Water in solar-type protostars

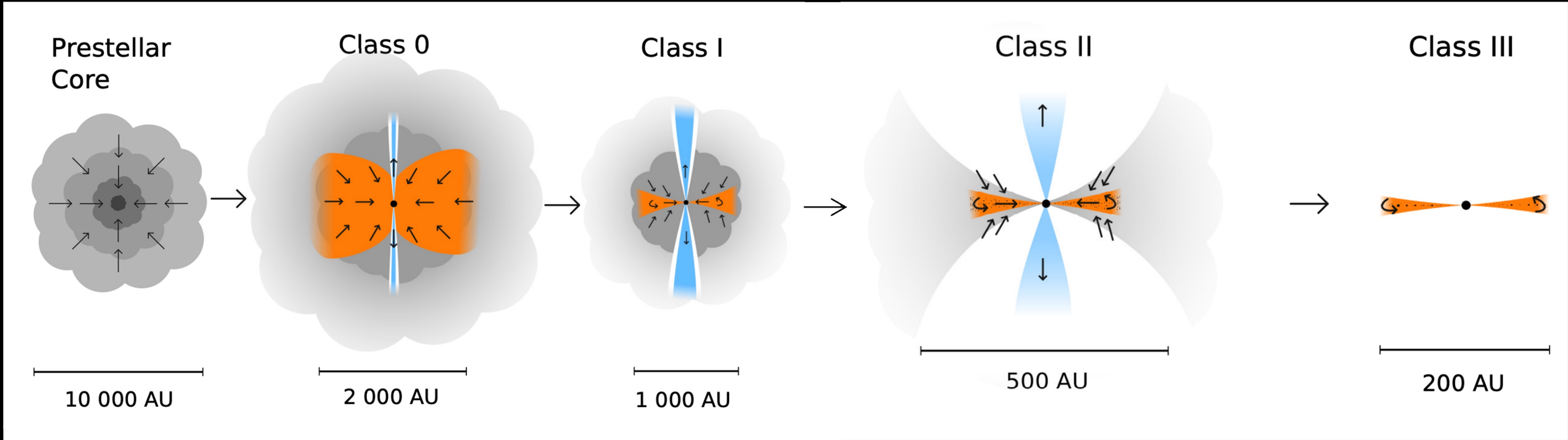
Audrey ANDREU & Audrey COUTENS

The CHEMical TRail In Protostars: From the deeply embedded phase to the planet-forming disk

