Herschel observations of cold H_2O and NH_3 in planet-forming disks

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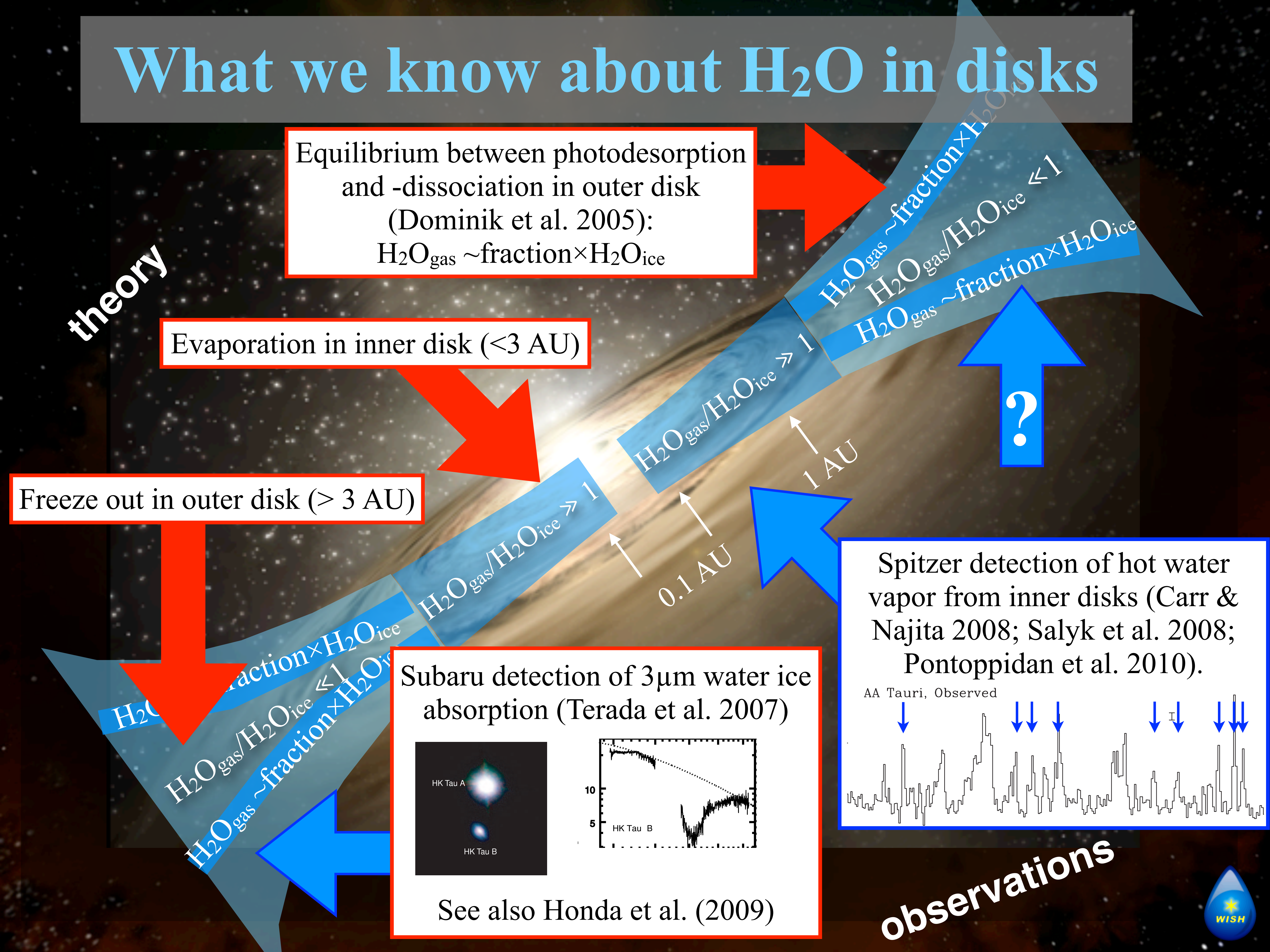
What is the origin of water on Earth?

- In the early Solar System
  - water **vapor** in the inner Solar System (T>100 K)
  - condensed as **ice** on dust grains outside the snow line at ~3 AU (Hayashi et al. 1981; Abe et al. 2000)

