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PHOTON SURFACES FOR ROBUST, UNBIASED VOLUMETRIC DENSITY ESTIMATION

Xi Deng*
Shaojie Jiao*
Benedikt Bitterli
Wojciech Jarosz

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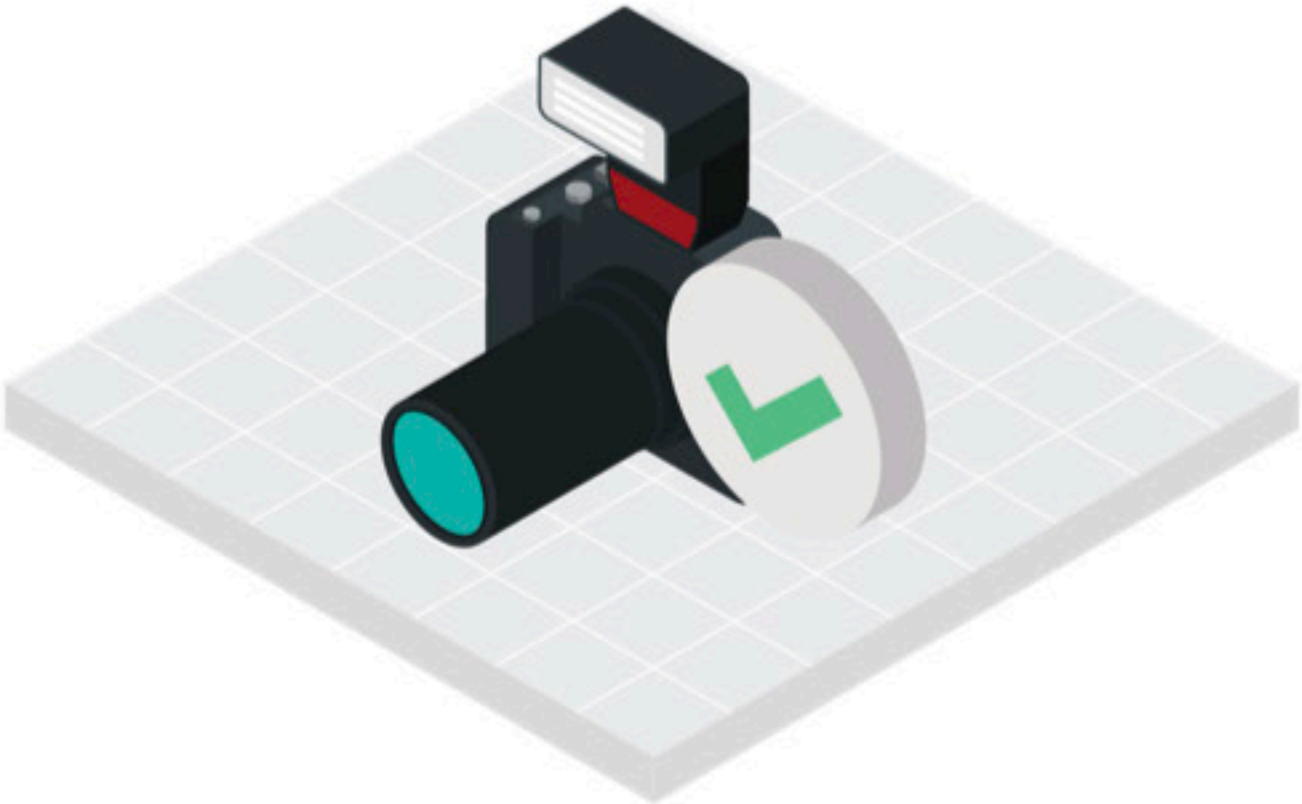

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DARTMOUTH
VISUAL COMPUTING LAB

