Participating media

15-468, 15-668, 15-868
Physics-based Rendering
Spring 2025, Lecture 12

http://graphics.cs.cmu.edu/courses/15-468

Course announcements

- Vote for PA2 competition!

Overview of today’s lecture

- Participating media.
- Scattering material characterization.
- Volume rendering equation.
- Ray marching.
- Volumetric path tracing.
- Delta tracking.

Slide credits

Most of these slides were directly adapted from:

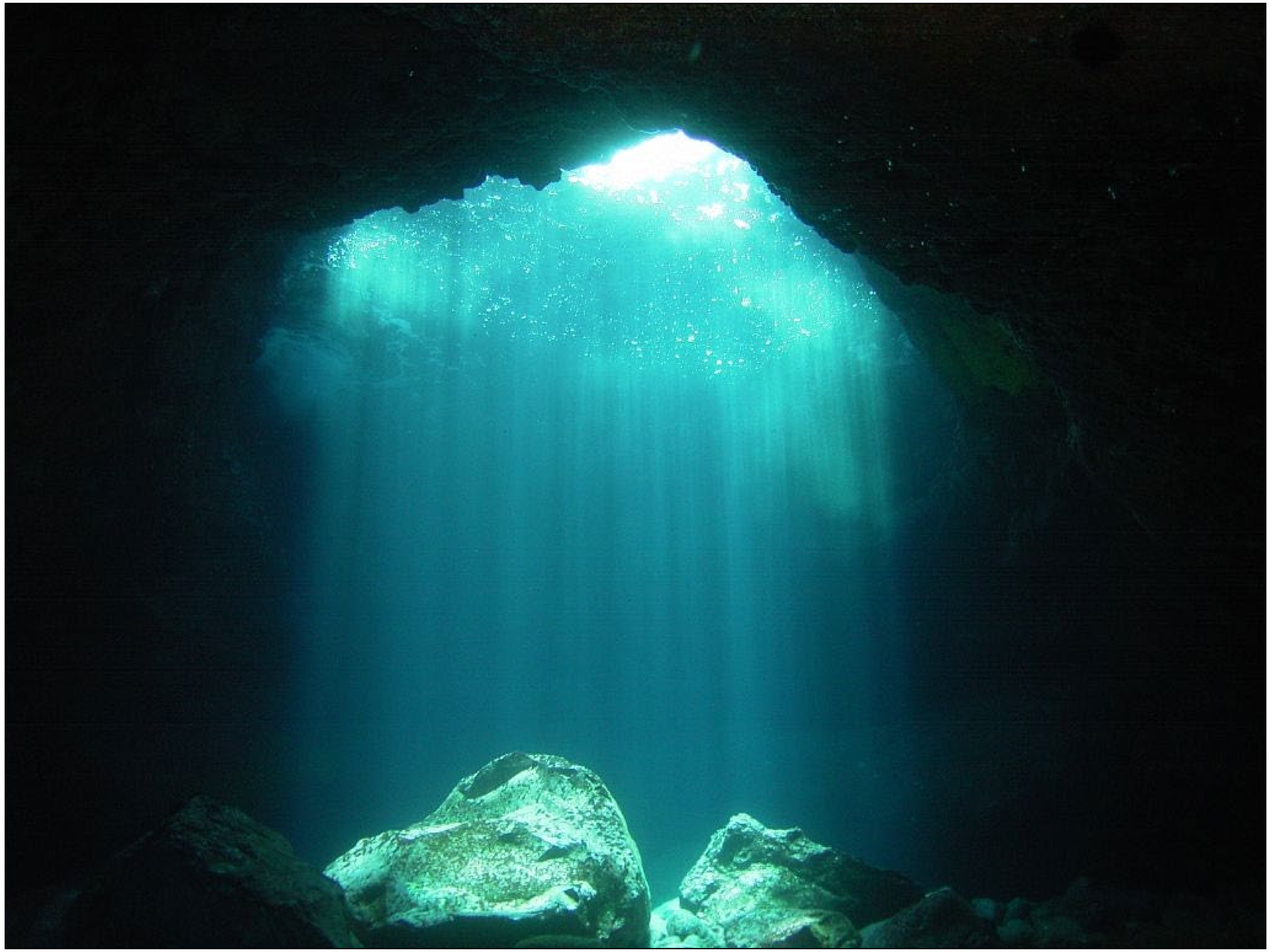
- Wojciech Jarosz (Dartmouth).

Fog

Clouds & Crepuscular rays

Fire

Underwater



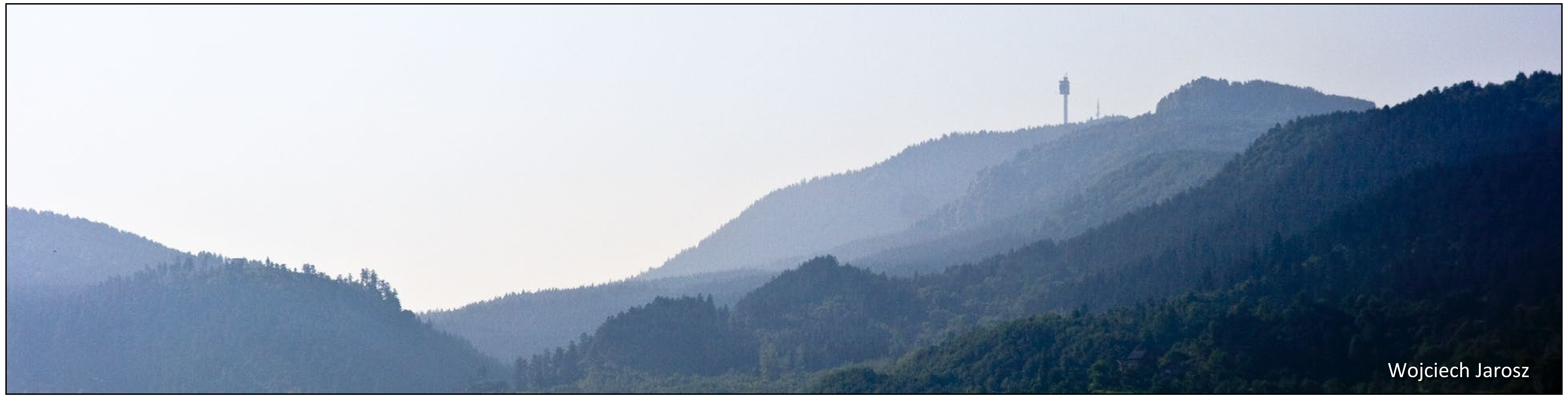
Surface or Volume?

source: Flickr

source: Studio Lernert & Sander

Antelope Canyon, Az.

Aerial (Atmospheric) Perspective

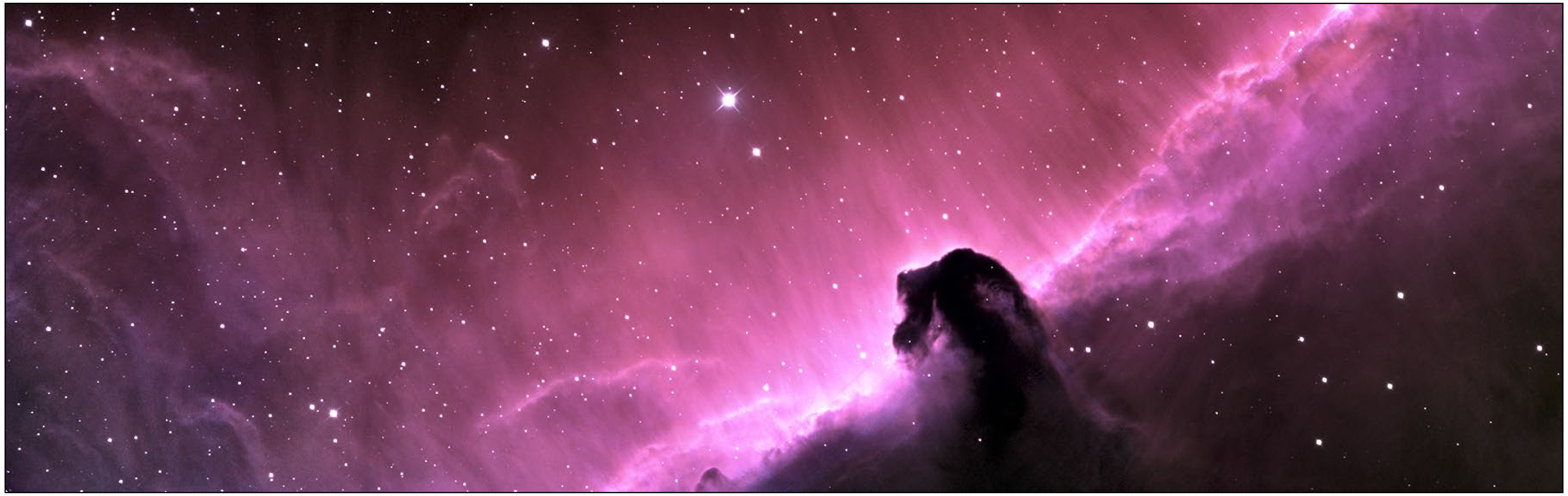


Leonardo da Vinci (1480)

Thus, if one is to be five times as distant, make it five times bluer.

—Treatise on Painting, Leonardo Da Vinci, pp 295, circa 1480.

Nebula



T.A.Rector (NOAO/AURA/NSF) and the Hubble Heritage Team (STScI/AURA/NASA)

Emission

Absorption

Scattering

Defining Participating Media

Typically, we do not model particles of a medium explicitly (wouldn’t fit in memory, completely impractical to ray trace)

The properties are described statistically using various coefficients and densities

- Conceptually similar idea as microfacet models

Defining Participating Media

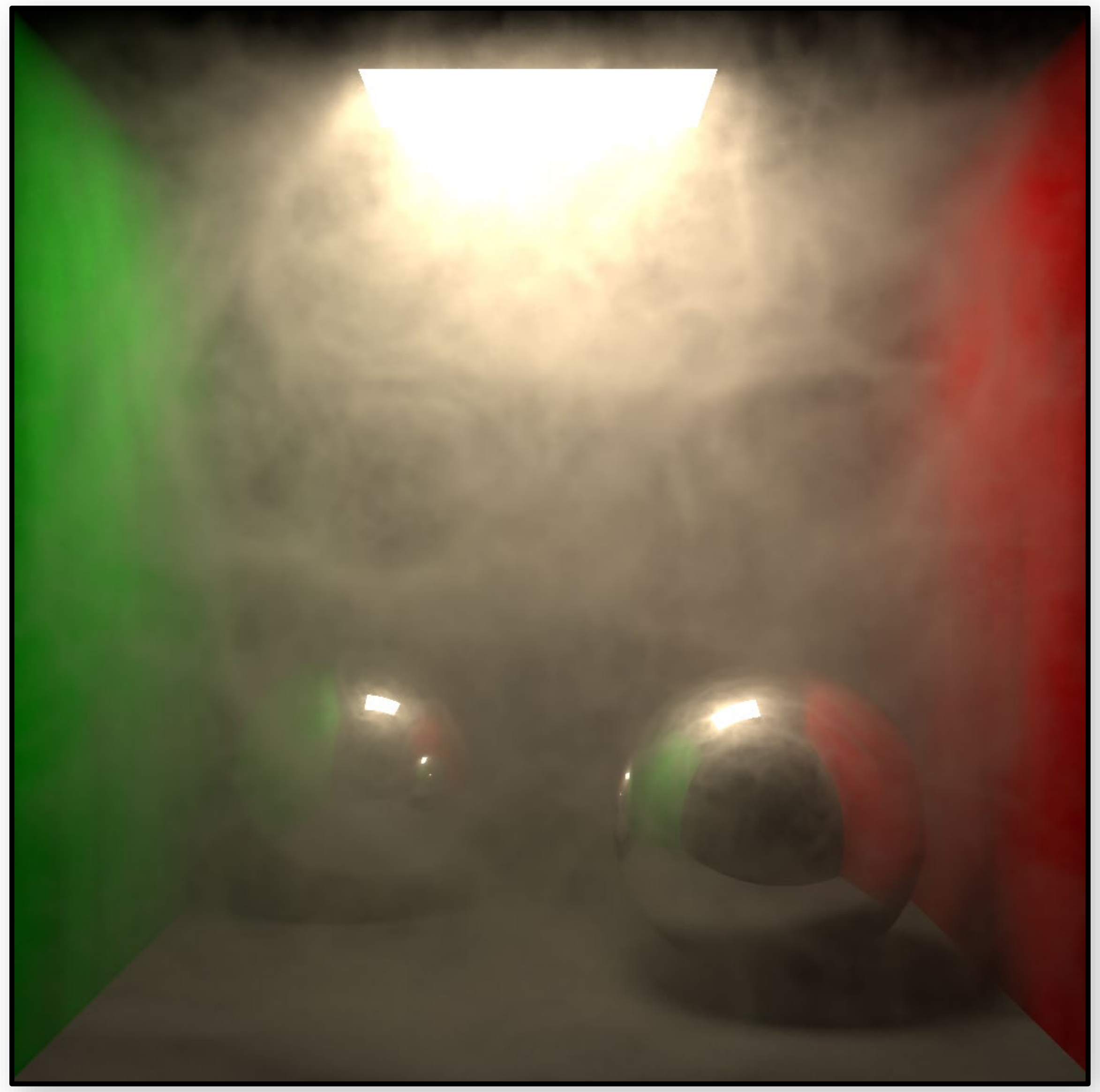
Homogeneous:

- Infinite or bounded by a surface or simple shape

Defining Participating Media

Heterogeneous (spatially varying coefficients):

- Procedurally, e.g., using a noise function
- Simulation + volume discretization, e.g., a voxel grid

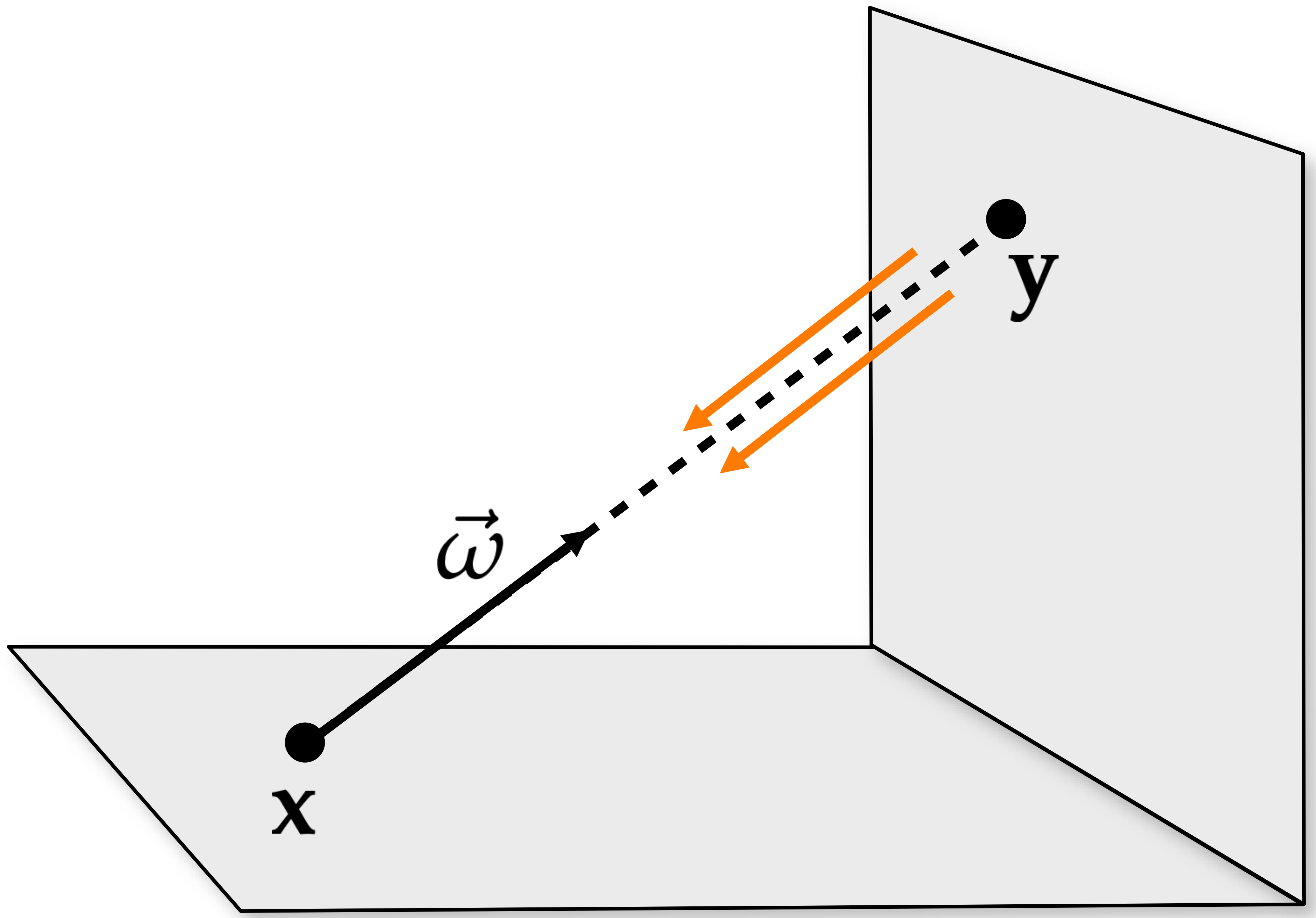


Radiance

The main quantity we are interested in for rendering is radiance

Previously: radiance *remains constant* along rays between surfaces

$$L_i(\mathbf{x}, \vec{\omega}) = L_o(\mathbf{y}, -\vec{\omega})$$
$$\mathbf{y} = r(\mathbf{x}, \vec{\omega})$$

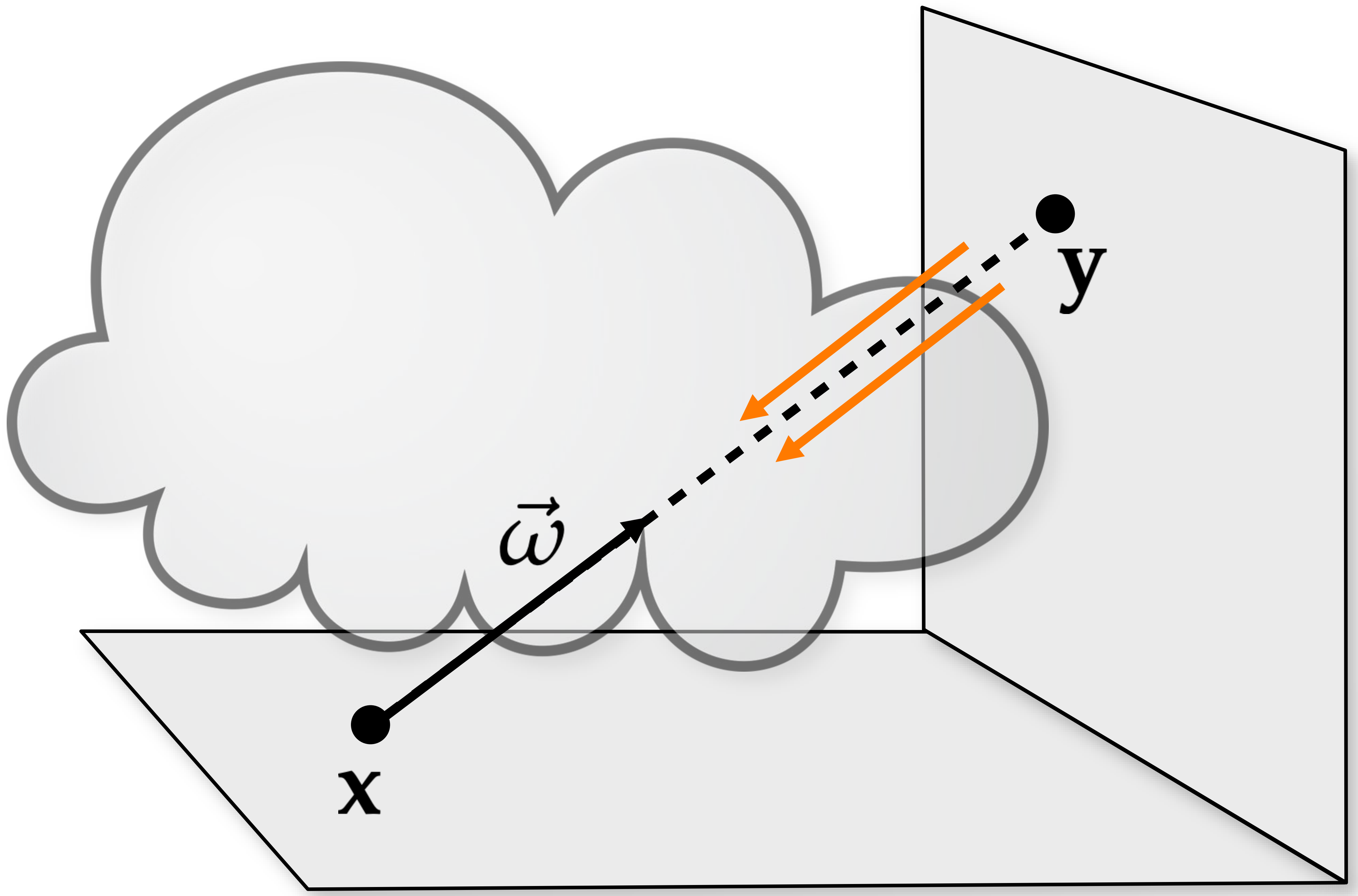


Radiance

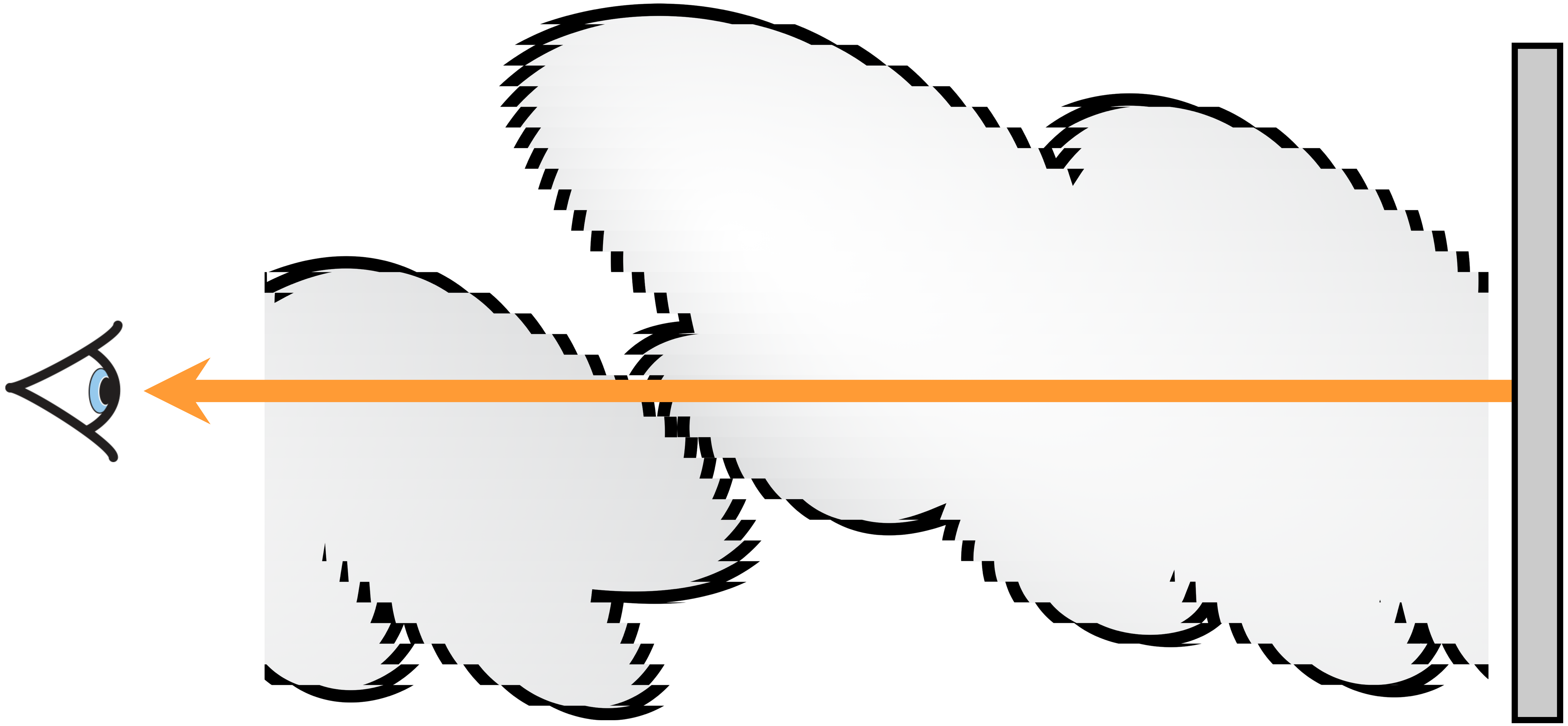
The main quantity we are interested in for rendering is radiance

Now: radiance may *change* along rays between surfaces

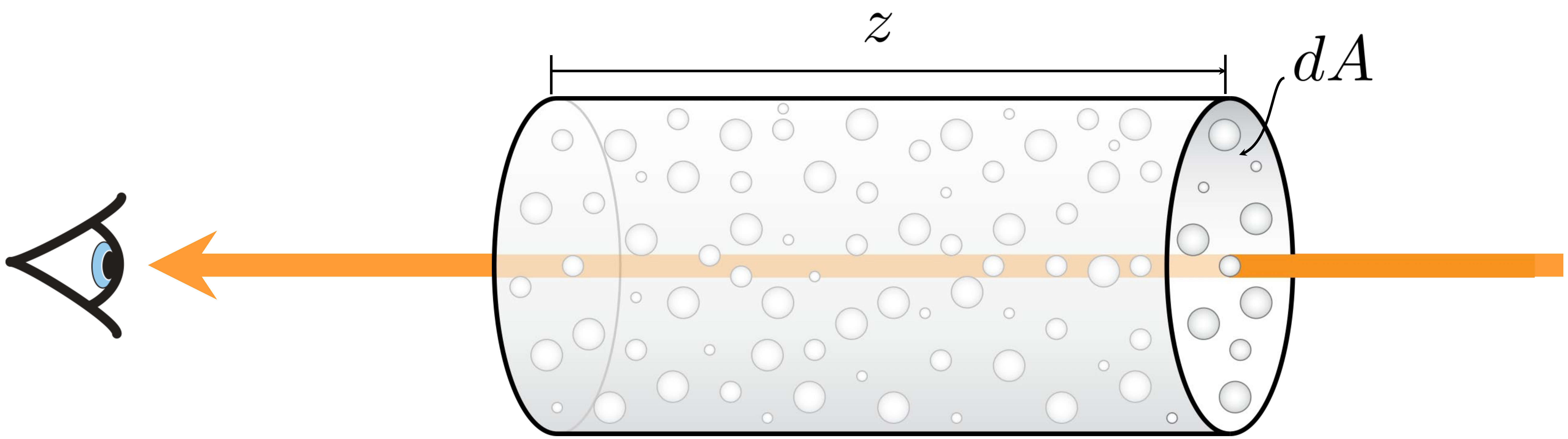
$$L_i(\mathbf{x}, \vec{\omega}) \neq L_o(\mathbf{y}, -\vec{\omega})$$
$$\mathbf{y} = r(\mathbf{x}, \vec{\omega})$$



Participating Media

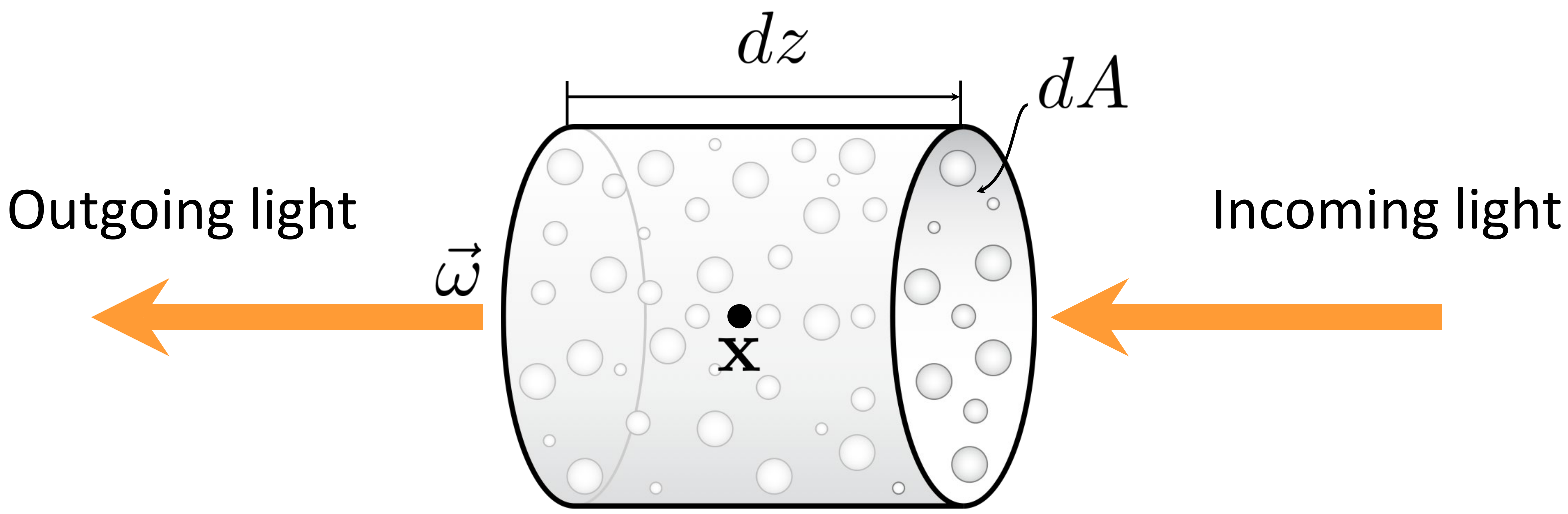


Differential Beam

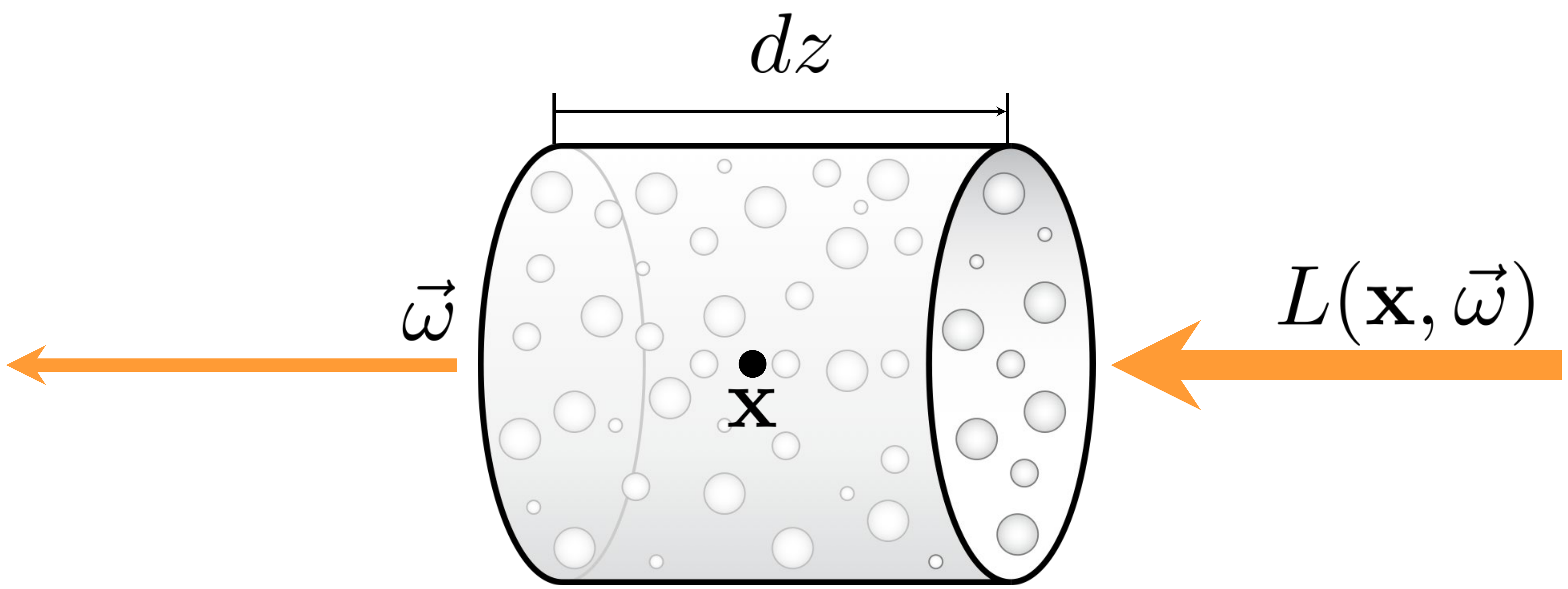


How much light is *lost/gained* along the differential beam
due to interactions of light with the medium?

Differential Beam Segment



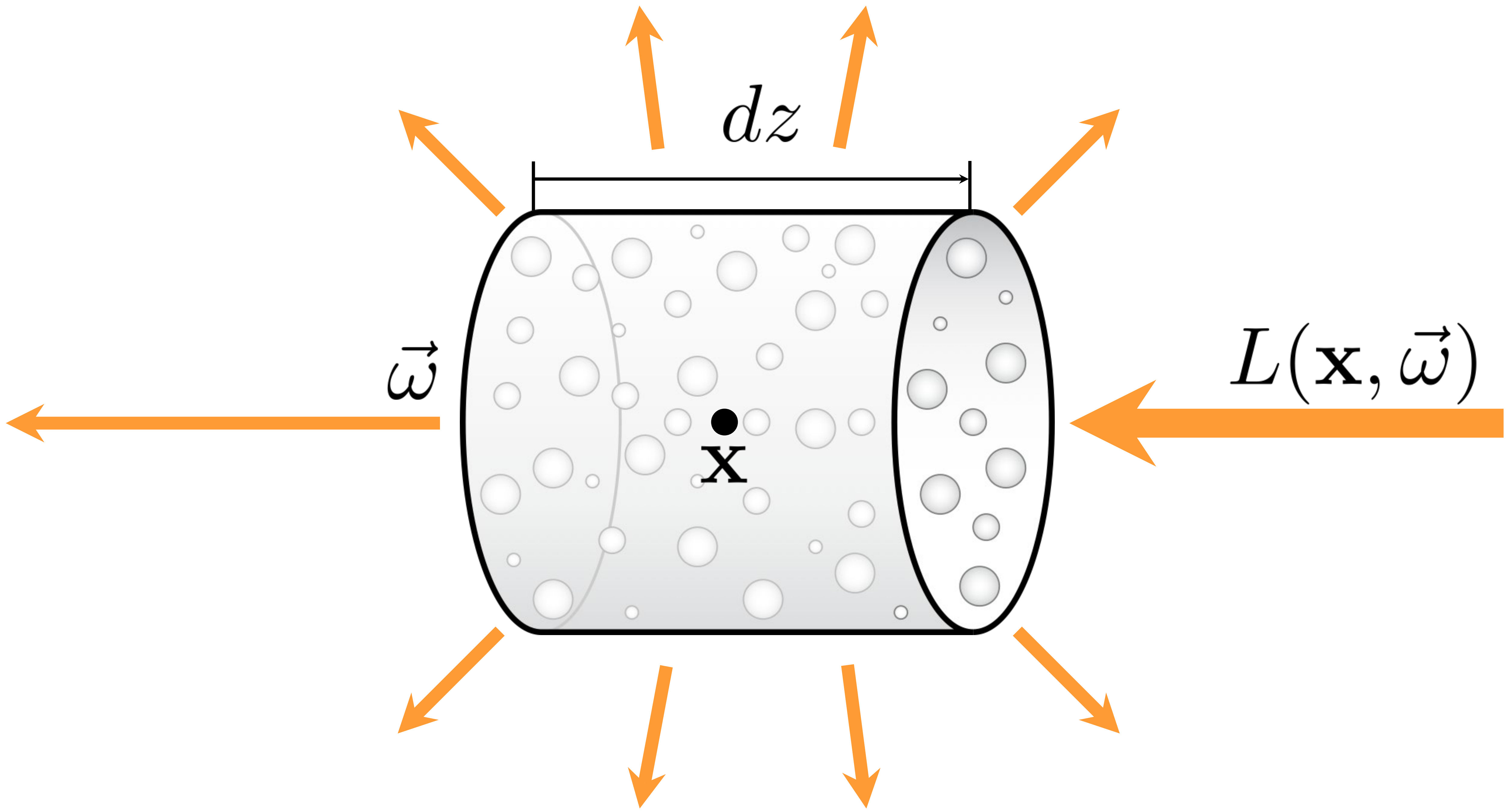
Absorption



$$dL(\mathbf{x}, \vec{\omega}) = -\sigma_a(\mathbf{x}) L(\mathbf{x}, \vec{\omega}) dz$$

$\sigma_a(\mathbf{x})$: absorption coefficient $\quad [m^{-1}]$

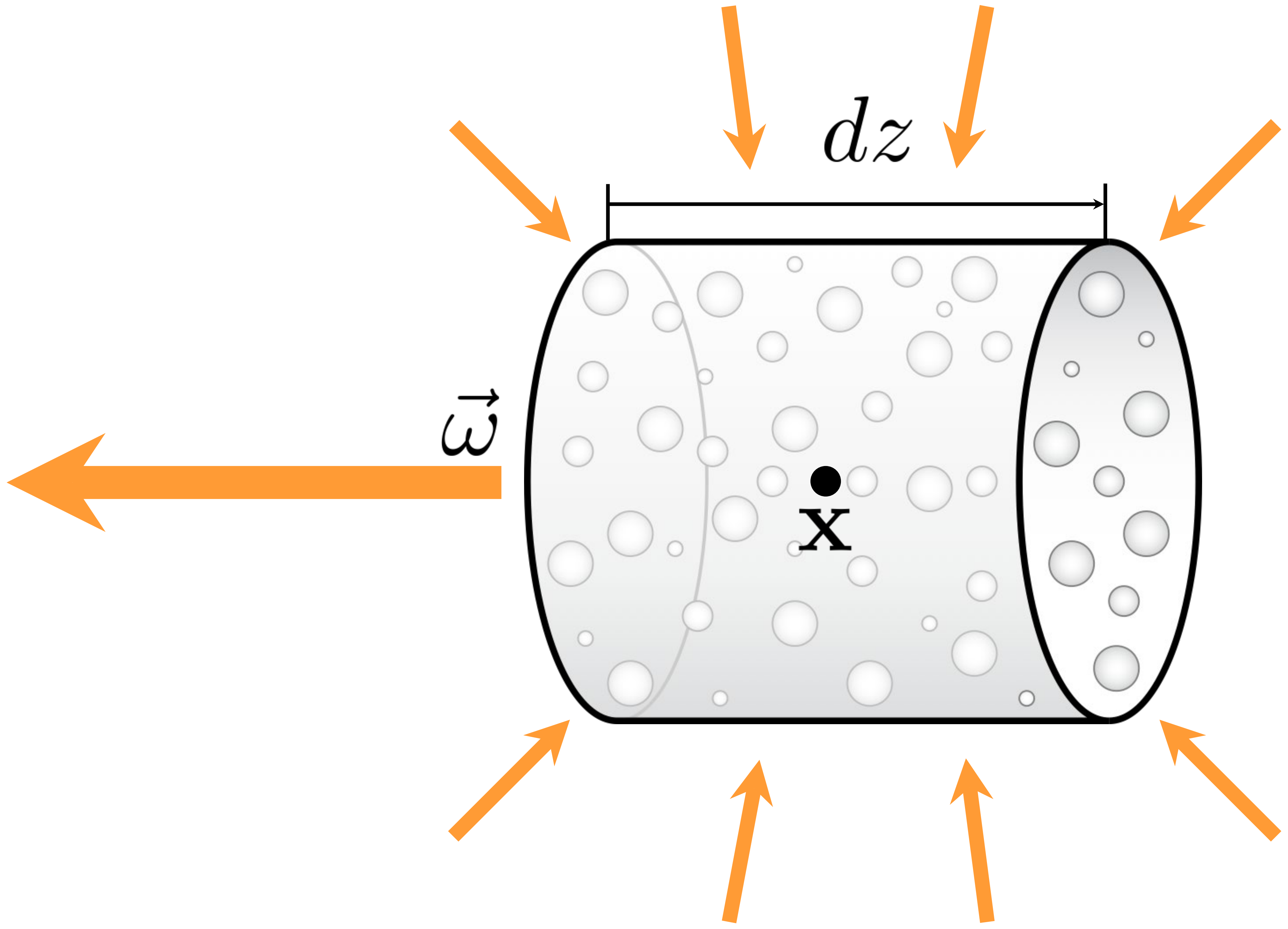
Out-scattering



$$dL(\mathbf{x}, \vec{\omega}) = -\sigma_s(\mathbf{x}) L(\mathbf{x}, \vec{\omega}) dz$$

$\sigma_s(\mathbf{x})$: scattering coefficient $[m^{-1}]$

In-scattering

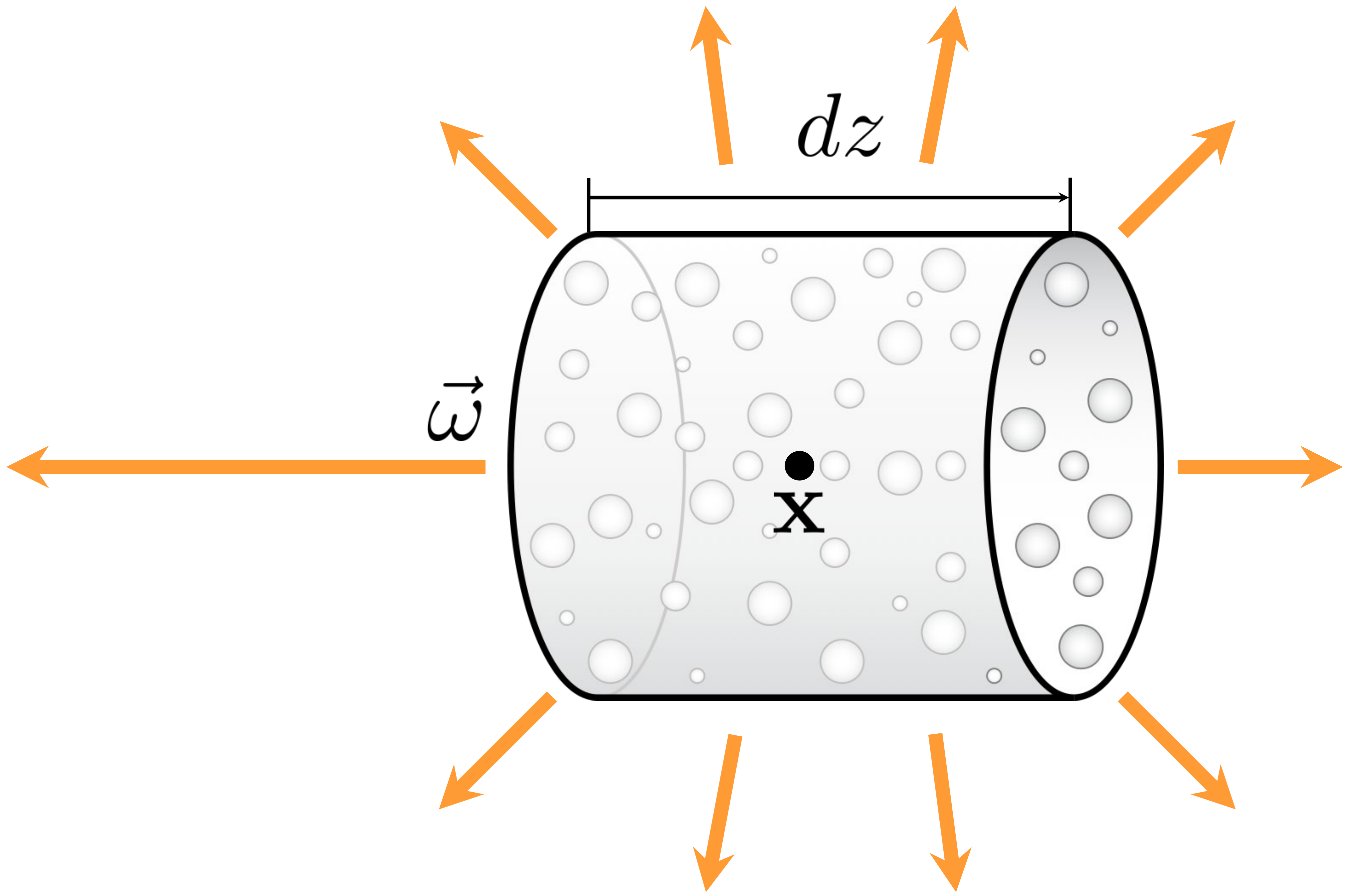


$$dL(\mathbf{x}, \vec{\omega}) = \sigma_s(\mathbf{x}) L_s(\mathbf{x}, \vec{\omega}) dz$$

$\sigma_s(\mathbf{x})$: scattering coefficient $[m^{-1}]$

$L_s(\mathbf{x}, \vec{\omega})$: in-scattered radiance

Emission



$$dL(\mathbf{x}, \vec{\omega}) = \sigma_a(\mathbf{x}) L_e(\mathbf{x}, \vec{\omega}) dz$$

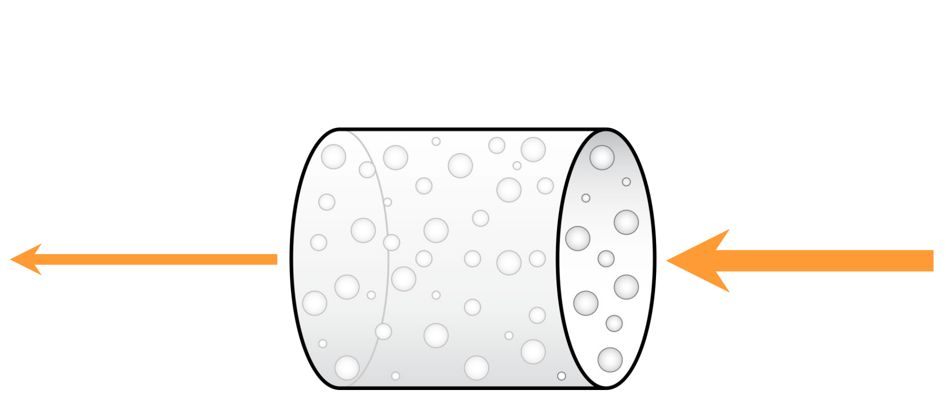
*Sometimes modeled without the absorption coefficient just by specifying a “source” term

$\sigma_a(\mathbf{x})$: absorption coefficient $[m^{-1}]$

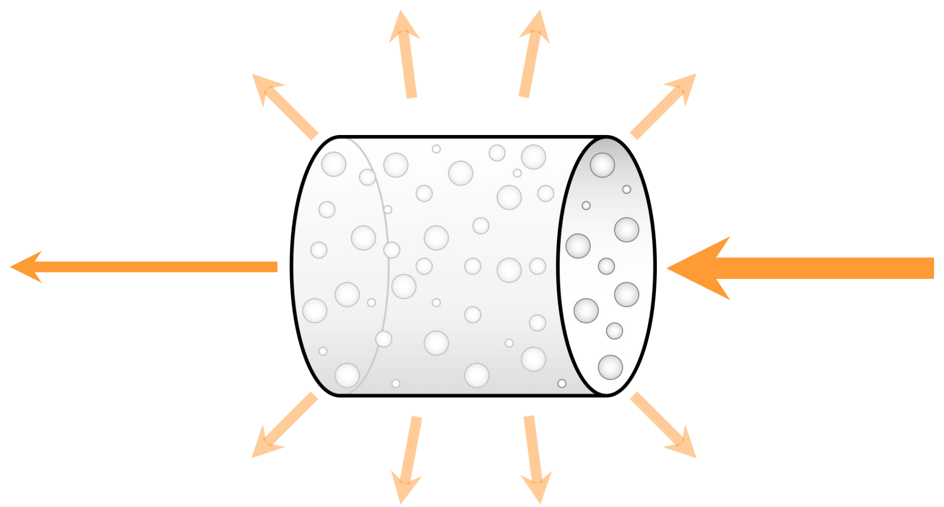
$L_e(\mathbf{x}, \vec{\omega})$: emitted radiance

Radiative Transfer Equation (RTE)

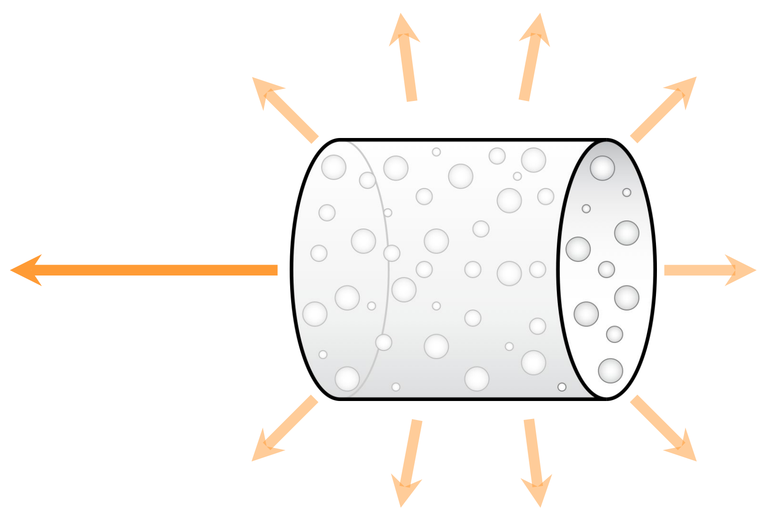
Absorption



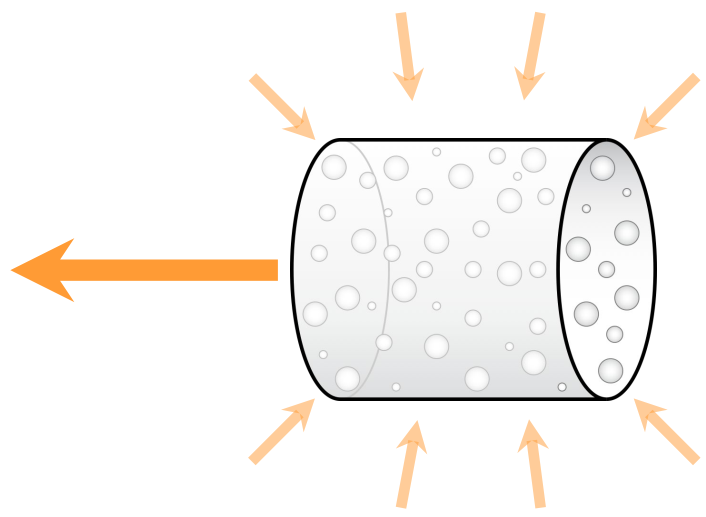
Out-scattering



$$\begin{aligned} dL(\mathbf{x},\vec{\omega}) = & \boxed{-\,\sigma_a(\mathbf{x})L(\mathbf{x},\vec{\omega})dz \quad -\,\sigma_s(\mathbf{x})L(\mathbf{x},\vec{\omega})dz} \quad \text{Losses} \\ & \boxed{+\,\sigma_a(\mathbf{x})L_e(\mathbf{x},\vec{\omega})dz \ +\sigma_s(\mathbf{x})L_s(\mathbf{x},\vec{\omega})dz} \quad \text{Gains} \end{aligned}$$



Emission



In-scattering

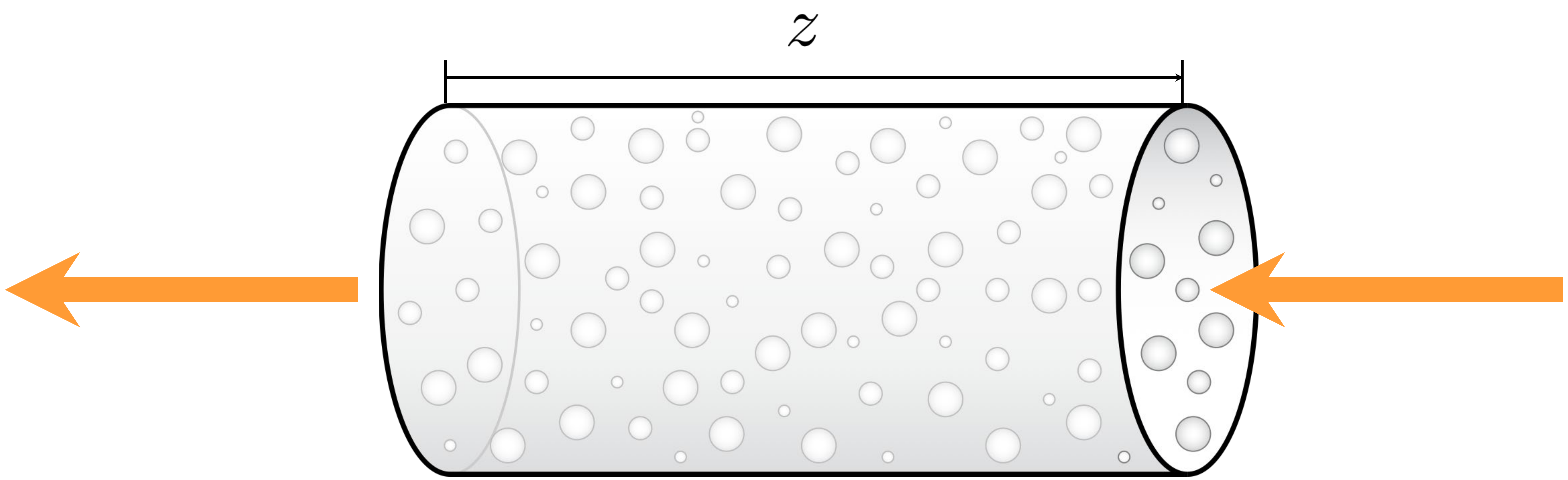
Losses (Extinction)

Absorption Out-scattering

$$dL(\mathbf{x},\vec{\omega}) = -\sigma_a(\mathbf{x})L(\mathbf{x},\vec{\omega})dz - \sigma_s(\mathbf{x})L(\mathbf{x},\vec{\omega})dz$$
$$= -\sigma_t(\mathbf{x})L(\mathbf{x},\vec{\omega})dz$$

$\sigma_t(\mathbf{x})$: extinction coefficient $[m^{-1}]$

: total loss of light per unit distance



What about a beam with a finite length?

