

Water in planet forming disks

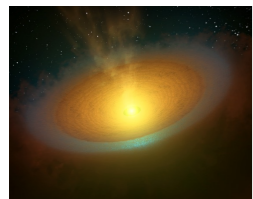


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Overview

- Introduction
- Basic processes: phases, spectroscopy, excitation, chemistry
- Structure and chemistry of planet forming disks
- Inheriting water from the ISM
- Observations: ice and gas-phase water across the disk
- Prospects for ALMA Band 5
- Conclusion



Introduction

- Water is a key molecule for habitability
- Water ice represents a significant amount of solids for planet building
- Water is formed in interstellar clouds and plays a role in cooling
- Incorporated in planet forming disks in the form of ice
- Inheritance vs local formation in disks not fully settled
- (Late) delivery to terrestrial planets actively studied
- Link with exoplanets: C/O budget; H₂O in atmosphere; exocomets
- **Observational characterisation of H₂O in disks essential**

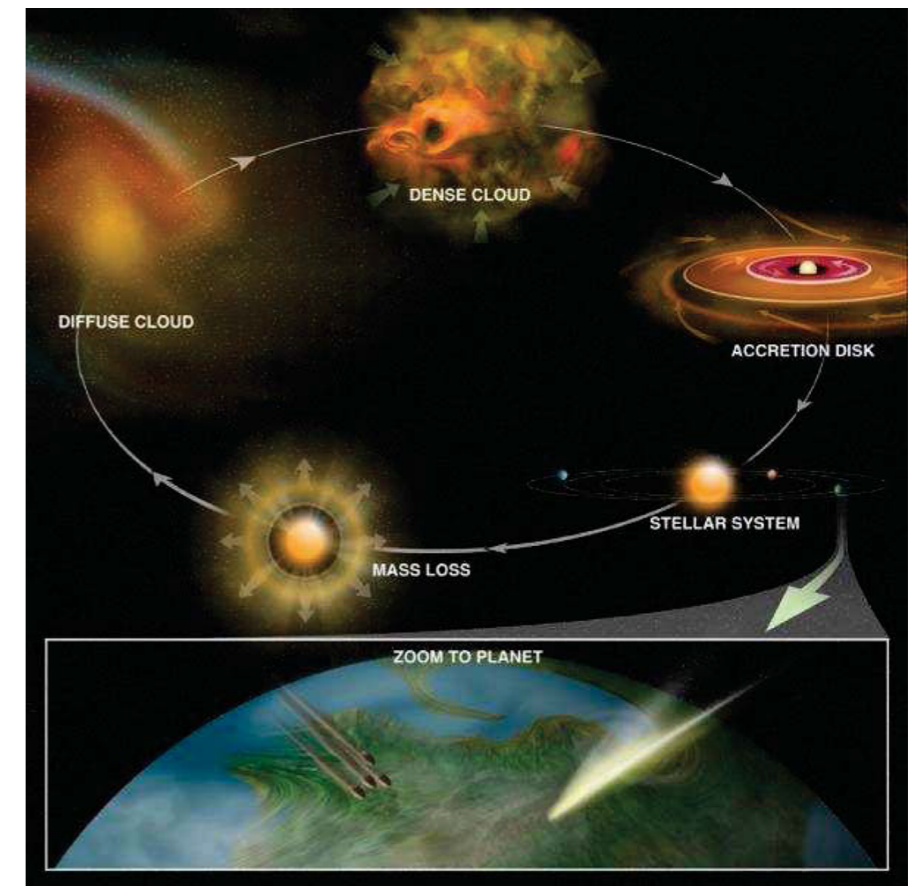
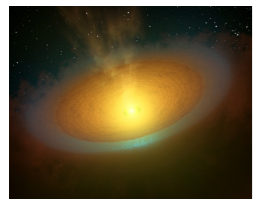


Image credit: B. Saxton, NRAO/AUI/NSF



Basic processes

- **Phases: ice and gas**

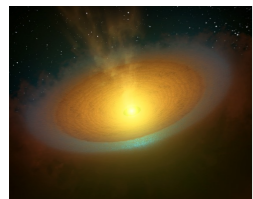
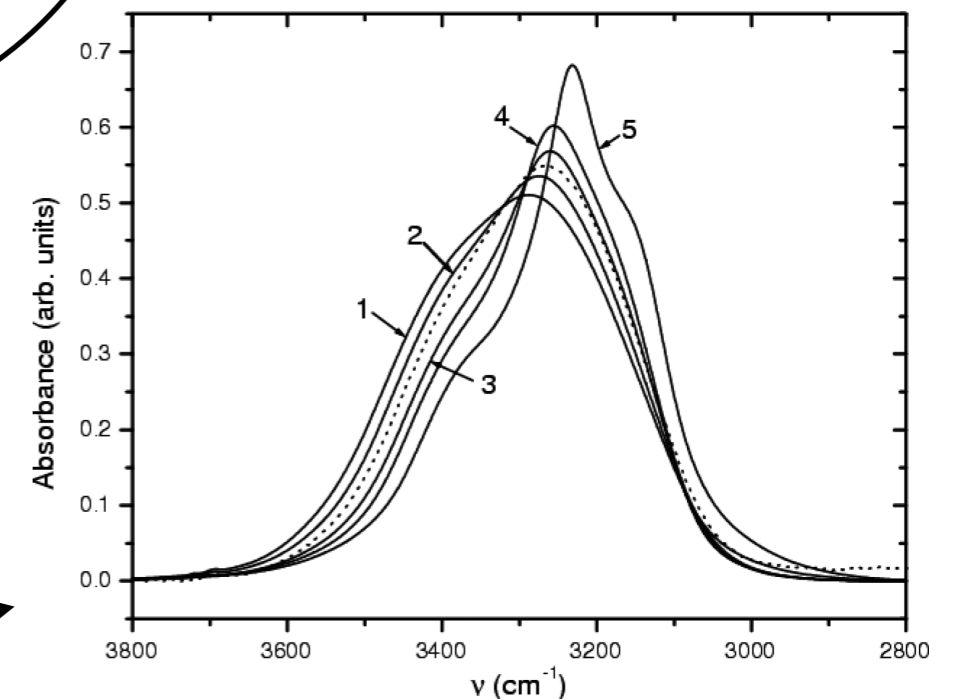
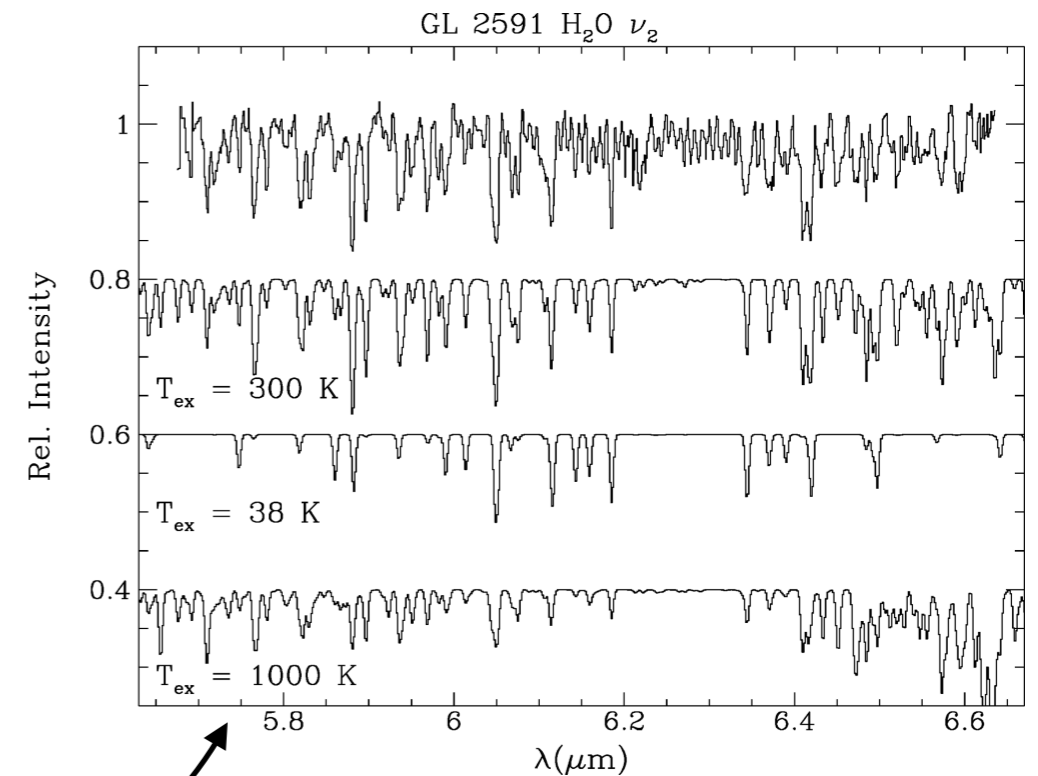
- Sublimation ('evaporation') at 100-160 K
- Ice mostly amorphous; crystalline above 90 K

- **Spectroscopy**

- Vibrational: (a)symmetric stretch (2.7, 2.65 μm), bending (6.2 μm)