Objective

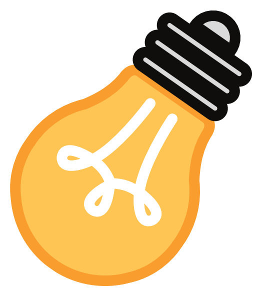




Problem setup

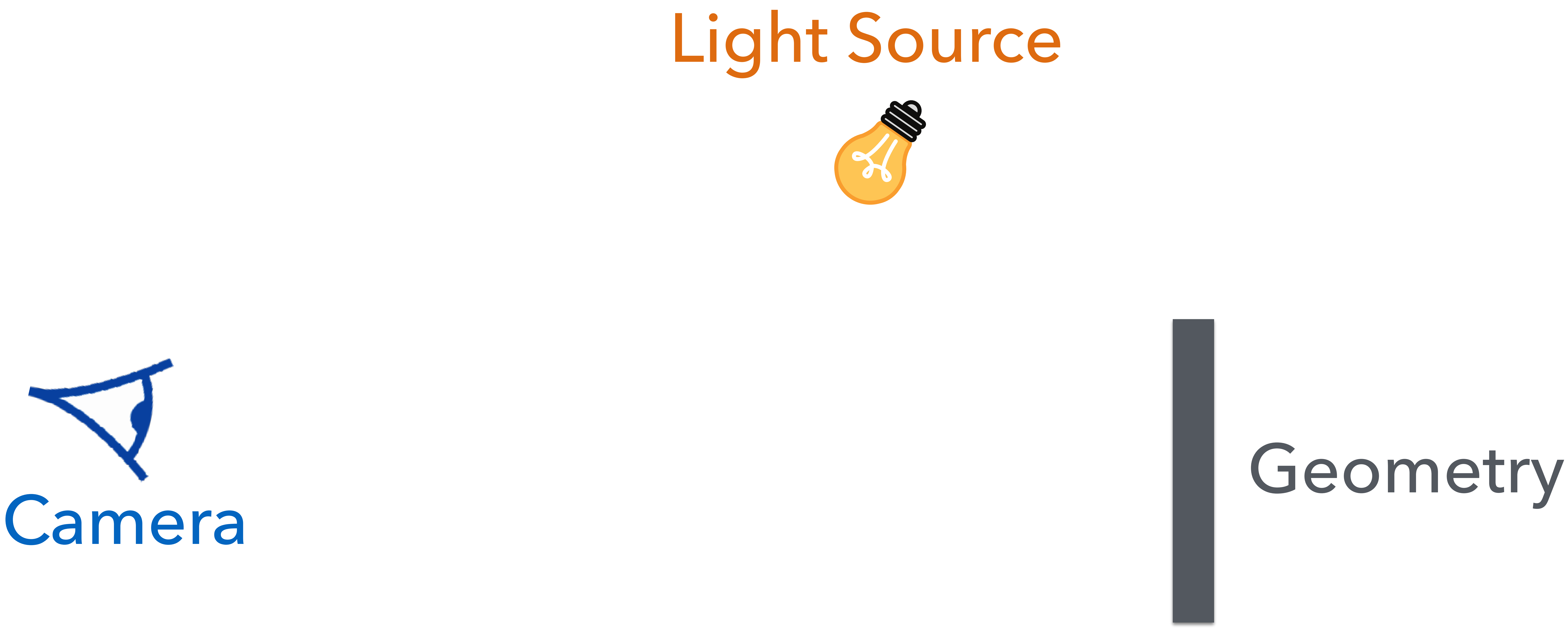
Problem setup

Light Source

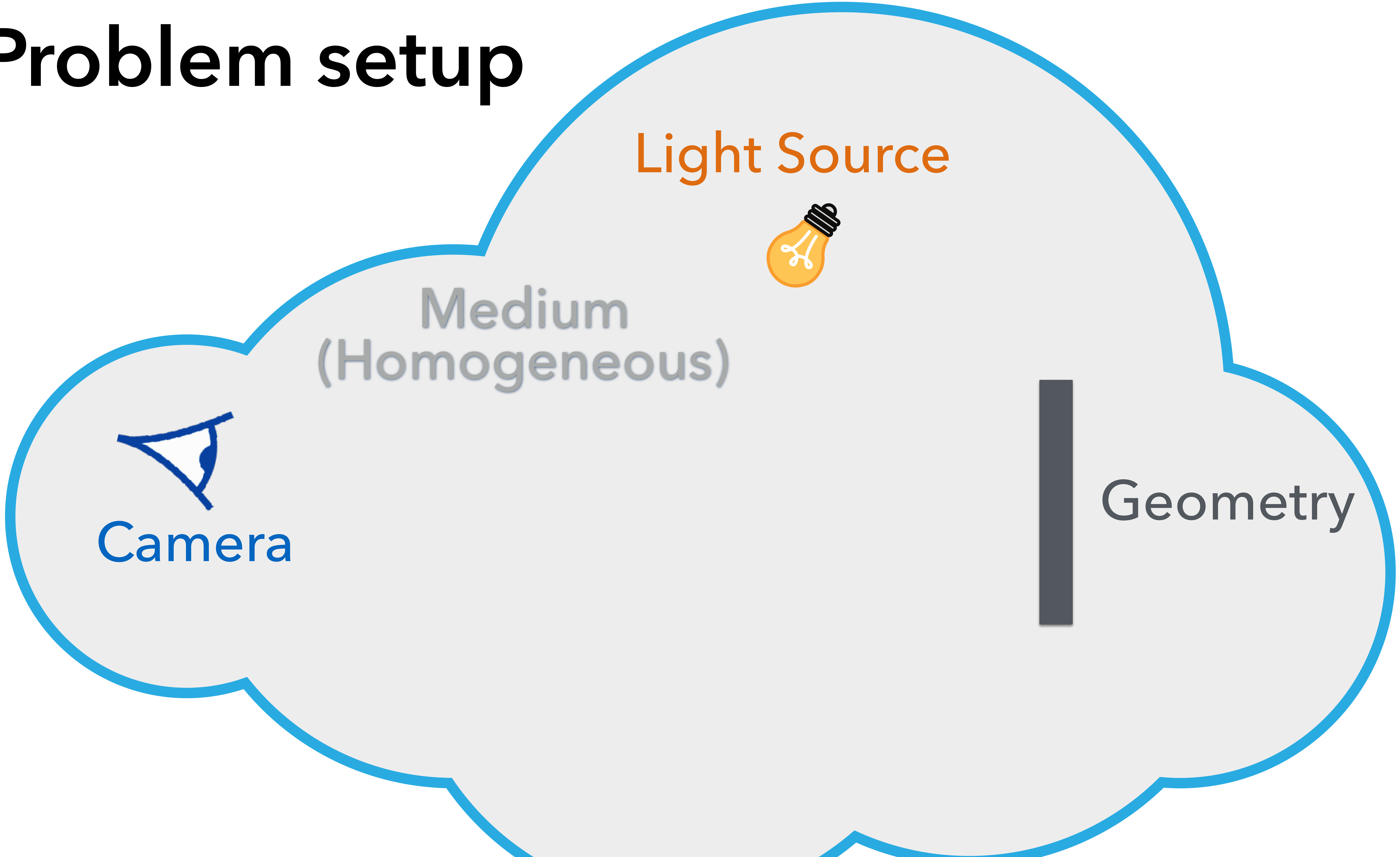


Camera

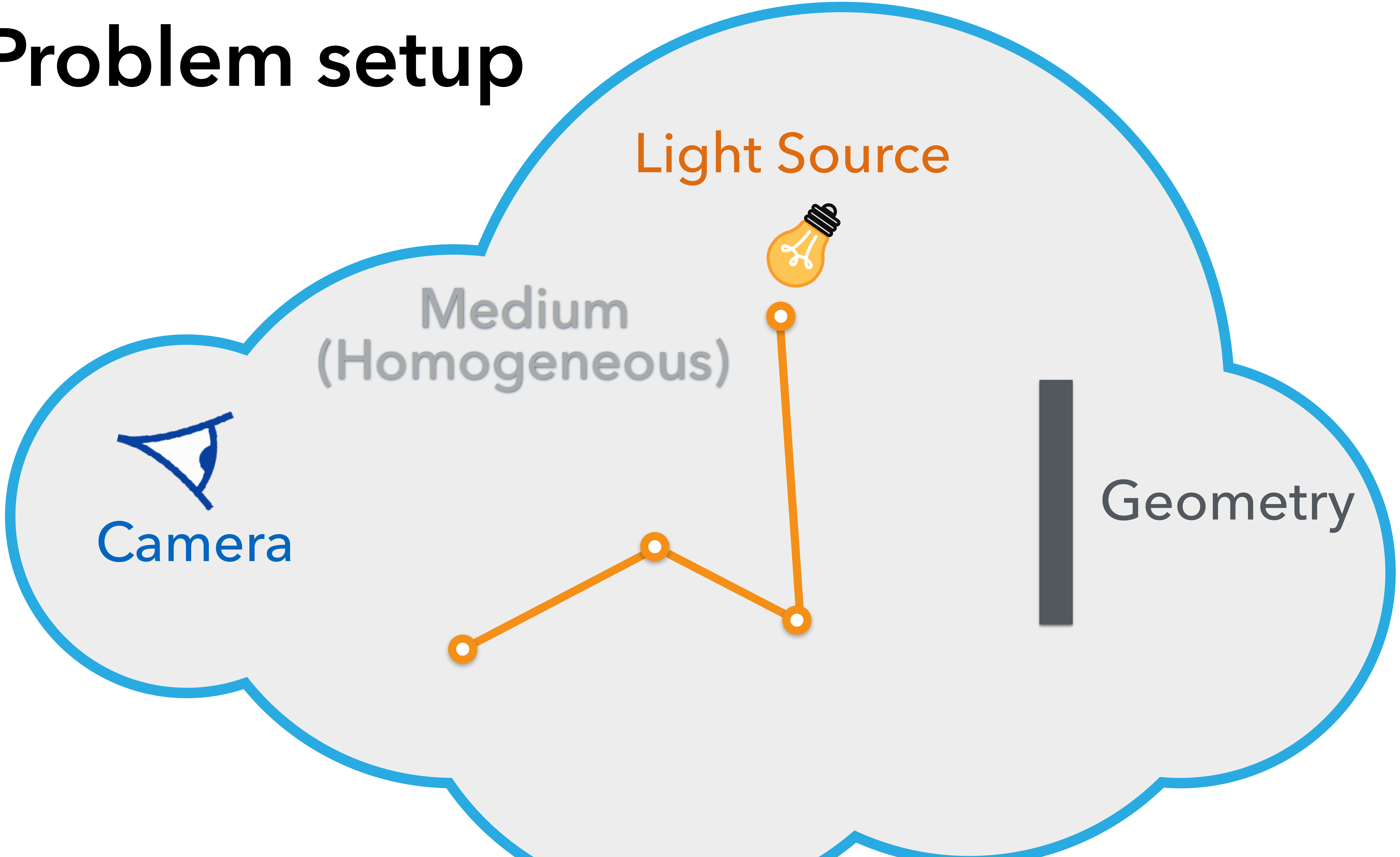
Problem setup



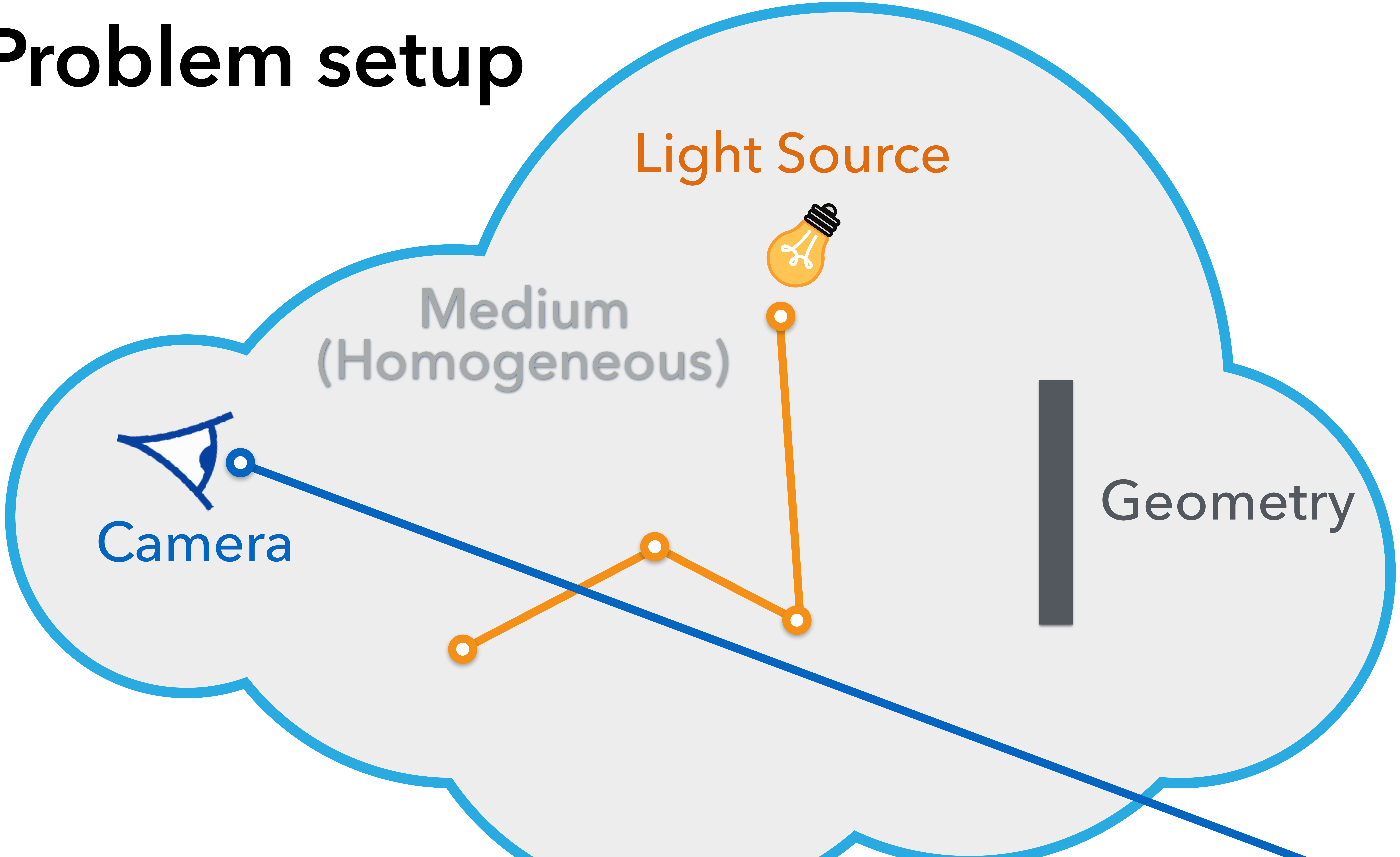
Problem setup



Problem setup



Problem setup

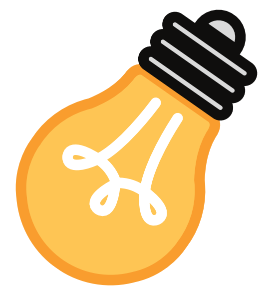


Full Light Transport

Previous Work

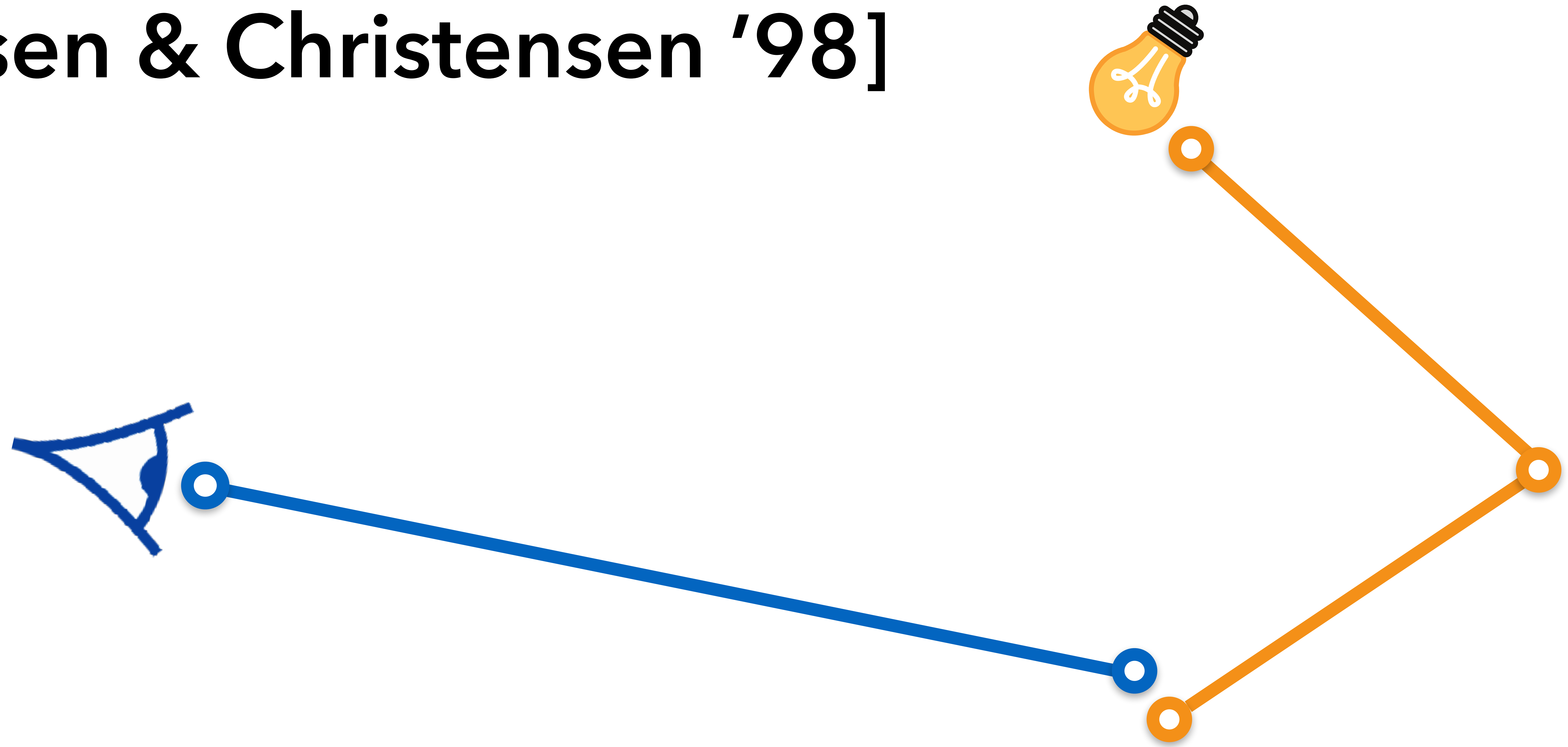
Volumetric photon mapping

[Jensen & Christensen ’98]



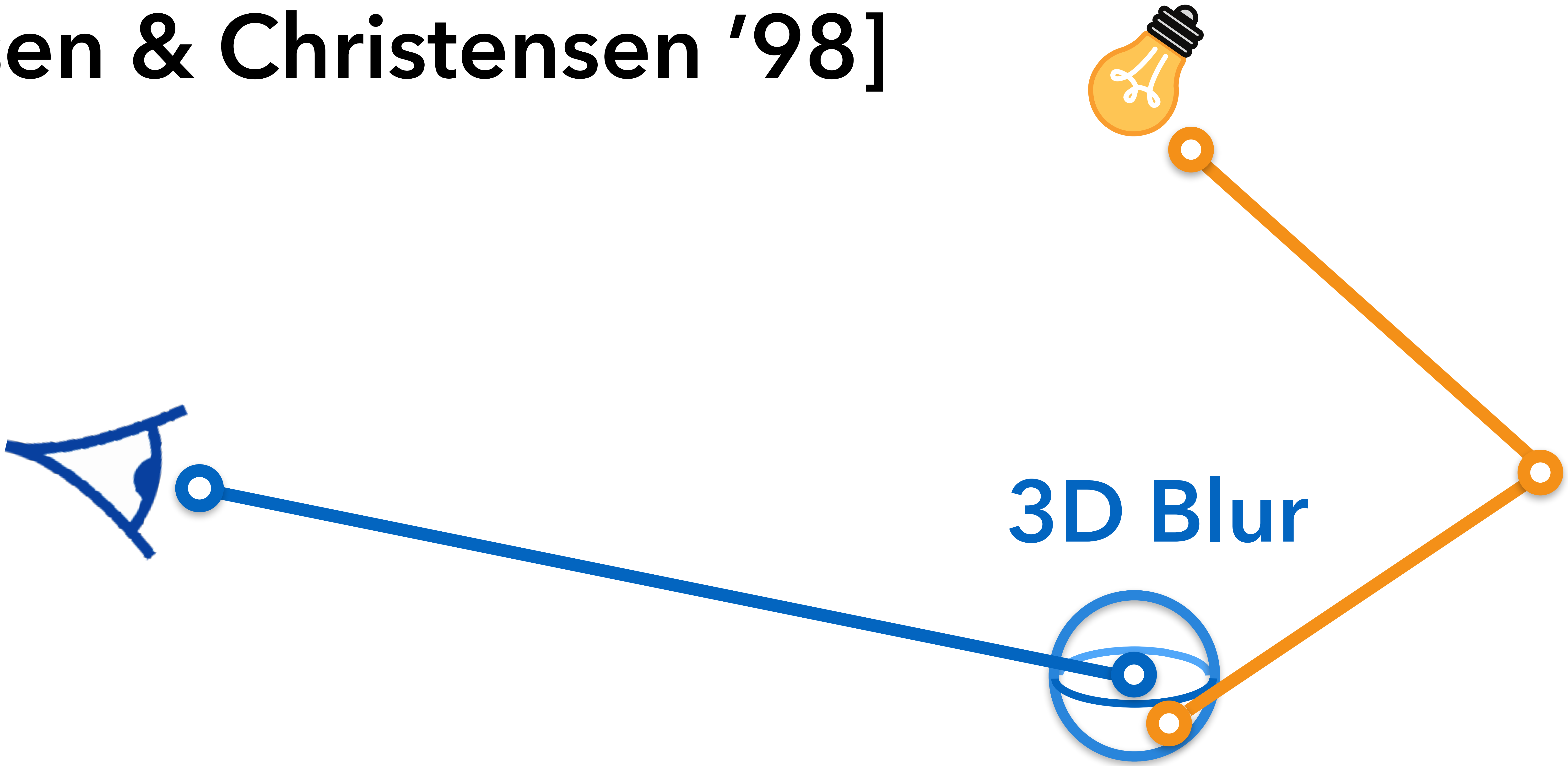
Volumetric photon mapping

[Jensen & Christensen '98]



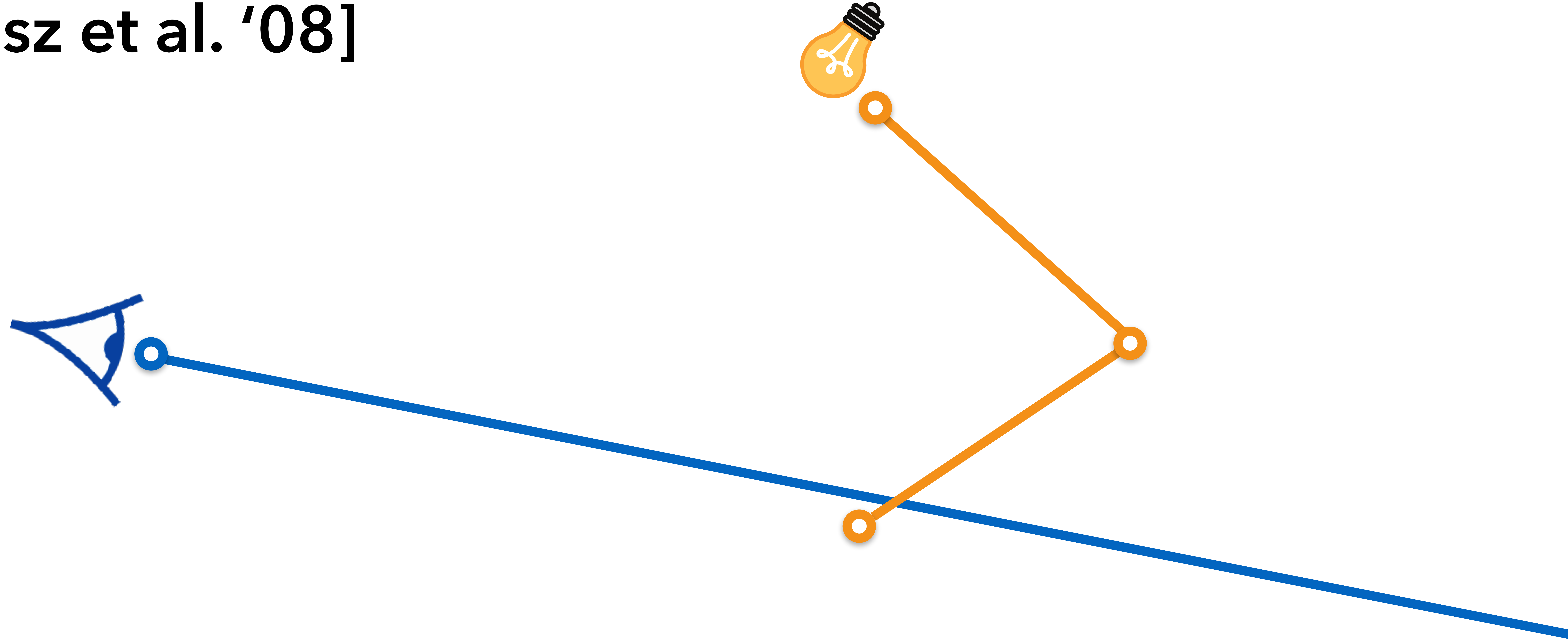
Volumetric photon mapping

[Jensen & Christensen '98]



