ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 14: Atmospheres

Logistics

- Masks are encouraged

- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**

- Remember to bring you response card to class

- Midterm will be handed back at the end of class

Review of the last class

- The adiabatic lapse rate of an atmosphere tells us:
  - (A) — How pressure changes with altitude
  - (B) — How density changes with altitude
  - (C) — How temperature changes with altitude
  - (D) — How mean molecular weight change with altitude

Review of the last class

- Compared to the dry adiabatic lapse rate, the moist adiabatic lapse rate is:
  - (A) — more steep (slower change in temperature with altitude) because water has a very different mean molecular weight than the dry atmosphere
  - (B) — less steep (faster change in temperature with altitude) because water has a very different mean molecular weight than the dry atmosphere
  - (C) — more steep (slower change in temperature with altitude) because energy can go into condensing or vaporizing water
  - (D) — less steep (faster change in temperature with altitude) because energy can go into condensing or vaporizing water

Review of the last class

- The moist adiabatic lapse rate in Earth's troposphere is about:
    - (A) — -6.5 K/km
    - (B) — -6.5 km/K
    - (C) — +6.5 K/km
    - (D) — +6.5 km/K

Review of the last class

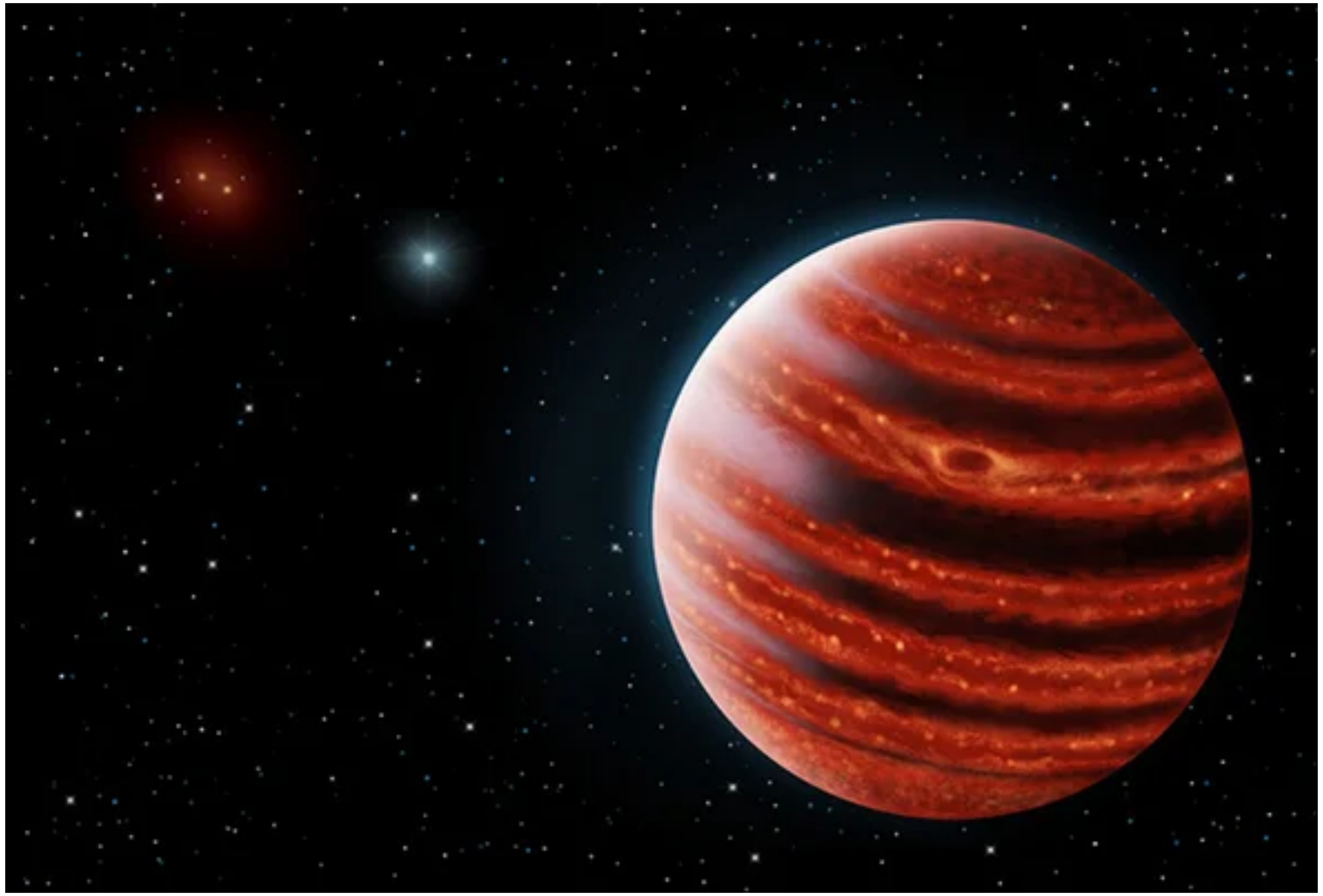
- If I lift an air parcel slightly in a stable, unstable, and neutral atmosphere, then let go, what happens?
  - (A) — Stable: keeps rising, Unstable: stays put, Neutral: sinks back down
  - (B) — Stable: stays put, Unstable: keeps rising, Neutral: sinks back down
  - (C) — Stable: stays put, Unstable: sinks back down, Neutral: keeps rising
  - (D) — Stable: keeps rising, Unstable: sinks back down, Neutral: stays put
  - (E) — Stable: sinks back down, Unstable: keeps rising, Neutral: stays put

Review of the last class

- I measure the environmental lapse rate at three locations in an atmosphere:
  Location A - environmental lapse rate is steeper (slower change in temperature with height) than adiabatic
  Location B: environmental lapse rate is shallower than adiabatic
  Location C: environmental lapse rate is equal to adiabatic
  - (A) — A: stable, B: unstable, C: neutral
  - (B) — A: unstable, B: stable, C: neutral
  - (C) — A: neutral, B: stable, C: unstable
  - (D) — A: neutral, B: unstable, C: stable
  - (E) — A: unstable, B: neutral, C: stable

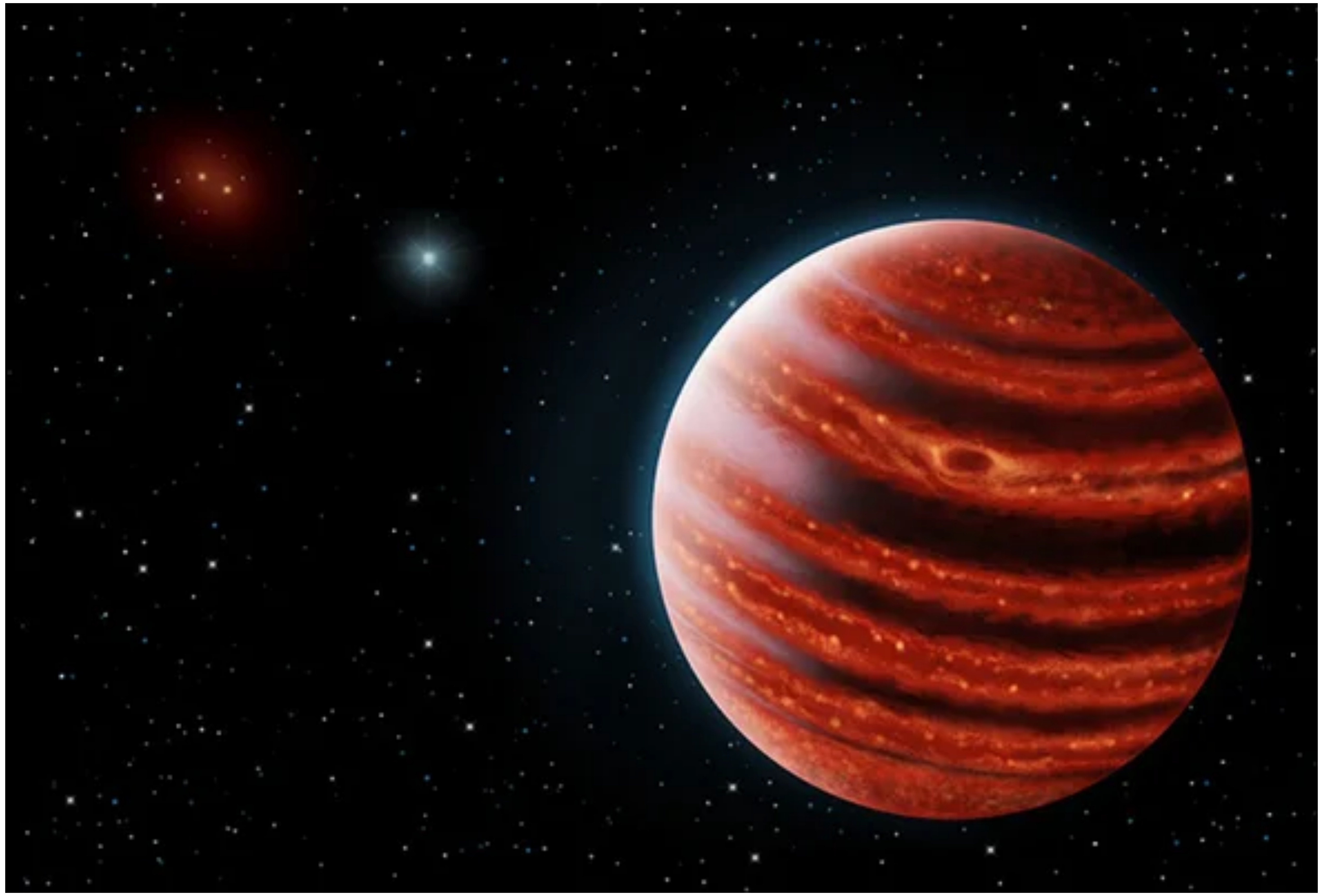
Radiative Transfer

- How light moves through a material
- For planetary atmospheres, the dominant light source is the Sun (or the star for exoplanets)
    - Exception: young planets are still hot from their initial formation (conservation of energy), and have significantly more blackbody emission than expected from their distance to the star
    - Jupiter today: about 50% of emitted light (at all wavelengths) is reprocessed sunlight, the other 50% is emission from its remaining formation heat



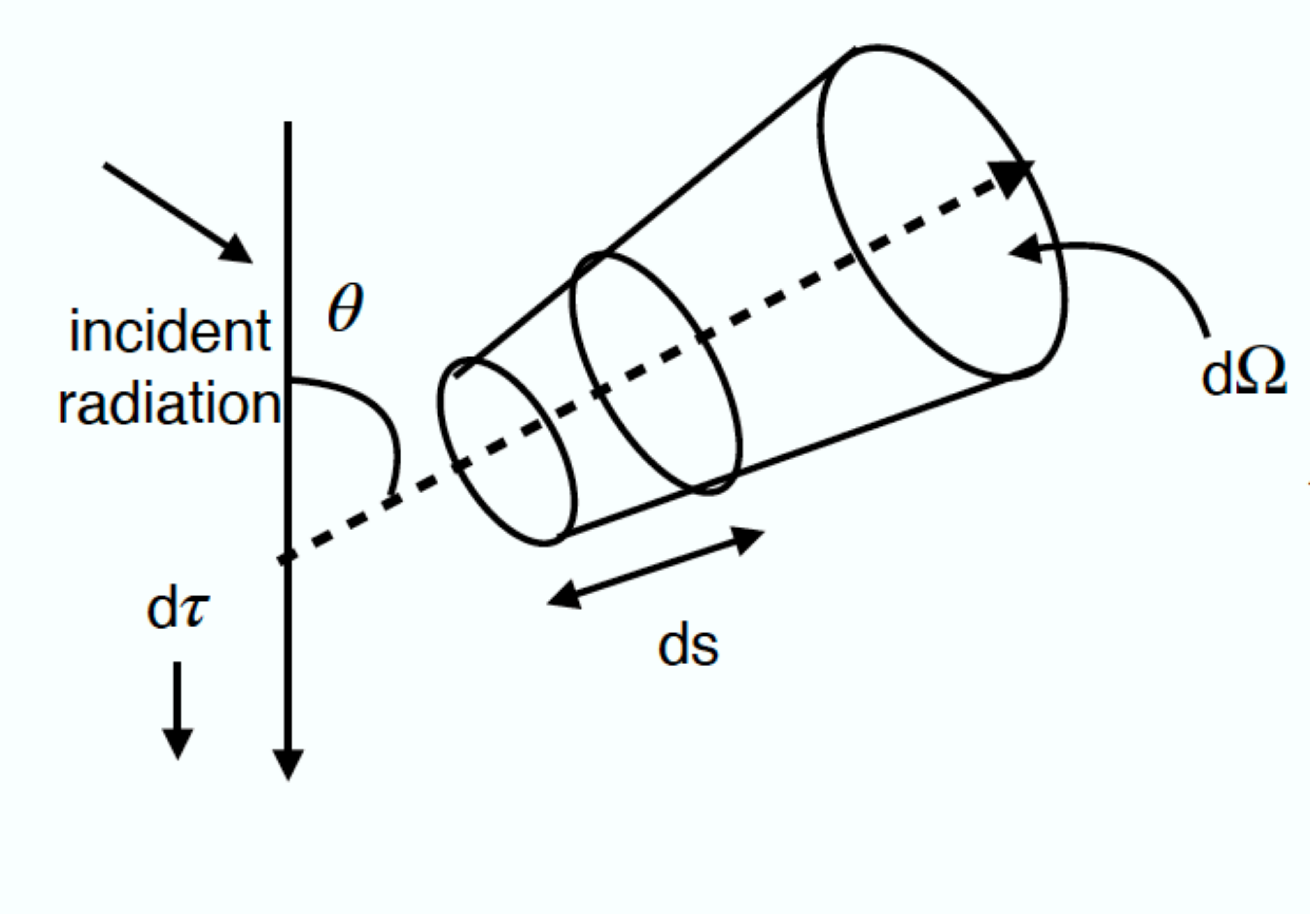
Radiative Transfer

- General process in an atmosphere:
  - A beam of light travels from a light source (direct sunlight, reflected sunlight, ground blackbody emission, etc)
  - Light in the beam can be scattered out of that beam by atmospheric particles
  - Light in the beam can be absorbed by atmospheric particles
  - New light can join the beam from scattering by atmospheric particles
  - New light can join the beam from emission by atmospheric particles



Radiative Transfer

- I_ν: Specific intensity ($\frac{erg}{cm^2\, s\, sr\, Hz}$)
- Amount of energy per:
  - unit area
  - second
  - solid angle
  - frequency of light

