

Physics 224

The Interstellar Medium

Lecture #9: HII Regions and DUST!!!!

Outline

- Part I: Nebular Diagnostics
- Part II: Heating & Cooling in HII Regions
- Part III: Dust

Part I: Nebular Diagnostics

Nebular Diagnostics

Collisionally excited lines from ionized gas that give us diagnostics for density, temperature, etc.

Two types:

- 1) temperature sensitive
- 2) density sensitive

Temperature Sensitive Line Ratios

What we want:

two levels that can both be collisionally excited at typical HII region temperatures ($\sim 10^4$ K) but which have different enough energies that the ratio of populations depends on temperature of the gas

Requires two energy levels with $E/k < 70,000$ K

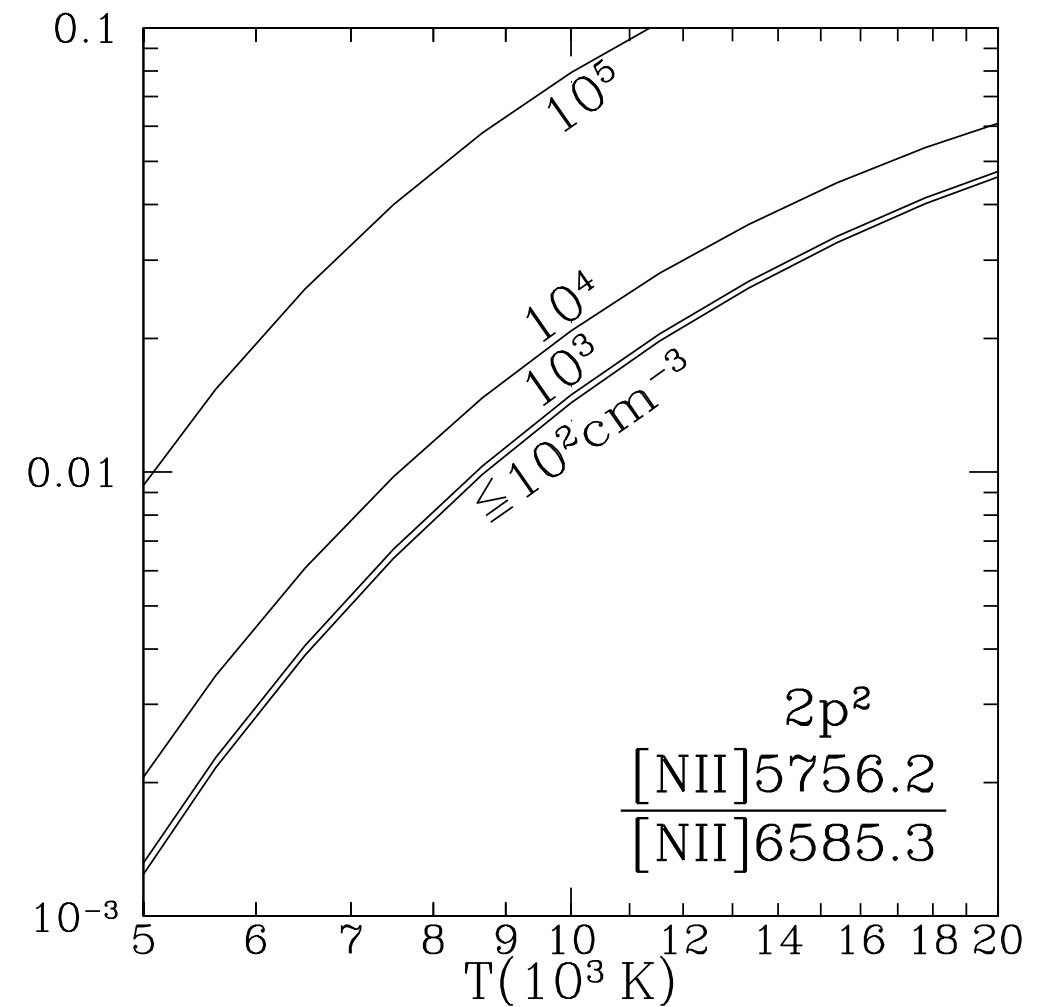
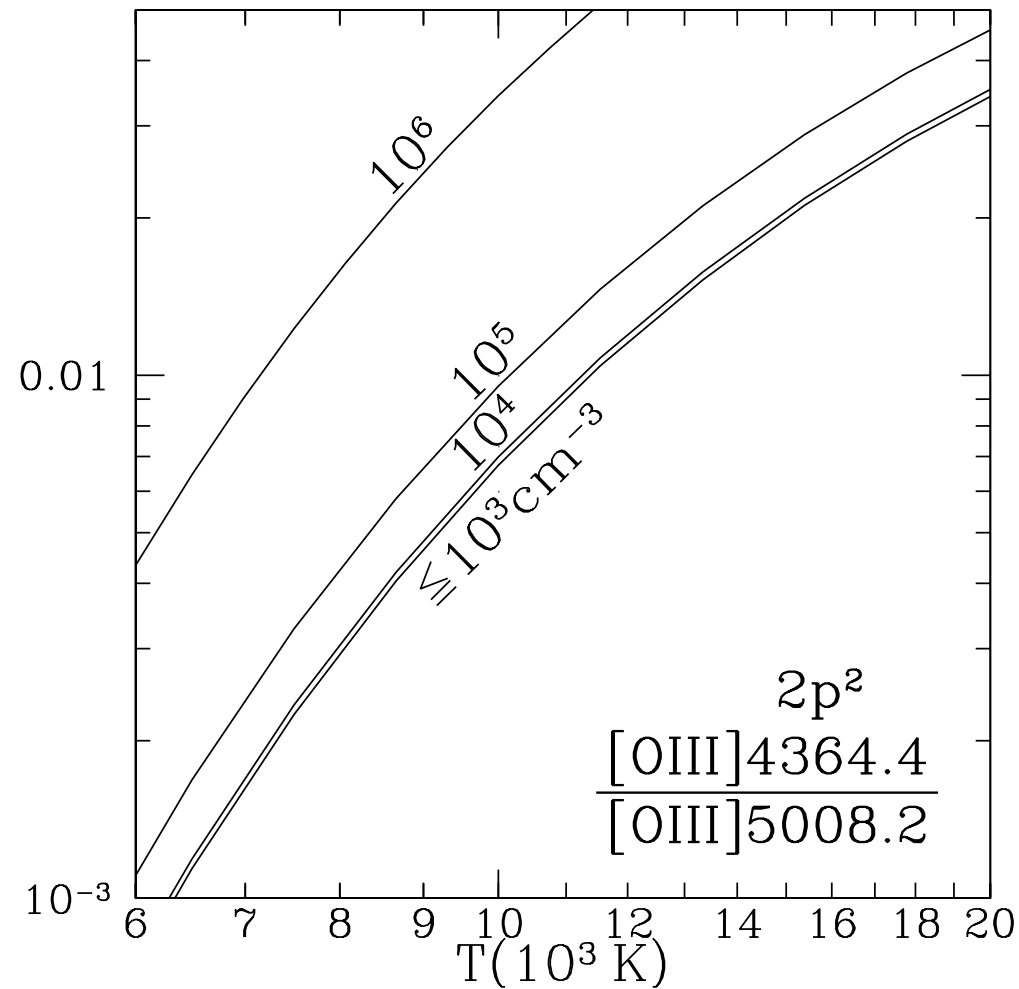
Temperature Sensitive Line Ratios

$$\frac{P(4 \rightarrow 3)}{P(3 \rightarrow 2)} = \frac{A_{43}E_{43}}{A_{32}E_{32}} \left[\frac{\Omega_{40}(A_{32} + A_{31})}{\Omega_{30}(A_{43} + A_{41})e^{E_{43}/kT} + \Omega_{40}A_{43}} \right]$$

Line ratio doesn't depend on density,
only on temperature.

Only density insensitive below the critical density.

