Measurement of the far-infrared absorption of crystalline water ice

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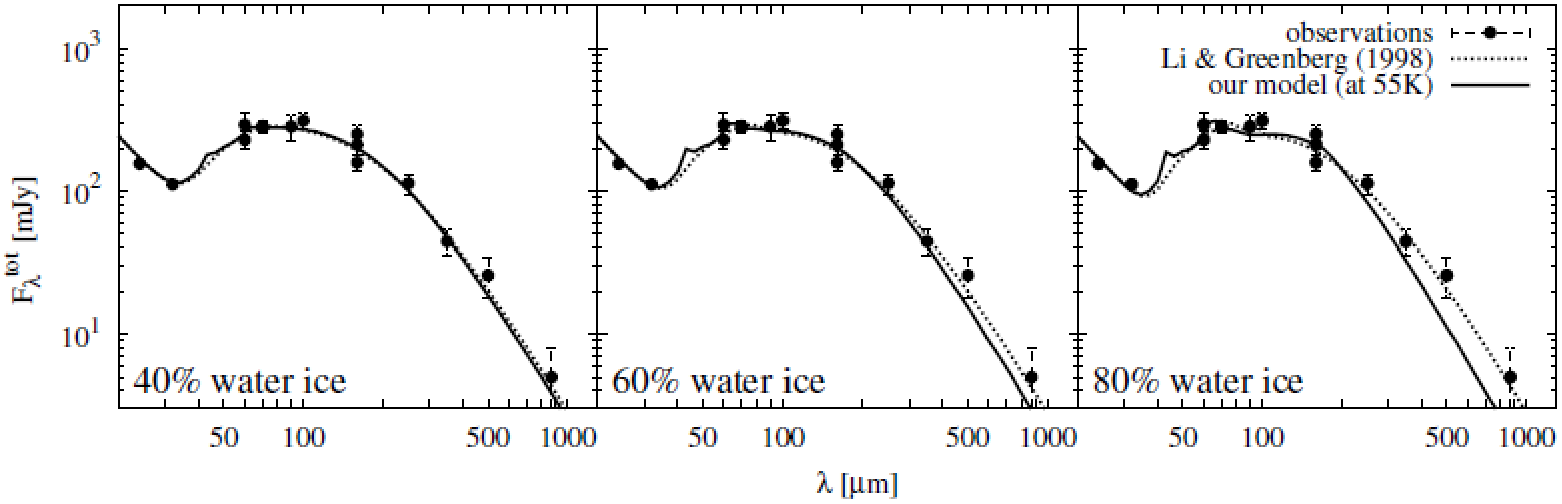
Motivation

- Water ice is abundant in molecular clouds, protoplanetary disks, and likely in **outer planetary systems (debris disks, Kuiper belts)**
- Cold dust emits thermal far-infrared continuum
- Thermal dust emission used to derive column densities, temperatures, disk structures
- Emissivity of the dust is primary model parameter
- Do we know the emissivity (= absorption coefficient) of water ice?

Dust emission of a debris disk



- SED of HD 207129 (G2V star, data points by IRAS, ISOPHOT, Spitzer IRS/MIPS, Herschel PACS/SPIRE, APEX)
- Dust mass ~0.01 Earth mass, temperature ~ 55K, distance 50-200 AU

Structure of water ice

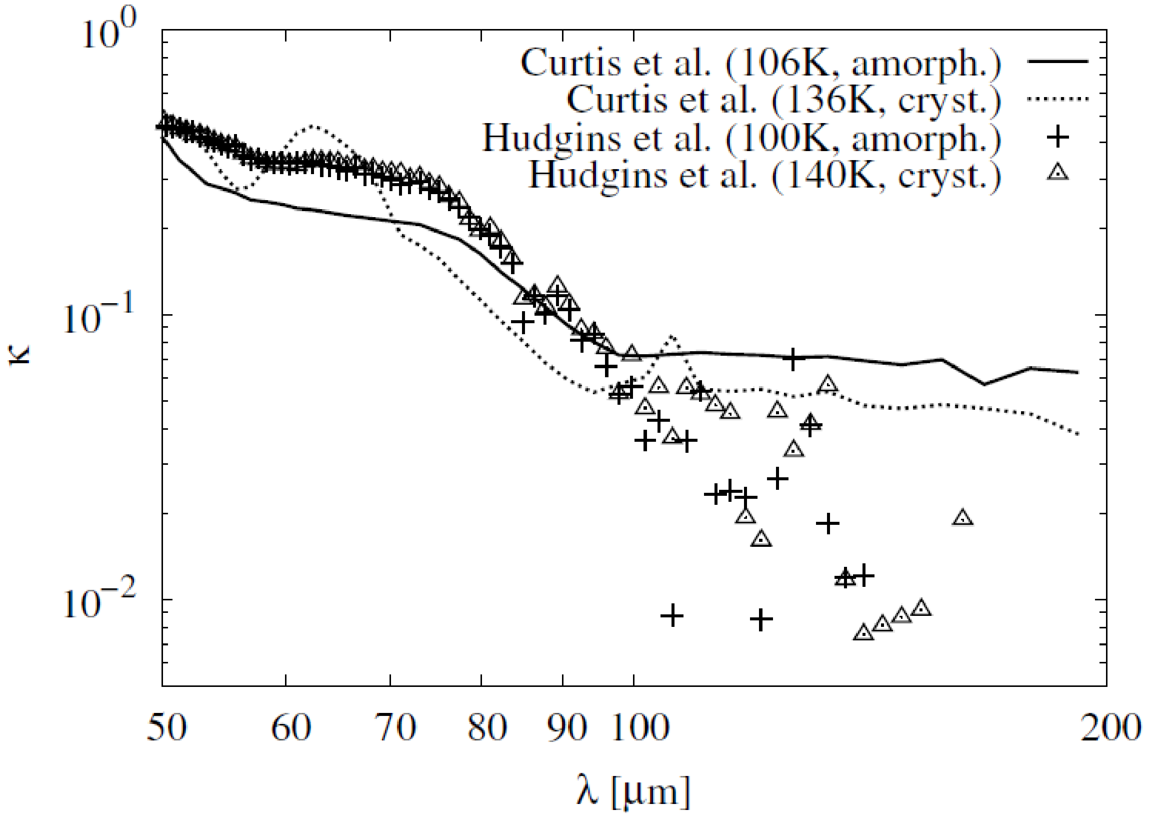
- If condensed below 110K:
  amorphous (several modifications)

