A Survey of Modelling and Rendering of the Earth's Atmosphere

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Talk Outline

- Introduction.
- Models of the atmosphere.
- Atmosphere composition.
- Light transfer through the atmosphere.
- Rendering of the atmosphere.

Motivation

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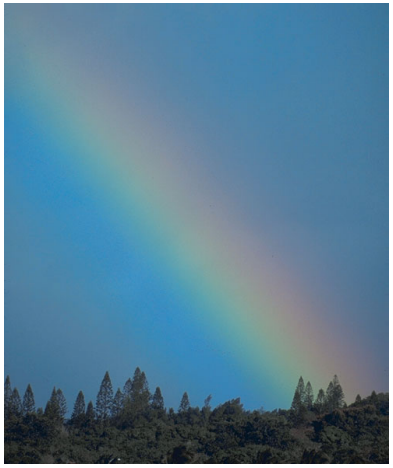
- **Photo-realistic image synthesis of outdoor scenes**
  - most of scene objects illumination comes directly from the sun and sky
  - sky forms the background of the scene
  - atmosphere causes change of colors of distant objects
- **Instance of participating media simulation problem**
  - long distances make the effects of atmosphere visible


Models of the Atmosphere

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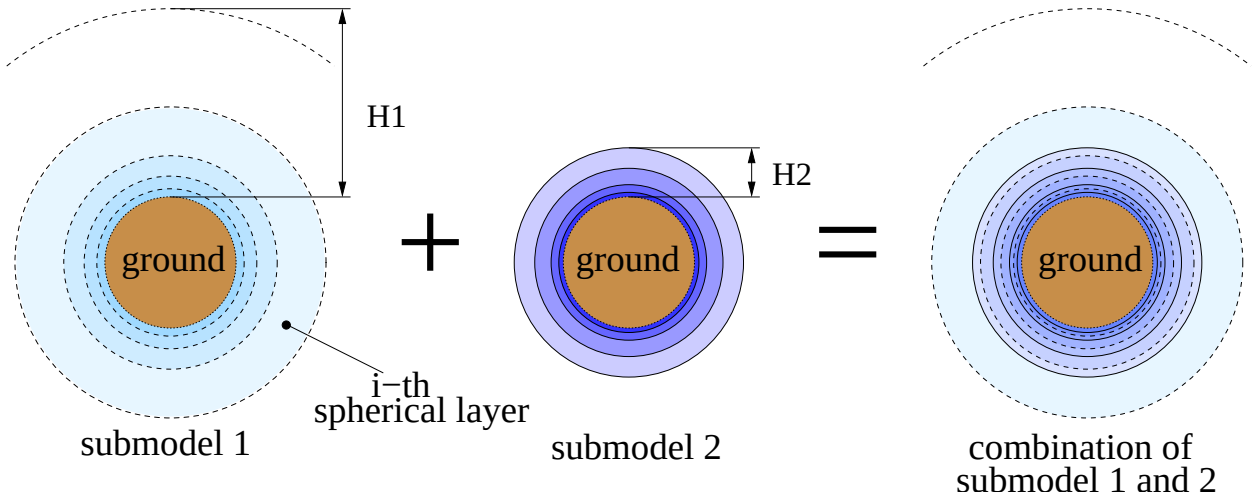
- **Plane-parallel model** Klassen [15]
  - approximates the atmosphere as a set of plane-parallel layers
  - neglects the sphericity of Earth
  - introduces large errors near the horizon
- **Spherical model** Nishita et al.[20,21], Irwin [8], Jackel et al. [10]
  - for each atmospheric component one submodel
  - submodel = a set of non-interleaving spherical layers



Composition of the Atmosphere

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- **Major atmospheric constituents**
  - clean dry air
  - aerosols
  - ozone
  - water vapour, rain drops and ice crystals
- **Constituents characteristics at point P**
  - extinction coefficient $\sigma_{e\lambda}(P)$ (losses by absorption and scattering)
  - scattering function $p_\lambda(P,\theta)$ (angular distribution of scattered light)
  - single scattering albedo $\varpi_\lambda(P)$

    (relation between absorption and scattering $\varpi_\lambda(P) = \frac{\int_\Omega p_\lambda(P,\theta)\,\mathrm{d}\theta}{\sigma_e}$)

Composition of the Atmosphere – cont.

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- **Constituents properties depend on**
  - particle size
  - wavelength of incident light λ
  - refractive index of the particle
  - number of particles in unit volume
- **Sources of constituents properties**
  - Mie scattering theory
  - Rayleigh scattering theory
  - geometric optics
  - measured data

Composition of the Atmosphere – cont.

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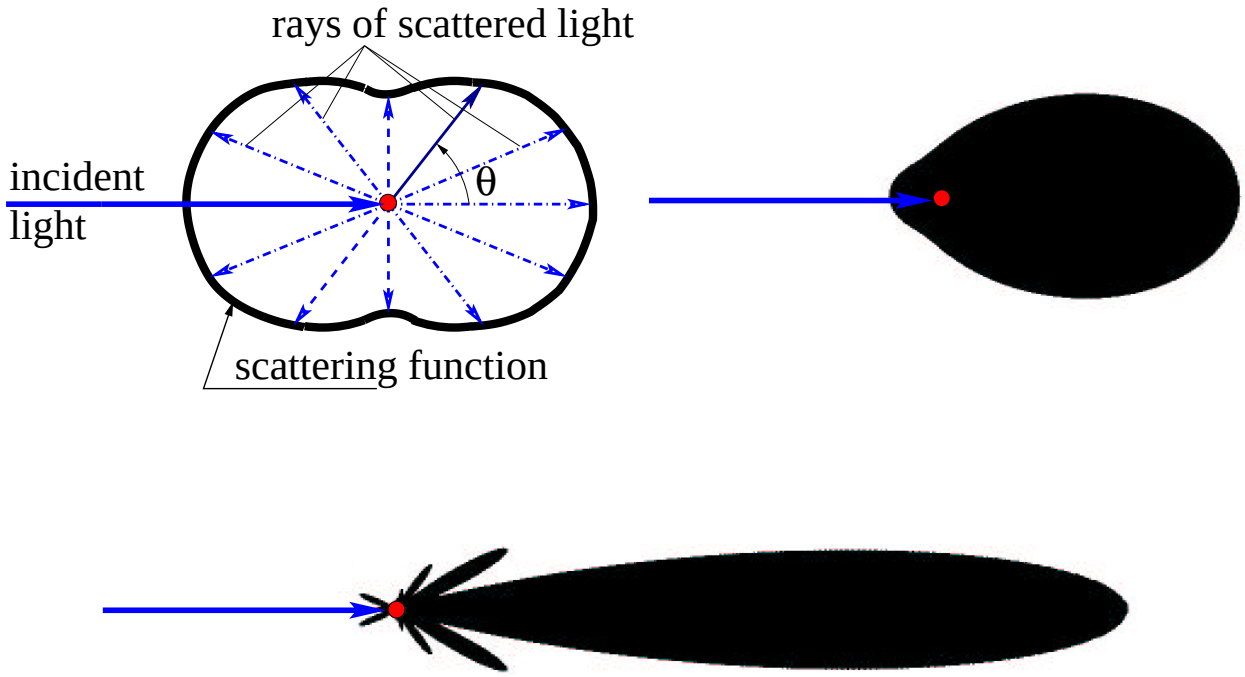
- **Mie Scattering Theory** developed by G.Mie(1908)
  - general theory - valid for all particle sizes
  - strong forward scattering
  - absorption of energy occurs
  - scattering function depends on particle size and wavelength



Composition of the Atmosphere – cont.