- Crystalline water: sharp feature at 3.1 μm

- Libration modes: 45, 63 μm



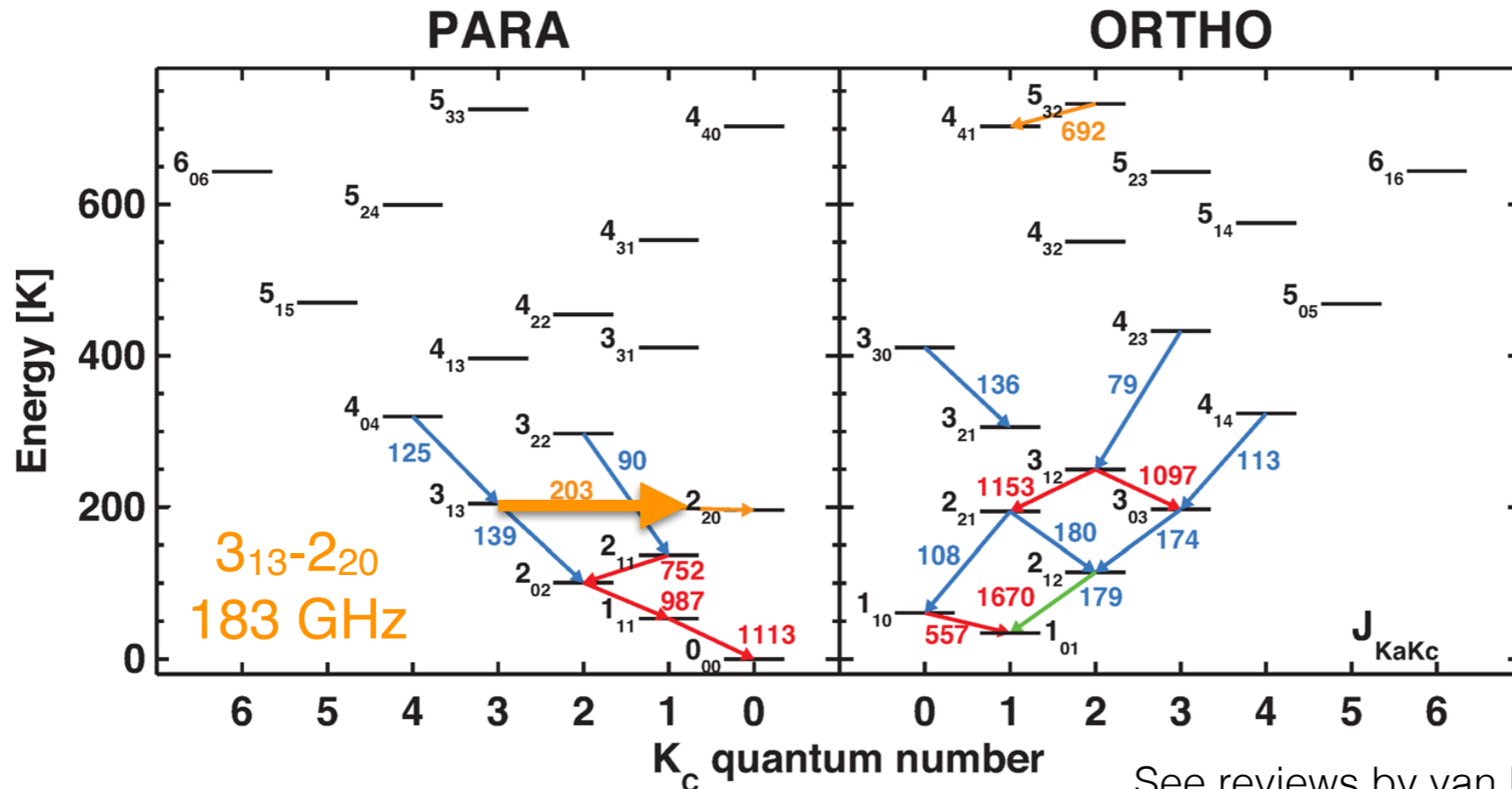
See reviews by van Dishoeck et al. (2013, 2014); Helmich et al. (1996); Schutte et al. (2002)

Michiel Hogerheijde: Water in planet forming disks - Getting ready for ALMA band 5: Synergy with APEX/SEPIA - ESO/Garching February 1-3 2017

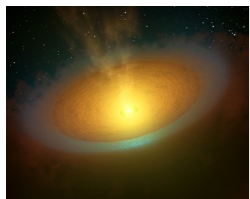
Basic processes

- Spectroscopy**

- Rotational levels J_{K_A, K_C} ; ortho- and para- H_2O (3:1 statistical)
 - Ground state transitions: $1_{10}-1_{01}$ (557 GHz/538 μ m), $1_{11}-0_{00}$ (1113 GHz/269 μ m)
 - Band 5: $3_{13}-2_{20}$ (183GHz; 203 GHz for $H_2^{18}O$)

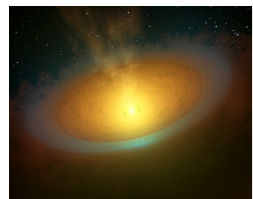


See reviews by van Dishoeck et al. (2013, 2014)



Basic processes: excitation

- H₂O has large permanent dipole moment (1.86 Debye)
 - high critical densities ($>10^8$ - 10^9 cm⁻³): sub-thermal excitation even in disks
 - high opacities: partially drives back excitation to LTE
- Strong dust thermal infrared: pumping
- Large differences in radiative decay rates of connected levels: masers
- **Translating water line fluxes into column densities and abundances challenging**
- Codes include: `prodimo`, `lime`, `dali`, `mollie`

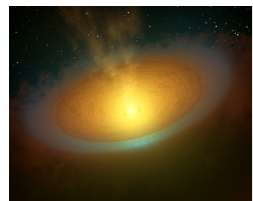


See reviews by van Dishoeck et al. (2013, 2014)

Woitke et al. (2009); Brinch & Hogerheijde (2010); Bruderer et al. (2012); Keto et al. (2014)

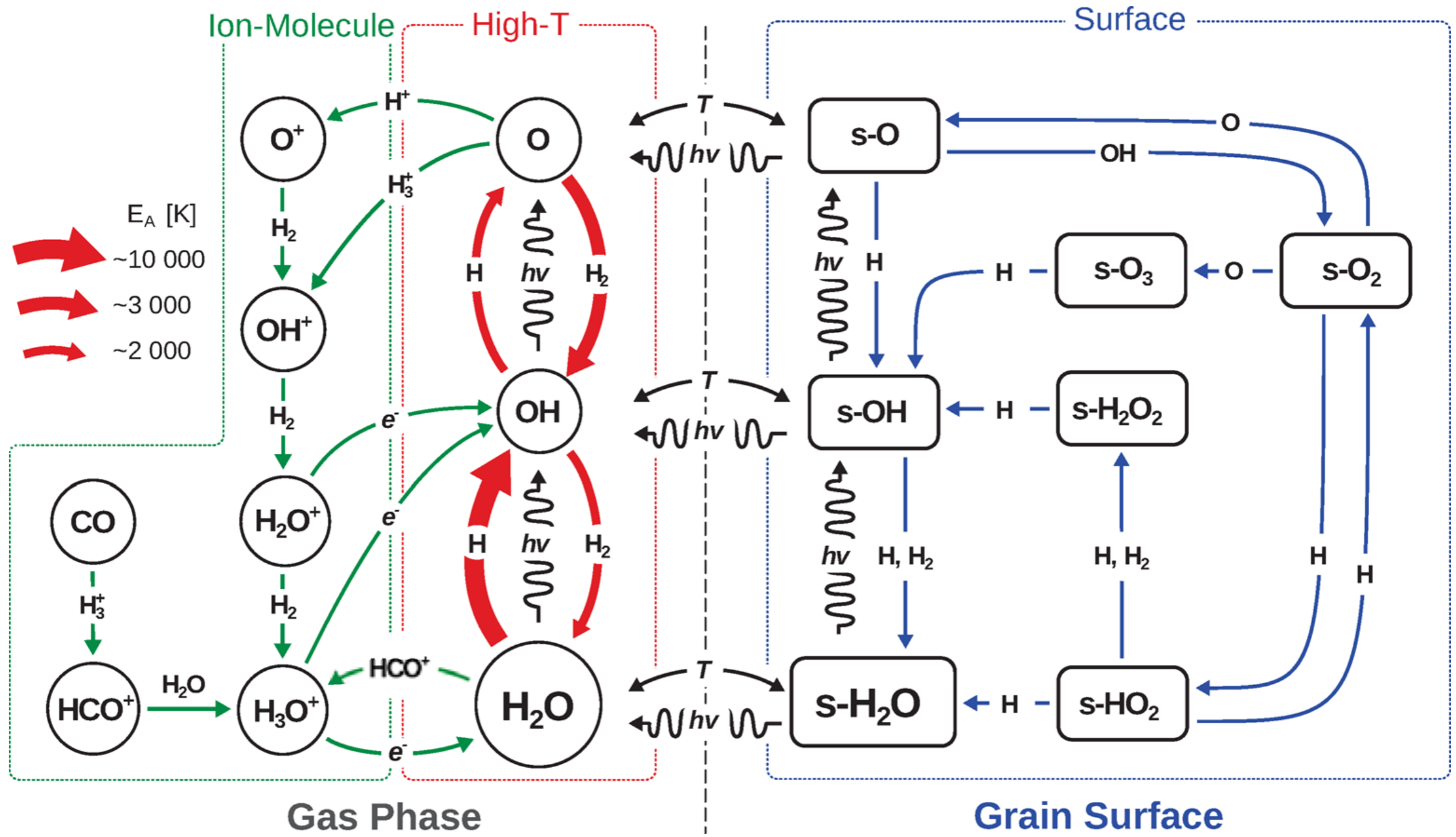
Basic processes: chemistry

- Dictated by kinetics of two body reactions; dissociation by ultraviolet radiation needs to be included
- **At low temperatures**
 - $\text{H}_2^+, \text{H}_3^+ + \text{O} \rightarrow \text{OH}^+, \text{H}_2\text{O}^+, \quad + \text{H}_2 \rightarrow \text{H}_3\text{O}^+, \quad + e \rightarrow \text{H}_2\text{O}$
(17%), OH (83%)
 - H_2O destroyed by $\text{C}^+, \text{H}_3^+, \text{HCO}^+$, UV photons with $\lambda < 1800 \text{ \AA}$ (incl Ly α !)
- **At $T > 230 \text{ K}$, activation barrier exceeded**
 - $\text{O} + \text{H}_2 \rightarrow \text{OH} + \text{H}, \quad + \text{H}_2 \rightarrow \text{H}_2\text{O}$
 - drives all available O into water unless UV strong enough to photodissociate. However, H_2O will self-shield.



