State of the Art in Photon Density Estimation

Participating Media Basics

Wojciech Jarosz

Fog

Clouds & Crepuscular rays

Surface or Volume?

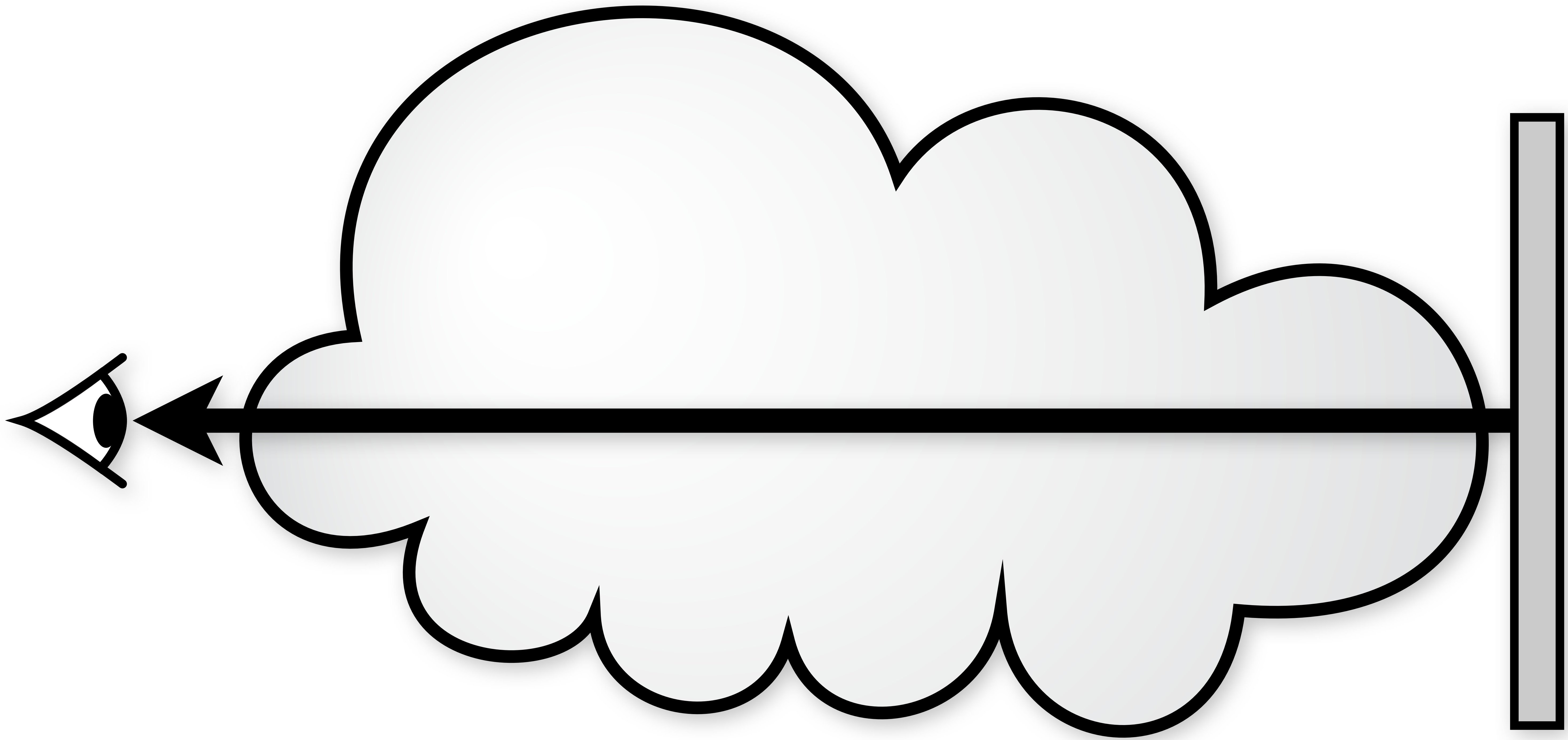
Surface or Volume?

Antelope Canyon, Az.

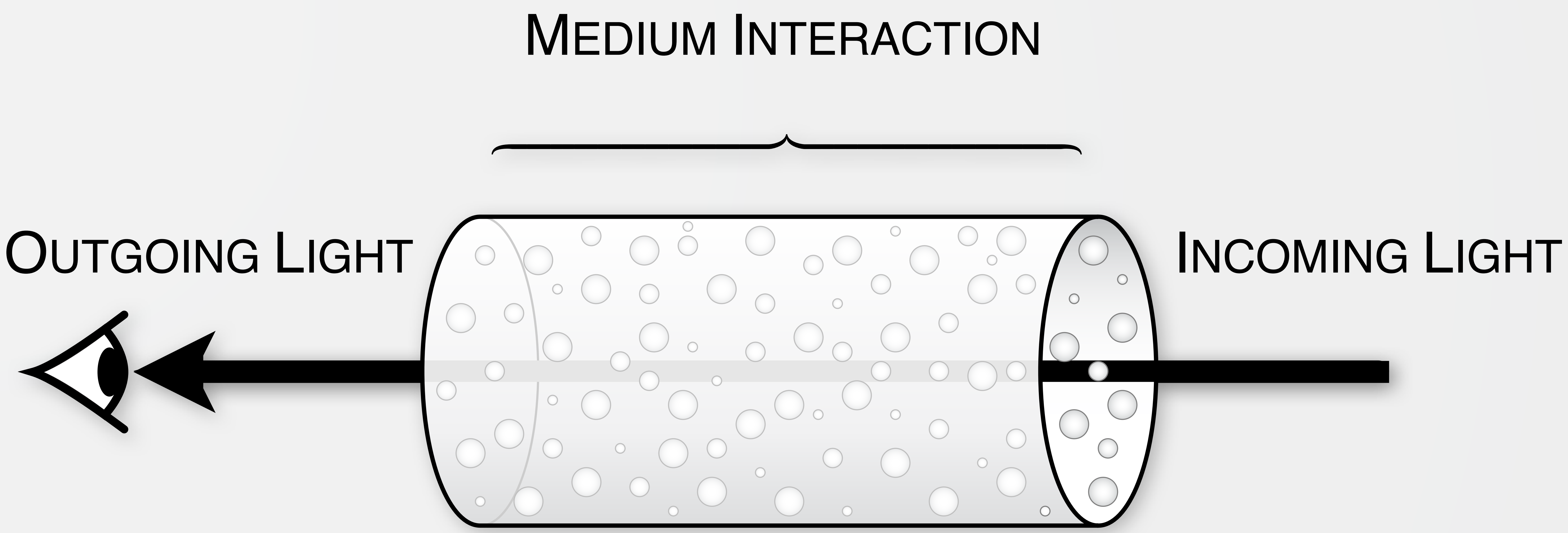
Outline

- Theoretical background
- Extending photon mapping to media

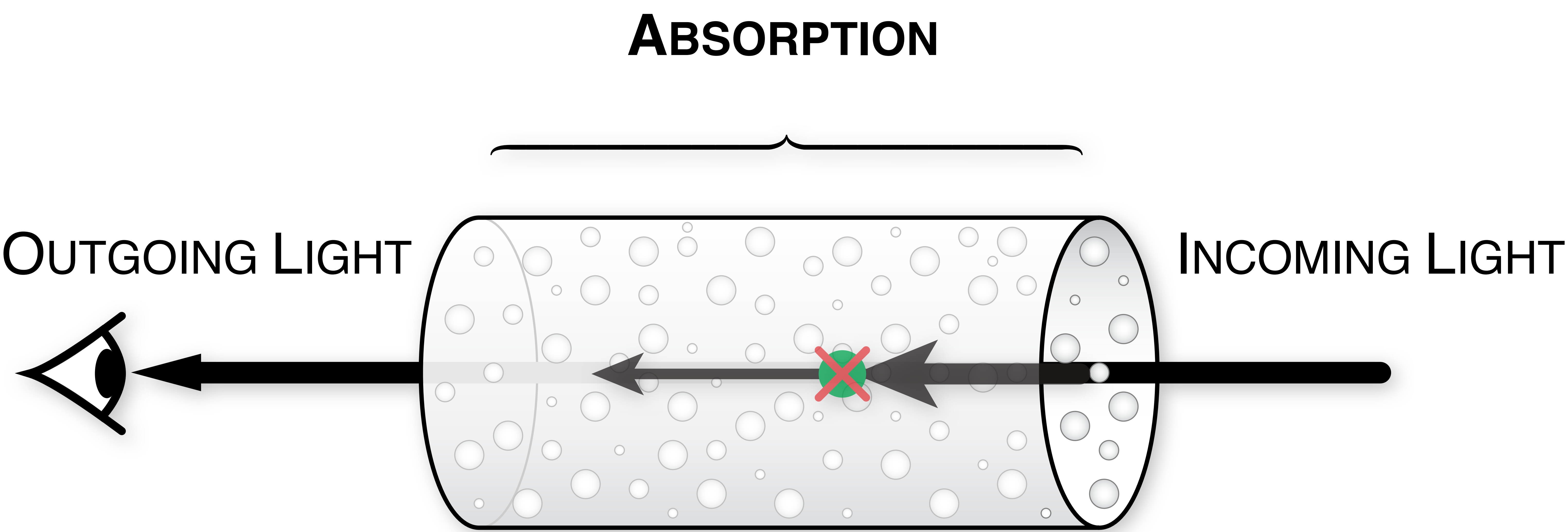
Participating Media



Participating Media

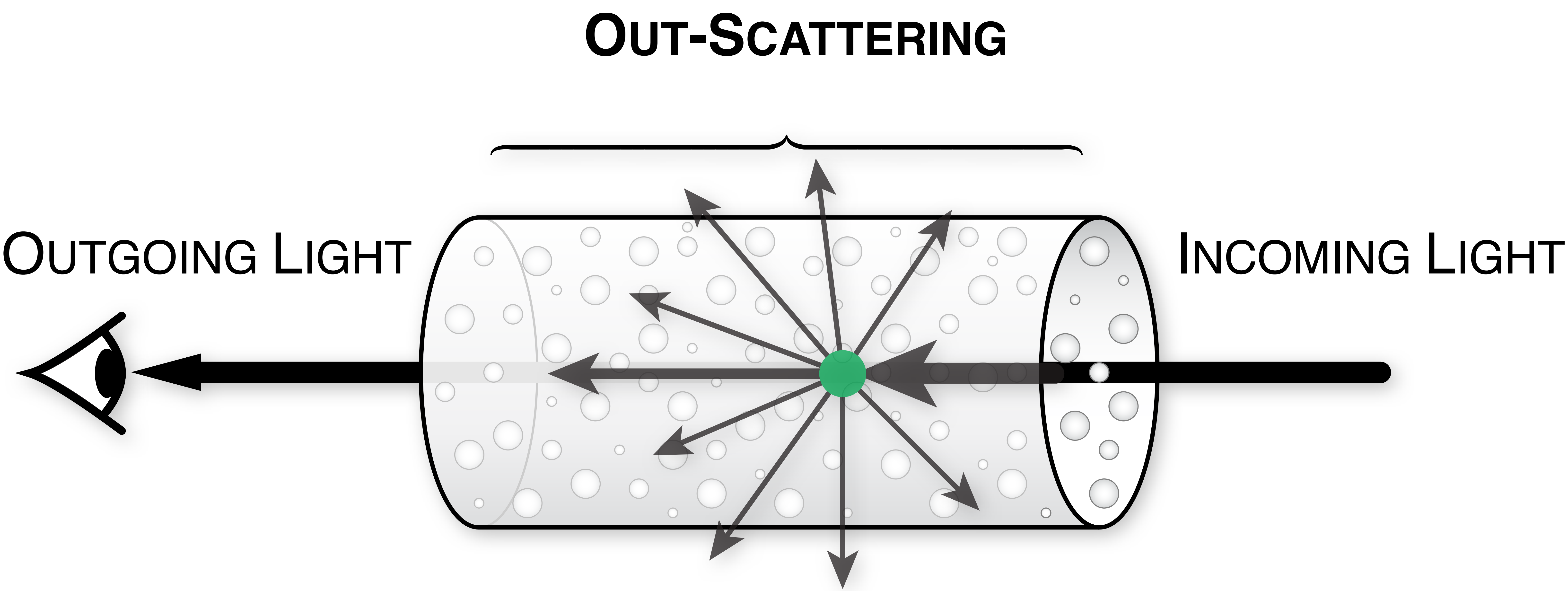


Participating Media



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

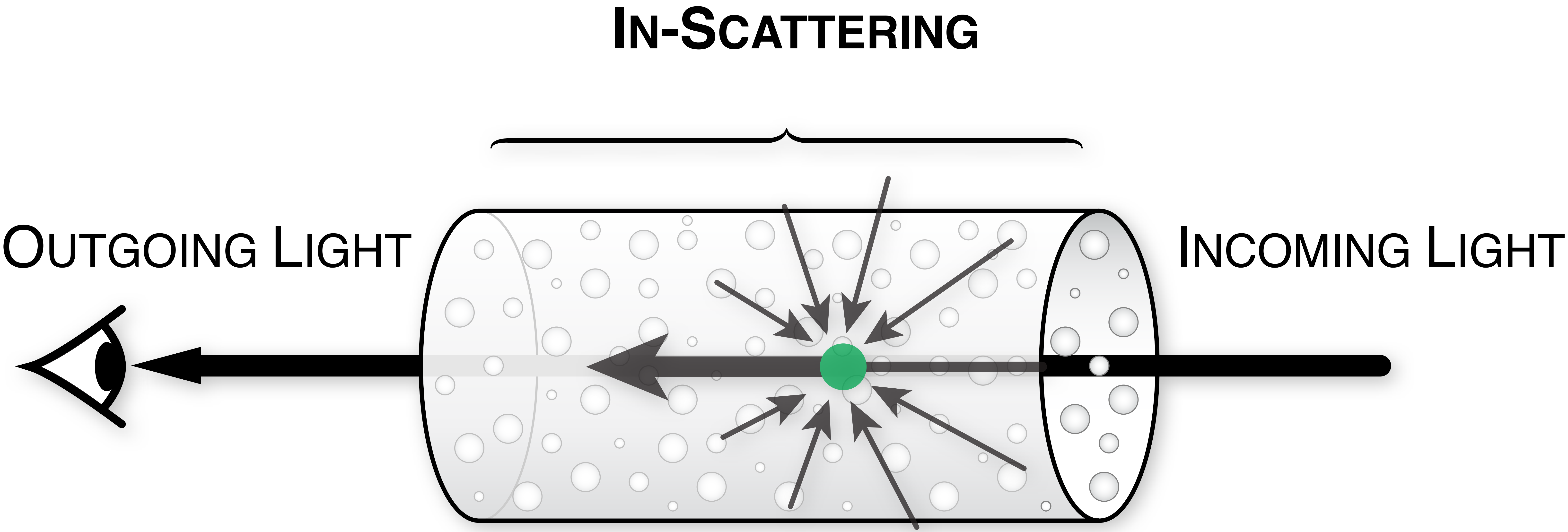
Participating Media



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

$p(\mathbf{x}, \vec{\omega}', \vec{\omega})$: phase function [1/sr]

Participating Media



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

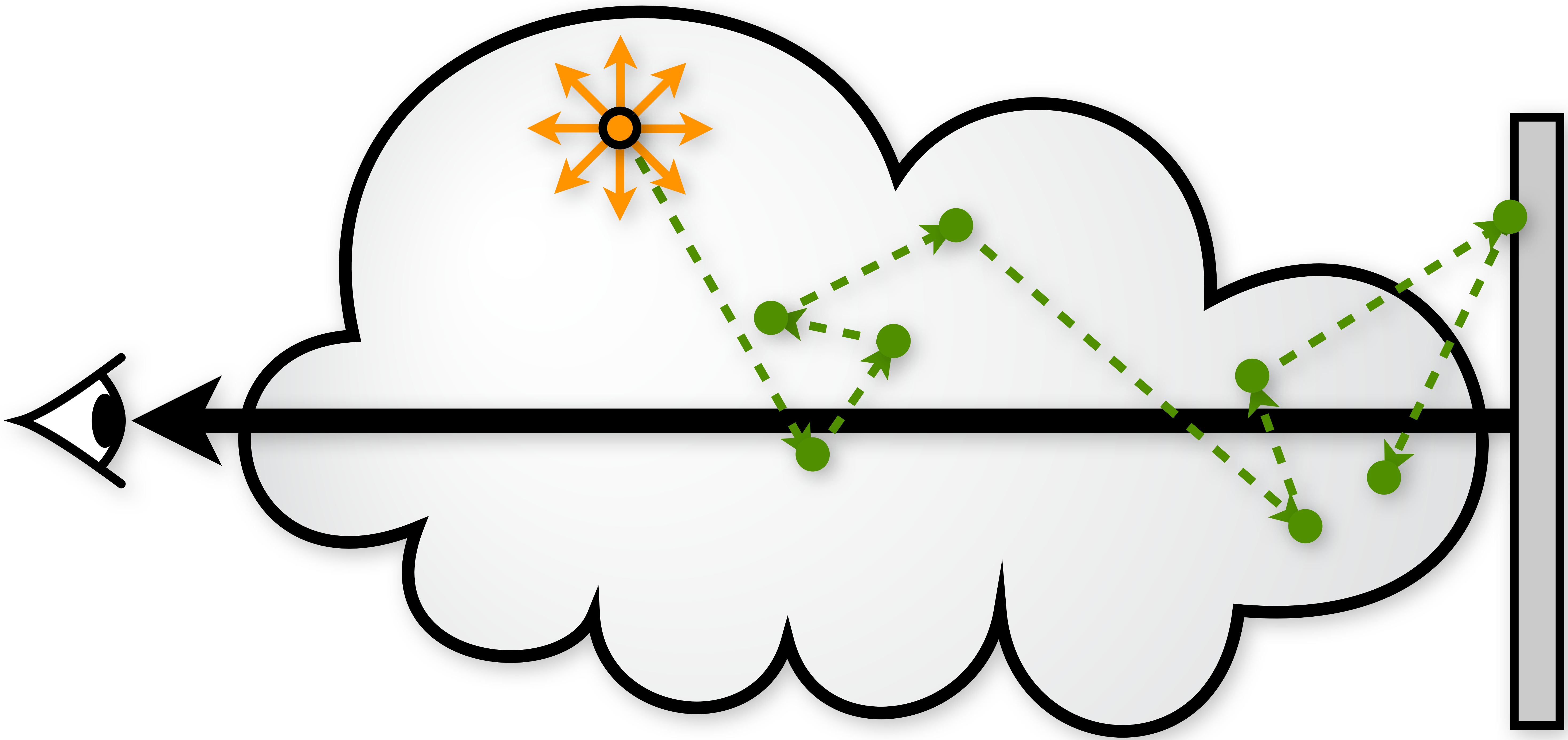
$p(\mathbf{x}, \vec{\omega}', \vec{\omega})$: phase function [1/sr]