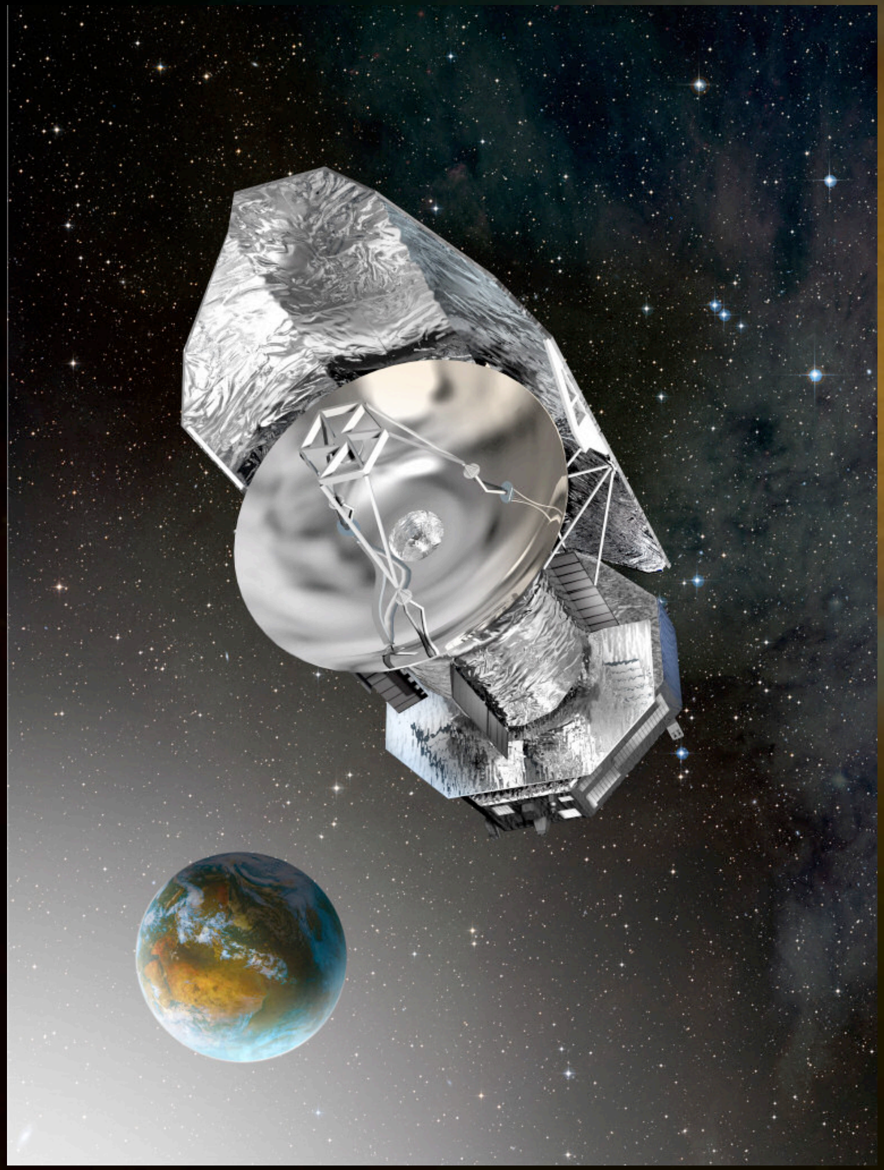
- Comets and asteroids may have delivered large amounts of water from beyond the snow line to the early Earth (Matsui & Abe 1986; Morbidelli et al. 2000; Raymond et al. 2004)

- **How large is the ice reservoir?**
  - 1 'Earth Ocean' = 1.5×10^{24} g of water



What we know about H_2O in disks
Equilibrium between photodesorption and -dissociation in outer disk (Dominik et al. 2005): H_2O_{gas} ~fraction×H_2O_{ice}
theory
Evaporation in inner disk (<3 AU)
Freeze out in outer disk (> 3 AU)
H_2O_{gas} ~fraction×H_2O_{ice}
$H_2O_{gas}/H_2O_{ice} \ll 1$
$H_2O_{gas}/H_2O_{ice} \gg 1$
0.1 AU
1 AU
?
Spitzer detection of hot water vapor from inner disks (Carr & Najita 2008; Salyk et al. 2008; Pontoppidan et al. 2010).
AA Tauri, Observed
Subaru detection of 3µm water ice absorption (Terada et al. 2007)
HK Tau A
HK Tau B
10
5
See also Honda et al. (2009)
observations
WISH

