Many Light Methods

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Philipp Slusalek

Karol Myszkowski

Captured: Andrey Vasiliskov
Owner: Gurprit Singh


363,036 Lights
Sony Imageworks

Creator and Credit: Paul Thouvenin Copyright: olweb


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Owner: Gurprit Singh


https://www.oberlin.edu/dye-lecture-hall

Overview

Instant Radiosity

Virtual Point Lights

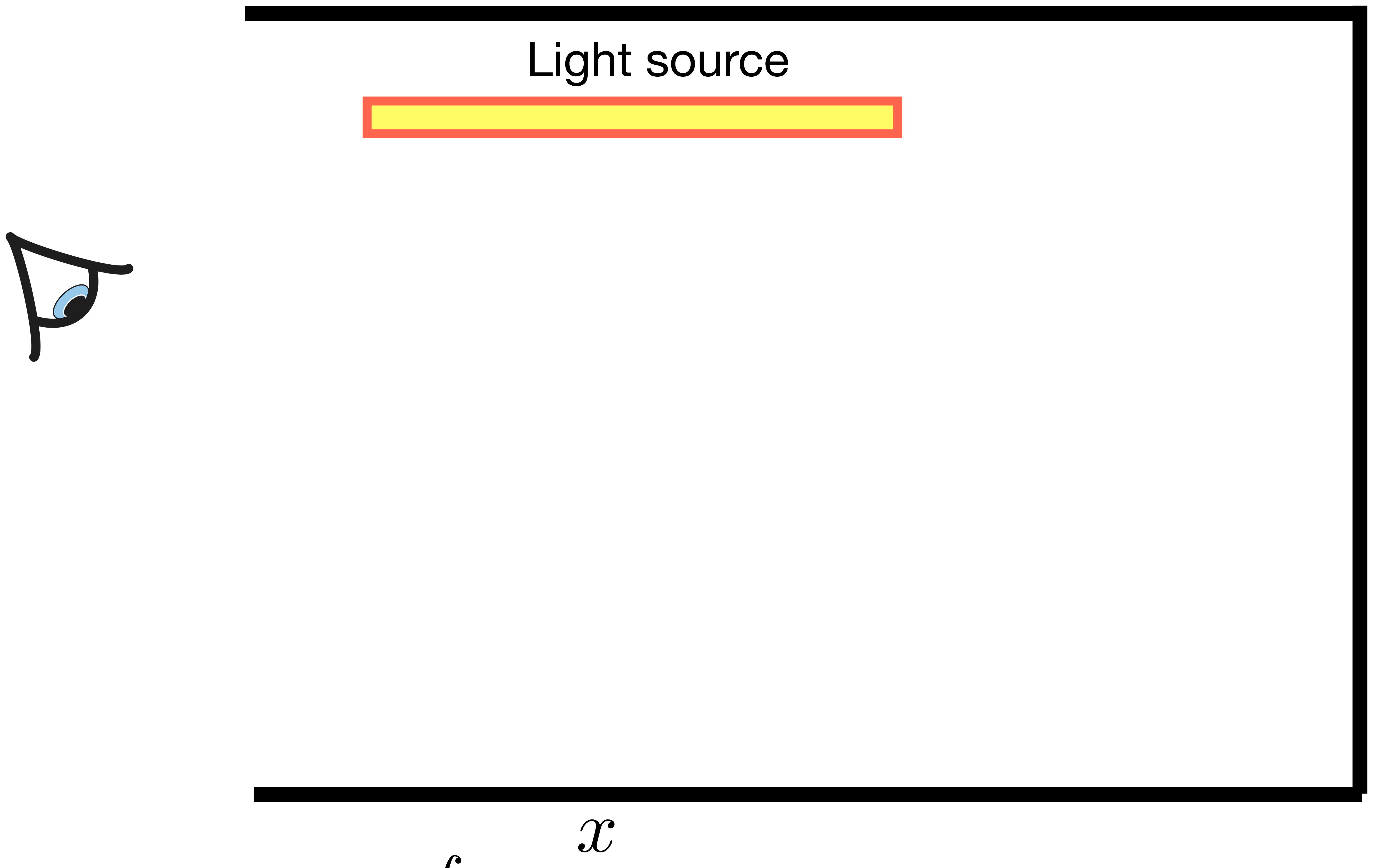
Virtual Ray Lights

LightCuts

Stochastic LightCuts

Lighting Grid Hierarchy

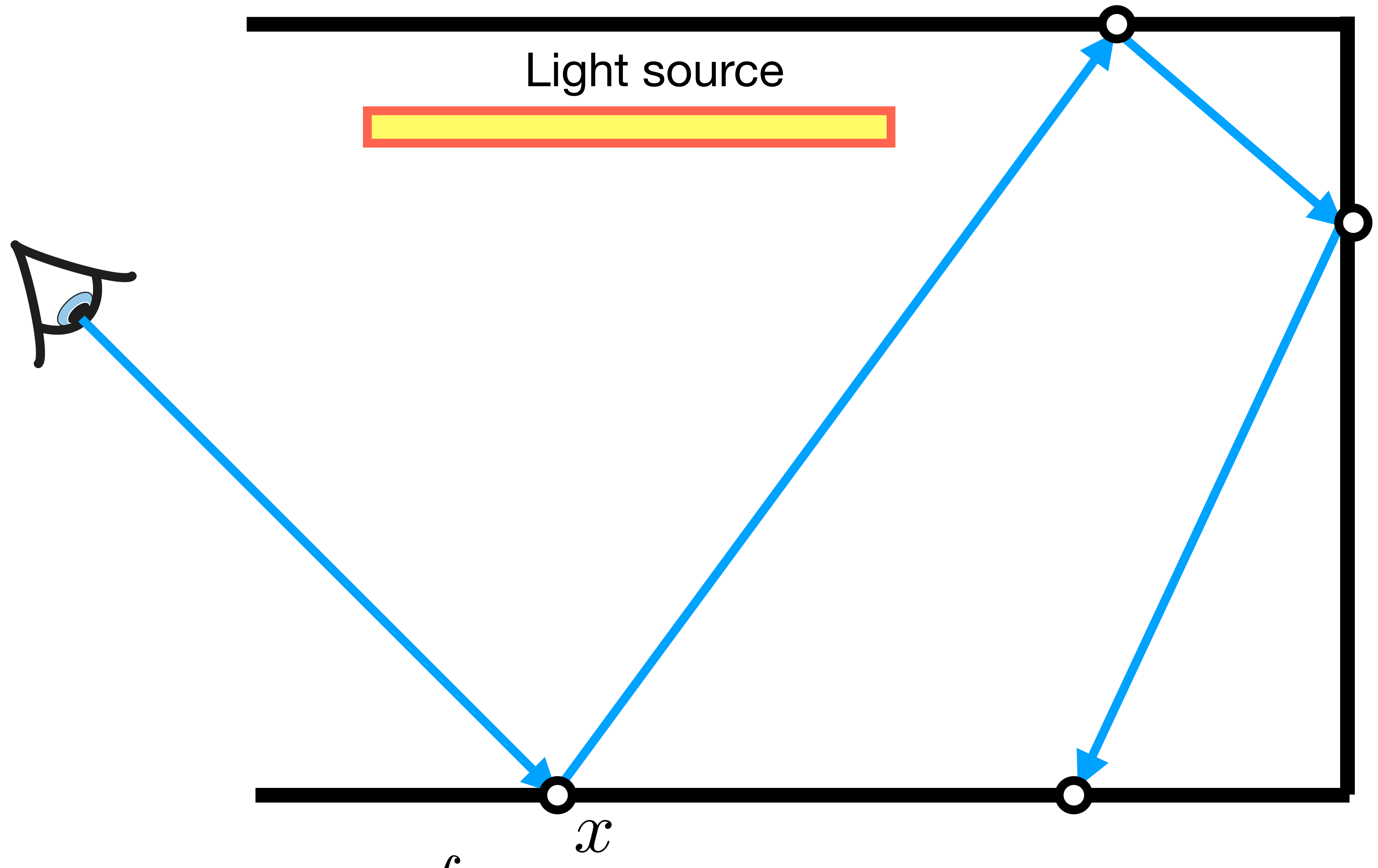
Bidirectional Path Tracing



$$L(x,\omega) = L_e(x,\omega) + \int_{\mathcal{H}^2} f(x,\omega',\omega) L(r(x,\omega'),-\omega') \cos\theta' d\omega'$$

$$\approx L_e(x,\omega) + \frac{f(x,\omega',\omega) L(r(x,\omega'),-\omega') \cos\theta'}{p(\omega')}$$

Bidirectional Path Tracing



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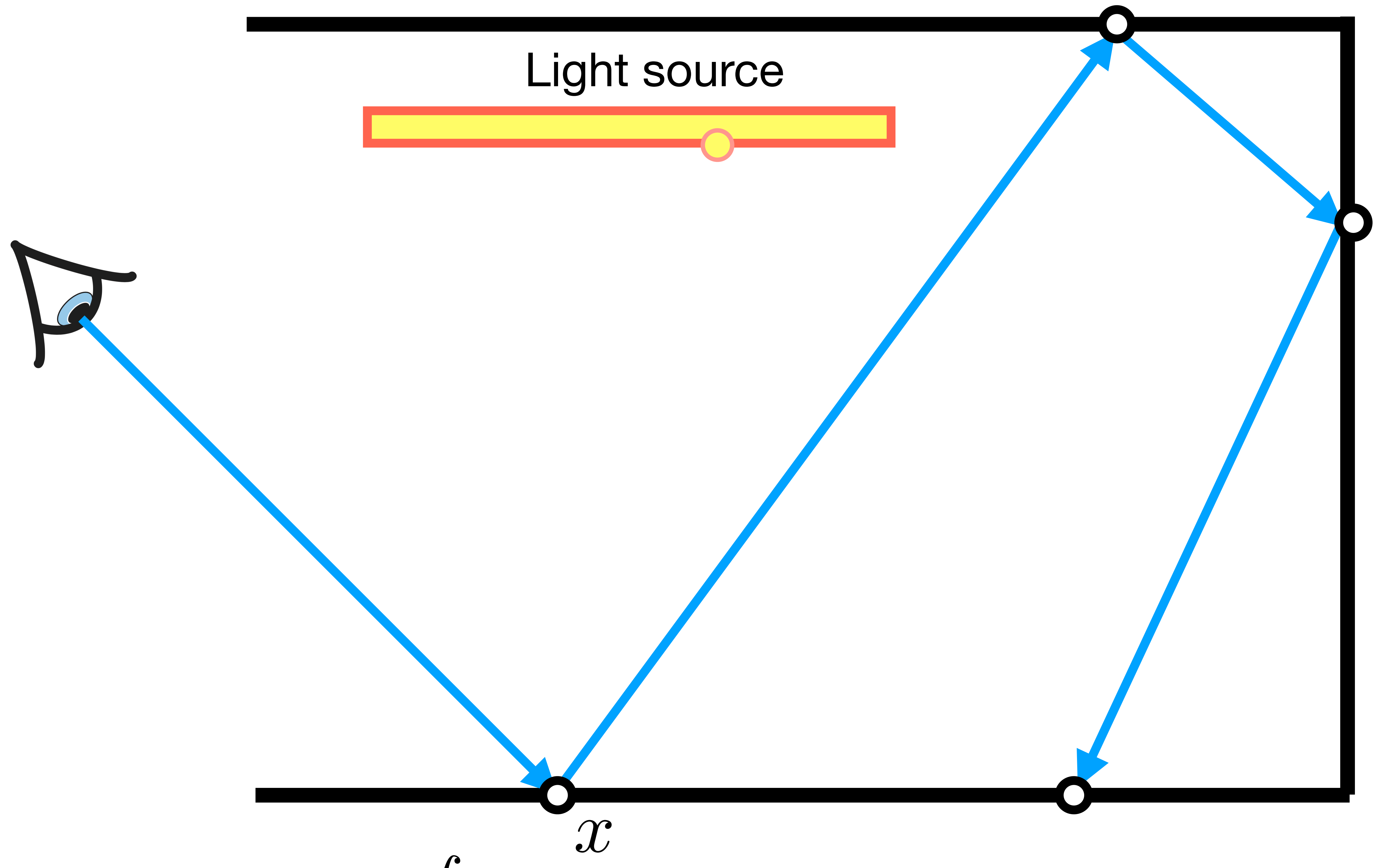

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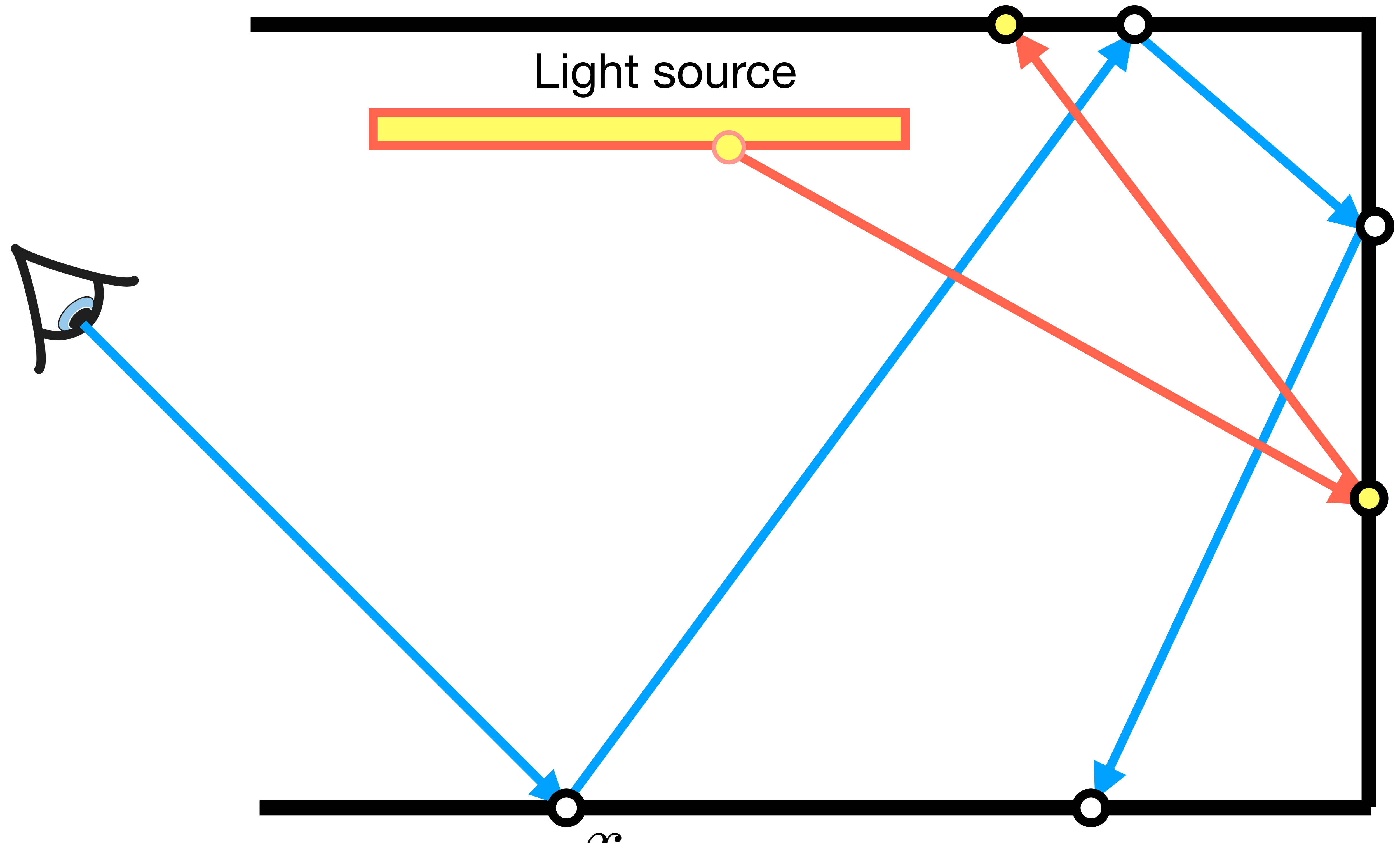

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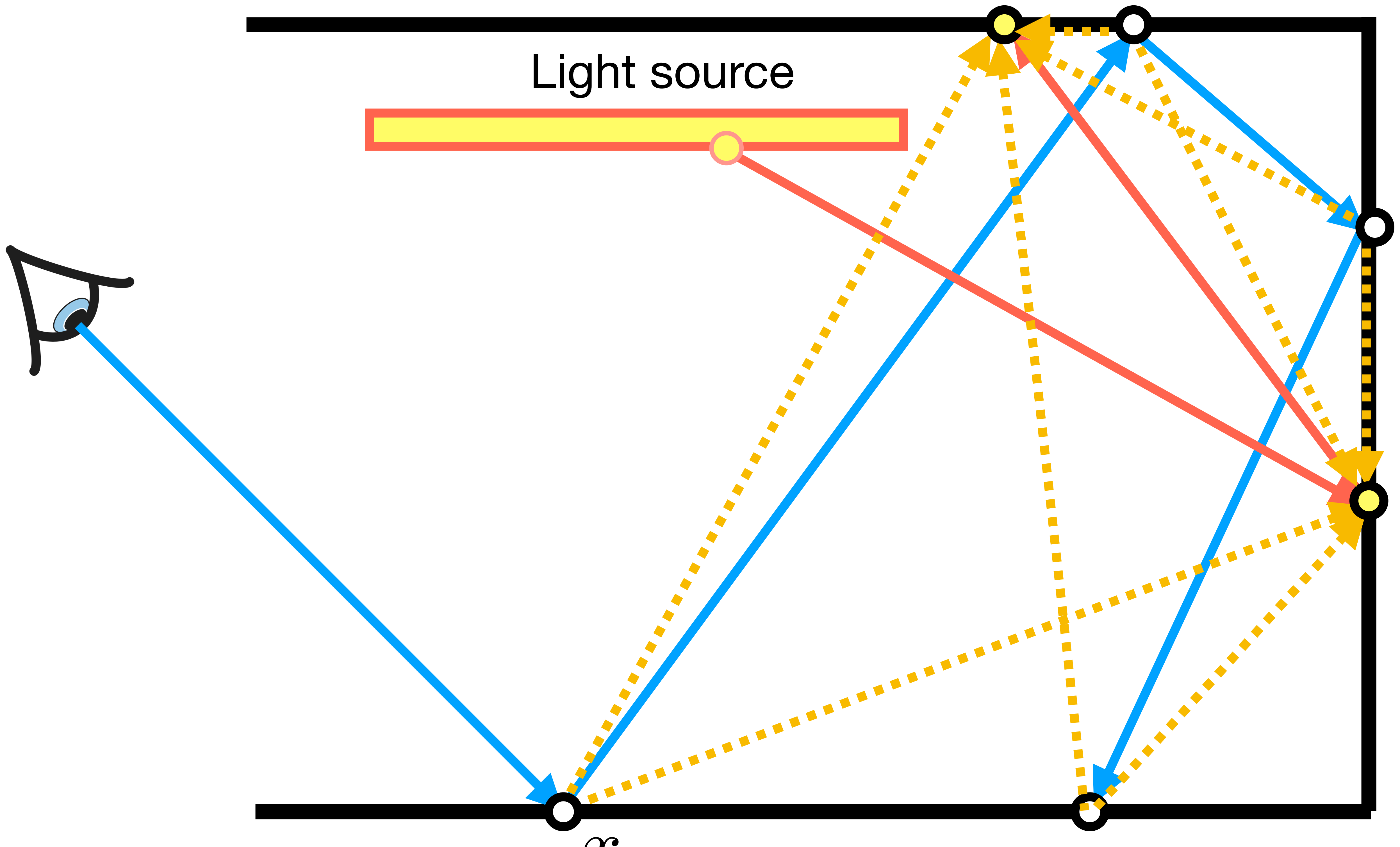

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Instant Radiosity

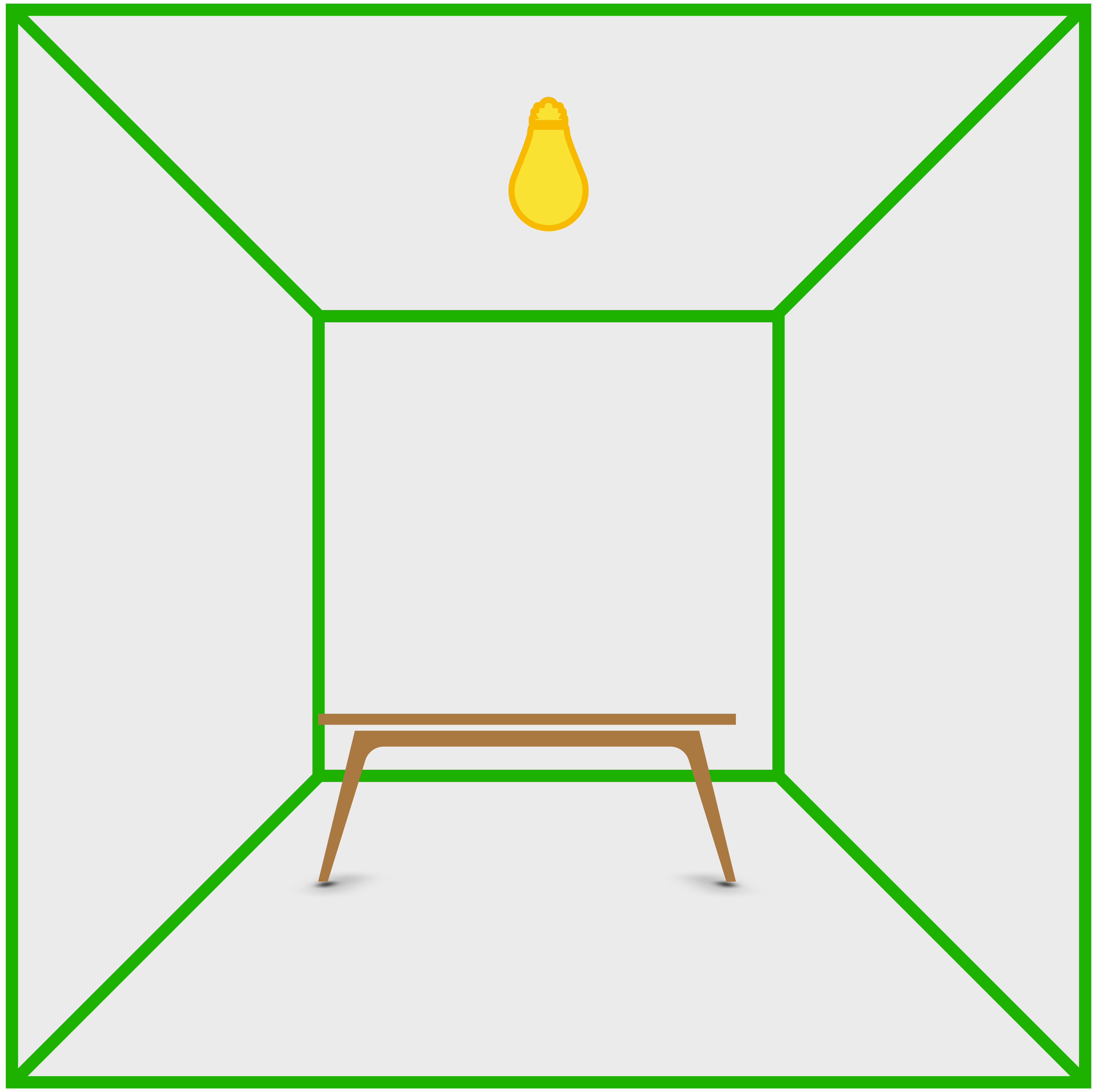
Virtual Point Light: Generation

Step 1:

- Trace paths from light source(s)

- Treat path vertices as Vritual Point Lights (VPLs)

Pass 1



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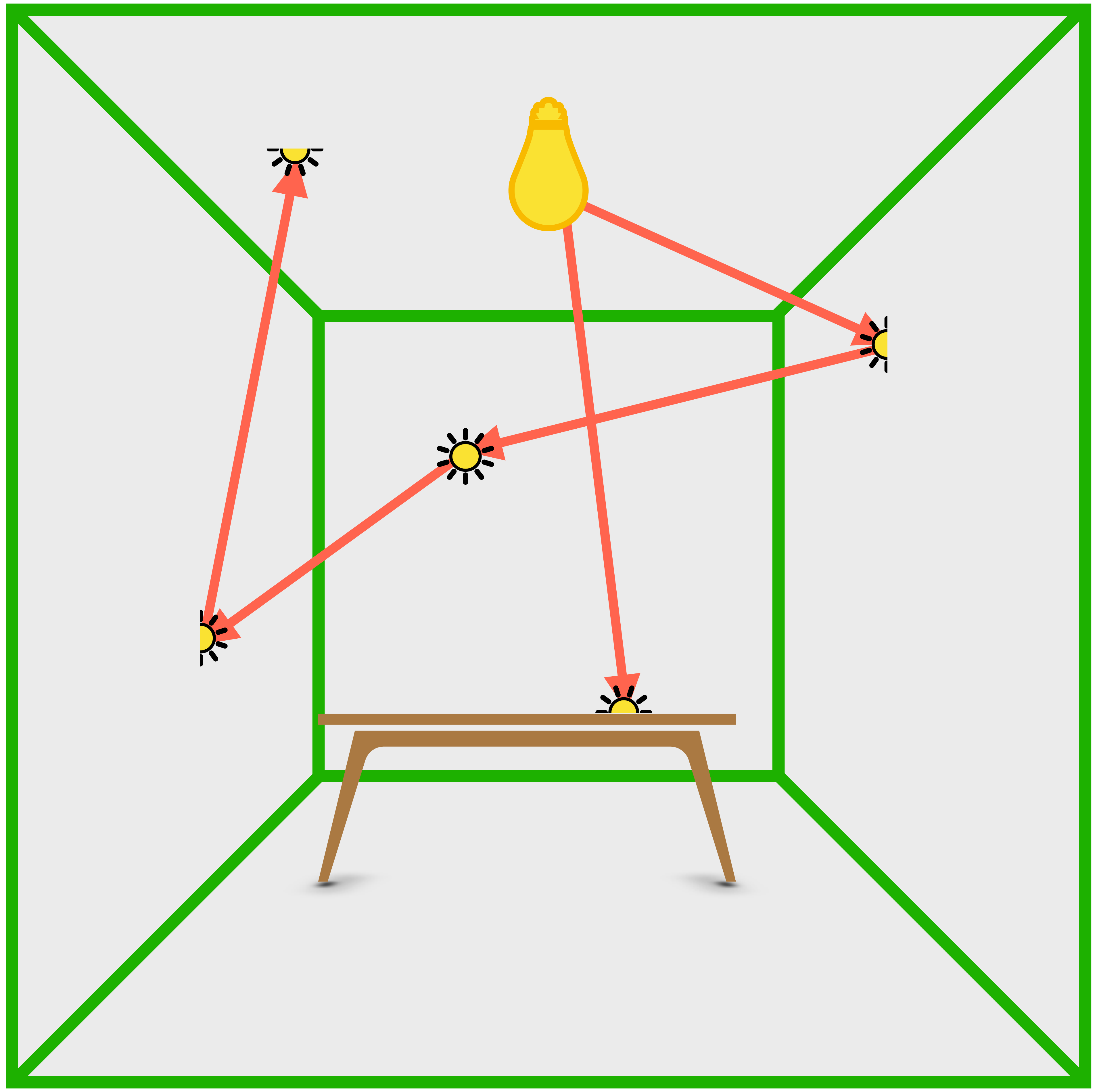

Virtual Point Light: Lighting

Step 1:

- Trace paths from light source(s)

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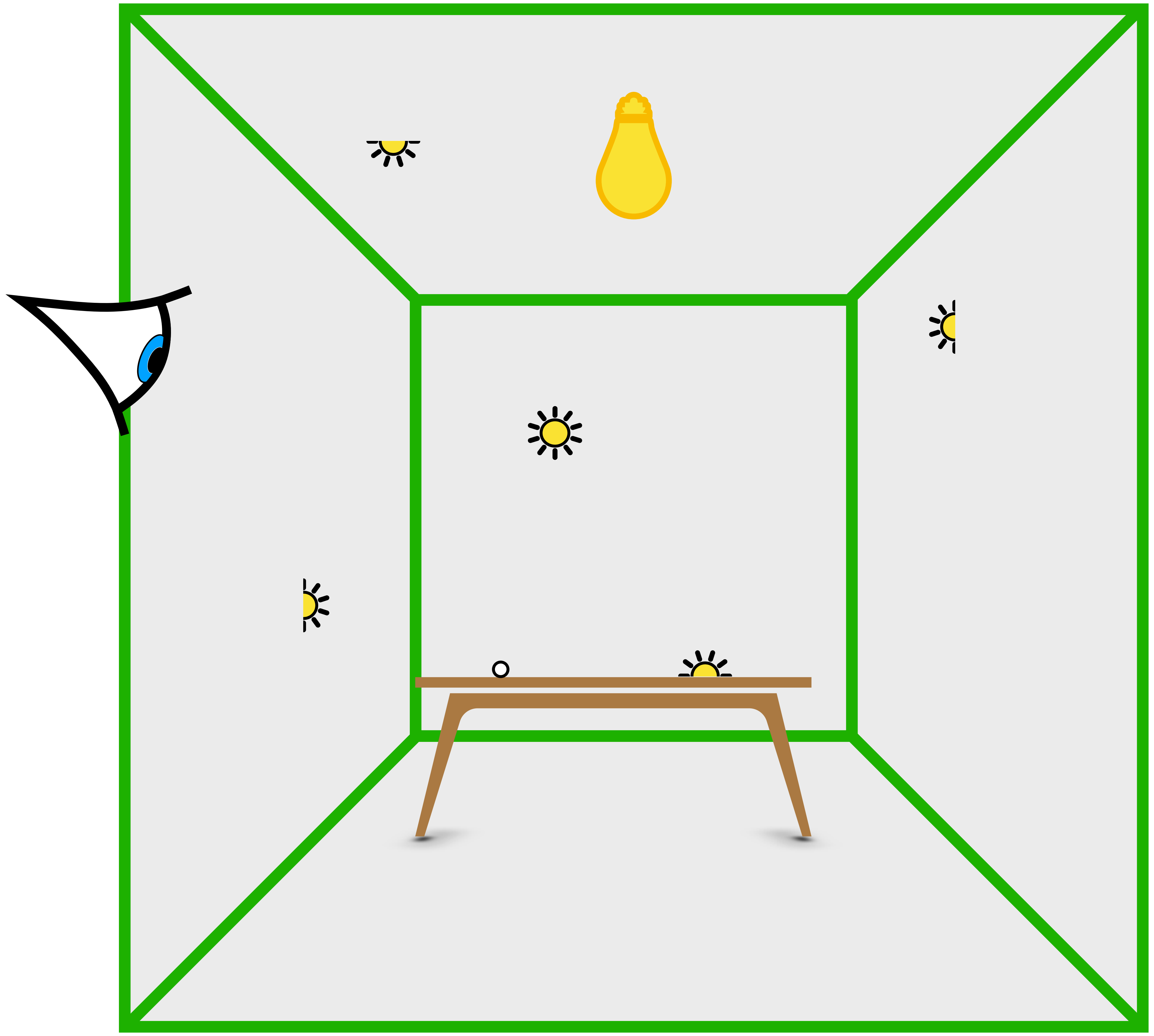
Step 2:

- Render scene with VPLs

Pass 2



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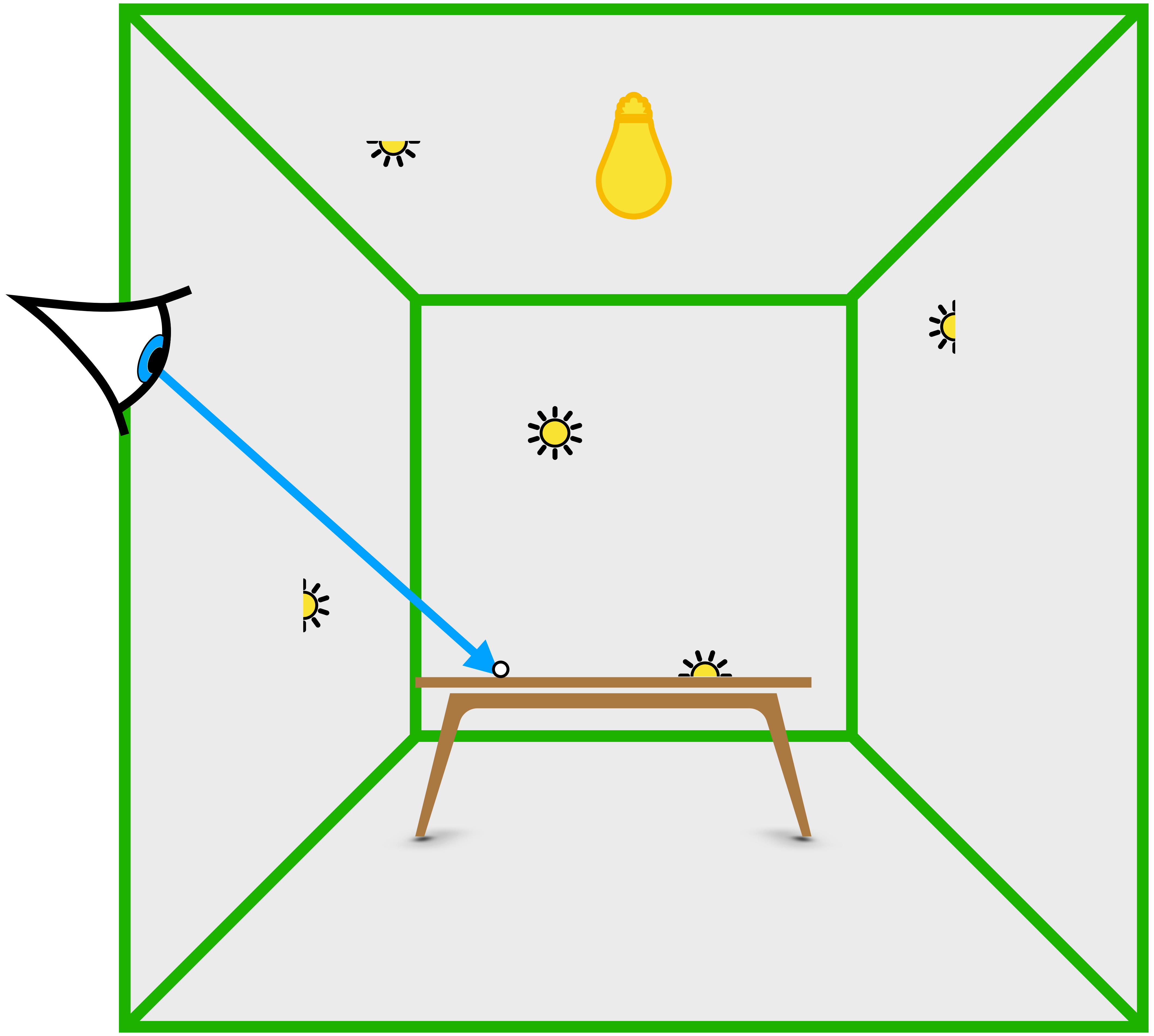

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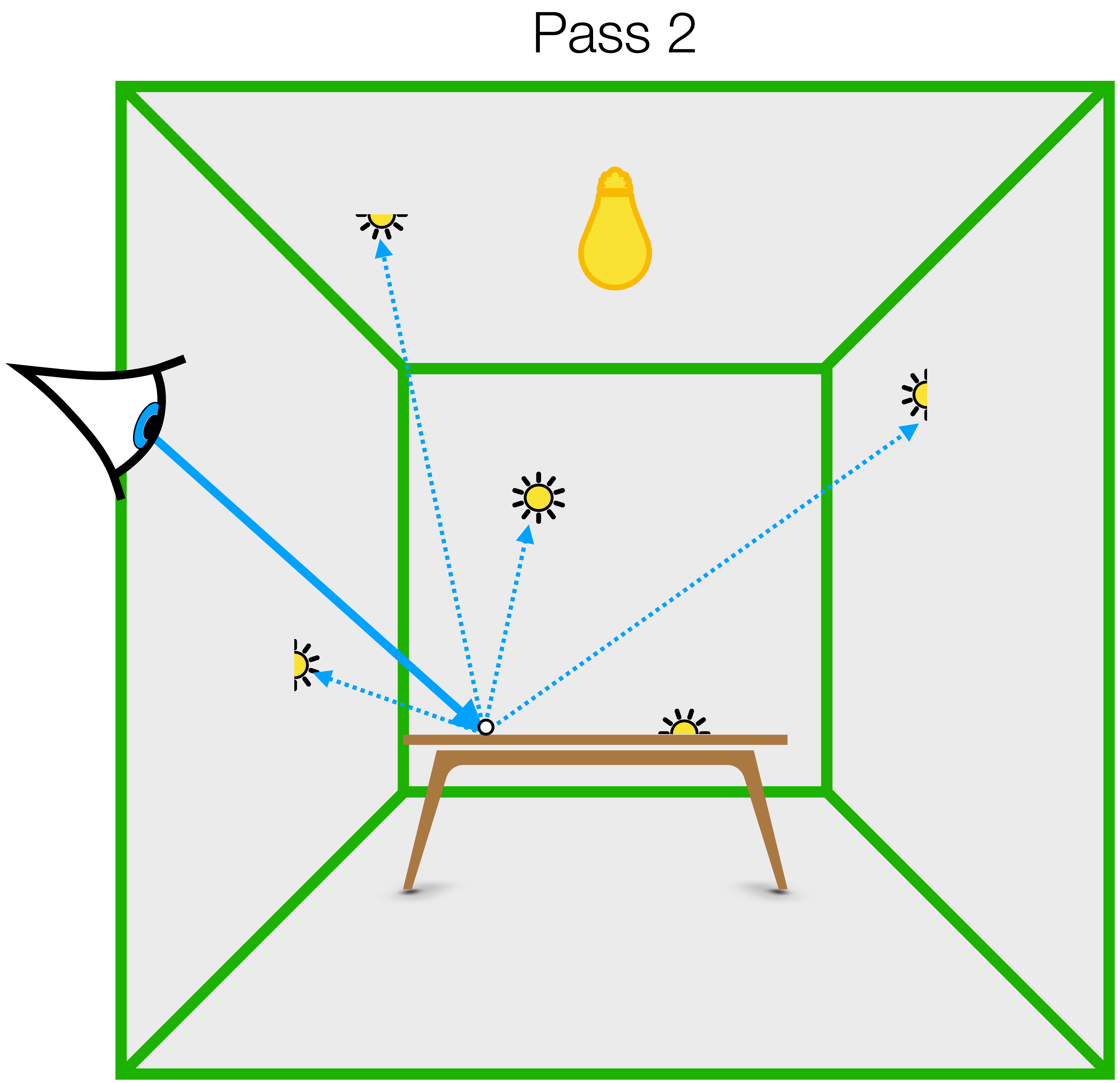
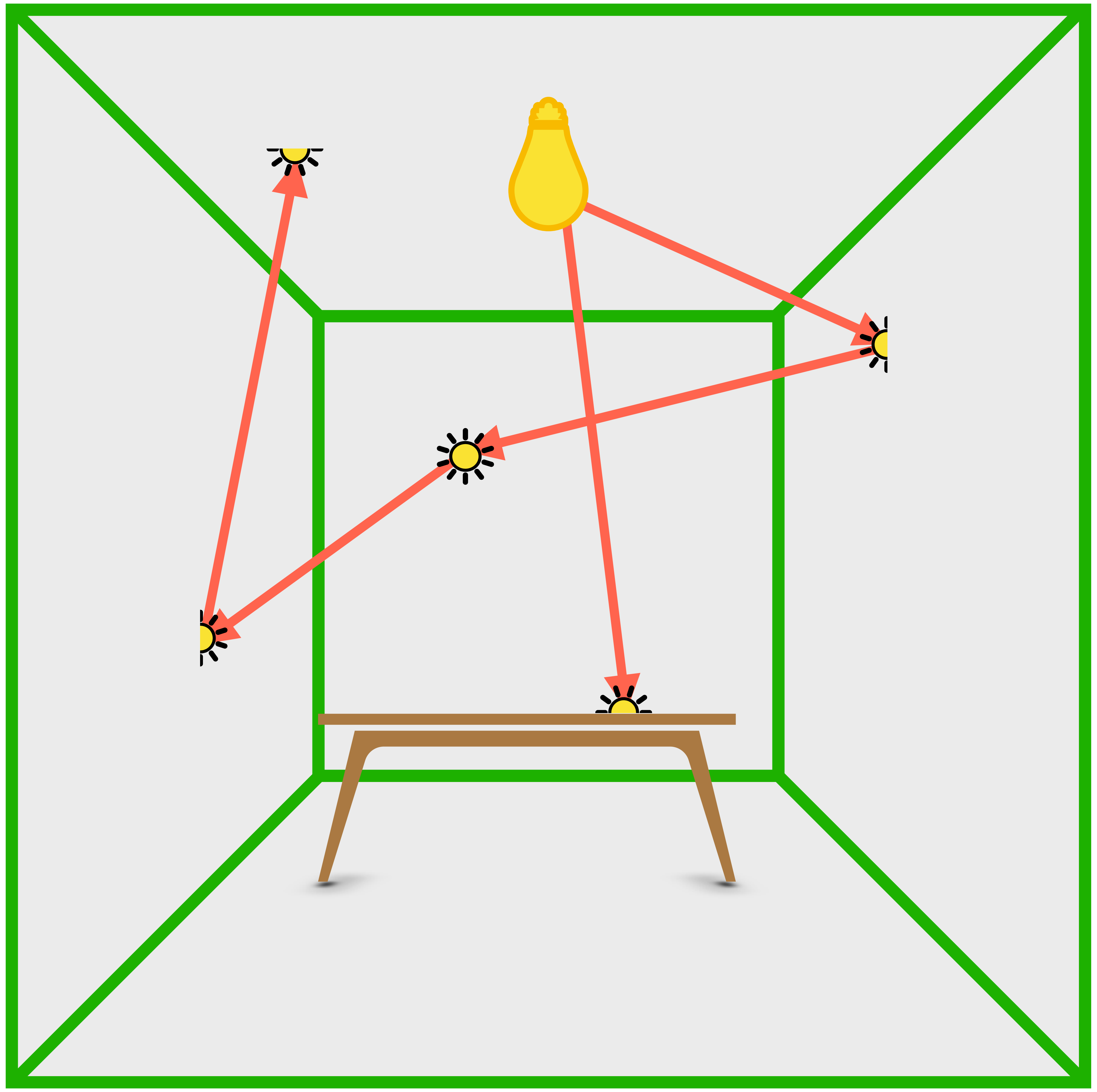
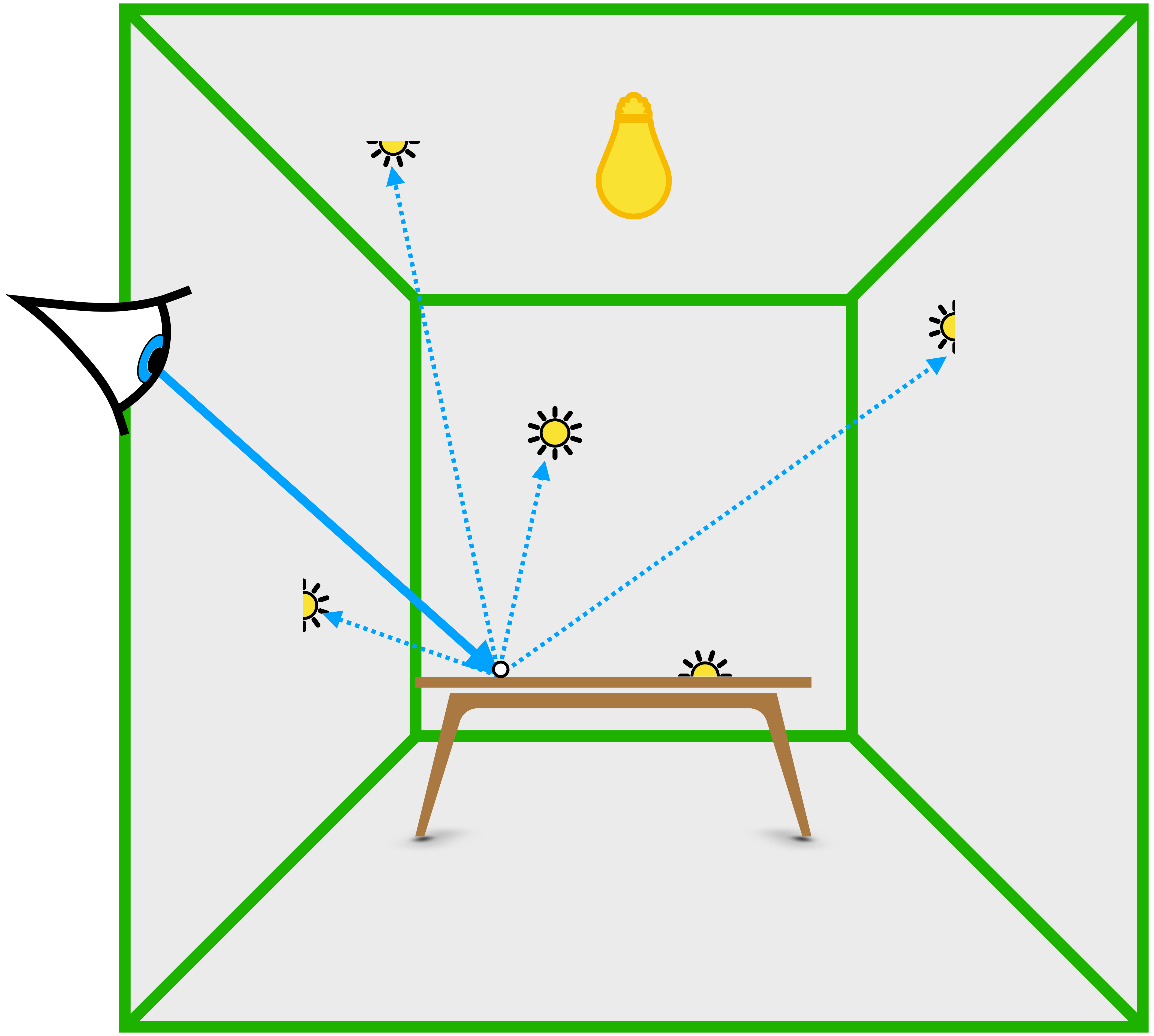


Virtual Point Light: Two-Pass

Pass 1: Generating VPLs



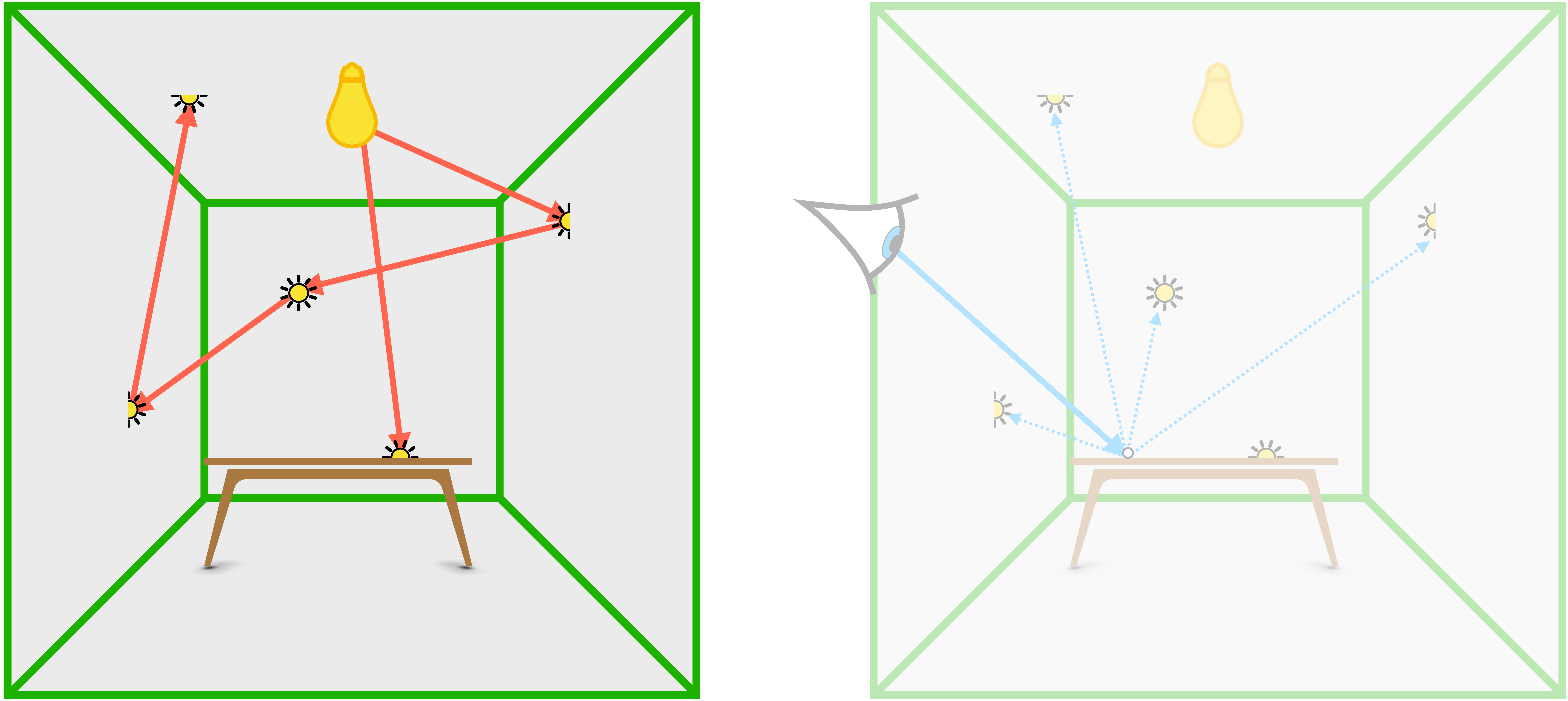
Pass 2: Lighting with VPLs



Virtual Point Light: Two-Pass

Pass 1: Generating VPLs

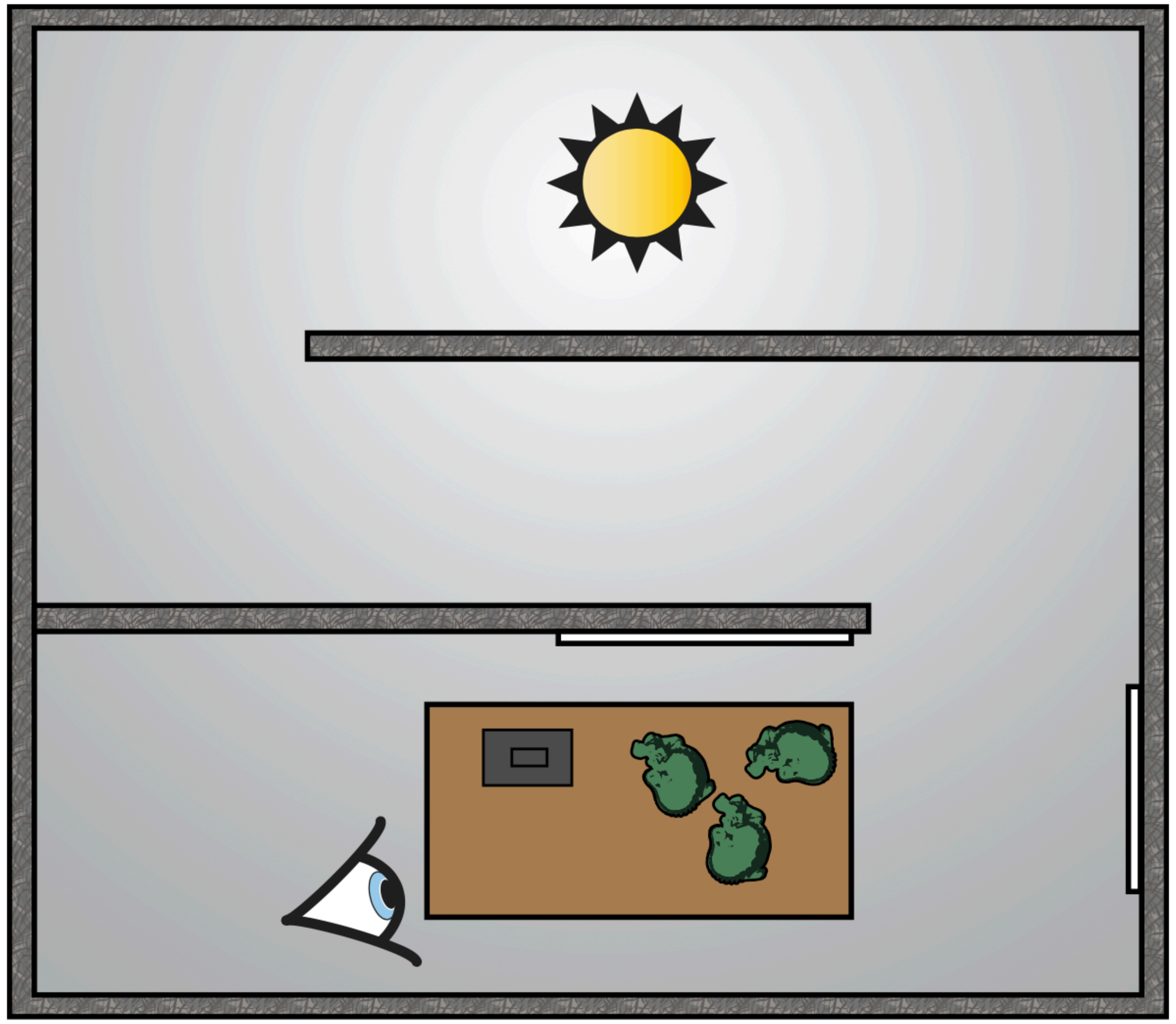
Pass 2: Lighting with VPLs



Generating Virtual Point Lights (VPLs)

Naive Generation of VPLs

Problem 1 (in complex scenes): - many VPLs do not contribute



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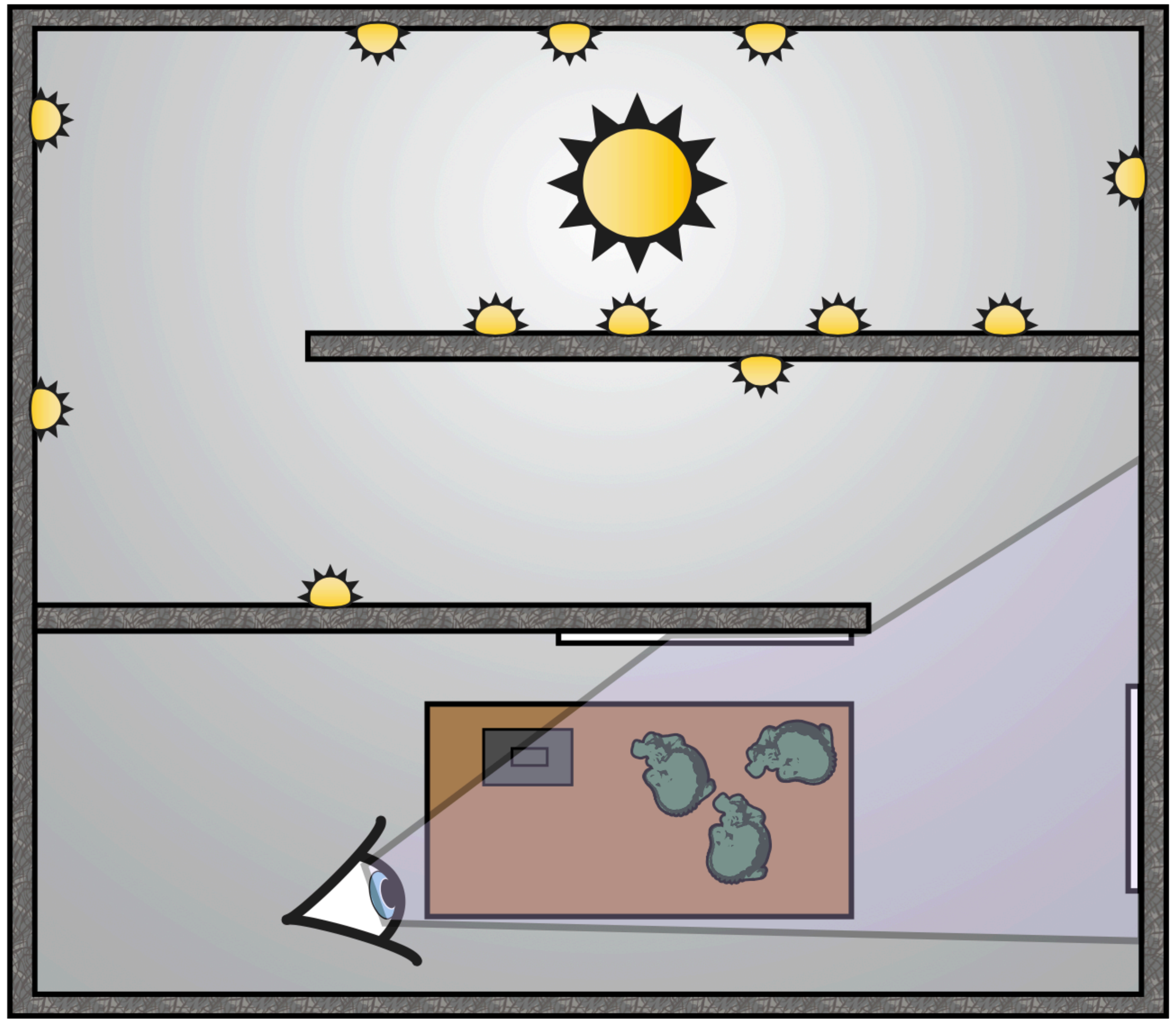

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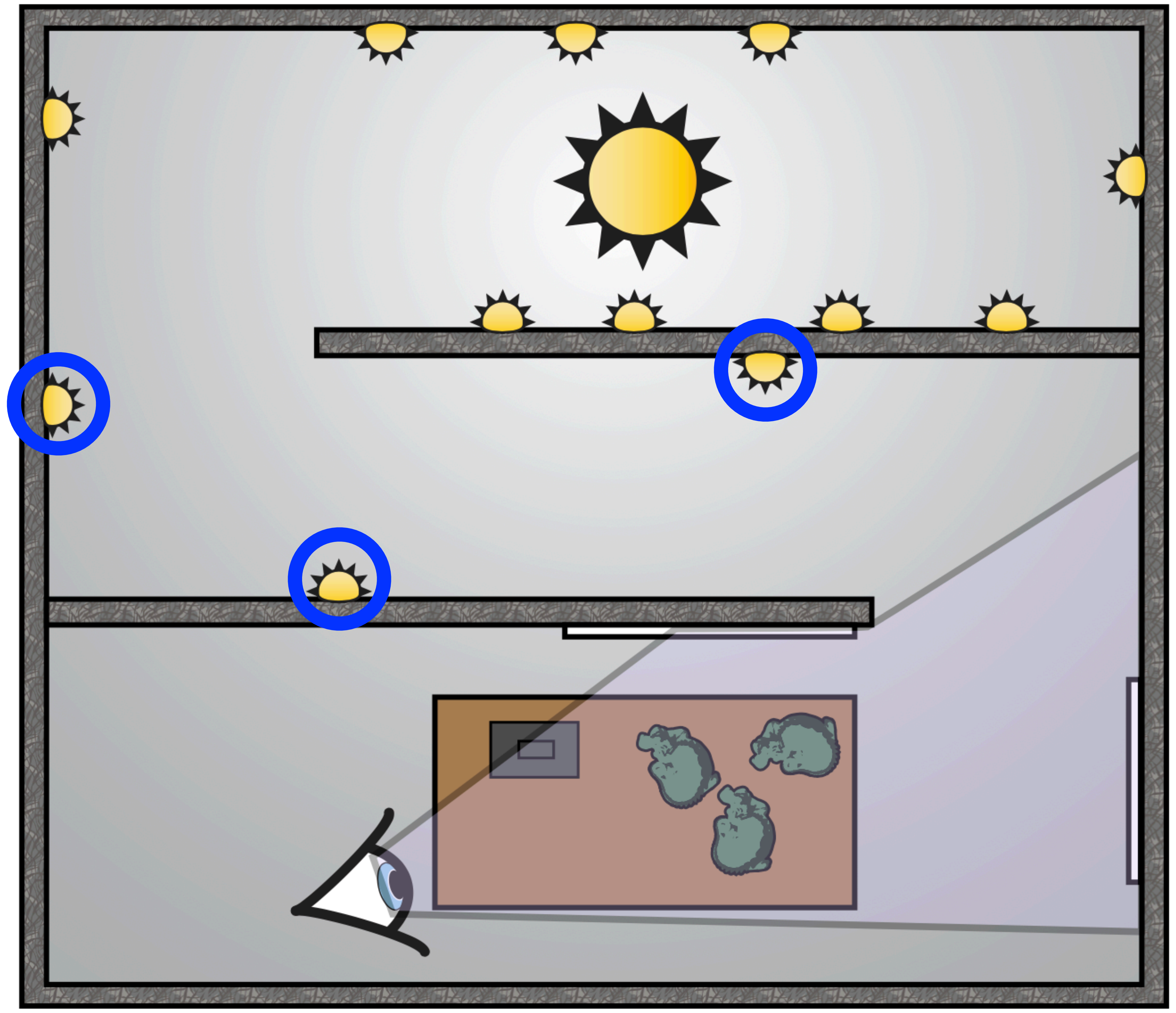

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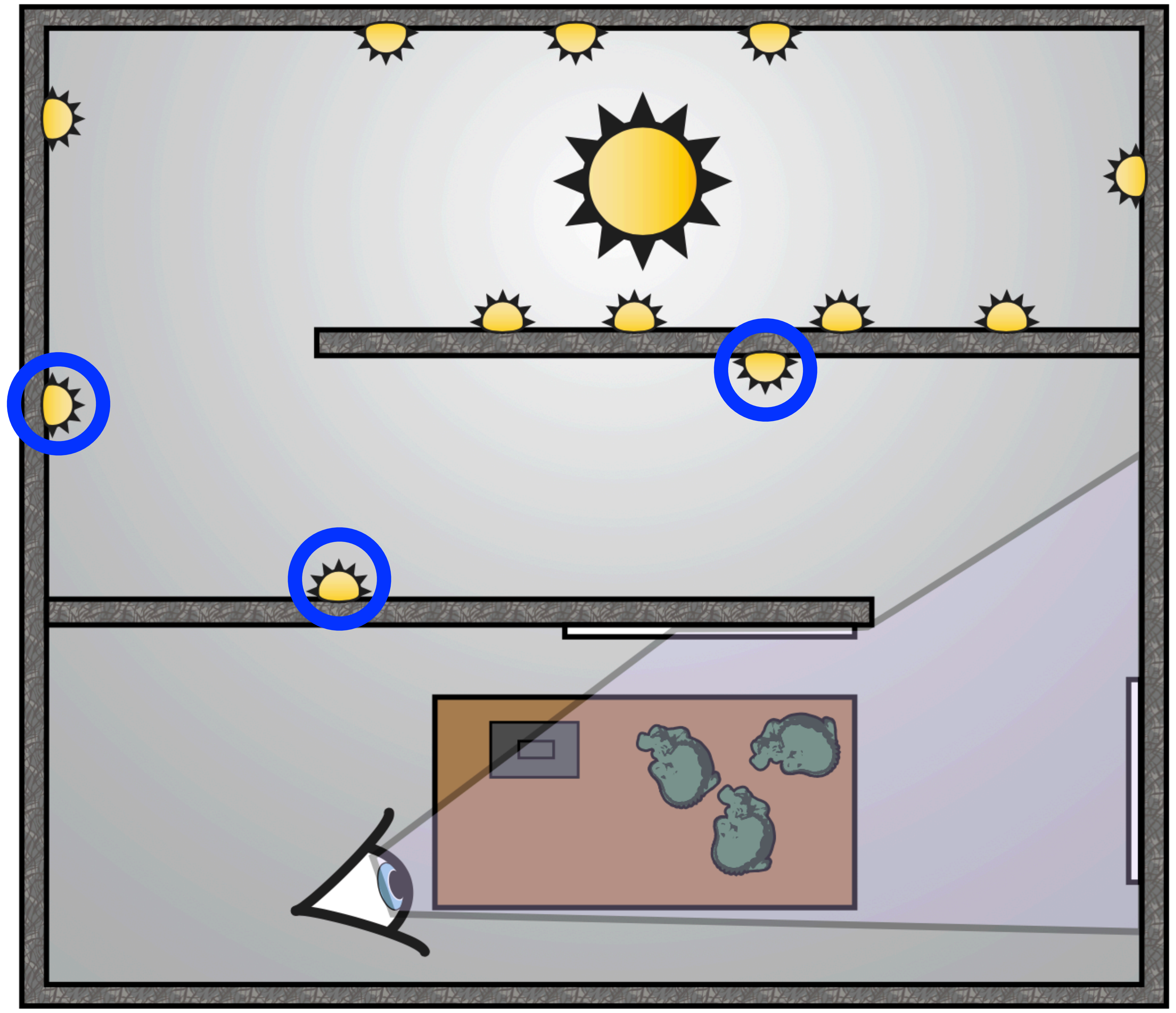

Instant Radiosity

Reference

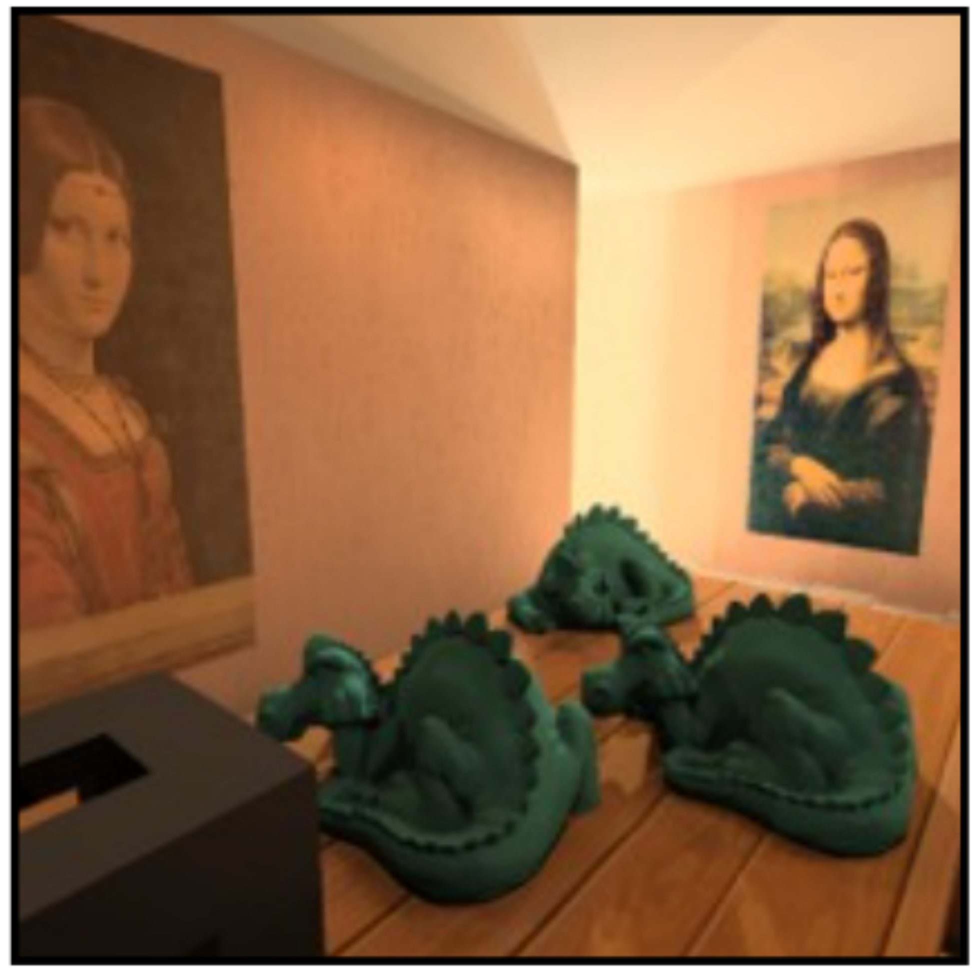

Image courtesy Segovia et al.

Naive Generation of VPLs

Problem 2 (in glossy scenes): - Glossy inter-reflections suffer from splotches

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Instant Radiosity

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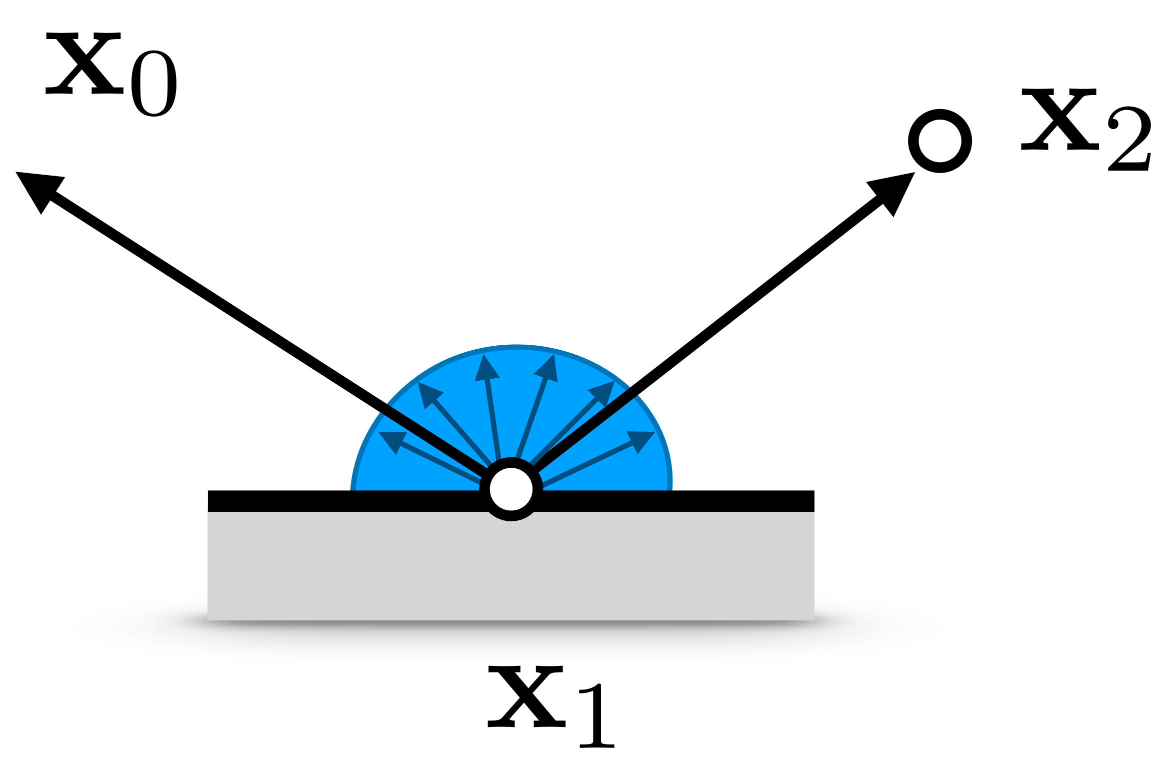
Instant Radiosity

Instant radiosity assumes all surfaces are diffuse



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Instant Radiosity

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Instant Radiosity

Clamped

Naive Generation of VPLs

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Naive Generation of VPLs

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- Insufficient number of VPLs in some regions

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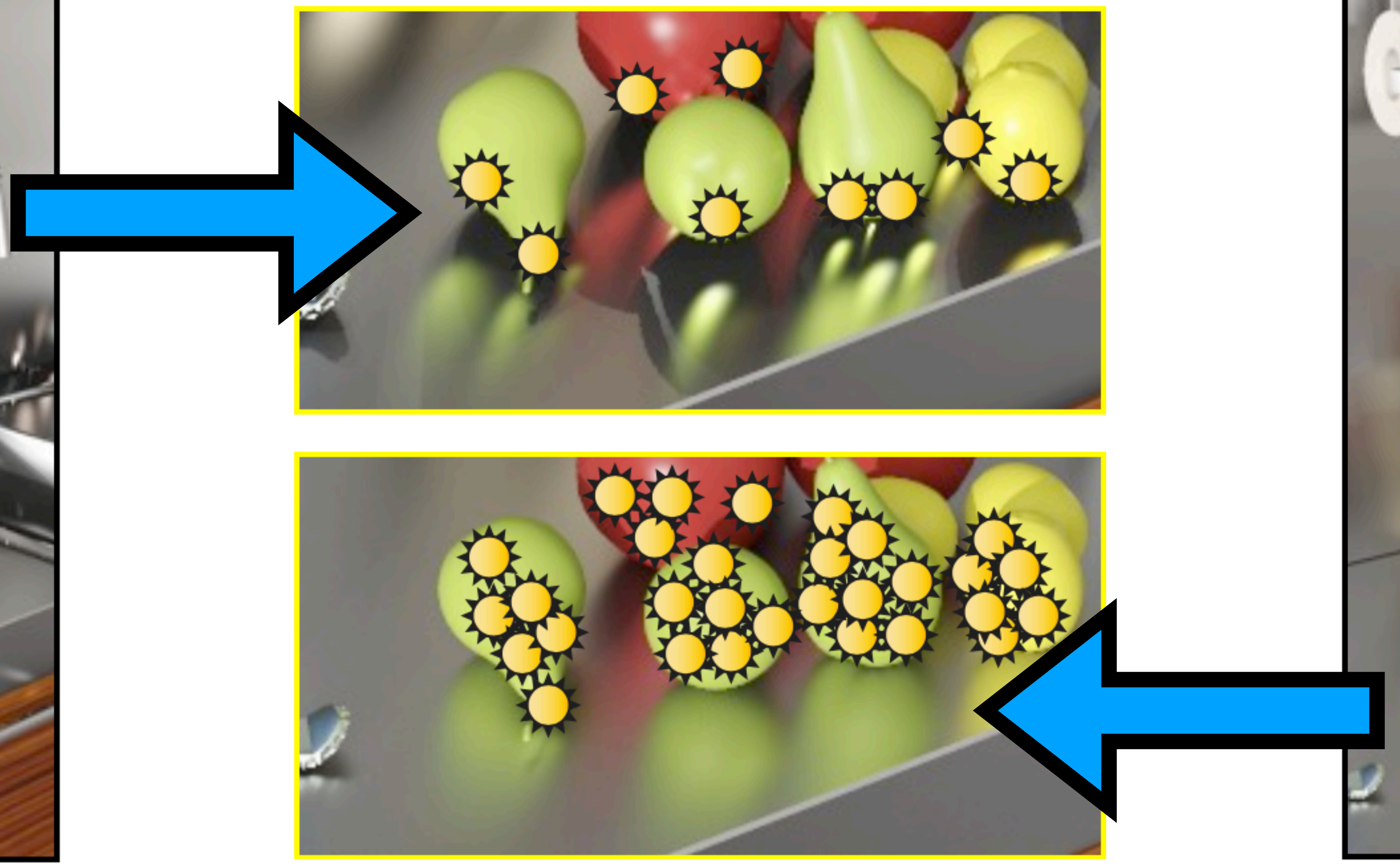


Reference

Improved Generation of VPLs

Goal:

- place VPLs only where needed

Approaches:

Rejection of unimportant VPLs [Gerogiev and Slusallek 2010]

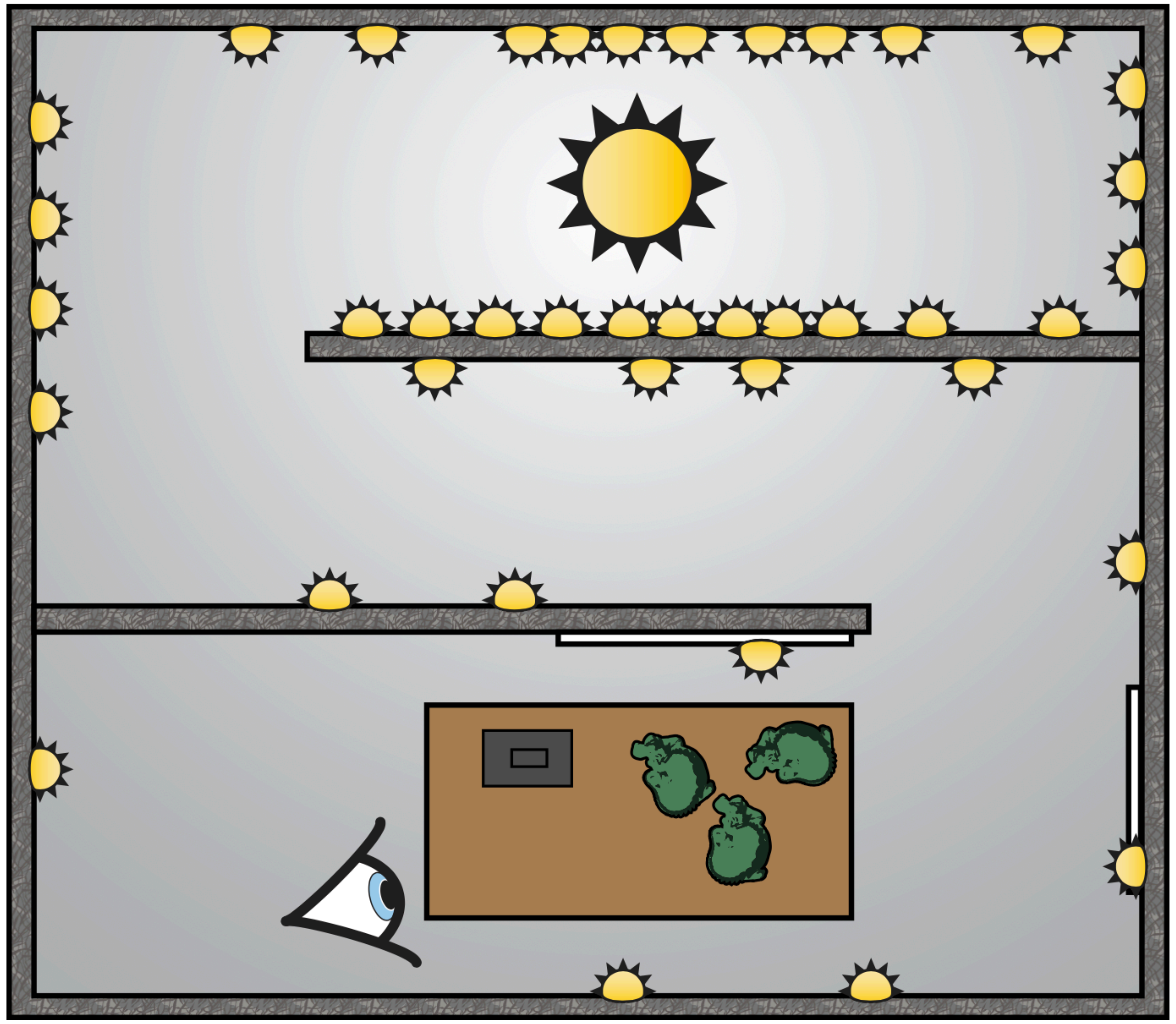
Bidirectional Instant Radiosity [Segovia et al. 2006]

Metropolis sampling for VPL distributions [Segovia et al. 2007]

Improved Generation of VPLs

Rejection of unimportant VPLs [Gerogiev and Slusallek 2010]

- probabilistically reject VPLs with low expected contribution



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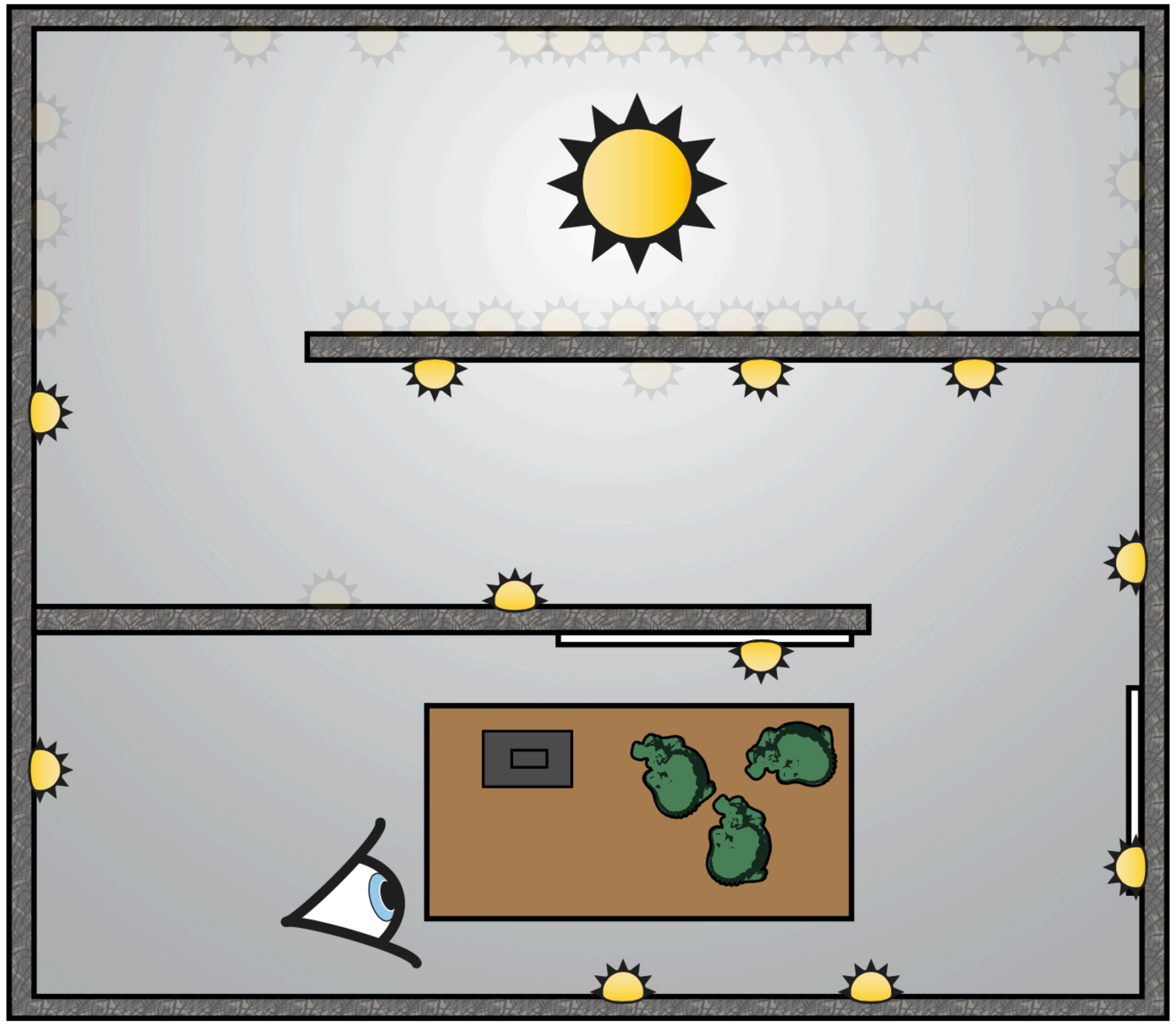

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Approach:

Improved Generation of VPLs

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1) estimate average contribution of a VPL Φ_v

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Russian roulette

Improved Generation of VPLs

Rejection of unimportant VPLs [Gerogiev and Slusallek 2010]

Advantages:

- Cheap and simple to implement!
- VPLs have roughly equal contribution
- Works well most of the time

Improved Generation of VPLs

Rejection of unimportant VPLs [Gerogiev and Slusallek 2010]

Advantages:

- Cheap and simple to implement!
- VPLs have roughly equal contribution
- Works well most of the time

Disadvantages:

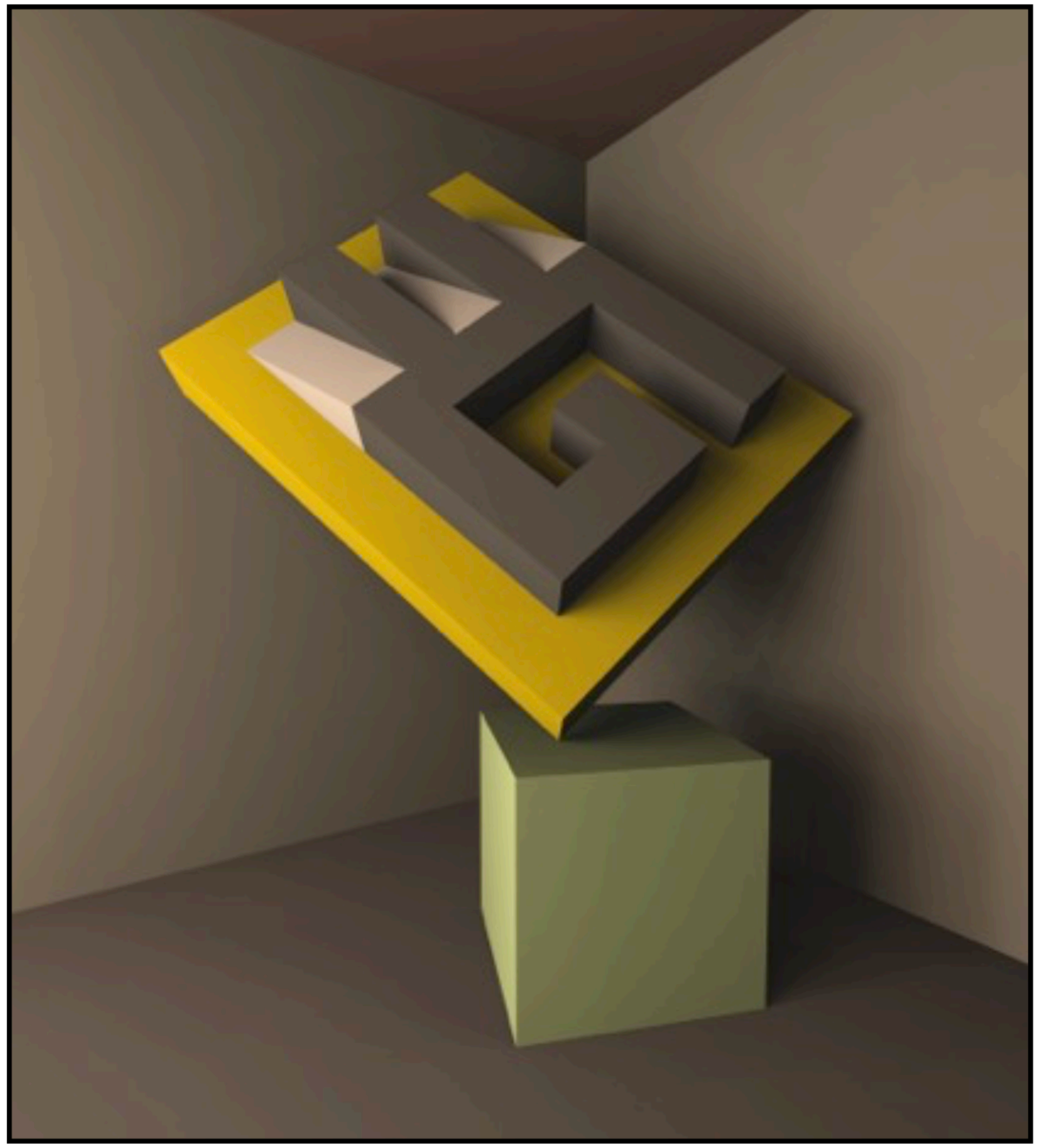
- Increase the cost of VPL distribution
- "one-pixel image" assumption
- Does not help with local inter-reflections

Improved Generation of VPLs

Rejection of unimportant VPLs [Gerogiev and Slusallek 2010]

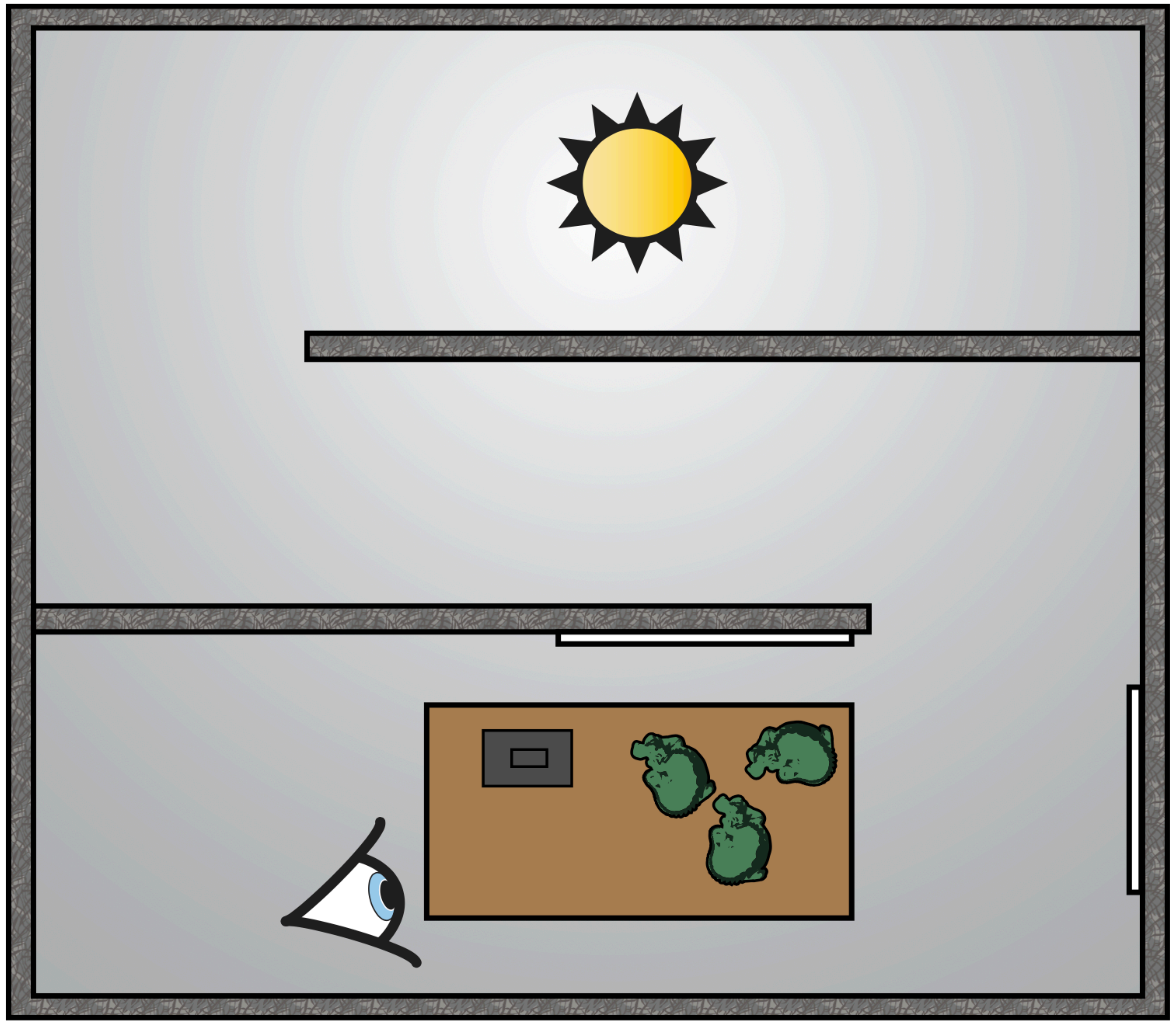
Without rejection

With rejection (7% acceptance)



Improved Generation of VPLs

Bidirectional Instant Radiosity [Segovia et al. 2006]



Create a VPL at the second bounce from the camera

Improved Generation of VPLs

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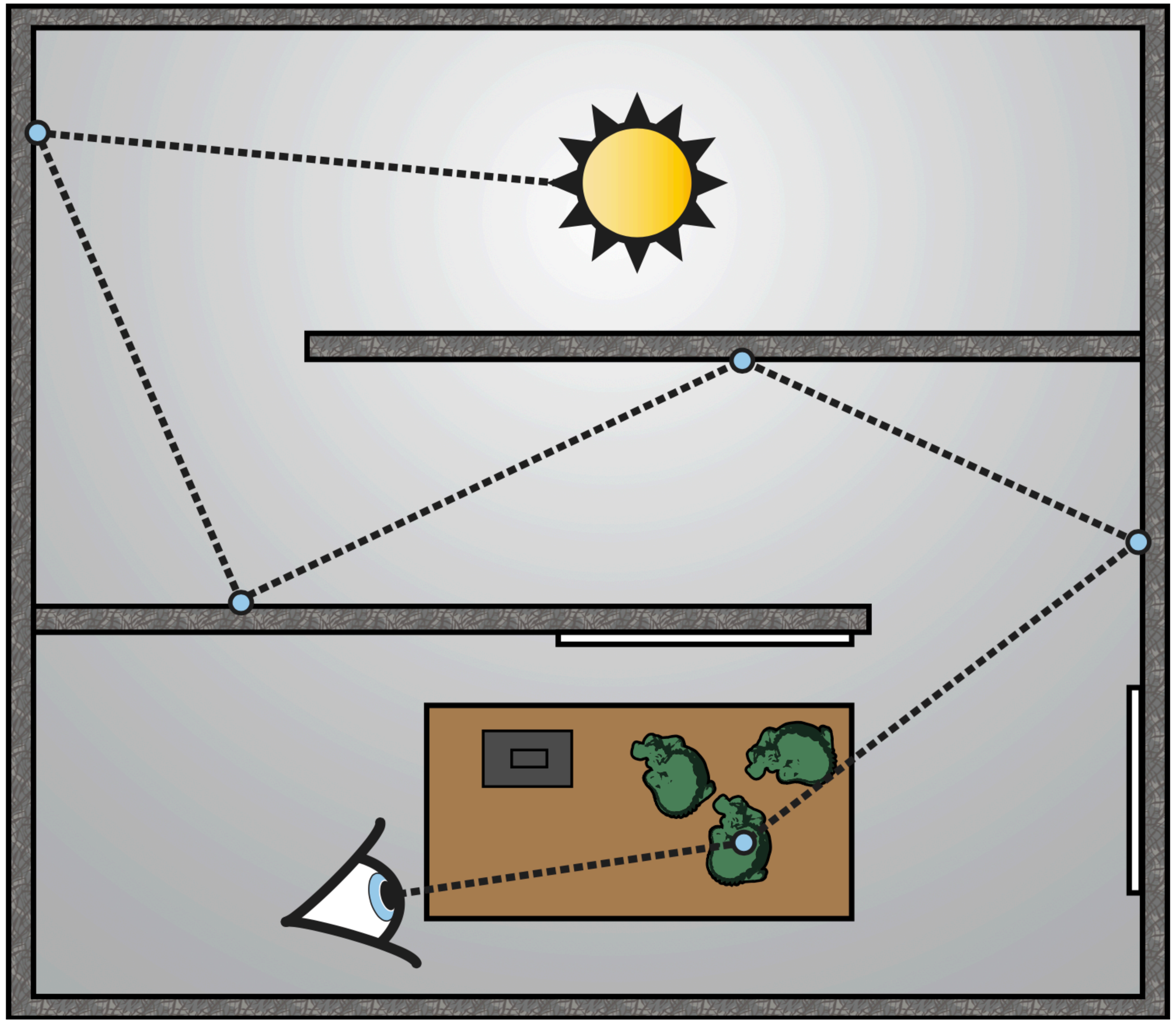

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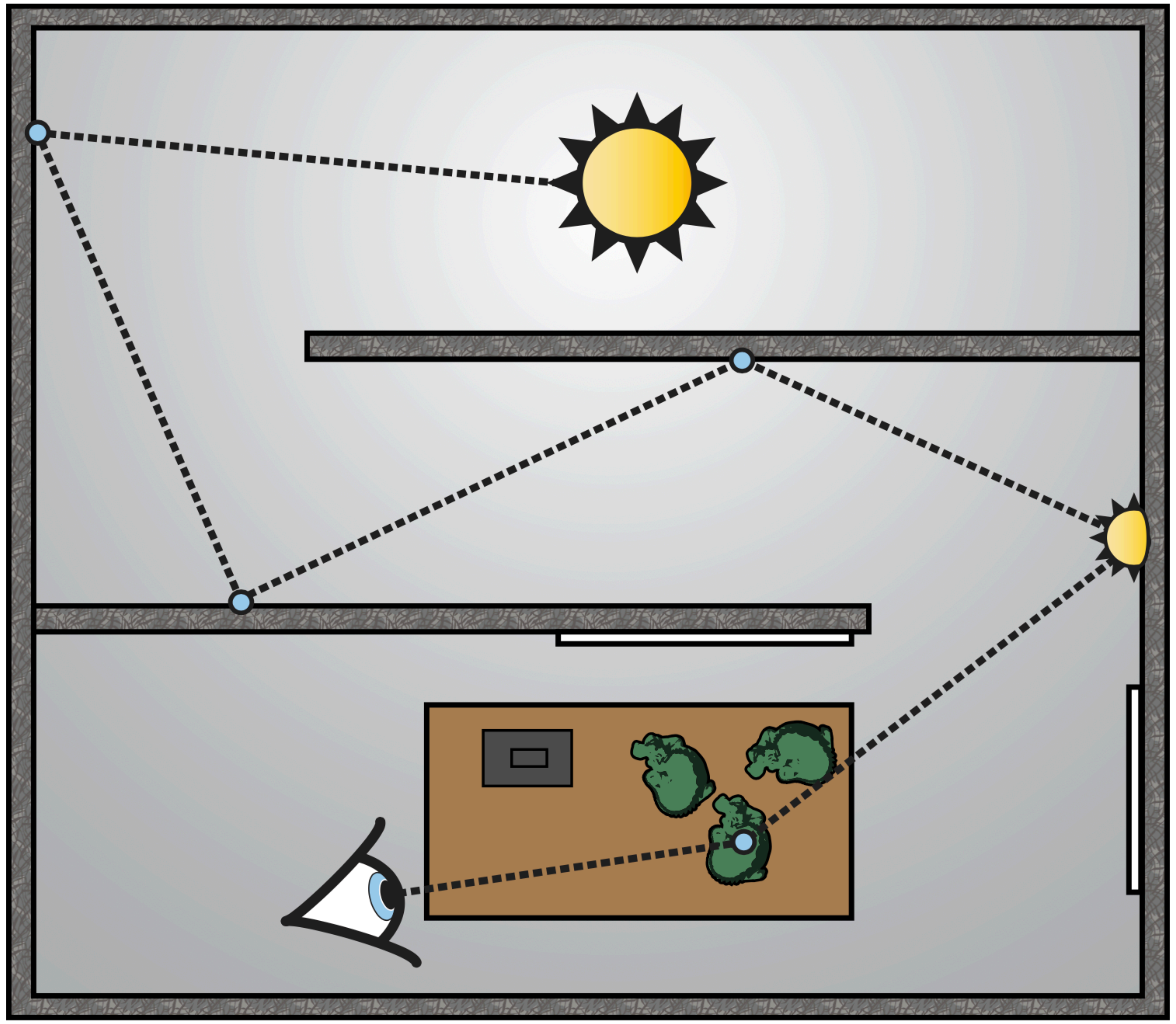

Create a VPL at the second bounce from the camera

2^{nd} vertex from camera

Improved Generation of VPLs

Metropolis Instant Radiosity [Segovia et al. 2007]

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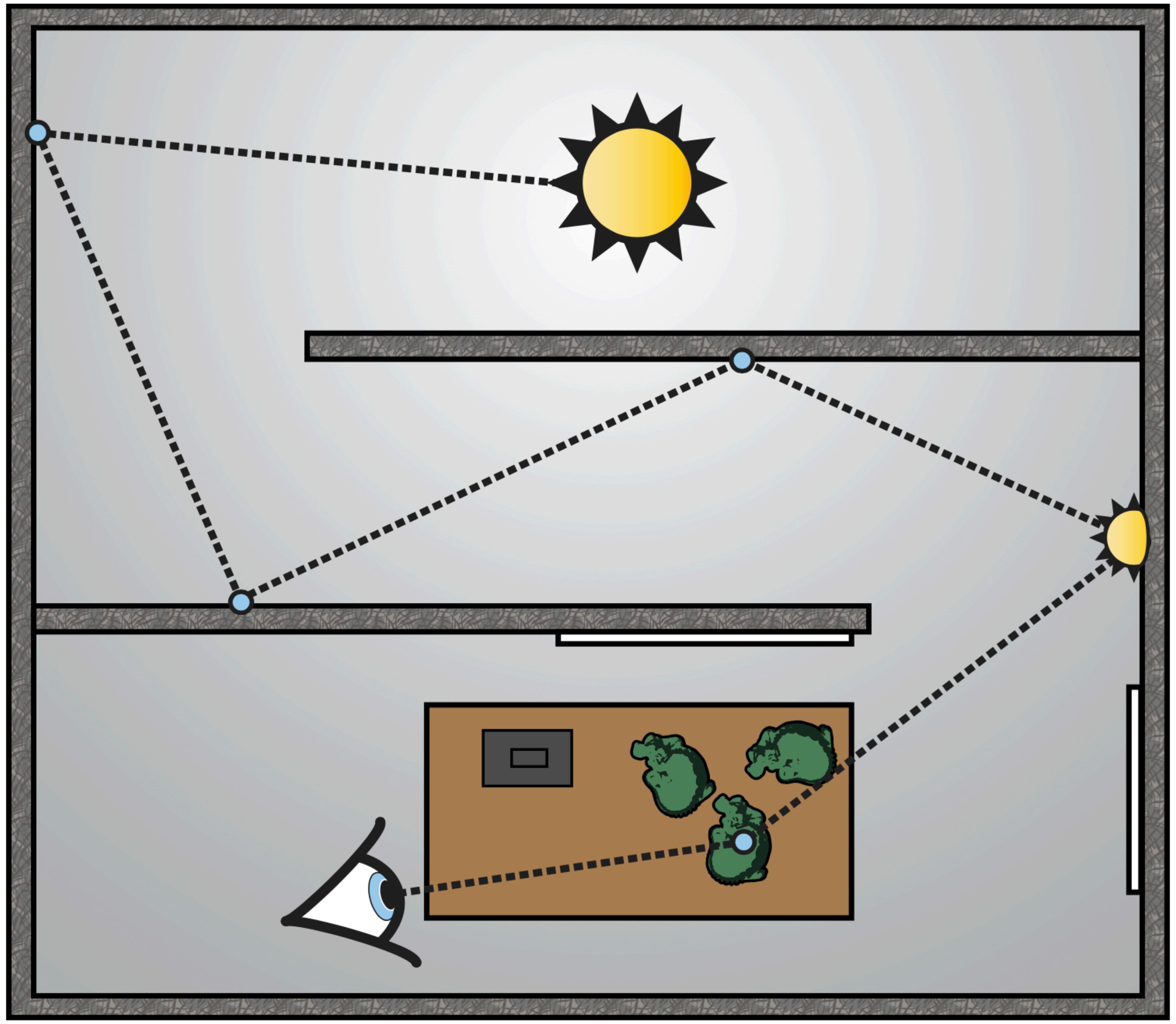

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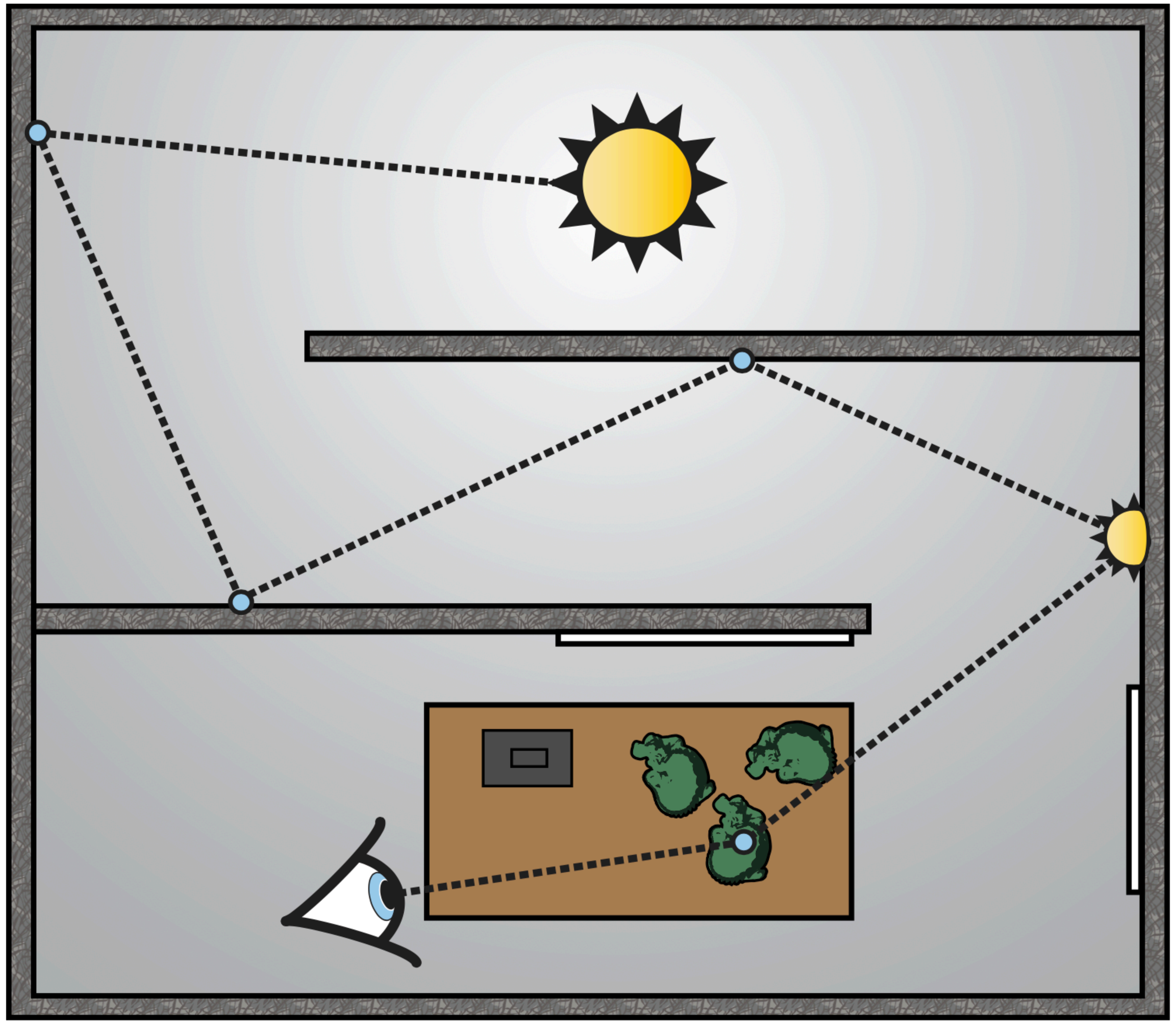

Generate VPLs by mutating paths

Improved Generation of VPLs

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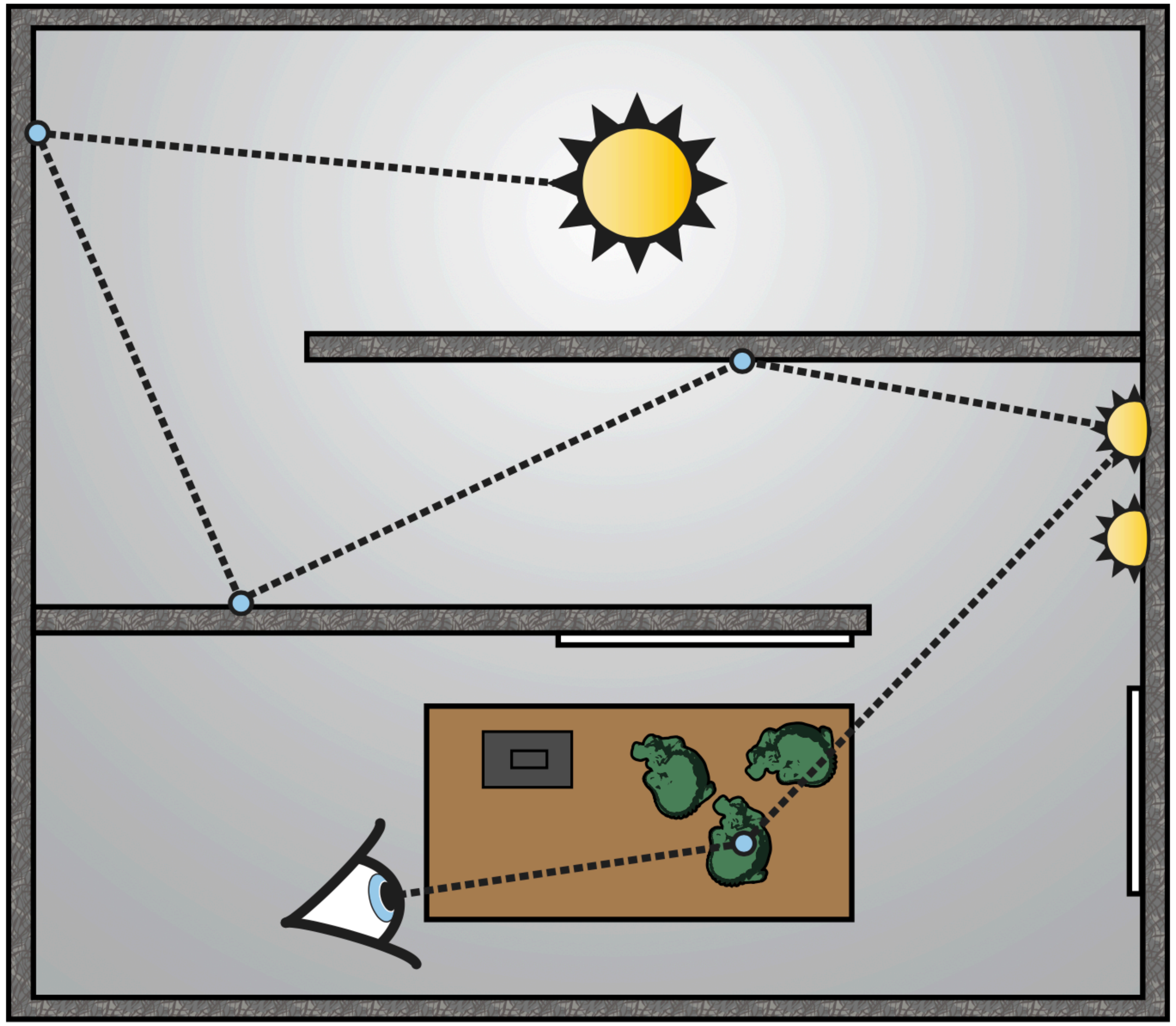

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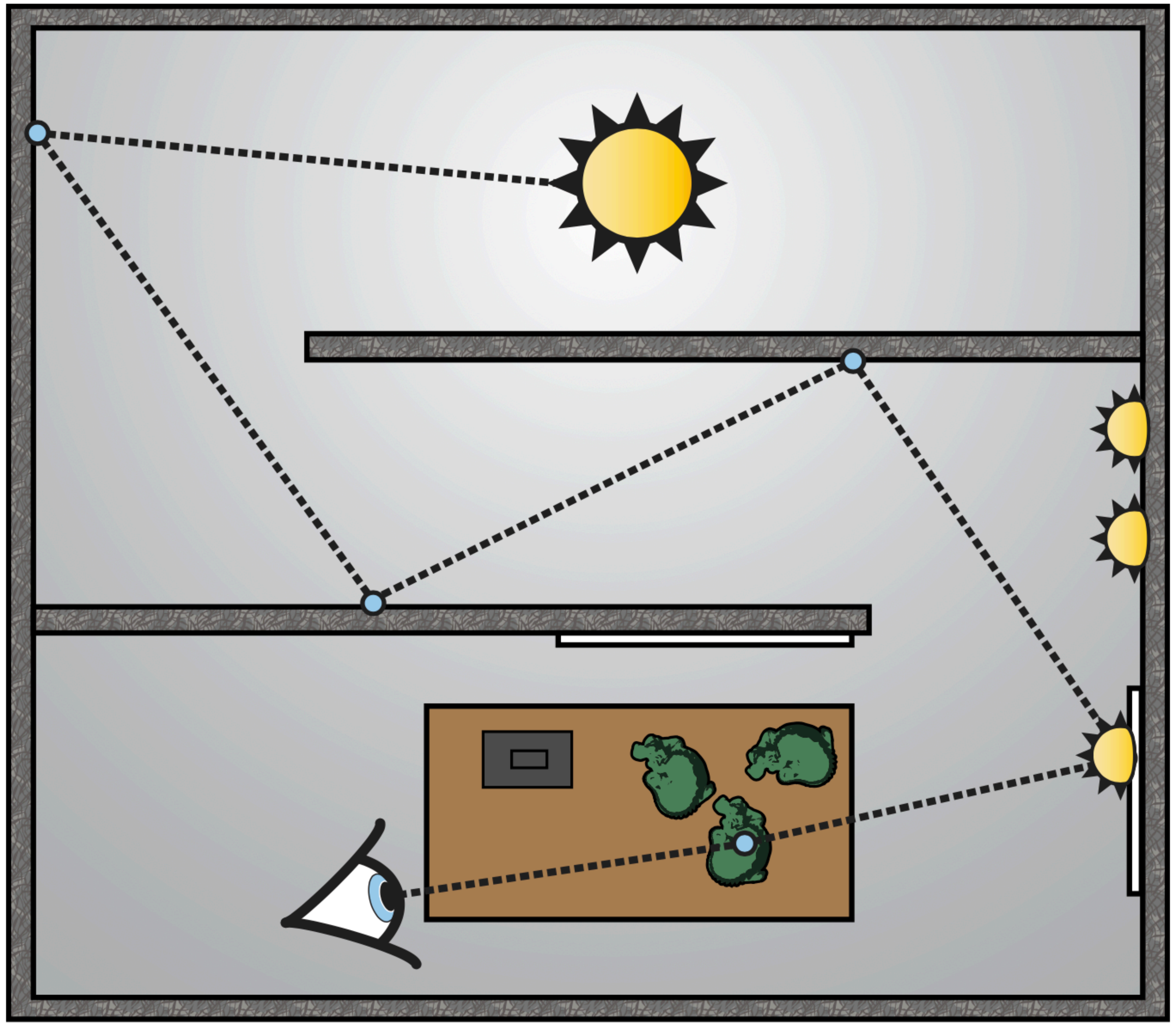
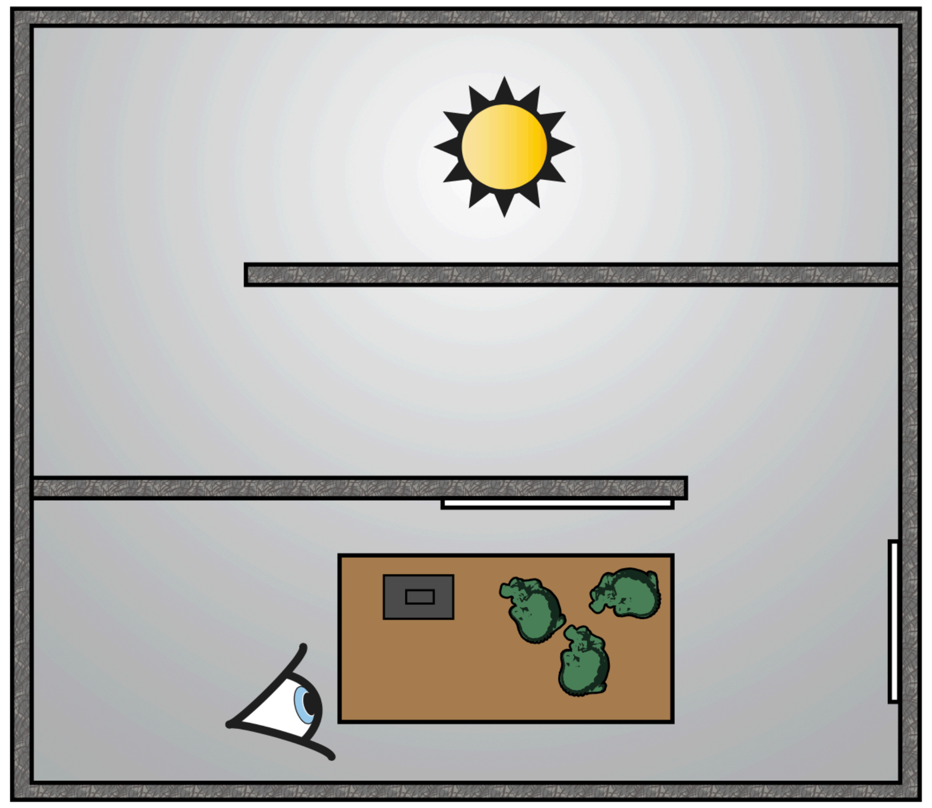


Generate VPLs by mutating paths

Comparisons

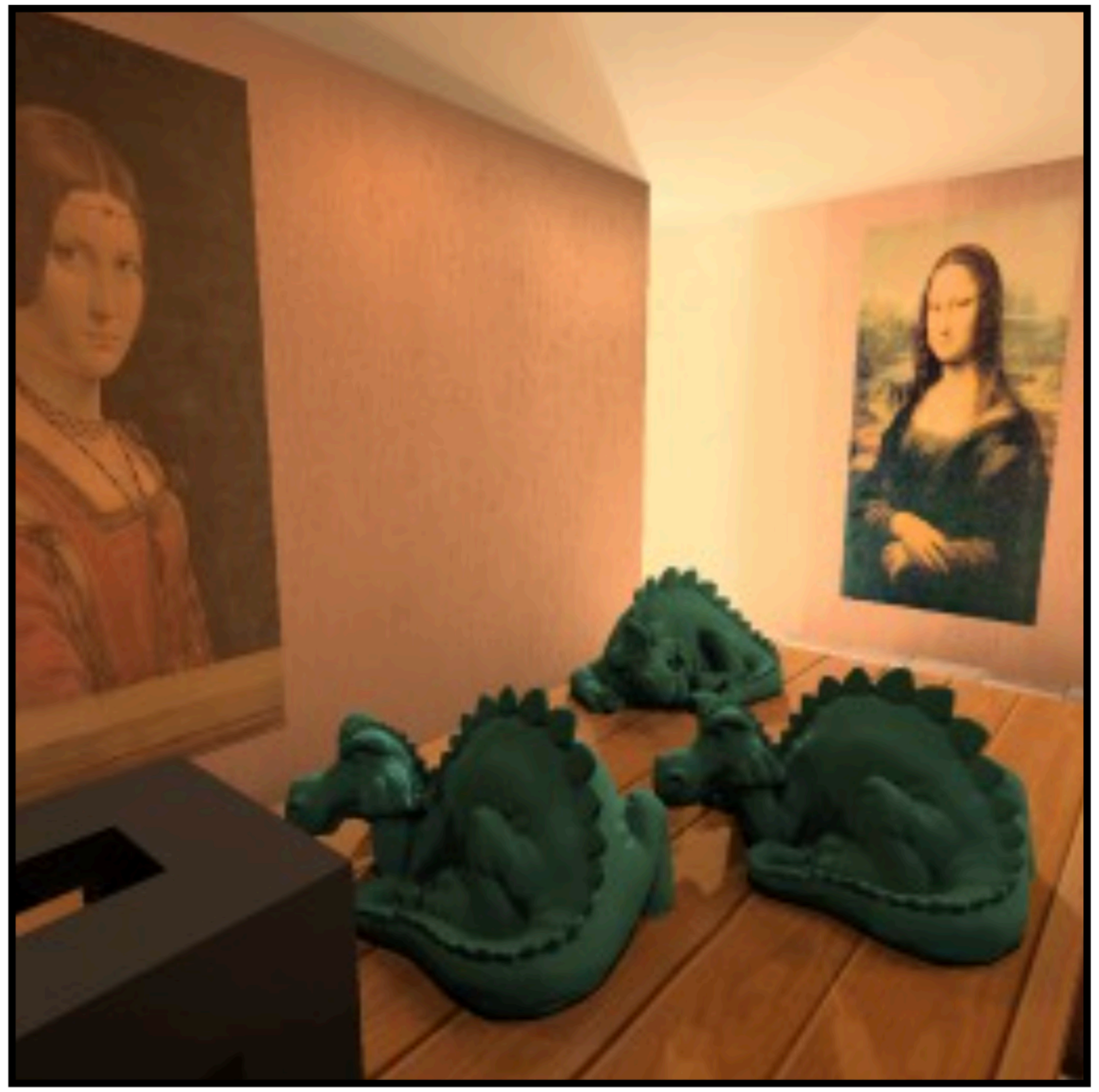


Metropolis Instant Radiosity [Segovia et al. 2006]

Instant Radiosity

Bidirectional Instant Radiosity

Metropolis Instant Radiosity



Comparisons

Metropolis Instant Radiosity [Segovia et al. 2006]

Advantages:

Handles large and difficult scenes

VPLs have equal contribution

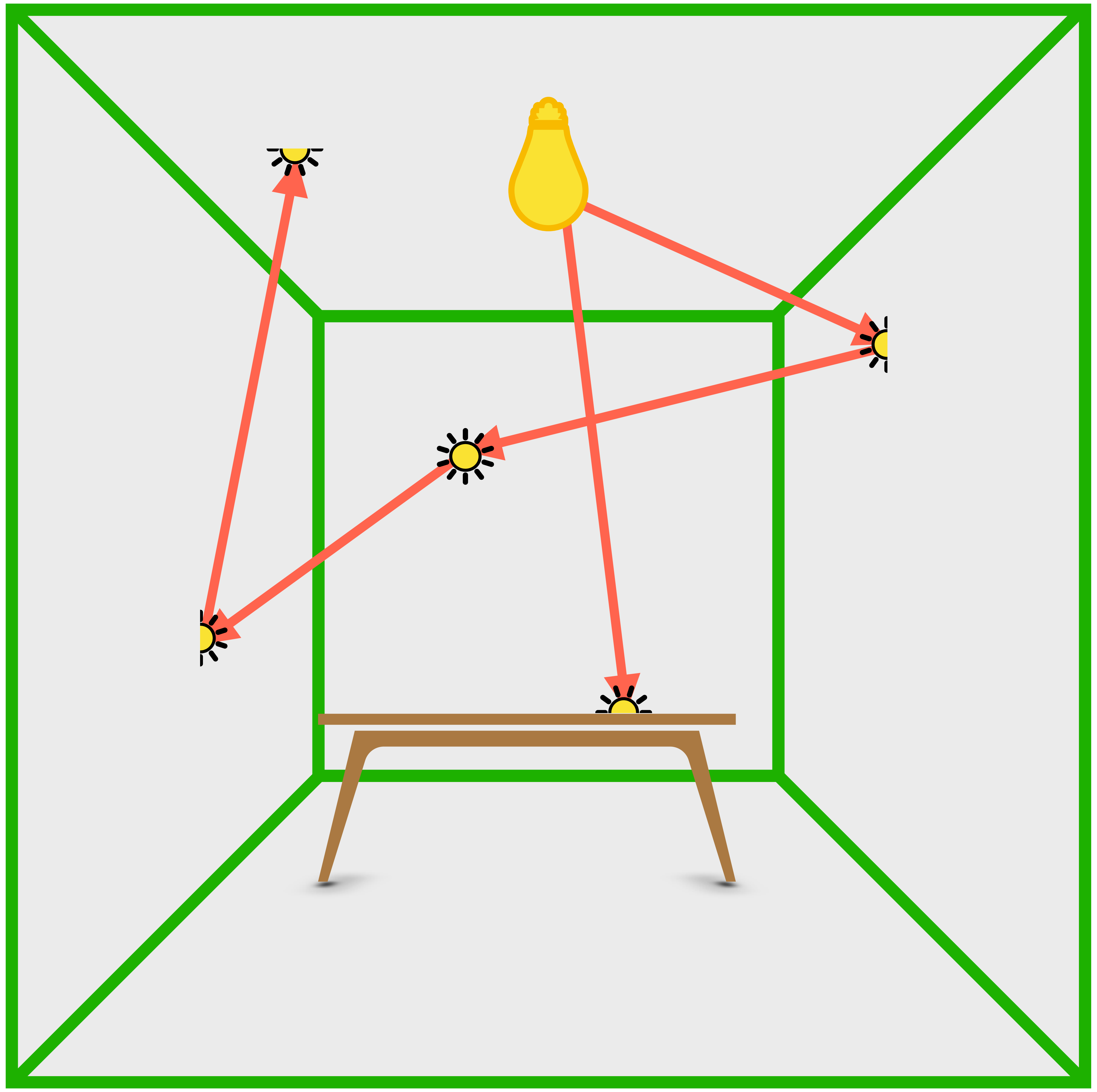
Disadvantages:

Complicated implementation

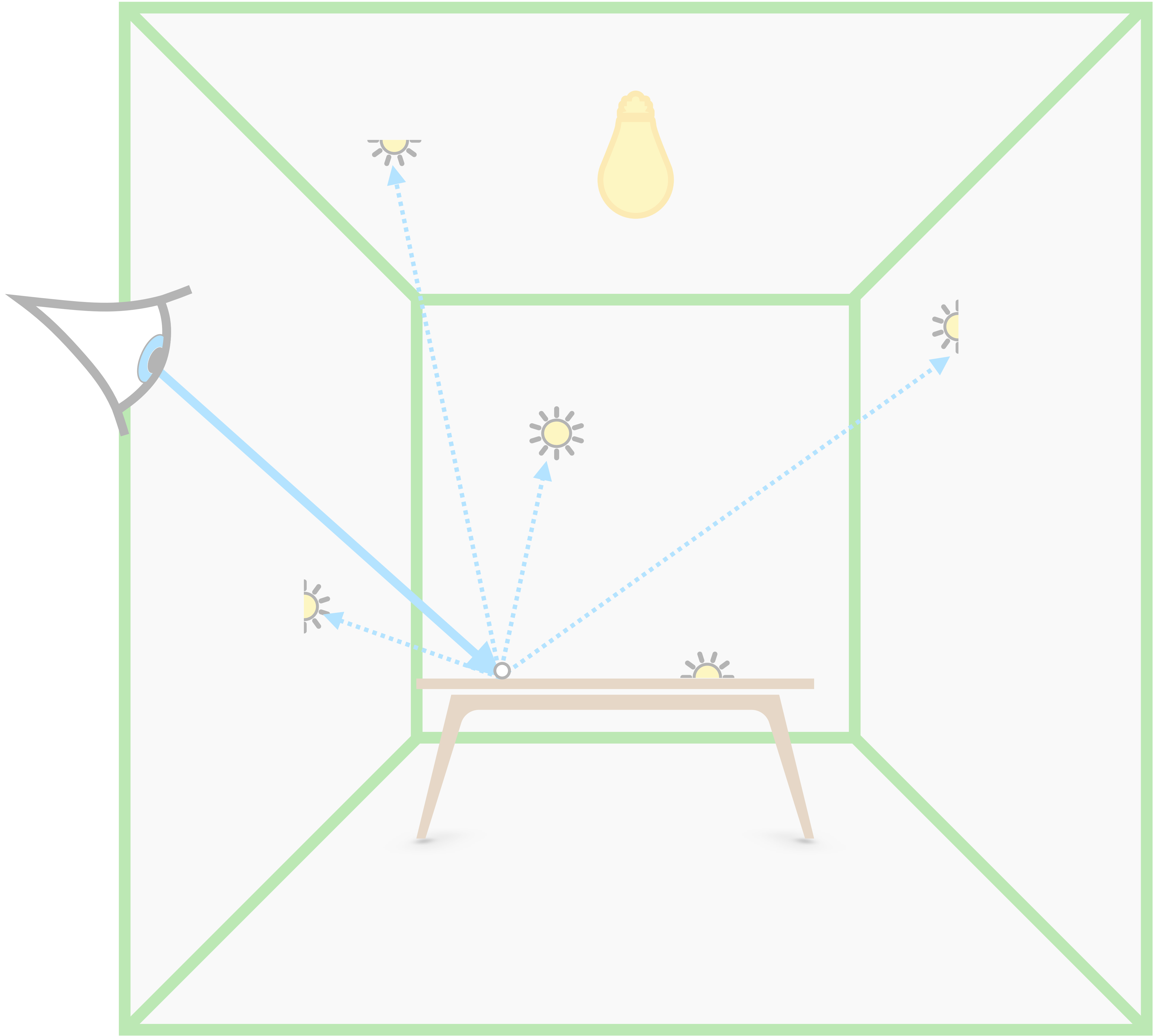
Does not help with local inter-reflections

Virtual Point Light: Two-Pass

Pass 1: Generating VPLs



Pass 2: Lighting with VPLs



Virtual Point Light: Two-Pass

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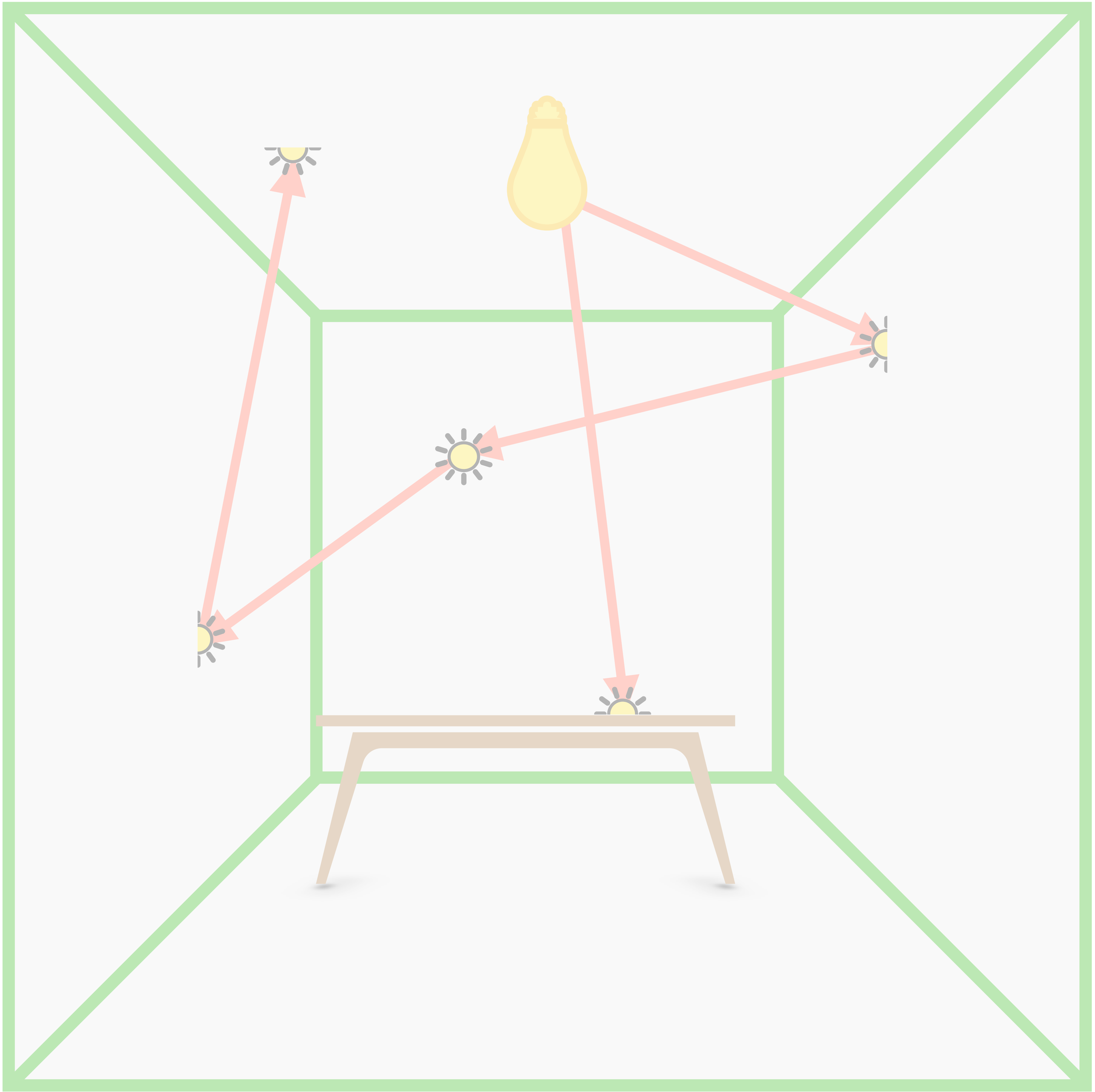

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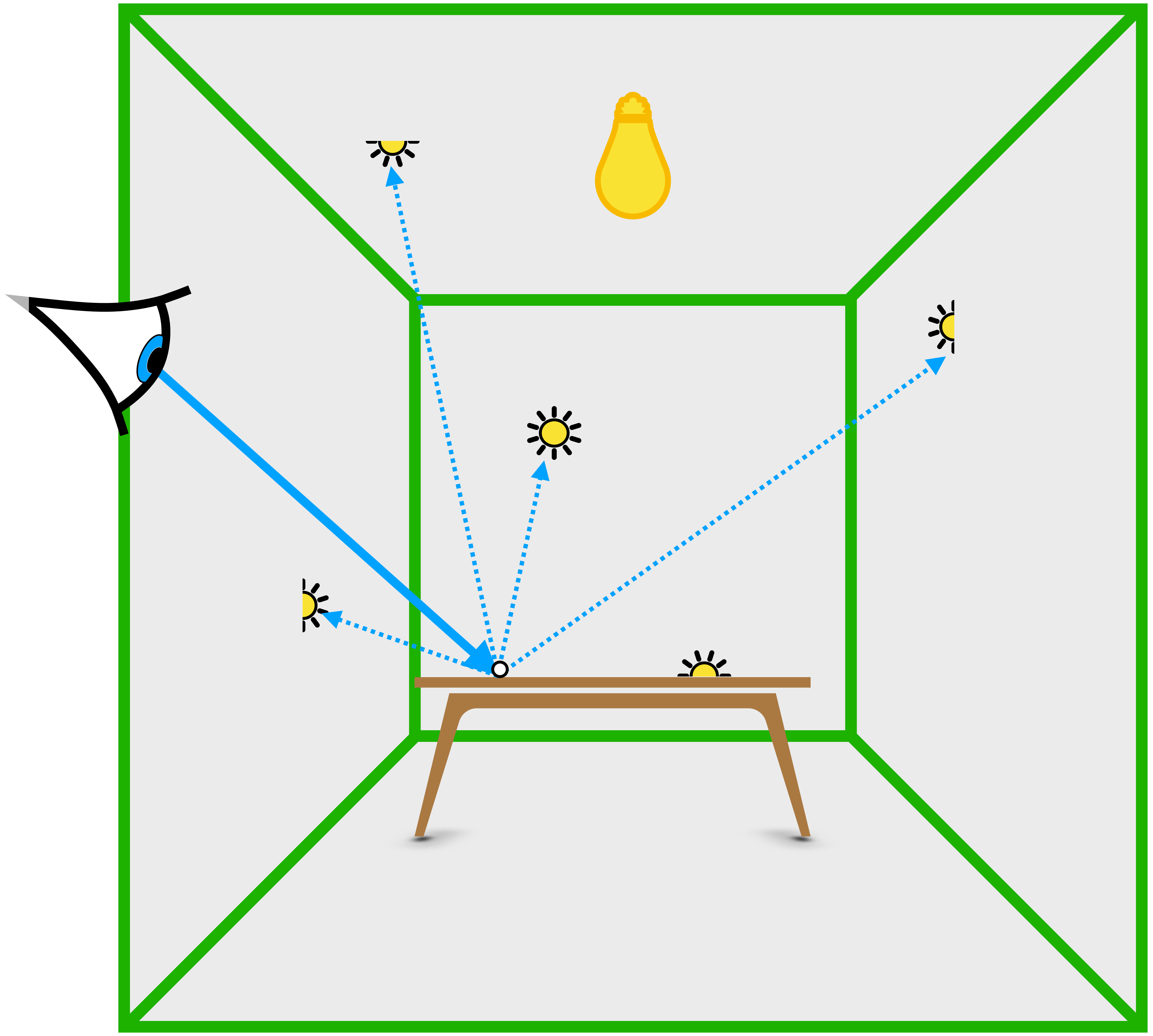
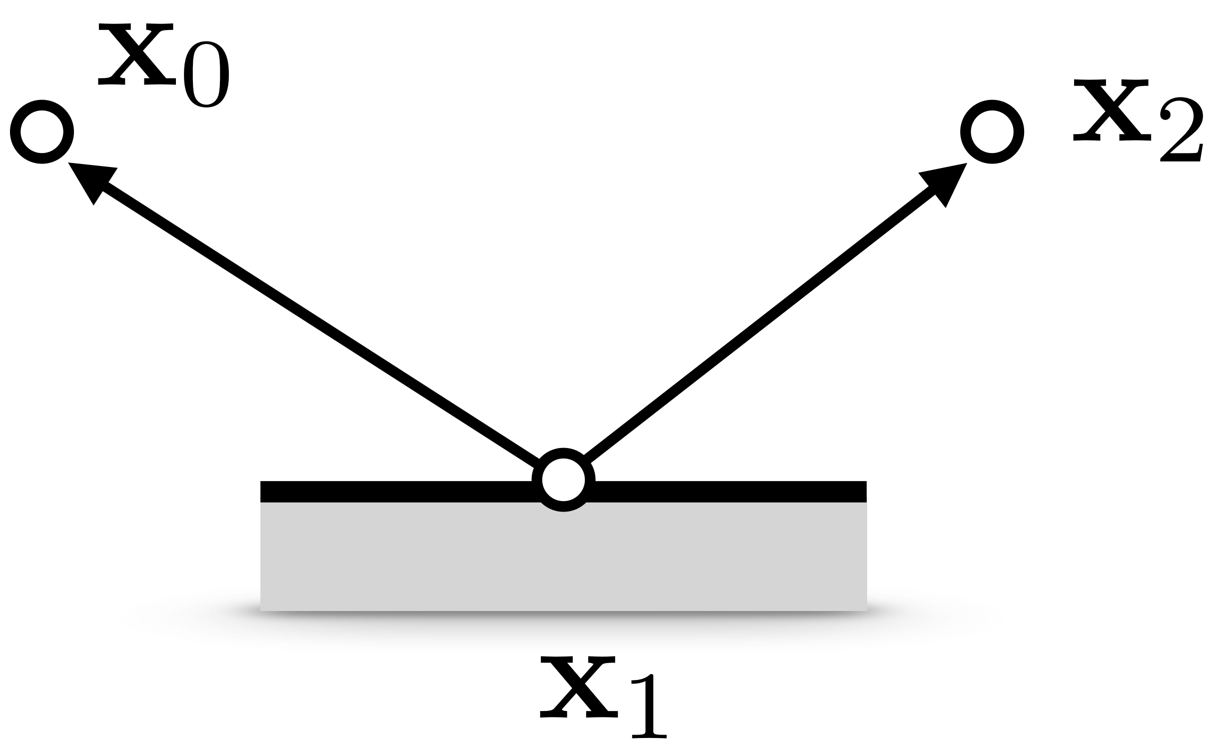