Photon Mapping

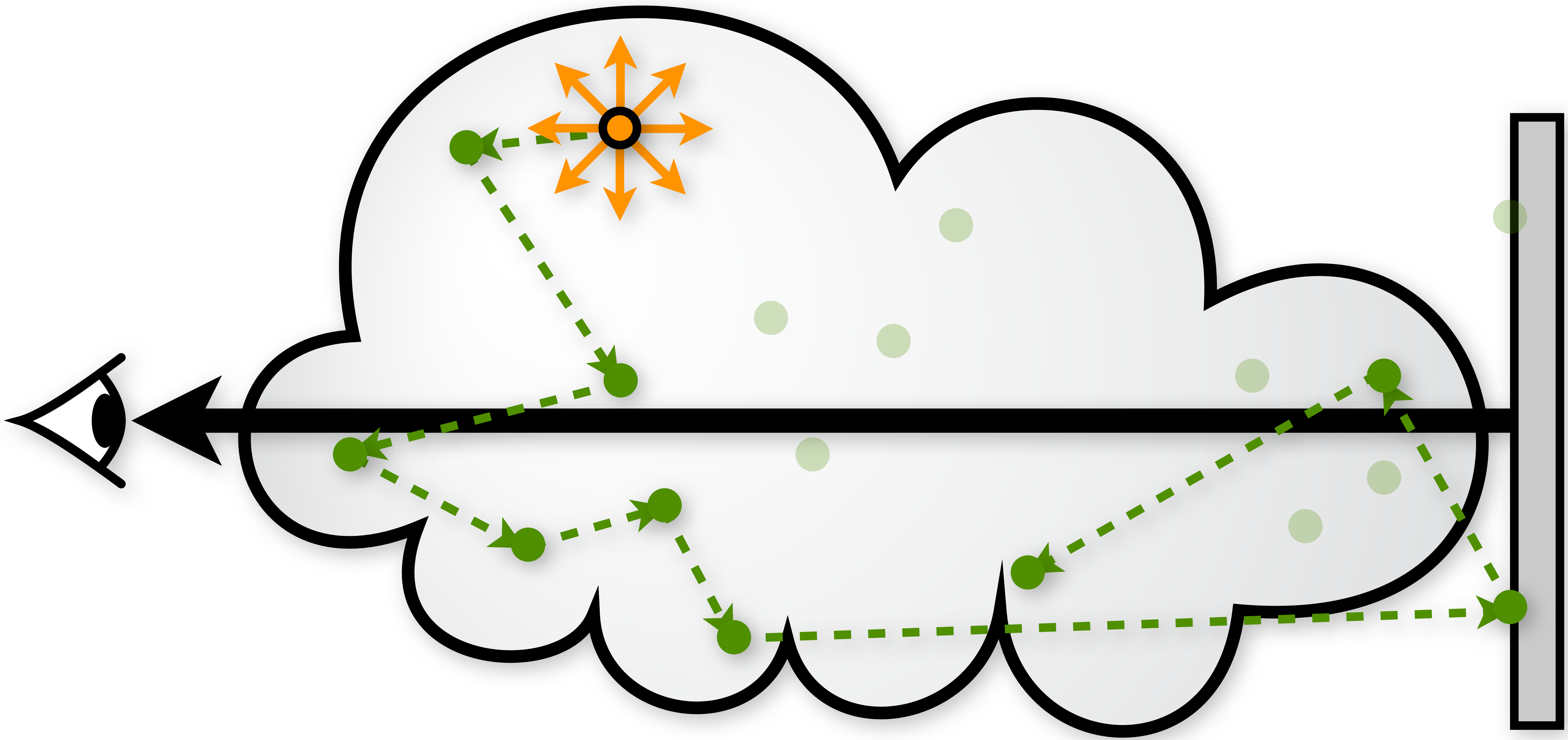
1) Photon tracing

2) Rendering / Radiance Estimation

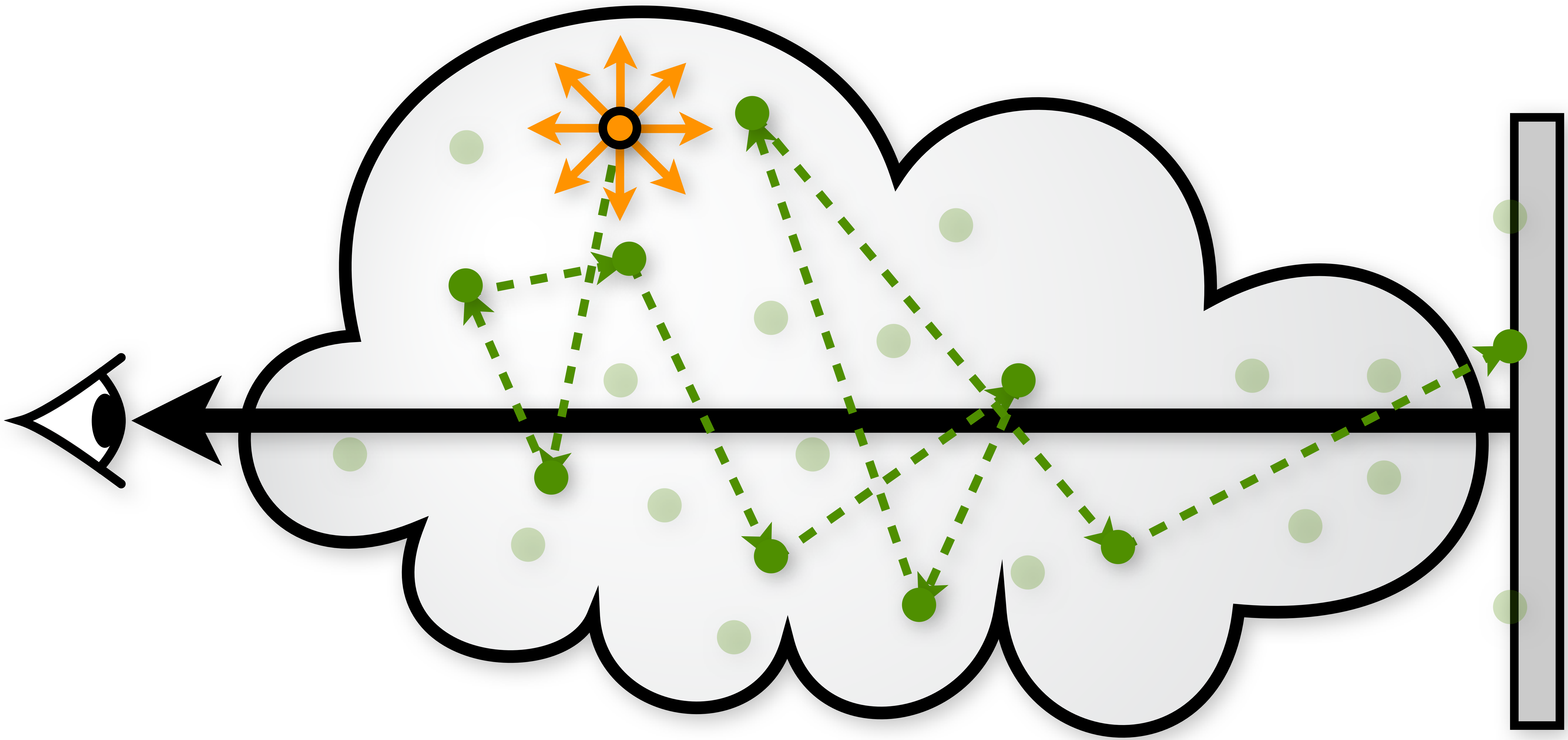
Photon Tracing in Participating Media



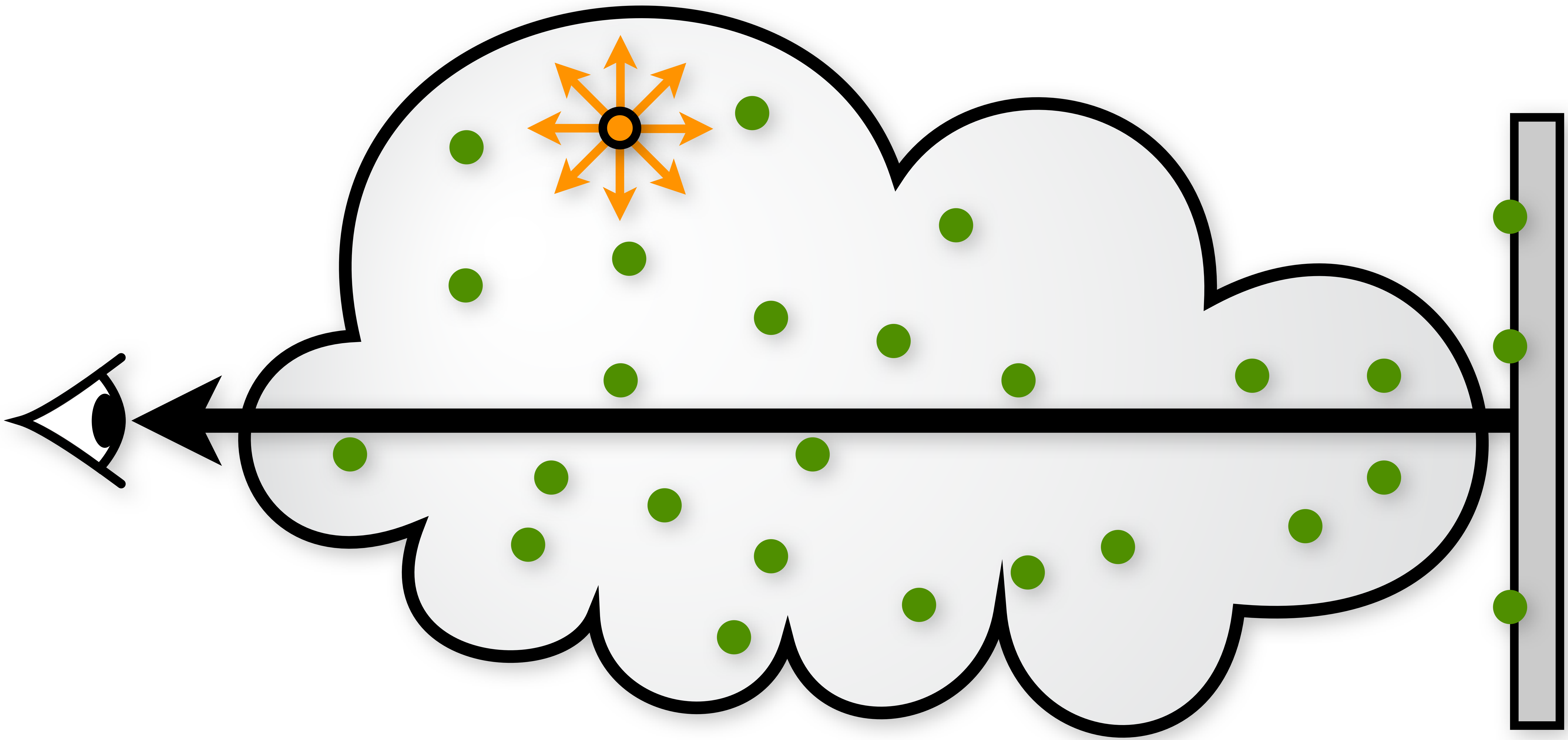
Photon Tracing in Participating Media



Photon Tracing in Participating Media

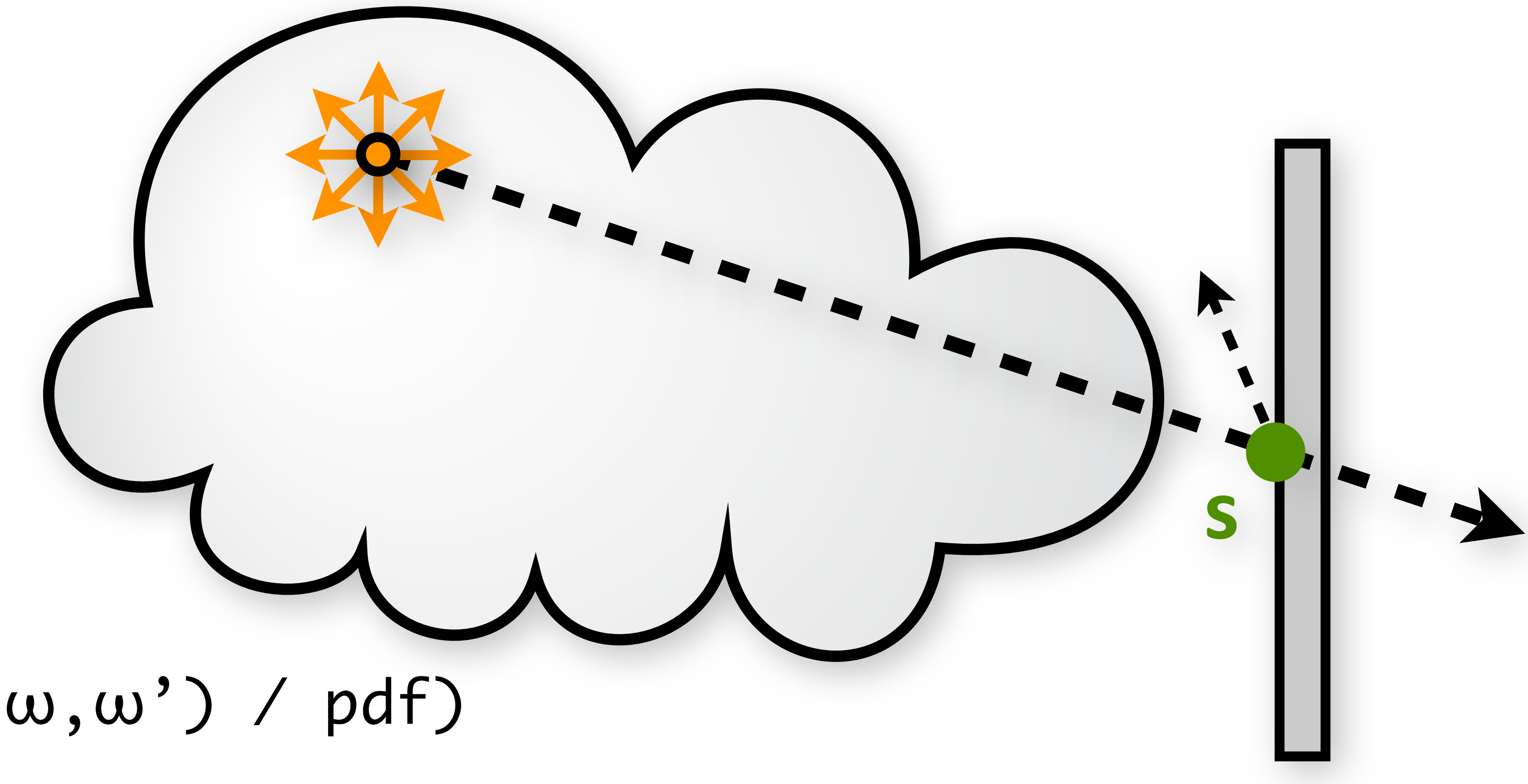


Photon Tracing in Participating Media



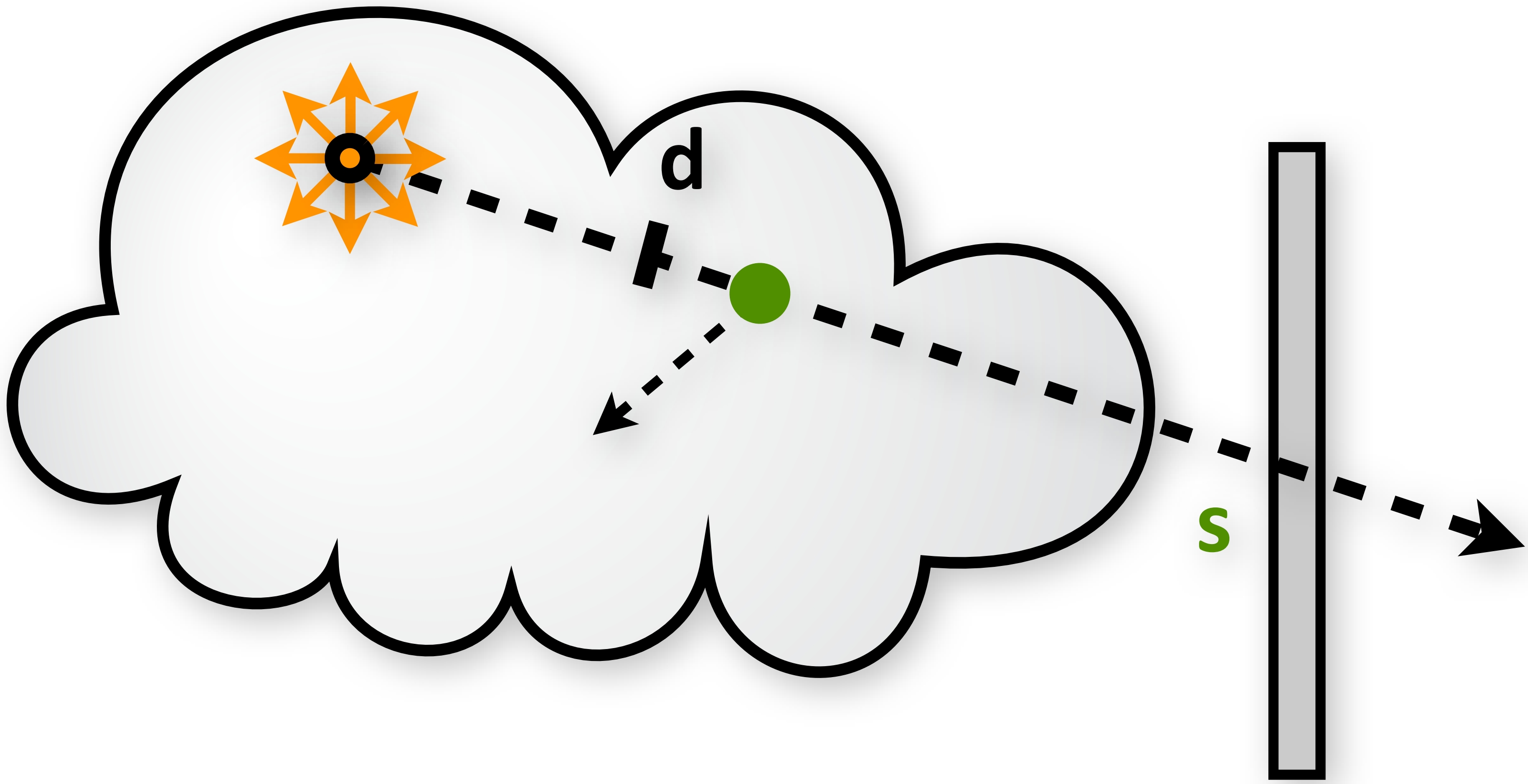
Basic Surface Photon Tracer

```
void tracePhoton(x, ω, Φ)
    s = nearestSurfaceHit(x, ω)
    x += s*ω          // propagate photon
    storeSurfacePhoton(x, ω, Φ)
    (ω', pdf) = sampleBxDF(x, ω)
    return tracePhoton(x, ω', Φ * BxDF(x,ω,ω') / pdf)
```

