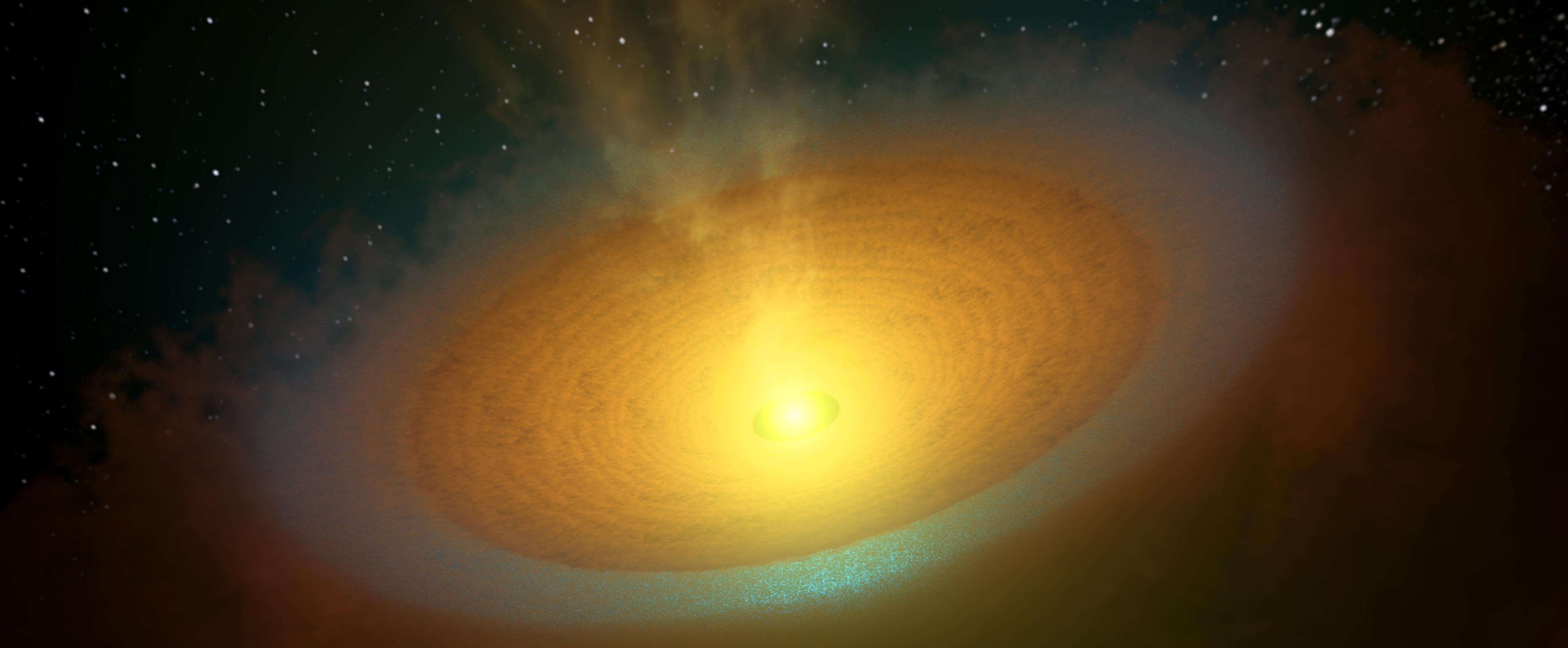
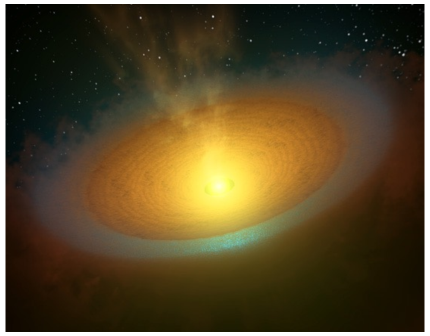


Finding Cold Water Vapor in Planet-forming Disks

Michiel Hogerheijde | *Leiden Observatory*

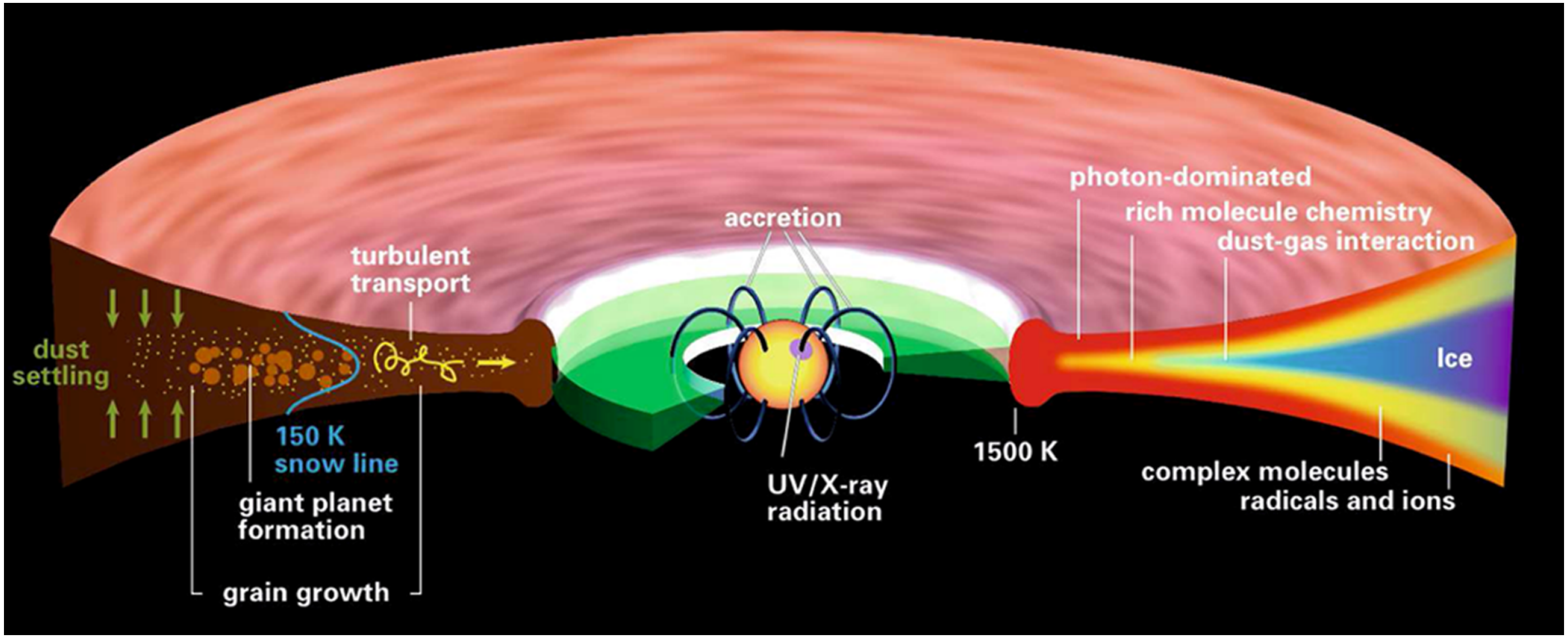
Ted Bergin, Ilse Cleeves, Geoff Blake, Christian Brinch, Carsten Dominik, Kees Dullemond, Lars Kristensen, Darek Lis, Gary Melnick, David Neufeld, Olja Panić, John Pearson, Vachail Salinas, Umut Yıldız, Ewine van Dishoeck

WISH

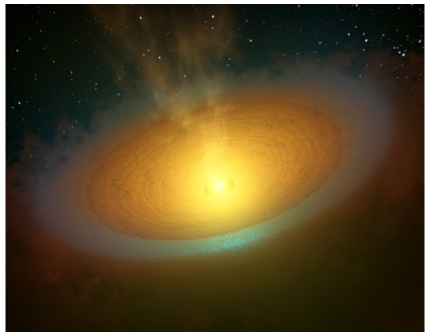


Planet-forming Disks

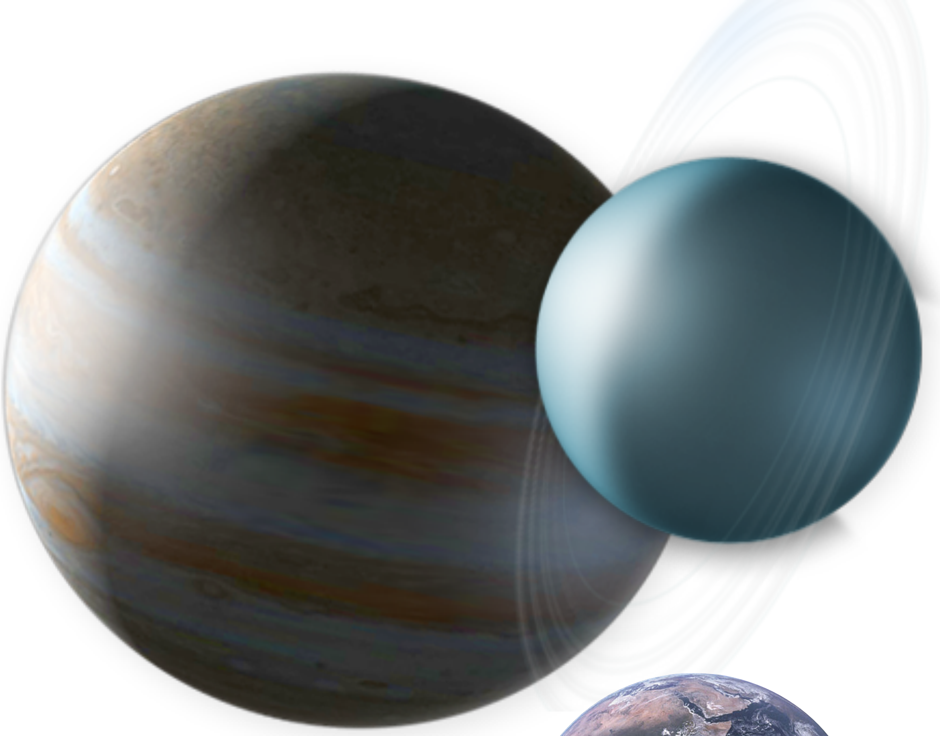
- Planets form in disks around young stars
- Basic structure:
  - hot | warm | cold
  - photoionized | molecular | ice



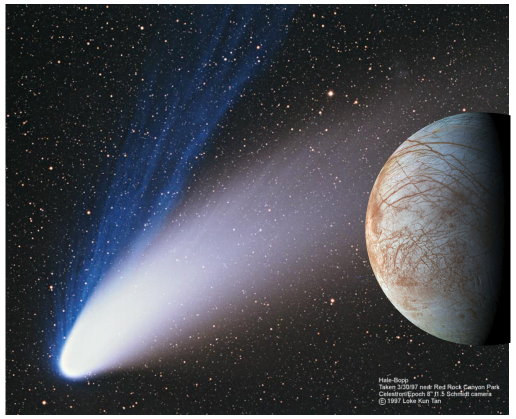
Henning & Semenov (2013)



Volatiles in disks



- Major volatile species frozen out in disks
  - H_2O, CO but also NH_3, CH_3OH, CO_2 , …
- Ices promote grain growth → planetesimals
  - Ice/rock cores of giant planets
- Reservoir for impact delivery to newly formed rocky planets
  - Oceans and atmospheres of terrestrial planets
  - Icy moons
  - Comets