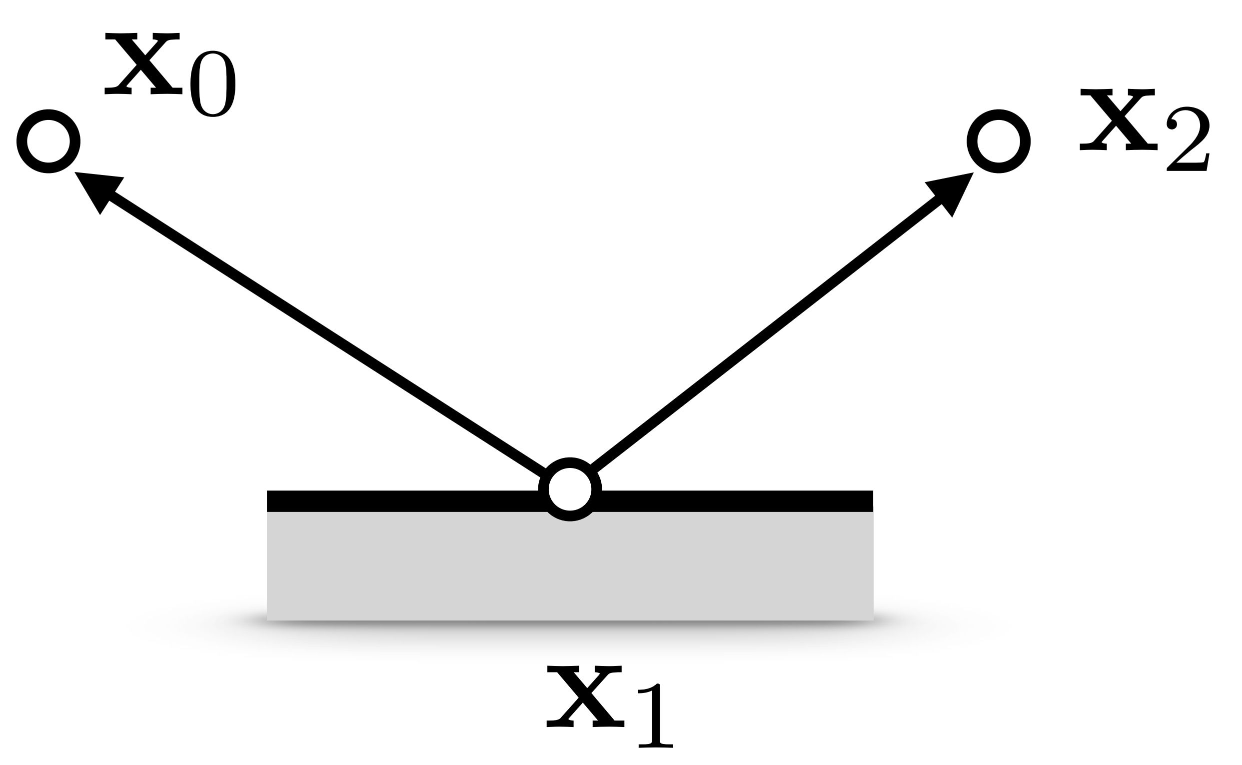
Lighting with Virtual Point Lights (VPLs)

Rendering Equation (area formulation)



Rendering Equation (area formulation)

$$L(\mathbf{x}_1 \rightarrow \mathbf{x}_0) = L_e(\mathbf{x}_1 \rightarrow \mathbf{x}_0) + \int_A f(\mathbf{x}_1) G(\mathbf{x}_1, \mathbf{x}_2) V(\mathbf{x}_1, \mathbf{x}_2) L(\mathbf{x}_2 \rightarrow \mathbf{x}_1) dA(\mathbf{x}_2)$$



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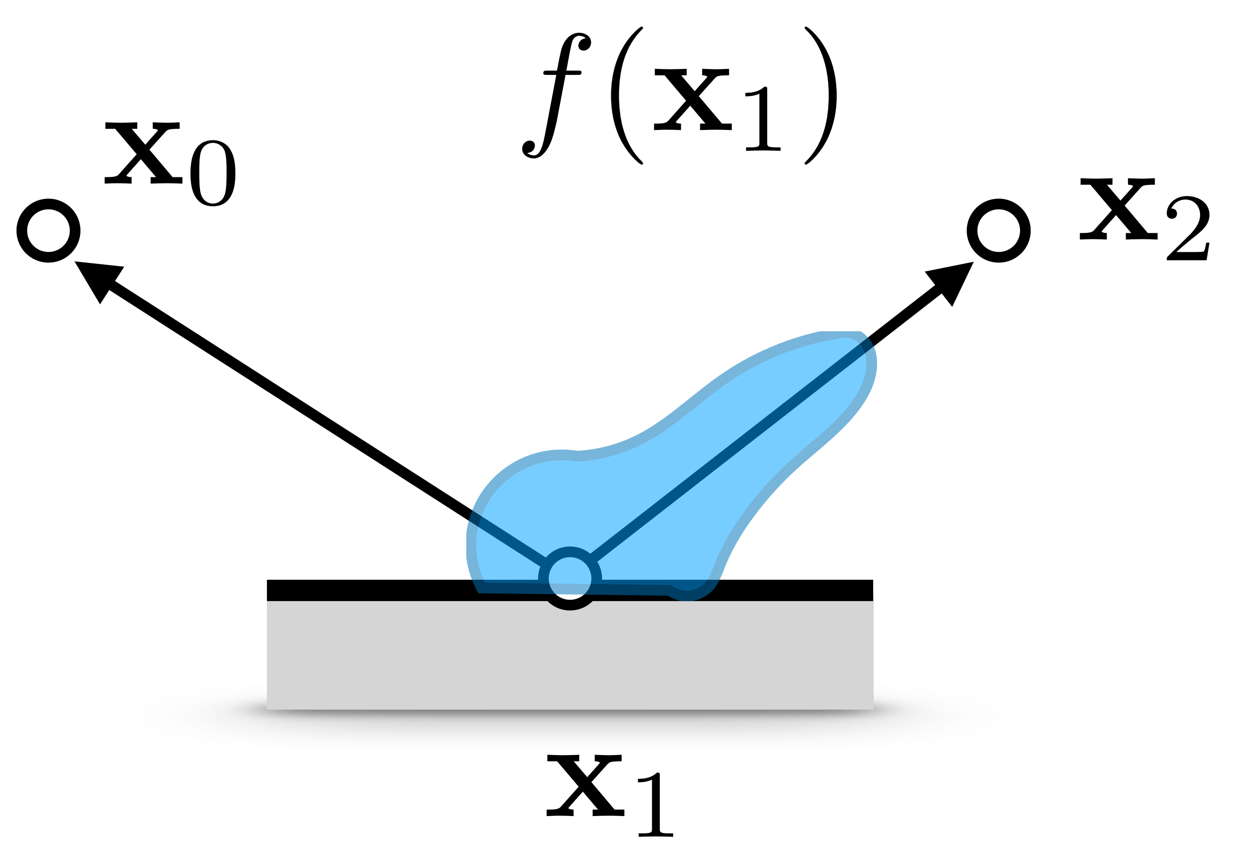

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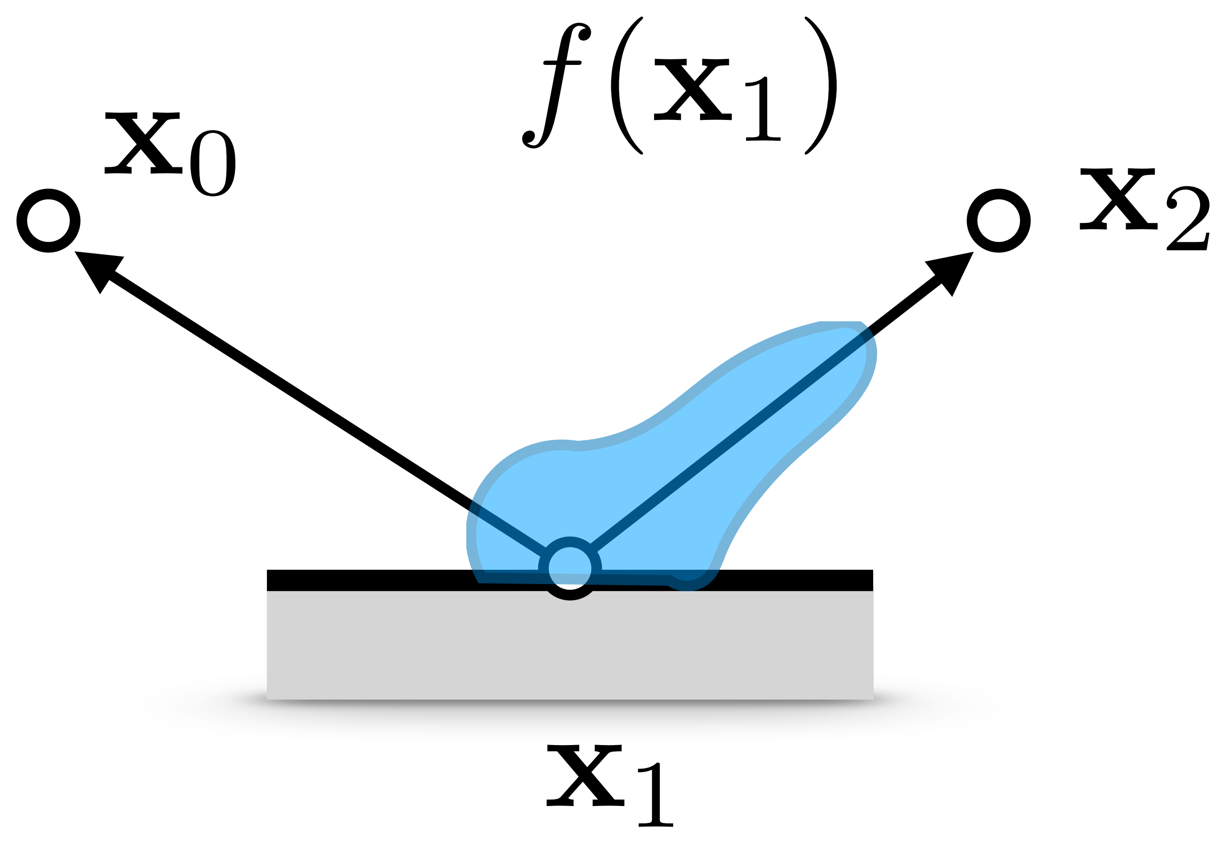

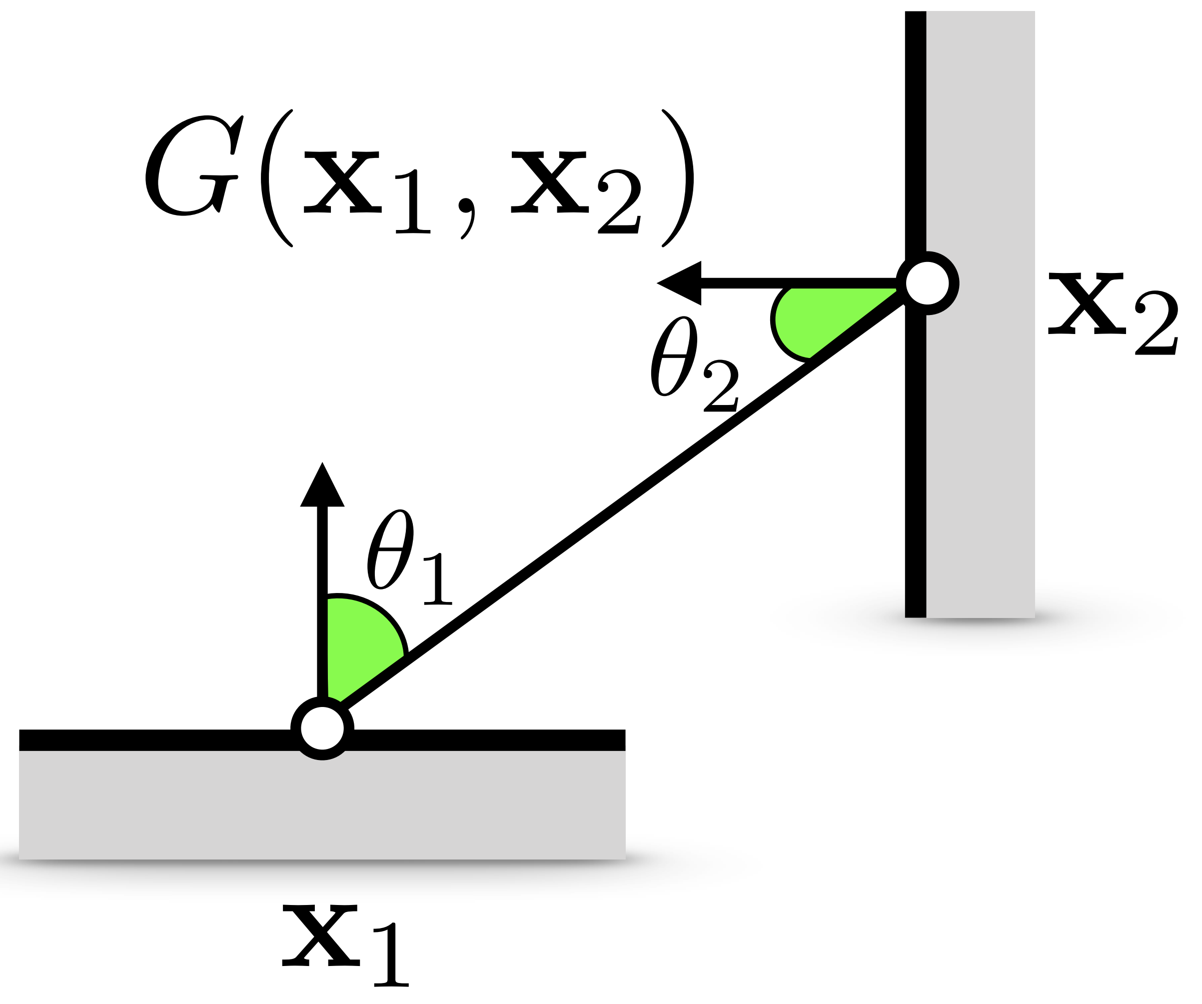

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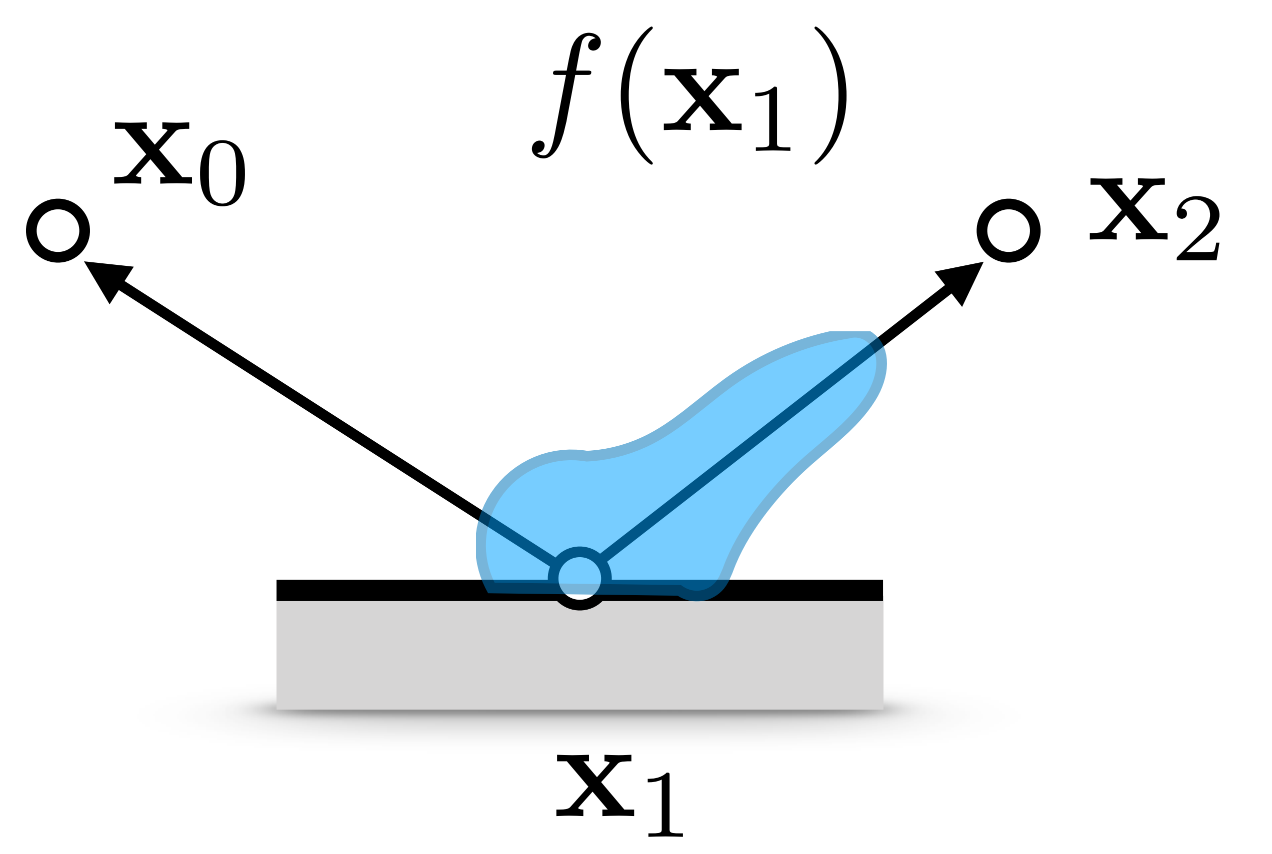
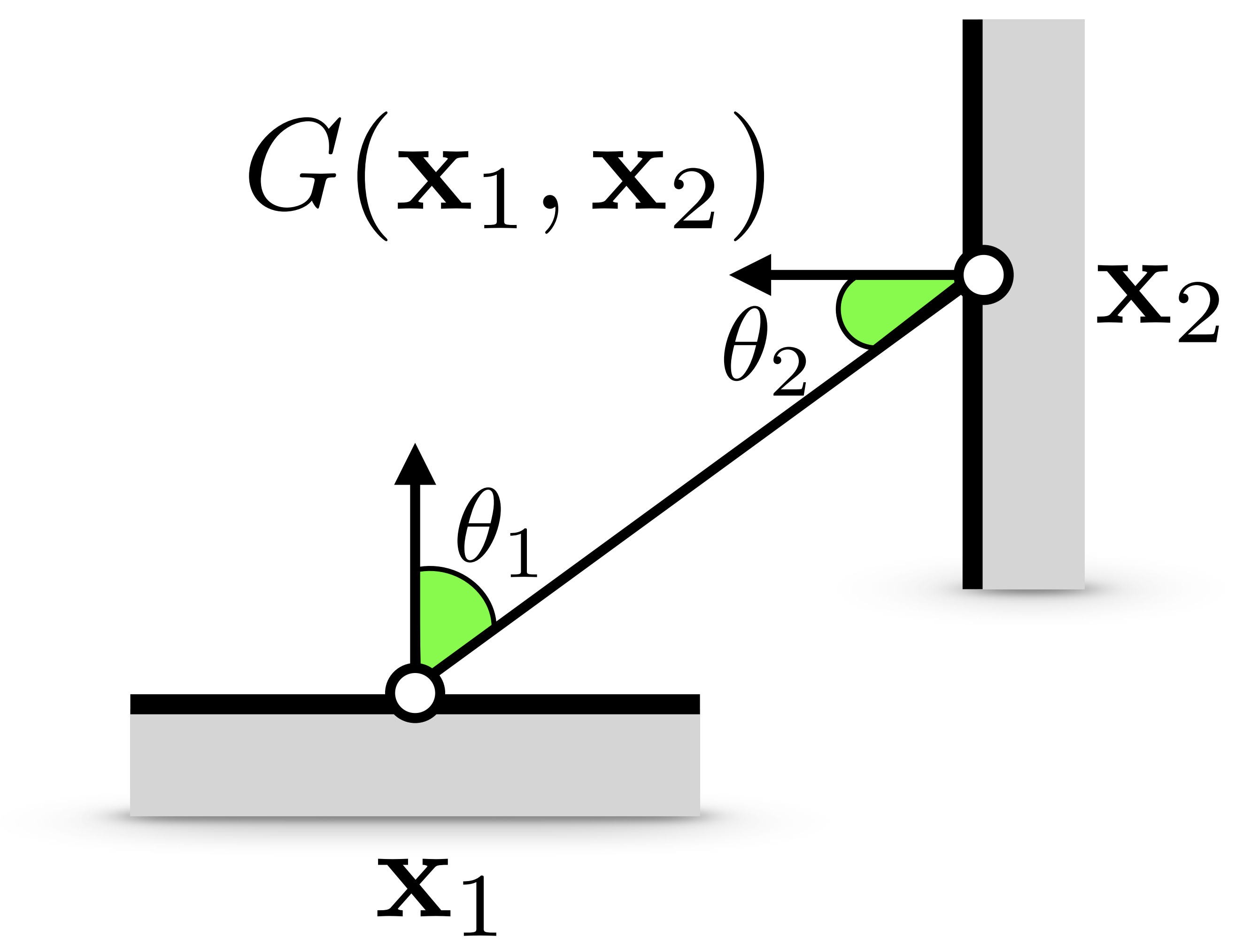
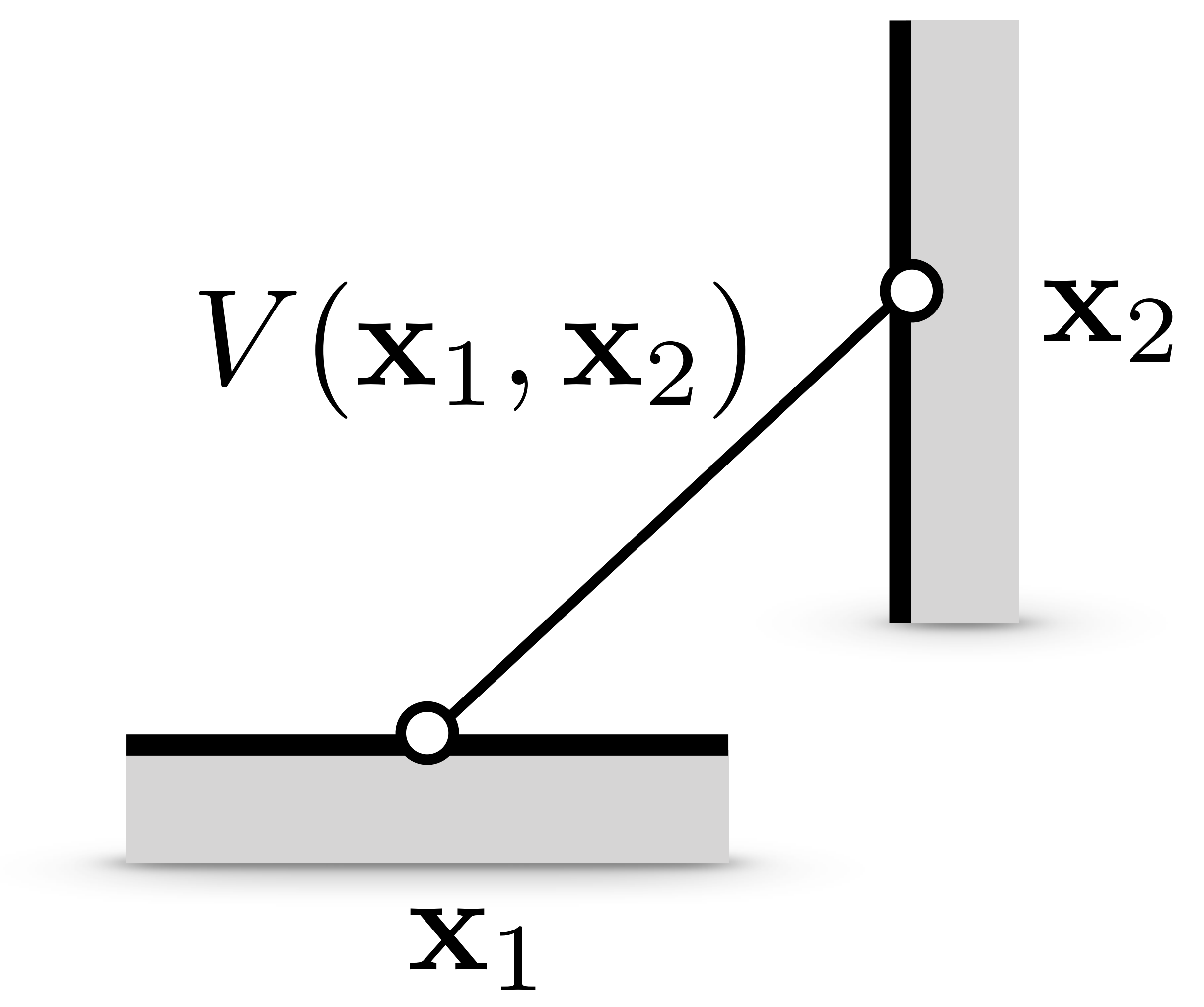
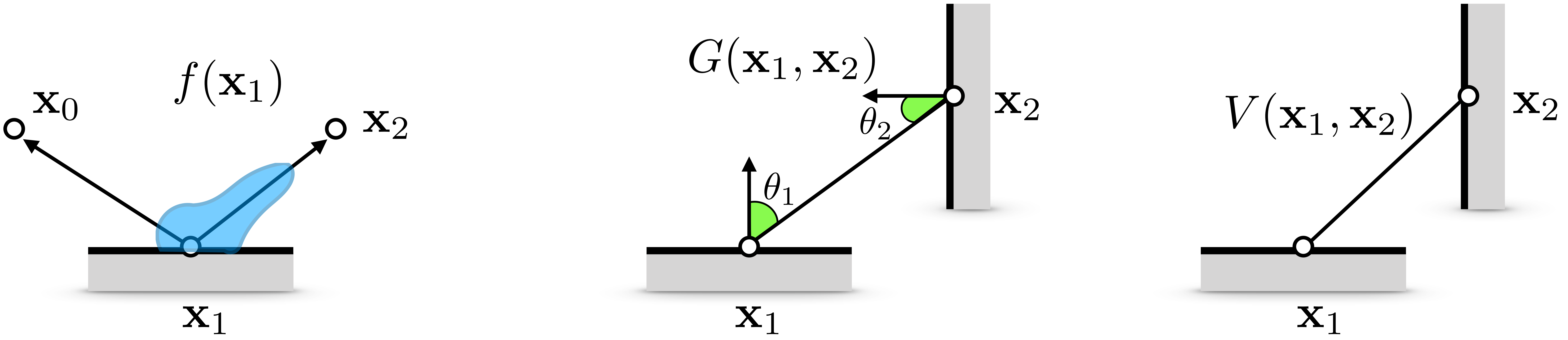




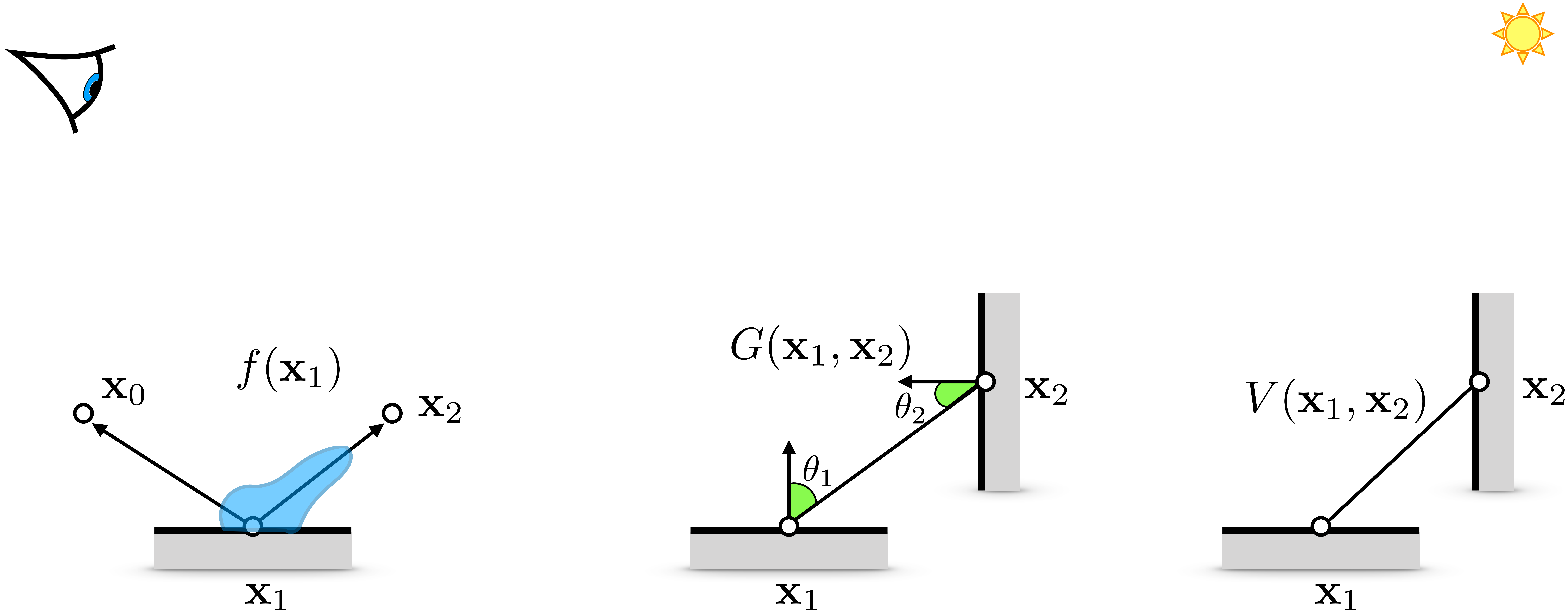


Rendering Equation (area formulation)

$$\boxed{L(\mathbf{x}_1 \to \mathbf{x}_0)} = L_e(\mathbf{x}_1 \to \mathbf{x}_0) + \int_A f(\mathbf{x}_1) G(\mathbf{x}_1, \mathbf{x}_2) \boxed{V(\mathbf{x}_1, \mathbf{x}_2)} \boxed{L(\mathbf{x}_2 \to \mathbf{x}_1)} dA(\mathbf{x}_2)$$



Rendering Equation (area formulation)



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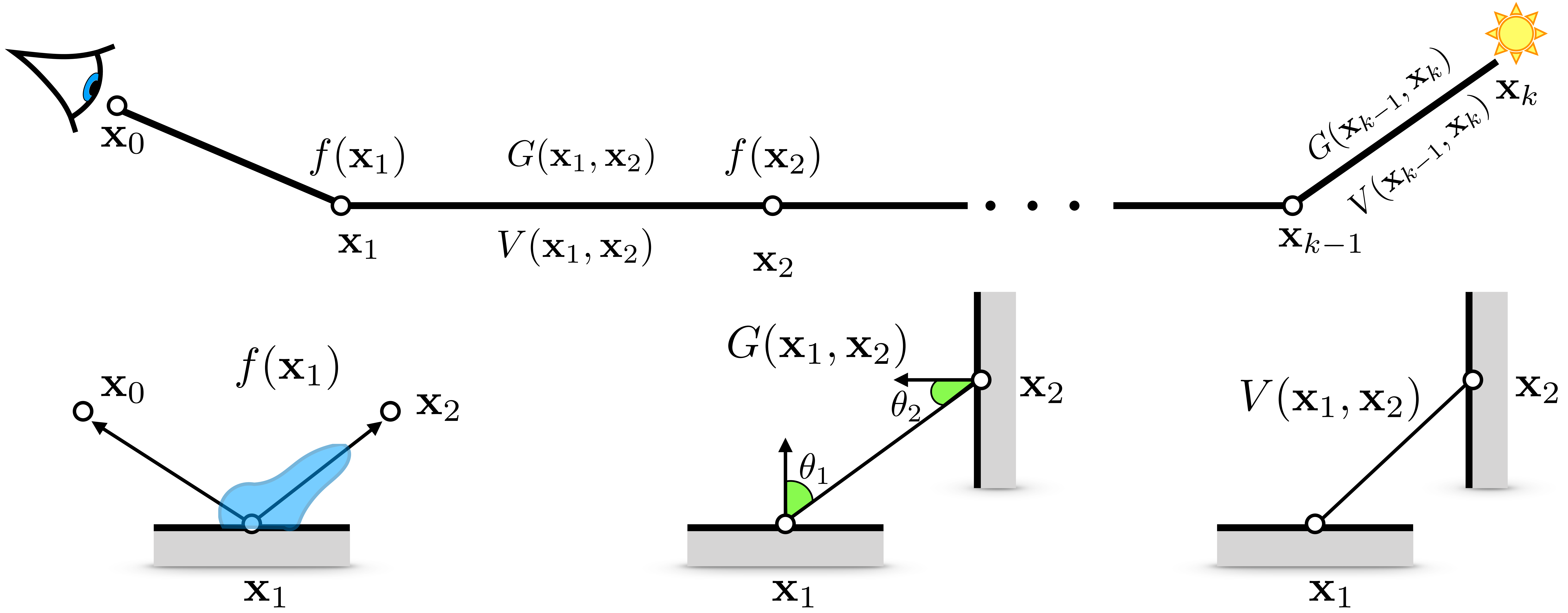
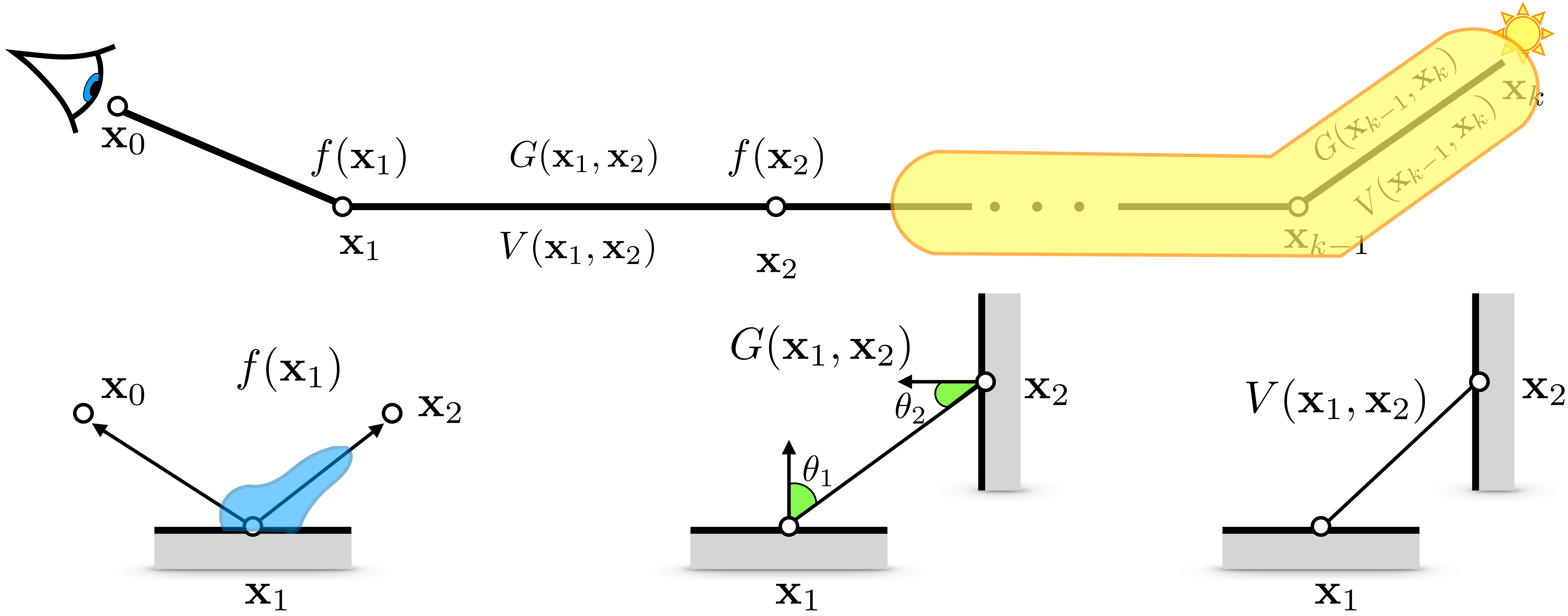
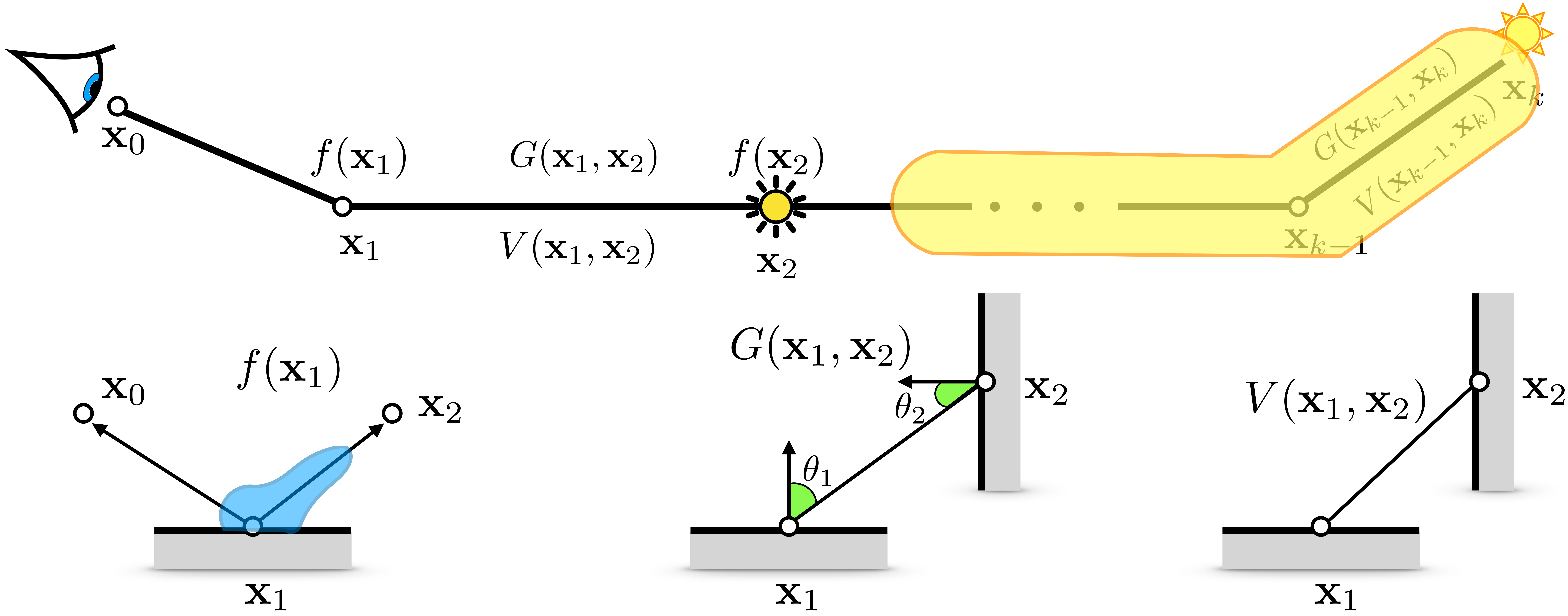


Rendering Equation (area formulation)



Rendering Equation (area formulation)



Lighting with VPLs

$$L(\mathbf{x}_1 \to \mathbf{x}_0) = L_e(\mathbf{x}_1 \to \mathbf{x}_0) + \int_A f(\mathbf{x}_1) G(\mathbf{x}_1, \mathbf{x}_2) V(\mathbf{x}_1, \mathbf{x}_2) L(\mathbf{x}_2 \to \mathbf{x}_1) dA(\mathbf{x}_2)$$

Lighting with VPLs

$$L(\mathbf{x}_1 \to \mathbf{x}_0) = L_e(\mathbf{x}_1 \to \mathbf{x}_0) + \int_A f(\mathbf{x}_1) G(\mathbf{x}_1, \mathbf{x}_2) V(\mathbf{x}_1, \mathbf{x}_2) L(\mathbf{x}_2 \to \mathbf{x}_1) dA(\mathbf{x}_2)$$

$$L(\mathbf{x}_1 \to \mathbf{x}_0) \approx L_e(\mathbf{x}_1 \to \mathbf{x}_0) + \sum_{k=1}^{N} f(\mathbf{x}_1) G(\mathbf{x}_1, \mathbf{x}_2^i) V(\mathbf{x}_1, \mathbf{x}_2^i) f(\mathbf{x}_2^i) \Phi_i$$

Lighting with VPLs

$$L(\mathbf{x}_1 \to \mathbf{x}_0) = L_e(\mathbf{x}_1 \to \mathbf{x}_0) + \int_A \boxed{f(\mathbf{x}_1)} G(\mathbf{x}_1, \mathbf{x}_2) V(\mathbf{x}_1, \mathbf{x}_2) L(\mathbf{x}_2 \to \mathbf{x}_1) dA(\mathbf{x}_2)$$

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Lighting with VPLs

$$L(\mathbf{x}_1 \to \mathbf{x}_0) = L_e(\mathbf{x}_1 \to \mathbf{x}_0) + \int_A f(\mathbf{x}_1)\boxed{G(\mathbf{x}_1, \mathbf{x}_2)}V(\mathbf{x}_1, \mathbf{x}_2)L(\mathbf{x}_2 \to \mathbf{x}_1)dA(\mathbf{x}_2)$$

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Lighting with VPLs

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Lighting with VPLs

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recursion is hidden
in the generation of VPLs

Approximation using VPLs

$\mathbf{x}_2^i$: position of the $i\text{-th}$ VPL

Φ^i : flux of the $i\text{-th}$ VPL

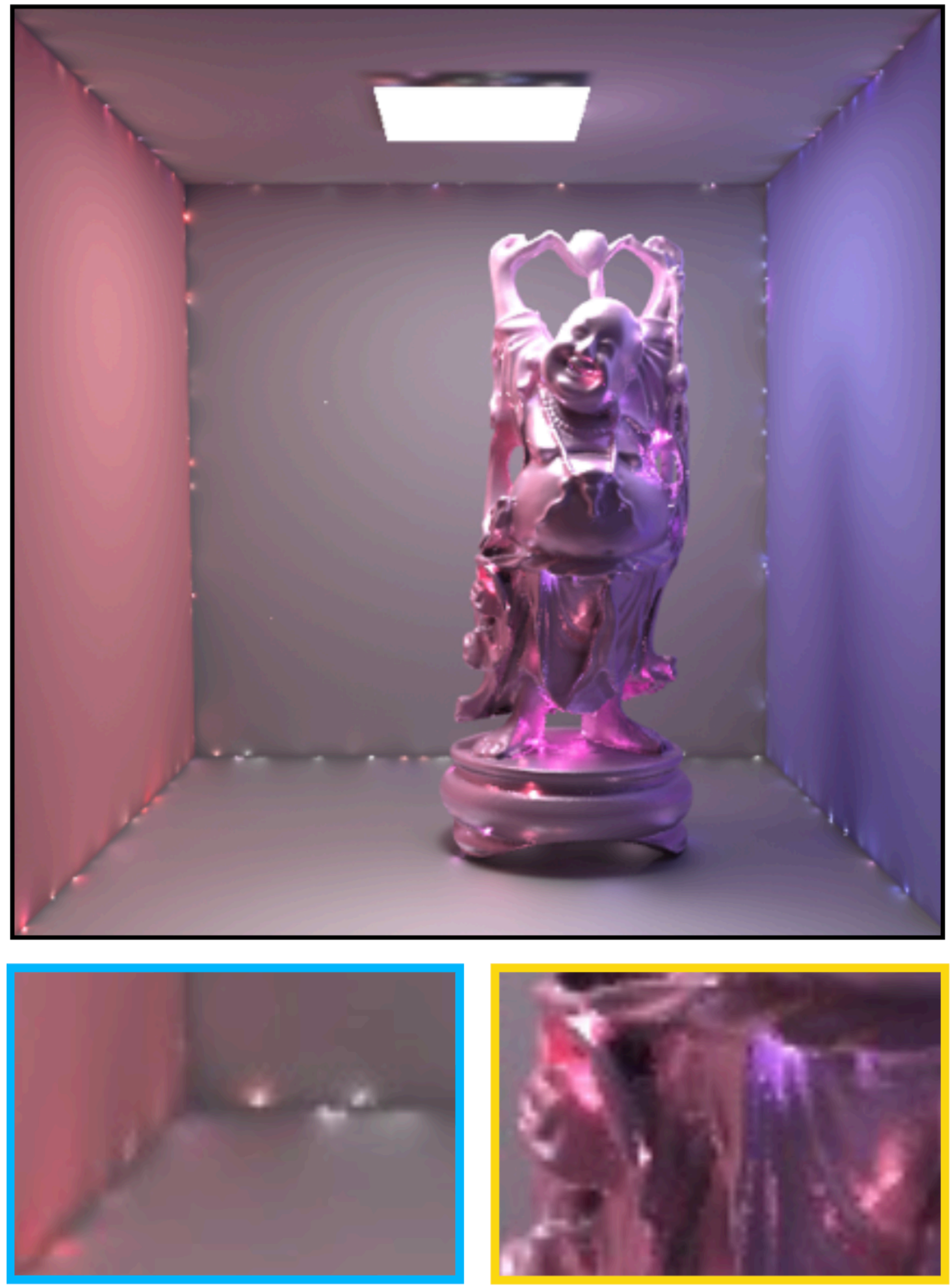
Lighting with VPLs

Reference

Lighting with VPLs

Reference

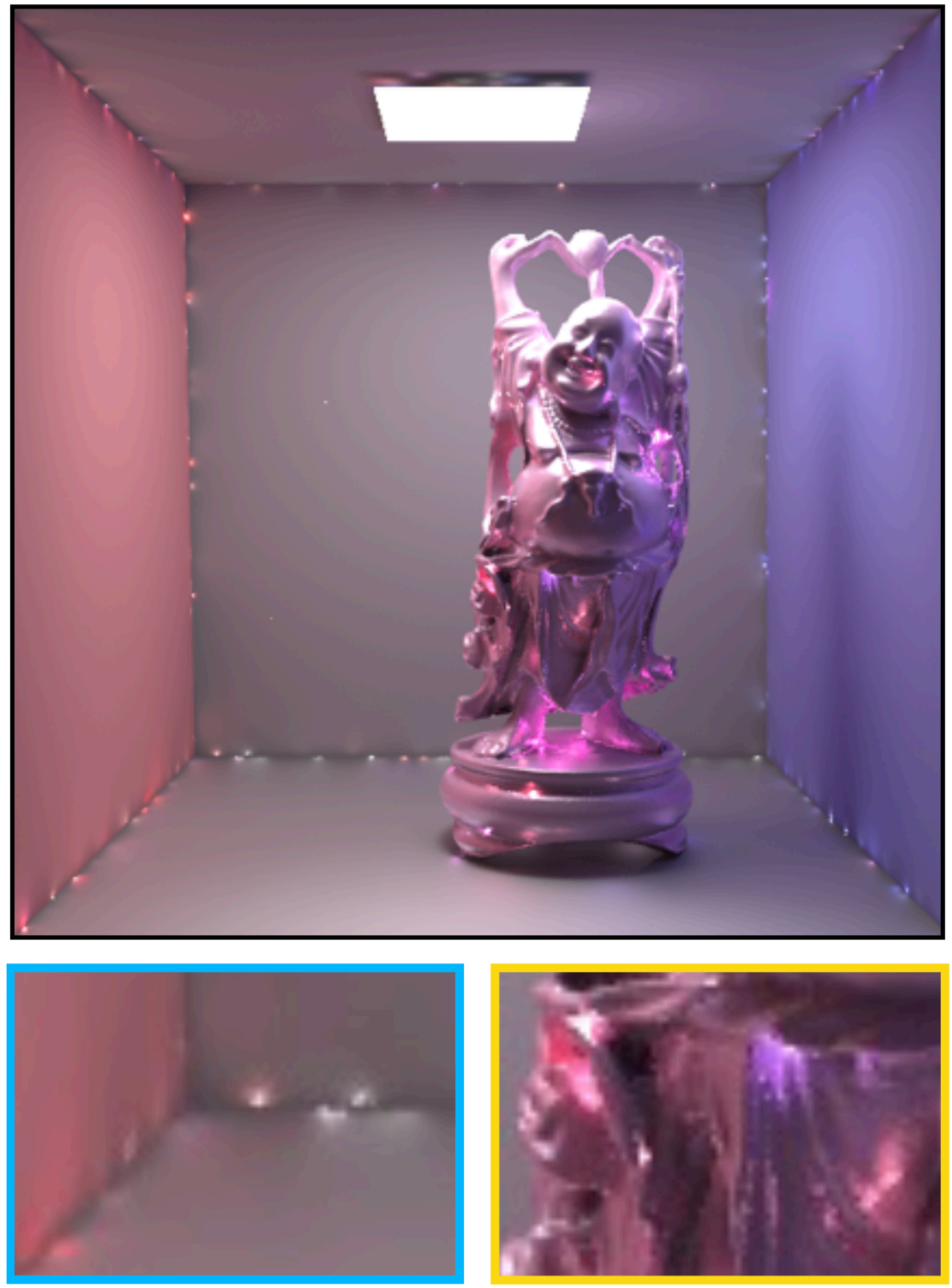
Approximation with VPLs



Lighting with VPLs

Why there are Splotches?

Approximation with VPLs

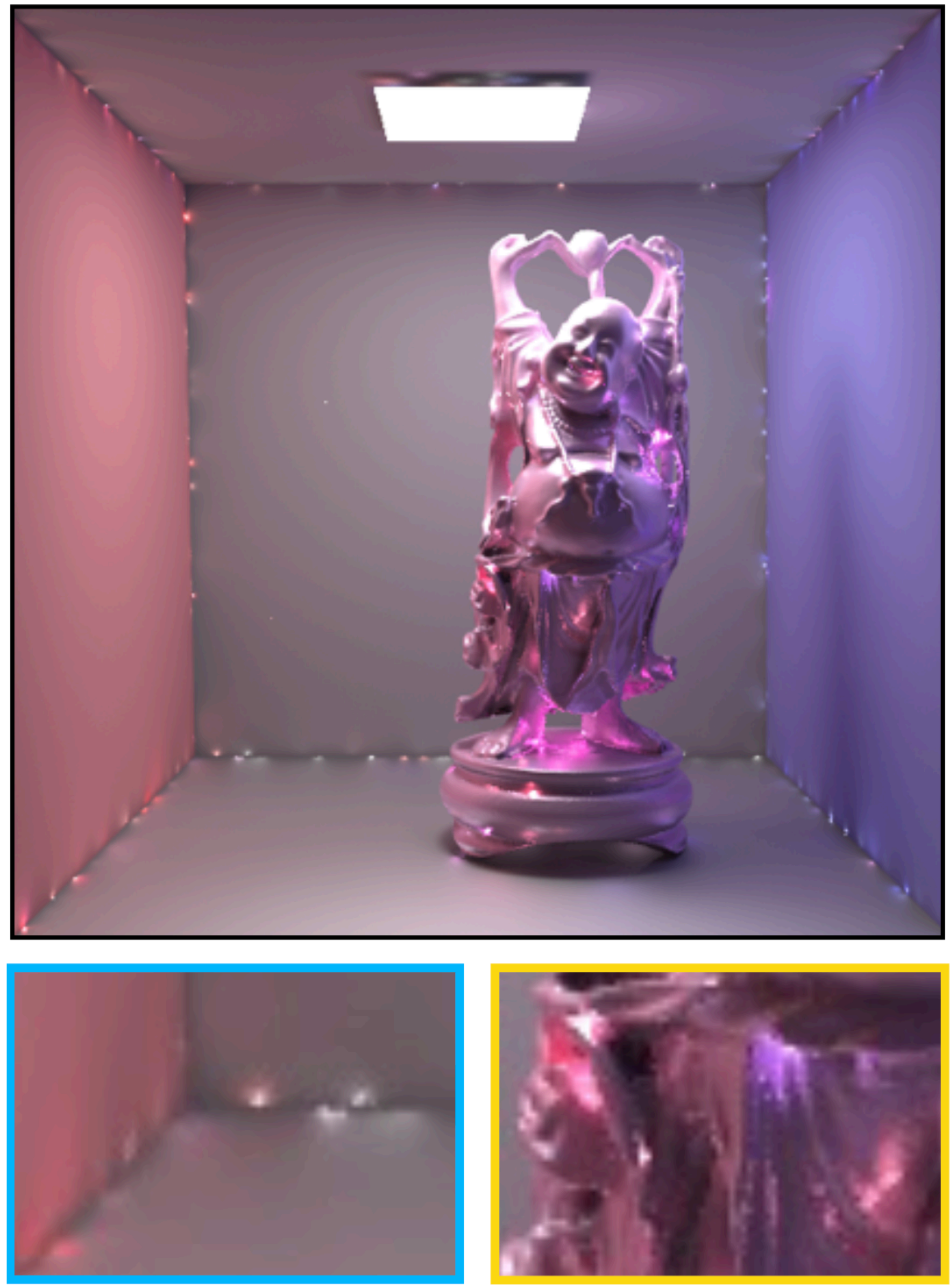


Lighting with VPLs

Why there are Splotches?

1. Have a look at the geometric term:

Approximation with VPLs

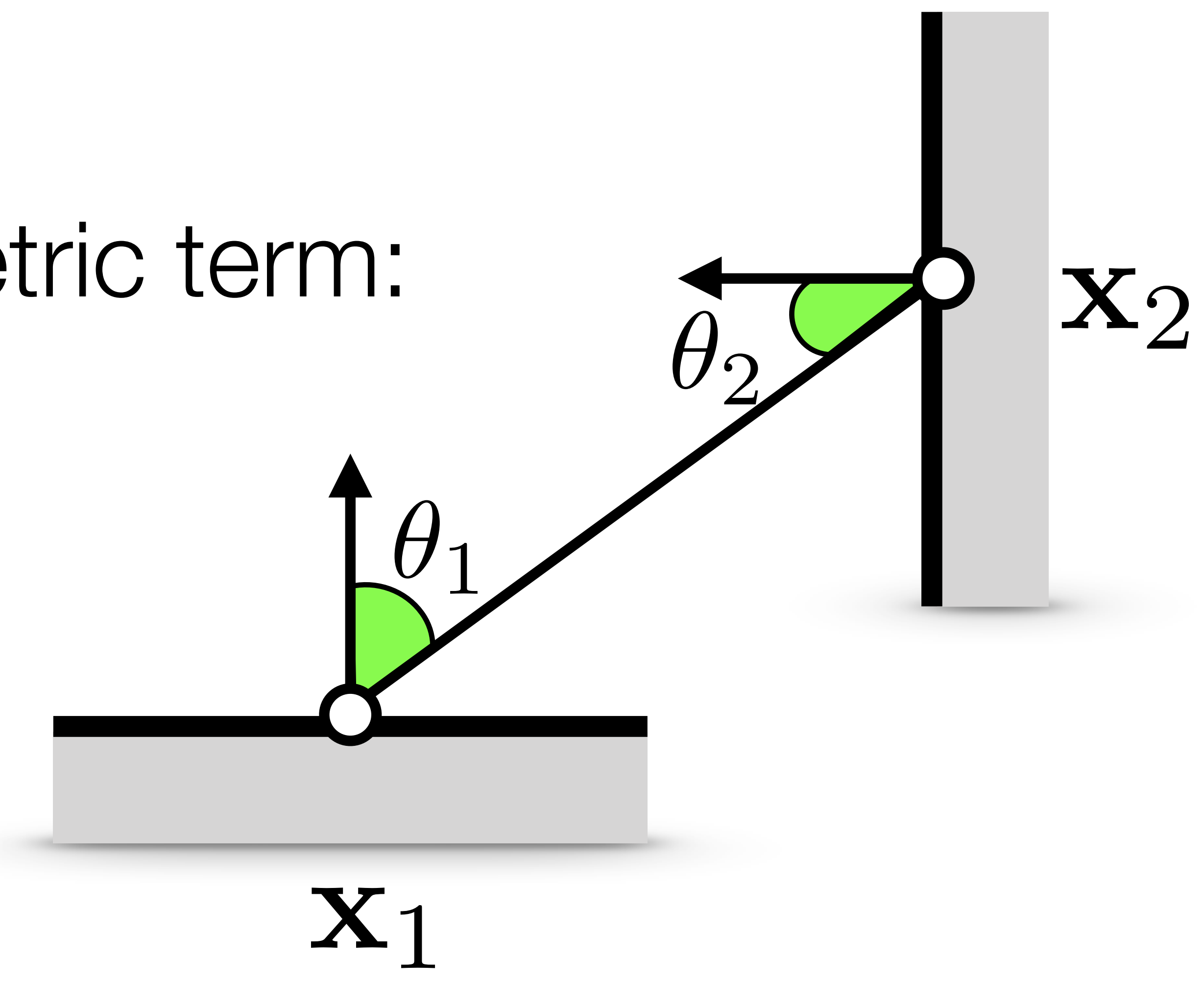


Lighting with VPLs

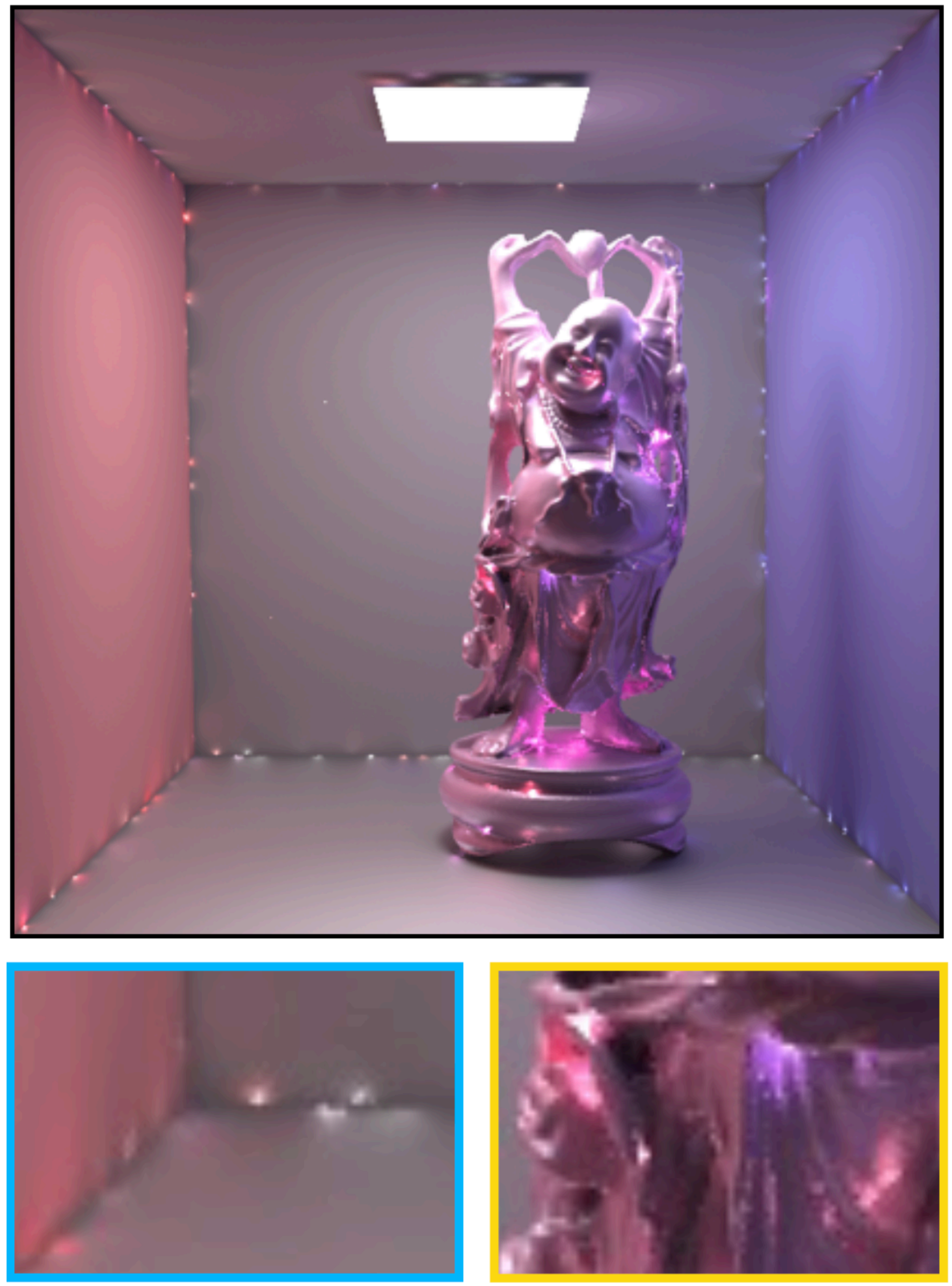
Why there are Splotches?

1. Have a look at the geometric term:

$$G(\mathbf{x}_1, \mathbf{x}_2) = \frac{\cos\theta_1 \cos\theta_2}{||\mathbf{x}_1 - \mathbf{x}_2||^2}$$



Approximation with VPLs



Lighting with VPLs

Why there are Splotches?

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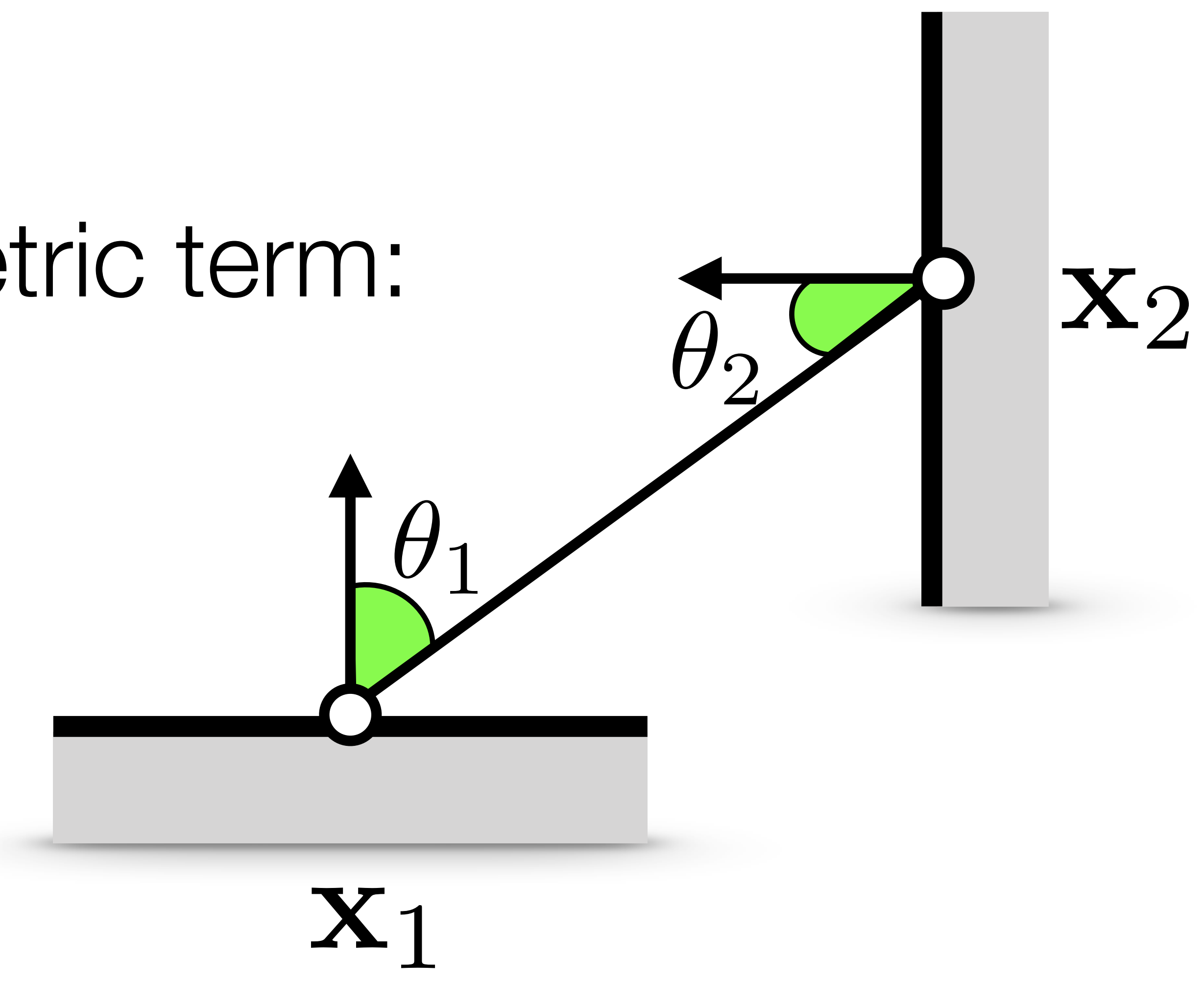
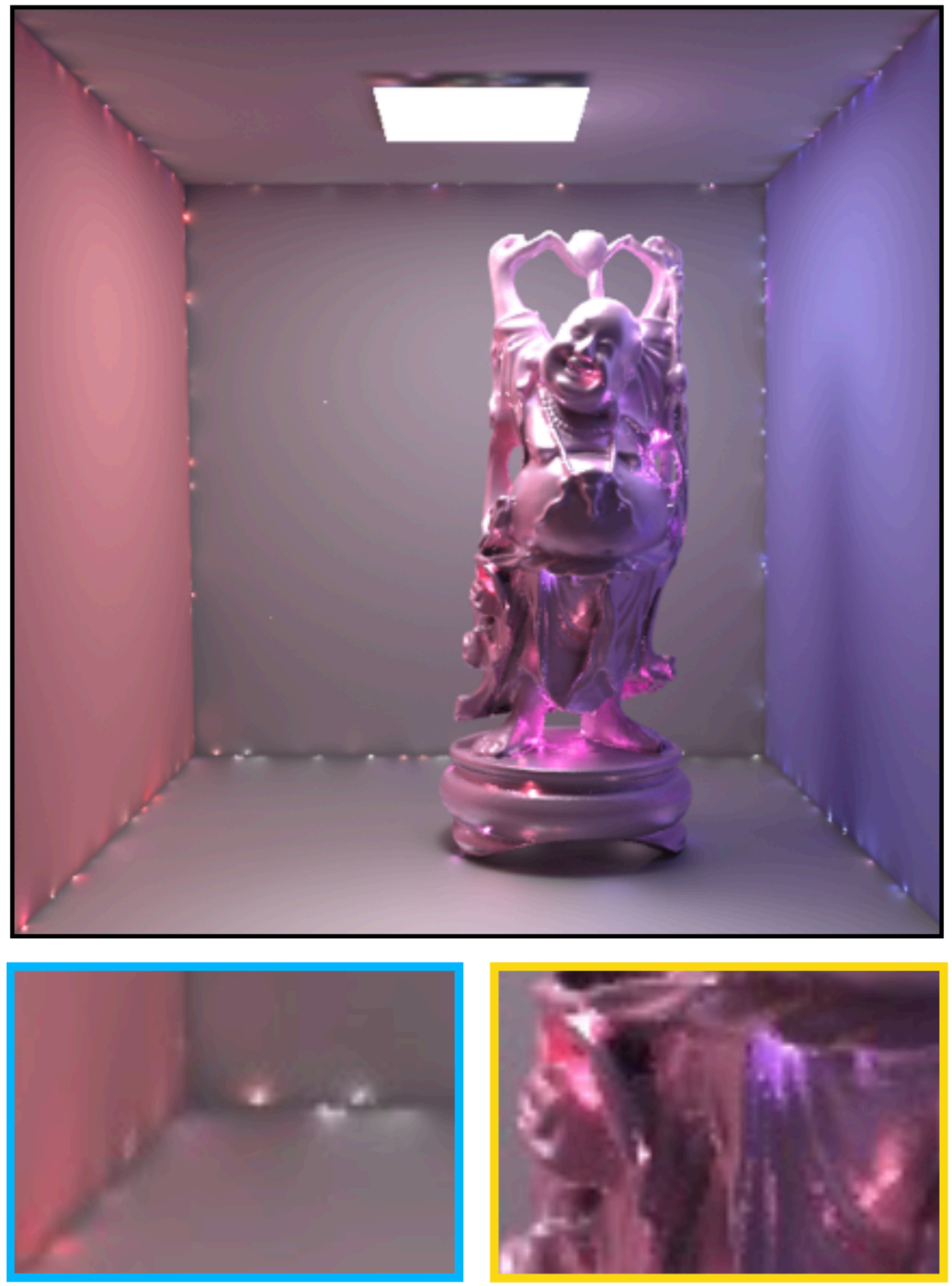
$$G(\mathbf{x}_1, \mathbf{x}_2) = \frac{\cos\theta_1 \cos\theta_2}{\boxed{||\mathbf{x}_1 - \mathbf{x}_2||^2}}$$



Approximation with VPLs



Lighting with VPLs

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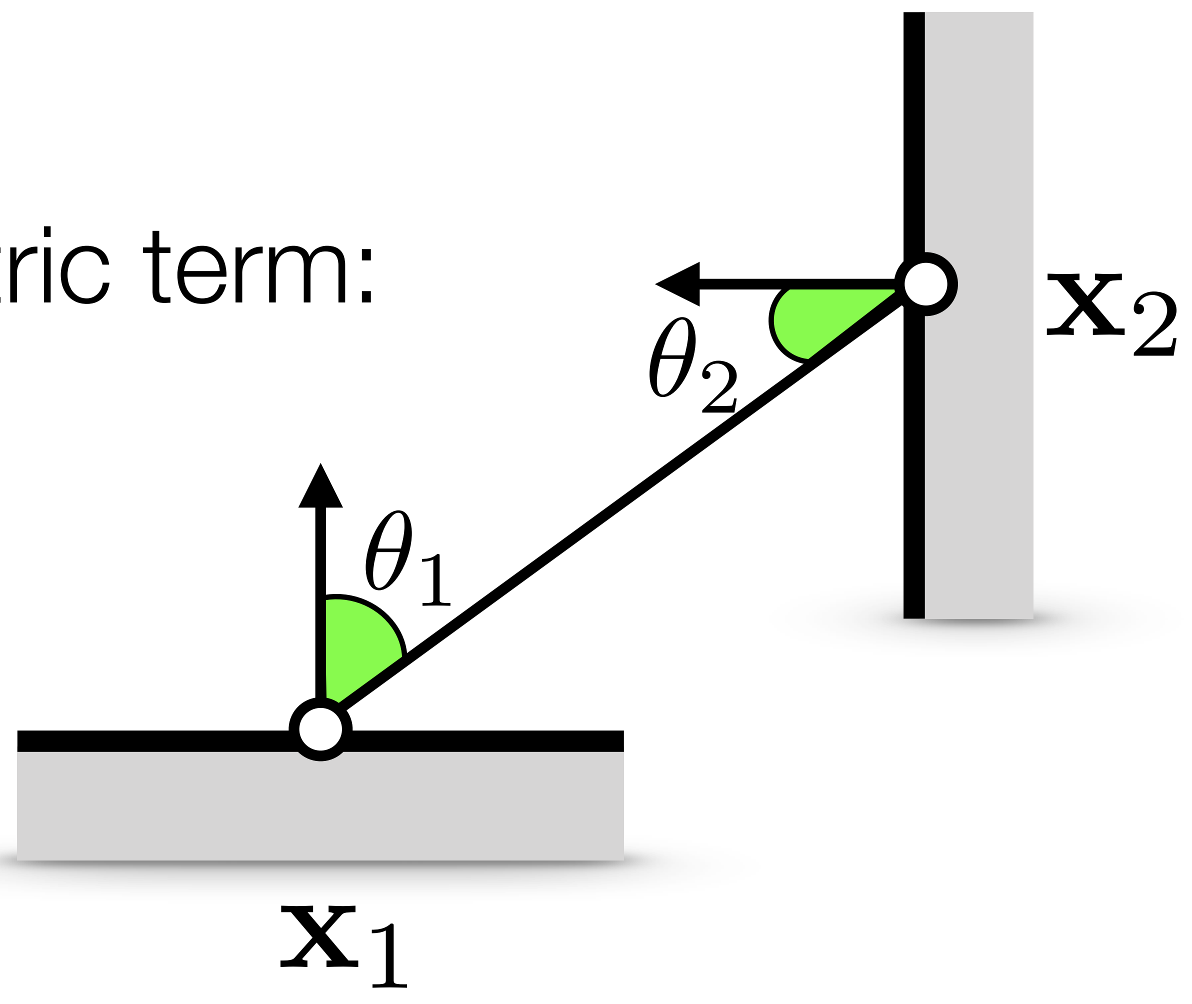
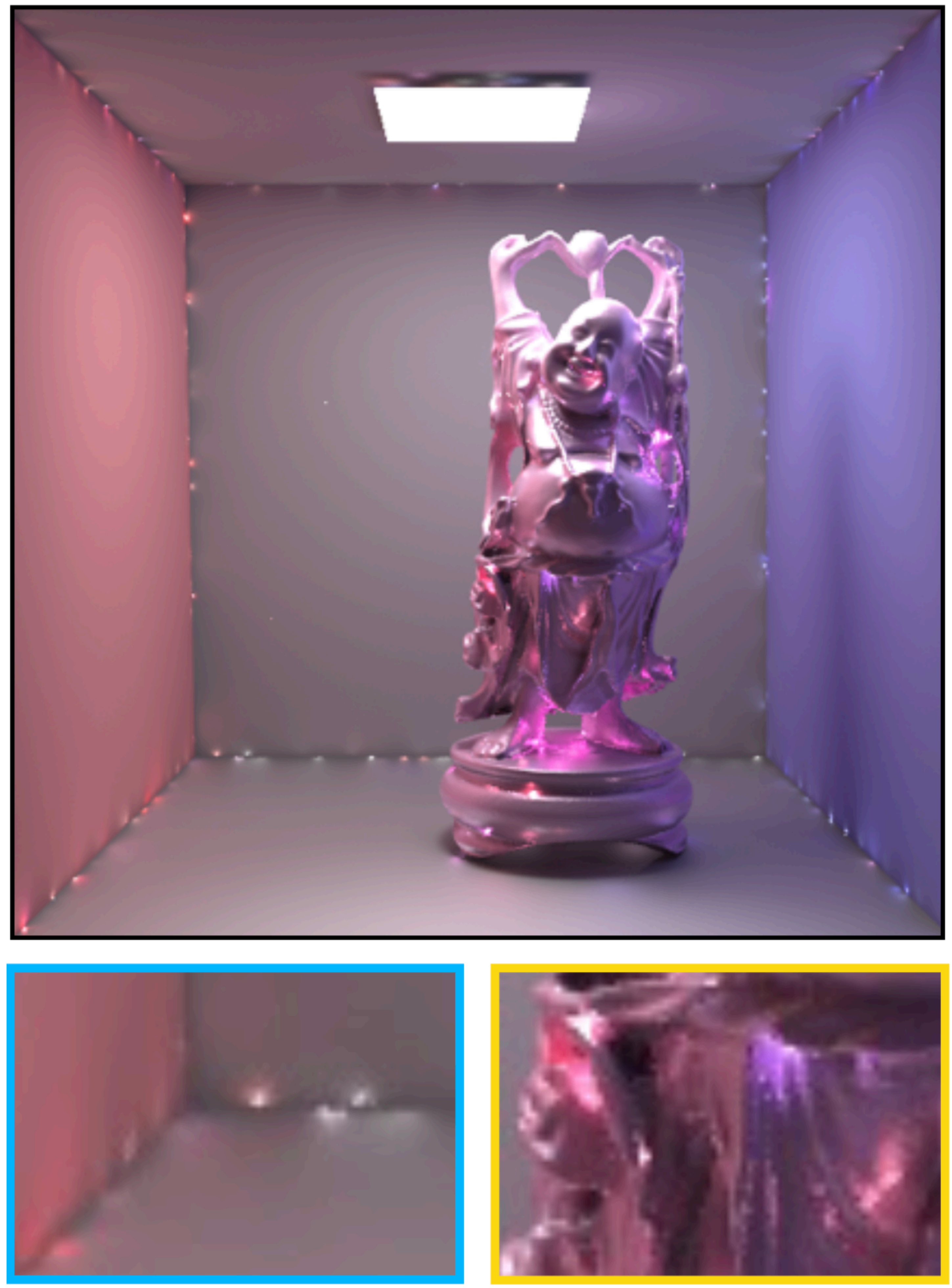
$$G(\mathbf{x}_1, \mathbf{x}_2) = \frac{\cos\theta_1 \cos\theta_2}{\boxed{||\mathbf{x}_1 - \mathbf{x}_2||^2}}$$

Singularity



Approximation with VPLs



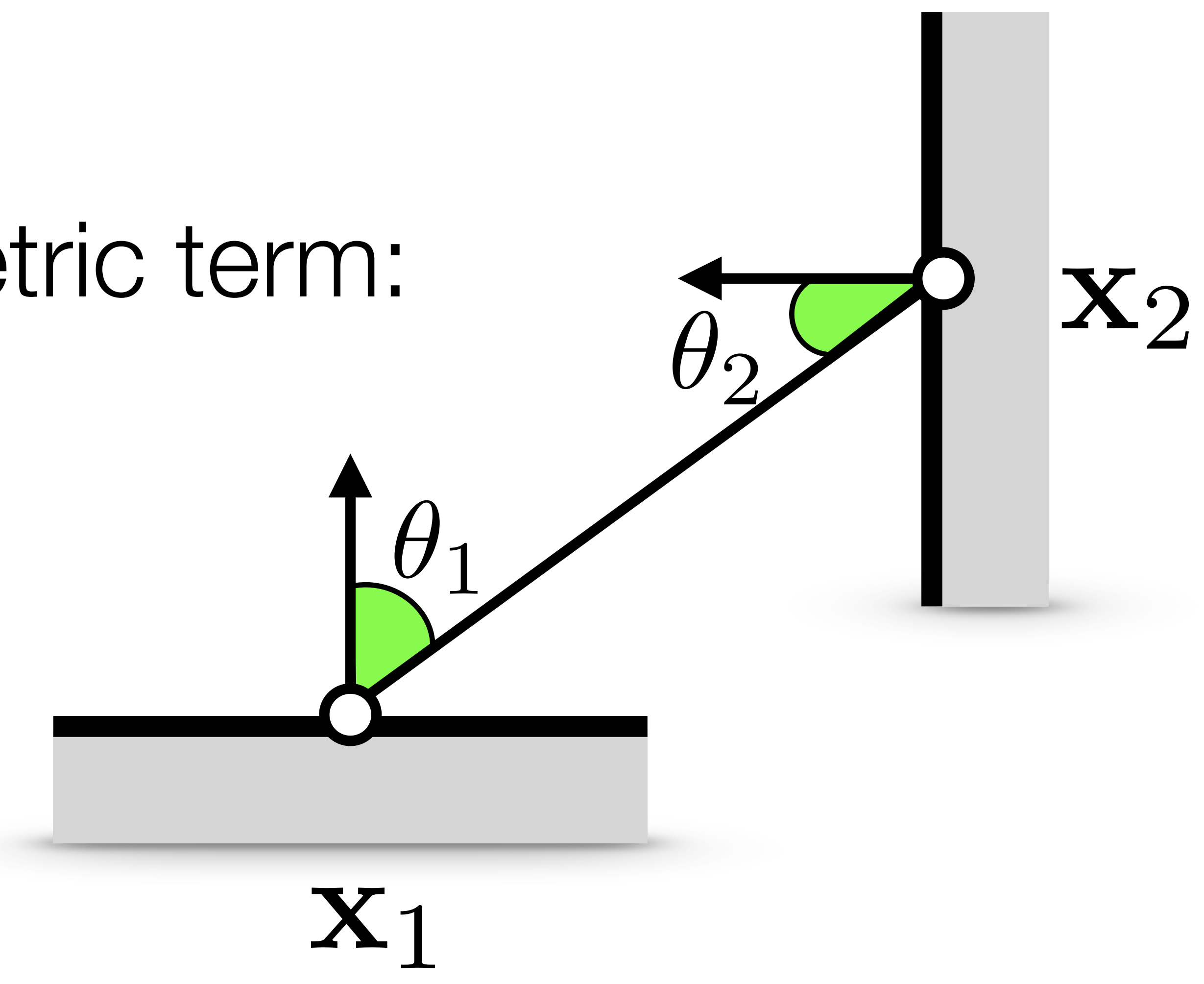
Lighting with VPLs

Why there are Splotches?

1. Have a look at the geometric term:

$$G(\mathbf{x}_1, \mathbf{x}_2) = \frac{\cos\theta_1 \cos\theta_2}{\boxed{||\mathbf{x}_1 - \mathbf{x}_2||^2}}$$

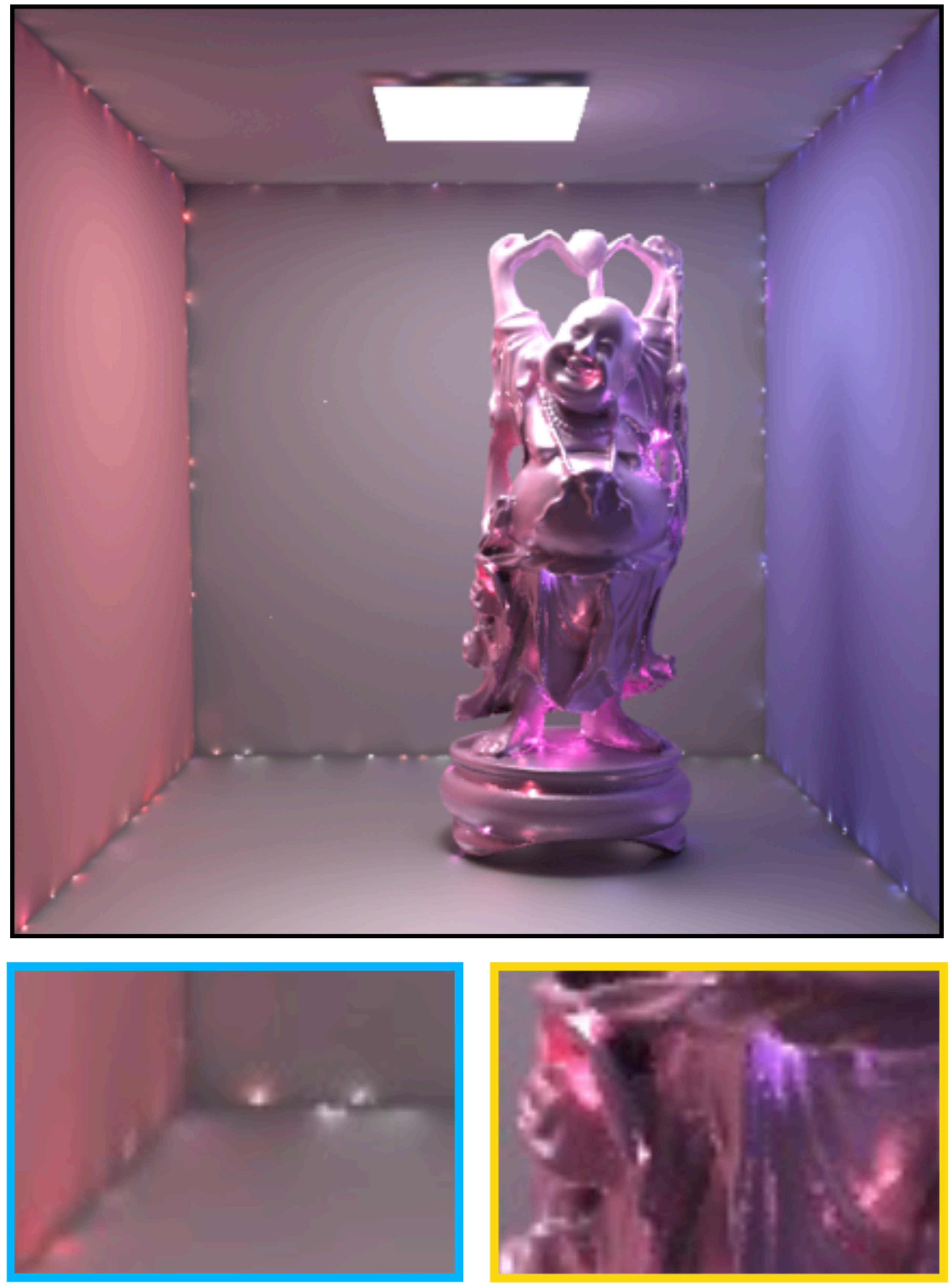
Singularity



2. All points are lit by the same set of VPLs

- introduce bad correlations

Approximation with VPLs



Lighting with VPLs

How to avoid Splotches?

Solutions:

1) Bound the geometry

- remove energy, darkens the image
- to get unbiased results, we need to compensate for the bounding

2) Distribute the flux of a VPL over area (volume)

- redistributes energy, blurs the illumination
- to get consistent results, progressively reduce the blurring

Lighting with VPLs

How to avoid Splotches?

Solutions:

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Lighting with VPLs

1) Bound the geometry

- prevent G from being very high
- user-defined maximum value

$$G_b(\mathbf{x}_1, \mathbf{x}_2) = \min(G(\mathbf{x}_1, \mathbf{x}_2), b)$$

Lighting with VPLs

1) Bound the geometry

- prevent G from being very high
- user-defined maximum value

$$G_b(\mathbf{x}_1, \mathbf{x}_2) = \min(G(\mathbf{x}_1, \mathbf{x}_2), b)$$

Advantage:

- extremely simple and fast

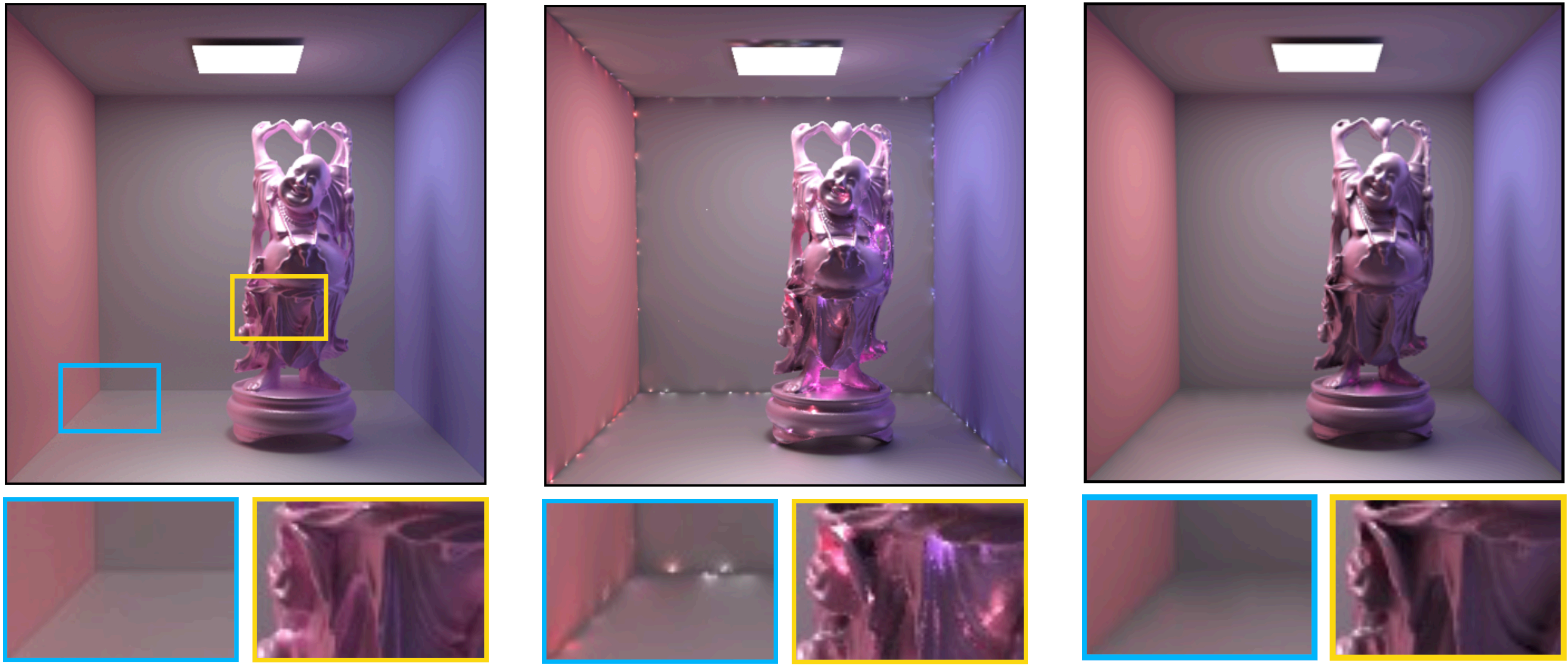
Disadvantages:

- removes energy, darkens the image

Reference

VPLs

VPLs with bounded G



using $G(\mathbf{x}_1, \mathbf{x}_2)$

using $G_b(\mathbf{x}_1, \mathbf{x}_2)$

Reference

Difference

$$G(\mathbf{x}_1, \mathbf{x}_2) - G_b(\mathbf{x}_1, \mathbf{x}_2)$$

We need to compensate for the energy loss!

VPLs with bounded G

using $G_b(\mathbf{x}_1, \mathbf{x}_2)$

Bounding and Compensation

Light transport operator $\mathbf{T}$

$$(\mathbf{T}L)(\mathbf{x}_1 \to \mathbf{x}_0) = \int_A f(\mathbf{x}_1)G(\mathbf{x}_1, \mathbf{x}_2)V(\mathbf{x}_1, \mathbf{x}_2)L(\mathbf{x}_2 \to \mathbf{x}_1)dA(\mathbf{x}_2)$$

Bounding and Compensation

Light transport operator $\mathbf{T}$

$$(\mathbf{T}L)(\mathbf{x}_1 \to \mathbf{x}_0) = \int_A f(\mathbf{x}_1)G(\mathbf{x}_1, \mathbf{x}_2)V(\mathbf{x}_1, \mathbf{x}_2)L(\mathbf{x}_2 \to \mathbf{x}_1)dA(\mathbf{x}_2)$$

Bounded light transport operator $\mathbf{T}_b$

$$(\mathbf{T}_b L)(\mathbf{x}_1 \to \mathbf{x}_0) = \int_A f(\mathbf{x}_1)\min(G(\mathbf{x}_1, \mathbf{x}_2), b)V(\mathbf{x}_1, \mathbf{x}_2)L(\mathbf{x}_2 \to \mathbf{x}_1)dA(\mathbf{x}_2)$$

Bounding and Compensation

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$$(\mathbf{T}L)(\mathbf{x}_1 \rightarrow \mathbf{x}_0) = \int_A f(\mathbf{x}_1) G(\mathbf{x}_1, \mathbf{x}_2) V(\mathbf{x}_1, \mathbf{x}_2) L(\mathbf{x}_2 \rightarrow \mathbf{x}_1) dA(\mathbf{x}_2)$$

Bounded light transport operator $\mathbf{T}_b$

$$(\mathbf{T}_b L)(\mathbf{x}_1 \rightarrow \mathbf{x}_0) = \int_A f(\mathbf{x}_1) \min(G(\mathbf{x}_1, \mathbf{x}_2), b) V(\mathbf{x}_1, \mathbf{x}_2) L(\mathbf{x}_2 \rightarrow \mathbf{x}_1) dA(\mathbf{x}_2)$$

Residual light transport operator $\mathbf{T}_r$

$$(\mathbf{T}_r L)(\mathbf{x}_1 \rightarrow \mathbf{x}_0) = \int_A f(\mathbf{x}_1) \max(G(\mathbf{x}_1, \mathbf{x}_2) - b, 0) V(\mathbf{x}_1, \mathbf{x}_2) L(\mathbf{x}_2 \rightarrow \mathbf{x}_1) dA(\mathbf{x}_2)$$

Bounding and Compensation

Light transport operator $\mathbf{T}$

$$(\mathbf{T}L)(\mathbf{x}_1 \to \mathbf{x}_0) = \int_A f(\mathbf{x}_1) G(\mathbf{x}_1, \mathbf{x}_2) V(\mathbf{x}_1, \mathbf{x}_2) L(\mathbf{x}_2 \to \mathbf{x}_1) dA(\mathbf{x}_2)$$

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Residual light transport operator $\mathbf{T}_r$

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Bounding and Compensation

Light transport operator $\mathbf{T}$

$$(\mathbf{T}L)(\mathbf{x}_1 \to \mathbf{x}_0) \;=\; (\mathbf{T}_b L)(\mathbf{x}_1 \to \mathbf{x}_0) \;+\; (\mathbf{T}_r L)(\mathbf{x}_1 \to \mathbf{x}_0)$$

Bounded light transport operator $\mathbf{T}_b$

$$(\mathbf{T}_b L)(\mathbf{x}_1 \to \mathbf{x}_0) = \int_A f(\mathbf{x}_1)\min(G(\mathbf{x}_1, \mathbf{x}_2), b)V(\mathbf{x}_1, \mathbf{x}_2)L(\mathbf{x}_2 \to \mathbf{x}_1)dA(\mathbf{x}_2)$$

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Bounding and Compensation

Light transport operator $\mathbf{T}$

$$(\mathbf{T}L)(\mathbf{x}_1 \rightarrow \mathbf{x}_0) \;=\; (\mathbf{T}_{b}L)(\mathbf{x}_1 \rightarrow \mathbf{x}_0) \;+\; (\mathbf{T}_{r}L)(\mathbf{x}_1 \rightarrow \mathbf{x}_0)$$

Bounding and Compensation

Light transport operator $\mathbf{T}$

$$(\mathbf{T}L)(\mathbf{x}_1 \to \mathbf{x}_0) \;=\; (\mathbf{T}_{b}L)(\mathbf{x}_1 \to \mathbf{x}_0) \;+\; (\mathbf{T}_{r}L)(\mathbf{x}_1 \to \mathbf{x}_0)$$

Bounding and Compensation

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$=$

Bounding and Compensation

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$$(\mathbf{T}L)(\mathbf{x}_1 \to \mathbf{x}_0) \;=\; (\mathbf{T}_b L)(\mathbf{x}_1 \to \mathbf{x}_0) \;+\; (\mathbf{T}_r L)(\mathbf{x}_1 \to \mathbf{x}_0)$$

$=$

Estimated
using VPLs

Bounding and Compensation

Light transport operator $\mathbf{T}$

$$(\mathbf{T}L)(\mathbf{x}_1 \to \mathbf{x}_0) = (\mathbf{T}_b L)(\mathbf{x}_1 \to \mathbf{x}_0) + (\mathbf{T}_r L)(\mathbf{x}_1 \to \mathbf{x}_0)$$

$=$

$+$

Estimated
using VPLs

Bounding and Compensation

Light transport operator $\mathbf{T}$

$$(\mathbf{T}L)(\mathbf{x}_1 \to \mathbf{x}_0) \;=\; (\mathbf{T}_{\color{blue}b}L)(\mathbf{x}_1 \to \mathbf{x}_0) \;+\; (\mathbf{T}_{\color{red}r}L)(\mathbf{x}_1 \to \mathbf{x}_0)$$

Estimated using VPLs

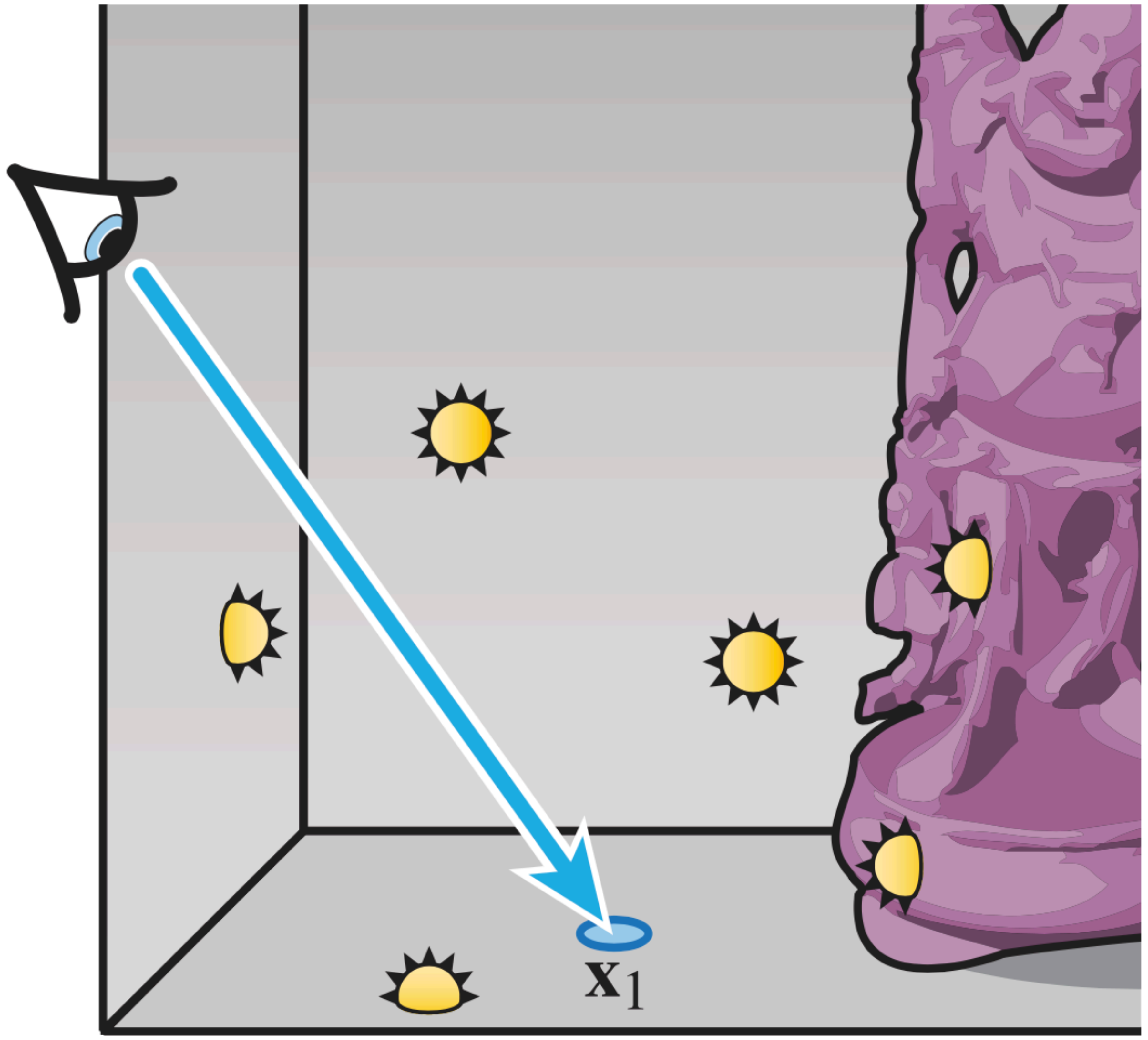
Estimated differently

How to compute residual transport?

Bounding and Compensation

Bias Compensation [Kollig and Keller 2004] [Raab et al. 2008]

Trace paths to compute the compensation term (residual transport)



Bounding and Compensation

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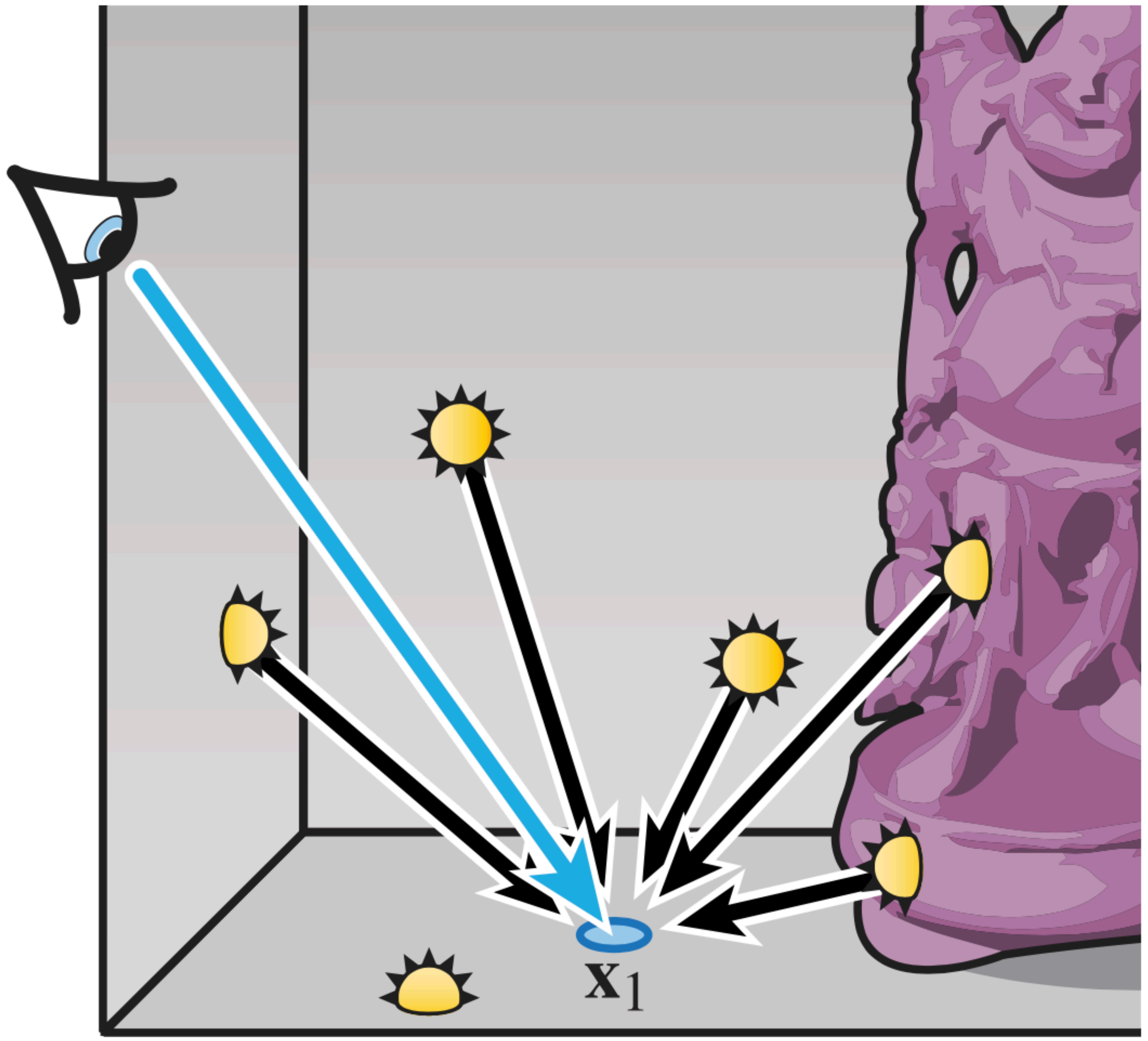

Bounding and Compensation

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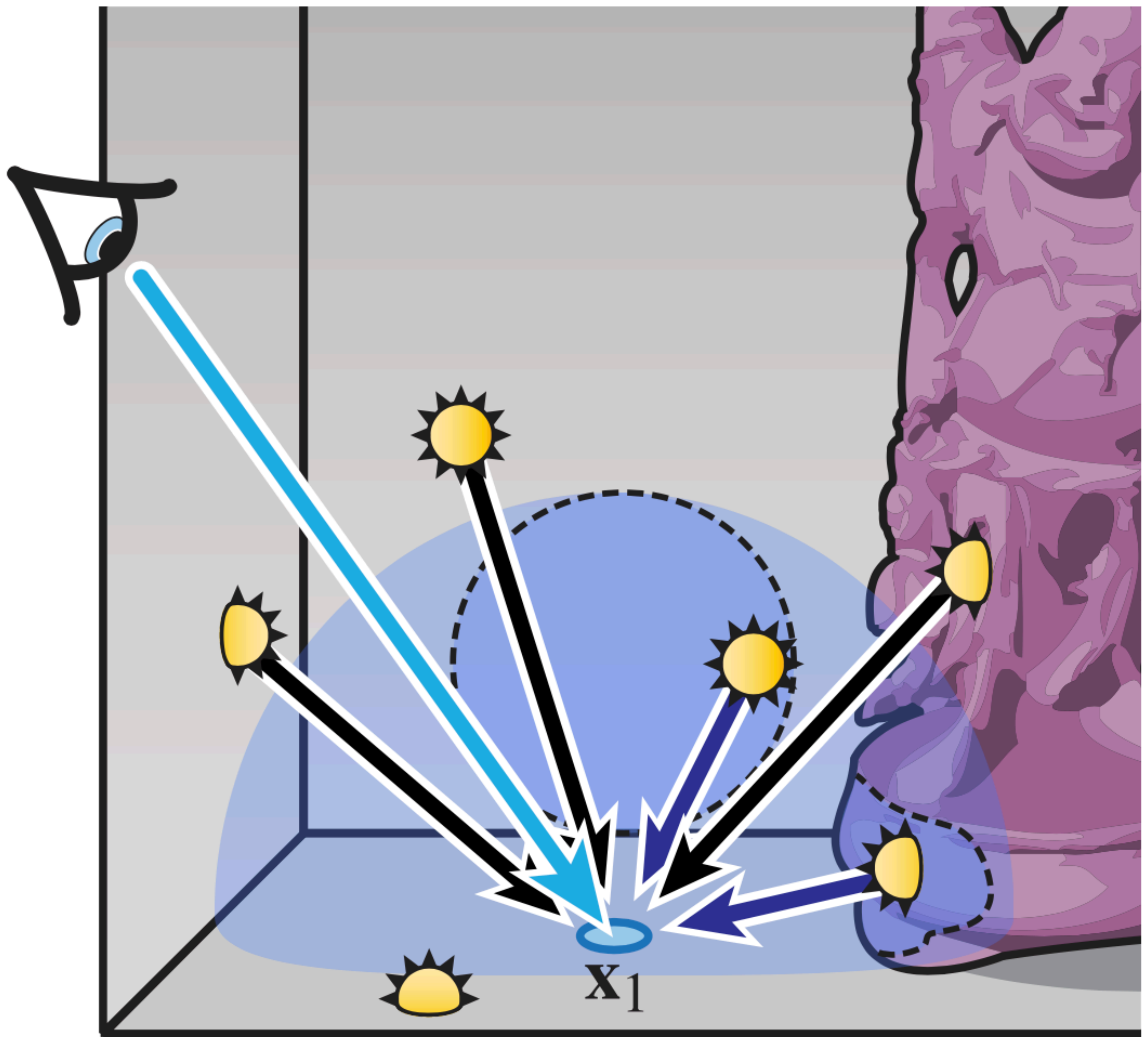
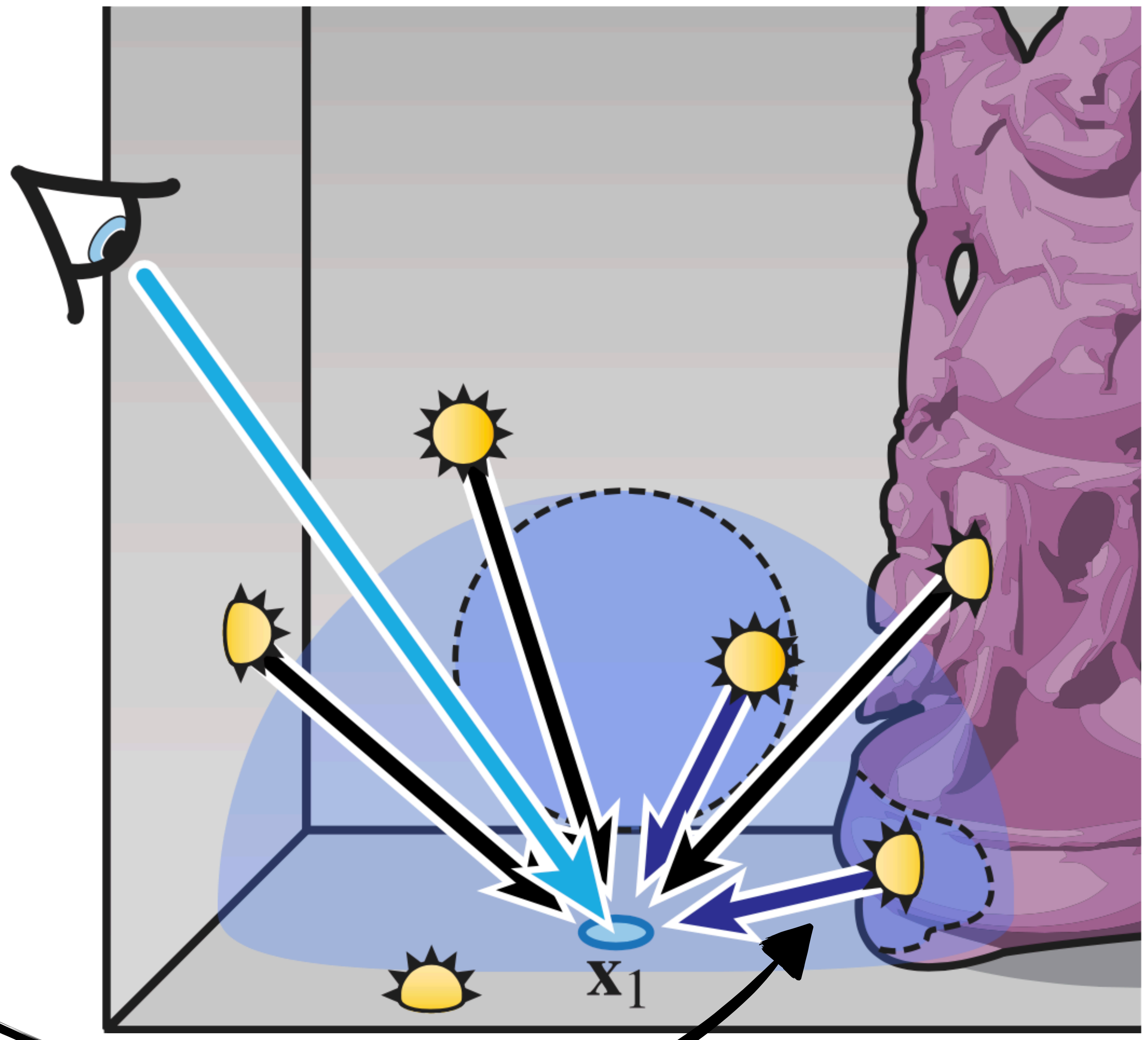


Bounding and Compensation

Bias Compensation [Kollig and Keller 2004] [Raab et al. 2008]

Trace paths to compute the compensation term (residual transport)

bounded contribution

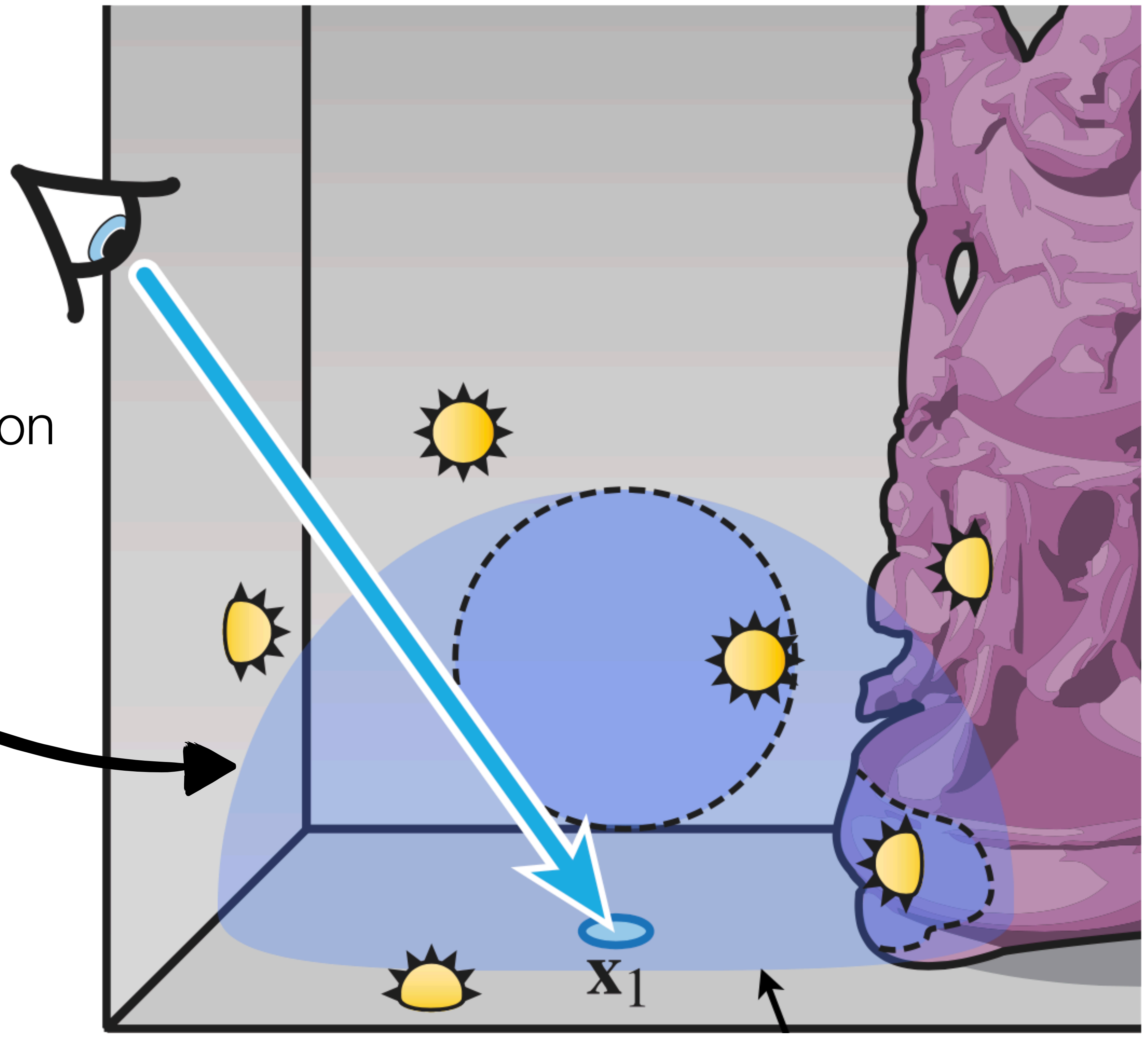


Bounding and Compensation

Bias Compensation [Kollig and Keller 2004] [Raab et al. 2008]

Trace paths to compute the compensation term (residual transport)

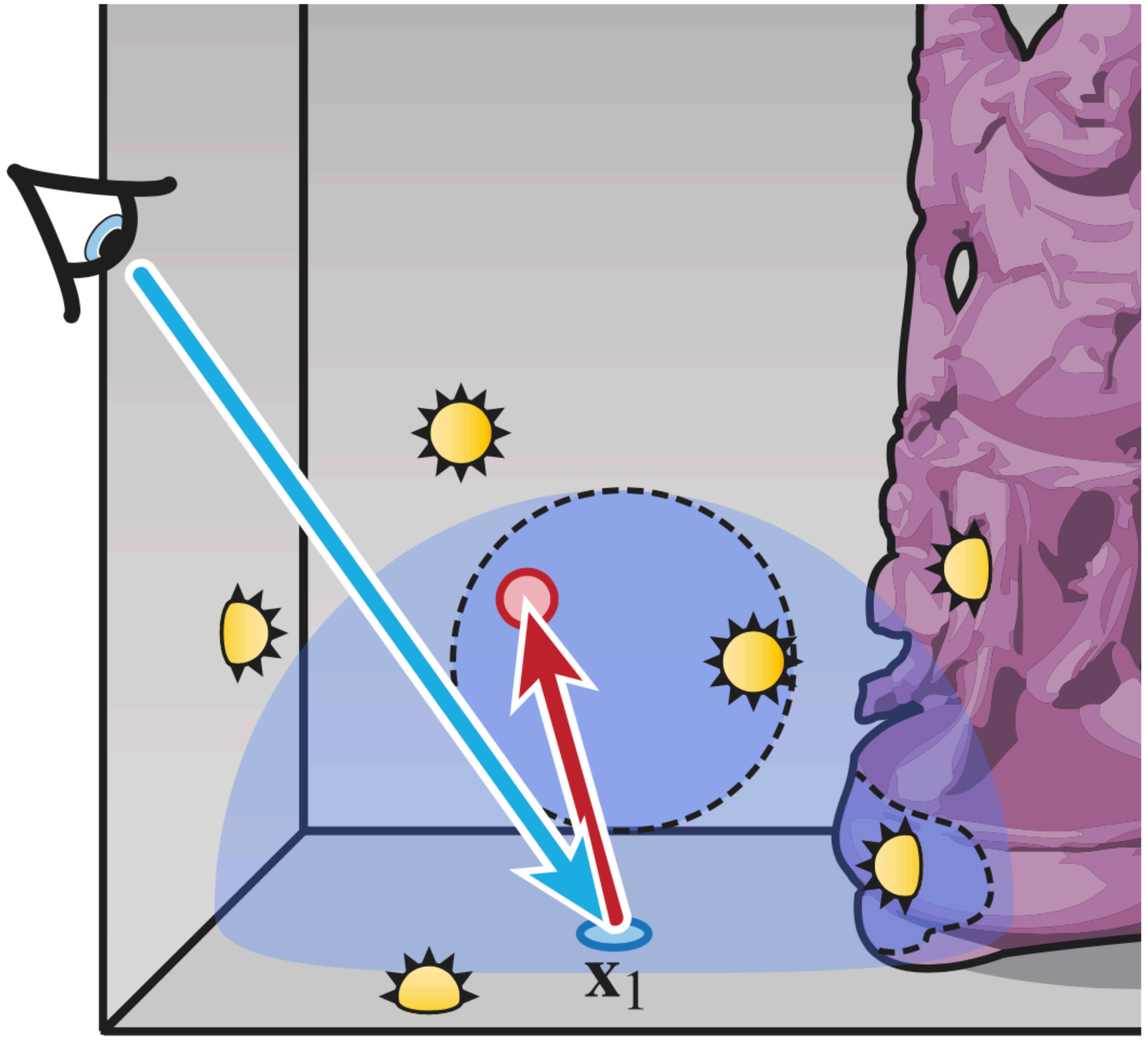
Region with bounded contribution



Bounding and Compensation

Bias Compensation [Kollig and Keller 2004] [Raab et al. 2008]

Trace paths to compute the compensation term (residual transport)



Bounding and Compensation

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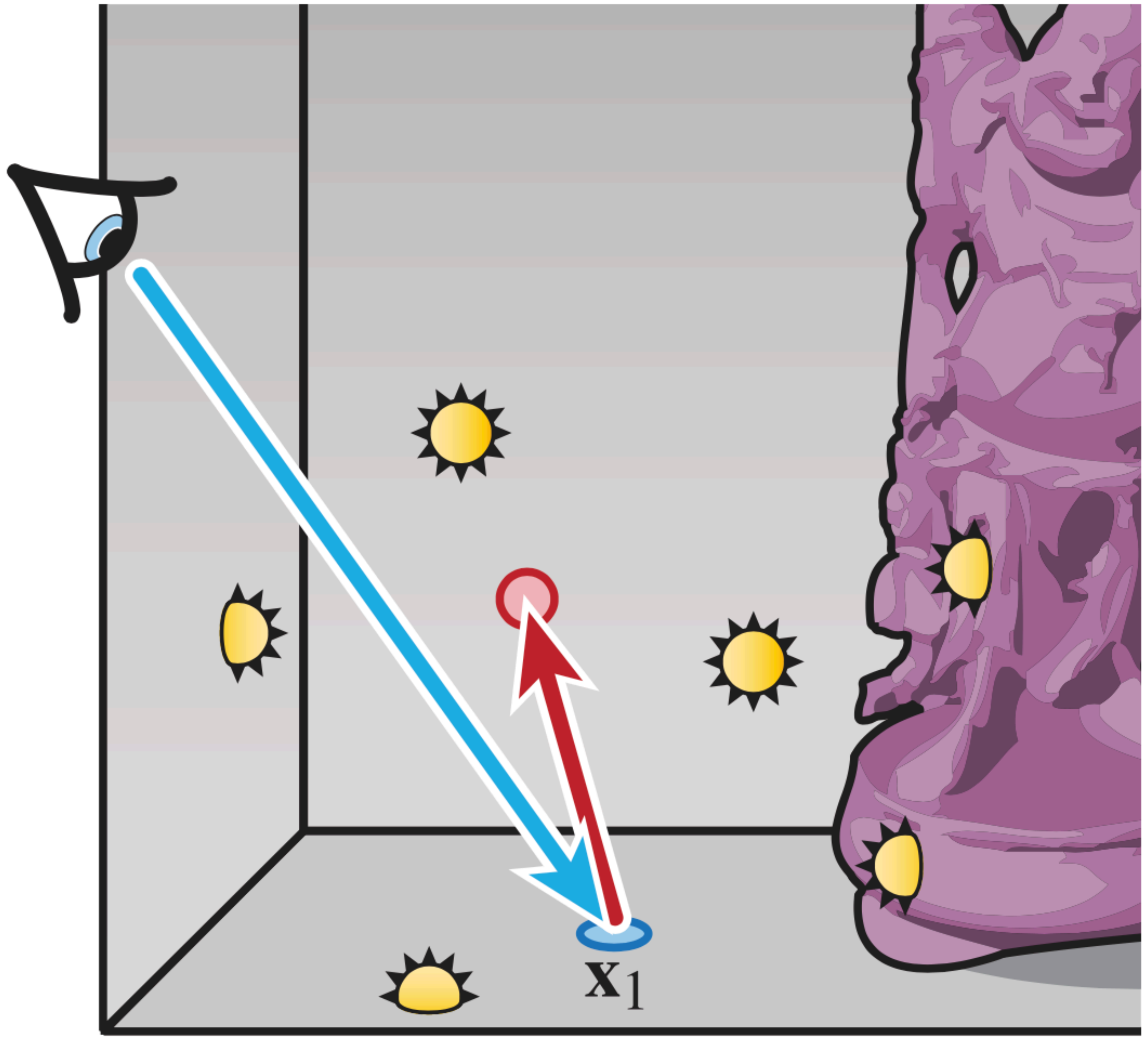

Bounding and Compensation

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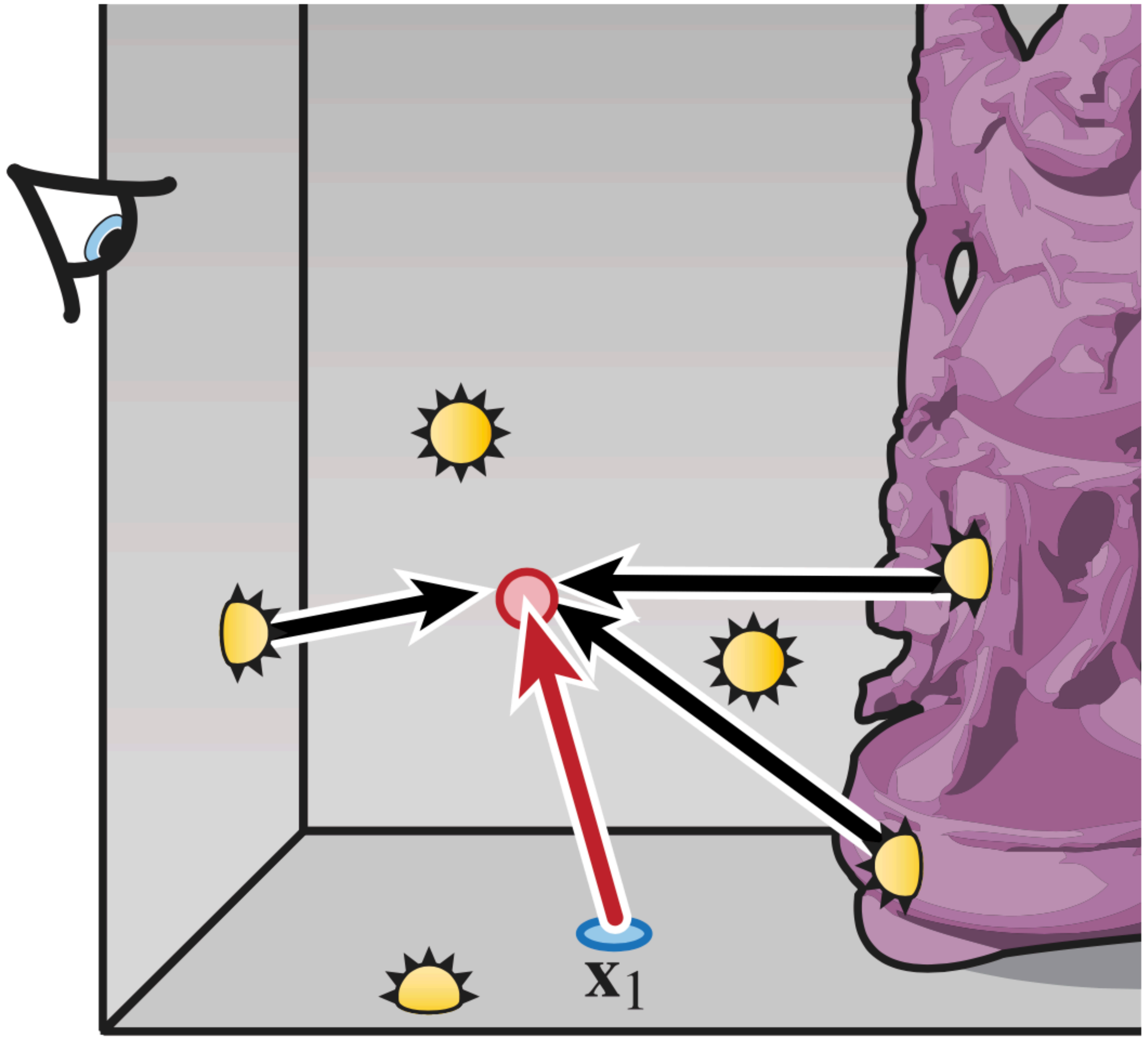
Trace paths to compute the compensation term (residual transport)



Bounding and Compensation

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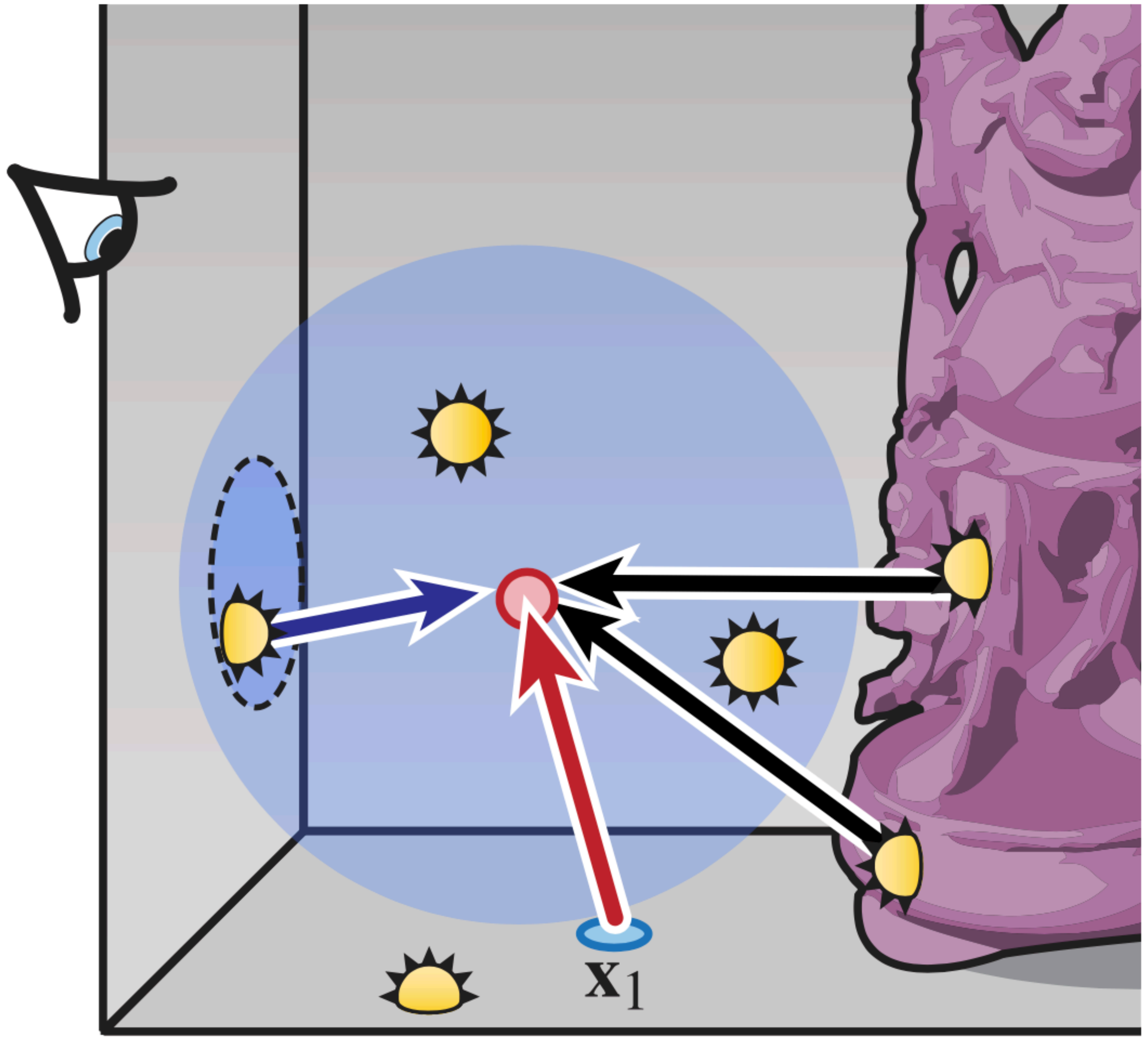

Bounding and Compensation

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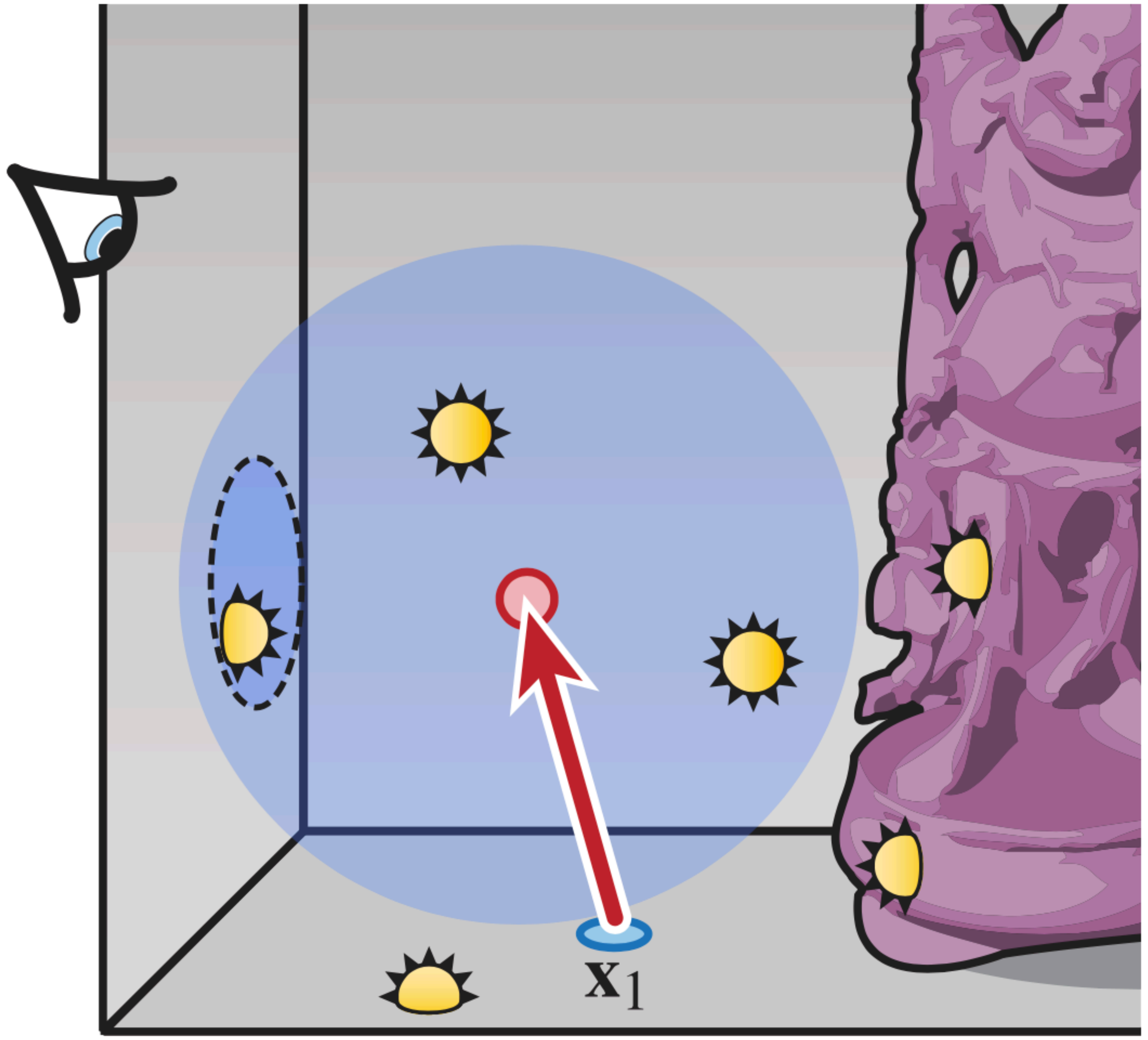

Bounding and Compensation

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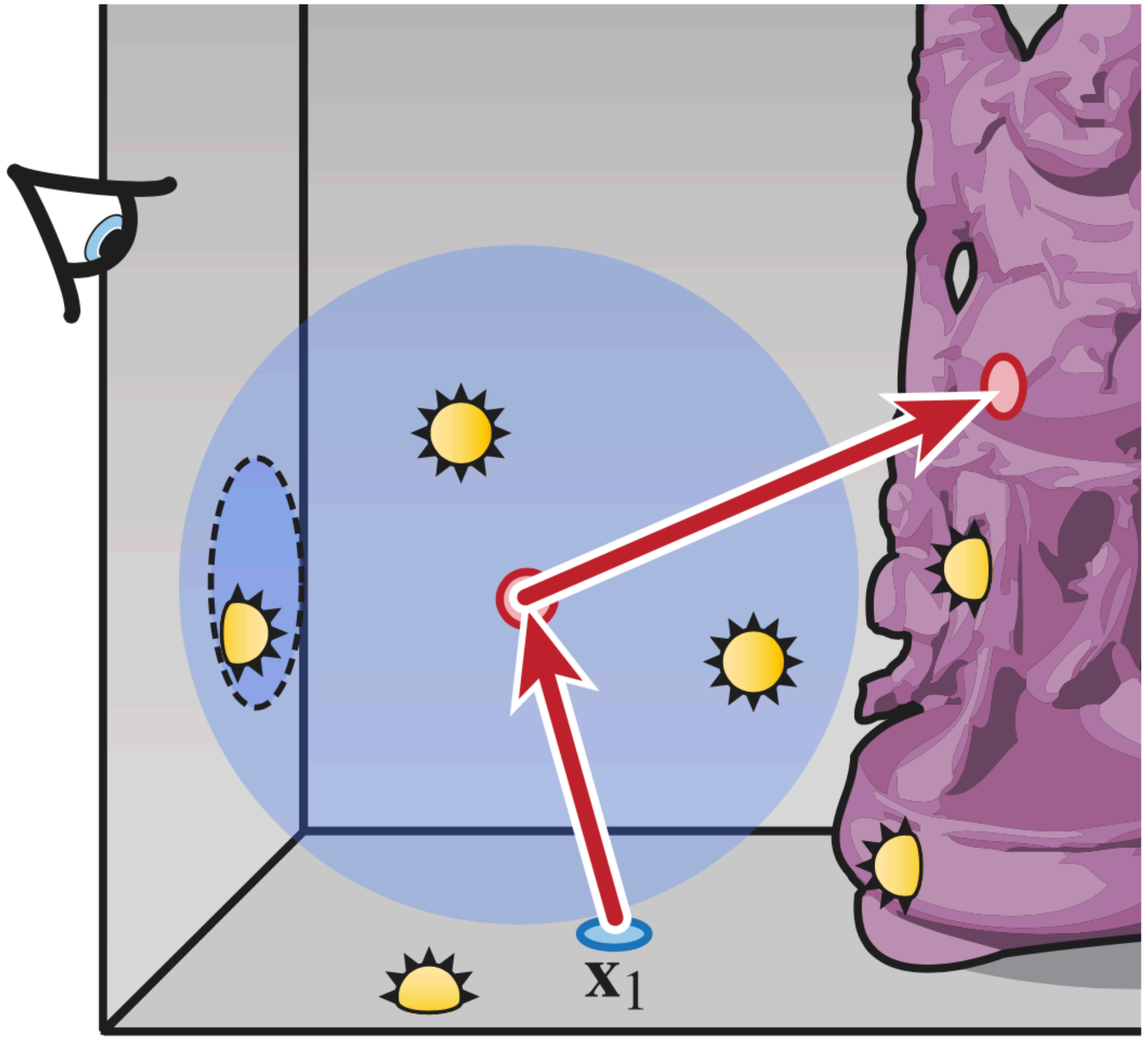

Bounding and Compensation

Bias Compensation [Kollig and Keller 2004] [Raab et al. 2008]

Advantages:

Recover all missing energy

Makes the algorithm unbiased

Disadvantages:

Recursive, degenerate to path tracing

Very expensive: recovering 10% of energy may take 90% of the rendering time

Bounding and Compensation

Bias Compensation [Kollig and Keller 2004] [Raab et al. 2008]

Bounding only

Bounding and Compensation

Image courtesy Kollig and Keller

Bounding and Compensation

Bias Compensation [Kollig and Keller 2004] [Raab et al. 2008]

Bounding only

Bounding and Compensation

Image courtesy Kollig and Keller

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

Rendering Equation:

$$L = L_{\mathrm{e}} + \mathbf{T}L$$

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

Rendering Equation:

$$
\begin{aligned}
L &= L_\mathrm{e} + \mathbf{T}L \\
&\approx L_\mathrm{e} + \mathbf{T}L_\mathrm{e} + \mathbf{T}\hat{L}
\end{aligned}
$$

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

Rendering Equation:

$$
\begin{aligned}
L &= L_{\mathrm{e}} + \mathbf{T}L \\
&\approx L_{\mathrm{e}} + \mathbf{T}L_{\mathrm{e}} + \mathbf{T}\hat{L} \\
&\approx L_{\mathrm{e}} + \mathbf{T}L_{\mathrm{e}} + \mathbf{T}_{\color{blue}{\mathbf{b}}}\hat{L} + \mathbf{T}_{\color{red}{\mathbf{r}}}\hat{L}
\end{aligned}
$$

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

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Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

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$$
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&\approx L_\mathrm{e} + \mathbf{T}L_\mathrm{e} + \mathbf{T}_\mathbf{b}\hat{L} + \mathbf{T}_\mathbf{r}(L - L_\mathrm{e}) \\
&\approx L_\mathrm{e} + \underbrace{\sum_{i=0}^{\infty} \mathbf{T}_\mathbf{r}^i}_{\text{iteratively apply } \mathbf{T}_\mathbf{r}} \underbrace{(\mathbf{T}L_\mathrm{e} + \mathbf{T}_\mathbf{b}\hat{L})}_{\text{compute once and store}}
\end{aligned}
$$

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

Rendering Equation: $$\approx L_e + \sum_{i=0}^{\infty} \mathbf{T}_{\mathbf{r}}^{i} (\mathbf{T}L_e + \mathbf{T}_{\mathbf{b}}\hat{L})$$

direct +
bounded indirect
illumination

residual transport
in screen-space

residual transport
in screen-space

$\mathbf{T}_{\mathbf{r}}^{0}(\mathbf{T}L_e + \mathbf{T}_{\mathbf{b}}\hat{L})$

Bounding and Compensation

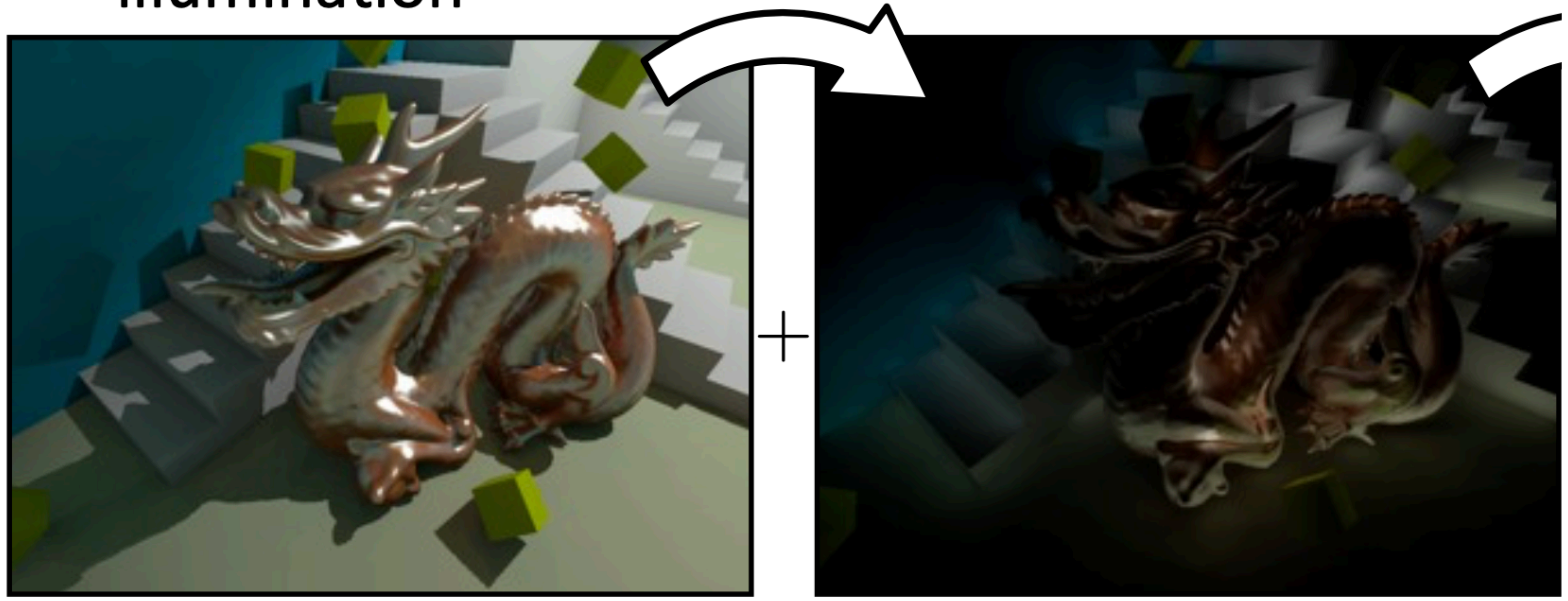
Screen space bias compensation [Novak et al. 2011]

Rendering Equation: $$\approx L_\mathrm{e} + \sum_{i=0}^{\infty} \mathbf{T}_\mathbf{r}^i (\mathbf{T} L_\mathrm{e} + \mathbf{T}_\mathbf{b} \hat{L})$$

direct + bounded indirect illumination

residual transport in screen-space

residual transport in screen-space



$\mathbf{T}_\mathbf{r}^0 (\mathbf{T} L_\mathrm{e} + \mathbf{T}_\mathbf{b} \hat{L})$ $+$ $\mathbf{T}_\mathbf{r}^1 (\mathbf{T} L_\mathrm{e} + \mathbf{T}_\mathbf{b} \hat{L})$

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

Rendering Equation: $\approx L_\mathrm{e} + \sum_{i=0}^{\infty} \mathbf{T}_{\mathbf{r}}^{i} (\mathbf{T} L_\mathrm{e} + \mathbf{T}_{\mathbf{b}} \hat{L})$

direct + bounded indirect illumination

residual transport in screen-space

residual transport in screen-space

$\mathbf{T}_{\mathbf{r}}^{0} (\mathbf{T} L_\mathrm{e} + \mathbf{T}_{\mathbf{b}} \hat{L})$ + $\mathbf{T}_{\mathbf{r}}^{1} (\mathbf{T} L_\mathrm{e} + \mathbf{T}_{\mathbf{b}} \hat{L})$ + $\mathbf{T}_{\mathbf{r}}^{2} (\mathbf{T} L_\mathrm{e} + \mathbf{T}_{\mathbf{b}} \hat{L})$ + ...