Extinction Along a Finite Beam

$$dL(\mathbf{x},\vec{\omega}) = -\sigma_t(\mathbf{x})L(\mathbf{x},\vec{\omega})dz$$ // Assume constant $\sigma_t(\mathbf{x})$, reorganize

$$\frac{dL(\mathbf{x},\vec{\omega})}{L(\mathbf{x},\vec{\omega})} = -\sigma_t dz$$ // Integrate along beam from 0 to z

$$\ln(L_z) - \ln(L_0) = -\sigma_t z$$

$$\ln\left(\frac{L_z}{L_0}\right) = -\sigma_t z$$ // Exponentiate

$$\frac{L_z}{L_0} = e^{-\sigma_t z}$$

Beer-Lambert Law

Expresses the remaining radiance after traveling a finite distance through a medium with constant extinction coefficient

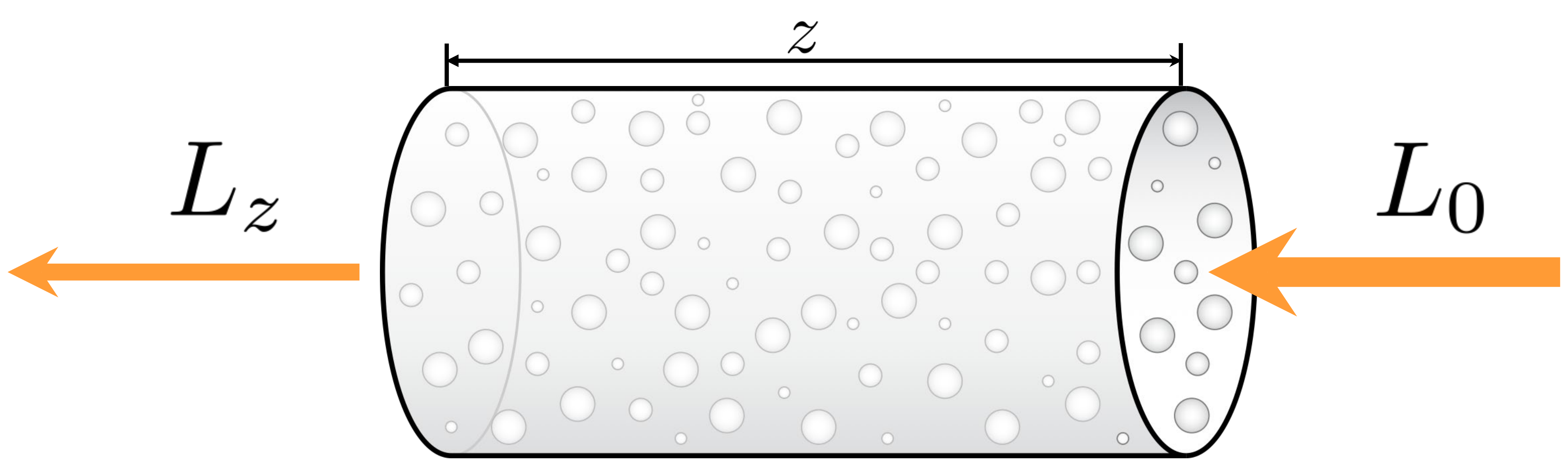
The fraction is referred to as the *transmittance*

Think of this as fractional visibility between points

Radiance at distance z

$$\frac{L_z}{L_0} = e^{-\sigma_t z}$$

Radiance at the beginning of the beam



Transmittance

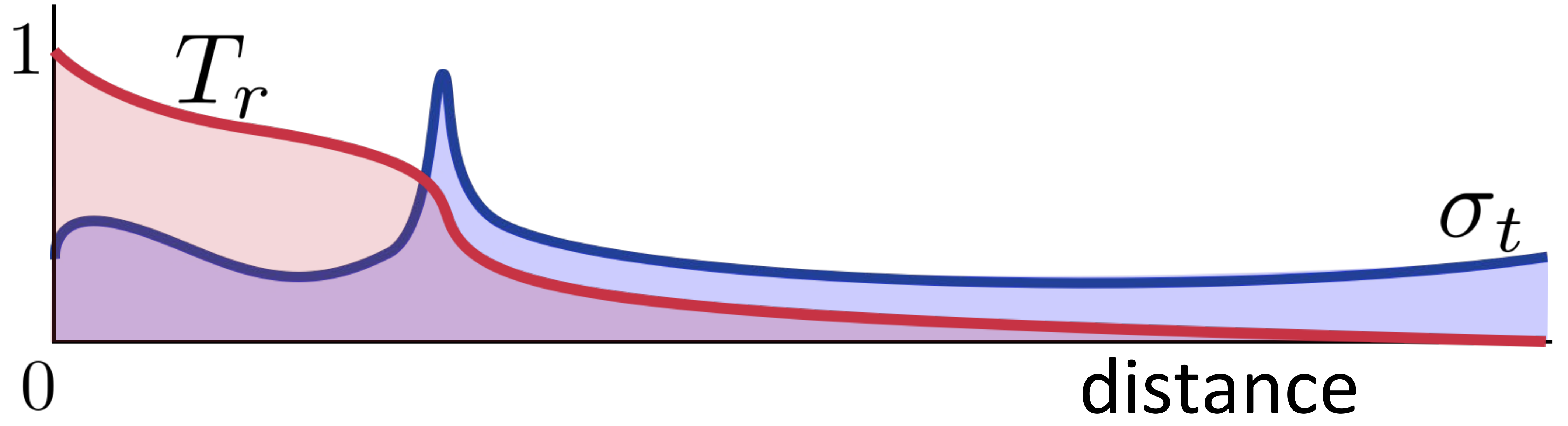
Homogeneous volume:

$$T_r(\mathbf{x},\mathbf{y}) = e^{-\boxed{\sigma_t \|\mathbf{x}-\mathbf{y}\|}}$$

Heterogeneous volume (spatially varying σ_t):

$$T_r(\mathbf{x},\mathbf{y}) = e^{-\boxed{\int_0^{\|\mathbf{x}-\mathbf{y}\|} \sigma_t(t)dt}}$$

Optical thickness



Transmittance

Homogeneous volume:

$$T_r(\mathbf{x},\mathbf{y}) = e^{-\boxed{\sigma_t \|\mathbf{x}-\mathbf{y}\|}}$$

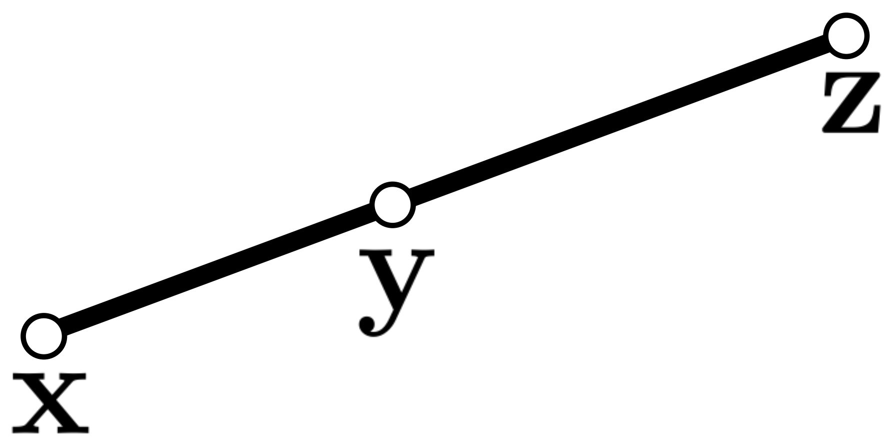
Heterogeneous volume (spatially varying σ_t):

$$T_r(\mathbf{x},\mathbf{y}) = e^{-\boxed{\int_0^{\|\mathbf{x}-\mathbf{y}\|} \sigma_t(t)dt}}$$

Optical thickness

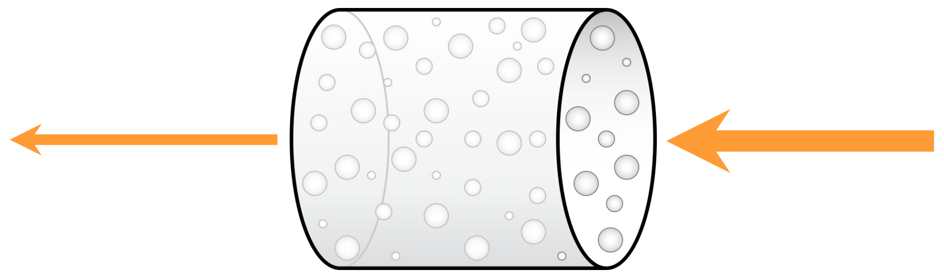
Transmittance is multiplicative:

$$T_r(\mathbf{x},\mathbf{z}) = T_r(\mathbf{x},\mathbf{y})T_r(\mathbf{y},\mathbf{z})$$

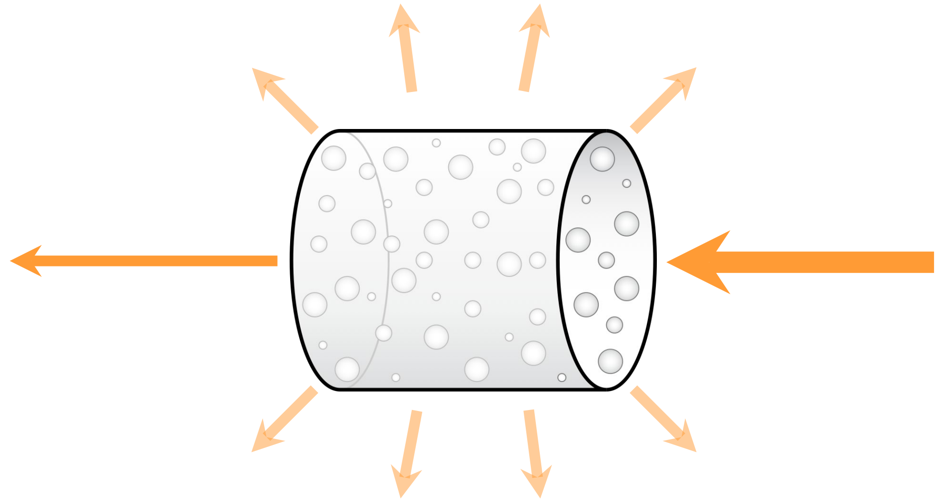


Radiative Transfer Equation (RTE)

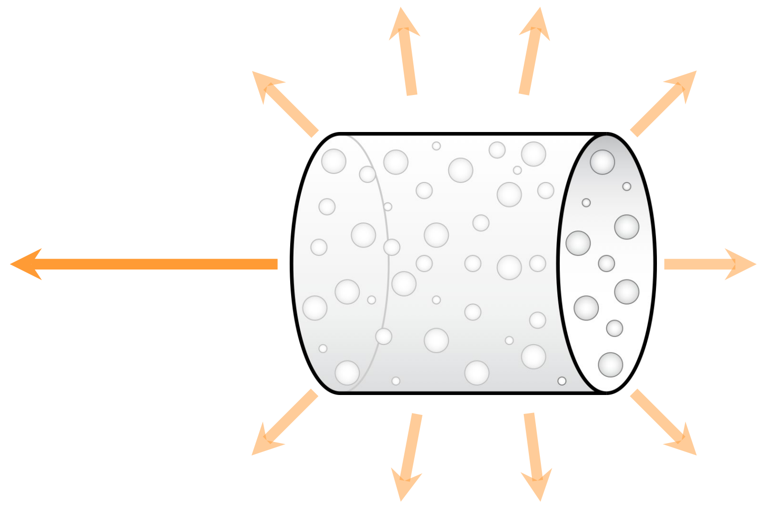
Absorption



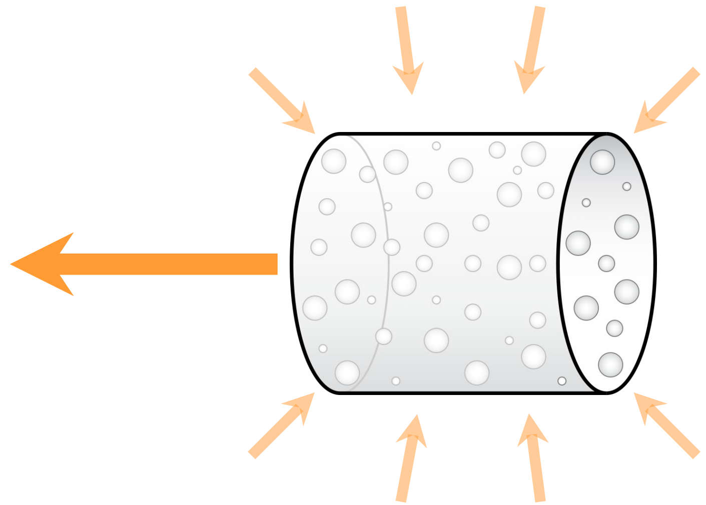
Out-scattering



$$dL(\mathbf{x},\vec{\omega}) = -\,\sigma_a(\mathbf{x})L(\mathbf{x},\vec{\omega})dz \quad -\,\sigma_s(\mathbf{x})L(\mathbf{x},\vec{\omega})dz$$
$$+\,\sigma_a(\mathbf{x})L_e(\mathbf{x},\vec{\omega})dz \; +\,\sigma_s(\mathbf{x})L_s(\mathbf{x},\vec{\omega})dz$$



Emission

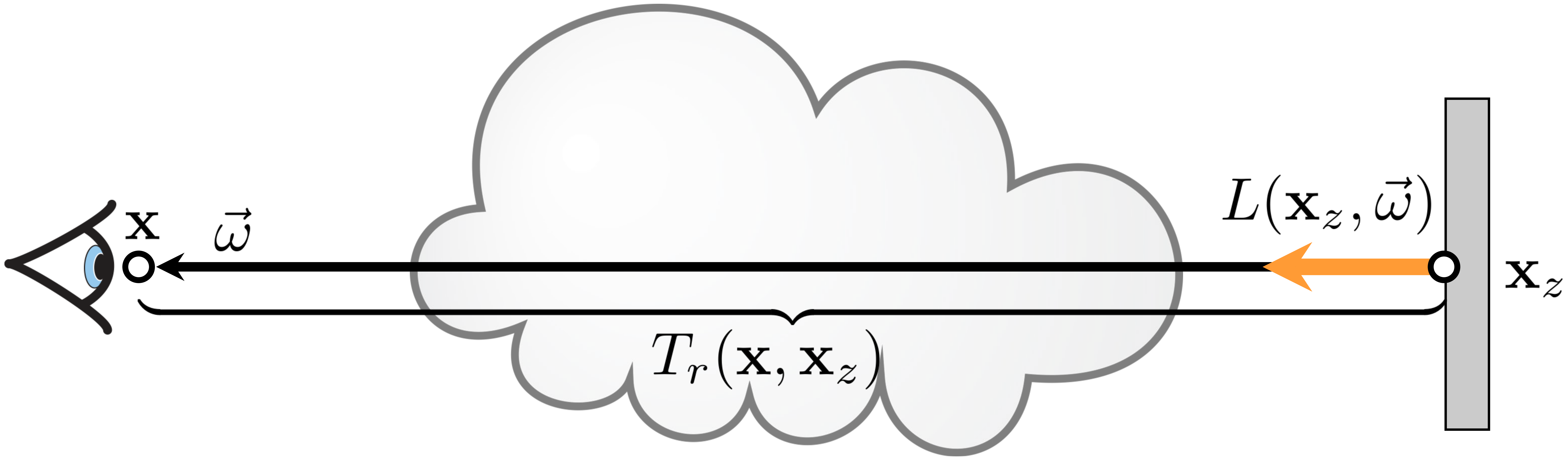


In-scattering

Volume Rendering Equation

$$L(\mathbf{x}, \vec{\omega}) = \boxed{T_r(\mathbf{x}, \mathbf{x}_z) L(\mathbf{x}_z, \vec{\omega})}$$

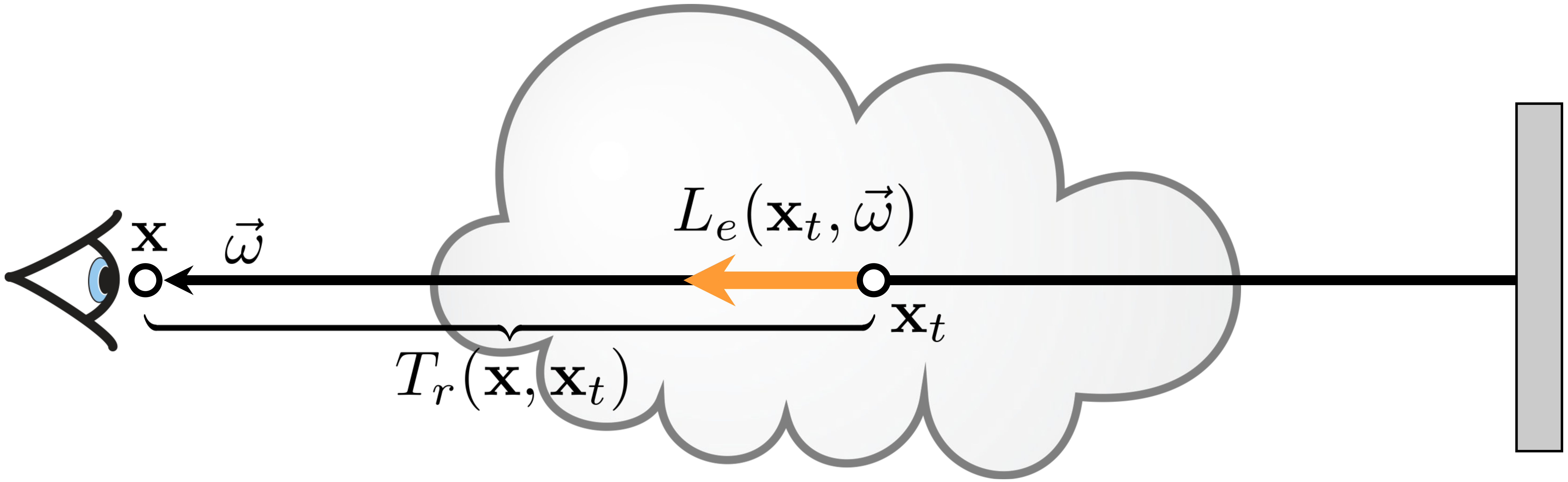
Reduced (background) surface radiance



Volume Rendering Equation

$$L(\mathbf{x}, \vec{\omega}) = T_r(\mathbf{x}, \mathbf{x}_z) L(\mathbf{x}_z, \vec{\omega}) + \boxed{\int_0^z T_r(\mathbf{x}, \mathbf{x}_t) \sigma_a(\mathbf{x}_t) L_e(\mathbf{x}_t, \vec{\omega}) dt}$$

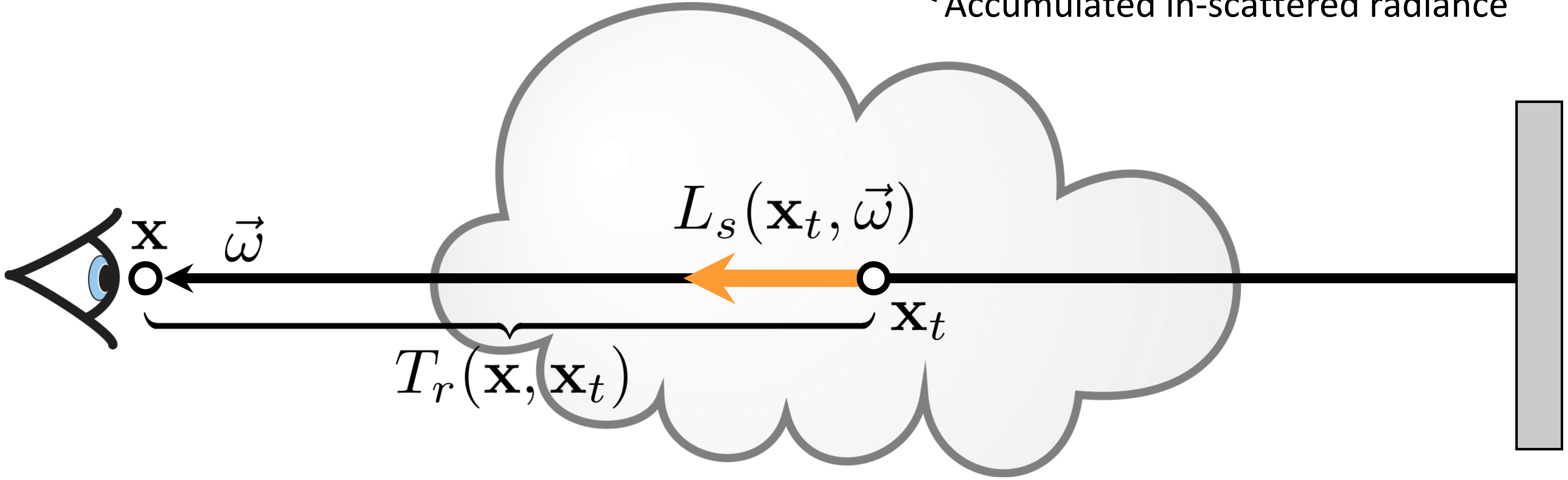
Accumulated emitted radiance



Volume Rendering Equation

$$L(\mathbf{x},\vec{\omega}) = T_r(\mathbf{x},\mathbf{x}_z)L(\mathbf{x}_z,\vec{\omega}) + \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega})dt + \boxed{\int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)L_s(\mathbf{x}_t,\vec{\omega})dt}$$

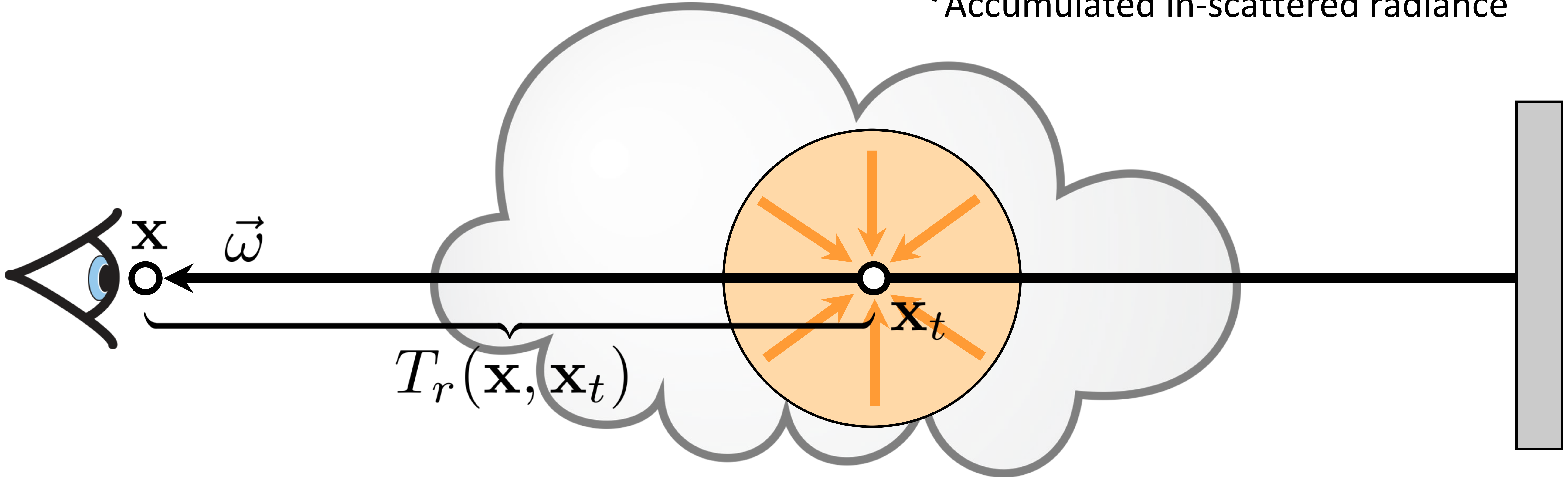
Accumulated in-scattered radiance



Volume Rendering Equation

$$L(\mathbf{x},\vec{\omega}) = T_r(\mathbf{x},\mathbf{x}_z)L(\mathbf{x}_z,\vec{\omega}) + \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega})dt + \boxed{\int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)\int_{S^2} f_p(\mathbf{x}_t,\vec{\omega}',\vec{\omega})L_i(\mathbf{x}_t,\vec{\omega}')d\vec{\omega}'dt}$$

Accumulated in-scattered radiance



Volume Rendering Equation

$$
\begin{aligned}
L(\mathbf{x}, \vec{\omega}) = & \; T_r(\mathbf{x}, \mathbf{x}_z) L(\mathbf{x}_z, \vec{\omega}) \\
& + \int_0^z T_r(\mathbf{x}, \mathbf{x}_t) \sigma_a(\mathbf{x}_t) L_e(\mathbf{x}_t, \vec{\omega}) dt \\
& + \int_0^z T_r(\mathbf{x}, \mathbf{x}_t) \sigma_s(\mathbf{x}_t) \int_{S^2} f_p(\mathbf{x}_t, \vec{\omega}', \vec{\omega}) L_i(\mathbf{x}_t, \vec{\omega}') d\vec{\omega}' dt
\end{aligned}
$$

Scattering in Media

Phase Function f_p

Describes distribution of scattered light

Analog of BRDF but for scattering in media

Integrates to unity (unlike BRDF)

$$\int_{S^2} f_p(\mathbf{x}, \vec{\omega}', \vec{\omega}) d\vec{\omega}' = 1$$

Why do we have this property?

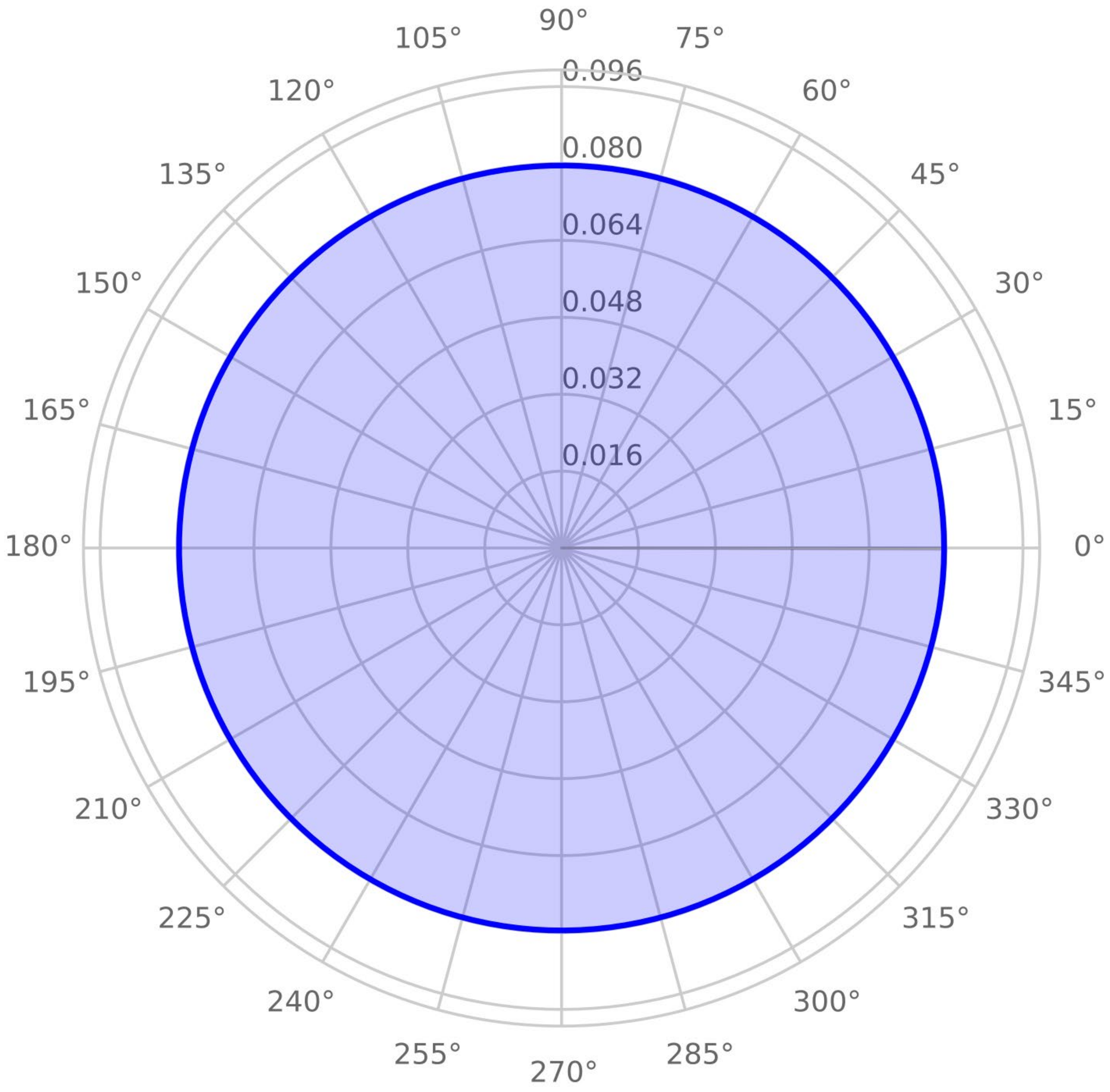
*We will use the same convention that phase function direction vectors always *point away* from the shading point **x**. Many publications, however, use a different convention for phase functions, in which direction vectors “follow” the light, i.e. one direction points *towards* **x** and the other *away* from **x**. When reading papers, be sure to clarify the meaning of the vectors to avoid misinterpretation.

Isotropic Scattering

Uniform scattering, analogous to Lambertian BRDF

$$f_p(\vec{\omega}', \vec{\omega}) = \frac{1}{4\pi}$$

Where does this value come from?



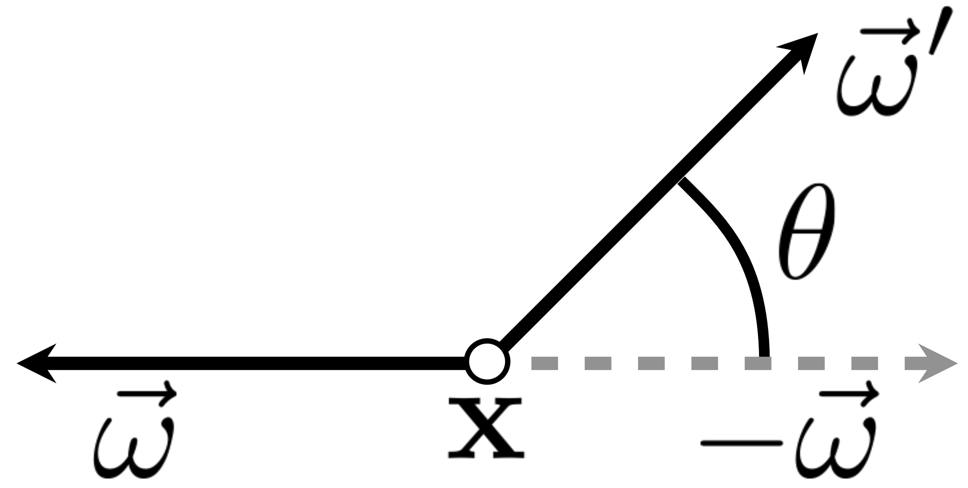
Anisotropic Scattering

Quantifying anisotropy (g, "average cosine"):

$$g = \int_{S^2} f_p(\mathbf{x}, \vec{\omega}', \vec{\omega}) \cos\theta \, d\vec{\omega}'$$

where:

$$\cos\theta = -\vec{\omega} \cdot \vec{\omega}'$$

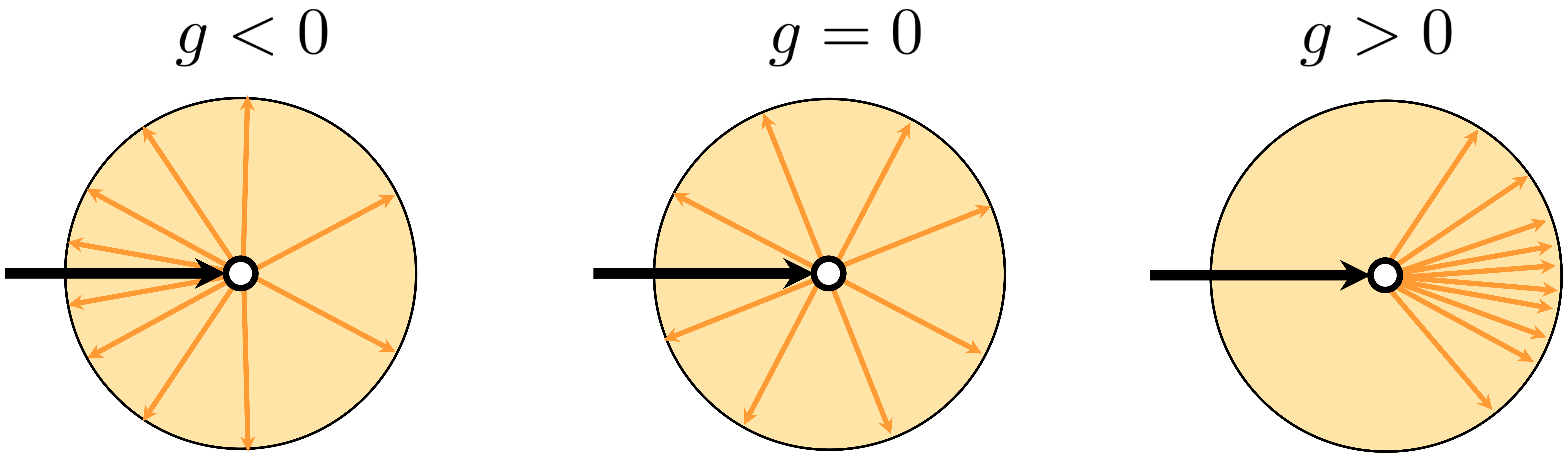


$g = 0$: isotropic scattering (on average)
$g > 0$: forward scattering
$g < 0$: backward scattering

Henyey-Greenstein Phase Function

Anisotropic scattering

$$f_{p\mathrm{HG}}(\theta) = \frac{1}{4\pi} \frac{1 - g^2}{(1 + g^2 - 2g\cos\theta)^{3/2}}$$

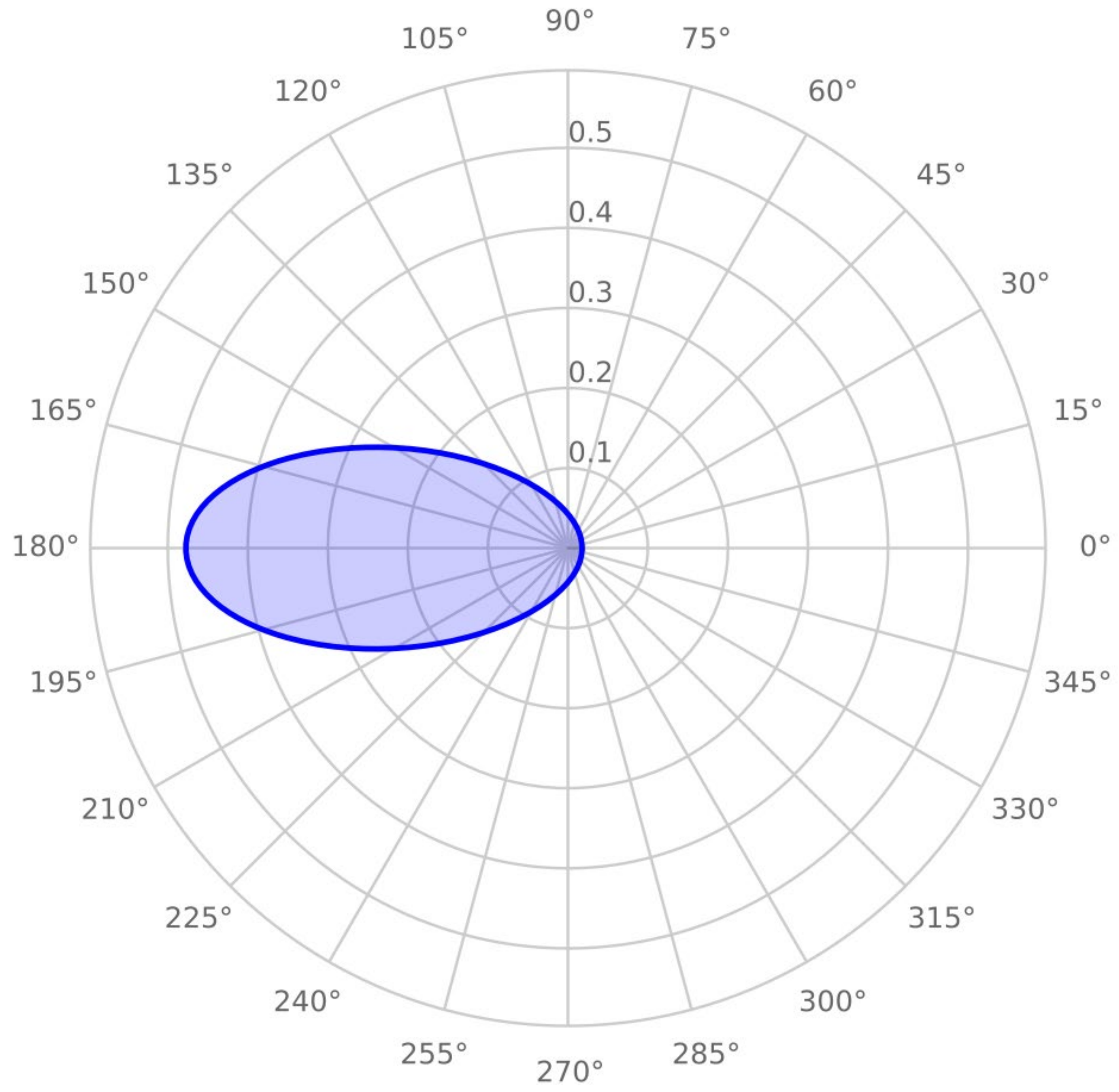


Henyey-Greenstein Phase Function

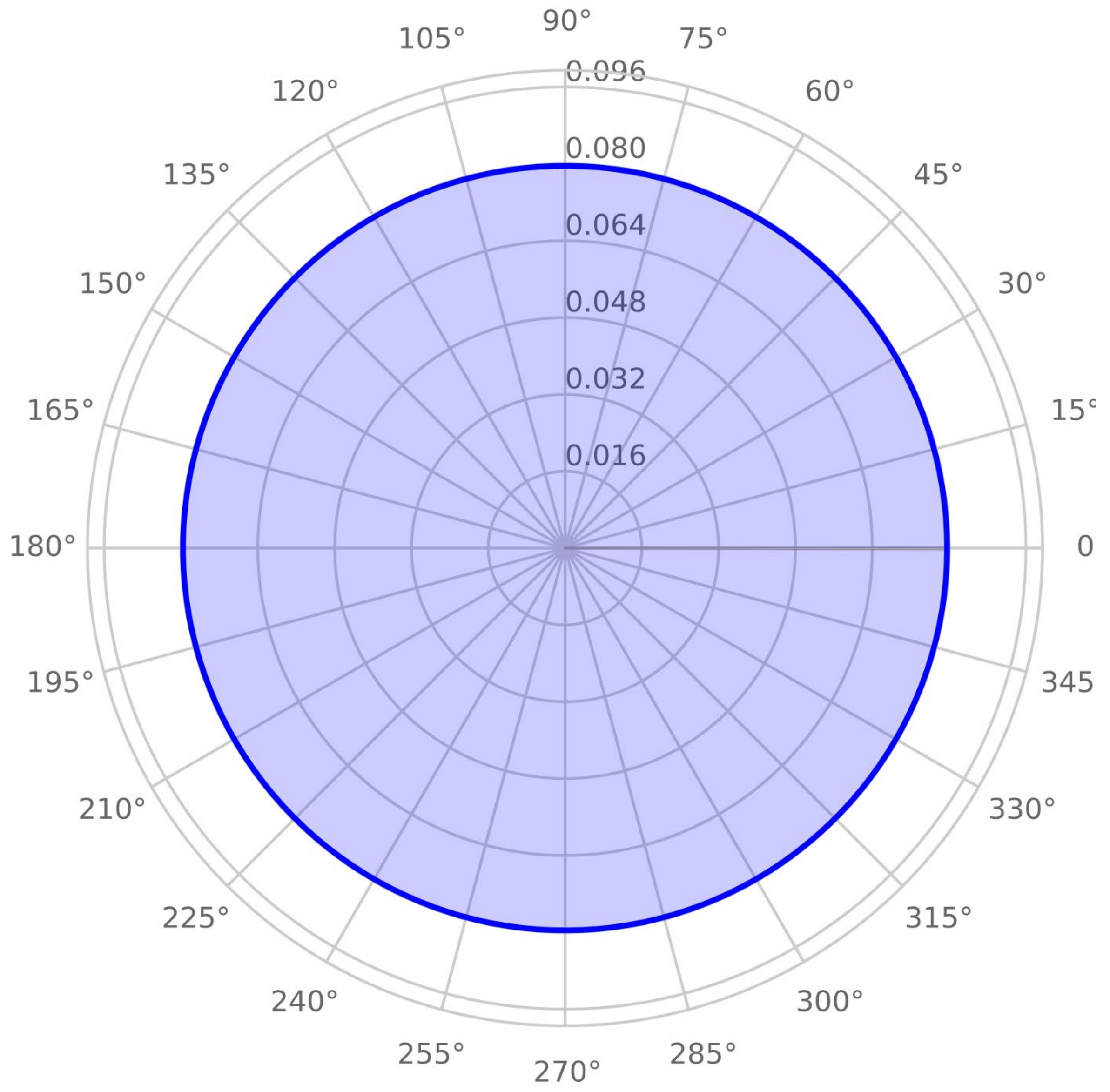
Anisotropic scattering

$$f_{p\mathrm{HG}}(\theta) = \frac{1}{4\pi}\frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}}$$

