2017年7月12日(水)
基研研究会「原始惑星系円盤」
(15+5分)

原始惑星系円盤の化学構造と、分光観測を用いたH_2Oスノーラインの検出可能性

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C. Walsh (Univ. of Leeds, UK)、T. J. Millar (Queens’ Univ. Belfast, UK) etc.

Reference: Notsu, S., et al. 2016 (ApJ, 827, 113); 2017a (ApJ, 836, 118); 2017b, 2017c (in prep.)

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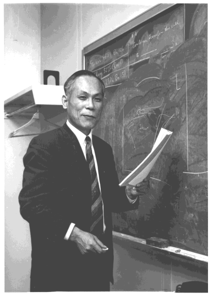
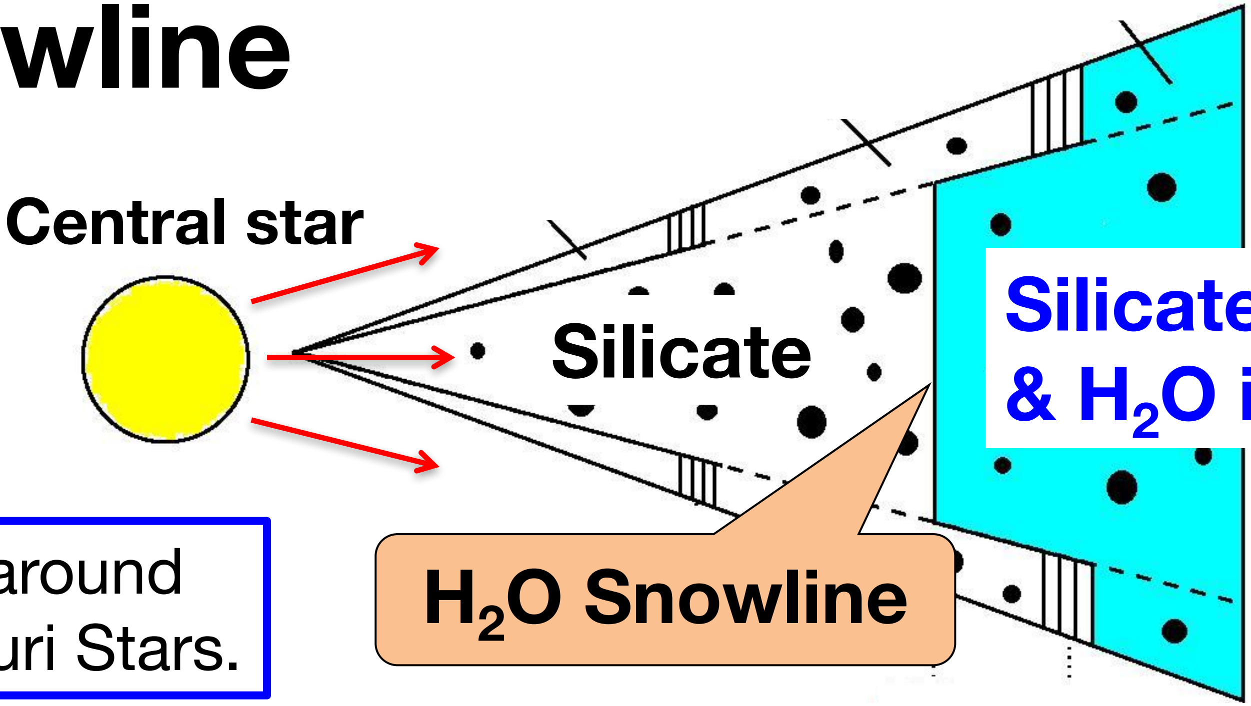
PPD: Protoplanetary Disks

H_2O Snowline


NASA G-68-10,414


Central star

Silicate

Silicate & H_2O ice

H_2O Snowline

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

High Temp.
H_2O evap. ↔ **Low Temp.**
H_2O freeze

Increase mass of solid material & Promote to dust grain growth @outer region in 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)

Spectral index α_{mm}

$F_\nu \propto \nu^{\alpha}$, $\kappa_\nu \propto \nu^{\beta}$, $\beta=\alpha-2$

- Optically thick: α~2 (Rayleigh-Jeans limit)

- Optically thin
  - Small size grains: α large (>3)
  - Large size grains: α small

