Lecture on Cosmic Dust

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Today's Contents:

1) Composition of dust
2) Extinction of stellar lights by dust
3) Thermal radiation from dust

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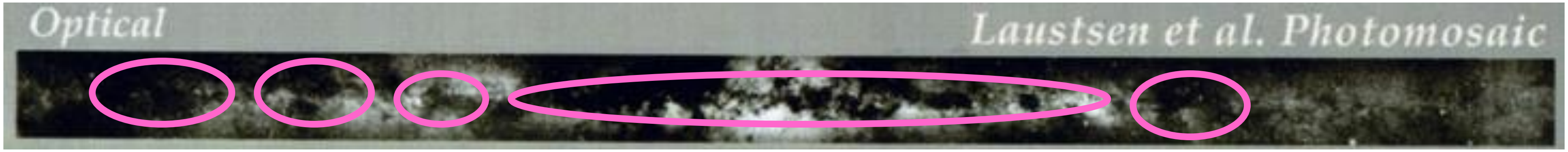
Introduction

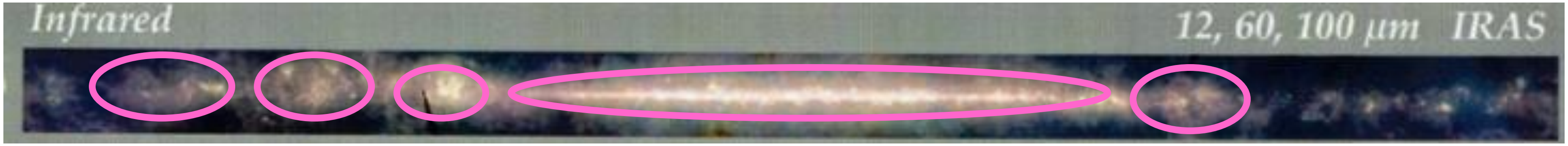
○ **Cosmic dust**: solid particle with size of a few Å to 1 mm

interplanetary dust, interstellar dust, intergalactic dust

Milky Way (optical)



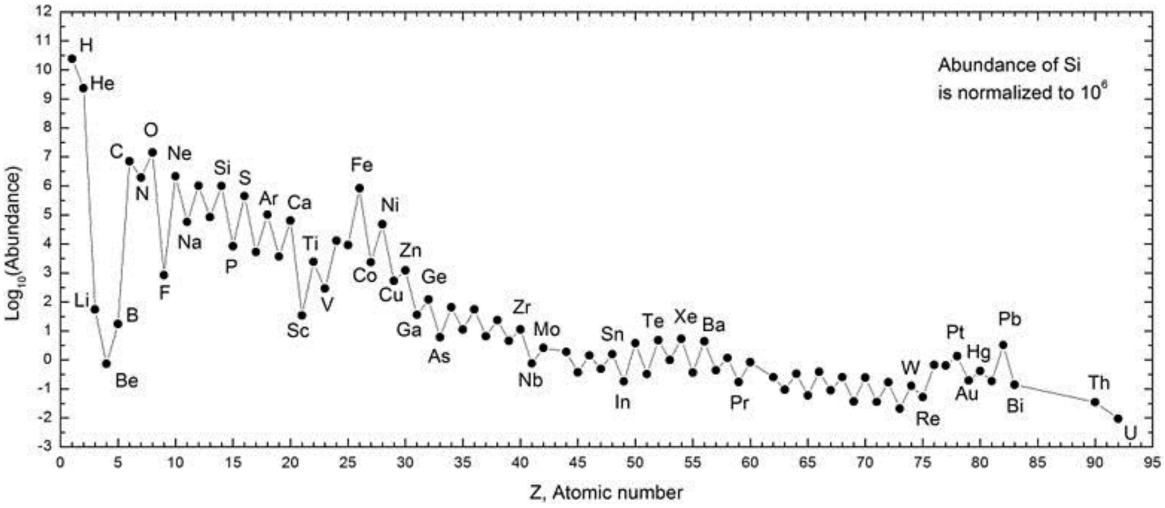
Milky Way (infrared)



Dust grains absorb UV/optical photons and reemit by thermal radiation at IR wavelengths!

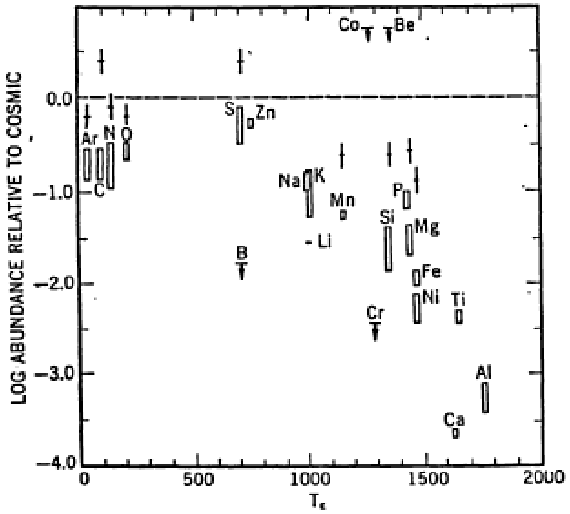
1-1. Hints as to composition of cosmic dust

Dust particles are composed of metals (N > 5)
➔ what are abundances of metals in space?



Solar elemental abundances
(Asplund+2009, ARAA, 47, 481)

Element	Log10(n)	Ratio to H
H	12.00	1.00
He	10.93	8.51x10-2
O	8.69	4.90x10-4
C	8.43	2.69x10-4
Ne	7.93	8.51x10-5
N	7.83	6.76x10-5
Mg	7.60	3.98x10-5
Si	7.51	3.24x10-5
Fe	7.50	3.16x10-5
S	7.12	1.32x10-5



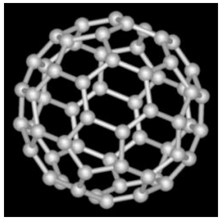
depletion of elements (Sakurai 1993)

More than 90 % of Si, Mg, Fe, Al, and Ca are depleted in the ISM

1-2. Expected composition of dust (1)

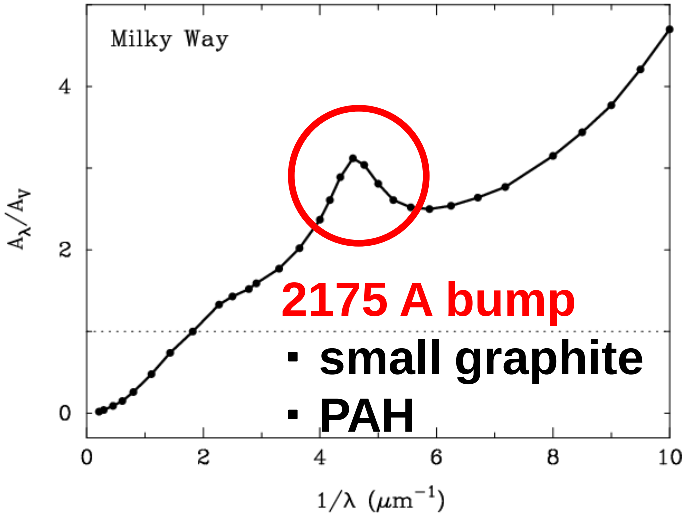
○ **Major candidates of cosmic dust**

- **carbonaceous grains (C-based)**
  - **graphite**
  - **amorphous carbon**
  - **diamond, C_{60} (fullerene)**



- **silicate grains (SiO_4^{2-}-based)**
  - **$Mg_xFe_{(1-x)}SiO_3$ (pyroxene):**
    - **$MgSiO_3$ (enstatite)**
    - **$FeSiO_3$ (ferrosilite)**
  - **$Mg_{2x}Fe_{2(1-x)}SiO_4$ (olivine):**
    - **Mg_2SiO_4 (forsterite)**
    - **Fe_2SiO_4 (fayalite)**
  - **SiO_2 (silica, quartz)**
  - **astronomical silicate ($MgFeSiO_4$)**

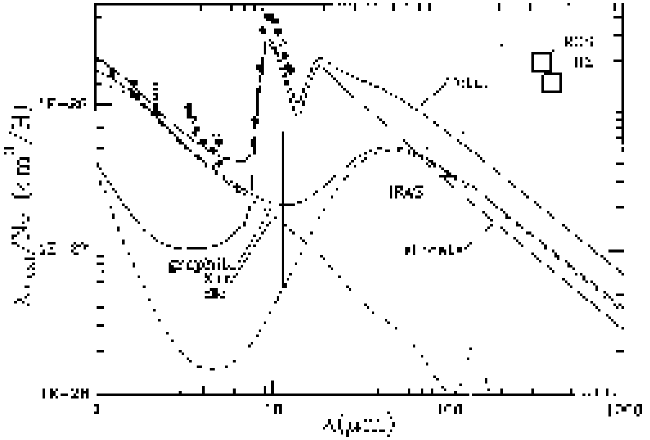
extinction curve



2175 A bump

- **small graphite**
- **PAH**

IR spectral feature



1-3. Expected composition of dust (2)

○ Minor candidates of dust composition

・ Iron-bearing dust (Fe-based) ??