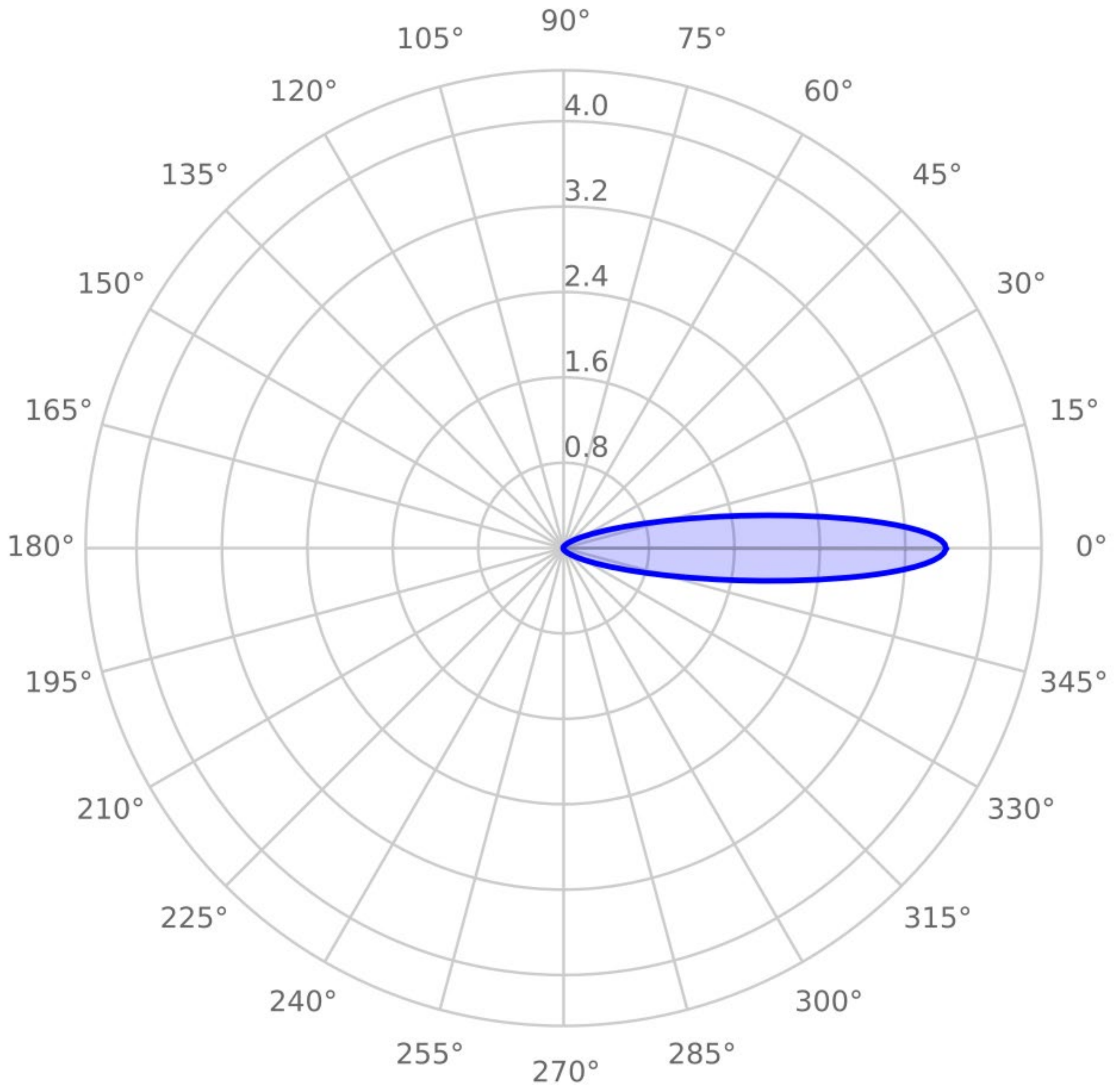
$g = -0.5$



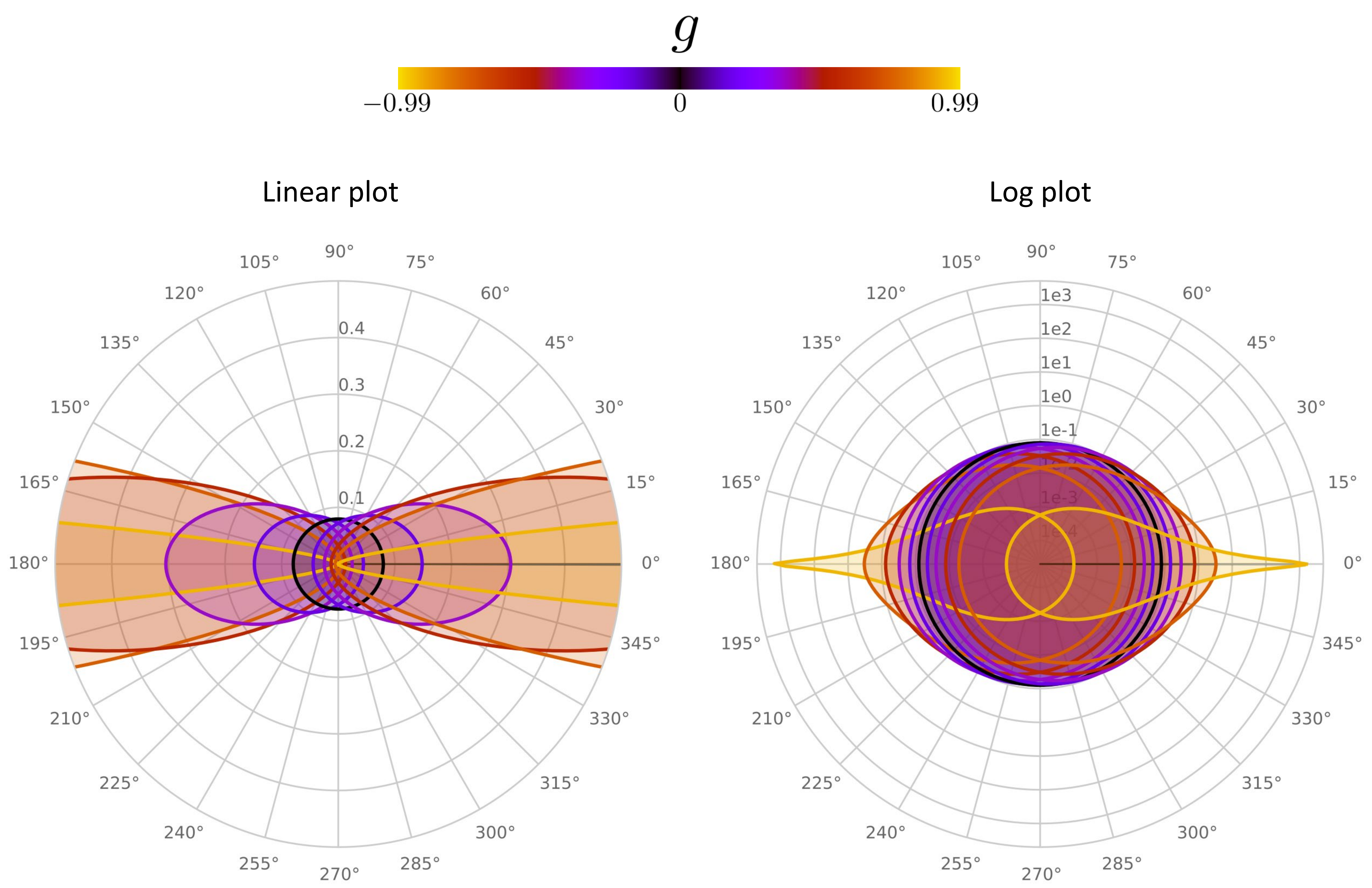
$g = 0$



$g = 0.8$



Henyey-Greenstein Phase Function



Henyey-Greenstein Phase Function

Empirical phase function

Introduced for intergalactic dust

Very popular in graphics and other fields

Schlick's Phase Function

Empirical phase function

Faster approximation of HG

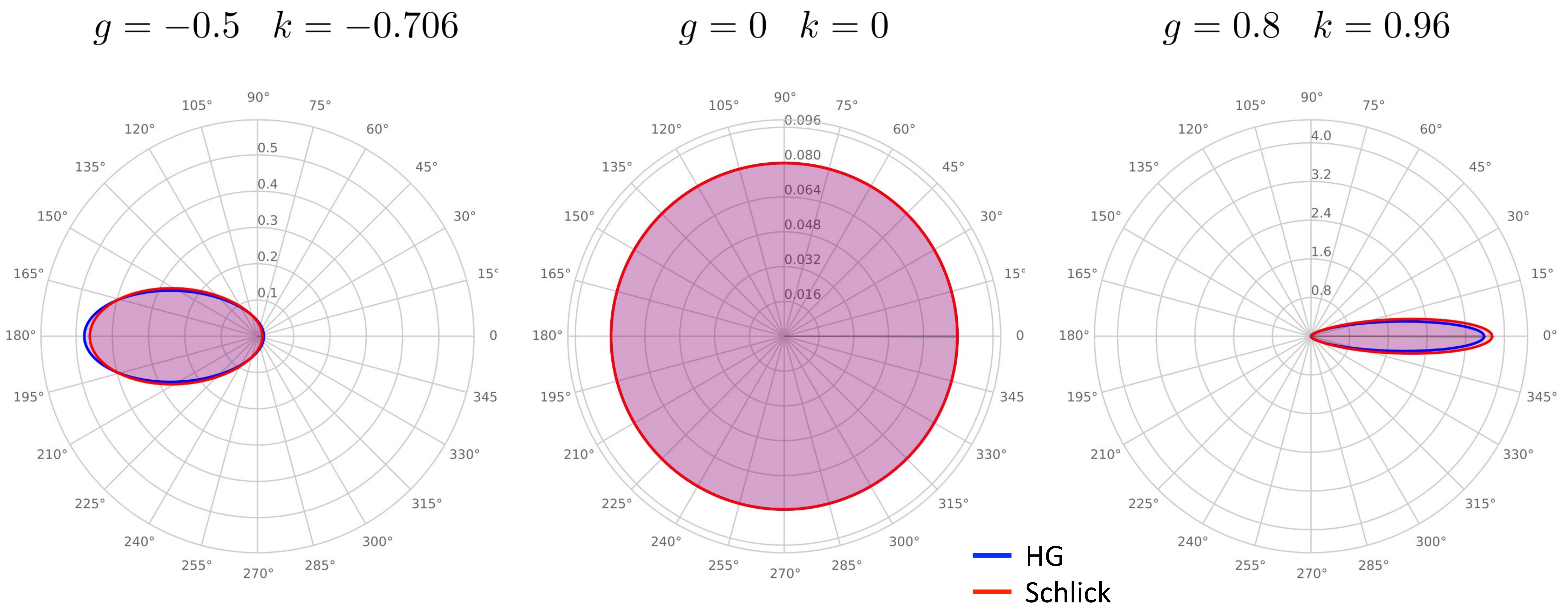
$$f_{p\mathrm{Schlick}}(\theta) = \frac{1}{4\pi} \frac{1 - k^2}{(1 - k\cos\theta)^2}$$

$$k = 1.55g - 0.55g^3$$

Schlick's Phase Function

Empirical phase function

Faster approximation of HG



Lorenz-Mie Scattering

If the diameter of scatterers is on the order of light wavelength, we cannot neglect the wave nature of light

Solution to Maxwell's equations for scattering from any spherical dielectric particle

Explains many phenomena

Complicated:

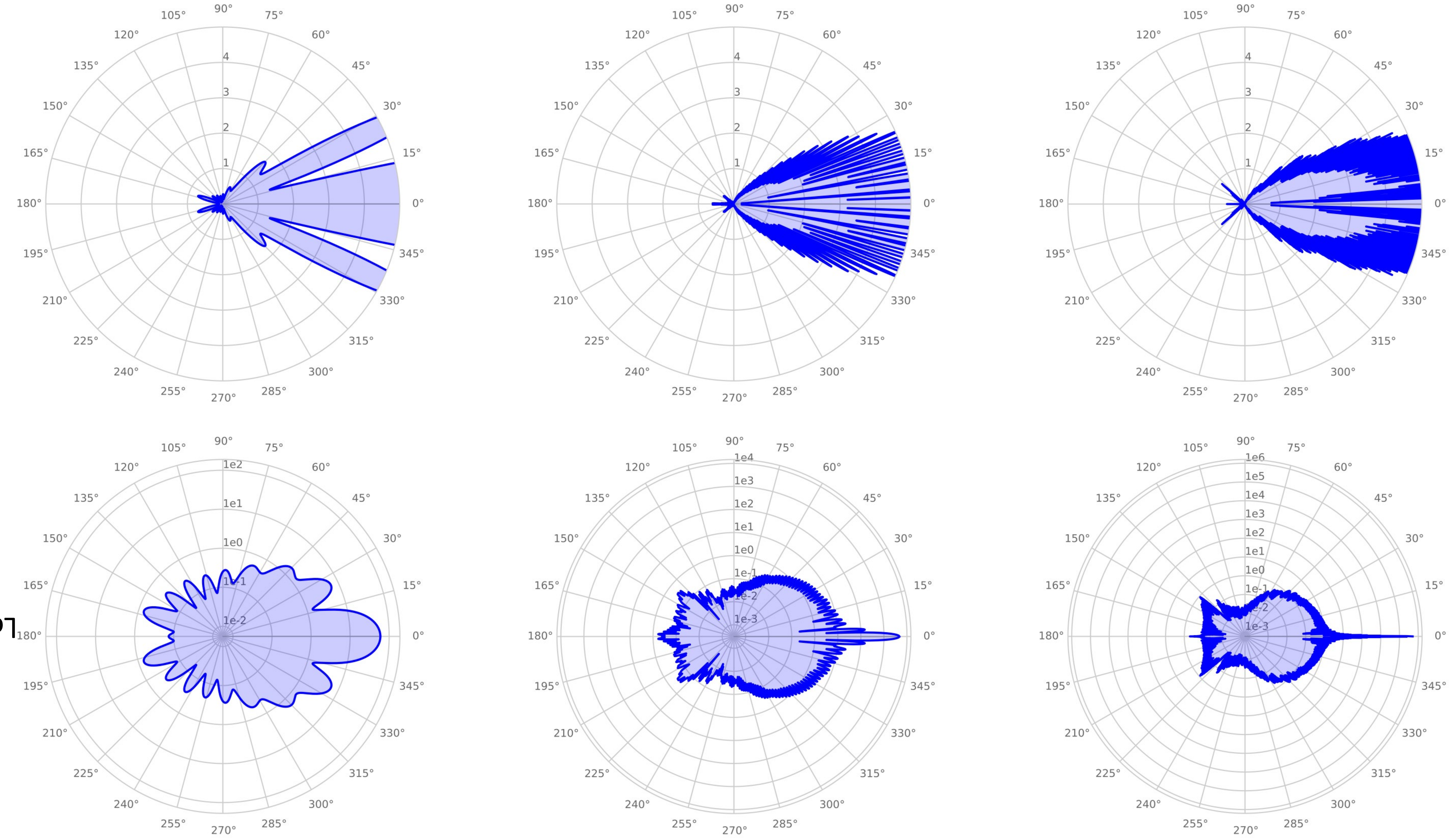
- Solution is an infinite analytic series

Lorenz-Mie Phase Function

Sphere diameter $= 1 \mu m$ | Sphere diameter $= 10 \mu m$ | Sphere diameter $= 100 \mu m$

Linear plots

Log plots



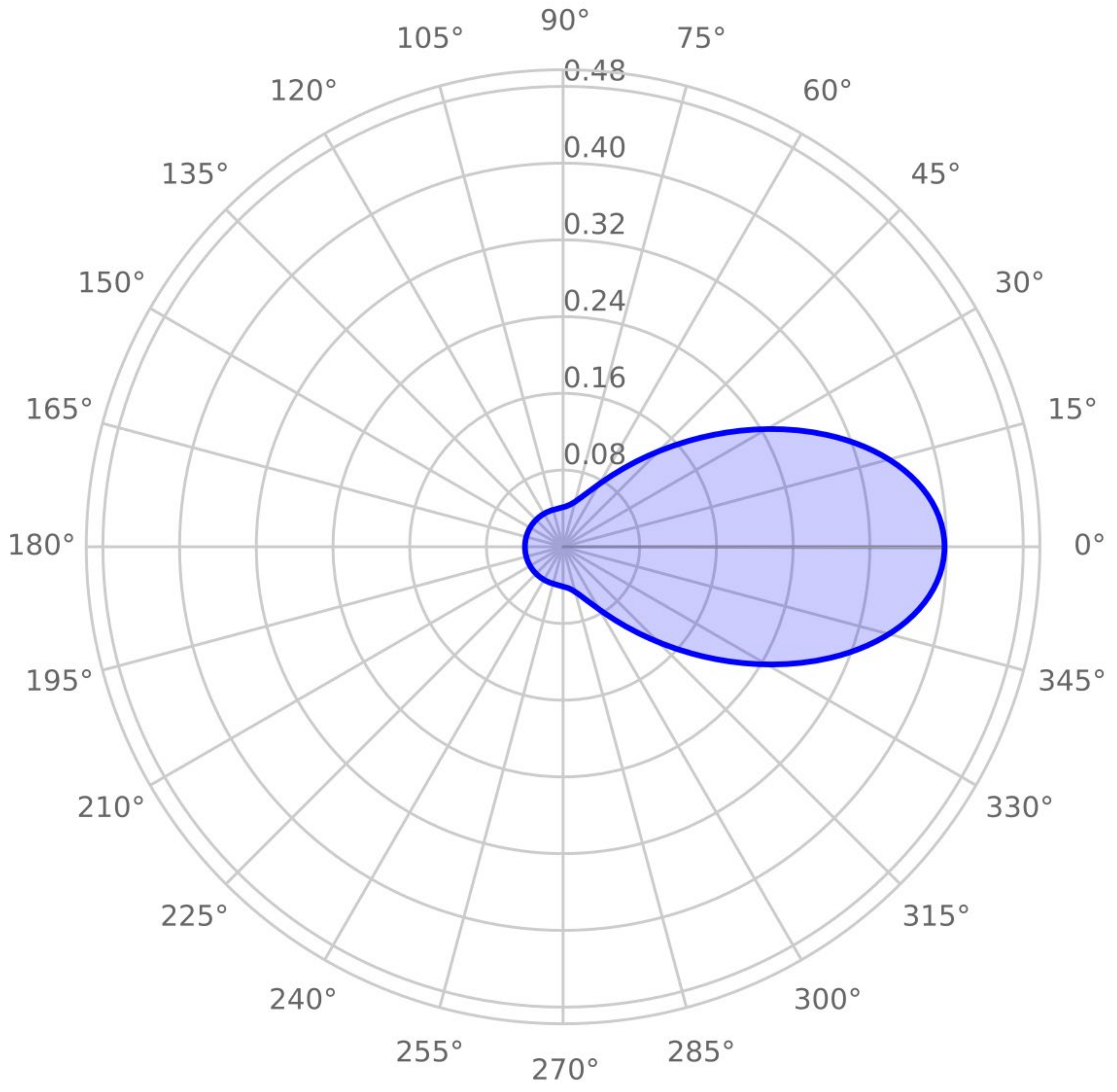
Data obtained from http://www.philiplaven.com/mieplot.htm

Rainbows

Lorenz-Mie Approximations

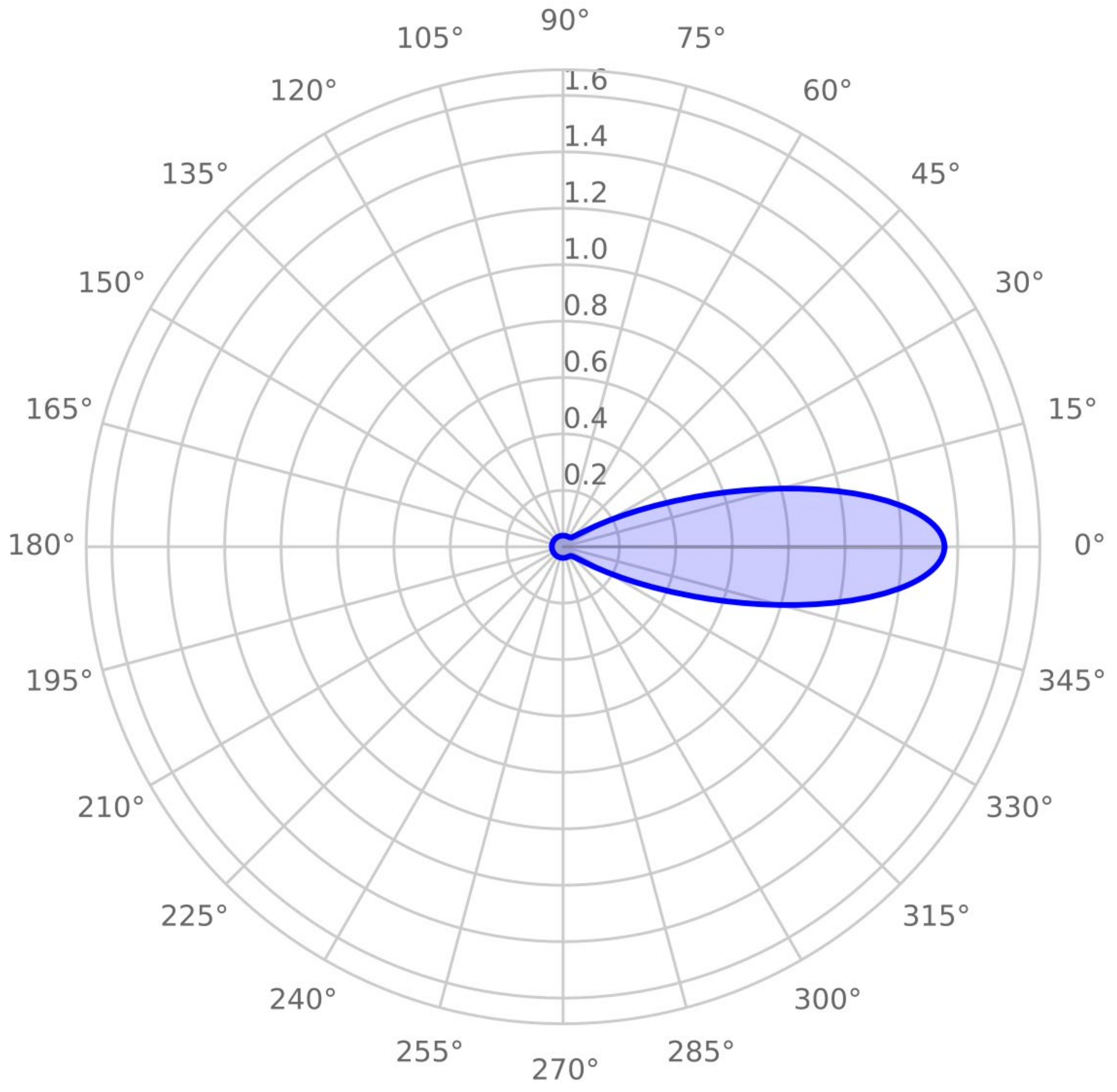
Hazy atmosphere

$$f_{p\,\mathrm{hazy}}(\theta) = \frac{1}{4\pi}\left(5 + \left(\frac{1+\cos\theta}{2}\right)^{8}\right)$$



Murky atmosphere

$$f_{p\,\mathrm{murky}}(\theta) = \frac{1}{4\pi}\left(17 + \left(\frac{1+\cos\theta}{2}\right)^{32}\right)$$



Lorenz-Mie Approximations

Hazy atmosphere

$$f_{p\,\mathrm{hazy}}(\theta) = \frac{1}{4\pi}\left(5 + \left(\frac{1+\cos\theta}{2}\right)^{8}\right)$$

Murky atmosphere

$$f_{p\,\mathrm{murky}}(\theta) = \frac{1}{4\pi}\left(17 + \left(\frac{1+\cos\theta}{2}\right)^{32}\right)$$

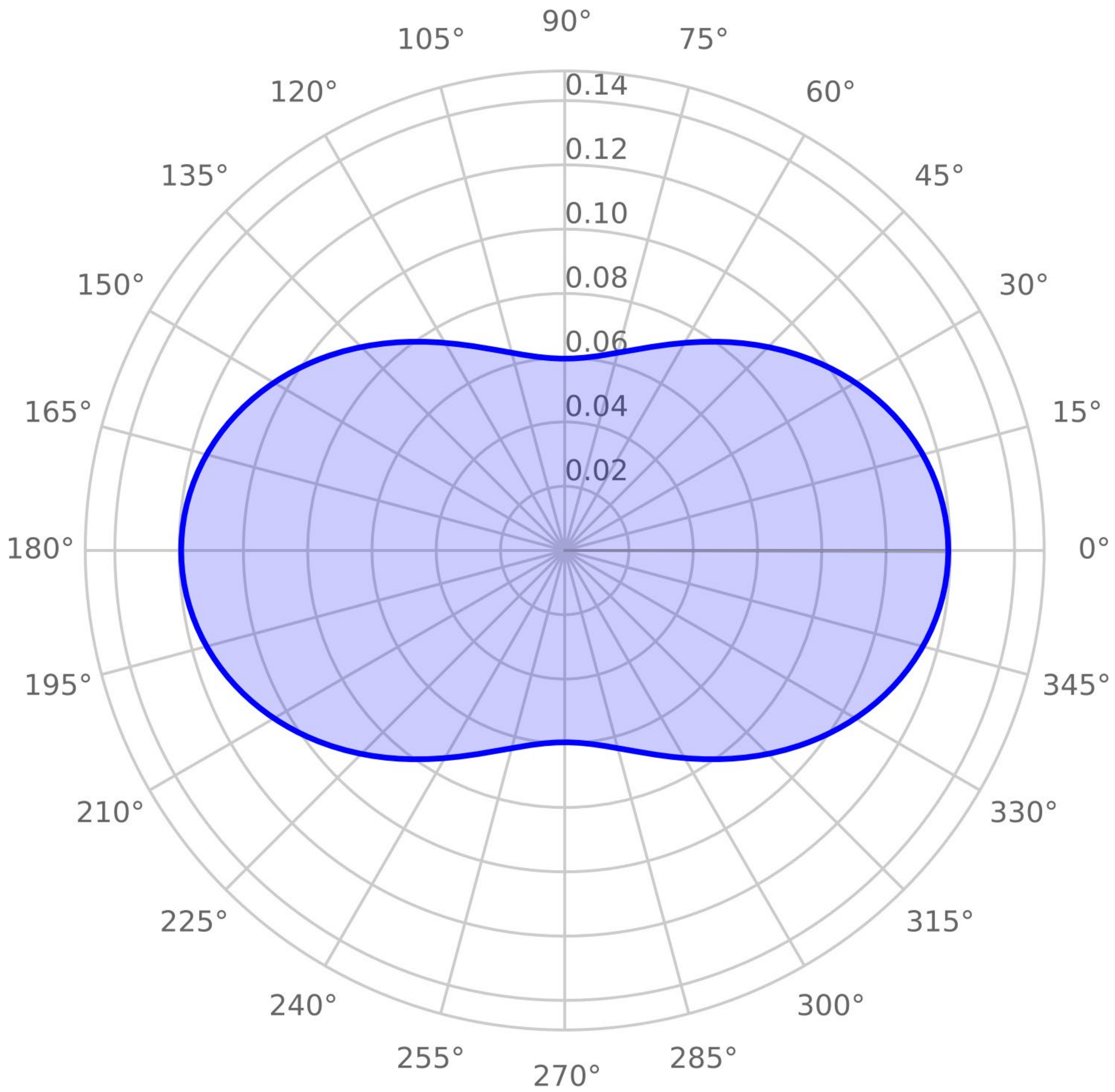
Rayleigh Scattering

Approximation of Lorenz-Mie for tiny scatterers that are typically smaller than 1/10th the wavelength of visible light

Used for atmospheric scattering, gasses, transparent solids

Highly wavelength dependent

Rayleigh Phase Function



$$f_{p\text{Rayleigh}}(\theta) = \frac{3}{16\pi}(1 + \cos^2\theta)$$

Scattering at right angles is half as likely as scattering forward or backward

Rayleigh Scattering

Wavelength

Index of refraction

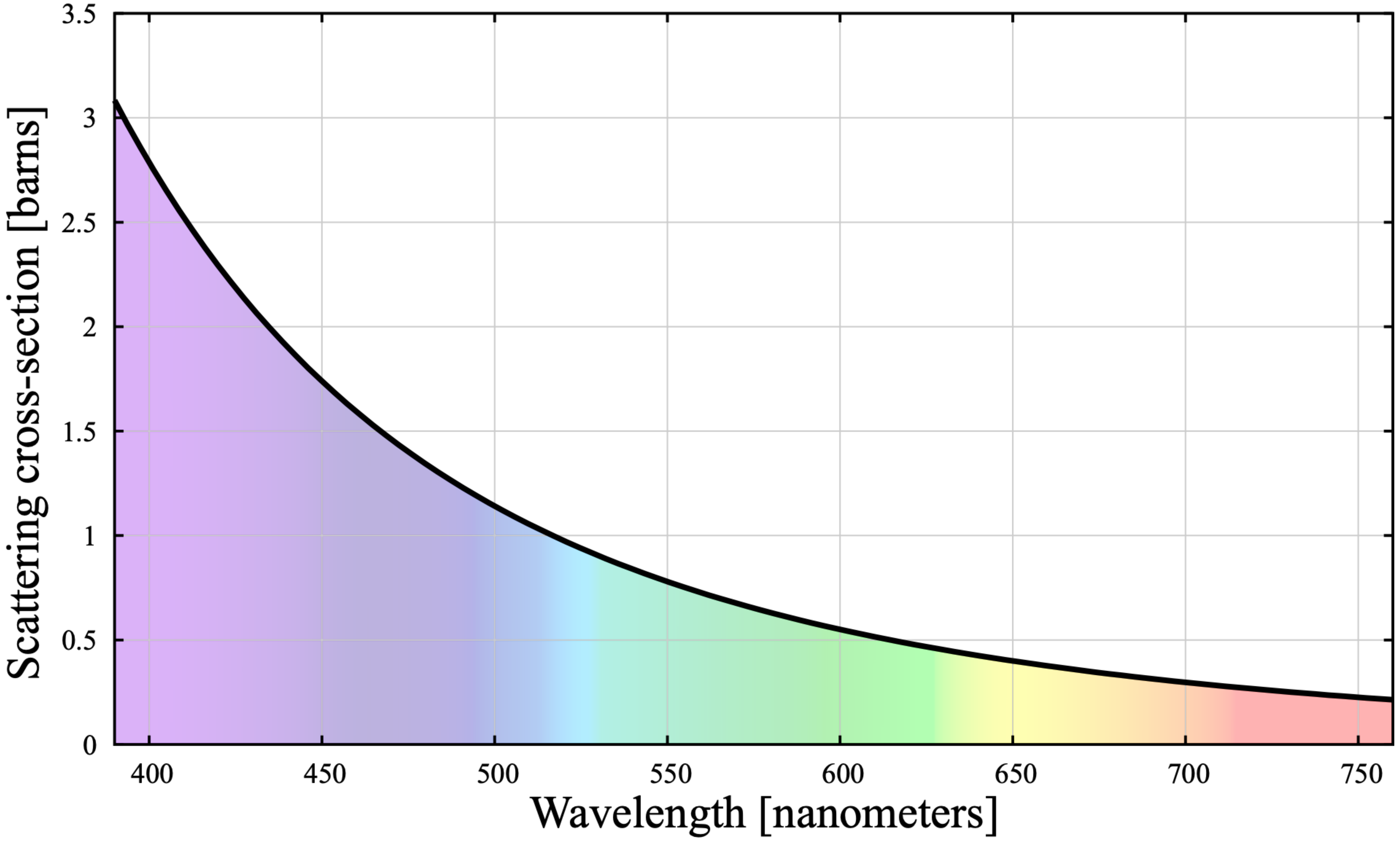
$$\sigma_{s\text{Rayleigh}}(\lambda, d, \eta, \rho) = \rho \, \frac{2\pi^5 d^6}{3\lambda^4} \left(\frac{\eta^2 - 1}{\eta^2 + 2} \right)^2$$

Density of scatterers

Diameter of scatterers

Rayleigh Scattering

$$\sigma_{s\text{Rayleigh}}(\lambda, d, \eta, \rho) = \rho \, \frac{2\pi^5 d^6}{3\lambda^4} \left(\frac{\eta^2 - 1}{\eta^2 + 2} \right)^2$$



Examples

Examples

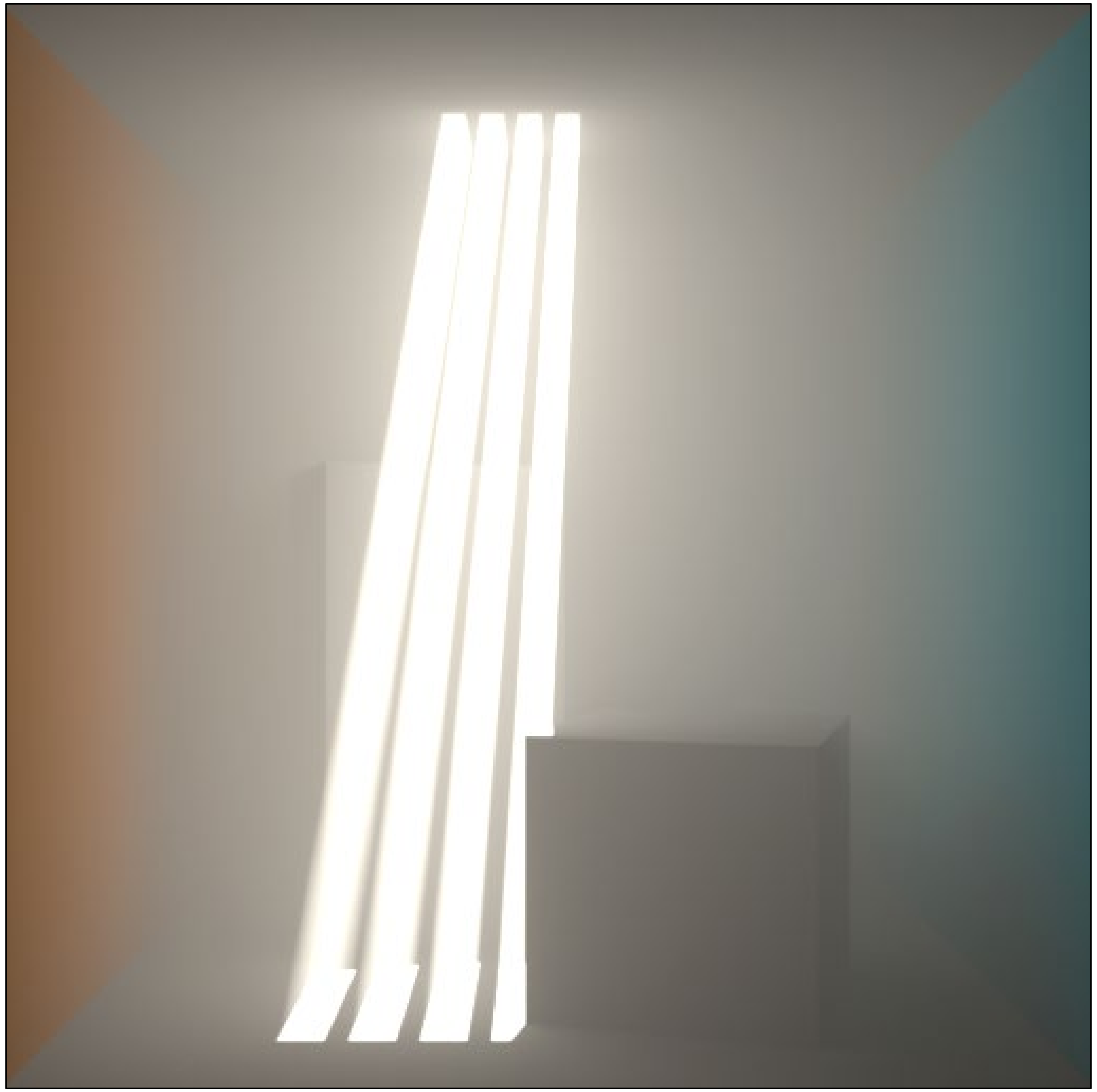
Steam

Forward scattering

Smoke

Backward scattering

Examples

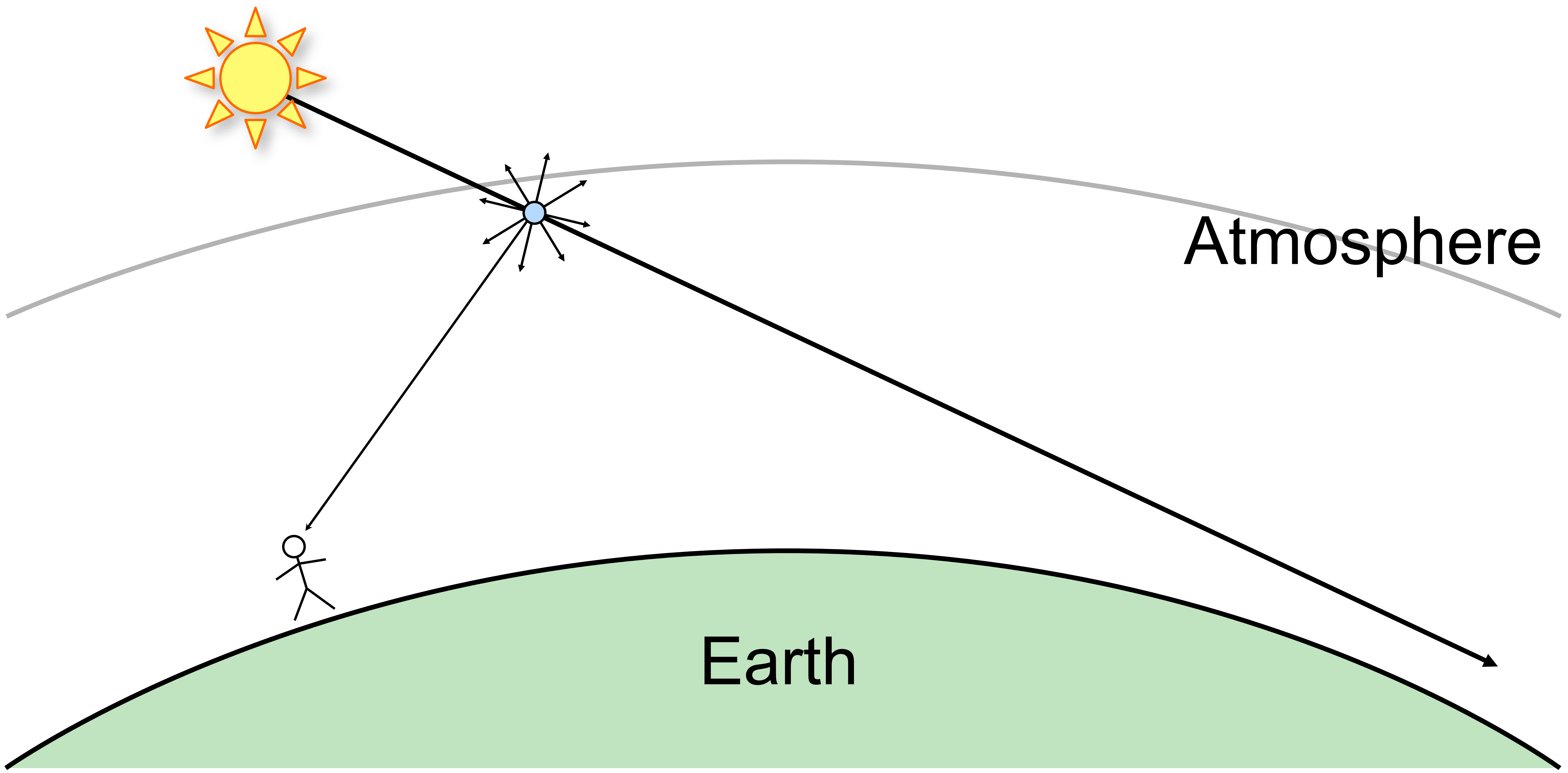


Isotropic scattering

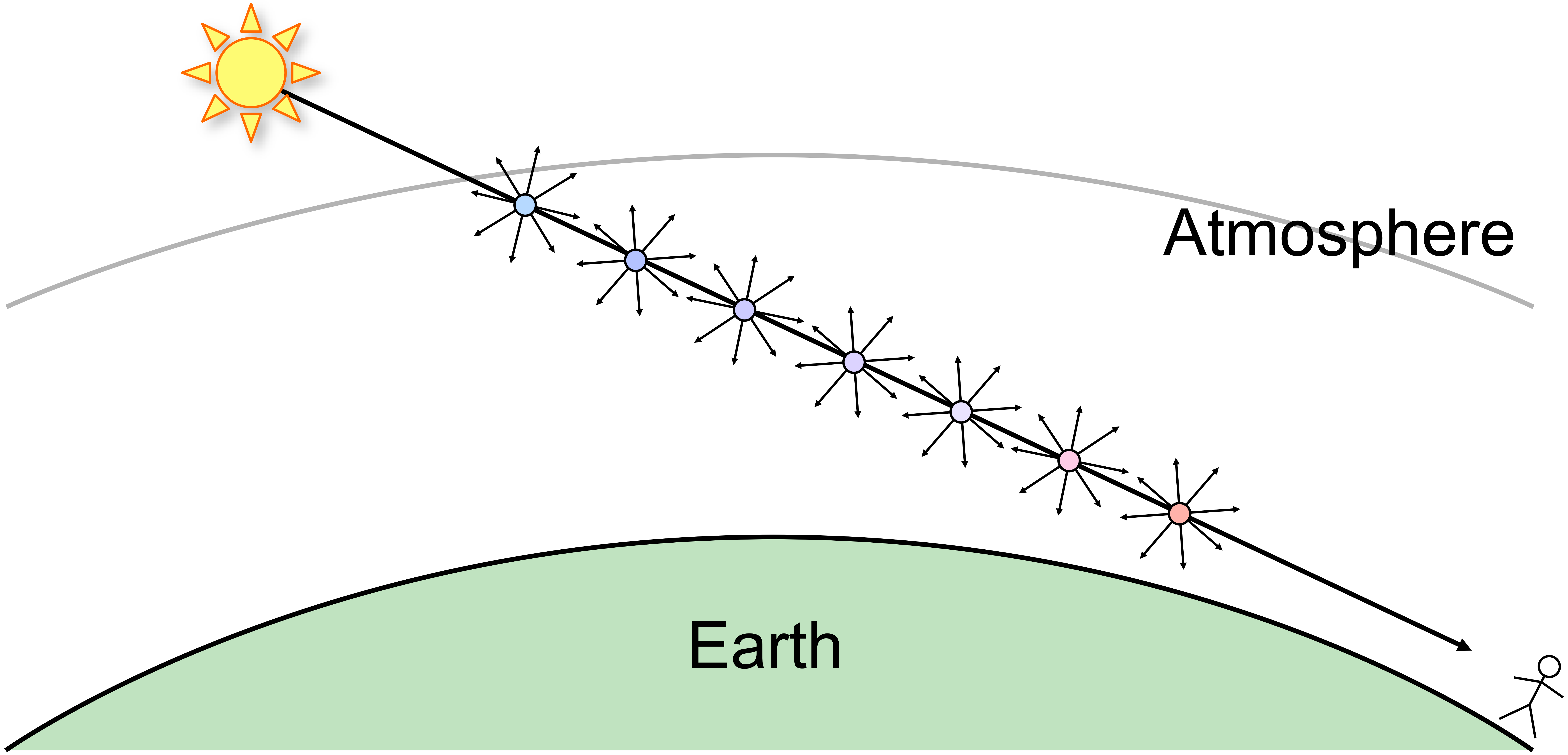
Examples

Forward scattering

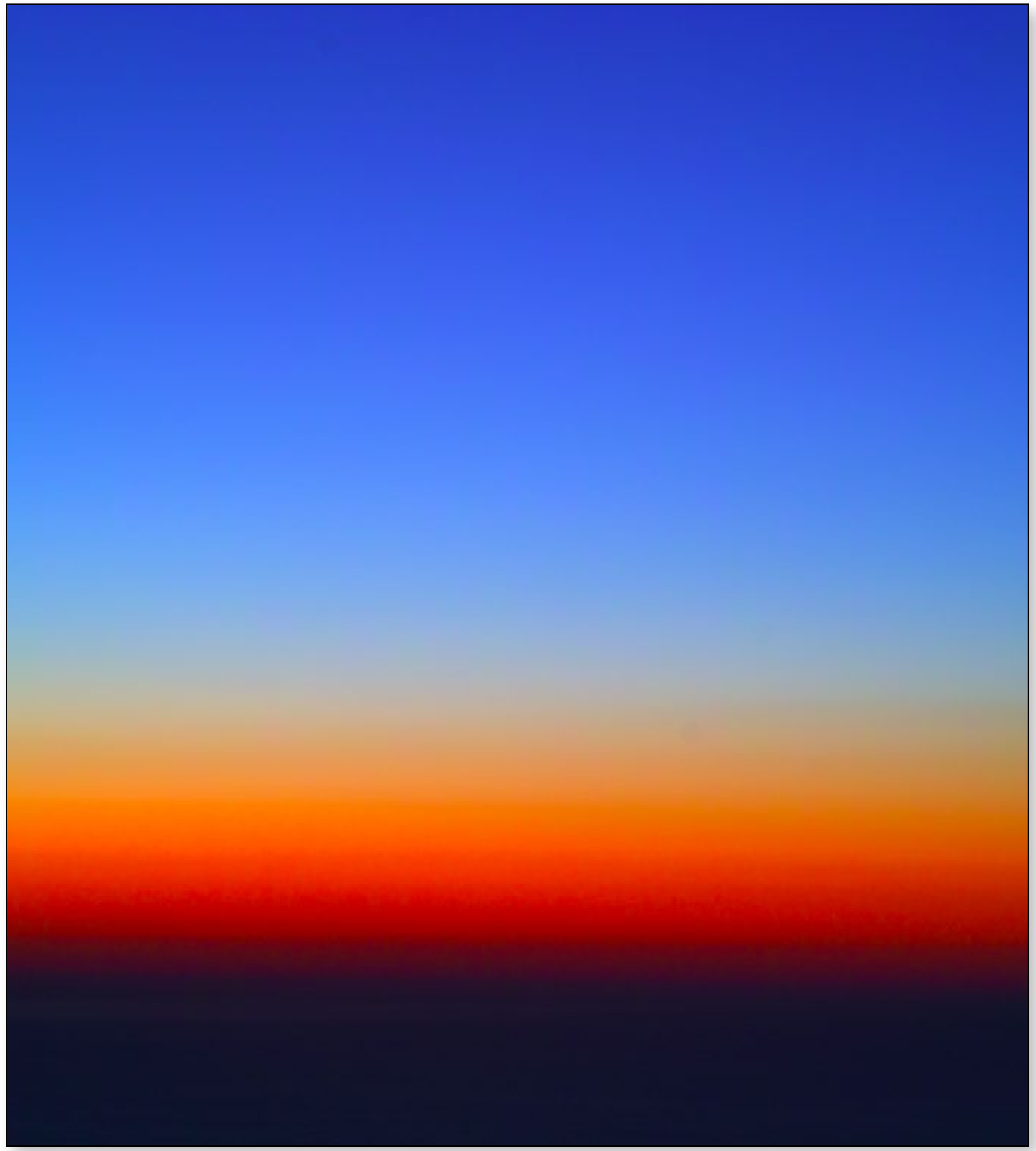
Why is the Sky Blue?

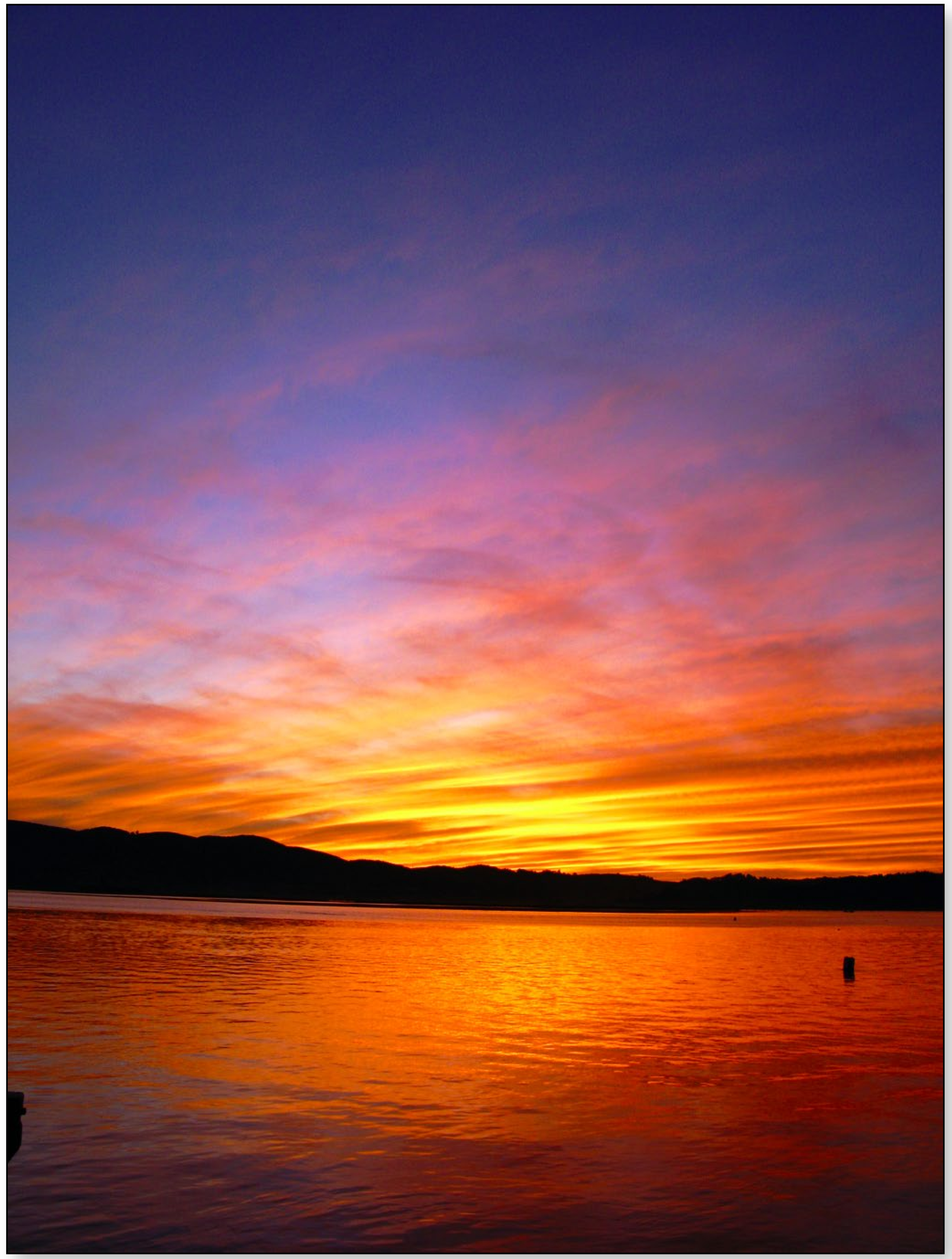


Why is the Sunset Red?



Rayleigh Scattering





Media Properties (Recap)

Given:

- Absorption coefficient $\sigma_a(\mathbf{x})$ $[\mathrm{m}^{-1}]$
- Scattering coefficient $\sigma_s(\mathbf{x})$ $[\mathrm{m}^{-1}]$
- Phase function $f_p(\mathbf{x}, \vec{\omega}', \vec{\omega})$ $[\mathrm{sr}^{-1}]$

Derived:

- Extinction coefficient $\sigma_t(\mathbf{x}) = \sigma_a(\mathbf{x}) + \sigma_s(\mathbf{x})$ $[\mathrm{m}^{-1}]$
- Albedo $\alpha(\mathbf{x}) = \sigma_s(\mathbf{x}) / \sigma_t(\mathbf{x})$ $[\mathrm{none}]$
- Mean-free path $1/\sigma_t(\mathbf{x})$ $[\mathrm{m}]$
- Transmittance $T_r(\mathbf{x}, \mathbf{y}) = e^{-\int_0^{\|\mathbf{x}-\mathbf{y}\|} \sigma_t(t)dt}$ $[\mathrm{none}]$

Homogeneous Isotropic Medium

Given:

- Absorption coefficient	σ_a	$[\mathrm{m}^{-1}]$
- Scattering coefficient	σ_s	$[\mathrm{m}^{-1}]$
- Phase function	$\frac{1}{4\pi}$	$[\mathrm{sr}^{-1}]$

Derived:

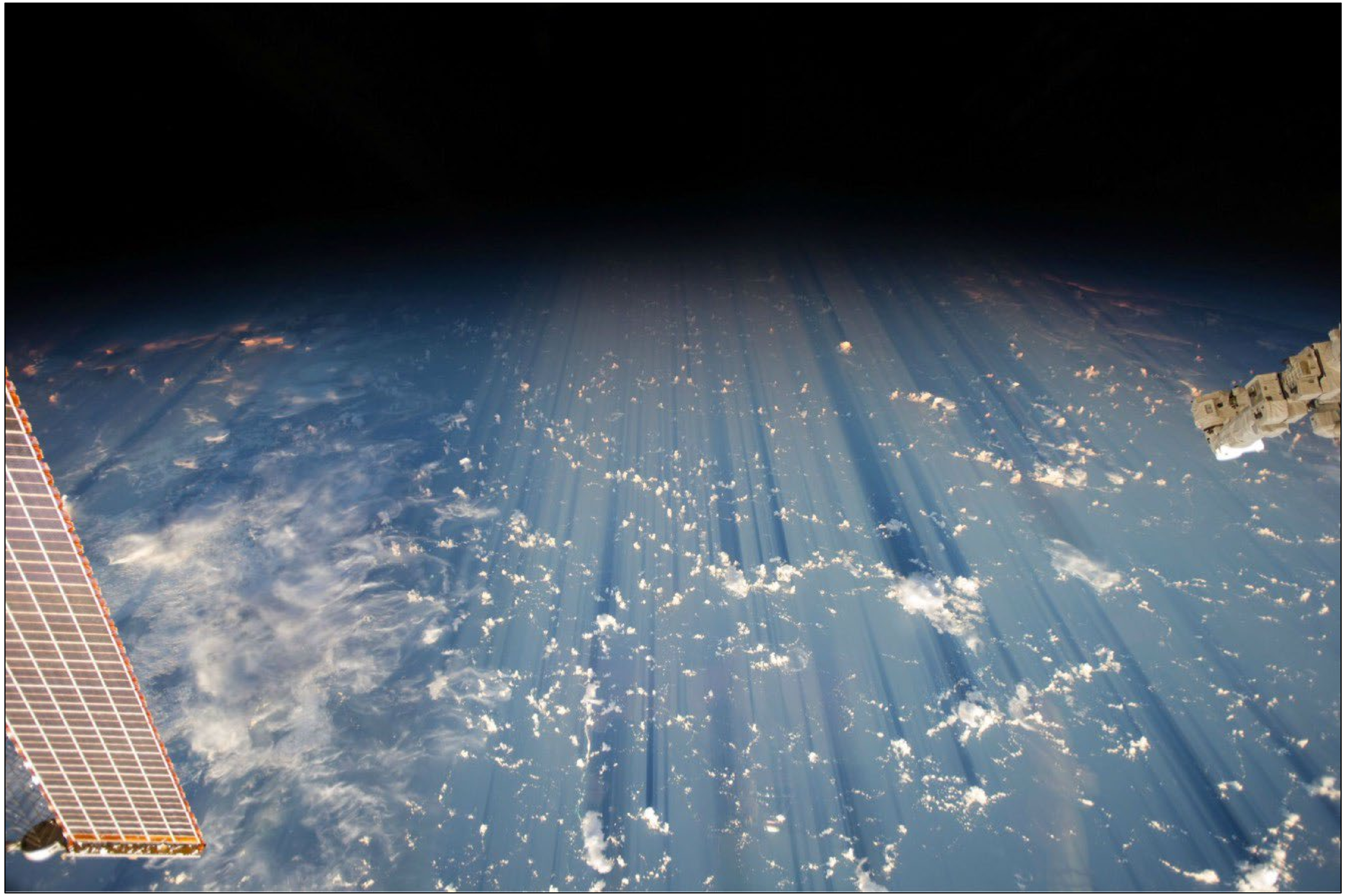
- Extinction coefficient	$\sigma_t = \sigma_a + \sigma_s$	$[\mathrm{m}^{-1}]$
- Albedo	$\alpha = \sigma_s / \sigma_t$	$[\mathrm{none}]$
- Mean-free path	$1/\sigma_t$	$[\mathrm{m}]$
- Transmittance	$T_r(\mathbf{x}, \mathbf{y}) = e^{-\sigma_t \lVert \mathbf{x} - \mathbf{y} \rVert}$	$[\mathrm{none}]$

What is this?

