The water trail: From star forming clouds to planet-forming disks

Michiel Hogerheijde
Leiden University & University of Amsterdam

In collaboration with: Ted Bergin, Christian Brinch, Ilse Cleeves, Fujun Du, **Helena La**, Melissa McClure, **Yke Rusticus**, Vachail Salinas, Leon Trapman, **Ivana van Leeuwen**, & the WISH team

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UNIVERSITY OF AMSTERDAM

From Herschel's Legacy to Millimetron's promise

- H_2O is major carrier of elemental O
  - At *T*>200 K, gas-phase chemistry drives all available O to H_2O → $X(H_2O)$~10^{-4}
  - At low *T*, water is formed as ice on cold grains

- H_2O is important coolant of warmer gas

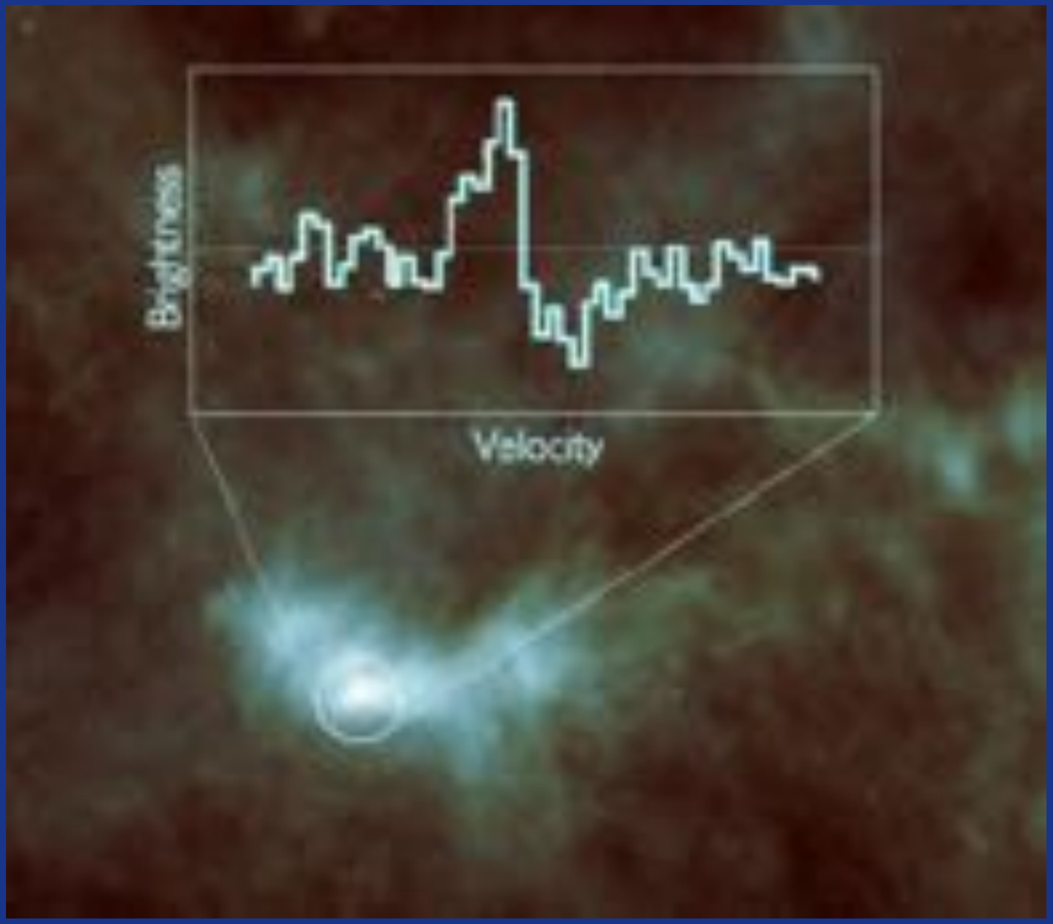
- H_2O fills *two* crucial roles in planet formation

  1. As ice layer on grains, it increases solid fraction and grain sticking
  2. Delivery of icy bodies to your terrestrial planets may contribute to oceans

See major reviews by Pontoppidan et al. (2014); van Dishoeck et al. (2013; 2014)

Water at the start of star formation

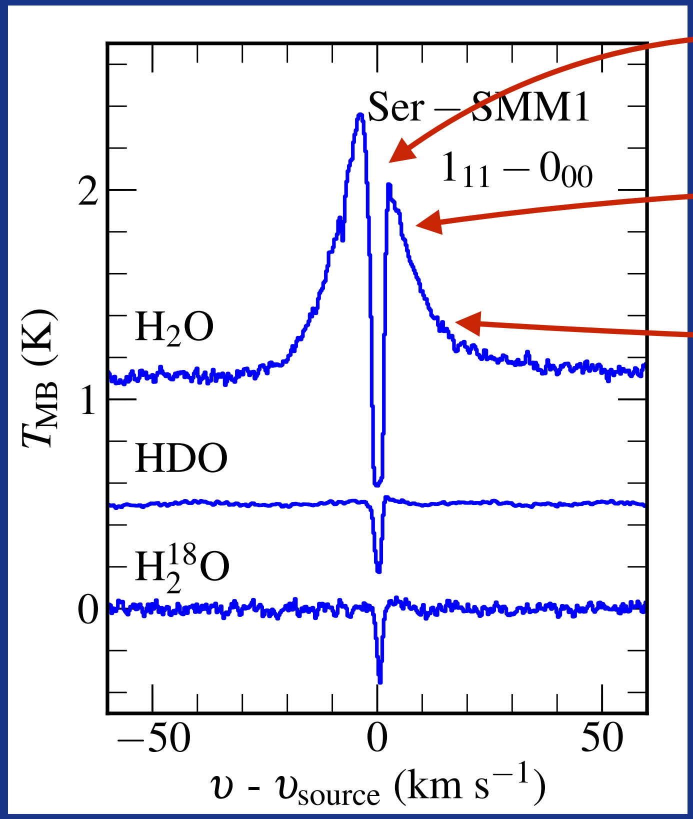
- In cold pre-stellar cores, most water is frozen out
  - Low gas-phase abundance due to *photodesorption* by ultraviolet photons
    - In these environments: secondary UV after cosmic-ray induces H_2 dissociation
  - $X(H_2O) \sim few \times 10^{-10}$



See talk by Paola Caselli; Caselli et al. (2012)

Water during star formation

- Water remains frozen out, except
  - Close to the star
    - Important for more luminous, high-mass stars; less obvious for low-mass stars
  - In the outflow



Many papers by, e.g., Mottram et al; Schmalzl et al.; Kristensen et al.; Summary figure from van Dishoeck et al. (in prep)

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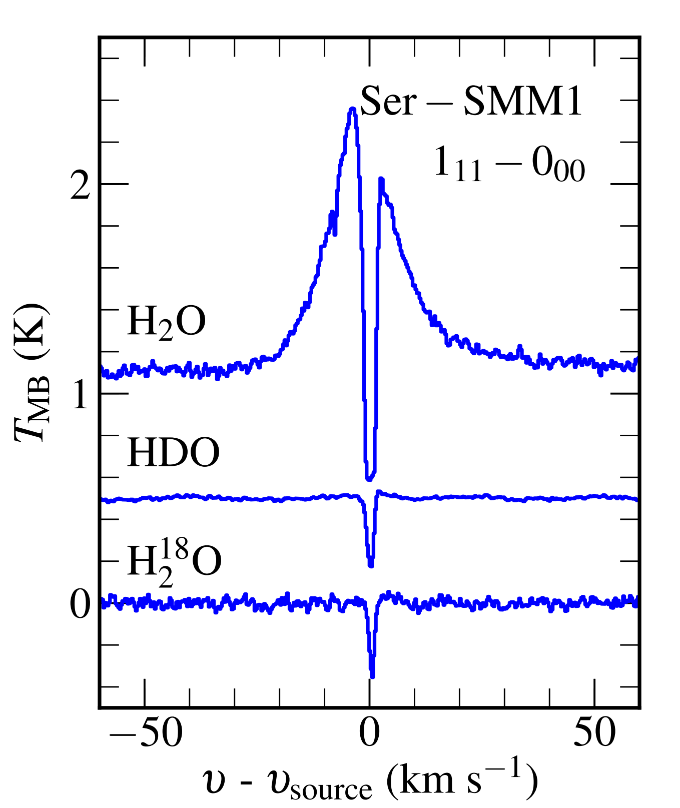