- If condensed above 110K
  or warmed above 110 - 130K (irreversible):
  crystalline (cubic, I_c)
  above ~140 K: crystalline (hexagonal, I_h)

- **Crystalline** water ice detected in protoplanetary disks
  (e.g. Molster et al. 2002, Terada & Tokunaga 2012)
  by features at ~44 and 63 μm (remember J. Bouwman‘s talk)

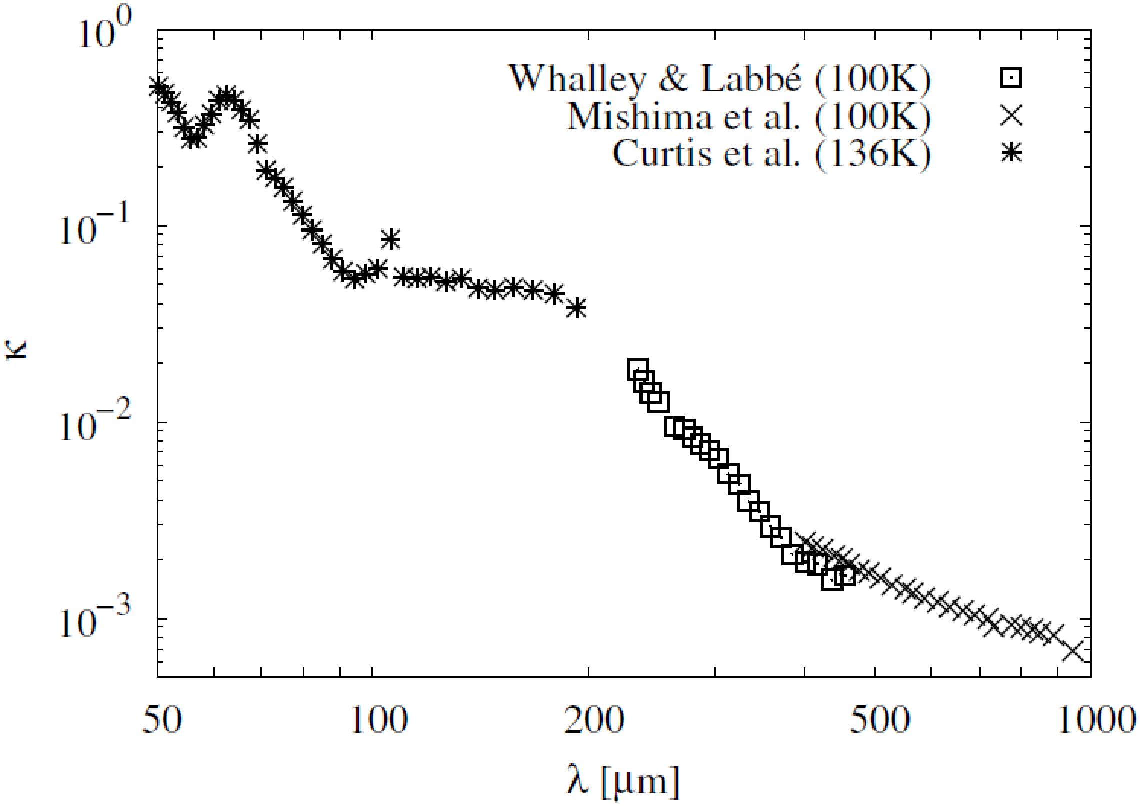
- For conditions to condense or preserve amorphous H_2O ice in space:
  Kouchi et al. (1994)

Measured absorption coefficients



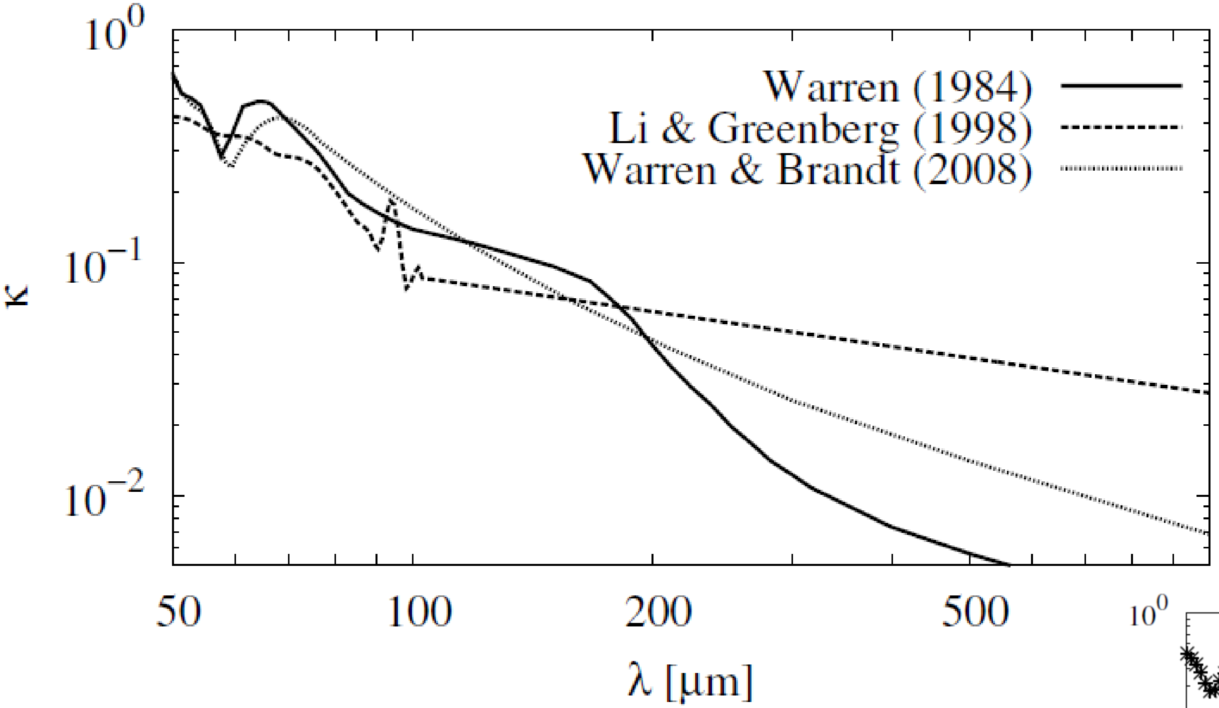
Method: micron-thick layers condensed on optical windows at various temperatures (+ warming, Hudgins+1993 10, 100, 140 K, Curtis+2005 106-176 K, 10K steps)