Crepuscular Rays

Anti-Crepuscular Rays

Crepuscular rays from space



Solving the Volume Rendering Equation

Complexity Progression

homogeneous vs. heterogeneous

scattering

- none
- fake ambient
- single
- multiple

Volume Rendering Equation

Attenuated background radiance

Accumulated emitted radiance

$$L(\mathbf{x},\vec{\omega}) = \boxed{T_r(\mathbf{x},\mathbf{x}_z)L(\mathbf{x}_z,\vec{\omega})}$$
$$+ \boxed{\int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega})dt}$$
$$+ \boxed{\int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)L_s(\mathbf{x}_t,\vec{\omega})dt}$$

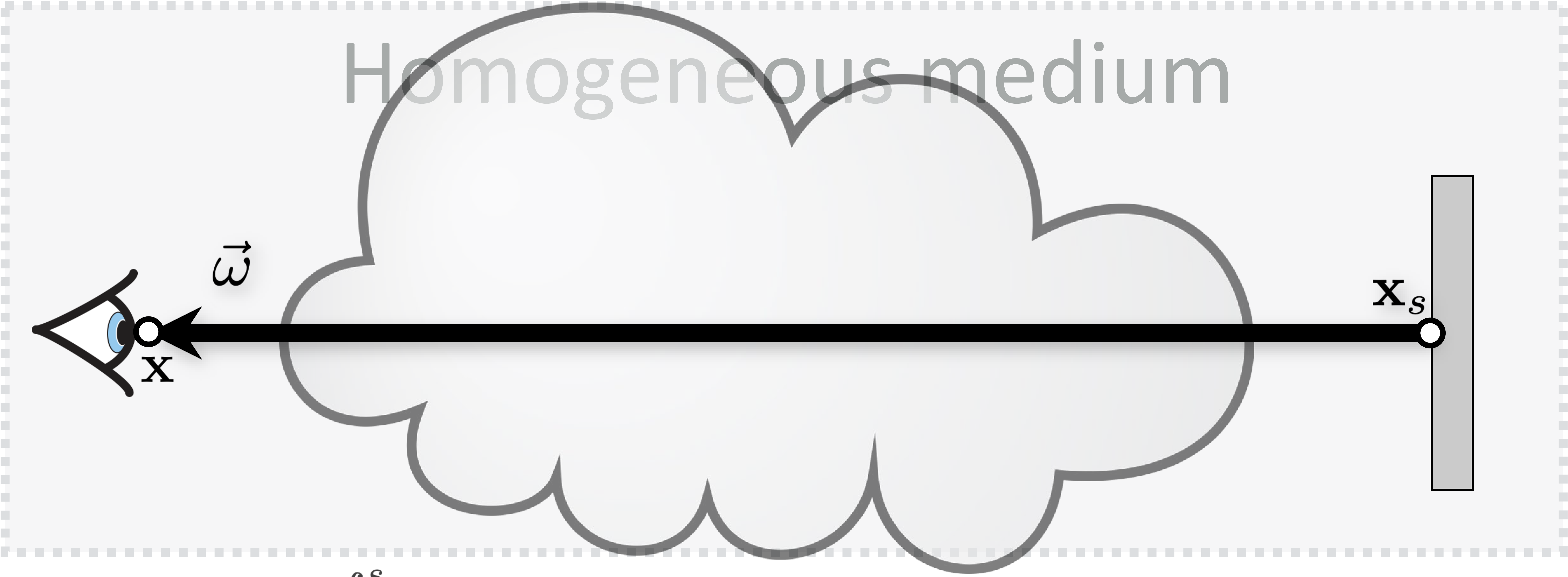
Accumulated in-scattered radiance

Purely absorbing media

$$L(\mathbf{x},\vec{\omega}) = \underbrace{\boxed{T_r(\mathbf{x},\mathbf{x}_z)L(\mathbf{x}_z,\vec{\omega})}}_{\text{Attenuated background radiance}}$$

Fog

Participating Media



$$L(\mathbf{x},\vec{\omega}) = \int_0^s T_r(\mathbf{x}\leftrightarrow\mathbf{x}_t)\boxed{\sigma_s(\mathbf{x}_t)}L_i(\mathbf{x}_t,\vec{\omega})\,dt + T_r(\mathbf{x}\leftrightarrow\mathbf{x}_s)L(\mathbf{x}_s,\vec{\omega})$$

$$L(\mathbf{x},\vec{\omega}) = \boxed{\sigma_s}\int_0^s \boxed{T_r(\mathbf{x}\leftrightarrow\mathbf{x}_t)}L_i(\mathbf{x}_t,\vec{\omega})\,dt + \boxed{T_r(\mathbf{x}\leftrightarrow\mathbf{x}_s)}L(\mathbf{x}_s,\vec{\omega})$$

$$L(\mathbf{x},\vec{\omega}) = \sigma_s\int_0^s \boxed{e^{-t\sigma_t}}L_i(\mathbf{x}_t,\vec{\omega})\,dt + \boxed{e^{-s\sigma_t}}L(\mathbf{x}_s,\vec{\omega})$$

Fog

$$L(\mathbf{x}, \vec{\omega}) = \sigma_s \int_0^s e^{-t\sigma_t} \, L_i(\mathbf{x}_t, \vec{\omega}) \, dt + e^{-s\sigma_t} L(\mathbf{x}_s, \vec{\omega})$$

Homogeneous Ambient Media

Assume in-scattered radiance is an ambient constant:

$$L(\mathbf{x},\vec{\omega}) = \sigma_s \int_0^s e^{-t\sigma_t} \boxed{L_i(\mathbf{x}_t,\vec{\omega})}\, dt + e^{-s\sigma_t} L(\mathbf{x}_s,\vec{\omega})$$

Homogeneous Ambient Media

Assume in-scattered radiance is an ambient constant:

$$L(\mathbf{x},\vec{\omega}) = \sigma_s \int_0^s e^{-t\sigma_t}\, L_i(\mathbf{x}_t,\vec{\omega})\, dt + e^{-s\sigma_t} L(\mathbf{x}_s,\vec{\omega})$$

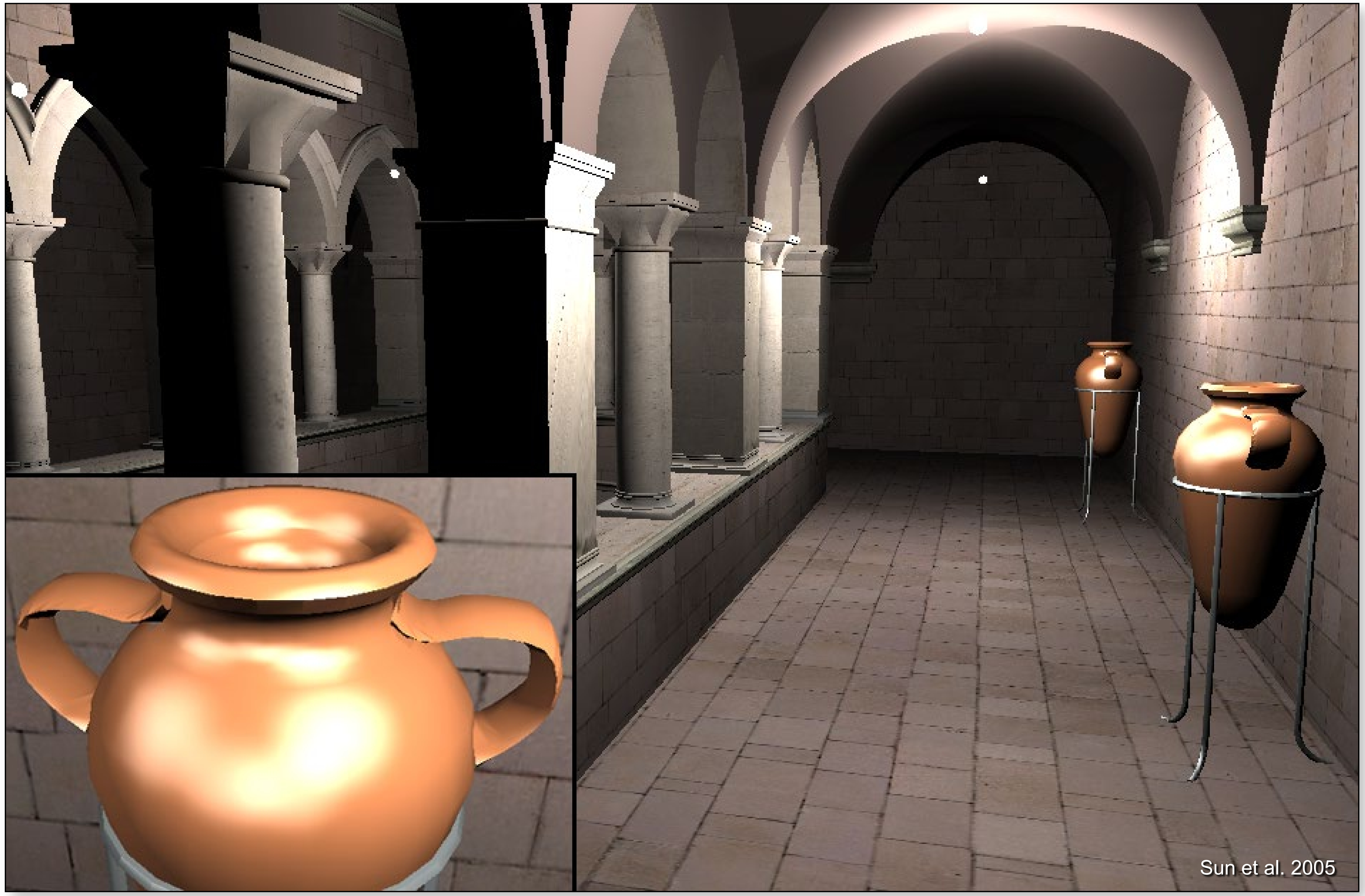
$$L(\mathbf{x},\vec{\omega}) = \sigma_s \boxed{L_i} \boxed{\int_0^s e^{-t\sigma_t}\, dt} + e^{-s\sigma_t} L(\mathbf{x}_s,\vec{\omega})$$

$$L(\mathbf{x},\vec{\omega}) = \sigma_s L_i \boxed{\frac{1 - e^{-s\sigma_t}}{\sigma_t}} + e^{-s\sigma_t} L(\mathbf{x}_s,\vec{\omega})$$

$$L(\mathbf{x},\vec{\omega}) = \mathrm{lerp}\left(\frac{\sigma_s}{\sigma_t} L_i,\ L(\mathbf{x}_s,\vec{\omega}),\ e^{-s\sigma_t}\right)$$

OpenGL Fog

OpenGL Clear Day



Fog


http://anordinarymom.wordpress.com

Andreas Levers

Andreas Levers

Volume Rendering Equation

$$
\begin{aligned}
L(\mathbf{x},\vec{\omega}) = {} & T_r(\mathbf{x},\mathbf{x}_z)L(\mathbf{x}_z,\vec{\omega}) \\
& + \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega})dt \\
& + \boxed{\int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)L_s(\mathbf{x}_t,\vec{\omega})dt}
\end{aligned}
$$

Accumulated in-scattered radiance

In-scattered Radiance

$$L(\mathbf{x},\vec{\omega}) = \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)\boxed{L_s(\mathbf{x}_t,\vec{\omega})}dt$$

$$\boxed{L_s(\mathbf{x}_t,\vec{\omega})} = \int_{S^2} f_p(\mathbf{x}_t,\vec{\omega}',\vec{\omega})\boxed{L_i(\mathbf{x}_t,\vec{\omega}')}d\vec{\omega}'$$

Single scattering

- L_i arrives directly from a light source (direct illum.) i.e.:

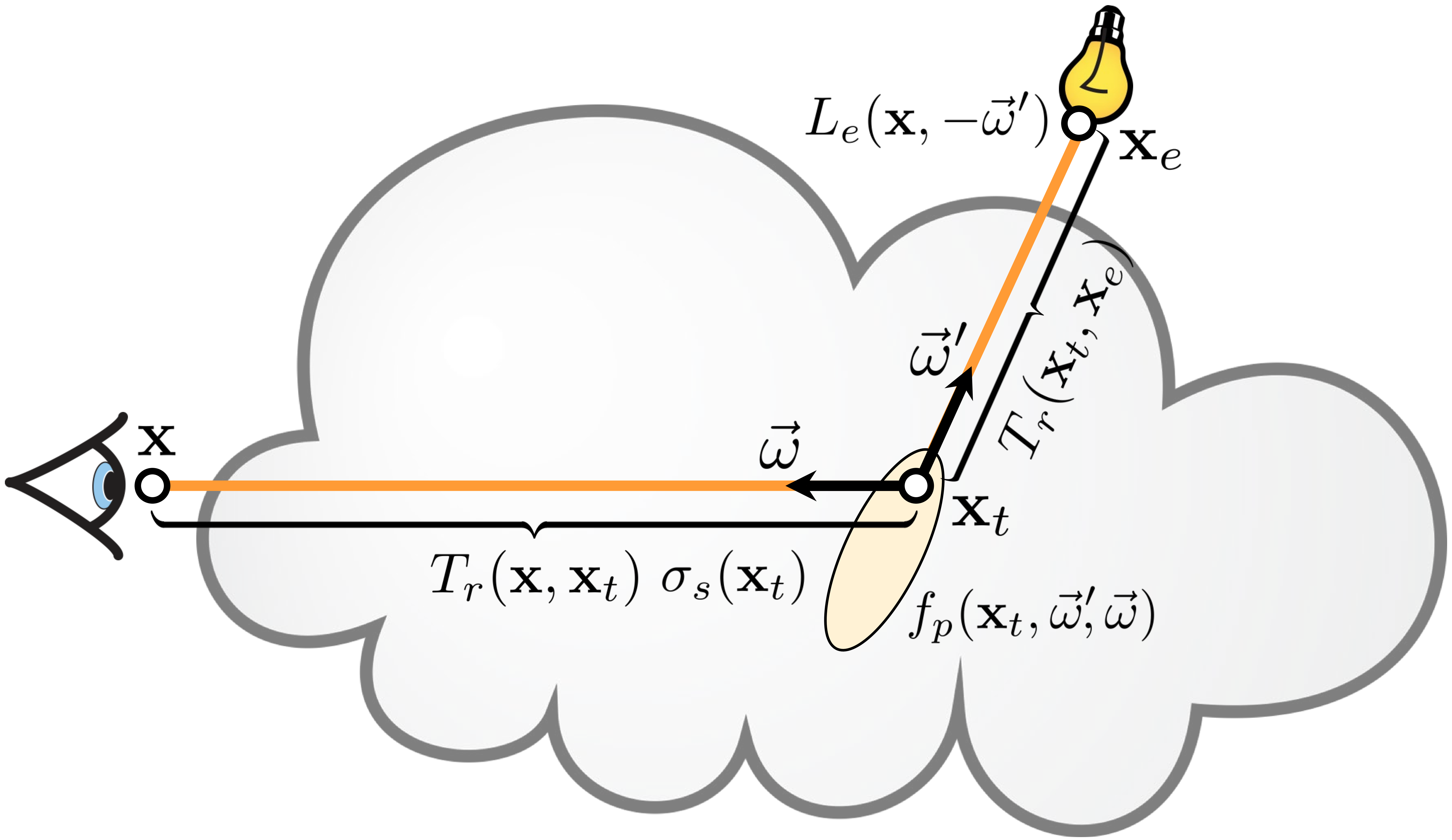
$$\boxed{L_i(\mathbf{x},\vec{\omega})} = T_r(\mathbf{x},r(\mathbf{x},\vec{\omega}))\,L_e(r(\mathbf{x},\vec{\omega}),-\vec{\omega})$$

Multiple scattering

- L_i arrives through multiple bounces (indirect illum.)

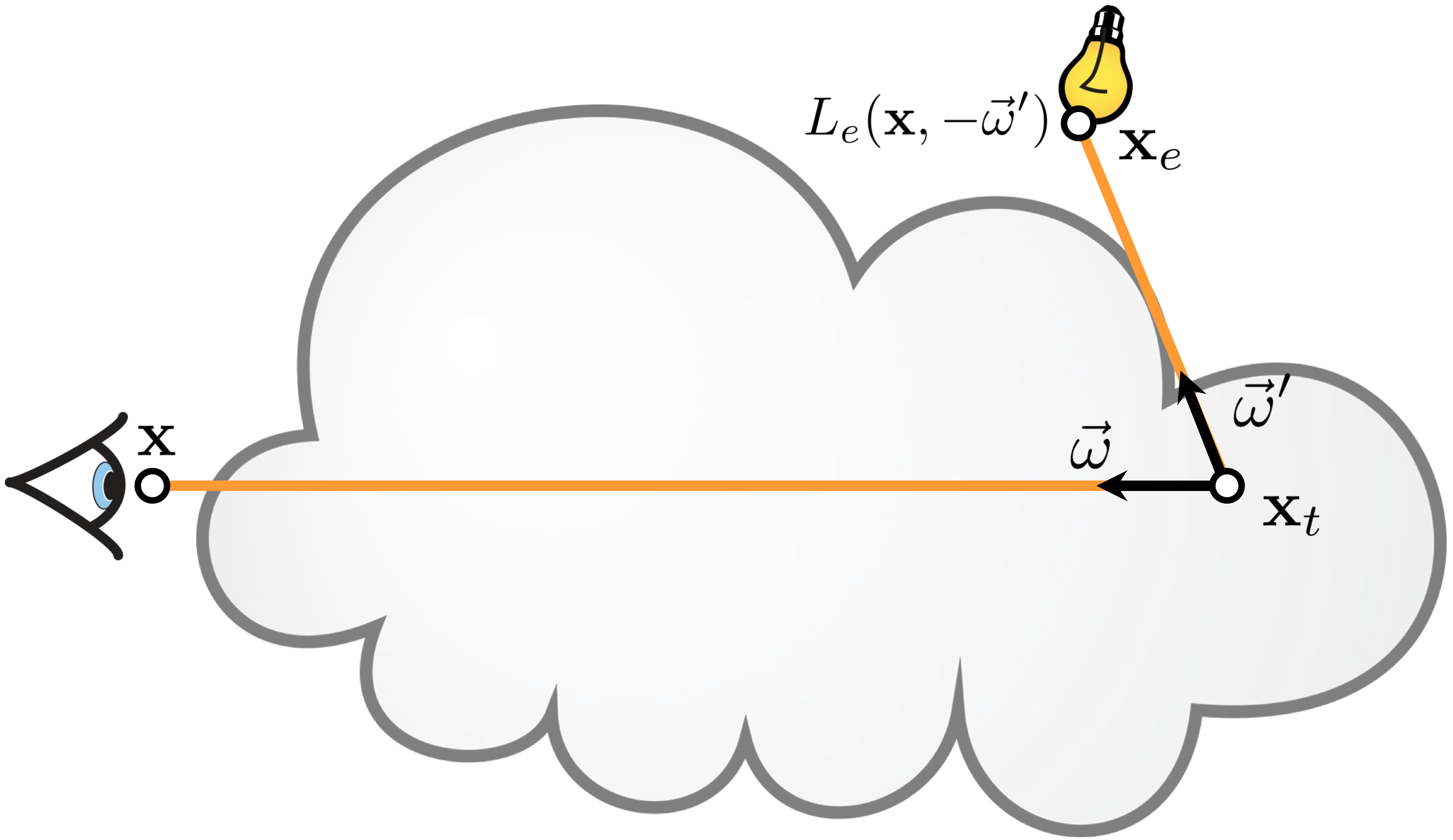
Single Scattering

$$L(\mathbf{x},\vec{\omega}) = \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)\int_{S^2} f_p(\mathbf{x}_t,\vec{\omega}',\vec{\omega})T_r(\mathbf{x}_t,\mathbf{x}_e)L_e(\mathbf{x}_e,-\vec{\omega}')d\vec{\omega}'dt$$



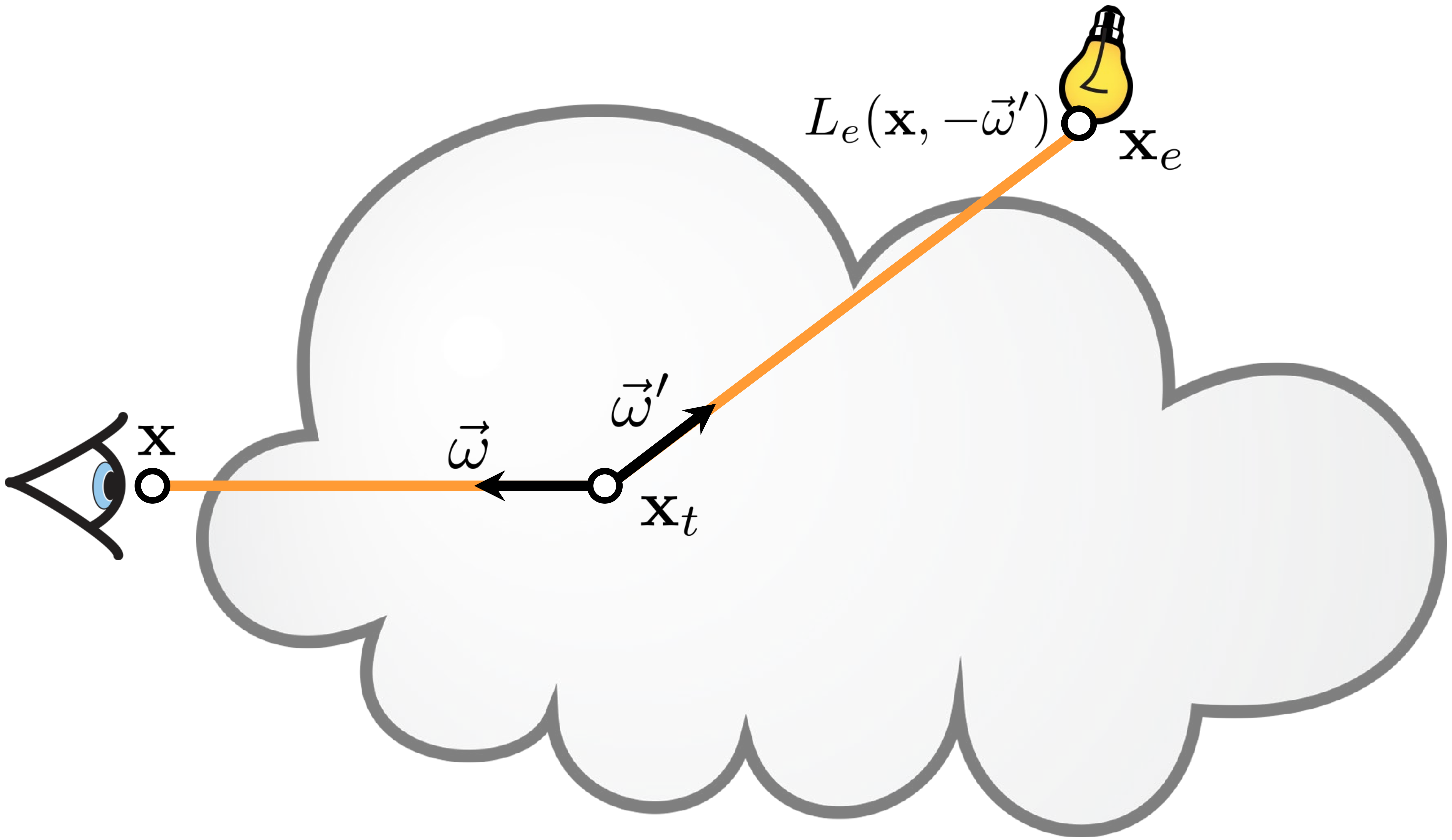
Single Scattering

$$L(\mathbf{x},\vec{\omega}) = \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)\int_{S^2} f_p(\mathbf{x}_t,\vec{\omega}',\vec{\omega})T_r(\mathbf{x}_t,\mathbf{x}_e)L_e(\mathbf{x}_e,-\vec{\omega}')d\vec{\omega}'dt$$



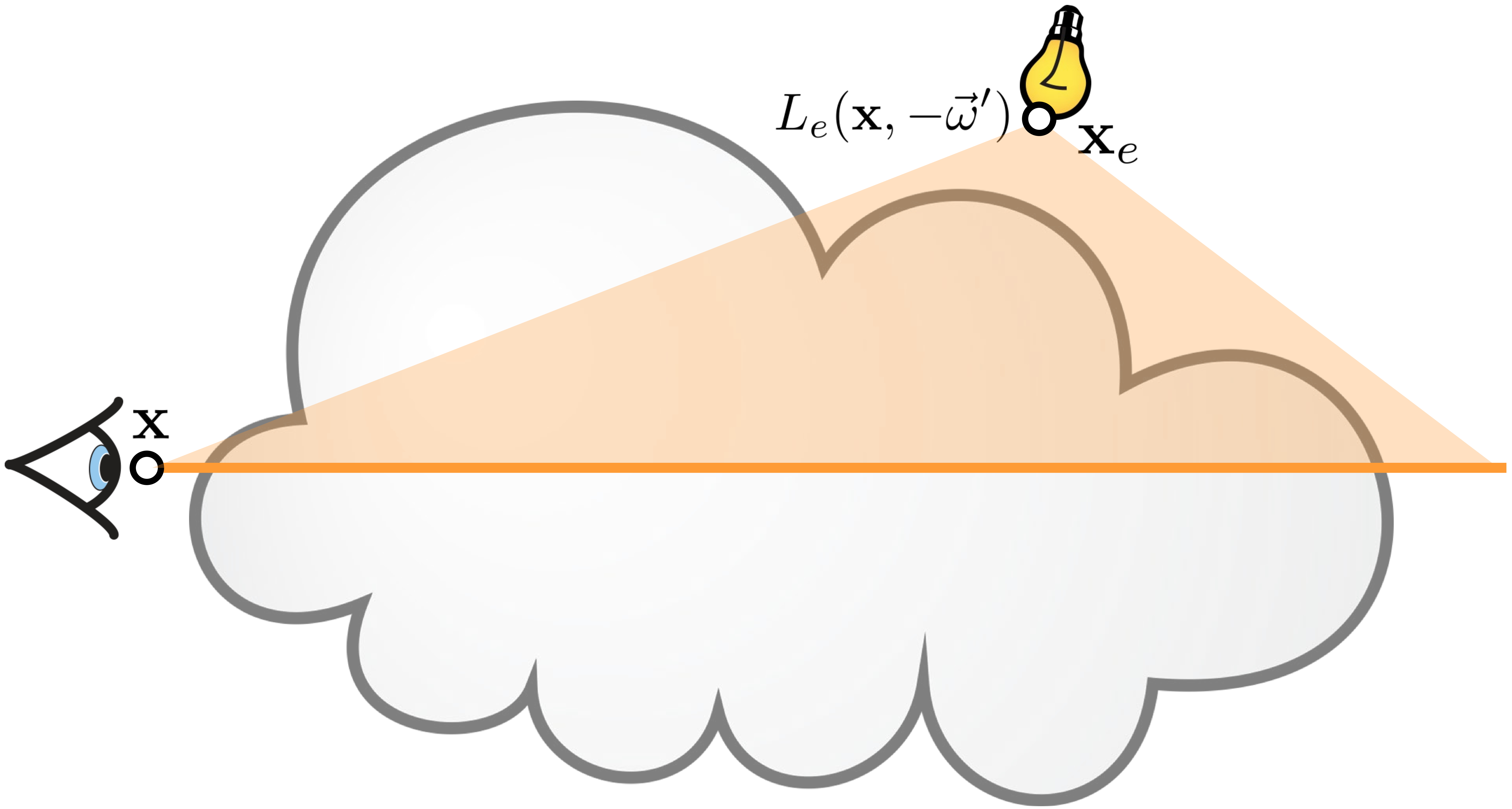
Single Scattering

$$L(\mathbf{x}, \vec{\omega}) = \int_0^z T_r(\mathbf{x}, \mathbf{x}_t)\sigma_s(\mathbf{x}_t) \int_{S^2} f_p(\mathbf{x}_t, \vec{\omega}', \vec{\omega}) T_r(\mathbf{x}_t, \mathbf{x}_e) L_e(\mathbf{x}_e, -\vec{\omega}') d\vec{\omega}' dt$$



Single Scattering

$$L(\mathbf{x},\vec{\omega}) = \boxed{\int_0^z} T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)\int_{S^2} f_p(\mathbf{x}_t,\vec{\omega}',\vec{\omega})T_r(\mathbf{x}_t,\mathbf{x}_e)L_e(\mathbf{x}_e,-\vec{\omega}')d\vec{\omega}'\,dt$$



Single Scattering

$$L(\mathbf{x}, \vec{\omega}) = \int_0^z T_r(\mathbf{x}, \mathbf{x}_t)\sigma_s(\mathbf{x}_t) \int_{S^2} f_p(\mathbf{x}_t, \vec{\omega}', \vec{\omega}) T_r(\mathbf{x}_t, \mathbf{x}_e) L_e(\mathbf{x}_e, -\vec{\omega}') d\vec{\omega}' dt$$

(Semi-)analytic solutions:

- Sun et al. [2005]
- Pegoraro et al. [2009, 2010]

Numerical solutions:

- Ray-marching
- Equiangular sampling

Analytic Single Scattering

$$L(\mathbf{x},\vec{\omega}) = \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)\int_{S^2} f_p(\mathbf{x}_t,\vec{\omega}',\vec{\omega})T_r(\mathbf{x}_t,\mathbf{x}_e)L_e(\mathbf{x}_e,-\vec{\omega}')d\vec{\omega}'dt$$

Assumptions:

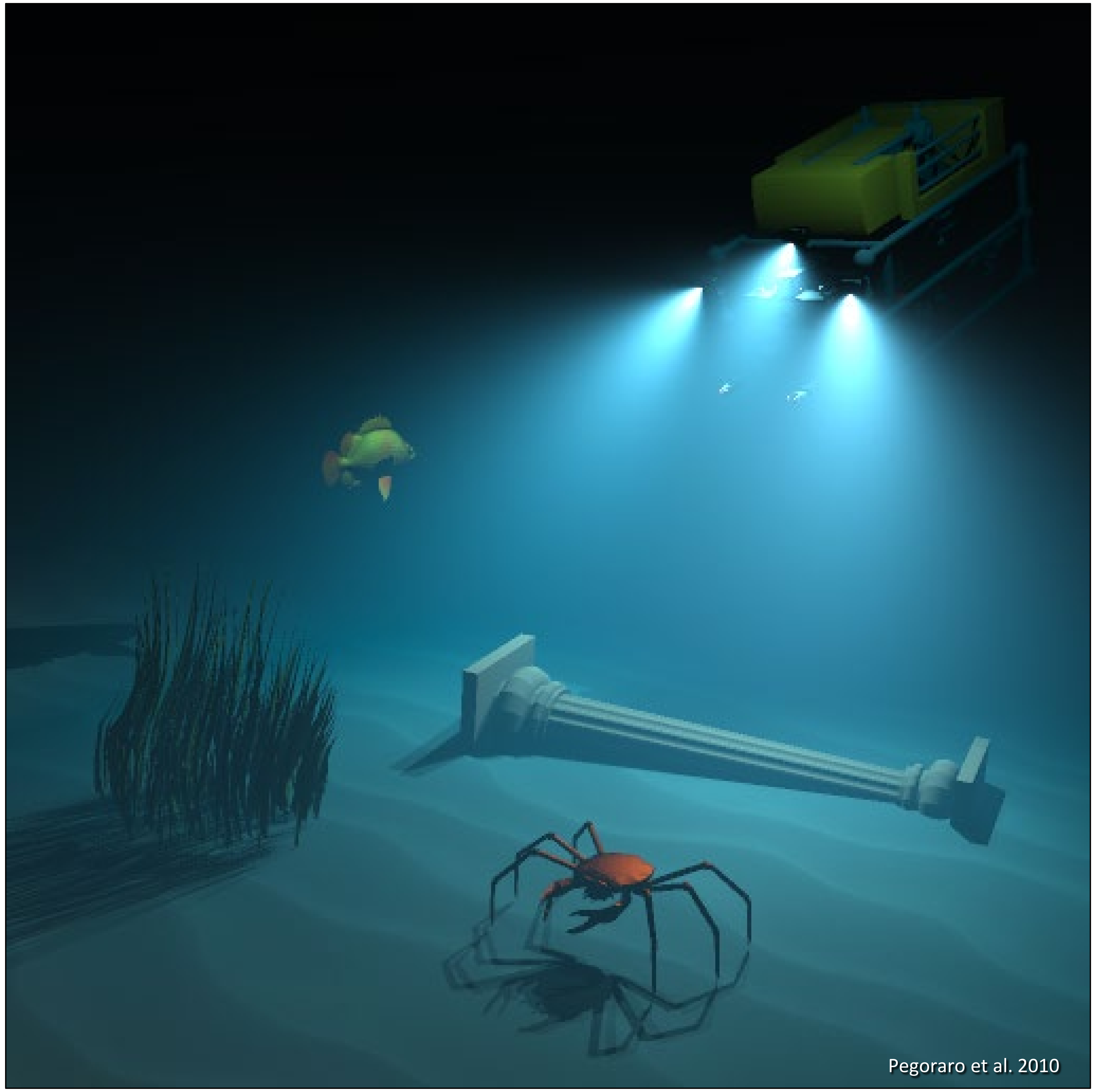
- Homogeneous medium
- Point or spot light
- Relatively simple phase function
- No occlusion

$$L(\mathbf{x},\vec{\omega}) = \frac{\Phi}{4\pi}\frac{1}{4\pi}\sigma_s\int_0^z e^{-\sigma_t\|\mathbf{x},\mathbf{x}_t\|}\frac{e^{-\sigma_t\|\mathbf{x}_t,\mathbf{x}_p\|}}{\|\mathbf{x}_t,\mathbf{x}_p\|^2}\mathrm{d}t$$

OpenGL Fog

Analytic Single Scattering

Analytic Single Scattering



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Analytic Single Scattering

$$L_m(x_a, x_b, \vec{\omega}) = \frac{\kappa_s}{h} e^{\kappa_t (x_a - x_h)} 2 \sum_{n=0}^{N-1} c(n) \sum_{k=0}^{2n} d(n,k) \int_{v_a}^{v_b} \frac{e^{-Hv}}{(v^2+1)^{n+1}} v^k \mathrm{d}v$$

$$\begin{aligned}\int \frac{e^{av}}{(v^2+1)^m} v^n \mathrm{d}v = \frac{1}{2^{m-1}} \sum_{l=0}^{m-1} \frac{1}{2^l} \binom{m-1+l}{m-1} \Bigg(\sum_{k=0}^{\min\{m-1-l,n\}} \binom{n}{k} \Bigg(\frac{a^{m-1-l-k}}{(m-1-l-k)!} E(a, v, m-n-l+k) \\ - e^{av} \sum_{j=1}^{m-1-l-k} \frac{(j-1)!}{(m-1-l-k)!} \frac{a^{m-1-l-k-j}}{(v^2+1)^j} \sum_{\substack{i=(m-n-l+k-j) \bmod 2 \\ i+=2}}^{\leq j} (-1)^{\frac{m-n-l+k-j+i}{2}} \binom{j}{i} v^i \Bigg) \\ + \frac{e^{av}}{a} \sum_{k=0}^{\leq n-m+l} \binom{n}{k} \sum_{j=0}^{n-m+l-k} \frac{(n-m+l-k)!}{j!} \frac{1}{(-a)^{n-m+l-k-j}} \sum_{\substack{i=(-m+l+k-j) \bmod 2 \\ i+=2}}^{\leq j} (-1)^{\frac{-m+l+k-j+i}{2}} \binom{j}{i} v^i \Bigg)\end{aligned}$$

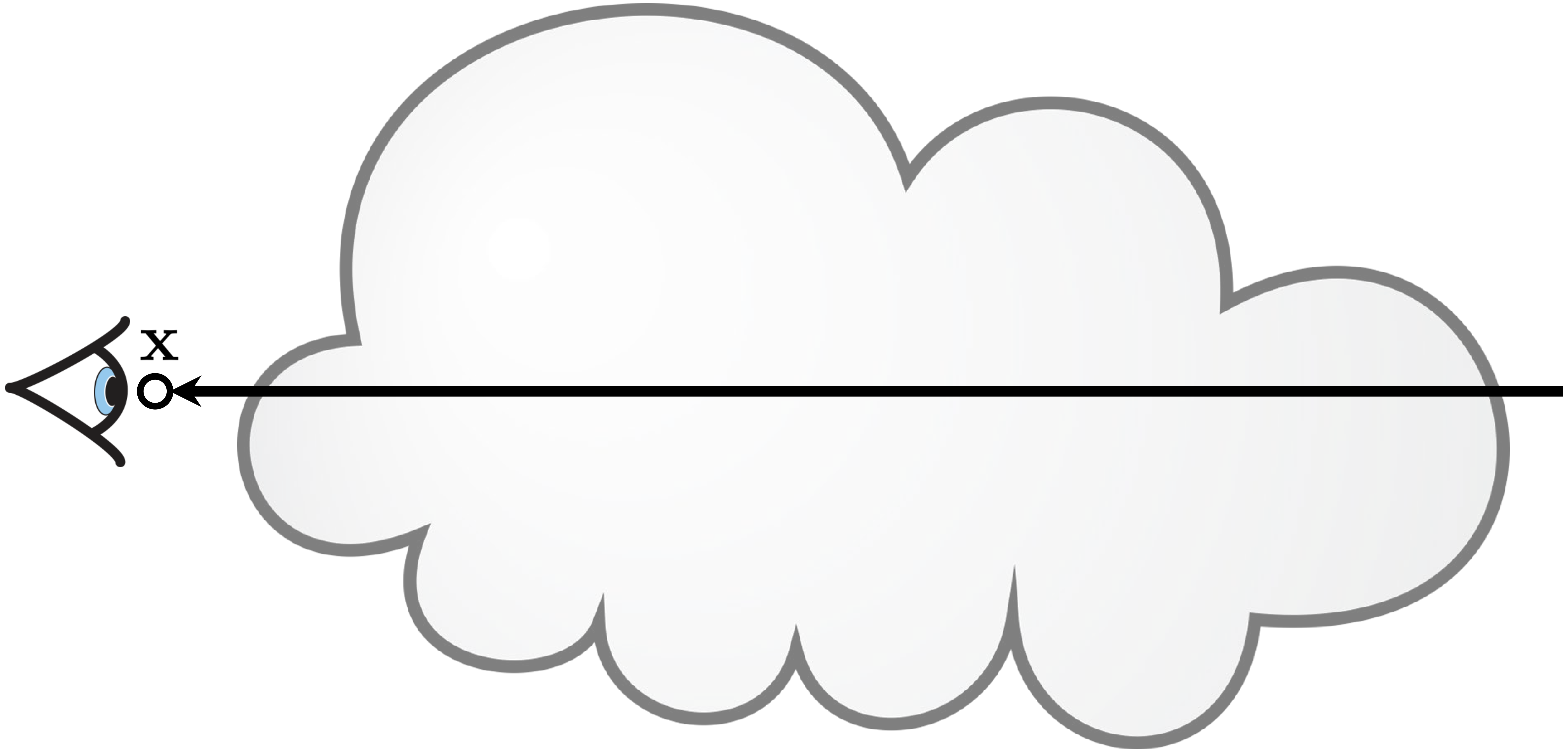
No shadows, implementation nightmare, computationally intensive...

Let’s try brute force!

Ray-Marching

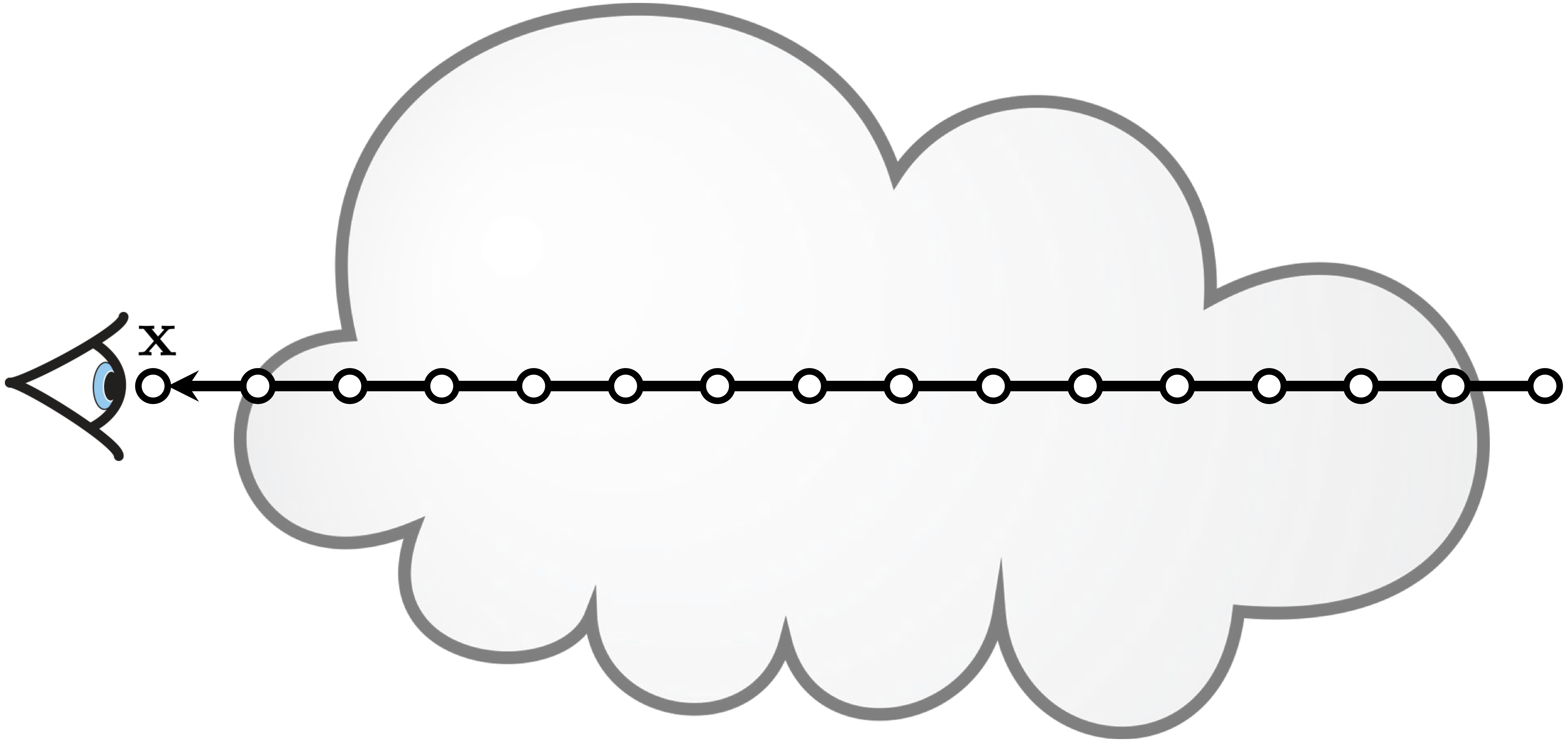
$$L(\mathbf{x},\vec{\omega}) = \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)L_s(\mathbf{x}_t,\vec{\omega})dt$$

Approximate with Riemann sum



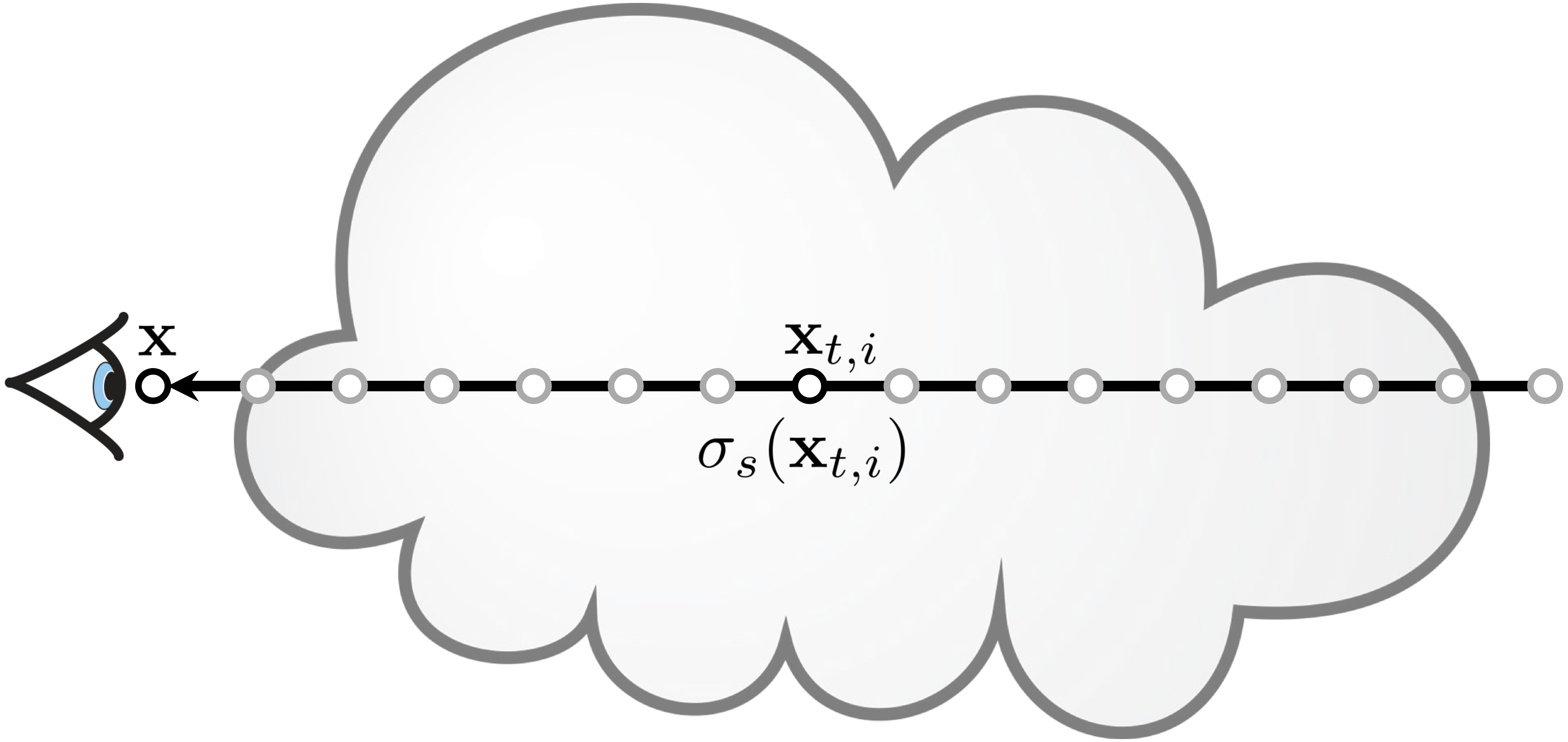
Ray-Marching

$$L(\mathbf{x}, \vec{\omega}) \approx \sum_{i=1}^{N} T_r(\mathbf{x}, \mathbf{x}_{t,i}) \sigma_s(\mathbf{x}_{t,i}) L_s(\mathbf{x}_{t,i}, \vec{\omega}) \Delta t$$



Ray-Marching

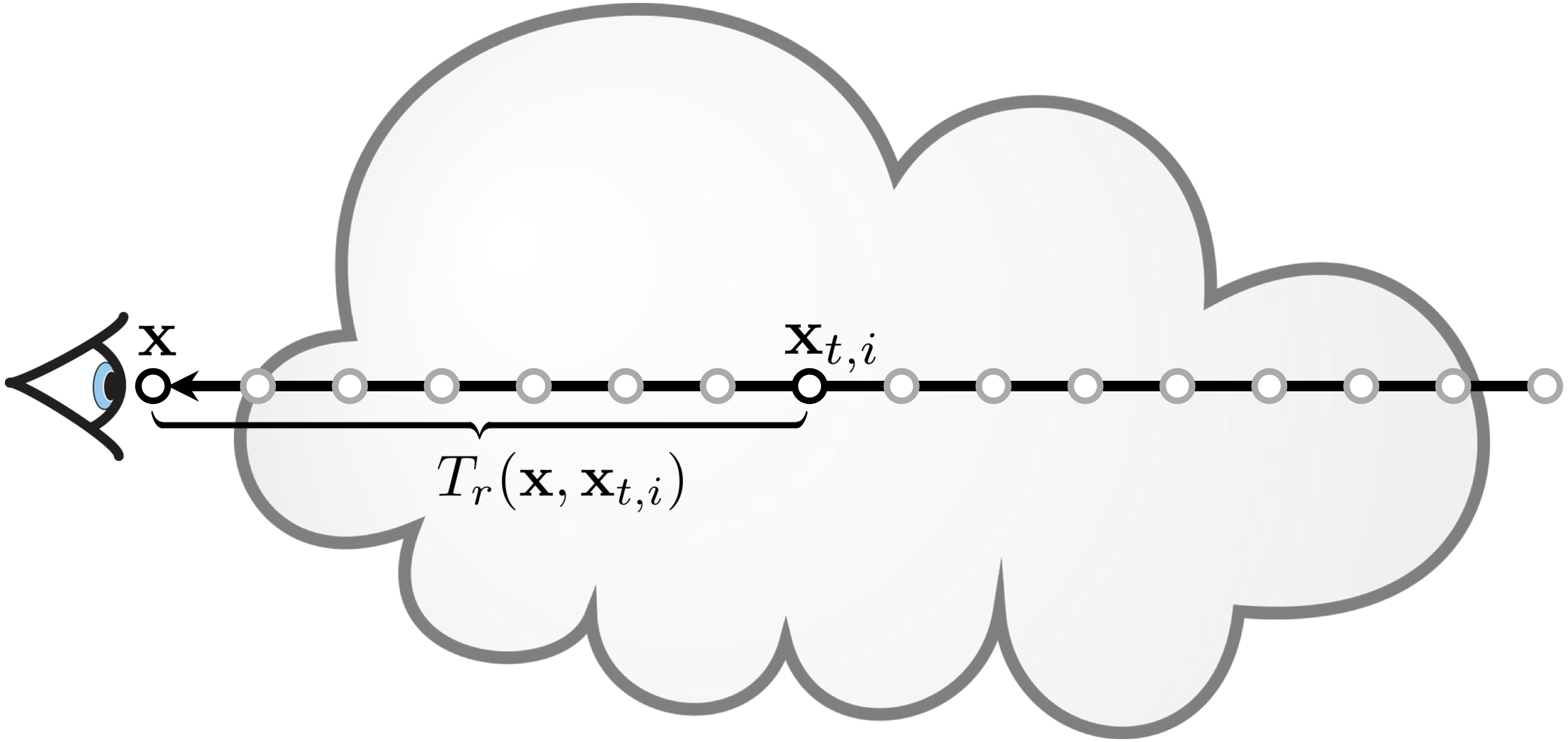
$$L(\mathbf{x}, \vec{\omega}) \approx \sum_{i=1}^{N} T_r(\mathbf{x}, \mathbf{x}_{t,i}) \boxed{\sigma_s(\mathbf{x}_{t,i})} L_s(\mathbf{x}_{t,i}, \vec{\omega}) \Delta t$$



