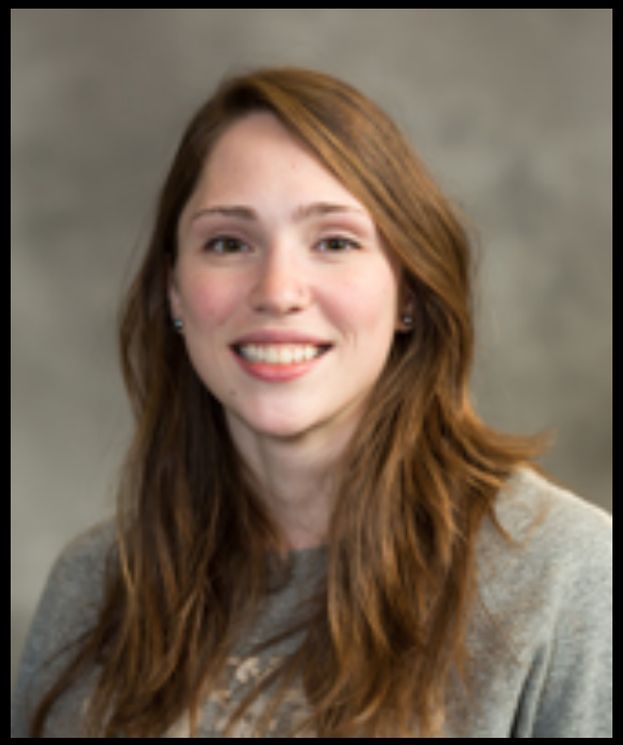
Water from Clouds to Disks

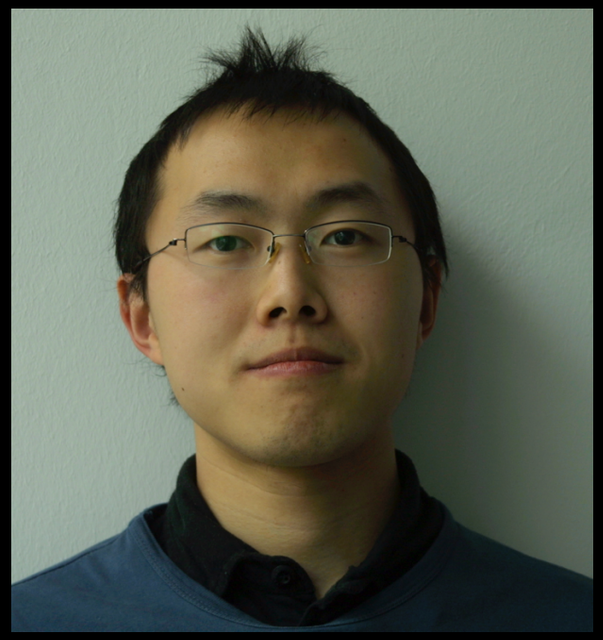
Edwin Bergin
University of Michigan

Collaborators

Ilse Cleeves



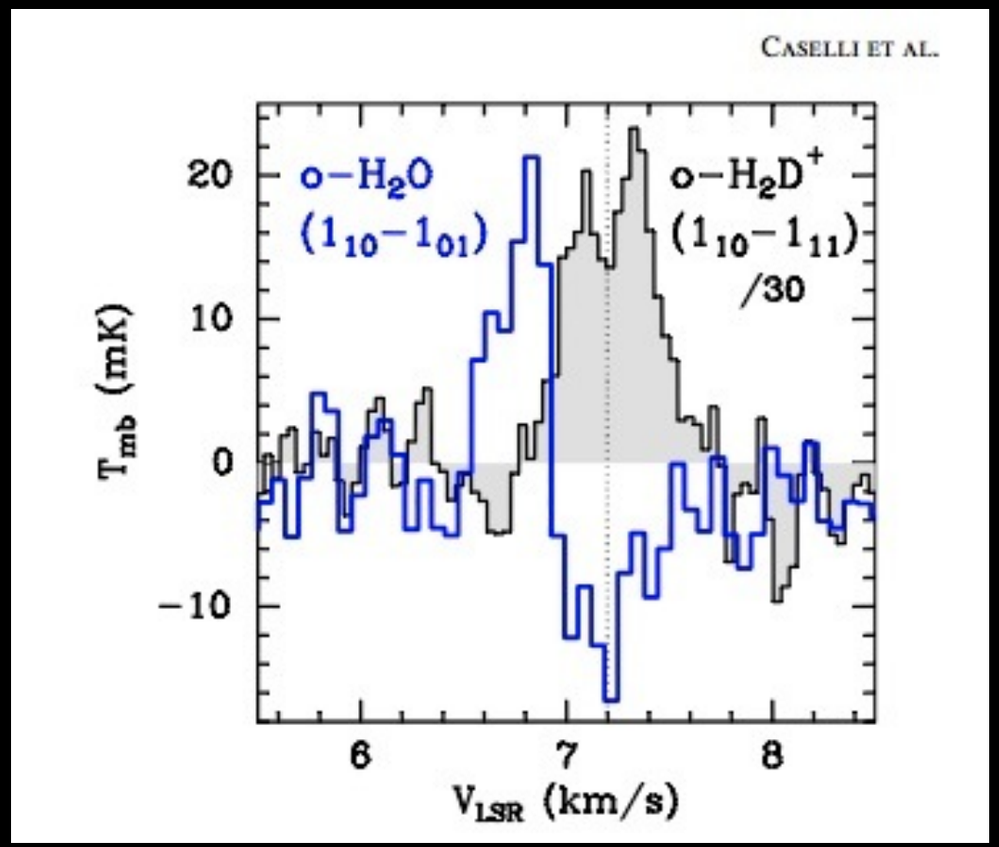
Fujun Du



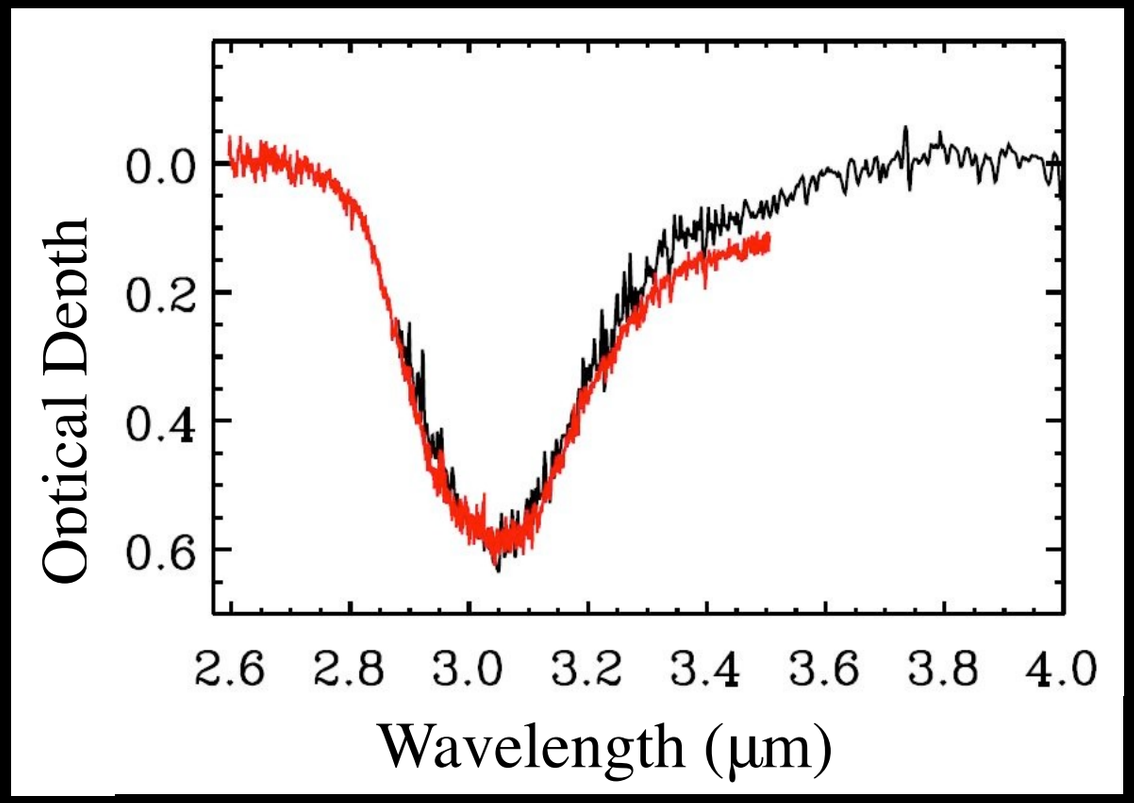
Herschel Wish Team; C. Alexander (DTM), D. Graninger (Harvard)
T. Harries - Exeter, M. Hogerheijde - Leiden, K. Öberg (Harvard)

see van Dishoeck PPVI chapter

Water Formation before Star Birth



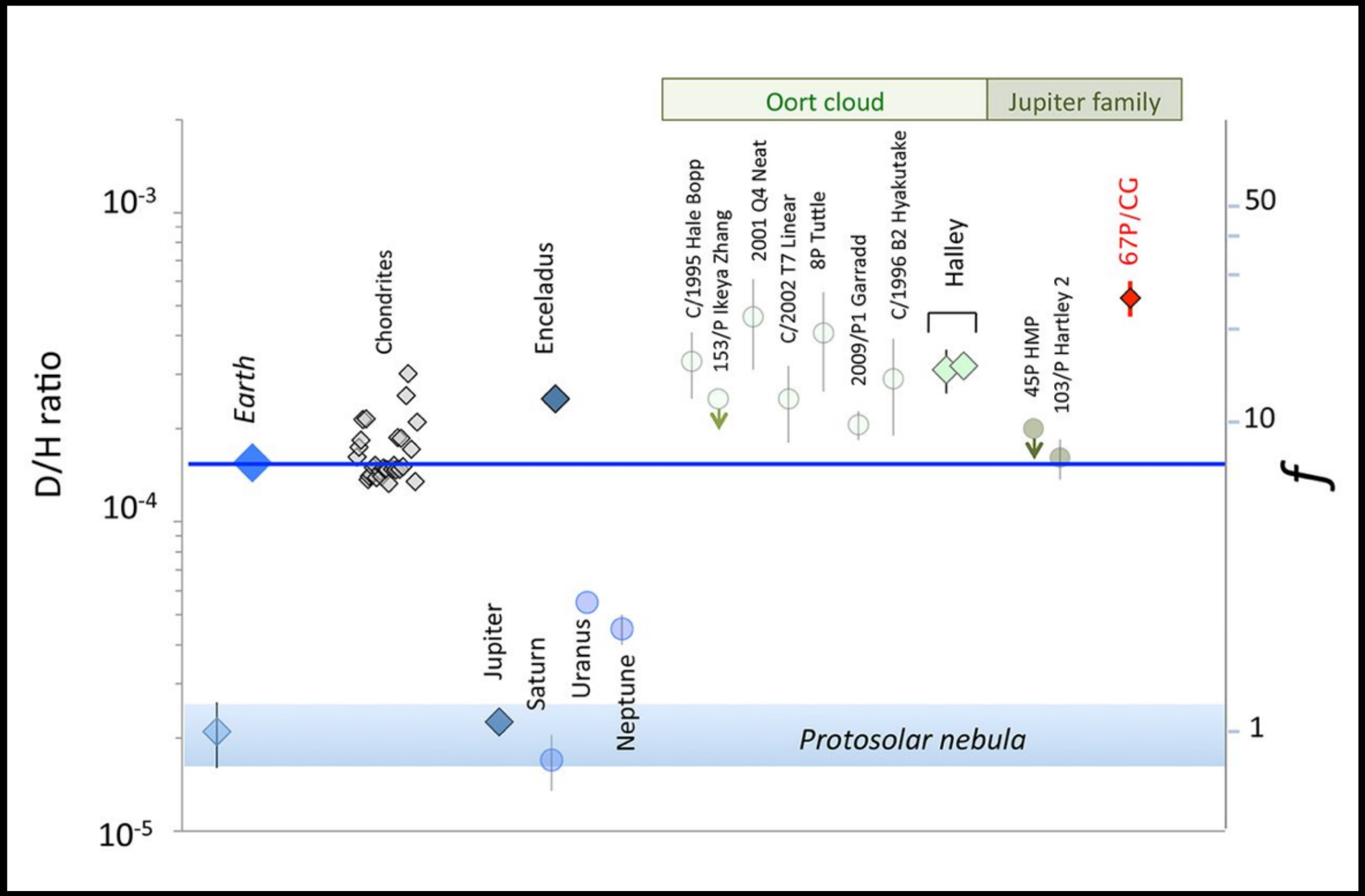
Caselli et al. 2012, Keto+ 2015
Hollenbach+ 2009, Klotz+ 2008



Whittet et al. 1983
Gibb+ 2004, Boogert+ 2013

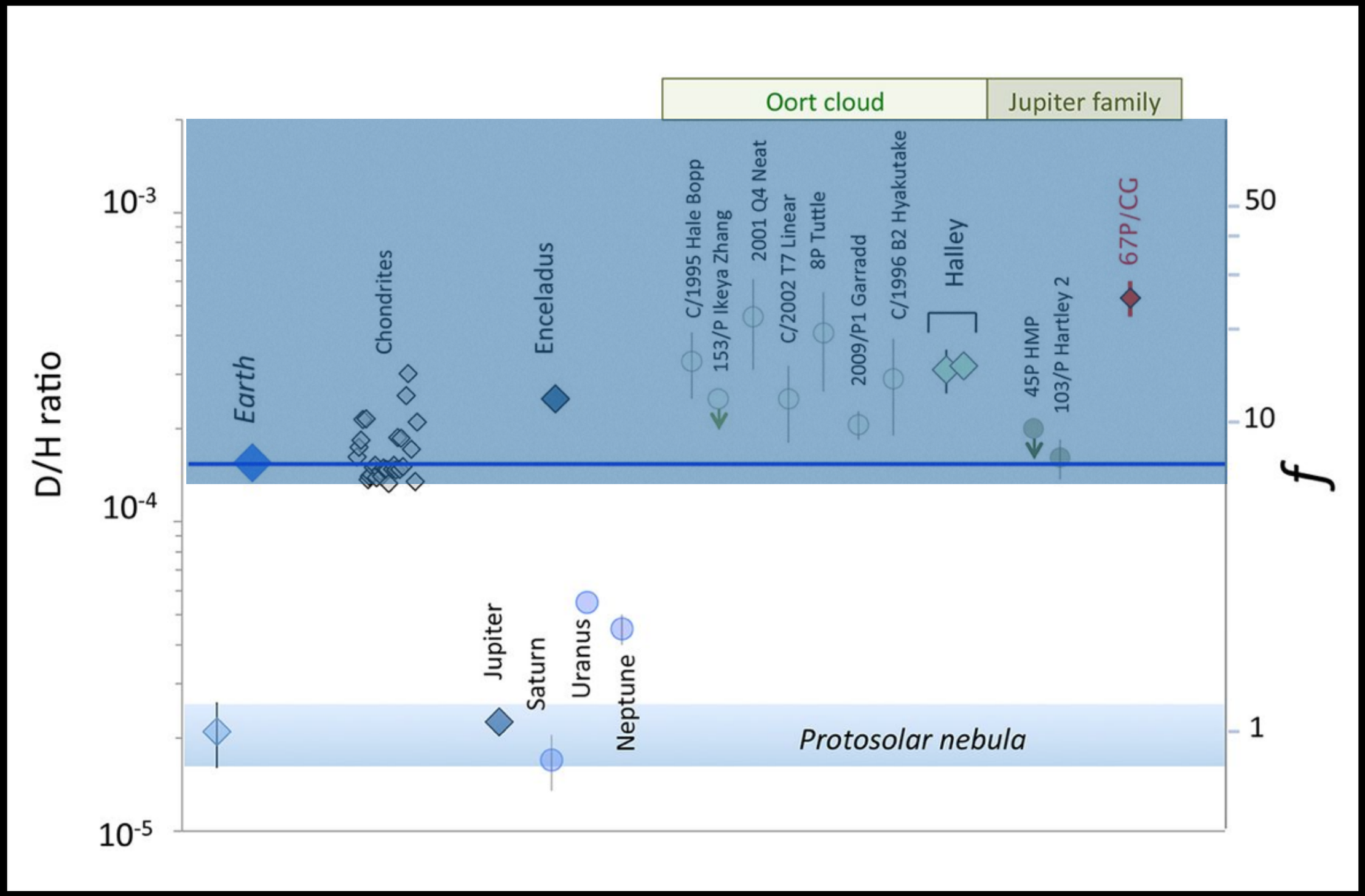
- ➡ Water vapor in emission - arising in dense ($n > 10^5$ cm^{-3}) gas
- ➡ Gas abundance is low/ice is high - water (and O) is in ice
- ➡ Current models (Visser+2009) suggest water ice supplied to disk is unaltered.
- ➡ Young disk is least understood stage