Fe (iron), FeO (wustite), Fe_2O_3 (hematite), Fe_3O_4 (magnetite), FeS (troilite), FeS_2 (pyrite)

・ Other carbides and oxides

SiC (silicon carbide), Al_2O_3 (corundum), MgO, TiC, …

・ Ices (appeared in MCs and YSOs)

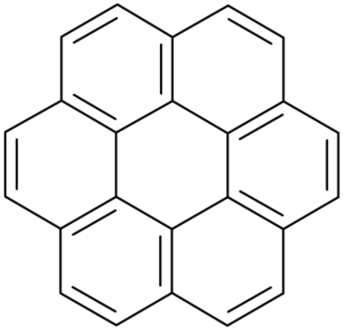
H_2O, CO, CO_2, NH_3, CH_4, CH_3OH, HCN, C_2H_2, …

・ large molecules

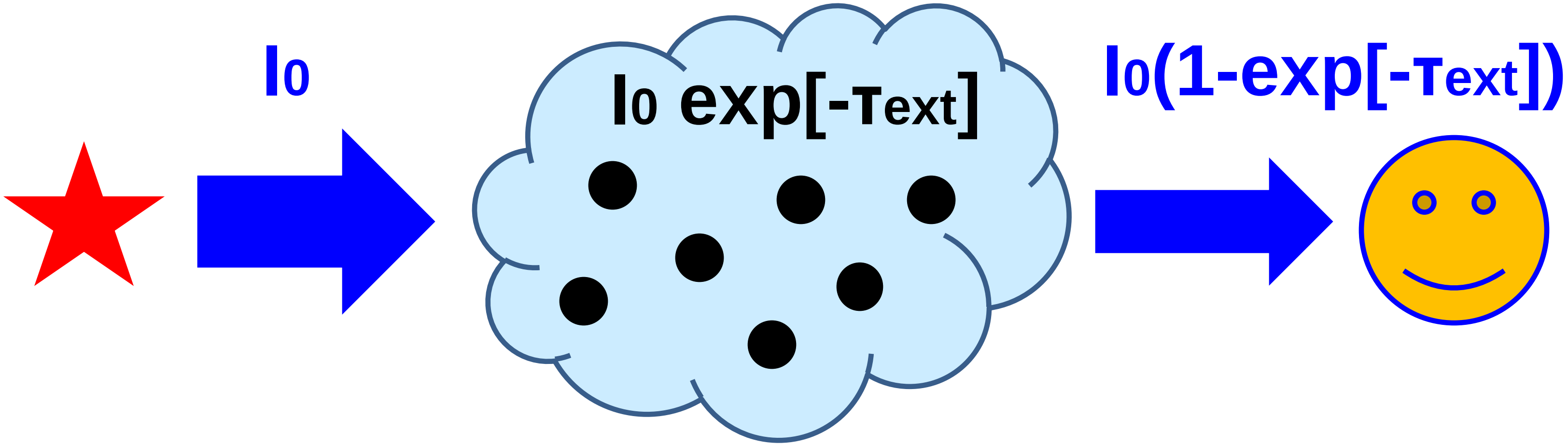
PAH (Polycyclic Aromatic Hydrocarbon):

$C_{24}H_{12}$ (coronene), etc.

HAC (Hydrogenated Amorphous Carbon)



2-1. Extinction by dust



○ Extinction = absorption + scattering

albedo = scattering / extinction : $w = \tau_{sca} / \tau_{ext}$

- **extinction curve**

  optically thin, slab-like geometry

  bright point source (OB stars, QSOs, GRB afterglow)

- **attenuation curve**

  effective extinction including effects of radiative transfer (Calzetti law for galaxies, Calzetti+1994, 2000)

2-2. Optical depth by dust

○ Optical depth produced by dust with a radius “a”

$$\tau_{ext}(a,\lambda) = \int dr\ n_{dust}(a,r)\ C_{ext}(a,\lambda)$$

$C_{ext}(a,\lambda)$: cross section of dust extinction

$$\tau_{ext}(a,\lambda) = \int dr\ n_{dust}(a,r)\ \pi a^2\ Q_{ext}(a,\lambda)$$

$Q_{ext}(a,\lambda) = C_{ext}(a,\lambda)\ /\ \pi a^2$: extinction coefficient

$Q_{ext}(a,\lambda) = Q_{abs}(a.\lambda) + Q_{sca}(a,\lambda)$, $w = Q_{sca}(a,\lambda)\ /\ Q_{ext}(a,\lambda)$

○ Total optical depth produced by dust

$$\tau_{ext,\lambda} = \int da \int dr\ f_{dust}(a,r)\ \pi a^2\ Q_{ext}(a,\lambda)$$

$f_{dust}(a) = dn_{dust}(a)/da$: size distribution of dust
(= number density of dust with radii between a and a+da)

$$A_\lambda = -2.5\ \log_{10}(\exp[-\tau_{ext,\lambda}]) = 1.068\ \tau_{ext,\lambda}$$

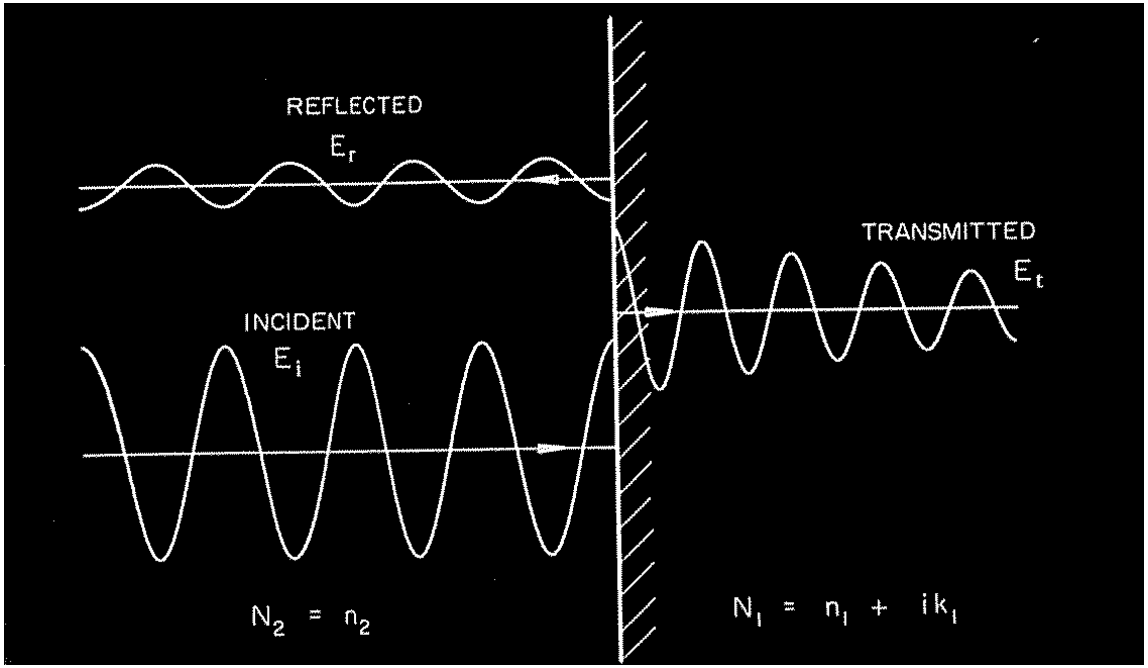
2-3. Evaluation of Q factors

How are Q-factors determined?