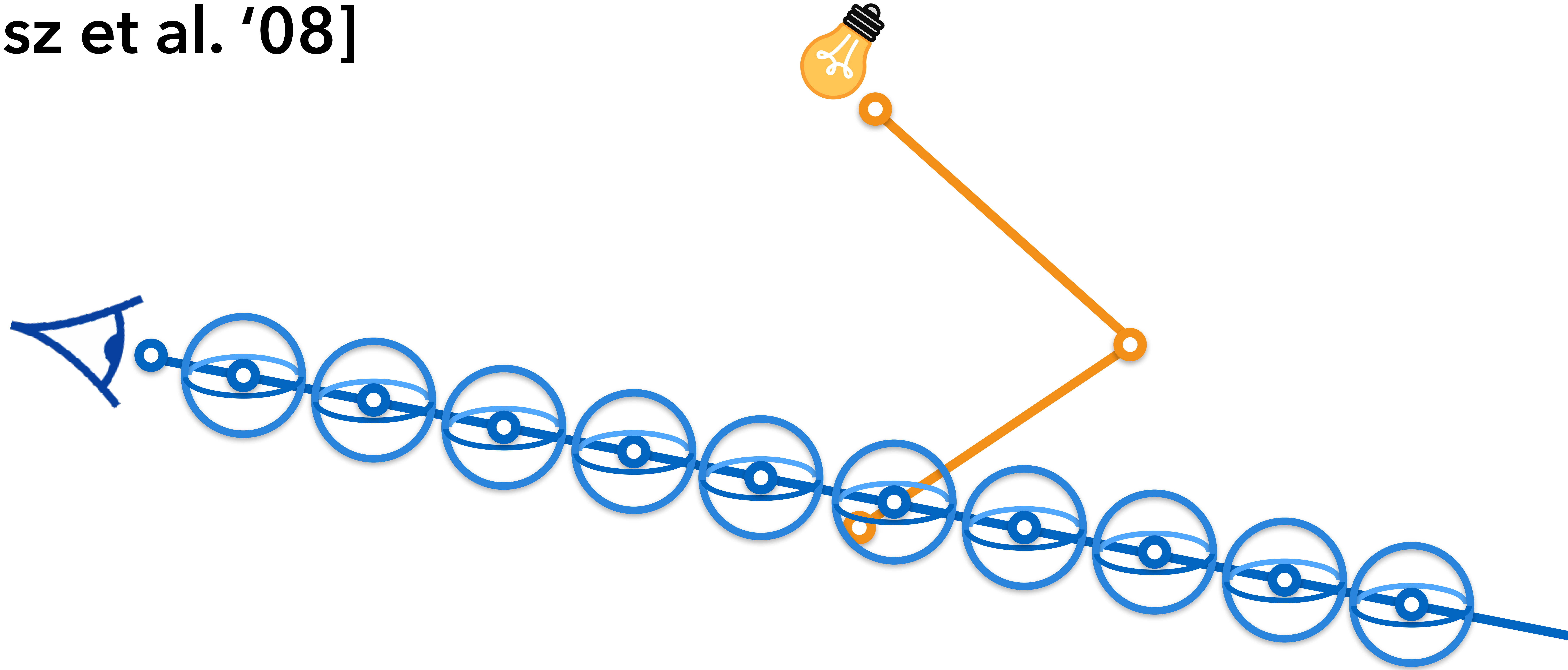
Sensor beam

[Jarosz et al. '08]



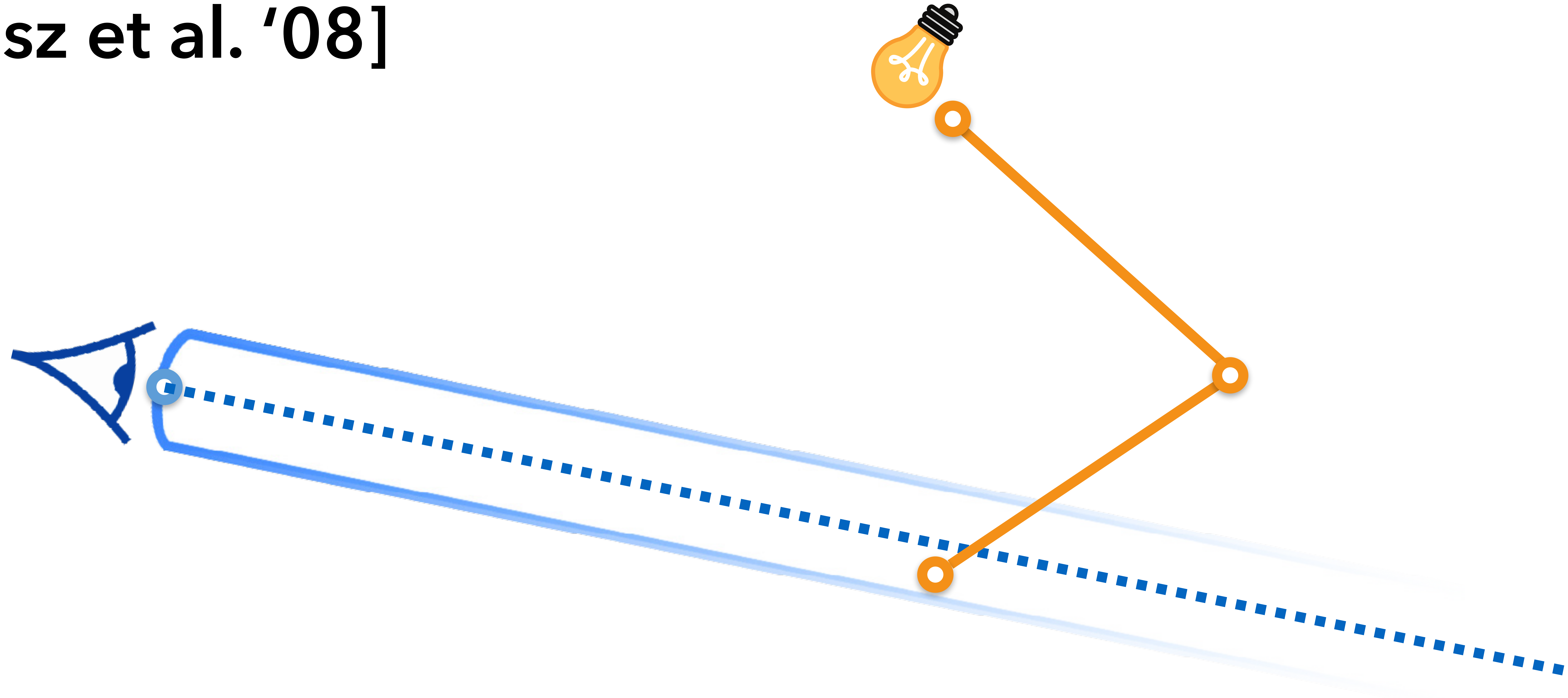
Sensor beam

[Jarosz et al. '08]



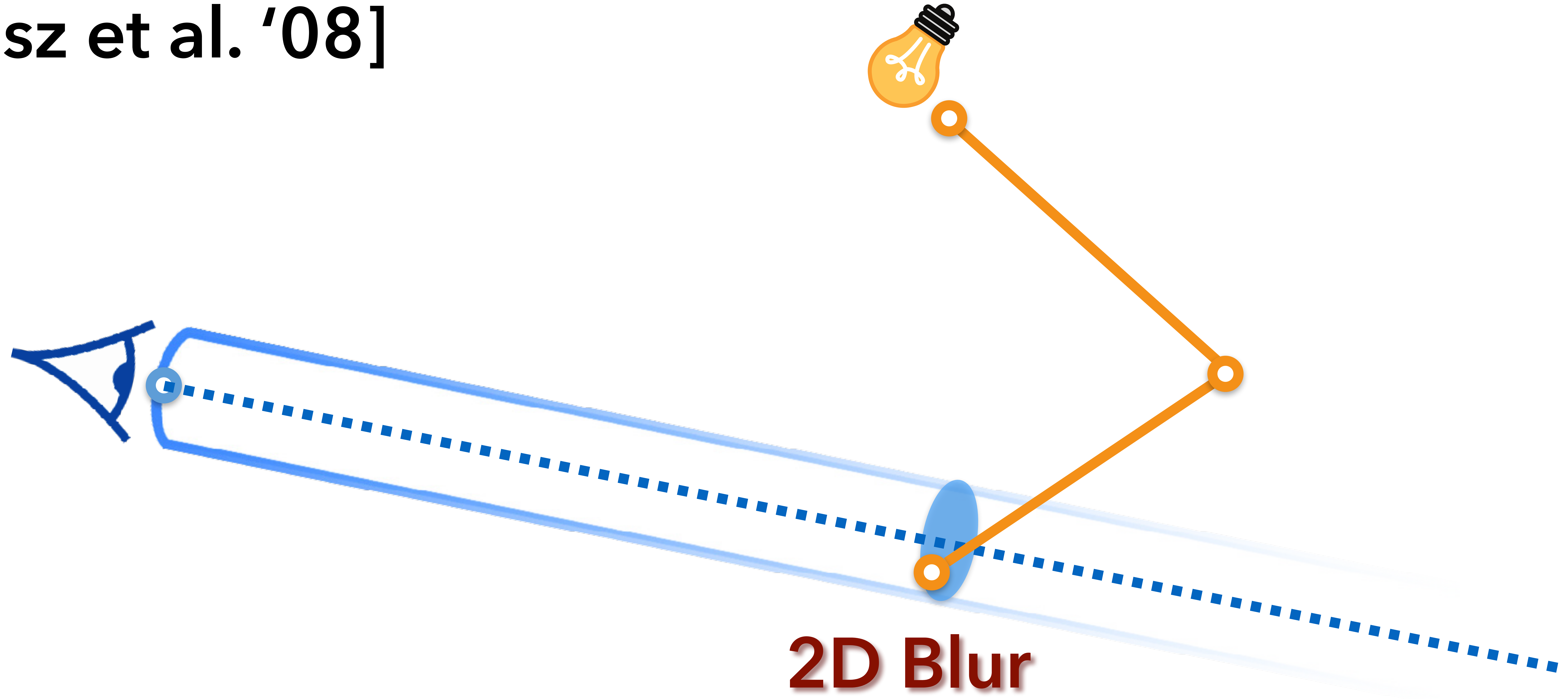
Sensor beam

[Jarosz et al. '08]



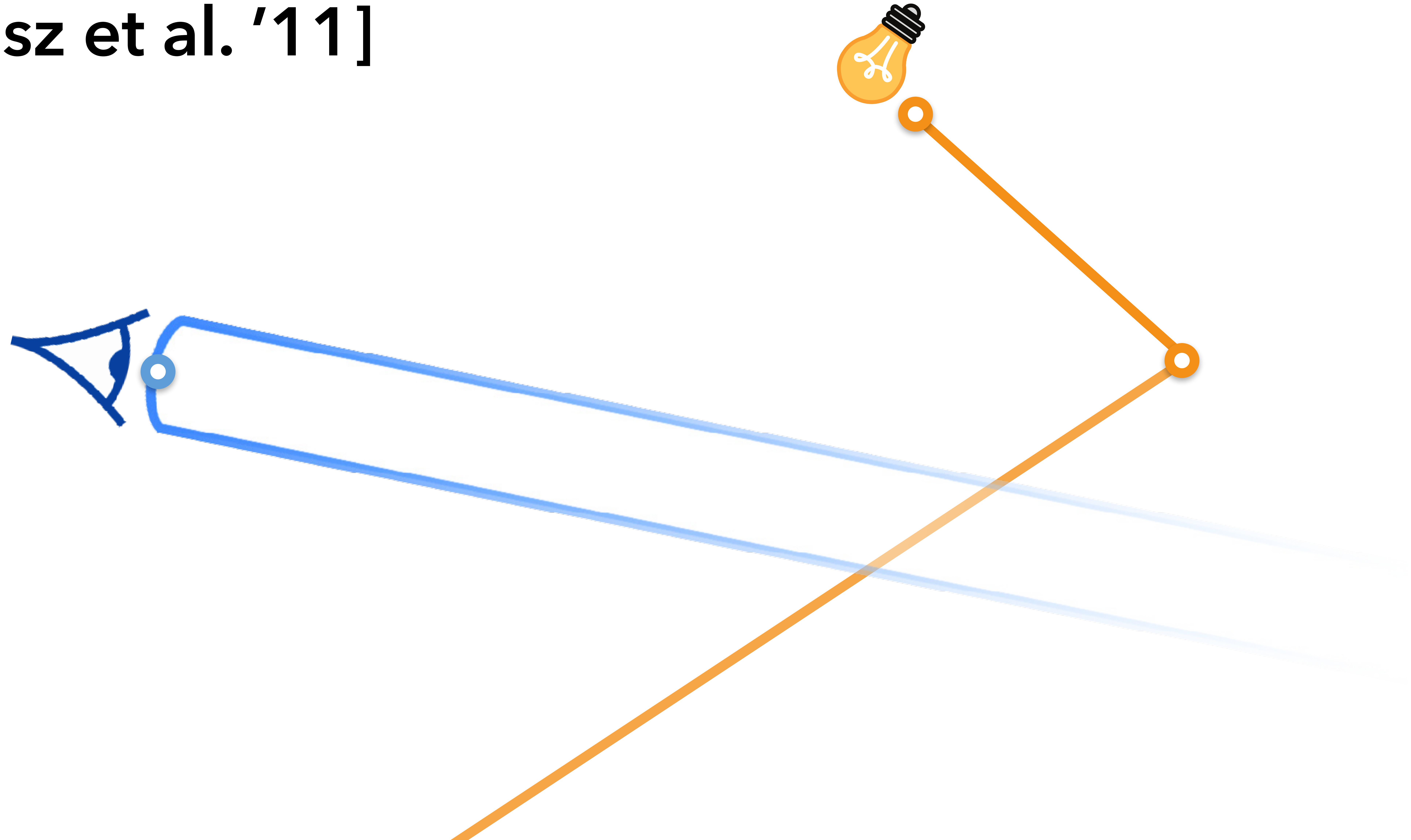
Sensor beam

[Jarosz et al. '08]



Photon beam

[Jarosz et al. '11]