Deuterium Fingerprint



Altwegg+ 2014

Deuterium Fingerprint

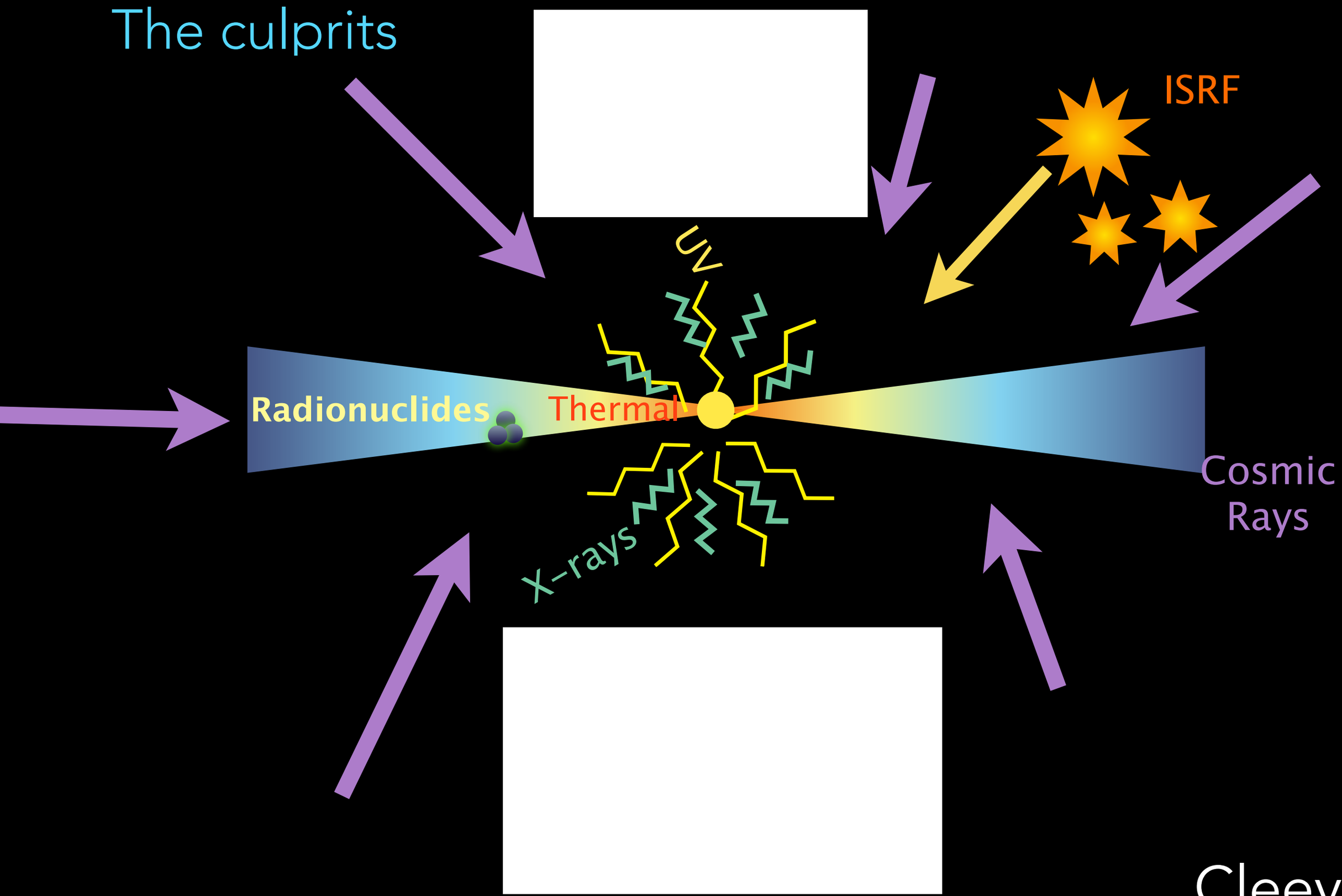


Altwegg+ 2014

Deuterium Chemistry

- Deuterium fractionation for water primarily powered by one reaction:
  - $H_3^+ + HD \Leftrightarrow H_2D^+ + H_2 + \Delta E$
- Requires 2 ingredients
  1. Source of Ionization
  2. Low temperatures (< 30 K)
- Most *disk* models assume initial D/H in water is high and it is lowered by mixing between hot and cold gas.
- Two potential environments - dense pre-stellar core or dense outerdisk.

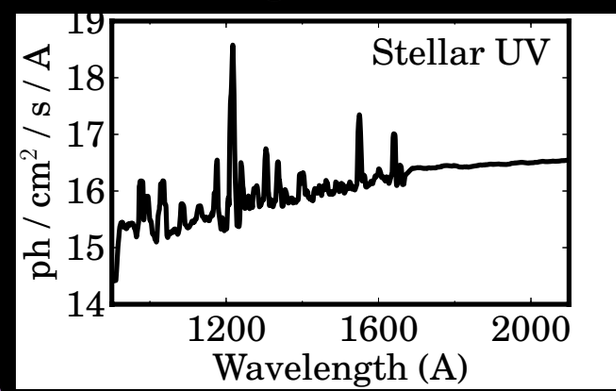
Ionization in Disks:
The culprits



Cleeves

Ionization in Disks: The culprits

Herczeg+2002,2004



ISRF

UV

Radionuclides

Thermal

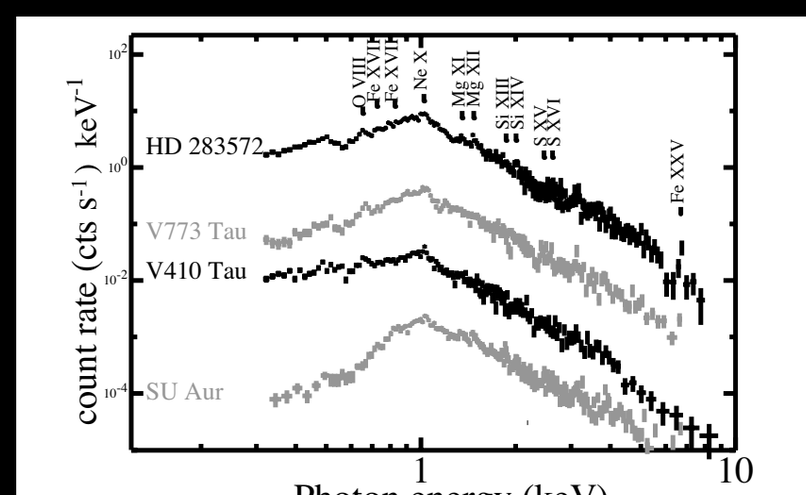
Cosmic Rays

X-rays

Stellar X-rays

Meteoritic Record

Excess of ^{26}Mg points to large quantities of ^{26}Al.

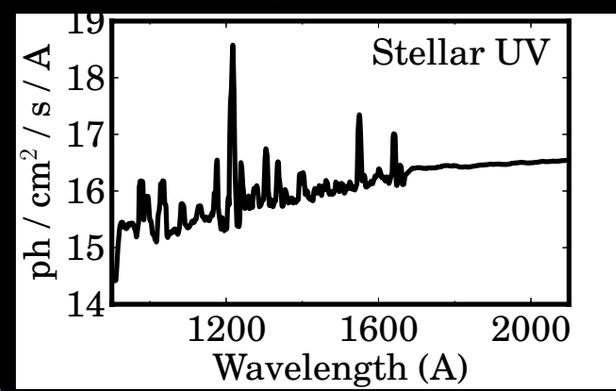


Telleschi+2007

Cleeves

Ionization in Disks: The culprits

Herczeg+2002,2004



ISRF

UV

Radionuclides

Thermal

?

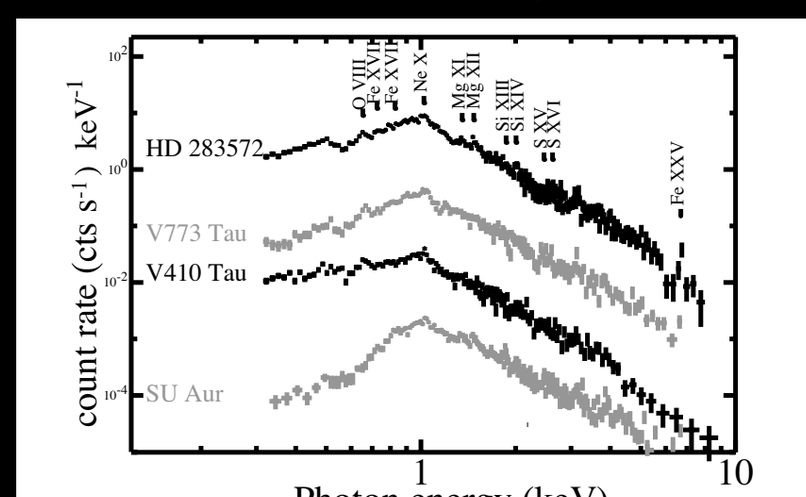
Cosmic Rays

X-rays

Stellar X-rays

Meteoritic Record

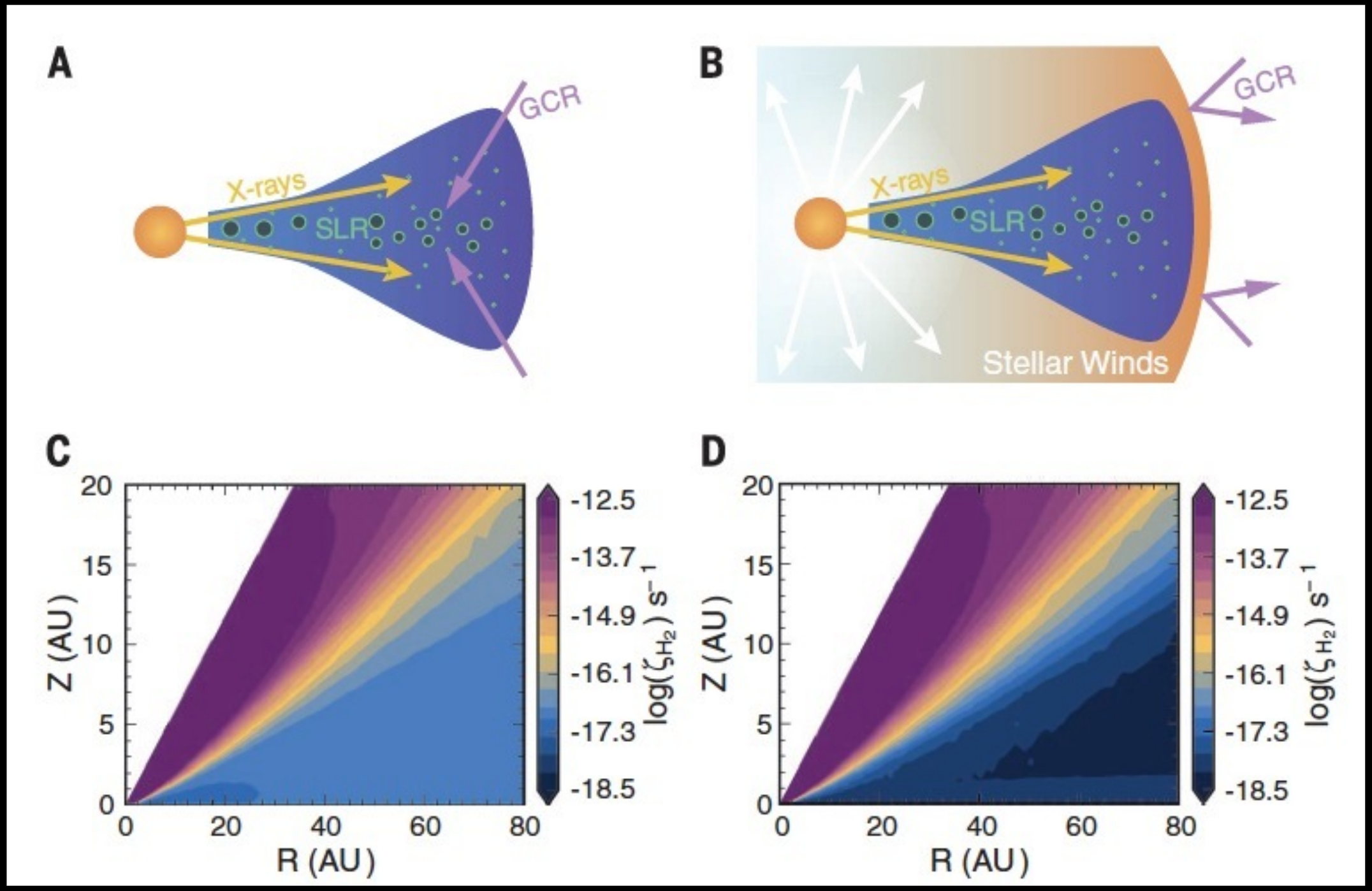
Excess of ^{26}Mg points to large quantities of ^{26}Al.