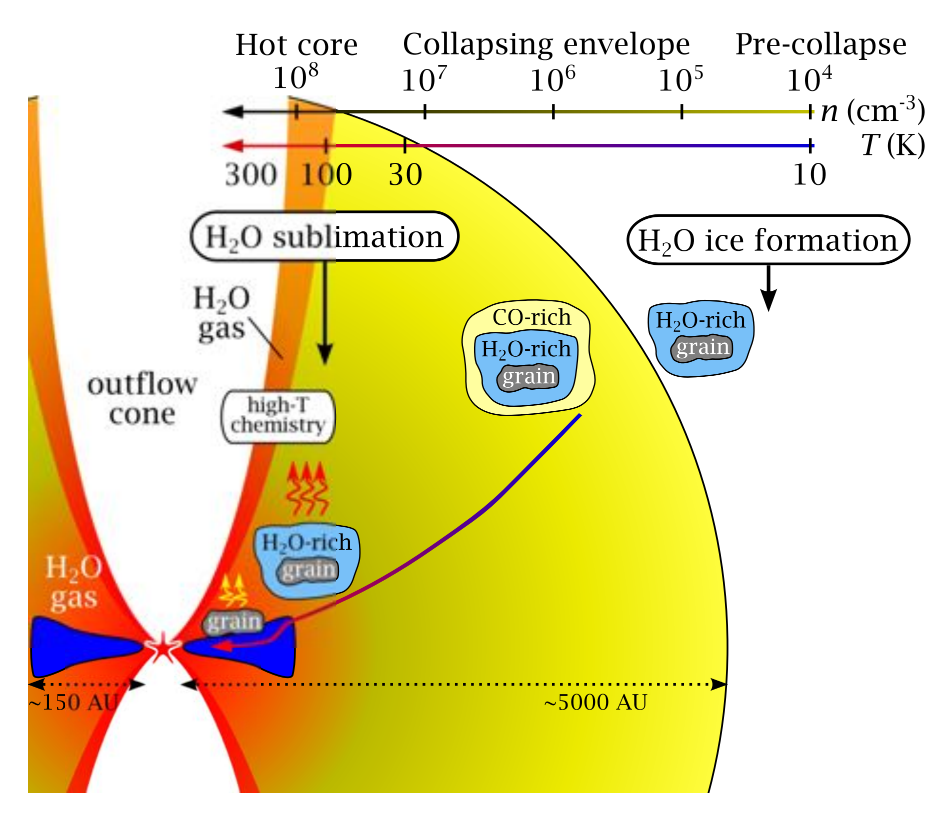

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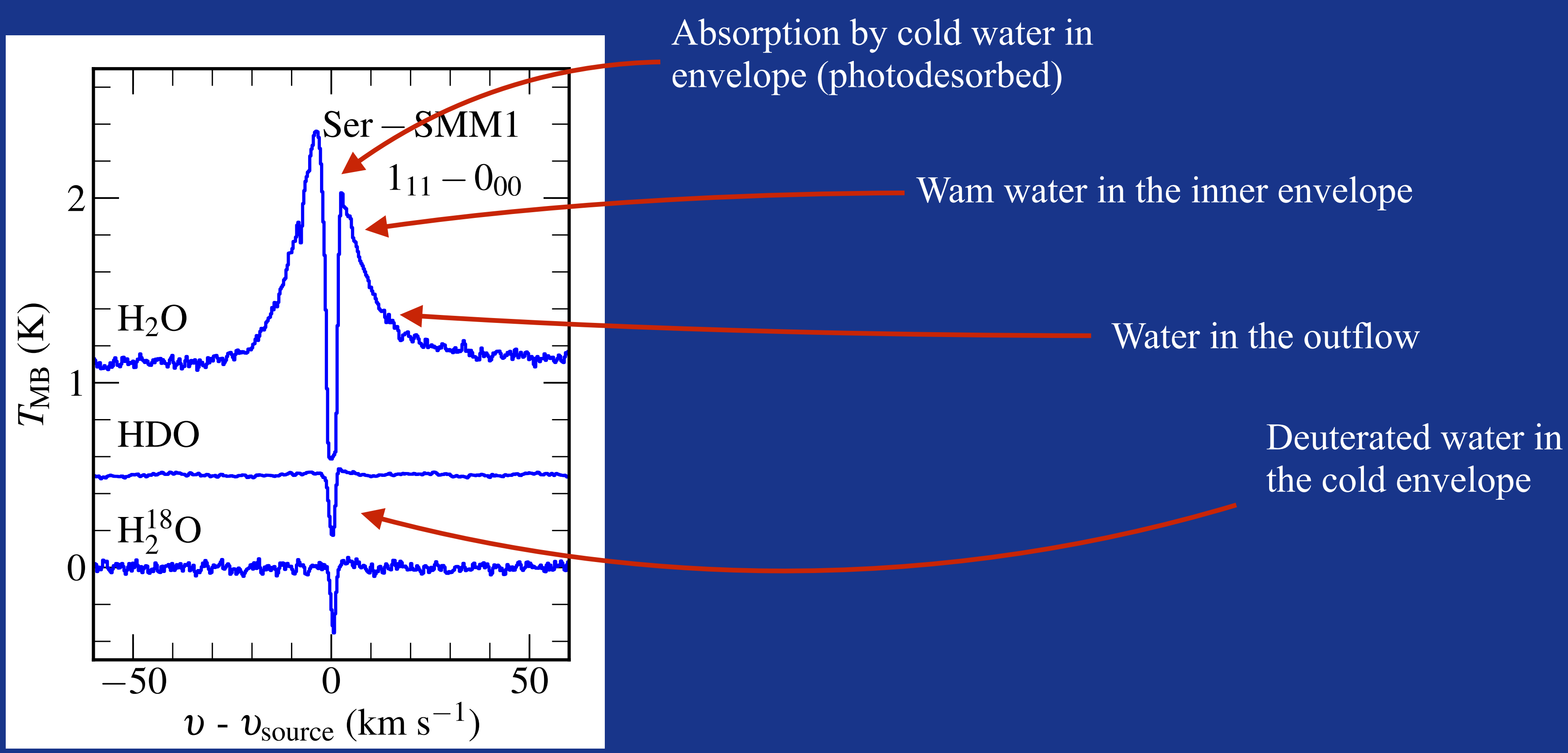
Deuteration of cold water

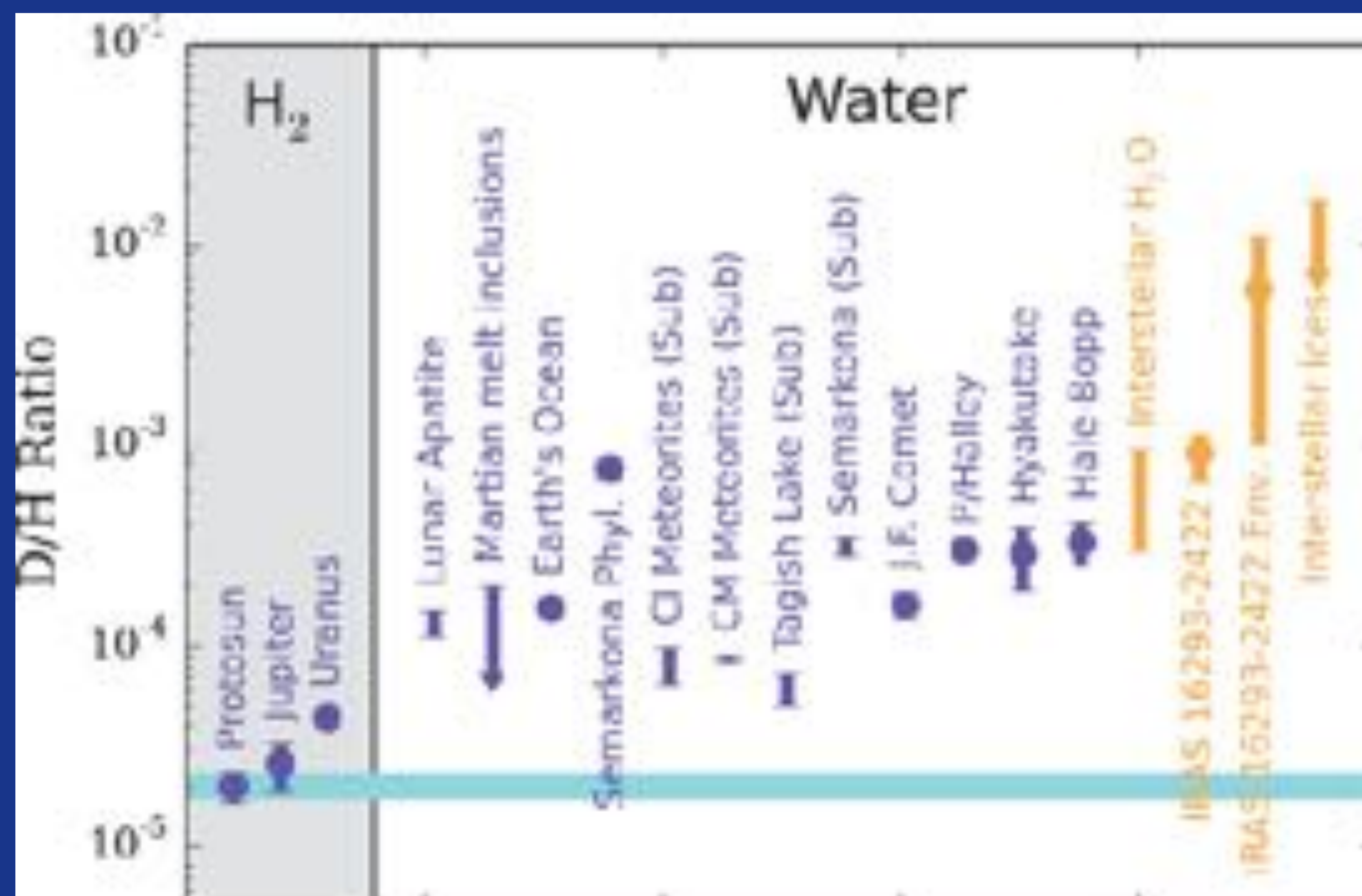
- At low *T*, D get incorporated in the chemistry
  - Increases abundances of HDO and D_2O



E.g., Furuya et al. (2017) for an application to disks
figure from van Dishoeck et al. (in prep)

Ocean water HDO/H_2O tracks its origins

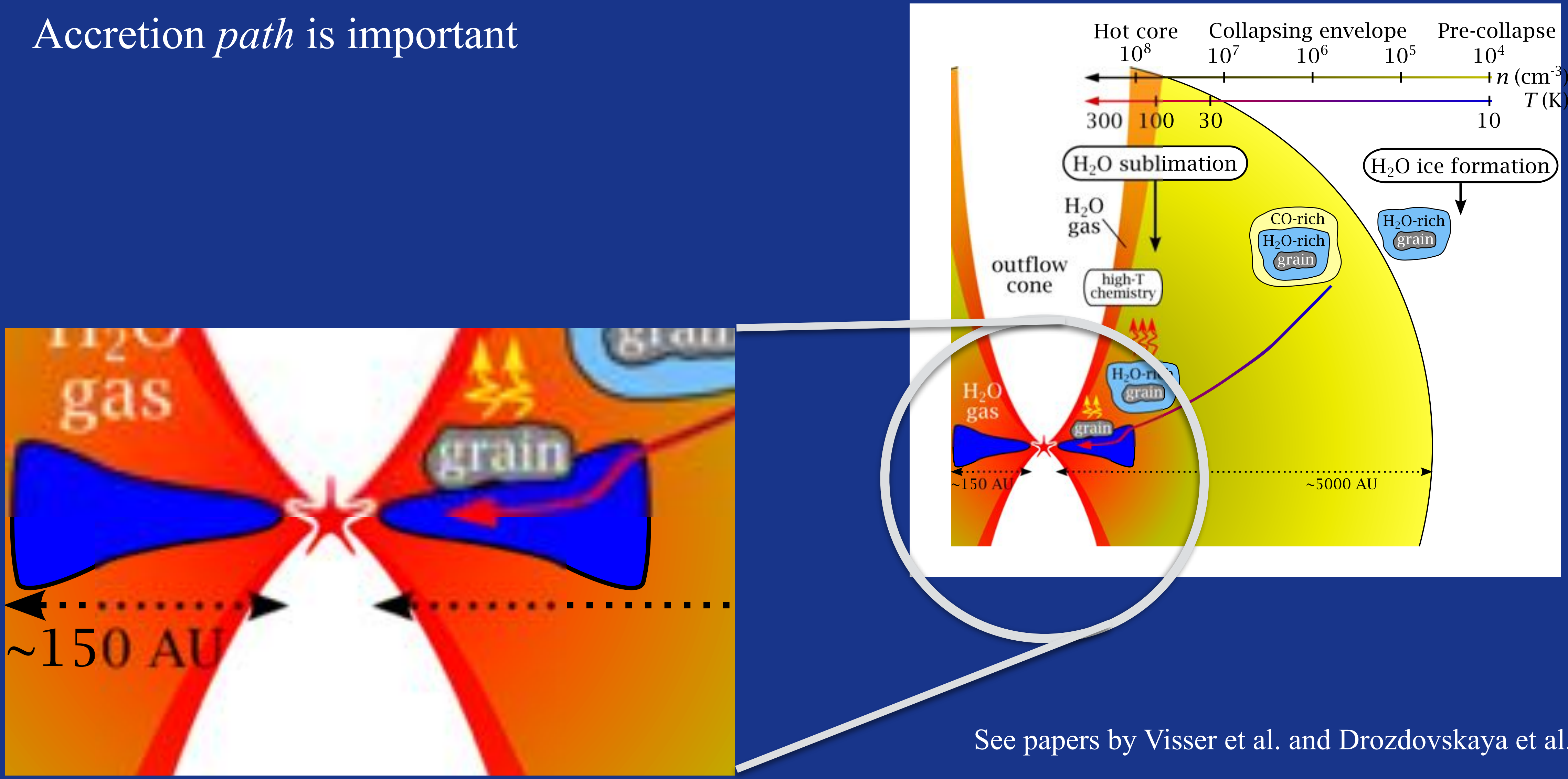
- D/H of ocean water is lower than ISM value
- …but higher than disk chemistry can produce → some fraction of water predates the disk (Cleeves et al. 2014)
- Depending on thermal history
  - produce layered ice with varying HDO/H_2O and D_2O/HDO ratios
  - Furuya et al. (2017)



DH plot from Cleeves et al., based on extsnive literature; see paper for complete references!

Water in the planet forming disk

- Planet forming disks inherits water from the star forming envelope
  - Directly as ice, if material stays < 100 K
  - In the gas-phase, followed by recondensation when *T* drops inside the disk
- Accretion *path* is important



See papers by Visser et al. and Drozdovskaya et al.