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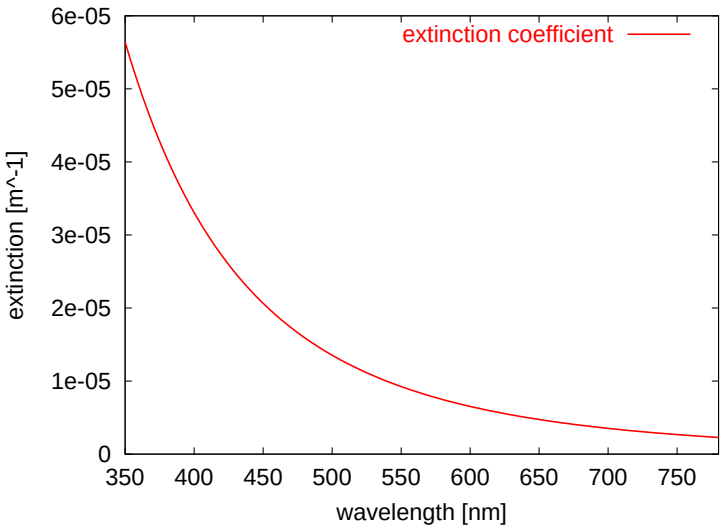
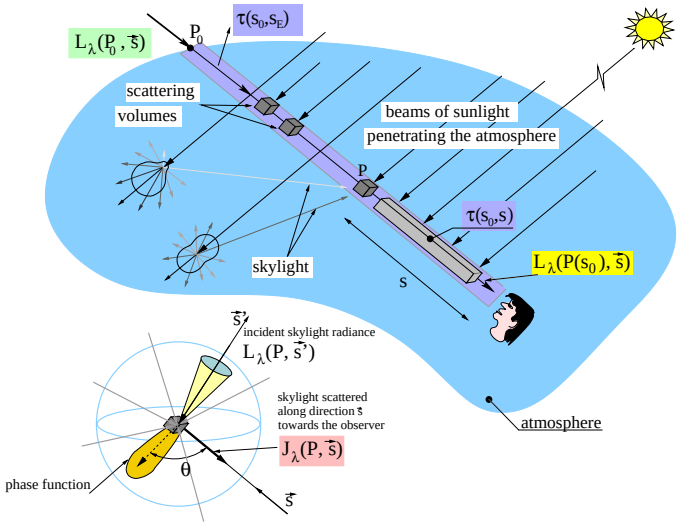
- **Rayleigh Scattering Theory** established by Lord Rayleigh (1871)
  - approximation for particles smaller than wavelength of light
  - no absorption of light
  - simple scattering function
  - radiance of scattered light is proportional to the ratio $\sim \frac{1}{\lambda^4}$

    $\longrightarrow$ blue color of the sky

    $\longrightarrow$ color of the sun (yellow $\longrightarrow$ orange $\longrightarrow$ red)



Light Transfer Equation



$$L_\lambda(P(s_0), \vec{s}) = L_\lambda(P_0, \vec{s})\,\tau(s_0, s_E) + \int_{s_0}^{s_E} J_\lambda(P(s), \vec{s})\,\tau(s_0, s)\,\sigma_{e\lambda}(P(s))\,\mathrm{d}s$$

initial ray radiance attenuated along the viewing ray by transmittance τ

integral of skylight radiance scattered towards the observer by volume elements along the viewing ray attenuated by τ

Light Transfer Equation – cont.

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- **Source function**

$$J_\lambda(P,\vec{s}) = \frac{1}{4\pi}\iint_\Omega \left[\sum_{i=1}^{n} \varpi_\lambda^i(P)\, p_\lambda^i(P,\theta)\right] L_\lambda(P,\vec{s'})\, \mathrm{d}\omega'$$

Light Transfer Equation – cont.

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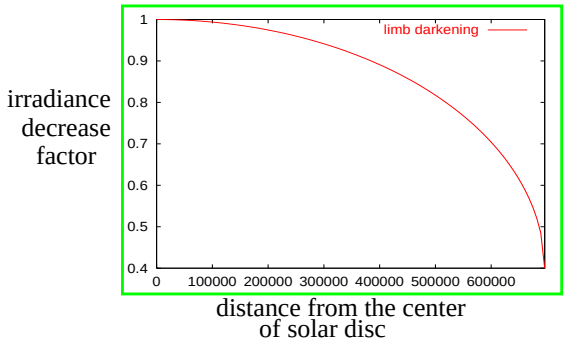
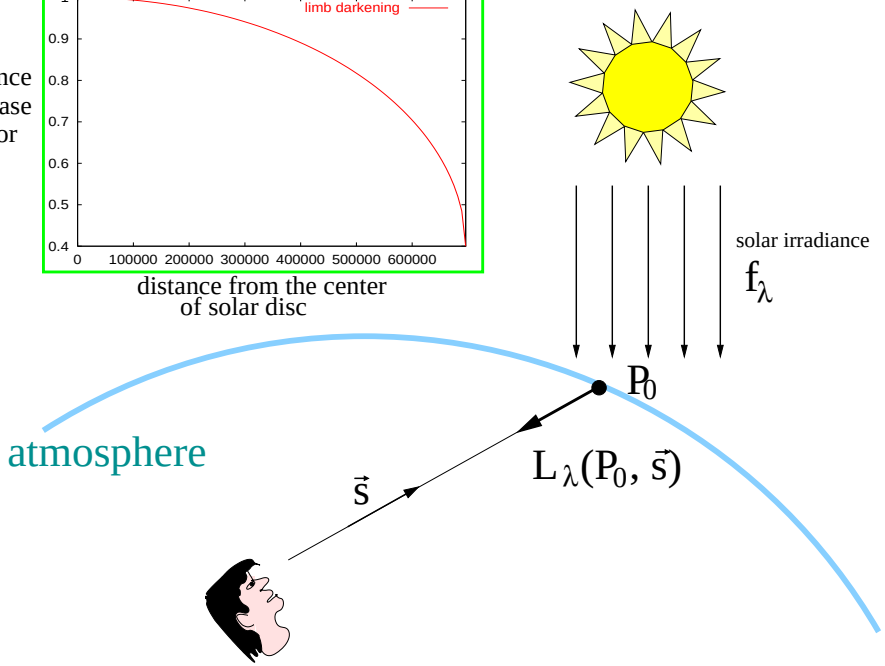
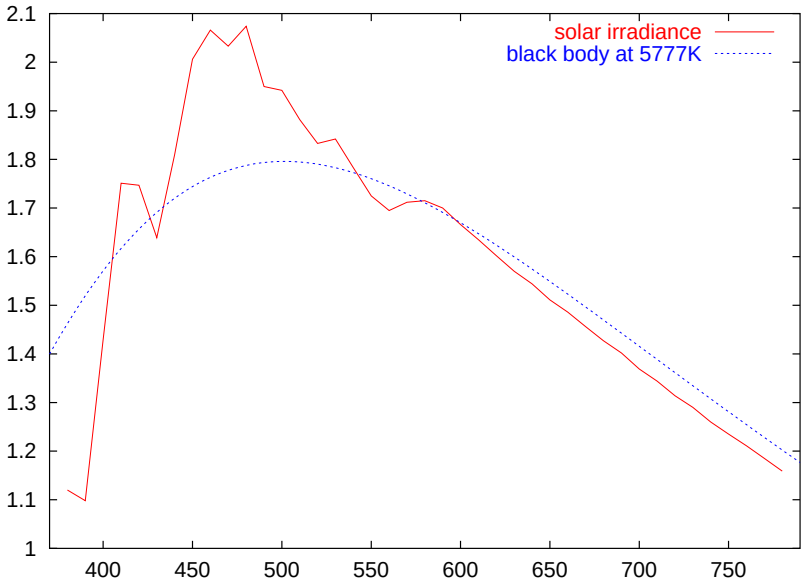
- **Boundary condition at the top of the atmosphere**

$$L_\lambda(P_0, \vec{s}) = \begin{cases} f_\lambda \boxed{\left[1 - u\left(1 - \sqrt{1 - \frac{d^2}{r_s^2}}\right)\right]} & \text{ray hits the solar disc} \\ 0.0 & \text{outside the solar disc} \end{cases}$$







Light Transfer Equation – cont.