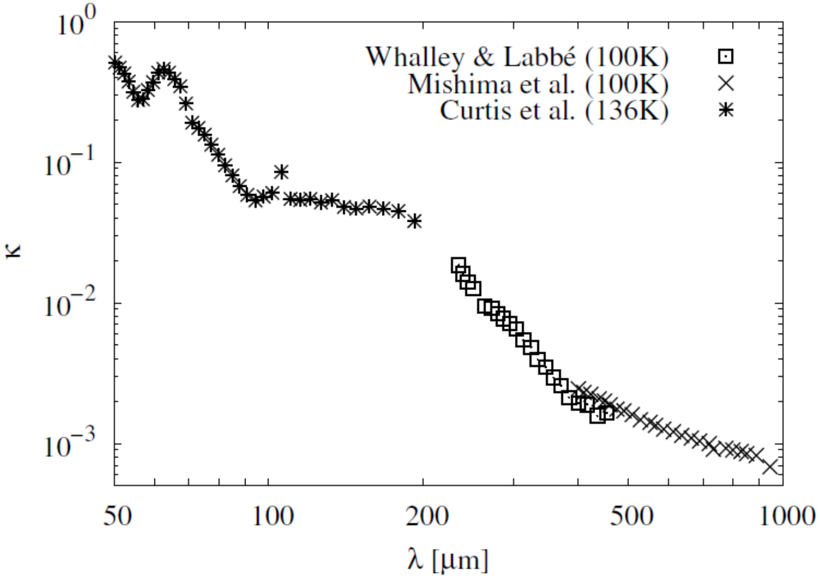
Measured absorption coefficients



Method: mm/cm-thick blocks of ice frozen from liquid **-> crystalline**
(Whalley&Labbé1969 100 K, 200 K,
Mishima+1983 80, 100, 200 K)

Sub-mm data used in astrophysics





- Li & Greenberg is for amorphous ice (Hudgins data + power law extrapolation)
- Warren (& Brandt) is for terrestrial ice (crystalline, T>250K)

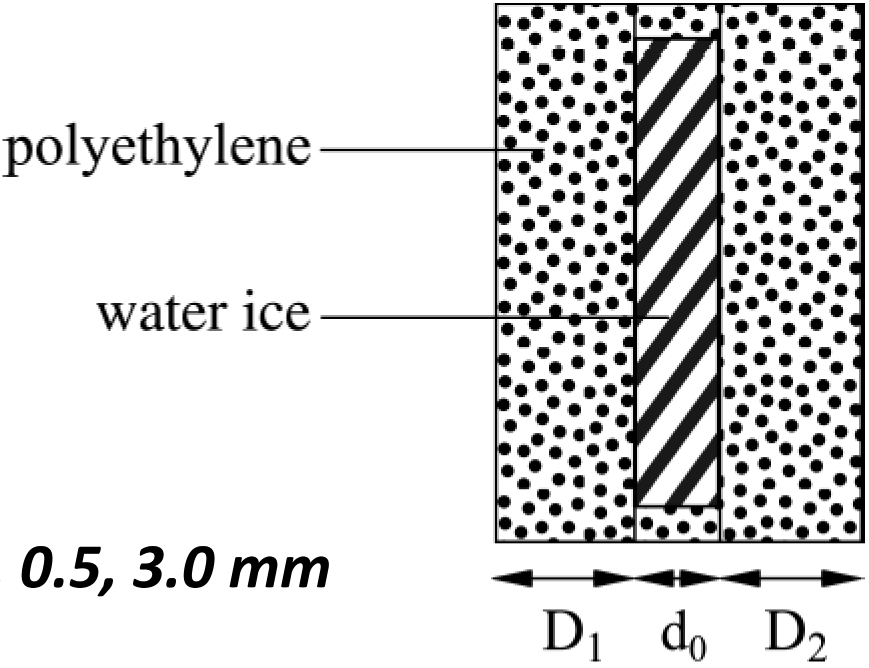
Experiment

- Liquid-Helium cryostat (10 – 300K)
- FTIR spectrometer (λ = 45 – 1000 μm)
- Small (13mm) PE containers filled with distilled water
- Frozen to 250K, 200K,

  150K, 100K, 10K

  (Whalley&Labbé

  approach)
- Hexagonal (I_h ice)



d_0 = 0.2, 0.5, 3.0 mm

Measured transmission (250 K)