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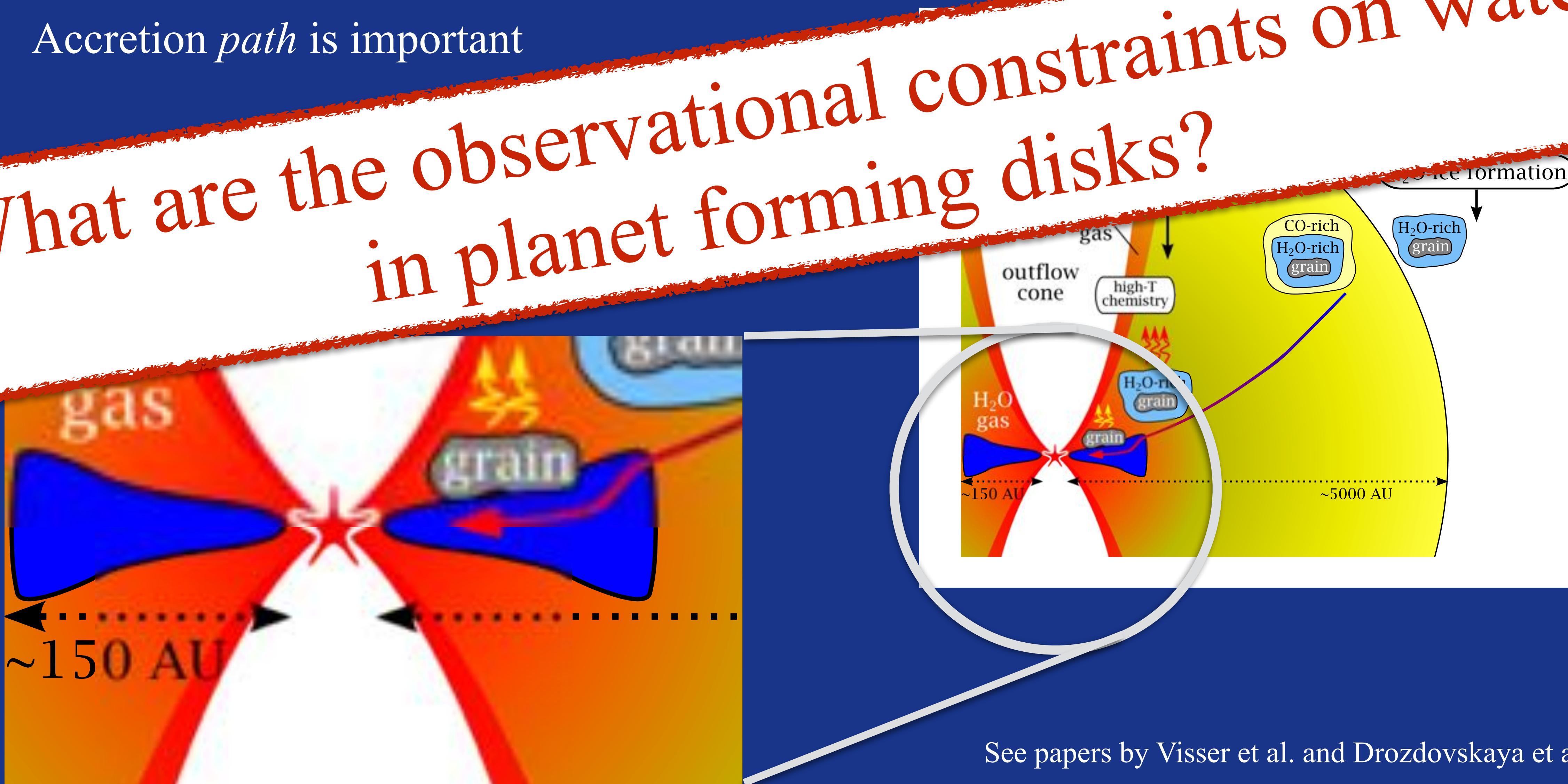
What are the observational constraints on water in planet forming disks?



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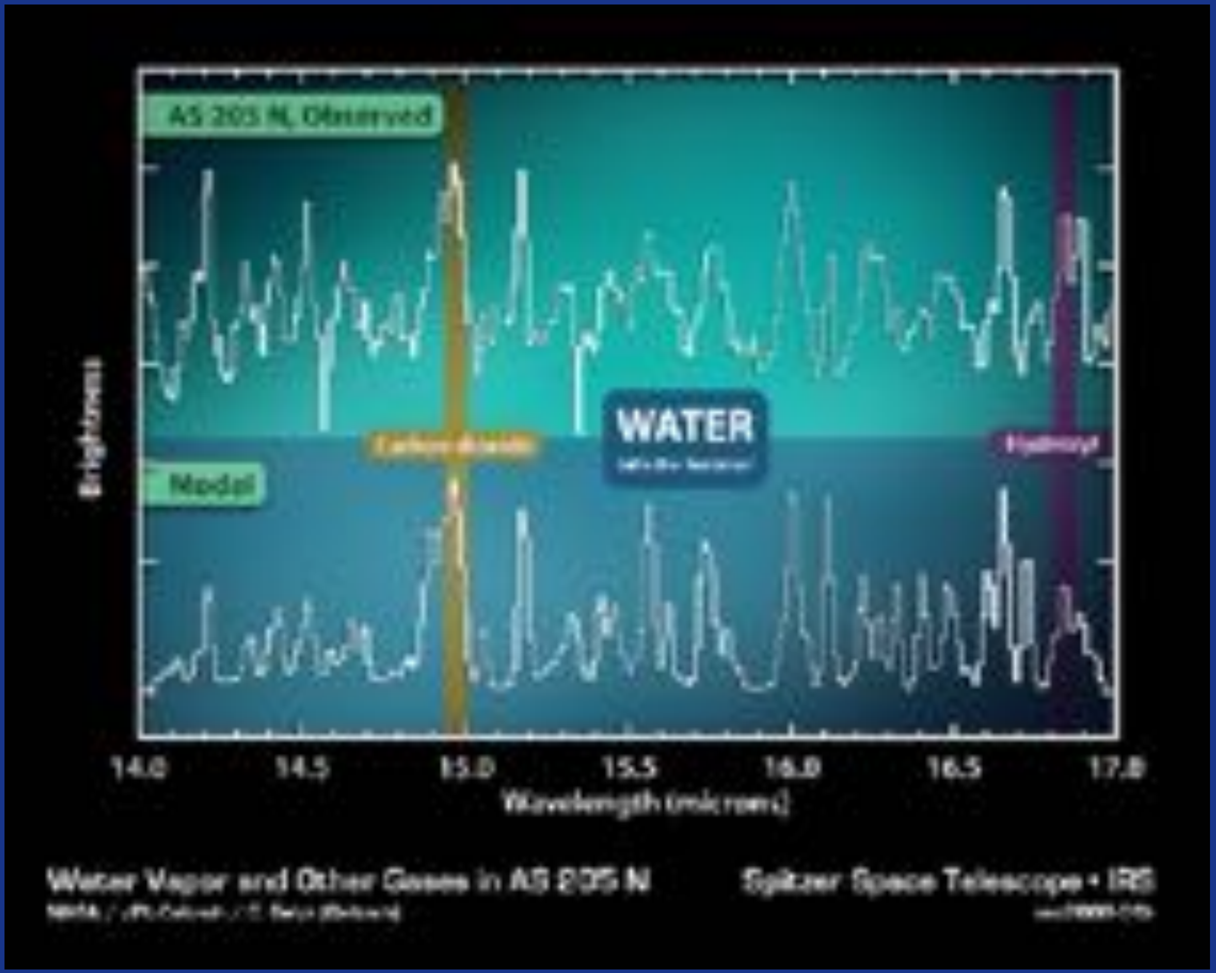
Water in planet forming disks

- **Copious warm (≈200 K) water in inner disk**
- Water ice main solid in outer disk (<100 K)
  - Important for planet formation & volatile delivery
- UV photons photodesorb H_2O off ice surfaces
  - Equilibrium /w photodissociation: thin layer of cold water vapor
  - Observe ground-state lines /w *Herschel* @ 557 & 1113 GHz



Carr & Najita 2008; Salyk et al. 20087, 2015; Pontoppidan et al. 2019; Meijerink et al. 2009; Zhang et al. 2013; Fedele et al. 2013; Fedele et al. 2012; Riviere-Machilar et al. 2012
Terada et al. 2007, 2012; **Honda et al.** 2009, **2016**; **McClure et al. 2015**
Dominik et al. 2005; Hollenbach et al. 2009; Andersson et al. 2006, 2008; Öberg et al. 2009

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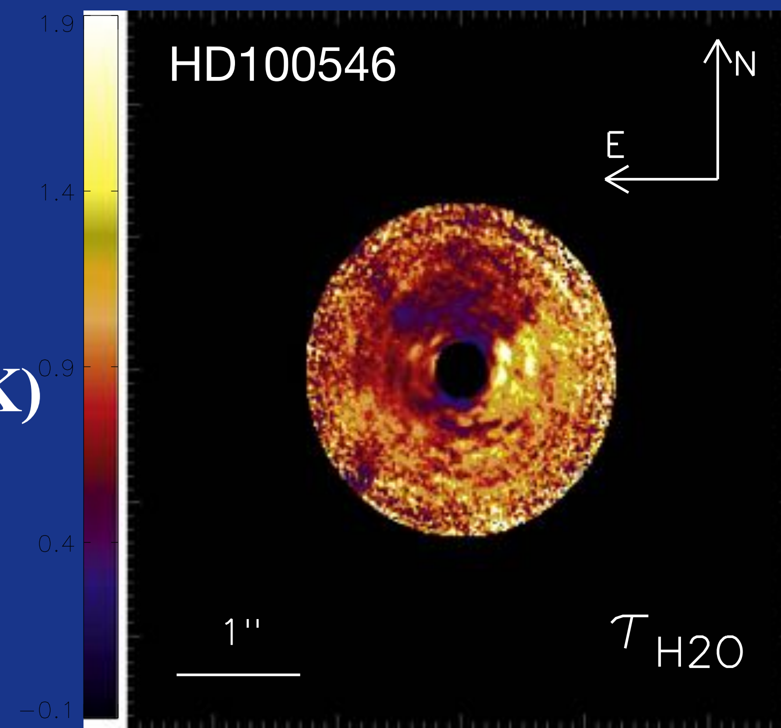

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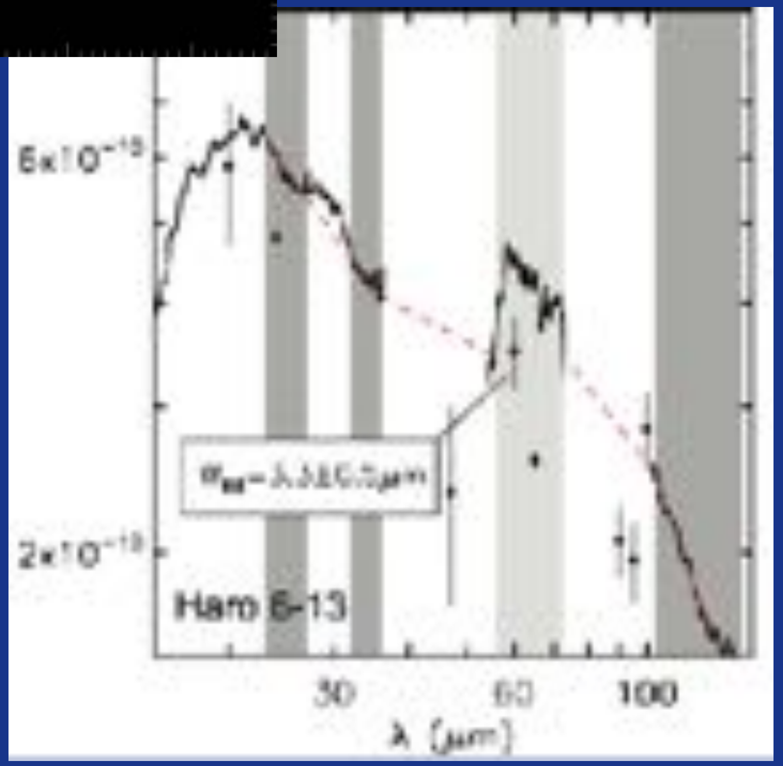