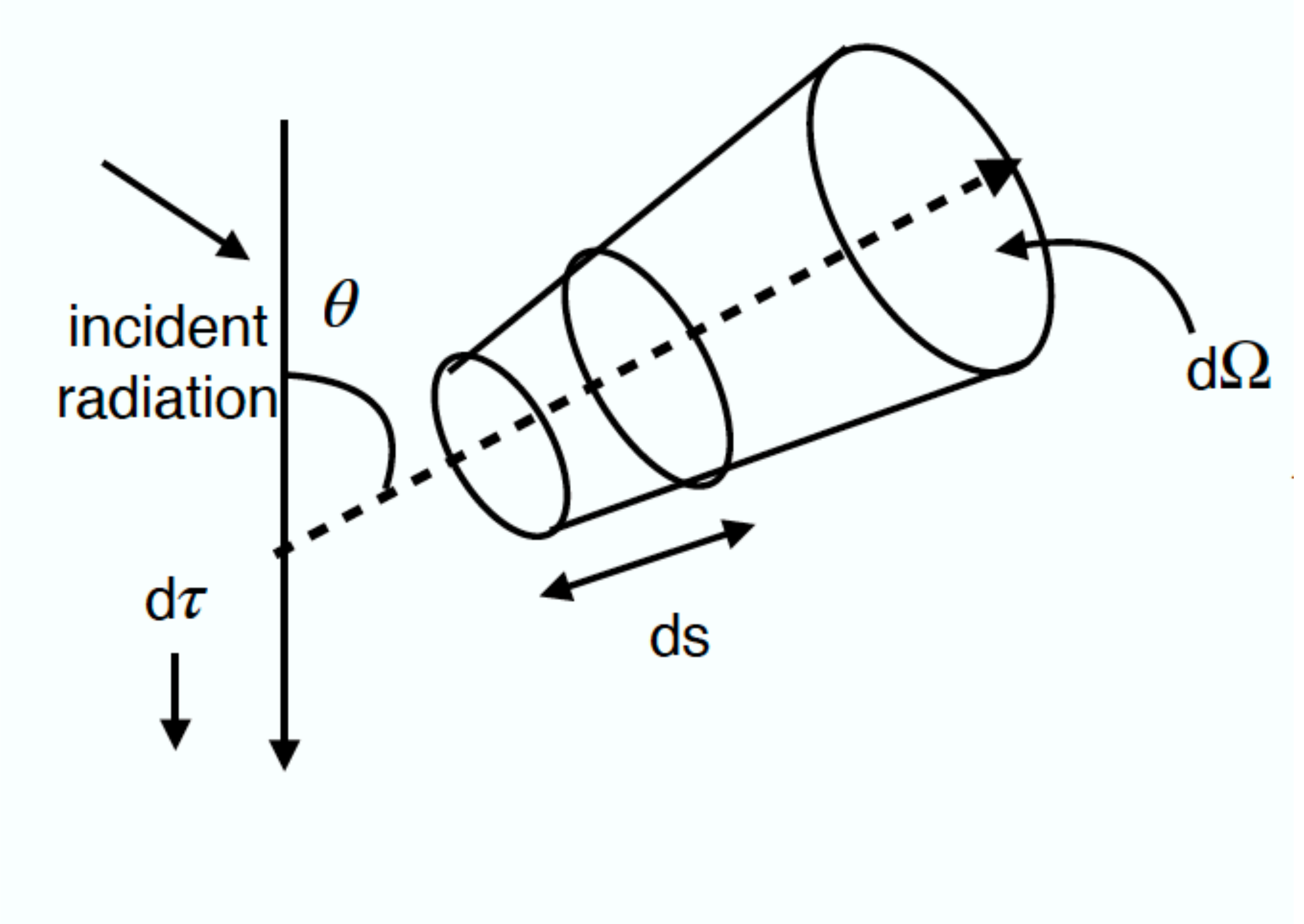


Radiative Transfer

- I_ν: Specific intensity ($\frac{erg}{cm^2\, s\, sr\, Hz}$)
- The specific intensity changes along the path ds by dI_ν

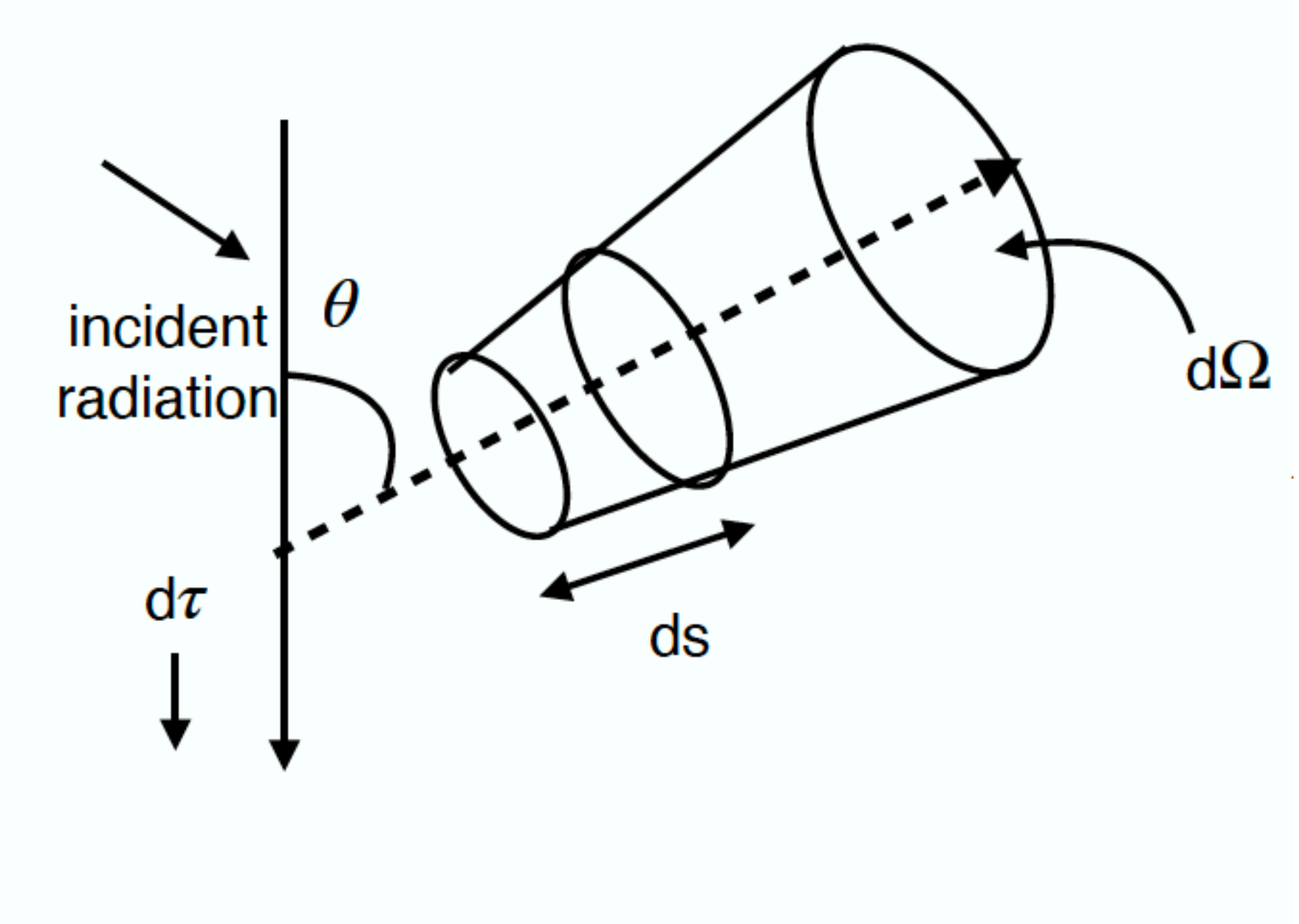
$$\frac{1}{\rho}\frac{dI_\nu}{ds} = -(\kappa_\nu + \sigma_\nu)I_\nu + j_\nu$$

- ρ: mass density (g/cm^3)
- κ_ν: mass absorption coefficient (cm^2/g)
- σ_ν: mass scattering coefficient (cm^2/g)
- j_ν: emission coefficient (erg/s/sr/Hz/g)



Radiative Transfer

- $\frac{1}{\rho}\frac{dI_\nu}{ds} = -(\kappa_\nu + \sigma_\nu)I_\nu + j_\nu$
- Extinction (light removed):
  - Sum of scattering and absorption
- Emission (light added):
  - Sum of scattering and thermal emission



Radiative Transfer

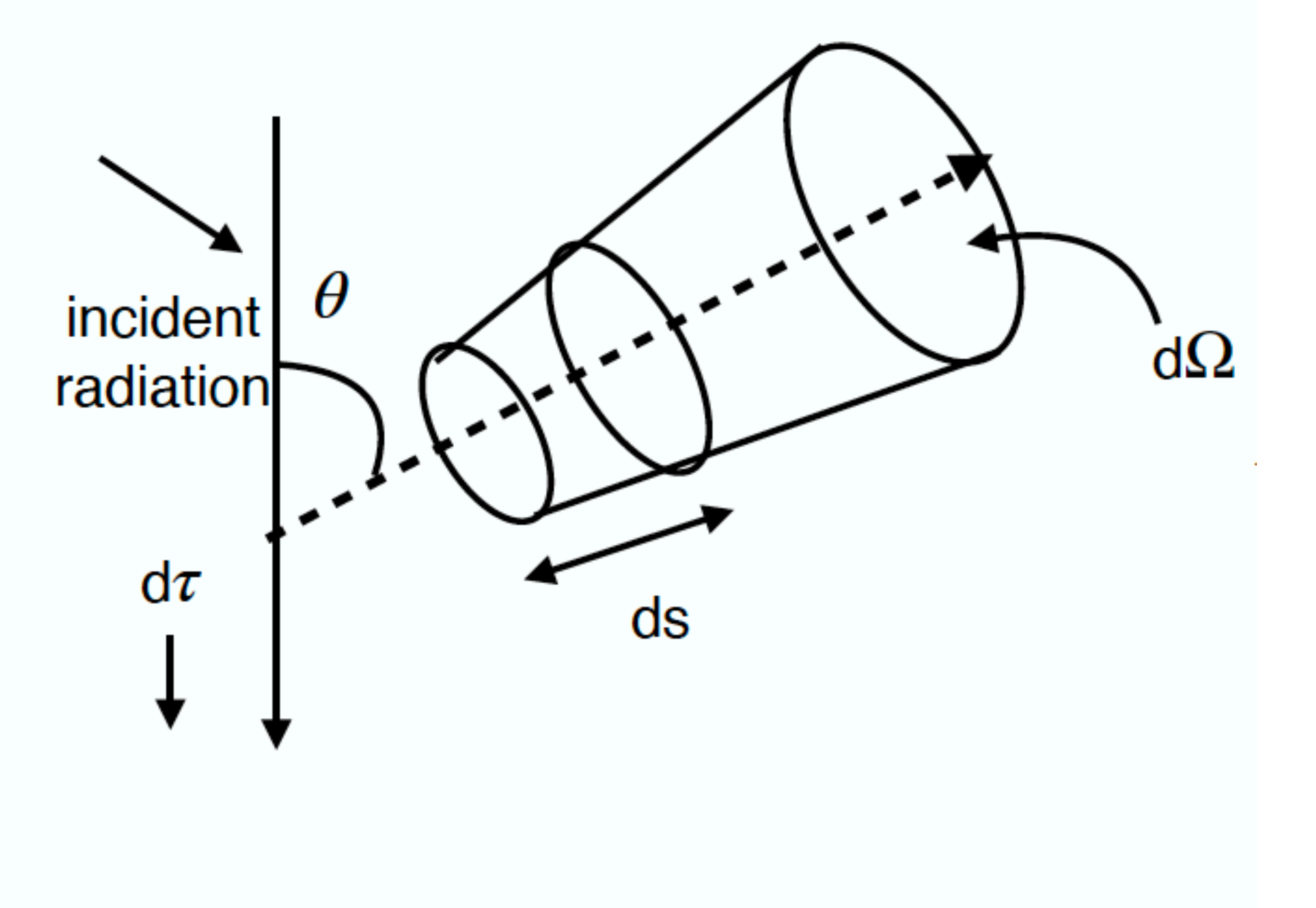
- $$\frac{1}{\rho}\frac{dI_\nu}{ds} = -(\kappa_\nu + \sigma_\nu)I_\nu + j_\nu$$
- If scattering into the beam and emission along the path are negligible:

$$\frac{1}{\rho}\frac{dI_\nu}{ds} = -(\kappa_\nu + \sigma_\nu)I_\nu$$

- The solution is an exponential:

$$I_\nu(s) = I_\nu(0)e^{-(\kappa_\nu+\sigma_\nu)\rho s}$$

- This is called Lambert's exponential absorption law (no sources, just sinks)



Radiative Transfer

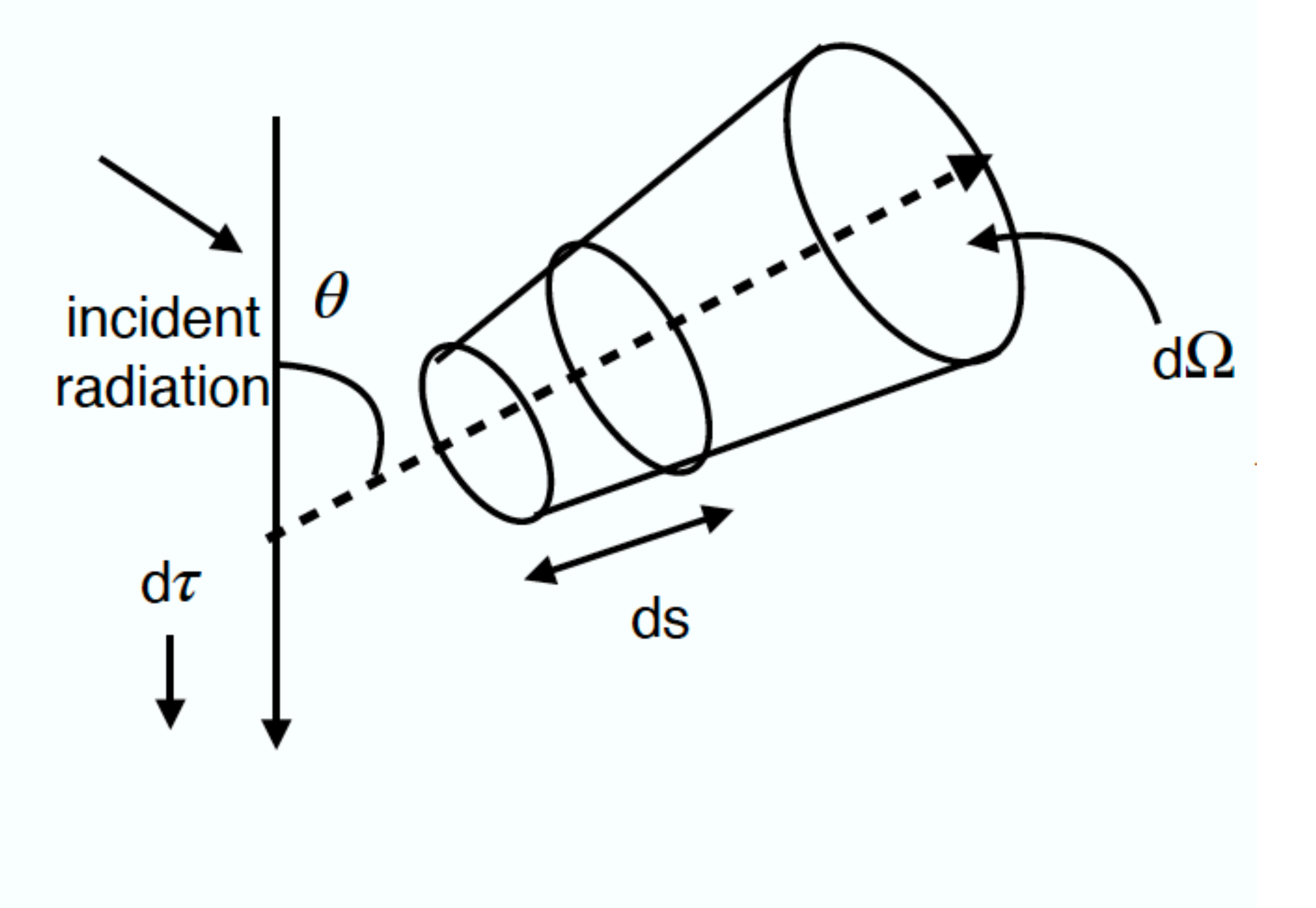
- To include scattering into the beam (for example, why the sky is blue) we need to include a scattering phase function

- Scattering phase function describes the angular distribution of radiation after it encounters a particle in the atmosphere

    - Isotropic?

