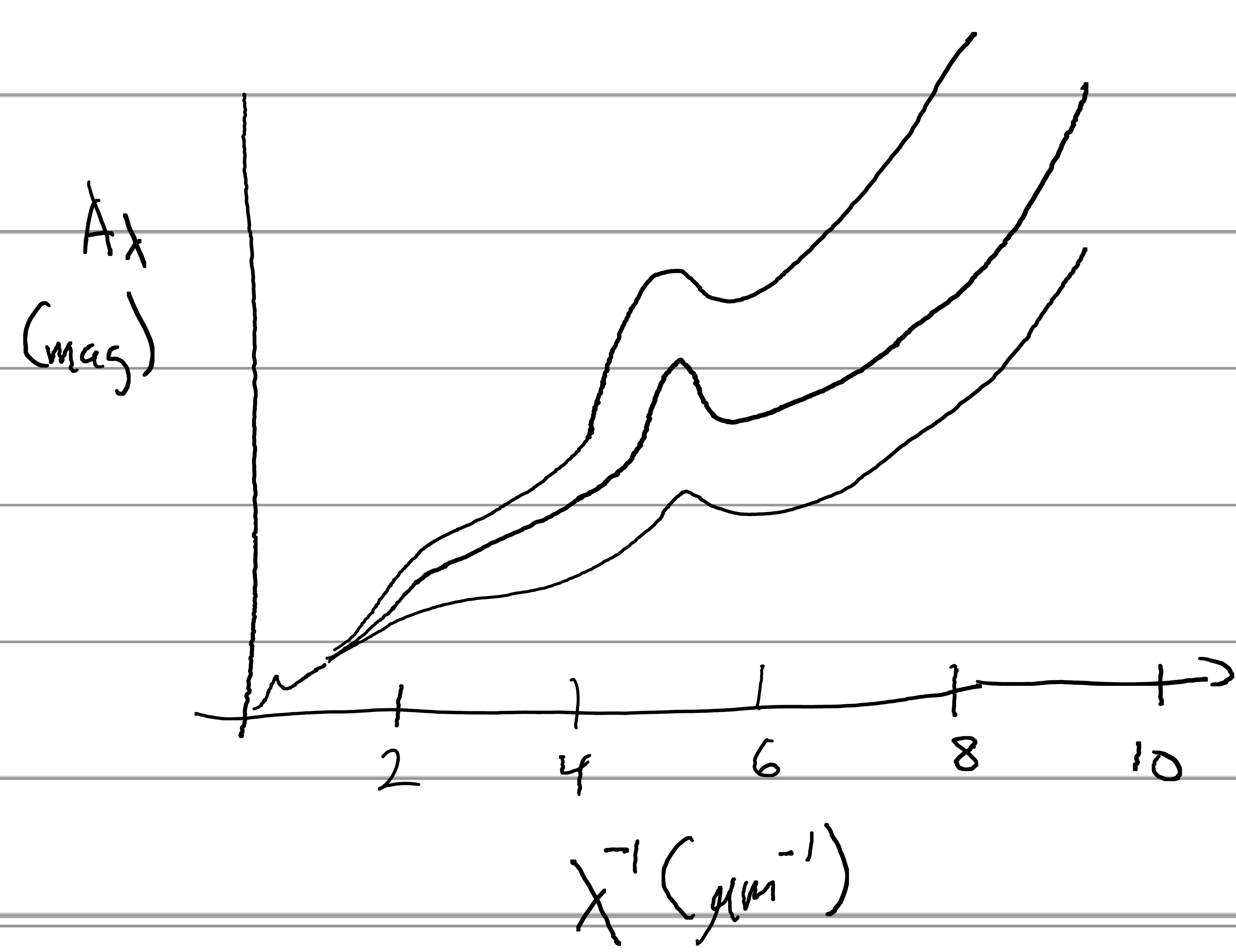
Interstellar Dust

Draine chapters 21 & 22

Dust is essential to understanding of astrophysics:

- extinction & reddening
- diagnostic of star-formation & AGN activity from emission
- Catalyze H_2 formation
- radiation pressure effects
- photoelectric heating
- most of C, Si, Mg, Fe in grains