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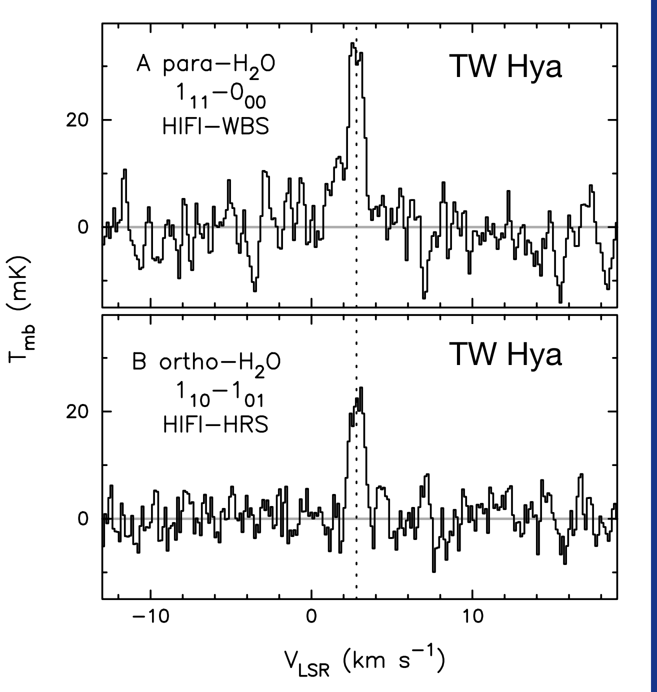
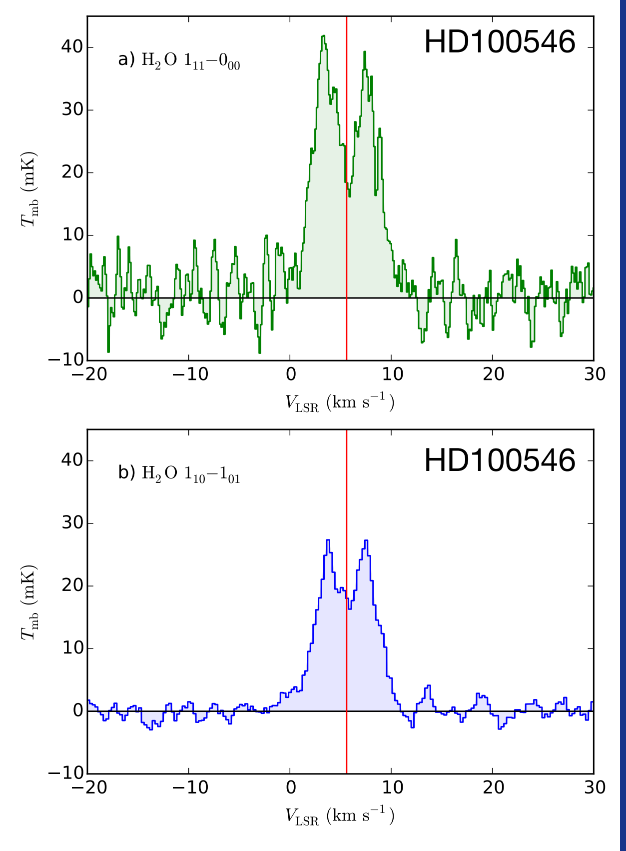
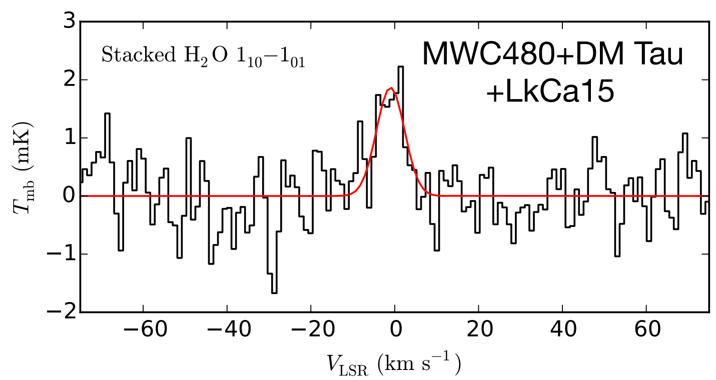
Few, and weak, detections

- TW Hya (d=56 pc)
- HD100546 (d=110 pc)
- Stacked MWC480+DM Tau+LkCa15
- DG Tau
  - Relation with jet and X-rays?
- Not detected in HD163296 (101 pc), AA Tau (140 pc)
  - And at lower sensitivity: AS209, BP Tau, GG Tau, GM Aur, MWC 758, T Cha







Bergin et al. 2010; **Hogerheijde et al. 2011**; Salinas et al 2016
Du et al. 2017; **Hogerheijde et al. in prep**
Podio et al. 2013

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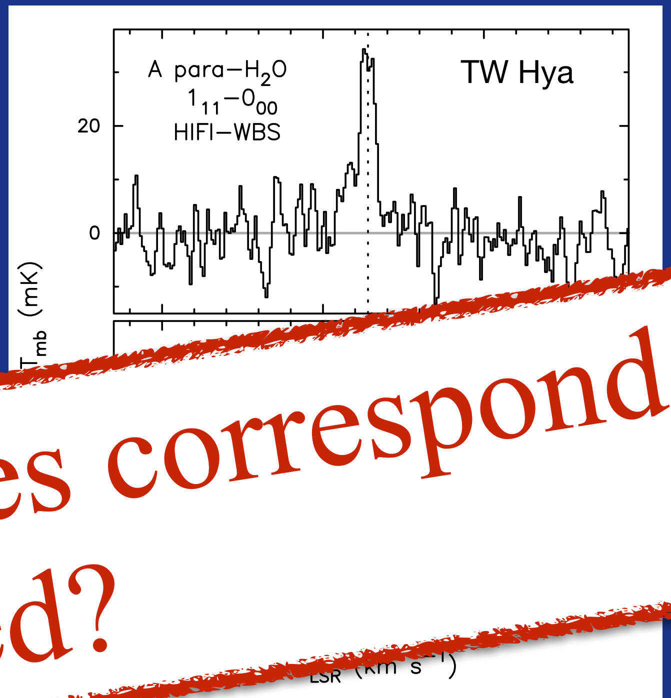
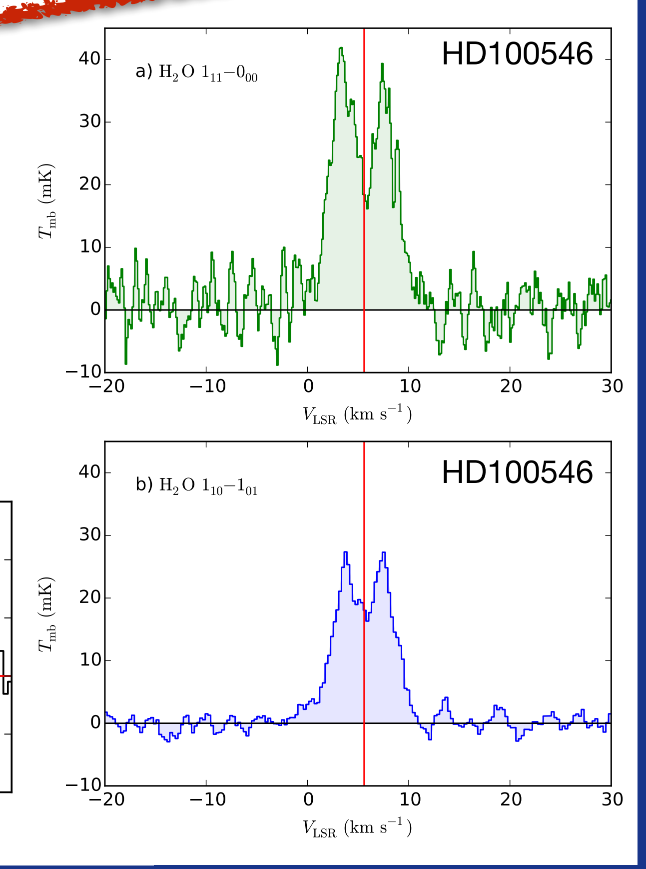
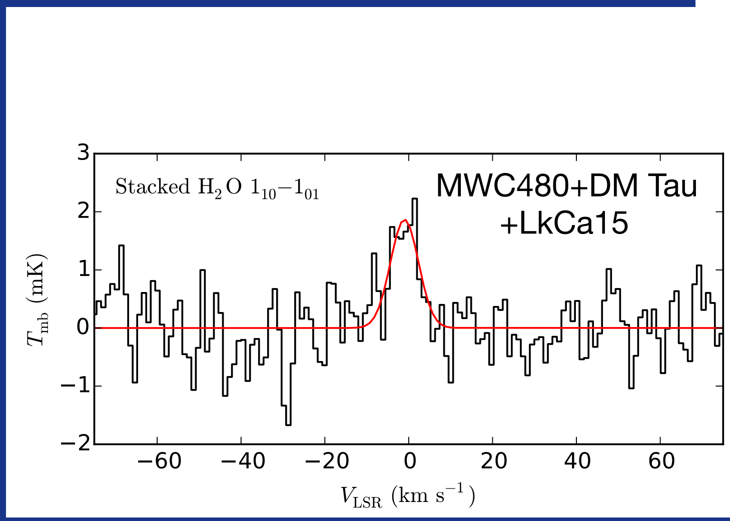
…, GG Tau, GM Aur,

How much water do these weak lines correspond to, and where is it located?







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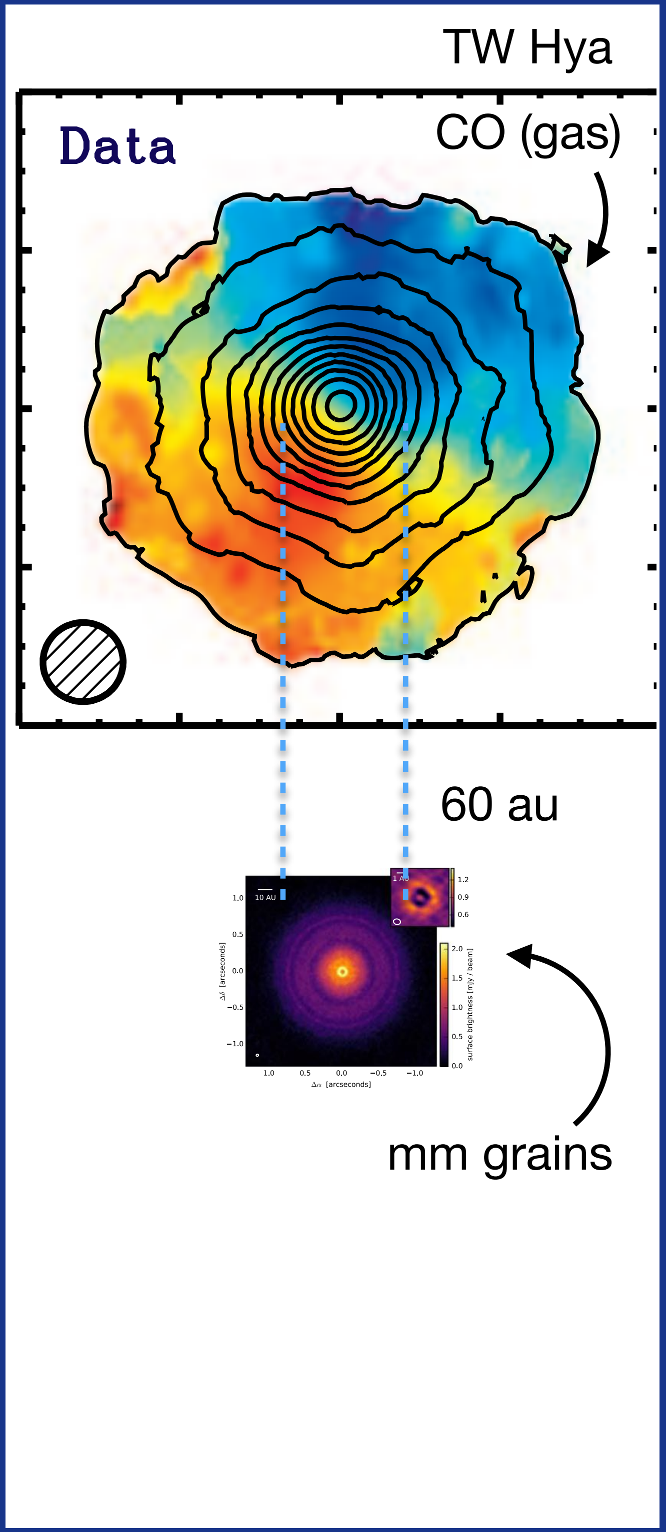
Podio et al. 2013

