# Water:

## from Clouds to Planets

Ewine van Dishoeck (Leiden Obs/MPE)

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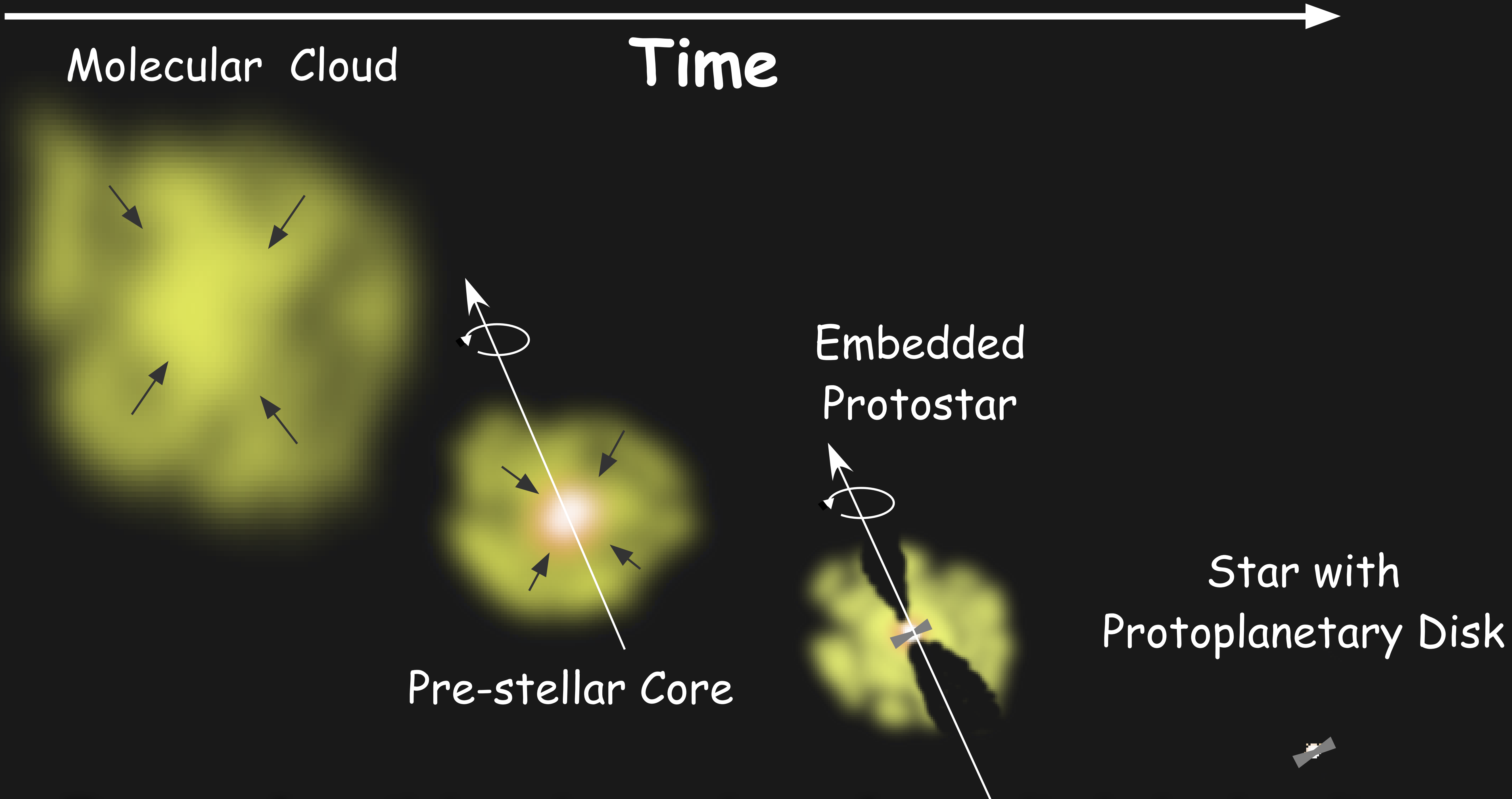



- Range of spatial scales, orders of magnitude in density and temperature
- Will affect water excitation and chemistry.
- ***Ultimate Goal: Follow trail of water from formation to supply to young planets***

image credit: NOAO +
Jack Cook (Woods Hole) & Howard Perlman (USGS)

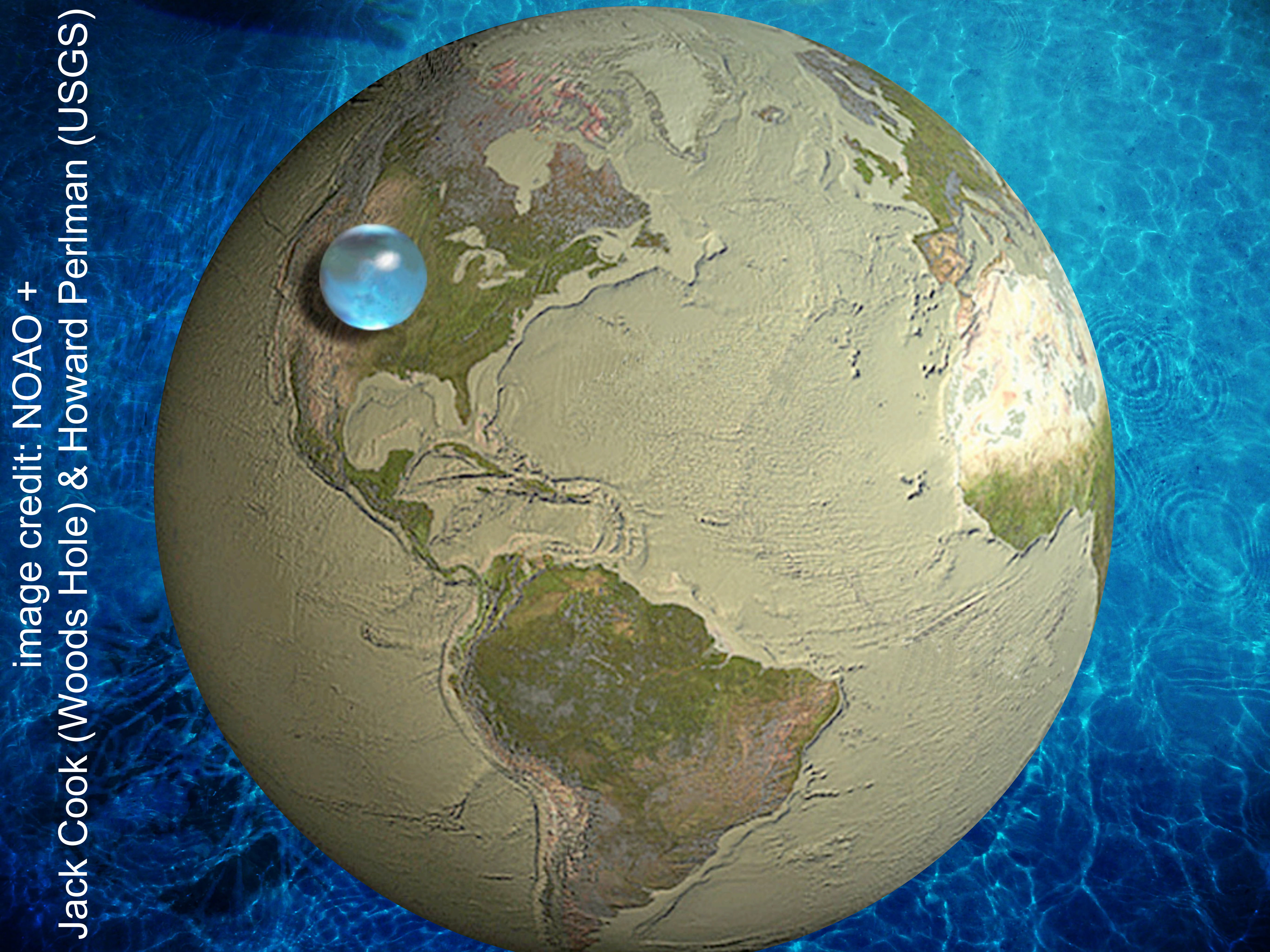
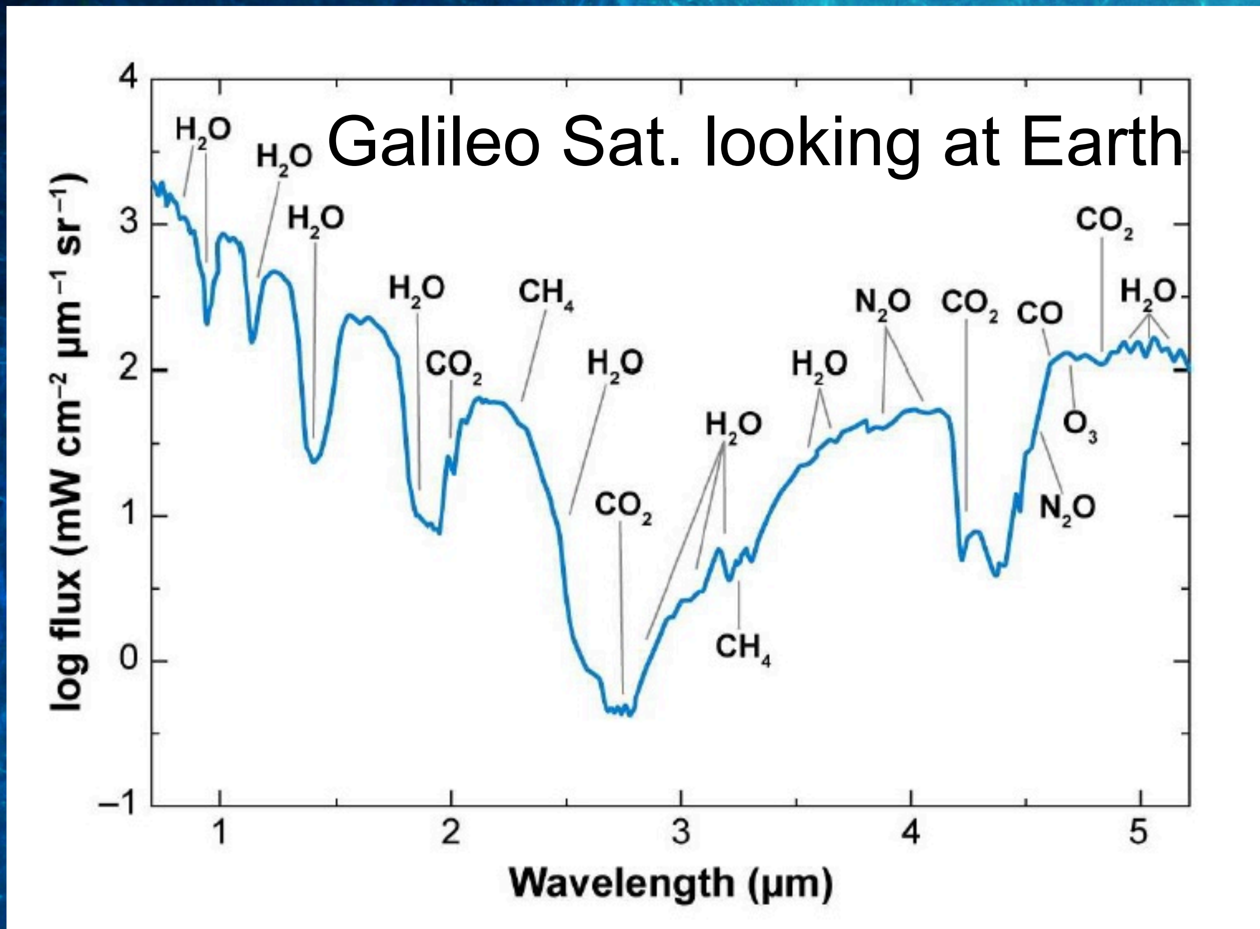


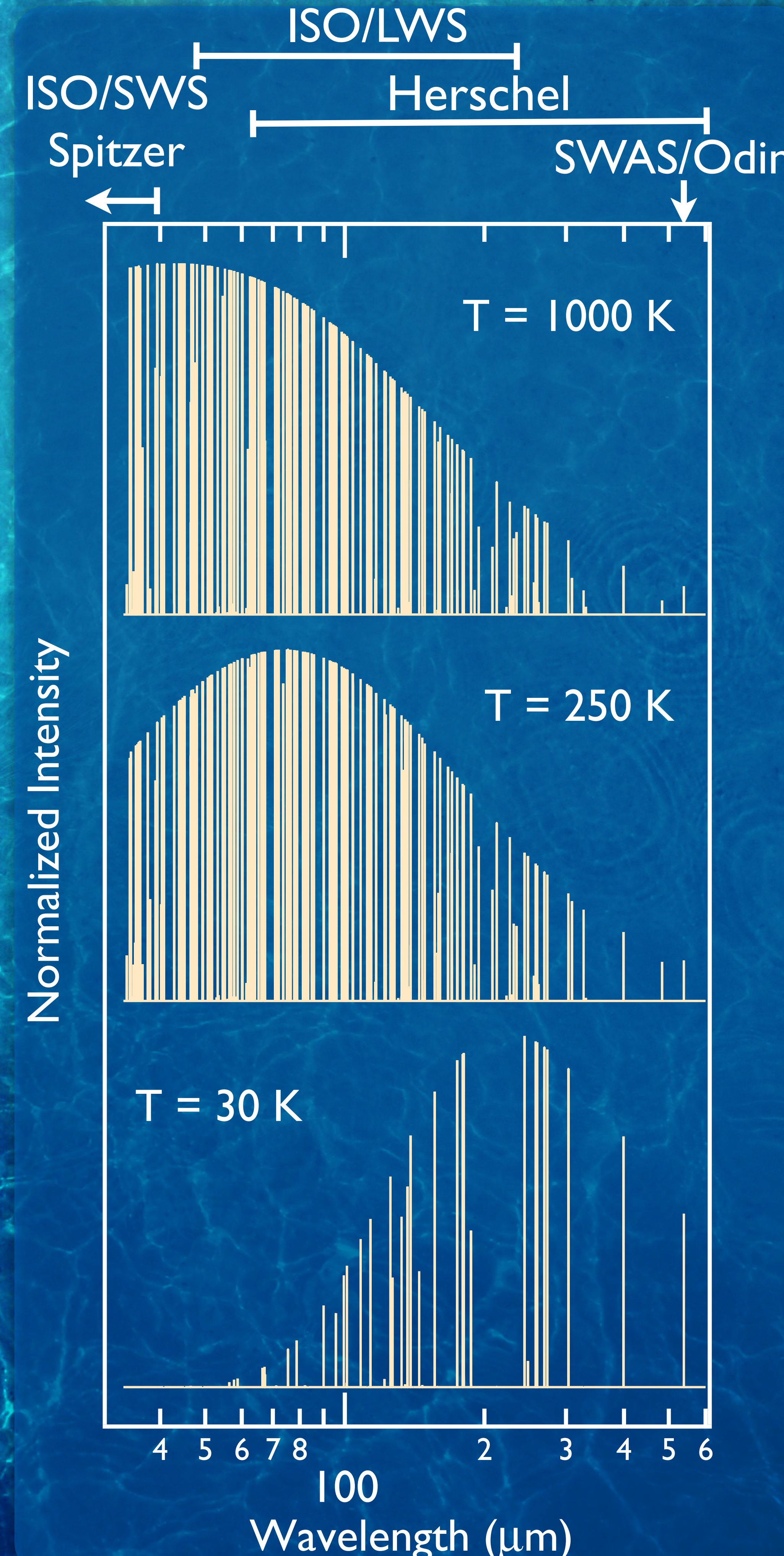
image credit: NOAO +
Jack Cook (Woods Hole) & Howard Perlman (USGS)