Interstellar extinction is a function of λ



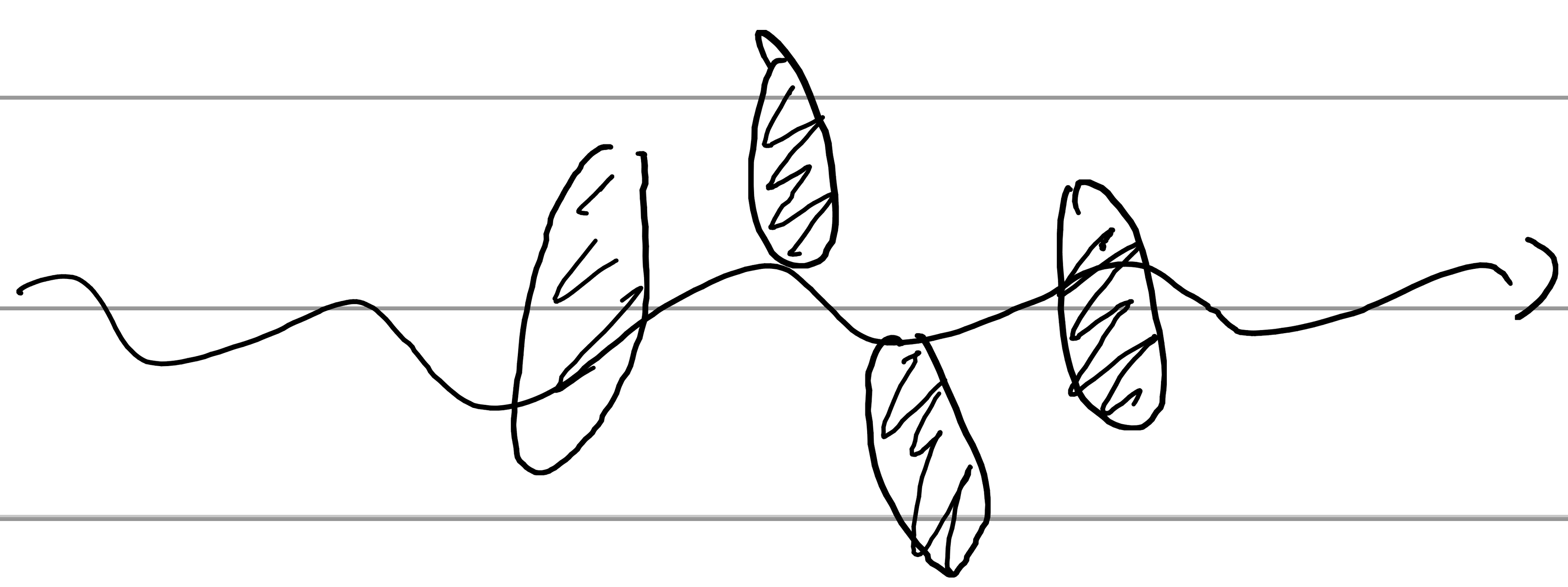
$f(\lambda; R_V)$

$$R_V = \frac{A_V}{A_B - A_V}$$

"E(B-V)"

This is an informative curve → if $a \gg \lambda$ then extinction should become "grey" → requires lots of dust w/ $a \lesssim 0.1\ \mu m$

However, the nature of the extinction depends on λ, in that the polarization of background stars is induced – meaning non-spherical, aligned grains – and <u>declines</u> towards UV.