TW Hya's weak H_2O lines

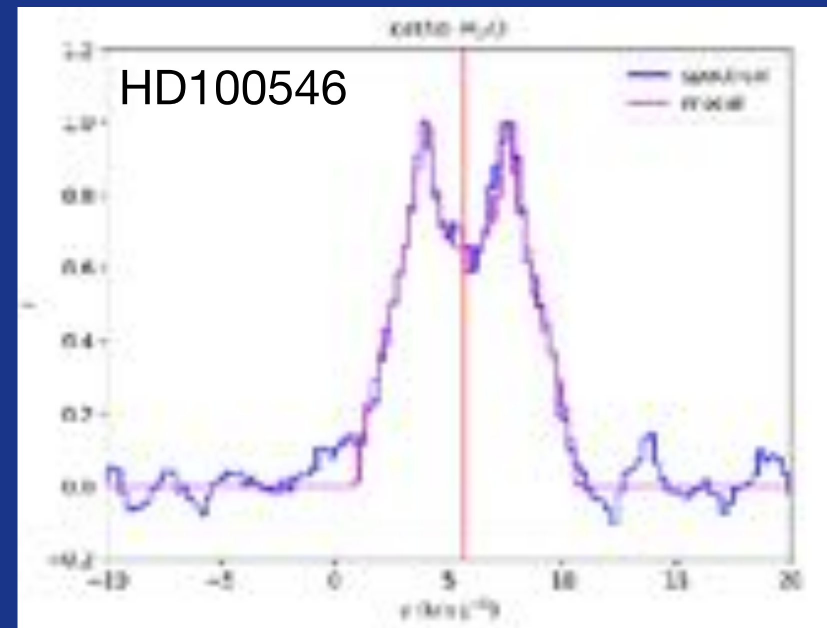
- To reproduce weak observed lines, *either*
  - Reduce the amount of H_2O ice subject to photodesorption
    - Lock up ices in larger bodies, settled to midplane
- *or*
  - Reduce the size over which water ice is distributed
    - Icy grains drift inward, as is observed for mm grains with ALMA
- Spatially and spectrally unresolved observations cannot distinguish between these solutions

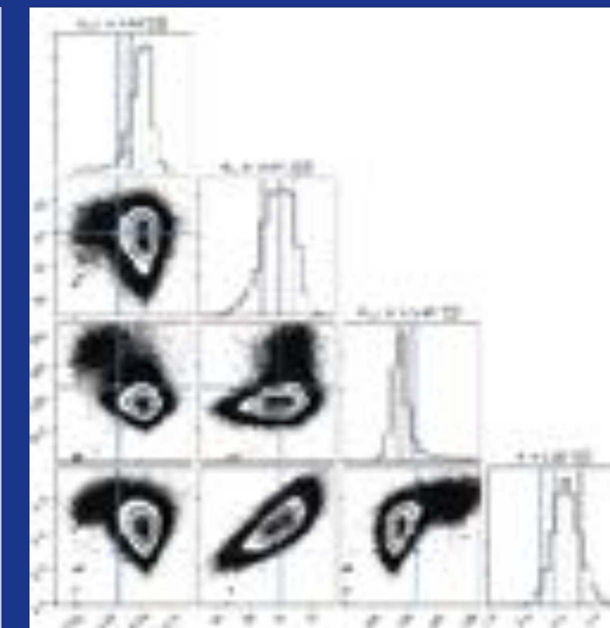


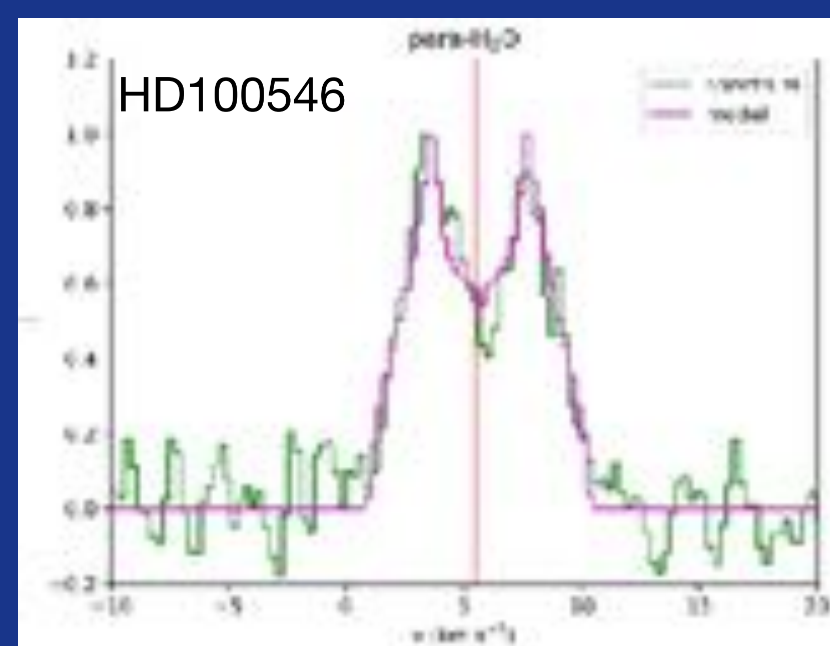
Hogerheijde et al. 2011; **Salinas et al 2016**
Andrews et al. 2011, 2016; Hogerheijde et al. 2016; **Schwarz et al. 2016; Tsukagoshi et al. (2019)**

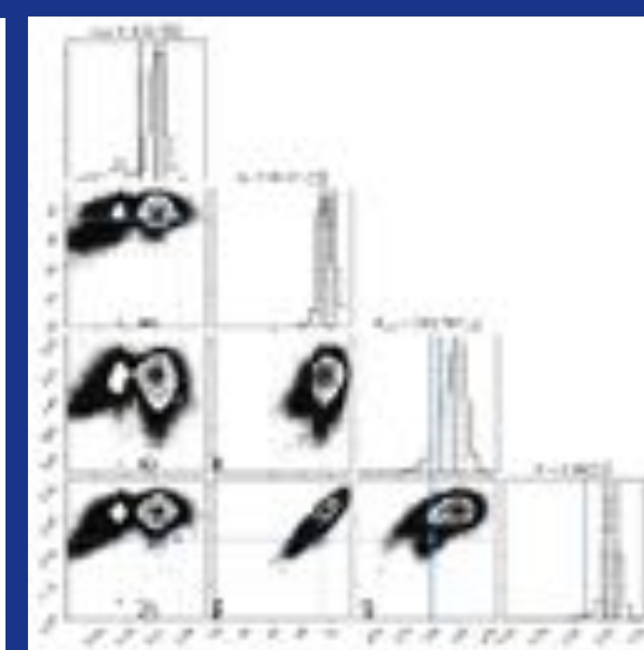
HD100546’s *resolved* lines

- i=42°→ velocity resolved line profile
- Parameterised model
  - $I_{\rm line} \propto R^{-p}$, from $R_{\rm in}$ to $R_{\rm out}$
  - mcmc
    - $R_{\rm in}$ = 40 au
    - $R_{\rm out}$ = 250 au (p-H_2O), = 325 au (o-H_2O)
      - excitation?
    - p = -2.5
      - $\Sigma_{\rm gas} \propto R^{-1.5}$?
      - $T \propto R^{-0.25}$?
      - excitation $\propto R^{-0.75}$?





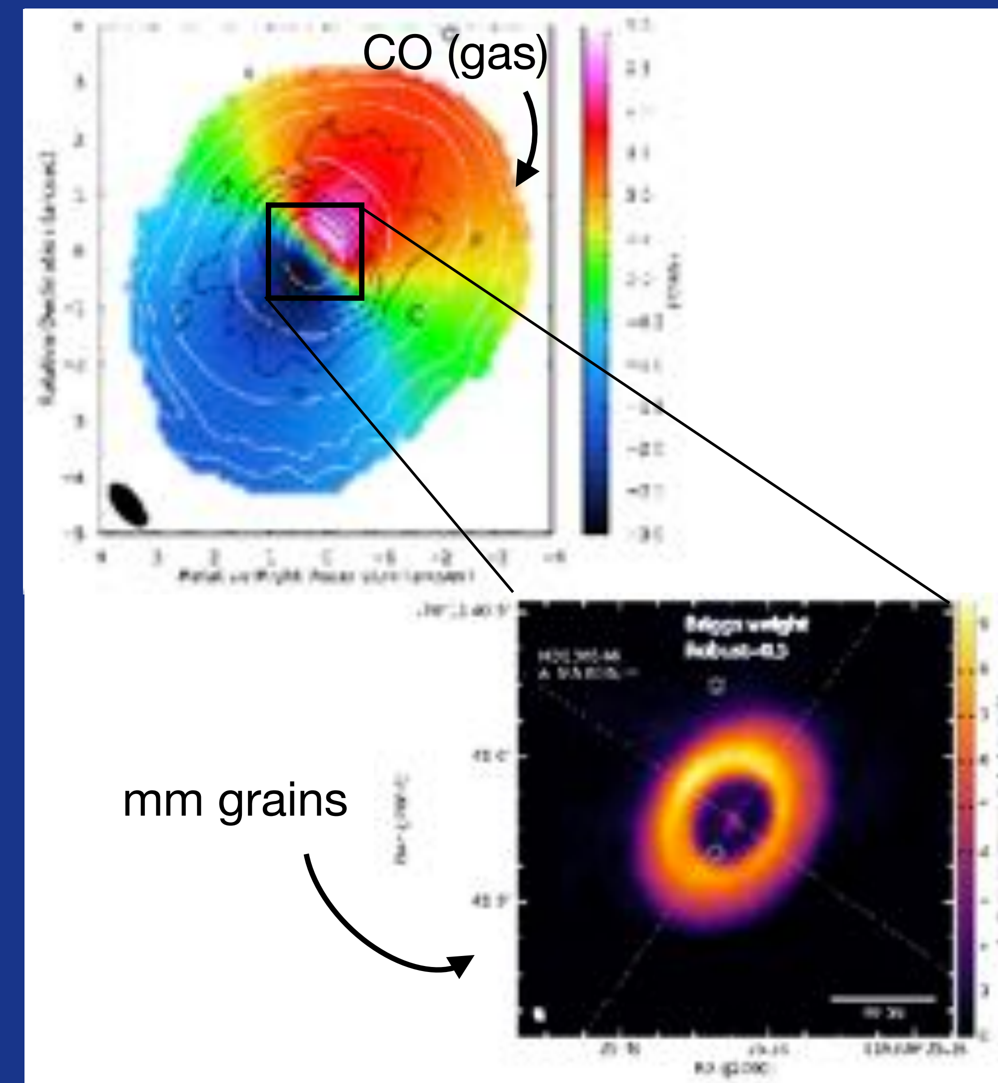




Hogerheijde et al. in prep; **BSc thesis Helena La, U Amsterdam**; MSc thesis van Leeuwen & Rusticus, U Leiden

HD100546: H_2O vs ALMA CO+dust

- ALMA: dust continuum
  - ring at ≈25 au (15-40 au)
  - extends to ≈240 au
- ALMA: CO emission
  - extends to ≈380 au
- **H_2O coincides /w bulk of surface density**



Walsh et al. 2014; Pineda et al. 2018

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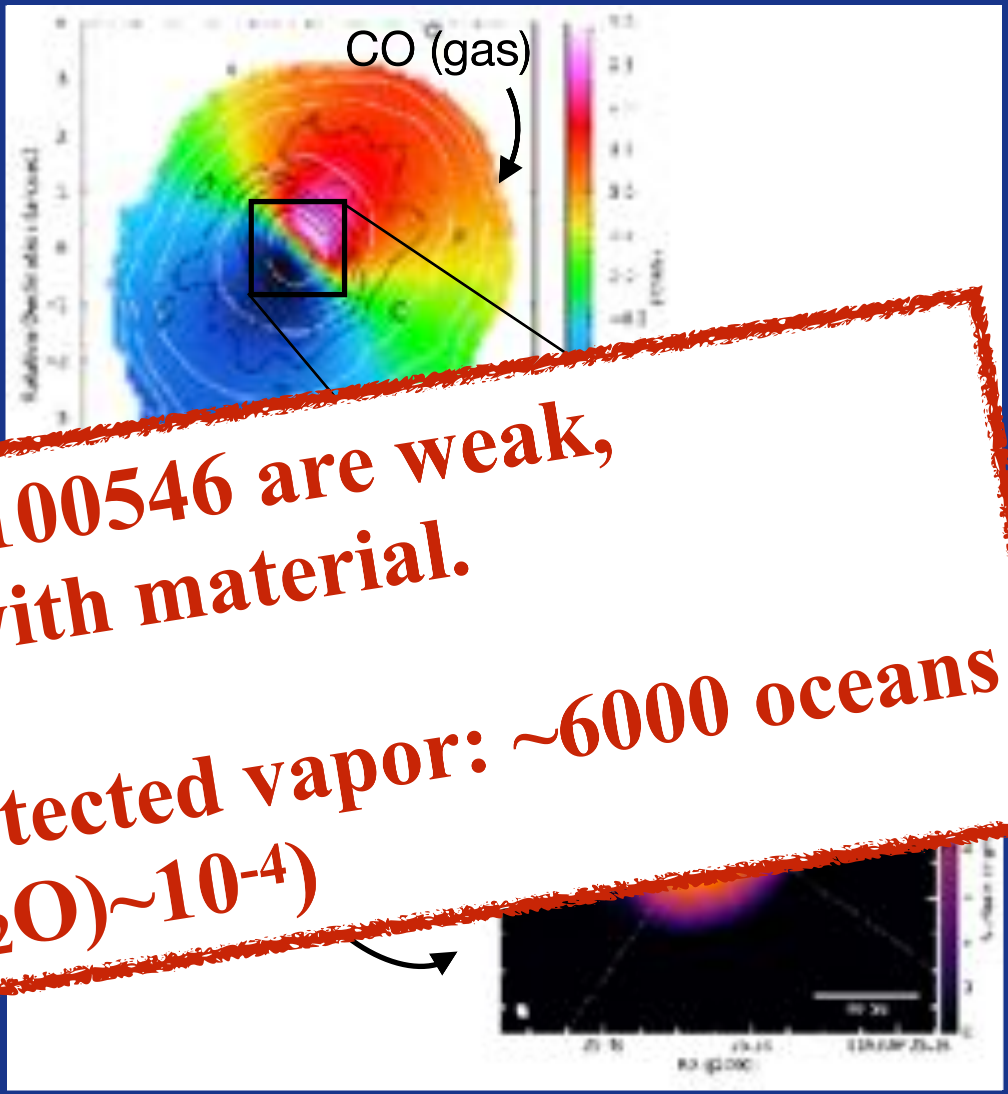