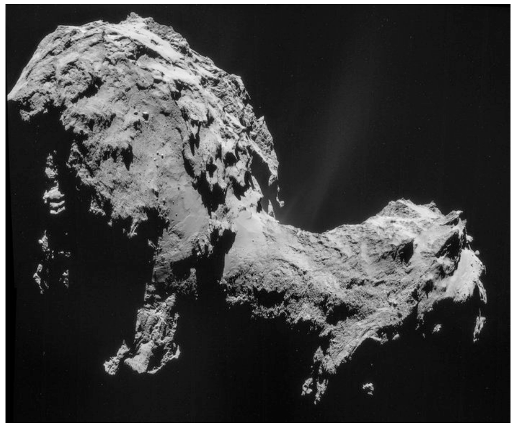
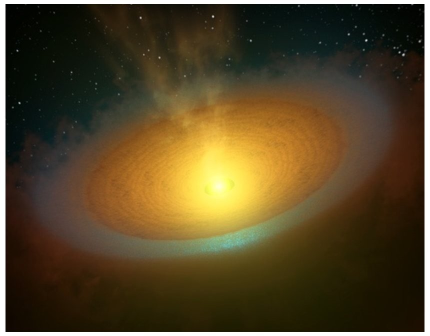
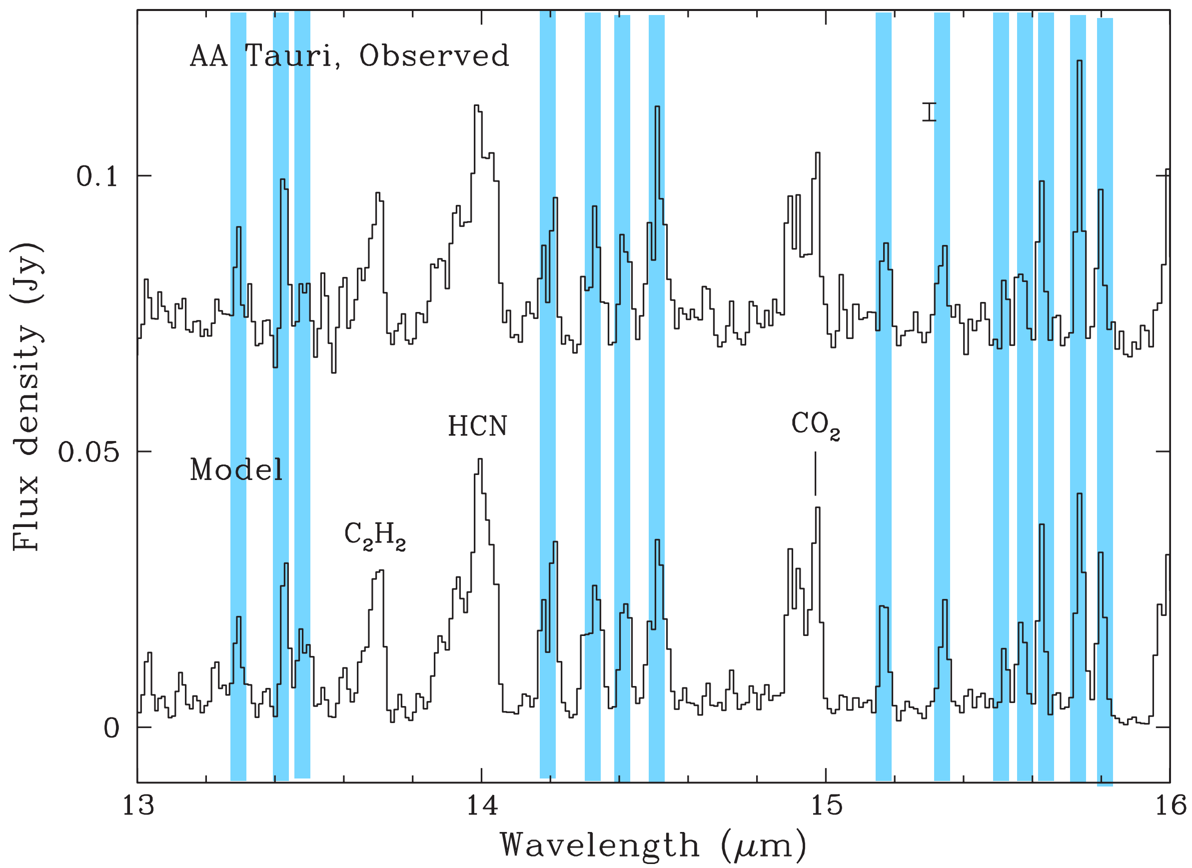


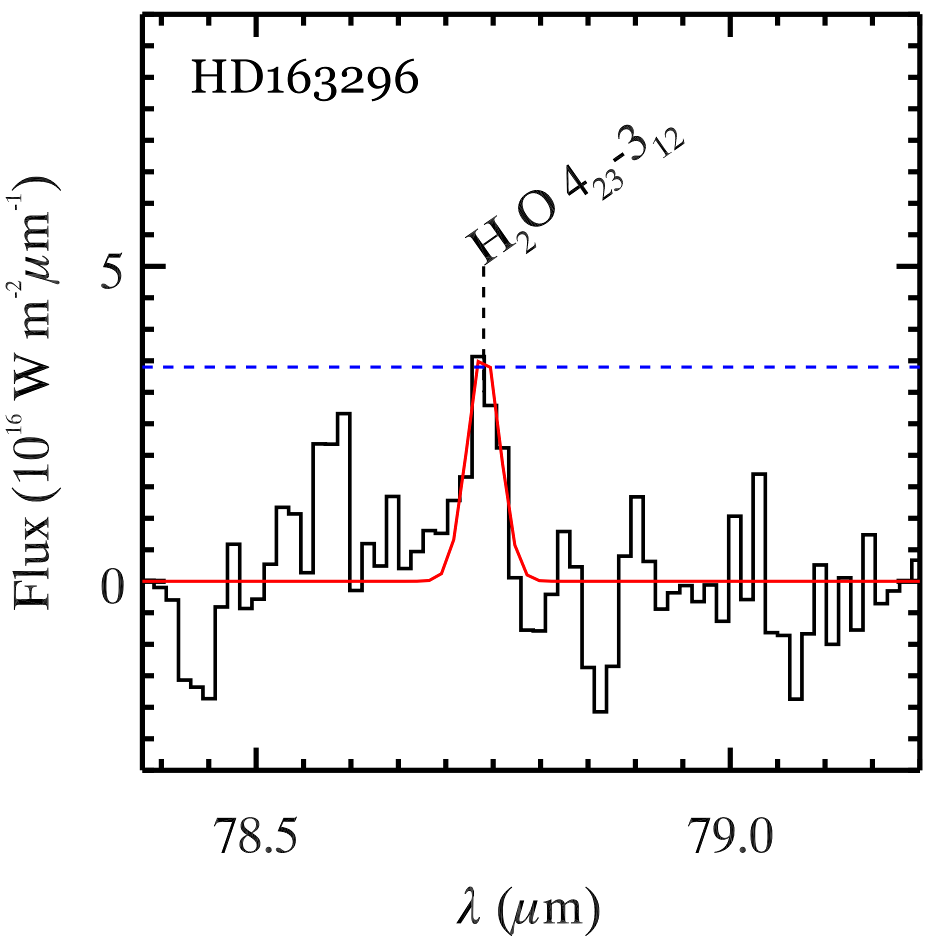
Image credits: ESA/NASA



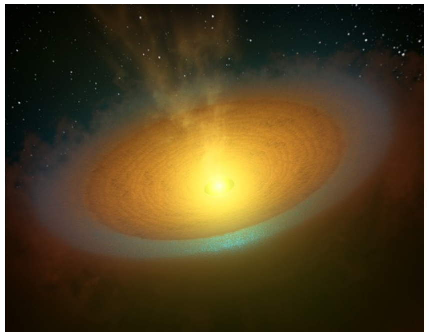
Warm/hot water in disks

- *Spitzer*, Herschel, VLT/CRIRES: warm (>100 K) water in disks
- Sudden drop in gas-phase abundance beyond few au: snow line





Carr & Najita (2008); Salyk et al. (2008, 2015); Pontoppidan et al. (2010); Meijerink et al. (2009); Zhang et al. (2013); Fedele et al. (2012); Riviere-Marichalar et al. (2012)

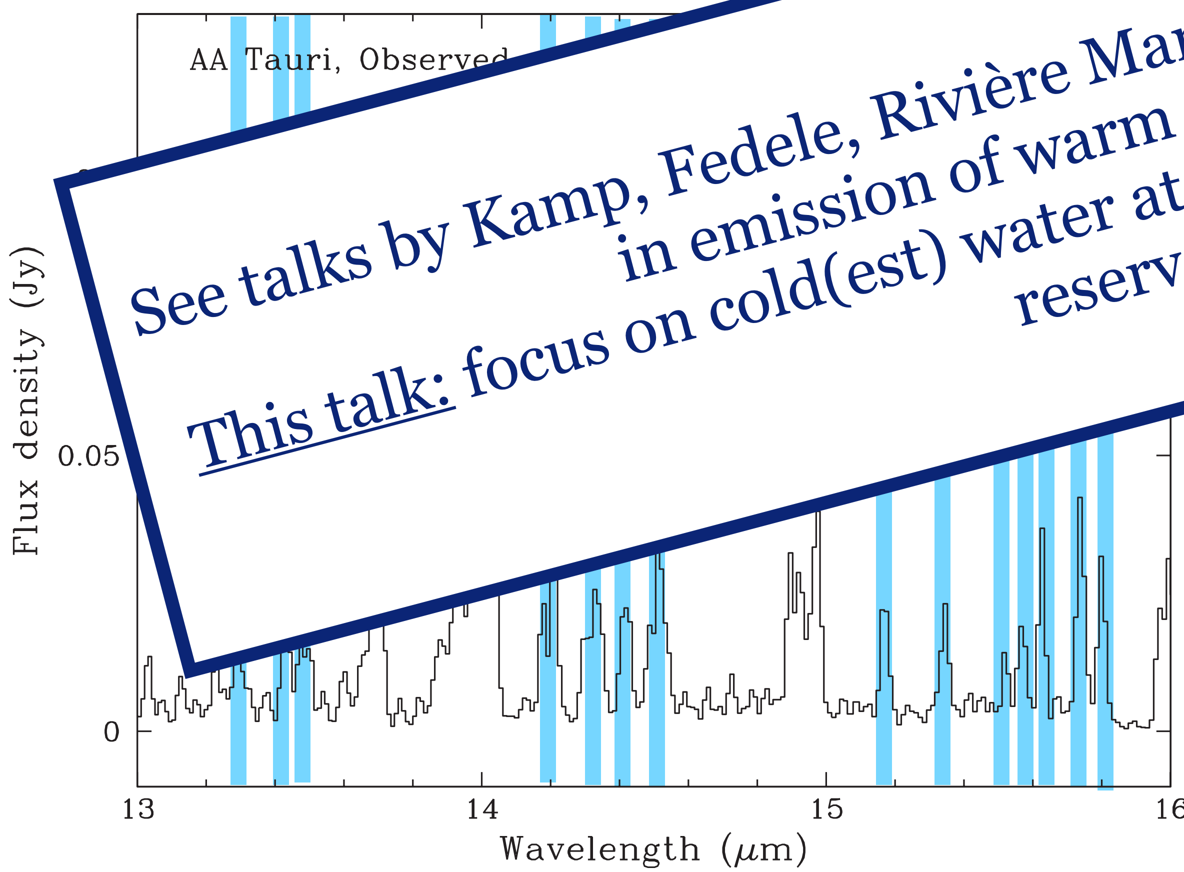


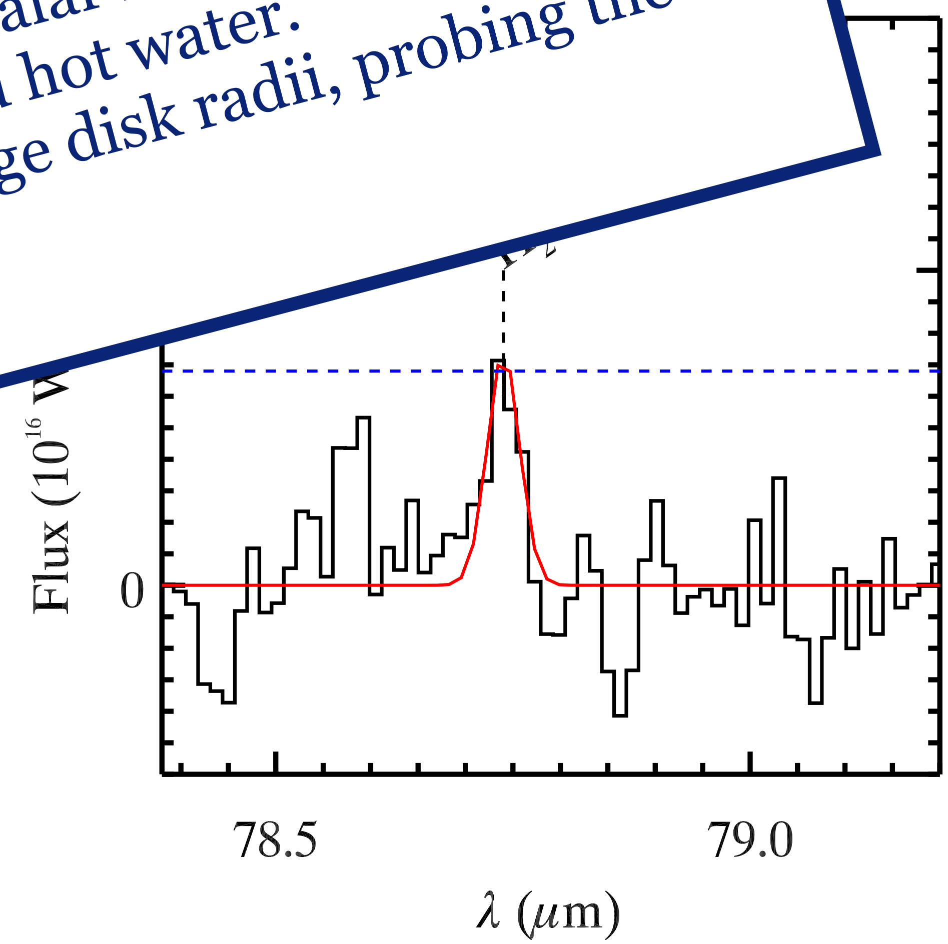
Warm water in disks

- *Spitzer*, Herschel, VLT/CRIRES: warm (>100 K) wate
- Sudden drop in gas-phase abundance be

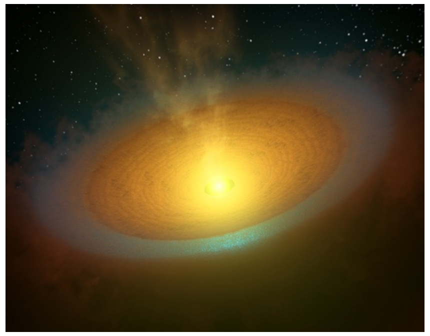
See talks by Kamp, Fedele, Rivière Marichalar for disk regions probed in emission of warm and hot water.