Telleschi+2007

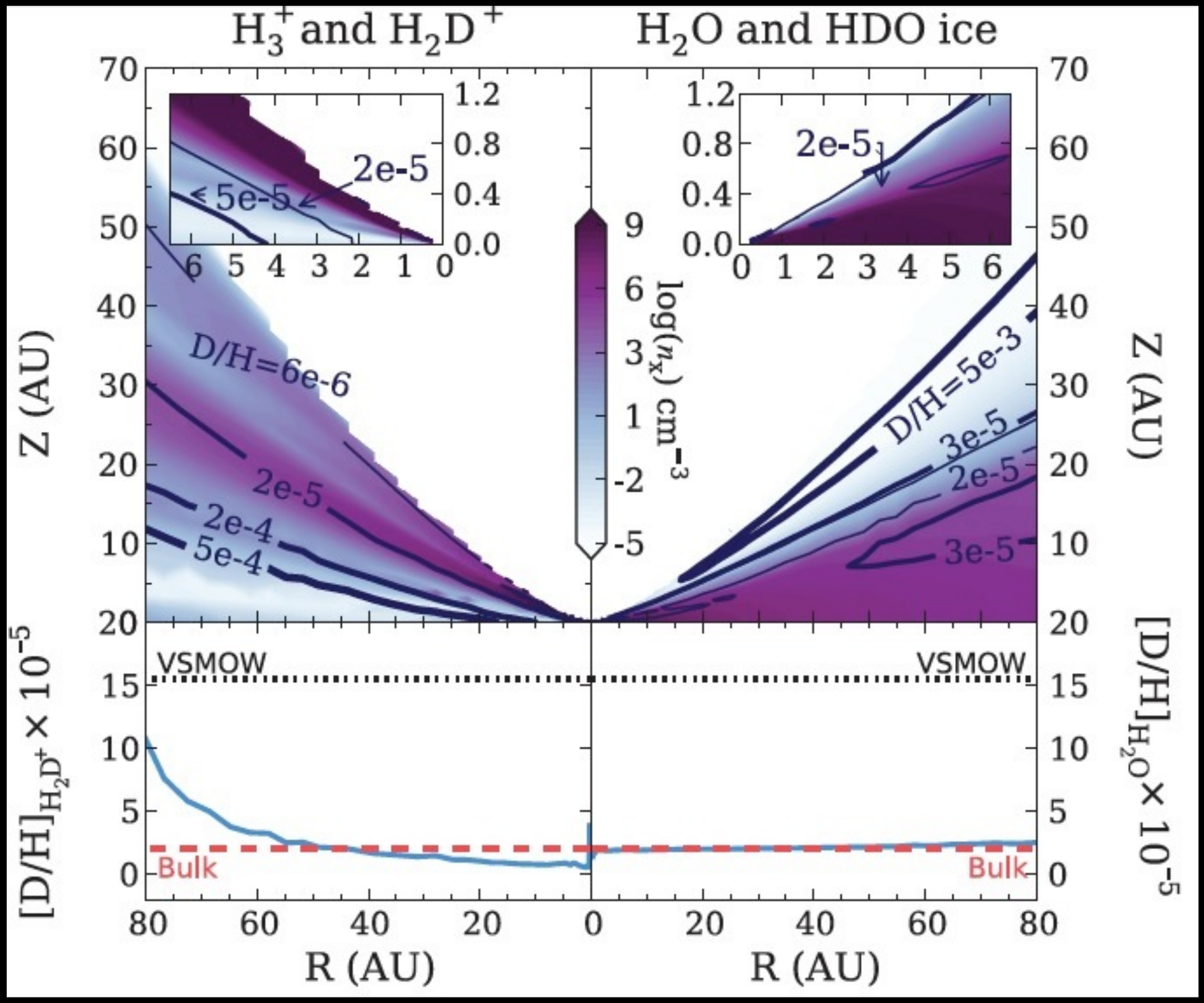
Cleeves

Disk Ionization



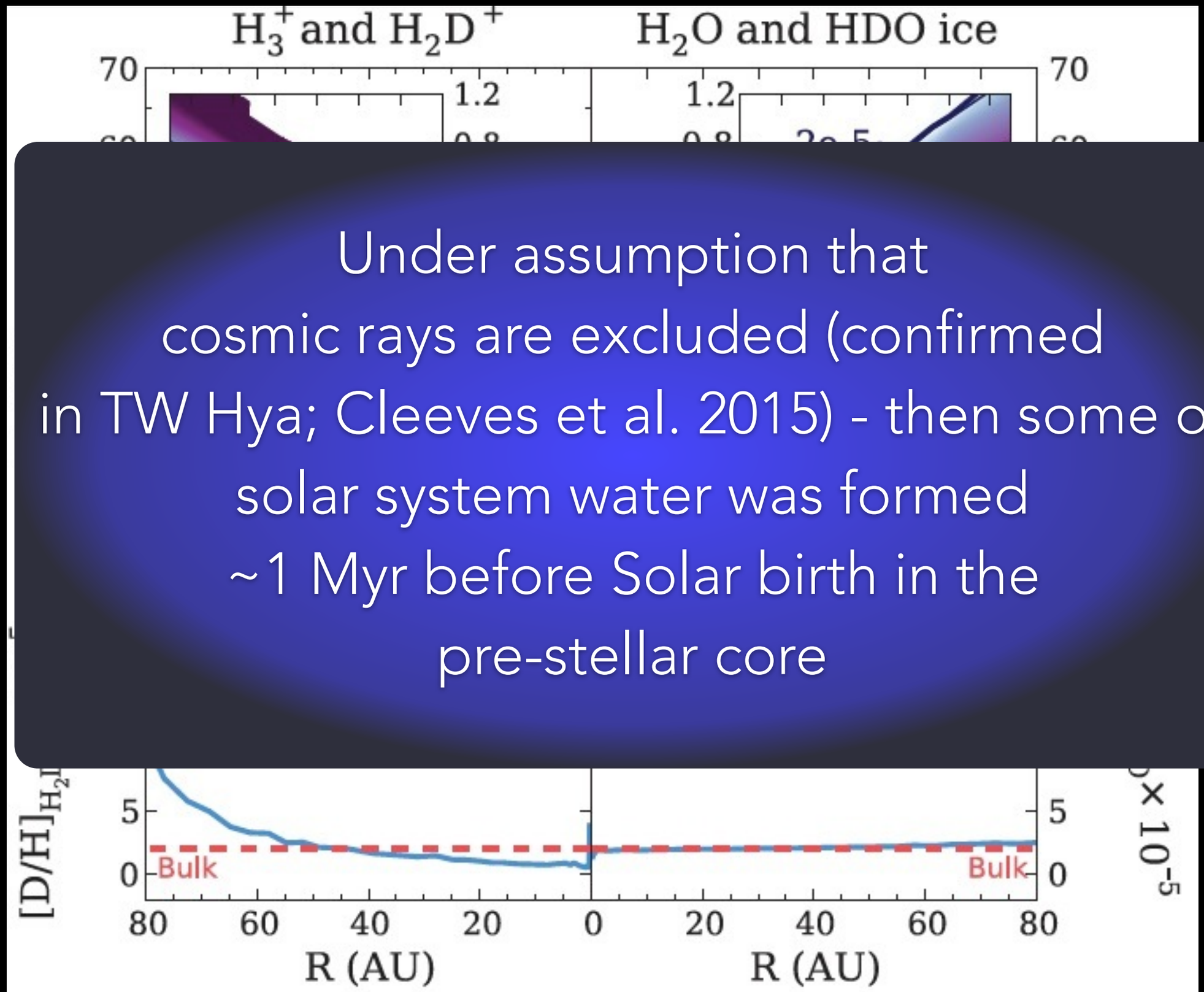
Cleeves, Adams, and Bergin 2013

D/H Ratio in Water



Cleeves et al. 2014

D/H Ratio in Water

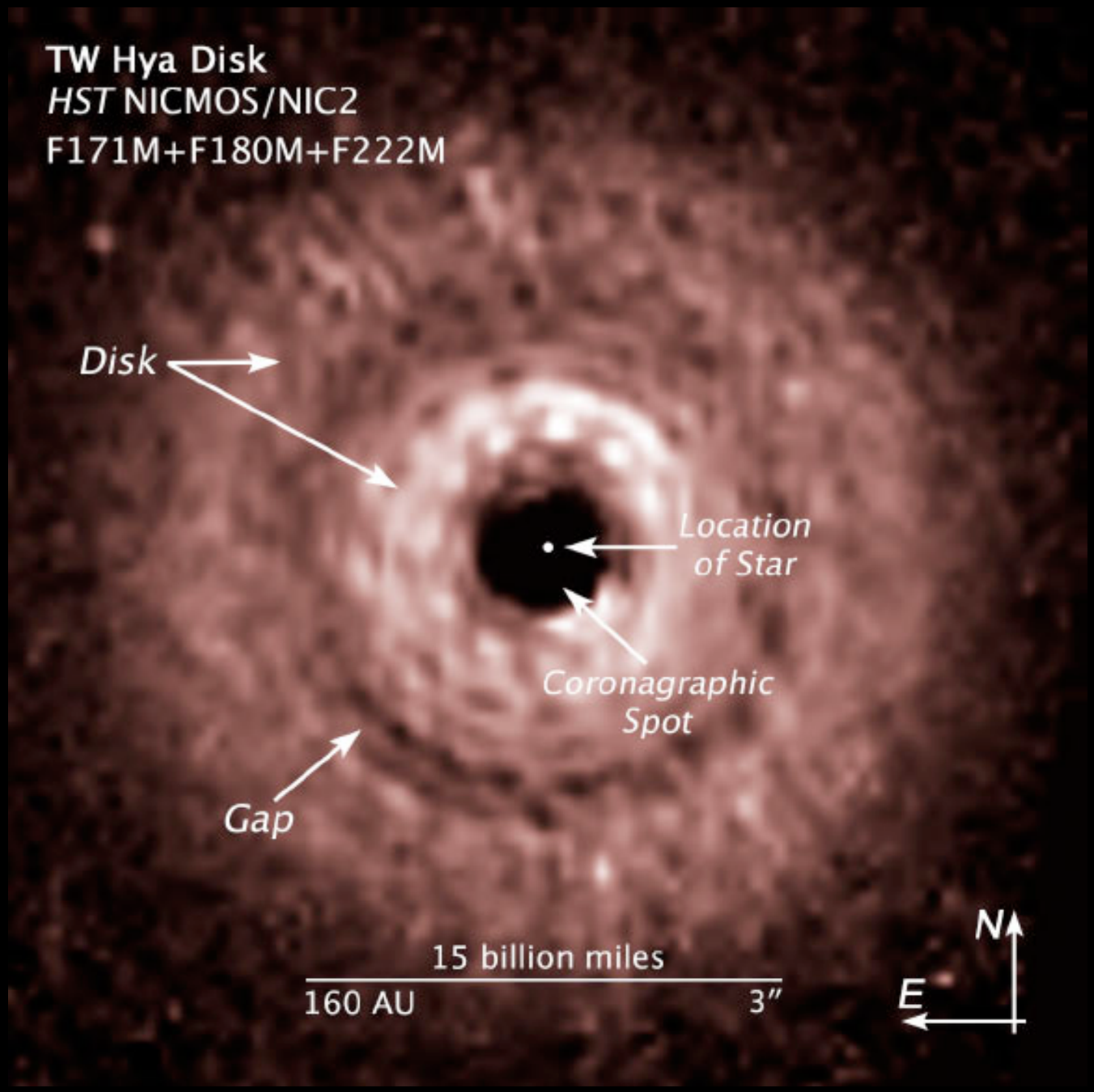


Under assumption that cosmic rays are excluded (confirmed in TW Hya; Cleeves et al. 2015) - then some of solar system water was formed ~1 Myr before Solar birth in the pre-stellar core

