Physics 224
The Interstellar Medium

Lecture #11

Dust!

We have talked fairly extensively now about
the interaction of radiation with gas.

This occurs at specific frequencies (absorption by atoms, ions, molecules)
or at certain frequency ranges (ionizing radiation).

Now we move on to talking about dust -
which interacts with light at a wide range of wavelengths.

<u>Dust is key for coupling radiation with the gas
in most ISM phases.</u>

How we learn about dust

- Extinction: wavelength dependence of how dust blocks (absorbs & scatters) light
- Polarization: of starlight and dust emission
- Thermal emission from grains
- Microwave emission from spinning small grains
- Depletion of elements from the gas relative to expected abundance
- Presolar grains in meteorites or ISM grains from Stardust mission (7 grains!), Cassini

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Dust/Light Interaction

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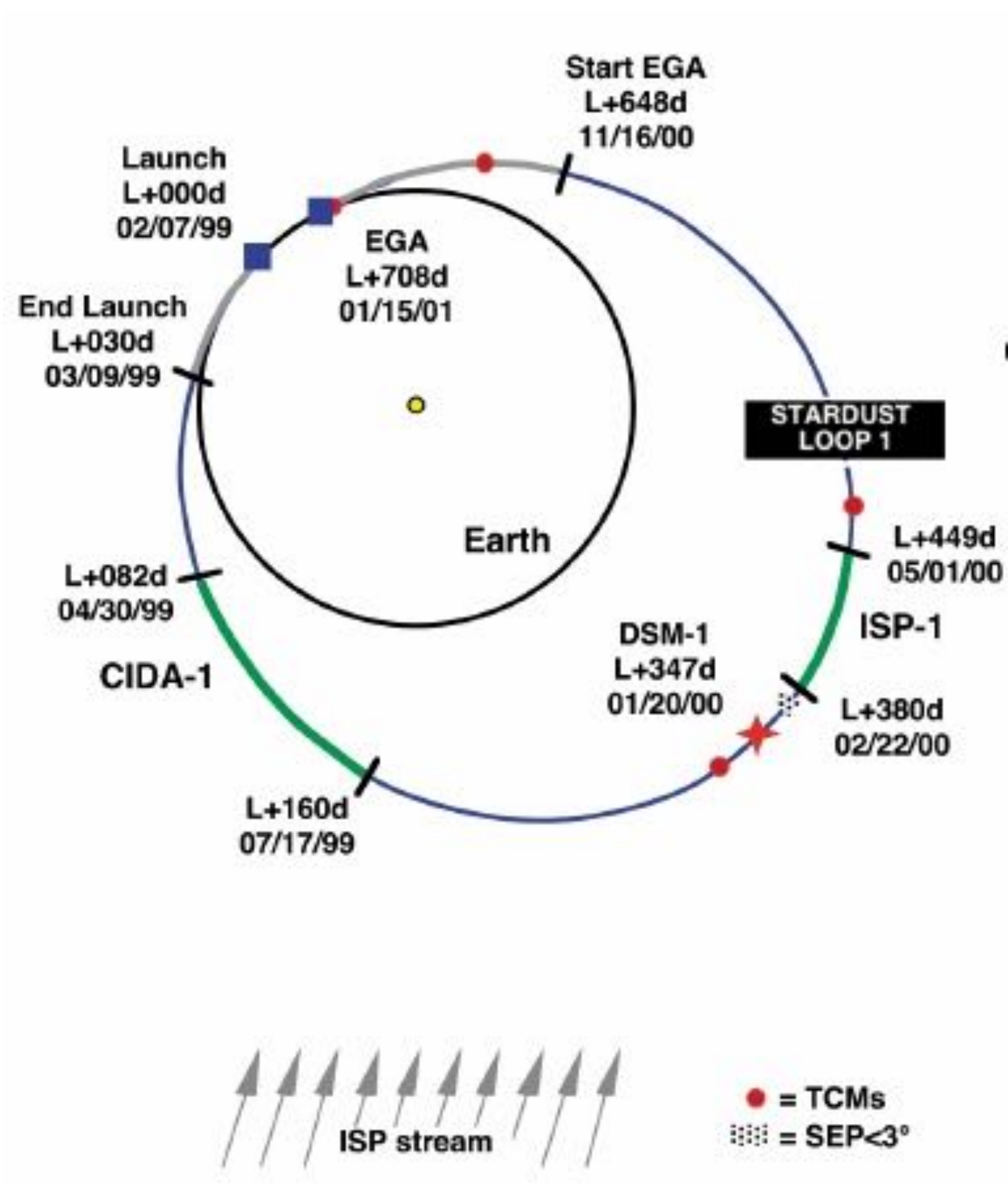
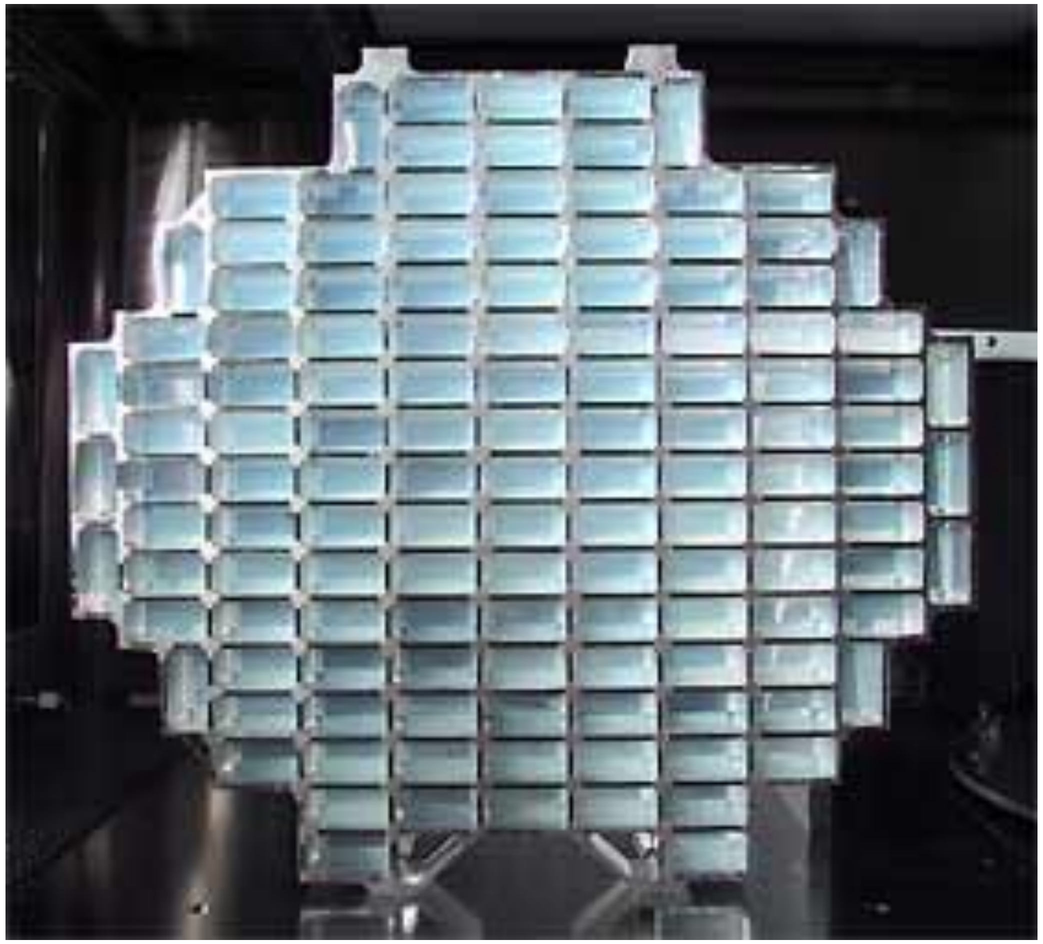
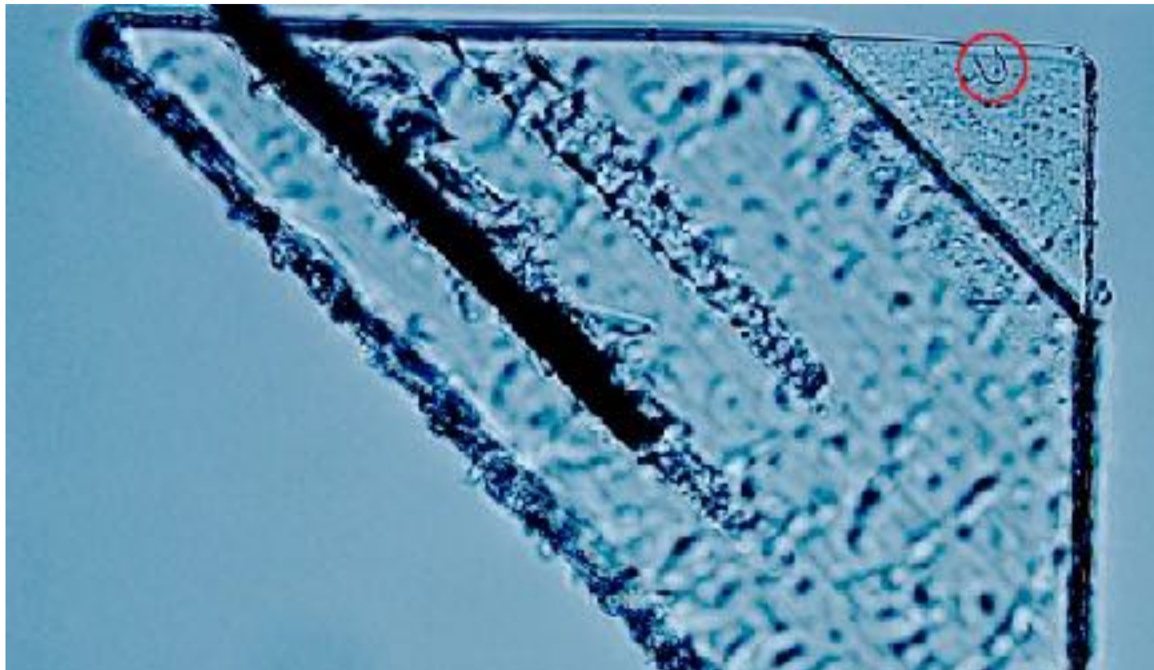
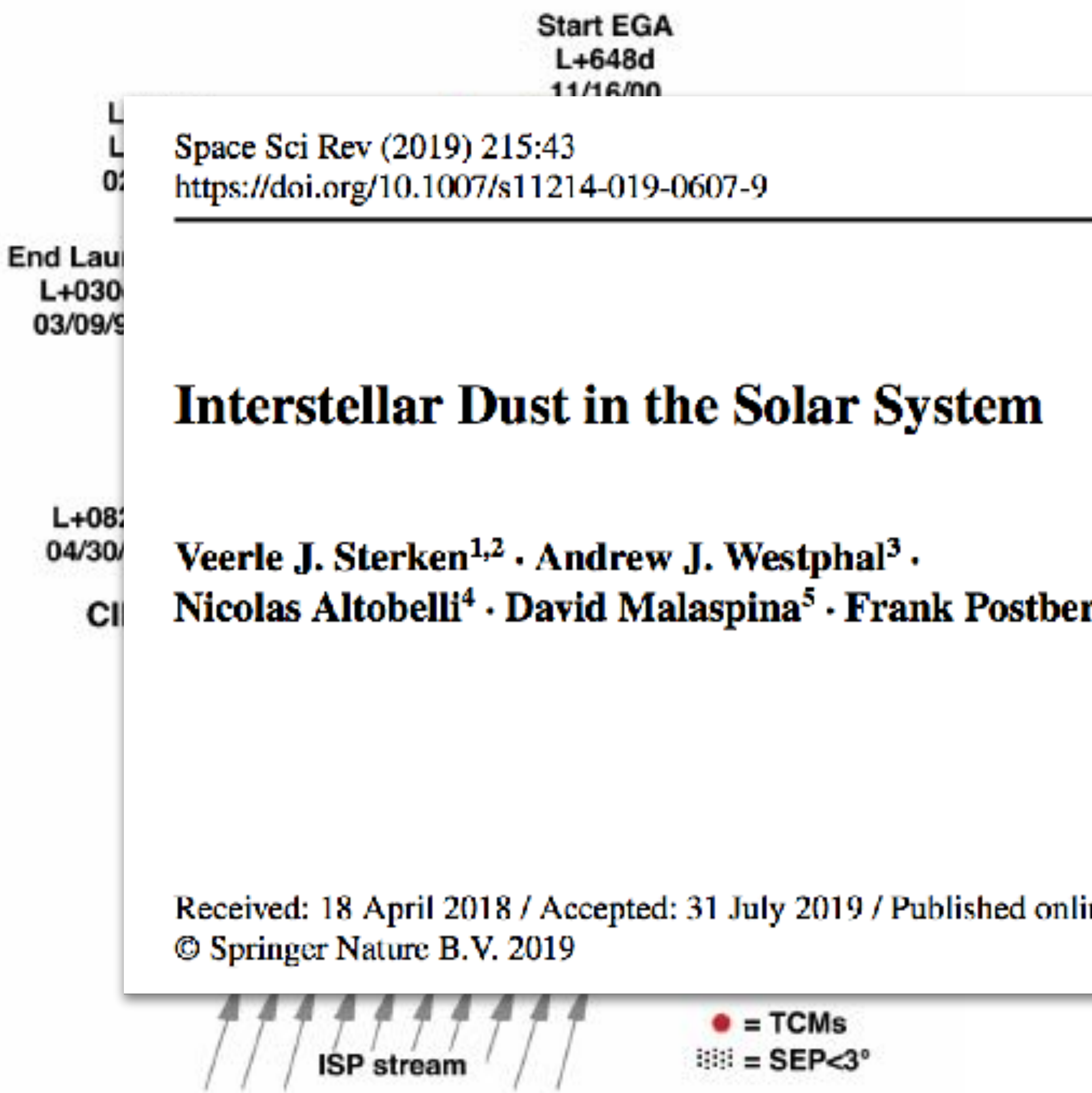
Stardust Mission

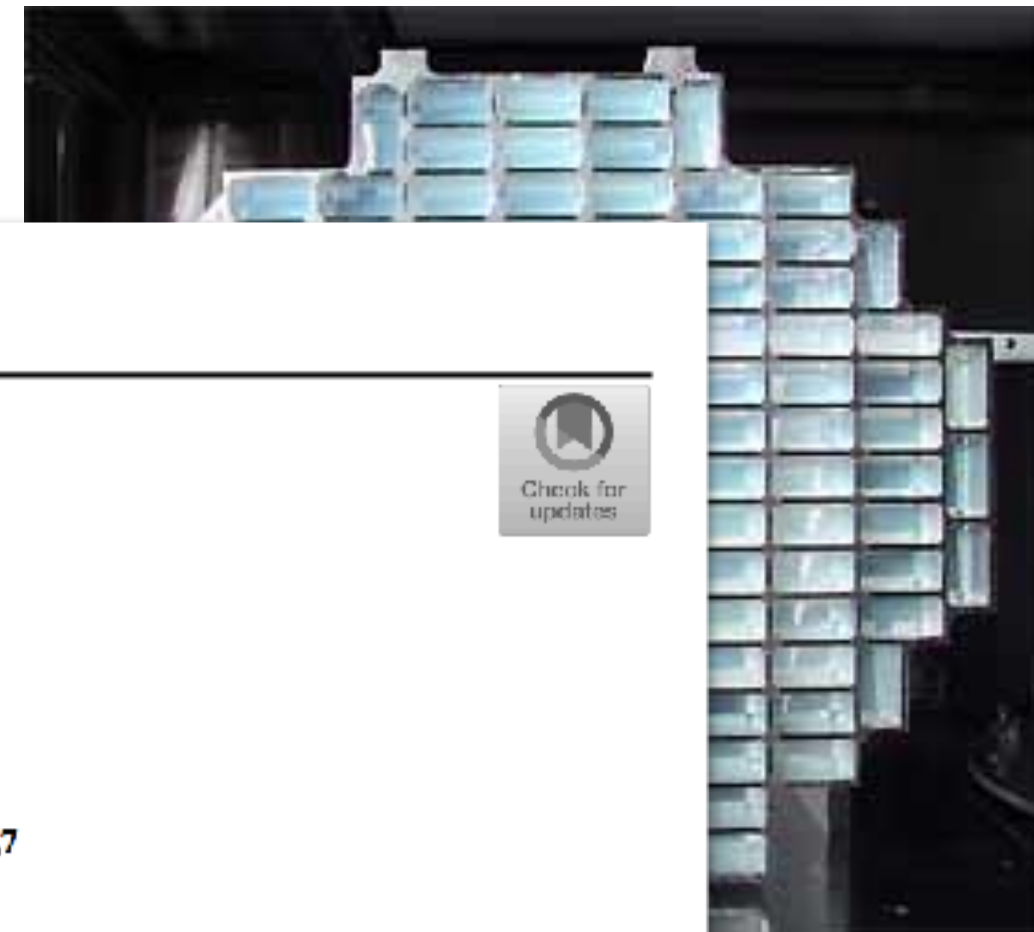






Stardust Mission





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Interstellar Dust in the Solar System