<u>This talk:</u> focus on cold(est) water at large disk radii, probing the ice reservoir



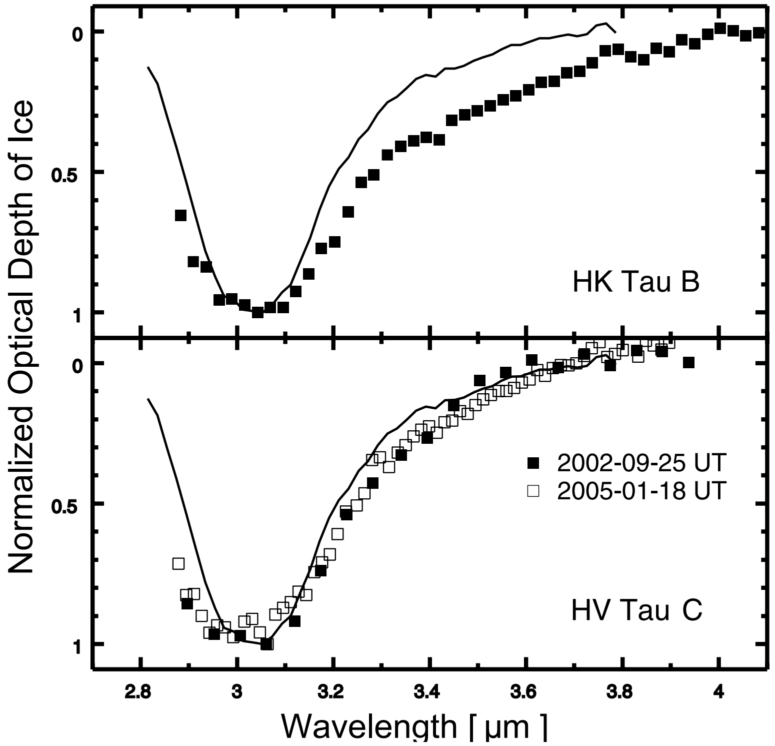


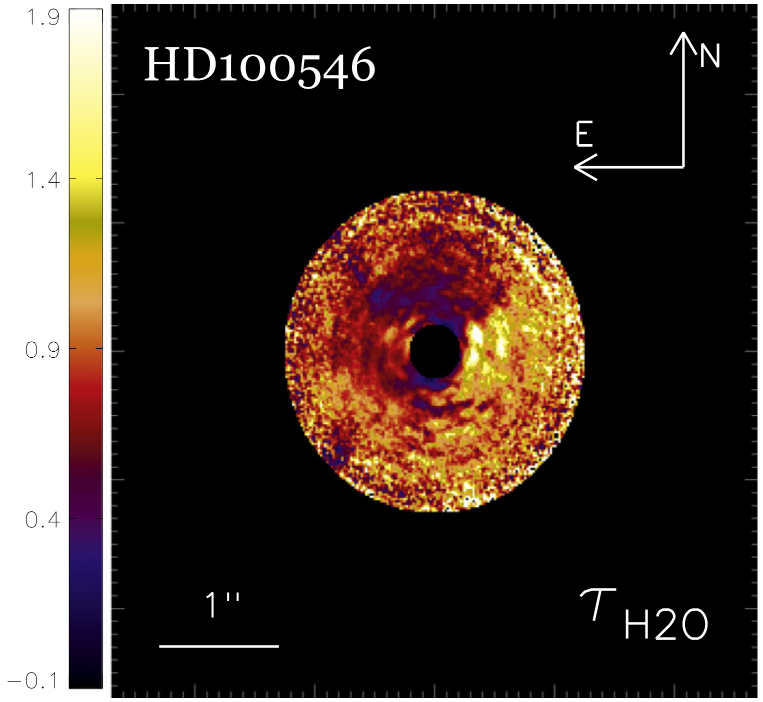
Carr & Najita (2008); Salyk et al. (2008, 2015); Pontoppidan et al. (2010); Meijerink et al. (2009); Zhang et al. (2013); Fedele et al. (2012); Riviere-Marichalar et al. (2012)

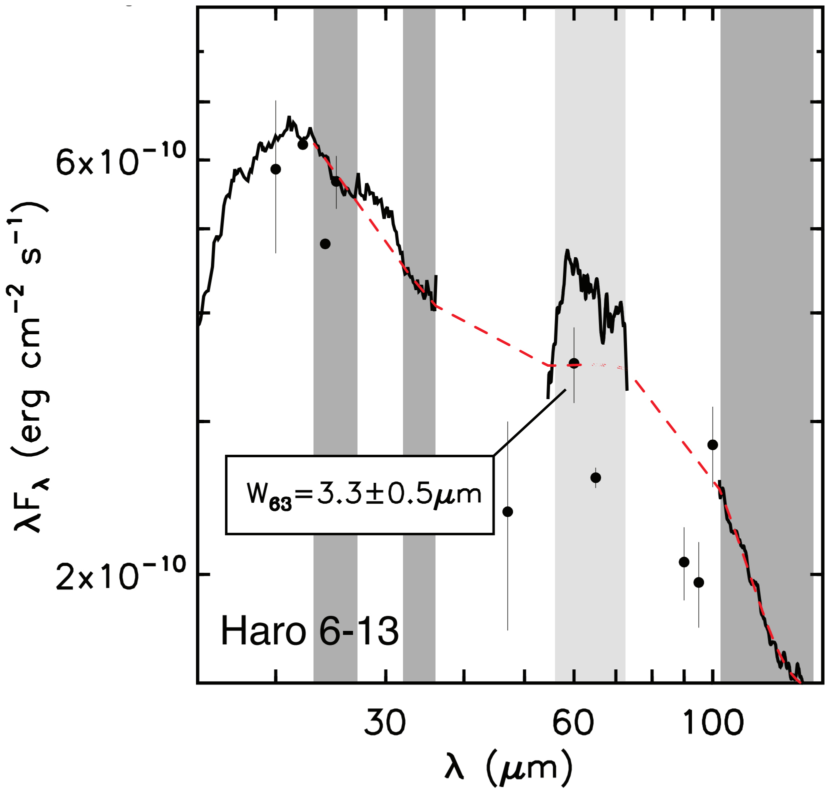


Ice in disks

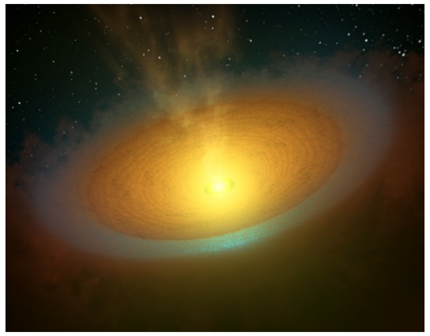
- Direct evidence for ices in disks
  - scattered light / absorption 3 μm
  - *Herschel*: emission 47 μm (amorphous), 63 μm (crystaline)





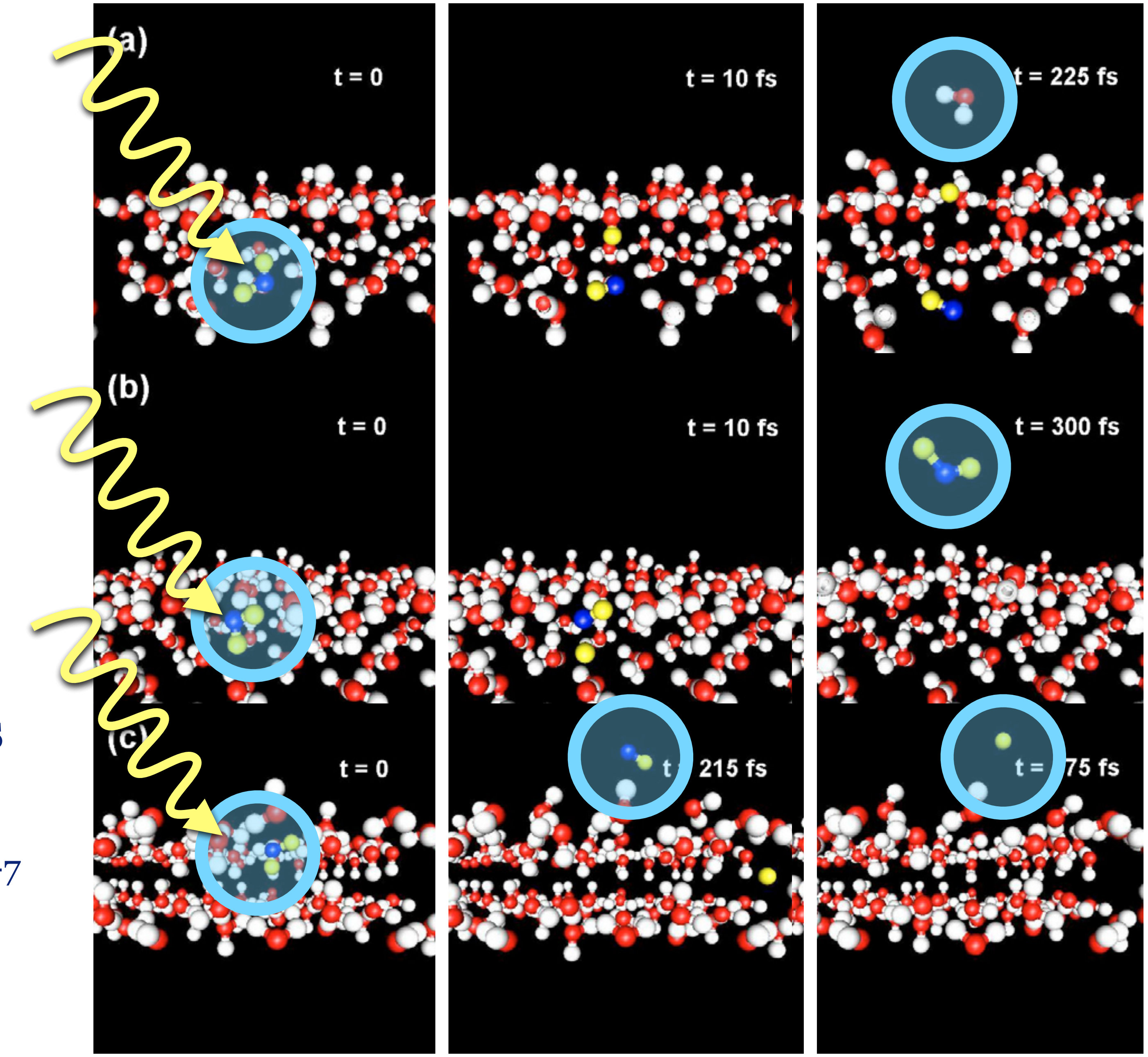


Terada et al. (2007, 2012); Honda et al. (2009, 2016); McClure et al. (2012, 2015); Bouwman et al. (in prep)



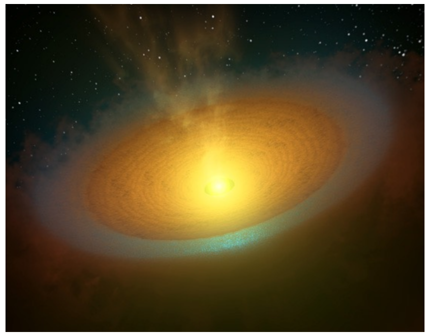
Photodesorption of water ice

- (Inter)stellar ultraviolet photons can librate H_2O from the ice: photodesorption
- Balanced by photodissociation → equilibrium column density ~independent of UV flux
- **Water vapor should exist in the UV irradiated surface of any disk *if* ice covered grains are present**
  - peak abundance w.r.t. H_2 ~10^{-7}



time →

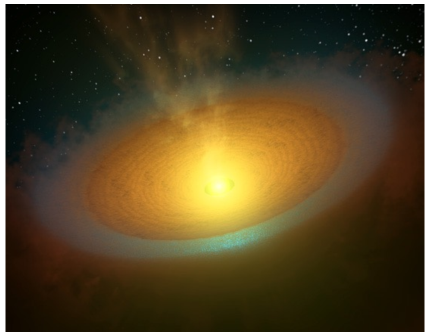
Dominik et al. (2005); Hollenbach et al. (2009); Andersson et al. (2006, 2008); Öberg et al. (2009)