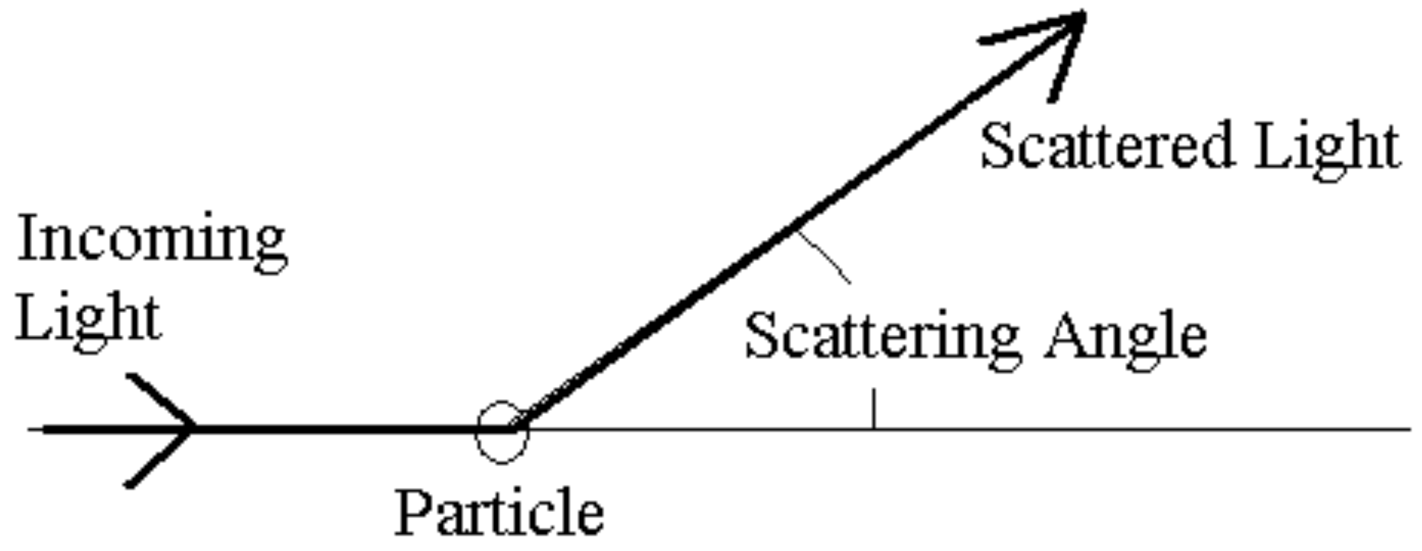
    - Strongly forward scattering?

    - Mildly backscattering?



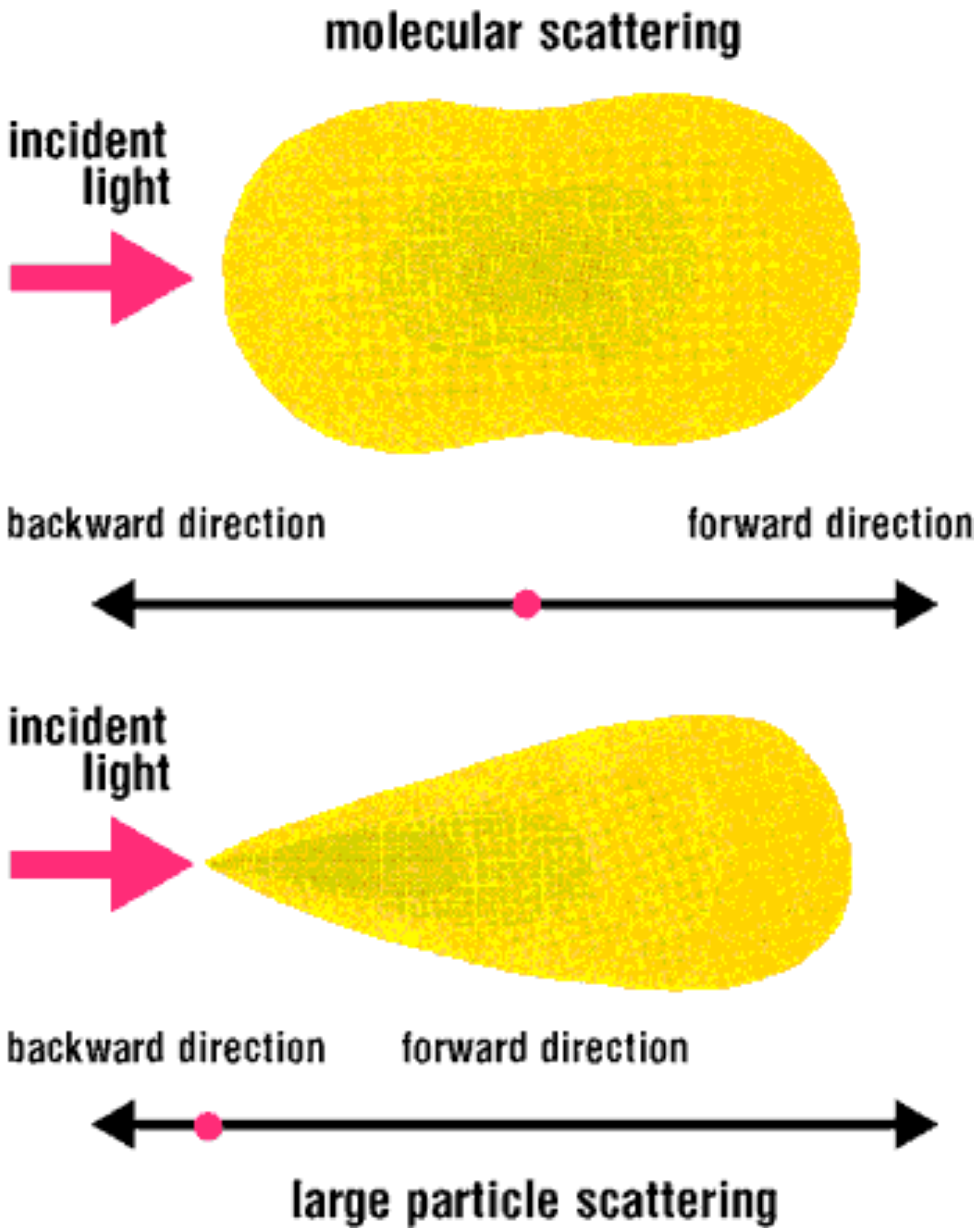
Scattering Phase Function

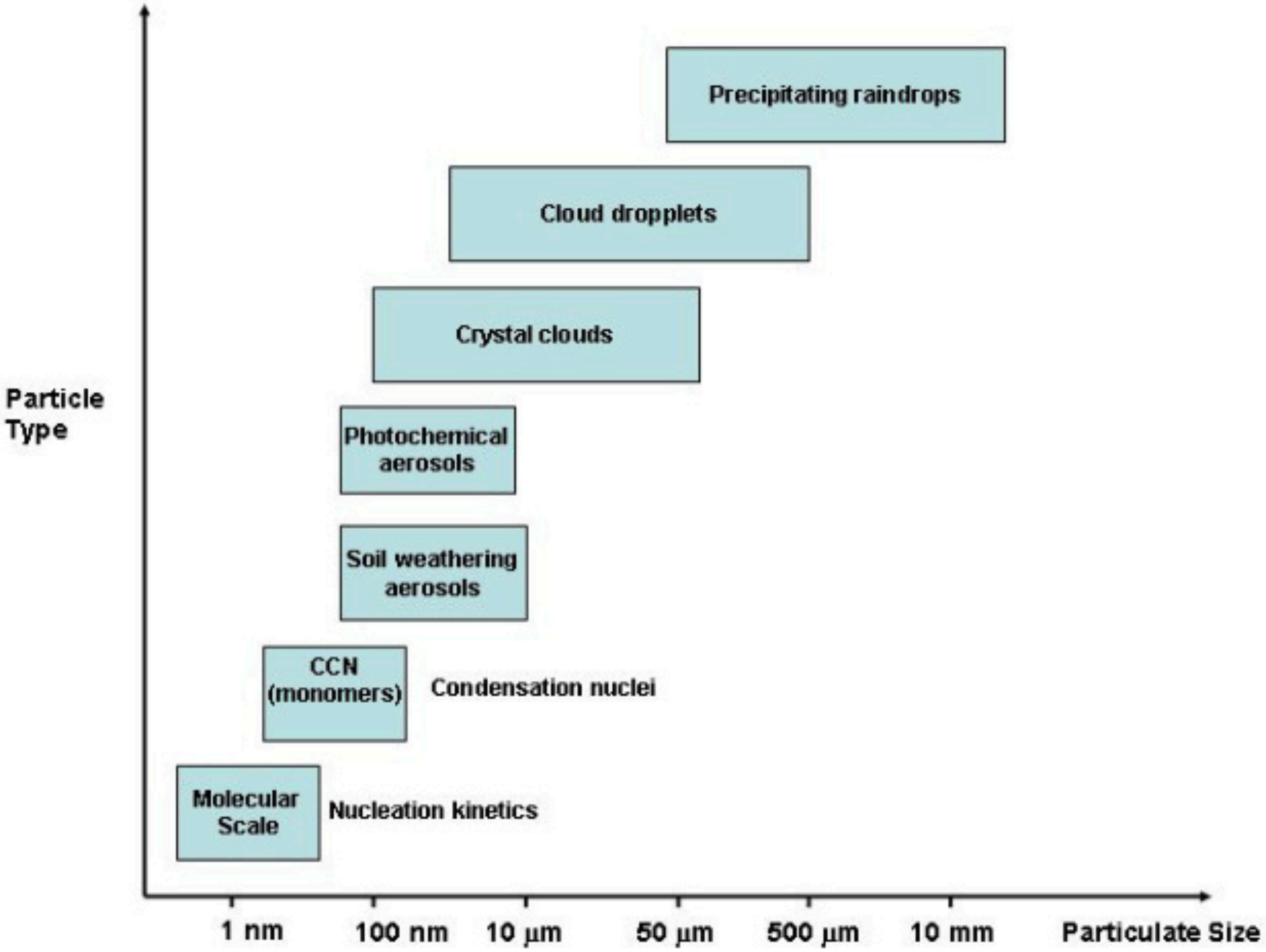
- Scattering phase function is given by $p(\cos\Theta)$
  - Probability density function for direction photons end up traveling after scattering
- Scattering angle Θ between incident light and emitted light
  - $\Theta \approx 0$: Forward scattering (After scattering, light continues in roughly original direction)
  - $\Theta \approx 180$: Back scattering (After scattering, light goes back in the way it came)



Scattering Phase Function

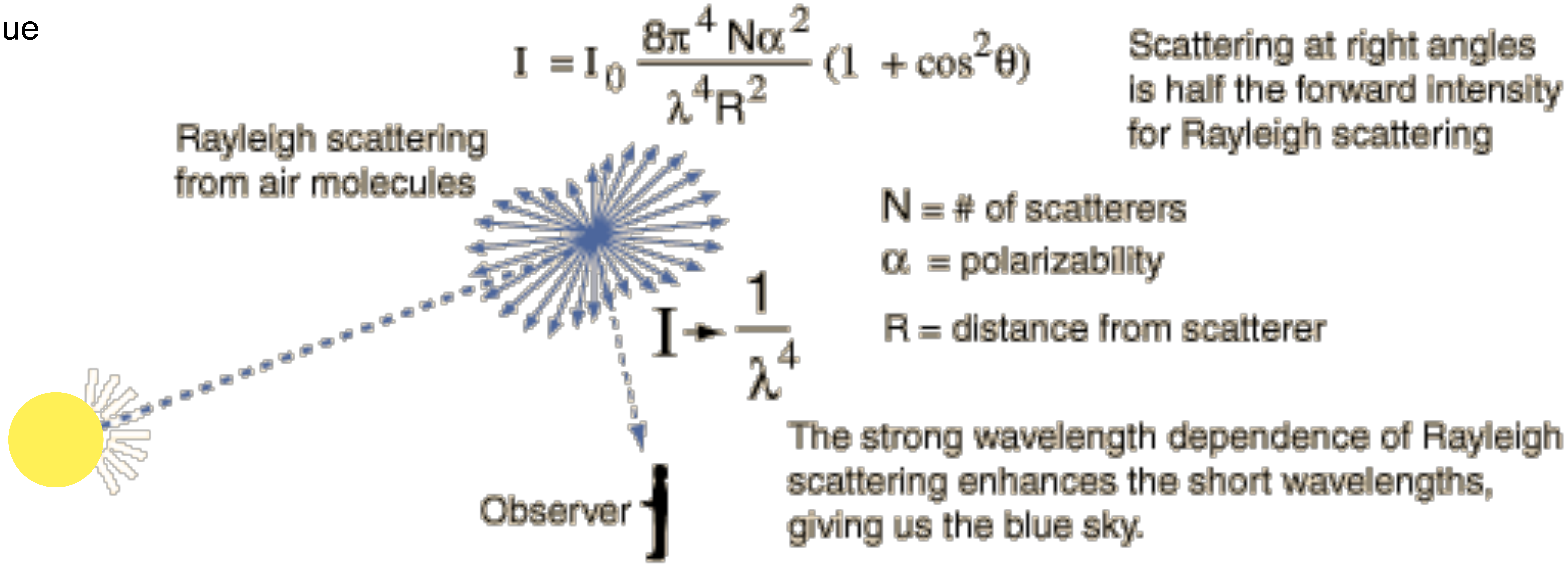
- Molecular scattering is mostly isotropic
- Larger particles (about the size of the wavelength of light) mostly forward scatter
- Largest objects (much larger than the wavelength of light) mostly back scatter (geometric optics)




Precipitating raindrops
Cloud dropplets
Crystal clouds
Particle
Type
Photochemical
aerosols
Soil weathering
aerosols
CCN
(monomers)
Condensation nuclei
Molecular
Scale
Nucleation kinetics
1 nm
100 nm
10 µm
50 µm
500 µm
10 mm
Particulate Size

Rayleigh Scattering

- Scattering by molecules much smaller than wavelength of light
- Mostly seen in gasses
- Why sky is blue

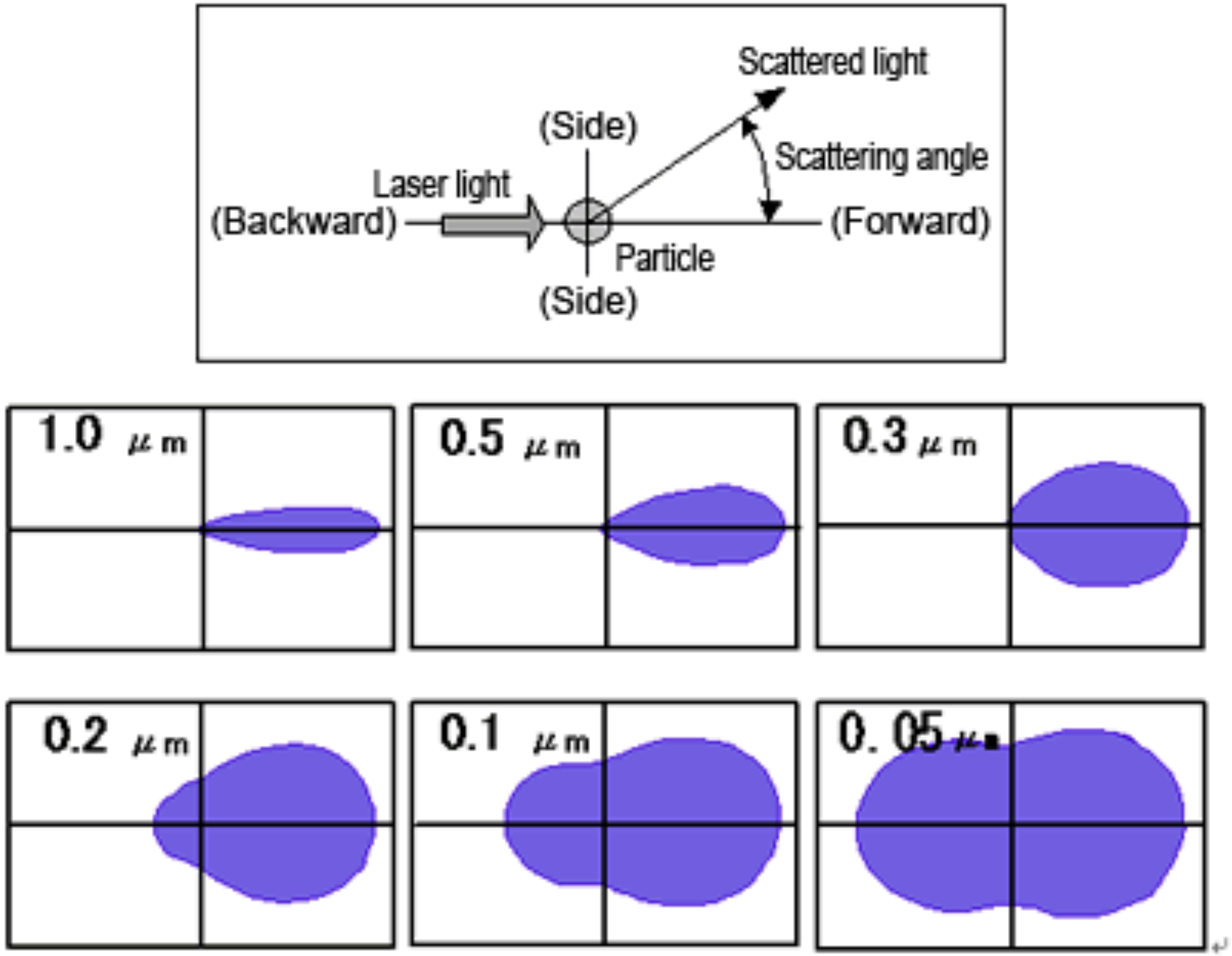


Size parameter

- Describe a scattering particle of radius r by its size parameter x:

$$x = \frac{2\pi r}{\lambda}$$

- Rayleigh scattering: $x \ll 1$
- Mie scattering: $x \approx 1$
- geometric optics: $x \gg 1$