Photon beam

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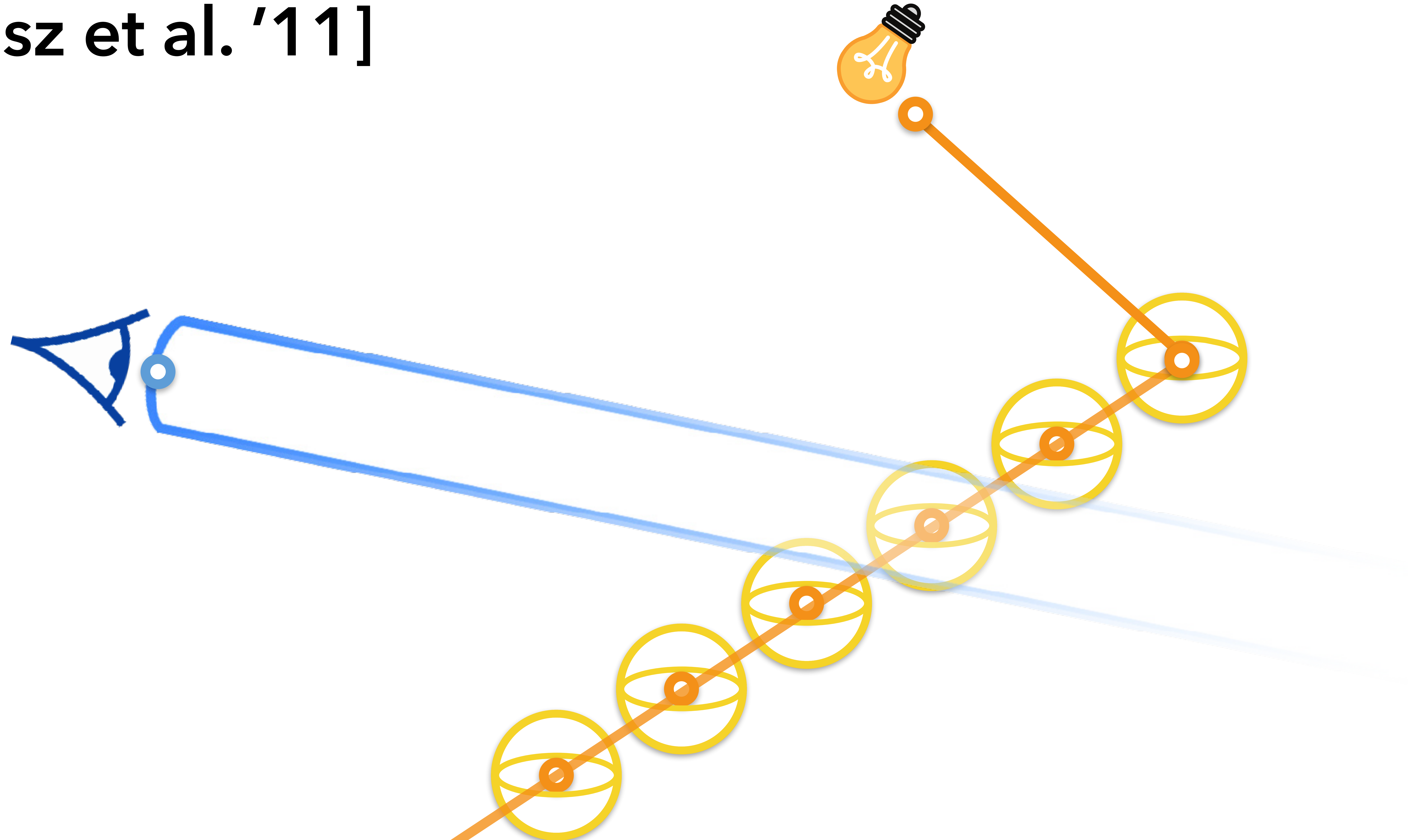
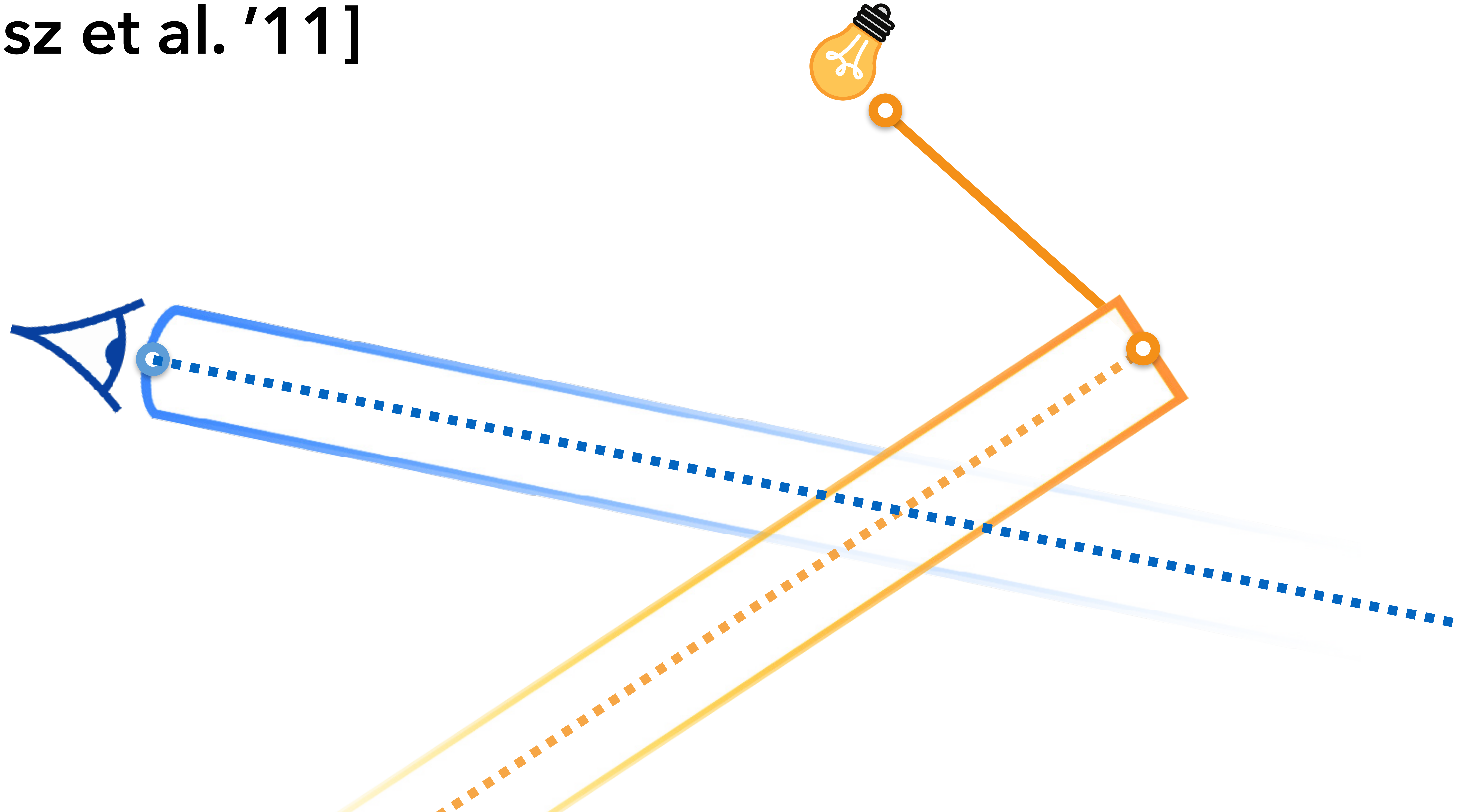


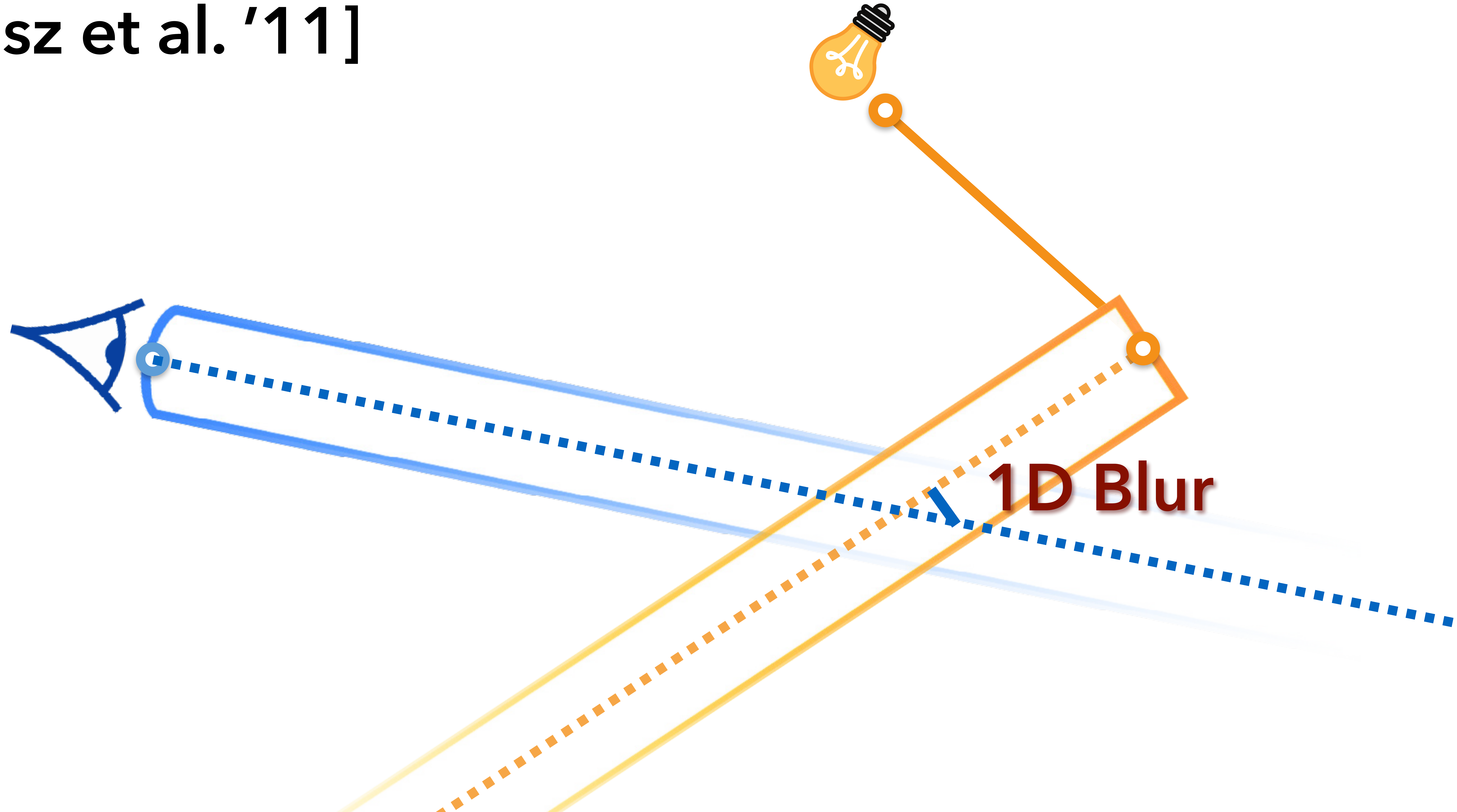
Photon beam

[Jarosz et al. '11]



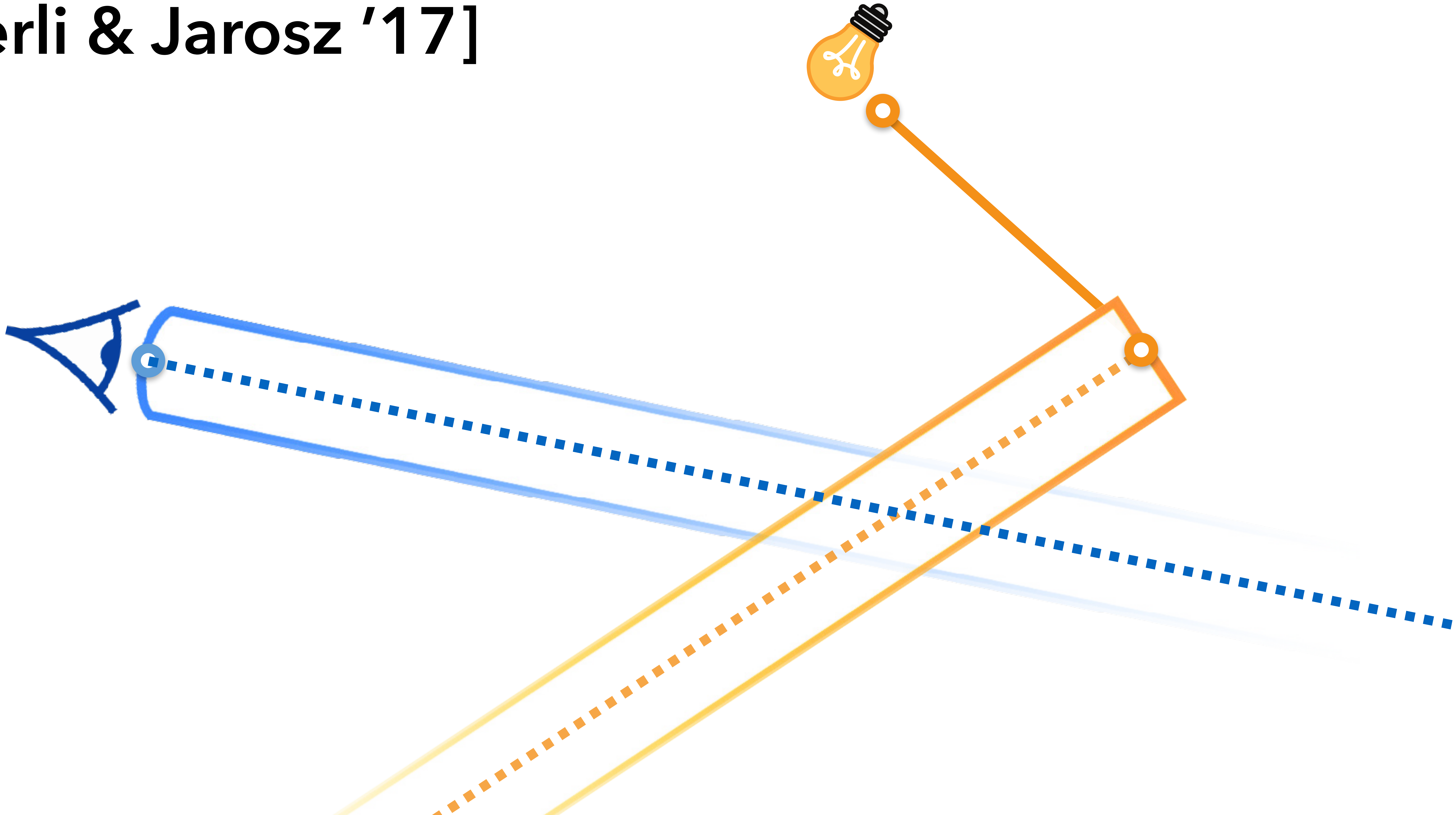
Photon beam

[Jarosz et al. '11]



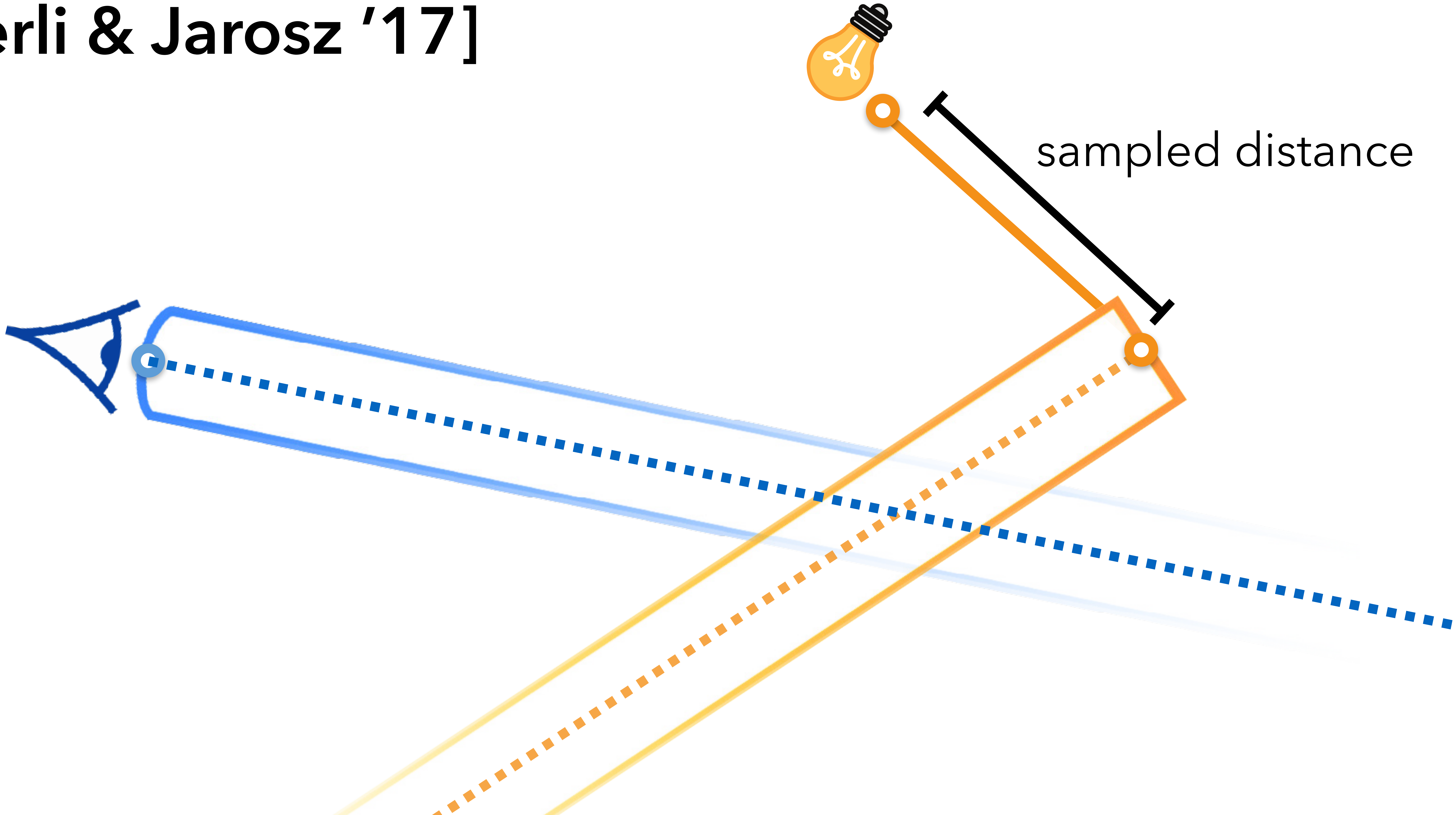
Photon beam

[Bitterli & Jarosz '17]



