Cold water and ammonia vapor in protoplanetary disks

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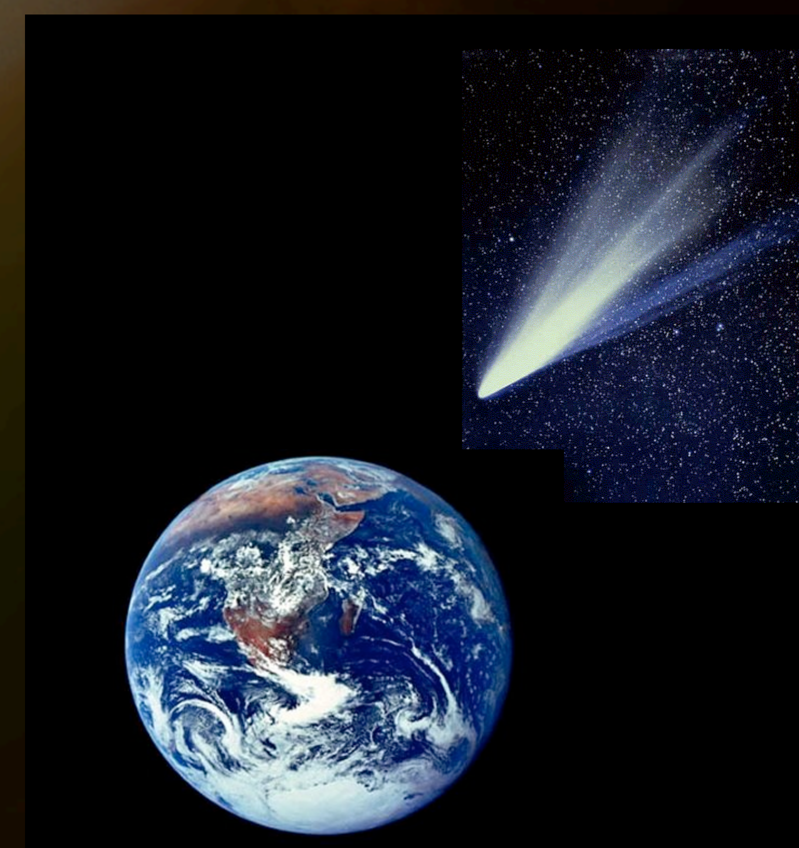
WISH

What is the origin of water on Earth?

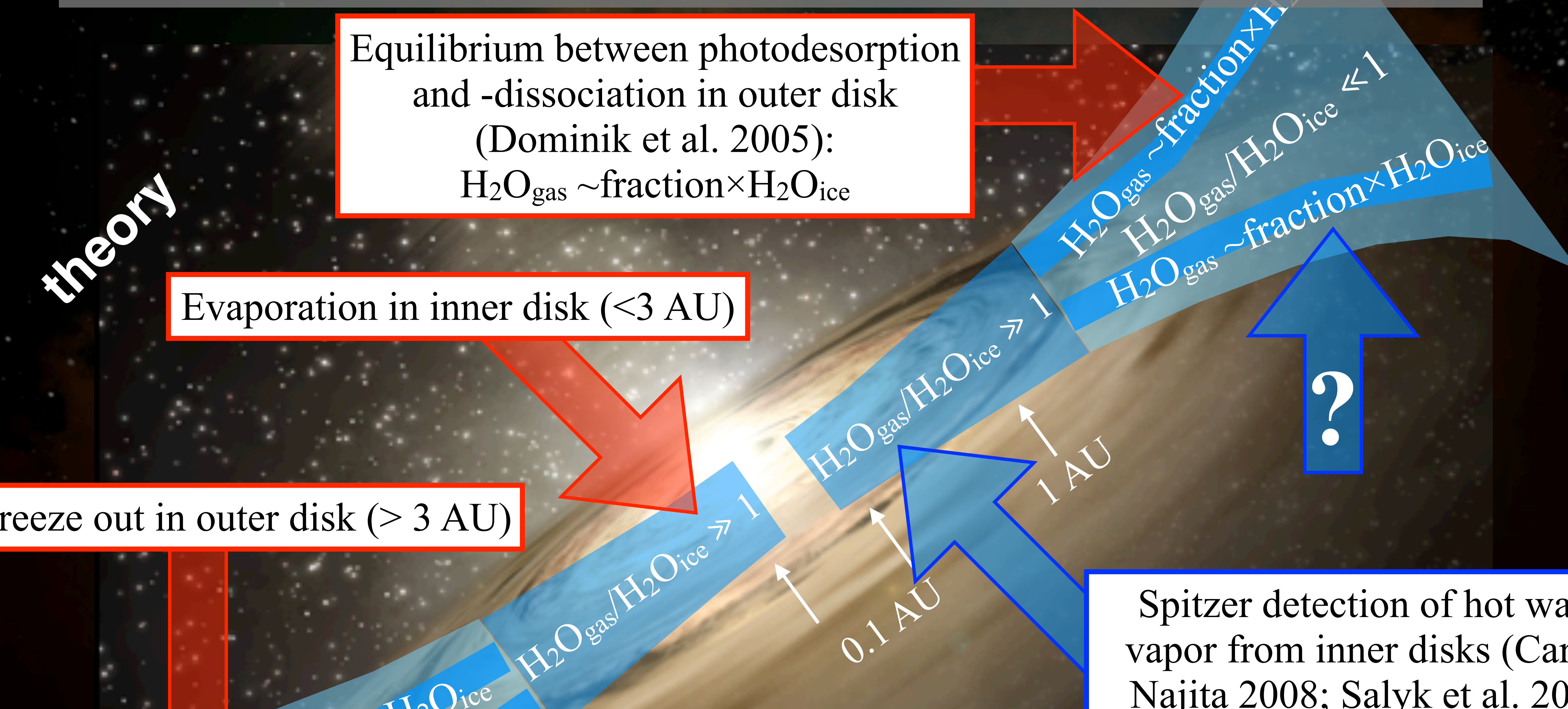
- In the early Solar System
  - water **vapor** in the inner Solar System (T>100 K)
  - condensed as **ice** on dust grains outside the snow line at ~3 AU (Hayashi et al. 1981; Abe et al. 2000)