See reviews by van Dishoeck et al. (2013, 2014)

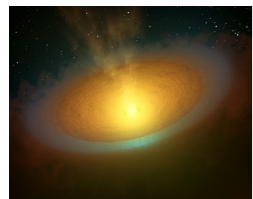
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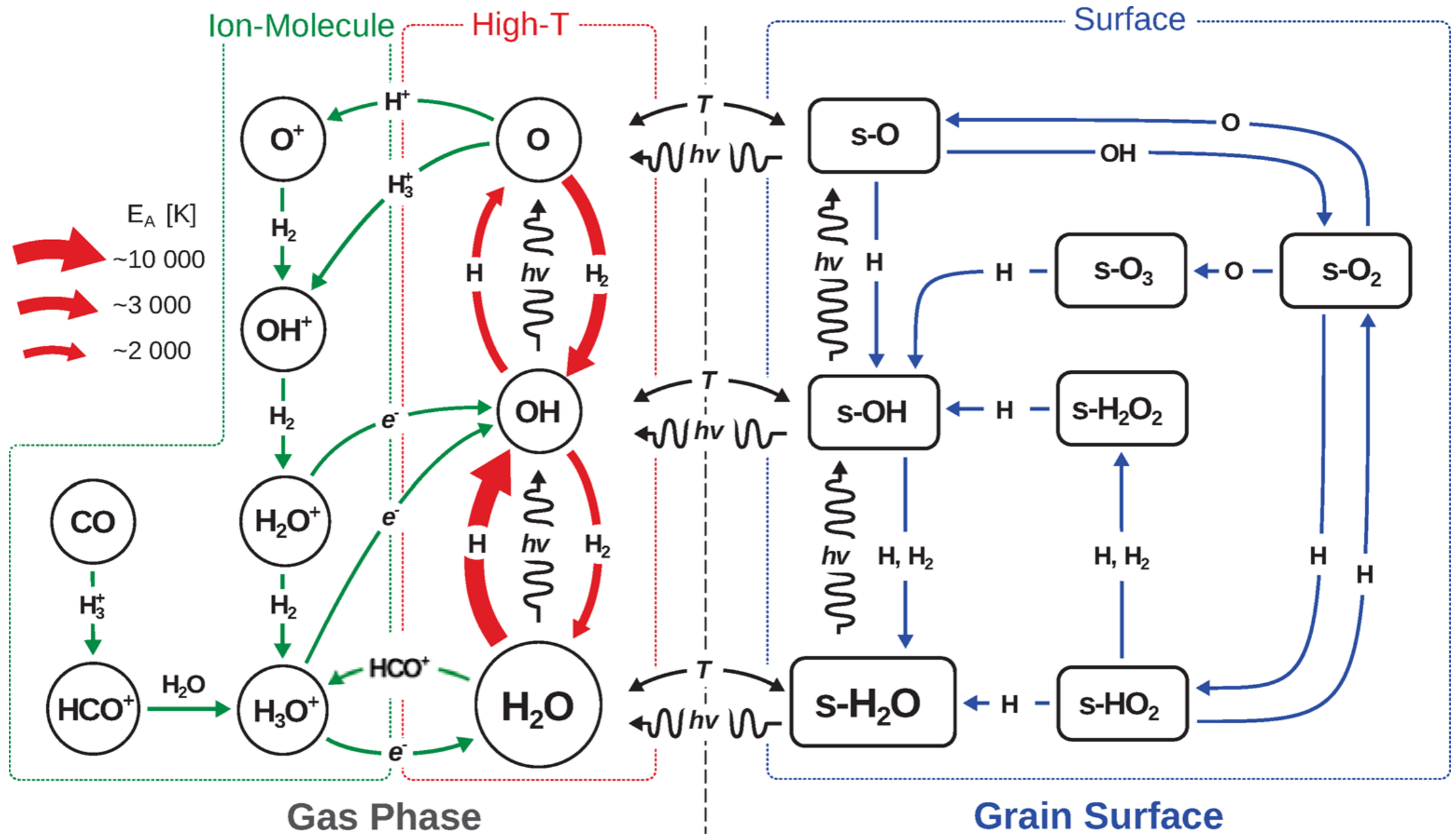
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Basic processes: chemistry



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Basic processes: chemistry

- **On grain surfaces**



- thermal desorption: $T_d > 100\text{-}160 \text{ K}$

- photodesorption: low yield, $\sim 10^{-3}$ /UV photon

- \sim equilibrium between photodesorption and -dissociation

- can be secondary UV generated by Xrays

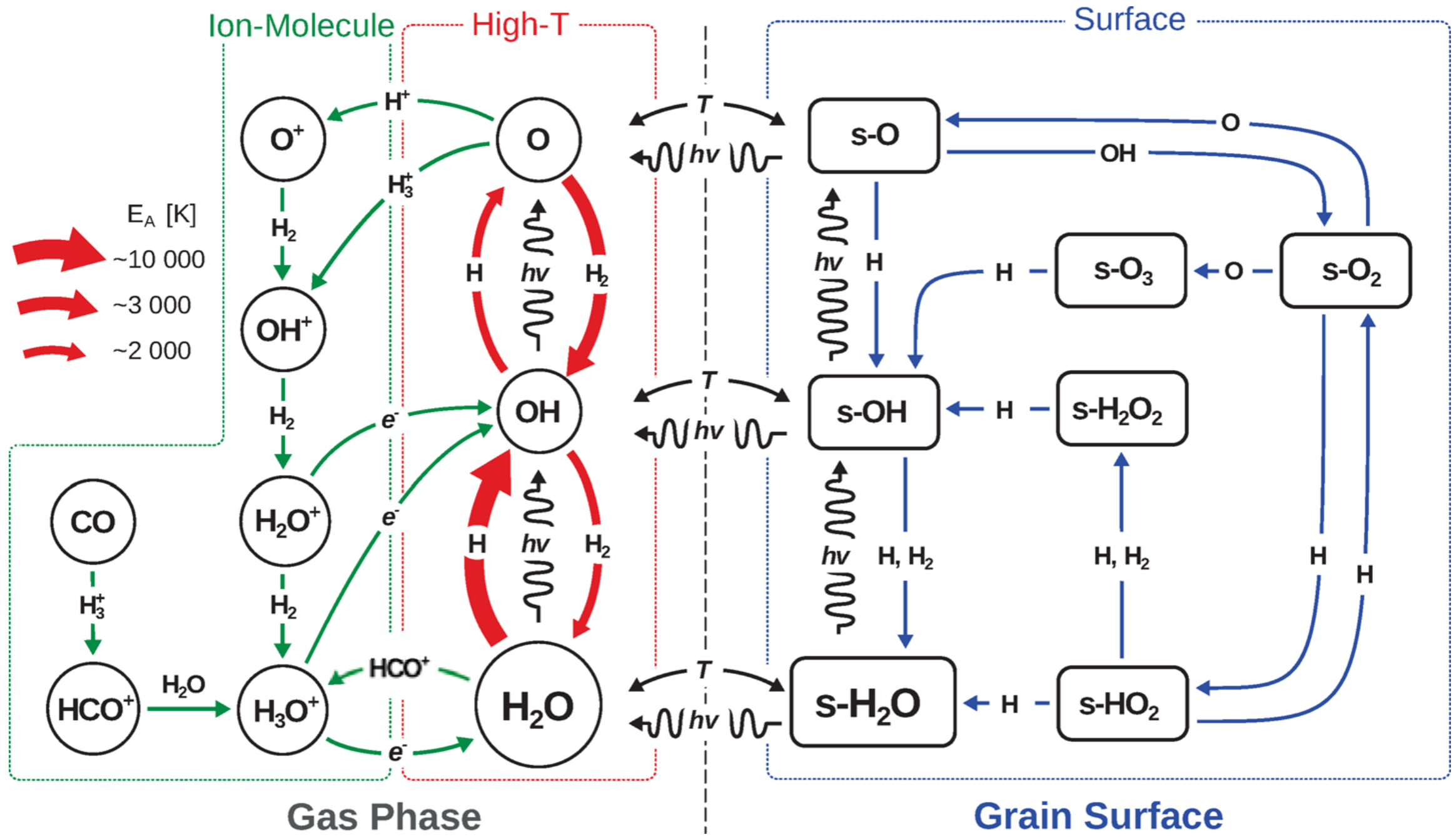
- **Freeze out** regulated by sticking probability (1?), density, and available dust grain surface

