

A fish out of water: unique observations of water in planet-forming disks



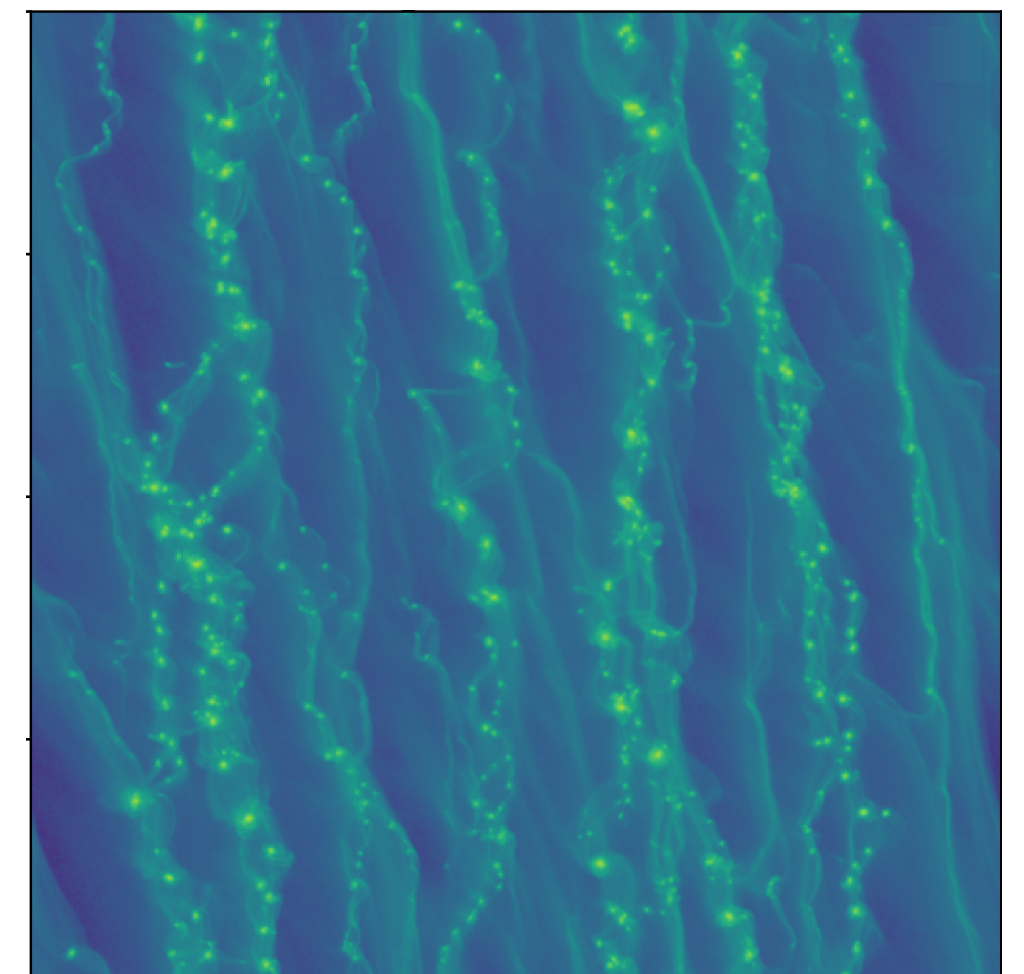
M. Leemker, S. Facchini, M. Benisty, A. S. Booth,
P. Curone, K. Furuya, A. Garufi, E. Humphreys,
M. L. R. van 't Hoff, L. Rampinelli, J.J. Tobin

Water (ice) is a key for planet formation

- Water is crucial for life known on Earth:
 - Great coolant during heatwaves
 - Good solvent
 - Major carrier of oxygen
- Water helps to form planets:
 - Streaming instability around snowline (e.g., Drażkowska et al. 2017, Schoonenberg et al. 2017)
 - Aid grain growth (Blum et al. 2008, Okuzumi et al. 2012)



Streaming instability



Trail of star and planet formation

Water ice
forms in cloud

**Does the water survive the journey from
cloud to disks and possibly planets?**

—> Inherit building blocks for life?

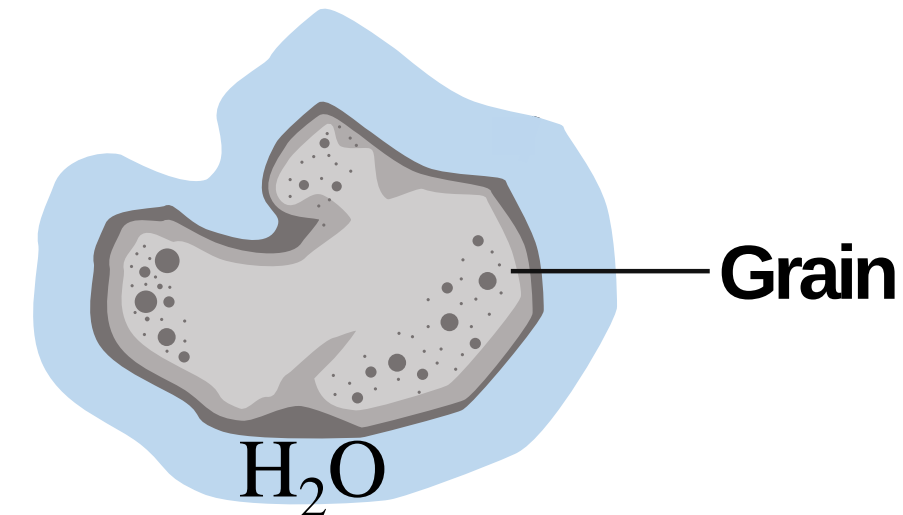
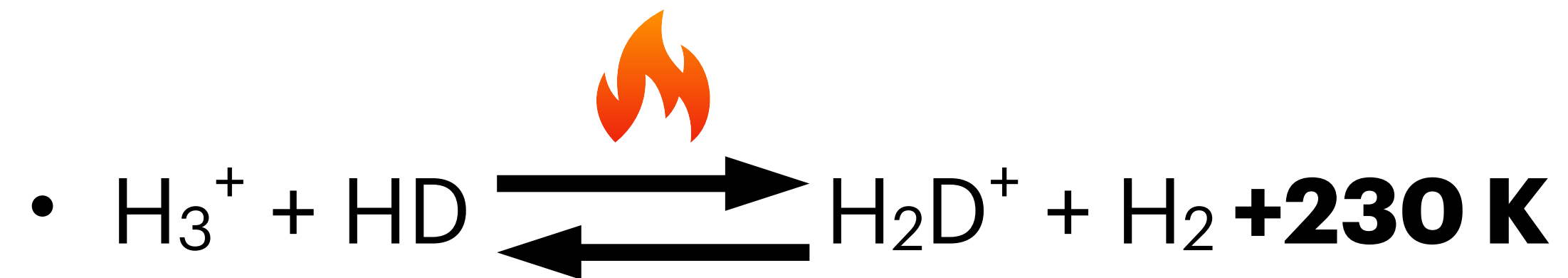
**Where is the water
located in disks?**

Layering of water isotopologues

Deuteration

cloud

- ISM D/H = 2×10^{-5} (Linsky et al. 2003)

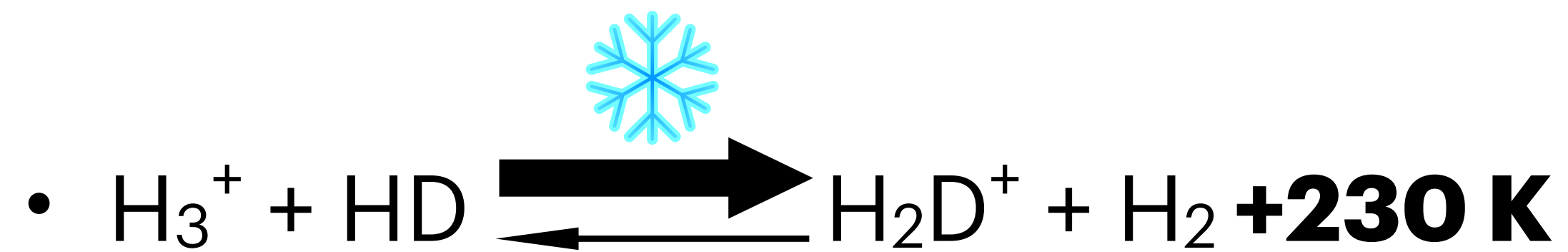


- $T > 25 \text{ K}$
- D **not** effective
- H_2O

Layering of water isotopologues

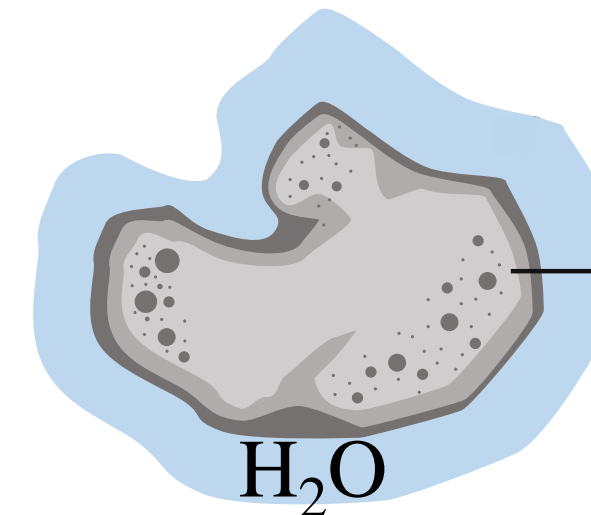
Deuteration

- ISM D/H = 2×10^{-5} (Linsky et al. 2003)



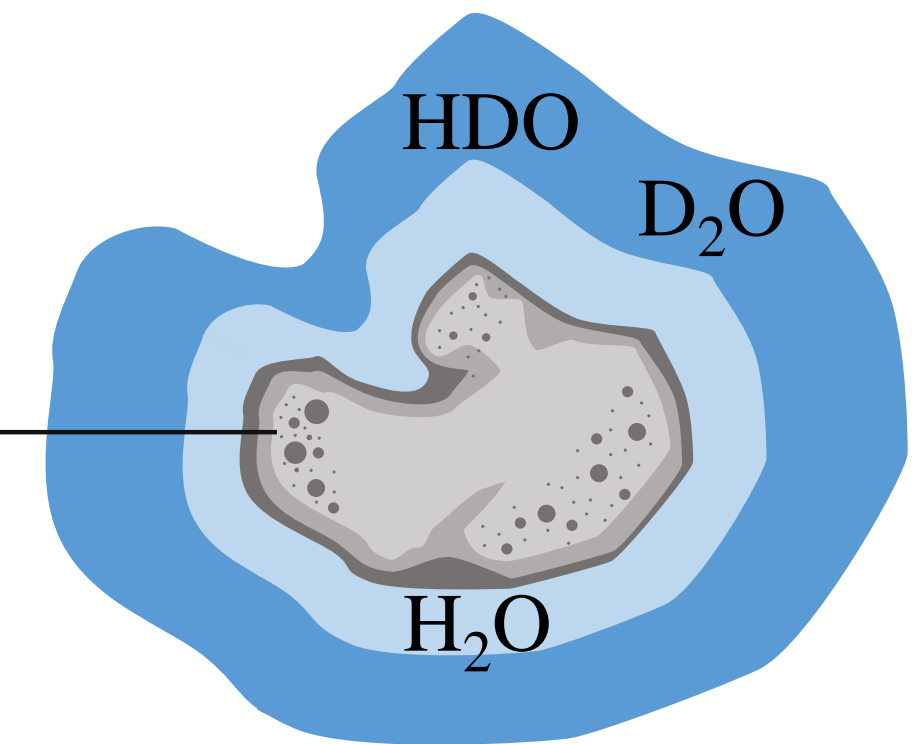
- Layered ice structure with different degrees of deuteration

cloud



Grain

dense core



- | | |
|--------------------------|-----------------------------|
| • $T > 25 \text{ K}$ | • $T < 25 \text{ K}$ |
| • D not effective | • D is effective |
| • H_2O | • HDO, D_2O |

Distinguishing inheritance vs reprocessing

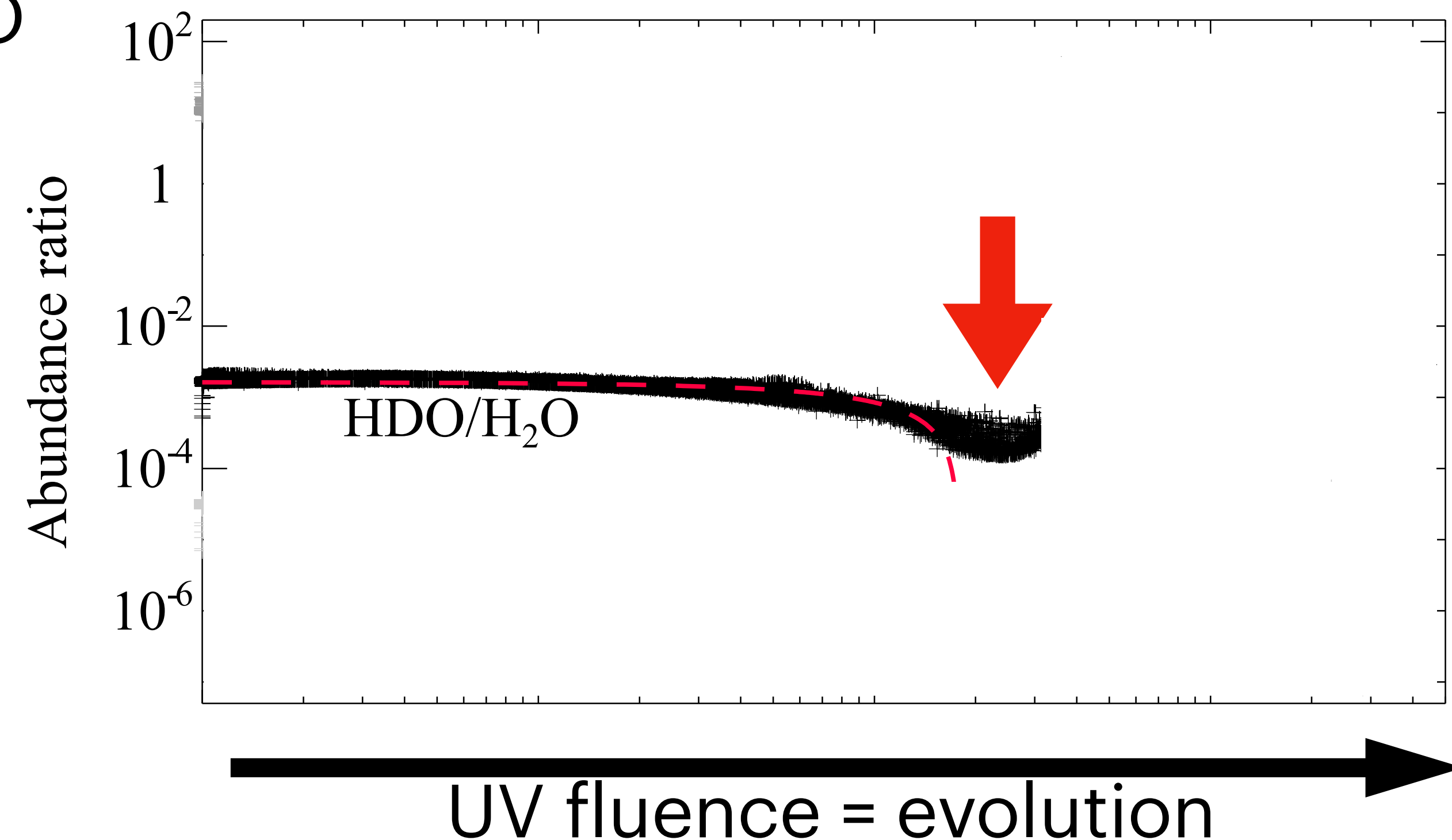
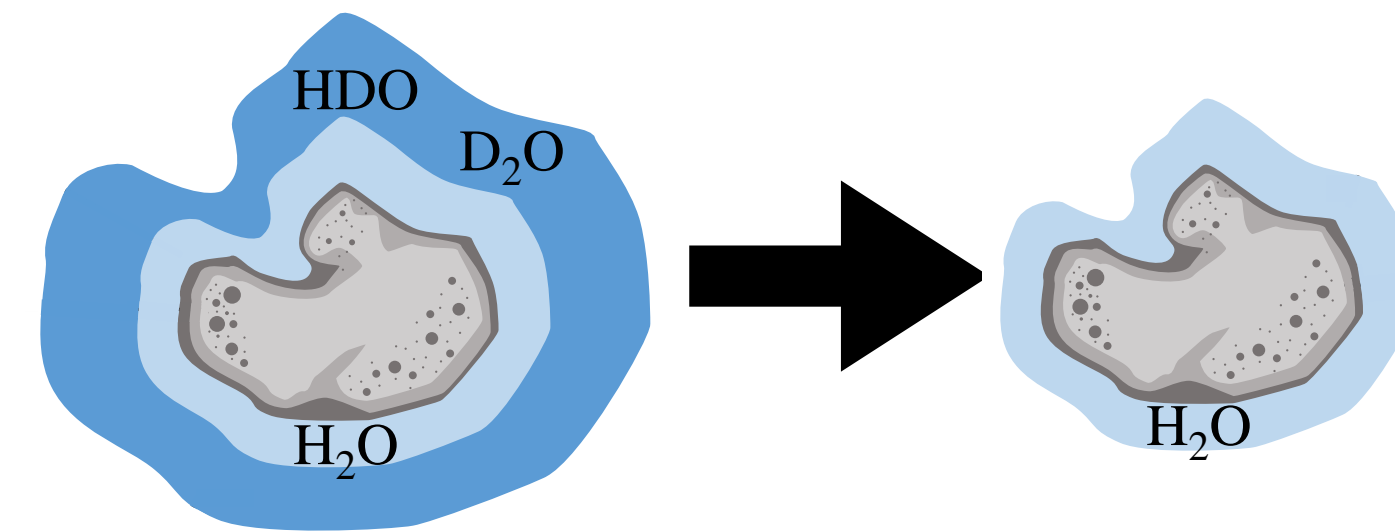
- Inheritance:

- High abundance of HDO w.r.t. H₂O

- Reprocessing:

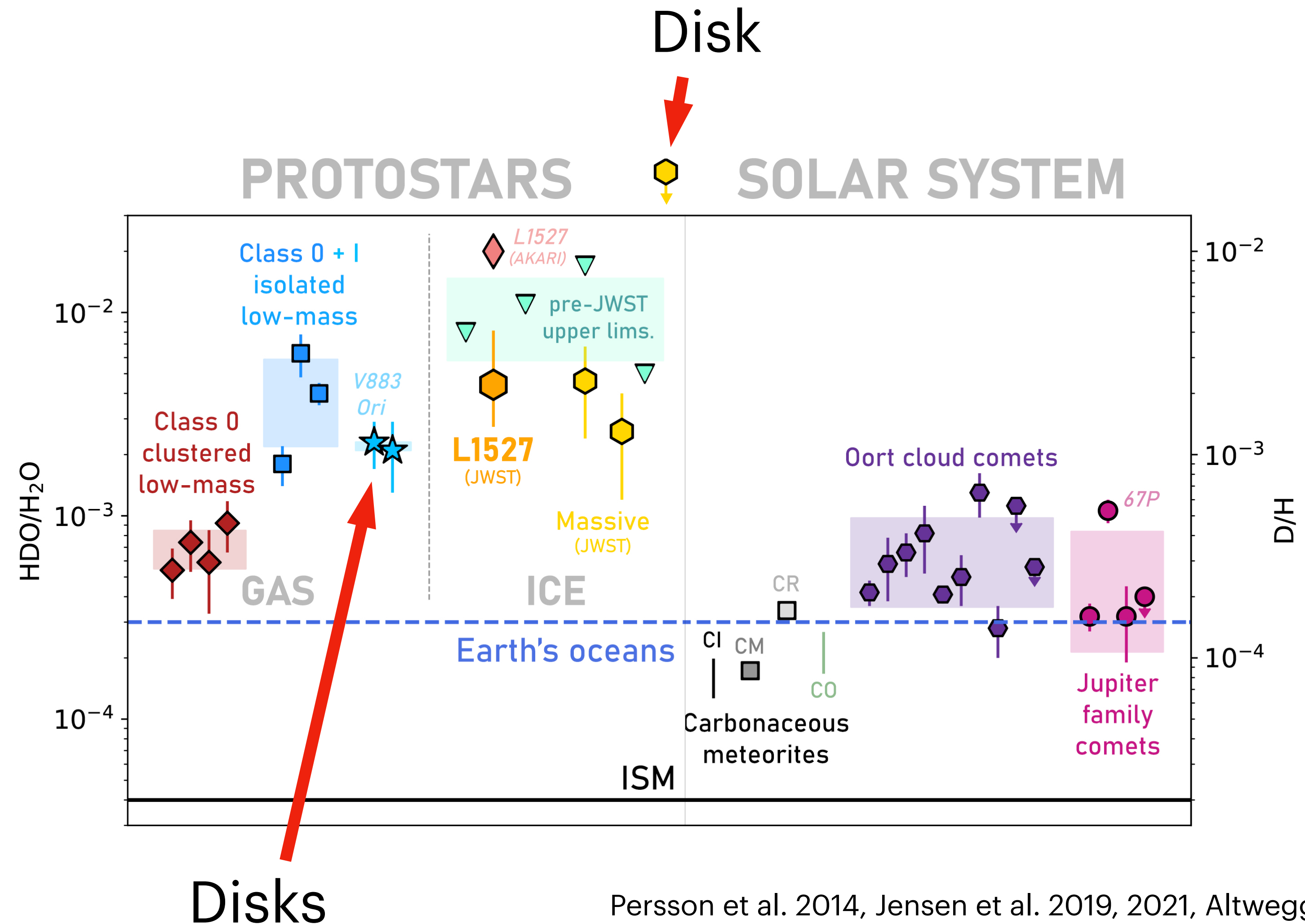
- Low HDO abundance w.r.t. H₂O

- HDO/H₂O traces inheritance vs reset*



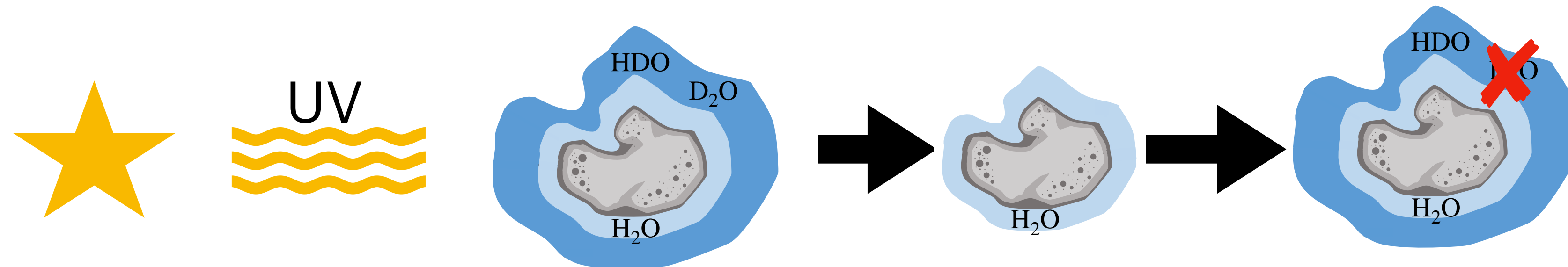
Water trail: HDO/H₂O

- Observe HDO
- Observe H₂¹⁸O x 560 (or H₂O for some comets)
- HDO/H₂O is higher than expected from the ISM
- **No significant chemical alteration of water**

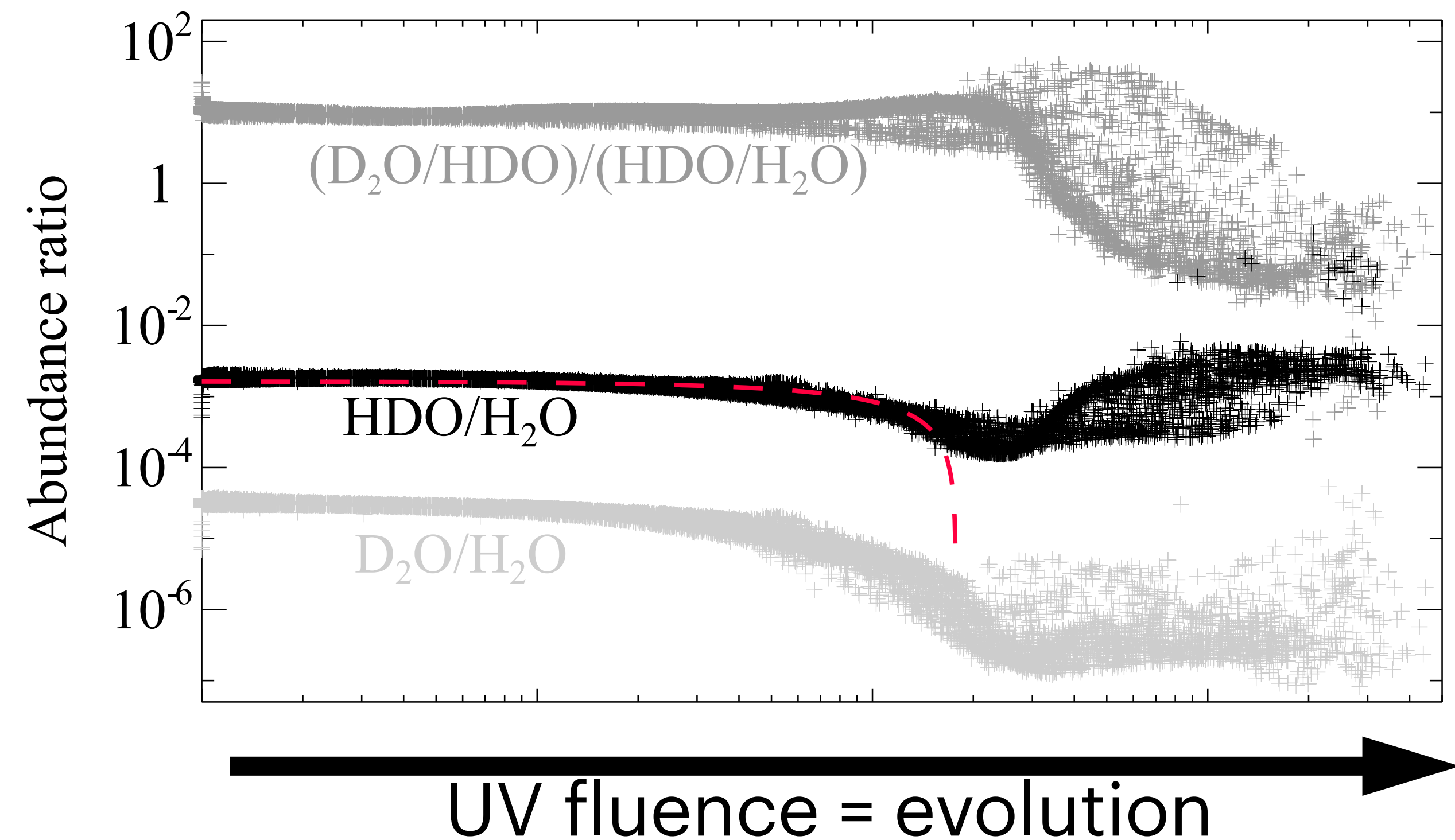


Persson et al. 2014, Jensen et al. 2019, 2021, Altwegg et al. 2015, 2019, Tobin et al. 2023, Andreu et al. 2023, Slavicinska et al. 2024, 2025, Potapov et al. 2026, and refs. therein

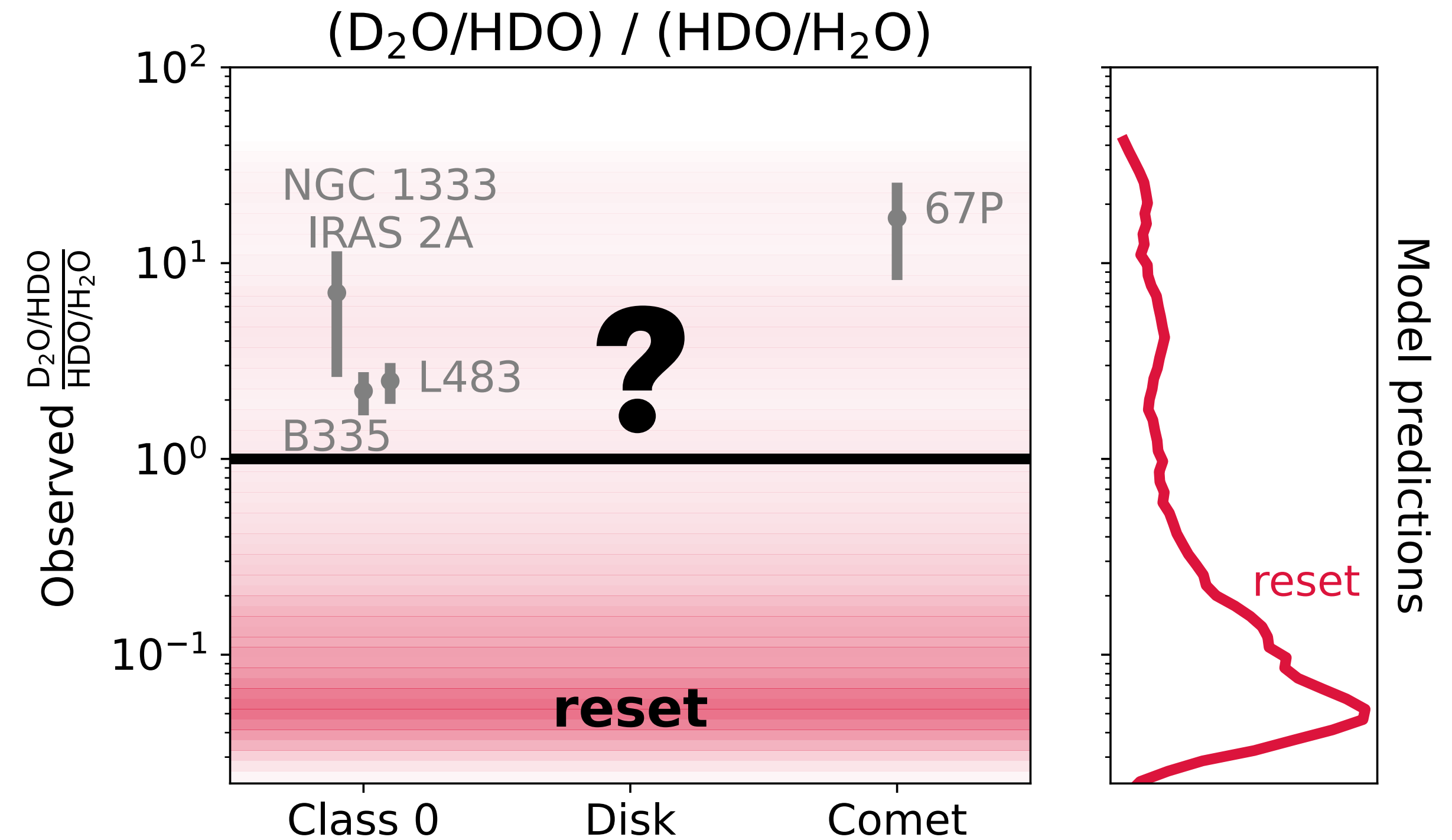
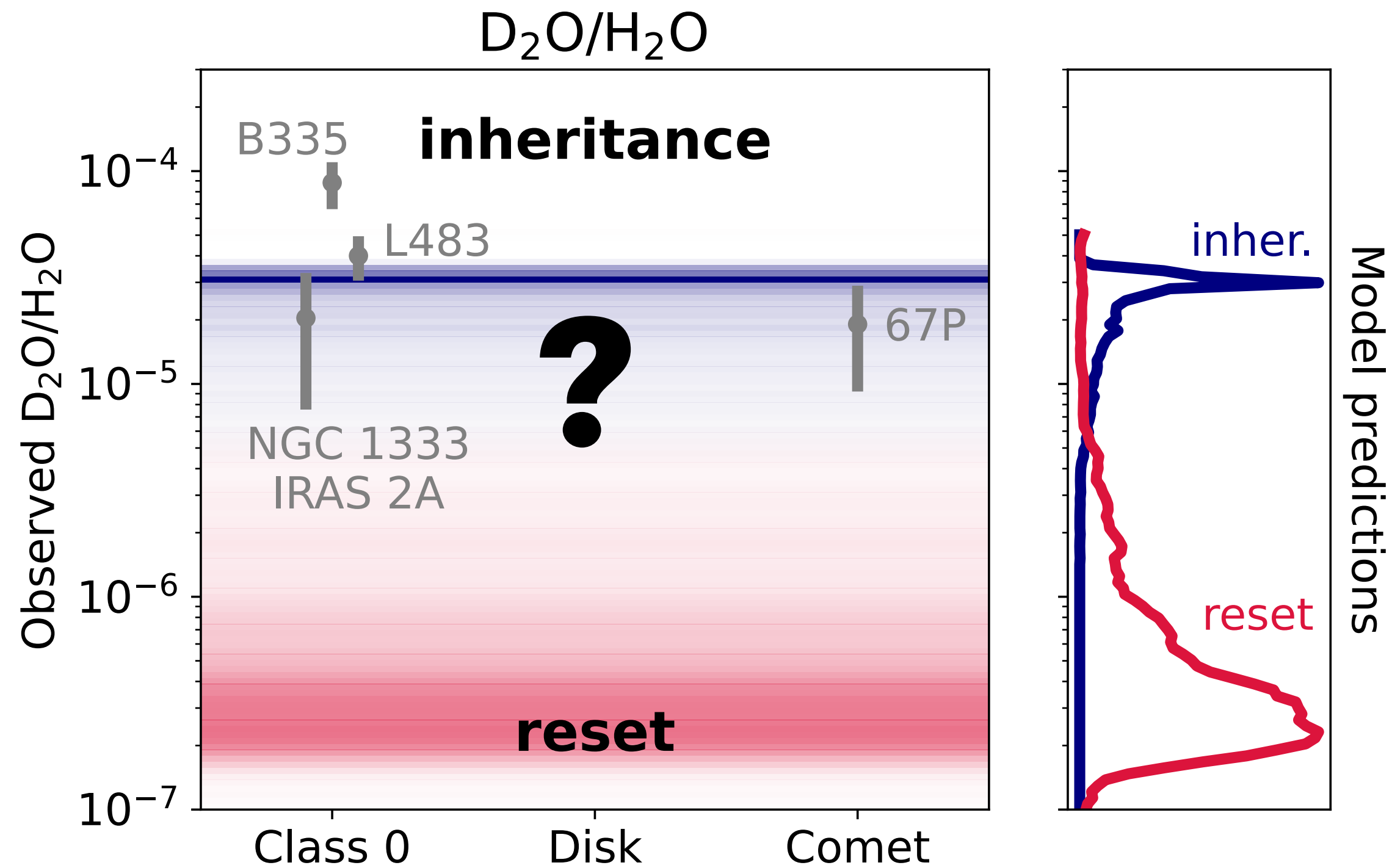
Distinguishing inheritance vs reprocessing



- HDO/H₂O traces inheritance vs reset*
- HDO/H₂O can be high even if water is reprocessed!
- Need D₂O to be sure about inheritance



Is water inherited?