- 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

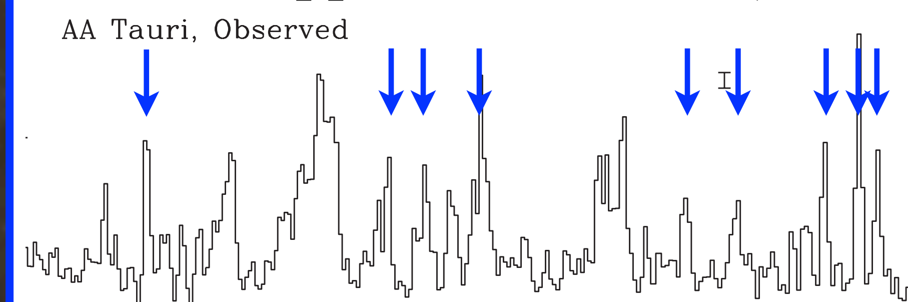


Equilibrium between photodesorption and -dissociation in outer disk (Dominik et al. 2005):
H_2O_{gas} ~fraction×H_2O_{ice}

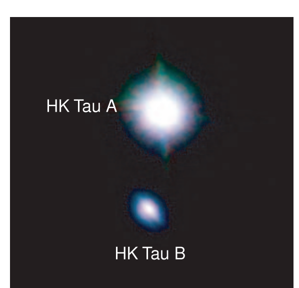
Evaporation in inner disk (<3 AU)

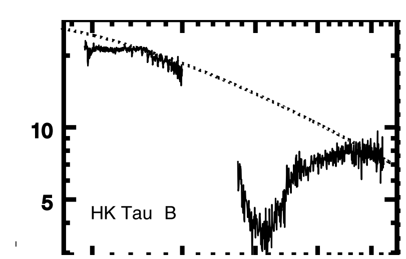
Freeze out in outer disk (> 3 AU)

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



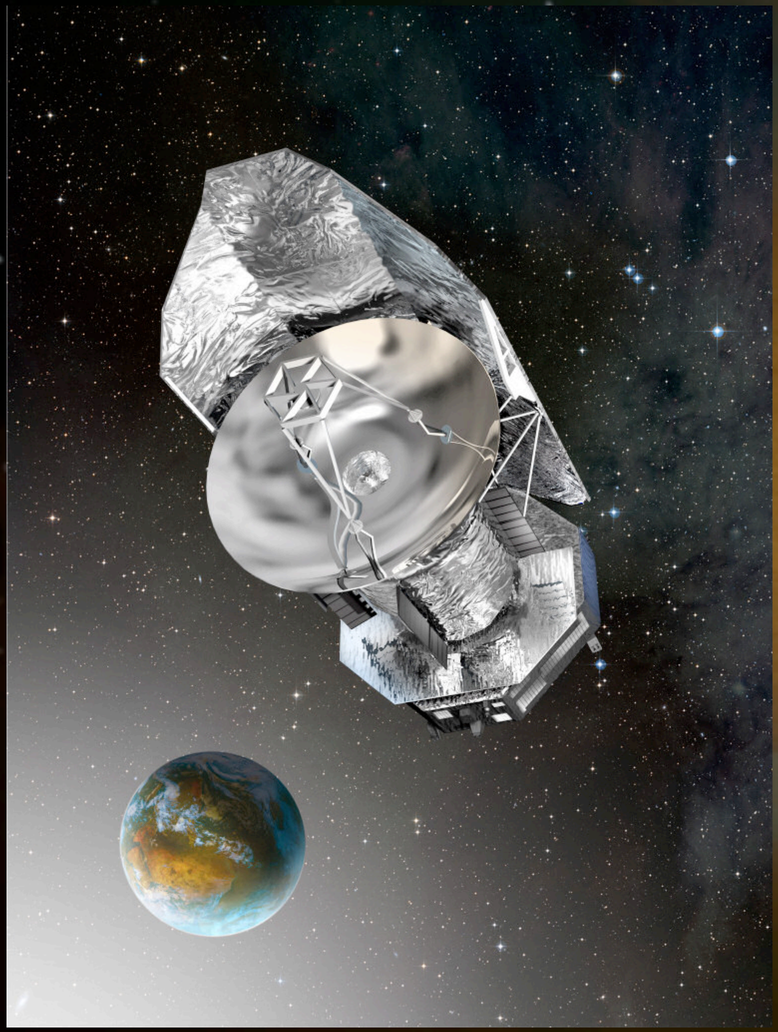
Subaru detection of 3μm water ice absorption (Terada et al. 2007)





