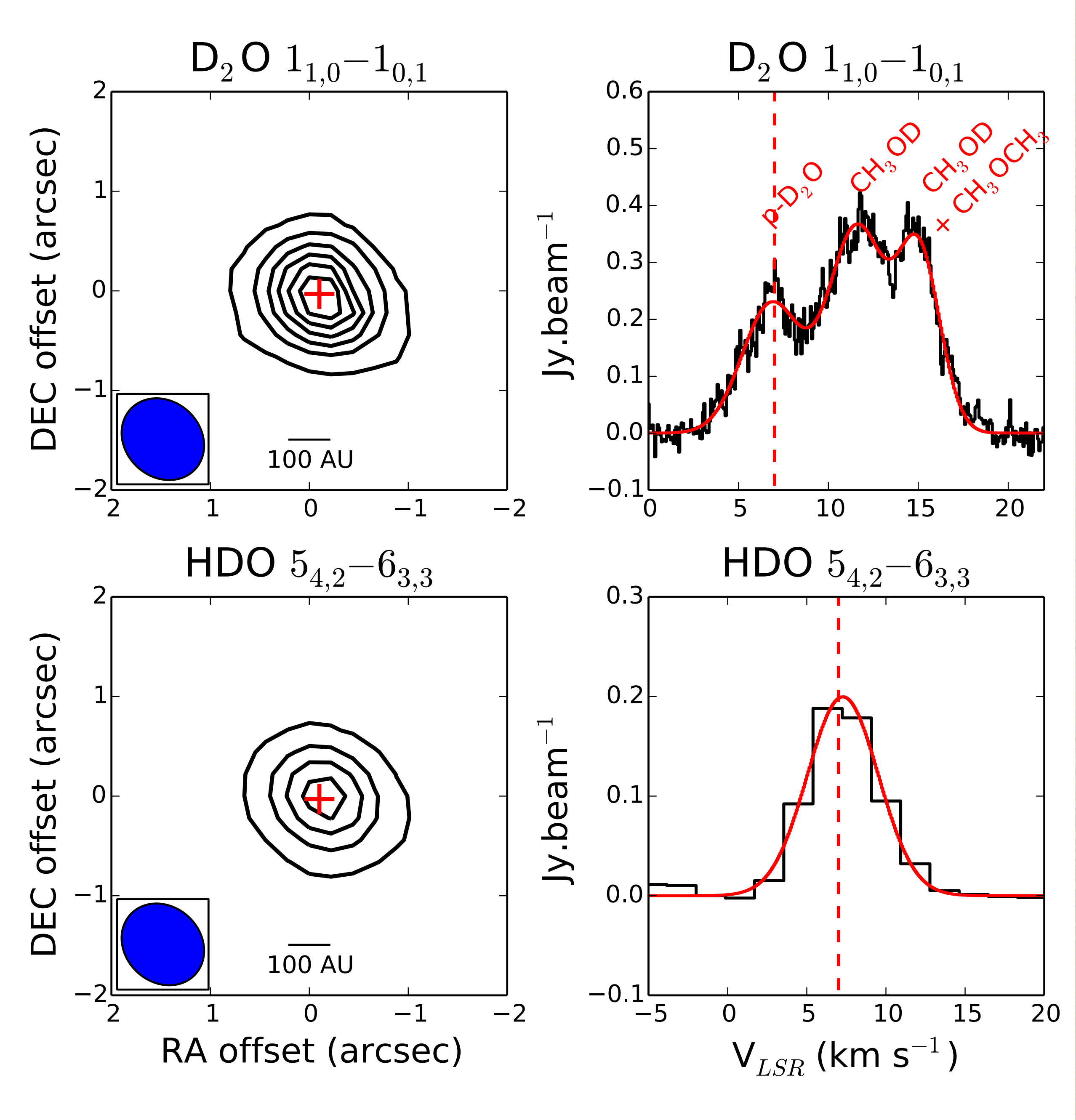
Detection of D_2O in the inner region of a solar-type protostar

- 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, $H_2{}^{18}O$)

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

$D_2O/HDO \sim 7 \times HDO/H_2O$



Coutens et al. (2014, ApJL)

High D_2O/HDO ratio in the inner region of a solar-type protostar

$D_2O/HDO \sim 7 \times HDO/H_2O$

- Statistically we would expect $D_2O/HDO \sim 1/4 \times HDO/H_2O$
- Surface grain chemical models also predict $D_2O/HDO \lesssim HDO/H_2O$