- for MRN size distribution: $t_{stick} = 3 \times 10^9 / n \text{ yr}$ (n : density in cm^{-3})

- grain growth reduces available surface and increases t_{stick}

See reviews by van Dishoeck et al. (2013, 2014)

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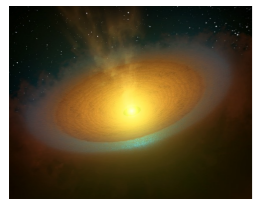
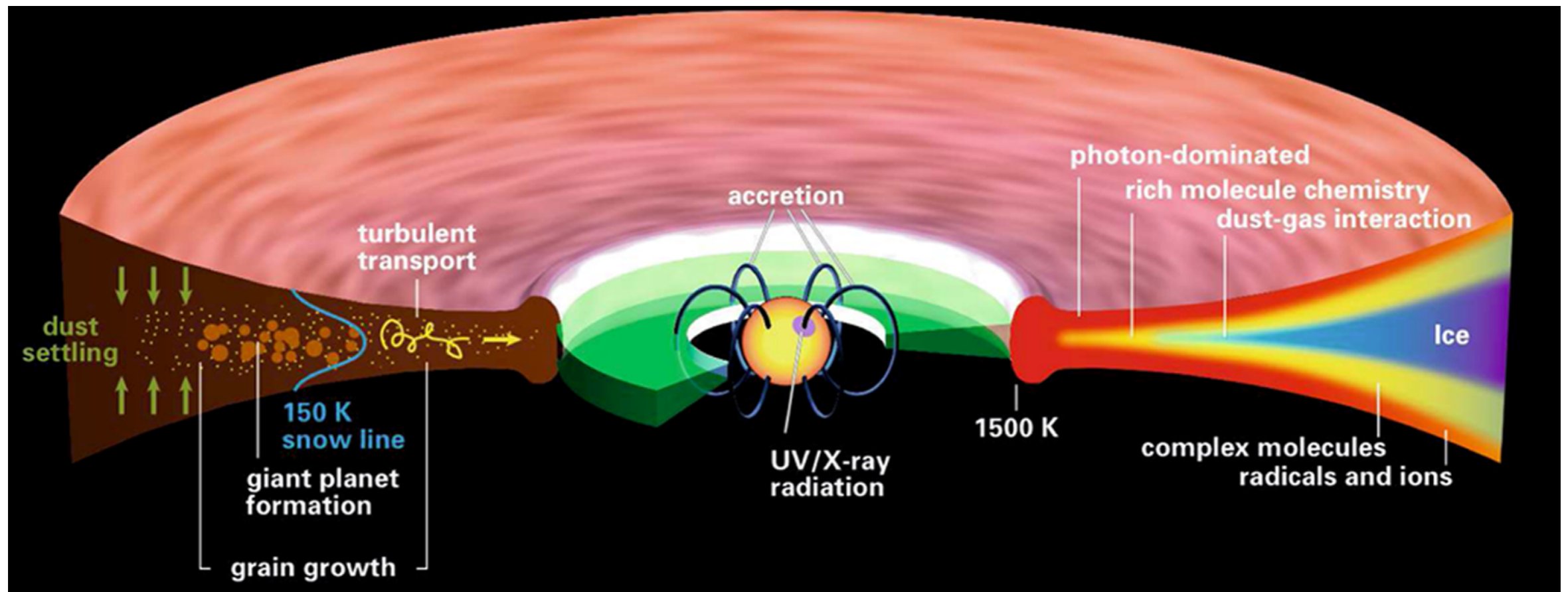
Planet forming disks

- **Radial and vertical structure:**

- density
- temperature

$$\Sigma_d(r) = \Sigma_c \left(\frac{r}{r_c} \right)^{-\gamma} \exp \left[- \left(\frac{r}{r_c} \right)^{2-\gamma} \right]$$

$$\rho_d(r, z) = \frac{\Sigma_d}{\sqrt{2\pi} z_d} \exp \left[- \frac{1}{2} \left(\frac{z}{z_d} \right)^2 \right]$$



See review by Henning & Semenov et al. (2013)
Woitke et al. (2009); Antonellini et al (2015)

Planet forming disks

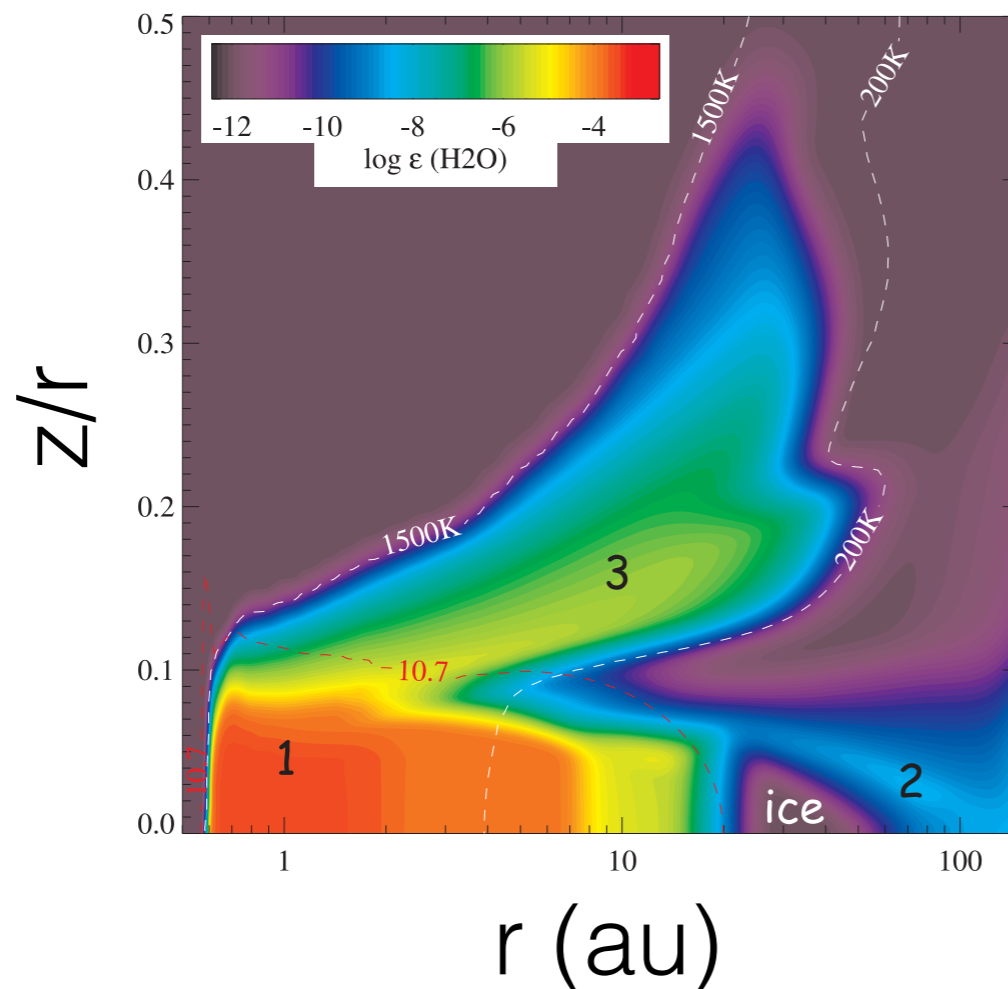
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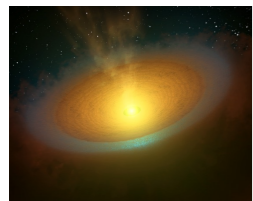
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- **Resulting distribution of gas-phase water**



- 1: high T gas-phase formation
- 2: UV photodesorption
- 3: hot surface layer



See review by Henning & Semenov et al. (2013)
Woitke et al. (2009); Antonellini et al (2015)