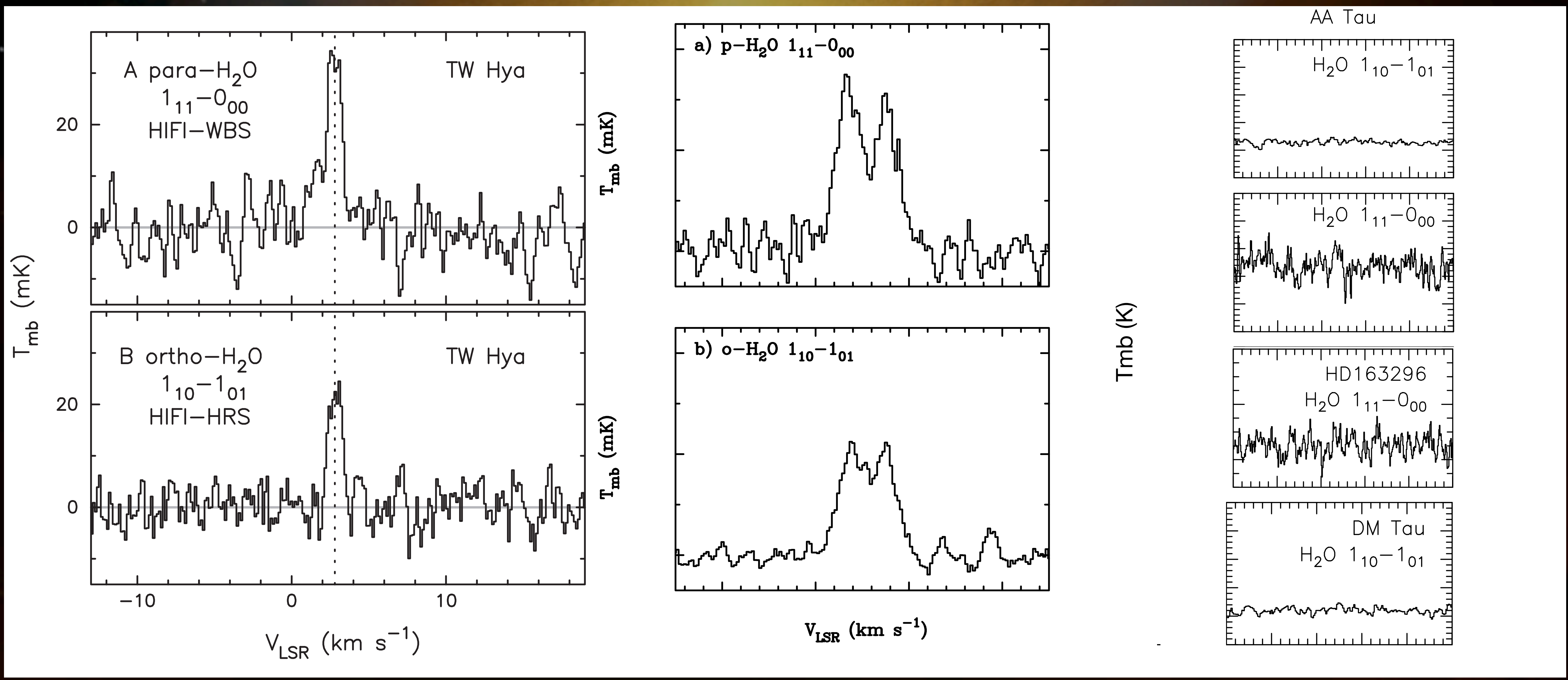
Herschel/HIFI observations



- Disks ≪ Herschel beam
  - HIFI *spectrally* resolves lines: disk ID
  - Beam dilution: long integrations
- ~200 hrs of observing time
  - ortho-H_2O 1_{10}-1_{01}, para-H_2O 1_{11}-0_{00}
  - o+p: TW Hya, HD100546, DM Tau, AA Tau
  - o: LkCa15, MWC480
  - p: HD163296

Detections and non-detections

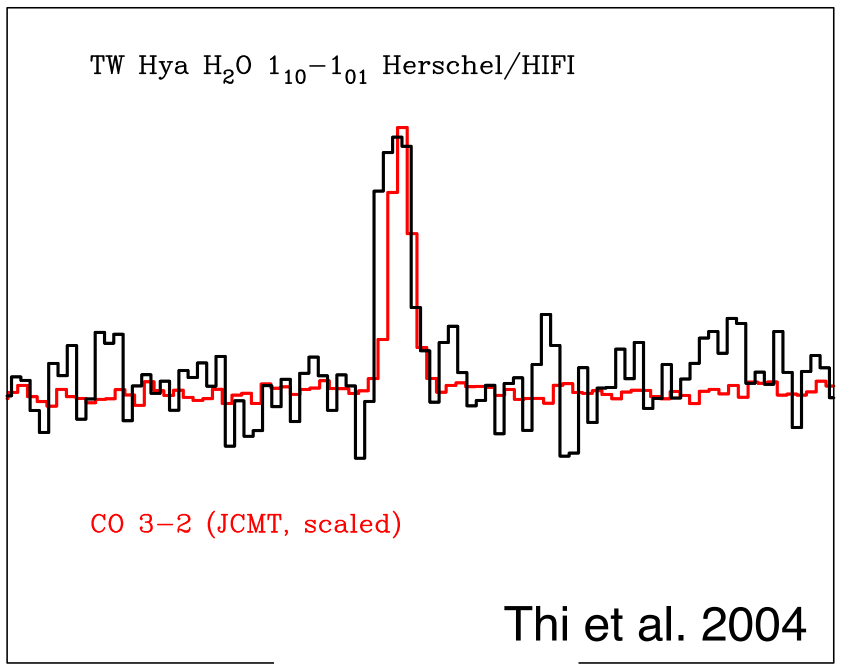
- Detections: TW Hya, HD100546
- Upper limits: AA Tau, DM Tau, LkCa15, HD163296, MWC 480
- Lines and upper limits lower than models predict