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

Direct + bounded indirect	**1- and 2-bounce residual**

+

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

Direct + bounded indirect | **1- and 2-bounce residual** | **Composited**

Bounding and Compensation

Screen space bias compensation [Novak et al. 2011]

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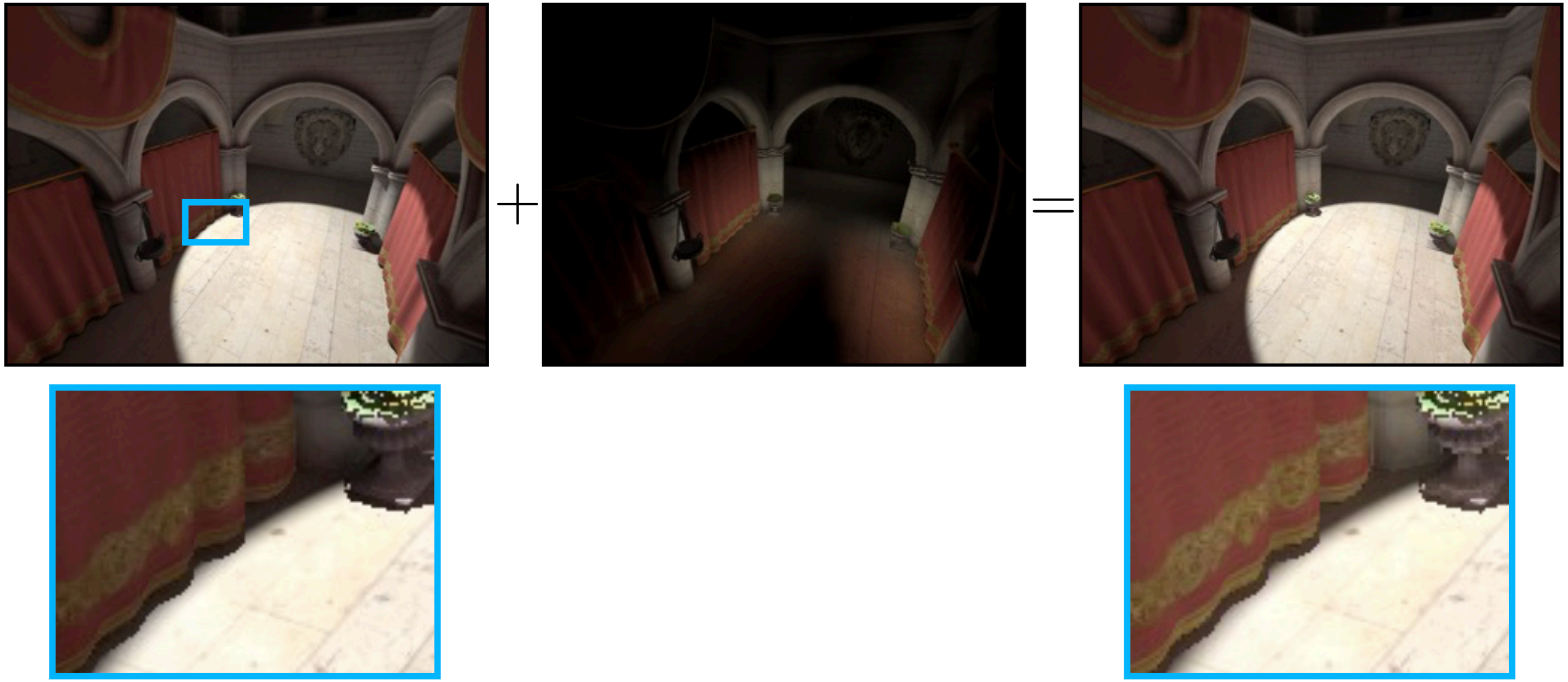

Bounding and Compensation

Approximate bias compensation [Engelhardt et al. 2012]

- efficient compensation for participating media

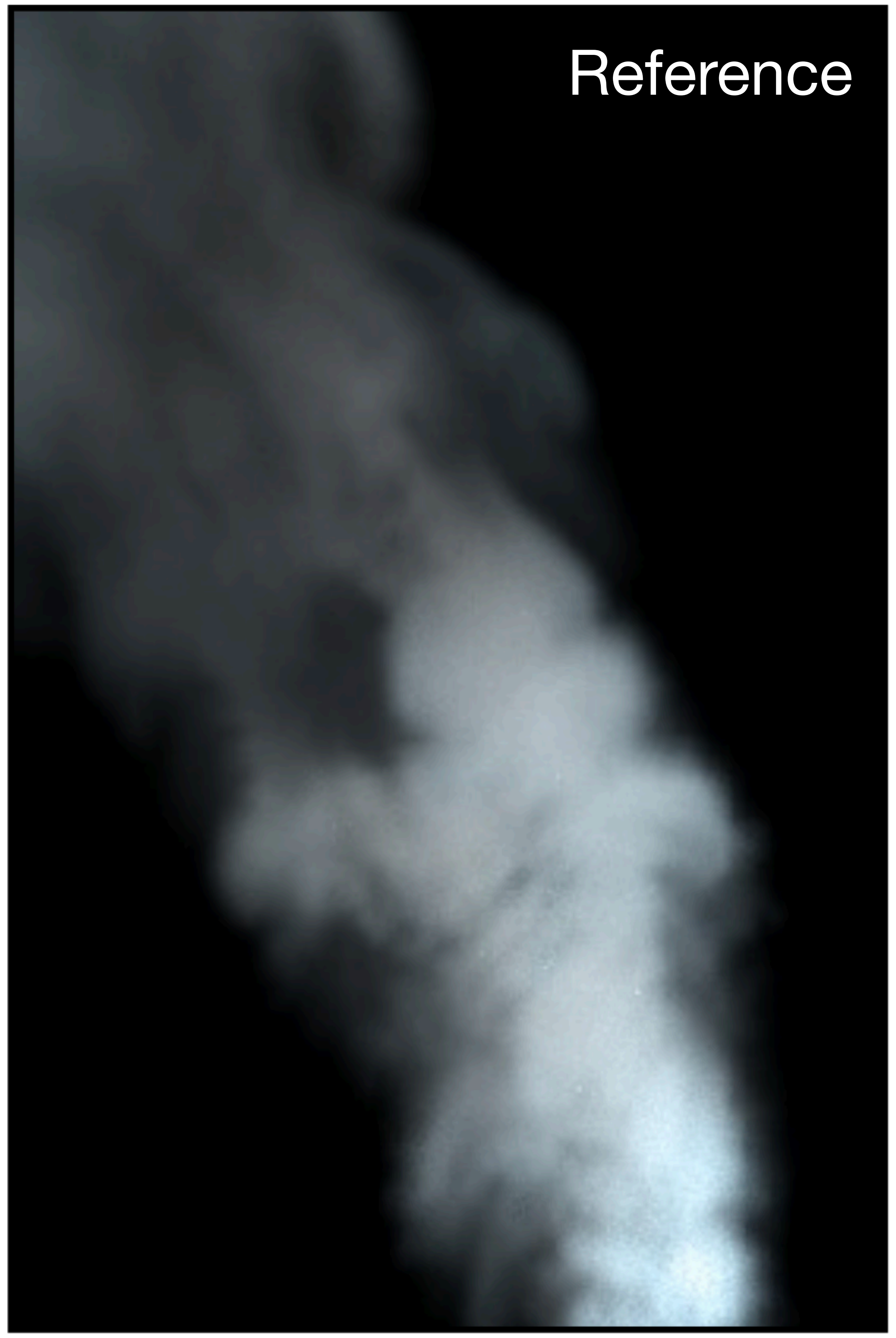

Image courtesy Engelhardt et al. [2012]

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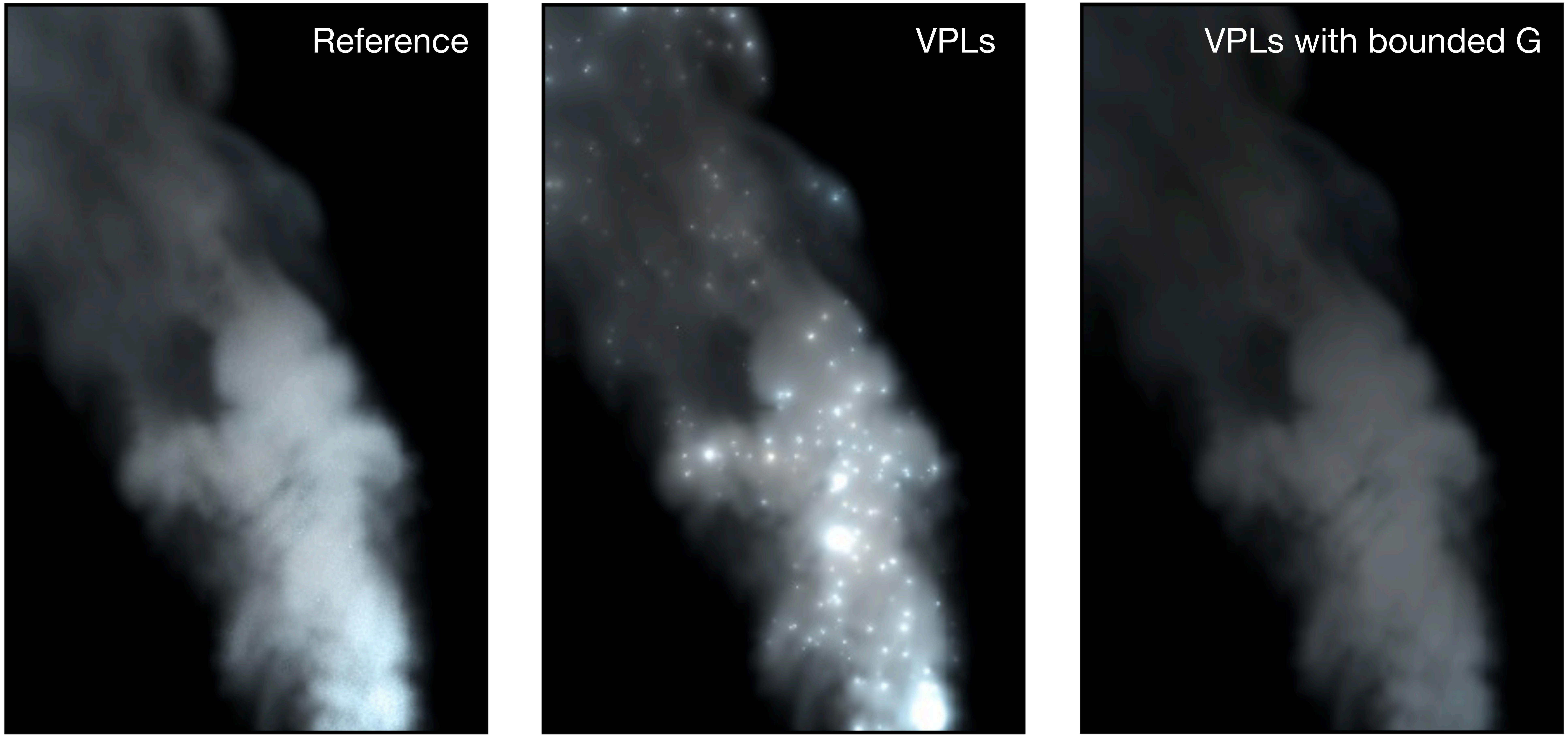

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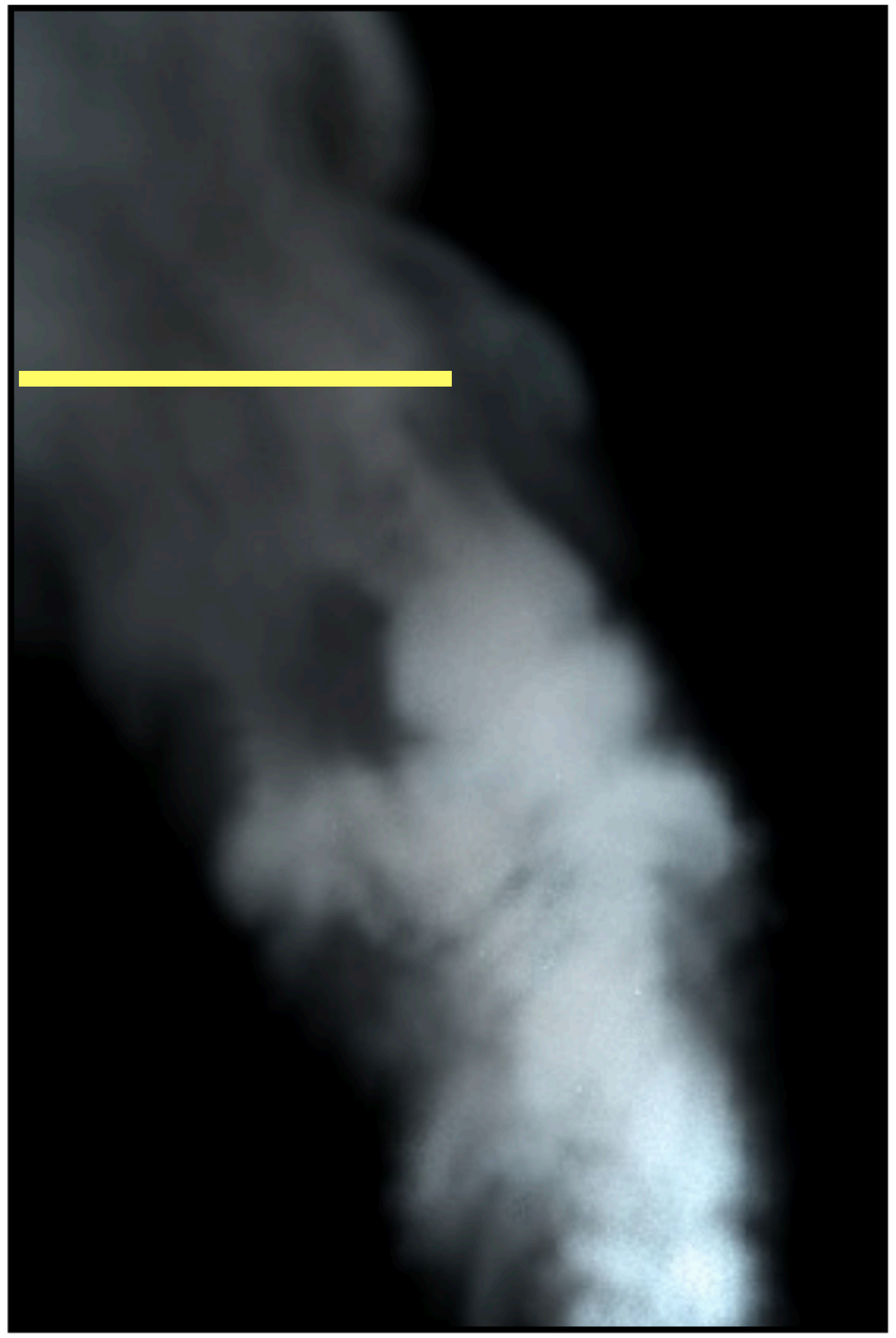

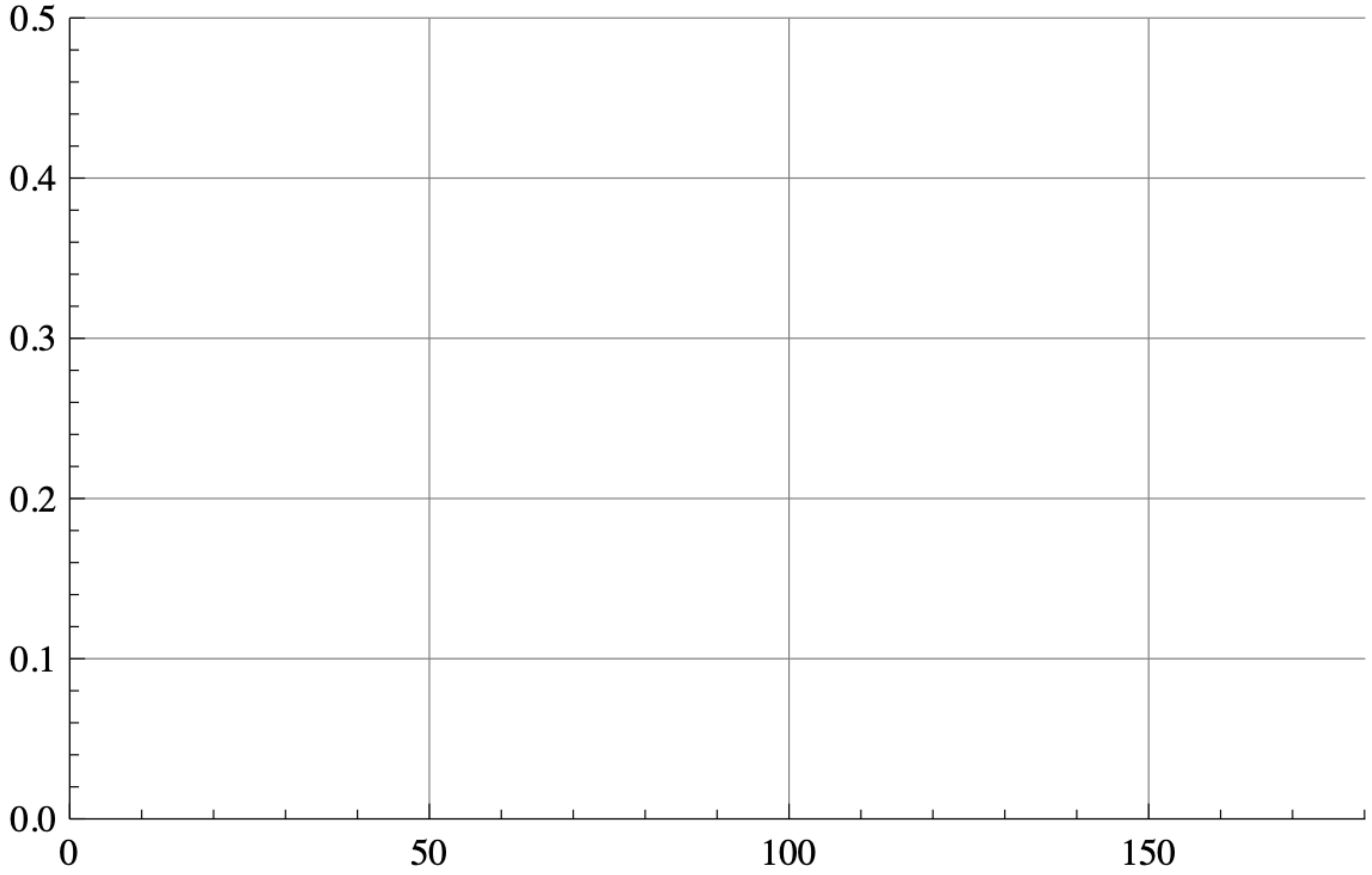

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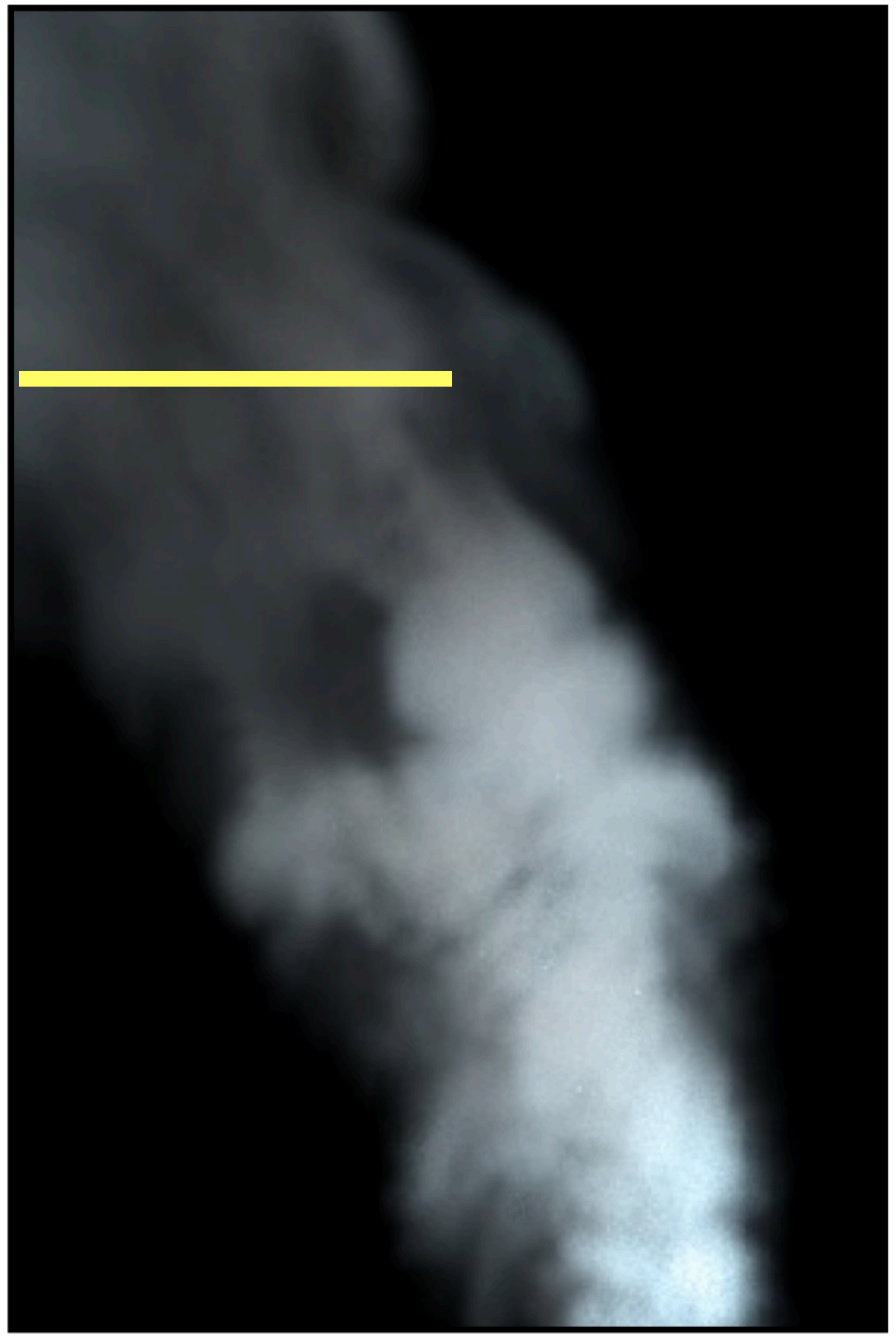

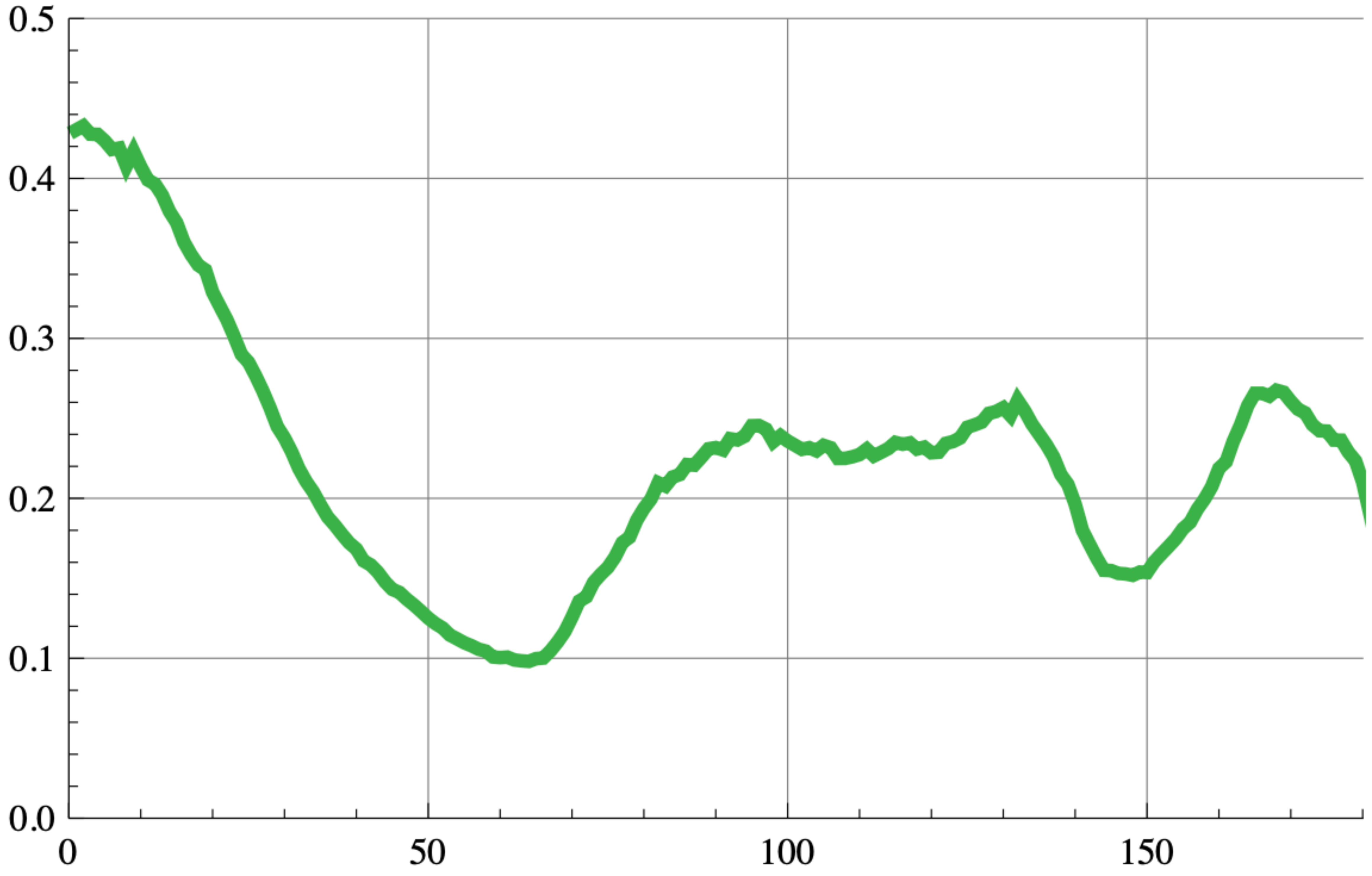

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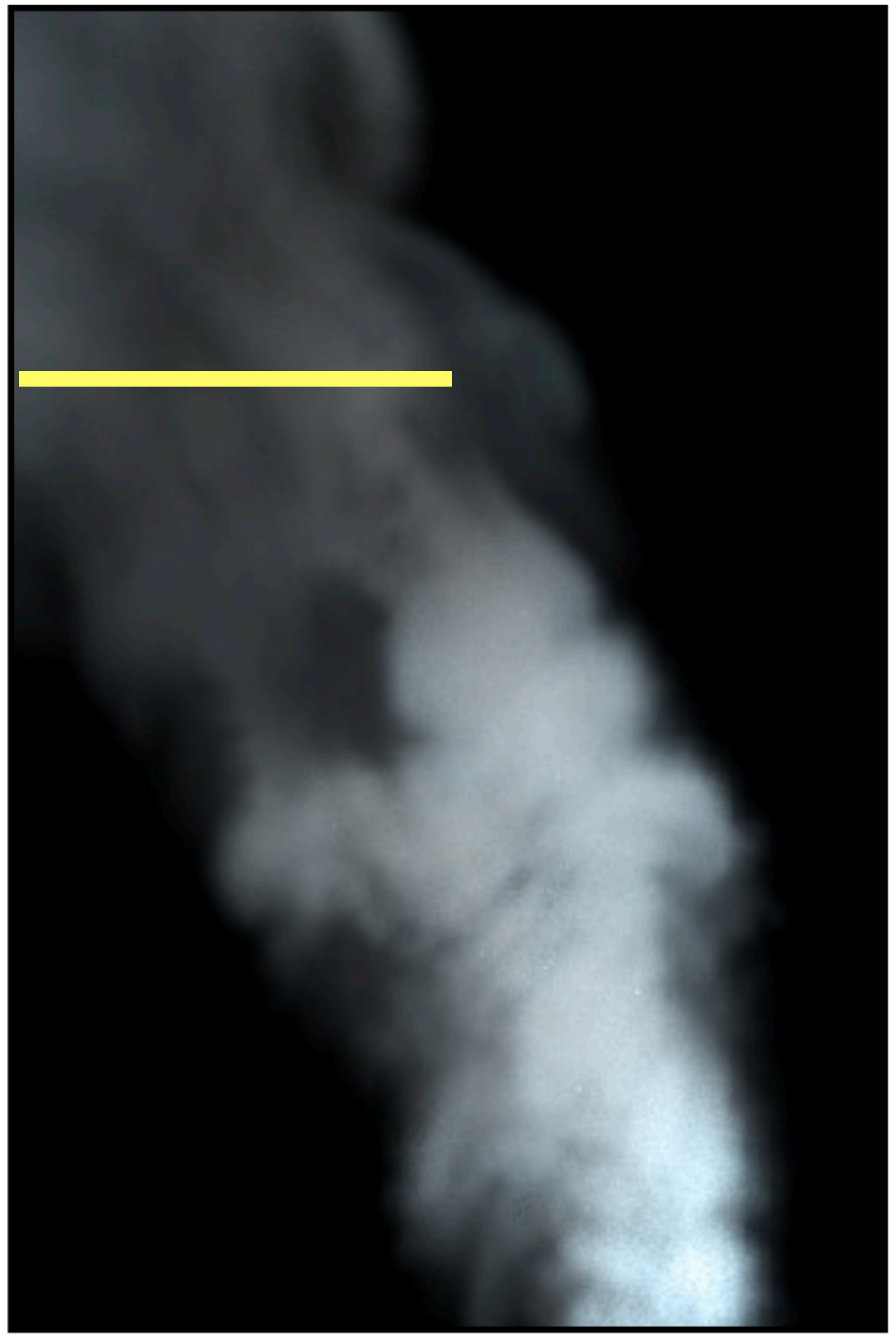

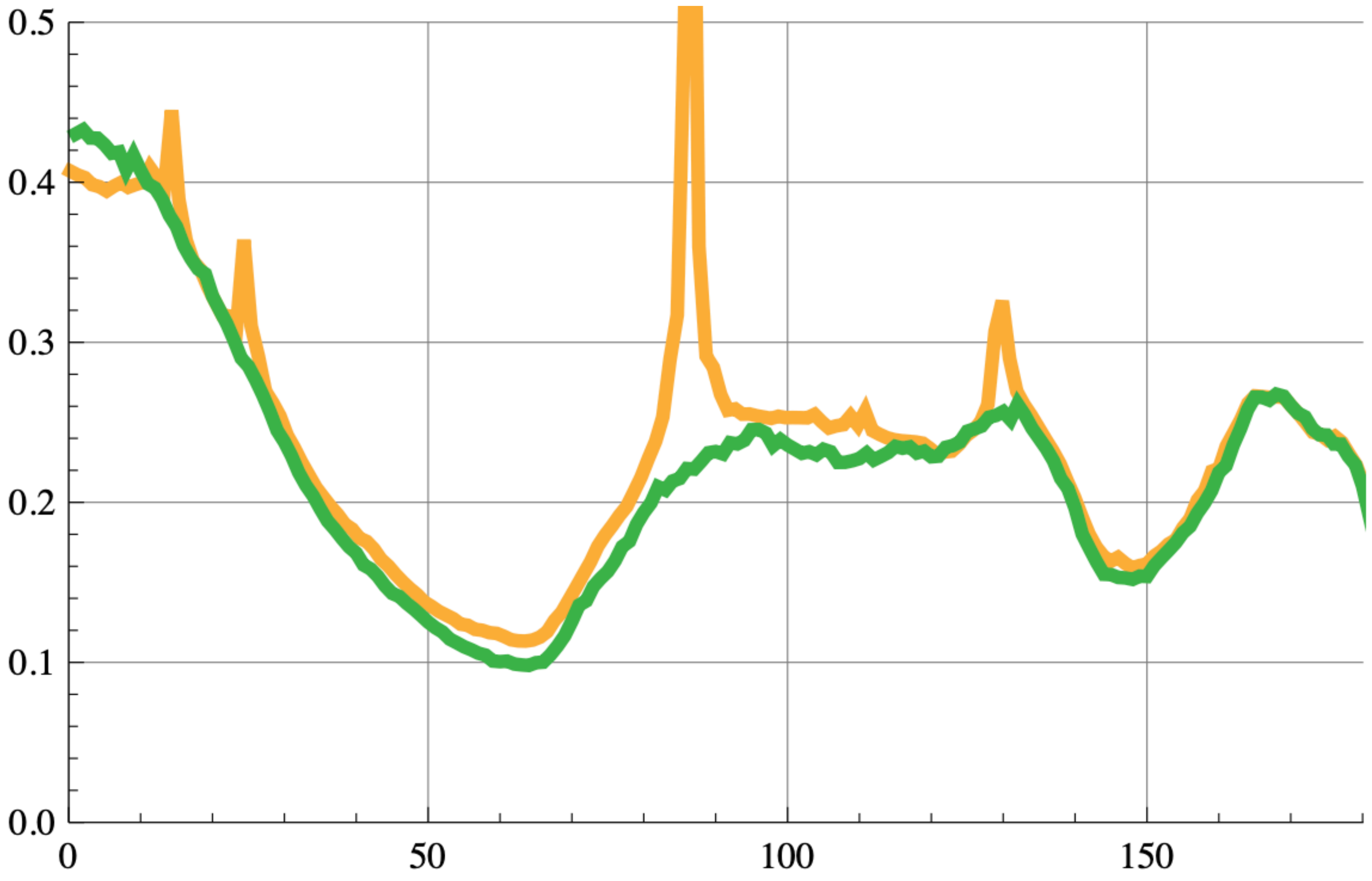

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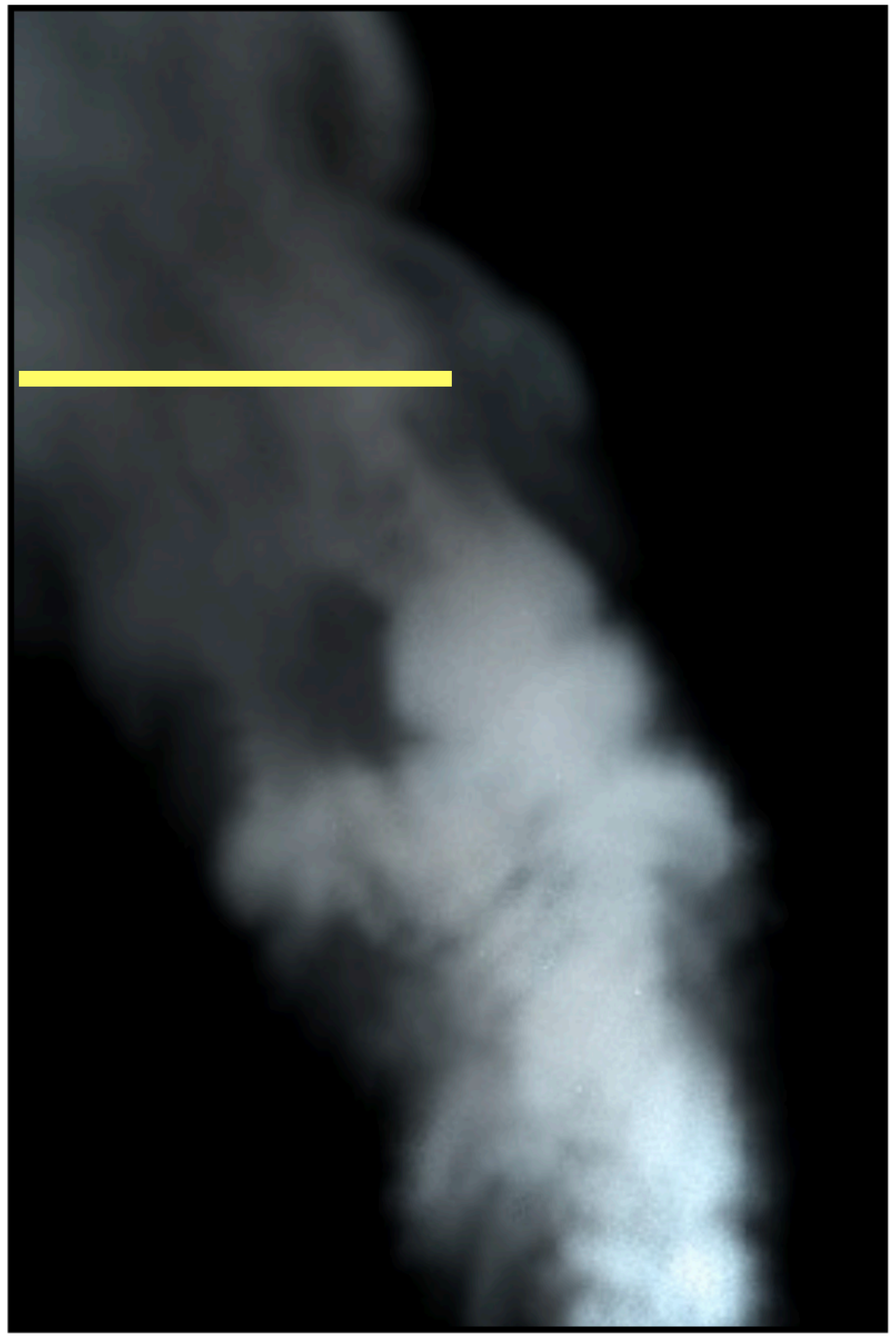

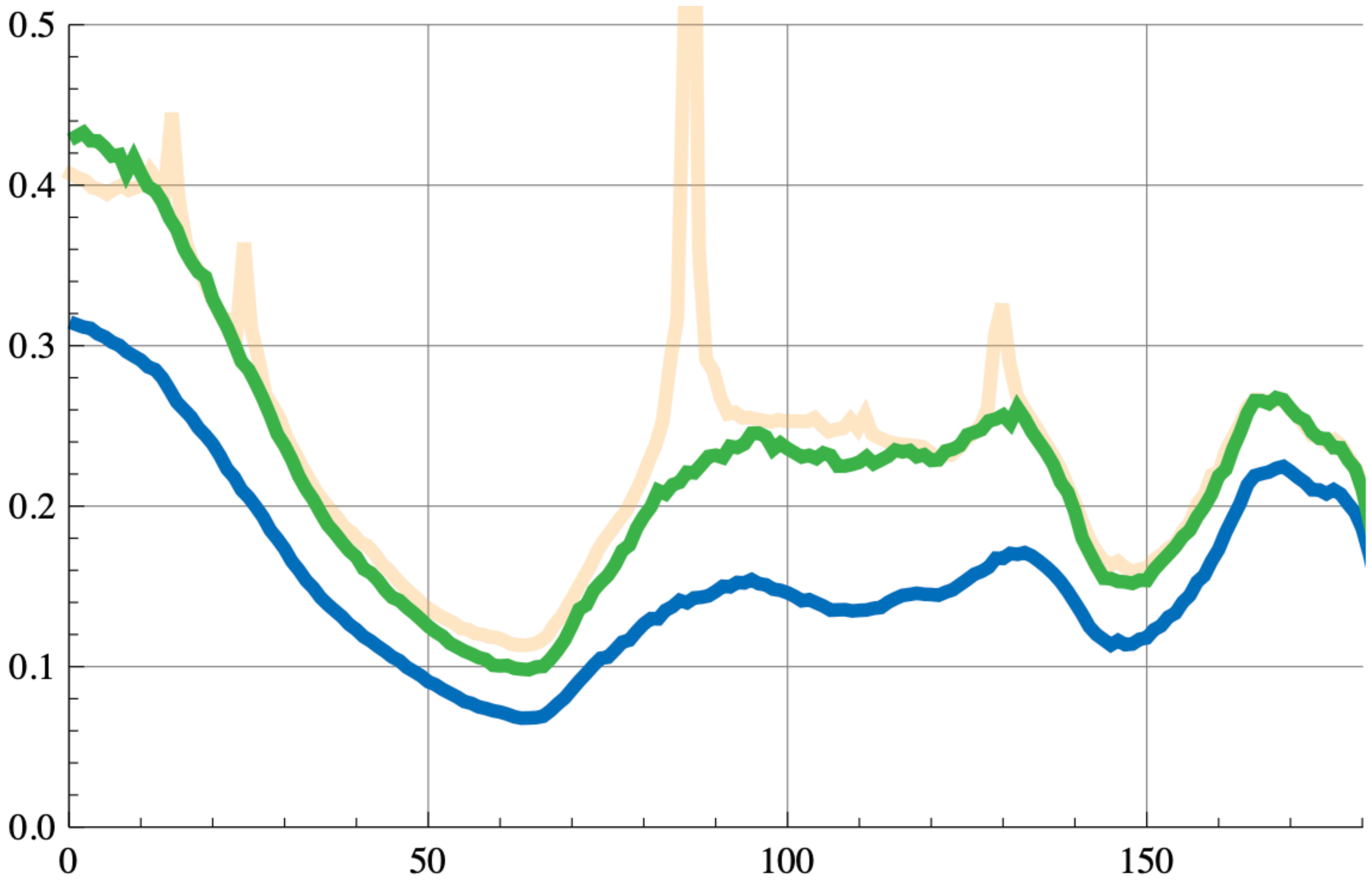

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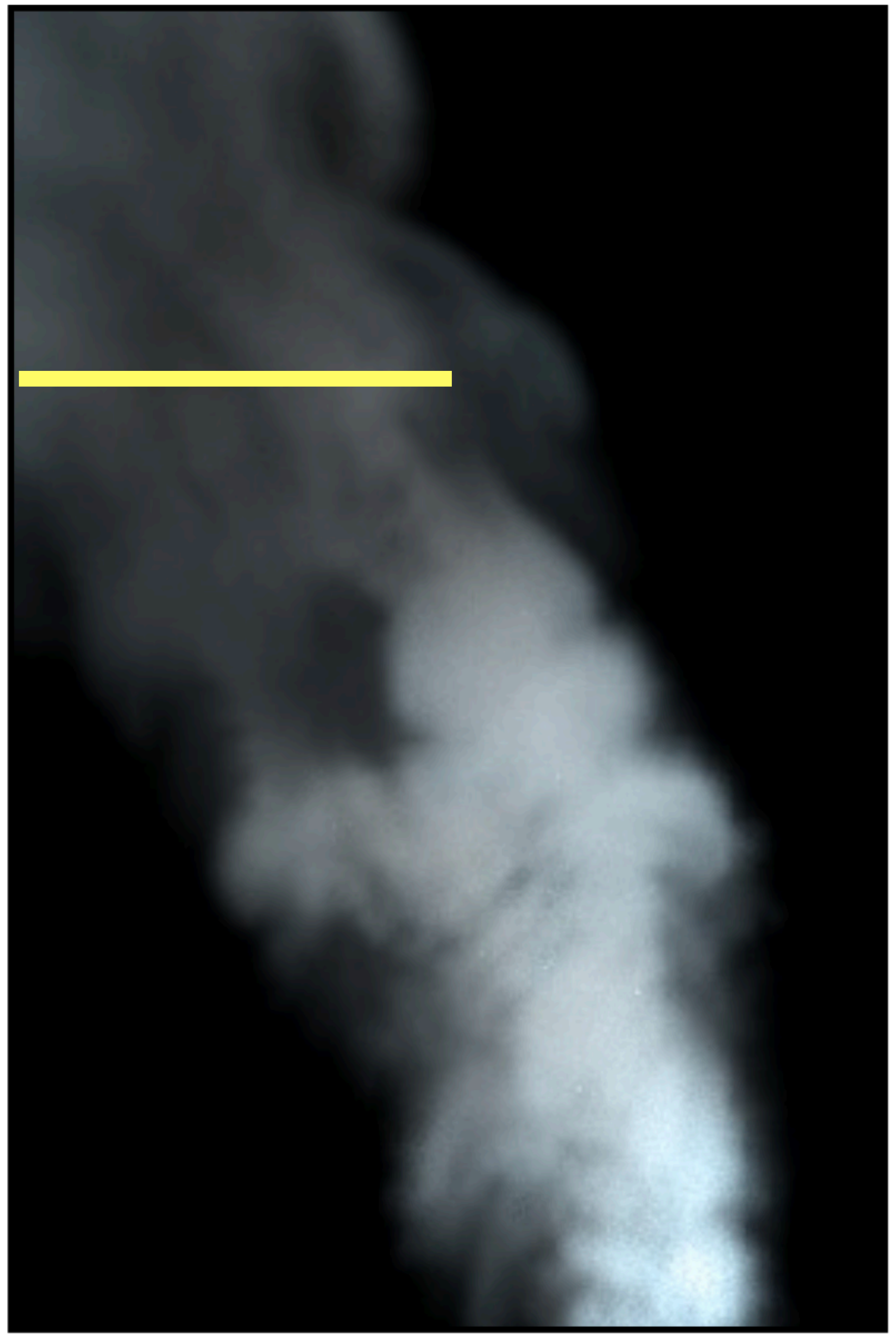

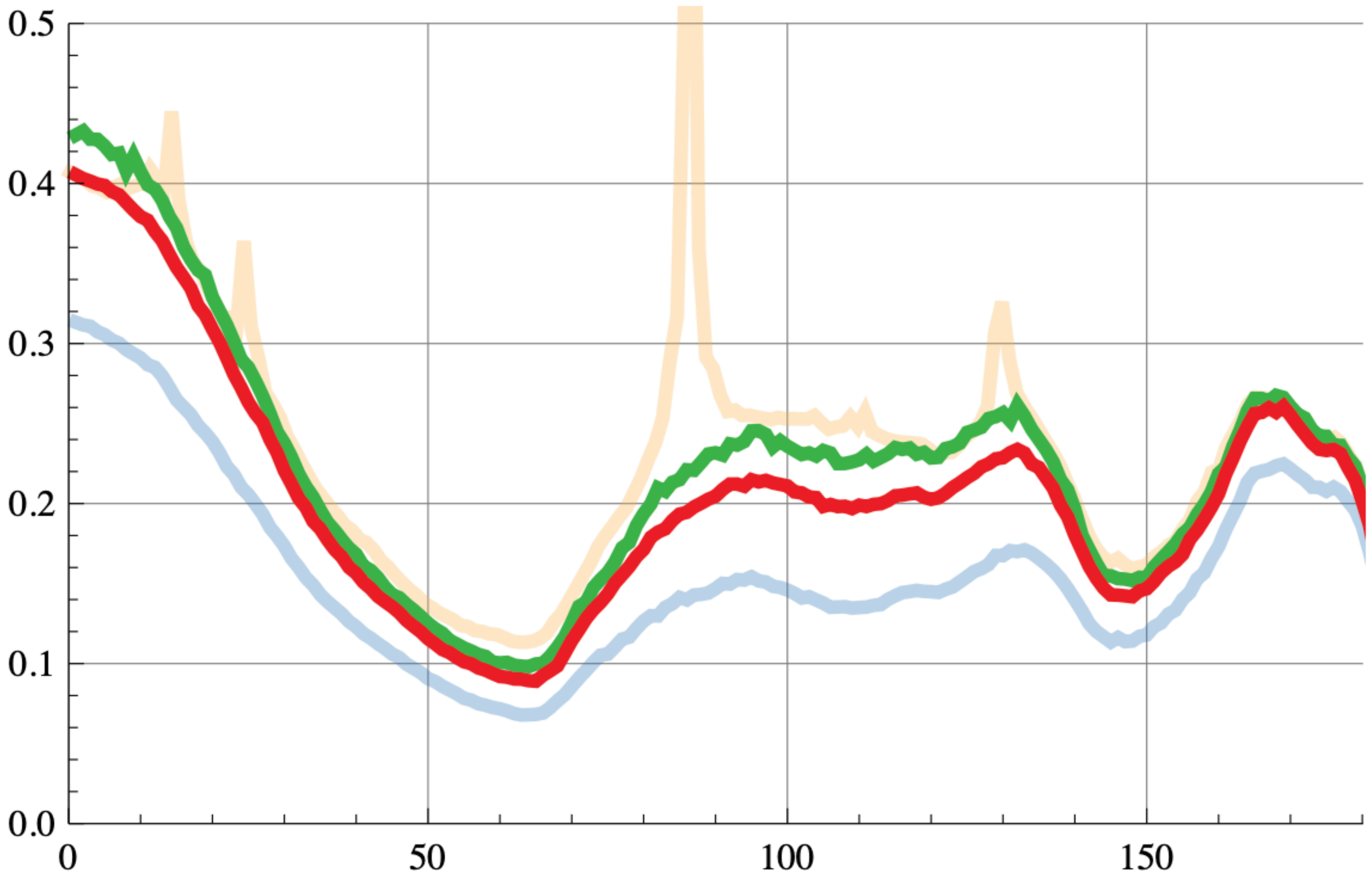

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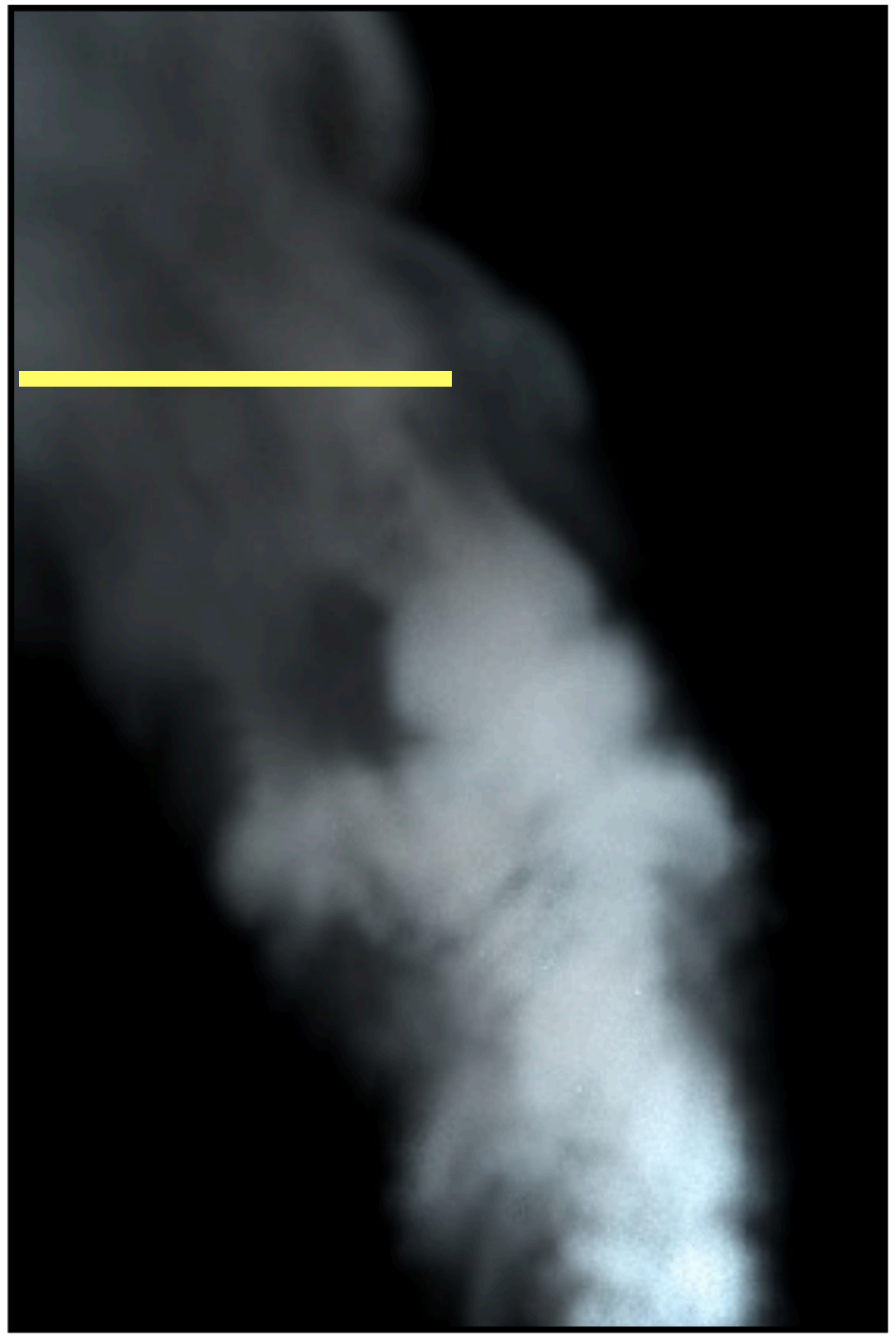

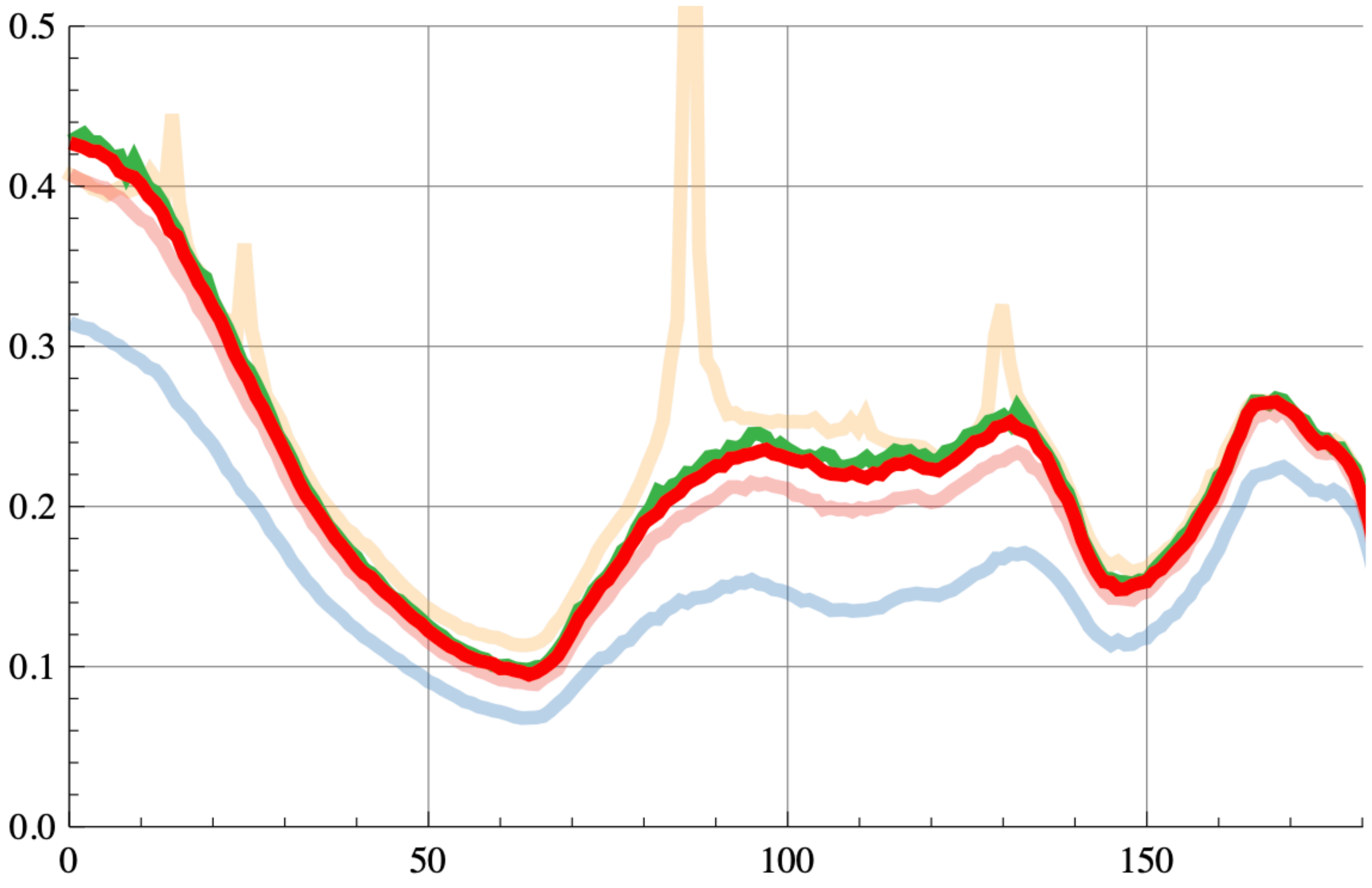

Image courtesy Engelhardt et al. [2012]

Bounding and Compensation

Approximate bias compensation [Engelhardt et al. 2012]

- efficient compensation for participating media

Optimizations used for Bias Compensation:

- Assumes locally homogeneous media
- Omit testing local visibility

Advantages:

Fast, GPU friendly

Disadvantages:

Approximate, complicated

Image courtesy Engelhardt et al. [2012]

Bounding and Compensation

Approximate bias compensation [Engelhardt et al. 2012]

Bounded: 39 mins

Approximate bias compensation: 13 mins

Lighting with VPLs

How to avoid Splotches?

Solutions:

1) Bound the geometry

- remove energy, darkens the image

- to get unbiased results, we need to compensate for the bounding

2) Distribute the flux of a VPL over area (volume)

- redistributes energy, blurs the illumination

- to get consistent results, progressively reduce the blurring

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Spreading the Energy

Problems with Instant Radiosity

Instant Radiosity does not handle glossy surfaces

Hasan et al. 2009

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Instant Radiosity does not handle glossy surfaces

Hasan et al. 2009

Bounding & Compensation

Compute the missing components by path tracing [Kollig and Keller 2004]

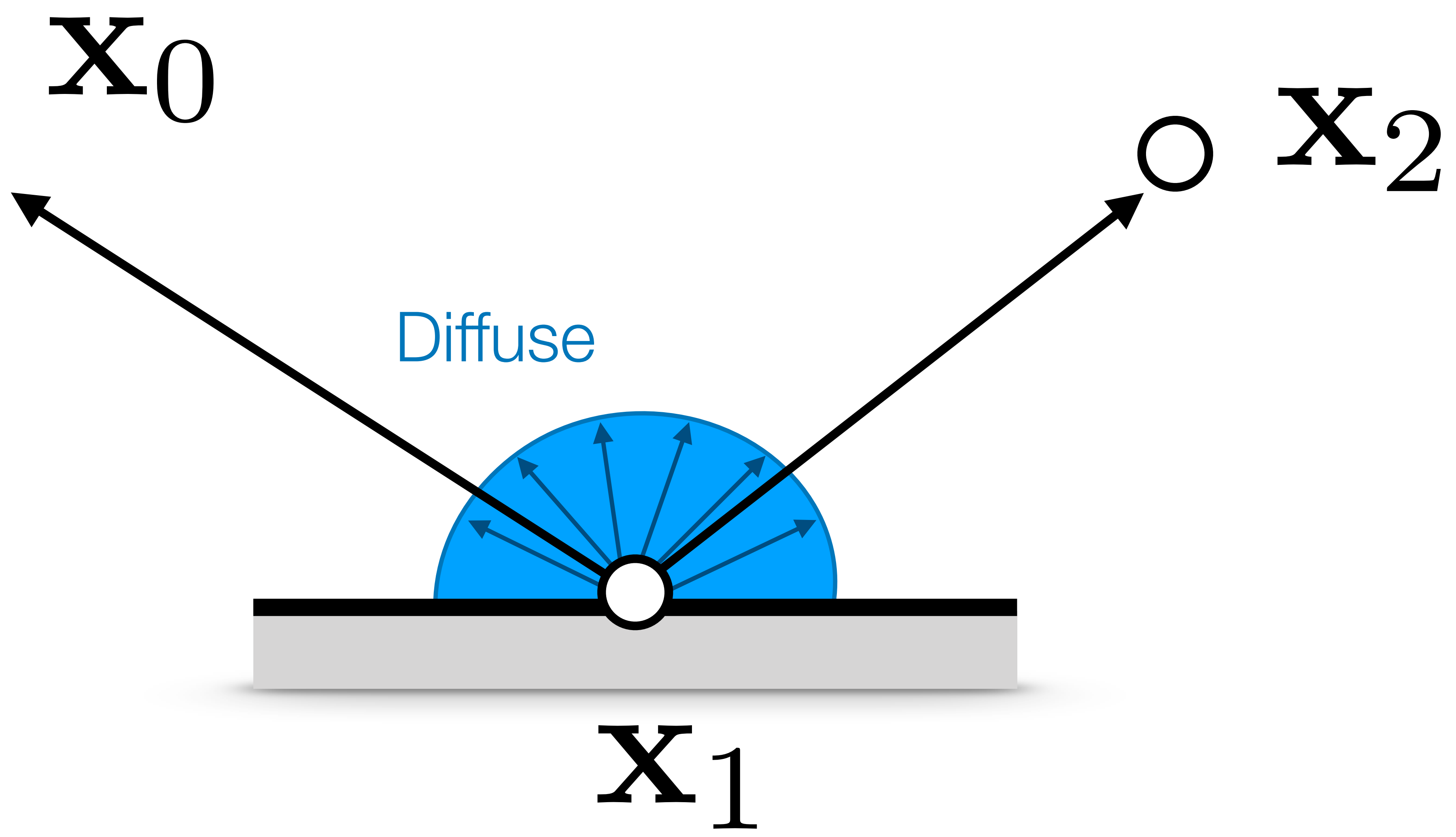
Hasan et al. 2009

Virtual Spherical Lights

Hasan et al. 2009

Instant Radiosity: Only Diffuse

Instant radiosity assumes all surfaces are diffuse



Hasan et al. 2009

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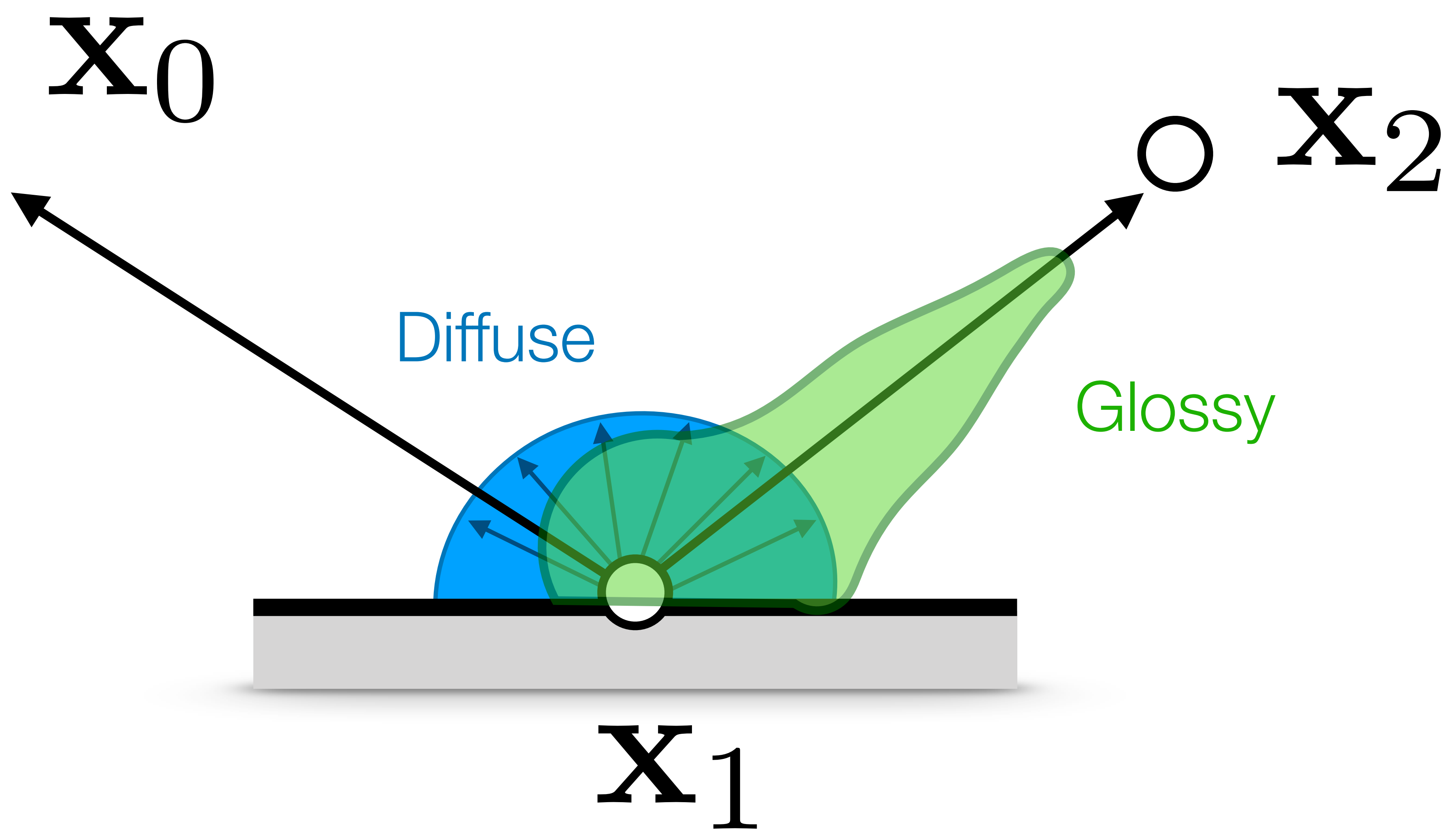
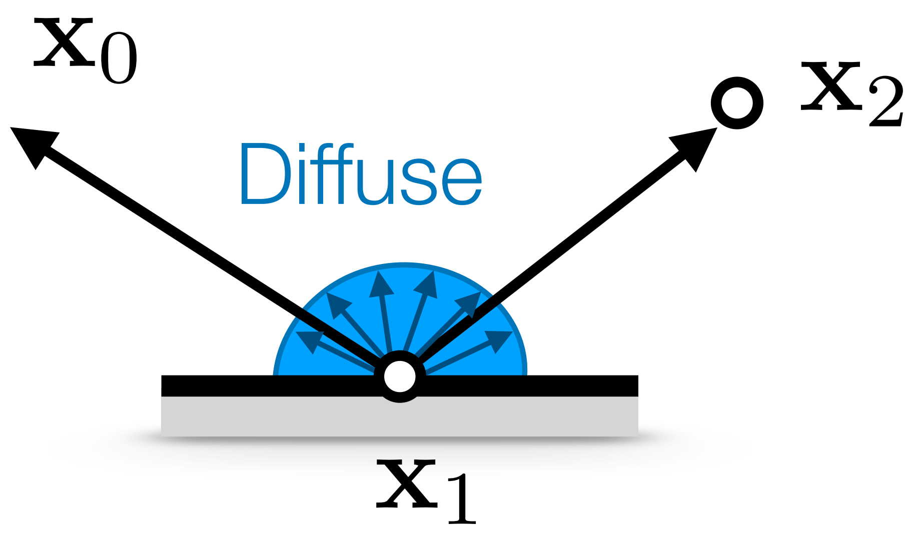


Hasan et al. 2009

Glossy VPL Emission: Illumination Spikes



Common solution:

Only diffuse BRDF at light locations

Streak on the ceiling is caused by a VPL located on a highly anisotropic glossy surface.

Hasan et al. 2009

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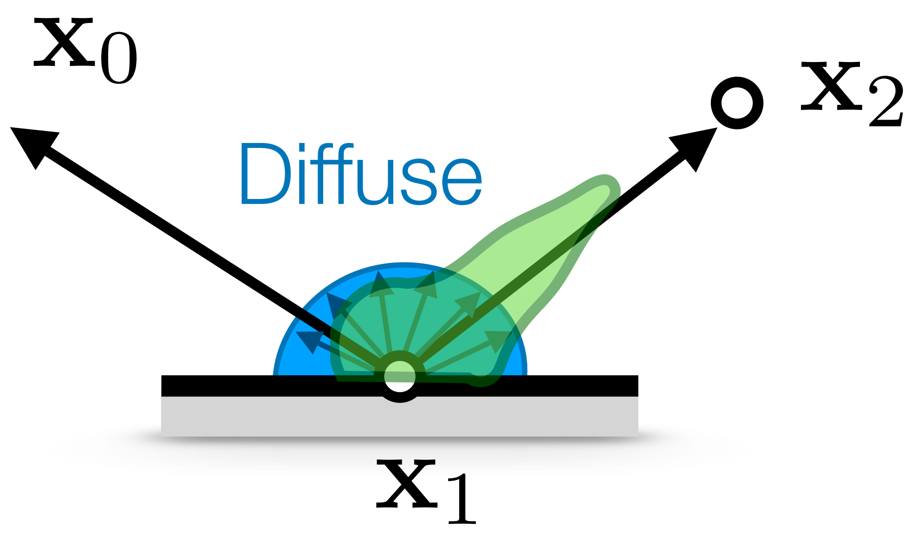

Common solution:

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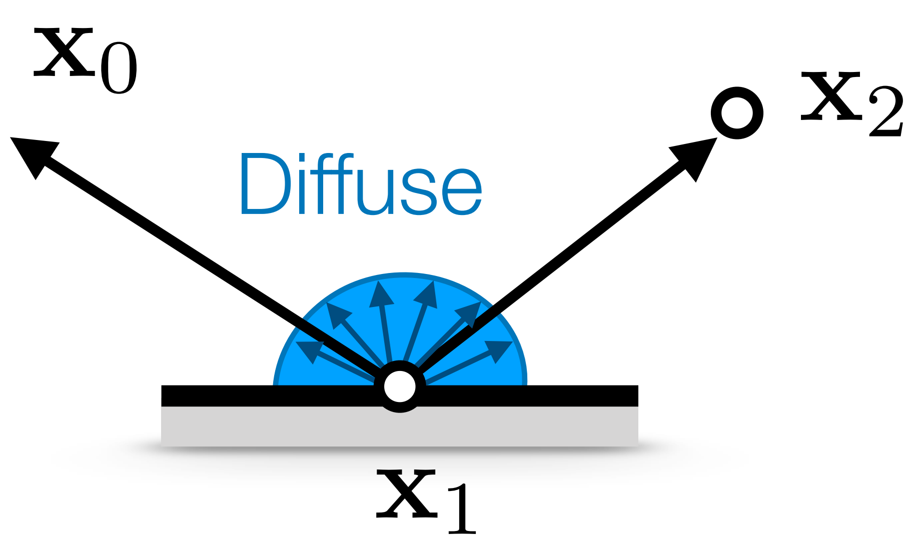
Hasan et al. 2009

Remaining Spikes

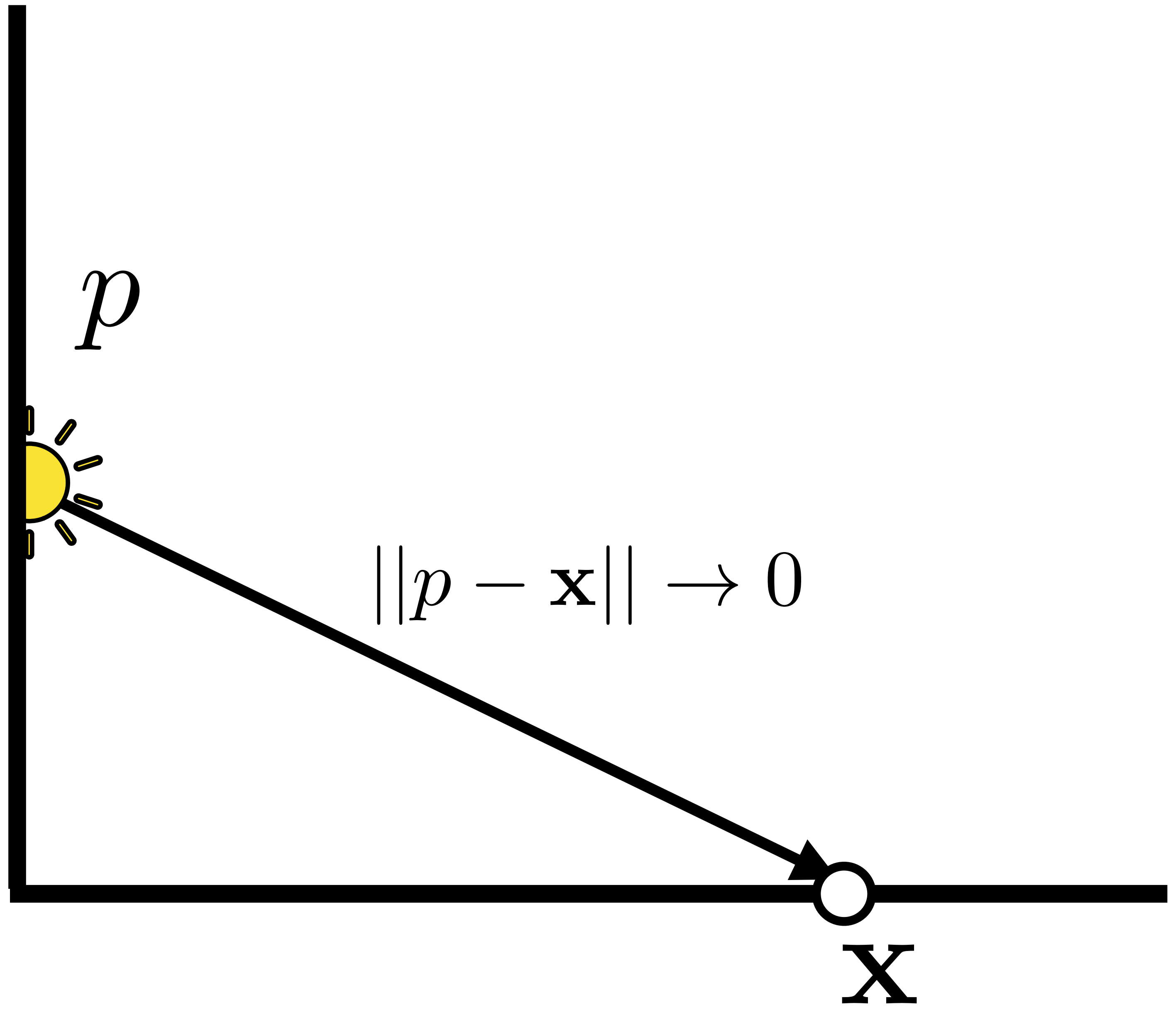


Common solution:

Only diffuse BRDF at light locations

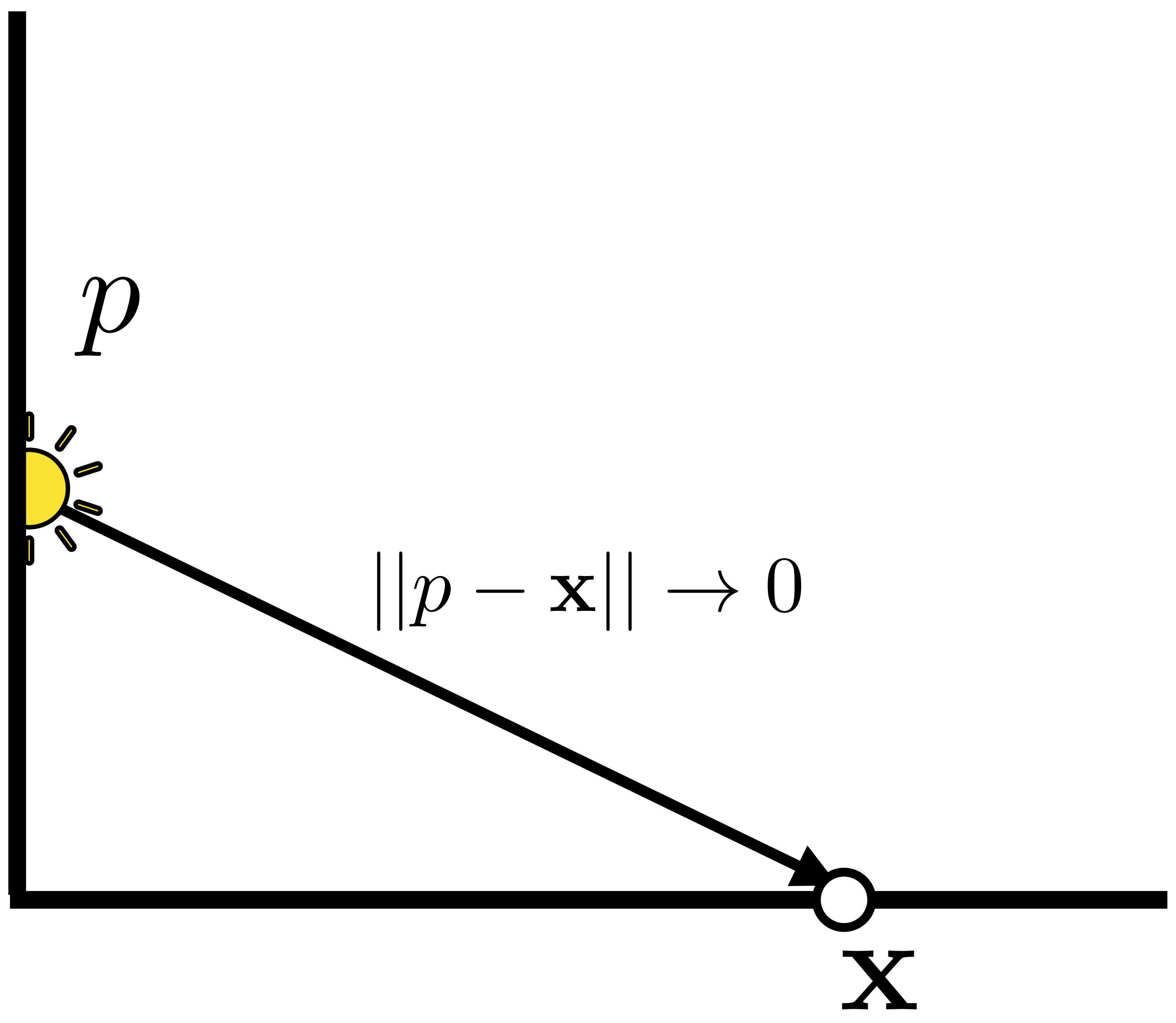
Hasan et al. 2009

VPL contribution affected by distance

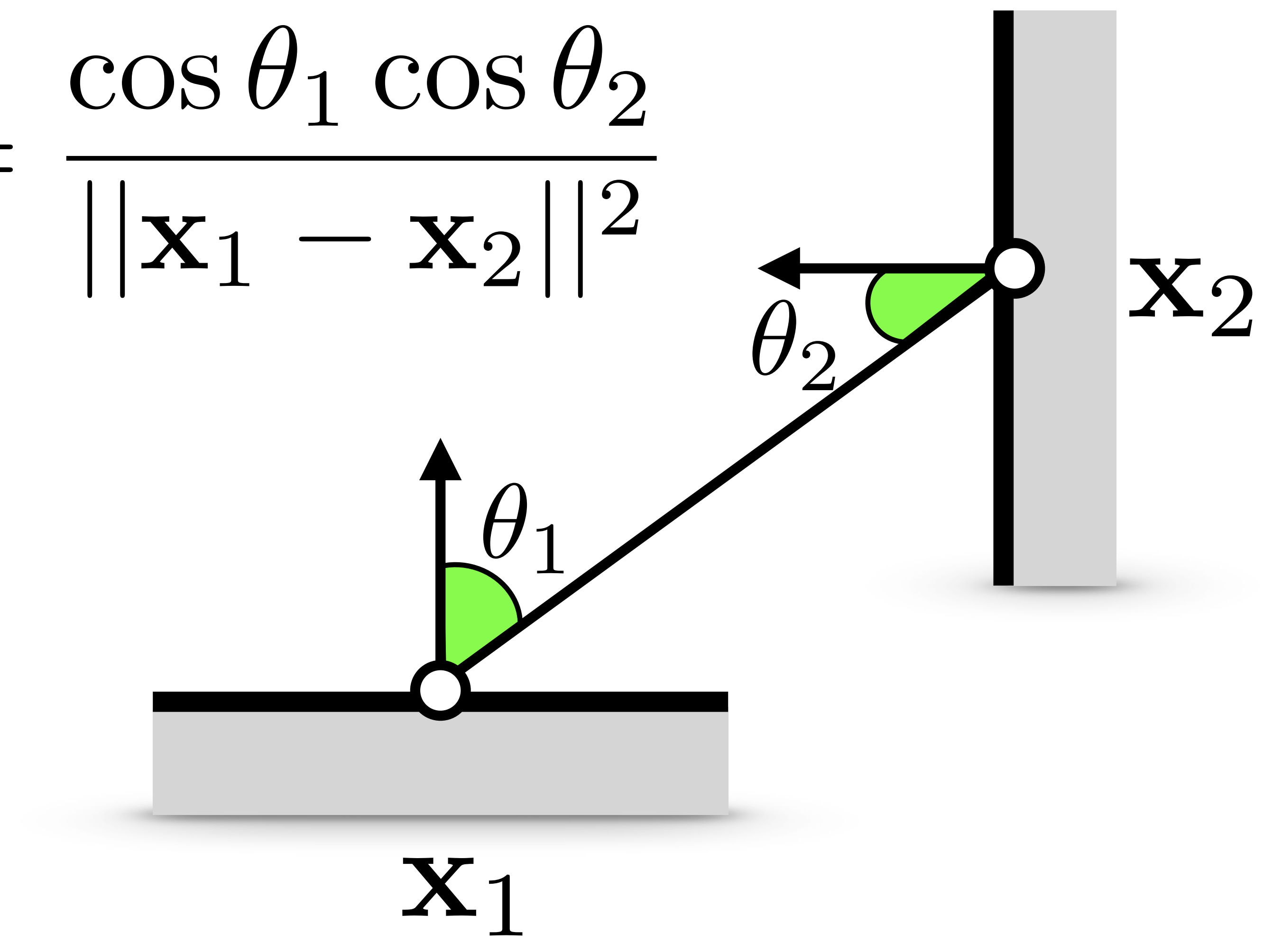


Hasan et al. 2009

VPL contribution affected by distance



$$G(\mathbf{x}_1, \mathbf{x}_2) = \frac{\cos\theta_1 \cos\theta_2}{||\mathbf{x}_1 - \mathbf{x}_2||^2}$$



Hasan et al. 2009

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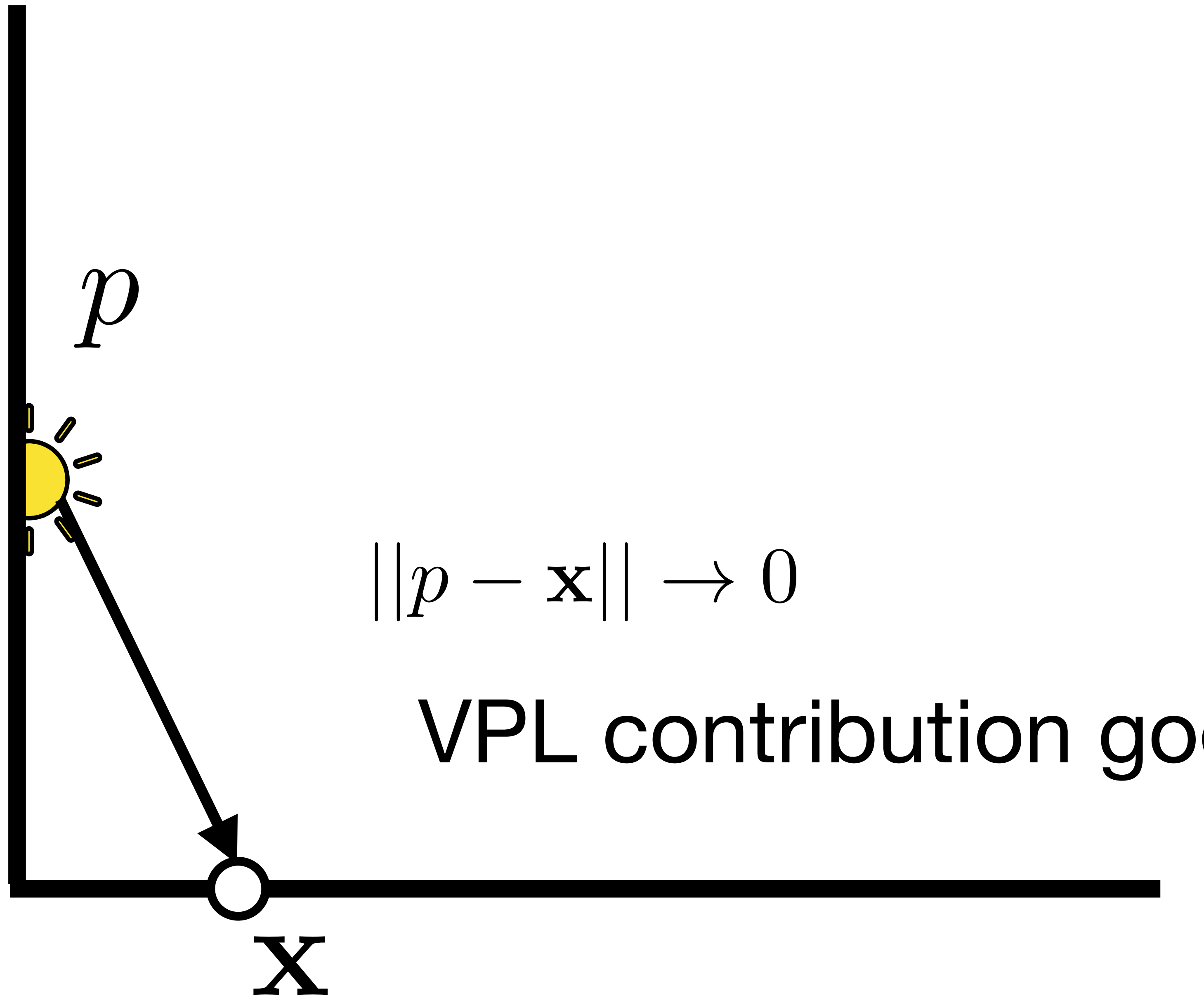
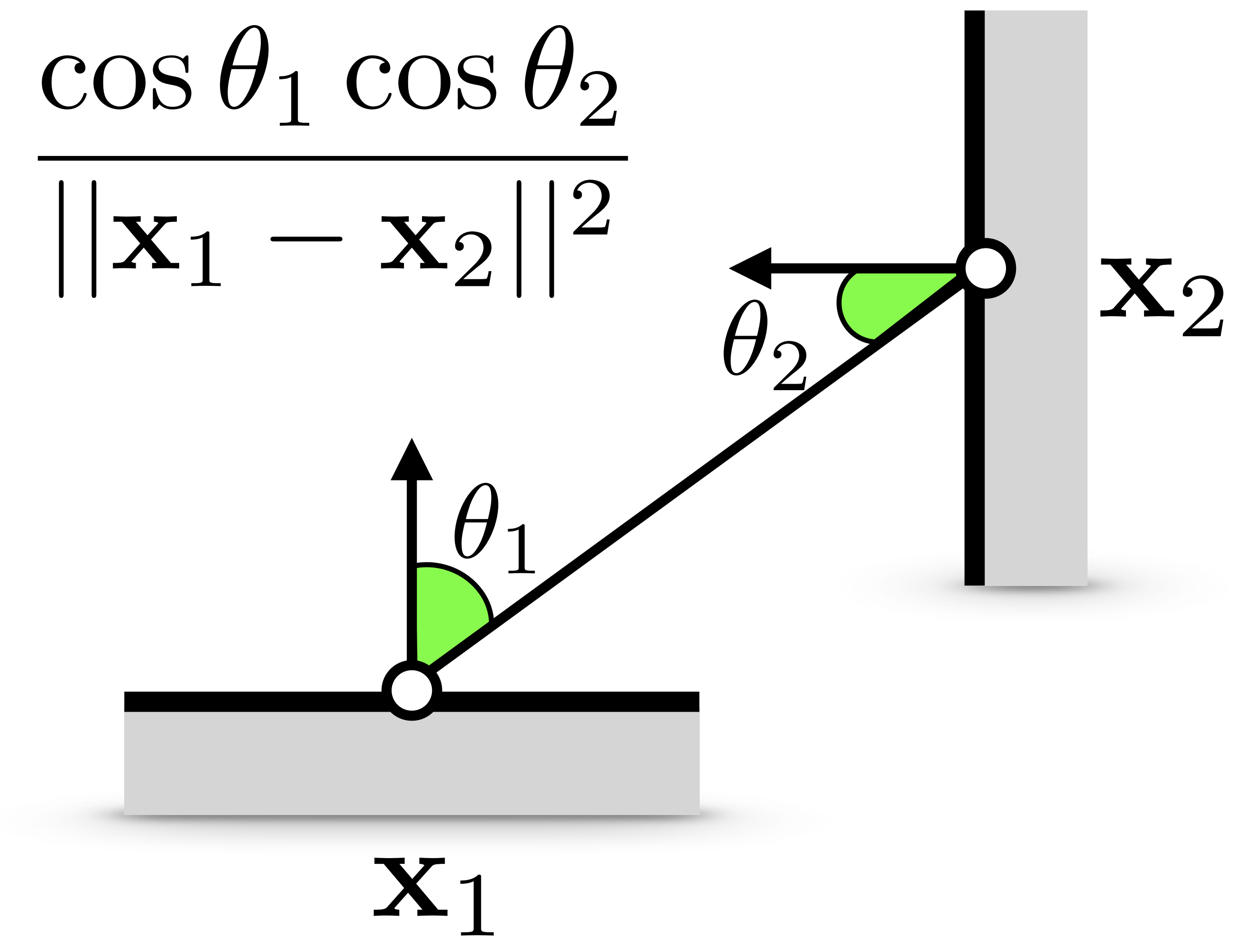


$||p - \mathbf{x}|| \to 0$

VPL contribution goes to ∞

Spike

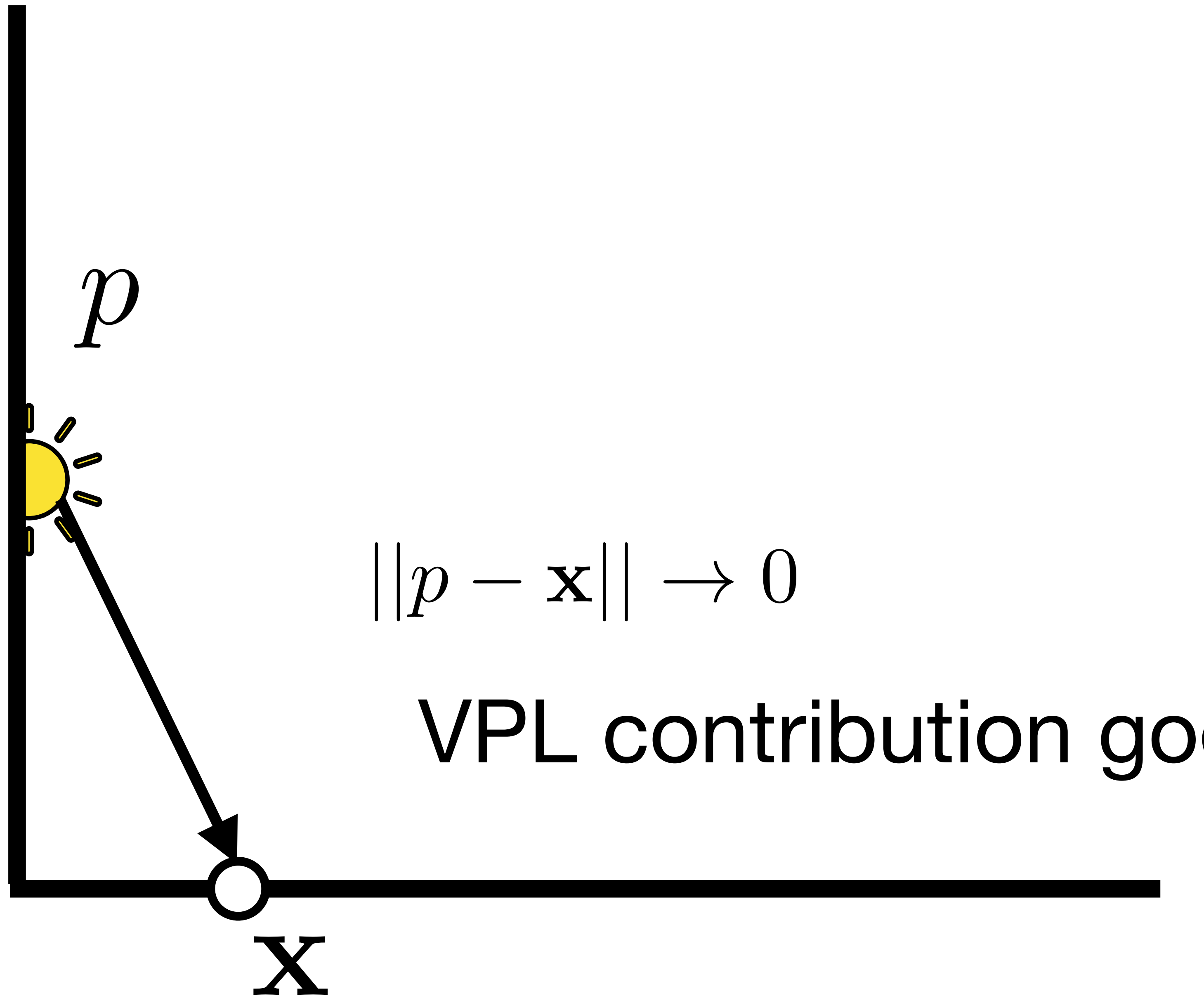
$$G(\mathbf{x}_1, \mathbf{x}_2) = \frac{\cos\theta_1 \cos\theta_2}{||\mathbf{x}_1 - \mathbf{x}_2||^2}$$



Hasan et al. 2009

VPL contribution affected by distance

Common solution: Clamp the VPL contribution



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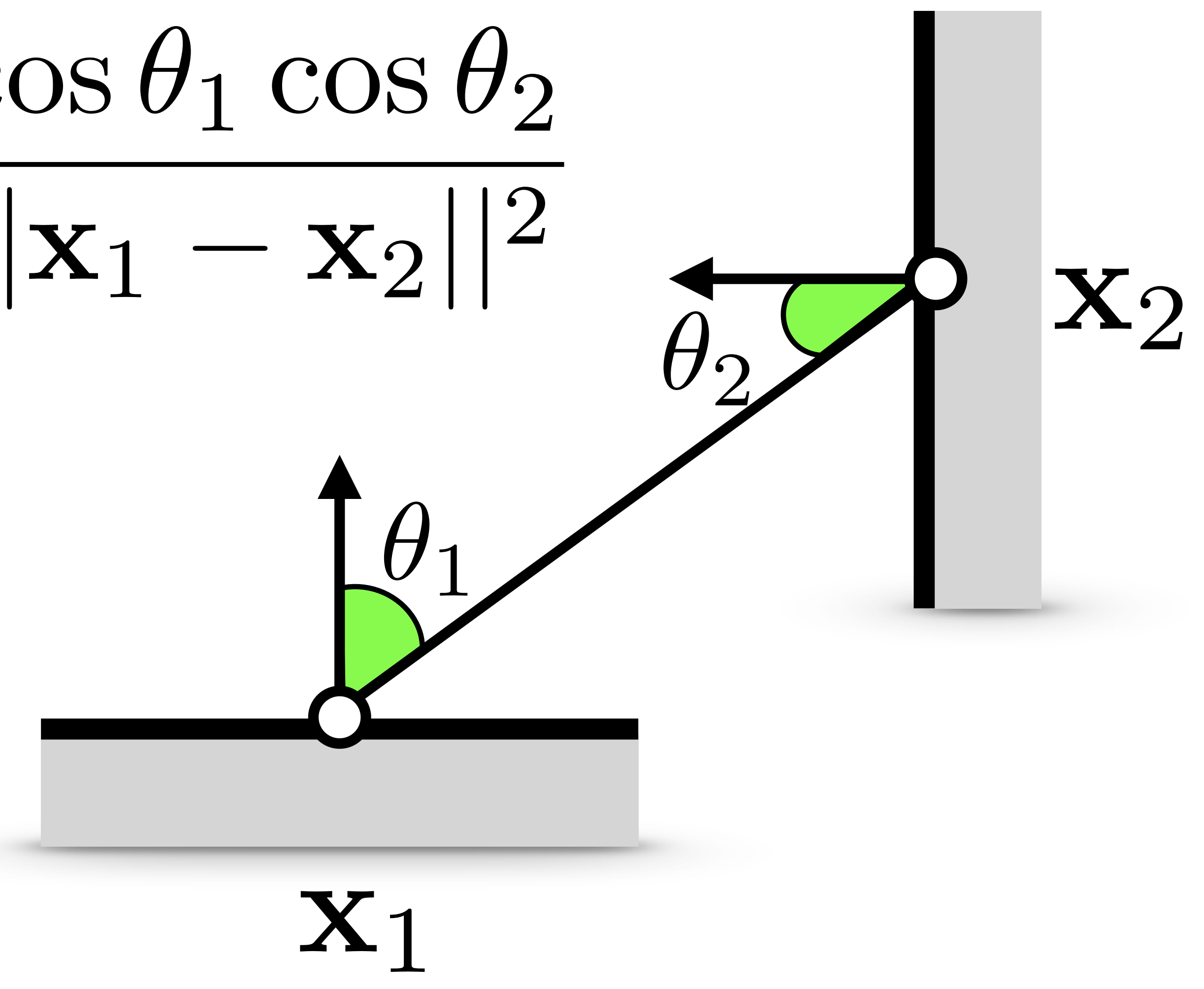
VPL contribution goes to ∞

Spike

$$G(\mathbf{x}_1, \mathbf{x}_2) = \frac{\cos\theta_1 \cos\theta_2}{||\mathbf{x}_1 - \mathbf{x}_2||^2}$$



Hasan et al. 2009

Motivation

VPLs: Image splotches due to

- Spikes in the VPL emission distribution
- $\dfrac{1}{||\mathbf{x}_1 - \mathbf{x}_2||^2}$ term

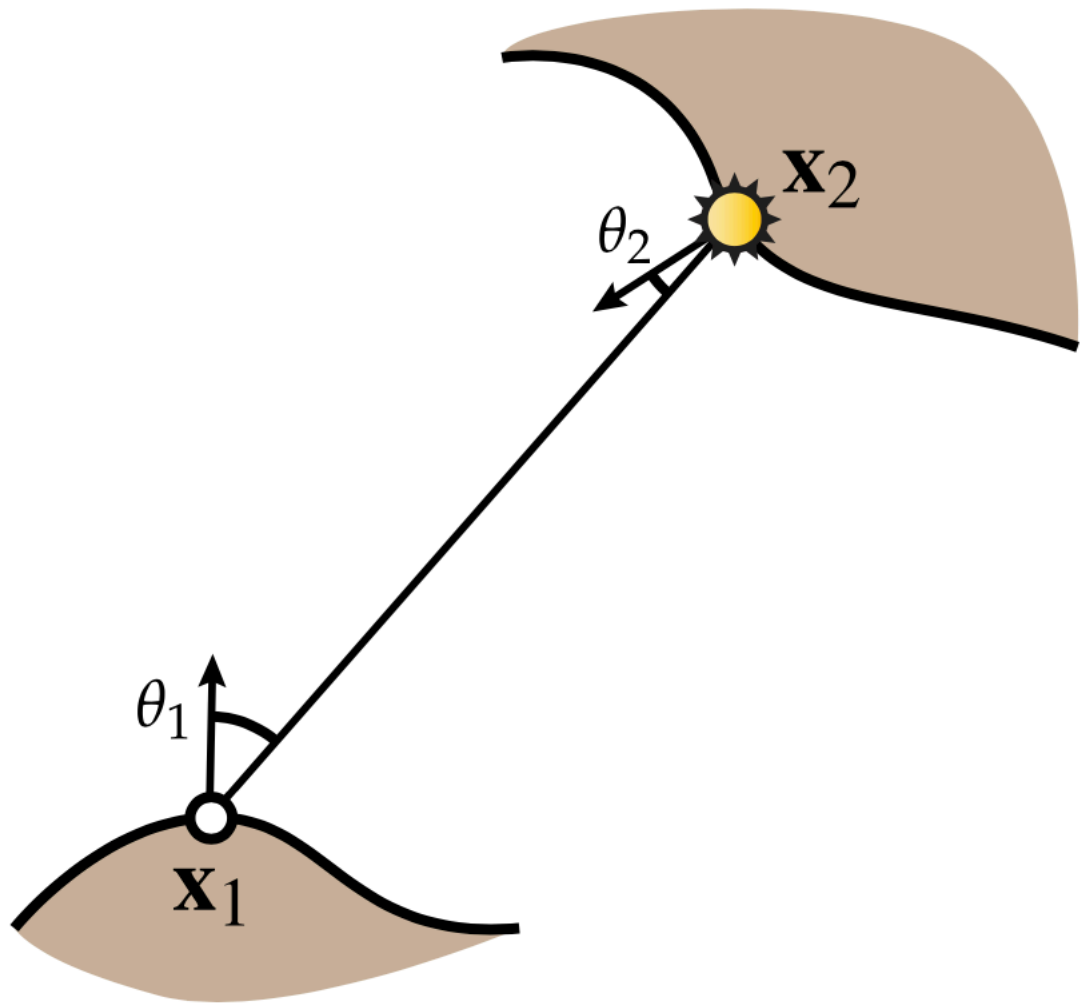
Virtual Spherical lights (VSL):

- Spread the energy of the infinitesimal VPL over a finite surface
- Computer contribution as a solid angle integral

Hasan et al. 2009

Spreading the Energy

Spread the energy of the infinitesimal VPL over a finite surface



Hasan et al. 2009

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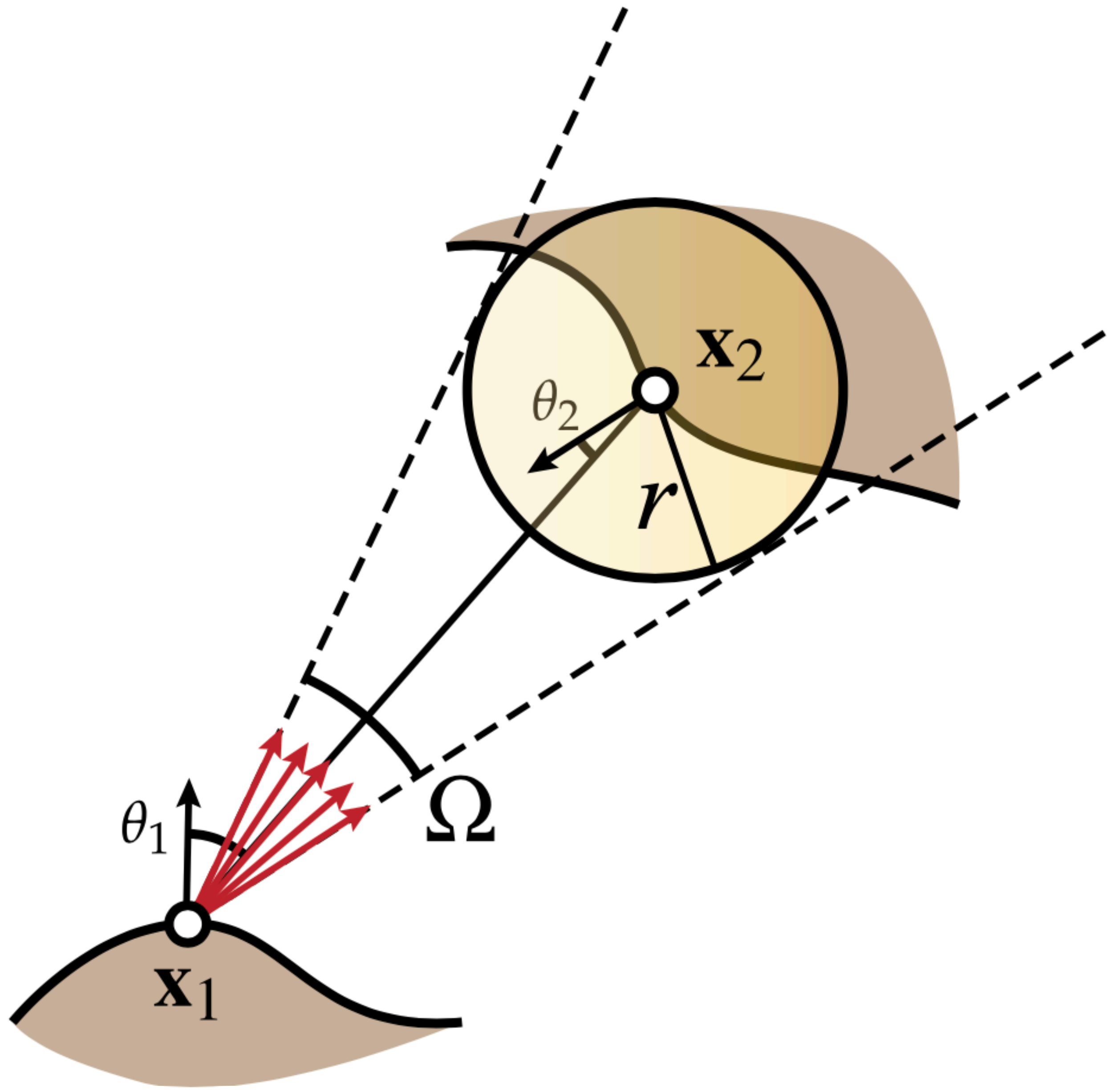
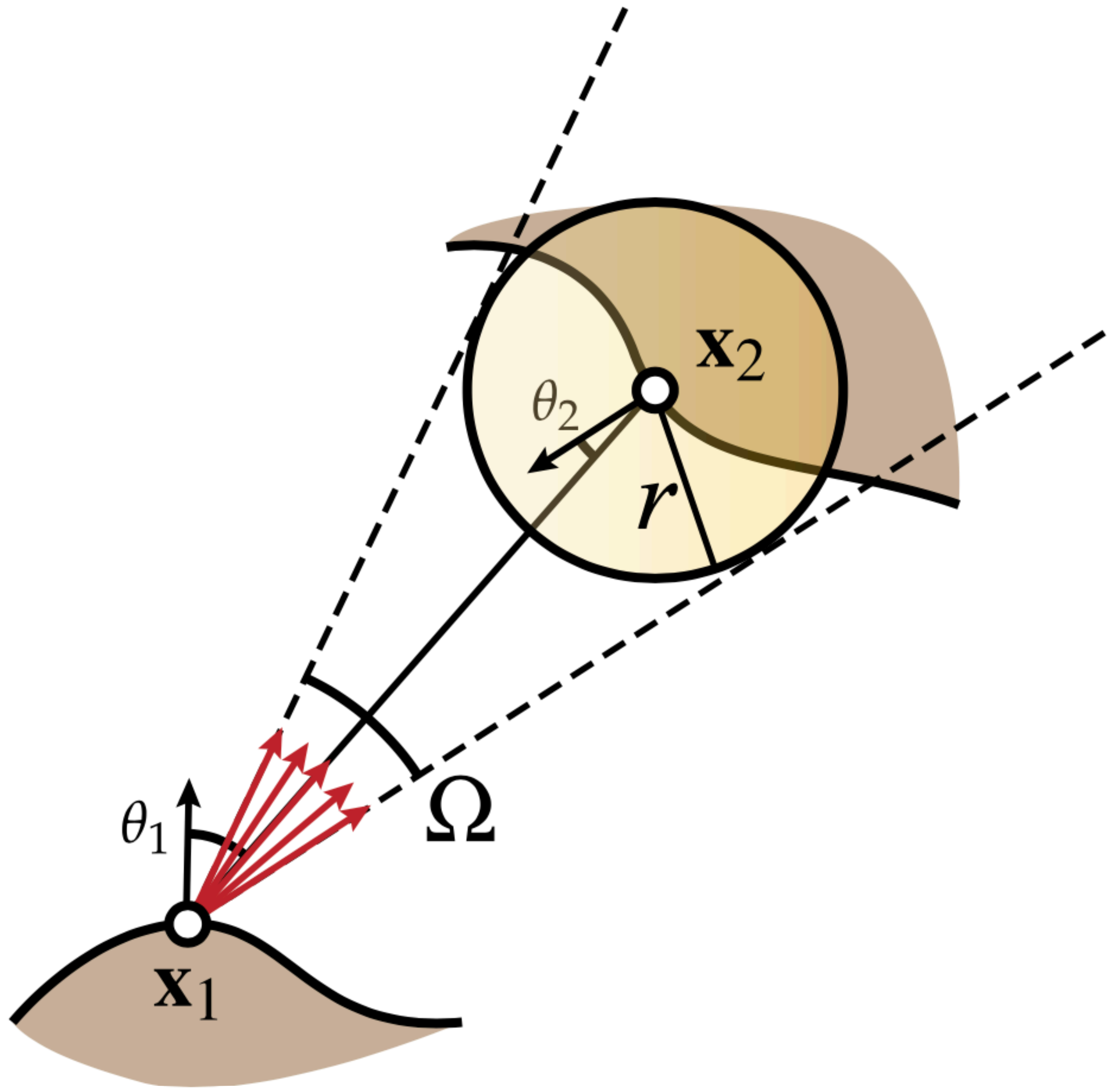


Hasan et al. 2009

Spreading the Energy

Spread the energy of the infinitesimal VPL over a finite surface

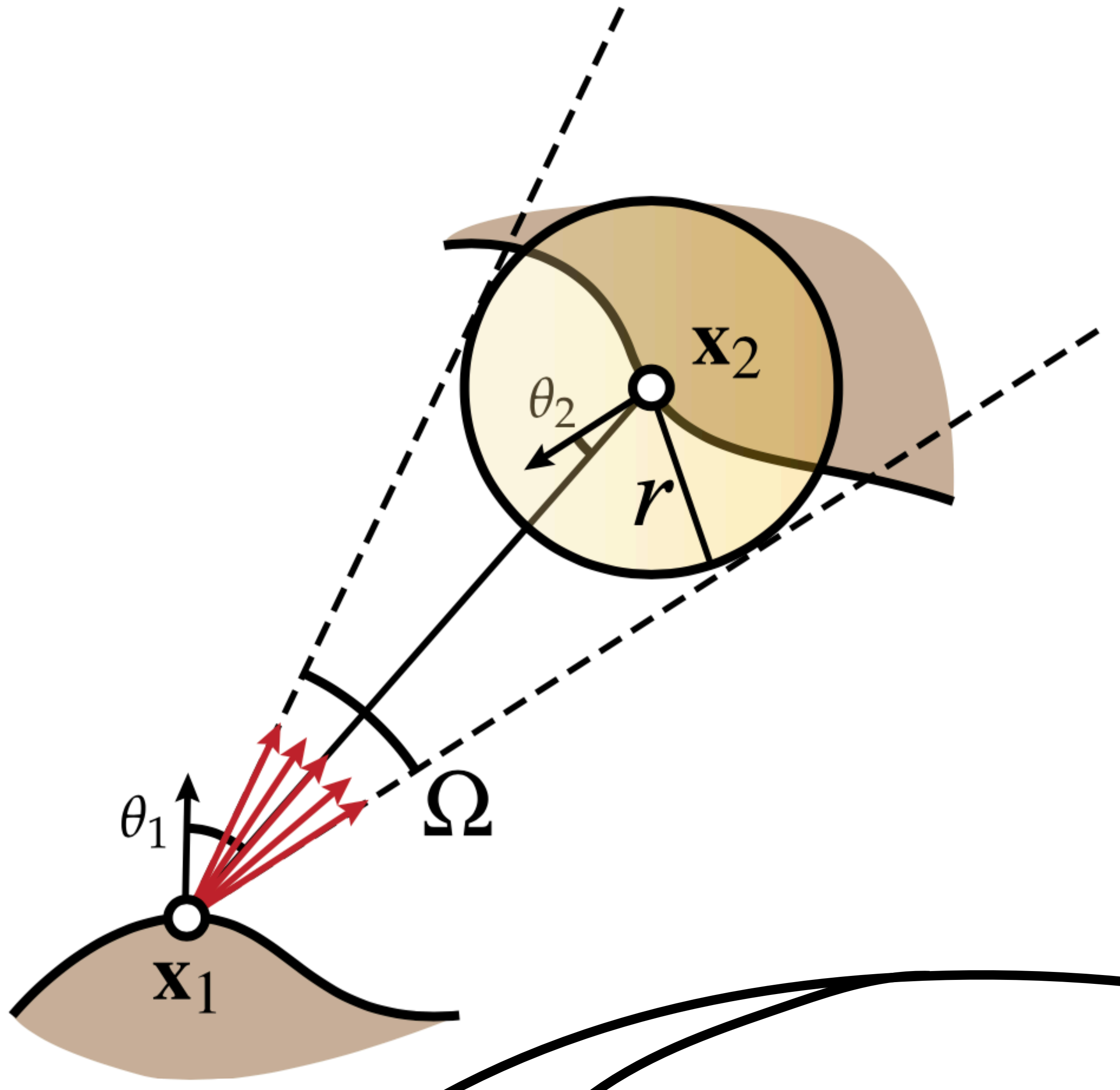


point-to-point: $$\Phi\, V(\mathbf{x}_1, \mathbf{x}_2) f(\mathbf{x}_1) f(\mathbf{x}_2) \frac{\cos\theta_1 \cos\theta_2}{||\mathbf{x}_1 - \mathbf{x}_2||^2}$$

Hasan et al. 2009

Spreading the Energy

Spread the energy of the infinitesimal VPL over a finite surface



Splotches!

point-to-point: $$\Phi\, V(\mathbf{x}_1, \mathbf{x}_2) f(\mathbf{x}_1) f(\mathbf{x}_2) \frac{\cos\theta_1 \cos\theta_2}{||\mathbf{x}_1 - \mathbf{x}_2||^2}$$

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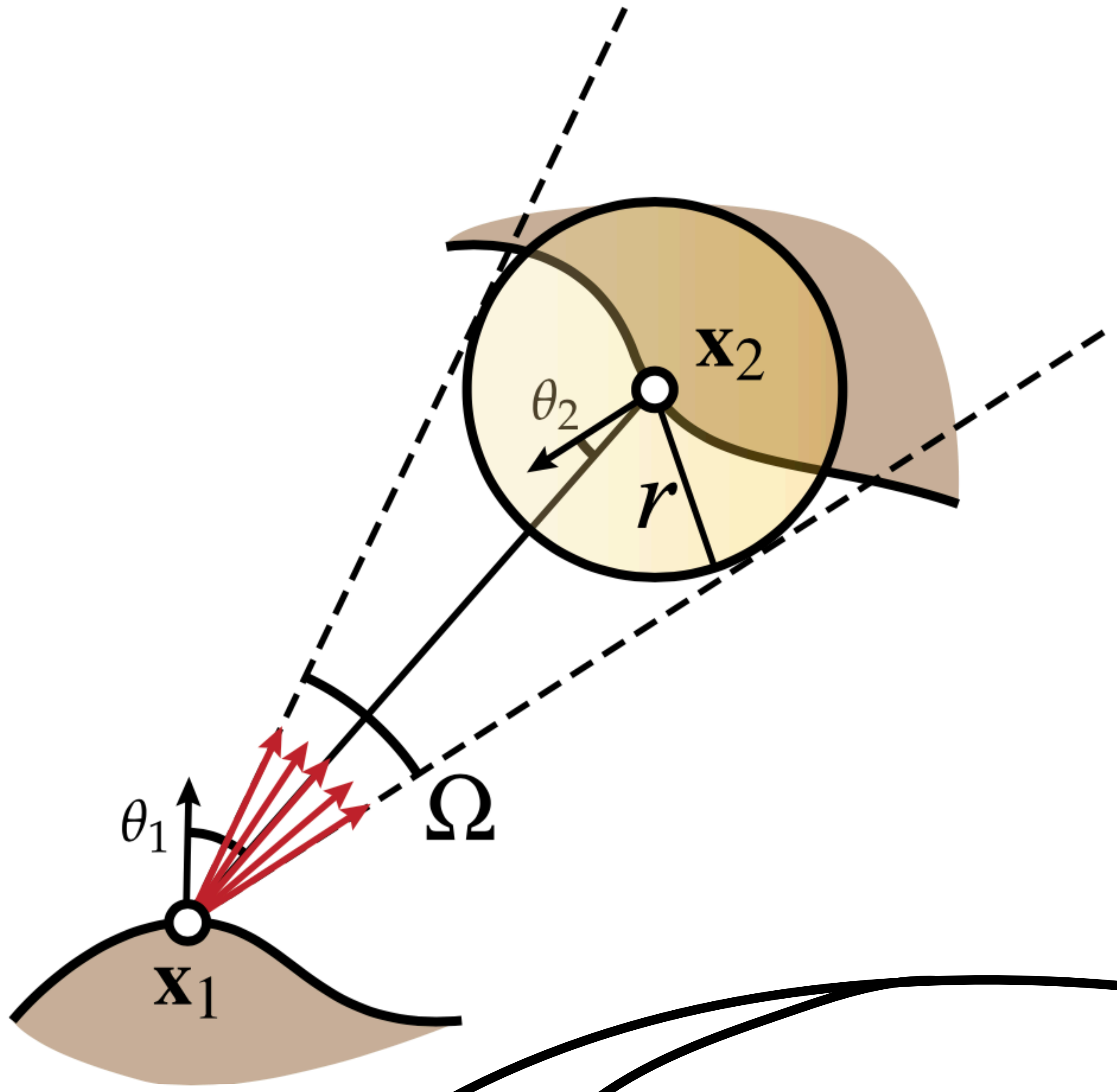


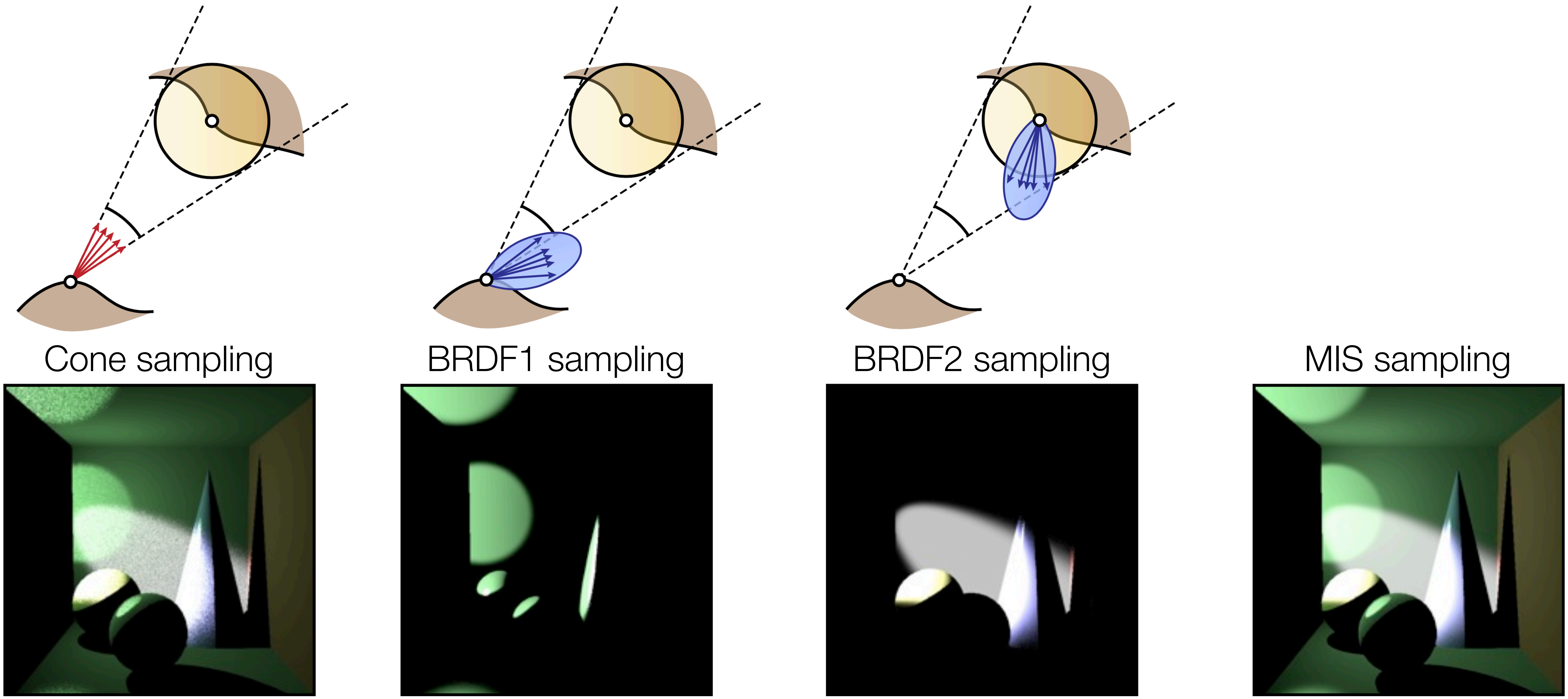
Splotches!

point-to-point: $$\Phi\, V(\mathbf{x}_1, \mathbf{x}_2) f(\mathbf{x}_1) f(\mathbf{x}_2) \frac{\cos\theta_1 \cos\theta_2}{||\mathbf{x}_1 - \mathbf{x}_2||^2}$$

Approx. sphere-to-point: $$\frac{\Phi}{\pi r^2} V(\mathbf{x}_1, \mathbf{x}_2) \int_{\mathcal{H}^2} f(\mathbf{x}_1) f(\mathbf{x}_2) \cos\theta_1 \cos\theta_2 d\vec{\omega}$$

Hasan et al. 2009

Spreading the Energy



Hasan et al. 2009

Spreading the Energy

Advantages:

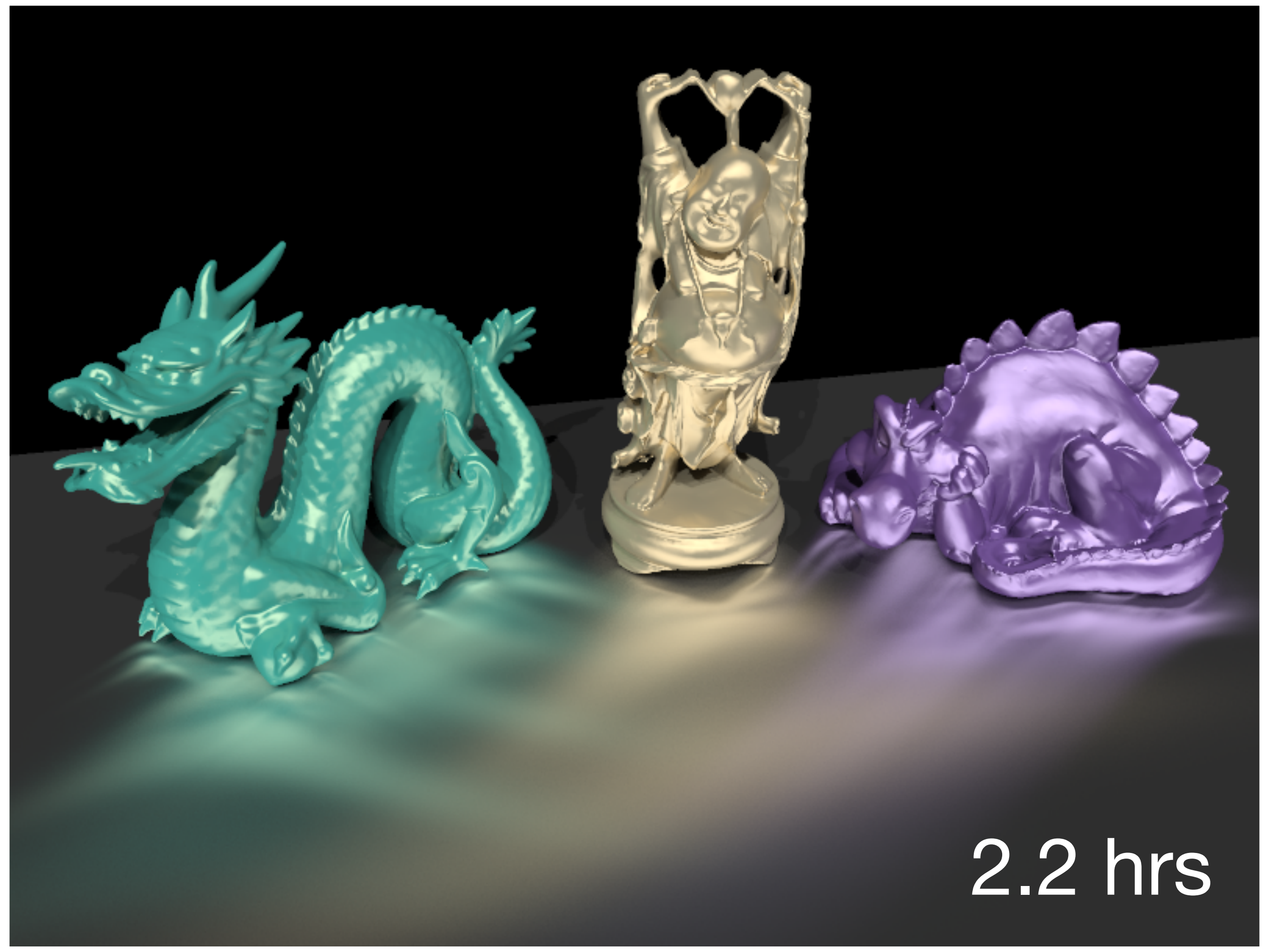
- Energy is blurred, not clamped

Disadvantages:

- Introduces bias
- Requires an extra integration over the solid angle

Hasan et al. 2009

Spreading the Energy



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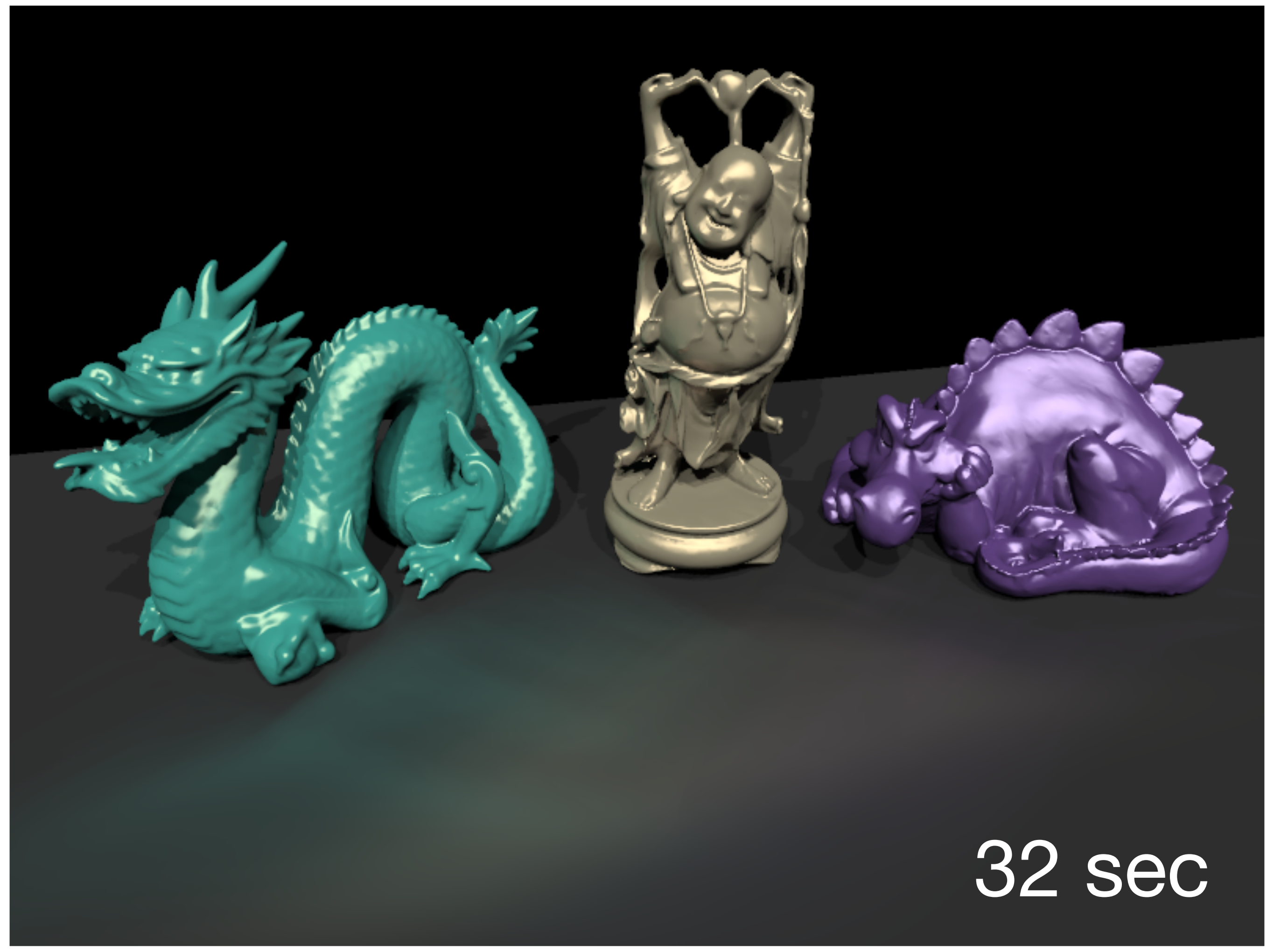
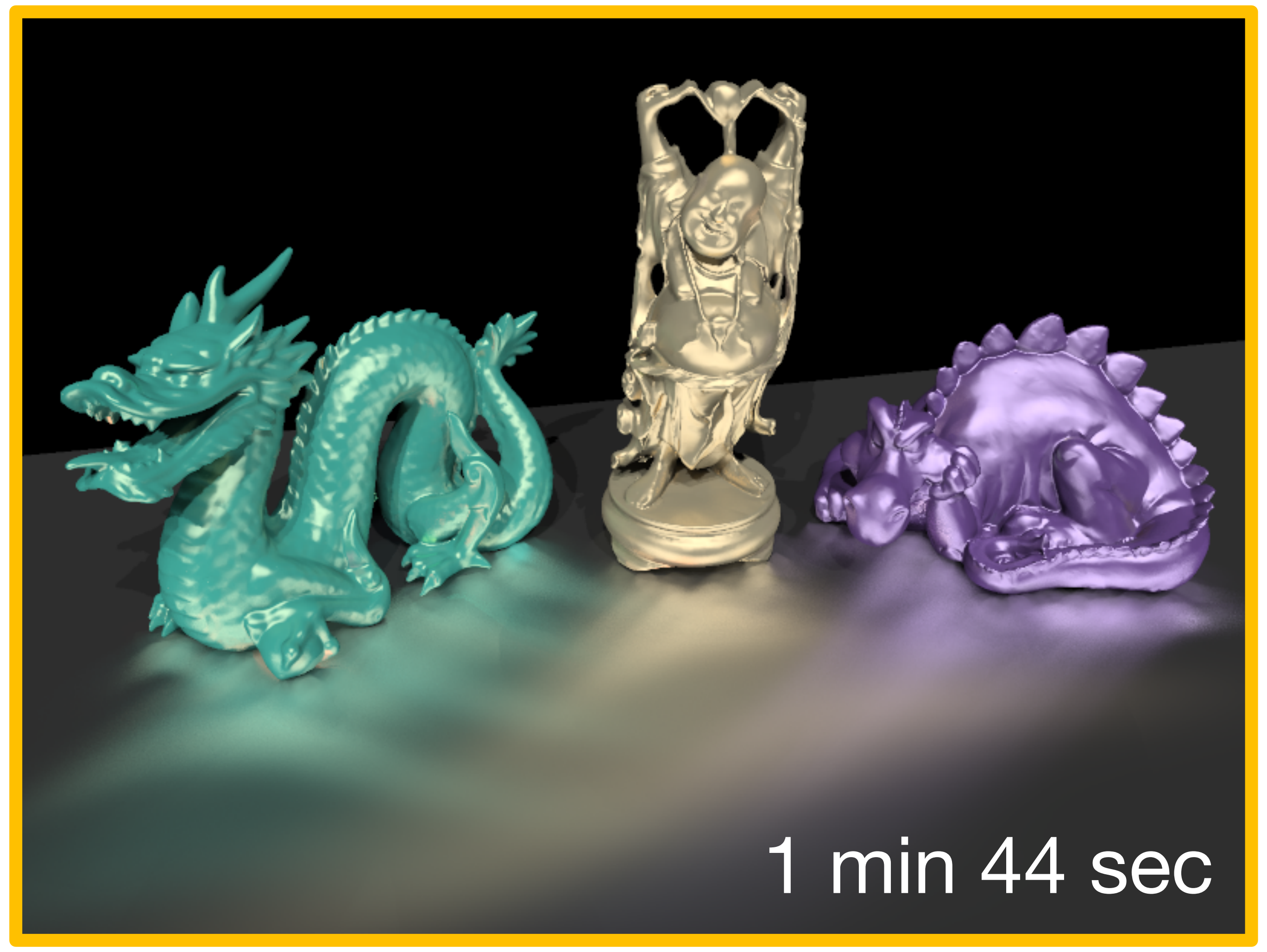


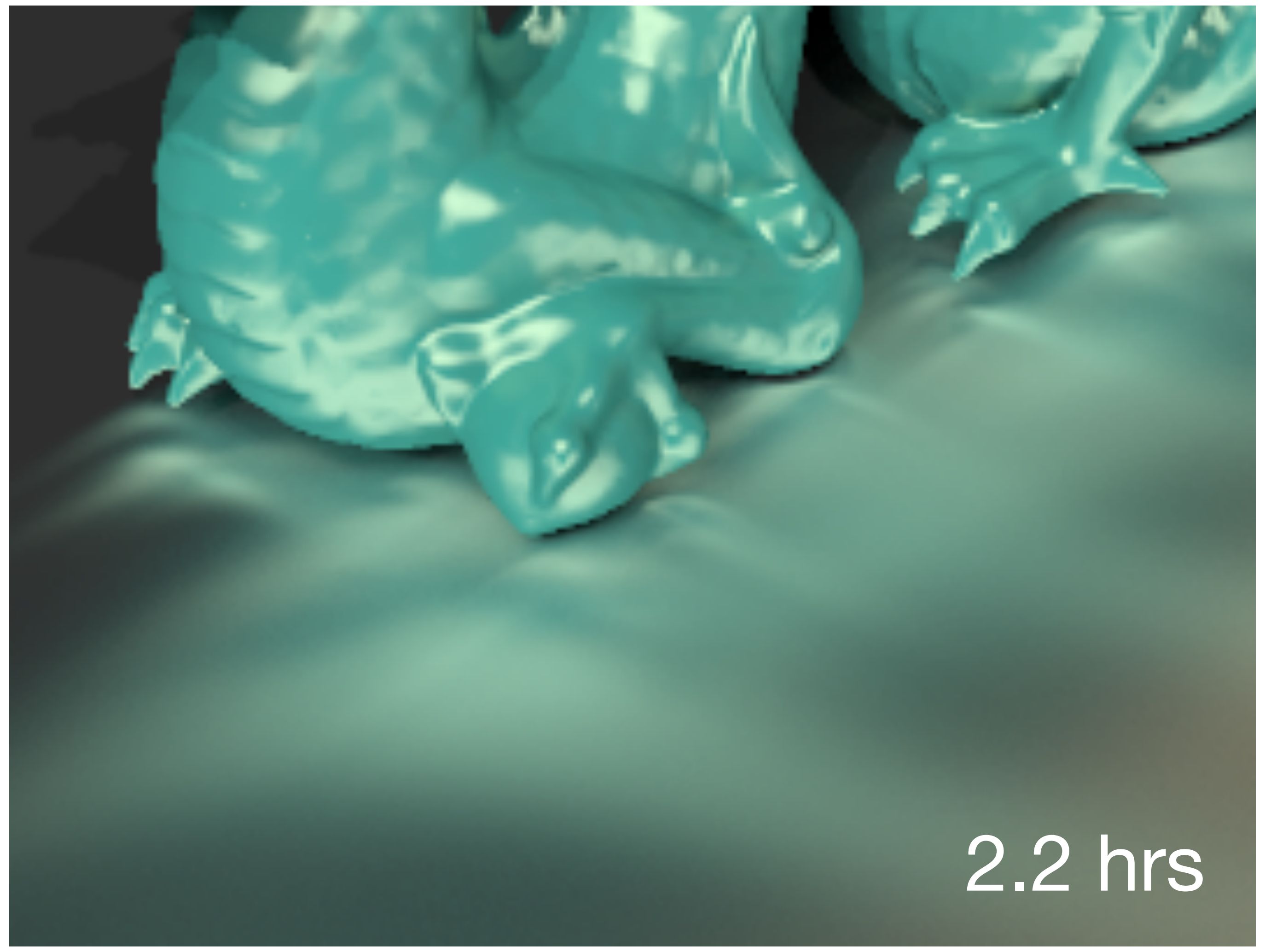
Clamped



VSLs

Hasan et al. 2009

Spreading the Energy



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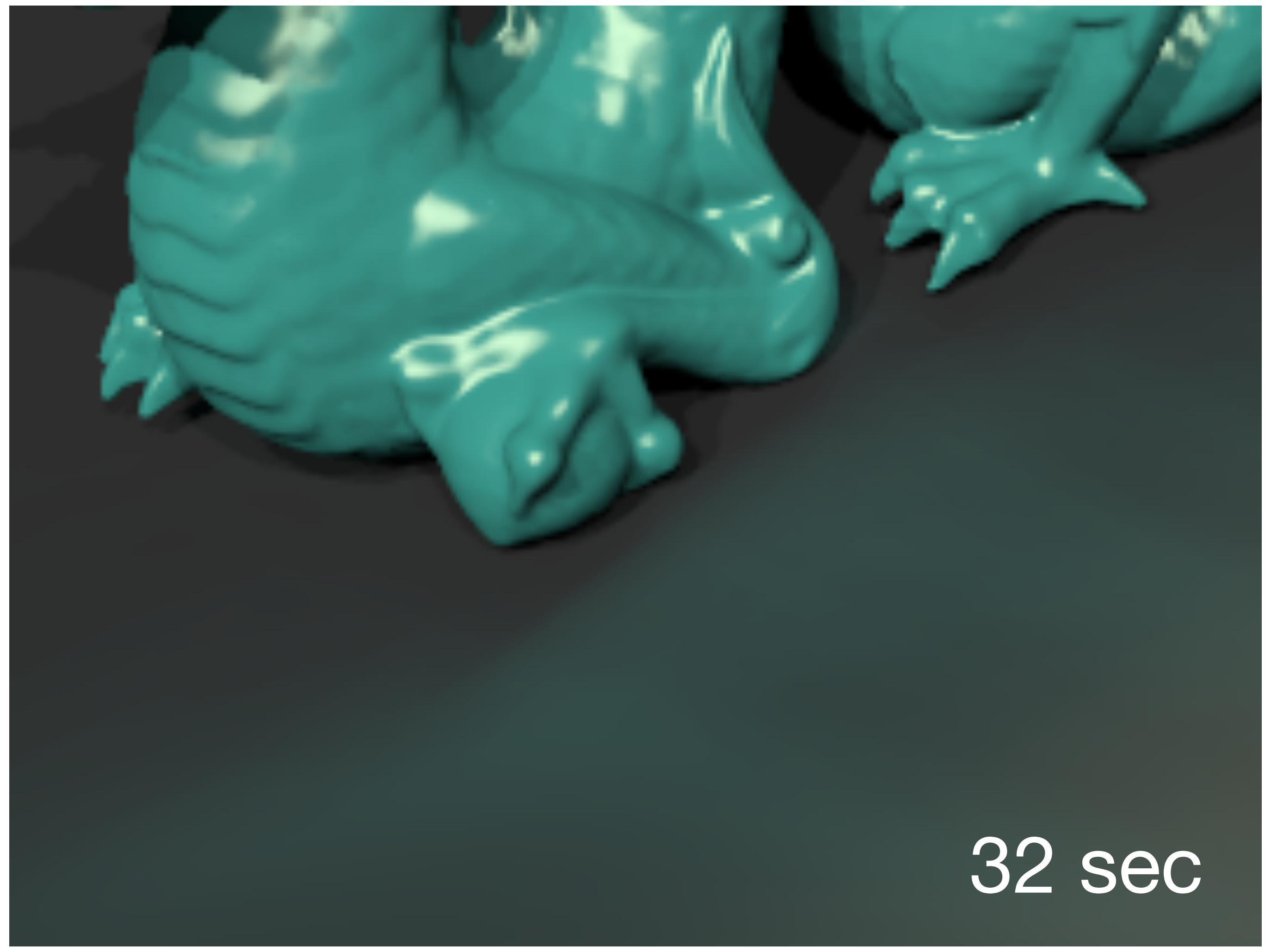

