TOWARD SOLID OBSERVATIONS OF SNOW LINE

M. Honda (Kurume University, Japan)

Collaborators :
H. Terada, T. Hattori, T. Kudo, J. Hashimoto, M. Tamura (NAOJ),
T. Nakamoto (TITech), M. Watanabe (Okayama Science Univ.),
A.K. Inoue (OsakaSangyo Univ.), et al.

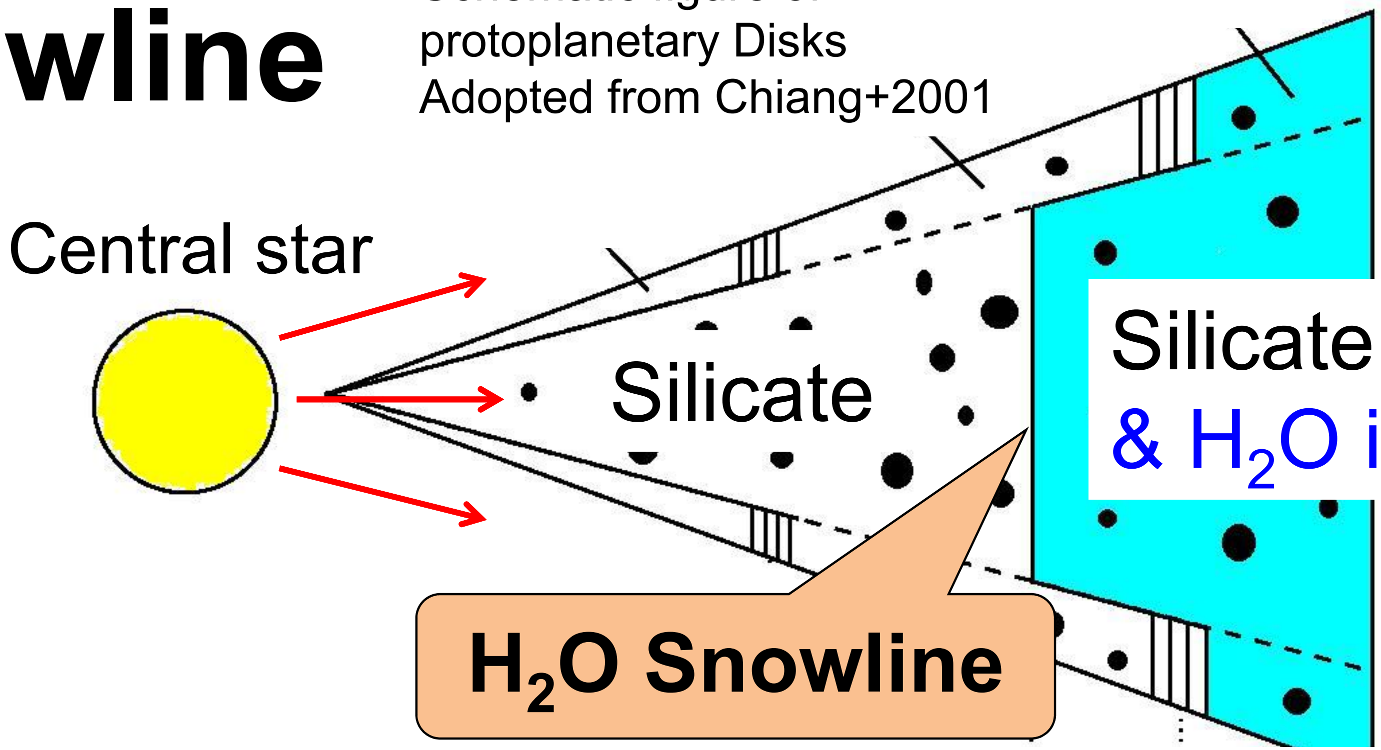
Thank you for giving me this opportunity

Outline

- Snowline and planet formation
  - The theme of this symposium !
- Brief review of current snowline observations
  - Indirect / direct observations of CO snowline
  - Indirect observations of H_2O snowline
- Future prospects on direct H_2O snowline observations

H_2O Snowline

Schematic figure of
protoplanetary Disks
Adopted from Chiang+2001

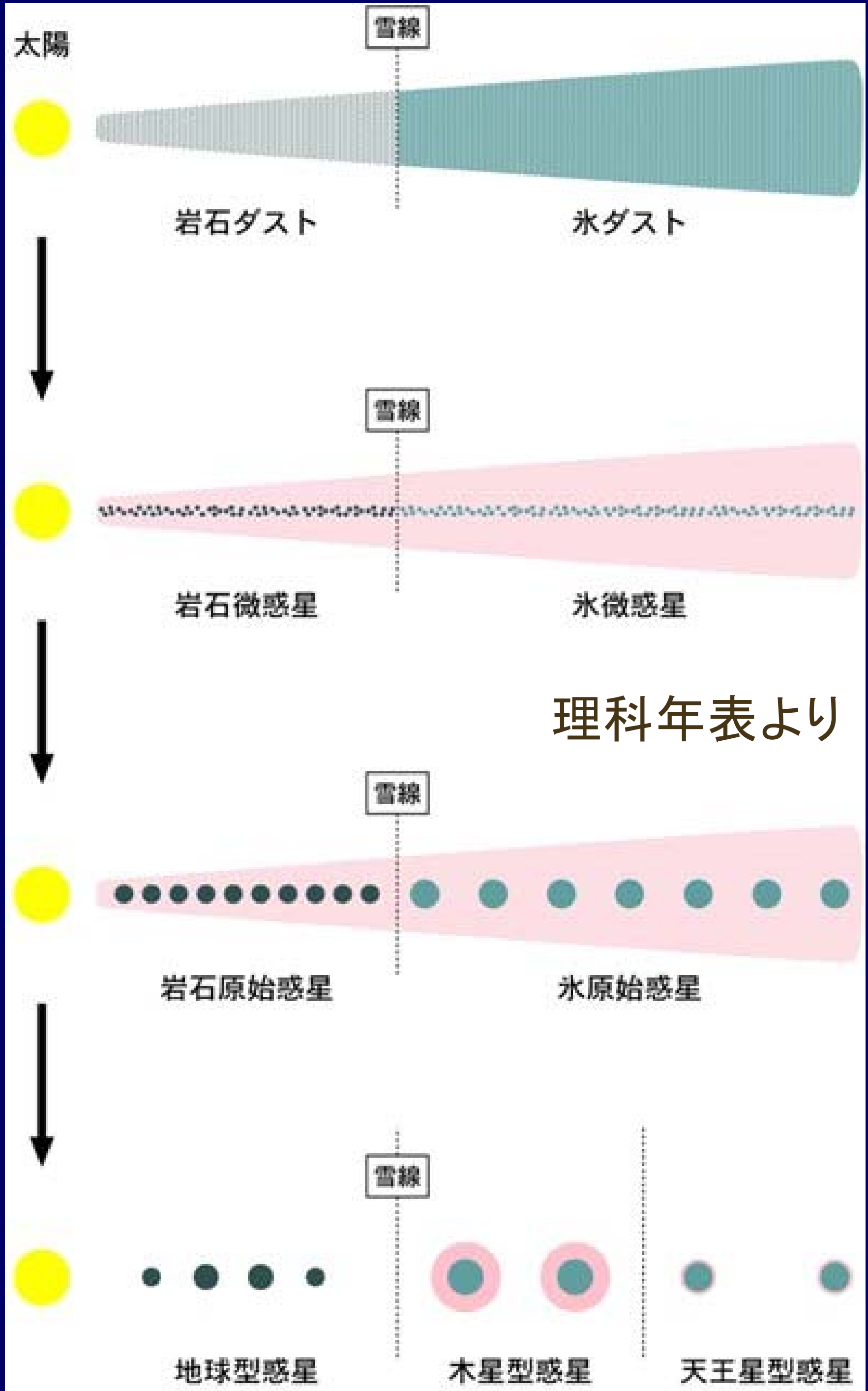


High Temp. **Low Temp.**

H_2O evap. ⟷ **H_2O freeze**

Snowline : condensation/evaporation front of volatiles

- For solar nebula, R ~ 2.7AU (T~140K) suggested (Hayashi+1981,1985)
- R ~ a few AU for T Tauri stars
- R ~ 10 AU for HAeBe stars

