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10th RESCEU/Planet² Symposium
Planet Formation around Snowline

Possibility to locate the position of the H_2O snowline in protoplanetary disks through spectroscopic observations

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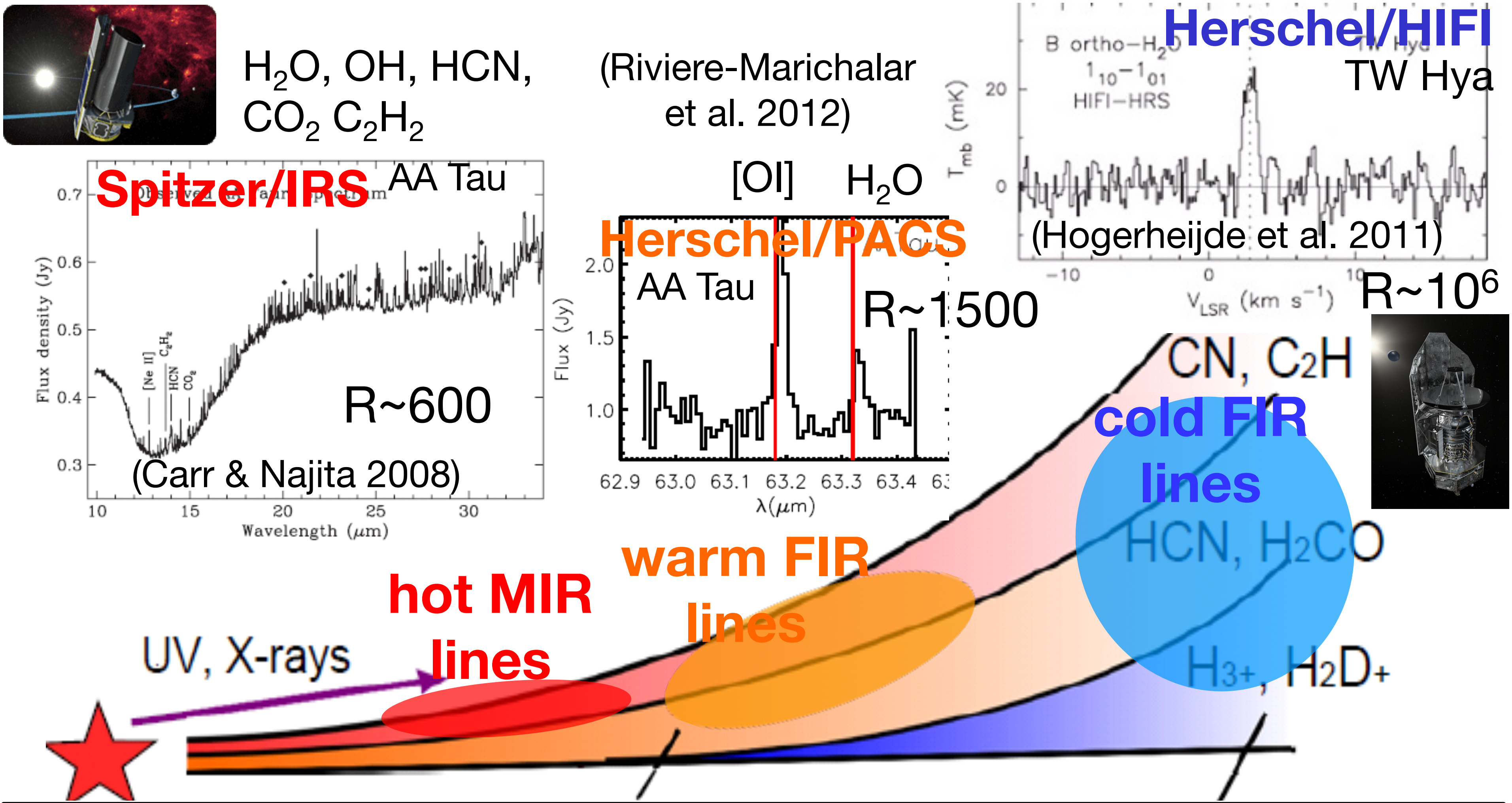
Notsu et al. 2016, ApJ, 827, 113; 2017a, ApJ, 836, 118; 2017b, ApJ submitted.

Space Obs. of H_2O lines from PPDs



Previous H_2O line observations trace the disk surface and the photodesorption region of the outer disk.

→They are not good tracer of the H_2O snowline in disk midplane.

Spectroastrometry of molecular lines

H_2O snowline: a few AU@PPD around Solar-mass T Tauri Stars.
→Direct imaging observations are difficult.

PPDs：(almost) Kepler rotation

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

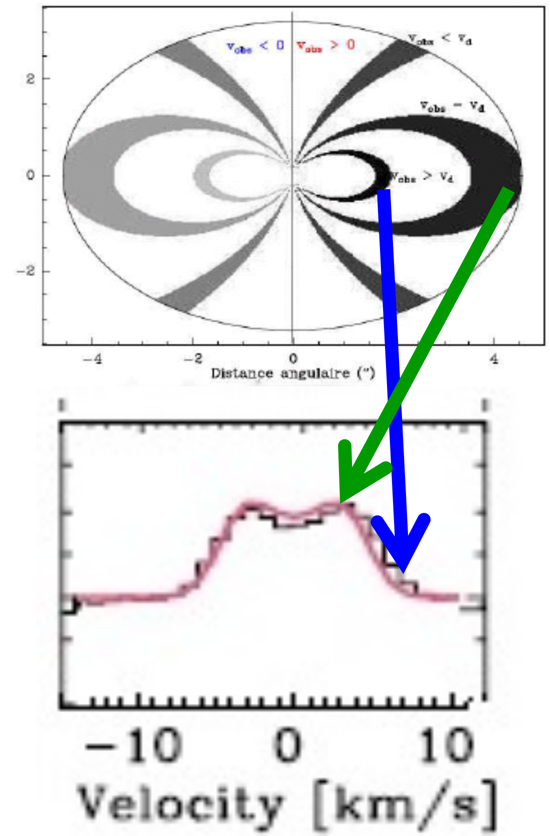
i: inclination angle

velocity profiles of emission lines

↓

location of snowlines

Ex. 4.7μm CO line profile→ Inner disk structure
(Pontoppidan et al. 2008)



Kepler rotation

R~λ/Δλ

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

Purposes and outlines of our work

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

PPD: Protoplanetary Disks

<u>Outline of this work</u>

We derive the position of the H_2O snowline through the calculation of chemical reactions of PPDs under the self-consistent physical models (T Tauri and Herbig Ae disks).

