# Infrared Spectroastrometric Imaging of the Water Snowline and C/O Ratio Distributions in Protoplanetary Disks

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# Protoplanetary Disk (PPD)

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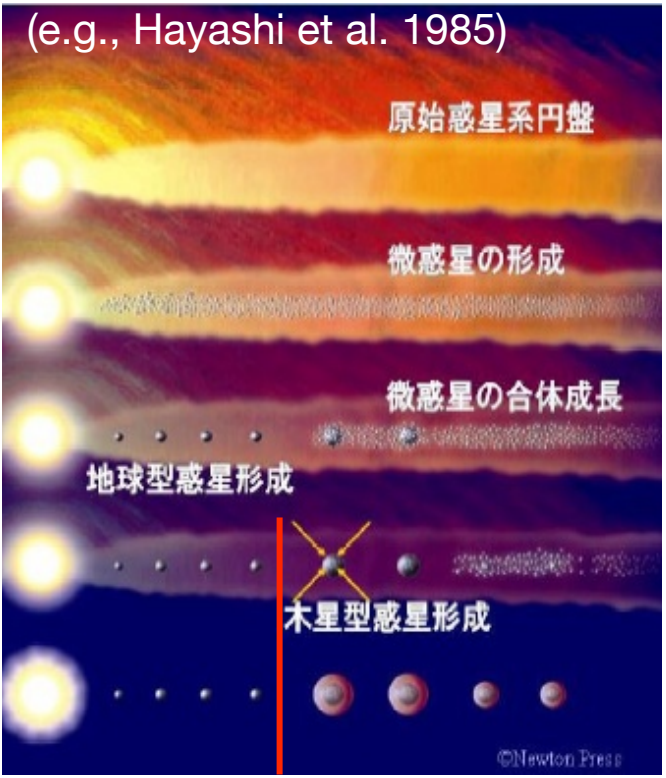
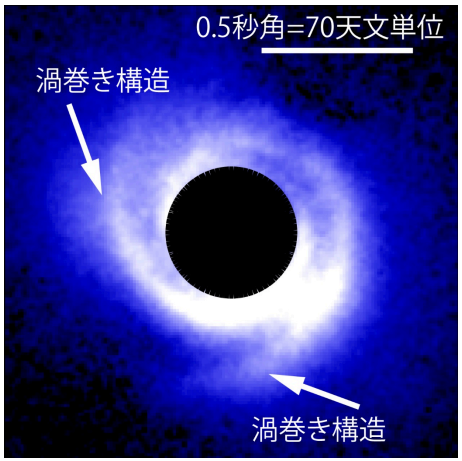
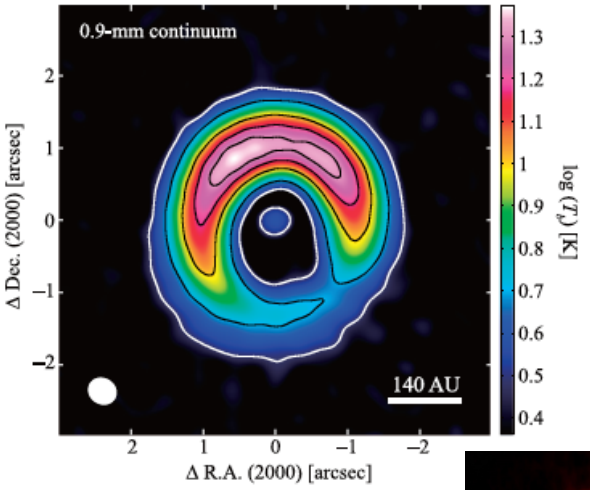



- Disks which are made from Gas & Dust grains.
  (Main component of gas : $H_2$ molecules )
- Planet formation fields.
- Some images of them have observed
  in infrared and sub-millimeter wavelengths.
  (Subaru/HiCIAO, SMA, ALMA etc.)