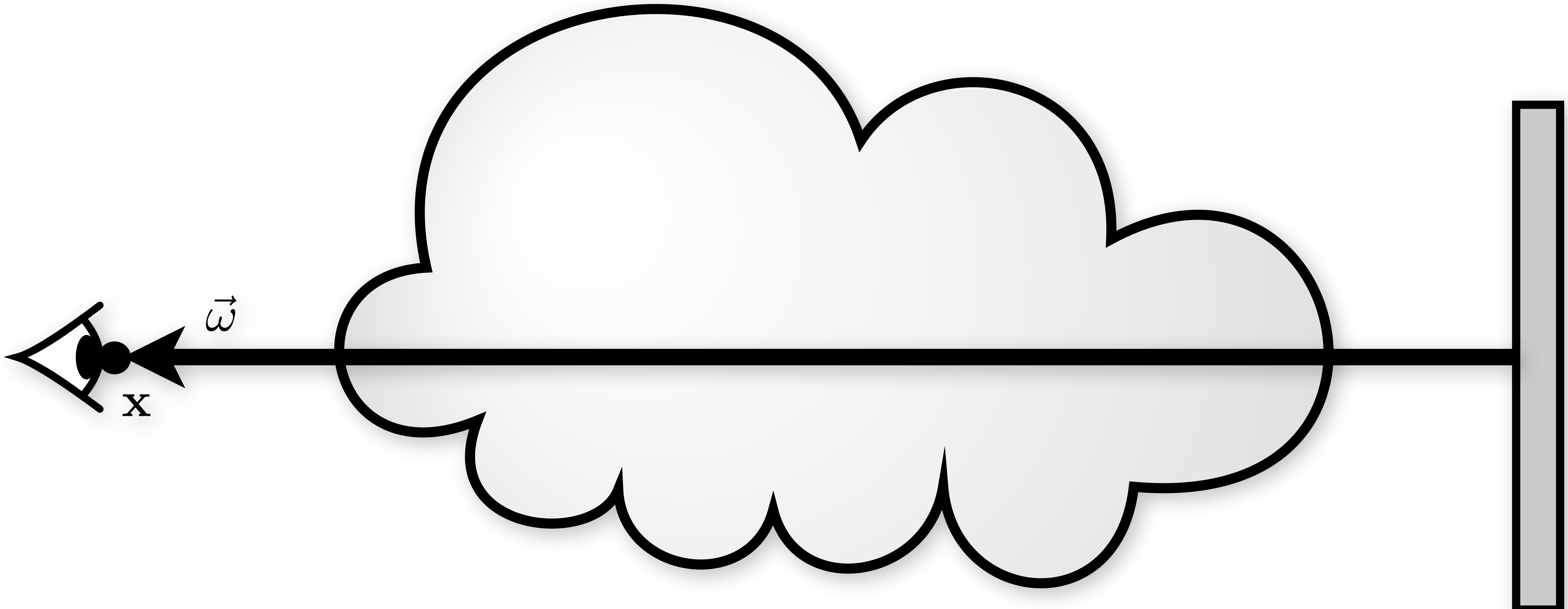


Basic Volumetric Photon Tracer

```
void tracePhoton(x, ω, Φ)
    s = nearestSurfaceHit(x, ω)
    d = freeFlightDistance(x, ω)
    if (d < s)          // media scattering
        x += d*ω        // propagate photon
        storeVolumePhoton(x, ω, Φ)
        return tracePhoton(x, samplePF(), Φ * σs / σt)
    else                // surface scattering
        x += s*ω        // propagate photon
        storeSurfacePhoton(x, ω, Φ)
        (ω', pdf) = sampleBxDF(x, ω)
        return tracePhoton(x, ω', Φ * BxDF(x,ω,ω') / pdf)
```