Two scenarios :

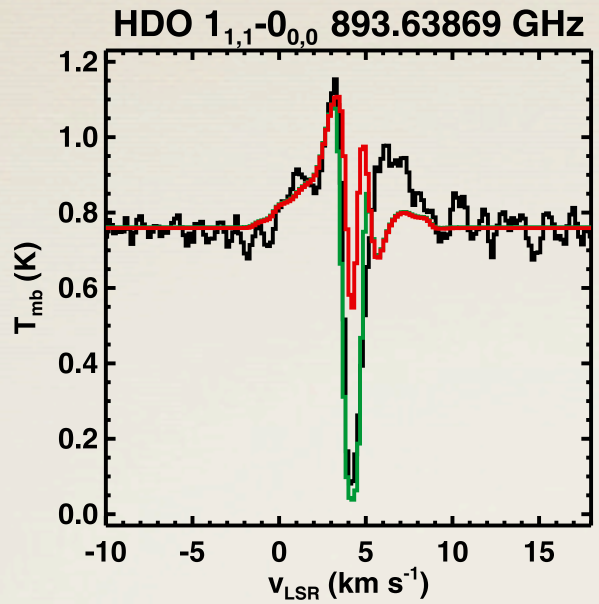
- **Missing ingredient in the understanding of the surface deuteration process ?**

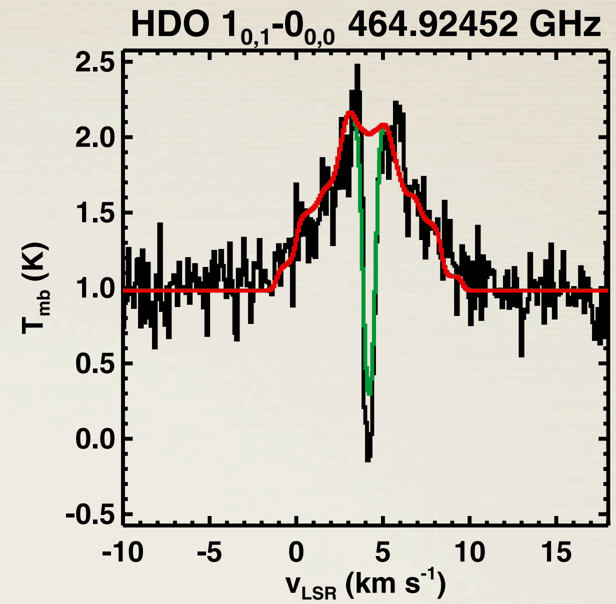
- **Thermal desorption + important production of H_2O at high temperature ?**
  - ✓ Thermal desorption of the grain mantles : high D_2O/HDO ratio
  - ✓ Water formed in the gas phase at high temperature (> 230 K) : decrease of the HDO/H_2O ratio