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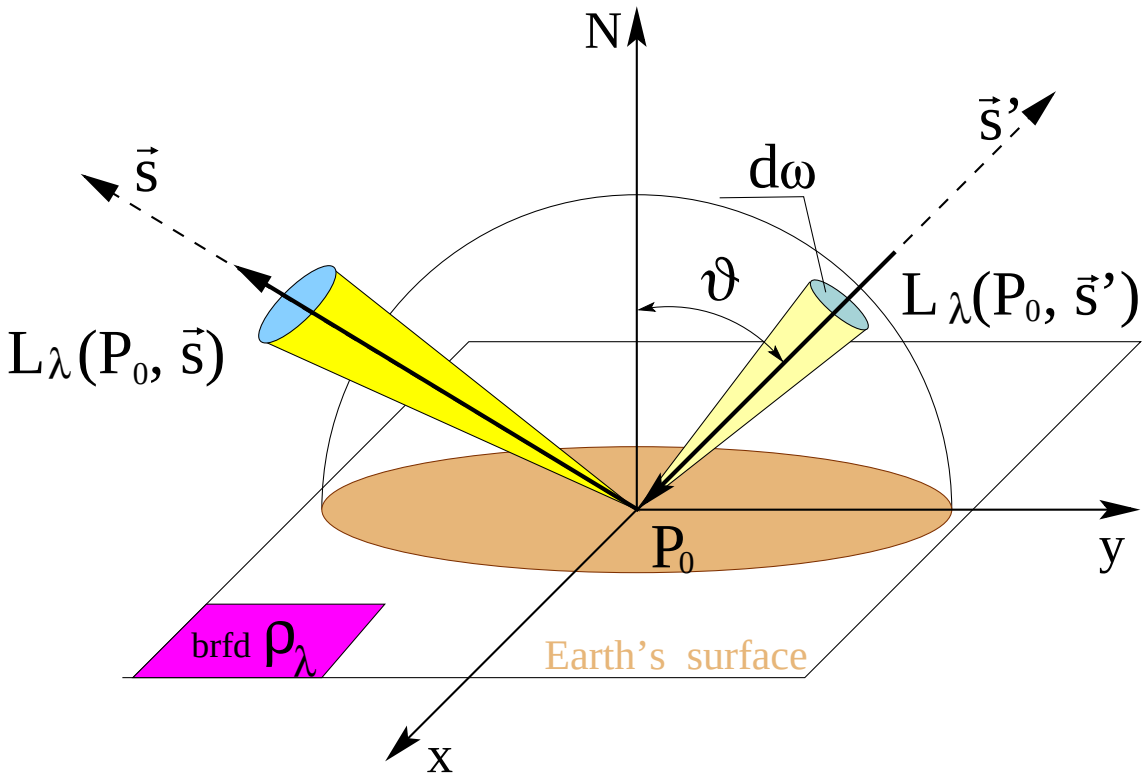
- **Boundary condition for ground reflection**

$$L_\lambda(P_0, \vec{s}) = \frac{1}{\pi} \iint_\Omega \rho_\lambda(\vec{s}, \vec{s'})\, L_\lambda(P_0, \vec{s'}) \cos\vartheta \, d\omega,$$



Rendering of the Atmosphere

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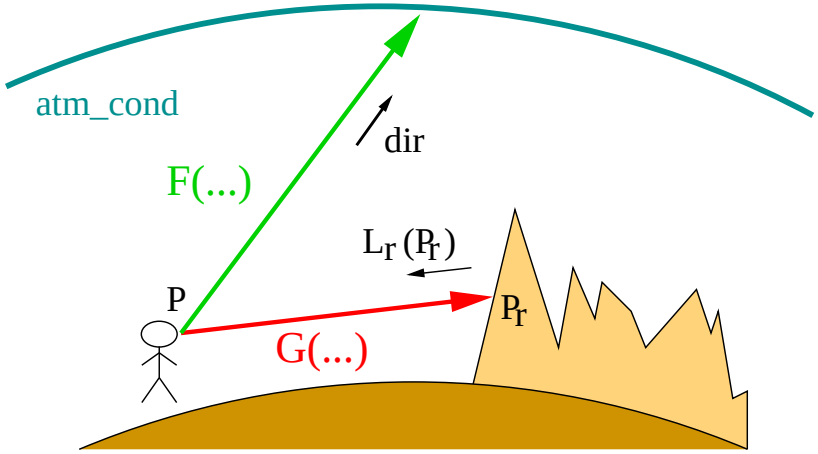
- **For rendering we need**
  - function $F(P, \vec{dir}, date, atm\_cond) \rightarrow$ spectral radiance
    to simulate the color of the sky and sun
  - function $G(P, \vec{dir}, date, atm\_cond, L_r(P_r)) \rightarrow$ spectral radiance
    to simulate the change of color of distant objects observed through the atmosphere



- F **and** G **are based on the light transfer equation**

Rendering of the Atmosphere – cont.

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Rendering of the sky color

- For every pixel covered by the sky do
  - evaluate LTE to determine amount of spectral radiance
  - convert spectral radiance $\rightarrow$ CIE XYZ color space
  - apply tone mapping techniques
  - convert CIE XYZ color $\rightarrow$ RGB color to be displayed

Simulation of the aerial perspective

- For all pixels not covered by the sky
  - find intersection with the scene object
  - calculate amount of light reflected towards the observer
  - evaluate LTE to calculate gains and losses of reflected light
  - tone mapping and conversion to the RGB color

Rendering of the Atmosphere – cont.

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- **Methods to solve the light transfer equation**
  - analytic methods
    + fast and easy to use
    – hardly extendable
  - numerical methods Nishita et al.[13,20,21], Jackel et al.[9,10]
    – still very difficult to solve
    – require a lot of computational time
    + work with arbitrarily complex atmospheric conditions
- **Simplifying assumptions**
  - uniform medium, simple geometry or very small albedo
  - restriction of order of scattering $\rightarrow$ single scattering methods

Rendering of the Atmosphere – cont.

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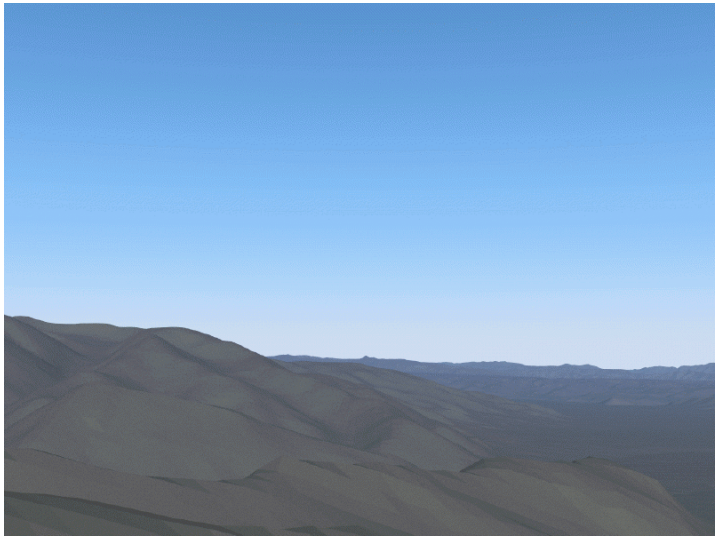
- **Hybrid methods** Dobashi et al.[3,4], Preetham et al.[23]
  - numerical solution ⇒ analytical approximation
  - sky approximated by hemisphere with a large radius
  - numerical solution

    ⇒ sky spectral radiance distribution for several sun altitudes

    ⇒ approximation by a series of basis functions / simple parametrically fitted formulas

    ⇒ weights / parameters values are stored in tables

Rendered Images



Preetham et al.[23]

Walter and Jackel [9,10]