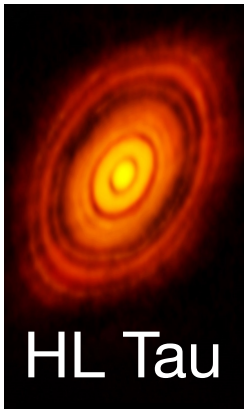



Near IR
(Subaru/HiCIAO)
Muto et al. (2012)




Sub-mm (ALMA)
Fukagawa et al. (2013)

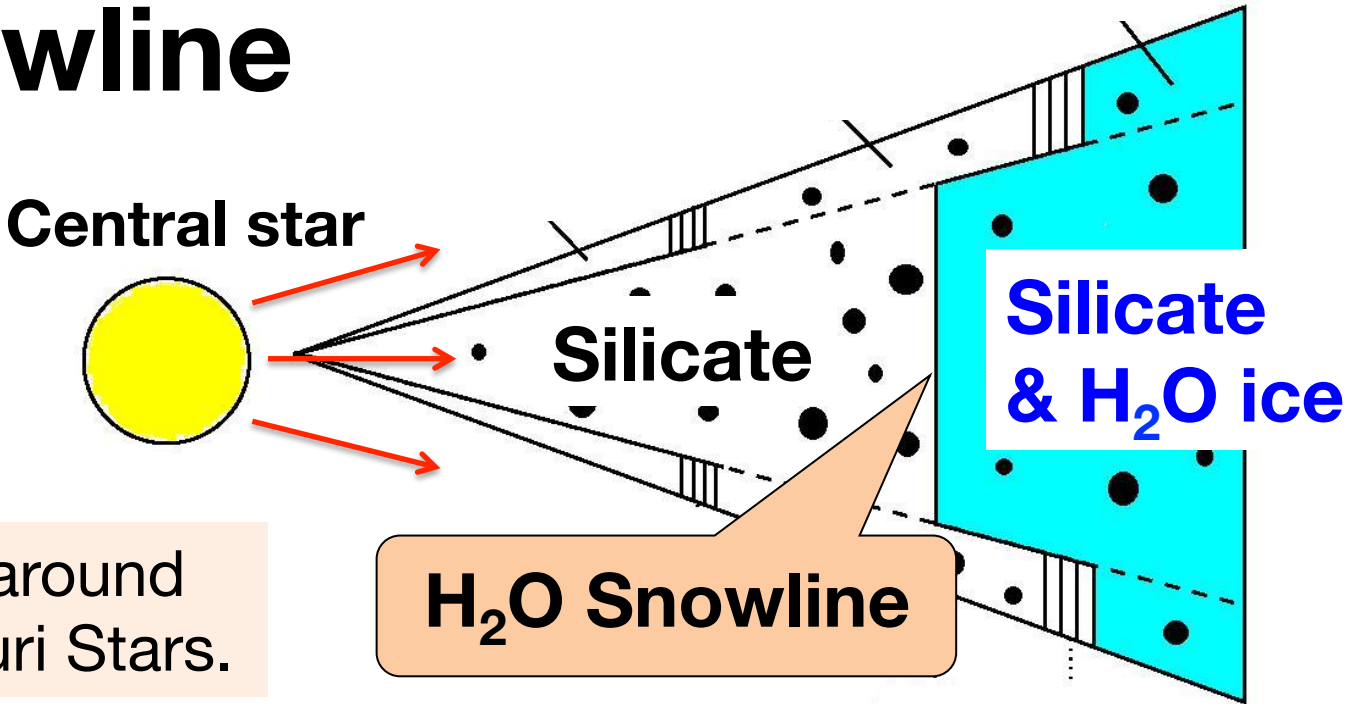
**High Temp.** ⟷ **Low Temp.**




- **Many molecules are formed by chemical reactions in the Gas and on the Dust grains!**

(©M. Honda)

# $H_2O$ Snowline




a few AU@PPD around
Solar-mass T-tauri Stars.