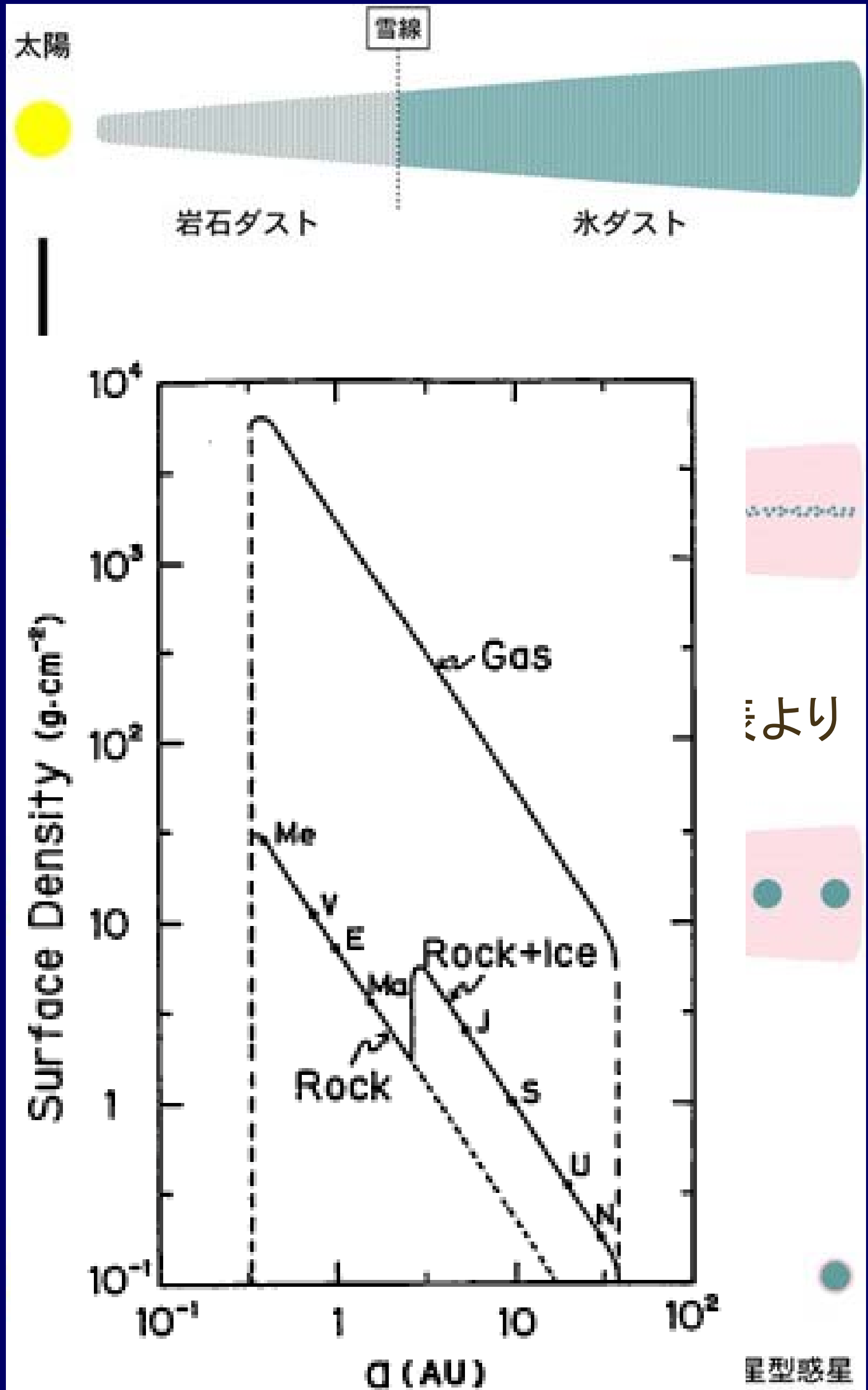


H_2O snowline and planet formation

- major solid matter in disk
  - ice and silicate (3:1)
  - H_2O is dominant in ice
- Role of H_2O ice grains in planet formation
  - enable formation of cores of gas giants (～$10M_E$)
  - Dividing regions of rocky terrestrial planet & gas giant planet regions
  - First planetesimals / protoplanets formed at snow line ? (e.g. Lecar+2006)

Solar System snowline ~2.7AU (Hayashi 1981,1985)

H_2O snowline and planet formation



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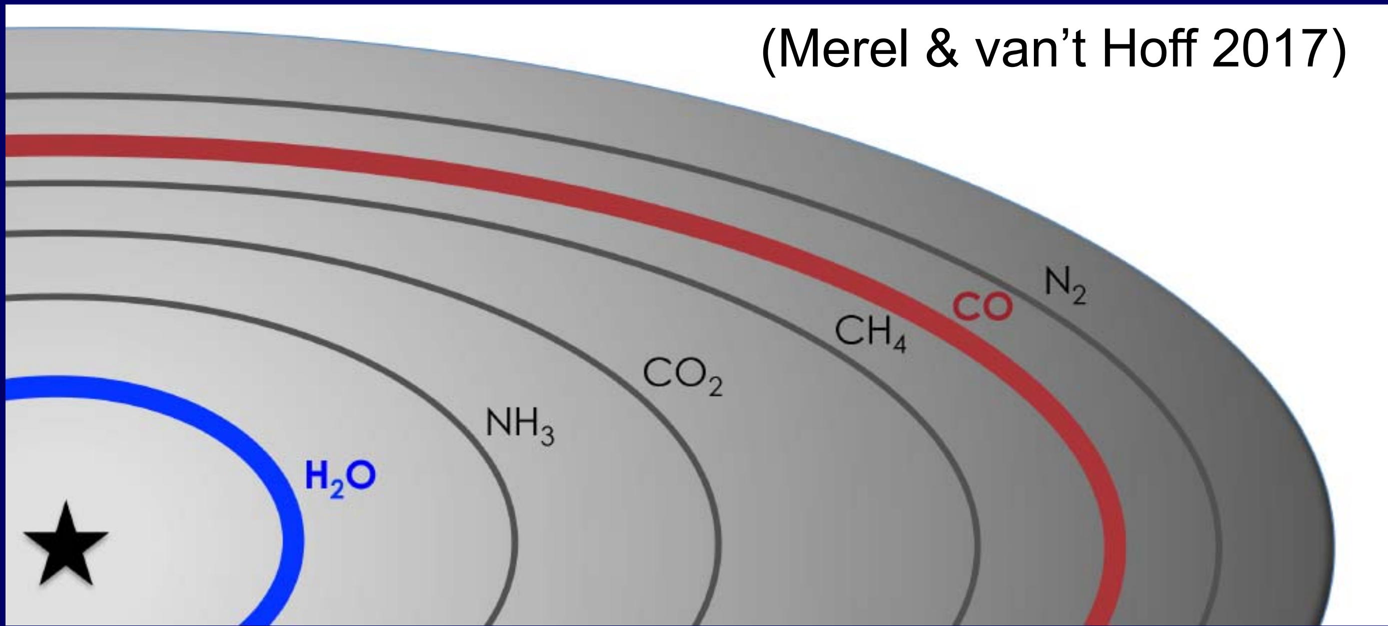
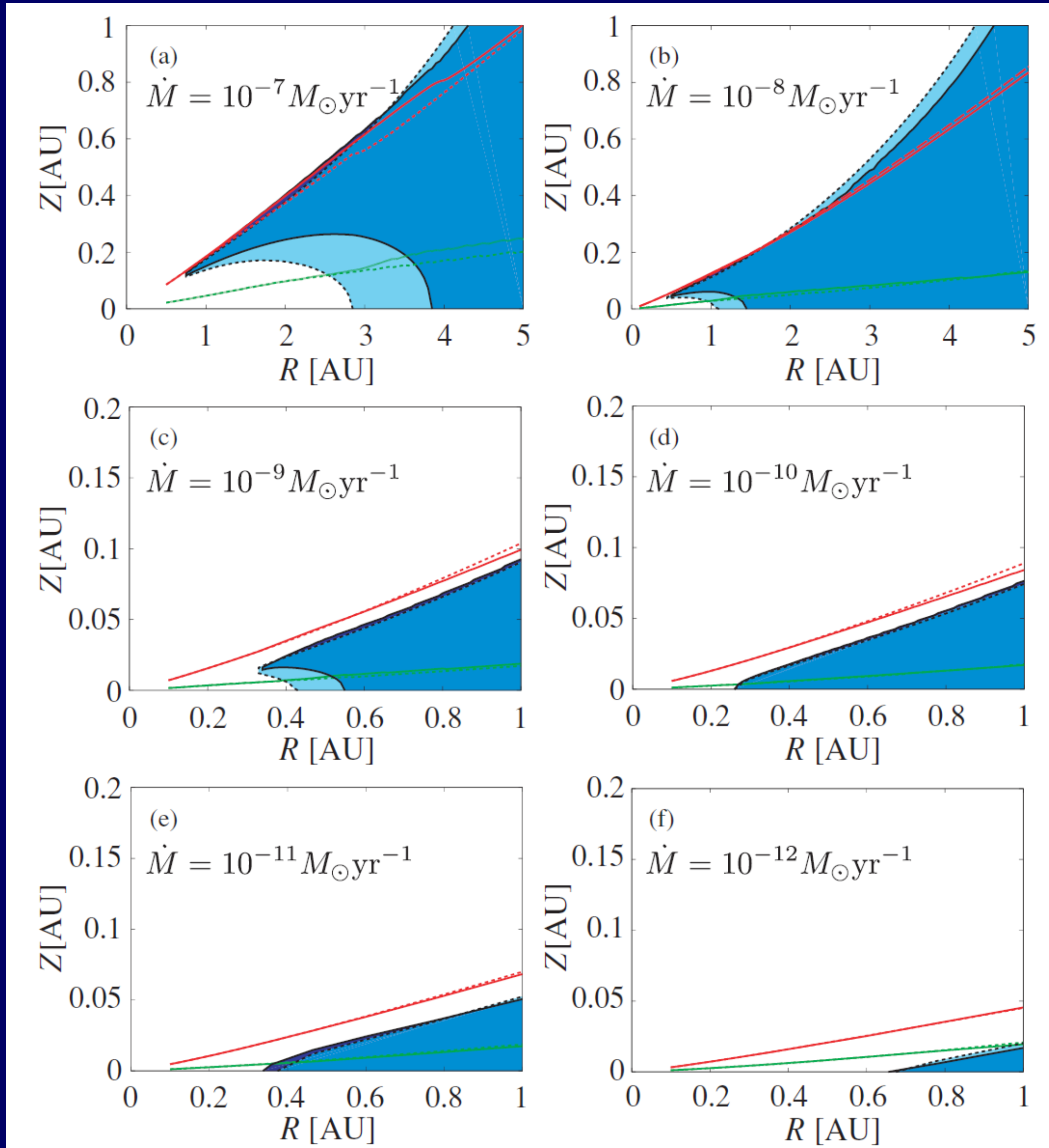
Snowline of other molecules



- H_2O is most abundant (T_{cond} = 128-155K)
- CO and CO_2 are next abundant molecules in comets (~30% to H_2O, Mumma & Charnley 2011)
  - T_{cond} = 60-72K (CO_2), 23-28K (CO)
  - Snowline radius is farther than that of H_2O
  - Observtionally easier to resolve spatially