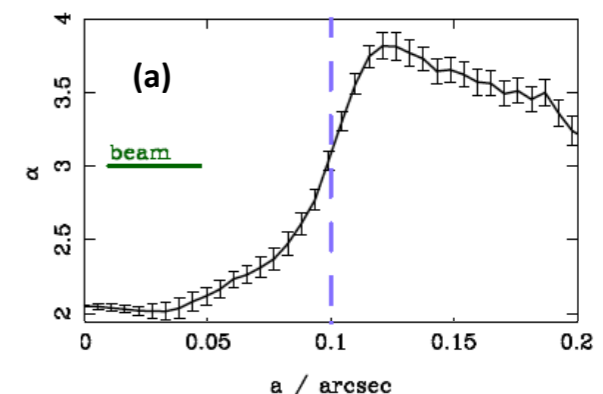
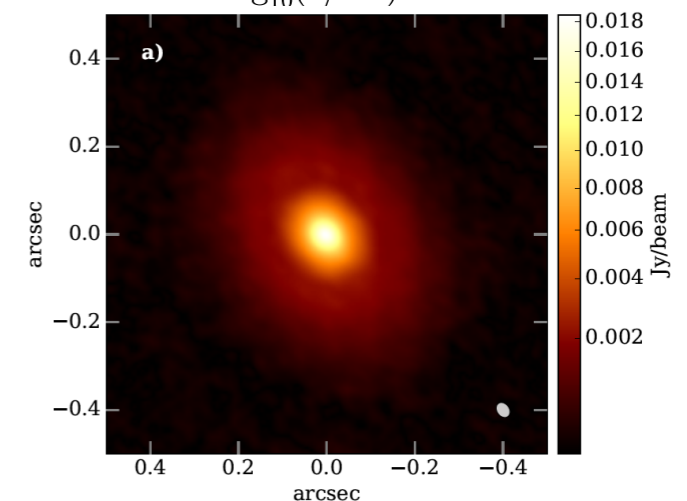
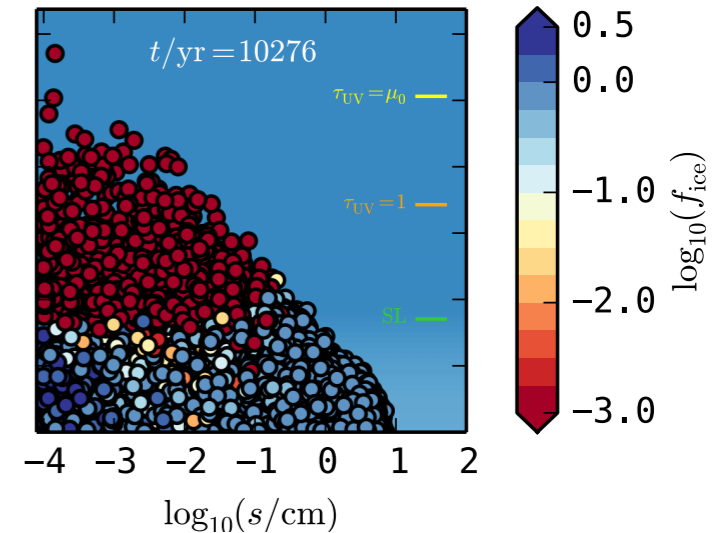
Planet forming disks

- **Grain growth, settling and migration**

- growth+settling: transports ice to larger grains near midplane
- migration: radial transport of ices

- **Snow line**

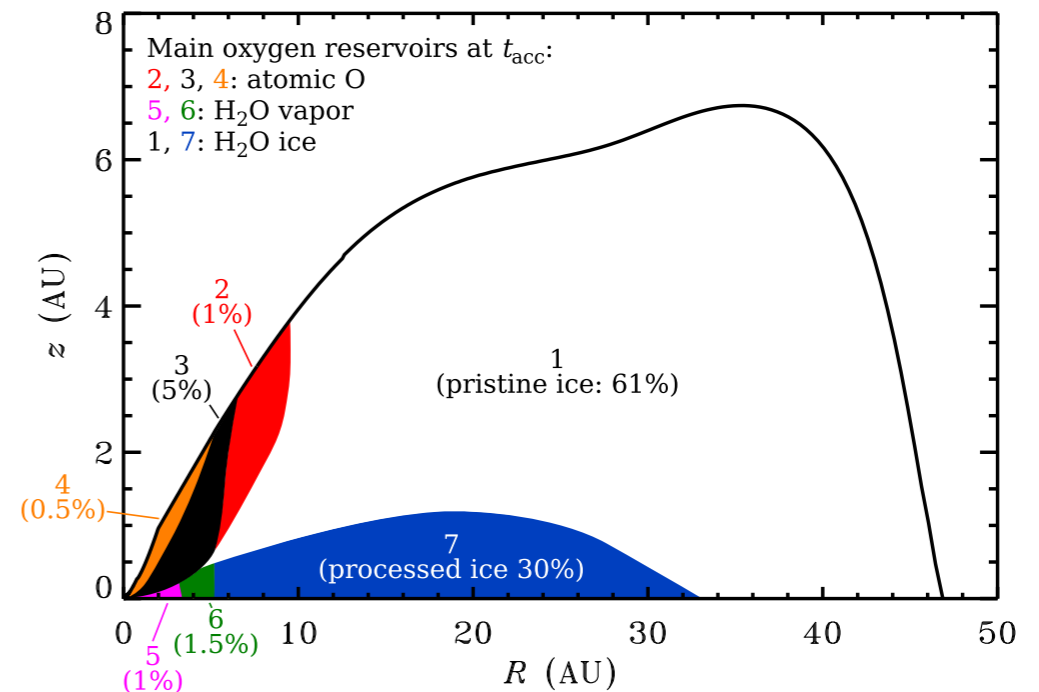
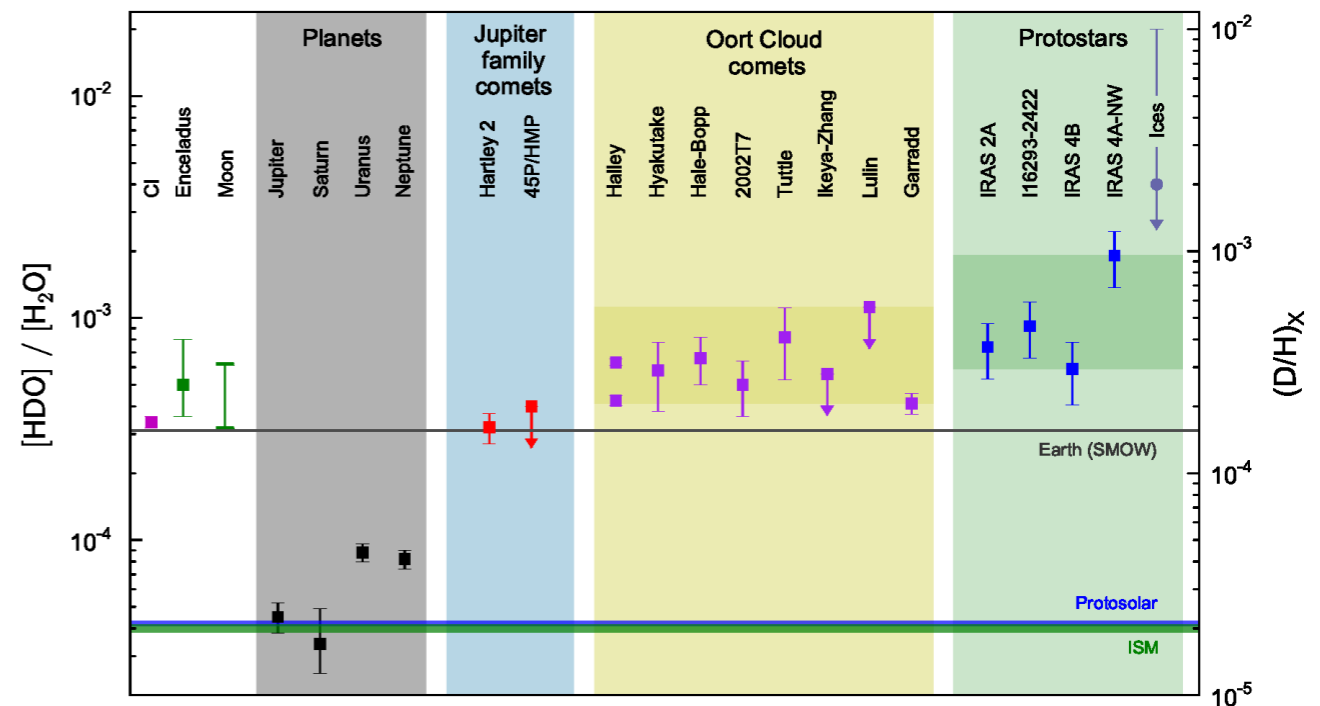
- sintering of coagulated grains on inward crossing of snow line
- accretion/luminosity outbursts move snow line outward
- grain size / spectral index linked to snow line (?)



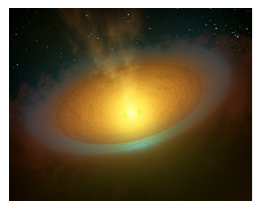
Krijt et al. (2016); Cieza et al. (2016); Banzatti et al. (2015); Okuzumi et al. (2016); Zhang et al. (2013, 1015)

Inheritance

- Gas-phase formation in inner disk (>200 K), but unlikely to make it into (terrestrial) planets
- Low temperature ion-molecule chemistry inefficient
- Majority of ice enters the disk likely as ice, formed in prestellar core on grains
- HDO/H₂O and D₂O/H₂O enhanced in cold environments (<20 K)
- Earth's oceans enriched, as much as chondritic meteors but less than comets
- **No observational information (yet) of HDO/H₂O in disks**