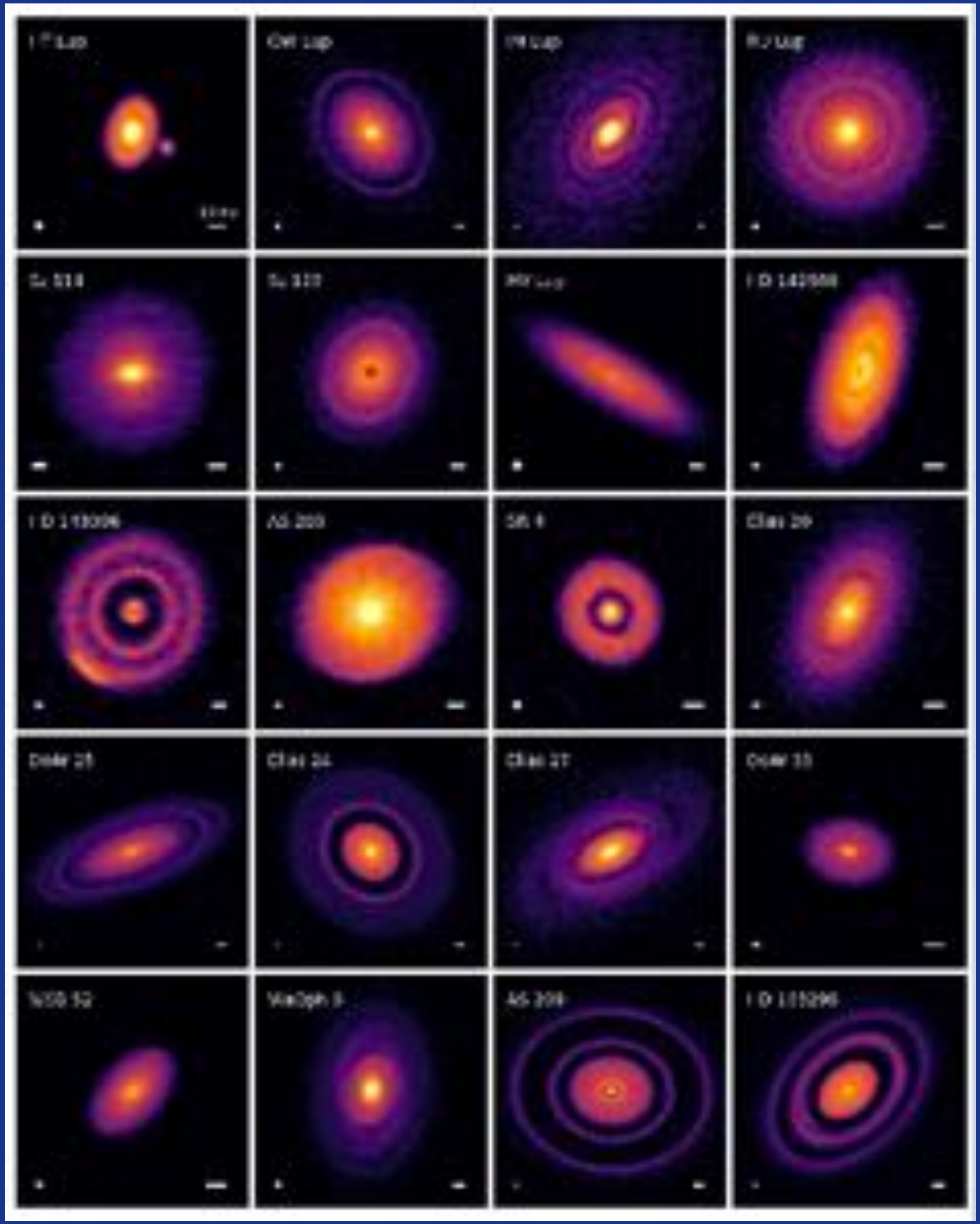
Water lines in TW Hya and HD100546 are weak, because disk is not 'filled' with material.

Water ice reservoir that underlies the detected vapor: ~6000 oceans (as expected for $X(H_2O)\sim10^{-4}$)

Walsh et al. 2014; Pineda et al. 2018

ALMA: disks have gaps, rings, …

- …so H_2O will be weak everywhere

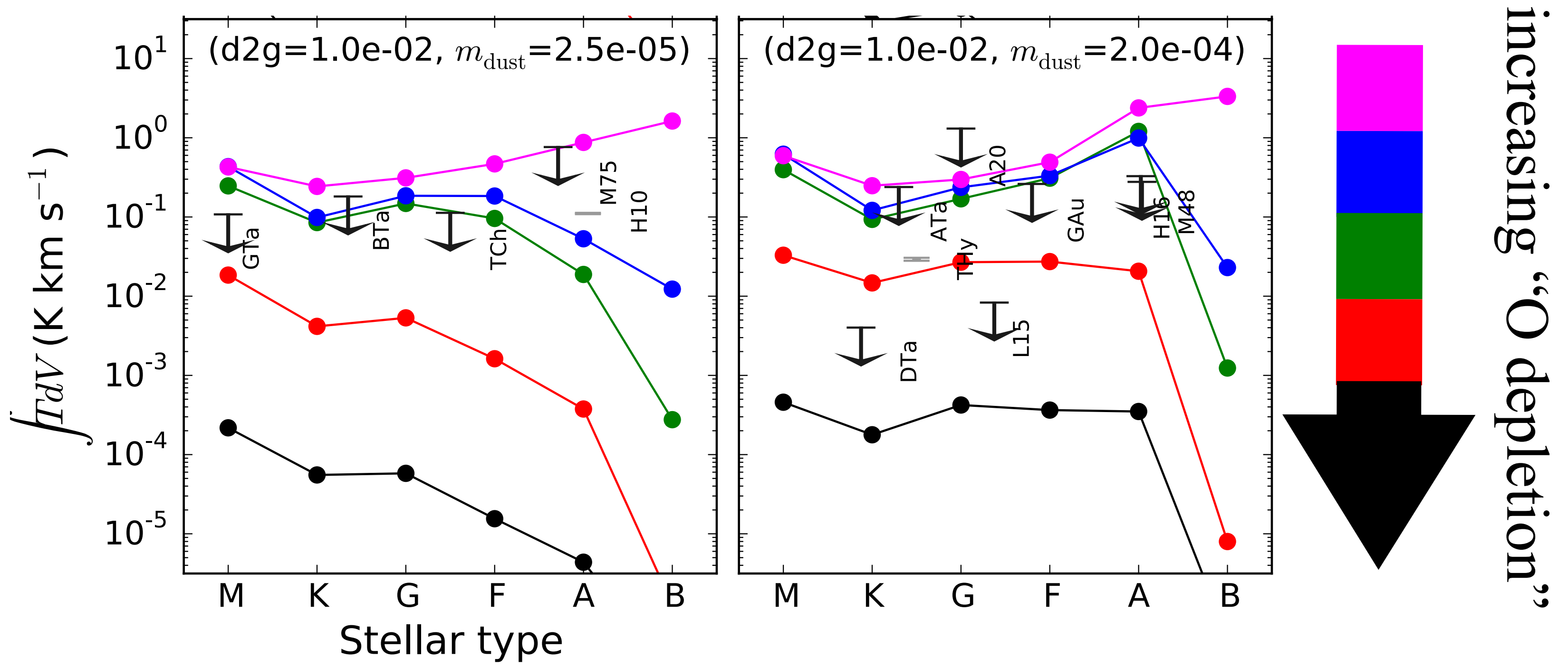


DSHARP: Andrews et al. (2018)

Overall reduction of water emission

Full Herschel sample, H_2O 110-101 (557 GHz)

m_{dust}=2×10^{-5} M_{sun} m_{dust}=2×10^{-4} M_{sun}



→ most disk need ×10 to ×100 reduction of available water to fit observations

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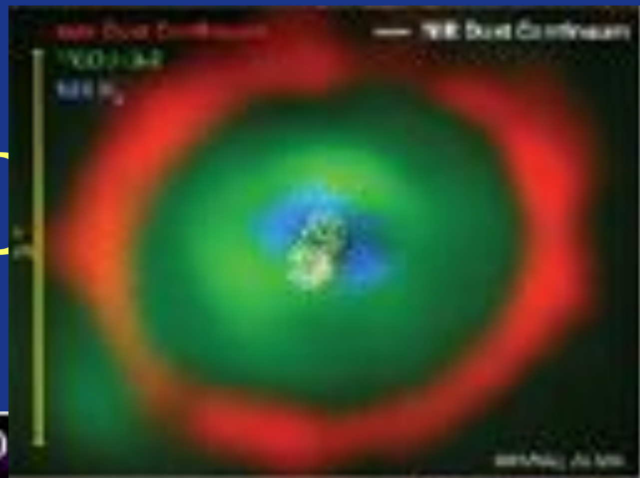
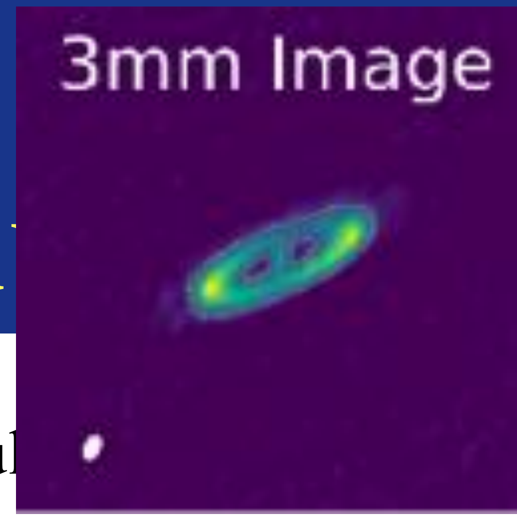