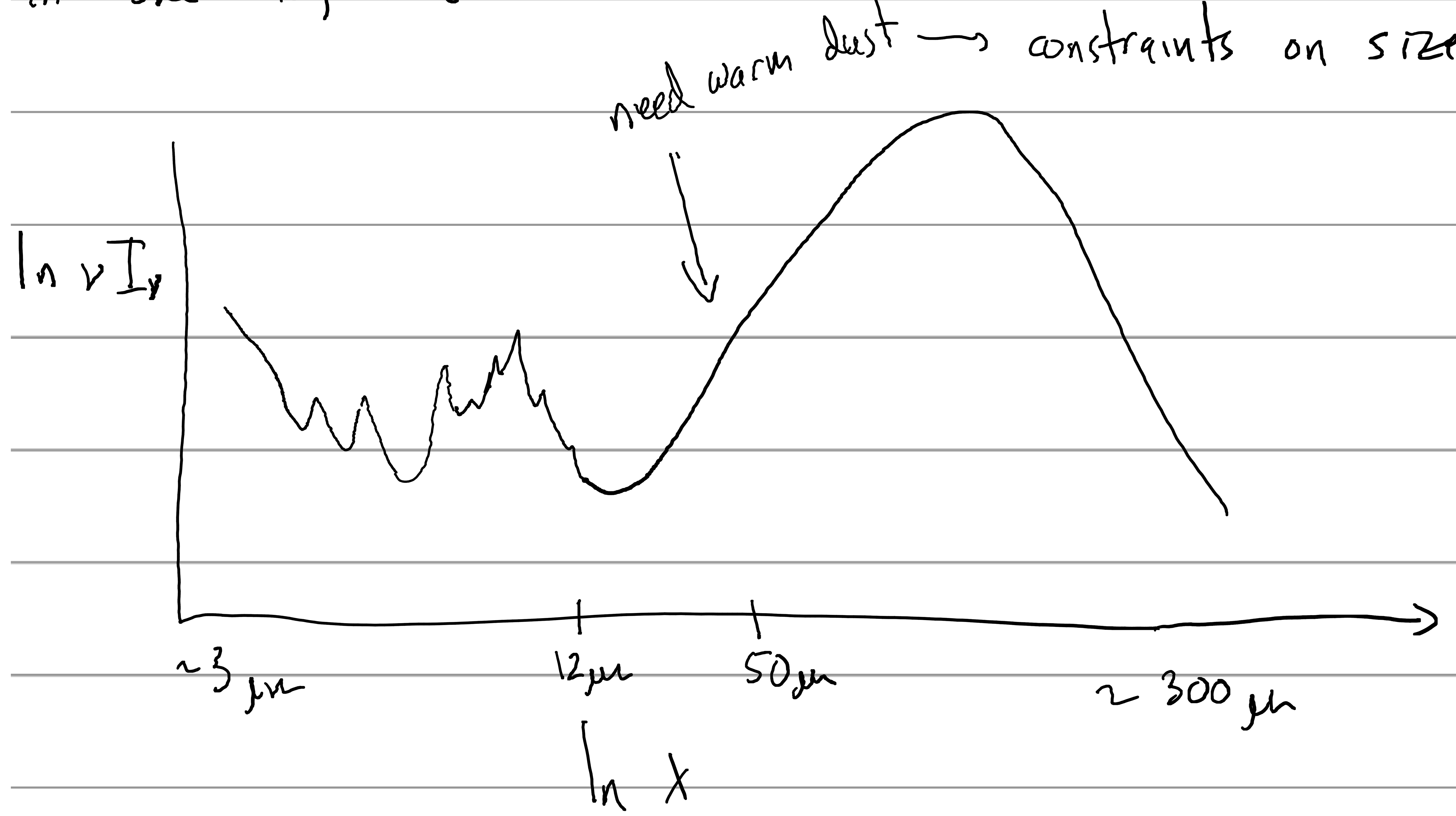


Conclusion is that there must be both large (aligned) grains and small ones (unaligned).

Alignment appears associated w/ Galactic $\vec{B}$-field.

Point is: there is a broad range of dust grain sizes.

Dust is heated by starlight and radiates its energy in the infrared.



Let us now consider some details:

- scattering & absorption
- heating & emission

We've progressed from electrons → atoms → molecules and at dust this is the most complex interaction, so we're not deriving from scratch.

We will consider grains with some complex index of refraction:

$$k = m(\omega)\,\frac{\omega}{c}$$

$$m(\omega) = \left[\epsilon + \frac{4\pi i \sigma}{\omega}\right]^{1/2}$$

σ = conductivity

ϵ = real part of dielectric constant

Interpret this in terms of a propagating wave

$$E \propto e^{i(kx-\omega t)} \propto e^{i\left(\frac{m\omega}{c}x - \omega t\right)}$$

$$\propto e^{i\left(\frac{Re(m)\omega}{c}x - \omega t\right)}\, \underbrace{e^{-\frac{Im(m)\omega x}{c}}}_{\text{decay}}$$

<u>absorption in grain</u>

$$P \propto e^{-\frac{2\,Im(m)\,\omega x}{c}}$$

$$L_{abs} = \frac{c}{2\omega\, Im(m)} = \frac{\lambda}{4\pi\, Im(m)}$$

<u>phase shift in grain</u>

$$\Delta\phi = \left(\frac{m\omega}{c}x - \omega t\right) - \left(\frac{\omega}{c}x - \omega t\right)$$

$$= (m-1)\frac{\omega x}{c}$$

$$|\Delta\phi|_a = |m-1|\,\frac{2\pi a}{\lambda}$$ ← for grain size "a"