Snow line position can move

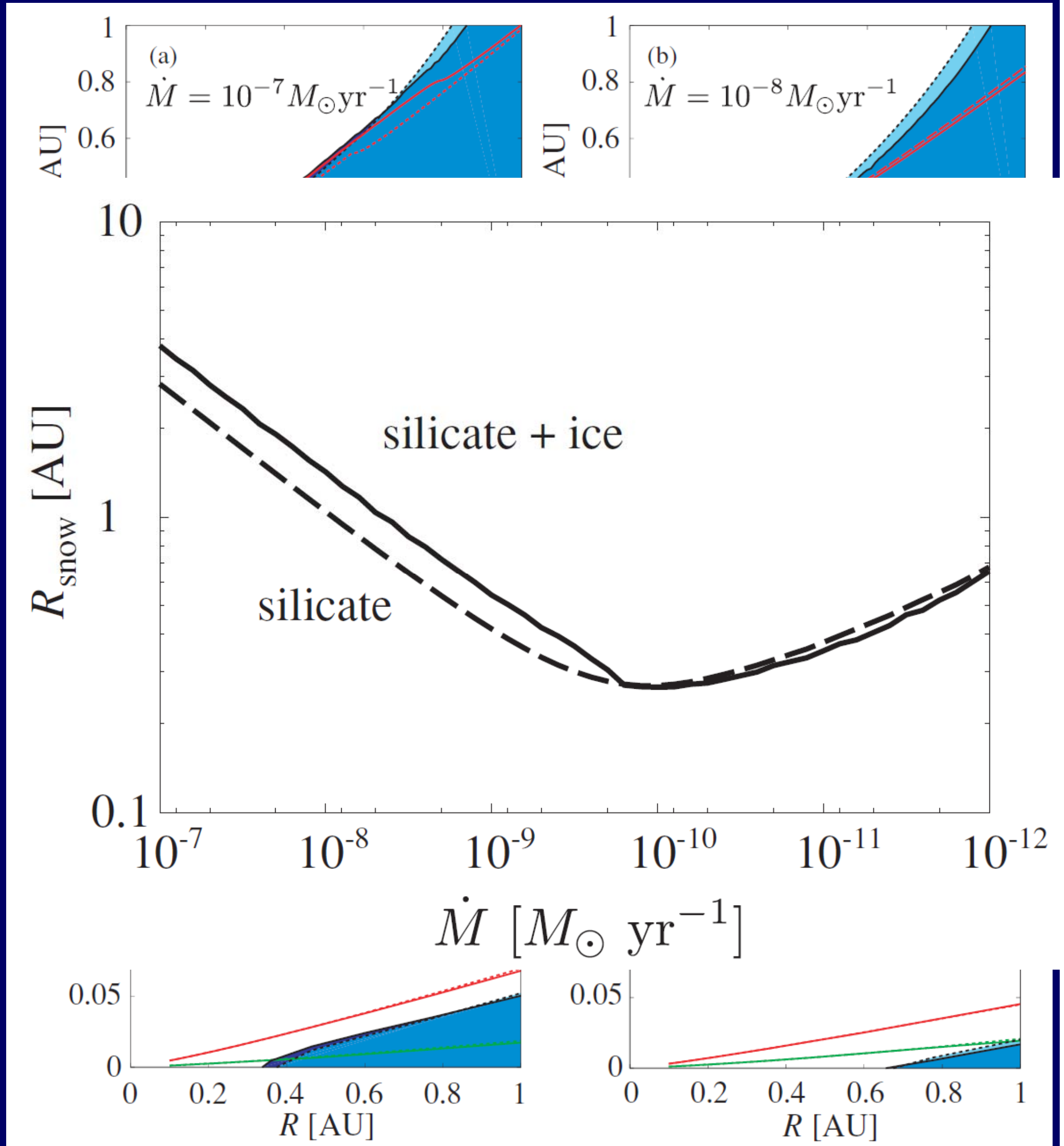
- Snowline depends on the thermal structure of the disk
- Thus depends on disk accretion rate $\dot{M}$
- $\dot{M} = 10^{-7} M_{\odot}\, yr^{-1}$ R_{snow} = 3~4 AU
- As $\dot{M}$ decreases, snowline moves inward



Evolution of T Tauri-like disk ($0.5 M_{\odot}$, $2 R_{\odot}$, T_{eff} = 3000 K, and a=0.1μm) Oka et al. 2011

Snow line position can move

- $\dot{M}$ vs R_{snow}
- For lower $\dot{M}$ phase (~optically thick, passive disk) R_{snow} reaches ~0.3 AU
- Within the supposed terrestrial planet forming region
- Huge water supplied to the terrestrial planets ?



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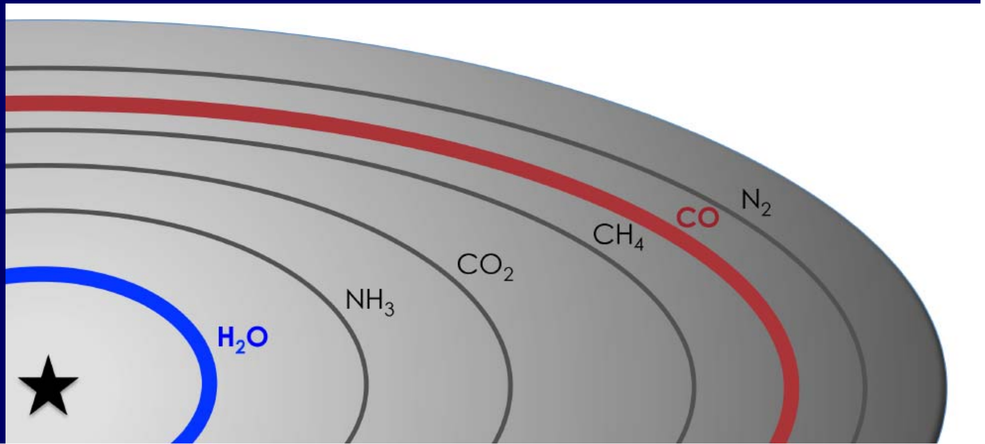
Observation of snow line position

- Many interesting theoretical studies related to snowline…
  → need observational constraint !
- Observation of the volatile **gas** or **dust(ice)** distribution in the disk
  - Gas → radio rotational transition lines of molecules
  - Dust(ice) → infrared solid state features
- Require high-spatial resolution
  - R ~ a few AU (~0.03”) H_2O snowline
  - R~ a few tenth AU (~0.3”) for CO snowline (easier)



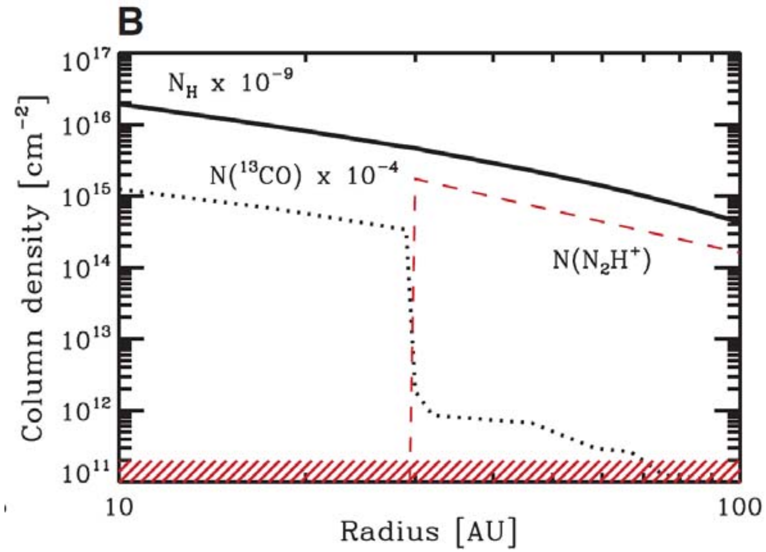
Observation of snow line position

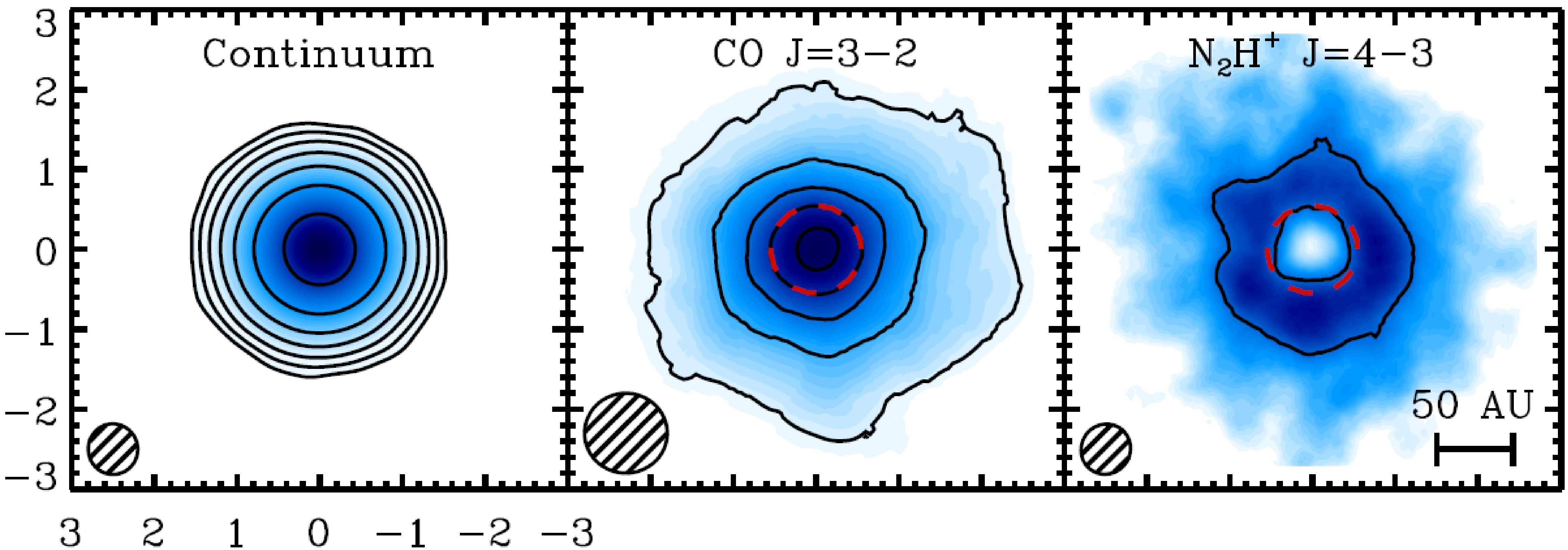
- Before ALMA…
  - not so much/little information available mainly due to lower spatial resolution (~1”)
- After ALMA
  - Order of magnitude improvement of spatial resolution ! (~0.1”)
  - Higher sensitivity