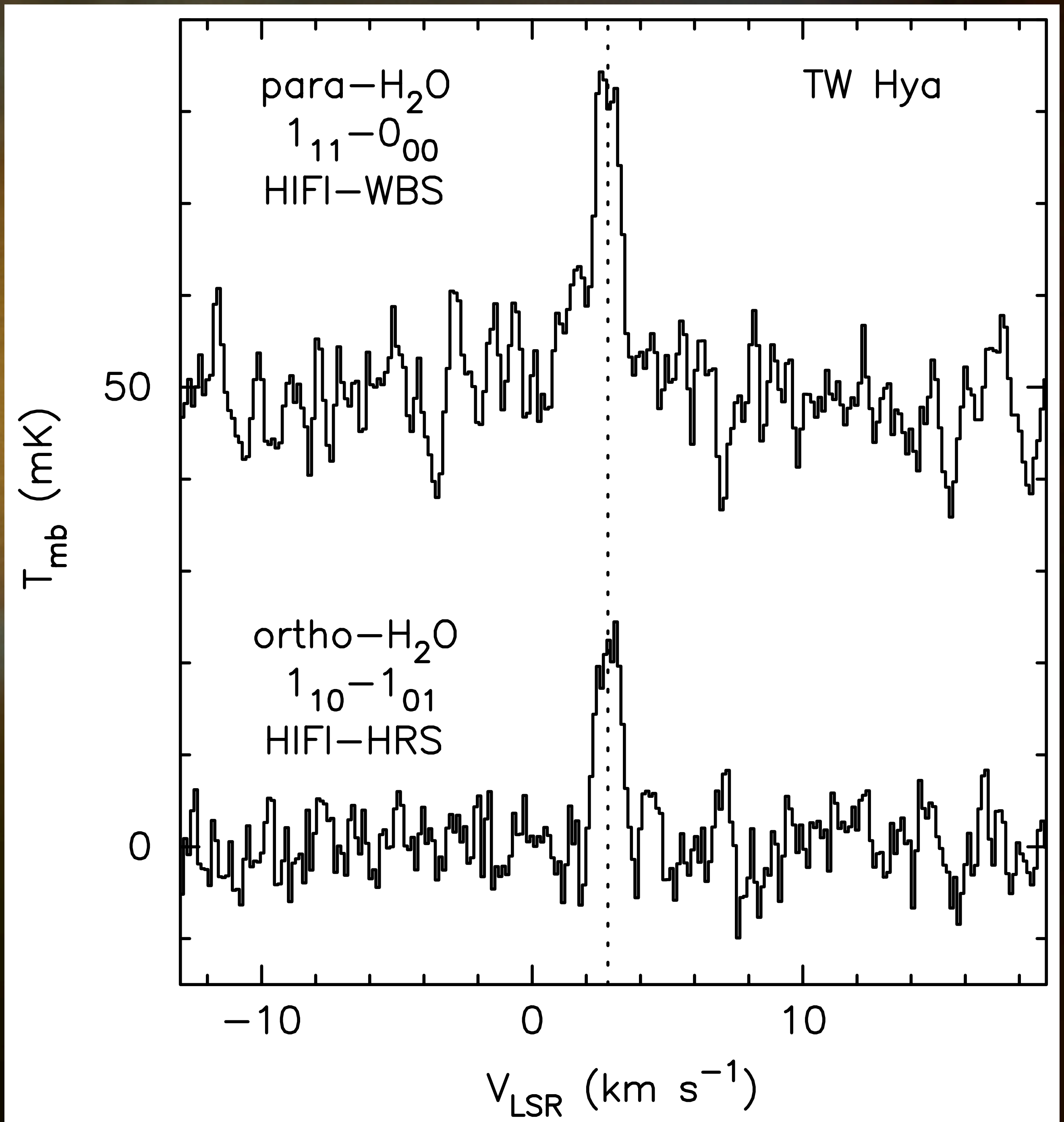
See also Honda et al. (2009)

Herschel/HIFI: Cold water vapor in TW Hya



Herschel/HIFI

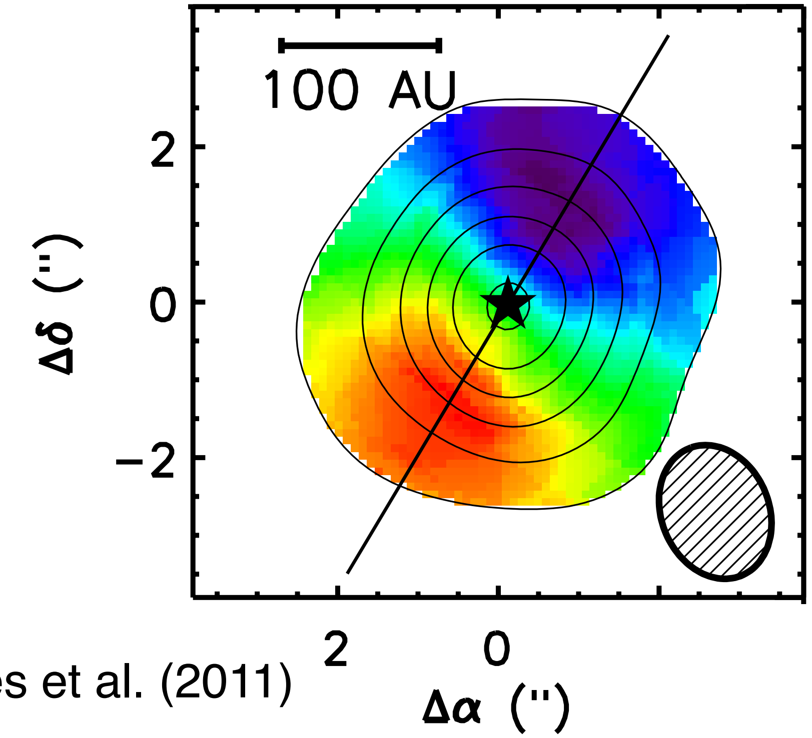
Total observing time: 6.6 hrs on o-H_2O and 14 hrs on p-H_2O (!)