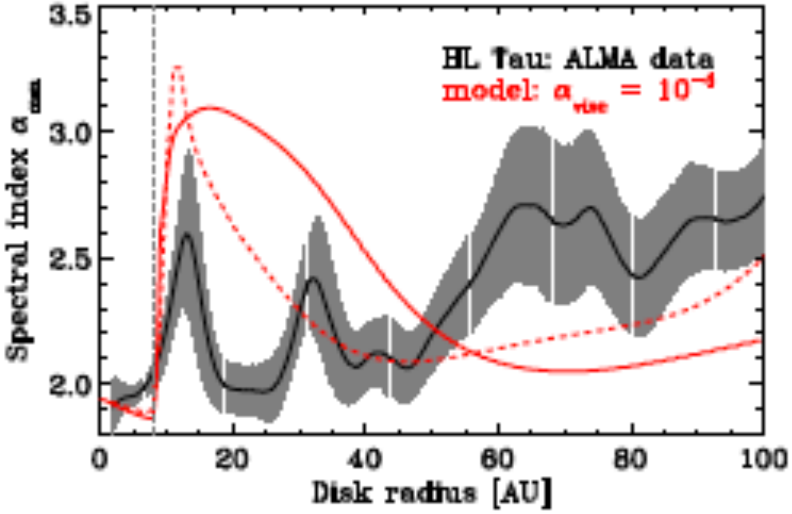
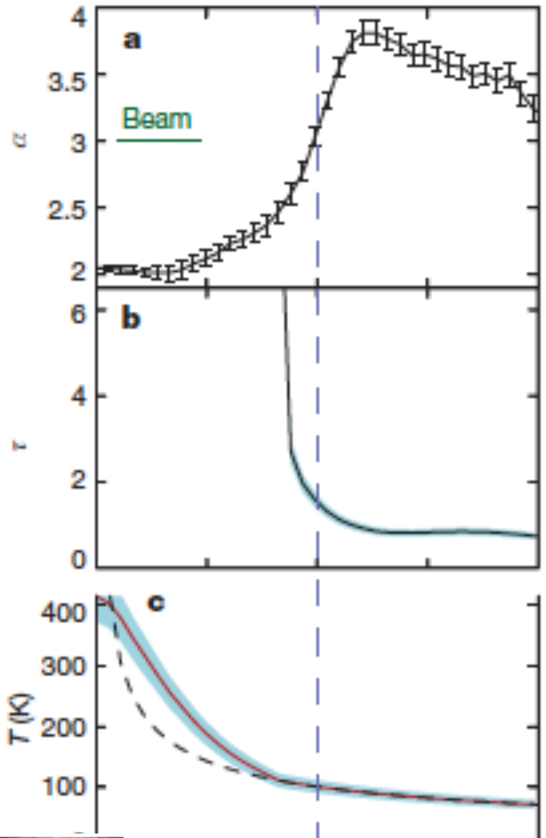


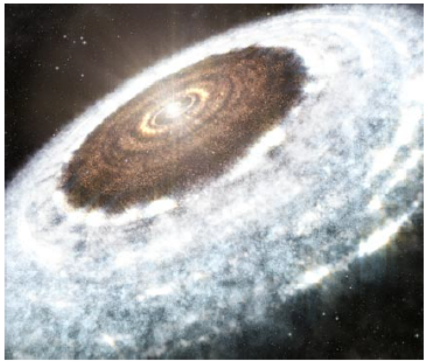
Figure 4. Our model with $\alpha_{visc} = 10^{-4}$ overplotted to the radial profile of the spectral index between 0.87 and 1.3 mm as measured in HL Tau using ALMA (gray shaded area; ALMA Partnership et al. 2015; Zhang et al. 2015; data courtesy of K. Zhang). The model is shown with the temperature profile used in this work (Equation (3), solid line) and the higher temperature (dashed line) used in Zhang et al. (2015).

snowline~10AU

HL Tau **Class I protostar**

Banzatti et al. 2015





Artist impression of the water snowline around the young star V883 Orionis, as detected with ALMA. Credit: A. Angelich (NRAO/AUI/NSF)

Snowline~42AU

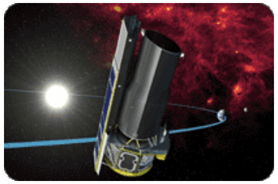
V 883 Ori

FU Ori type star

Cieza et al. 2016, Nature

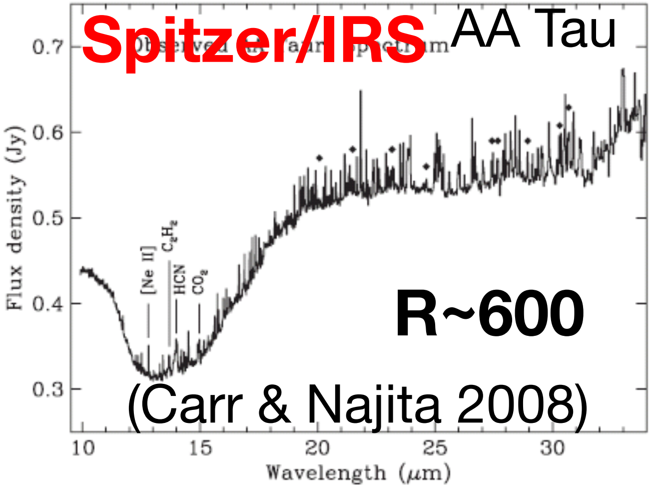
ALMA band 7

Space Obs. of H_2O lines from PPDs



H_2O, OH, HCN, CO_2 C_2H_2

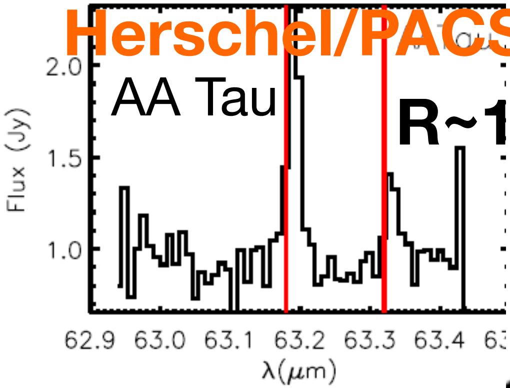
(Riviere-Marichalar et al. 2012)



Spitzer/IRS AA Tau

R~600

(Carr & Najita 2008)