Cleeves et al. 2014

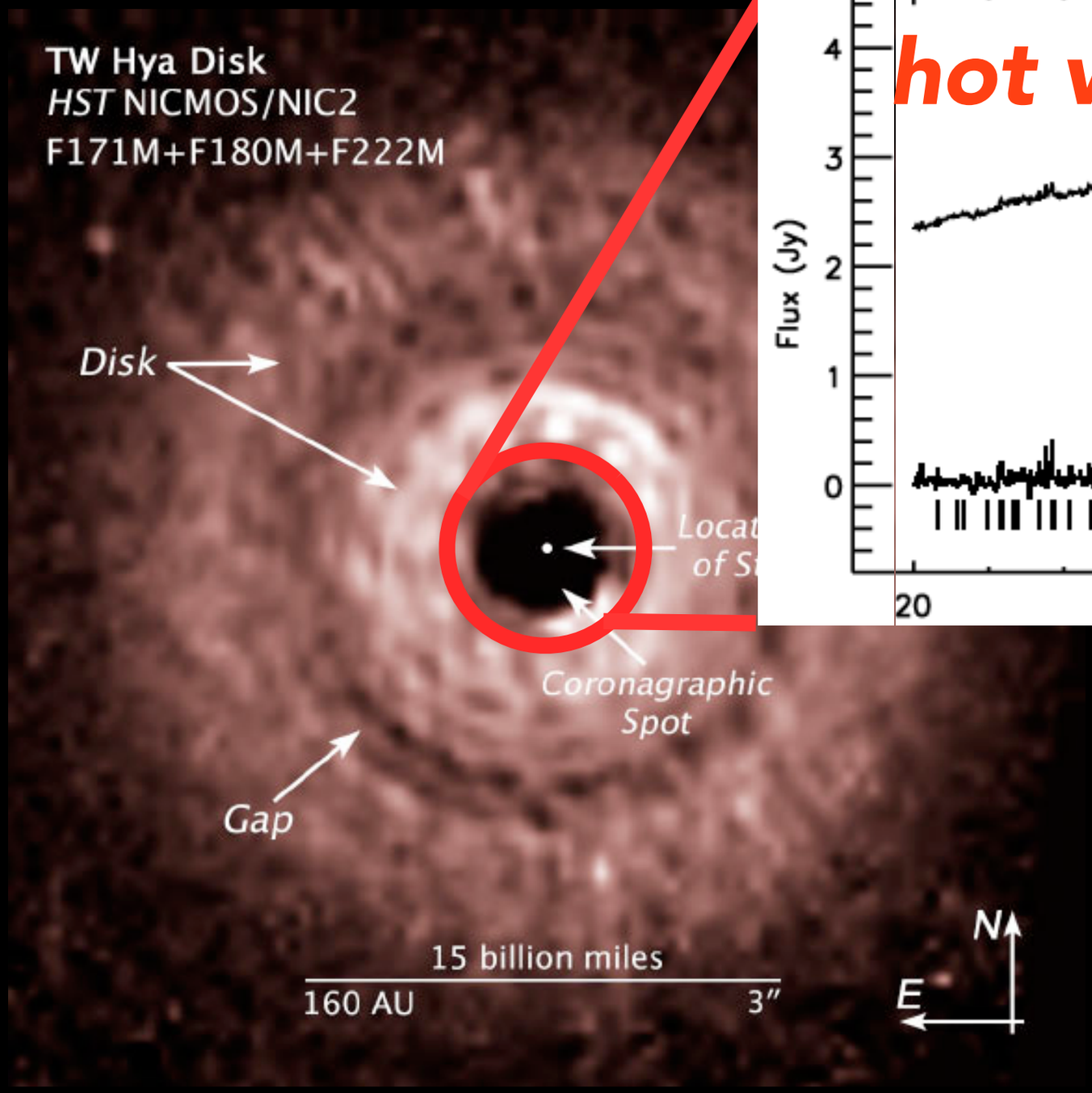
Oxygen in TW Hya

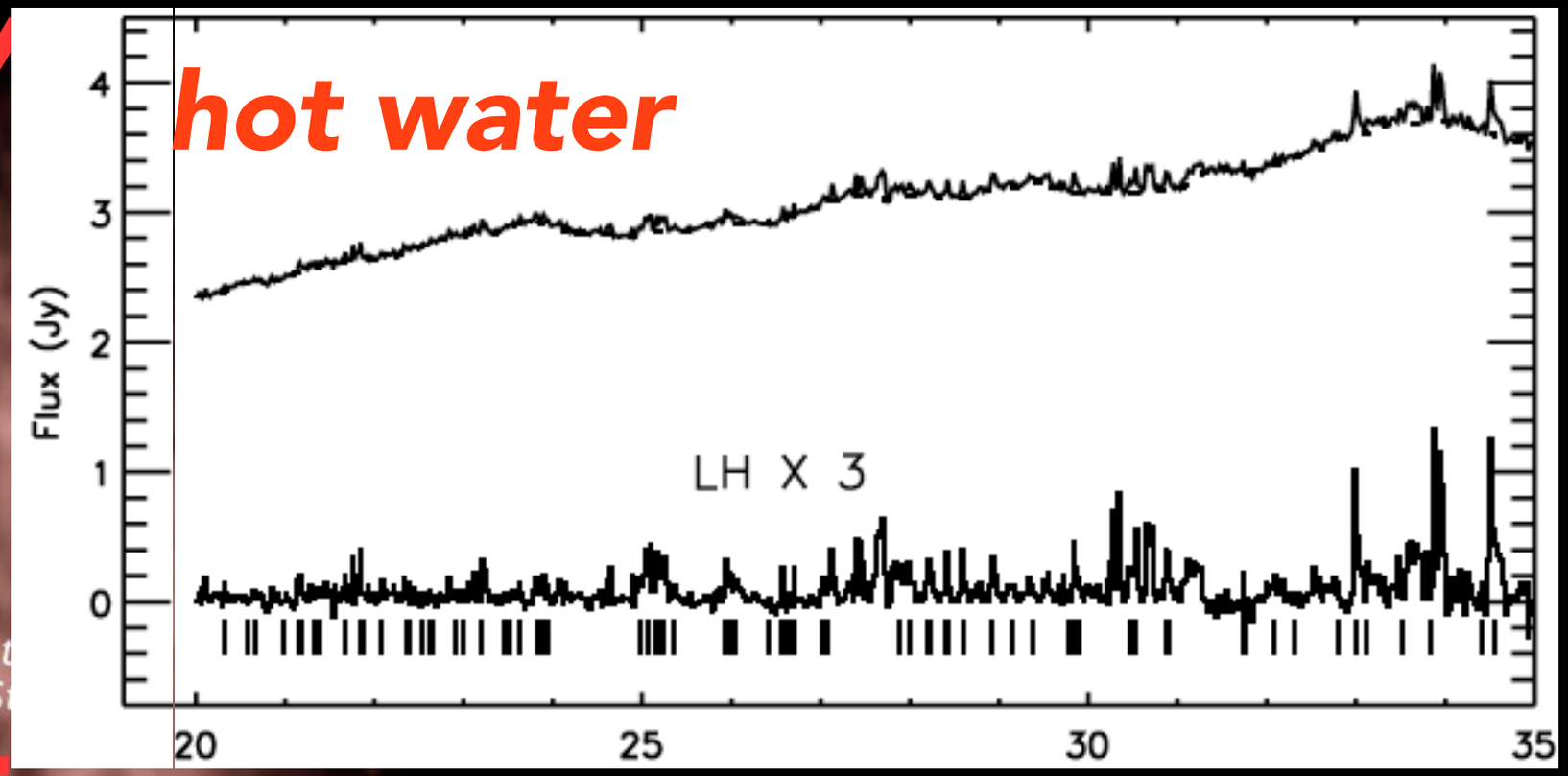
Debes et al. 2013



Oxygen in TW Hya

Debes et al. 2013

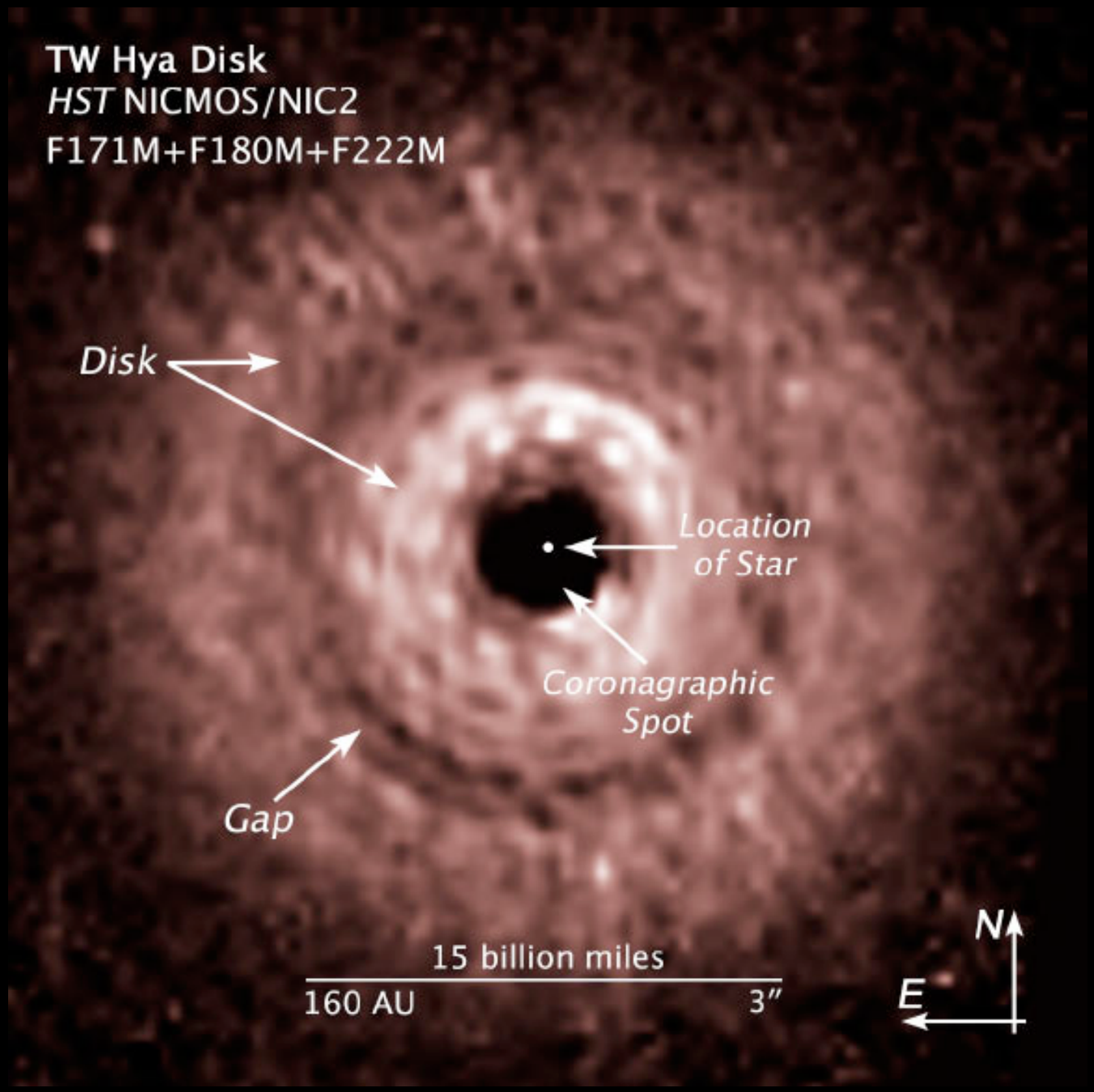




Zhang et al. 2013

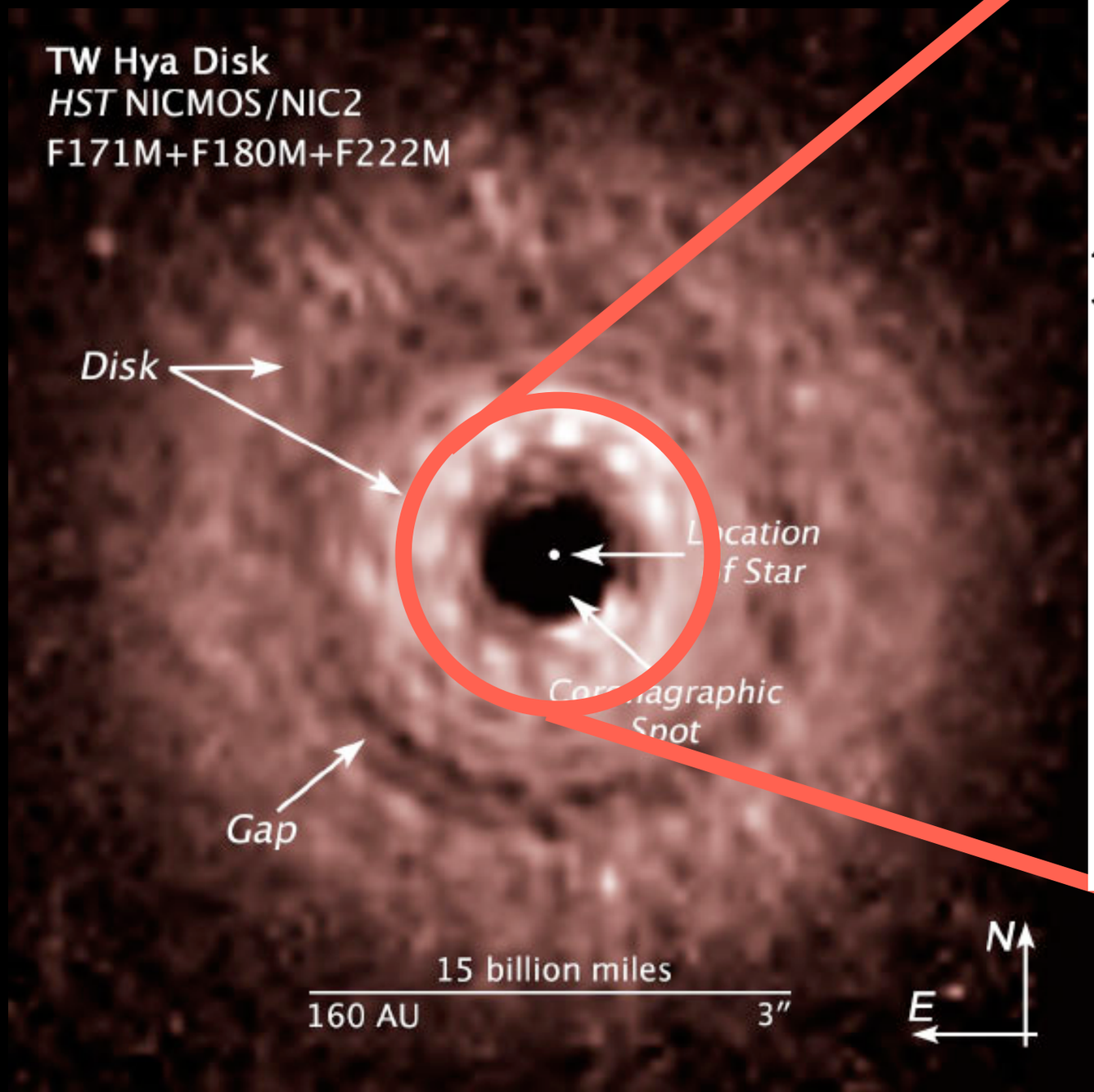
Oxygen in TW Hya

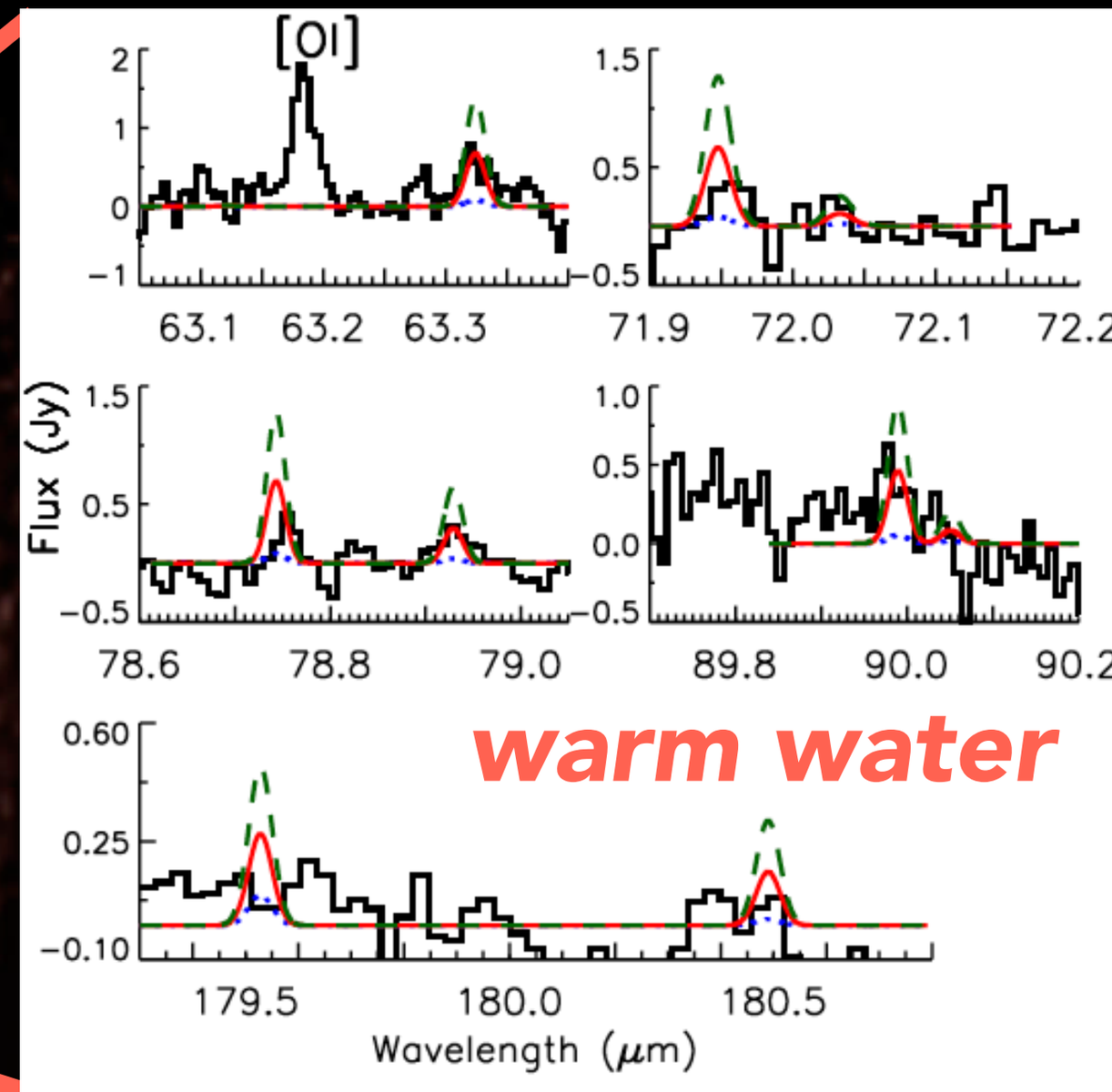
Debes et al. 2013



Oxygen in TW Hya

Debes et al. 2013

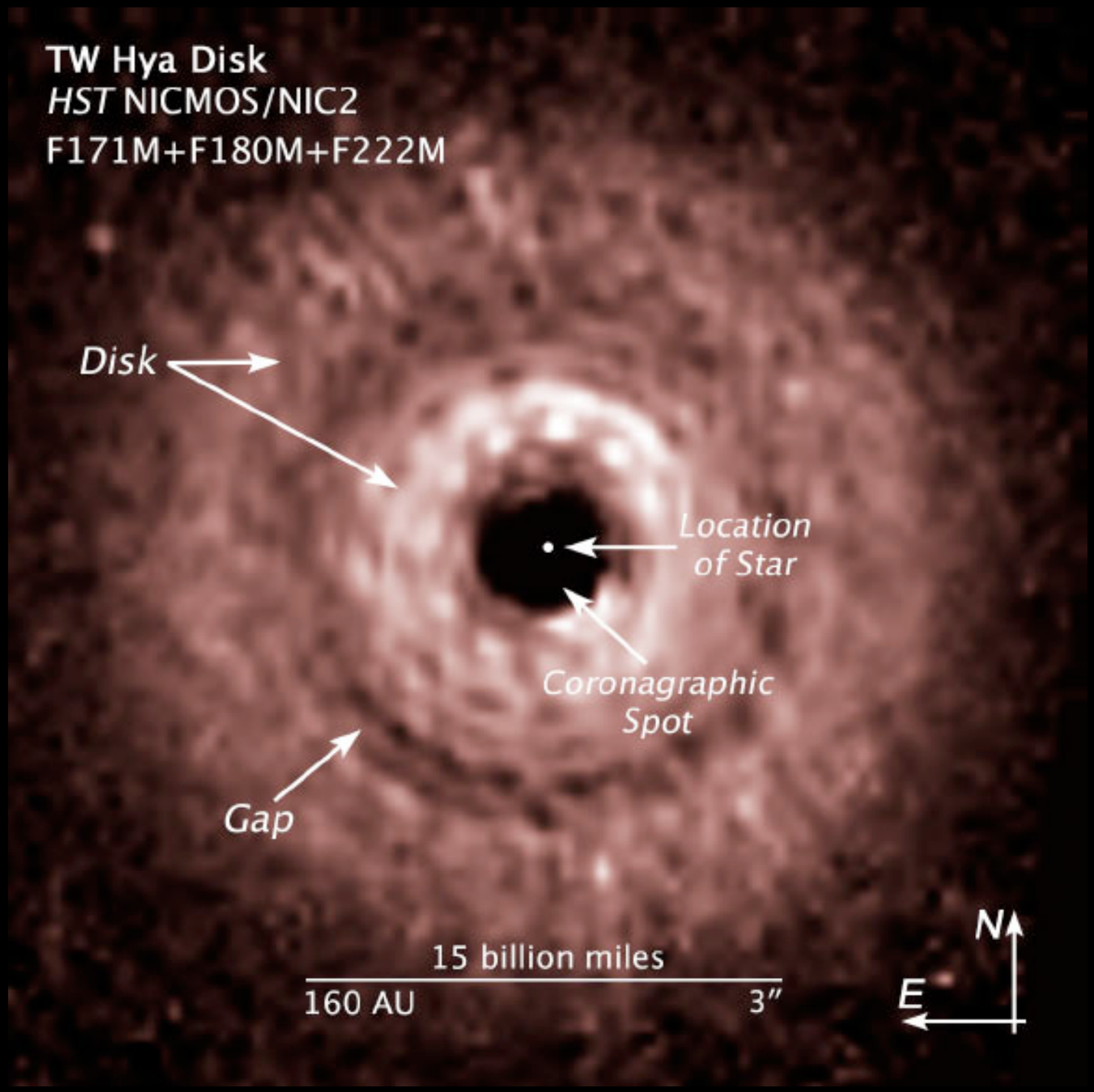




Zhang et al. 2013

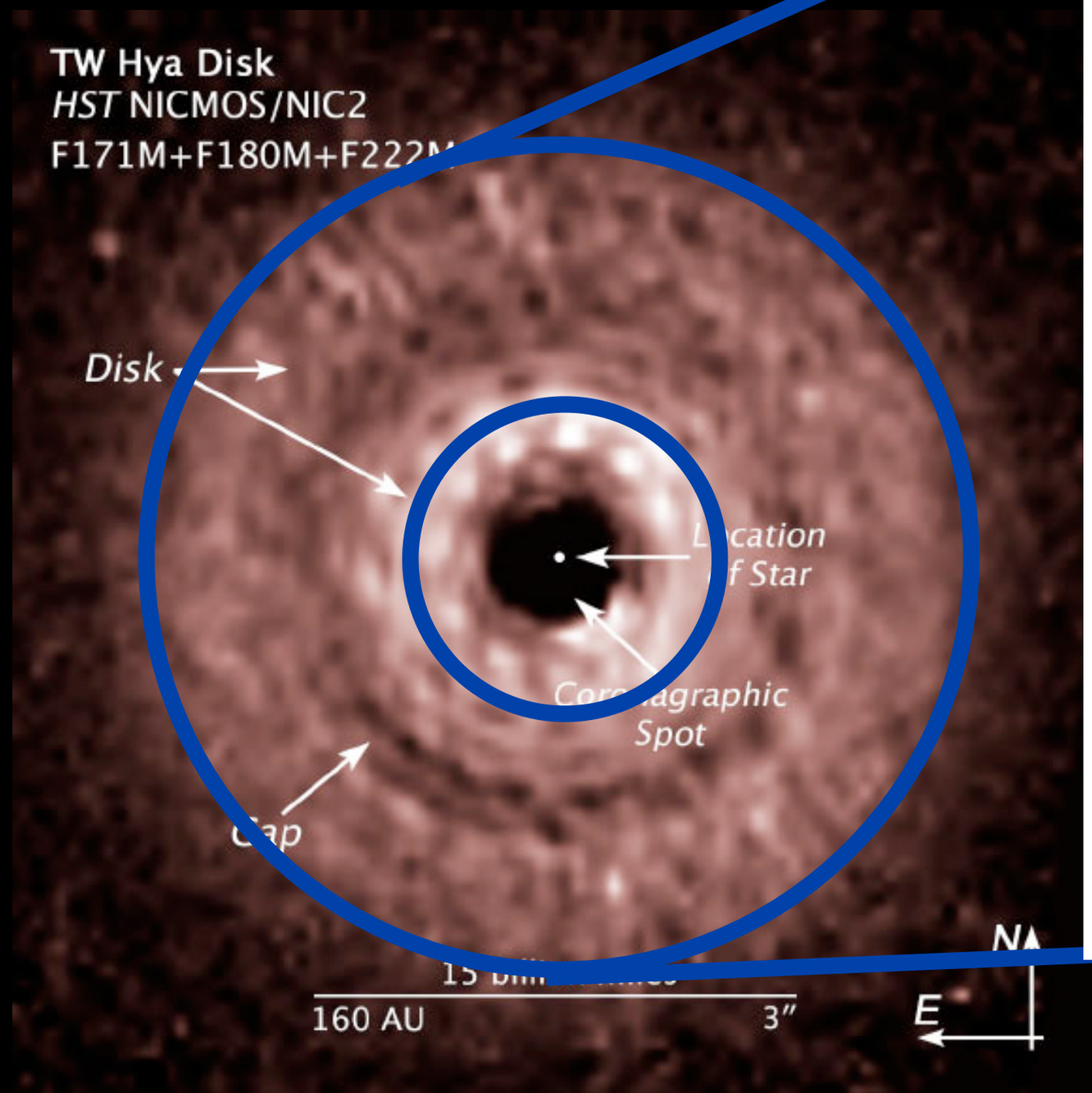
Oxygen in TW Hya

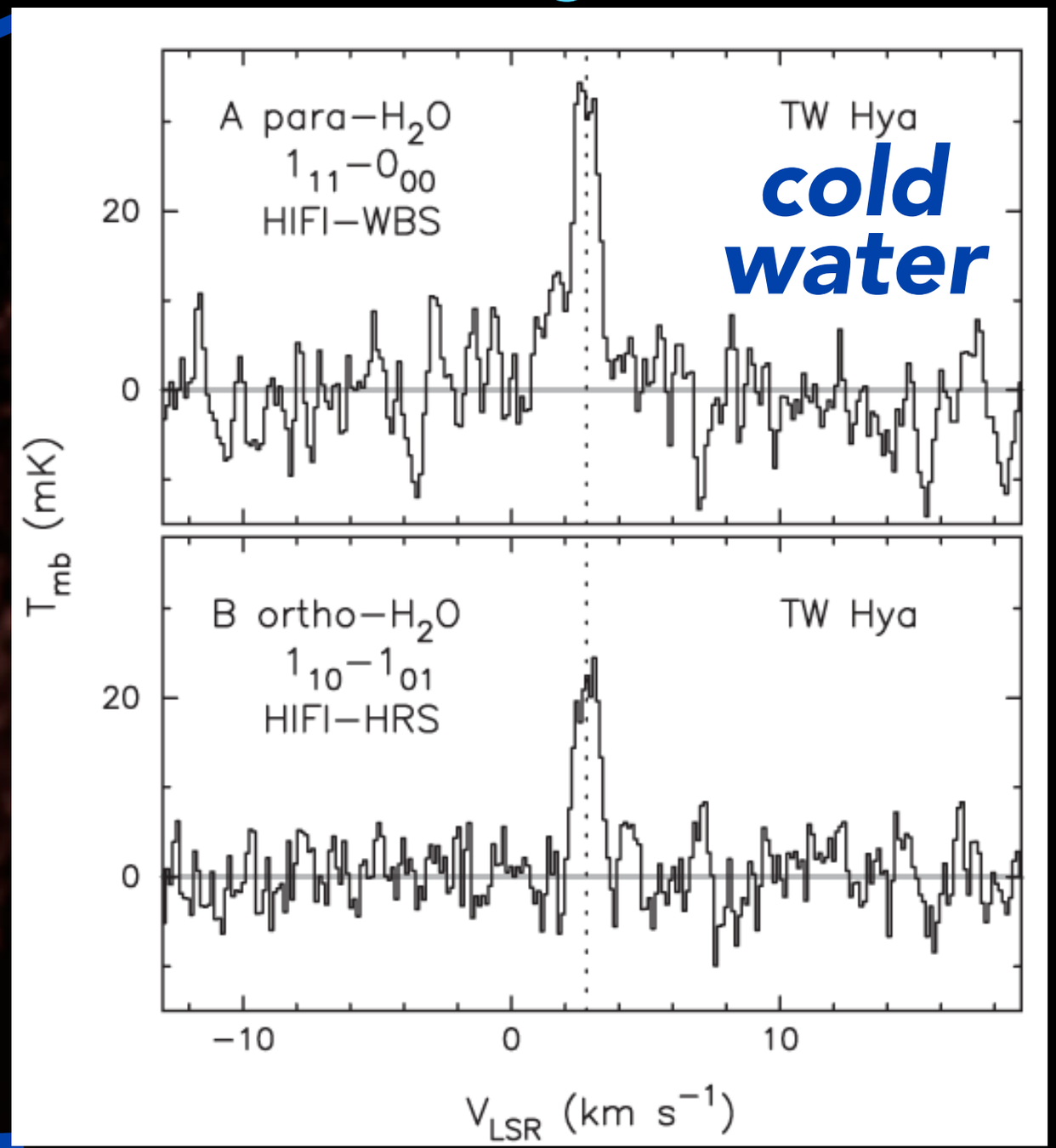