↓

We calculate the profiles of water lines, and find candidate water lines to locate the H_2O snowline through high-dispersion spectroscopic observations.

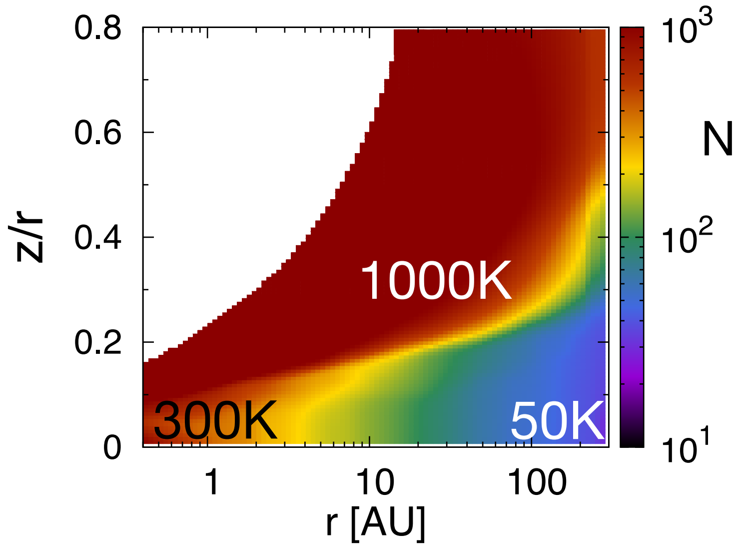
(Notsu et al. 2016, ApJ, 827, 113; 2017a, ApJ, 836, 118; 2017b, ApJ submitted.)

Distributions of H_2O vapor

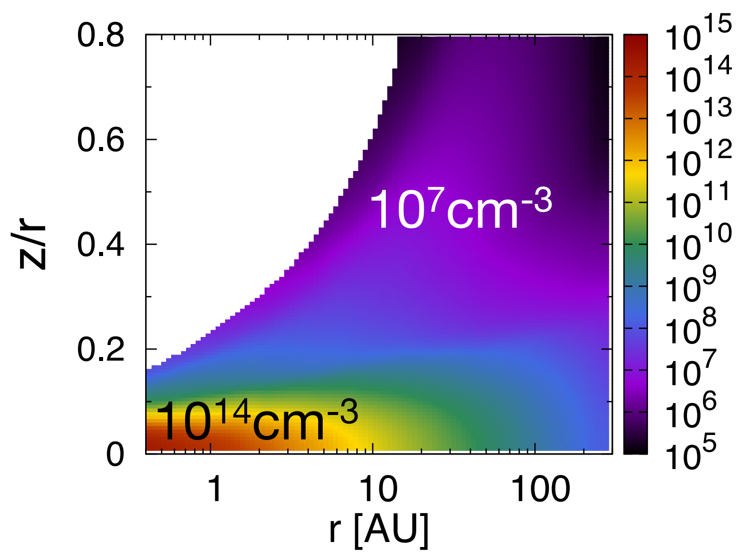
Herbig Ae disk
($M=2.5M_{sun}$ $T_{eff}=10,000K$ $R=2R_{sun}$)

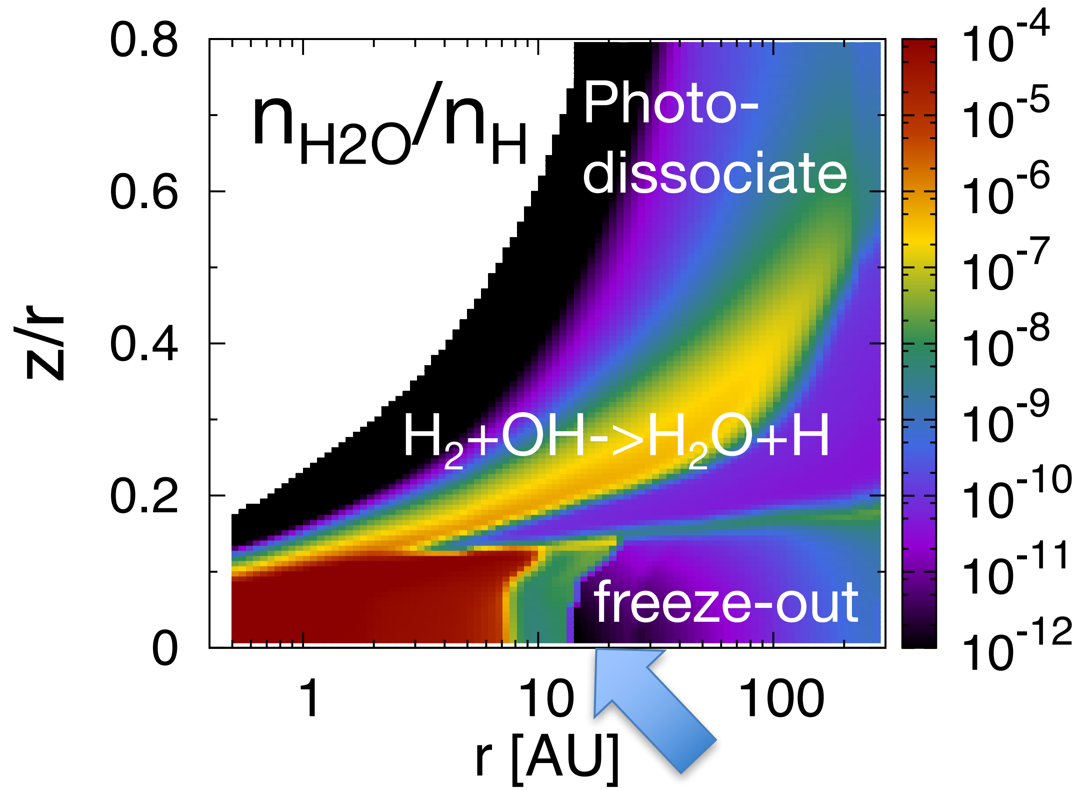
Notsu et al. (2017a)