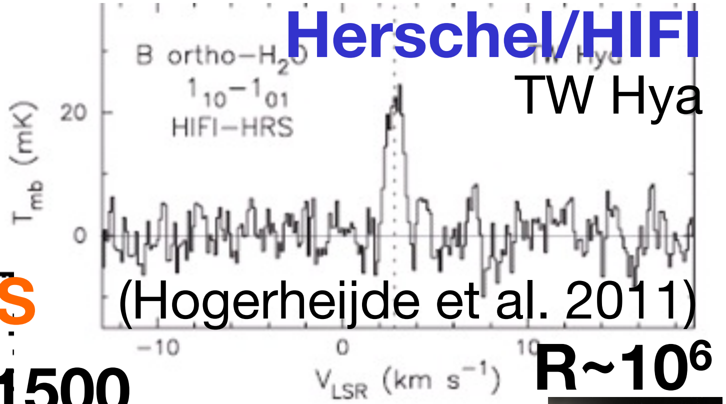


[OI] H_2O

Herschel/PACS

AA Tau

R~1500

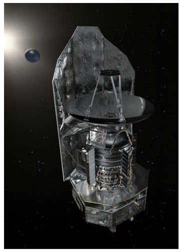


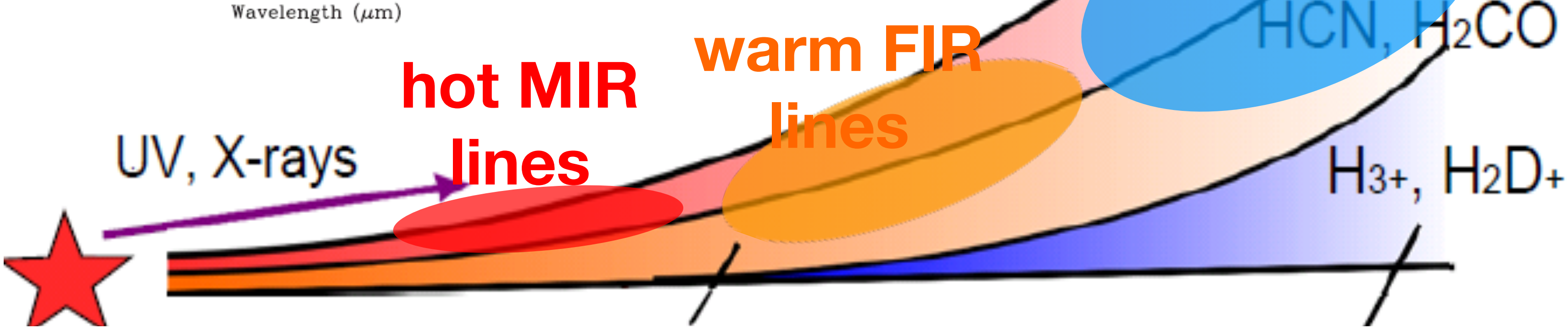
Herschel/HIFI

TW Hya

(Hogerheijde et al. 2011)

R~10^6





cold FIR lines

warm FIR lines

hot MIR lines

Spitzer **hot** H_2O : T-Tauri stars, Herbig Ae/Be star (**Upper limit**) @10-35μm

Herschel **warm** H_2O : T-Tauri, Herbig Ae/Be stars: @55-180μm

Herschel **cold** H_2O : TW Hya, HD100546, DG Tau@**269μm, 538μm**

Purposes and outlines of our work

The line ratios methods：their results are dependent to the assumed temperature distributions (T_{eff} vs r) in PPDs.

PPD: Protoplanetary Disks

If we can conduct high dispersion spectroscopic observations of H_2O lines from PPDs, we can locate the positions of the H_2O snowline more directly! (e.g., ALMA, SPICA/SMI-HRS).

Outline of this work

We derive the position of the H_2O snowline through the calculation of chemical reactions of PPDs under the self-consistent disk physical models.

↓

We calculate the profiles of H_2O emission lines, and find candidates of H_2O lines to locate the H_2O snowline through high-dispersions spectroscopic observations in the near future.

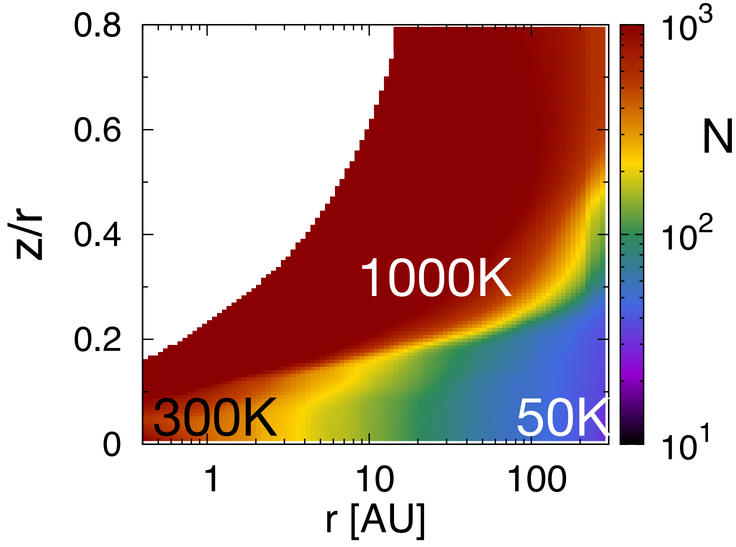
(Notsu et al. 2016, ApJ, 827, 113; 2017a, ApJ, 836, 118, 2017b in prep.).