➔ using the Mie (scattering) theory

○ **Mie solution** (Bohren & Huffmann 1983)

describes the scattering of electromagnetic radiation by a sphere (solving Maxwell equations)



refractive index

$m(\lambda) = n(\lambda) + i\,k(\lambda)$

n, k: optical constant

dielectric permeability

$\varepsilon = \varepsilon_1 + i\,\varepsilon_2$

$\varepsilon_1 = n^2 - k^2$

$\varepsilon_2 = 2nk$

2-4. Behaviors of Q factors

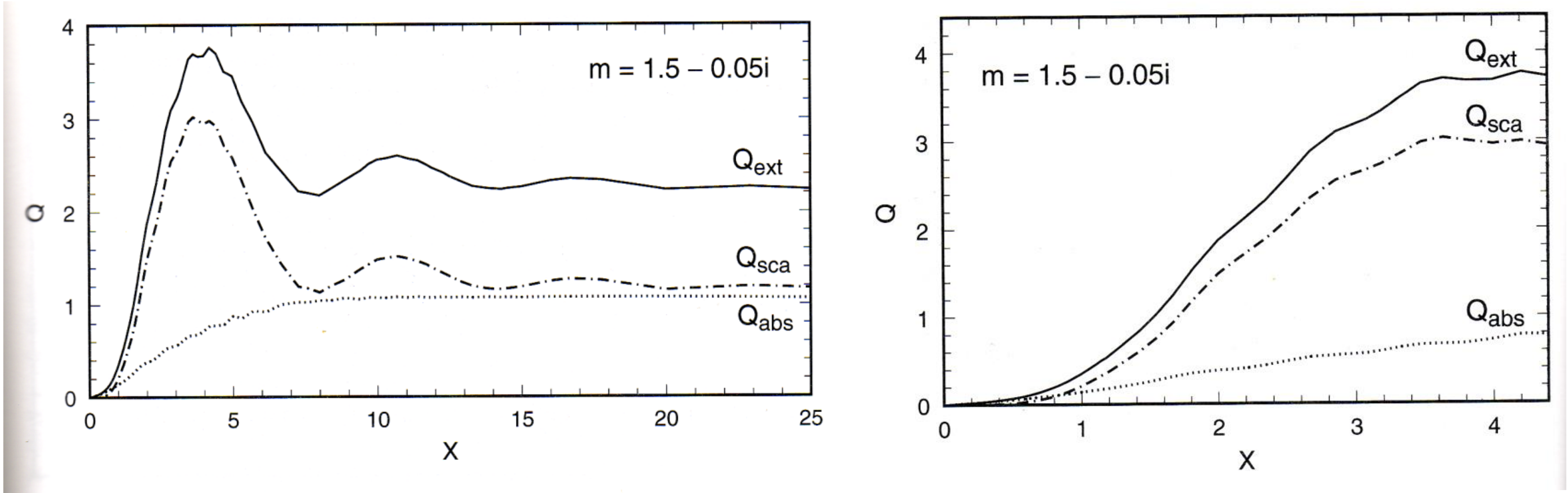


Figure 3.1. Results of Mie theory calculations for spherical grains of refractive index $m = 1.5 - 0.05i$. Efficiency factors Q_{ext}, Q_{sca} and Q_{abs} are plotted against the dimensionless size parameter $X = 2\pi a/\lambda$.

size parameter : $x = 2\pi a / \lambda$

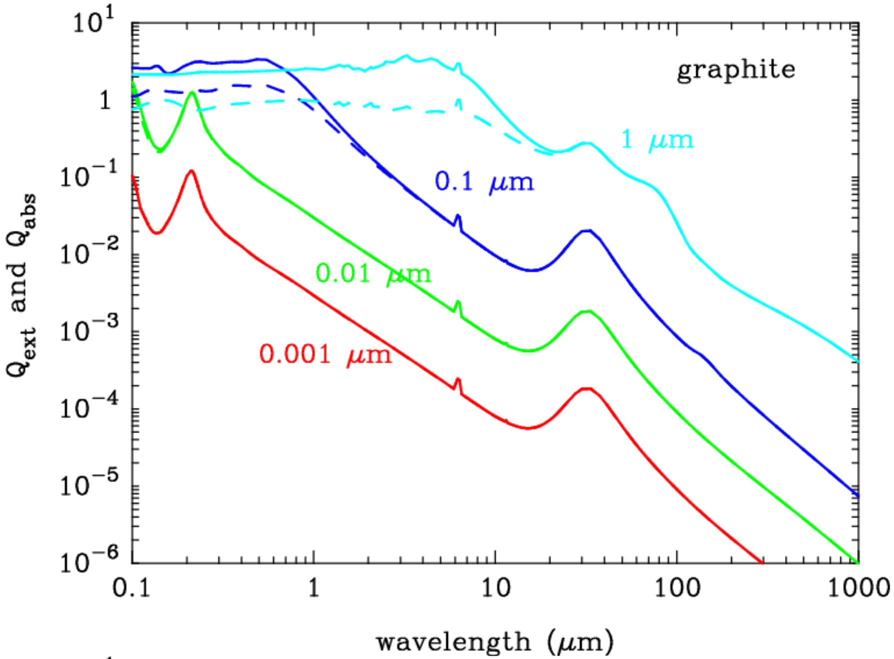
- $x \sim 3\text{-}4$ ($a \sim \lambda$) ➔ Q_{sca} has a peak with $Q_{sca} > \sim 2$
- $x \gg 1$ ($a \gg \lambda$) ➔ $Q_{ext} = Q_{sca} + Q_{abs} \sim 2$
- $x \ll 1$ ($a \ll \lambda$, Rayleigh limit)

