First Herschel Detection of Crystalline Water Ice in a T-Tauri Star

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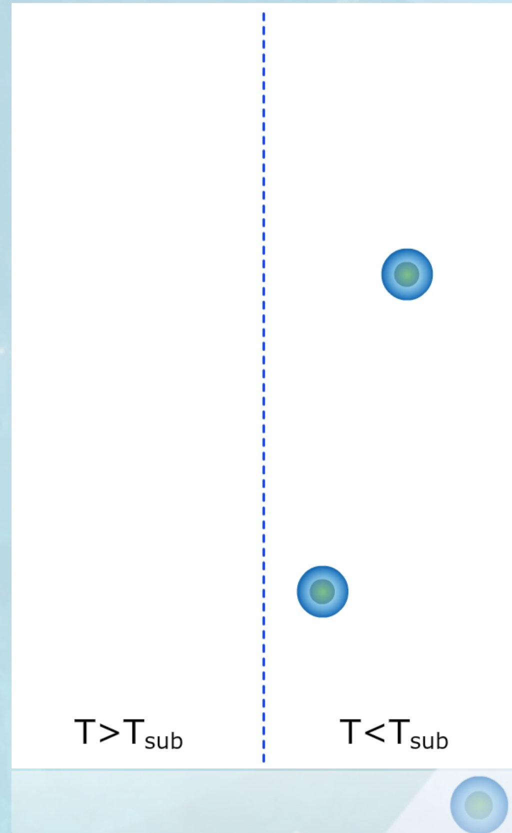
EFFECTS OF ICE ON GRAIN GROWTH

- ice-covered grains stickier than silicates →100 times larger a_{max} than bare grains

- growth via vapor condensation up to 10 cm sizes at snowline

- pressure traps at snowline lead to increase in local density, more grain growth

Condensation growth (movie)



(Ormel et al. 2011, Kuroiwa & Sirono 2011, Ros & Johanson 2013 (in press), Kretke & Lin 2008)

Open Questions

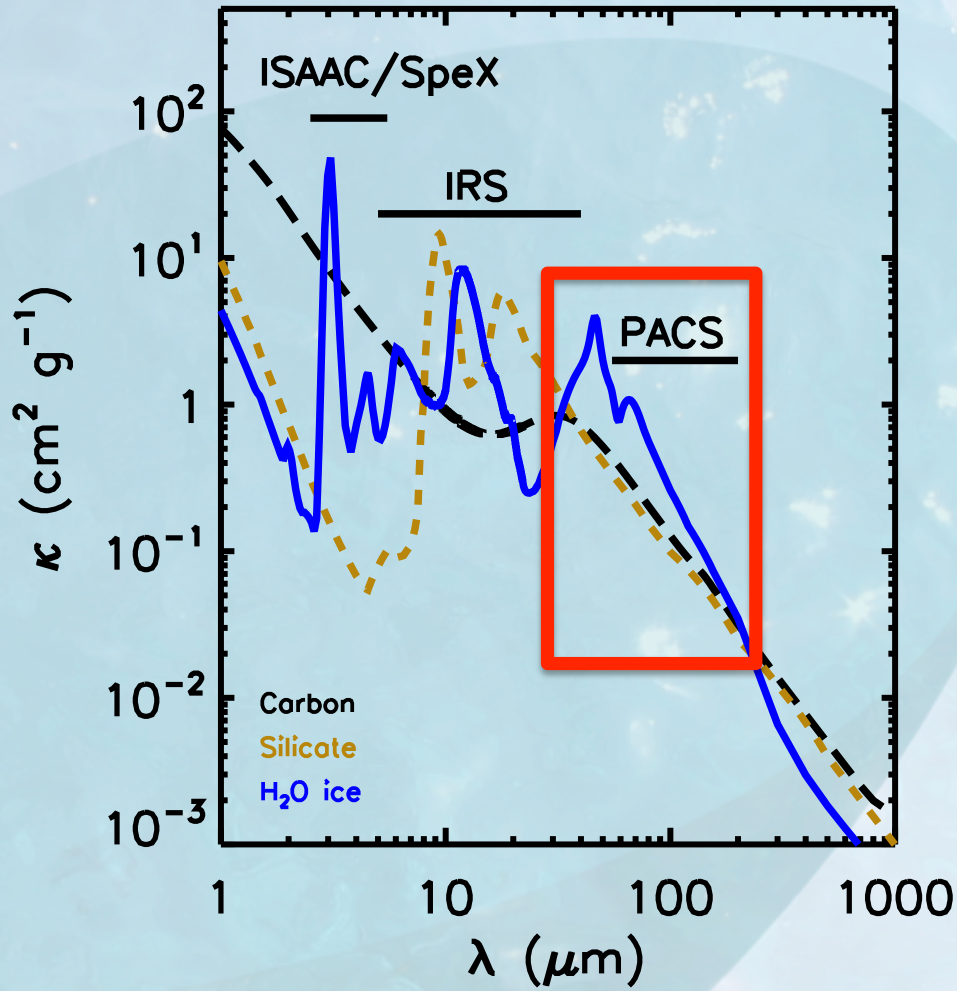
- ❑ What is the abundance of ice in the disk?
- ❑ (How) does ice enhance grain growth?
- ❑ Correlations between dust content and disk structure?
- ❑ Where is the snow line?

Direct detection of water ice

- Most ice bands (e.g. 3µm) in spectral regions typically sampling hot dust

- Seen in absorption through upper layers of edge-on disks ($n_{ice} = 9x10^{-5}\ n_{H2}$, Pontoppidan et al. 2008)

- Herschel PACS ice should be seen in emission (cool midplane/warmer upper layers)



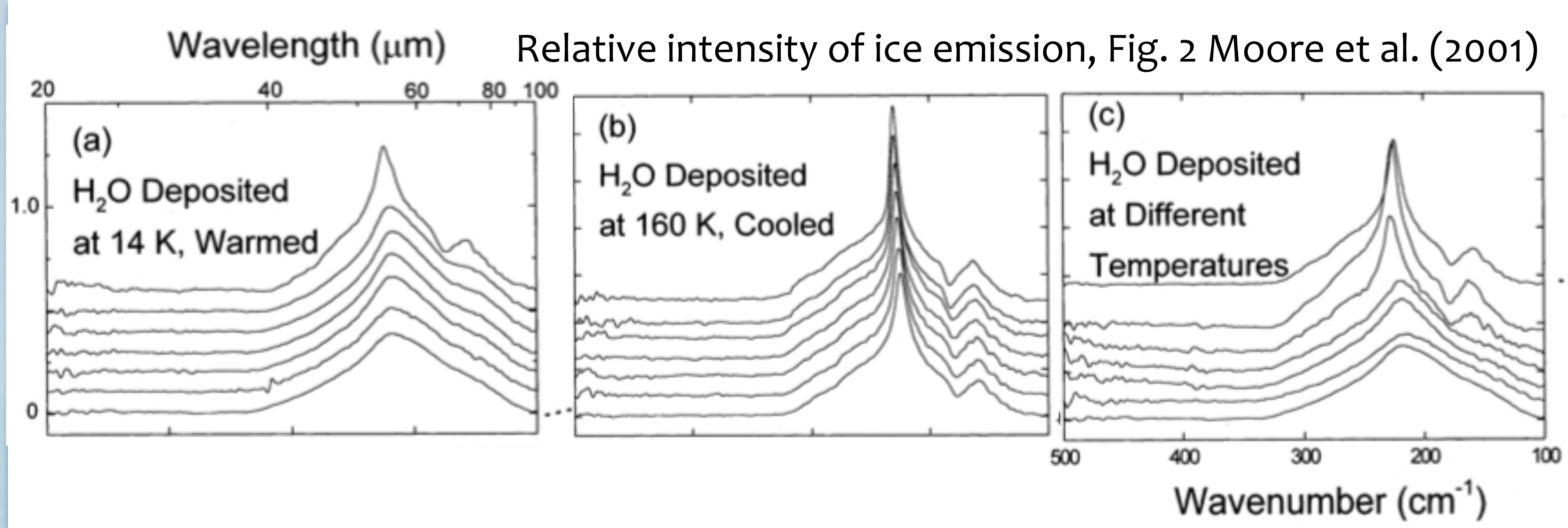
(Draine & Li 1984, Dorschner et al. 1995 + Jena database, Warren & Brandt 2008, Pontoppidan et al. 2005)

