Herschel observations of cold water vapor and ammonia in protoplanetary disks

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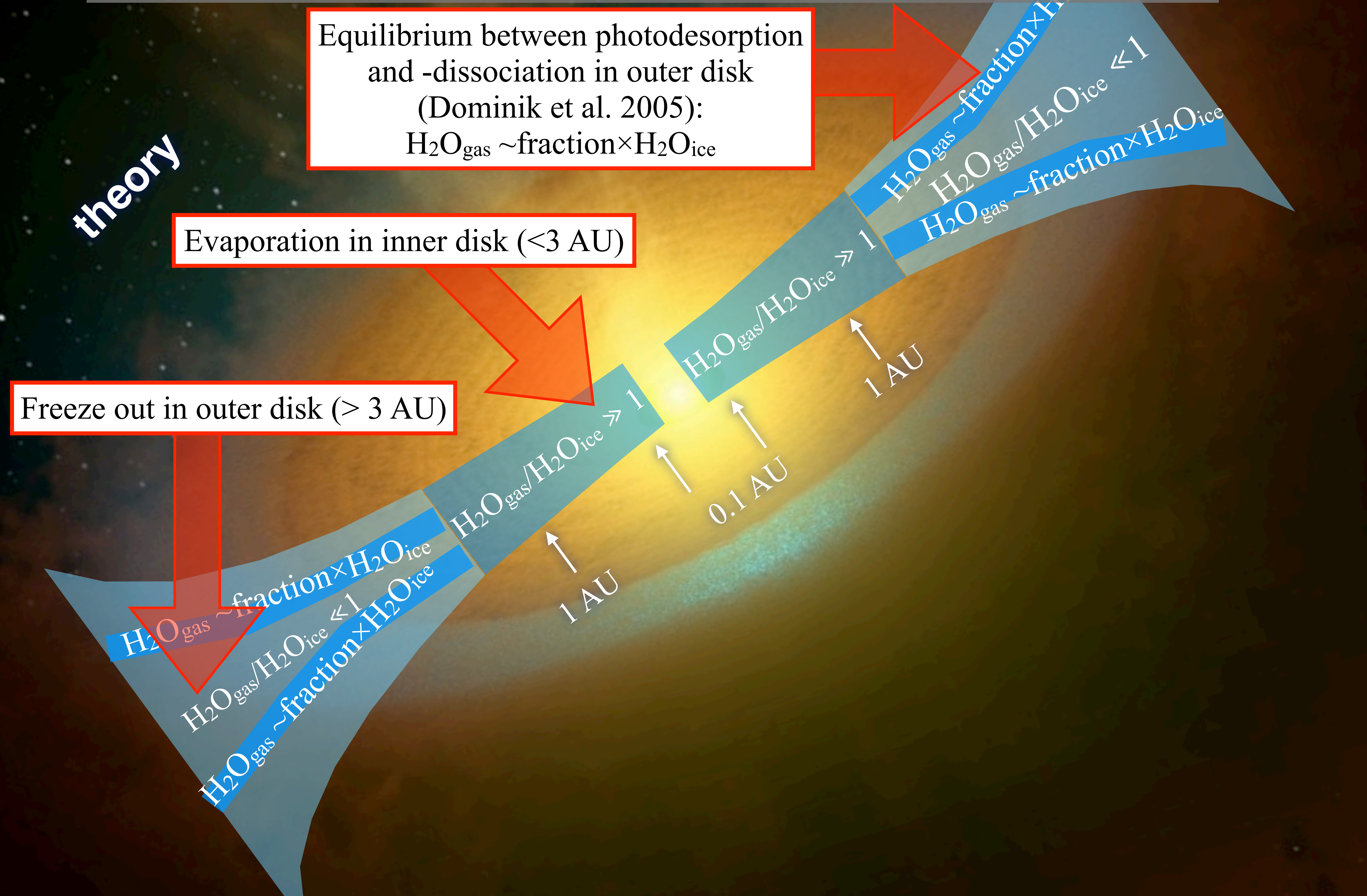
What is the origin of water on Earth?

- 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



What we know about H_2O in disks

theory

Equilibrium between photodesorption and -dissociation in outer disk (Dominik et al. 2005): $H_2O_{gas} \sim \text{fraction} \times H_2O_{ice}$

Evaporation in inner disk (<3 AU)

Freeze out in outer disk (> 3 AU)

$H_2O_{gas}/H_2O_{ice} \gg 1$

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$H_2O_{gas} \sim \text{fraction} \times H_2O_{ice}$

$H_2O_{gas}/H_2O_{ice} \ll 1$

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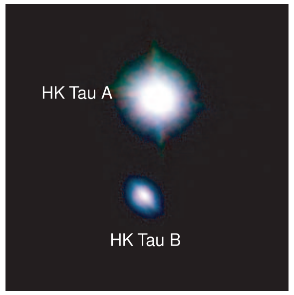
$H_2O_{gas} \sim \text{fraction} \times H_2O_{ice}$

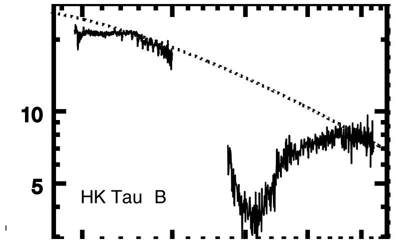
0.1 AU

1 AU

?