# *Water Basics*

# $H_2O$ Spectroscopy

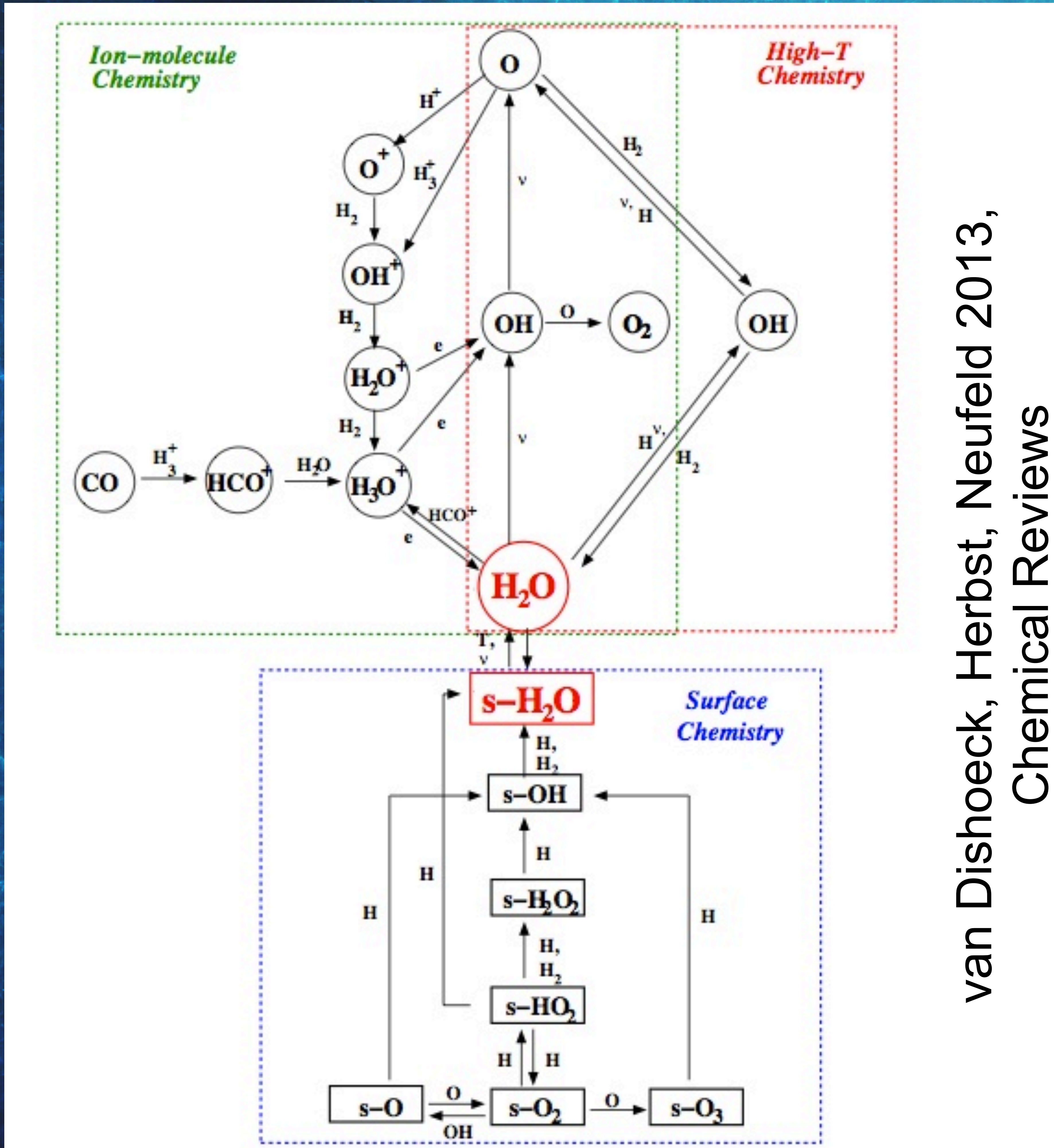



Encrenaz 2008, ARA&A,46, 57



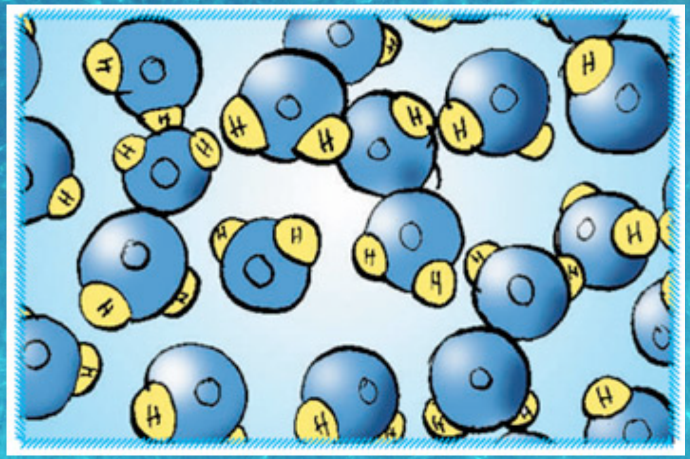

Bergin & van Dishoeck 2012, RSPTA, 370, 2778

# Water Chemistry




van Dishoeck, Herbst, Neufeld 2013, Chemical Reviews

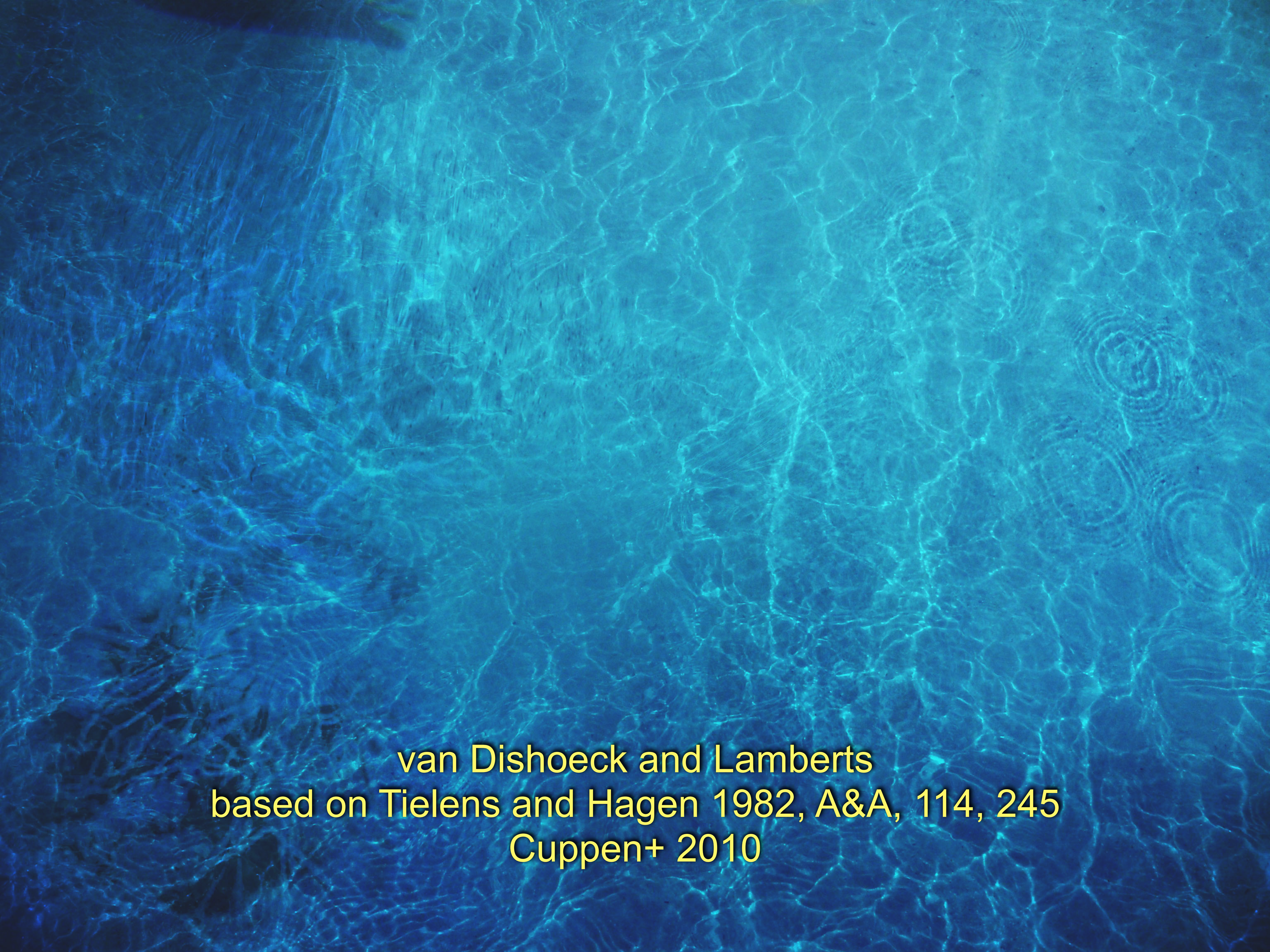
# Gas Formation

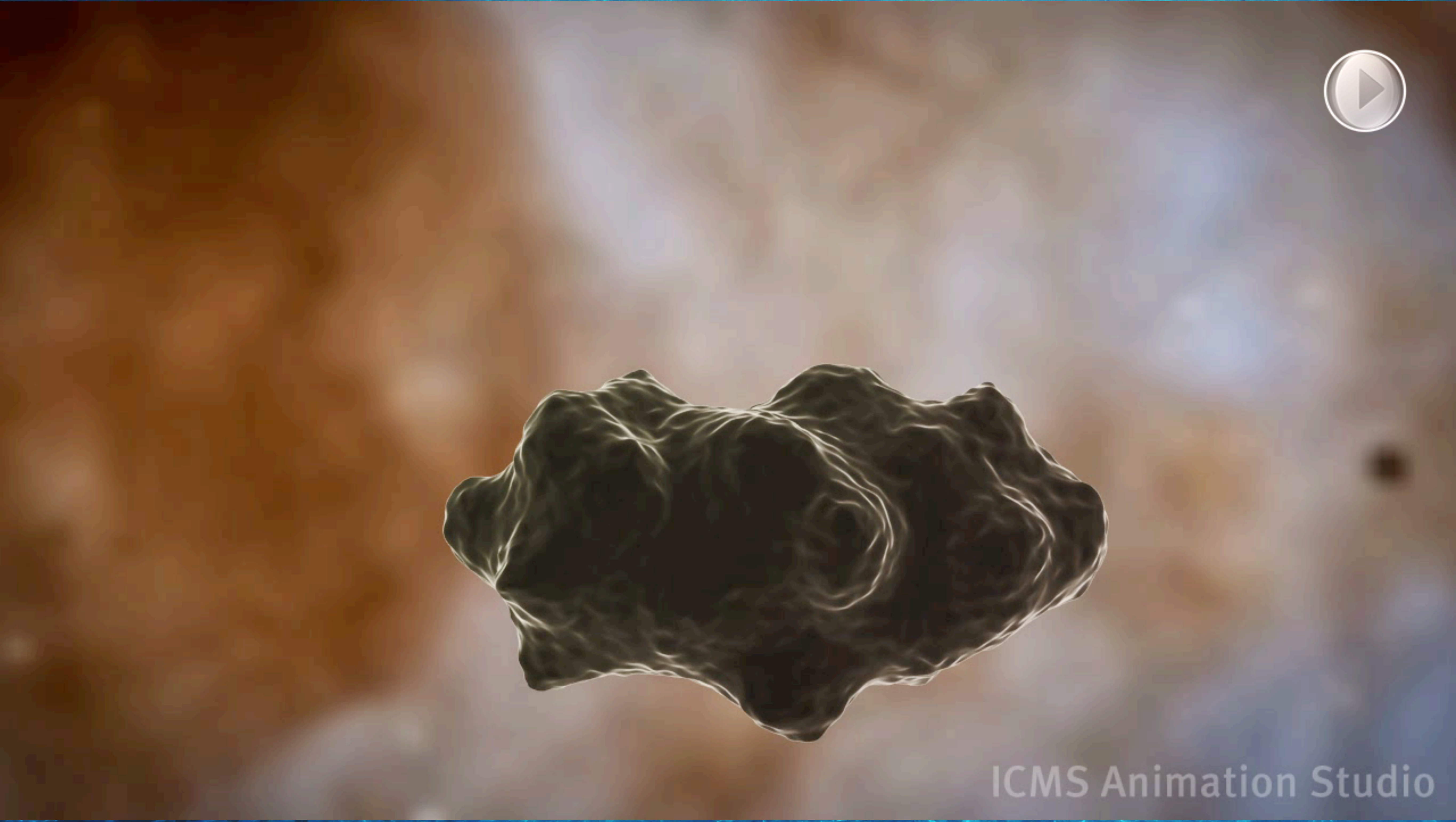


- **LTE**
  - ➡ all free O converted to $H_2O$
- **$T_{gas}$ > 400 K**
  - ➡ efficient - all free O converted to $H_2O$
- **$T_{gas}$ < 400 K**
  - ➡ need ionization
  - ➡ inefficient ~1% of free oxygen to $H_2O$

# Solid Formation

- **$T_{dust}$ < 150 K**
  - ➡ Freeze-out
- **$T_{dust}$ < 30 K**
  - ➡ surface chemistry
  - ➡ production of H atoms in $H_2$ dominated gas

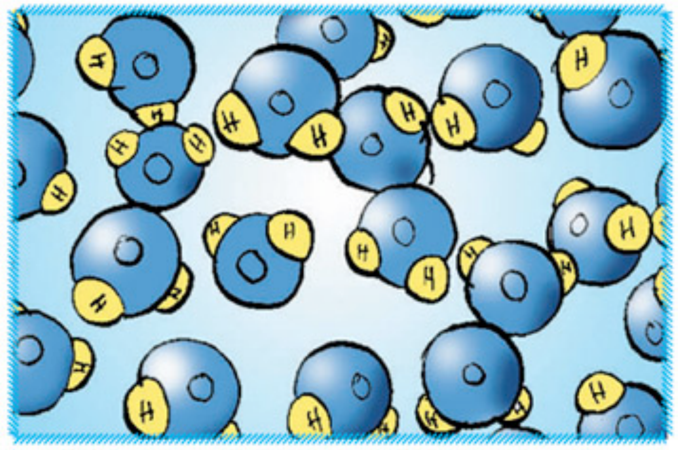

van Dishoeck and Lamberts
based on Tielens and Hagen 1982, A&A, 114, 245
Cuppen+ 2010




van Dishoeck and Lamberts
based on Tielens and Hagen 1982, A&A, 114, 245
Cuppen+ 2010

Destruction

# Gas



# Solid

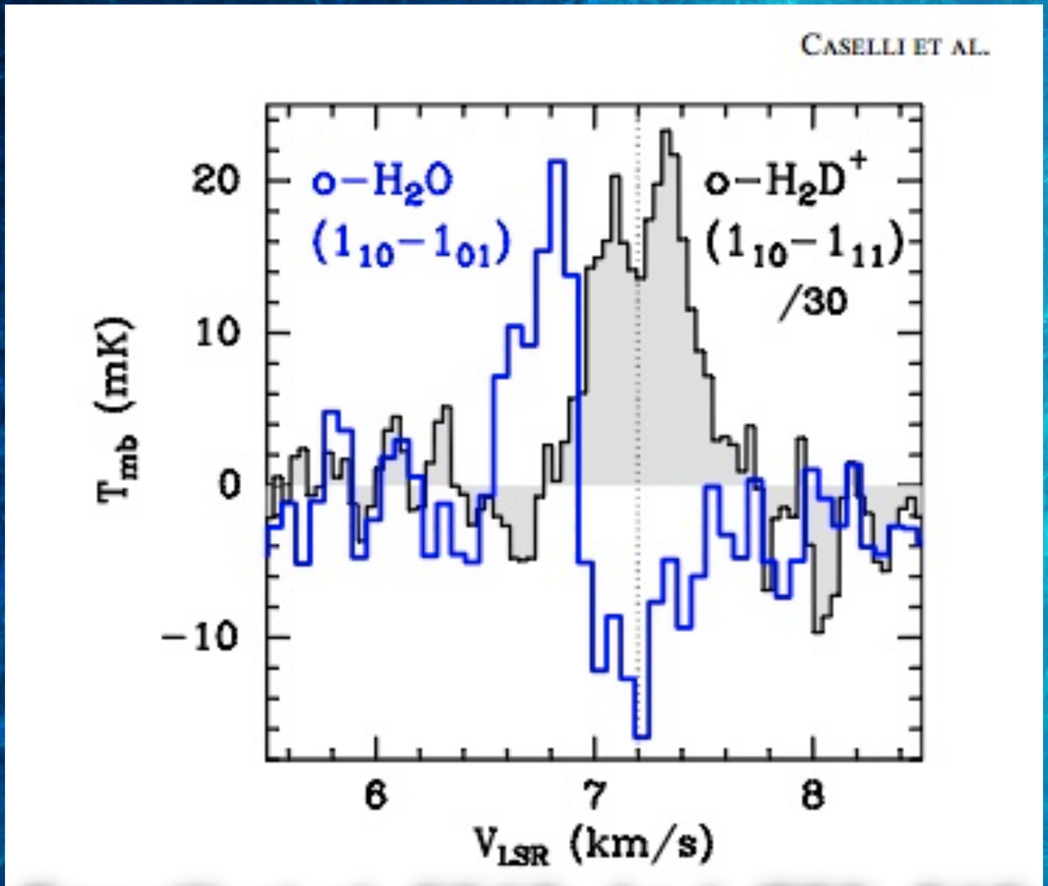
Destruction

- $T_{gas}$ > 400 K
  - ➡ UV photons
- $T_{gas}$ < 400 K
  - ➡ reprocessed by ion-molecule chemistry
  - ➡ ionization needed to power ion-molecule chemistry

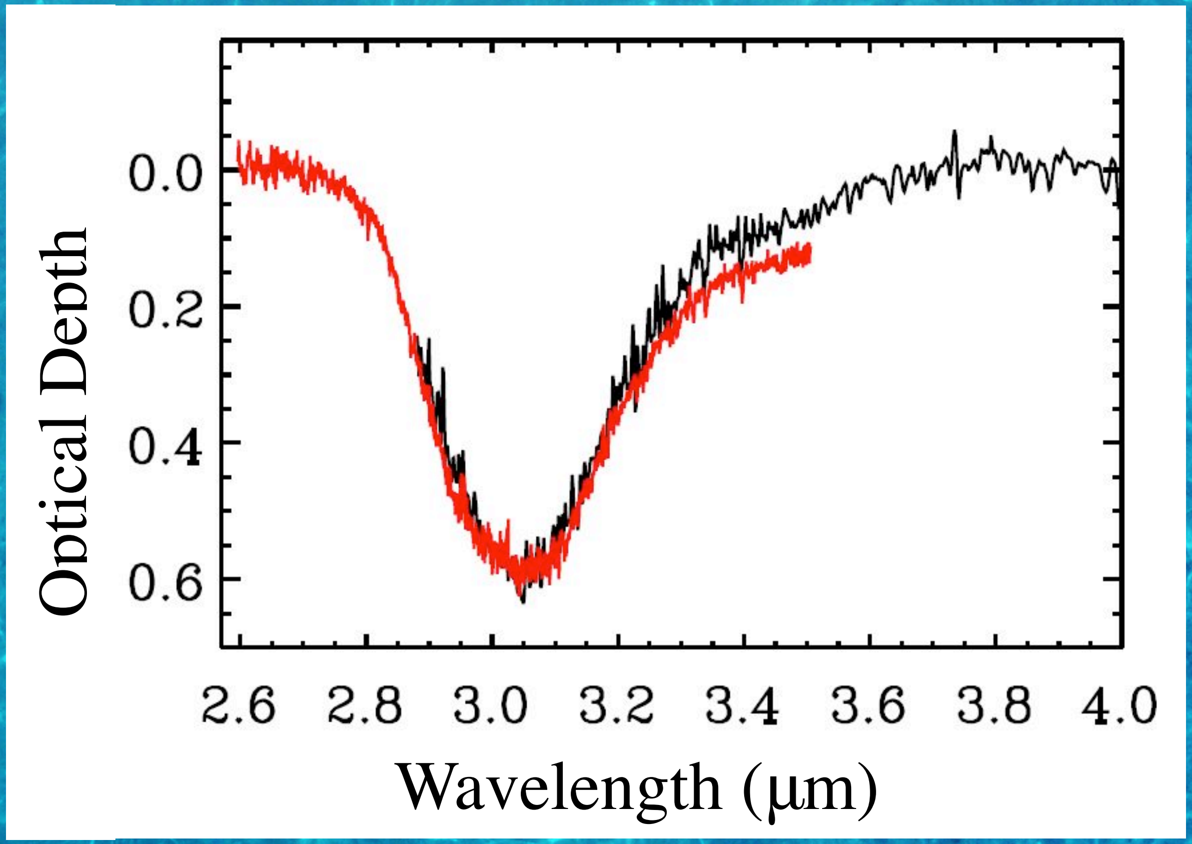
- $T_{dust}$ > 150 K (Pressure dependent)
  - ➡ Ice thermal evaporation
- $T_{dust}$ < 150 K
  - ➡ Ice non-thermal desorption

# Water Formation in Space

# Water Formation before Star Birth




Caselli et al. 2012, ApJ, 759, 212,
Hollenbach+ 2009, Klotz+ 2008,
Bergin+ 2002




Whittet et al. 1983, Nat, 303, 218
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
- ➡ Note: $O_2$ and its detection/non-dectection is part of this story