Herschel Observations

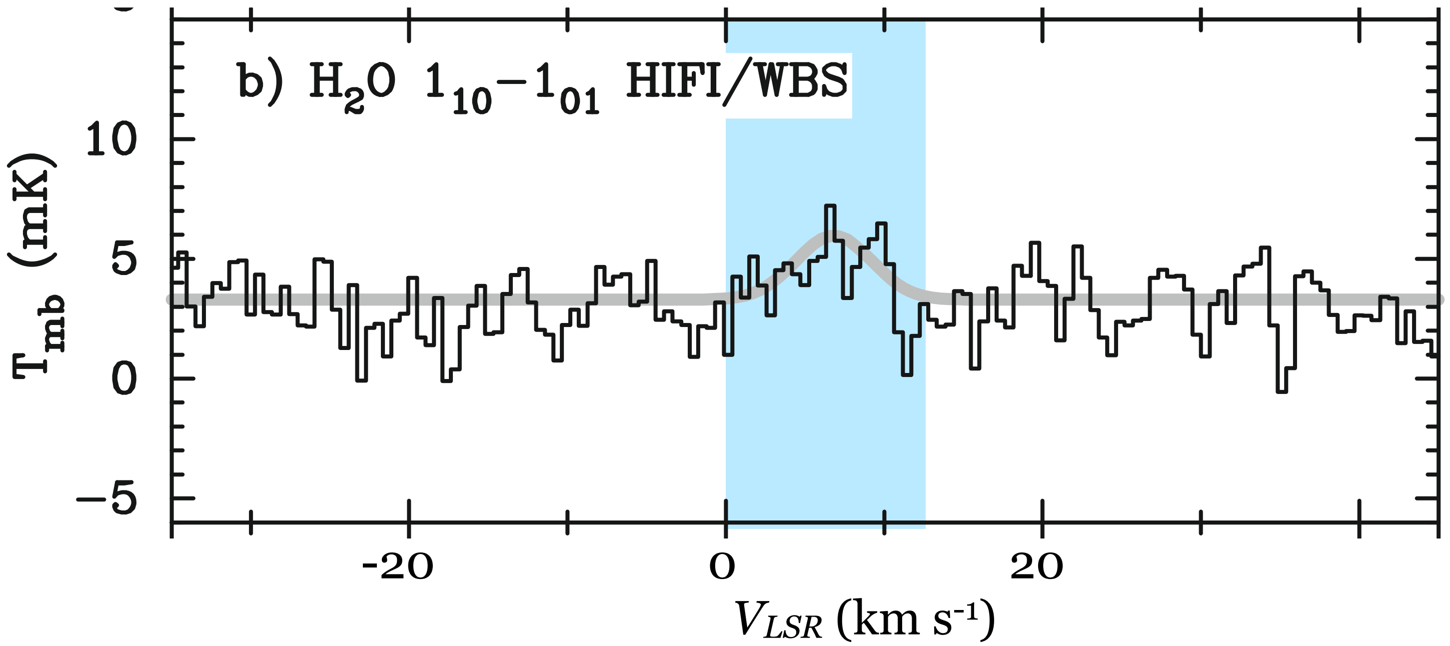
- *Herschel* Guaranteed Time Key Program: Water in Star-forming Regions
- *Herschel* Open Time observations
- Rotational ground state lines
  - ortho-H_2O 1_{10}-1_{01} (557 GHz)
    - **TW Hya, DM Tau, AA Tau, HD100546,** Lk Ca15, MWC 480: t_{obs}=6-15 h
    - shallow sample (8 disks*): t_{obs}=30 min
  - para-H_2O 1_{11}-0_{00} (1113 GHz)
    - **TW Hya, DM Tau, AA Tau, HD100546,** HD163296: t_{obs}= 11–31 h
- *Herschel*'s large beam (19"-38") does not resolve disk and only samples cold, outer disk

*) AS209, BP Tau, GG Tau, GM Aur, MWC758, T Cha, Im Lup, HD163296



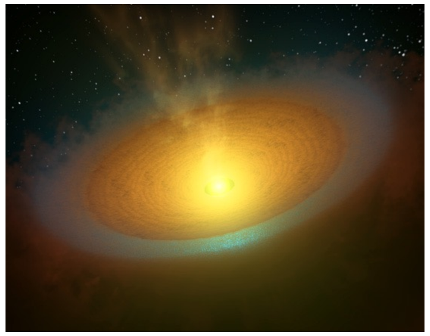
Tentative detection: DM Tau

- *Tentative* detection of H_2O 1_{10}-1_{01}: 2.7 mK
    - Partial, WISH data only



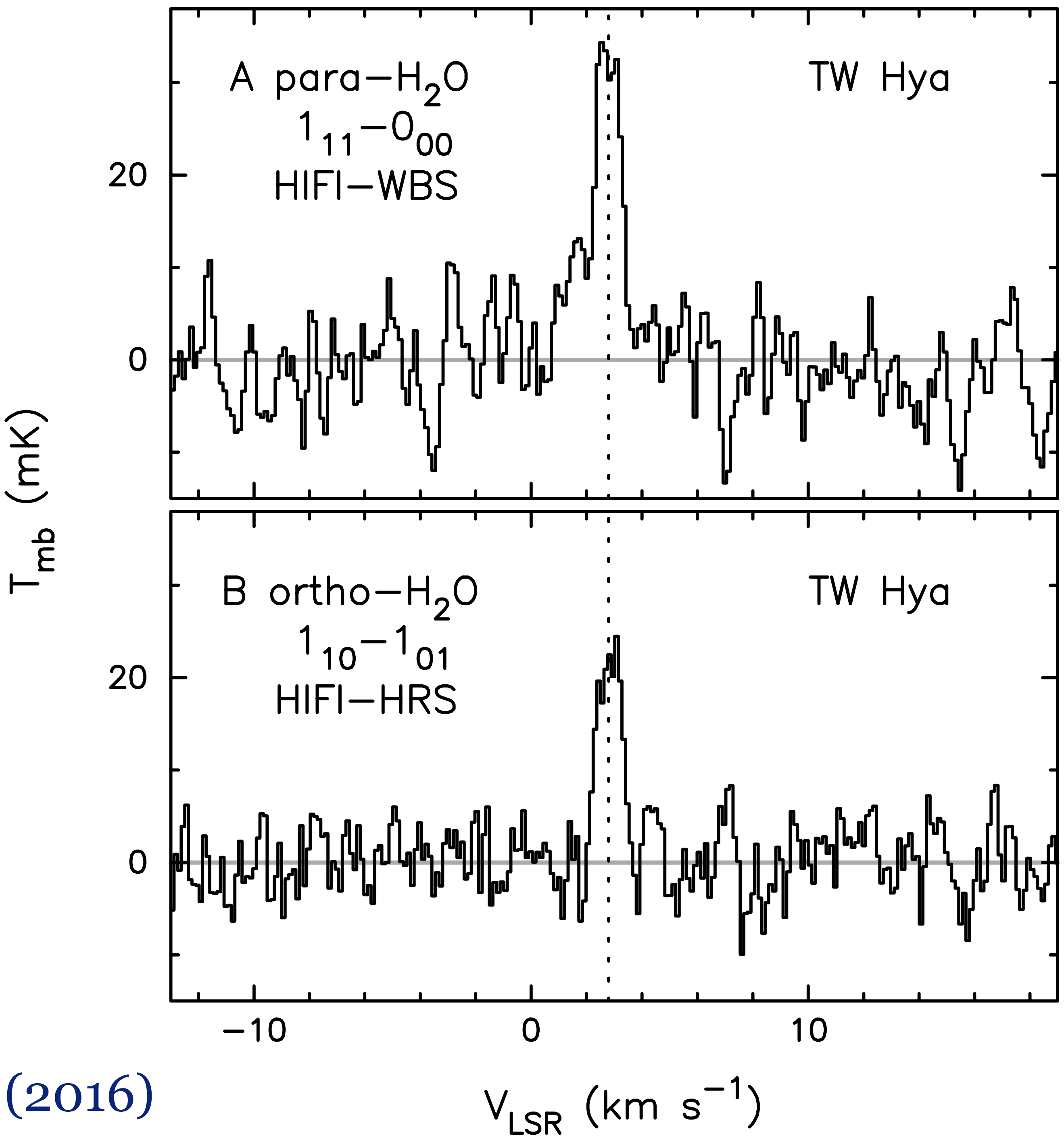
Bergin et al. (2010)

- Irrespective of detection or upper limit:
    - Much weaker than expected if ices intermixed throughout disk
    - Low ice abundance in UV irradiated zone (reduced to <5%)
    - Locked up in large(r) grains that have settled to the midplane?

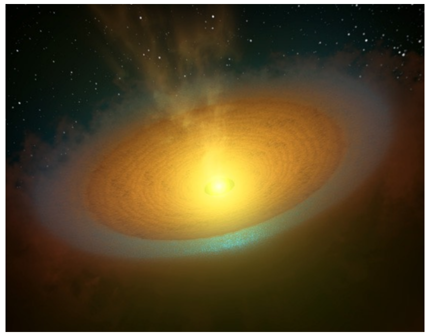


First clear detection: TW Hya

- Firm detection (20-30 mK)
  - factor 3–5 lower than expected if ices intermixed throughout 200 au disk
- Both spin isomers
  - OPR ratio

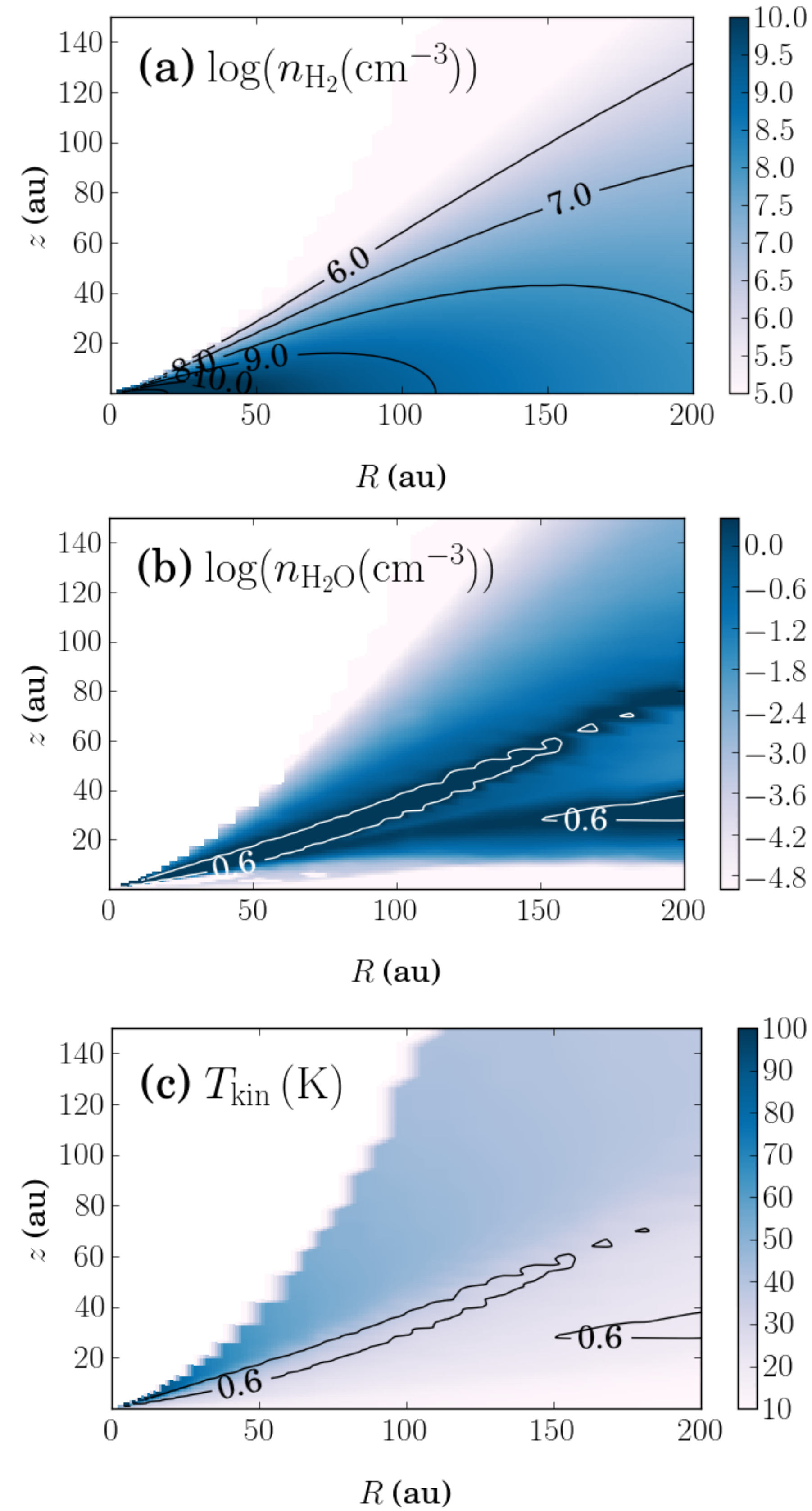


Hogerheijde et al. (2011); Salinas et al. (2016)

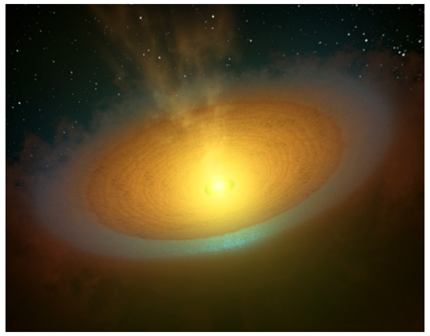


Settling of icy grains

- Modeling attempt 1: fully intermixed icy grains
- Results in lines too bright by factor 3–5
- Chemistry from Fogel et al. (2011), Cleeves et al. (2014); photodesorption rate from Öberg et al. (2009)
- Non-LTE excitation and radiation transfer: LIME: Brinch & Hogerheijde 2010
- Settling of (larger) icy grains
  - factor 10 depletion in UV irradiated zone
  - 7.3×10^{21} $M_\odot$ of water vapor
  - apparent low OPR of 0.8±0.1