Summary

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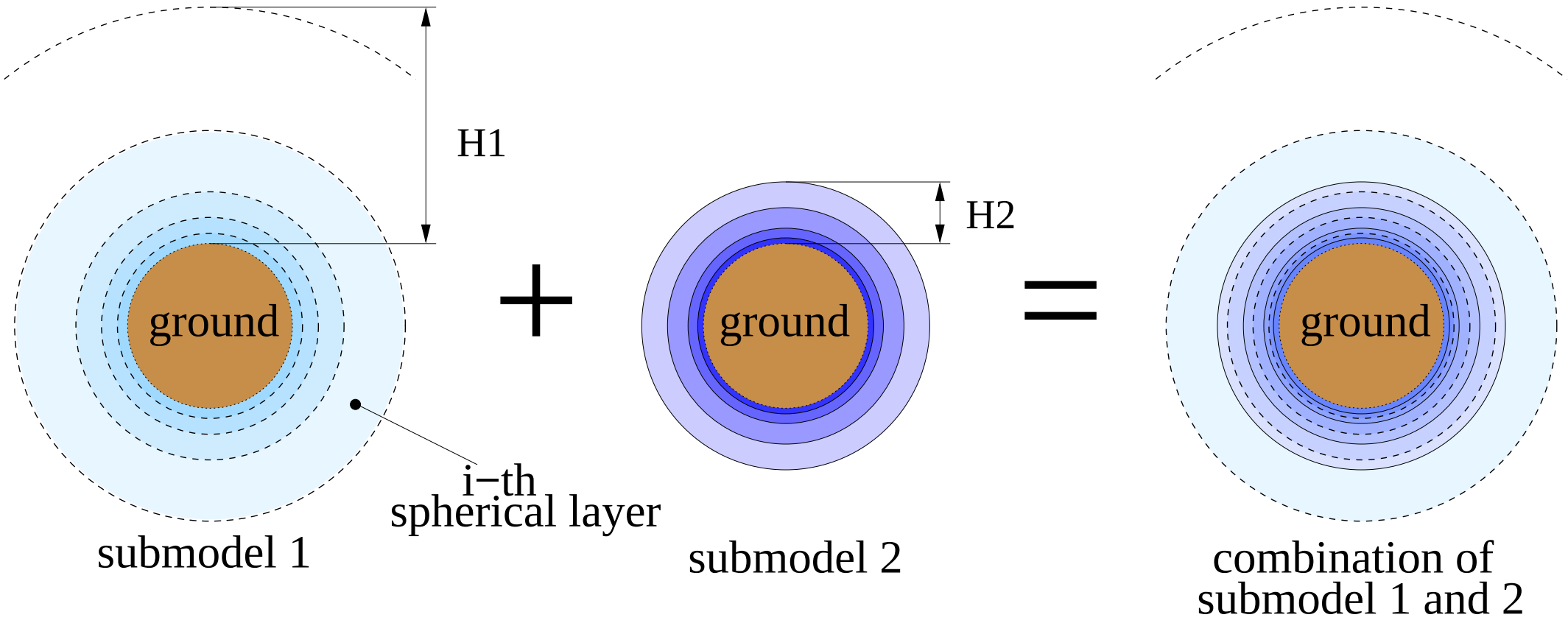
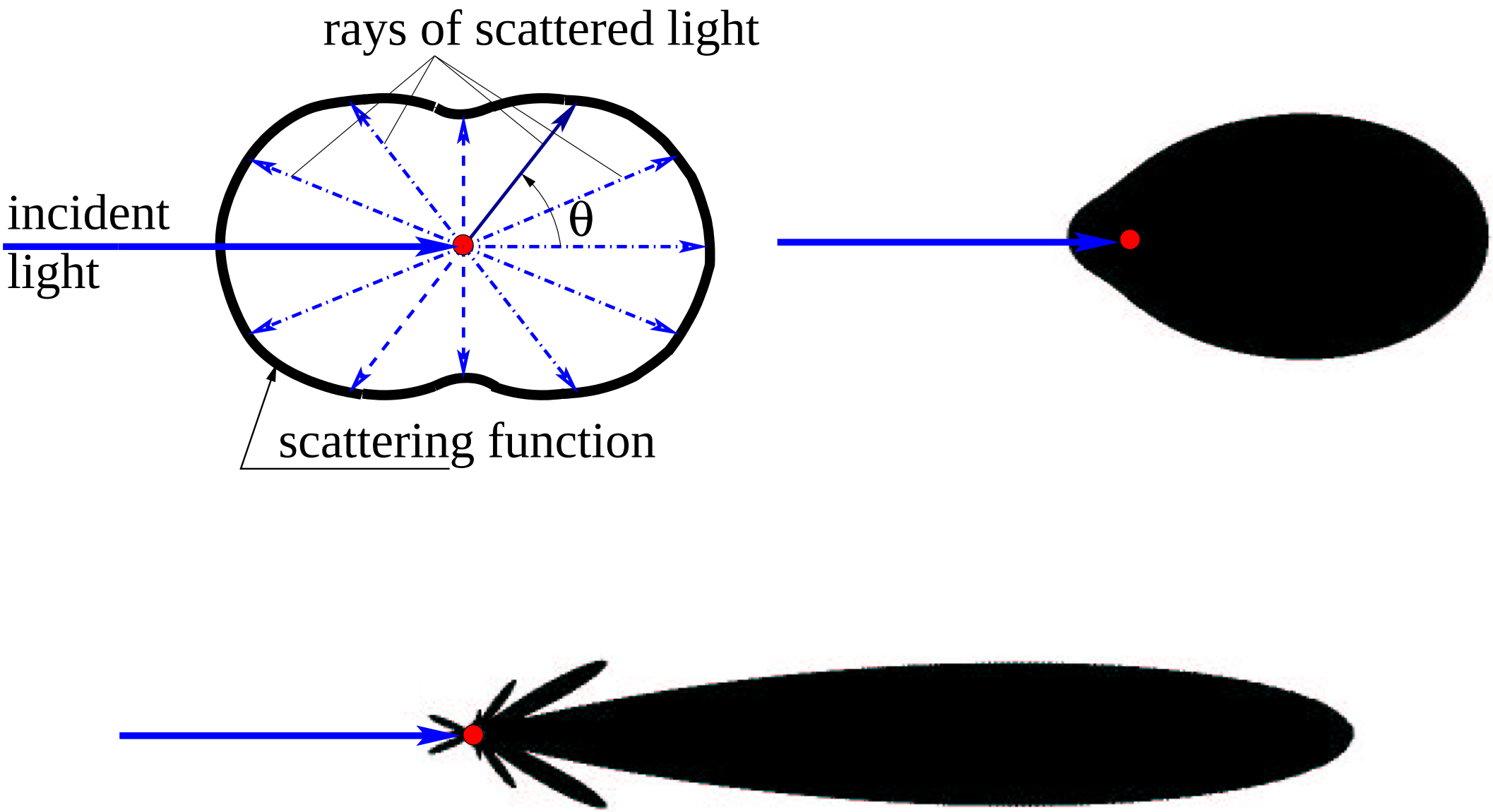
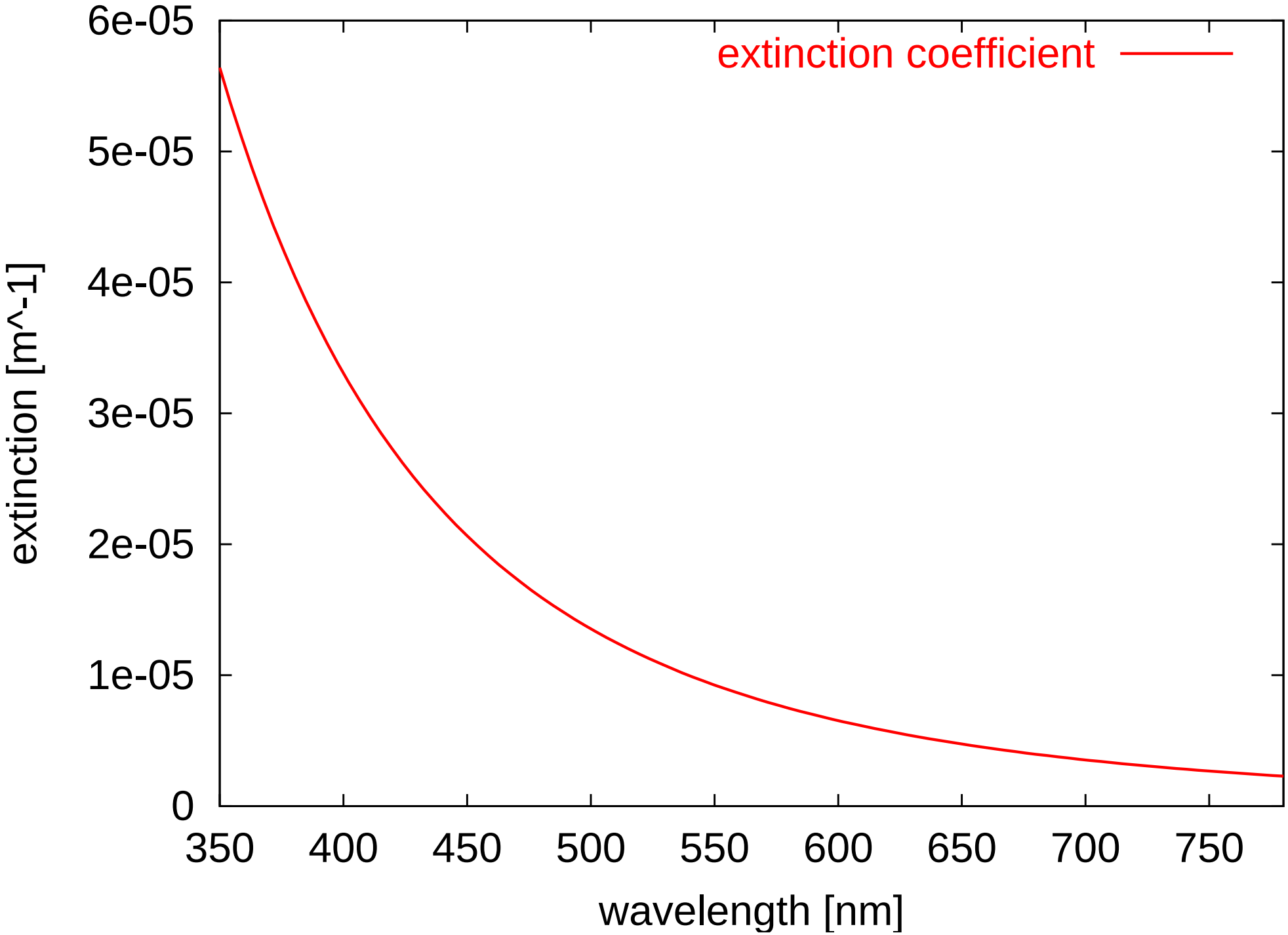
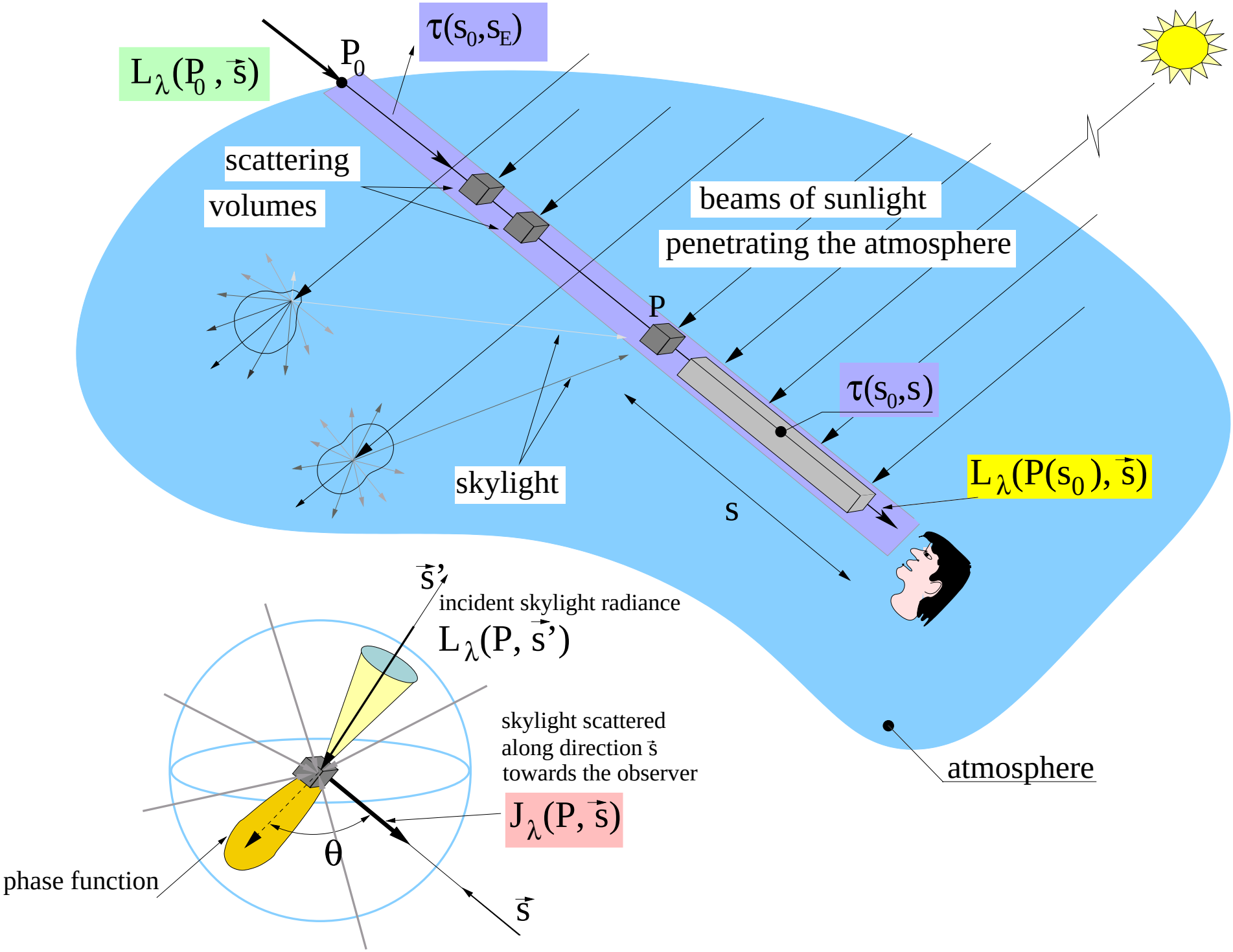
- **We discussed**
  - two models of the atmosphere
  - atmosphere composition and properties of the major atmospheric constituents
  - light transfer equation
  - overview of methods used for rendering of the atmosphere