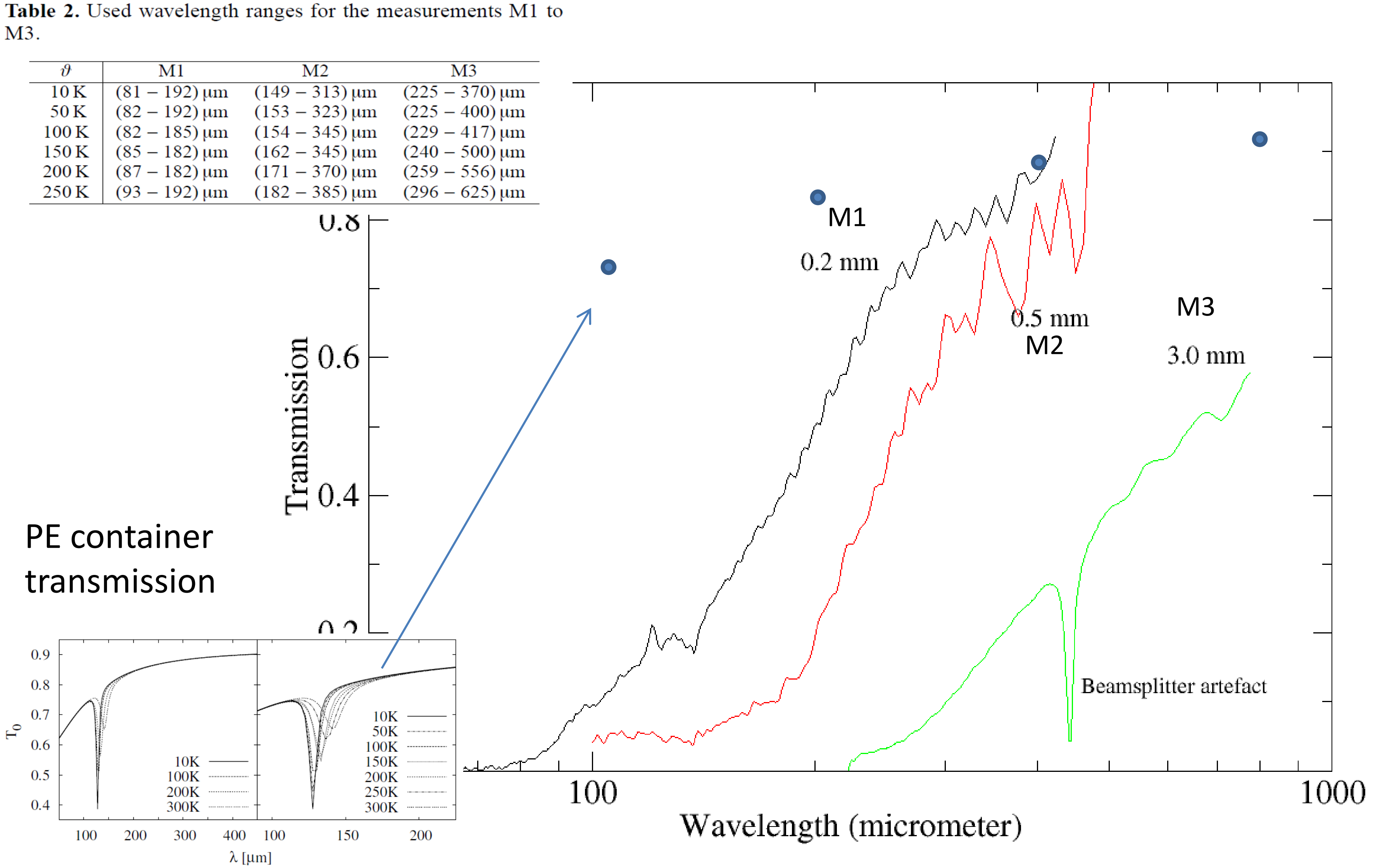


Table 2. Used wavelength ranges for the measurements M1 to M3.

ϑ	M1	M2	M3
10 K	(81 – 192) µm	(149 – 313) µm	(225 – 370) µm
50 K	(82 – 192) µm	(153 – 323) µm	(225 – 400) µm
100 K	(82 – 185) µm	(154 – 345) µm	(229 – 417) µm
150 K	(85 – 182) µm	(162 – 345) µm	(240 – 500) µm
200 K	(87 – 182) µm	(171 – 370) µm	(259 – 556) µm
250 K	(93 – 192) µm	(182 – 385) µm	(296 – 625) µm

PE container transmission

Measured transmission (250 +10 K)

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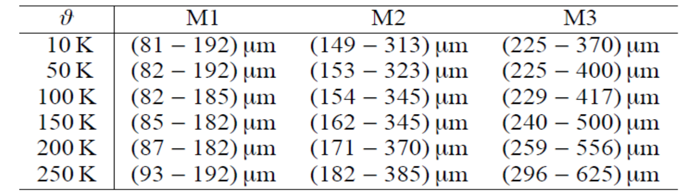