Star formation

Credit: Bill Saxton/NRAO/AUI/NSF

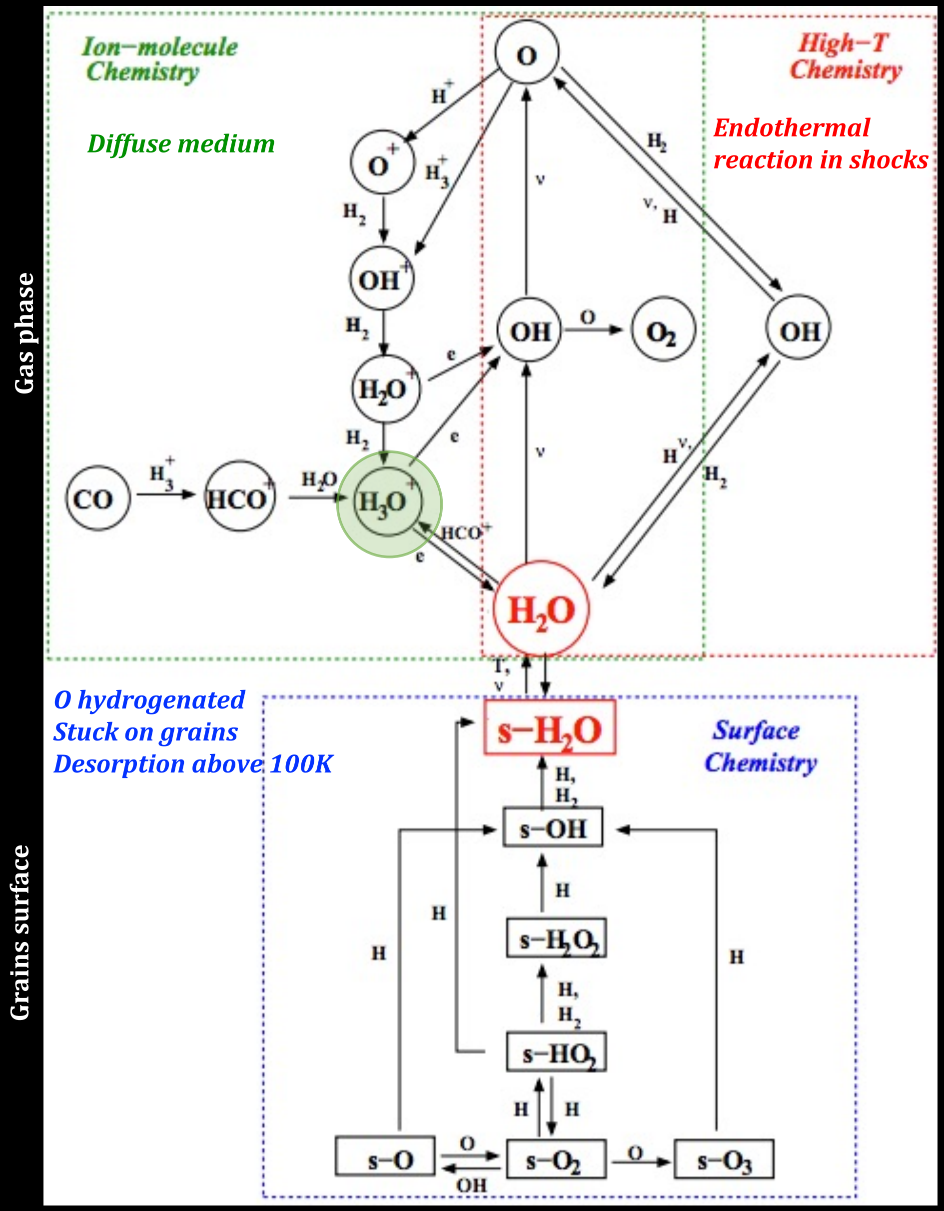
Star formation



Adapted from *Persson, 2013*

Water deuteration

- Water abundant and essential for life emergence
- Deuteration sensitive to physical conditions in which molecules form *(Ceccarelli et al. 2014)* *e*ffective when T ~ 10 K
- Found on asteroids and comets, possible delivery on Earth *(e.g. Altwegg et al. 2015)*