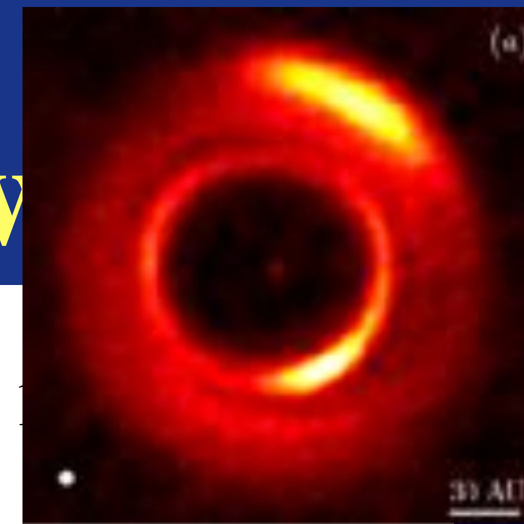

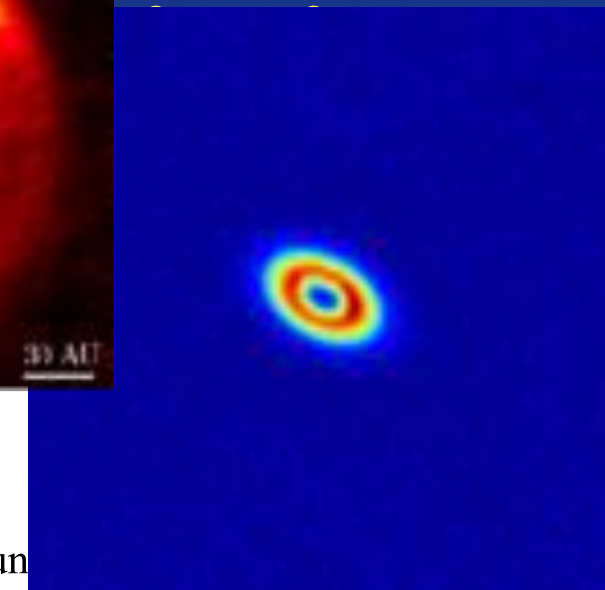
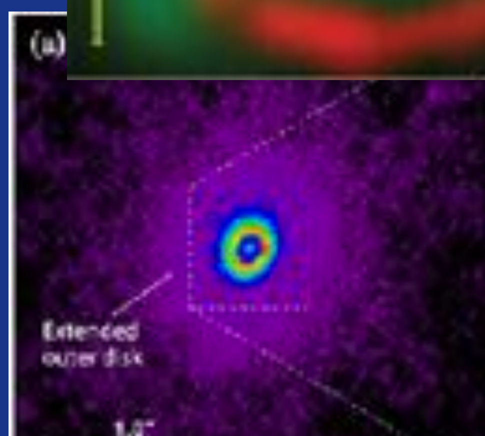

ul ... H_2O

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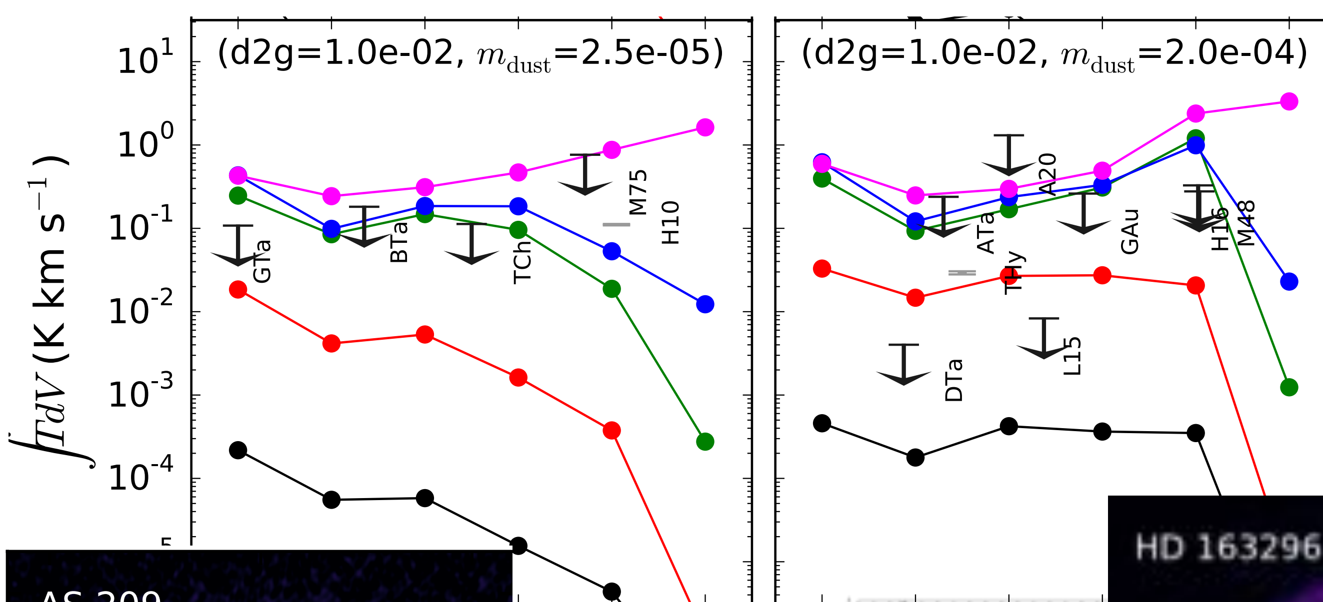
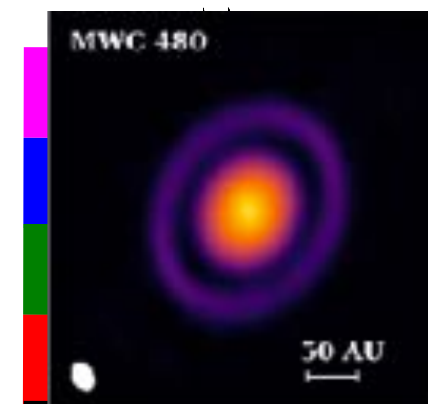
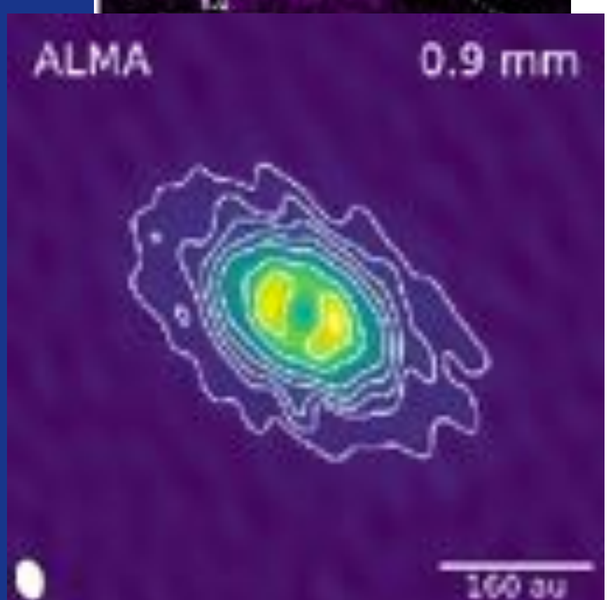
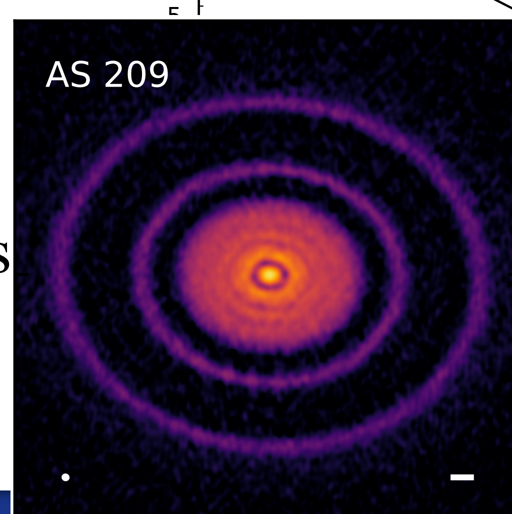
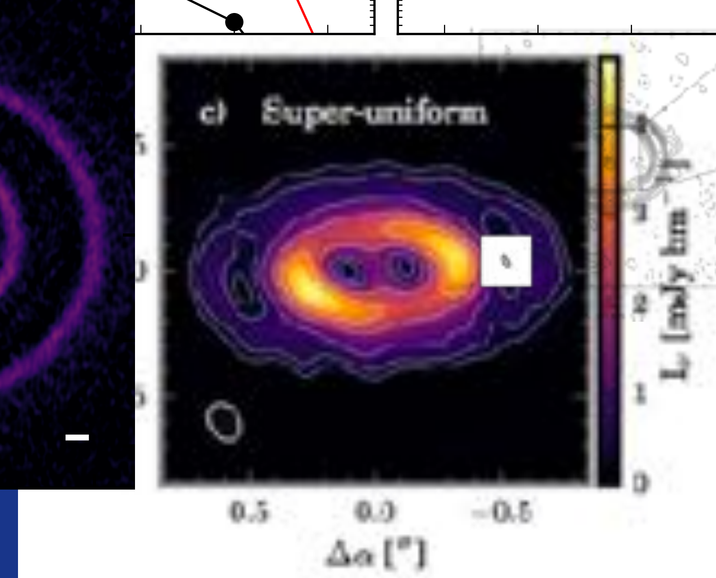
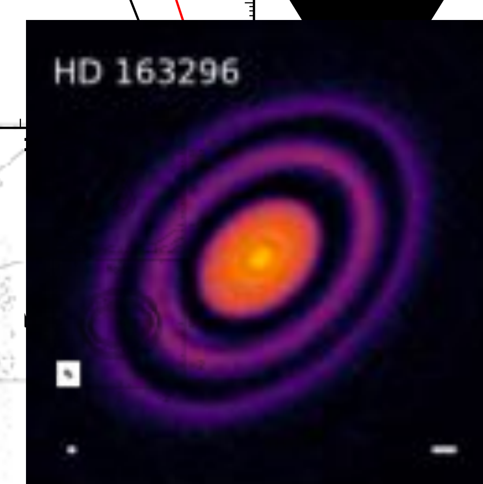








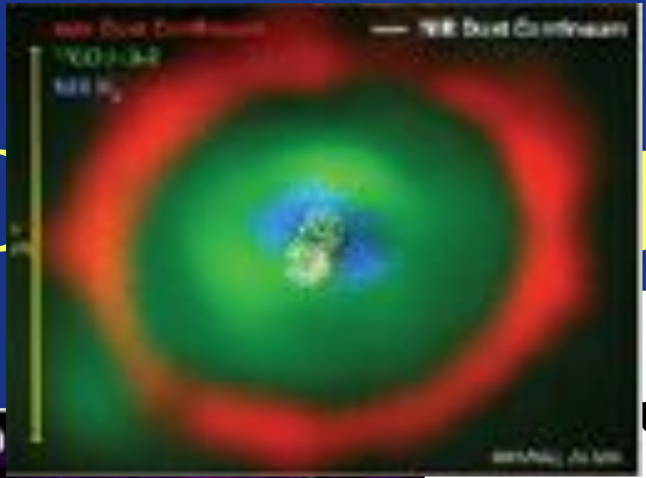


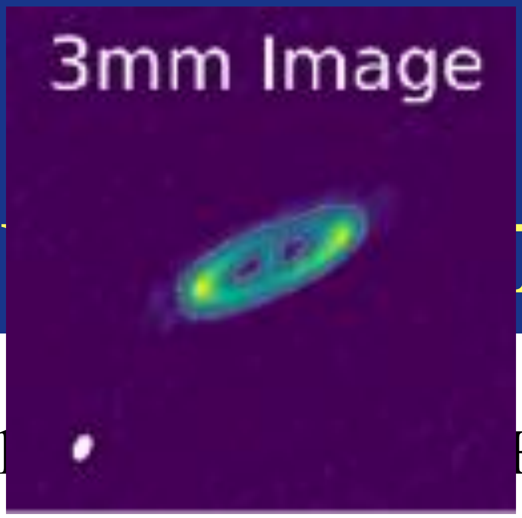


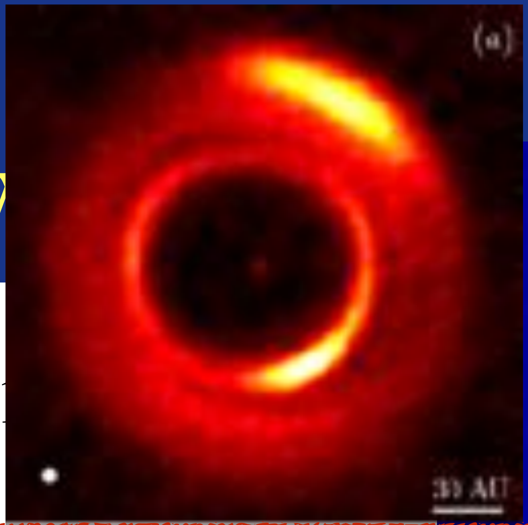
epletion”