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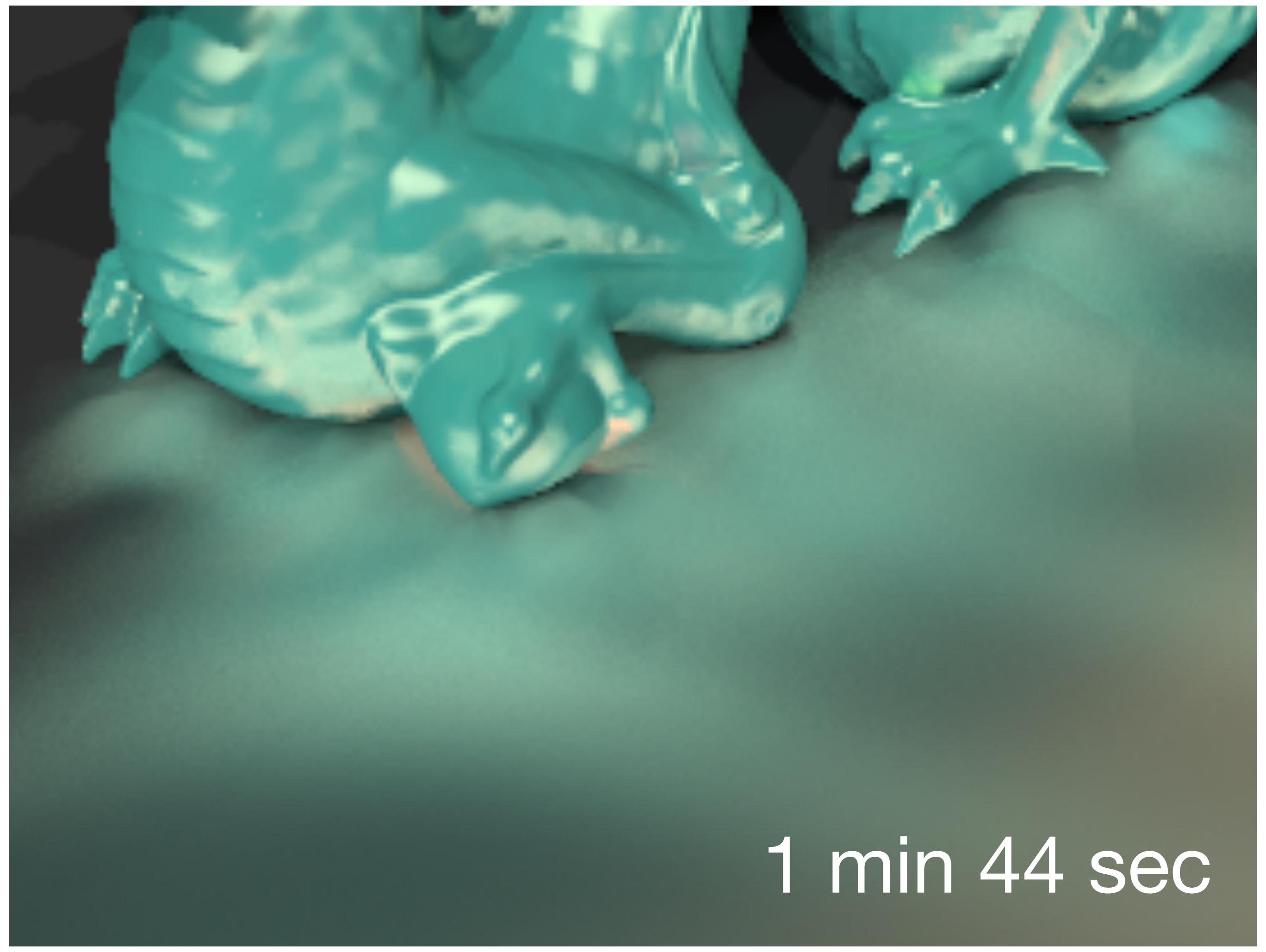


VSLs

Hasan et al. 2009

Virtual Ray Lights

Novak et al. 2012

Motivation

Motivation

Motivation

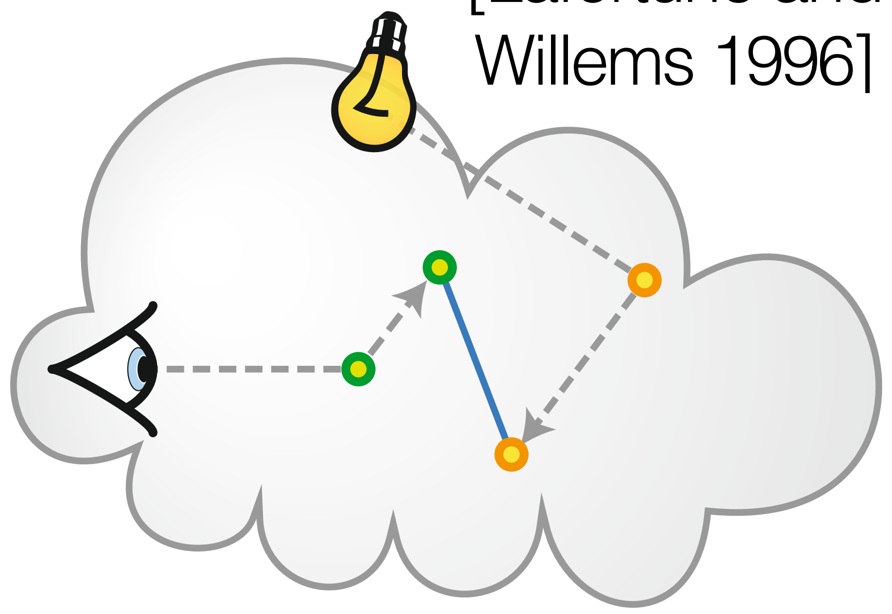
Motivation

Motivation

Previous work

Bidirectional Path Tracing

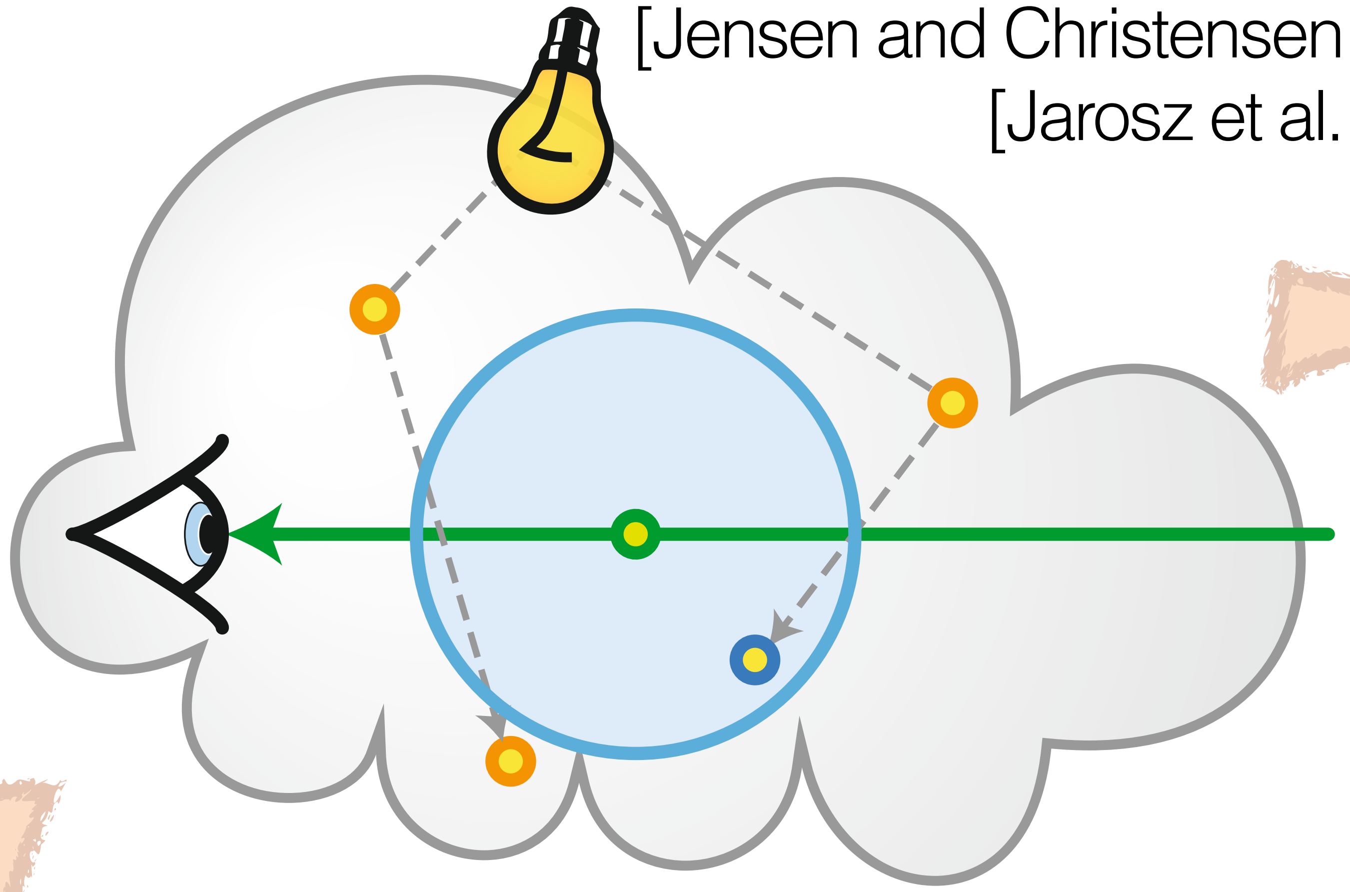
[Lafortune and Willems 1996]



Previous work

Volumetric Photon Mapping

[Jensen and Christensen 1998]
[Jarosz et al. 2008]



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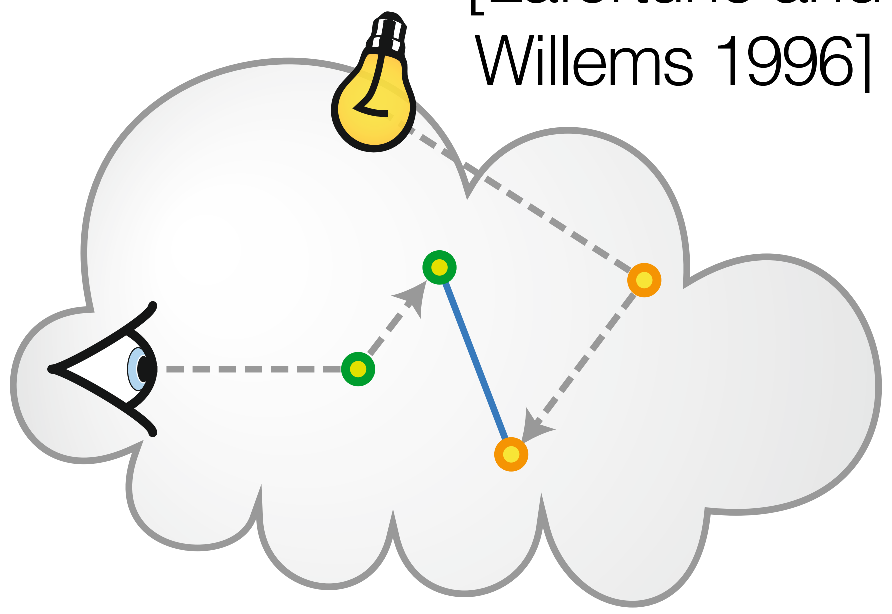

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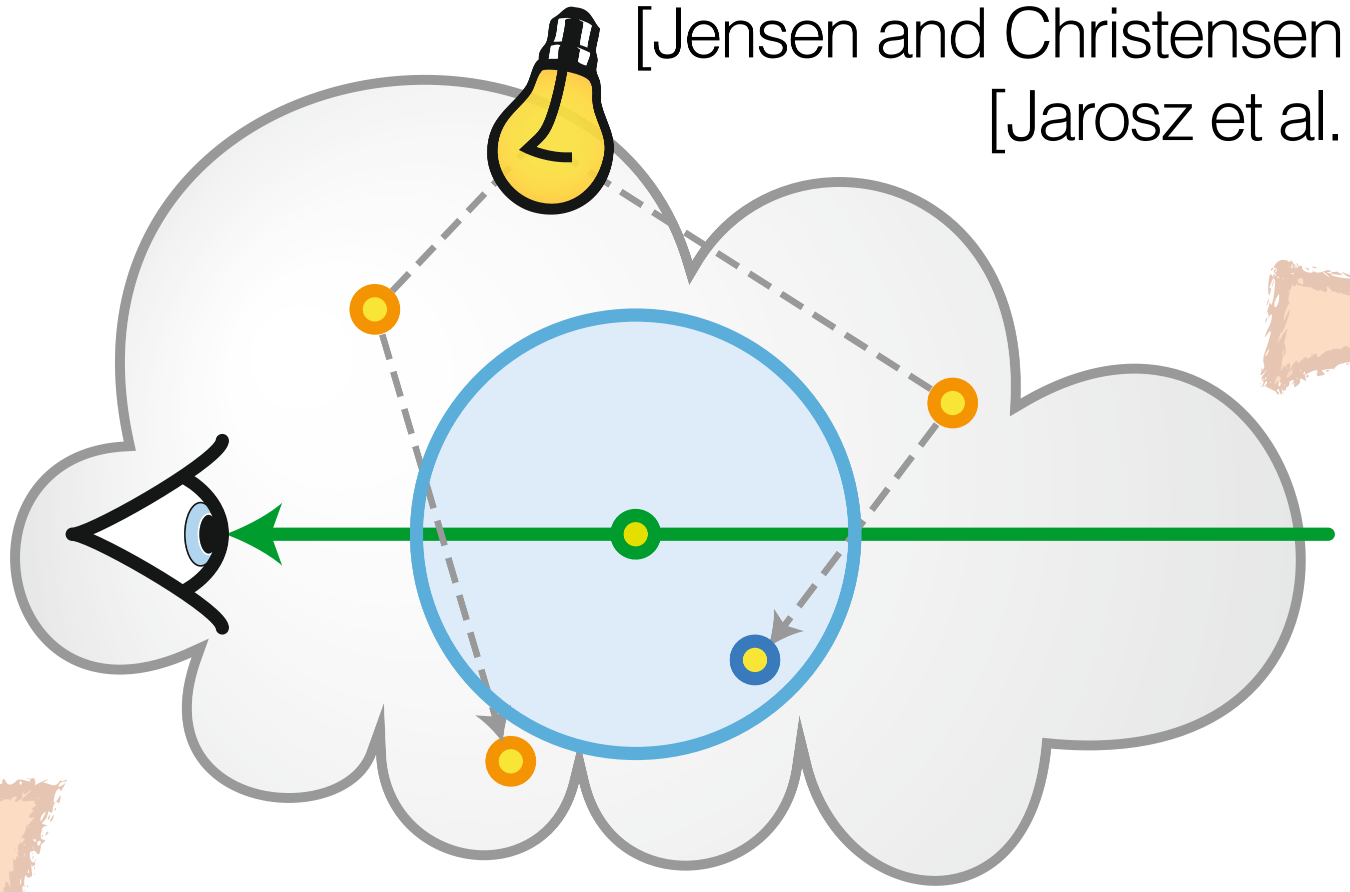

requires a lot of photons

Bidirectional Path Tracing

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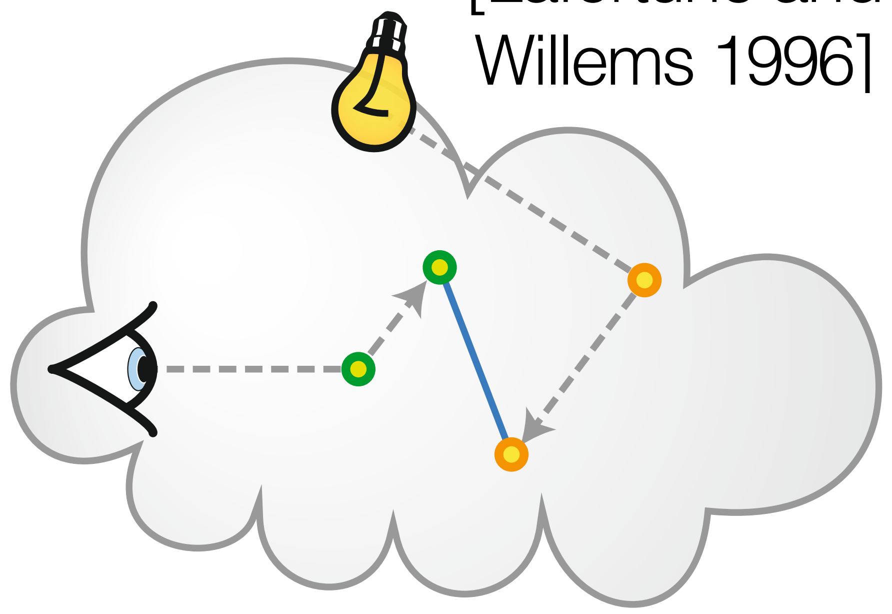

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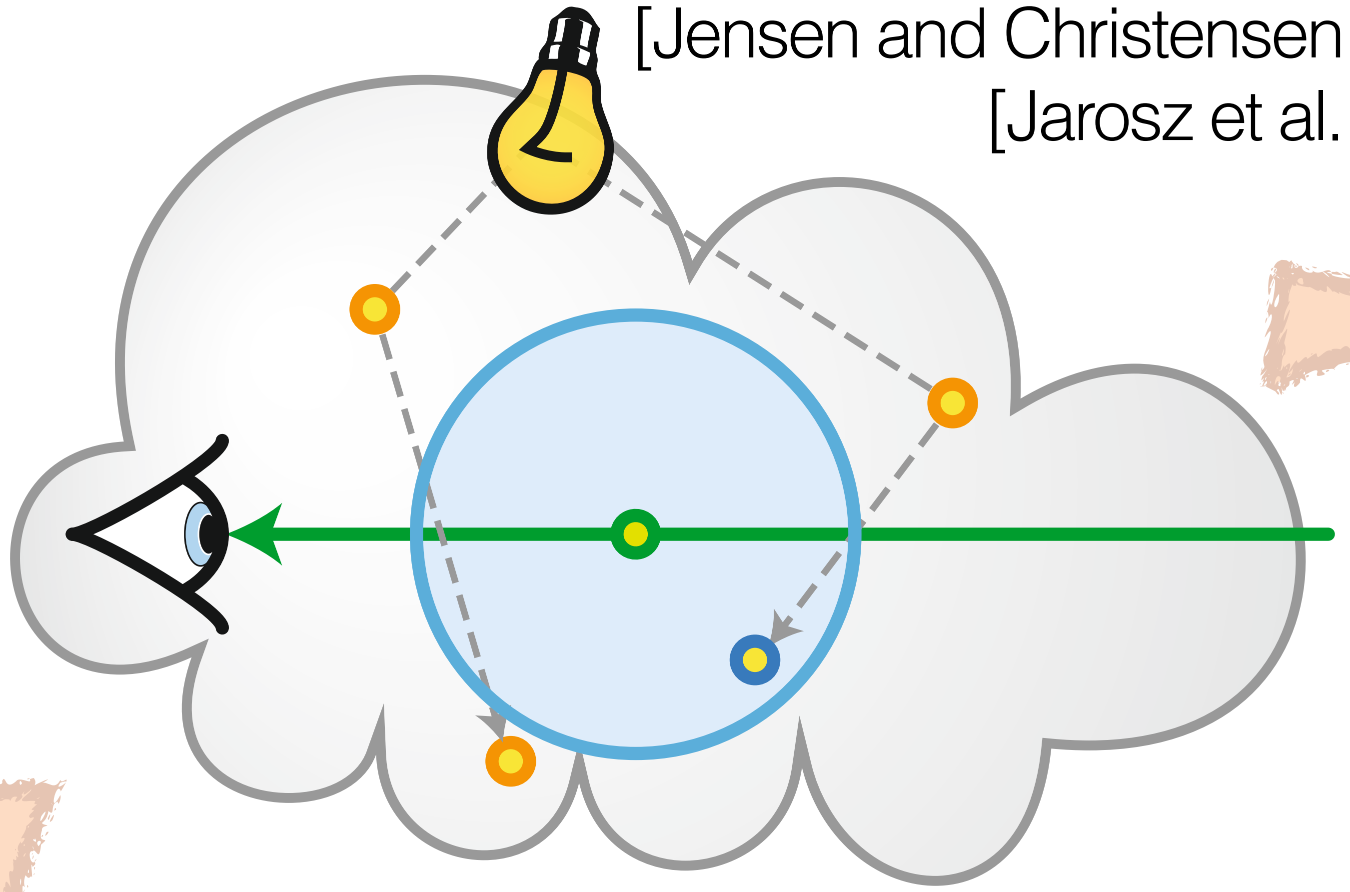
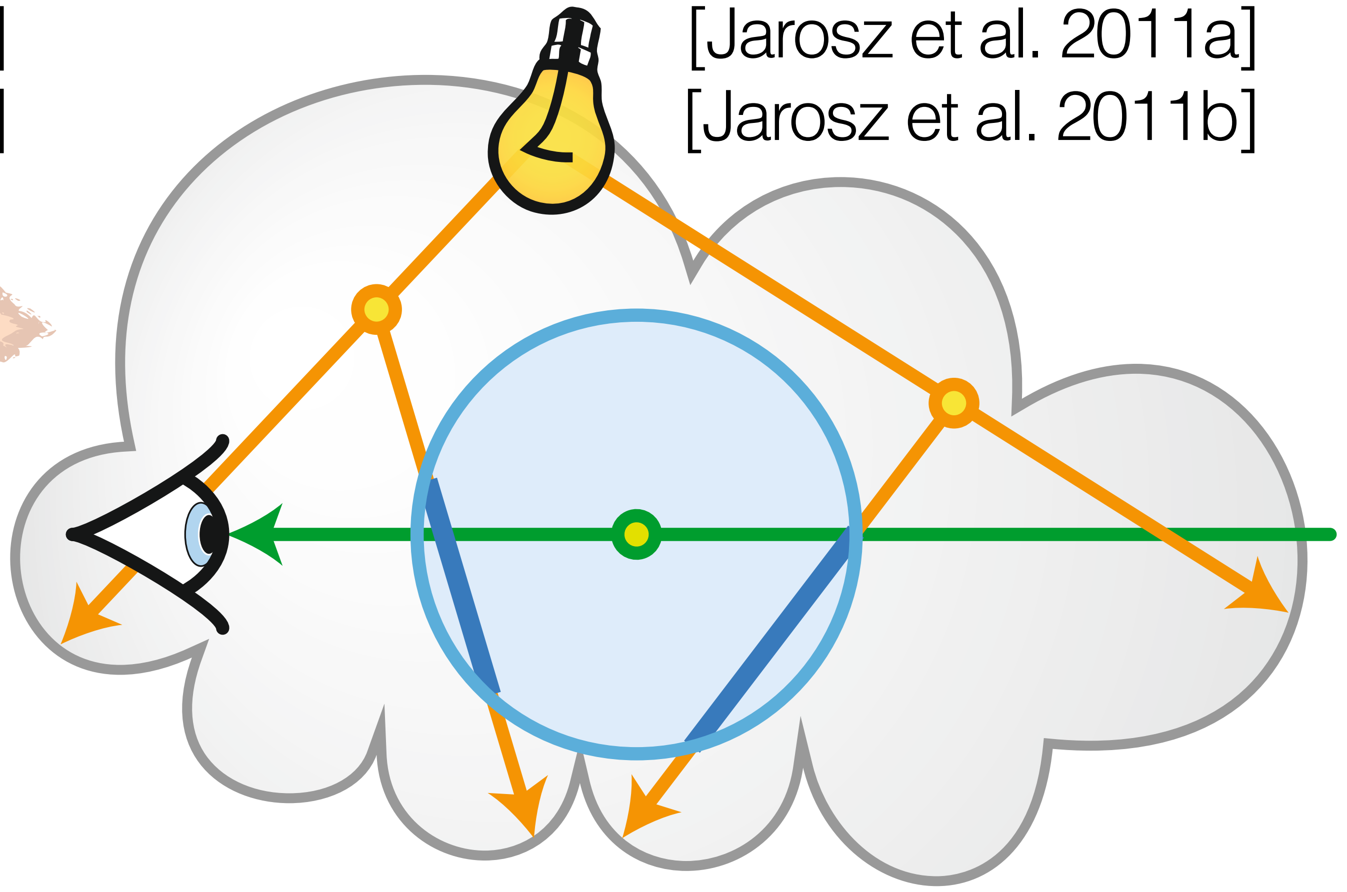


requires a lot of photons

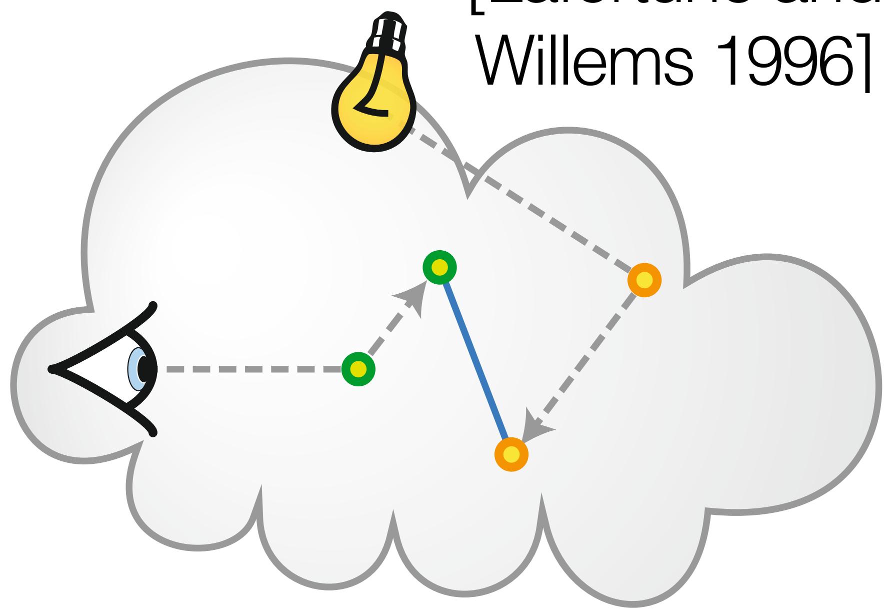
Photon Beams

[Jarosz et al. 2011a]
[Jarosz et al. 2011b]



Bidirectional Path Tracing

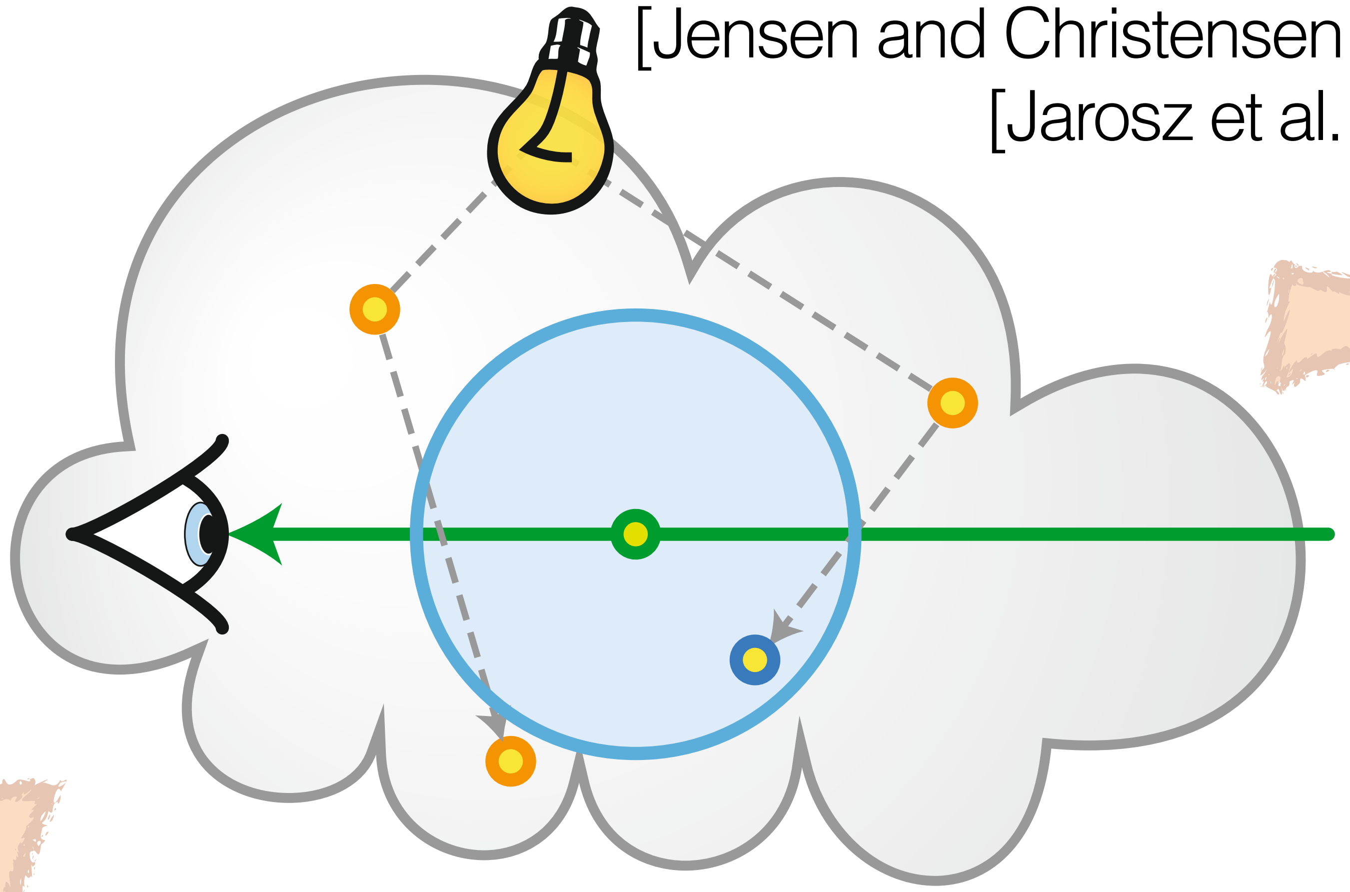
[Lafortune and Willems 1996]



Previous work

Volumetric Photon Mapping

[Jensen and Christensen 1998]
[Jarosz et al. 2008]



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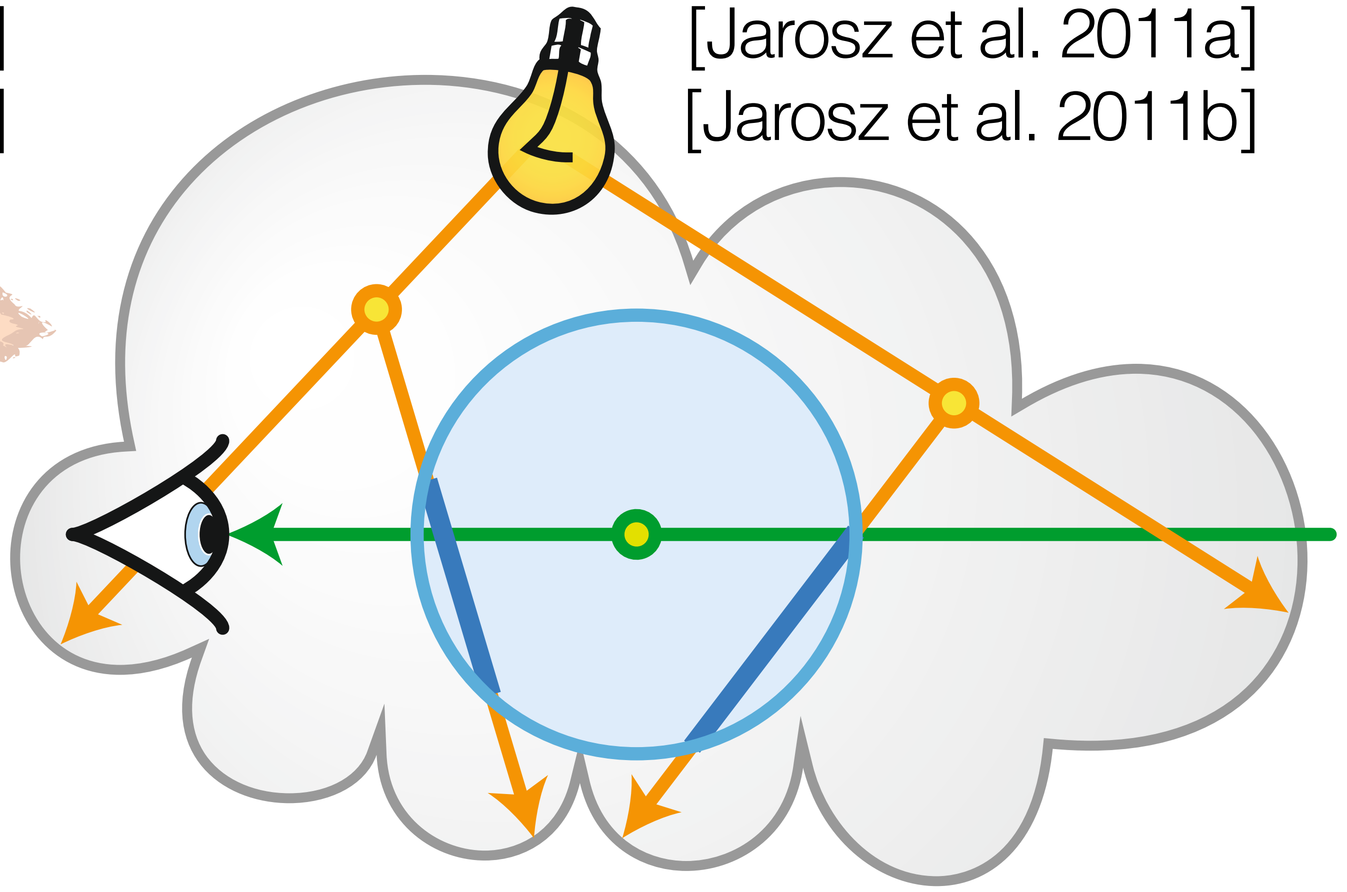

great caustics,
MS not so...

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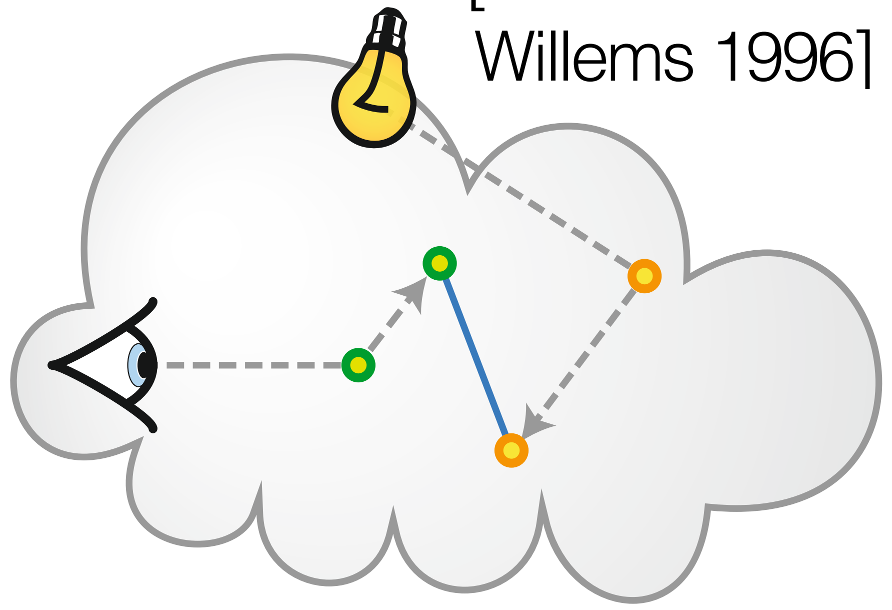

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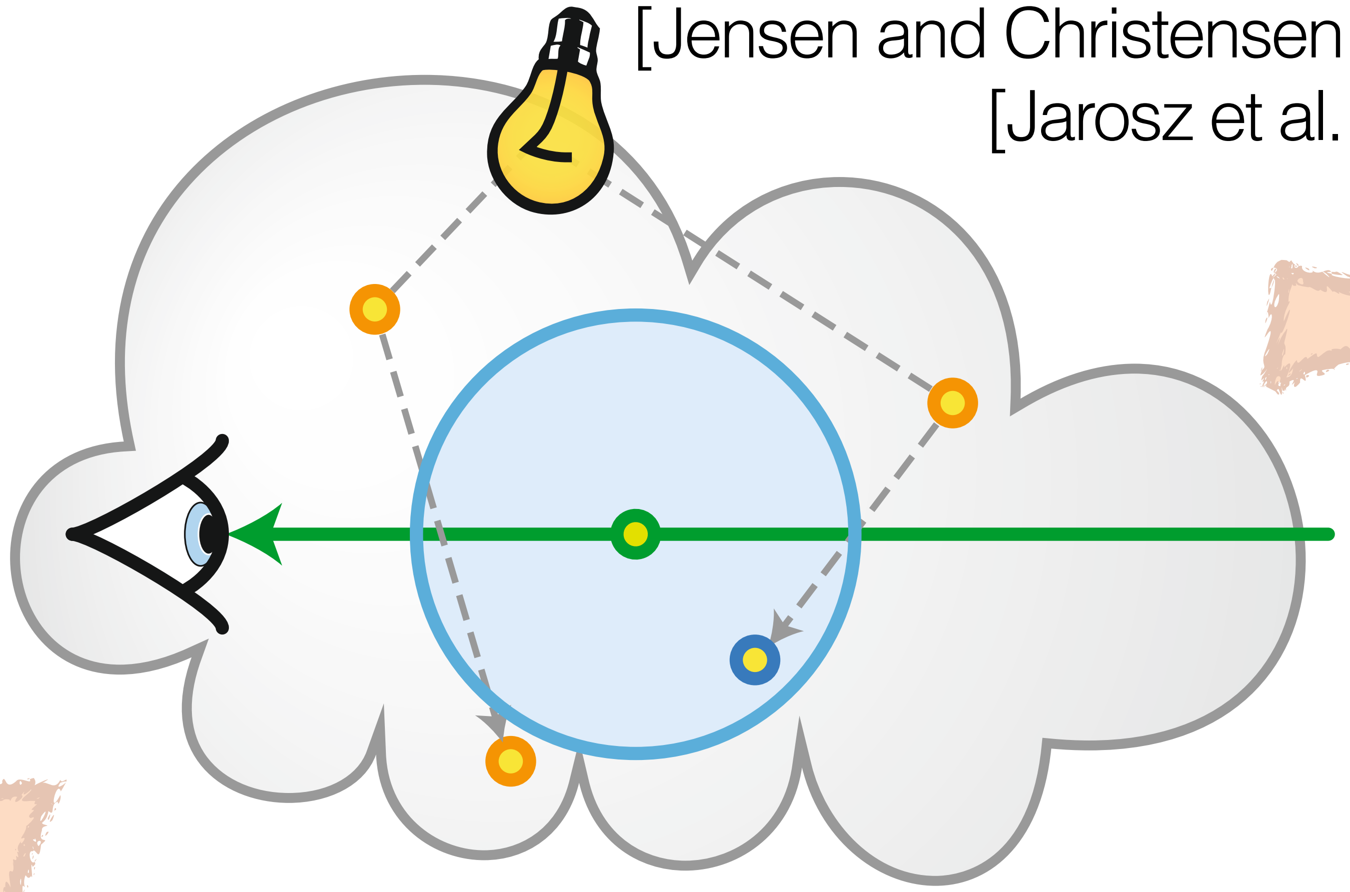

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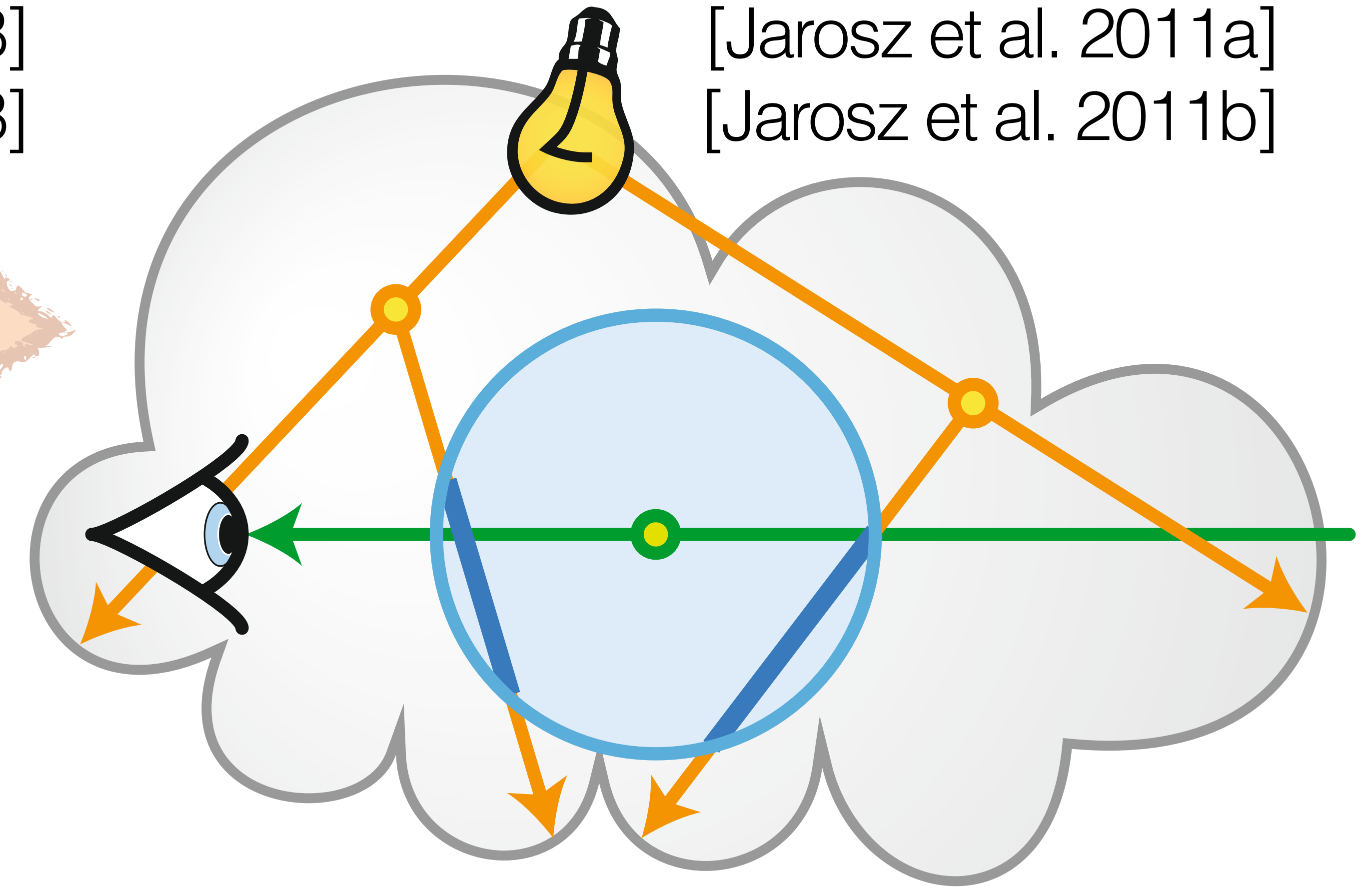

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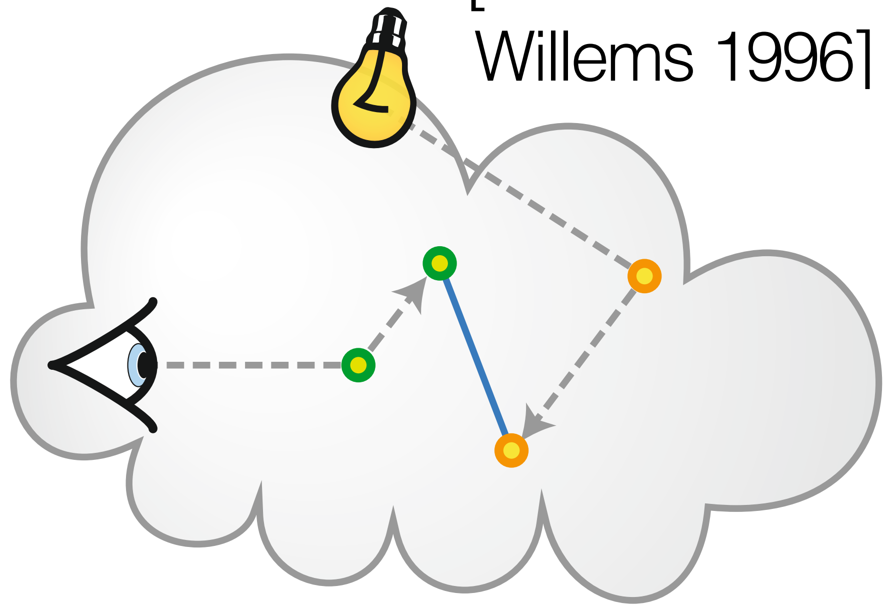
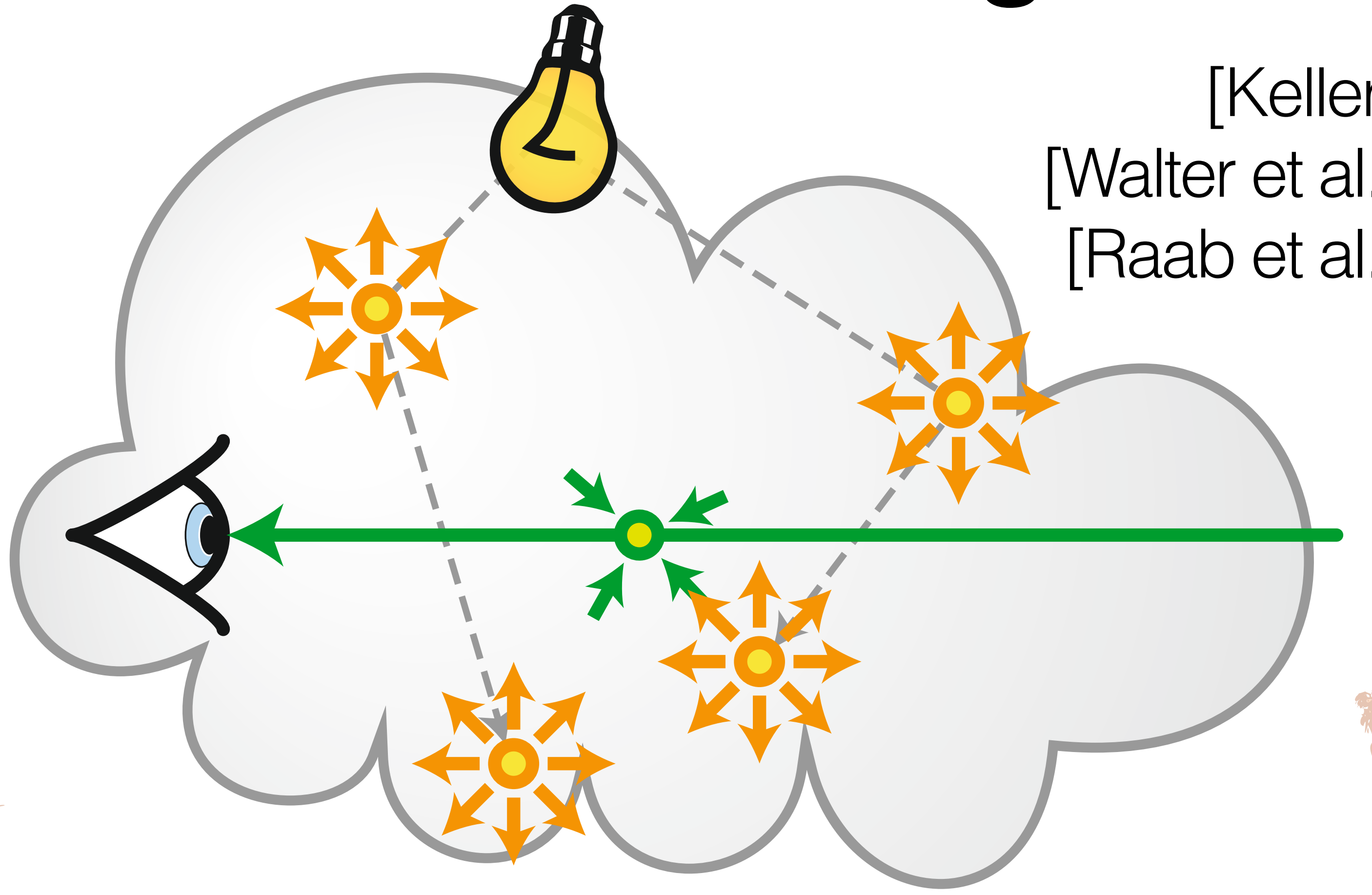


Virtual Point Lights

[Keller 1997]
[Walter et al. 2005]
[Raab et al. 2008]



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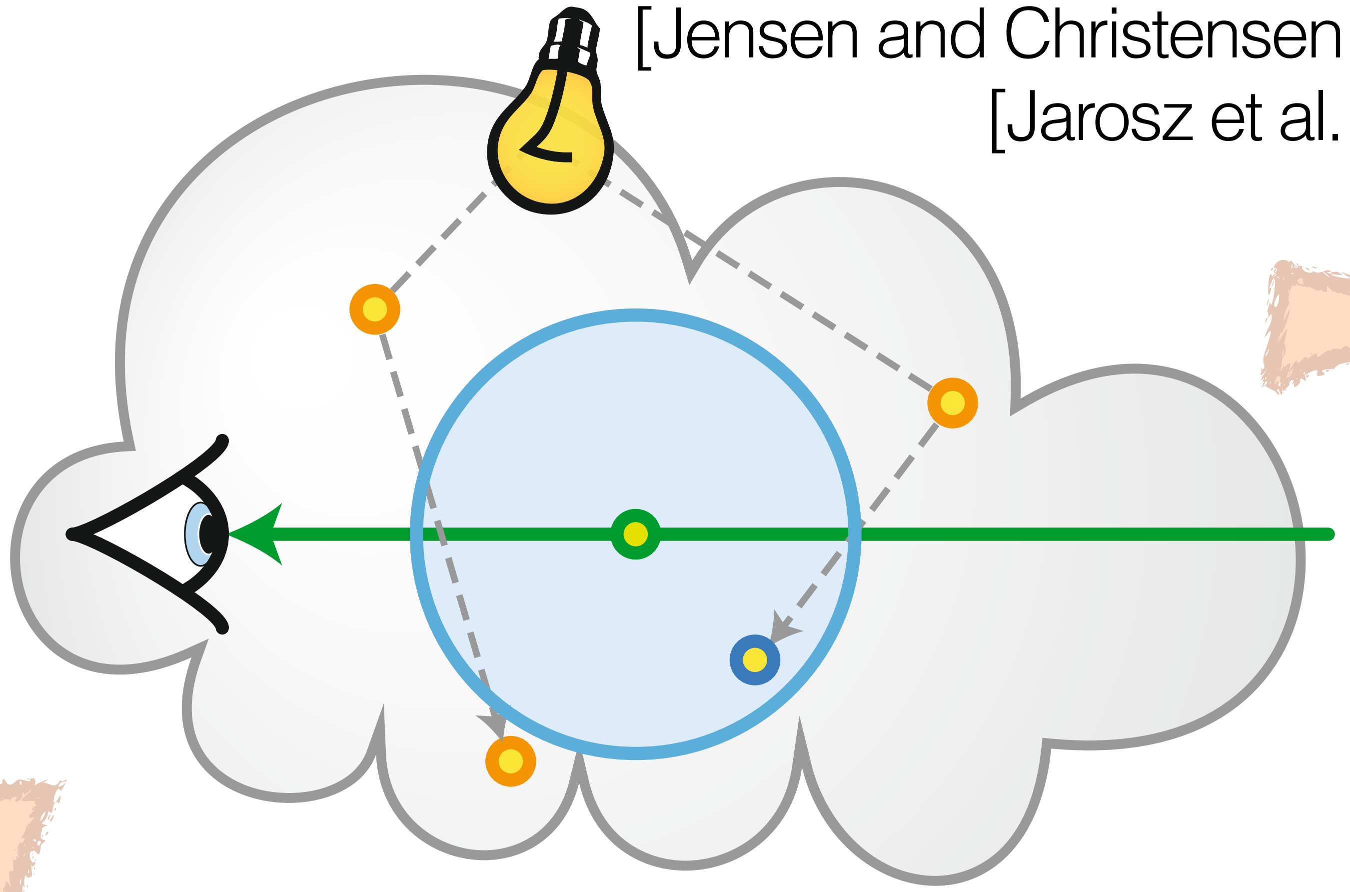

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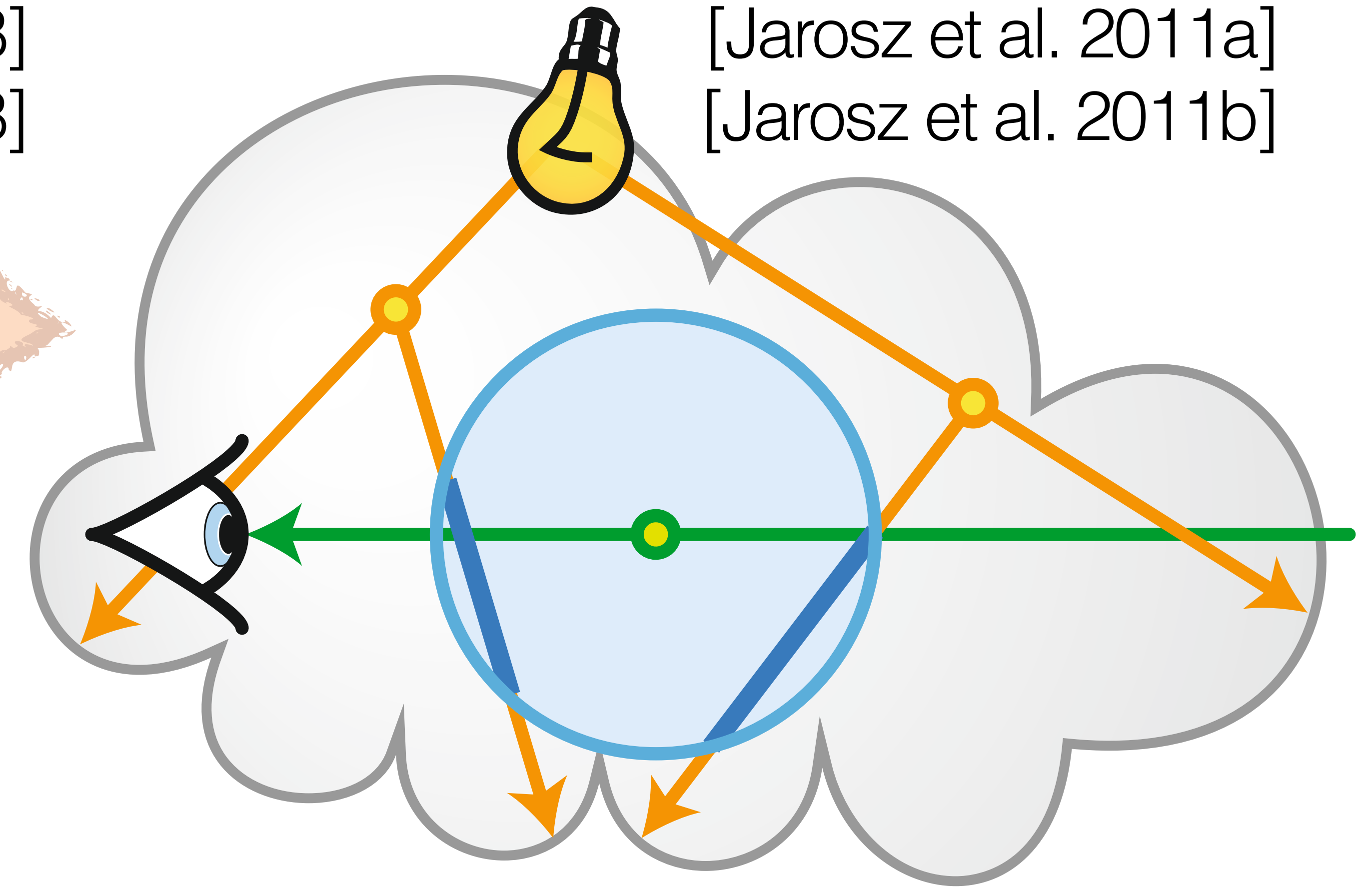

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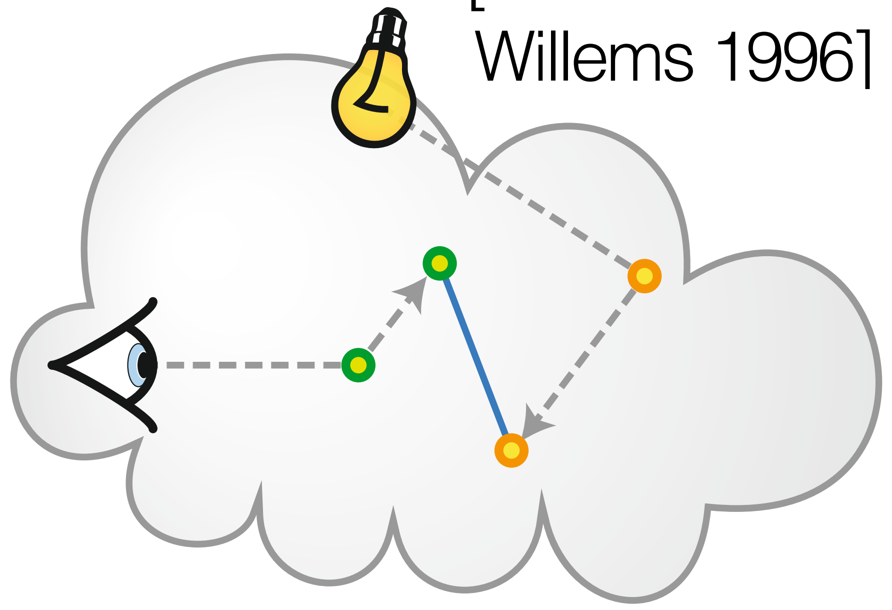

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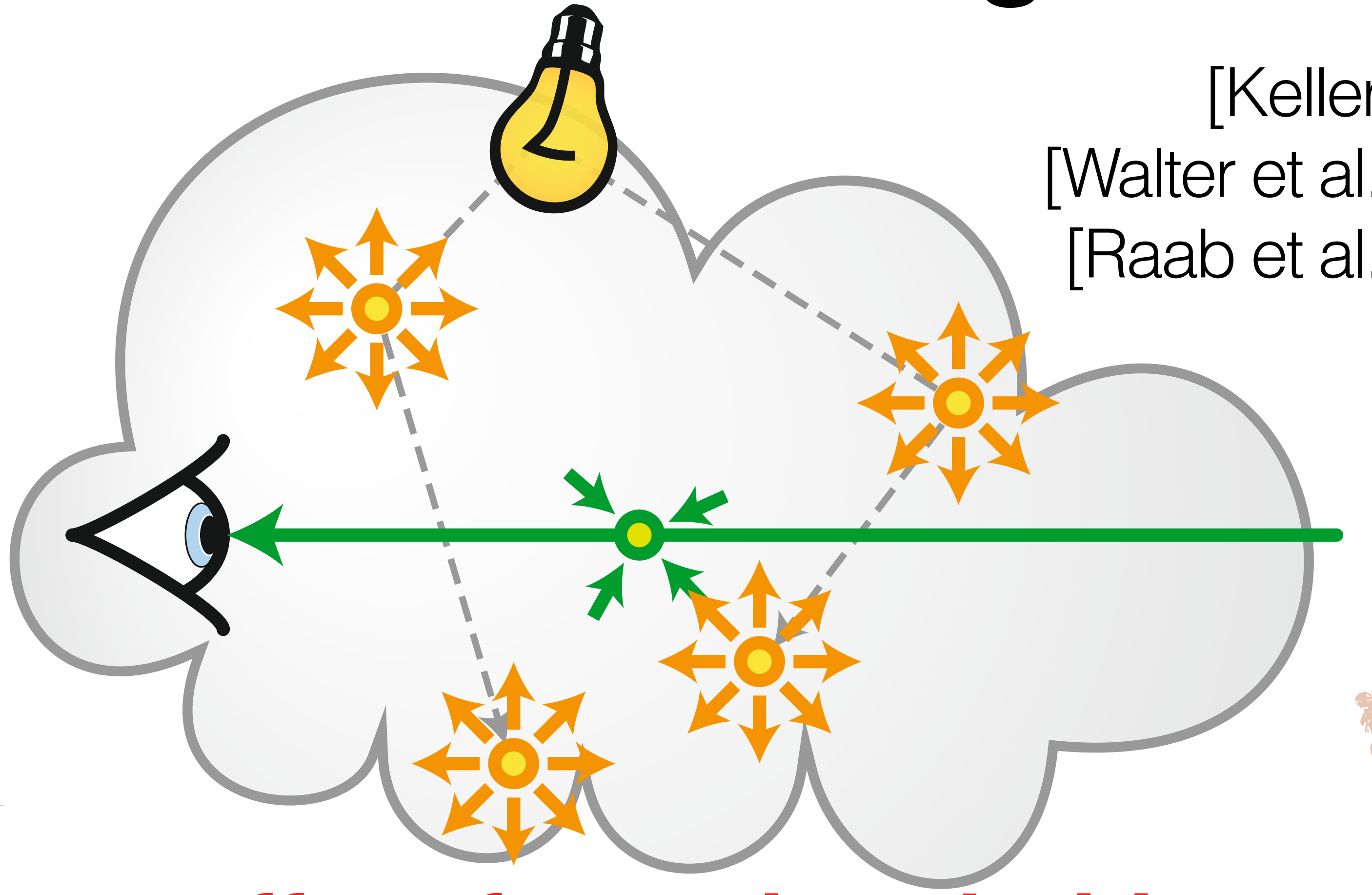

suffers from singularities

Previous work

Volumetric Photon Mapping

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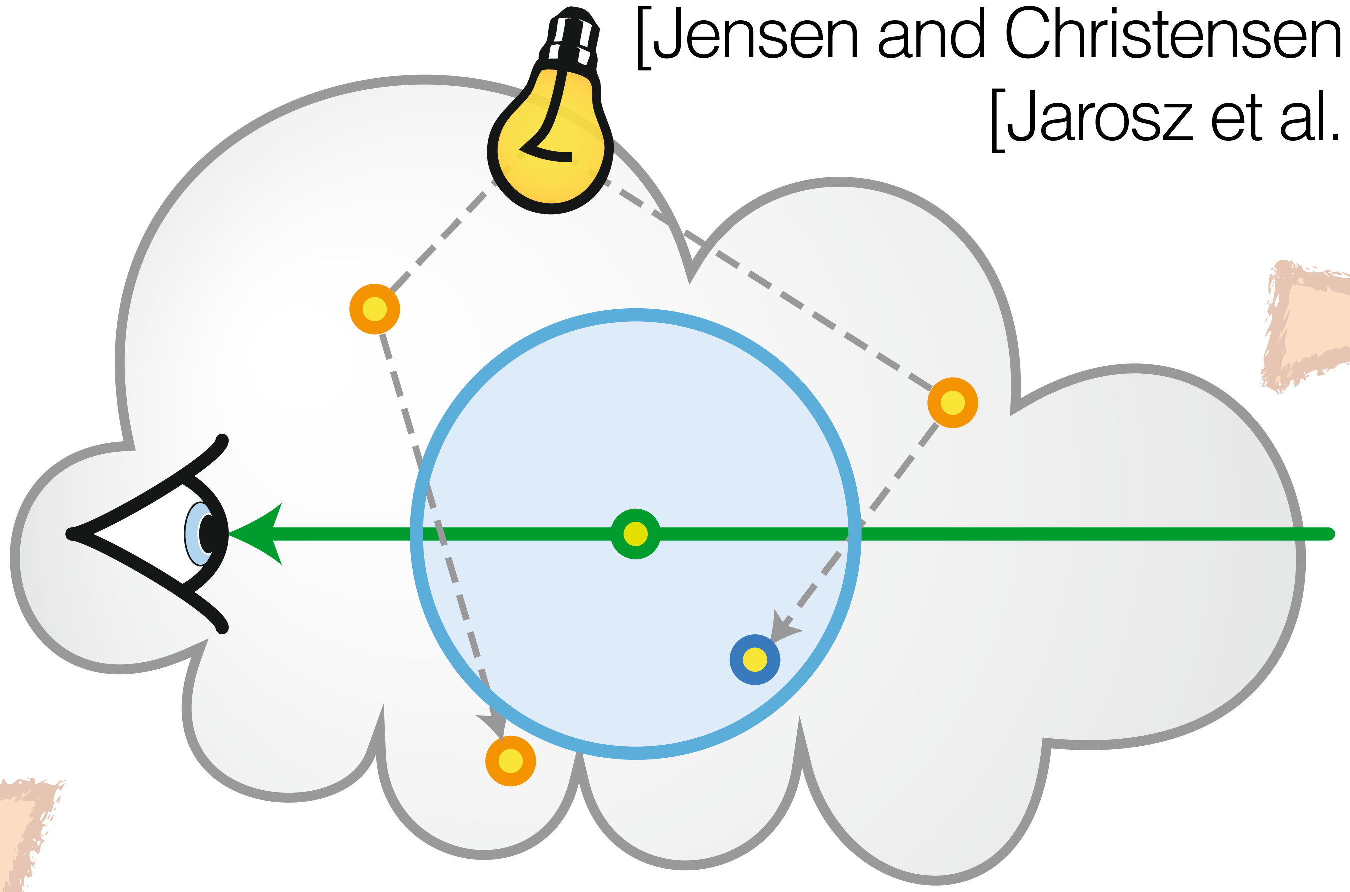

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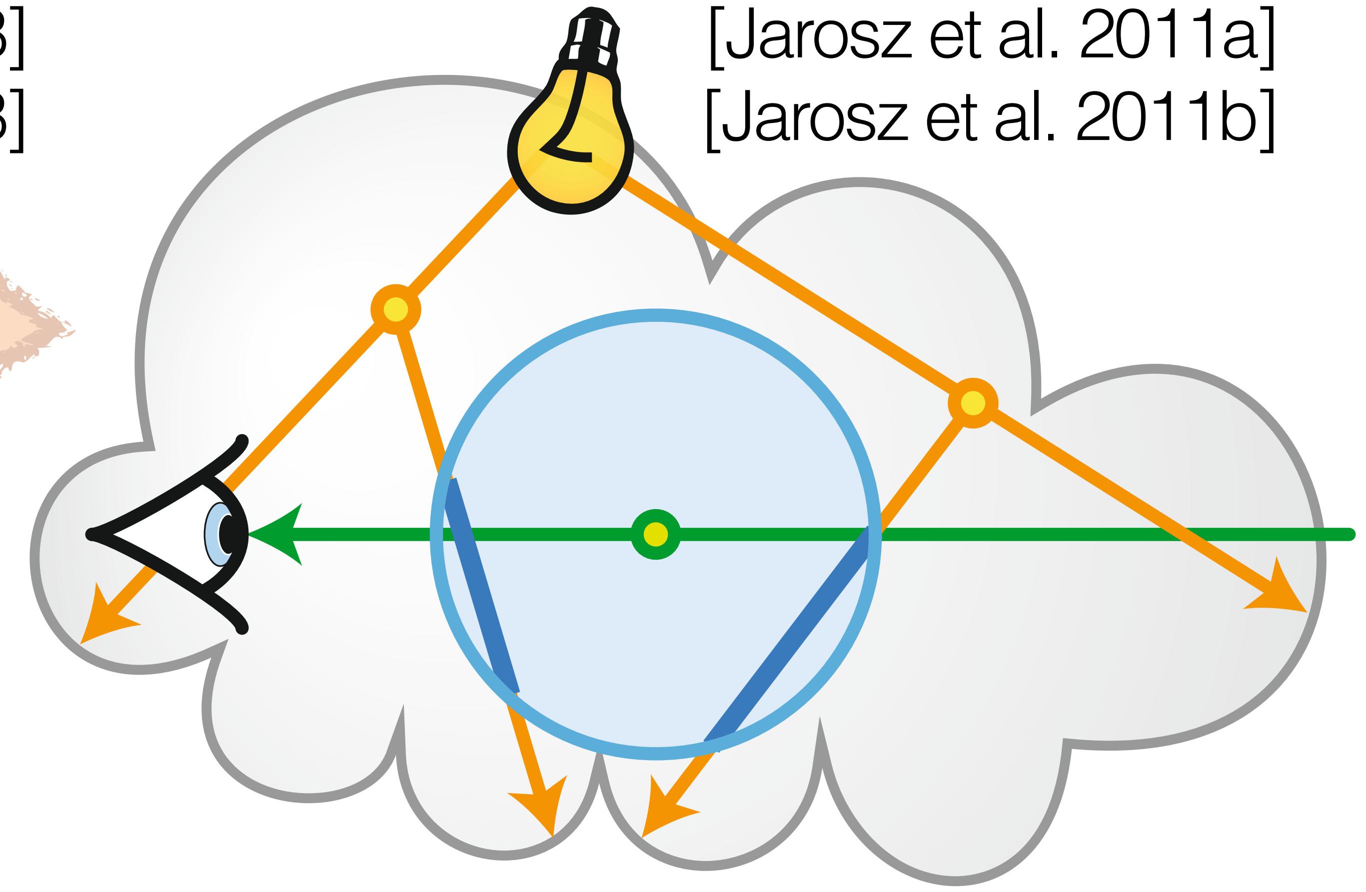

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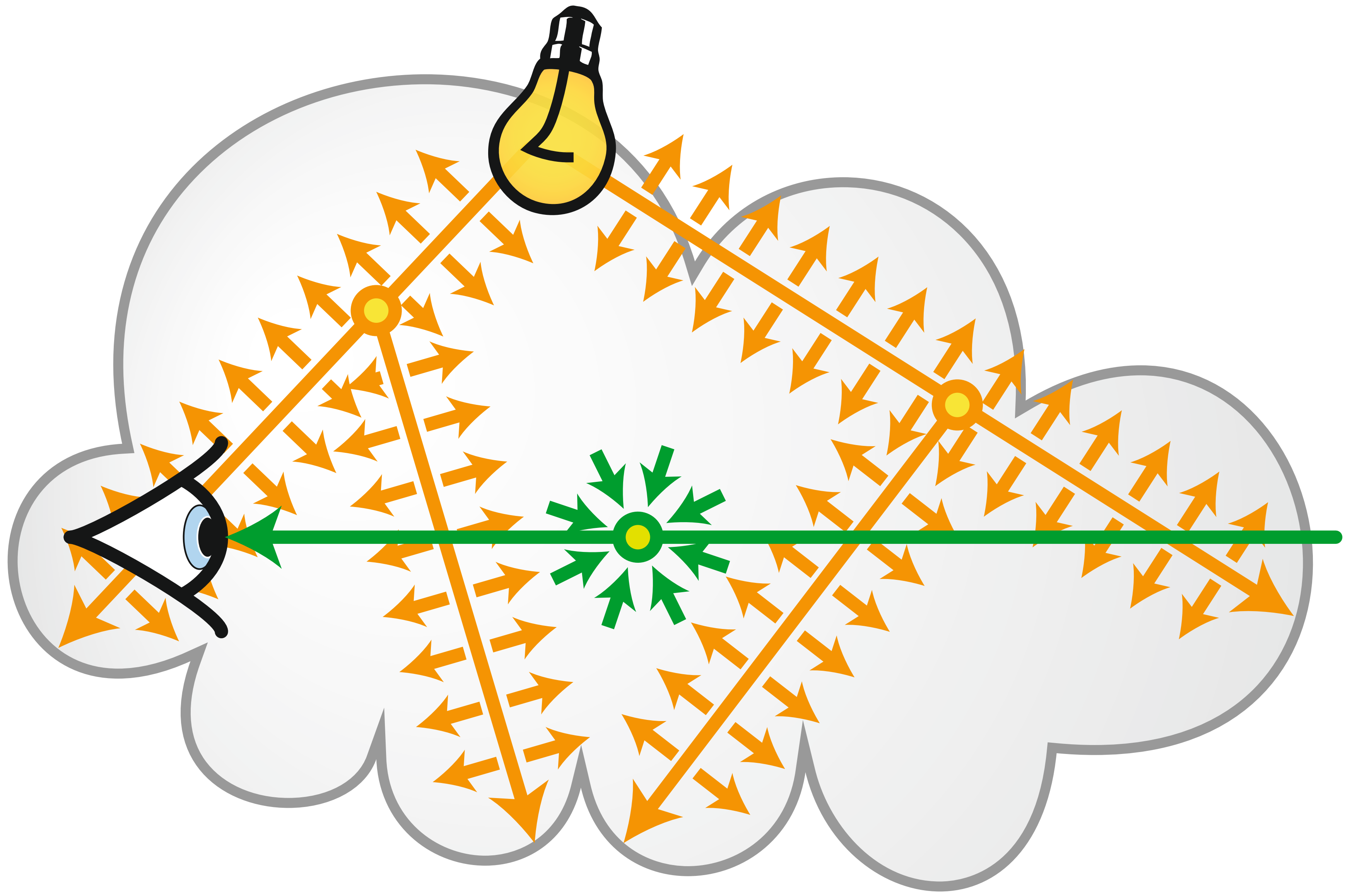
Virtual Ray Lights



Bidirectional Path Tracing

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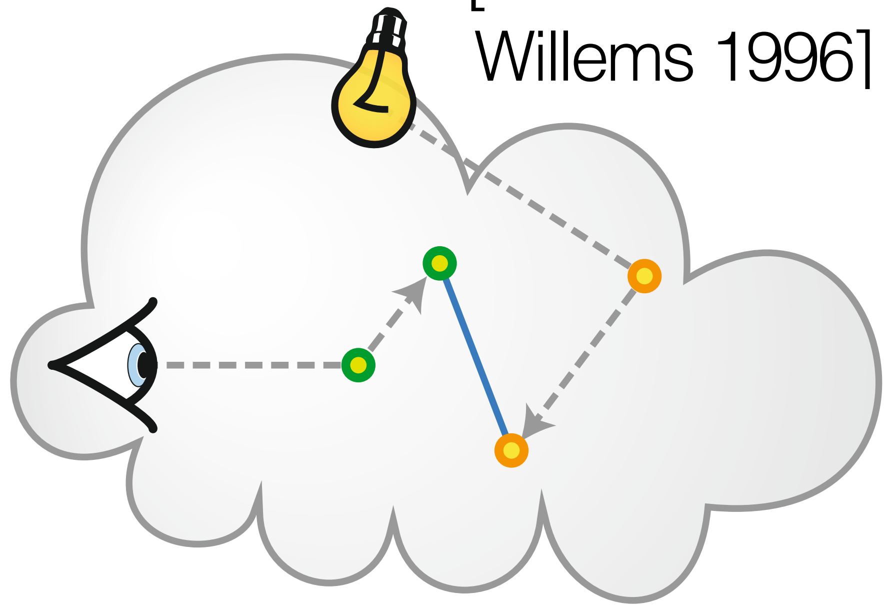

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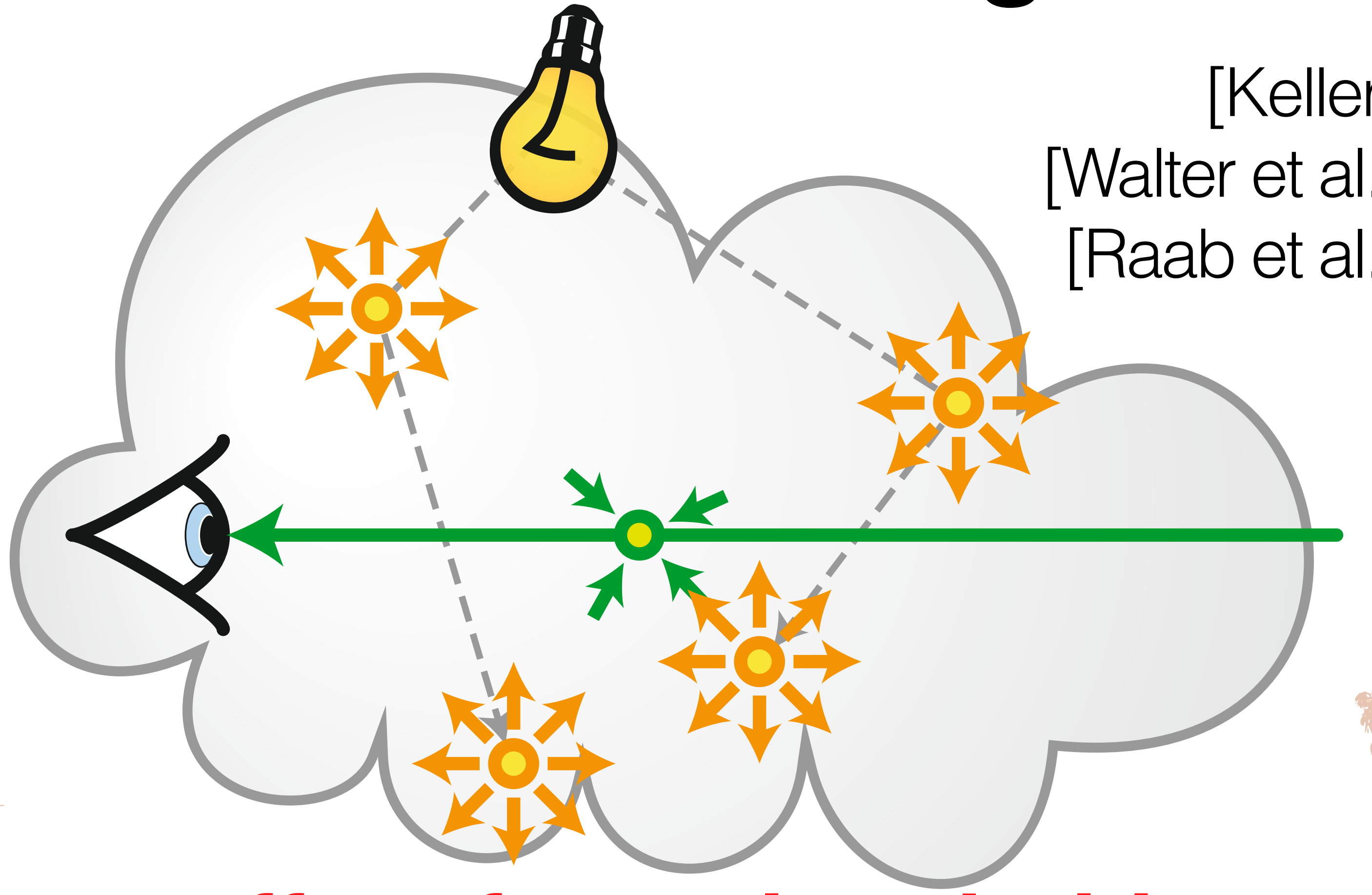
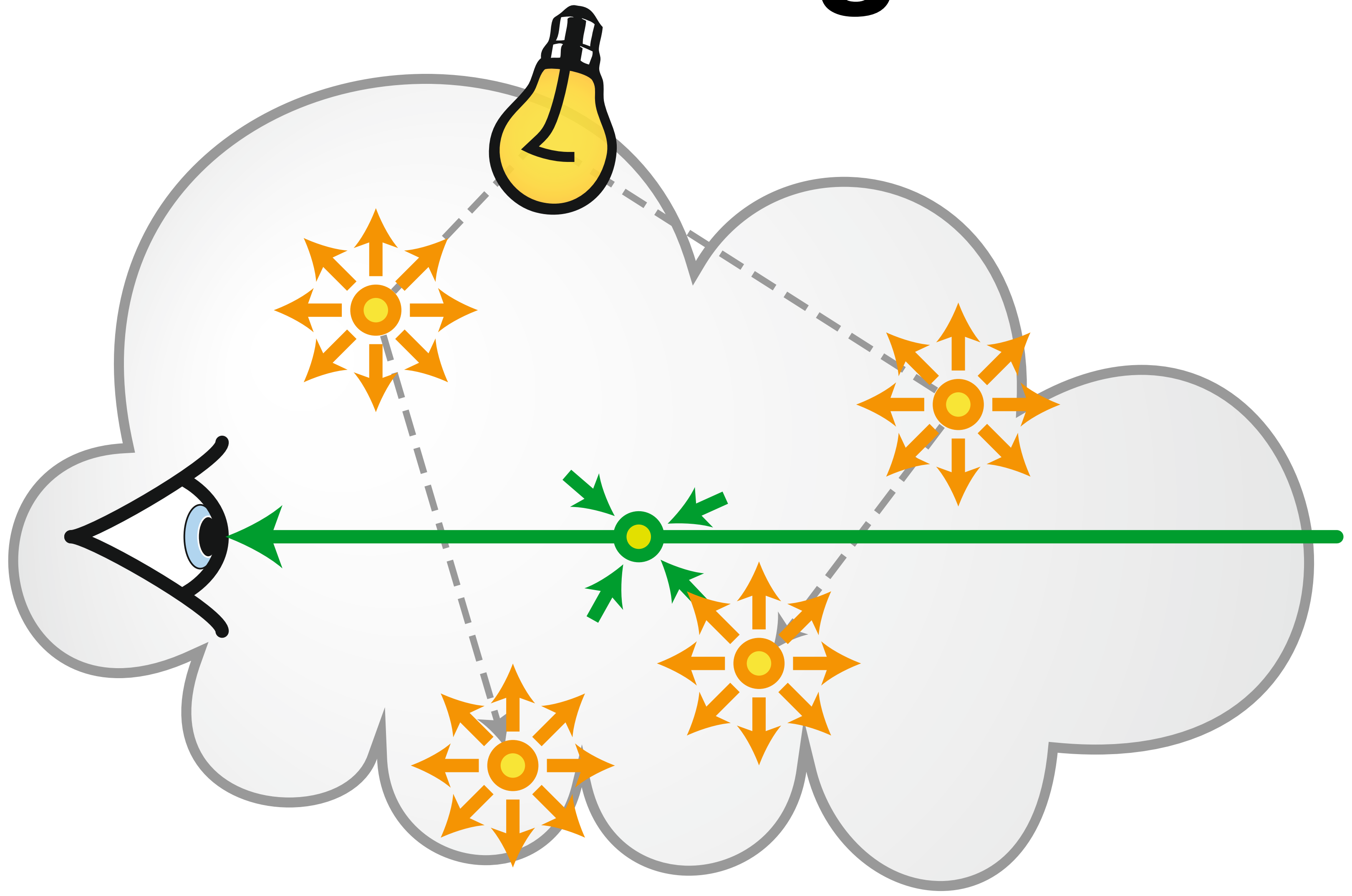


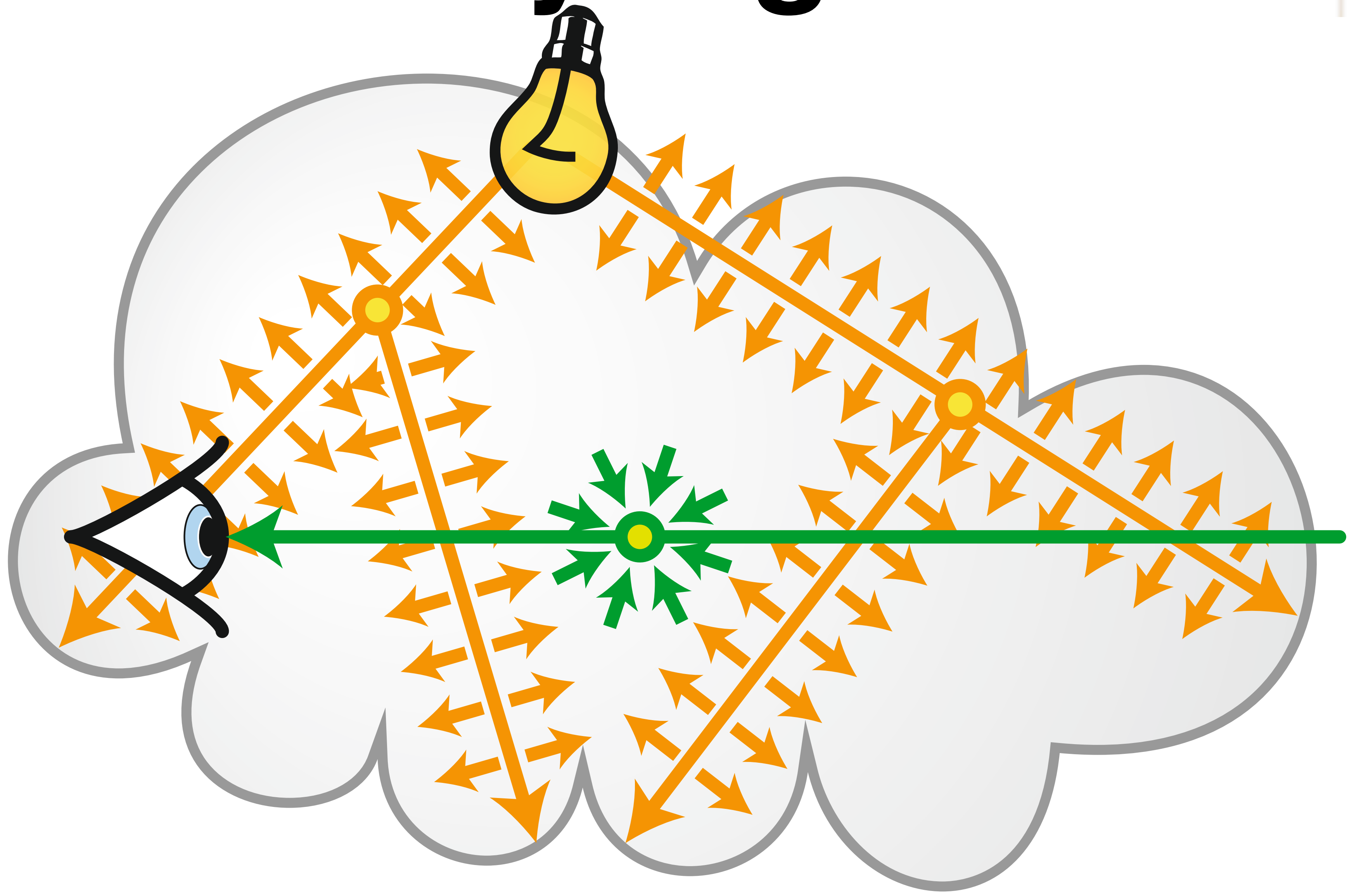
suffers from singularities

From points to rays

Point Lights

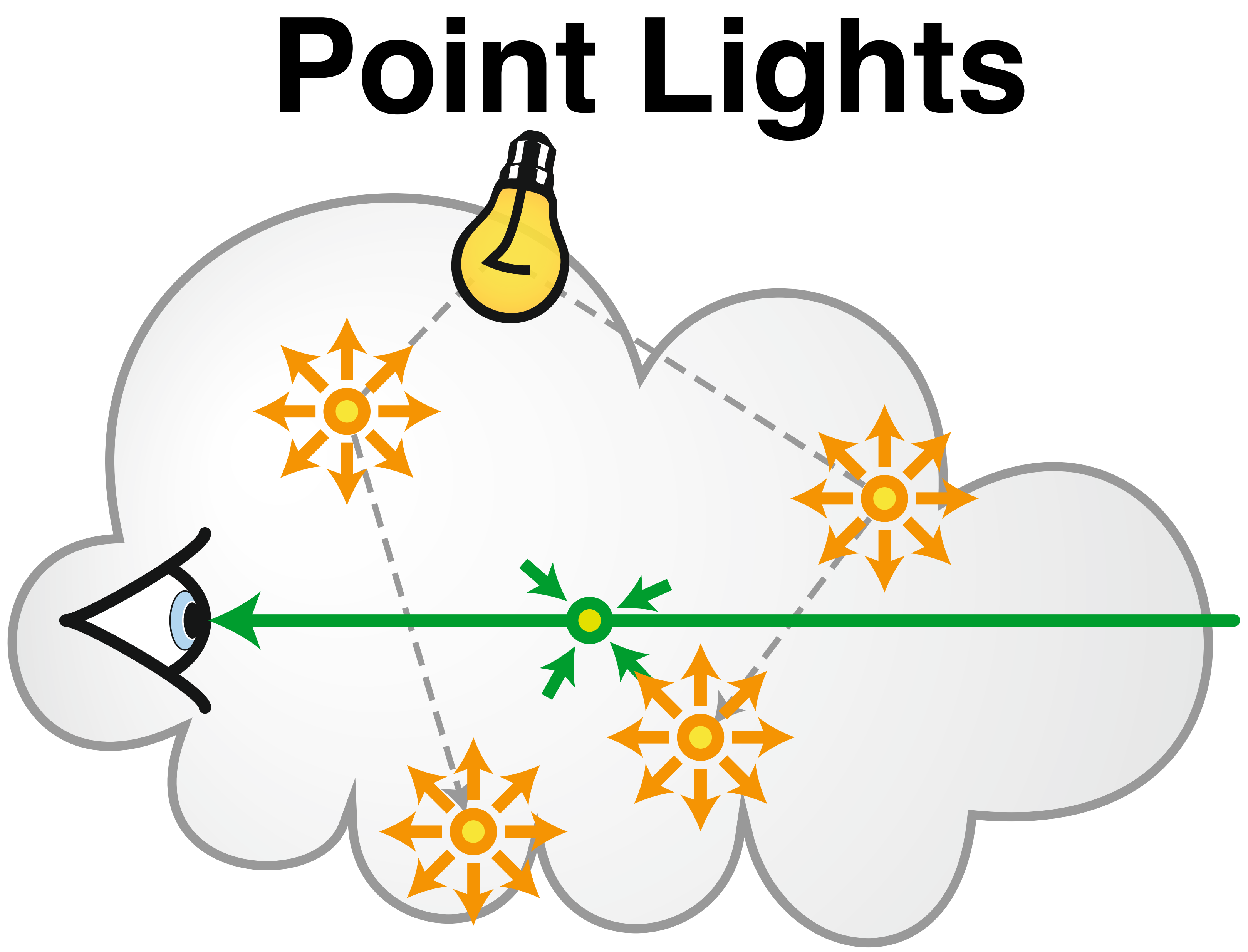


Ray Lights



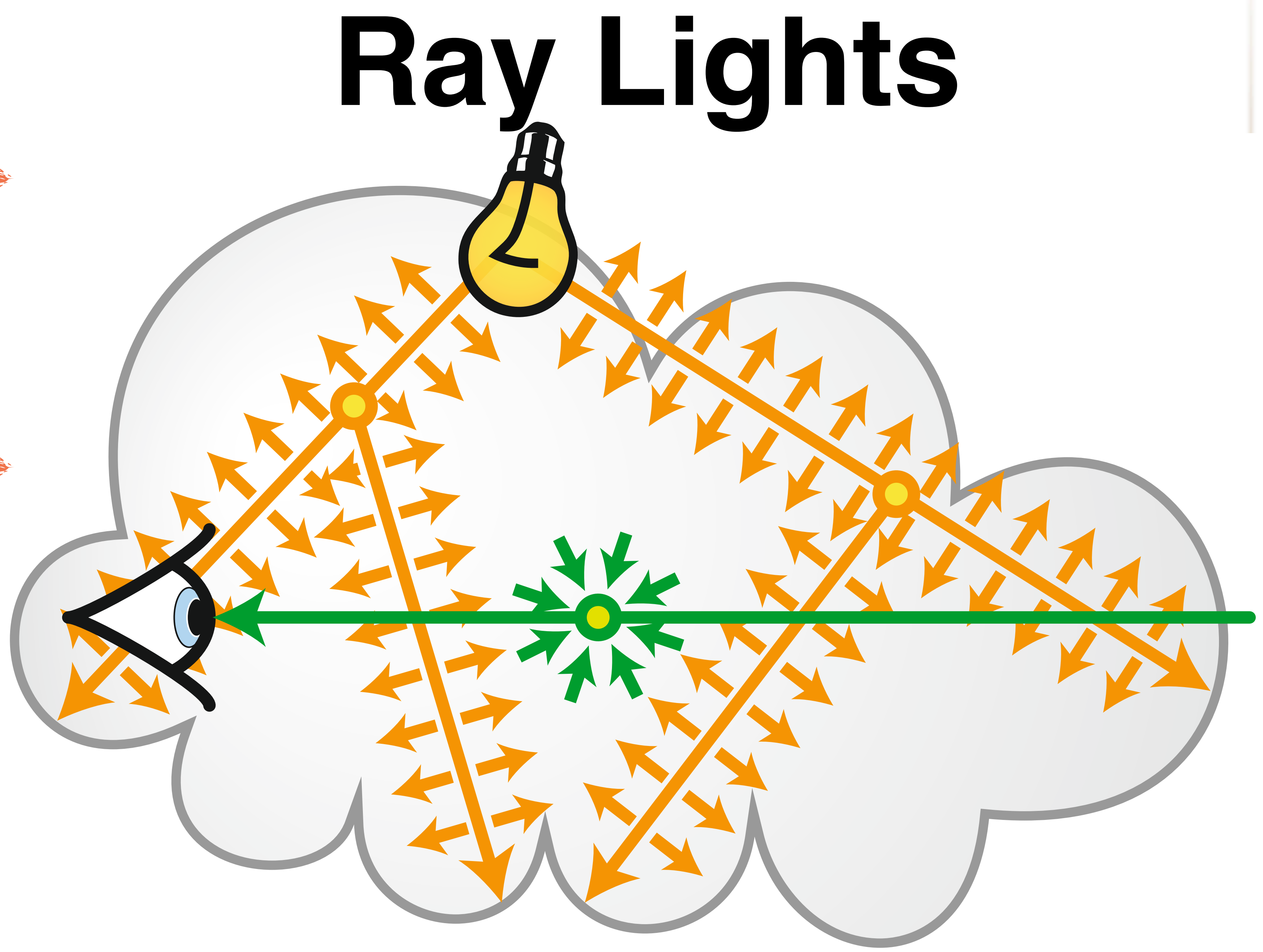
From points to rays

From points to rays



provably reduce singularities

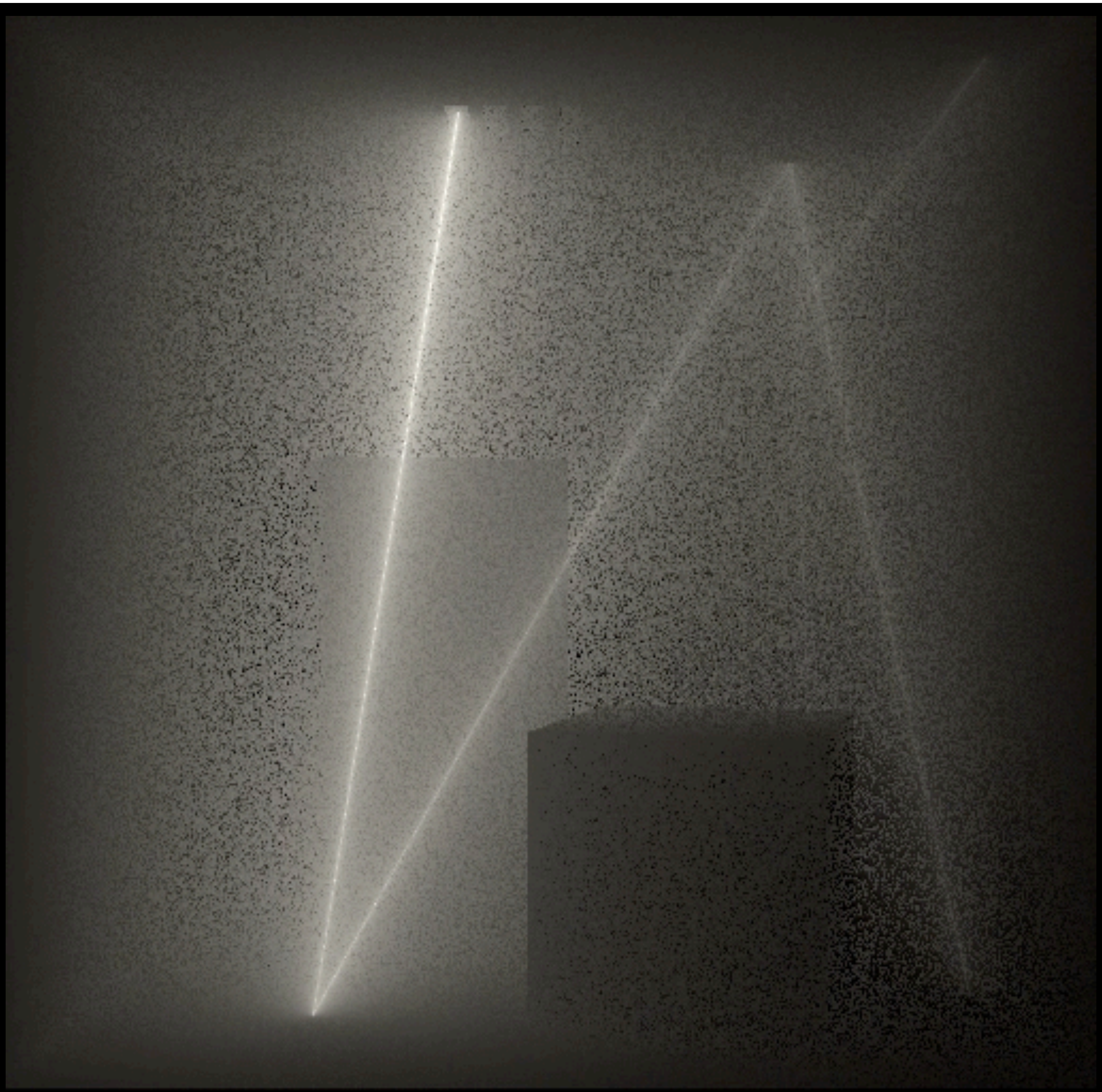
no need to clamp, unbiased



From points to rays

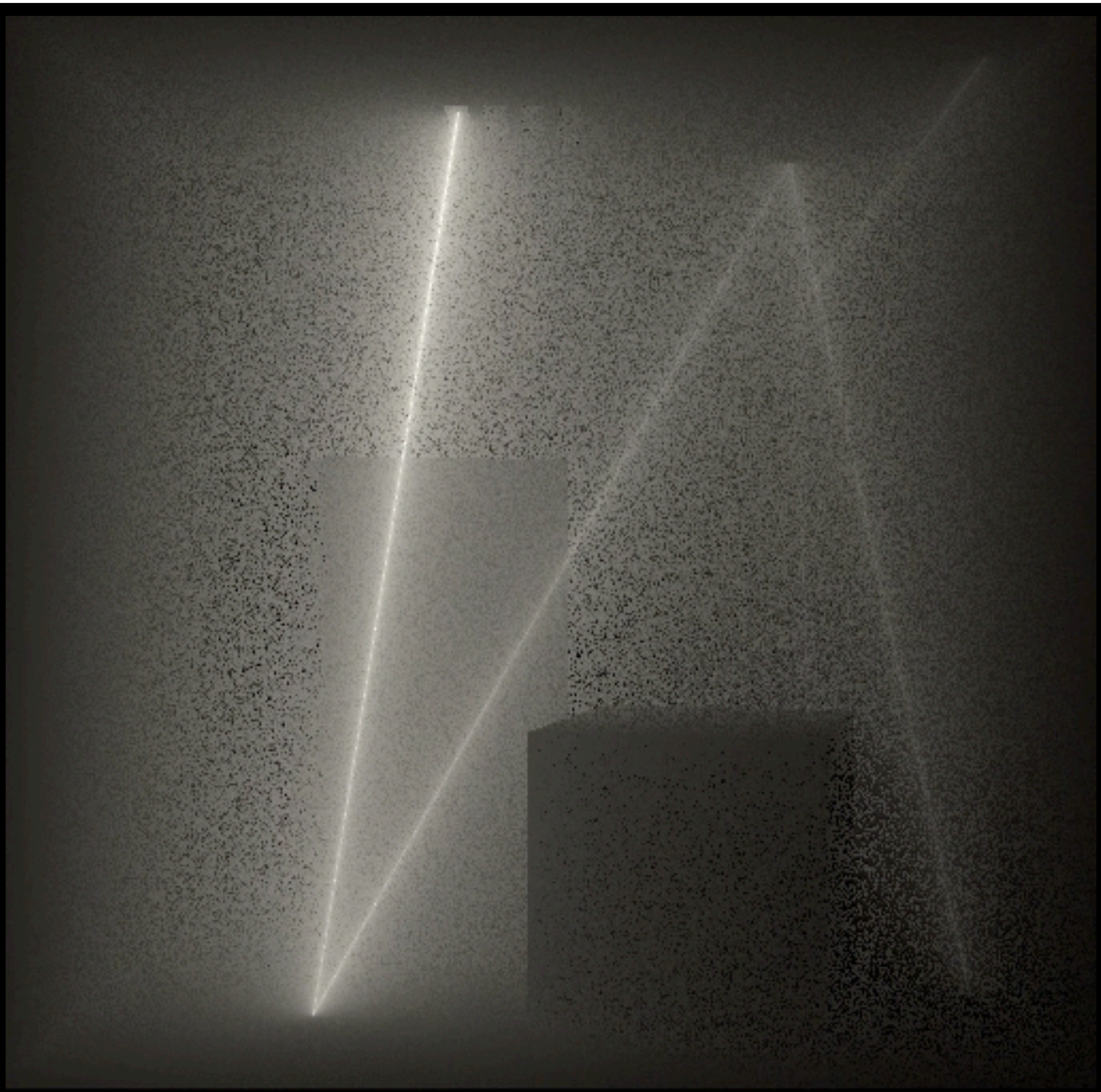
From points to rays

Quick demo



6 VRLs

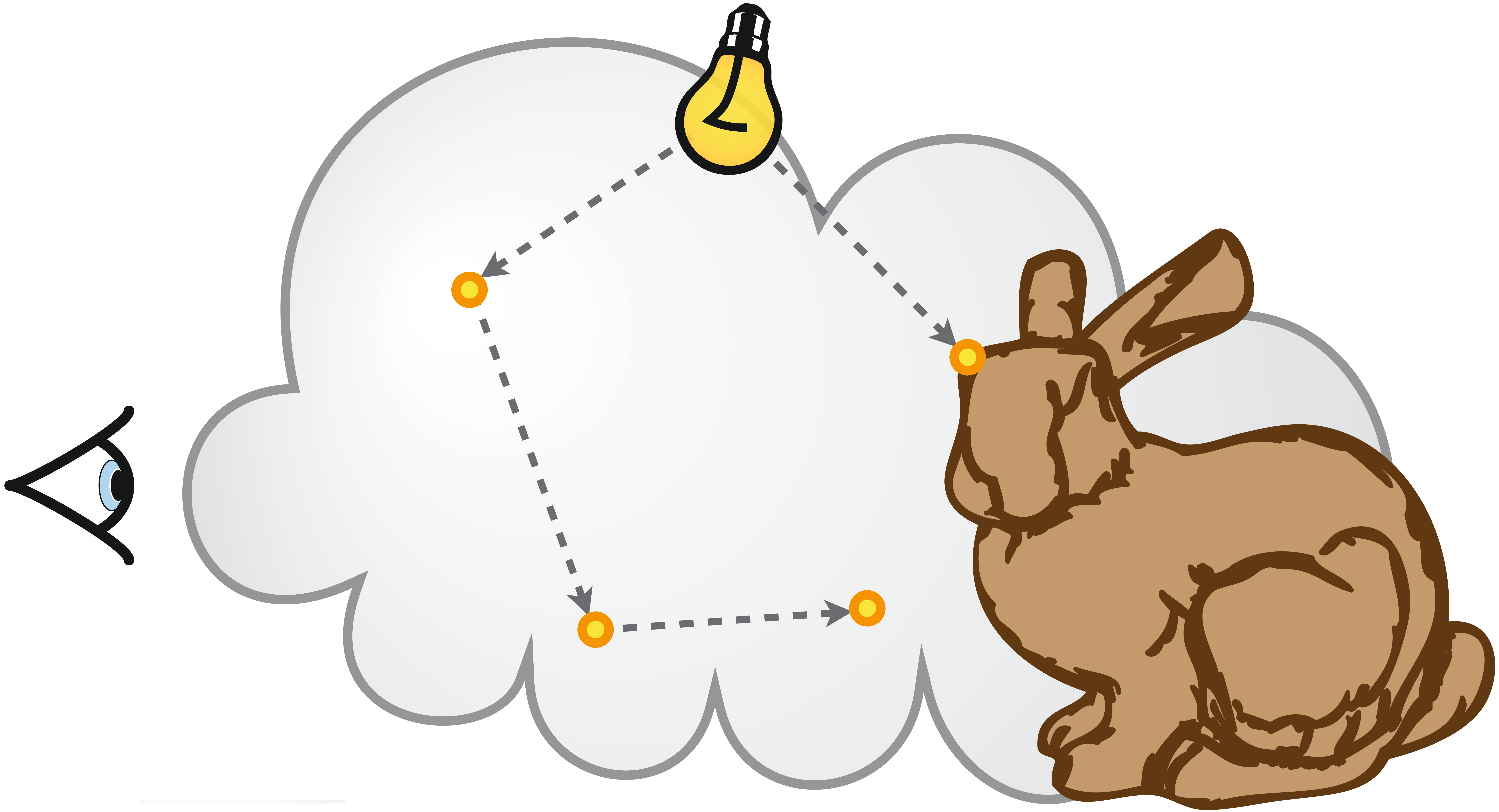
Quick demo



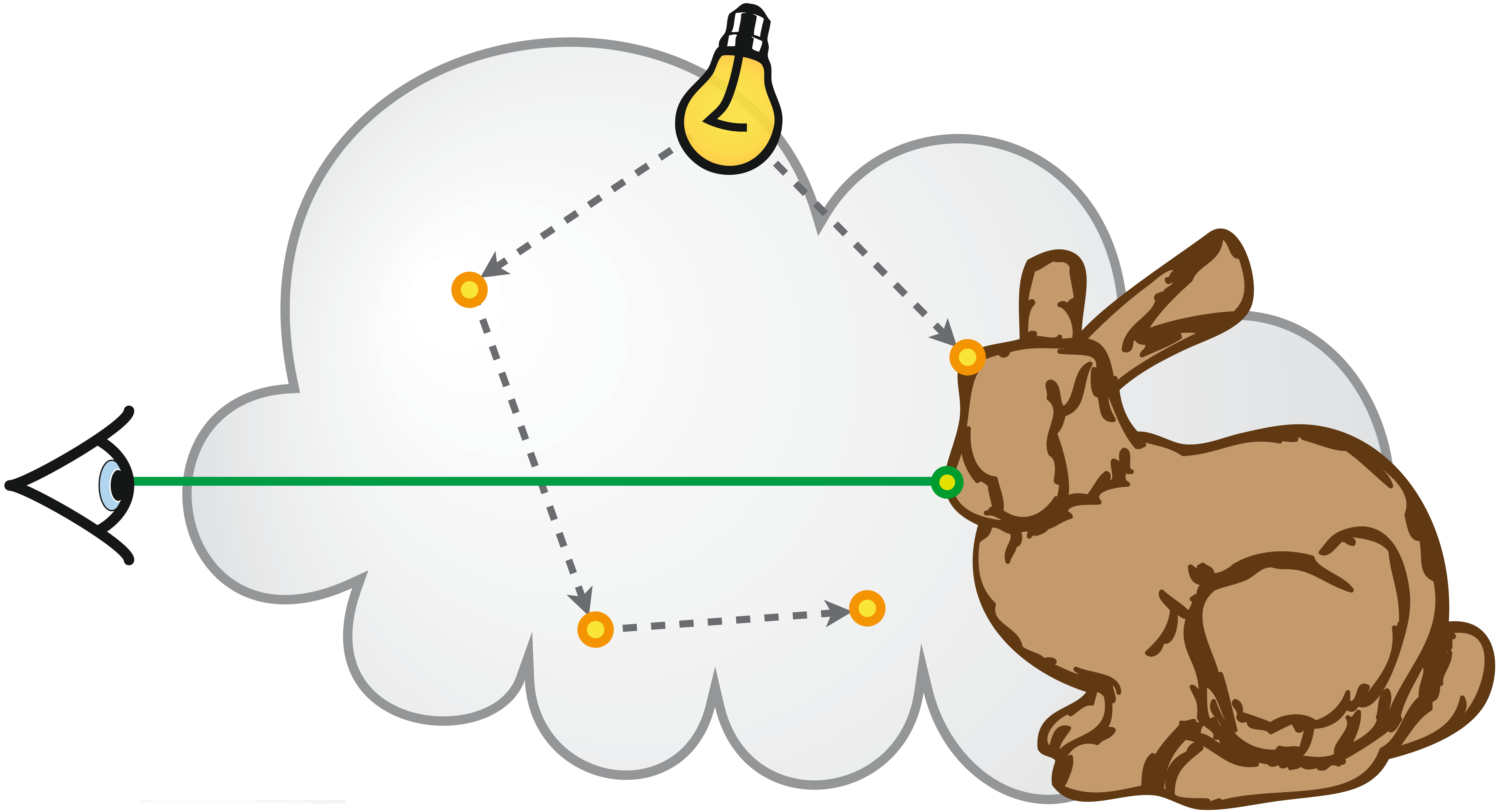
6 VRLs

Algorithm overview

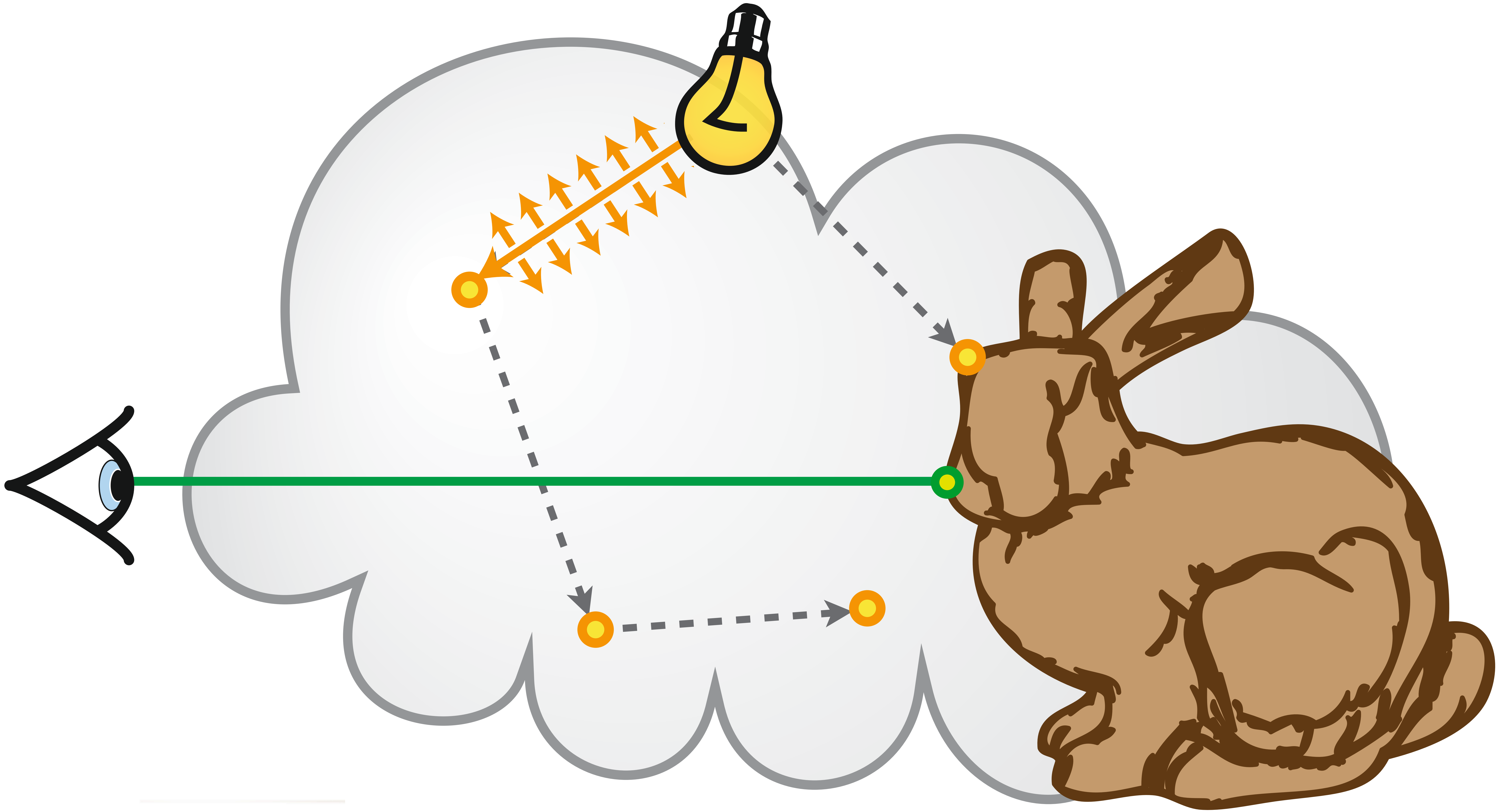
Algorithm overview



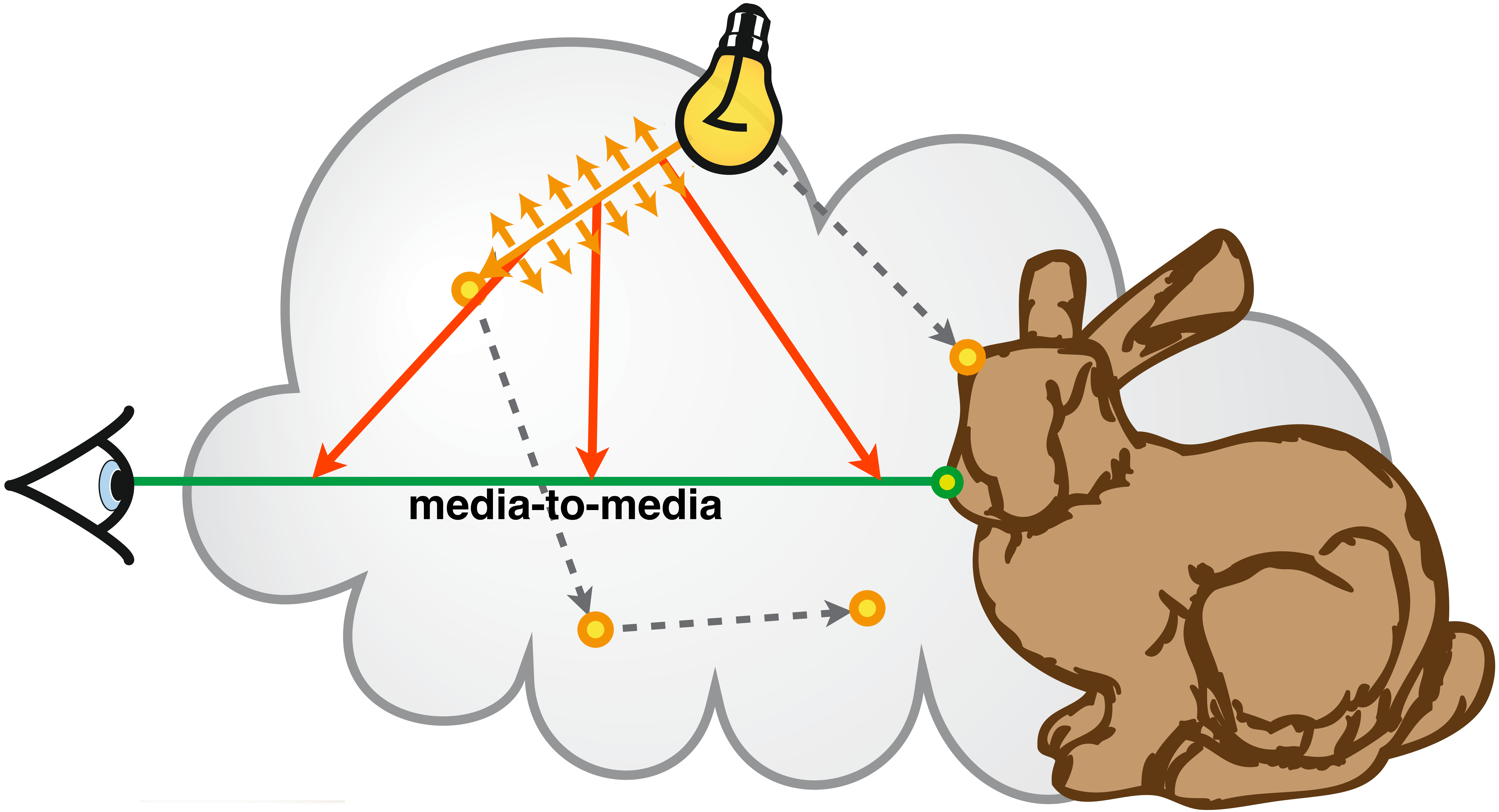
Algorithm overview



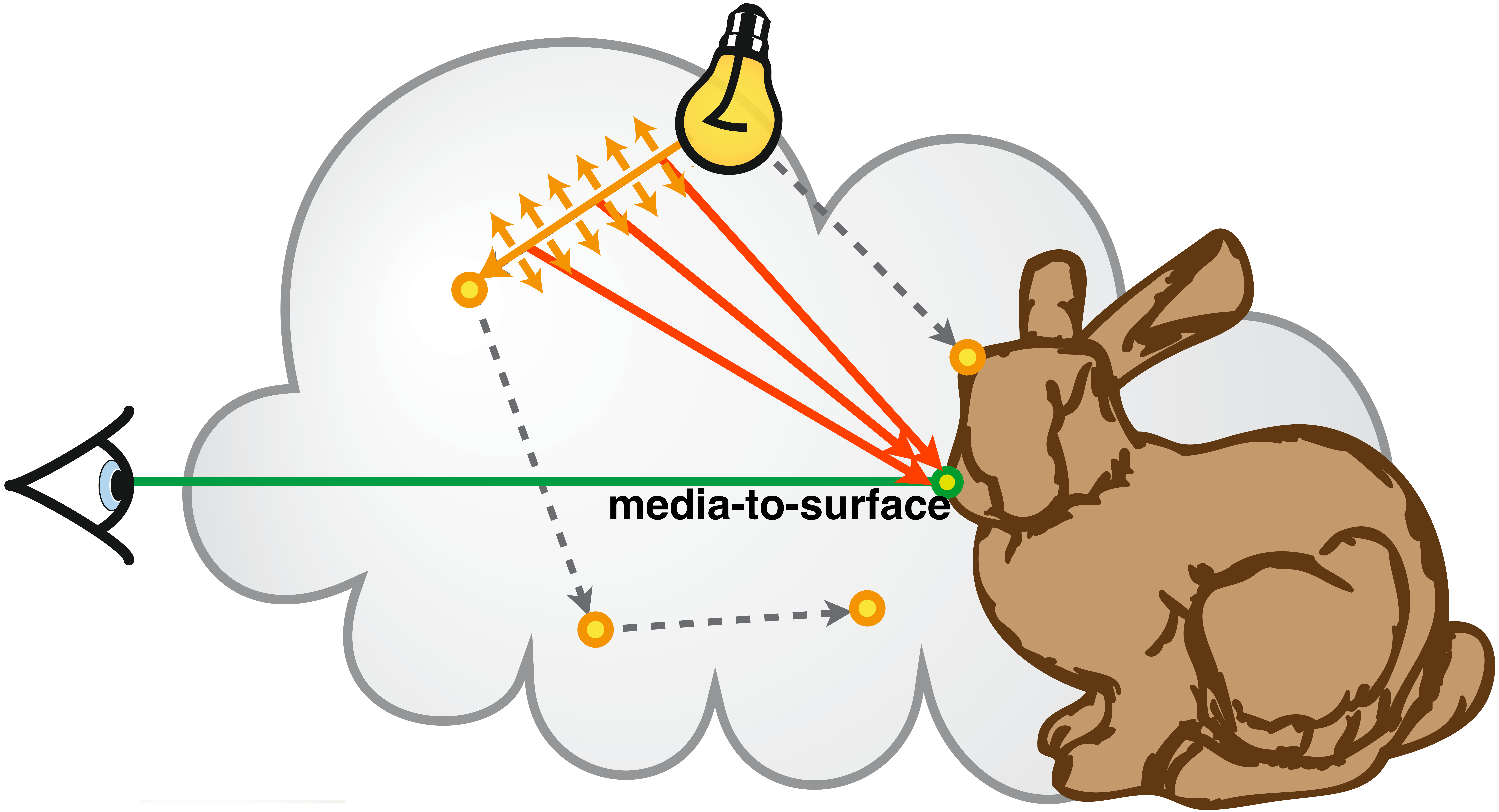
Algorithm overview



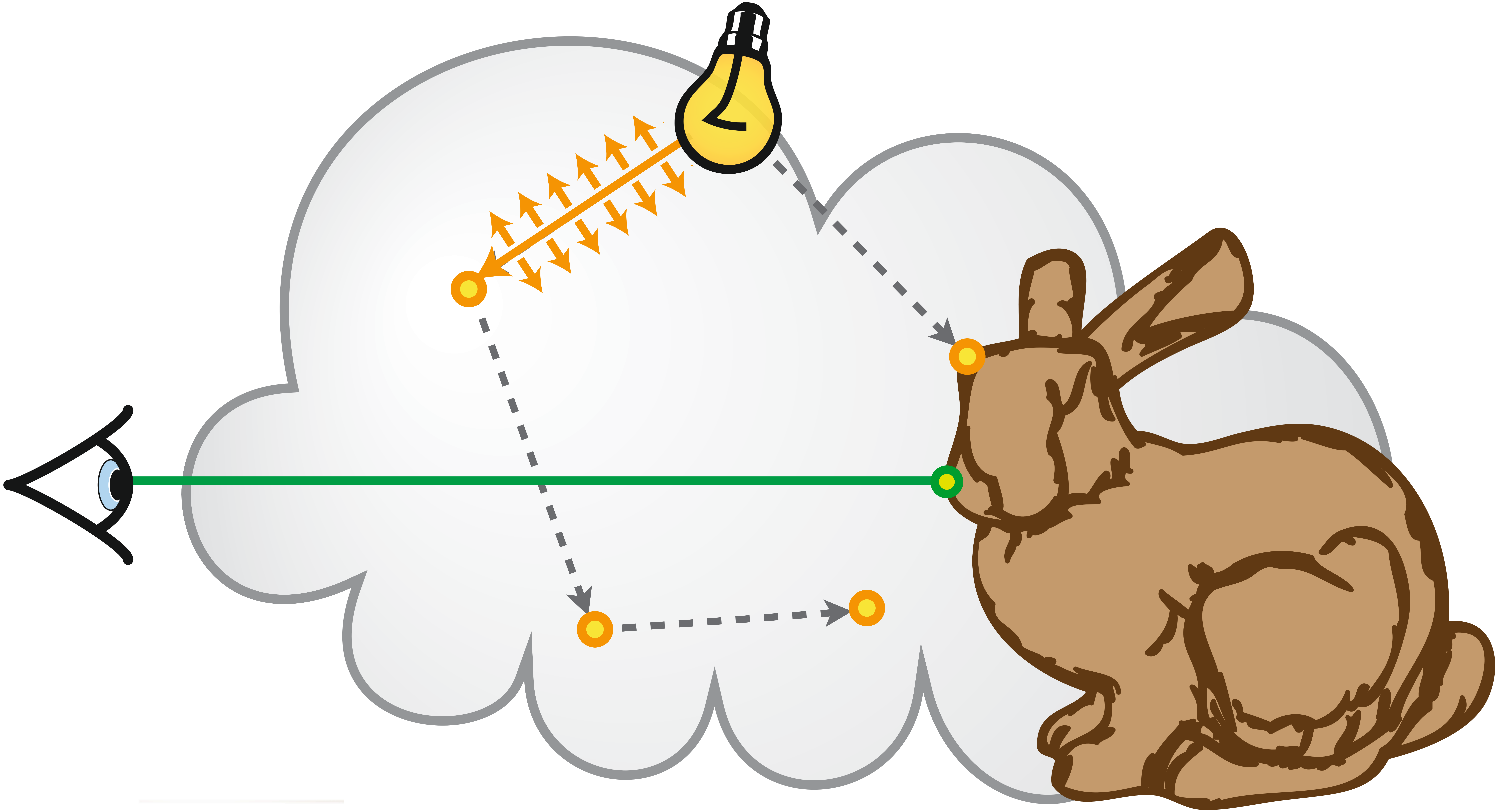
Algorithm overview



Algorithm overview



Algorithm overview



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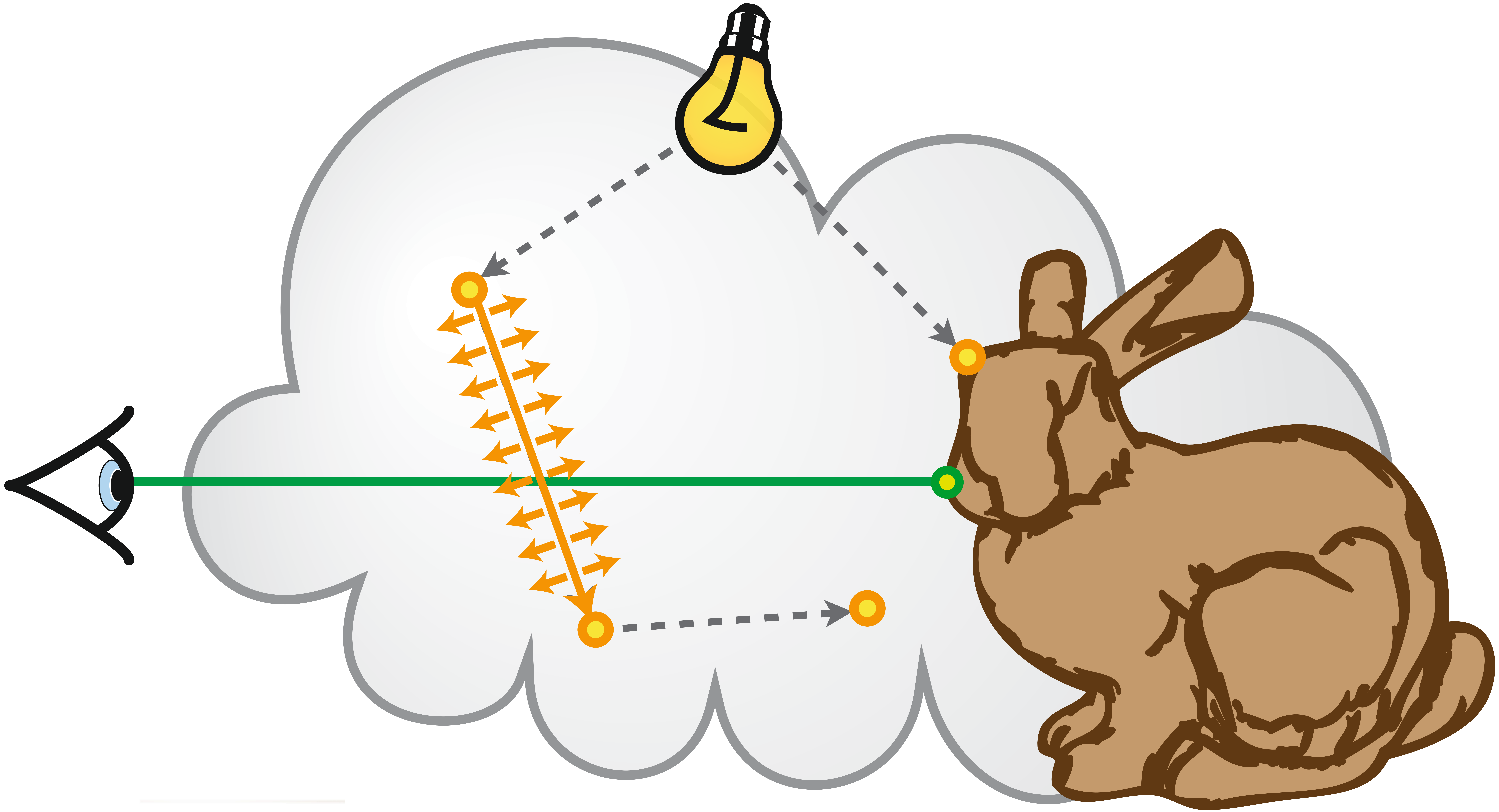

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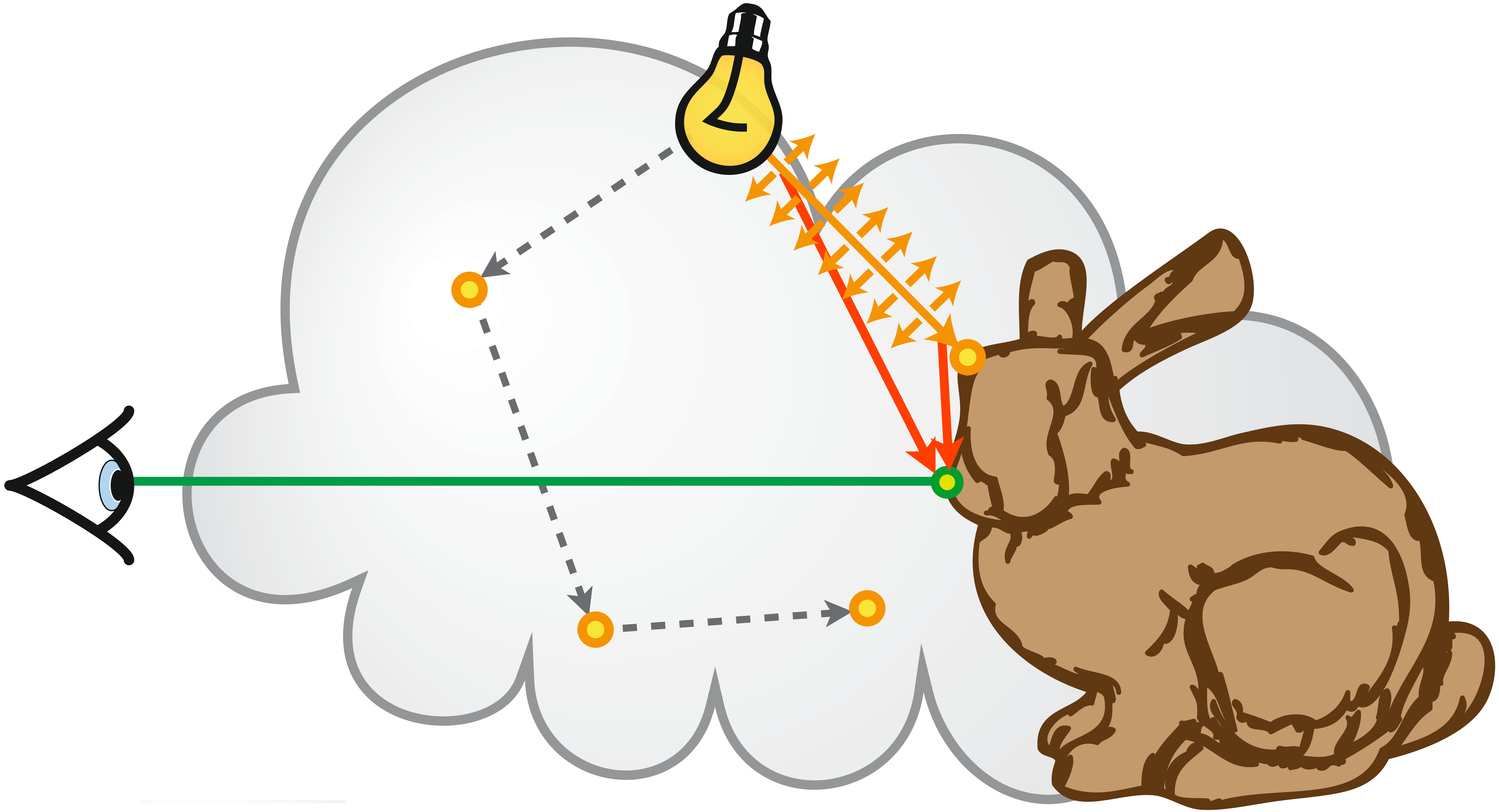
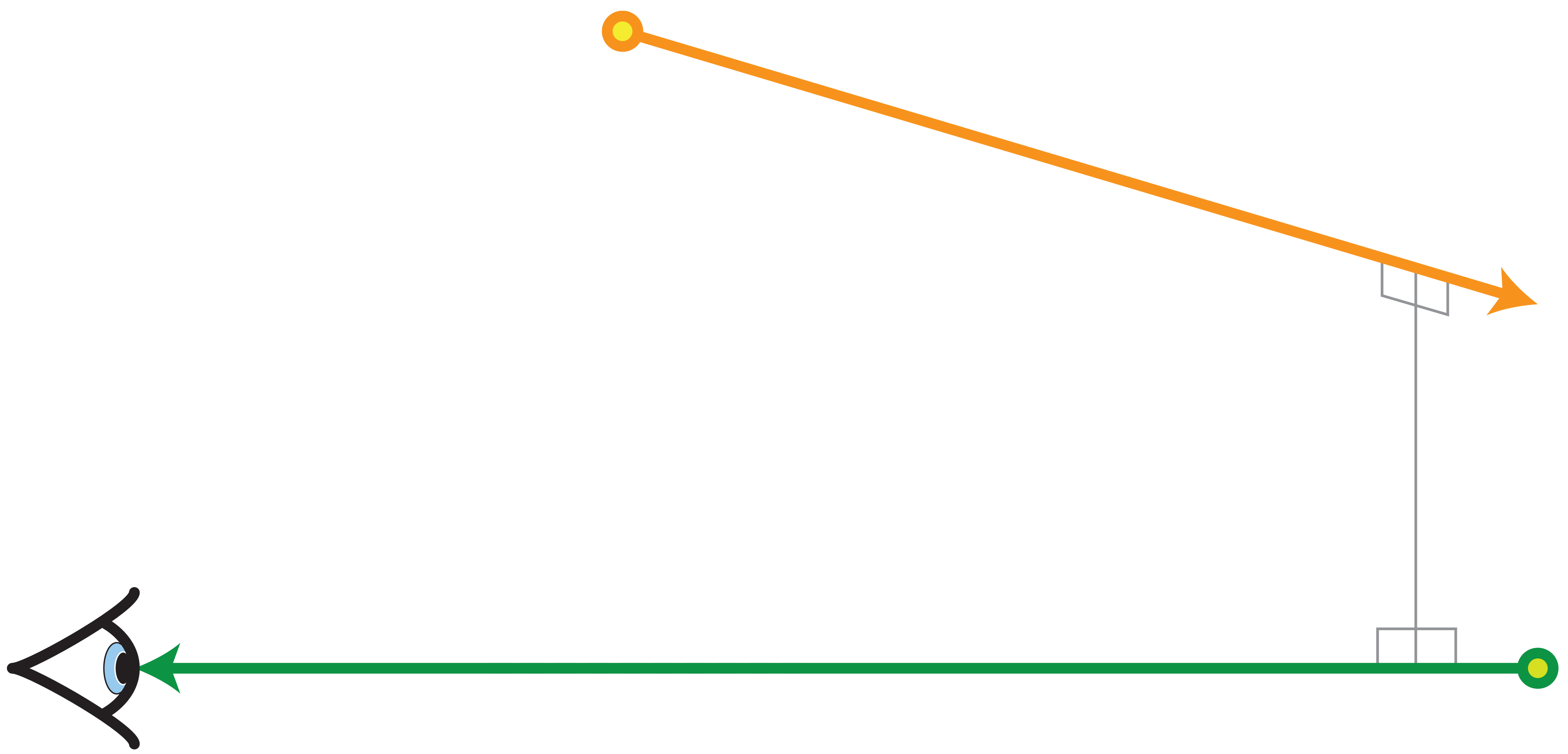