**High Temp.** ⟷ **Low Temp.**

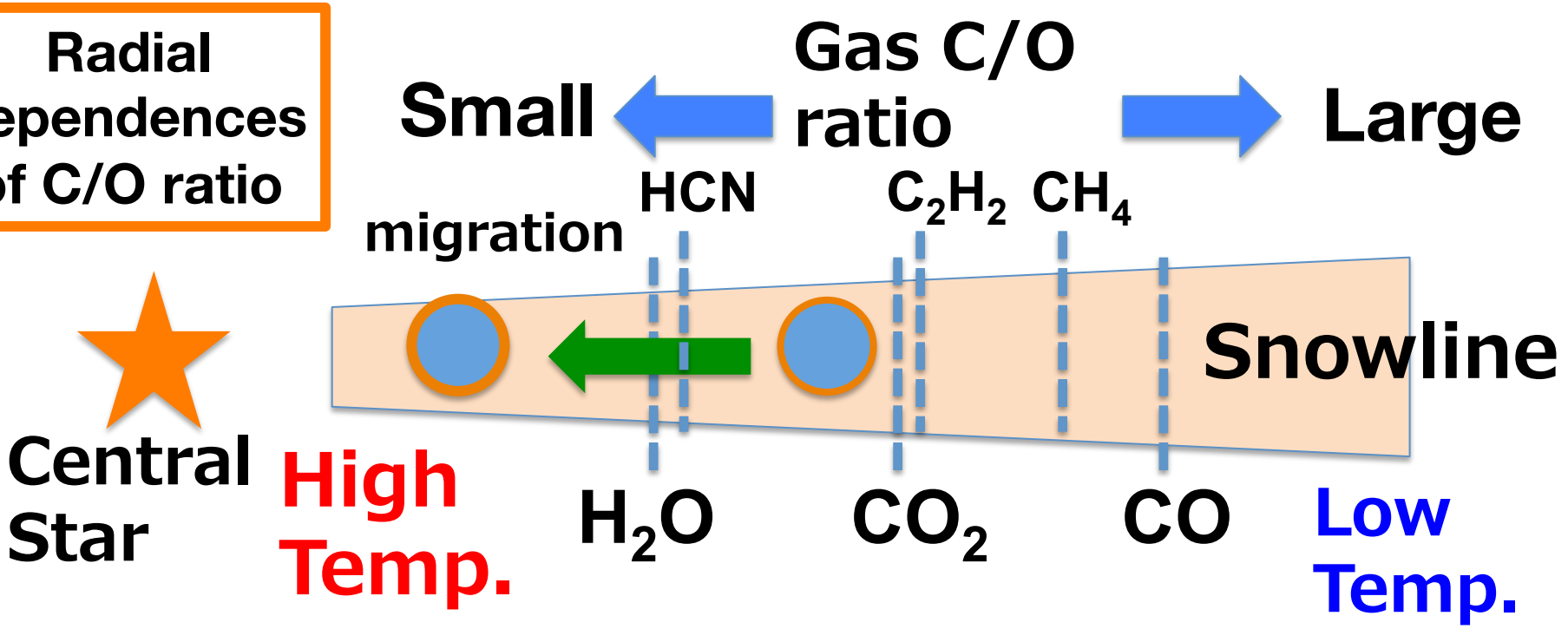
**$H_2O$ evap.** ⟷ **$H_2O$ freeze**

**Increase mass of solid material & Promote to dust grain growth @outer region of PPDs**

**⇒ Giant cores are formed & Much gas are obtained.**

**$H_2O$ snowline (midplane)** : Dividing regions of **rocky planet** & **gas giant planet formation** (e.g., Hayashi et al. 1981,1985)

**Radial dependences of C/O ratio**




**There are radial dependences of snowlines and Gas & Dust C/O ratio in PPDs**

e.g., Oberg et al. 2011
Pontoppidan et al. 2014, PPVI

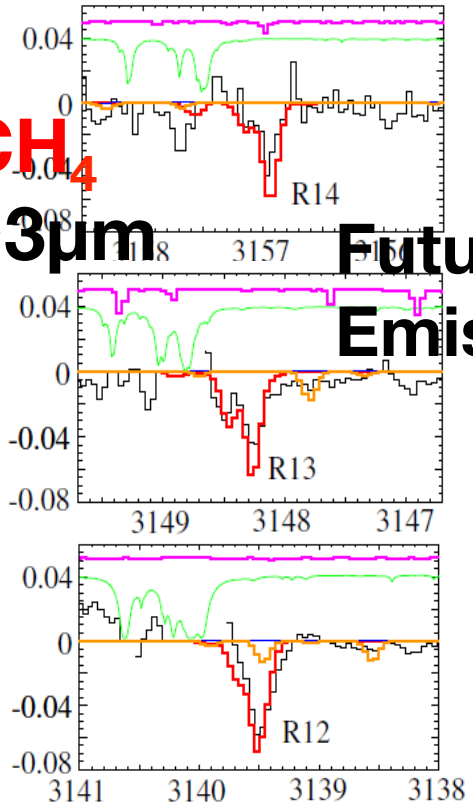
PPD: Protoplanetary Disks

C/O in PPDs (lines of CO, $H_2O$, HCN, $CH_4$, $CO_2$)
↔ C/O in Planetary atmosphere (Obs. of CO, CH4, $H_2O$, $CO_2$ etc.)
**=> Give constrain on the Planet Formation region & Planet migration process**