Temperature Sensitive Line Ratios

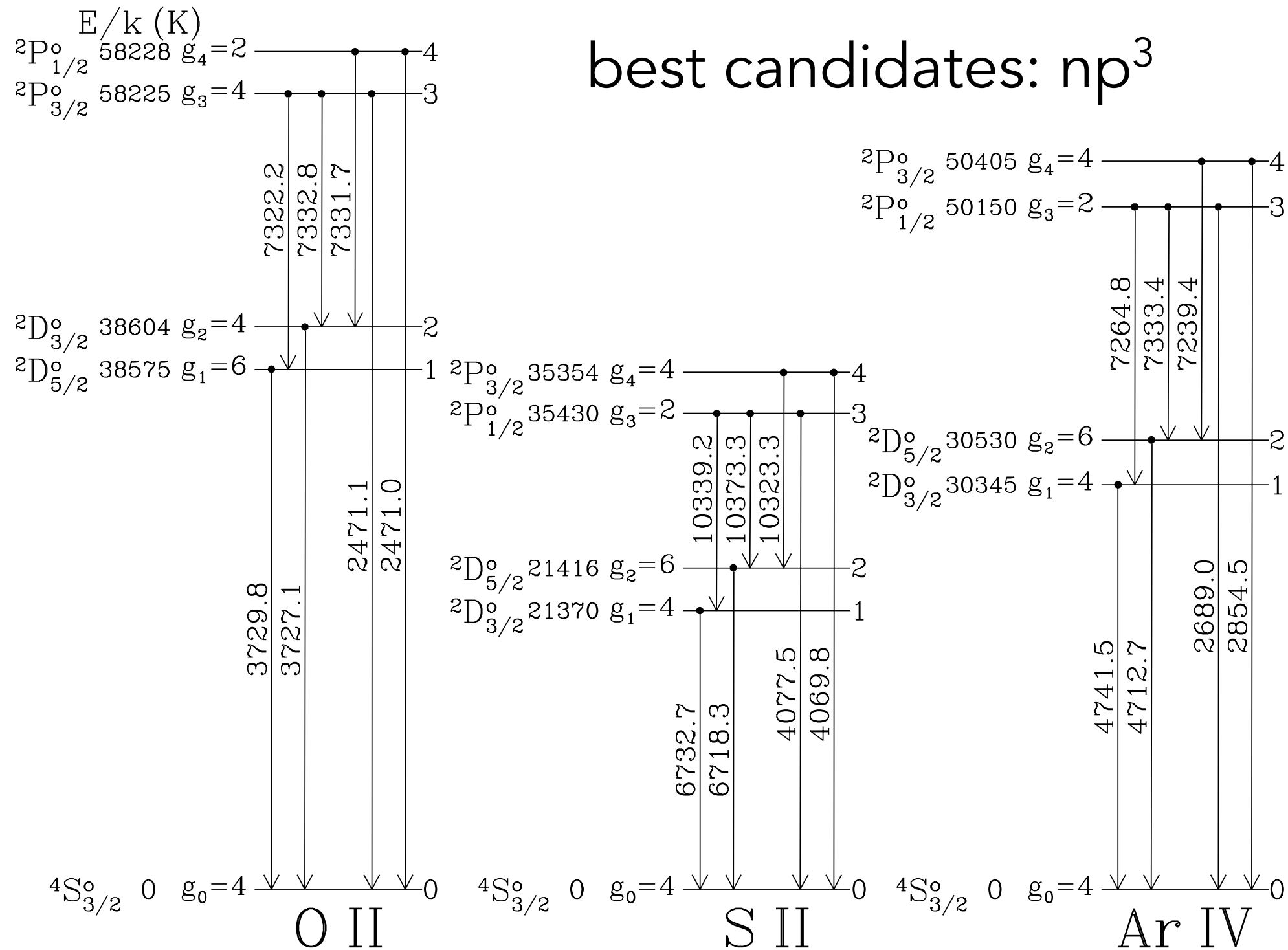


Density Sensitive Line Ratios

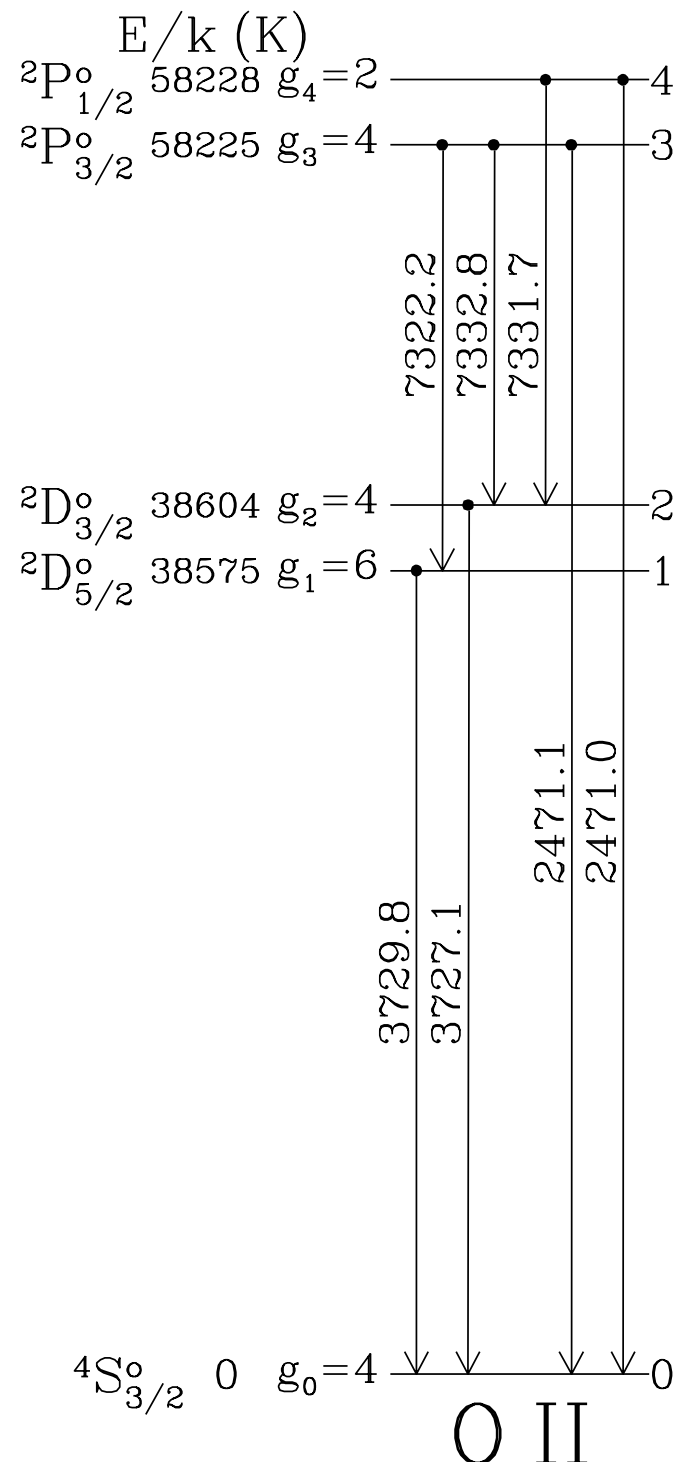
What we want:

two levels at approximately the same energy
that can be collisionally excited so that
line ratio doesn't depend on temperature but
does depend on collisional excitation rate

Density Sensitive Line Ratios



Density Sensitive Line Ratios



Lets look at $2 \rightarrow 0$ and $1 \rightarrow 0$ transitions

Low Density Limit

at low densities, every collisional excitation leads to a radiative transition

$$P(2 \rightarrow 0) = n_e k_{02} E_{20}$$

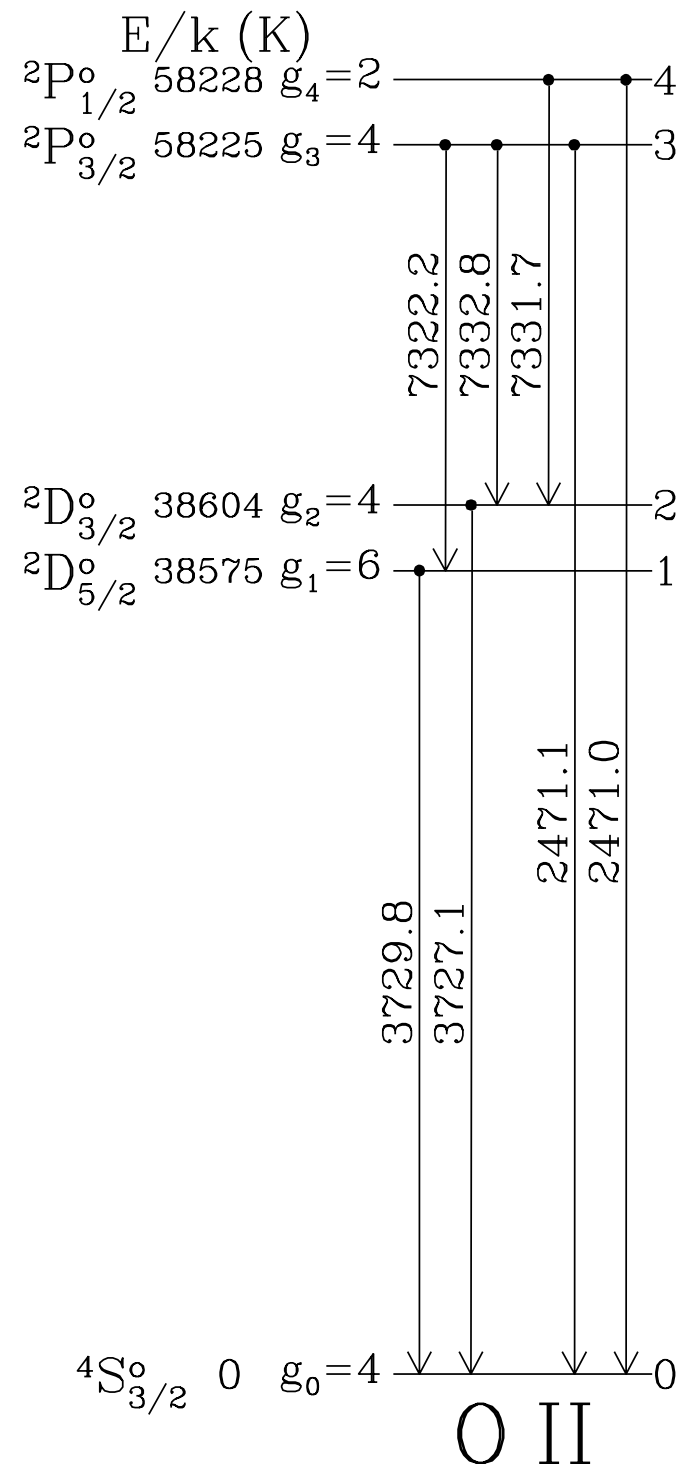
$$P(1 \rightarrow 0) = n_e k_{01} E_{10}$$

$$\frac{P(2 \rightarrow 0)}{P(1 \rightarrow 0)} = \frac{E_{20} k_{02}}{E_{10} k_{01}} = \frac{E_{20} \Omega_{20}}{E_{10} \Omega_{10}} e^{-E_{21}/kT}$$

approximately equal

~ 1

Density Sensitive Line Ratios



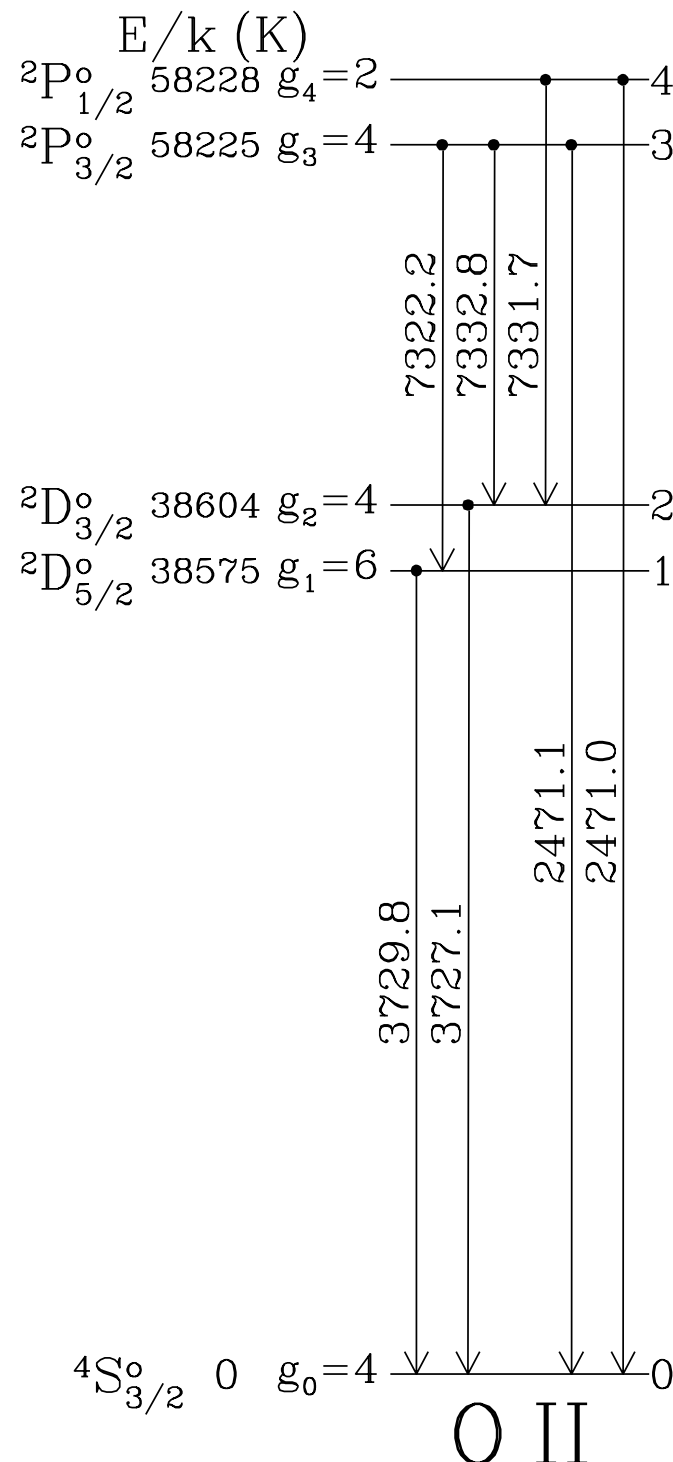
Lets look at $2 \rightarrow 0$ and $1 \rightarrow 0$ transitions

High Density Limit

Level populations set by collisions,
radiative transitions occur but don't
control the level populations

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} e^{-E_{21}/kT} \sim 1$$

Density Sensitive Line Ratios



Lets look at $2 \rightarrow 0$ and $1 \rightarrow 0$ transitions

High Density Limit

Rate of spontaneous emission:

$$(2 \rightarrow 0): n_2 A_{20}$$

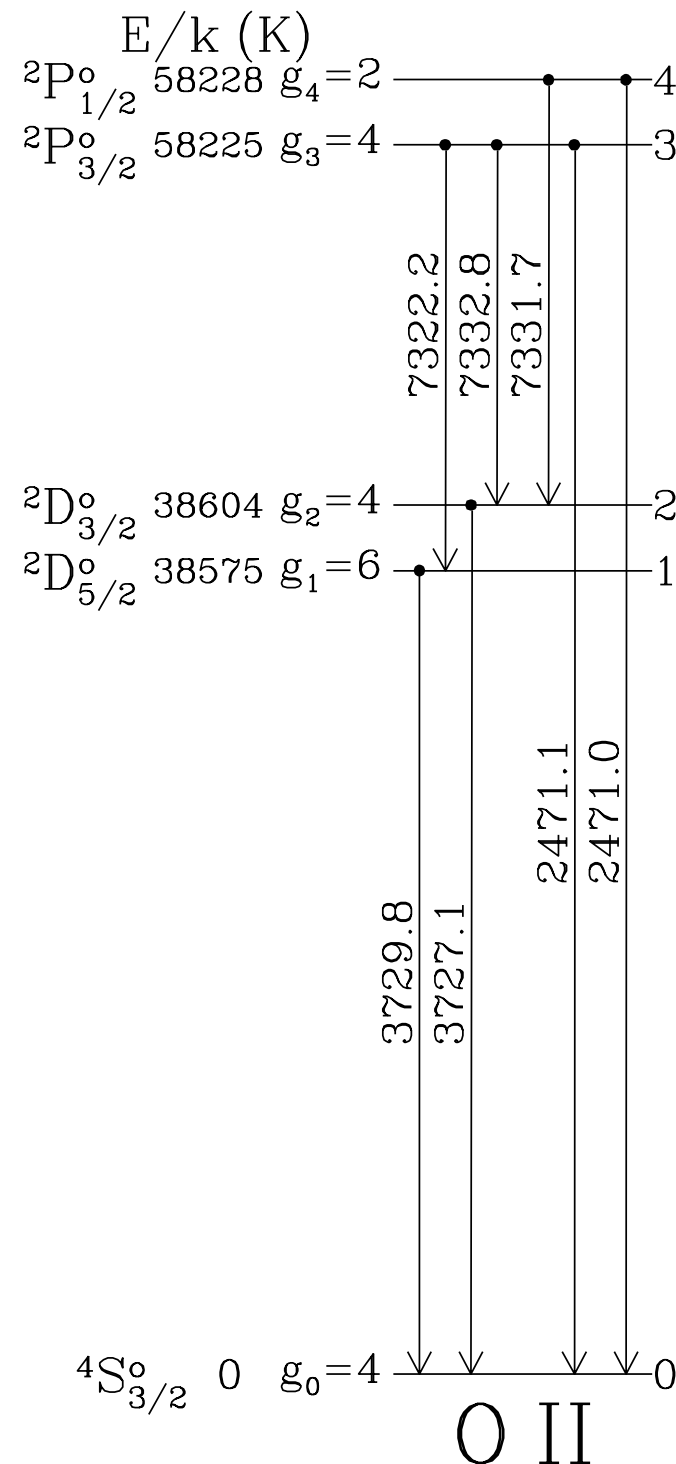
$$(1 \rightarrow 0): n_1 A_{10}$$

$$\frac{P(2 \rightarrow 0)}{P(1 \rightarrow 0)} = \frac{E_{20} A_{20} g_2}{E_{10} A_{10} g_1} e^{-E_{21}/kT}$$