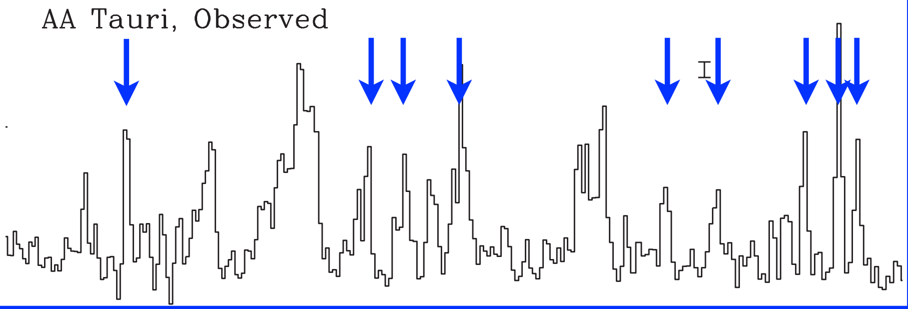
Subaru detection of 3µm water ice absorption (Terada et al. 2007)





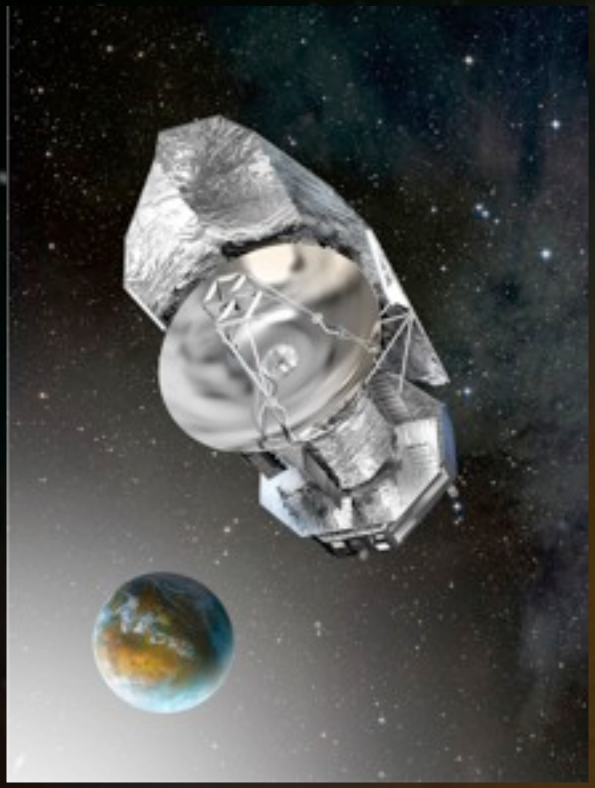
See also Honda et al. (2009)

Spitzer detection of hot water vapor from inner disks (Carr & Najita 2008; Salyk et al. 2008; Pontoppidan et al. 2010).