# Molecular lines from Protoplanetary disks

## GV Tau N: Infrared source

First Detection !! (Absorption)




**$CH_4$ ~3μm**

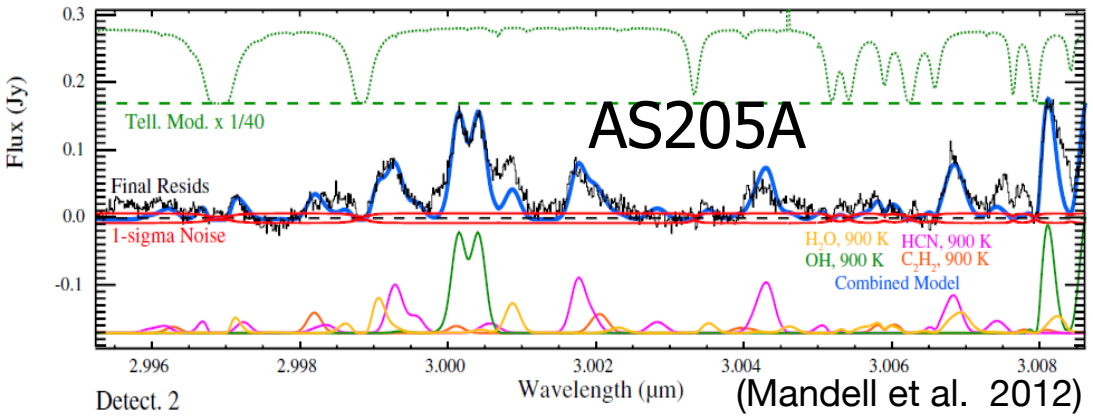
**Future: Emission?!**

(Gibb & Horne 2013)

## Obs. of HCN, $C_2H_2$, $H_2O$, OH

(Emission)

Keck/NIRSPEC ~3μm, R~25,000



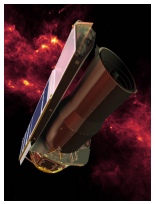

(Mandell et al. 2012)

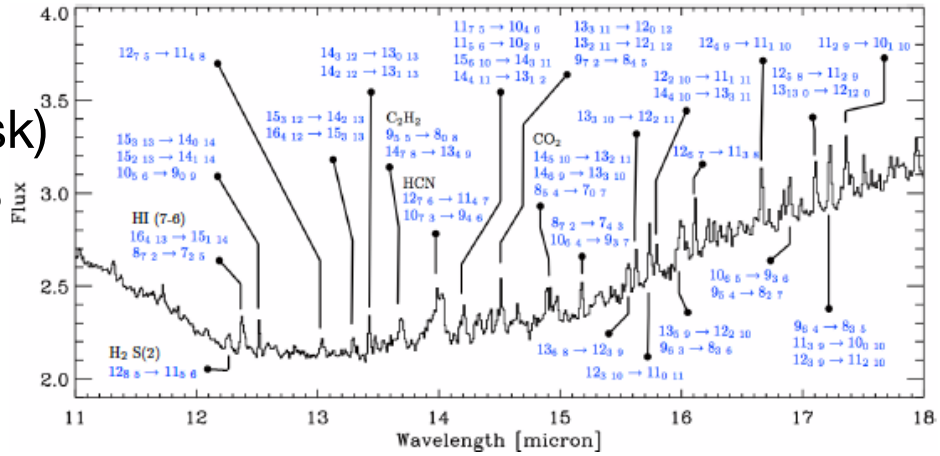
## HCN, $C_2H_2$, $H_2O$, OH, $CO_2$ (Emission)

RNO 90

(T Tauri disk)

*Spitzer*/IRS






Pontoppidan et al. (2010)

**※ CH4,CO2, $C_2H_2$: No Lines@Sub-millimeter**

**Line ratio of various lines →Molecular distributions!**

**HCN, CO, $H_2O$, $CO_2$, $CH_4$, $C_2H_2$, etc.→ C/O ratio**

But, the line ratios methods： their results are dependent to the assumed temperature distributions ($T_{eff}$ vs r) in PPD.