For example, we believe lots of the dust is in "astrosilicates" $\rightarrow$ $MgFeSiO_4$ "olivine". In the optical, $Im(m) \sim 0.1$, and at a few eV this starts to rise to ~ 3. $|m-1| \gtrsim 0.3$

But let's look first at generic expectations.
First, we expect the cross-section to be:

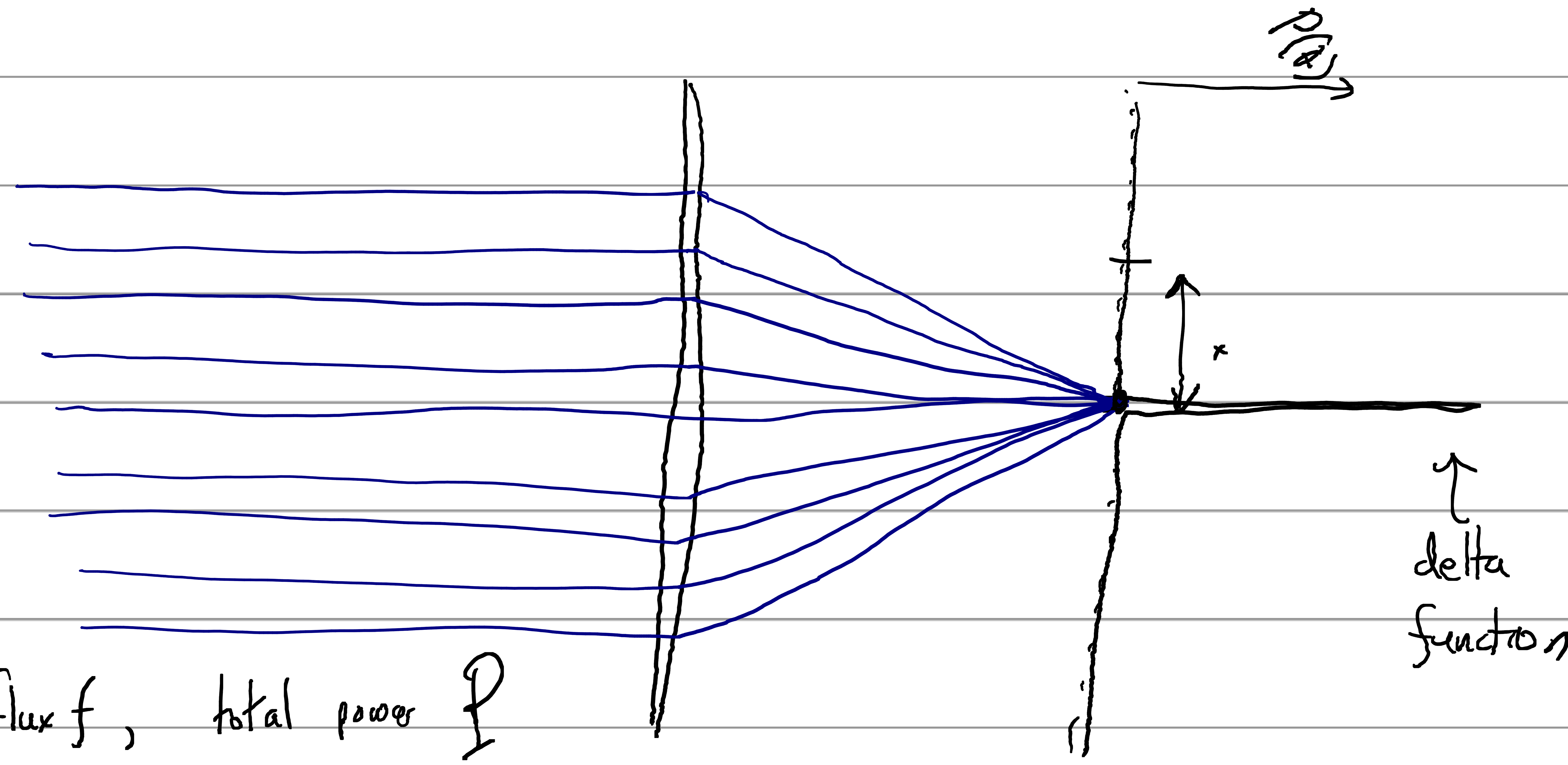
$$\sigma \propto \pi a^2 \quad \text{and we define} \quad \sigma = Q \pi a^2$$