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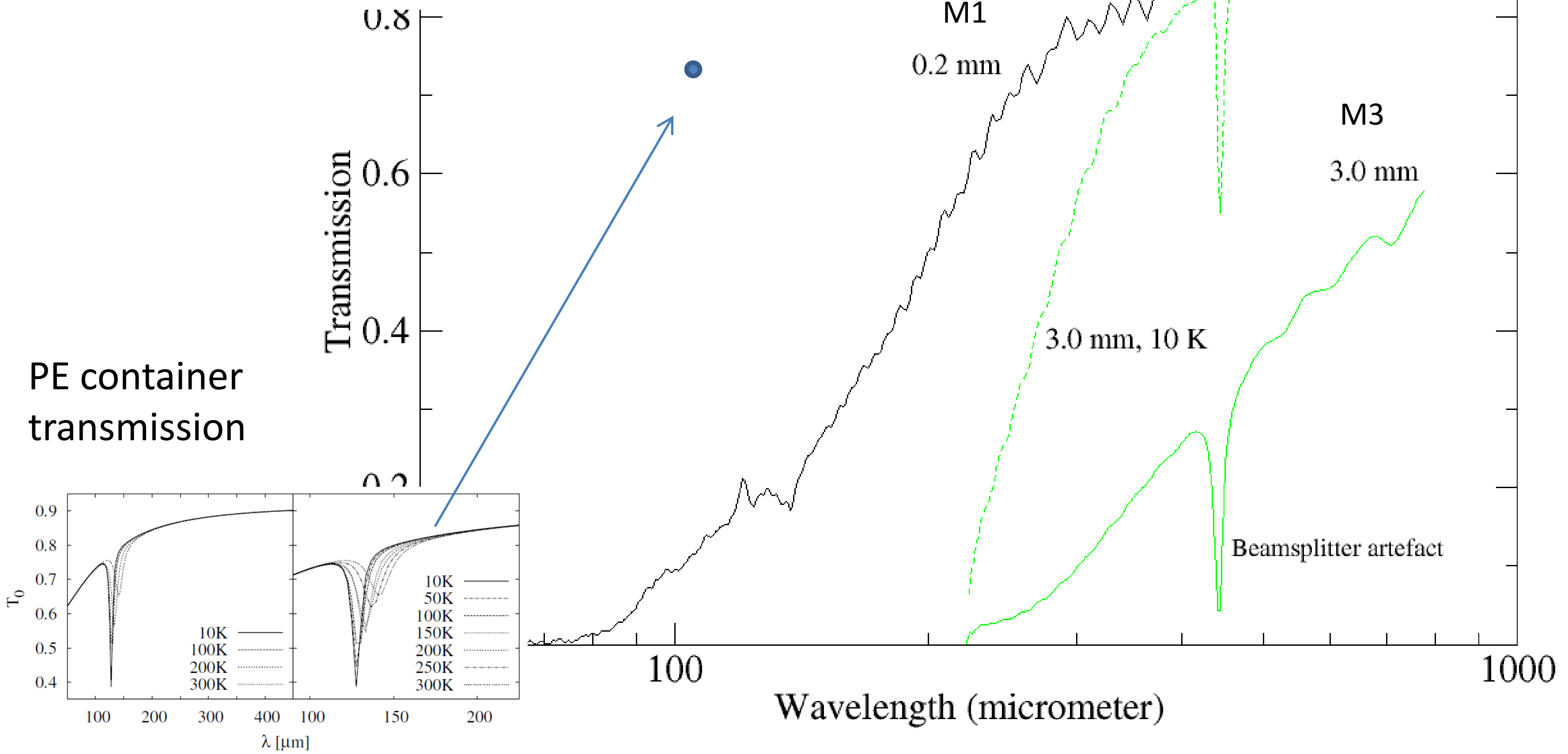
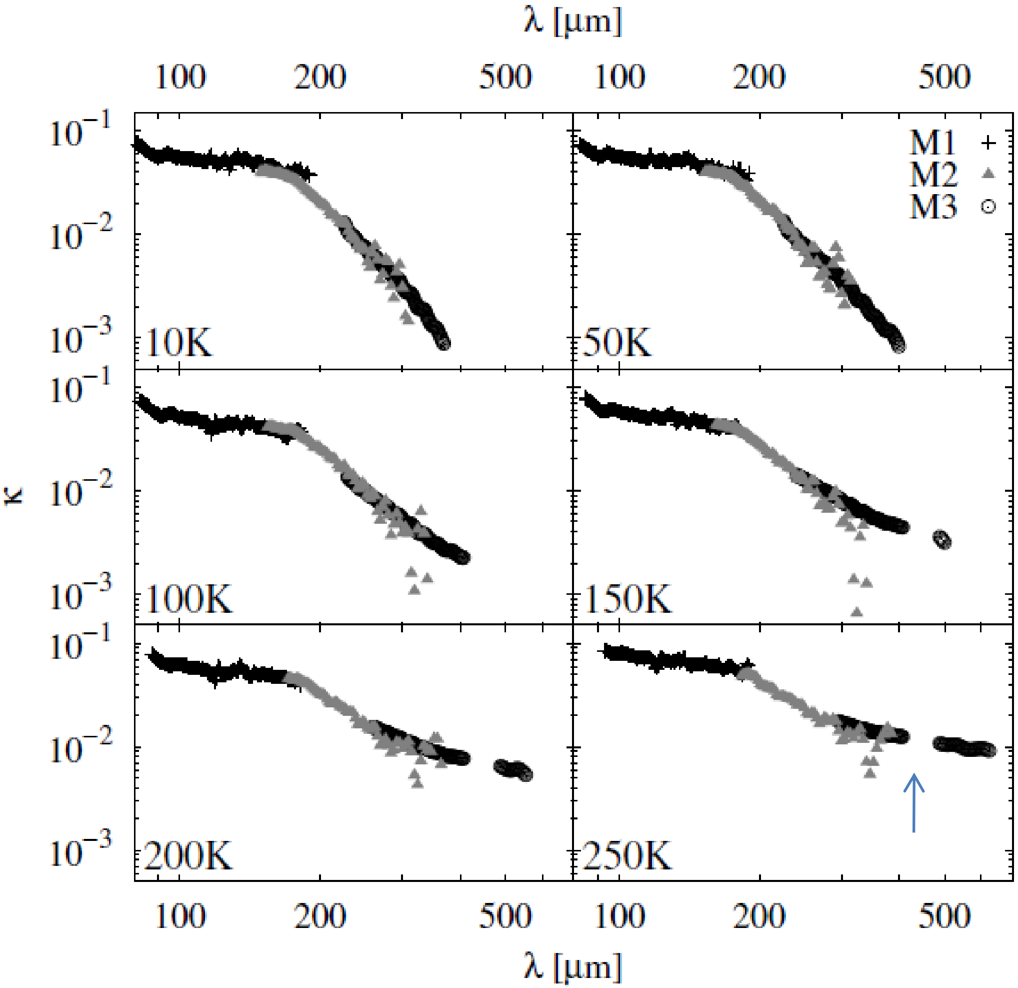


PE container transmission

Calculation of absorption index



$$\kappa = -\ln(T / T_{0,corr}) / (4\pi d_{corr} / \lambda)$$

(Imaginary part of refractive index)

M1, M2 corrected
(fitted) to M3
Same correction for all
Temperatures!

Broad feature at ~180 µm
Previously noted (predicted)
by Bertie & Whalley (1967)
Maximum of TA phonon density

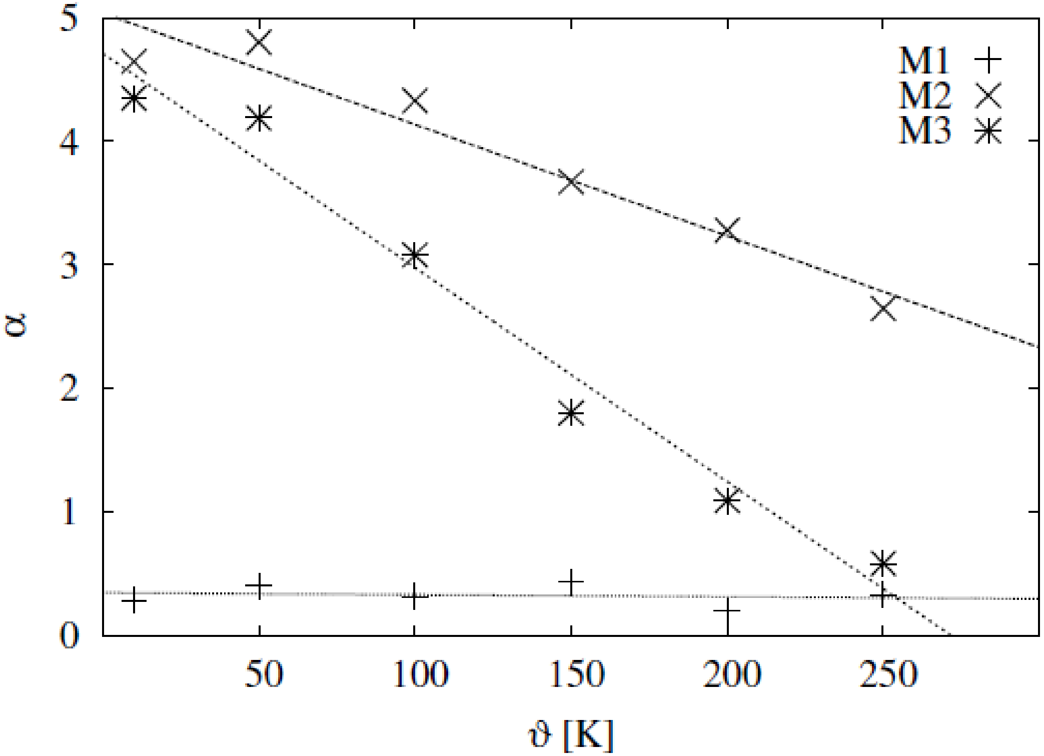
Phonon difference processes
At λ>250µm, proportional T