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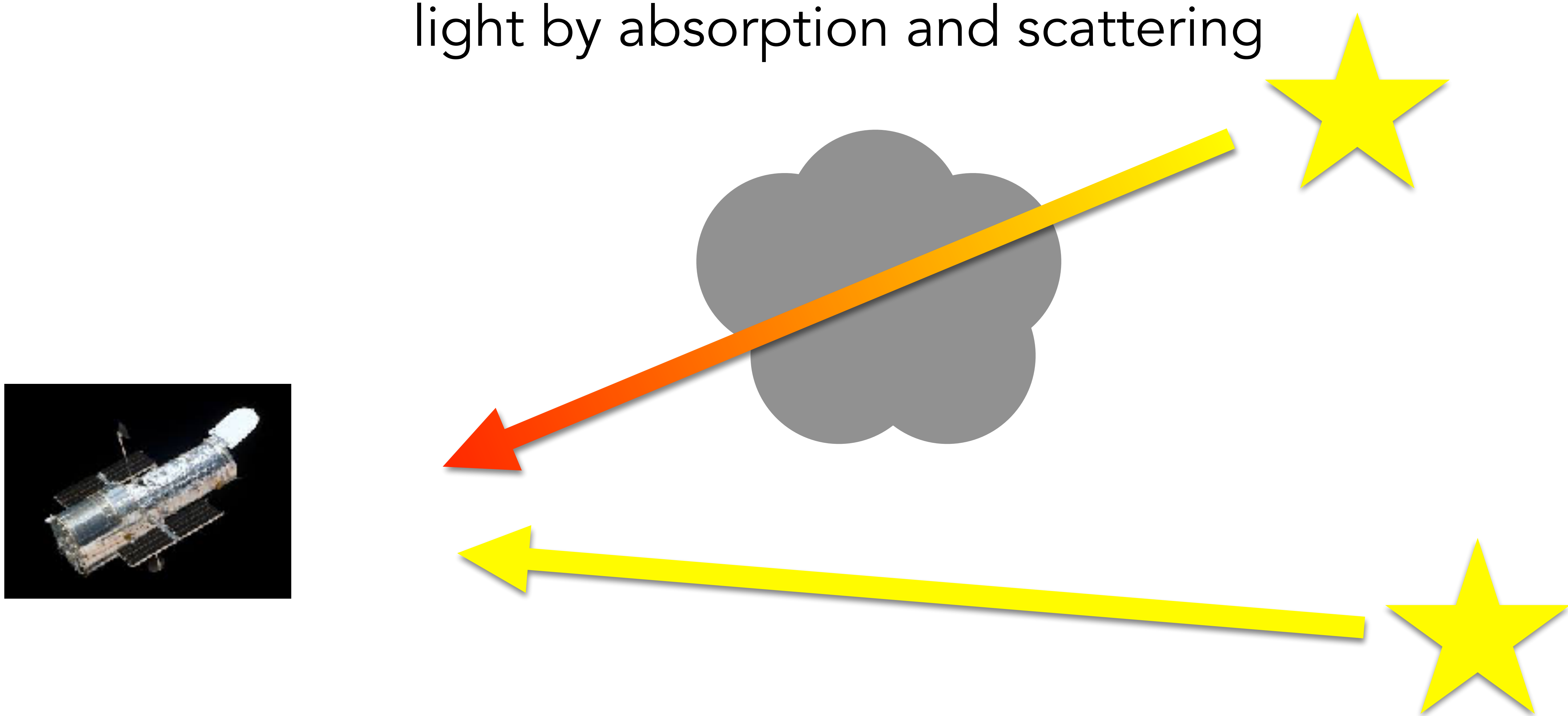
Dust/Light Interaction

First: definitions

Then: dust optical properties

Extinction

wavelength dependent attenuation of
light by absorption and scattering



Basic method for measuring extinction:
"pair method" - two stars of the same type behind
differing amounts of dust

Extinction

$$\frac{A_\lambda}{\text{mag}} = 2.5 \log_{10}[F_\lambda^0/F_\lambda]$$

Extinction at wavelength λ

expected flux w/o dust

observed flux

Extinction

$$\frac{A_\lambda}{\text{mag}} = 2.5\log_{10}[F_\lambda^0/F_\lambda]$$

Extinction at
wavelength λ

expected
flux w/o dust

observed
flux

$$[F_\lambda^0/F_\lambda] = e^{\tau_\lambda}$$

$$\frac{A_\lambda}{\text{mag}} = 2.5\log_{10}[e^{\tau_\lambda}] = 1.086\tau_\lambda$$

Extinction

$$\frac{A_\lambda}{\text{mag}} = 2.5\log_{10}[F_\lambda^0/F_\lambda]$$

Extinction at wavelength λ

expected flux w/o dust

observed flux

note: τ_λ includes both absorption & scattering

$$[F_\lambda^0/F_\lambda] = e^{\tau_\lambda}$$

$$\frac{A_\lambda}{\text{mag}} = 2.5\log_{10}[e^{\tau_\lambda}] = 1.086\tau_\lambda$$

Extinction

$$\frac{A_\lambda}{\mathrm{mag}} = 2.5 \log_{10}[F_\lambda^0 / F_\lambda]$$

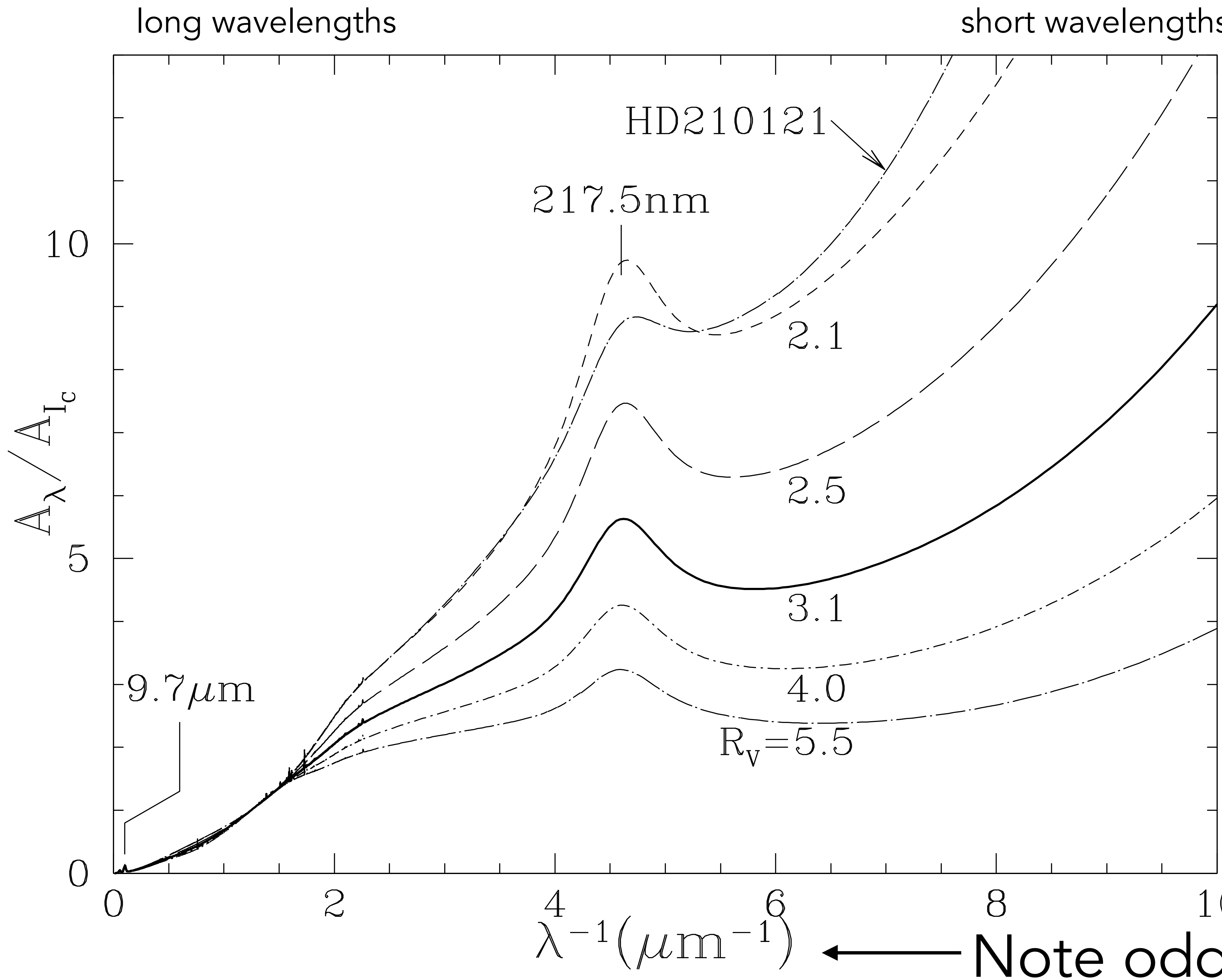
Extinction at wavelength λ

expected flux w/o dust

observed flux

This can be tough to measure, because to know the expected flux we need to know both the stellar spectrum and the distance to the star.

Milky Way Dust Extinction Curves



A_λ normalized to a long wavelength

Note odd units

Reddening or "Color Excess"

Reddening or “Color Excess”

If we don’t know the distance, we can still measure the change in the color of a star due to dust.

Reddening or “Color Excess”

If we don’t know the distance, we can still measure the change in the color of a star due to dust.

“color” = difference in magnitude at 2 wavelengths for example B band (4405 Å) and V band (5470 Å)

intrinsic $$(B-V)_0 = 2.5\log_{10}[F_B^0/F_V^0]$$

observed $$(B-V) = 2.5\log_{10}[F_B/F_V]$$

Reddening or "Color Excess"

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intrinsic $$(B-V)_0 = 2.5\log_{10}[F_B^0/F_V^0]$$

observed $$(B-V) = 2.5\log_{10}[F_B/F_V]$$

dependence on distance cancels, since it is the same at both wavelengths

Reddening or "Color Excess"

If we don't know the distance, we can still measure the change in the color of a star due to dust.

$$E(B-V) = (B-V)_0 - (B-V) = 2.5\log_{10}\left[\frac{F_B^0/F_V^0}{F_B/F_V}\right]$$

"color excess"
or "reddening"

Reddening or "Color Excess"

If we don't know the distance, we can still measure the change in the color of a star due to dust.

$$E(B-V) = (B-V)_0 - (B-V) = \boxed{2.5\log_{10}\left[\frac{F_B^0/F_V^0}{F_B/F_V}\right]}$$

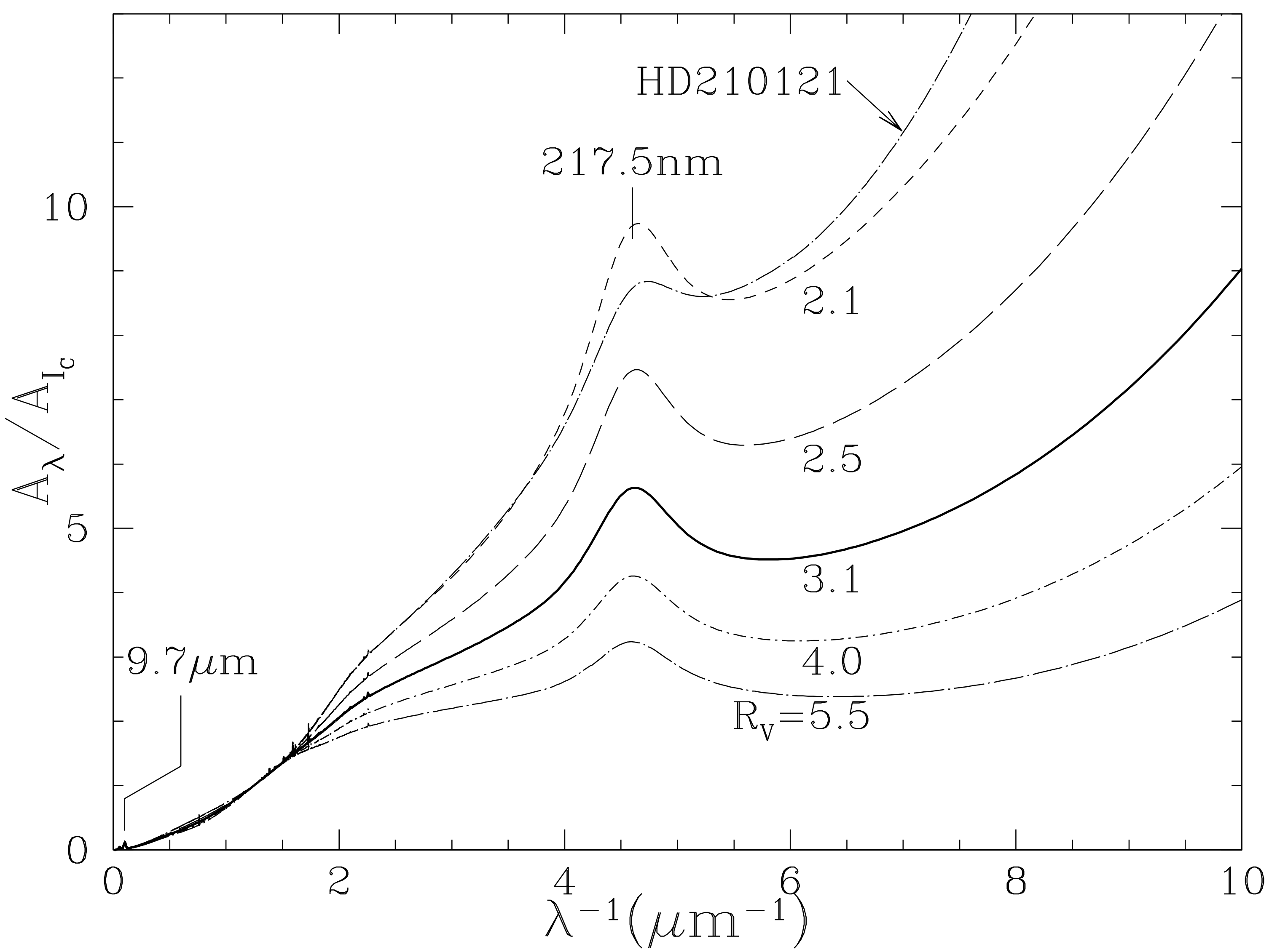
"color excess" or "reddening"

rearrange this

$$E(B-V) = 2.5\log_{10}[F_B^0/F_B] - 2.5\log_e[F_V^0/F_V] = A_B - A_V$$

Selective Extinction R_V

$$R_V \equiv \frac{A_V}{A_B - A_V} \equiv \frac{A_V}{E(B-V)}$$



R_V = slope of extinction curve in optical B & V bands

MW average R_V = 3.1 but it varies!