Gas Temperature



Gas Number Density

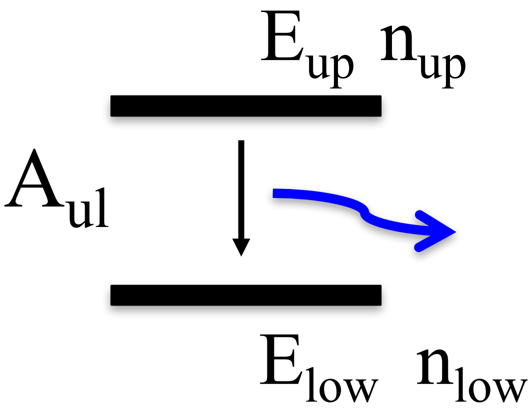




H_2O snowline ~ 14AU

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

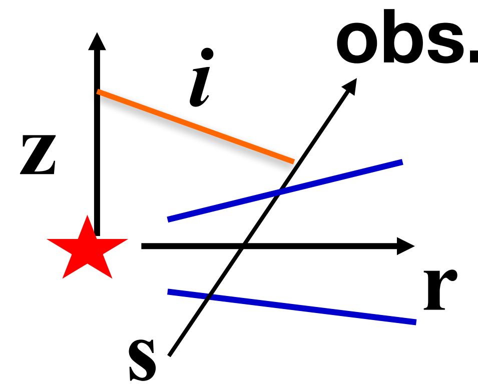
The calculation methods of emission lines



A_{ul} : Einstein A coefficient [s^{-1}]
E_{up} : energy in upper state [K]

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

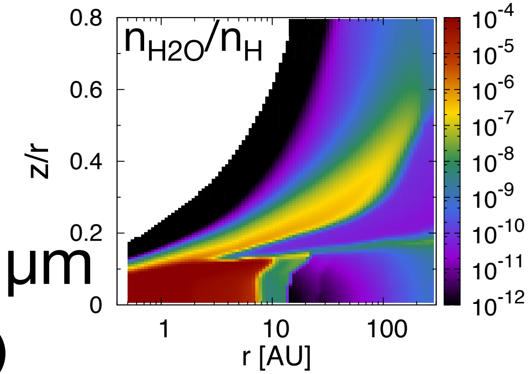
- Velocity profile $\Phi(\nu)$: Keplerian rotation + c_s
- τ_{ul} : gas + dust
-LTE is assumed.
-line data: LAMDA ($H_2{}^{16}O$) & HITRAN ($H_2{}^{18}O$)



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

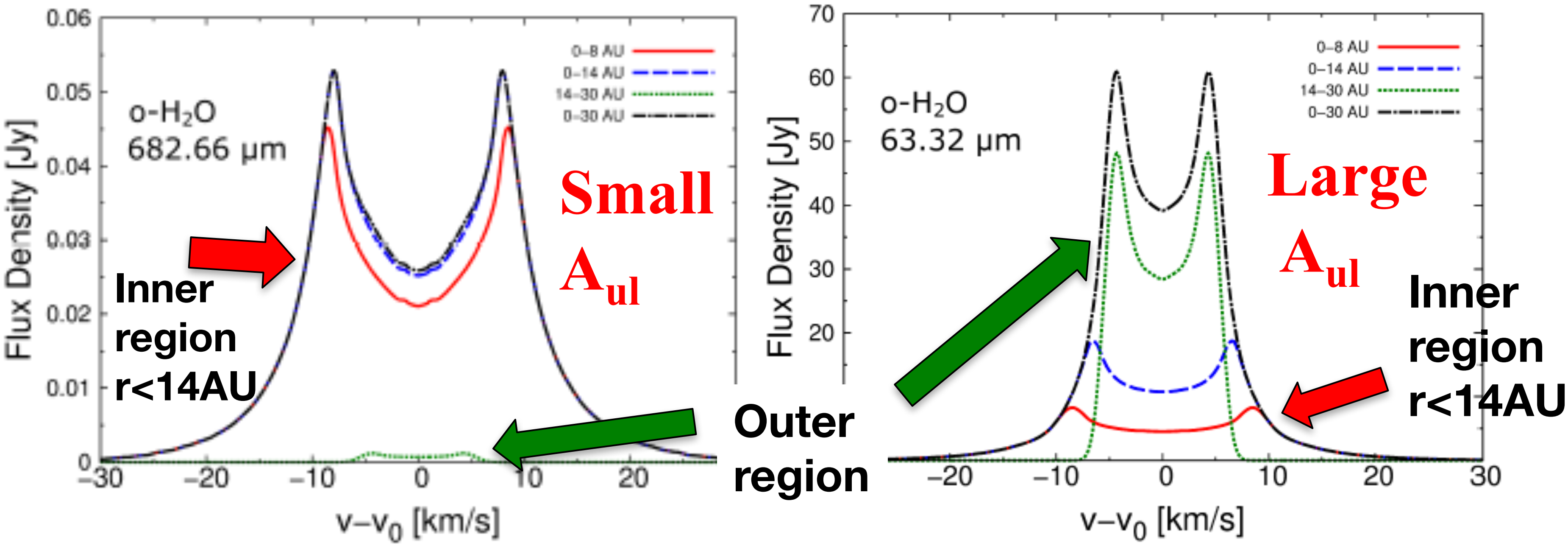
Notsu et al. (2016, 2017a,b)