Debes et al. 2013



Oxygen in TW Hya

Debes et al. 2013

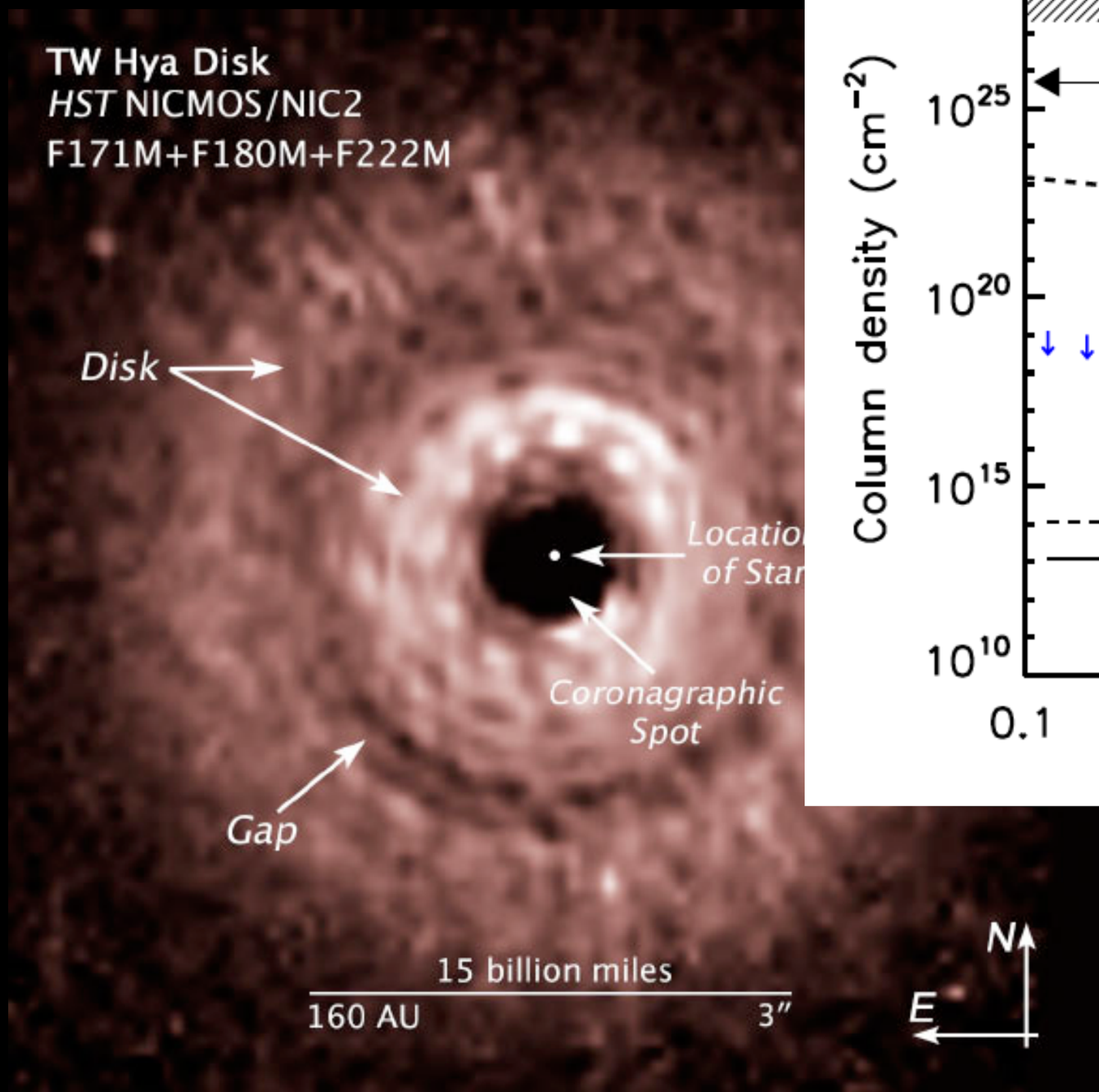


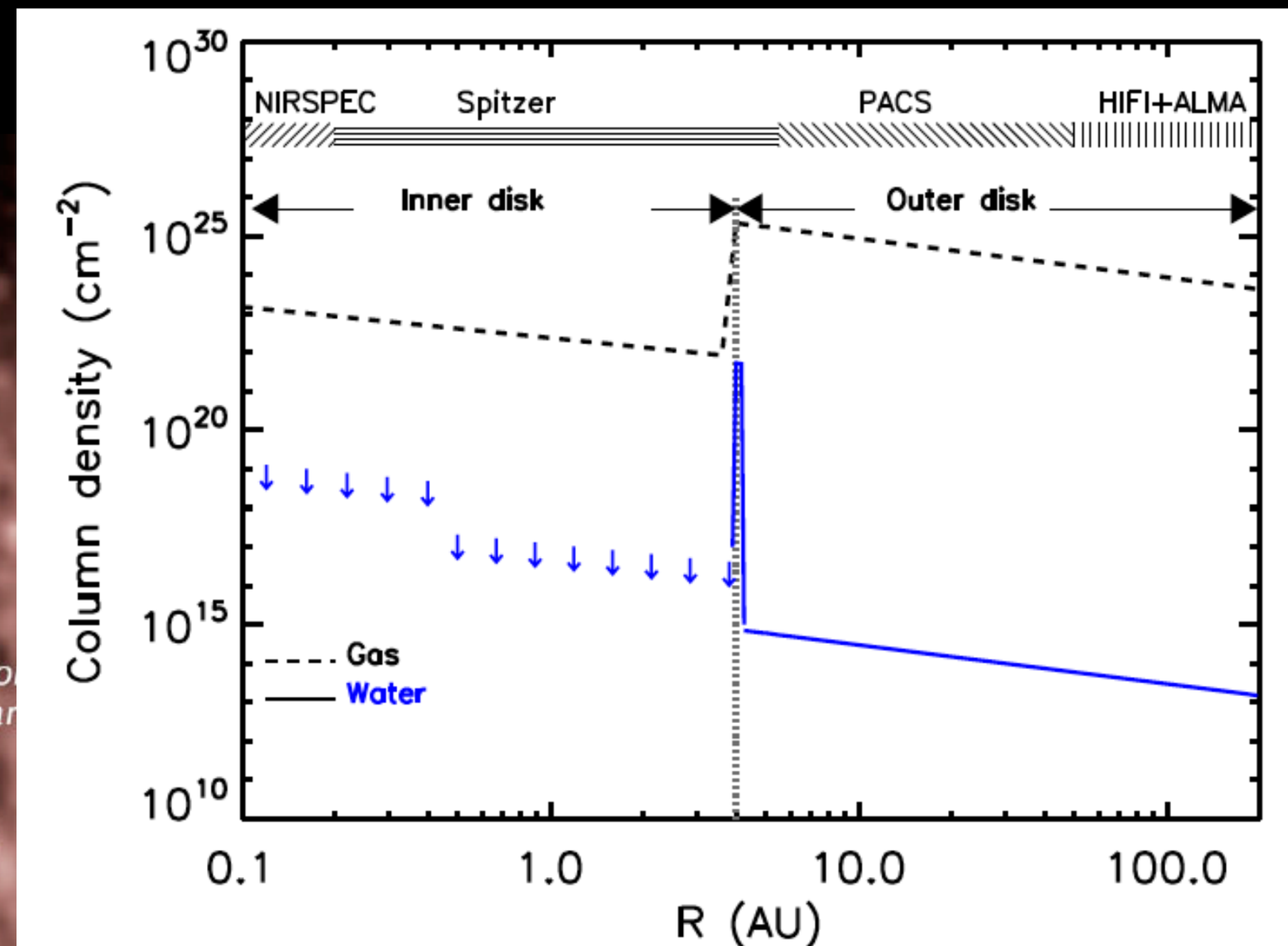


Hogerheijde et al. 2011

Oxygen in TW Hya

Debes et al. 2013





Zhang et al. 2013

Thermo-Chemical Model
Du & Bergin 2014

- adopt physical model of gas and dust distribution - fit the dust SED
- solve (2D) dust radiation transfer
- propagate UV (continuum/Ly **α**) and X-ray photon - solve in concert with H_2 & H_2O (Bethell & Bergin 2011)
- solve coupled chemistry (> 500 species and > 5000 reactions) and thermal physics
