Artist 's illustration of HD142527

Toward observationally resolving the snowline location in proto-planetary disks

Snowline in proto-planetary disks

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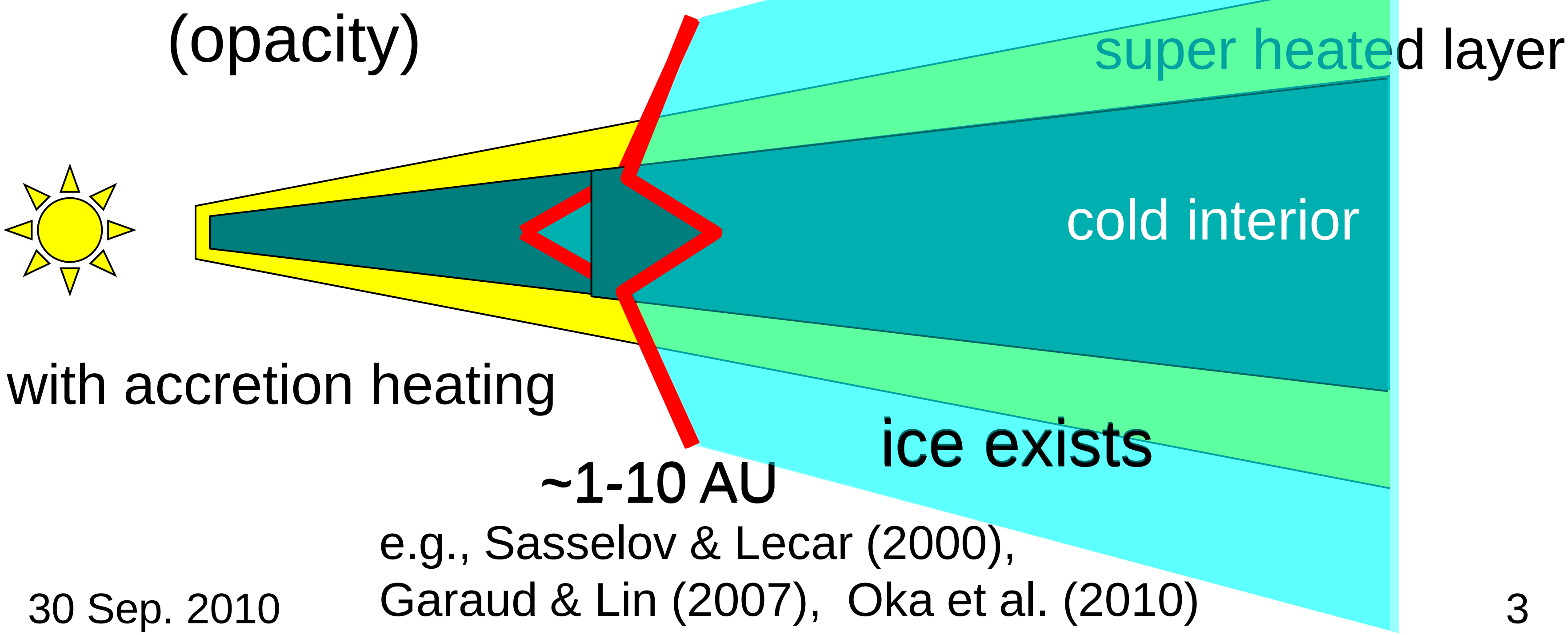
Planet formation and icy dust

1. Increase of opacity (e.g., Lin & Papaloizou 1980)
    - Disk structure of density and temperature
2. Increase of solid material (e.g., Hayashi et al. 1985)
    - Core formation of gas giants
3. Isotopic anomaly (Yurimoto & Kuramoto 2004)
    - Transport of $^{17,18}O$ by icy dust
4. Origin of ocean (e.g., Morbidelli et al. 2000)
    - Transport of H_2O by icy bodies

Snowline

- Condensation front of H_2O ice
  - <150 K of surface temperature of dust
  - dependency of dust size and material (opacity)



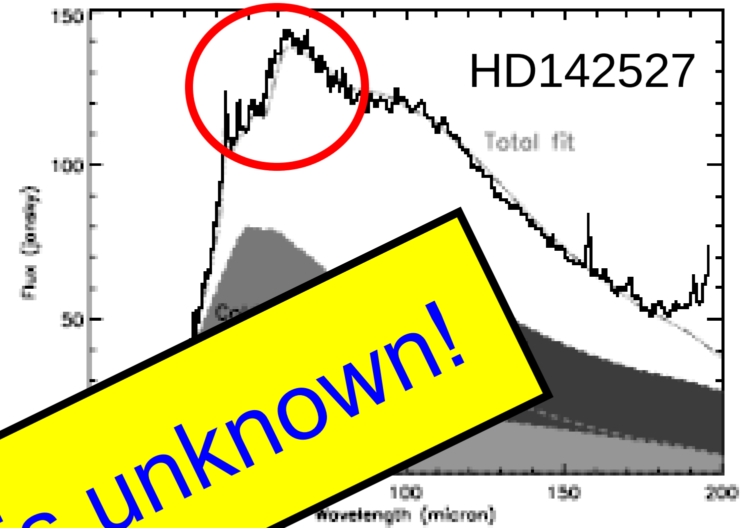
e.g., Sasselov & Lecar (2000), Garaud & Lin (2007), Oka et al. (2010)

Obs. of H_2O ice

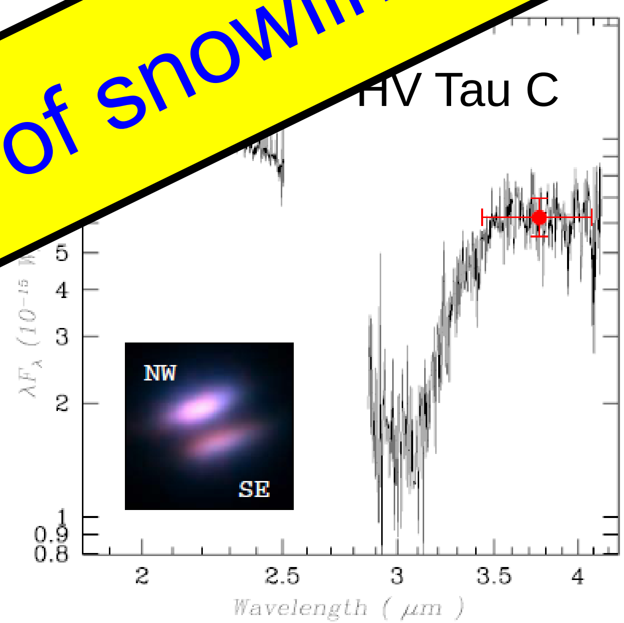
- Detection of 40-60 μm feature (Malfait et al. 1999)
  - HD142527
- Detection of 3 μm feature

  (Terada et al

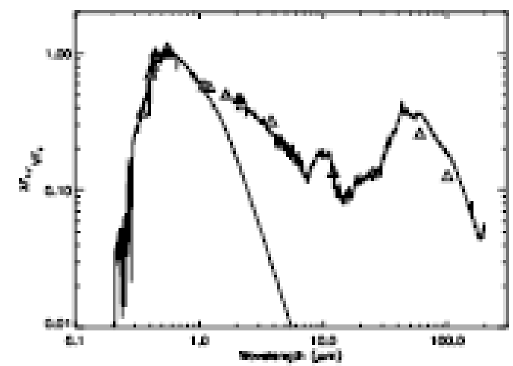
  - H
  - H au C



Location of snowline is unknown!