approximately equal

~ 1

Density Sensitive Line Ratios



Lets look at $2 \rightarrow 0$ and $1 \rightarrow 0$ transitions

High Density Limit

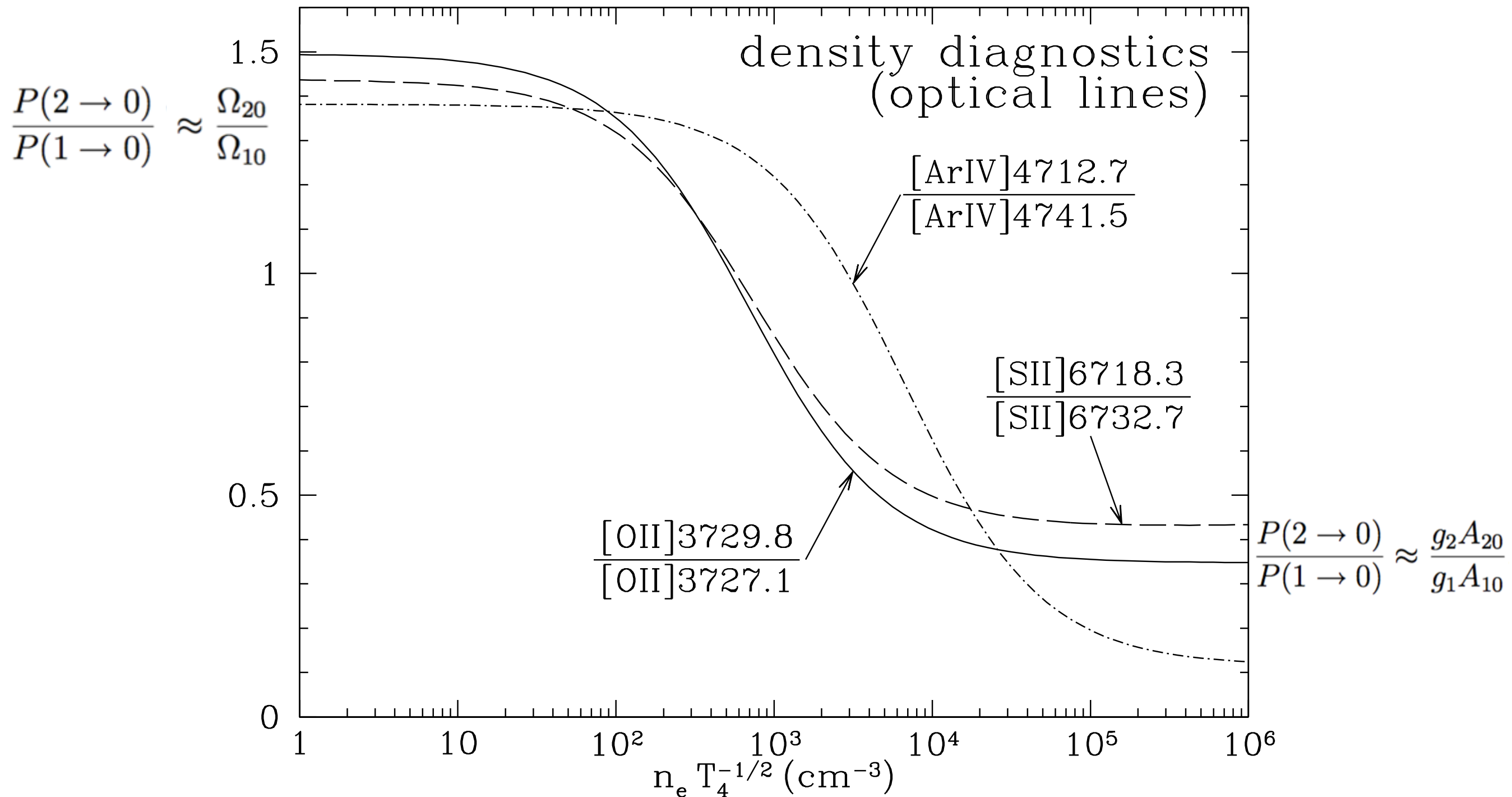
Rate of spontaneous emission:

$$(2 \rightarrow 0): n_2 A_{20}$$

$$(1 \rightarrow 0): n_1 A_{10}$$

$$\frac{P(2 \rightarrow 0)}{P(1 \rightarrow 0)} \approx \frac{g_2 A_{20}}{g_1 A_{10}}$$

Density Sensitive Line Ratios



Part IV: Heating & Cooling in HII Regions

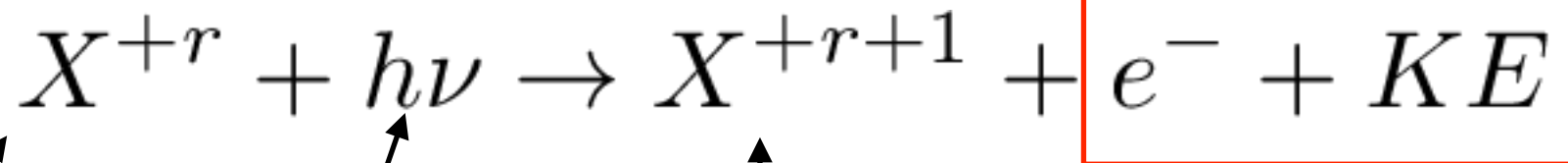
Heating

- Photoionization heating

*Dominates in almost
all circumstances*

- Photoelectric Emission from dust
- Cosmic Rays
- Damping of magnetohydrodynamic waves

Heating



Species X
in ionization state r

Species X
in ionization state $r+1$

initial photon energy

electron carries away
some kinetic energy

If $h\nu_0$ = ionization threshold energy
each photoionization injects an electron with $E_{\text{kin}} = (h\nu - h\nu_0)$

Heating

heating rate
per unit volume

$$\Gamma_{\text{pi}} = n(X^{+r}) \int_{\nu_0}^{\infty} \sigma_{\text{pi}}(\nu) c \left[\frac{u_{\nu}}{h\nu} \right] (h\nu - h\nu_0) d\nu$$

collision rate per unit volume
of atoms/ions in state r with photons

kinetic energy
produced per
ionization



Heating

To estimate heating rates we can define:

$$\psi \equiv \frac{E_{\text{pi}}(X^{+r})}{kT_c}$$

← average photoelectron energy
← "color temperature" of star

"color temperature" means the temperature of a blackbody spectrum that approximates the spectrum of the star

Heating

Right near the star, before any of the stellar spectrum has been absorbed.

$$\psi_0 \equiv \frac{1}{kT_c} \frac{\int_{\nu_0}^{\infty} \sigma_{\text{pi}}(\nu) \frac{B_{\nu}(T_c)}{h\nu} h(\nu - \nu_0) d\nu}{\int_{\nu_0}^{\infty} \sigma_{\text{pi}}(\nu) \frac{B_{\nu}(T_c)}{h\nu} d\nu}$$

ψ should be ~ 1

Because $T_{13.6 \text{ eV}} \gg T_c$ we are in the low freq part of the blackbody, where slope with ν is fixed.

Heating

heating rate
per unit volume

$$\boxed{\Gamma_{\text{pi}}} = n(X^{+r}) \int_{\nu_0}^{\infty} \sigma_{\text{pi}}(\nu) c \left[\frac{u_{\nu}}{h\nu} \right] (h\nu - h\nu_0) d\nu$$

Depends on density of species being ionized.

Heating

heating rate
per unit volume

$$\Gamma_{\text{pi}} = \frac{n(X^{+r}) \int_{\nu_0}^{\infty} \sigma_{\text{pi}}(\nu) c \left[\frac{u_{\nu}}{h\nu} \right] (h\nu - h\nu_0) d\nu}{\alpha_B n_e n(X^{+r+1}) \psi k T_c}$$

In ionization equilibrium
rate of ionization = rate of recombination

Cooling

- Recombination
- Free-free Emission
- Collisional excitation

*All can be important,
collisional excitation is
dominant.*

Cooling

Recombination removes kinetic energy from the gas

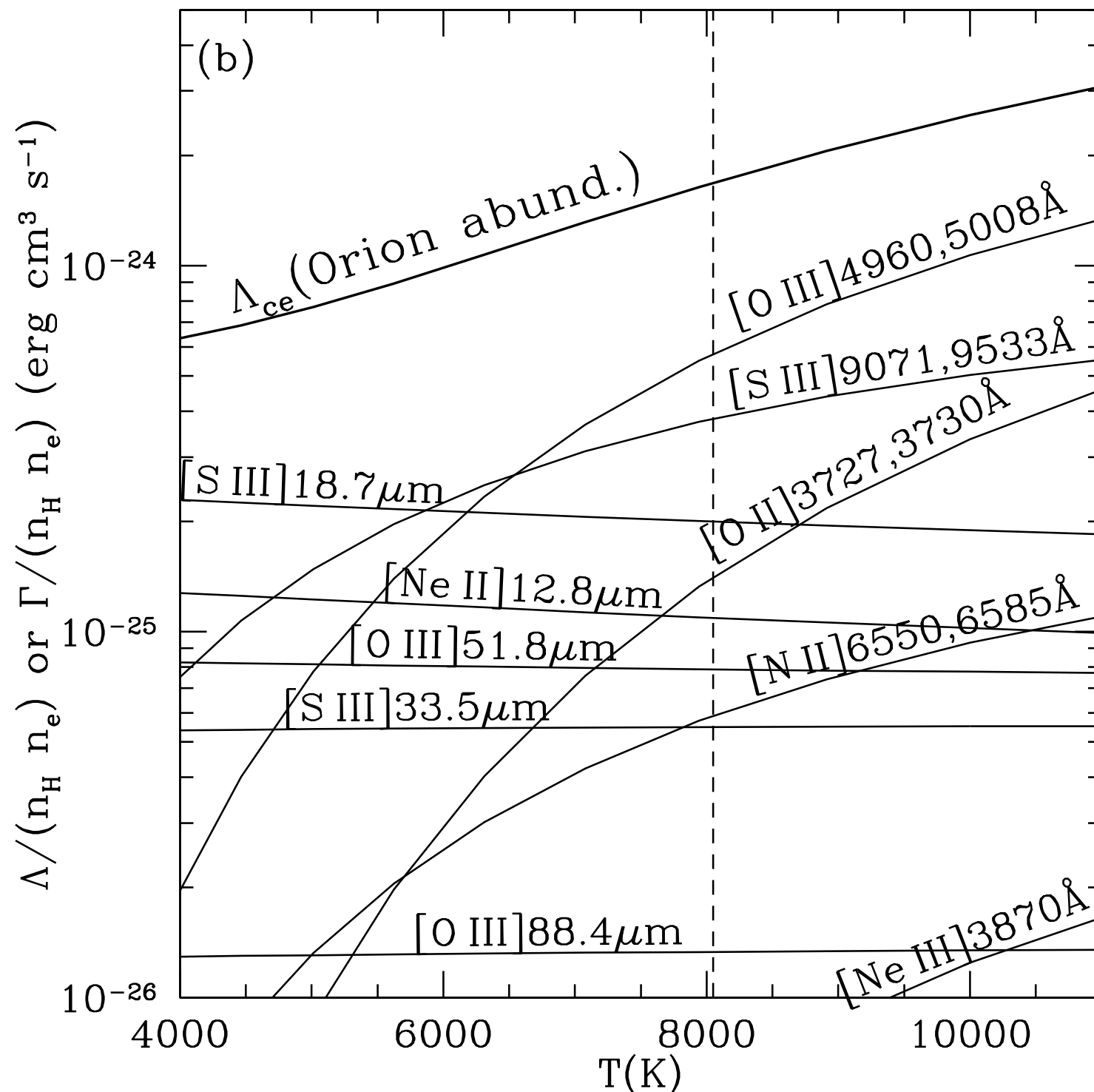
$$\Lambda_{\text{rr}} = \alpha_{A,B} n_e n_{\text{H}^+} \langle E_{\text{rr}} \rangle$$