Distributions of H_2O vapor

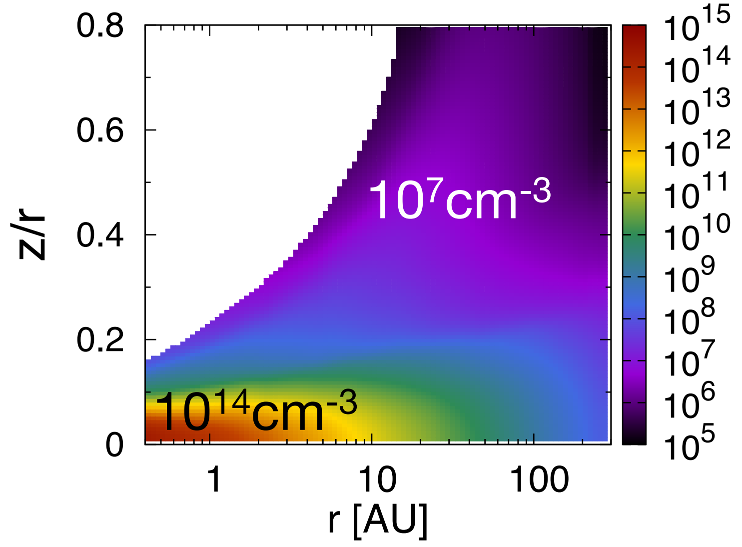
Herbig Ae disk

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

Gas Temperature

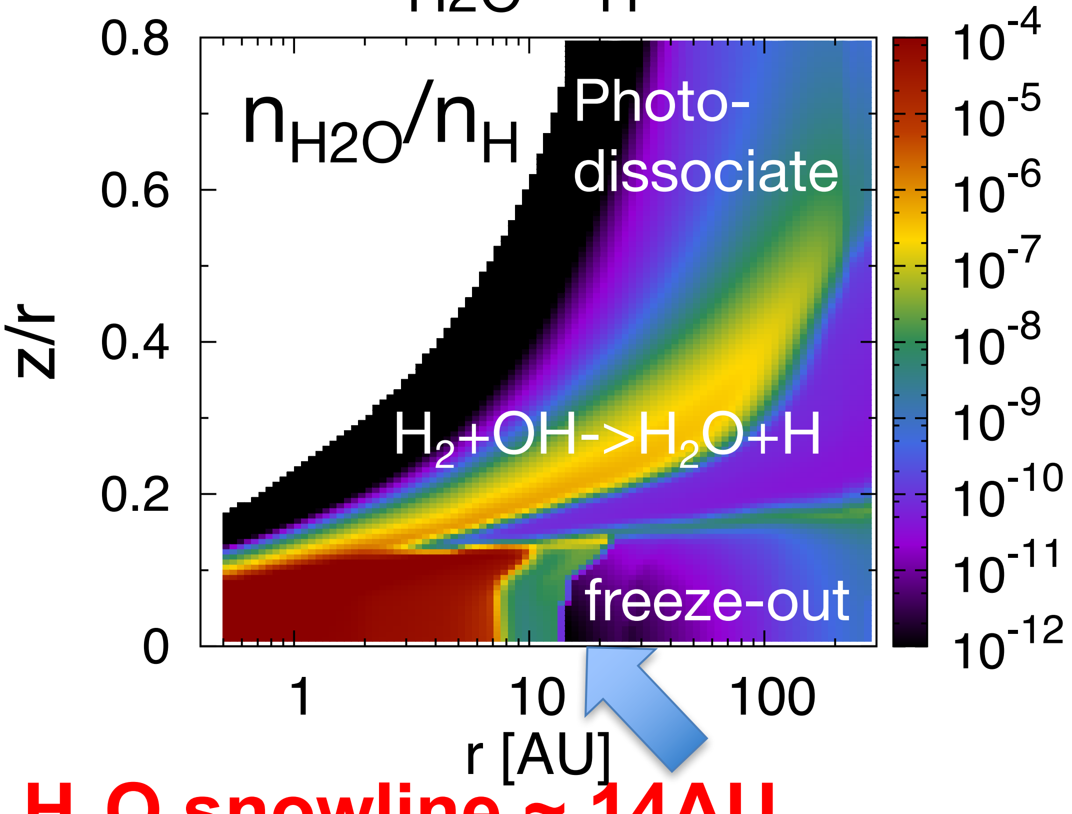


Gas Number Density



Notsu et al. (2017a)