Selective Extinction R_V

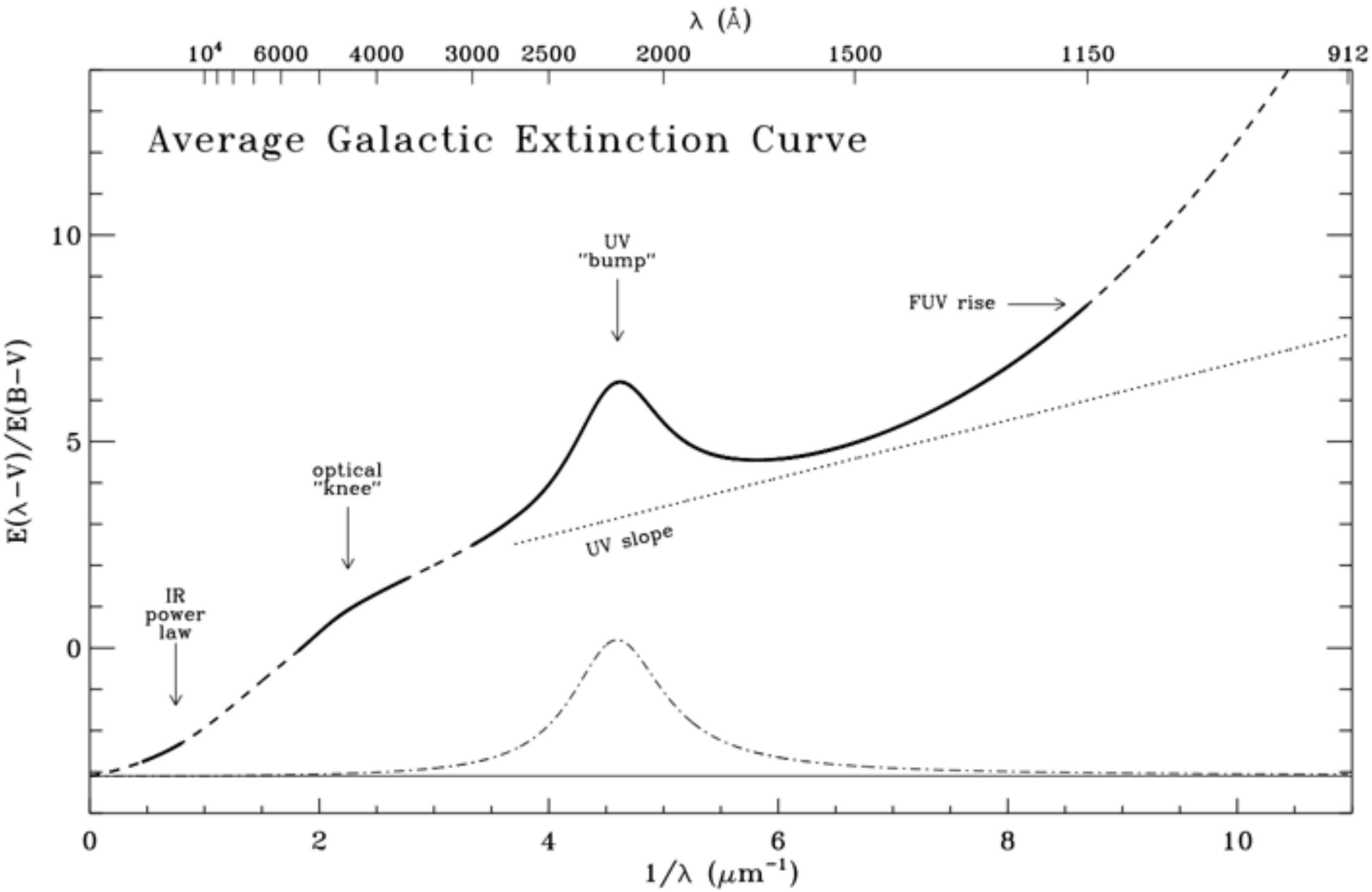
$$R_V \equiv \frac{A_V}{A_B - A_V} \equiv \frac{A_V}{E(B-V)}$$

$V) - A_V/E(B-V)$. The quantity $A_V/E(B-V)$, i.e., the ratio of total extinction to color excess in the optical region, is usually denoted R_V. If its value can be determined for a line of sight, then the easily-measured normalized extinction can be converted into total extinction.

It has been noted often that $E(B-V)$ is a less-than-ideal normalization factor. Certainly a physically unambiguous quantity, such as the dust mass column density, would be preferred, or even a measure of the total extinction at some particular wavelength, such as A_V. However, the issue is simply measurability. We have no model-independent ways to assess dust mass and total extinction requires either that we have precise stellar distances or can measure the stellar SEDs in the far-IR where extinction is negligible. While IR photometry is now available for many stars through the *2MASS* survey, the determination of total extinction from these data still requires assumptions about the λ-dependence of extinction longward of 2μm and can be compromised by emission or scattering by dust grains near the stars. In this paper, all the observed extinction curves will be presented in the standard form of $E(\lambda - V)/E(B-V)$. Only in the case

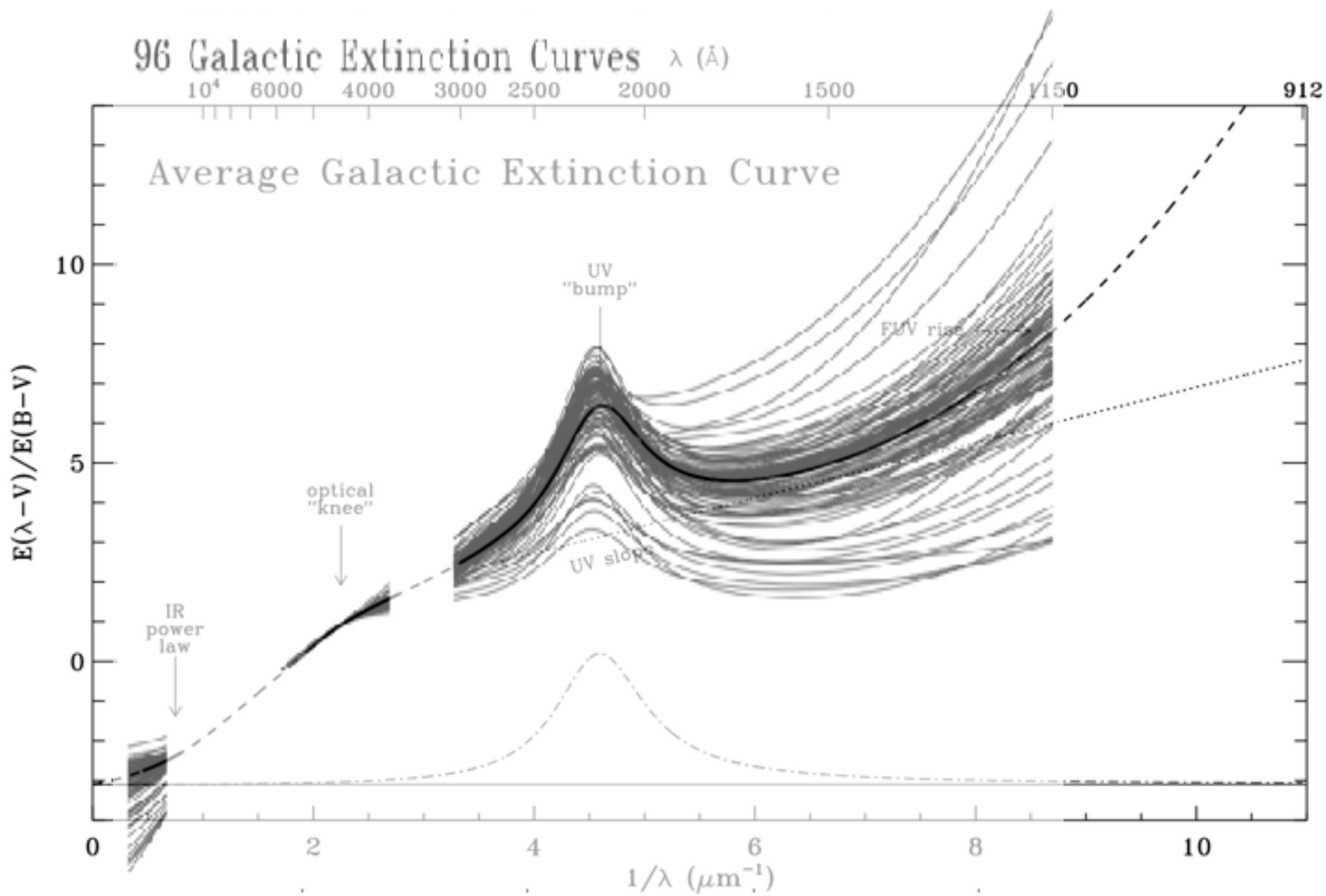
- Fitzpatrick 2004 review “Astrophysics of Dust”

Milky Way Dust Extinction Curves



from Fitzpatrick 2004 review "Astrophysics of Dust"

Milky Way Dust Extinction Curves



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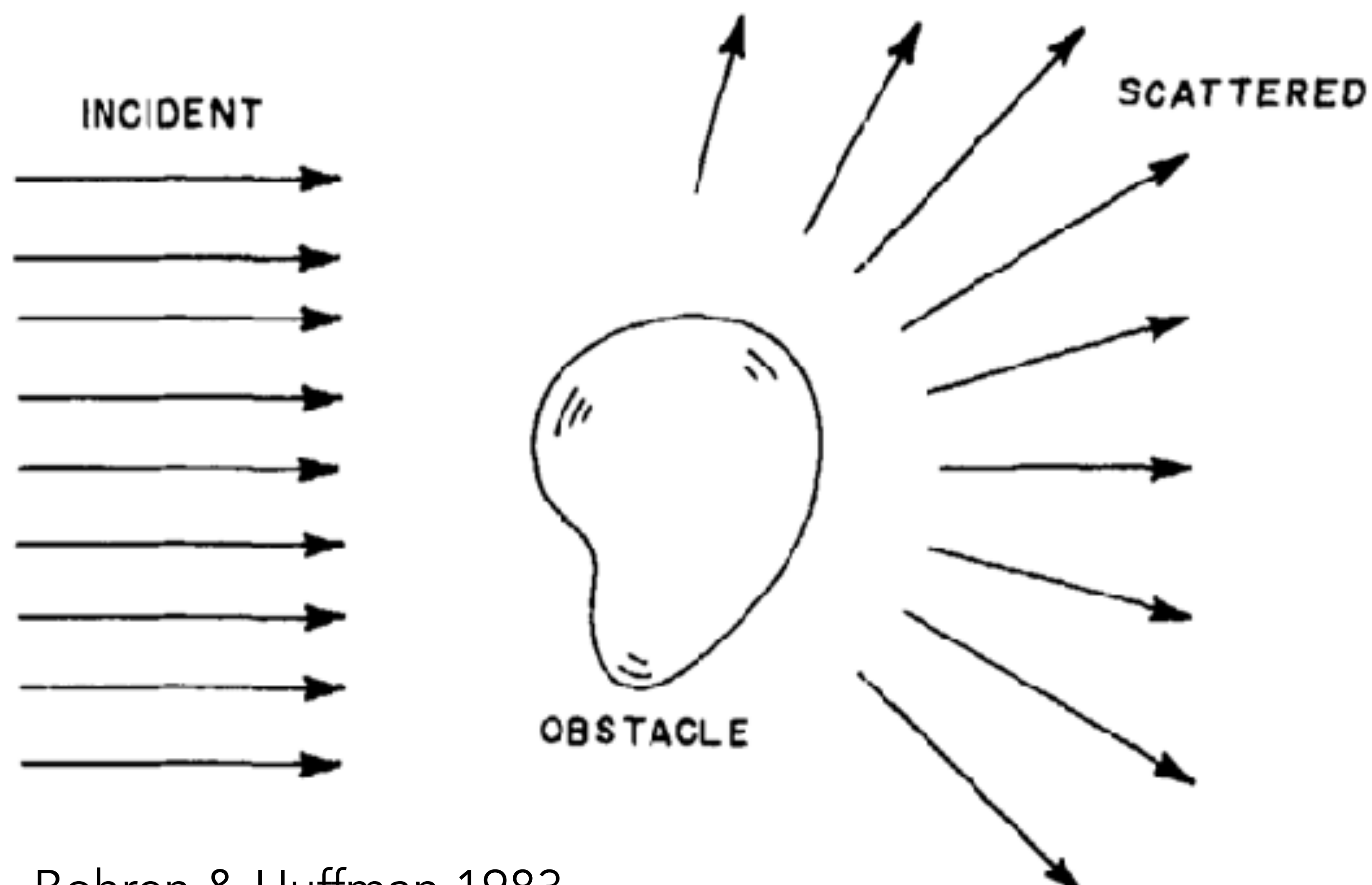
Optical Properties of Dust Grains

Scattering & Absorption of Light by Small Particles

Incoming EM wave, oscillations excited in scatterer, acceleration of charges causes re-radiation of EM waves in various directions.



Bohren & Huffman 1983

Scattering & Absorption of Light by Small Particles

define $x = 2\pi a/\lambda$ where a is the size of the object

can't treat entire grain as on dipole once $\lambda \sim a$, e.g., when $x \sim 1$ - need Mie Theory

$x \ll 1$: Rayleigh scattering

$x \sim 1$: Mie scattering

$x \gg 1$: Geometric scattering

Scattering & Absorption of Light by Small Particles

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treat scatterers as dipoles

x ≪ **1**: Rayleigh scattering

x ~ 1: Mie scattering

x ≫ **1**: Geometric scattering

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x ≪ **1**: Rayleigh scattering

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x ≫ **1**: Geometric scattering

geometric optics,
reflection, refraction, etc

Scattering & Absorption of Light by Small Particles

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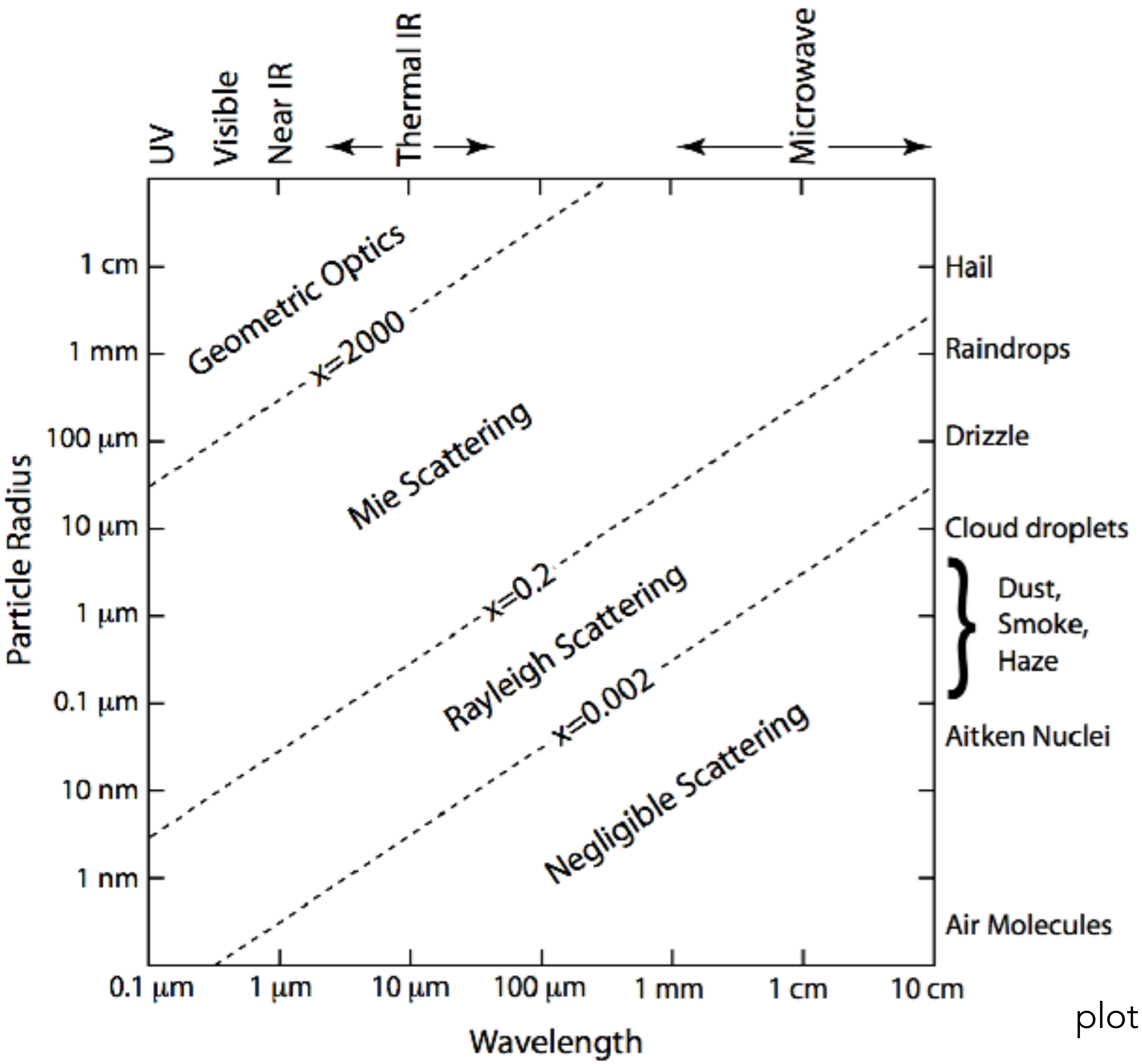
x ≪ **1**: Rayleigh scattering → treat scatterers as dipoles