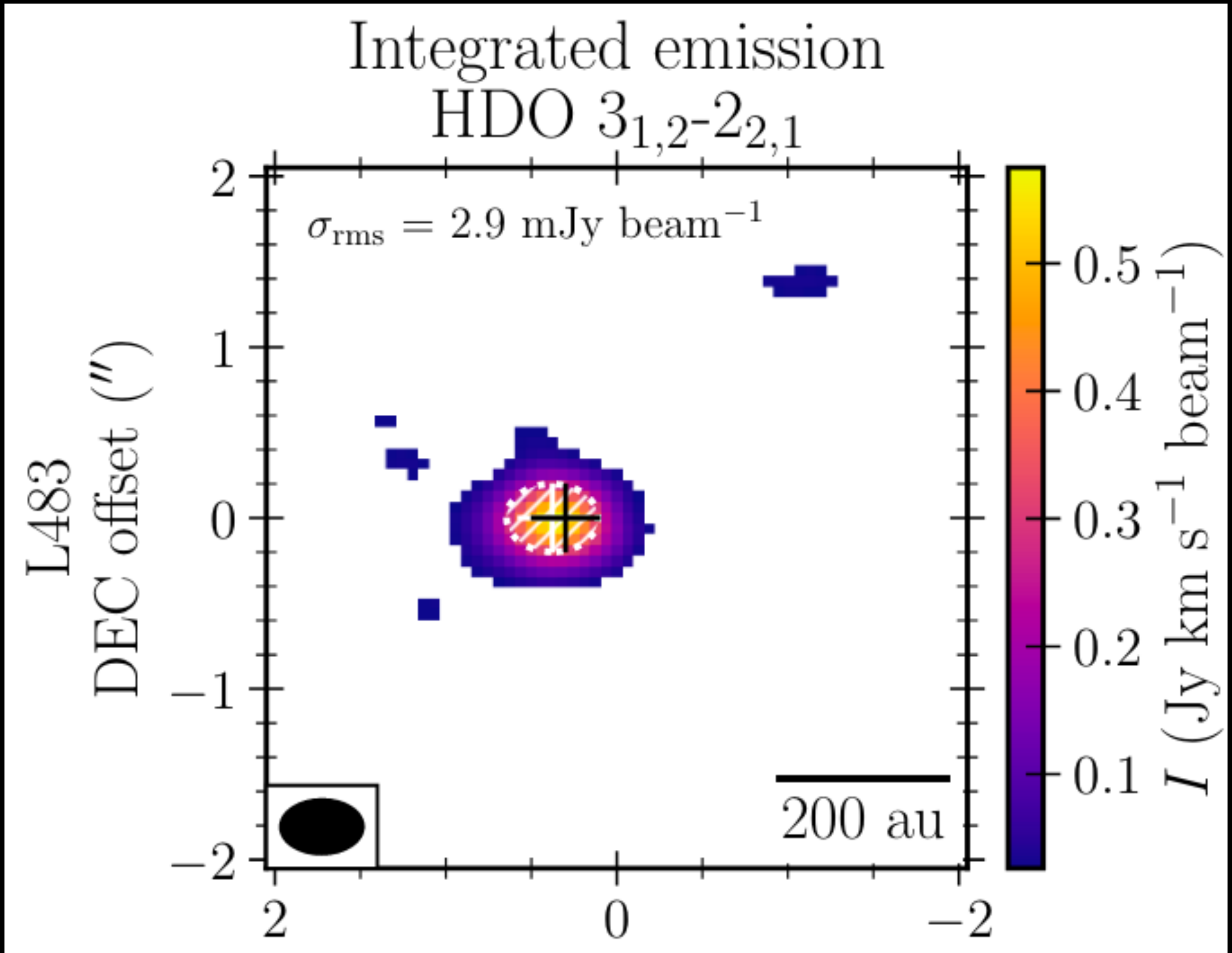


Main water formation and destruction paths
Van Dishoeck et al. 2011

Compact emission

- 1^{st} water interferometric detection
  Jørgensen & van Dishoeck 2010

- Compact emission ~ 200 – 250 AU

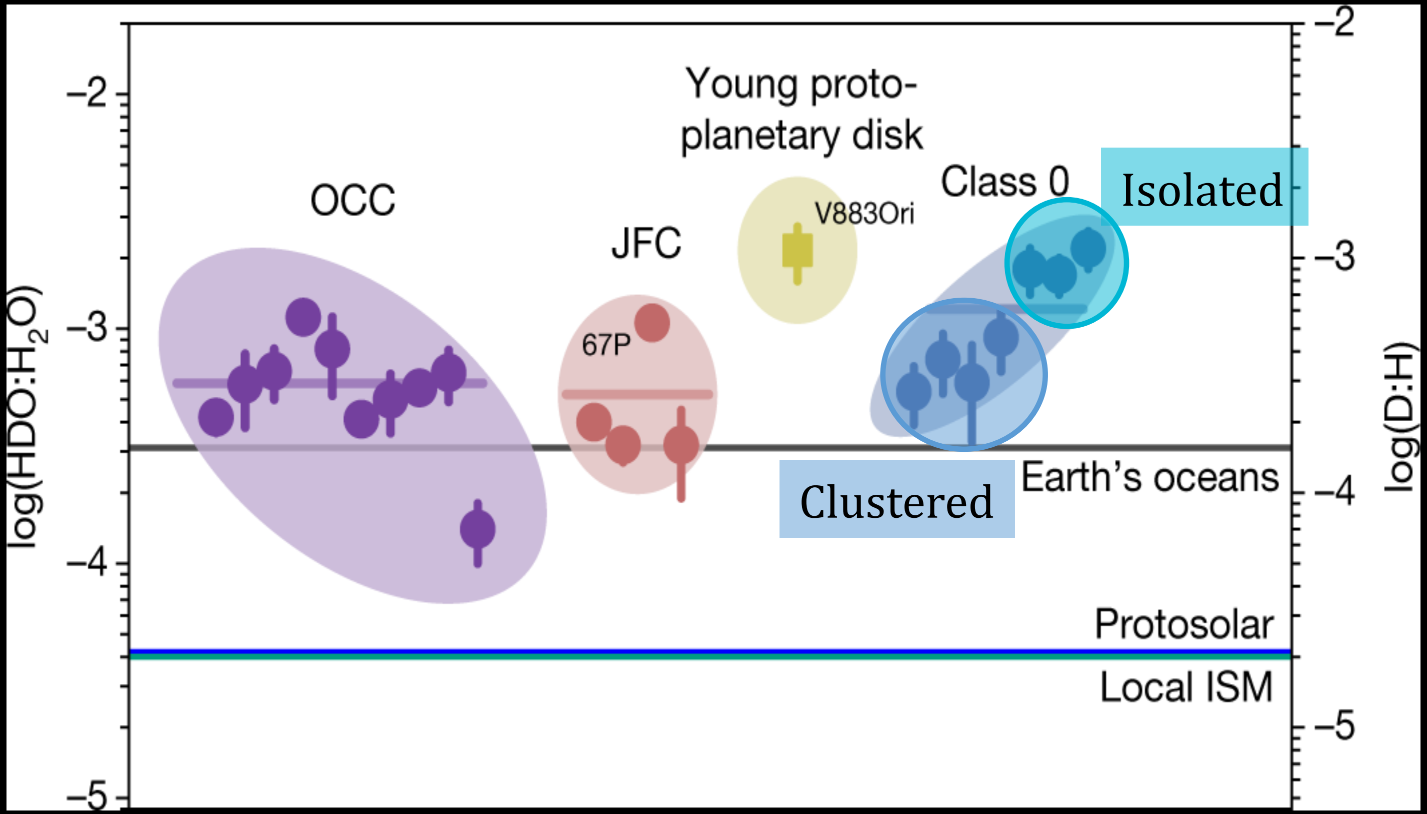


Jensen et al. 2019

Water deuteration in protostars

Jorgensen et al. 2010, Person et al. 2013, 2014, Coutens et al. 2014, Taquet et al. 2014, Jensen et al. 2019, Tobin et al. 2023

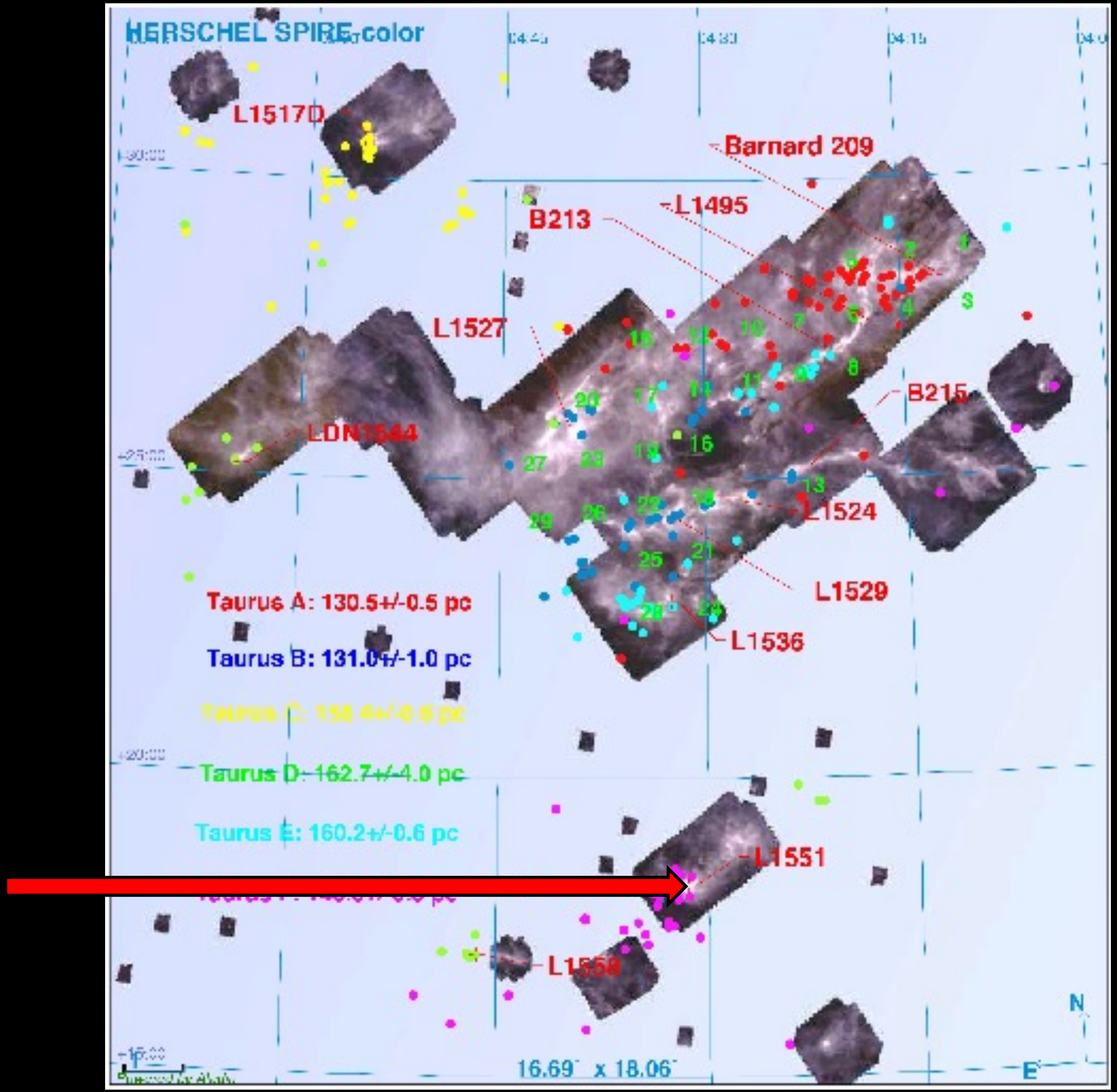
- Similar ratios for comets and clustered protostars
- Isolated vs clustered sources: HDO/H_2O ratios 2 times higher in clustered protostars *(Jensen et al. 2019)*
- Faster formation of clustered sources or higher temperatures in the molecular cloud could explain the differences in the ratio *(Jensen et al. 2021)*
- $D_2O/HDO \sim 10^{-2}$ comet 67P and Class 0 clustered *(Altwegg et al. 2017, Coutens et al. 2014)*