ALMA observations of IRAS 16293

ALMA observations of IRAS 16293

Deuterated water in the cold envelope of protostars

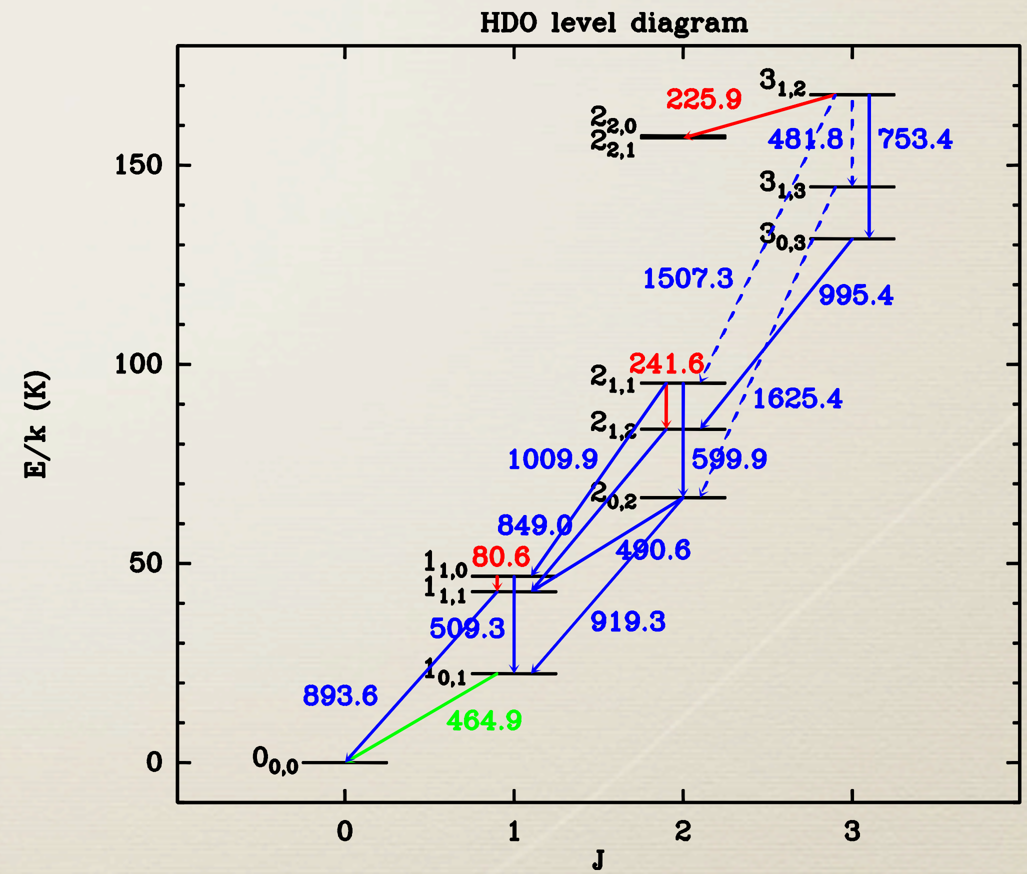




- Fundamental HDO lines at 894 GHz and 465 GHz detected with *Herschel*/HIFI and JCMT show deep absorption.

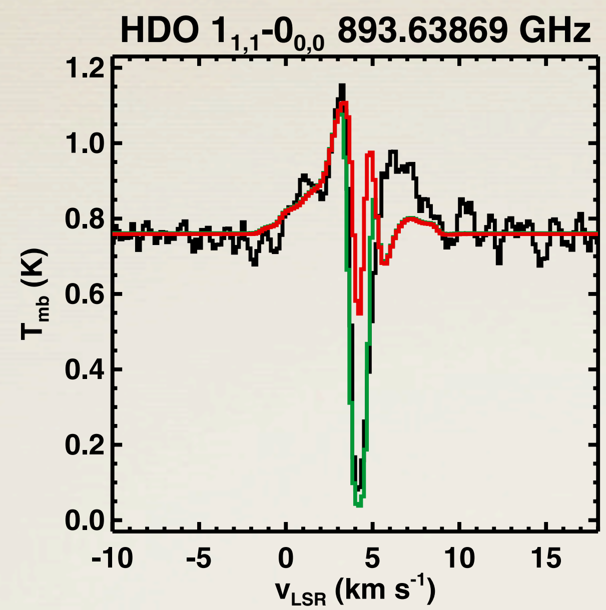
- 3 fundamental D_2O lines detected in absorption towards IRAS16293 with Herschel/HIFI (Vastel et al. 2010, Coutens et al. 2013) and the JCMT (Butner et al. 2007)

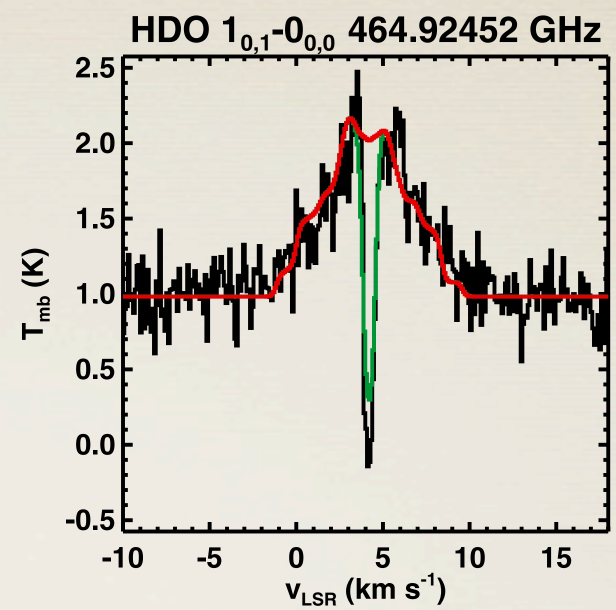
➡ Probe of the cold regions



Coutens et al. (2012)