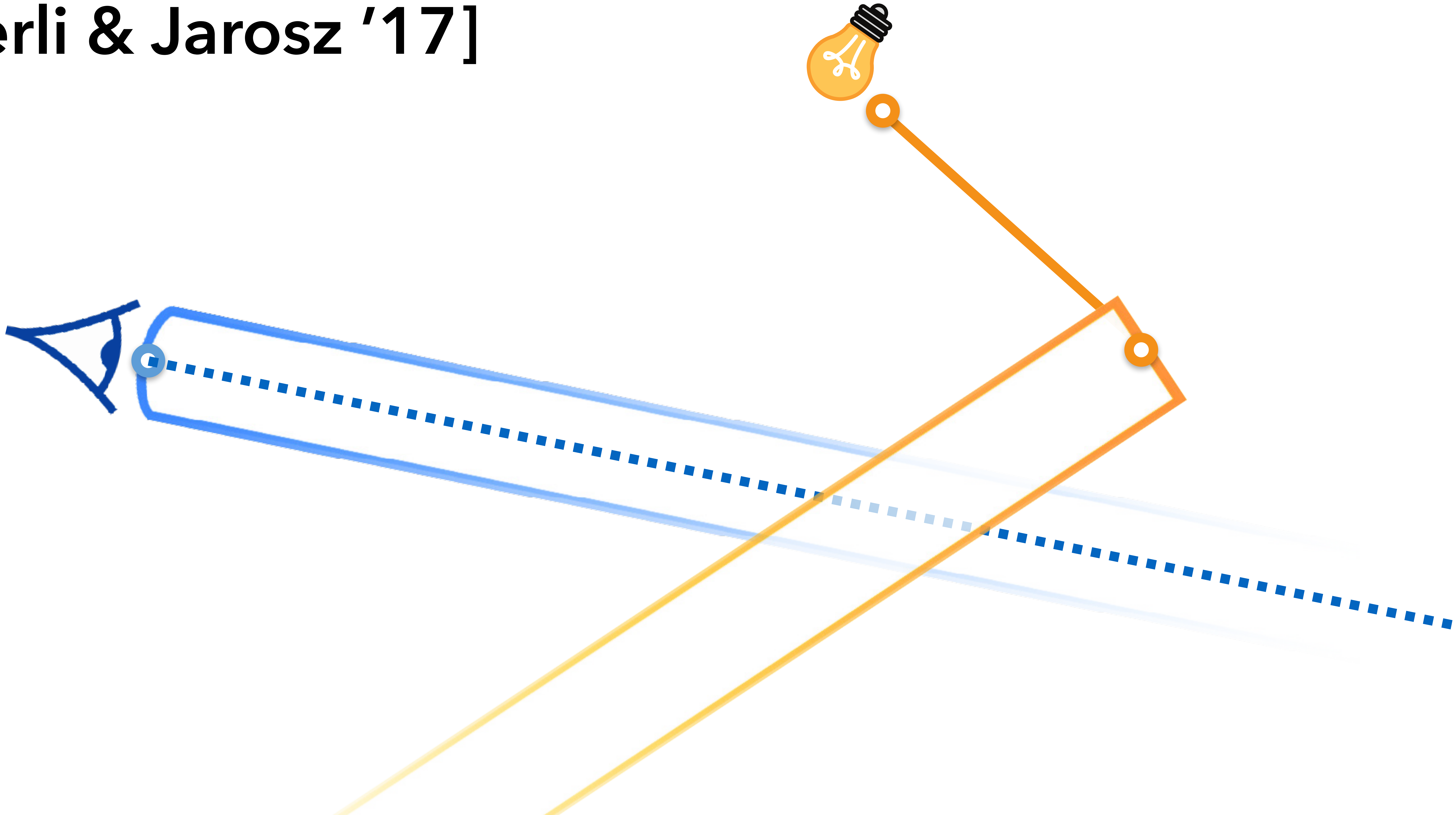
Photon beam

[Bitterli & Jarosz '17]



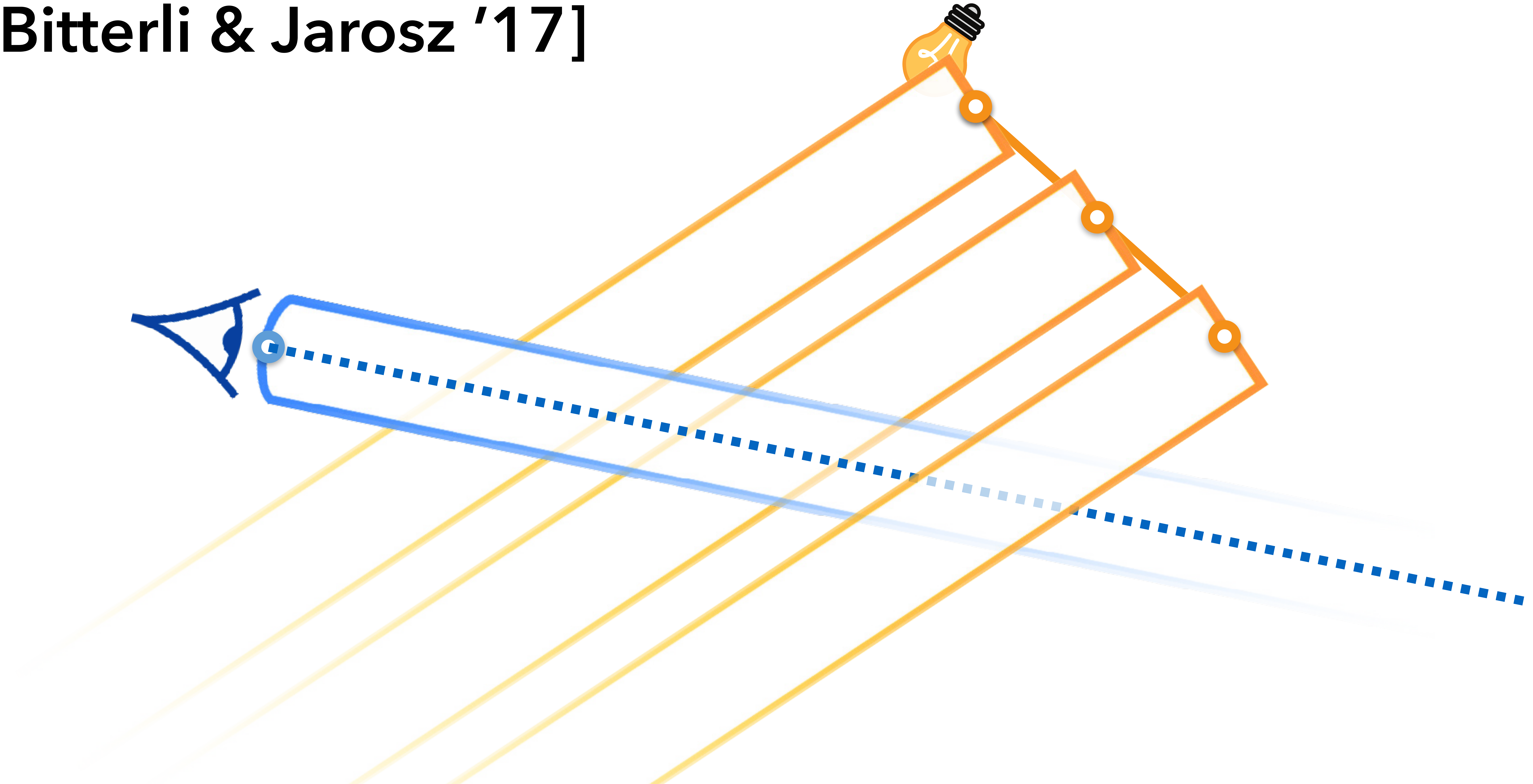
Photon plane

[Bitterli & Jarosz ’17]



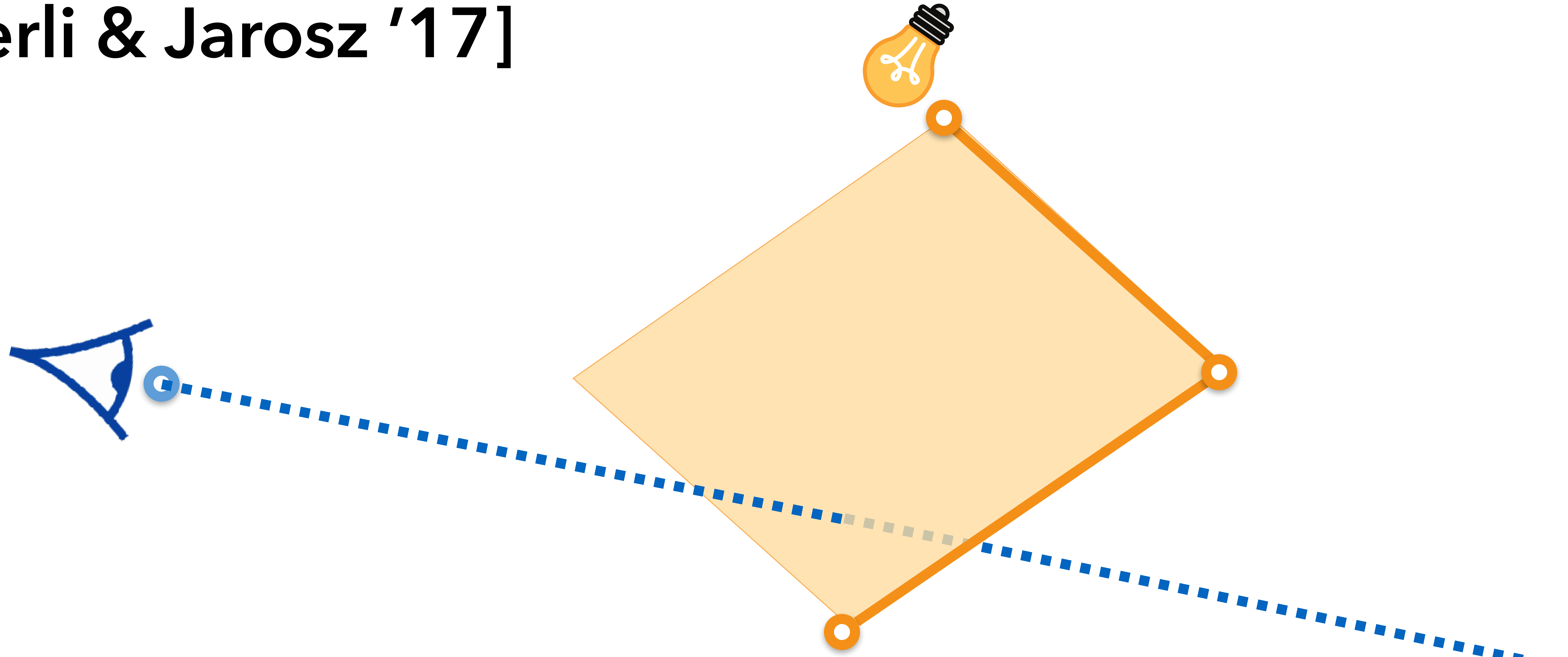
Photon plane

[Bitterli & Jarosz ’17]



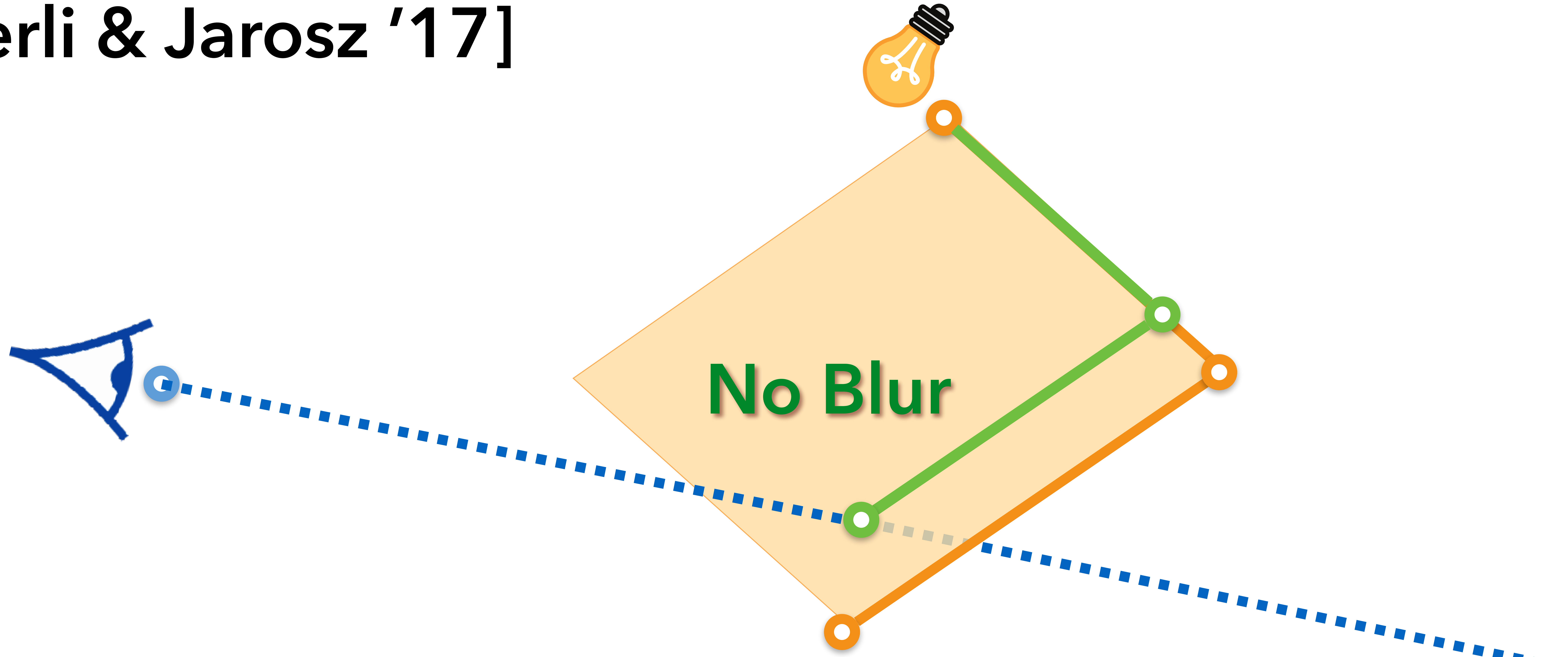
Photon plane

[Bitterli & Jarosz '17]