## Take home message

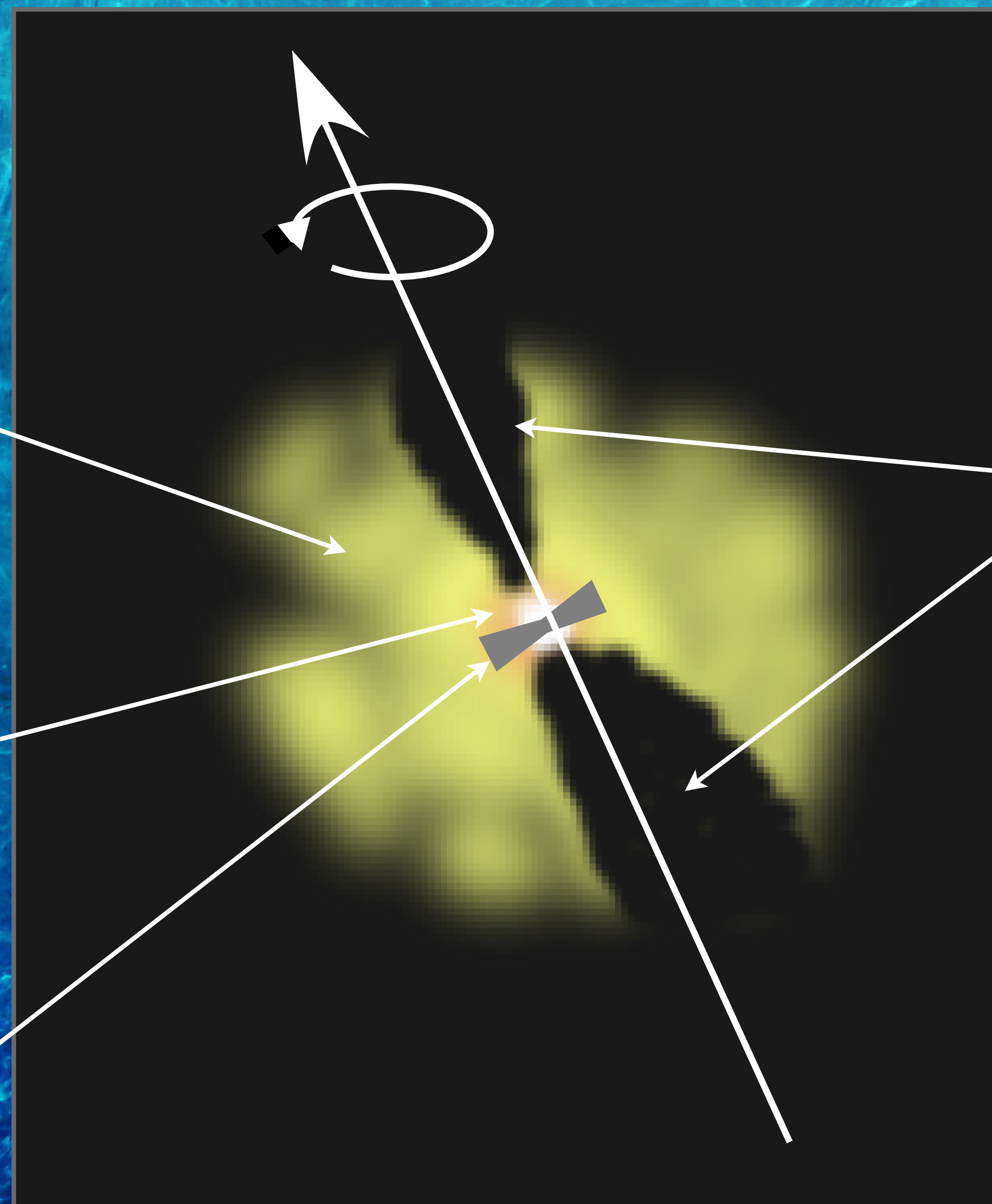
*Water is formed as ice during pre-stellar stage via grain surface reactions.*

# Low Mass (Sun-like) Protostar

Cold (T ~ 10-20 K) outer "envelope"

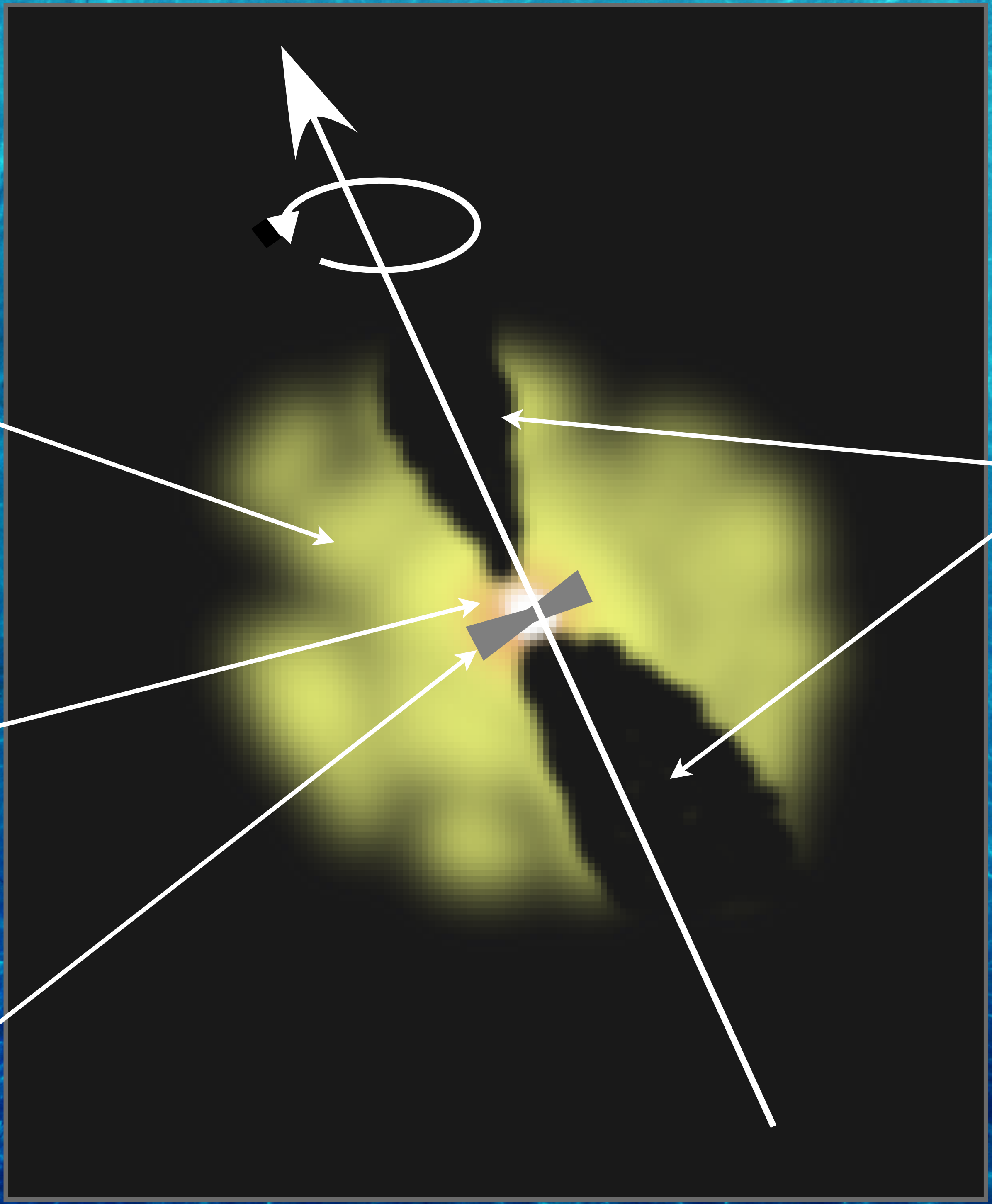
Warm (T > 100 K) inner "envelope" - hot core

Forming disk (small size)



outflow shock heated gas (T > 400 K)

# Low Mass (Sun-like) Protostar



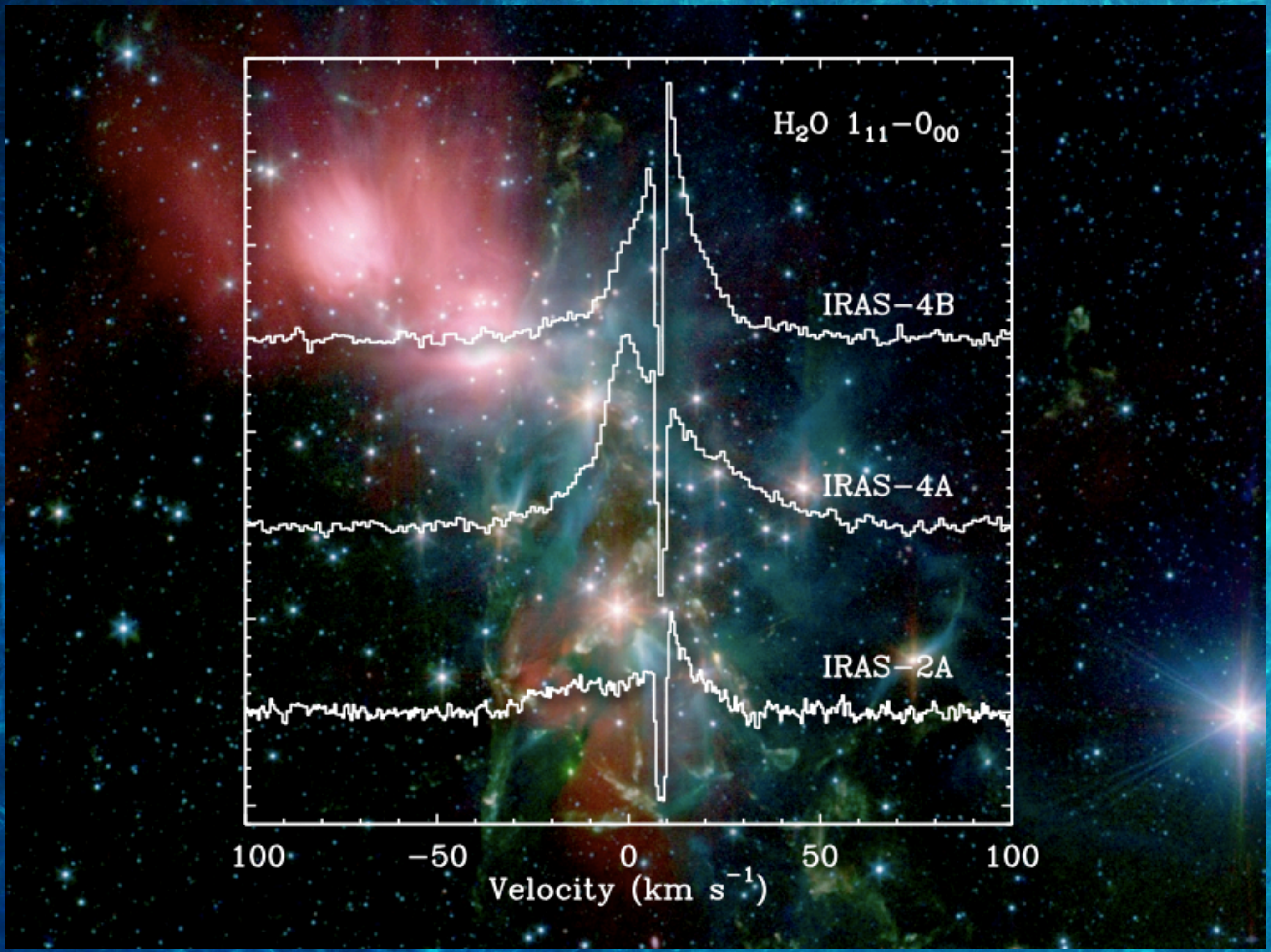
Freeze-out water vapor poor

ice evaporation water vapor rich

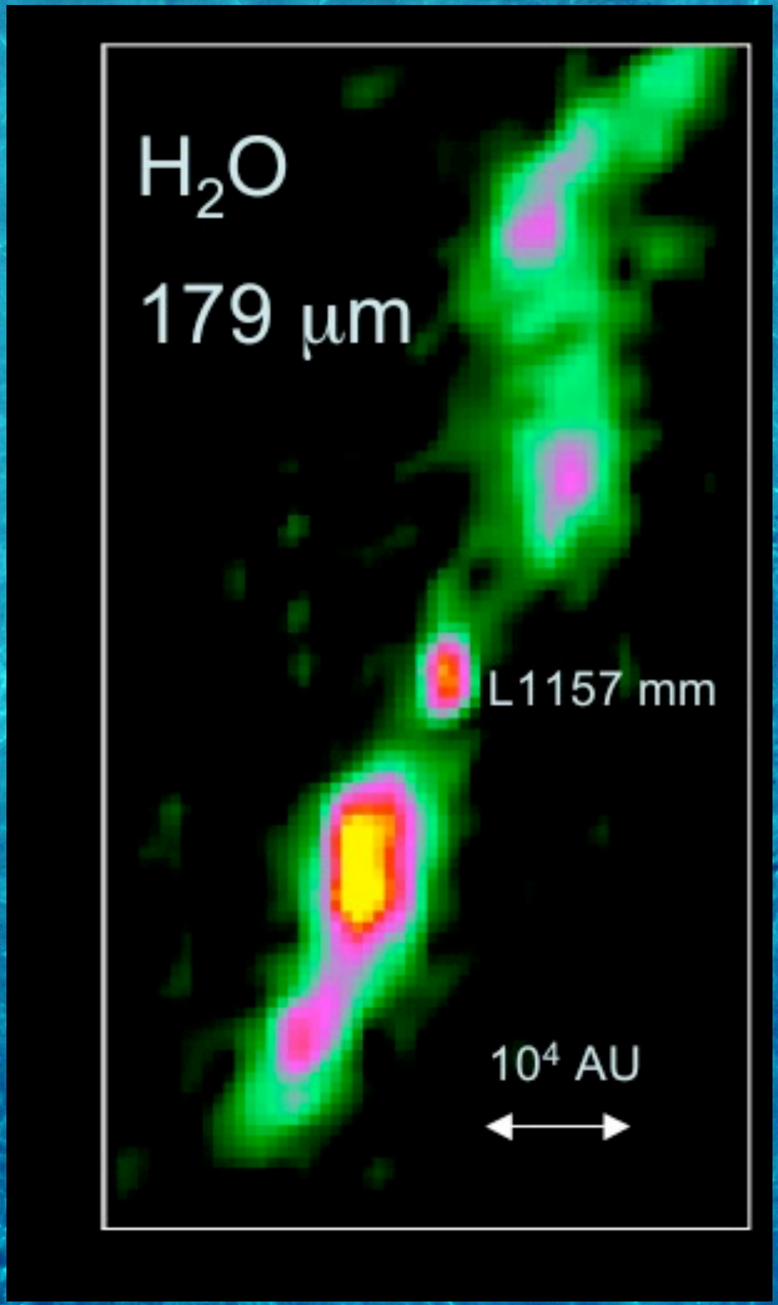
hard to detect, critical stage

water vapor rich

# Water Emission in Outflows




Kristensen et al. 2012, 542, 8




Nisini et al. 2010 A&A, 518, L120, Codella+ 2010 Tafalla+ 2013

- Water is abundant (relative to the pre-stellar stage) in molecular outflows/ shocks.
- Dominates emission: key part of the water story in the interstellar medium

## Take home message

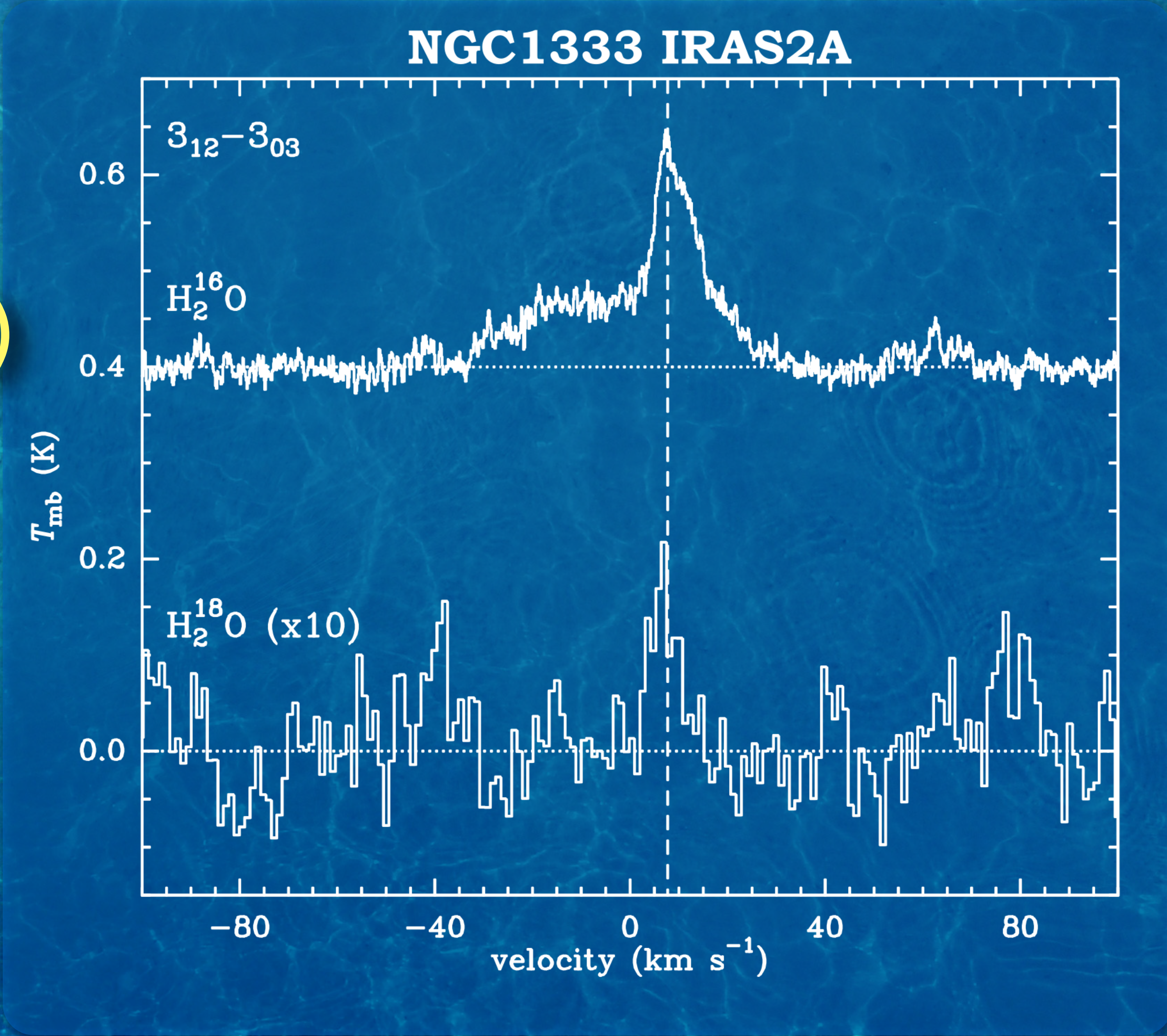
*Water in outflows is lost to space.*
*Not part of planet formation.*