⬇

**If we can conduct high dispersion spectroscopic observations of emission lines (e.g., $H_2O$, HCN, CO, $CO_2$) from PPDs, we can locate the positions of snowlines and the C/O ratio distributions more directly! (e.g., TMT/MICHI, SPICA/SMI-HRS).**

**-contents-**

**1. Chemical modeling of PPDs.**

**2. Calculations of molecular emission line profiles.**

**$H_2O$ lines (to locate oxygen distributions)**

**HCN lines (to locate carbon distributions)**

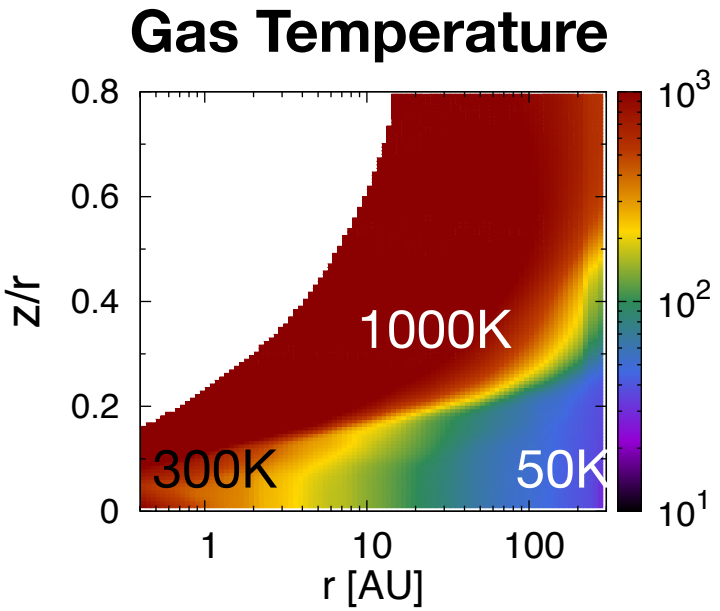
# Distributions of $H_2O$ vapor in PPDs

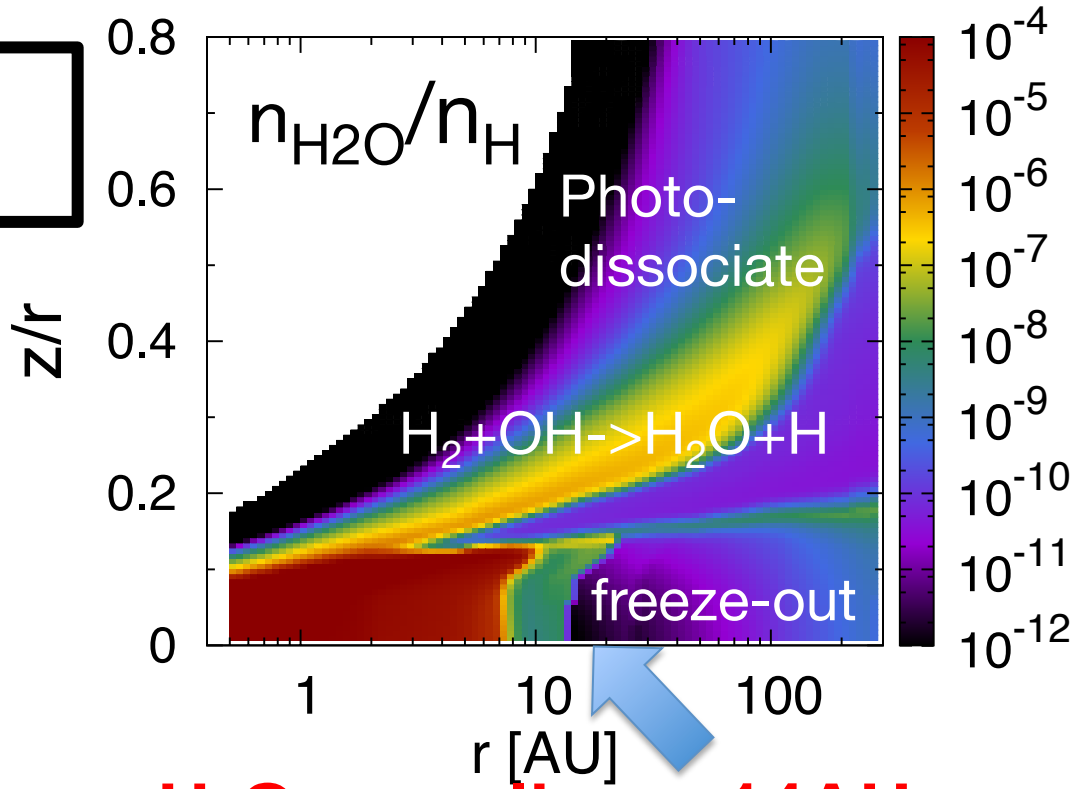
## Physical disk model + Chemical reactions