Construction of user-friendly data

- a model for all temperatures
- using power laws

$$\kappa_i(\varphi_i, \alpha_i) = \varphi_i \times \left(\frac{\lambda}{\lambda_0}\right)^{-\alpha_i}$$

$$\lambda_0 = 200\,\mu m$$



Power-law slopes of κ depending on temperature for the three spectral ranges M1, M2, M3

$$\begin{aligned}\alpha_1 &= const. = 0.35,\\ \alpha_2 &= -0.009 \times \vartheta + 5.0,\\ \alpha_3 &= -0.017 \times \vartheta + 4.7.\end{aligned}$$

Normalization factors

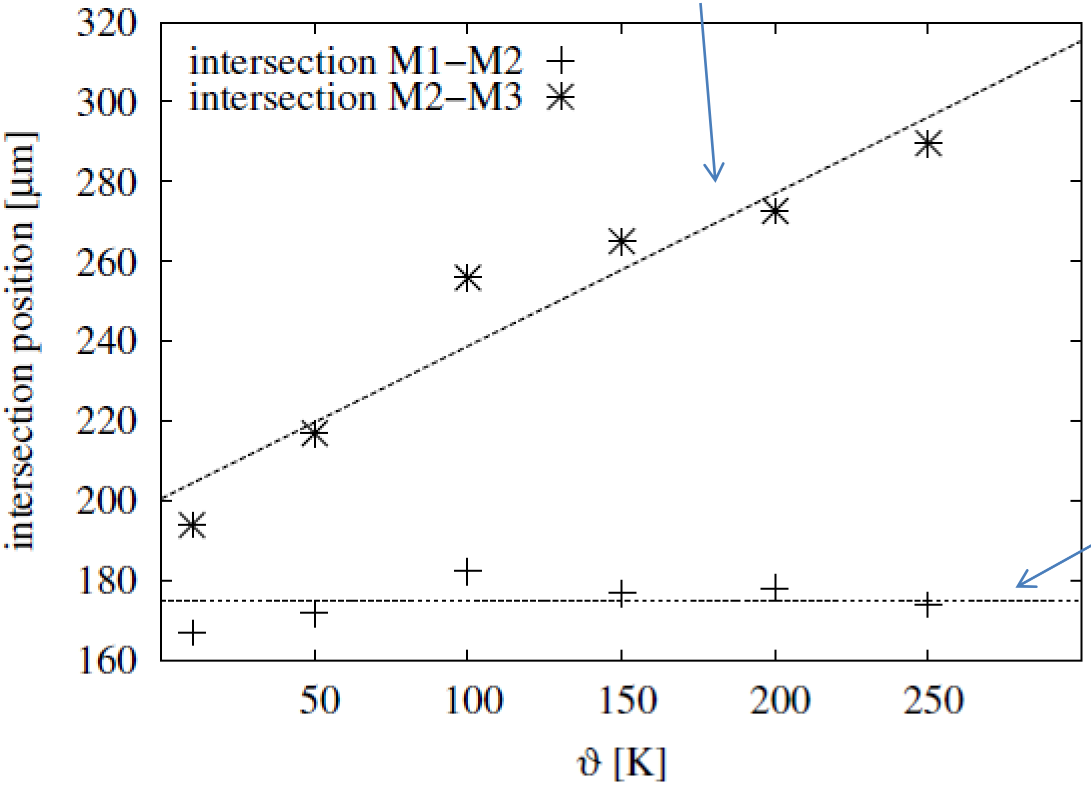
$$\begin{aligned}\varphi_1 &= 0.0188,\\ \varphi_2 &= 0.017 + (9 \times 10^{-5}) \times \vartheta,\\ \varphi_3 &= 0.034 + (8.9 \times 10^{-5}) \times \vartheta.\end{aligned}$$

Construction of user-friendly data

- a model for all temperatures
- using power laws

$$\kappa_i(\varphi_i, \alpha_i) = \varphi_i \times \left(\frac{\lambda}{\lambda_0}\right)^{-\alpha_i}$$

$$\lambda_{\text{intersec. 2-3}} = (0.38 \pm 0.06)\,\mu\text{m}\,\text{K}^{-1} \times \vartheta + (201 \pm 9)\,\mu\text{m}.$$



Intersection wavelengths of the three power laws depending on temperatures

(Feature position)

$$\lambda_{\text{intersec. 1-2}} = (175 \pm 2)\,\mu\text{m}$$

Maximum wavelength

$$\lambda_{\max} = 1.1 \times \vartheta + 341\ \mu\text{m}.$$

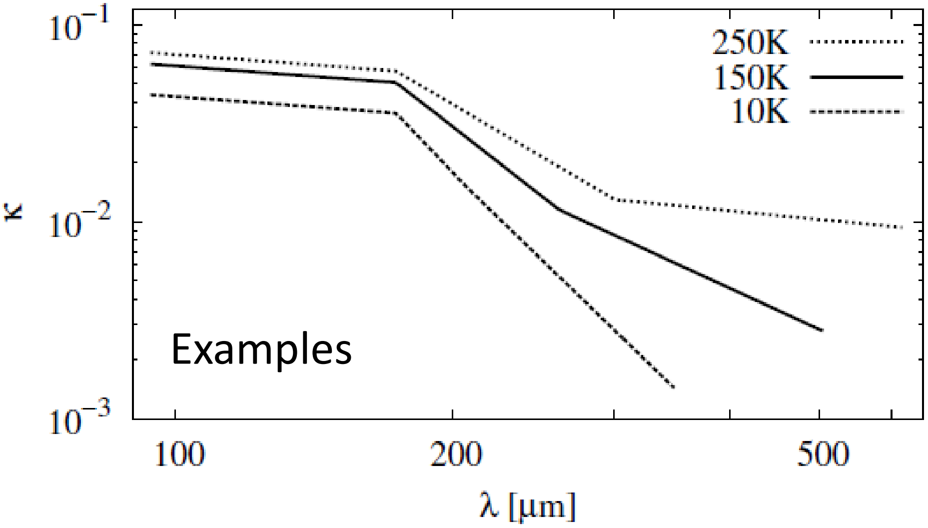
Construction of user-friendly data

- a model for all temperatures

$$\kappa_i(\varphi_i, \alpha_i) = \varphi_i \times \left(\frac{\lambda}{\lambda_0}\right)^{-\alpha_i}$$