- For CO snowline (~0.3”), now it’s possible to spatially resolved it !
  - Indirect way using N_2H^+
  - Direct way using $^{13}C^{18}O$

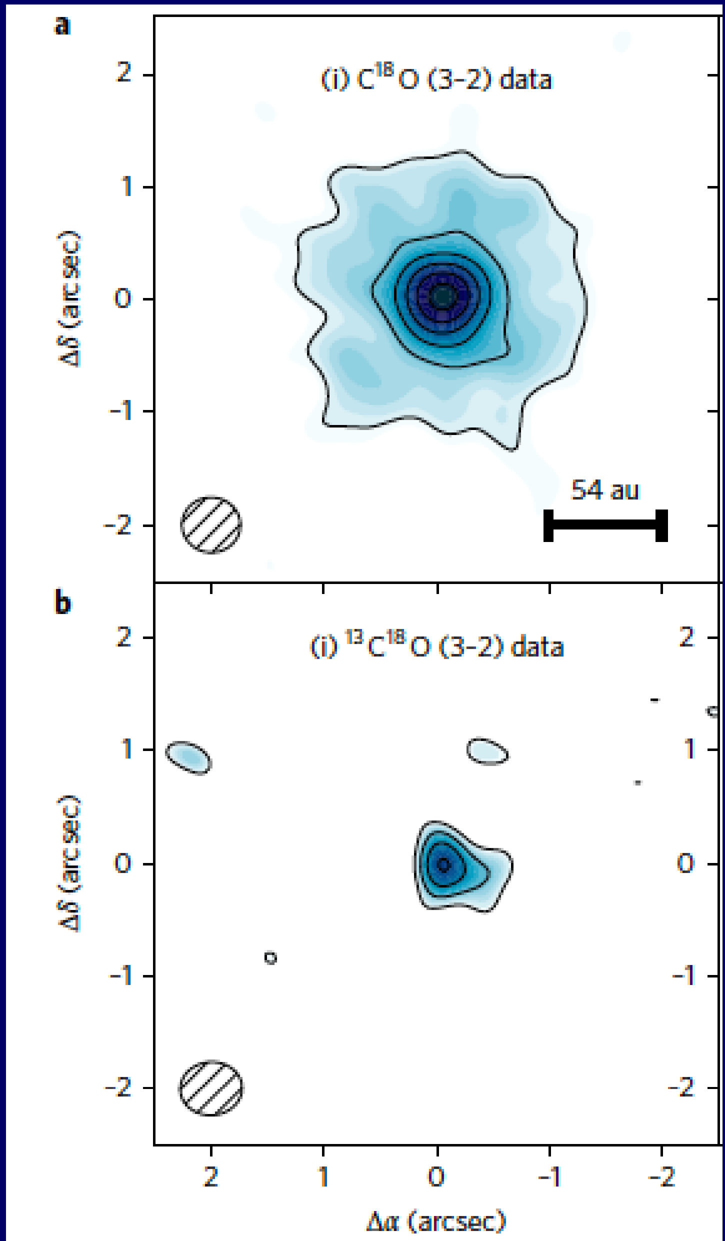
ALMA resolved CO snow line (Qi et al. 2013 Science)

- TWHya face-on disk show inner hole **(r~30AU)** in the intensity map of N_2H^+
- N_2H^+ is produced under low CO gas condition
  - $N_2 + H_3^+ \rightarrow N_2H^+ + H_2$
- Higher CO gas abundance stops/destroy N_2H^+
  - $CO + H_3^+ \rightarrow HCO^+ + H_2$
  - $N_2H^+ + CO \rightarrow HCO^+ + N_2$
- N_2H^+ shows inverse correlation with CO gas
  - Inner hole edge traces
    CO snow line **indirectly** !!



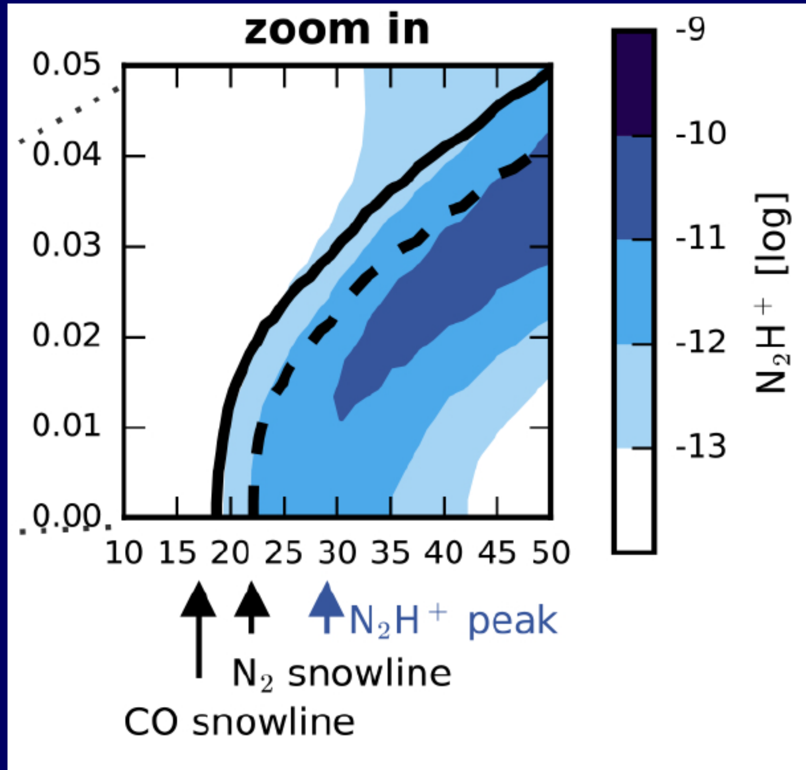


TWHya CO snowline revisited (Zhang+2017)



- Recent $^{13}C^{18}O$ observations showed CO snowline radius ~20 AU for TWHya
- Usually CO line easily becomes optically thick
  - not so good surface density tracer especially for $^{12}C^{16}O$
- $^{13}C^{18}O$ line is still optically thin ($\tau < 0.2$) due to its rareness (abundance $\sim 10^{-10}$)
  - Good tracer for surface density and CO snowline !

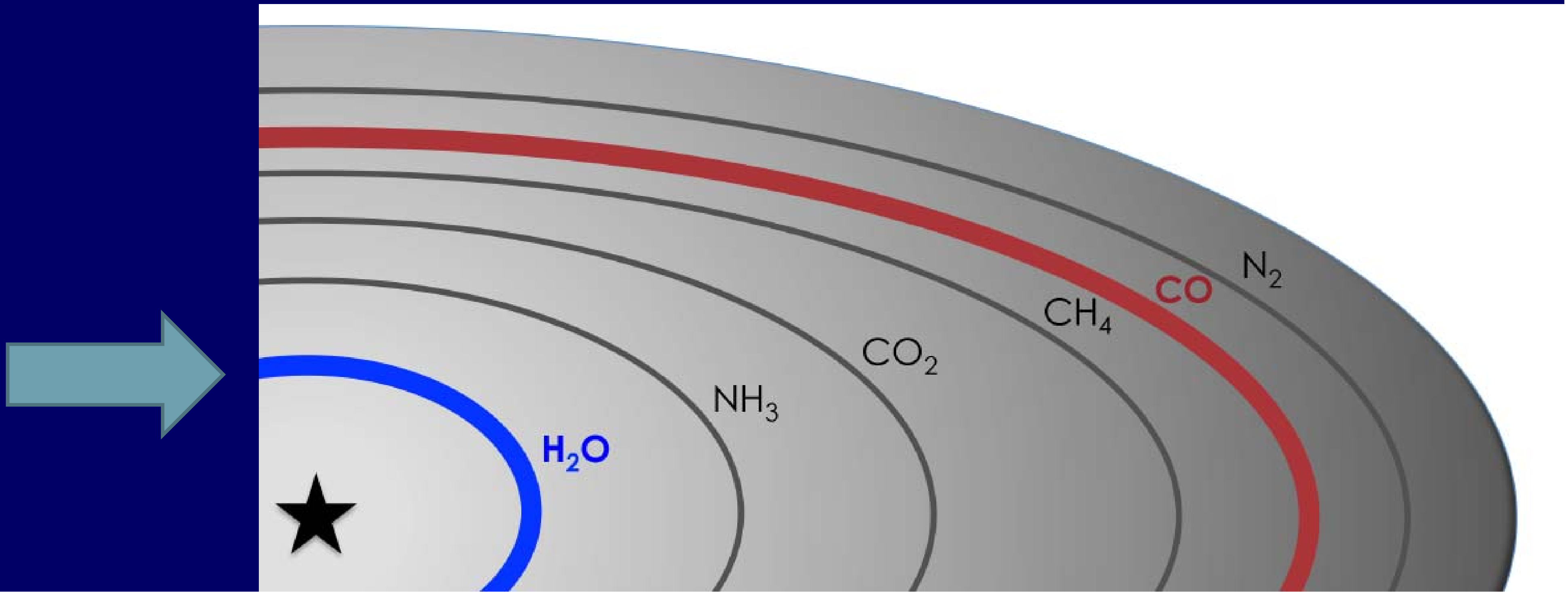
lesson learned from indirect/direct tracer for CO snowline