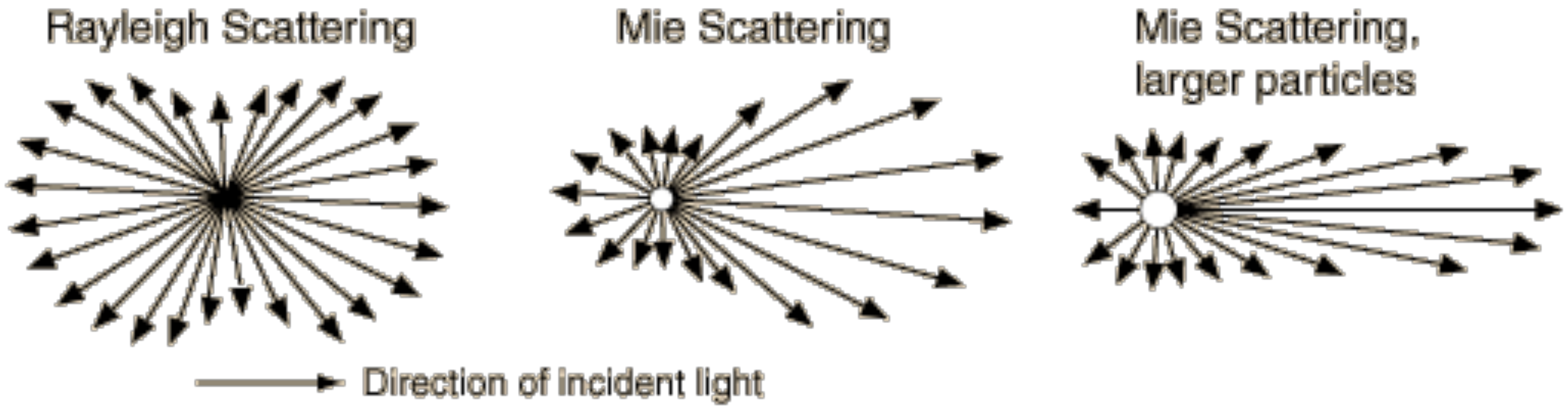


Mie Scattering

- Scattering by particles about the same size as wavelength of light

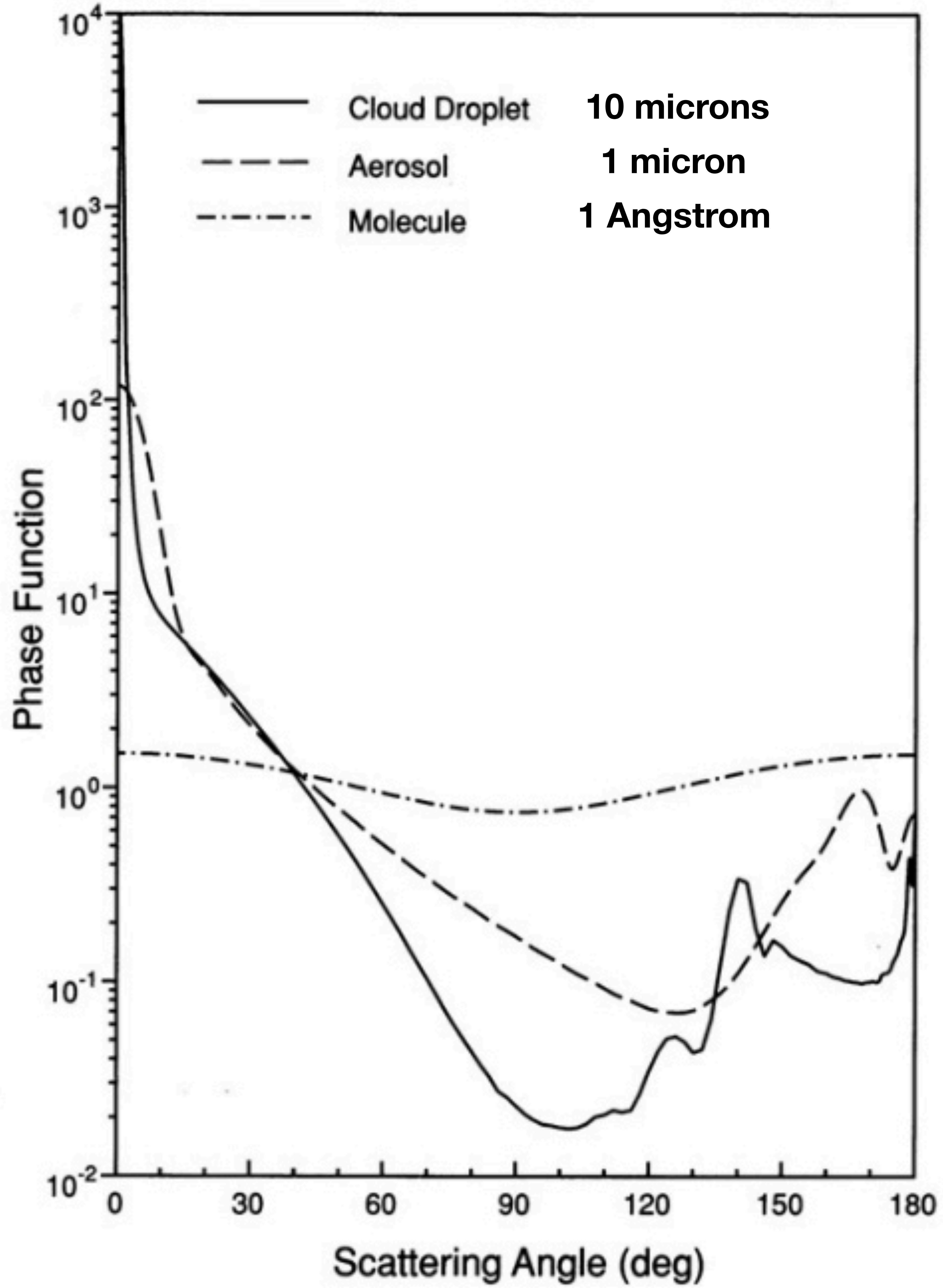
$$x = \frac{2\pi r}{\lambda}$$

- Mie scattering: $x \approx 1$



Mie Scattering

- Mie theory comes from solving Maxwell's Equations
- "Phase Function" is amount of incident radiation that scatters, as a function of scattering angle Θ



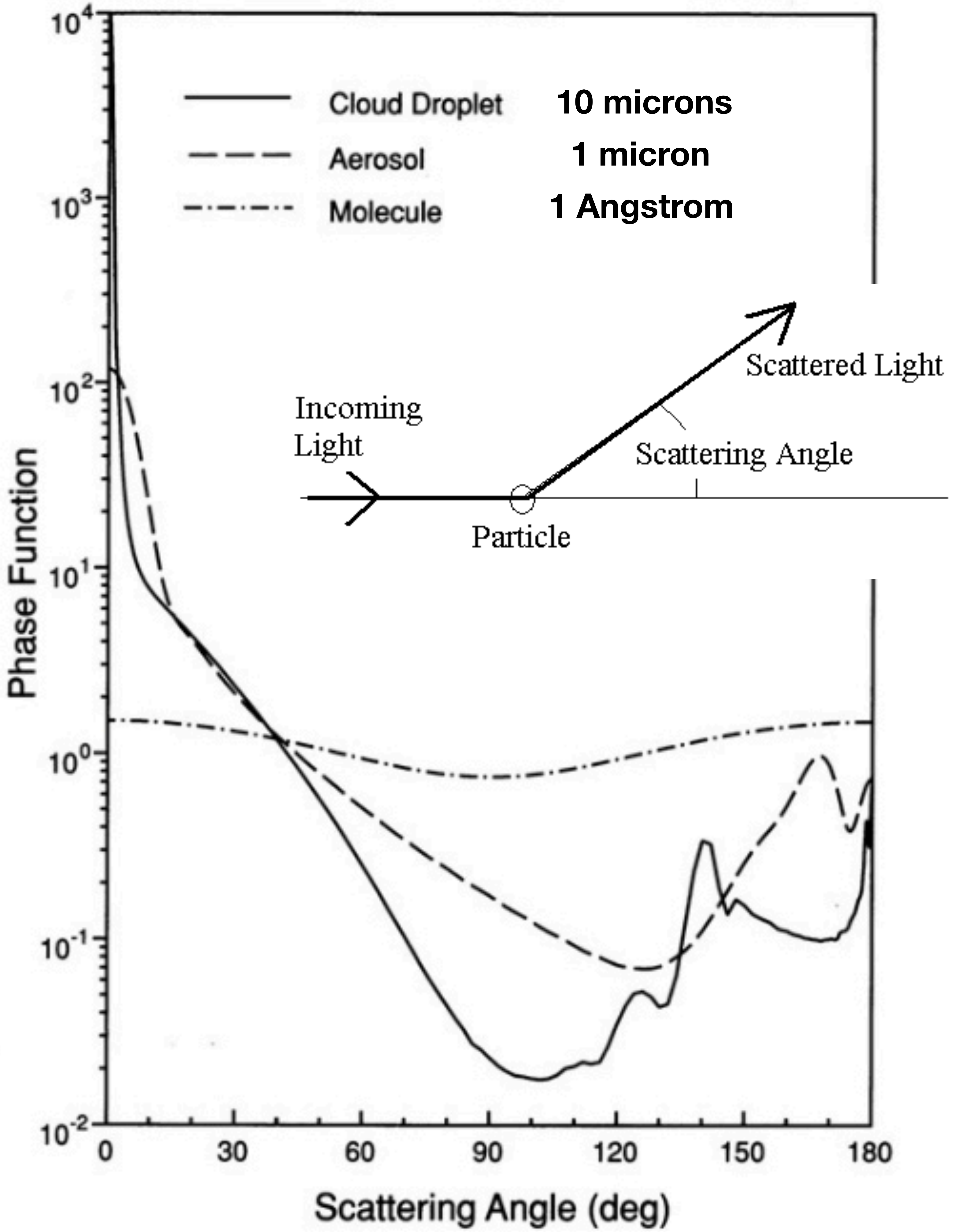
Break

Response Card Question

- What is the (approximate) semi-major axis of Venus, Jupiter, and Saturn?
  - (A) — Venus: 0.1 AU, Jupiter: 10 AU, Saturn: 20 AU
  - (B) — Venus: 0.1 AU, Jupiter: 5 AU, Saturn: 10 AU
  - (C) — Venus: 0.7 AU, Jupiter: 10 AU, Saturn: 20 AU
  - (D) — Venus: 0.7 AU, Jupiter: 5 AU, Saturn: 10 AU

In-class Activity: Phase Function

- Suppose we want to measure the phase function of particles in the atmosphere of Venus, from telescopes here on Earth, over multiple orbits of Venus and Earth over the Sun (assume light from the Sun scatters only once in Venus' atmosphere)
- (1) Draw three pictures of Earth, Venus, and the Sun when we'd make a measurement, each picture at a scattering angle of:
  ~0 degrees
  ~90 degrees
  ~180 degrees
- (2) Why would measurements at (very close to) 0 and 180 degrees be observationally challenging?
- (3) If we wanted to make similar measurements for the phase function of particles in Jupiter's atmosphere from Earth, what's the (approximate) minimum scattering angle we could observe, and what's the approximate maximum scattering angle we could observe?
  - Draw two pictures of Earth, Jupiter, and the Sun for these two observations



In-class Activity: Phase Function

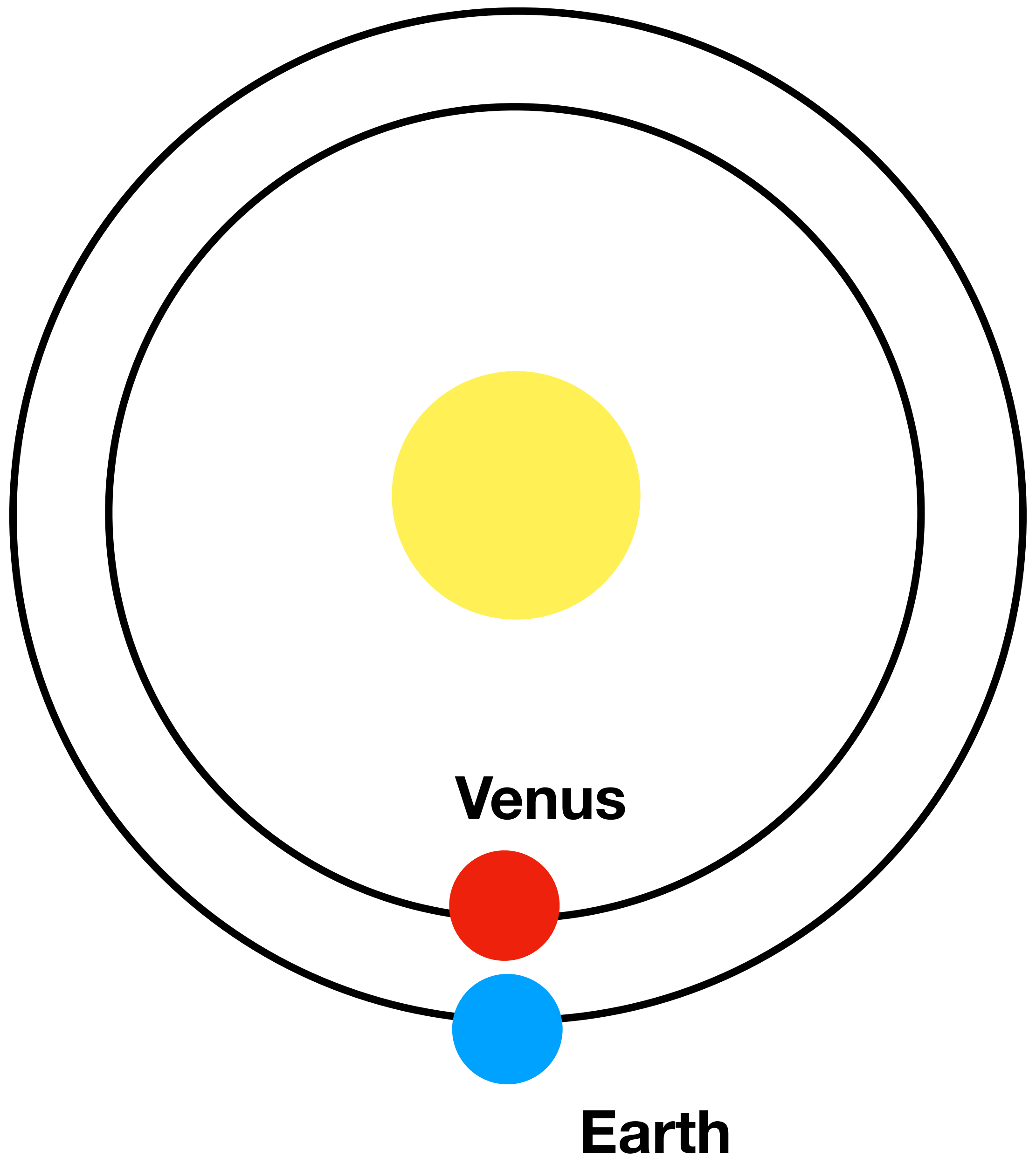
- Suppose we want to measure the phase function of particles in the atmosphere of Venus, from telescopes here on Earth, over multiple orbits of Venus and Earth over the Sun