- Observations of D_2O in disks are missing

V883 Ori

**water
snowline
@ 80 au**

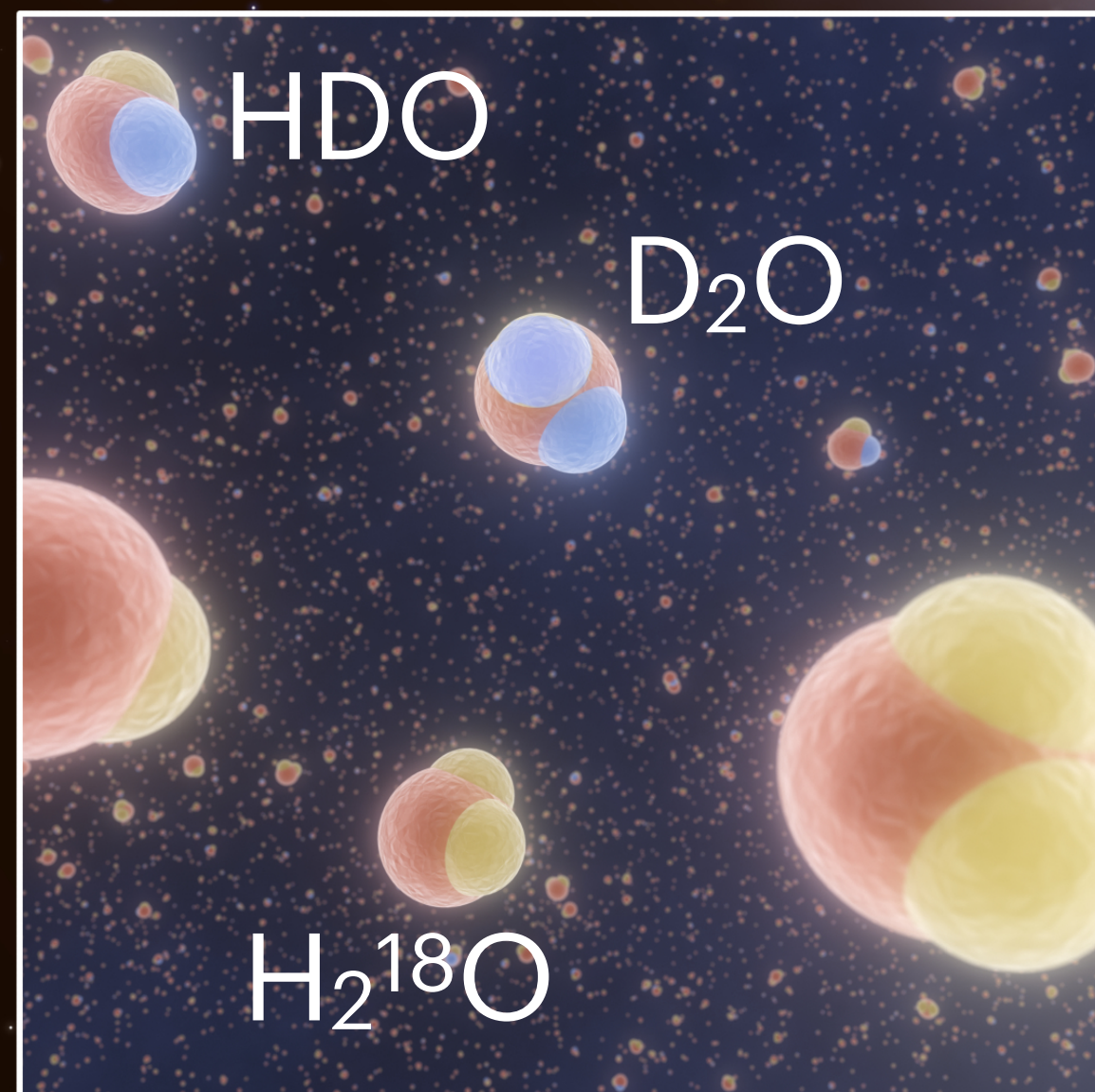
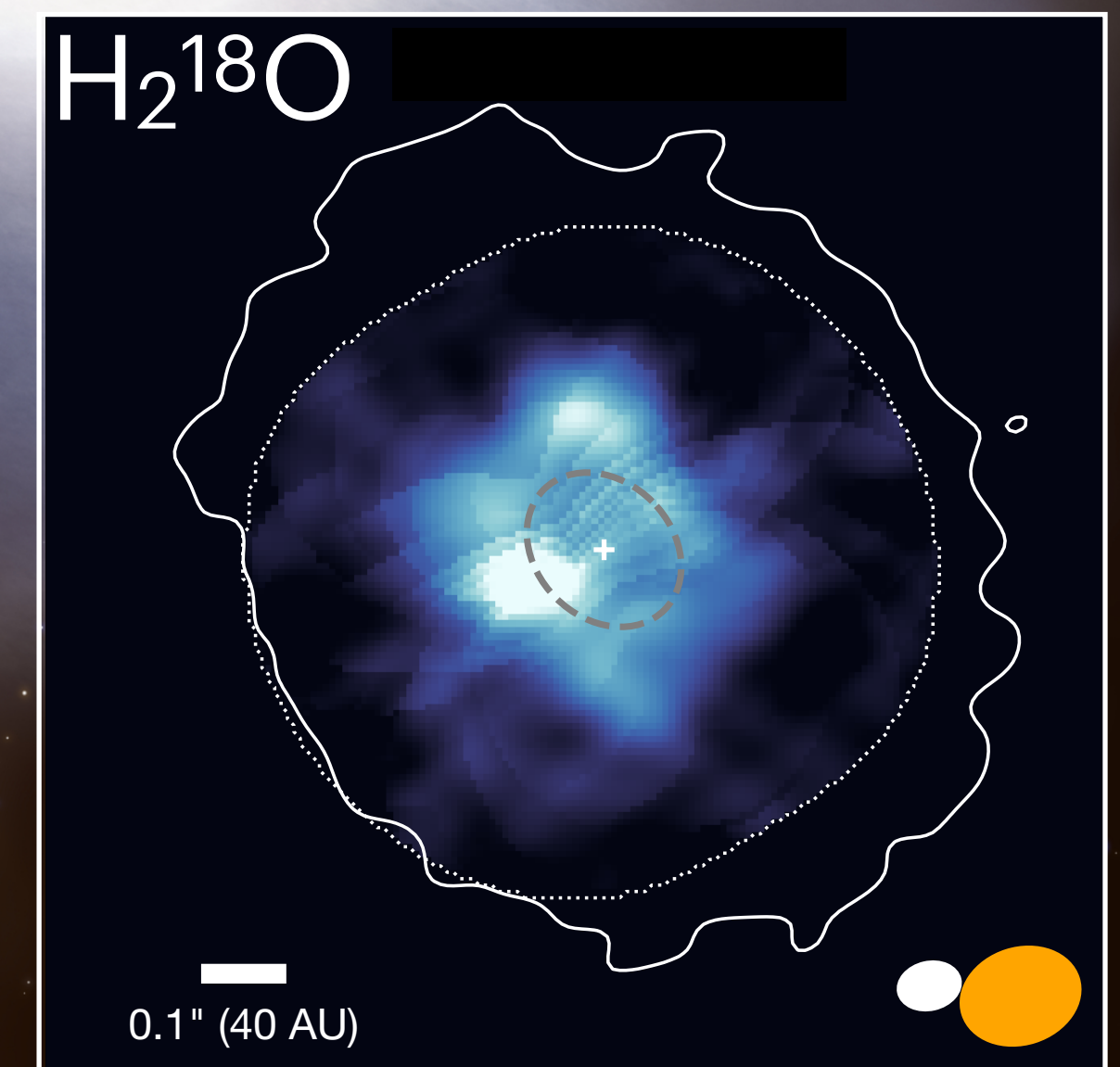
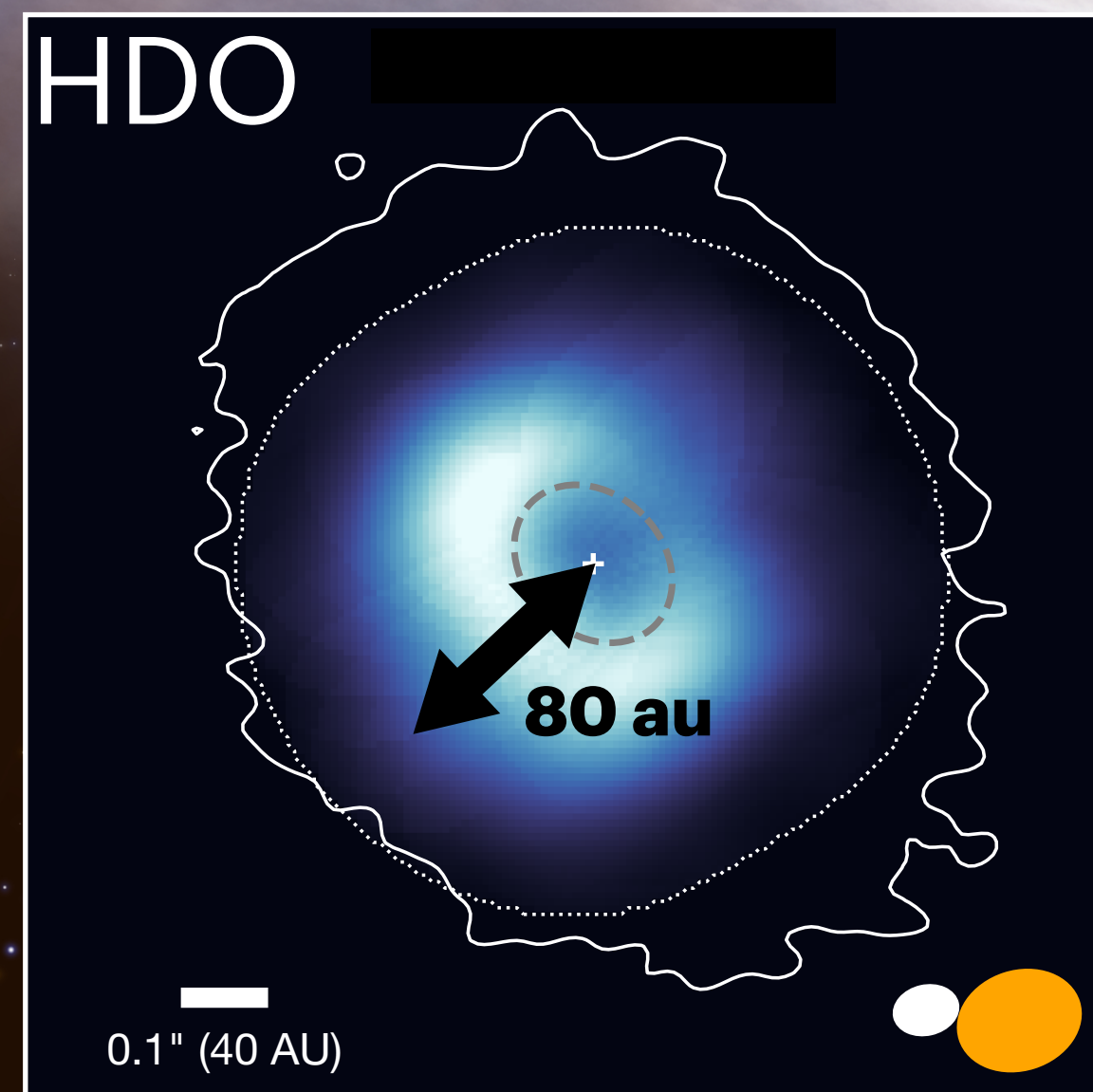


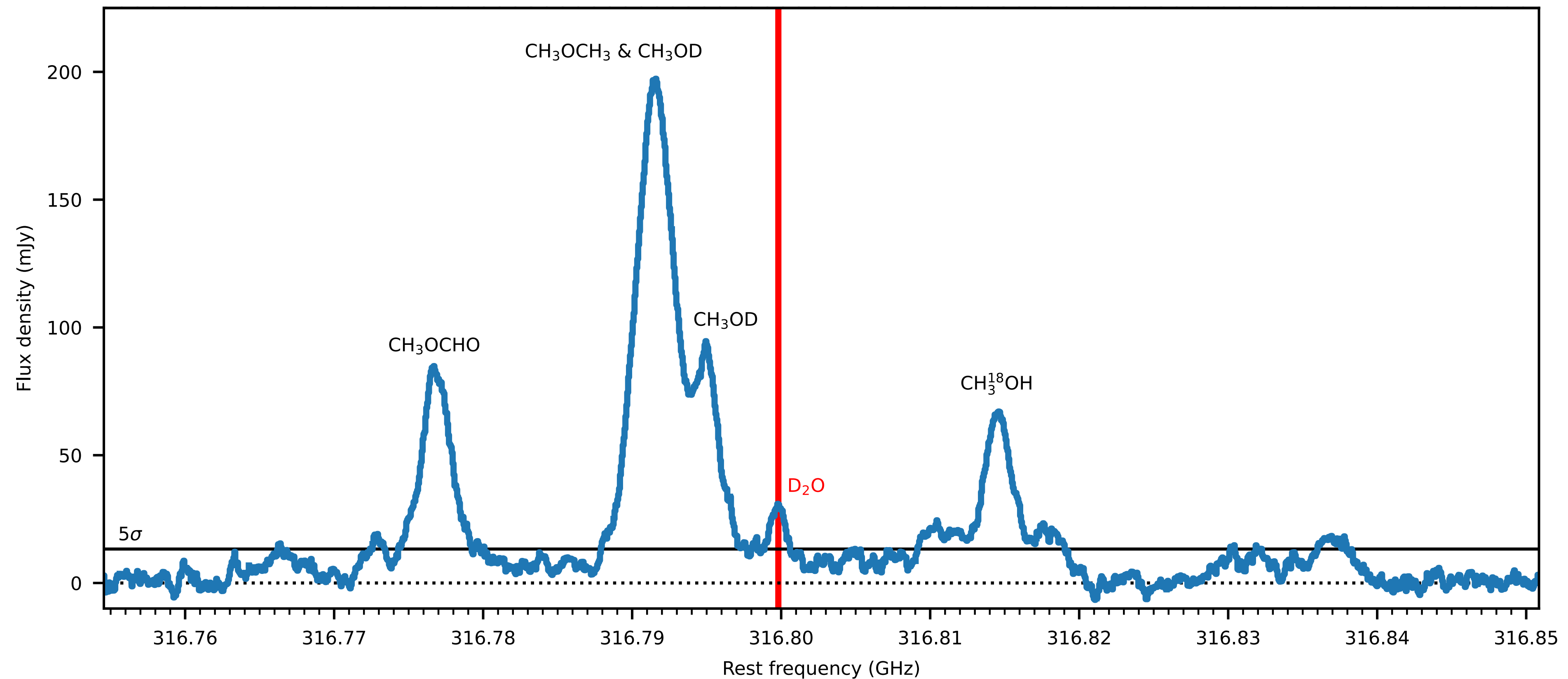
Image credit:
ESO/L. Calçada

e.g., Cieza et
al. 2016, van 't
Hoff et al. 2018,
Leemker et al.
2021, Tobin et
al. 2023, Wang
et al. 2025