Subaru／IRCS
(Terada 2005)



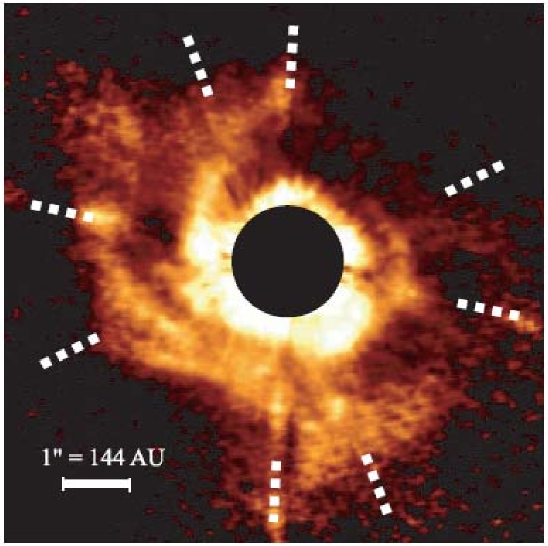
(Malfait et al. 1999)
ISO

NIR scattered light from disks

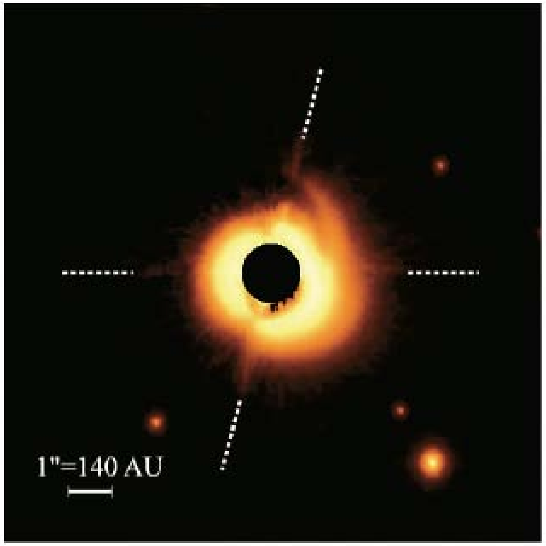
- Spatially resolved imaging of the scattered light with 8m telescope＋AO

H-band scattered light images (Fukagawa et al. 2004, 2006)

AB Aurigae



HD142527



Subaru／CIAO

Inoue et al. 2008, PASJ, 60, 557

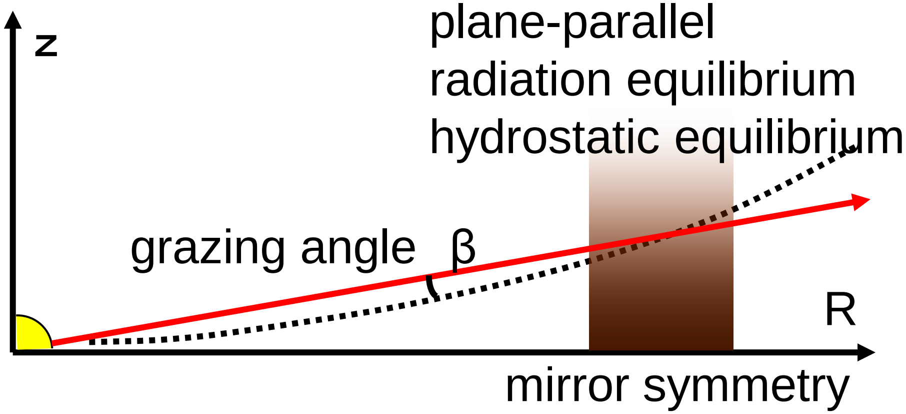
How to find snowline?

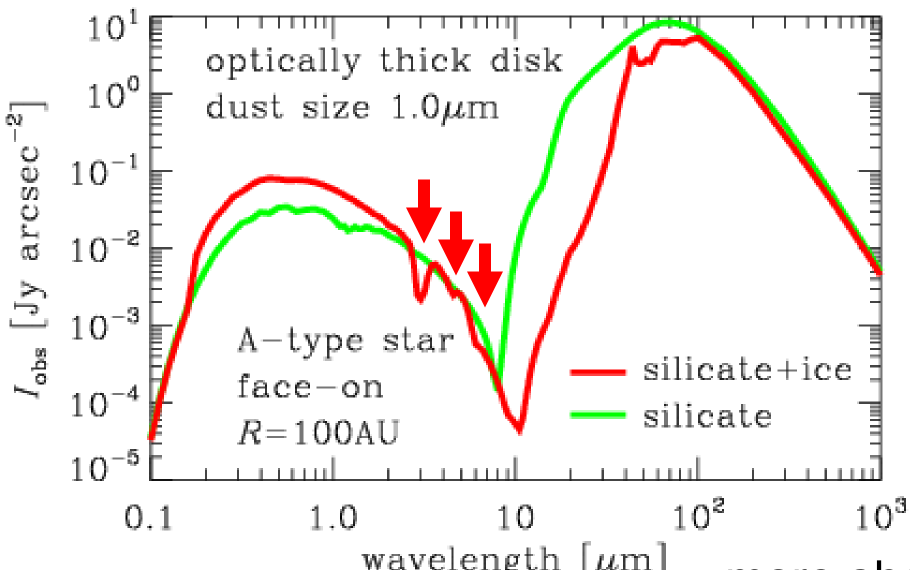
- In NIR, we can resolve disk with scattered light
- If ice feature is imprinted in the scattered light, we can resolve ice distribution!
- But, is ice feature really imprinted in the scattered light?

YES !

Inoue et al. 2008, PASJ, 60, 557

Numerical radiation transfer



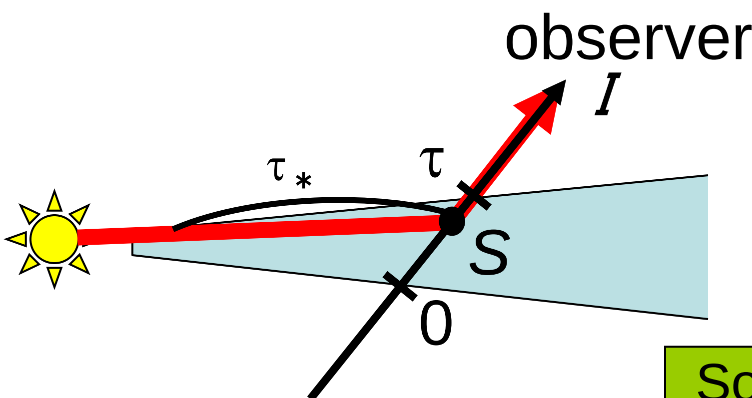


- 1D plane-parallel RT of an annulus
  - grazing angle recipe
  - variable Eddington Factor method
  - accelerated convergence of iteration
  - radiation equilibrium
  - hydrostatic equilibrium
  - isotropic scattering

more about numerical scheme?
see Inoue et al. 2009, MNRAS, 393, 1377

Inoue et al. 2008, PASJ, 60, 557

Analytic interpretation



Only single scattering

scattered light intensity (no incidence)

$$I = \int_0^{\tau} S e^{-(\tau - t)} dt$$

Source function of scattered light	$S = \omega J_* \exp(-\tau_*)$
Optical depth from star	$\tau_* \approx (\tau - t) / \beta$
Stellar intensity	$J_* = B(T_*)\Omega_* / 4\pi$

For small β

optically thick case (τ>>1) $I \propto \beta \omega B(T_*)$

albedo

Inoue et al. 2008, PASJ, 60, 557

Analytic interpretation

- Multiple scatterings

  ➔ Chandrasekhar (1960)

  – “The H-function”