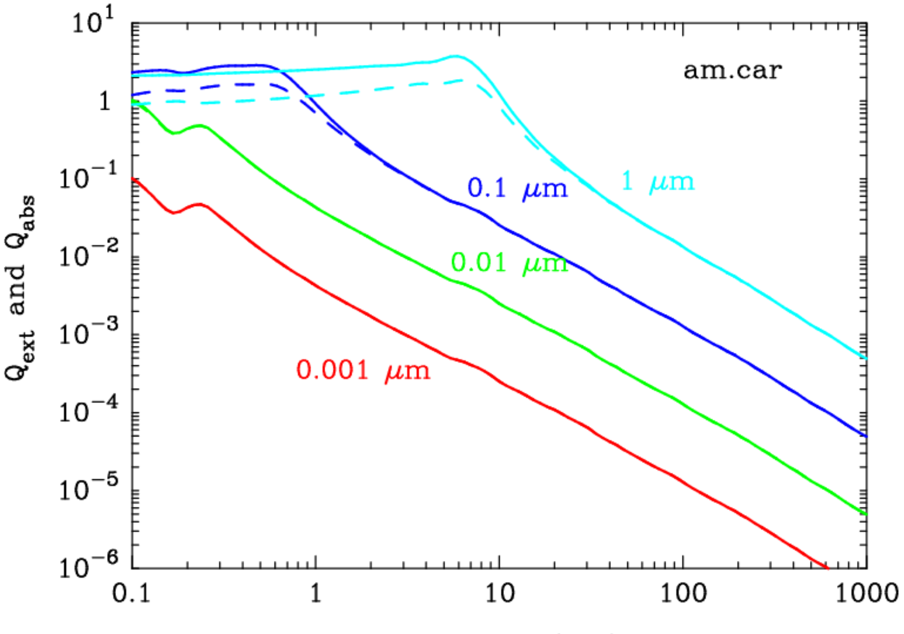
➔ $Q_{sca} \propto x^4 \propto a^4$

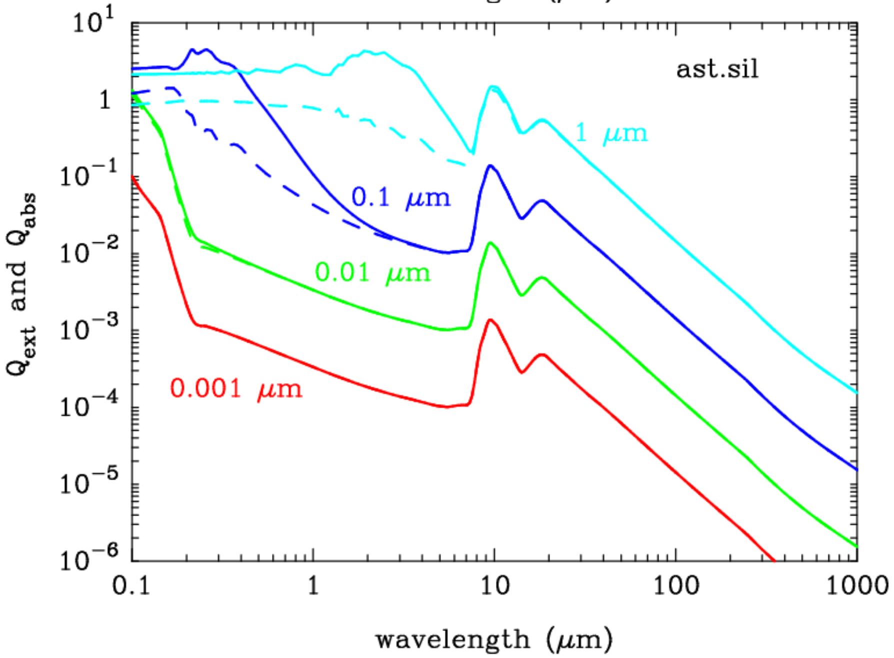
$Q_{abs} \propto x \propto a$

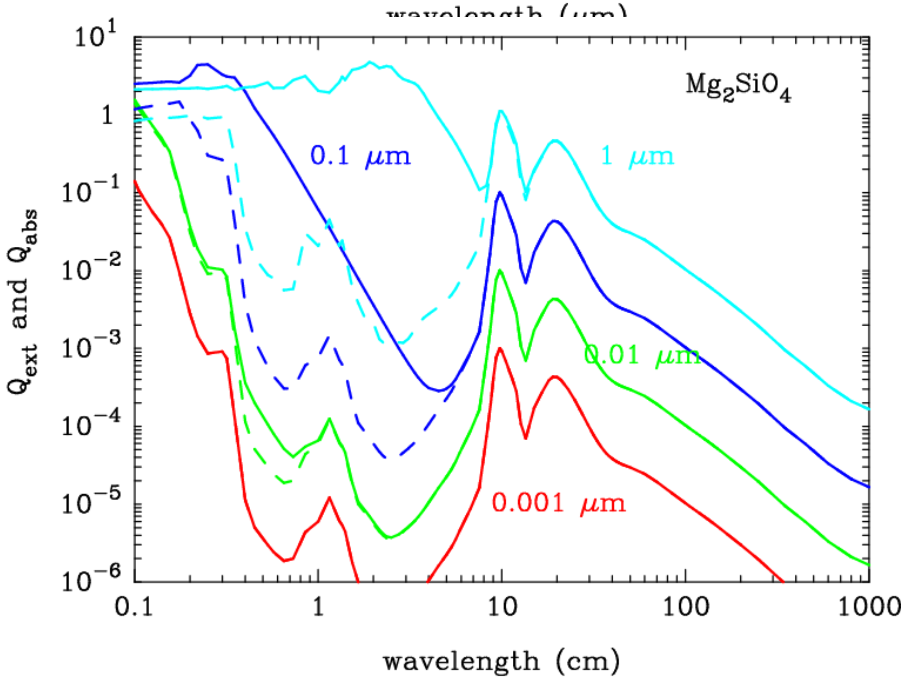
➔ $Q_{ext} = Q_{abs} \propto a$

2-5. Q factors as a function of wavelengths

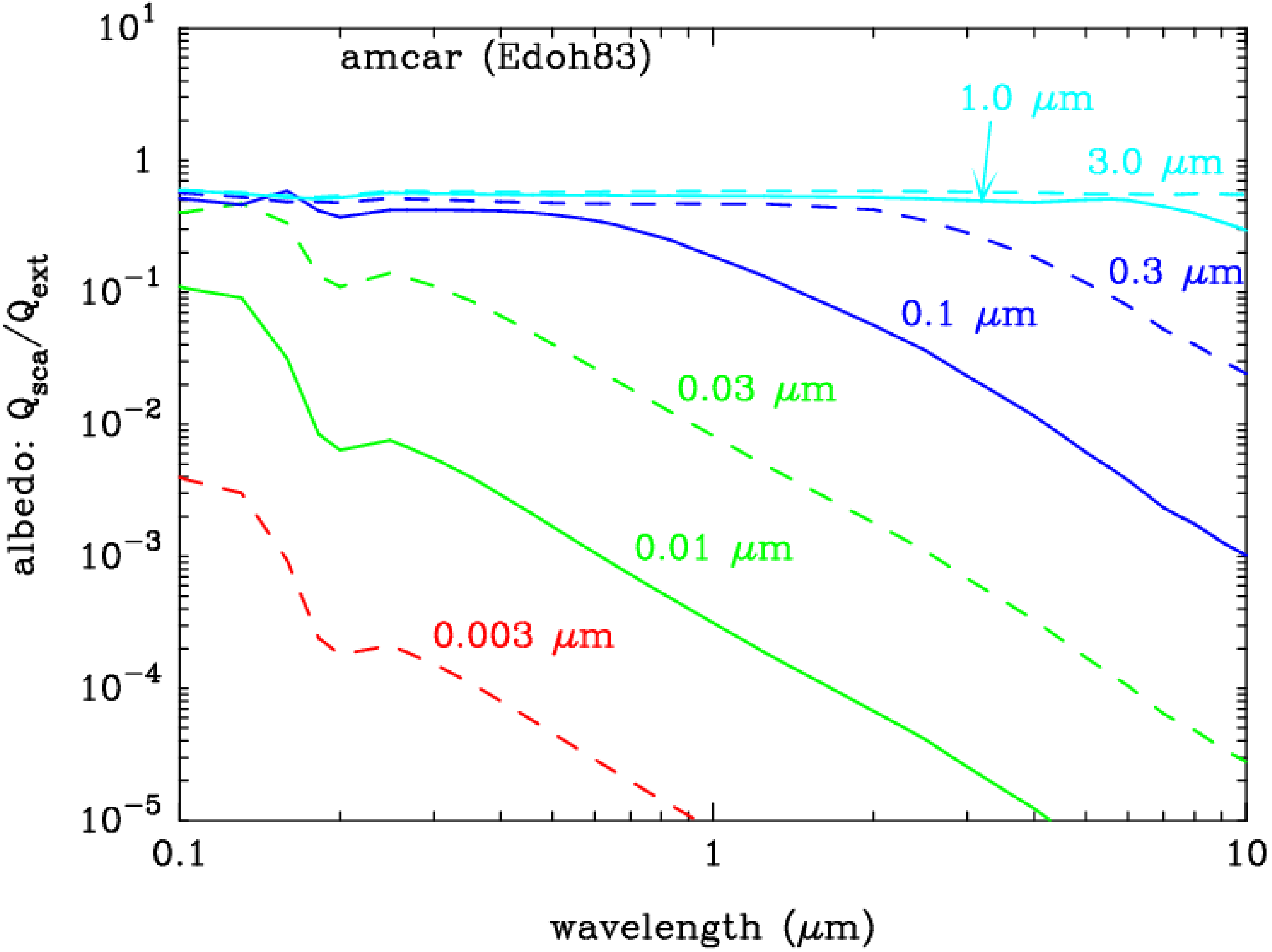








2-6. Dependence of albedo on grain radius

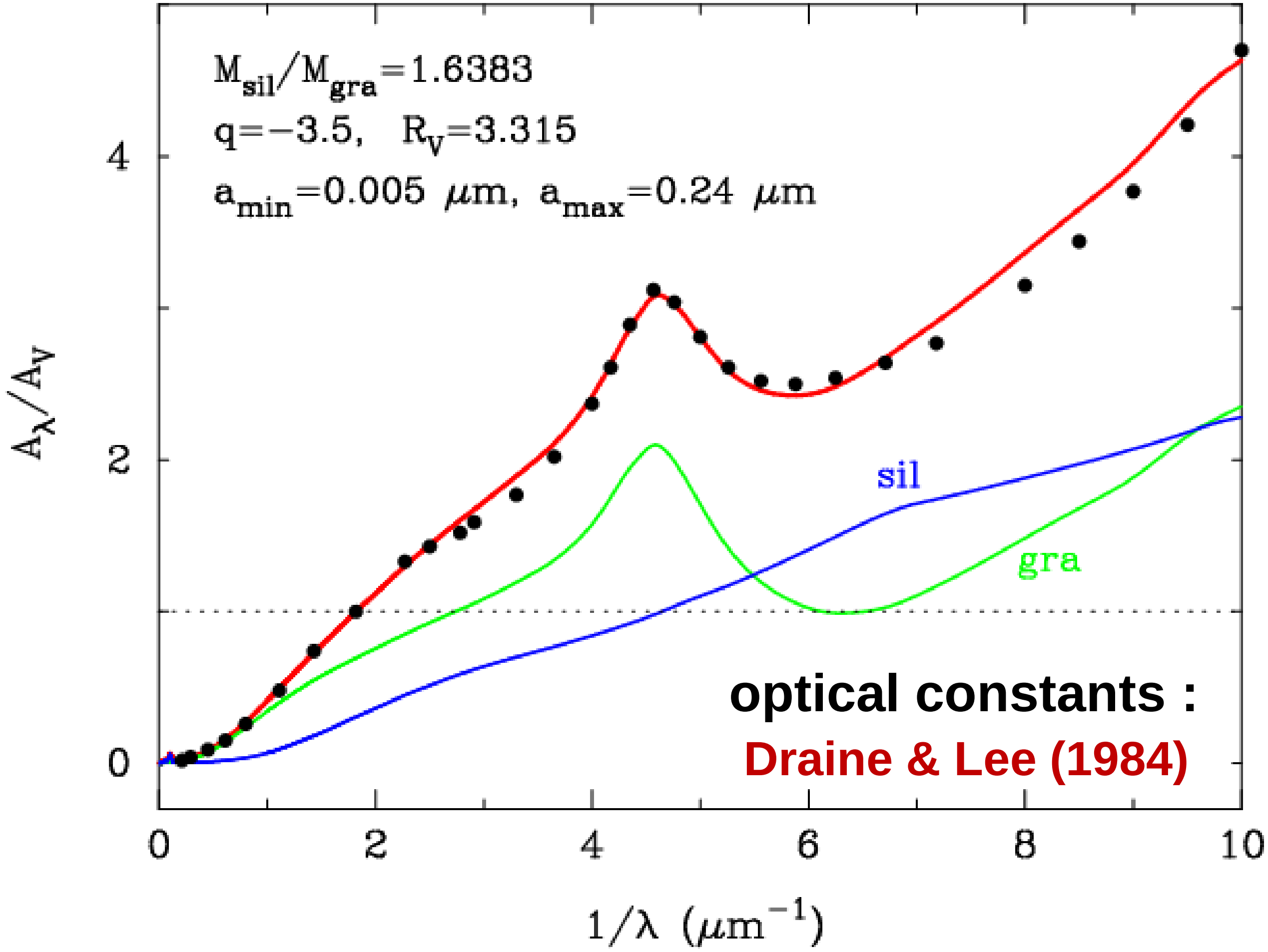