Ray-Marching

$$L(\mathbf{x},\vec{\omega}) \approx \sum_{i=1}^{N} \boxed{T_r(\mathbf{x},\mathbf{x}_{t,i})}\,\sigma_s(\mathbf{x}_{t,i})L_s(\mathbf{x}_{t,i},\vec{\omega})\Delta t$$

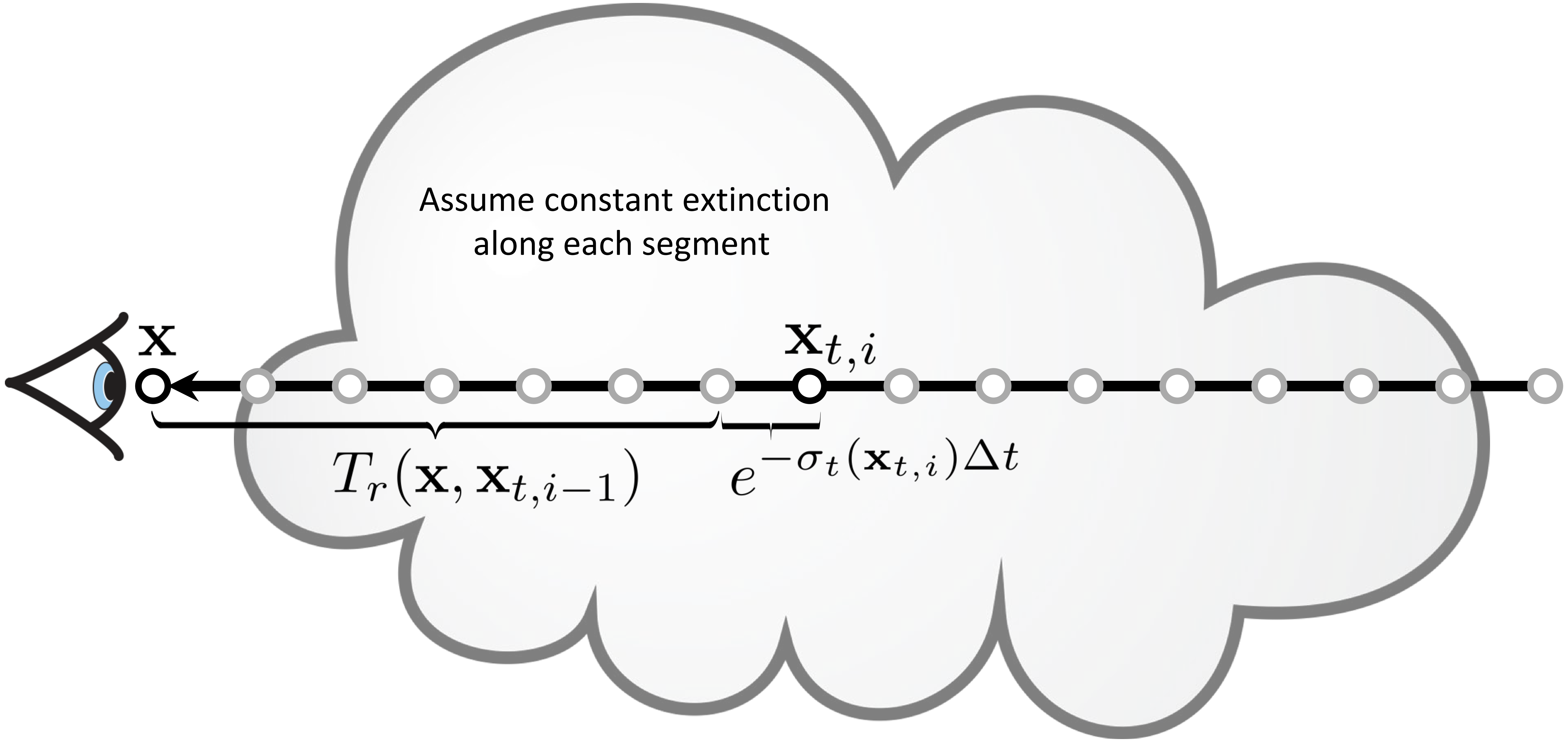
Homogeneous volume: $T_r(\mathbf{x},\mathbf{x}_{t,i}) = e^{-\sigma_t\|\mathbf{x},\mathbf{x}_{t,i}\|}$



Ray-Marching

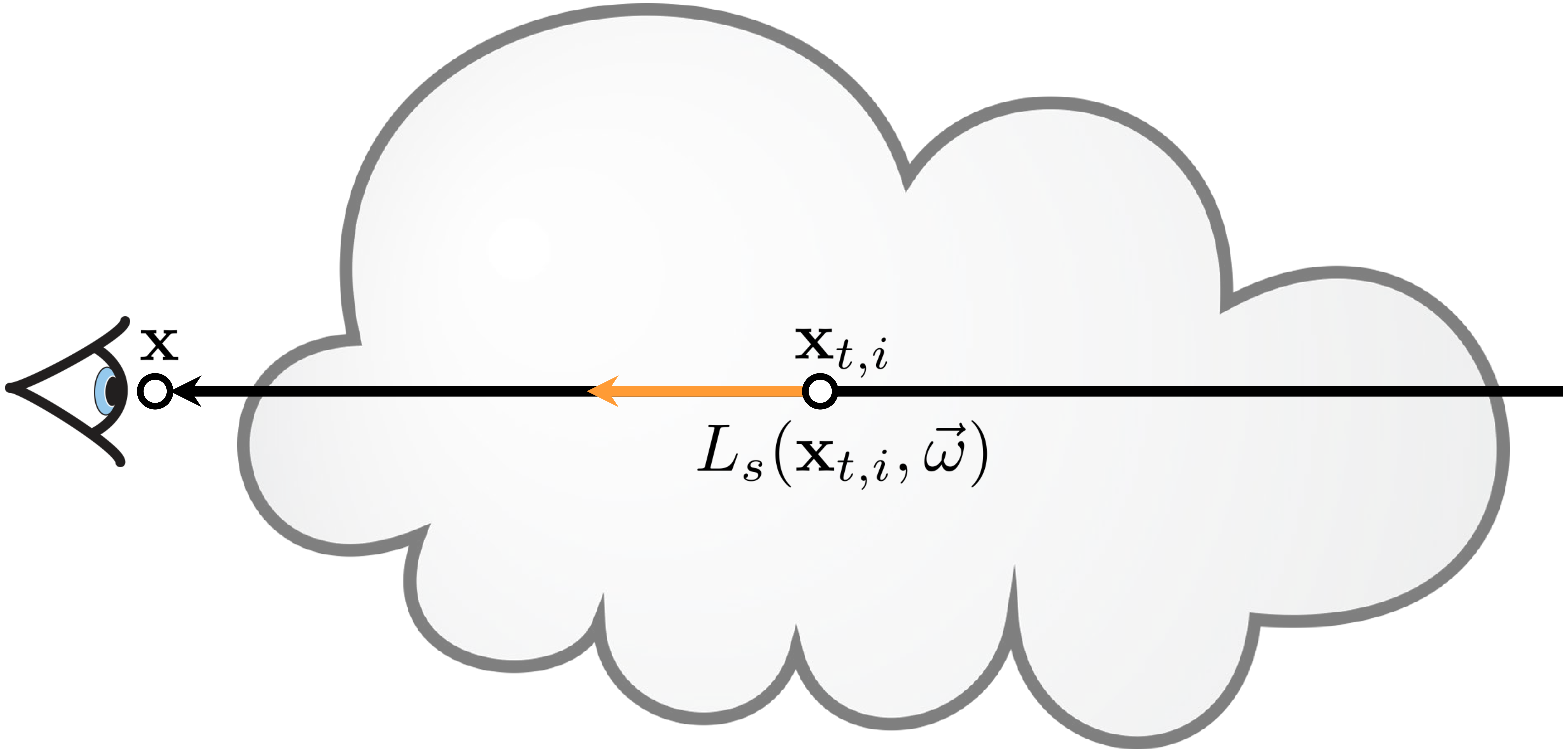
$$L(\mathbf{x},\vec{\omega}) \approx \sum_{i=1}^{N} \boxed{T_r(\mathbf{x},\mathbf{x}_{t,i})}\sigma_s(\mathbf{x}_{t,i})L_s(\mathbf{x}_{t,i},\vec{\omega})\Delta t$$

Heterogeneous volume: $T_r(\mathbf{x},\mathbf{x}_{t,i}) = T_r(\mathbf{x},\mathbf{x}_{t,i-1})\, e^{-\sigma_t(\mathbf{x}_{t,i})\Delta t}$



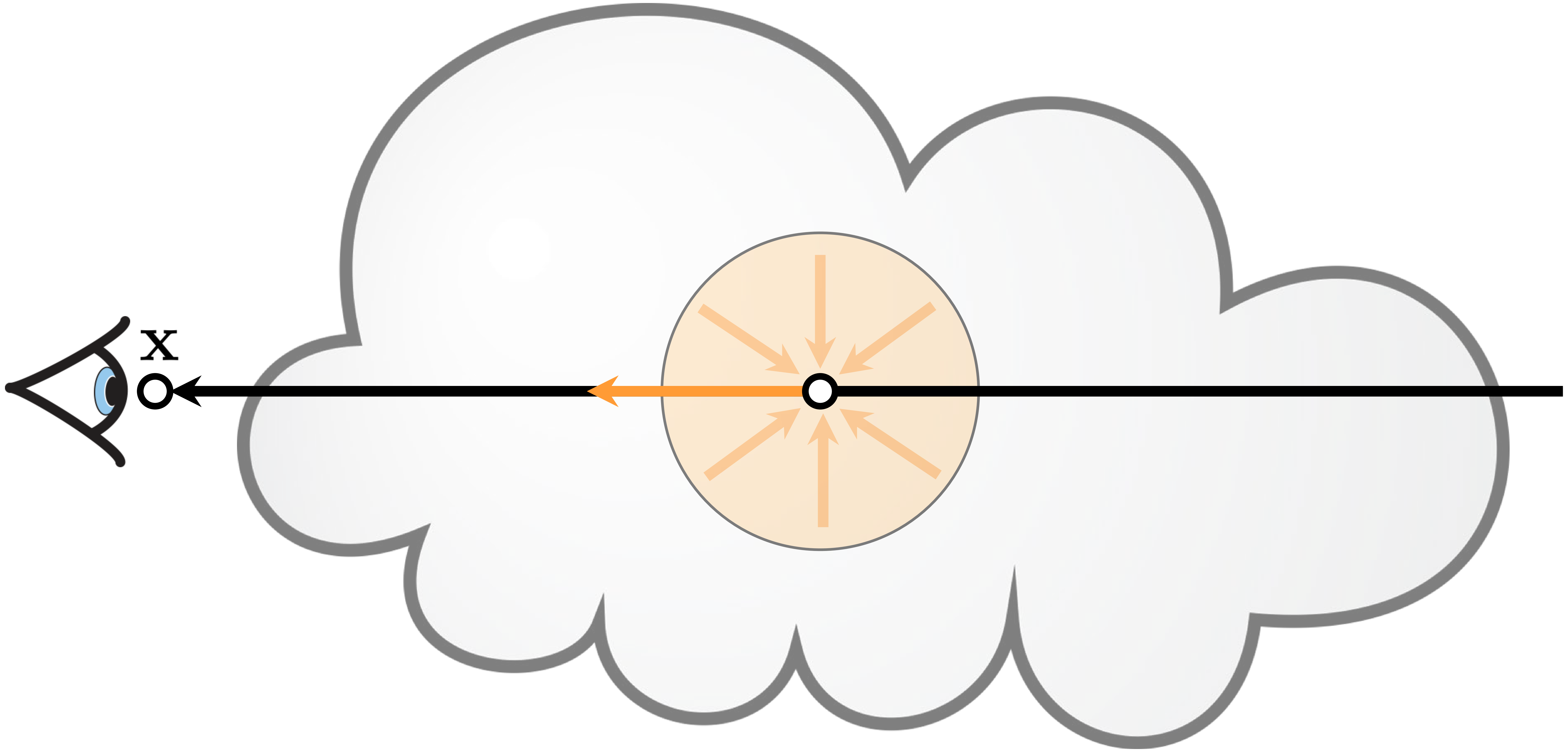
Ray-Marching

$$L(\mathbf{x},\vec{\omega}) \approx \sum_{i=1}^{N} T_r(\mathbf{x},\mathbf{x}_{t,i})\sigma_s(\mathbf{x}_{t,i})\boxed{L_s(\mathbf{x}_{t,i},\vec{\omega})}\Delta t$$



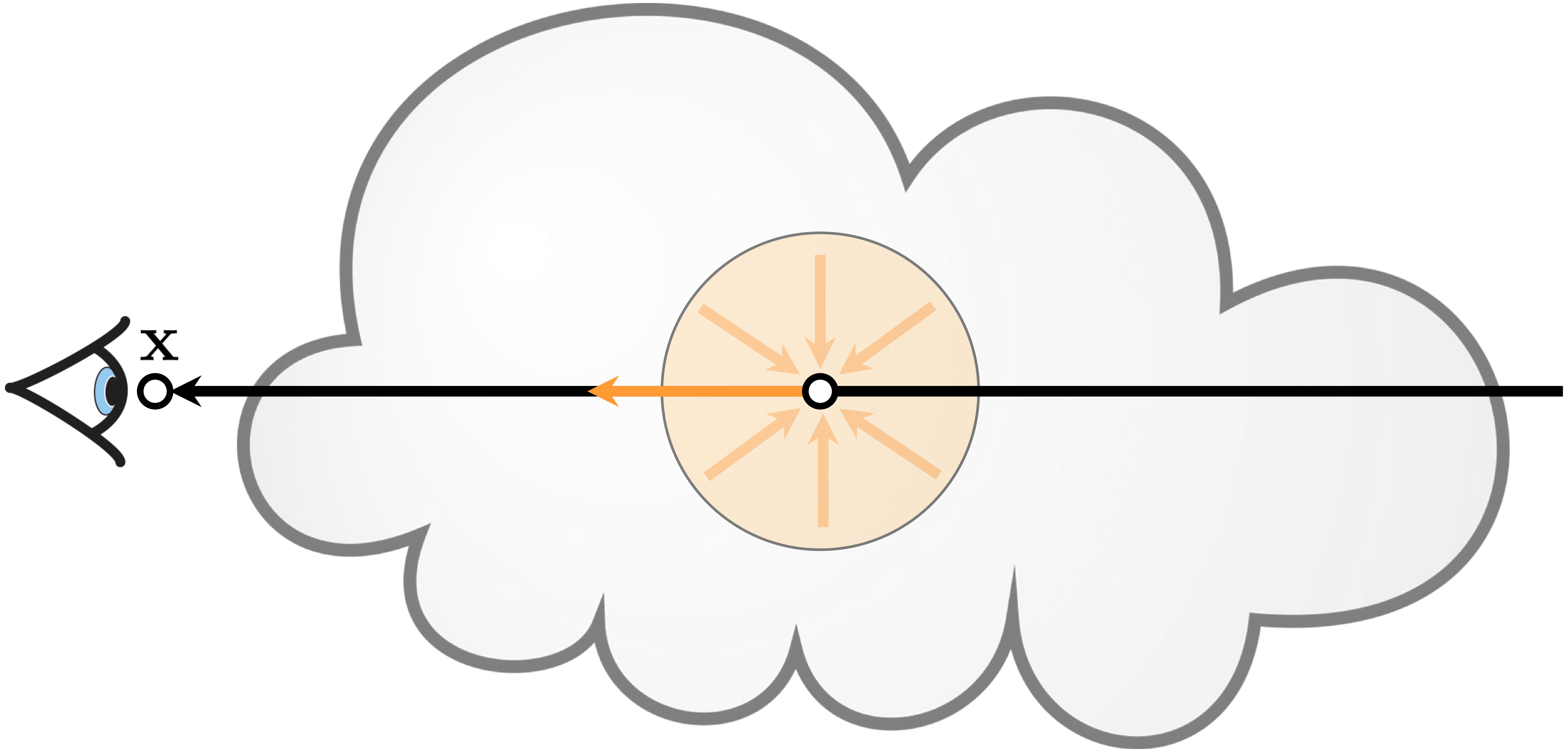
Ray-Marching

$$L_s(\mathbf{x}_t, \vec{\omega}) = \boxed{\int_{S^2}} f_p(\mathbf{x}_t, \vec{\omega}', \vec{\omega}) L_i(\mathbf{x}_t, \vec{\omega}') d\vec{\omega}'$$



Ray-Marching

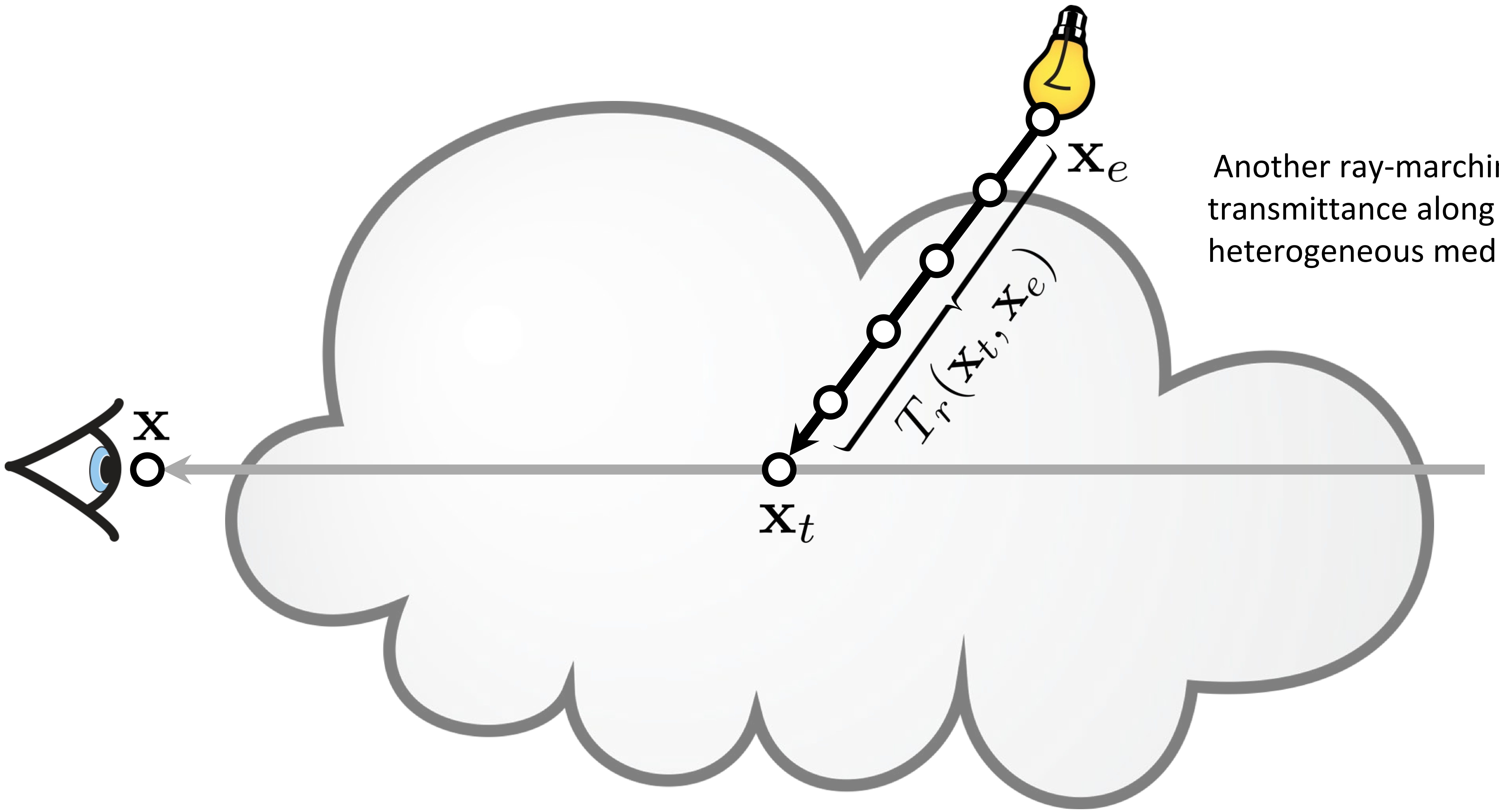
$$L_s(\mathbf{x}_t, \vec{\omega}) \approx \frac{1}{M} \sum_{j=0}^{M} \frac{f_p(\mathbf{x}_t, \vec{\omega}'_j, \vec{\omega}) \boxed{L_i(\mathbf{x}_t, \vec{\omega}'_j)}}{p(\vec{\omega}'_j)}$$



Ray-Marching

Single scattering:

$$L_i(\mathbf{x}_t, \vec{\omega}) = T_r(\mathbf{x}_t, \mathbf{x}_e)\, L_e(\mathbf{x}_e, -\vec{\omega})$$

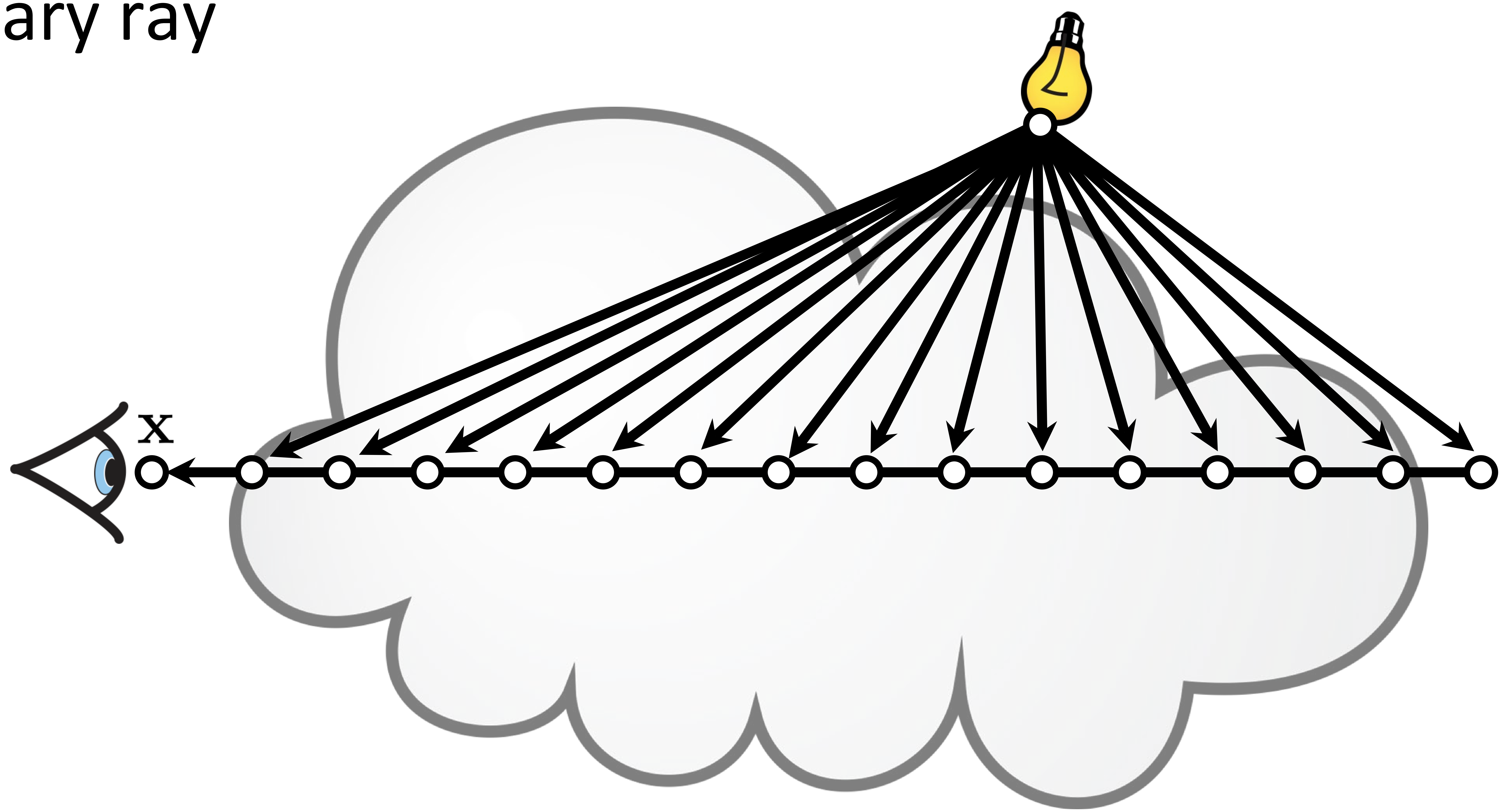


Another ray-marching needed to estimate the transmittance along the connection ray (in heterogeneous media)

Ray-Marching in Heterogeneous Media

Marching towards the light source

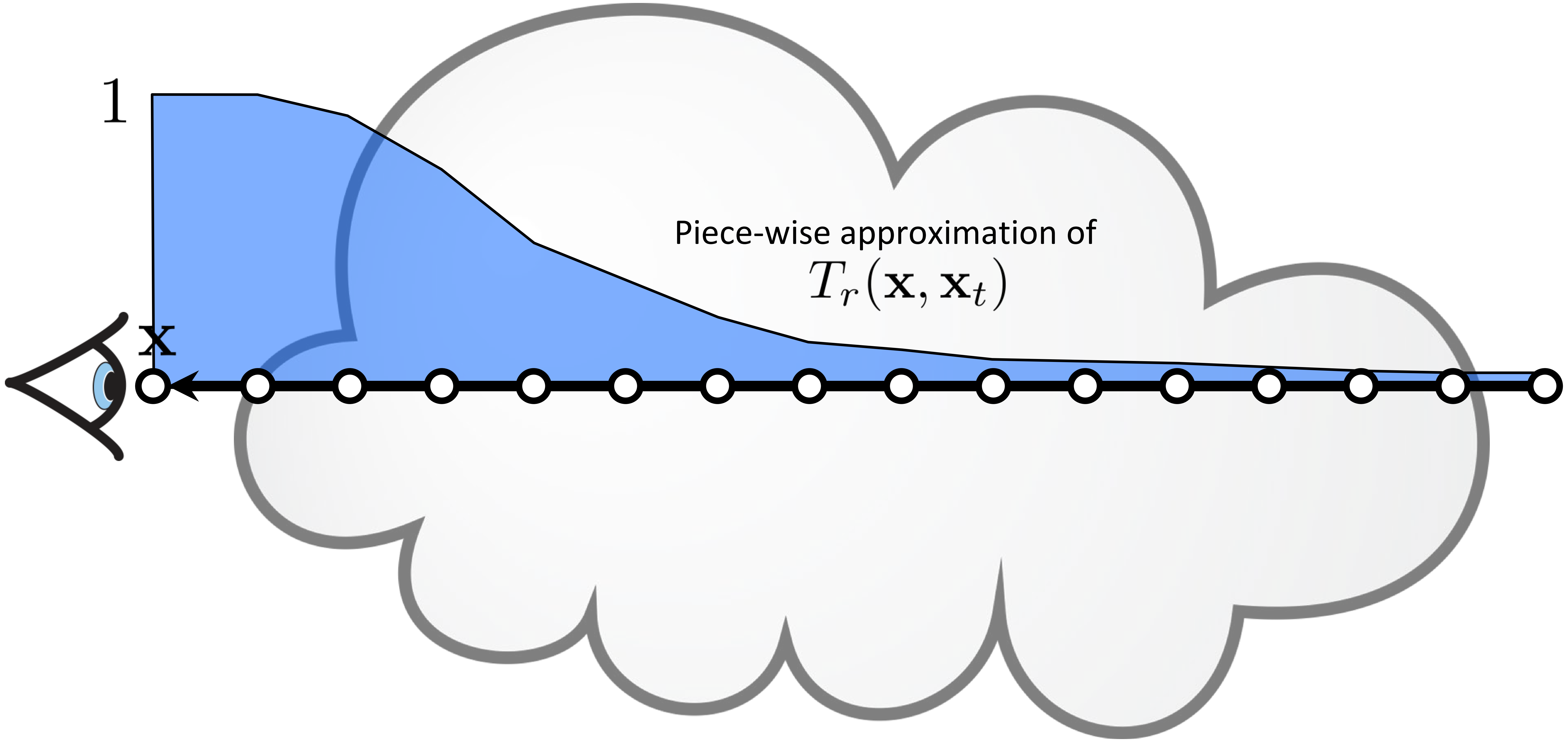
- Connections are expensive, many, and uniformly distributed along the primary ray



Decoupled Transmittance and In-scattering

1. Ray-march and cache transmittance

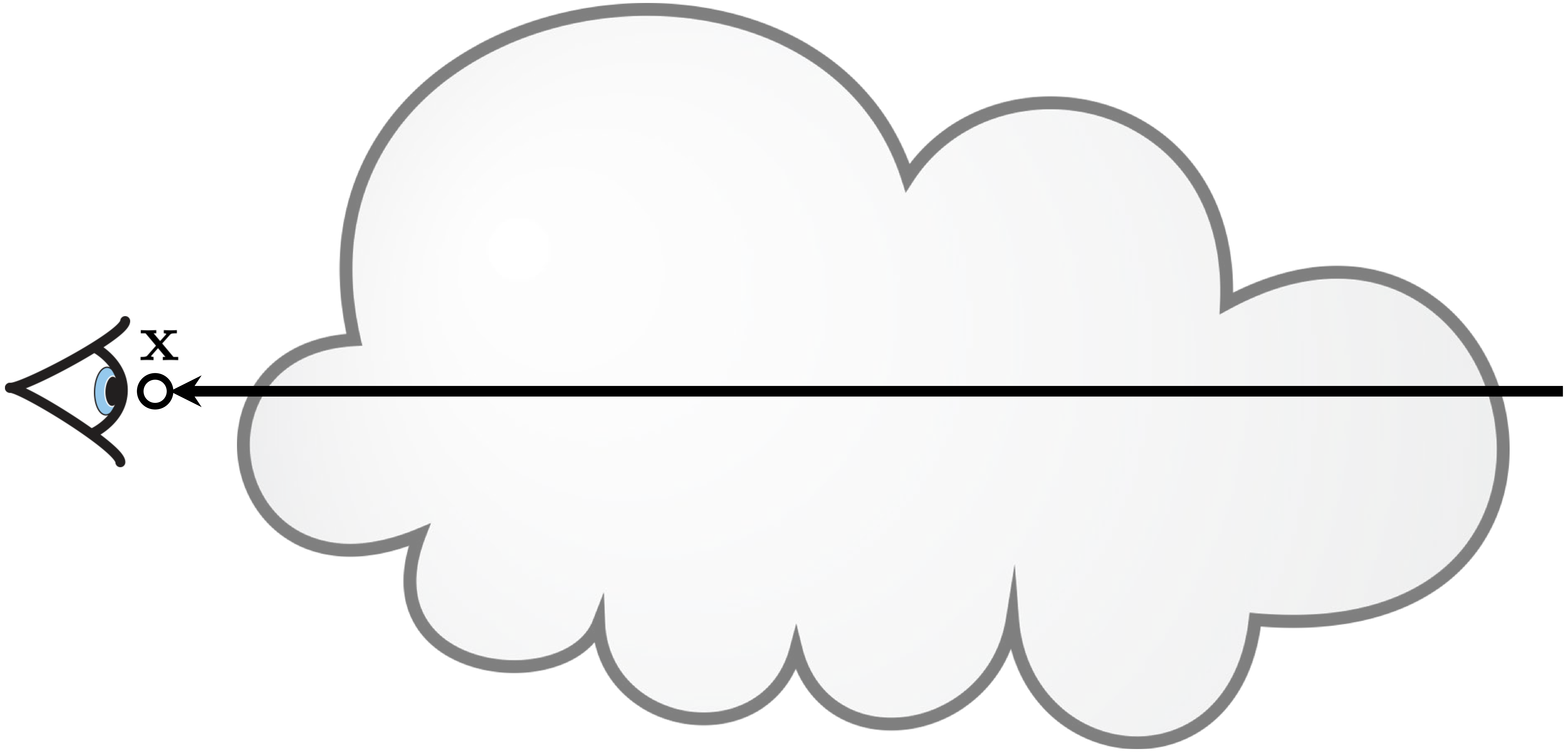
- Choose step-size w.r.t. frequency content to accurately capture variations



Decoupled Transmittance and In-scattering

2. Estimate in-scattering using MC integration

- Distribute samples ∝ (part of) the integrand



Decoupled Transmittance and In-scattering

2. Estimate in-scattering using MC integration

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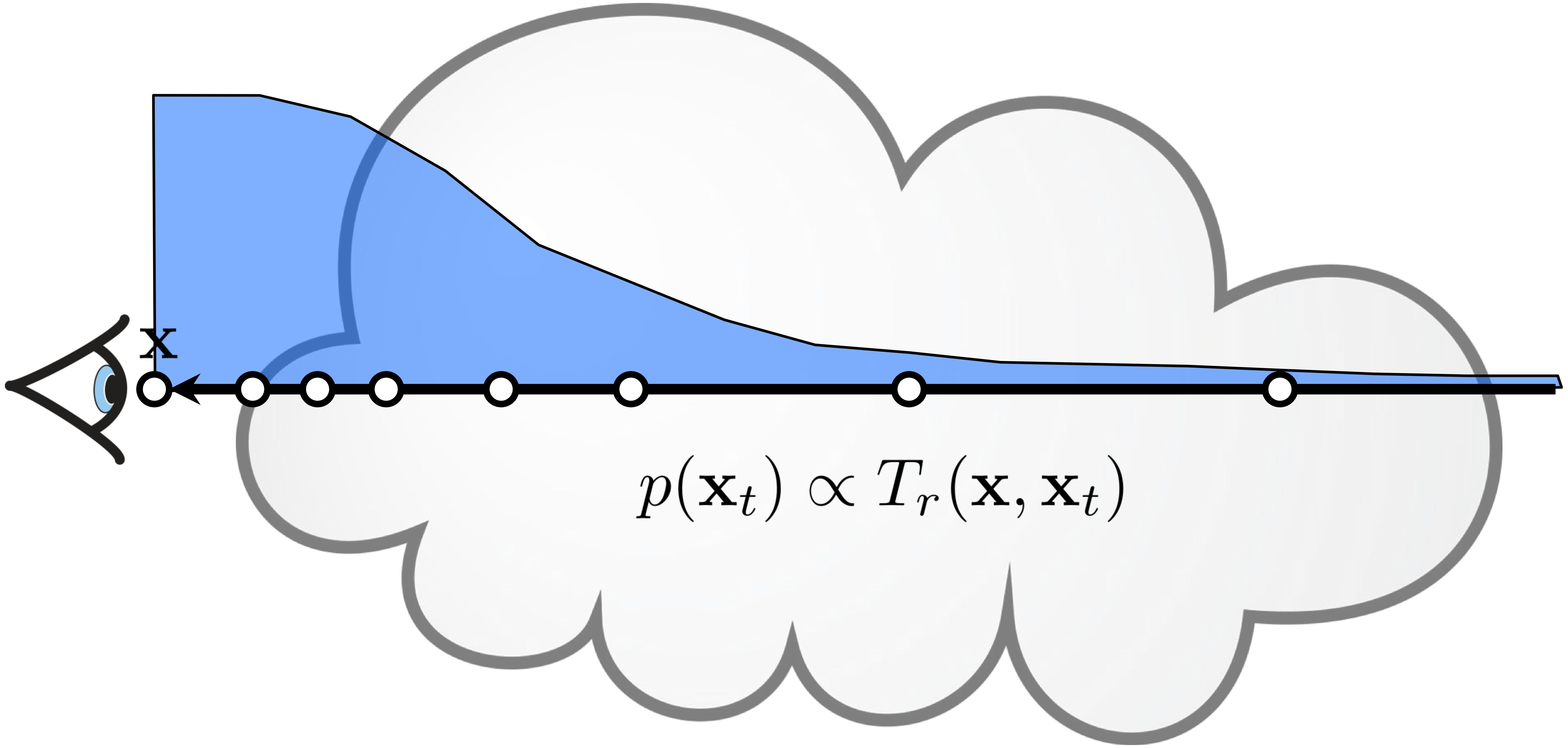

Decoupled Transmittance and In-scattering

2. Estimate in-scattering using MC integration

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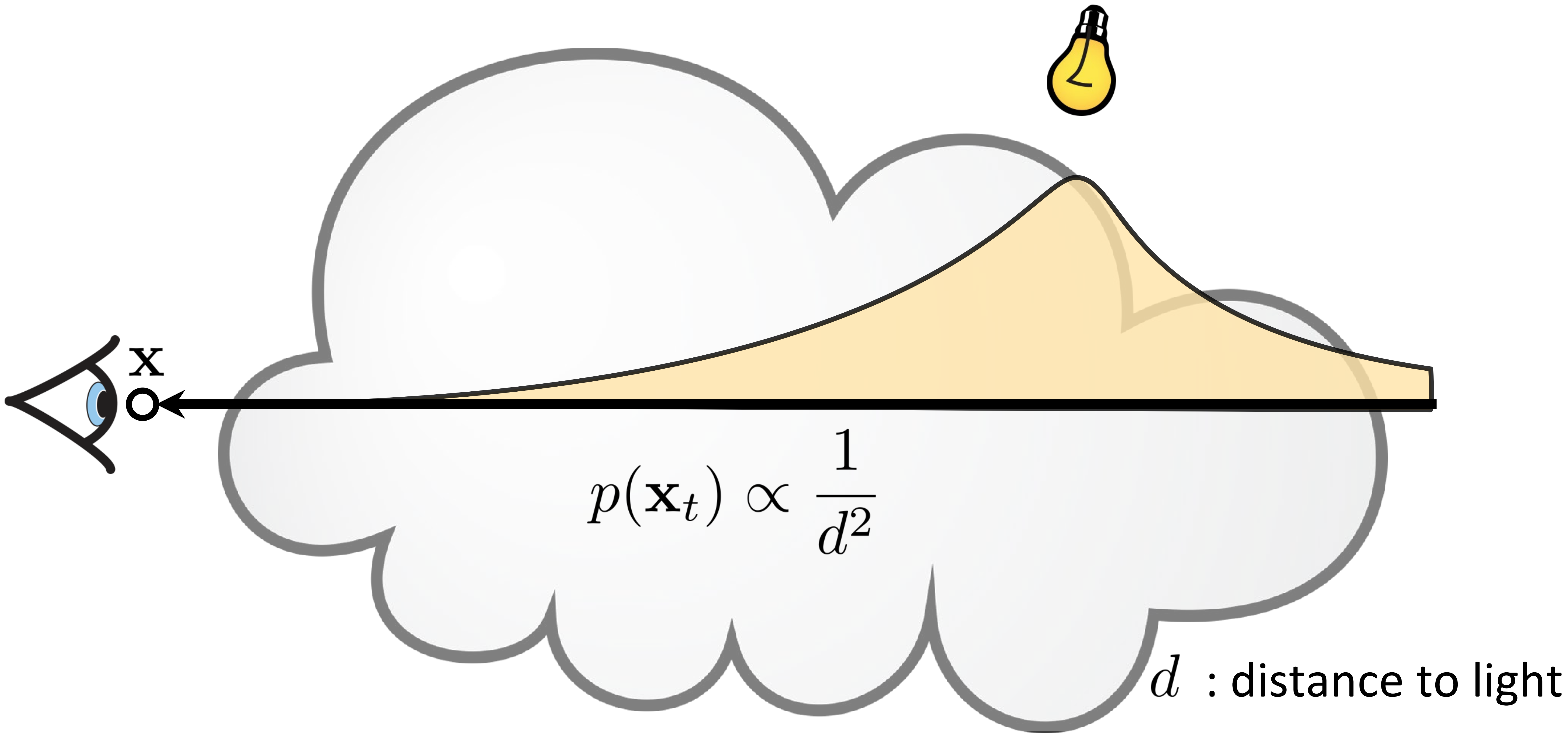
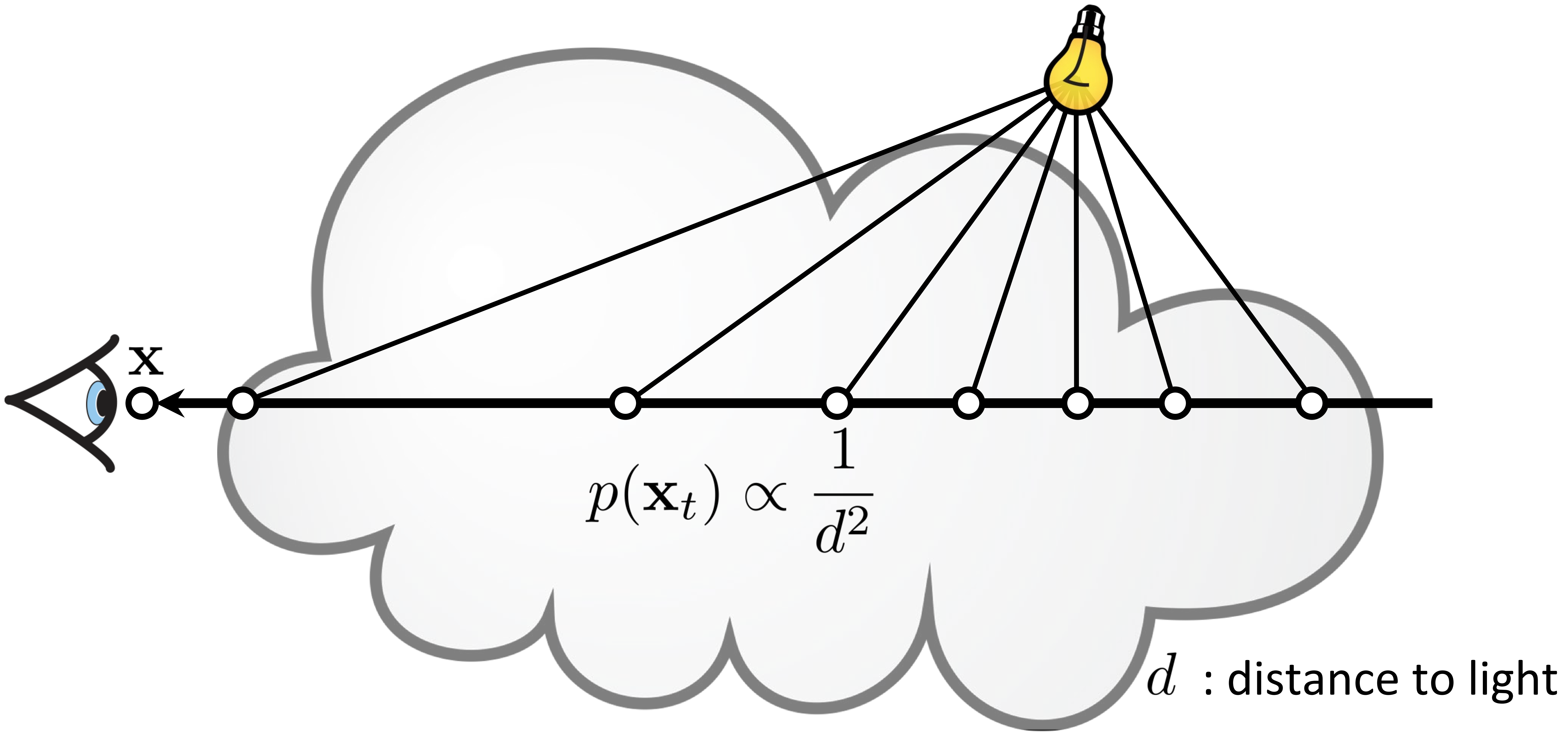


Decoupled Transmittance and In-scattering

2. Estimate in-scattering using MC integration

- Distribute samples ∝ (part of) the integrand



Decoupled Transmittance and In-scattering

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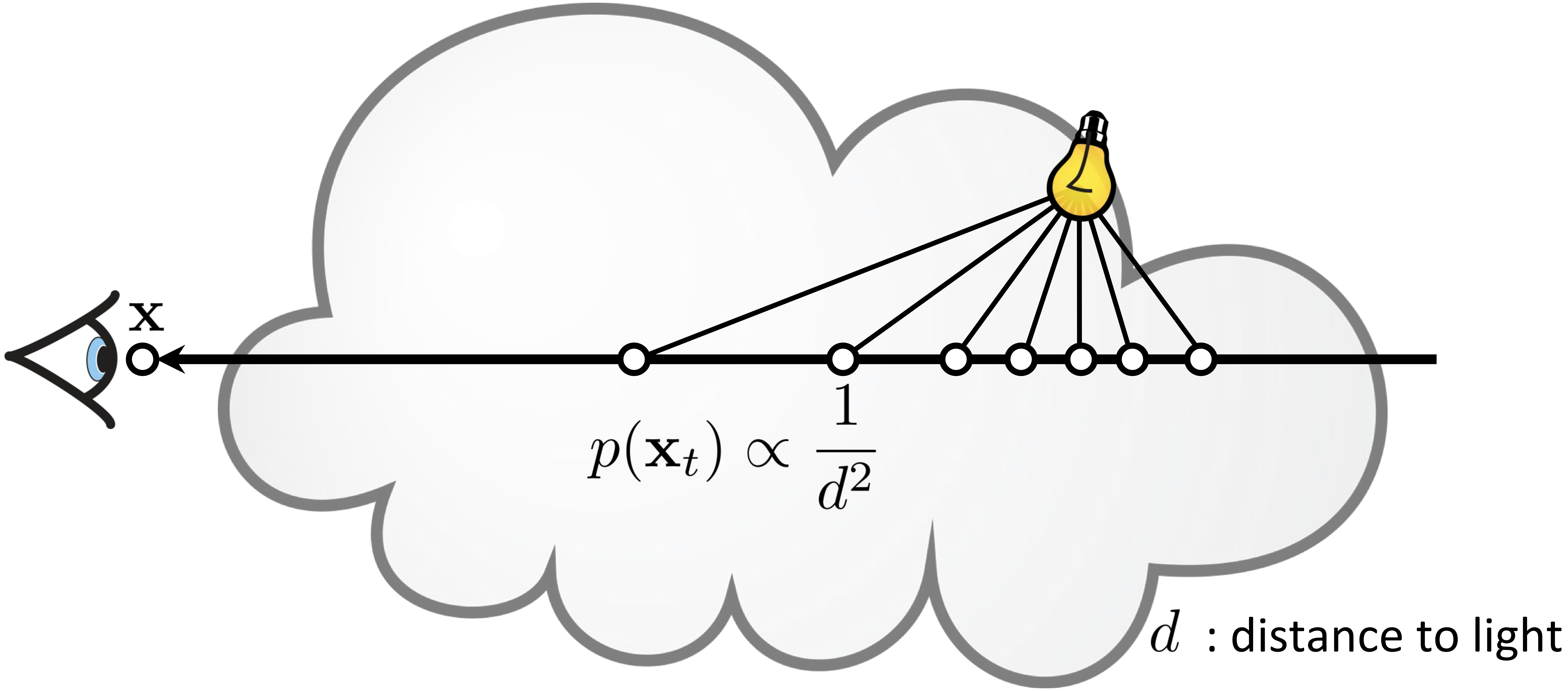
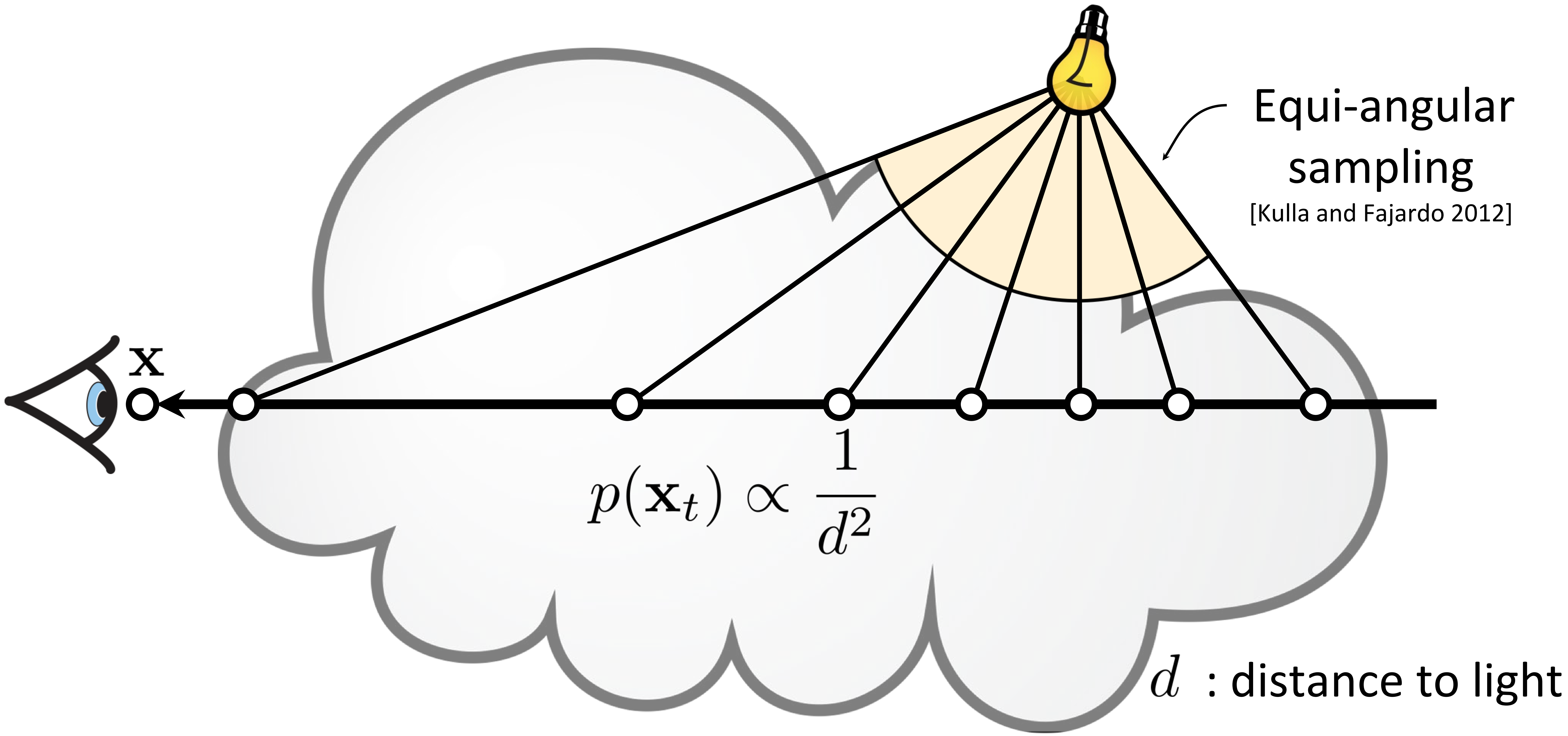