Deuterated water in the cold envelope of protostars

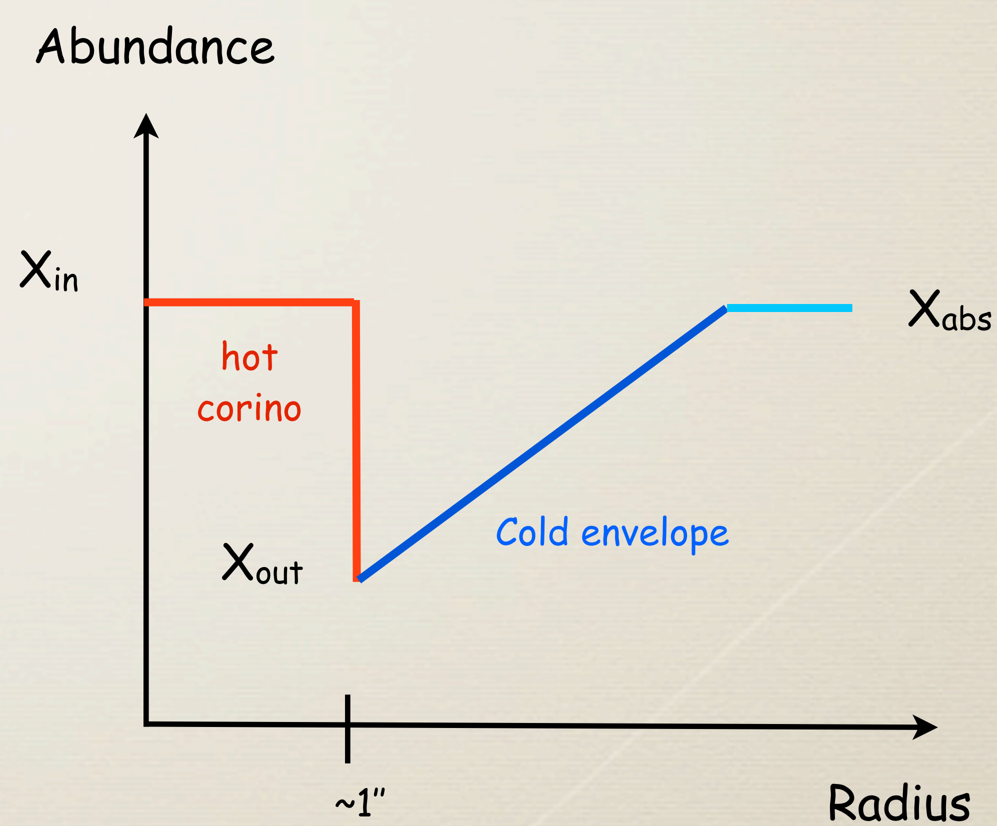




- Spherical non-LTE modeling of the HDO lines show that a very rich water layer surrounds the protostars (Coutens et al. 2012, 2013)

- Probably formed by photodesorption by the (external/cosmic ray induced) UV field