For small β and isotropic scattering case

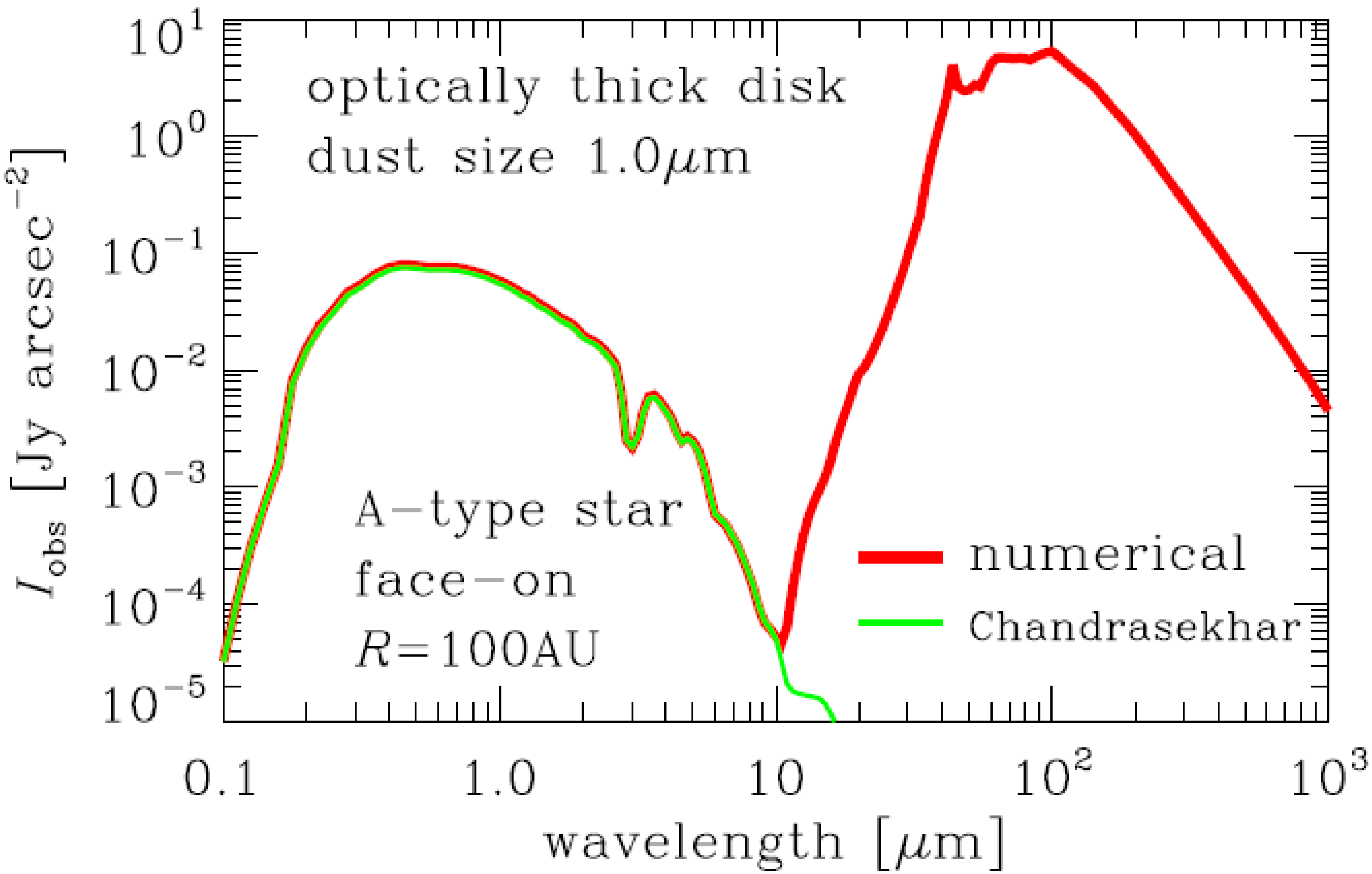
optically thick case (τ>>1)