Decoupled Transmittance and In-scattering

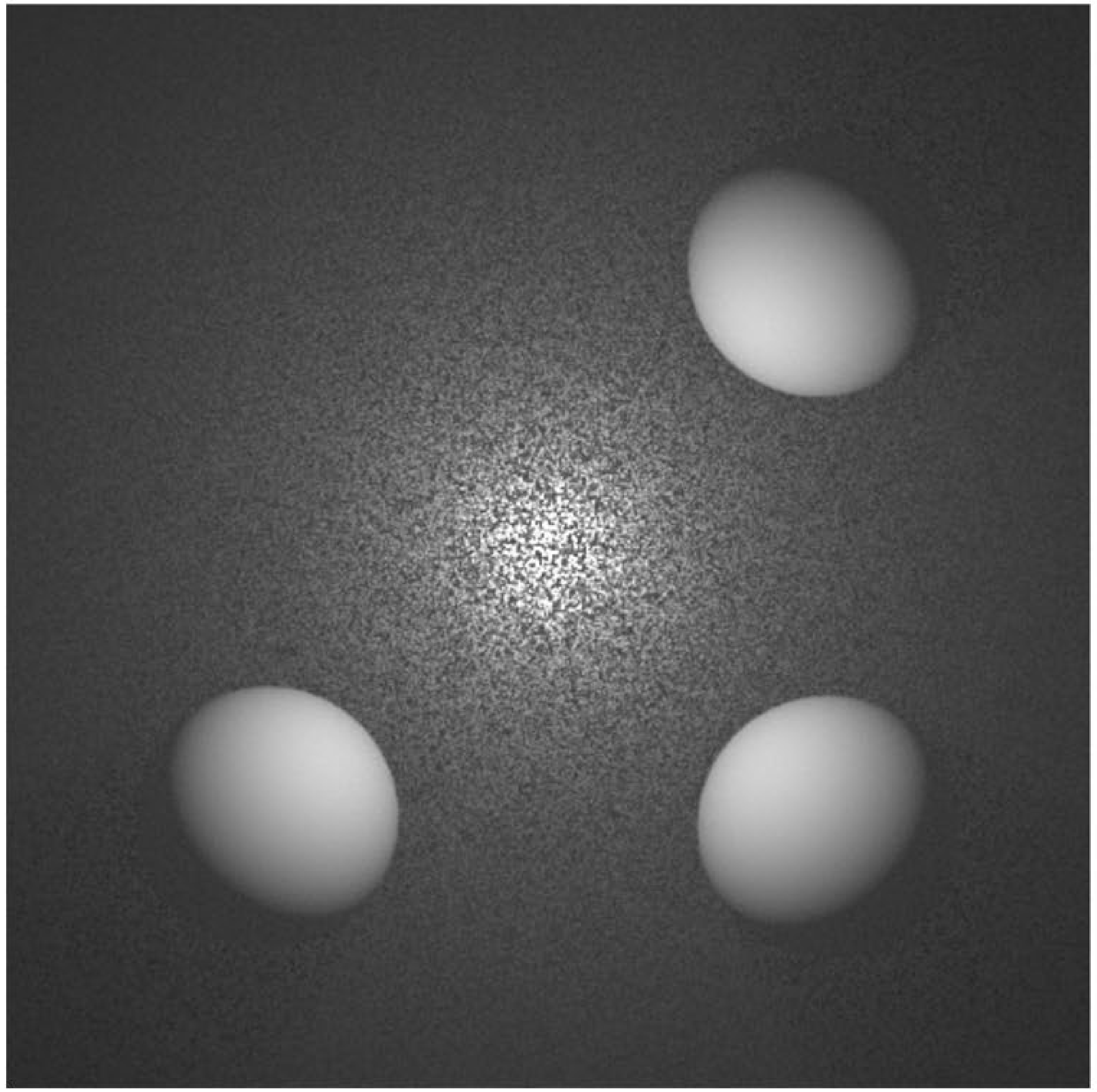
2. Estimate in-scattering using MC integration

- Distribute samples ∝ (part of) the integrand

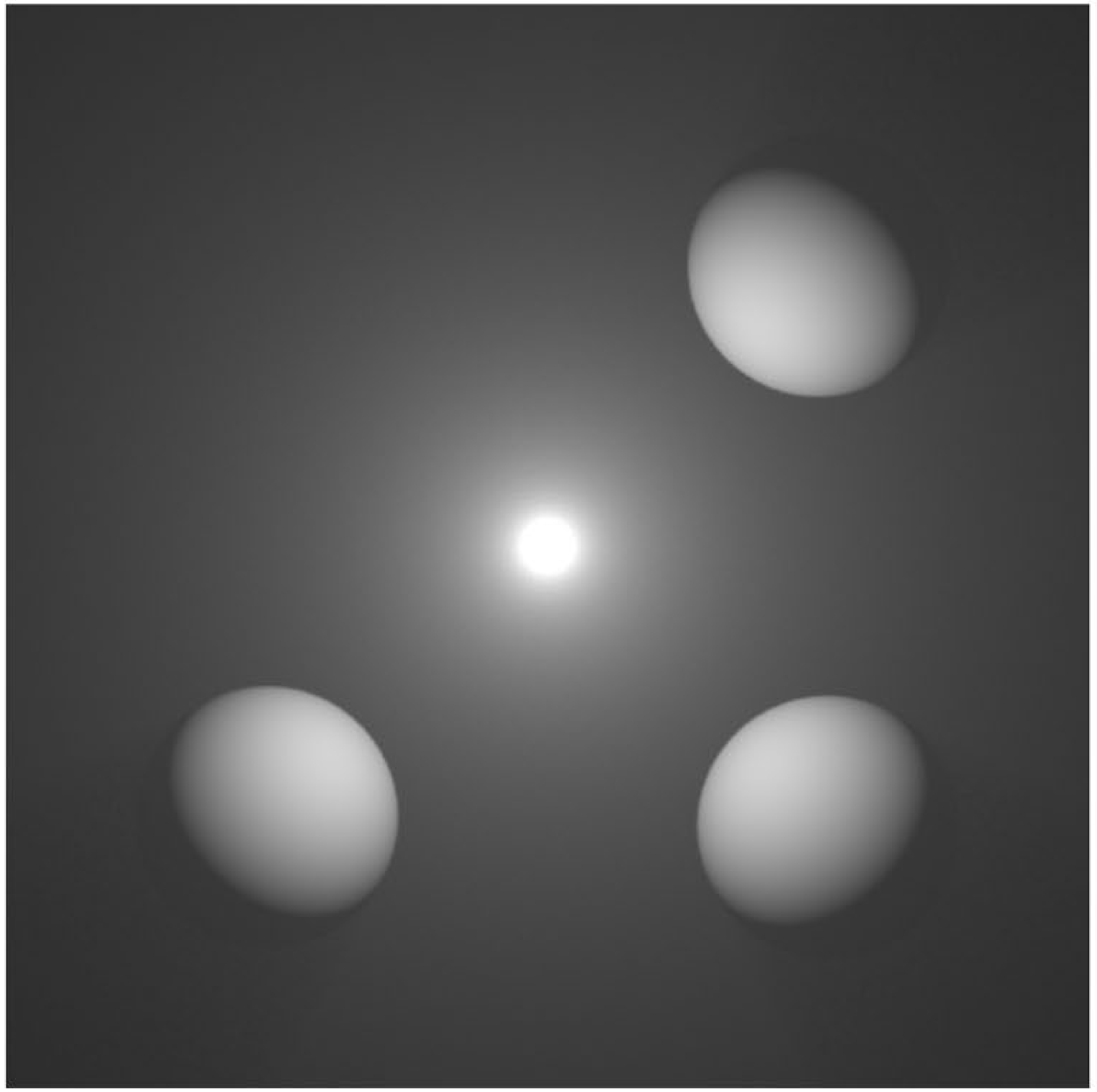


Decoupled Transmittance and In-scattering

Ray-marching



Equiangular sampling

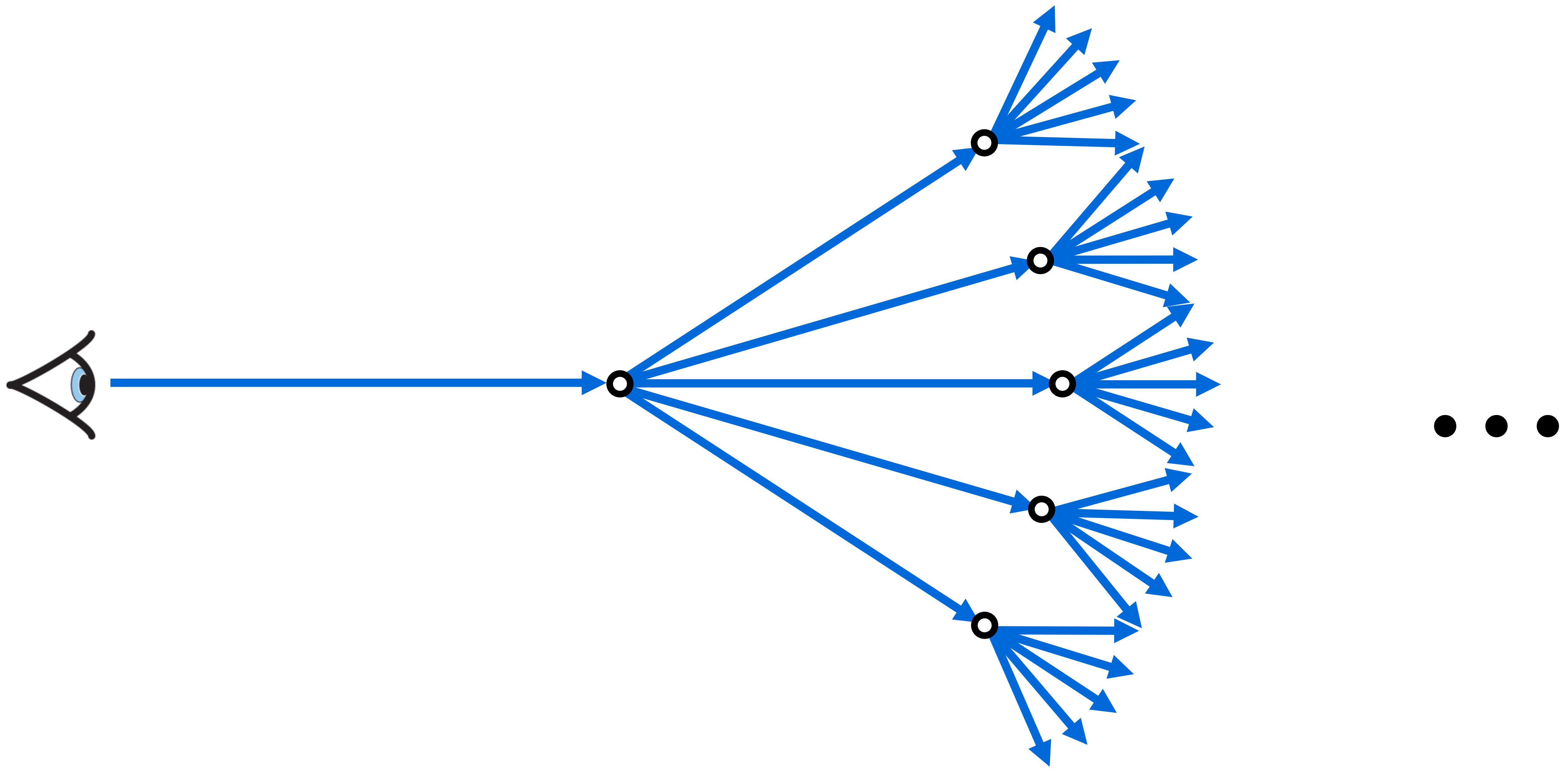


Images courtesy of Kulla and Fajardo

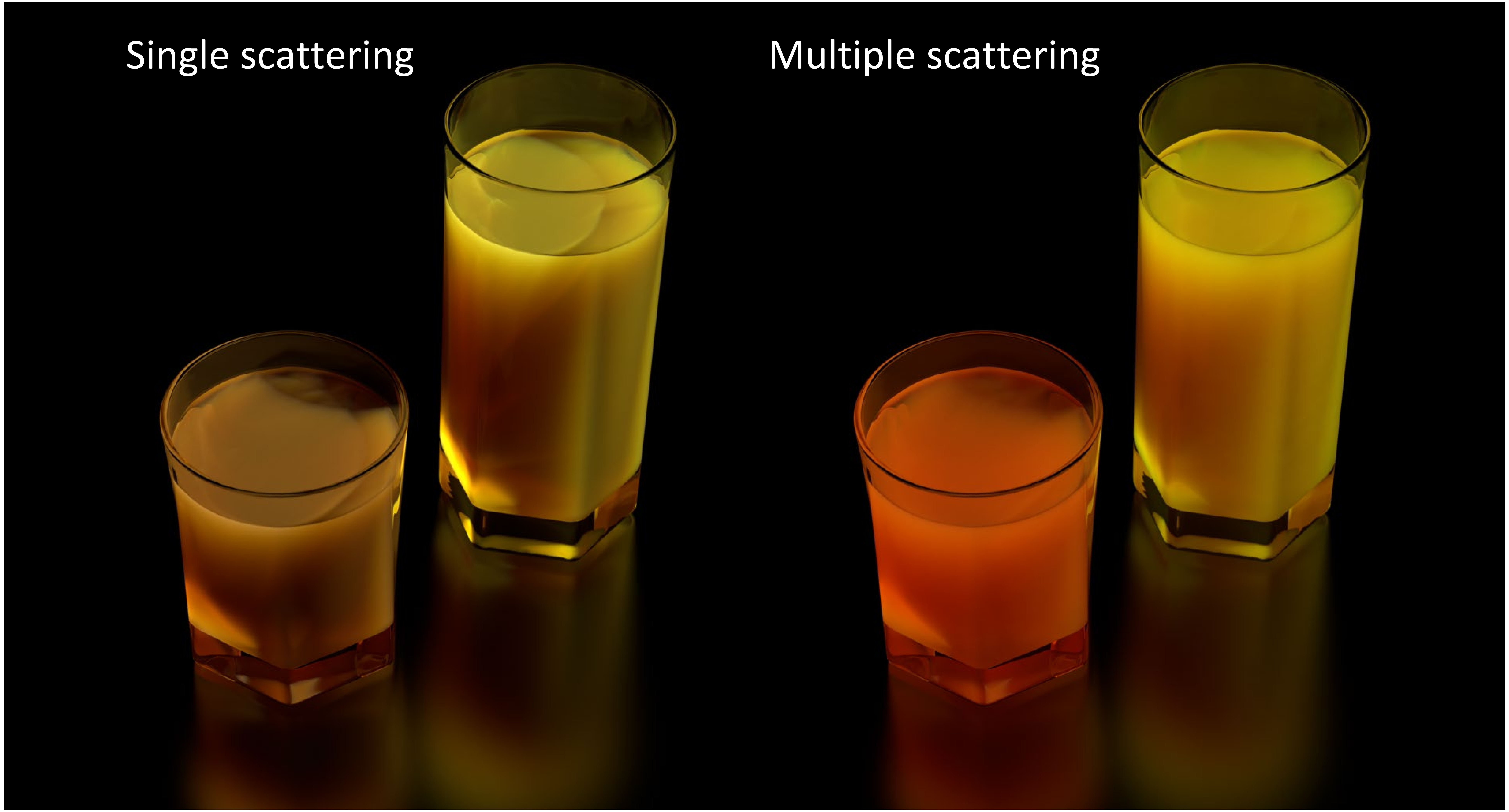
Multiple Bounces

Same concept as in recursive Monte Carlo ray tracing, but taking into account volumetric scattering

Exponential growth:



Visual Break



Volumetric Path Tracing

Volumetric Path Tracing

Motivation:

- Same as with standard path tracing: avoid the exponential growth

Paths can:

- Reflect/refract off surfaces
- Scatter inside a volume

Volume Rendering Equation

Accumulated emitted radiance

$$L(\mathbf{x},\vec{\omega}) = \boxed{\int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega})\,\mathrm{d}t} + \boxed{\int_0^z T_r(\mathbf{x},\mathbf{x}_t)\sigma_s(\mathbf{x}_t)L_s(\mathbf{x}_t,\vec{\omega})\,\mathrm{d}t} + \boxed{T_r(\mathbf{x},\mathbf{x}_z)L(\mathbf{x}_z,\vec{\omega})}$$

Accumulated in-scattered radiance

Attenuated background radiance

Volume Rendering Equation

Accumulated emitted + in-scattered radiance

$$L(\mathbf{x},\vec{\omega}) = \boxed{\int_0^z T_r(\mathbf{x},\mathbf{x}_t)\left[\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega}) + \sigma_s(\mathbf{x}_t)L_s(\mathbf{x}_t,\vec{\omega})\right]\,\mathrm{d}t} \\ + \boxed{T_r(\mathbf{x},\mathbf{x}_z)L(\mathbf{x}_z,\vec{\omega})}$$

Attenuated background radiance

Volume Rendering Equation

$$L(\mathbf{x},\vec{\omega}) = \int_0^z T_r(\mathbf{x},\mathbf{x}_t)\left[\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega}) + \sigma_s(\mathbf{x}_t)L_s(\mathbf{x}_t,\vec{\omega})\right]\,\mathrm{d}t$$
$$+\,T_r(\mathbf{x},\mathbf{x}_z)L(\mathbf{x}_z,\vec{\omega})$$

1-Sample Monte Carlo Estimator

$$\langle L(\mathbf{x},\vec{\omega})\rangle = \frac{T_r(\mathbf{x},\mathbf{x}_t)}{p(t)}\left[\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega}) + \sigma_s(\mathbf{x}_t)L_s(\mathbf{x}_t,\vec{\omega})\right] + \frac{T_r(\mathbf{x},\mathbf{x}_z)}{P(z)}L(\mathbf{x}_z,\vec{\omega})$$

$p(t)$ - probability *density* of distance t

$P(z)$ - *probability* of exceeding distance z

1-Sample Monte Carlo Estimator

$$\langle L(\mathbf{x},\vec{\omega})\rangle = \frac{T_r(\mathbf{x},\mathbf{x}_t)}{p(t)}\left[\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega}) + \sigma_s(\mathbf{x}_t)\frac{f_p(\vec{\omega},\vec{\omega}_i)L(\mathbf{x}_t,\vec{\omega}_i)}{p(\vec{\omega}_i)}\right]$$
$$+ \frac{T_r(\mathbf{x},\mathbf{x}_z)}{P(z)}L(\mathbf{x}_z,\vec{\omega})$$

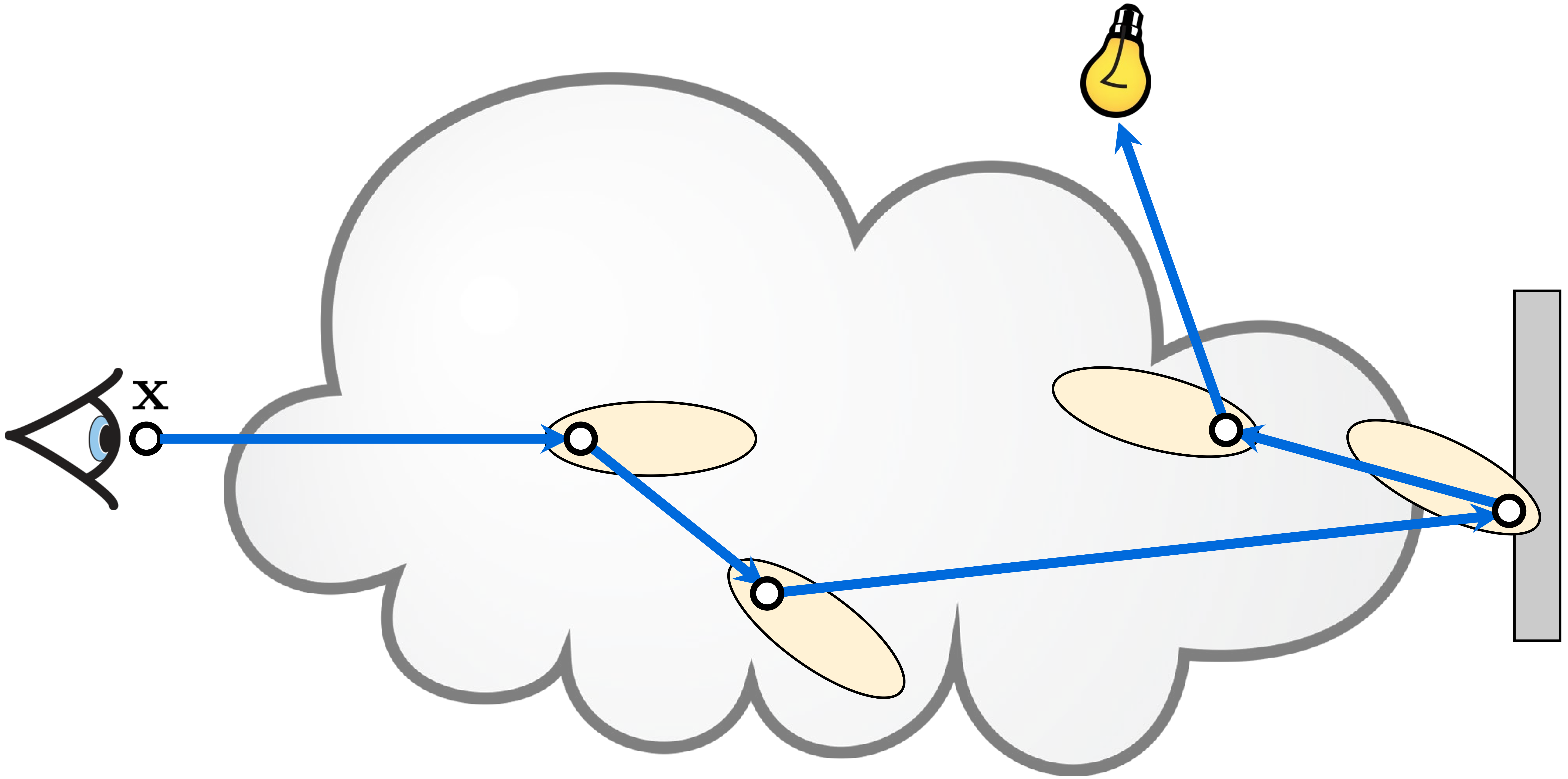
$p(t)$ - probability *density* of distance t

$P(z)$ - *probability* of exceeding distance z

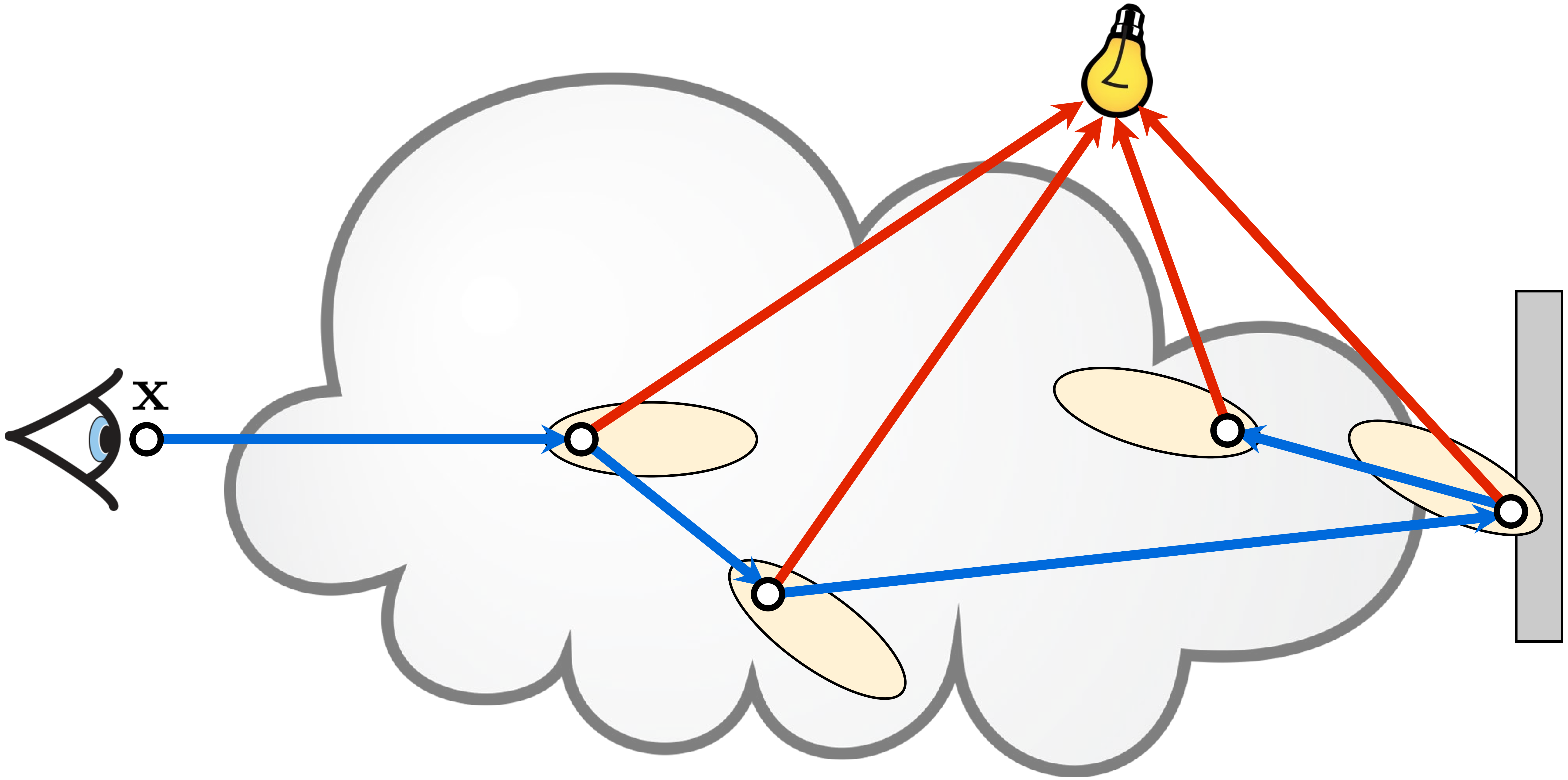
$p(\vec{\omega}_i)$ - probability *density* of direction $\vec{\omega}_i$

Volumetric Path Tracing

1. Sample distance to next interaction
2. Scatter in the volume or bounce off a surface



Volumetric Path Tracing with NEE



Sampling the Phase Function

Isotropic:

- Uniform sphere sampling

Henyey-Greenstein:

- Using the inversion method we can derive

$$\cos\theta = \frac{1}{2g}\left(1+g^2-\left(\frac{1-g^2}{1-g+2g\xi_1}\right)^2\right)$$

$$\phi = 2\pi\xi_2$$

- PDF is the value of the HG phase function

Free-path Sampling

Free-path (or free-flight distance):

- Distance to the next interaction within the medium
- Dense media (e.g. milk): short mean-free path
- Thin media (e.g. atmosphere): long mean-free path

Ideally, we want to sample proportional to (part of) integrand, e.g. transmittance:

$$p(\mathbf{x}_t|(\mathbf{x},\vec{\omega})) \propto T_r(\mathbf{x},\mathbf{x}_t)$$

simplified notation for brevity

$$p(t) \propto T_r(t)$$

Free-path Sampling

Homogeneous media: $T_r(t) = e^{-\sigma_t t}$

- PDF: $p(t) \propto e^{-\sigma_t t}$

$$p(t) = \frac{e^{-\sigma_t t}}{\int_0^\infty e^{-\sigma_t s} ds} = \sigma_t e^{-\sigma_t t}$$

- CDF: $P(t) = \int_0^t \sigma_t e^{-\sigma_t s} ds = 1 - e^{-\sigma_t t}$

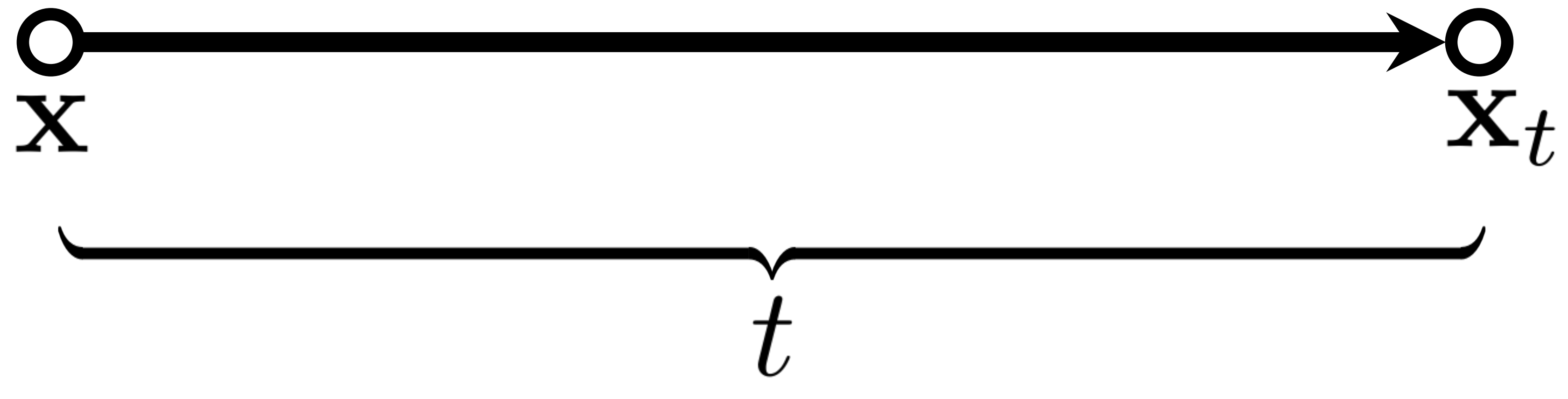
- Inverted CDF: $P^{-1}(\xi) = -\frac{\ln(1-\xi)}{\sigma_t}$

Free-path Sampling

Homogeneous media: $T_r(t) = e^{-\sigma_t t}$

Recipe:

- Generate random number ξ
- Sample distance $t = -\frac{\ln(1-\xi)}{\sigma_t}$
- Compute PDF $p(t) = \sigma_t e^{-\sigma_t t}$



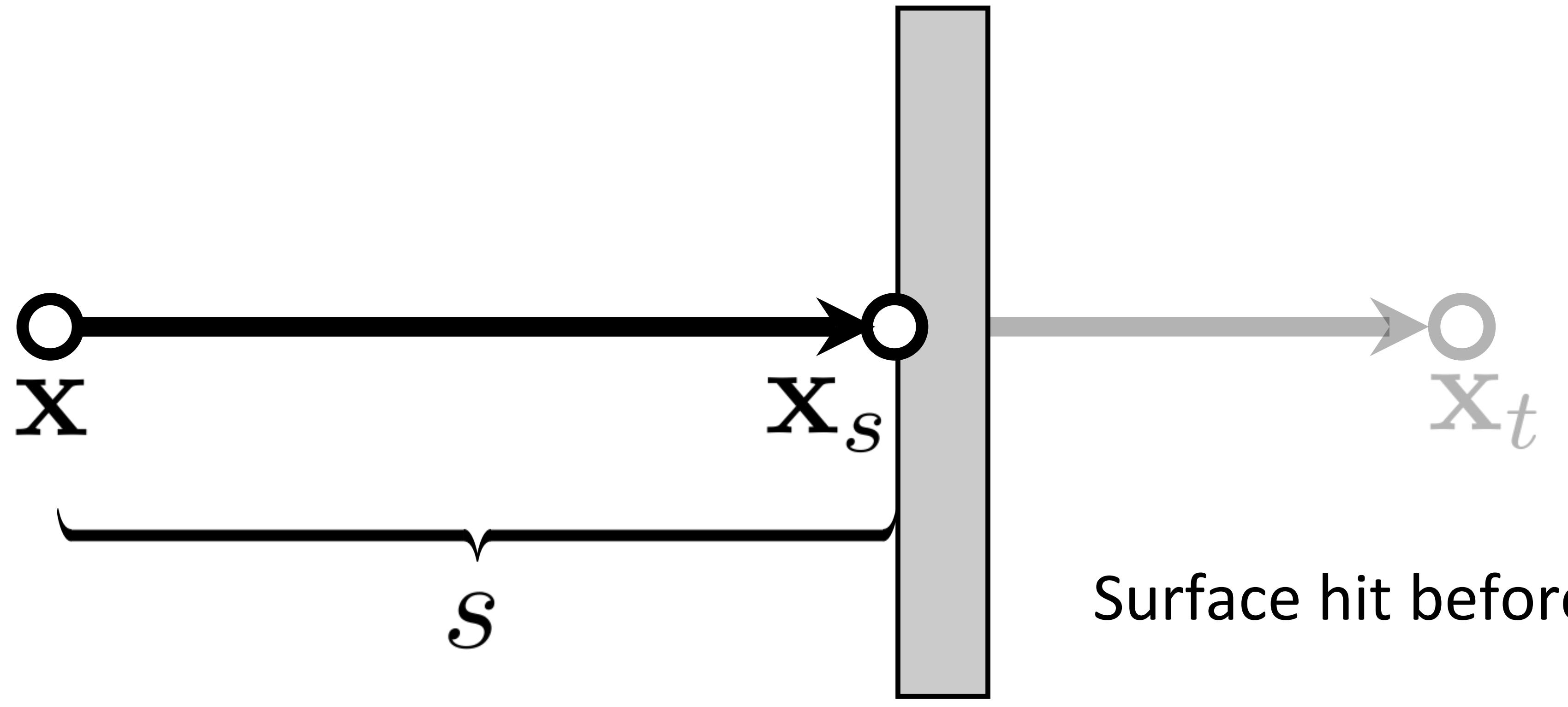
Free-path Sampling

Homogeneous media: $T_r(t) = e^{-\sigma_t t}$

Recipe:

- Generate random number ξ
- Sample distance $t = \cancel{-\frac{\ln(1-\xi)}{\sigma_t}} = s$
- Compute PDF $p(t) = \cancel{\sigma_t e^{-\sigma_t t}} = e^{-\sigma_t s}$

Note: This is now a probability, not a probability density!



Surface hit before reaching t

Volumetric PT for Homogeneous Volumes

```
Color vPT(x, ω)
tmax = nearestSurface(x, ω)
t = -log(1 - randf()) / σt   // Sample free path
if t < tmax: // Volume interaction
x += t * ω
pdf_t = σt * exp(-σt * t)
(ω', pdf_ω') = samplePF(ω)
return Tr(t) / pdf_t * (σa * Le(x, ω) + σs * PF(ω, ω') * vPT(x, ω') / pdf_ω')
else: // Surface interaction
x += tmax * ω
Pr_tmax = exp(-σt * tmax)
(ω', pdf_ω') = sampleBRDF(n, ω)
return Tr(tmax) / Pr_tmax * (Le(x, ω) + BRDF(ω, ω') * vPT(x, ω') / pdf_ω')
```

$$\langle L(\mathbf{x},\vec{\omega})\rangle = \frac{T_r(\mathbf{x},\mathbf{x}_t)}{p(t)}\left[\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega}) + \sigma_s(\mathbf{x}_t)\frac{f_p(\vec{\omega},\vec{\omega}_i)L(\mathbf{x}_t,\vec{\omega}_i)}{p(\vec{\omega}_i)}\right] + \frac{T_r(\mathbf{x},\mathbf{x}_z)}{P(z)}L(\mathbf{x}_z,\vec{\omega})$$

Volumetric PT for Homogeneous Volumes

```
Color vPT(x, ω)
tmax = nearestSurface(x, ω)
t = -log(1 - randf()) / σt   // Sample free path
if t < tmax: // Volume interaction
x += t * ω
pdf_t = σt * exp(-σt * t)
(ω', pdf_ω') = samplePF(ω)
// Note: transmittance and PF cancel out with PDFs except for a constant factor 1/σt
return Tr(t) / pdf_t * (σa * Le(x, ω) + σs * PF(ω, ω') * vPT(x, ω') / pdf_ω')
else: // Surface interaction
x += tmax * ω
Pr_tmax = exp(-σt * tmax)
(ω', pdf_ω') = sampleBRDF(n, ω)
// Note: transmittance and prob of sampling the distance cancel out
return Tr(tmax) / Pr_tmax * (Le(x, ω) + BRDF(ω, ω') * vPT(x, ω') / pdf_ω')
```

$$\langle L(\mathbf{x},\vec{\omega})\rangle = \frac{T_r(\mathbf{x},\mathbf{x}_t)}{p(t)}\left[\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega}) + \sigma_s(\mathbf{x}_t)\frac{f_p(\vec{\omega},\vec{\omega}_i)L(\mathbf{x}_t,\vec{\omega}_i)}{p(\vec{\omega}_i)}\right] + \frac{T_r(\mathbf{x},\mathbf{x}_z)}{P(z)}L(\mathbf{x}_z,\vec{\omega})$$