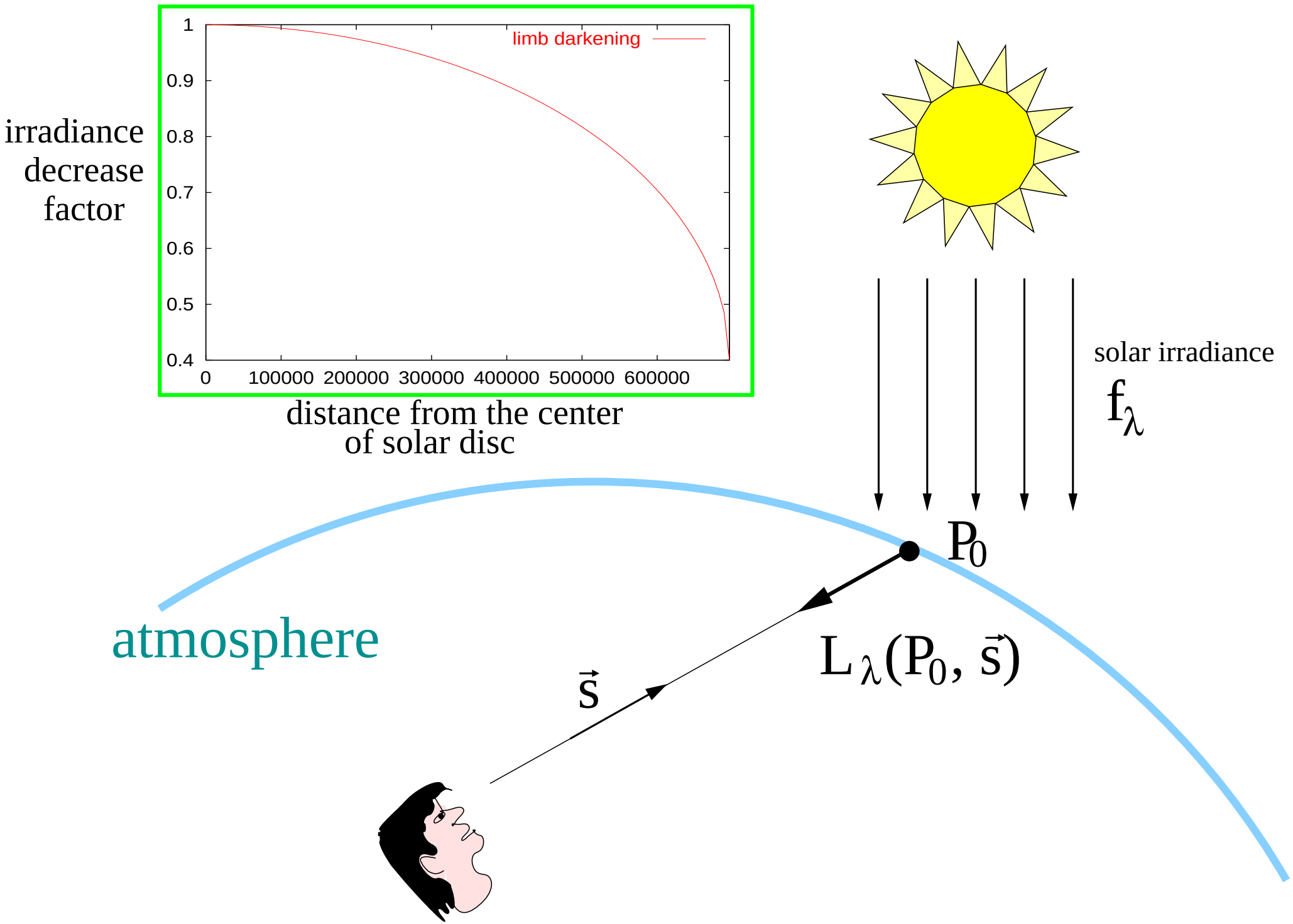
QUESTIONS ?