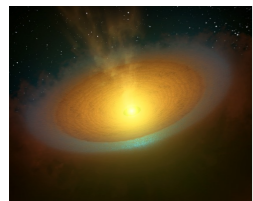
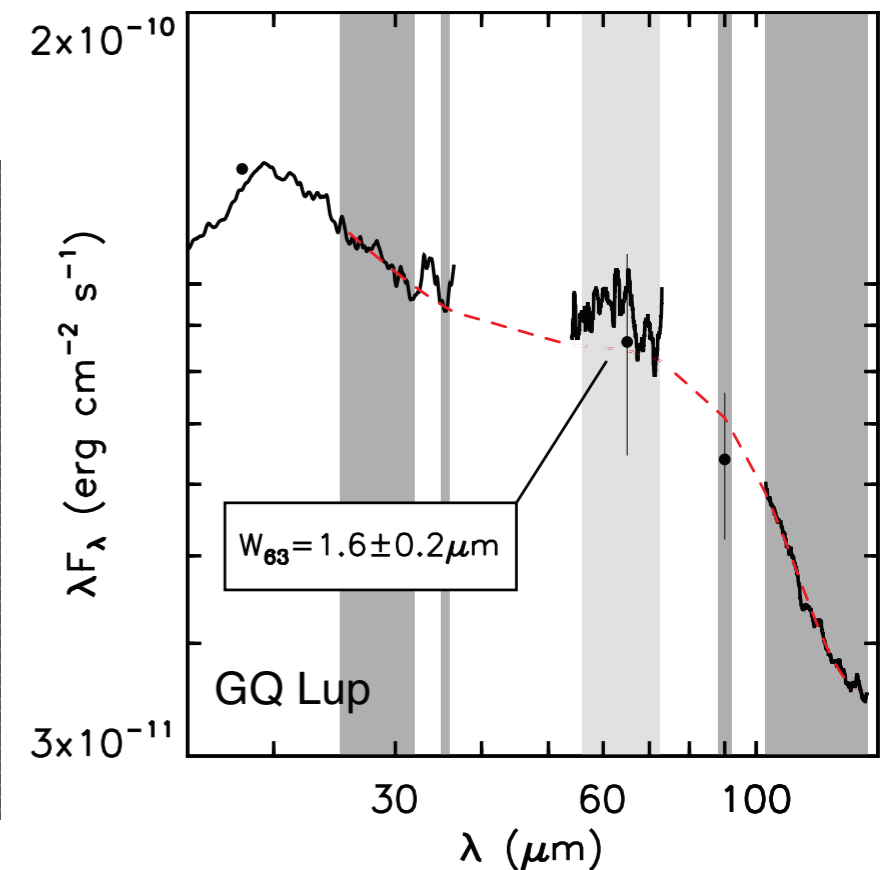
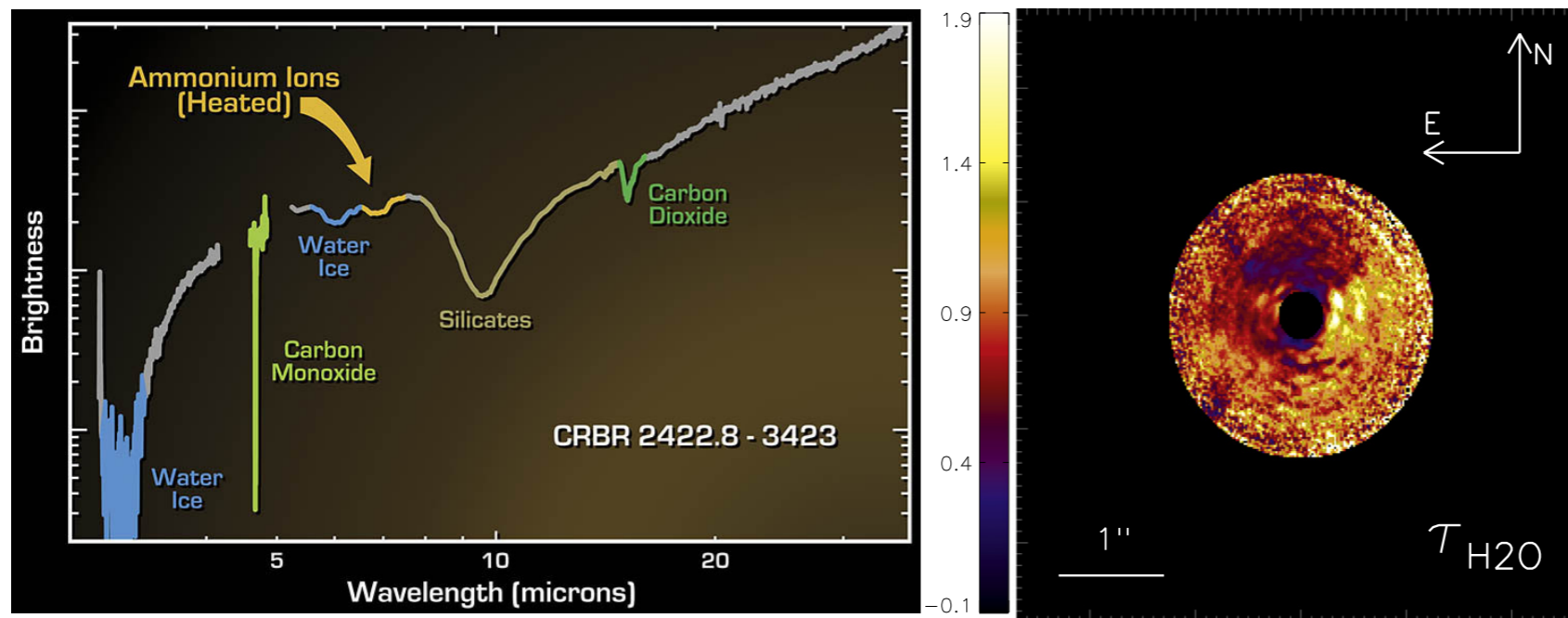


Cleeves et al. (2014); Visser et al. (2011);
 Salum et al. (); Furuya et al. (2016); Drosdosvkaya et al. (2016)



Observations: ice

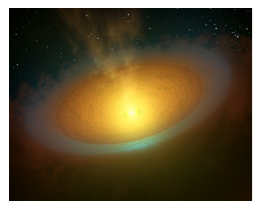
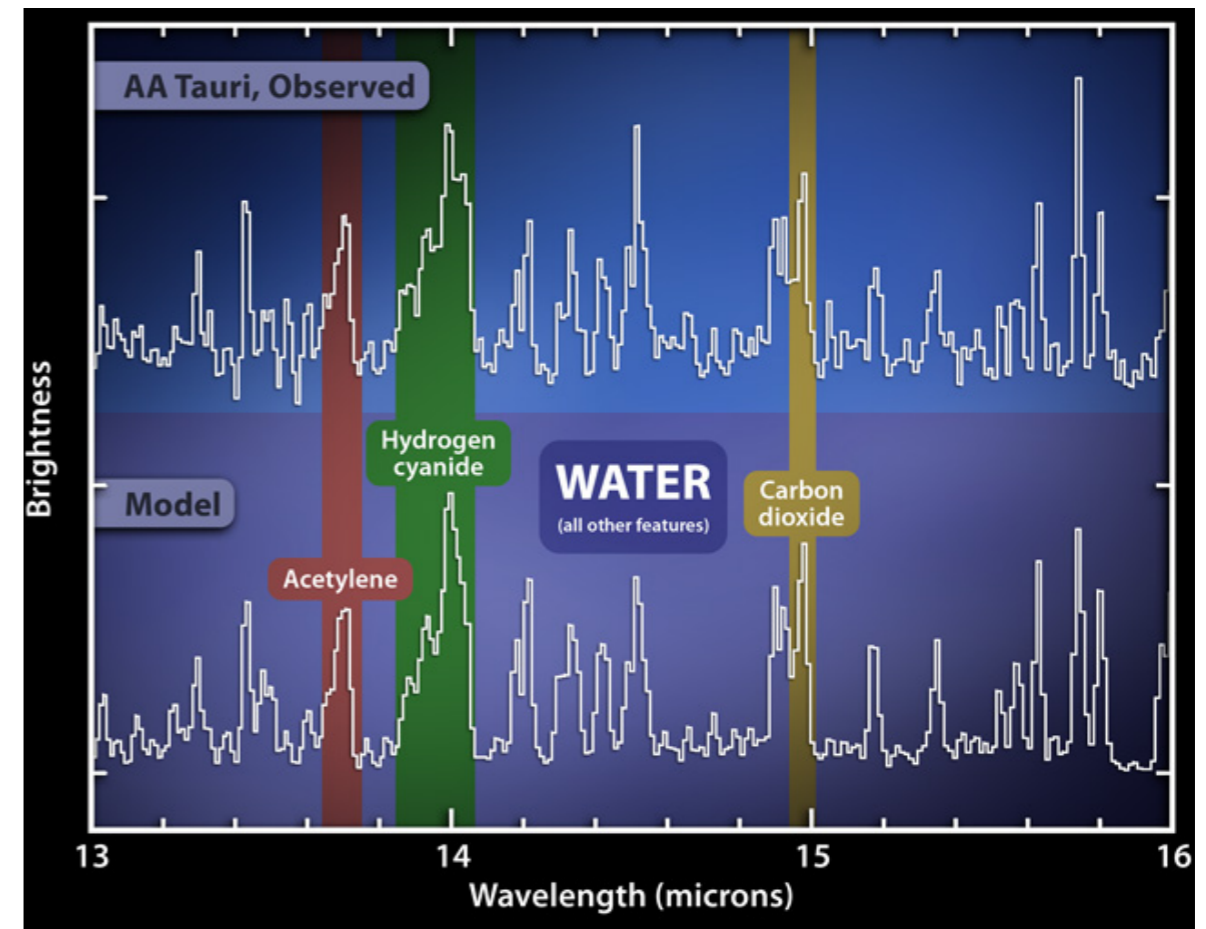
- Evidence for ice in disks
 - Near- and mid-IR absorption and scattered light
 - Far-IR libration mode
- Difficult to turn into ice mass estimates



Pontoppidan et al. (2005); Honda et al. (2016); Terada et al. (2007, 2016); McClure et al. (2014); Bouwman et al. (in prep)