D₂O observations in a disk

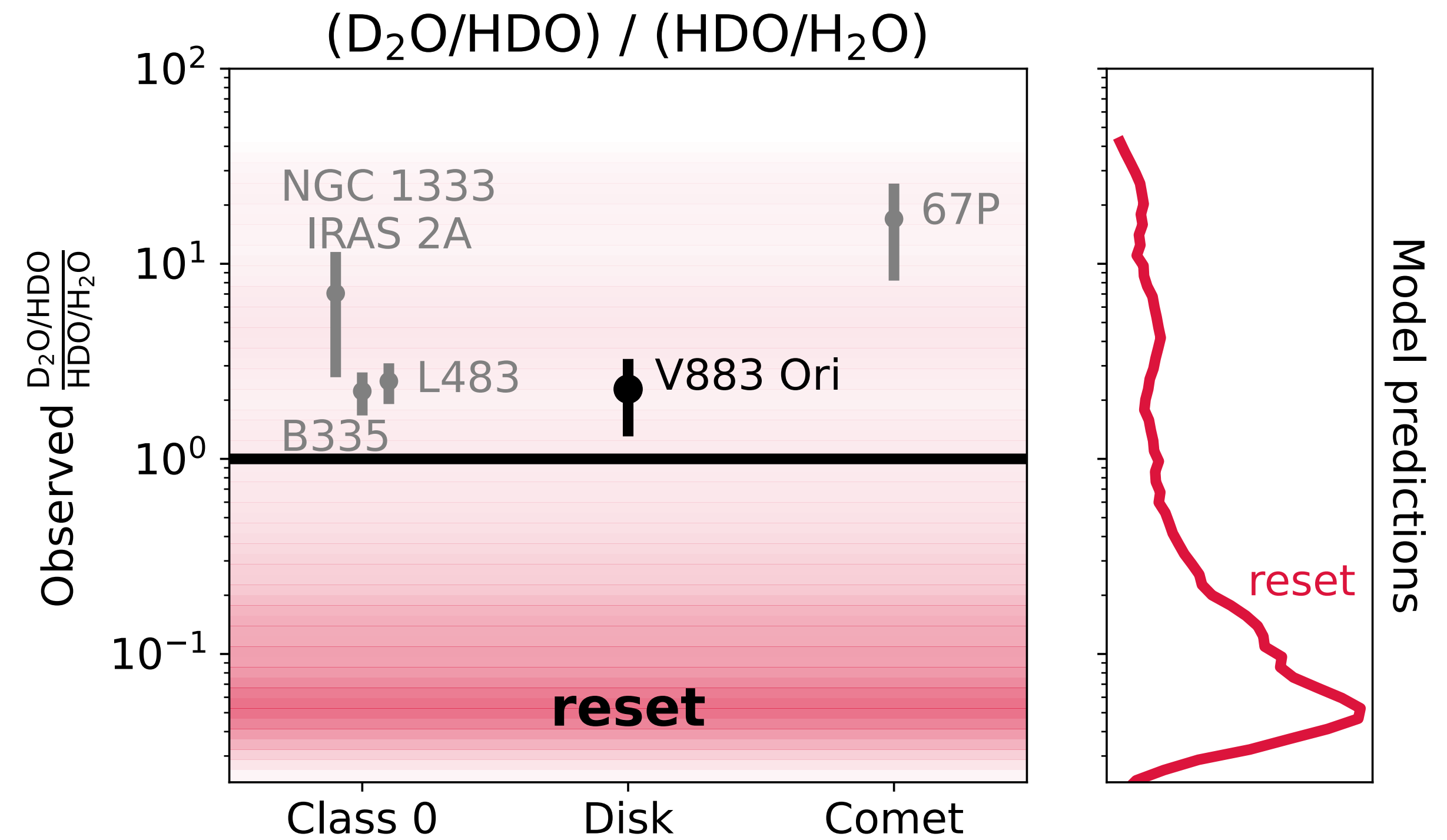
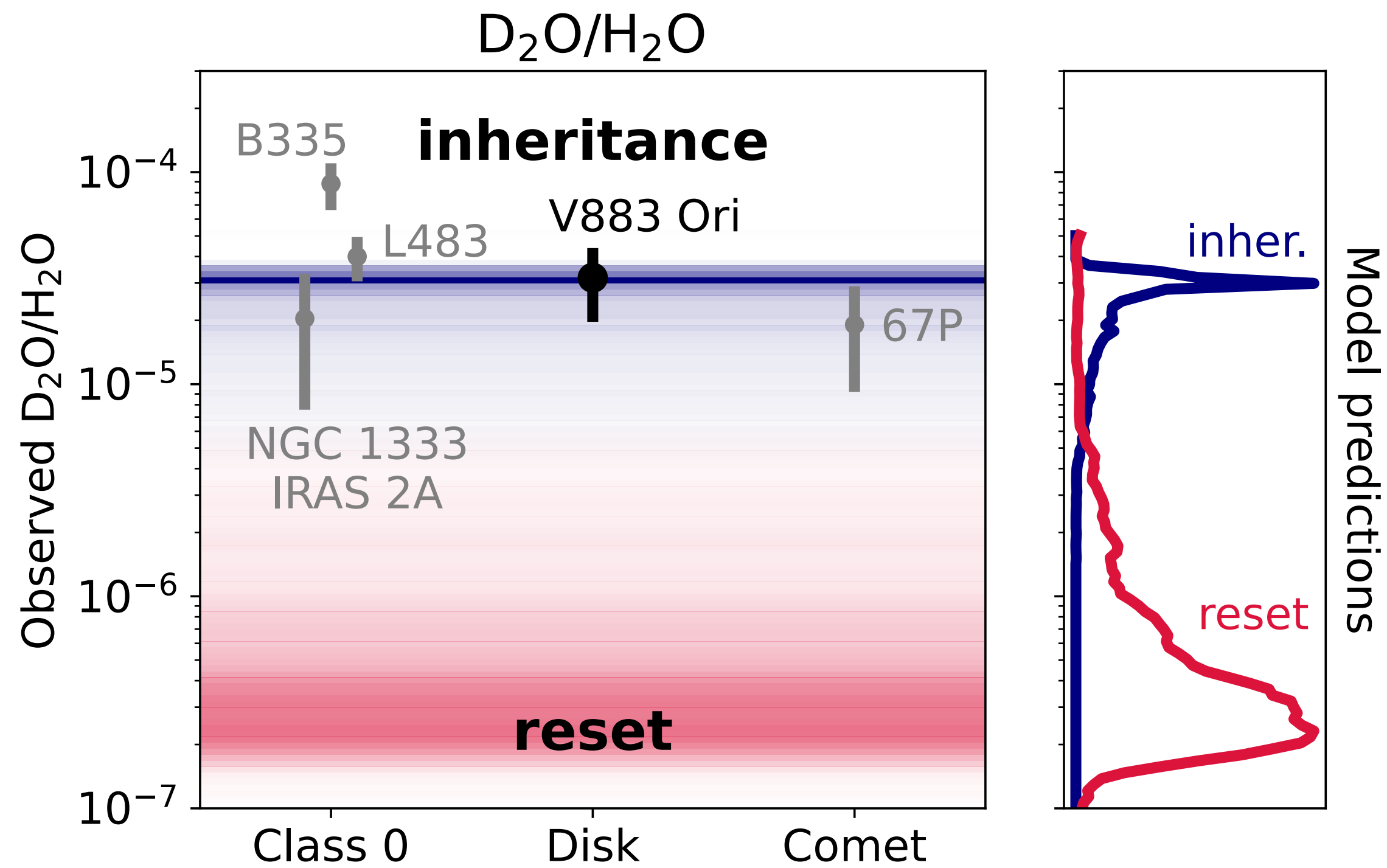
V883 Ori



First detection of D₂O in a disk

Is water inherited?

Yes!

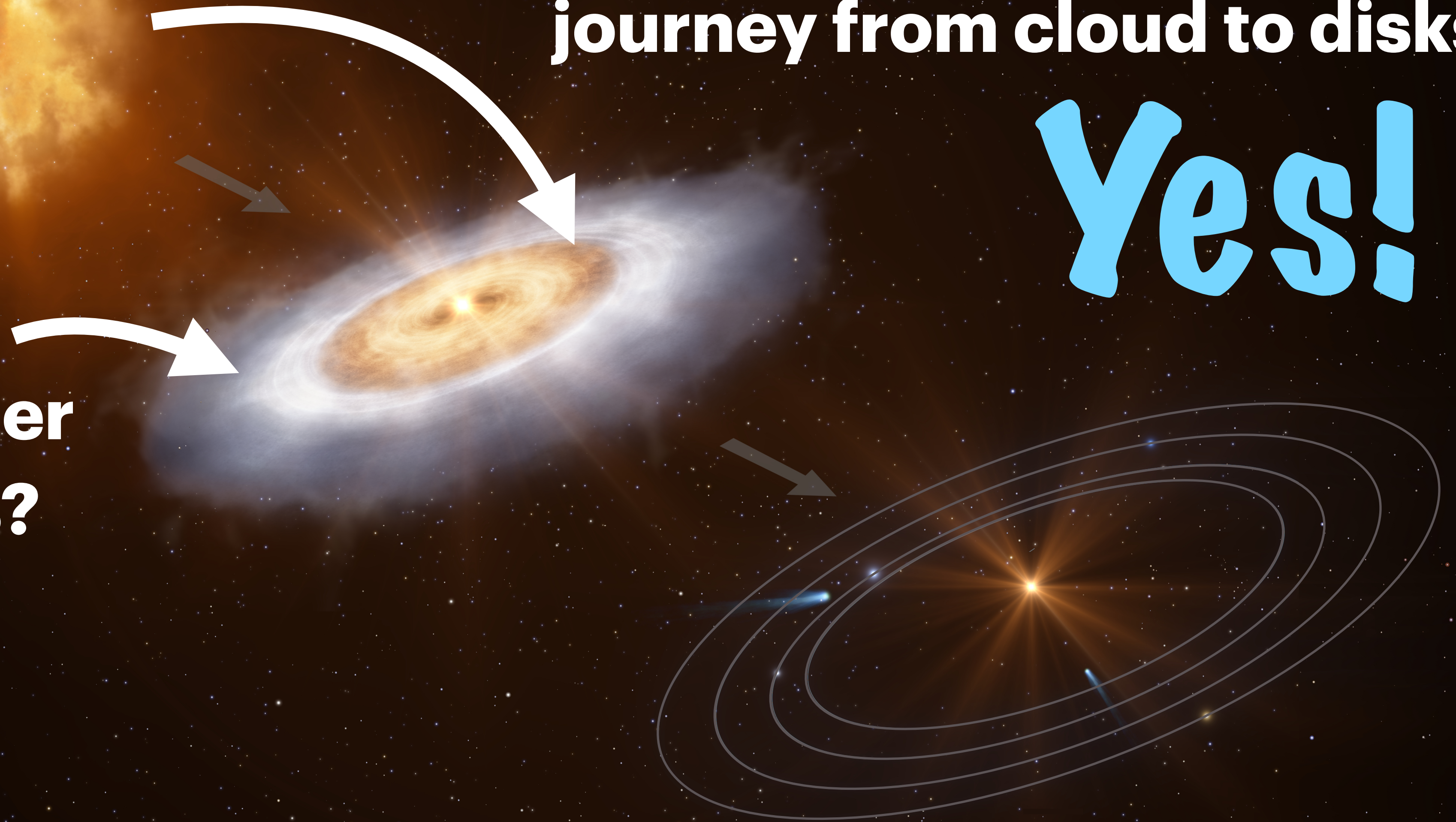


Trail of star and planet formation

Does the water survive the journey from cloud to disks?

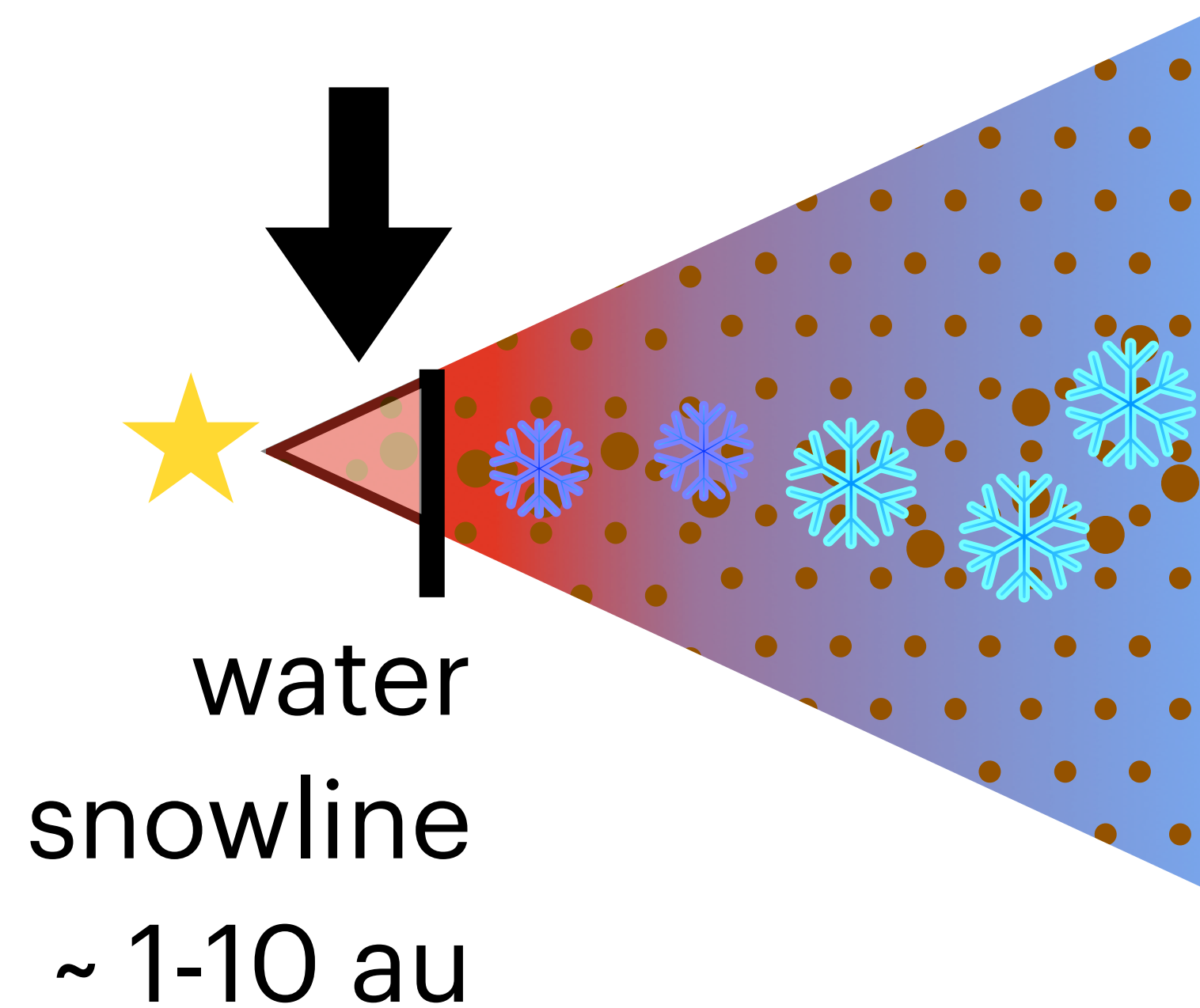
Yes!

Where is the water located in disks?