Profiles of ortho-$H_2{}^{16}O$ lines



o-$H_2{}^{16}O$ 682.66μm — E_{up}~1000K — o-$H_2{}^{16}O$ 63.32μm

$A_{ul} \sim 2.82\times10^{-5}$ (s^{-1}) — $A_{ul} \sim 1.7$ (s^{-1})



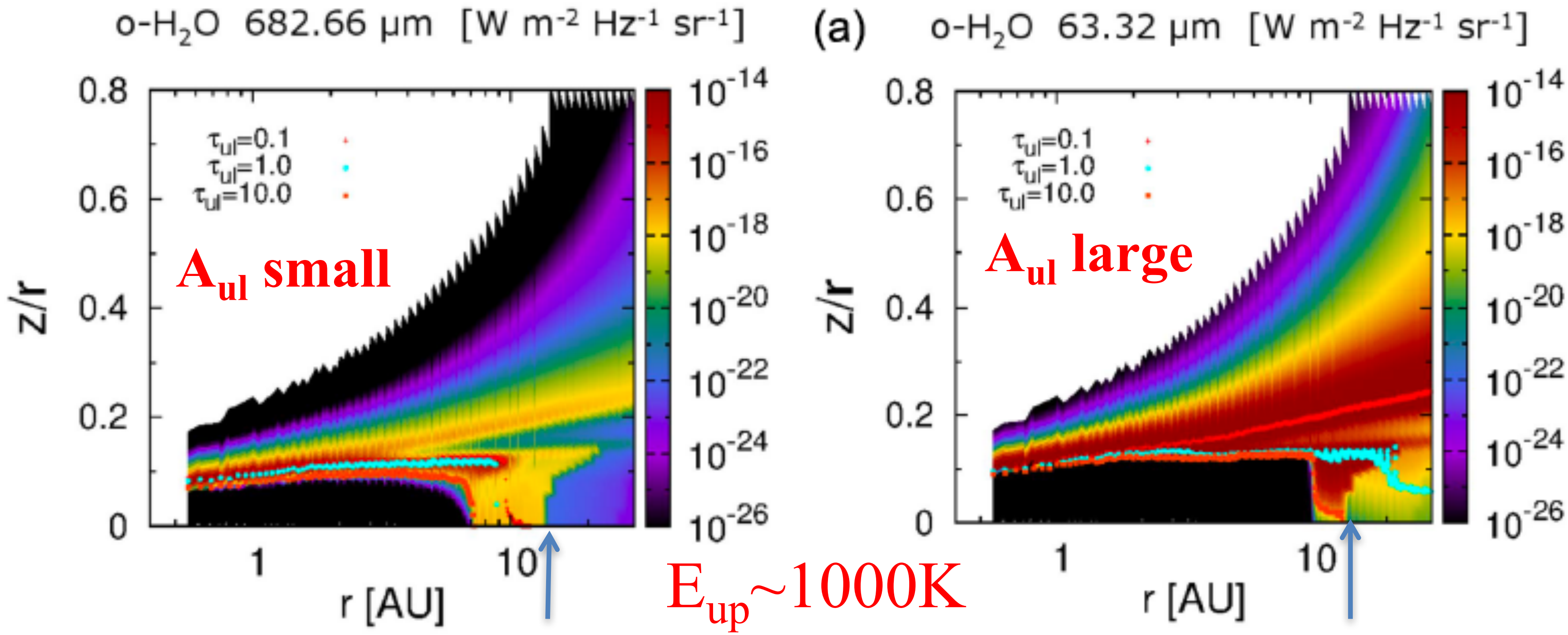
Notsu et al. (2016, 2017a)

i=30° Distance:140pc

We can locate the positions of the H_2O snowline from the profiles of emission lines with small A_{ul} (10^{-6}~10^{-3} s^{-1}) and relatively large E_{up} (~1000K).

Emitting region distributions (i=0°, line of sight)

emissivity*exp($-\tau_{ul}$)



ortho-$H_2{}^{16}O$ 682.66 μm
A_{ul}= 2.82×10^{-5} (s^{-1})

Herbig Ae disk

Notsu et al. (2016, 2017a)

ortho-$H_2{}^{16}O$ 63.32μm
A_{ul}= 1.7 (s^{-1})

Small A_{ul} → emission from the outer optically thin surface layer
<< emission from the optically thick region inside the H_2O snowline
→ H_2O snowline tracer !

Optically thin (τ_ν<<1)