cooling rate
per unit volume

average energy of
recombining electron

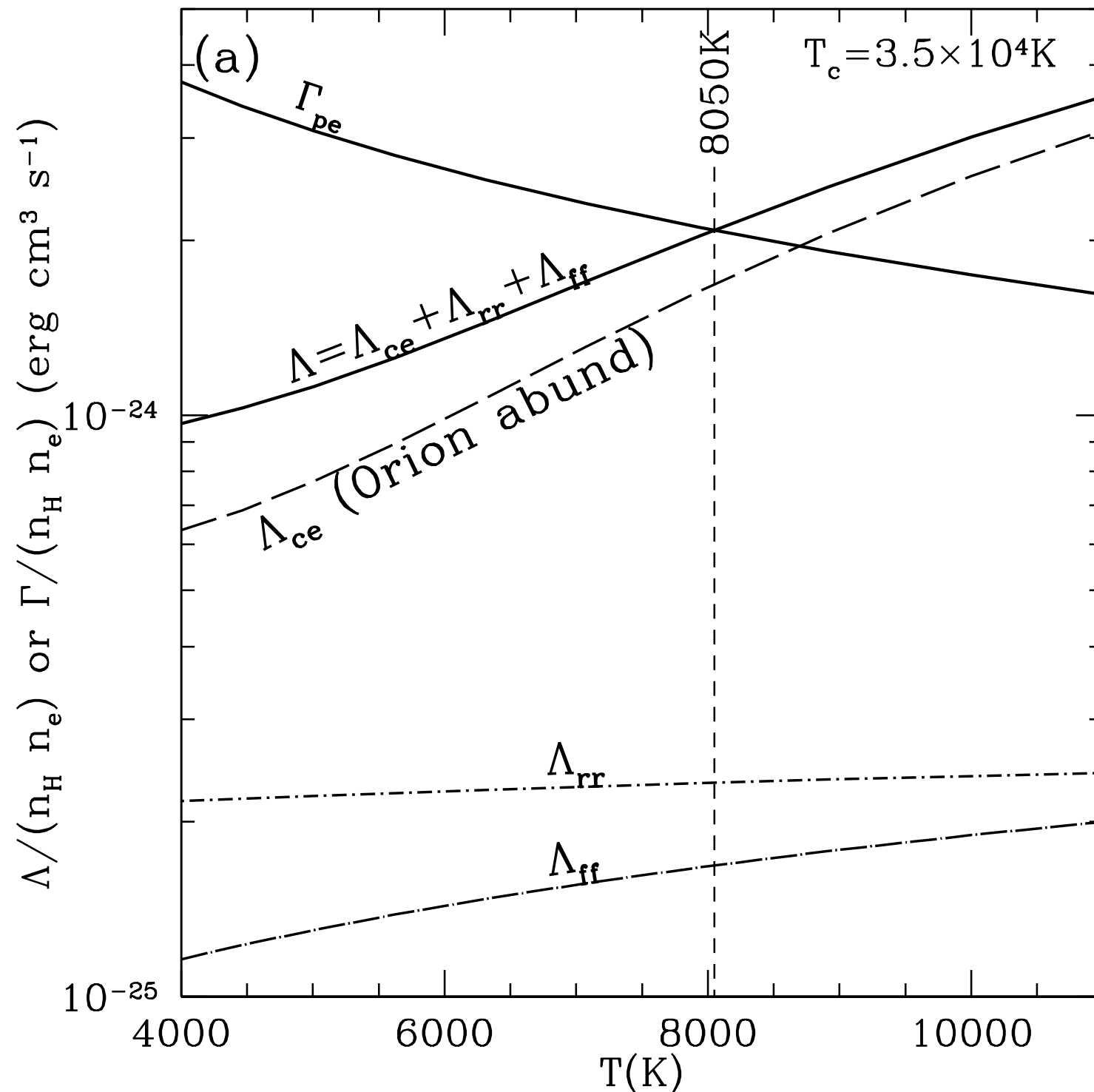
$\langle E_{\text{rr}} \rangle <$ mean electron kinetic energy of the gas
because the recombination cross section is weighted
towards low energy electrons!

Cooling



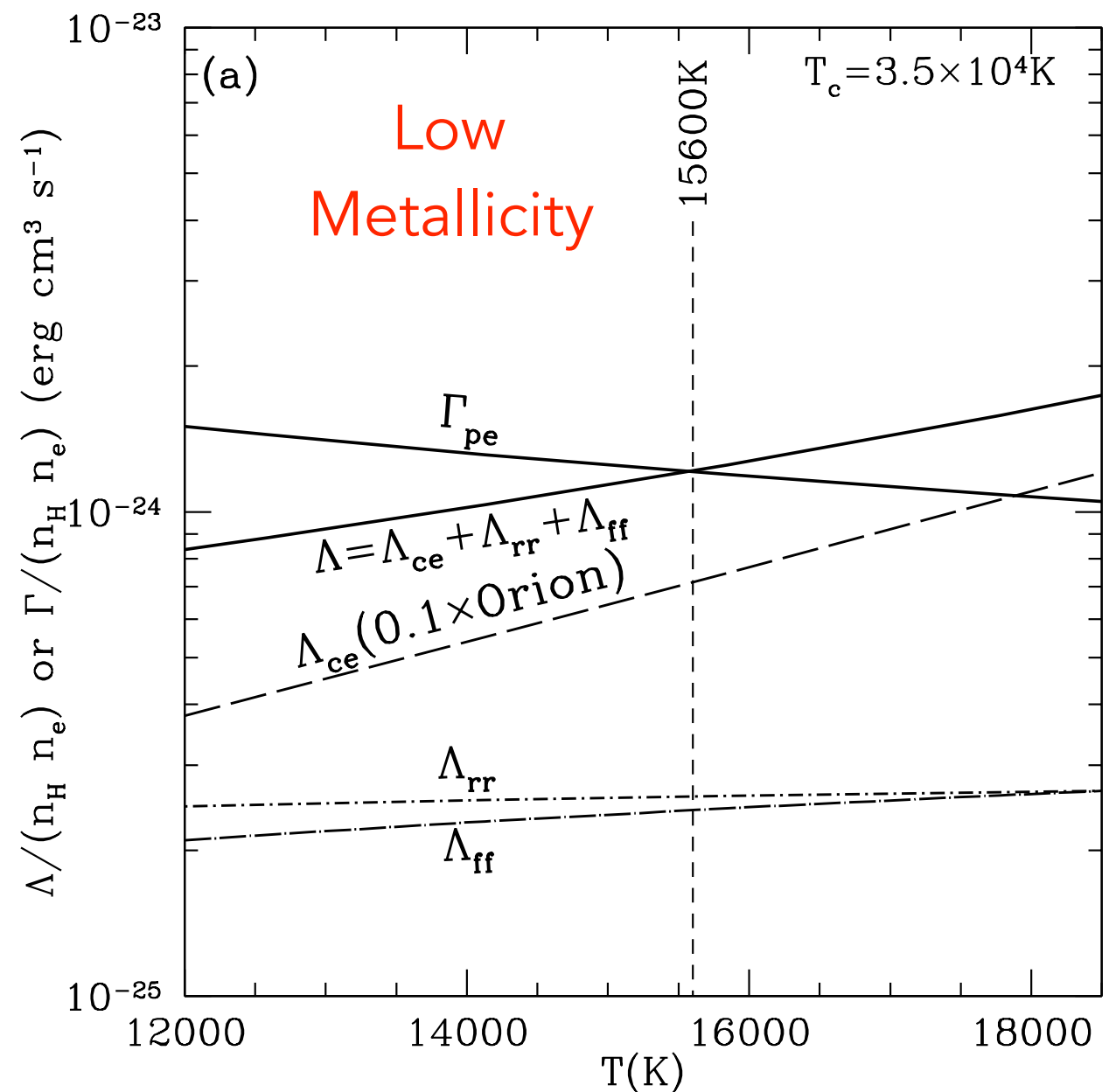
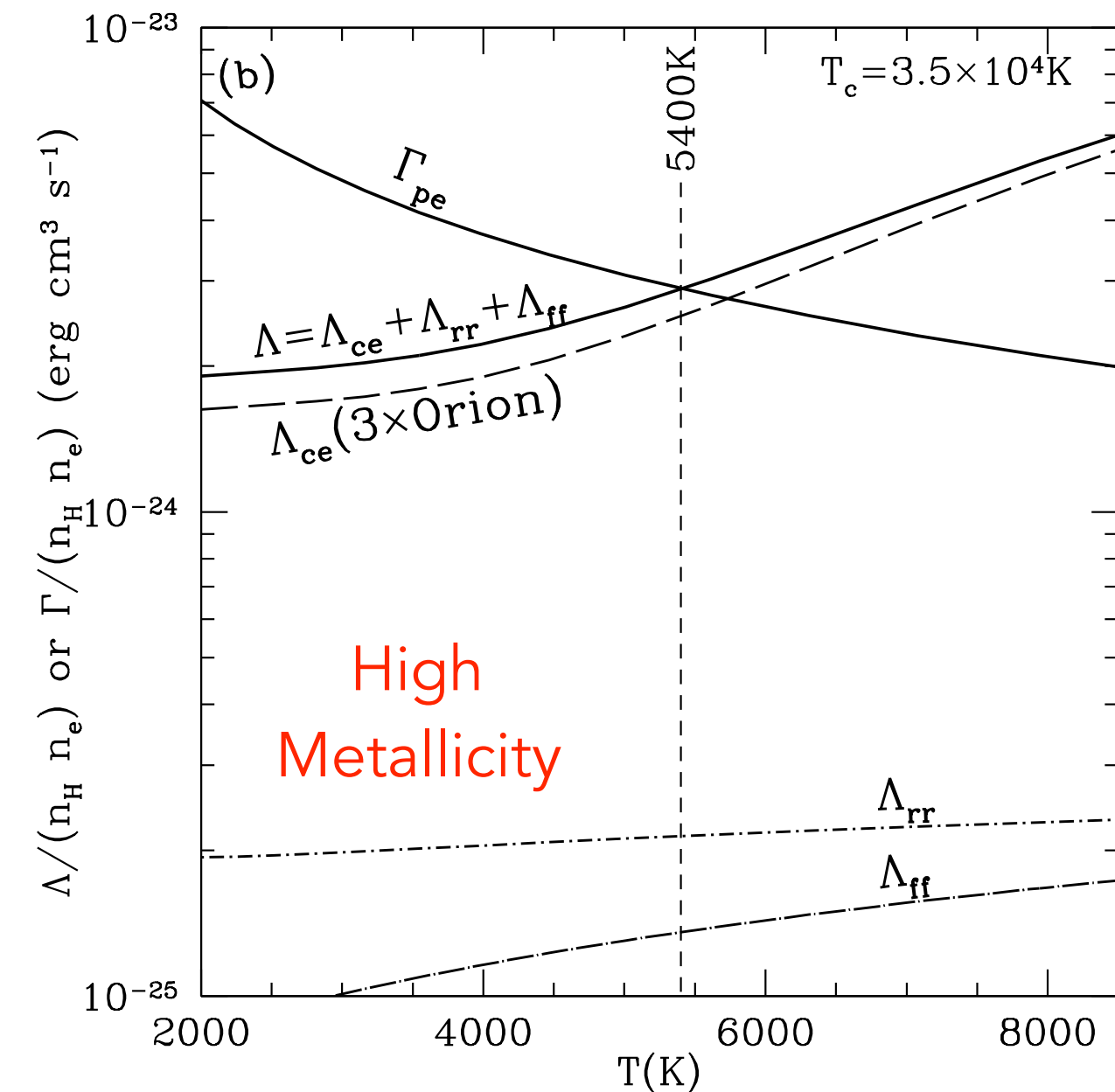
Cooling from collisionally excited emission lines is the most important coolant of HII regions.