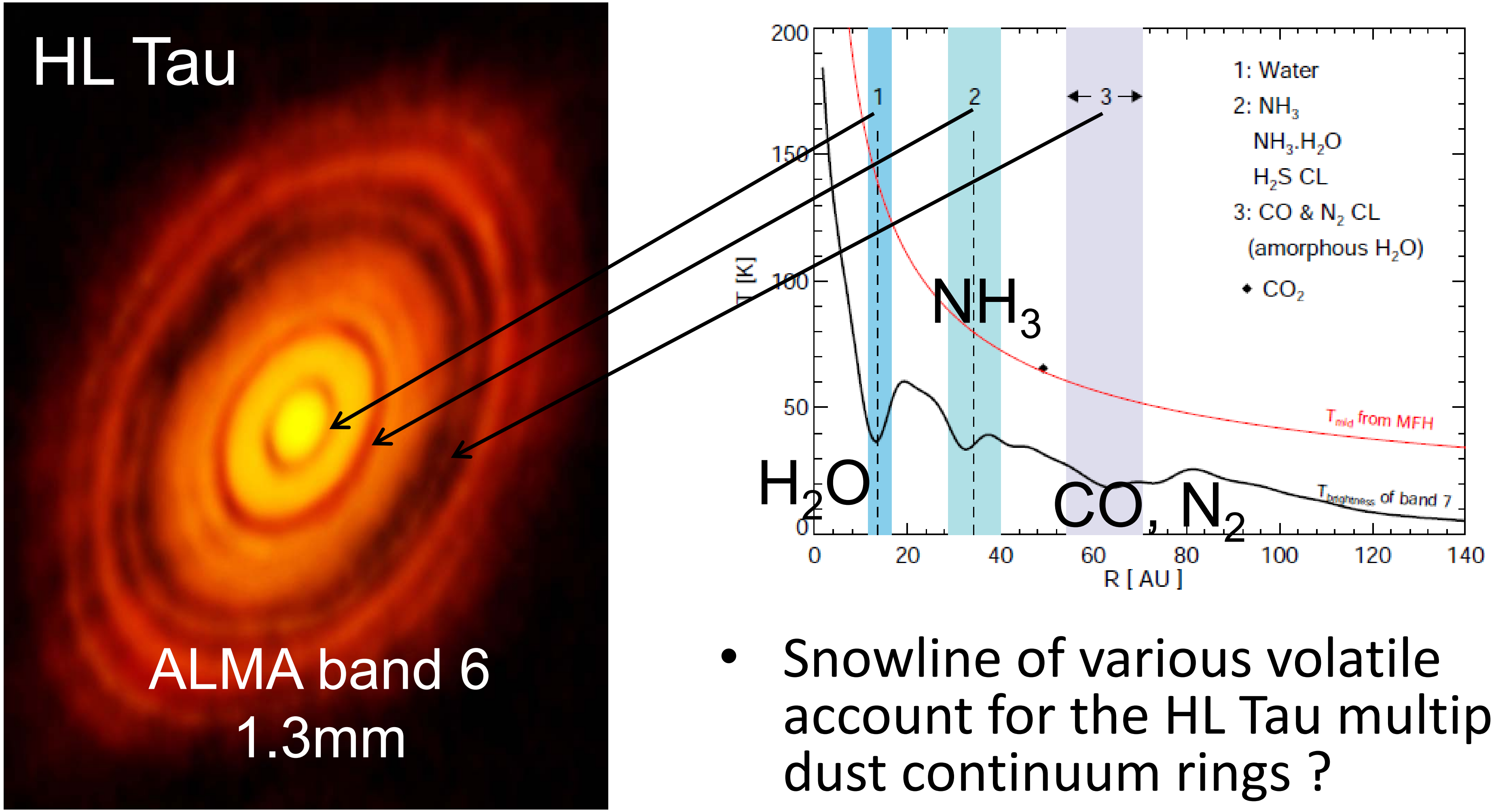
- TW Hya CO snowline
  - Indirect N_2H^+ ~30AU (Qi+2013)
  - Direct $^{13}C^{18}O$ ~20AU (Zhang+2017)
- Chemical modeling suggest that the relationship between N_2H^+ and CO is more complicated (van't Hoff 2017)
  - Depend also on N_2 distribution
- N_2H^+ emission alone then merely provides and upper limit for the CO snowline locataion
- **We need to be careful to use indirect tracers** for observations of H_2O snowlines…

Difficulties of H_2O snowline detection

- Require ***much*** <u>high-spatial resolution</u>
  - R ~ a few AU (~0.03”) H_2O snowline due to its relatively high T_{cond}= 128-155K (Zhang+2015)
  - Comparable to ALMA spatial resolution limit → challenging



Fast Pebble Growth @ Snow Lines?



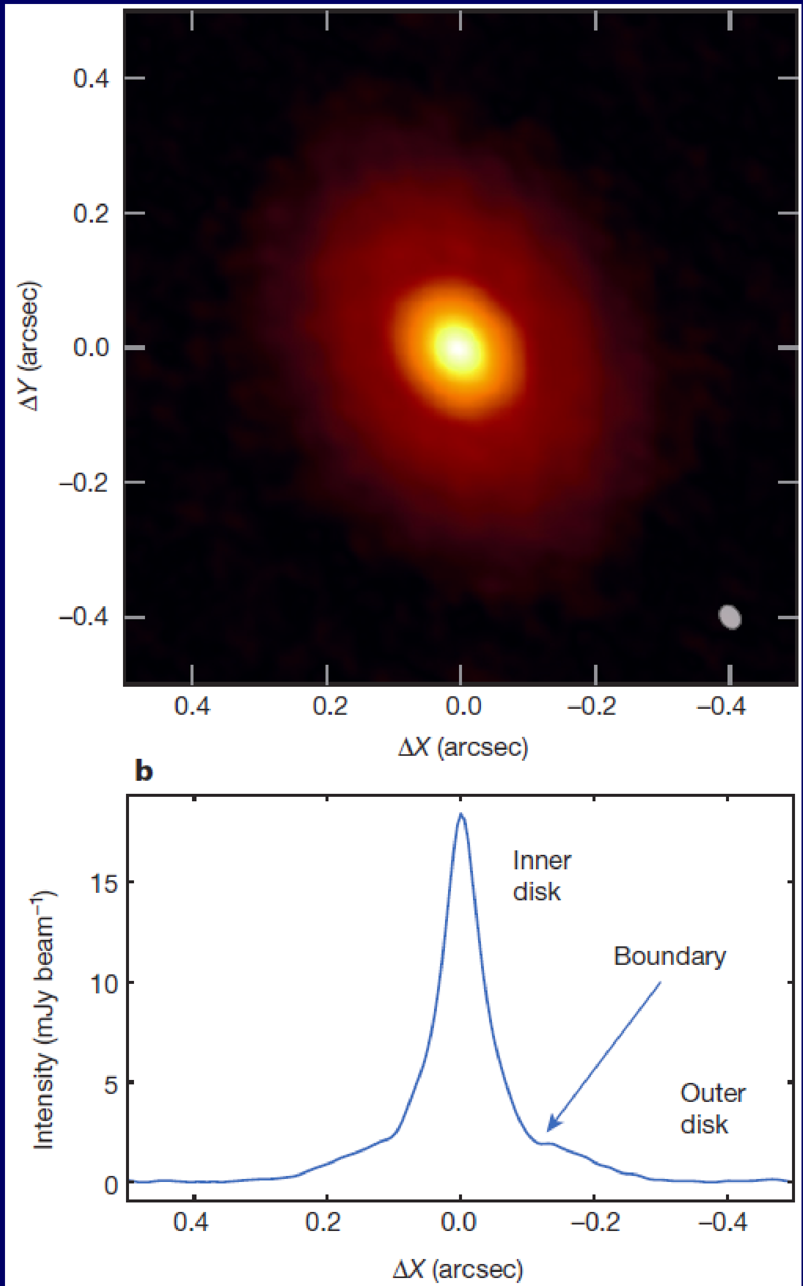
Grain growth @ snow lines?

e.g., Zhang et al. 2015, Banzatti et al. 2015

- Snowline of various volatile account for the HL Tau multiple dust continuum rings ?
  - Fast pebble growth at dark gap ?
- Sintering related ? (Okuzumi+2016)

ALMA Detection of H_2O snow line !?