- predict emission lines (non-LTE approx)
- *include HD (Bergin et al. 2013) to constrain mass*

Constrained Disk Chemistry

➡ Re-examine all TW Hya Data with knowledge of HD

➡ use new thermochemical model (Du and Bergin 2014)

$C^+ \, {}^2P_{3/2} - {}^2P_{1/2}$

O I ${}^3P_1 - {}^3P_2 + {}^3P_0 - {}^3P_1$

CO 2-1, 3-2, 6-5, 10-9, 23-22

${}^{13}CO$ 2-1, $C^{18}O$ 2-1

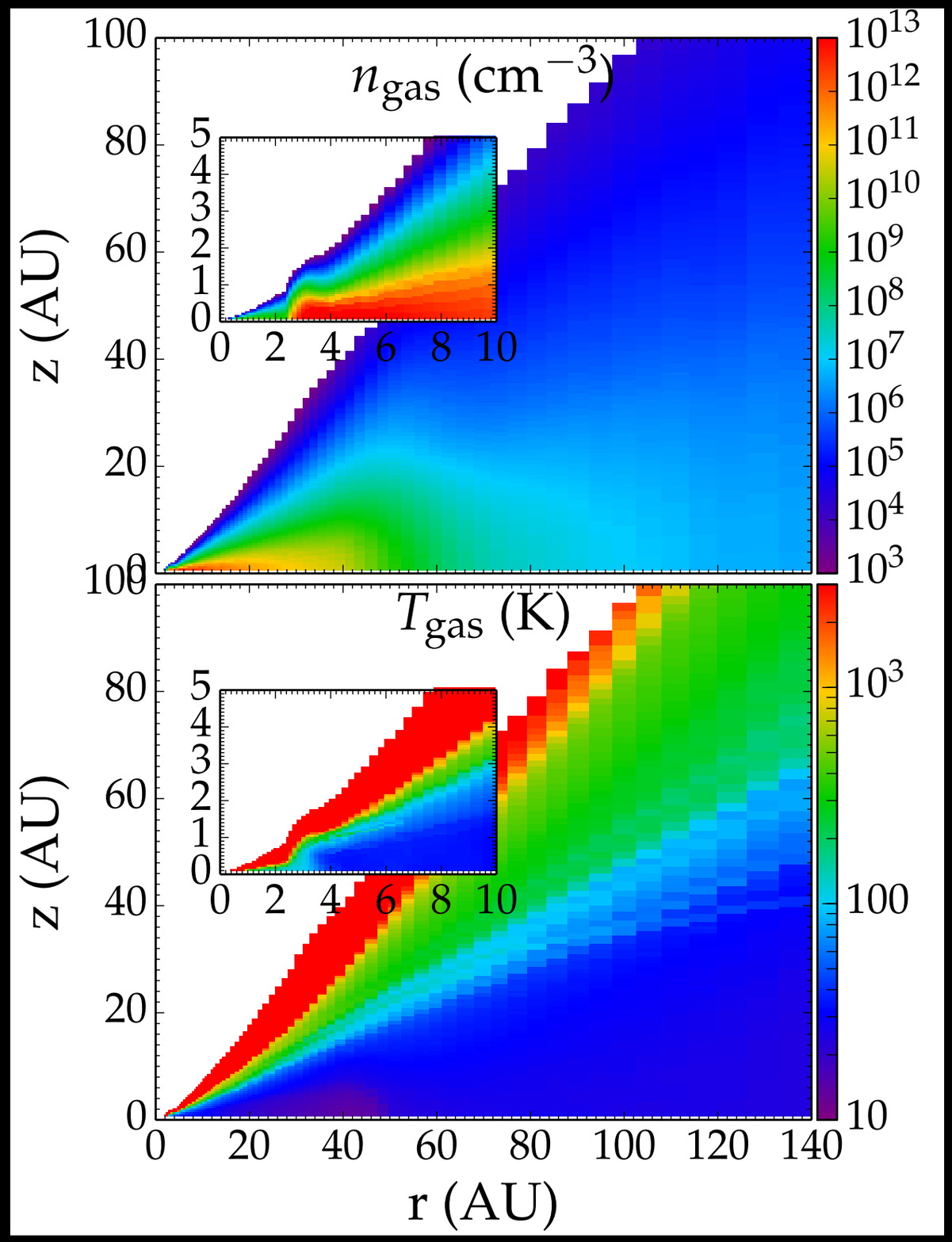
HD 1-0 (detection) + HD 2-1 (limit)

H2O (Spitzer/IRS, Herschel/PACS, Herschel/HIFI)

OH (Spitzer/IRS)