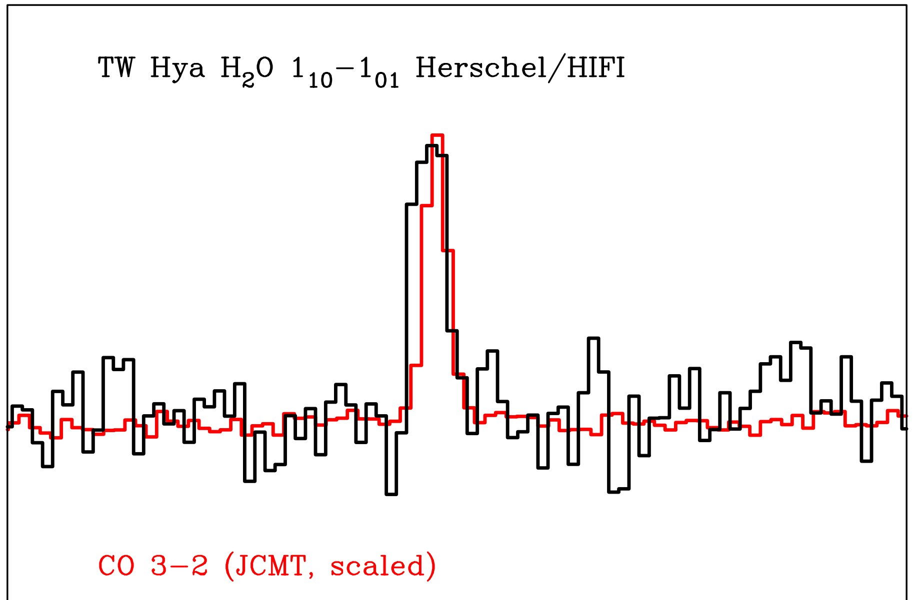
Hogerheijde, Bergin, et al. (2011)

Disk origin of the H_2O emission

- M_{star}=0.6 $M_\odot$ (Webb et al. 1999)
- Distance 53.7±6.2 pc (Akeson et al. 2011)
- R_{disk}=196 AU; i=7°: nearly face-on
- **Narrow line width confirms H_2O emission extends out to >115 AU**



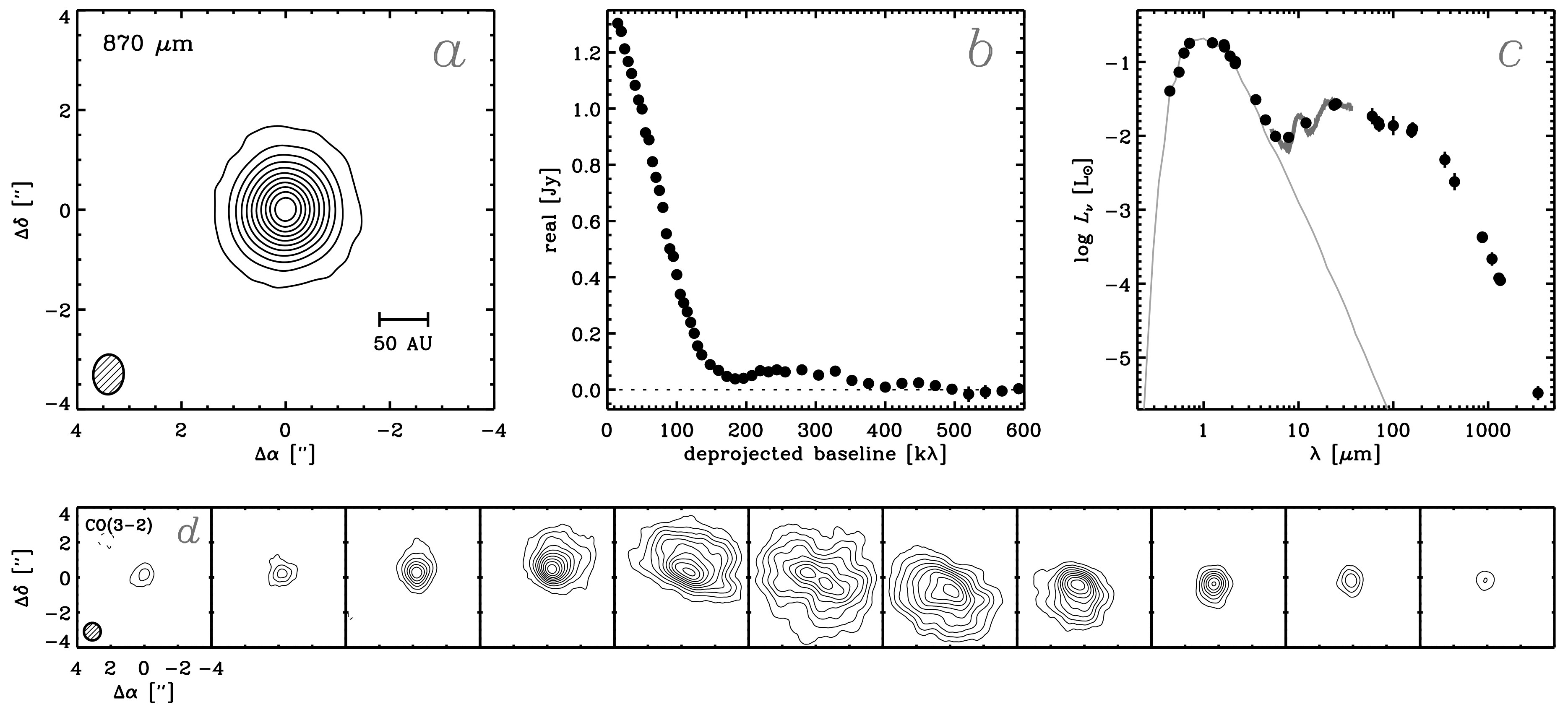
(Hughes et al. (2011)



Thi et al. 2004

TW Hya's disk

- R_{disk}=196 AU; i=7°: nearly face-on
  - Millimeter-sized dust grains confined to <60 AU (Andrews et al. 2011)
- M_{disk}=2–6×10^{-4} M$_{\odot}$ in dust
- M_{disk}=5×10^{-4}...5×10^{-2} M$_{\odot}$ in gas
  - (Calvet et al. 2002; Thi et al. 2010; Hughes et al. 2011)



Andrews et al. (2011)