Comparison between the D/H ratio and the HDO/H_2O ratio inside comets and protostars
Tobin et al. 2023

L1551 IRS5

- Class I protostar *(Chen et al. 1995)* and FUor object *(Connelley & Reipurth 2018)*
- Binary system N and S separated by 0.36'' *(Biegen & Cohen 1985)*
- Located in the L1551 molecular cloud in the Taurus star forming region *(Strom et al. 1976)*, at ~155pc *(Zucker et al. 2019)*
- Relatively isolated *(Adams 2010)*
- L_{bol} = 30-40 $L_{\odot}$ with $L_N > L_S$ *(Liseau et al. 2005)*



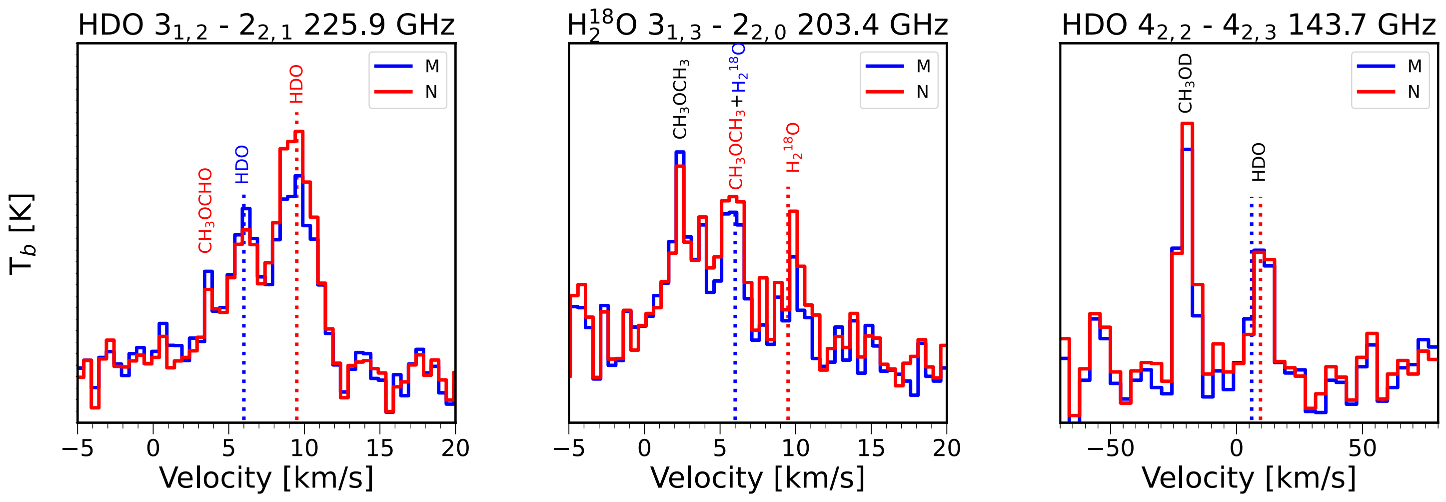
L1551 molecular cloud
Roccatagliata et al. 2020