$$I = \beta\omega B(T_*)H(\mu,\omega)\Omega_* / 4\pi$$

albedo

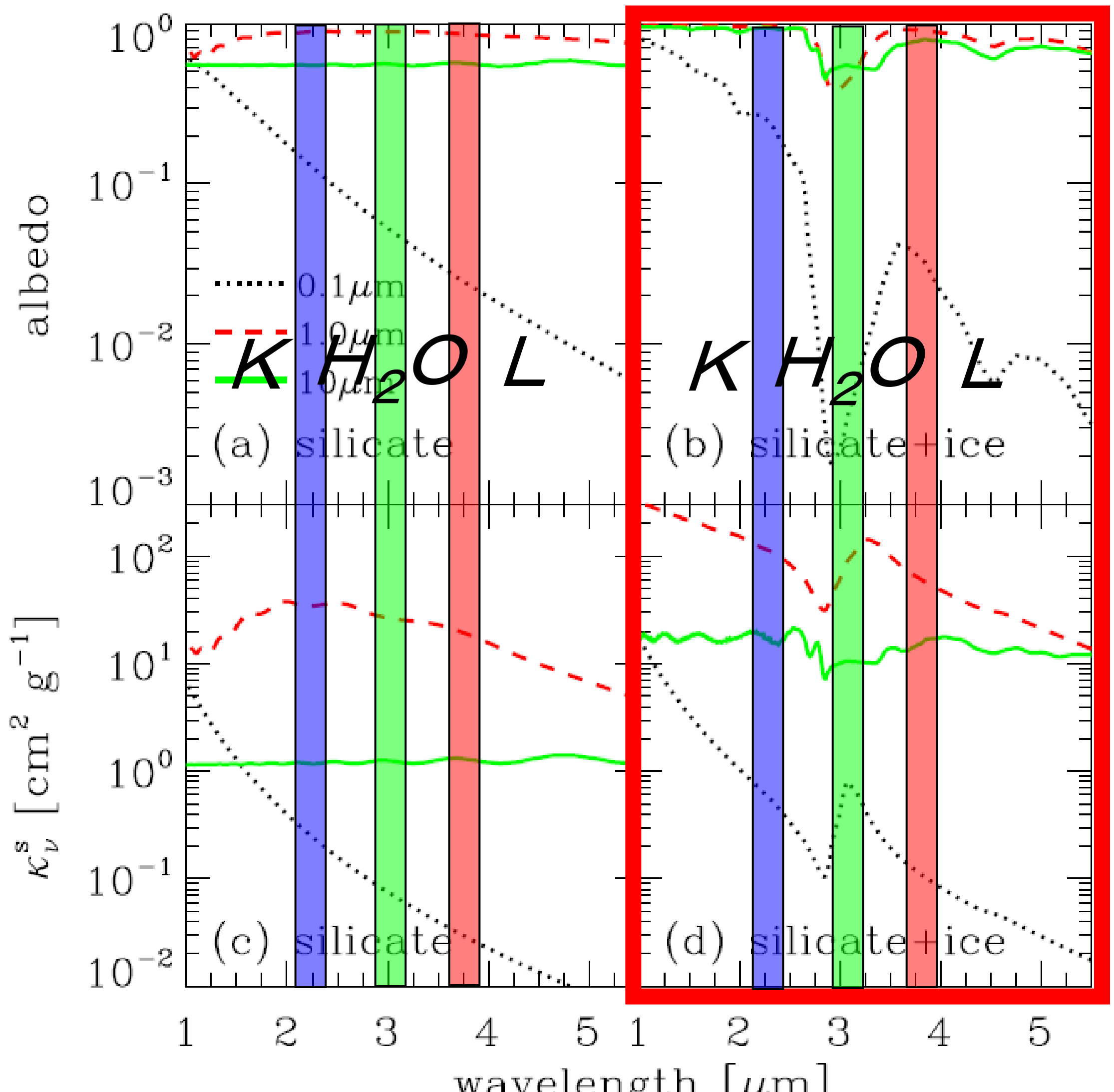
Inoue et al. 2008, PASJ, 60, 557

Numerical vs. Analytical



Inoue et al. 2008, PASJ, 60, 557

Scattering coefficient of H_2O ice

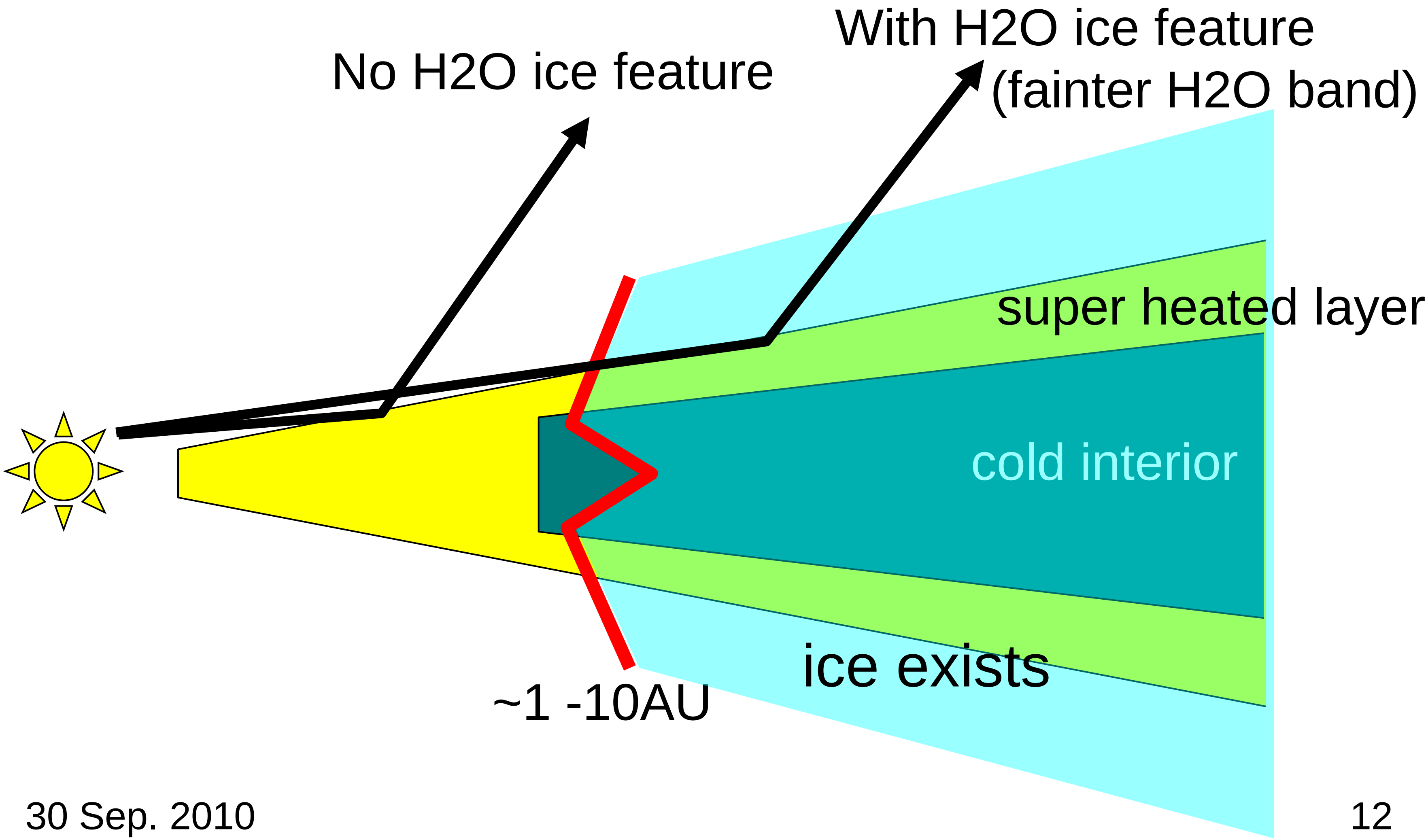


with ice

Dust size
black : 0.1micron
red : 1micron
green : 10micron

Inoue et al. 2008, PASJ, 60, 557

Resolving the snowline location

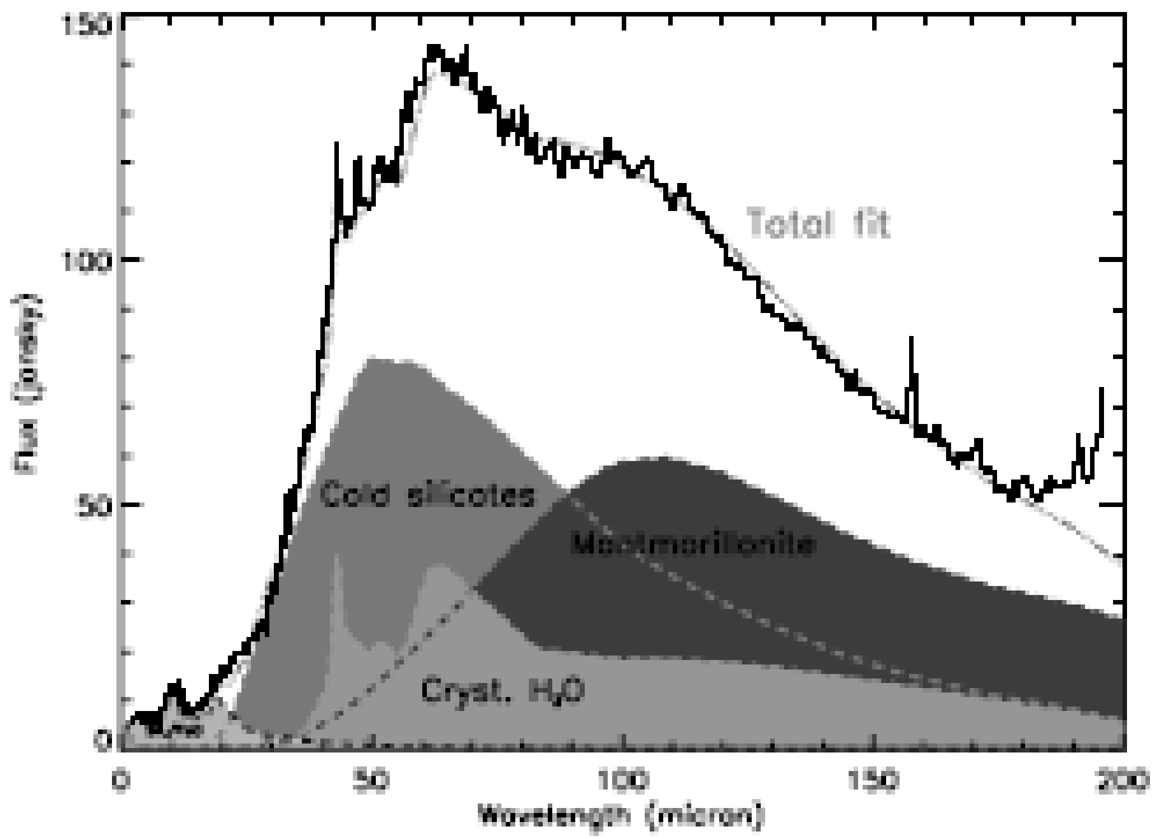


Honda, Inoue, et al. 2009, ApJ, 690, L110

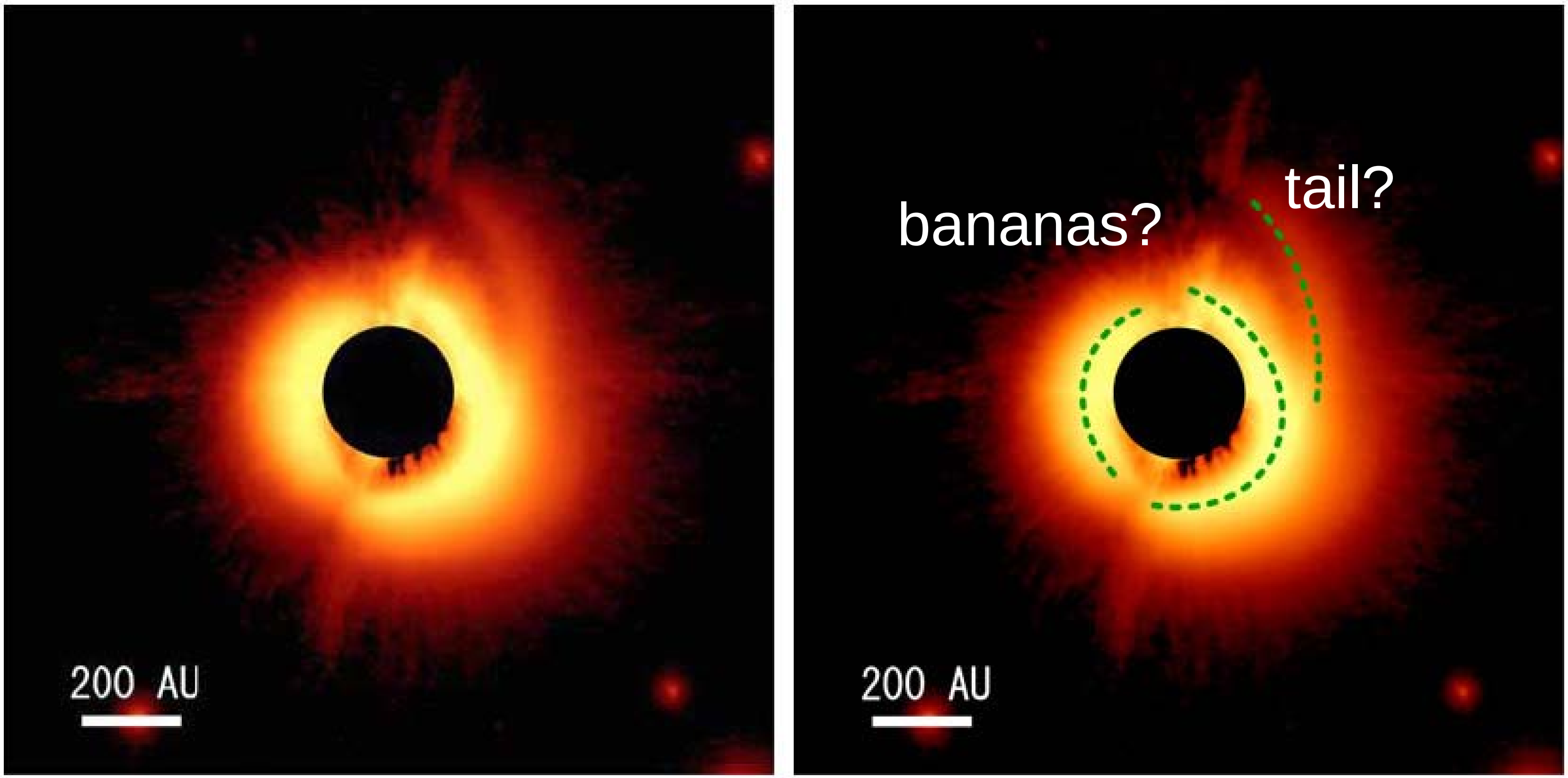
Target: HD142527

- Herbig Ae star
- Teff=6250K
- 15 Lsun
- ~2 Msun
- 140 pc
- ice emission features