- (1) Draw three pictures of Earth, Venus, and the Sun when we'd make a measurement, each picture at a scattering angle of:
  ~0 degrees
  ~90 degrees
  ~180 degrees

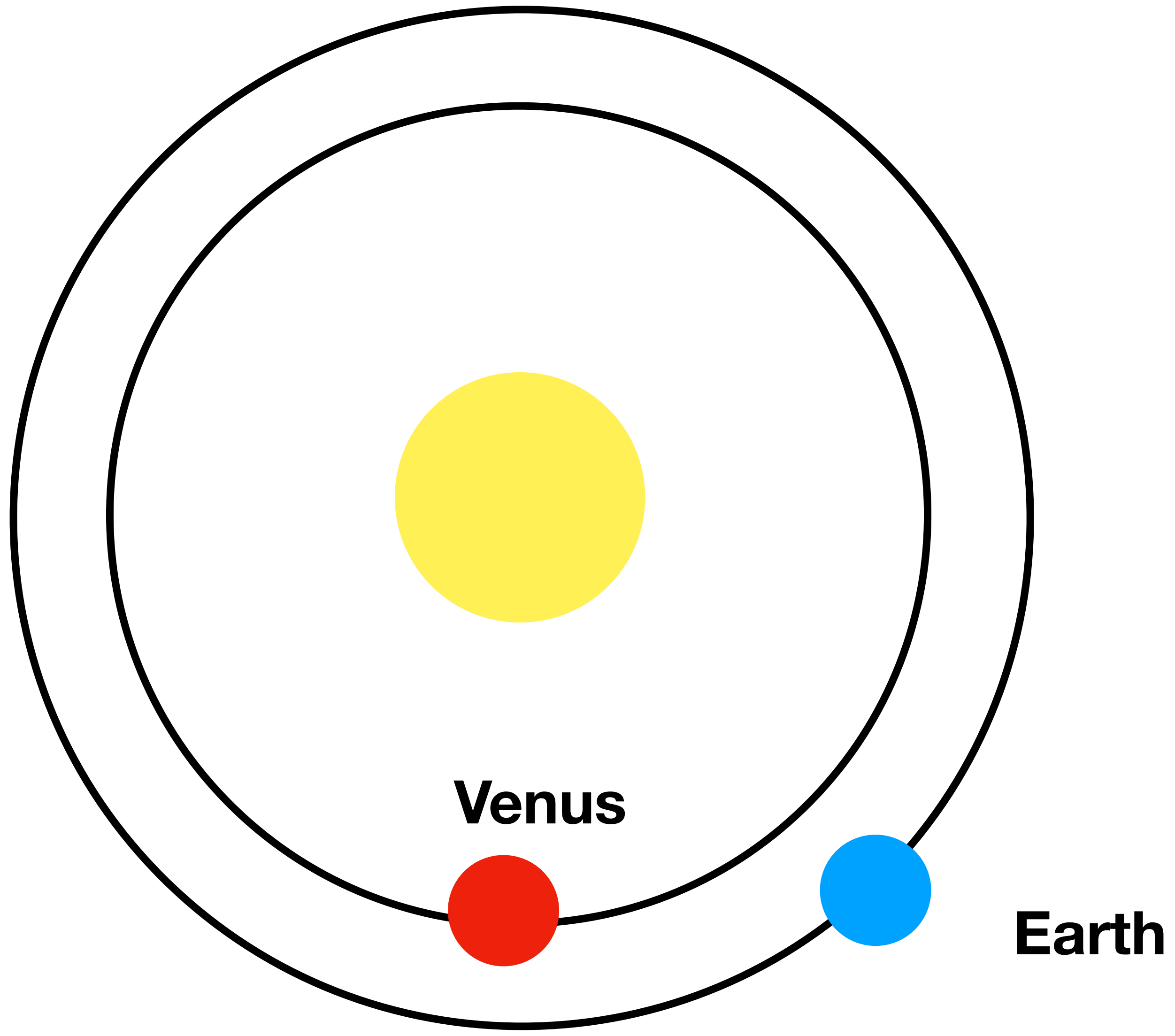
- 0 degrees is forward scattering, so light would go straight from Sun to Venus to Earth: during a Venus transit. 180 degrees is back scattering, light going from Sun, to Venus, "bouncing off," and heading back to Earth, so when Venus is behind the star. And 90 degrees would be in between

In-class Activity: Phase Function

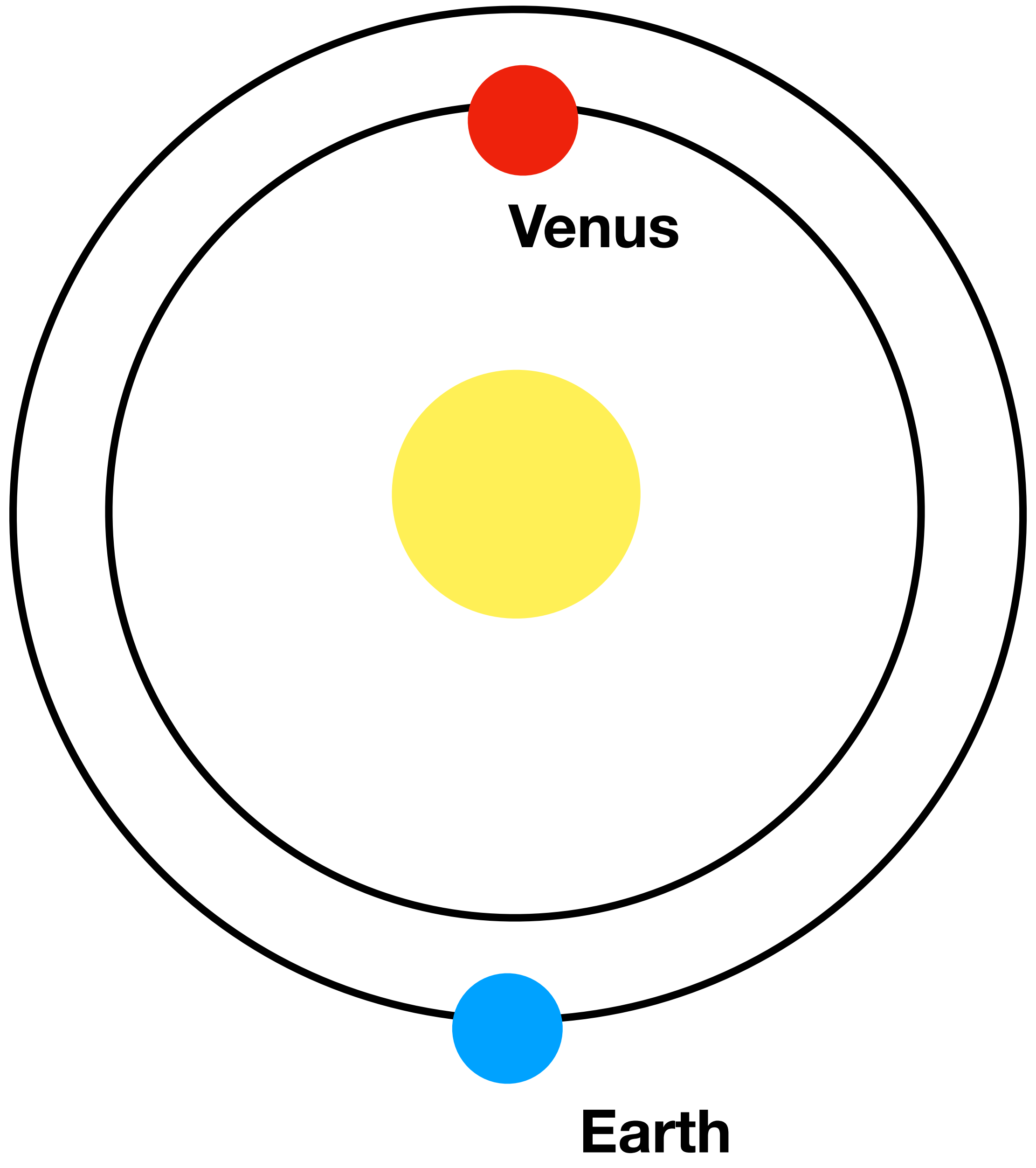
- (2) 0 and 180 are tough because from Earth you're looking directly at the Sun, either during a transit of Venus, or when Venus is behind the Sun as seen from Earth.