# *Water Transport from Cores to Disks*

# Protostars

## Hot Core ≥100 AU Scale

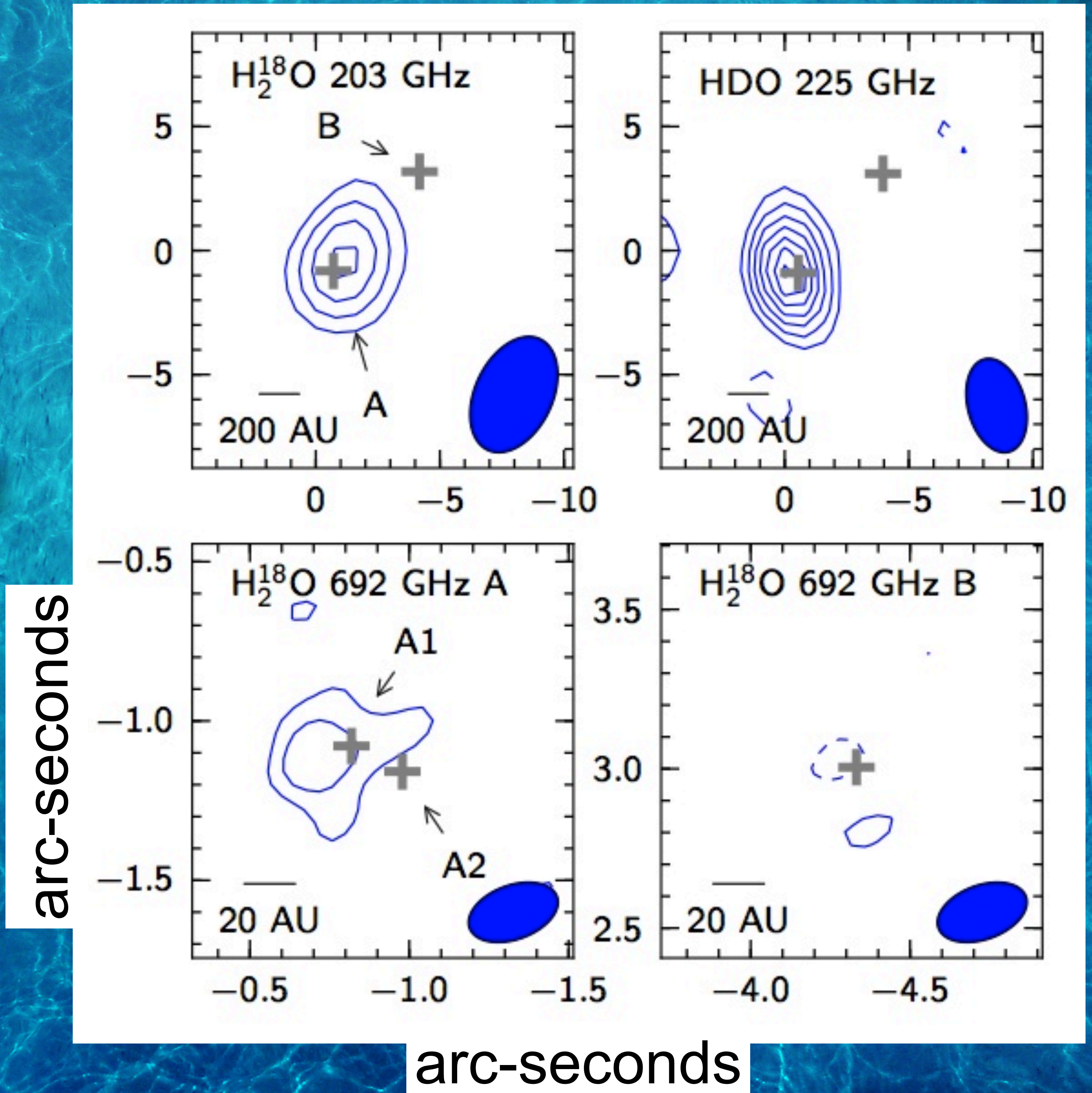
- Water is present in hot core (spatially unresolved emission)
- Abundance consistent with ice evaporation?
- This water may not be part of the planet formation story.




Visser et al. 2013, ApJ, 769, 19
Coutens+ 2012

# Protostars

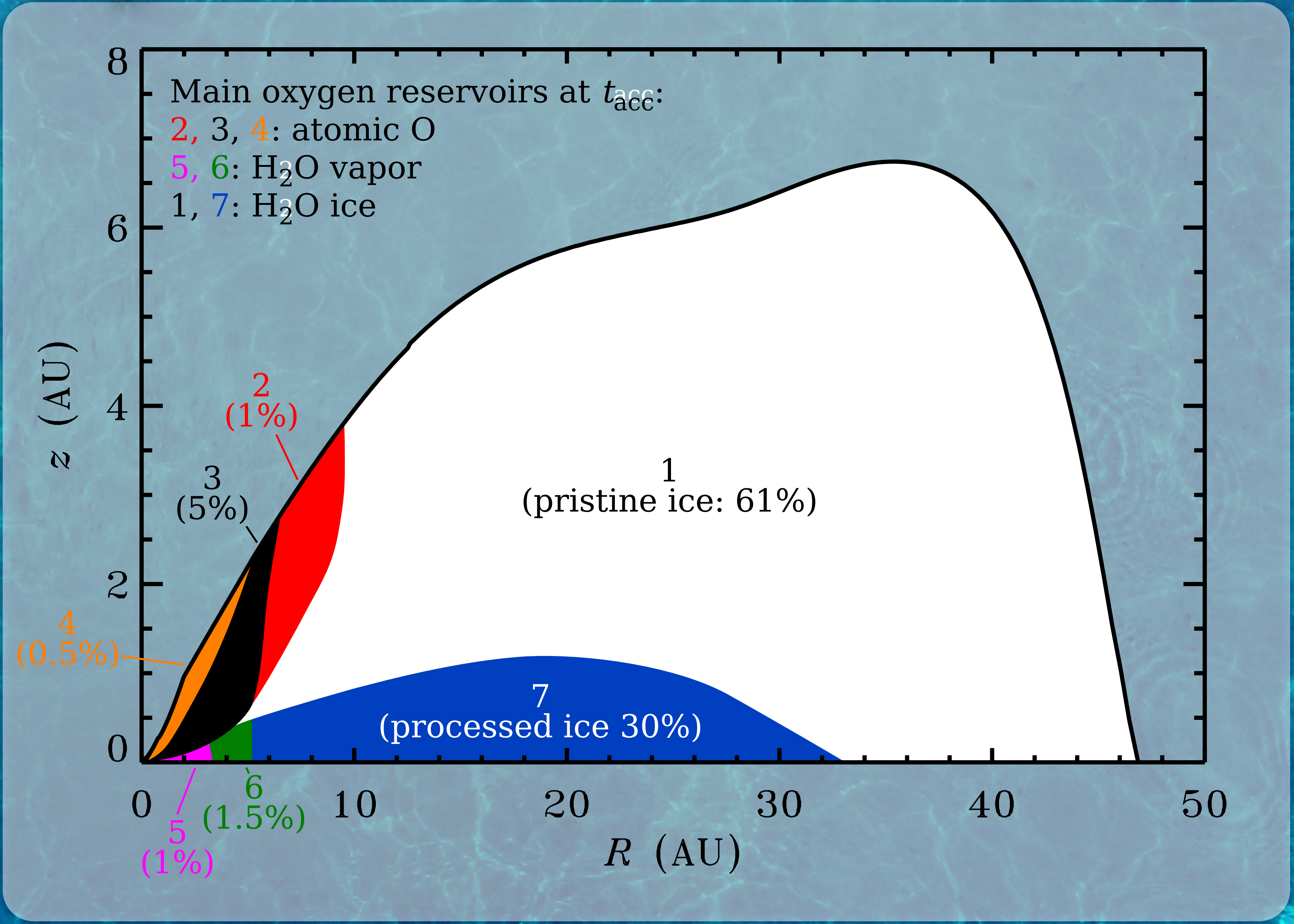
- Water is detected on small scales (< 100 AU)
- Water vapor abundance is <$10^{-4}$ -- water is mostly as ice




Persson et al. 2013, A&A, 549, L3
Persson+ 2012, A&A, 541, A31
Taquet+ 2013, A&A, 768, L29

# Protostellar Collapse --- Disk Formation

- Issue #1: does material fall onto disk and suffer accretion shock?
- Issue #2: is material altered by thermal or photo-driven processes?
- Models suggest that material that would suffer accretion shock goes into star.
- Most ices go into disk unaltered.




Visser et al. 2009, ApJ, 485, 889

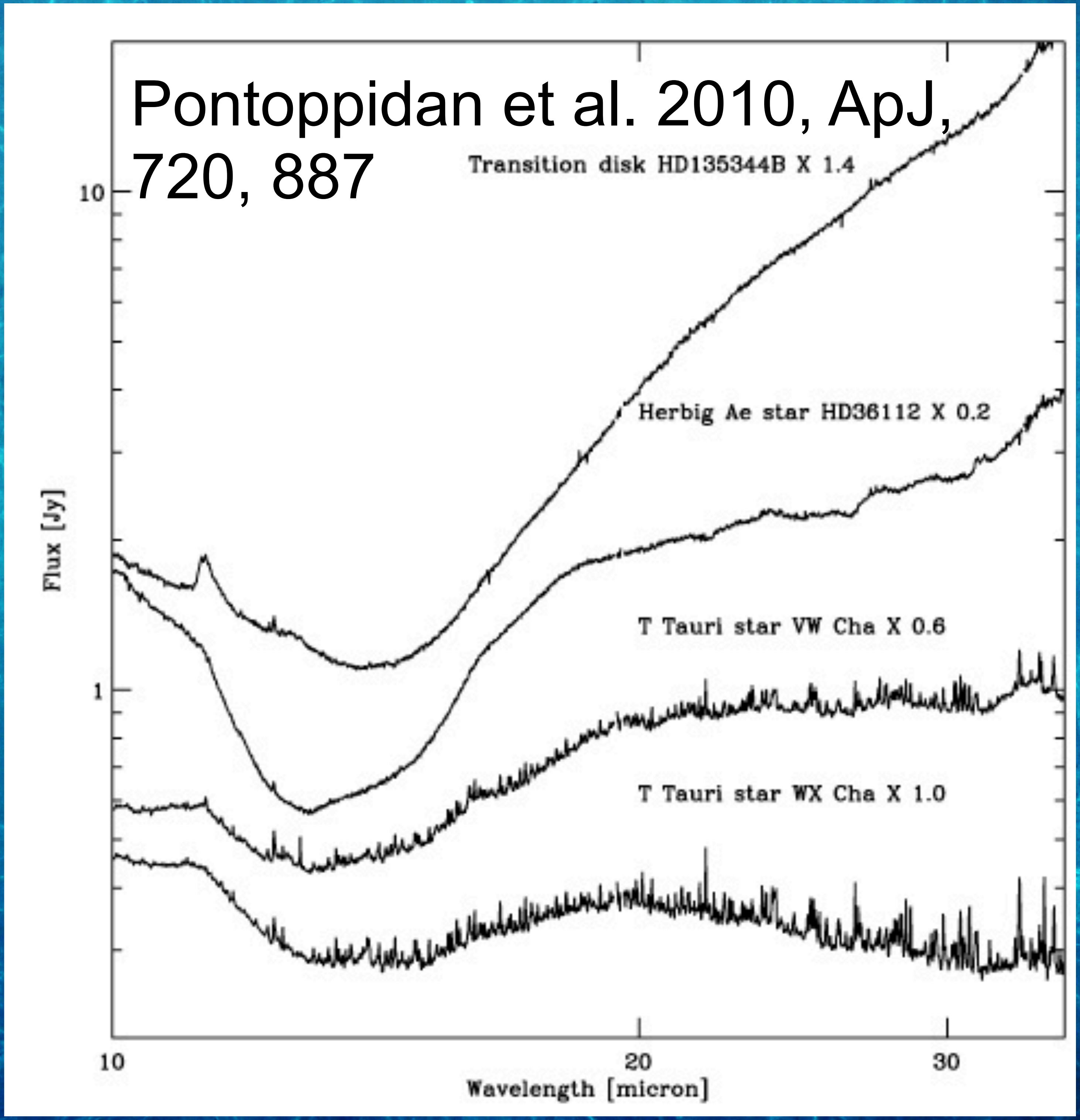
## Take home message

- Water is provided to the disk as mostly unaltered ice.
- Infall stream onto disks does not evaporate water ice -- does not trap volatiles for delivery
- Caveat: disk formation is the least probed stage

# *Water Reservoirs in Disks*

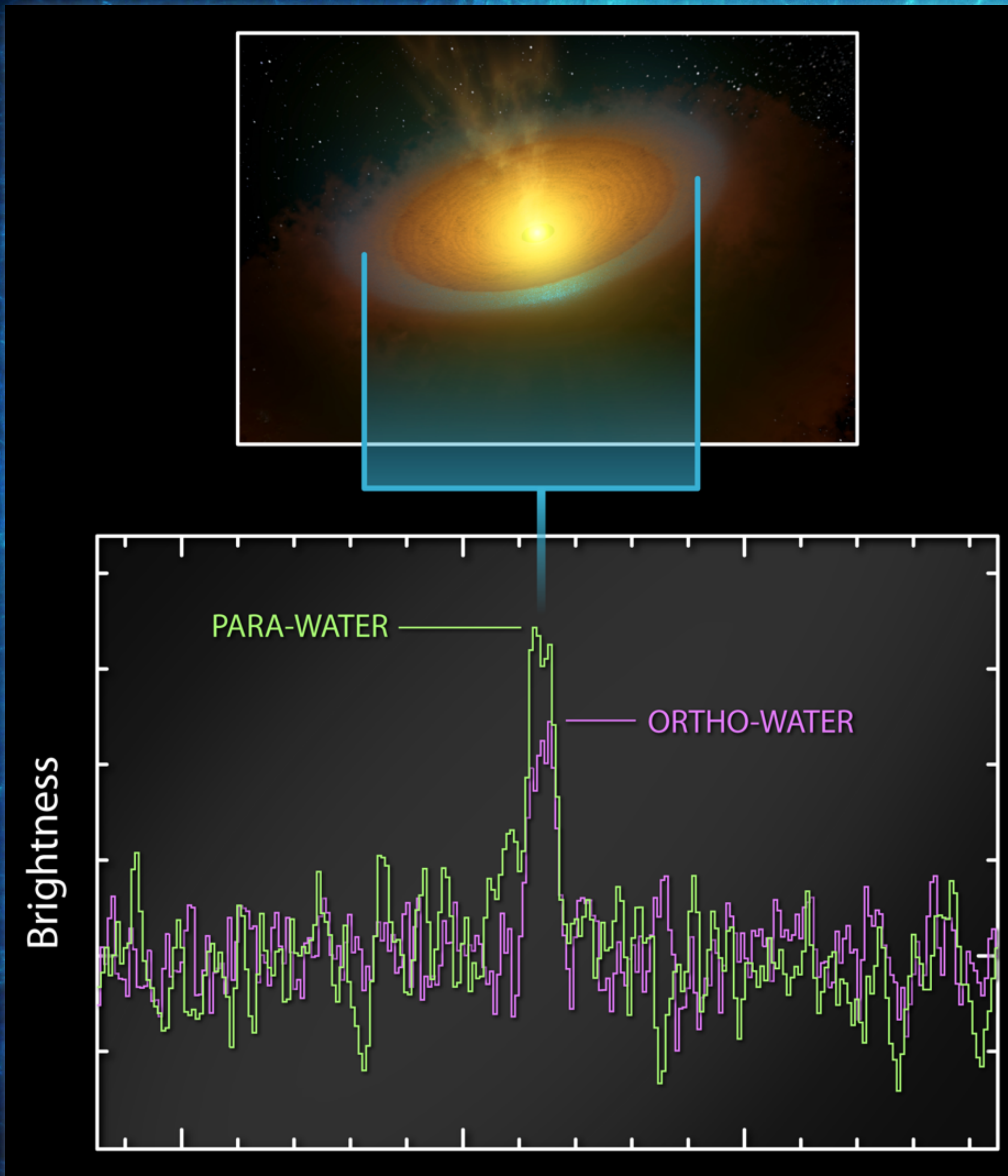
# Hot Water in the Inner Disk (R < few AU)

- Demographics of Warm Water Emission
  - ➡ $H_2O/CO \sim 0.1 - 1$
  - ➡ Emission from warm ~500 K gas
  - ➡ high column density (≳ $10^{17}$ $cm^{-2}$)
  - ➡ Emission not found inside gaps of transition disks
  - ➡ Emission not detected in A stars




Pontippidan+, Salyk+, Carr+, Najita+, Fedele+, Mandell+, Meeus+, Riviere-Marichalar+