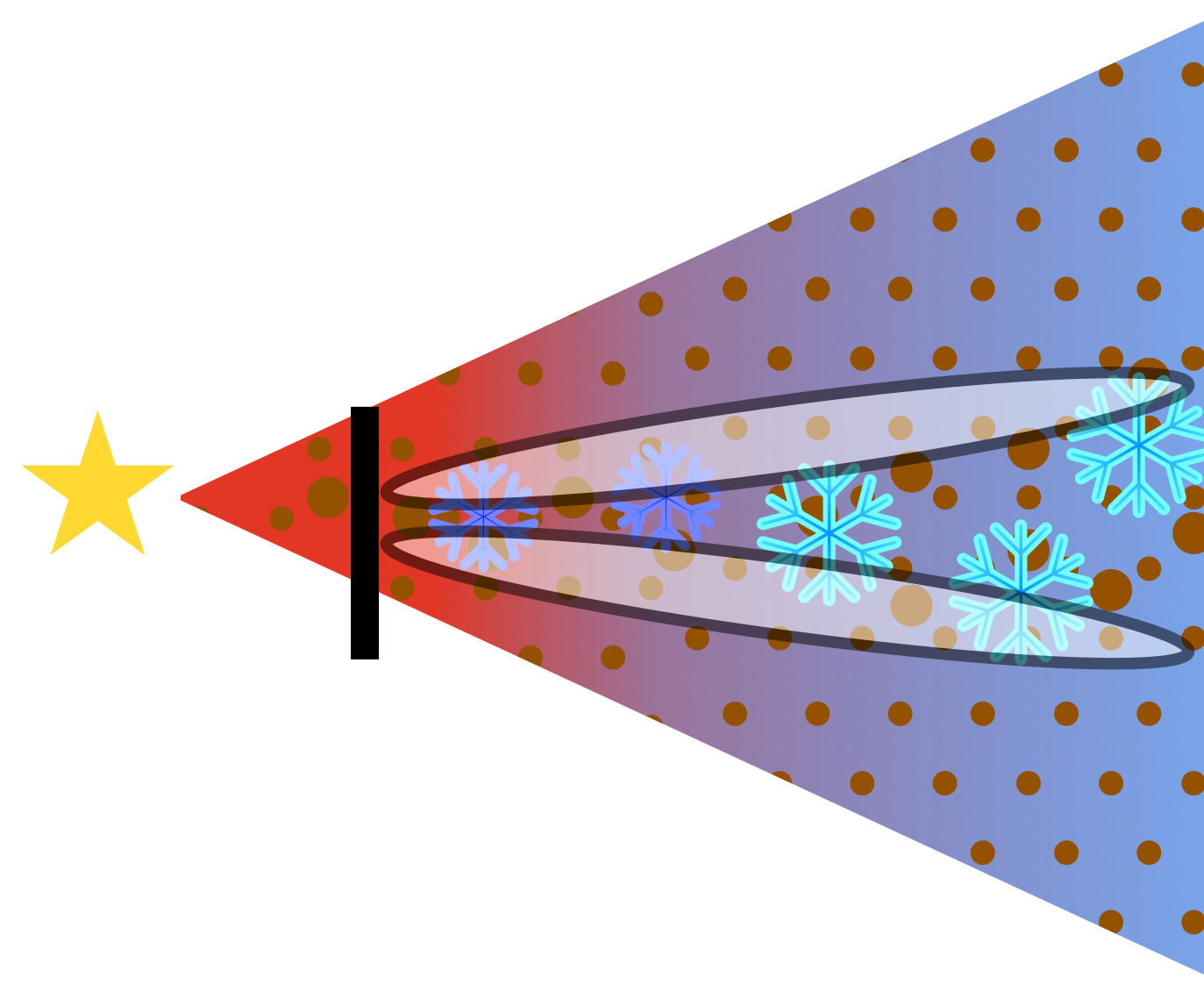


3 reservoirs of water

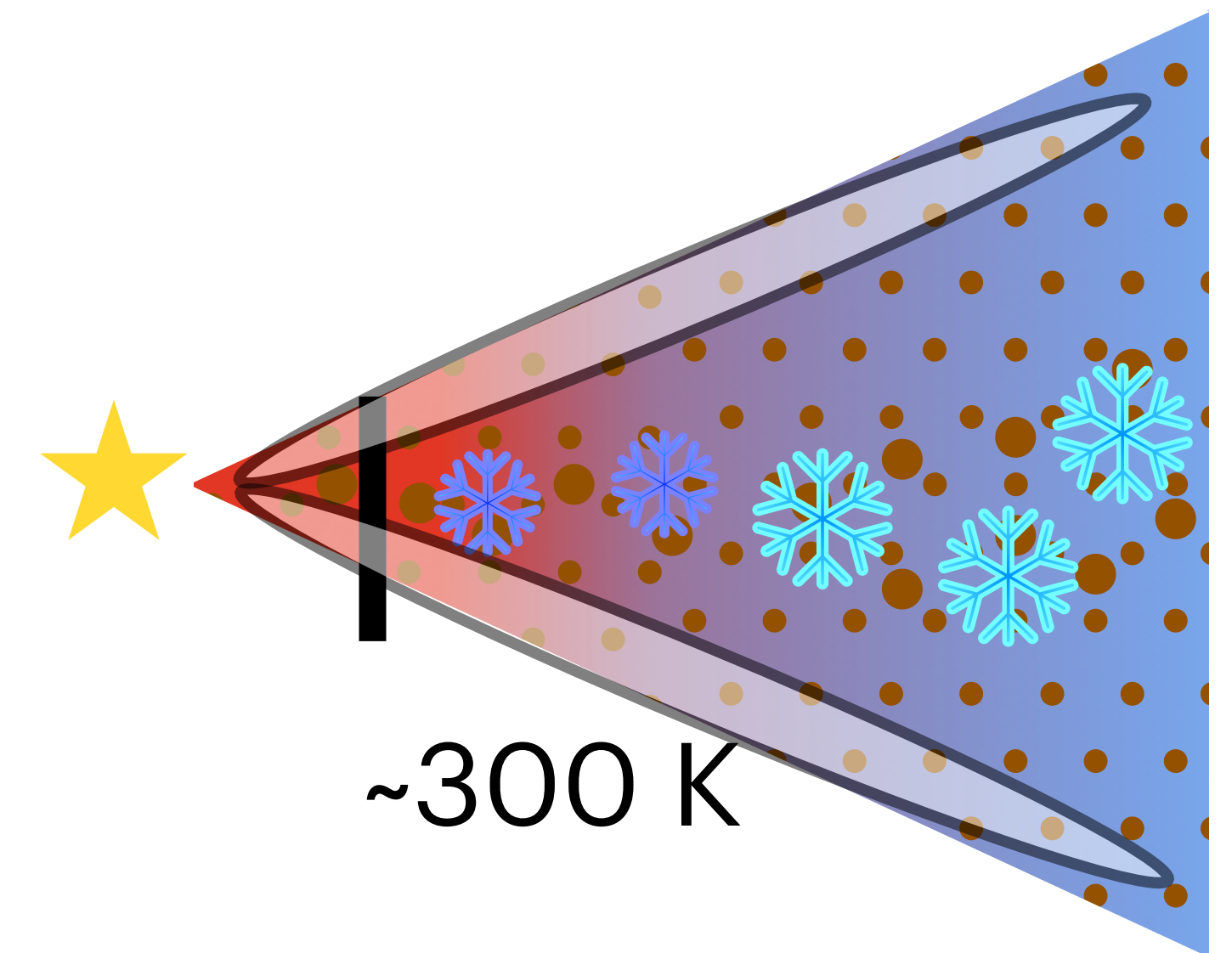
Reservoir 1:
thermally desorbed
water



Reservoir 2:
photodesorbed
water

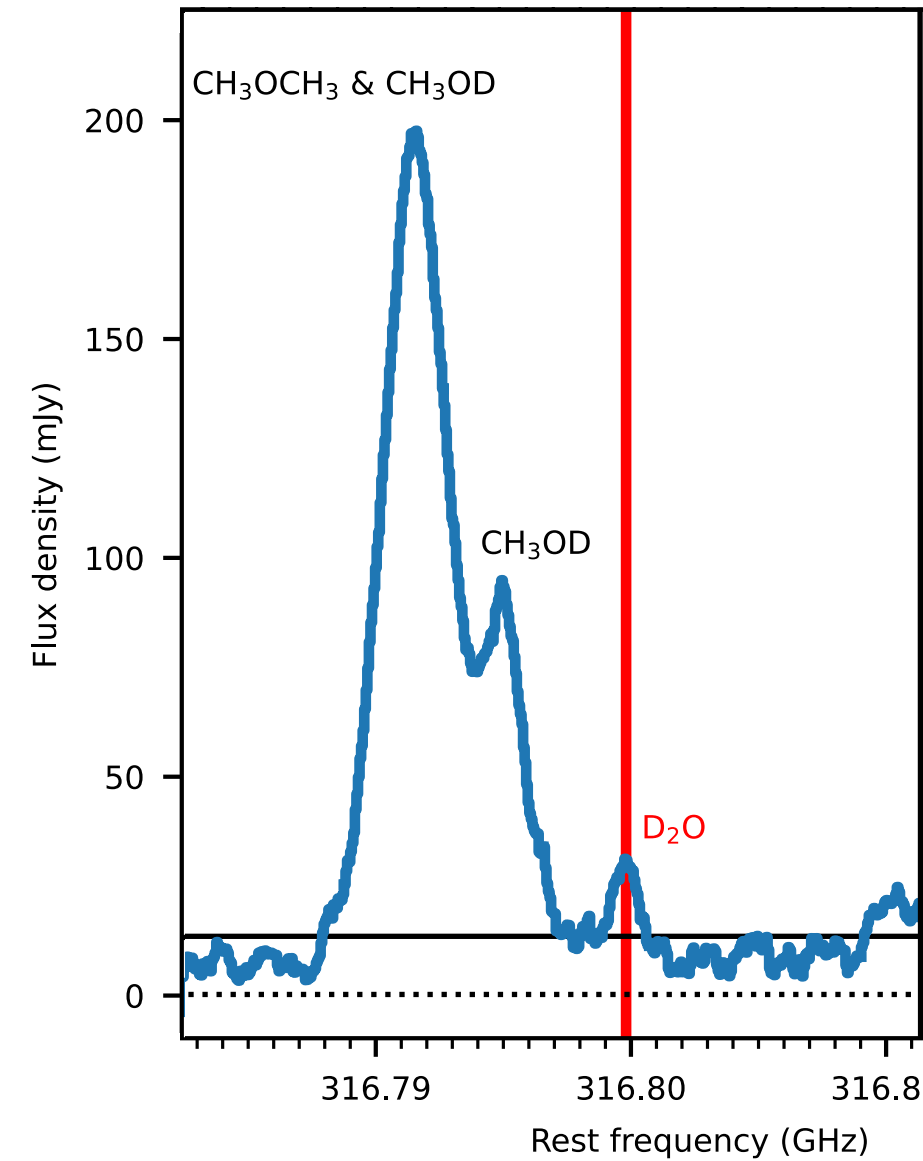


Reservoir 3:
reformed water

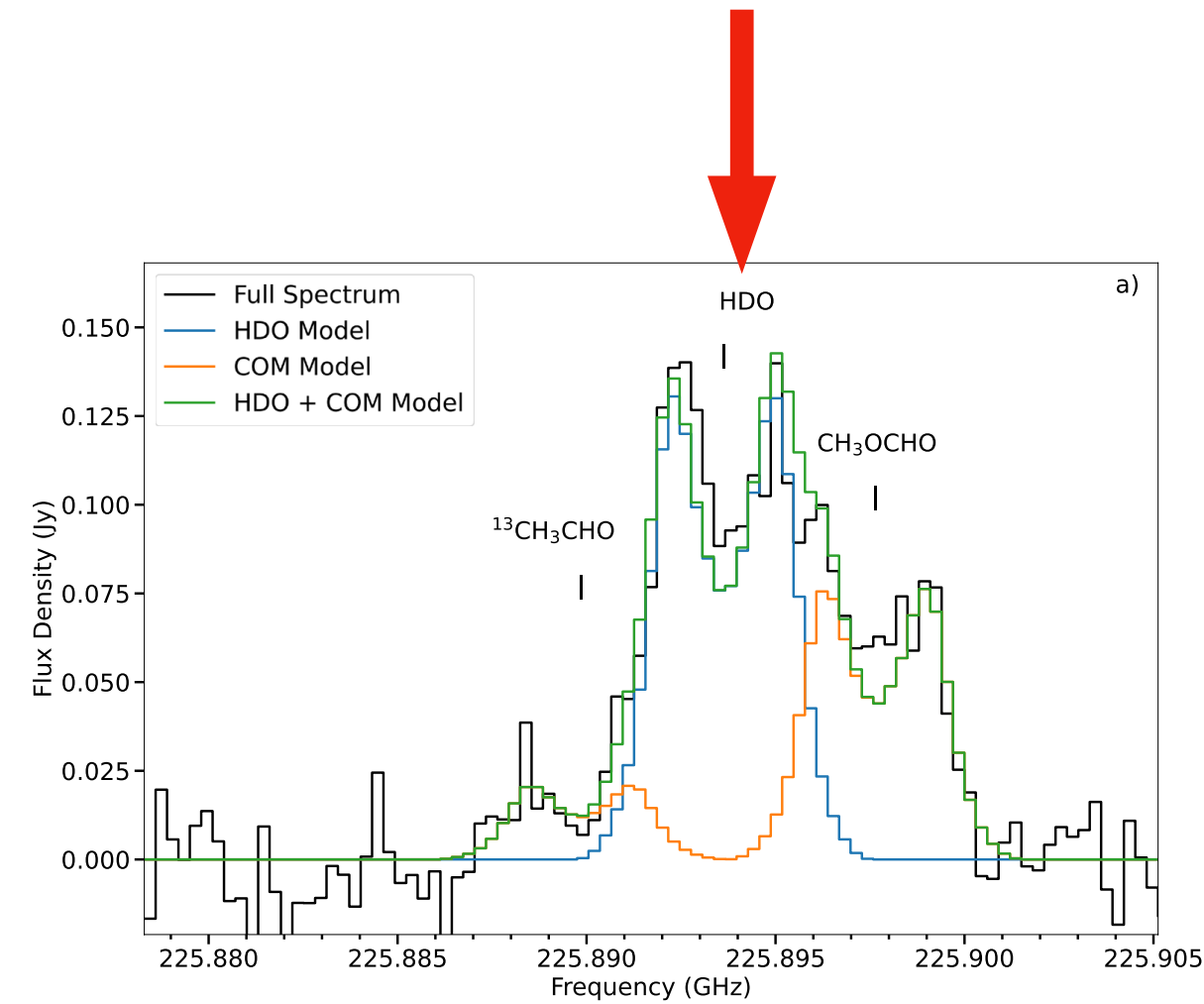


ALMA can distinguish these water reservoirs

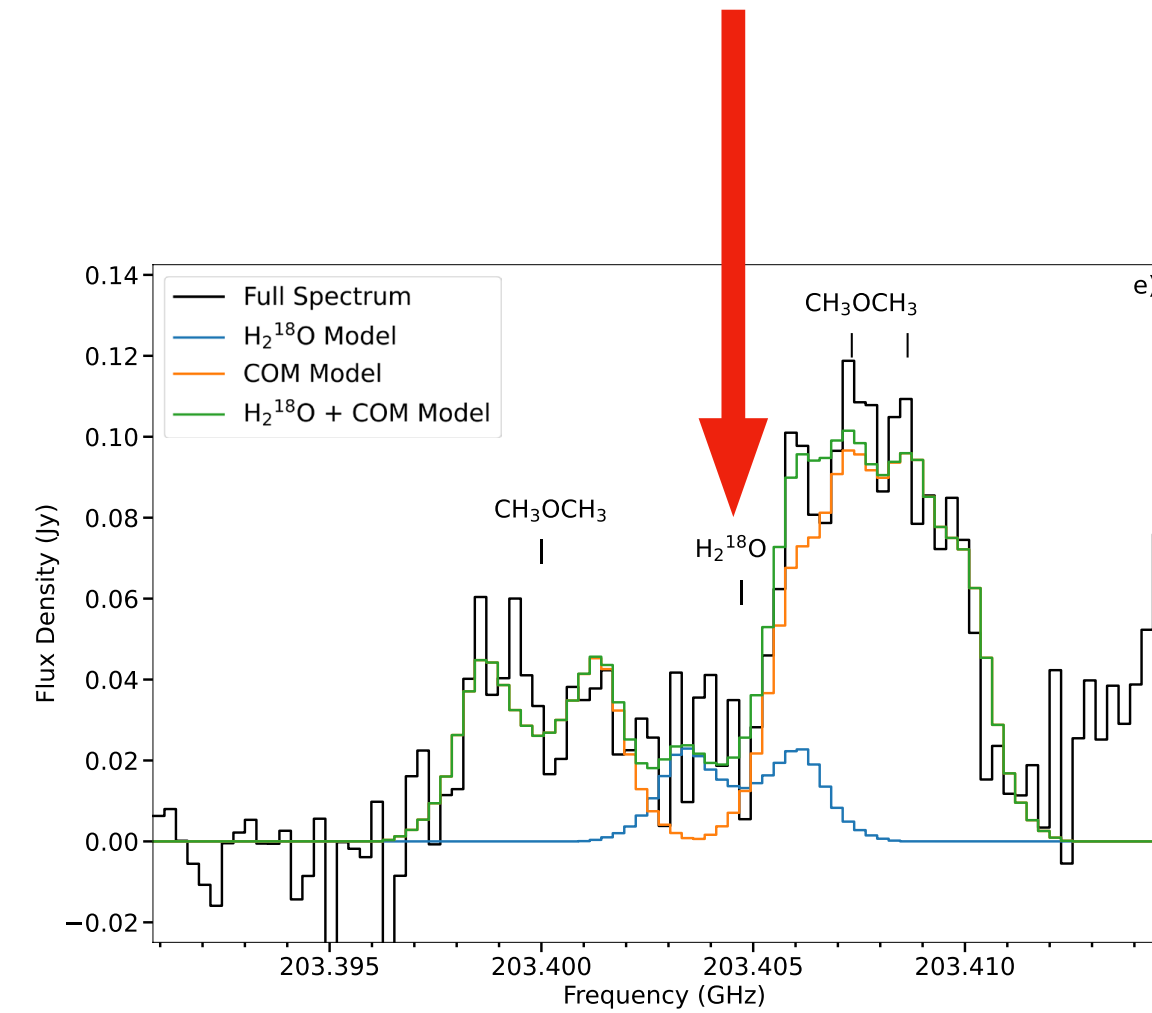
D₂O



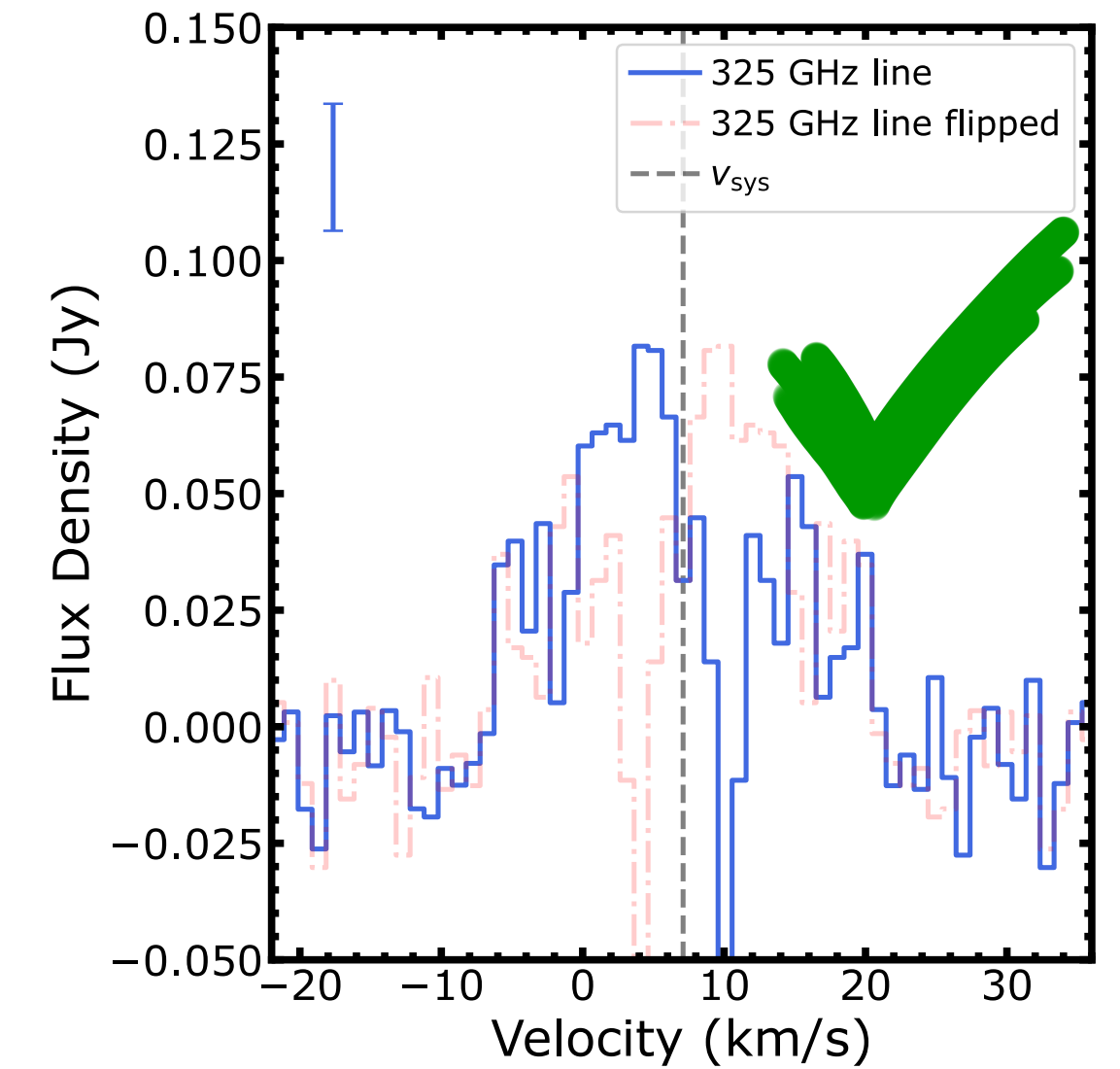
HDO



H₂¹⁸O



H₂O



- Expensive
- Inheritance vs reset

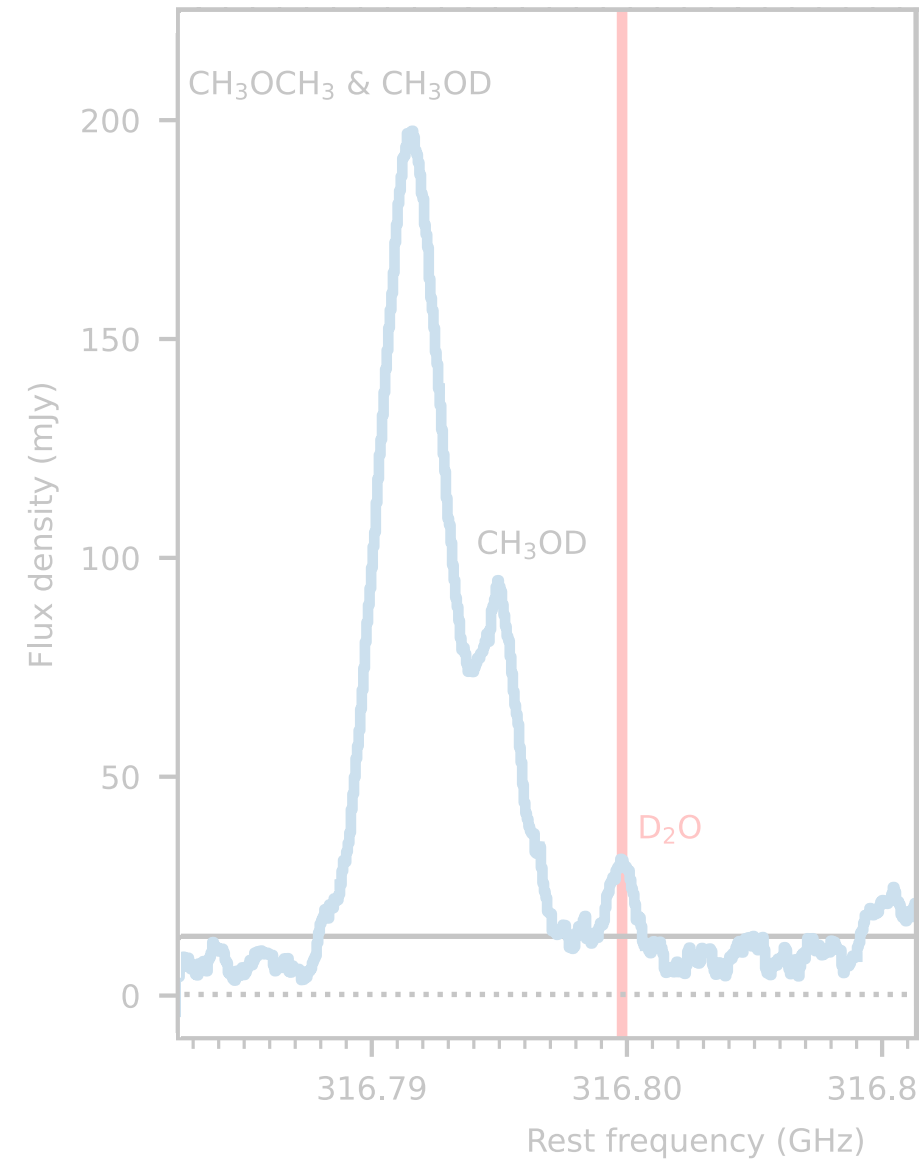
- Line blending
- Inheritance vs reset