2-7. Classical interstellar dust model in MW

○ **MRN dust model (Mathis, Rumpl, & Nordsieck 1977)**

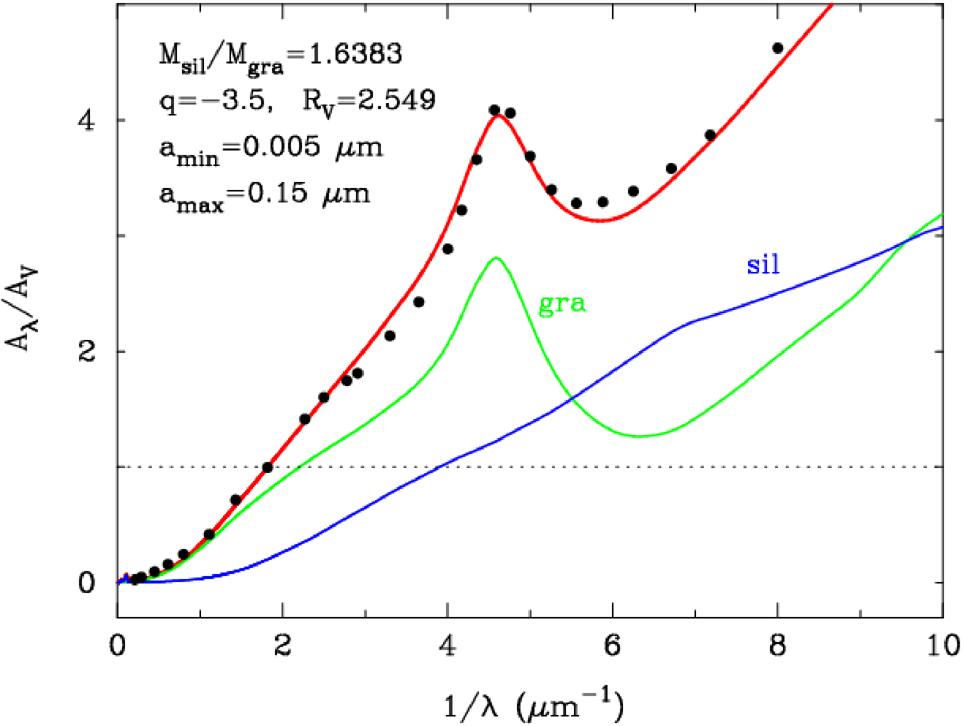
- **dust composition : silicate ($MgFeSiO_4$) & graphite (C)**
- **size distribution : power-law distribution**

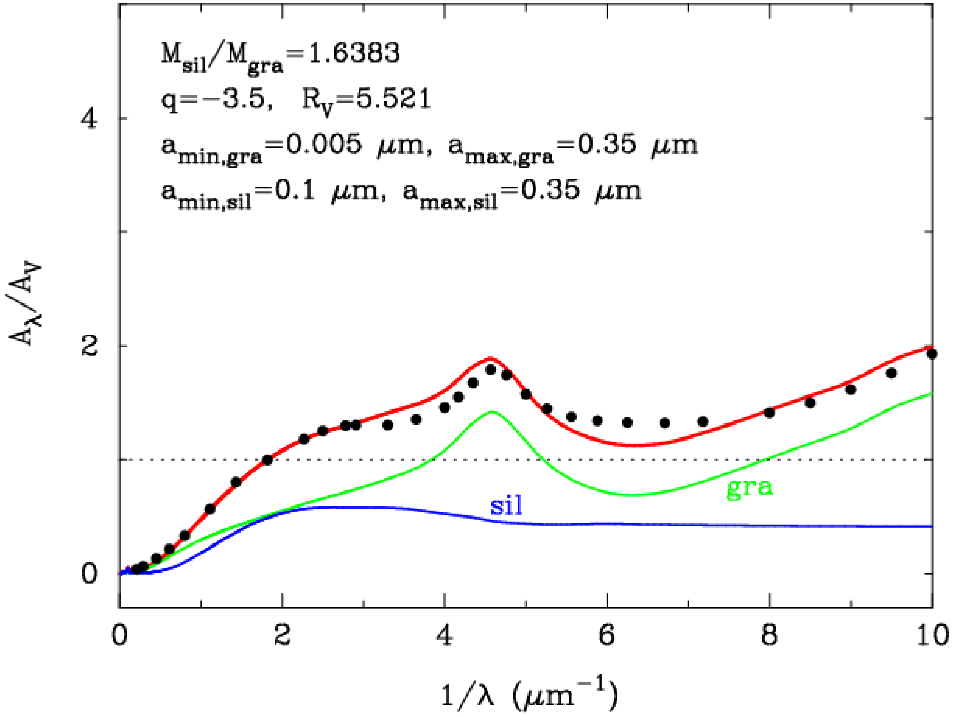
$n(a) \propto a^{-q}$ with q=3.5, $0.005\ \mu m \le a \le 0.25\ \mu m$



optical constants : Draine & Lee (1984)