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

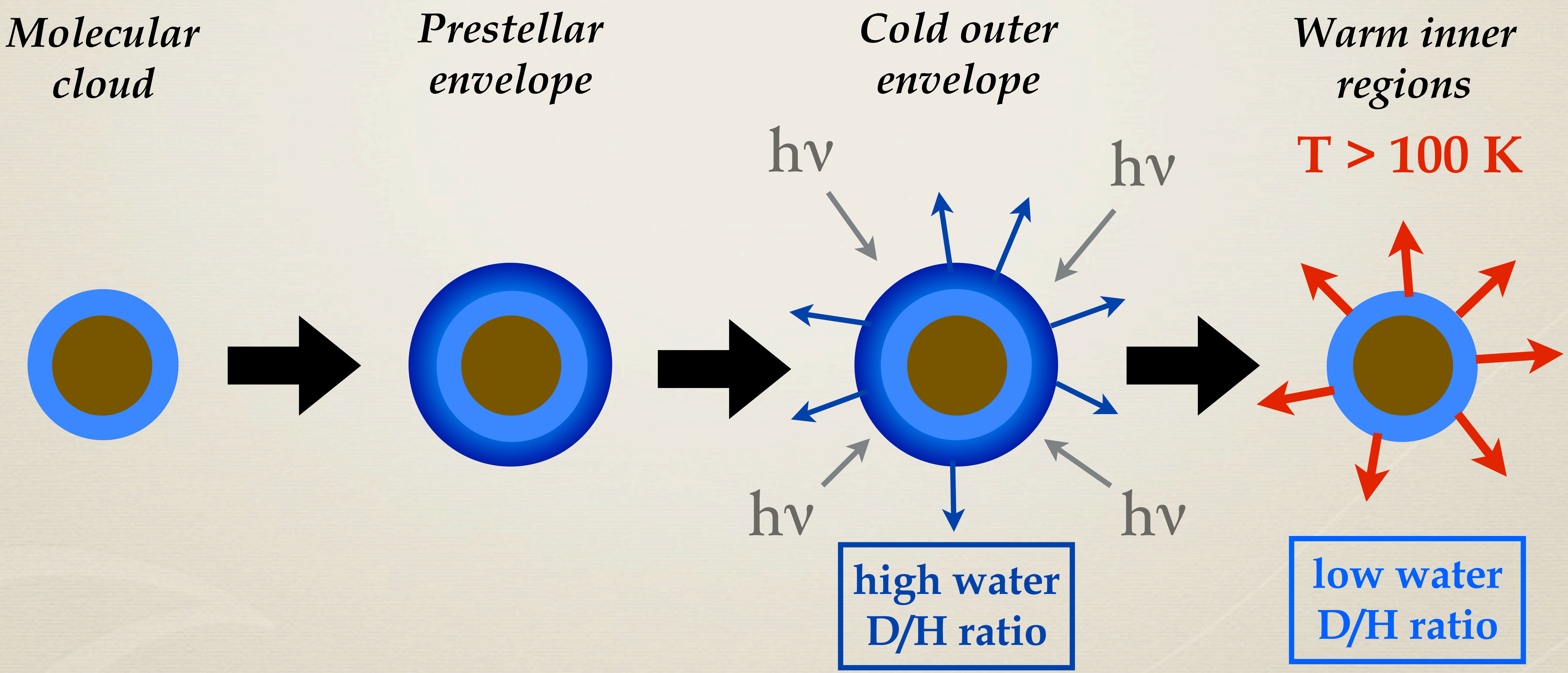


Decreasing water D/H ratio towards the inner regions

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

Possible explanations:

- additional formation of water in the gas phase at high temperature
- partially thermally reprocessed
- gradient of water D/H ratios in the grain mantles (Taquet et al. 2014)



Conclusion

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

- **Interferometric detection of D_2O towards NGC1333 IRAS2A**
  - ➡ $D_2O/HDO > HDO/H_2O$
  - ➡ Thermal desorption of grain mantles + extra production of H_2O in the gas phase at high temperature ?

- **Similar results for IRAS16293 (ALMA preliminary results)**

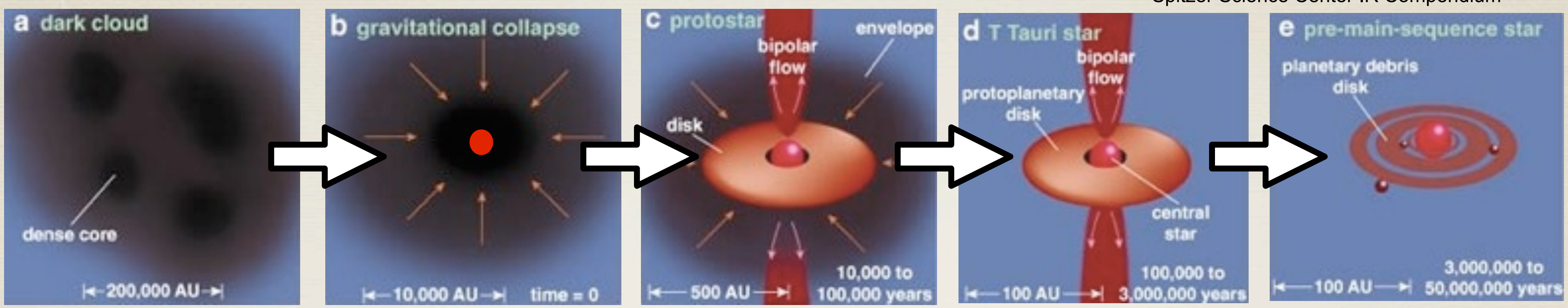
- **Decrease of the water deuterium fractionation from the cold outer regions to the warm inner regions**

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

Future

Star formation

Spitzer Science Center IR Compendium



Prestellar core | **Class 0 protostar** | **Class I protostar** | **Class II protostar**

? ?

- **Measurements of the HDO/H_2O ratios at different stages would help us to follow the evolution of water.**

- **Water is supposed to be on the grains in the disk mid-plane: it could be challenging to detect the deuterated water form.**