Volumetric PT for Homogeneous Volumes

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Color vPT(x, ω)
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pdf_t = σt * exp(-σt * t)
(ω', pdf_ω') = samplePF(ω)
// Note: transmittance and PF cancel out with PDFs except for a constant factor 1/σt
return σa/σt * Le(x, ω) + σs/σt * vPT(x, ω')
else: // Surface interaction
x += tmax * ω
Pr_tmax = exp(-σt * tmax)
(ω', pdf_ω') = sampleBRDF(n, ω)
// Note: transmittance and prob of sampling the distance cancel out
return Le(x, ω) + BRDF(ω, ω') * vPT(x, ω') / pdf_ω'
```

$$\langle L(\mathbf{x},\vec{\omega})\rangle = \frac{T_r(\mathbf{x},\mathbf{x}_t)}{p(t)}\left[\sigma_a(\mathbf{x}_t)L_e(\mathbf{x}_t,\vec{\omega}) + \sigma_s(\mathbf{x}_t)\frac{f_p(\vec{\omega},\vec{\omega}_i)L(\mathbf{x}_t,\vec{\omega}_i)}{p(\vec{\omega}_i)}\right] + \frac{T_r(\mathbf{x},\mathbf{x}_z)}{P(z)}L(\mathbf{x}_z,\vec{\omega})$$

What about heterogeneous media?

Free-path Sampling

Heterogeneous media: $T_r(t) = e^{\int_0^t -\sigma_t(s)ds}$

- Closed-form solutions exist only for simple media
  - e.g. linearly or exponentially varying extinction
- Other solutions:
  - Regular tracking (3D DDA)
  - Ray marching
  - Delta tracking

Free-path Sampling

How to sample the flight distance to the next interaction?

Random variable representing flight distance

$$T(t) = \mathrm{e}^{-\int_0^t \sigma_t(s)\,\mathrm{d}s} = \boxed{\begin{array}{l} P(X > t) \\ P(X \leq t) \end{array}} = F(t)$$

CDF

Partition of unity

$$F(t) = 1 - T(t)$$

Recipe for generating samples

Free-path Sampling

Cumulative distribution function (**CDF**)

$$F(t) = 1 - T(t) = 1 - \mathrm{e}^{-\tau(t)}$$

Probability density function (**PDF**)

$$p(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(1 - \mathrm{e}^{-\tau(t)}\right) = \sigma_{\mathrm{t}}(t)\mathrm{e}^{-\tau(t)}$$

Inverted cumulative distr. function (**CDF^{-1}**)

$$\xi = 1 - \mathrm{e}^{-\tau(t)}$$

Solve for t

$$\int_0^t \sigma_{\mathrm{t}}(s)\,\mathrm{d}s = -\ln(1-\xi)$$

Approaches for finding t:

1) **ANALYTIC (closed-form CDF^{-1})**
2) **SEMI-ANALYTIC (regular tracking)**
3) **APPROXIMATE (ray marching)**

Regular Tracking (Semi-Analytic)

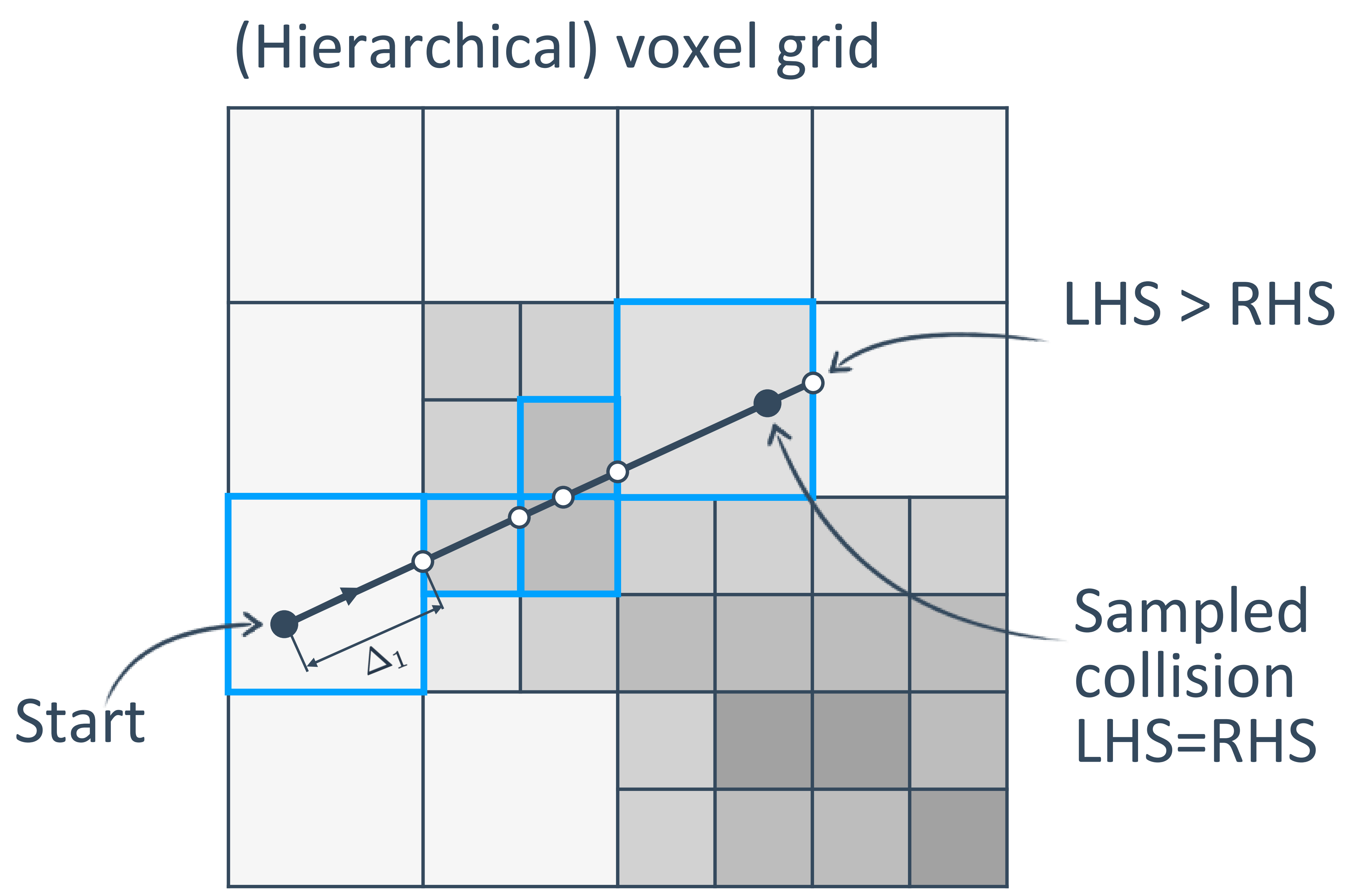
For piecewise-simple (e.g. piecewise-constant), summation replaces integration

$$\int_0^t \sigma_{\mathrm{t}}(s)\,\mathrm{d}s = -\ln(1-\xi)$$

$$\sum_{i=1}^{k} \sigma_{\mathrm{t},i}\,\Delta_i = -\ln(1-\xi)$$

Regular tracking:

1) Draw a random number ξ
2) While LHS < RHS
   move to the next intersection
3) Find the exact location
   in the last segment analytically



Ray Marching

Find the collision distance approximately

$$\int_0^t \sigma_t(s)\,\mathrm{d}s = -\ln(1-\xi)$$

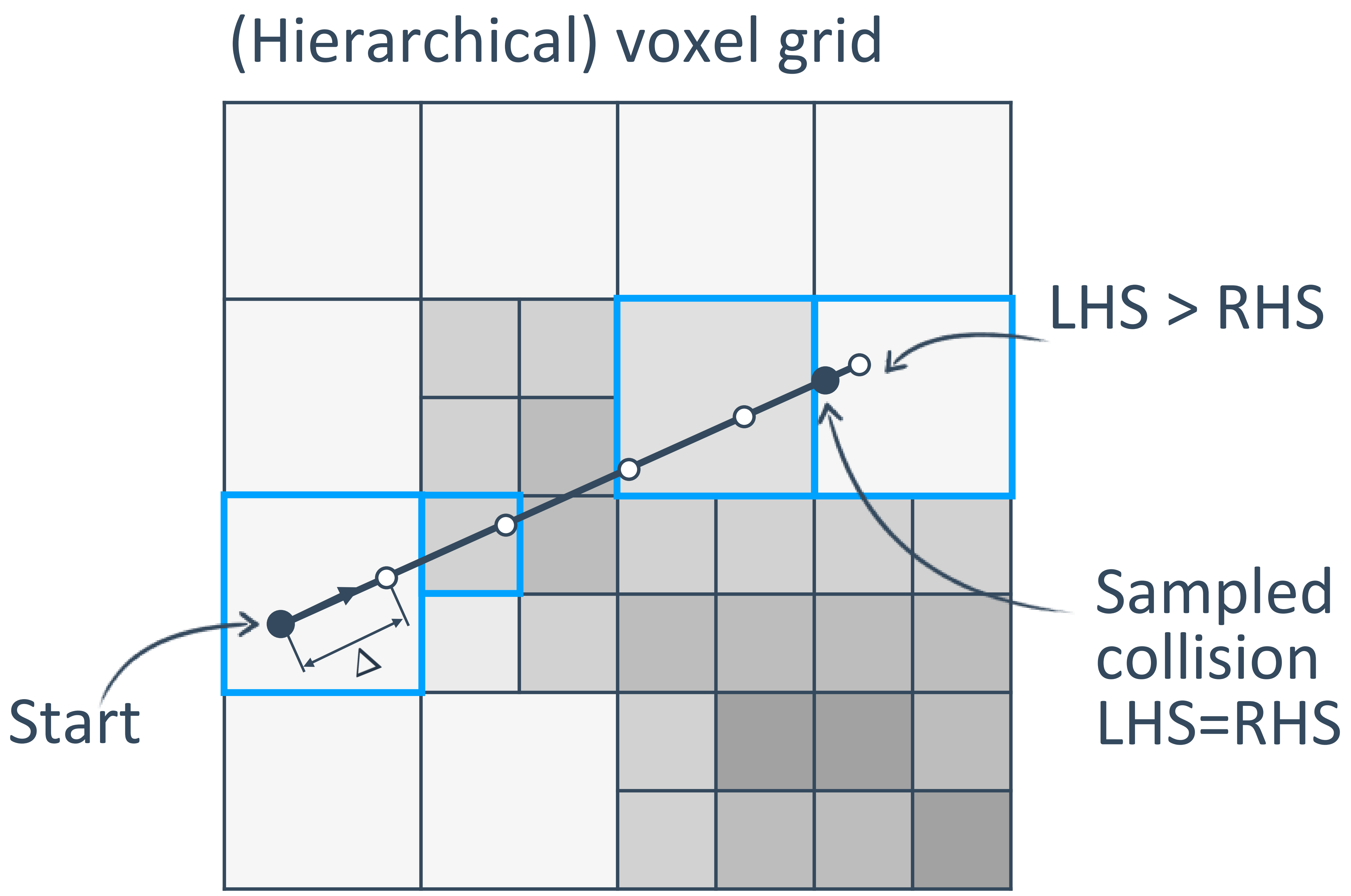
$$\neq$$

$$\sum_{i=1}^{k} \sigma_{t,i}\,\Delta \;=\; -\ln(1-\xi)$$

Constant step

Ray marching:

1) Draw a random number ξ
2) While LHS < RHS
   make a (fixed-size) step
3) Find the exact location
   in the last segment analytically



Ray Marching

Find the collision distance approximately

$$\int_0^t \sigma_t(s)\, ds = -\ln(1-\xi)$$

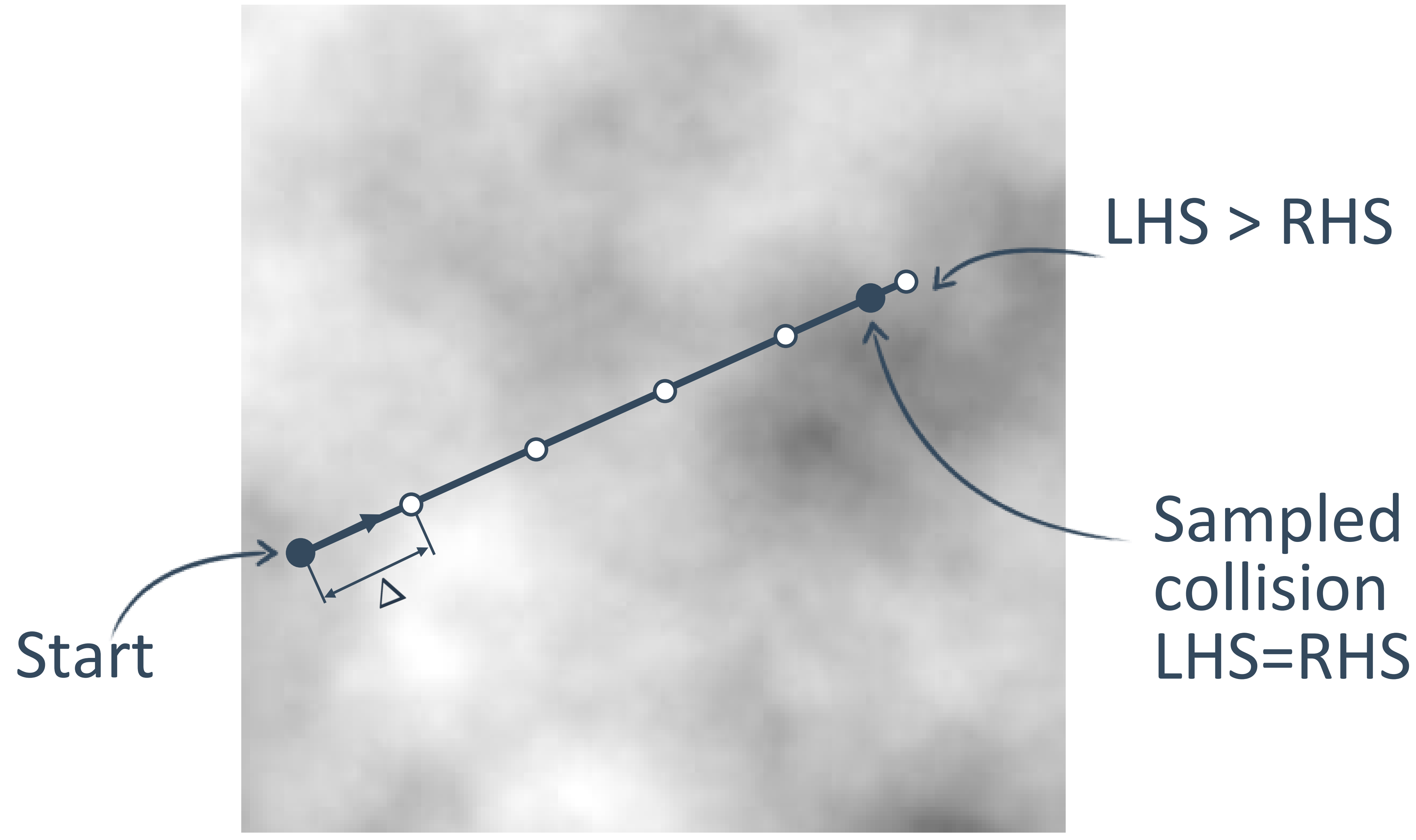
$$\sum_{i=1}^{k} \sigma_{t,i}\, \Delta \;=\; -\ln(1-\xi)$$

Constant step

Ray marching:

1) Draw a random number ξ
2) While LHS < RHS
   make a (fixed-size) step
3) Find the exact location
   in the last segment analytically

General volume



Ray Marching

Find the collision distance approximately

$$\int_0^t \sigma_t(s)\,\mathrm{d}s = -\ln(1-\xi)$$

$$\neq$$

$$\sum_{i=1}^{k} \sigma_{t,i}\,\Delta \;=\; -\ln(1-\xi)$$

Constant step

Ray marching:

1) Draw a random number ξ
2) While LHS < RHS
   make a (fixed-size) step