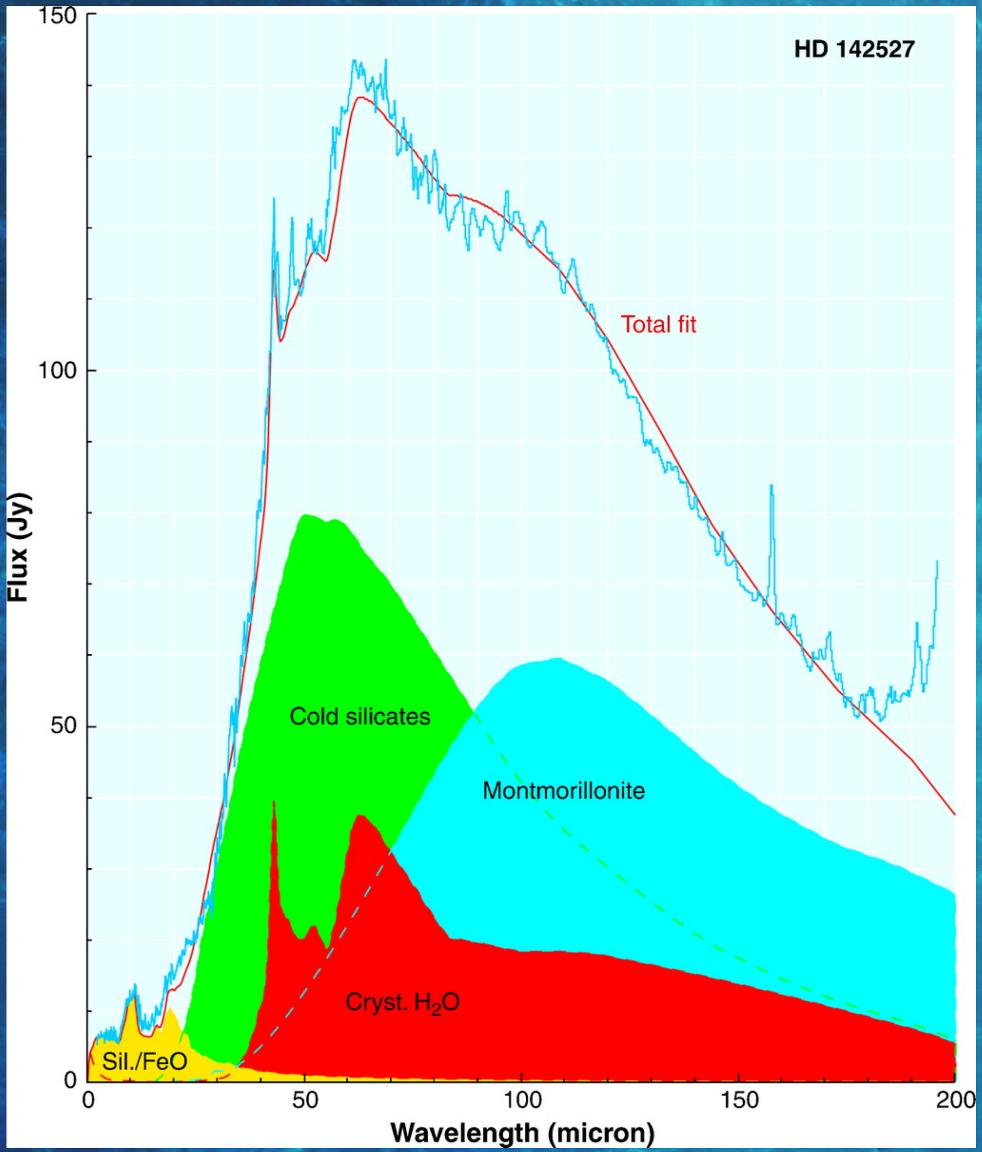
# Cold Water in Outer Disk (R > 10 AU)



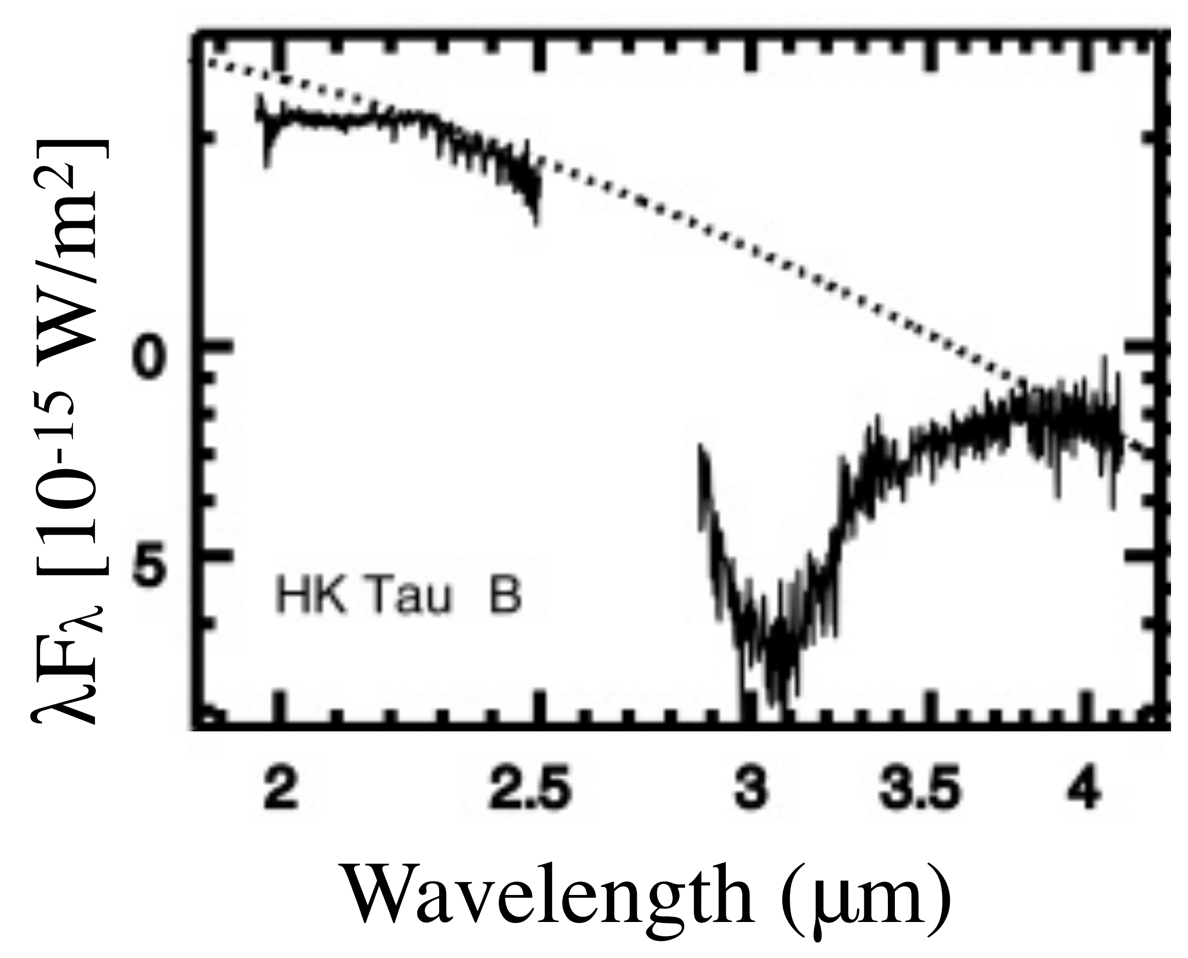

Hogerheijde et al. 2011, Science, 334, 338

- water vapor present with low abundance in gas with temperature below freeze-out
- Demographics (Hogerheijde et al. 2013, in prep.)
  - ➡ 7 systems with similar deep integrations for T Tauri stars + Ae/Be, only 2 detections
  - ➡ Shallower surveys in more systems do not see emission

# Observations of Water Ice




Malfait et al. 1999, A&A, 345, 181
also McClure+ 2012, ApJ, 759, L10




Terada et al. 2007, ApJ, 667, 303
also Honda+ 2009, ApJ, 690, L110

- Ices are detected in emission (crystalline) and absorption (amorphous): 20 - 50% of cosmic O in $H_2O$ in emissive layer
- More sensitive Herschel obs. do not confirm hydrated silicates

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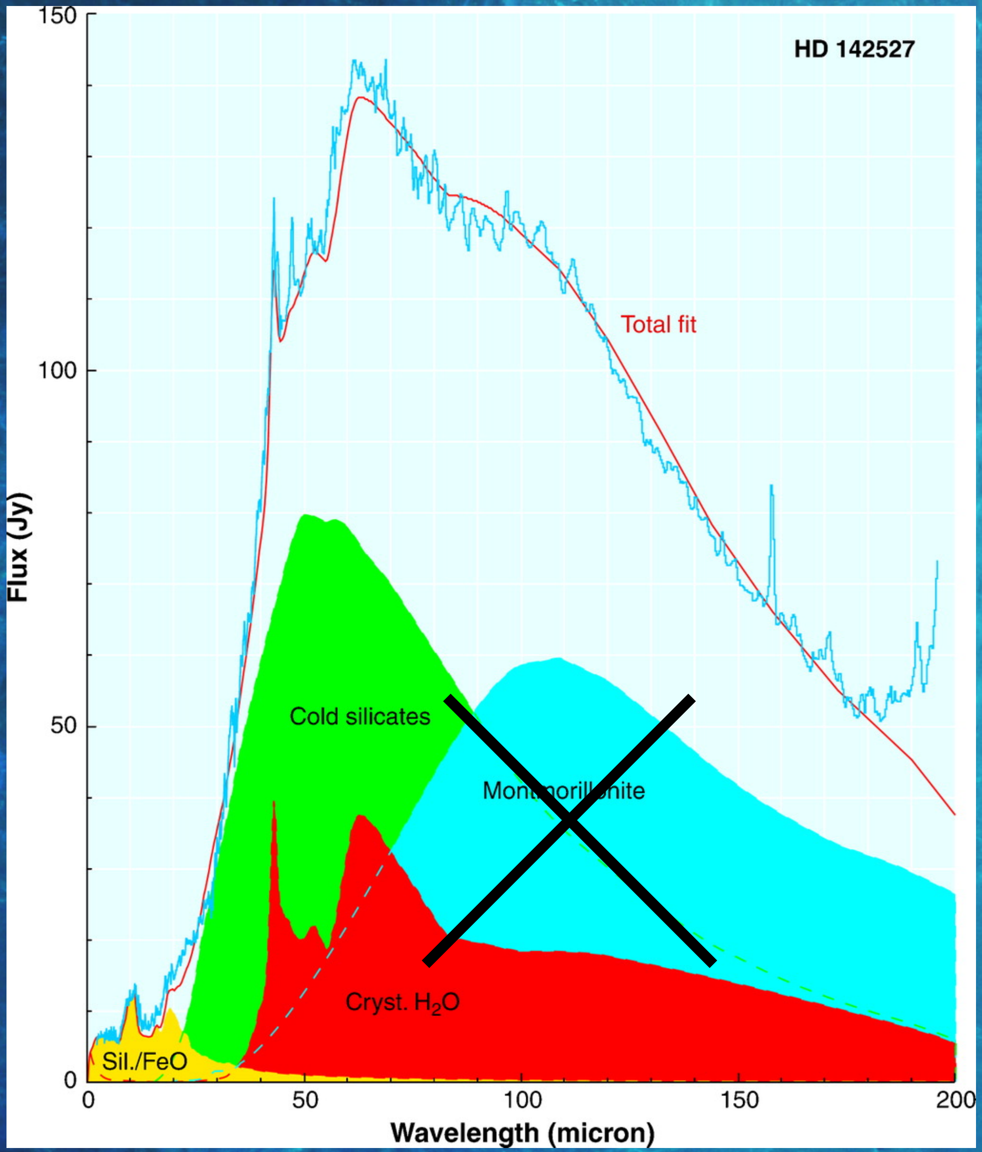


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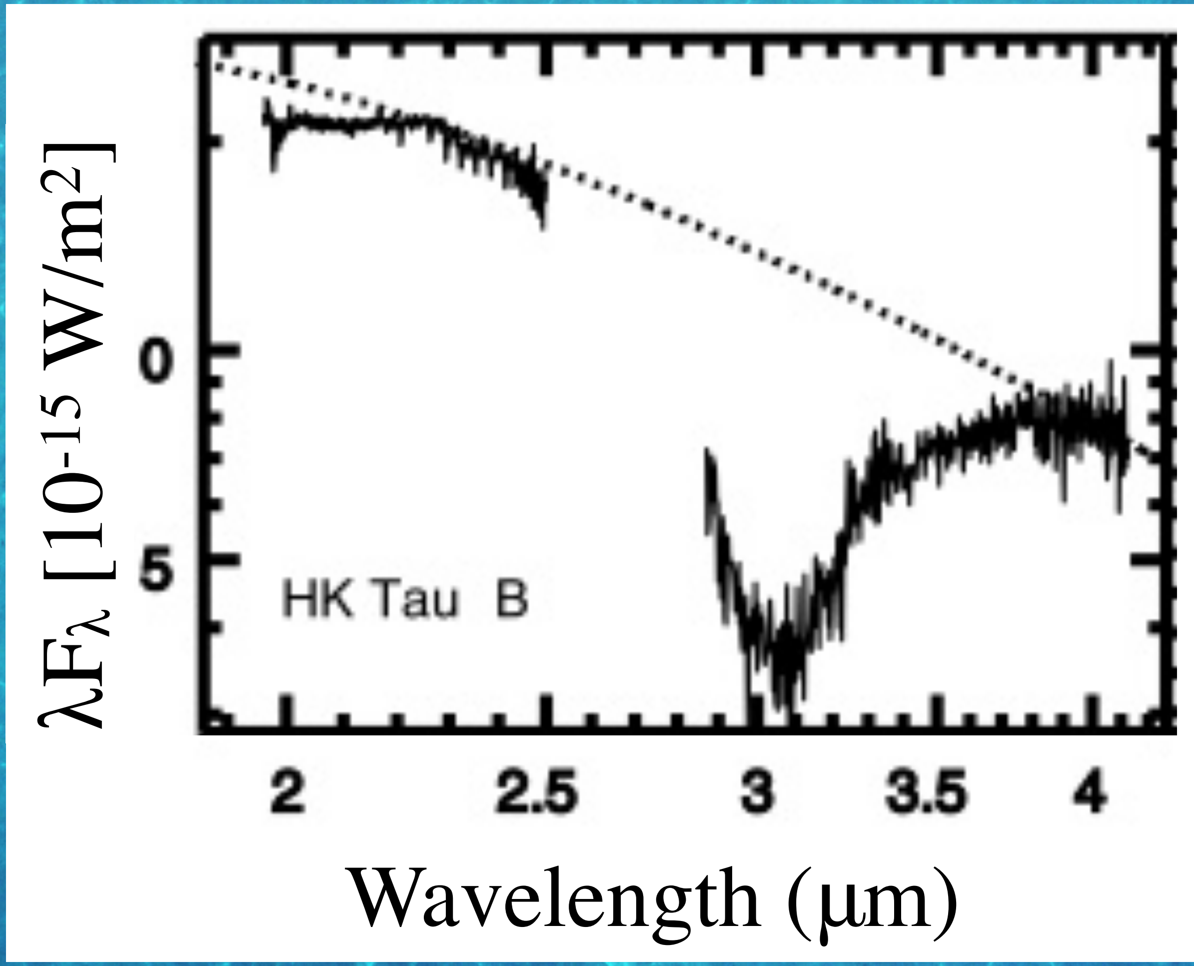


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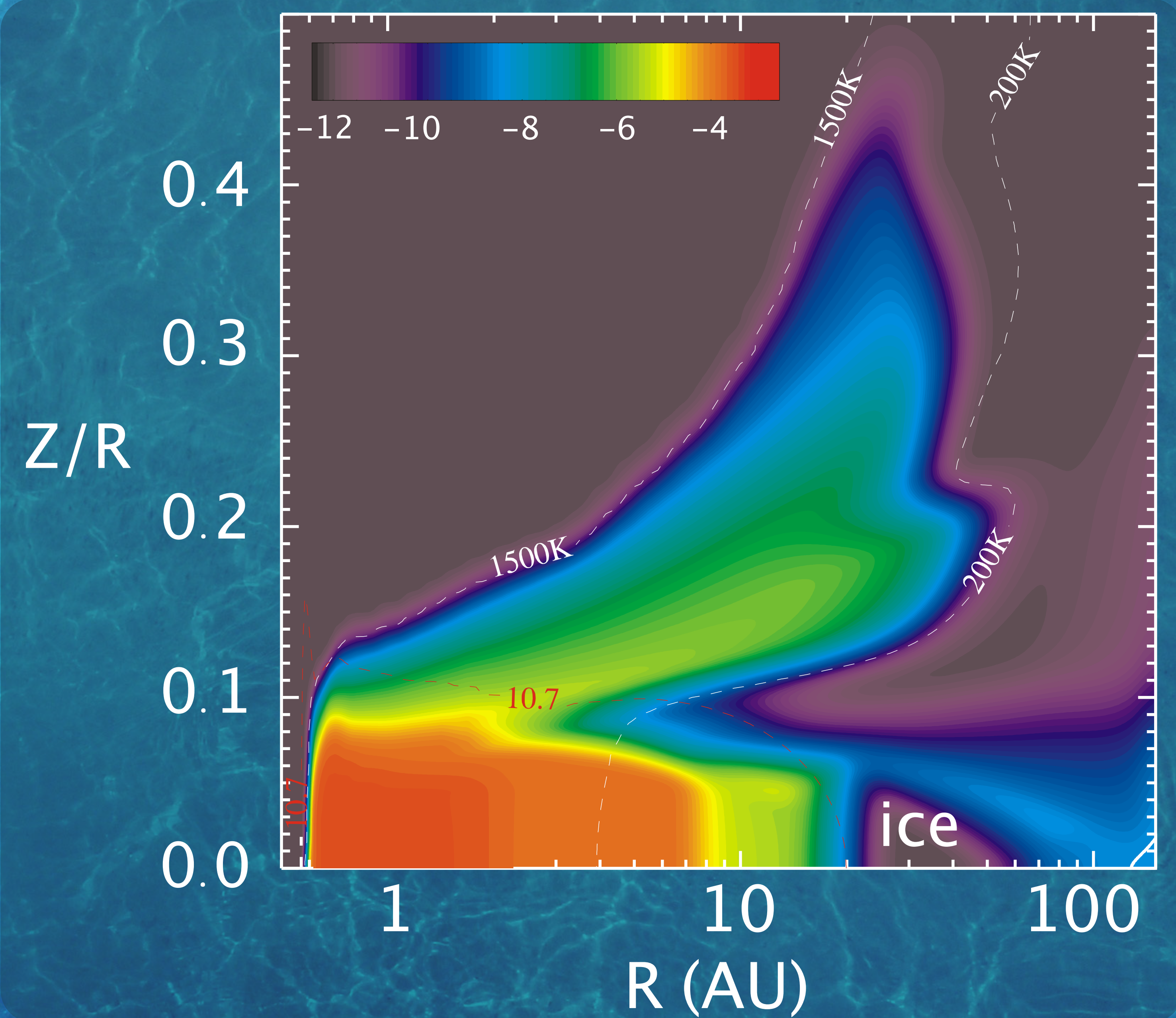
Woitke et al. 2009, A&A, 501, L5