CRYSTALLINE VS. AMORPHOUS ICE

- 63 µm band is crystalline ice, → heated > 130 K

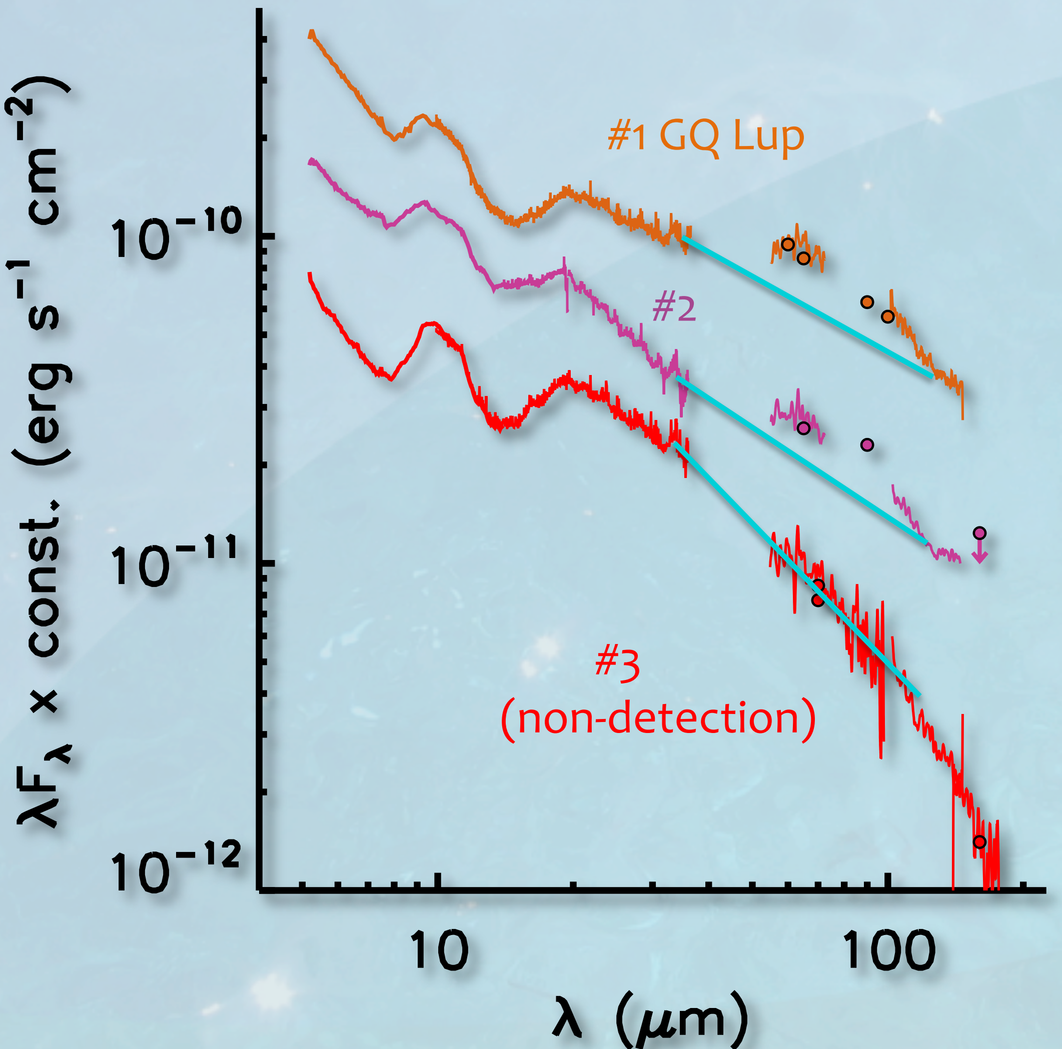
- different shapes from 44 – 63 µm depending deposition temperature, heating/cooling history

Relative intensity of ice emission, Fig. 2 Moore et al. (2001)



(Bertie 1969, Moore et al. 2001)

FIRST HERSCHEL ICE DETECTIONS!

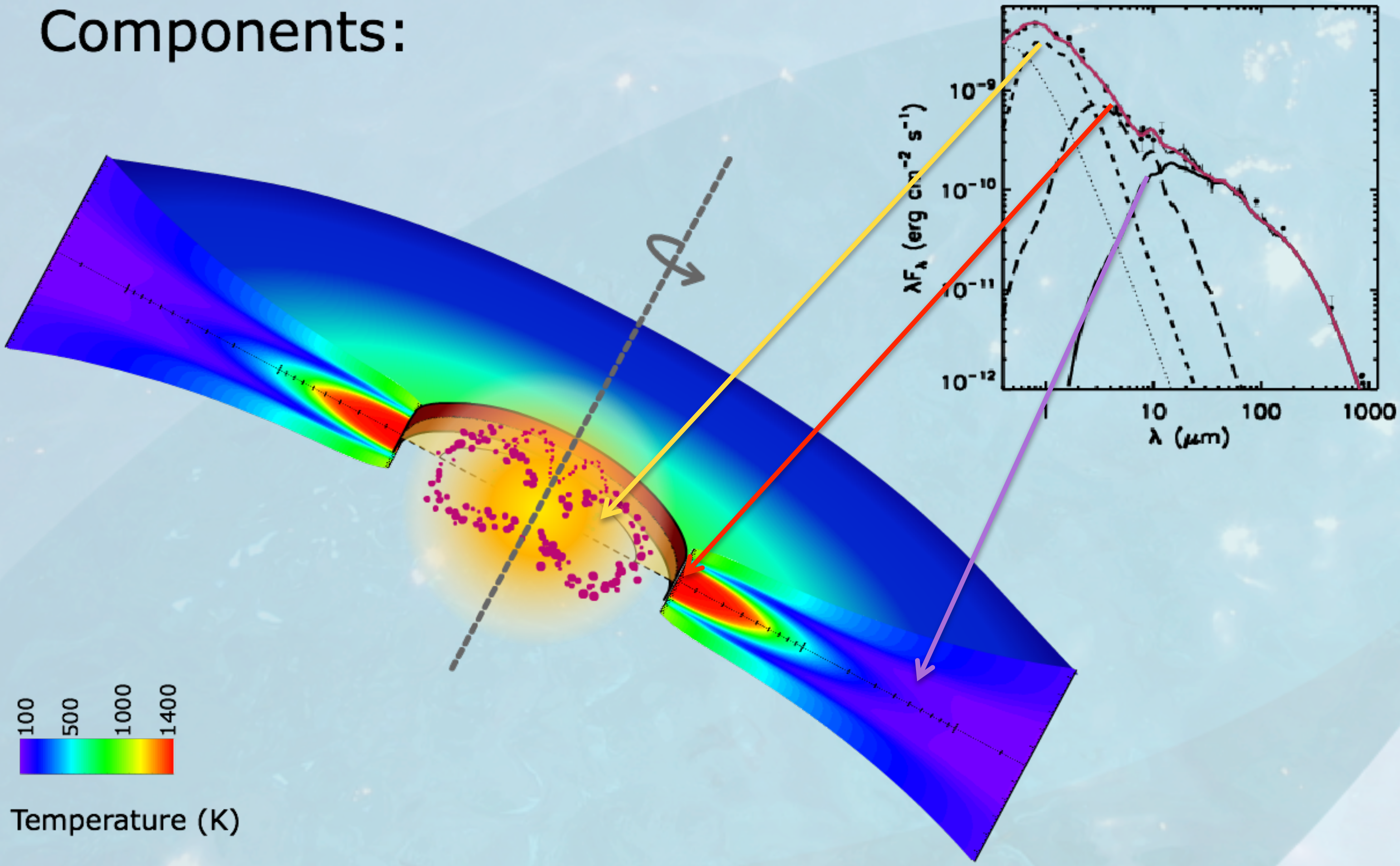


Similar stars	
T_{eff}	4350 – 4050 K (solar type precursors)
$L_\star$	1.6 – 2.0 $L_\odot$
$\dot{M}$	$10^{-7} – 10^{-8}$ $M_\odot$/yr
i	40 – 50°

Different disks
Silicate profile 10μm → maximum grain size
FIR slope → degree of dust settling
Binarity → R_{disk}

DISK STRUCTURE MODELS

Components:



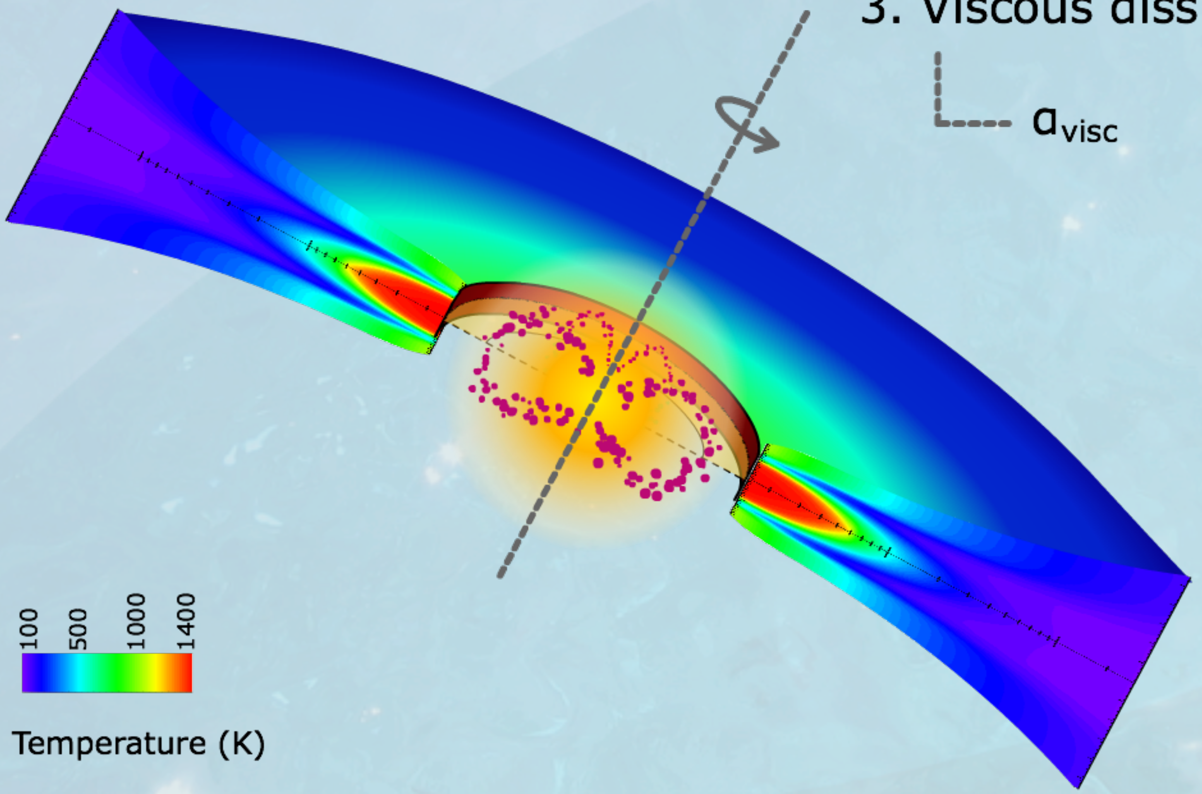
D'Alessio et al. 1998, 1998, 2001, 2004, 2006

DISK STRUCTURE MODELS

Heating:

1. Stellar irradiation
2. Accretion shock irradiation
3. Viscous dissipation

   └ α_{visc}



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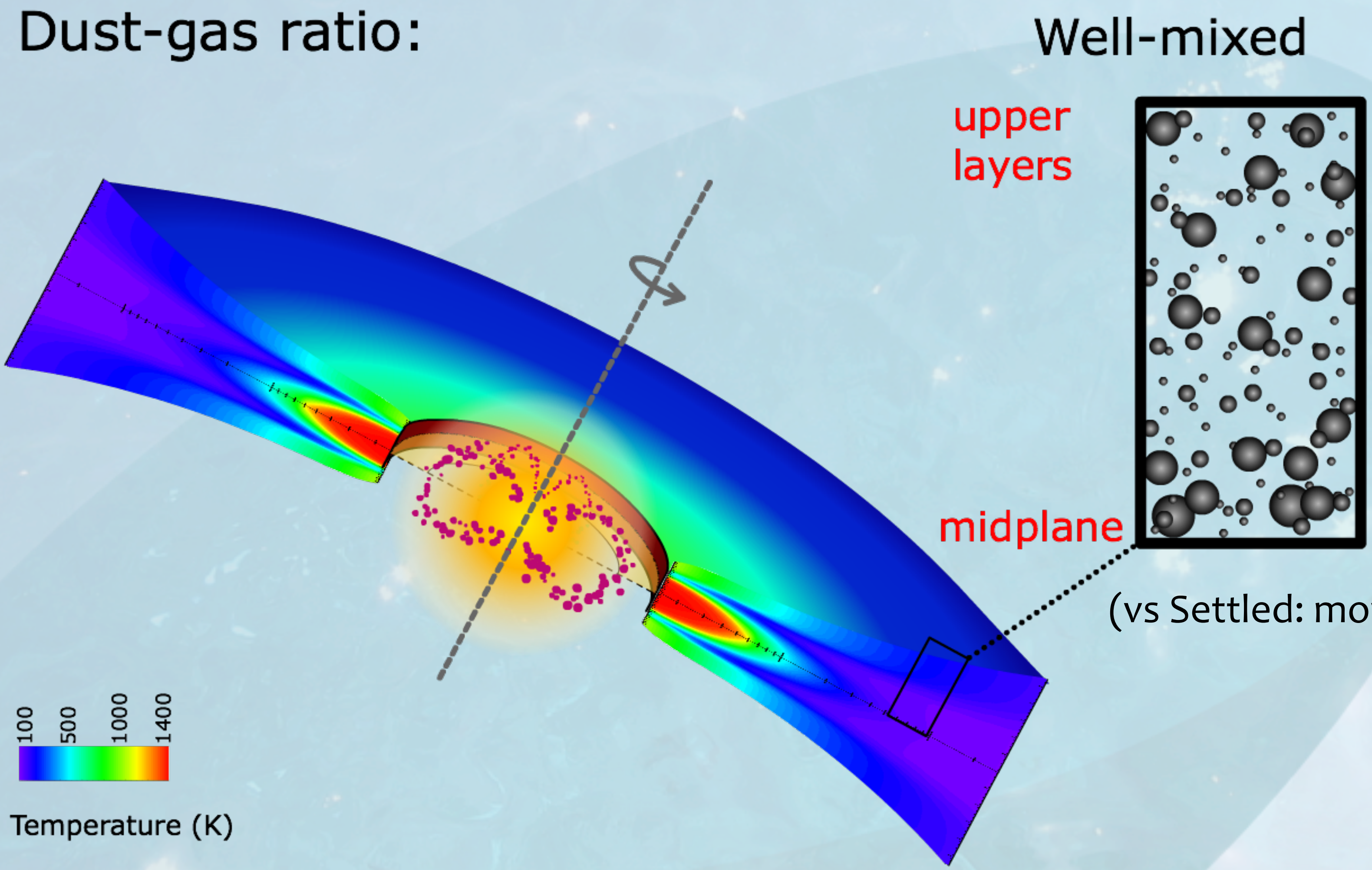
Disk structure models

Dust-gas ratio:

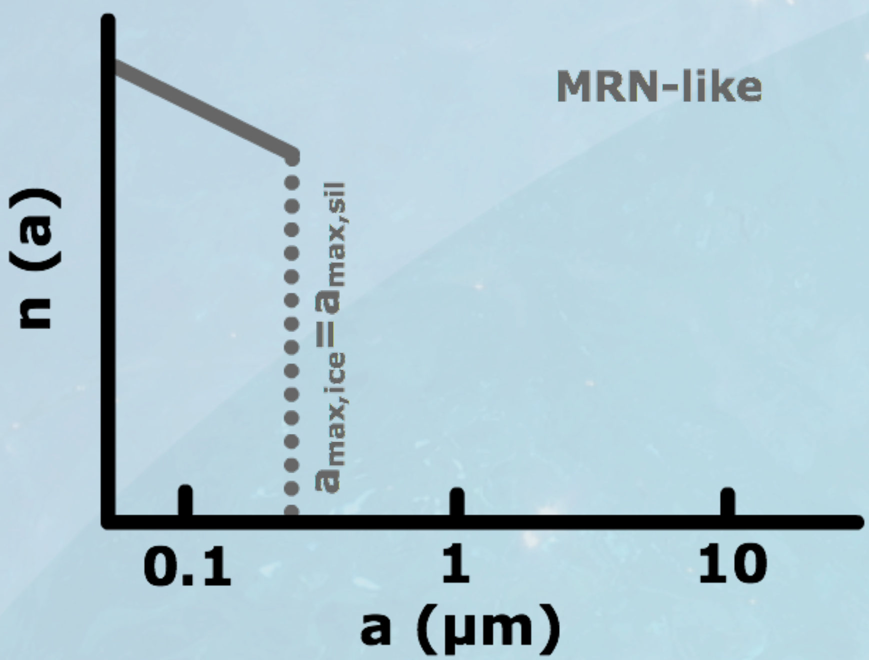


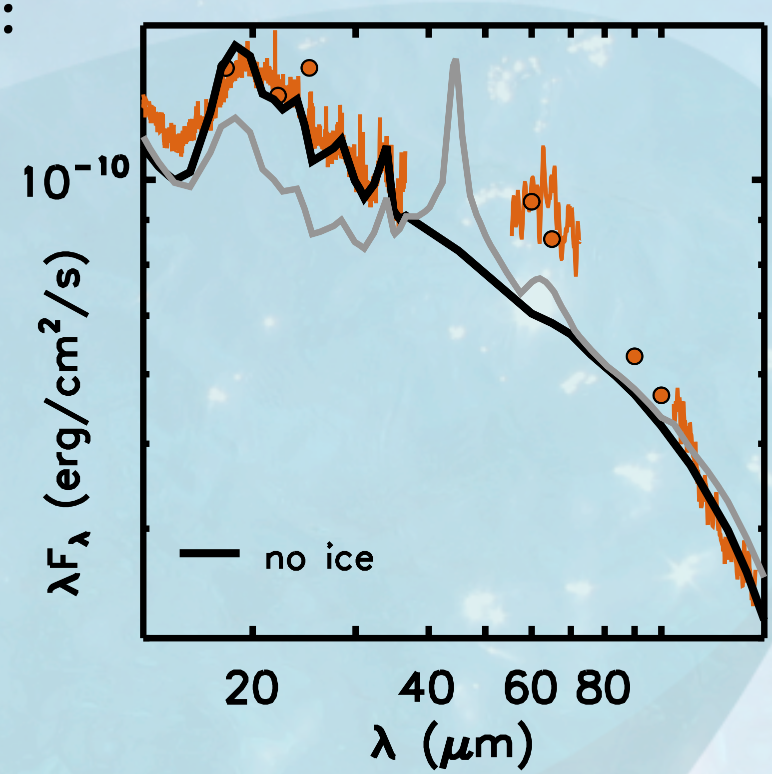
(vs Settled: movie)

D'Alessio et al. 1998, 1998, 2001, 2004, 2006

ICE–ENHANCED GRAIN GROWTH

Test via ice grain-size distributions:





- IRS + PACS best-fit with condensation growth, $n(a) \sim a^{2.0}$
- a_{max} of ice grains ~60x larger than sil./carb.

Based on Figure 5, Kuroiwa & Sirono (2011)

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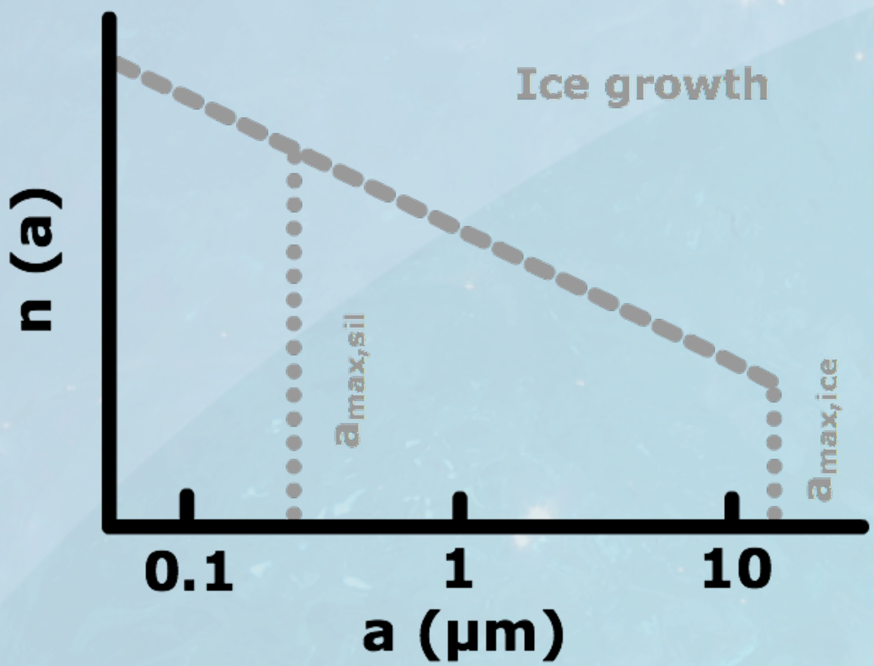

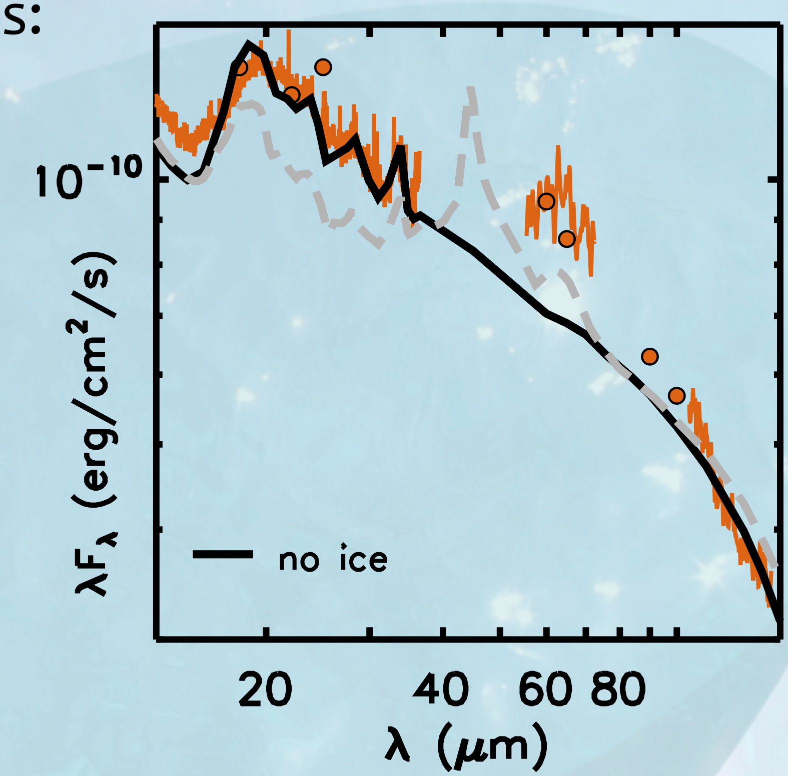

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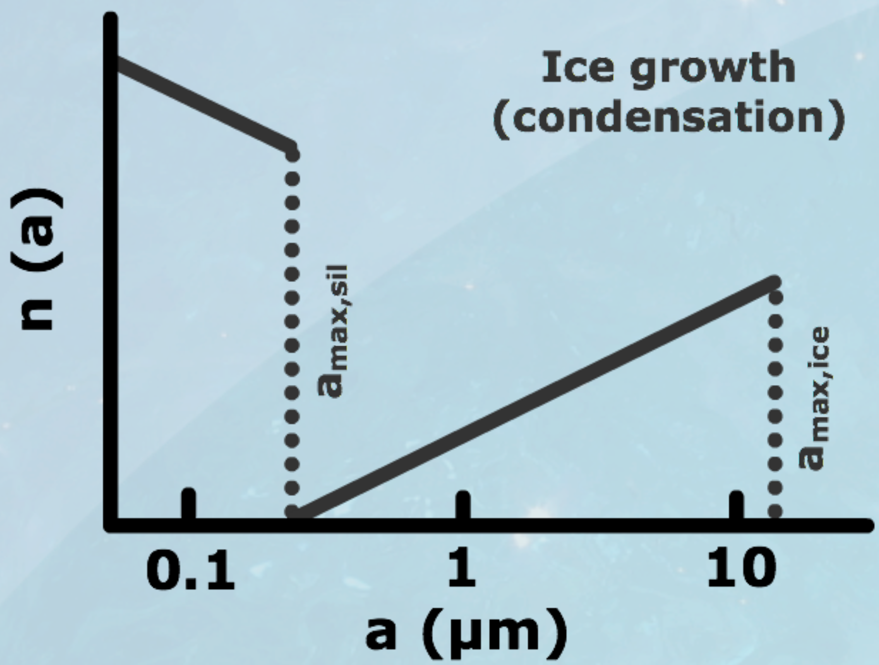