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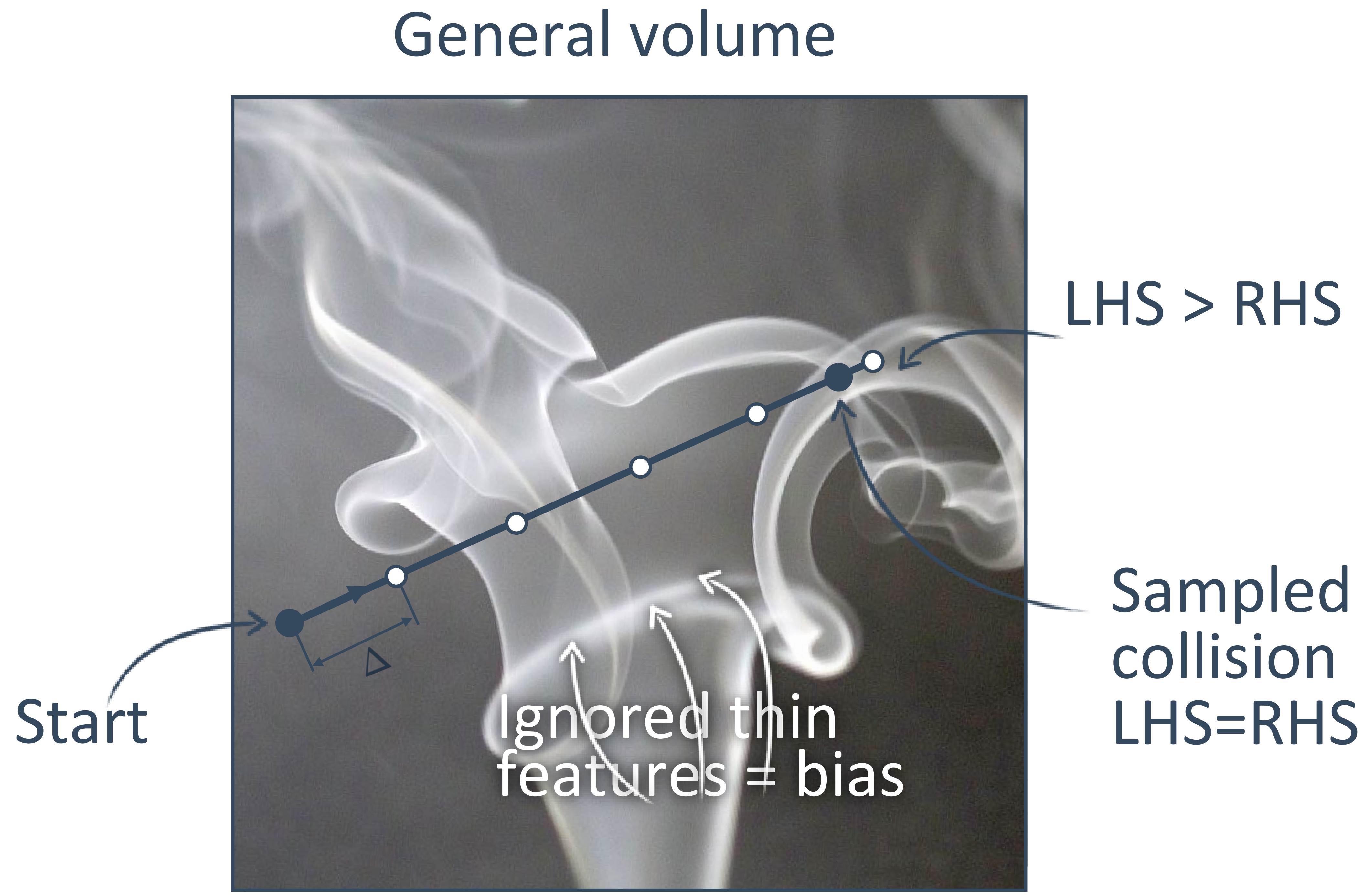


Free-path Sampling

ANALYTIC CDF^{-1}	REGULAR TRACKING	RAY MARCHING
▸ Efficient & simple, limited to few volumes	▸ Iterative, inefficient if free paths cross many boundaries	▸ Iterative, inaccurate (or inefficient) for media with high frequencies
▸ Simple volumes (e.g. homogeneous)	▸ Piecewise-simple volumes	▸ Any volume
▸ Unbiased	▸ Unbiased	▸ Biased

Common approach: sample optical thickness, find corresponding distance

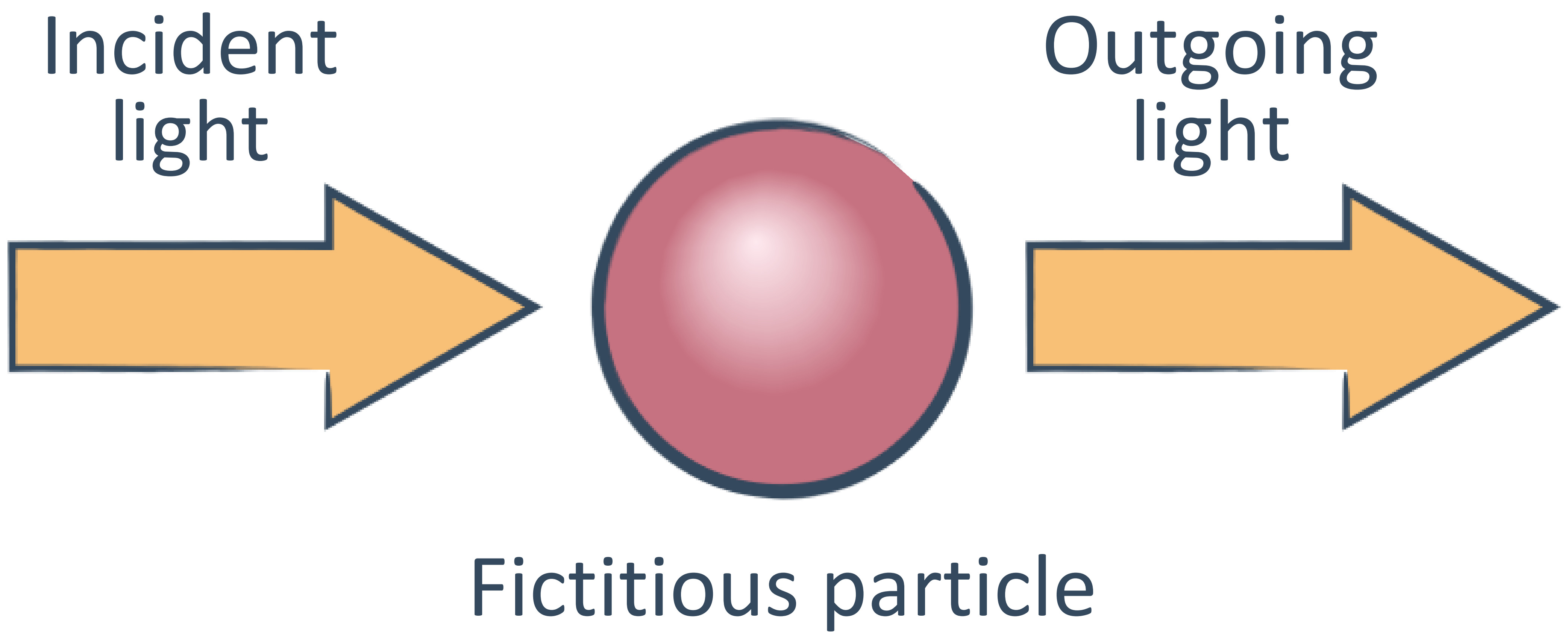
Delta Tracking

(a.k.a. Woodcock tracking, pseudo scattering, hole tracking, null-collision method,…)

Delta tracking idea

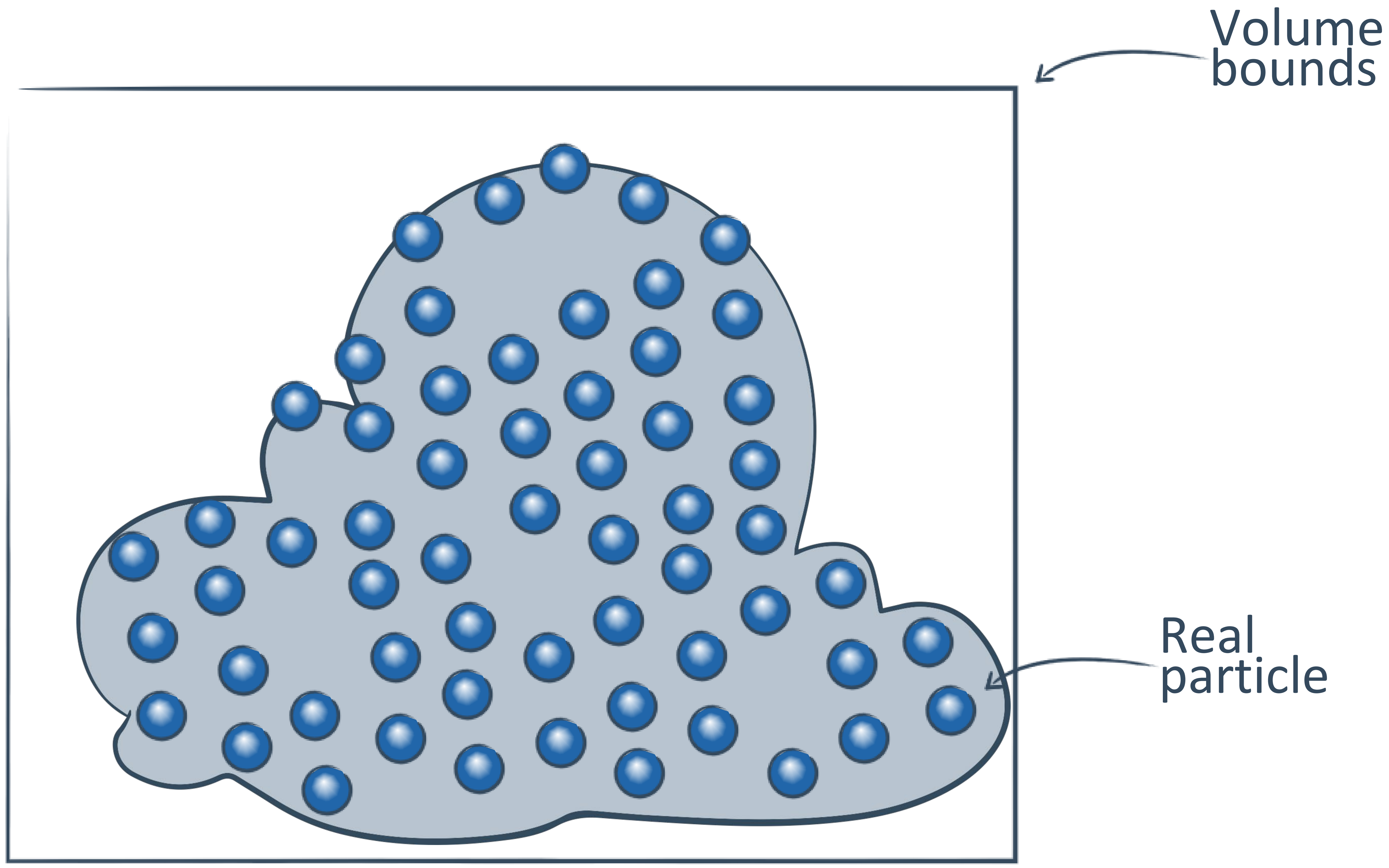
Add **FICTITIOUS MATTER** to homogenize medium

- albedo: $\alpha(\mathbf{x}) = 1$
- phase function: $f_p(\vec{\omega}, \vec{\omega}') = \delta(\vec{\omega} - \vec{\omega}')$

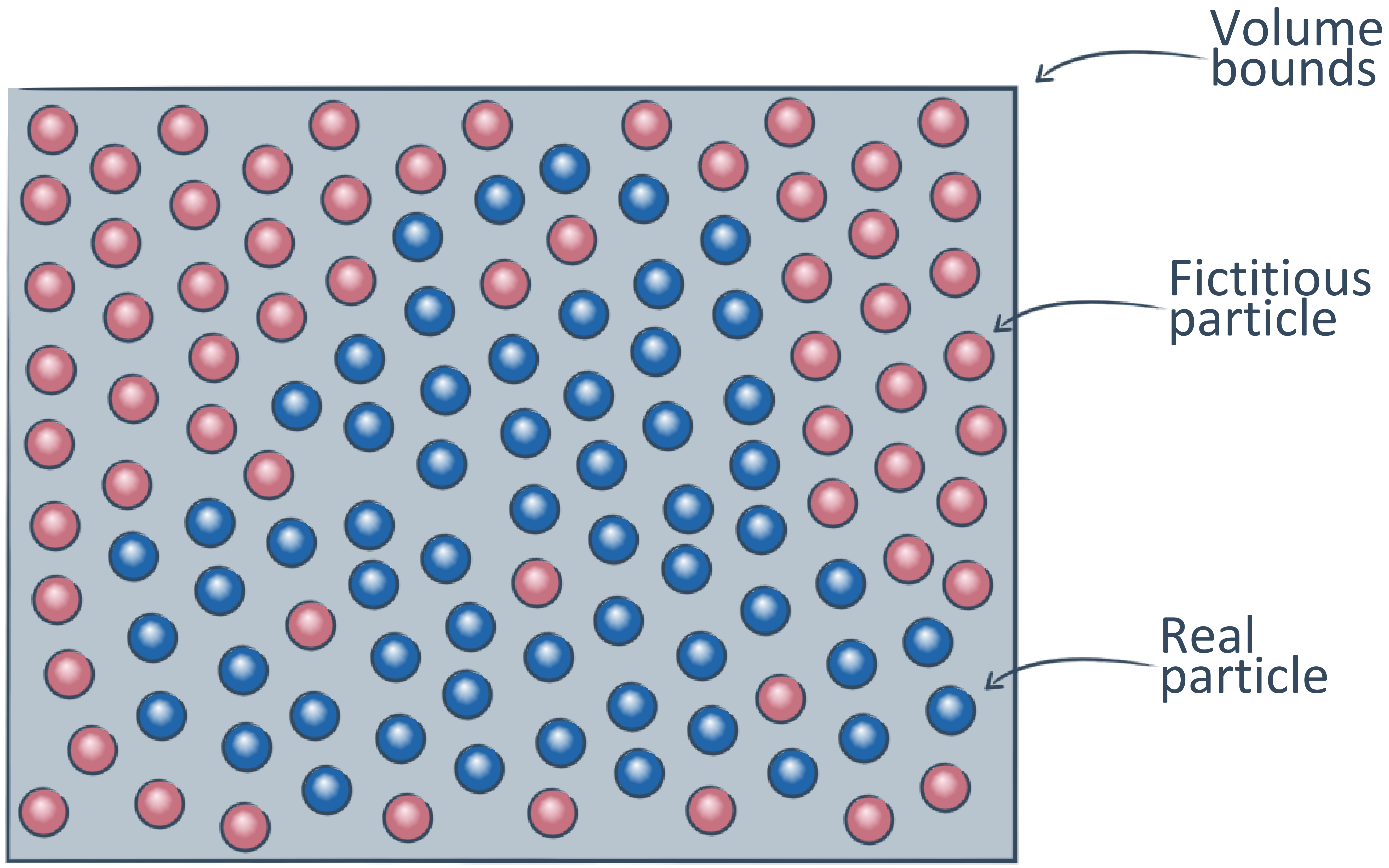


Presence of fictitious matter does not impact light transport

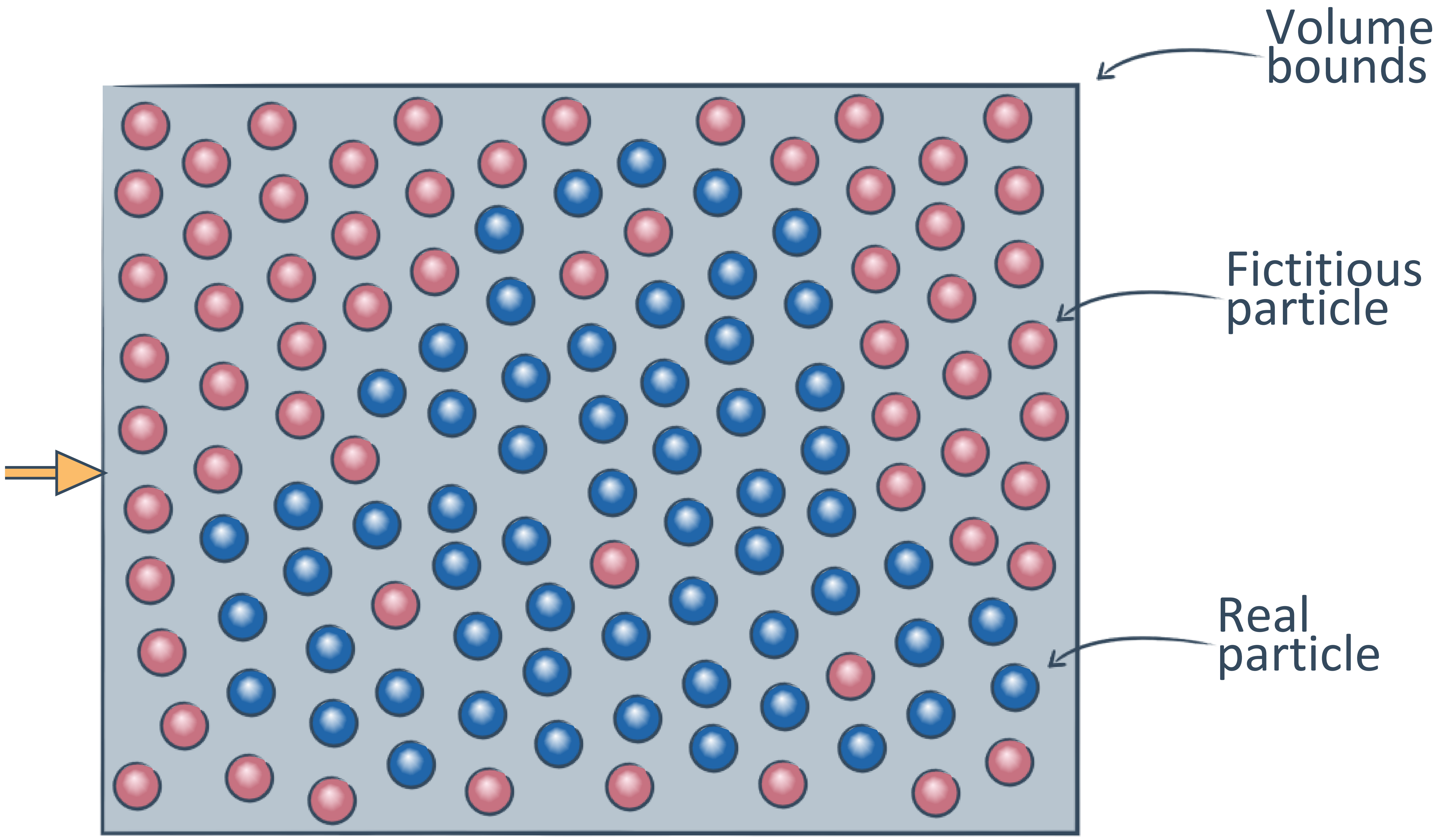
Homogenization



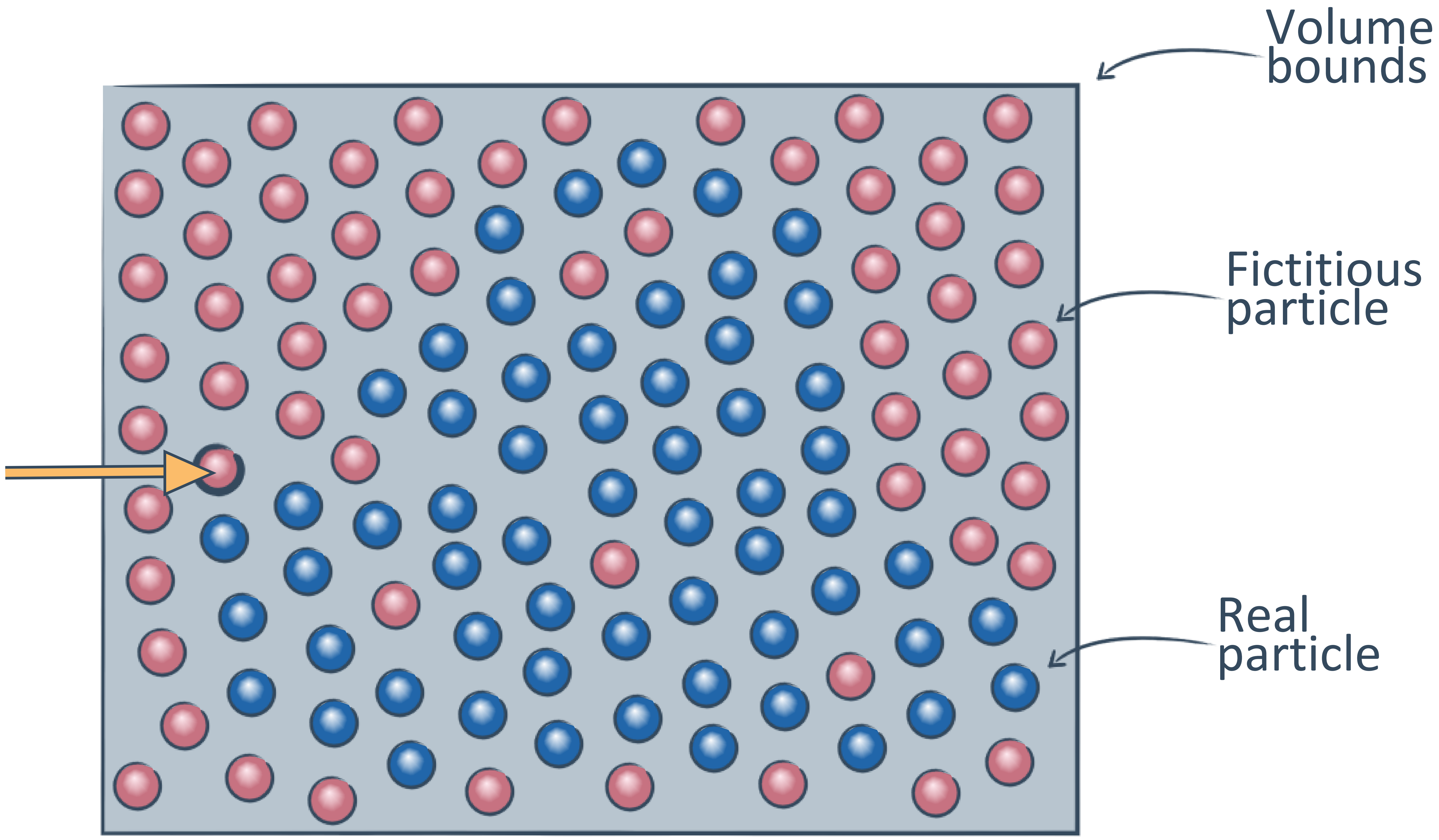
Homogenization



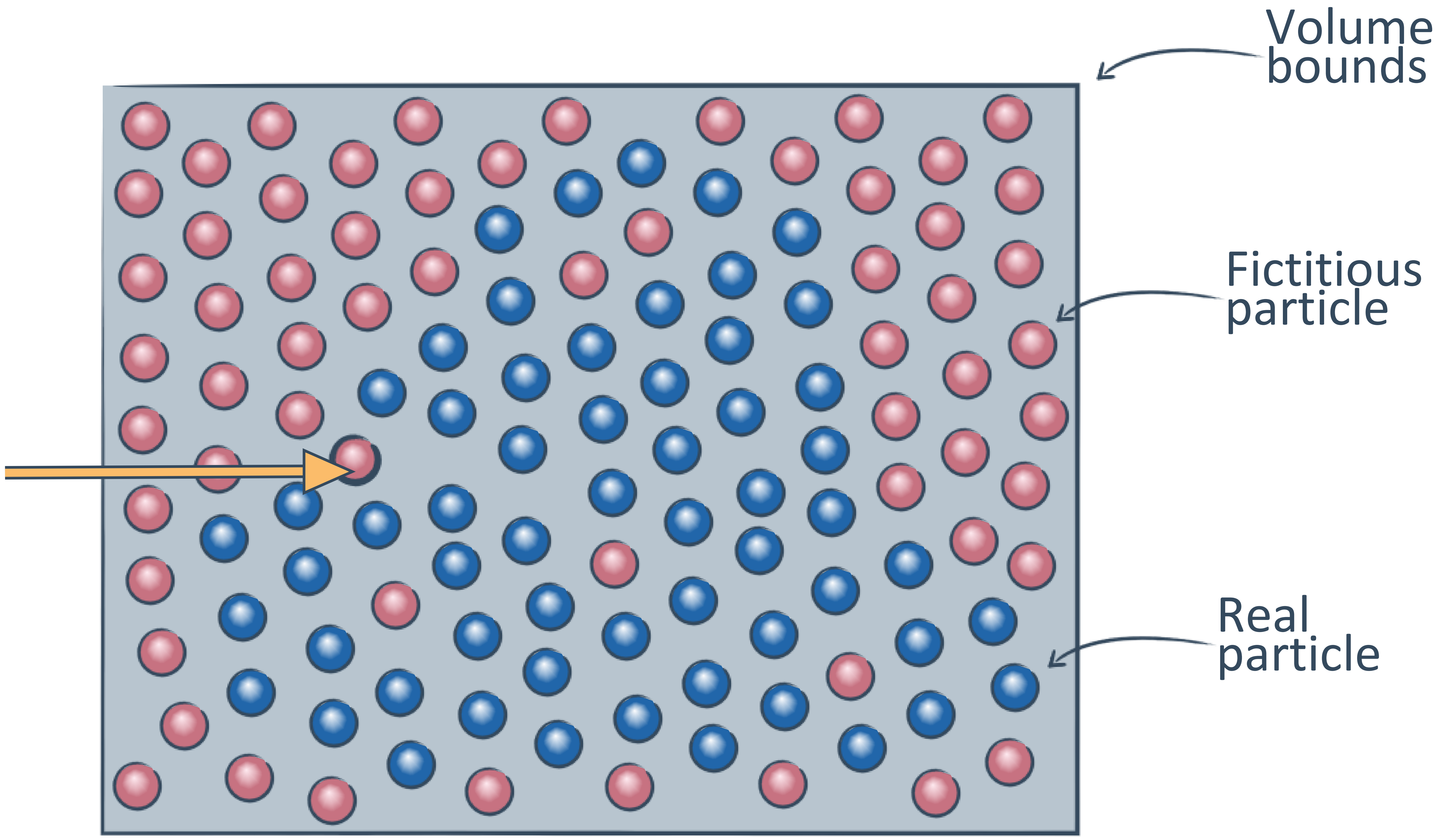
Homogenization



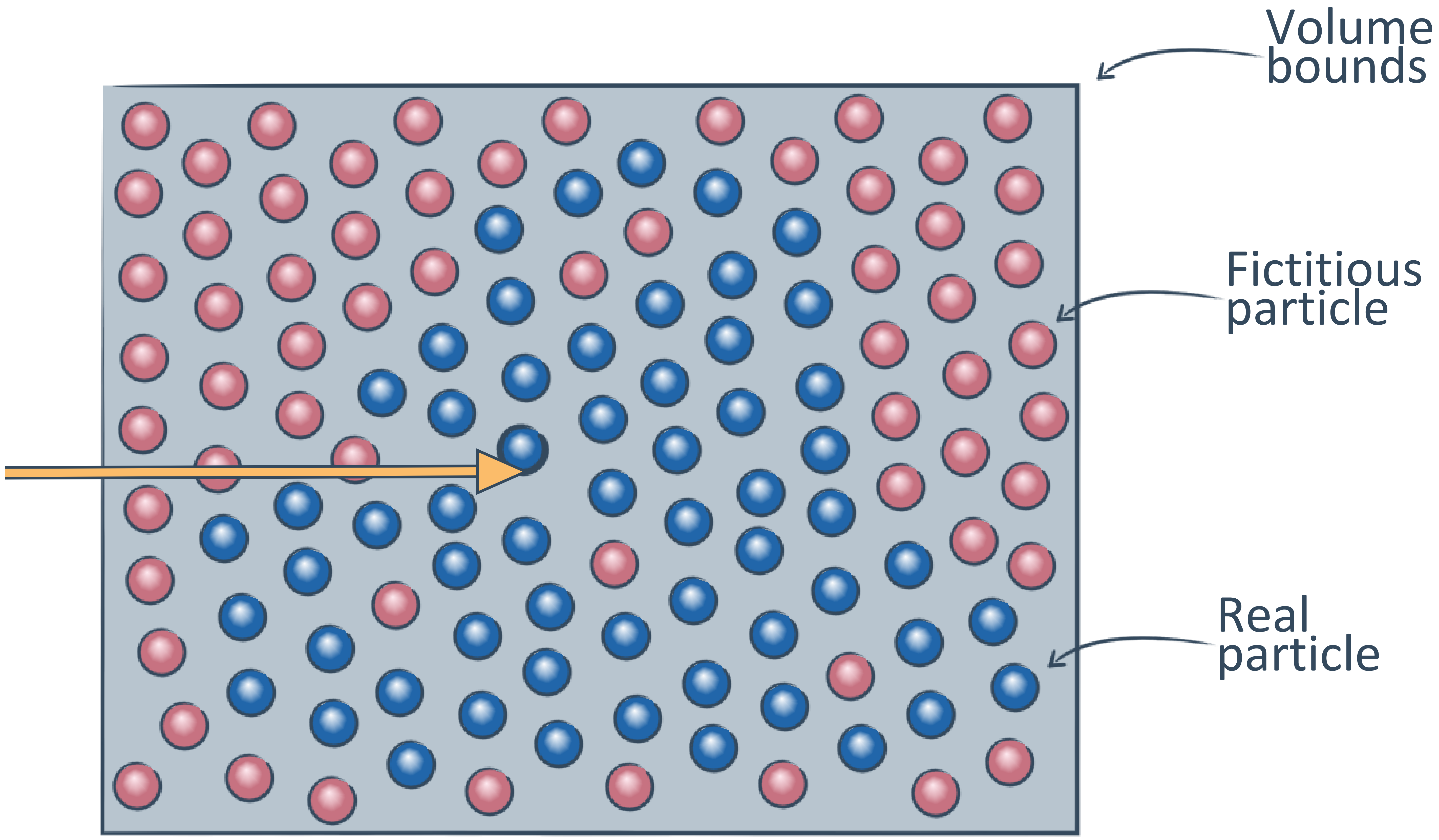
Homogenization



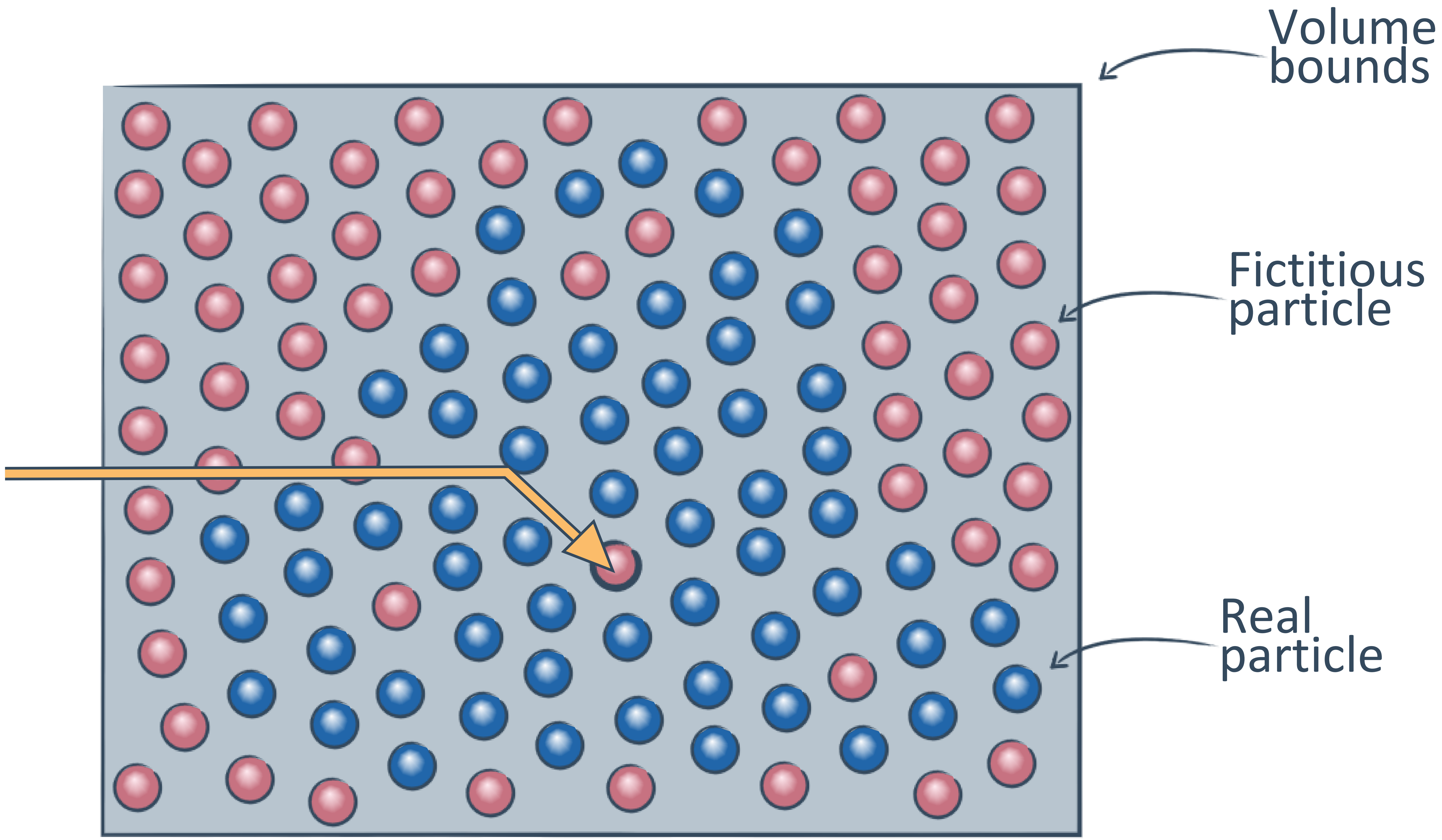
Homogenization



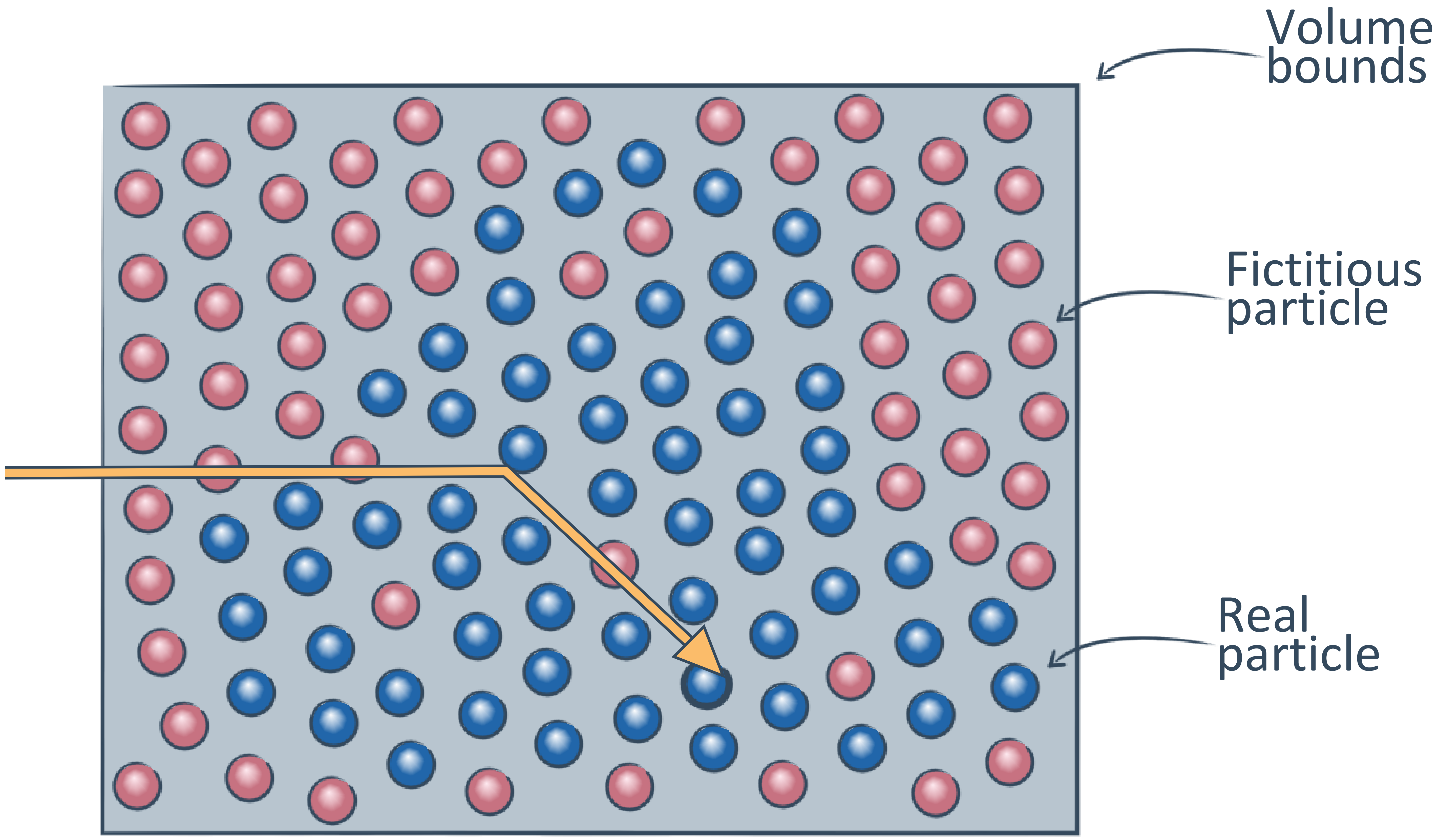
Homogenization



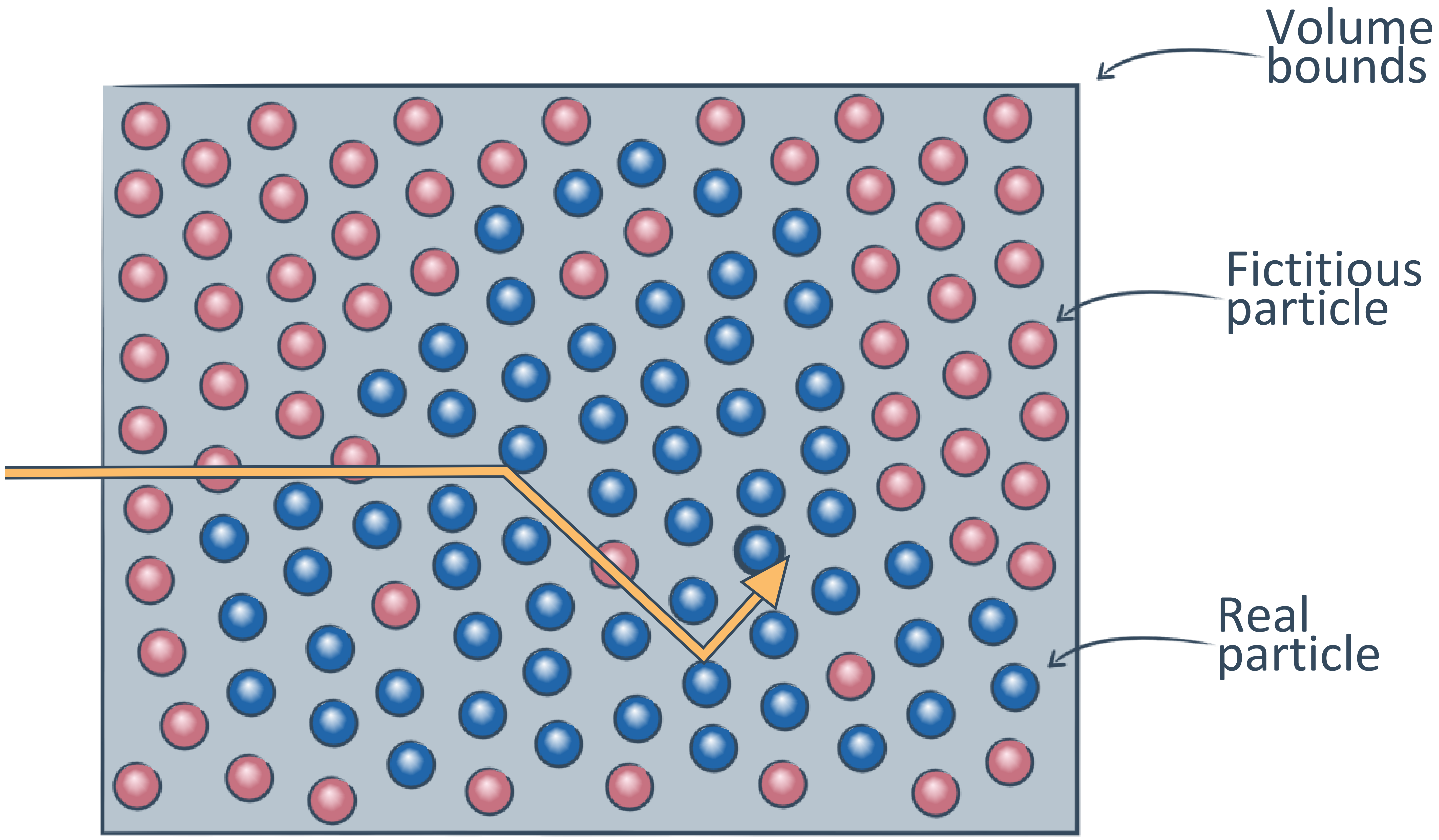
Homogenization



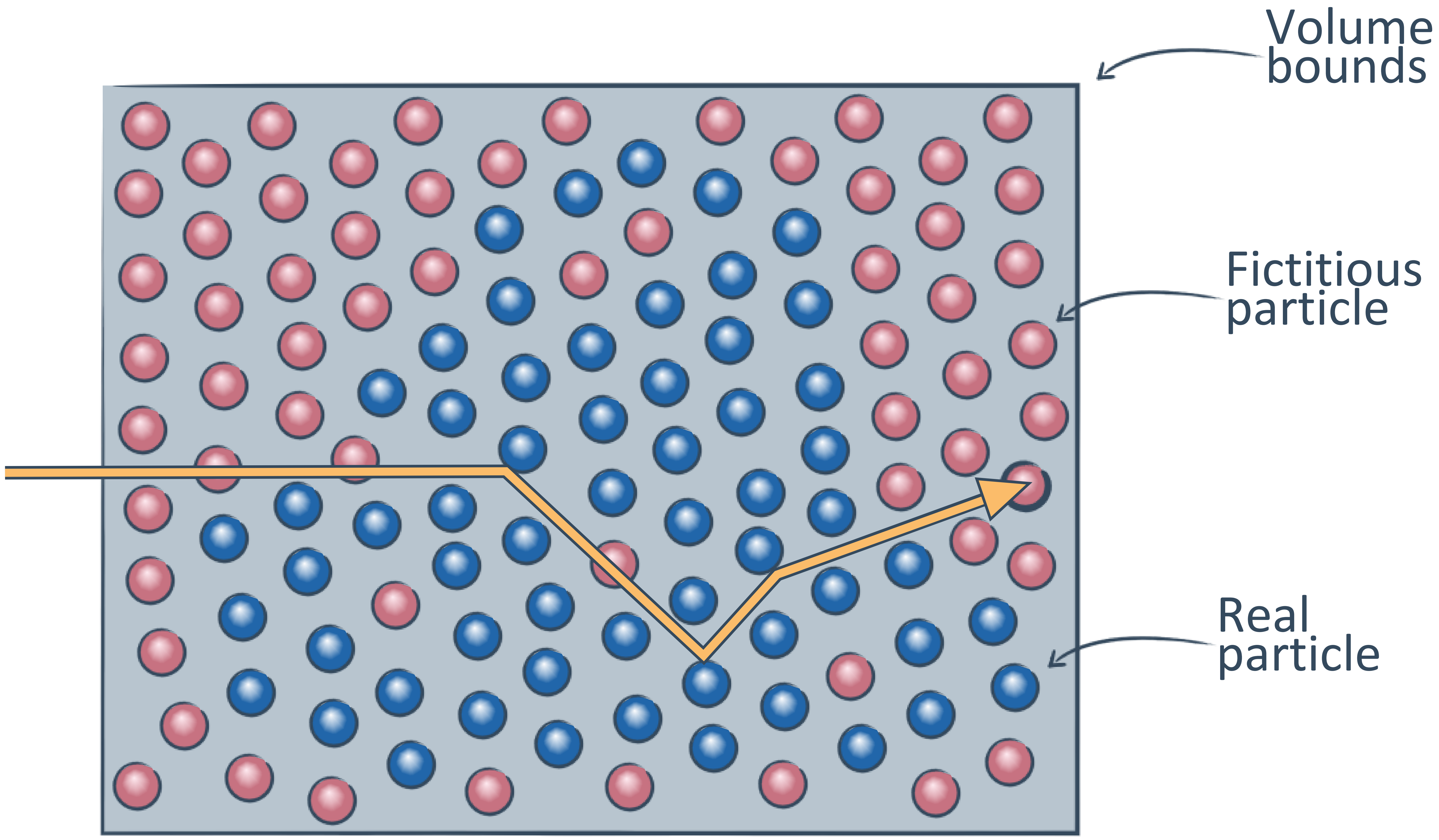
Homogenization



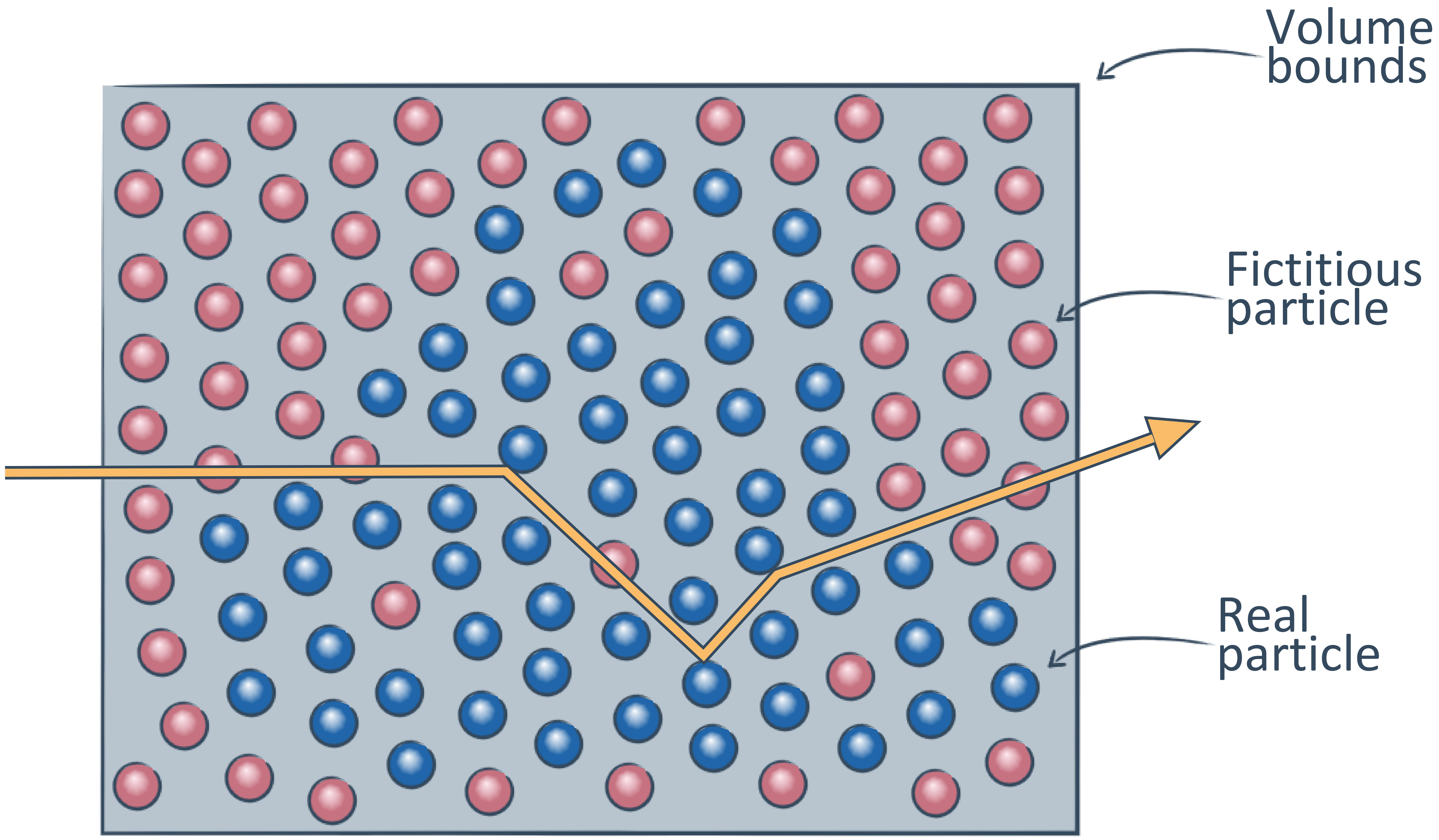
Homogenization



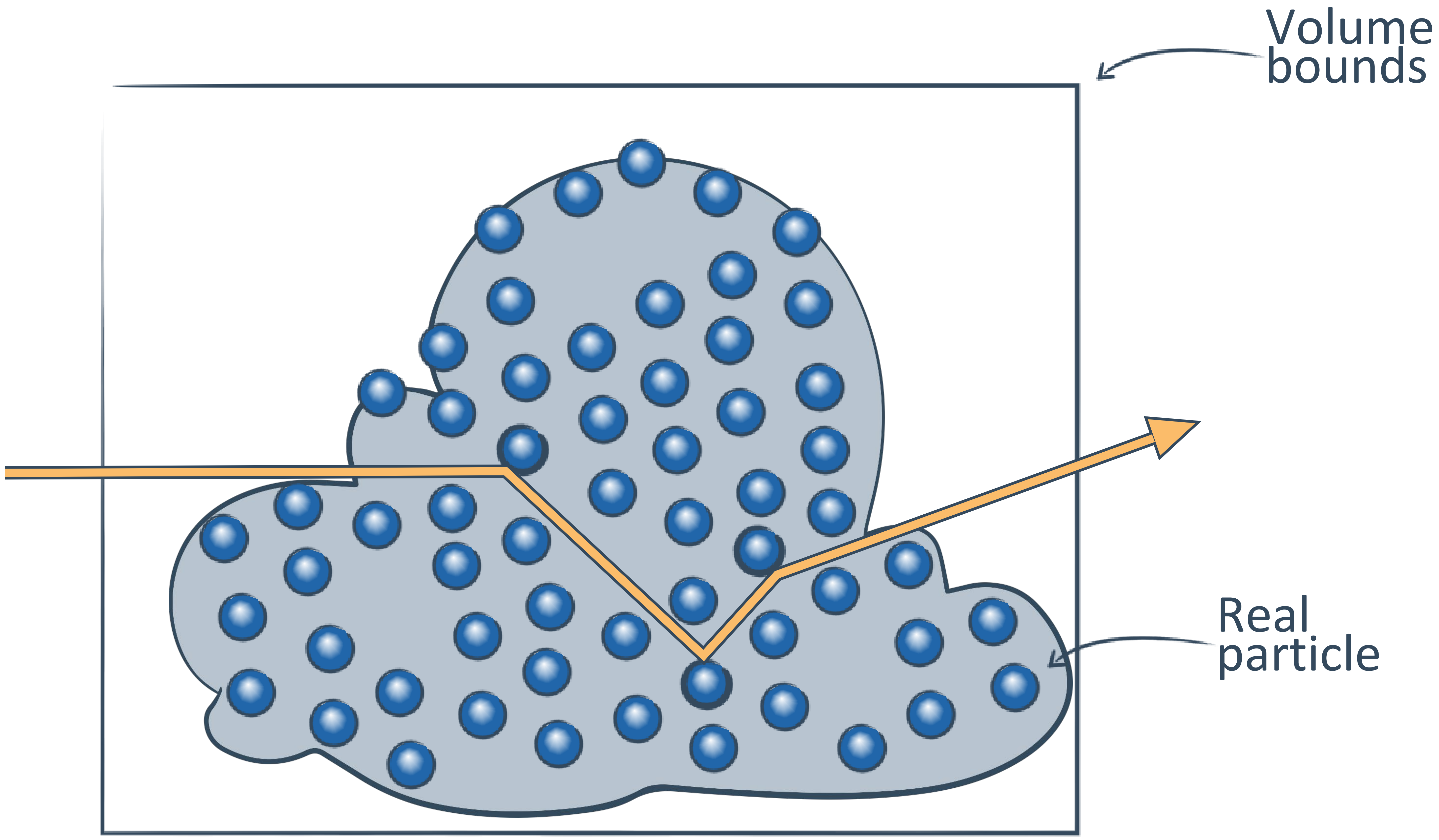
Homogenization



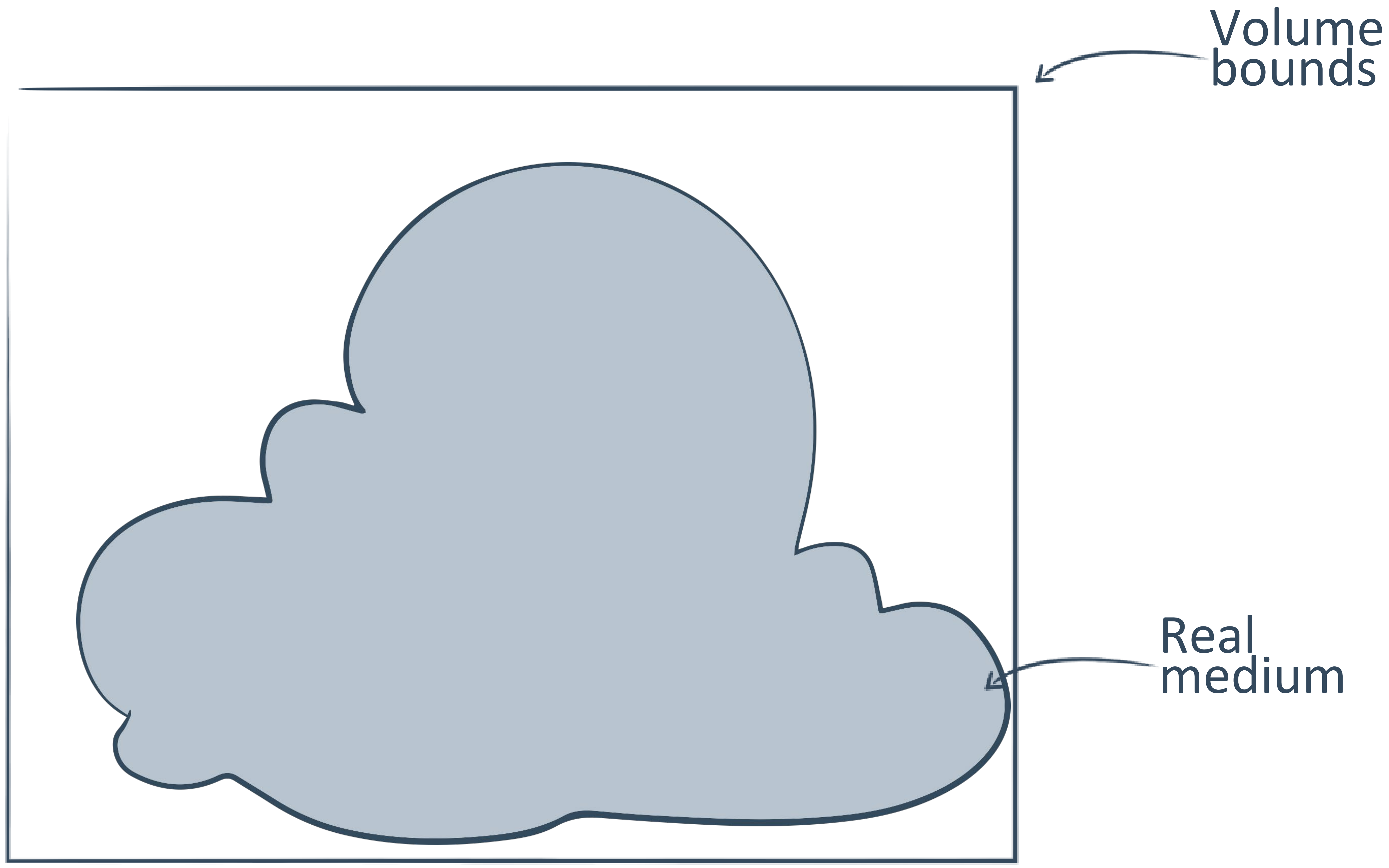
Homogenization



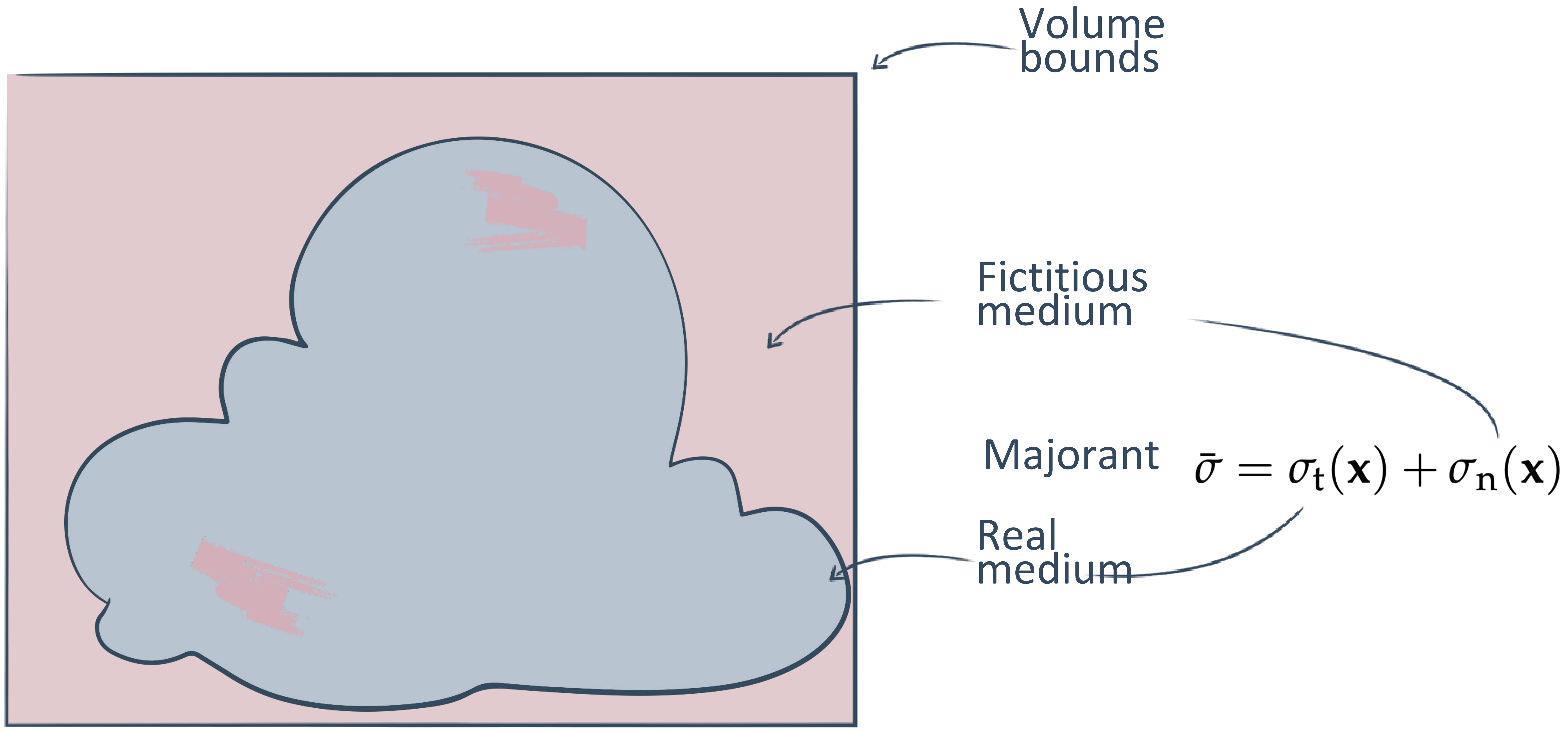
Homogenization



Stochastic Sampling

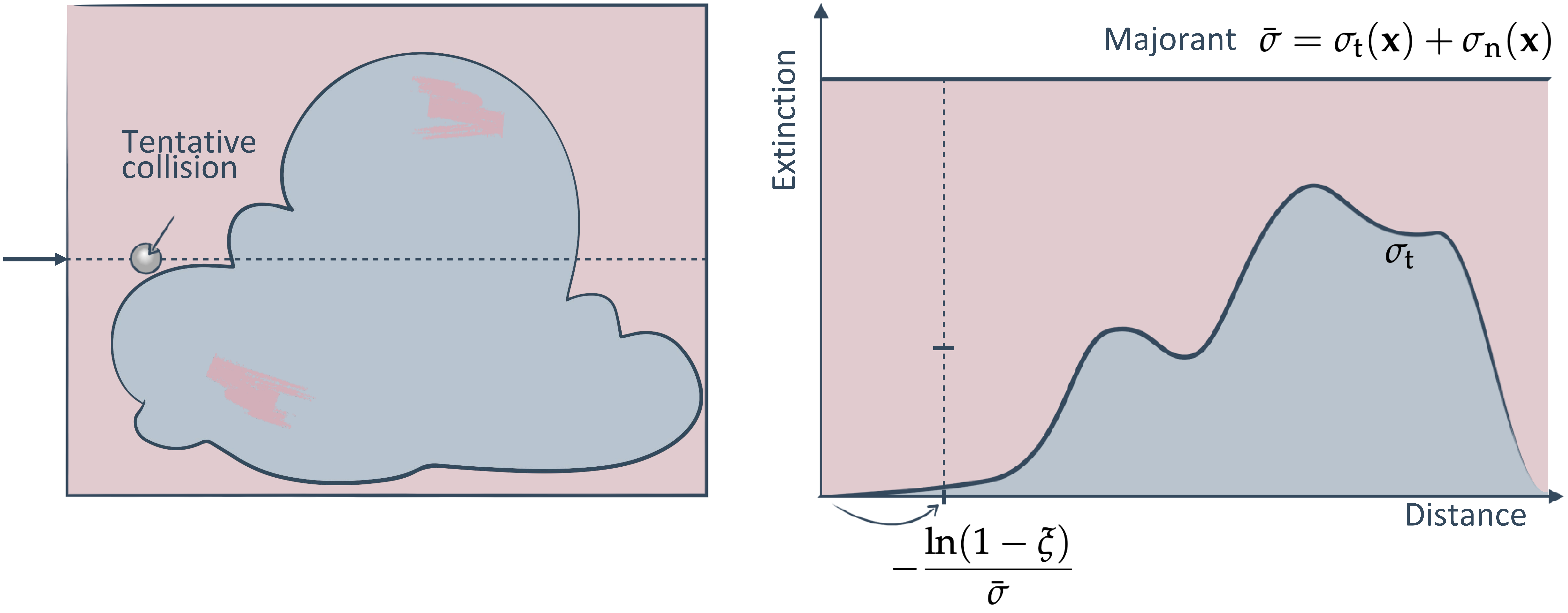


Stochastic Sampling



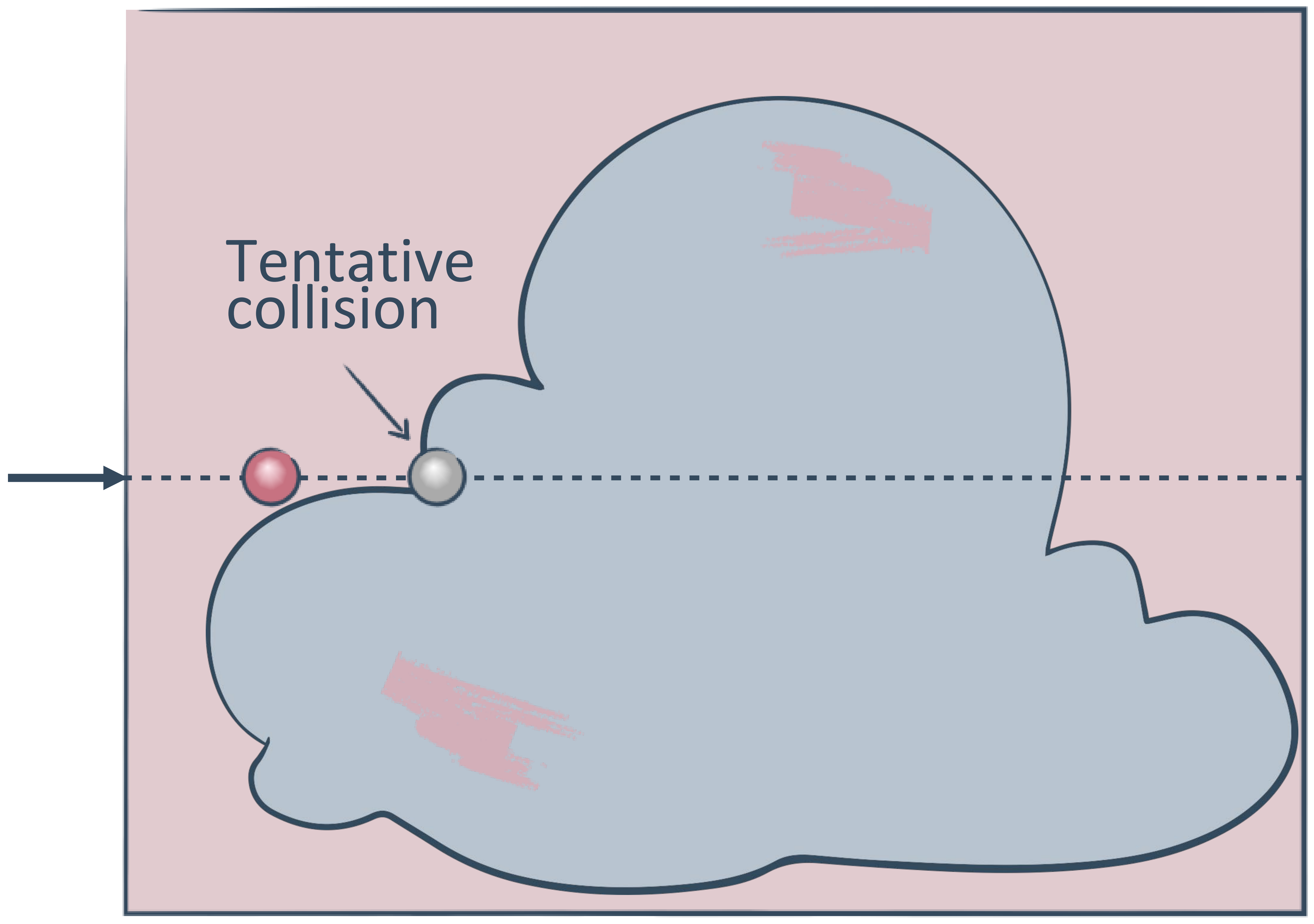
Stochastic Sampling

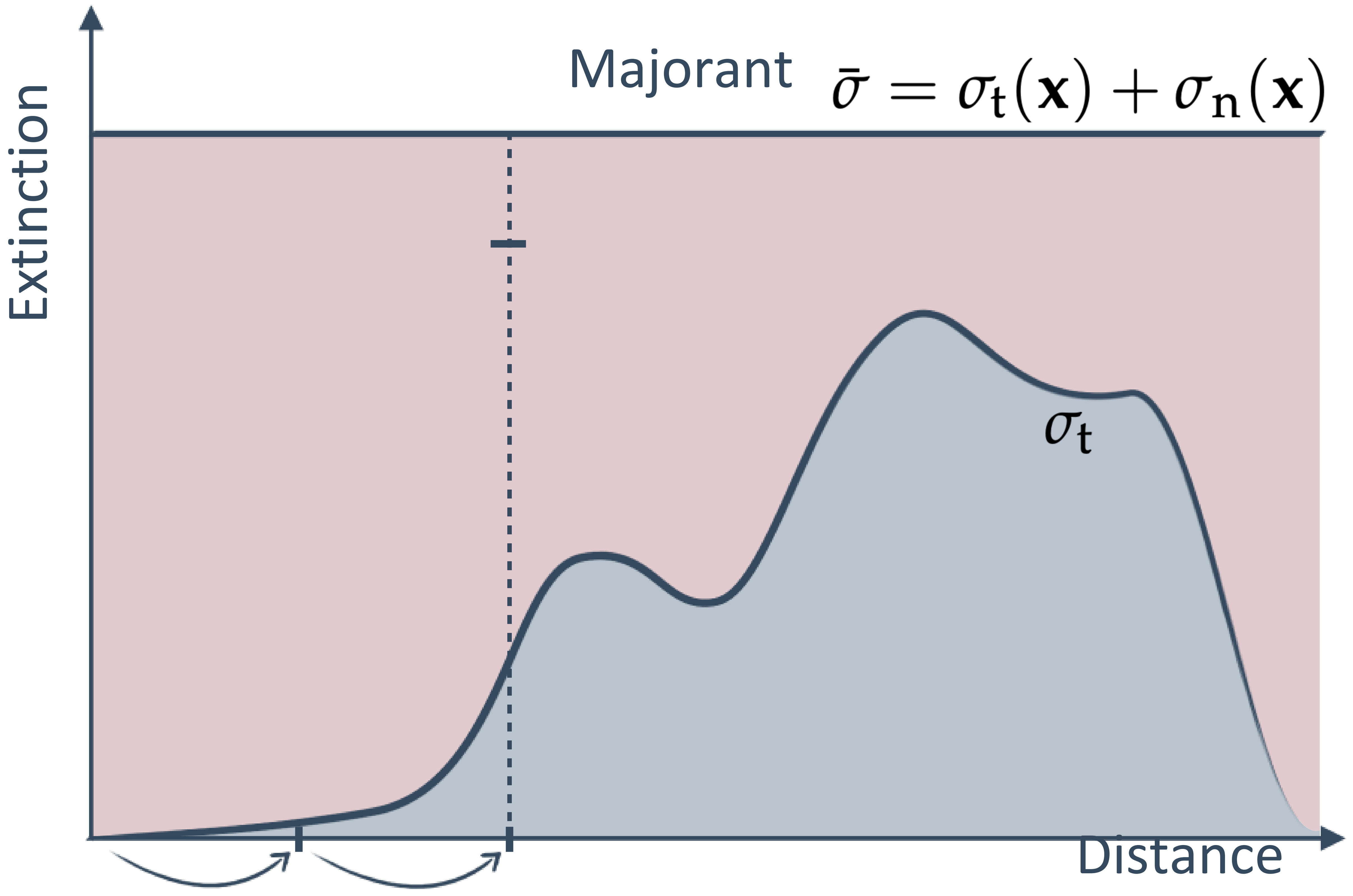
$$P_{\mathrm{r}}(\mathbf{x}) = \frac{\sigma_{\mathrm{t}}(\mathbf{x})}{\bar{\sigma}} \qquad P_{\mathrm{n}}(\mathbf{x}) = \frac{\sigma_{\mathrm{n}}(\mathbf{x})}{\bar{\sigma}}$$



Stochastic Sampling

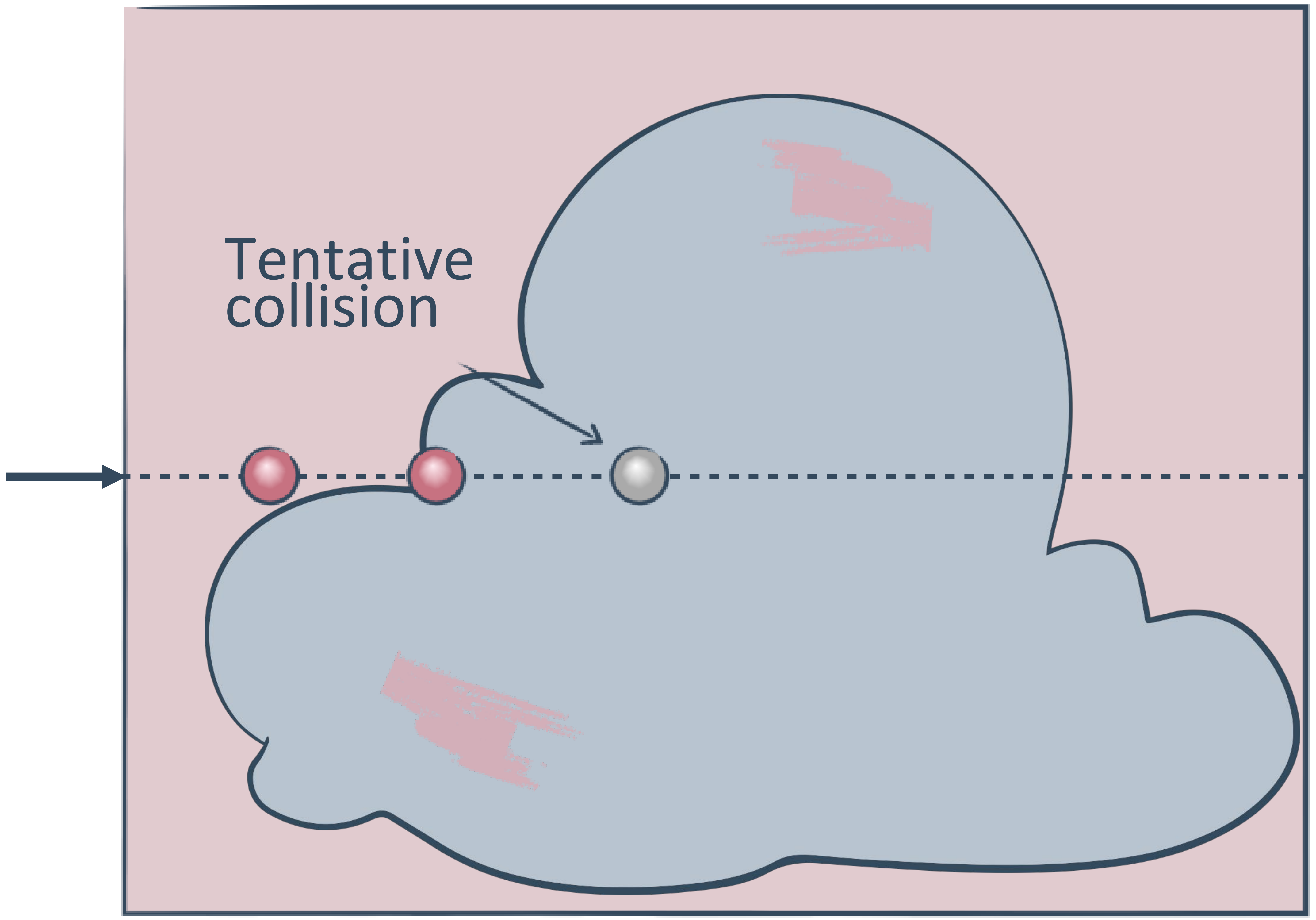
$$P_{\mathrm{r}}(\mathbf{x}) = \frac{\sigma_{\mathrm{t}}(\mathbf{x})}{\bar{\sigma}} \qquad P_{\mathrm{n}}(\mathbf{x}) = \frac{\sigma_{\mathrm{n}}(\mathbf{x})}{\bar{\sigma}}$$

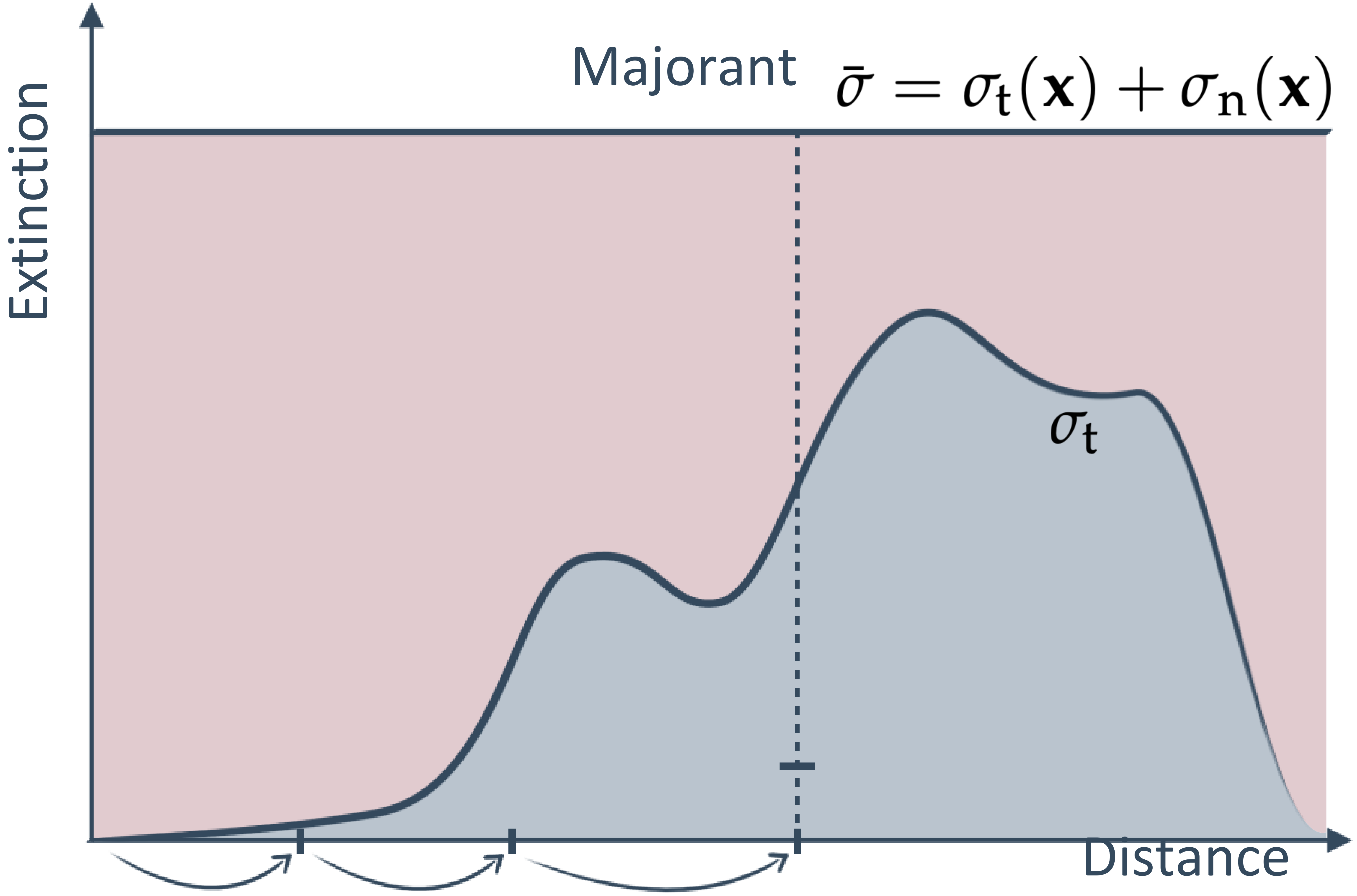




Stochastic Sampling

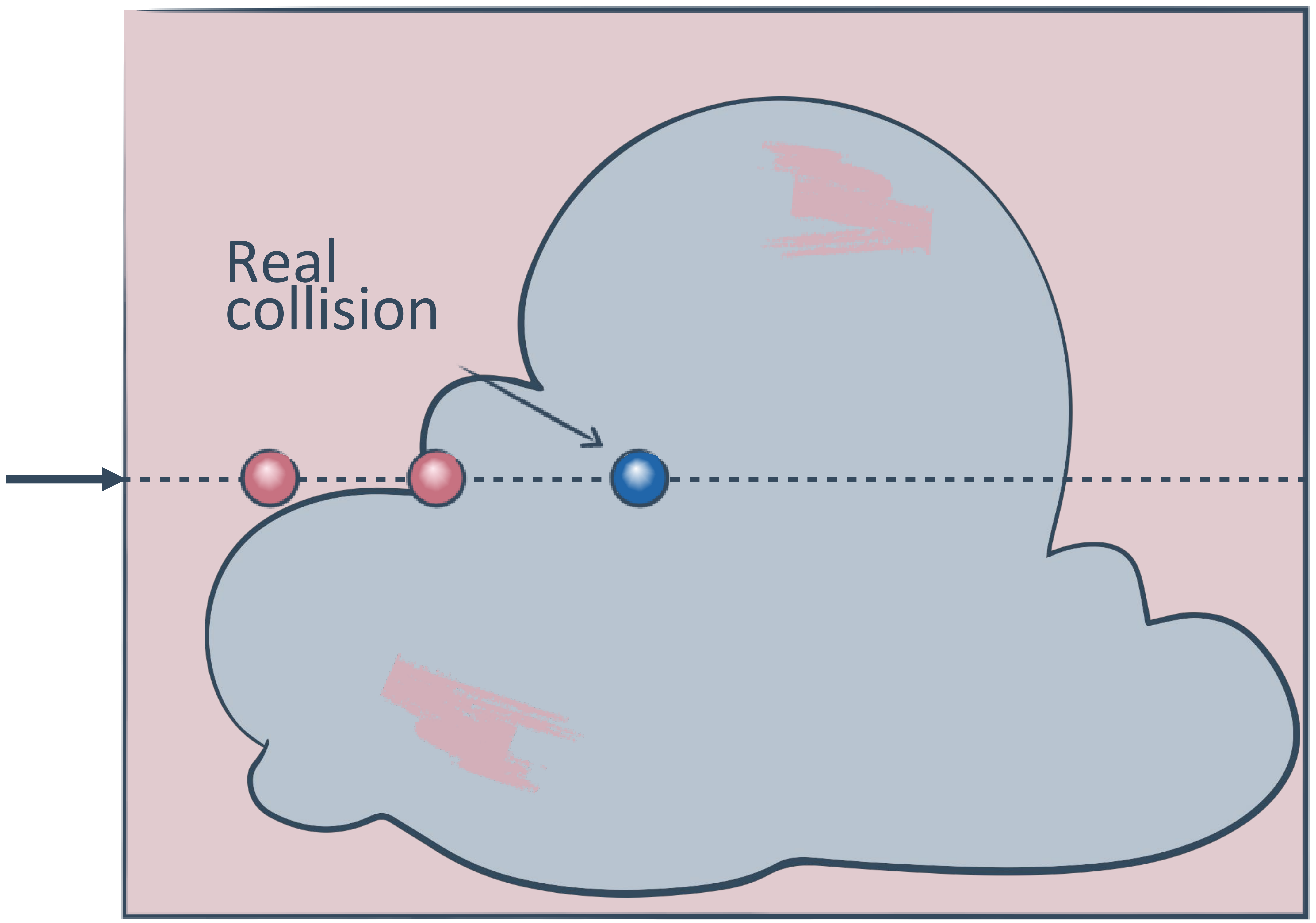
$$P_\mathrm{r}(\mathbf{x}) = \frac{\sigma_\mathrm{t}(\mathbf{x})}{\bar{\sigma}} \qquad P_\mathrm{n}(\mathbf{x}) = \frac{\sigma_\mathrm{n}(\mathbf{x})}{\bar{\sigma}}$$

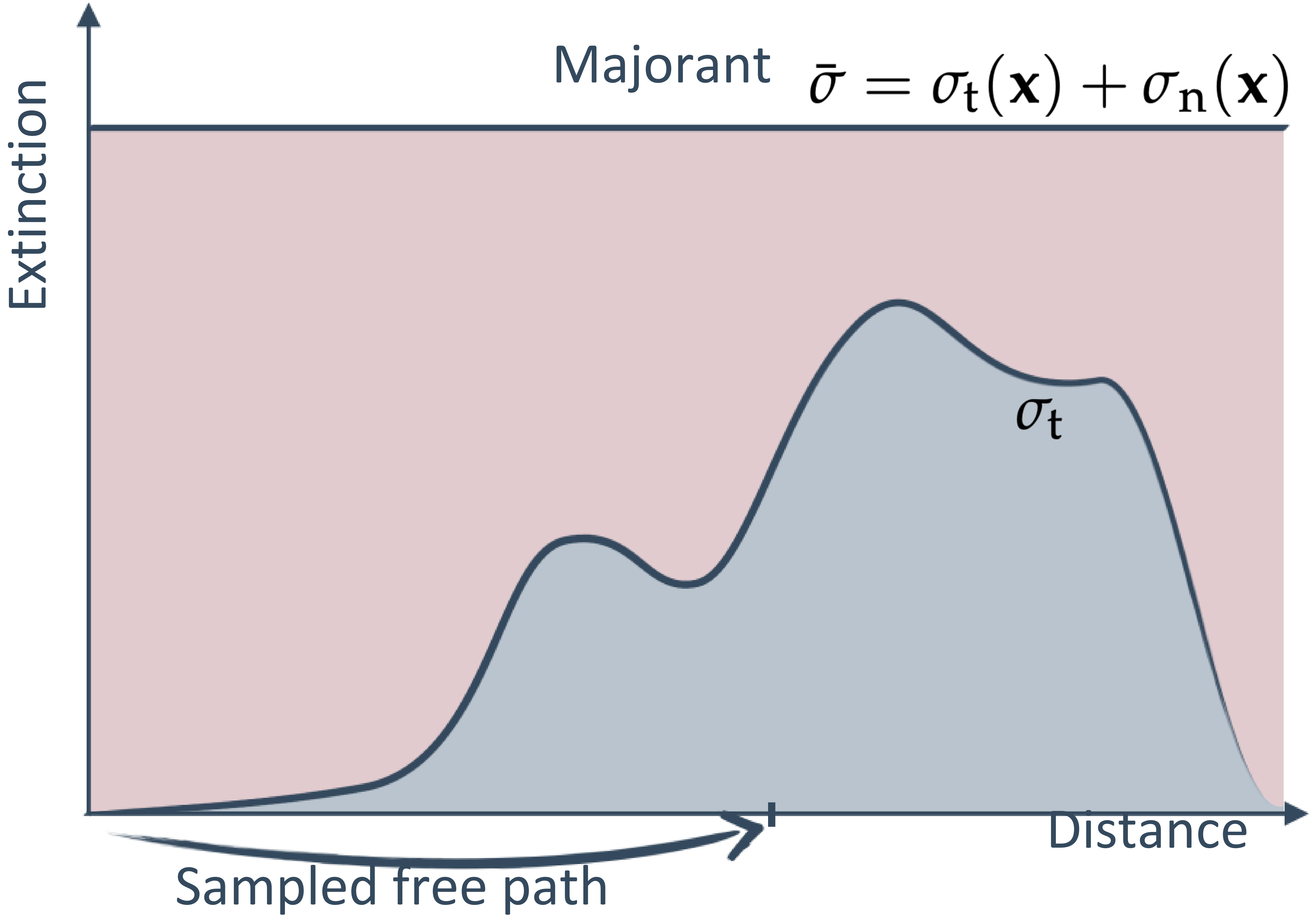




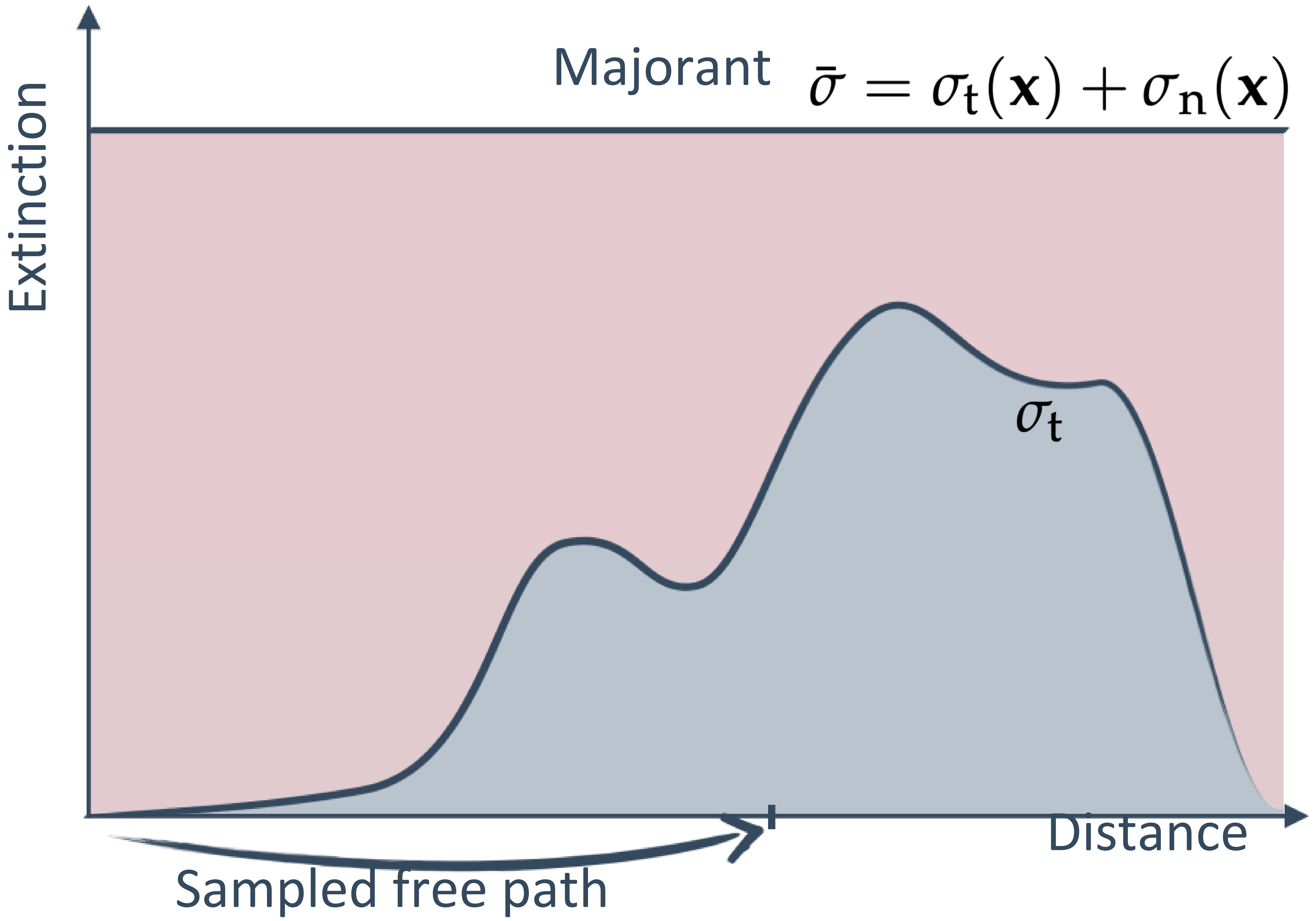
Stochastic Sampling

$$P_{\mathrm{r}}(\mathbf{x}) = \frac{\sigma_{\mathrm{t}}(\mathbf{x})}{\bar{\sigma}} \qquad P_{\mathrm{n}}(\mathbf{x}) = \frac{\sigma_{\mathrm{n}}(\mathbf{x})}{\bar{\sigma}}$$



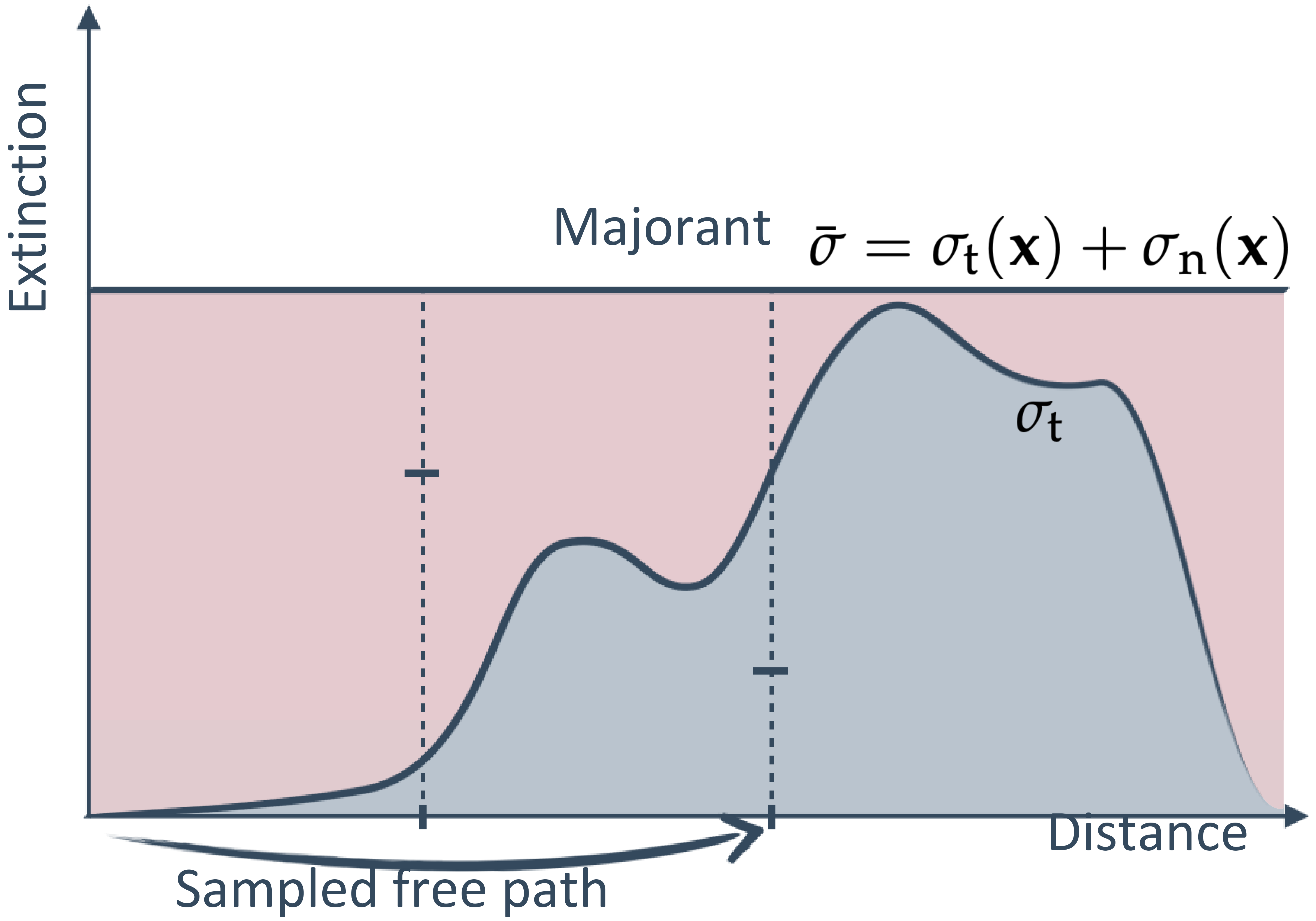


Impact of Majorant



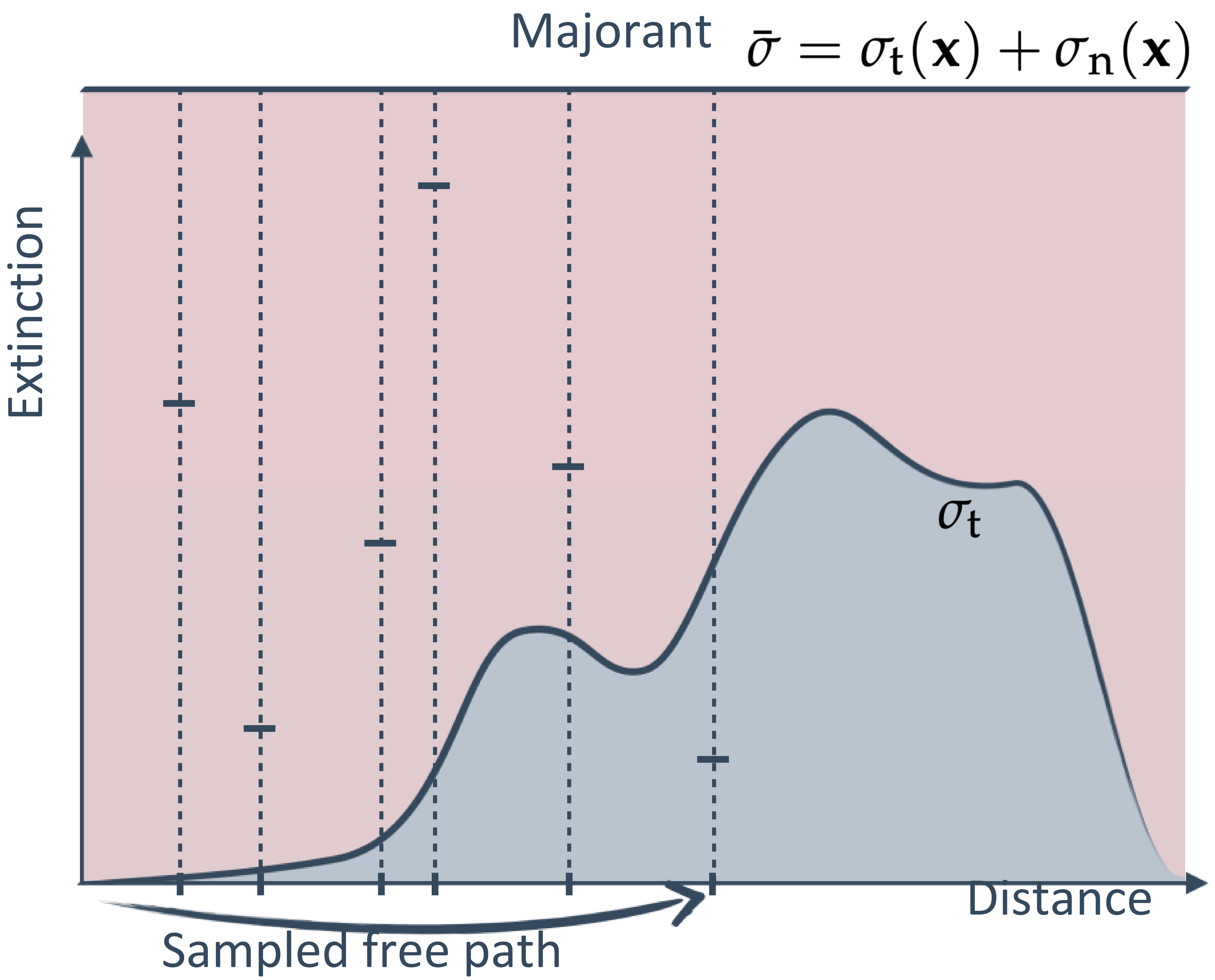
Impact of Majorant

Tight majorant = GOOD
(few rejected collisions)



Impact of Majorant

Loose majorant = BAD
(many expensive rejected collisions)



Delta Tracking

```
void preprocess()
majorant = findMaximumExtinction()

void sampleFreePath(x, ω)
t = 0
do:
// Sample distance to next tentative collision
t += -ln(1 - randf()) / majorant
// Compute probability of a real collision
Pr = getExtinction(x + t*ω) / majorant
while Pr < randf()
return t
```

Delta Tracking Summary

Unbiased, see [Coleman 68] for a proof

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Unbiased, see [Coleman 68] for a proof

Majorant extinction

- defines the combined homogeneous volume
- must bound the real extinction
- loose majorants lead to many fictitious collisions