Thermal Balance



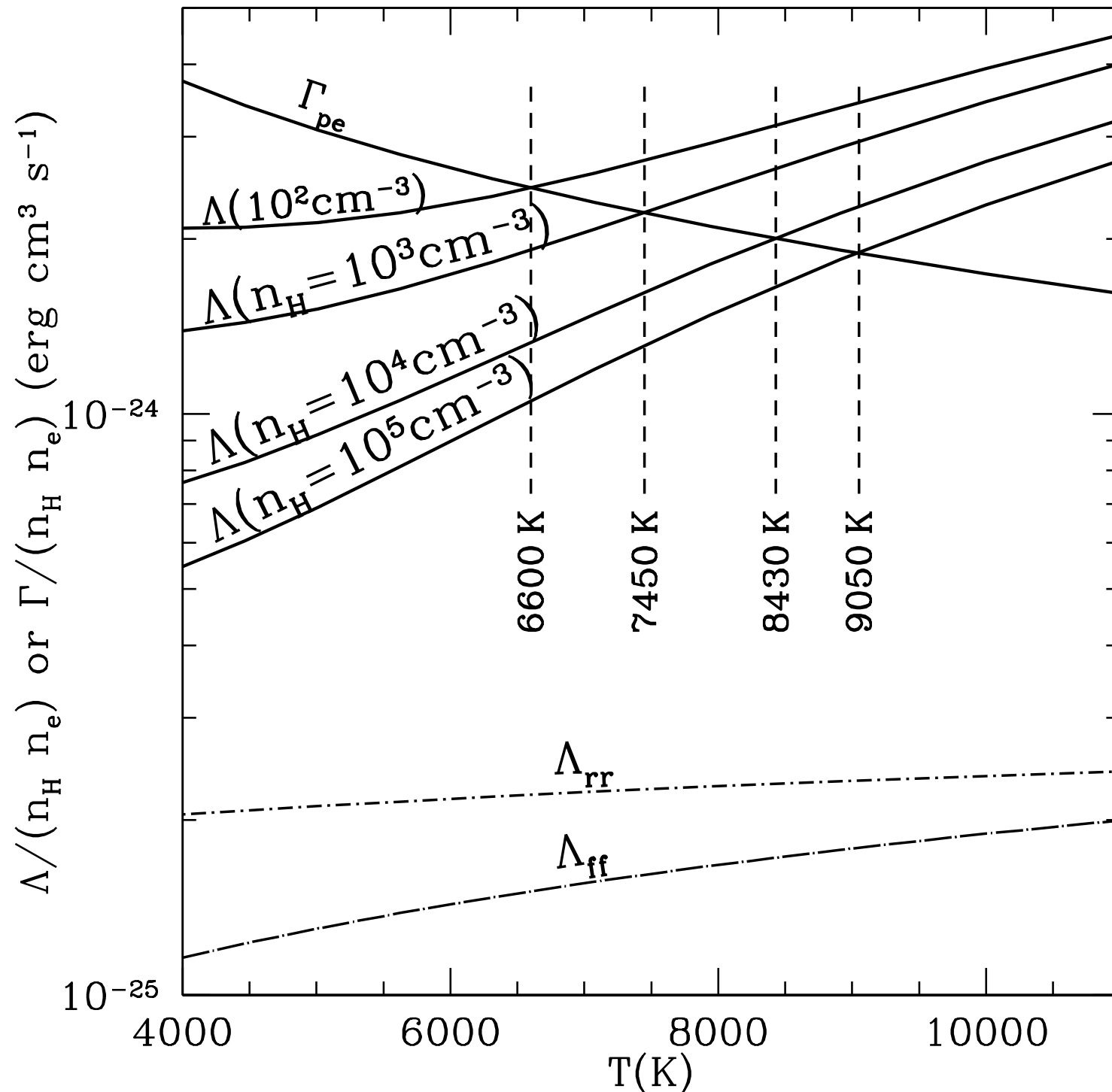
Balance between
photoionization heating
and collisional excitation
cooling sets temperature
of HII region.

Thermal Balance



Abundance of heavy elements (e.g. coolants) greatly changes
HII region temperature!!

Thermal Balance



Density changes thermal balance.

At densities above the critical density of the coolants, cooling is less efficient (not every collision results in a photon).



Credit: NASA,ESA, M. Robberto (Space Telescope Science Institute/ESA)
and the Hubble Space Telescope Orion Treasury Project Team

Part III: 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.

Dust is key for coupling radiation with the gas.

How we learn about dust

- Extinction: wavelength dependence of how dust attenuates (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!)

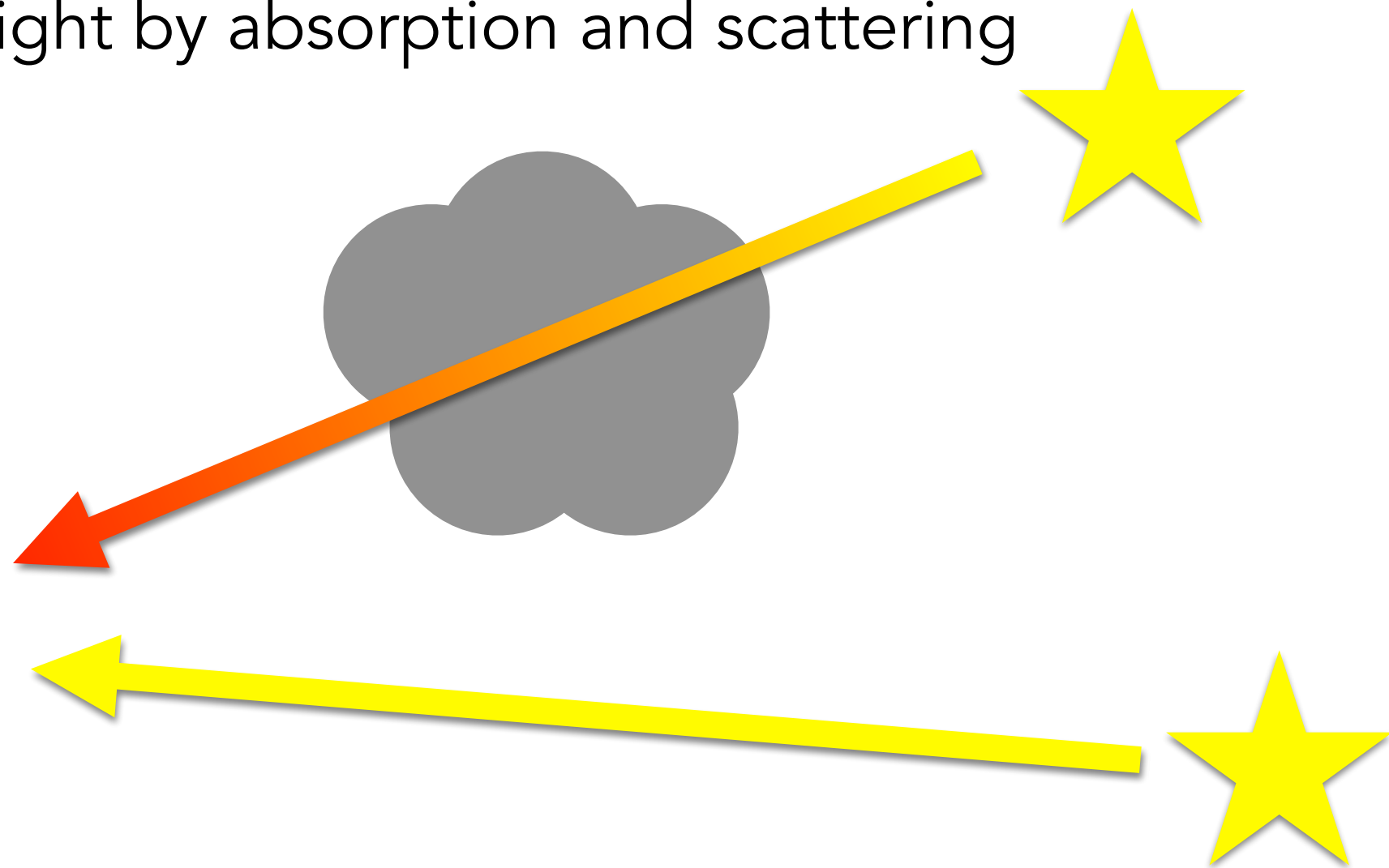
Dust/Light
Interaction

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

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

note: τ_λ includes both
absorption & scattering

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

Extinction

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

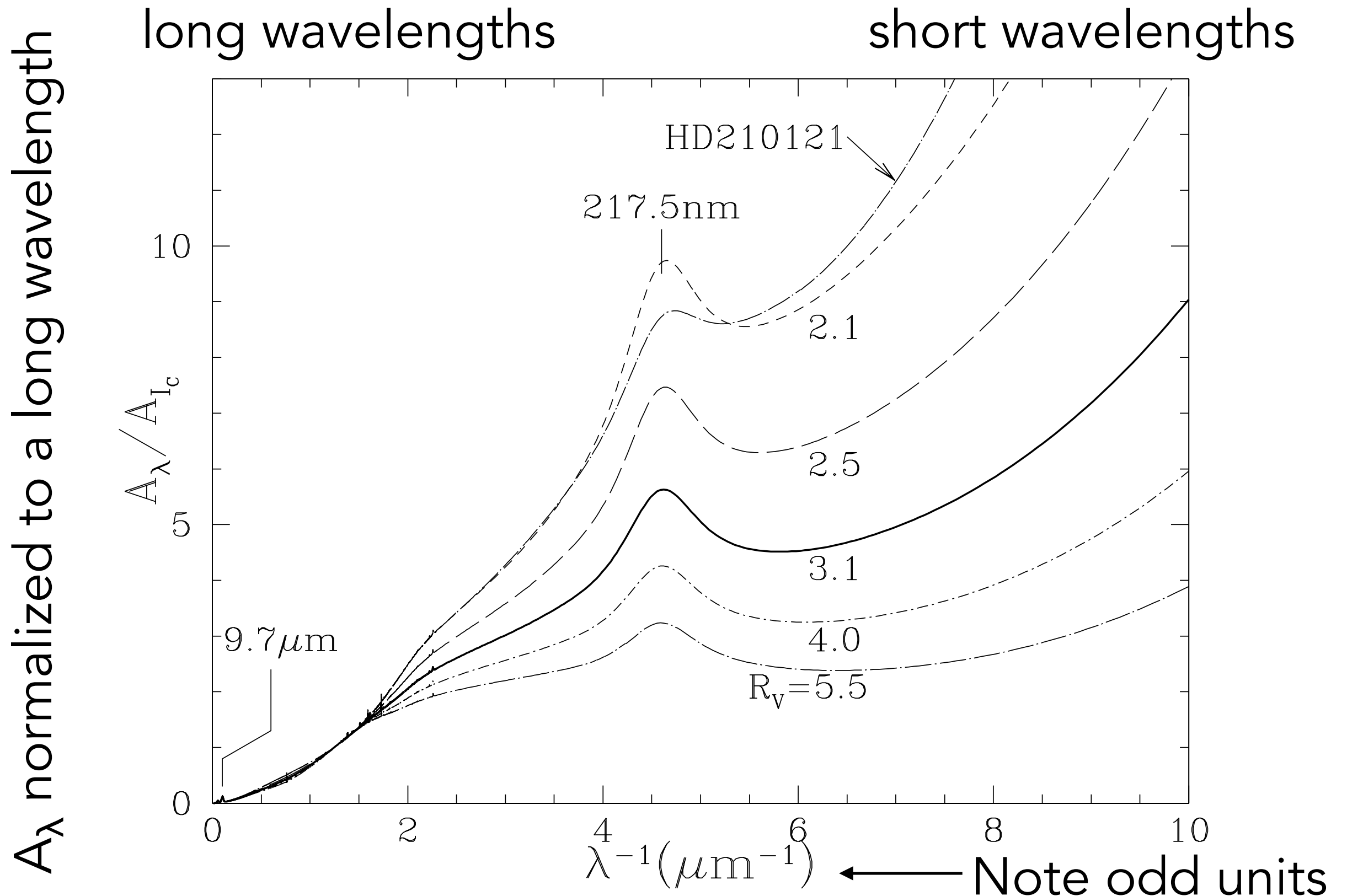
Extinction at
wavelength λ

expected
flux w/o dust

observed
flux

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



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.

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

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.