where we want to know Q_{abs} and Q_{scat}

Large grains

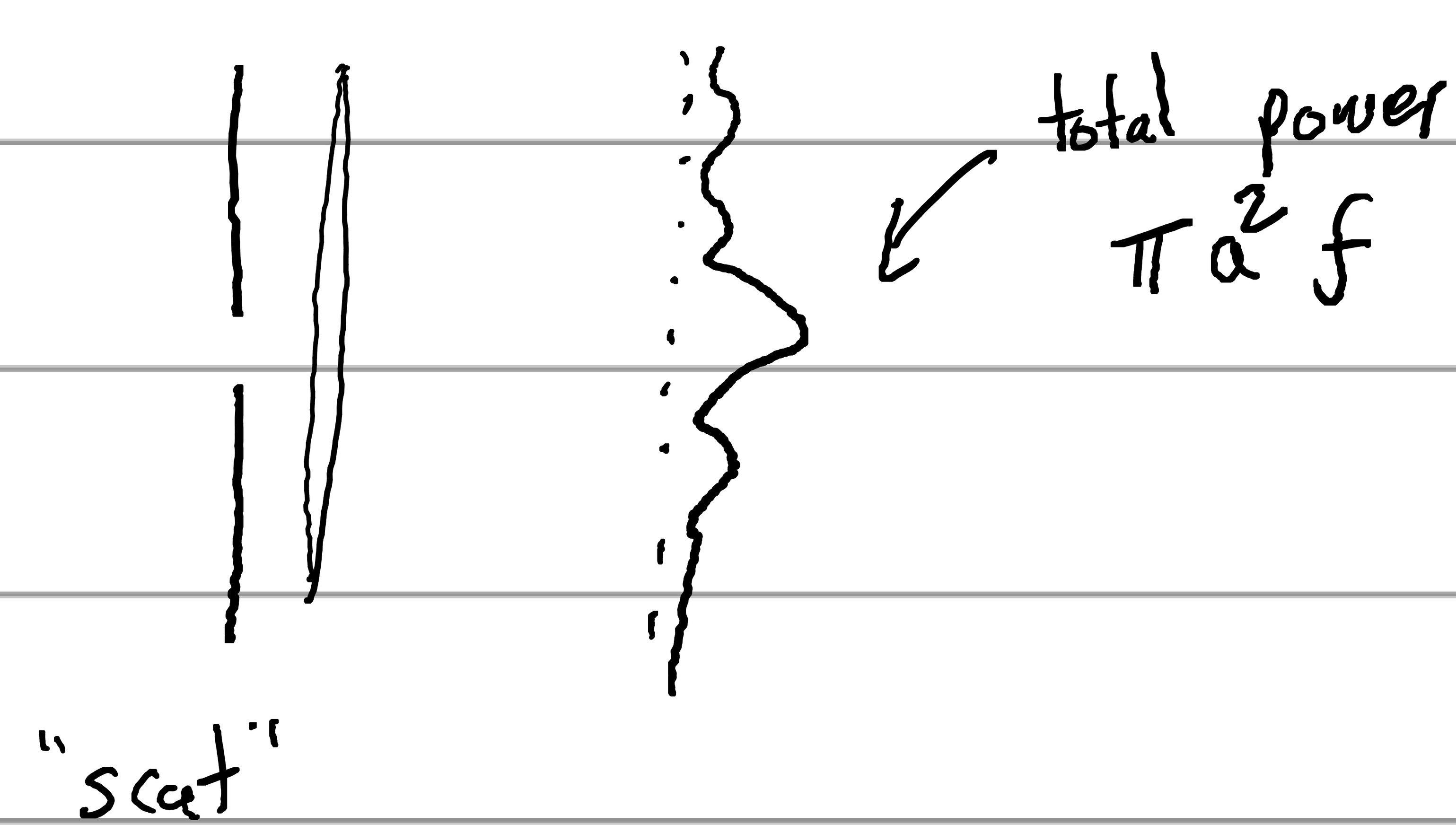
Consider scattering + absorption of light for which $\lambda \ll a$, and each grain is optically thick ($L_{abs} \sim \lambda \ll a$). Can show that $Q_{abs} + Q_{scat} = 2$. !