Photon plane

[Bitterli & Jarosz '17]




Photon Points
(biased)
Photon Beams
(biased)
Photon Planes
(unbiased)


Photon Points
(biased)
Photon Beams
(biased)
Photon Planes
(unbiased)


Photon Points
(biased)
Photon Beams
(biased)
Photon Planes
(unbiased)


Photon Points
(biased)
Photon Beams
(biased)
Photon Planes
(unbiased)

Equal-time comparison

The limitations of photon planes

[Bitterli and Jarosz. ’17]

The limitations of photon planes

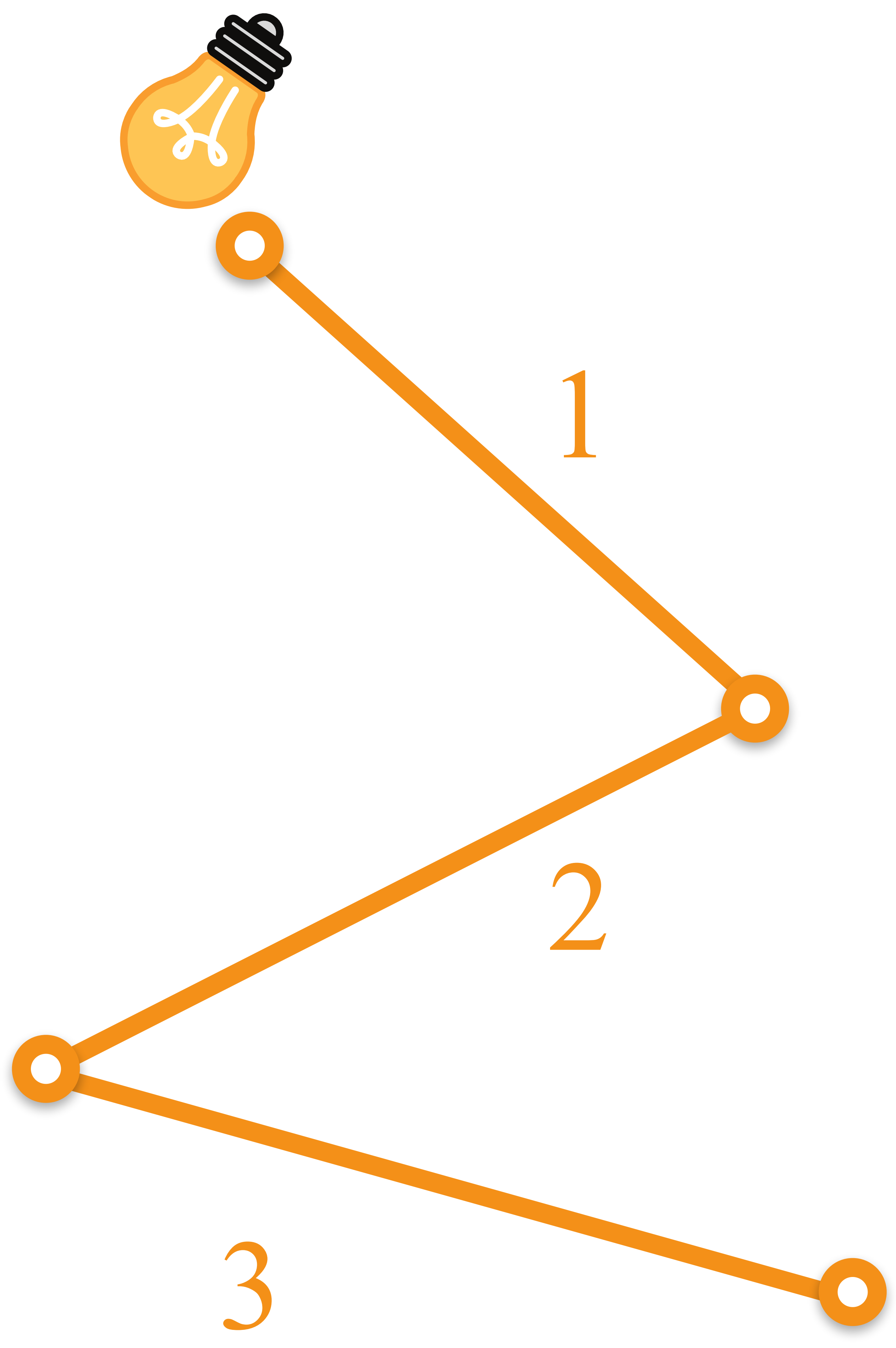
[Bitterli and Jarosz. '17]

The limitations of photon planes

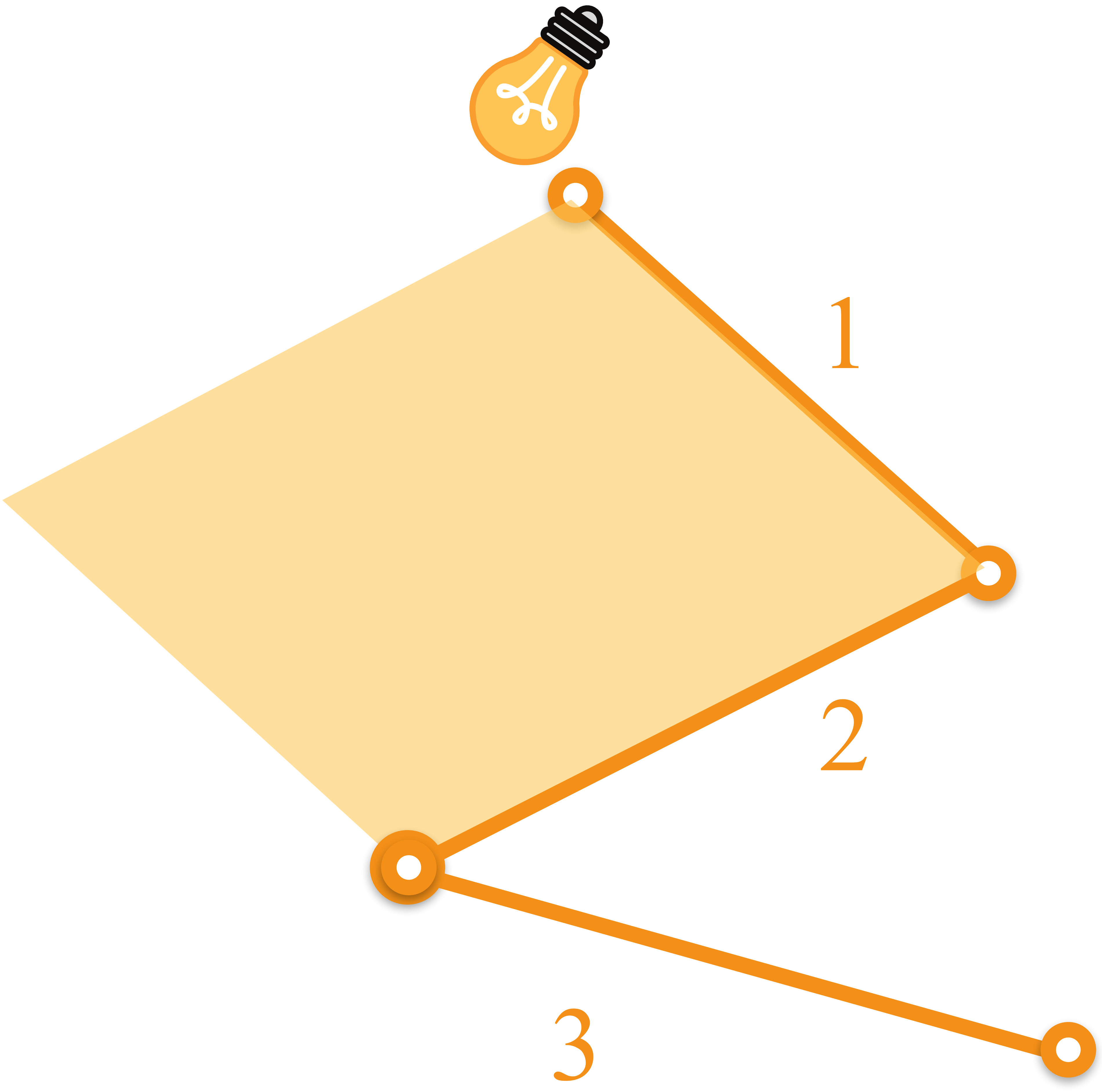
Singularities

[Bitterli and Jarosz. ’17]