x ~ **1**: Mie scattering → the hard stuff in between

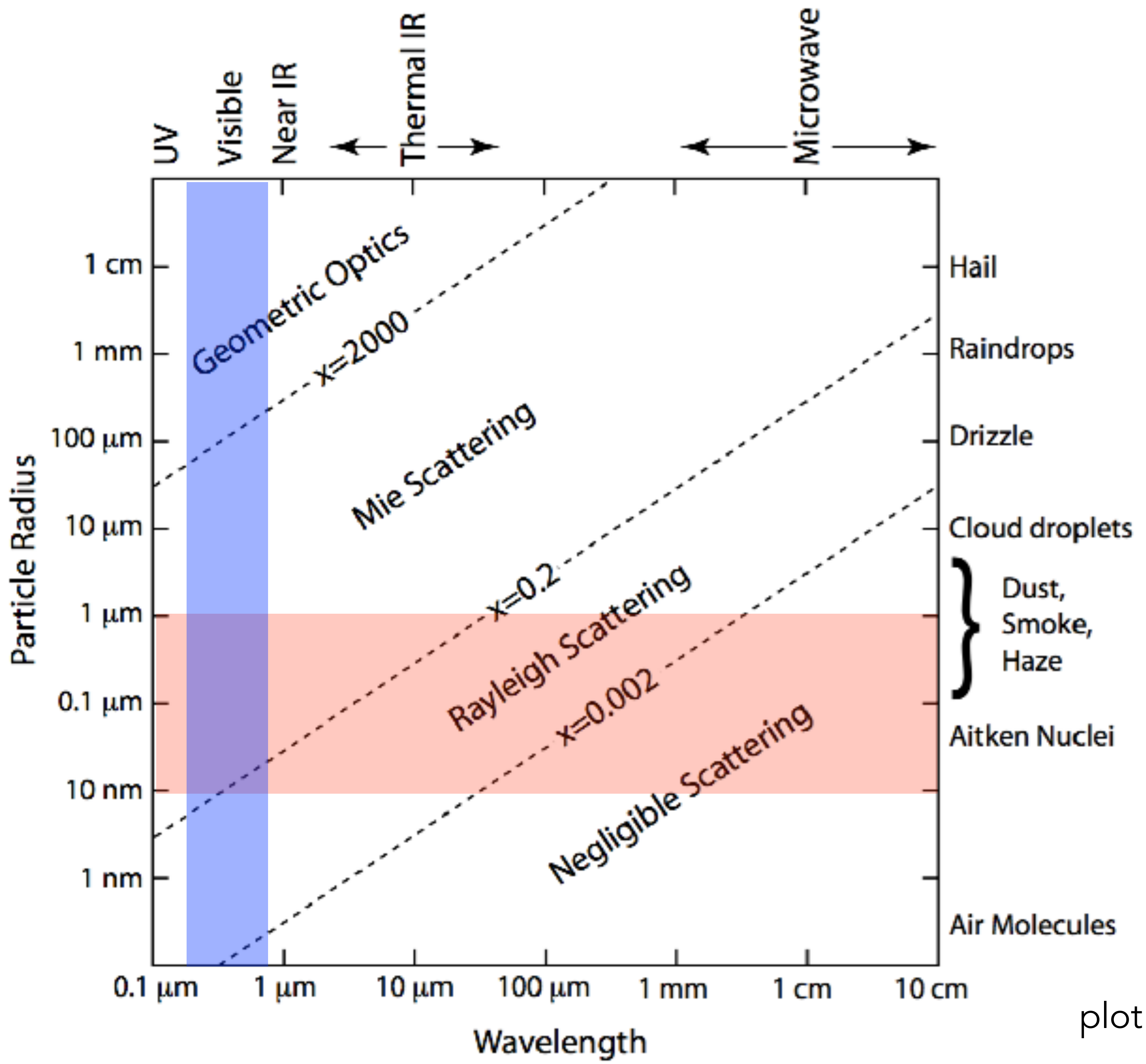
x ≫ **1**: Geometric scattering → geometric optics, reflection, refraction, etc

Scattering & Absorption of Light by Small Particles



plot from L. Lelli WS2014 slides

Scattering & Absorption of Light by Small Particles



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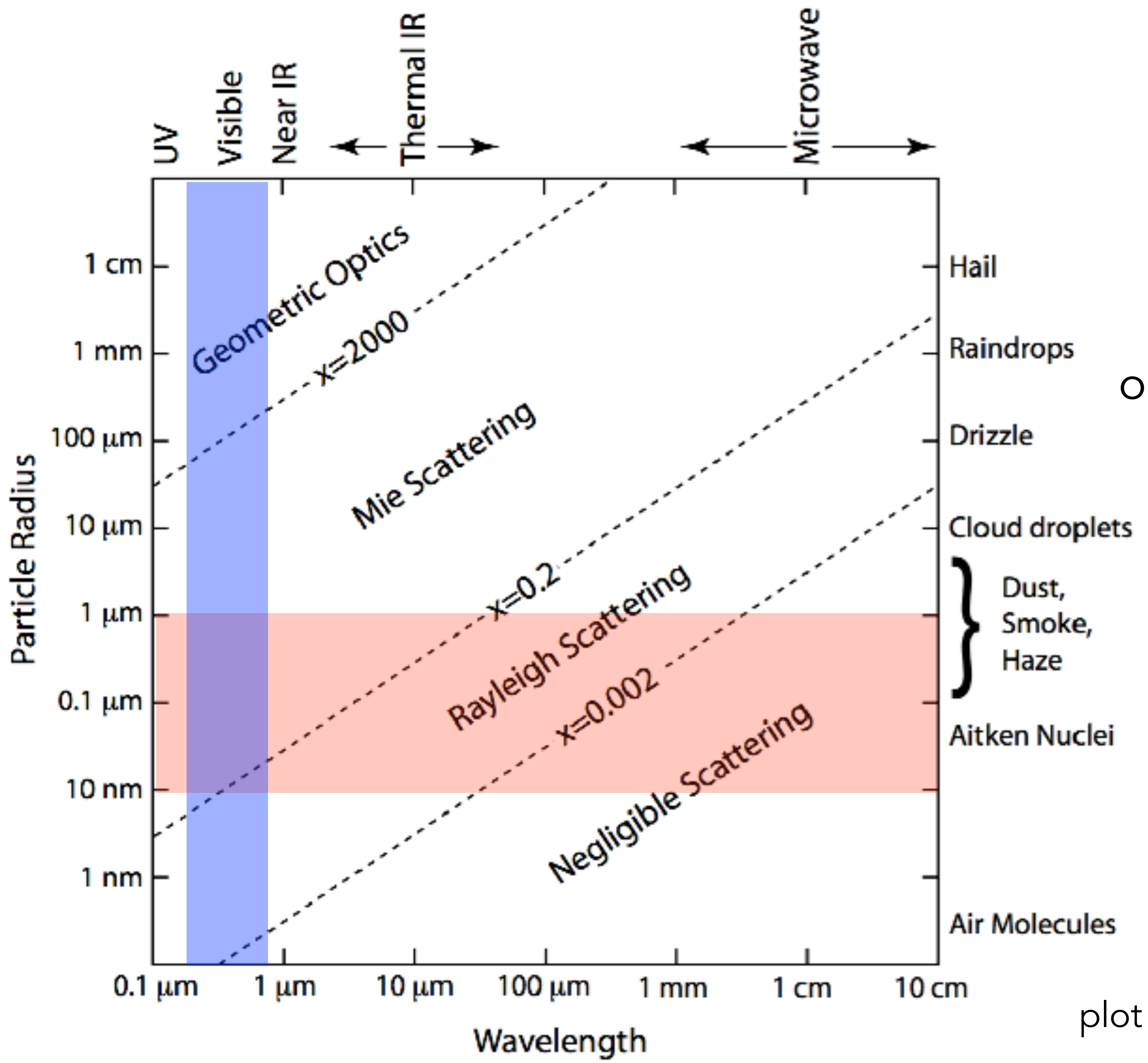
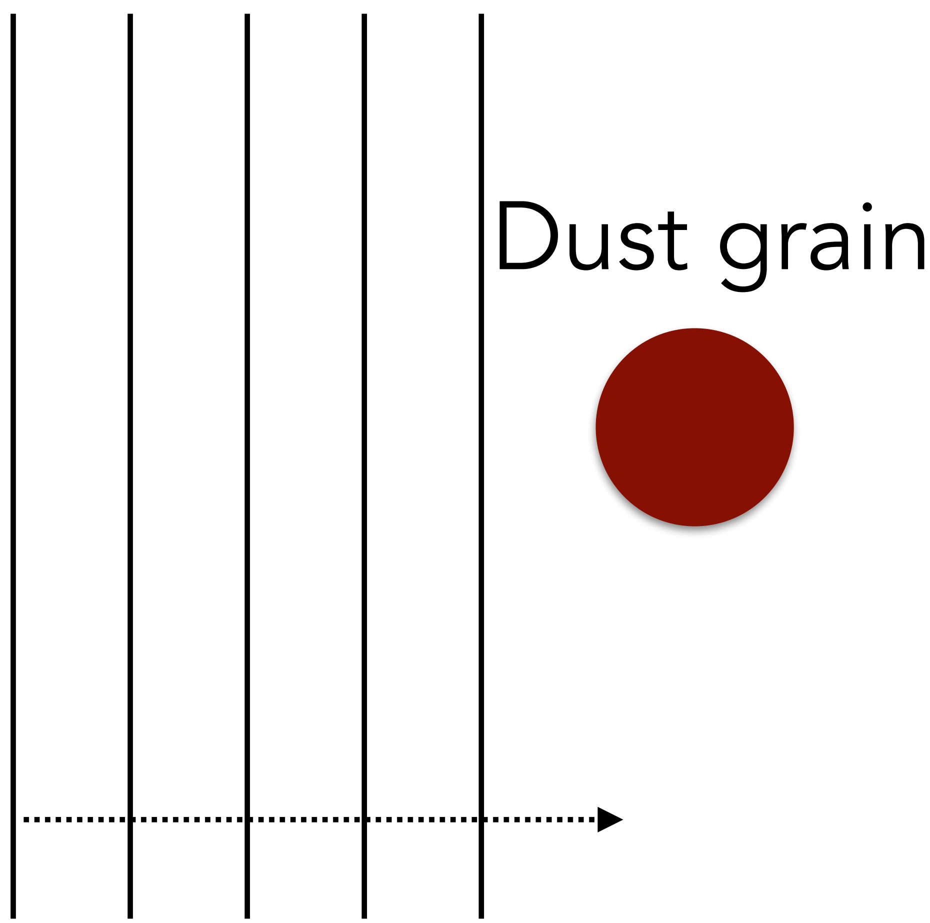


interstellar dust interaction with optical light is firmly in Mie scattering

plot from L. Lelli WS2014 slides

Scattering & Absorption of Light by Small Particles

key reference: Bohren & Huffman textbook



plane EM wave $\lambda = 2\pi c/\omega$

$E = E_0\, e^{i\mathbf{k}\cdot\mathbf{r} - i\omega t}$

Scattering & absorption result from interaction of grain material with oscillating E & B field

when wavelength of light is < mm
magnetic permeability = 1
can ignore magnetic field interaction

Scattering & Absorption of Light by Small Particles

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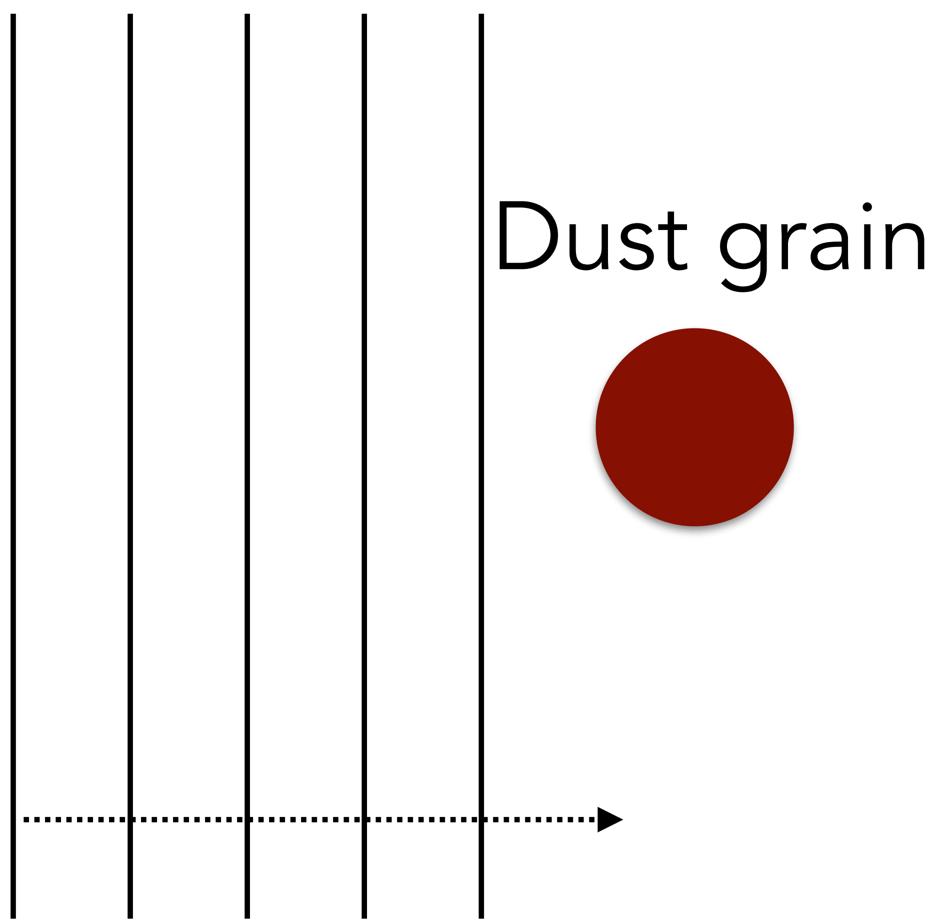


plane EM wave

$E = E_0 \, e^{i\mathbf{k}\cdot\mathbf{r} - i\omega t}$

Scattering & absorption result from interaction of grain material with oscillating E & B field

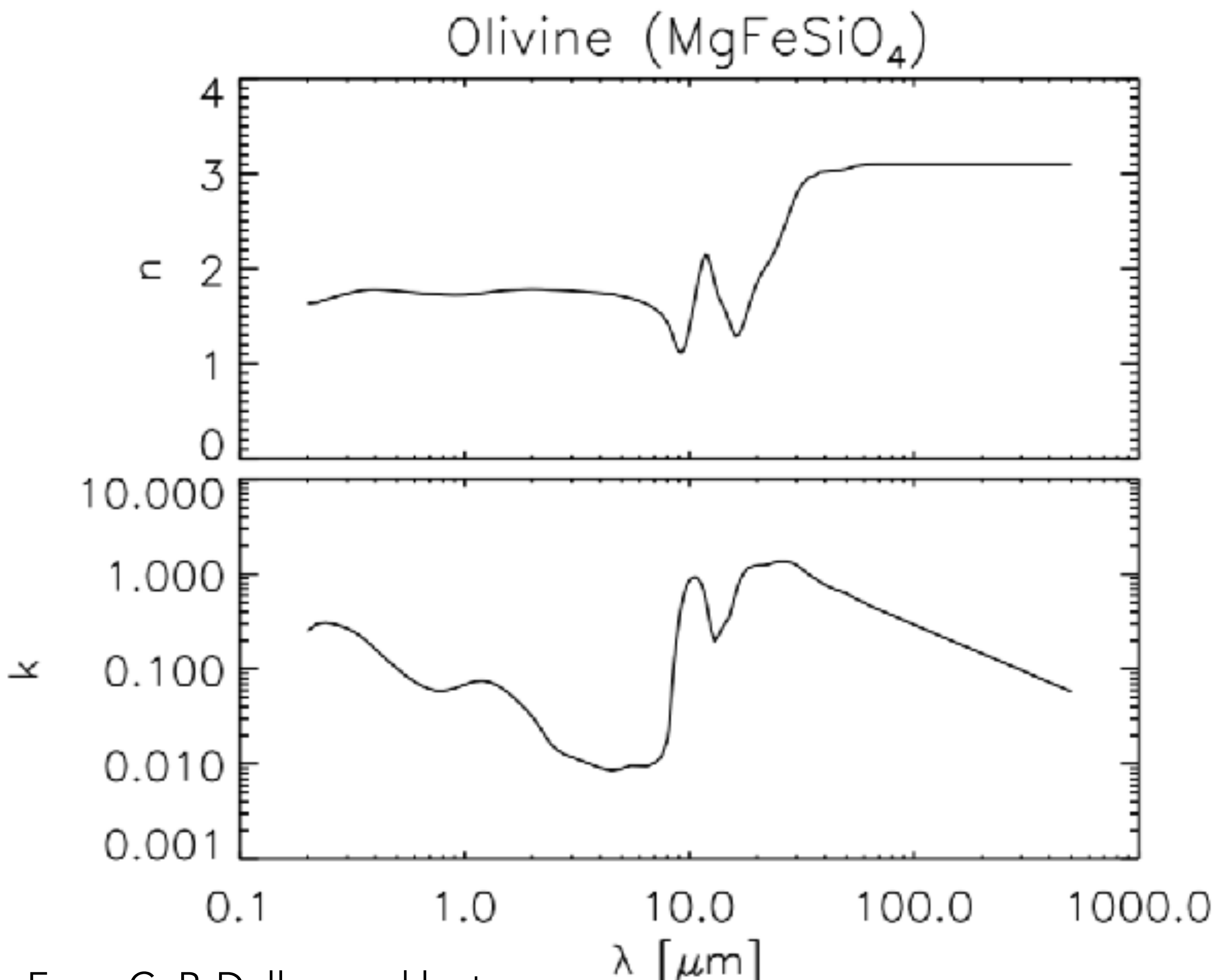
response of material to E field set by *dielectric function*