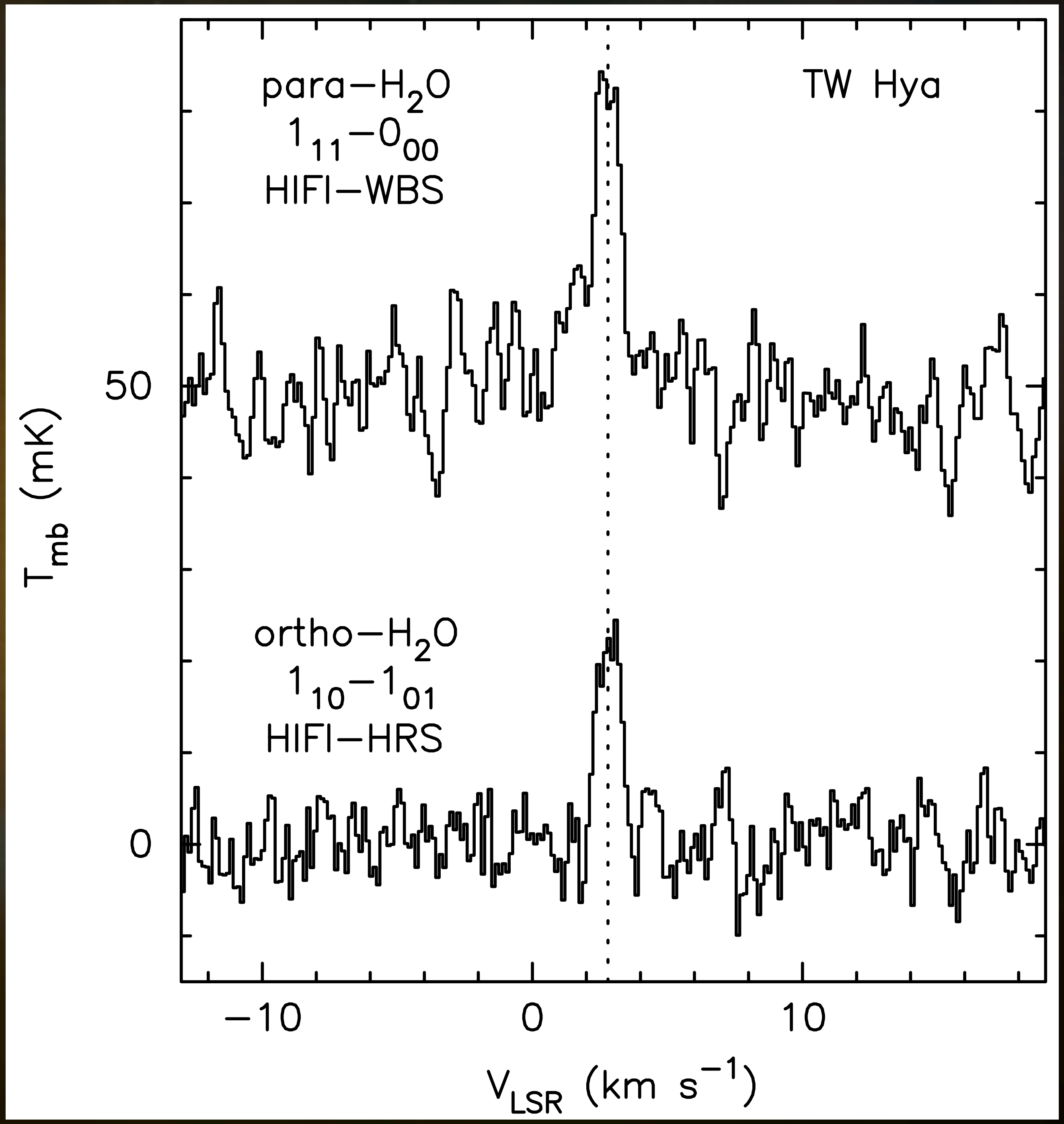


observations

Herschel/HIFI:
Cold water vapor in TW Hya



Total observing time: 17 hrs (!)



Hogerheijde et al. (2011)

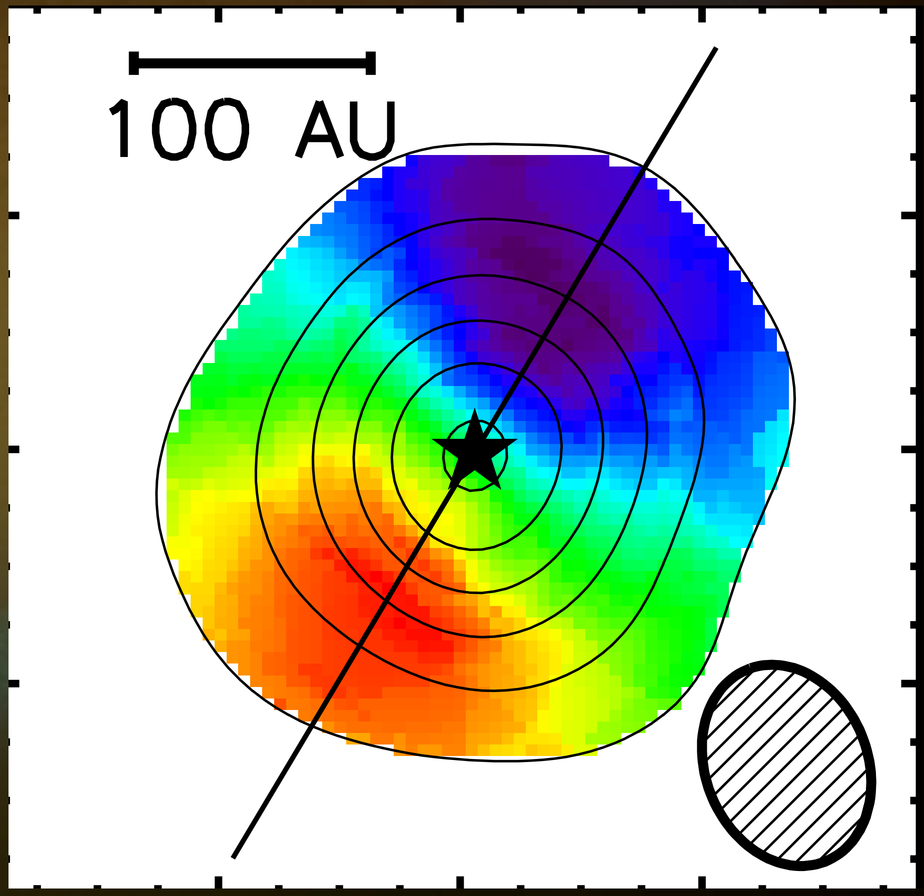
The disk around TW Hya

- Closest gas-rich disk to Earth
  - Distance 53.7±6.2 pc (van Leeuwen et al. 2010)