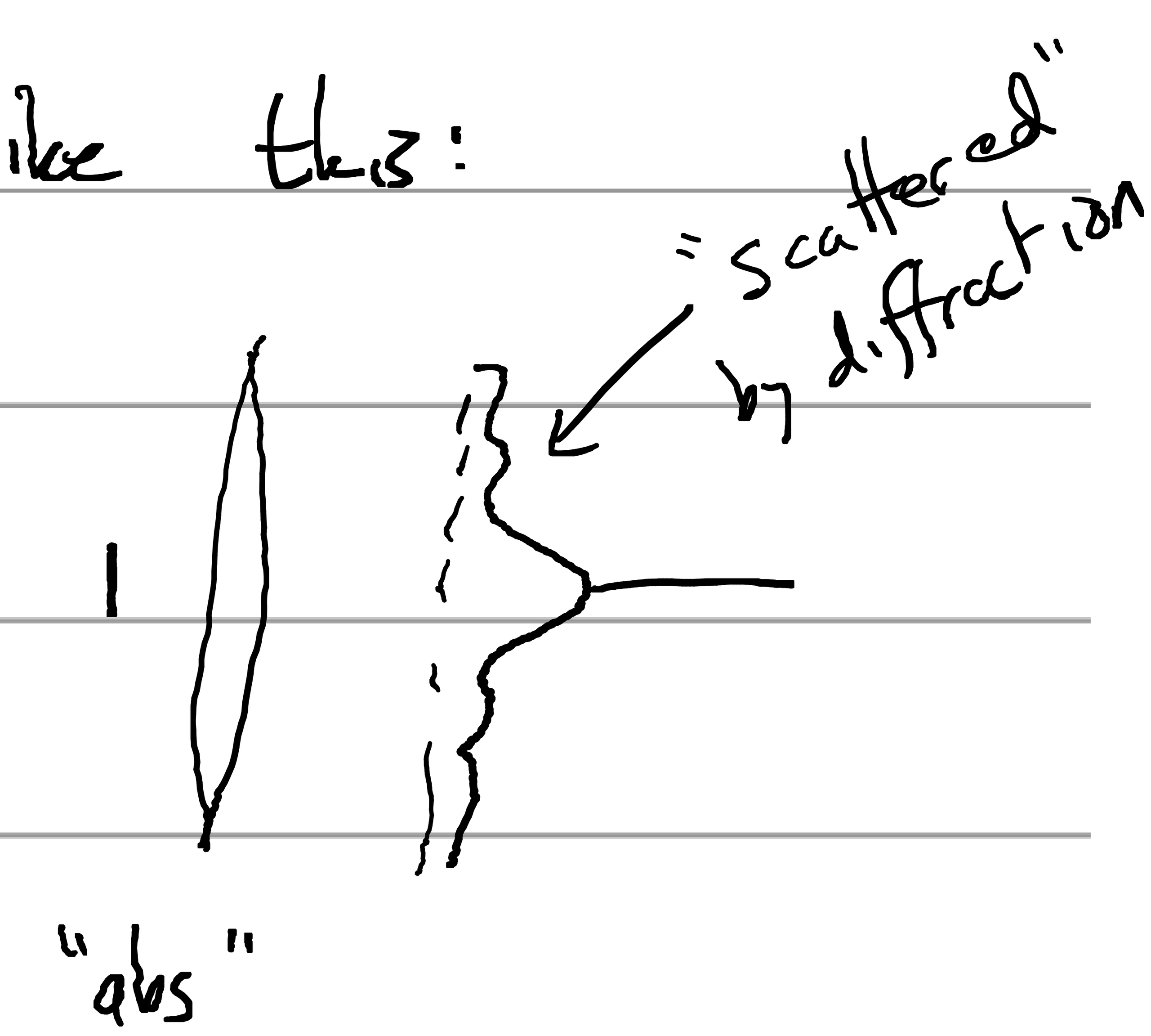
Proof follows from "Babinet's principle." Consider a lens focusing an infinite plane wave:



flux f, total power P

Imagine an aperture like this: and like this:





If we look at location x, $\vec{E}_{scat}$ must be $-\vec{E}_{abs}$

so $P_{scat} = P_{abs}$ except δ-function. δ-function loses power $\pi a^2 f$ due to aperture, and another $\pi a^2 f$ due to diffraction (even for $\lambda \ll a$). $\rightarrow$ $\boxed{Q_{abs} + Q_{scat} = 2}$