$$\epsilon(\omega) = \epsilon_1 + i\epsilon_2$$

related to *index of refraction*

$$m = \sqrt{\epsilon}$$

Index of Refraction

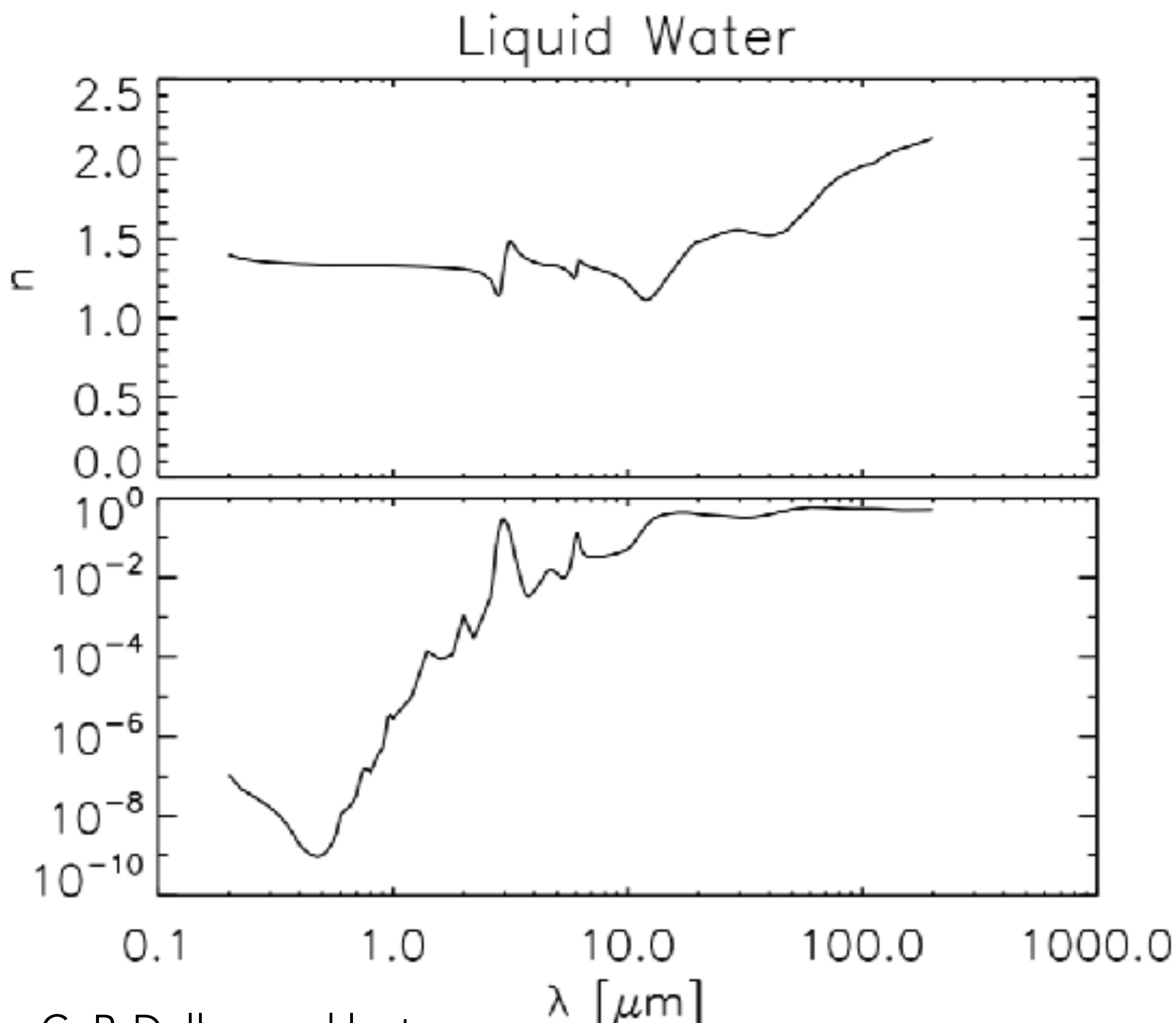


From C. P. Dullemond lectures on radiative transfer

$$m(\lambda) = n(\lambda) - ik(\lambda)$$

Complex number, wavelength dependent.

Index of Refraction



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Complex number, wavelength dependent.

Scattering & Absorption of Light by Small Particles

Define:

Geometrical Cross Section: πa^2

Absorption Cross Section: $C_{abs}(\lambda)$

Scattering Cross Section: $C_{sca}(\lambda)$

Extinction Cross Section: $C_{ext}(\lambda) = C_{abs}(\lambda) + C_{sca}(\lambda)$

Scattering & Absorption of Light by Small Particles

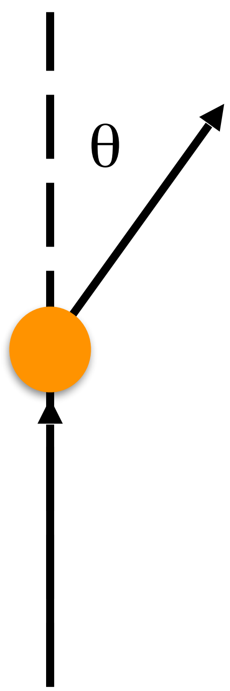
Define:

Geometrical Cross Section: πa^2

Scattering & Absorption Efficiency Factors

$Q_{abs} = C_{abs}/\pi a^2$ $\qquad\qquad$ $Q_{sca} = C_{sca}/\pi a^2$

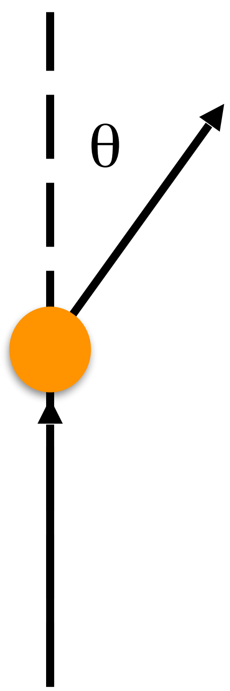
Scattering & Absorption of Light by Small Particles



Scattering Definitions:

Albedo = C_{sca}/C_{ext}

Scattering & Absorption of Light by Small Particles



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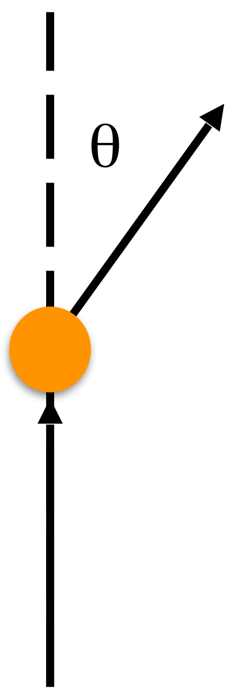
Differential scattering angle $$\frac{dC_{sca}(\theta)}{d\Omega}$$

Scattering & Absorption of Light by Small Particles



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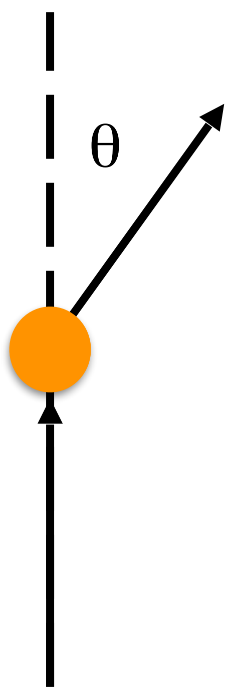
Scattering asymmetry factor $$\langle \cos\theta \rangle = \frac{1}{C_{sca}} \int_0^{\pi} \cos\theta \frac{dC_{sca}(\theta)}{d\Omega} 2\pi \sin\theta d\theta$$

Scattering & Absorption of Light by Small Particles



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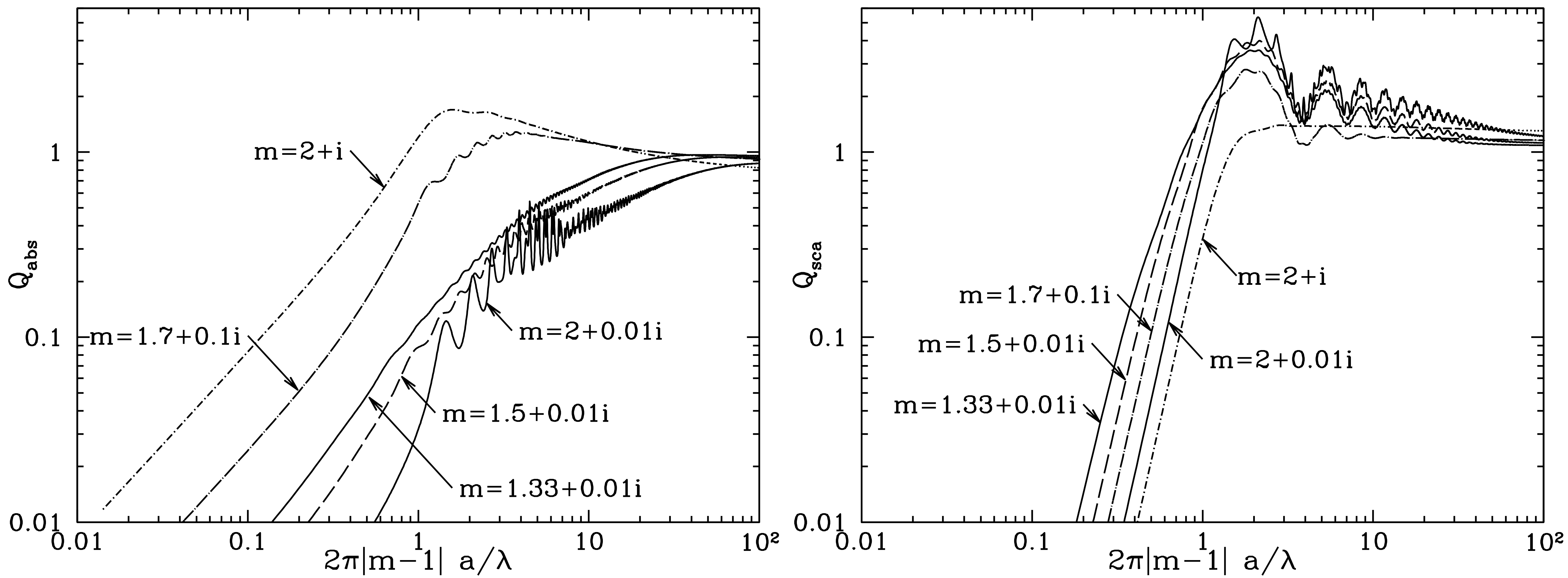
- Isotropic scattering $\langle \cos\theta \rangle = 0$
- Forward scattering $\langle \cos\theta \rangle = 1$
- Back scattering $\langle \cos\theta \rangle = -1$

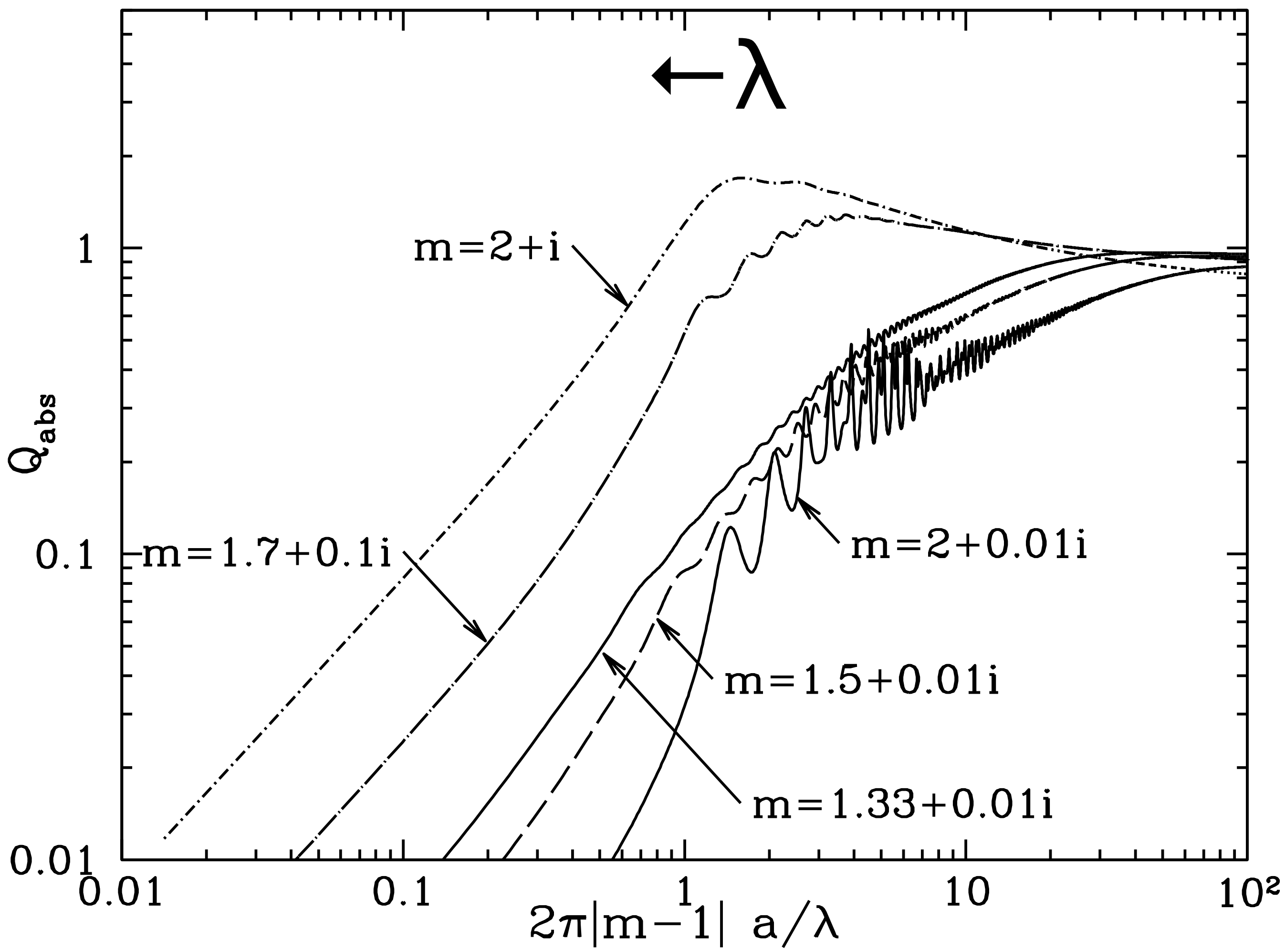
Scattering & Absorption of Light by Small Particles