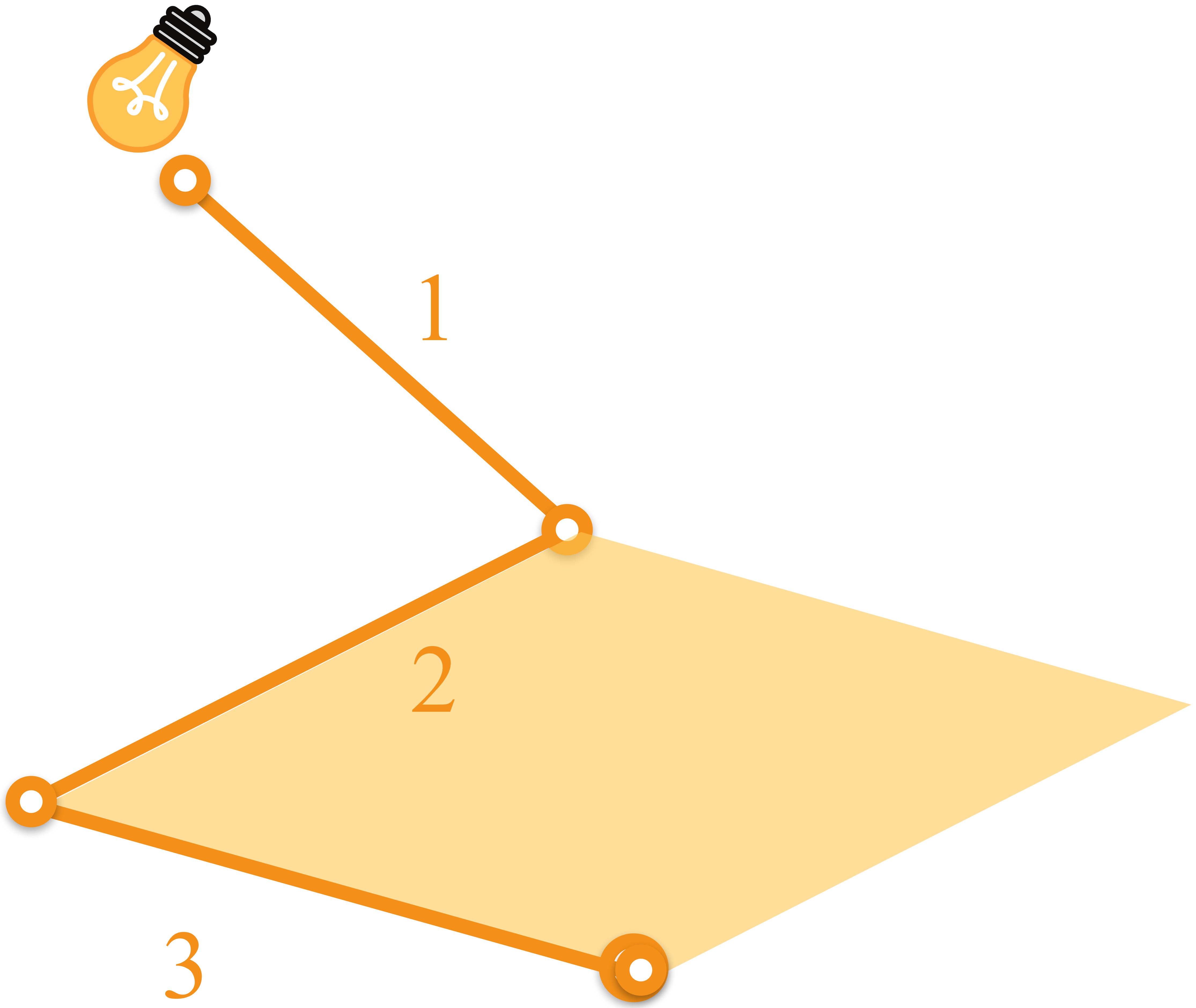
The limitations of photon planes



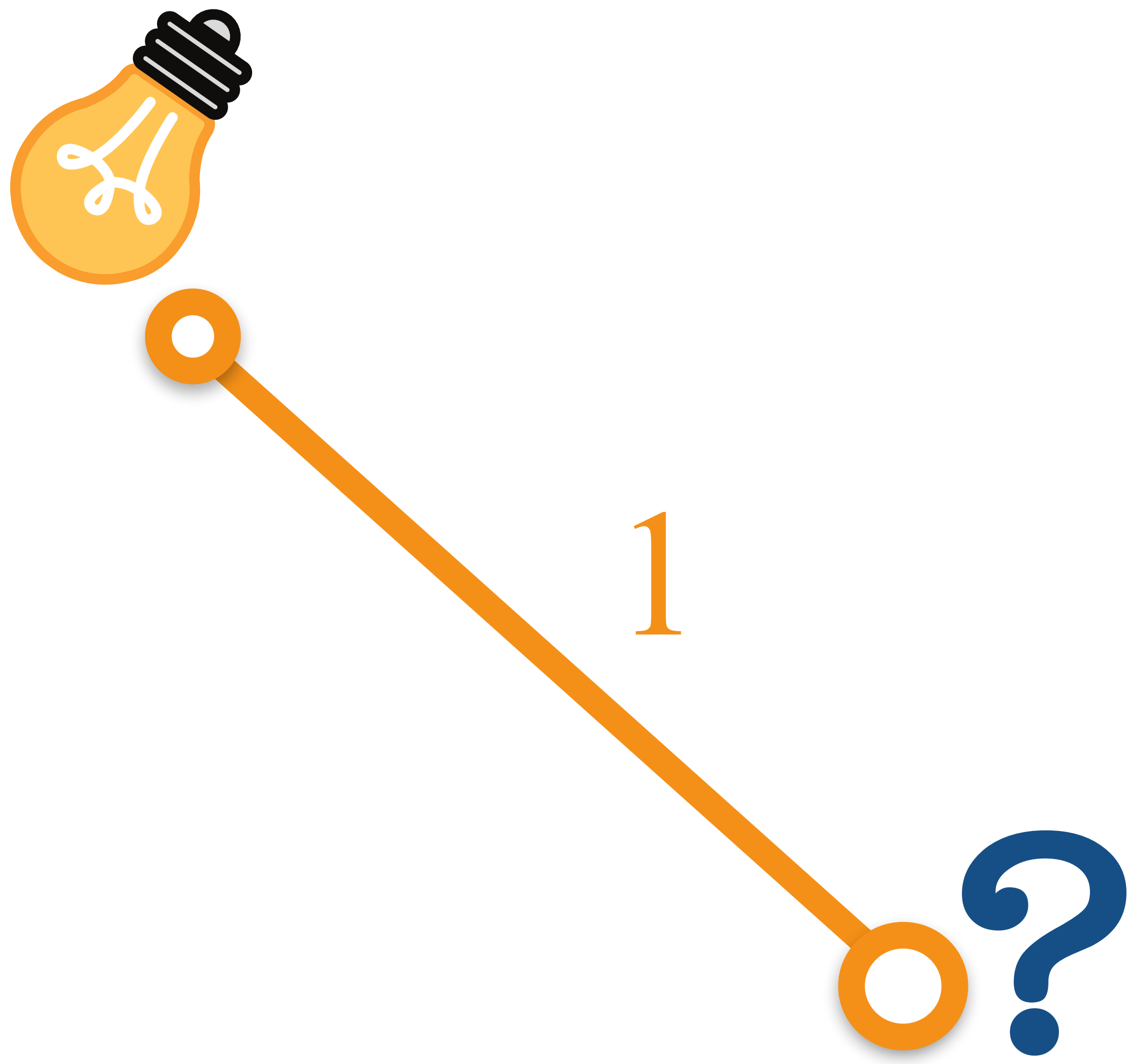
The limitations of photon planes



The limitations of photon planes

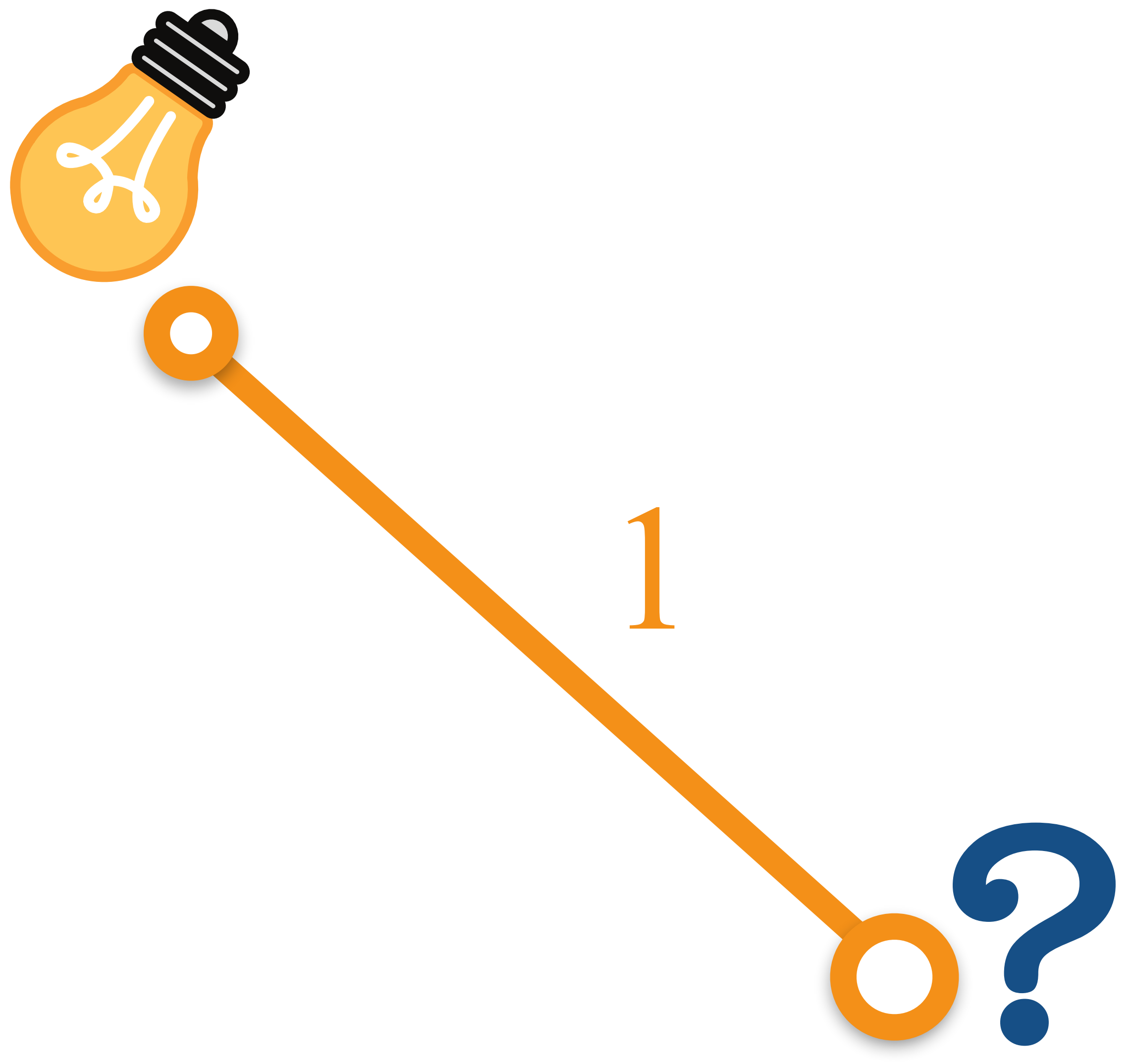


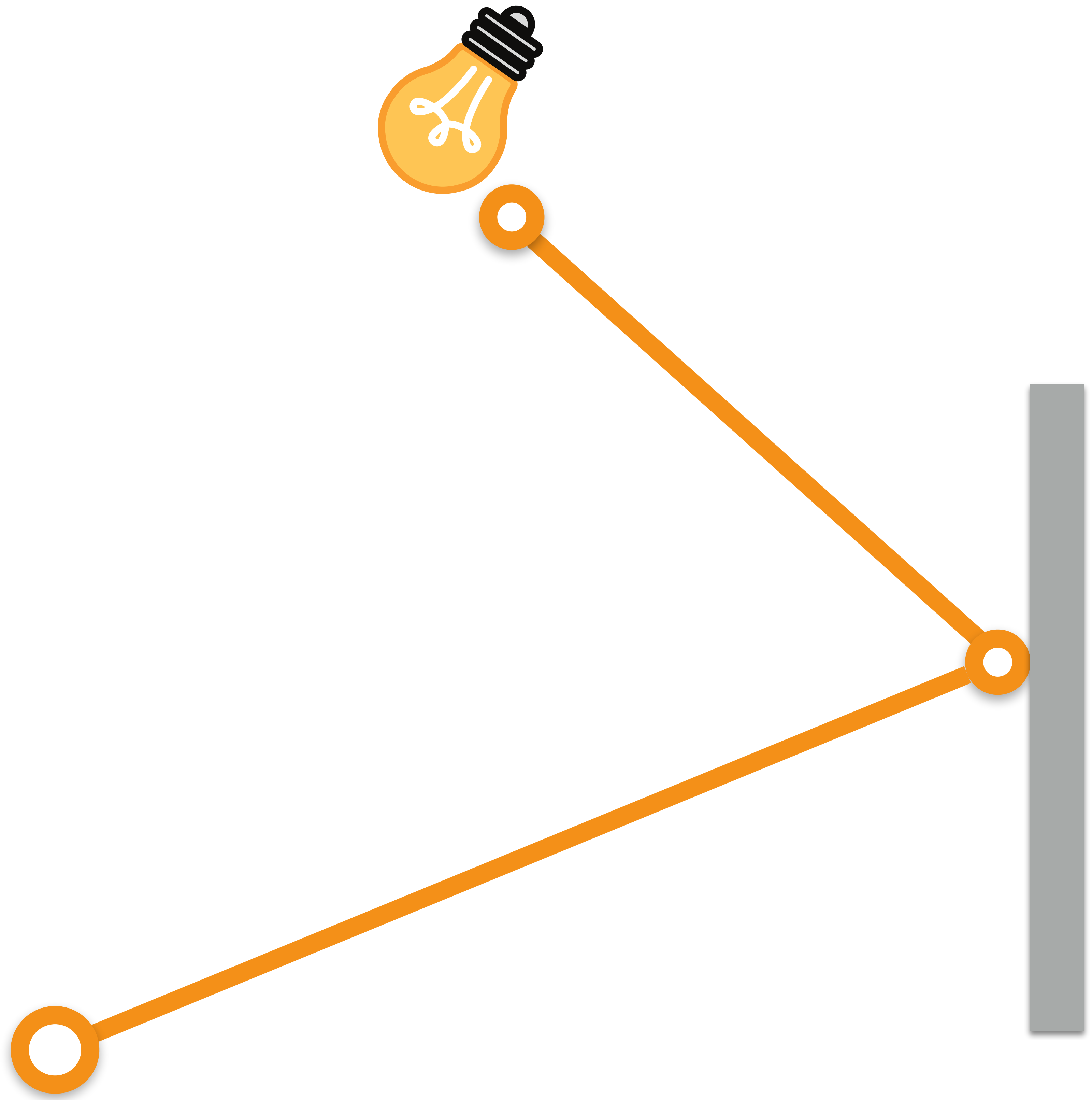
The limitations of photon planes



single scattering

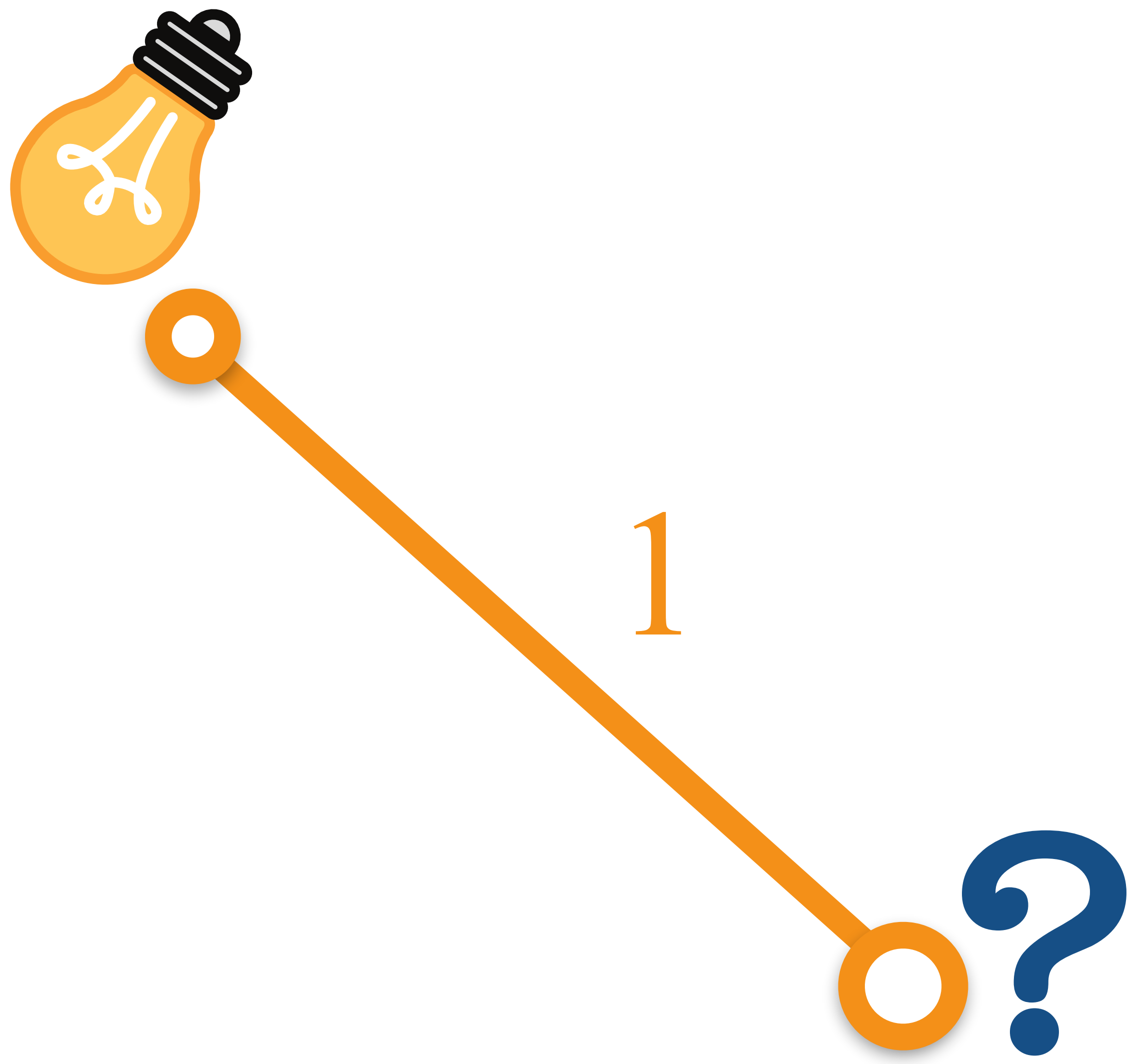
The limitations of photon planes



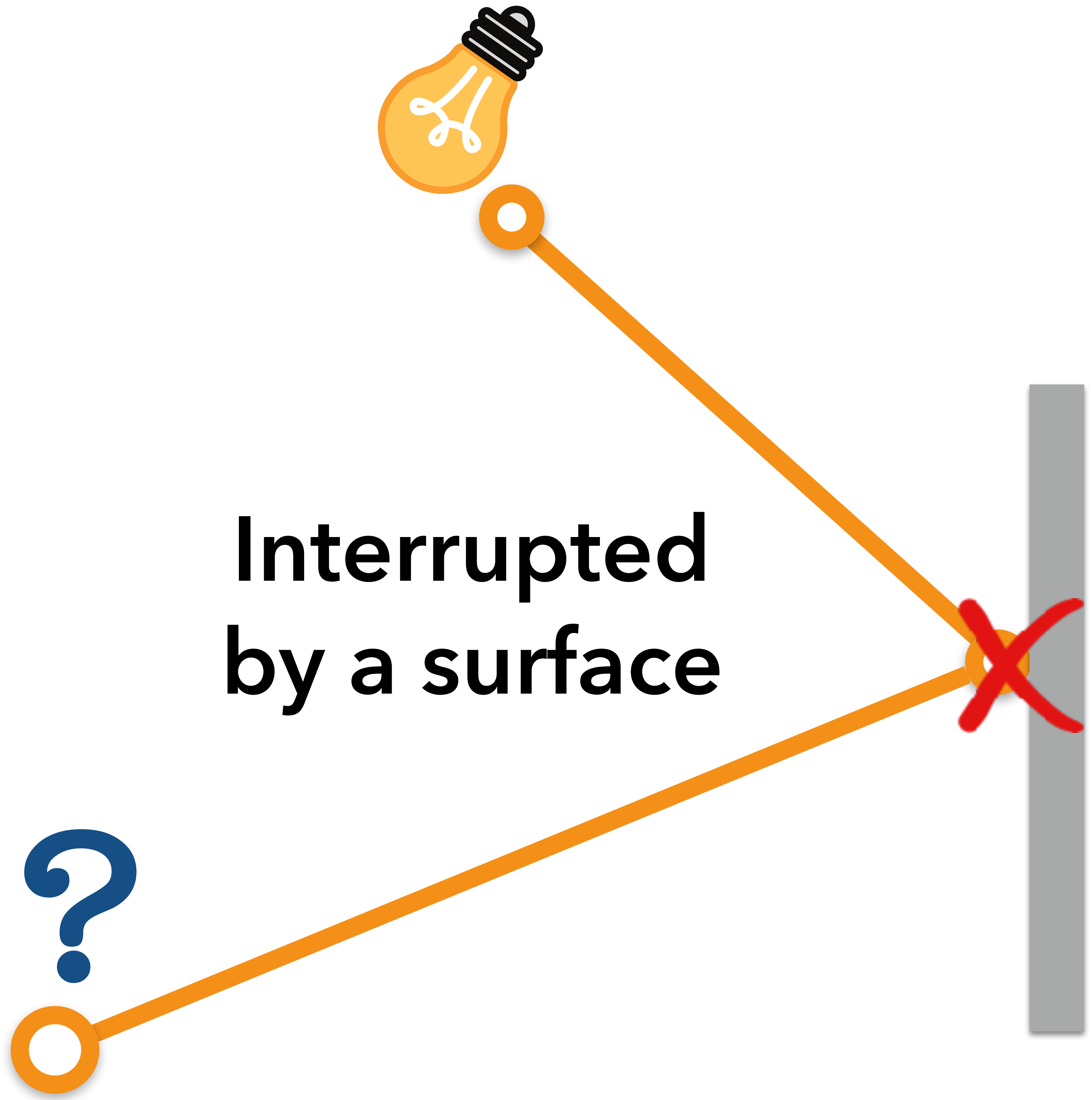


single scattering

The limitations of photon planes



single scattering



surface-medium

Our Work

Contributions

1. New derivation

$$+\int_{\mathbf{x}}^{\mathbf{x}_t} Tr(\mathbf{x}_{t'},\mathbf{x}_t)\,\sigma_s(\mathbf{x}_{t'})\left(\int_{S^2}\rho_p(\mathbf{x}_{t'},\omega,\omega_i)L(\mathbf{x}_{t'},\omega_i)\mathrm{d}\omega_i\right)\mathrm{d}\mathbf{x}_{t'}$$

$$I=\int_\Omega f(\xi)\,K(\mathbf{g}(\xi))\,f_\omega^{1,1}\,\mathrm{d}\xi$$

$$L(\mathbf{x}_t,\omega)= \quad t_i\omega_i$$

$$\mathbf{y}_0=\mathbf{y}_l+\coprod_{i=k} s_i\psi_i$$

$$I=\int f(\bar{\xi})\,K(\mathbf{g}(\bar{\xi}))\,f_\omega^{1,1}\,\mathrm{d}\bar{\xi}$$

$$+Tr(\mathbf{x},\mathbf{x}_t)L(\mathbf{x},\omega)$$

$$\mathbf{g}(\bar{\xi})=\mathbf{x}_0(\bar{\xi})-\mathbf{y}_0(\bar{\xi})=\left(\mathbf{x}_l+\sum_{i=l}^{1}t_i\omega_i\right)-\left(\mathbf{y}_k+\sum_{i=l}s_i\psi_i\right)$$

$$K(\mathbf{g})=\delta^3(\mathbf{g})=\delta^1(x(\mathbf{g}))\delta^1(y(\mathbf{g}))\delta^1($$