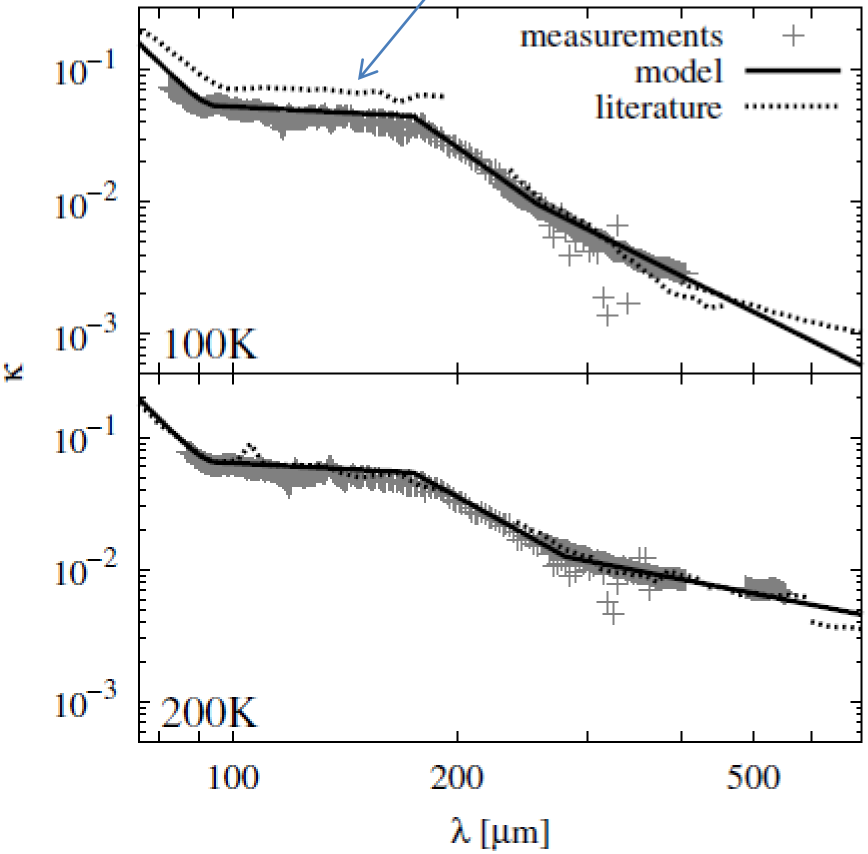
$$\lambda_0 = 200\,\mu m,$$

$$\varphi_i(\vartheta), \alpha_i(\vartheta)$$



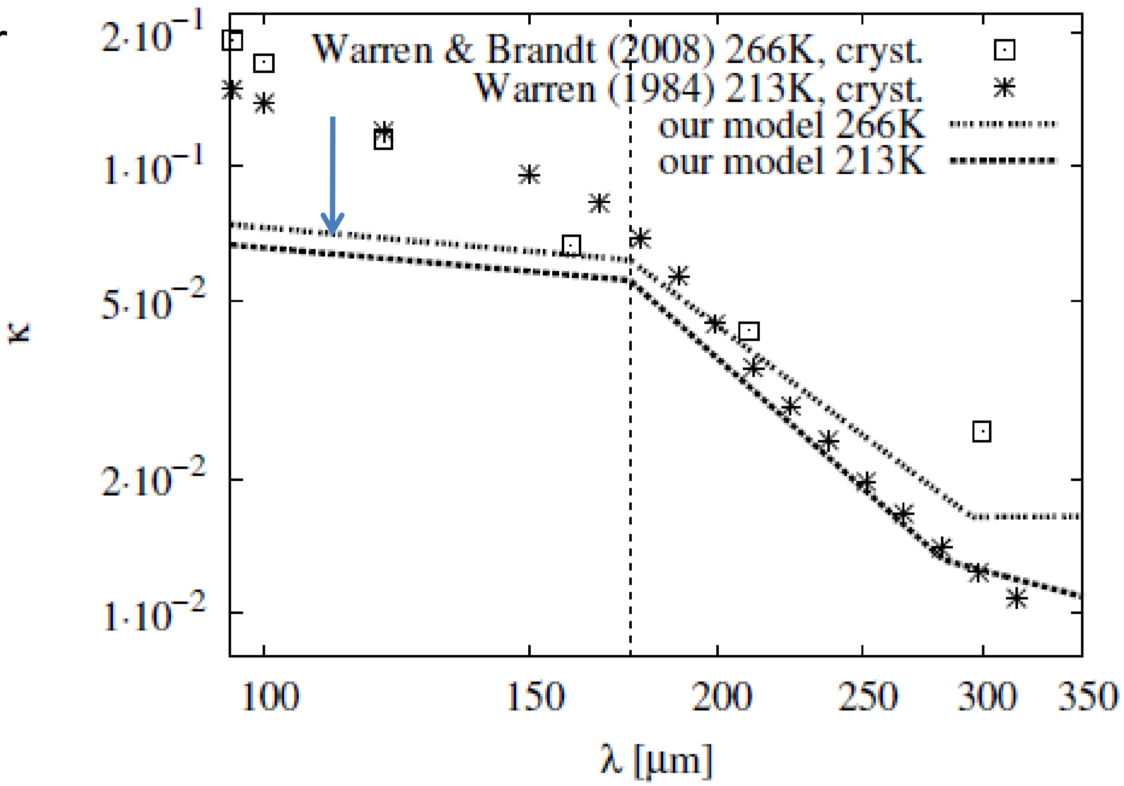
amorphous

Comparison with measurements

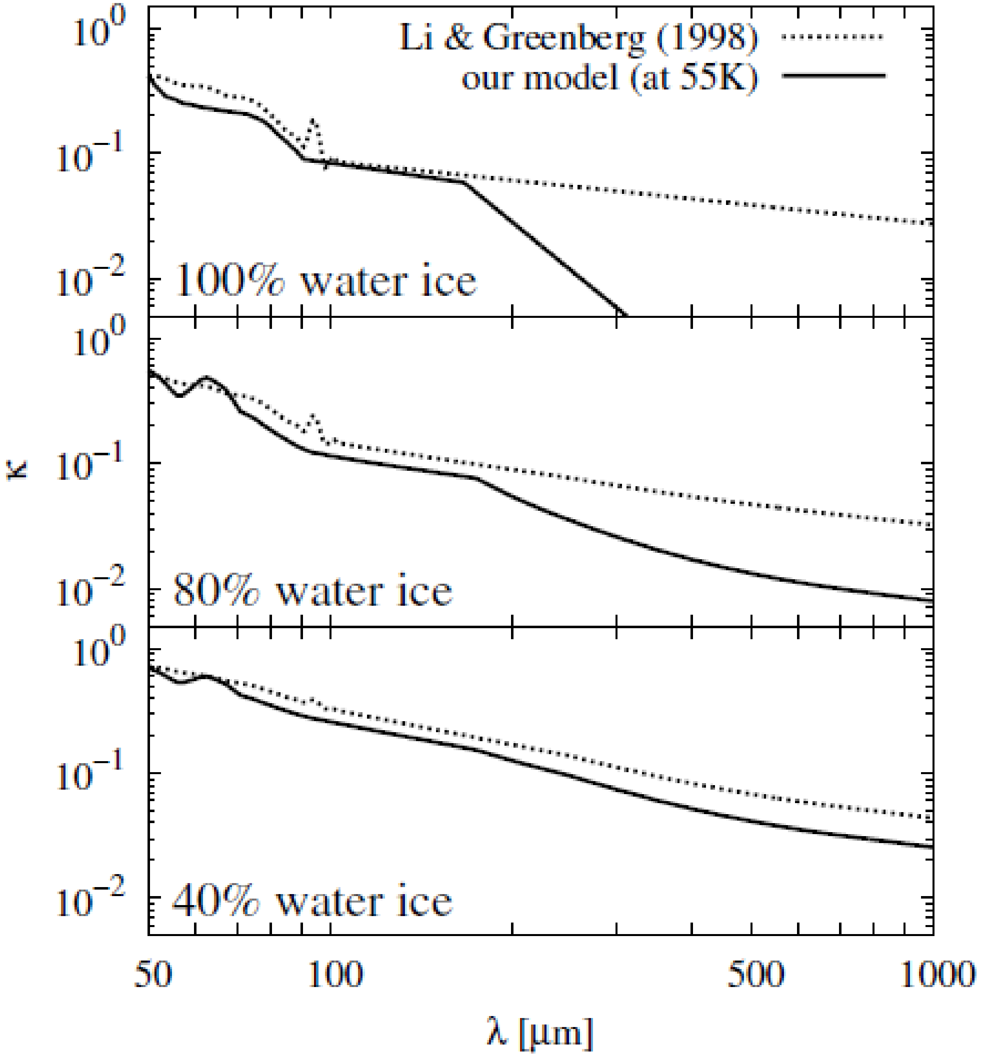


Comparison of data at high T

Warren data higher than ours at >200K (extrapolated from Bertie and Whalley 1967)



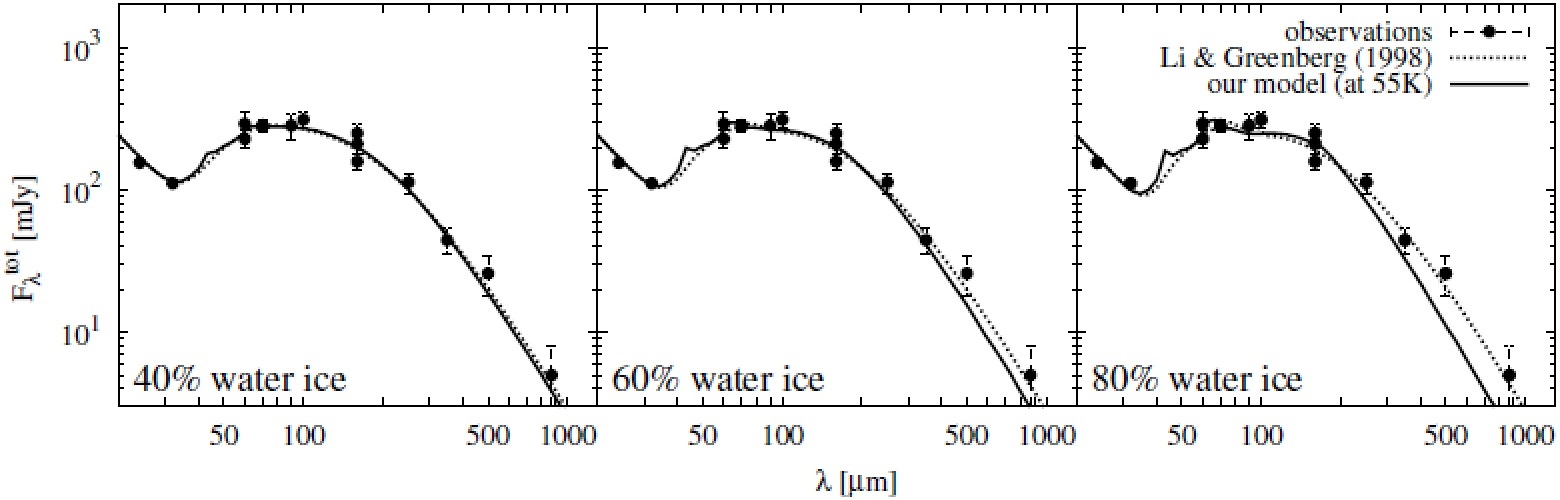
Low T - Mixtures silicate / ice



Is the Li & Greenberg extrapolation appropriate for amorphous ice?

Application to debris disk

SED of HD 207129



At higher ice contents, the model makes a difference.

Conclusions

- Simple T-dependent model of FIR optical constants of crystalline water ice (up to 350-600 μm)

- Broad absorption band at about 175 μm

- Emissivity is lower than that of amorphous silicates

- For **amorphous ice**: no data above λ=200 μm (Curtis et al. 2005 recommended)