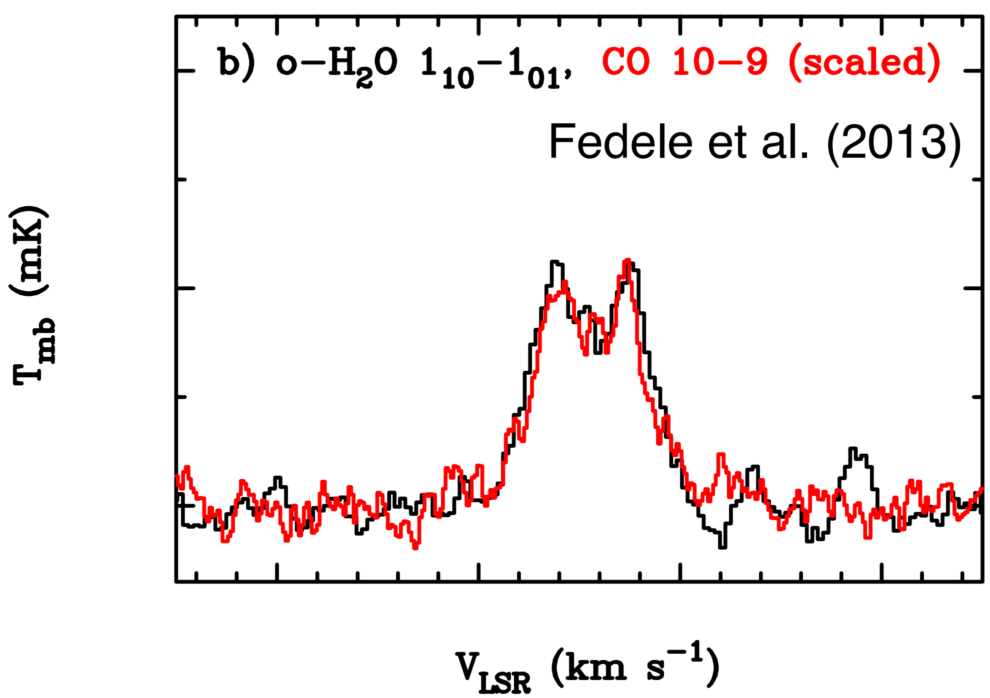


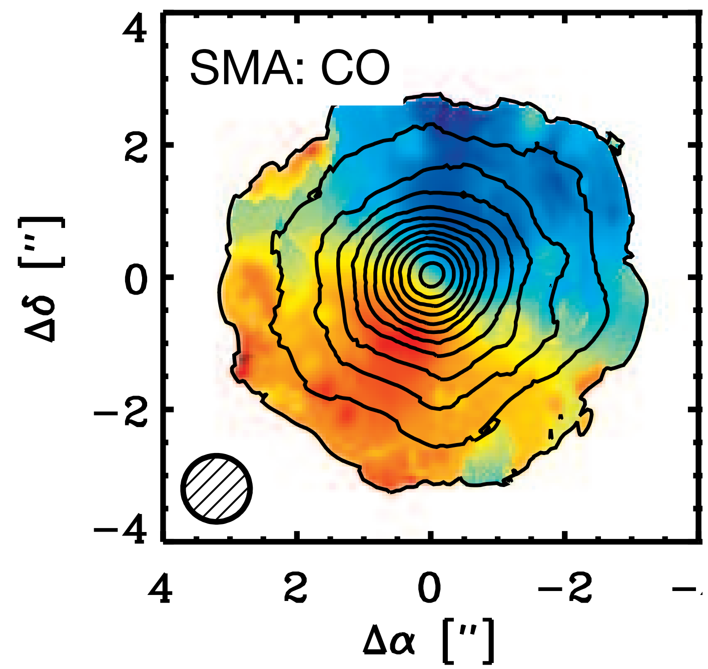
Bergin et al. (2010); Hogerheijde et al. (2011, and in prep)

Disk origin of the H_2O emission

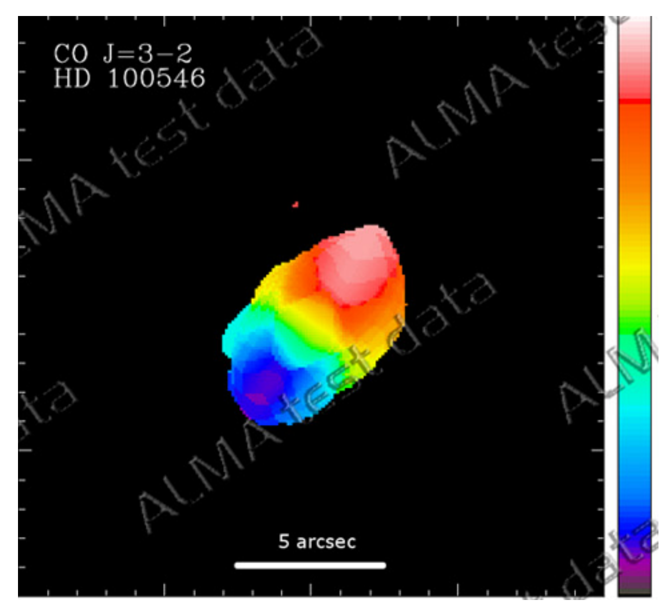
- Confirmed by line width, line profile, and V_{LSR}







Andrews et al. (2011)



ALMA test data

Modeling approach

Disk **mass**, **size**, **density** distribution: best possible description from literature

Self-consistent **temperature** distribution

Propagation of stellar **UV**, **X-rays**; **CR**

Gas-phase chemistry incl. **H_2+OH** & **ion/molecule**

Photodissociation, and H_2 and CO self-shielding

X-ray and CR ionization

Adsorption and **(photo)desorption** on grains
photodesorption rates from Öberg et al. (2007)