Ray-to-Ray transport

Ray-to-Ray transport



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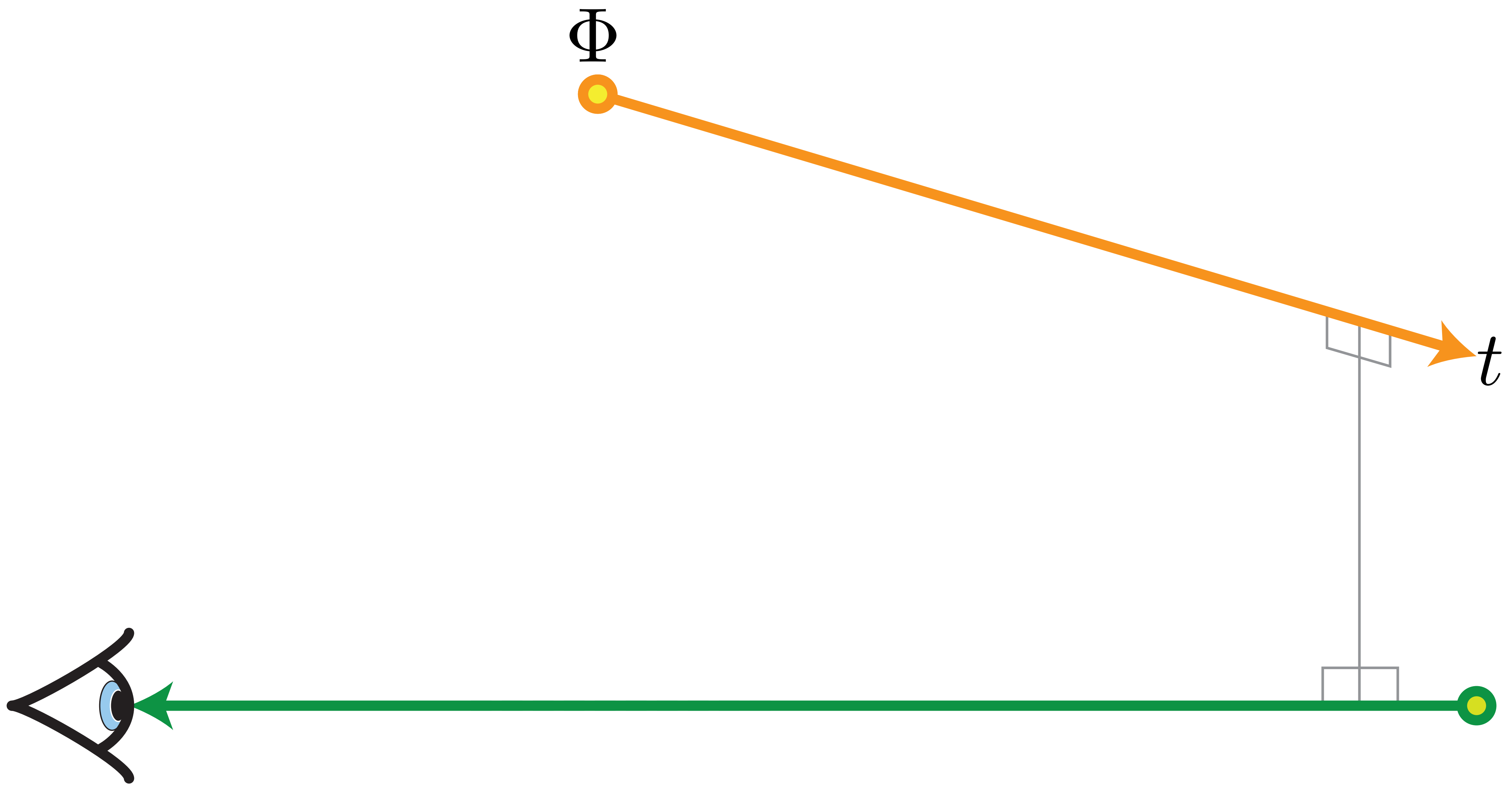
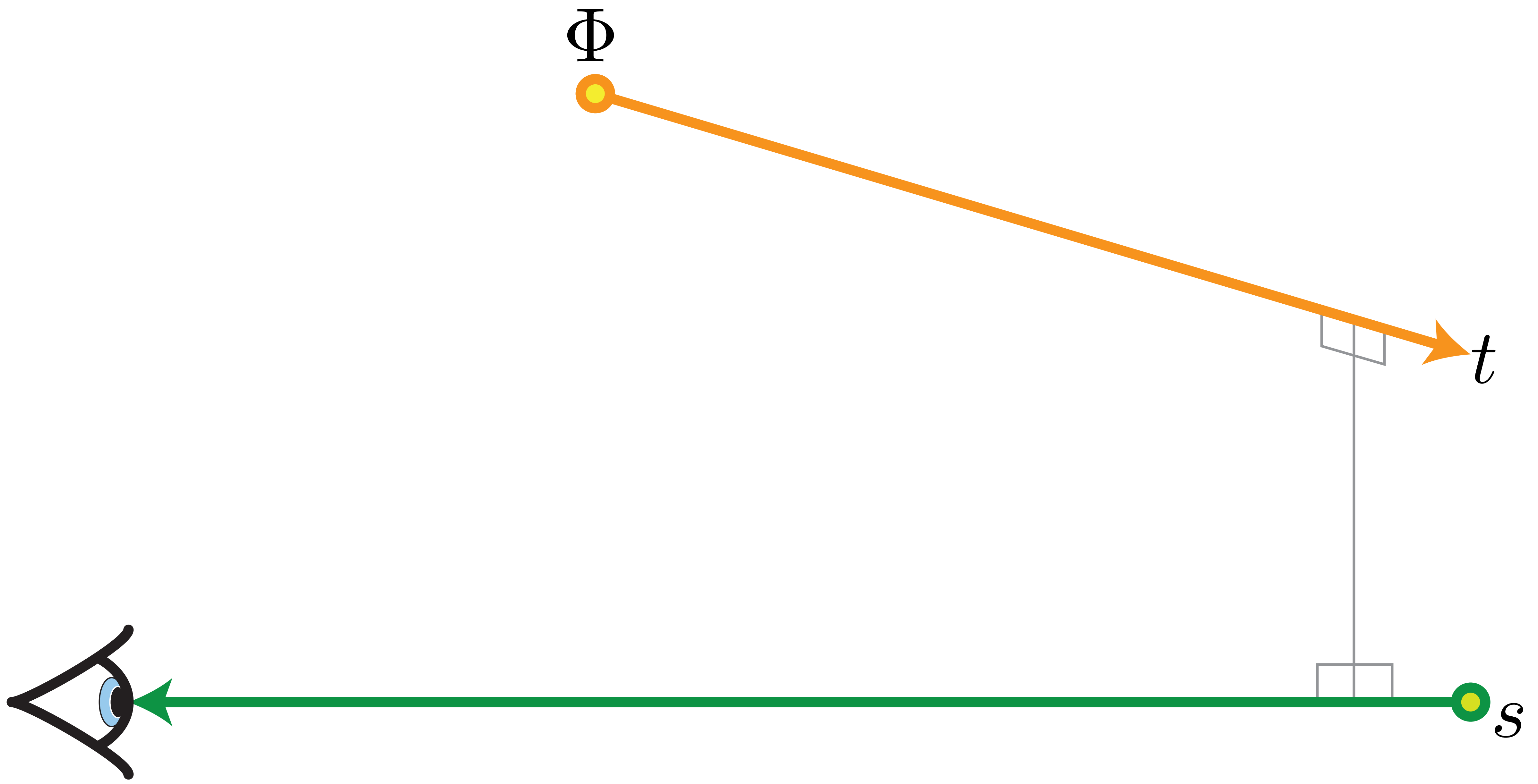
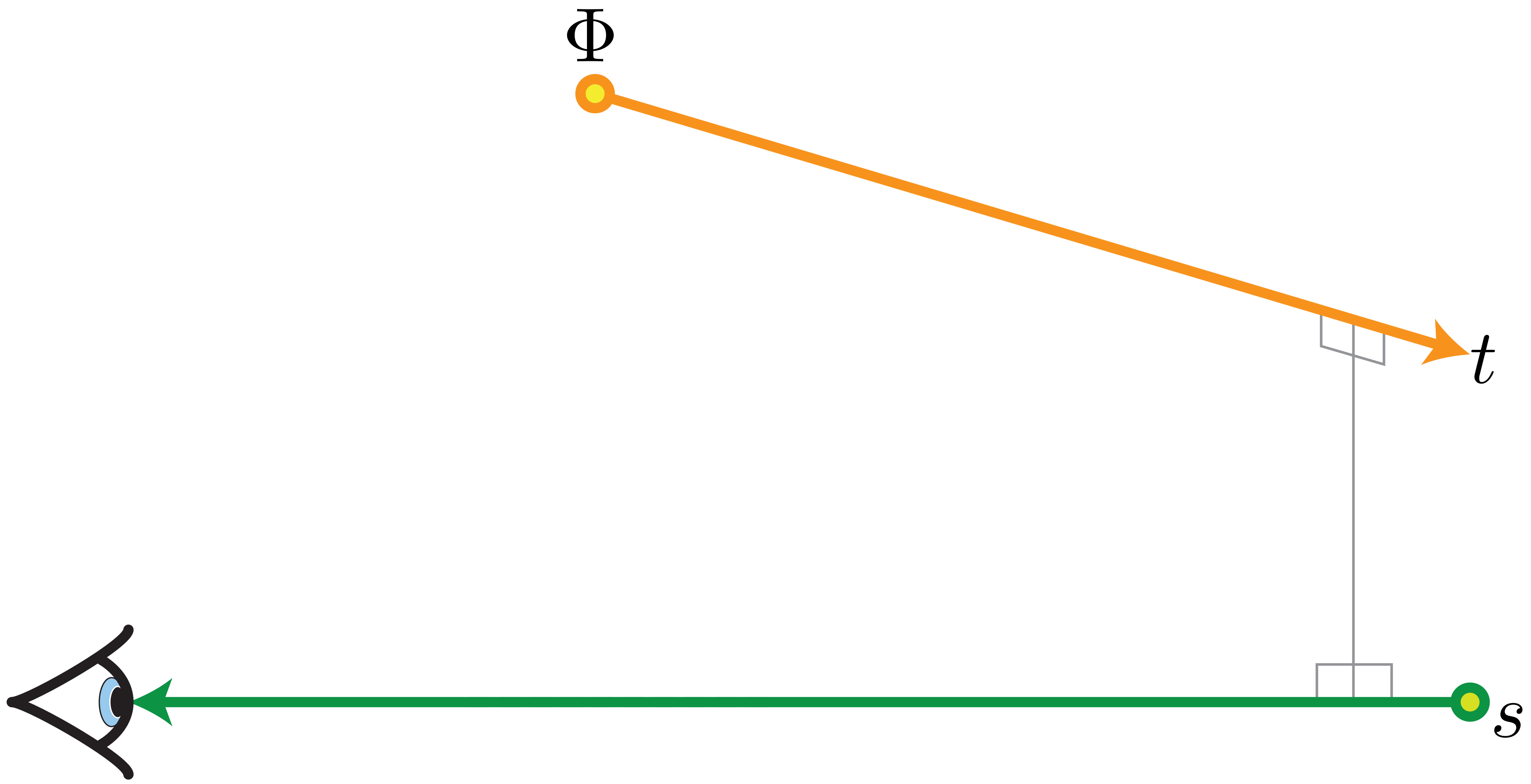


Ray-to-Ray transport



Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \rule{10em}{0.4pt}\, \mathrm{d}v\mathrm{d}u$$



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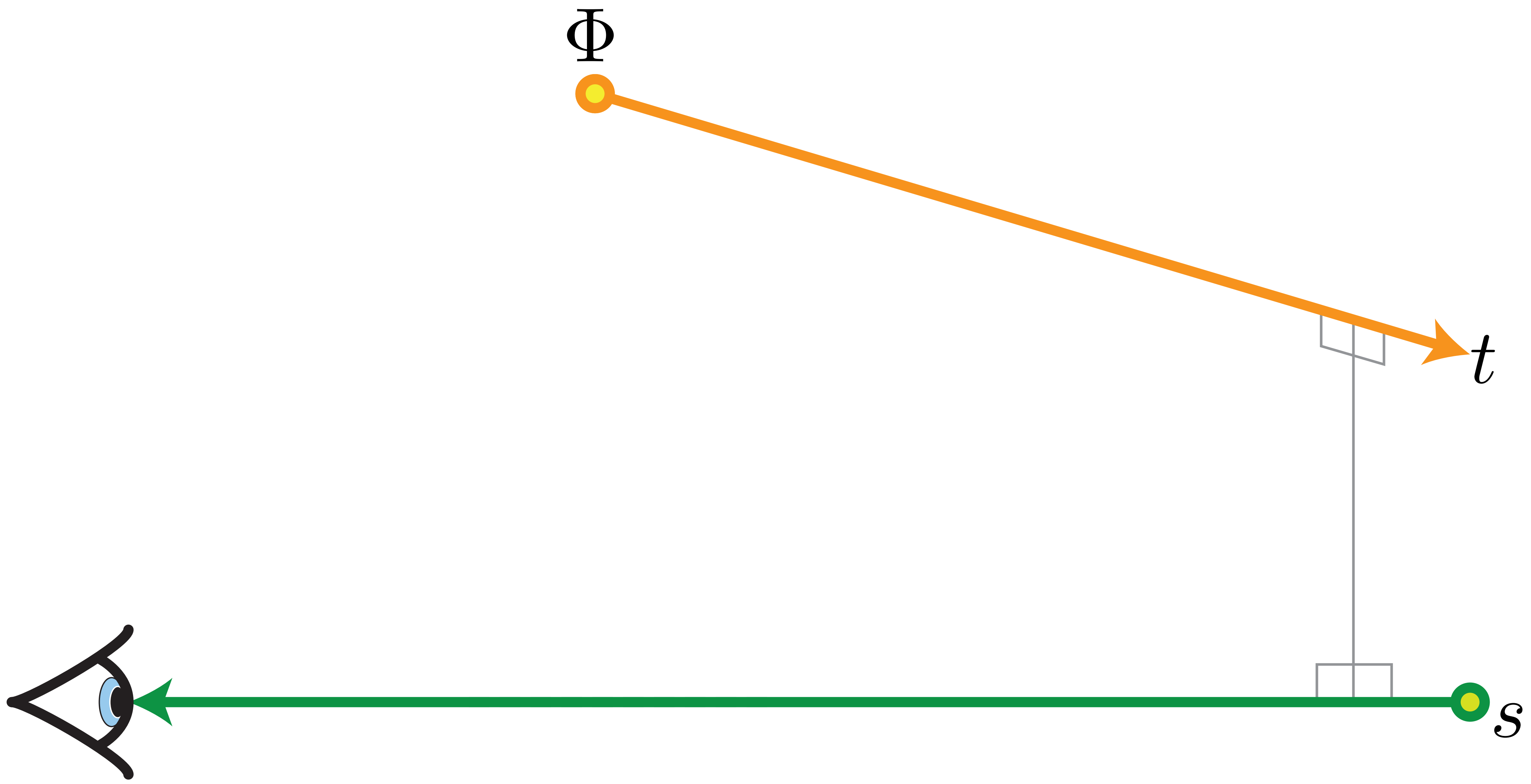
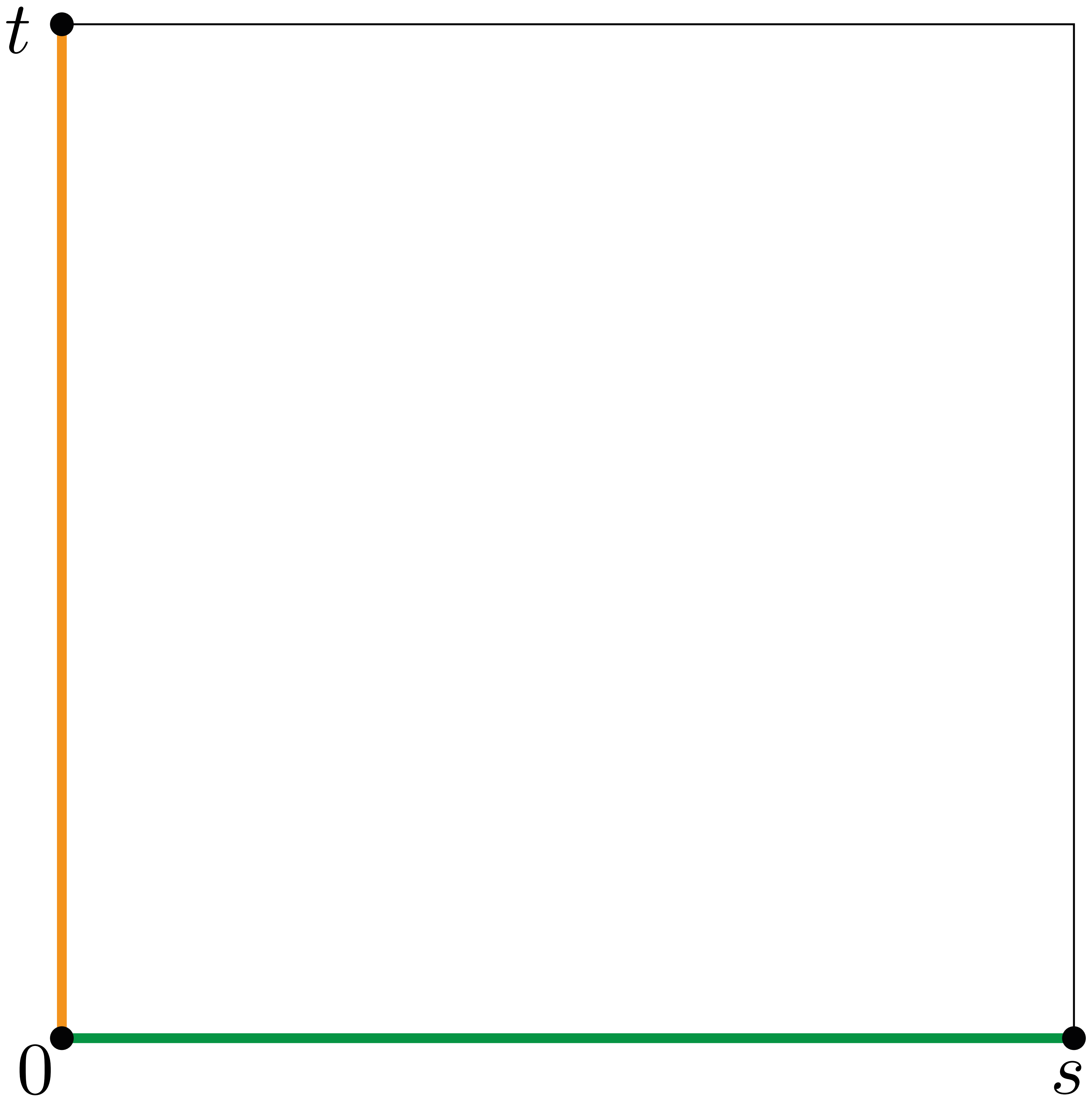
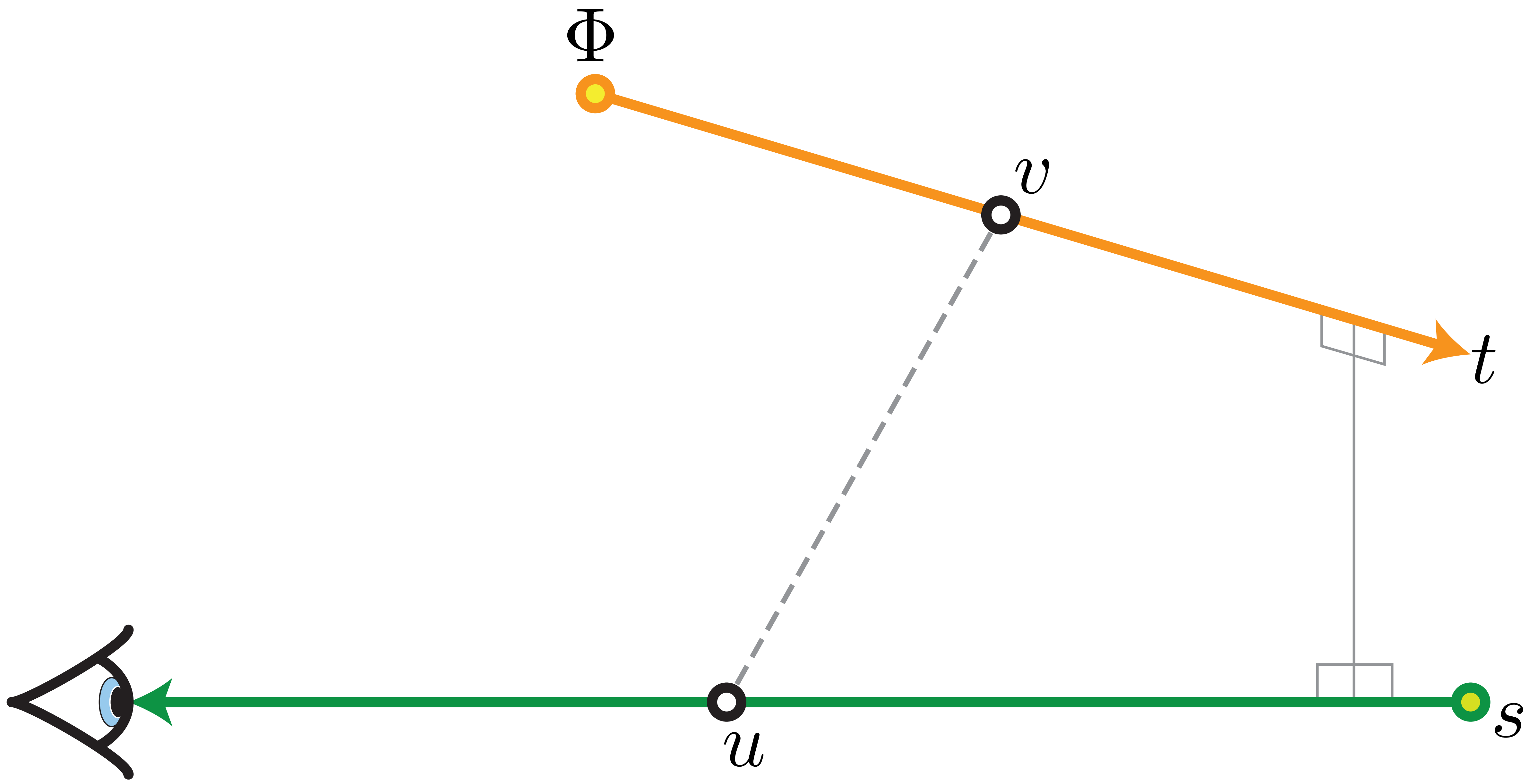
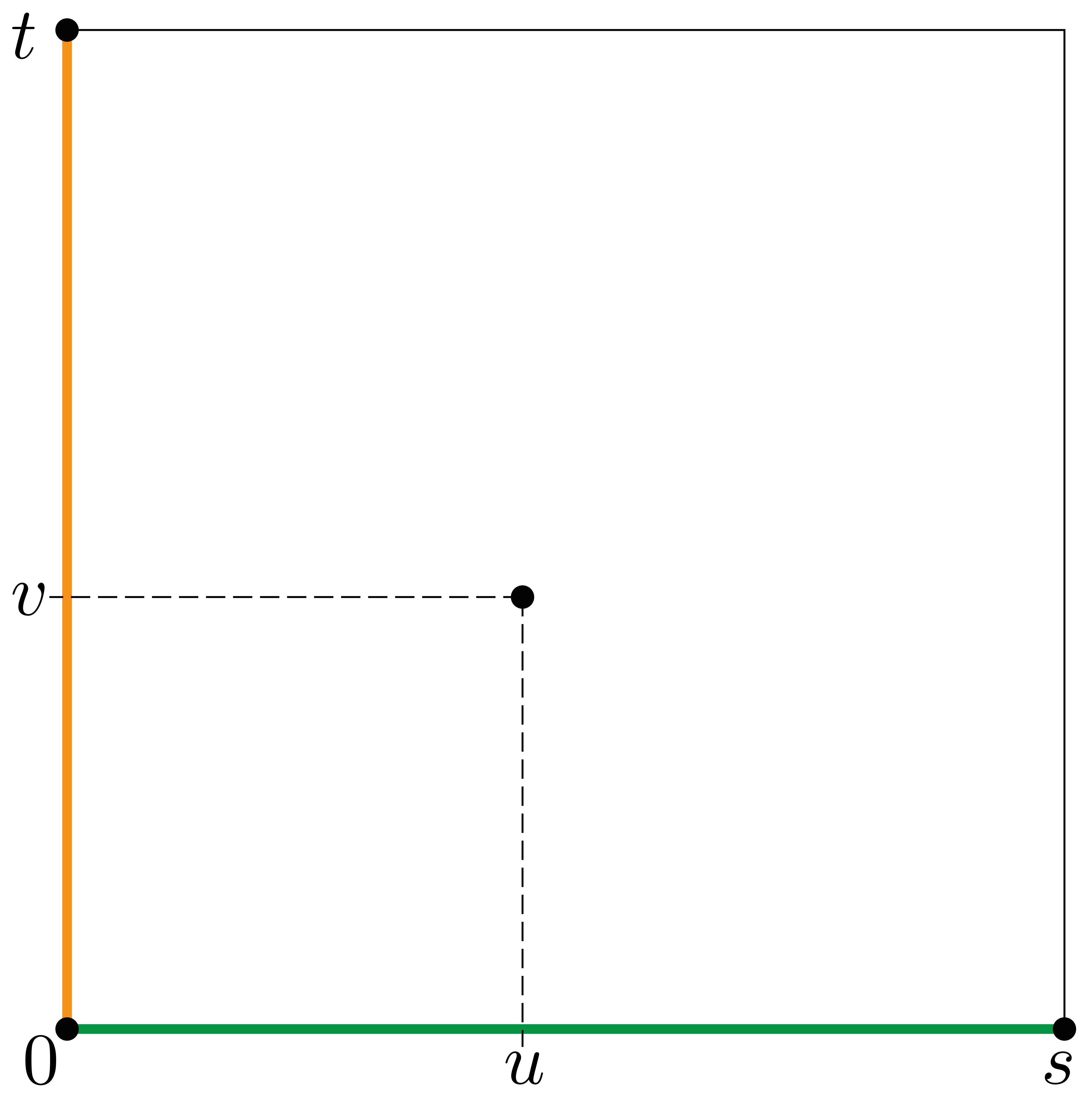




Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{\quad}{\quad} \mathrm{d}v\mathrm{d}u$$

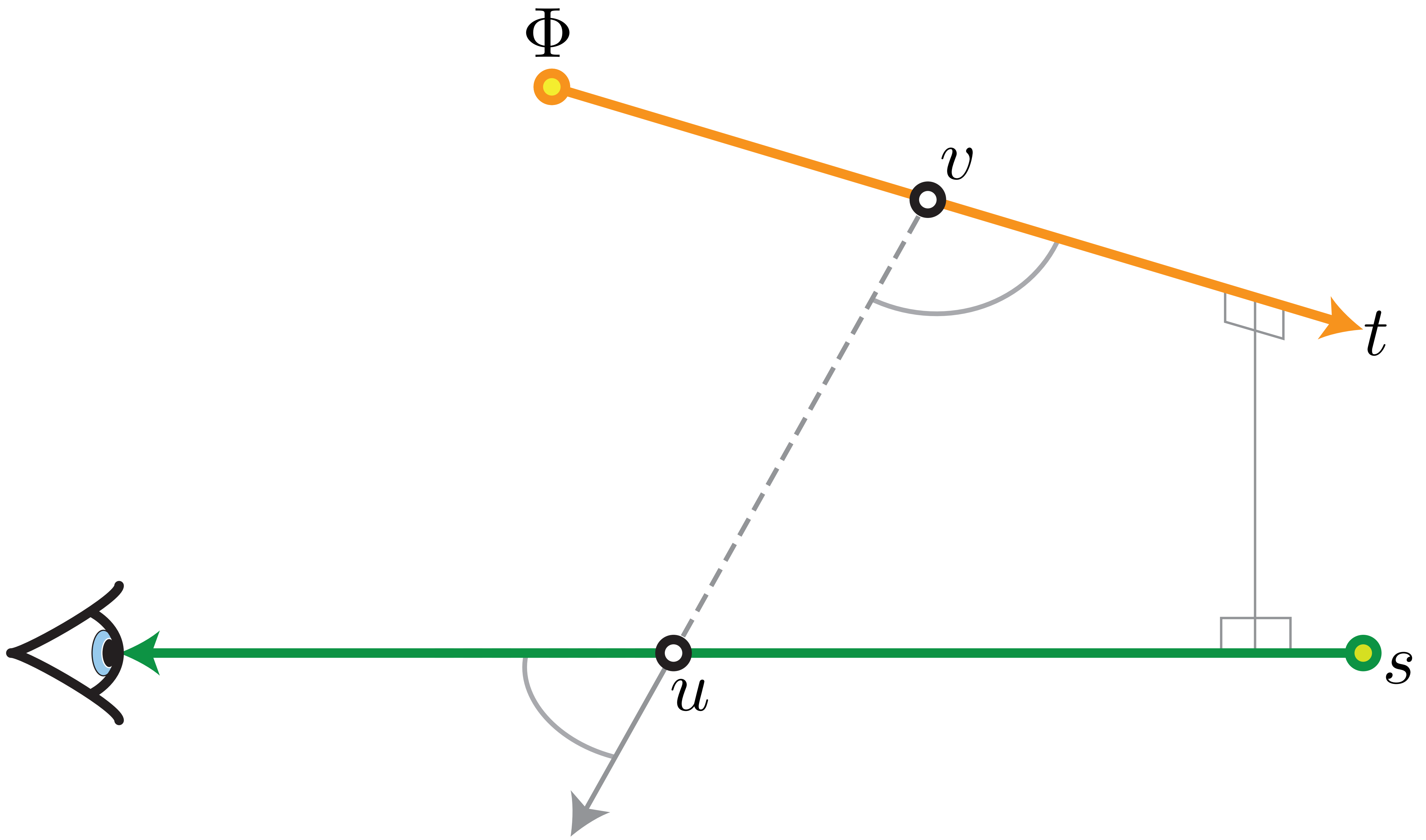


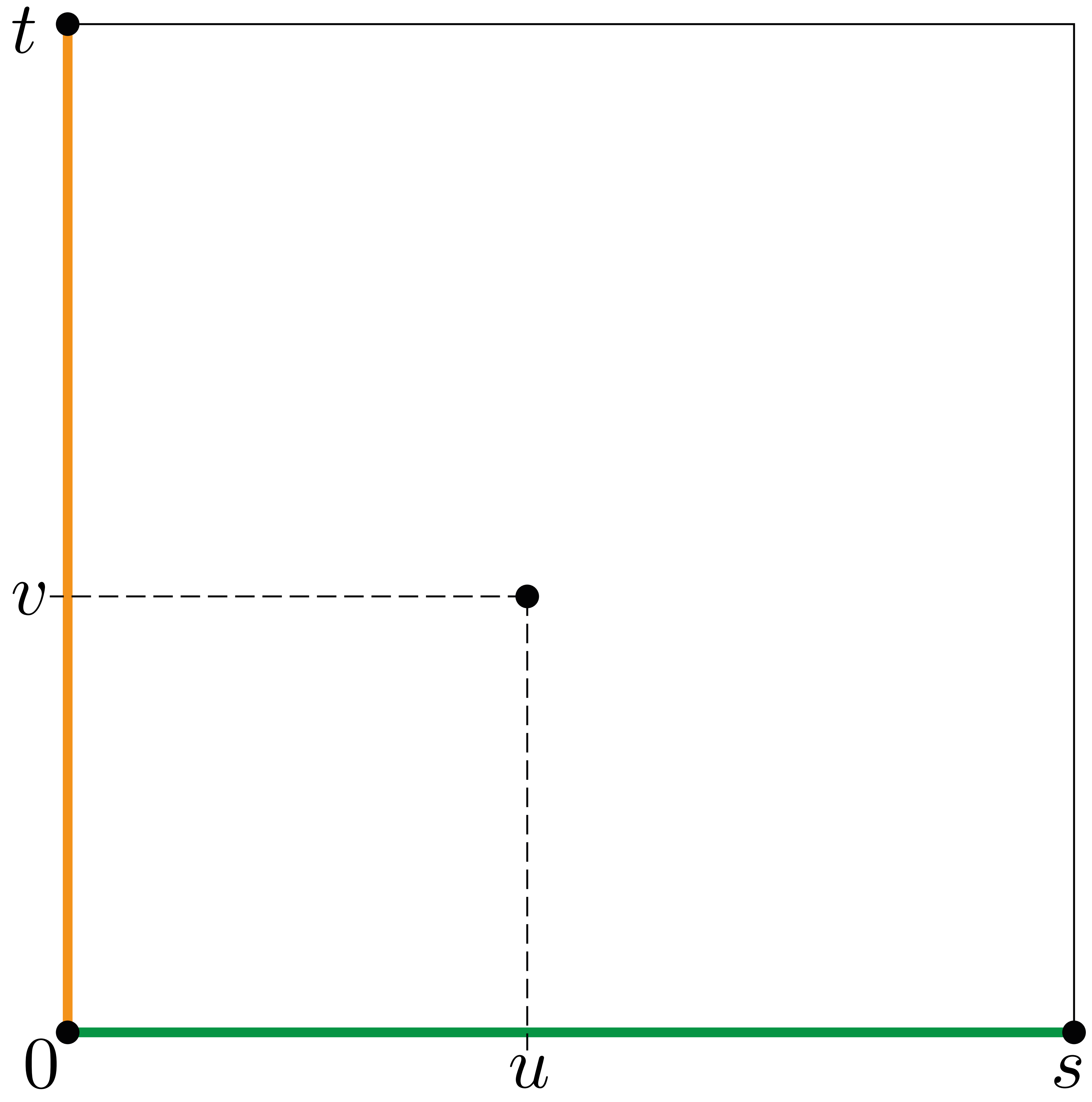


Ray-to-Ray transport

phase functions

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)}{} \mathrm{d}v\mathrm{d}u$$





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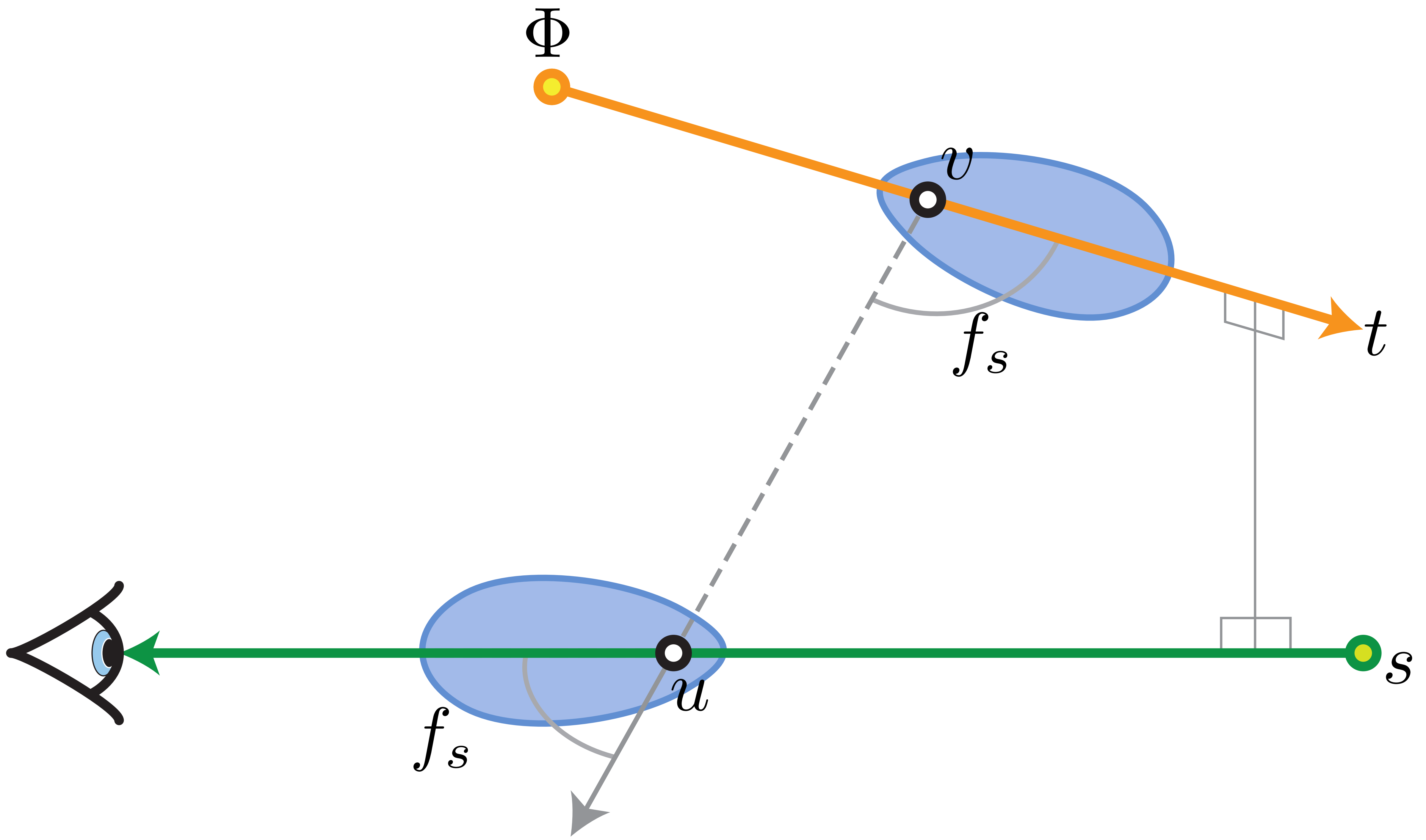

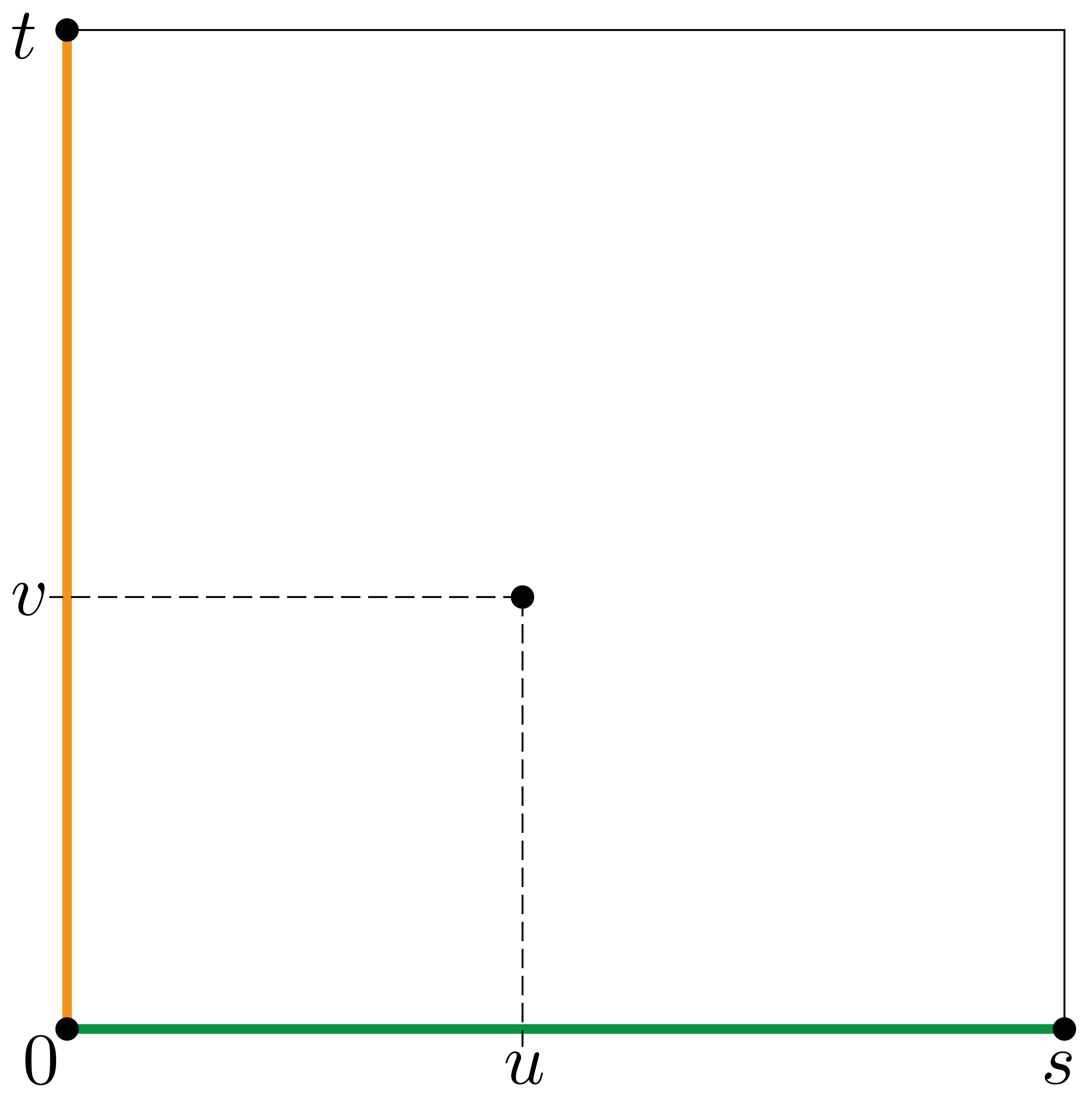

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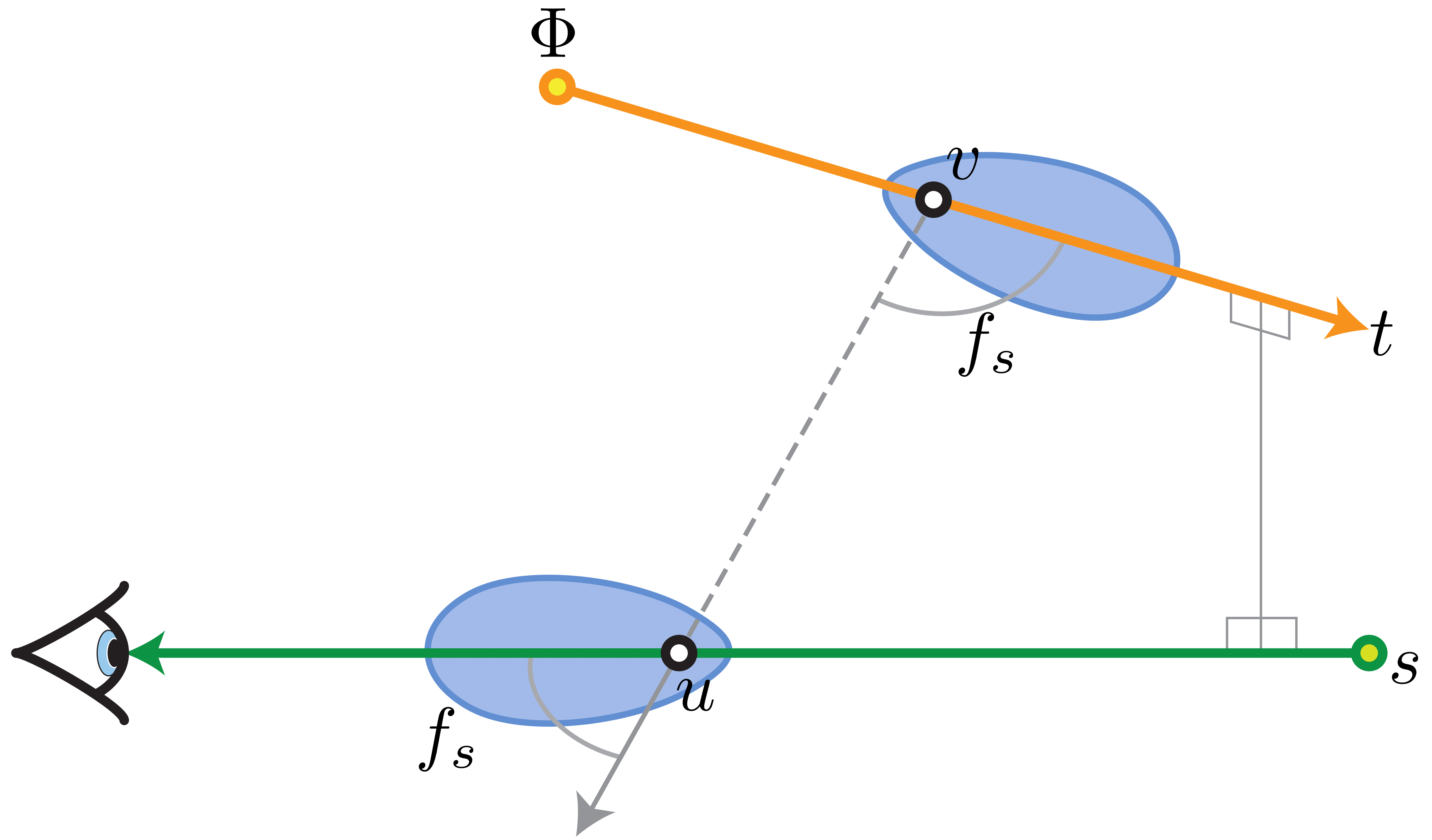
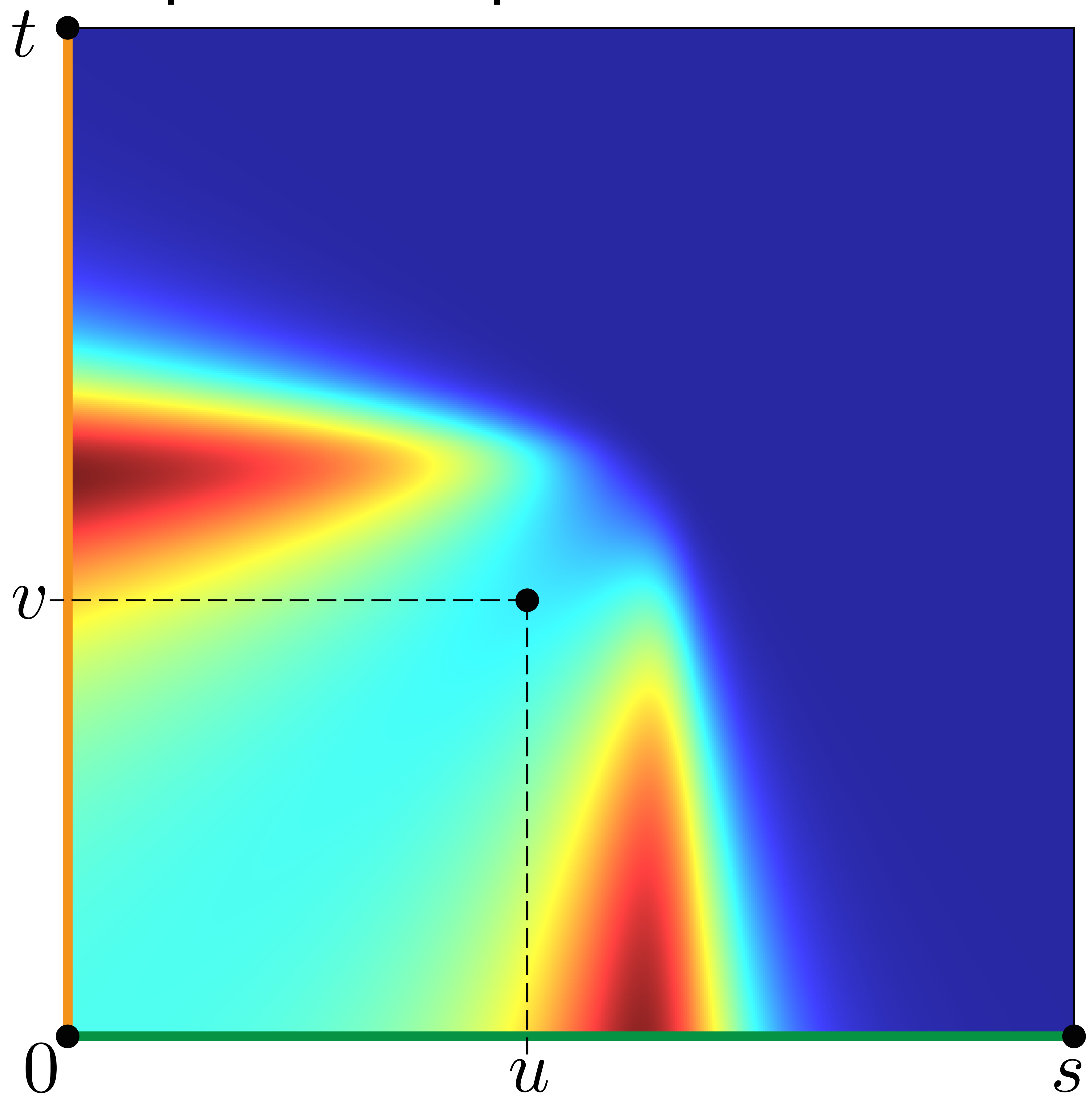
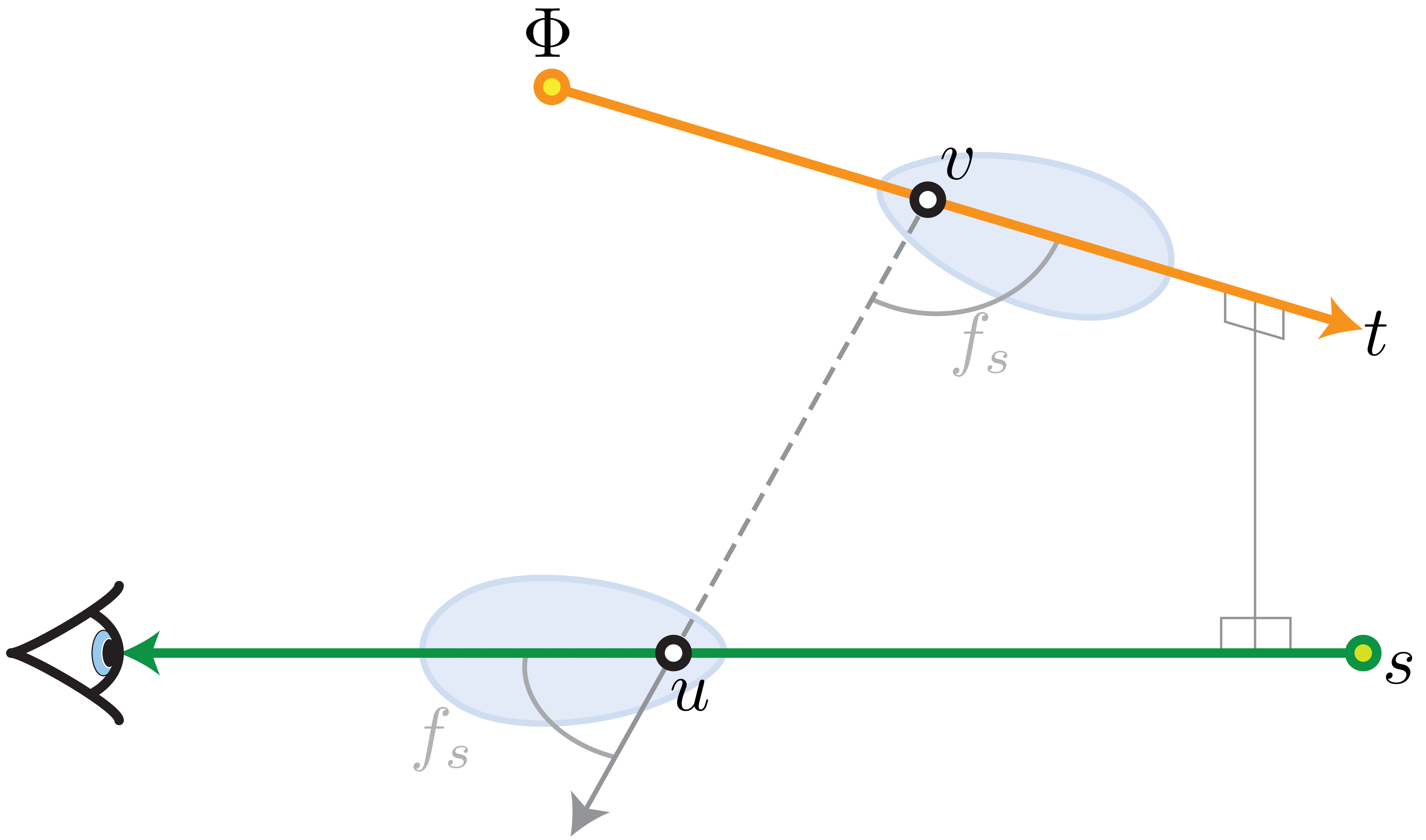


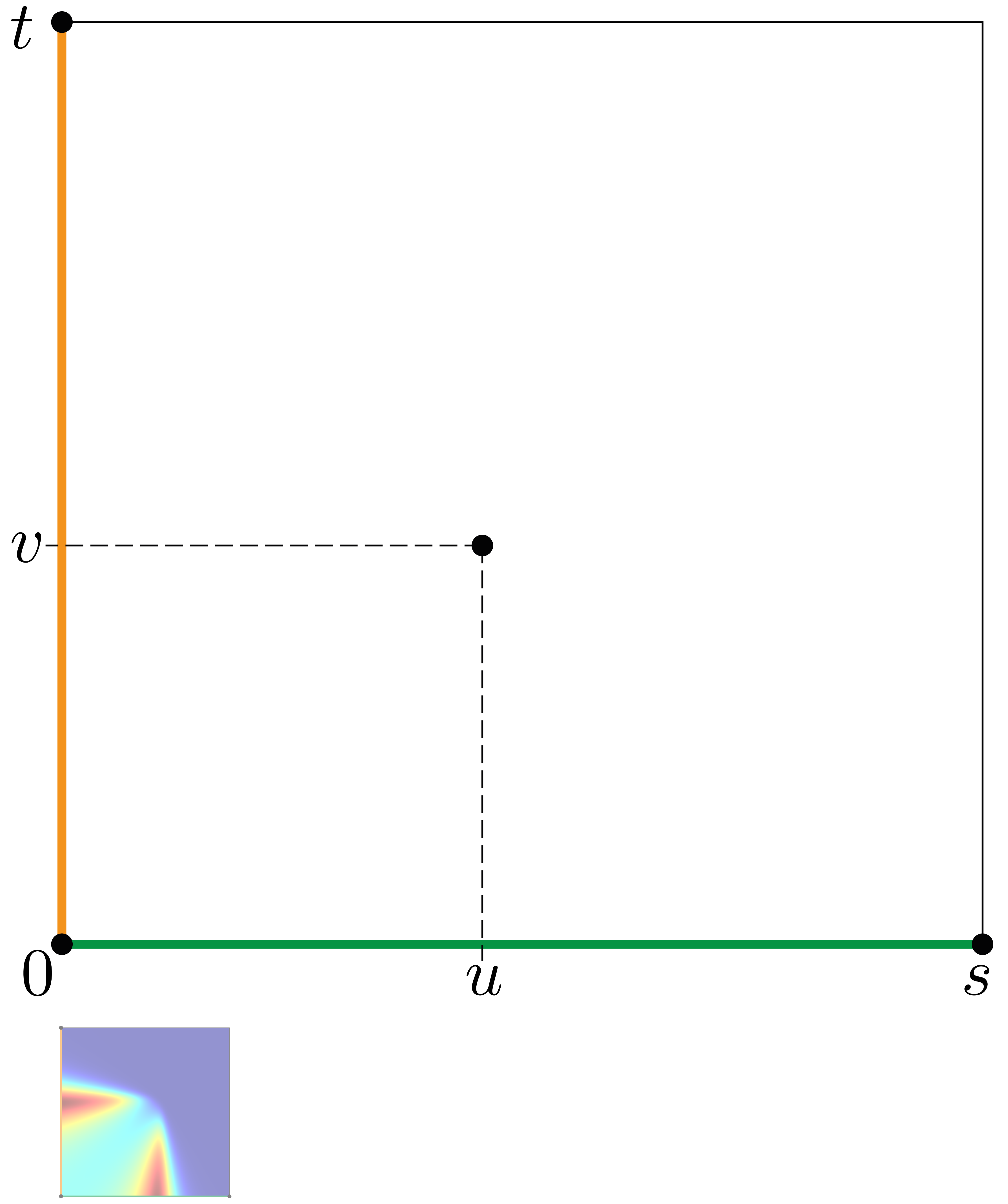
product of phase functions



Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)}{\qquad\qquad} \mathrm{d}v\mathrm{d}u$$

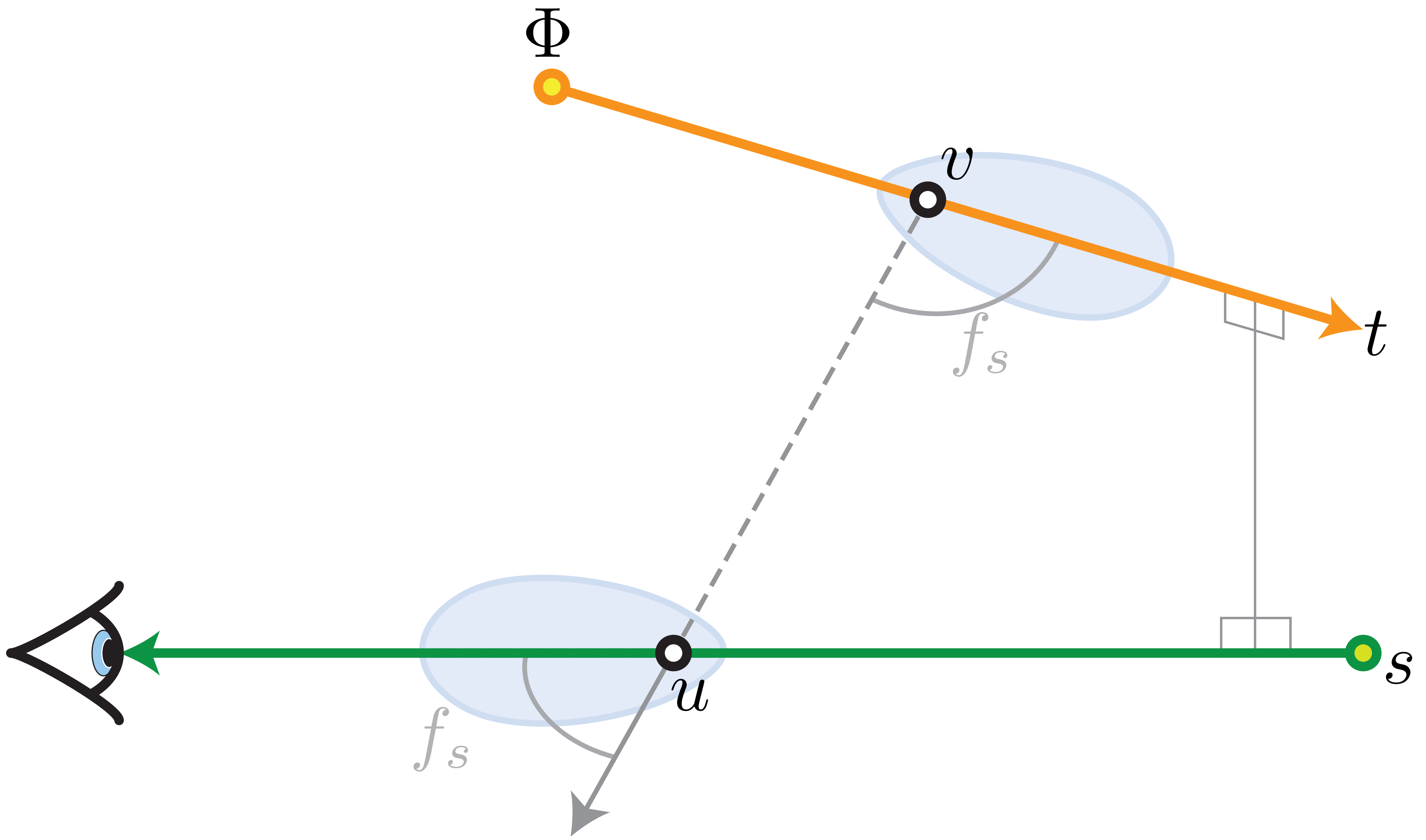


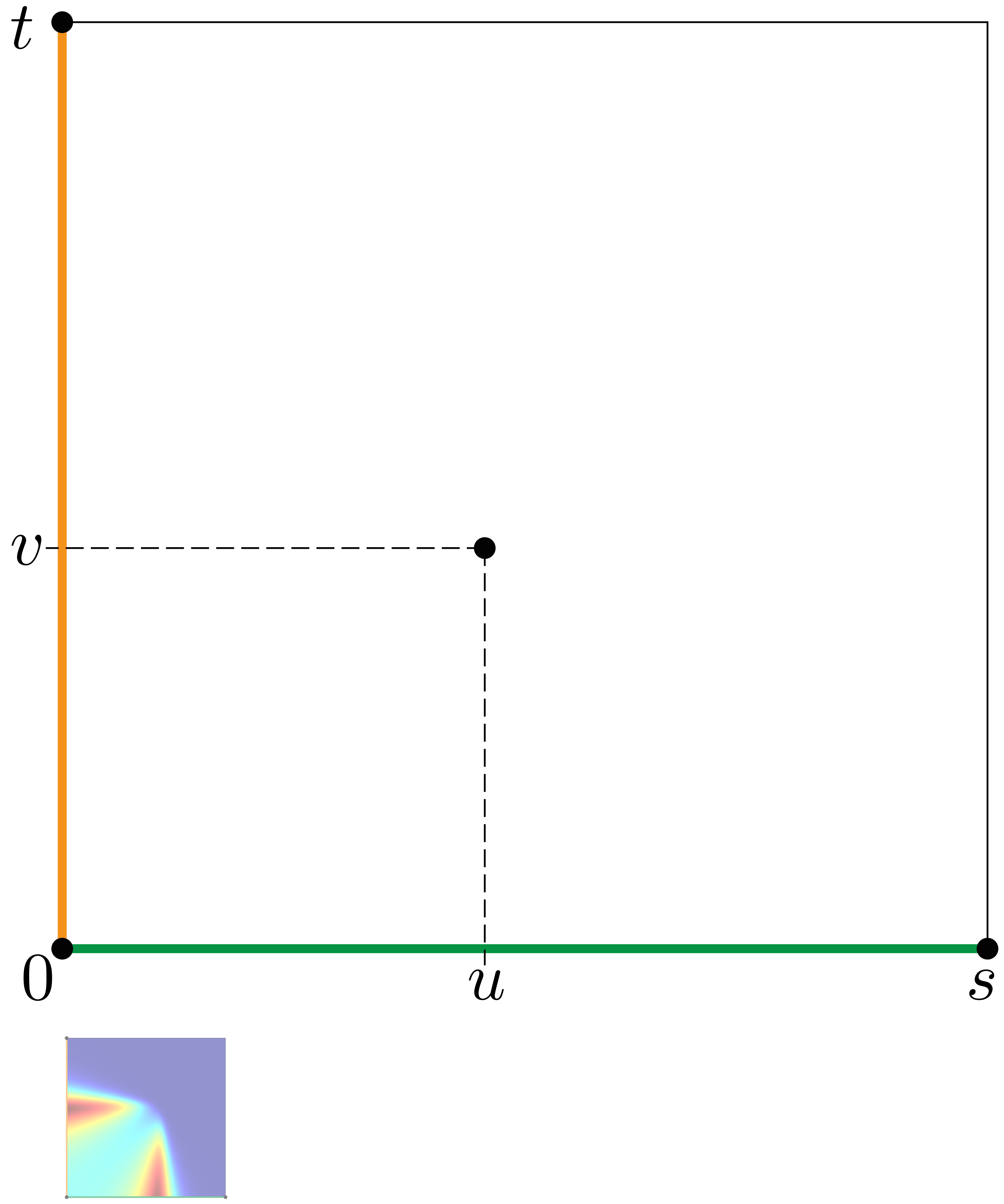


Ray-to-Ray transport

scattering

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)}{} \mathrm{d}v \mathrm{d}u$$

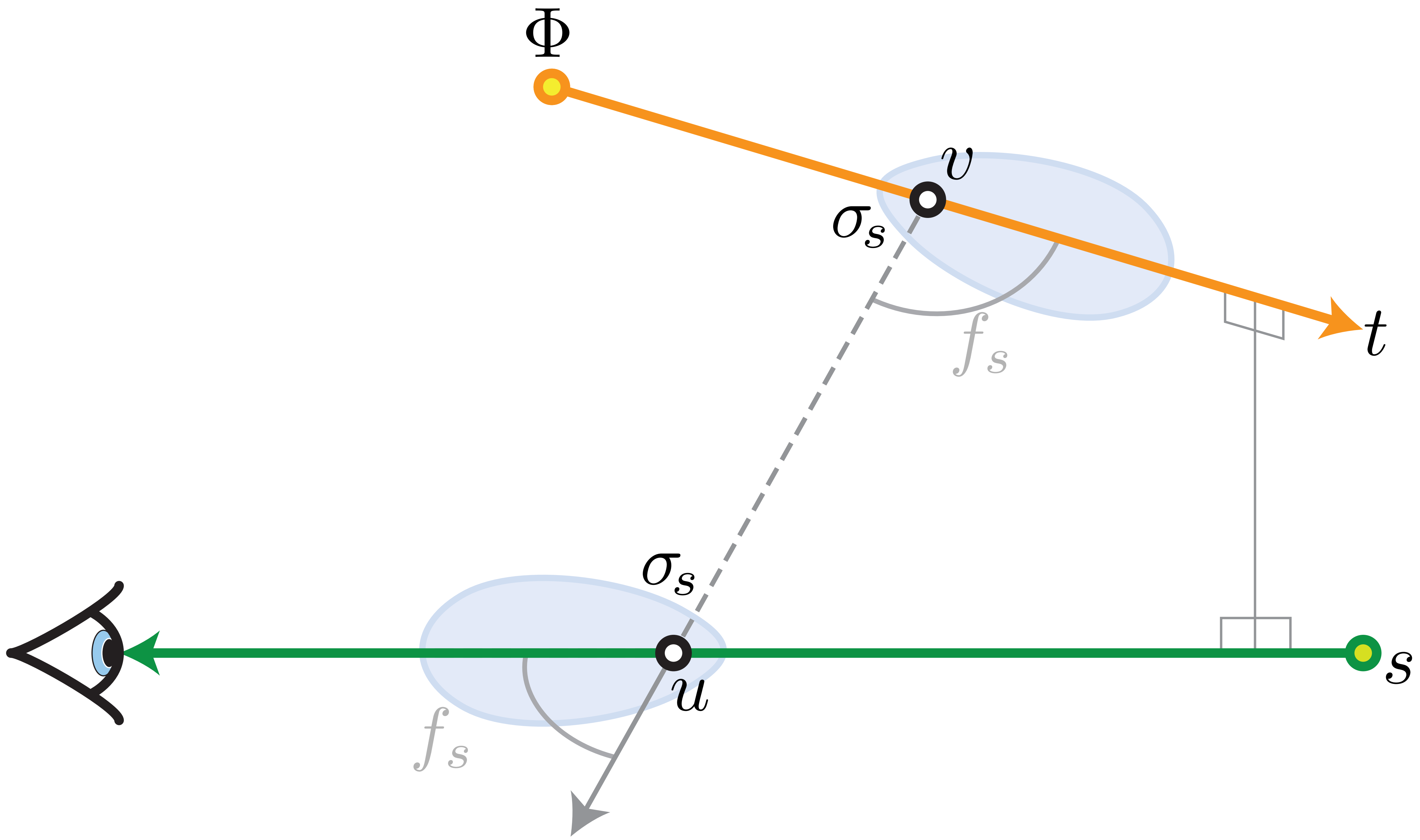


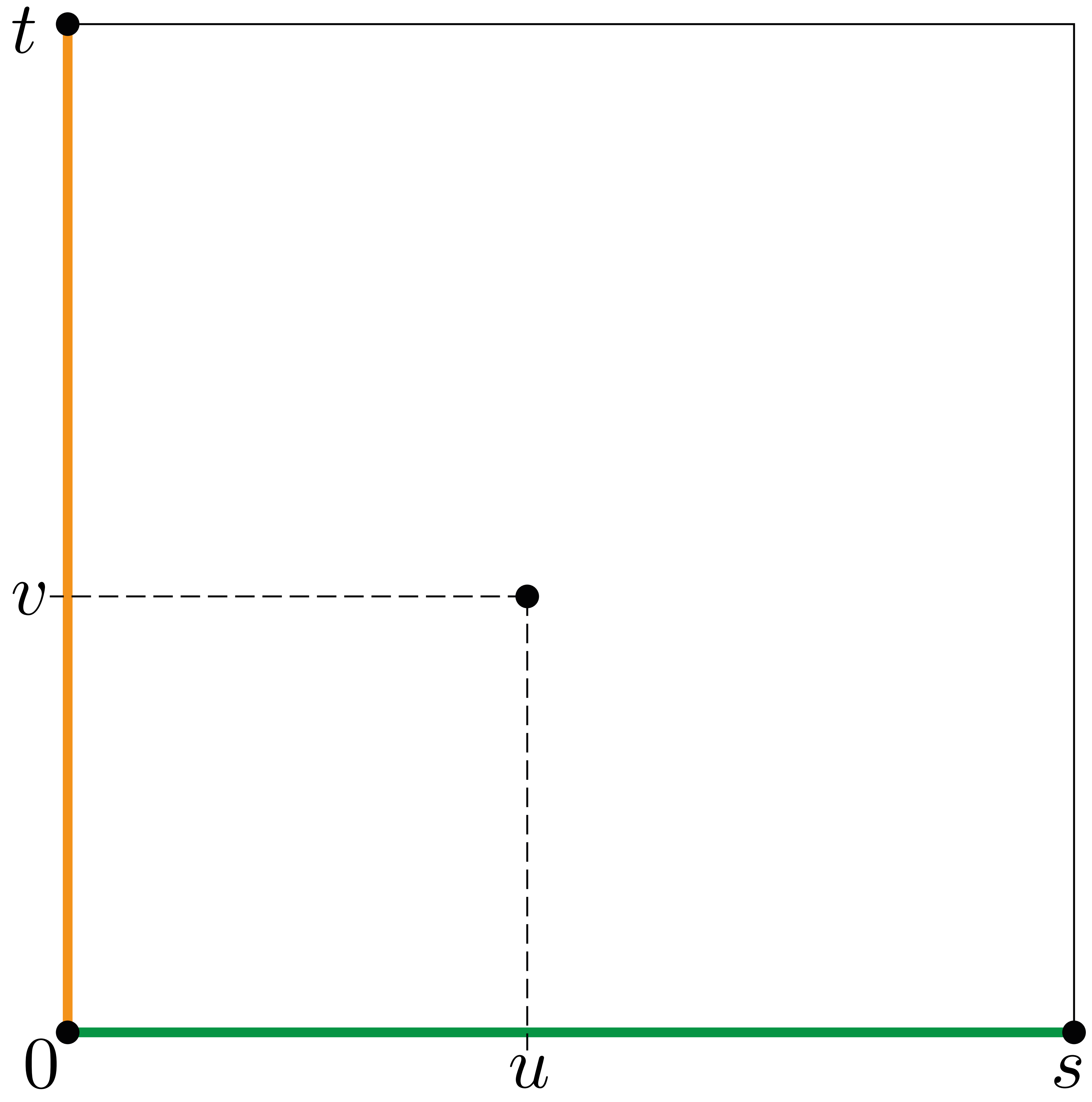


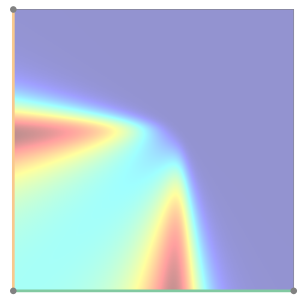
Ray-to-Ray transport

scattering

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)}{\qquad\qquad\qquad\qquad\qquad\qquad\qquad} \mathrm{d}v\mathrm{d}u$$



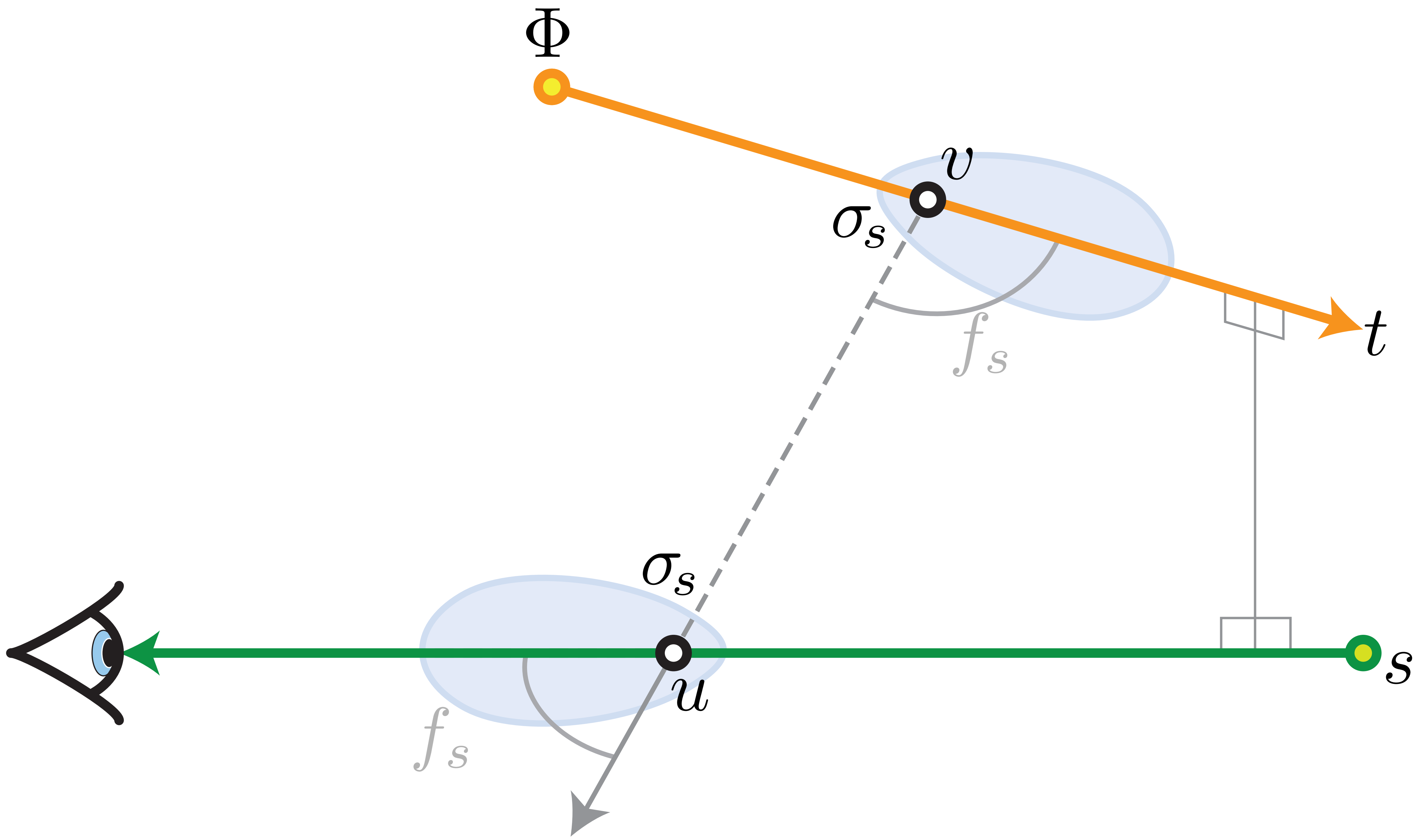




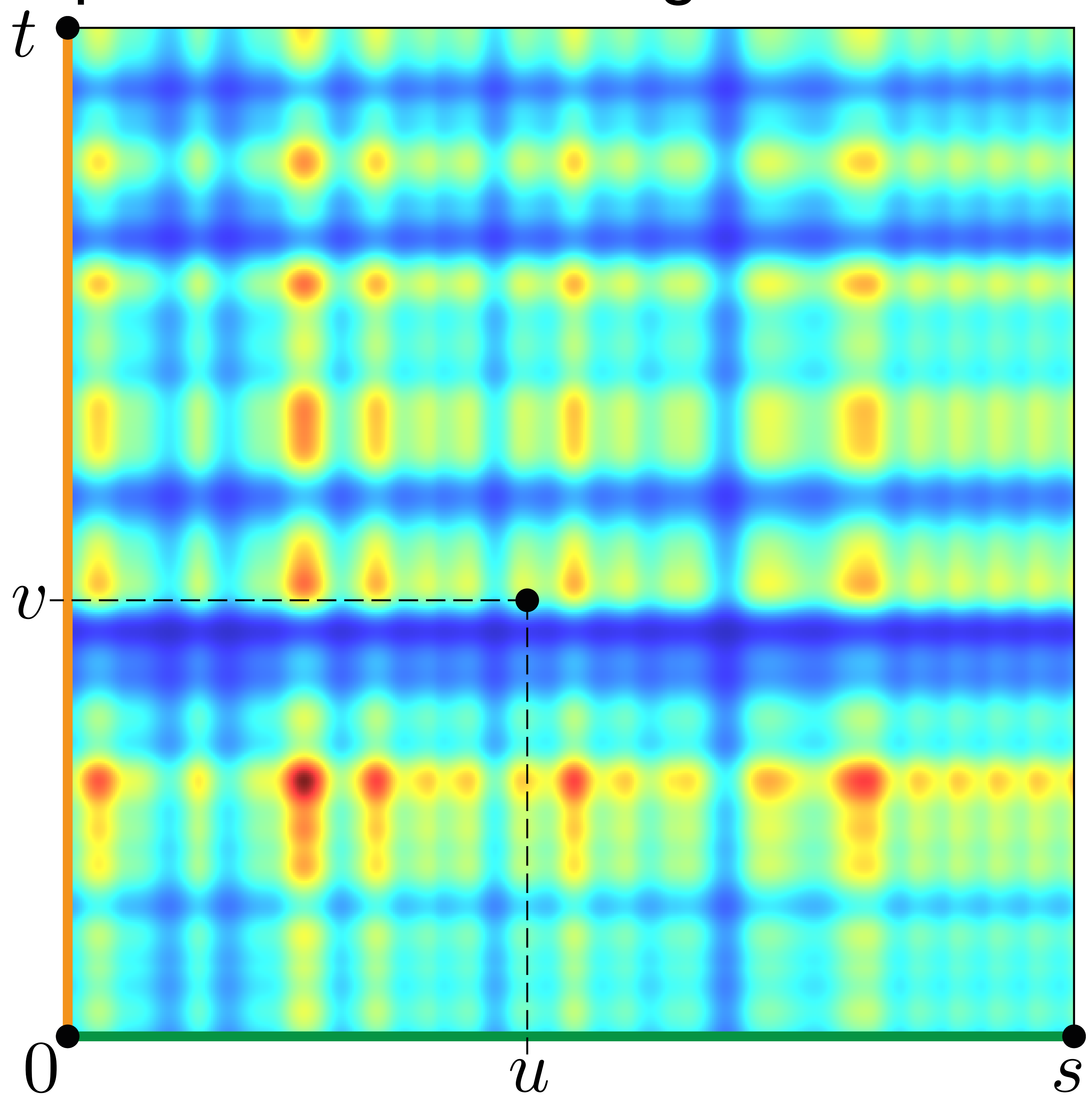
Ray-to-Ray transport

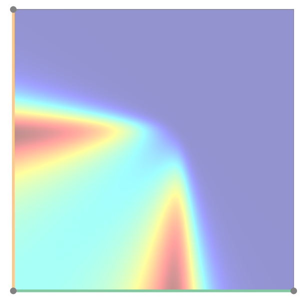
scattering

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)}{} \mathrm{d}v\mathrm{d}u$$



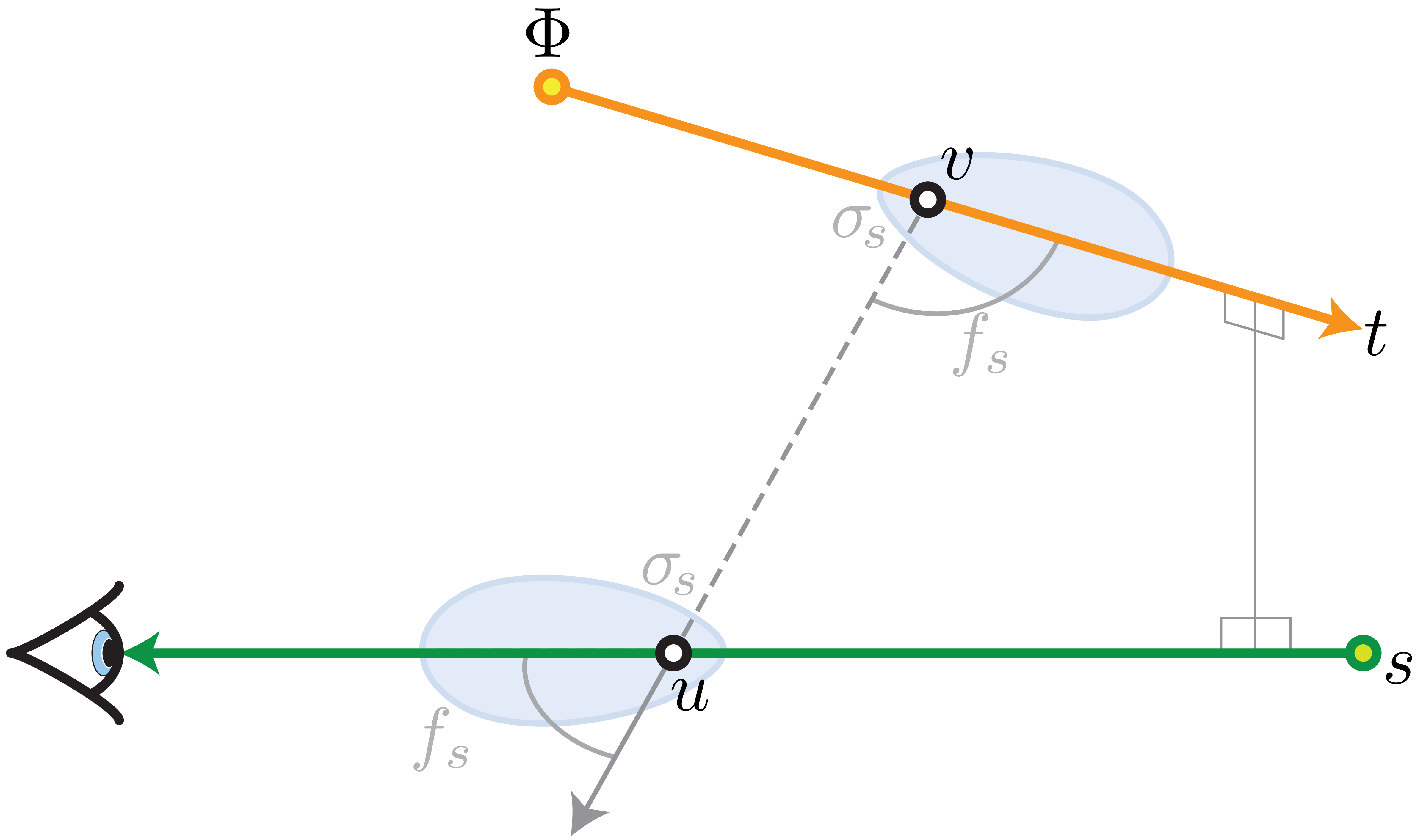
product of scattering coefficients

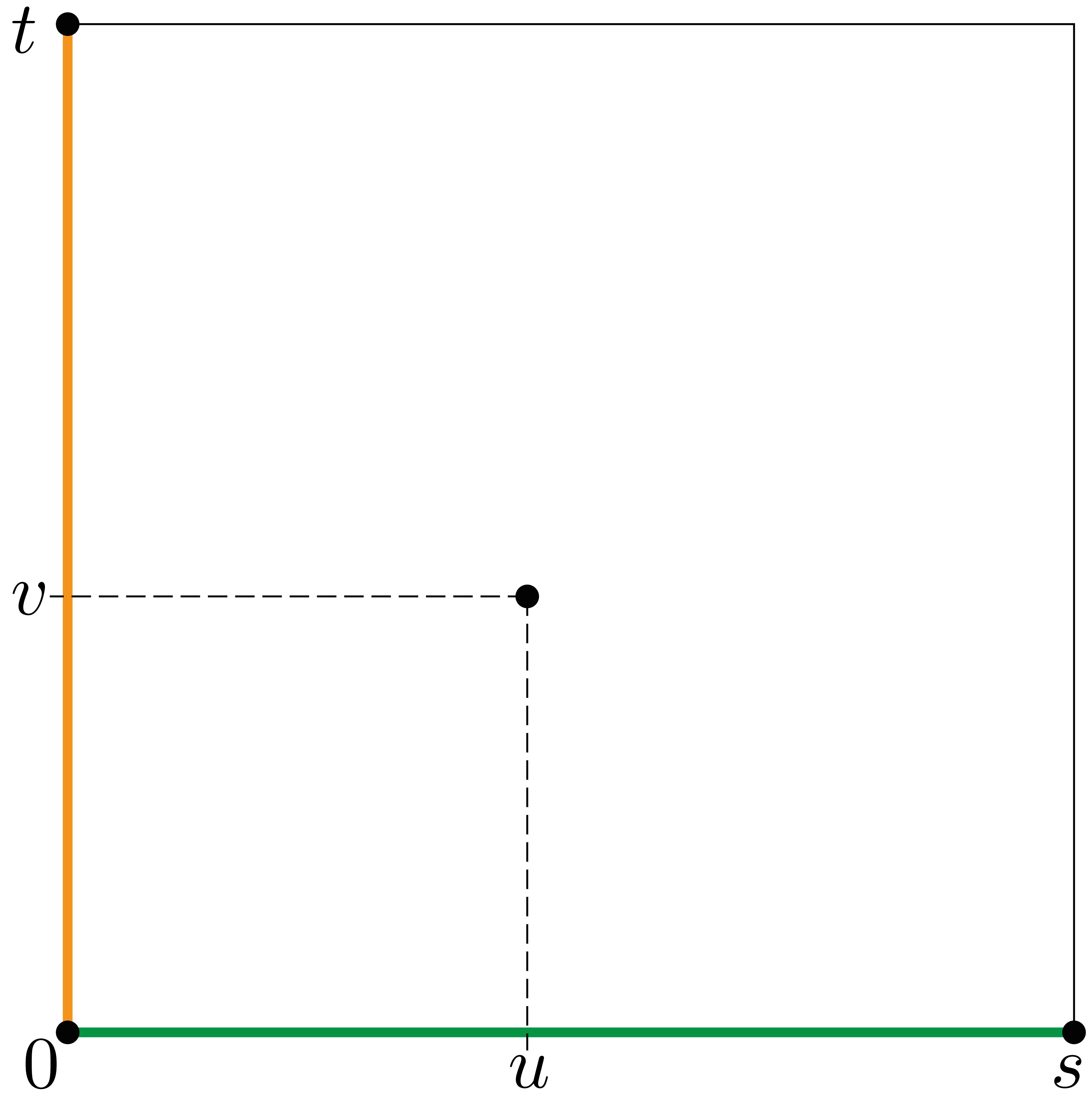


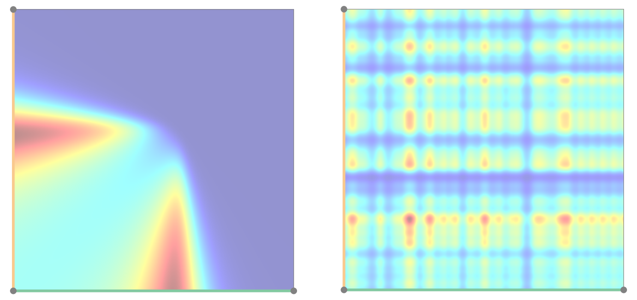


Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)}{} \mathrm{d}v\mathrm{d}u$$



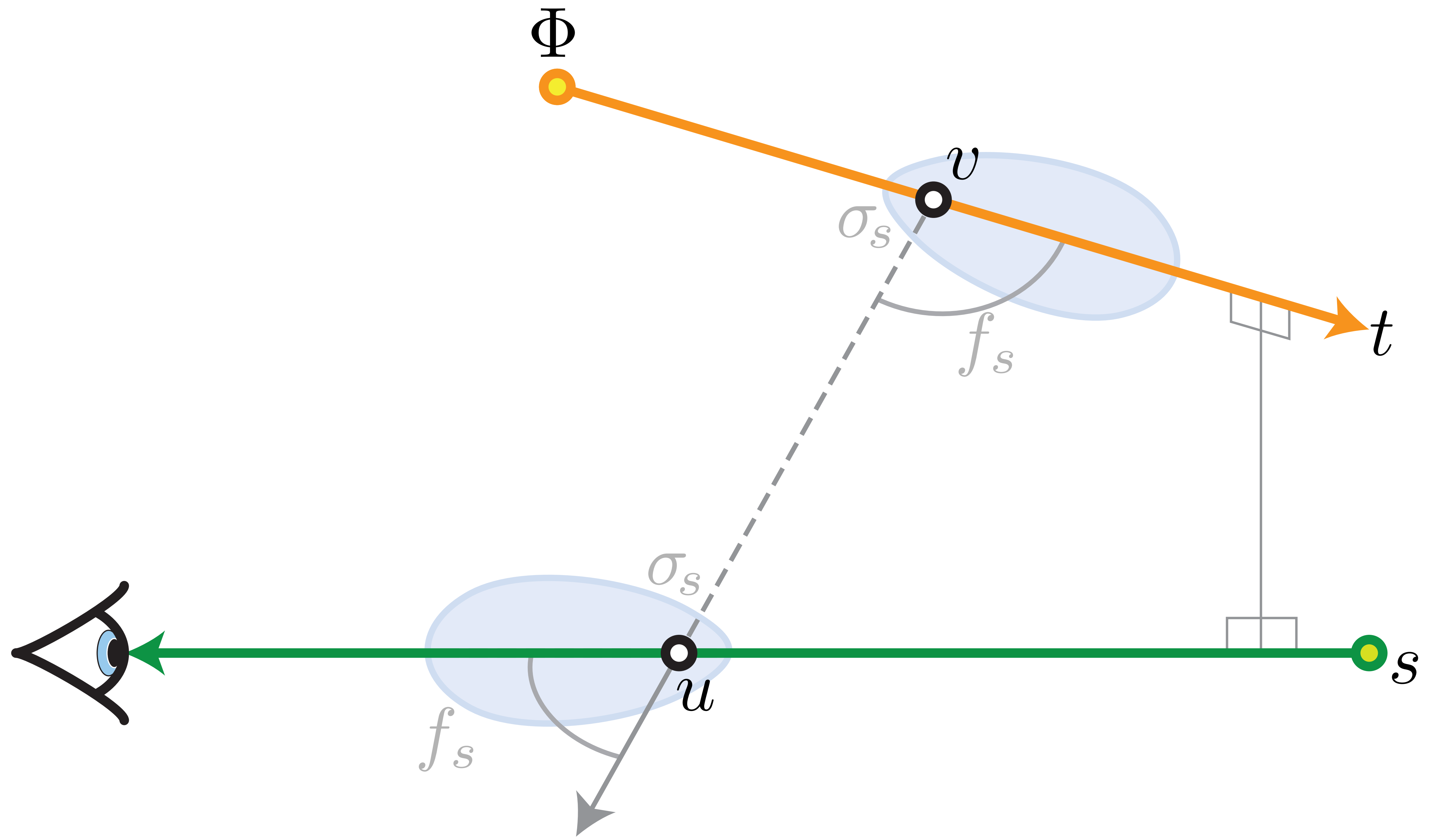


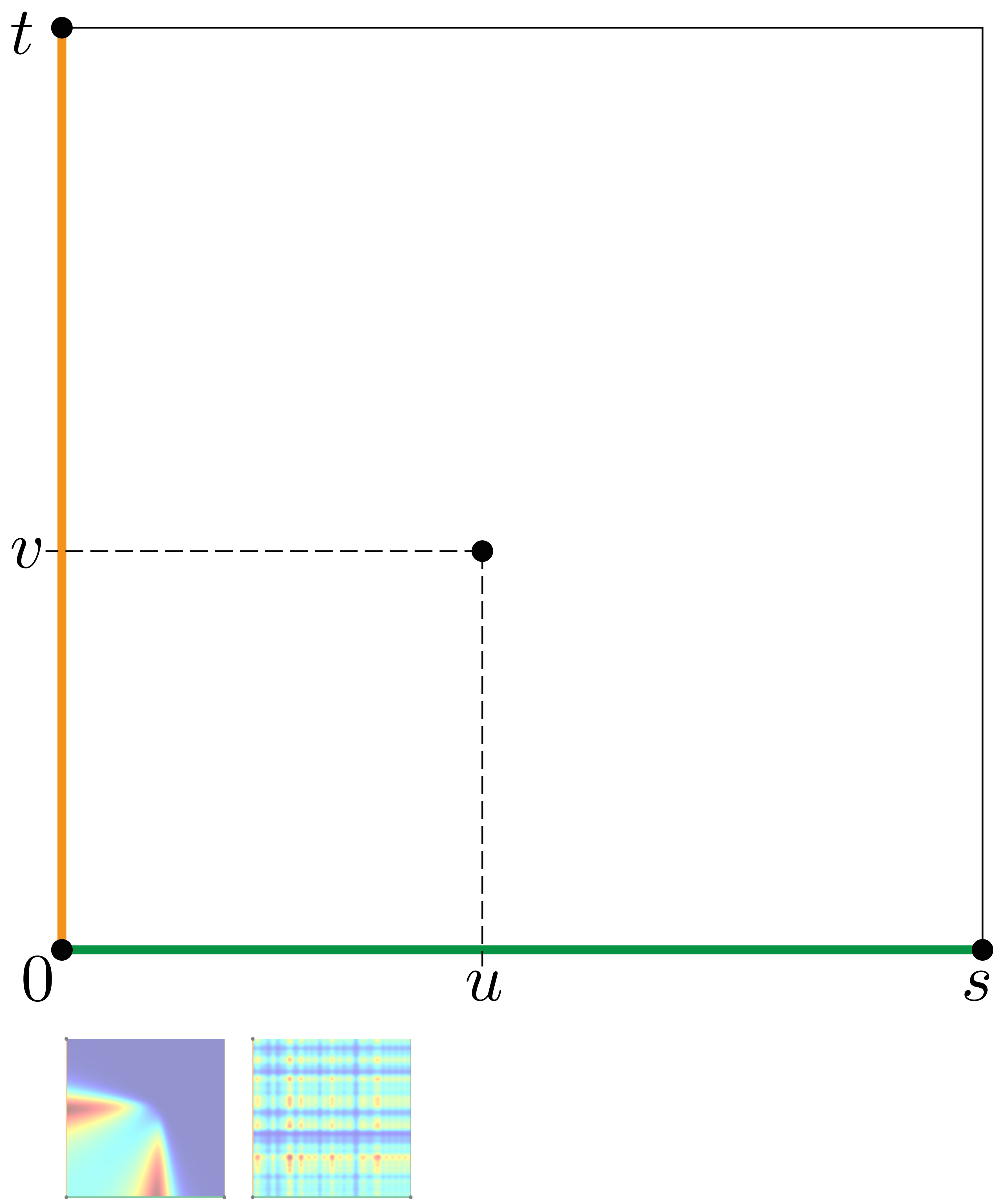


Ray-to-Ray transport

transmittance

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)\, T(u)T(v)T(w)}{} \mathrm{d}v\mathrm{d}u$$

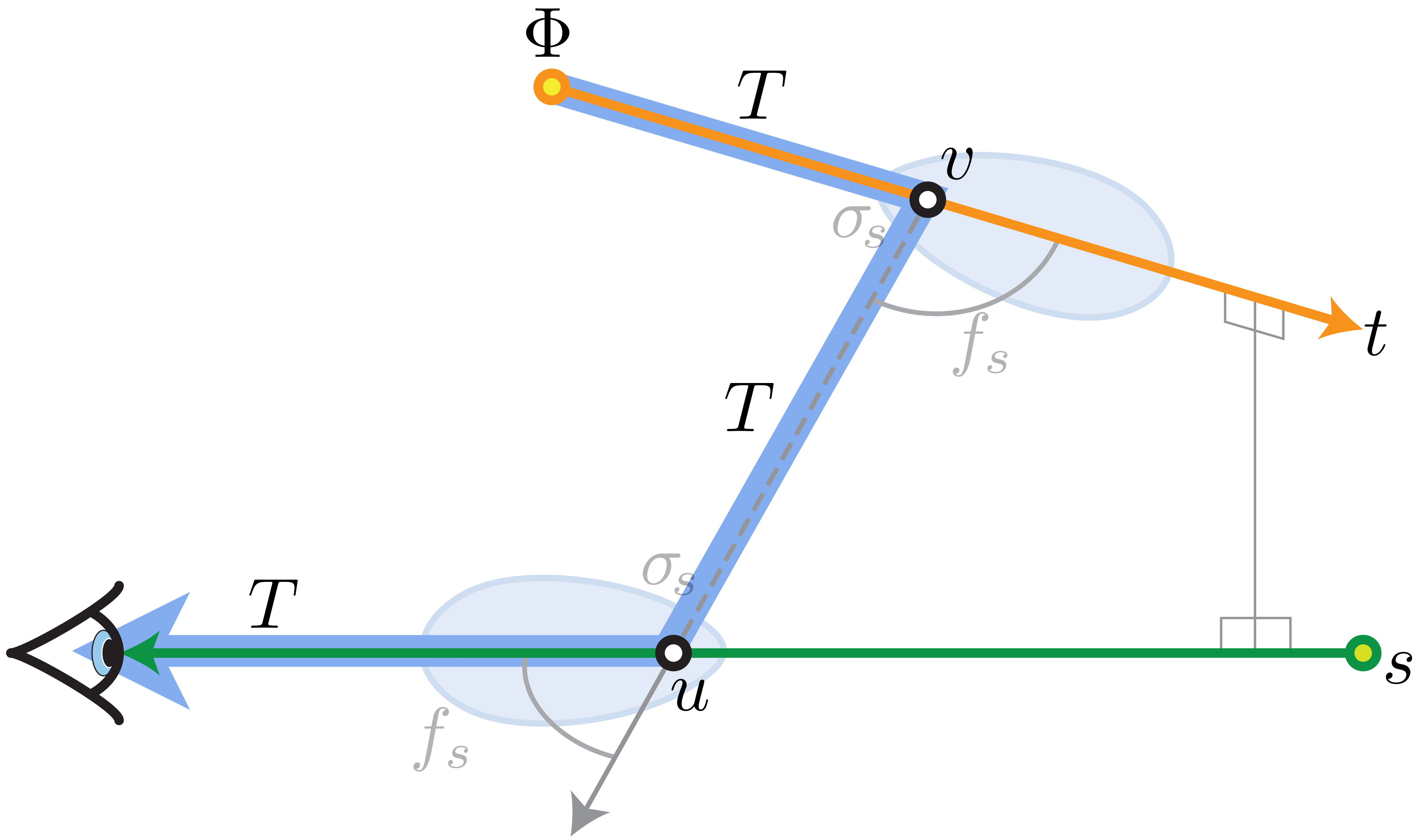


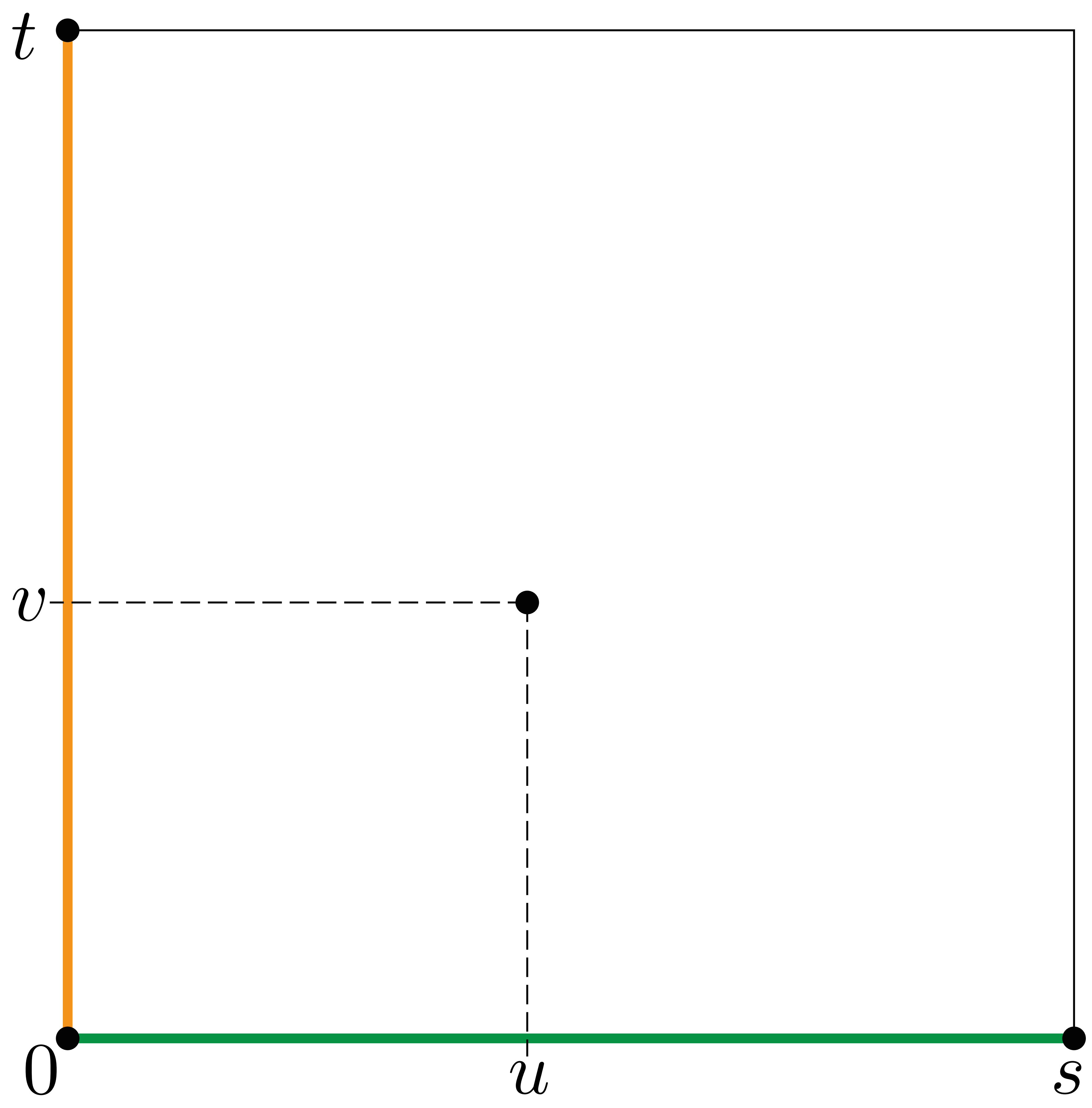


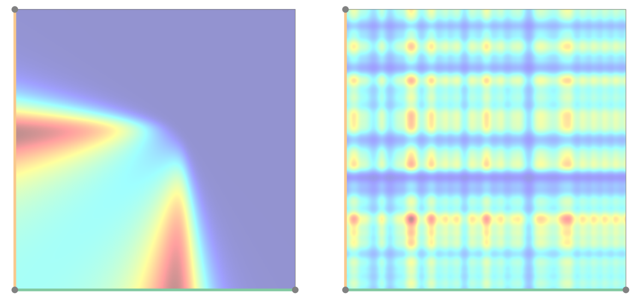
Ray-to-Ray transport

transmittance

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)\, T(u)T(v)T(w)}{} \mathrm{d}v\mathrm{d}u$$



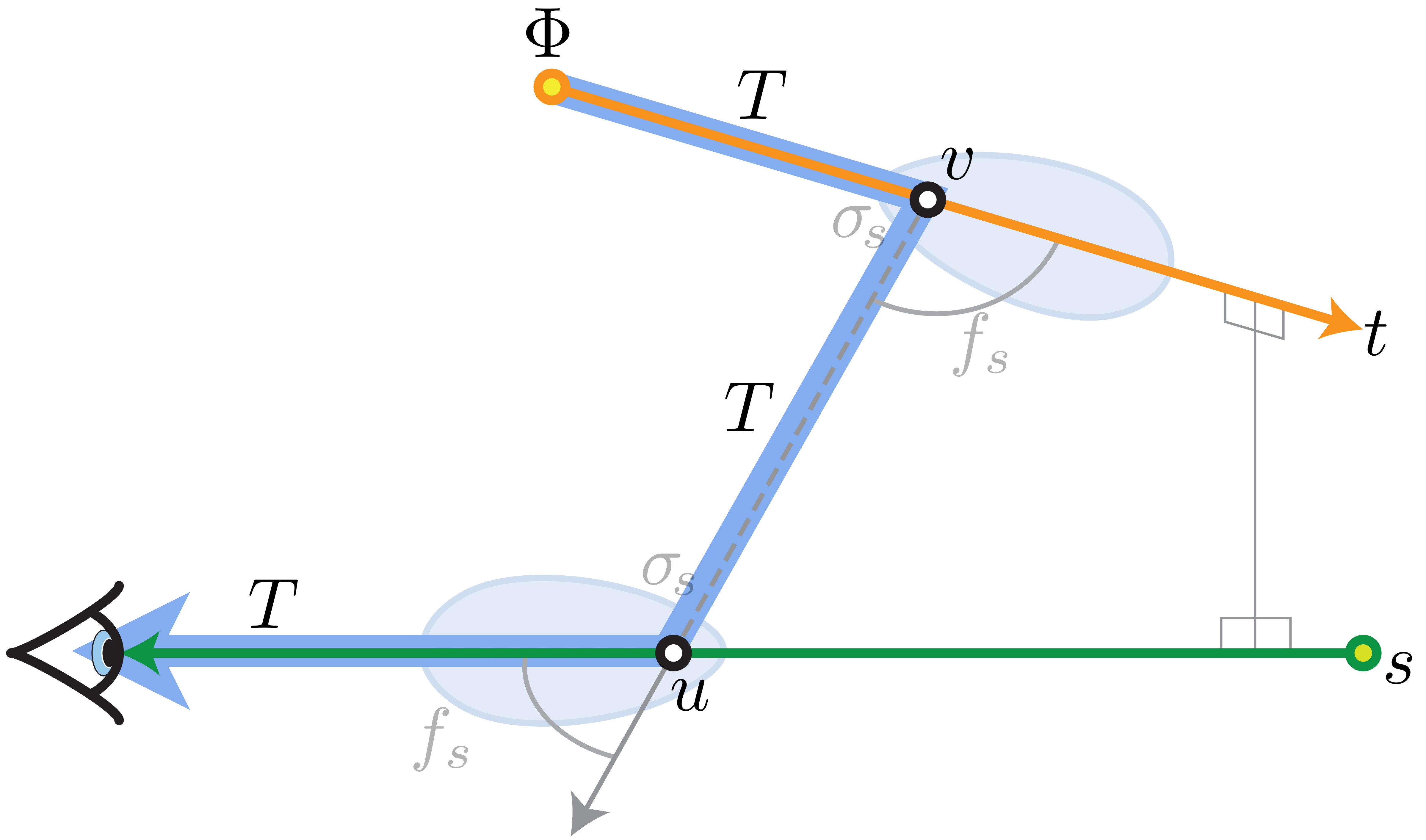


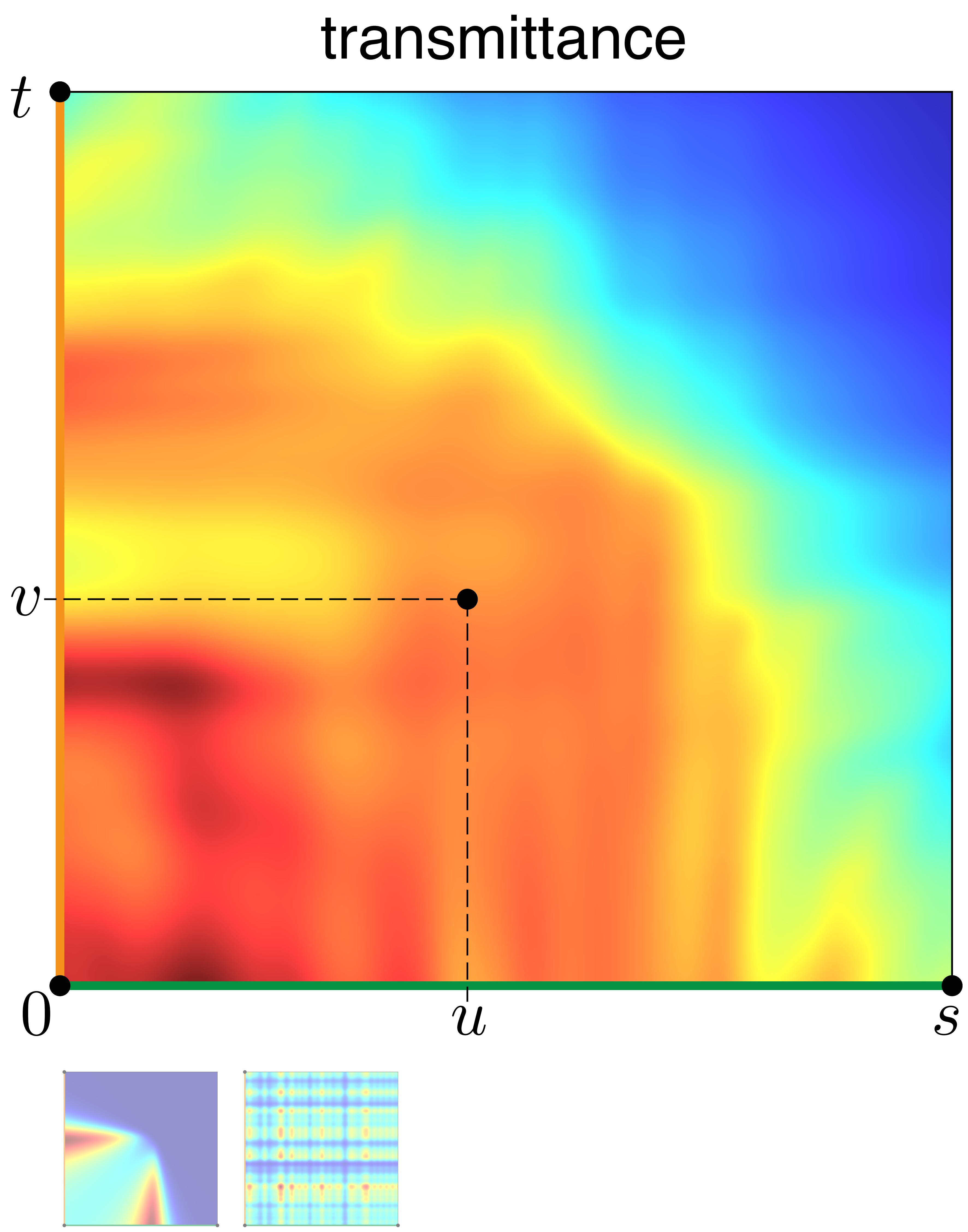


Ray-to-Ray transport

transmittance

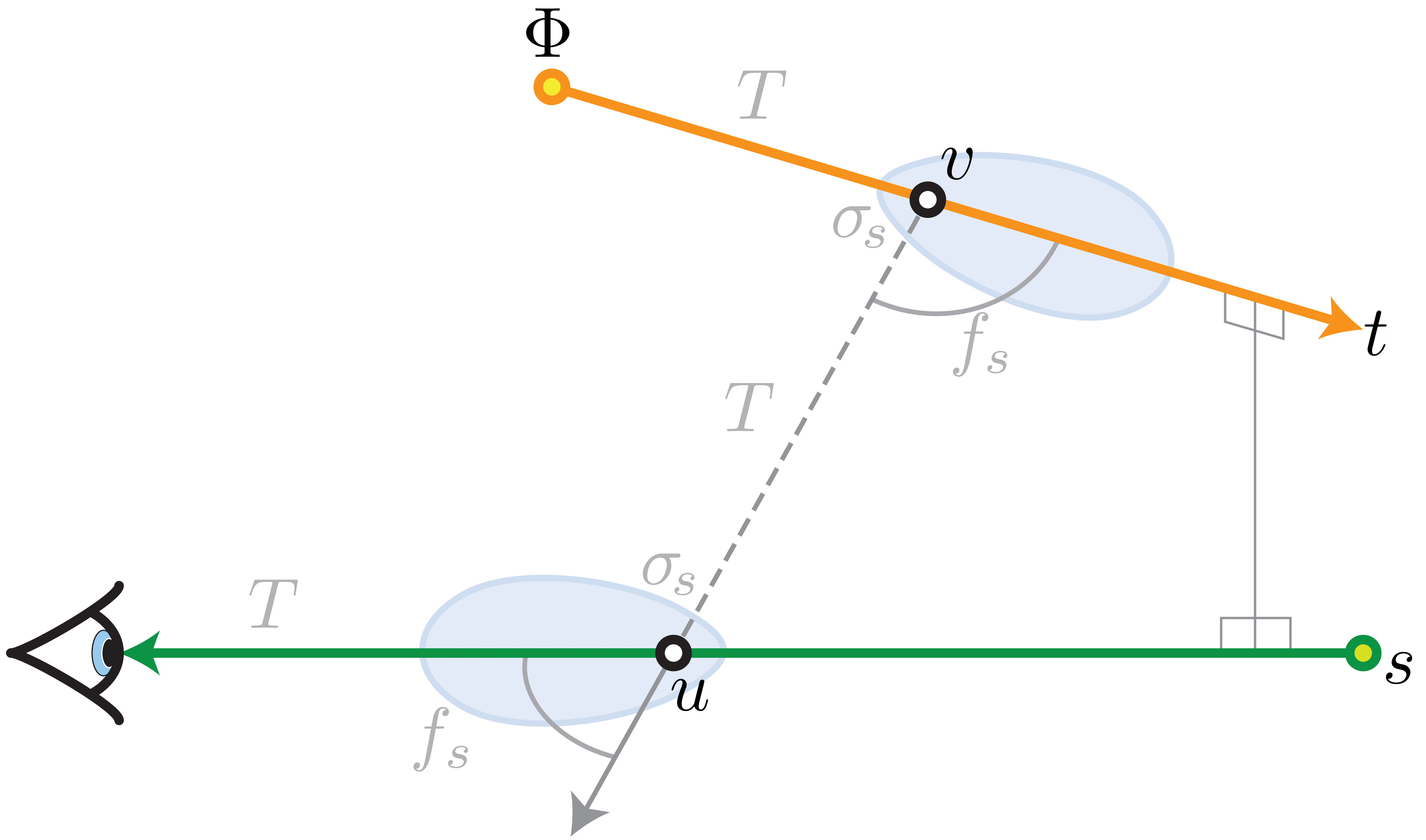
$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)\, T(u) T(v) T(w)}{} \mathrm{d}v \mathrm{d}u$$

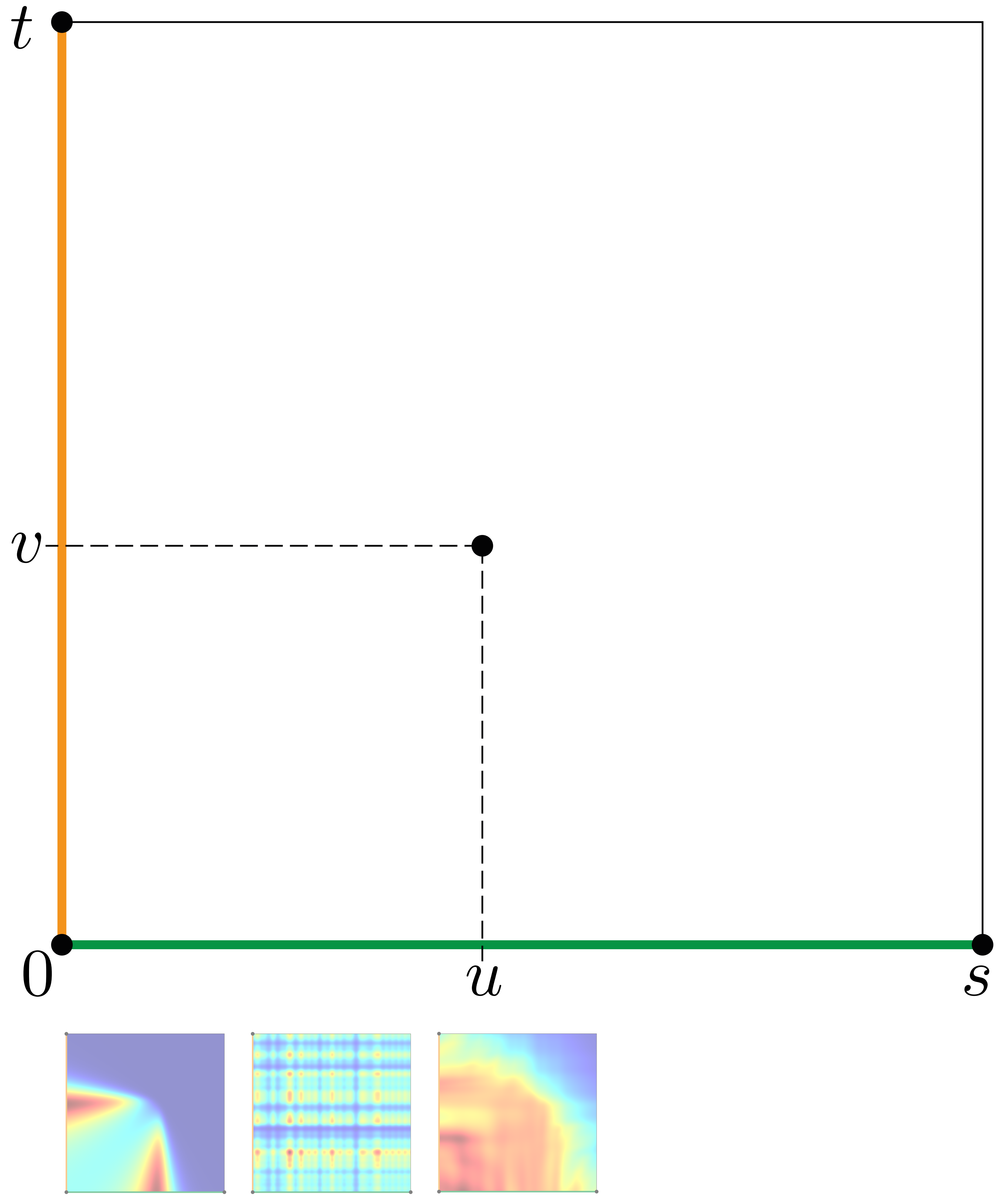




Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)\, T(u) T(v) T(w)}{} \mathrm{d}v \mathrm{d}u$$

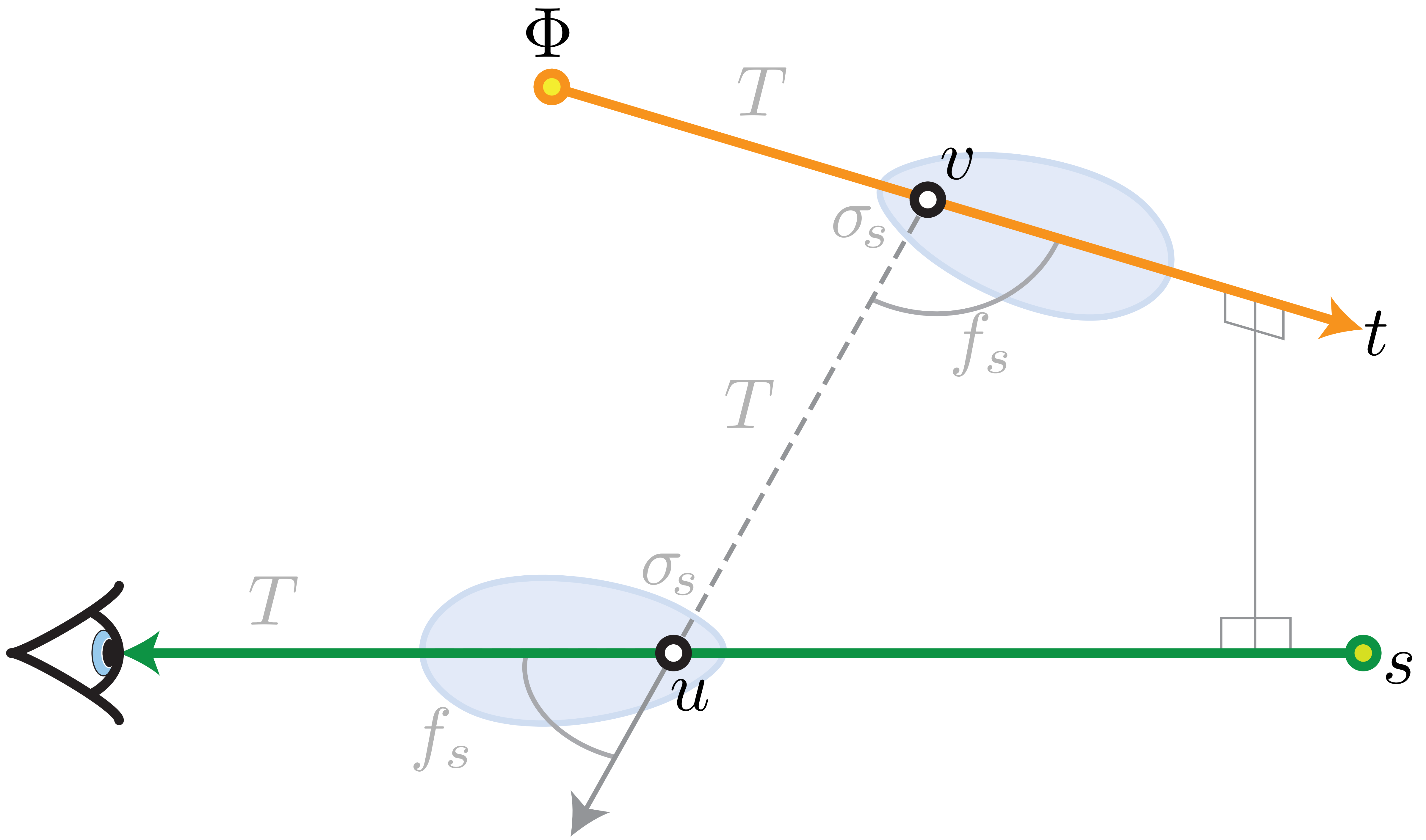


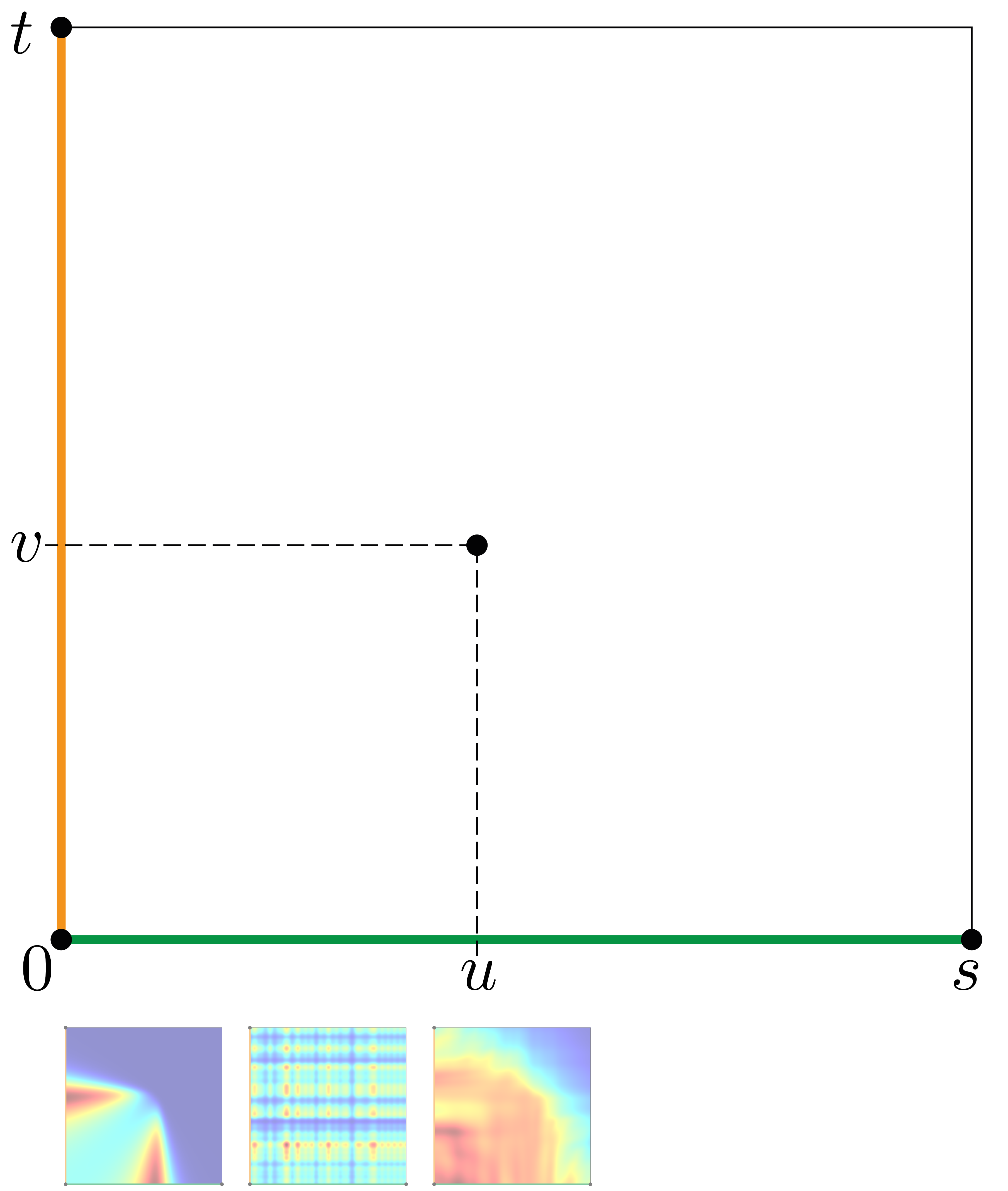


Ray-to-Ray transport

visibility

$$L = \Phi \int_0^s \int_0^t \underline{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)\, T(u)T(v)T(w)\, V}\, \mathrm{d}v\mathrm{d}u$$

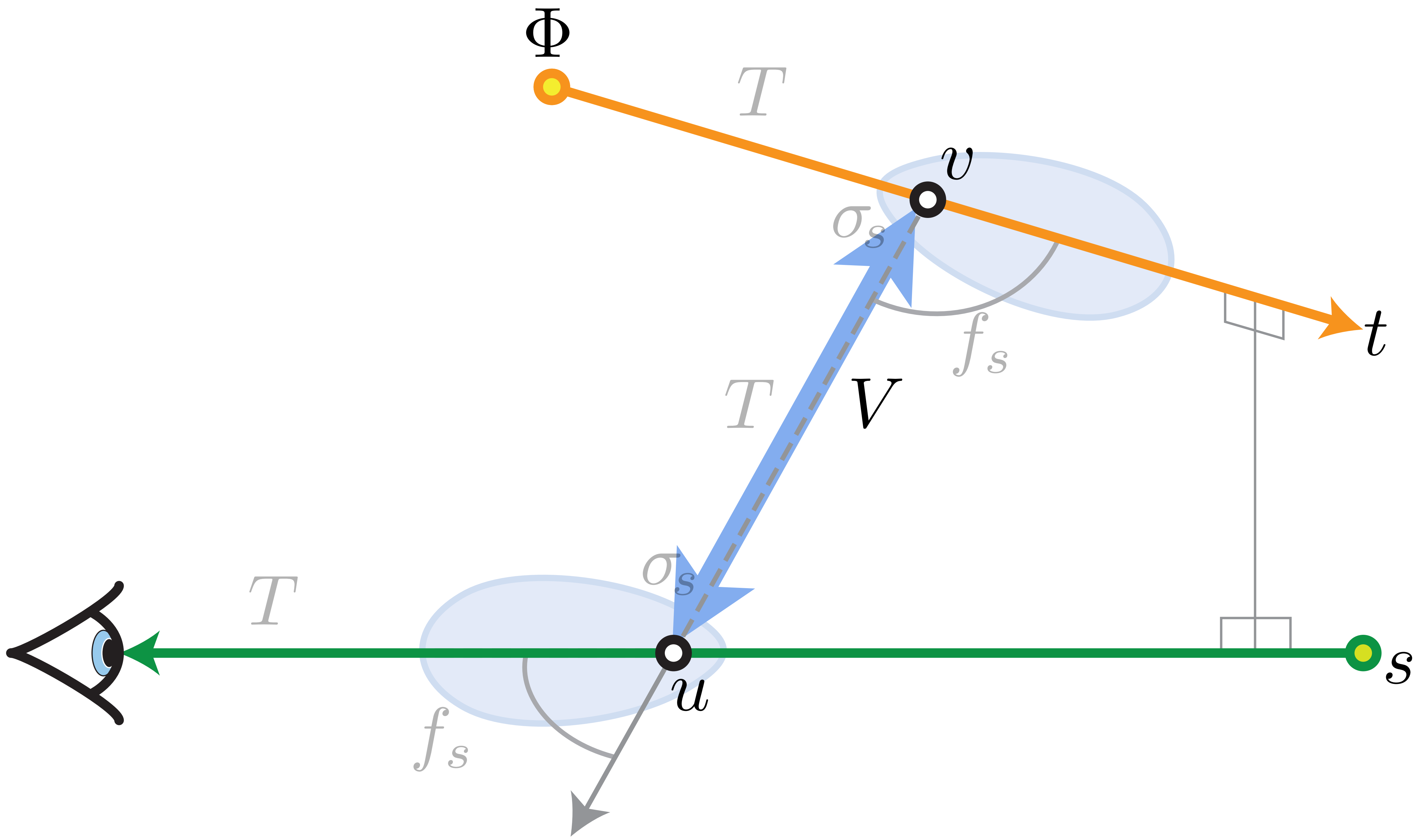


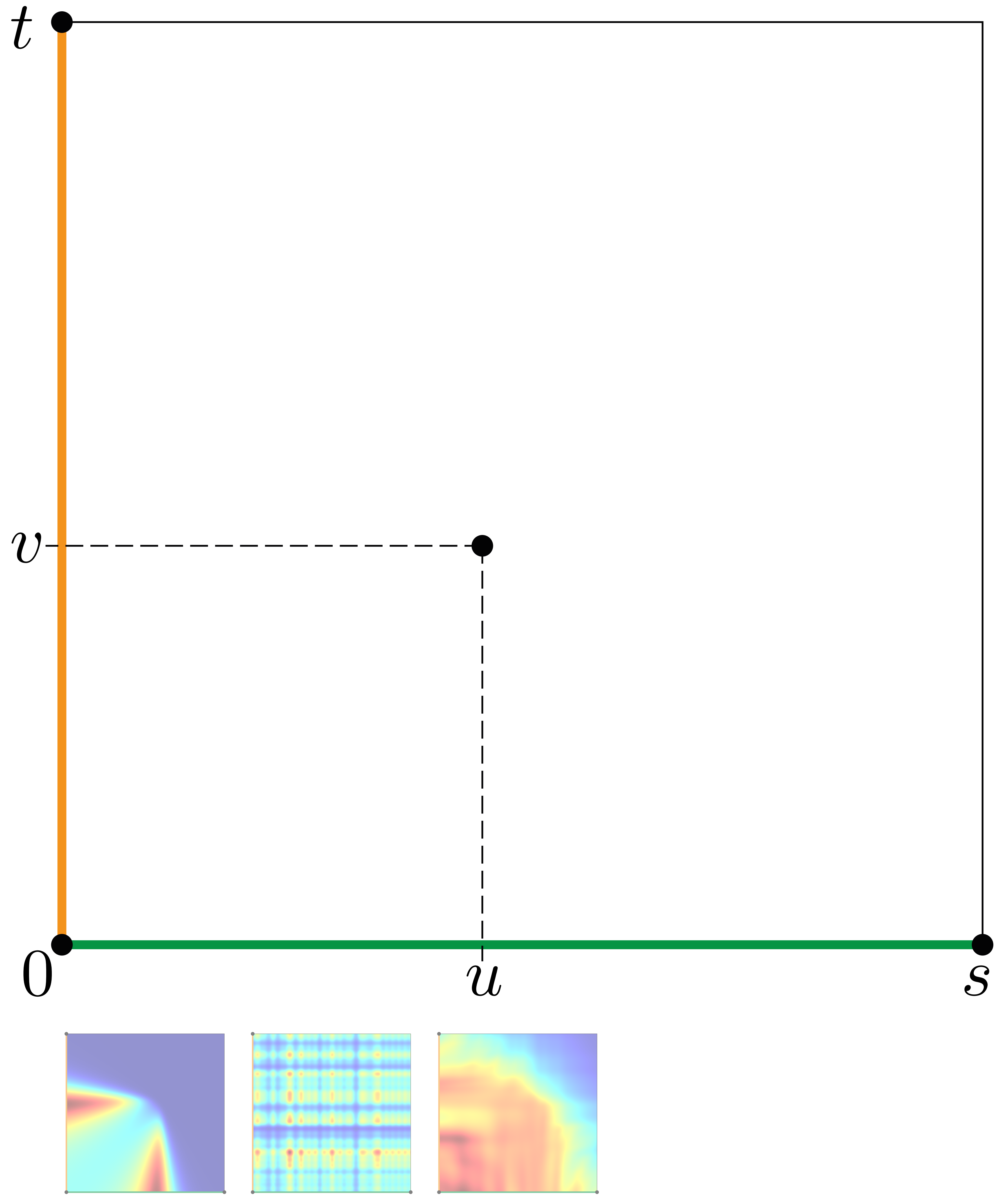


Ray-to-Ray transport

visibility

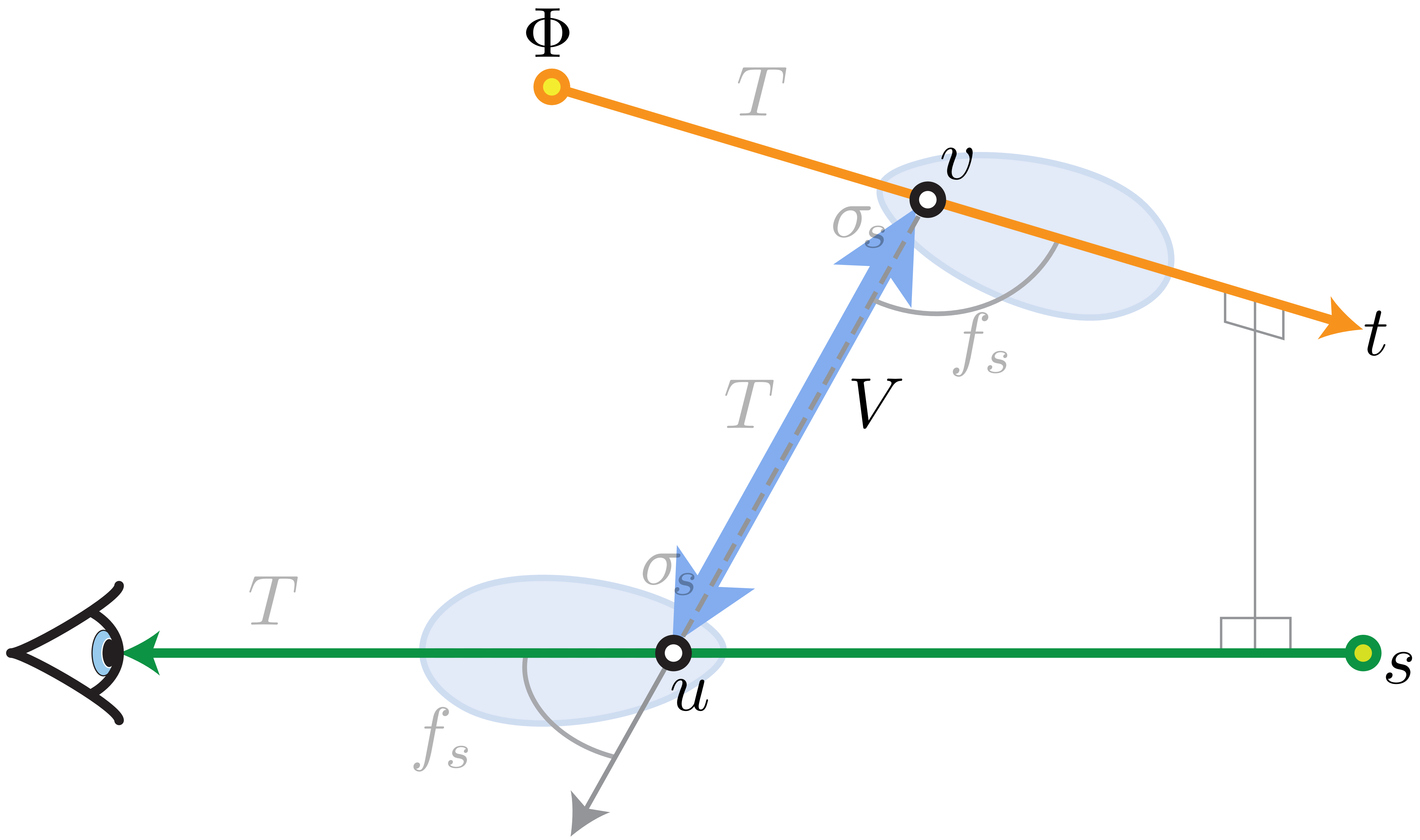
$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)\, T(u)T(v)T(w)\, V}{} \mathrm{d}v\mathrm{d}u$$



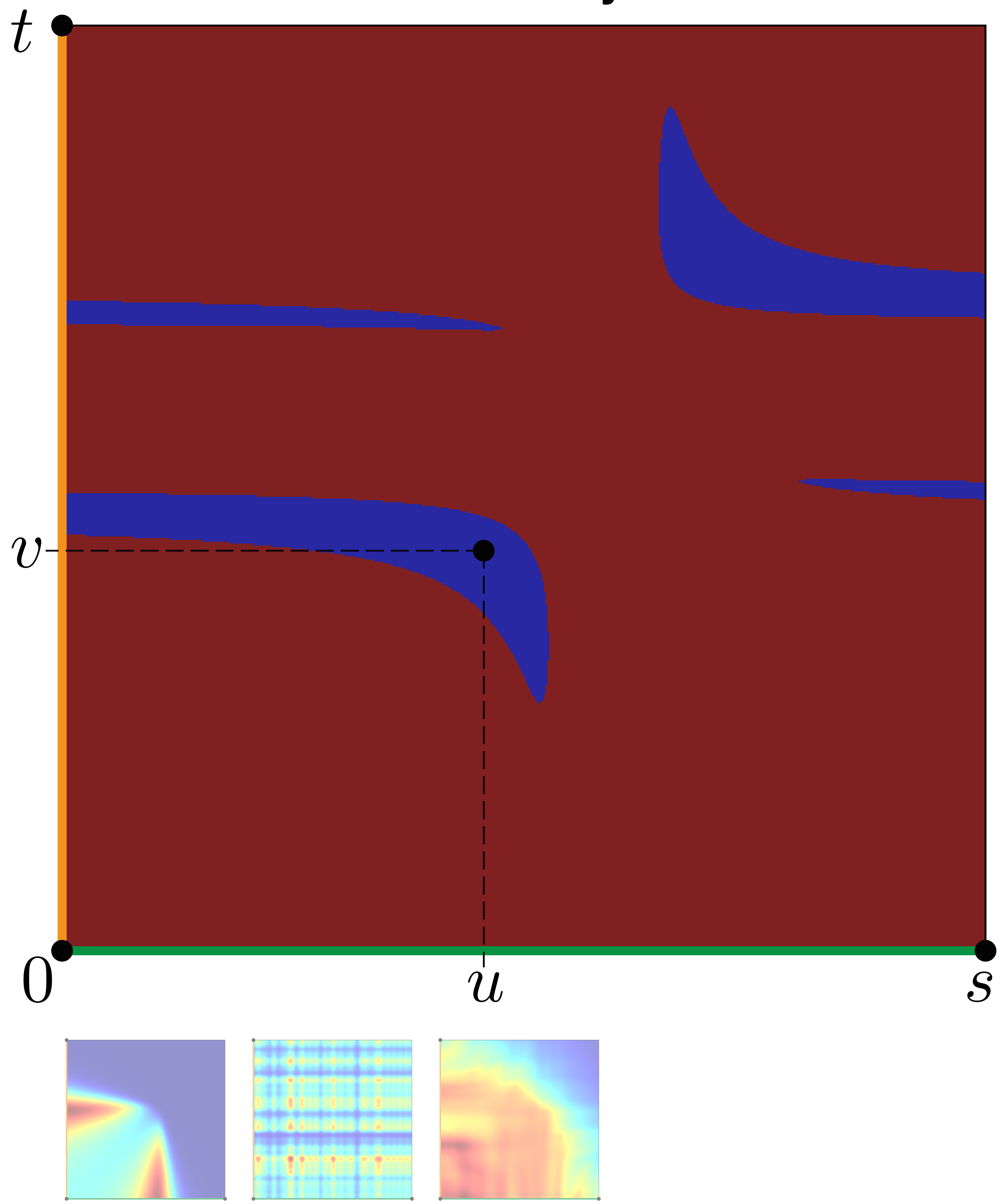


Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)\, T(u) T(v) T(w)\, \overset{\text{visibility}}{V}}{} \mathrm{d}v\mathrm{d}u$$