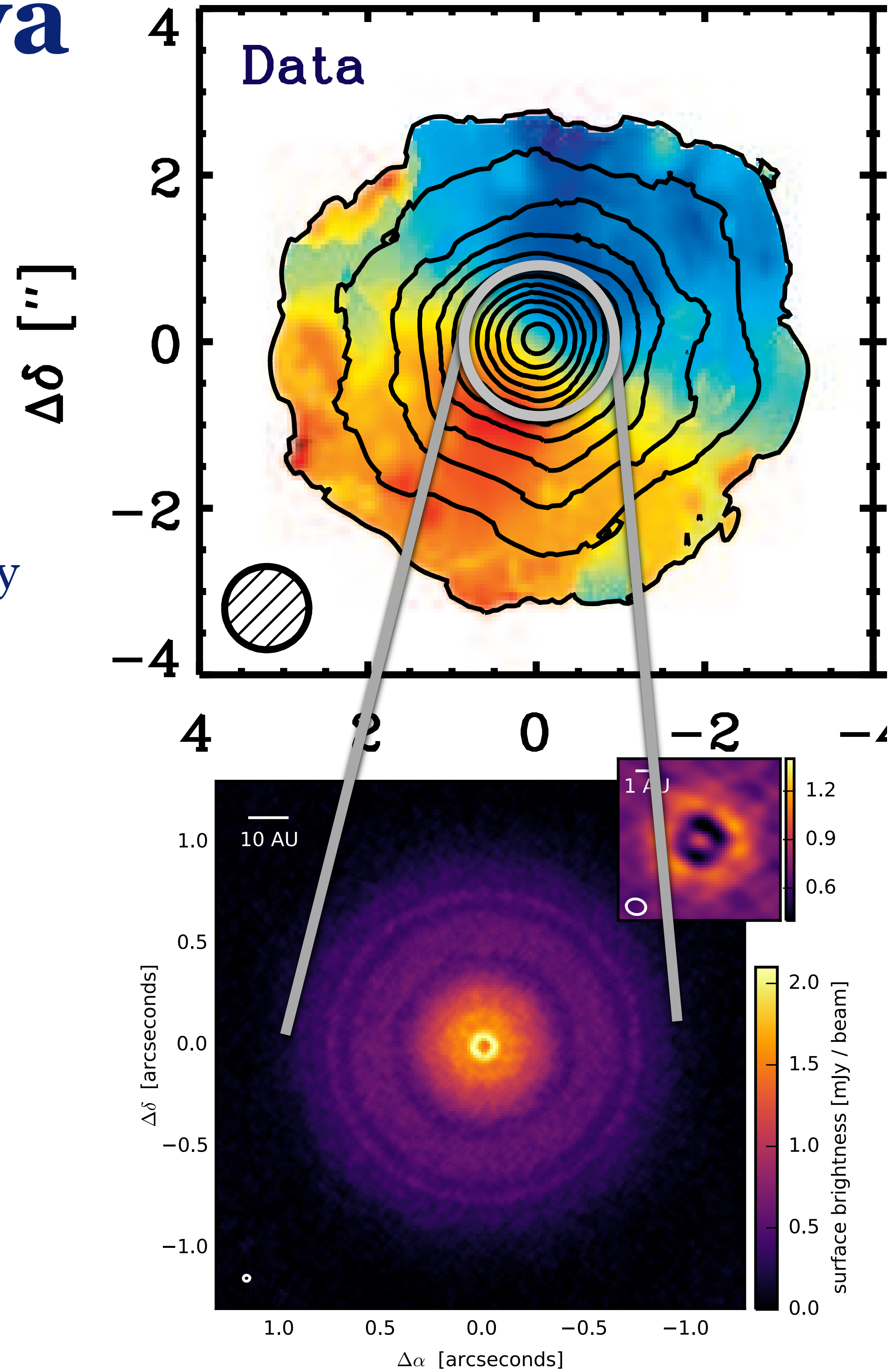


Hogerheijde et al. (2011); Salinas et al. (2016)

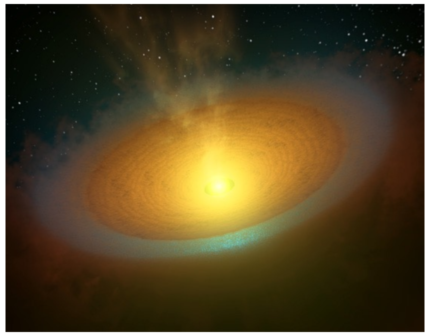


Grains in TW Hya

- Millimeter-sized grains in TW Hya have drifted radially
- Locked in series of rings/gaps
- Settling is faster than drift: these grains surely must have settled

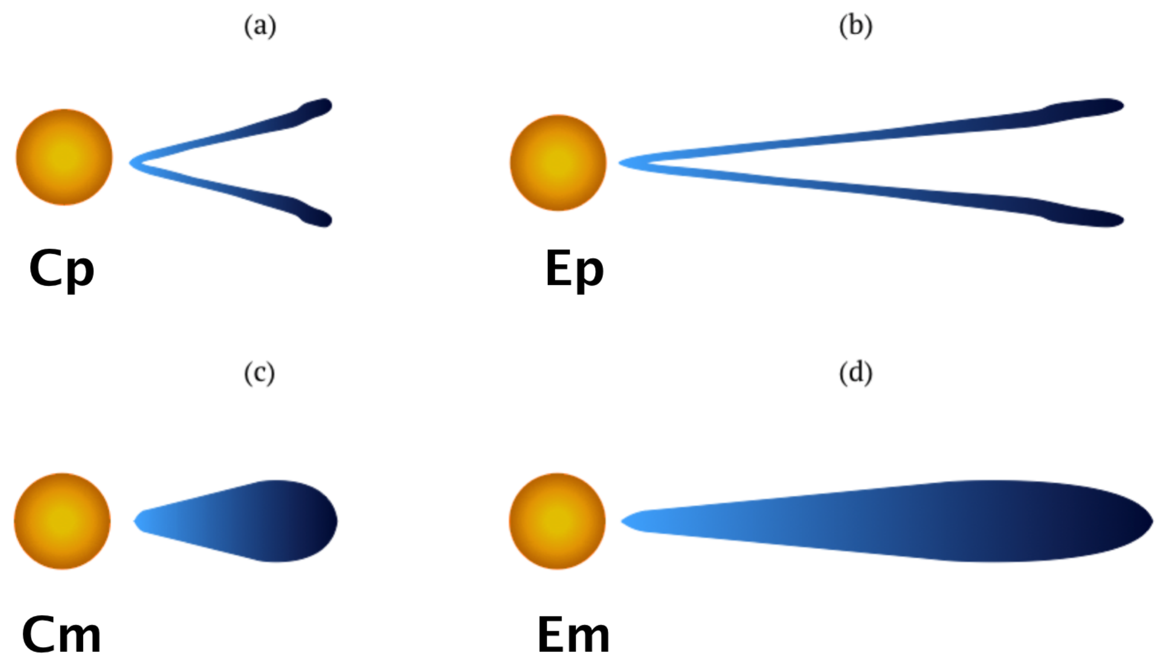


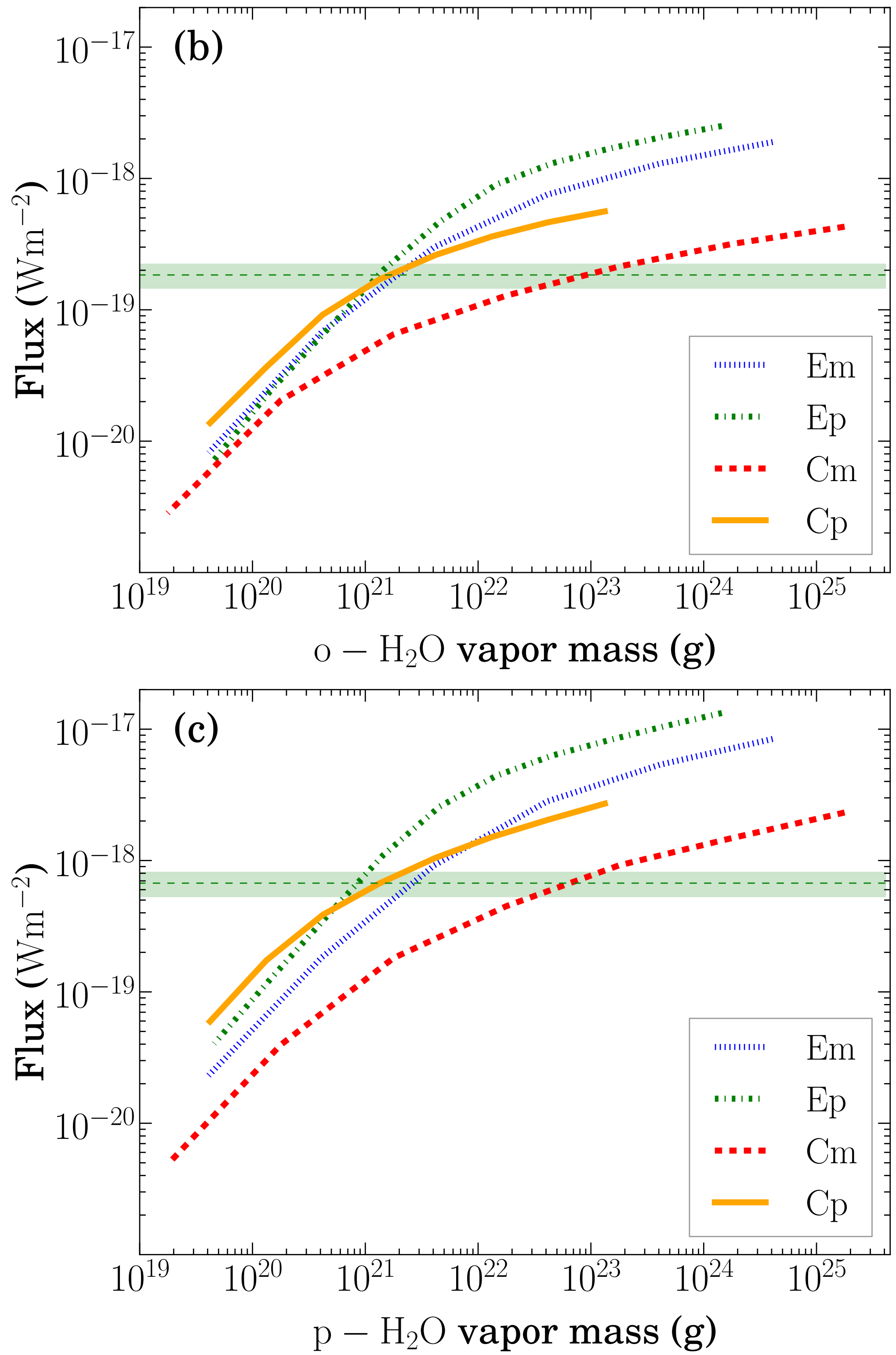
Andrews et al. (2012); Hogerheijde et al. (2016); Andrews et al. (2016)



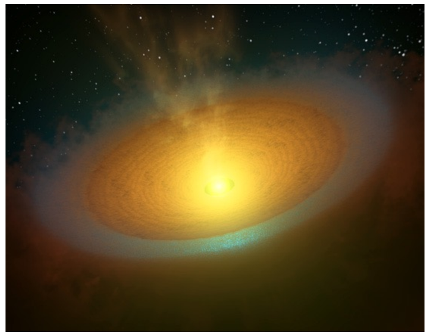
Drift of icy grains

- Modeling attempt 2: Radially migrated and settled grains
- …and other extreme distributions
- using HD-derived disk mass of 0.04 M⊙





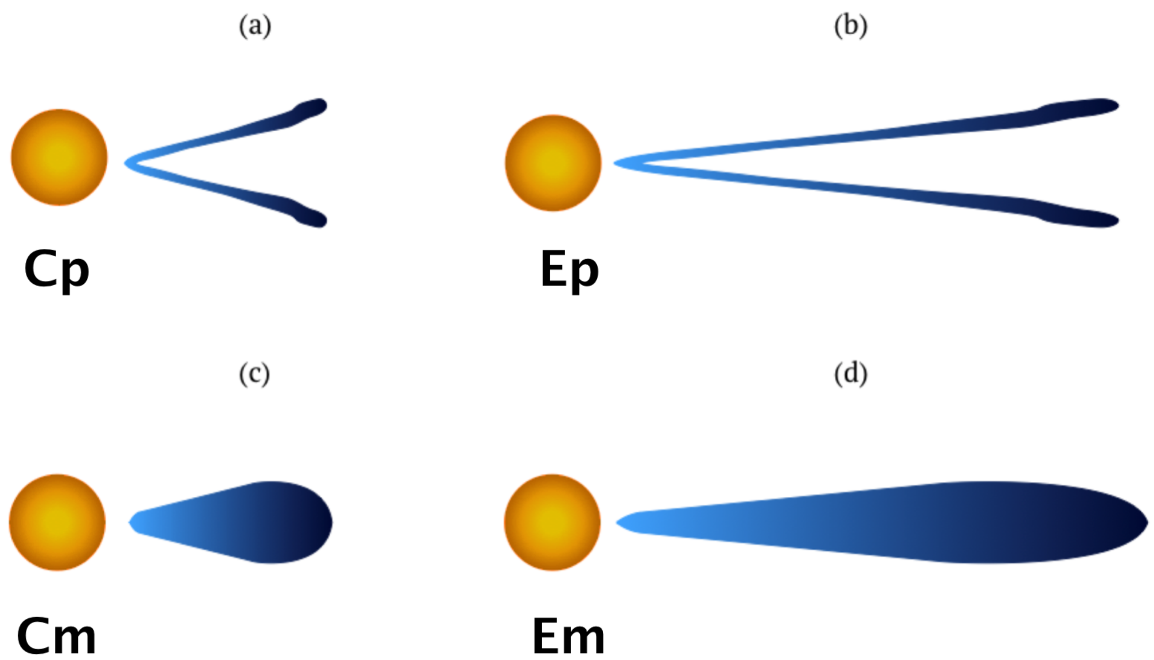
Salinas et al. (2016)