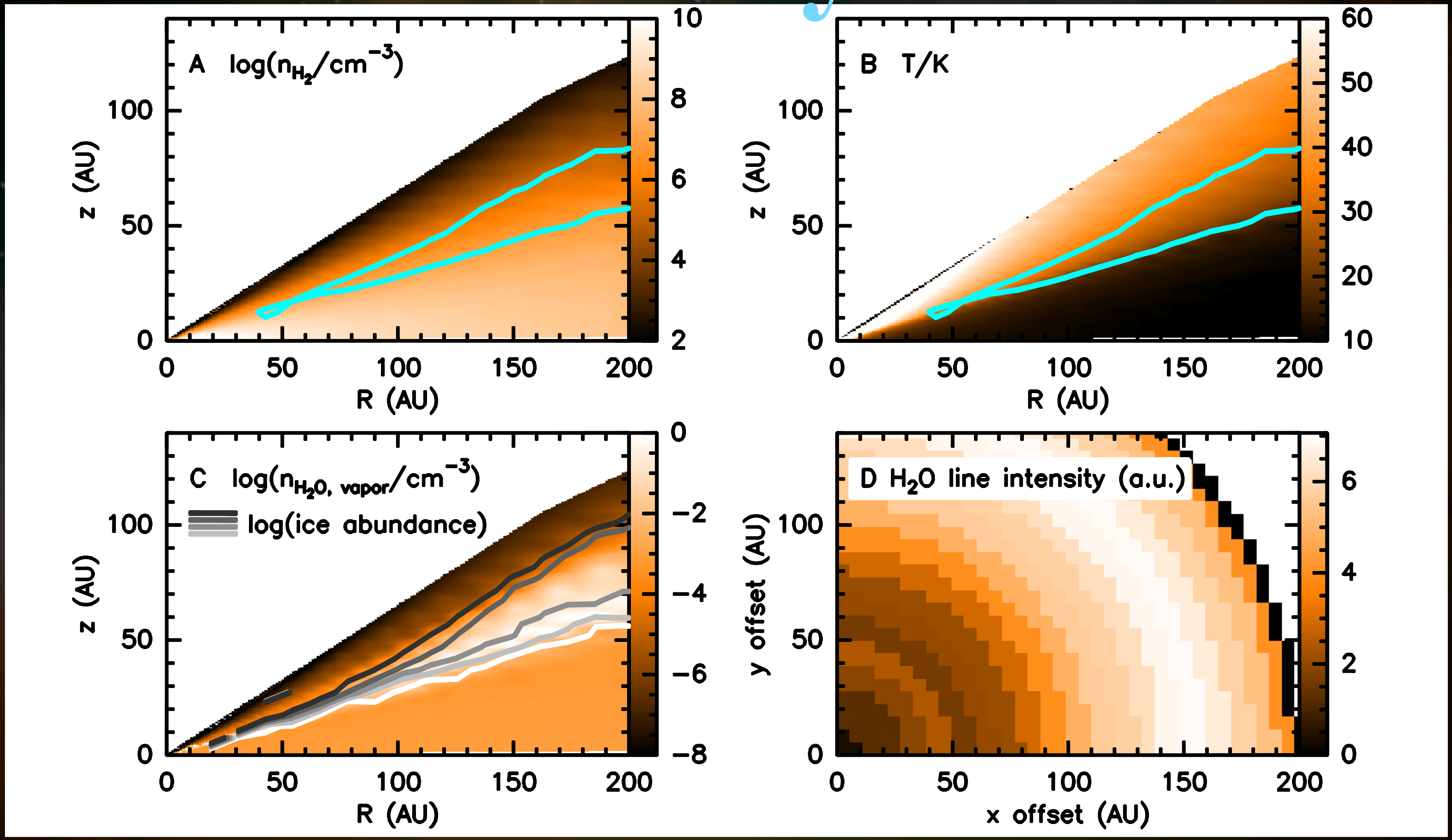
Distribution of **gas-phase H_2O**

non-LTE **excitation** and **radiative transfer**

beam-convolved emission lines

Refs: Fogel et al. 2011; Hogerheijde et al. 2011; Cleeves et al. 2013

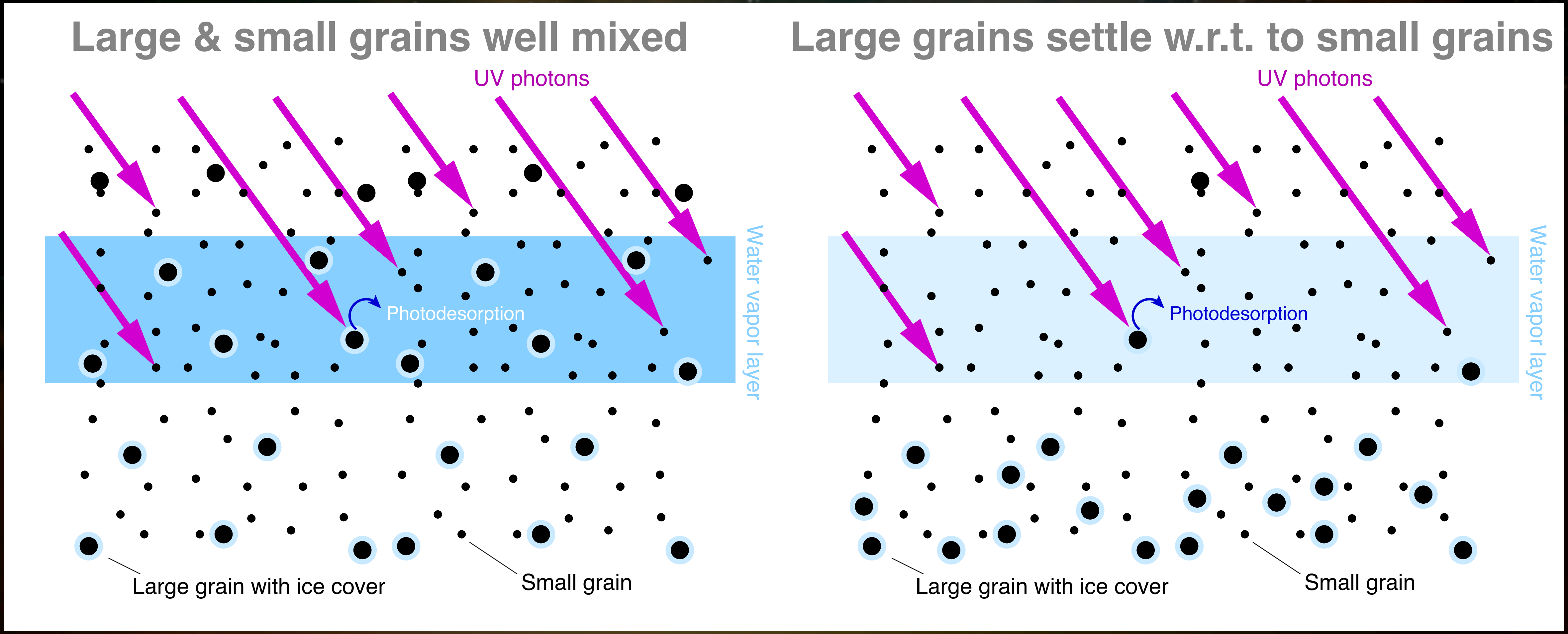
TW Hya



- $R_{\rm disk}$=196 AU; i=7°: nearly face-on
- $M_{\rm disk}$=2–6×10^{-4} M$_\odot$ in dust, >0.05 M$_\odot$ in gas (Bergin et al. 2013)
  - 6300 Earth oceans of water ice
  - See also Calvet et al. 2002; Thi et al. 2010; Hughes et al. 2011)
- → **0.04 Earth oceans of water vapor, lines 3–5× brighter than observed**

Andrews et al. (2011)