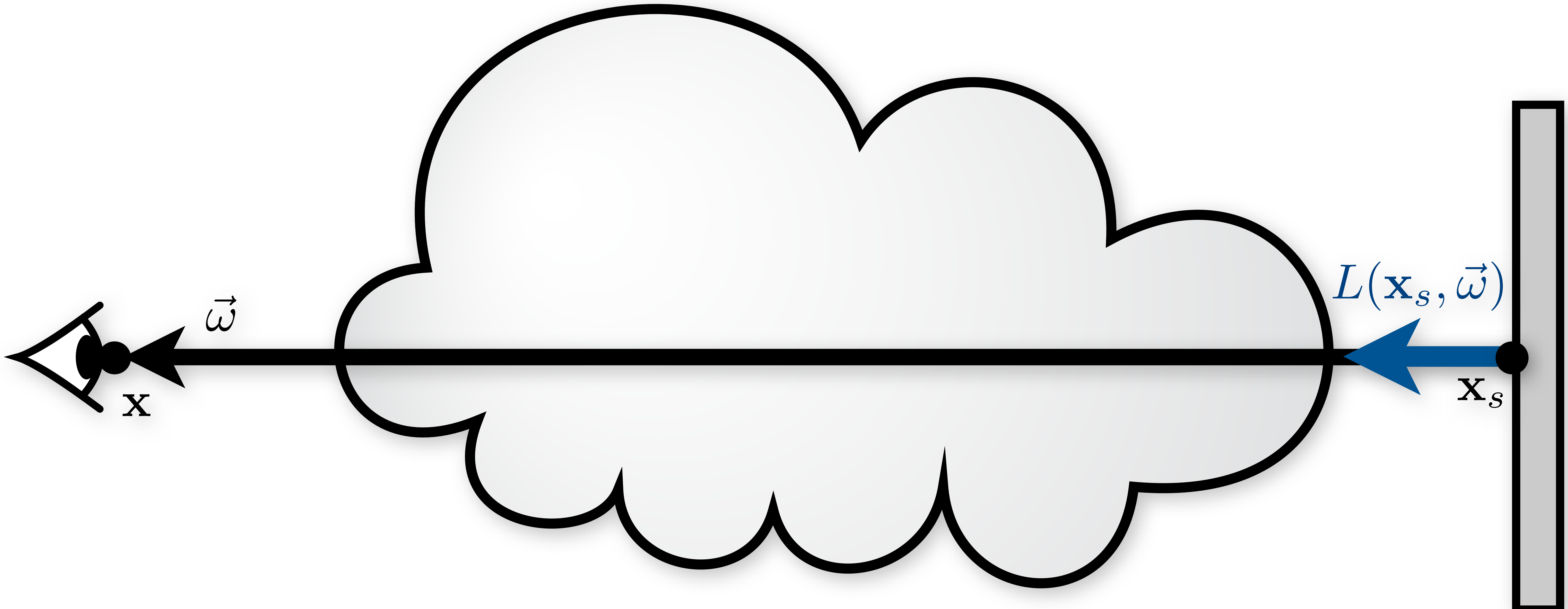


Volume Rendering Equation



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

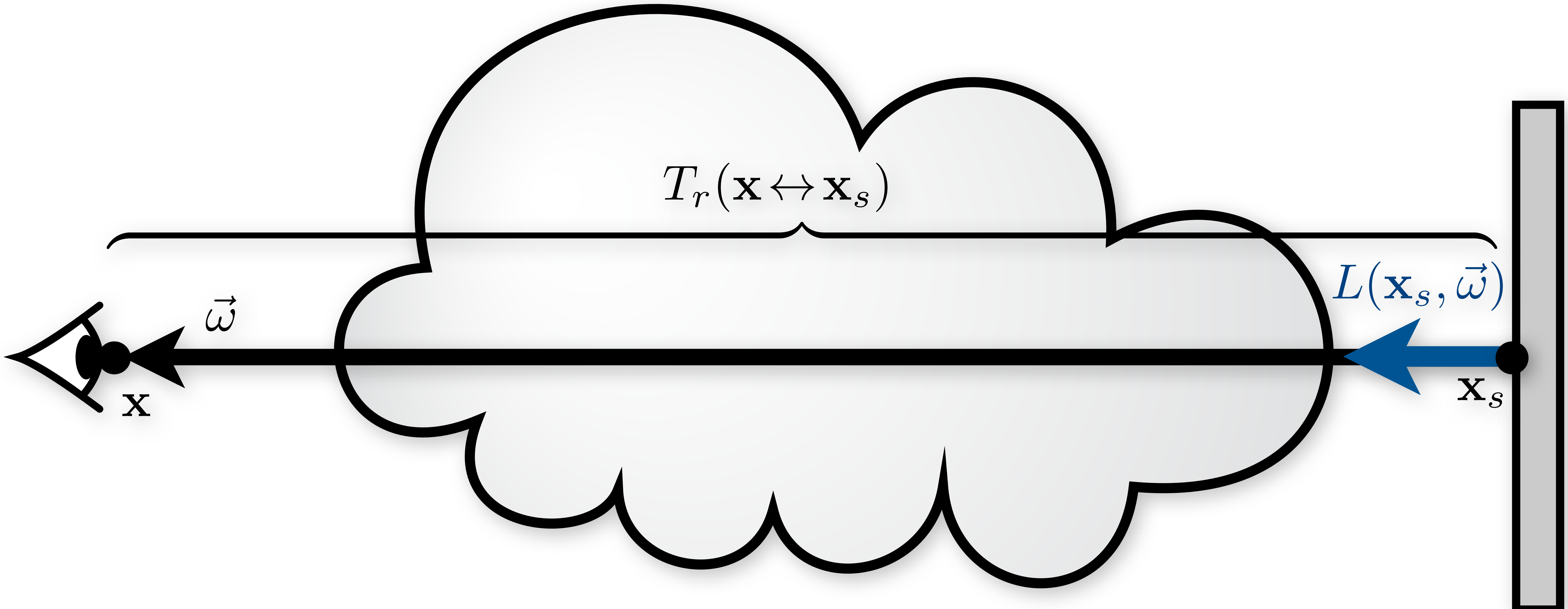
Volume Rendering Equation



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

Reduced surface radiance

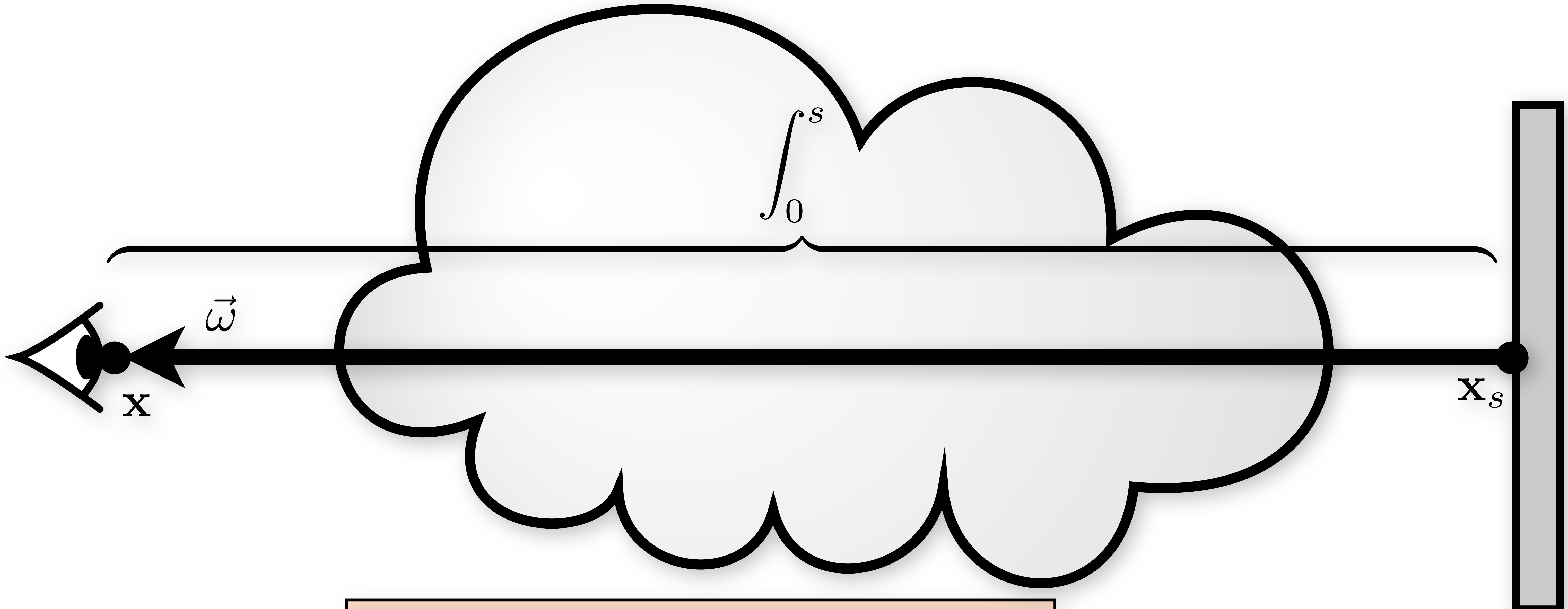
Volume Rendering Equation



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

Transmittance: fractional visibility between two points

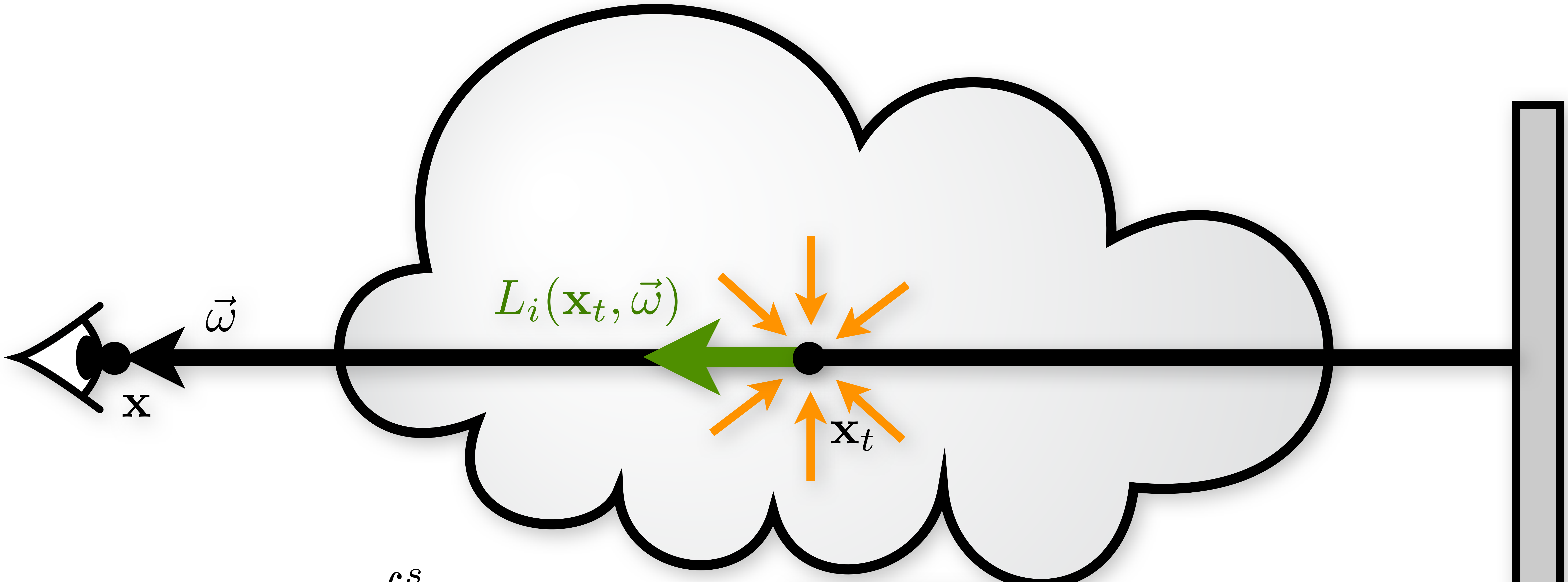
Volume Rendering Equation



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

Accumulated in-scattered radiance

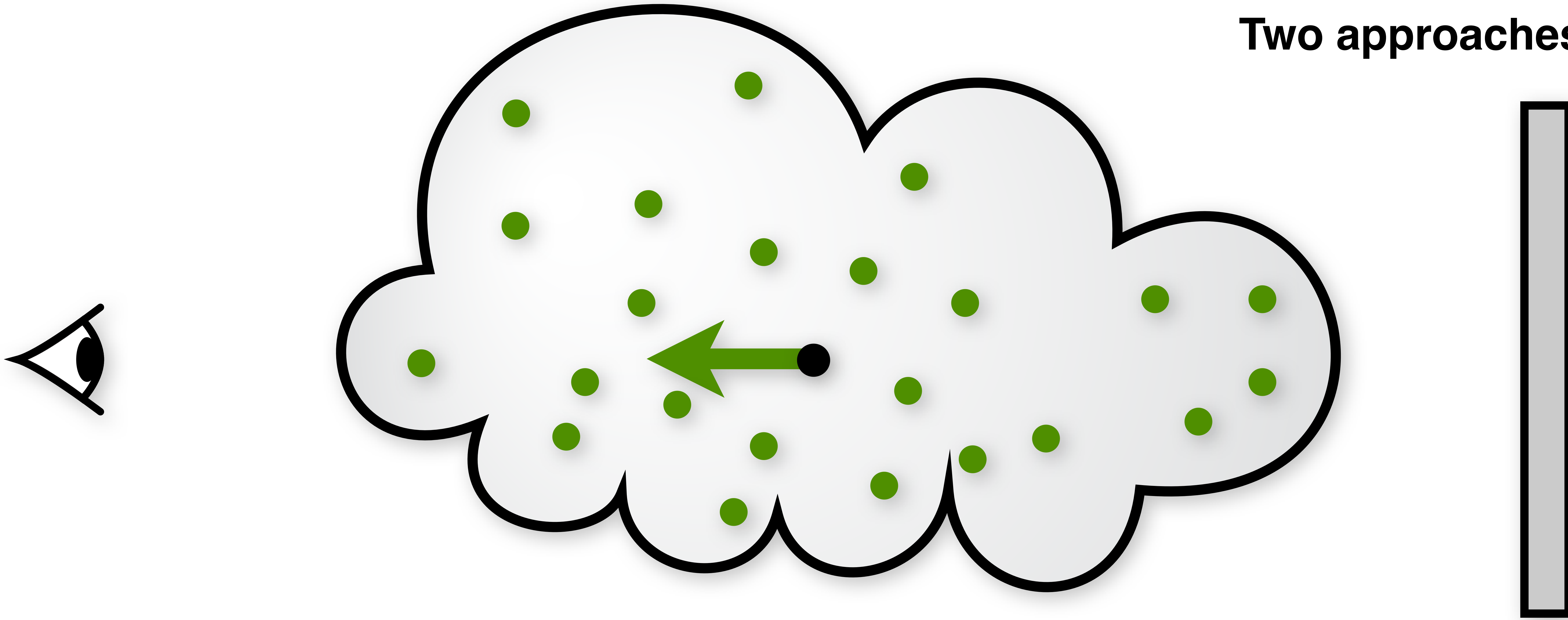
Volume Rendering Equation



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

$$\boxed{L_i(\mathbf{x}_t, \vec{\omega})} = \int_{\Omega_{4\pi}} p(\mathbf{x}_t, \vec{\omega}_t, \vec{\omega})L(\mathbf{x}_t, \vec{\omega}_t)\, d\omega_t$$

Volume Rendering Equation

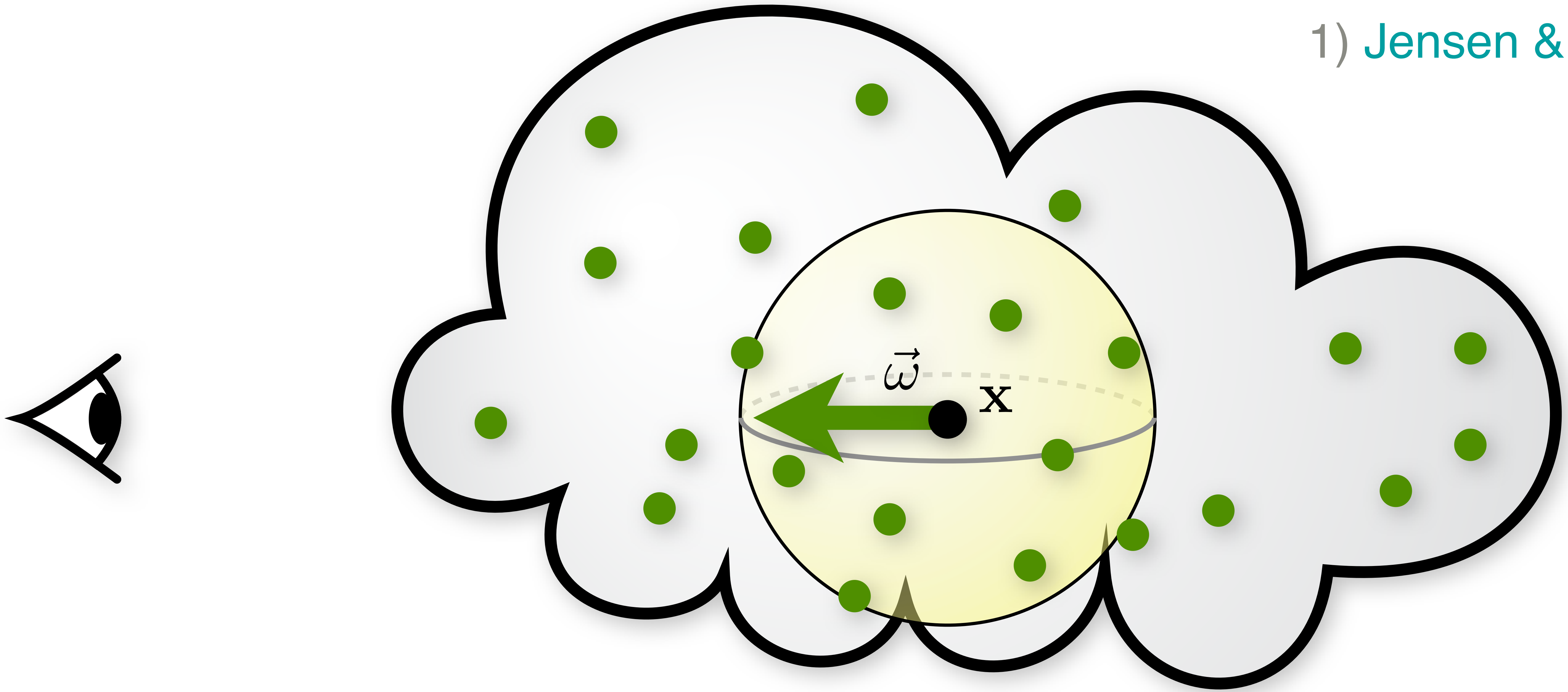


Two approaches

$$L_i(\mathbf{x}_t, \vec{\omega}) = \int_{\Omega_{4\pi}} p(\mathbf{x}_t, \vec{\omega}_t, \vec{\omega}) L(\mathbf{x}_t, \vec{\omega}_t)\, d\omega_t$$