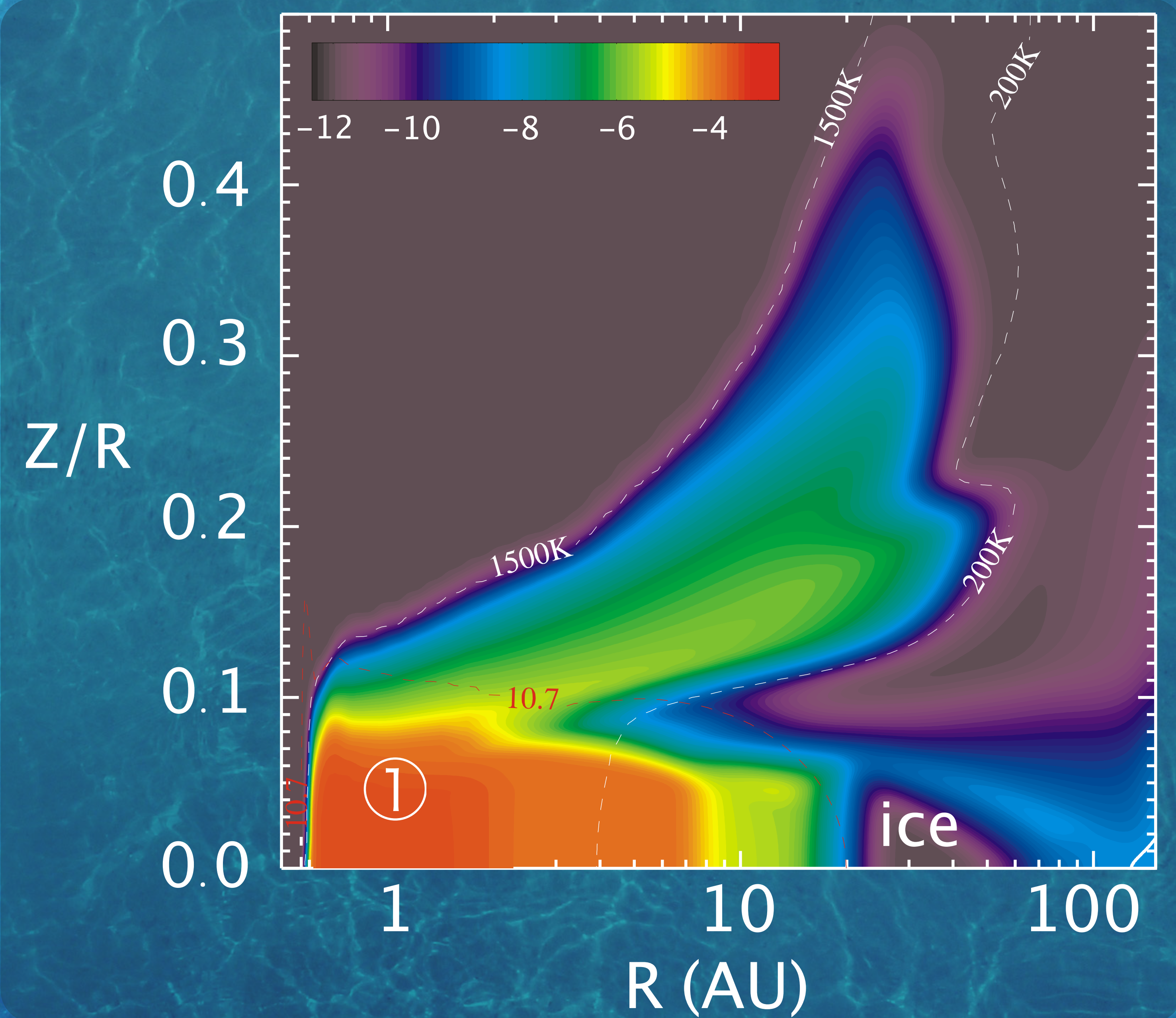

Glassgold+ 2009, Woitke + 2009, Dodson-Robinson+ 2009, Willacy+ 2009, Bethell+ 2009, Najita+ 2011, Fogel+ 2011, Vasynin+ 2011, Walsh+ 2012, Bruderer+ 2012, Ádámkovics+ 2013

# Reservoirs of Gaseous Water

Woitke et al. 2009, A&A, 501, L5

①

ice evaporation/high-T chemistry in midplane – abundance limited by ionization and density

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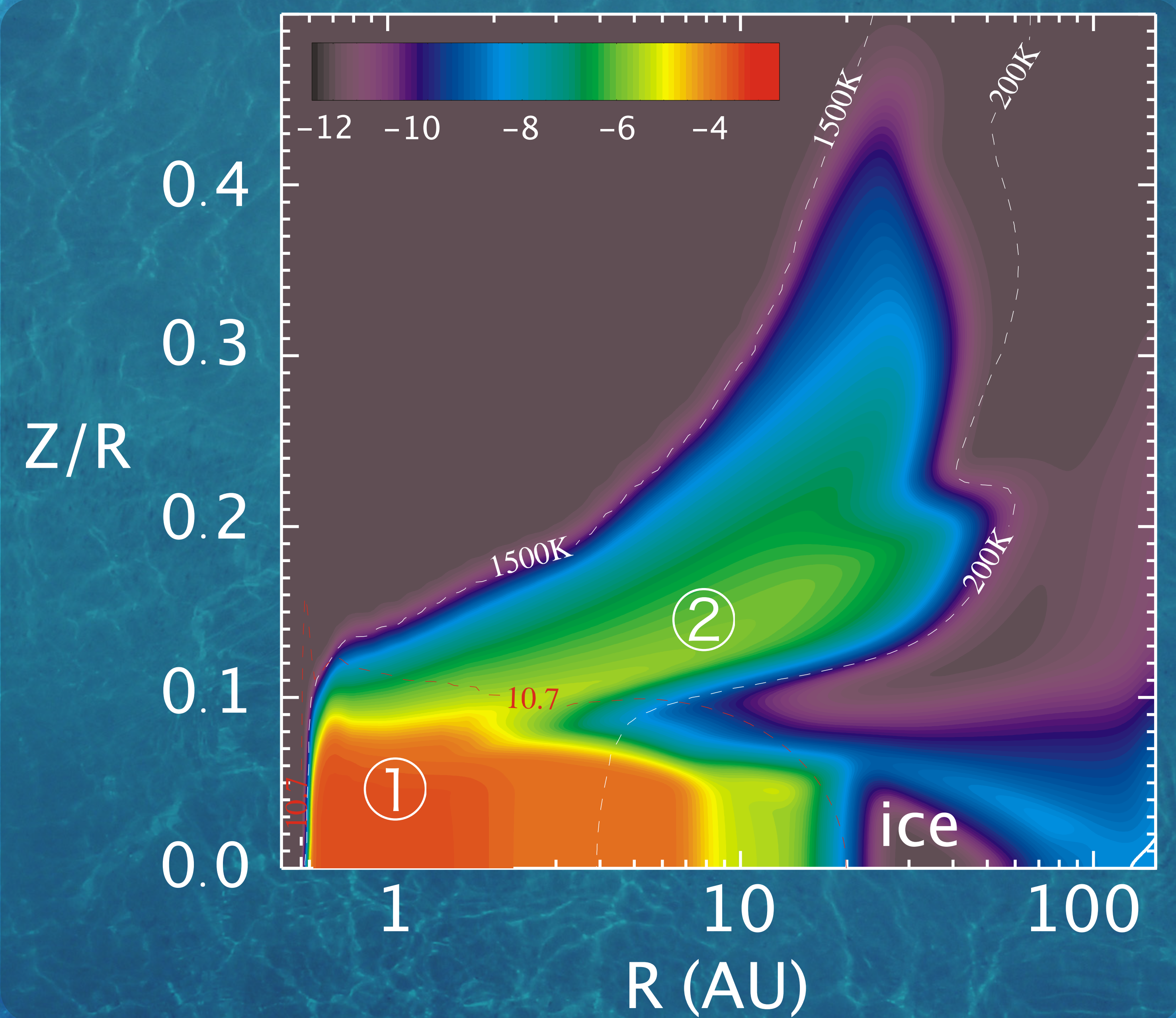
high-T chemistry on surface – abundance limited by density, UV exposure, and $H_2$ and import of $H_2O$ self-shielding




Glassgold+ 2009, Woitke + 2009, Dodson-Robinson+ 2009, Willacy+ 2009, Bethell+ 2009, Najita+ 2011, Fogel+ 2011, Vasynin+ 2011, Walsh+ 2012, Bruderer+ 2012, Ádámkovics+ 2013

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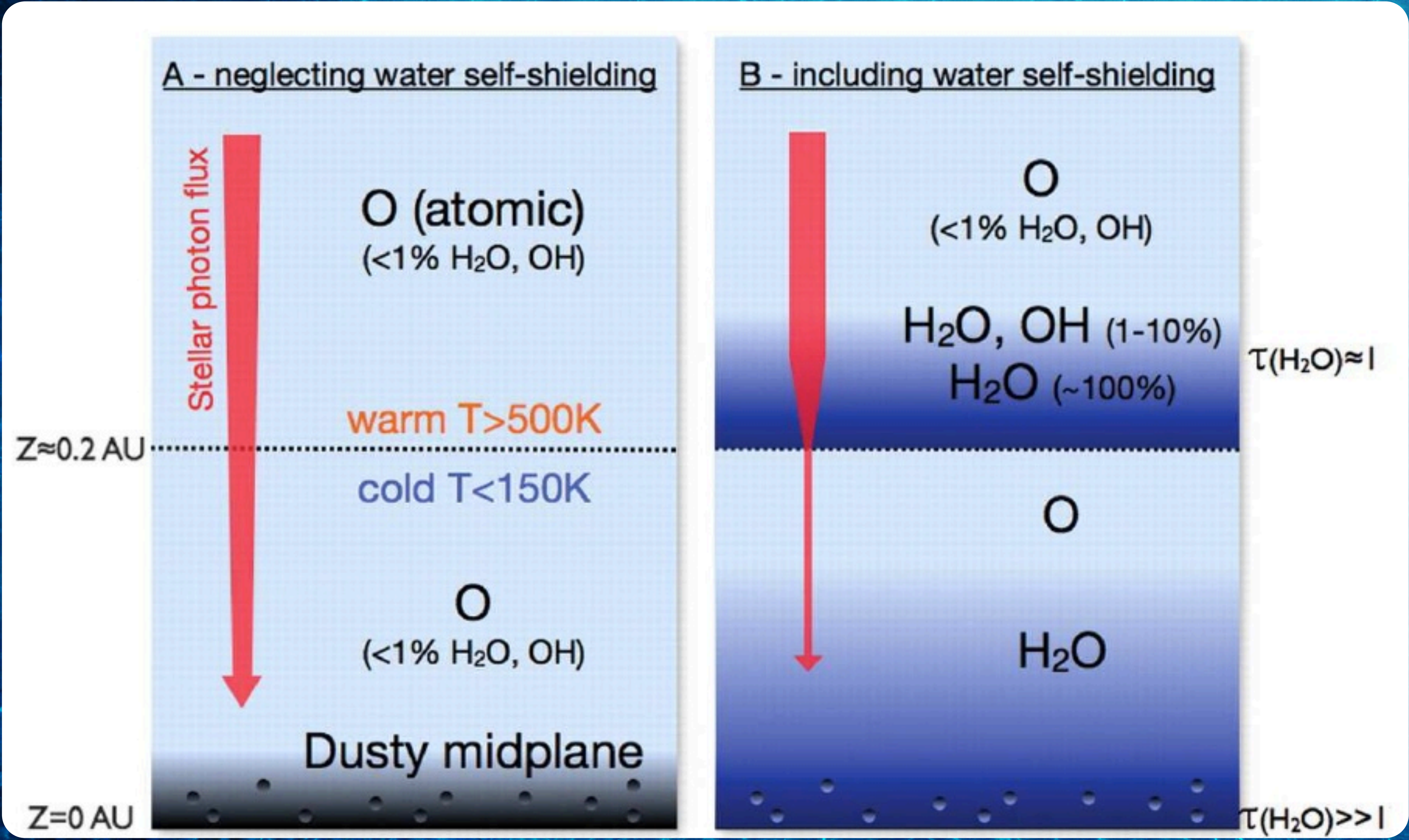


Bethell & Bergin 2009, Science, 326, 1675

Disk surface water can survive longer in a harsher environment and protect chemistry in the midplane from destructive UV

Woitke et al. 2009, A&A, 501, L5

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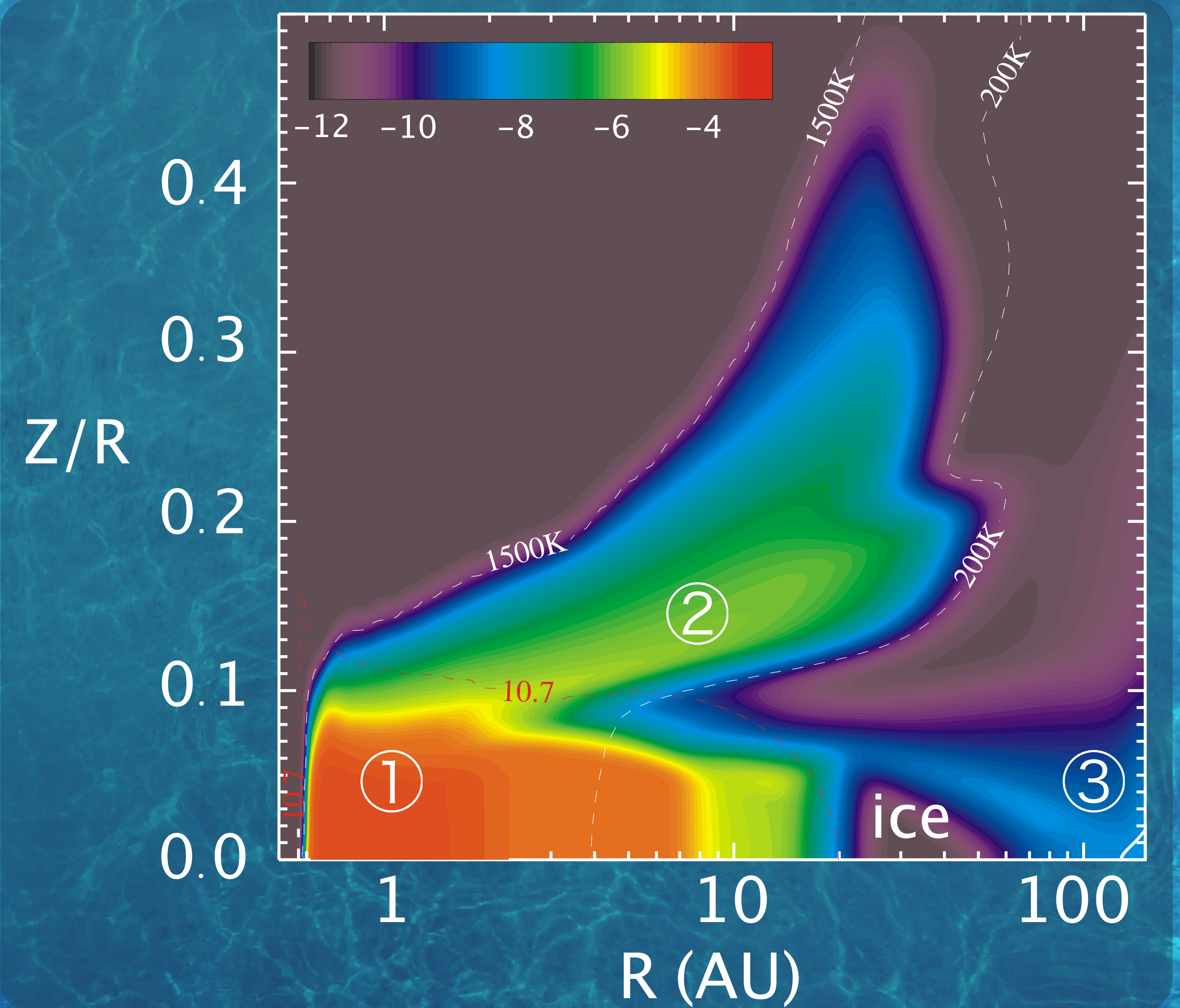
ice evaporation/high-T chemistry in midplane – abundance limited by ionization and density

②

high-T chemistry on surface – abundance limited by density, UV exposure, and $H_2$ and import of $H_2O$ self-shielding

③

photodesorption layer – abundance limited by UV photons, grain surface area, and supply of ice