n_{H2O}/n_H



H_2O snowline ~ 14AU

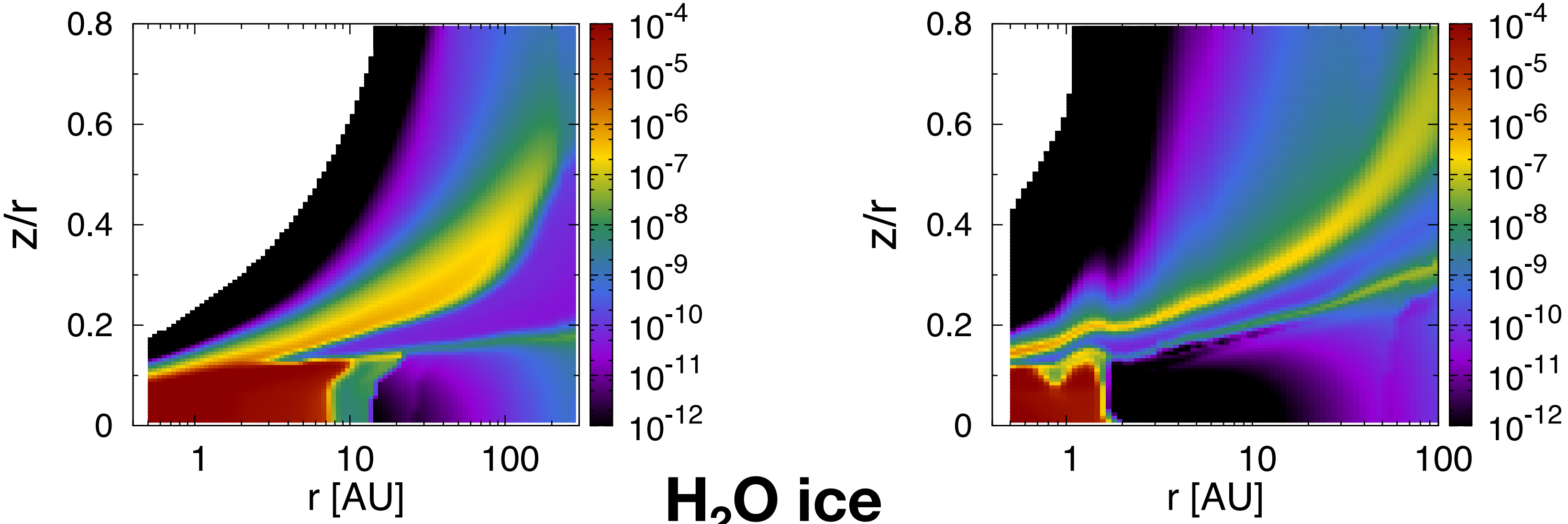
<8AU: n_{H2O} increase!

(T_{gas} >170K)

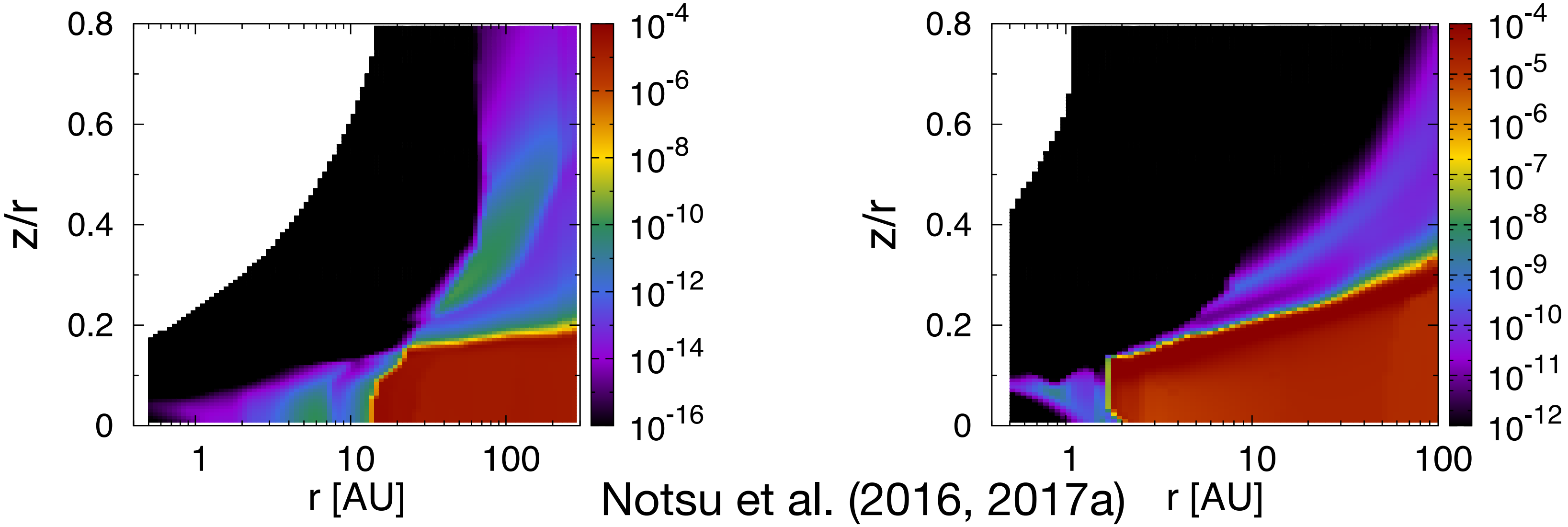
H_2O gas

Herbig Ae disk

T Tauri disk



H_2O ice



Notsu et al. (2016, 2017a)