2-8. Dependence of extinction on grain size

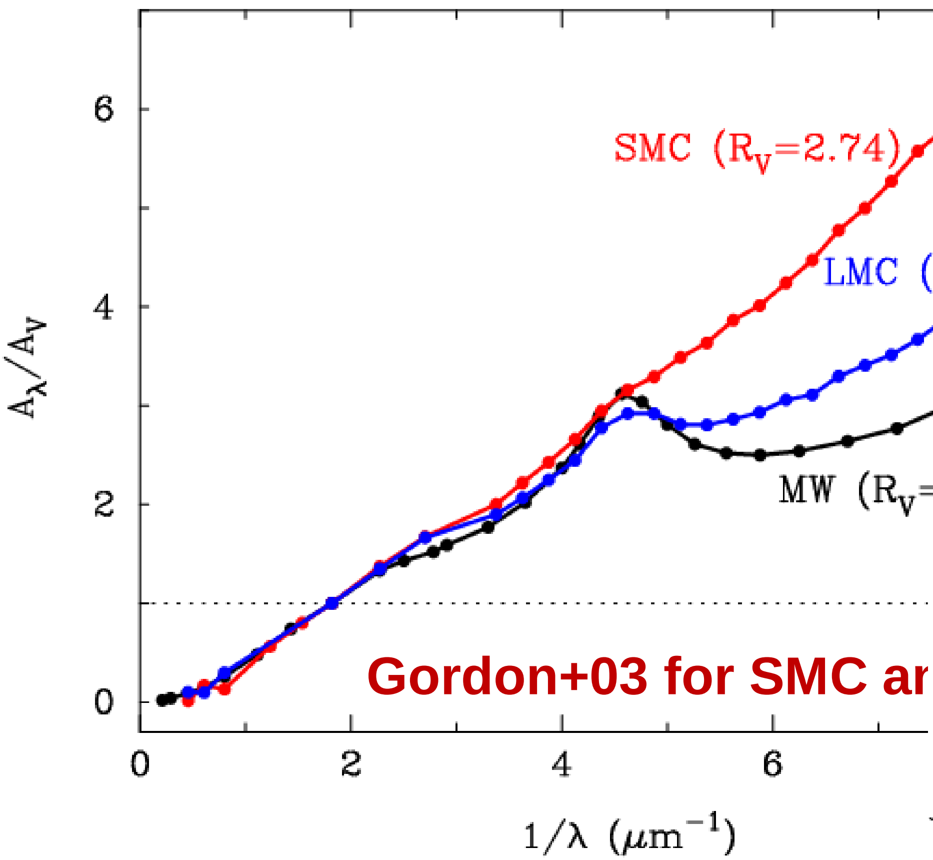




○ Rv provides a rough estimate of grain size

- smaller Rv ➔ steeper curve ➔ smaller grain radius
- larger Rv ➔ flatter curve ➔ larger grain radius

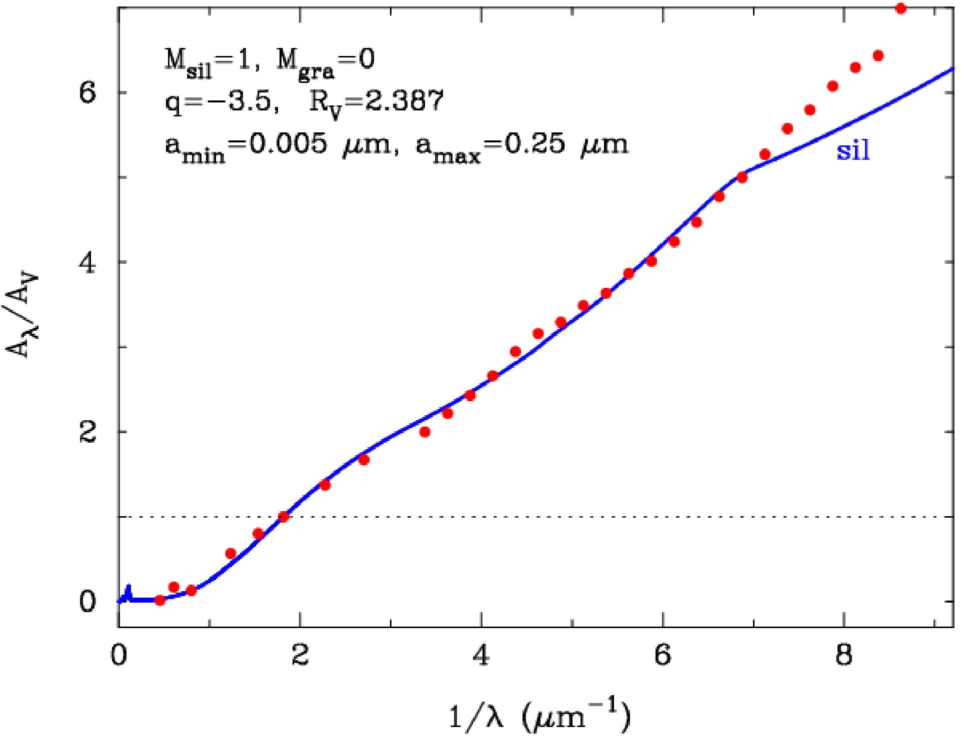
2-9. Extinction curves in Magellanic Clouds



Gordon+03 for SMC ar

no 2175 A bump
steep far-UV rise

SMC extinction curve can be explained by the MRN model without graphite (Pei 1992)



○ SMC extinction curve

- implying different properti
- being used as an ideal ana

cf. extinction curves of red

3-1. Thermal emission from dust grains

○ Luminosity density emitted by dust grains

$$L_\lambda(a) = 4\, N_{\mathrm{dust}}(a)\, C_{\mathrm{emi}}(a,\lambda)\, \pi B_\lambda(T_{\mathrm{dust}}[a])$$

$$= 4\pi a^2\, N_{\mathrm{dust}}(a)\, Q_{\mathrm{abs}}(a,\lambda)\, \pi B_\lambda(T_{\mathrm{dust}}[a])$$

$C_{\mathrm{emi}}(a,\lambda) = \pi a^2 Q_{\mathrm{abs}}(a,\lambda)$

Kirchhoff law: $Q_{\mathrm{emi}}(a,\lambda) = Q_{\mathrm{abs}}(a,\lambda)$

○ at IR wavelengths ($Q_{\mathrm{abs}} \propto a$ for $a \ll \lambda$)

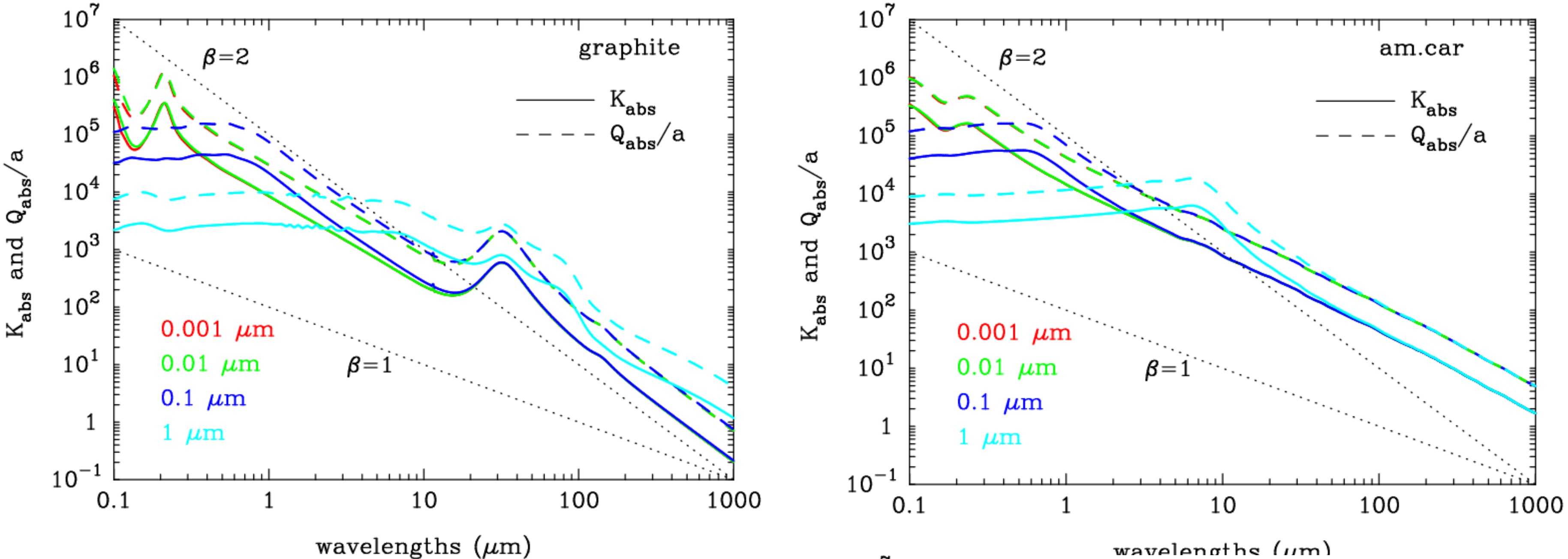
$$L_\lambda(a) = 4\, N_{\mathrm{dust}}(a)\, (4\pi\rho a^3/3)\, (3Q_{\mathrm{abs}}[a,\lambda]/4\rho a)\, \pi B_\lambda(T_{\mathrm{dust}}[a])$$