(Malfait et al. 1999)



Fukagawa et al. 2006

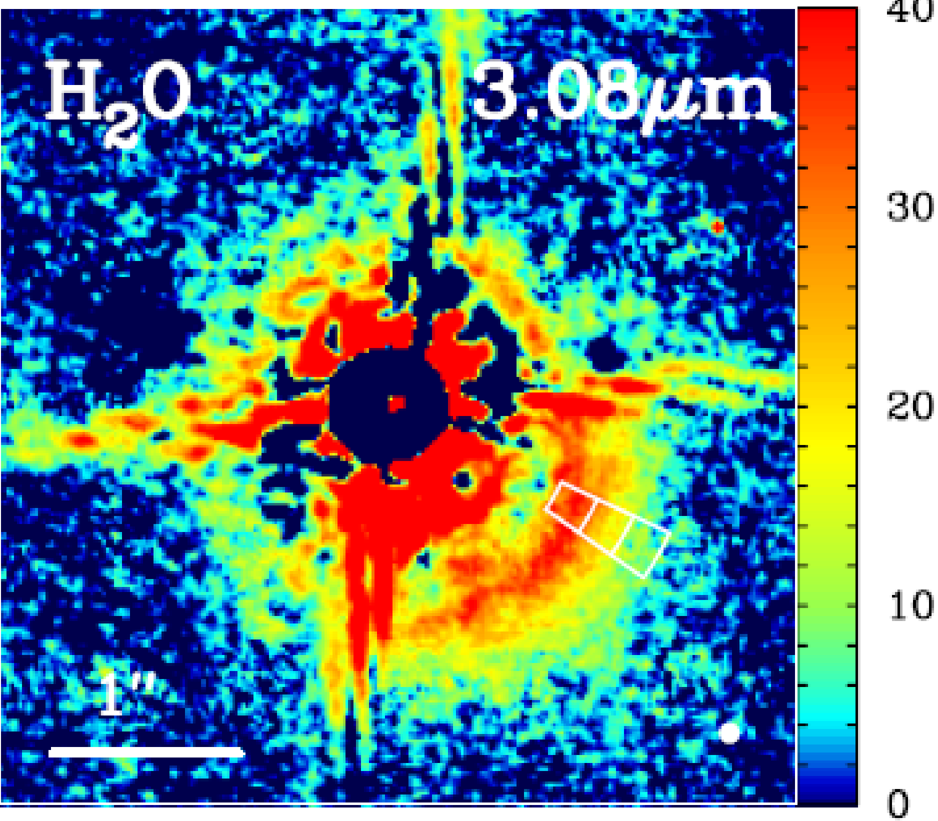


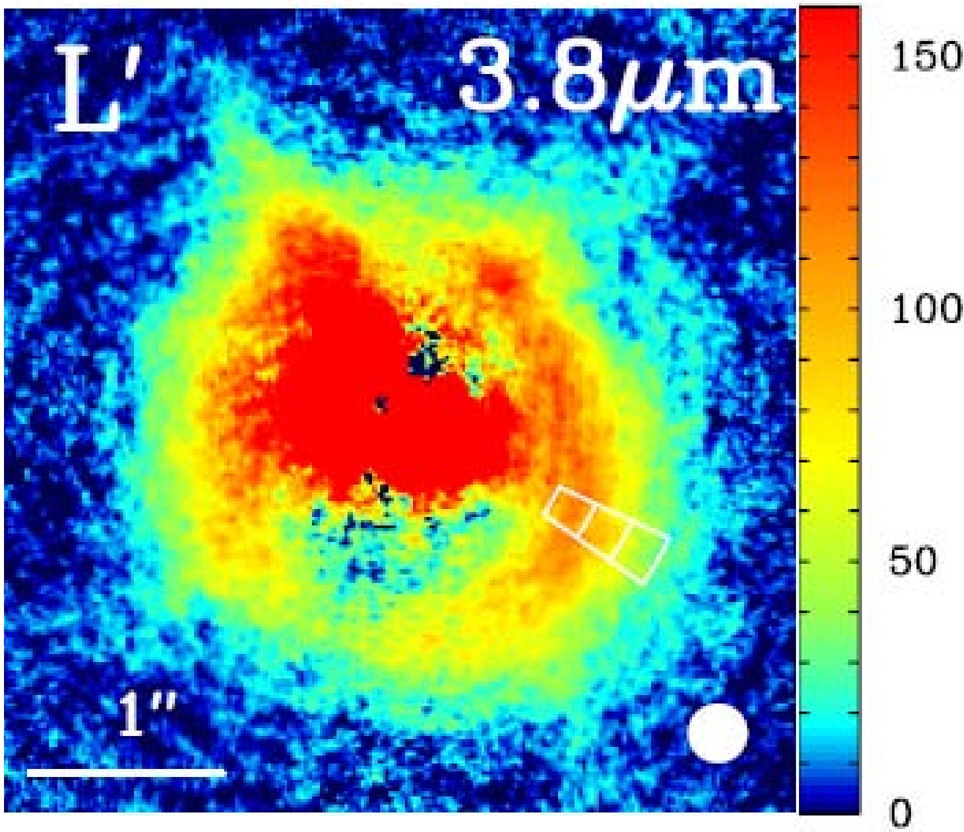
H(1.65micron)