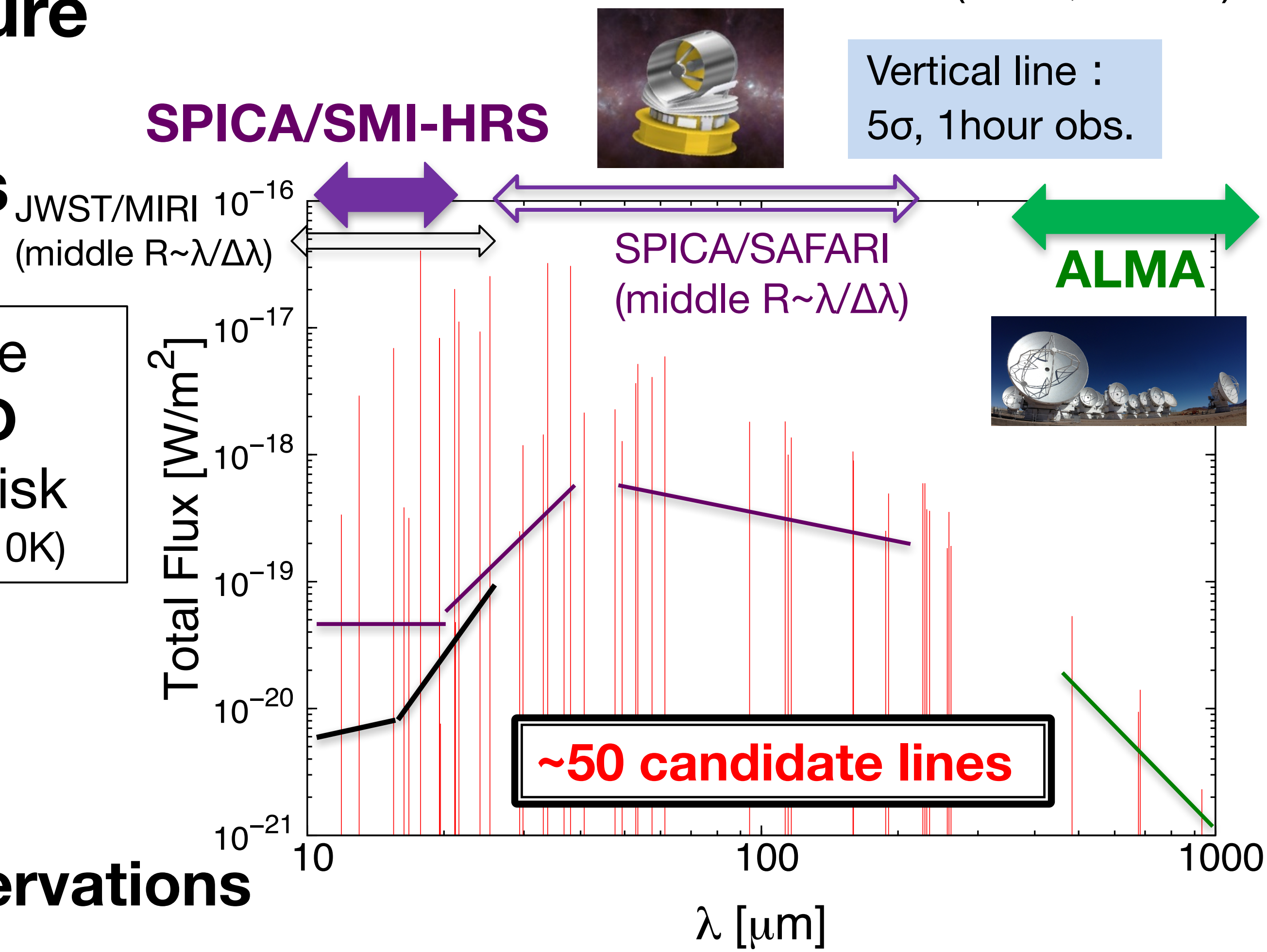
$F_\nu \propto n_{up}(E_{up})\, A_{ul}$

Optically thick (τ_ν>>1)

$F_\nu \propto B_\nu(T)$

Notsu et al. (2016, 2017a)

Possibility of future observations of ortho-$H_2{}^{16}O$ lines



Flux distributions of the candidate **ortho-$H_2{}^{16}O$** lines for a Herbig Ae disk ($10^{-6}<A_{ul}<10^{-2}$ s^{-1}, $700K<E_u<2010K$)

i=30° distance: 140pc

High Dispersion Spectroscopic observations

- **H_2O lines that can locate the H_2O snowline exist from mid-infrared (Q band) to sub-millimeter wavelengths.**

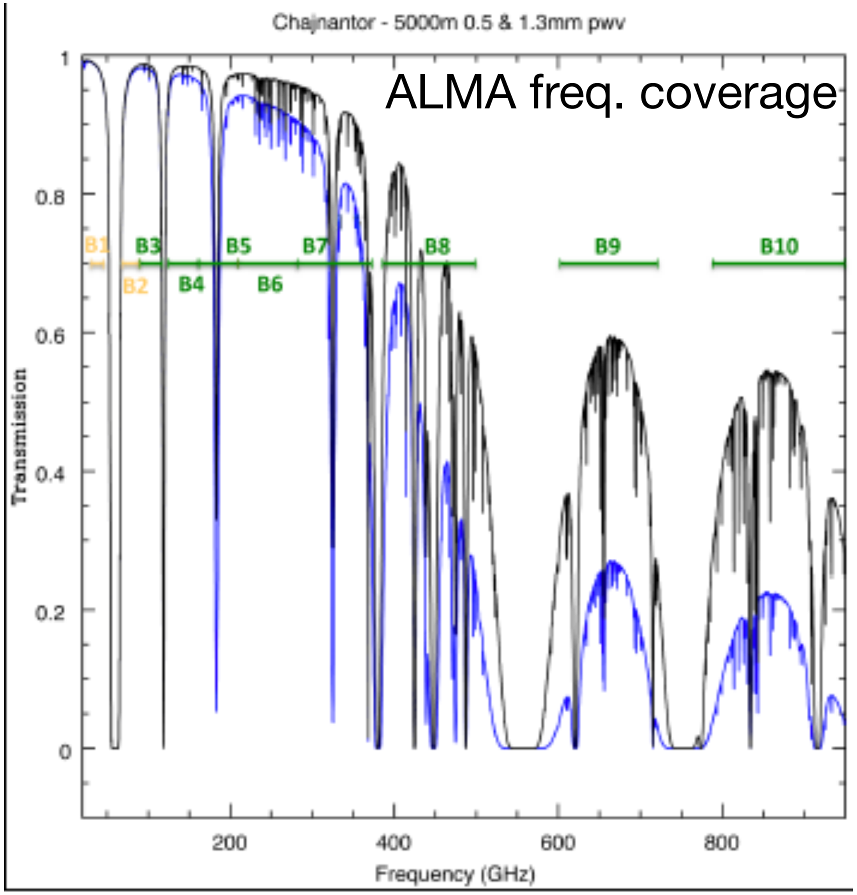
-Sub-millimeter : ALMA/Cycle 3 proposal accepted. (partially observed)