0 degrees



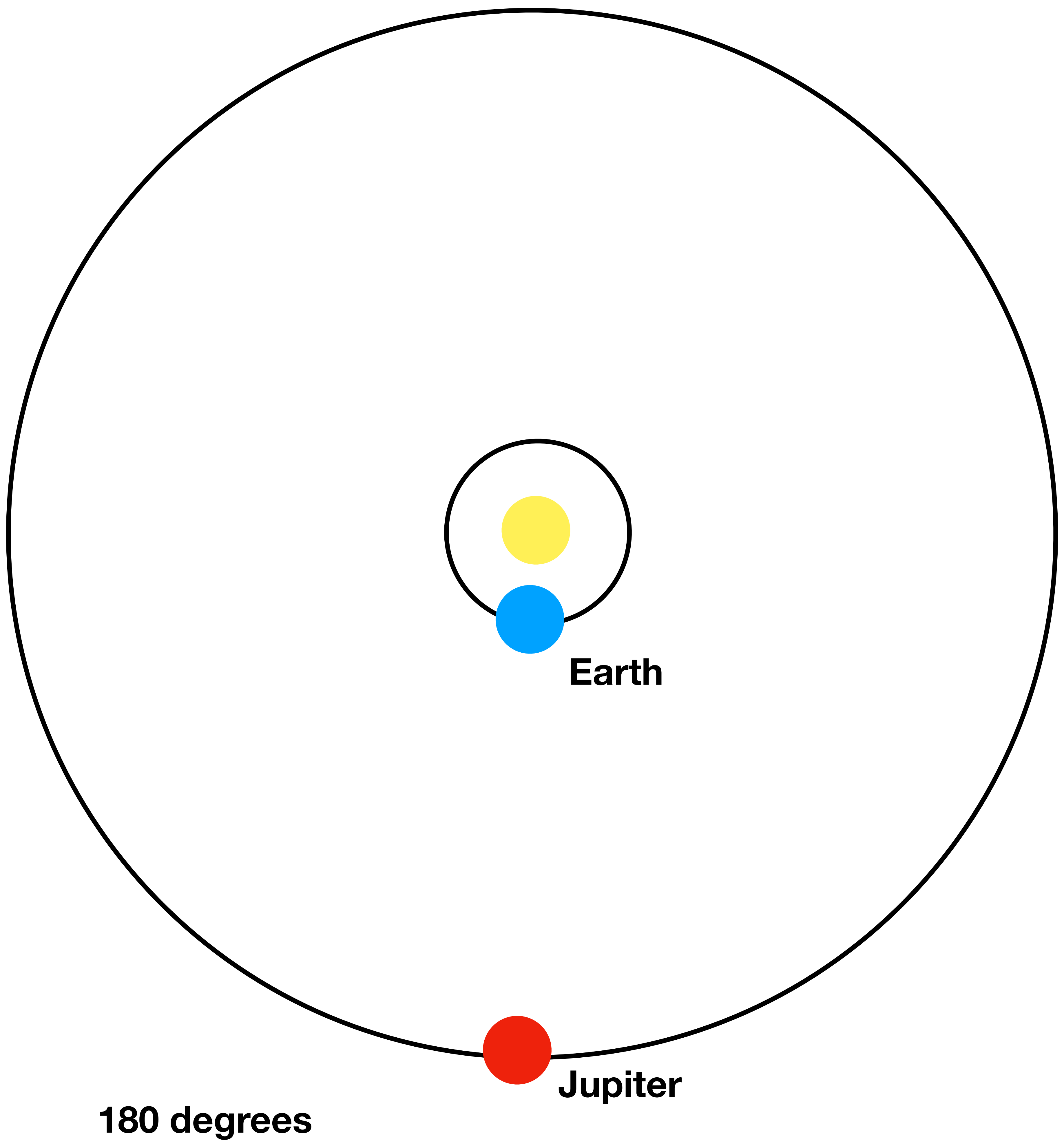
90 degrees

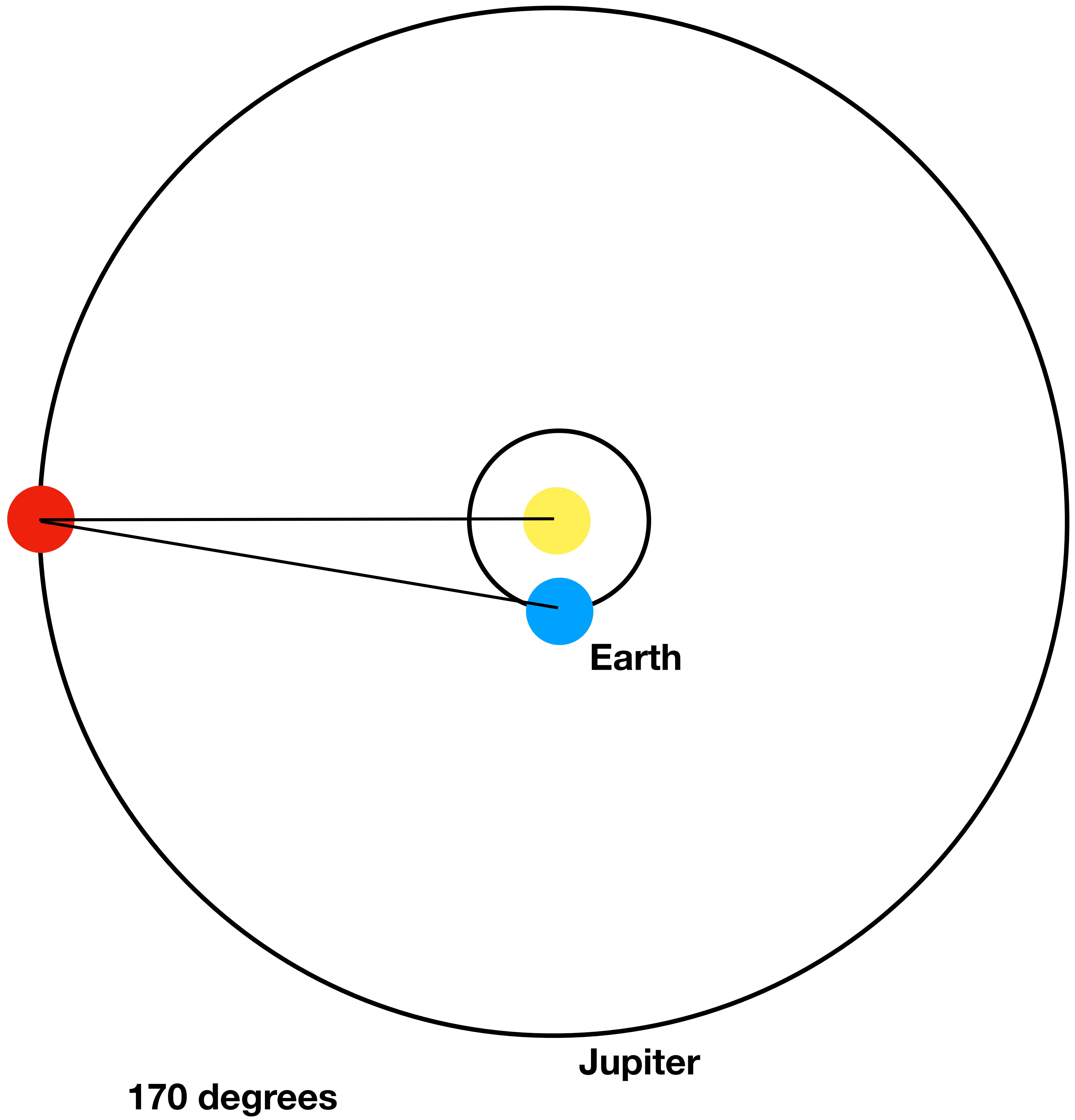


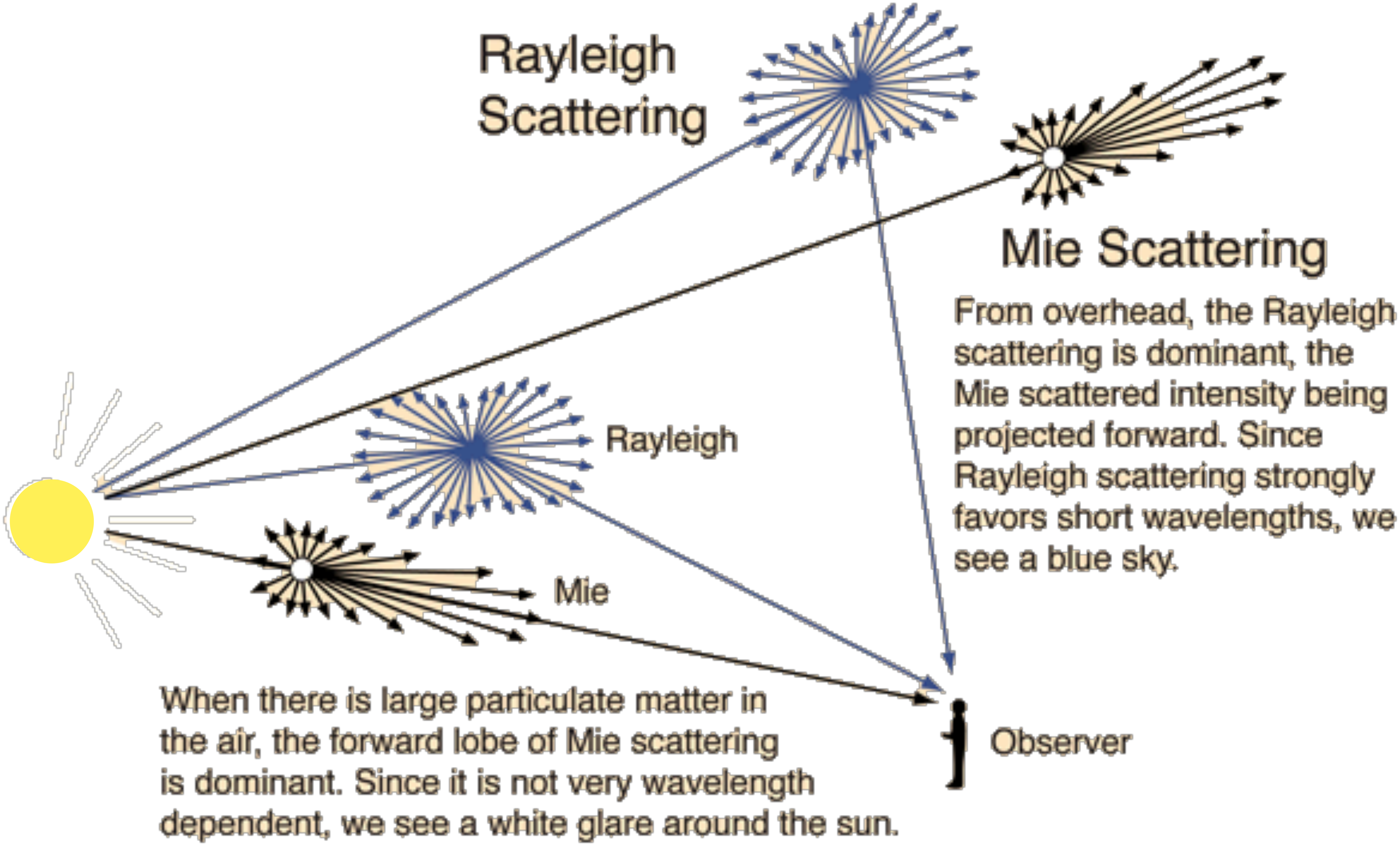
180 degrees

In-class Activity: Phase Function

- (3) Jupiter being further away from the Sun (5 AU instead of 1 AU) means we’re typically looking at the lit-up side of Jupiter, so scattering angle will always be very close to 180 degrees. The smallest angle that seems to be possible is about 180-10 degrees, it looks like. So minimum value 170 degrees, maximum 180 degrees.






Rayleigh Scattering
Mie Scattering
From overhead, the Rayleigh scattering is dominant, the Mie scattered intensity being projected forward. Since Rayleigh scattering strongly favors short wavelengths, we see a blue sky.
Rayleigh
Mie
When there is large particulate matter in the air, the forward lobe of Mie scattering is dominant. Since it is not very wavelength dependent, we see a white glare around the sun.
Observer

Single Scattering Albedo

- Measure of the fraction of a light beam that undergoes a scattering event

- Ratio of volume scattering coefficient to volume extinction coefficient

- $\omega_0 = \frac{\beta_s}{\beta_e} = \frac{\beta_s}{\beta_s + \beta_a}$

$\omega_0 = 0$: particles do not scatter

$\omega_0 = 1$: particles do not absorb

Scattering Phase Functions

- Isotropic scattering:

$$p(\Theta) = \omega_0$$

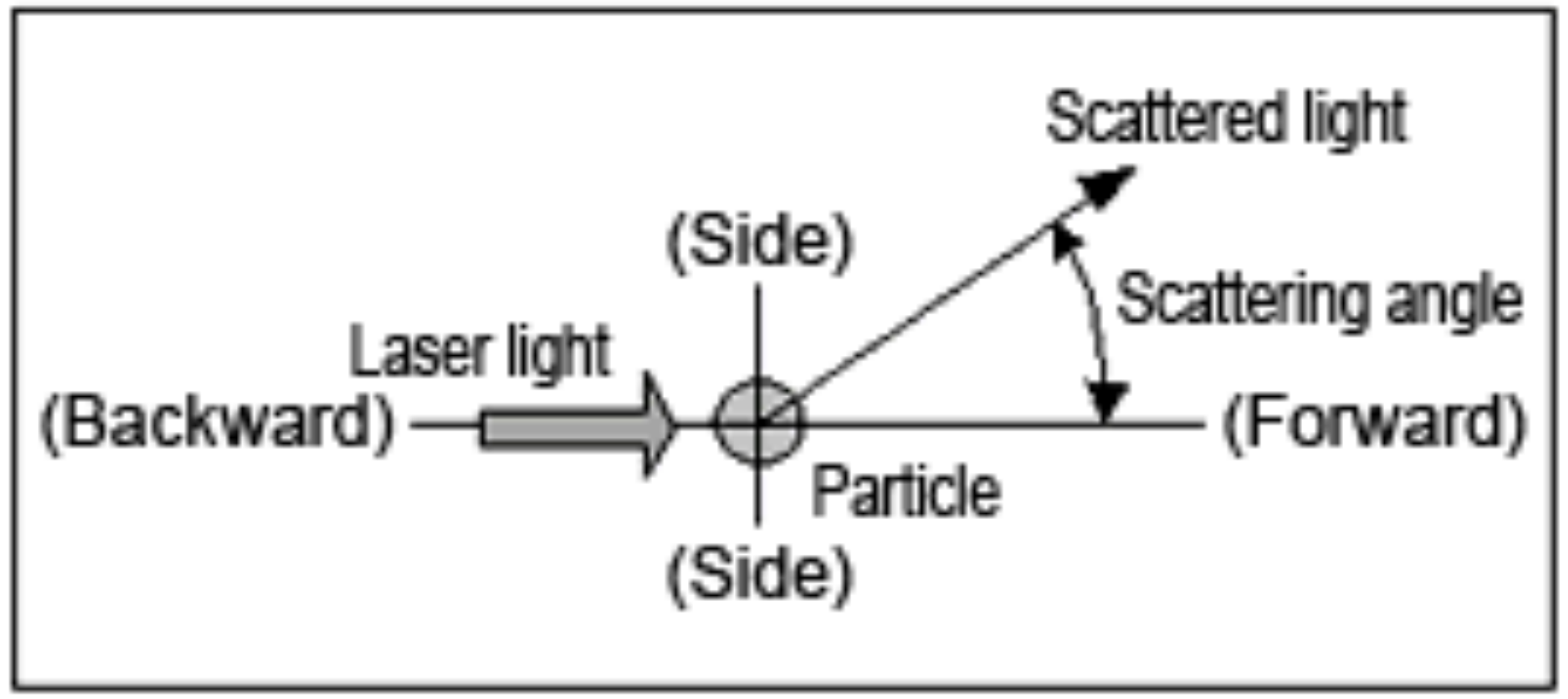
- Rayleigh scattering:

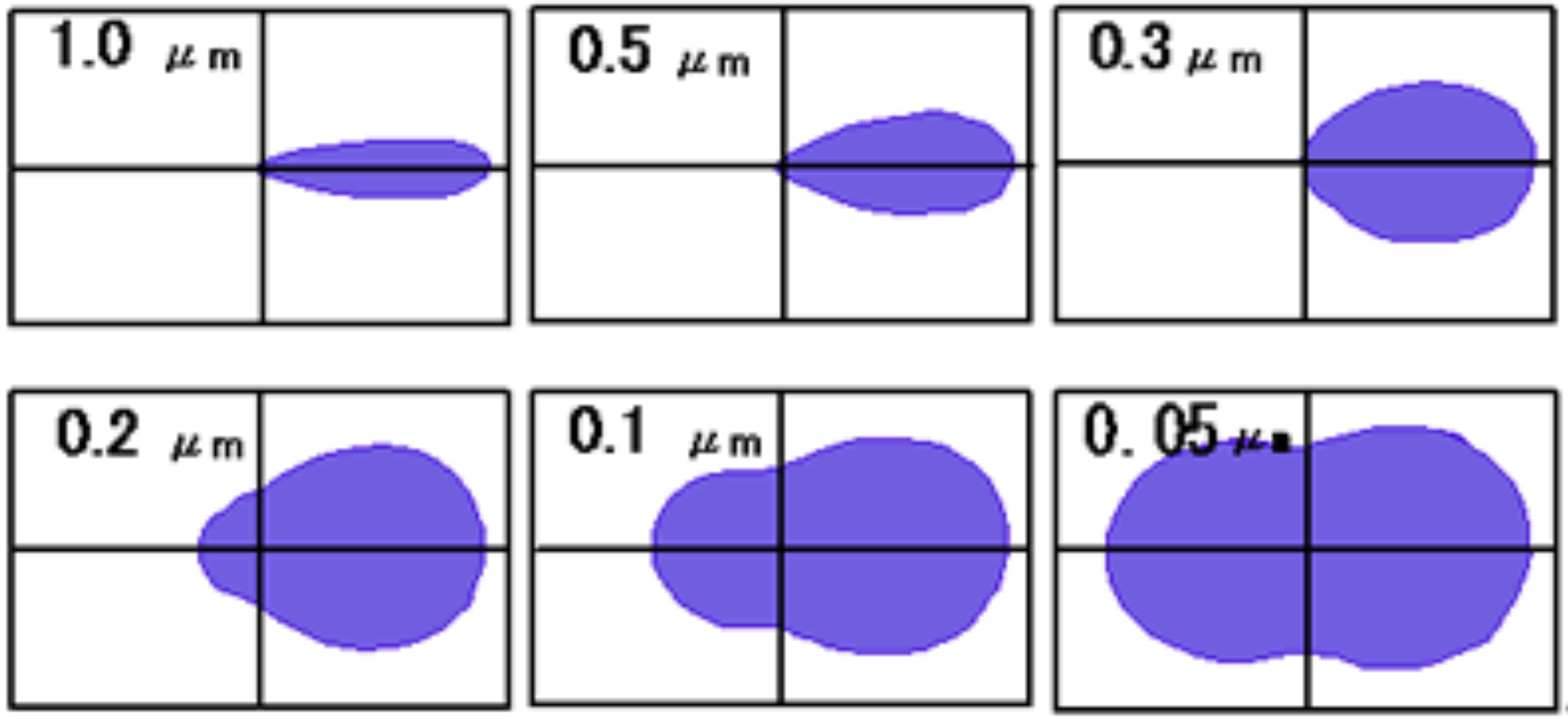
$$p_R(\Theta) = \frac{3}{4}(1 + \cos^2\Theta)$$

- Henyey-Greenstein Function:

$$p_{HG}(\Theta) = \frac{1 - g_s^2}{(1 + g_s^2 - 2g_s\cos\Theta)^{3/2}}$$

g_s: asymmetry factor
$g_s \approx 1$: very forward-scattering
$g_s \approx -1$: very back-scattering





Scattering Phase Functions

- Henyey-Greenstein Function:

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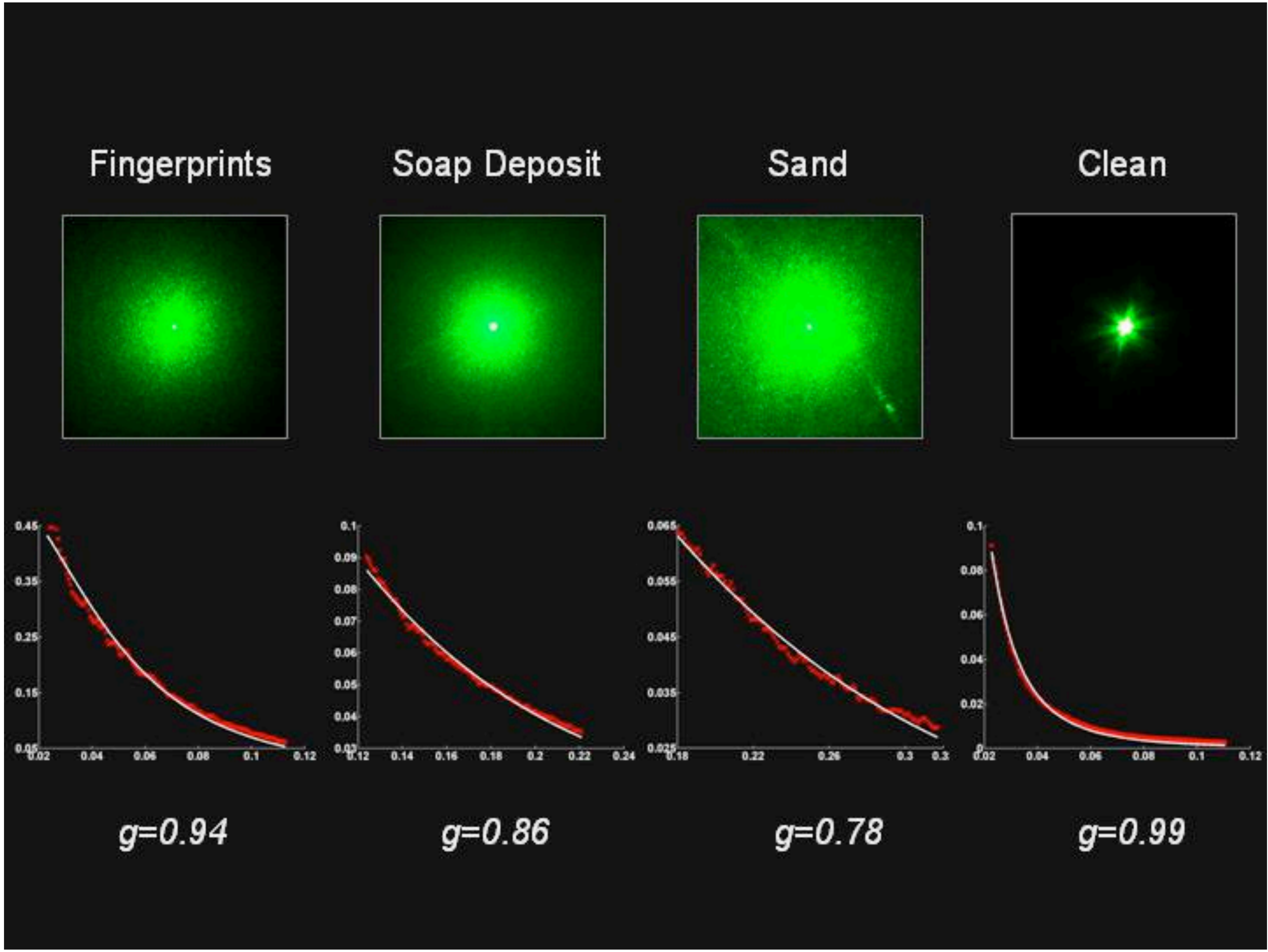