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

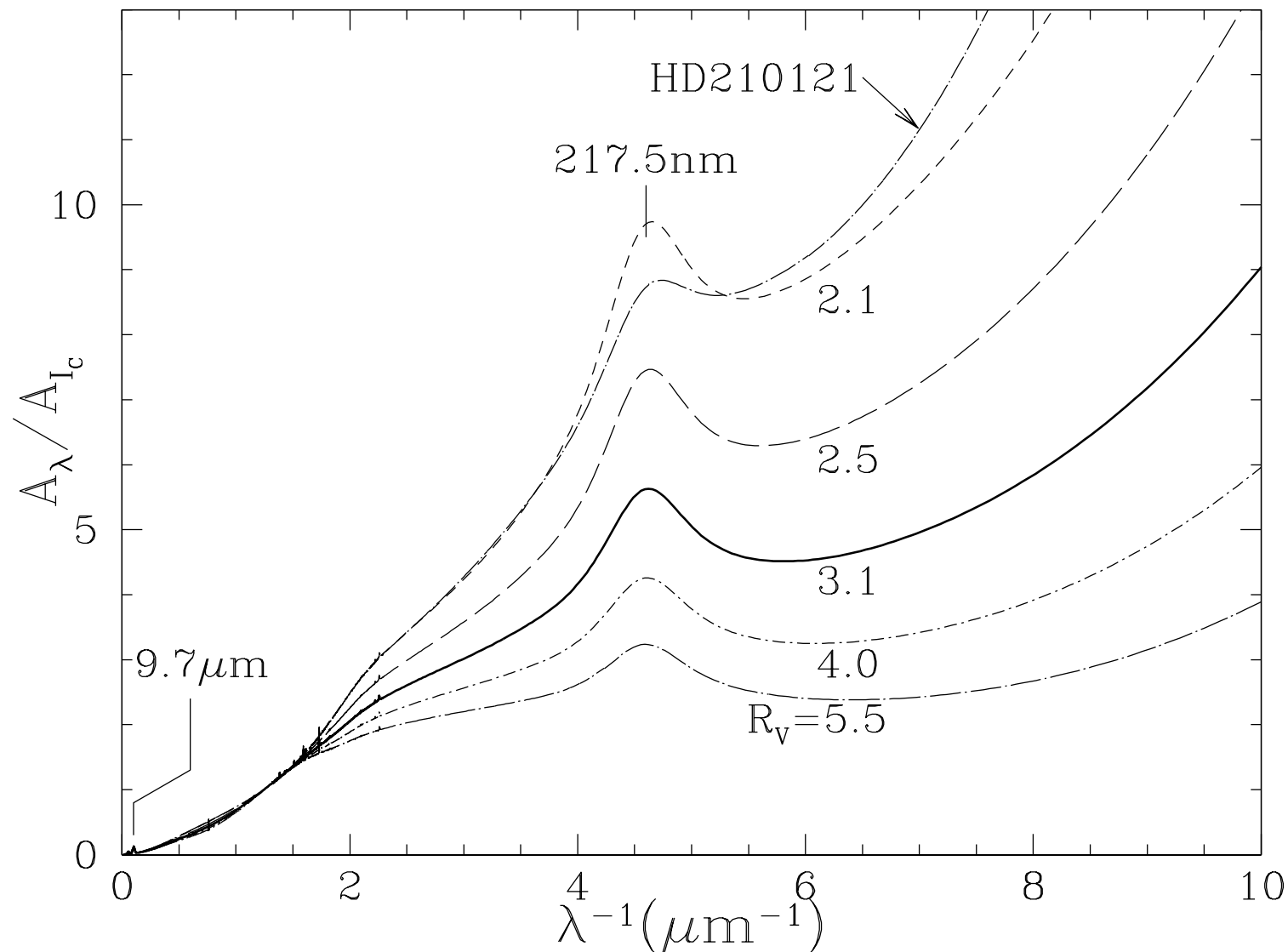
“color excess”
or “reddening”

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

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

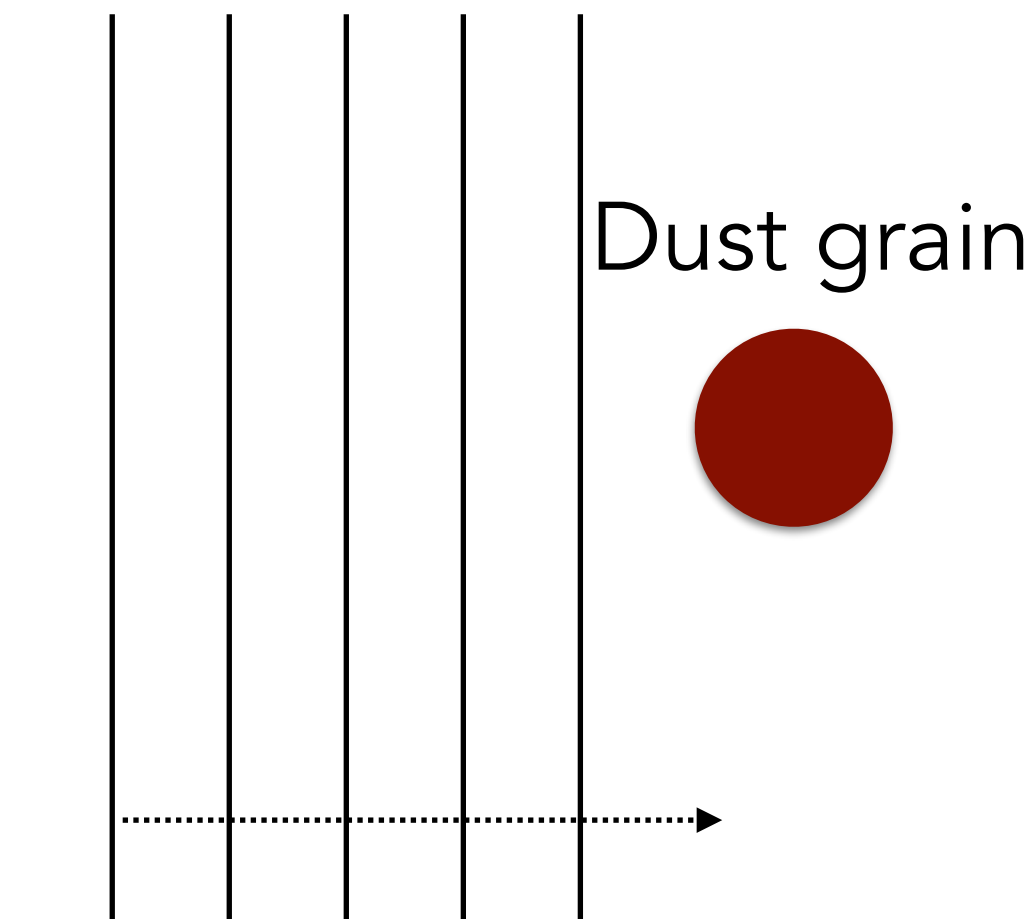


R_V = slope of extinction
curve in optical
B & V bands

MW average $R_V = 3.1$
but it varies!

Scattering & Absorption by Small Particles

key reference: Bohren & Huffman textbook



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

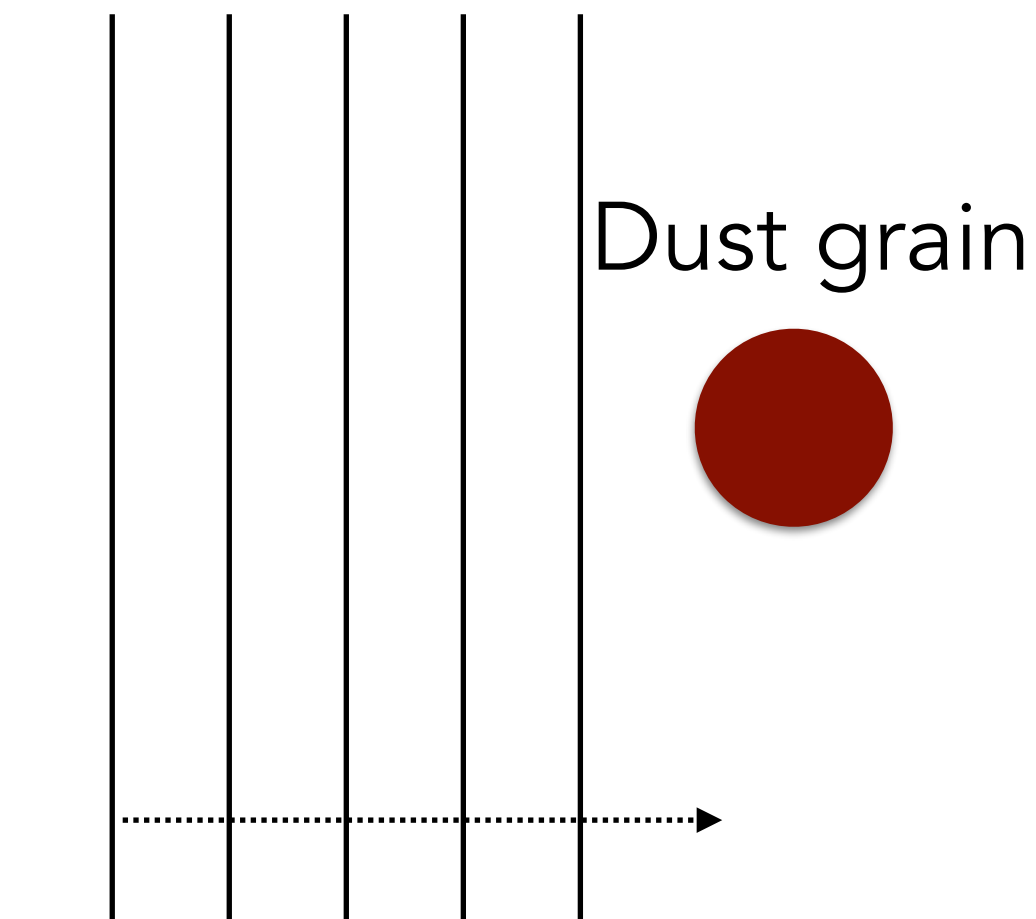
when wavelength of light is $< \text{mm}$
magnetic permeability = 1
can ignore magnetic field interaction

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

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

Scattering & Absorption by Small Particles

key reference: Bohren & Huffman textbook



plane EM wave

$$E = E_0 e^{ik \cdot r - i\omega t}$$

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 *refractive index*

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

Scattering & Absorption by Small Particles

Define:

Geometrical Cross Section: πa^2

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

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

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

Scattering & Absorption by Small Particles

Define:

Geometrical Cross Section: πa^2

Scattering & Absorption Efficiency Factors

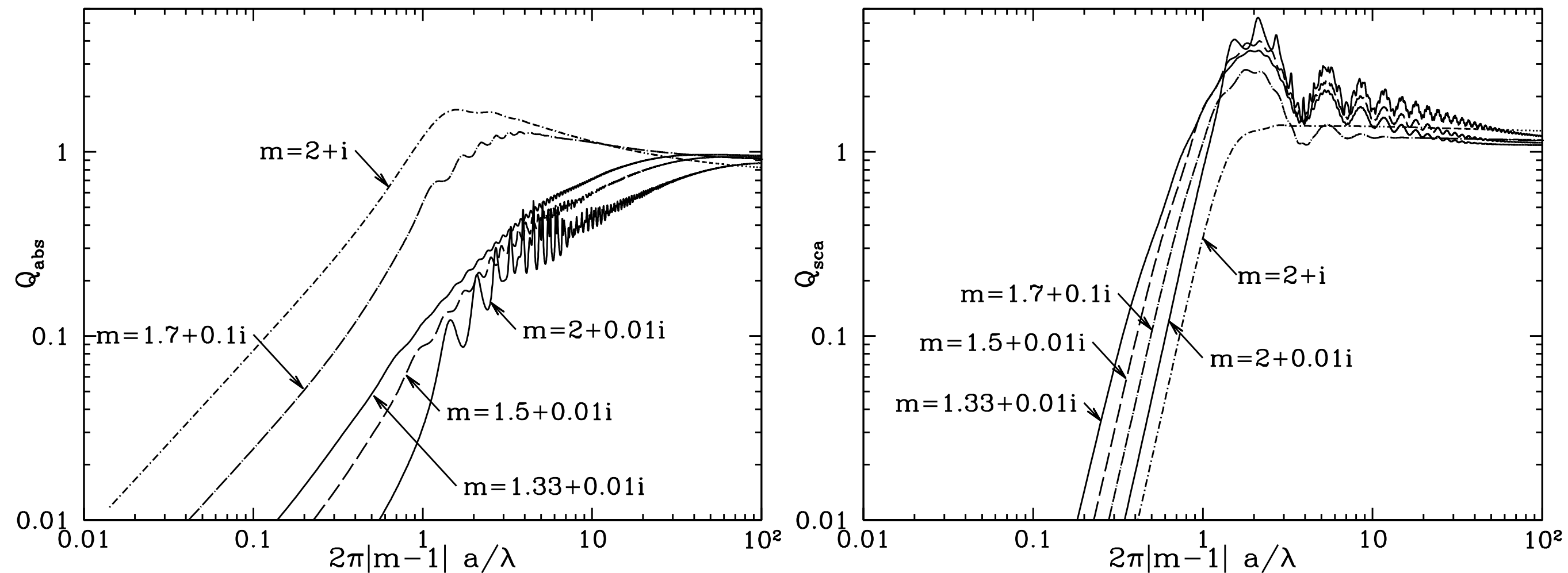
$$Q_{\text{abs}} = C_{\text{abs}}/\pi a^2$$