NOEMA observations

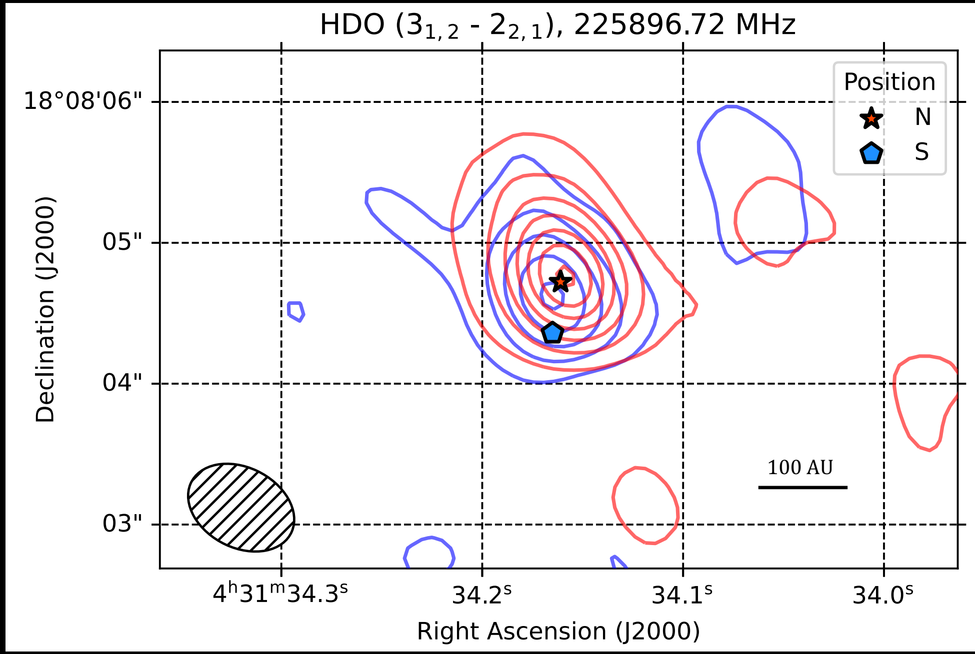
Molecule	Transition	Frequency [MHz]	E_{up} [K]	A_{ij} [s^{-1}]	g_{up}	Beam size [$'' \times ''$]	PA [°]	rms [mJy beam^{-1}]	dv [km s^{-1}]	Project
HDO	$3_{1,2}$ - $2_{2,1}$	225896.72	168	1.3×10^{-5}	7	0.76 × 0.51	21.7	4.2	0.5	W18AO
$H_2^{18}O$	$3_{1,3}$ - $2_{2,0}$	203407.52	204	4.8×10^{-6}	7	0.83 × 0.57	24.0	3.7	0.5	W18AO
HDO	$4_{2,2}$ - $4_{2,3}$	143727.21	319	2.8×10^{-6}	9	2.51 × 2.05	37.1	2.1	4.0	S16AE

NOEMA interferometer, *credits: Karin ZACHER*

- Two components with different velocities (~ 6.0 km.s^{-1} and ~ 9.5 km.s^{-1})
- Compact emission ~ 220 AU



Spectra superposition, *Andreu et al. to be submitted*



Integrated emission maps *Andreu et al. to be submitted*

Temperature dependency

- Derived column density from gaussian fitting of the lines assuming LTE conditions

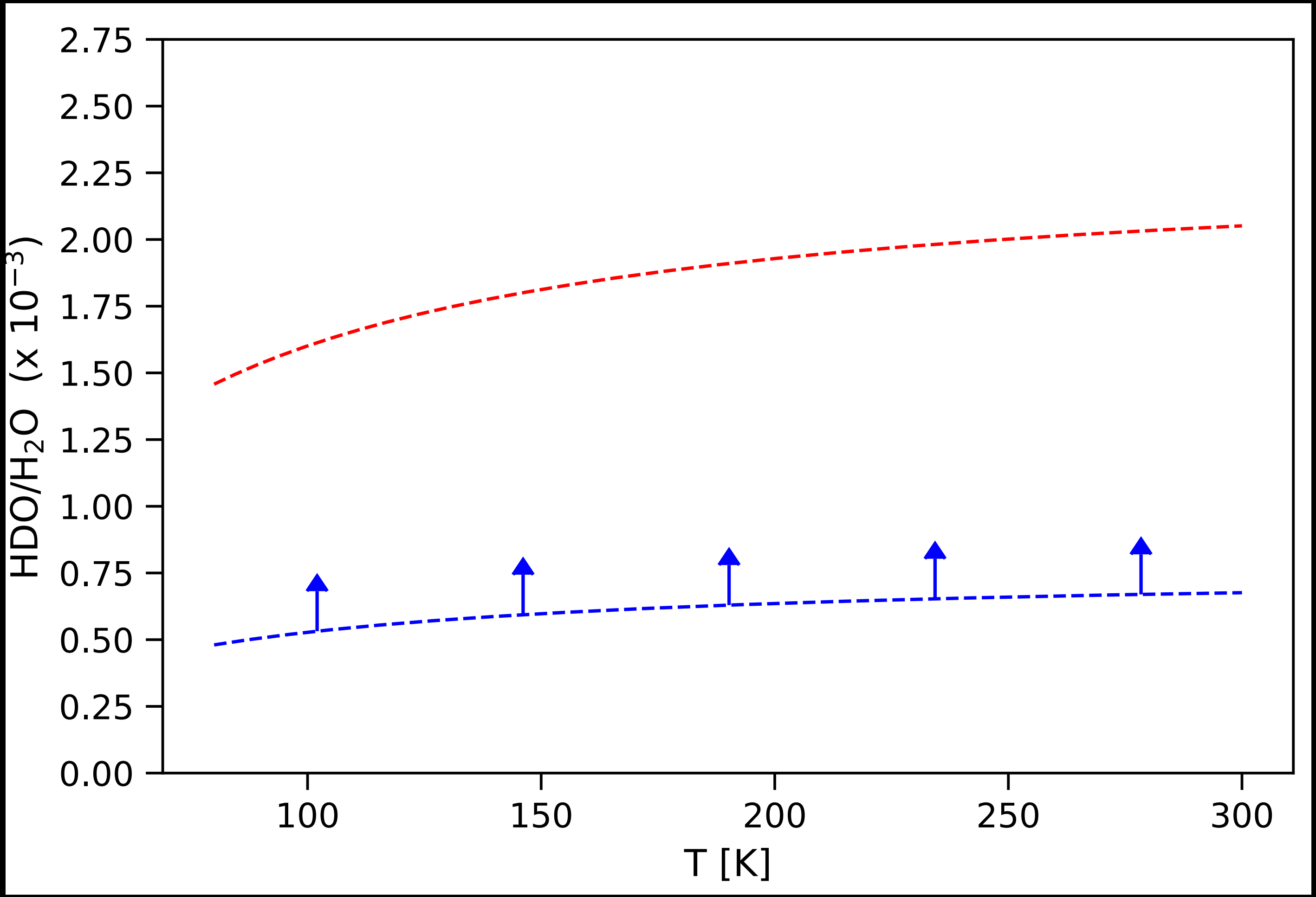
- Obtained the HDO/H_2O ratios using $^{16}O/^{18}O$ = 560 *(Wilson & Rood 1994)*