- $M_{\rm star}$=0.6 $M_\odot$
- spectral type K7V
- $L_{\rm star}$=0.23 $L_\odot$ (Webb et al. 1999)
- age ~10 Myr

- $R_{\rm disk}$=196 AU; i=7°: nearly face-on

- $M_{\rm disk}$=2–6×10^{-4} $M_\odot$ in dust
- 5×10^{-4}...5×10^{-2} $M_\odot$ in gas
- (Calvet et al. 2002; Qi et al. 2004; Thi et al. 2010)



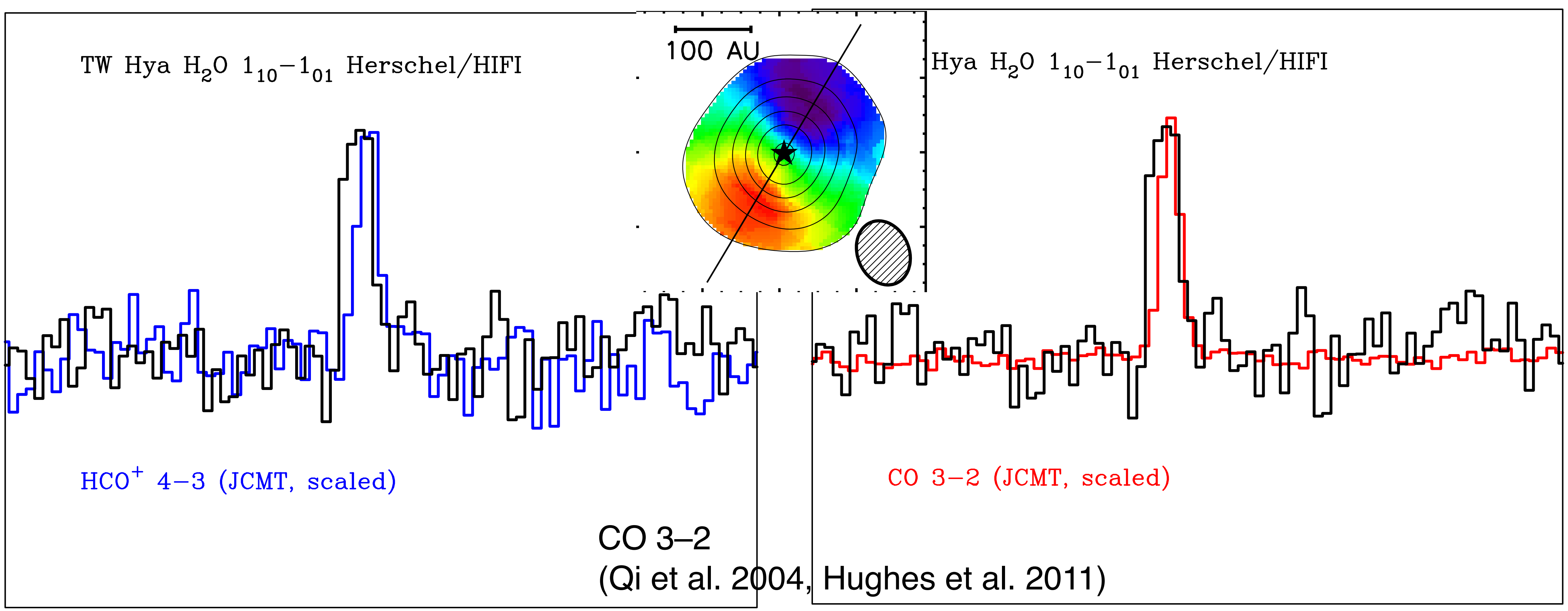
CO 3–2
(Qi et al. 2004,
Hughes et al.
2011)

(Thi et al. 2004)