-Mid-infrared (Q band) : (Future) SPICA/SMI-HRS

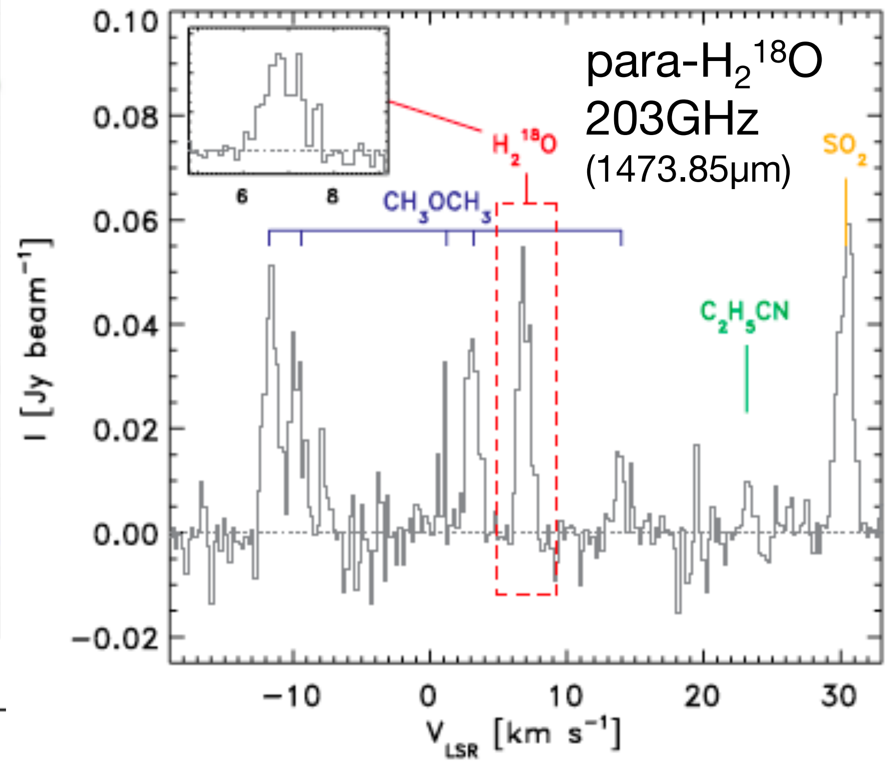
(Herbig Ae disk: $>10^{-18}$ [W m^{-2}] T Tauri disk: $>10^{-20}$ [W m^{-2}])

There are also para-$H_2^{16}O$ and $H_2^{18}O$ lines within ALMA frequency coverage.
→ **We investigate the line properties in disks.**

(Notsu et al. 2017b, ApJ submitted.)



2017/10- : ALMA Cycle 5
→ **New Frequency Band 5 (163-211GHz) will open.**

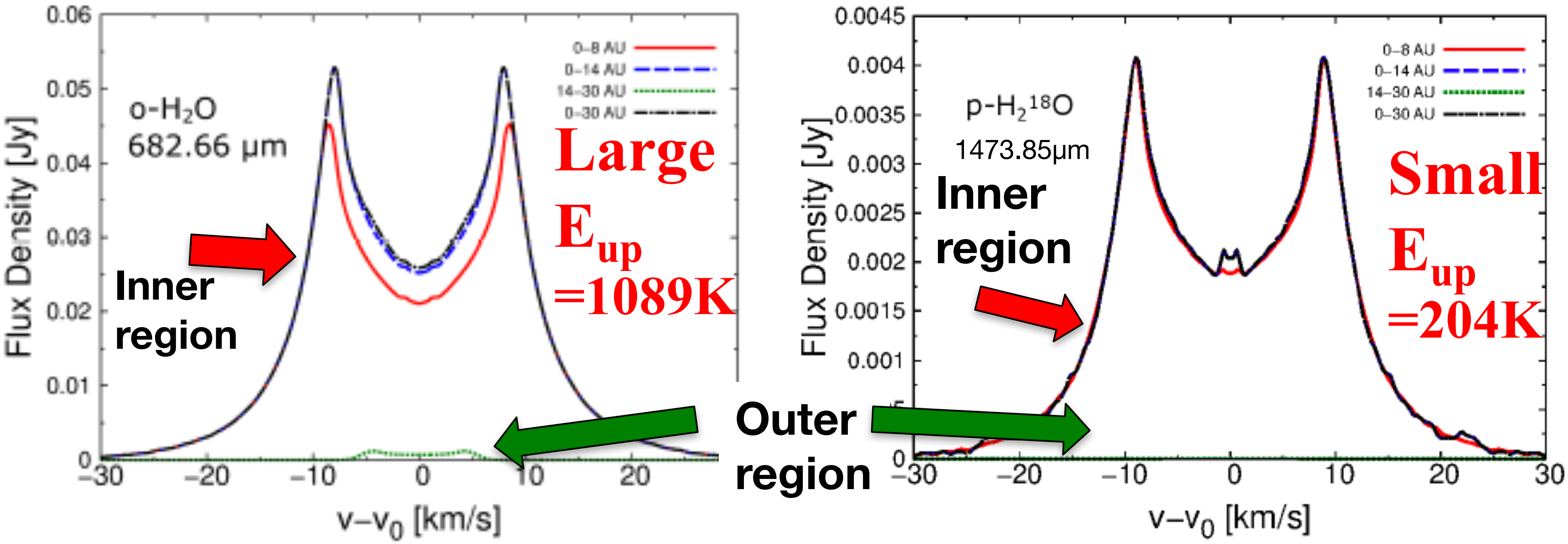


Jorgensen et al. 2010
Class 0 protostar: NGC 1333-IRAS4B

Profiles of o-$H_2{}^{16}O$ and p-$H_2{}^{18}O$ lines

ortho-$H_2{}^{16}O$ 682.66μm para-$H_2{}^{18}O$ 1473.85μm

$A_{ul} = 2.82\times10^{-5}$ (s^{-1}) $A_{ul} = 4.81\times10^{-6}$ (s^{-1})