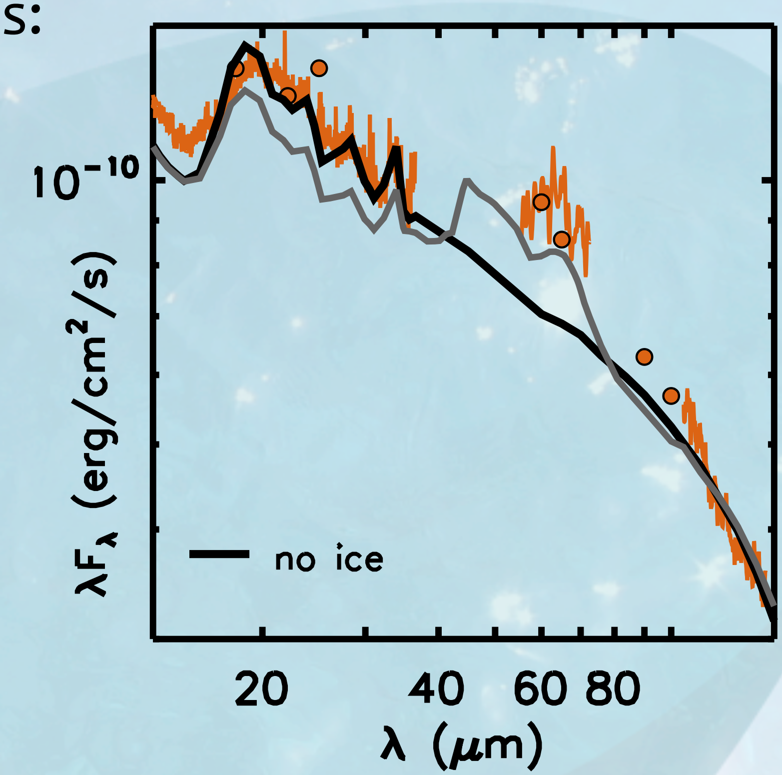

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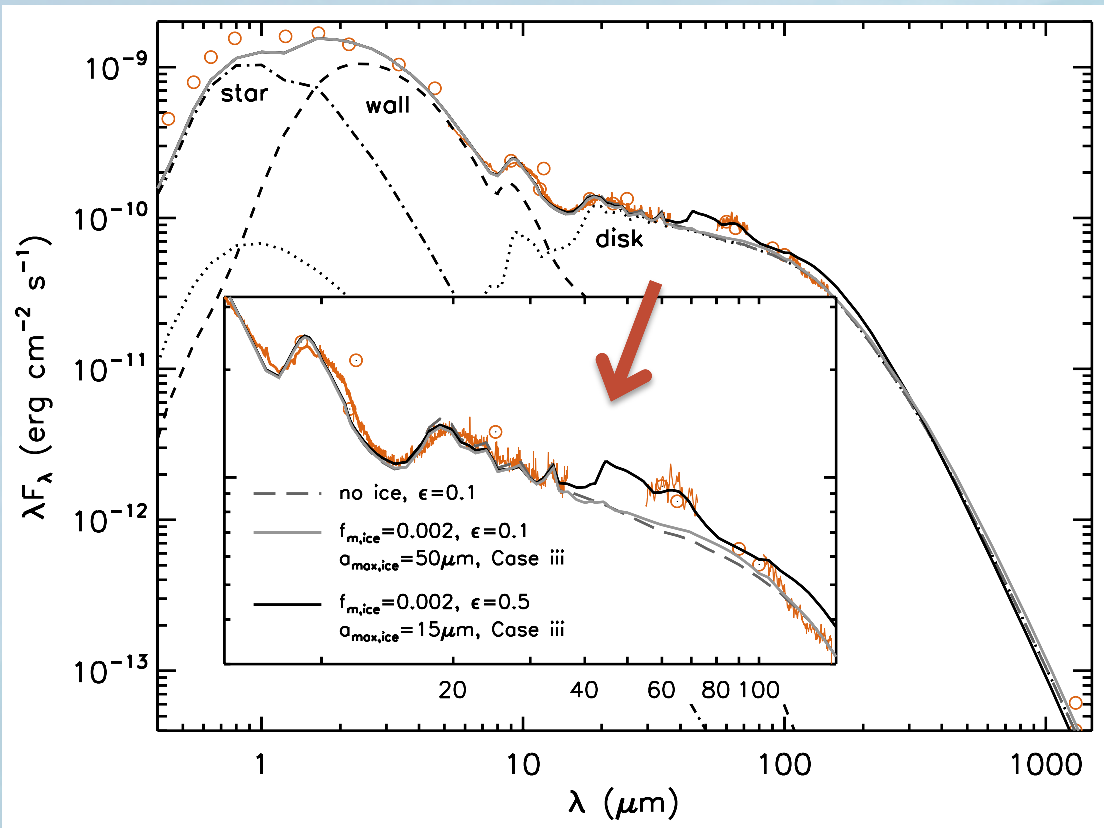
CRYSTALLINE WATER ICE IN GQ LUP

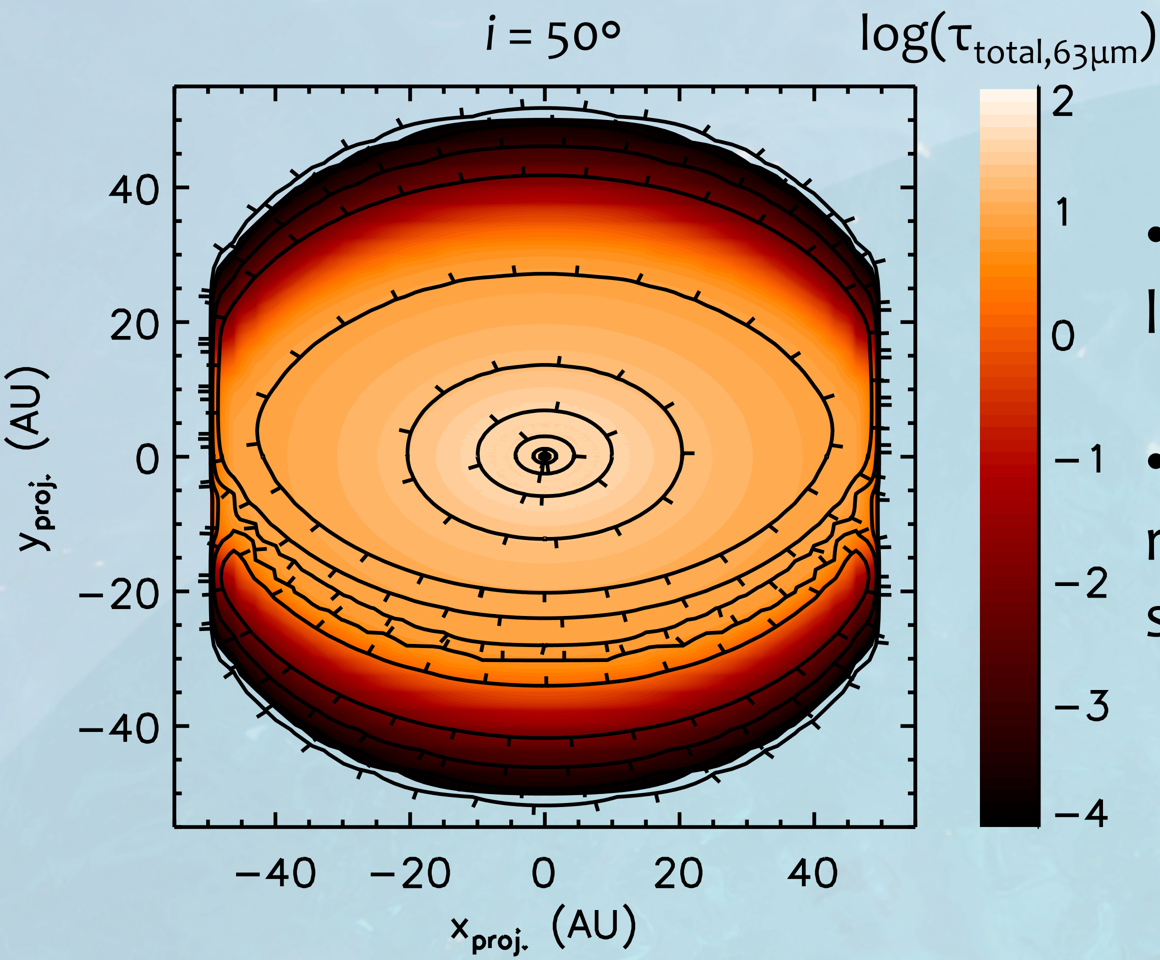
Cannot fit *Herschel* & IRS/submm data with dry grains!