  $$HDO/H_2O = \frac{N(HDO)}{560\ N(H_2{}^{18}O)}$$

- N depends on θ_s and Tex

- Source sizes found from circular gaussian fitting of the emission in the uv-plane

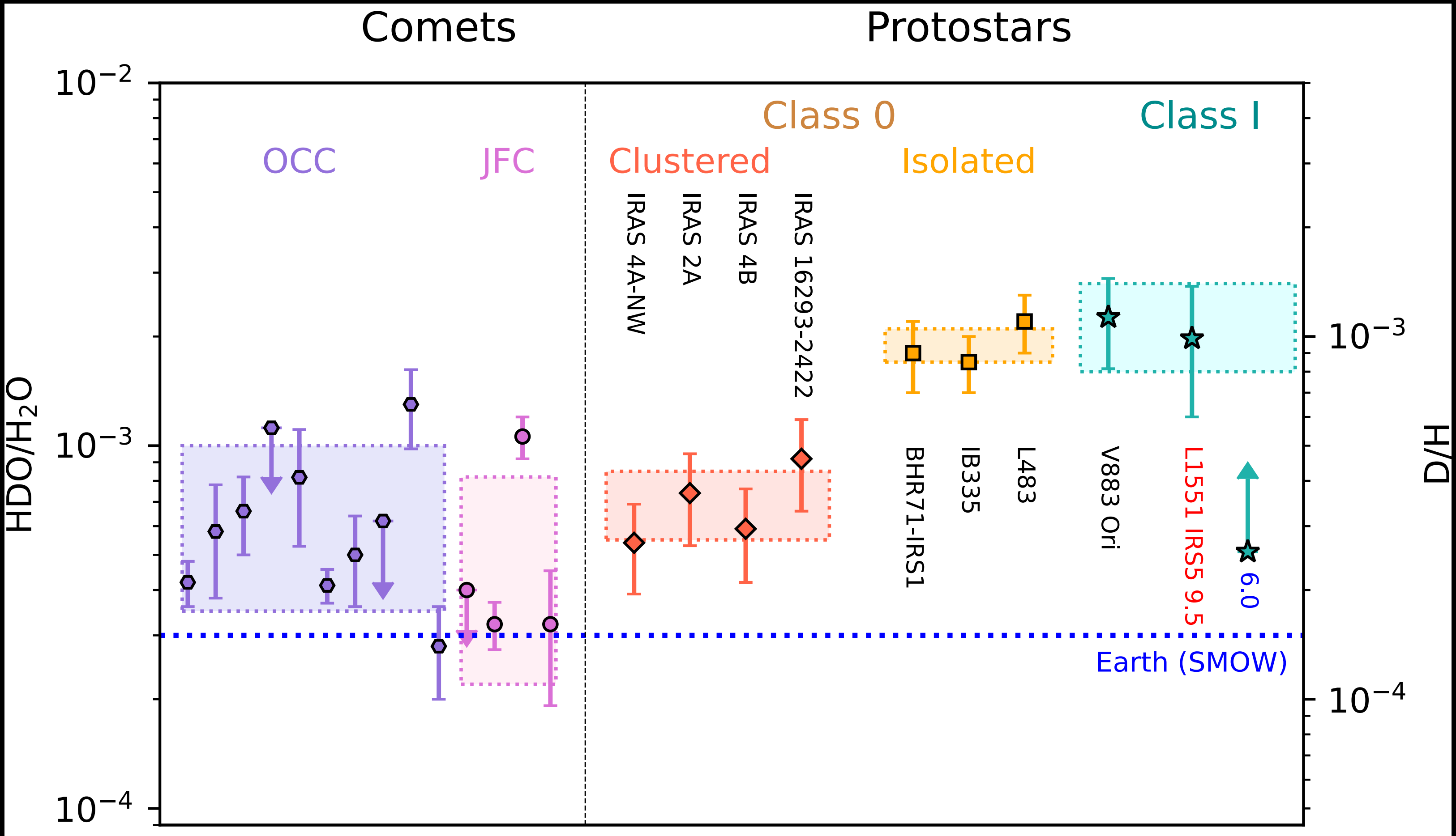
- Ratio almost constant above 150 K



T-dependence in the HDO/H_2O ratio, *Andreu et al. to be submitted*

Ratio comparison

$HDO/H_20 = (2.0 \pm 0.8) \times 10^{-3}$ $HDO/H_20 > 0.5 \times 10^{-3}$



Comparison of HDO/H_2O ratios in comets and protostars.
Andreu et al. to be submitted, adapted from *Jensen et al. 2019*