Volumetric Radiance Estimate

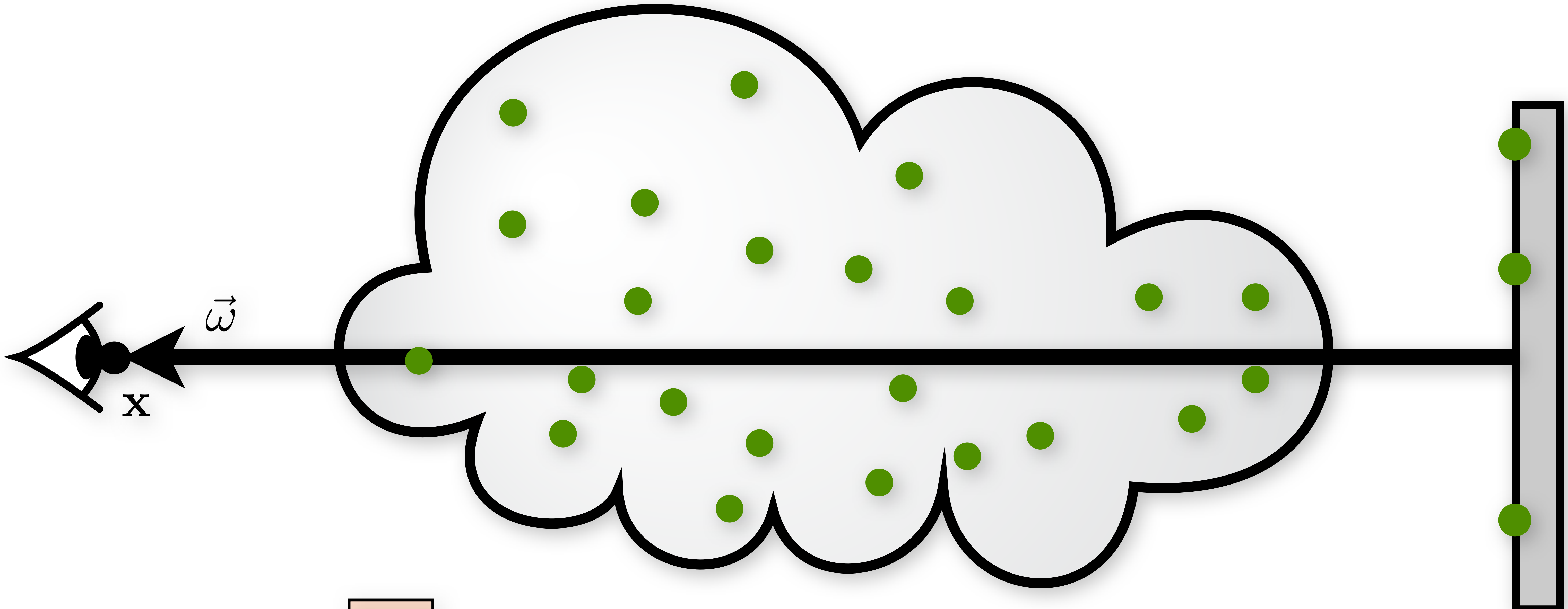
1) Jensen & Christensen 98



$$L_i(\mathbf{x}_t, \vec{\omega}) = \int_{\Omega_{4\pi}} p(\mathbf{x}_t, \vec{\omega}_t, \vec{\omega}) L(\mathbf{x}_t, \vec{\omega}_t) \, d\omega_t$$

$$L_i(\mathbf{x}, \vec{\omega}) \approx \sum_{i=1}^{k} p(\mathbf{x}, \vec{\omega}_i, \vec{\omega}) \frac{\Phi_i(\mathbf{x}, \vec{\omega}_i)}{\boxed{\frac{4}{3}\pi r(\mathbf{x})^3}}$$

Volume Rendering Equation

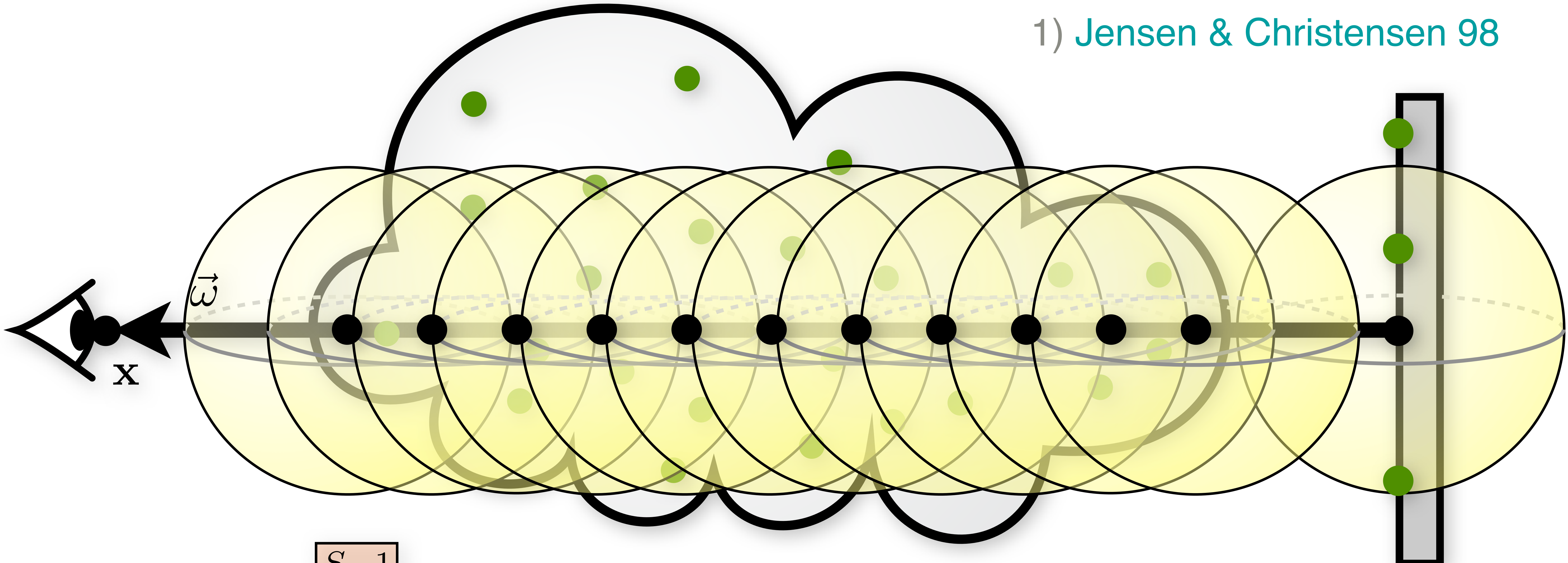


$$L(\mathbf{x},\vec{\omega}) = \boxed{\int_0^s} T_r(\mathbf{x}\leftrightarrow\mathbf{x}_t)\sigma_s(\mathbf{x}_t)L_i(\mathbf{x}_t,\vec{\omega})\,\boxed{dt} + T_r(\mathbf{x}\leftrightarrow\mathbf{x}_s)L(\mathbf{x}_s,\vec{\omega})$$

Approximate/compute using Riemann sum

Ray Marching

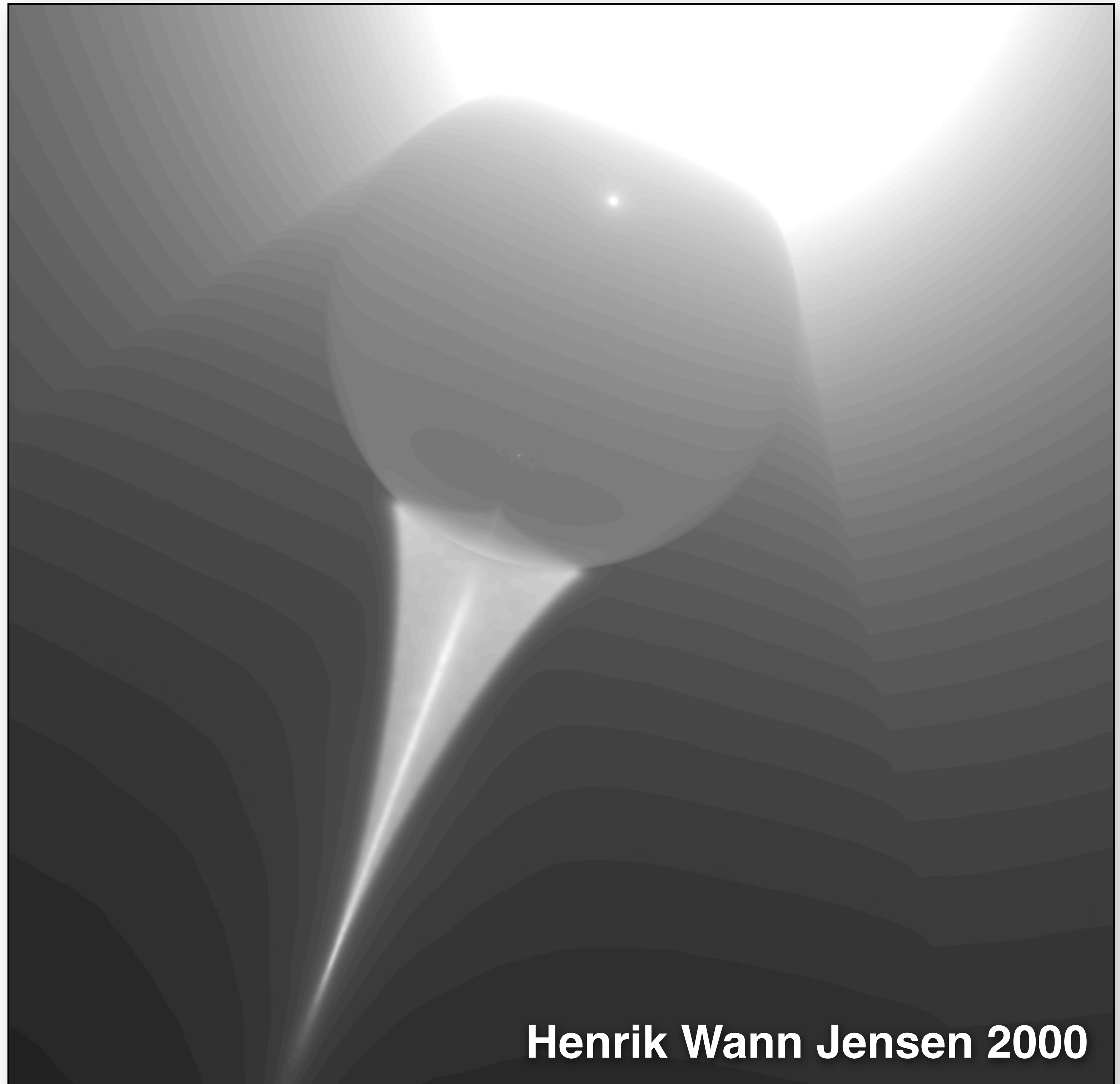
1) Jensen & Christensen 98



$$L(\mathbf{x},\vec{\omega}) \approx \boxed{\sum_{t=0}^{S-1}} T_r(\mathbf{x}\leftrightarrow\mathbf{x}_t)\sigma_s(\mathbf{x}_t)L_i(\mathbf{x}_t,\vec{\omega})\boxed{\Delta_t} + T_r(\mathbf{x}\leftrightarrow\mathbf{x}_s)\boxed{L(\mathbf{x}_s,\vec{\omega})}$$