cf.Nomura & Millar 2005, Nomura et al. 2007, Walsh et al. 2015

**Herbig Ae star**
($M=2.5M_{sun}$ $T_{eff}=10000K$ $R=2R_{sun}$)

Notsu et al. (2016a, ApJ, submitted)
Notsu et al. (2016b in prep.)




**$H_2O$ snowline ~ 14AU**

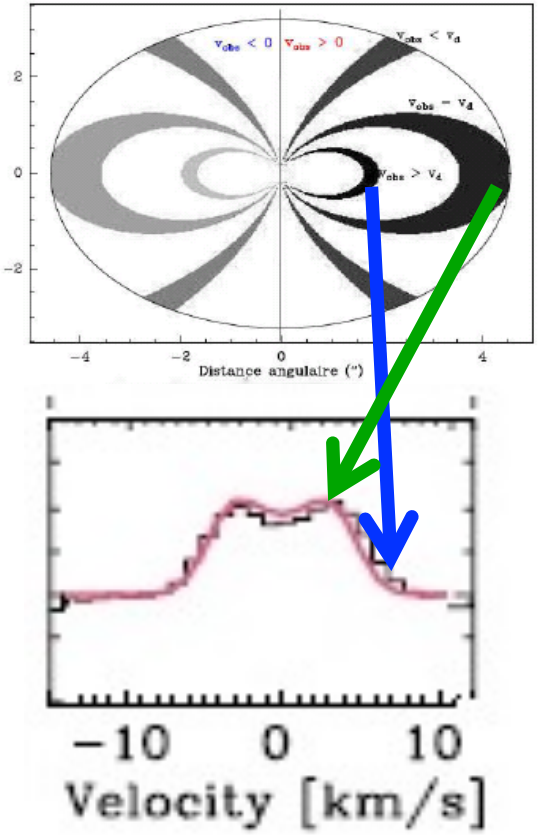
**<8AU: $n_{H2O}$ increase!**
($T_{gas}$ >170K)