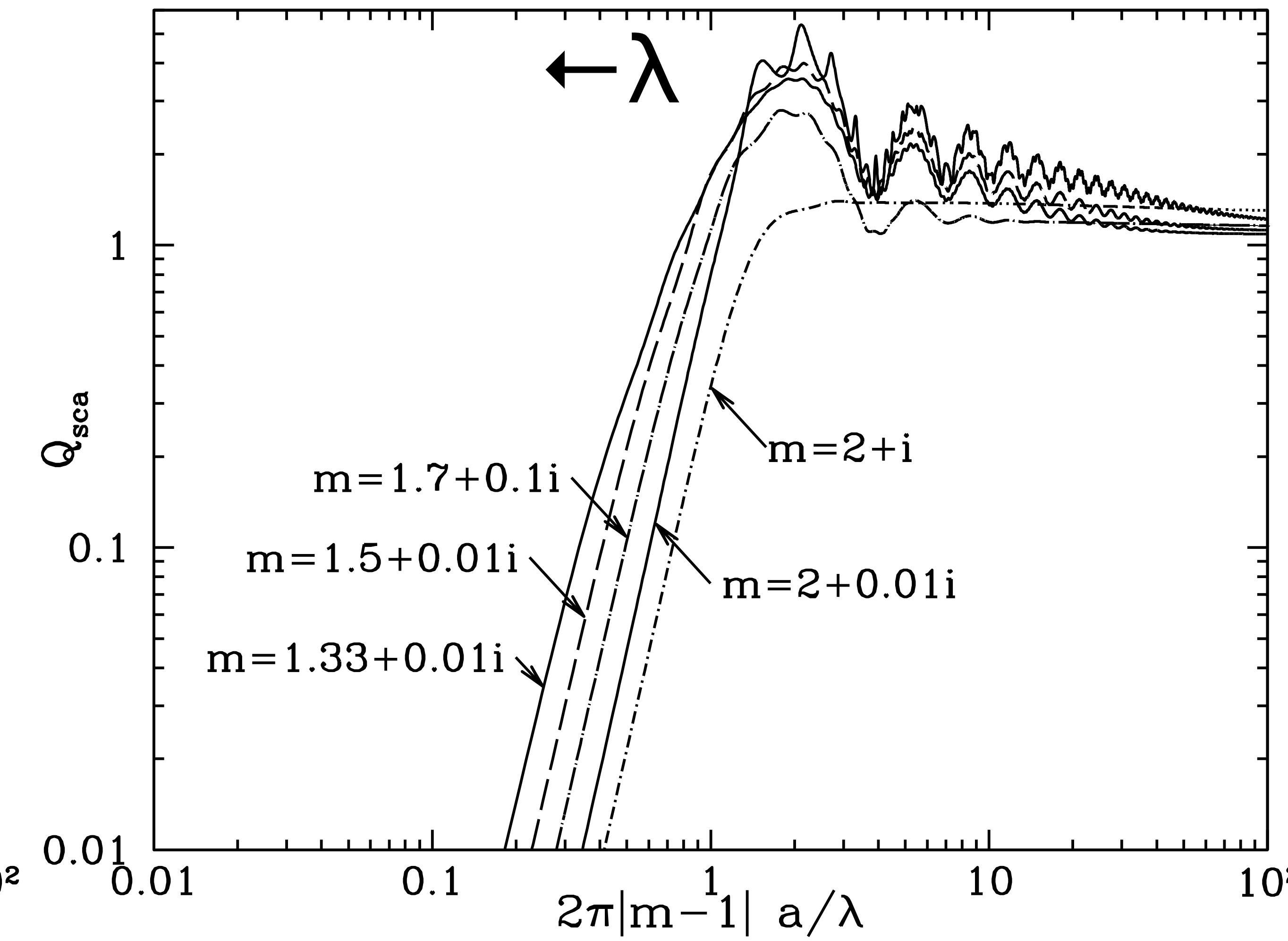
a/λ - grain size relative to wavelength of light defines different regimes

Scattering & Absorption of Light by Small Particles

for fixed a



for fixed a



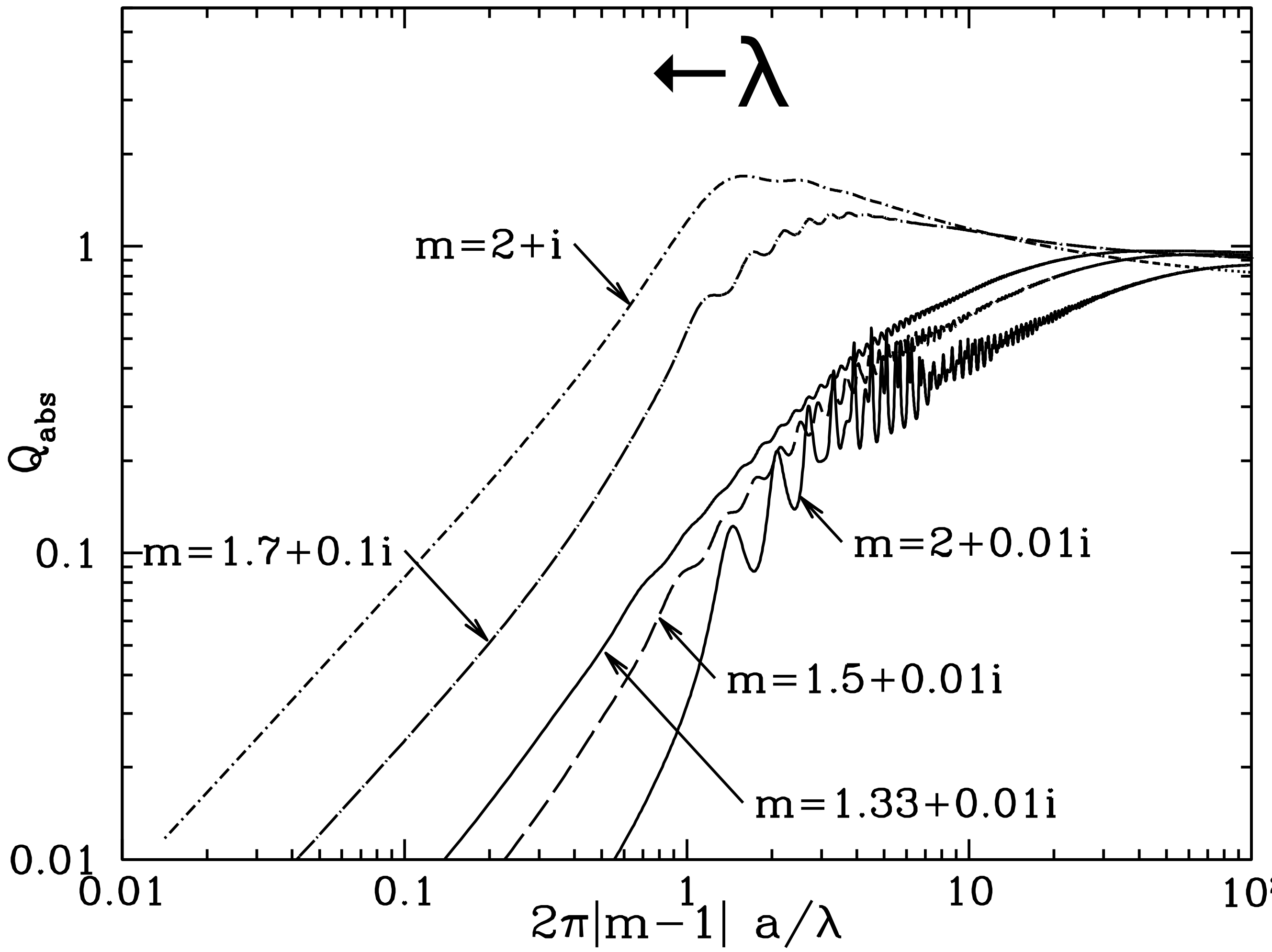
a/λ << 1 grain much smaller than wavelength - analytic soln's

$$Q_{\rm abs} = 4\frac{2\pi a}{\lambda}{\rm Im}\left(\frac{\epsilon-1}{\epsilon+2}\right)$$

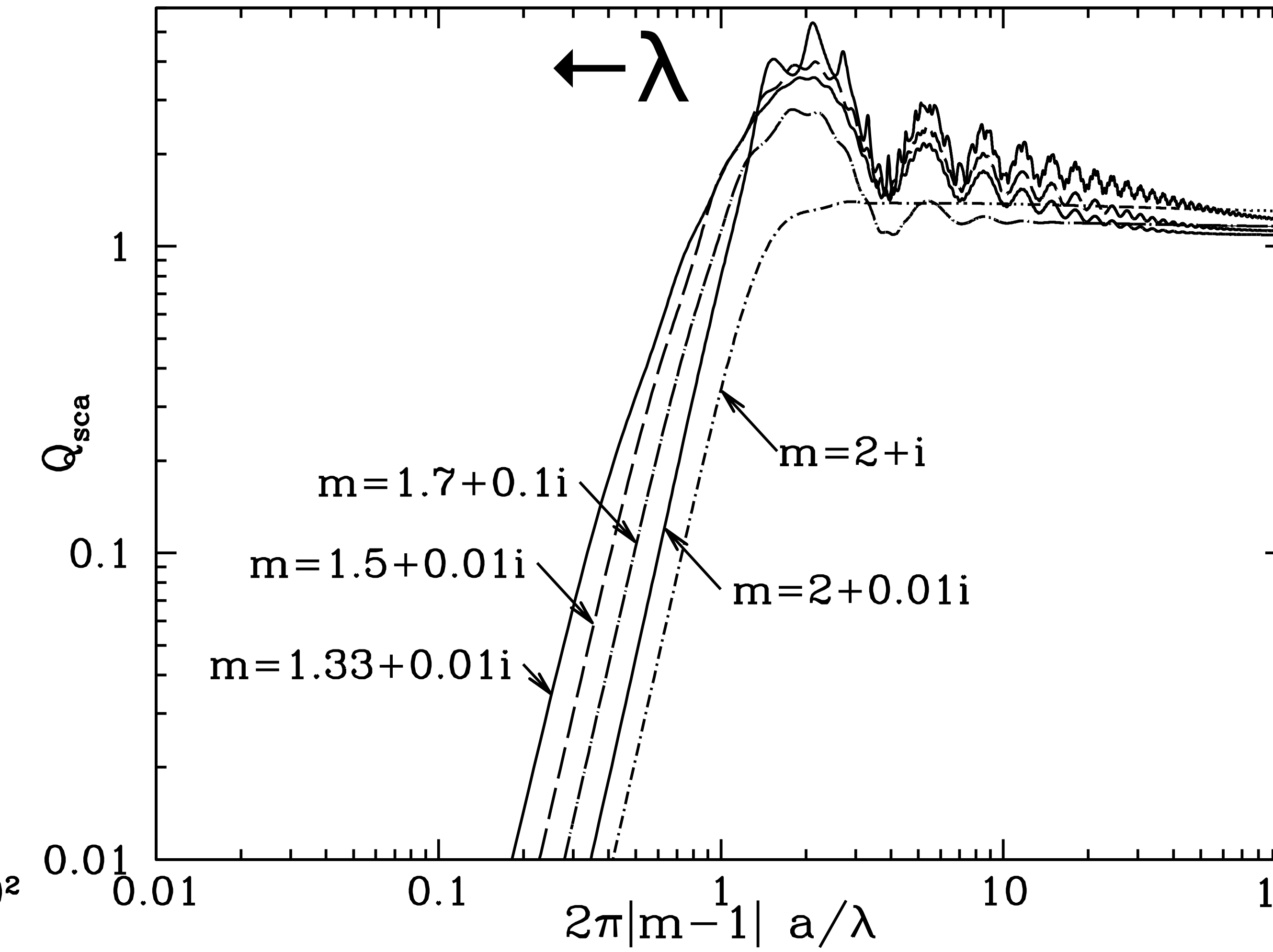
$$Q_{\rm sca} = \frac{8}{3}\left(\frac{2\pi a}{\lambda}\right)^4\left|\frac{\epsilon-1}{\epsilon+2}\right|^2$$

Scattering & Absorption of Light by Small Particles

for fixed a



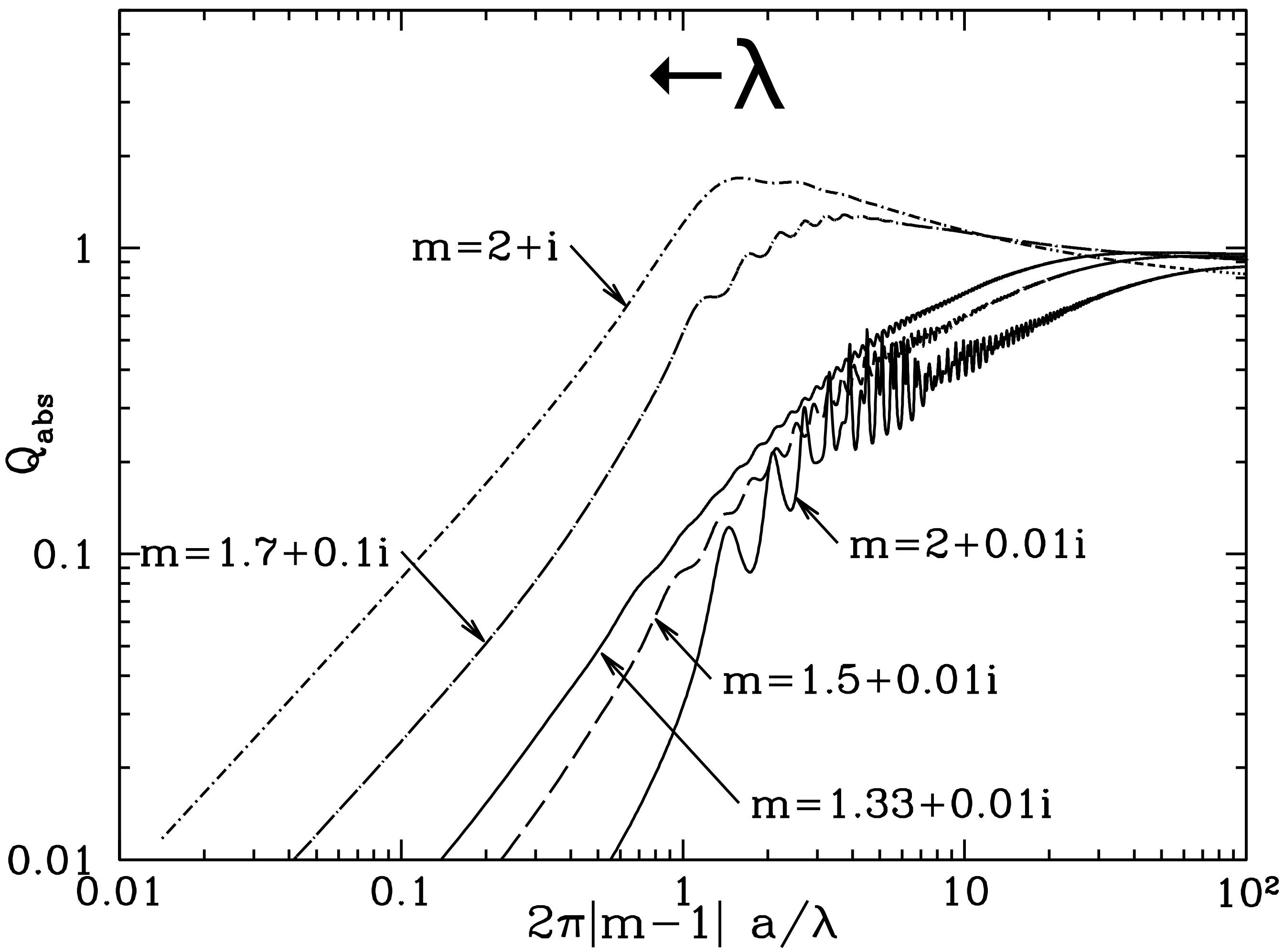
for fixed a



$a/\lambda \sim 1$ use Mie theory

Scattering & Absorption of Light by Small Particles

for fixed a



Absorption

note that
at long wavelength:

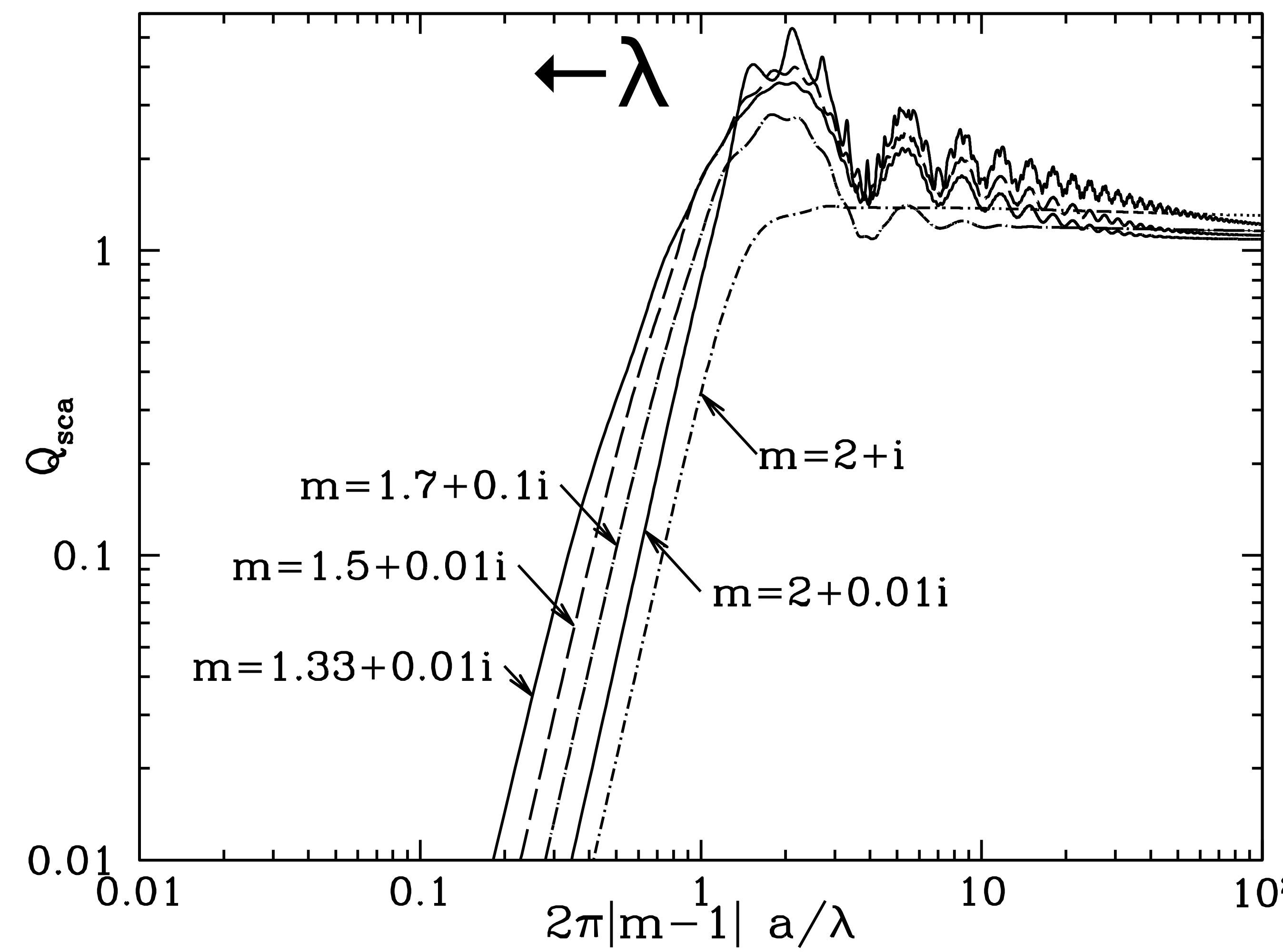
$C_{abs} = Q_{abs}\pi a^2 \propto a^3 \propto m_{dust}$

absorption efficiency when
$a >> \lambda$
levels off to 1, $C_{abs} = \pi a^2$

$$Q_{\rm abs} = 4\frac{2\pi a}{\lambda}{\rm Im}\left(\frac{\epsilon-1}{\epsilon+2}\right)$$

Scattering & Absorption of Light by Small Particles

for fixed a



<u>Scattering</u>

scattering efficiency drops steeply with wavelength when a/λ << 1

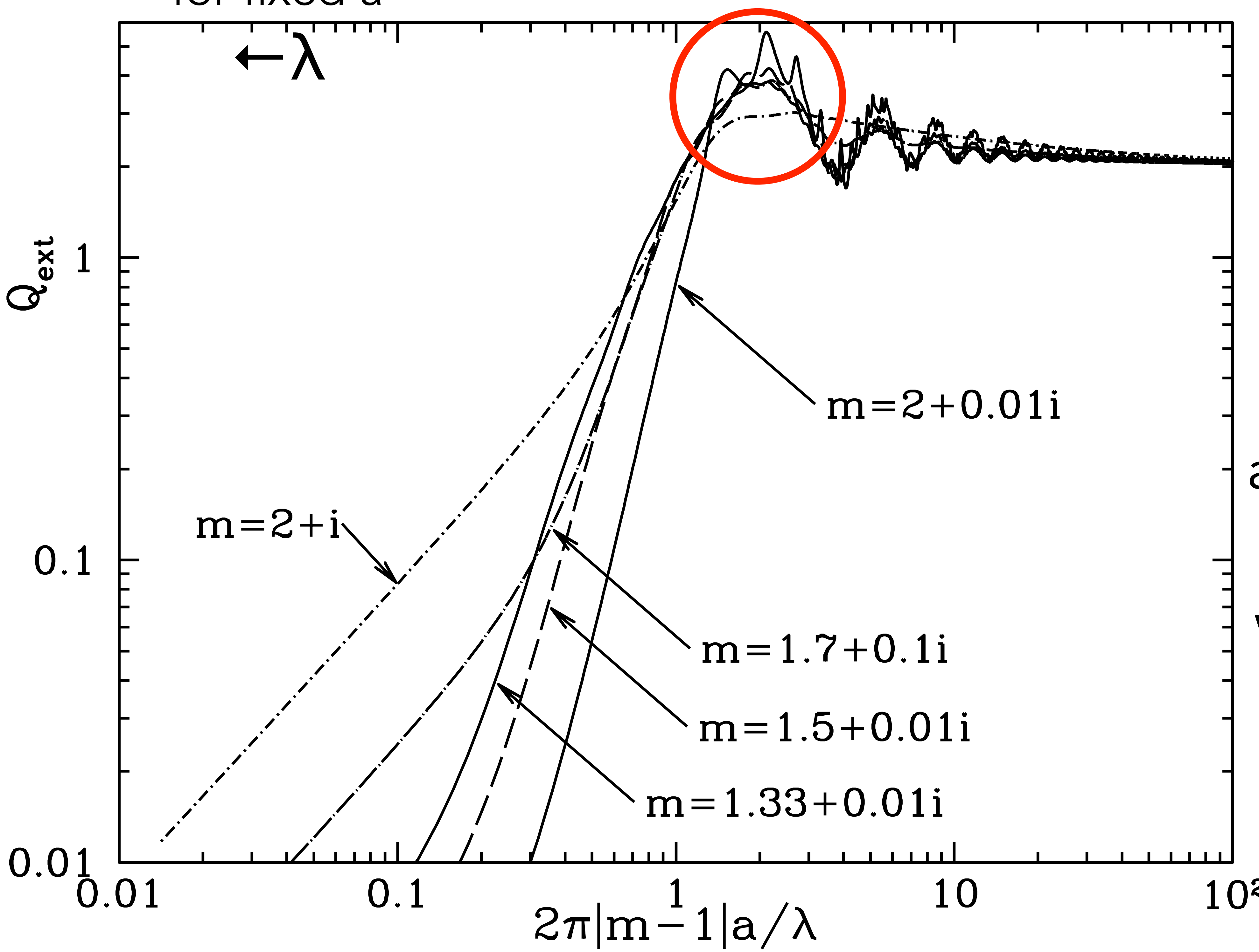
Rayleigh scattering λ^{-4}

$$Q_{\rm sca} = \frac{8}{3}\left(\frac{2\pi a}{\lambda}\right)^4 \left|\frac{\epsilon - 1}{\epsilon + 2}\right|^2$$

Reflection Nebula vdB1
Image Credit & Copyright: Adam Block,
Mt. Lemmon SkyCenter, University of Arizona

Scattering & Absorption of Light by Small Particles

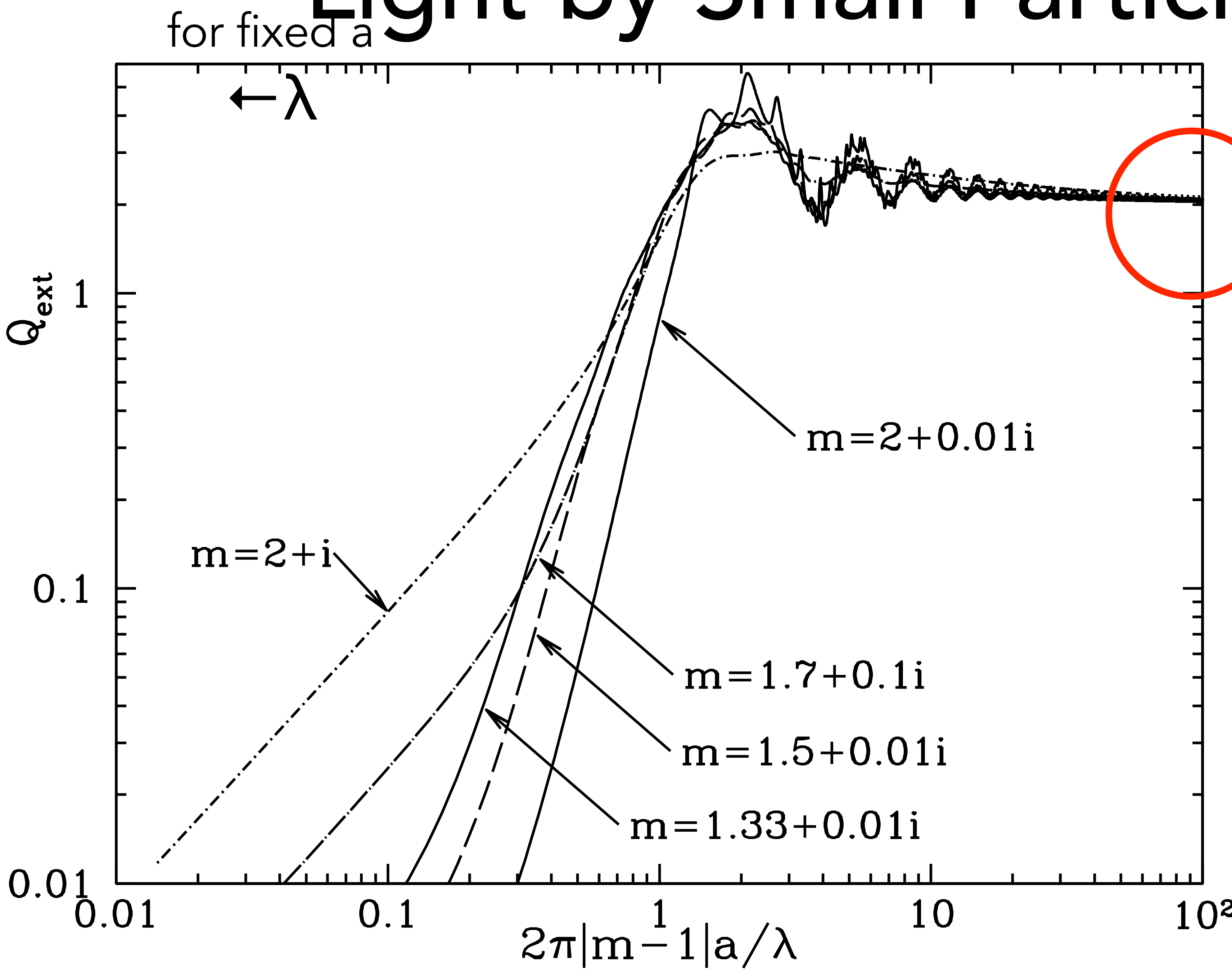
for fixed a



Maximum Q_{ext} occurs where $\lambda \sim a$

i.e. dust grains are most effective at blocking light with wavelengths close to their sizes

Scattering & Absorption of Light by Small Particles



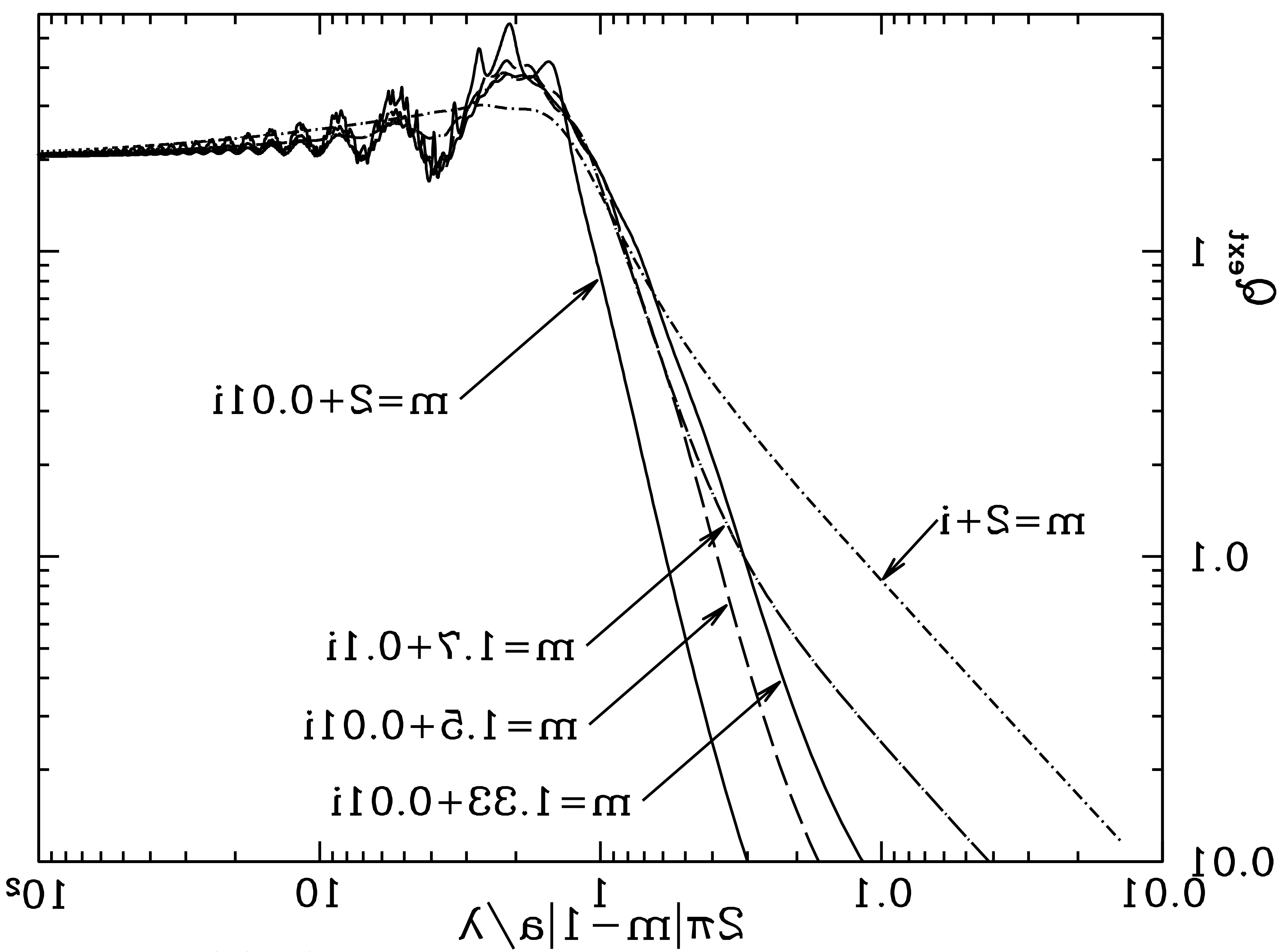
when a>>λ

Q_{ext} ~ 2

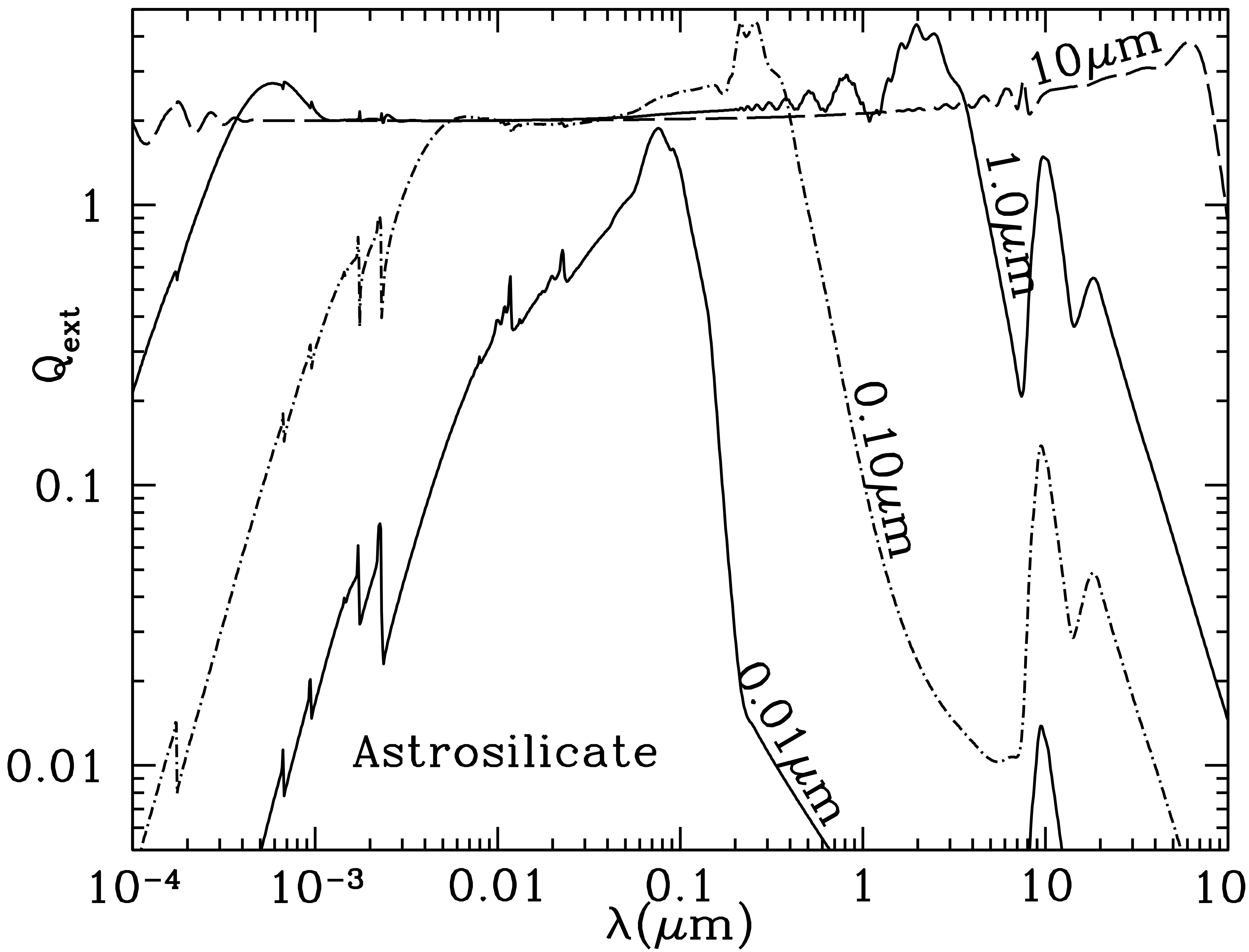
i.e. twice the geometrical cross sec

b.c. diffraction!!