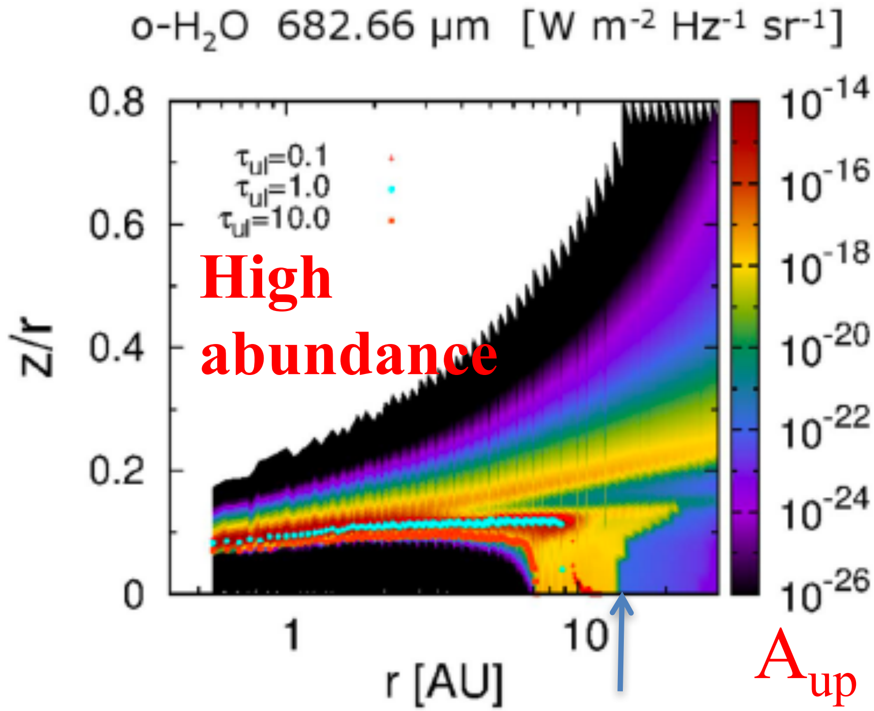
Notsu et al. (2017a,b)

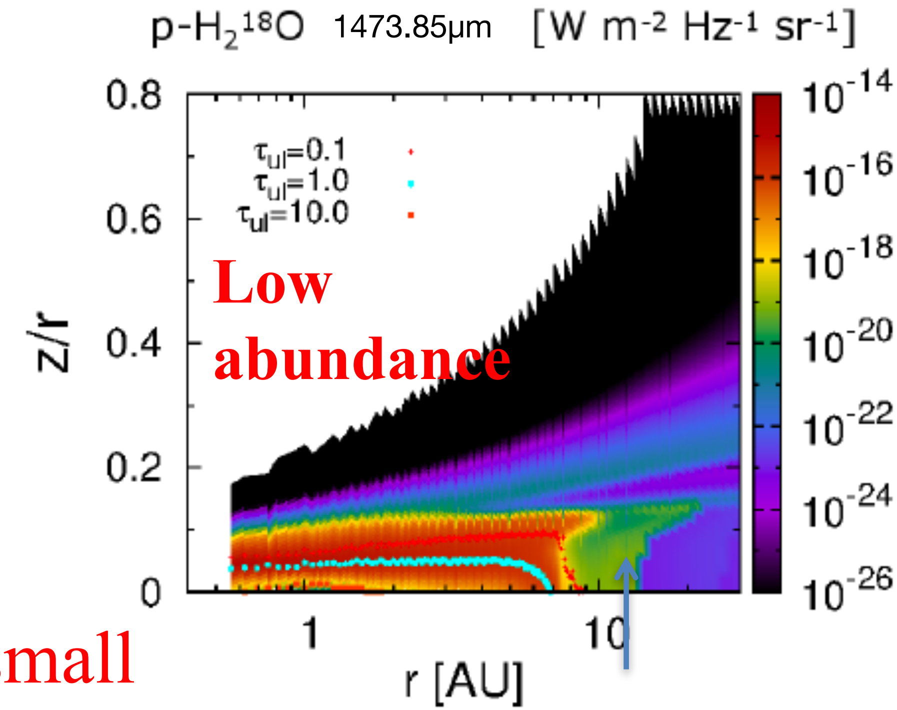
i=30° Distance:140pc

para-$H_2{}^{16}O$ and $H_2{}^{18}O$ lines: the outer component is much smaller, and lower E_{up} (~200K) lines can locate the H_2O snowline.
[o/p=3, $^{16}O/^{18}O$=560]

Emitting region distributions (i=0°, line of sight)

emissivity*exp($-\tau_{ul}$)





A_{up} small

ortho-$H_2{}^{16}O$ 682.66 μm
A_{ul}= 2.8×10^{-5} (s^{-1}) **E_{up}=1089K**

Herbig Ae disk

Notsu et al. (2017a,b)

para-$H_2{}^{18}O$ 1473.85 μm
A_{ul}= 4.8×10^{-6} (s^{-1}) **E_{up}=204K**

para-$H_2{}^{16}O$ and $H_2{}^{18}O$ lines can trace deeper region in the disk midplane. [o/p=3,$^{16}O/^{18}O$=560]