Honda, Inoue, et al. 2009, ApJ, 690, L110

Subaru/CIAO results

mJy/arcsec2





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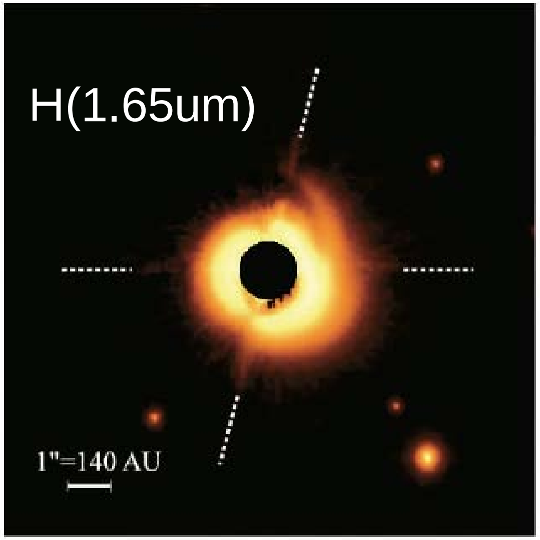
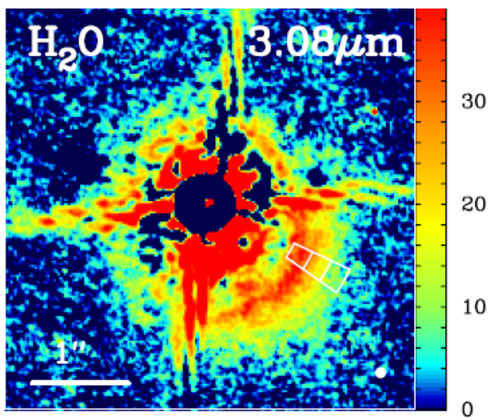
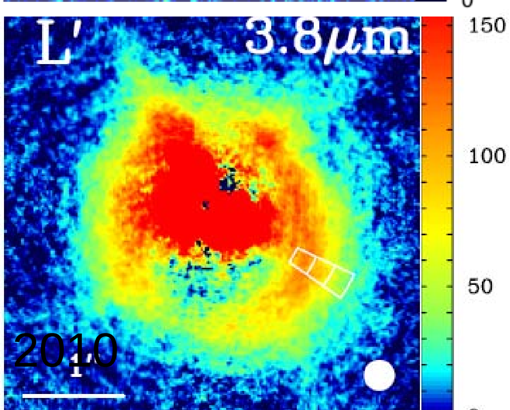
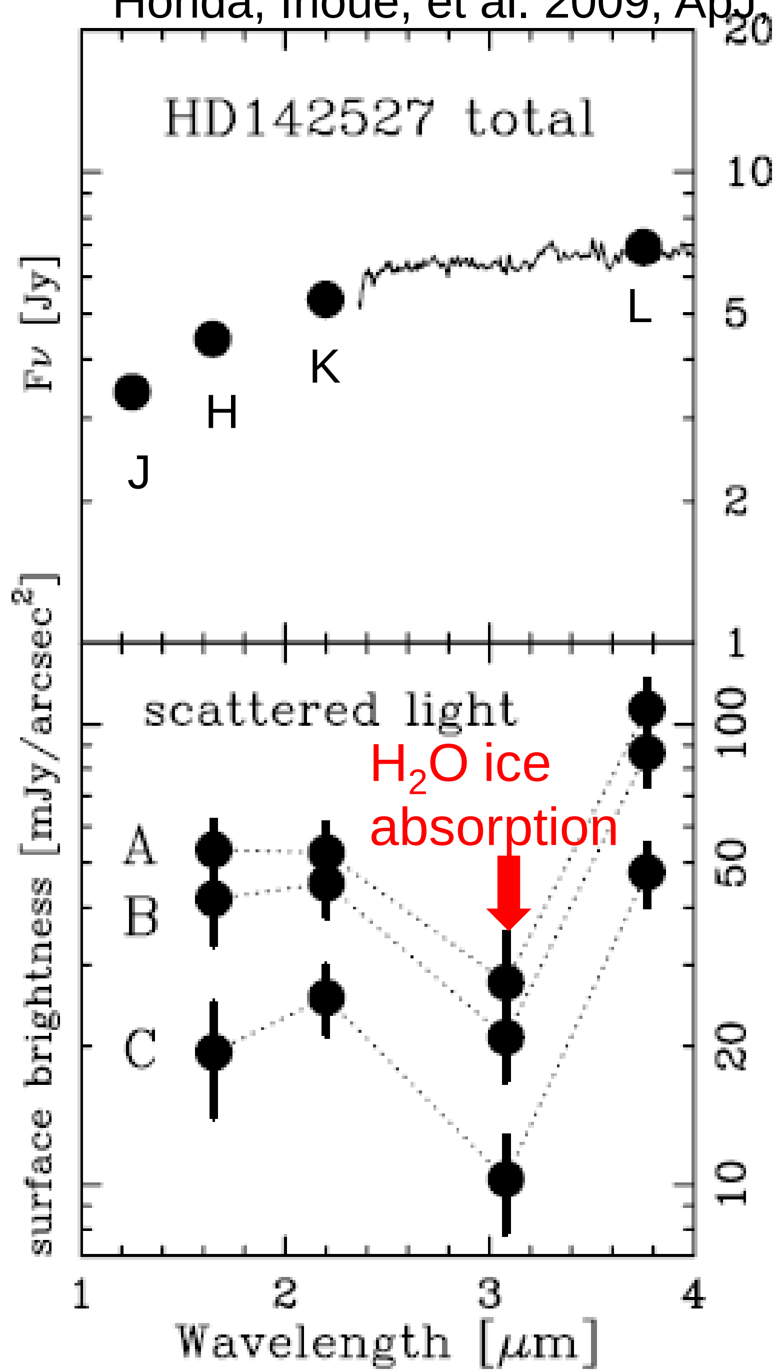








Honda, Inoue, et al. 2009, ApJ, 690, L110

HD142527

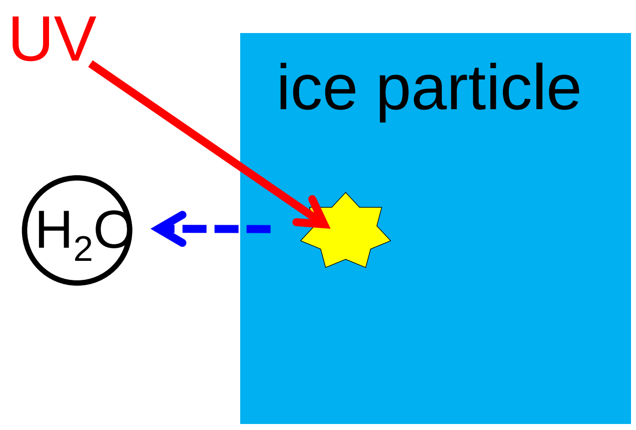
- H_2O ice exists on the disk surface.
- This observation probes radius>140 AU: the surface of the “outer disk”.
- The temperature there is low enough (<80K) for H_2O ice, given the central stellar luminosity.

- But, what about photo-sputtering?

Oka, Inoue, et al. 2010, in prep.

Photo-sputtering

desorption of H2O molecule by UV radiation



Sputtering yield・・・ large uncertainty

MD calculation (Anderson et al. 2008)

$Y=3.7\times10^{-4}$ (T=10K, λ=1300-1500Å)

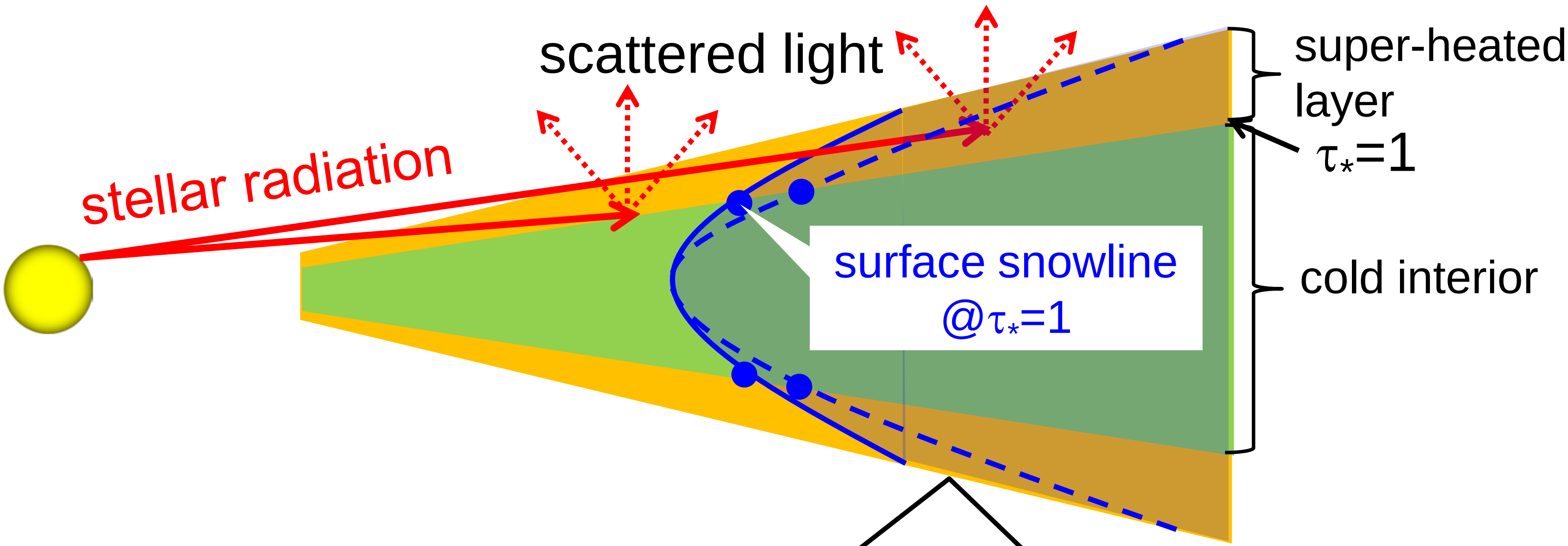
Experiments (Westley et al. 1995)

$Y=10^{-3}\sim10^{-2}$(T=35~100K, Lya)

Oka, Inoue, et al. 2010, in prep.