Scattering & Absorption of Light by Small Particles

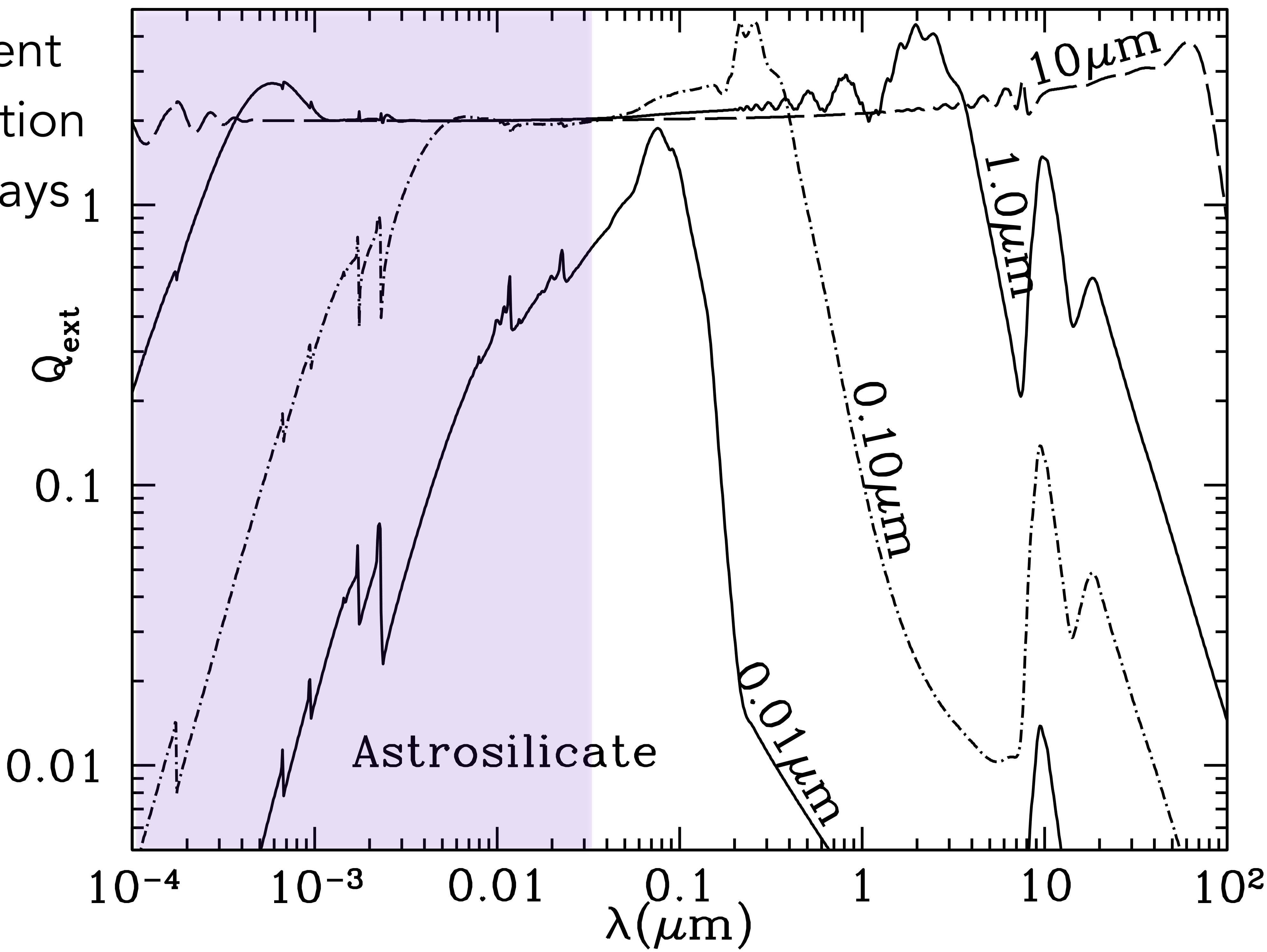


Astronomical Dust

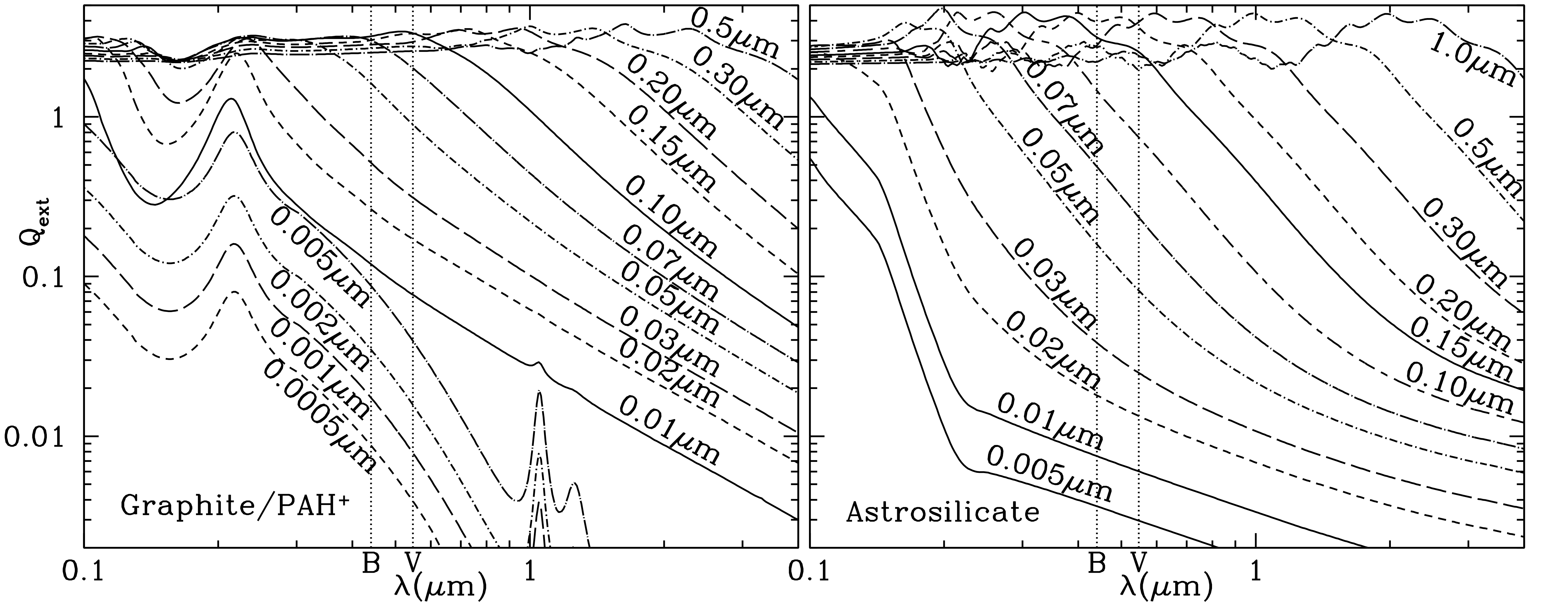


Astronomical Dust

Need different calculation for x-rays

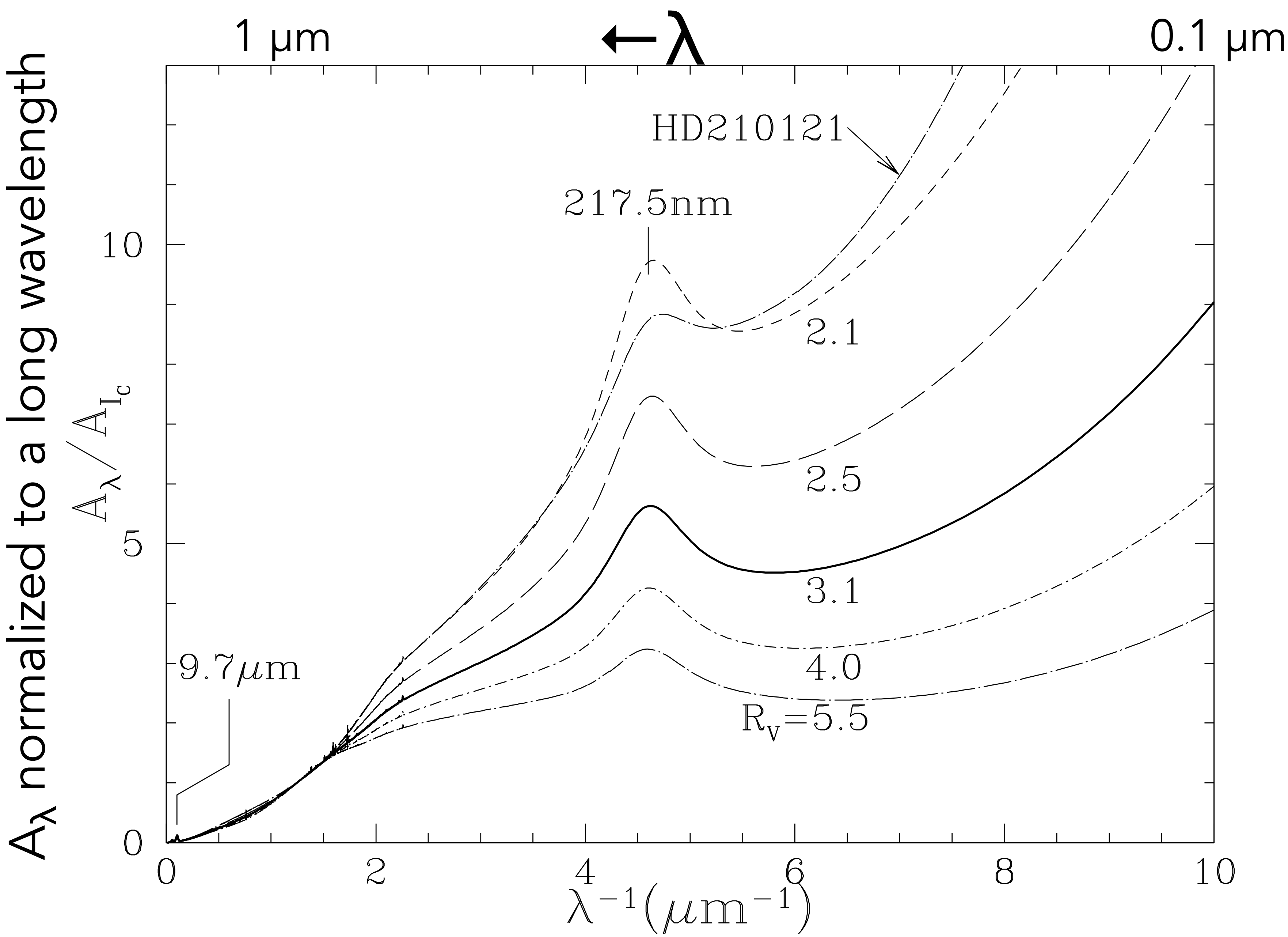


Astronomical Dust



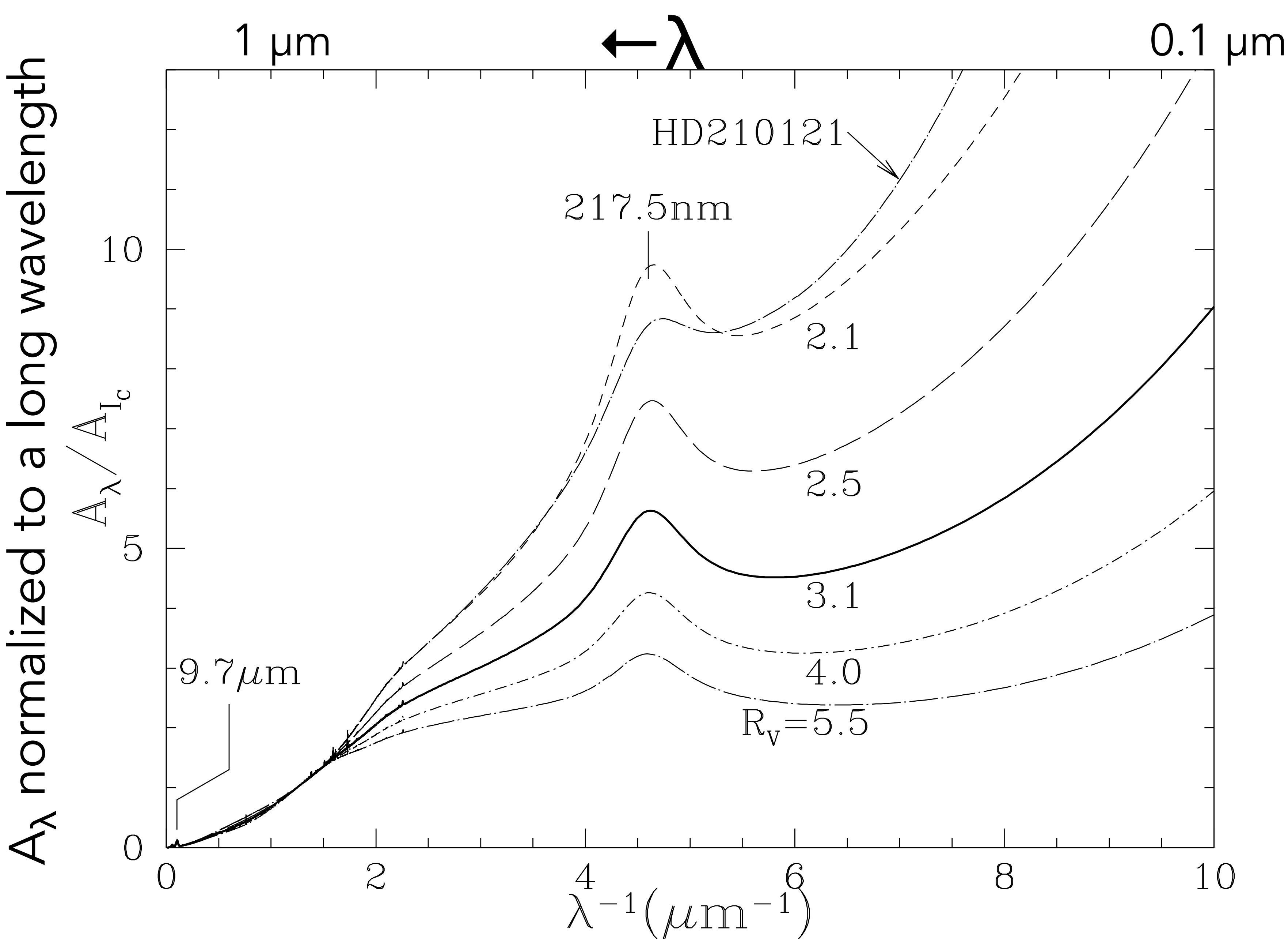
Q_{ext} for astronomical dust analogs

Extinction Curve



This does not look like the Q_{ext} plots from before - why?

Extinction Curve



This does not look like the Q_{ext} plots from before - why?

There is a range of grain sizes!