Gas-phase water in the inner disk

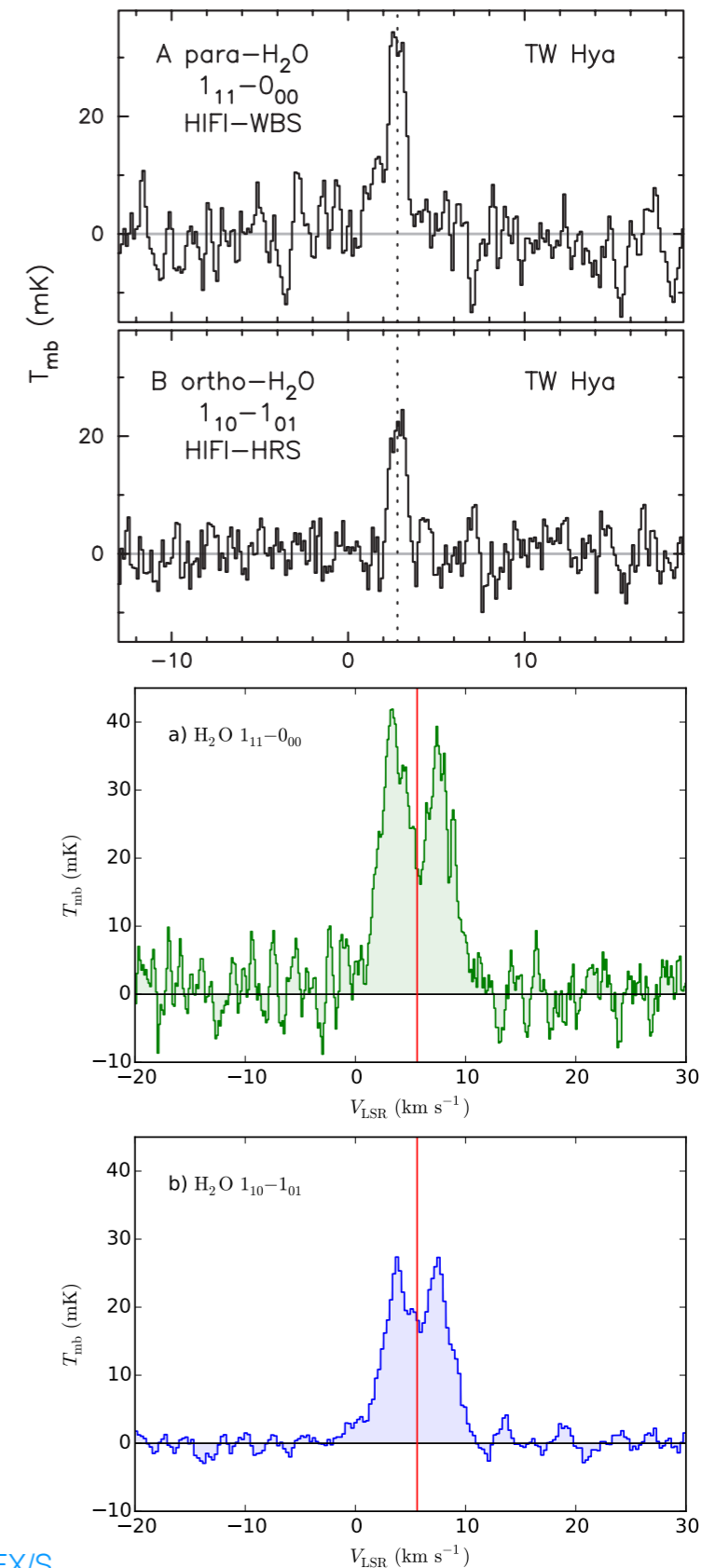
- Near- and mid-IR detections
 - 2.9-33 μm
 - excitation temperature ~ 500 K
 - inner few au
 - $\text{CO}/\text{H}_2\text{O} \sim 1$
- impact of UV photodissociation: largely absent in A,B stars; 50% of GM stars; 67% of K stars
- During EX Lup outburst: water column density and emitting area increased



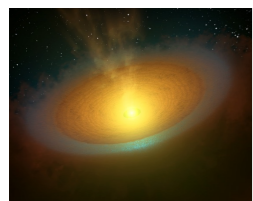
Carr & Najita (2008, 2011); Pontoppidan et al. (2010a,b); Salyk et al. (2008, 2011, 2015); Banzetti et al. (2012, 2015, 2016)

Gas-phase water in the outer disk

- Ground state rotational emission detected in very few disks
 - 557, 1113 GHz: Herschel
 - TW Hya, HD100546, DG Tau, (LkCa15+DMTau+MWC480) & upper limits
 - traces water vapor released by photodesorption
 - low detection statistics suggests ice may have settled to midplane, where it is shielded from UV

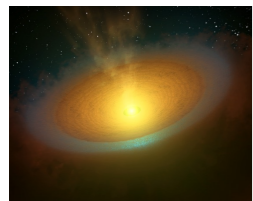
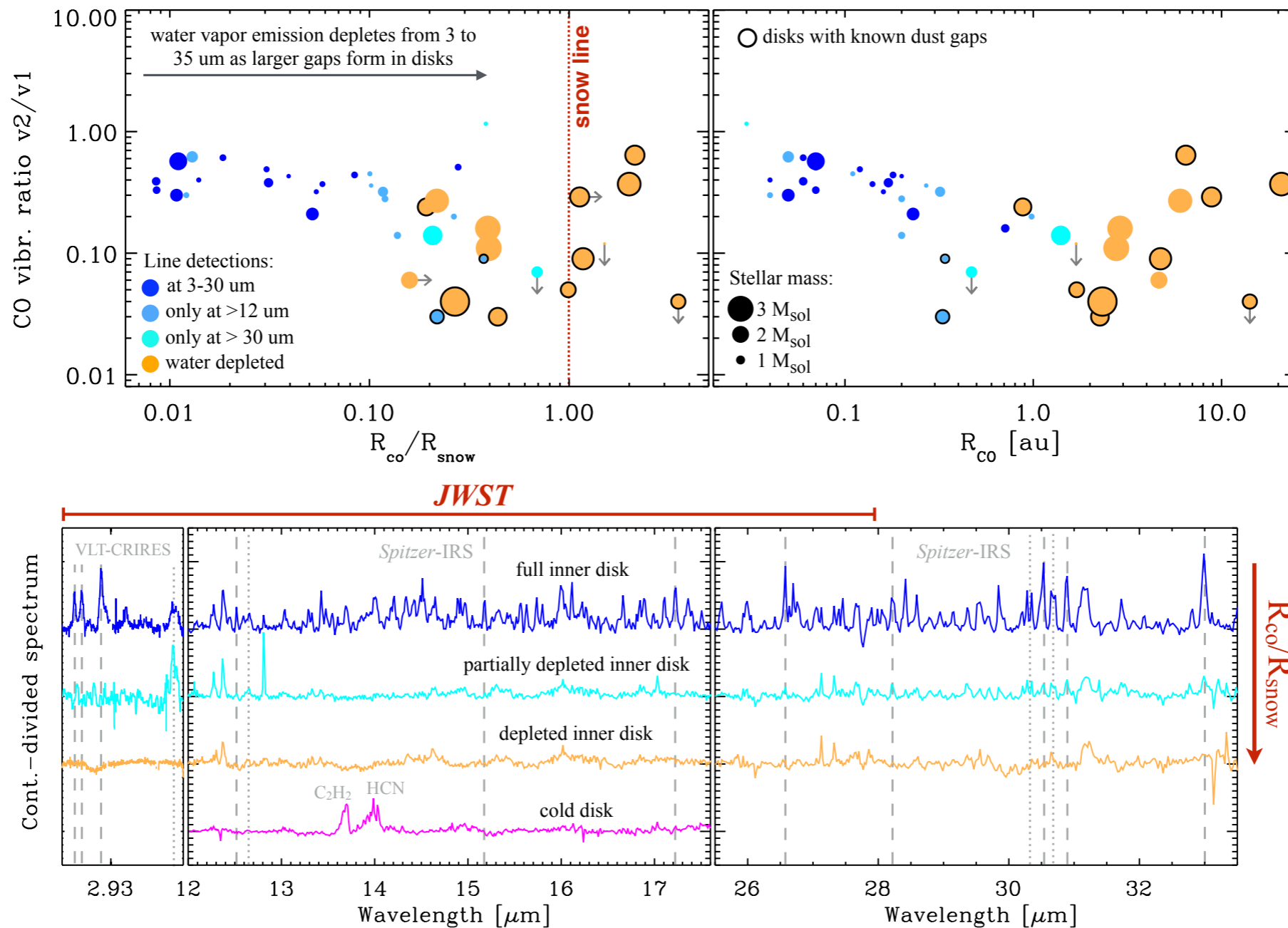


Hogerheijde et al. (2011, in prep); Salinas et al. (2016);
Podio et al. (2013); Du et al. (2015, submitted)