H_2O Snowline : ~13-14AU

H_2O snowline : 1.6AU

Spectroastrometry of molecular lines

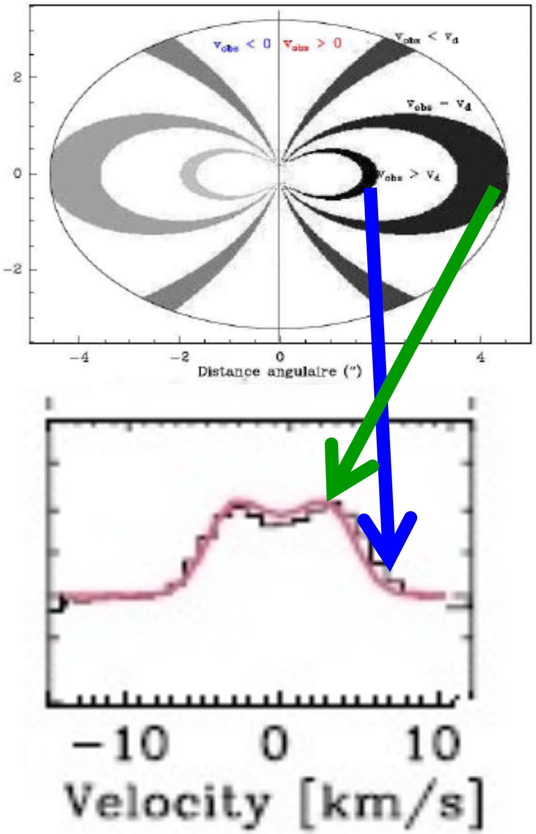
PPDs : (almost) Kepler rotation

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

i: inclination angle

⇩

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



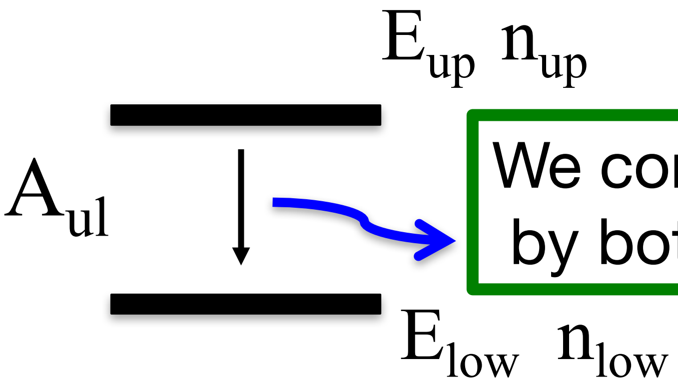
Kepler rotation

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

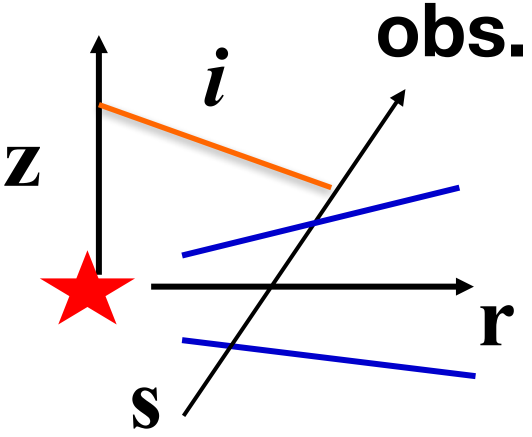
$R \sim \lambda/\Delta\lambda$

Typical width of 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



We consider the absorption by both gas and dust grains



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

E_{up} : **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 $\Phi(\nu)$: **Keplerian rotation** + c_s

We adopt the distributions under LTE.

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

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

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

Notsu et al. (2016, 2017a)