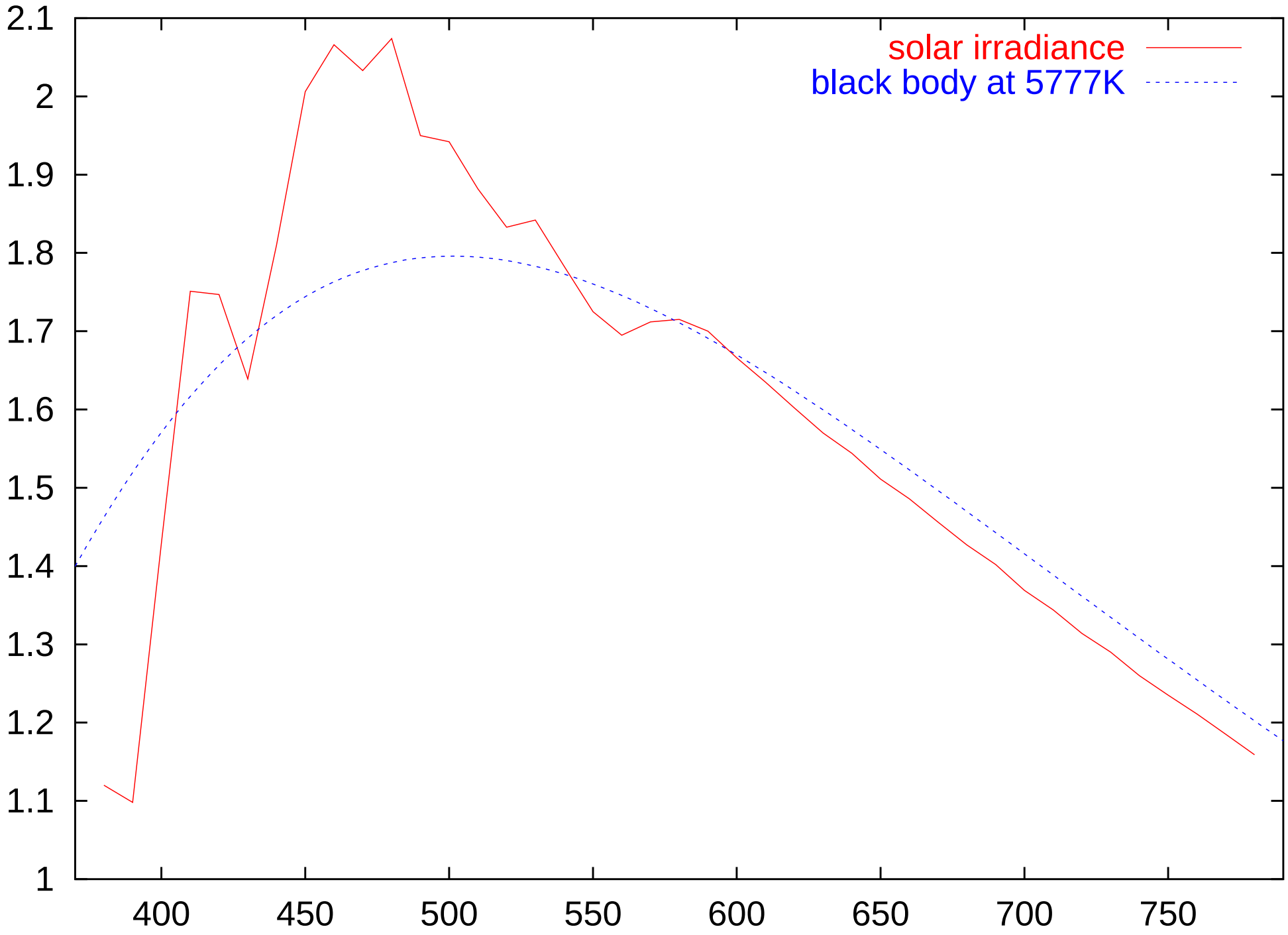

H1
ground
i−th
spherical layer
submodel 1
+
H2
ground
submodel 2
=
ground
combination of
submodel 1 and 2