Our model approach

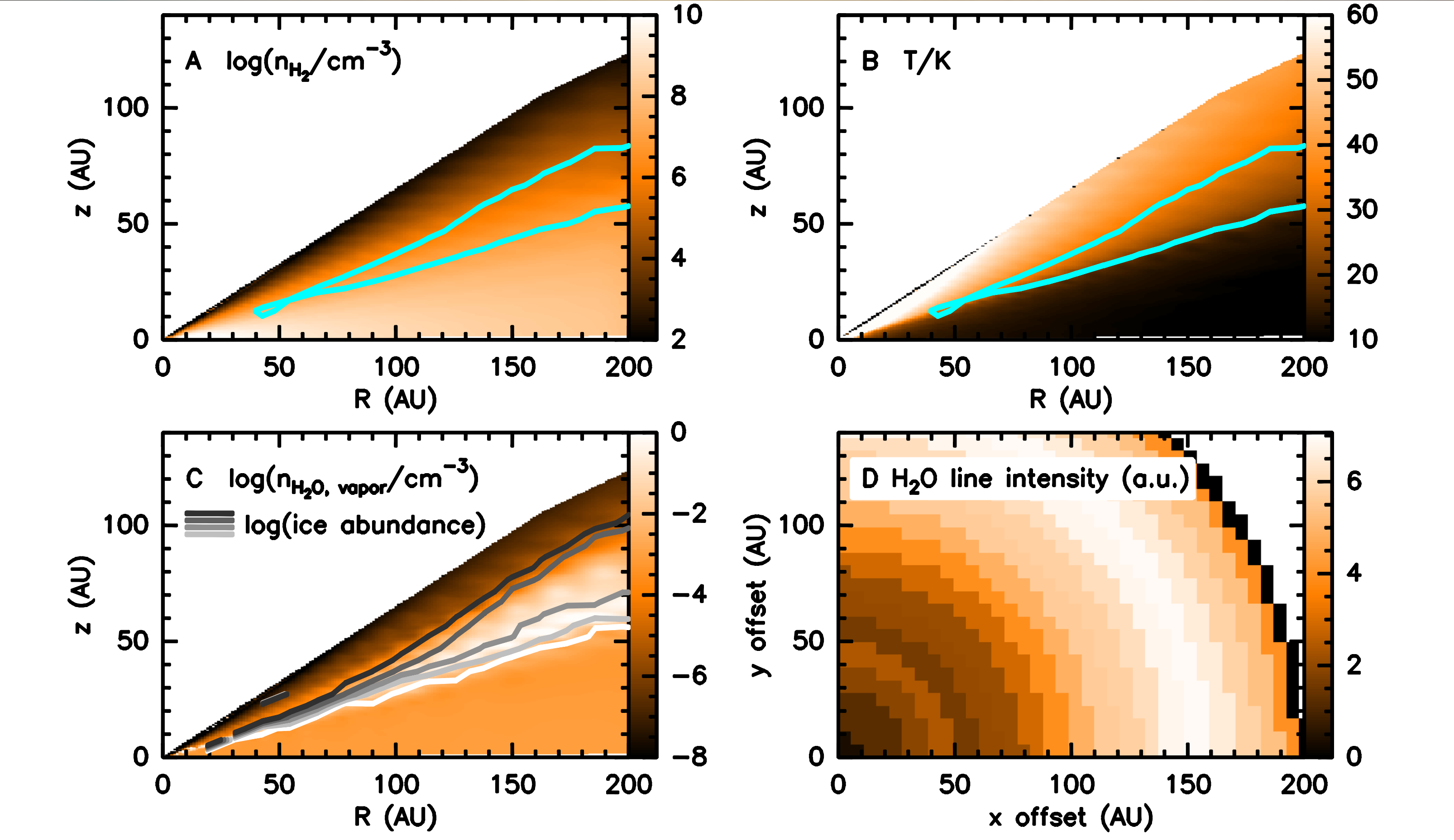
- Starting point: Thi et al. (2010)
  - $M_{\rm dust} = 1.9\times10^{-4}\ M_\odot$
  - $\rightarrow M_{\rm gas} = 1.9\times10^{-2}\ M_\odot$

- $R_{\rm out}$=196 AU, $R_{\rm in}$=4 AU (neglect inner disk)
- Vertical exponential scale height

- *Temperature structure* calculated from stellar irradiation (RADMC; Dullemond & Dominik 2004)
- Calculate radiative transfer of UV into disk, and calculate *resulting chemistry* (Fogel et al. 2010)
- Calculate resulting *water excitation and line formation* (LIME; Brinch & Hogerheijde 2010)

How much water?

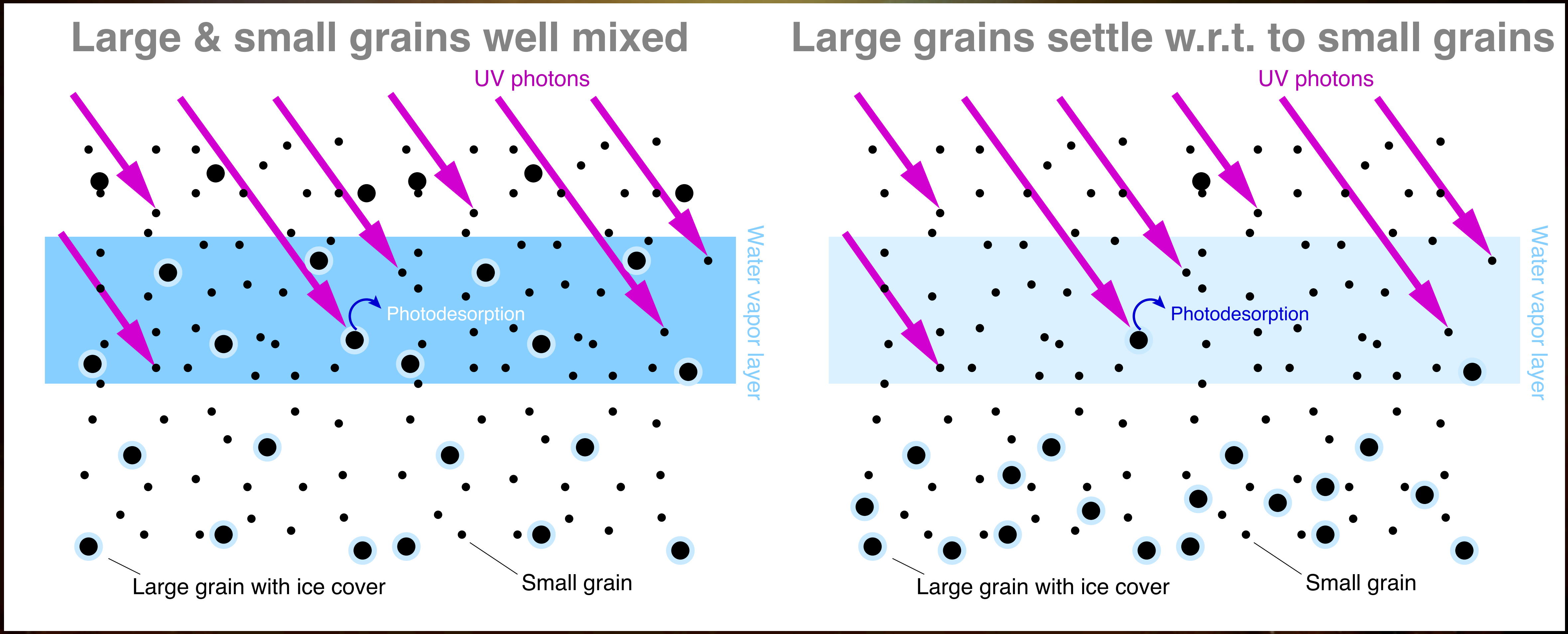
- Ice reservoir: 6300 Earth Oceans
- Water vapor content: 0.04 Earth Oceans