Drift & settling of icy grains

$M_{\text{vapor}} = 3.0\times10^{21}$ g
OPR~0.5-2.1

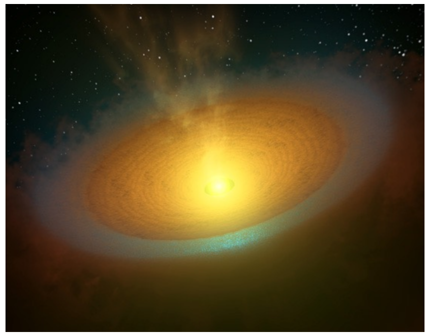
$M_{\text{vapor}} = 2.2\times10^{21}$ g
OPR~1.0-2.1



$M_{\text{vapor}} = 1.6\times10^{\mathbf{23}}$ g
OPR~0.2-**3.5**

$M_{\text{vapor}} = 4.5\times10^{21}$ g
OPR~0.5-1.1

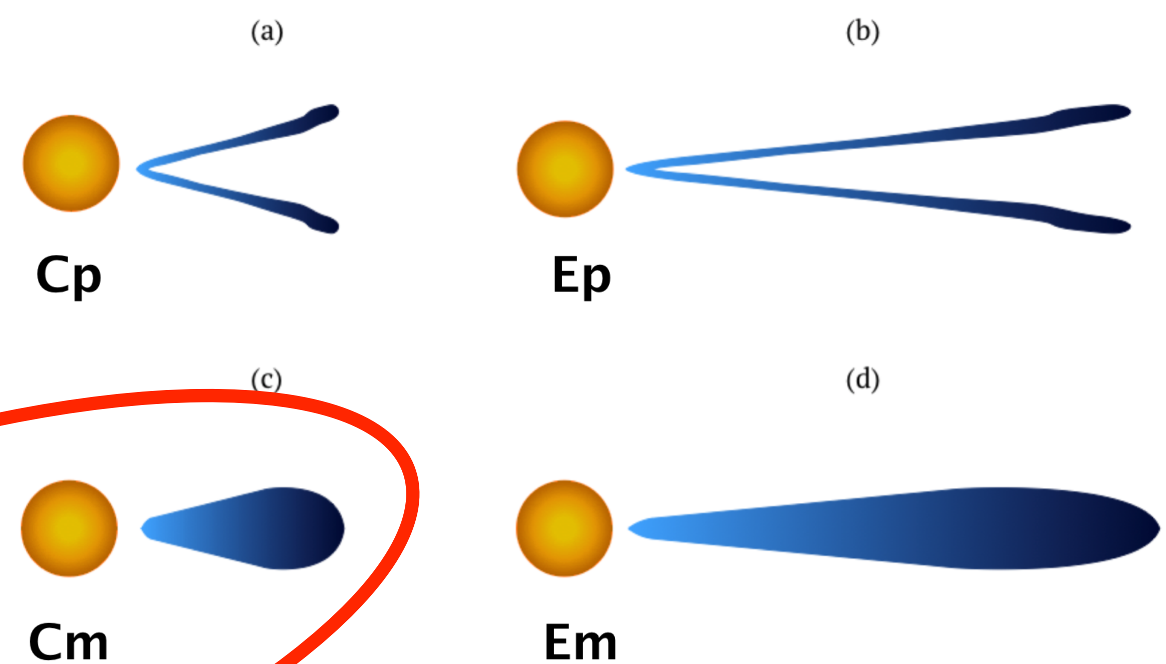
Salinas et al. (2016)



Drift & settling of icy grains

$M_{\mathrm{vapor}} = 3.0\times10^{21}$ g
OPR~0.5-2.1

$M_{\mathrm{vapor}} = 2.2\times10^{21}$ g
OPR~1.0-2.1

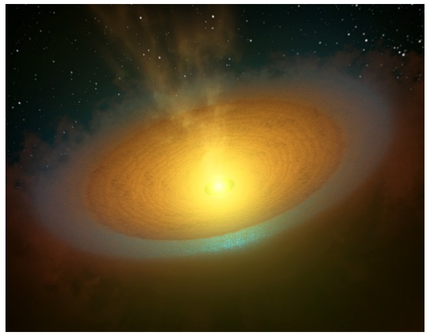


$M_{\mathrm{vapor}} = 1.6\times10^{\mathbf{23}}$ g
OPR~0.2-**3.5**

$M_{\mathrm{vapor}} = 4.5\times10^{21}$ g
OPR~0.5-1.1

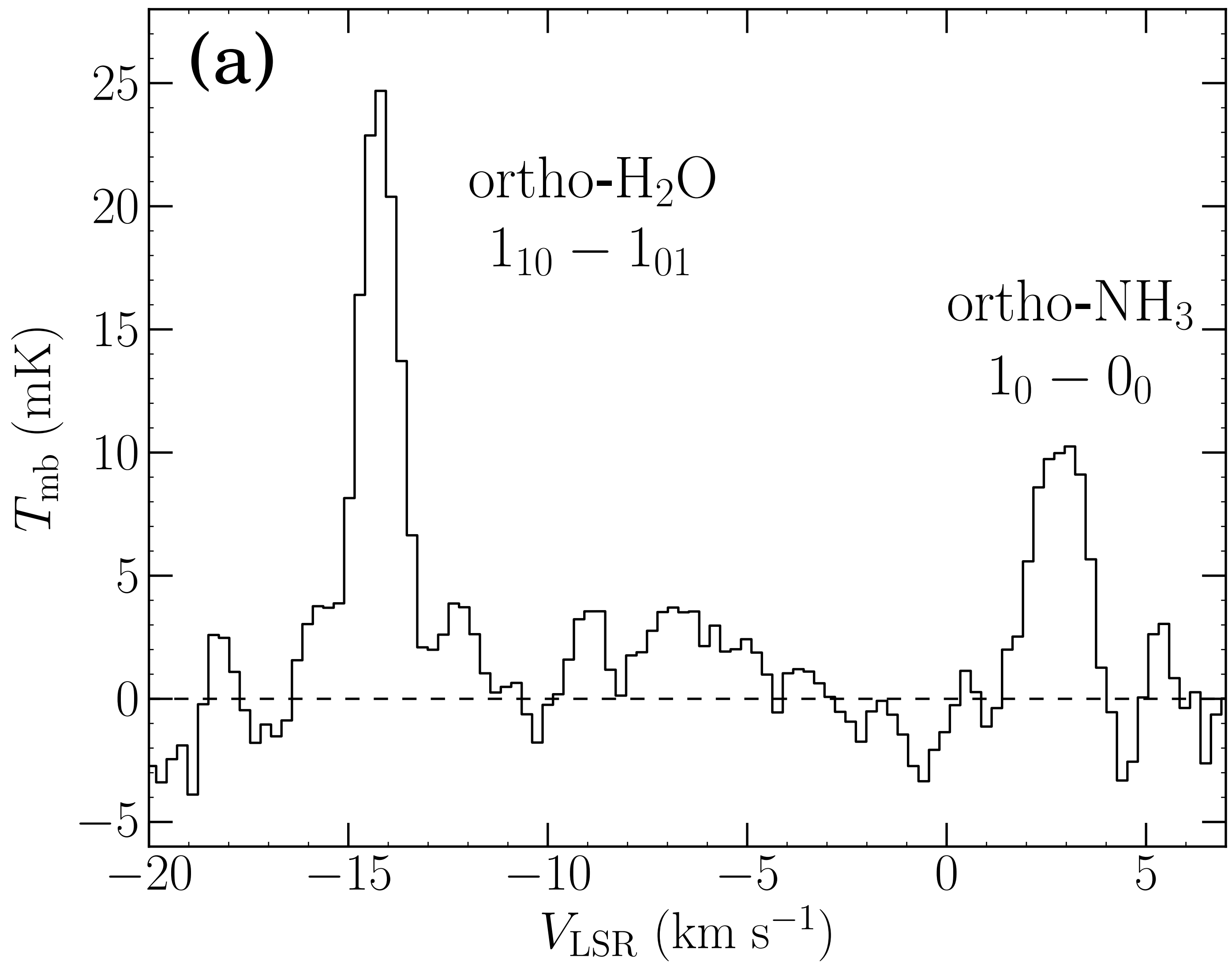
Hama et al. (2015):
OPR of photodesorbing water = 3

Salinas et al. (2016)

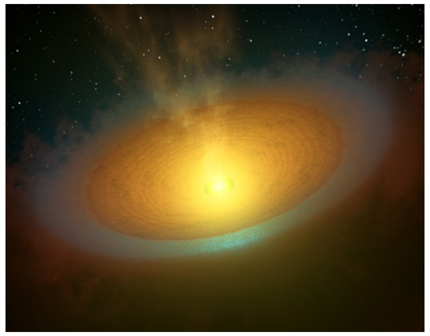


H_2O and NH_3

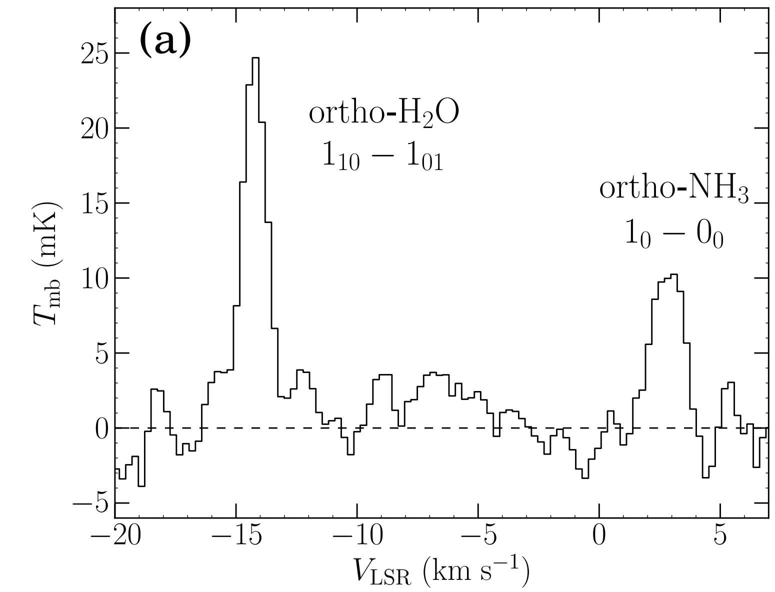
- Simultaneous detection of ammonia vapor (a first!)



Salinas et al. (2016)

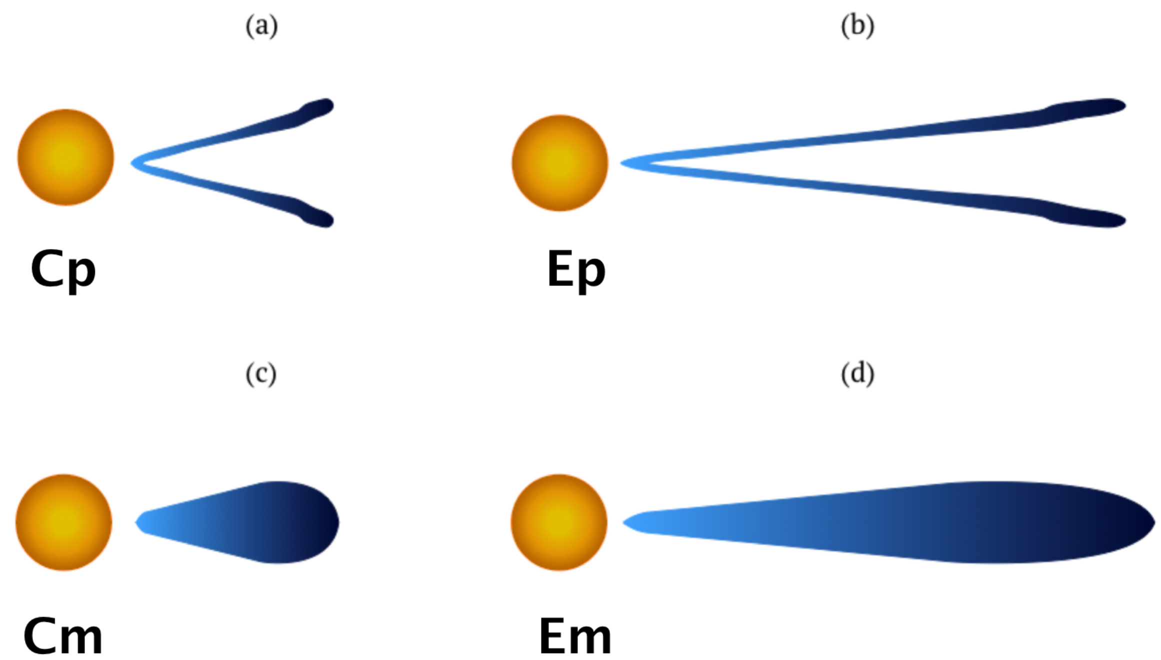


H_2O and <u>NH_3</u>



$M_{vapor} = 1.2 \times 10^{21}$ g
NH_3/H_2O=24-100%

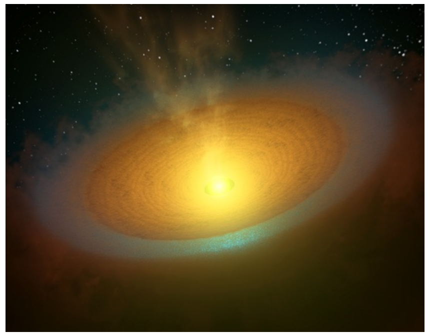
$M_{vapor} = 8.0 \times 10^{20}$ g
NH_3/H_2O=22-77%