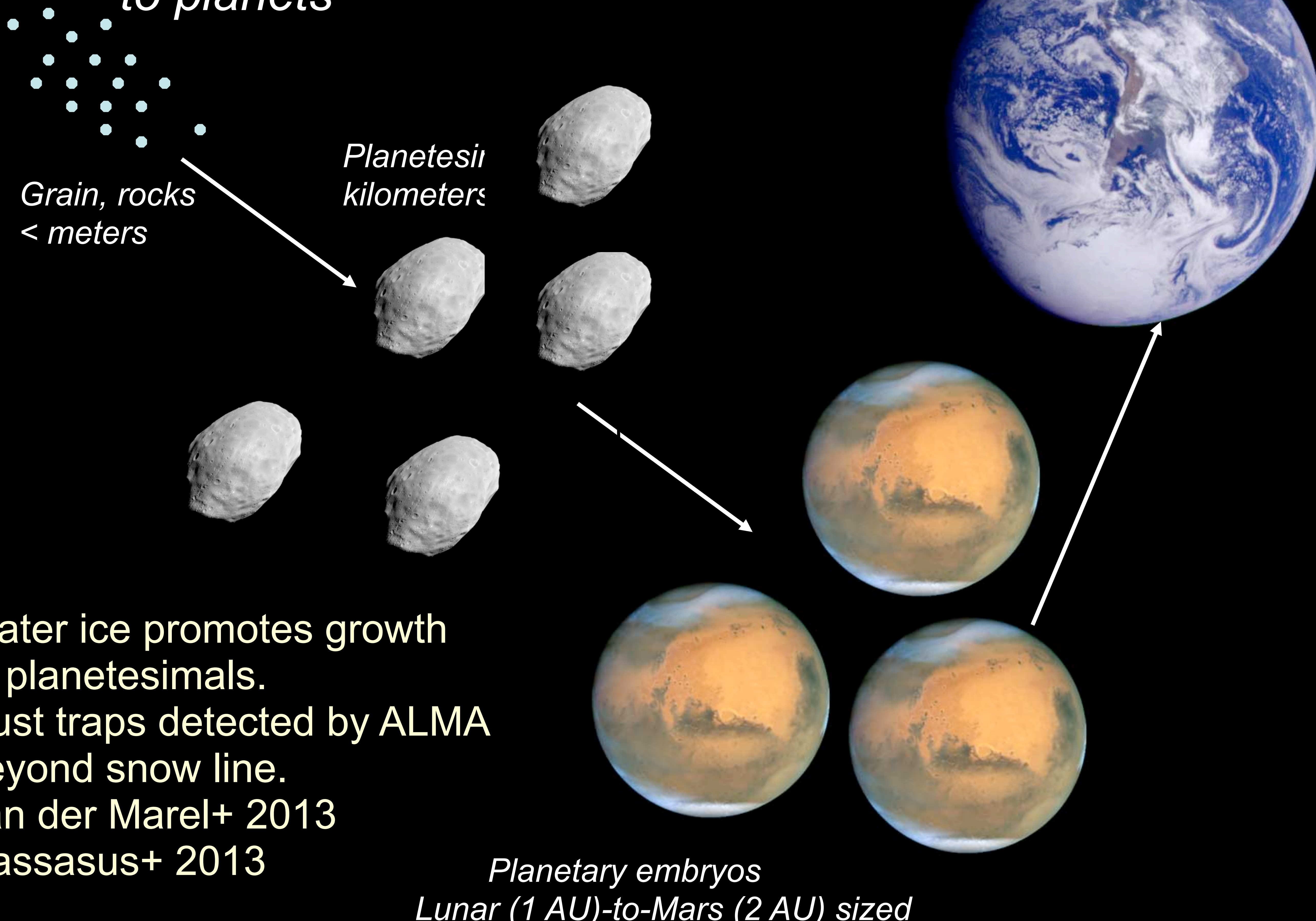



# Reservoirs of Gaseous Water

## Take home message

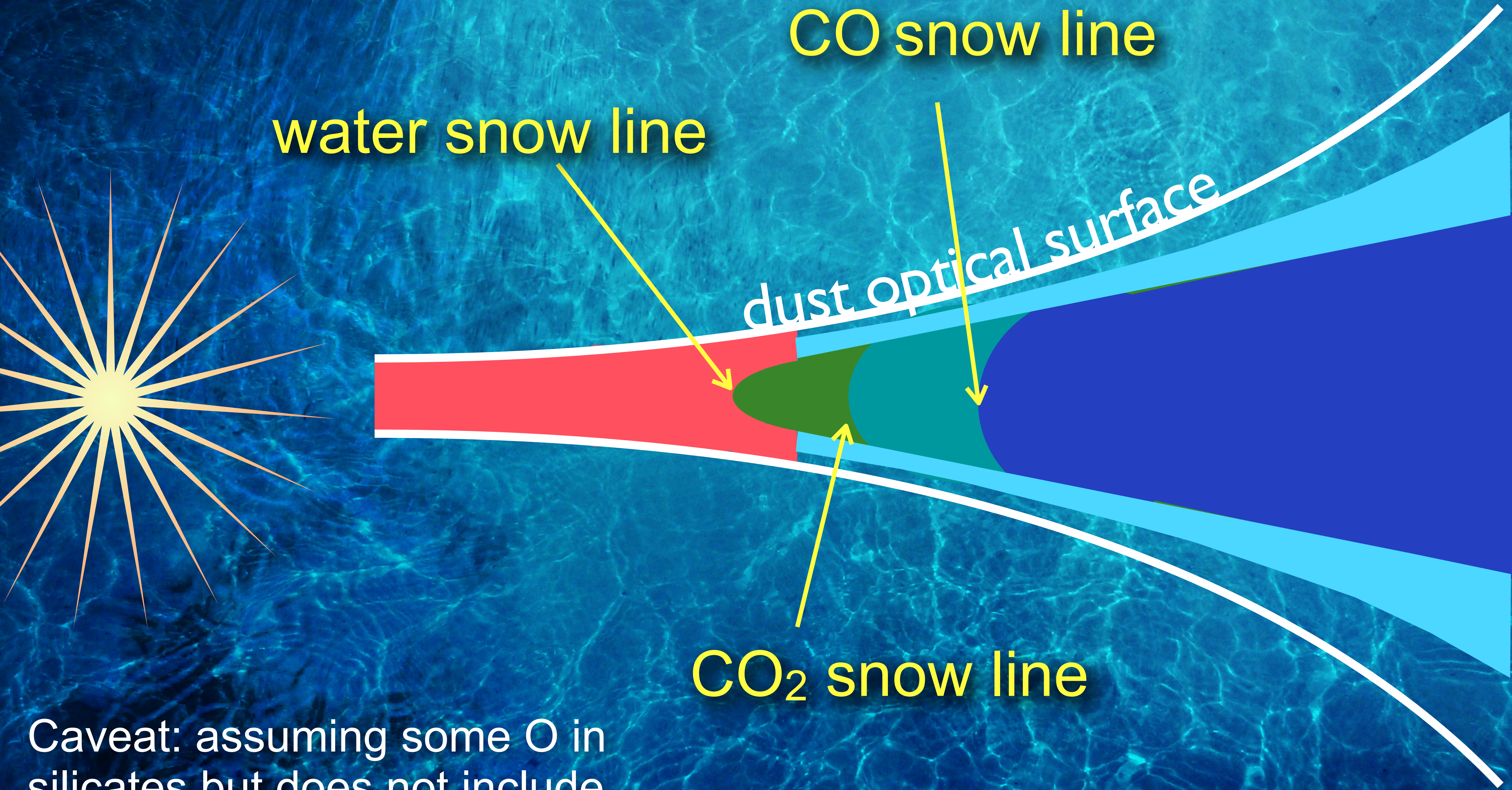
- Surface layer is emissive: what is detected by Spitzer/Herschel.
- Hot water is common, cold water is not.
- 2 of 3 reservoirs of gaseous water are detected -- midplane remains hidden.
- Ice reservoir is detected directly (emission/absorption) and indirectly (photodesorption).

# *From planetesimals to planetary embryos to planets*




Water ice promotes growth
to planetesimals.
Dust traps detected by ALMA
beyond snow line.
van der Marel+ 2013
Cassasus+ 2013

# C/O Distribution



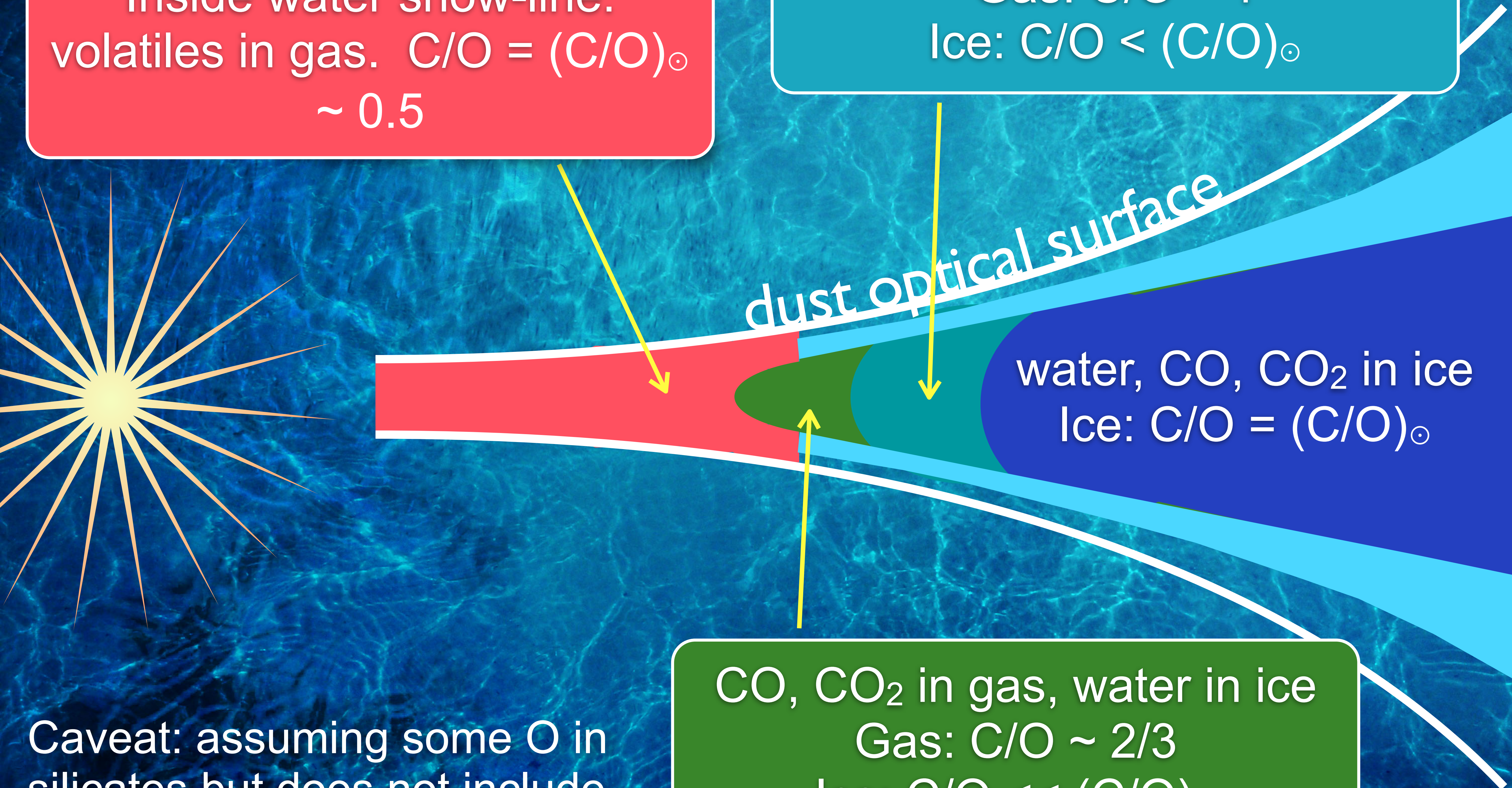

Caveat: assuming some O in silicates but does not include organics (C-rich + O) and additional unidentified oxygen component

Oberg+, Mousis+

# C/O Distribution

Inside water snow-line: volatiles in gas. $C/O = (C/O)_\odot \sim 0.5$

$CO$ in gas, water, $CO_2$ in ice
Gas: $C/O \sim 1$
Ice: $C/O < (C/O)_\odot$




$CO$, $CO_2$ in gas, water in ice
Gas: $C/O \sim 2/3$
Ice: $C/O << (C/O)_\odot$

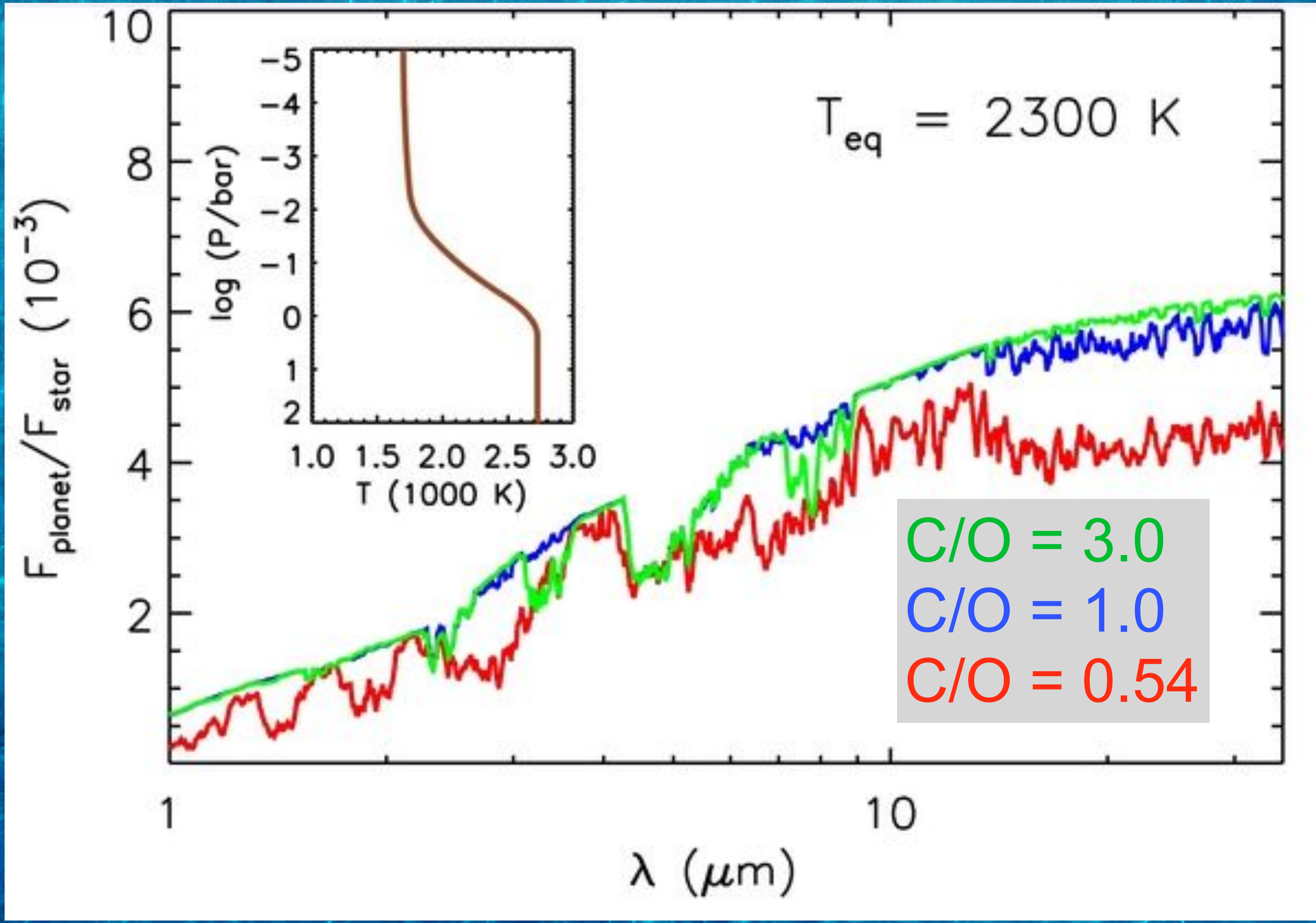
Caveat: assuming some O in silicates but does not include organics (C-rich + O) and additional unidentified oxygen component

Oberg+, Mousis+

# Ice and Planet Formation

Madhusudhan et al. 2011, ApJ, 743, 191

Johnson+ 2012
Moses+ 2013

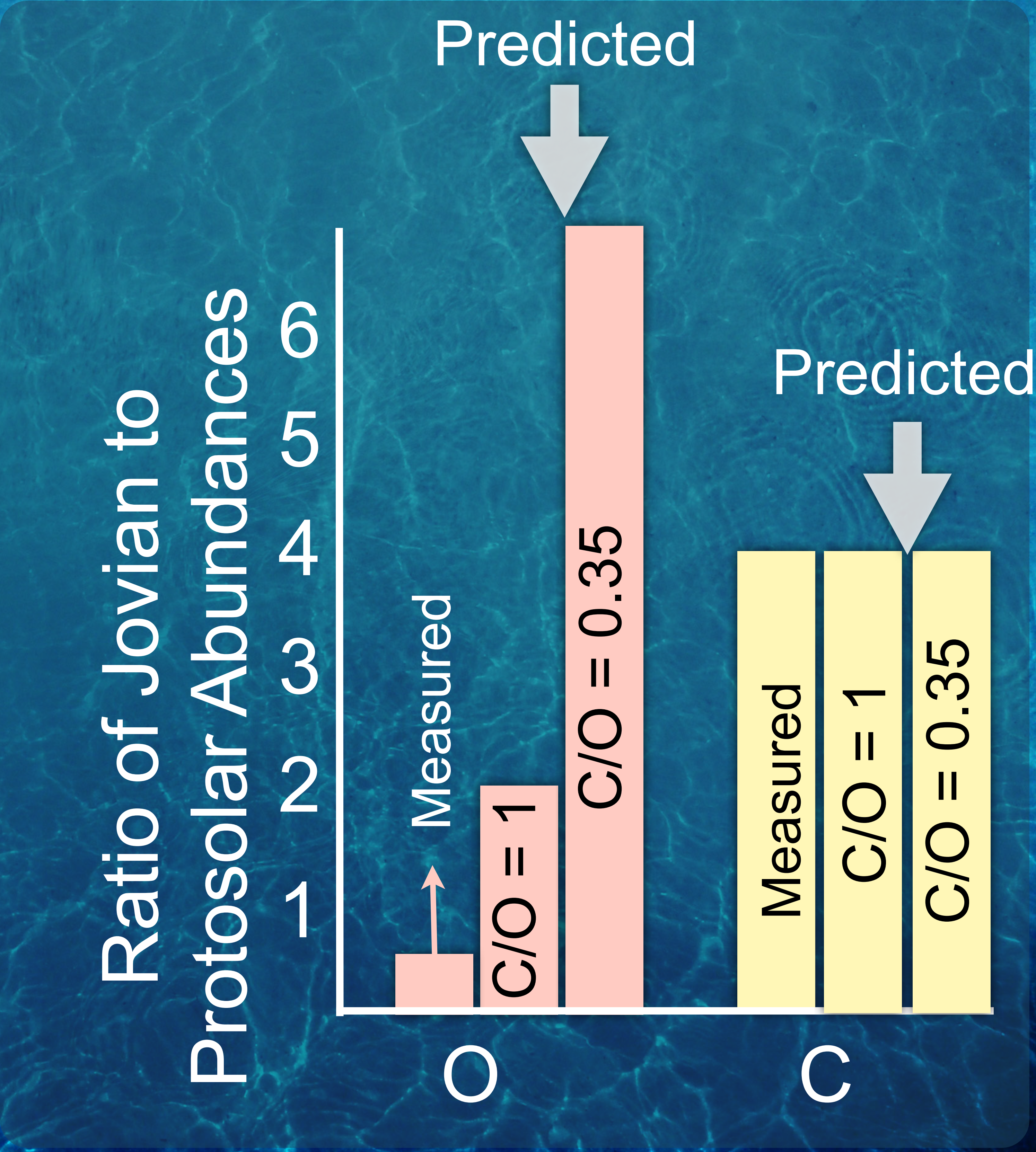



- Amount of water in giant planet atmosphere depends on C/O ratio of accreted gas and planetesimal pollution

# C/O Ratio in Solar System

- Oxygen abundance in Jupiter is uncertain and critical for testing this theory.
- Juno to Jupiter August 2016