Gas-phase water across the disk

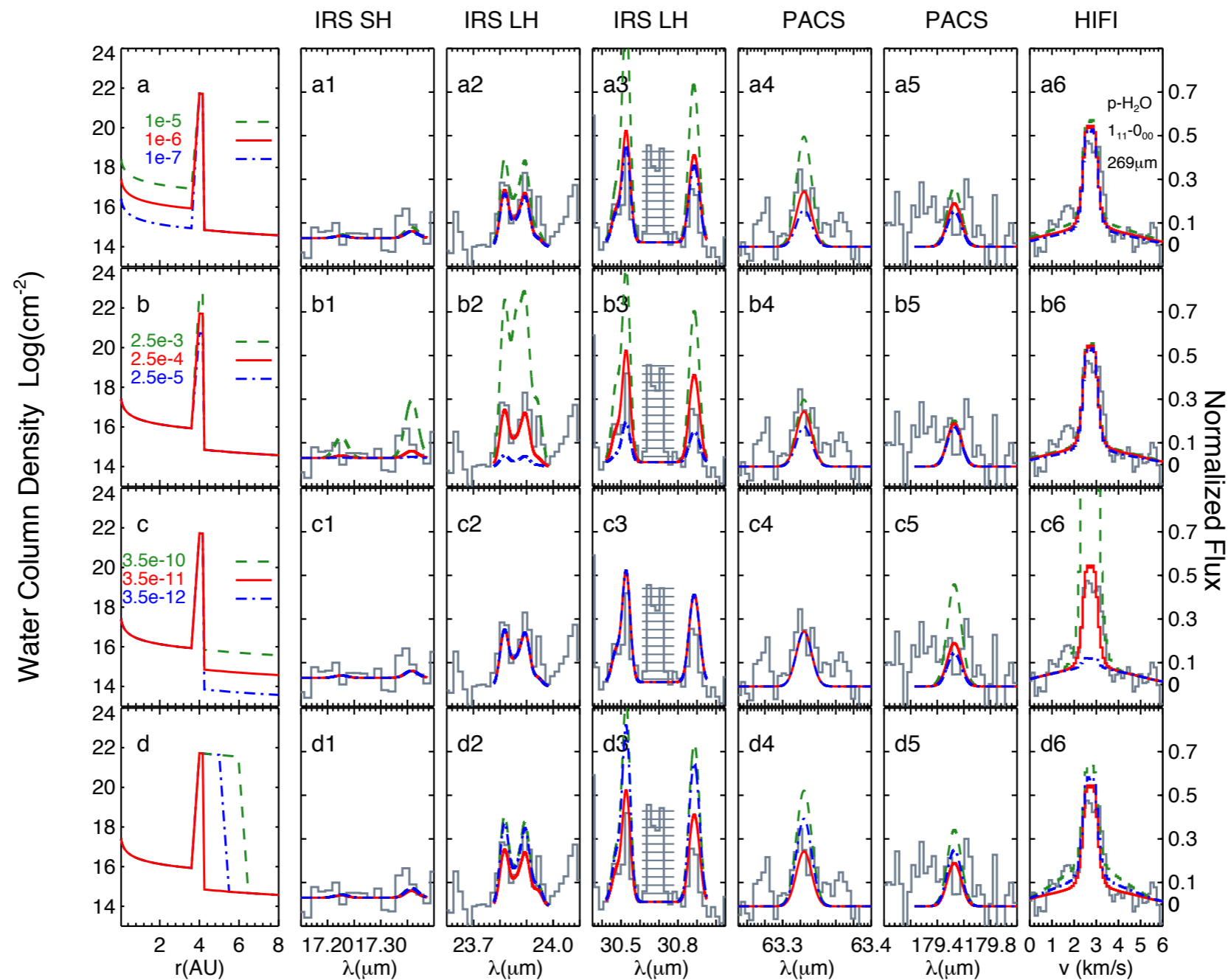
- H₂O line disappear as R_{CO} increases



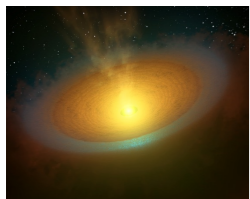
Banzatti et al. (2016); Zhang et al. 2013); Blevins et al. (2016); Meijerink et al. 2009); Fedele et al. (2011, 2012, 2013); Riviere-Marichalar et al. (2012, 2015, 2016)

Gas-phase water across the disk

- Significant abundance drop outside ~ 1 au: snow line

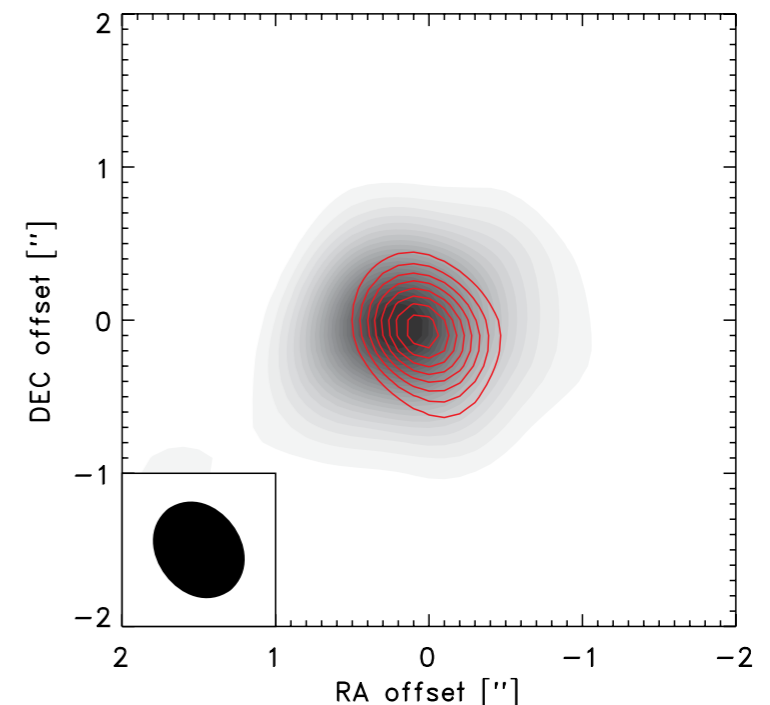
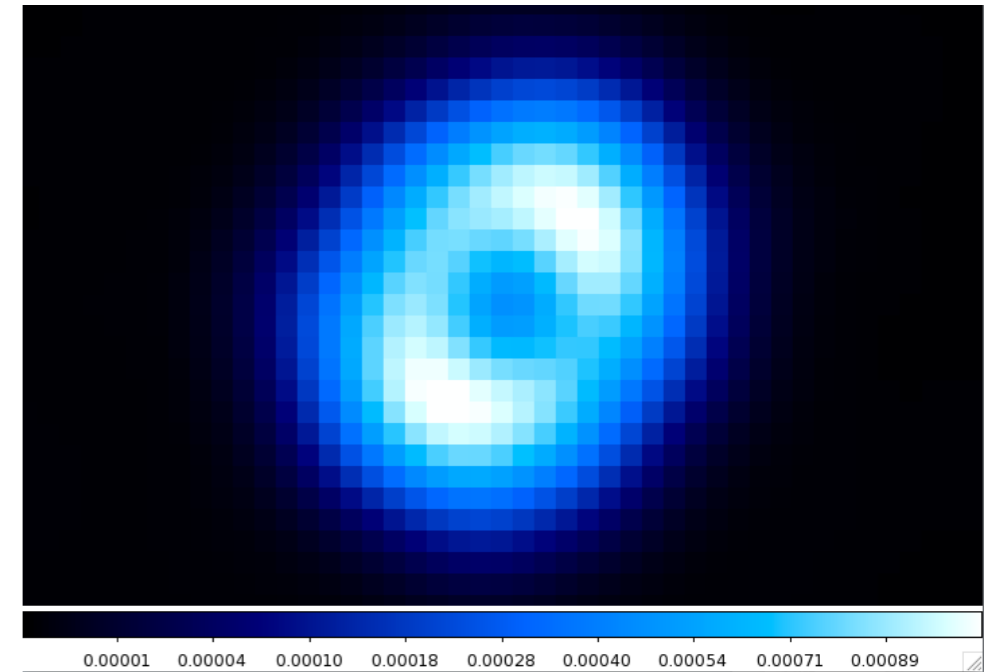


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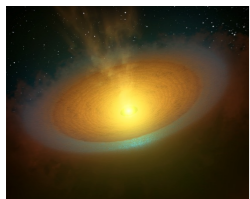


Prospects for ALMA Band 5

- **Band 5 covers**
 - H_2O $3_{13}-2_{20}$ at 183 GHz
 - H_2^{18}O $3_{13}-2_{20}$ at 203 GHz
 - Upper level energies ~ 200 K
- **HD100546 model** for H_2O ground-state lines:
 - H_2O $3_{13}-2_{20}$ (@0.5''): $1.1 \text{ mJy } \text{bm}^{-1} \text{ km s}^{-1}$.
 - Would take 60 days to detect at 183 GHz; 1.5 days at 203 GHz.
 - Adding a $\sim 10 \text{ au}$ $>200 \text{ K}$ region boosts signal by factor 10-100.
- **HDO $1_{01}-0_{00}$ and $1_{11}-0_{00}$** are at 465 and 894 GHz (Bands 8,10)
 - Upper level energies $\sim 20, 40 \text{ K}$



Jørgensen et al. (2010): H_2^{18}O $3_{13}-2_{20}$ detected to an embedded disk, at 50 mJy/beam level (0.5'' beam)



Conclusion

- Water likely enters disks as ice formed during prestellar stage
- Water ice has been detected in disks; mass estimates have caveats
- Water vapor detected across the disk
 - large columns in the inner few au
 - low columns beyond a few au
- Consistent with
 - efficient gas-phase formation in >200 K gas in inner disk
 - inefficient photodesorption off icy grains in outer disk
 - latter requires significant settling of large(r) icy ices to midplane
- ALMA B5 183 GHz H₂O line (& 203 GHz) diagnostic of >200 K gas