Discussion

- HDO/H_2O almost independent of θ_s and T_{ex} (source parameters)
- Ratio of relatively isolated Class I L1551 IRS5 similar to isolated Class 0 protostars
- Ratio of binary Class I L1551 IRS5 similar to single Class I V883 Ori
- Seems no evolution in the ratio during star formation process

Thank you for your attention

Audrey ANDREU

astrophysique & planétologie

European Research Council
Established by the European Commission

Deuteration

- Replacement of a H for a D atom

$H^+ + D \leftrightarrow H + D^+$

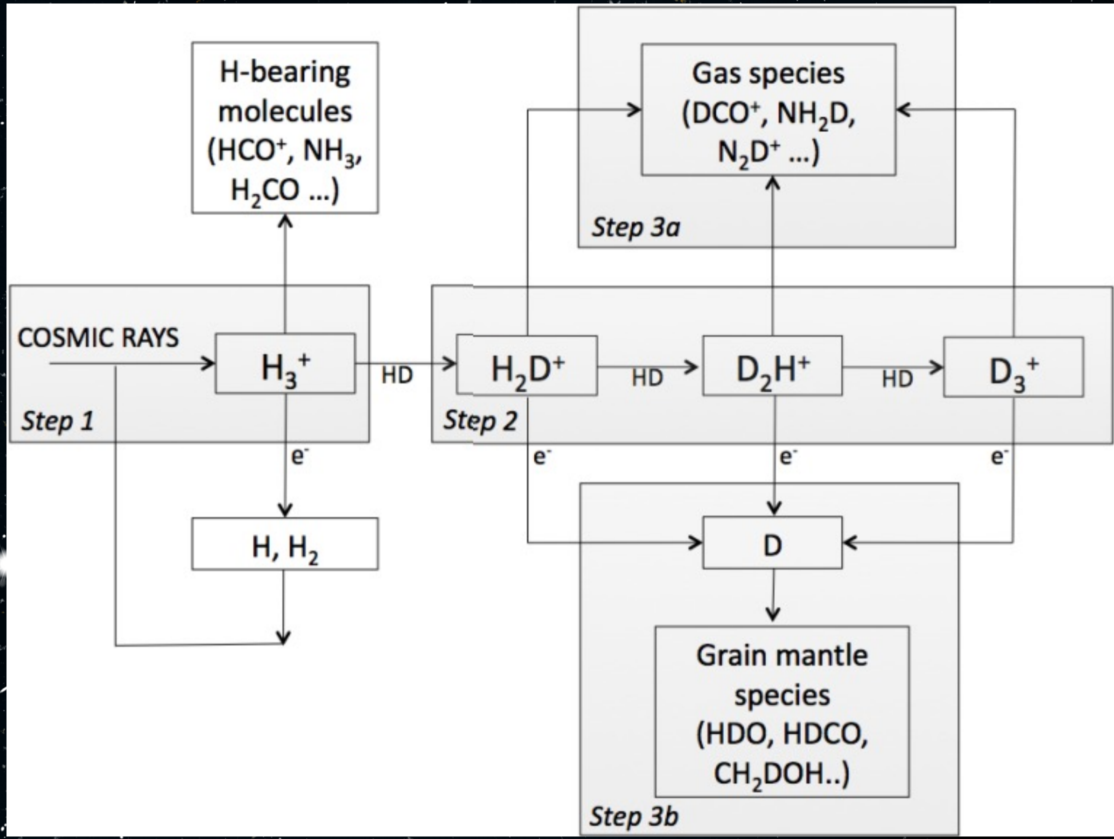
$D^+ + H_2 \rightarrow HD + H^+ + \Delta E_1$

$D^+ + HD \rightarrow D_2 + H^+ + \Delta E_2$

$H_3^+ + HD \rightarrow H_2 + H_2D^+ + \Delta E_3$

- Effective when temperature is low

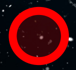
- Deuteration very sensitive to the physical conditions in which molecules form *(Ceccarelli et al. 2014)*



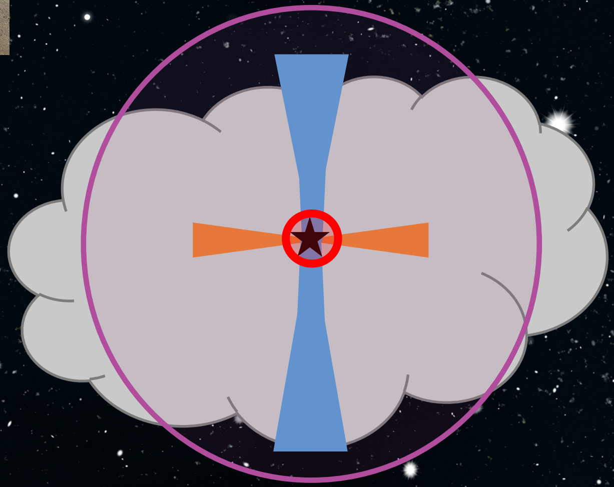
Deuterium fractionation processes in cold gas
Ceccarelli et al. 2014

Interferometer VS single-dish

Credits: Karin ZACHER



Beam size comparison



Water deuteration with single-dish telescopes

- e.g, IRAS16293-2422, NGC1333 IRAS4A and IRAS4B, SVS13-A *(e.g., Liu et al. 2011, Coutens et al. 2013, Codella et al. 2016)*