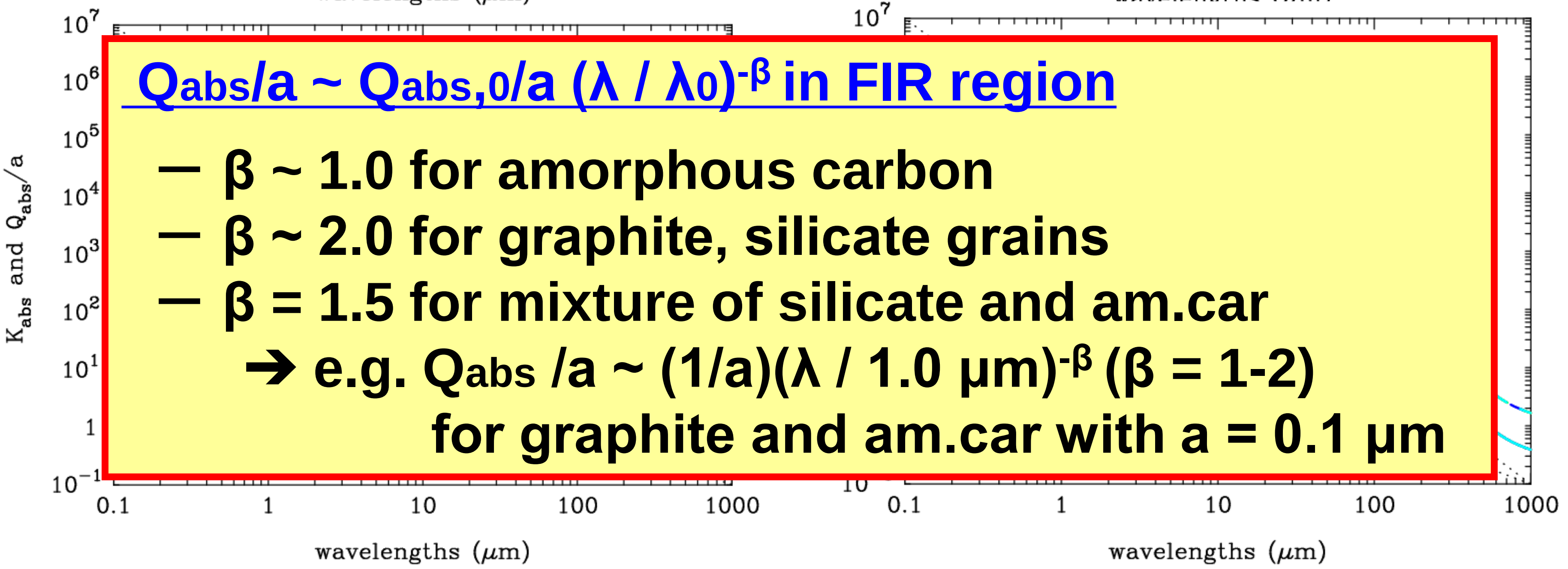
$$= 4\, M_{\mathrm{dust}}\, \kappa_{\mathrm{abs}}(\lambda)\, \pi B_\lambda(T_{\mathrm{dust}}[a])$$

$\kappa_{\mathrm{abs}}(a,\lambda) = 3Q_{\mathrm{abs}}/4\rho a$: mass absorption coefficient

➔ IR emission is derived given M_{dust}, κ_{abs}, and T_{dust}

3-2. Dependence of Q/a on wavelengths



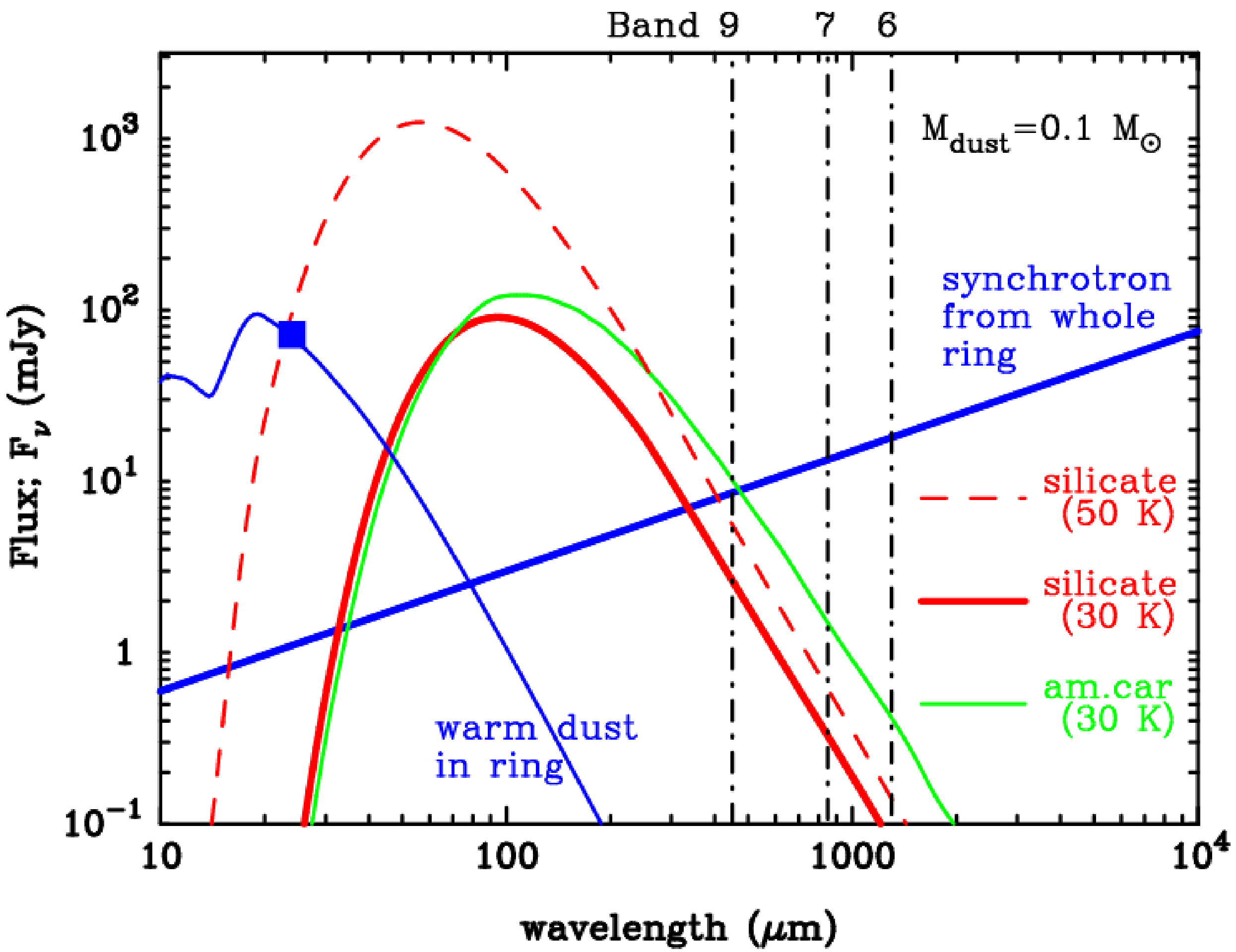


$Q_{abs}/a \sim Q_{abs,0}/a\ (\lambda / \lambda_0)^{-\beta}$ in FIR region

- **β ~ 1.0 for amorphous carbon**
- **β ~ 2.0 for graphite, silicate grains**
- **β = 1.5 for mixture of silicate and am.car**

➔ e.g. $Q_{abs}/a \sim (1/a)(\lambda / 1.0\ \mu m)^{-\beta}$ (β = 1-2)
for graphite and am.car with a = 0.1 μm