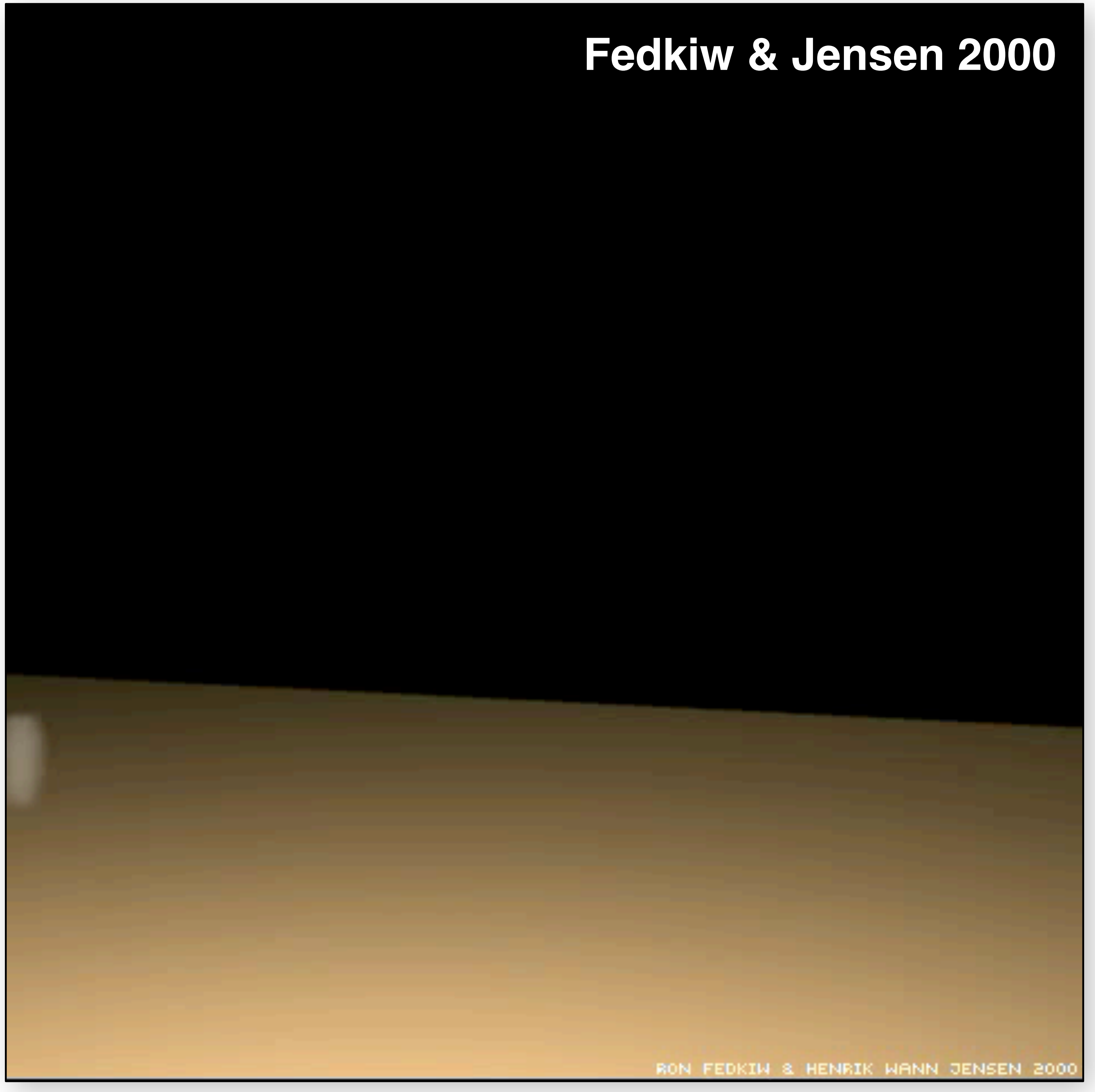
Approximate/compute using Riemann sum

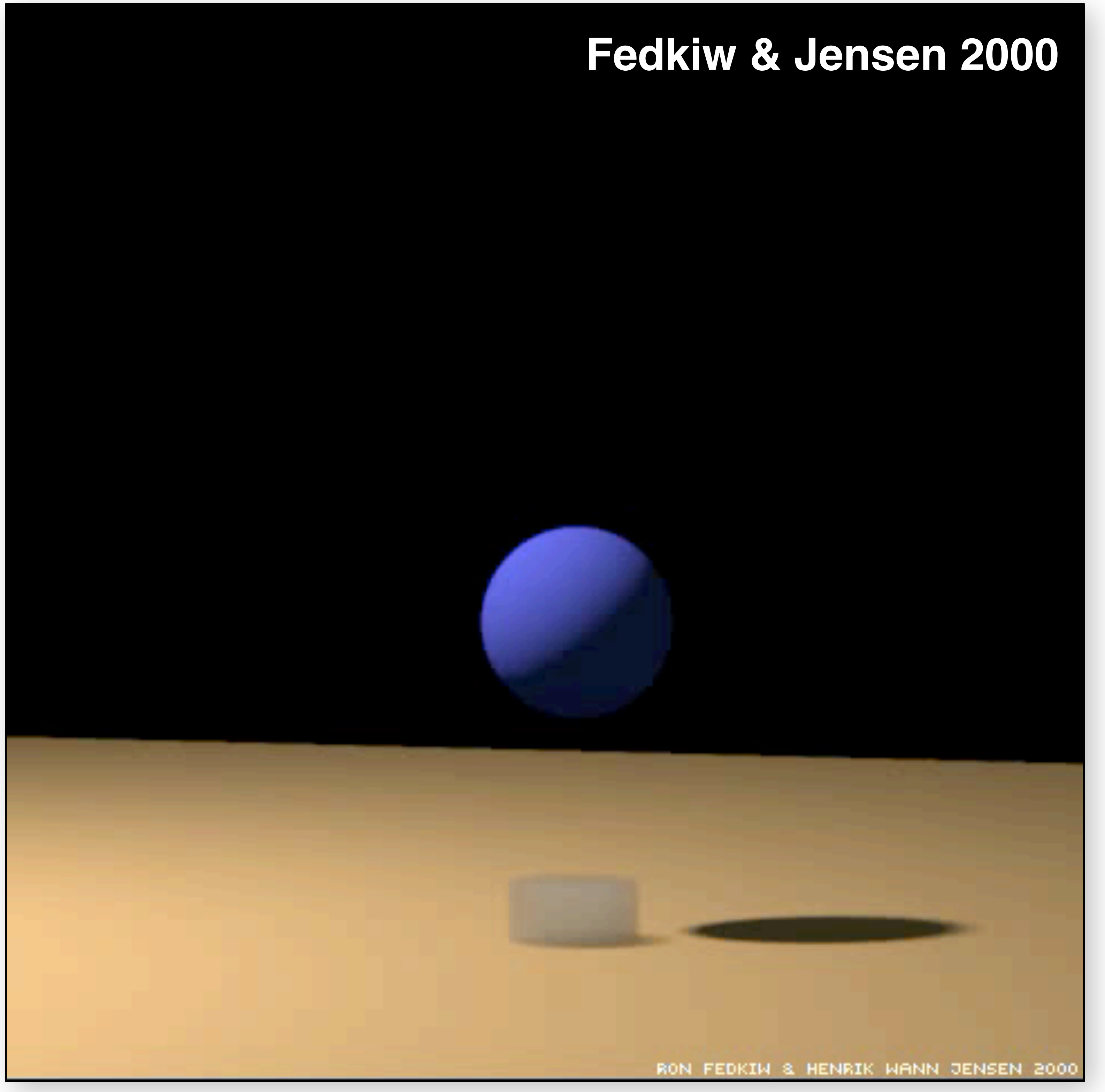
Volume Caustics



Subsurface Scattering

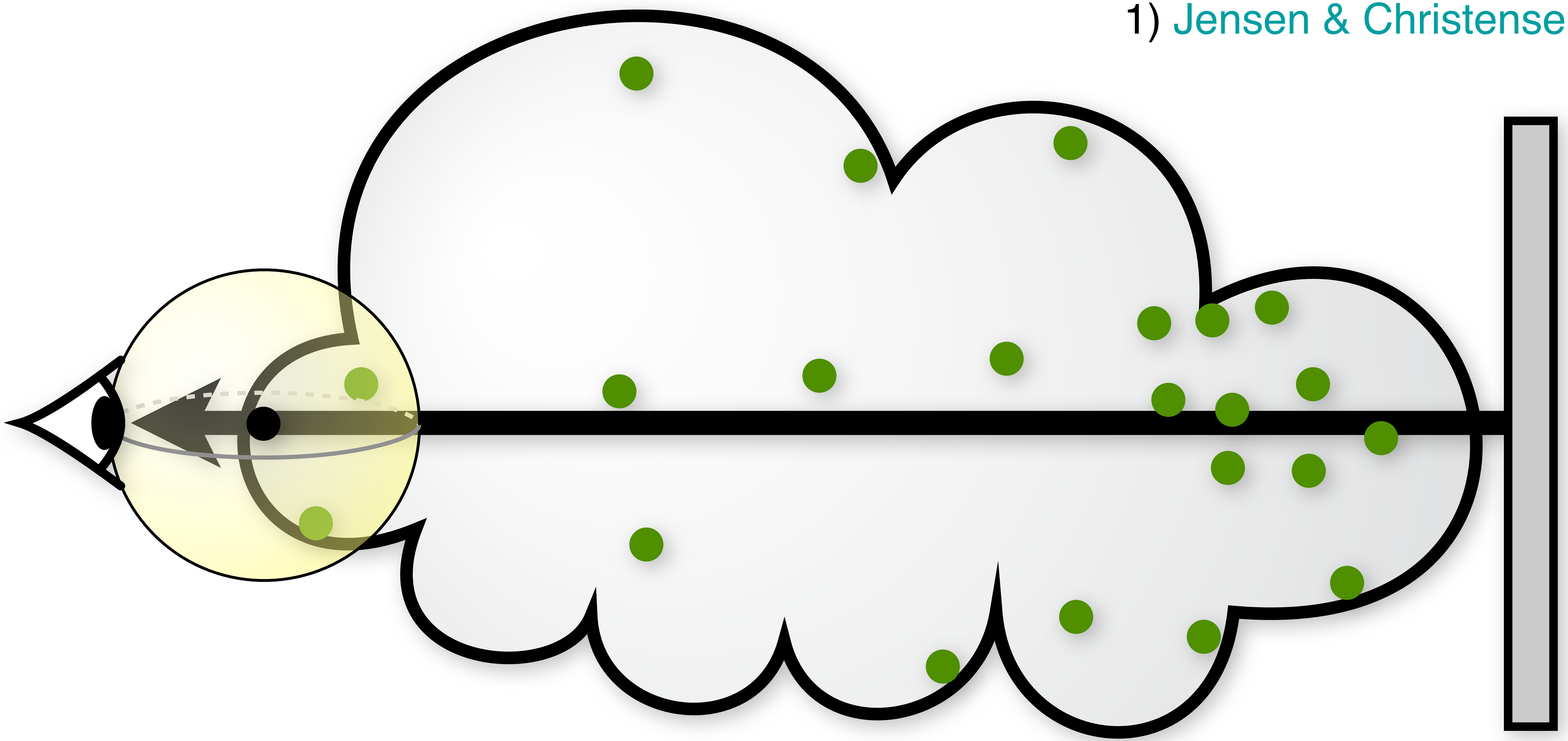
Rising Smoke





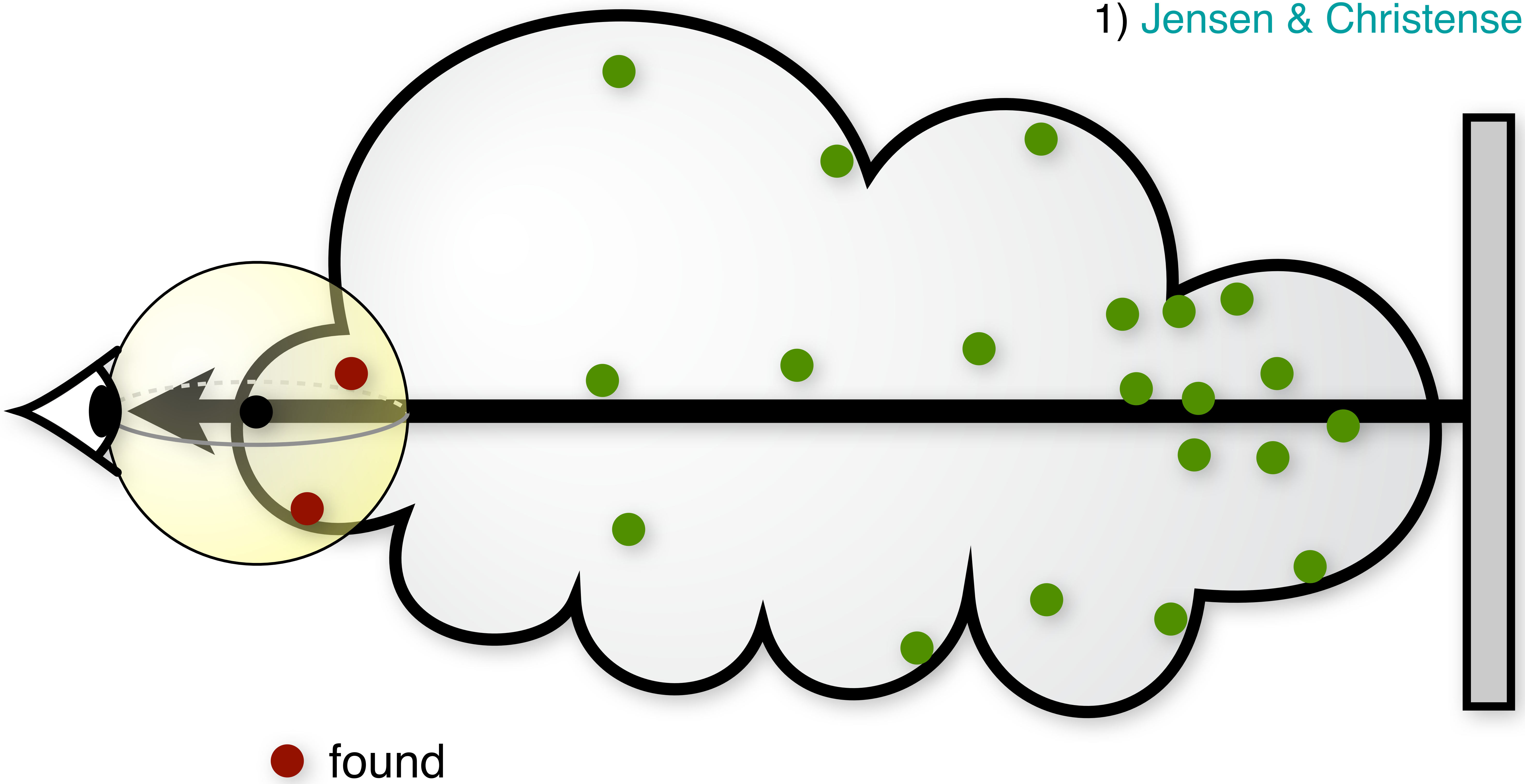
Volumetric Photon Mapping

1) Jensen & Christensen 98



Volumetric Photon Mapping

1) Jensen & Christensen 98



Volumetric Photon Mapping

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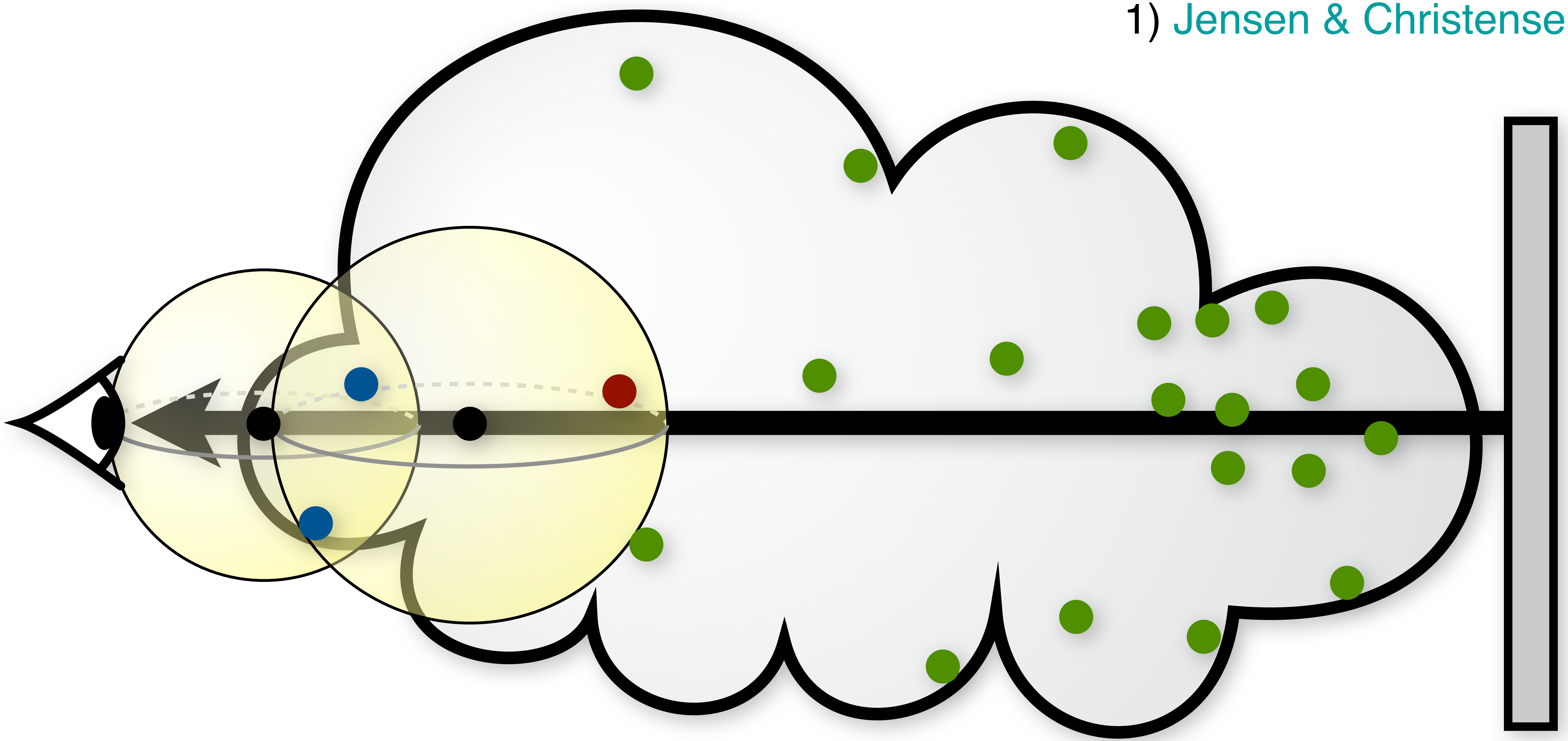
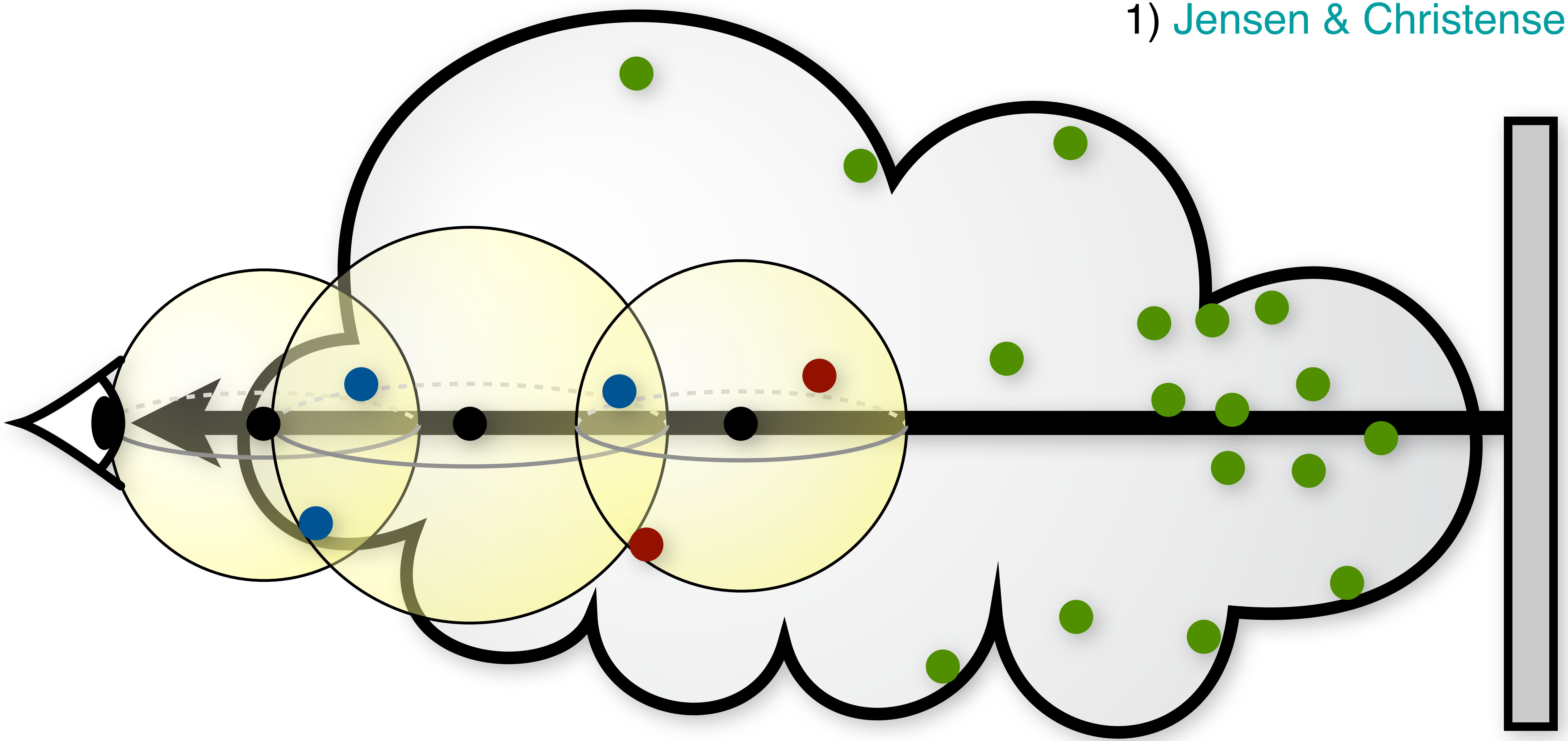
1) Jensen & Christensen 98



● found ● found multiple times

Volumetric Photon Mapping

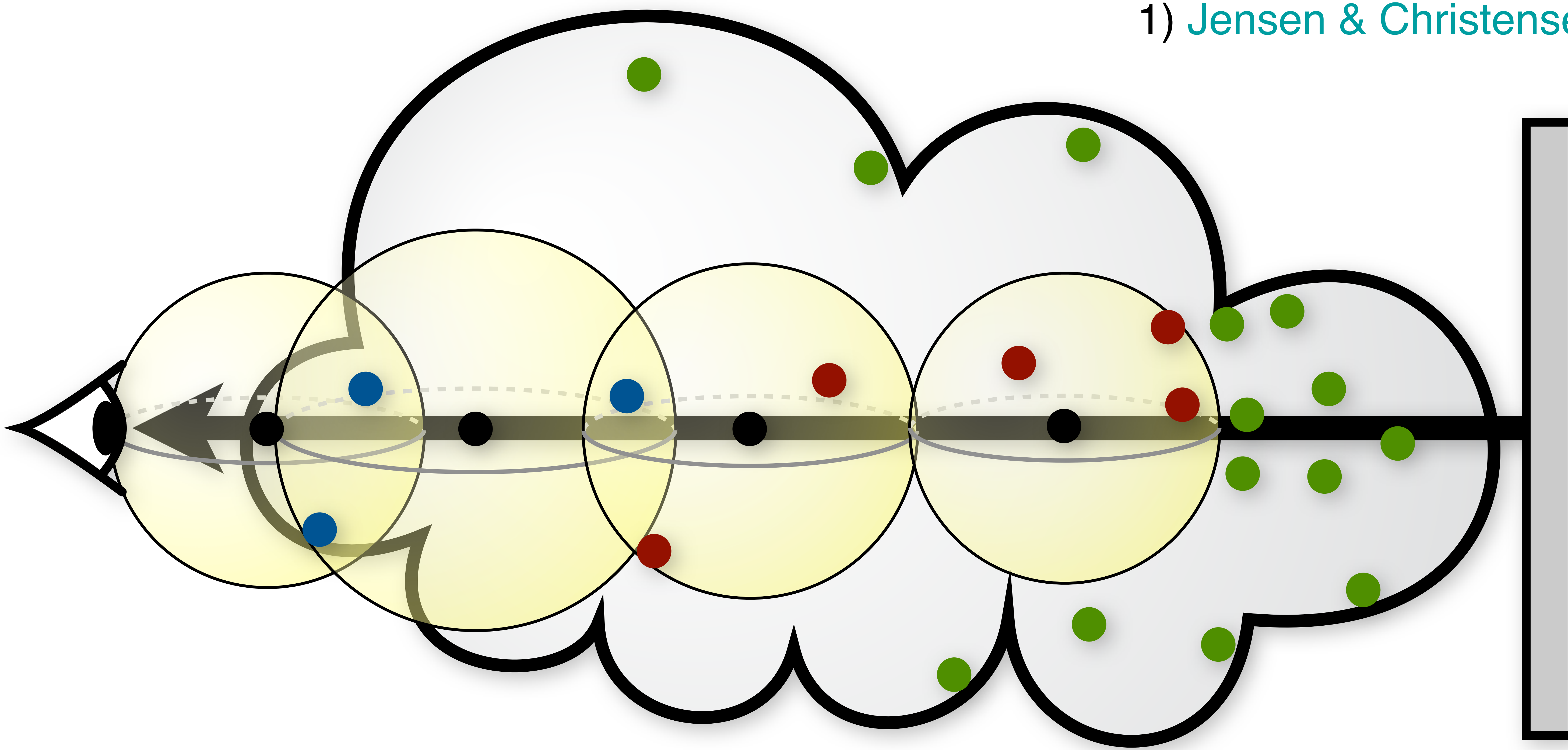
1) Jensen & Christensen 98



● found ● found multiple times

Volumetric Photon Mapping

1) Jensen & Christensen 98



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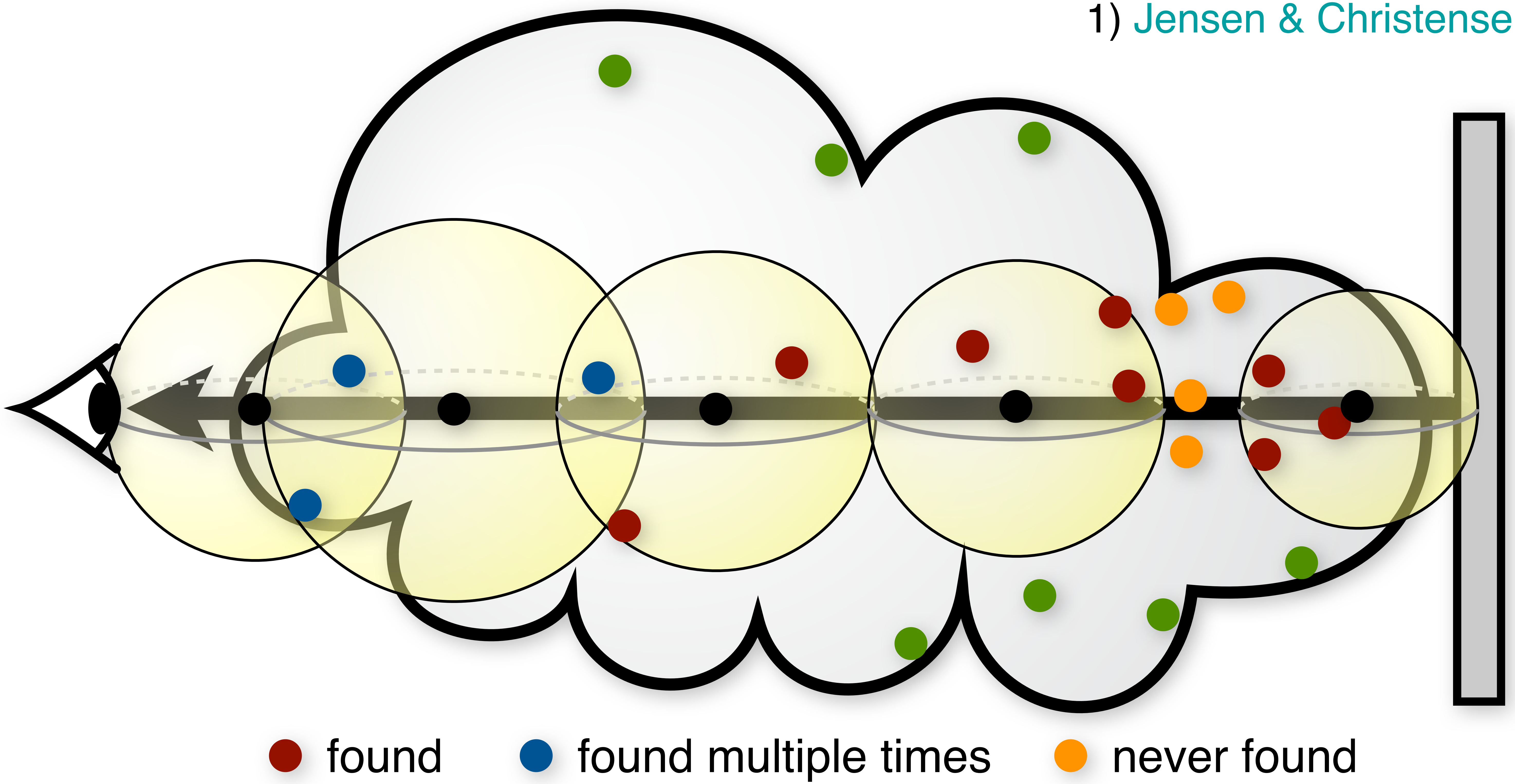
Volumetric Photon Mapping