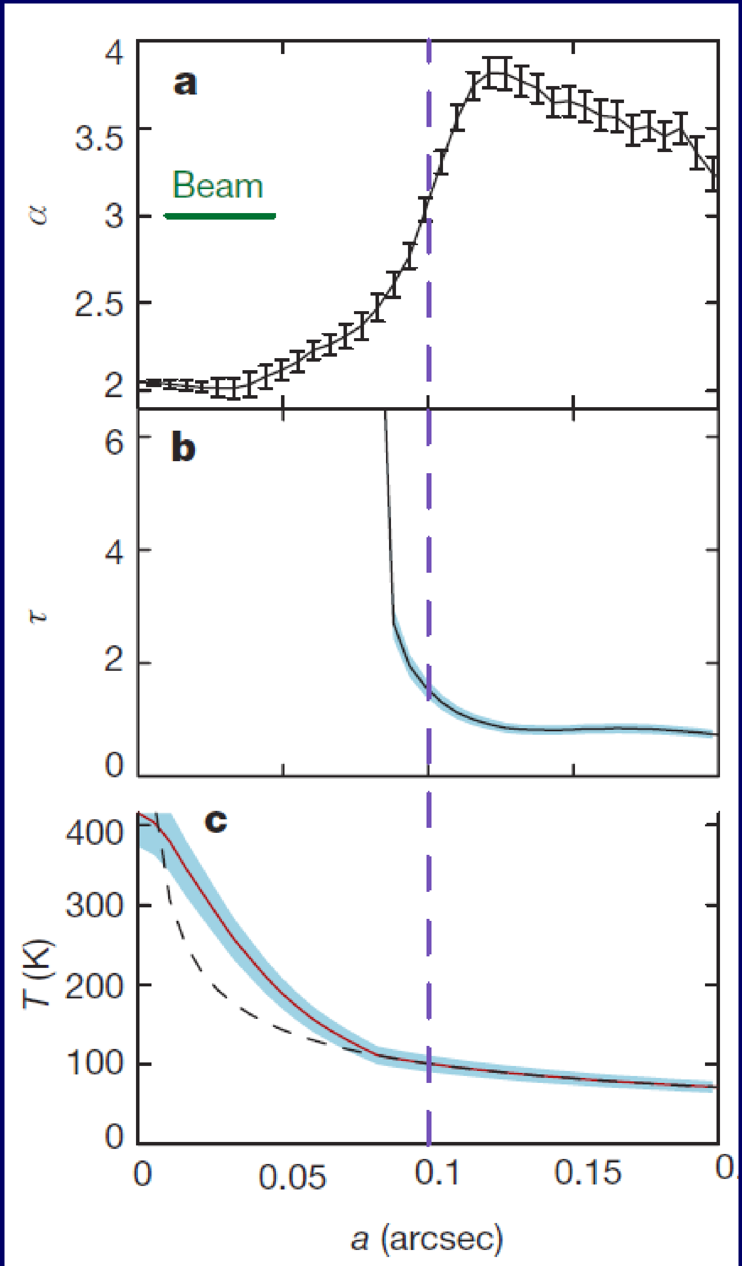
Cieza+2016, Nature



- V883 Ori
  - FU Ori type-star
  - Distance: 414pc
  - Episodic outbursting object
  - luminosity of $400L_{\odot}$
  - $\dot{M} = 7 \times 10^{-5} M_{\odot}$ per year
- ALMA Band 6 continuum
- Spectral slope α change at 0.1”(~42AU) found

ALMA Detection of H_2O snow line !?

Cieza+2016, Nature



- The temperature at the radius of spectral slope α change is T=105±11K, which agrees with H_2O condensation temperature
  - Elevated temperature due to temporal outburst
- The α radial profile is also consistent with Banzatti+2015 model which include dust drift/growth/destruction at the snowline

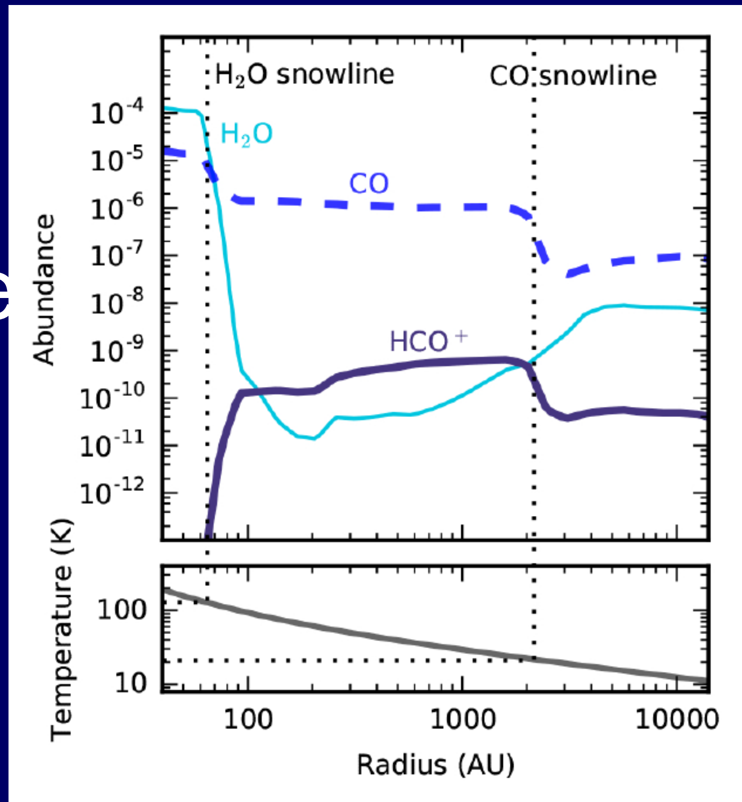
Remember that these are indirect observations…

- These studies are solely based on dust continuum observations (of unknow material)
- ***numerous possible other interpretations***
  - Planet disk interactions (e.g. Zhu+2011)
  - Secular gravitational instability (e.g. Takahashi&Inutsuka 2014)
  - Spatial variation of the disk viscosity (e.g. Pinilla+2016)
  - …etc, …etc…
- Snowline is one of the possible interpretations for these observations

Yet another example of water snowline indirect, but *chemical* tracer $H^{13}CO^+$

- Like N_2H^+ for CO, $H^{13}CO^+$ could be the (anti-correlated) *chemical* tracer for H_2O gas and its snowline
  - H_2O gas destroys HCO^+
    $HCO^+ + H_2O \rightarrow H_3O^+ + CO$
- But still indirect chemical trace…

van't Hoff 2017



Radial abundance distribution for NGC1333 IRAS2 protostellar envelope
(Kristensen+ 2012)

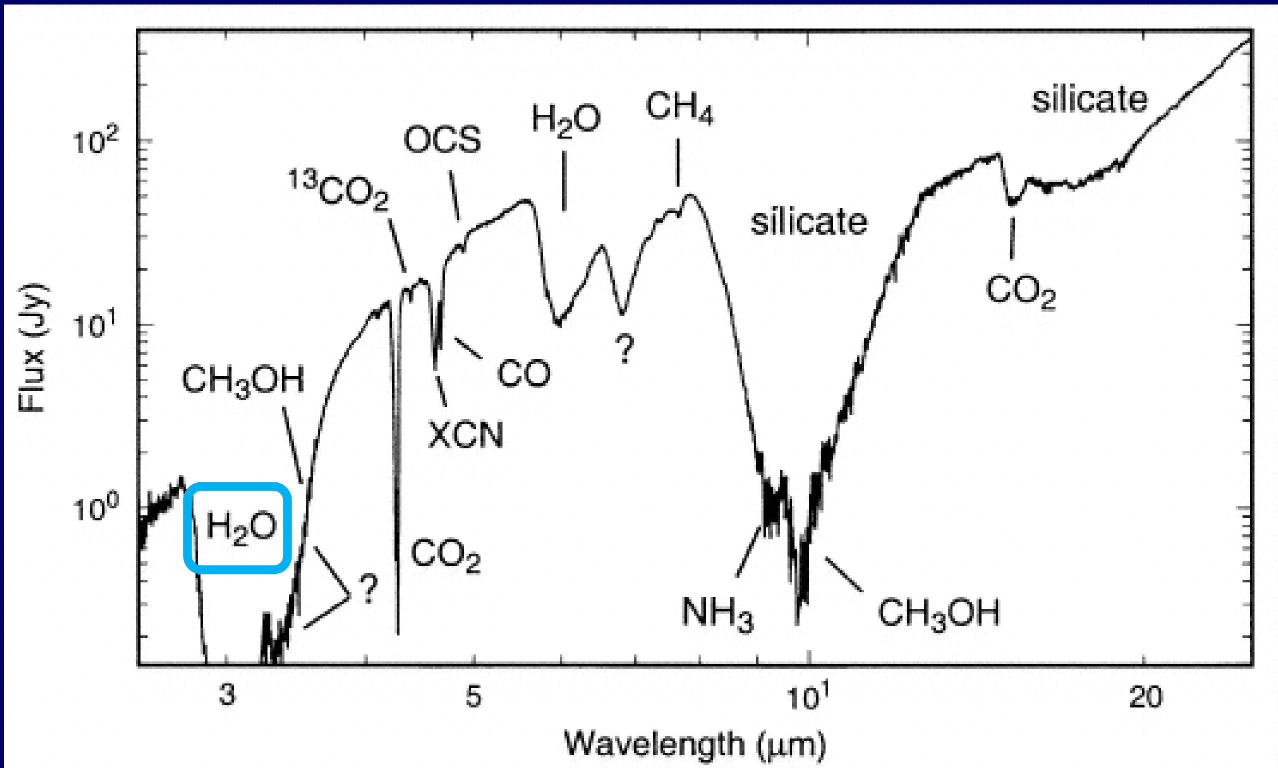
Toward direct observations of H_2O snowline

- At this moment, no direct solid measurements of H_2O snowline position (radius) is achieved
- How to make direct observations of H_2O snowline ? → observation of water itself !
  - Spatially resolved optically thin H_2O gas line observations such as $H_2{}^{18}O$ (challenging) ← like $^{13}C^{18}O$ for CO (van’t Hoff 2017)
  - Spectrally resolved H_2O line observations whose line shape is sensitive to the snowline position (Notsu-san’s talk later)
- Further complemental method : observations of water ***ice*** distribution in the ***IR***