3-3. Example of thermal emission from dust

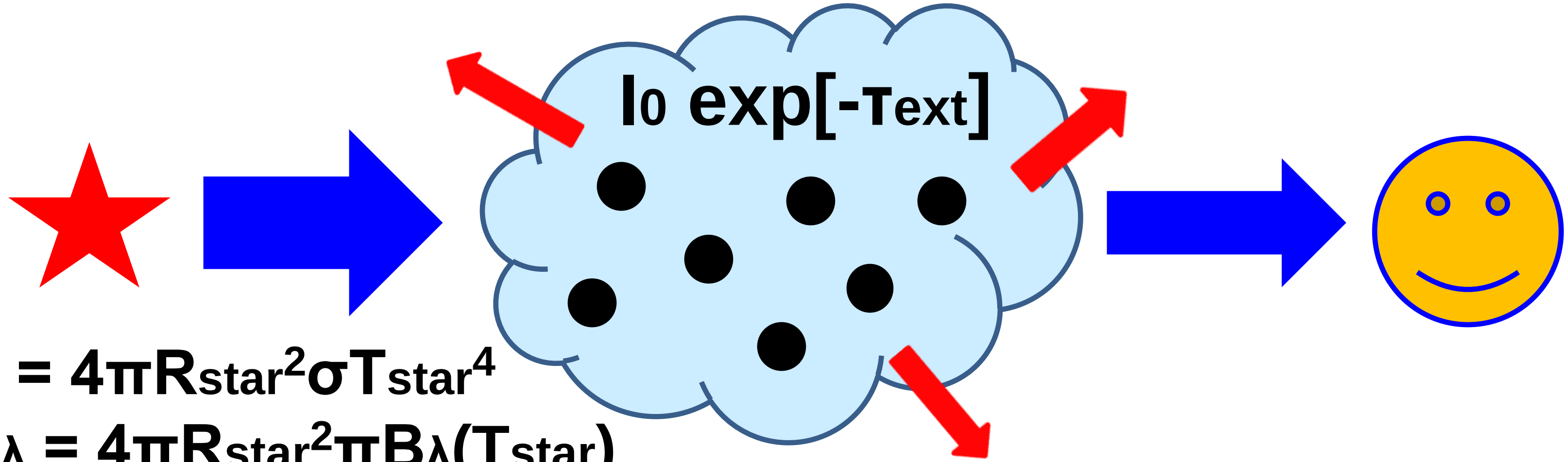


○ at IR wavelengths ($Q_{abs} \propto a$ for $a \ll \lambda$)

$$L_\lambda(a) = 4\, M_{dust}\, \kappa_{abs}(\lambda)\, \pi B_\lambda(T_{dust}[a])$$

➔ IR emission is derived given M_{dust}, κ_{abs}, and T_{dust}

3-4. Reemission of stellar light by dust



$L = 4\pi R_{star}^2 \sigma T_{star}^4$

$L_\lambda = 4\pi R_{star}^2 \pi B_\lambda(T_{star})$

How is dust temperature determined?

➔ approaching from conservation of energy

○ energy reemitted by dust = energy absorbed by dust

time during which dust is thermalized

extremely short < 10^{-5} s

3-5. Luminosity of dust emission

○ Luminosity emitted by a dust grain

$$L_{emi} = \int d\lambda\, 4\pi a^2\, Q_{abs}(a,\lambda)\, \pi B_\lambda(T_{dust}[a])$$

$$= 4\pi a^2\, \sigma T_{dust}^4 \langle Q_{abs}(T_{dust})\rangle$$

$\langle Q_{abs}(T_{dust})\rangle$: plank-mean absorption coefficient

$$= \int Q_{abs}(a,\lambda)\, \pi B_\lambda(T_{dust}[a])\, d\lambda \;\; / \;\; \int \pi B_\lambda(T_{dust}[a])\, d\lambda$$

○ Stellar luminosity absorbed by a dust grain

$$L_{abs} = \int d\lambda\, \pi a^2\, Q_{abs}(a,\lambda)\, F_\lambda(T_{star})$$

$$= (R_{star}/D)^2\, \pi a^2\, \sigma T_{star}^4 \langle Q_{abs}(T_{star})\rangle$$

$$= L_{star}/4\pi D^2\, \pi a^2 \langle Q_{abs}(T_{star})\rangle$$

a star is assumed to be a blackbody:

$$F_\lambda(T_{star}) = L_\lambda/4\pi D^2 = (R_{star}/D)^2\, \pi B_\lambda(T_{star})$$

3-6. Temperature of dust grains (1)

○ $L_{abs} = L_{emi}$ (dust is assumed to be in thermal equilibrium)

$$(R_{star}/D)^2\ T_{star}^4 \langle Q_{abs}(T_{star})\rangle = 4T_{dust}^4 \langle Q_{abs}(T_{dust})\rangle$$

or

$$L_{star}/4\pi D^2 \langle Q_{abs}(T_{star})\rangle = 4\sigma T_{dust}^4 \langle Q_{abs}(T_{dust})\rangle$$

○ analytical solutions, assuming $\langle Q_{abs}(T_{star})\rangle = 1$ and $Q_{abs} = Q_{abs,0}\ (\lambda / \lambda_0)^{-\beta}$

➔ $\langle Q_{abs}(T_{dust})\rangle = Q_{abs,0}\lambda_0^{\beta}\ (15/\pi^4)\ (kT_{dust}/hc)^{\beta}\ \zeta(\beta+4)\Gamma(\beta+4)$

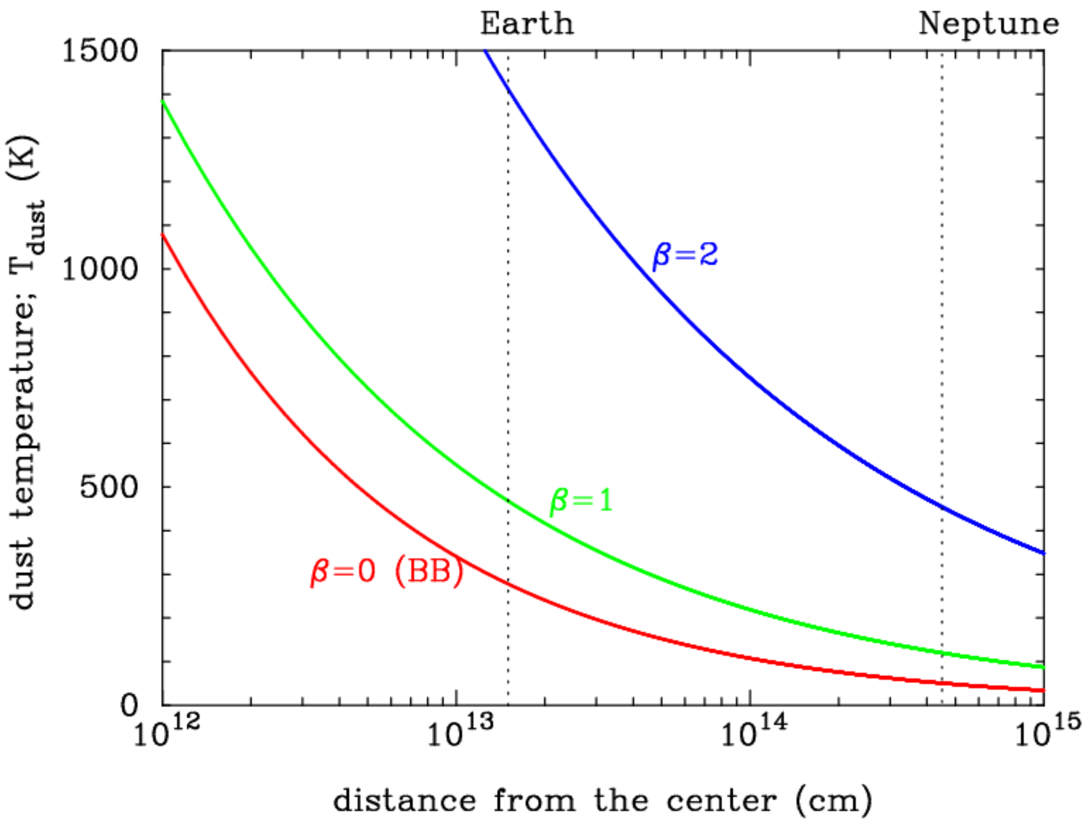
$(\beta=0)\ L_{star}/4\pi D^2 = 4Q_{abs,0}\ \sigma T_{dust}^4$

$(\beta=1)\ L_{star}/4\pi D^2 = 4Q_{abs,0}\ (k\lambda_0/hc)\ \sigma T_{dust}^5\ (373.3/\pi^4)$

$(\beta=2)\ L_{star}/4\pi D^2 = 4Q_{abs,0}\ (k\lambda_0/hc)^2\ \sigma T_{dust}^6\ (\pi^2/63)$

3-7. Temperature of dust grains (2)

○ Dust temperatures as functions of D (distance) and β for $L_{star} = L_{sun} = 3.85 \times 10^{33}$ erg s^{-1}, $Q_{abs,0} = 1$, $\lambda_0 = 1.0$ μm



Dust temperature is higher for higher β

➔ Higher β causes lower efficiency of radiative cooling