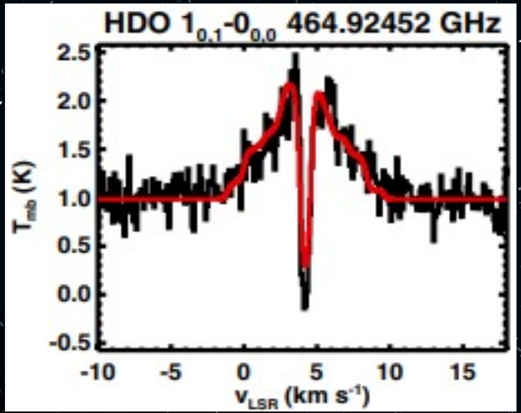
- HDO/H_2O ~ 5% in the photodesorption layer and D_2O/H_2O ~ 0.5% *(Coutens et al. 2013a)*

- Deuteration of water lower than formaldehyde and methanol

- $^{16}O/^{18}O$ = 560 *(Wilson and Rood 1994)*

$$HDO/H_2O = \frac{N(HDO)}{560\,N(H_2{}^{18}O)}$$

Artist concept of the Herschel Space Observatory in space, Herschel Caltech website



Example of HDO line in absorption
Coutens et al. 2012

IRAM 30m, credits: Karin ZACHER

Clustered vs Isolated

Clustered = group of stars physically related, “a group of 35 or more physically related stars whose stellar mass density exceeds $1.0 M_{\odot}/pc^3$ *(Lada et al. 2003)*

$\langle n_c \rangle \gtrsim 10^6 - 10^7$ cm^{-3}, more compact, $diameter_{cluster} \sim 0.02\text{-}0.03$ pc, more closely spaced $l_{cluster} \sim 0.03$ pc
Taurus cores isolated: $\langle n_{isolated} \rangle \gtrsim 10^5$ cm^{-3}, $D_{isolated} \sim 0.1$pc, $l_{isolated} \sim 0.25$ pc *(Ward-Thompson et al. 2007)*

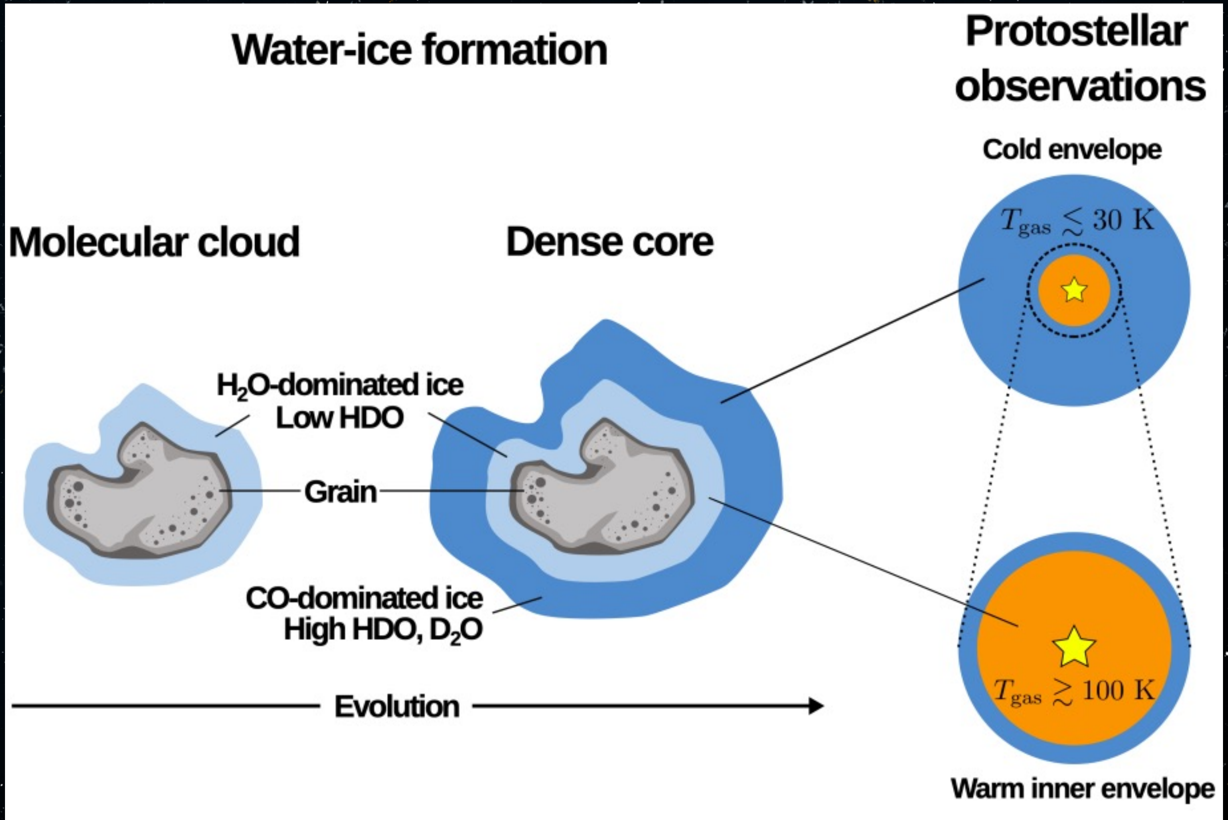
Presence (clustered) or absence (isolated) of a massive protostar, > 25 YSO/pc^2 or < 10 YSO/pc^2 *(Bergin et al. 2023)*

density of sources in the Taurus only a few tens in ~1 pc^3 *(Gomez et al. 1993)*
in Ophiuchus and in NGC1333, a few 10^2–10^3 *(Bontemps et al. 2001; Jørgensen et al. 2006)*

Model of surface grain chemistry

Chemical model developed by *Furuya et al. 2015, 2016*. to explain observations:

Decreasing HDO/H_2O ratio from the external regions (~1%) to the internal ones



Schematics of the observed water deuterium fractionation towards embedded low-mass protostars
S. S. Jensen et al. 2021