Du, Bergin, & Hogerheijde 2015

Physical Structure



<u>Two models</u>

1. O + C depleted beyond snow lines
2. O +C undepleted

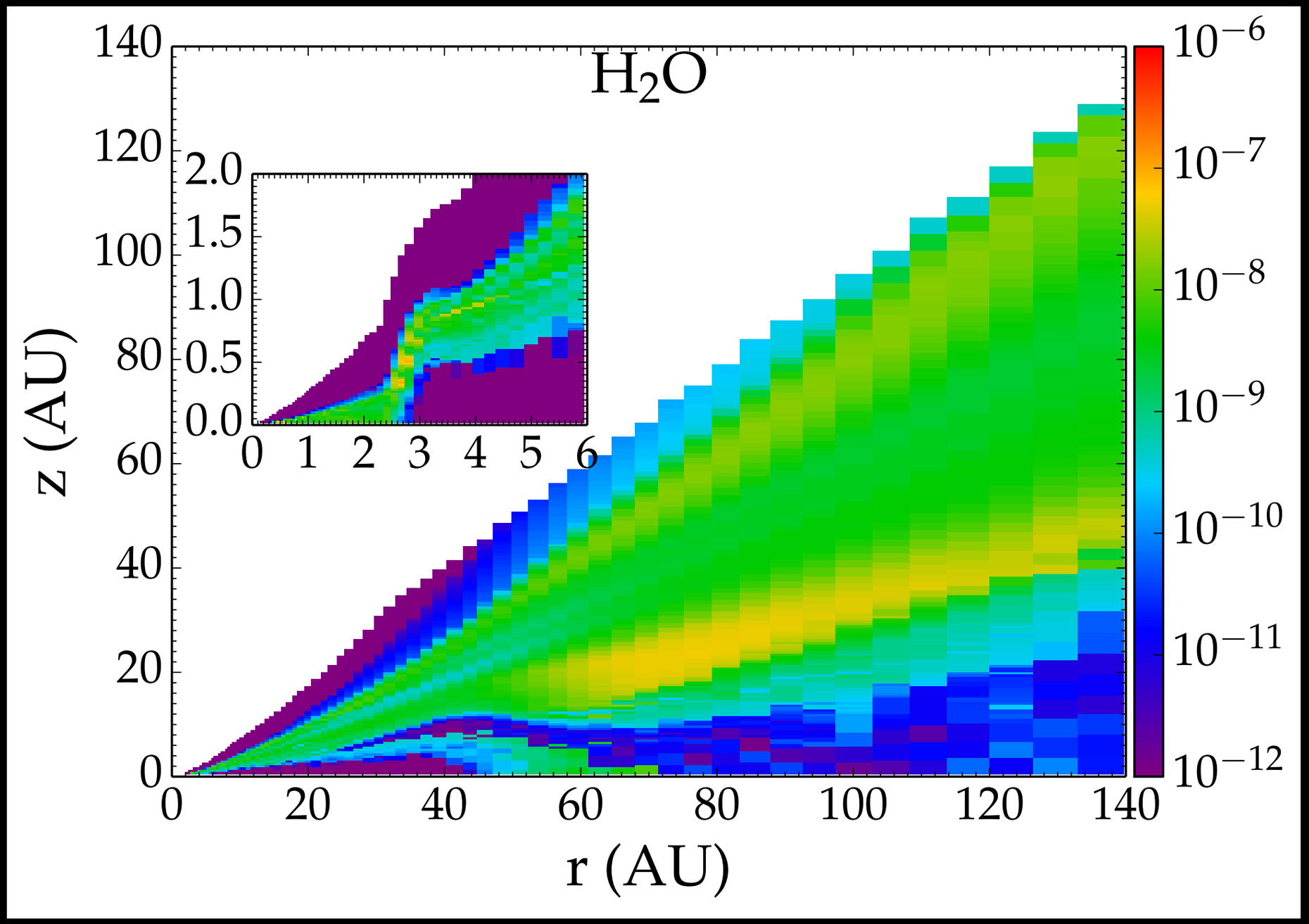
Main elemental carriers -

O: H_2O (ice and gas), CO, O I

C: CO (ice + gas), organics

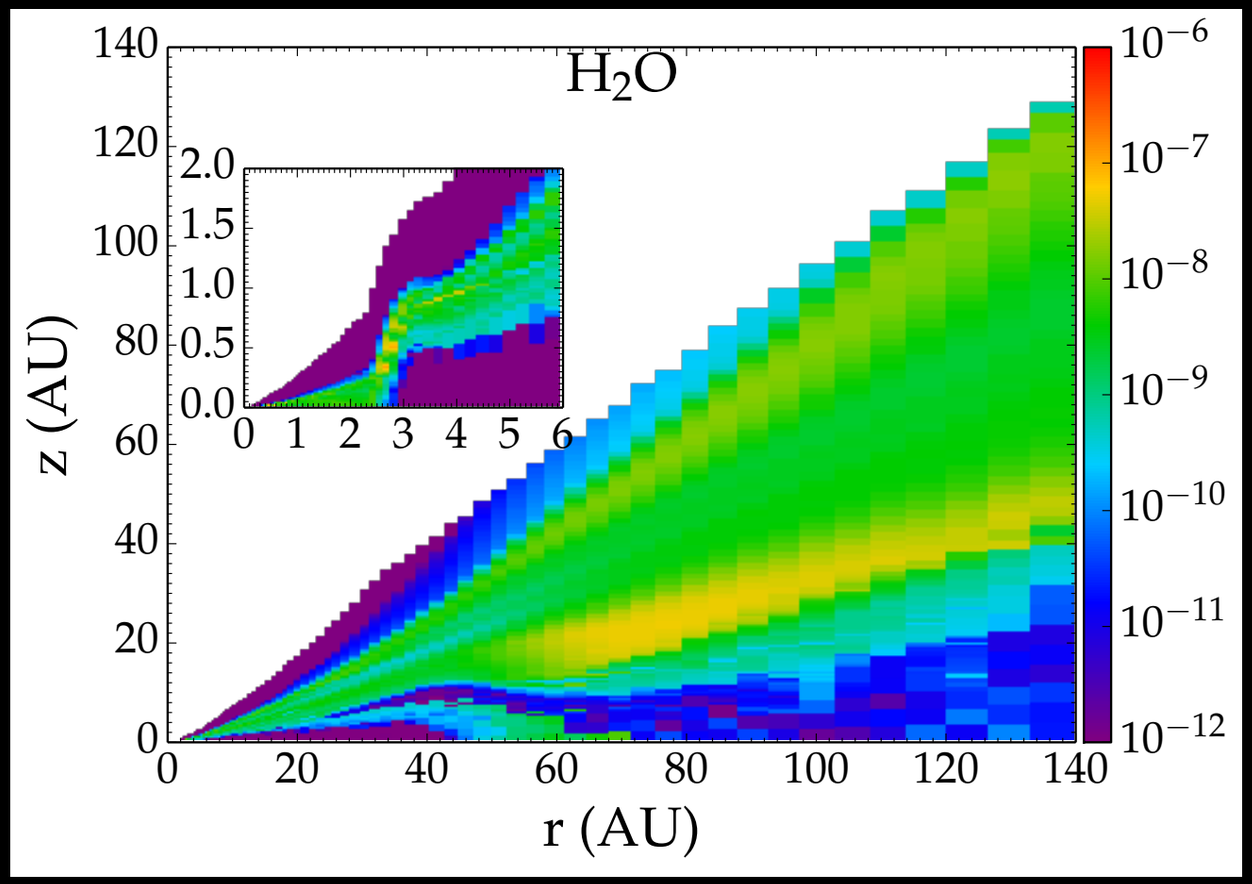
Du, Bergin, & Hogerheijde 2015

Water Abundance undepleted O

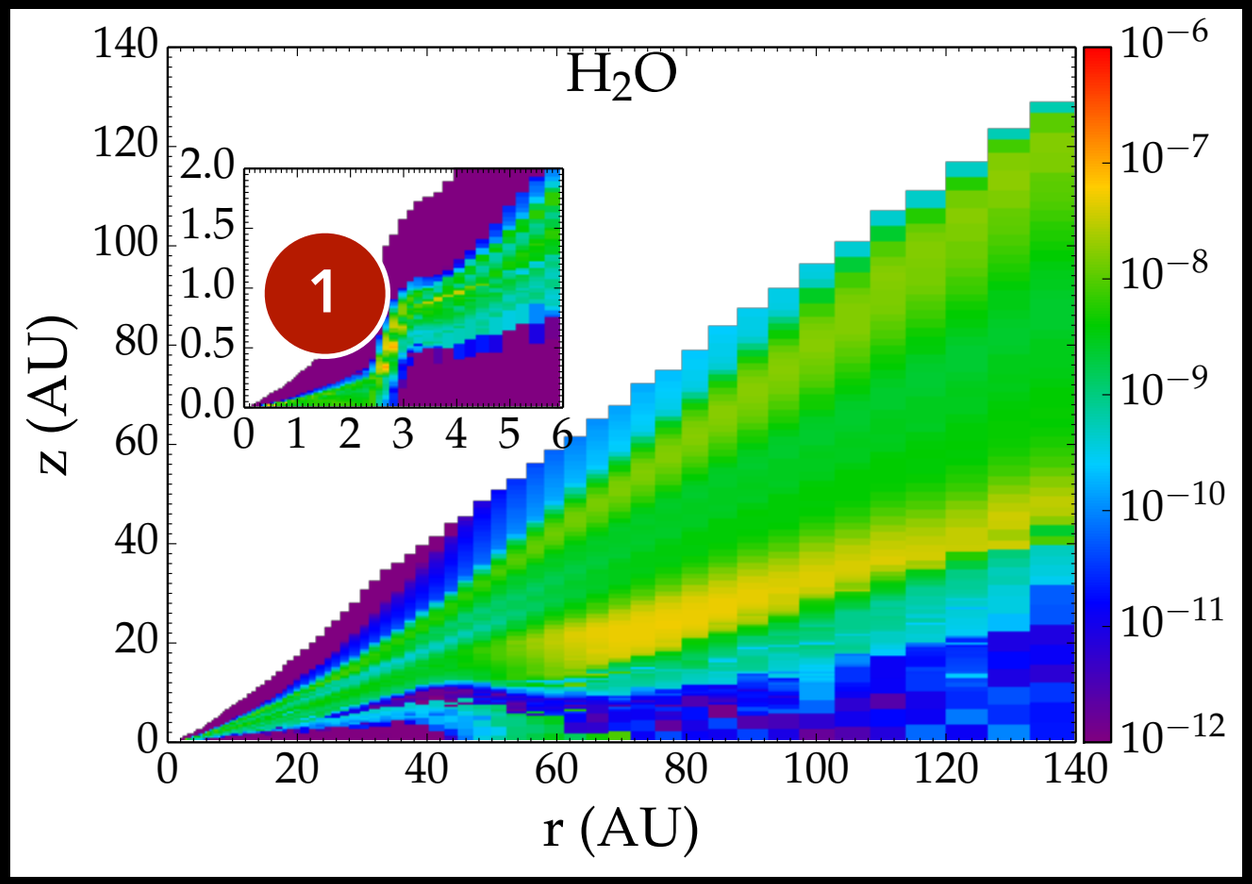


Du, Bergin, & Hogerheijde 2015

Water Abundance undepleted O

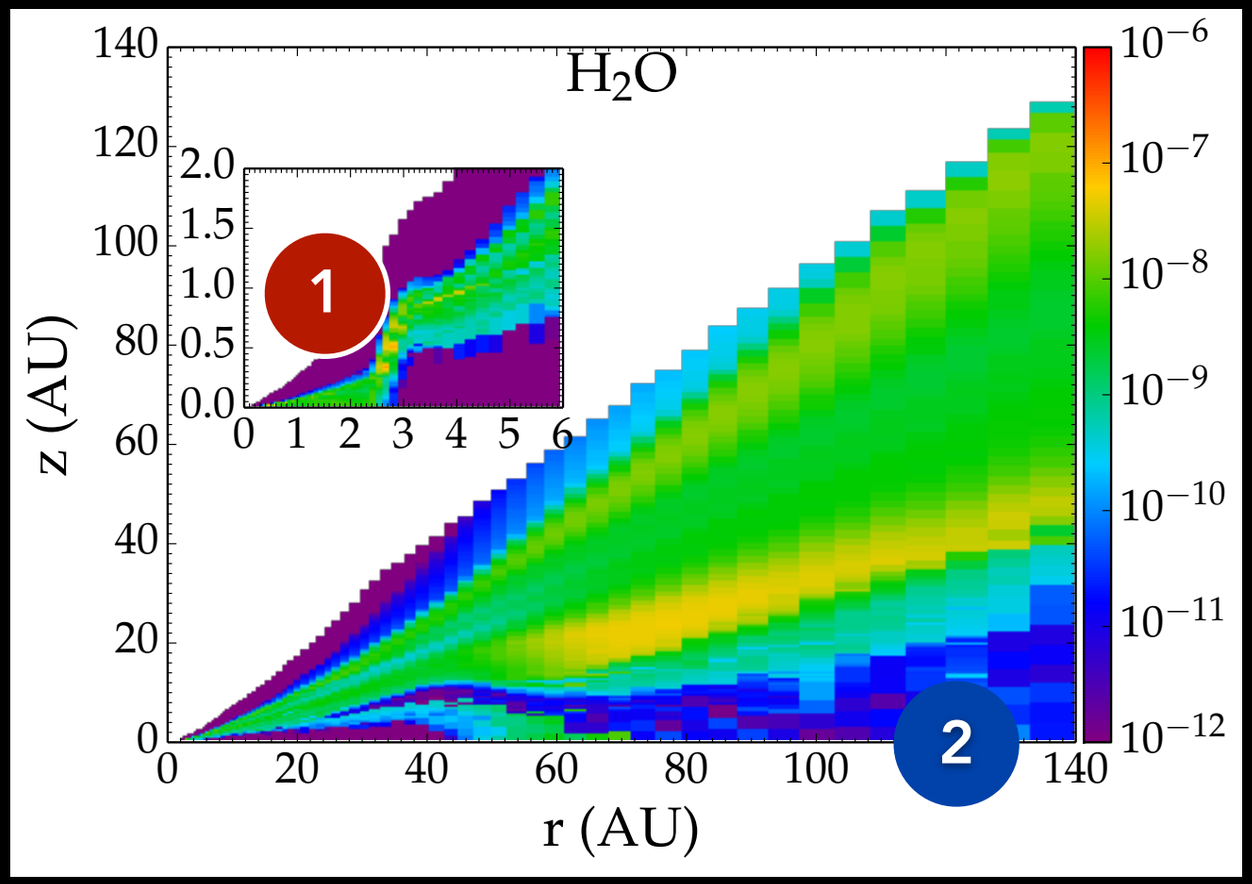


Water Abundance undepleted O



1. Hot water chemistry and ice evaporation - balanced by exposure to stellar irradiation

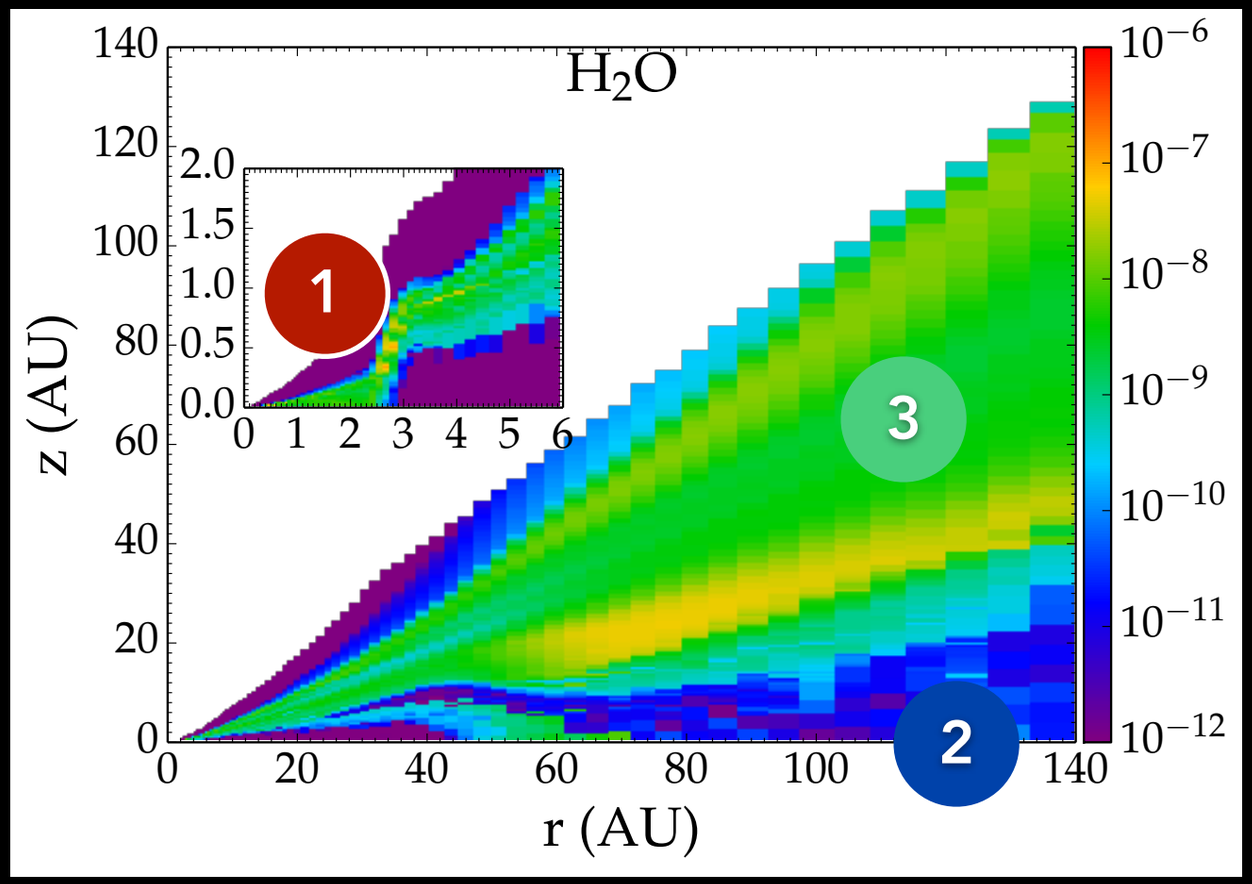
Water Abundance undepleted O



1. Hot water chemistry and ice evaporation - balanced by exposure to stellar irradiation

2. Water ice dominated - beyond snow line (4 AU for TW Hya) no ice evaporation in midplane

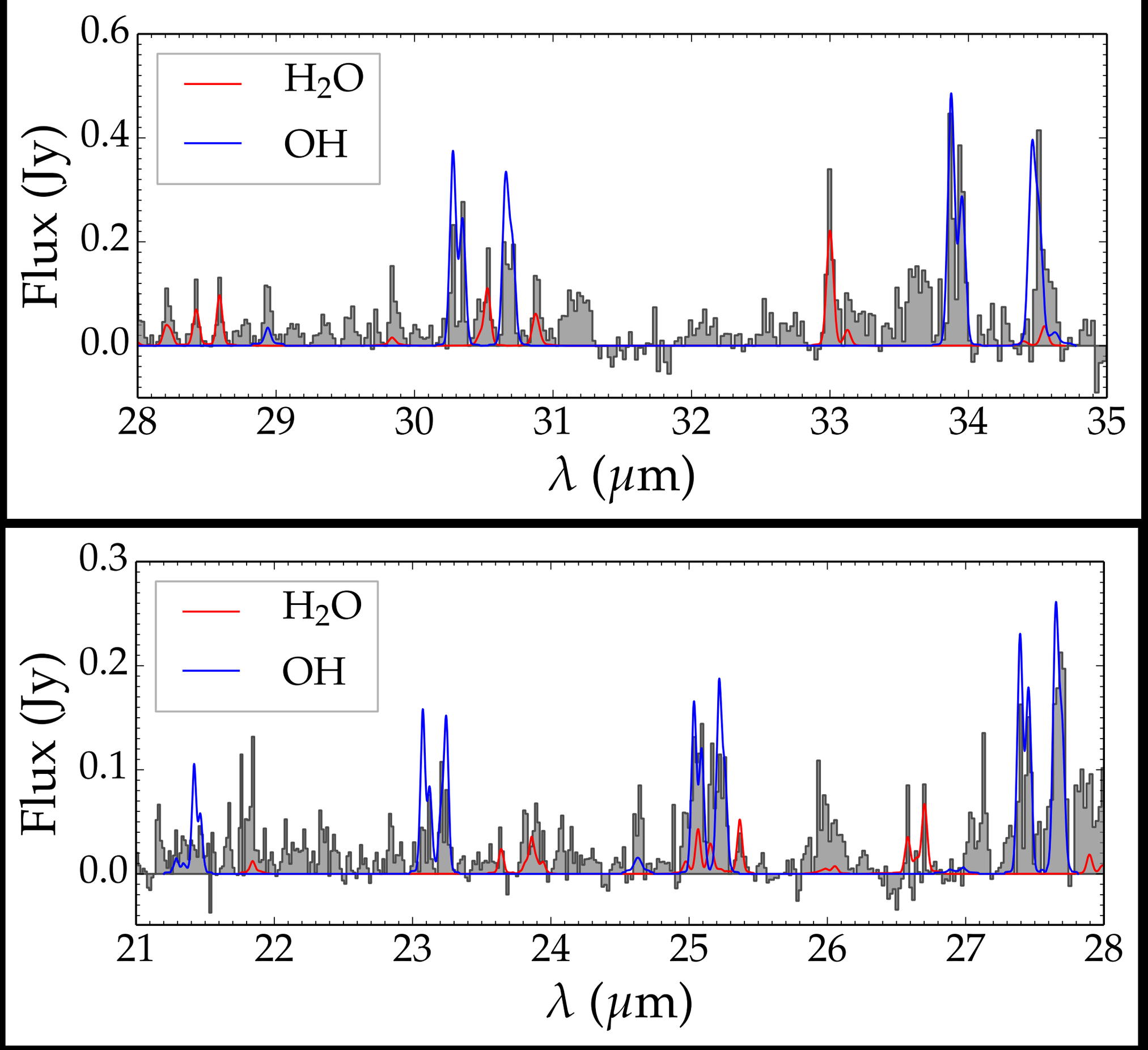
Water Abundance undepleted O



1. Hot water chemistry and ice evaporation - balanced by exposure to stellar irradiation

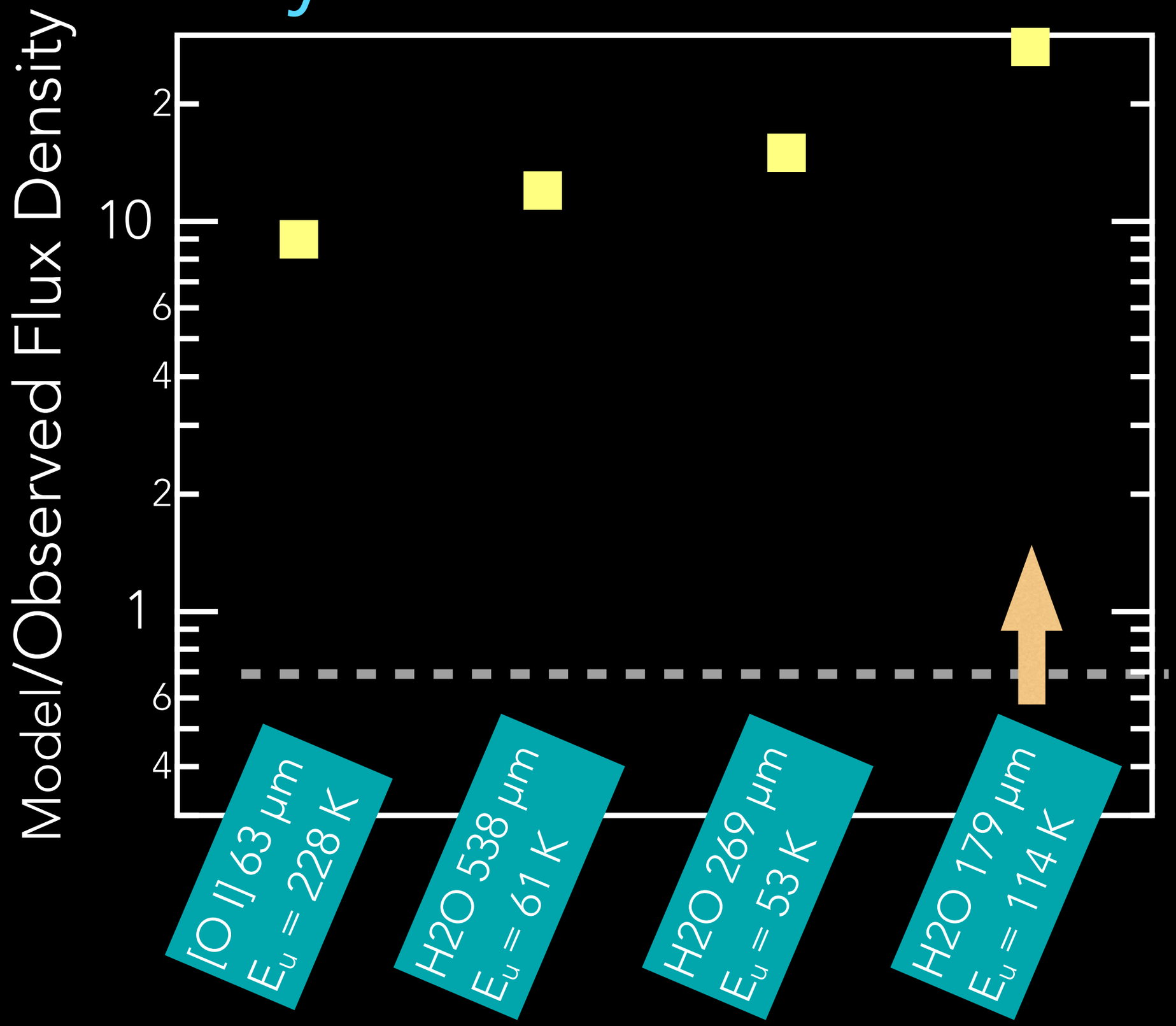
2. Water ice dominated - beyond snow line (4 AU for TW Hya) no ice evaporation in midplane