- $f_{mass,ice} = 0.002 * f_{mass,gas}$
  → $n_{ice} = 2x10^{-4}\ n_{H_2}$
- 350 Earth oceans, ¼ of total oxygen budget
- Very little dust settling: dust/gas = $4x10^{-3}$ in upper layers

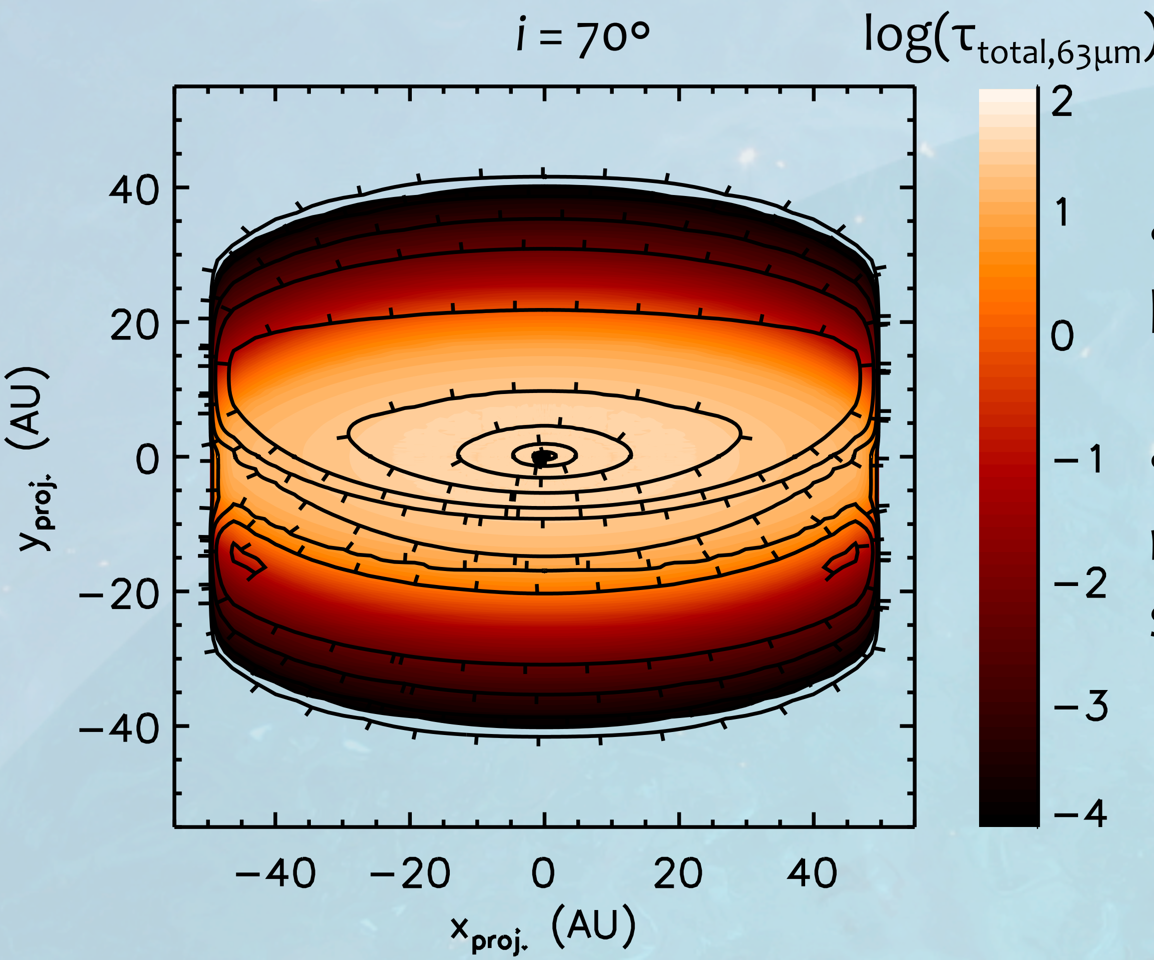
(McClure et al. 2012)

WHERE IS THE EMITTING REGION?



- probing upper layers, not midplane
- sample range of radii; not just the snowline

Where is the emitting region?



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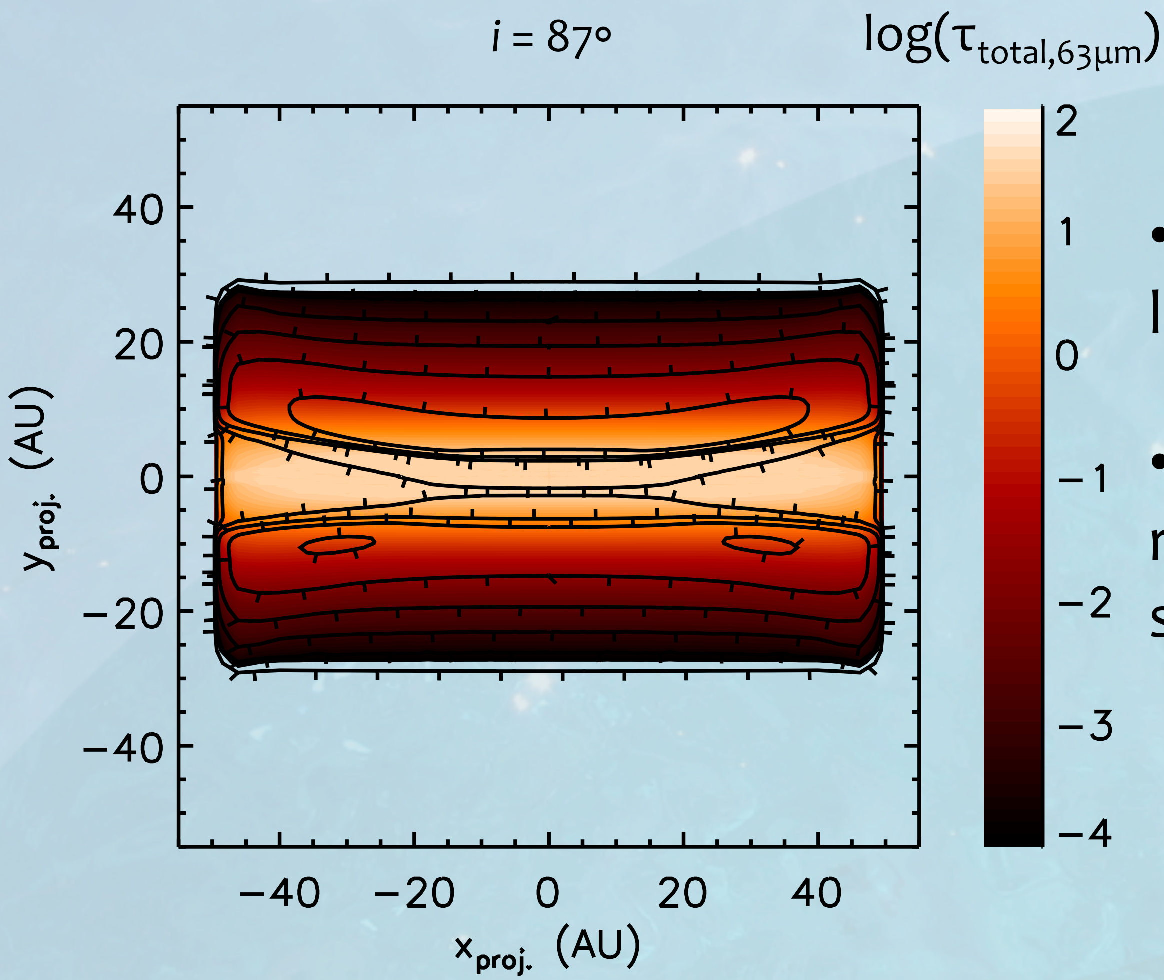


- probing upper layers, not midplane
- sample range of radii; not just the snowline