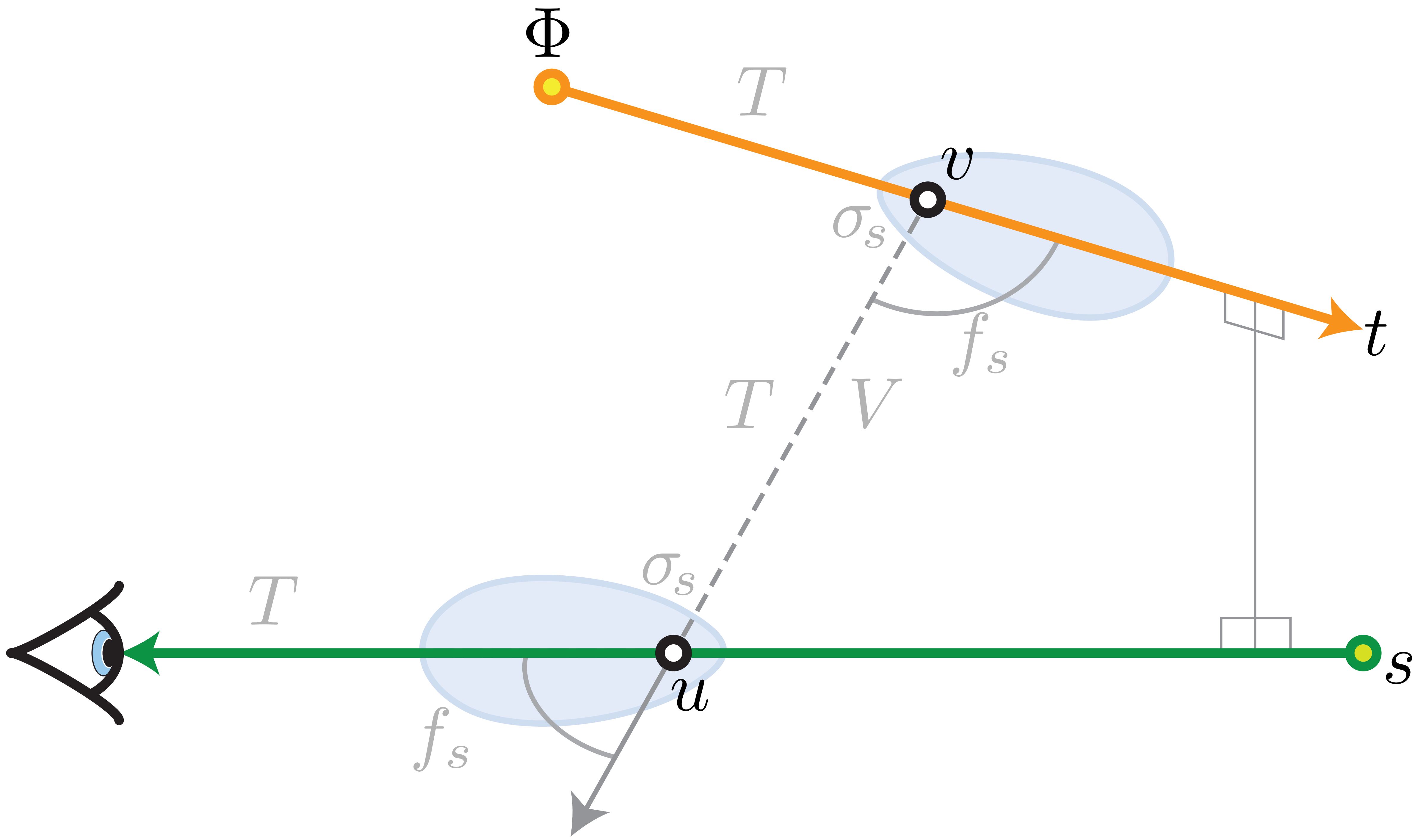


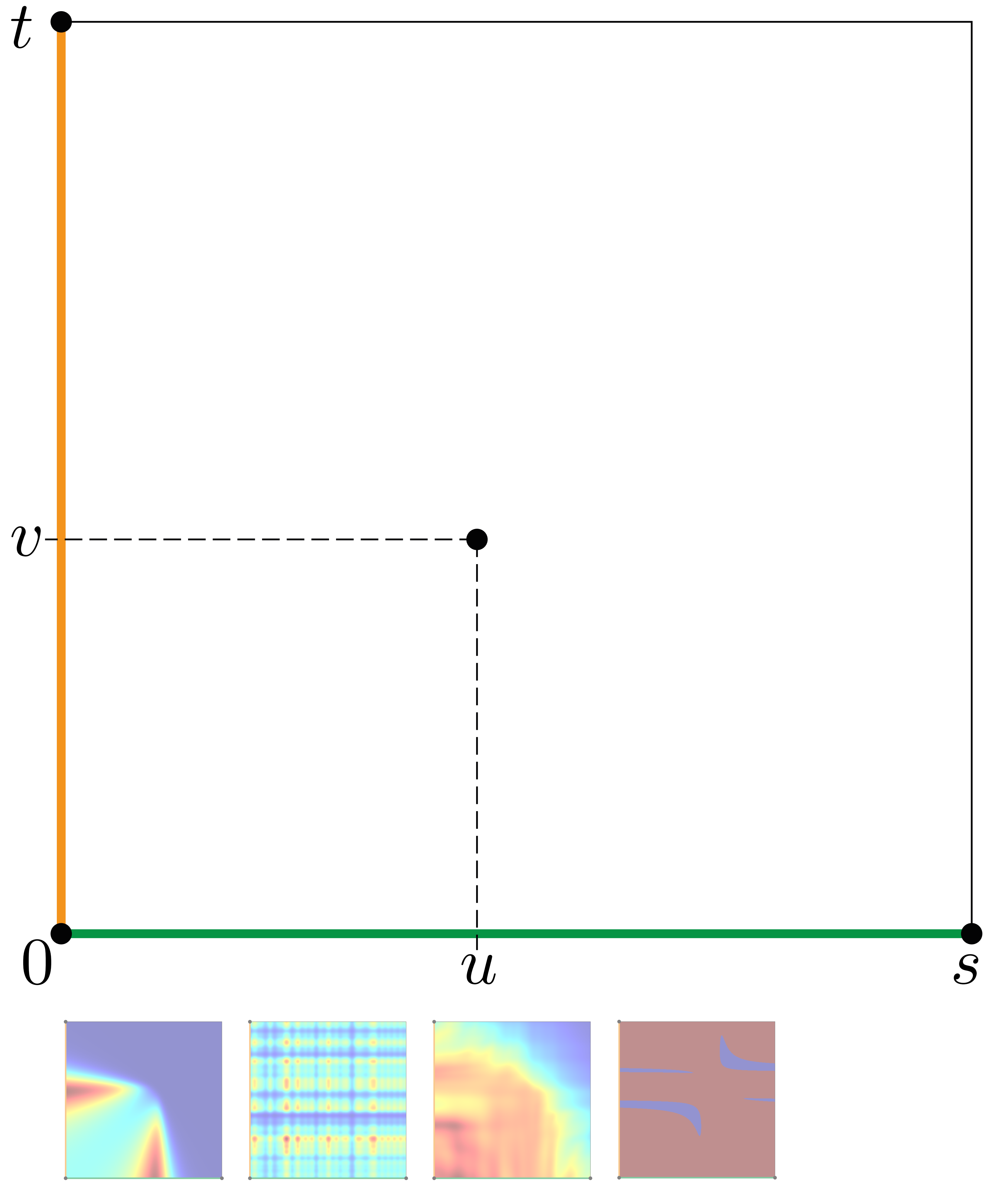
visibility



Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)\, T(u) T(v) T(w)\, V}{} \mathrm{d}v \mathrm{d}u$$

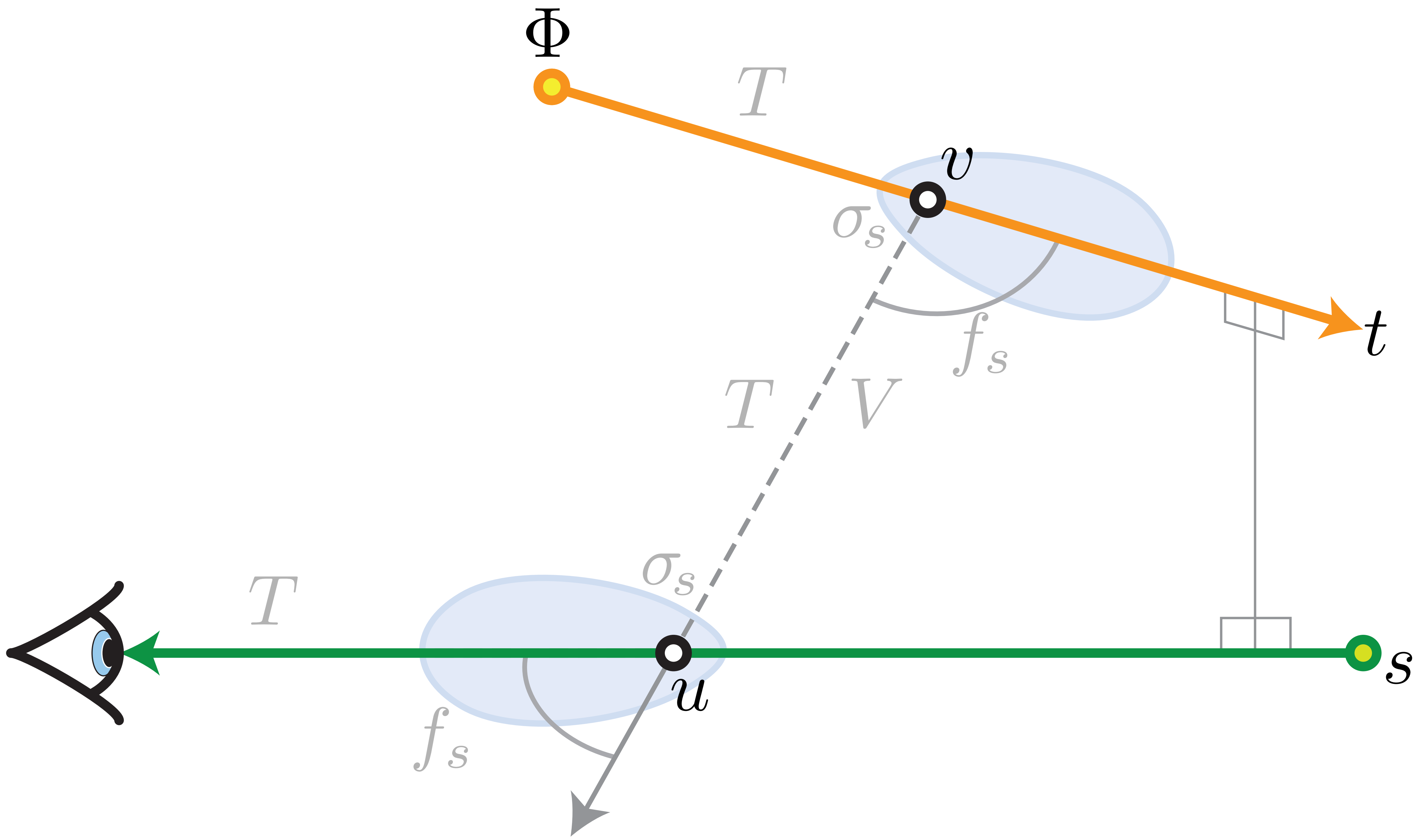


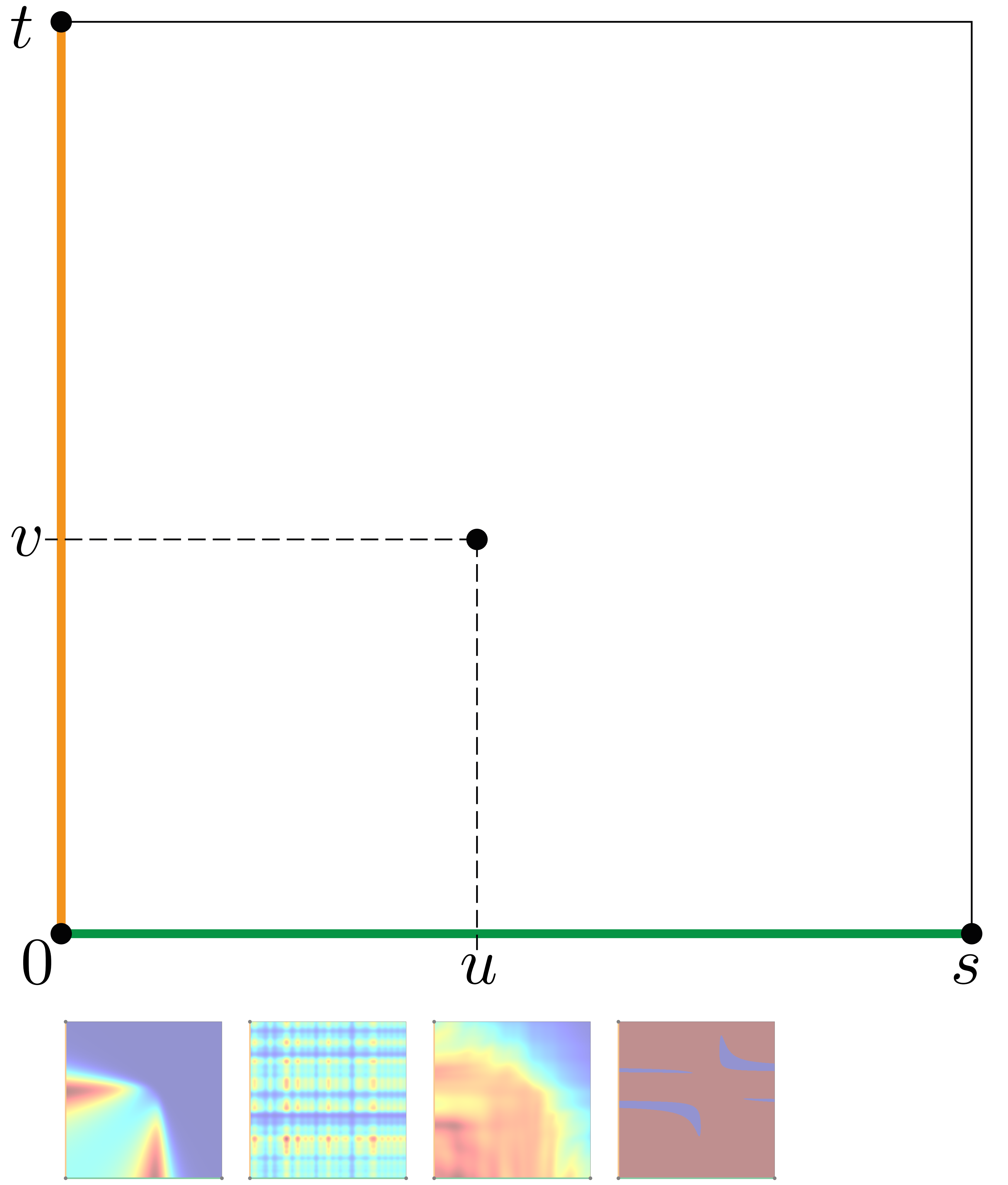


Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)\, T(u) T(v) T(w)\, V}{w(u,v)^2} \mathrm{d}v\mathrm{d}u$$

squared distance

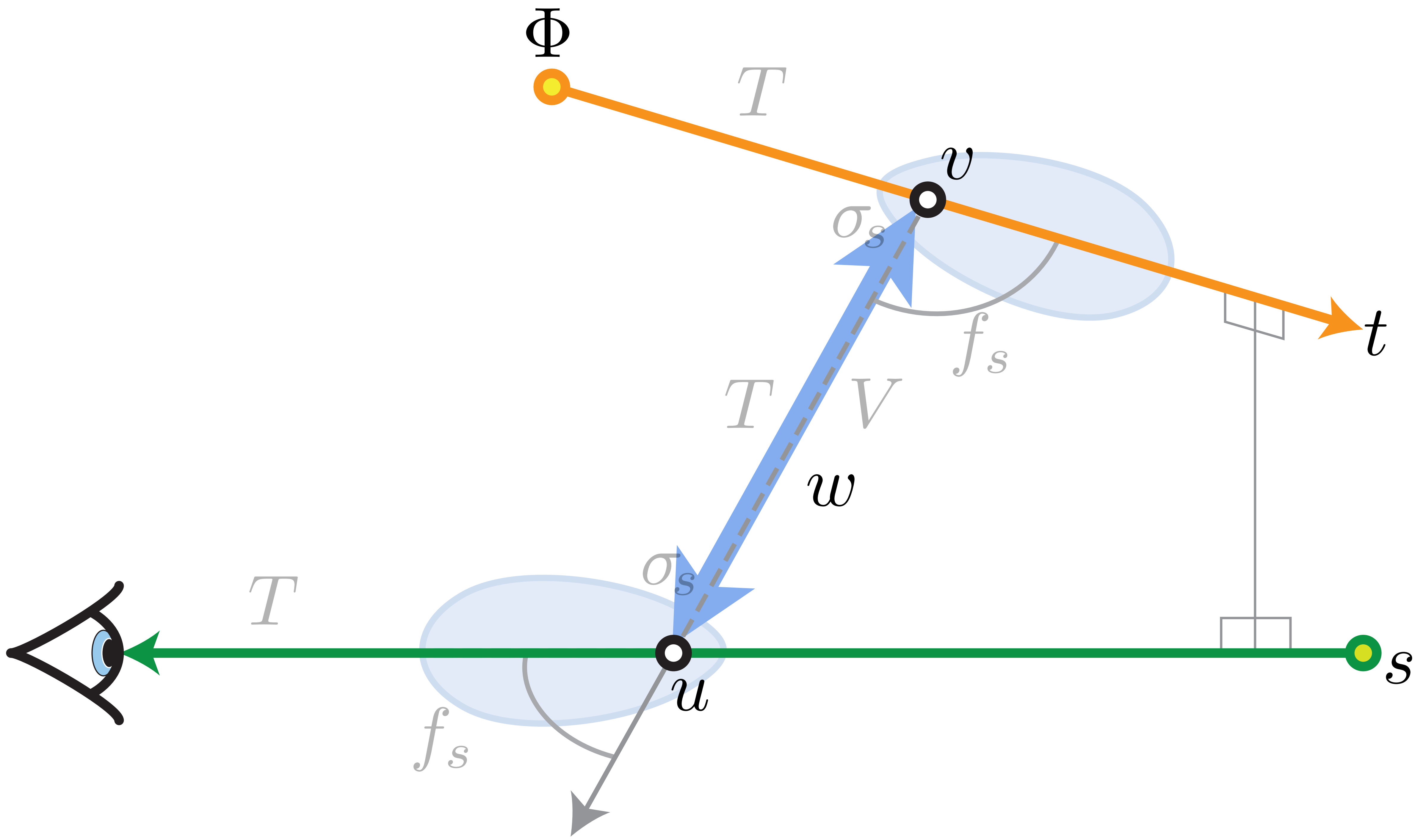


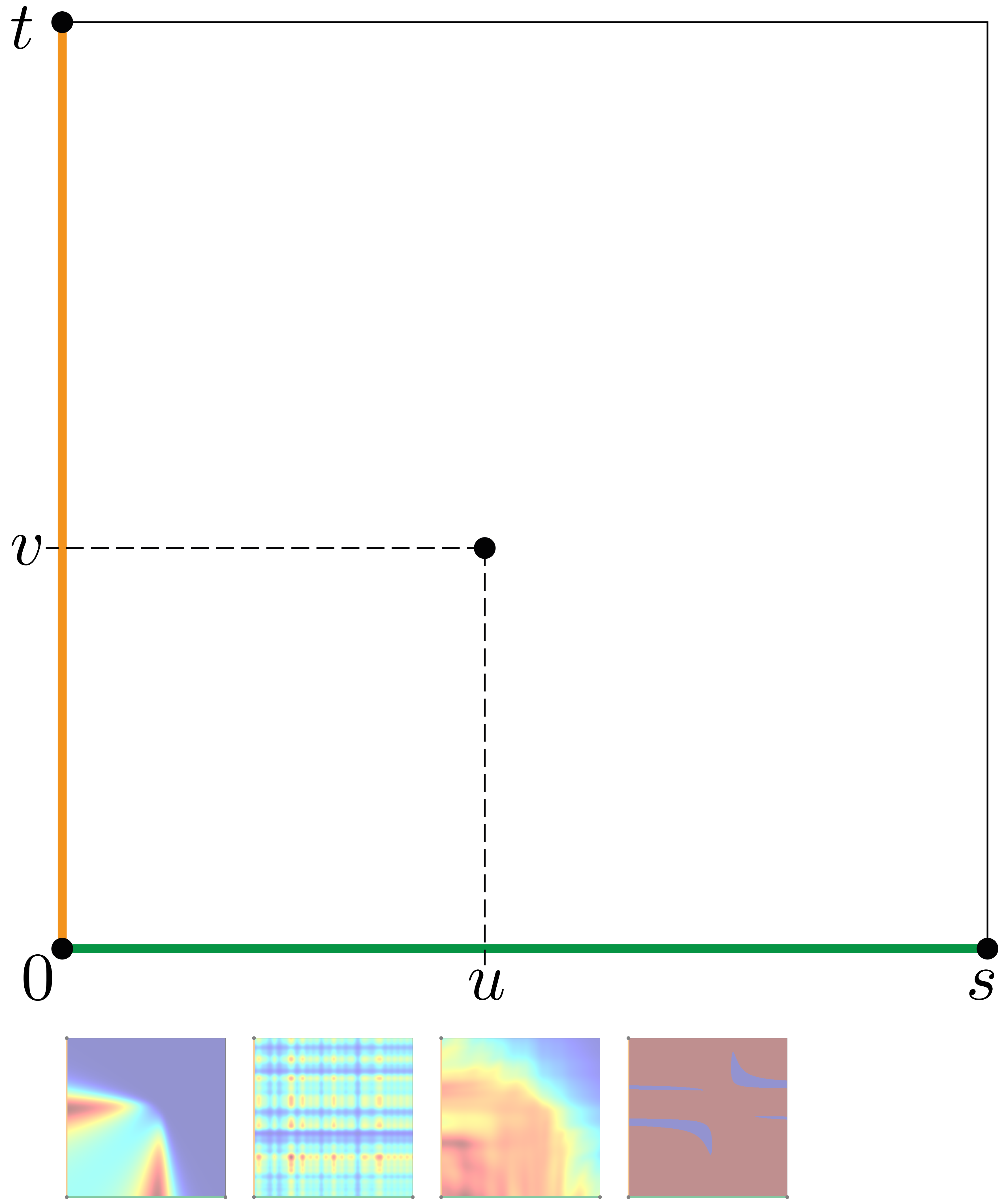


Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)\, T(u)T(v)T(w)\, V}{w(u,v)^2} \mathrm{d}v \mathrm{d}u$$

squared distance

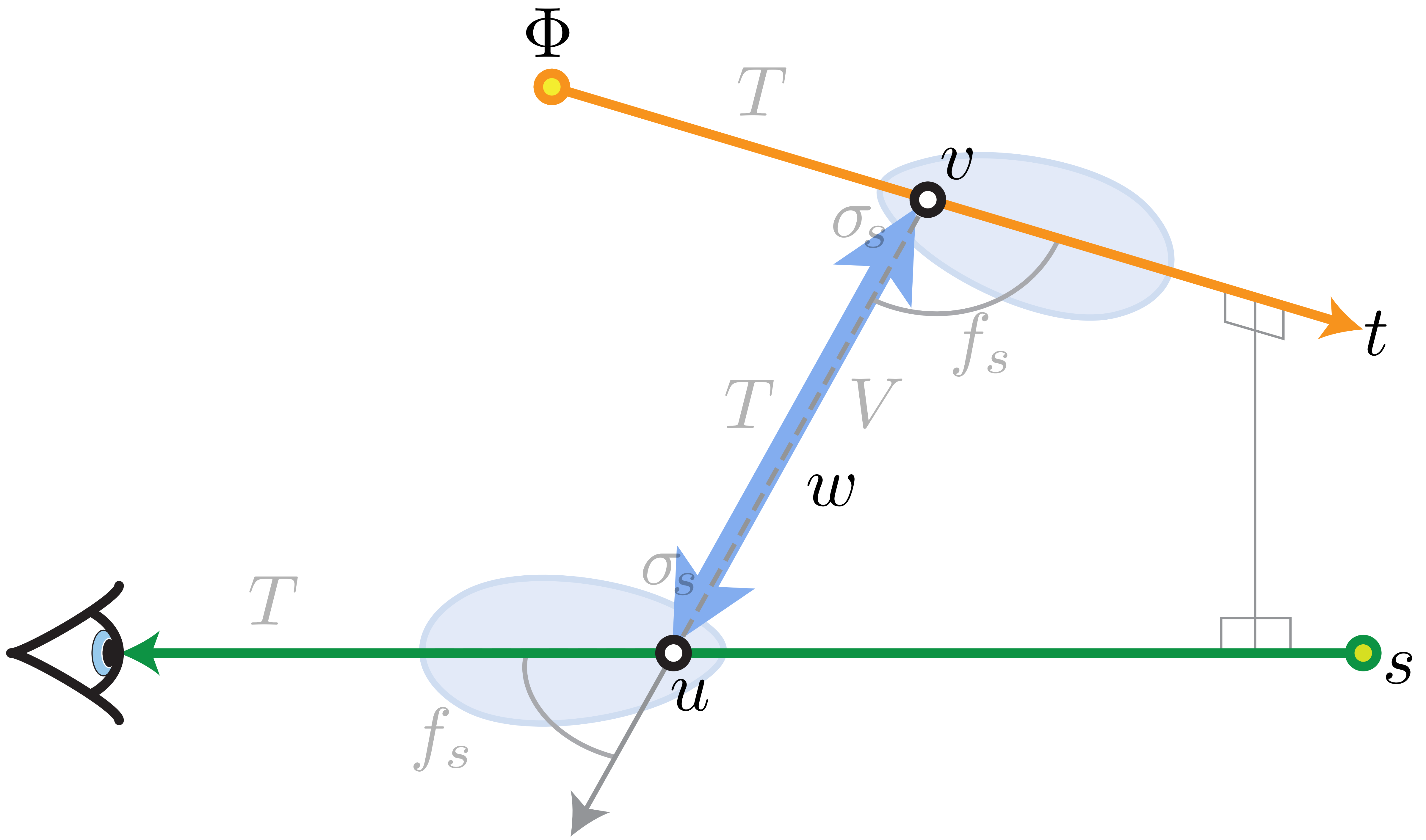


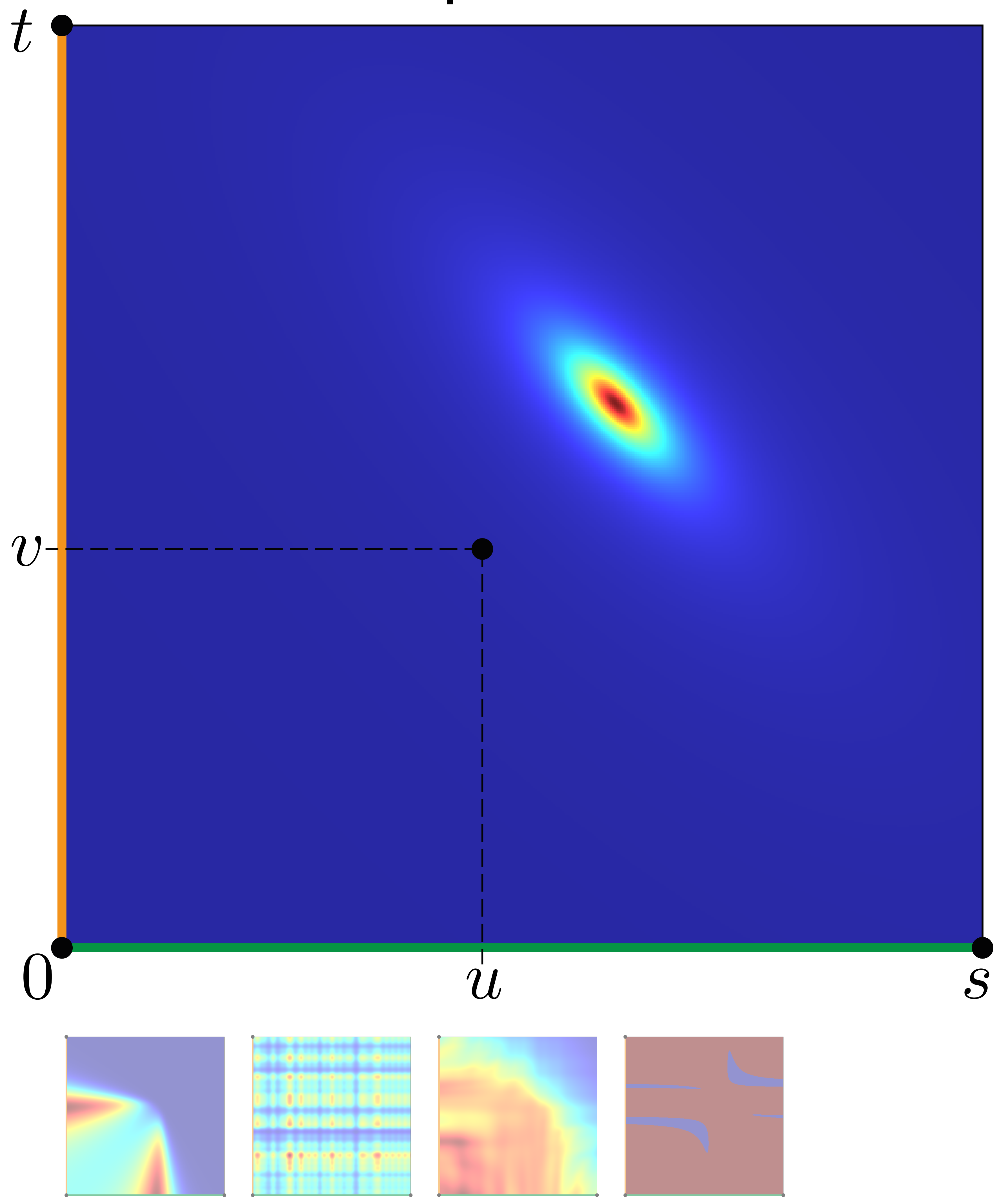


Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)\, T(u)T(v)T(w)\, V}{w(u,v)^2} \mathrm{d}v\mathrm{d}u$$

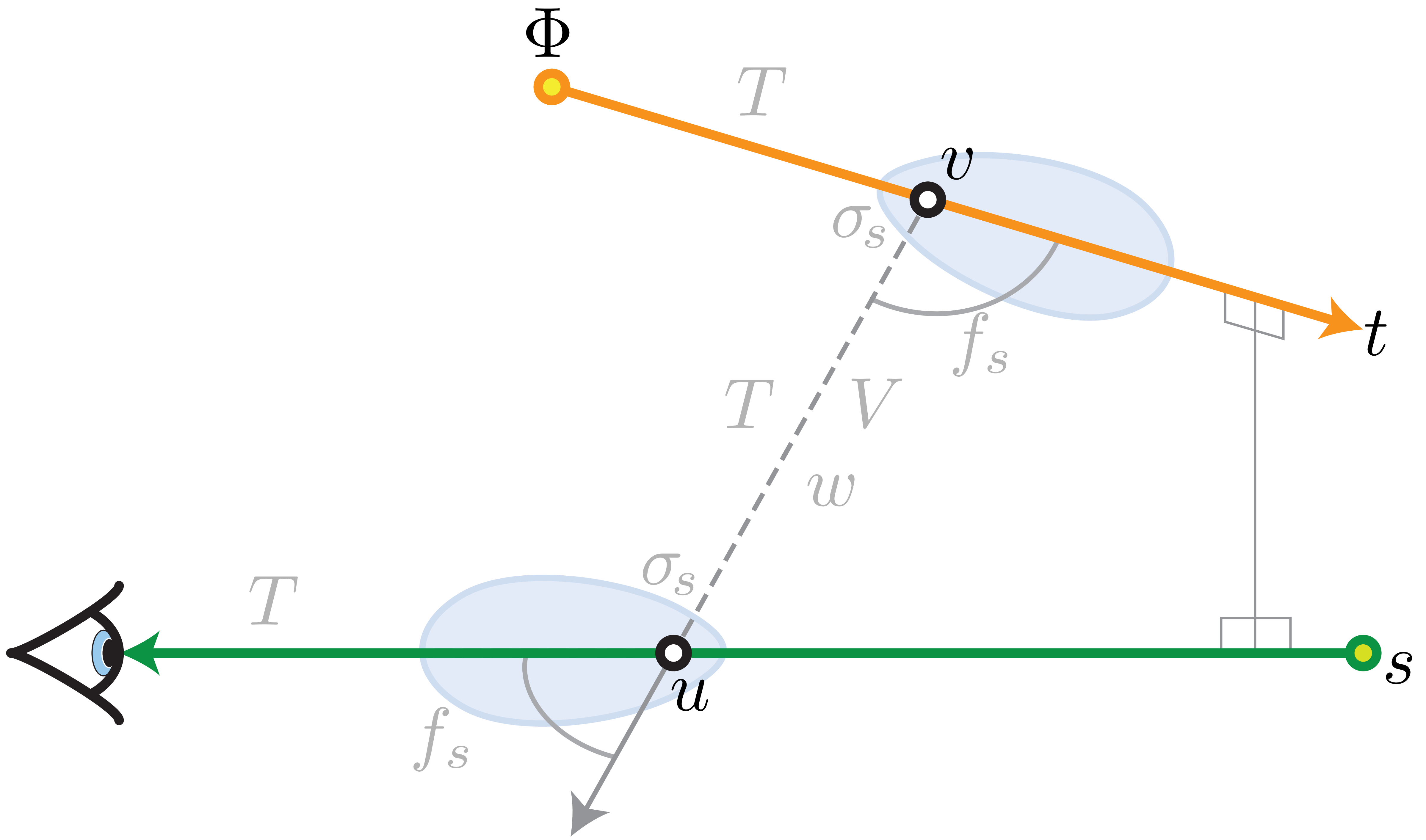
squared distance

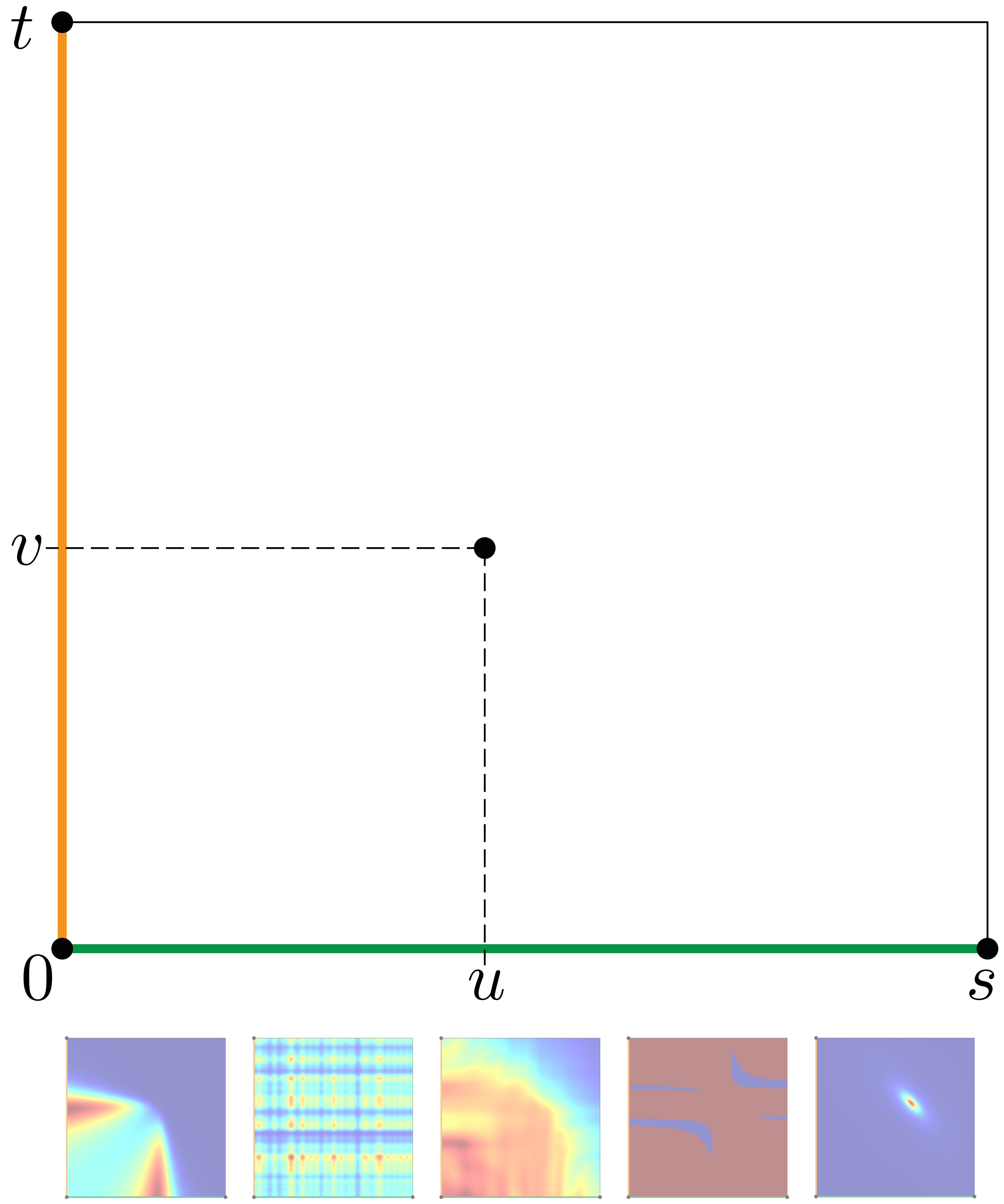




Ray-to-Ray transport

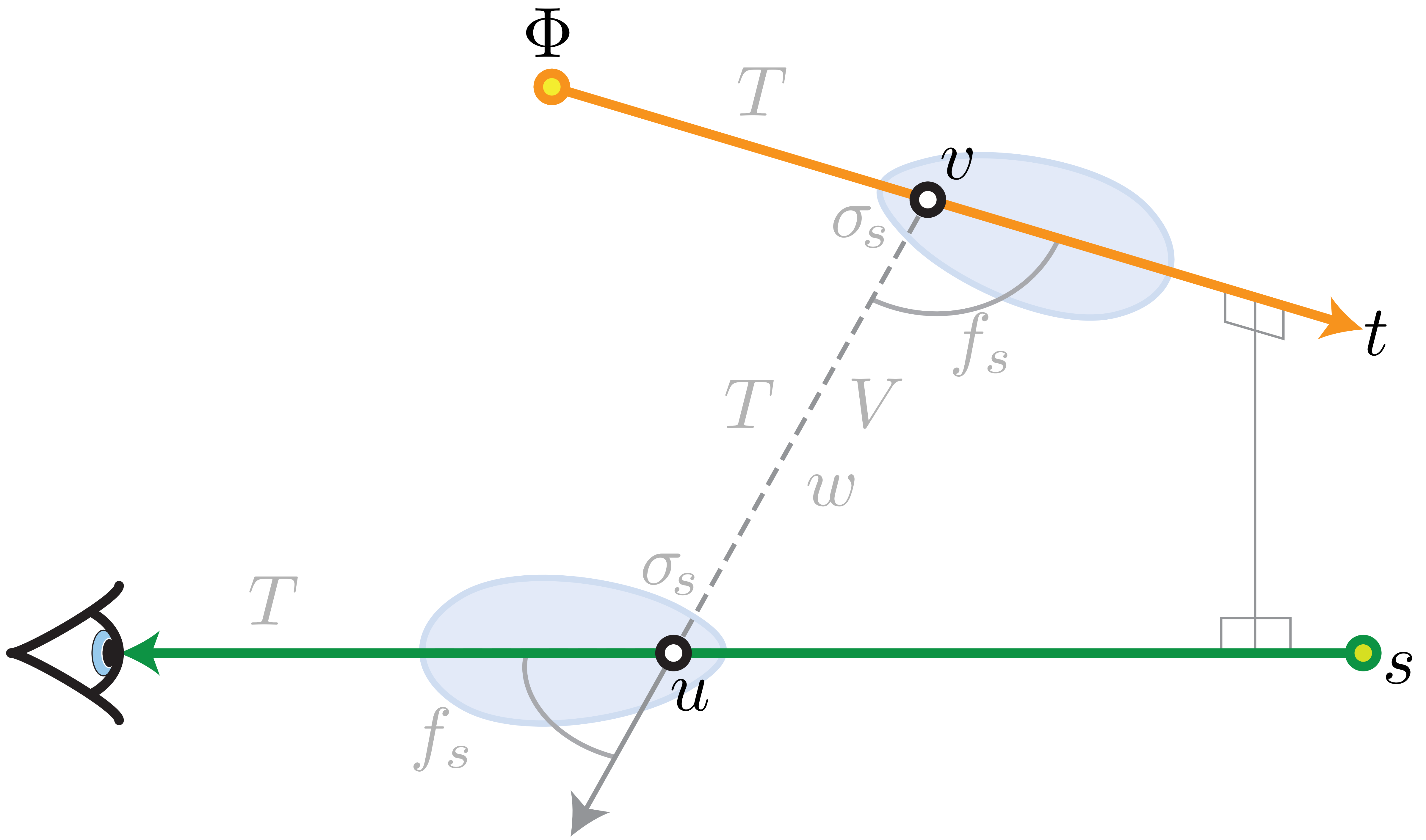
$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)\, T(u) T(v) T(w)\, V}{w(u,v)^2} \mathrm{d}v \mathrm{d}u$$

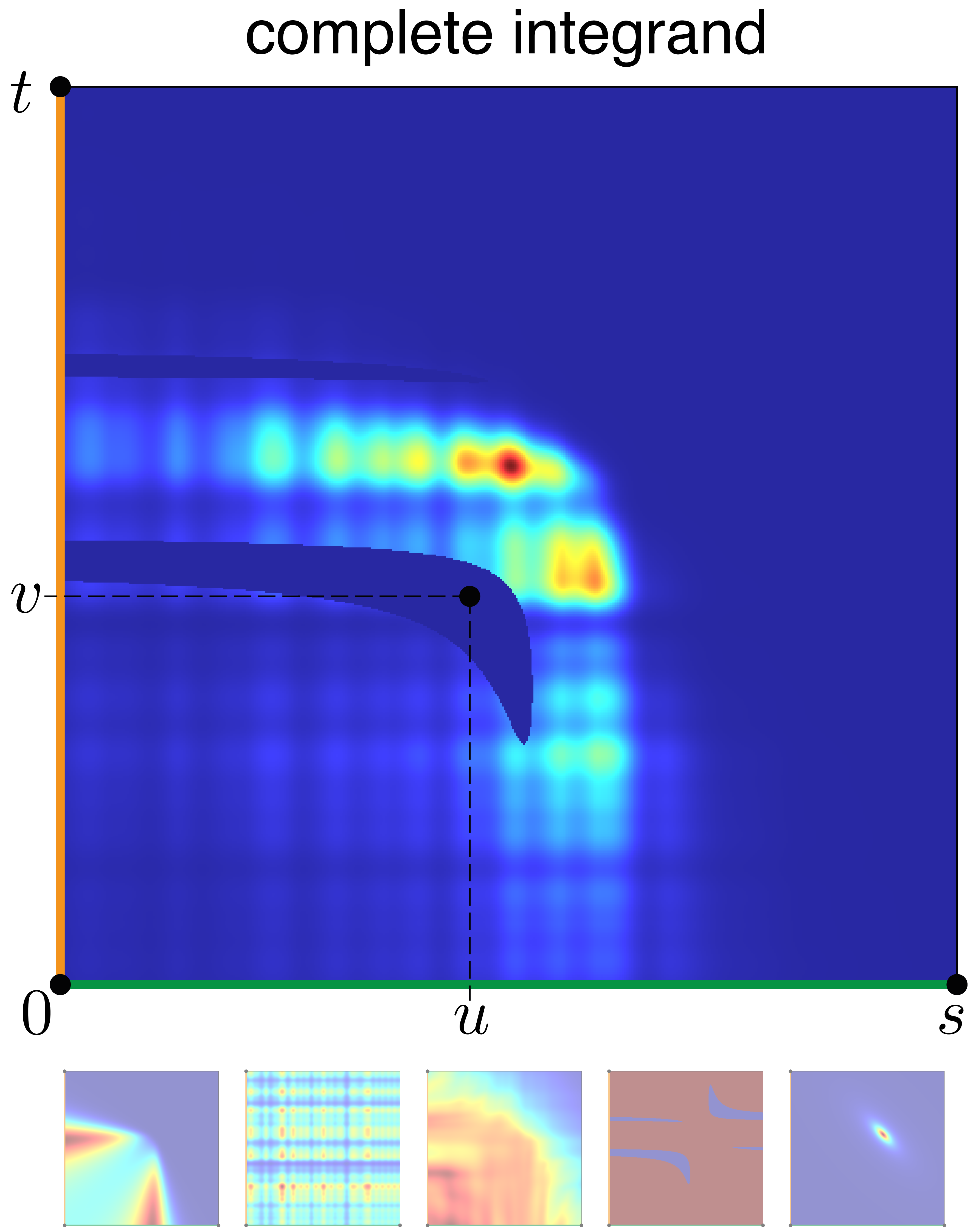




Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u)\sigma_s(v)\, T(u)T(v)T(w)\, V}{w(u,v)^2} \mathrm{d}v\mathrm{d}u$$

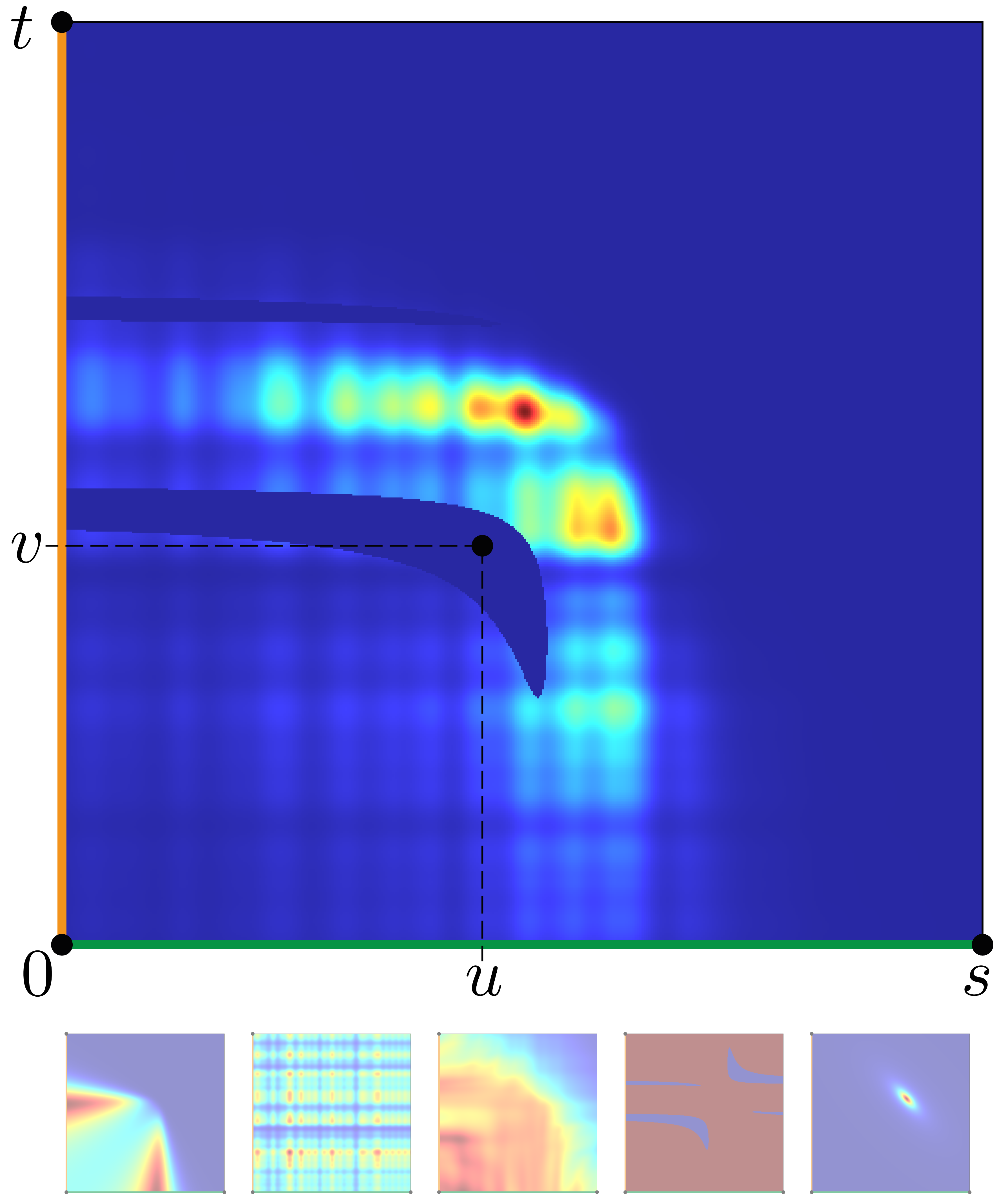




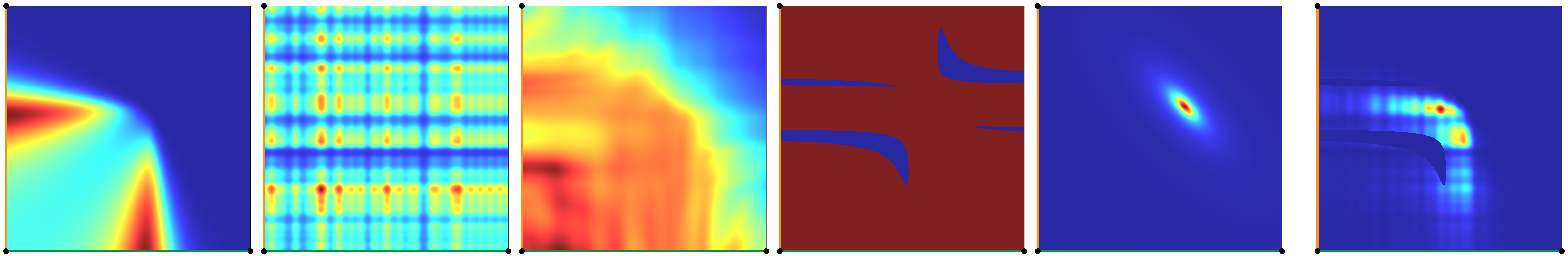
Ray-to-Ray transport

$$L = \Phi \int_0^s \int_0^t \frac{f_s(\theta_u) f_s(\theta_v)\, \sigma_s(u) \sigma_s(v)\, T(u) T(v) T(w)\, V}{w(u,v)^2} \mathrm{d}v \mathrm{d}u$$

approximate using Monte Carlo with importance sampling

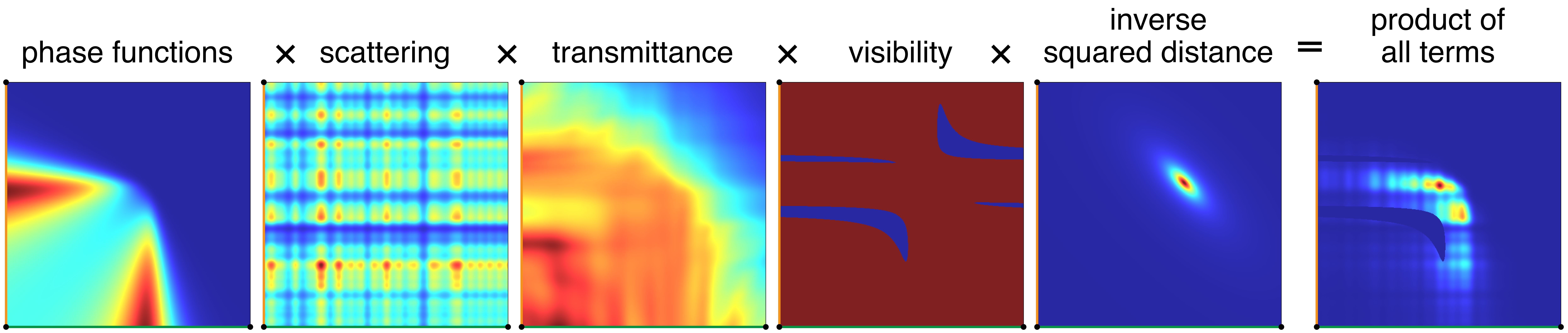


Importance sampling



Importance sampling

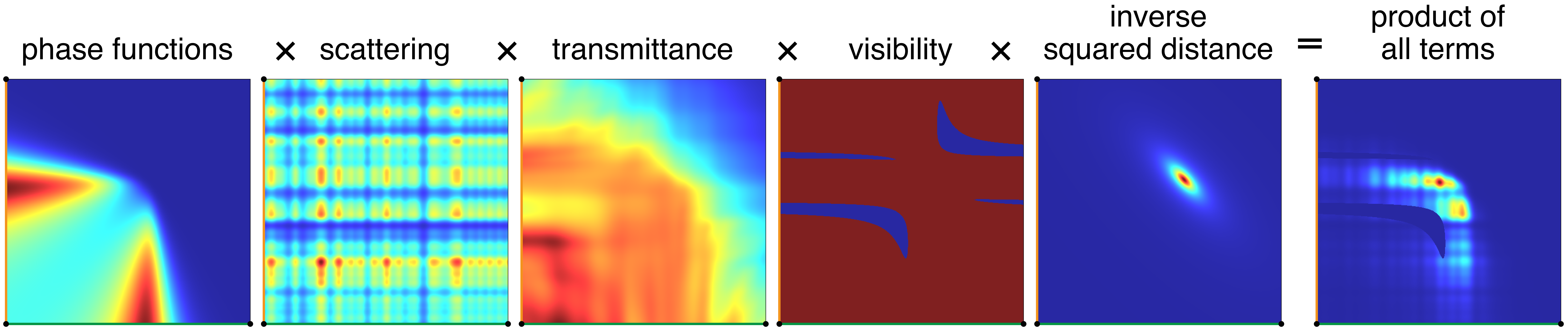
How to (importance) sample?



Importance sampling

How to (importance) sample?

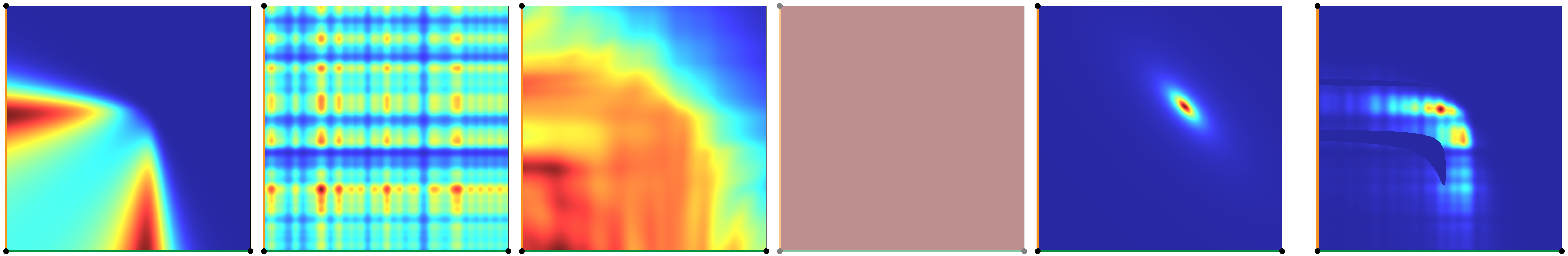
Simple cases first!



Importance sampling

How to (importance) sample?

Simple cases first!

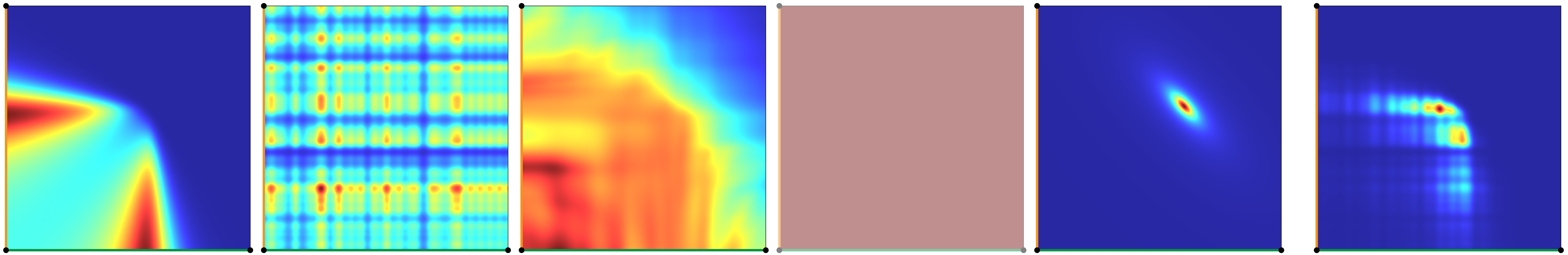


Importance sampling

How to (importance) sample?

Simple cases first!

phase functions × scattering × transmittance × visibility × inverse squared distance = product of all terms

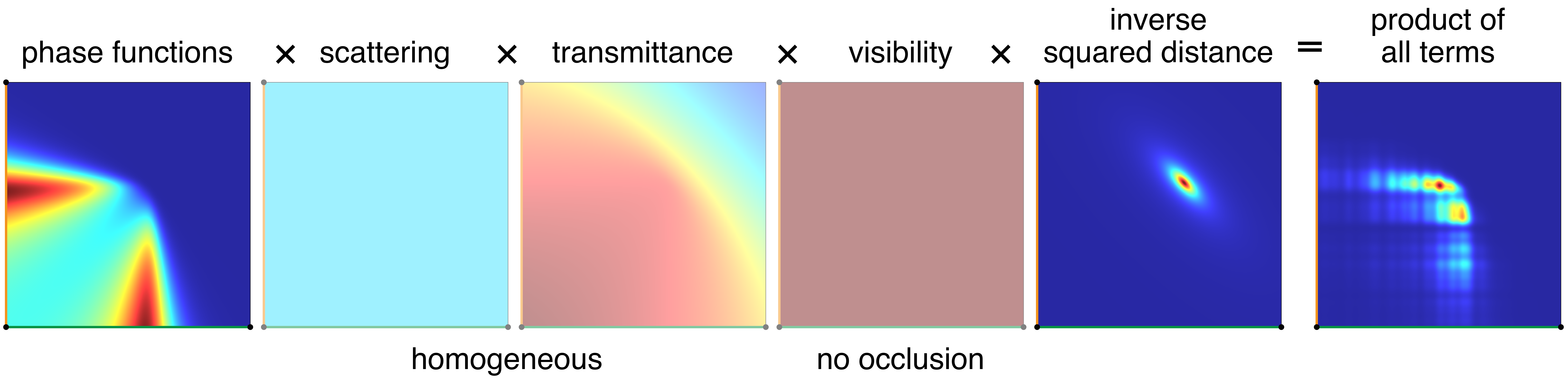


no occlusion

Importance sampling

How to (importance) sample?

Simple cases first!

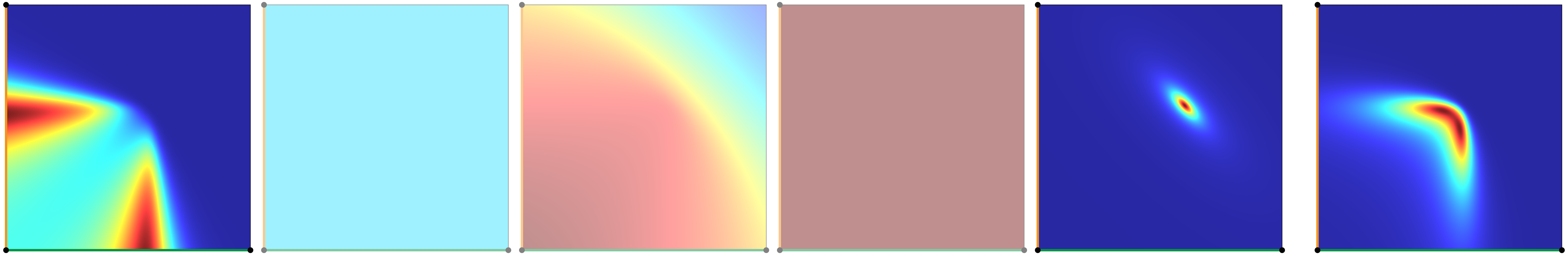


Importance sampling

How to (importance) sample?

Simple cases first!

phase functions × scattering × transcendence × visibility × inverse squared distance = product of all terms



homogeneous

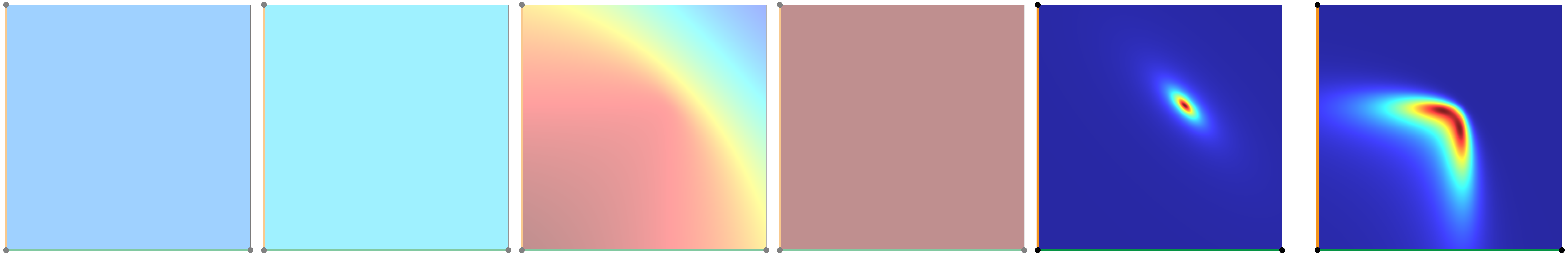
no occlusion

Importance sampling

How to (importance) sample?

Simple cases first!

phase functions × scattering × transmittance × visibility × inverse squared distance = product of all terms



isotropic

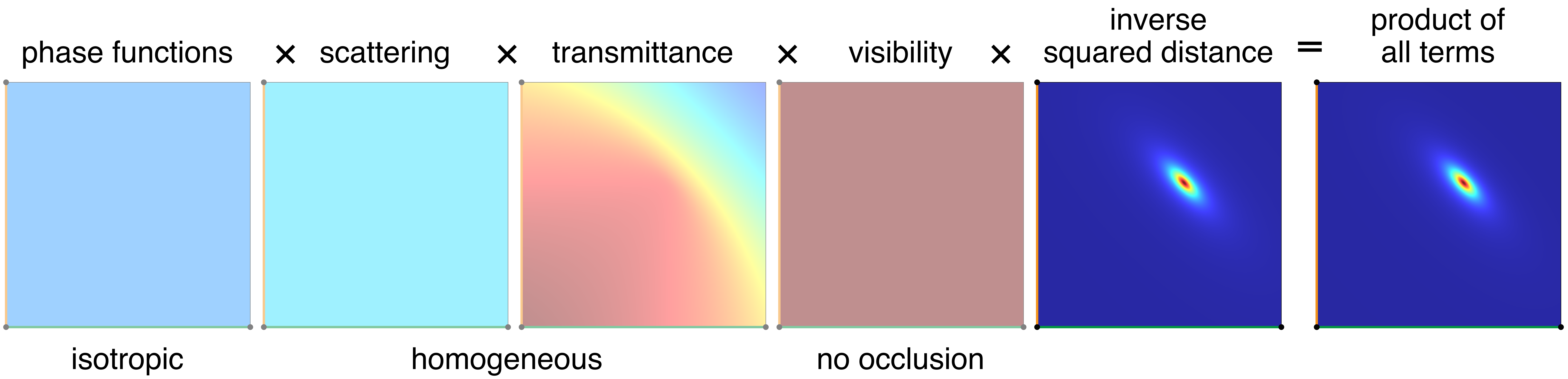
homogeneous

no occlusion

Importance sampling

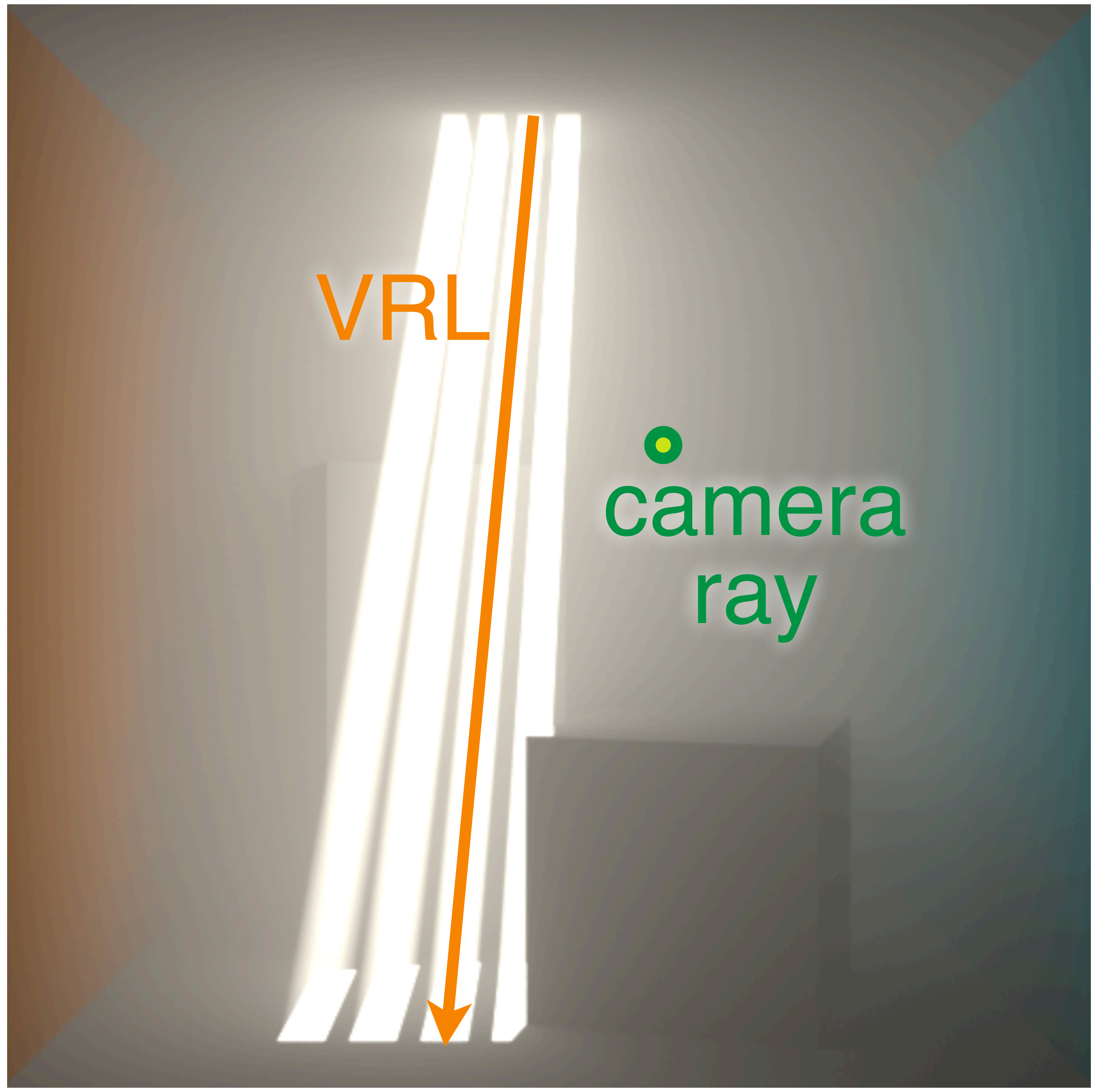
How to (importance) sample?

Simple cases first!

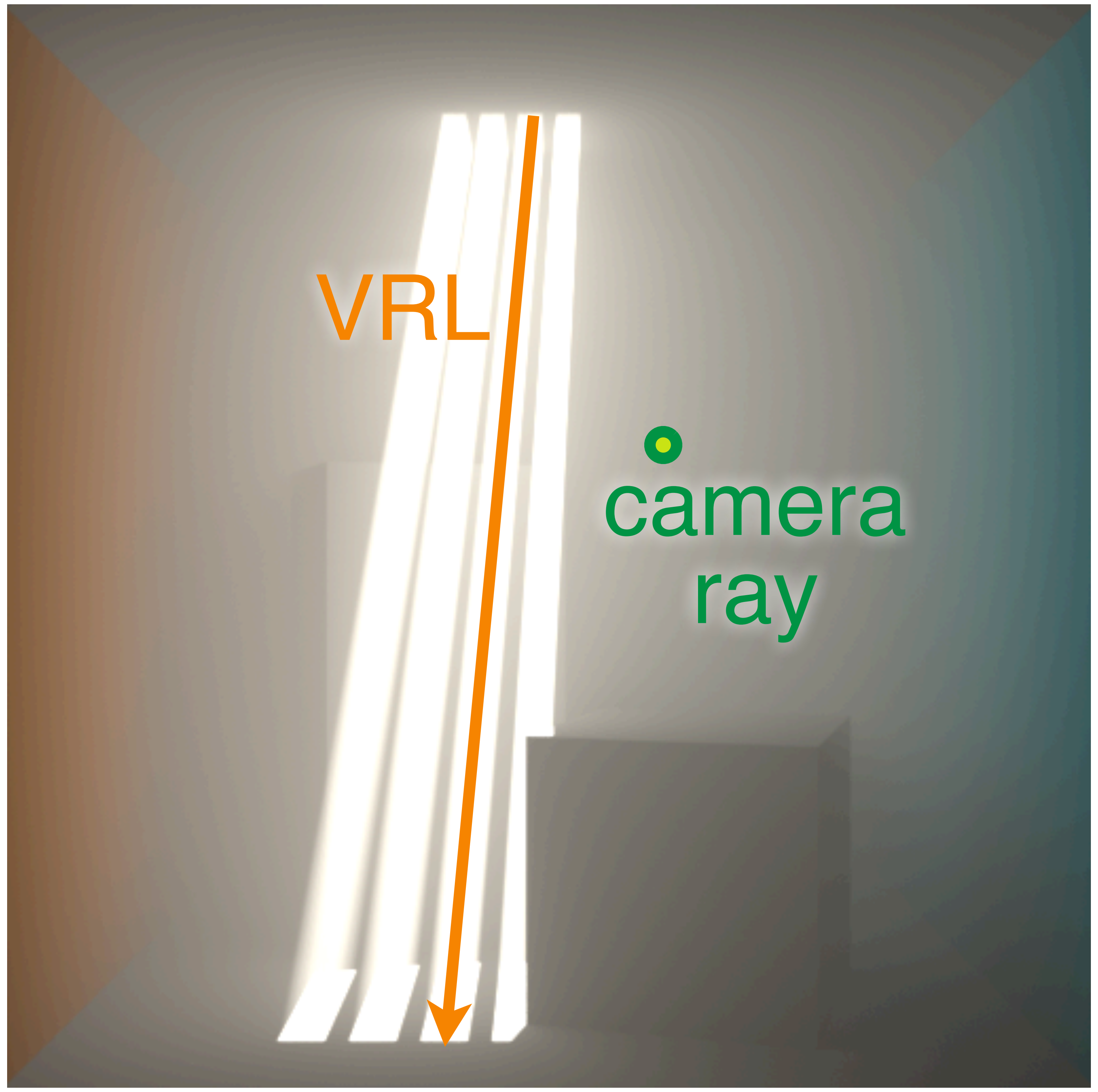


Isotropic media

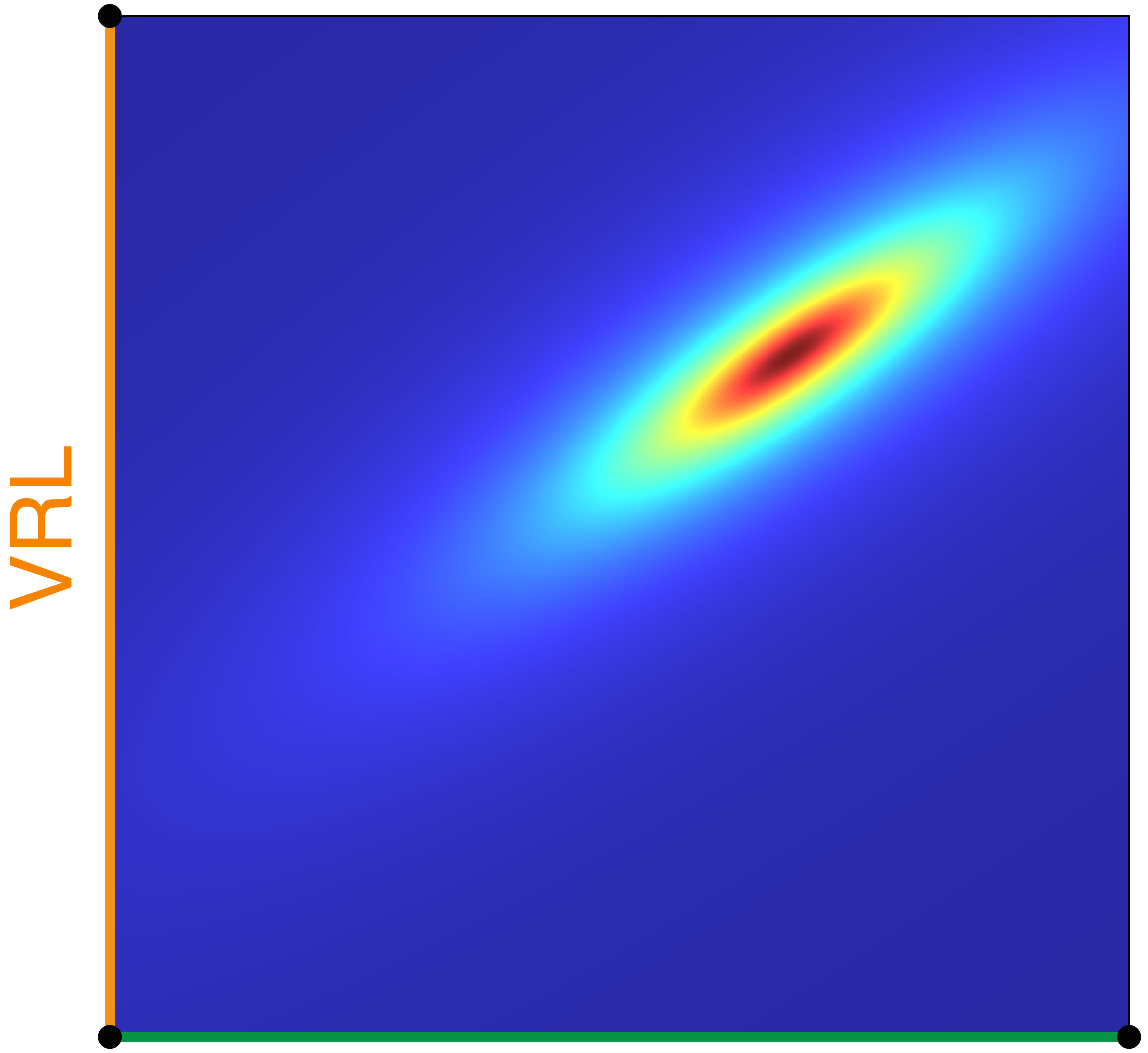
Isotropic media



Isotropic media

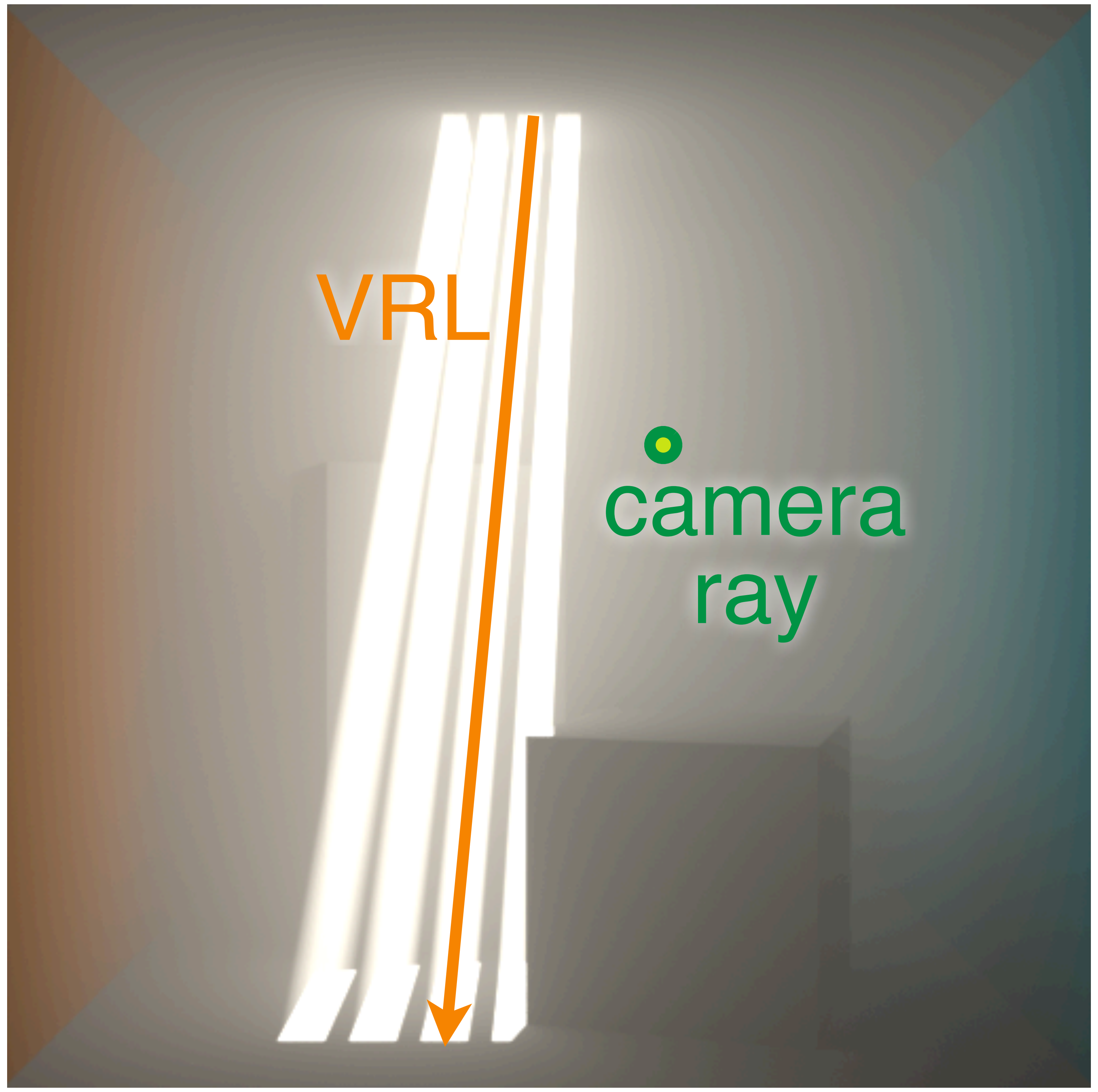


inverse squared distance

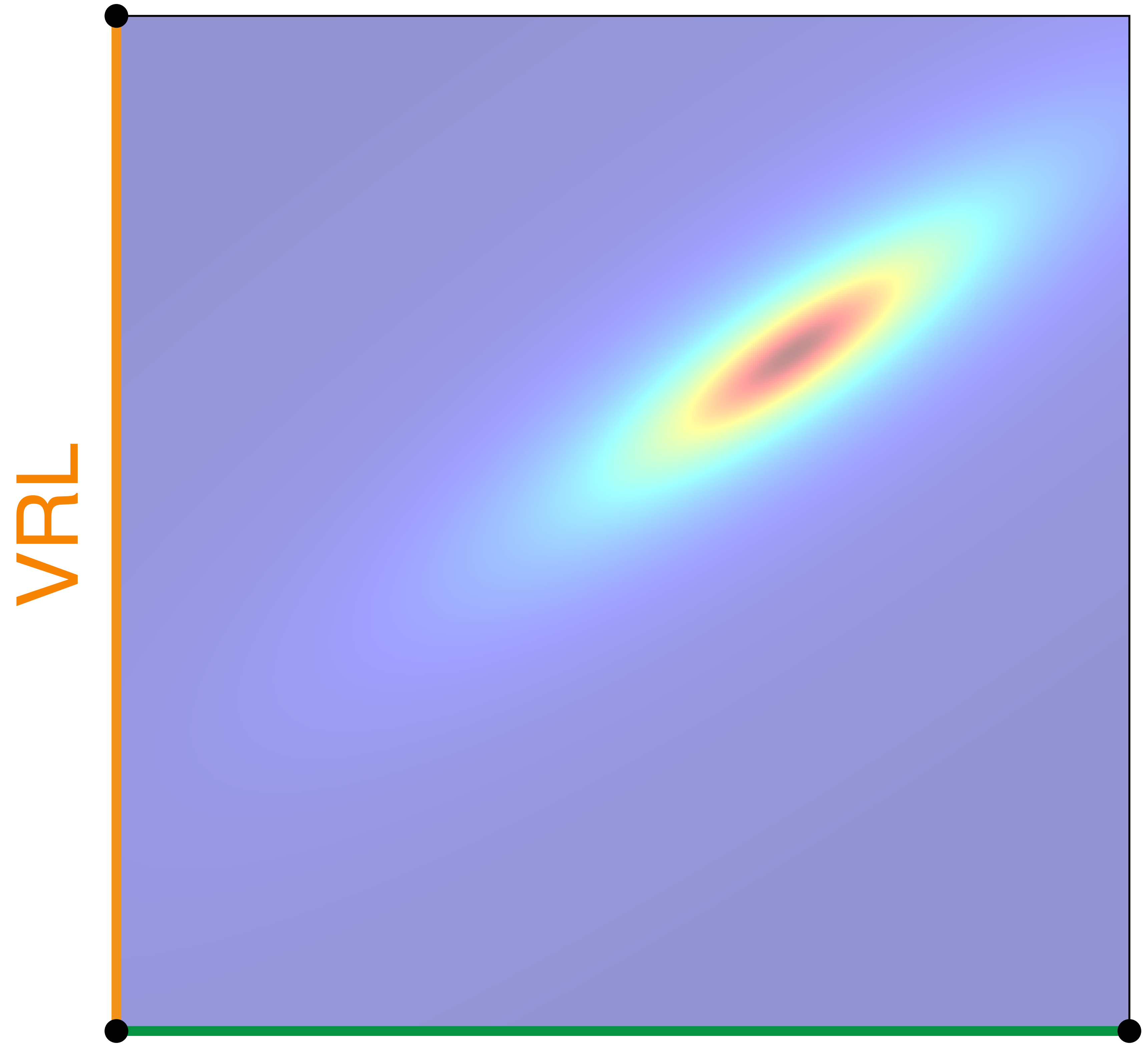


camera ray

Isotropic media

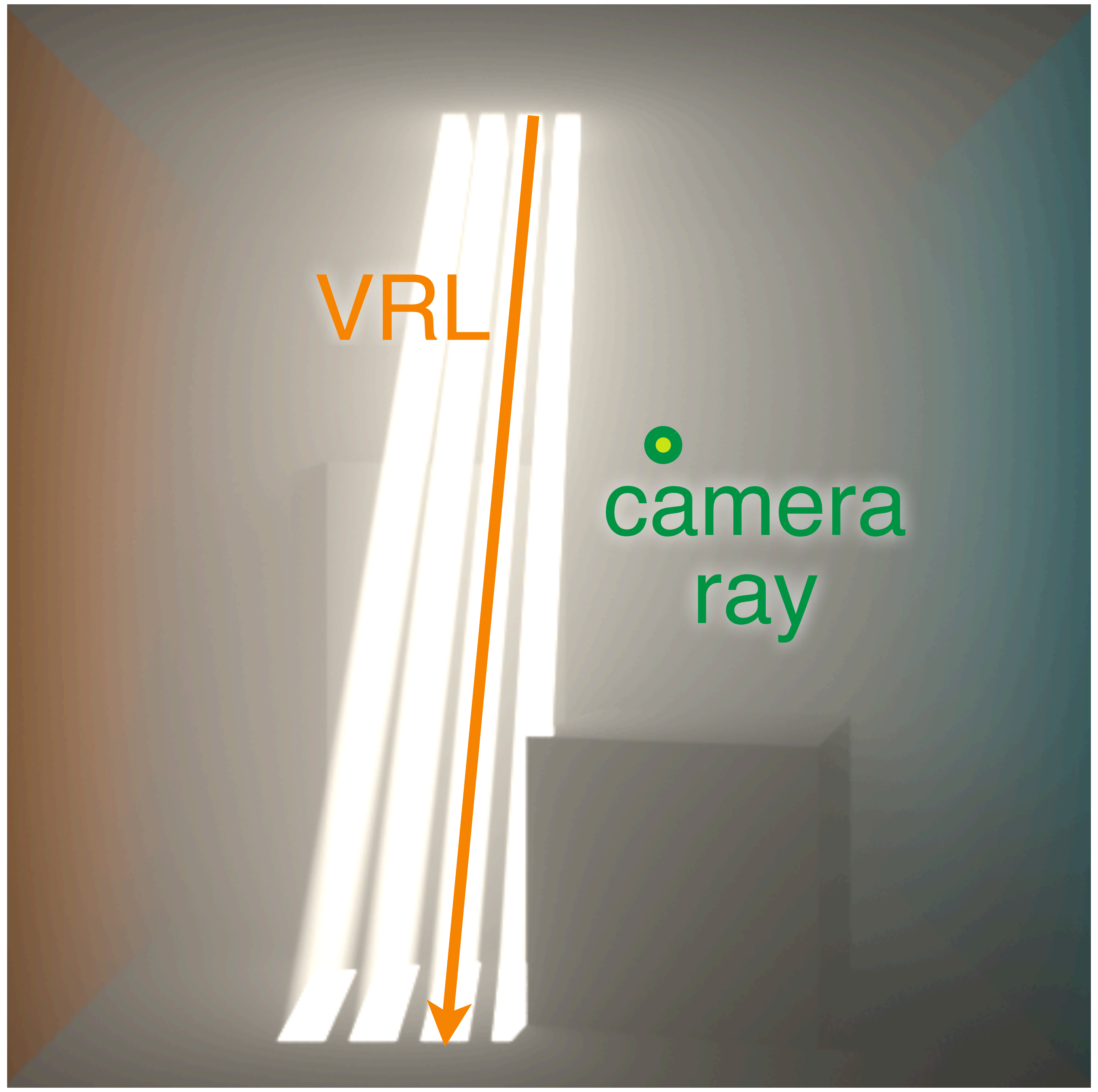


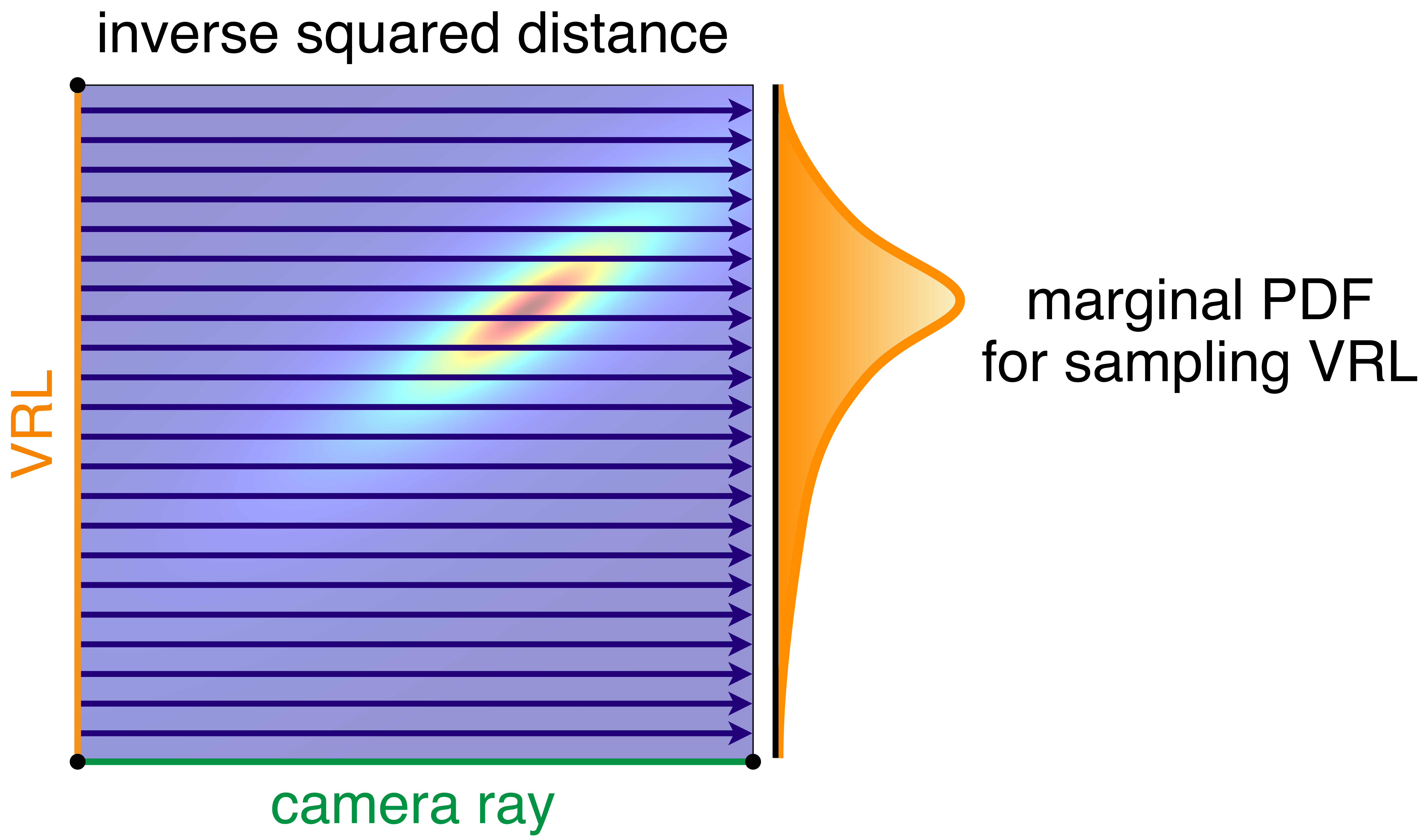
inverse squared distance



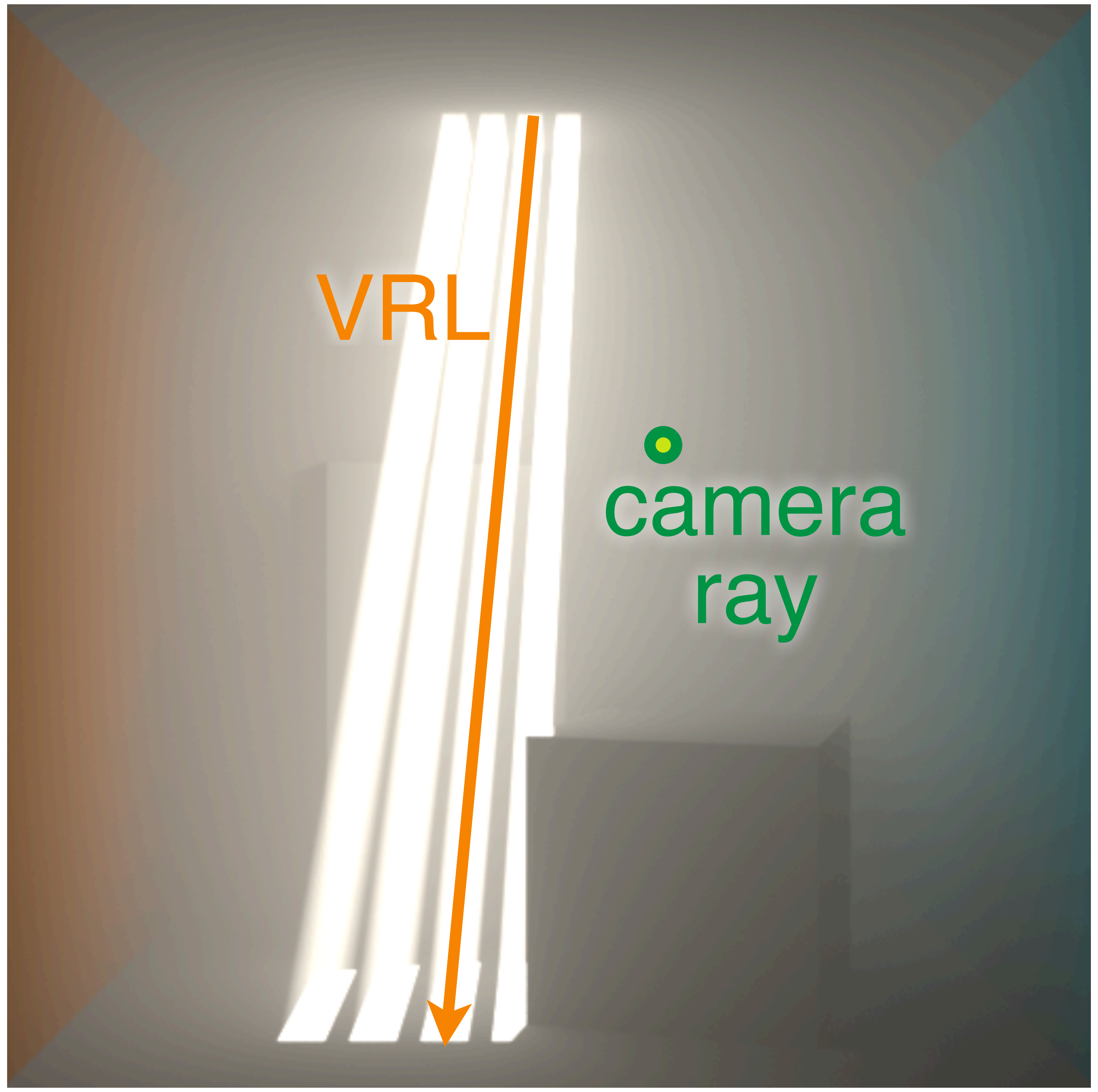
camera ray

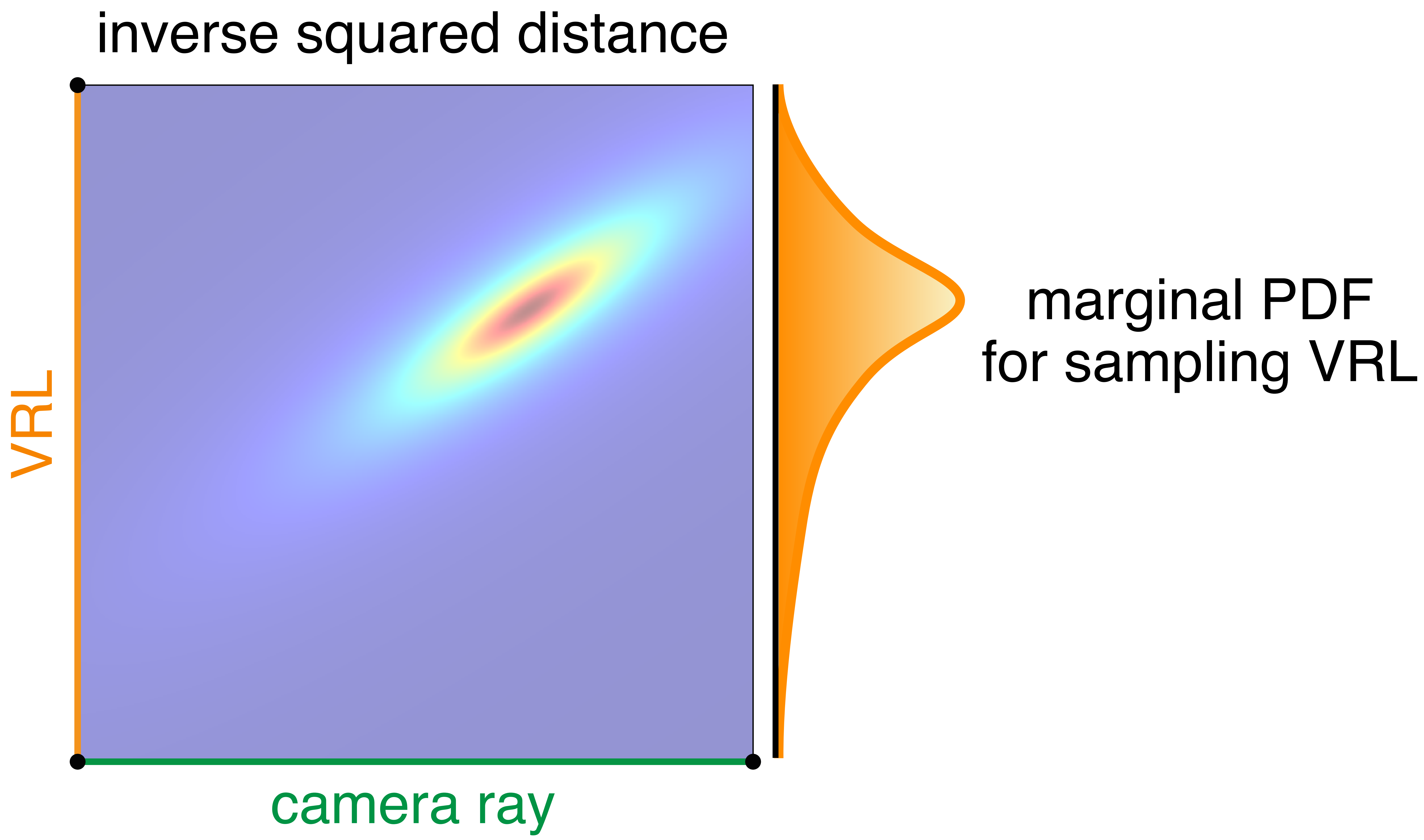
Isotropic media



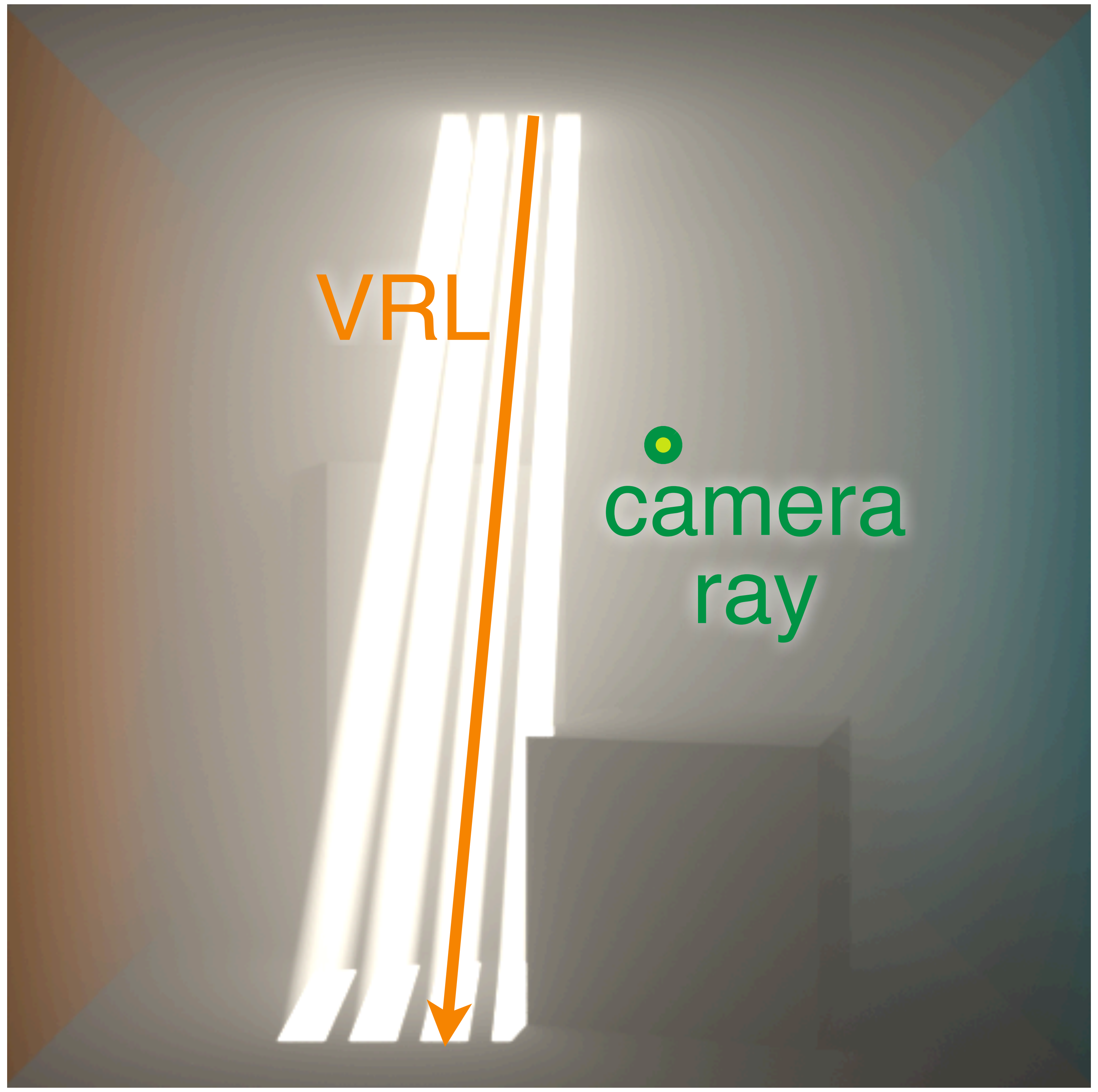


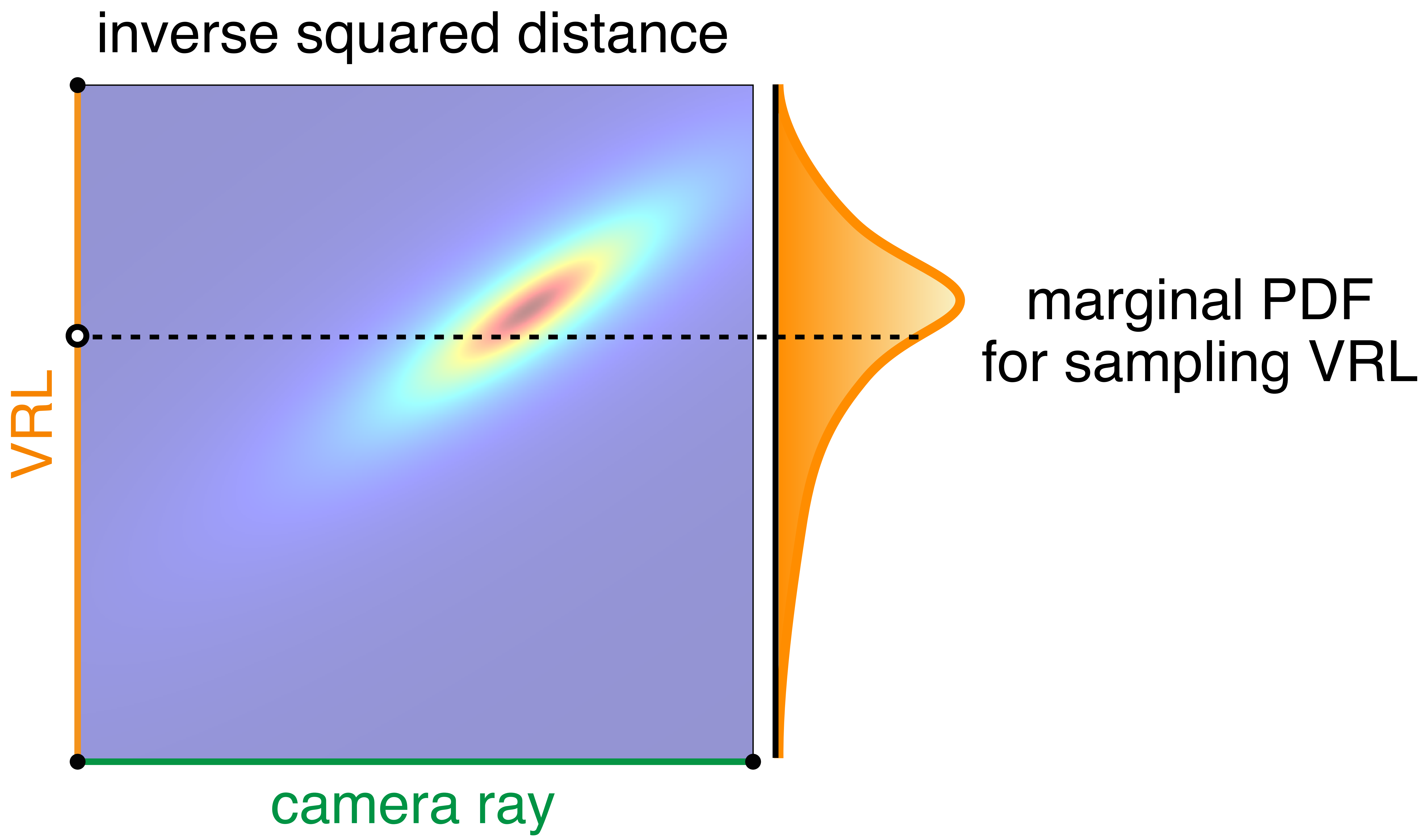
Isotropic media



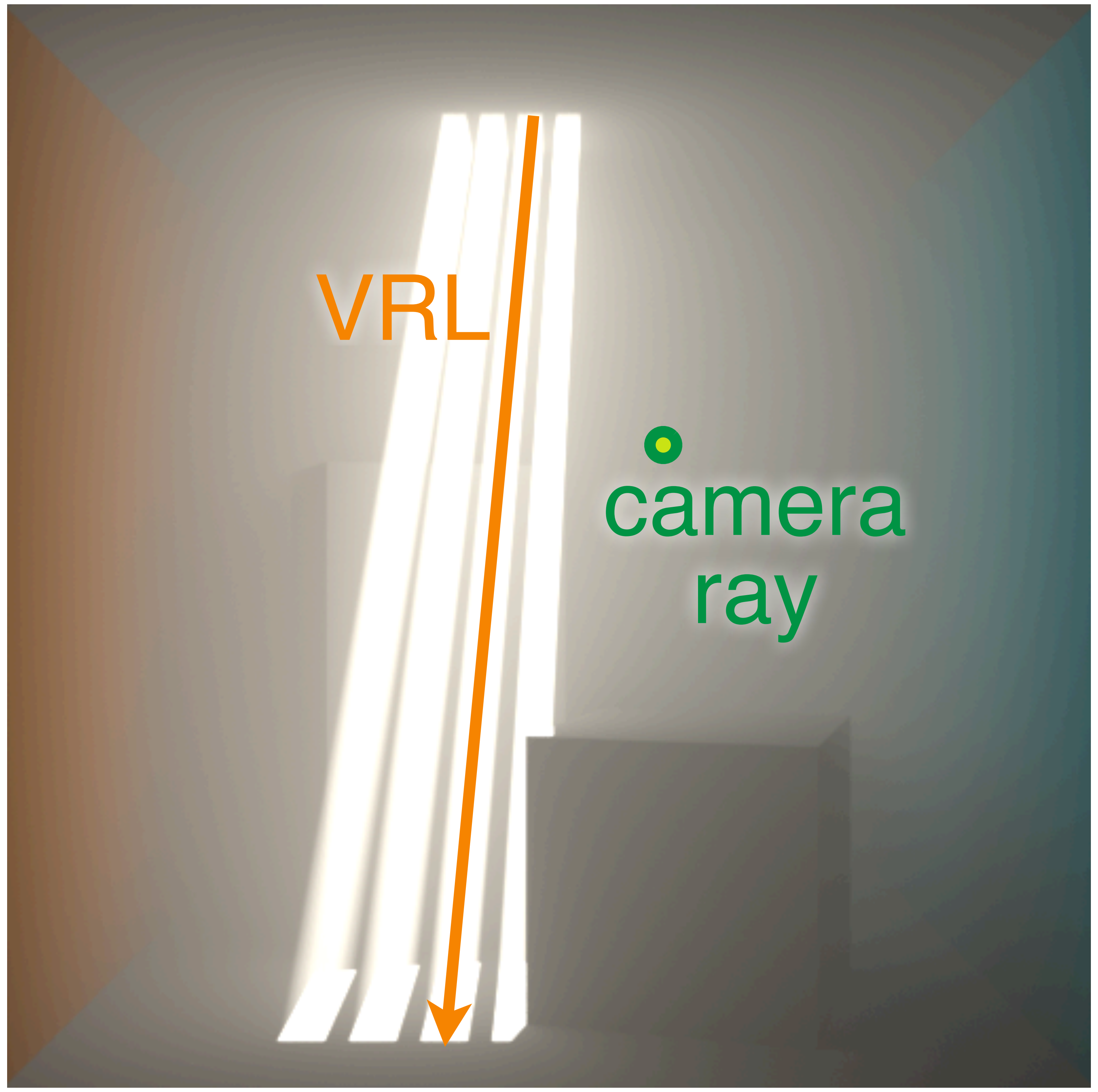


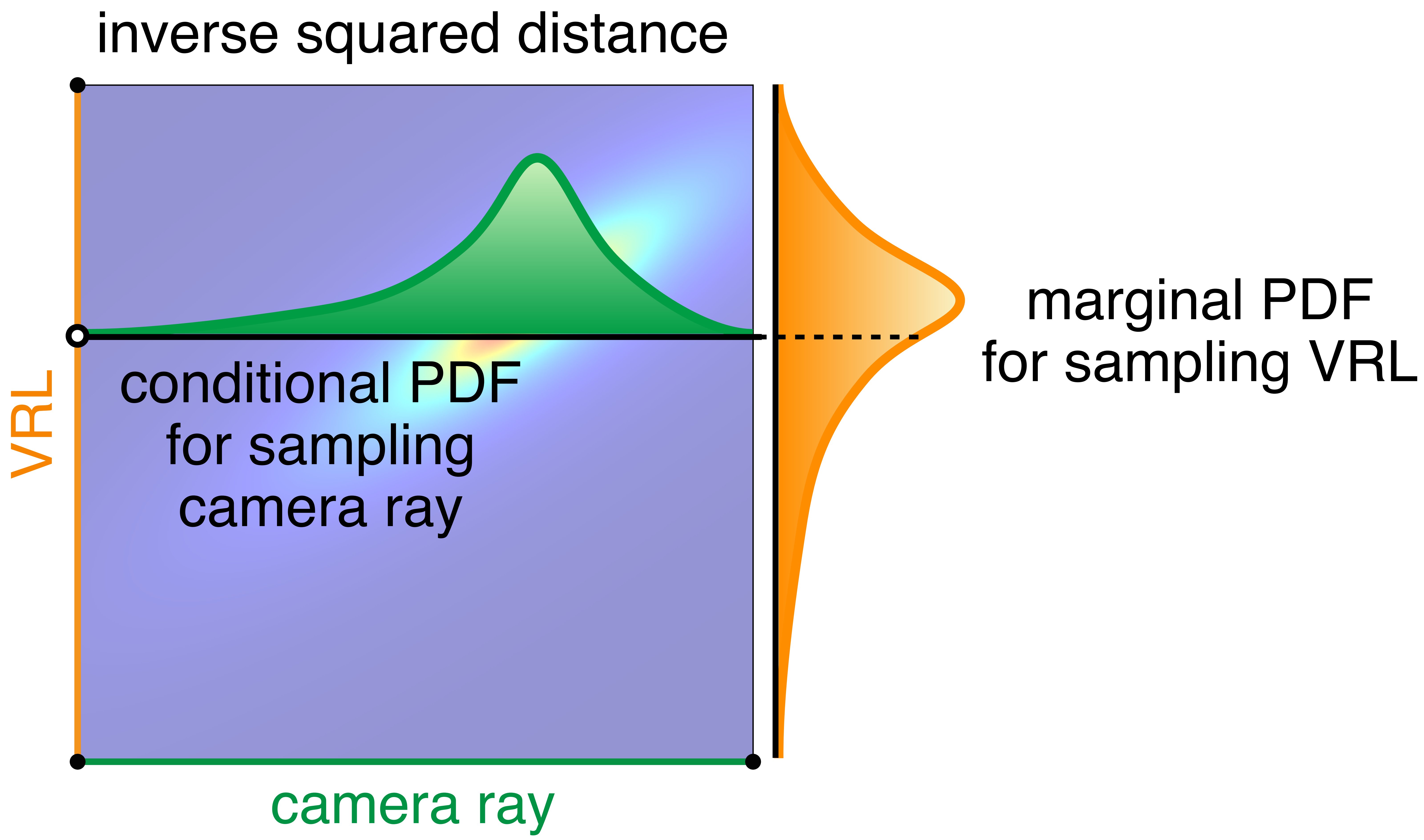
Isotropic media



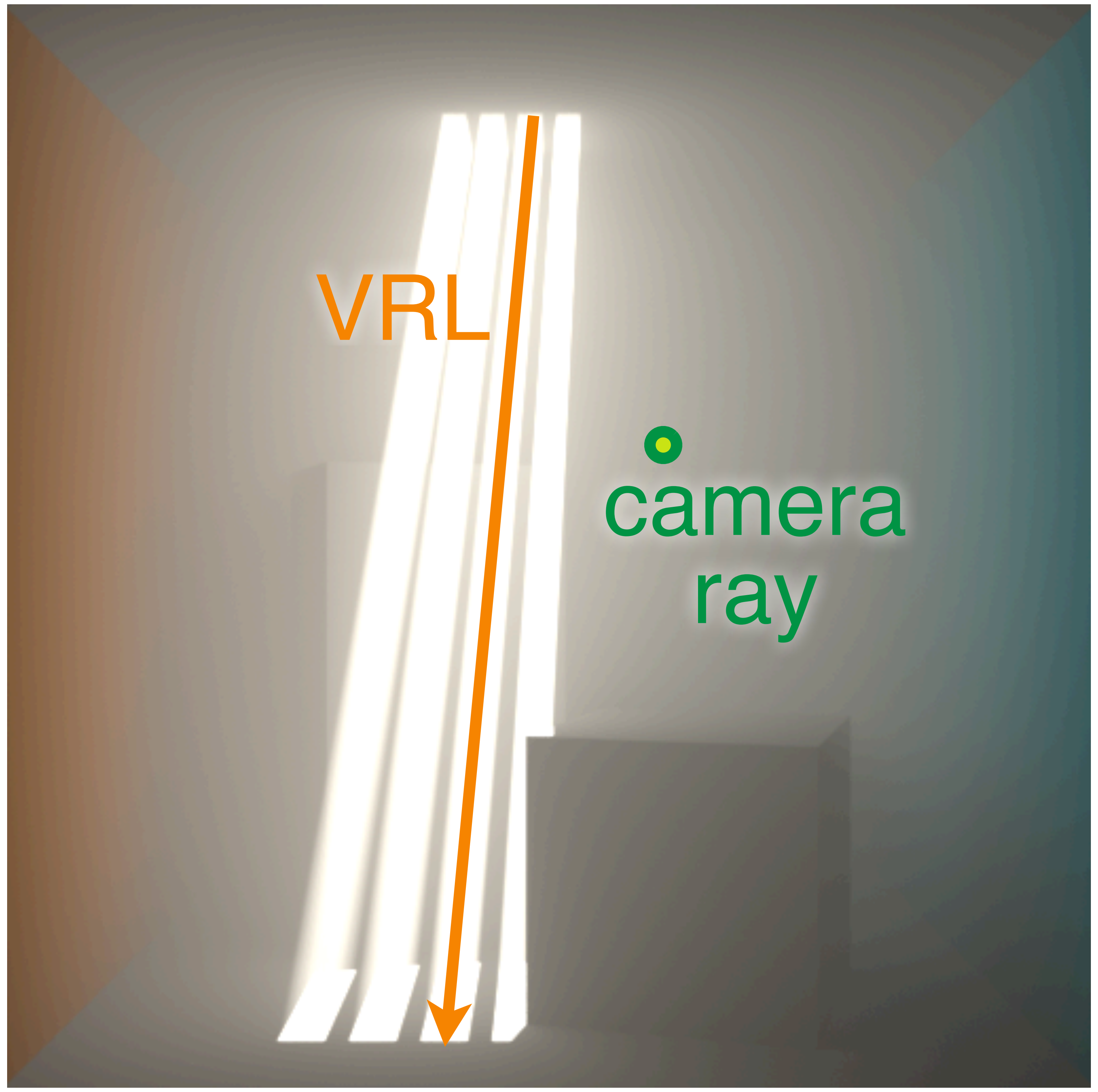


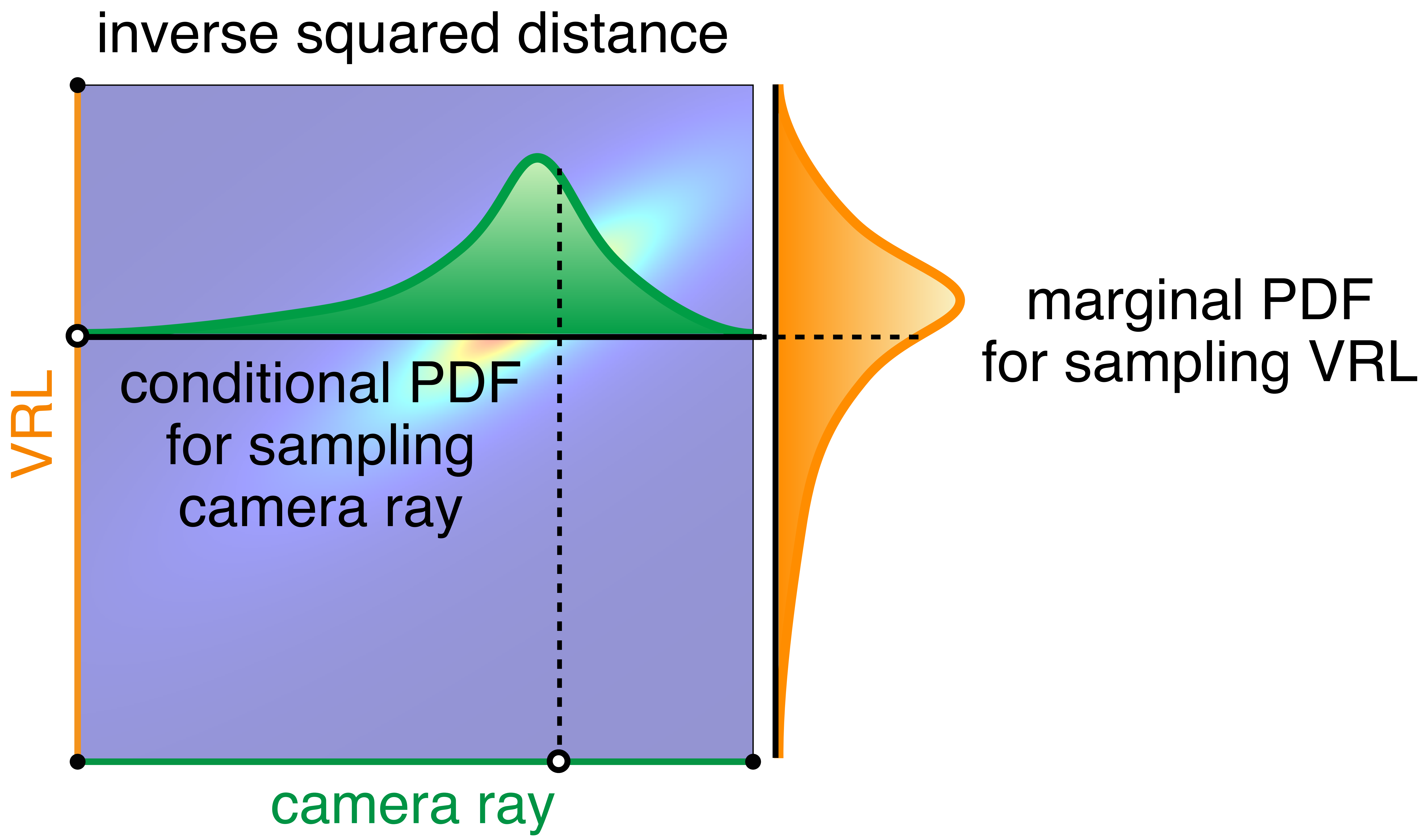
Isotropic media



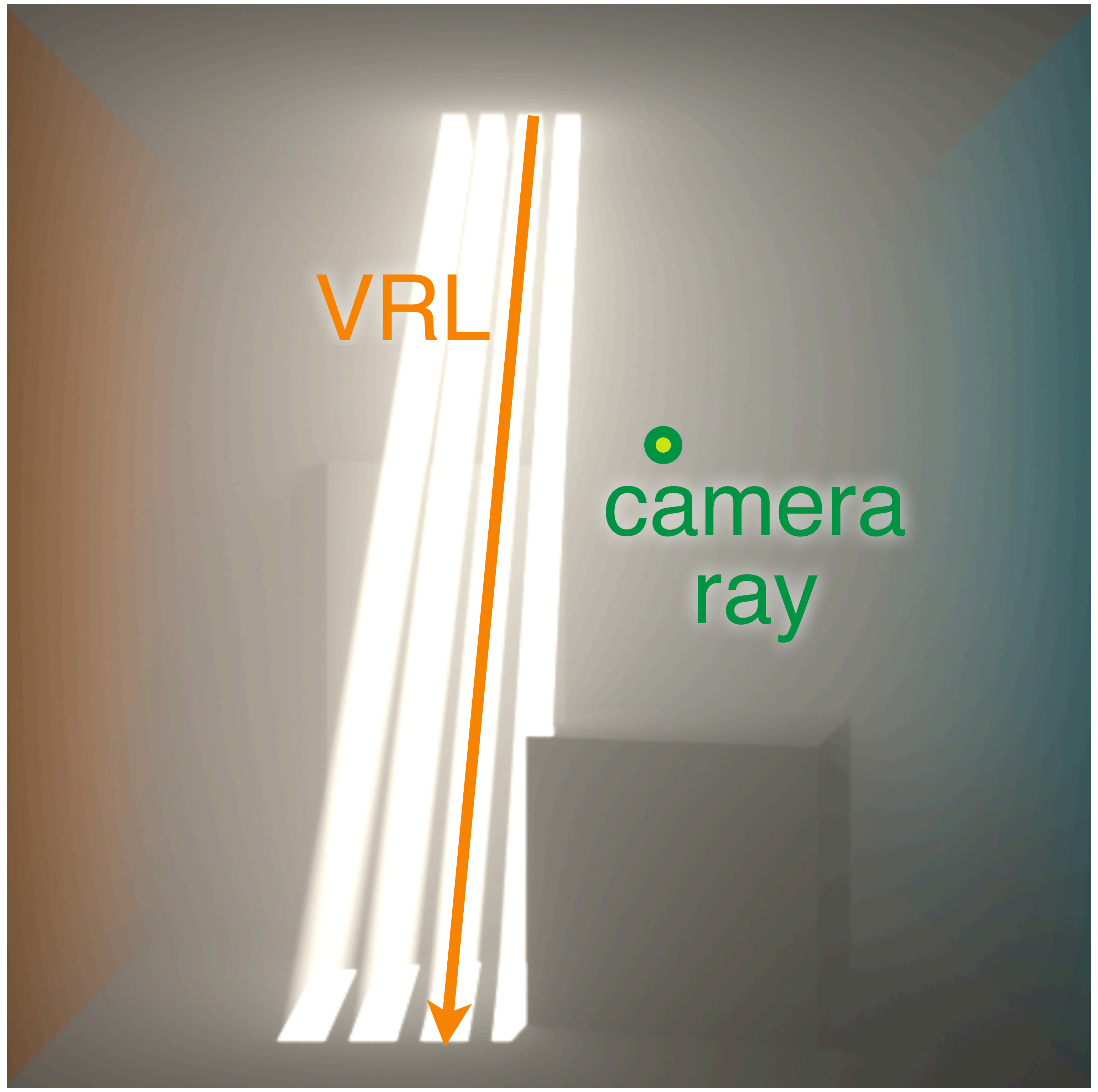


Isotropic media

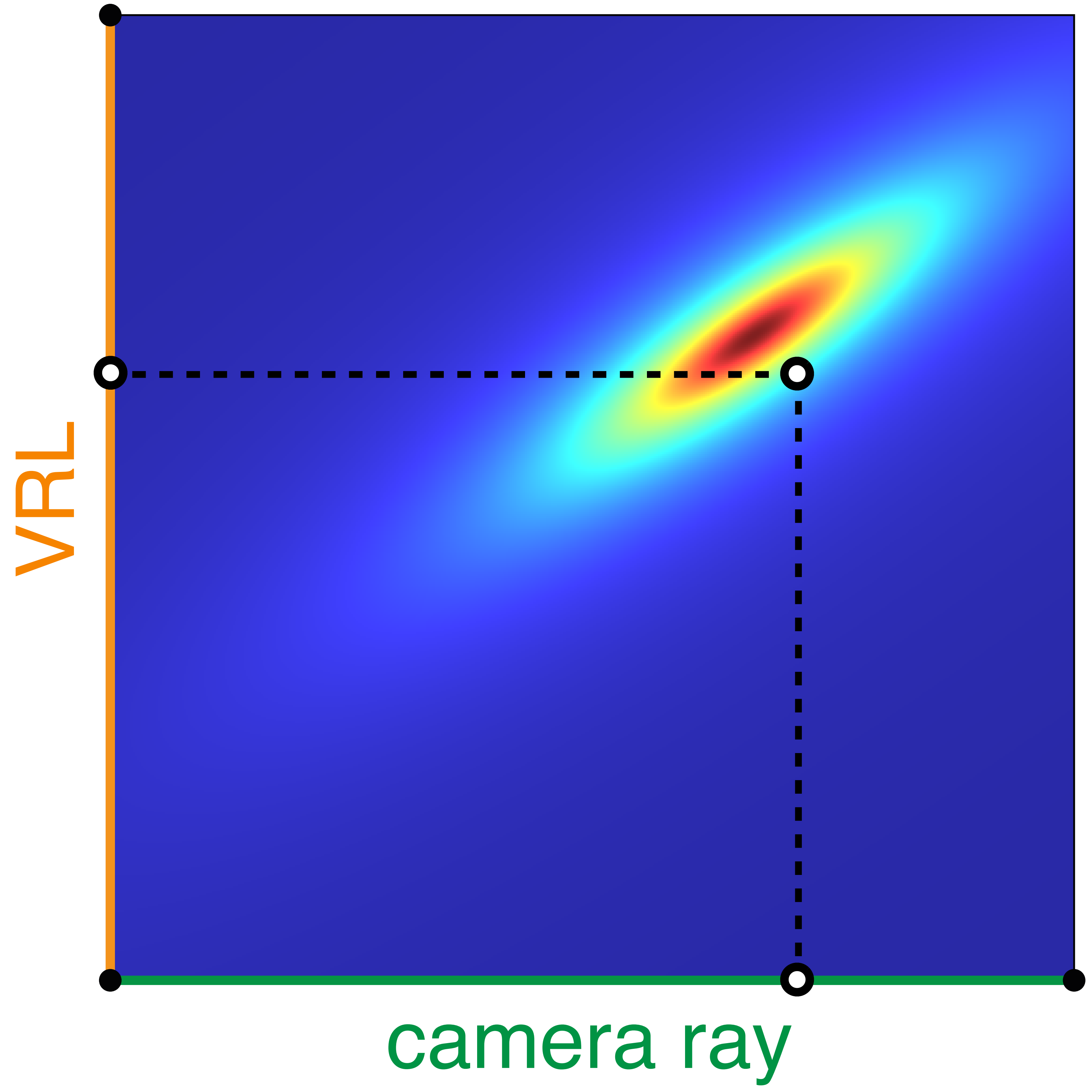




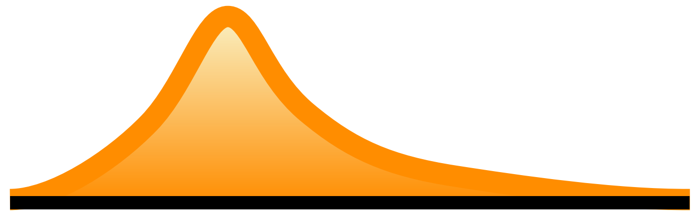
Isotropic media



inverse squared distance



Isotropic media

- **Marginal PDF** 

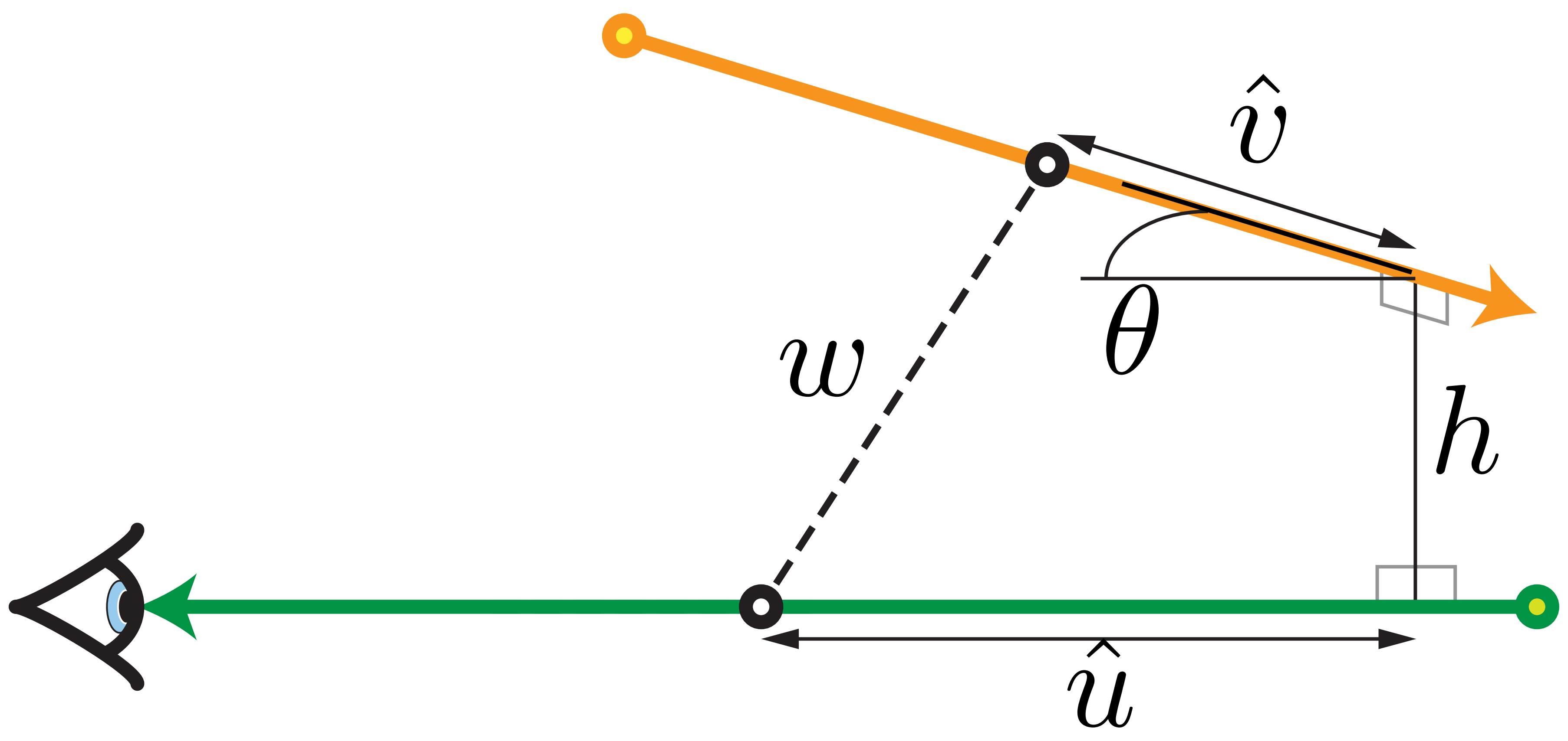
$$\mathrm{pdf}(v) = \frac{\int_0^s w^{-2}\ \mathrm{d}u}{\int_0^t \int_0^s w^{-2}\ \mathrm{d}u\mathrm{d}v}$$

Isotropic media

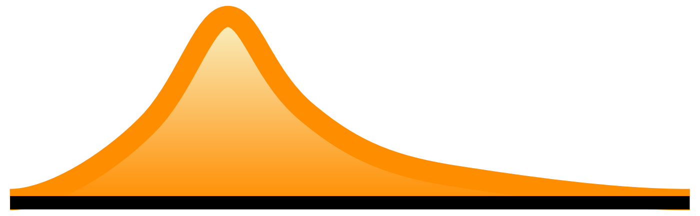
- **Marginal PDF**

$$\mathrm{pdf}(v) = \frac{\int_0^s w^{-2}\,\mathrm{d}u}{\int_0^t \int_0^s w^{-2}\,\mathrm{d}u\mathrm{d}v}$$

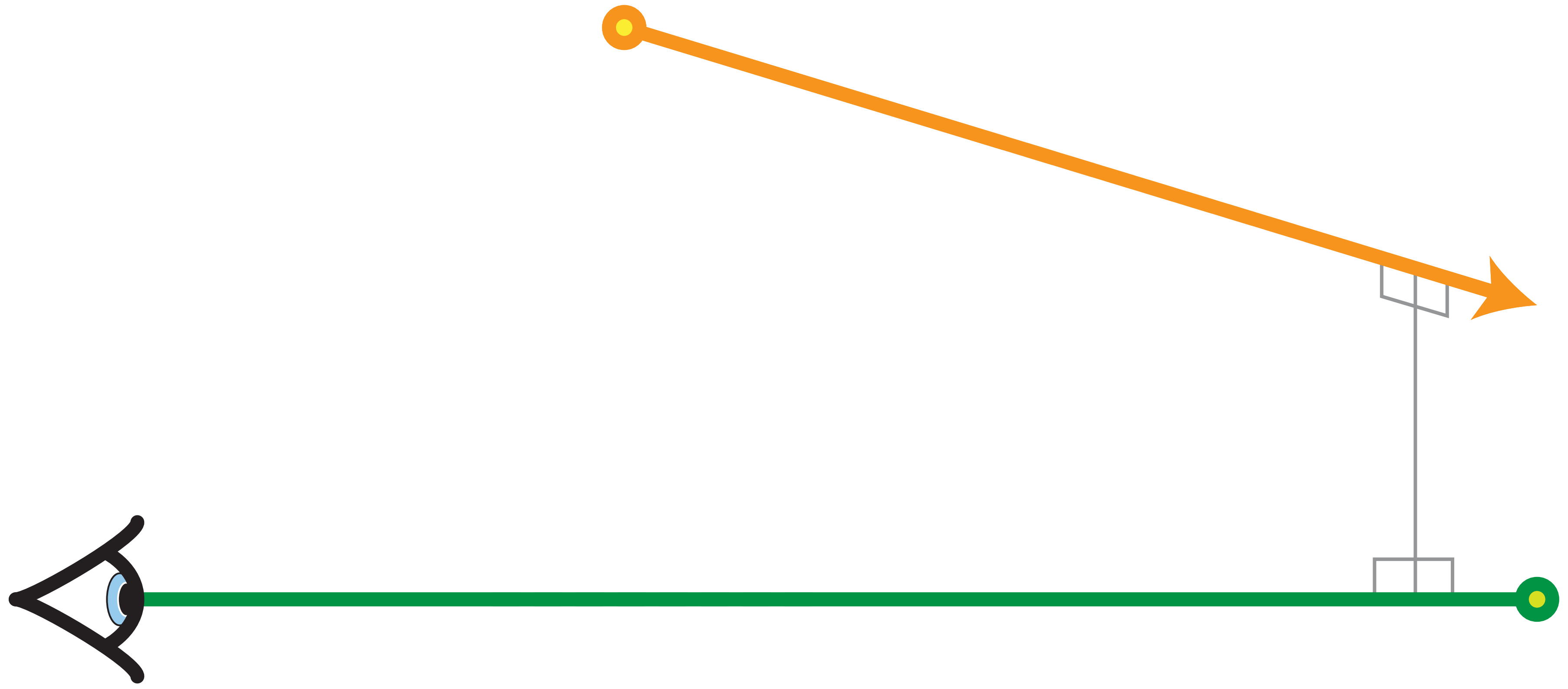
$$w = \sqrt{h^2 + \hat{u}^2 + \hat{v}^2 - 2\hat{u}\hat{v}\cos\theta}$$



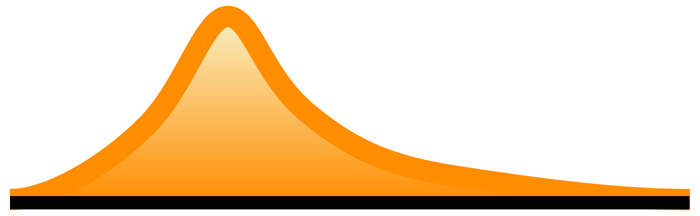
Isotropic media

- **Marginal PDF** 

$$\mathrm{pdf}(v) = \frac{\int_0^s w^{-2}\, \mathrm{d}u}{\int_0^t \int_0^s w^{-2}\, \mathrm{d}u\mathrm{d}v} \approx \frac{\int_{-\infty}^{\infty} w^{-2}\, \mathrm{d}u}{\int_0^t \int_{-\infty}^{\infty} w^{-2}\, \mathrm{d}u\mathrm{d}v}$$