Differential settling of icy grains

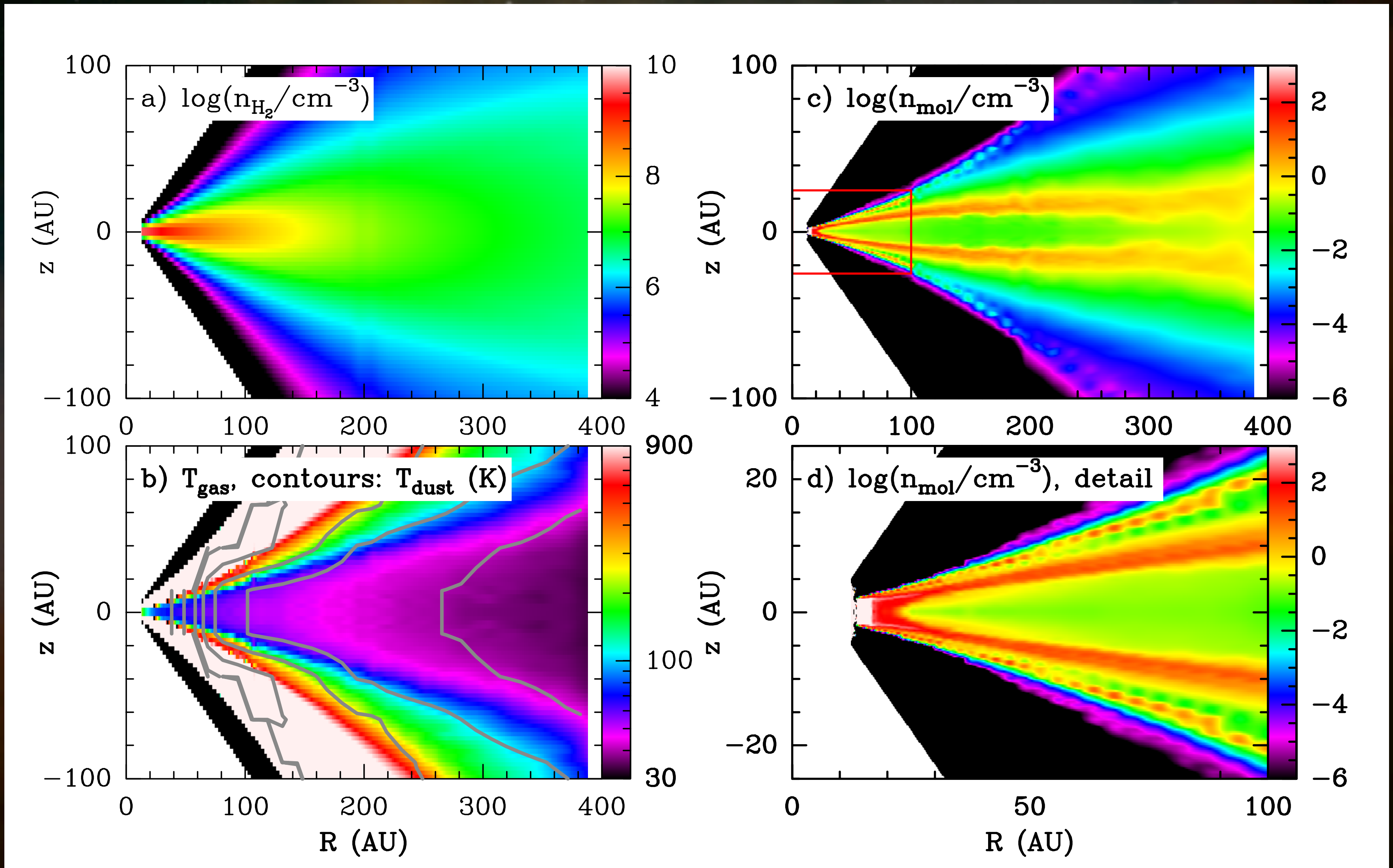


- Remove 88% of ice from UV-affected layers
- Settling of larger, icy grains *relative* to the small grains which dominate the UV absorption
- Only 12% of ice remains in upper disk
  - Gives rise to 0.005 Earth Oceans of water vapor
- **Underlying ice reservoir unchanged: > thousands of Earth Oceans**
  - key assumption: elemental oxygen efficiently forms water on grains