- Line blending
- Expensive

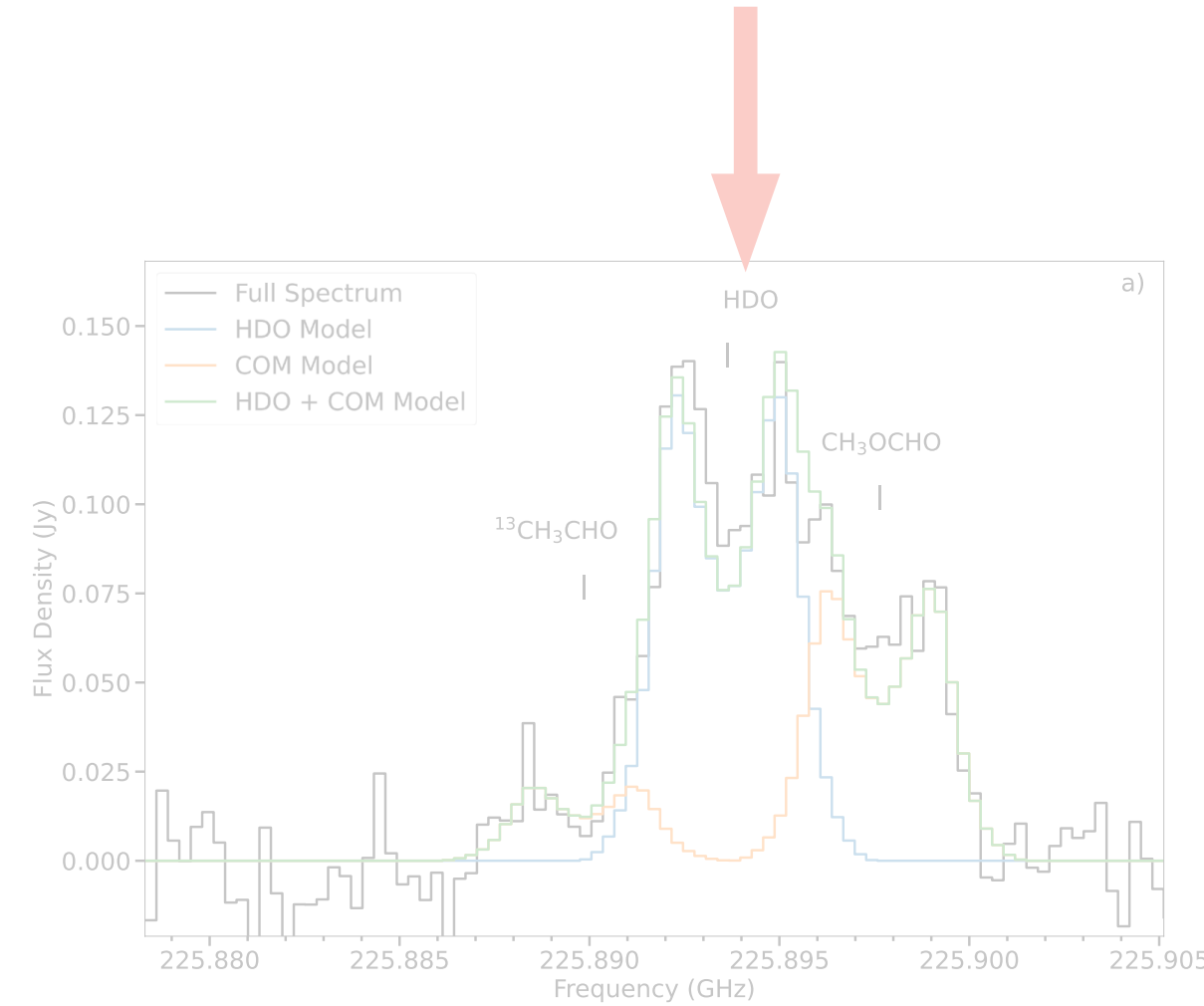
- Detectable

ALMA can distinguish these water reservoirs

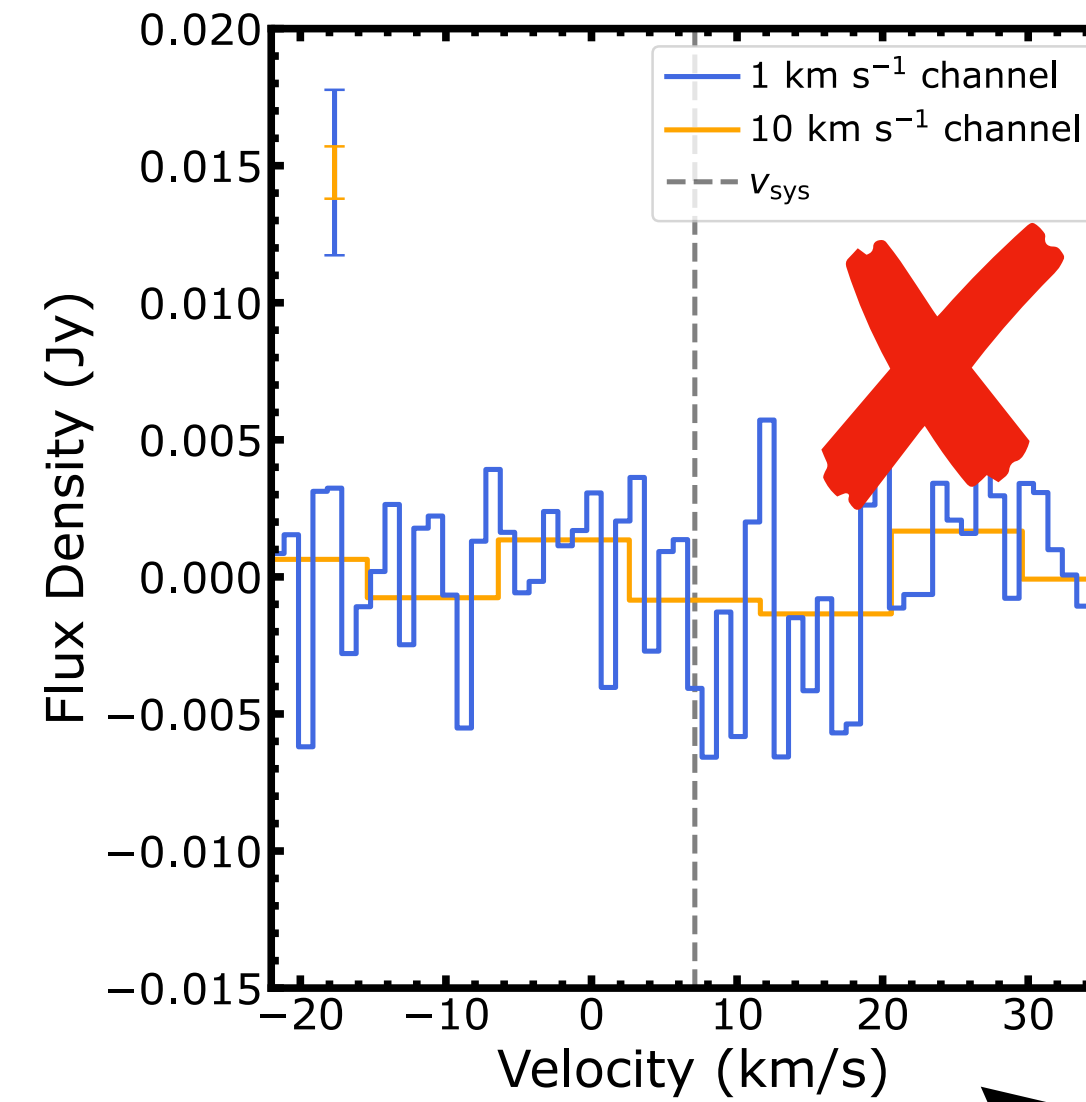
D₂O



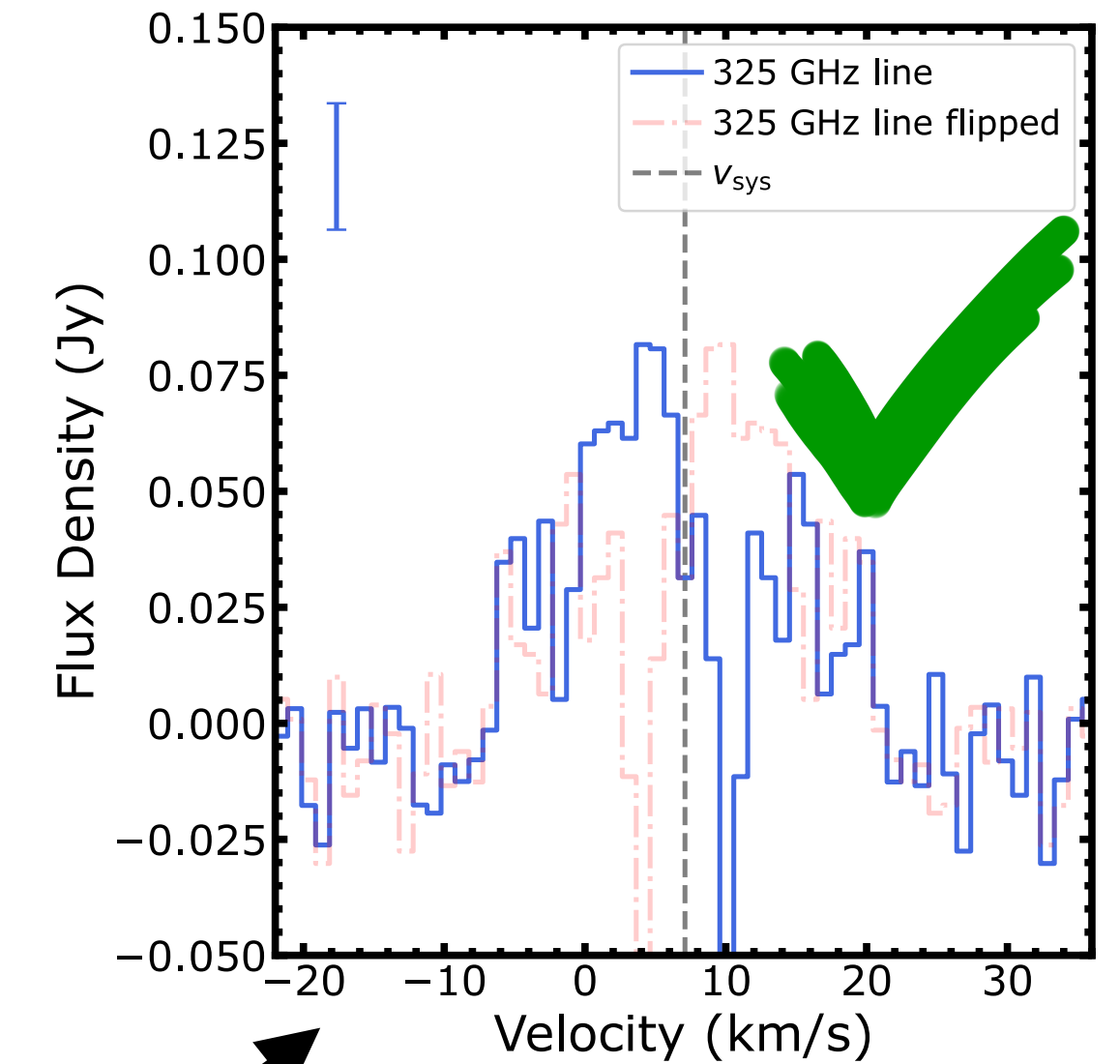
HDO



H₂¹⁸O



H₂O



Same transition

- Expensive
- Inheritance vs reset

- Line blending
- Inheritance vs reset

- Line blending
- Expensive

- Detectable
- **More efficient than H₂¹⁸O**

Spatially and/or spectrally resolved H₂O in disks with ALMA

321 GHz line

$E_{\text{up}} = 1861 \text{ K}$

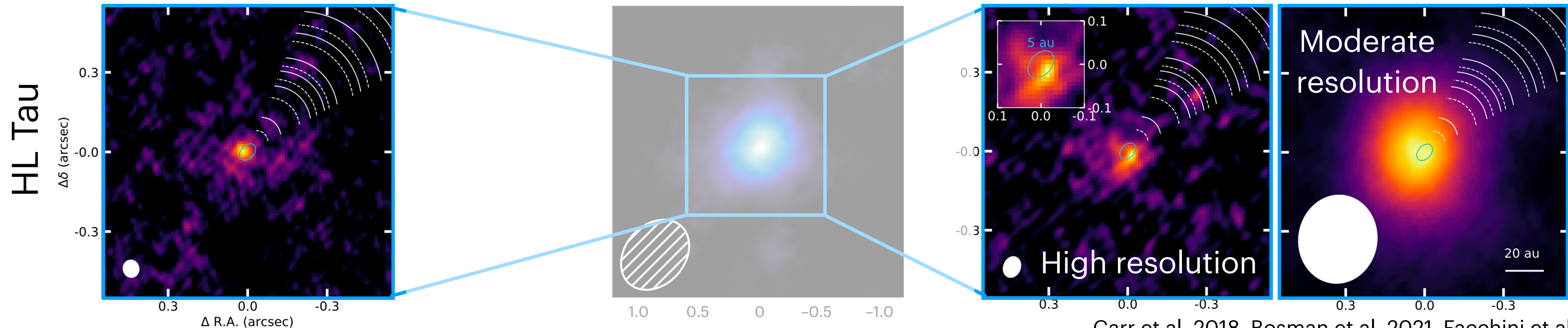
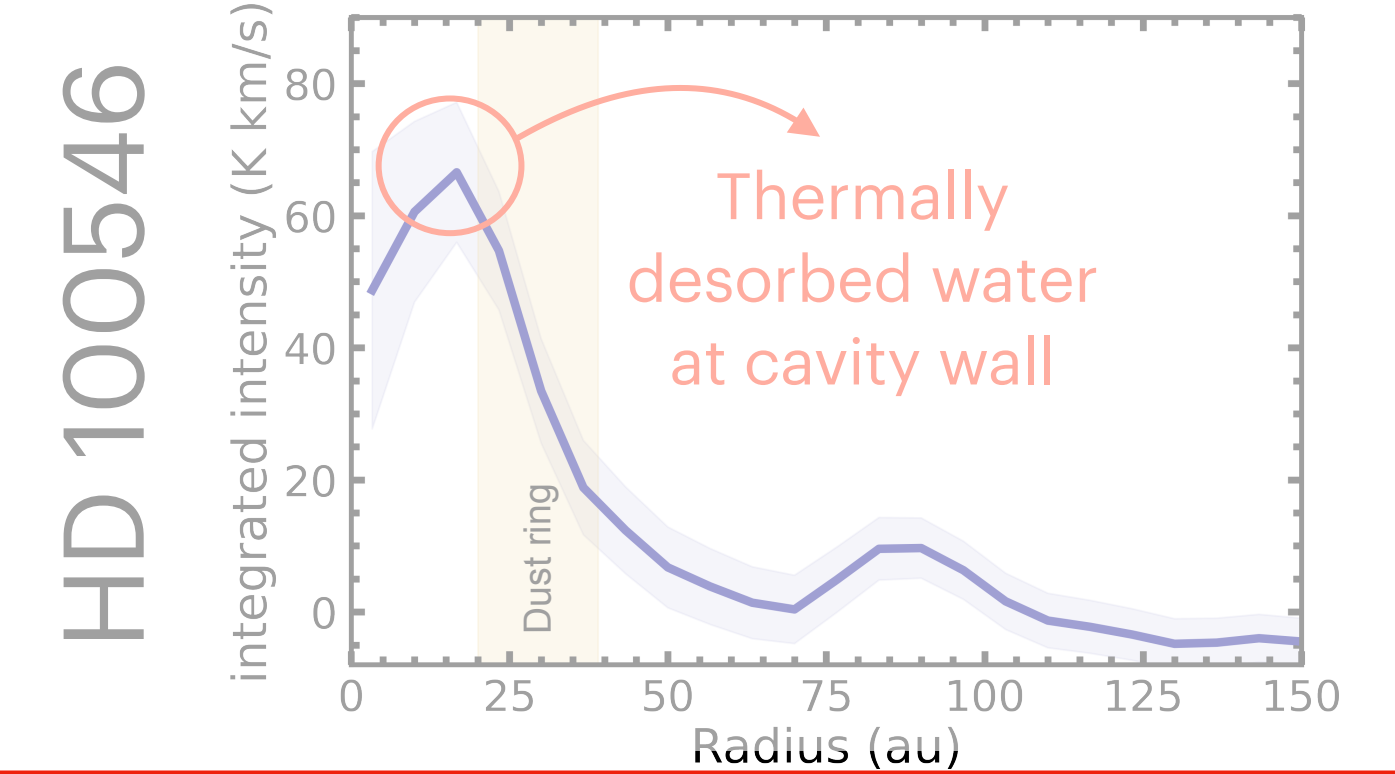