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

Other definitions: albedo = $C_{\text{sca}}/C_{\text{ext}}$

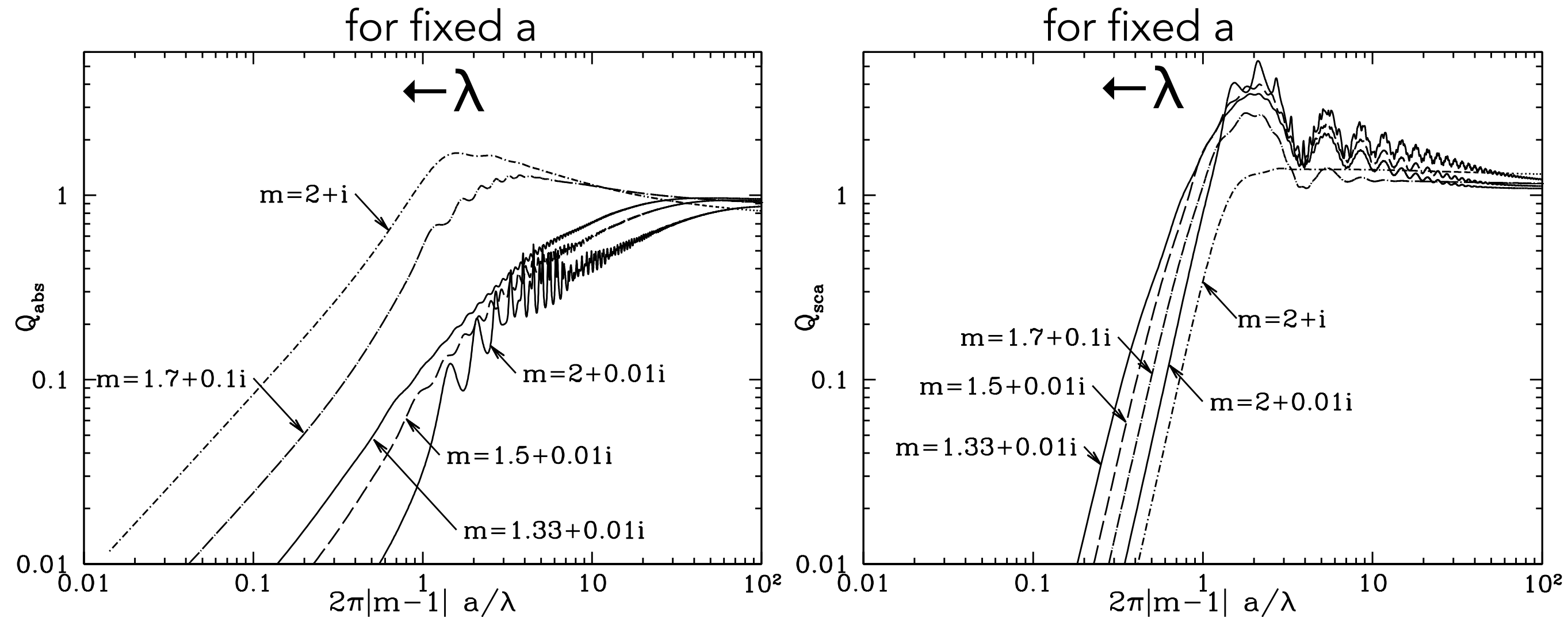
angular behavior of scattering

Scattering & Absorption by Small Particles



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

Scattering & Absorption by Small Particles

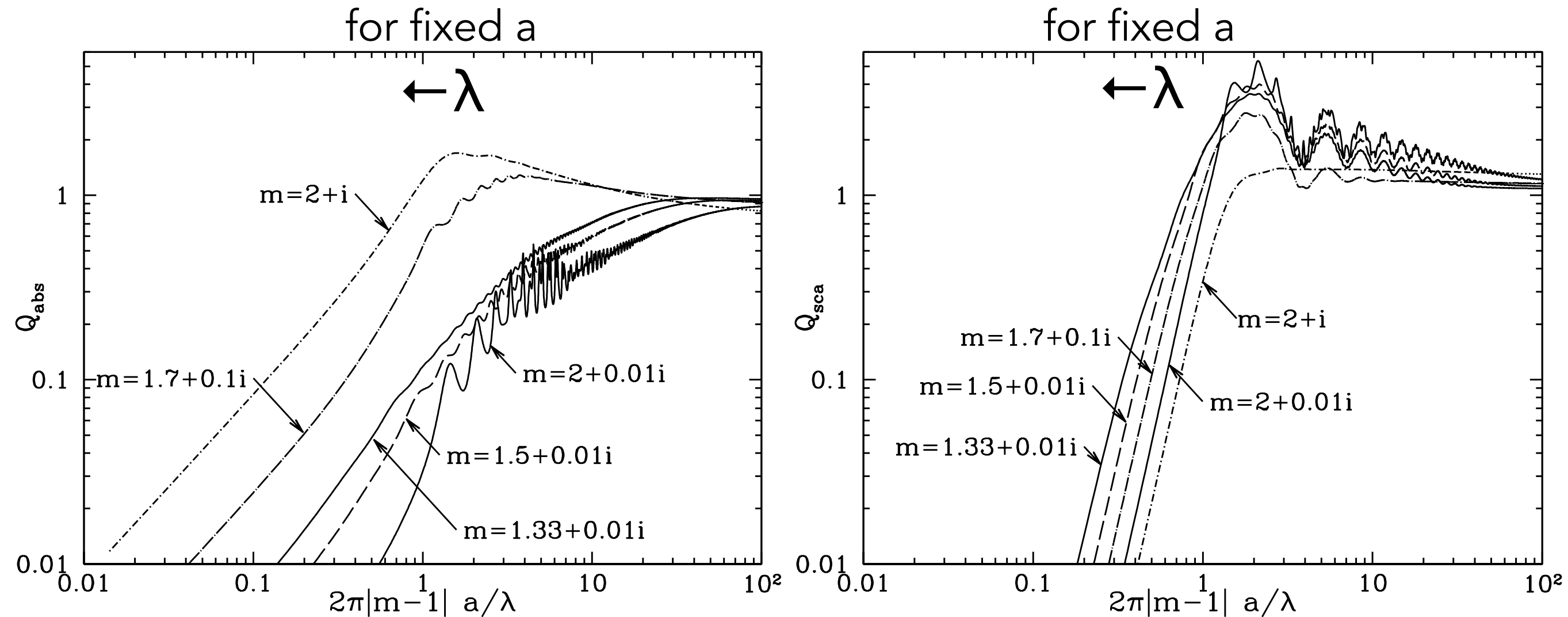


$a/\lambda \ll 1$ grain much smaller than wavelength - analytic soln's

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

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

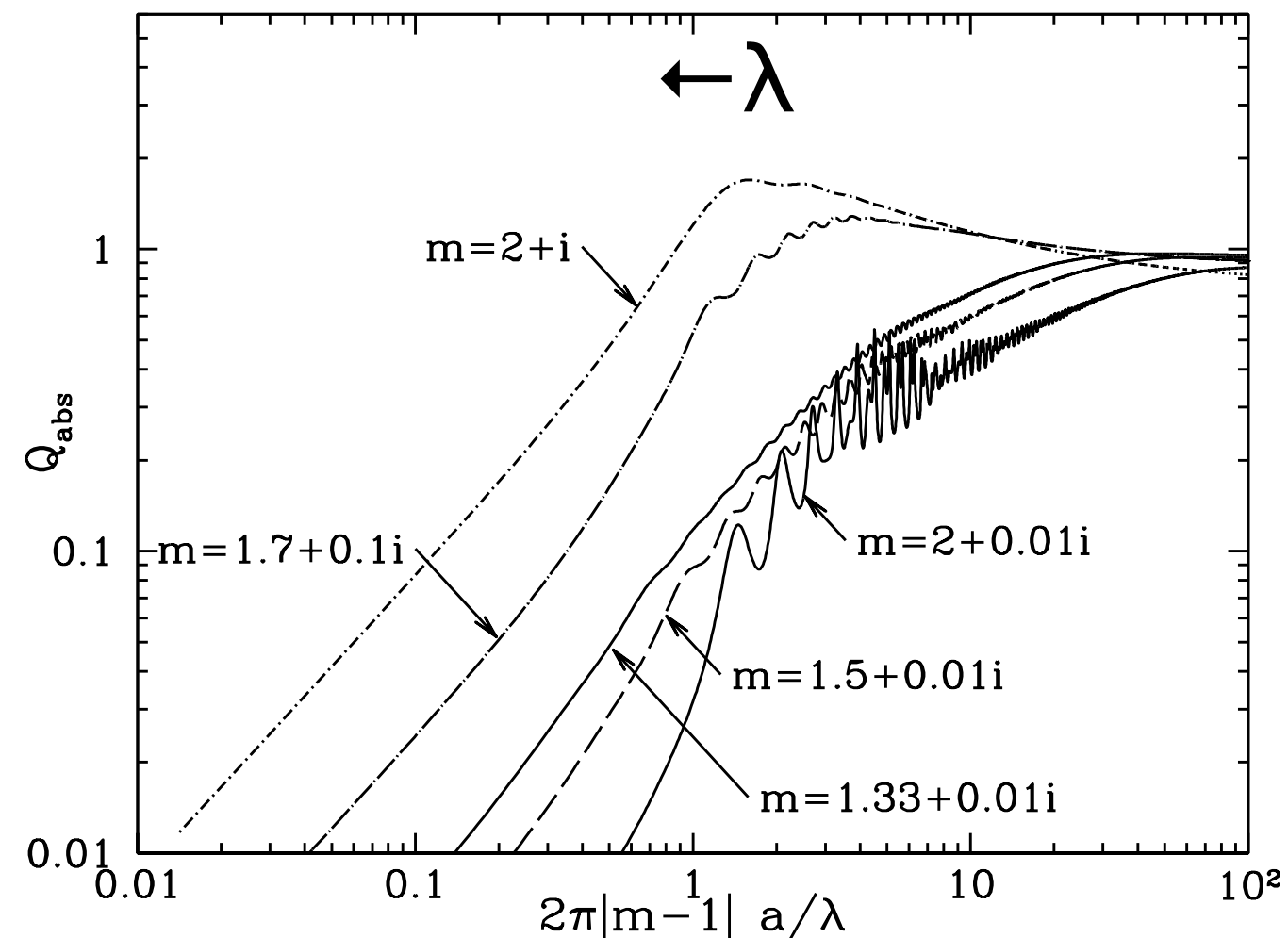
Scattering & Absorption by Small Particles



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

Scattering & Absorption by Small Particles

for fixed a



worth noting that
at long wavelength:

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

absorption efficiency when

$$a \gg \lambda$$

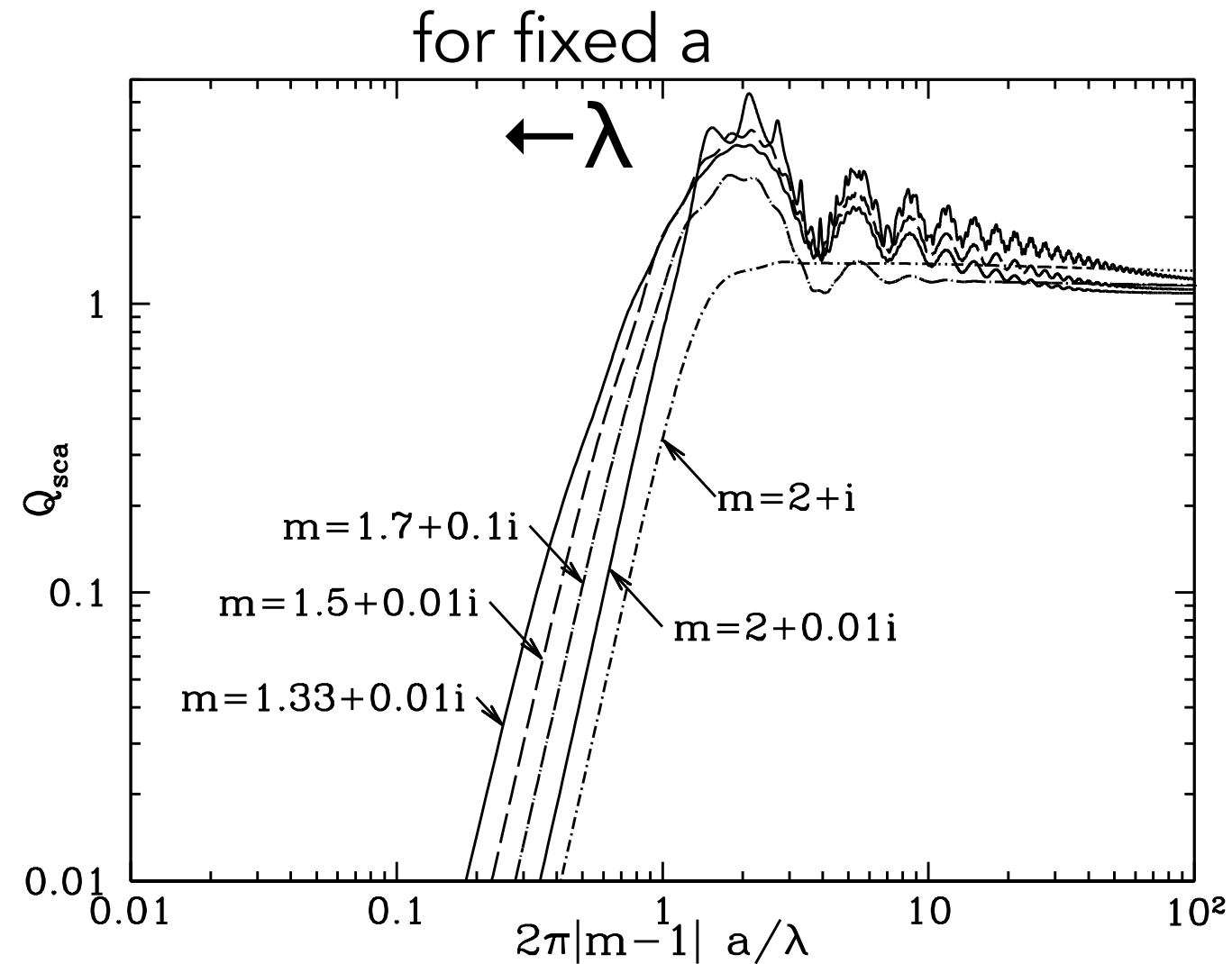
levels off to 1, $C_{\text{abs}} = \pi a^2$