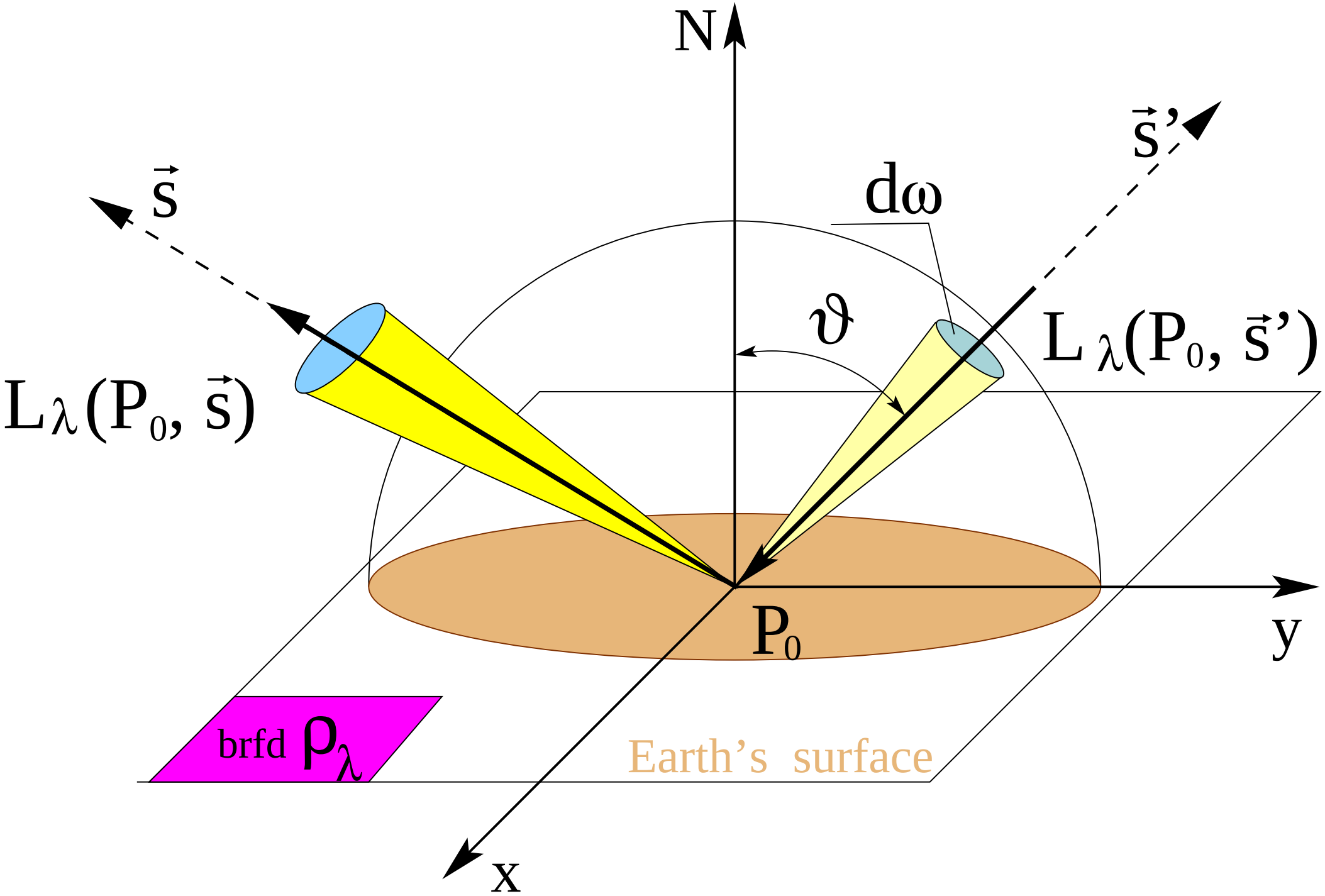

rays of scattered light
incident
light
θ
scattering function

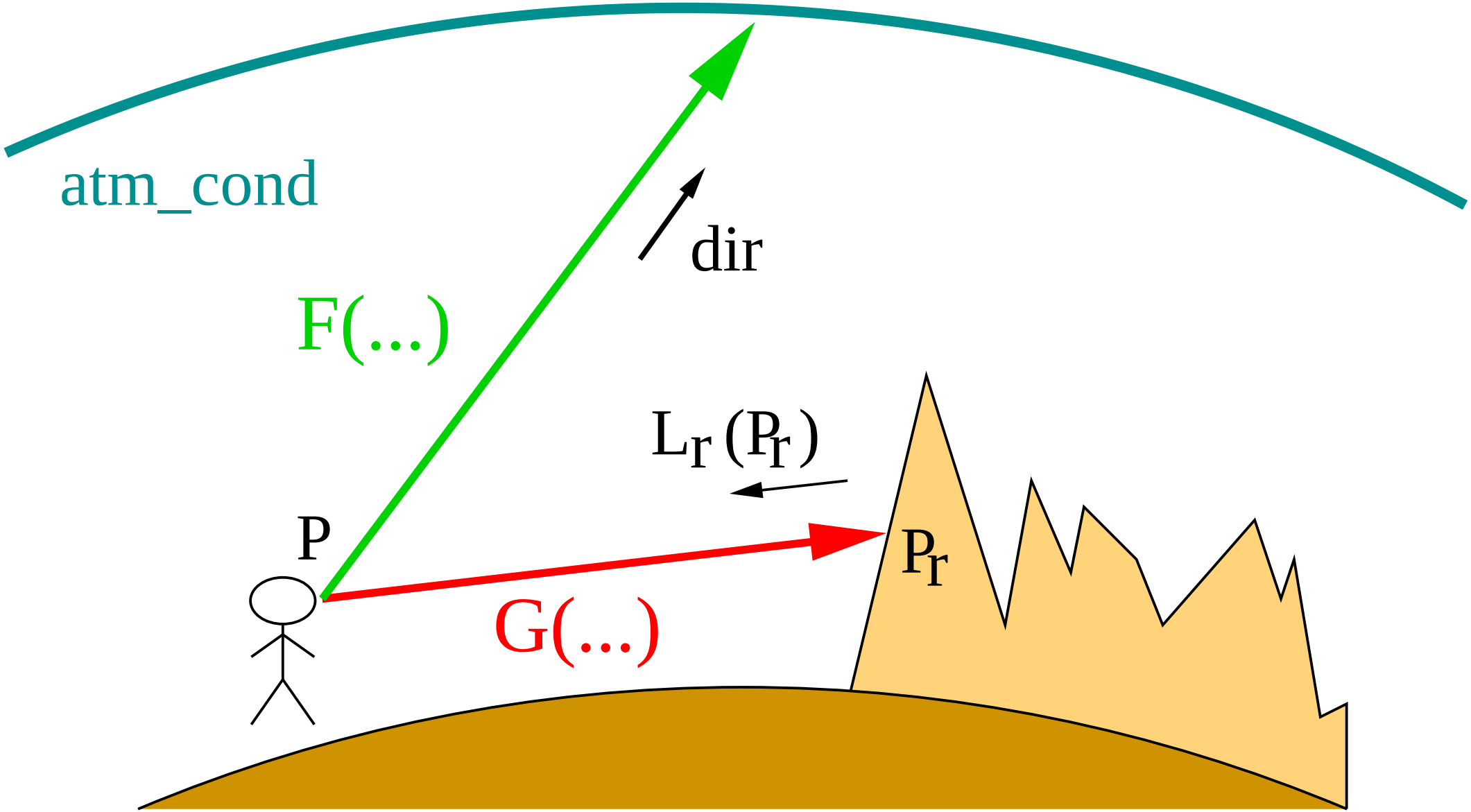

extinction coefficient
6e-05
5e-05
4e-05
3e-05
2e-05
1e-05
0
extinction [m^-1]
350
400
450
500
550
600
650
700
750
wavelength [nm]