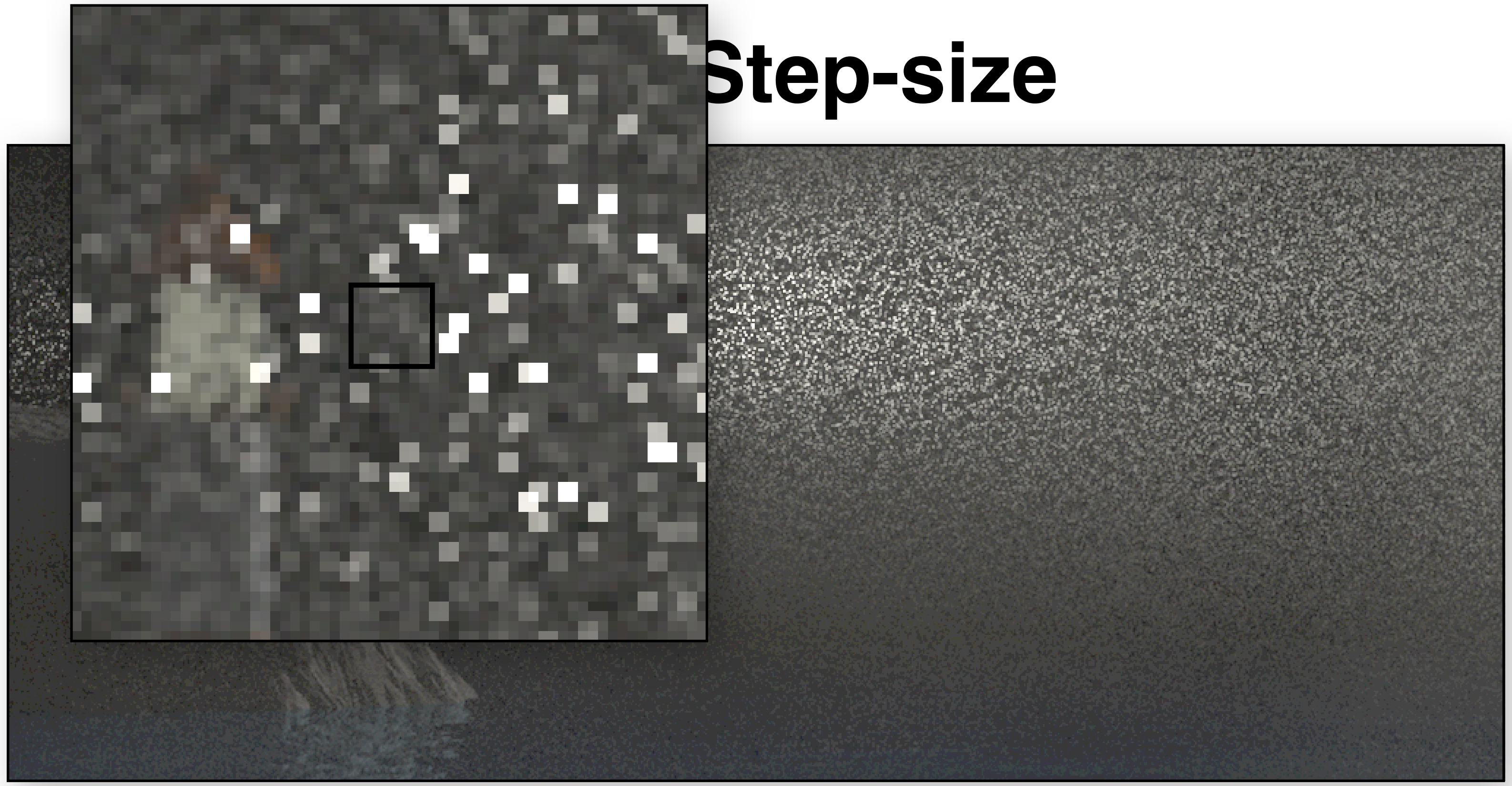
1) Jensen & Christensen 98

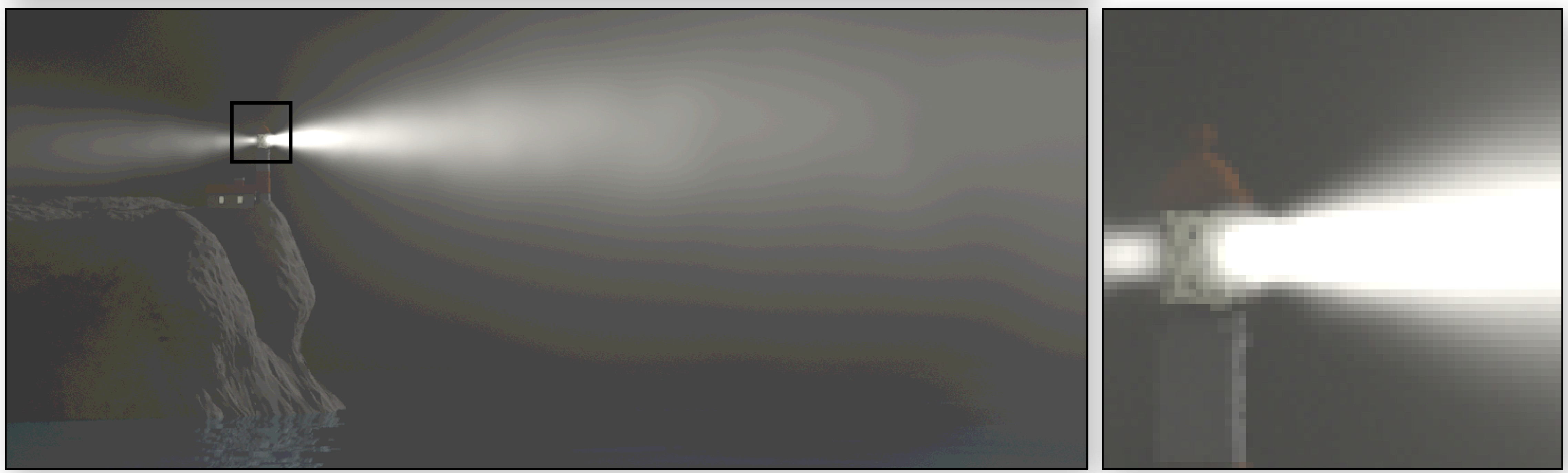


Drawbacks

1) Jensen & Christensen 98

Step-size

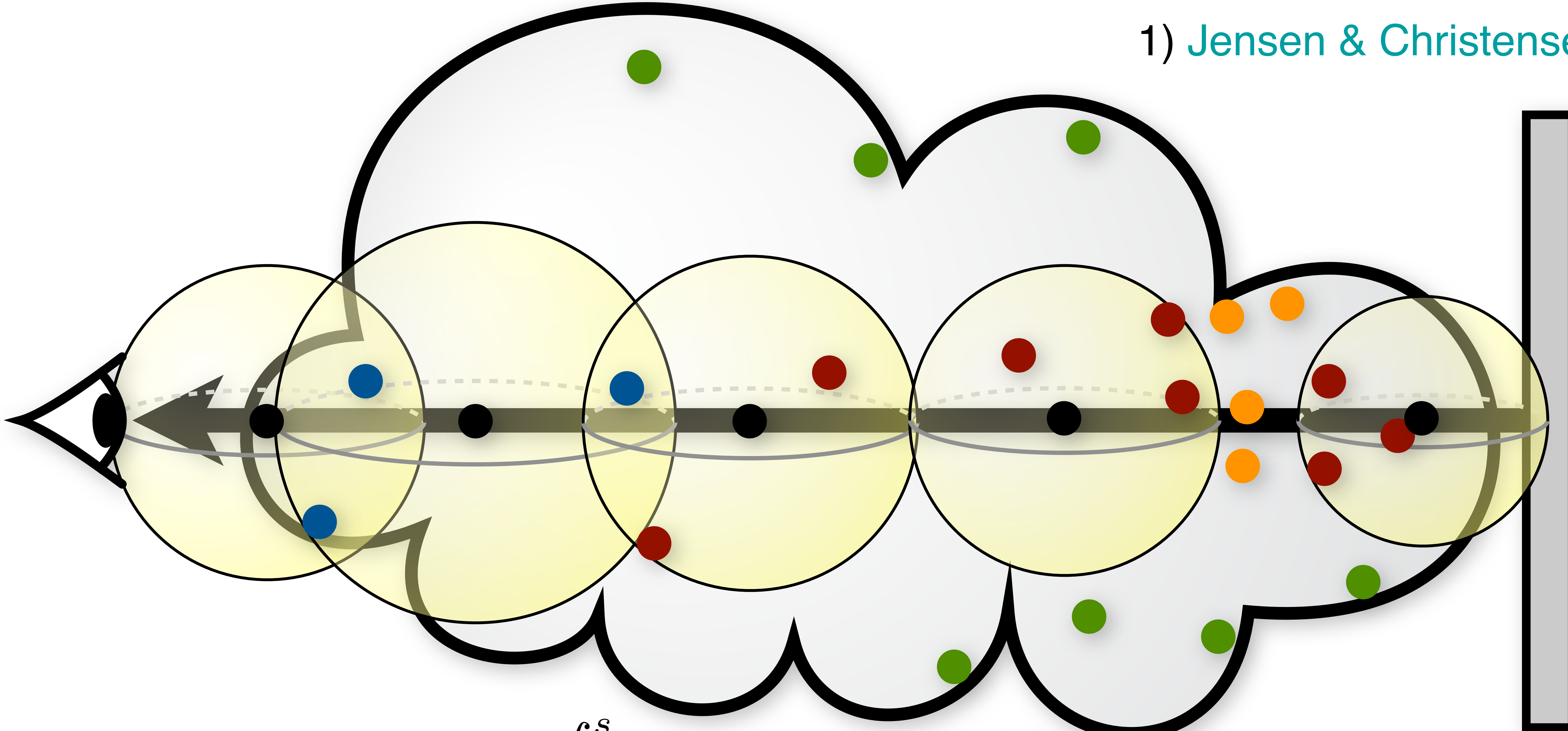




Very Small Step-size

Volumetric Photon Mapping

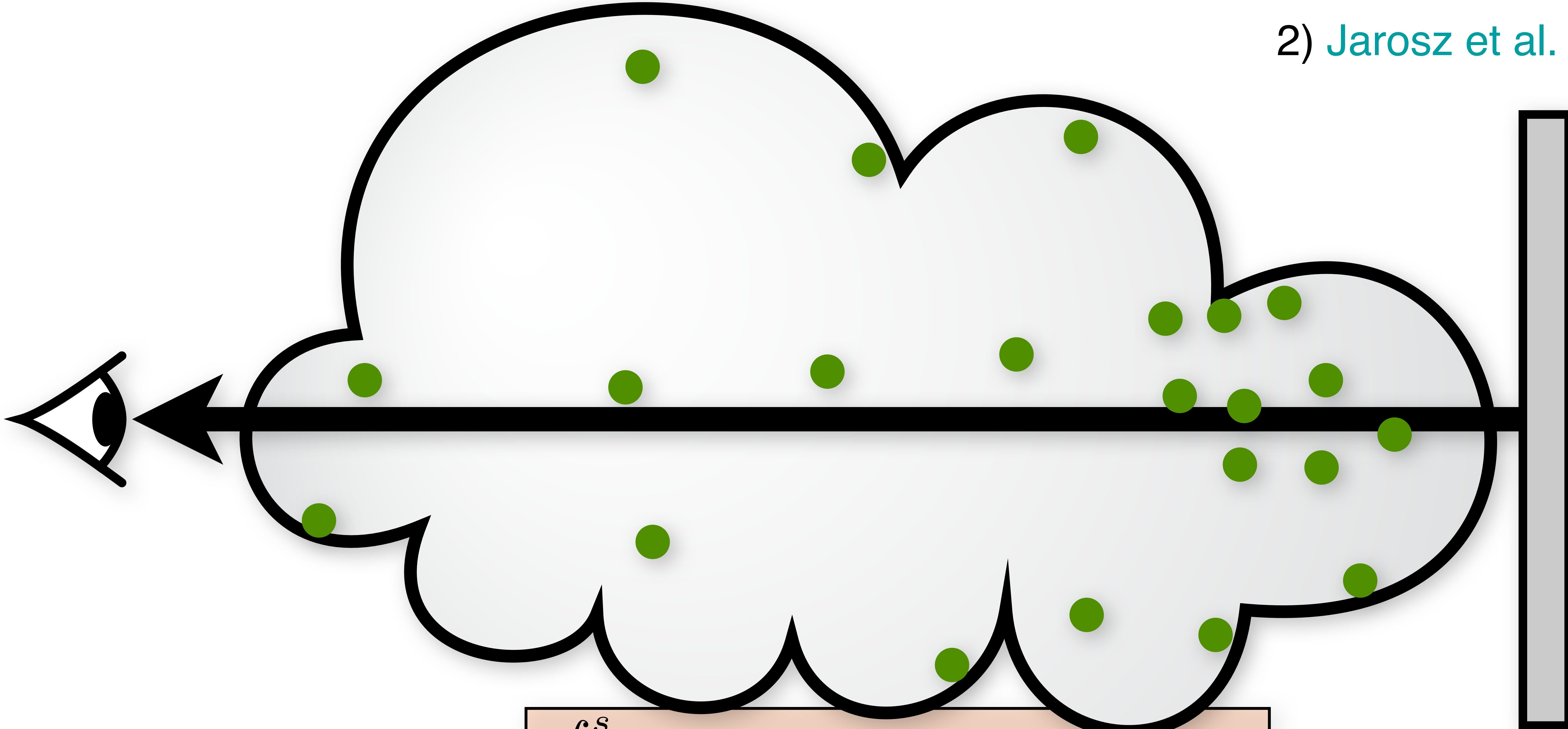
1) Jensen & Christensen 98



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

Beam Radiance Integral

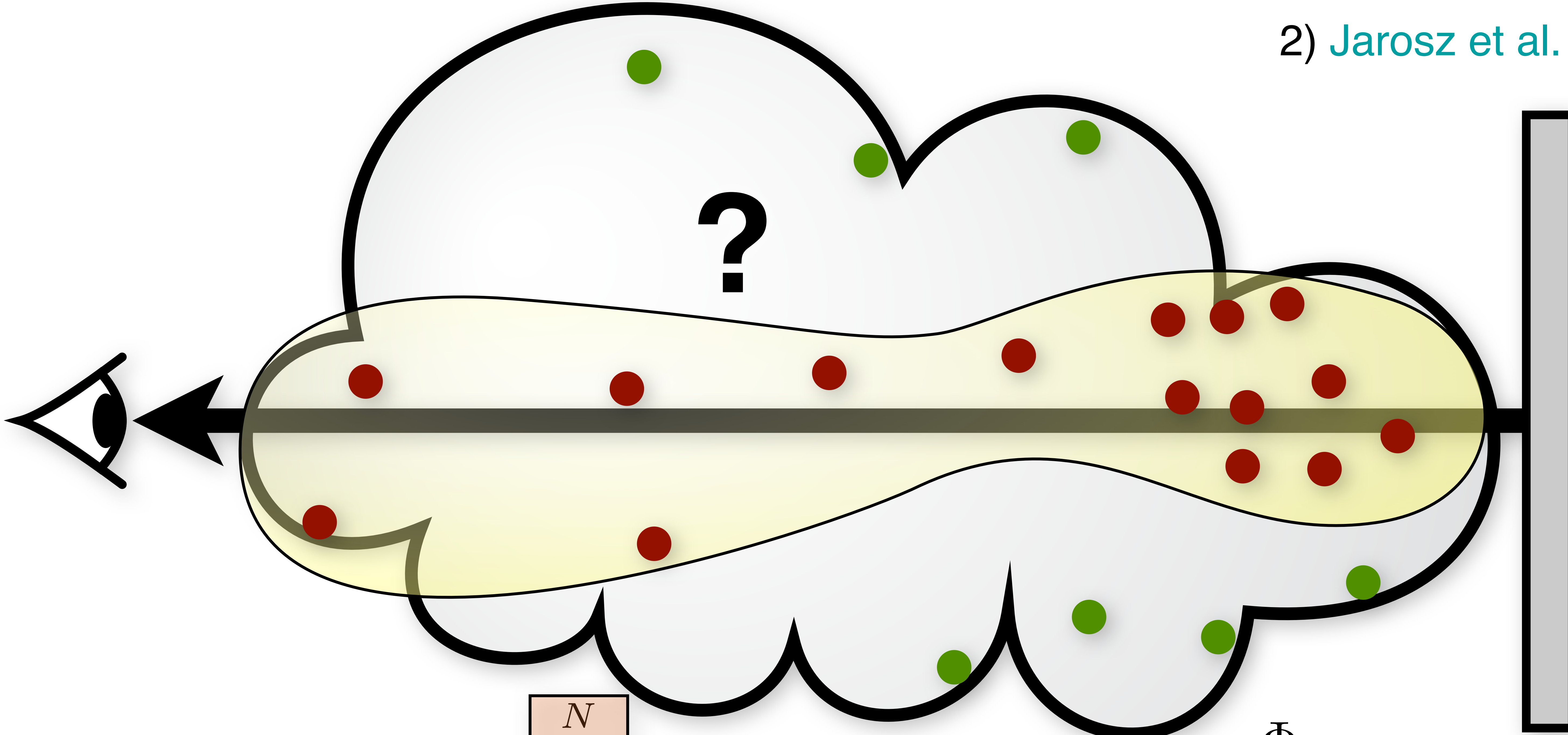
2) Jarosz et al. 2008



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

Beam Radiance Estimation

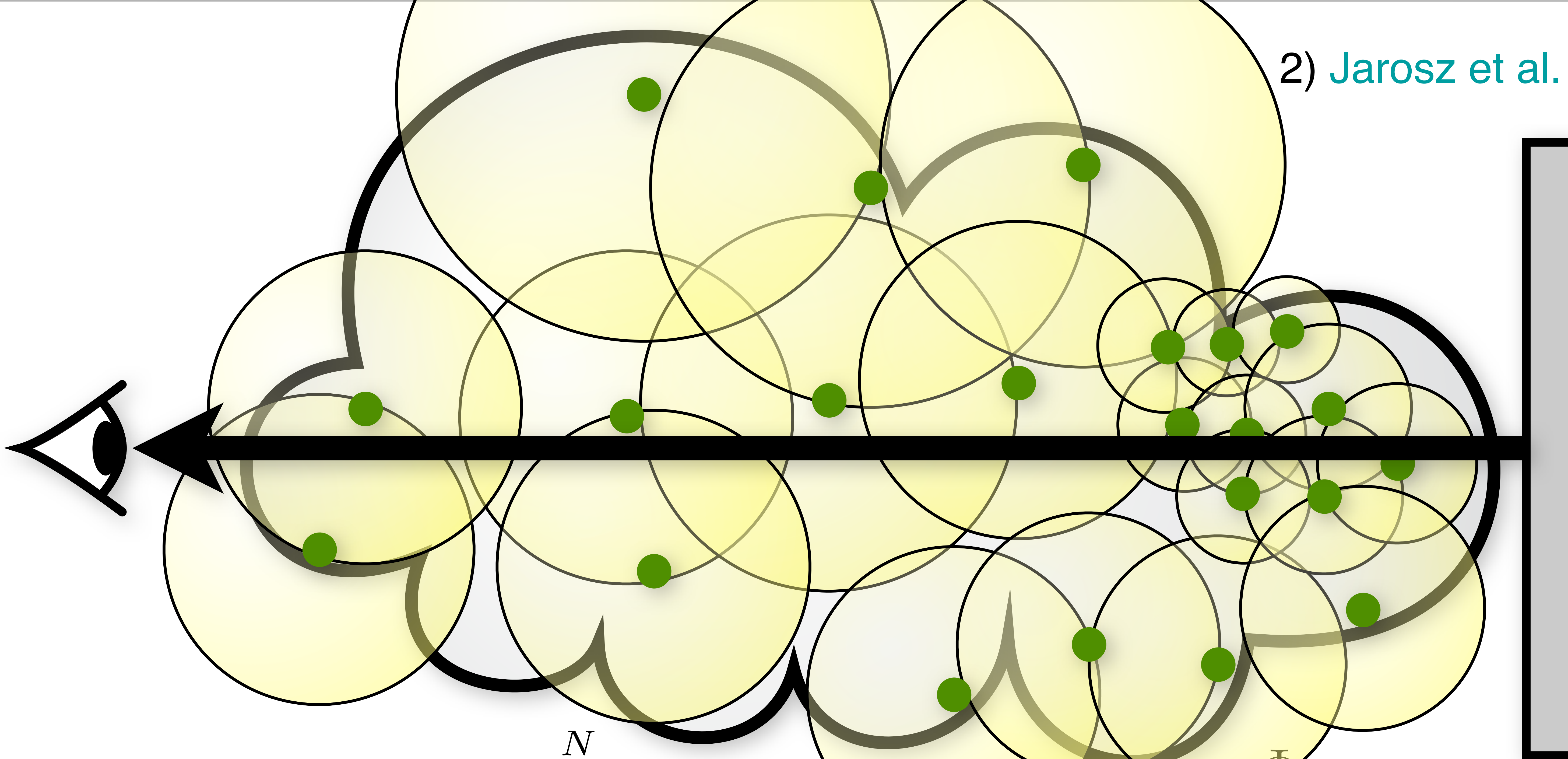
2) Jarosz et al. 2008



$$L_m(\mathbf{x},\vec{\omega}) \approx \boxed{\sum_{i=1}^{N}} T_r(\mathbf{x}\leftrightarrow\mathbf{x}_i)\sigma_s(\mathbf{x}_i)p(\mathbf{x}_i,\vec{\omega},\vec{\omega}_i)\frac{\Phi_i}{\pi r_i^2}$$

Photon Radius Estimation

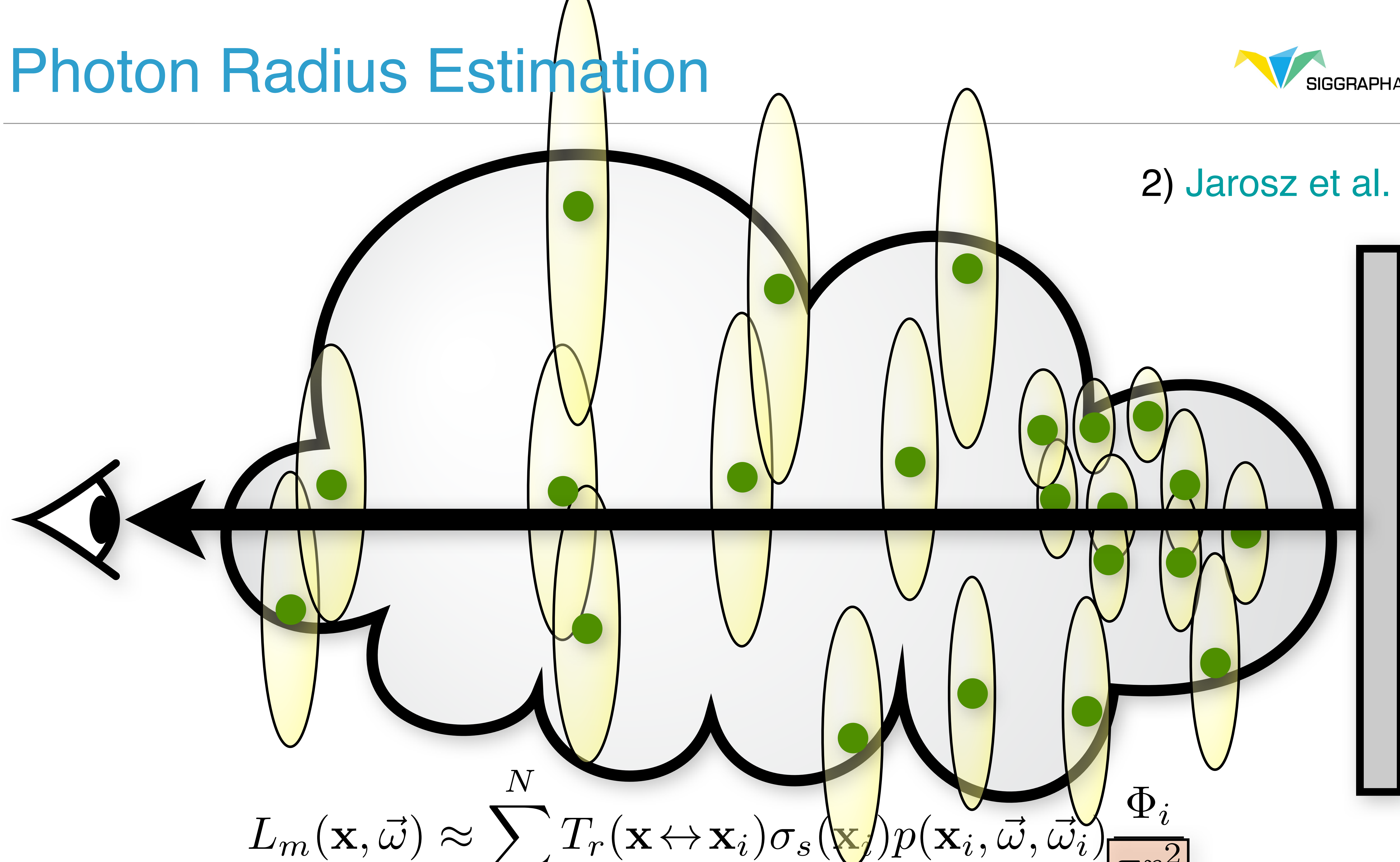
2) Jarosz et al. 2008



$$L_m(\mathbf{x},\vec{\omega}) \approx \sum_{i=1}^{N} T_r(\mathbf{x}\leftrightarrow\mathbf{x}_i)\,\sigma_s(\mathbf{x}_i)\,p(\mathbf{x}_i,\vec{\omega},\vec{\omega}_i)\,\frac{\Phi_i}{\boxed{\pi r_i^2}}$$