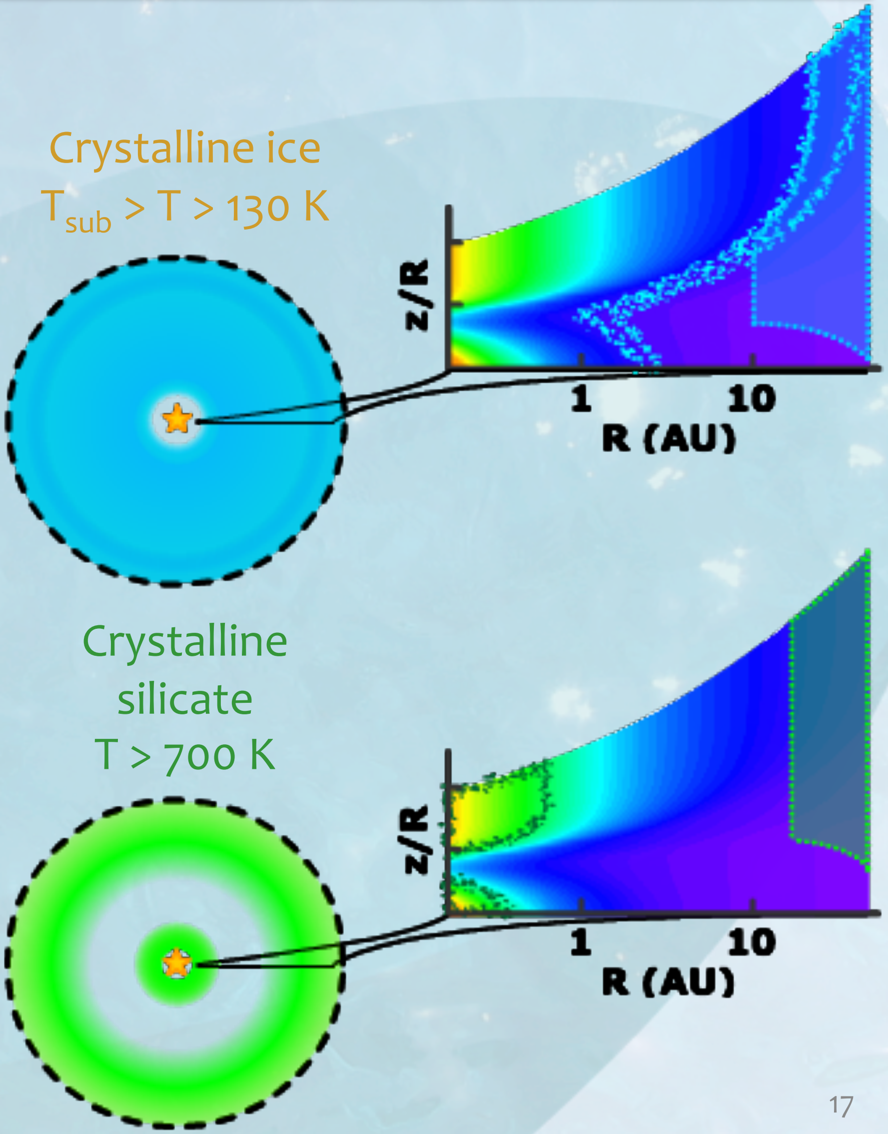
CRYSTALIZATION VIA DISK DYNAMICS?

- T_{sub} - 130 K << region contributing to ice feature

- crystalline silicate ring in GQ Lup at 20 – 50 AU → in-situ heating (shocks, planetismal dynamics)

- silicate crystallization even could also heat outer regions to T>130 K

(Harker & Desch 2002, Voroboyev 2011)



Implications of Ice Detection

✓ Empirical evidence of ice condensation-enhanced grain growth

✓ Crystalline water ice implies thermal cycling:

- Local heating in the outer disk?
- Transport from snowline to outer disk?

o May see ice due to lack of dust settling; prevents UV from penetrating disk as deeply (less photodesorption)

o If disk is planetesimal-rich, could stir midplane, replenish ice in upper layers

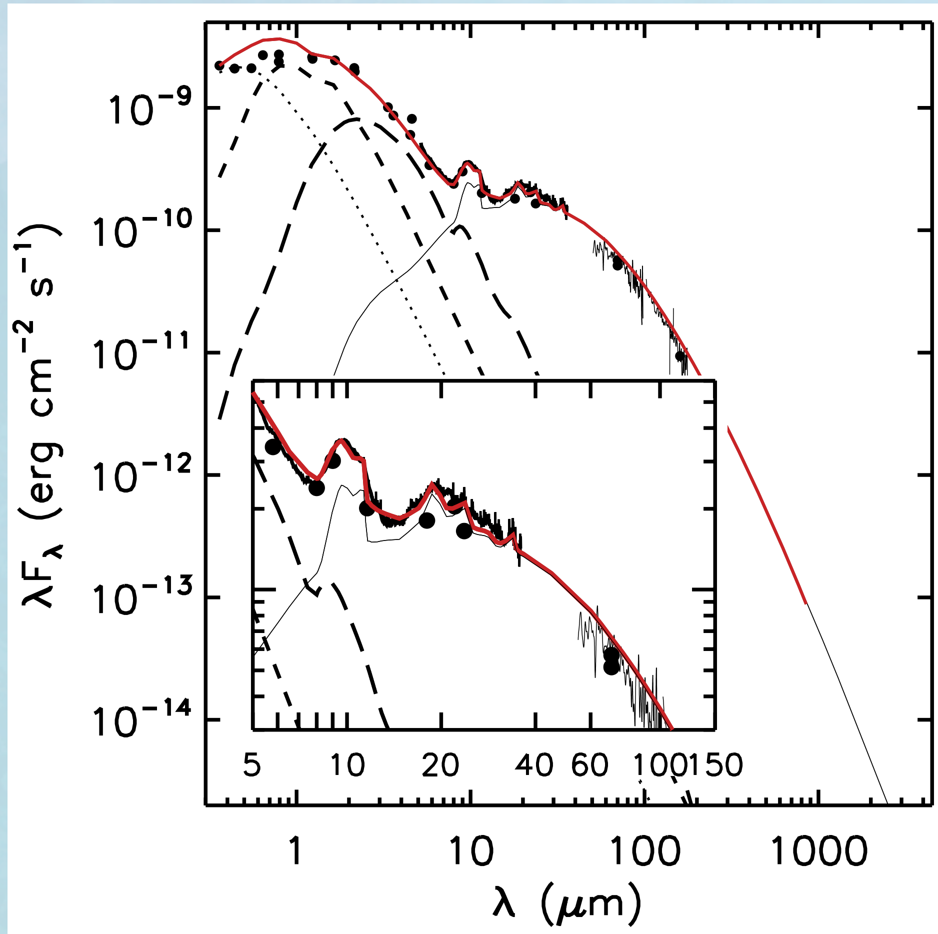
In progress: Model–independent ice confirmation