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

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

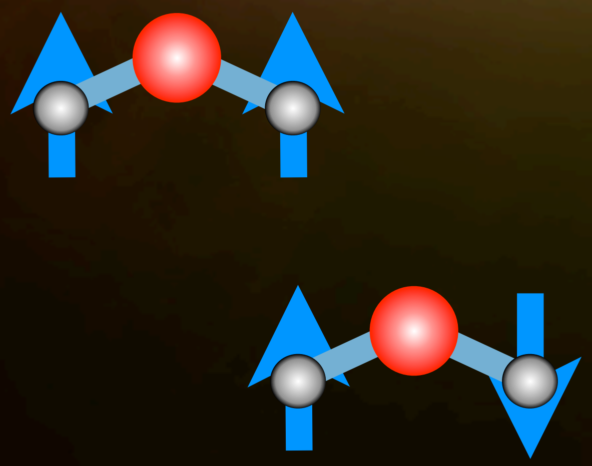


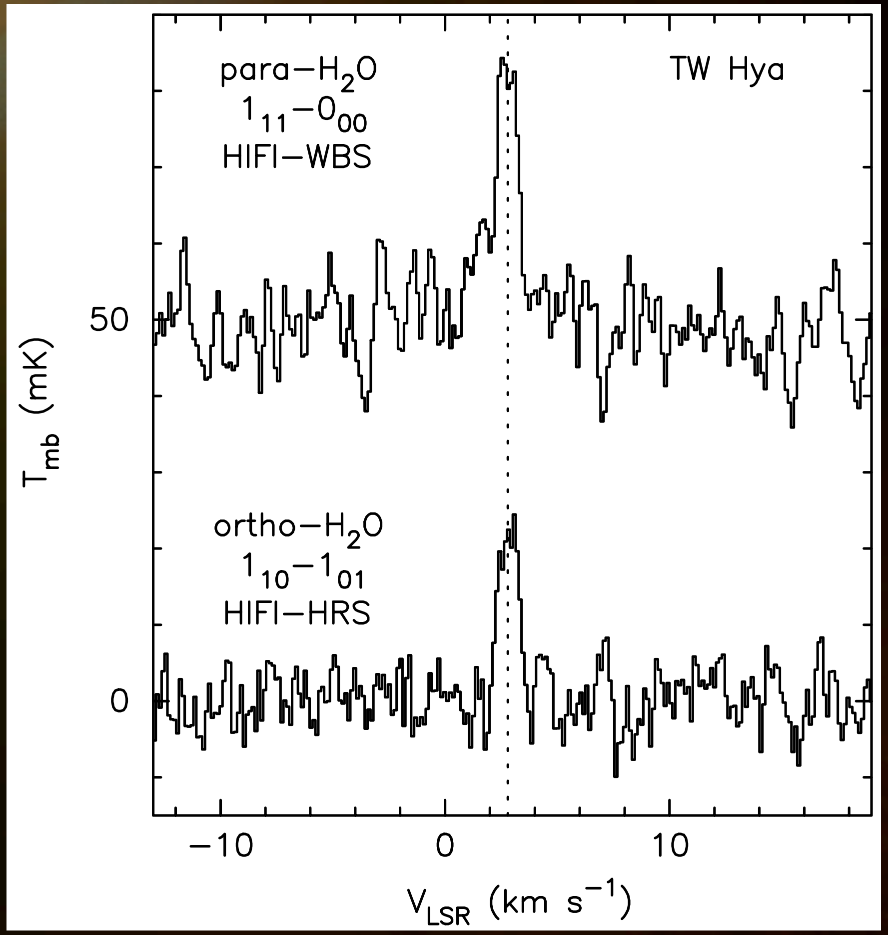
Lines yield H_2O ortho/para

- Lines are optically thin
  - ...because only 12% 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)**