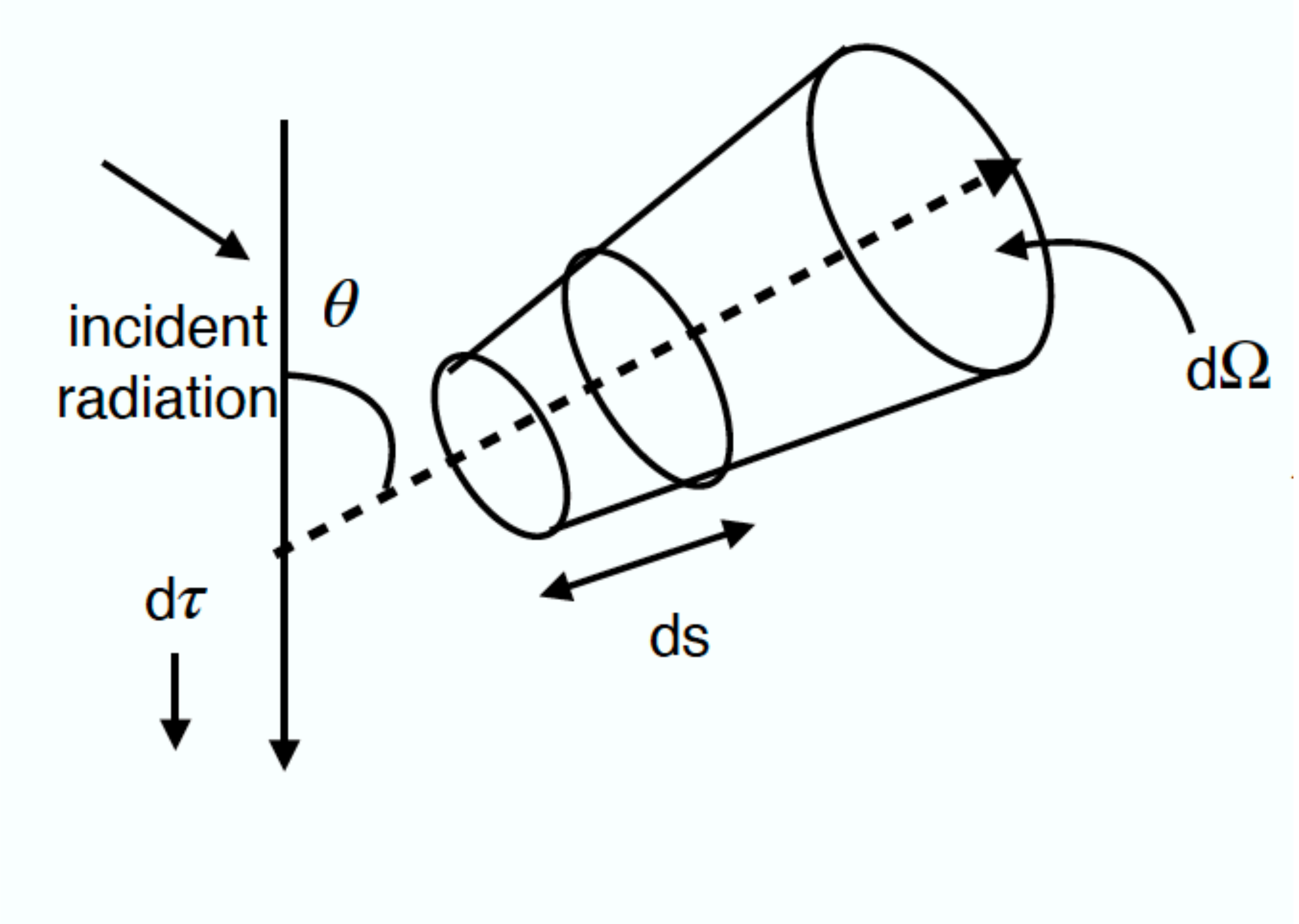
Radiative Transfer, only scattering, no emission

- $$\frac{1}{\rho}\frac{dI_\nu}{ds} = -(\kappa_\nu + \sigma_\nu)I_\nu + j_\nu$$

- If j_ν is entirely due to scattering into the beam (no thermal emission):

$$j_\nu = \frac{\kappa_\nu + \sigma_\nu}{4\pi}\int I_\nu(\cos\Theta)p(\cos\Theta)d\Omega$$

- $$\frac{1}{\rho}\frac{dI_\nu}{ds} = -(\kappa_\nu + \sigma_\nu)I_\nu + \frac{\kappa_\nu + \sigma_\nu}{4\pi}\int I_\nu(\cos\Theta)p(\cos\Theta)d\Omega$$

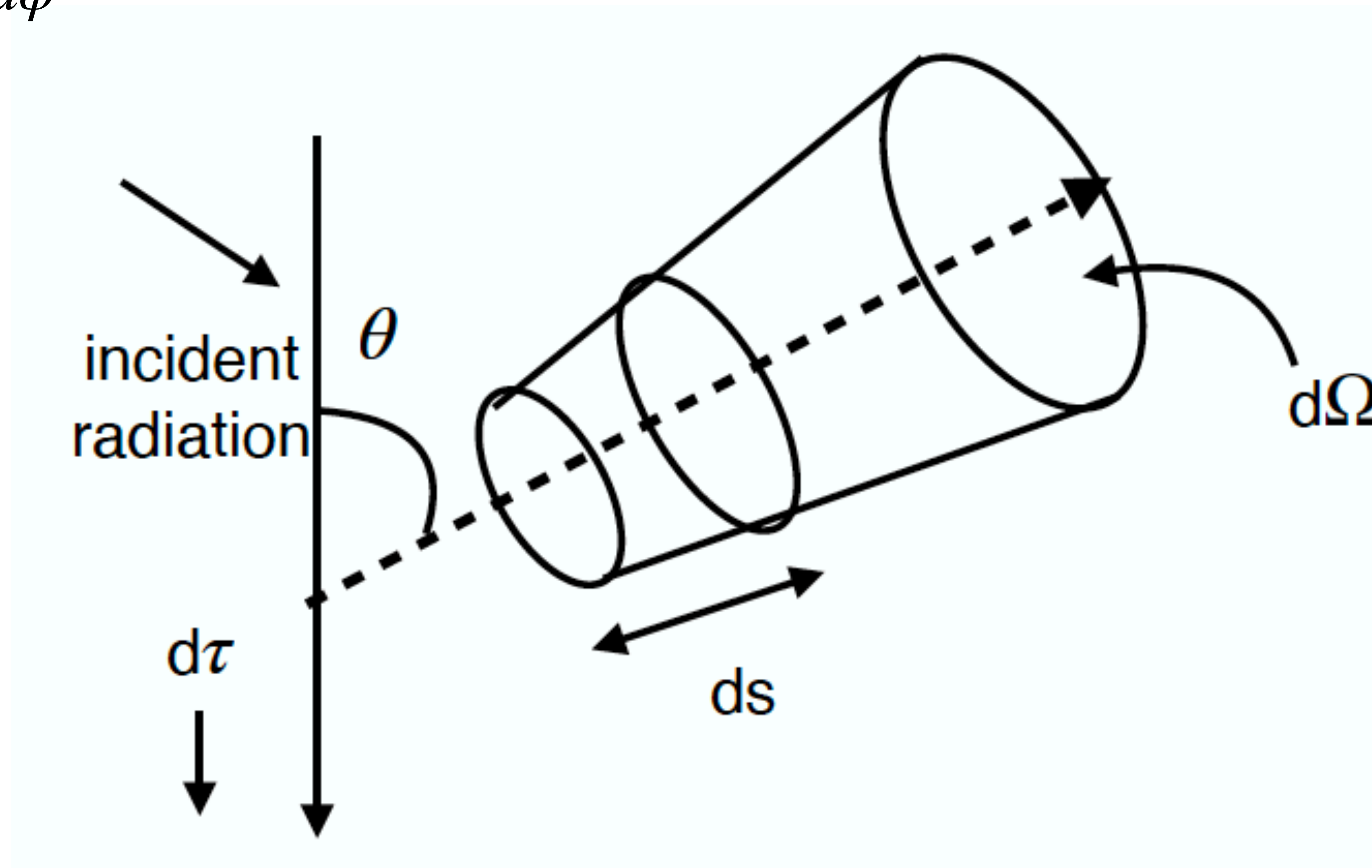


Radiative Transfer, only scattering, no emission

- $$\frac{1}{\rho}\frac{dI_\nu}{ds} = -(\kappa_\nu + \sigma_\nu) I_\nu + \frac{\kappa_\nu + \sigma_\nu}{4\pi} \int I_\nu(\cos\Theta) p(\cos\Theta) d\Omega$$

- $$\frac{dI_\nu(\theta,\phi)}{(\kappa_\nu + \sigma_\nu)\rho ds} = -I_\nu(\theta,\phi) + \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} I_\nu(\theta',\phi') p(\theta,\phi,\theta',\phi') \sin(\theta') d\theta' d\phi'$$

- θ, ϕ: direction of the beam along path s
- θ', ϕ': direction in incoming light



Radiative Transfer, only thermal emission

- If the atmosphere is in LTE (local thermodynamic equilibrium):

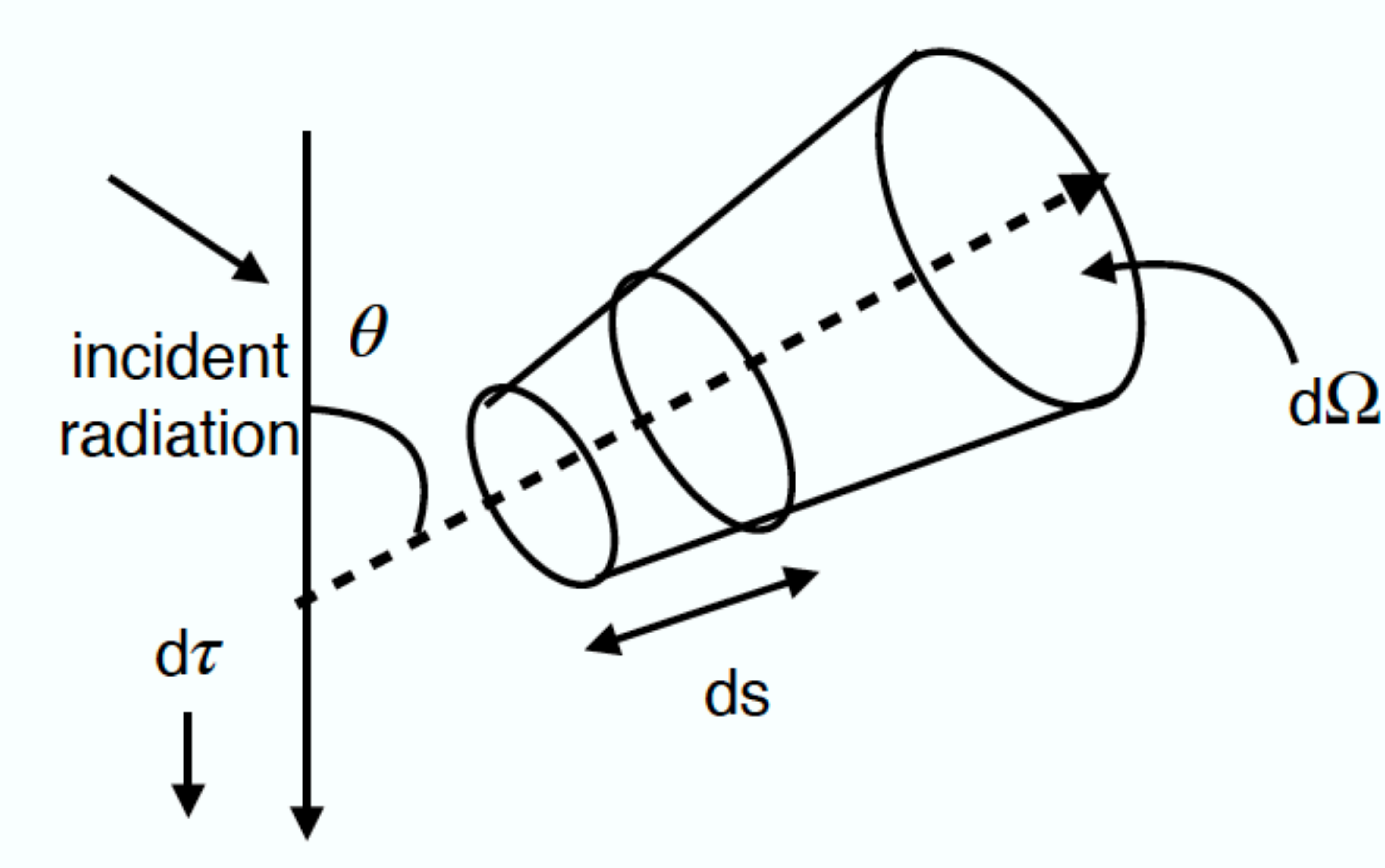
$$j_\nu = \kappa_\nu B_\nu(T) = \kappa_\nu \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