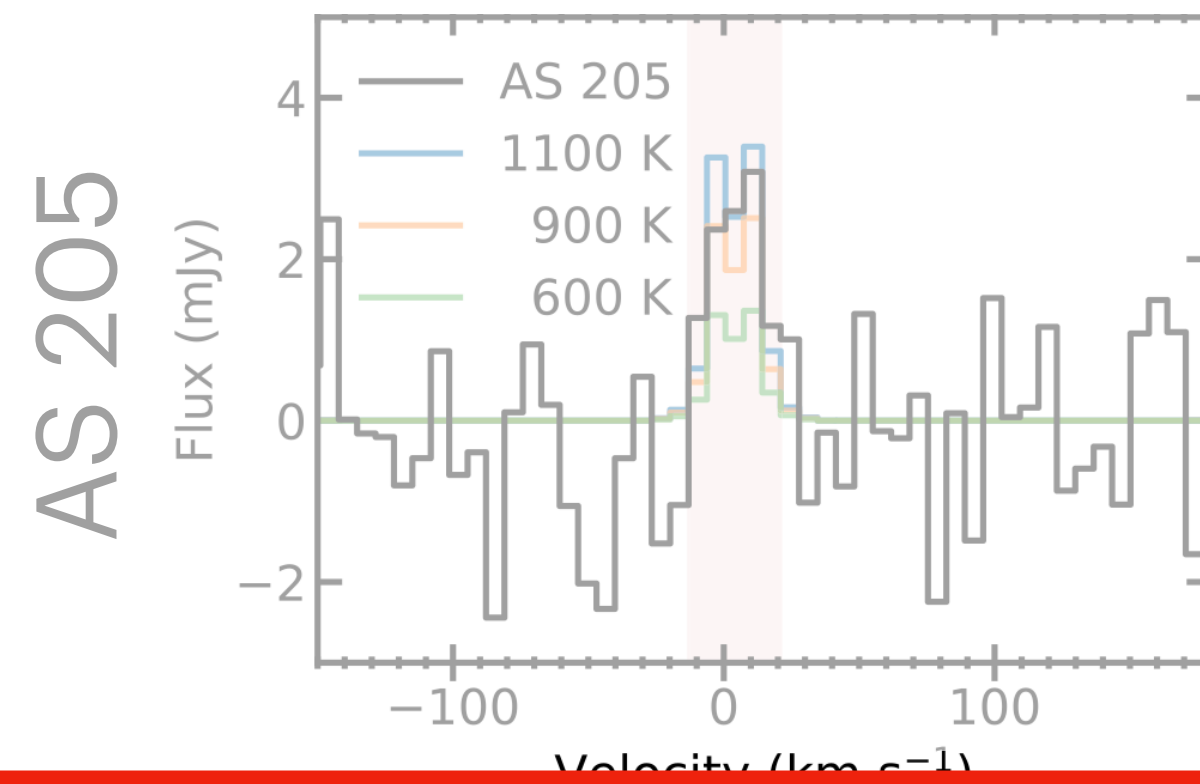


325 GHz line

$E_{\text{up}} = 470 \text{ K}$

183 GHz line

$E_{\text{up}} = 205 \text{ K}$



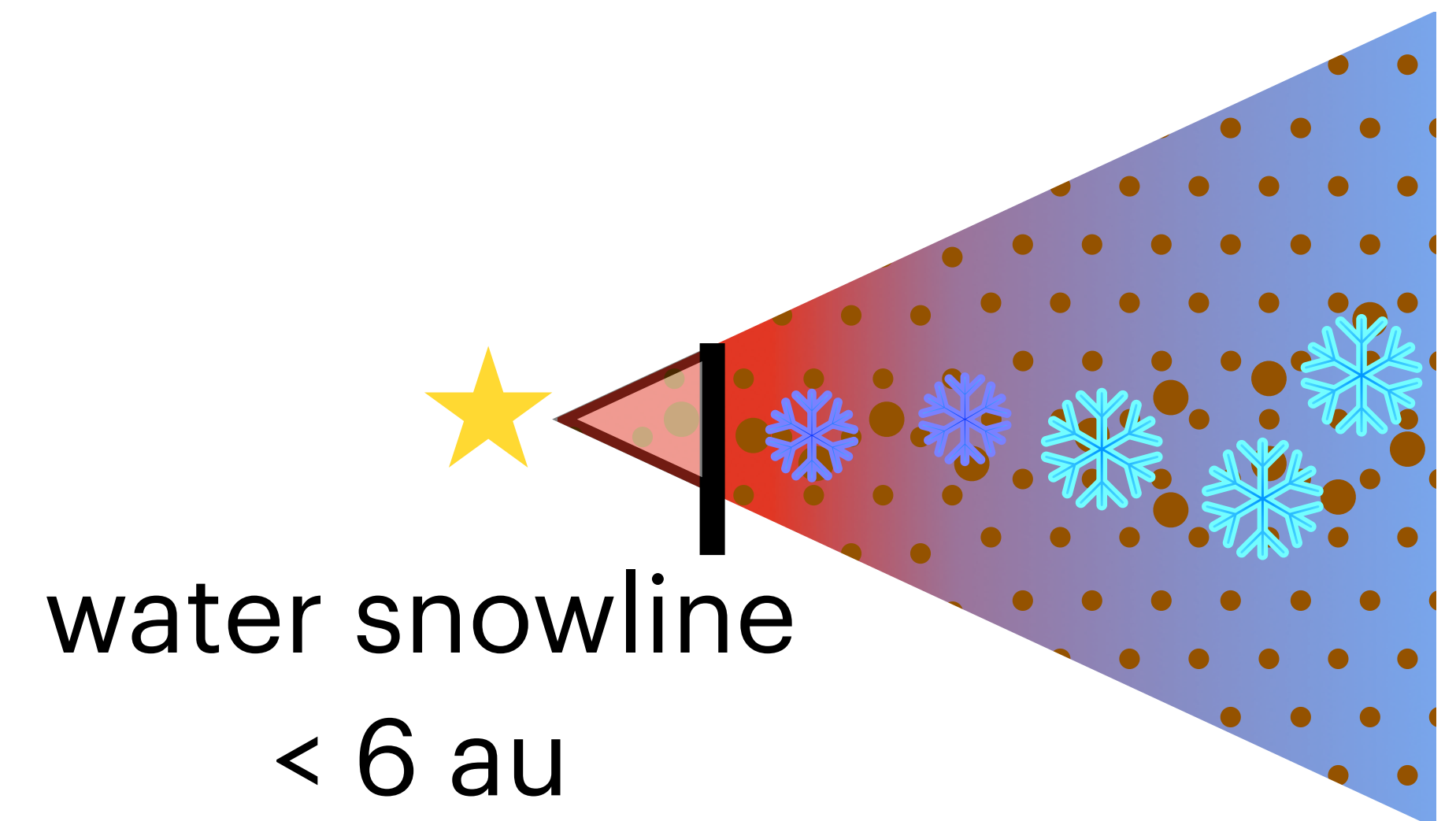
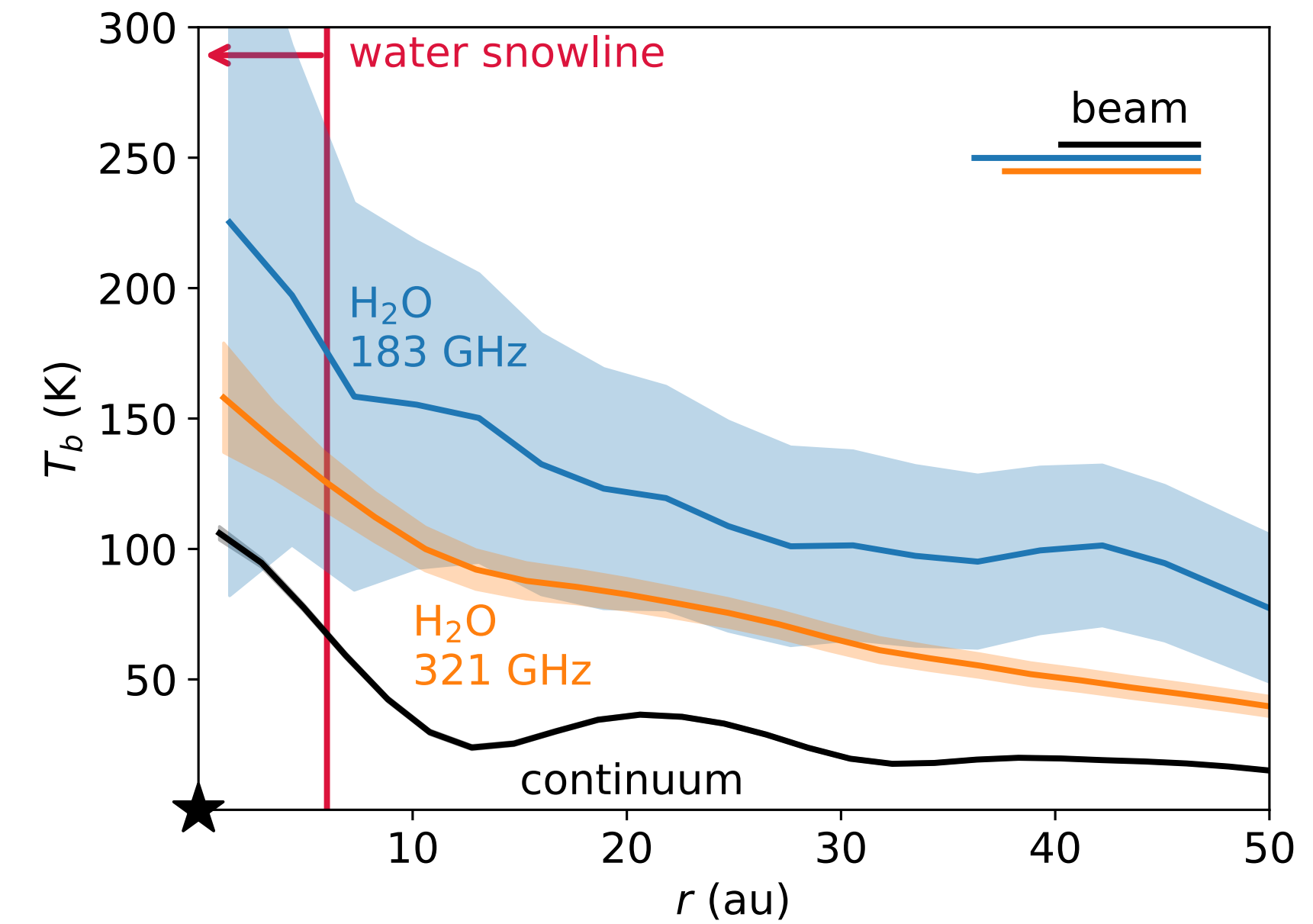
Carr et al. 2018, Bosman et al. 2021, Facchini et al.

2024, Rampinelli et al. 2020, Leininger et al. 2020

Two H₂O components in HL Tau

1. Compact emission

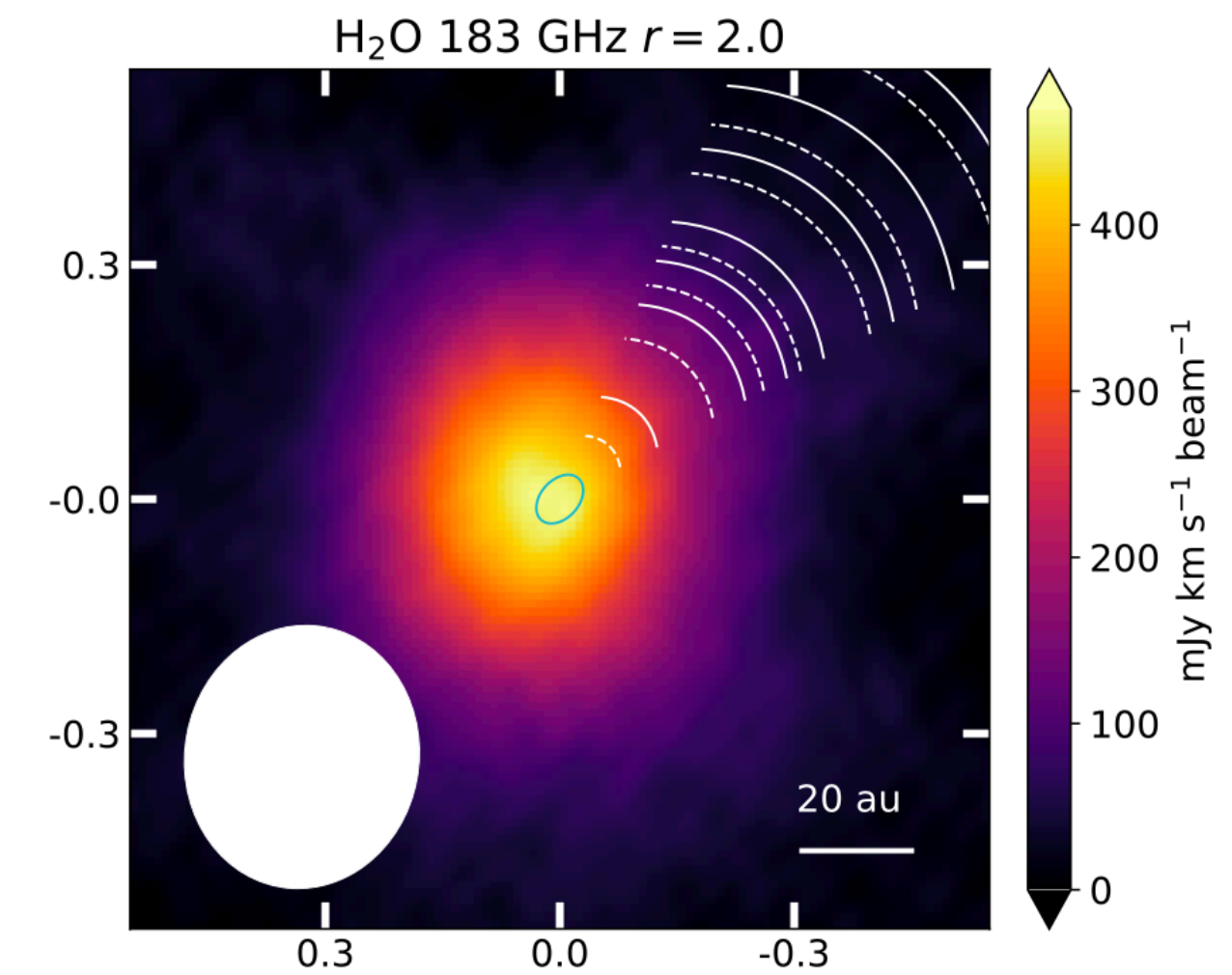
- Compact, unresolved component on source
- Large column of water
- $T_b \gtrsim T_{\text{snowline}}$
- **Water snowline @ < 6 au**