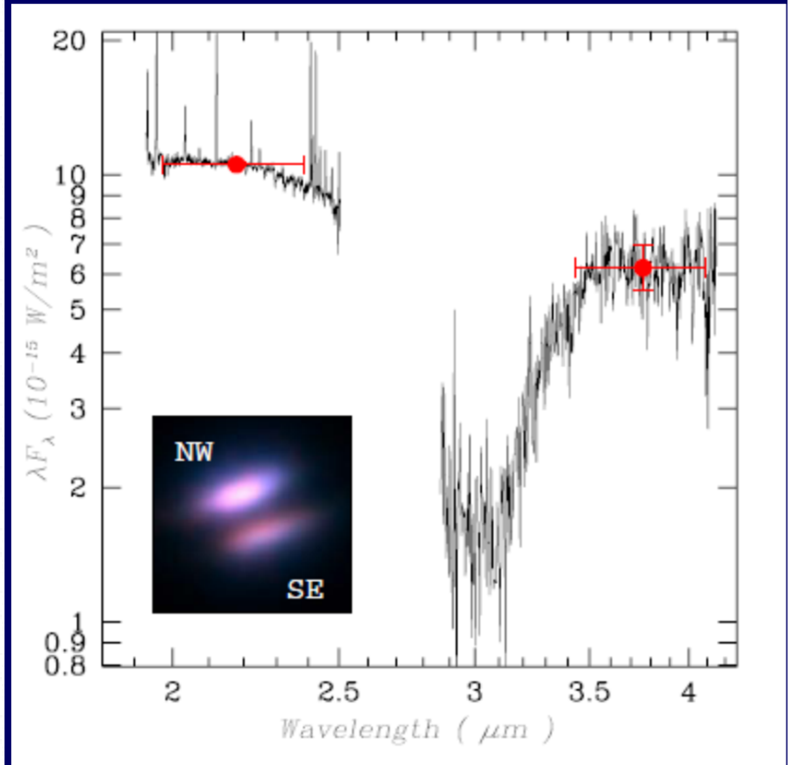
InfraRed(IR) absorption features of ices/solids

- In the IR, various ice absorption feature exist
- Prominent ~3μm water ice absorption (OH vib.)
- Also observed toward edge-on protoplanetary disk

ISO spectra of massive protostar W33A



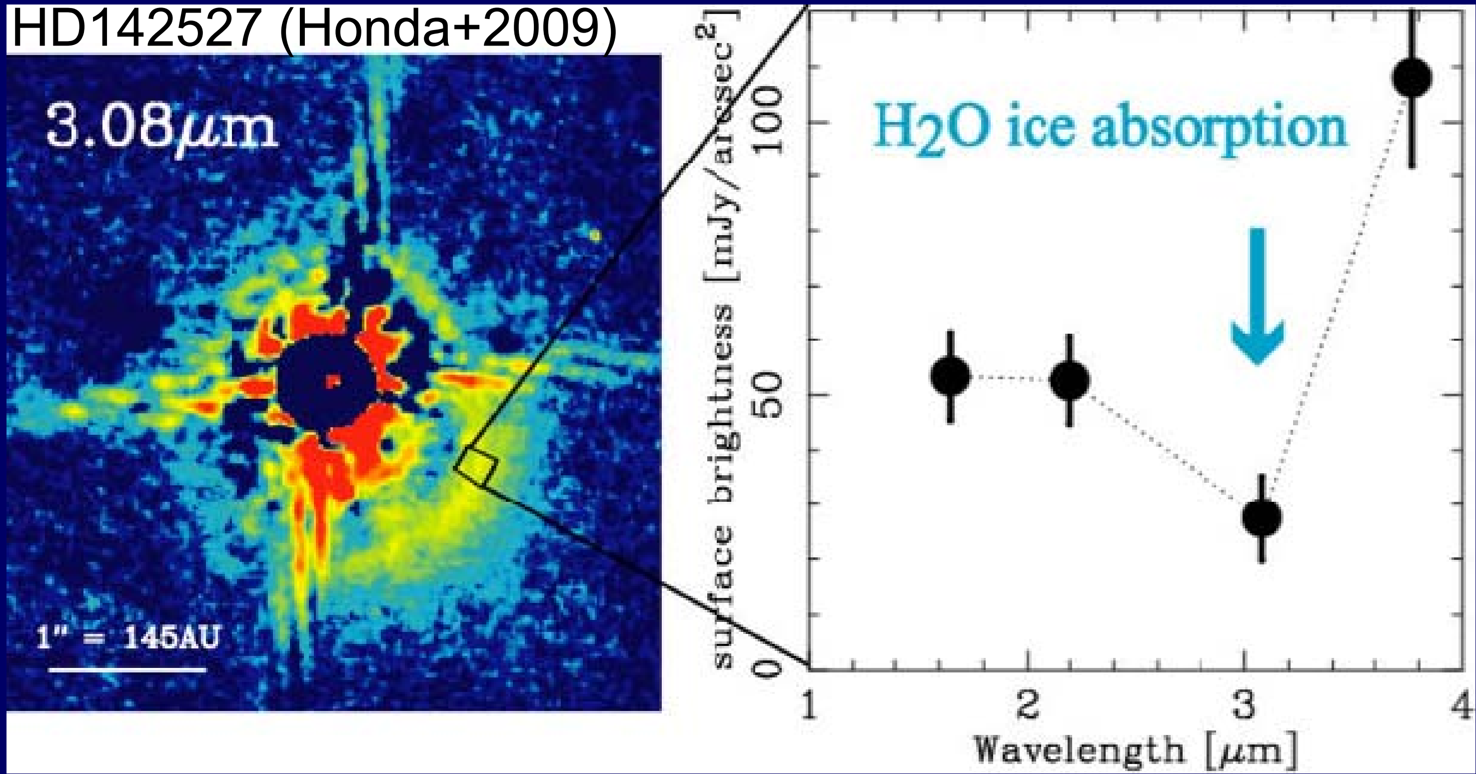
HK Tau 3μm water ice feature (Terada et al. 2007)



Chiang et al. 2001

Ice absorption mapping to trace ice distribution

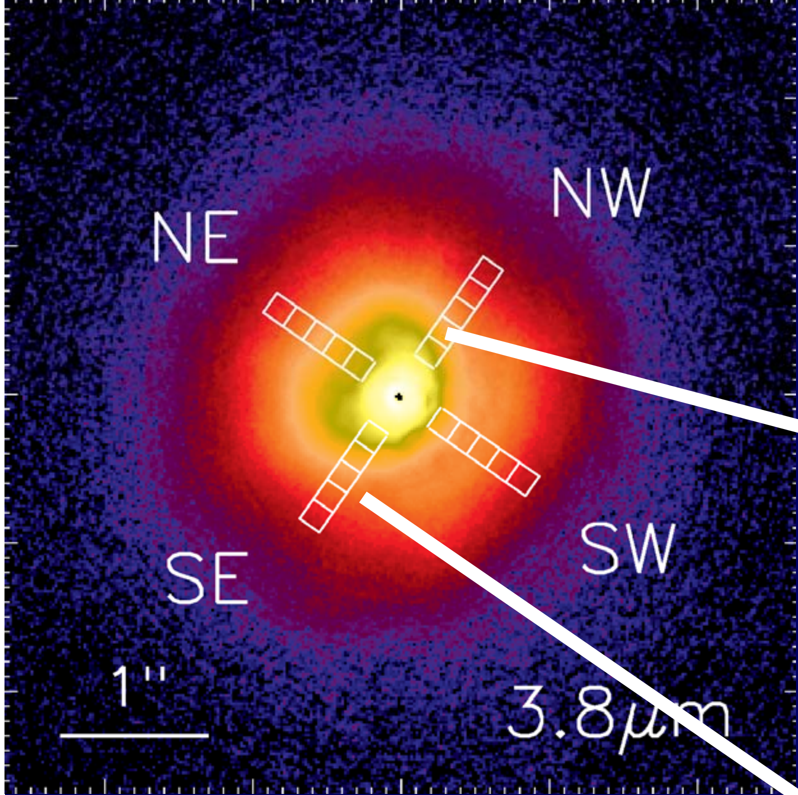
2-4μm "spectra" of face-on disk scattered light