PS effect on surface snowline

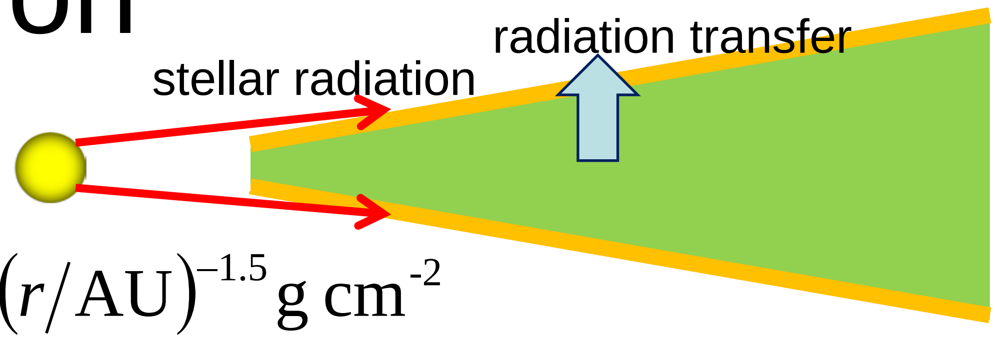
2D structure of snowline (snow front)



snowline is pushed away by PS?

Oka, Inoue, et al. 2010, in prep.

Model calculation



Surface density $\Sigma = 1700 (r/\mathrm{AU})^{-1.5} \mathrm{g\ cm^{-2}}$

Dust
ice and silicate (1 micron)
constant abundance of H2O
(Miyake & Nakagawa 1993)
ice abundance･･･evaporation/condensation/PS

Stellar radiation Planck function + FUV excess

$L_{\mathrm{FUV}} = 10^{-3} L_* \quad h\nu = 1.6 \times 10^{-11} \mathrm{erg}$ (Lya)

Scheme 1+1D RT（Dullemond *et al.* 2002）

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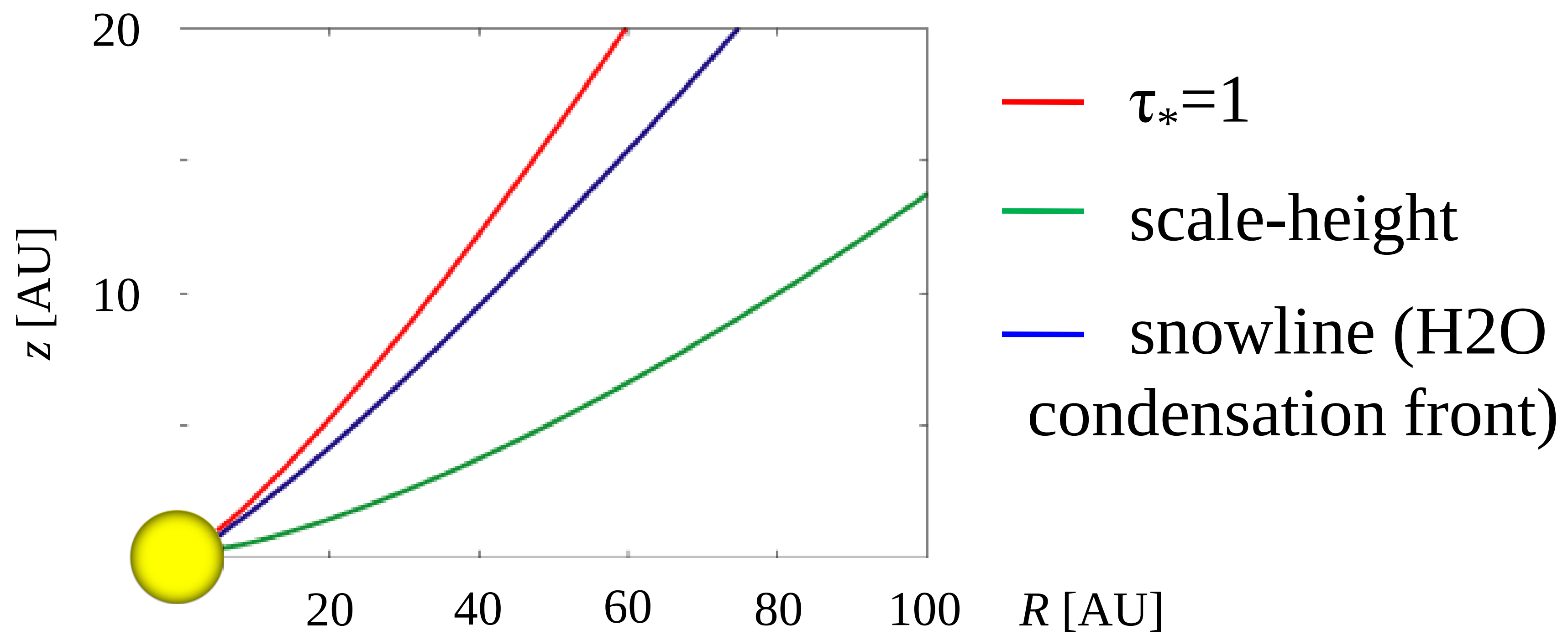
Oka, Inoue, et al. 2010, in prep.

Result1: Snowline on (R, z)

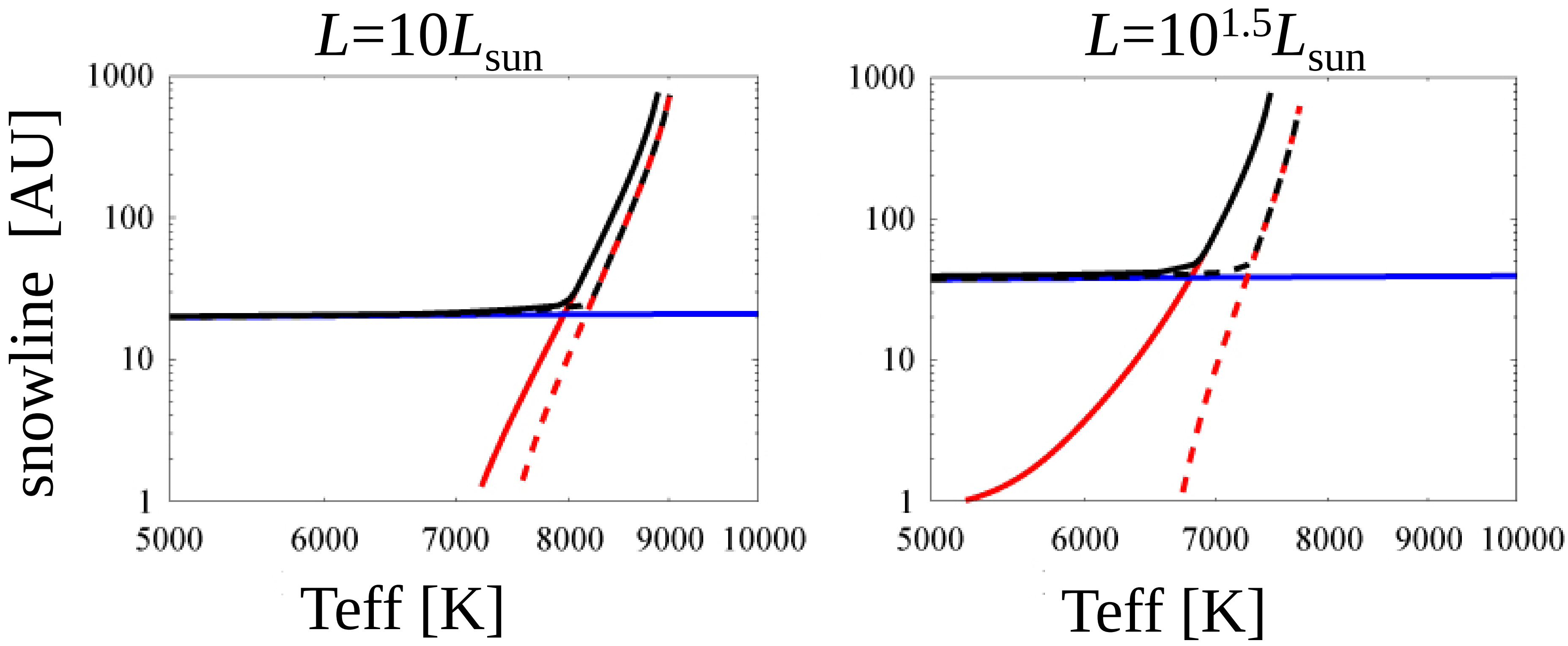
L=10L_{sun} T_{eff}=10000K With Photo-sputtering



1. Photo-sputtering pushes snowline out
2. If Teff higher than a critical value
   ➔ no surface snowline due to strong UV

Oka, Inoue, et al. 2010, in prep.