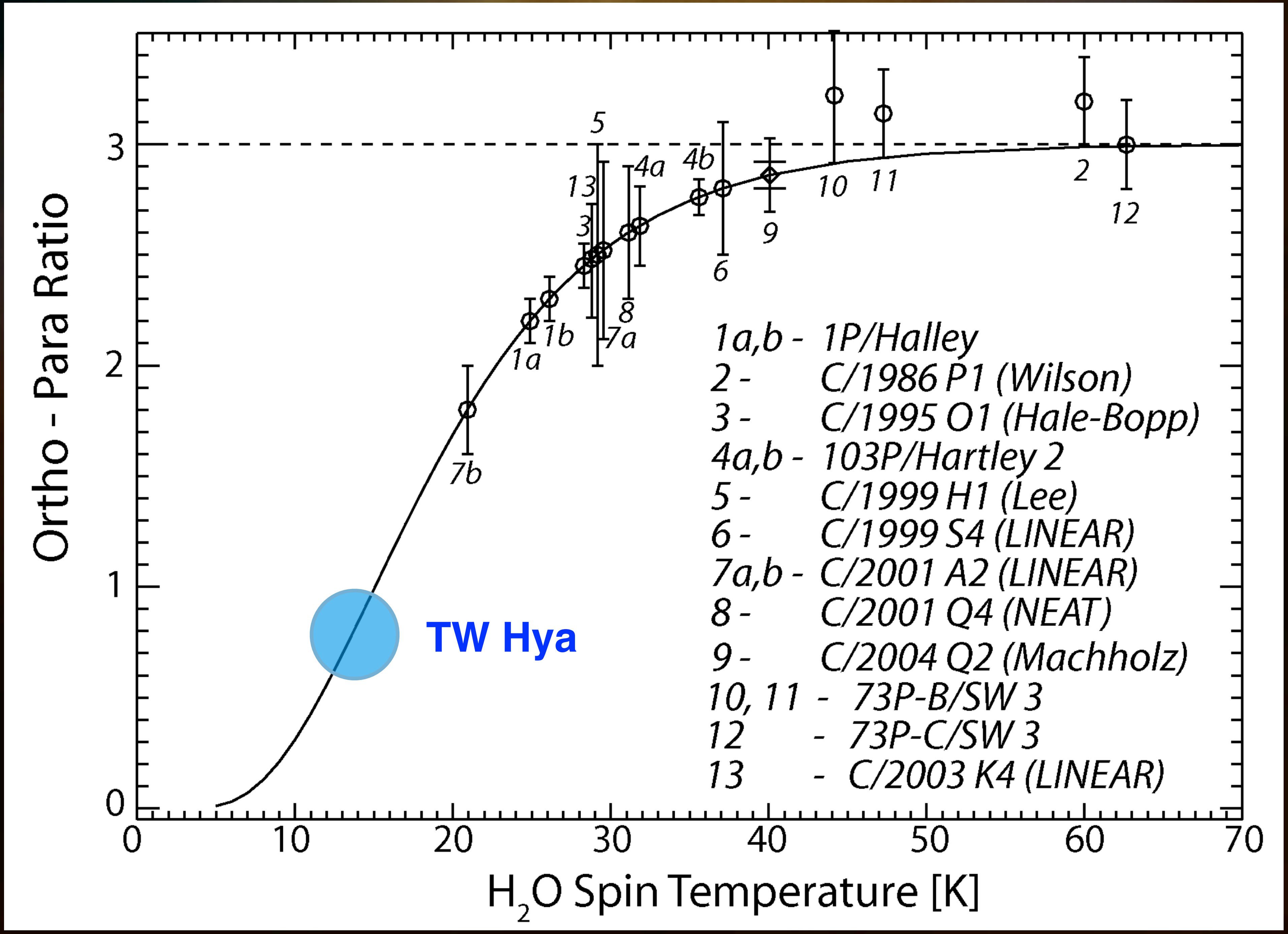
  - Observations yield OPR=0.77±0.07





A low H_2O ortho/para in TW Hya

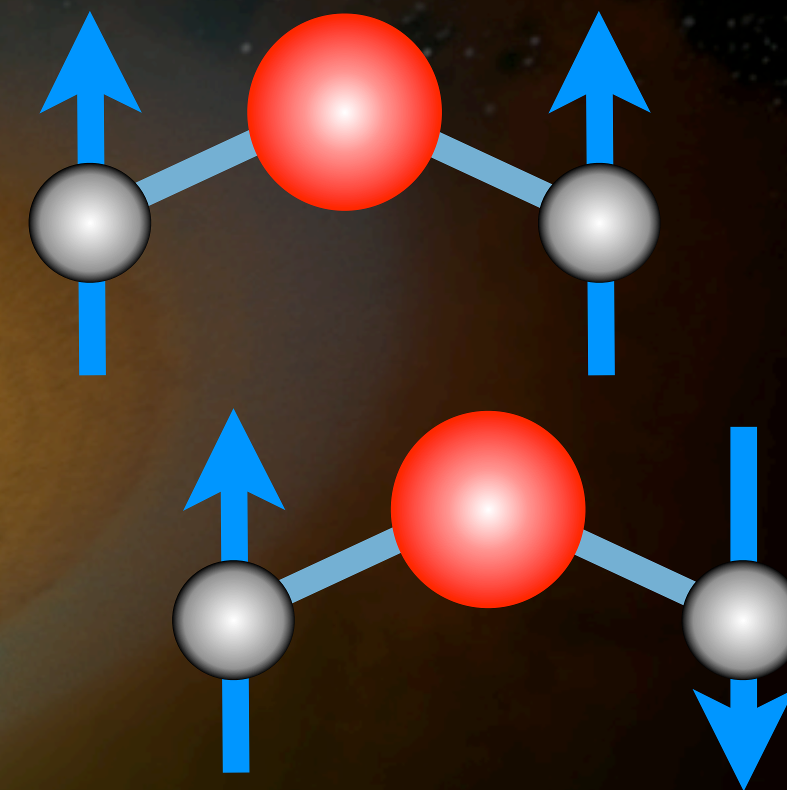
- H_2O OPR in TW Hya's disk of 0.77 ≪ Solar System comets (1.5–3)



Bonev et al. 2007; Mumma & Charnley (2011)