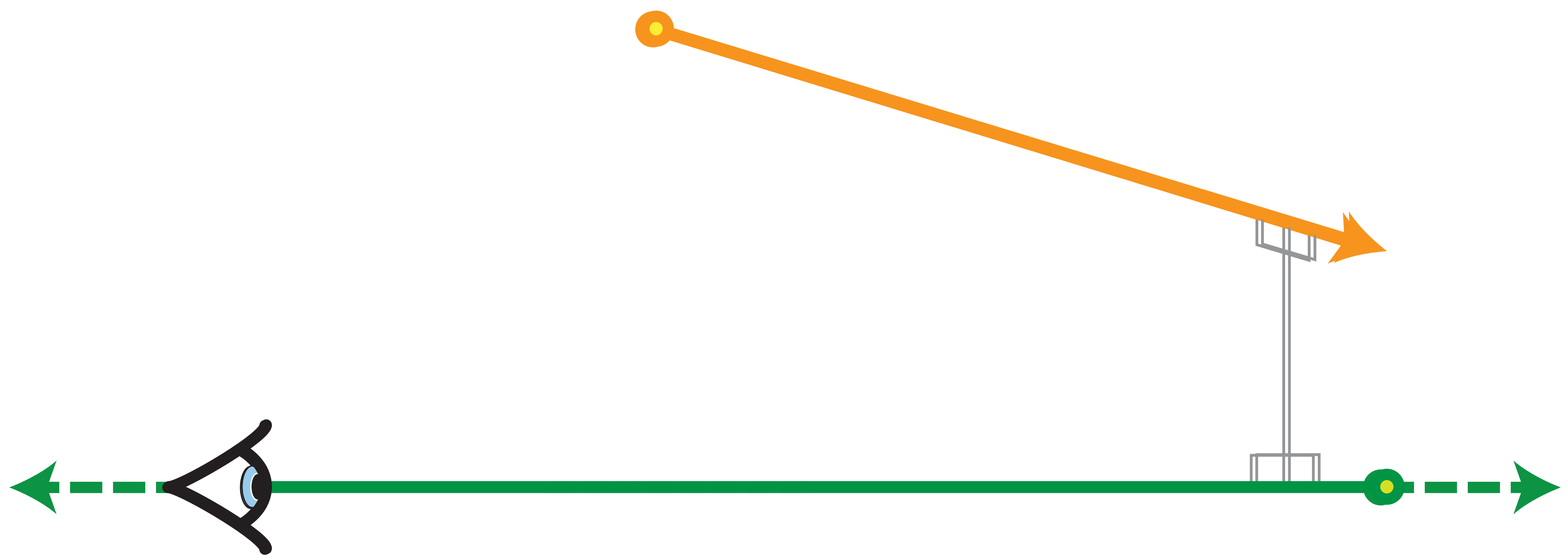


Isotropic media

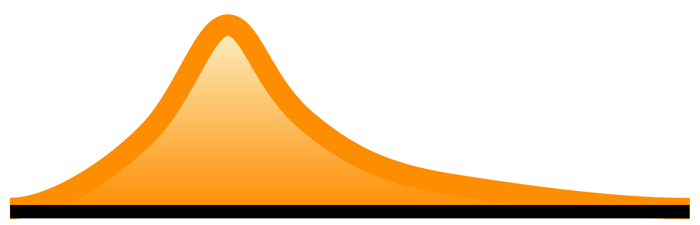
- **Marginal PDF** 

$$\mathrm{pdf}(v) = \frac{\int_0^s w^{-2}\,\mathrm{d}u}{\int_0^t \int_0^s w^{-2}\,\mathrm{d}u\mathrm{d}v} \approx \frac{\int_{-\infty}^{\infty} w^{-2}\,\mathrm{d}u}{\int_0^t \int_{-\infty}^{\infty} w^{-2}\,\mathrm{d}u\mathrm{d}v}$$

assume infinite camera ray

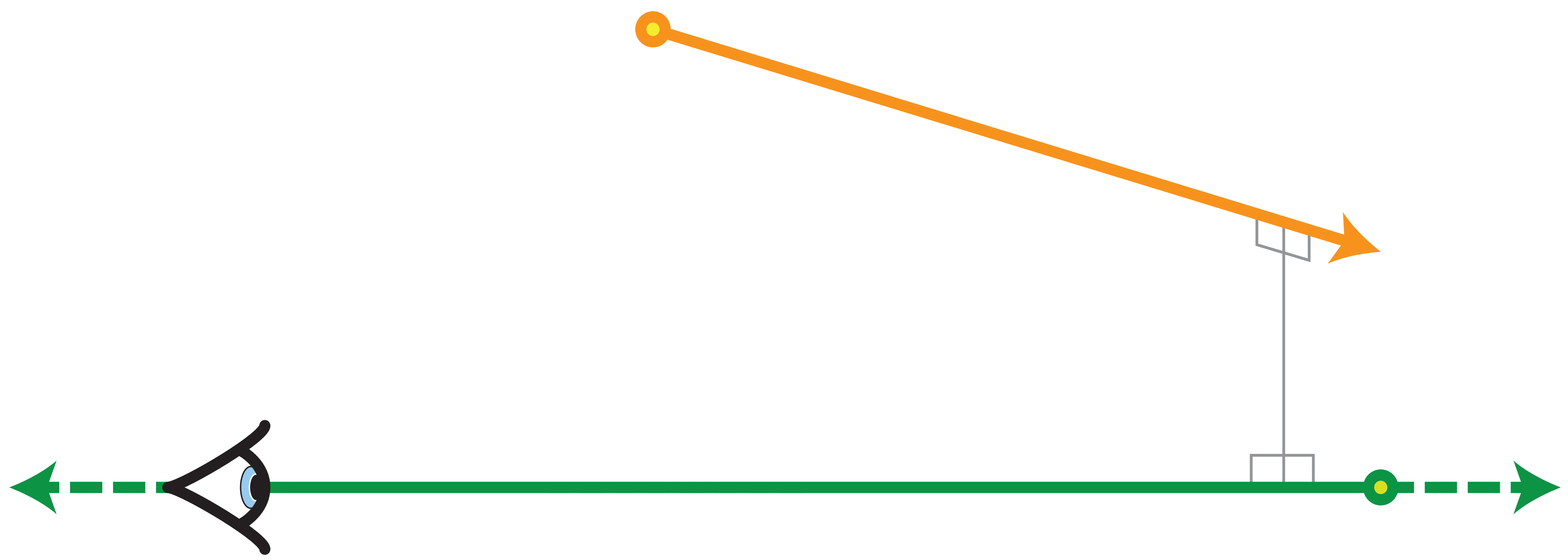


Isotropic media

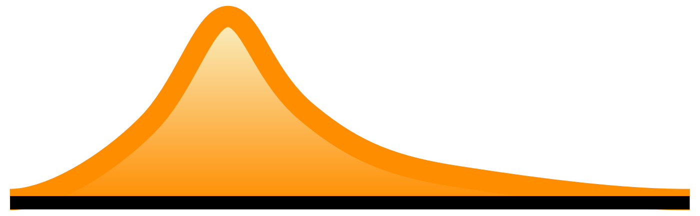


$$\mathrm{pdf}(v) = \frac{\int_0^s w^{-2}\,\mathrm{d}u}{\int_0^t \int_0^s w^{-2}\,\mathrm{d}u\mathrm{d}v} \approx \frac{\int_{-\infty}^{\infty} w^{-2}\,\mathrm{d}u}{\int_0^t \int_{-\infty}^{\infty} w^{-2}\,\mathrm{d}u\mathrm{d}v} = \frac{\sin\theta}{(A(\hat{v}_1) - A(\hat{v}_0))\sqrt{h^2 + v^2 \sin^2\theta}}$$

assume infinite camera ray



Isotropic media



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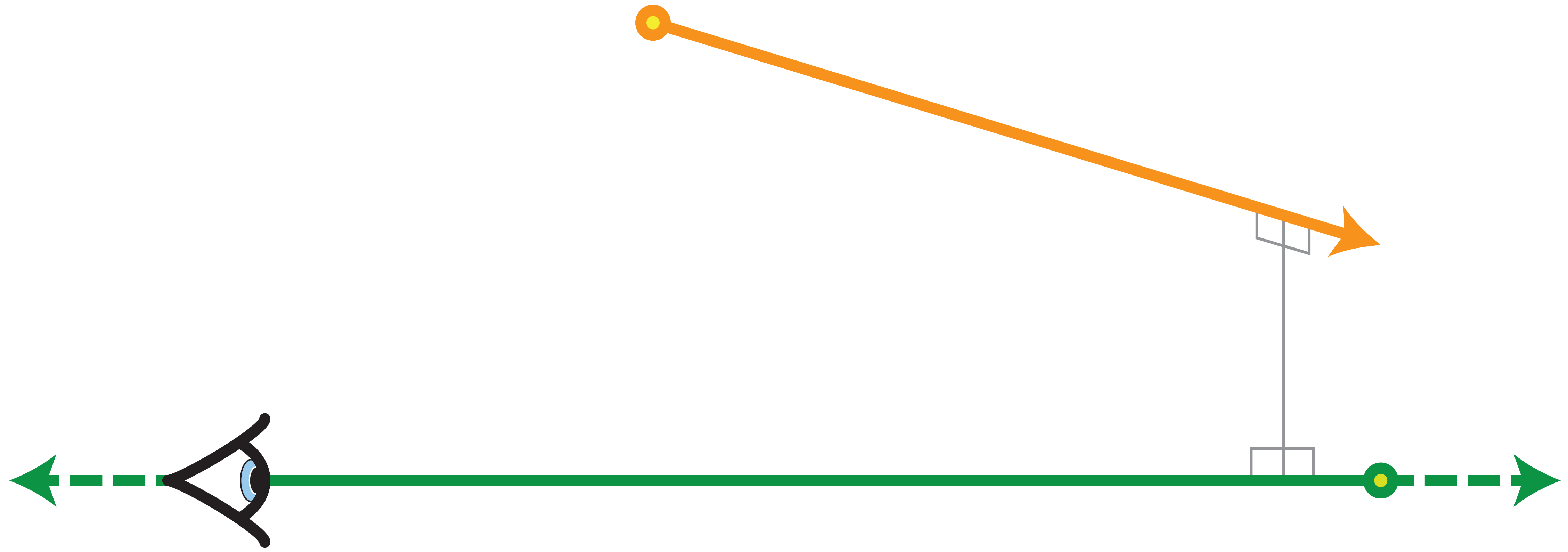
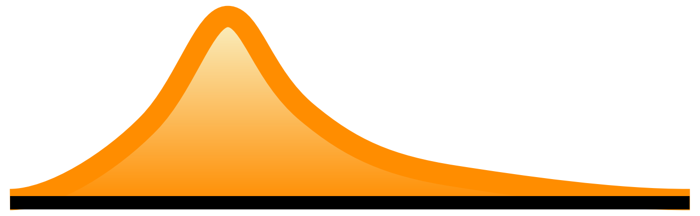
assume infinite camera ray

$$A(x) = \sinh^{-1}\left(\frac{x}{h}\sin\theta\right)$$



Isotropic media

- **Marginal PDF** 

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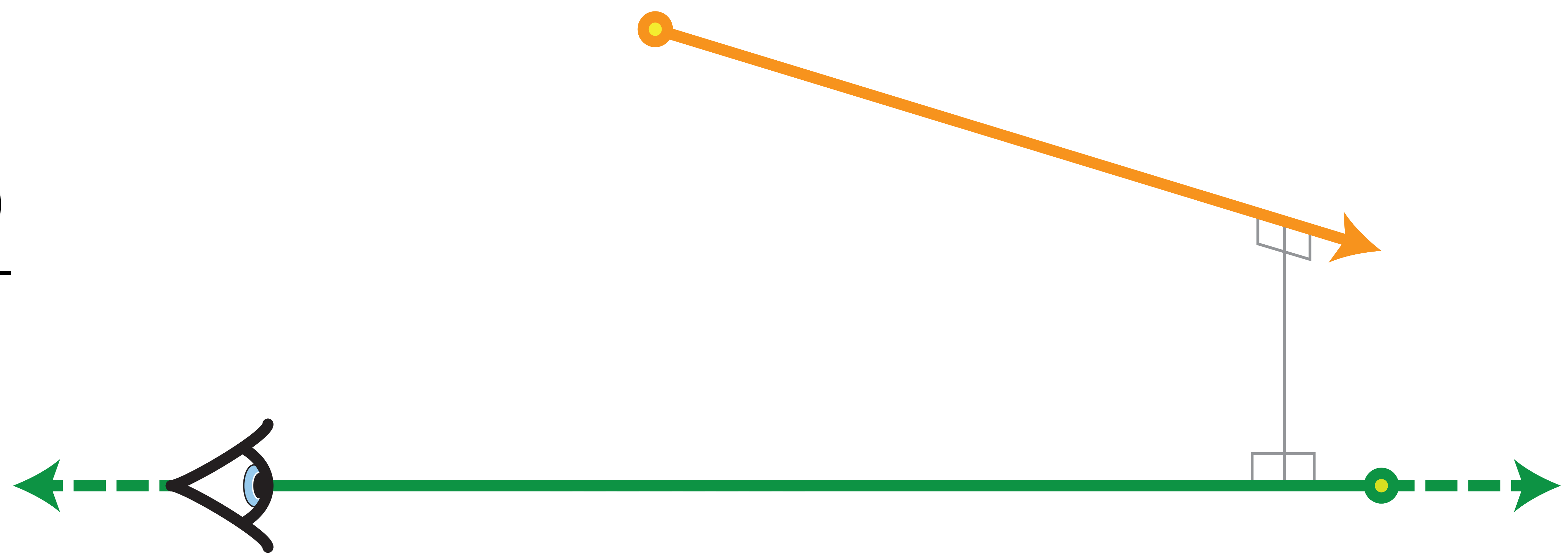
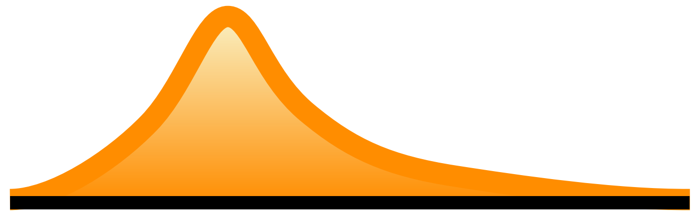
assume infinite camera ray

$$A(x) = \sinh^{-1}\left(\frac{x}{h}\sin\theta\right)$$

$$\mathrm{cdf}^{-1}(\xi) = \frac{h\sinh(\mathrm{lerp}(A(\hat{v}_0), A(\hat{v}_1), \xi))}{\sin\theta}$$



Isotropic media

- **Marginal PDF** 

$$\mathrm{pdf}(v) = \frac{\int_0^s w^{-2}\,\mathrm{d}u}{\int_0^t \int_0^s w^{-2}\,\mathrm{d}u\mathrm{d}v} \approx \frac{\int_{-\infty}^{\infty} w^{-2}\,\mathrm{d}u}{\int_0^t \int_{-\infty}^{\infty} w^{-2}\,\mathrm{d}u\mathrm{d}v} = \frac{\sin\theta}{(A(\hat{v}_1) - A(\hat{v}_0))\sqrt{h^2 + v^2\sin^2\theta}}$$

assume infinite camera ray

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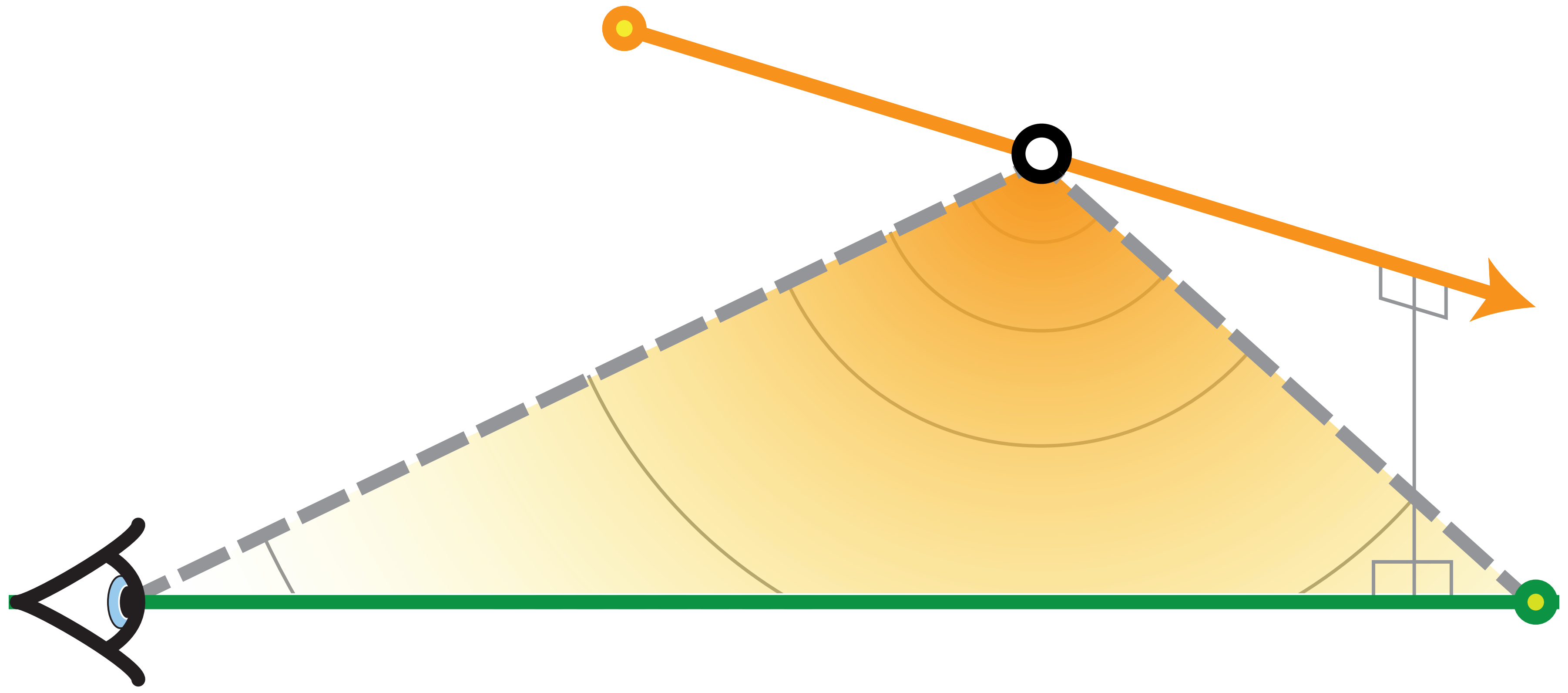
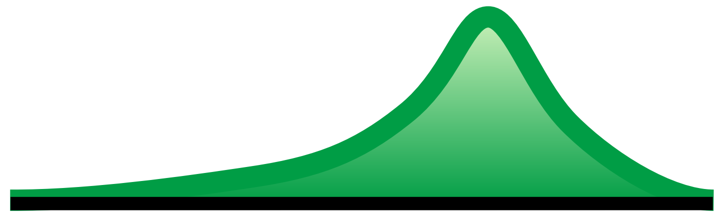
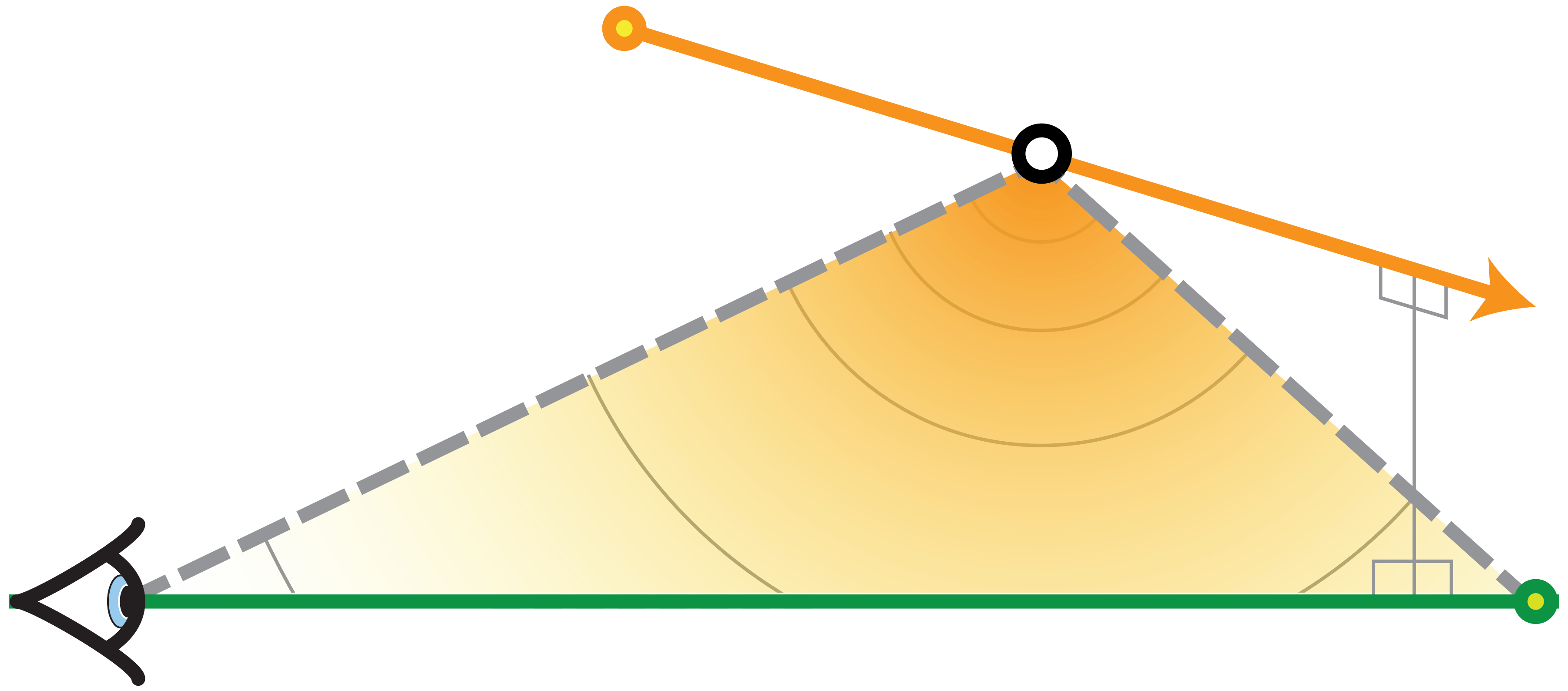
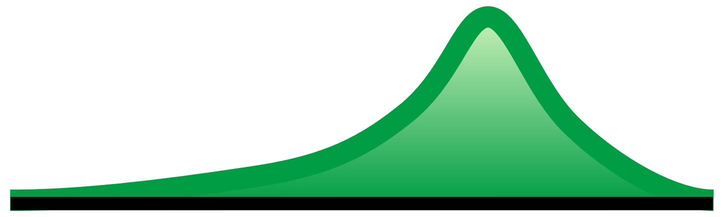


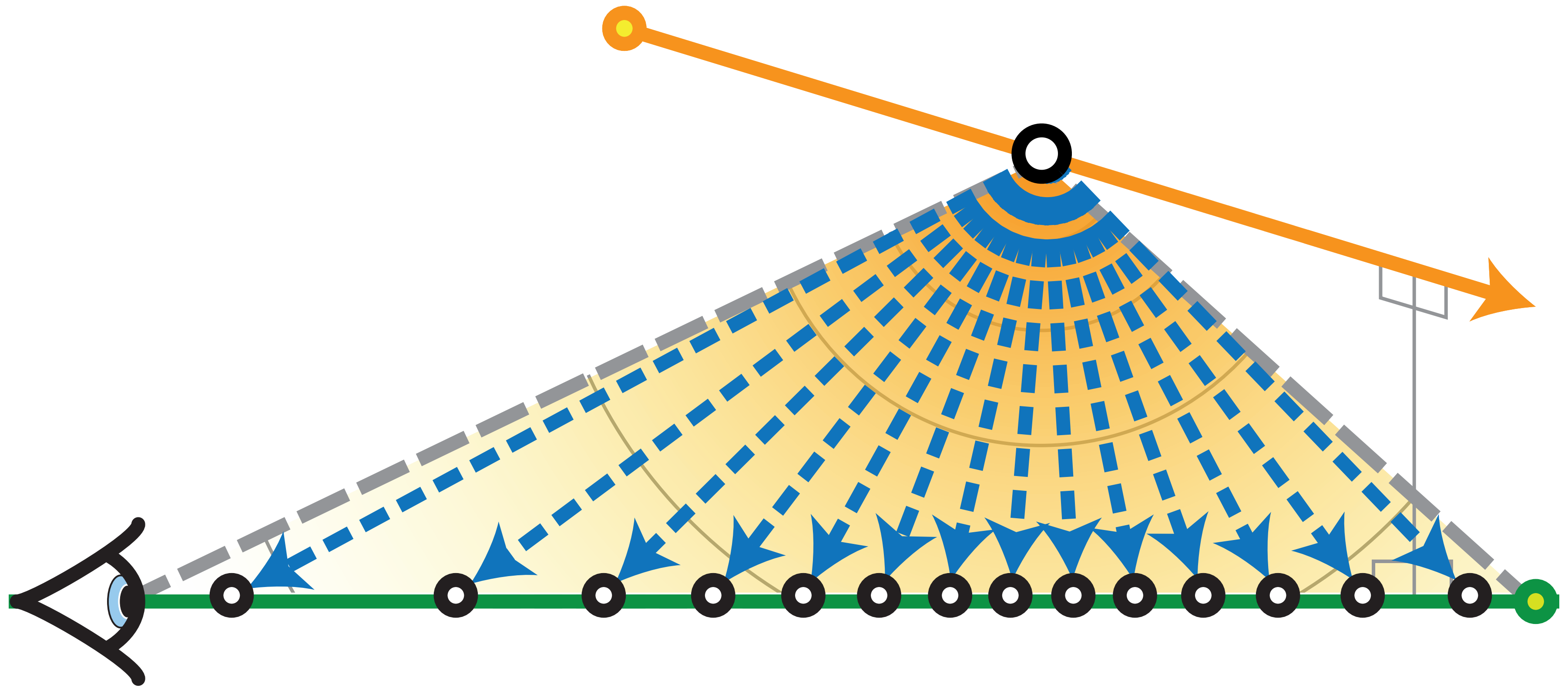
Isotropic media

- **Conditional PDF** 



Isotropic media

- **Conditional PDF** 

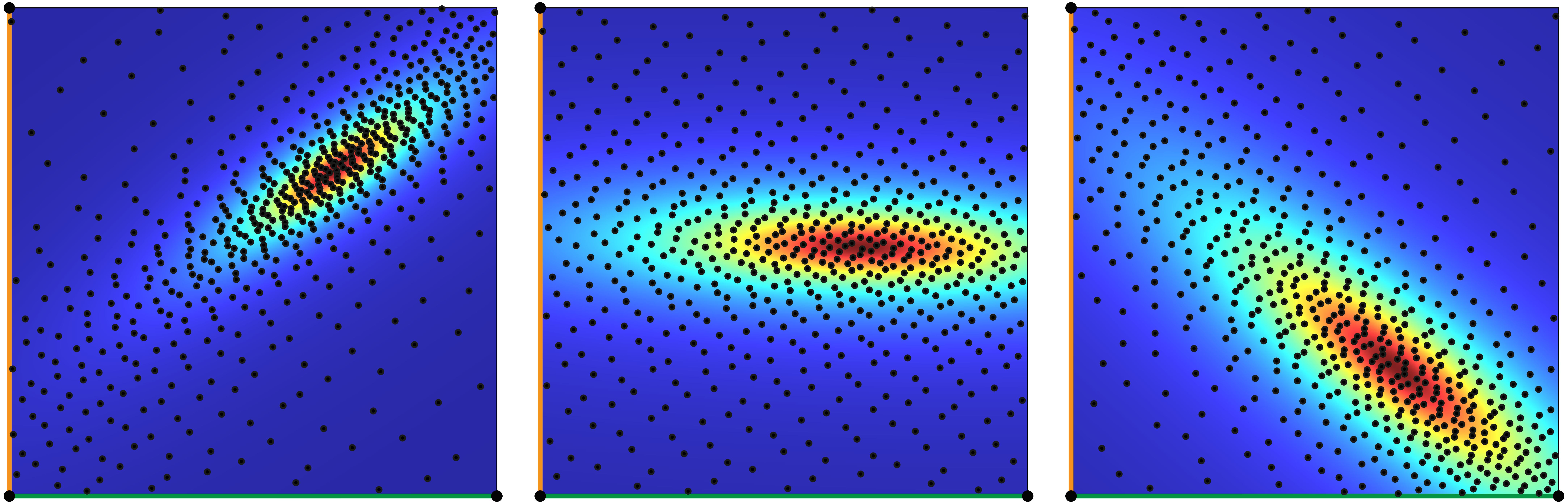


Isotropic media

Summary of isotropic media:

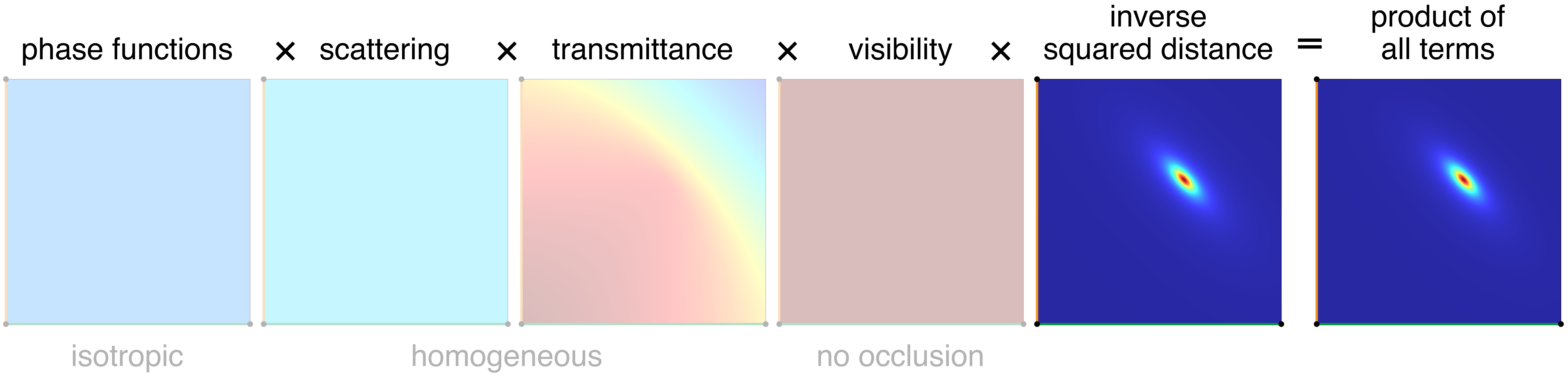
Isotropic media

Summary of isotropic media:



Importance sampling

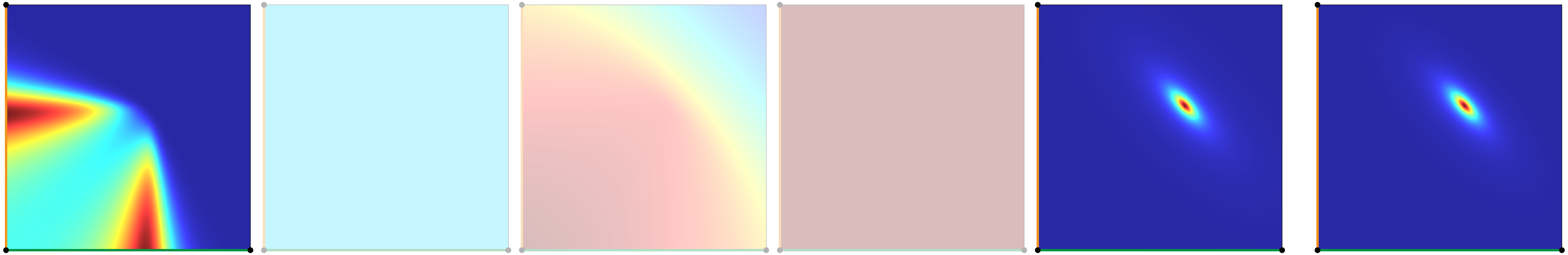
How to (importance) sample?



Importance sampling

How to (importance) sample?

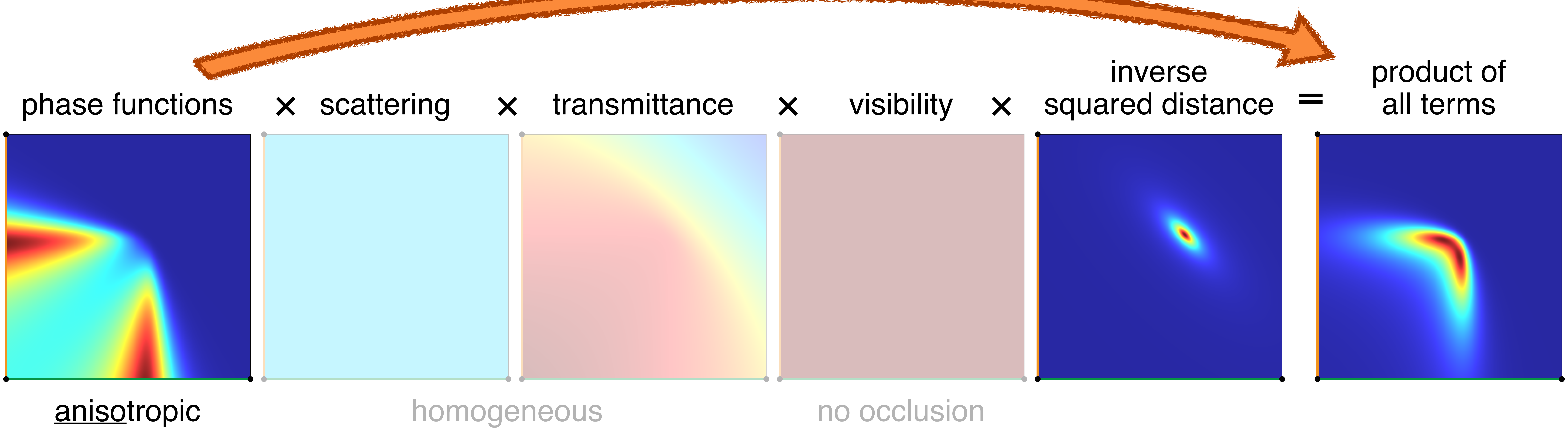
phase functions × scattering × transmittance × visibility × inverse squared distance = product of all terms



anisotropic homogeneous no occlusion

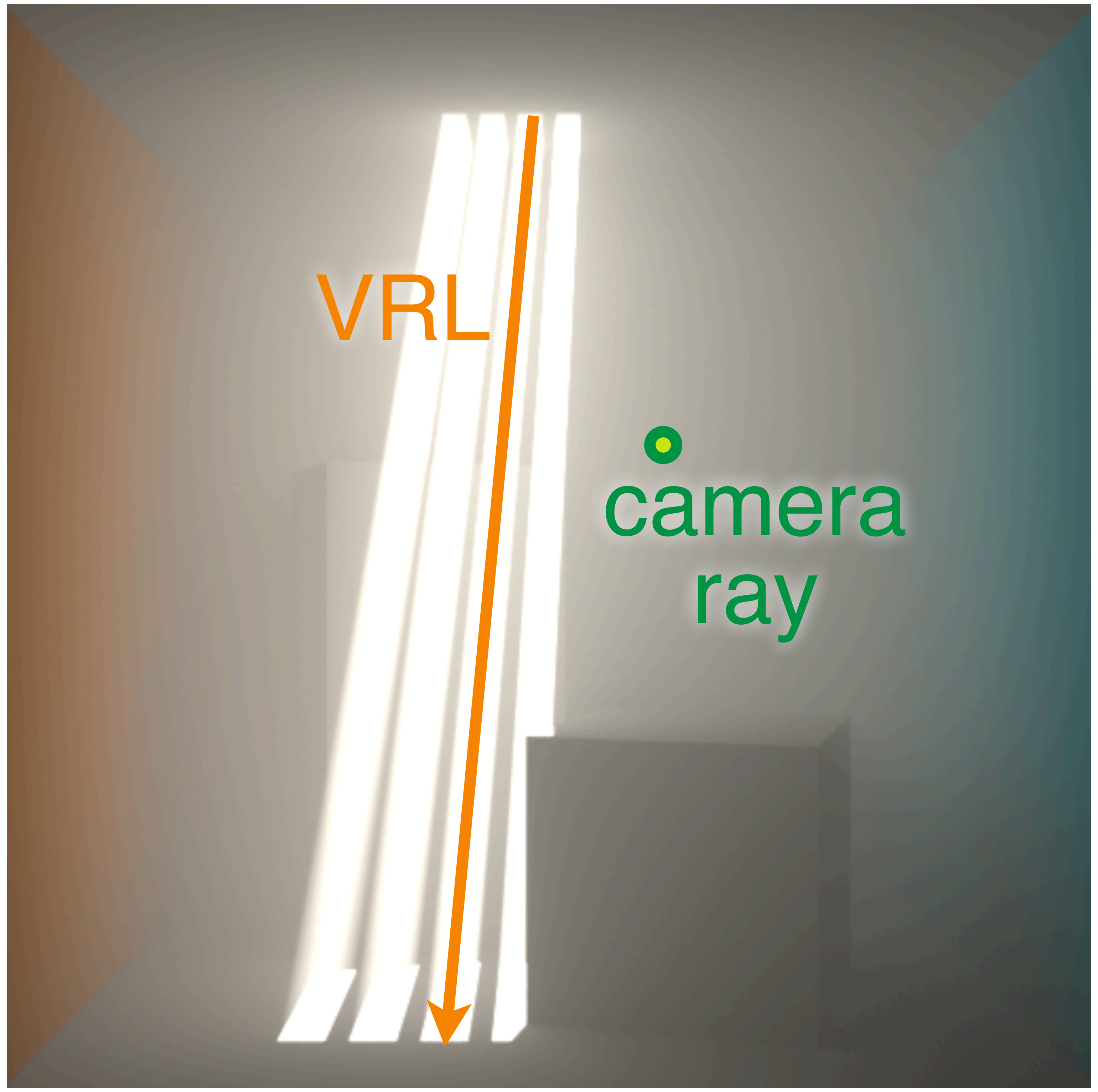
Importance sampling

How to (importance) sample?

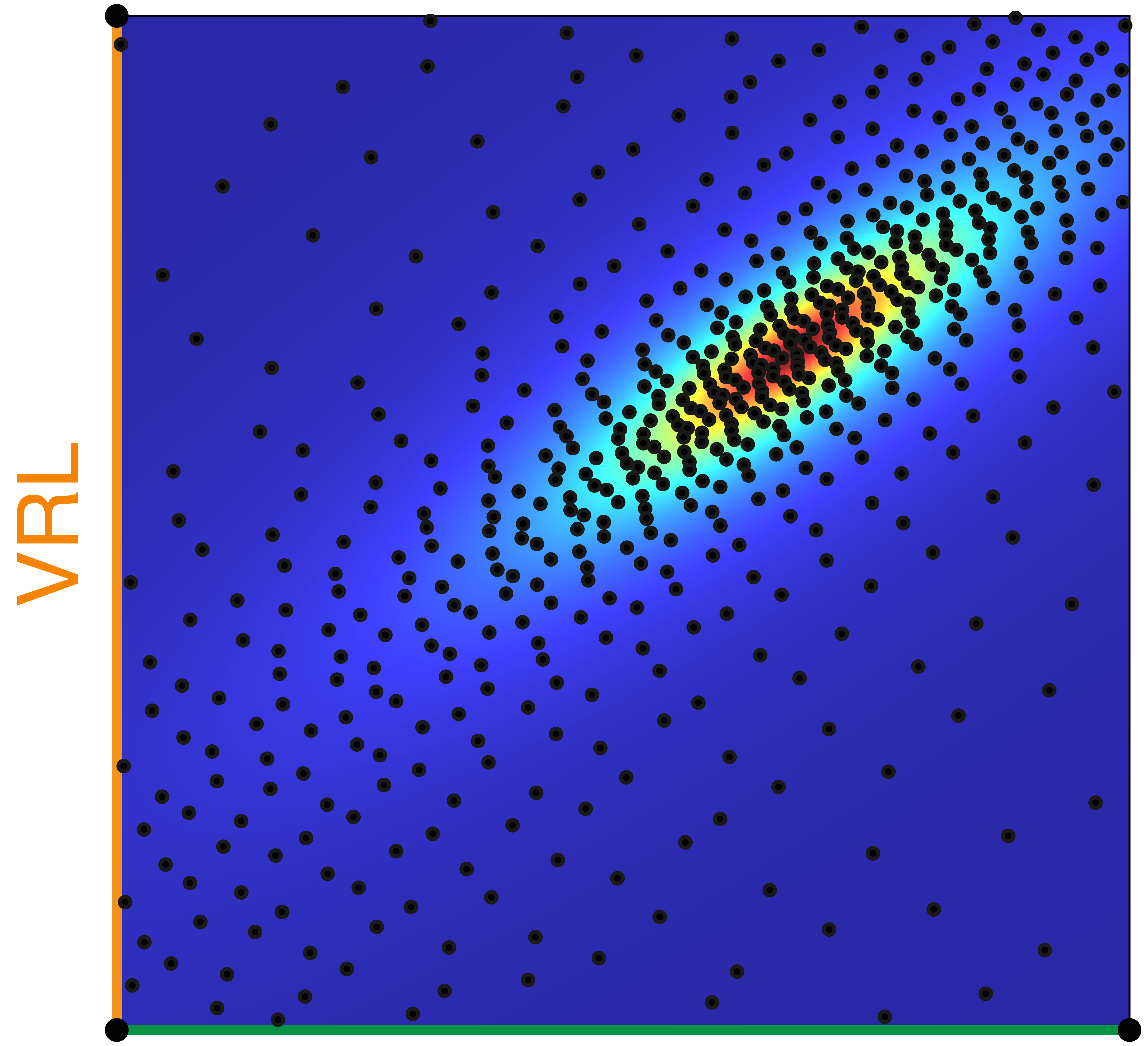


Anisotropic media

isotropic

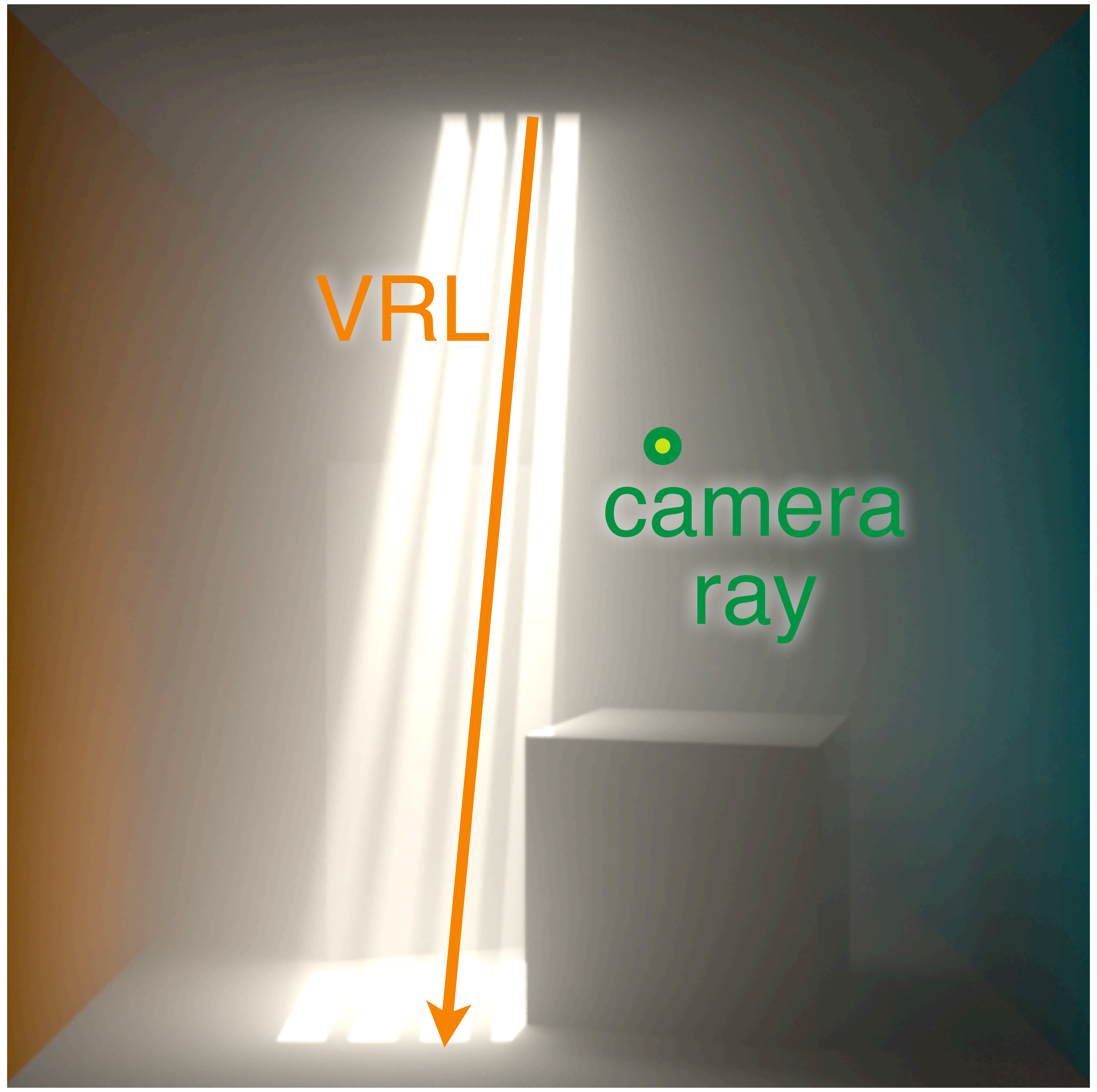


inverse squared distance

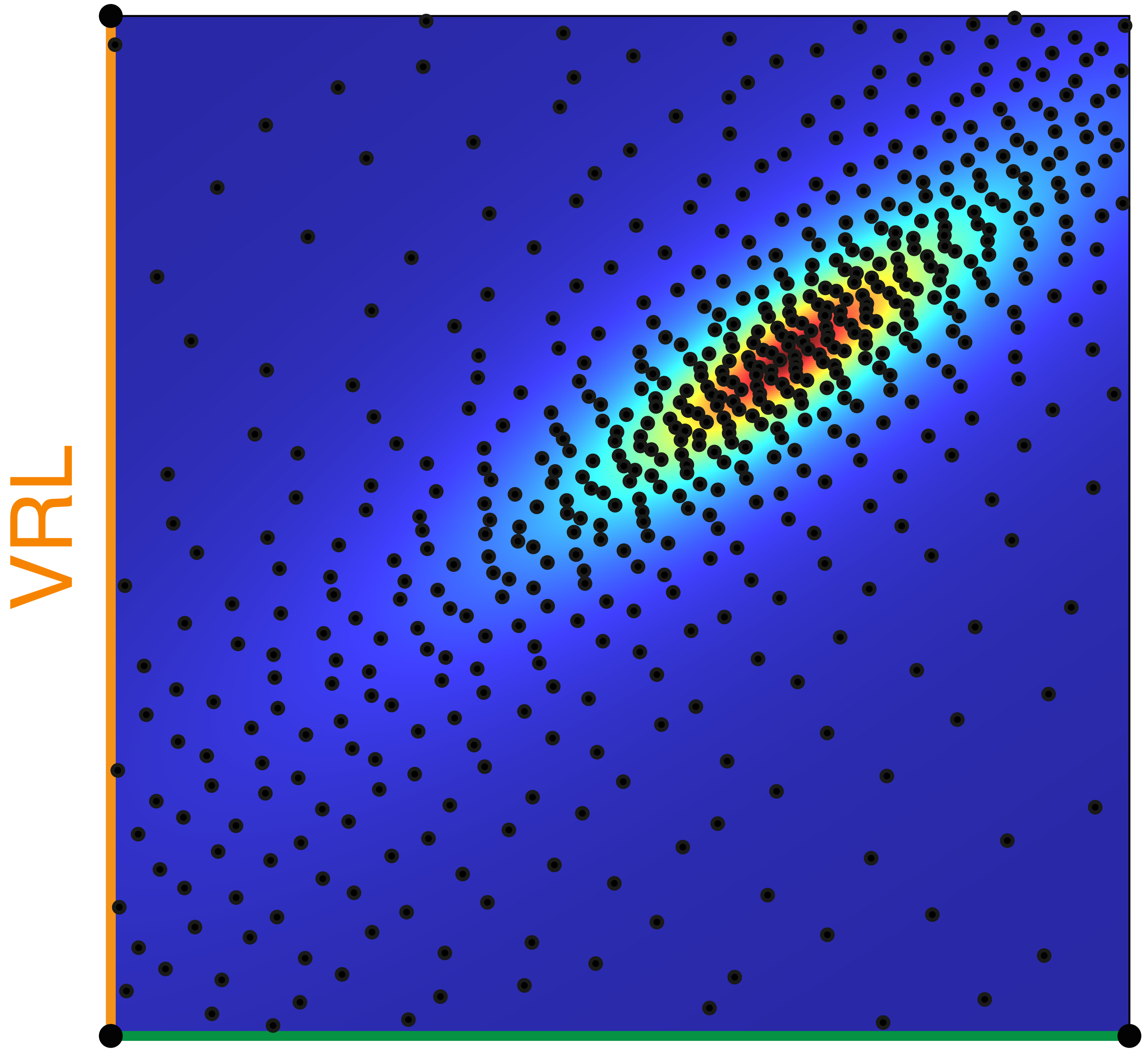


Anisotropic media

anisotropic

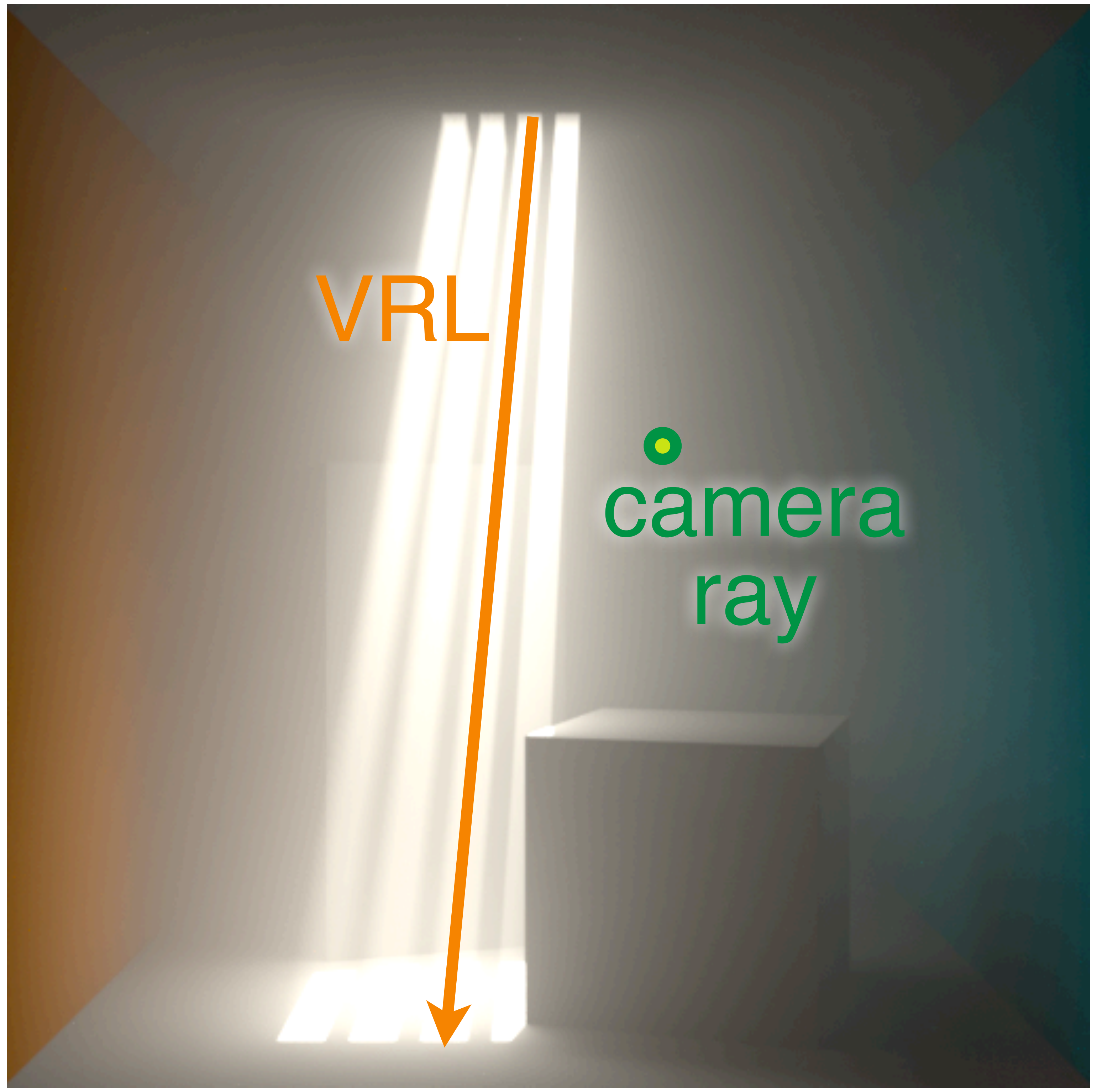


inverse squared distance

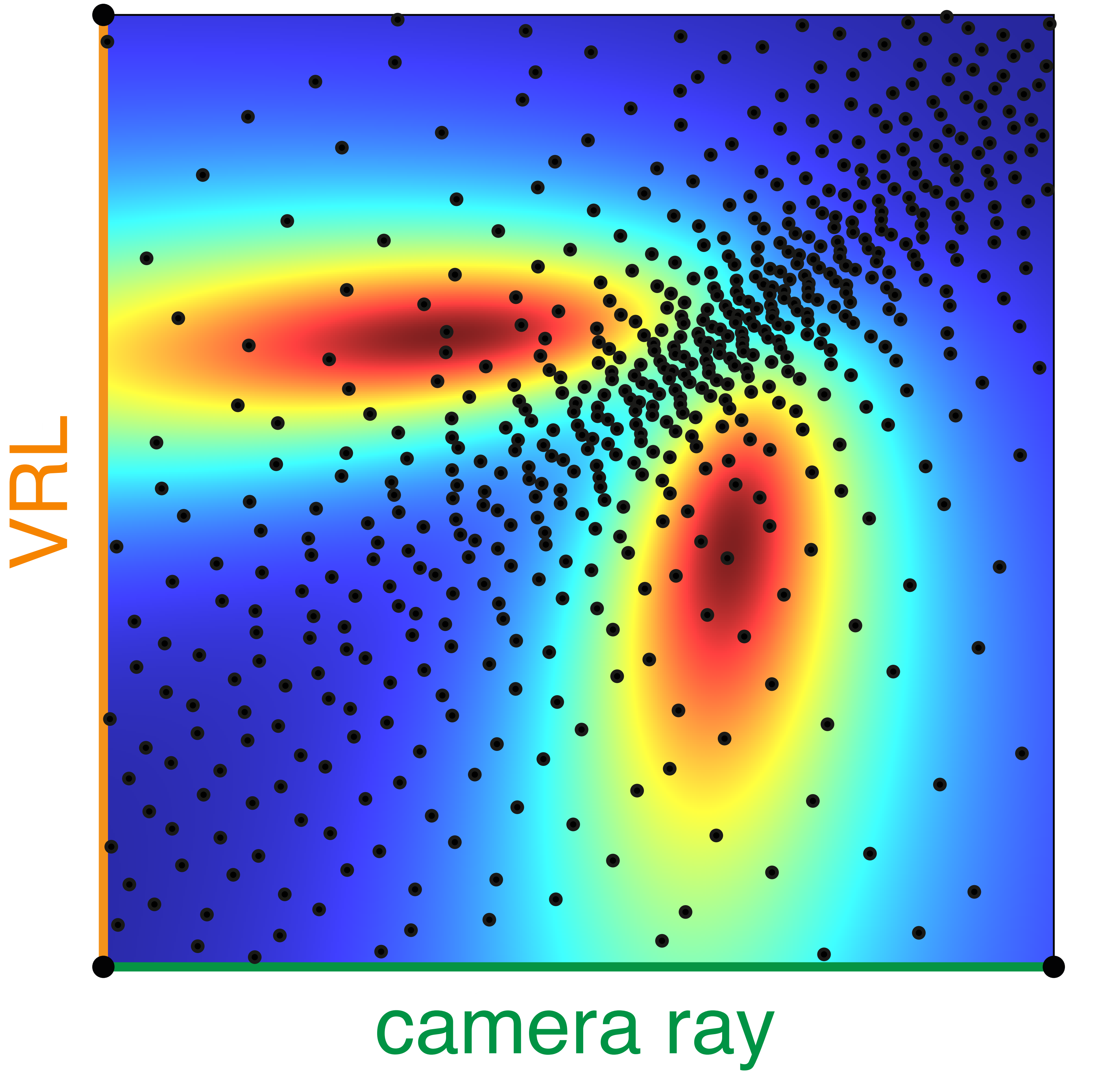


Anisotropic media

anisotropic

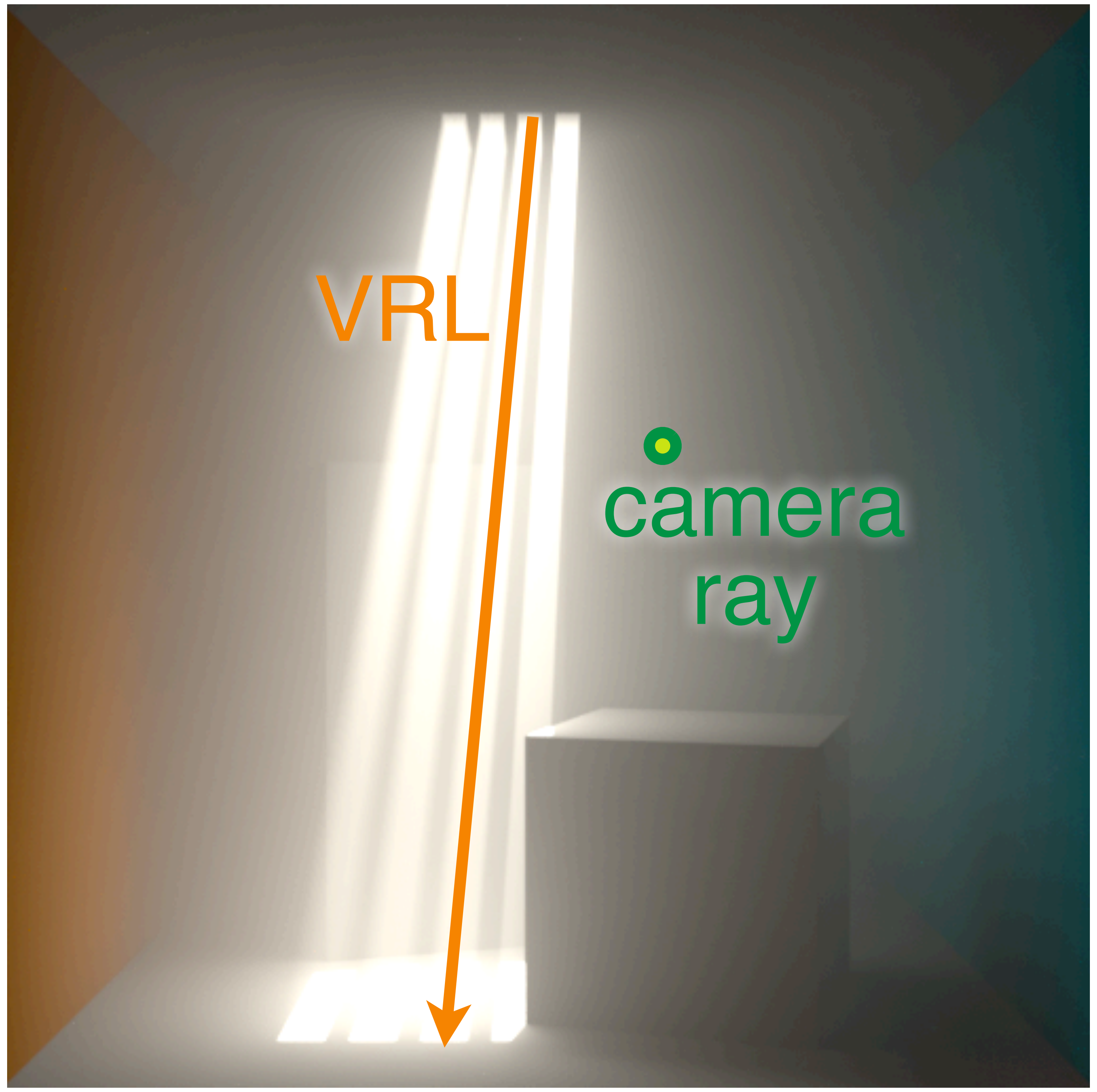


PF product / squared distance

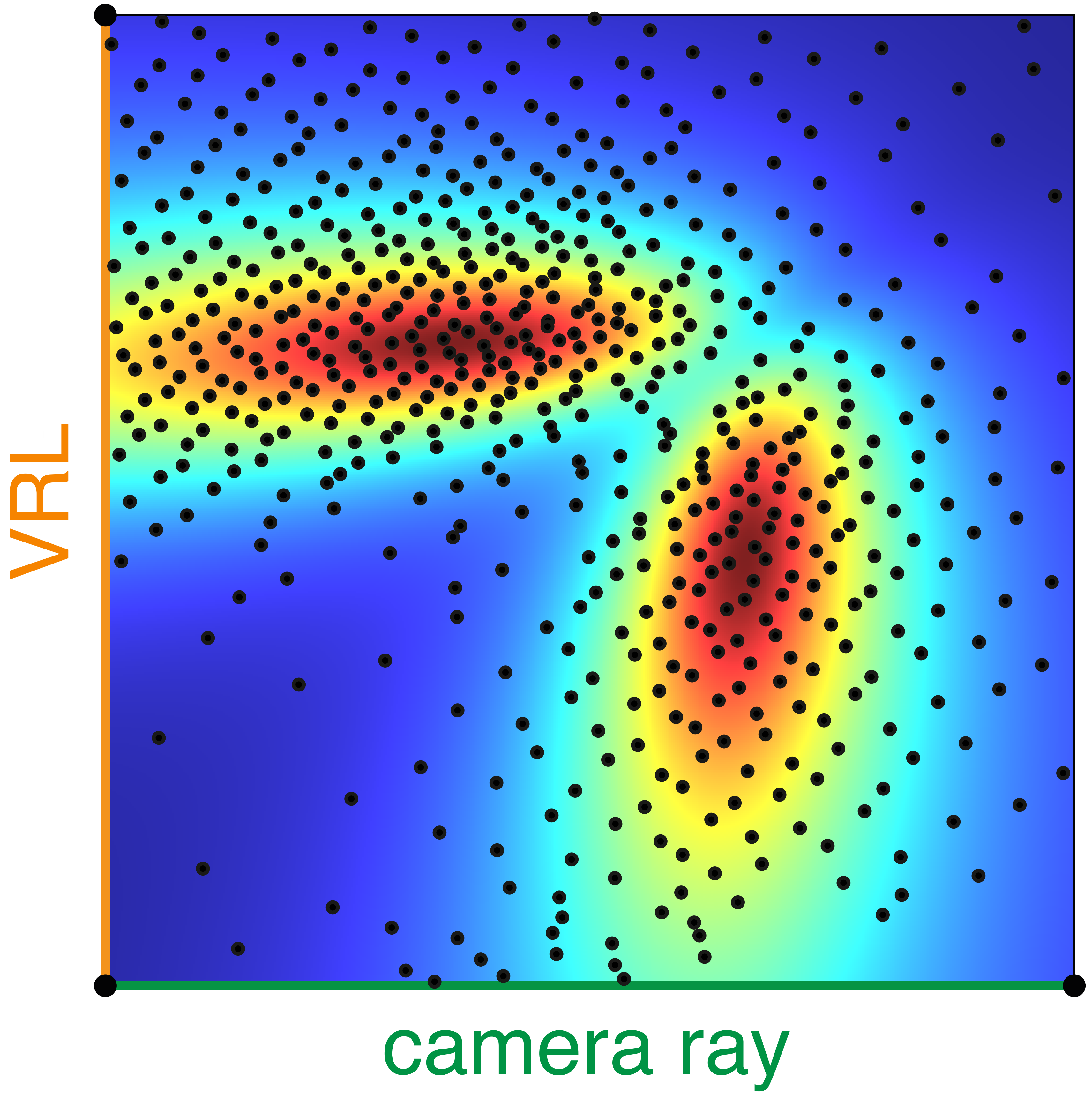


Anisotropic media

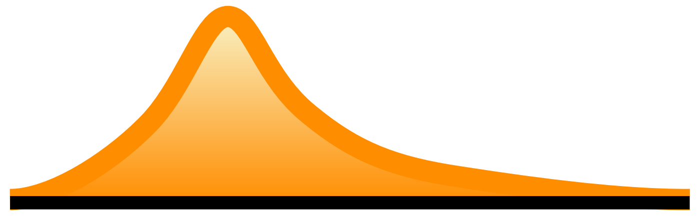
anisotropic



PF product / squared distance

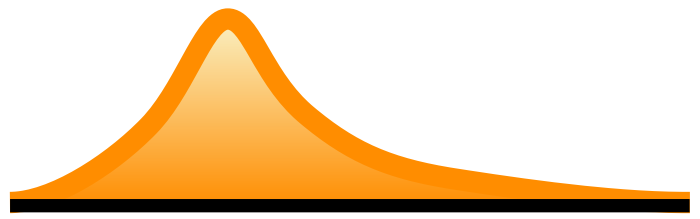


Anisotropic media

- **Marginal PDF** 

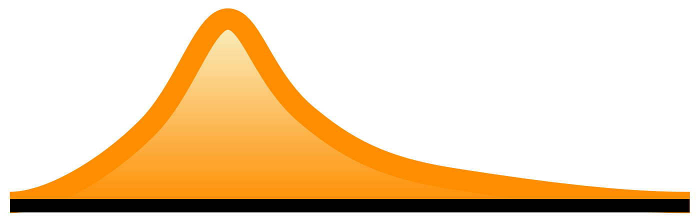
$$\mathrm{pdf}(v) = \frac{\int_0^s f_s(u) f_s(v)\, w^{-2}\,\mathrm{d}u}{\int_0^t \int_0^s f_s(u) f_s(v)\, w^{-2}\,\mathrm{d}u\,\mathrm{d}v}$$

Anisotropic media

- **Marginal PDF** 

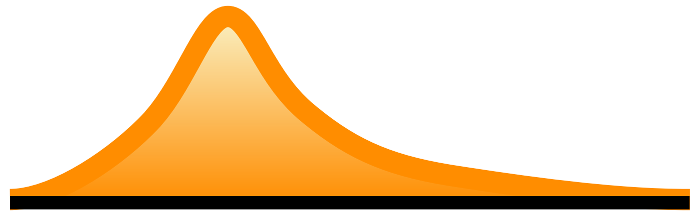
$$\mathrm{pdf}(v) = \frac{\int_0^s \boxed{f_s(u) f_s(v)}\, w^{-2}\, \mathrm{d}u}{\int_0^t \int_0^s \boxed{f_s(u) f_s(v)}\, w^{-2}\, \mathrm{d}u\, \mathrm{d}v}$$

Anisotropic media

- **Marginal PDF** 

$$\mathrm{pdf}(v) = \frac{\int_0^s f_s(u) f_s(v)\, w^{-2}\, \mathrm{d}u}{\int_0^t \int_0^s f_s(u) f_s(v)\, w^{-2}\, \mathrm{d}u\, \mathrm{d}v} \approx \frac{\int_{-\infty}^{\infty} w^{-2}\, \mathrm{d}u}{\int_0^t \int_{-\infty}^{\infty} w^{-2}\, \mathrm{d}u\, \mathrm{d}v}$$

Anisotropic media

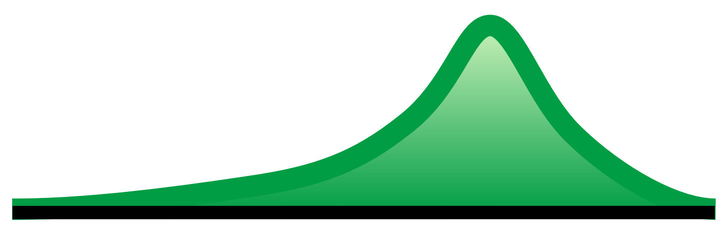
- **Marginal PDF** 

$$\mathrm{pdf}(v) = \frac{\int_0^s f_s(u) f_s(v)\, w^{-2}\, \mathrm{d}u}{\int_0^t \int_0^s f_s(u) f_s(v)\, w^{-2}\, \mathrm{d}u\, \mathrm{d}v} \approx \frac{\int_{-\infty}^{\infty} w^{-2}\, \mathrm{d}u}{\int_0^t \int_{-\infty}^{\infty} w^{-2}\, \mathrm{d}u\, \mathrm{d}v}$$

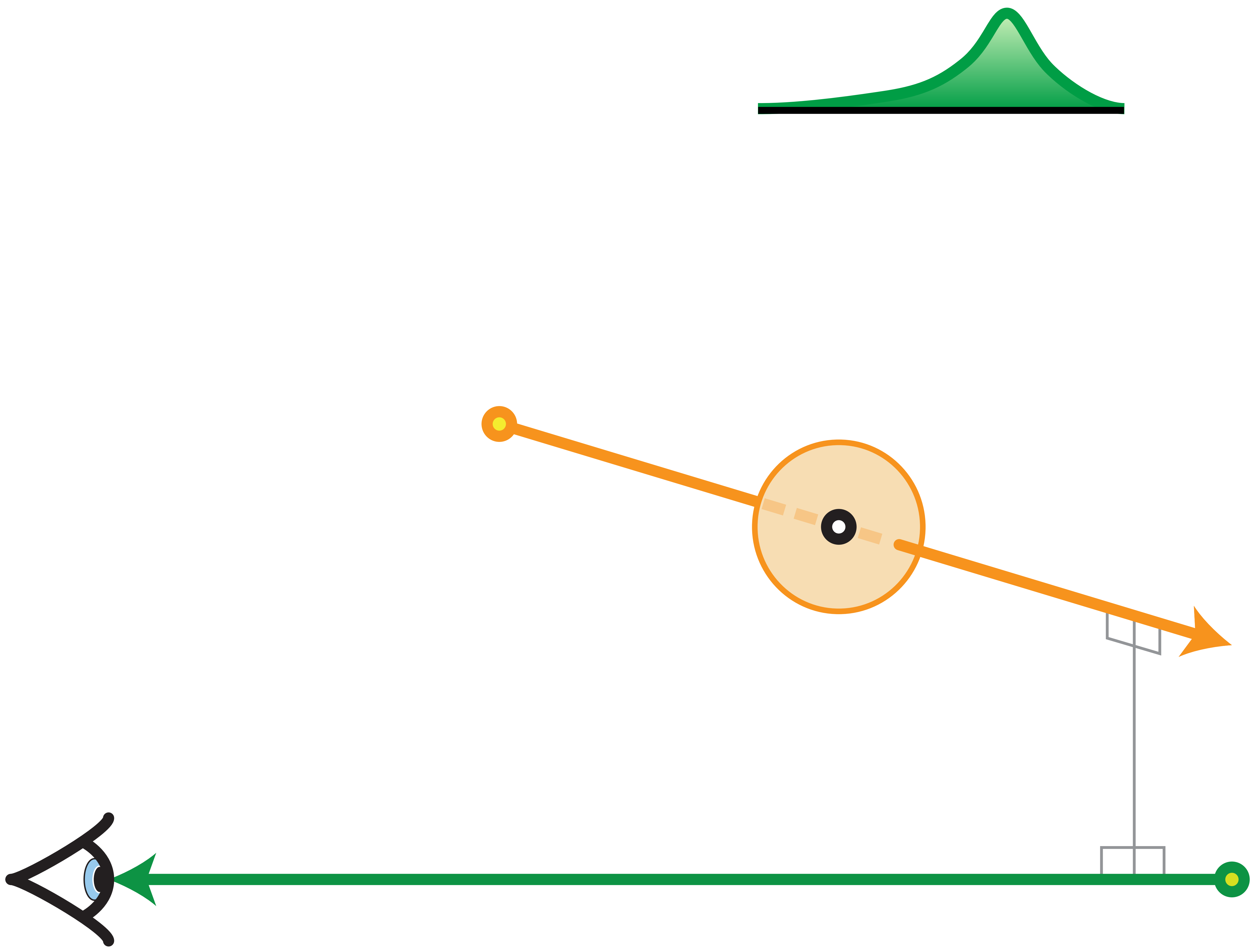
identical to isotropic medium

Anisotropic media

Anisotropic media

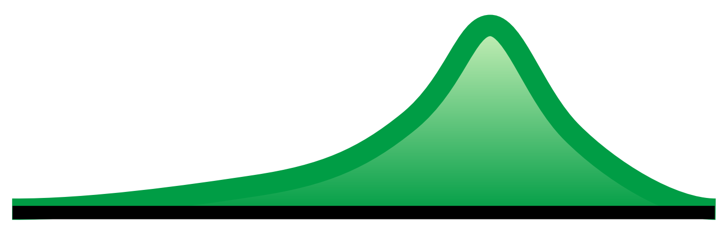


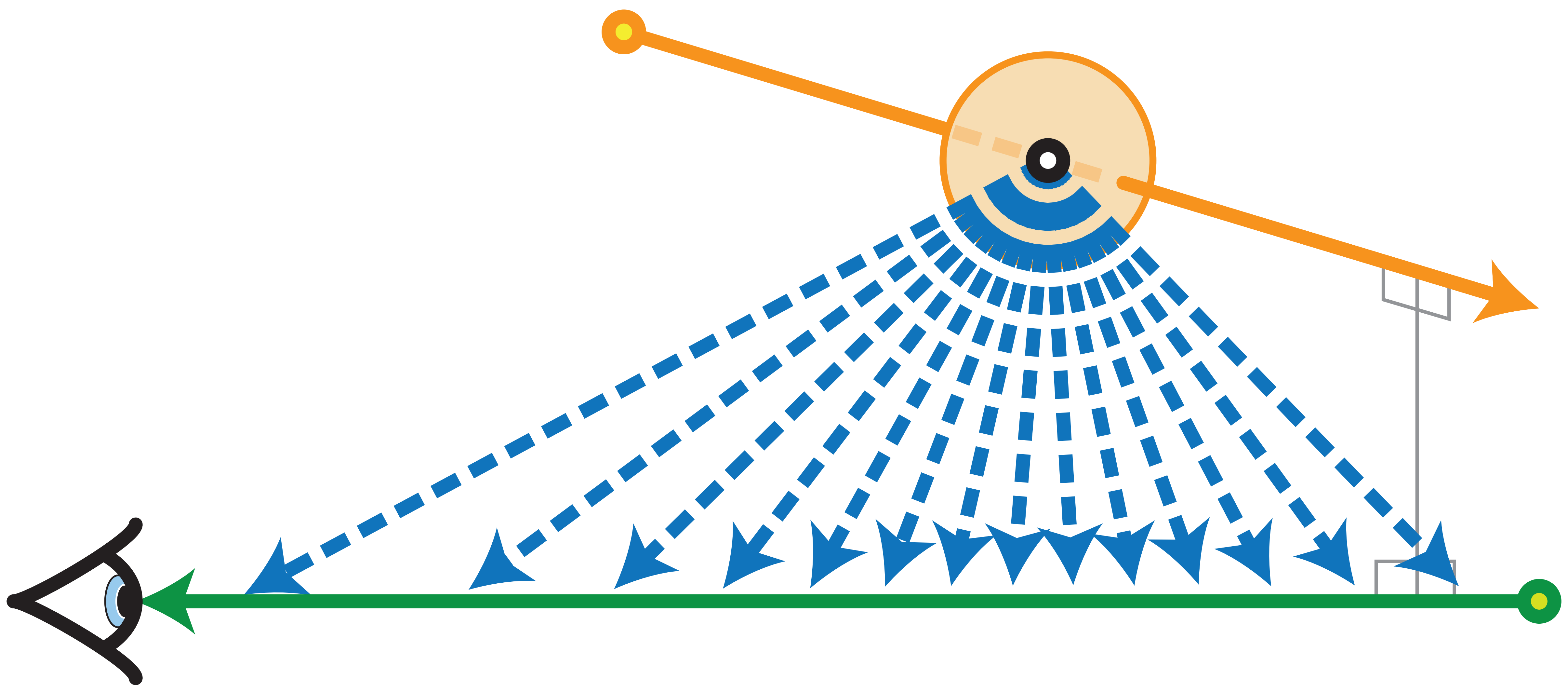
Anisotropic media



isotropic ~ equi-angular

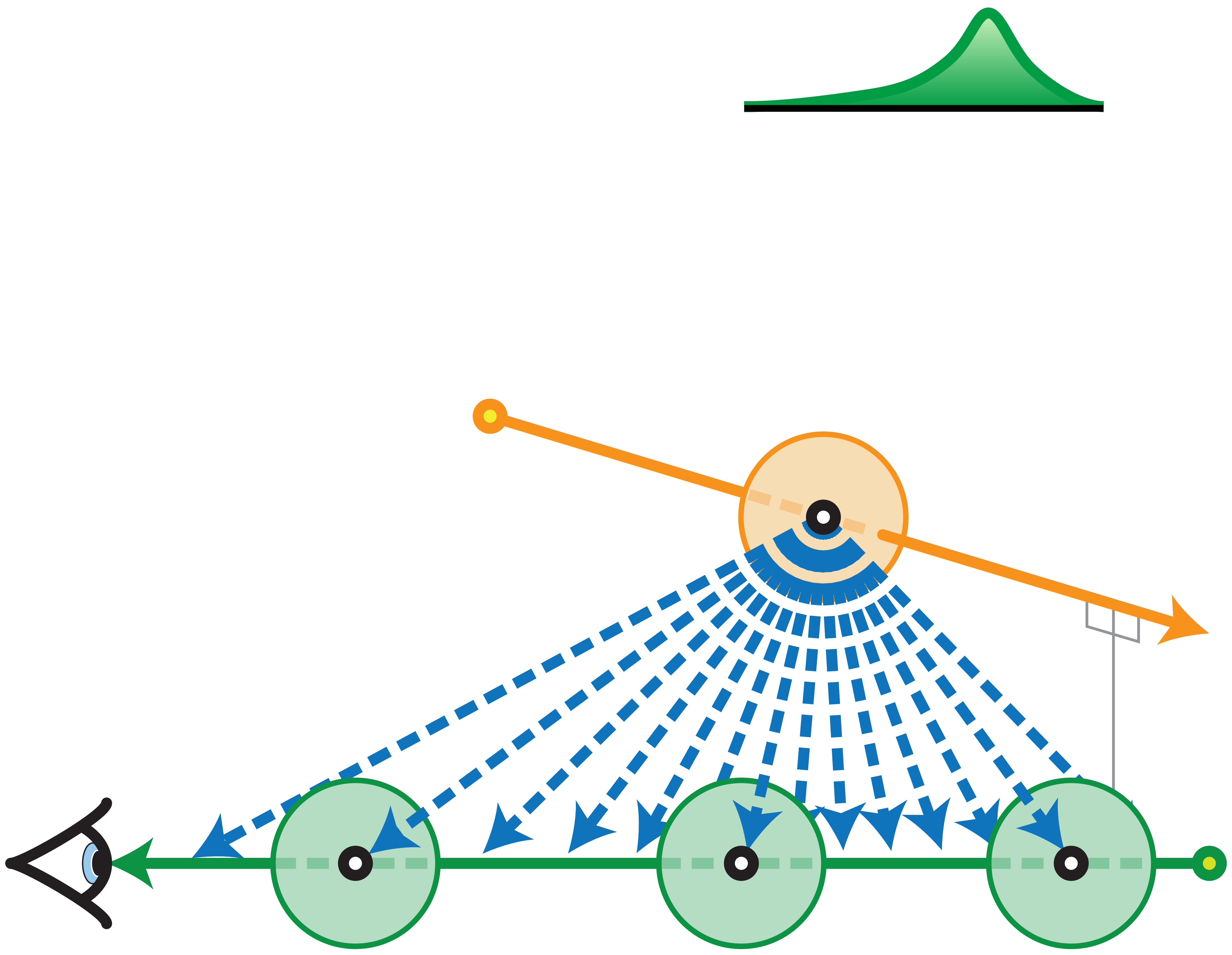
Anisotropic media





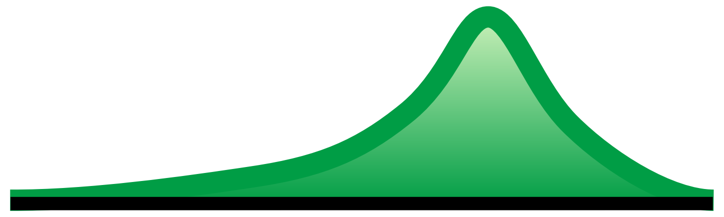
isotropic ~ equi-angular

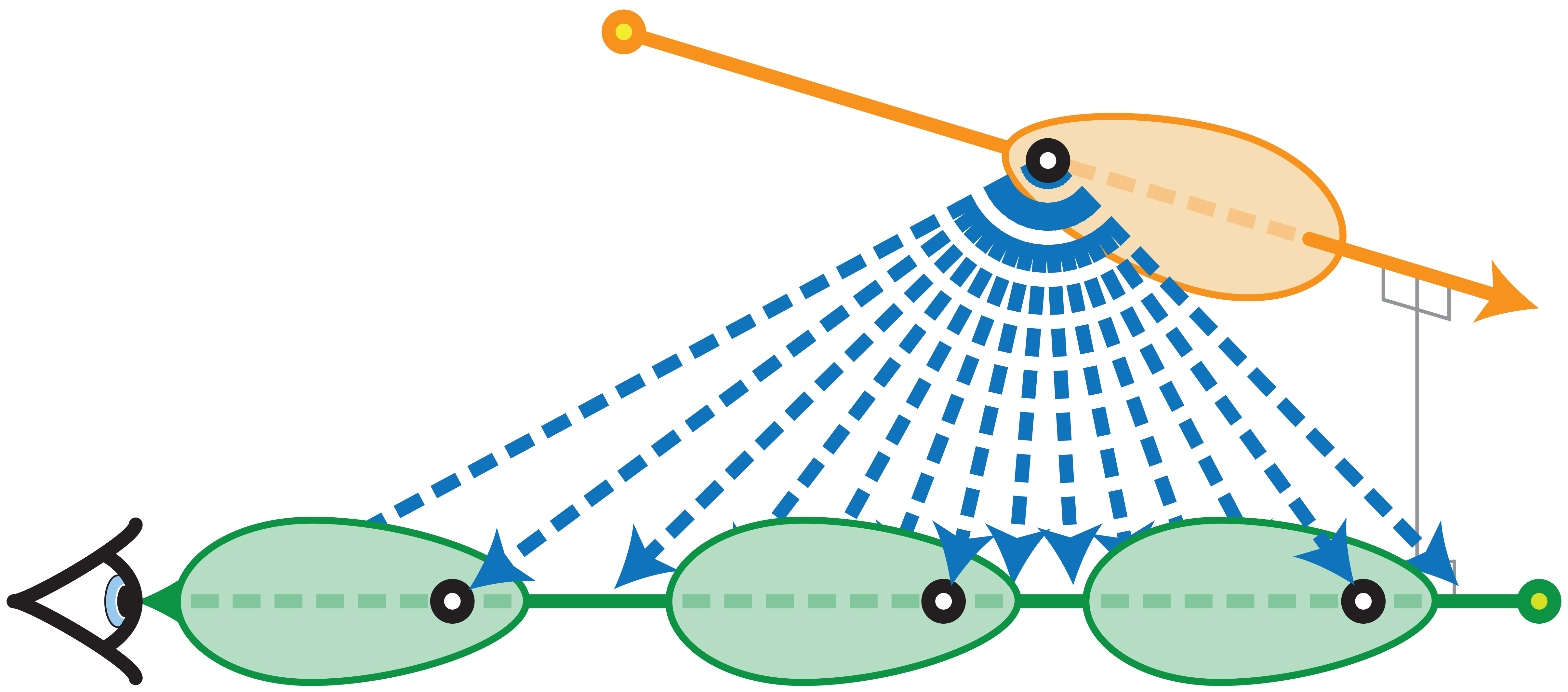
Anisotropic media



isotropic ~ equi-angular

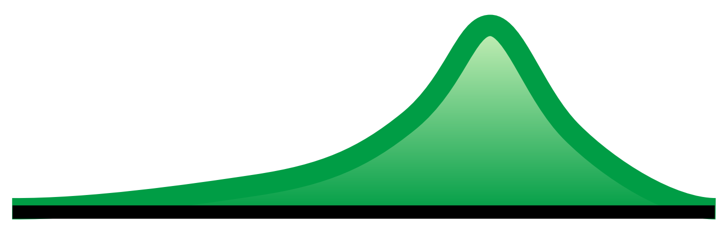
Anisotropic media

- **Conditional PDF** 
  - replace equi-angular sampling by **importance sampling the PF product**



anisotropic

Anisotropic media

- **Conditional PDF** 
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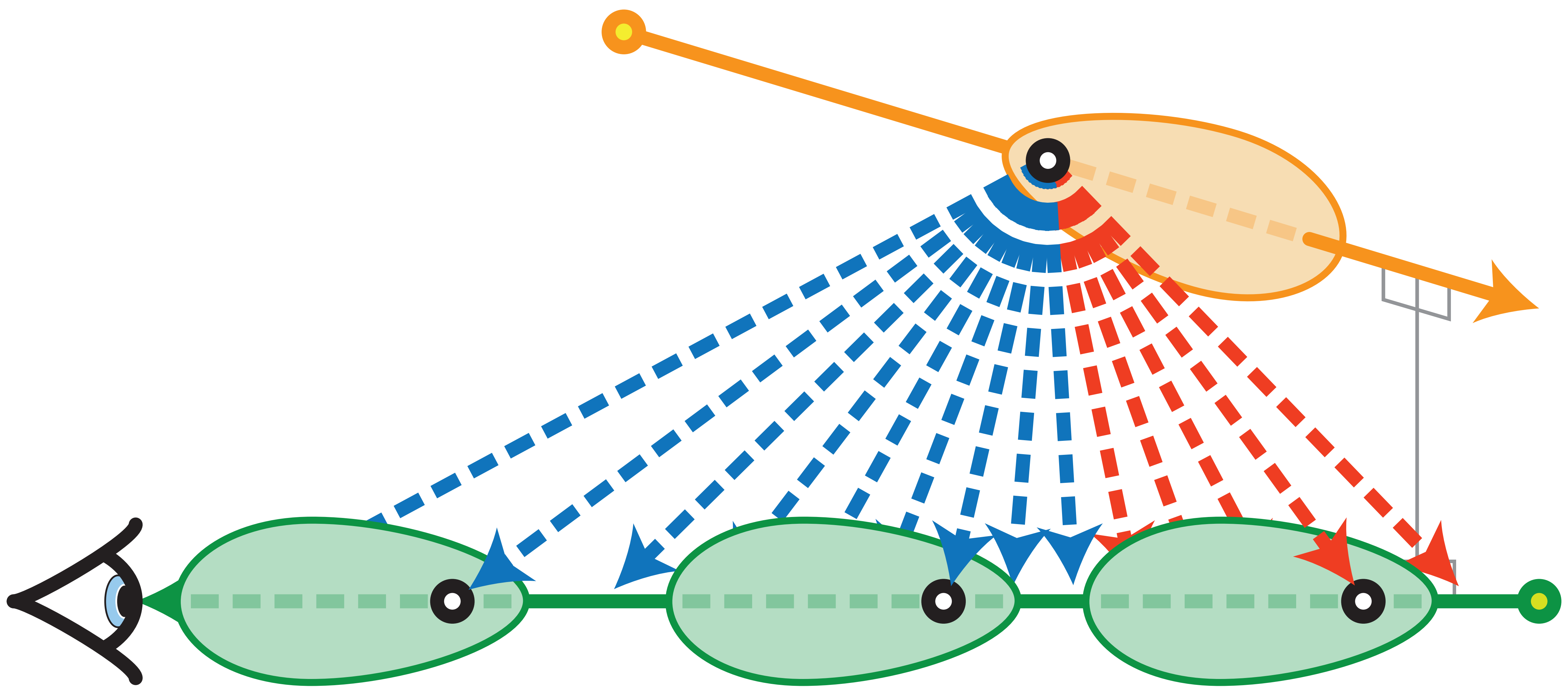
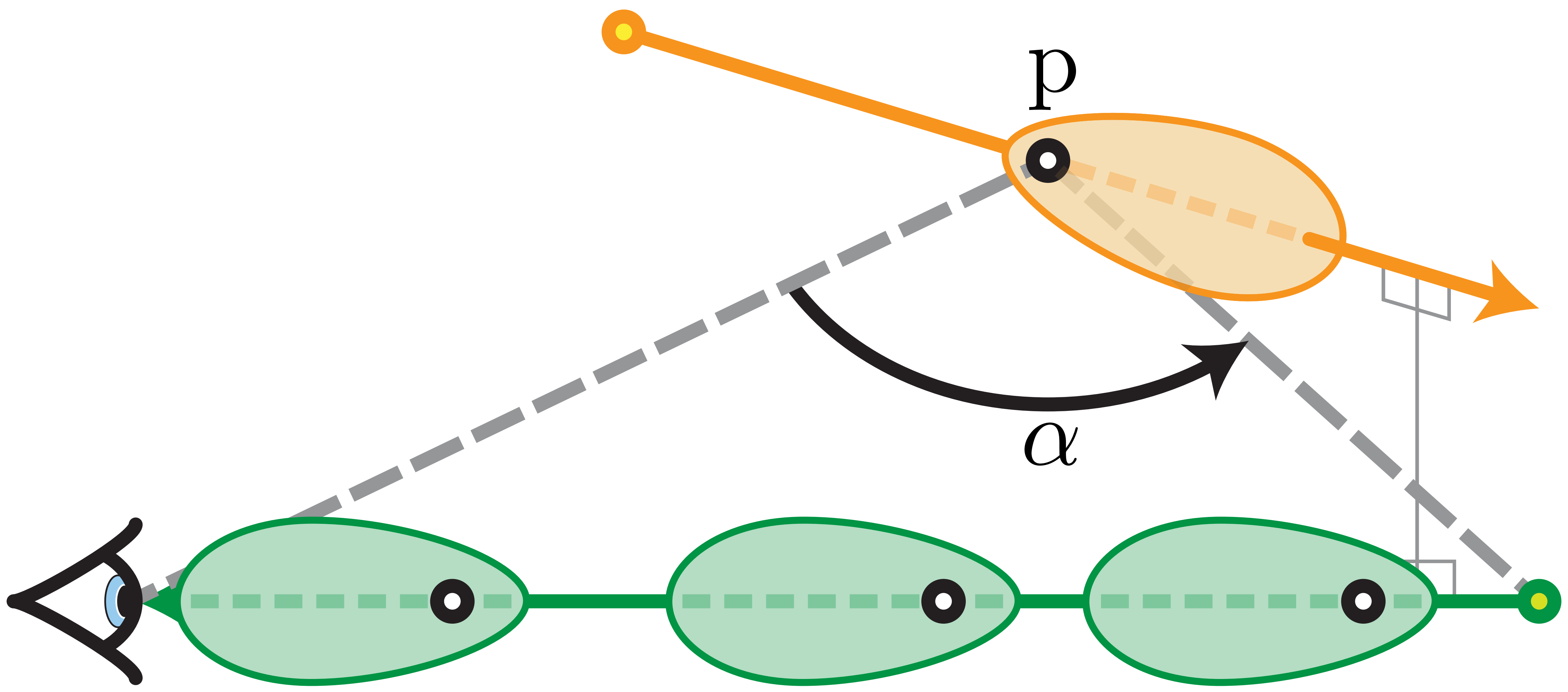


anisotropic

Anisotropic media

- **Conditional PDF**
  - replace equi-angular sampling by **importance sampling the PF product**



anisotropic

Anisotropic media

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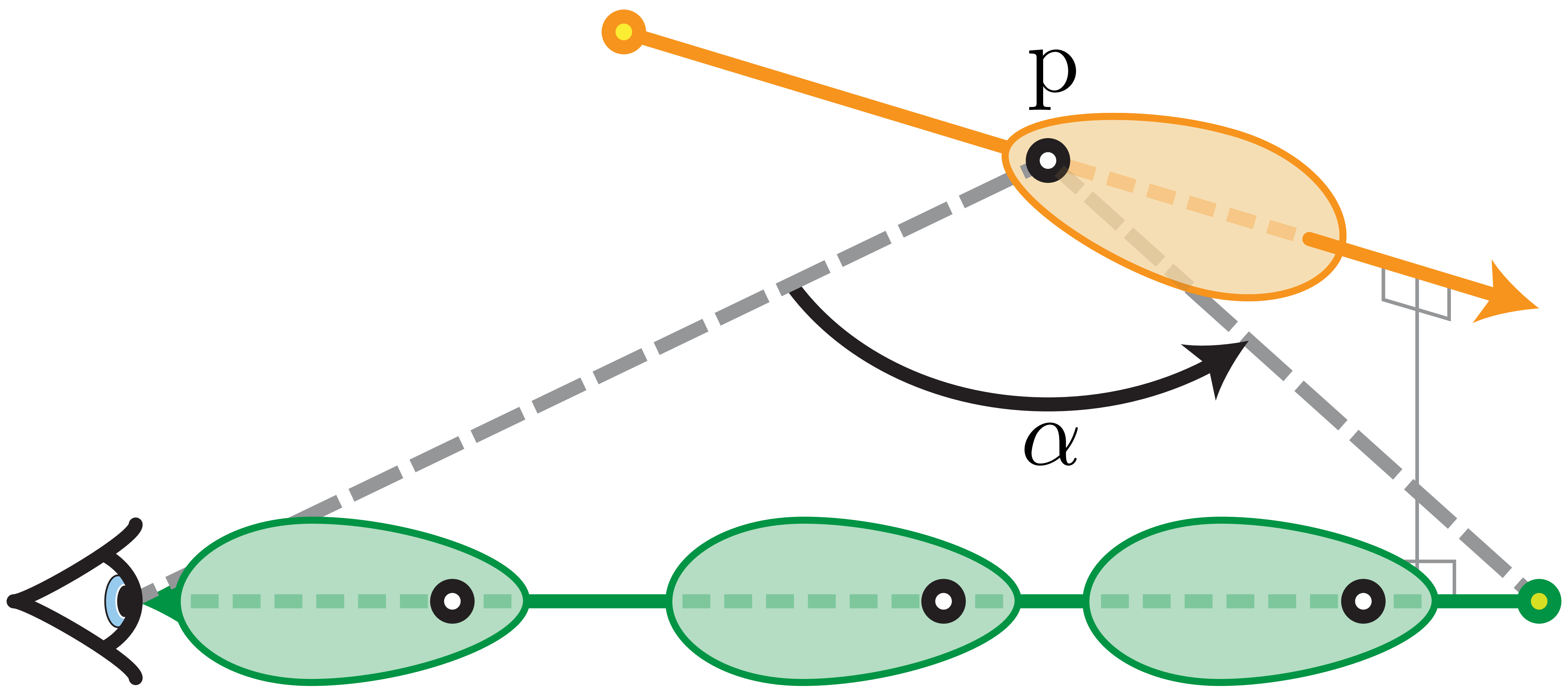
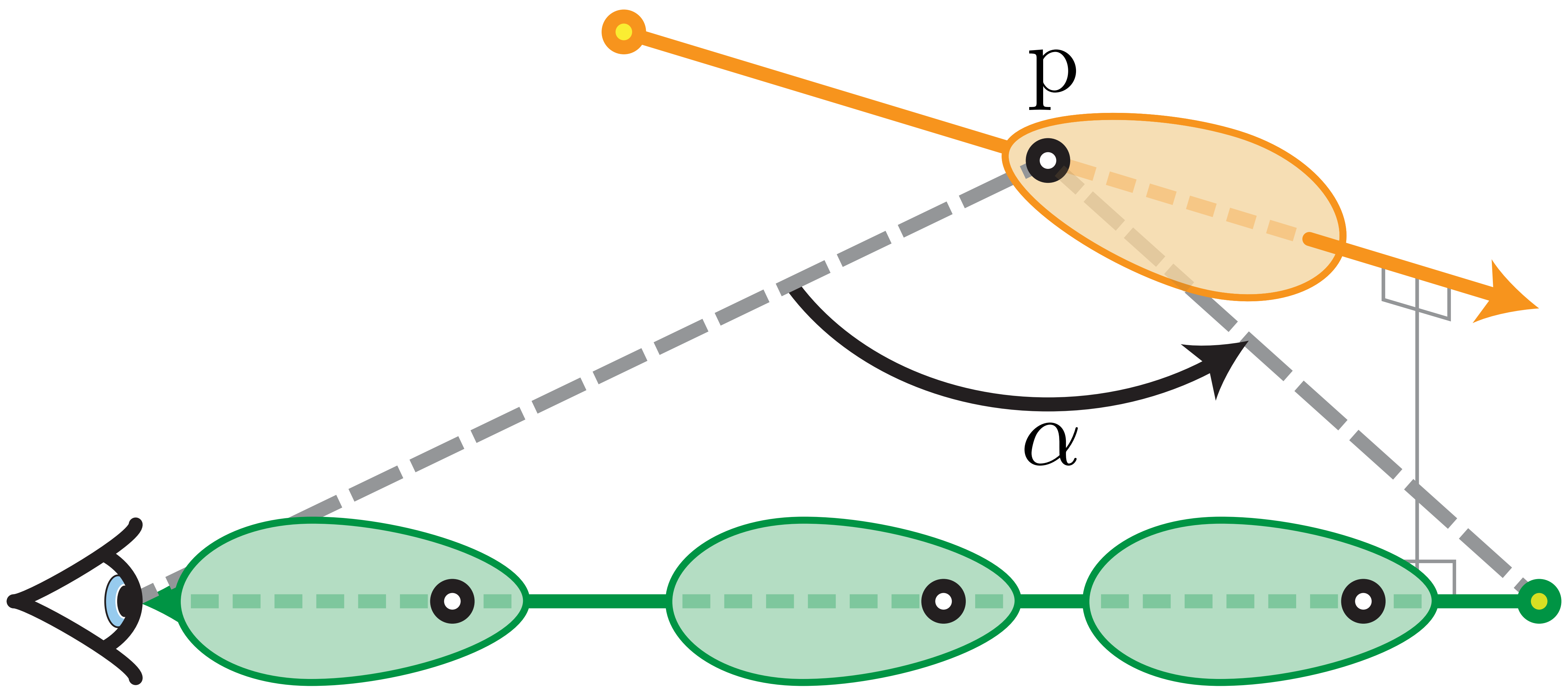


anisotropic

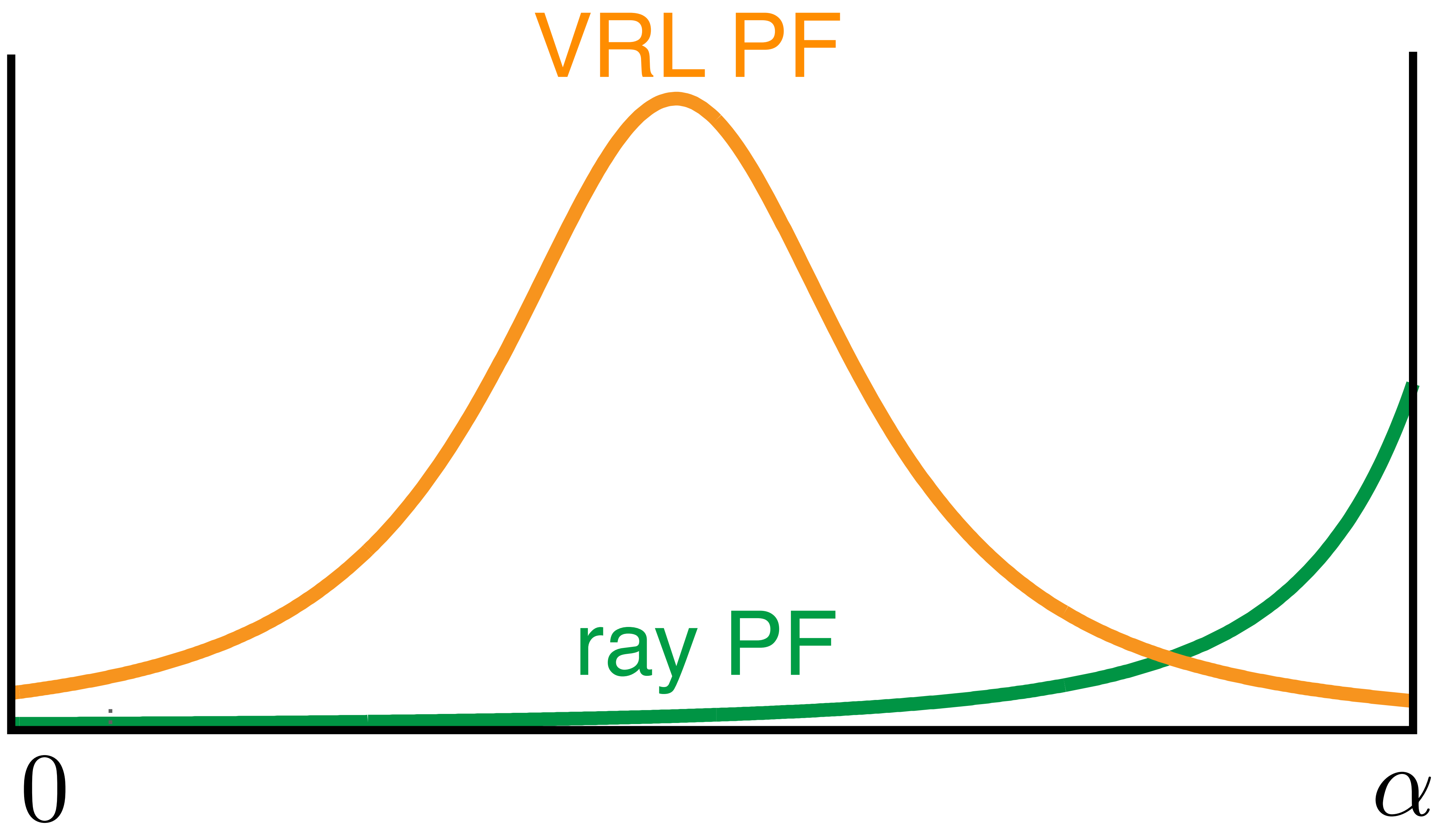
angular domain about p

Anisotropic media

- **Conditional PDF**
  - replace equi-angular sampling by **importance sampling the PF product**



anisotropic



angular domain about p

Anisotropic media

- **Conditional PDF**
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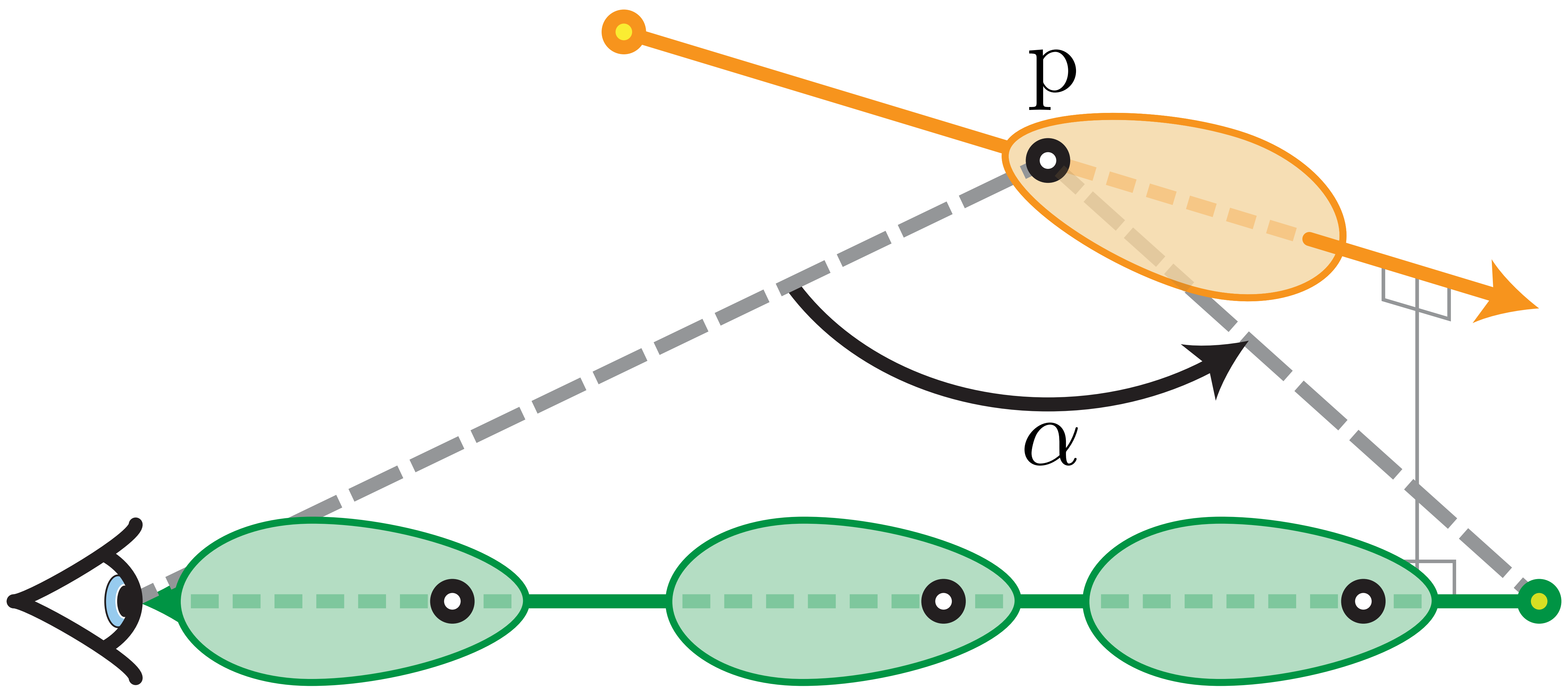
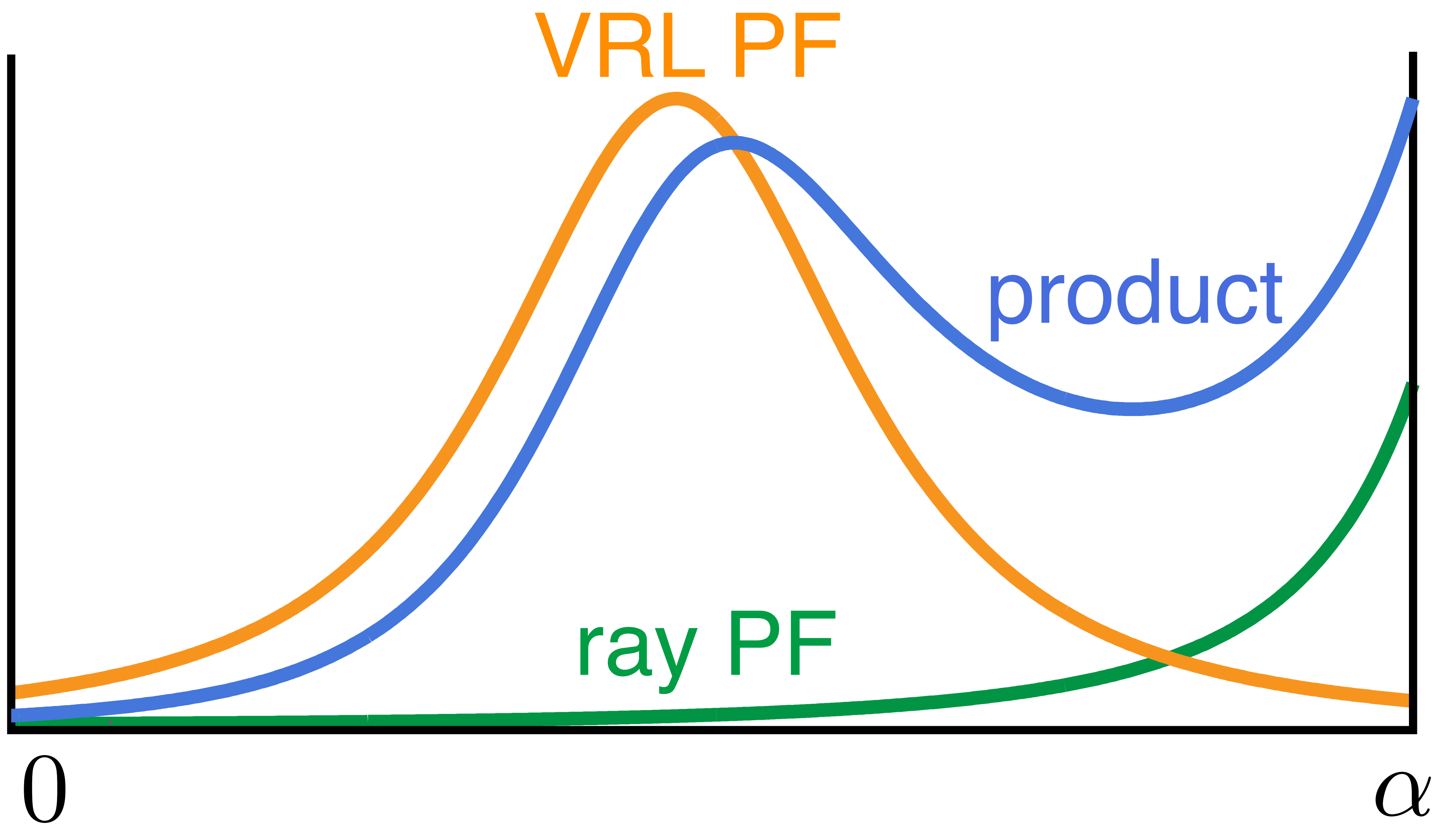


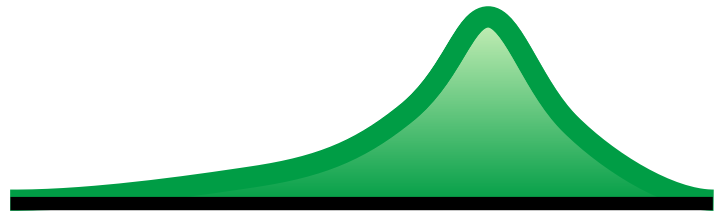
anisotropic



angular domain about p

Anisotropic media

- **Conditional PDF**



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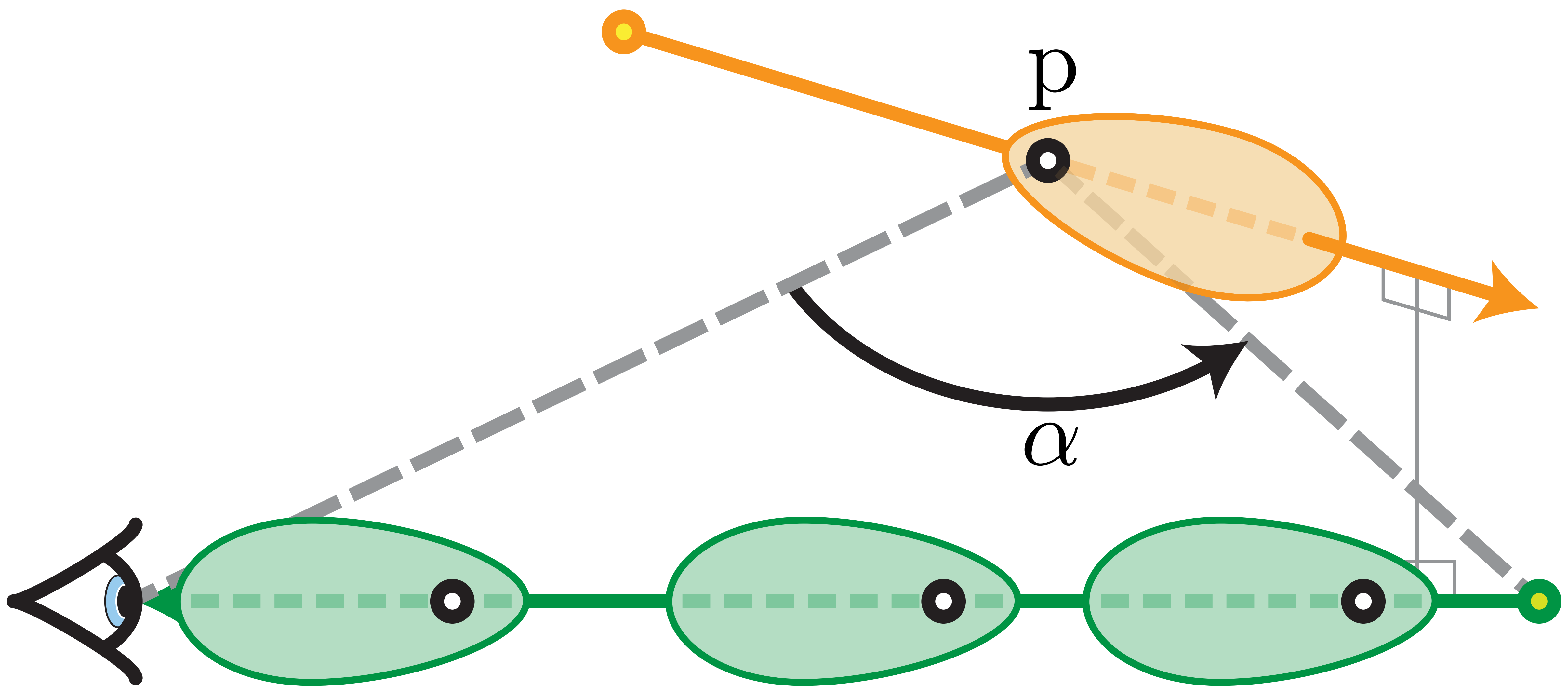
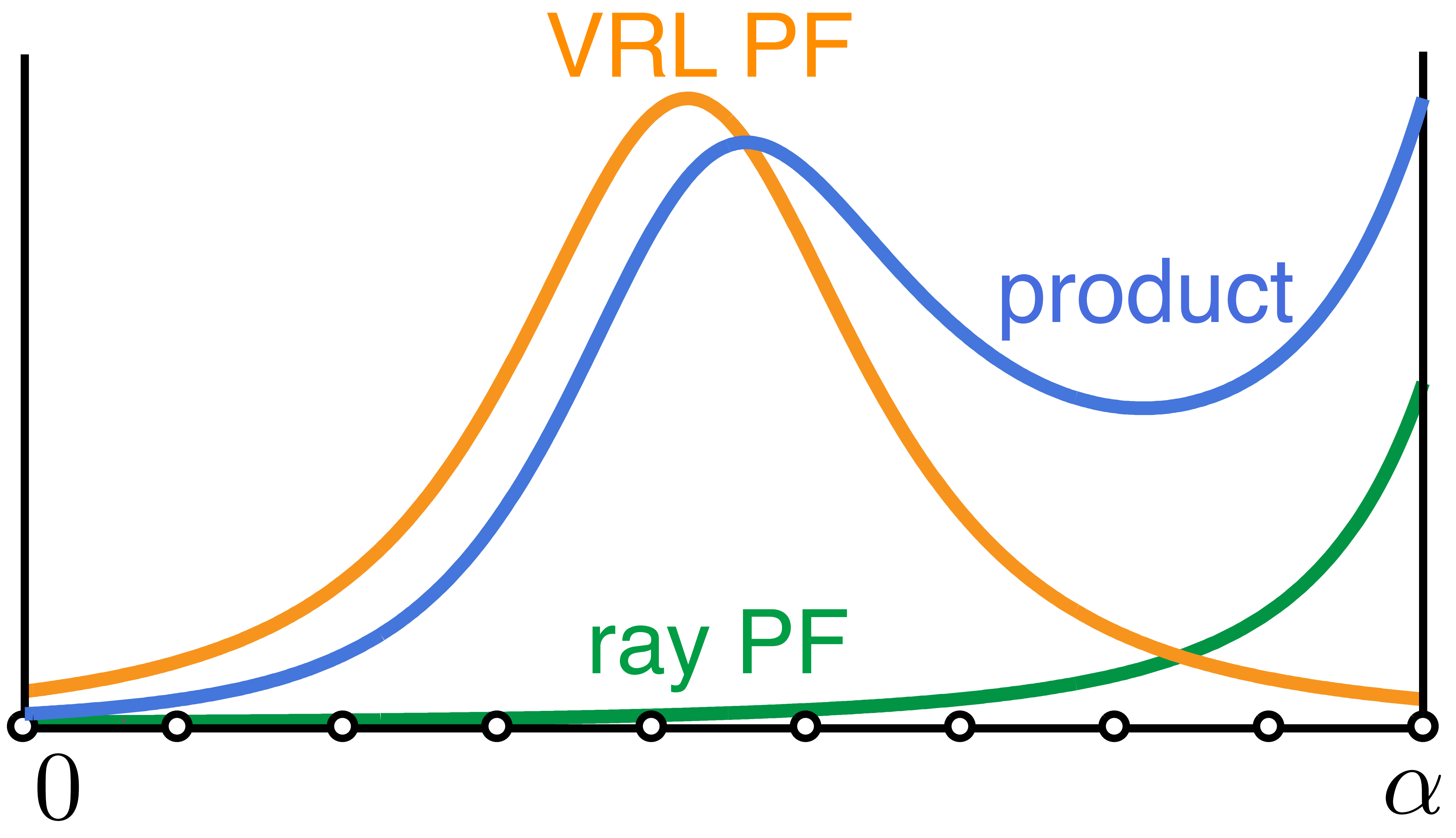
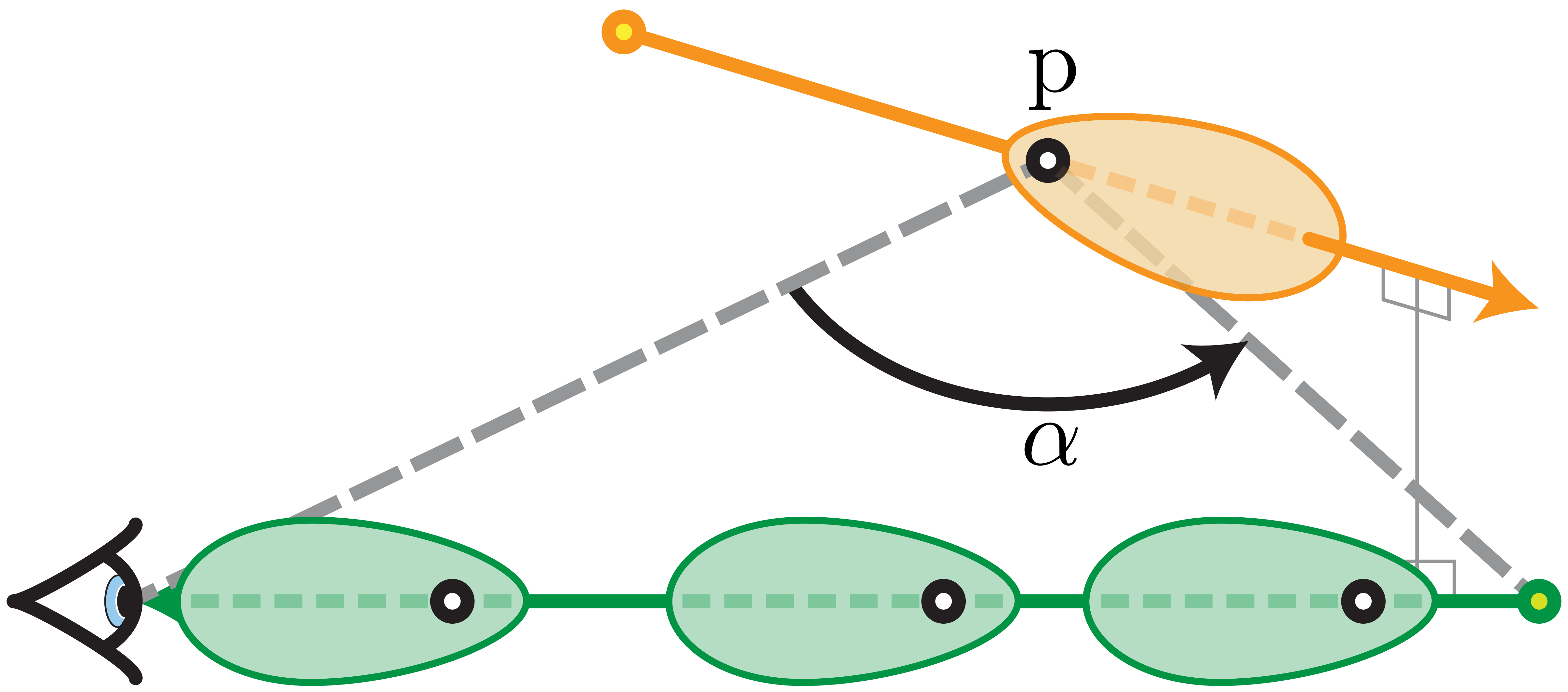


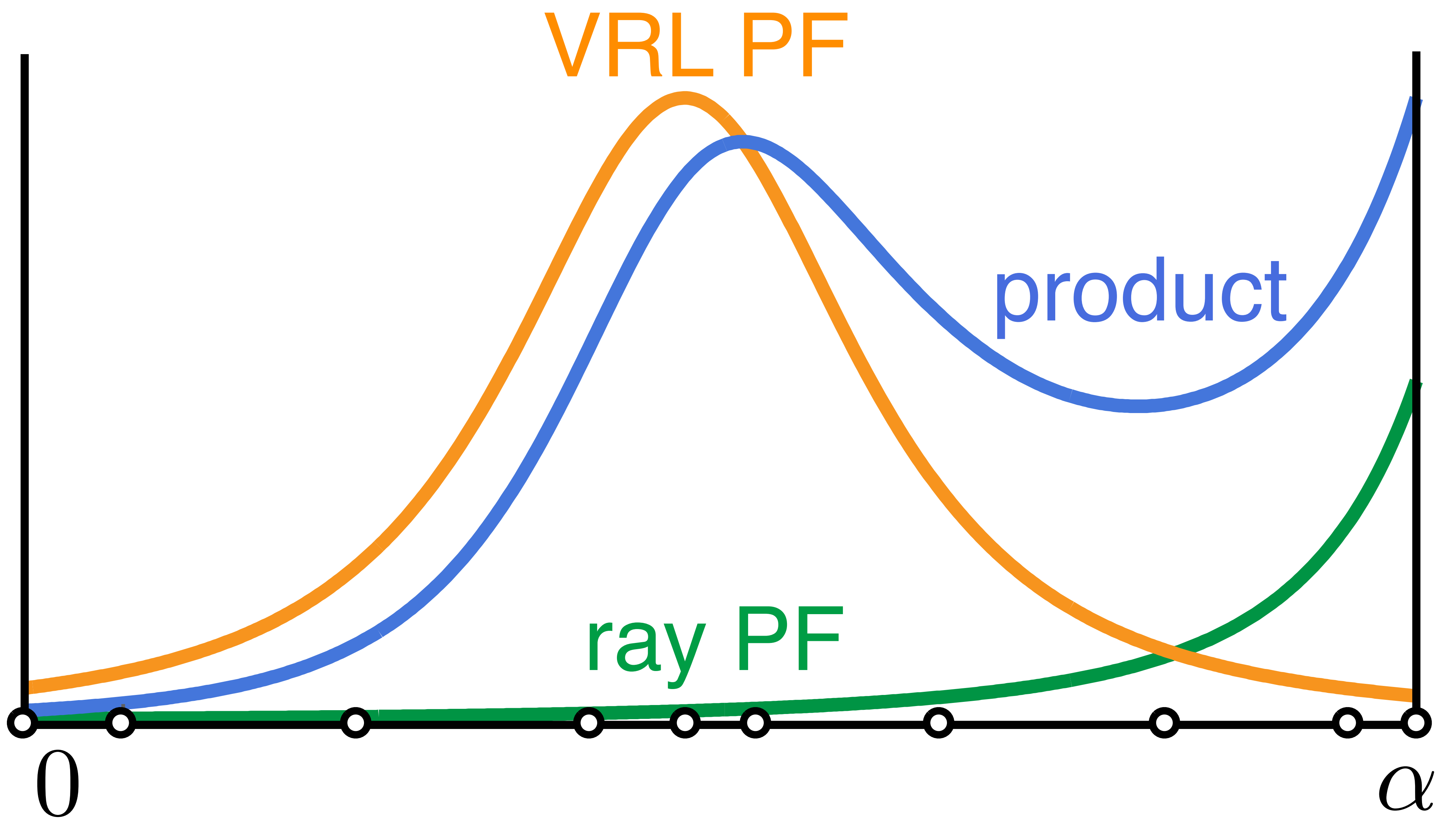


Anisotropic media

- **Conditional PDF**
  - replace equi-angular sampling by **importance sampling the PF product**

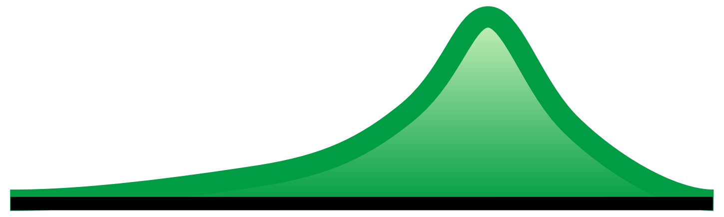


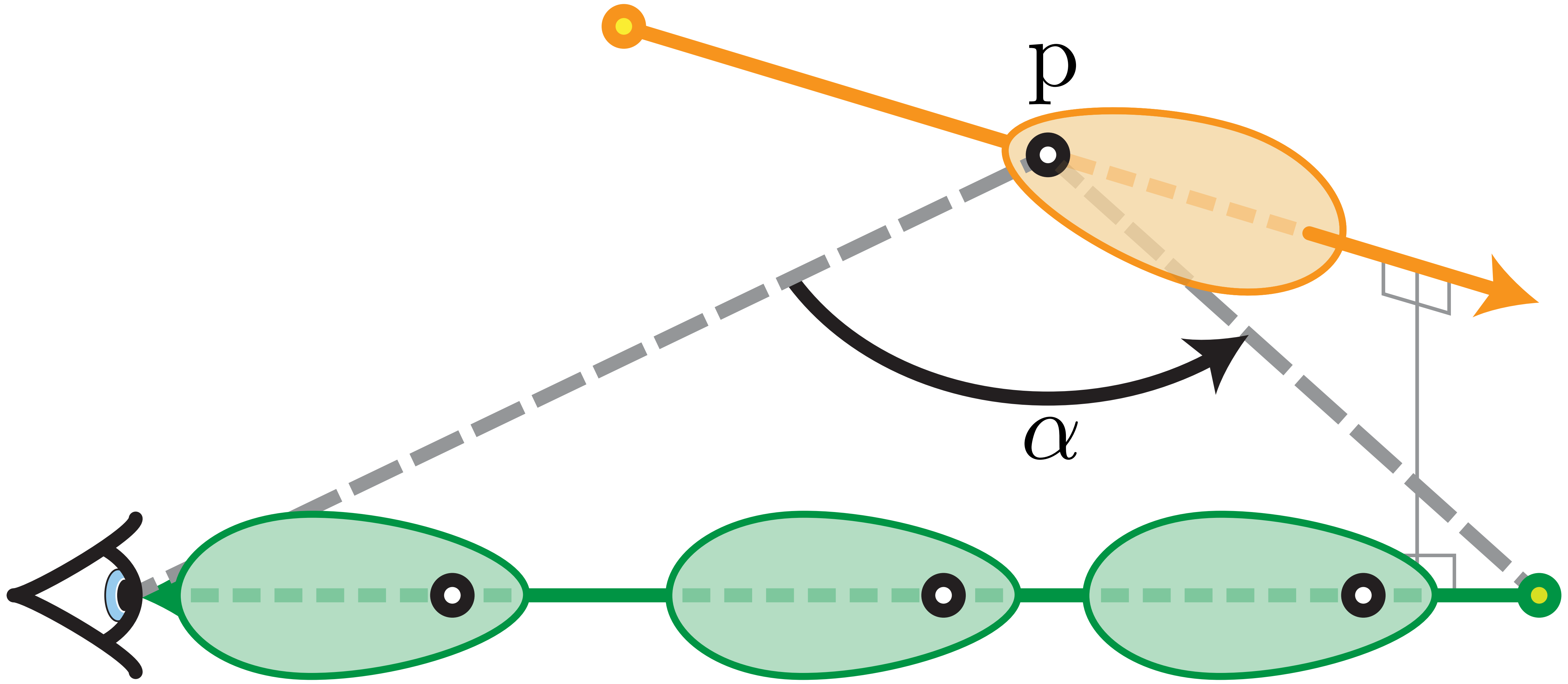
anisotropic



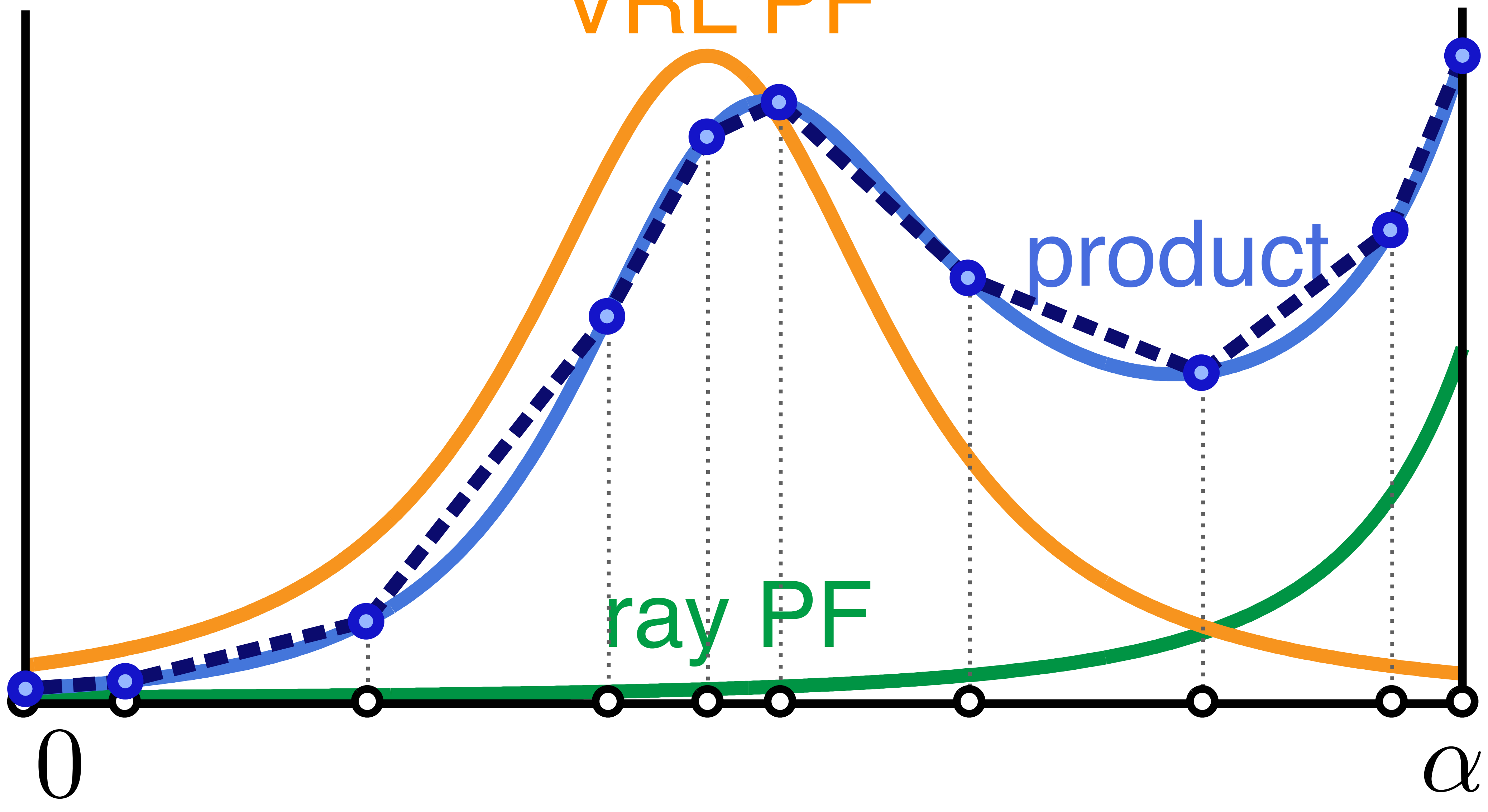
angular domain about p

Anisotropic media

- **Conditional PDF** 
  - replace equi-angular sampling by **importance sampling the PF product**

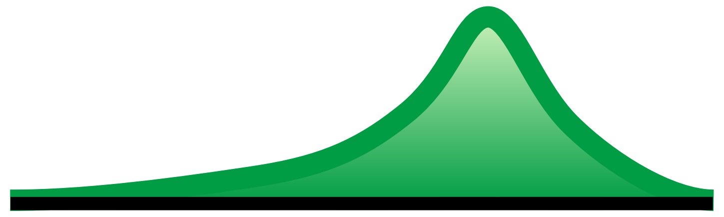


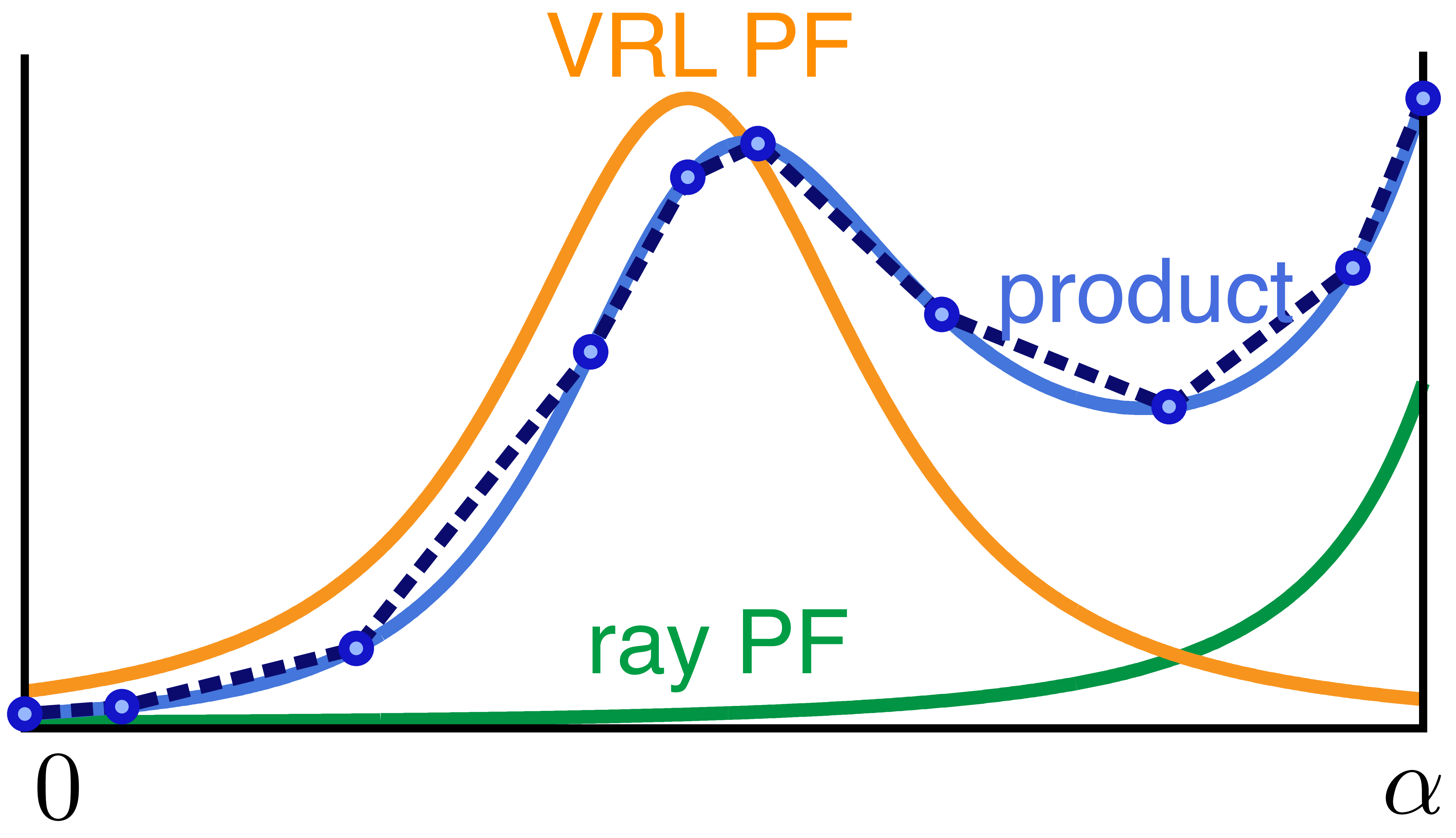
anisotropic



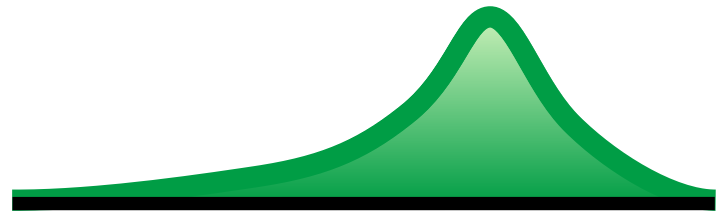
angular domain about p

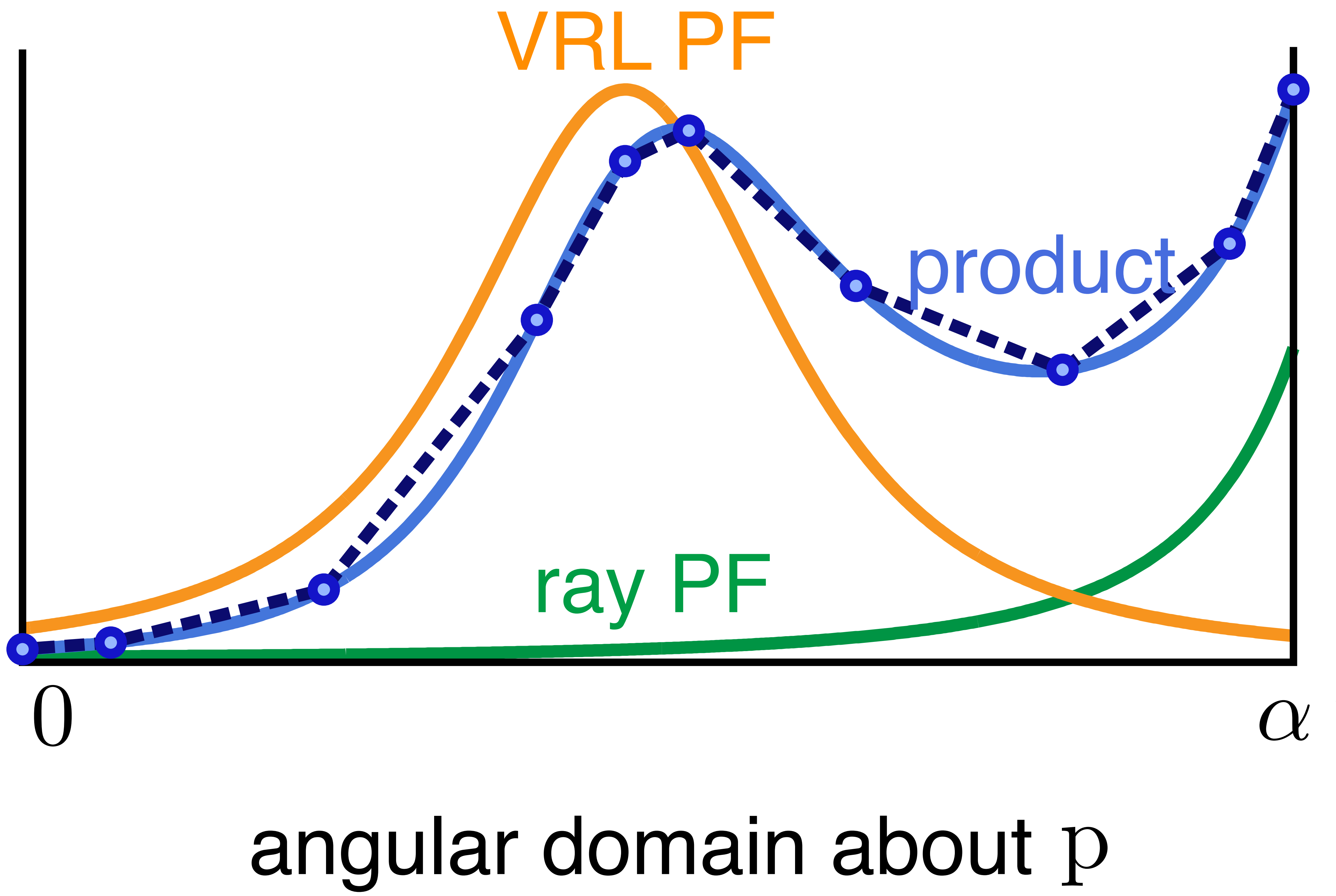
Anisotropic media

- **Conditional PDF** 
  - replace equi-angular sampling by **importance sampling the PF product**
  - piece-wise **linear PDF**

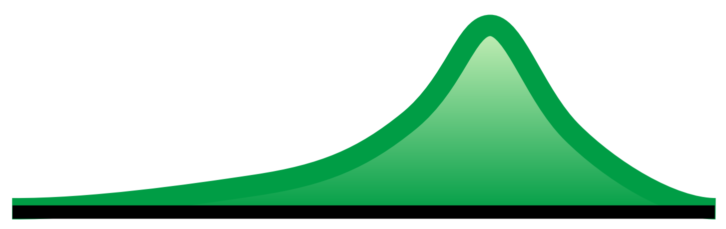


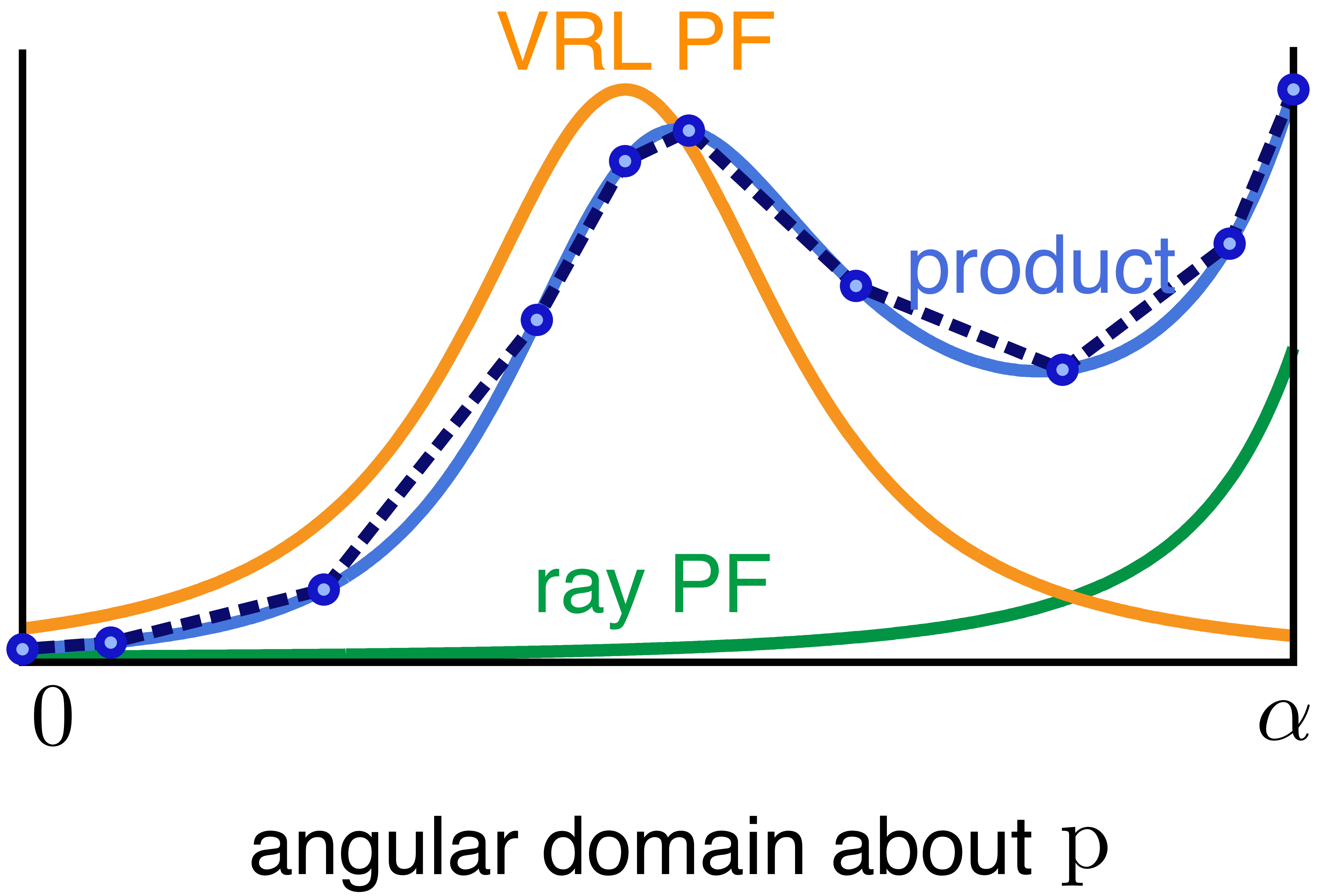
Anisotropic media

- **Conditional PDF** 
  - replace equi-angular sampling by **importance sampling the PF product**
  - piece-wise **linear PDF**
  - piece-wise **quadratic CDF**

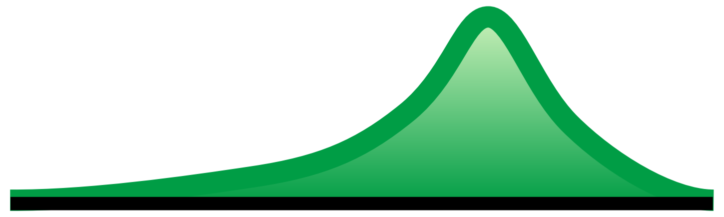


Anisotropic media

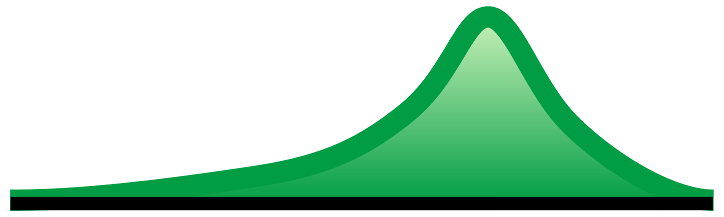
- **Conditional PDF** 
  - replace equi-angular sampling by **importance sampling the PF product**
  - piece-wise **linear PDF**
  - piece-wise **quadratic CDF**
  - 10 adaptively distributed vertices
    balance between speed and quality

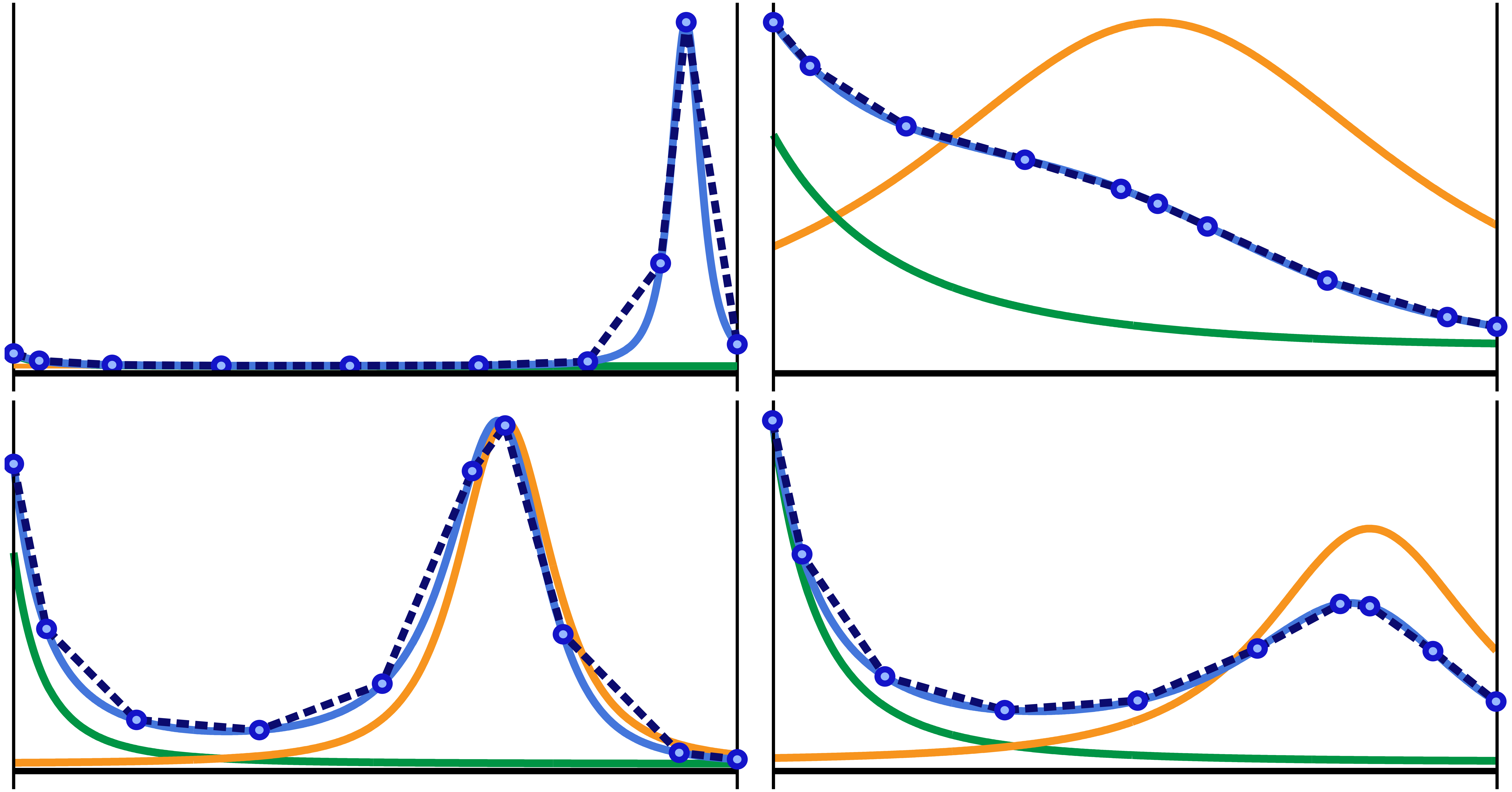


Anisotropic media

- **Conditional PDF** 
  - examples for Henyey-Greenstein PF with g = 0.95

Anisotropic media

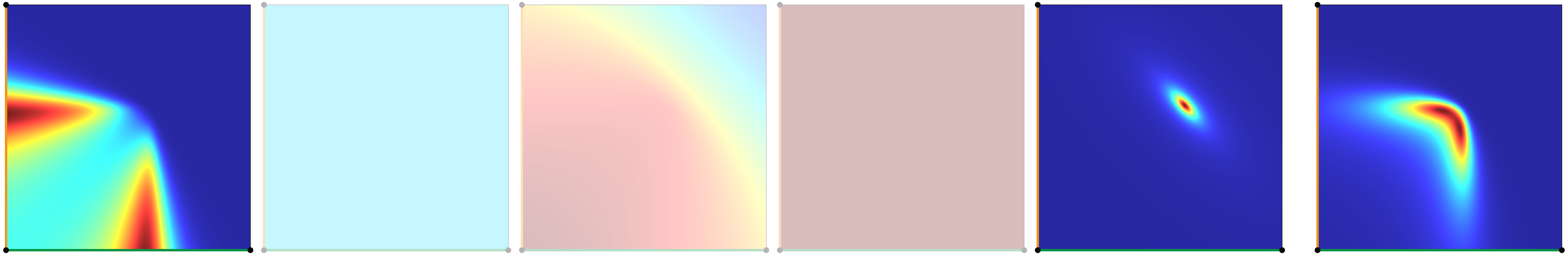
- **Conditional PDF** 
  - examples for Henyey-Greenstein PF with g = 0.95



Importance sampling

How to (importance) sample?