Alternative: Radial drift in TW Hya's disk

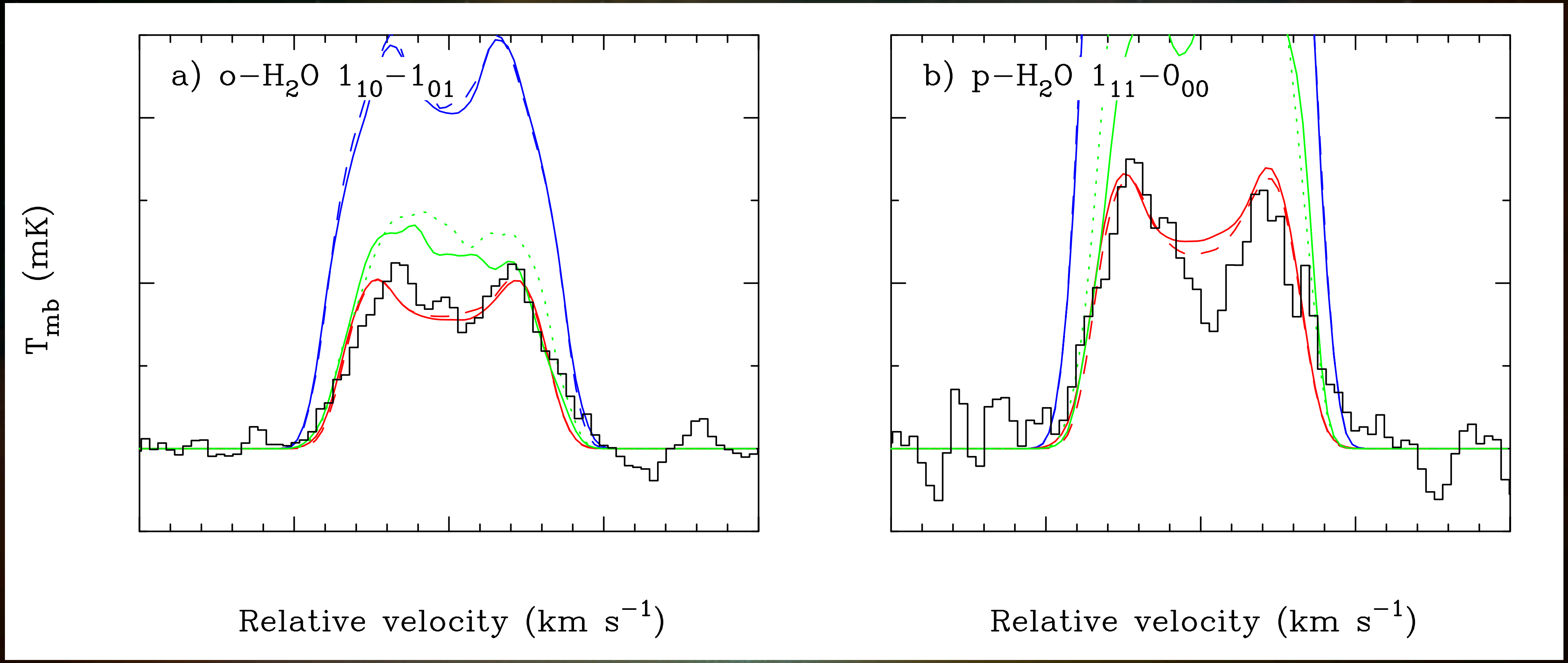
- Andrews et al. (2011) conclude that the mm-sidez grains have drifted inward to <60 AU (see also Debes et al. 2013)
- If we assume that the bulk of the ices are carried on mm-sized grains, the larger beam dilution resulting from the smaller spatial extent reproduces the observations, without further need to vertical settling.
- Further analysis required.