3. Photodesorption layer - UV radiation must be present



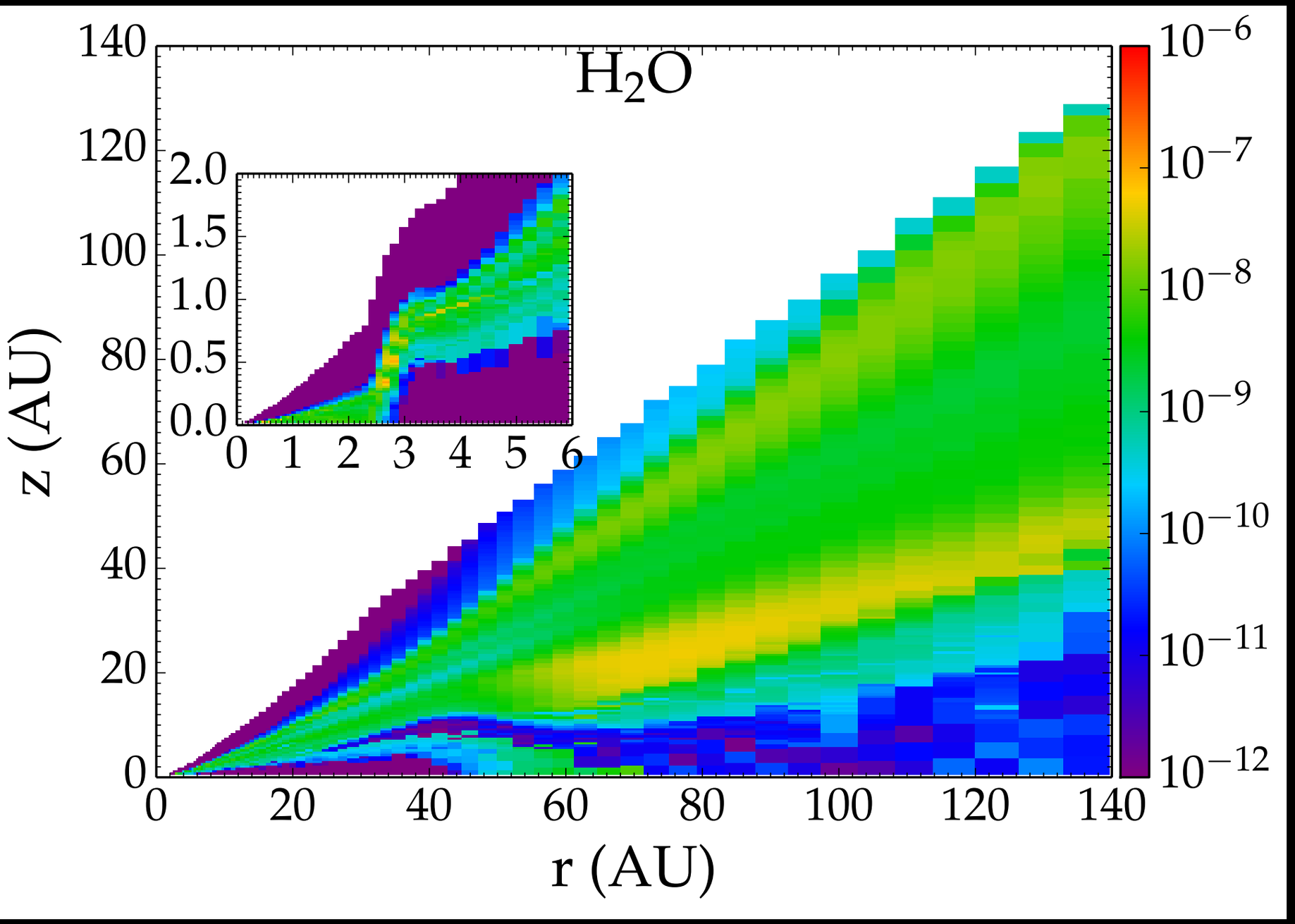
Du, Bergin, & Hogerheijde 2015

Water beyond the snow line..



Du, Bergin, & Hogerheijde 2015

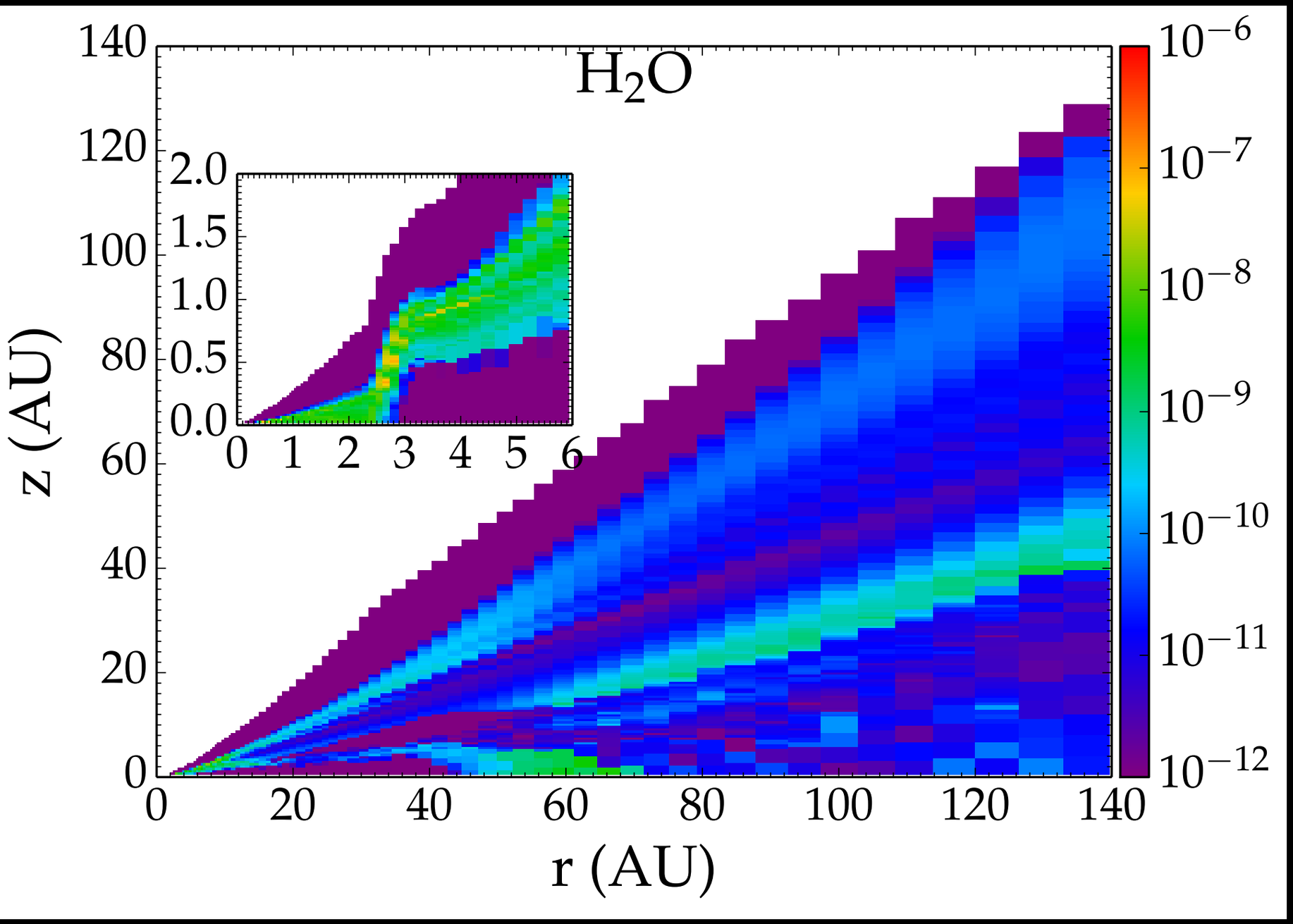
Water Abundance depleted O



- Need to remove water ice from layers with UV (i.e. reduce photodes. efficiency)
- Also in 5-20 AU need to reduce available O to form water via gas phase reactions

Du, Bergin, & Hogerheijde 2015

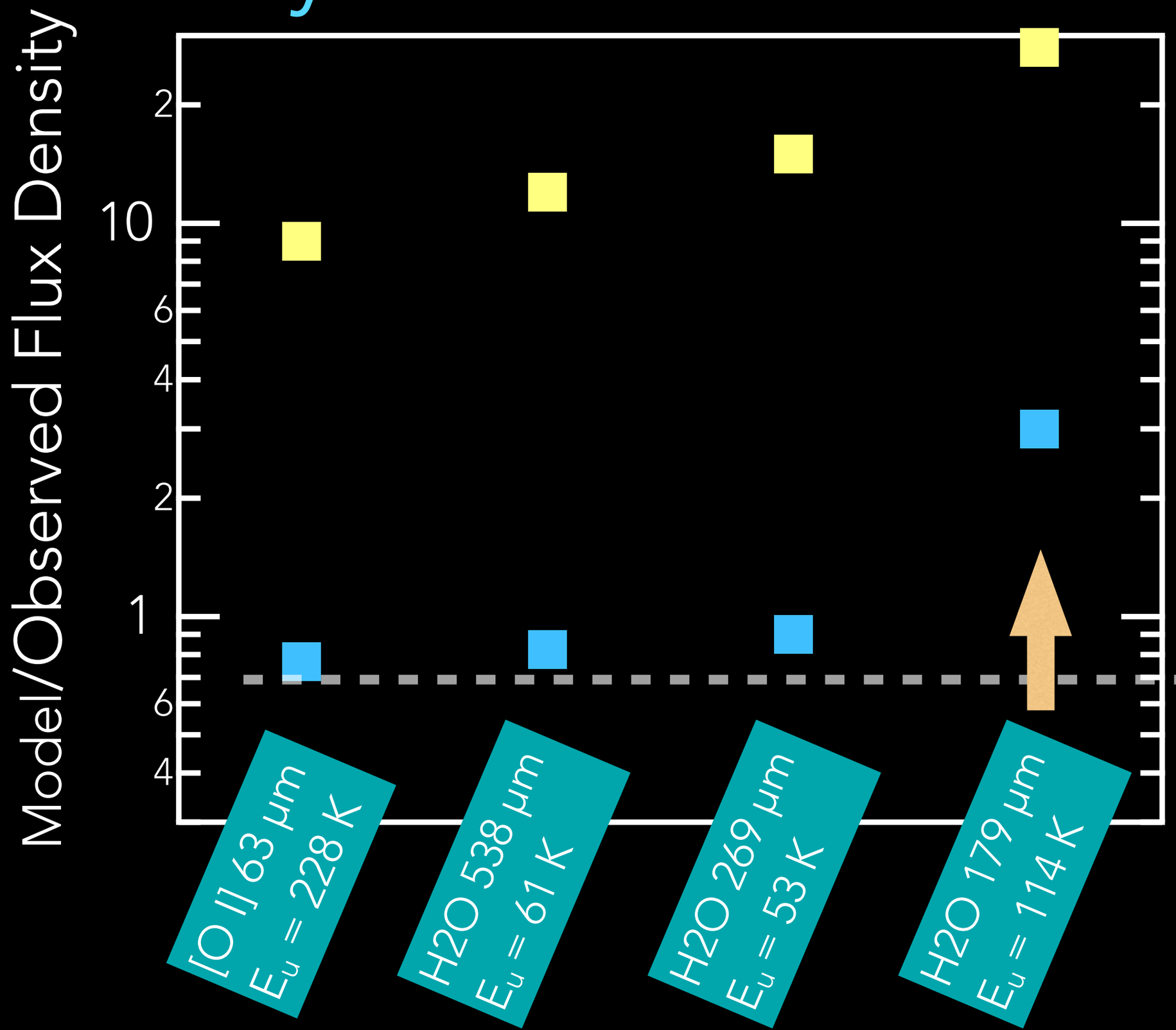
Water Abundance depleted O



- Need to remove water ice from layers with UV (i.e. reduce photodes. efficiency)
- Also in 5-20 AU need to reduce available O to form water via gas phase reactions

Du, Bergin, & Hogerheijde 2015

Water beyond the snow line..



Du, Bergin, & Hogerheijde 2015, in prep.

Systematic Effect

- Cold water emission survey

  ➡ 7+ systems surveyed - no detections beyond TW Hya and HD100546 (Du et al., in prep.)

- O I less emissive compared to continuum in sample of 21 transition disks (Keane et al. 2014)
- $C^{18}O$/HD ratio in TW Hya gives $CO/H_2 << 10^{-4}$ (Favre et al. 2013)
- C^+ detected in 27% out of 47 T Tauri stars surveyed by Herschel -- all have UV excess (Dent et al. 2013)

Systematic Effect

- Cold water emission survey

➡ [illegible] d

- O I [illegible] ple of 2

- $C^{18}O$ [illegible] (Fav

Where are the volatiles?
Likely trapped in pebbles or larger bodies in the midplane. Need reduced return of micron sized ice coated grains that can be lofted to the surface

- C^{+} detected in 27% out of 47 T Tauri stars surveyed by Herschel -- all have UV excess (Dent et al. 2013)

Summary

- Water is formed as ice in pre-stellar stage, with D signature implanted at this time.
- Cosmic rays may not be present in the disk which has implications for disk chemistry and physics.
- Detection of HD combined with observations of volatiles suggest presence of hidden reservoirs -> pebbles
- Effect of missing volatiles in upper layers is systematic — we are tracing the carriers of volatiles to forming worlds
- Timescale of ice sequestration/volatile depletion is intertwined with gas dispersal timescale and gas mass estimates from CO