Disk origin of the H_2O emission

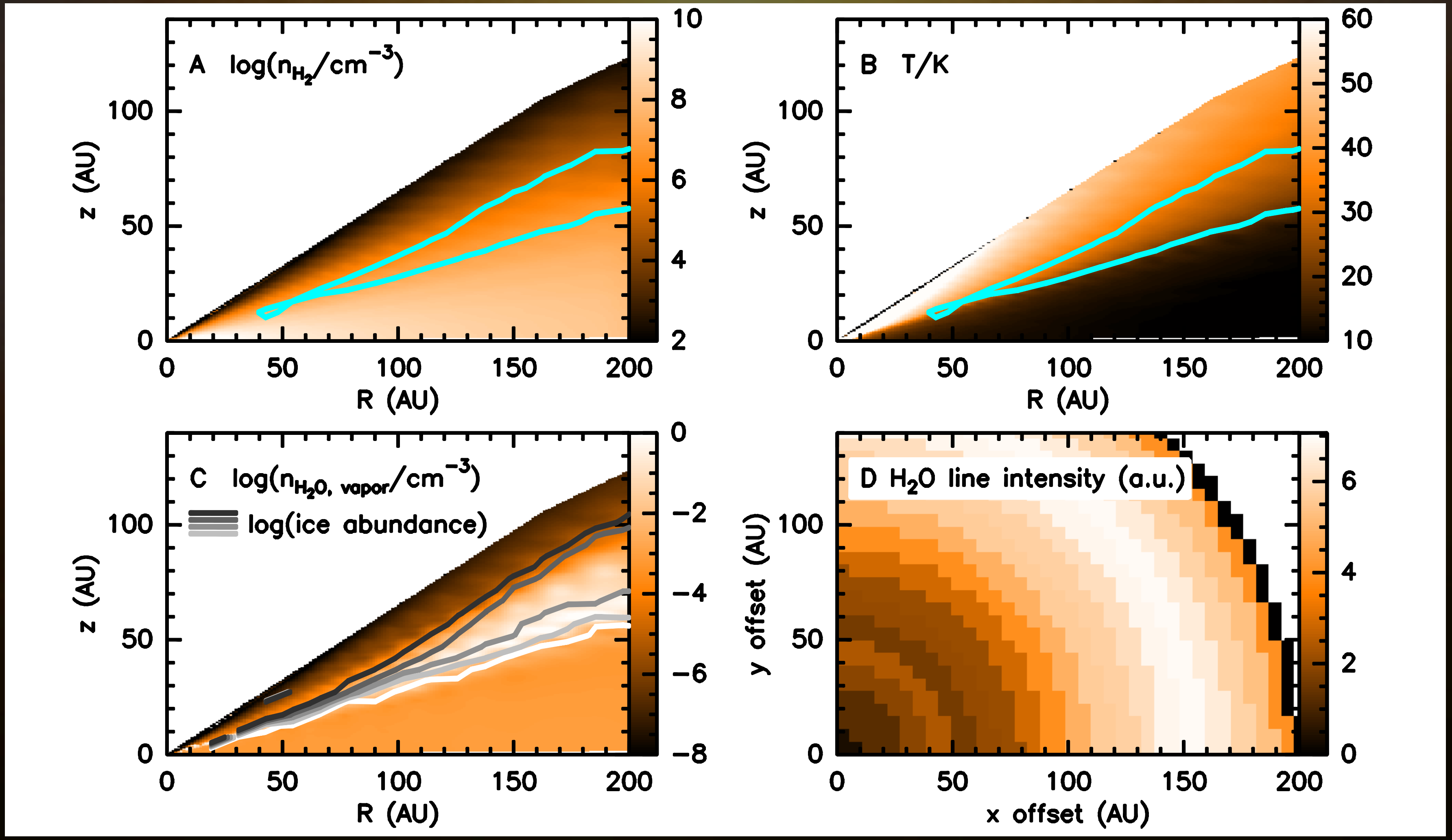
- Herschel observations are spatially unresolved
  - but HIFI resolves the spectral line

- **Narrow line width confirms H_2O emission extends out to ~115 A**
  - consistent with recent indications that dust disk extends to similar distances from the star (Andrews et al. 2011)



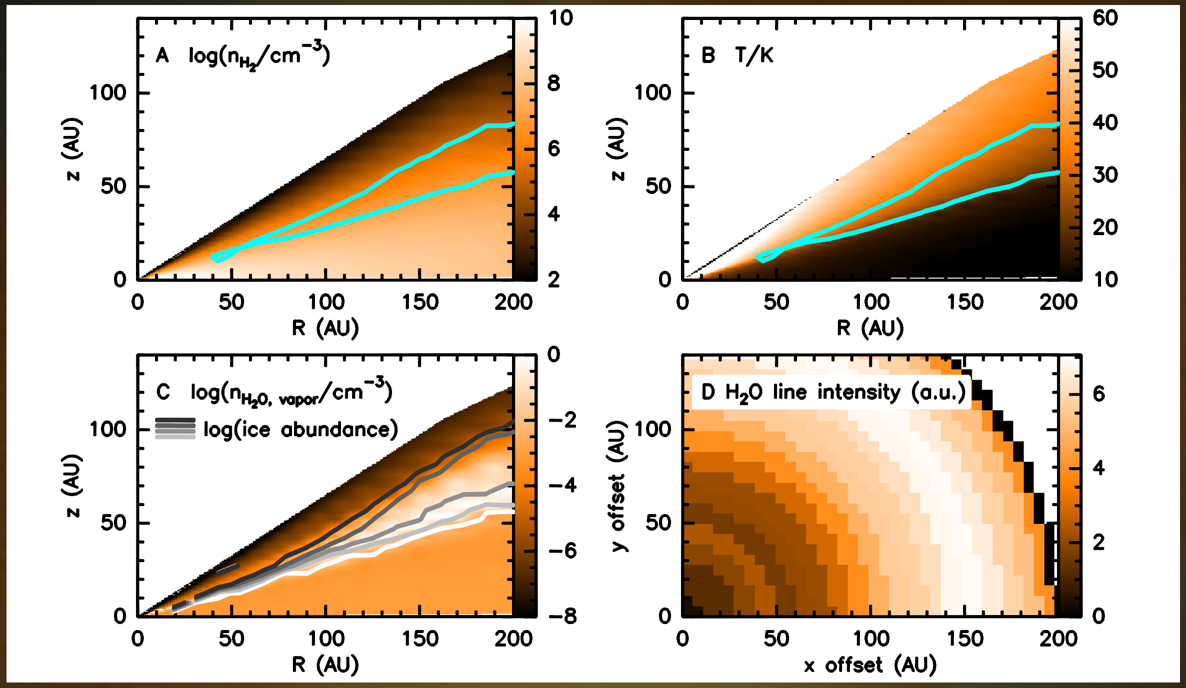
How much water?