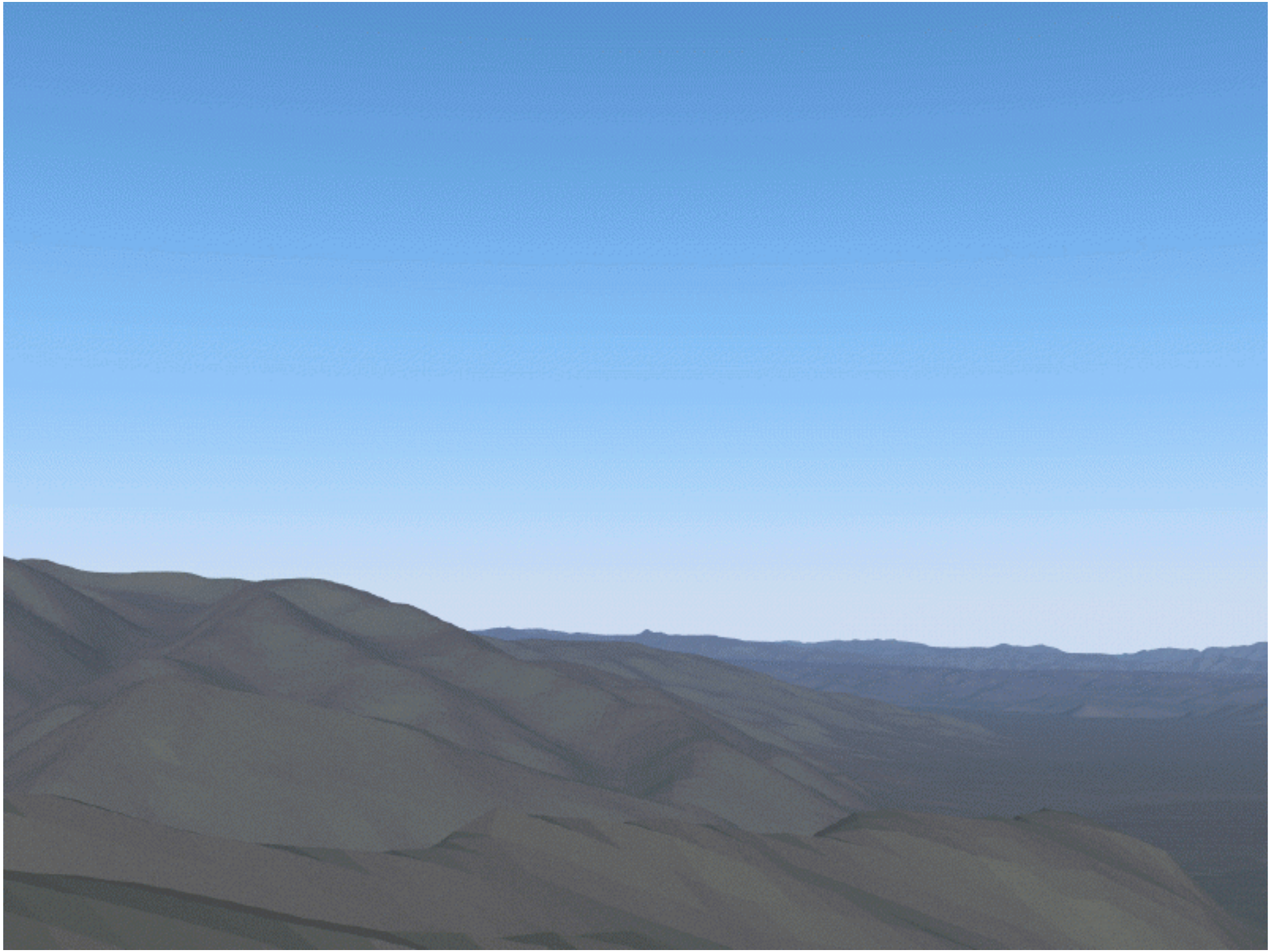

$L_\lambda(P_0, \vec{s})$
P_0
$\tau(s_0,s_E)$
scattering
volumes
beams of sunlight
penetrating the atmosphere
P
$\tau(s_0,s)$
$L_\lambda(P(s_0), \vec{s})$
skylight
s
atmosphere
$\vec{s}'$
incident skylight radiance
$L_\lambda(P, \vec{s}')$
skylight scattered
along direction $\vec{s}$
towards the observer
$J_\lambda(P, \vec{s})$
θ
phase function
$\vec{s}$

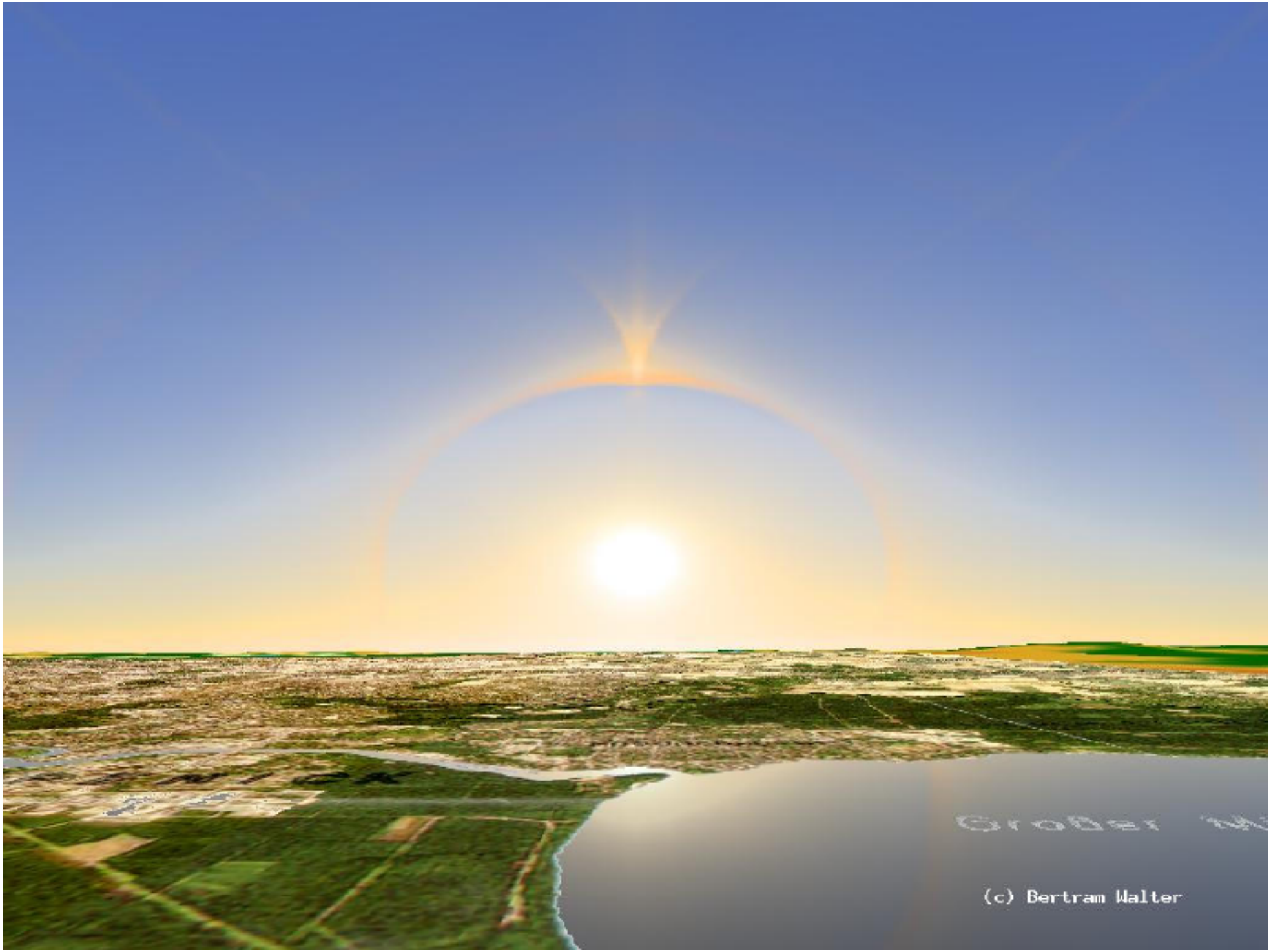

irradiance decrease factor
1
0.9
0.8
0.7
0.6
0.5
0.4
0
100000
200000
300000
400000
500000
600000
limb darkening
distance from the center of solar disc
solar irradiance
f_λ
P_0
$L_\lambda(P_0, \vec{s})$
$\vec{s}$
atmosphere


solar irradiance
black body at 5777K
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
400
450
500
550
600
650
700
750


N
$\vec{s}$
$\vec{s}'$
dω
ϑ
$L_\lambda(P_0, \vec{s})$
$L_\lambda(P_0, \vec{s}')$
P_0
y
x
brfd ρ_λ
Earth's surface


atm_cond
dir
F(...)
$L_r(P_r)$
P
P_r
G(...)




(c) Bertram Walter

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