Small grain limit

In the small grain limit, scattering can be treated the same way we treated it back in the Thomson atomic model → as a polarizability. In that case you get Rayleigh scattering:

$$Q_{scat} \propto \left(\frac{a}{\lambda}\right)^4 \quad \Rightarrow \text{note then } \sigma_{scat} \propto \frac{a^6}{\lambda^4} \propto \frac{V^2}{\lambda^4}$$

The absorption we can treat using the same methodology as:

$$x_0 = \frac{eE_0}{m}\left[\omega_0^2 - \omega^2 + i\omega_0^2\omega\tau\right]^{-1}$$

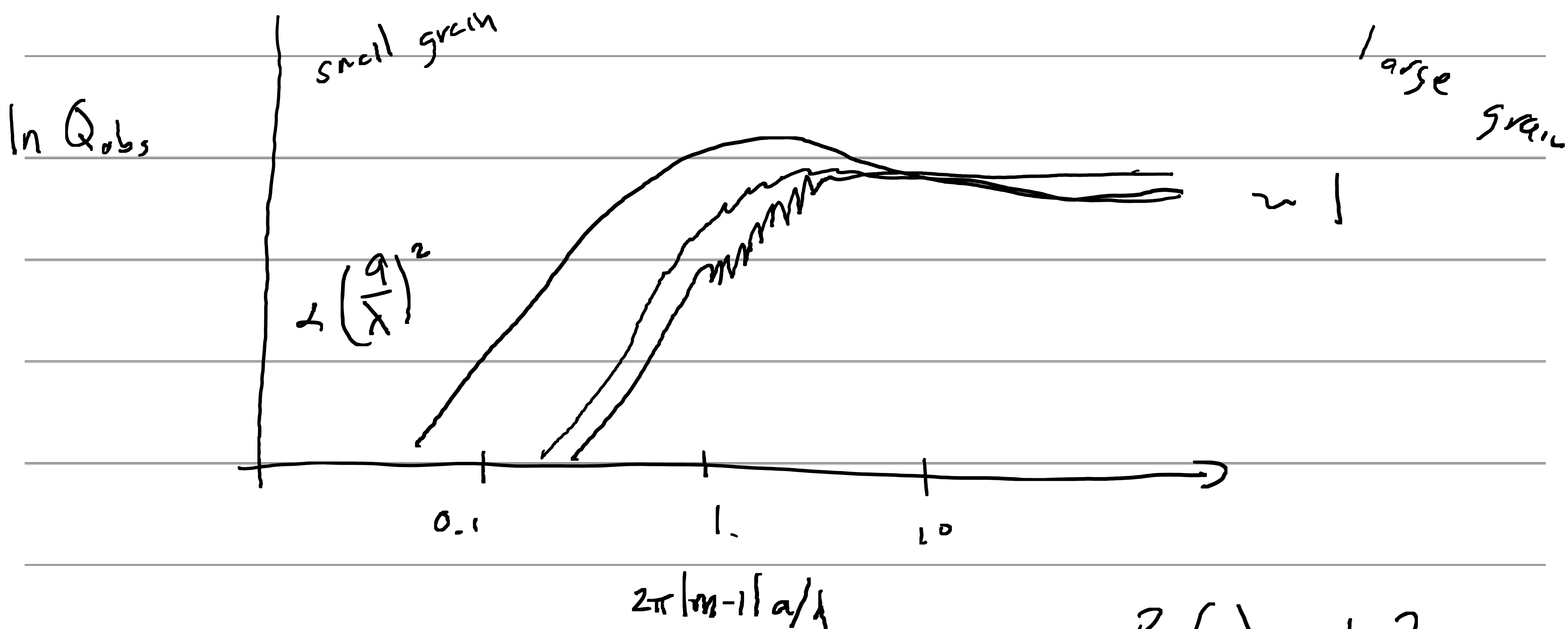
$\tau \rightarrow$ damping constant

$$= \frac{eE_0}{m}\,\frac{(\omega_0^2-\omega^2) - i\omega_0^2\omega\tau}{(\omega_0^2-\omega^2) + \omega_0^2\omega\tau}$$

imaginary part is dissipative $\propto \frac{1}{\lambda}$

$$Q_{abs} \propto \mathrm{Im}(x_0)^2 \propto \frac{1}{\lambda^2} \quad \text{in fact} \quad Q_{abs} \propto \frac{V}{\lambda^2}$$

Transition depends on specific m for material and for spherical grains is captured by Mie theory



$Re(m) \sim 1-2$

$Im(m) \sim 0.01-0.1$