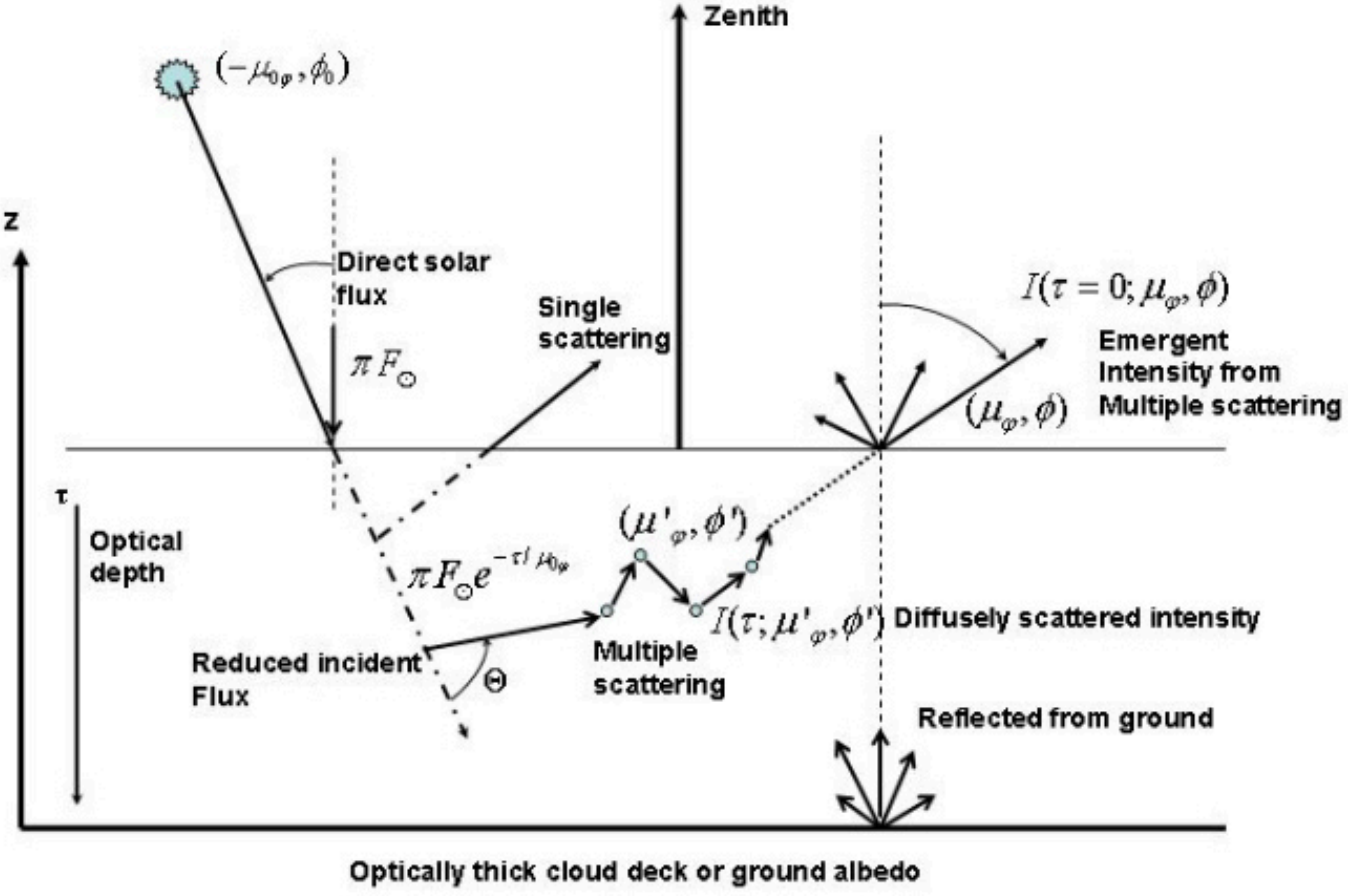
  - Note there must be an opacity source (κ_ν) to have emission

- A purely emitting atmosphere implies no scattering ($\sigma_\nu = 0$):

$$\frac{1}{\rho}\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + j_\nu$$

- $$\frac{dI_\nu(\theta,\phi)}{\kappa_\nu \rho ds} = -I_\nu(\theta,\phi) + B_\nu(T)$$




Zenith
$(-\mu_{0\varphi}, \phi_0)$
z
Direct solar flux
$\pi F_{\odot}$
Single scattering
$I(\tau = 0; \mu_{\varphi}, \phi)$
Emergent Intensity from Multiple scattering
(μ_{φ}, ϕ)
τ
Optical depth
(μ'_{φ}, ϕ')
$\pi F_{\odot} e^{-\tau/\mu_{0\varphi}}$
$I(\tau; \mu'_{\varphi}, \phi')$ Diffusely scattered intensity
Reduced incident Flux
Θ
Multiple scattering
Reflected from ground
Optically thick cloud deck or ground albedo

Brightness Temperature

- Brightness Temperature (T_b): the temperature that a blackbody would have in order to produce the observed radiation at some particular frequency:

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT_b} - 1}$$

- NOT a physical temperature! Used to characterize intensity

- For a 60 mW HeNe laser, coherence length of 20 cm, and a spot size of 10 microns:

    - $T_b \approx 14x10^9 K$

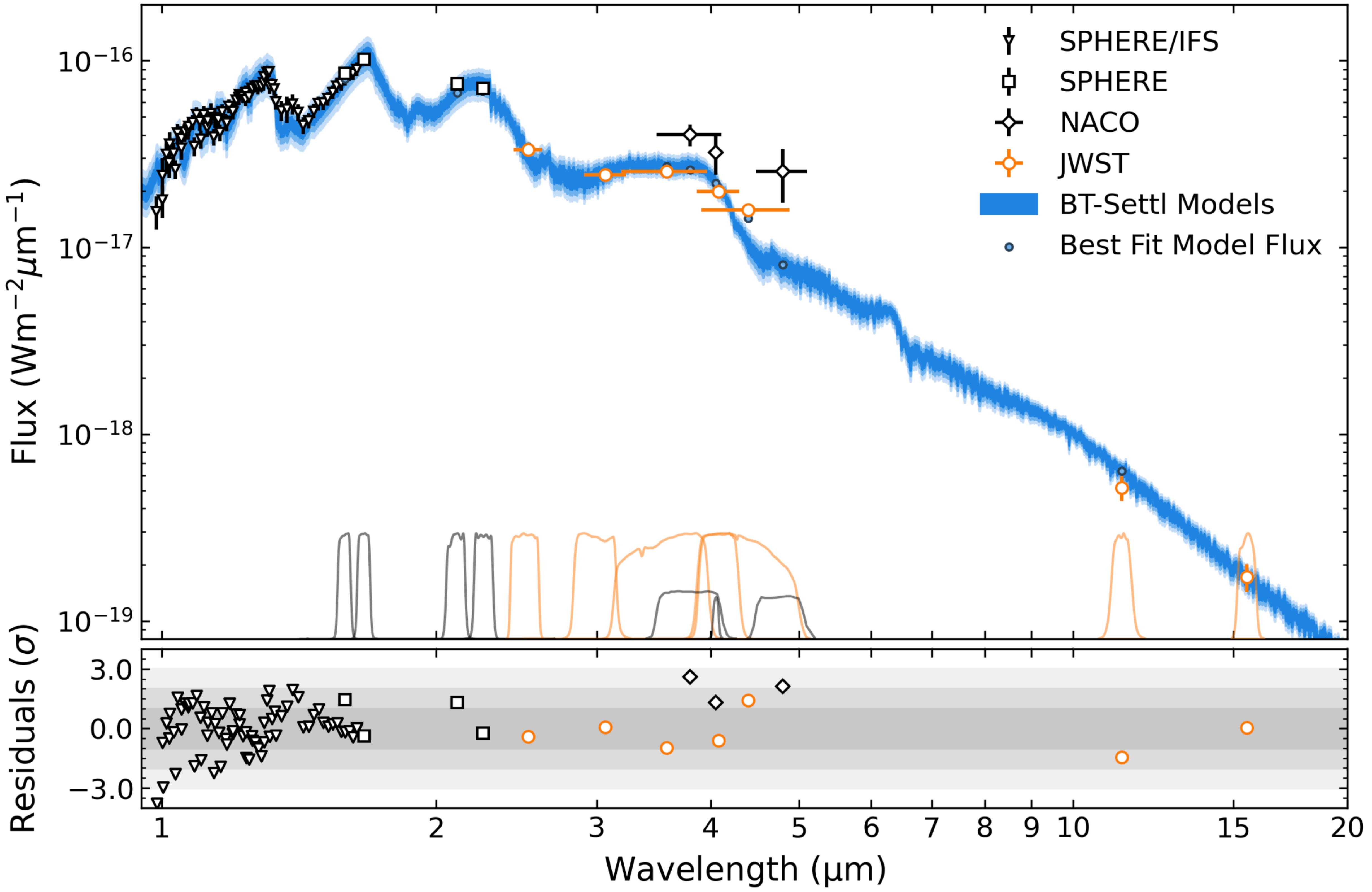
Effective Temperature

- Effective Temperature (T_{eff}): if you can integrate the flux from a source over all frequencies, then effective temperature is the temperature of a blackbody that would have the same total luminosity

$$F_{bol} = \sigma T_{eff}^4$$

$$L = 4\pi R^2 \sigma T_{eff}^4$$

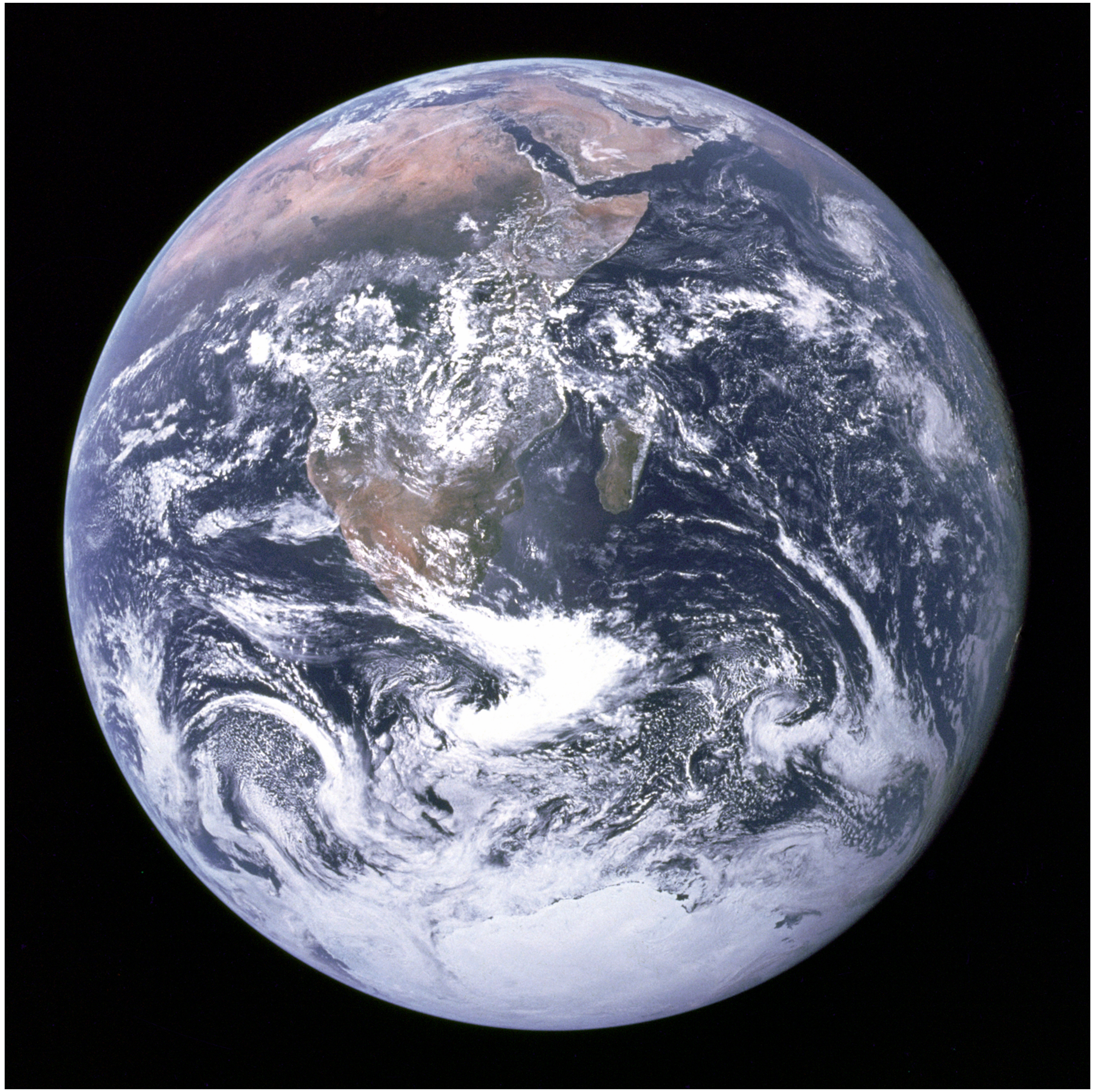
- If an object is mostly a blackbody, effective temperature probably matches physical temperature of the emitting layer
    - Planets typically aren't perfect blackbodies



Carter et al. 2022

Equilibrium Temperature

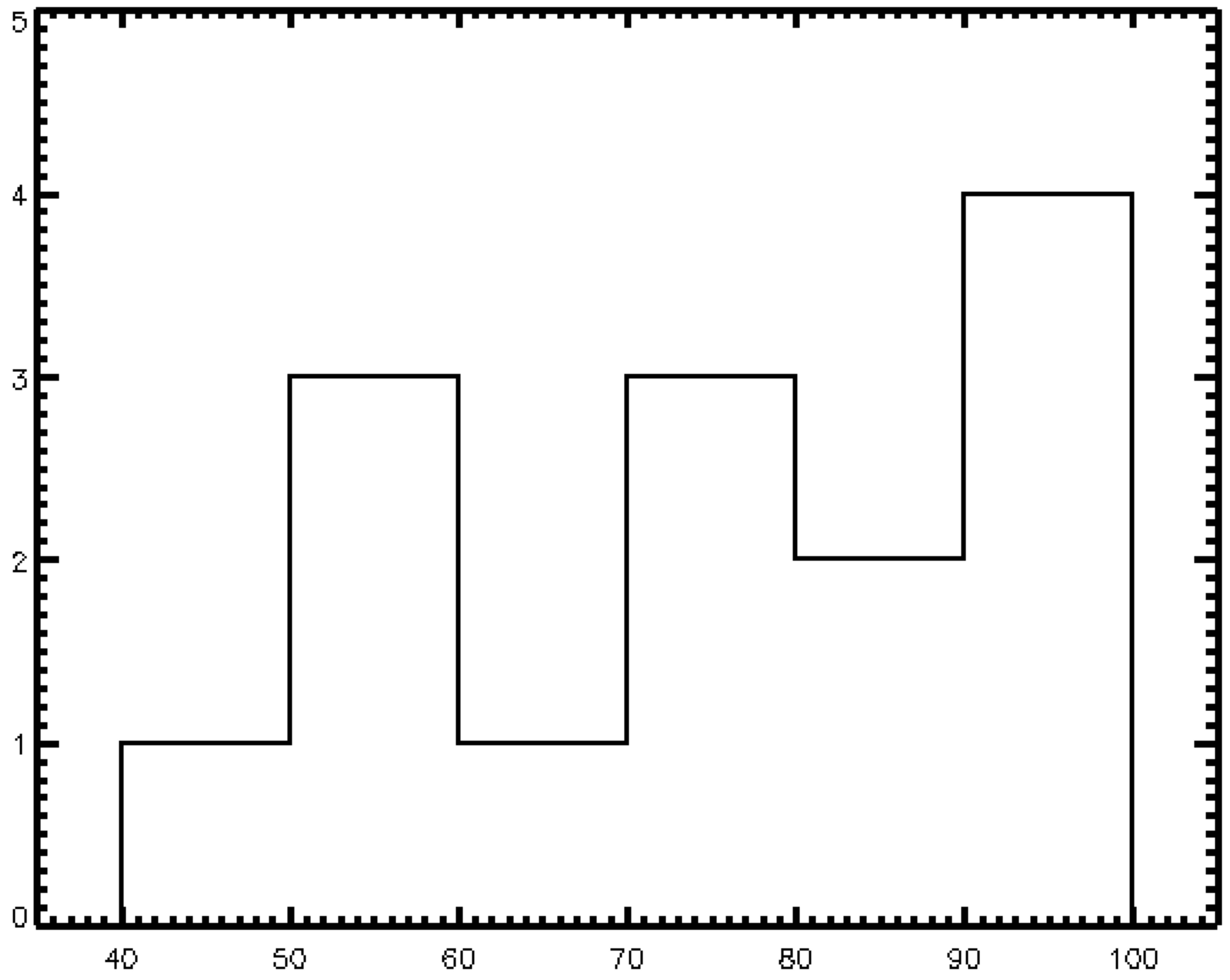
- Equilibrium Temperature (T_{eq}): temperature derived by balancing incoming solar radiation (mostly visible) and outgoing radiation (mostly thermal infrared)
  - If temperature of a body is solely determined by incident solar flux, then $T_{eff} = T_{eq}$



Midterm

- Final class grade will be curved

- Optional midterm review: today at 4pm (this room)



For next time

- Reading: Planetary Science, 3.3.2