• disk #3 truncated at 7 AU

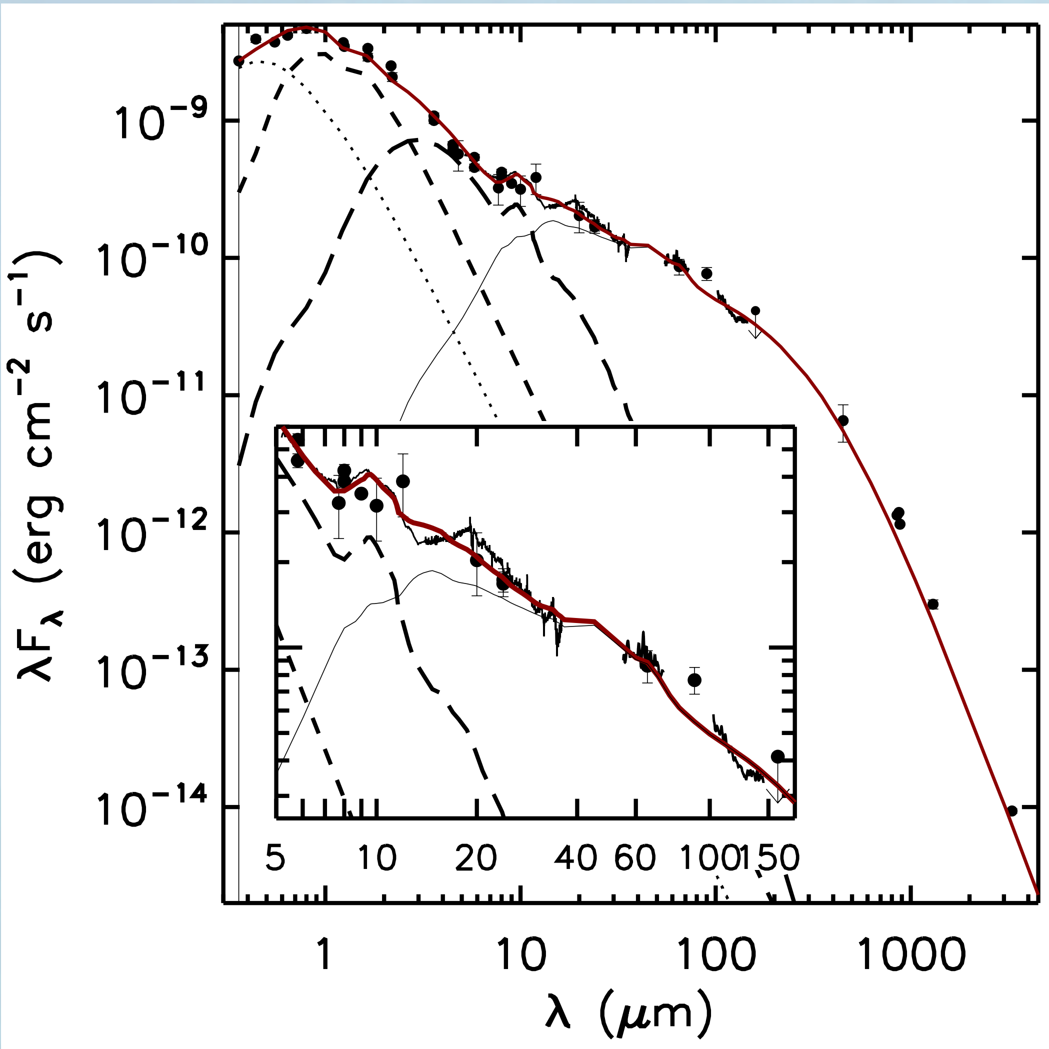
• no 63 μm ice emission

• Even $f_{mass, ice} = 0.002$ does not produce a feature

→ feature probes radii > atmospheric snowline



Detection #2: Ice in a settled disk



- dust/gas = 2×10^{-6} in upper layers (=0.11 in midplane), so lack of settling not responsible for feature presence

- large (3μm) silicate grains, no signs of shocks (e.g. forsterite ring)

- seeing inner disk with such low epsilon, closer to snowline?

Conclusions & new questions

✓ First two Herschel detections of water ice in emission from T Tauri disks.

✓ Evidence for condensation-enhanced grain growth of ice grains in upper layers

❑ Does ice enhance grain growth in the midplane as well? (need larger ice sample from *Herschel*)

❑ Is the crystalline ice created at snowline (from condensation) or via local heating events in outer disk, with T>130K? (radial location of dust rings with ALMA)

❑ How does the water vapor distribution compare with the ice? (need resolved line observations with ALMA)

BuS#1: Grain Size Distributions

Test ice-enhanced grain growth with different distributions:

$$n(a)da = a^p da\ ,\ 0.005 \leq a \leq a_{max}$$

- standard MRN
  $p = -3.5$ (all grains),
  $a_{max,ice} = a_{max,sil/carb}$
- ice growth
  $p = -3.5$ (all grains),
  $a_{max,ice} > a_{max,sil/carb}$
- ice growth by condensation
  $p = -3.5$ (sil/carb), $p = 2.0$ (ice)
  $a_{max,ice} > a_{max,sil/carb}$

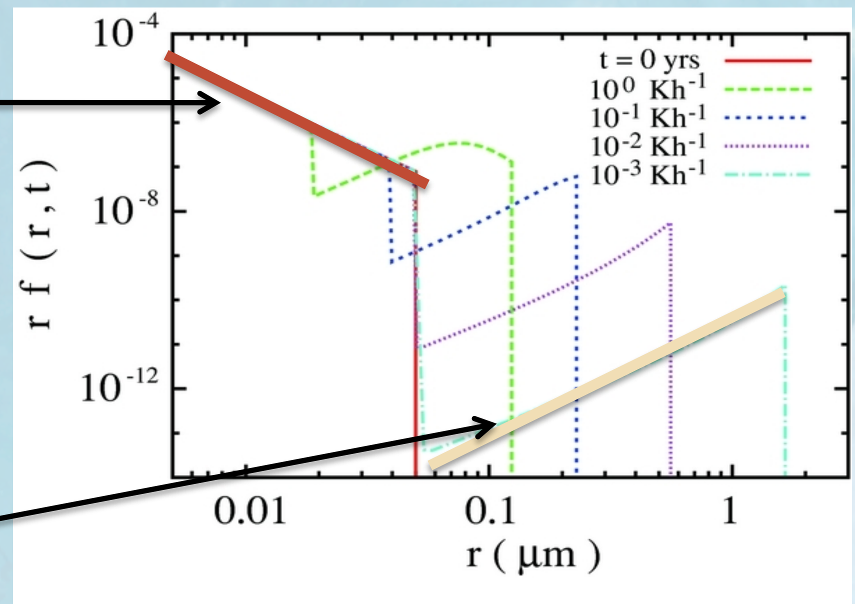
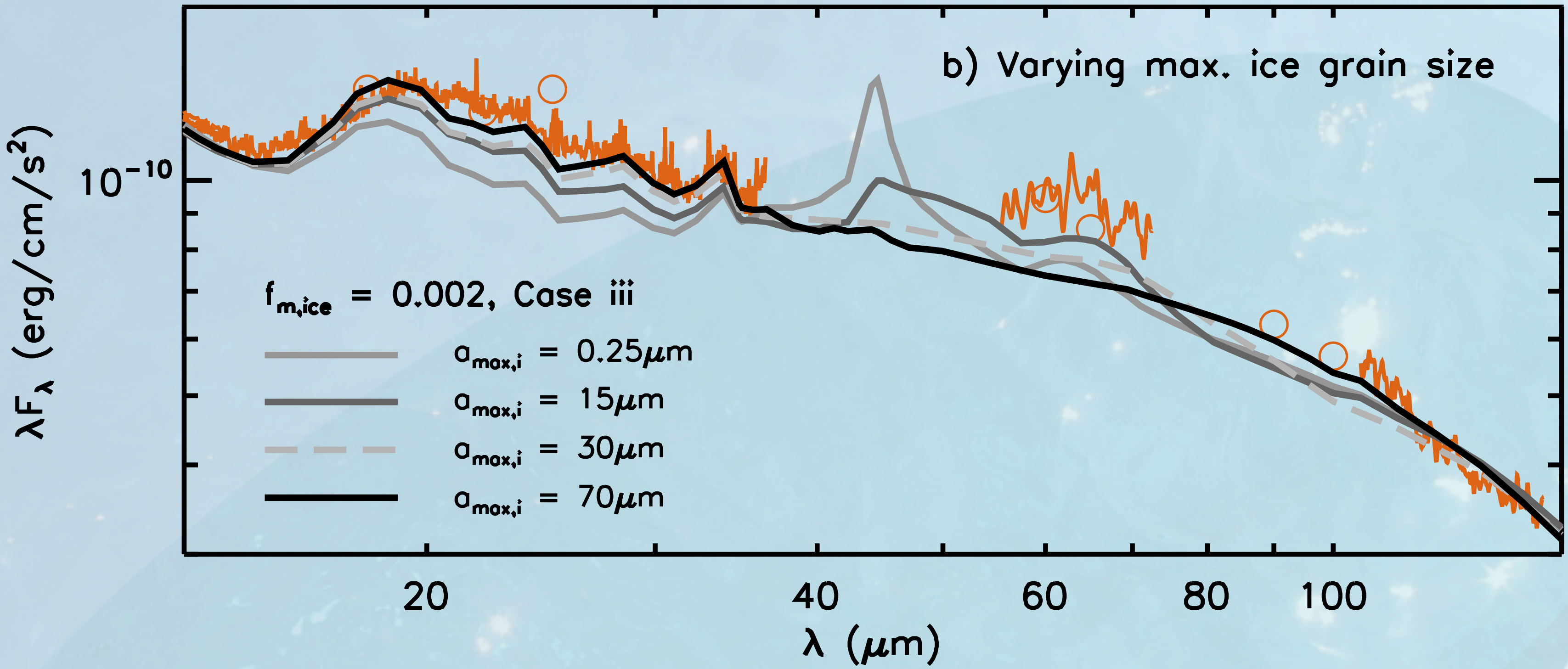


Fig. 5, Kuroiwa & Sirono (2011)

BuS#2: A_{MAX} AND CONDENSATION



For ice a_{max} > ~60μm, far-infrared SED model shape looks identical to ice-free models.