- Fiducial disk structure model: Thi et al. (2010)
  - $M_{dust} = 1.9\times10^{-4}\ M_\odot \rightarrow M_{gas} = 1.9\times10^{-2}\ M_\odot$
- Temperature from stellar irradiation (RADMC; Dullemond & Dominik 2004)
- UV radiative transfer into disk and resulting chemistry (Fogel et al. 2010)
- Water excitation and line formation (LIME; Brinch & Hogerheijde 2010)



Predicted lines too strong

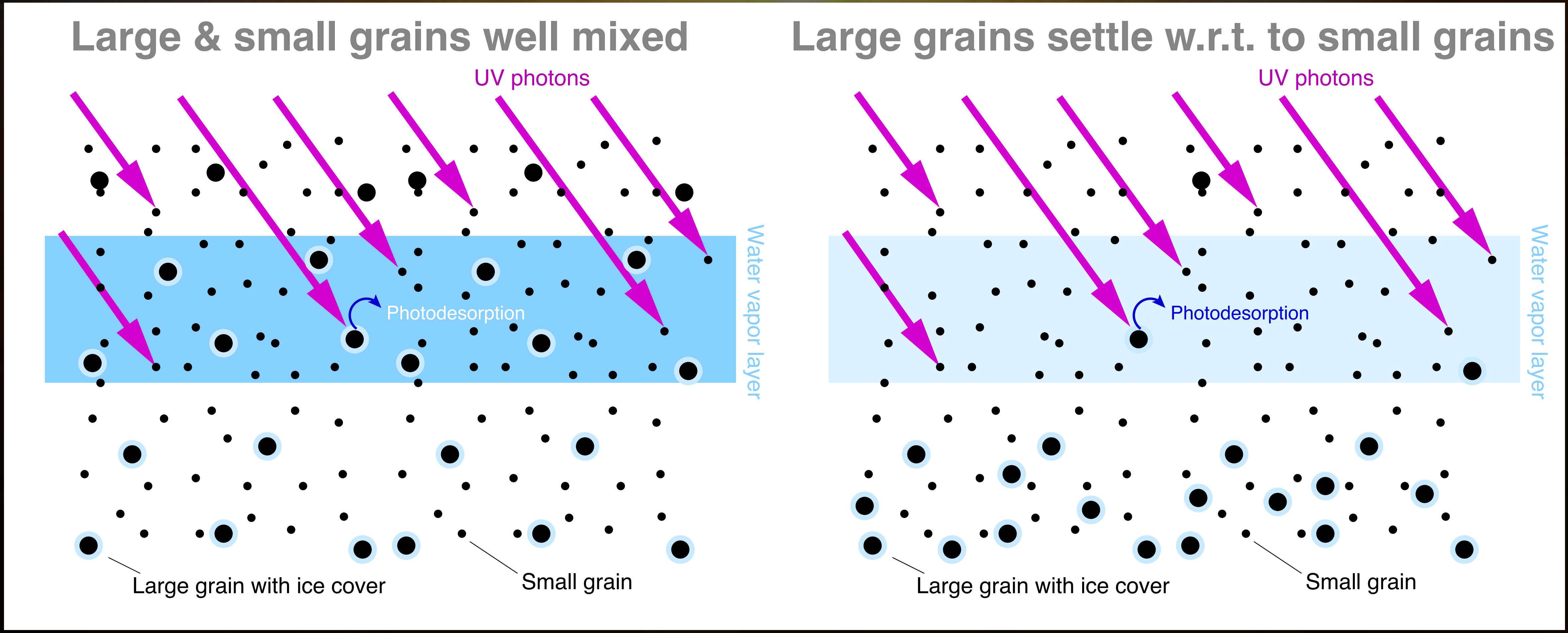
- **This model overestimates the line intensities by factors 3.3–5.3.**



- Lowering gas mass does not reduce the line intensity
  - Water vapor derives from icy grains
  - Grains are suspended by the gas, stay at same ambient pressure
- Varying collision rates or changing o/p-H_2 ratio also does not decrease line strengths
  - used rates from Faure et al. (2007) and Dubernet et al. (2009)