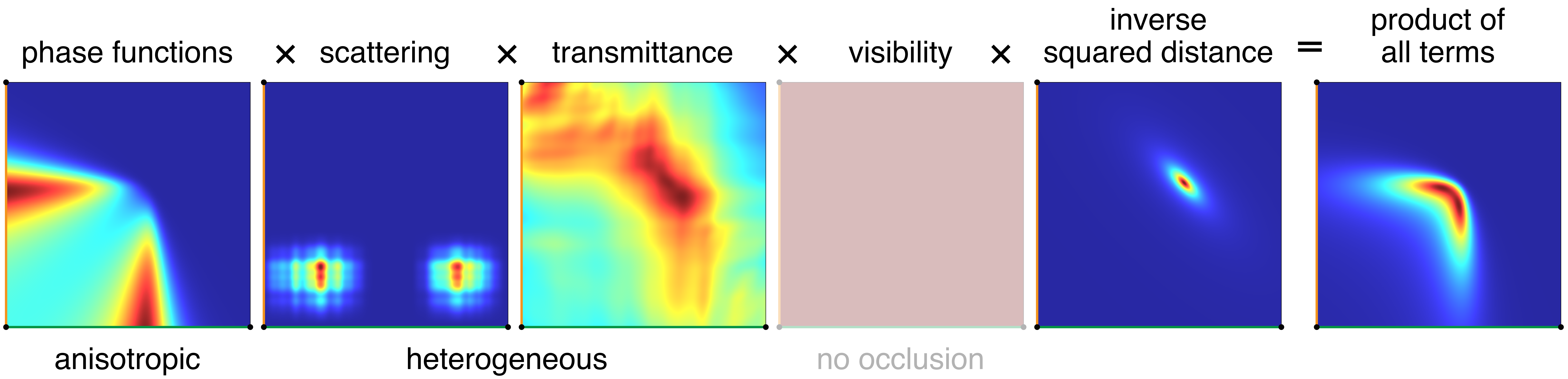
phase functions × scattering × transmittance × visibility × inverse squared distance = product of all terms



anisotropic homogeneous no occlusion

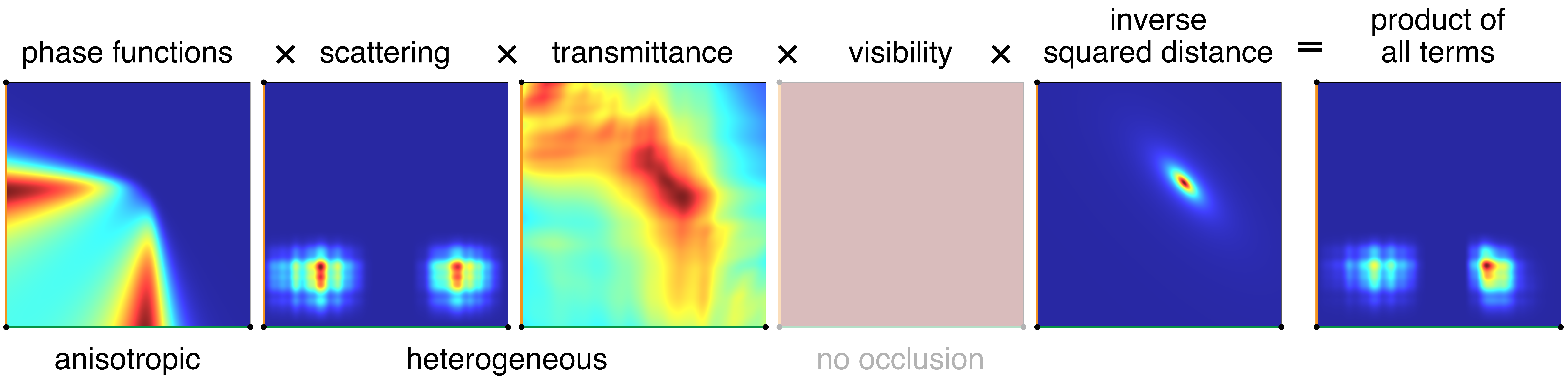
Importance sampling

How to (importance) sample?



Importance sampling

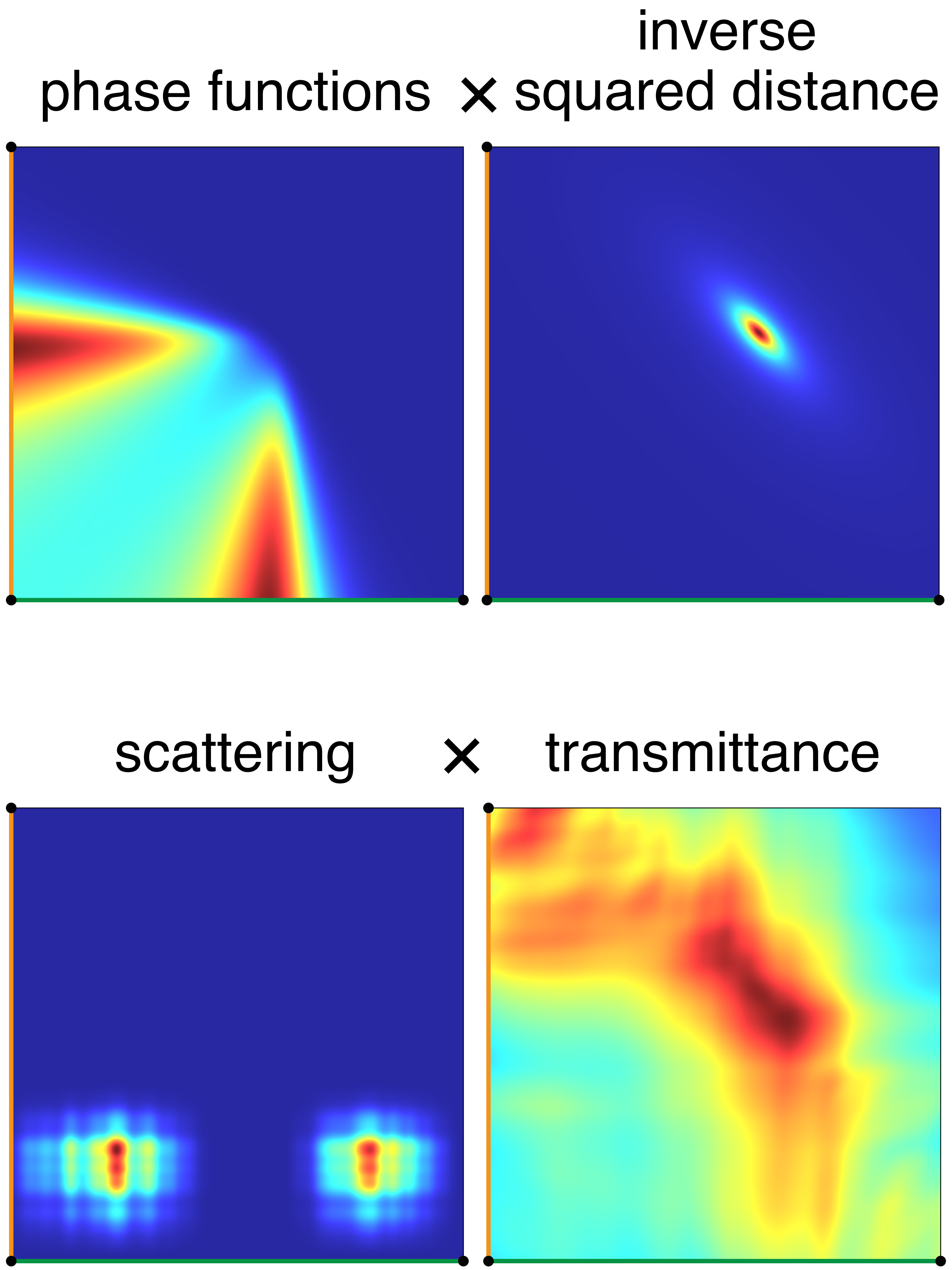
How to (importance) sample?



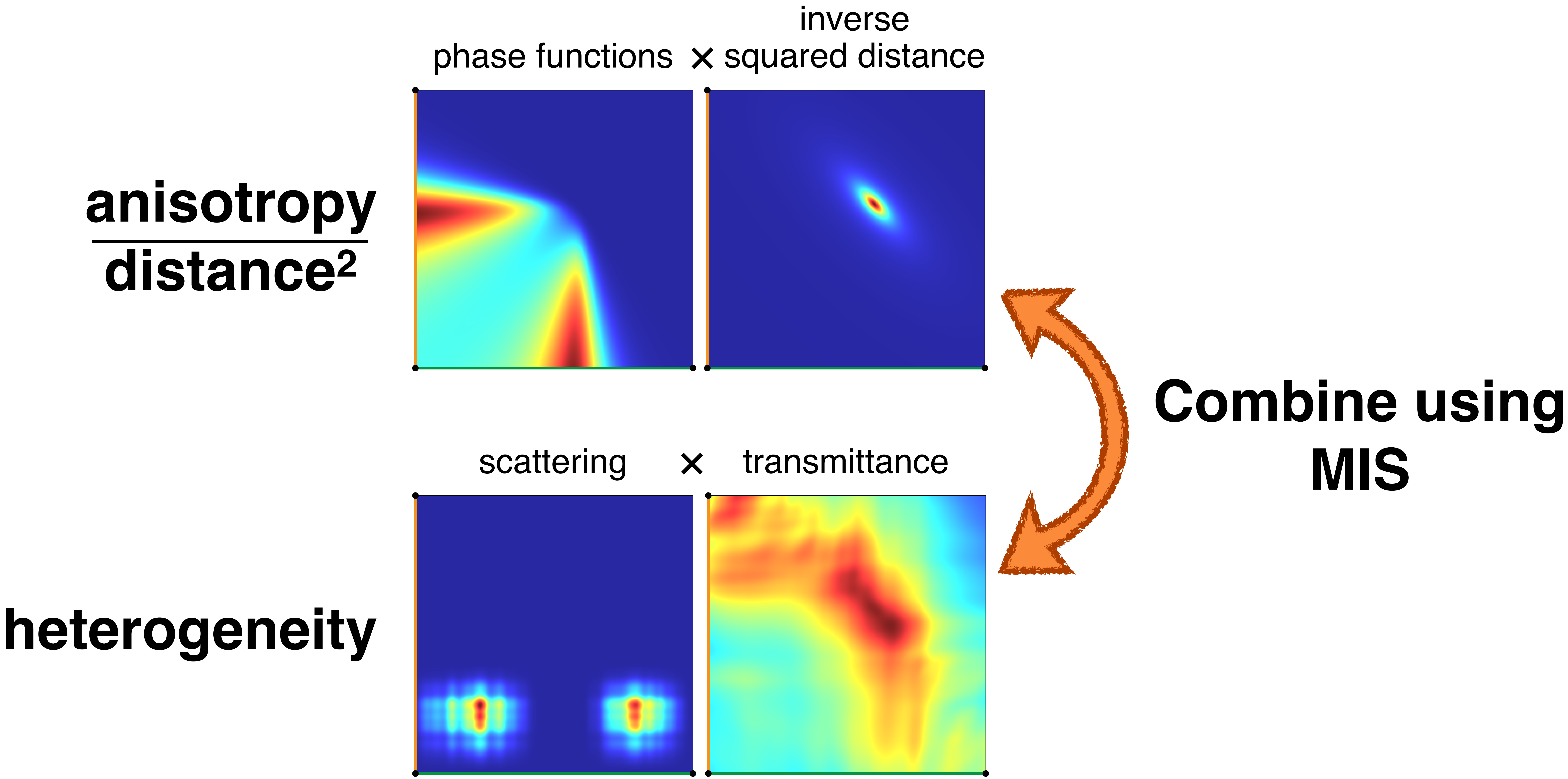
Importance sampling

anisotropy / distance²

heterogeneity



Importance sampling



Heterogeneity

Heterogeneity

$$\mathrm{pdf}(u, v) = \sigma_s(u)\, T(u)\ \sigma_s(v)\, T(v)\ T(u, v)$$

Heterogeneity

$$\mathrm{pdf}(u,v) = \sigma_s(u)\,T(u)\;\sigma_s(v)\,T(v)\;T(u,v)$$

Heterogeneity

$$\mathrm{pdf}(u,v) = \underbrace{\sigma_s(u)\,T(u)}_{\text{along camera ray}}\ \underbrace{\sigma_s(v)\,T(v)}_{\text{along VRL}}\ T(u,v)$$

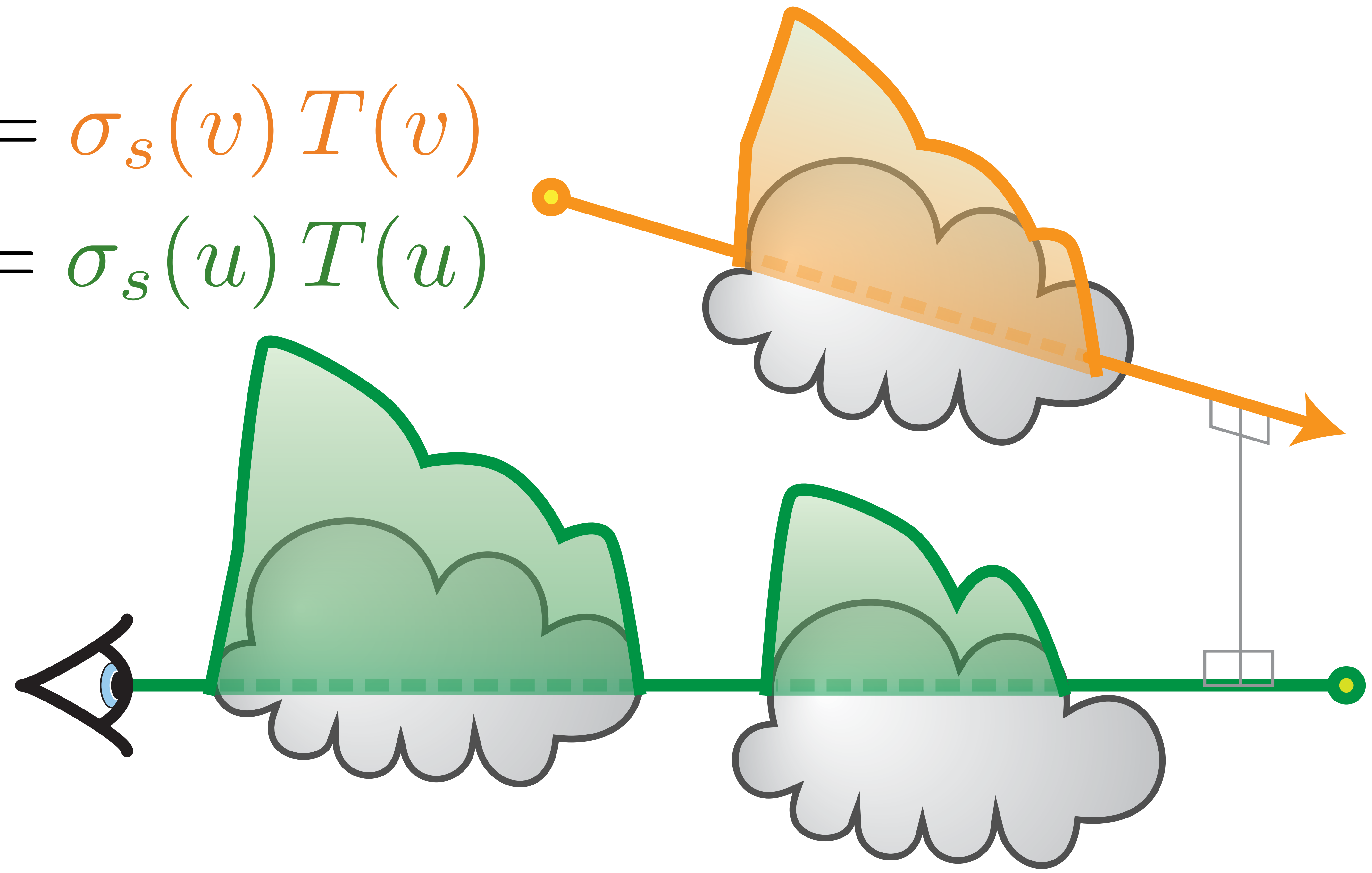
Separable!

Heterogeneity

$$\mathrm{pdf}(u,v) = \underbrace{\sigma_s(u)\,T(u)}_{\text{along camera ray}}\ \underbrace{\sigma_s(v)\,T(v)}_{\text{along VRL}}\ T(u,v)$$

Separable!

$$\mathrm{pdf}(v) = \sigma_s(v)\,T(v)$$
$$\mathrm{pdf}(u) = \sigma_s(u)\,T(u)$$

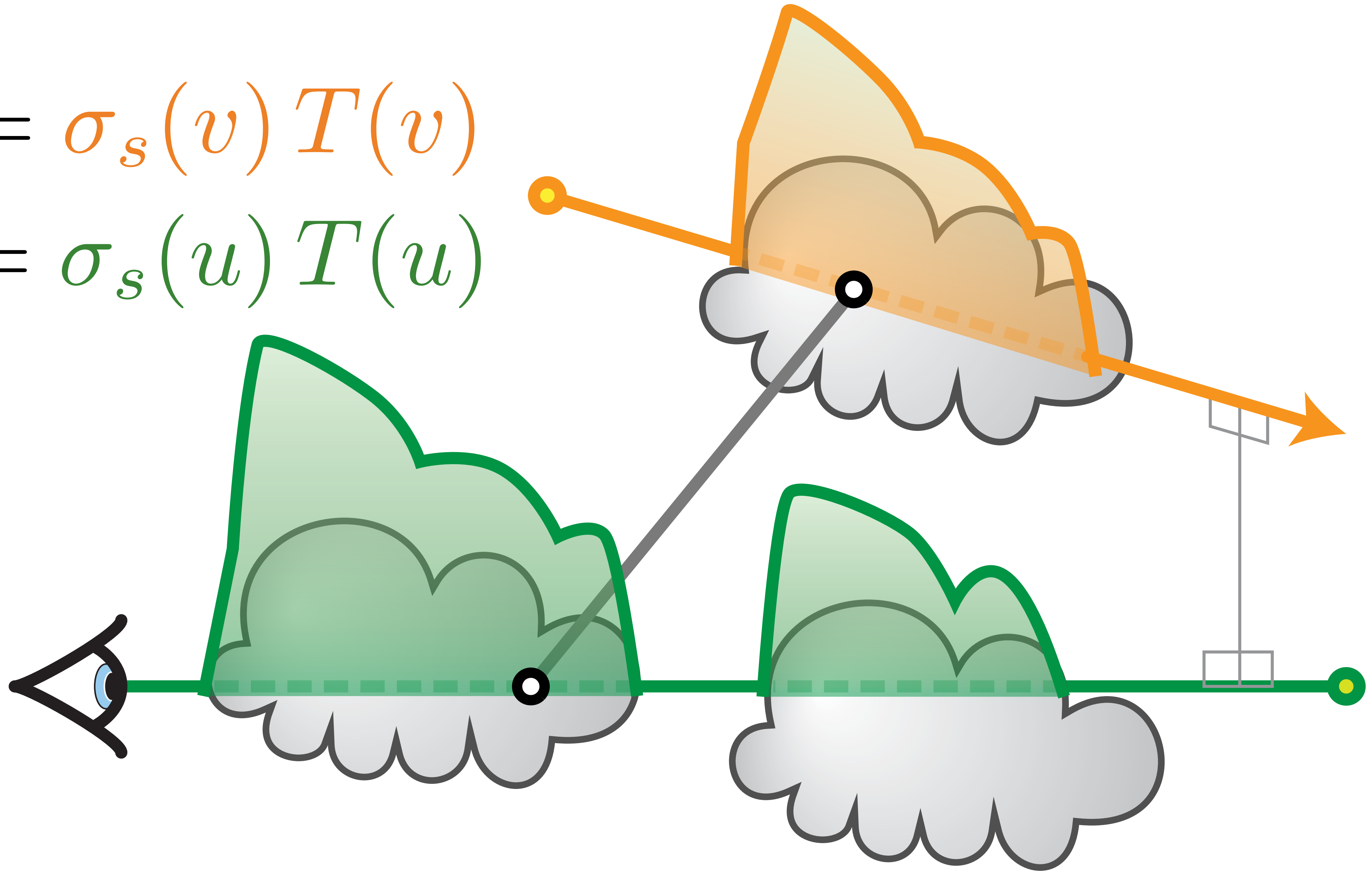


Heterogeneity

$$\mathrm{pdf}(u,v) = \underbrace{\sigma_s(u)\,T(u)}_{\text{along camera ray}}\;\underbrace{\sigma_s(v)\,T(v)}_{\text{along VRL}}\;T(u,v)$$

Separable!

$$\mathrm{pdf}(v) = \sigma_s(v)\,T(v)$$
$$\mathrm{pdf}(u) = \sigma_s(u)\,T(u)$$



Analysis and Results

Fruit Juice

homogeneous

anisotropic (HG g = 0.55)

512x512

Multiple Scattering

Virtual Ray Lights

4K VRLs

Virtual Point Lights

4K VPLs

6 seconds

Multiple Scattering

Virtual Ray Lights

4K VRLs

Virtual Point Lights

4K VPLs

6 seconds

Multiple Scattering

Virtual Ray Lights

60 s   1200 s

Virtual Point Lights

60 s   1200 s

Smoky Room

heterogeneous

1280x720

Media-to-Media

Virtual Ray Lights

6K VRLs

Virtual Point Lights

8K VPLs

5 seconds

Media-to-Media

Virtual Ray Lights

Virtual Point Lights

6K VRLs

8K VPLs

5 seconds

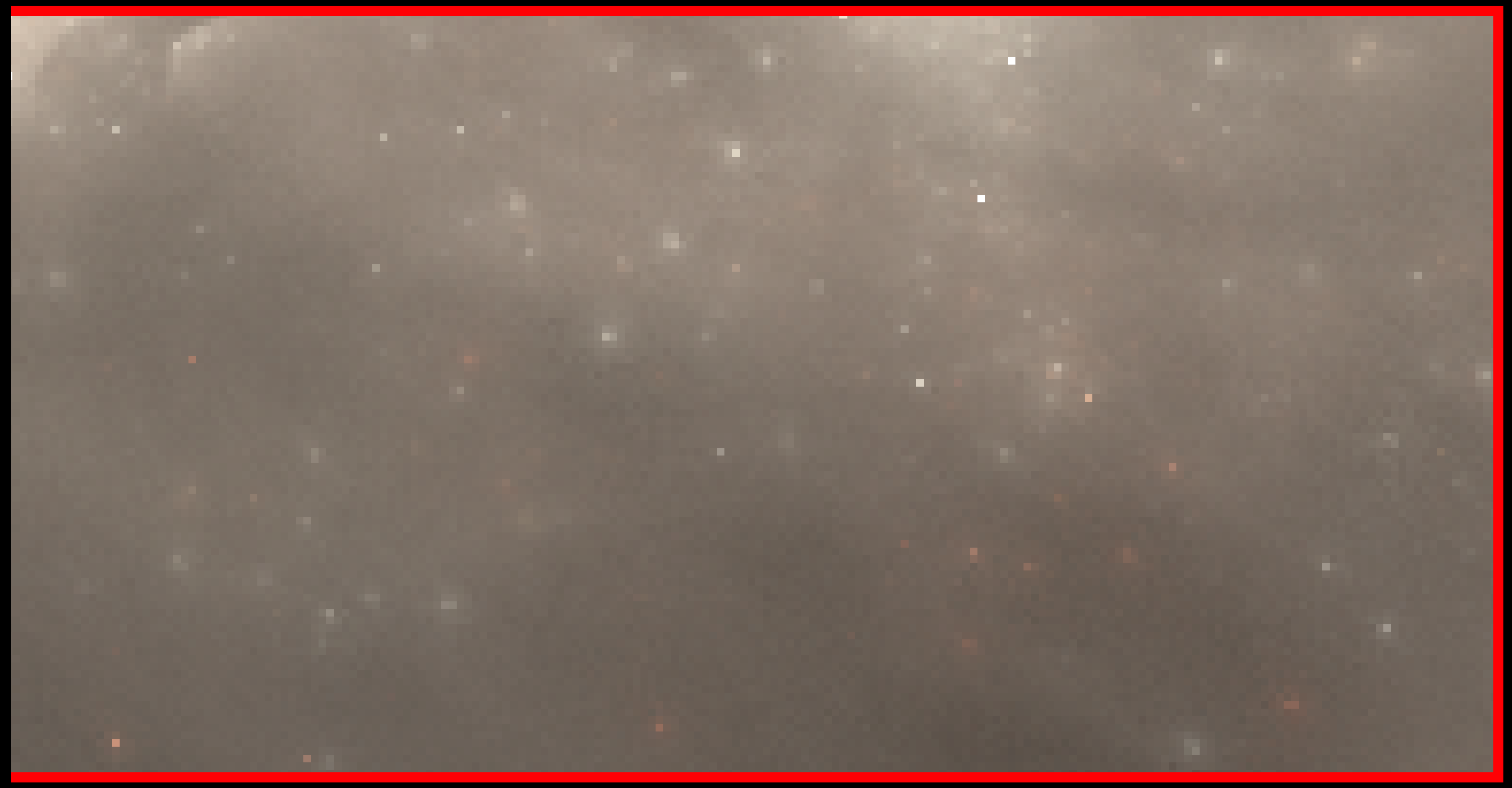
Media-to-Media

Virtual Ray Lights

101 seconds

Virtual Point Lights

102 seconds



Media-to-Surface

Virtual Ray Lights

600 seconds

Virtual Point Lights

600 seconds

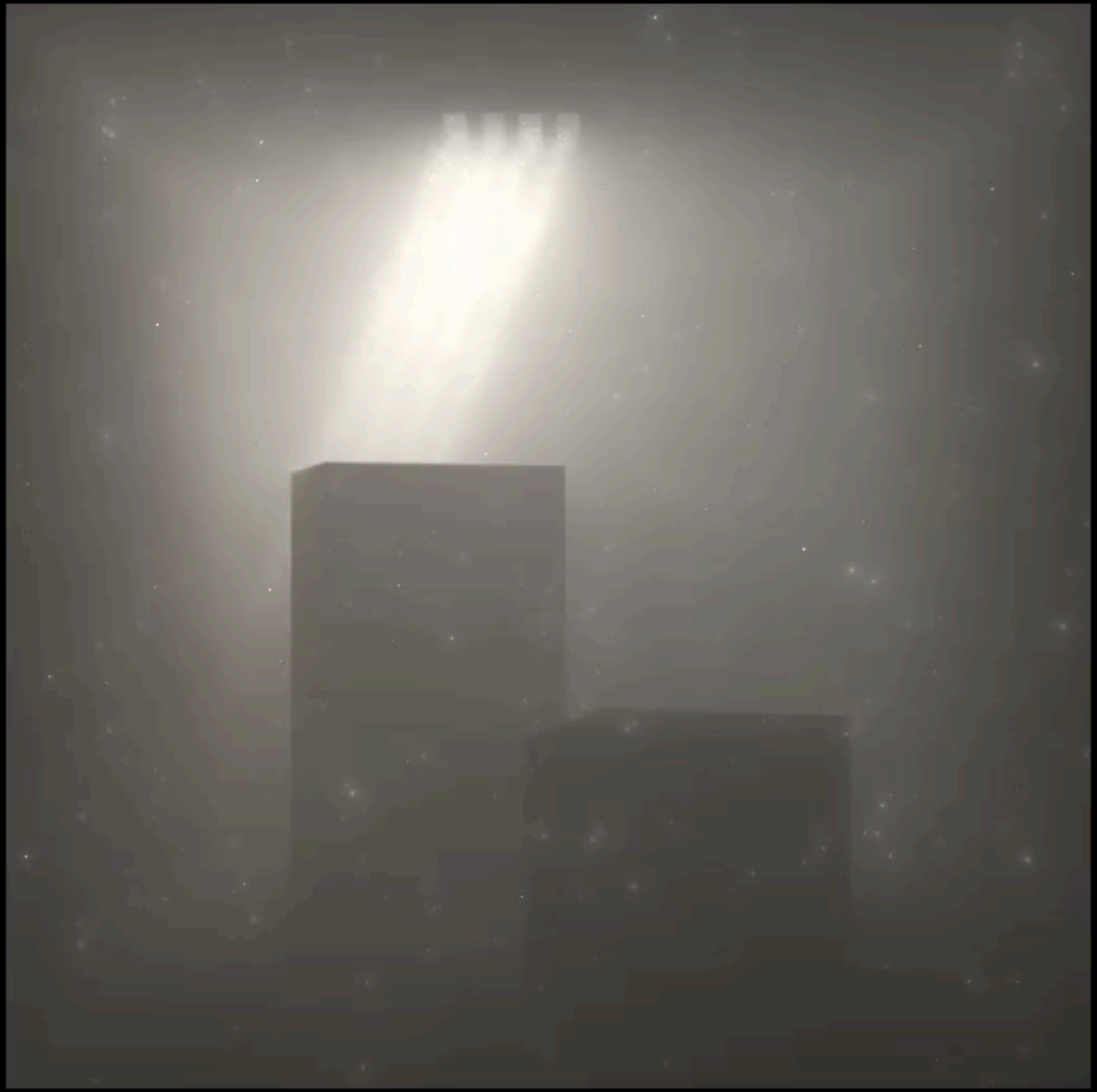
Temporal coherence
VPLs vs. VRLs

Media-to-Media

Virtual Ray Lights

1 minute/frame

Virtual Point Lights



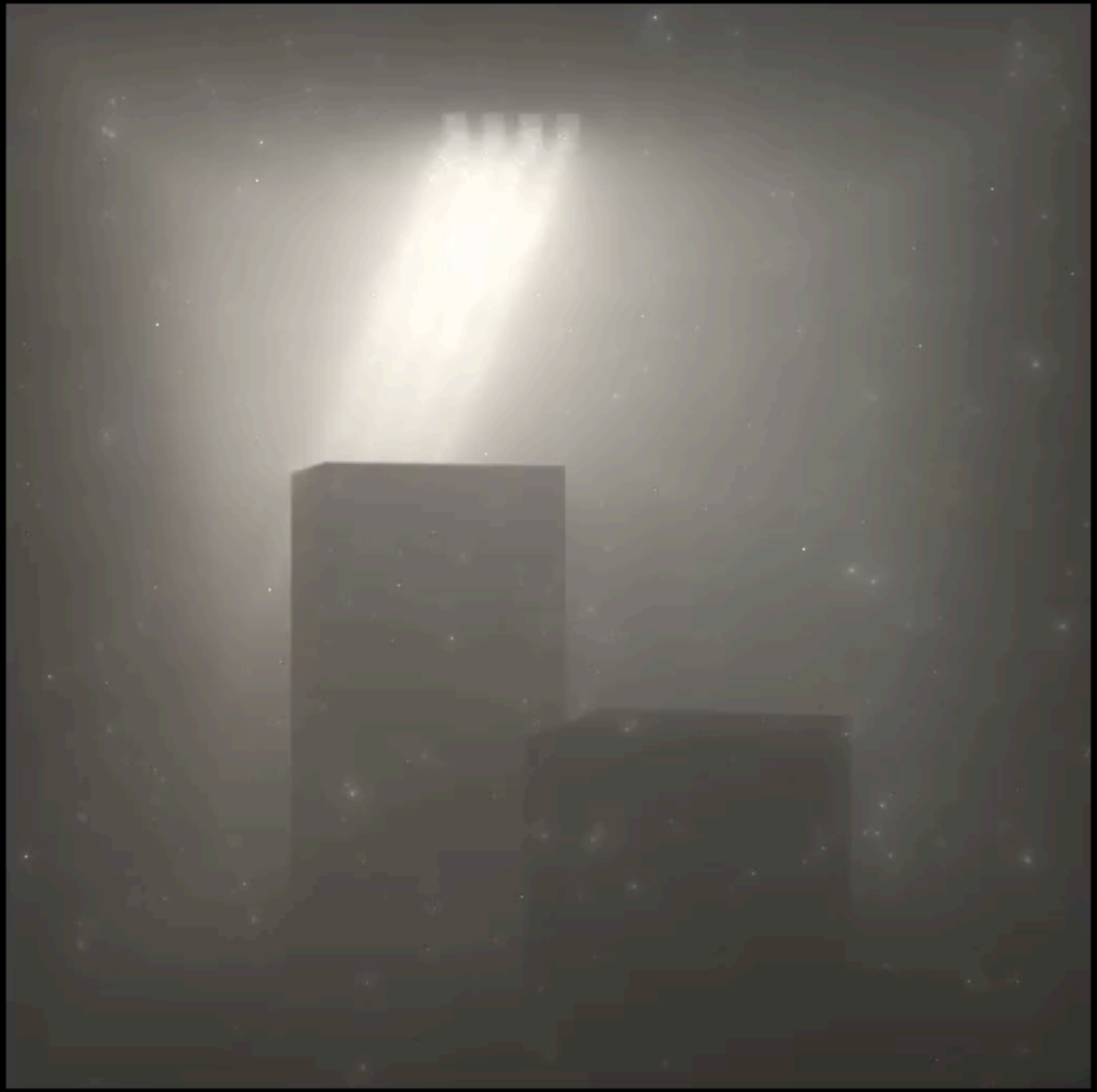
1 minute/frame

Media-to-Media

Virtual Ray Lights

1 minute/frame

Virtual Point Lights



1 minute/frame

Media-to-Media

Virtual Ray Lights

1 minute/frame

Virtual Point Lights

Media-to-Media

Virtual Ray Lights

1 minute/frame

Virtual Point Lights

3 minutes/frame

Spreading the Energy

Turn segments of paths into light sources

Advantages:

- energy is spread along lines, singularity is reduced (not removed)
- unbiased, temporally stable

Disadvantages:

- requires 2D integration (along both rays)

LightCuts

Only for Virtual Point Lights

Walter et al. [2005]

Scalability

Why Many Lights?

Simulate complex illumination using point lights

- Area lights
- Environment map lighting
- Sun and Sky lights
- Indirect Illumination

Unified Illumination: Enable trade-offs among components

Many-Lights Problem

Brute Force: Consider all lights

Too Slow

Many-Lights Problem

Brute Force: Consider all lights

Too Slow

Importance Sampling: Shirley et al. [1996]

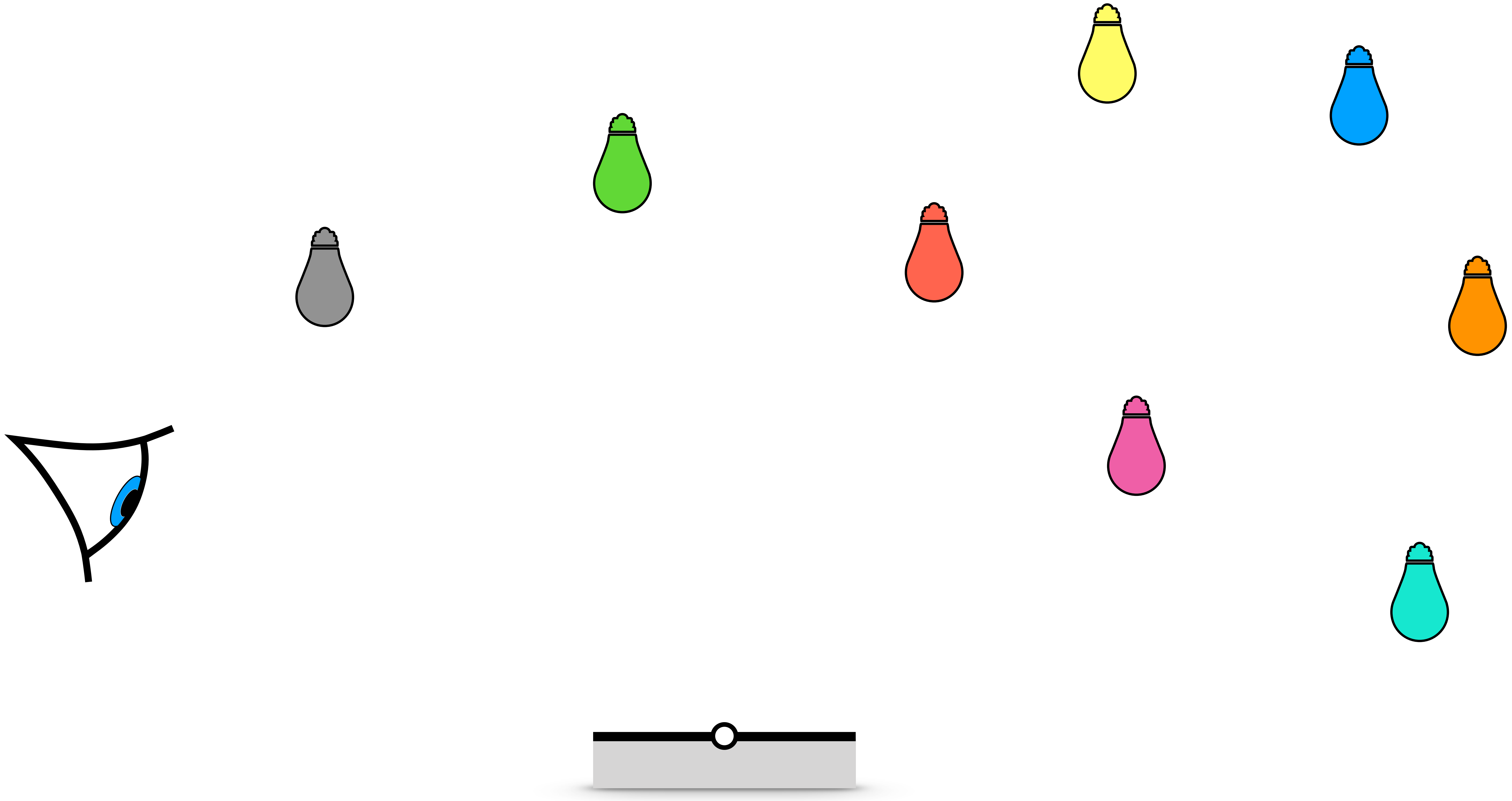
- By considering only a fraction of lights.

- The method suggests using light intensities as importance weights

- Does not give different set of weights, on different parts of the scenes.

Too Noisy

LightCuts Problem



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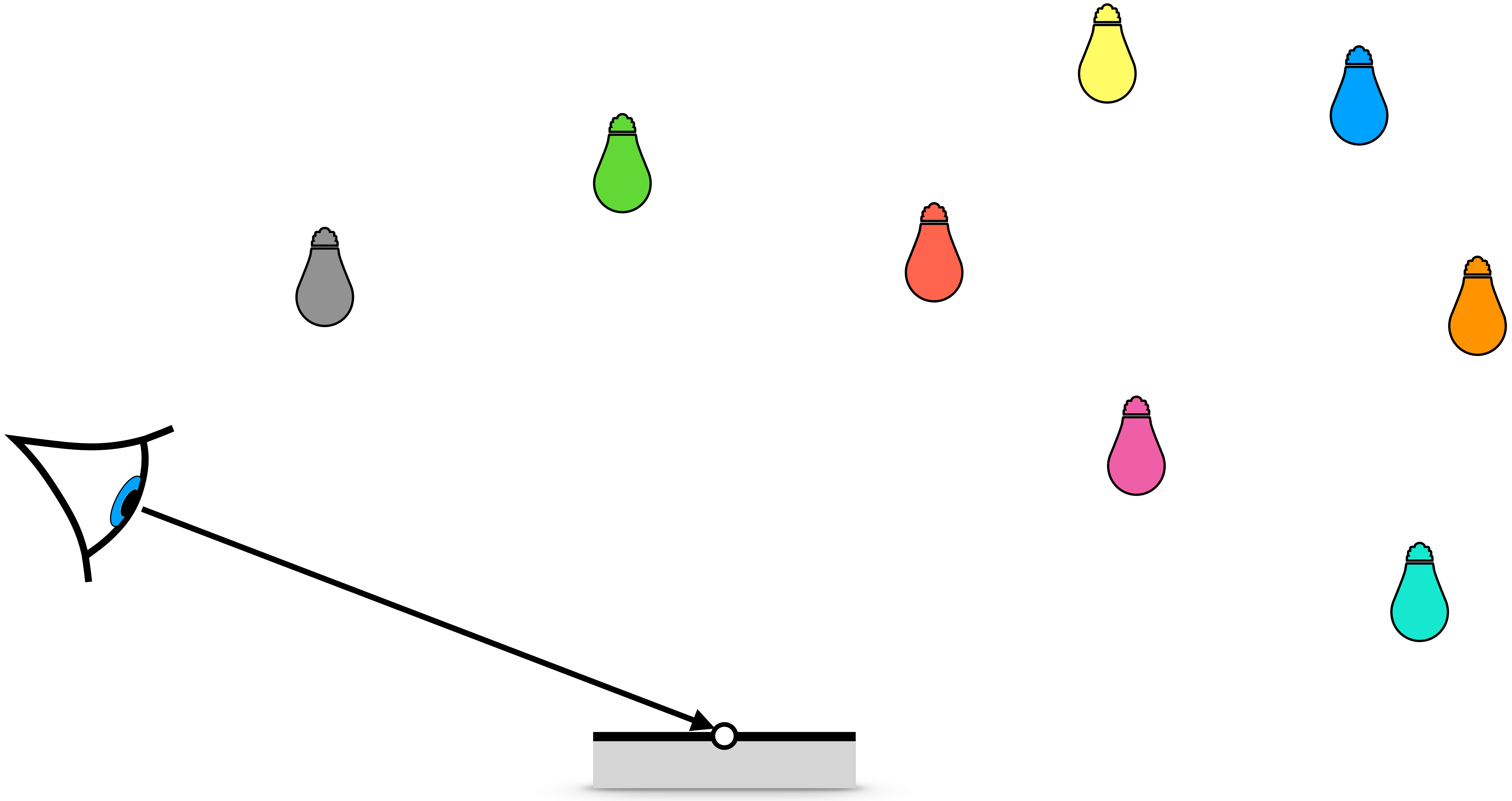
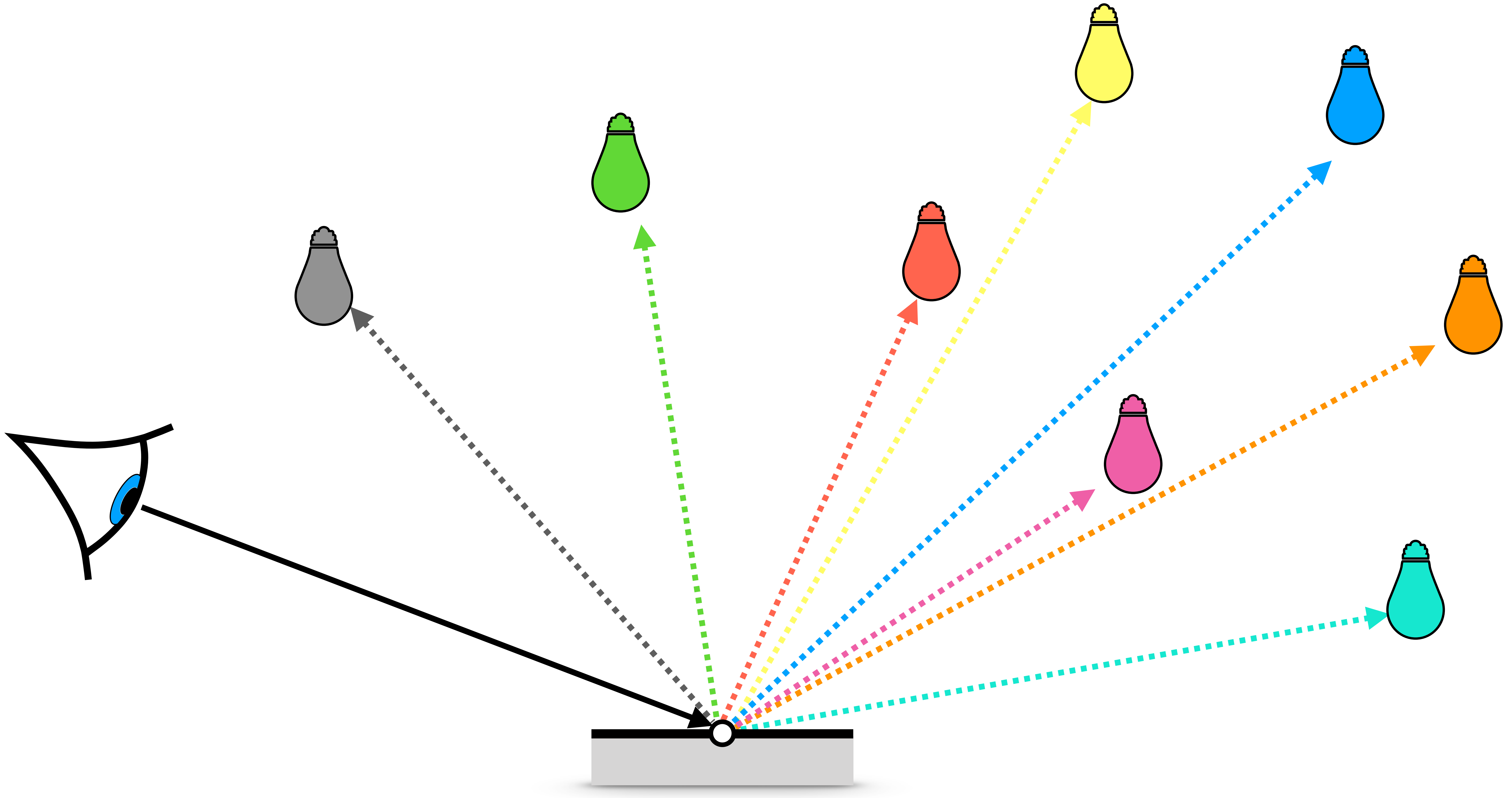
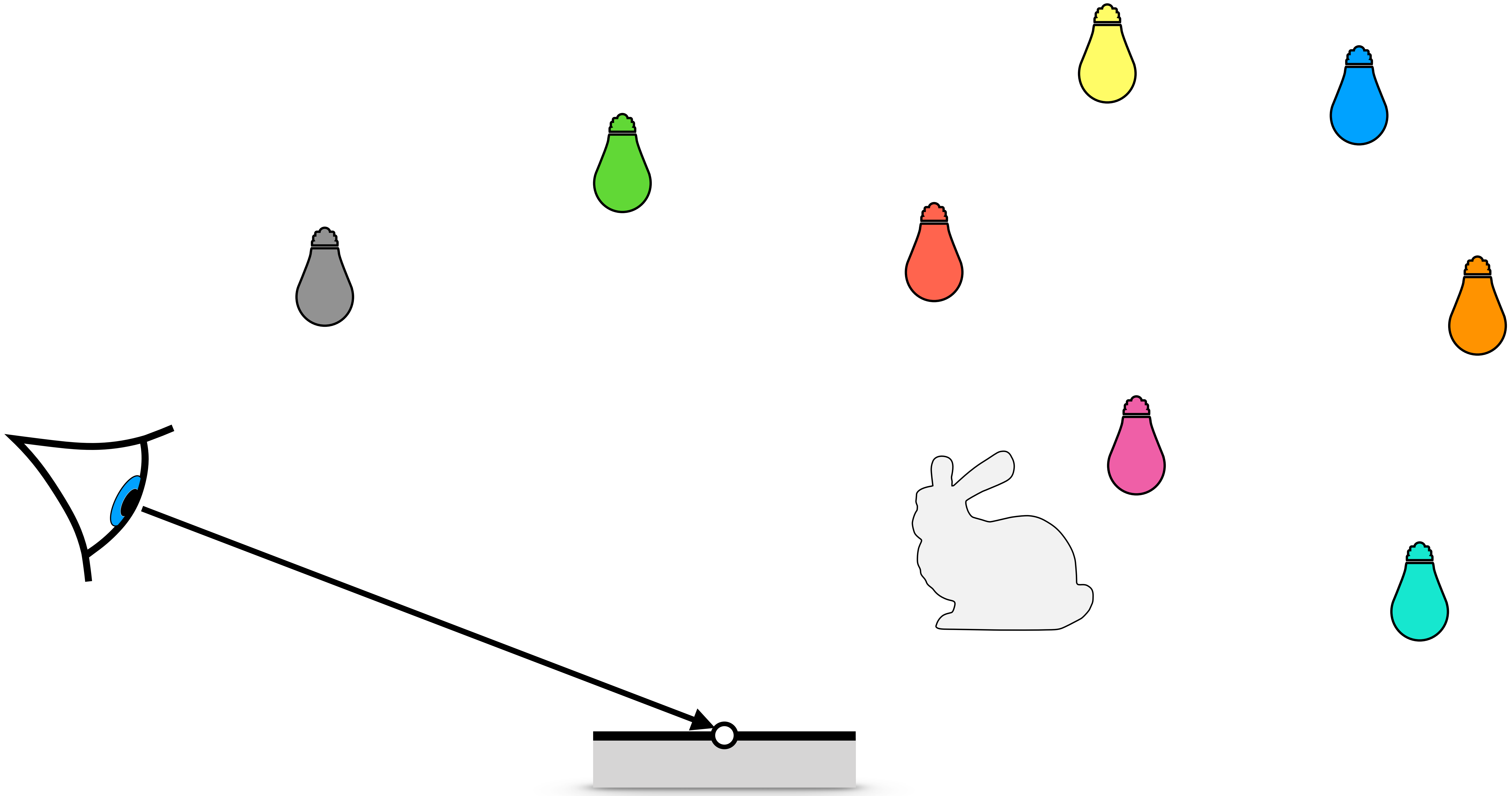
LightCuts Problem



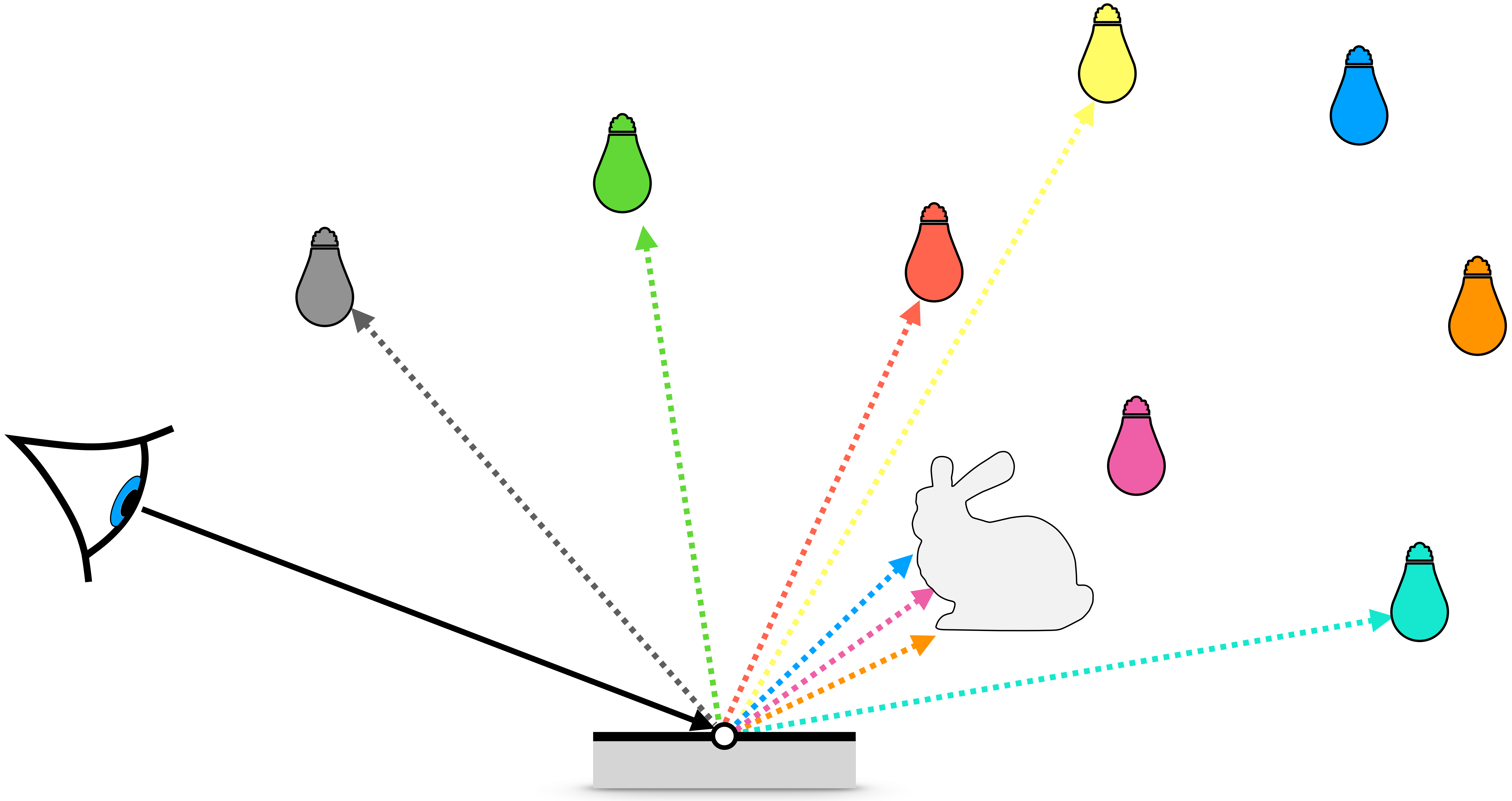
LightCuts Problem



LightCuts Problem



LightCuts Problem

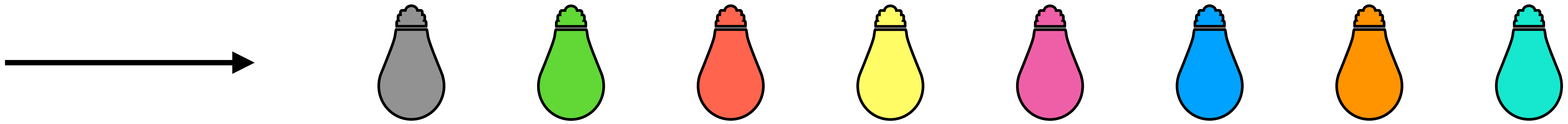


LightCuts: Key Concept

Light Clusters

Light Tree

Original lights



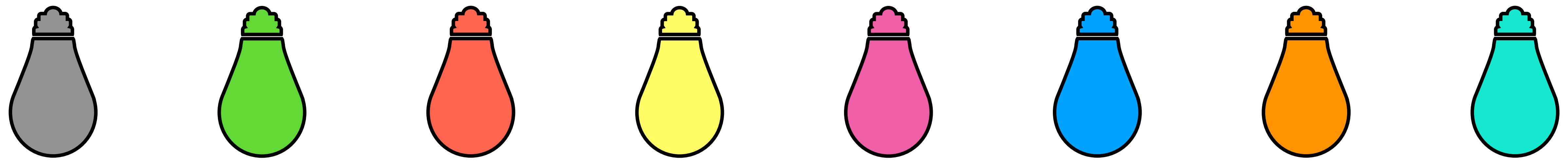
LightCuts: Key Concept

Light Clusters

Light Tree

Light Clusters

Original lights



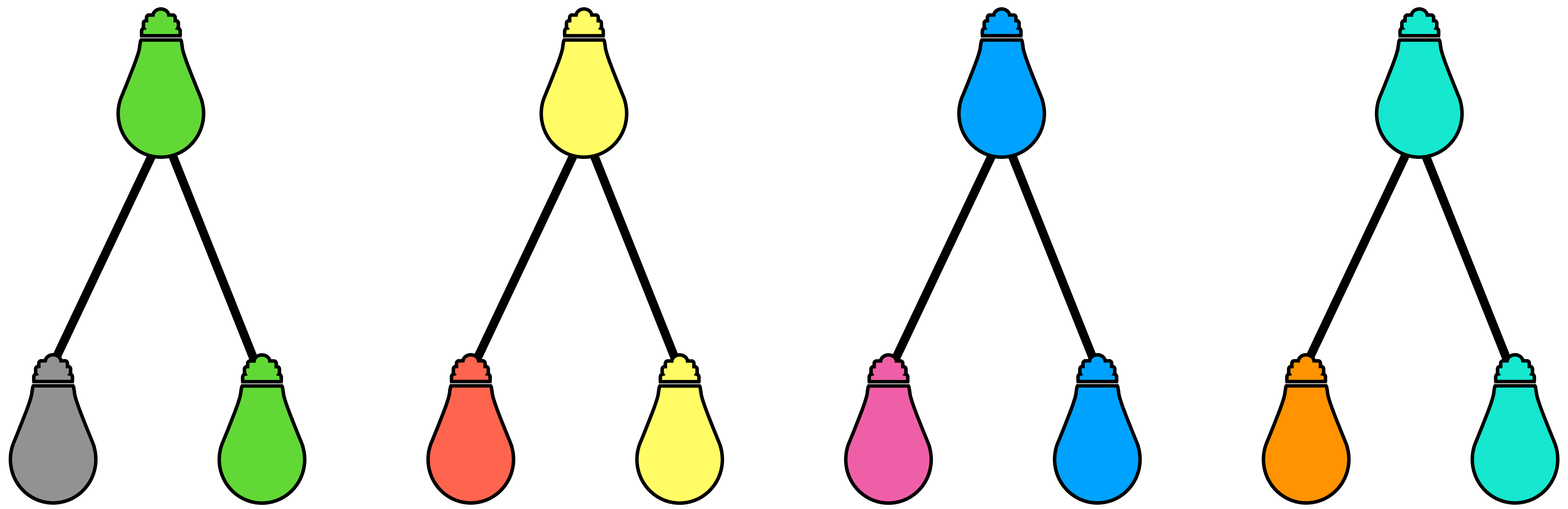
LightCuts: Key Concept

Light Clusters

Light Tree

Light Clusters

Original lights



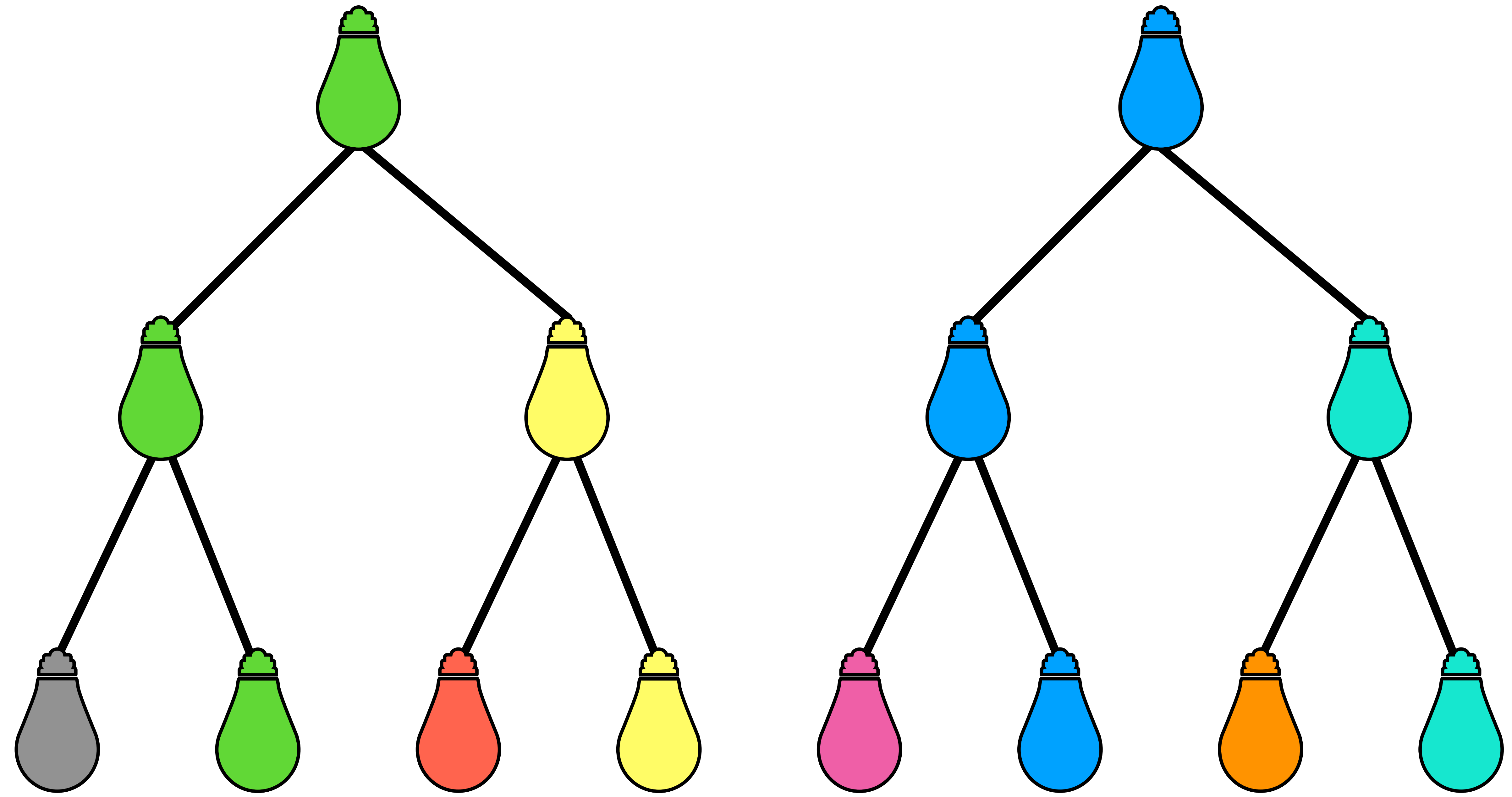
LightCuts: Key Concept

Light Clusters

Light Tree

Light Clusters

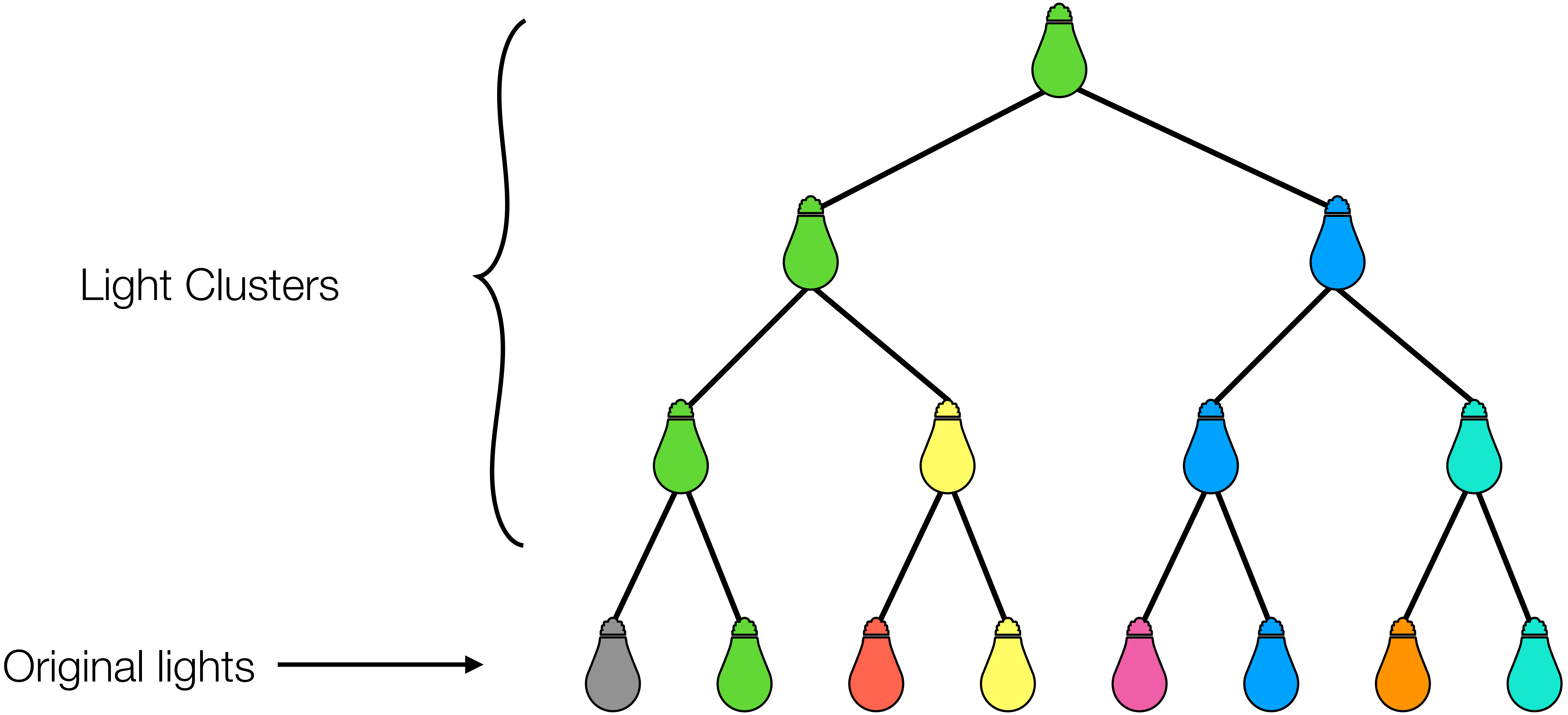
Original lights



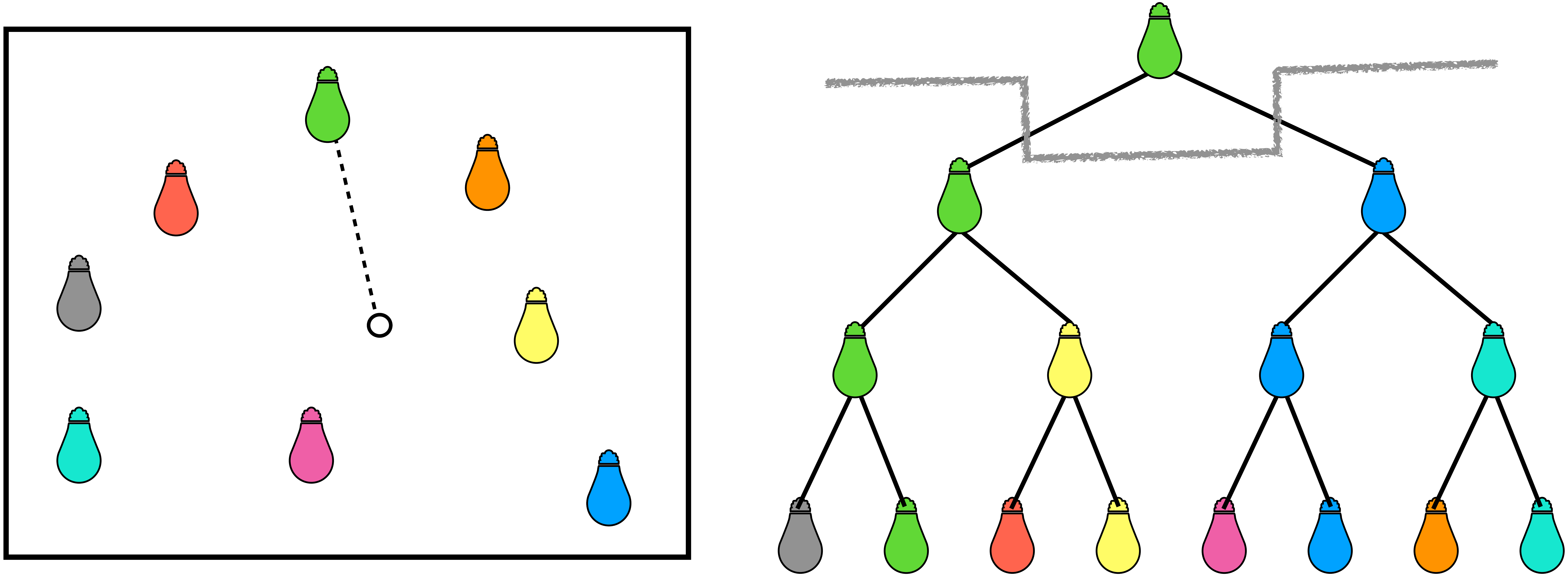
LightCuts: Key Concept

Light Clusters

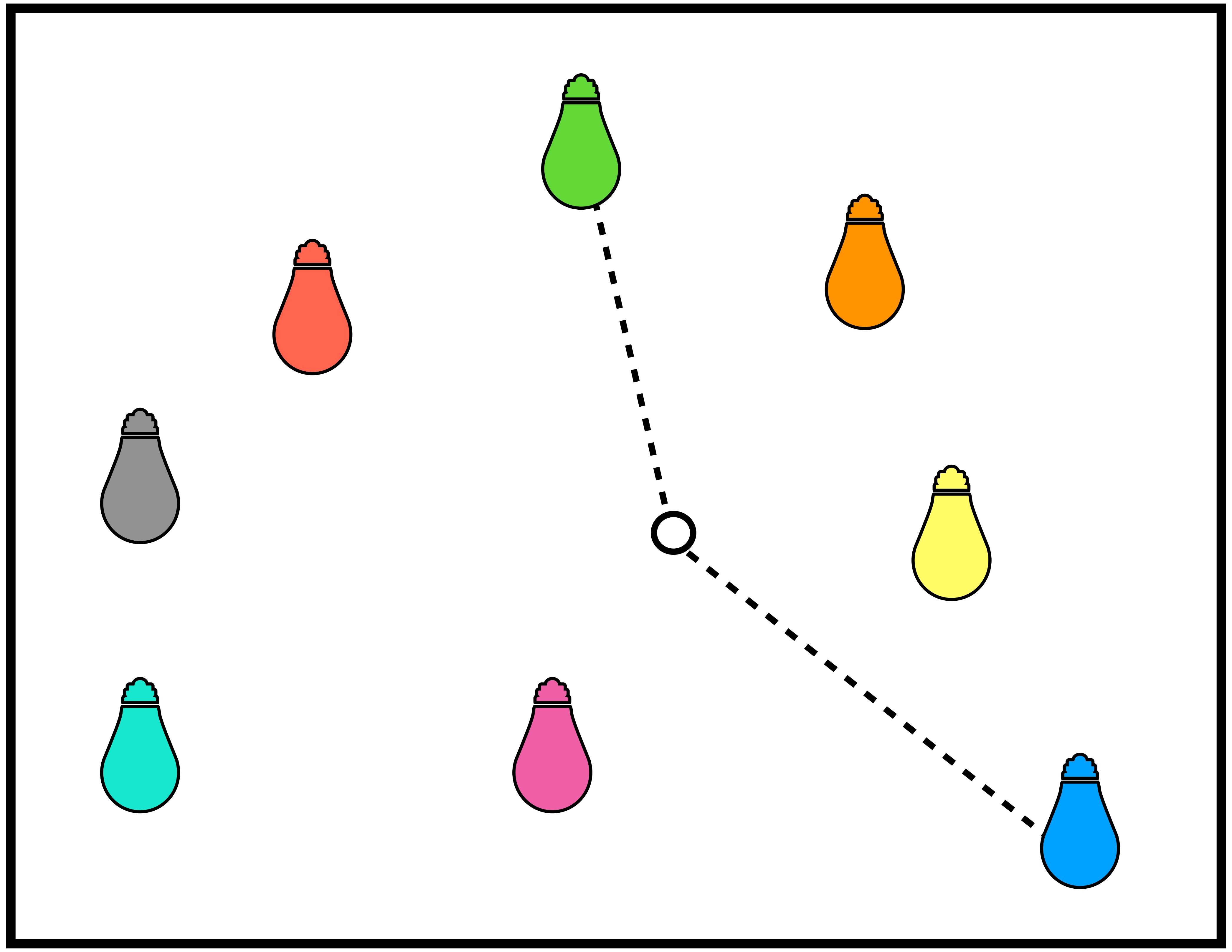
Light Tree

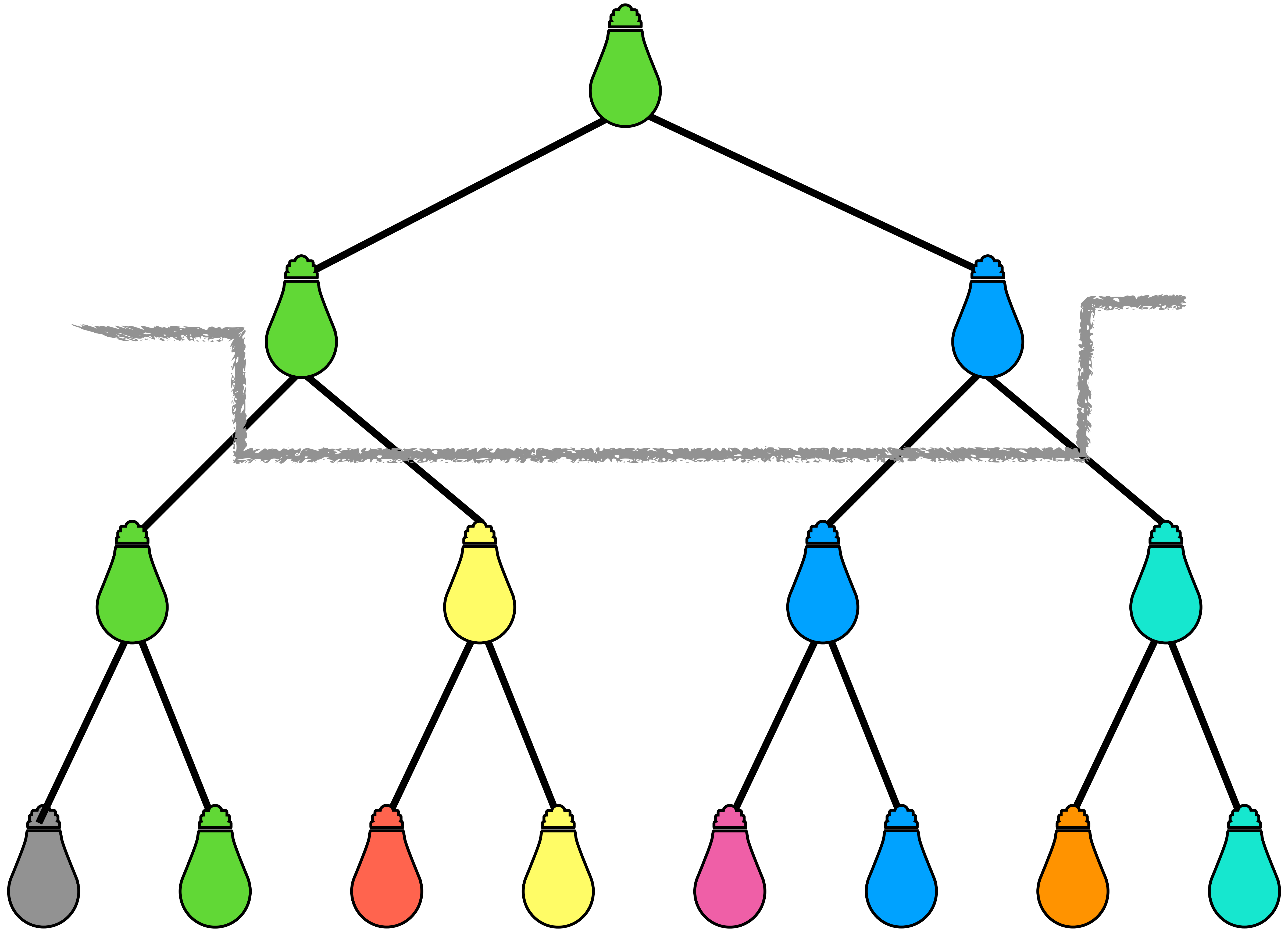


LightCuts: Key Concept

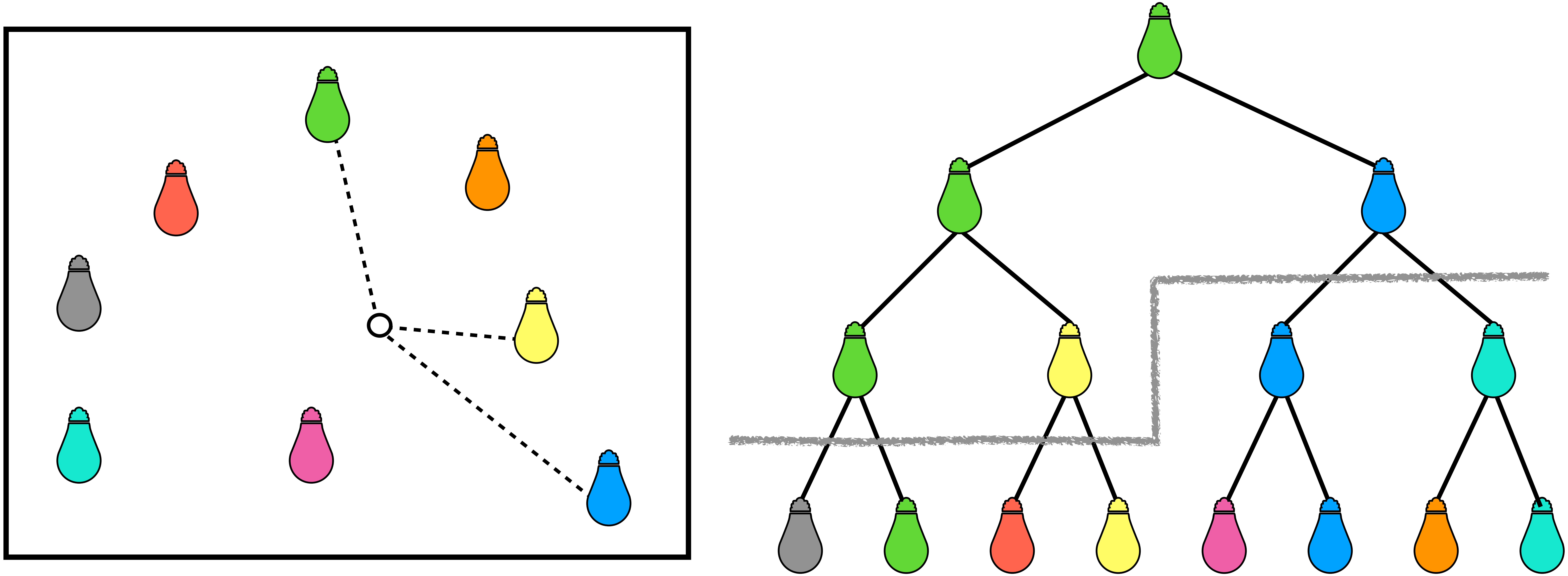


LightCuts: Key Concept

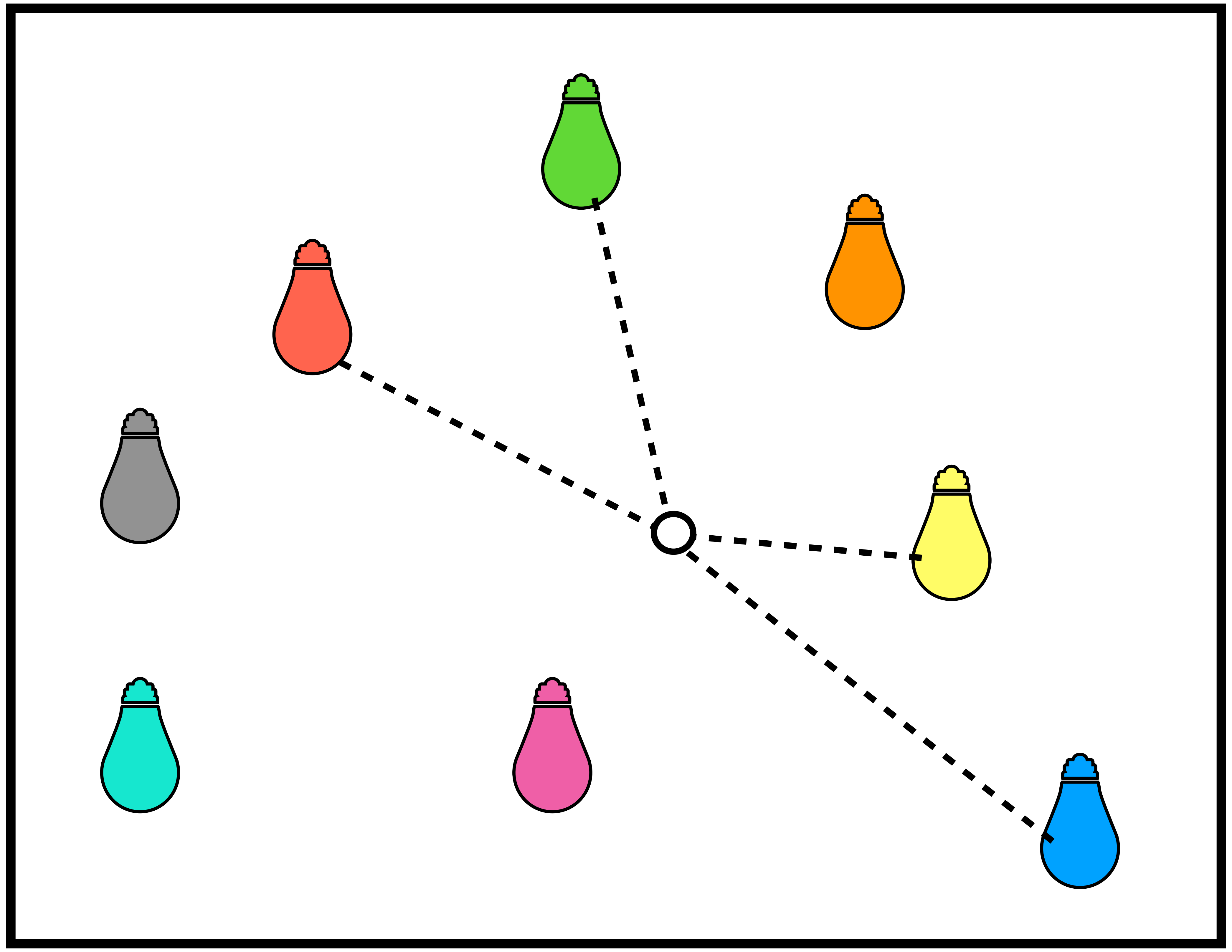


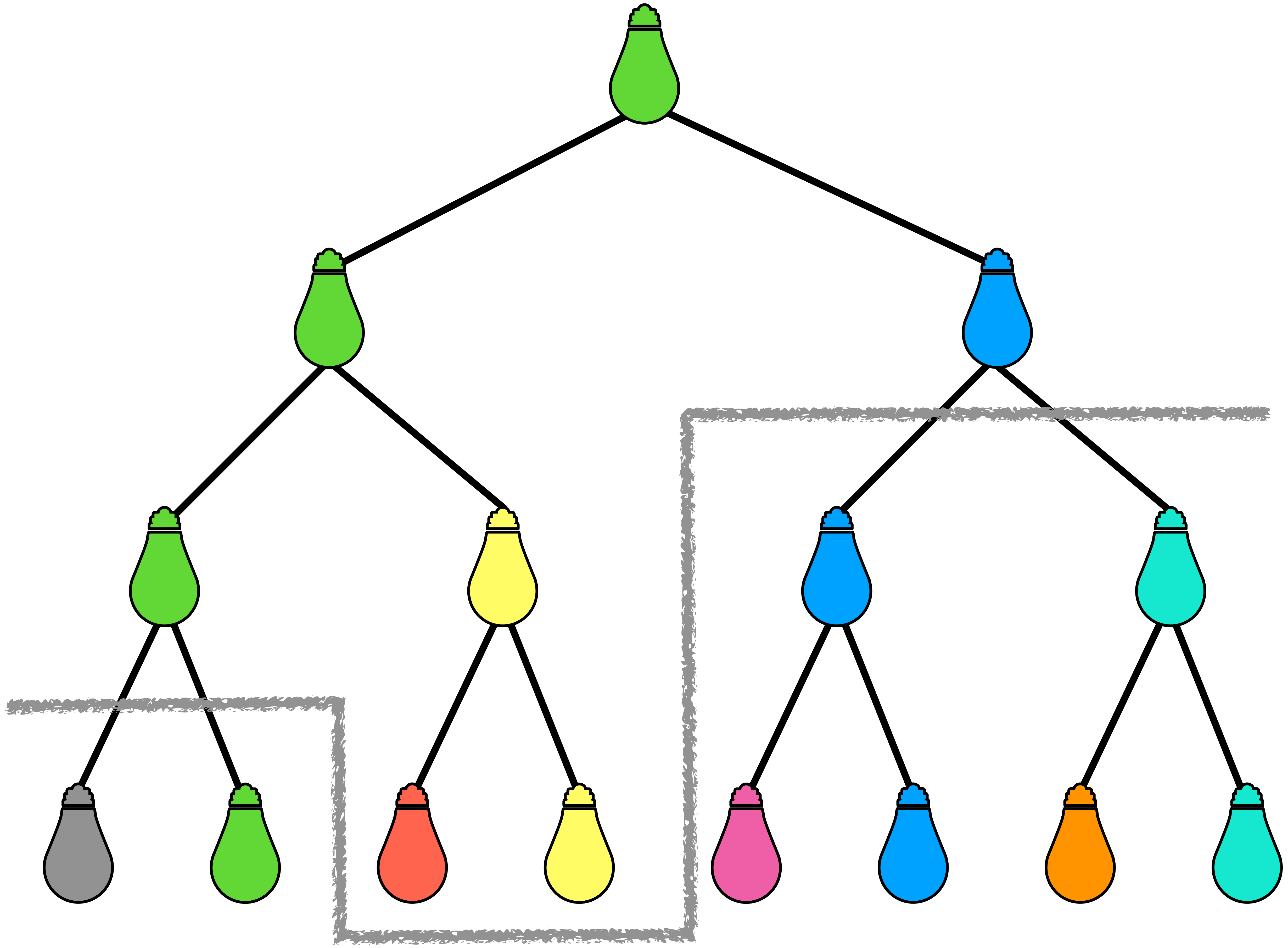


LightCuts: Key Concept

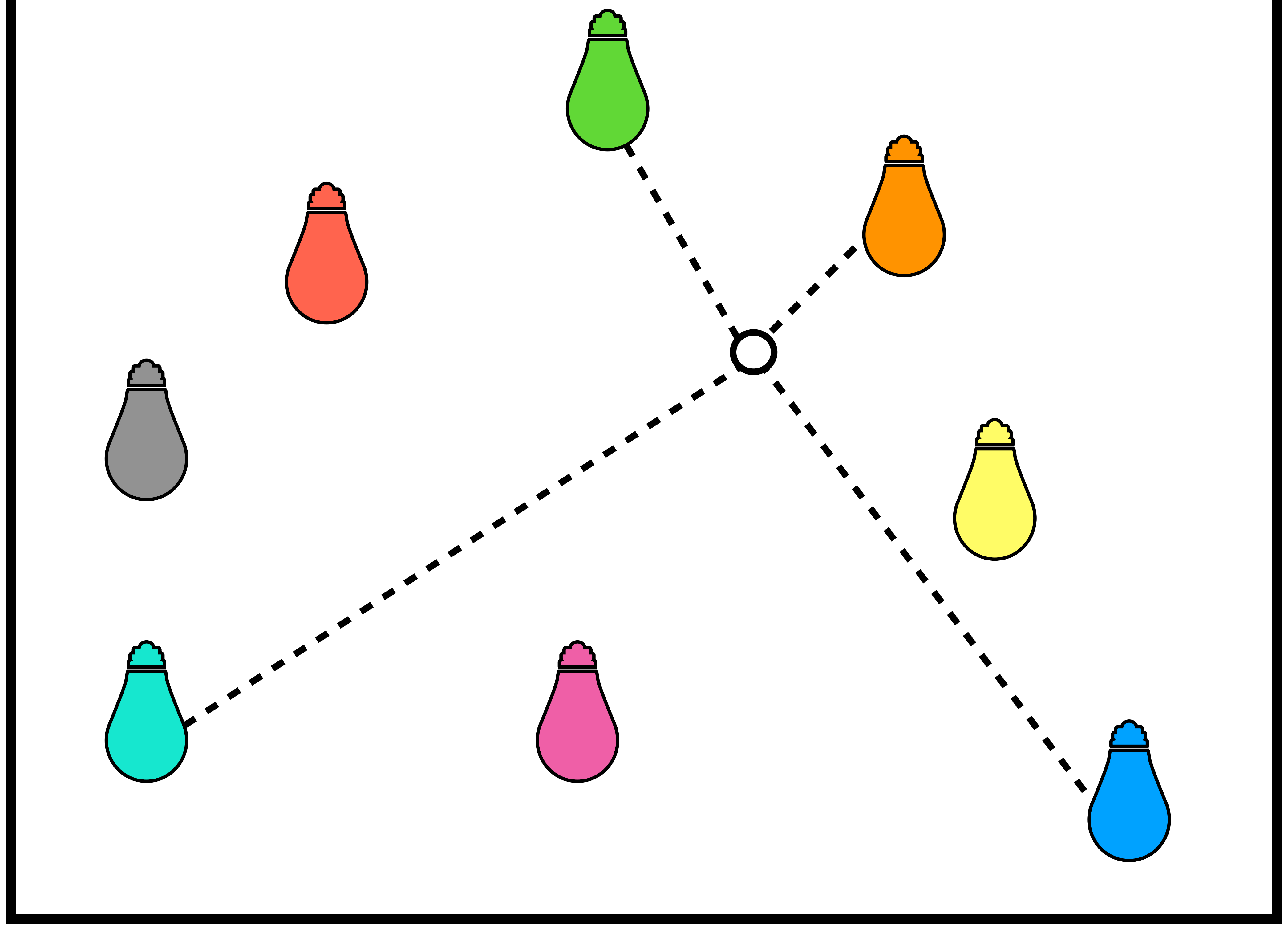


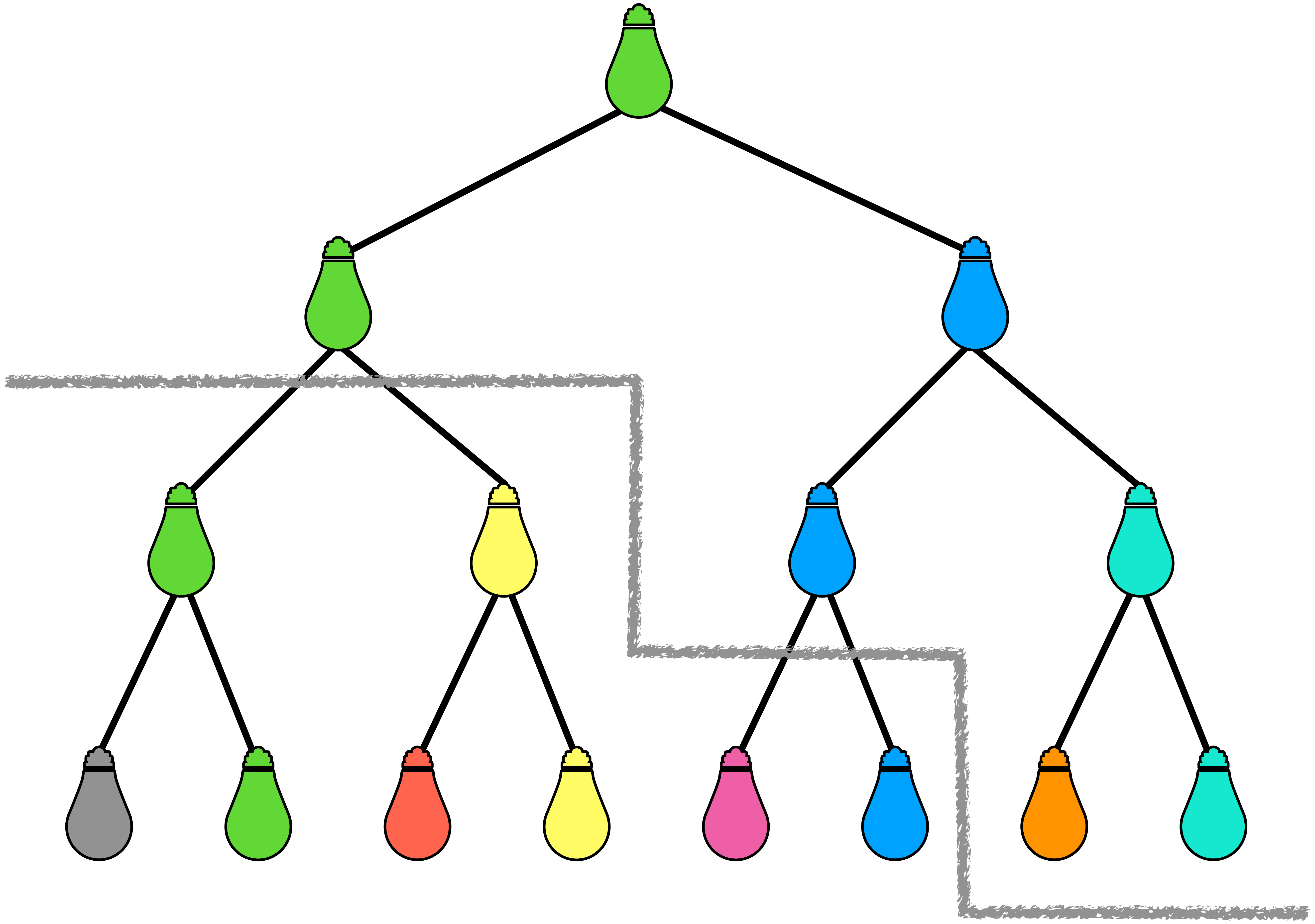
LightCuts: Key Concept



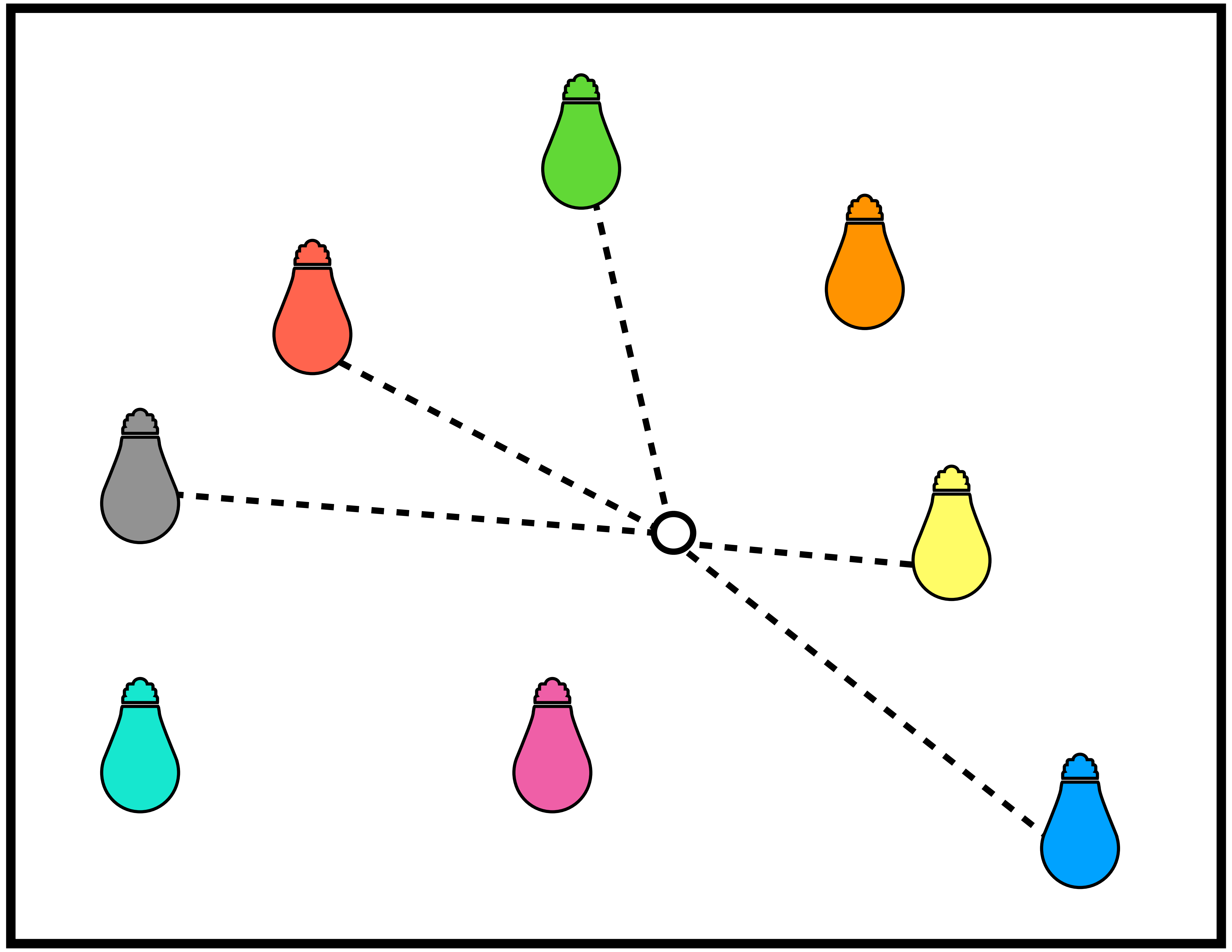


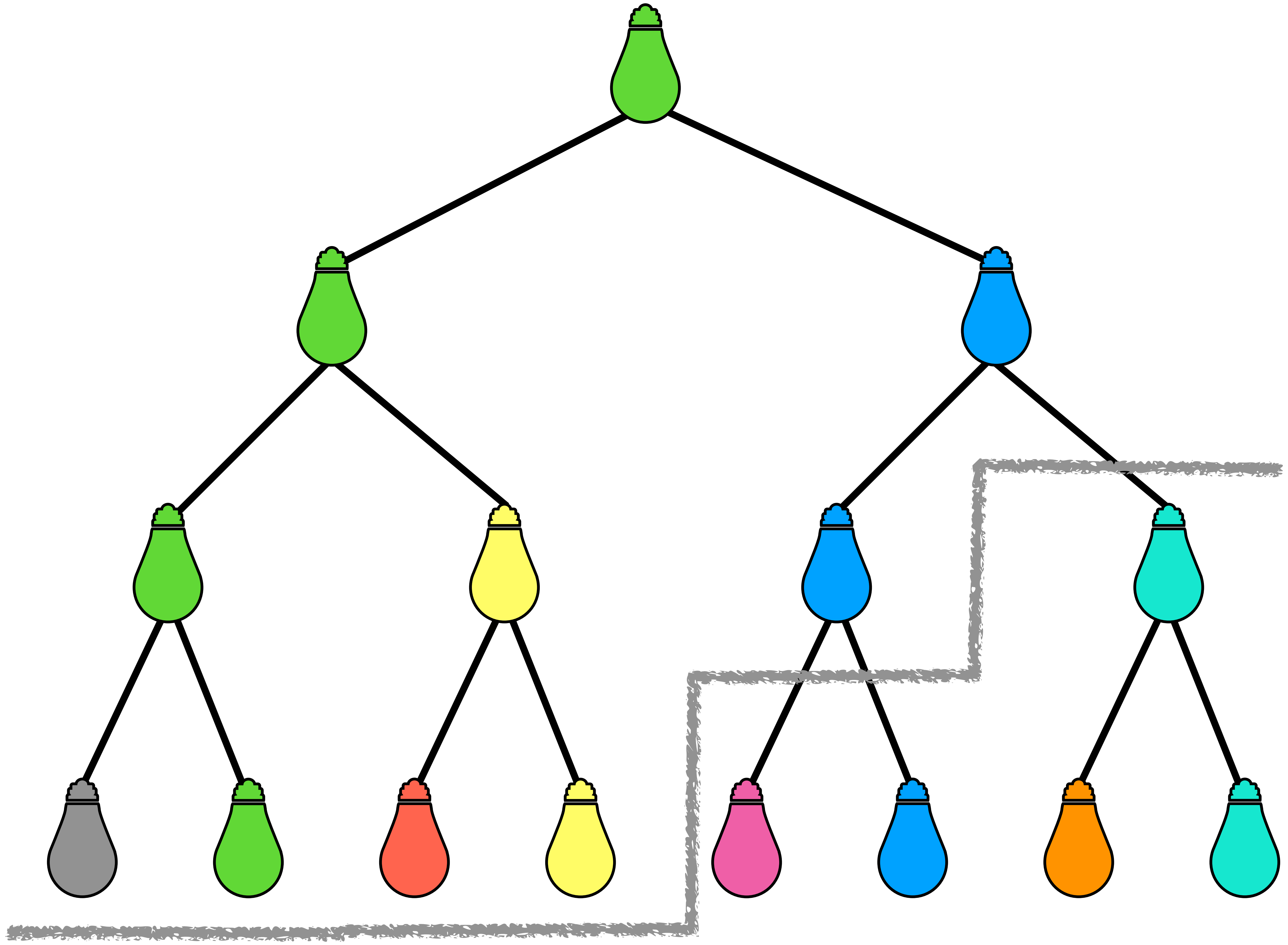
LightCuts: Key Concept





LightCuts: Key Concept





LightCuts: Algorithm Overview

Pre-process:

- Convert illumination to virtual point light sources

- Build light tree

For each ray:

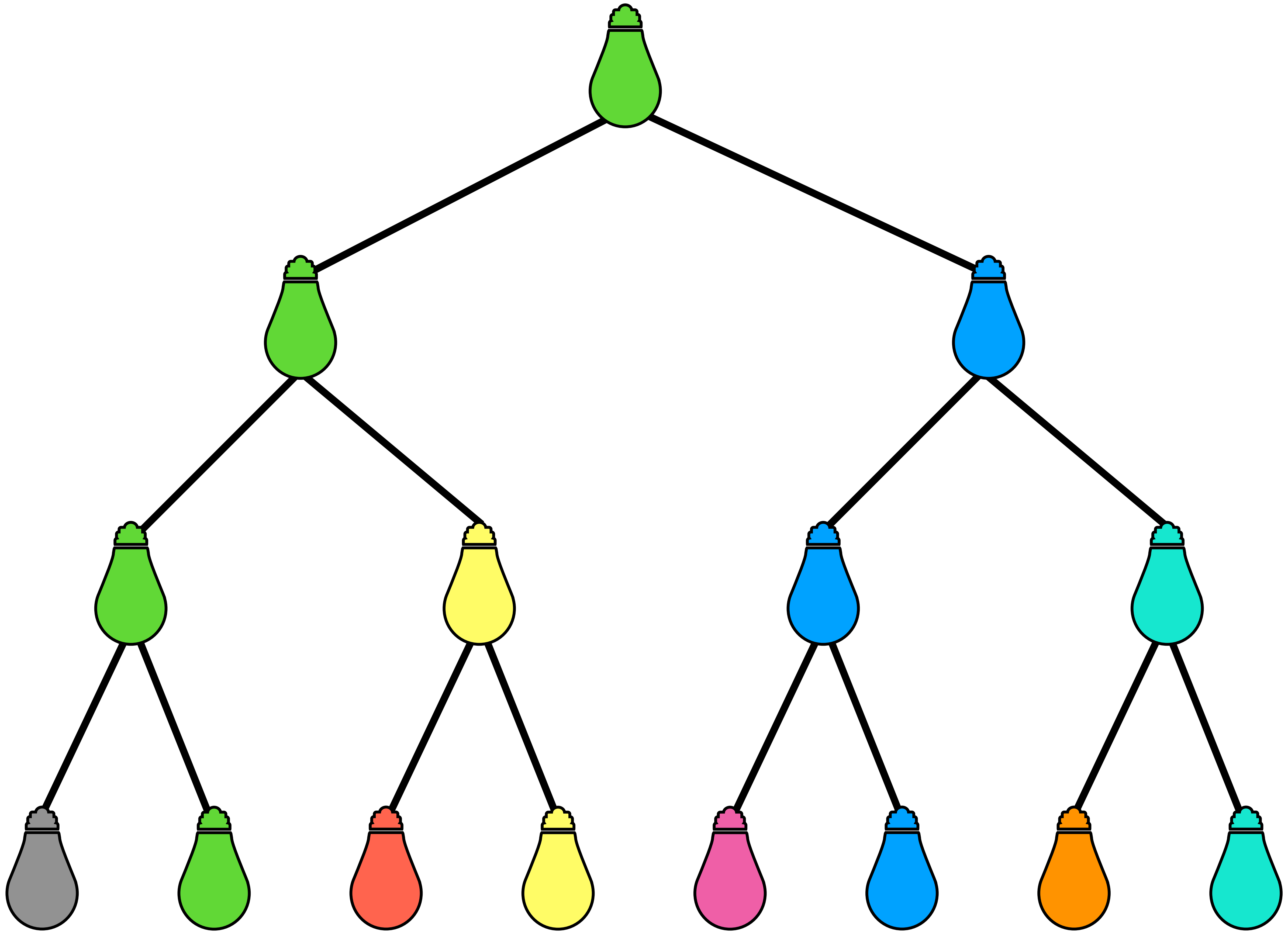
- Choose a cut to approximate the illumination

LightCuts: Issues

Light near the top of the tree more likely to be sampled

Sampling correlations

Different light trees favor different lights



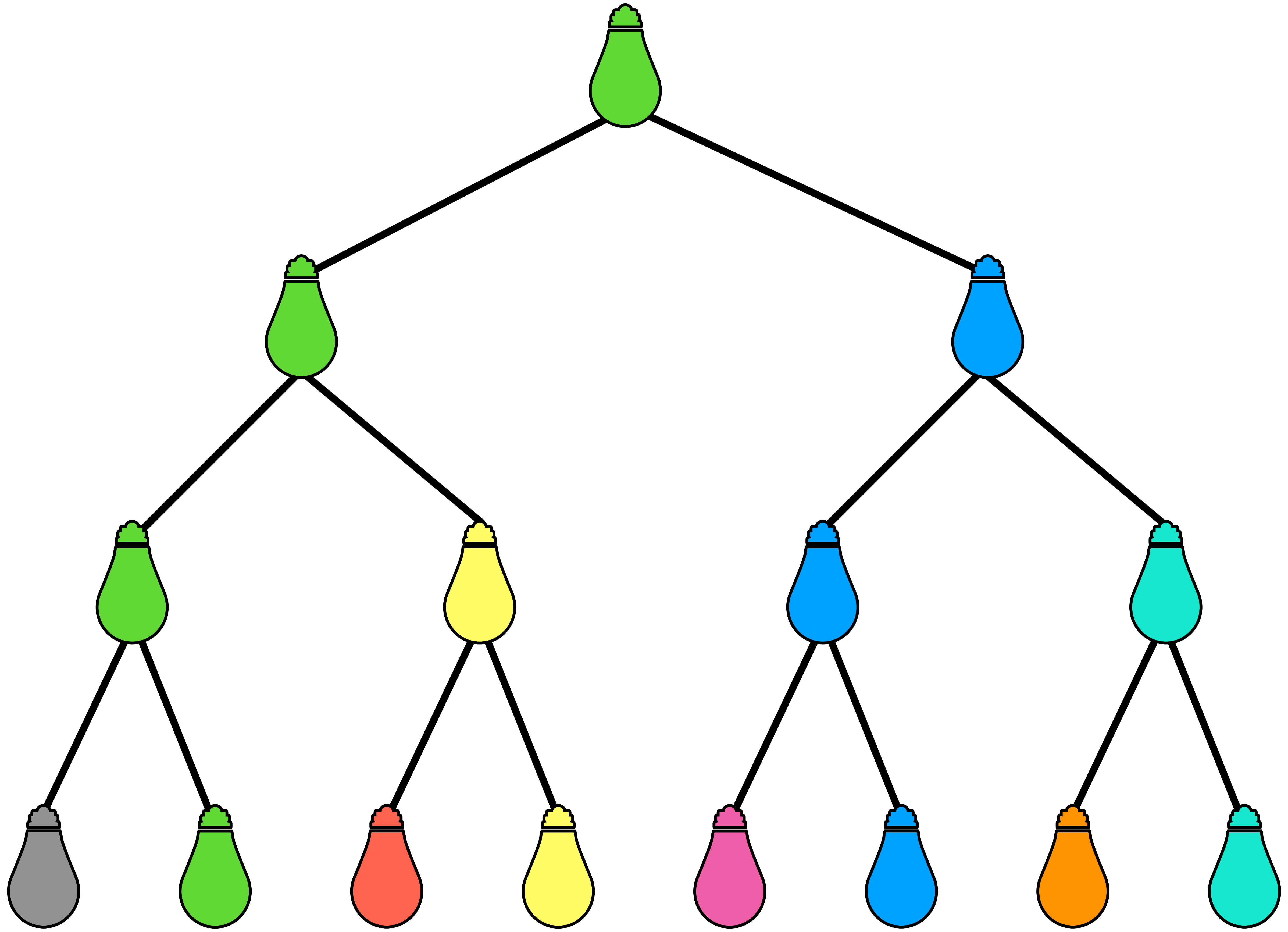
Stochastic LightCuts

Only for Virtual Point Lights

Cem Yuksel [2019]

Stochastic LightCut

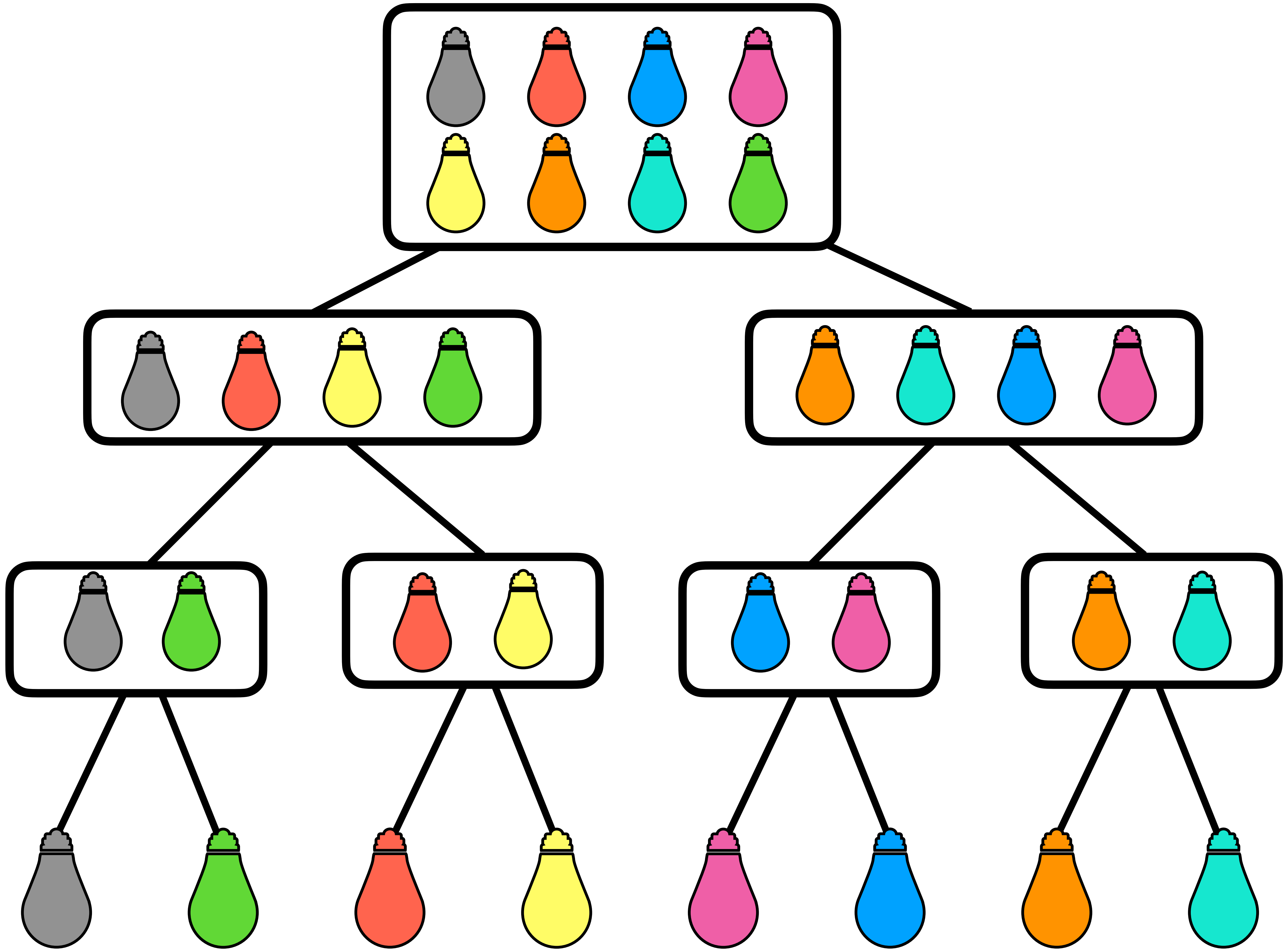
No representative lights



Stochastic LightCut

No representative lights

Randomly select lights



Light Tree

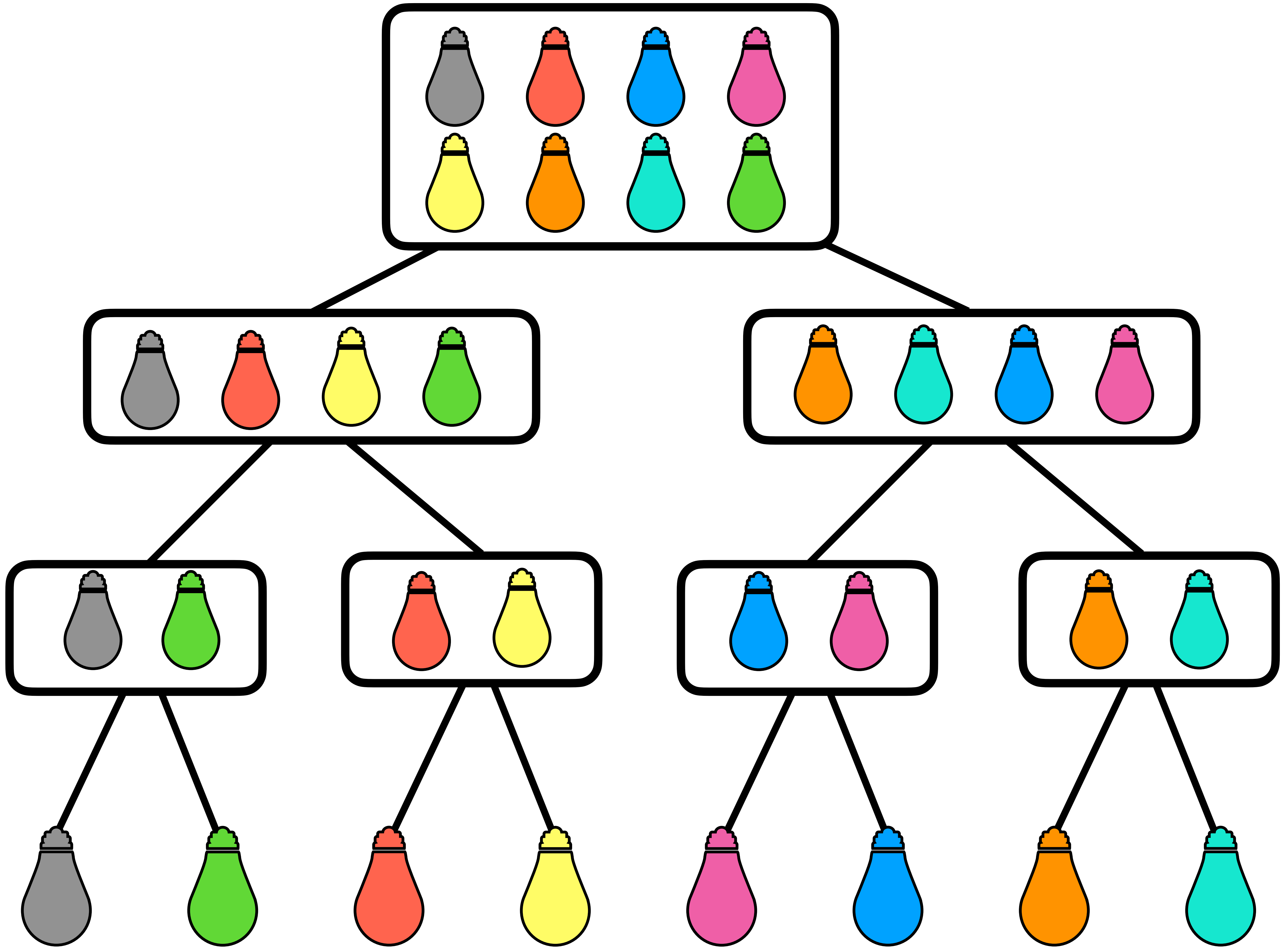
Stochastic LightCut

No sampling correlation
(i.e. no flickering)

Any type of light

(no representative light)

Light sample count can be limited



Light Tree

Direct Illumination
1400 light sources
Cem Yuksel [2019]


Direct Illumination
1400 light sources
Cem Yuksel [2019]

Lighting Grid Hierarchy

Only for Virtual Point Lights

Yuksel and Yuksel [2017]

Explosion Rendering

Challenges:

- Animated volumetric light source

- High variation in fire

- Shadows from a heavy smoke layer

Industry Practices

Smoke illumination by the fire of the explosion :

- No illumination
- 2D filtering in compositing
- 3D filtering / diffusion techniques

Environment illumination by the fire of the explosion :

- No illumination
- Few hand-placed lights to approximate illumination
- Some inferior representation of the fire volume as light source

Lighting Grid Hierarchy

- Convert **volume** to many **point lights**
- Build **Lighting Grid Hierarchy**
- Pre-compute volumetric **shadows**
- Add **multiple scattering**, if desired
- Finally, **render** using hierarchy

Lighting Grid Hierarchy

A multi-resolution representation of lighting

Temporary coherency:

- No clustering
- No binary decisions
- No sharp thresholds

Lighting Grid Hierarchy

Lighting Grid Hierarchy

Volume Data

Point Lights

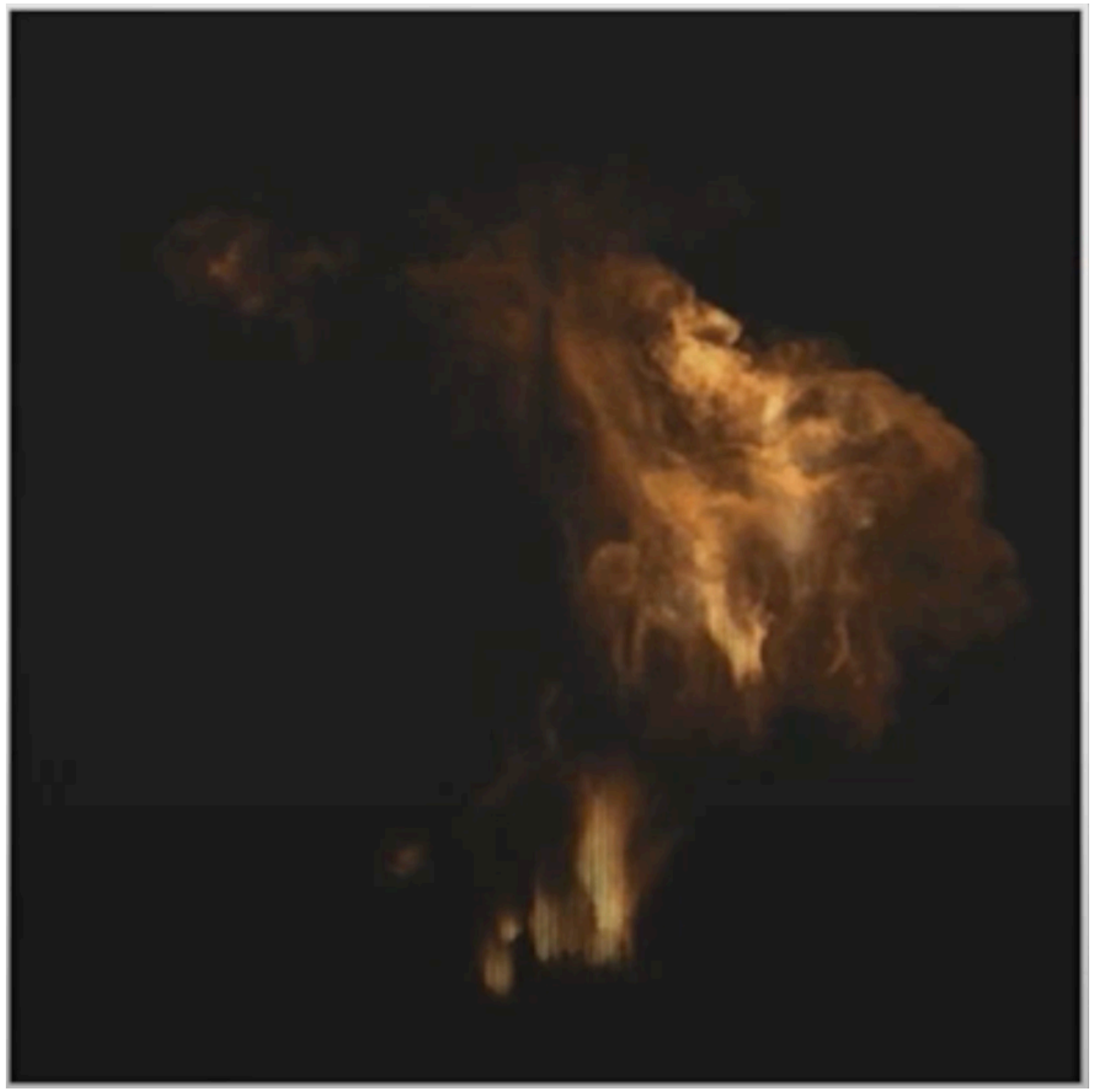
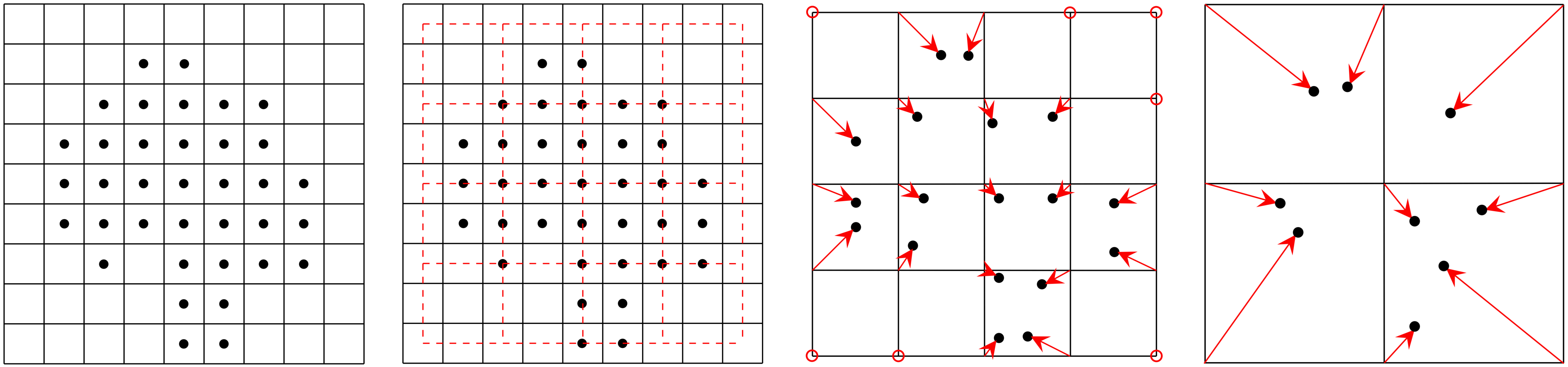


Image courtesy Yuksel and Yuksel [2017]

Generation



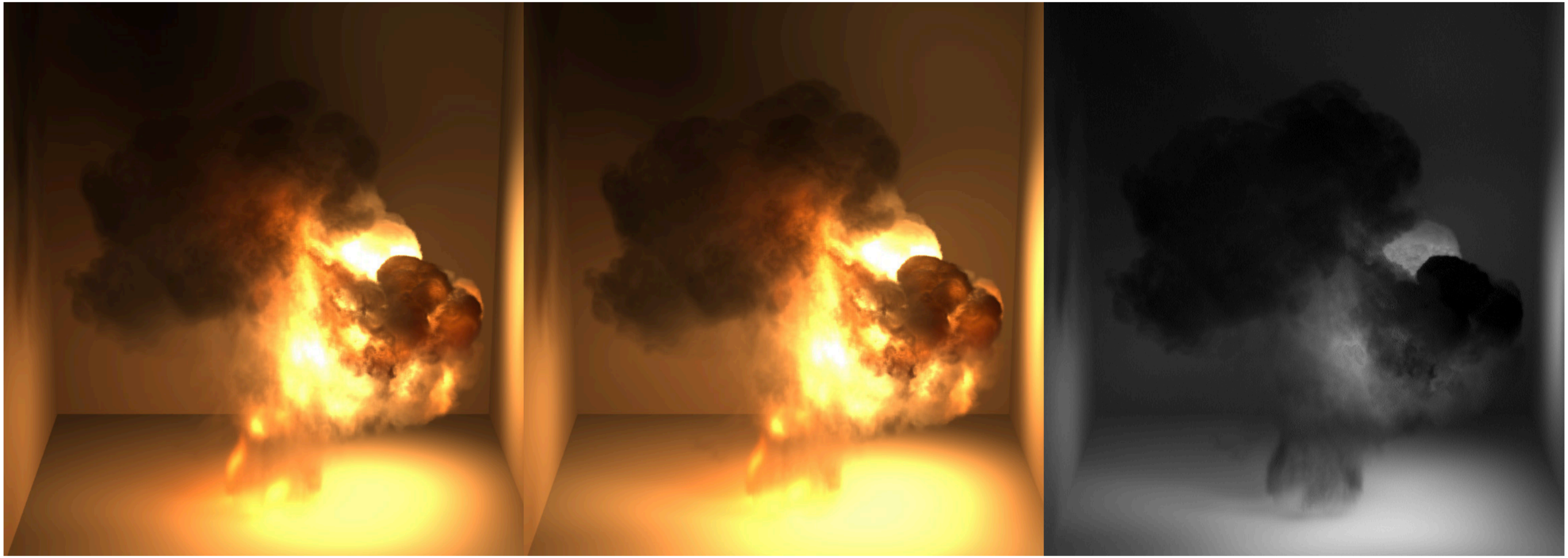
Simulation Grid 0-th level | Level-1 grid over simulation grid | Level-1 grid | Level-2 grid

Lighting Grid Hierarchy

Blending Function

Shading

Multiple Scattering



Single Scattering Multiple Scattering Luminance Diff. ×2

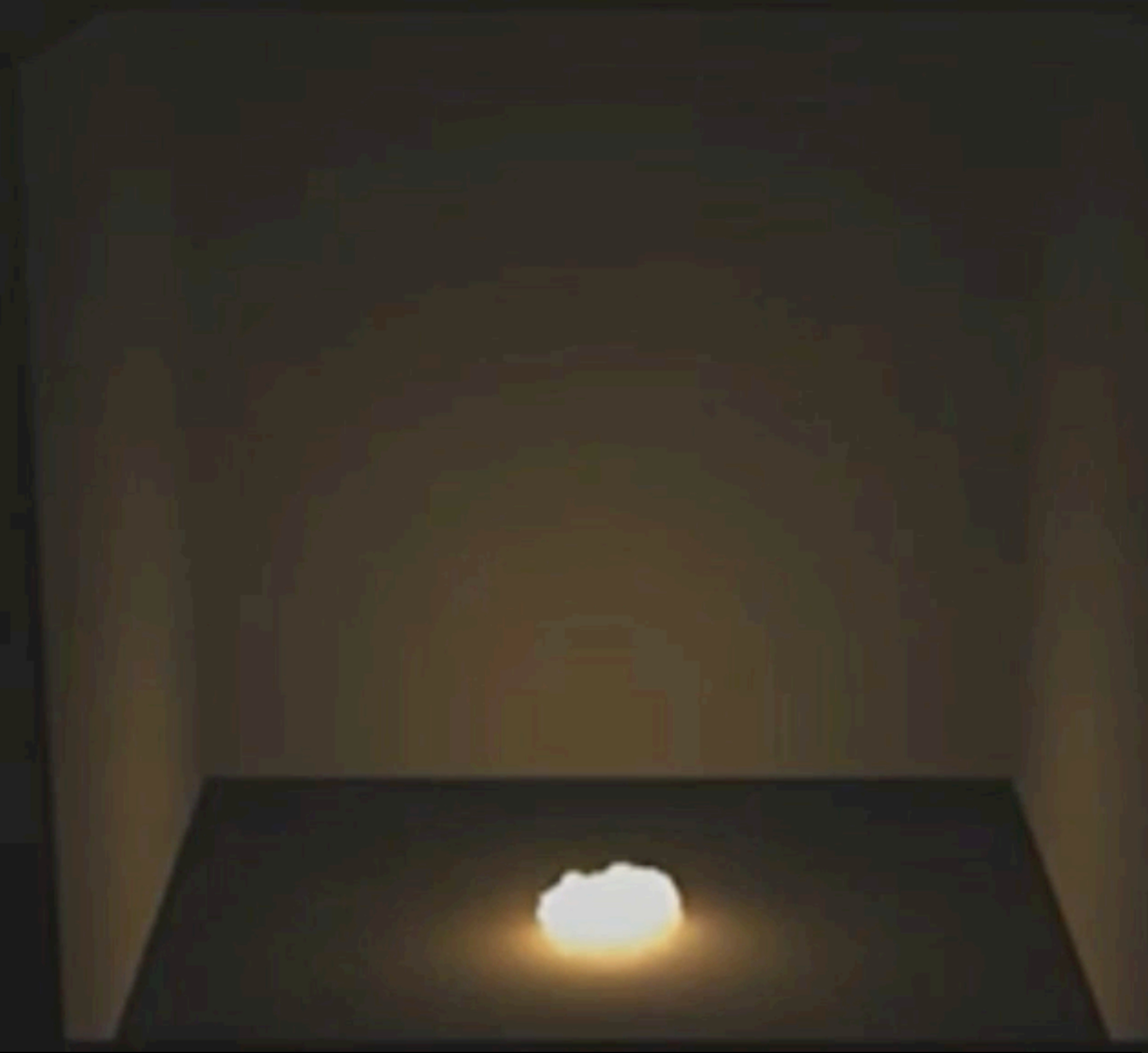
Yuksel and Yuksel [2017]

Path Tracing

Lighting Grid Hierarchchy

Yuksel and Yuksel [2017]

Path Tracing



Lighting Grid Hierarchcy

Yuksel and Yuksel [2017]

Yuksel and Yuksel [2017]

Acknowledgements

We thank all the people who make their work available online which helped shape these slides.

Special thanks to Walter et al., Hasan et al., Carsten Dachsbacher et al., Jan Novak et al. for making their EG STAR Many-Light methods slides online, Can Yuksel and Cem Yuksel for making their slides and videos available online.

Scalable Realistic Rendering with Many-Light Methods [Dachsbacher et al. 2013]

Virtual Ray Lights for Rendering Scenes with Participating Media [Jan Novak et al. 2012]

LightCuts [Walter et al. 2005]

Stochastic LightCuts [Cem Yuksel 2019]