$\tau_{ul} \propto n_{H2O}$

Optically thin (τ_ν<<1)

$F_\nu \propto n_{up}(E_{up}) A_{ul}$

Optically thick (τ_ν>>1)

$F_\nu \propto B_\nu(T)$

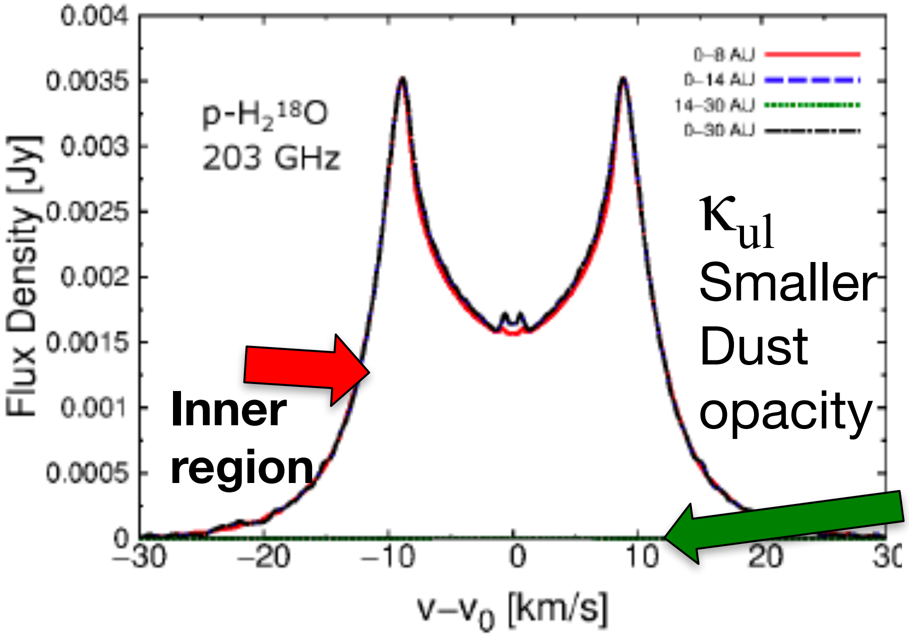
Line Profiles with dust emission

Notsu et al. (2017b)

para-$H_2{}^{18}O$ 1473.85 μm
$A_{ul}= 4.8\times10^{-6}$ (s^{-1}) E_{up}=204K

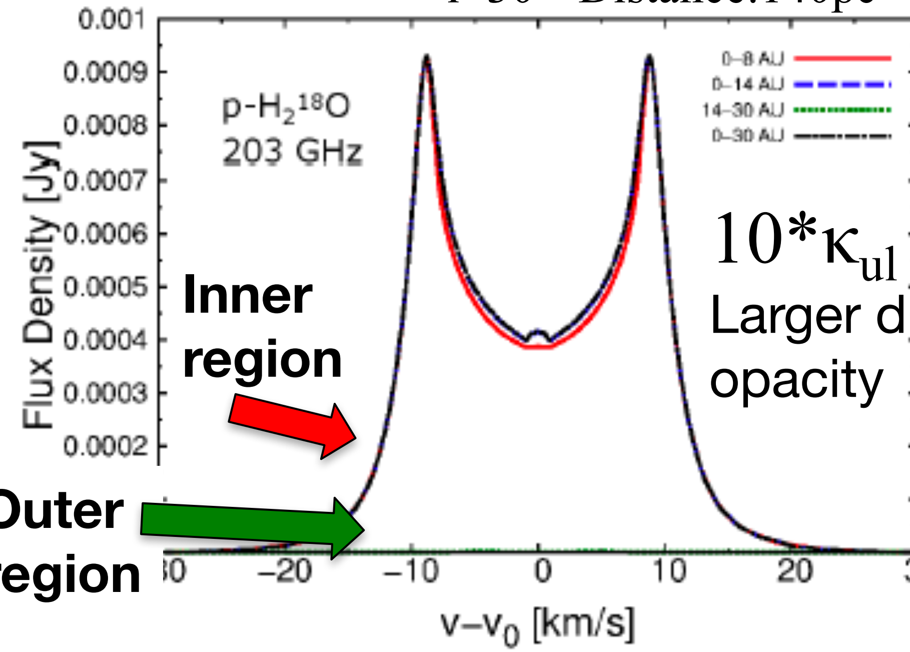
Including both line and dust emission

i=30° Distance:140pc



$\tau_{dust,\ 203GHz}$~ 0.4-0.05 (r~0-8 au)

Outer region



$\tau_{dust,\ 203GHz}$~ 4-0.5 (r~0-8 au)

In the larger dust opacity case, the effect of the dust emission becomes stronger and the values of peak line flux densities smaller.

$H_2{}^{18}O$ lines and shorter wavelength lines: the dust opacity effect is stronger.

-Today's Content (Summary)-

SPICA

ALMA

1. Chemical modeling of PPDs.

2. Calculations of water emission line profiles.

→ We can locate the position of H_2O snowline through the profiles of water lines with small Einstein A coefficient (A_{ul}) and relatively high energies in upper state (E_{up}).

→ para-$H_2{}^{16}O$ and $H_2{}^{18}O$ lines: they can trace deeper region in the disk (z~0). The outer component is much smaller, and thus lower E_{up} (~200K) lines can locate the H_2O snowline.

Future: We will constrain the positions of H_2O snowline in protoplanetary disks through candidate water line observations using high dispersion spectrographs (e.g., ALMA, SPICA/SMI-HRS).

Notsu et al. 2016, ApJ, 827, 113; 2017a, ApJ, 836, 118; 2017b, ApJ submitted.