Differential settling of icy grains

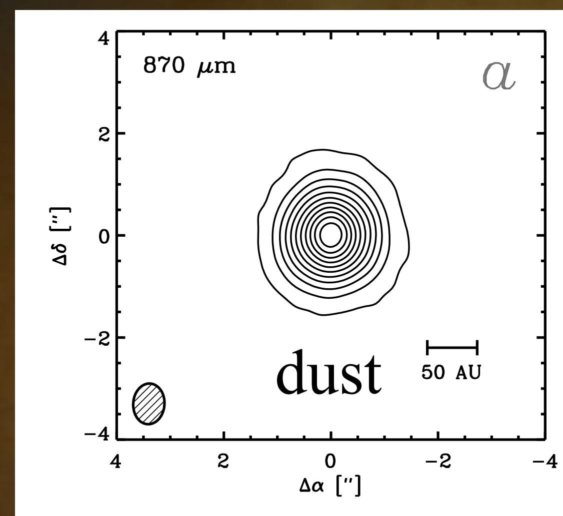
- Remove 90% of orignal ice from UV-affected layers
- Settling of larger, icy grains *relative* to the small grains which dominate the UV absorption
- Only 10% of original ice remains in upper disk
  - Gives rise to 0.005 Earth Oceans of water vapor
- **Underlying ice reservoir of at least several thousands of Earth Oceans**
  - key assumption: elemental oxygen efficiently forms water on grains

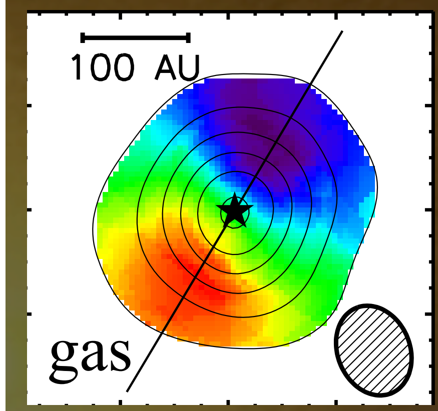


Alternative explanation

- Andrews et al. (2011) show that the the TW Hya disk
    - in gas extends to 215 AU
    - in (mm-sized) dust has a sharp drop at 60 AU

Also see poster by Inga Kamp for other models for TW Hya.





- This suggests water ice, and therefore water vapor, also limited to 60 AU
    - consistent with width of line seen by HIFI
    - reduces intensity by factor ~4–6

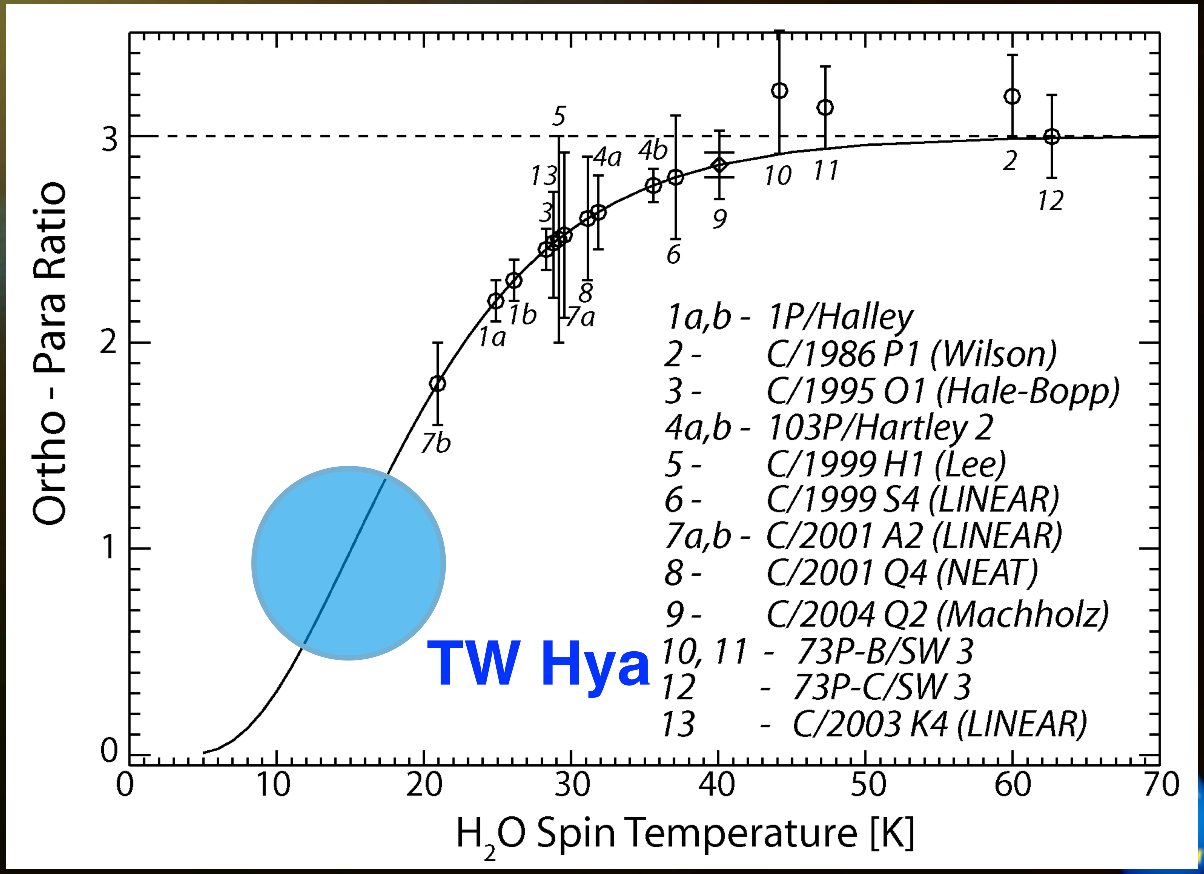
- Requires a model of radial migration of bigger dust grains
    - as opposed to vertical settling of bigger dust dust grains as in previous scenario
- In either case: **H_2O traces dynamics of the dust population**