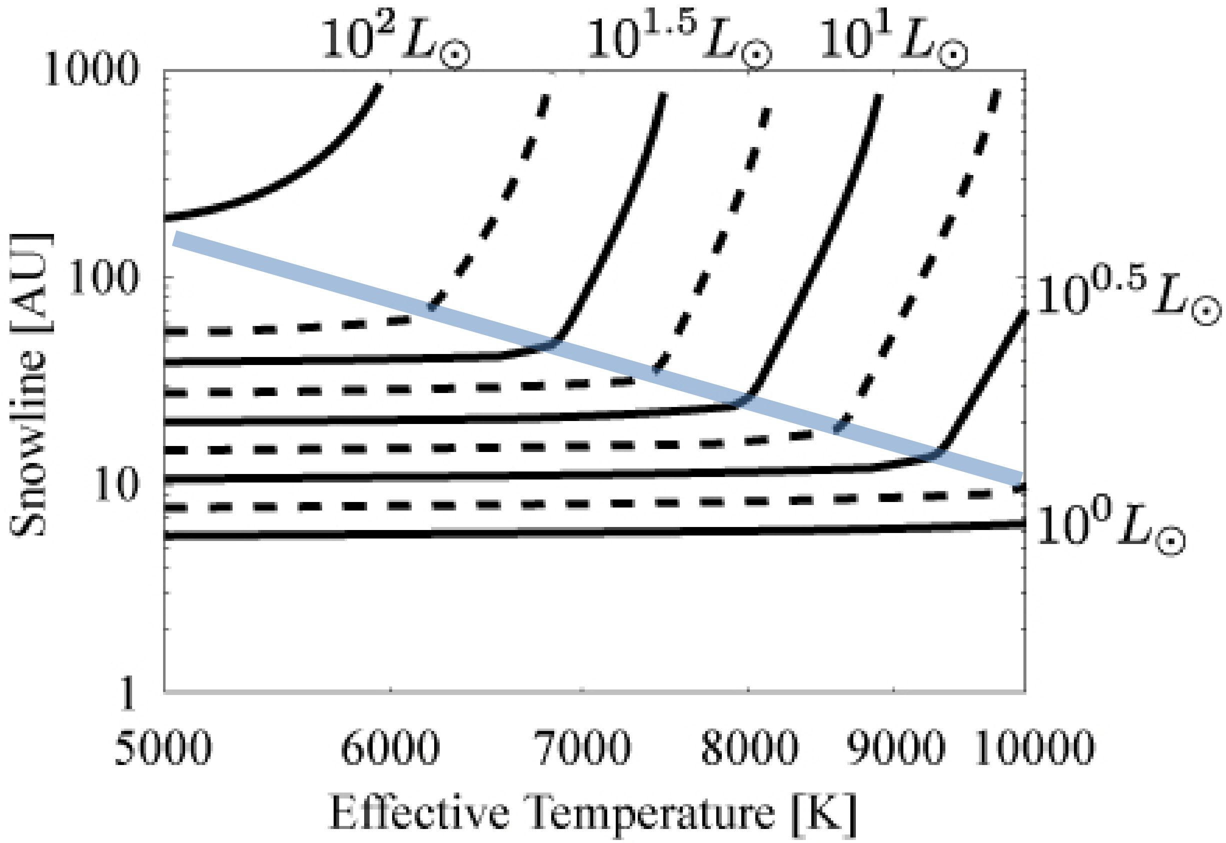
Result2: Teff dependency



1. $T_{eff} < T_c$ ➔ balance between evaporation and condensation
2. $T_{eff} > T_c$ ➔ balance between PS and condensation

Oka, Inoue, et al. 2010, in prep.

Result3: L dependence of Tc



Larger luminosity ➡

1. Lower Tc (PS dominant)
2. Larger snowline radius

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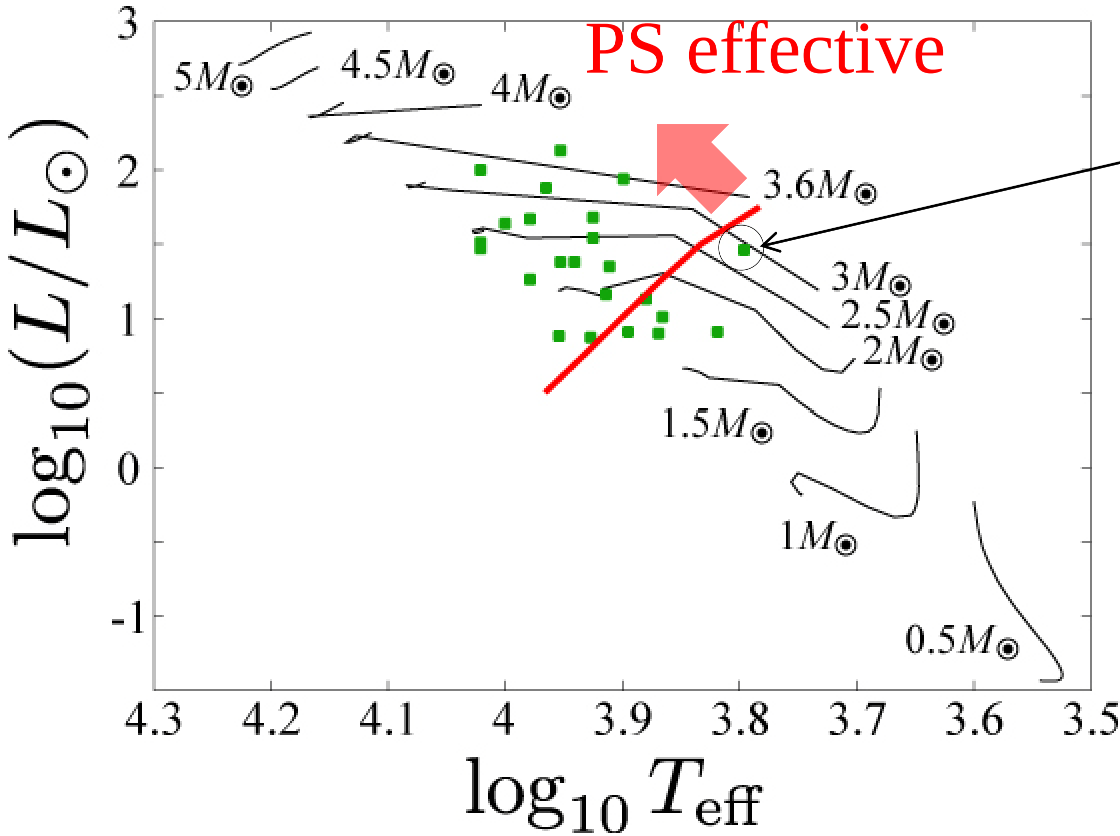
Oka, Inoue, et al. 2010, in prep.

Result4: PS effective area



Honda *et al.* (2009)
HD142527

■ Herbig Ae/Be stars
（van Boekle *et al.* 2005）

— Evolutionary tracks
(Solar abundance)
: Yi *et al.* (2001)

- Disks around relatively massive stars are affected by PS
  ➔ There would be no H_2O ice above the disk surface

Summary

- Location of snowline is important but unknown yet.
- Using NIR scattered light, we can image the snowline on the disk surface
  - but, snowline in the disk interior cannot be seen.
- HD142527 was observed with Subaru/CIAO through 3 micron H2O band.
  - H2O ice absorption feature was detected at the disk radius > 140 AU.
- UV photo-sputtering can push the surface snowline outward of the disk.
  - HD142527 is a case where photo-sputtering is not very effective.

Future prospects

- Gemini/NICI observations with a new 3-micron filter
  - Subaru/HiCIAO does not have sensitivity at 3-micron
- To relate the surface snowline to the mid-plane snowline
  - More theoretical works are required.
- H_2O ice distribution in debris disks are also very interesting.
  - Scattering intensity is much fainter…

- Spatially resolved FIR observations for H_2O emission features
  - Need space interferometers!
  - But, the mid-plane would not be seen yet…