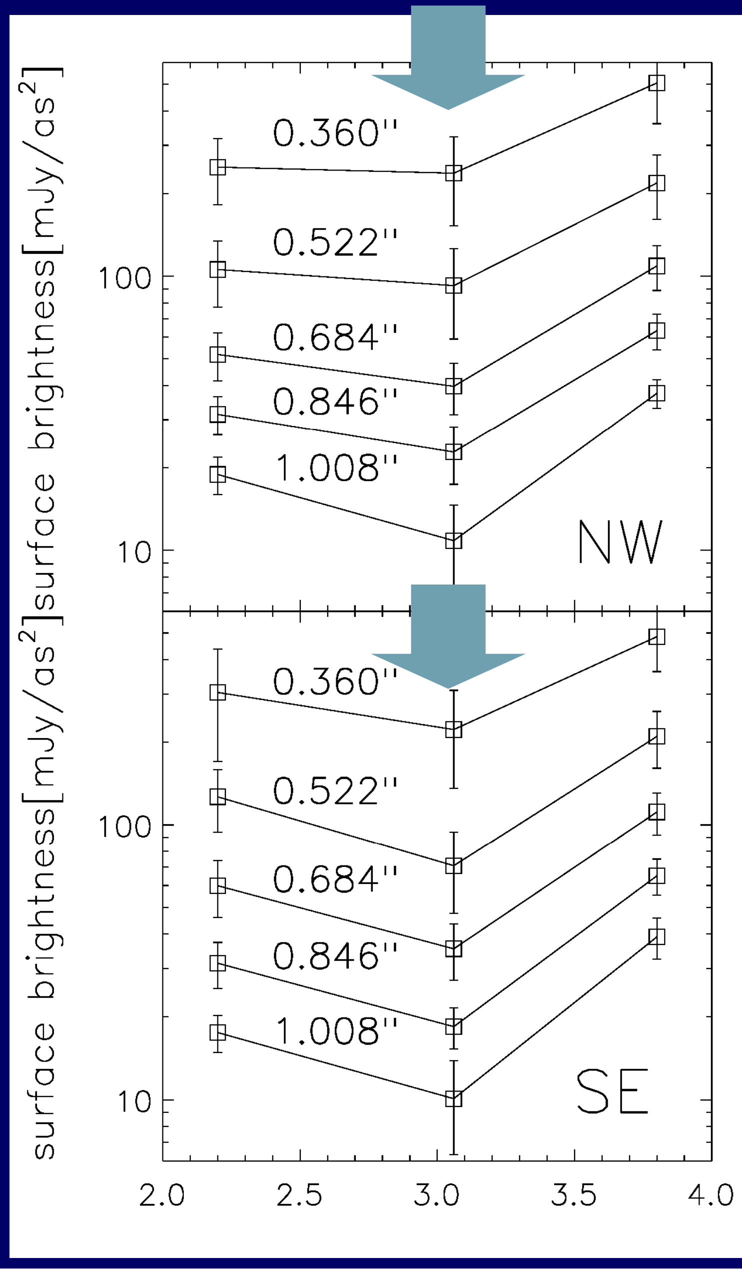
IWA~0.7"
→ much improvement needed…

- By high-spatial resoltuion **water ice absorption mapping,** we can reveal the water snow line
- However, the bright stellar speckle noise hampers us to trace inner regions → improvement of inner working angle (IWA) needed as close as ~0.1"

2-4μm "spectra" of HD100546 disk scattered light



HD100546 disk by Gemini/NICI
(Honda et al. 2016)



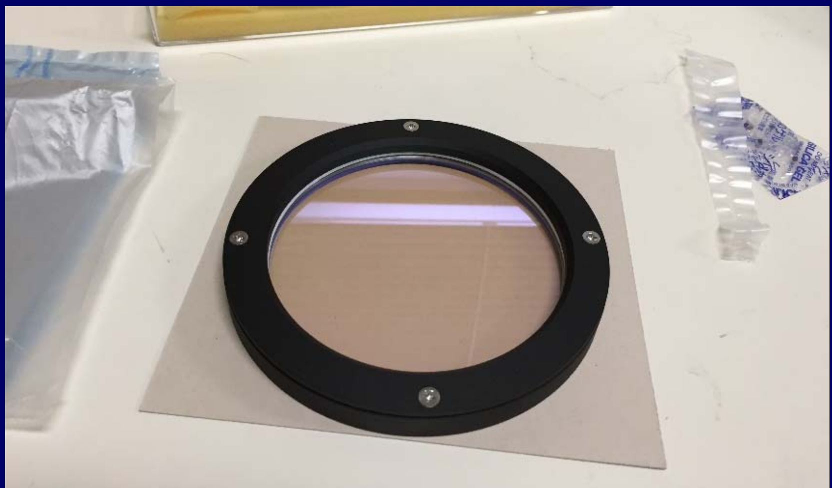
shallow 3.1μm water ice absorption detected as close as ~40AU to the star

IWA ~ 0.3"

→ Still IWA improvement needed to trace surface snowline

Toward direct detection of H_2O snow line by water *ice* observations

IRCS+AO188 at Nasmyth
2-5um Half-wave plate Φ=94mm



Improvement of IWA is key to detect snowline in the infrared

→PDI (Polarimetric Differential Imaging) improves IWA

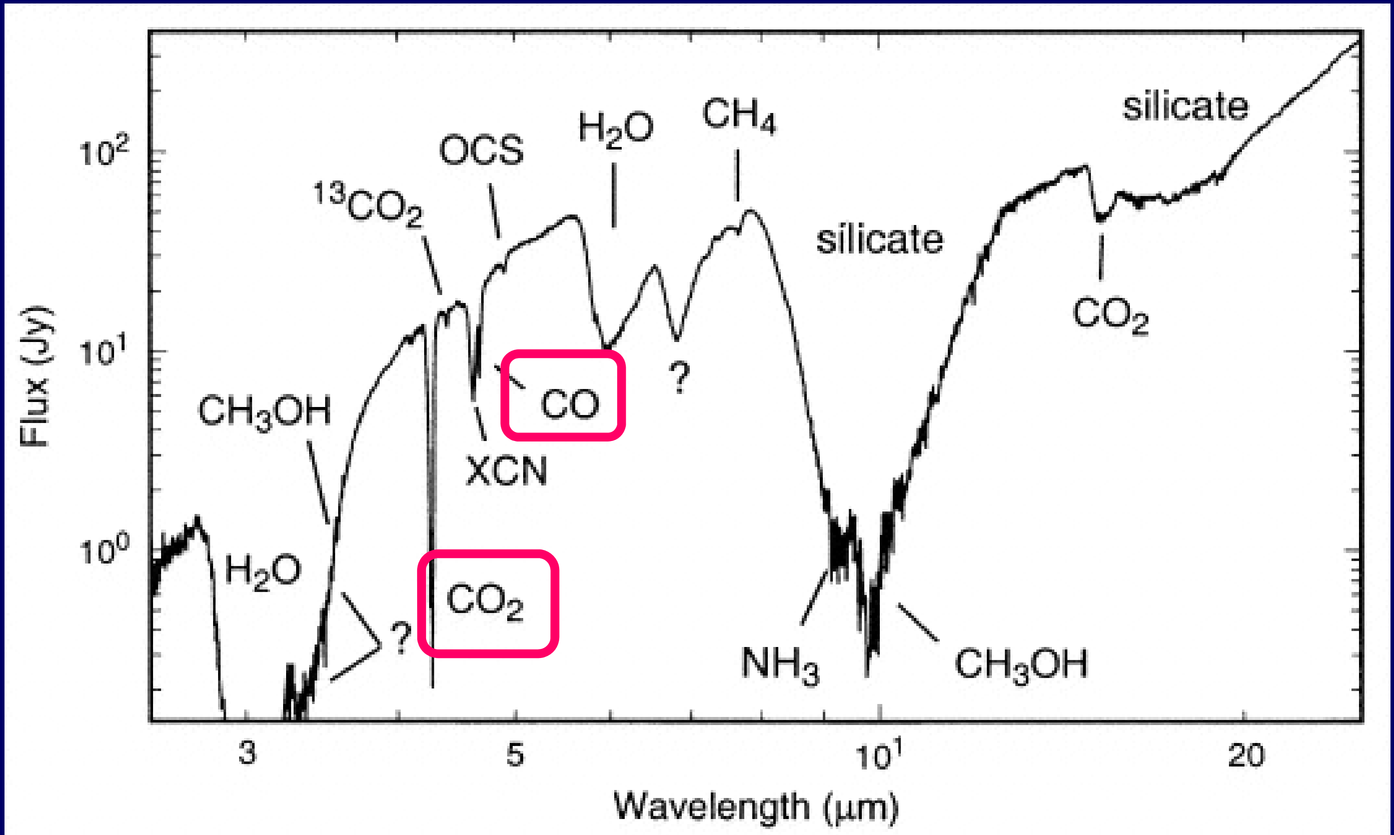
No PDI capability among 8m telescope in 3-5μm

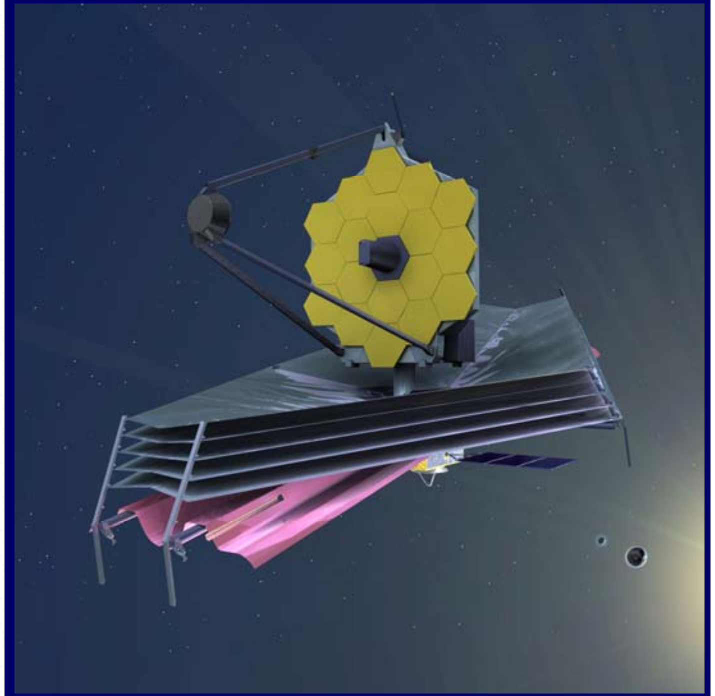
→ We developed PDI capability of Subaru/IRCS in 2-5μm（unique among 8m-class telescope）

- Engineering/performance evaluation on-going
- Opened for public in S18A with risk-share mode
- Observation scheduled in S18A

JWST mapping of ice in the disk

- JWST will provide much higher sensitivity in λ>2μm
- Not only water ice, but also CO (4.67μm) and CO_2 ice (4.25μm) mapping possible





summary

- ALMA has started to reveal the snowline position (radius) of volatile in disks
- indirect and direct CO snowline obs.
- only indirect observations of H_2O snowline so far (be careful !)
  - Direct H_2O snowline detection is next milestone !
- IR observations of ***ices*** are also complementl to radio observations of ***gas***
  - current telescope and JWST may contribute
- We are now moving toward more solid/reliable observations of snowlines