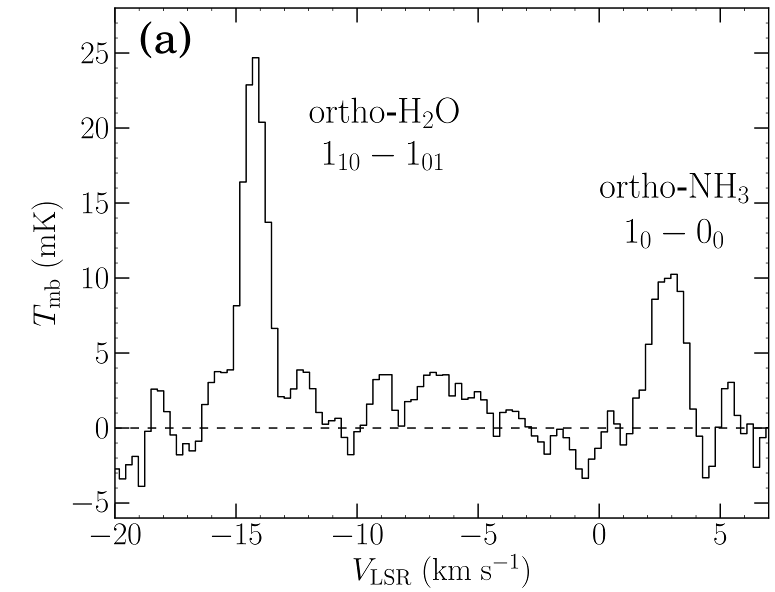
$M_{vapor} = 1.1 \times 10^{22}$ g
NH_3/H_2O=**2-35**%

$M_{vapor} = 8.0 \times 10^{20}$ g
NH_3/H_2O=12-55%

Salinas et al. (2016)

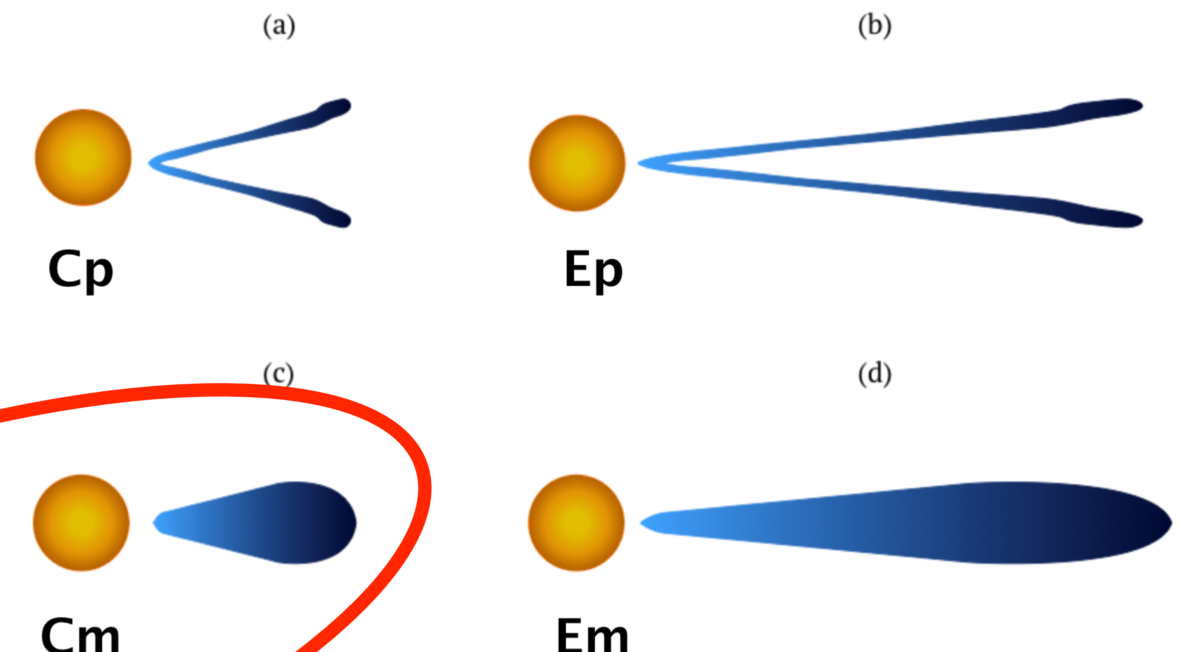


H_2O and NH_3



$M_{\rm vapor}=1.2\times10^{21}$ g
NH_3/H_2O=24-100%

$M_{\rm vapor}=8.0\times10^{20}$ g
NH_3/H_2O=22-77%

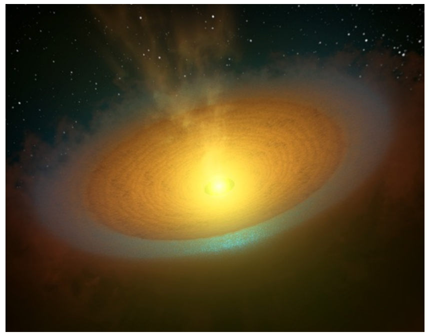


$M_{\rm vapor}=1.1\times10^{\mathbf{22}}$ g
NH_3/H_2O=**2-35**%

$M_{\rm vapor}=8.0\times10^{20}$ g
NH_3/H_2O=12-55%

Protostellar cores; solar system objects: NH_3/H_2O~few% (Öberg et al. 2011; Mumma & Charnley 2011)

Salinas et al. (2016)



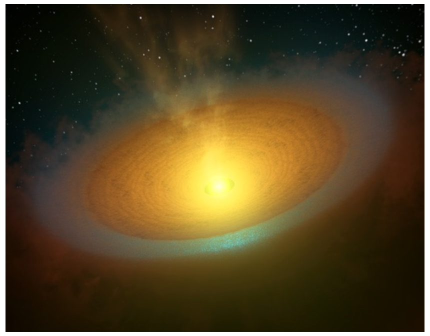
Location of the volatiles

- Low H_2O and NH_3 vapor abundance matched by low CO and C abundance
  - Locked up on grains near midplane
  - Favre et al. (2013), Kama et al. (2016)

- How are observed (small) amounts of volatiles librated?
  - Dredged up by turbulent mixing?
    - But: low turbulence
  - Residual ice mantles on small (non-settled) grains?
    - But: scattered light suggests dry grains
  - Colliding (large) icy bodies (~proto-comets)?
    - But: suppress subsequent freeze out by depleting small dust content

Salinas et al. (2016)

Image credit: Planetary Science Institute/William K. Hartmann



Location of the volatiles

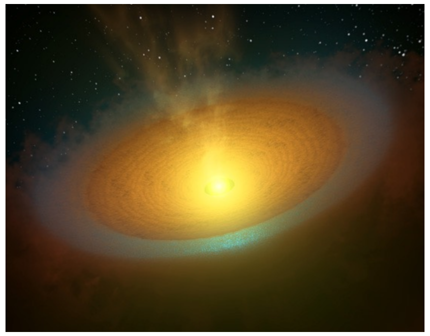
- Low H_2O and NH_3 vapor abundance matched by low CO… …ance
  - Locked up on grains near midplane
  - Favre et al. (2013), Ka…
-
  - …s on small (non-settled) grains?
    - …ut: scattered light suggests dry grains
  - Colliding (large) icy bodies (~proto-comets)?
    - But: suppress subsequent freeze out by depleting small dust content

<u>Bottom line</u>: Location of volatile reservoir closely tied to *dust settling, migration, and growth*

See also poster P.02 (Salinas)

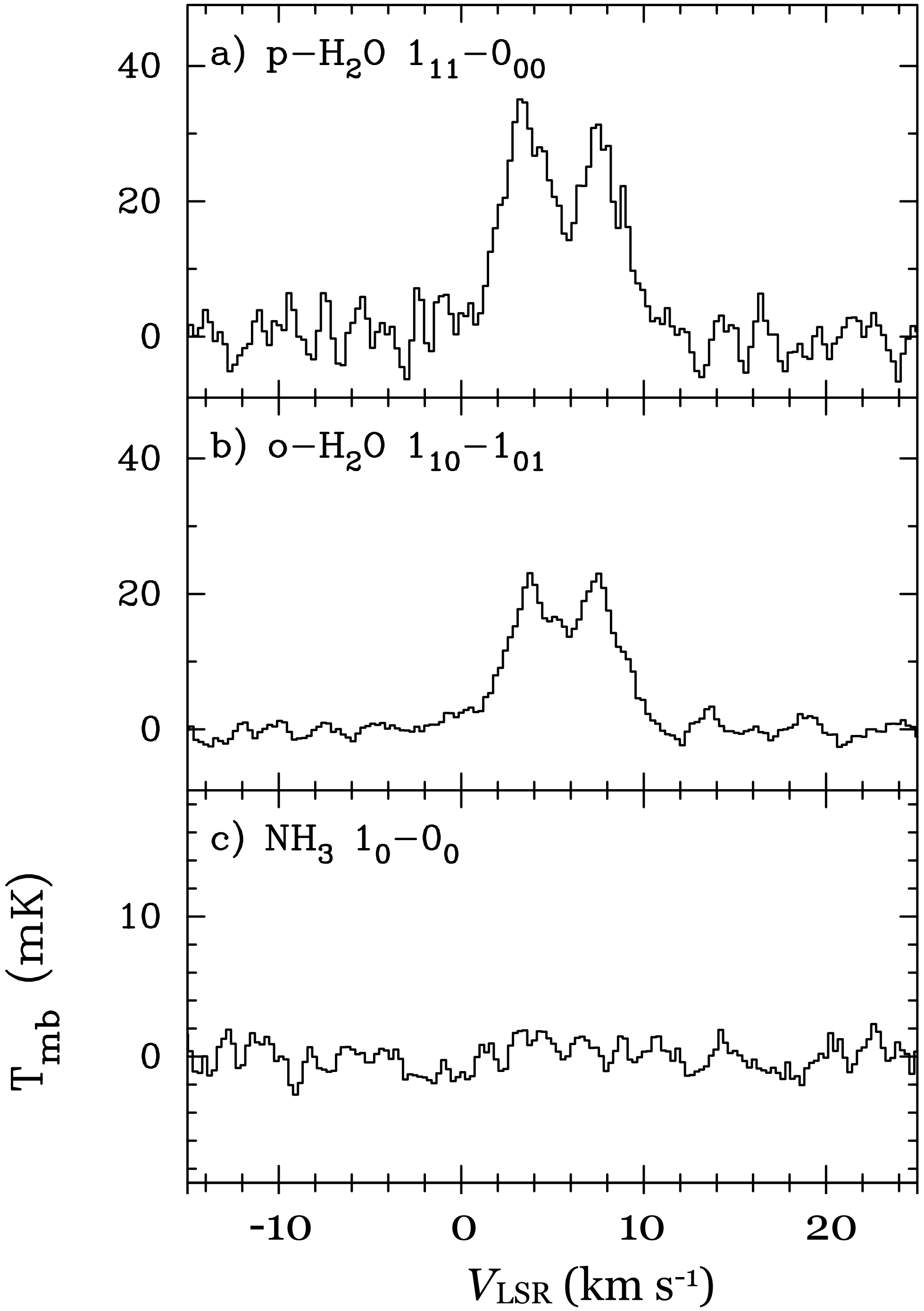
Image credit: Planetary Science Institute/William K. Hartmann

Salinas et al. (2016)

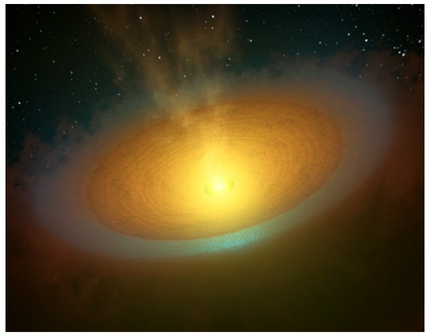


Second detection: HD100546

Hogerheijde et al. (in prep)