Two H₂O components in HL Tau

2. Diffuse emission

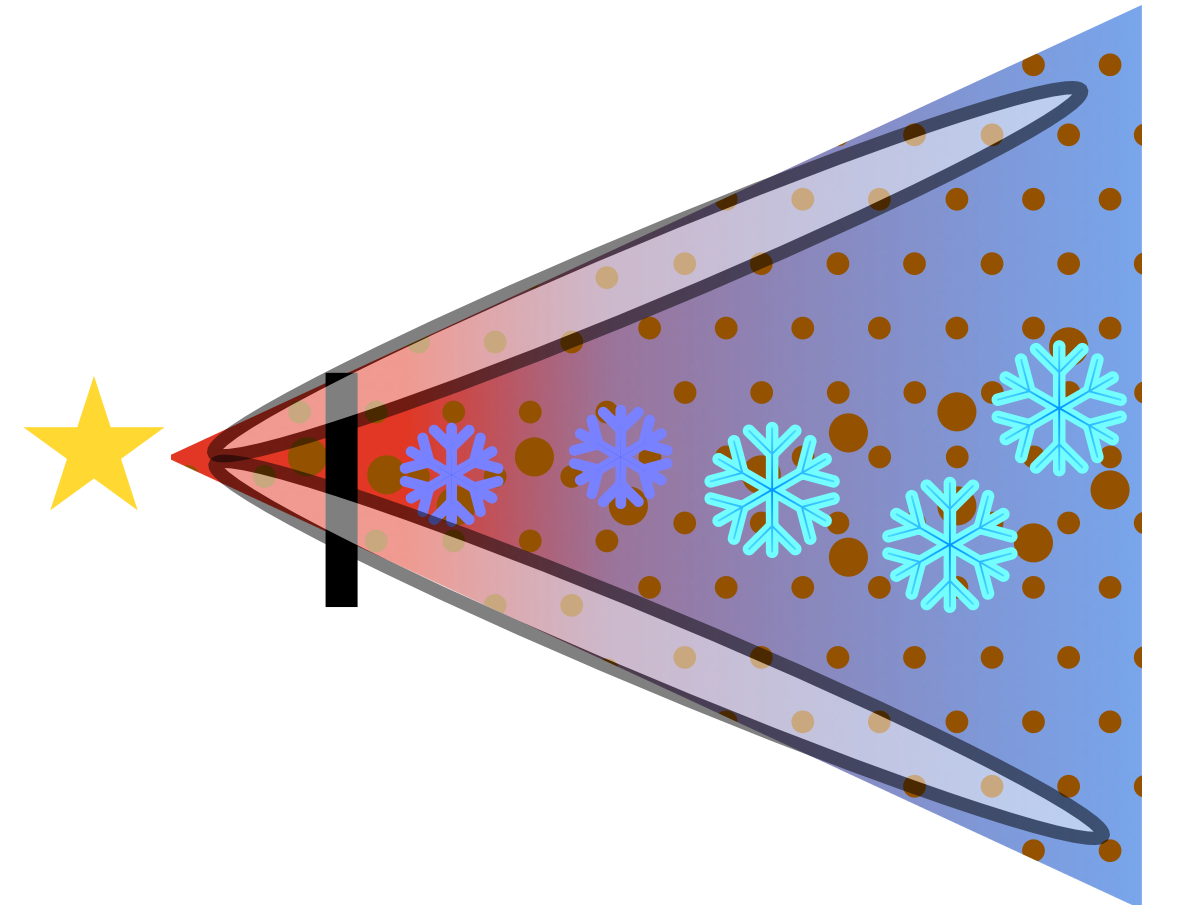
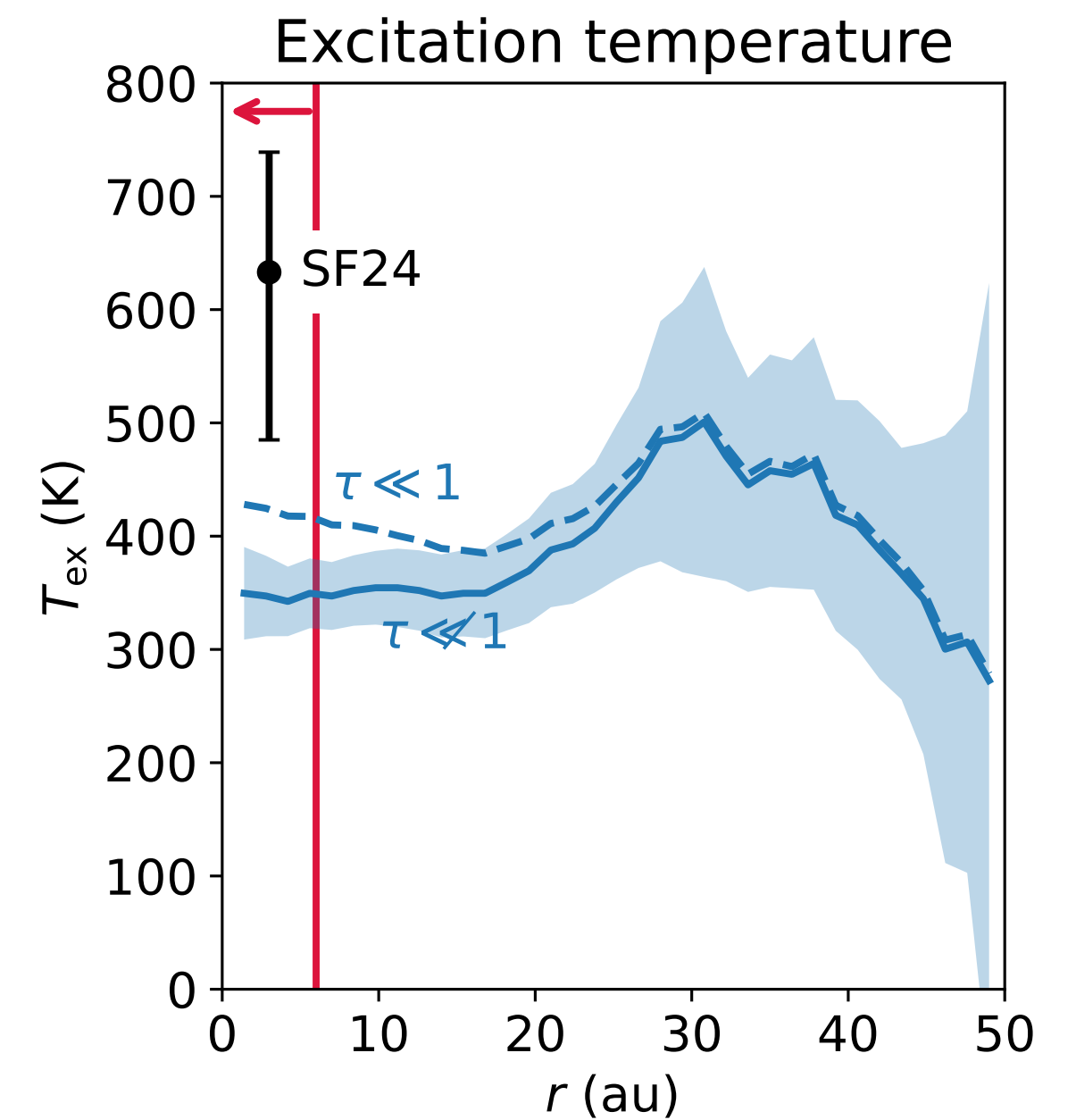
- Moderate resolution data of 183 GHz line:
 - Water is spatially resolved & detected out to ~75 au



Two H₂O components in HL Tau

2. Diffuse emission

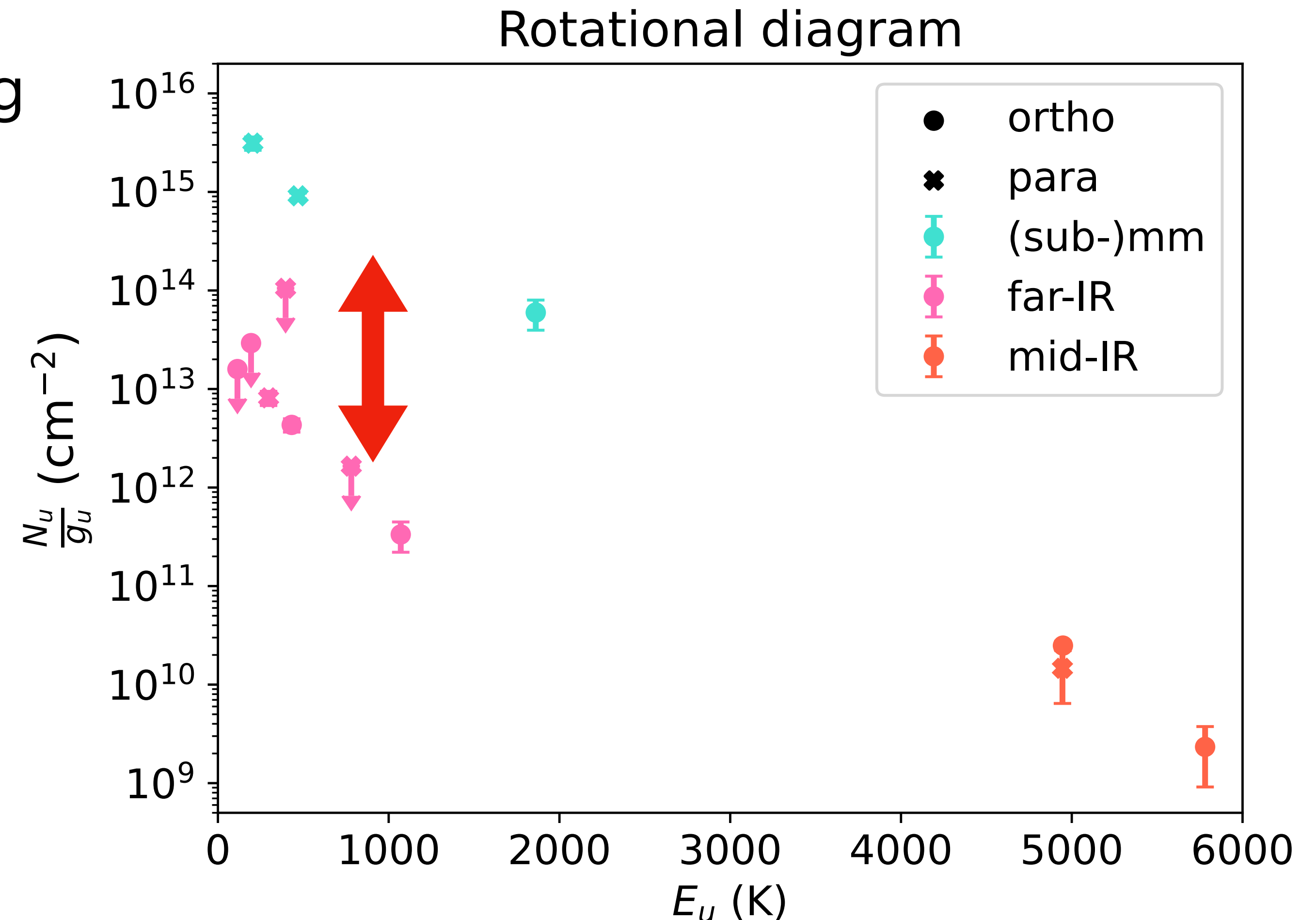
- Moderate resolution data of 183 GHz line:
 - Water is spatially resolved & detected out to ~75 au
- Rotational diagram on 183 GHz & 321 GHz lines:
 - Diffuse component is warm at ~350 K
 - Tracing the reformed water in disk surface



(Non-)LTE excitation of water?

HL Tau

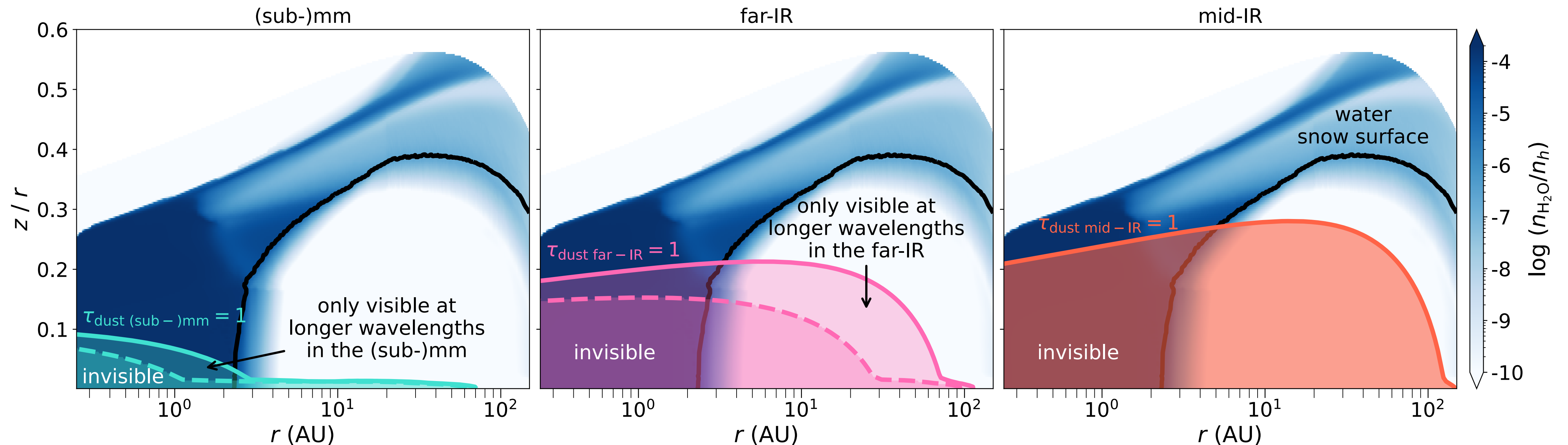
- Some H₂O lines prone to masing
- ALMA lines much brighter than (F)IR lines
- Possible causes:
 - Non-LTE excitation
 - Continuum optical depth



Riviere-Marichalar et al. 2012, Alonso-Martinez et al. 2017,
Salyk et al. 2019, Facchini et al. 2024, **Leemker** et al. 2026

Optically thick dust hides less water in (sub-)mm

HL Tau

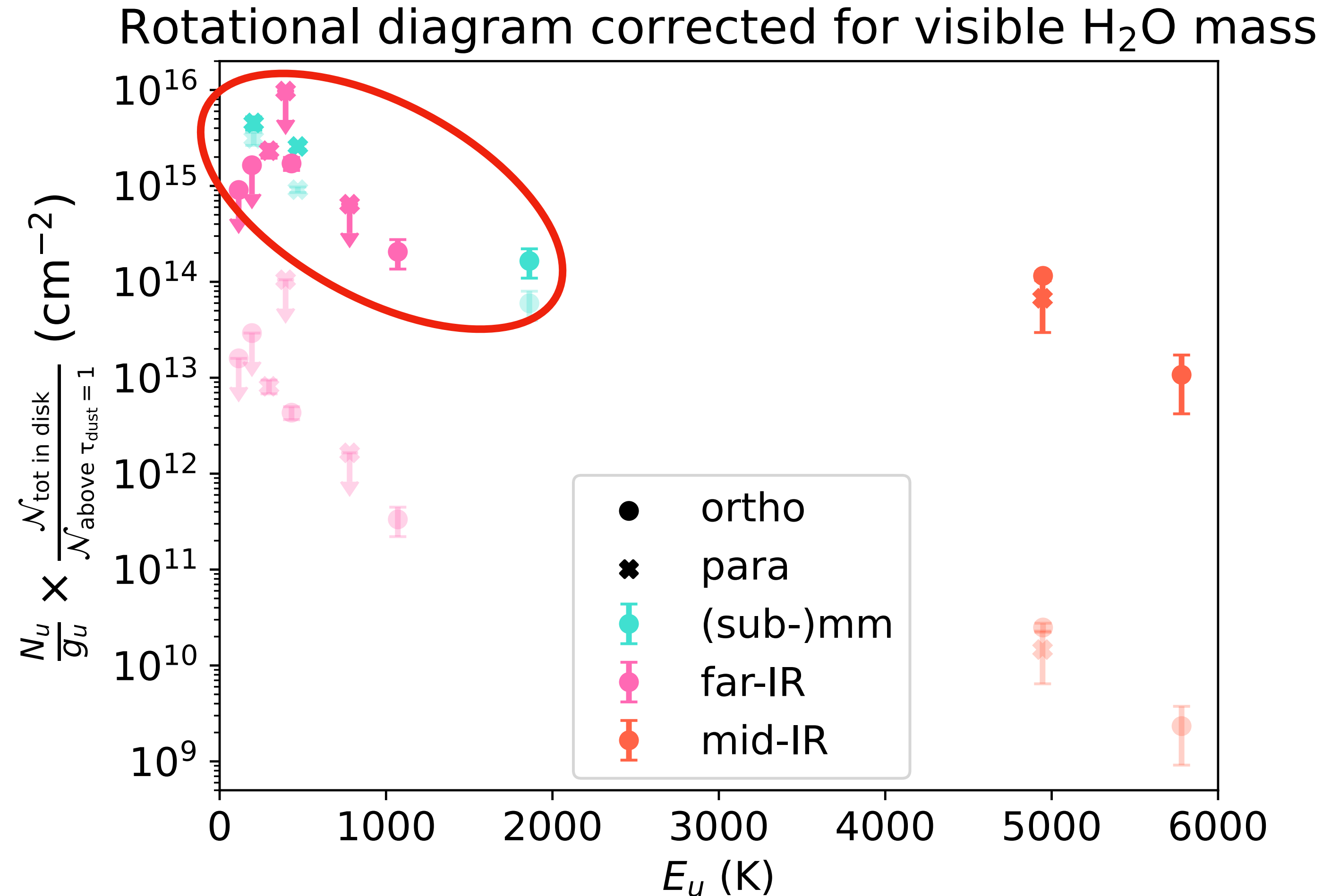


- 30-70% of all gas-phase H₂O is visible in (sub-)mm, 0.02-2% in MIR-FIR
- Much more water visible at longer wavelengths

(Non-)LTE excitation of water?

HL Tau

- Correct each line for
$$\frac{N_{\text{H}_2\text{O gas above opt. thick dust}}}{N_{\text{H}_2\text{O gas total}}}$$
- Corrected (sub-)mm fluxes and FIR fluxes are similar
- **H₂O is not strongly masing**



Does the water survive the journey from cloud to disks?

- Yes!
- First detection of D₂O in disk
- Water isotopologue ratios involving D₂O confirm inheritance of material traced by HDO/H₂O

Leemker et al. 2025

Where is the water located in disks?

- Water snowline is at < 6 au in the HL Tau disk
- Diffuse water is warm (~350 K)
- Water is likely not strongly masing

Leemker et al. 2026

Credit: ESO/L. Calçada