HD100546



- Same modeling philosophy
- Disk structure from Bruderer et al. (2012)
- M_{disk}=0.07 M_{sun}
- d=97 pc; M_*=2.5 M_{sun}; i=42°; R_{out}=400 AU

HD100546



- → **Lines up to 15× too strong compared to observations**

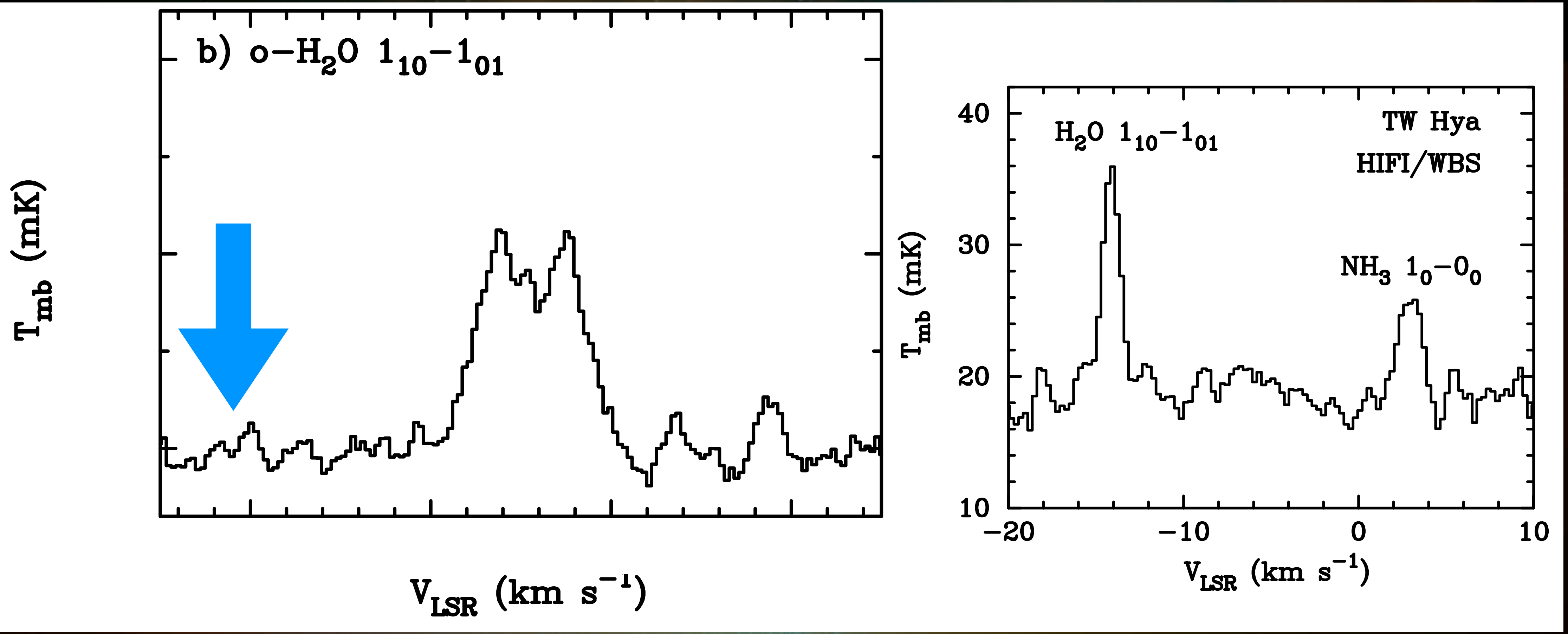
- Solution: (shown in red)
  - suppress photodesorption (settling/surface alteration)
  - emission *only* from 100-200 AU
    - detected H_2O formed via CR ionization

Nature of the weak H_2O lines

- Upper limits to AA Tau, HD163296, LkCa15, MWC 480, and DM Tau
  - consistent with weak lines to TW Hya and Hd100546, taking into account larger distances, disk sizes

- Water vapor emission lines from disks are weak
  - in TW Hya because of the radial drift of the mm-grains
    - a *small* size of photodesorbed water ice
  - in HD100546 because of additional suppression of photodesorption
    - detected water produced by CR ionization

Ammonia



- H_2O 1_{10}-1_{01} line setting also covered NH_3 1_0-0_0
- Detected to TW Hya, not detected to HD100546

- NH_3 forms in water ice mantles and photodesorbs with water
  - explains presence in TW Hya and absence in HD100546.
- NH_3/H_2O~4%, consistent with interstellar ices and Solar System comets.

Summary

- Herschel detects cold water vapor in the disks from TW Hya and HD100546
- In TW Hya the H_2O is likely generated by photodesorption from ices
  - requires radial drift to <60 AU and/or settling of mm-sized, ice-carrying grains
- in HD100546 photodesorption needs to be strongly suppressed, and water, produced via CR ionization, confined to 100-200 AU
- Presence of NH_3 toward TW Hya and absence toward HD100546 consistent with presence in ammonia in water ice at ~4%
- Upper limits to other sources consistent with larger distances, but detailed calculations to be done.