# Spectroastrometry of water lines

**PPDs : (almost) Kepler rotation**

$$\Delta v = \sqrt{\frac{GM_s}{r}} \sin i$$

⇩ $i$: inclination angle



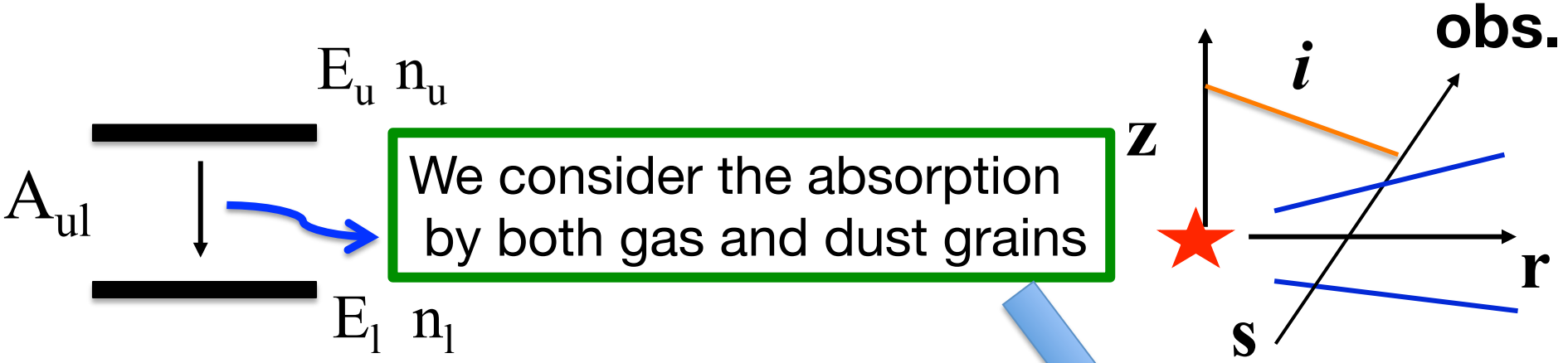

Analyzing profiles of emission lines, We obtain the information about the distances of emitting regions, **especially the positions of the snowlines**.

Ex.) **4.7μm CO line profiles**
→ Inner disk structures
(Pontoppidan et al. 2008)

$R \sim \lambda/\Delta\lambda$ **Kepler rotation**

Typical width of IR lines from PPDs : **Δv~10-20km/s**
→ need high-R spectroscopy (R~15,000) for detections.
**need very high-R (R~100,000) for analyzing profiles.**

# The calculation methods of emission lines




$A_{ul}$ : **Einstein A coefficient [$s^{-1}$]**

$E_u$ : **energy in upper state**

$$F_{ul}(r,\nu)=\int_{-s_\infty}^{s_\infty} n_u A_{ul}\frac{h\nu_{ul}}{4\pi}\varphi(\nu)\exp(-\tau_{ul})ds$$

Velocity profile $\Phi(v)$ : **Kepler rotation** + $c_s$

We adopt the distributions under LTE.

$$\Delta v=\sqrt{\frac{GM_s}{r}}\sin i$$

**Optically thin** ($\tau_\nu$<<1) : $F_\nu \propto n_{up}(E_{up})\,A_{ul}$

**Optically thick** ($\tau_\nu$>>1) : $F_\nu \propto B_\nu(T)$

Notsu et al. (2016a&b)

# Calculations of $H_2O$ emission lines

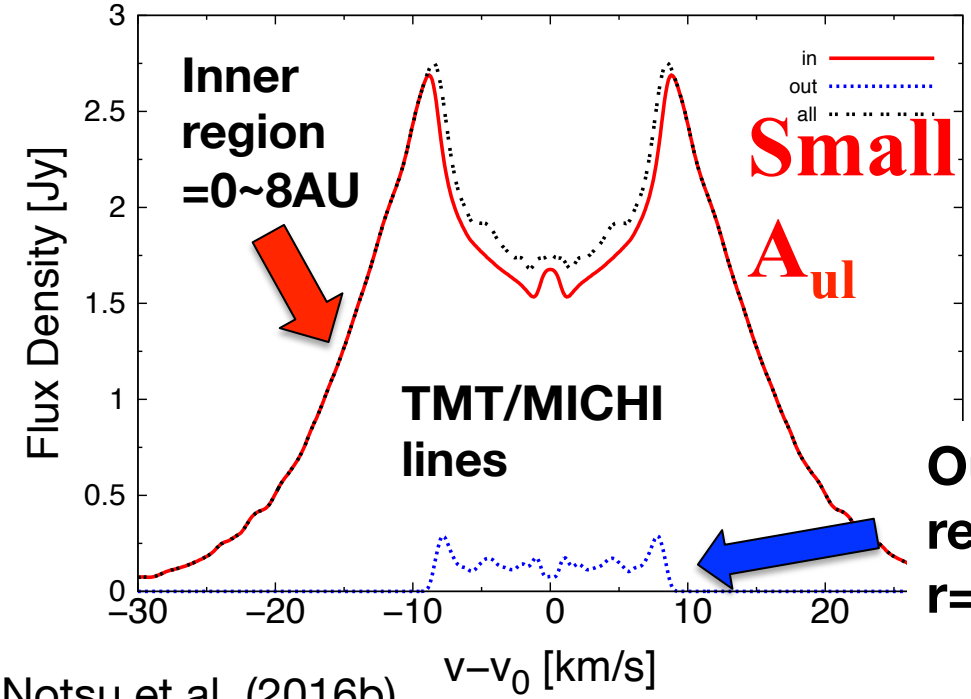
o-$H_2O$ **17.77**μm

$A_{ul}$ ~ **0.0029** ($s^{-1}$)