Calculations of o-H_2O emission lines

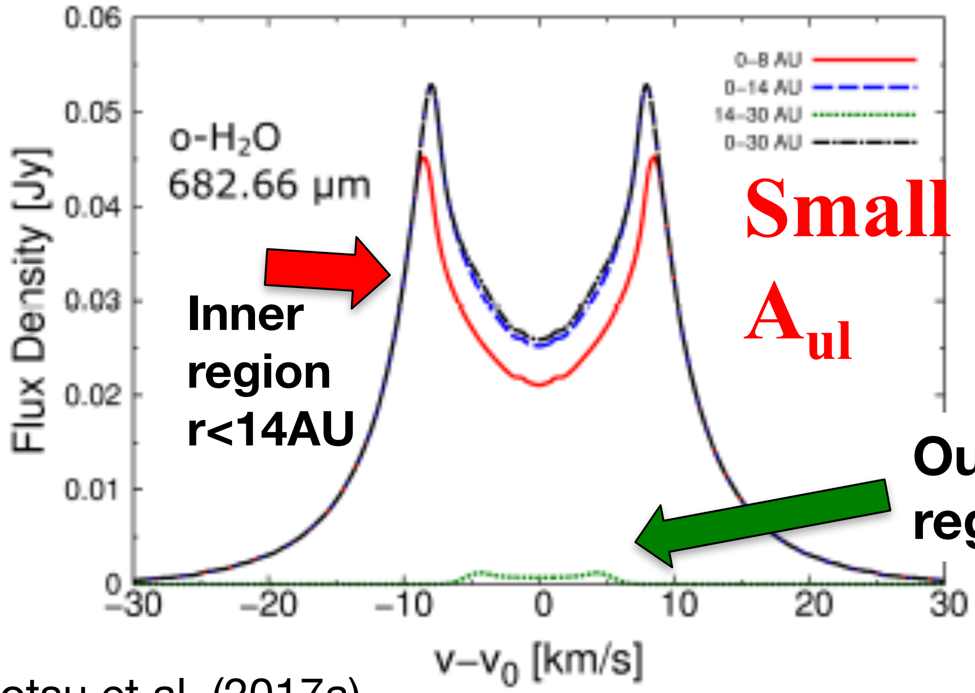
o-H_2O **682.66**μm

A_{ul} ~ **2.816 × 10^{-5} (s^{-1})**

Herbig Ae disk

o-H_2O **63.32**μm

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

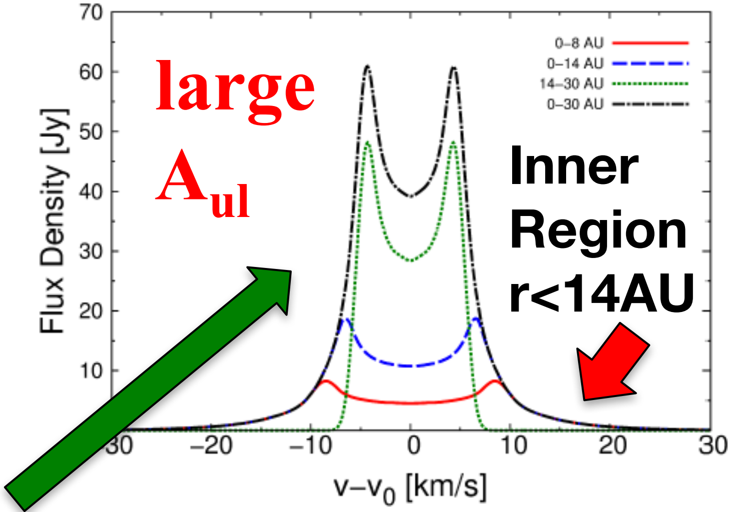


Inner region r<14AU

Small A_{ul}

Outer region

Notsu et al. (2017a)



large A_{ul}

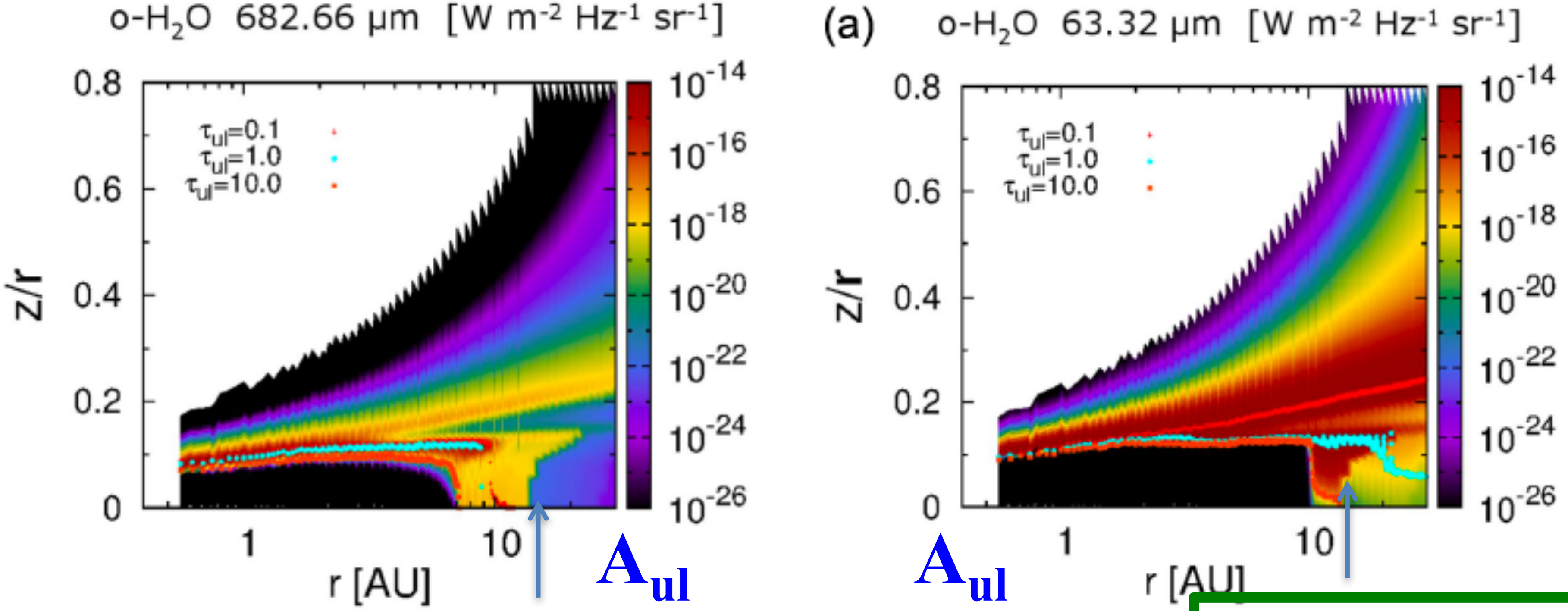
Inner Region r<14AU

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}.

Herbig Ae disk Emissivity distributions (*i*=0°, line of sight)



A_{ul} small

A_{ul} large

o-H_2O 682.66 μm
A_{ul}= 2.816 × 10^{-5} (s^{-1})

Notsu et al. (2017a)

o-H_2O 63.32μm
A_{ul}= 1.7 (s^{-1})

If A_{ul} is small, the contribution from optically thin surface layer of the outer disk becomes small compared with that of optically thick region of the inner disk.