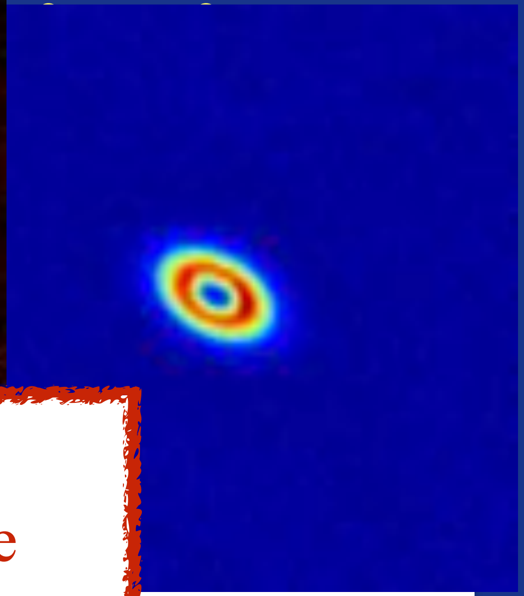
→ most dis ... tions

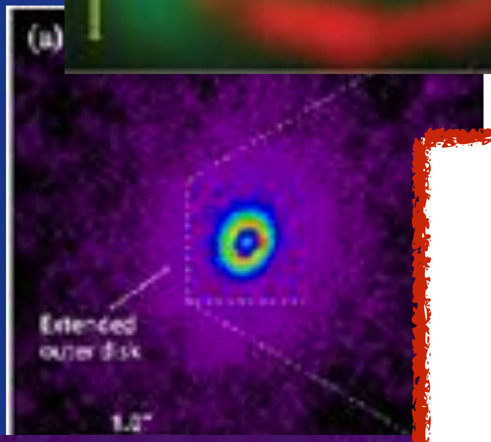
Full Herschel sample: Du et al. (2017)

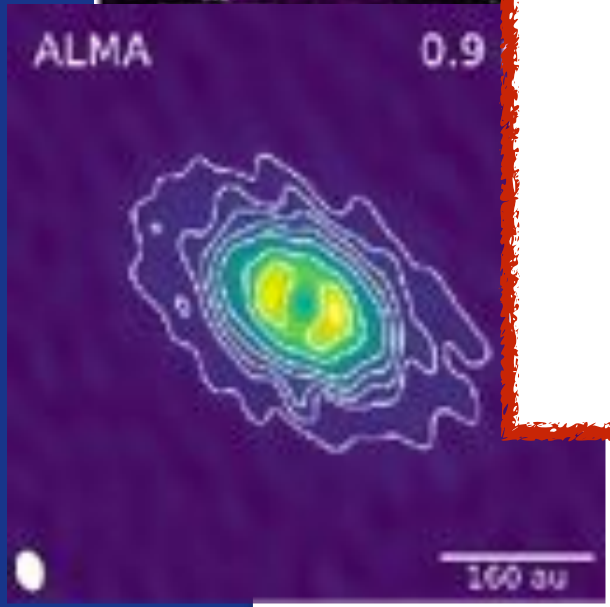


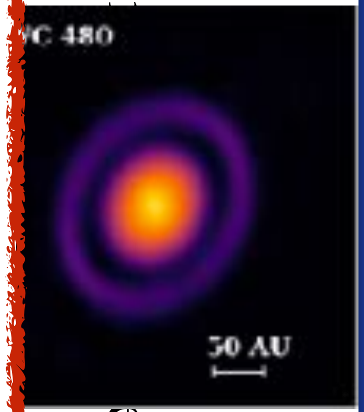






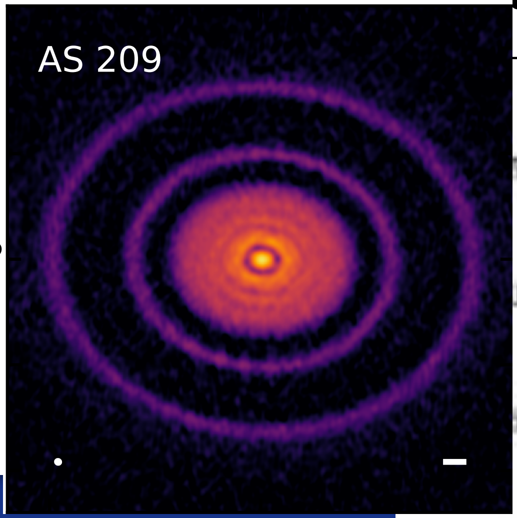


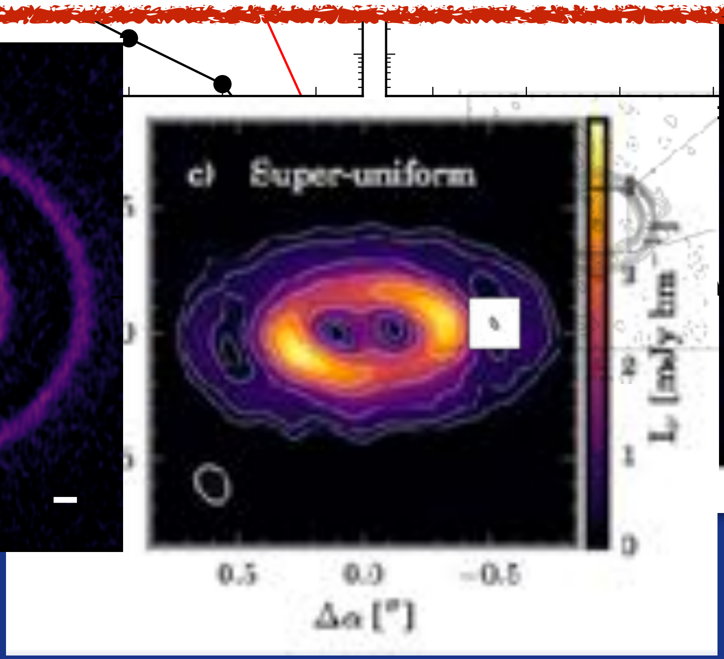




→ most disk need ×10 to ×100 reduction of available water to fit observations
→ all observed disks turn out to have gaps/rings, cavities…

⇒If H_2O vapor largely follows mm-sized grains, non-detections with Herschel are to be expected



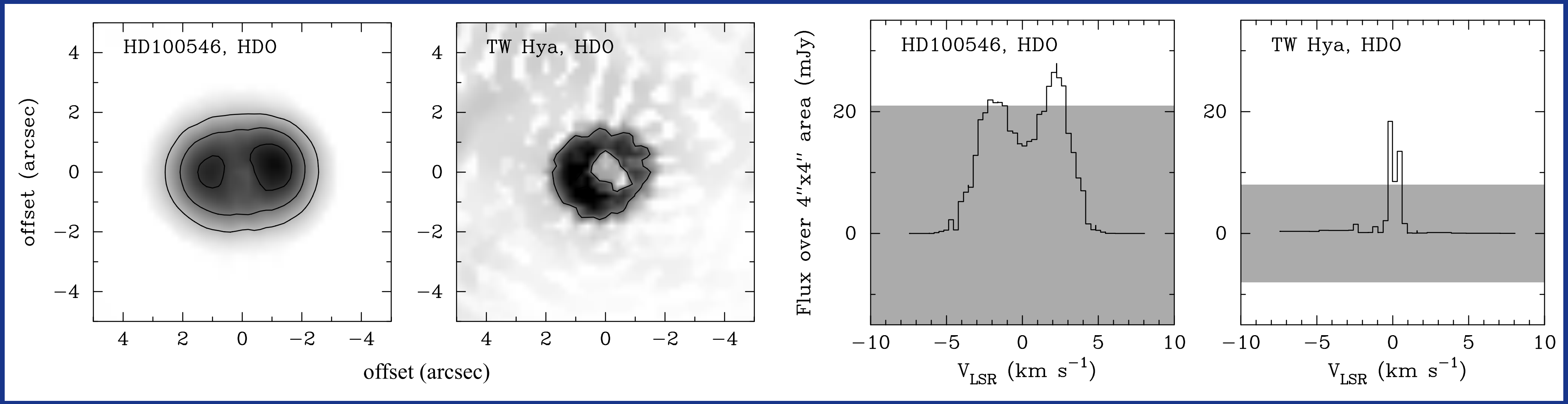


→ most dis … tions

Full Herschel sample: Du et al. (2017)

Water with ALMA

- Strong water lines are by definition off-limits for ALMA
- Leaves
  - isotopic lines: HDO, $H_2{}^{18}O$
    - weak! Simulation for 14 hrs ALMA, adopting a high HDO/H_2O of 10^{-2}; longer for $H_2{}^{18}O$



  - excited lines: 3_{13}-2_{20} 183 GHz line
    - also predicted to be weak → requires >1 day of observing time
    - possibly a maser line !

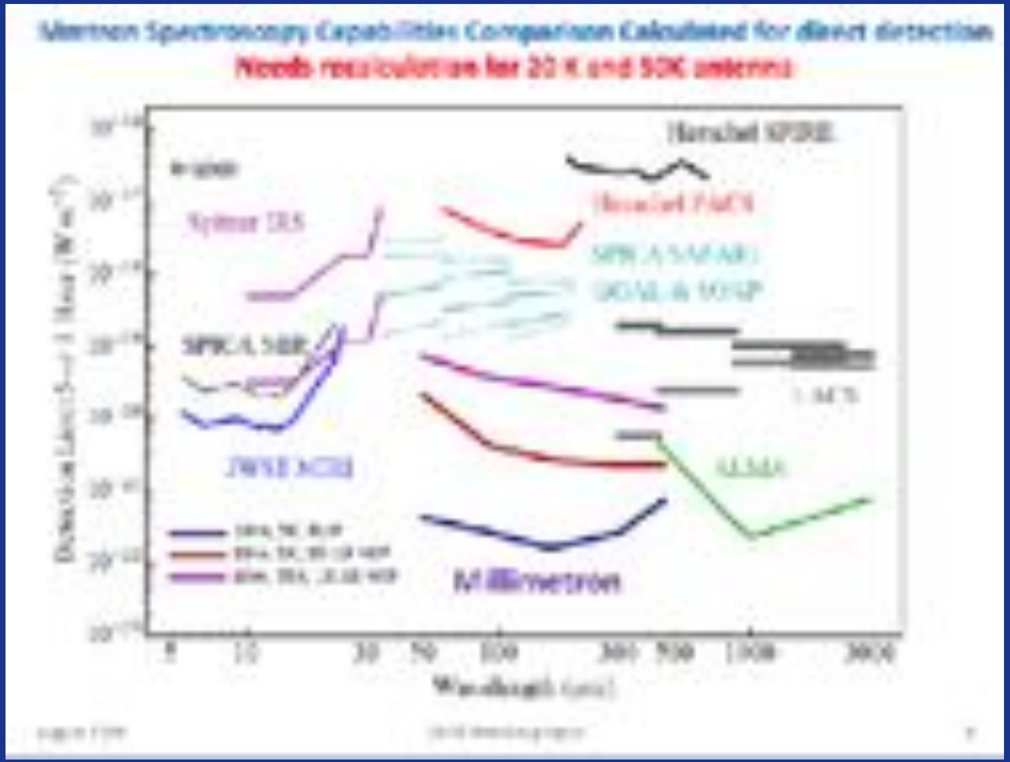
Water with millimetron

- Compared to Herschel: Larger collecting area (+less beam dilution), cold reflector, MHIFI better sensitivity
- Search for ground-state transitions of ortho- and para-water

  - in a larger sample for disks: population statistics
    - Herschel integration times 10-20 hrs
    - Same sensitivity with mmtron in ~1 hr
  - deeper searches of 10+ hrs on selected targets

  - “better” targets based on ALMA mm-dust imaging

  - also cover NH_3 1_0-0_0
  - also cover higher excitation water lines (~PACS)



Summary

- Planet forming disks inherit a large water reservoir ($X(H_2O) \sim 10^{-4}$)
  - either frozen out on grains
  - or as vapor and subsequently recondensed (→affects HDO/H_2O and D_2O/HDO)
- *Warm* water is detected in inner AU of disks (lost to planet formation…)
- *Water ice* is detected in a few disks (difficult…)
- *Cold water vapor* is detected by Herschel/HIFI toward HD100546 and TW Hya
  - at levels below expectation
    - possibly water ice locked up in larger bodies that have settled to midplane
    - likely that *disk structure* (gaps/rings/cavities) reduces emitting surface

    - ⇒ cold H_2O vapor originates from ices coincident with mm-sized grains

- **ALMA struggles to detect H_2O vapor, but millimetron has an opportunity to survey 10+ disks**