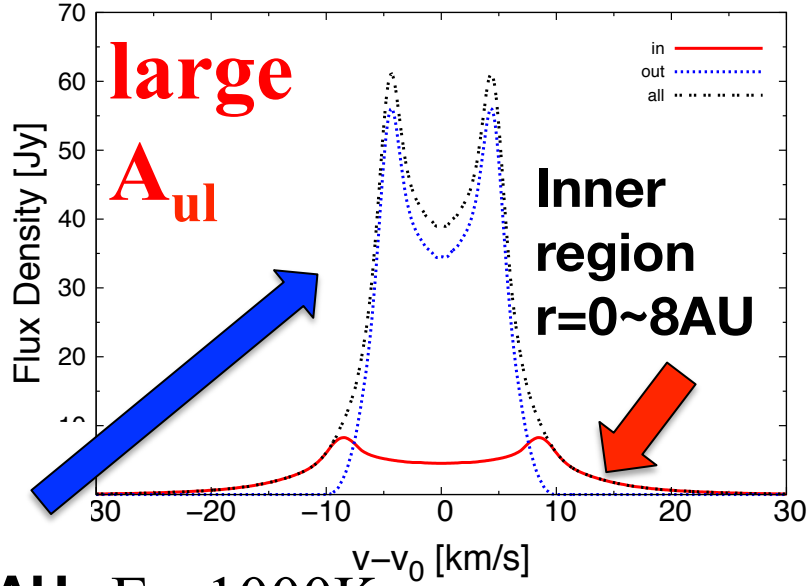
**Herbig Ae star**

o-$H_2O$ **63.37**μm

$A_{ul}$ ~ **1.7** ($s^{-1}$)




Notsu et al. (2016b)

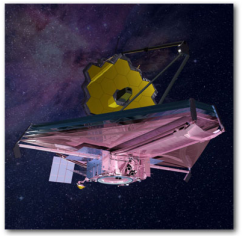



$E_u$~1000K

i=30° Distance:140pc

**We can locate the positions of $H_2O$ snowline through investigating the profiles of emissions that have small $A_{ul}$ ($10^{-6}$~$10^{-3}$ $s^{-1}$) and relatively large $E_{up}$.**

# Comments: Other related telescopes.



## vs JWST/MIRI (R~3000)

- High R(~100’000) =>We can detect the profiles and locate the positions of snowlines and C/O ratios in TMT/MICHI.
- We can use the JWST data to survey the candidates.

## vs ALMA (λ>300μm)

- High sensitivity=>We can observe more objects with TMT/MICHI.
- CH4,CO2, $C_2H_2$: No lines @sub-millimeter

## vs SPICA/HRS-SMI (13-18μm, R~25000)

- Wide wavelength range => We can also detect the L,M band, which have some useful lines (e.g., CO, $CH_4$) to trace the C/O ratios in various regions of disks with TMT/MICHI.

- We also observe the suitable 25μm water line.
- Higher R => We can detect the profiles in detail.

(※ 15μm strong $CO_2$ lines => only SPICA)

# -Summary-

・NIR & MIR line profiles of Keplerian protoplanetary disks

=> Constrain on **inner disk structure** !!

・Our calculations: We can obtain the information of $H_2O$ & HCN distributions through the profiles of some emission lines with different Einstein A coefficient ($A_{ul}$) and energies in upper state ($E_u$)**.**

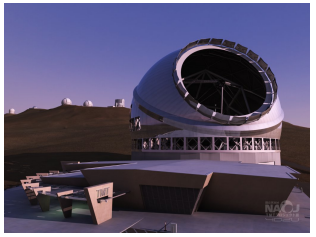
Notsu et al. (2016a, ApJ, submitted)
Notsu et al. (2016b in prep.)

Using TMT, we will know

- **$H_2O$ Snowline** of PPDs (using $H_2O$ emissions at Q band)
- **C/O ratio** (PPDs & Exoplanetary atmospheres)

=> **Constrain planet formation theory!!**

(Using L,M, N,Q band at TMT/MICHI)



TMT

cf. Our talk at TMT/MICHI WS (5/23)