Photon Radius Estimation

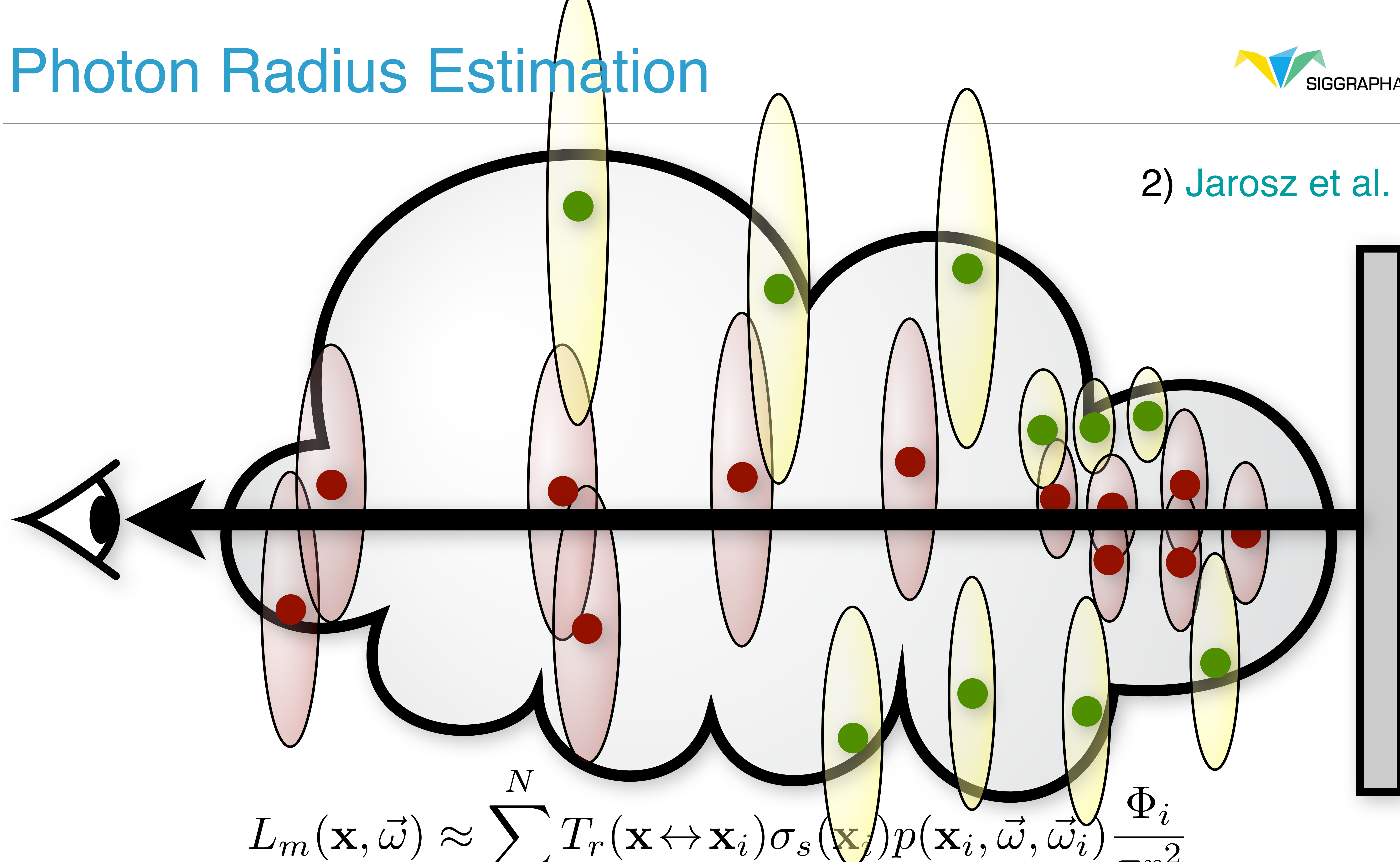
2) Jarosz et al. 2008



$$L_m(\mathbf{x},\vec{\omega}) \approx \sum_{i=1}^{N} T_r(\mathbf{x}\leftrightarrow\mathbf{x}_i)\sigma_s(\mathbf{x}_i)p(\mathbf{x}_i,\vec{\omega},\vec{\omega}_i)\frac{\Phi_i}{\boxed{\pi r_i^2}}$$

Photon Radius Estimation

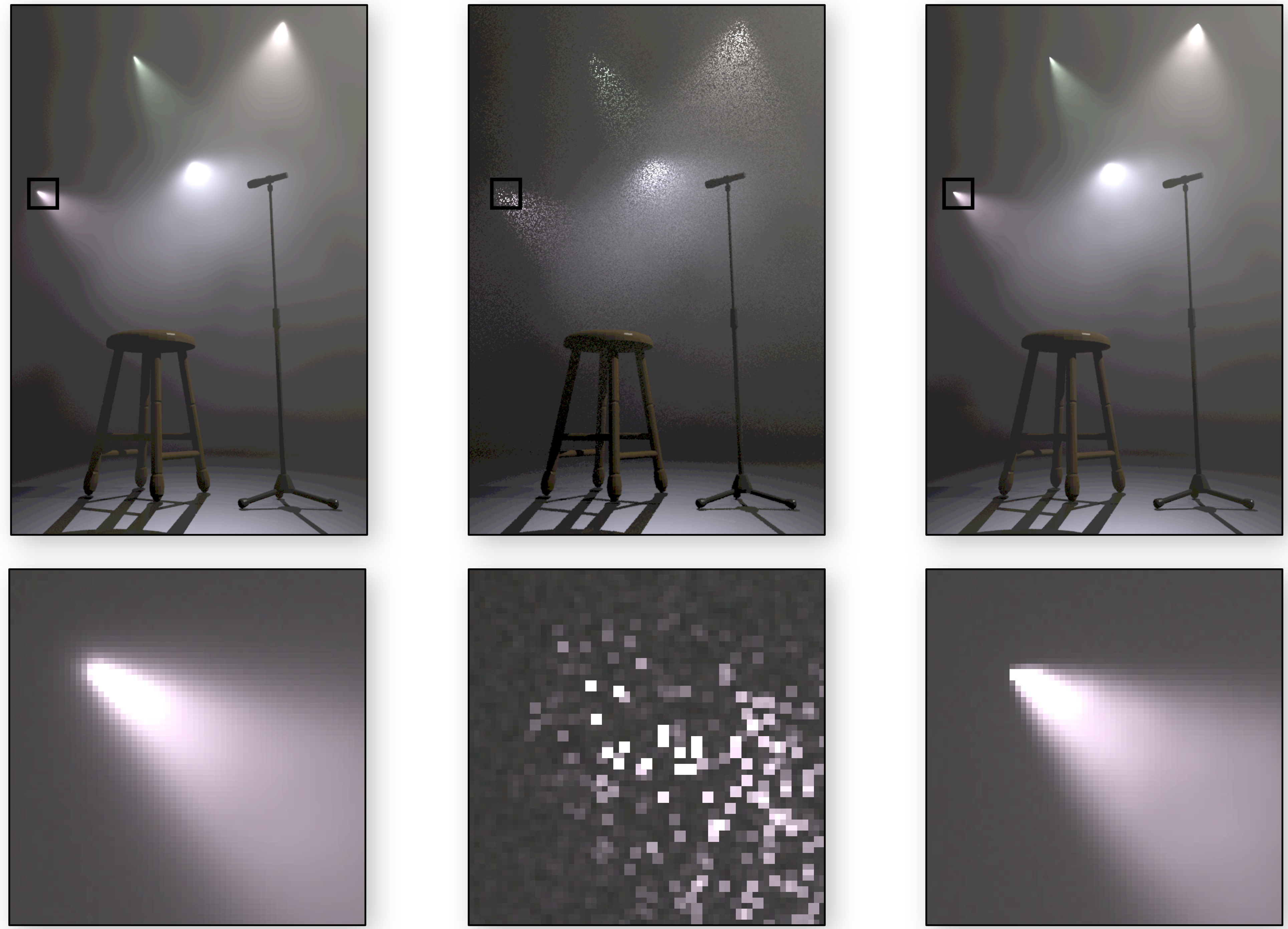
2) Jarosz et al. 2008



$$L_m(\mathbf{x},\vec{\omega}) \approx \sum_{i=1}^{N} T_r(\mathbf{x}\leftrightarrow\mathbf{x}_i)\sigma_s(\mathbf{x}_i)p(\mathbf{x}_i,\vec{\omega},\vec{\omega}_i)\frac{\Phi_i}{\pi r_i^2}$$

Concert Stage

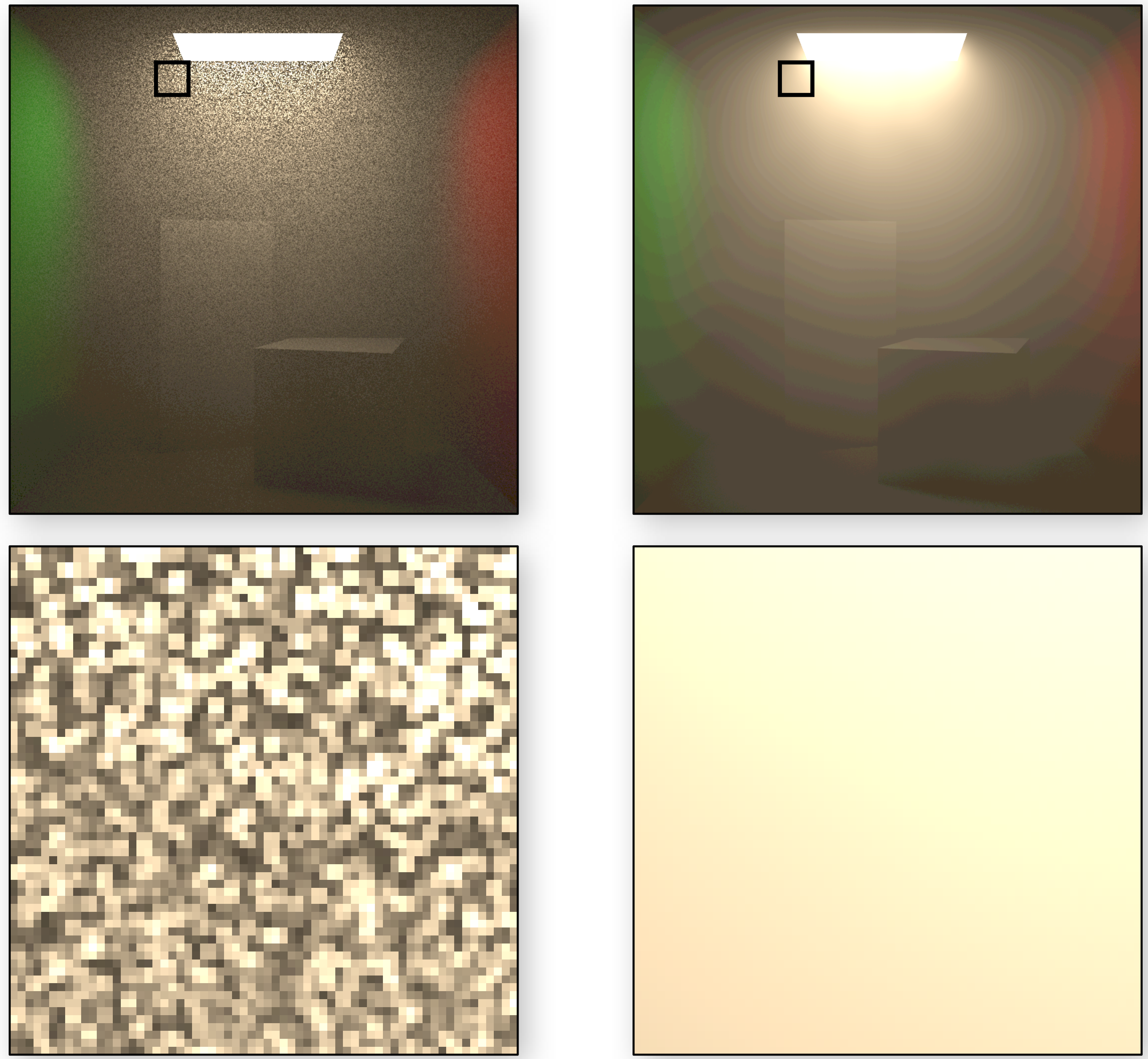
Trad. Estimate | Trad. Estimate | Beam Estimate



(∞) | (6:38) | (6:22)

Smoky Cornell Box

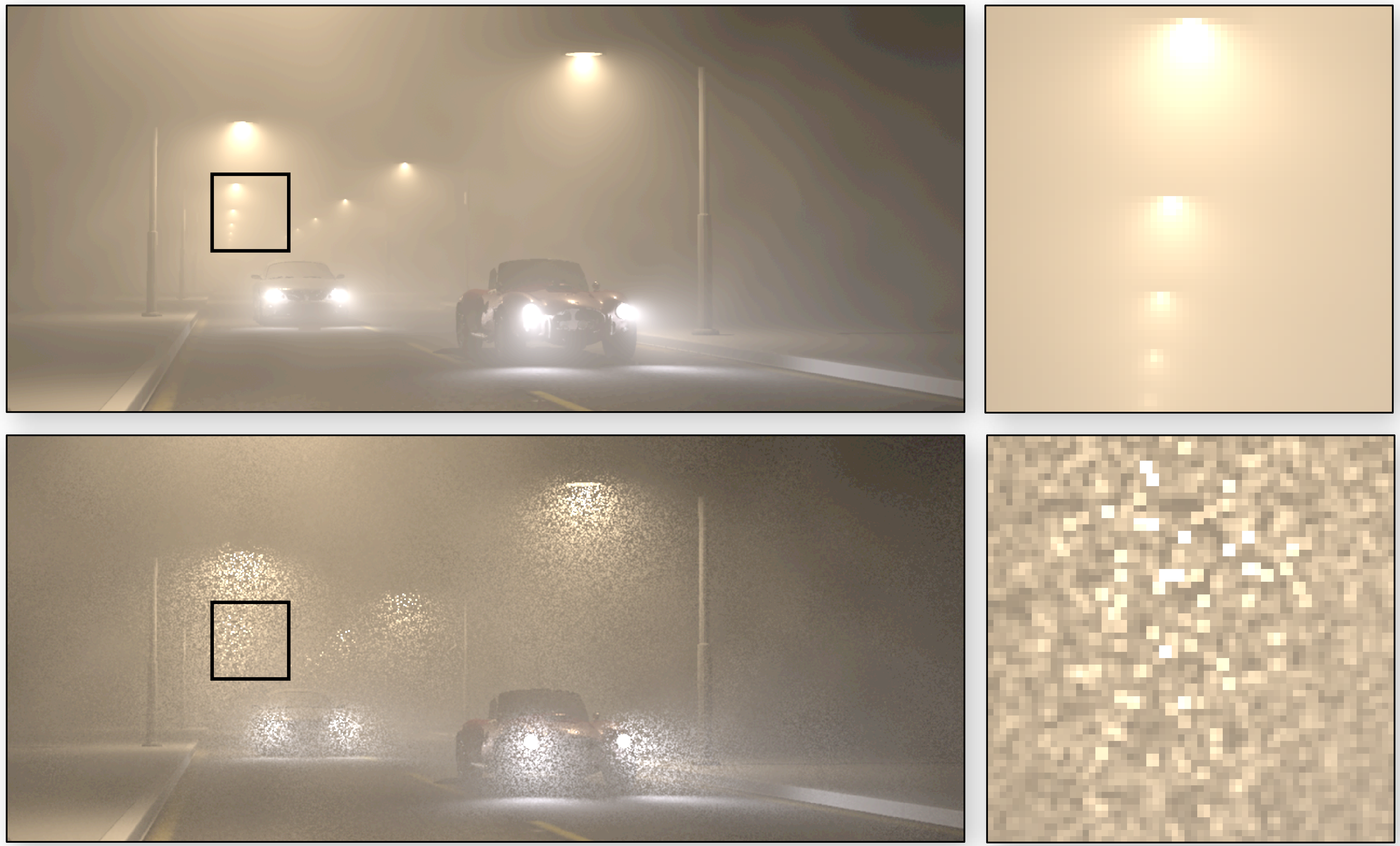
Trad. Estimate | Beam Estimate



(4:03) | (3:35)

Cars on Foggy Street

Beam Estimate (1:53)



Traditional Estimate (2:02)

Questions?