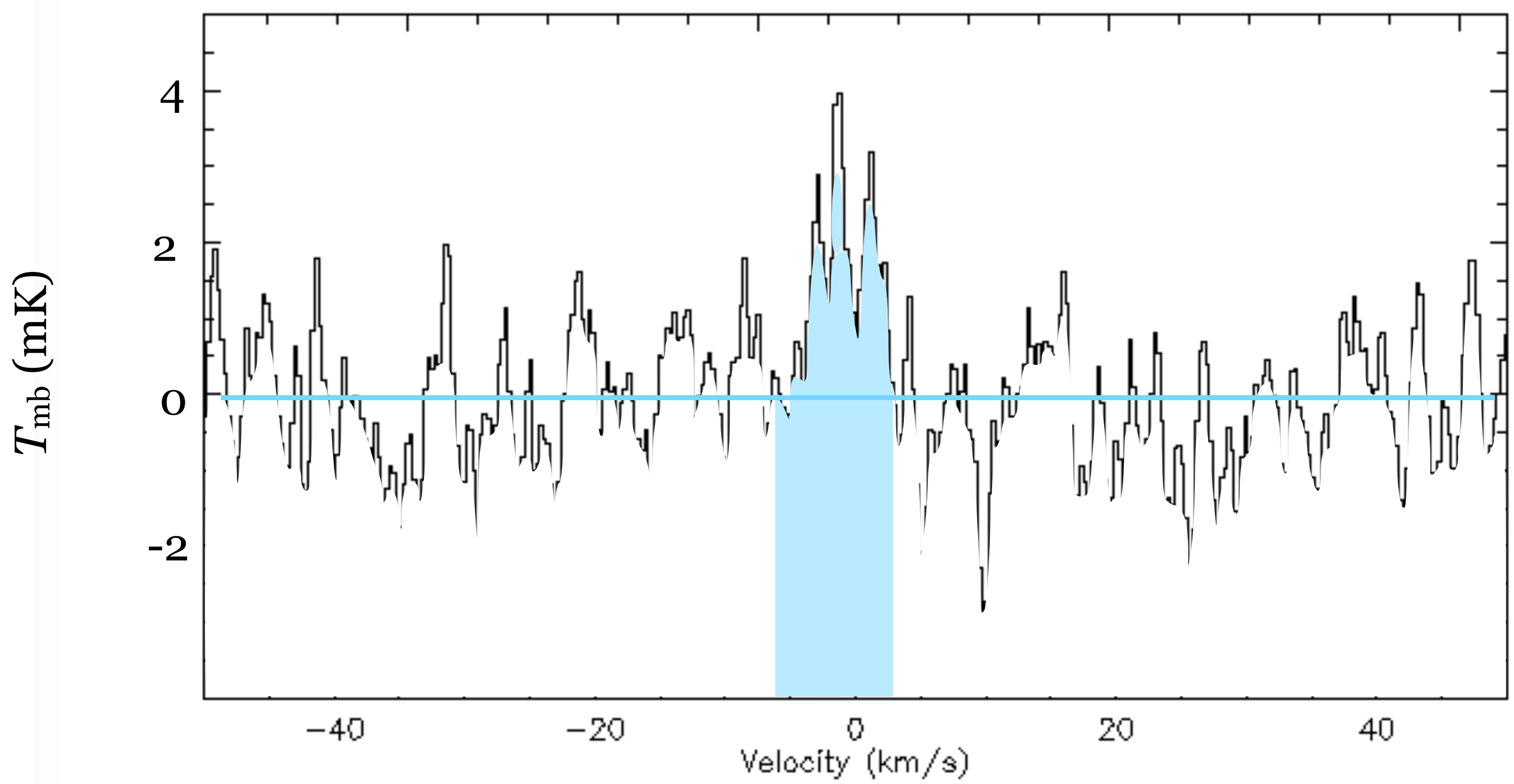


- Unlike TW Hya (i=7°), HD100546 has i=42° (and 2.5 $M_\odot$) → line profile ⇒ radial location
- Like TW Hya
  - emitting region < full disk size (400 au)
    - ~75 au – 300 au assuming $L \propto R^{-(0.5\text{-}2.5)}$
    - detailed models: H_2O mass and emitting region are degenerate in matching line *flux* and *profile* (work in progress)
    - relation to mm-size grains: two 'rings' 22-43 au & 152-228 au (Walsh et al. 2013)?
  - vapor mass ~10^{22} g = few % of expectation
  - H_2O OPR ~3
- Unlike TW Hya (?), no NH3

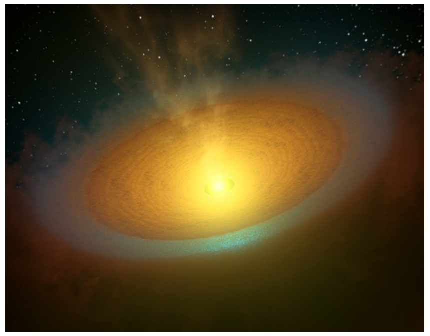


Upper limits and stacked detection

- No other direct detections to *individual* disks
- Stacked deep H_2O 1_{10}-1_{01} : **DM Tau+MWC480+LkCa15 (~~+AA Tau~~)**
  - Confirms earlier tentative DM Tau results
  - Consistent with distance-scaled TW Hua line flux
  - No NH_3 (and none would be expected at S/N, distance scaled)



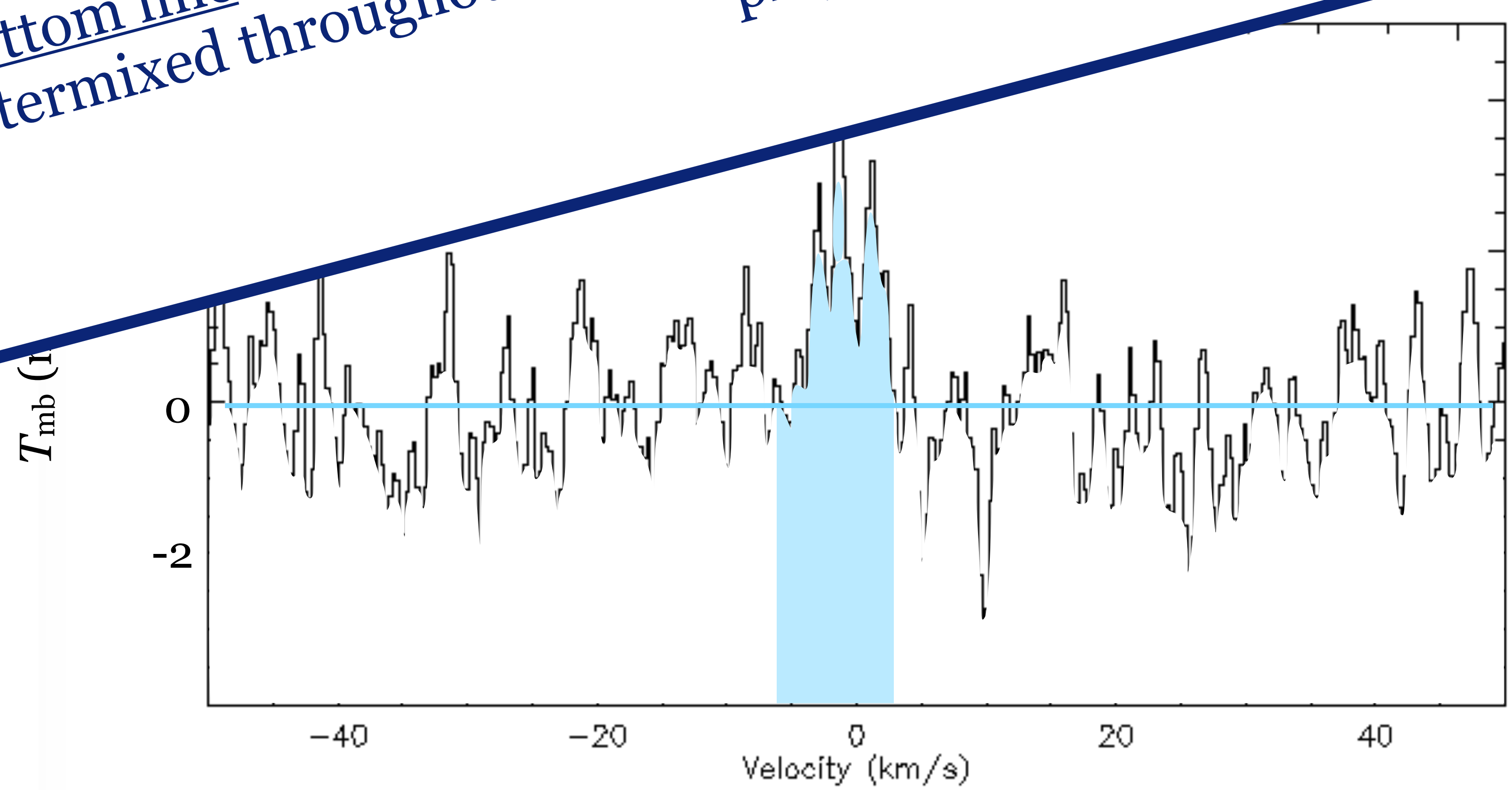
Du et al. (in prep)



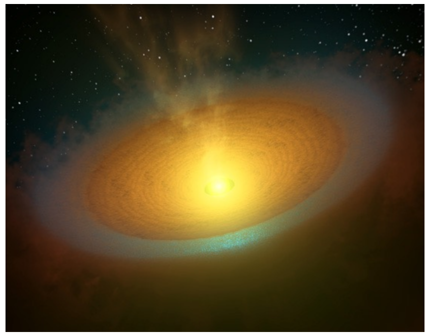
Upper limits and stacked detection

- No other direct detections to *individual* disks
- Stacked deep H_2O 1_{10}-1_{01} : **DM Tau+MW**
  - Confirms earlier tent
  - Consist

<u>Bottom line</u>: H_2O vapor is much lower than expected if ice is fully intermixed throughout disk → locked up in midplane (Du et al. in prep)



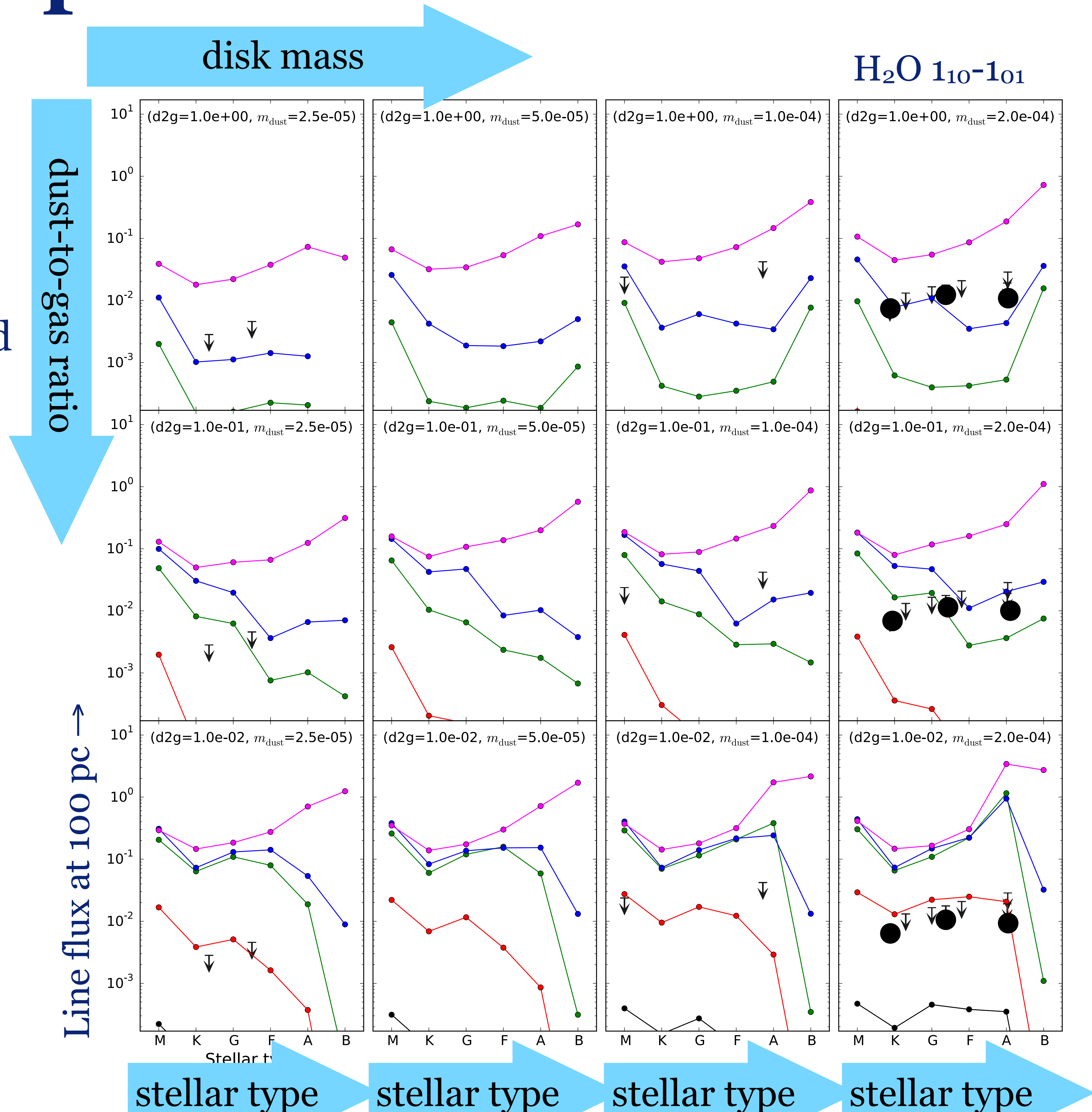
Du et al. (in prep)



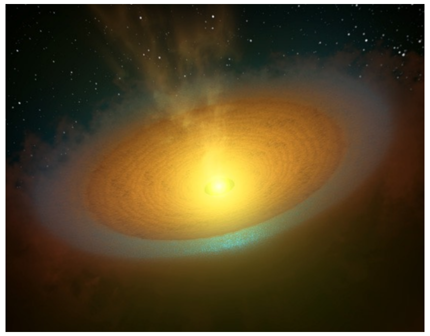
Locked up ices

- Detections and upper limits are consistent with upper disk layers depleted in ice (Du et al. in prep)

  - elemental oxygen depletion:
    - 1.0 (undepleted)
    - 0.1
    - 0.01
    - 0.0001
    - 0.000001



Du et al. (in prep)



Summary

- **Ground-state rotational emission of H_2O from disks is weak**
  - Only detected to TW Hya, HD100546, and (DM Tau+MWC480+LkC15)
  - Vapor mass ~few% of expectation for ices fully mixed throughout disk
  - Ice reservoir largely sequestered in disk midplane
- **Simultaneous detection of NH_3 to TW Hya only**
  - NH_3/H_2O~5-10% if ices co-located with mm-sized grains in midplane
  - Otherwise, gas-phase production of NH_3 needed
- **Location of water (ice and vapor) closely connected to dust settling, migration and growth**
  - Resolve degeneracy between emitting region and line flux and profile → future ALMA observations of complementary tracers
  - Identify mechanism(s) liberating ice molecules into vapor phase