Optically thin (τ_ν<<1) :
$F_\nu \propto n_{up}(E_{up})\, A_{ul}$
Optically thick (τ_ν>>1) :
$F_\nu \propto B_\nu(T)$

Possibility of future observations of H_2O lines

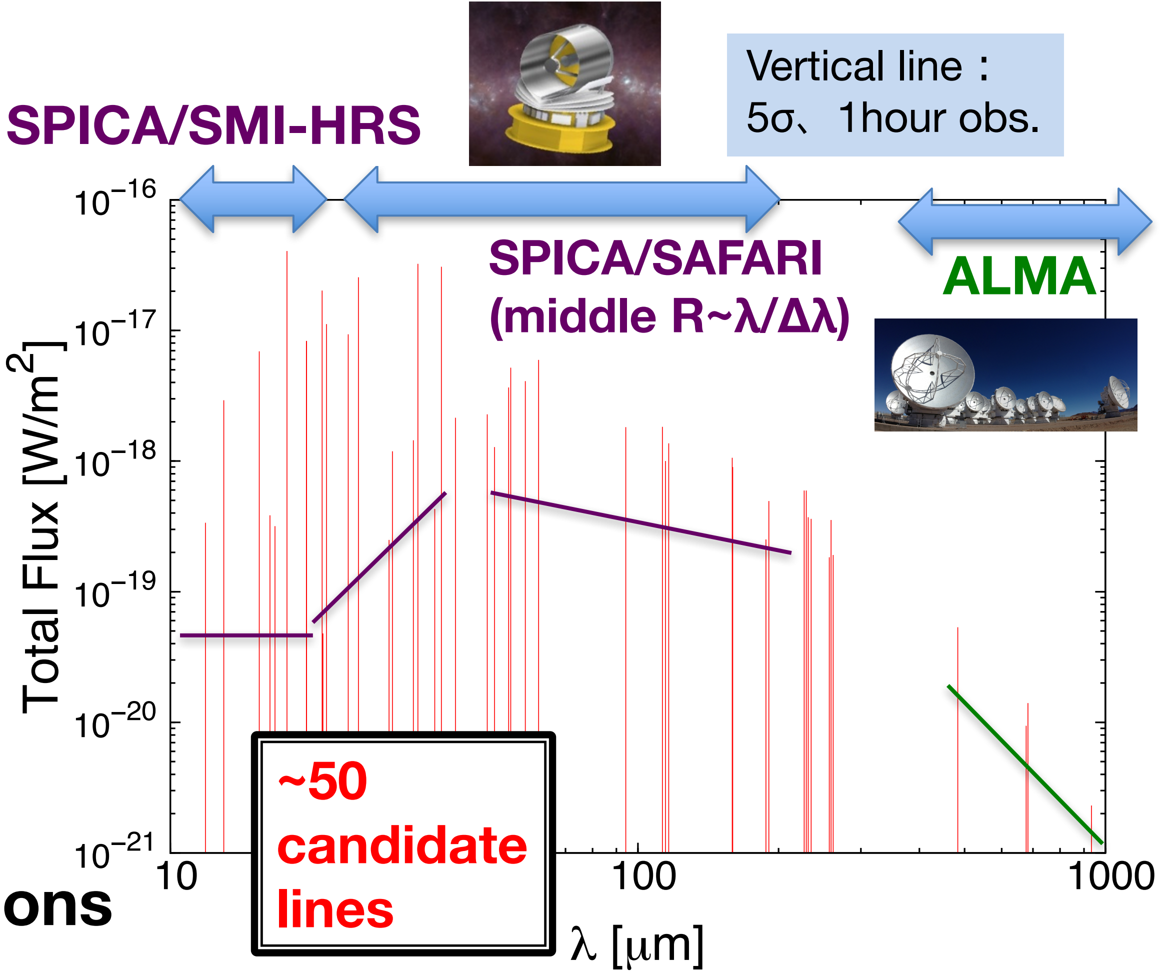
Notsu et al. (2016, 2017a)

Flux distributions of the candidate **ortho-H_2O** lines
($10^{-6} < A_{ul} < 10^{-2}\ s^{-1}$, $700K < E_u < 2010K$)

i=30° distance: 140pc

Herbig Ae disk

High Dispersion Spectroscopic observations



Vertical line：
5σ、1hour obs.

- **H_2O lines that can locate the H_2O snowline exist from mid-infrared (Q band) to sub-millimeter wavelengths.**
  - **sub-millimeter :** ALMA/Cycle 3 proposal accepted. (partially observed)
  - **mid-infrared (Q band) : (Future) SPICA/SMI-HRS**
    (Herbig Ae disk: $>10^{-18}$ [W m^{-2}] T Tauri disk: $>10^{-20}$ [W m^{-2}])

本研究 まとめ

- 原始惑星系円盤の化学反応計算を行いH_2Oの円盤内分布を調査。

➡ **H_2Oスノーライン~1.6AU (T Tauri星), ~13-14AU (Herbig Ae星)**

円盤外側表層部・光脱離領域もH_2Oガスの存在量が多い。

- H_2O輝線プロファイルの計算 (赤外線～サブミリ波)

➡-**放射係数(A_{ul})が小さく励起エネルギー(E_u)が比較的高い輝線が、H_2Oスノーラインを同定に使用できることを初発見(高分散分光観測が必要)**

-将来の高分散分光観測(e.g., SPICA, ALMA)での観測可能性を議論。

- para-$H_2{}^{16}O$, $H_2{}^{18}O$輝線の場合も計算(Notsu et al. 2017b)

理論モデル：Notsu et al. 2016, ApJ, 827, 113; 2017a, ApJ, 836, 118, 2017b in prep.

今後の見通し

- モデル計算を更に進めるのみならず、ALMA等による実際の観測を進める事も重要。
- **ALMAに観測Proposal (P.I.)→Cycle 3で一部観測**(Notsu et al. 2017c)

  Cycle 5観測提案投稿済み