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

Scattering & Absorption by Small Particles

scattering efficiency drops steeply with wavelength when $a/\lambda \ll 1$

Rayleigh scattering λ^{-4}

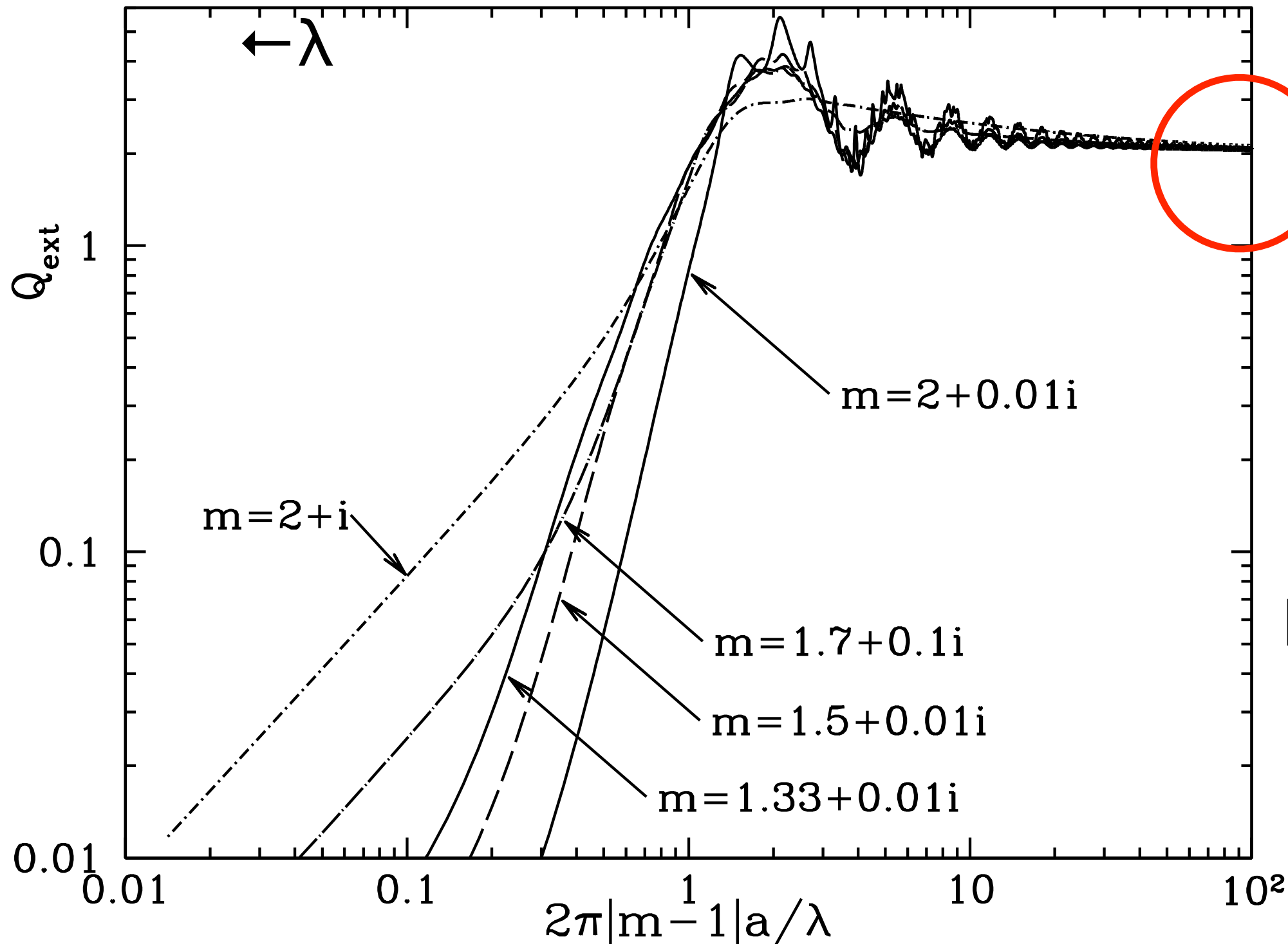


$$Q_{\text{sca}} = \frac{8}{3} \left(\frac{2\pi a}{\lambda} \right)^4 \left| \frac{\epsilon - 1}{\epsilon + 2} \right|^2$$

Scattering & Absorption by Small Particles

for fixed a

$\leftarrow \lambda$



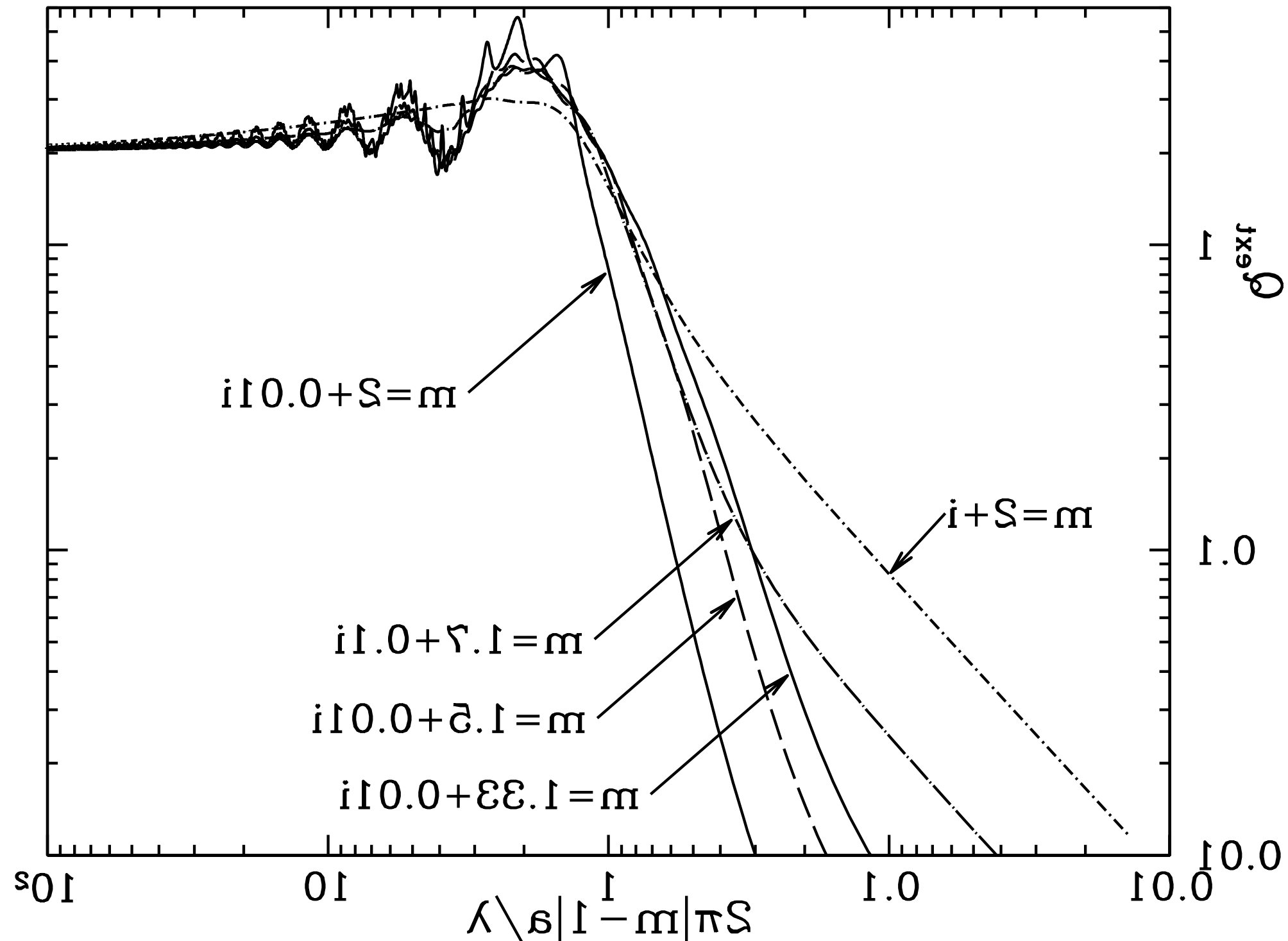
when $a \gg \lambda$

$$Q_{\text{ext}} \sim 2$$

i.e. twice the
geometrical
cross sec

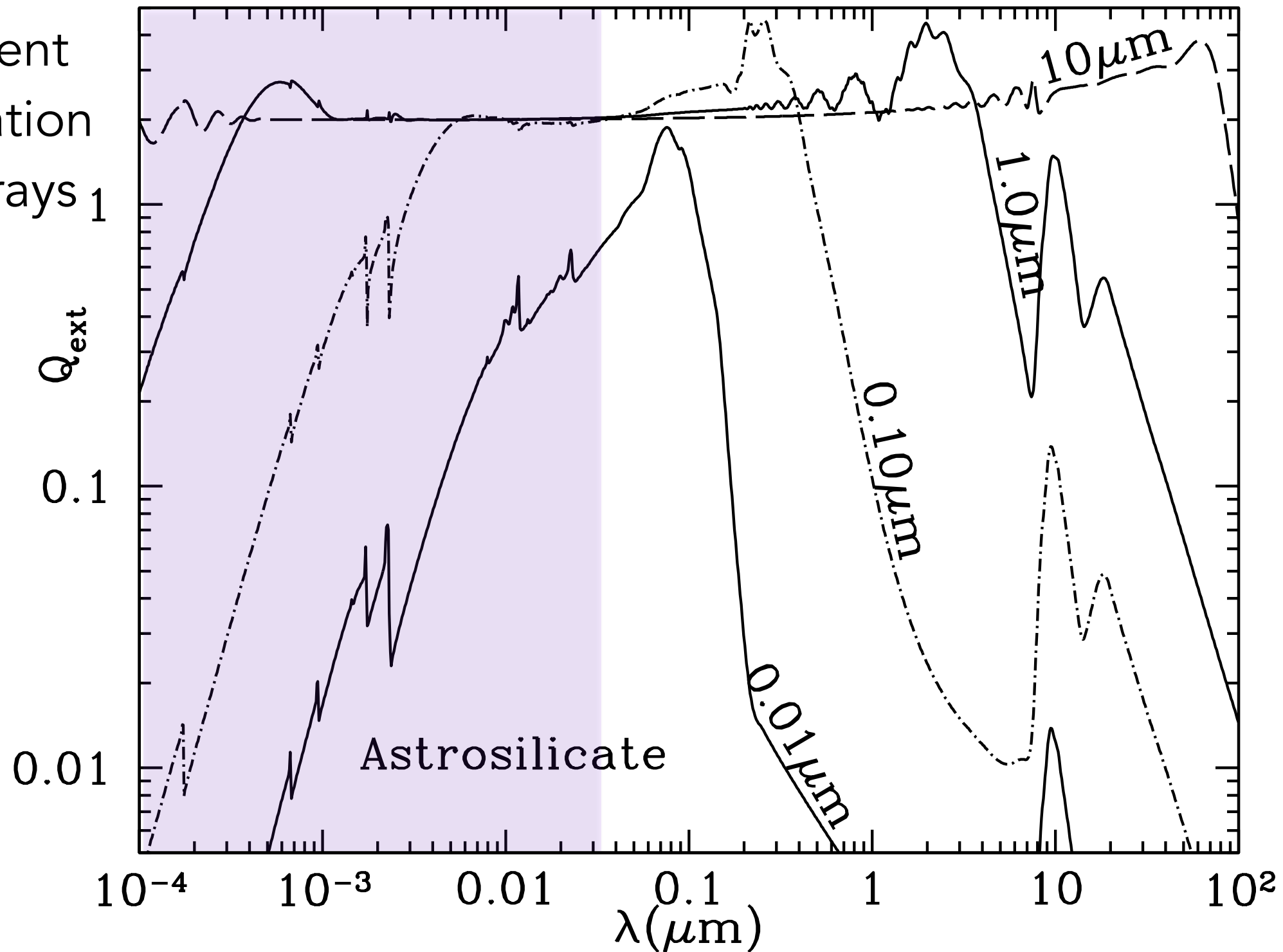
b.c. diffraction!!

Scattering & Absorption by Small Particles



Astronomical Dust

Need
different
calculation
for x-rays 1



Astronomical Dust