Long-range mixing of volatiles

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



- No radiative conversion of OPR in gas phase

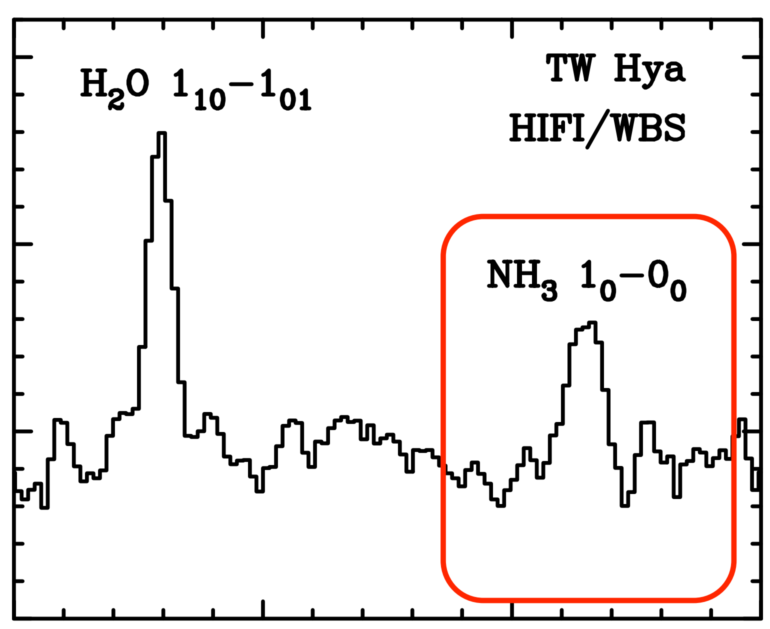
- Thermal evaporation preserves OPR (→ comets)
    - Equate T_{spin} with T_{grain} at ice formation (?)

- Photodesorption may preserve OPR (→ TW Hya observations)
    - ...or drive OPR to unity, implying even lower OPR for the ice (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**

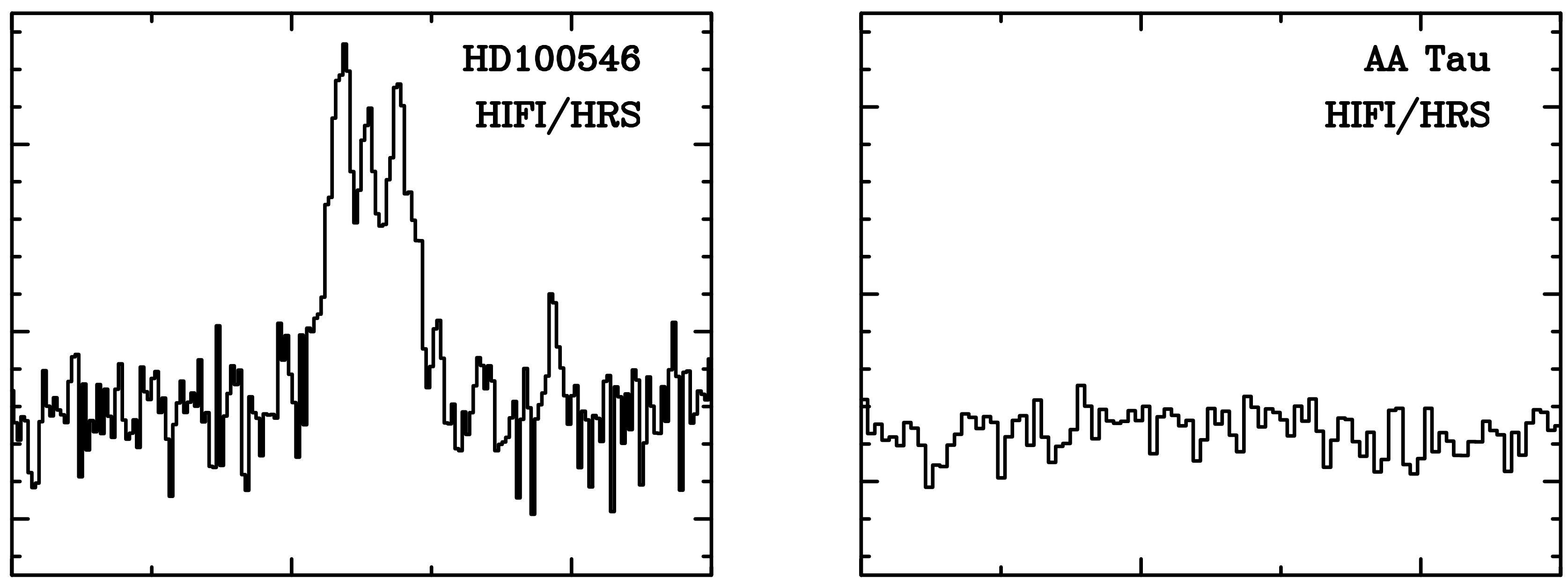
More results: cold NH_3

- In the same observation as o-H_2O, HIFI also detected emission from the groundstate transition of ortho-NH_3.
  - Line strength can be reproduced by a 3% NH_3/H_2O mixing ratio, assuming NH_3 also is released through photodesorption.
    - Comparable to ice measurements (2%–15%; e.g., Bottinelli et al. 2010) and Solar System comets (0.3–2%; e.g., Mumma & Charnley 2011).
  - Alternatively, if gas-phase chemistry forms NH_3 at a similar abundance as N_2H^+, the emission can also be explained.



More, *even deeper* searches for cold water vapor

- OT1 and OT2 program to search for groundtstate emission of o-H_2O and p-H_2O to HD100546, AA Tau, and DM Tau
  - Total integration time ~140 hrs for all three sources and both lines (!)



- Early modeling results suggest that cold water vapor in HD100546 and AA Tau is just as scarce as in TW Hya.

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.
- Ammonia is present in the disk of TW Hya at a mixing ratio w.r.t. to water of ~3%.
- Cold water vapor is also detected in HD100546 but *not* in AA Tau.
- Stay tuned...!