Mousis et al. 2012, ApJ, 751, L12



# Terrestrial Planet Formation and Volatiles

- Refractory component: Silicates, carbonaceous grains

  ➡ silicates are seeds of terrestrial worlds

- Volatiles: $H_2$, He, water, organics, CO, $CH_4$, $N_2$, $NH_3$, noble gases

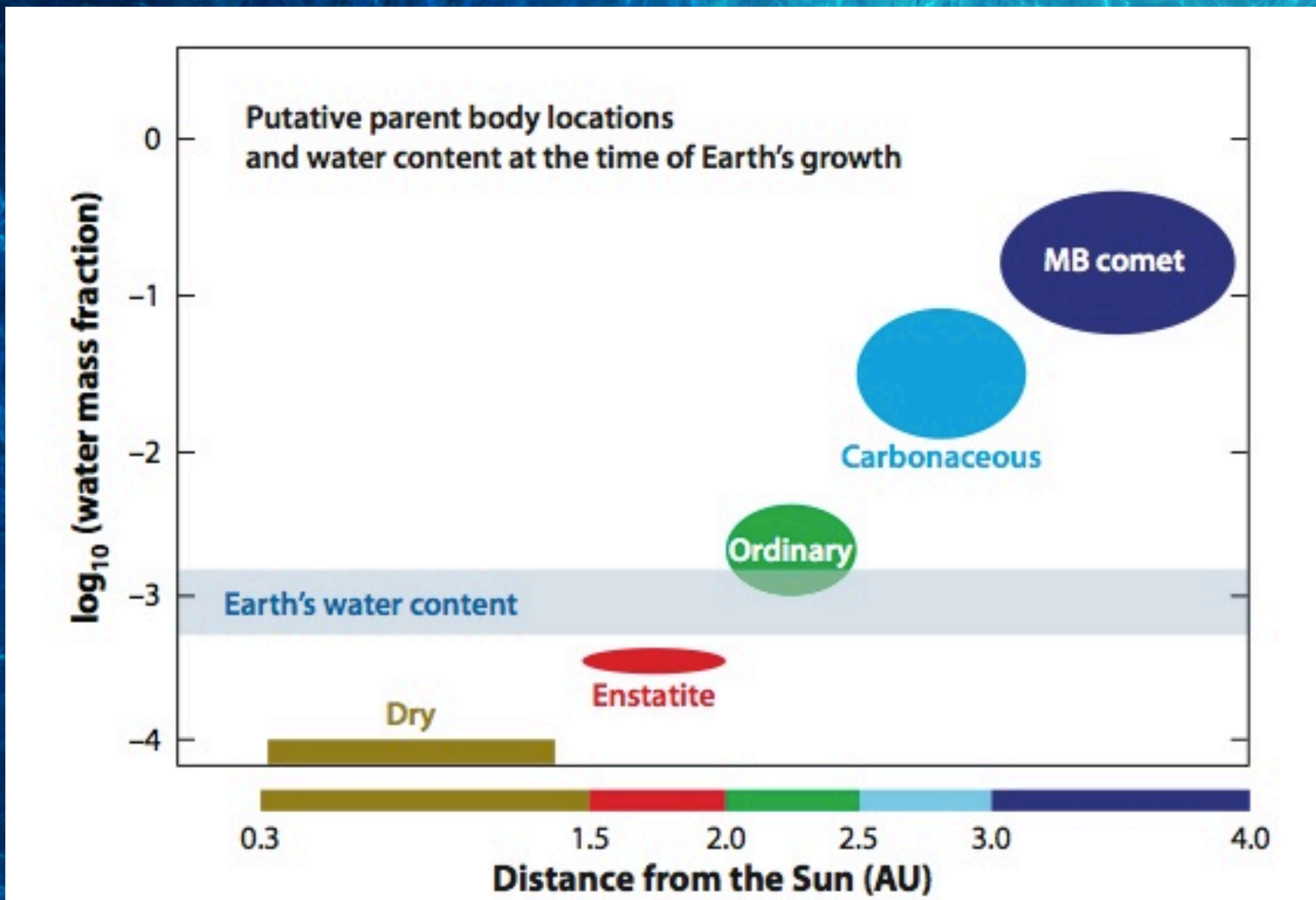
  ➡ $H_2$ and He most volatile -- present in gas

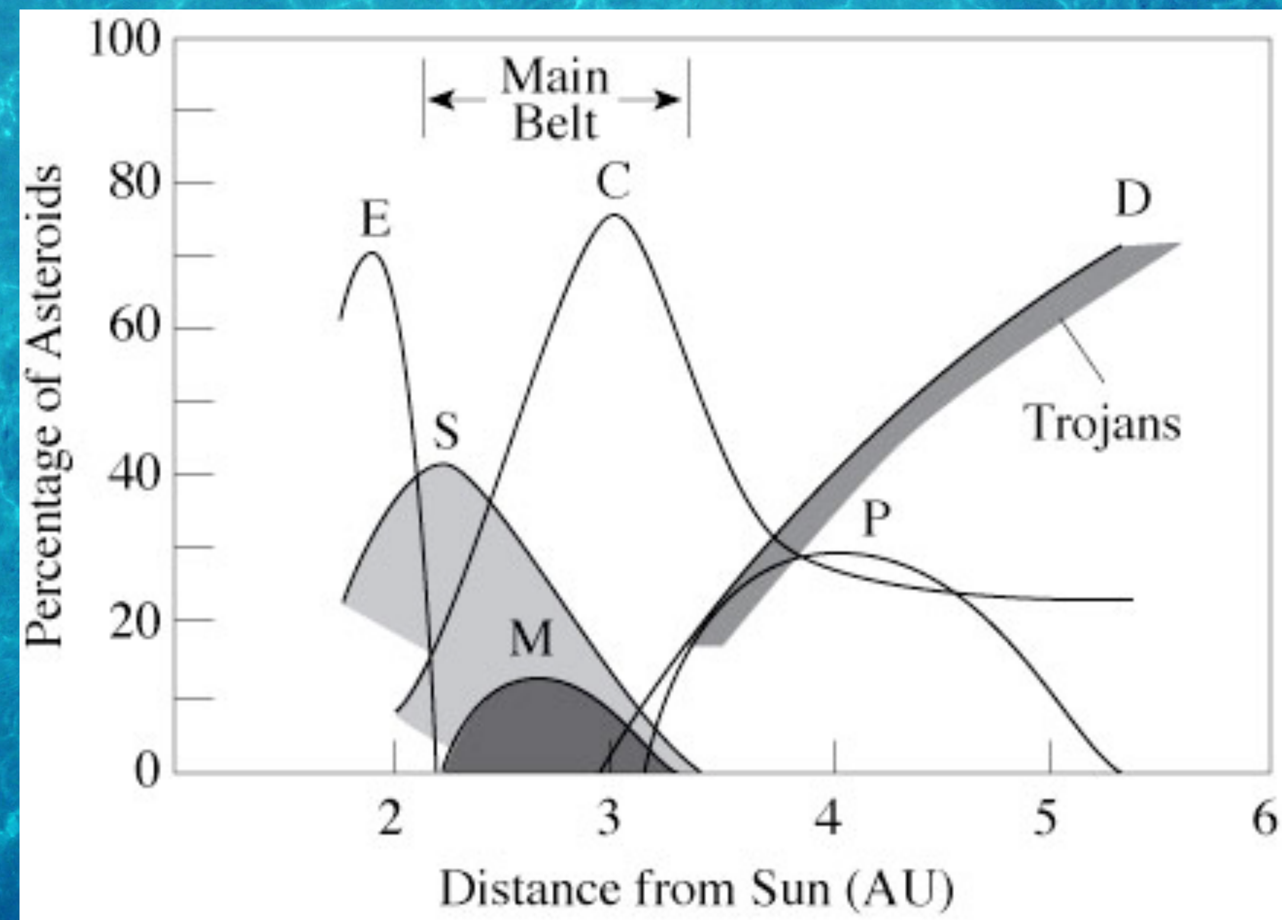
  ➡ water and organics are intermediate - $T_{evap}$ ~ 100-200 K

  ➡ CO, $CH_4$, Noble gases are very volatile -- need extremely cold temps.

# Water in Solar System

Morbidelli et al. 2012, AREPS, 40, 251 ©K. Lang 2010



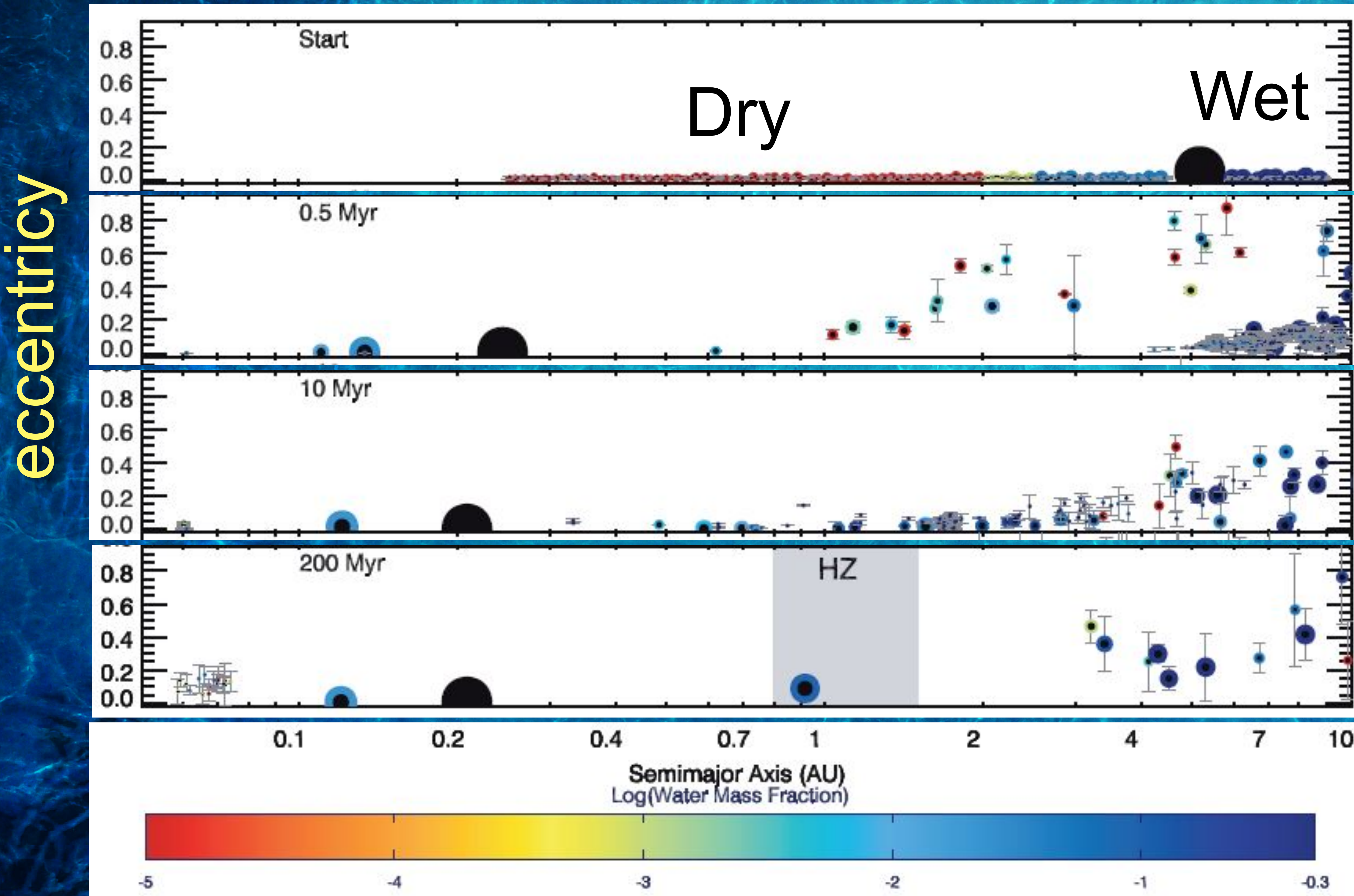




- ➡Enstatite chondrites linked to E-type asteroids
- ➡Ordinary chondrites linked to S-type
- ➡Cabonaceous Chondrite linked to C/D type

# Water on Terrestrial Planets

- Earth formed dry -- small dust grains too hot
  - ➡ Planetesimal delivery: plausible sources beyond snow line (Morbidelli+ 2000) - early or late?
- Earth formed wet
  1. Atmospheric Capture of $H_2O$ in inner disk (Ikoma+ 2006)
     - Timescale is an issue
     - generally accepted that Earth atmosphere generated by outgassing and by proxy water as well
  2. Hot (T > 150 K) grains trap water (Muralidharan+ 2008)
     - Porous aggregates -- trap water in valleys
     - if these grains exist there is no record

# Planetesimal Motion




Raymond et. al. 2006 Science, 313, 1413,

- Habitable zone can be seeded with water during formation
- Key factors: giant planet formation time/orbit/motion

# Deuterium Fractionation: Chemical Fossil

- D abundance ~100,000 times below that of H
- At low temp. (T < 50 K) chemistry favors transfer of D AND produces excess of D atoms relative to H

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<u>T > 50 K</u>

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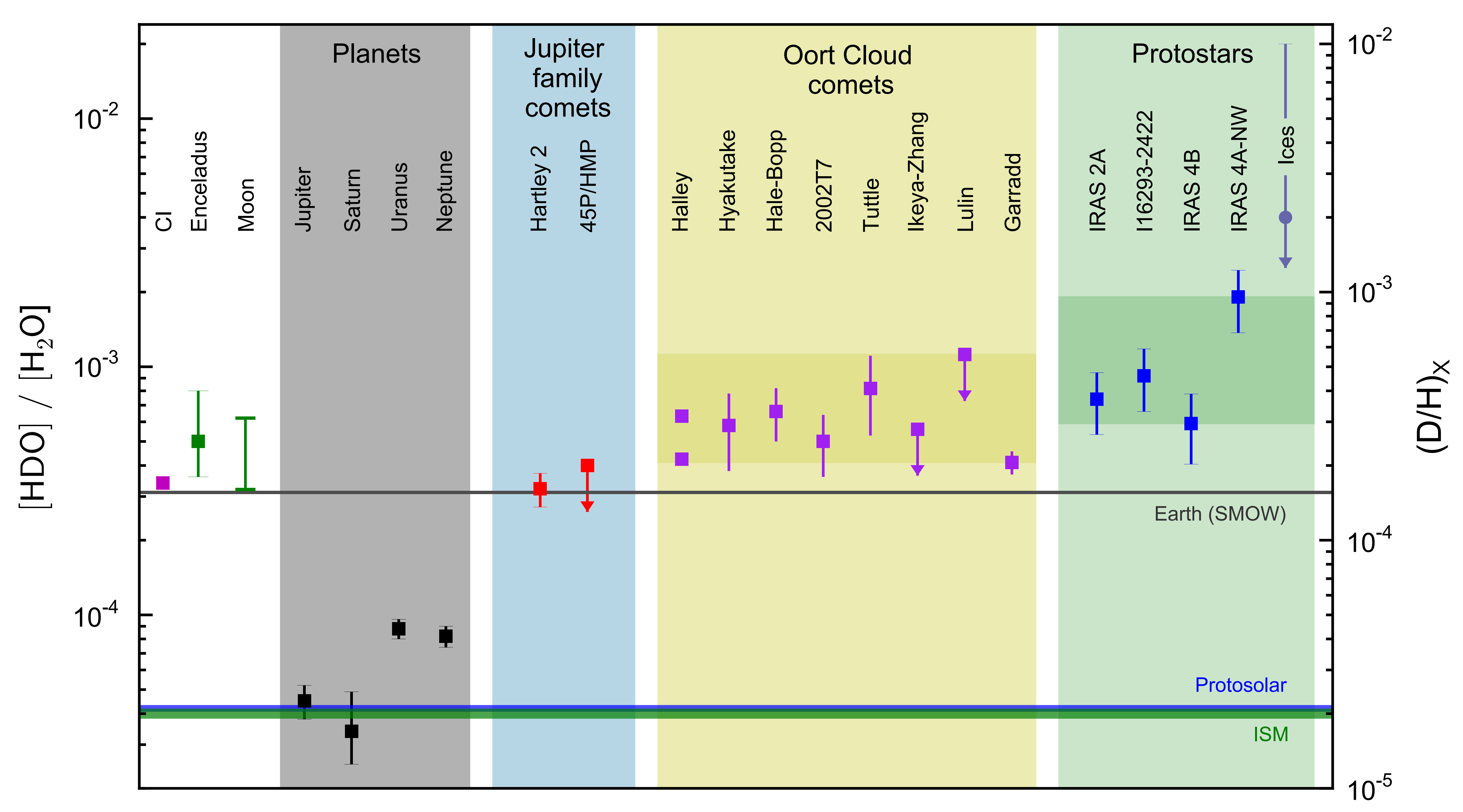
**T > 50 K**

- $(D/H)_X = HD/H_2$
- reprocess in gas D/H ⬇

**T > 100 K**

- ice evaporation (and photodesorption) no change
- reprocess in gas D/H ⬇
- LTE $HDO/H_2O$ factor of 3 enriched
- Surface enhancments (Thi et al. 2011)

# Deuterium Enrichments




Persson et al., in prep.

*LTE only gives factor of 3 - fractionation at cold temperatures*

# Isotopic Tracers: D/H

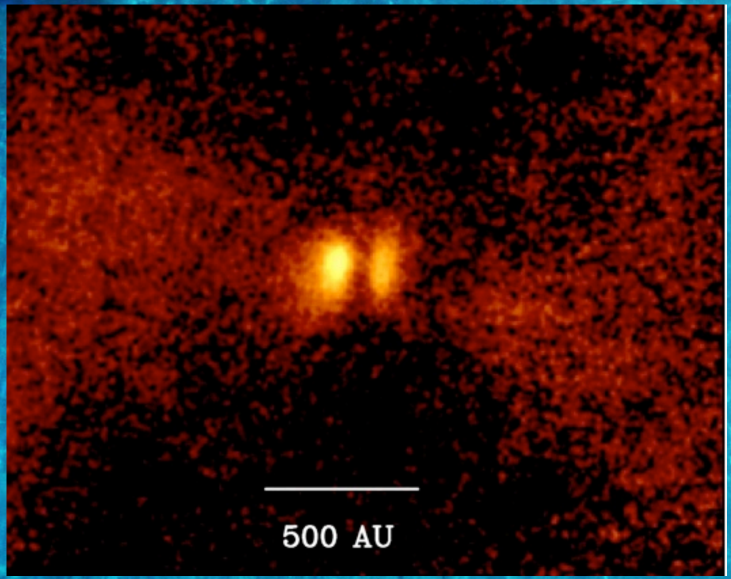
- Planetesimal delivery: again plausible sources
  - ➡ water D/H ratio implanted during pre-stellar phase
- Atmospheric Capture of $H_2O$ in inner disk
  - ➡ D/H ratio of water vapor at 1 AU should not be enhanced
    - But Thi et al. (2011) - disk surface?
  - ➡ Atmospheric escape is mass dependent (Genda & Ikoma 2008)
- Hot (T > 150 K) grains trap water
  - ➡ Hard to get fractionated water as gas temperature is too high, but Thi model....

## Take home message

- Water is an important tracer of giant and terrestrial planet formation
- Planetesimal delivery models for Earth water currently favored but processes at 1 AU need to be probed.
- Water partially formed under cold conditions

credit: ESO

Tobin+2012, Nat, 492, 83




credit: ESO

1. Water is made in prestellar phase under cold conditions as ice, D enrichments implanted.

2. Collapse seeds disk with water ice. initial suggestions are this is mostly unaltered.

3. Water vapor is readily detected on disk surface in inner and rarely in outer disk.  Seen as ice in outer disk - midplane remains hidden.

credit: NASA

4. Water is important to facilitate planet formation.  Accretion by giant planets may depend on birth location.  Water is common - delivery to young Earth’s may also be common.

# Going Forward

- Supply of material from core to disk is key - little observational constraints (Li talk, Stutz talk)
- Effect of movement of materials -- both ice and gas -- needs observational basis
- Observations see surface - what does this tells us about planets (both giant and terrestrial delivery)?
  - ➡ Deuterium fractionation and oxygen isotopes
- How can we detect midplane?
  - ➡ $HCO^+$ will strongly react with water -- probe of snowline?
  - ➡ But need ionization in midplane
- Juno measurement of deep O abundance is critical
- More understanding of cometary D/H diversity