A low H_2O ortho/para in TW Hya

- Lines are optically thin
  - ...because only 10% of water vapor remains compared to standard model
  - ...because sub-thermal excitation leads to resonant scattering rather than absorption of line photons

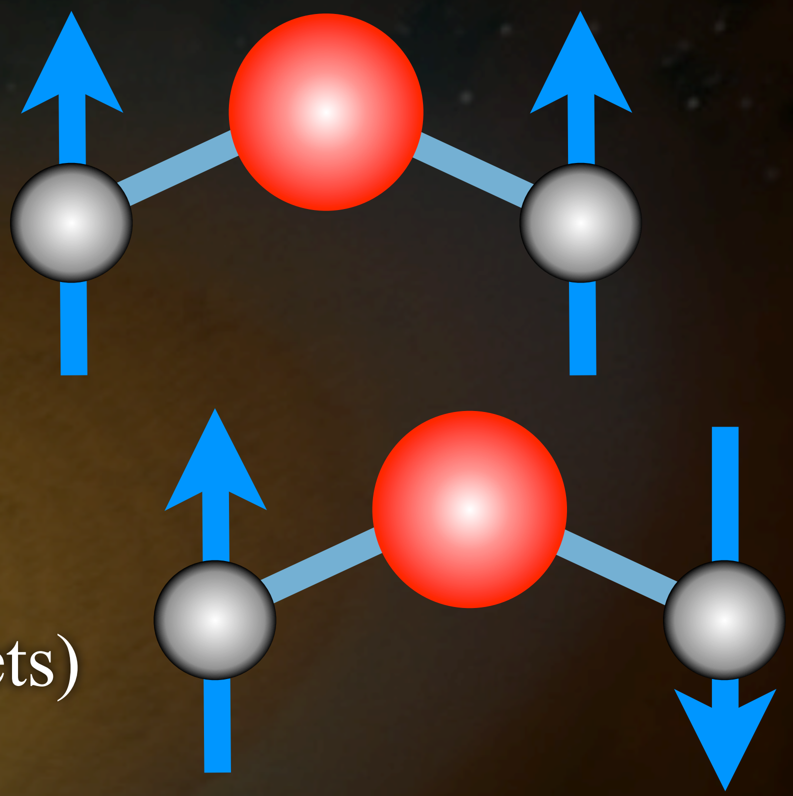
- **Ratio of H_2O 1_{10}-1_{01}/1_{11}-0_{00} ∝ ortho-to-para ratio (OPR)**
- Observations yield OPR=0.77±0.07

- **H_2O OPR in TW Hya's disk ≪ Solar System comets (1.5–3)**



Mumma & Charnley (2011)

Long-range mixing of volatiles



- TW Hya OPR=0.77 $\Leftrightarrow$ T_{spin}=13.5 K
- Comets OPR>1.5 $\Leftrightarrow$ T_{spin}>20 K

- No radiative conversion of OPR in gas phase

- Thermal evaporation preserves OPR (→ comets)
  - Equate T_{spin} with T_{grain} at ice formation (?)

- Effect of photodesorption on OPR unknown; may drive OPR to unity (e.g., Andersson et al. 2008; Arasa et al. 2010)

- Range of cometary OPR: heterogeneous mixture of ices from small (>50 K) and large (<15 K) radii (just like refractory component; Sandford et al. 2006)
  - **Long-range mixing of volatiles in the Solar Nebula**

Summary

- We have detected emission from cold water vapor from the full extent of the planet-forming disk around TW Hya.
- The line intensities hint at a 'hidden' reservoir of at least several thousands of Earth Oceans of ice in the disk.
- The low ortho-to-para ratio of the water vapor in TW Hya compared to Solar System comets suggest long-range mixing of volatiles in the Solar Nebula.