$\mathbf{g}(\bar{\xi}_a)$ is a shorthand for $\mathbf{g}(\bar{\xi}_a,\bar{\xi}_n)$

$$L_o(\mathbf{x},\omega_o)=L_e(\mathbf{x},\omega_o)+L_s(\mathbf{x},\omega_o)$$
$$=L_e(\mathbf{x},\omega_o)+\int_{S^2}\rho_s(\mathbf{x},\omega_i,\omega_o)L(\mathbf{x},\omega_i)|\mathbf{n}(\mathbf{x})\cdot\omega_i|\mathrm{d}\omega_i$$

$$\int_{\mathbf{x}}^{\mathbf{x}_t} Tr(\mathbf{x}_{t'},\mathbf{x}_t)L_e(\mathbf{x}_{t'},\omega)d\mathbf{x}_{t'}$$

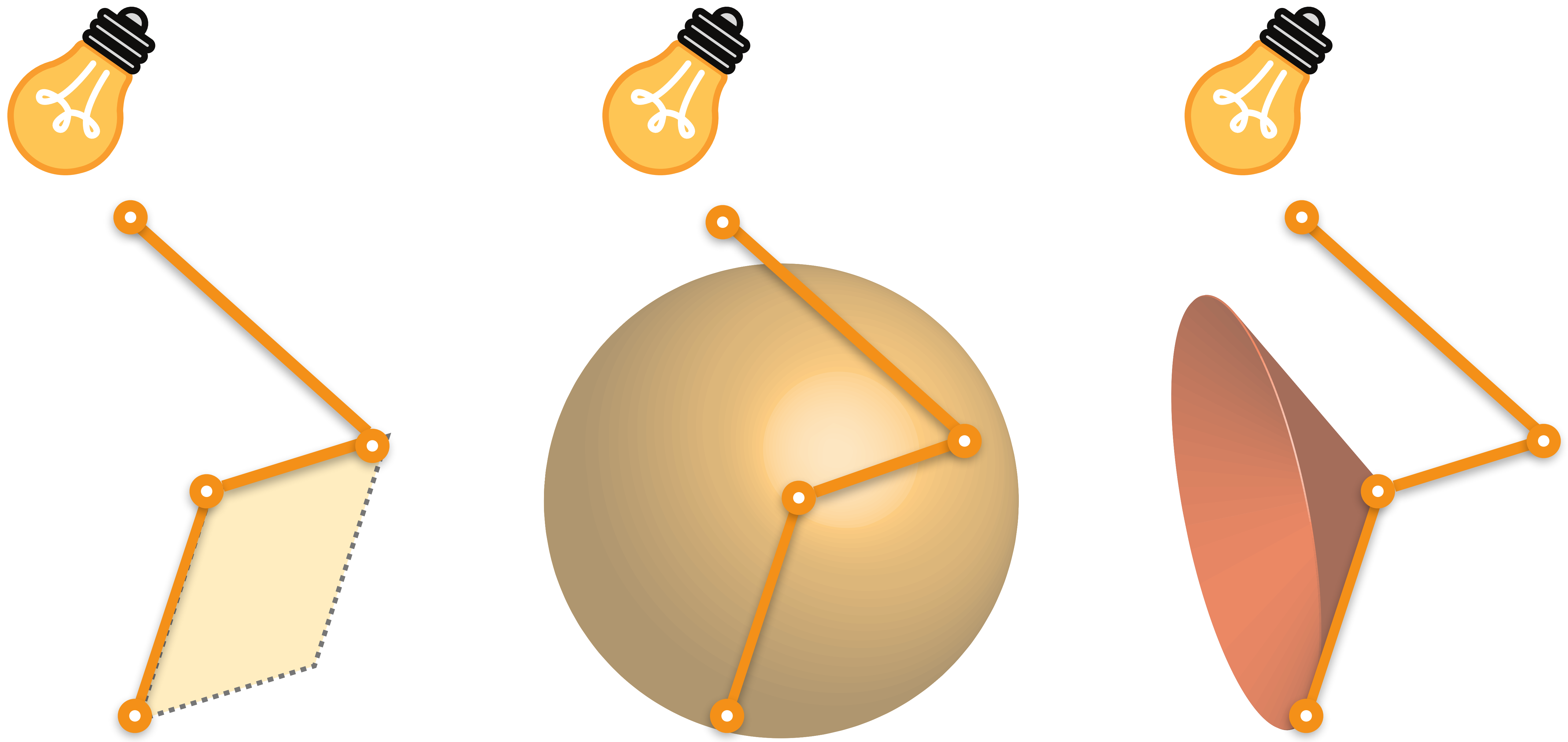
$$I=\int_\Omega f(\bar{\xi}_n)\underbrace{\int_{\Omega_a(\bar{\xi}_n)} f(\bar{\xi}_a)\,\delta^3(\mathbf{g}(\bar{\xi}_a))\,f_\omega^{1,1}\,\mathrm{d}\bar{\xi}_a}_{I_a}\,\mathrm{d}\bar{\xi}_n$$

$$I=\int_A\int_{H^2}W_e(\mathbf{x},\omega)L(\mathbf{x},\omega)\mathrm{d}\omega\mathrm{d}\mathbf{x}$$

$$I=\frac{f(\bar{\xi}_n)I_a(\bar{\xi}_n)}{p(\bar{\xi}_n)}$$

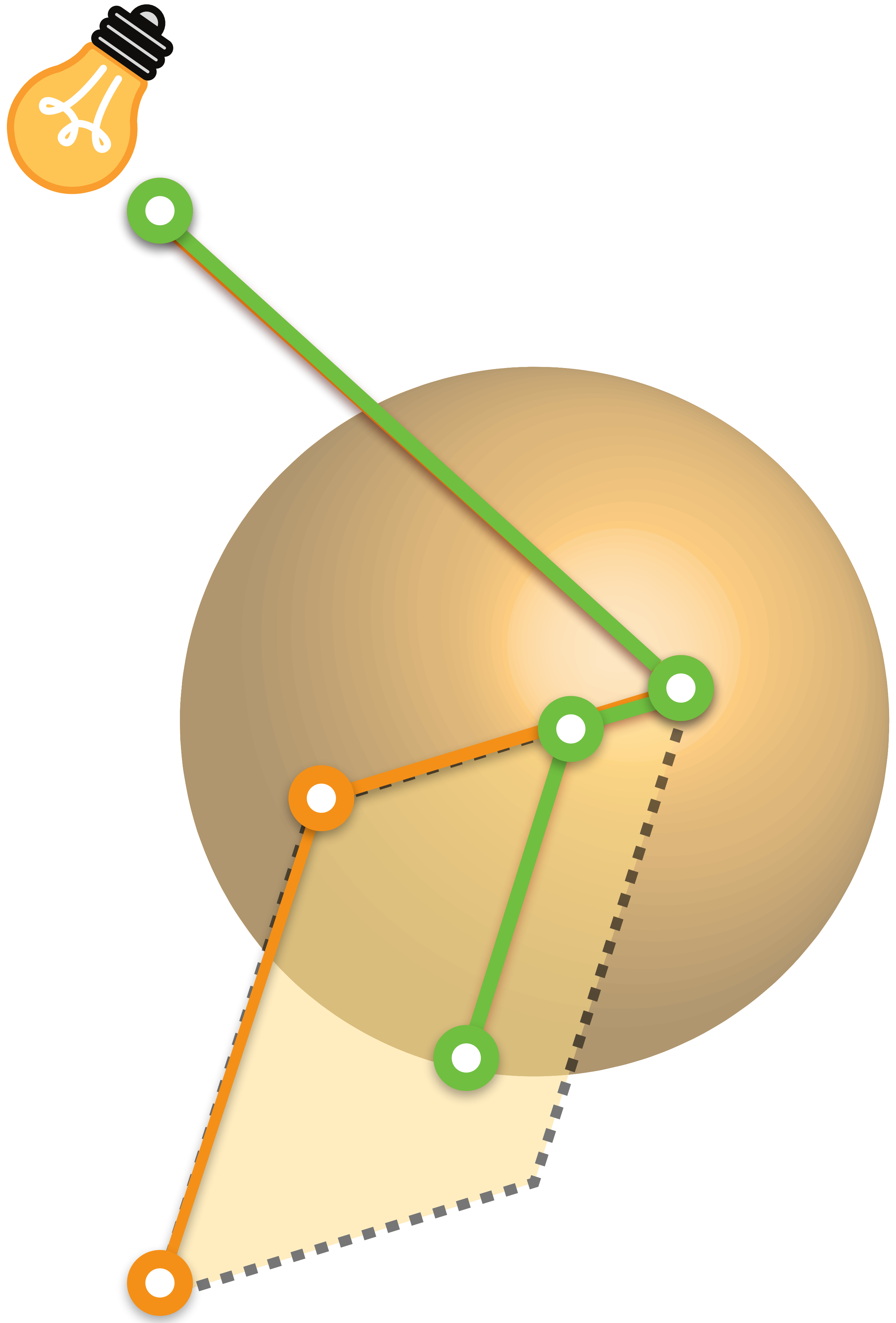
Contributions

1. New derivation
2. Photon surfaces



Contributions

1. New derivation
2. Photon surfaces
3. Combine using MIS

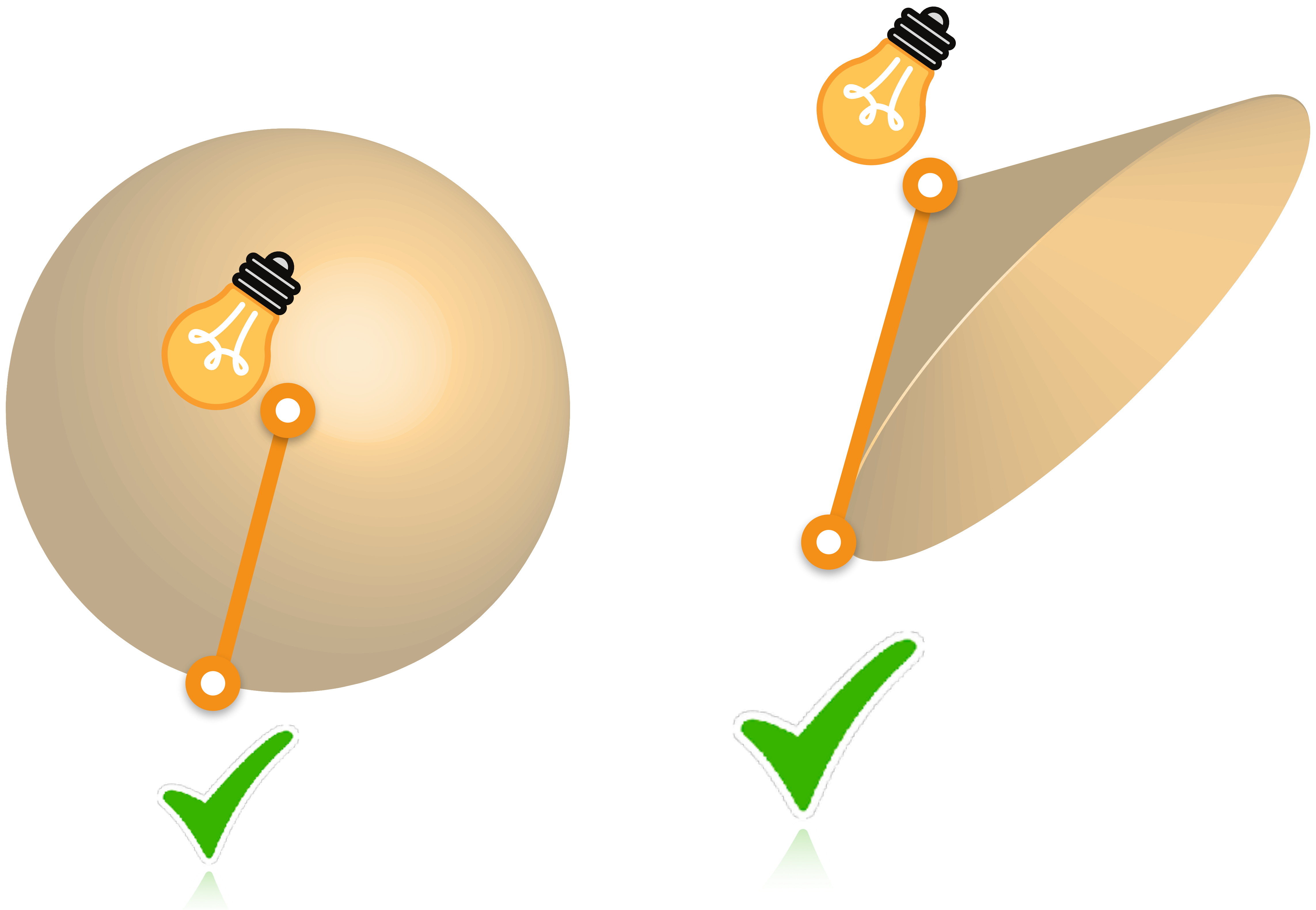



Photon planes
Ours
Var: 0.209x


Photon planes
Ours
Var: 0.209x
The combination resolves singularities

Contributions

1. New derivation
2. Photon surfaces
3. Combine using MIS
4. Single scattering




Photon beams
Ours
Var: 0.155x

Single-scattering is supported

Theory

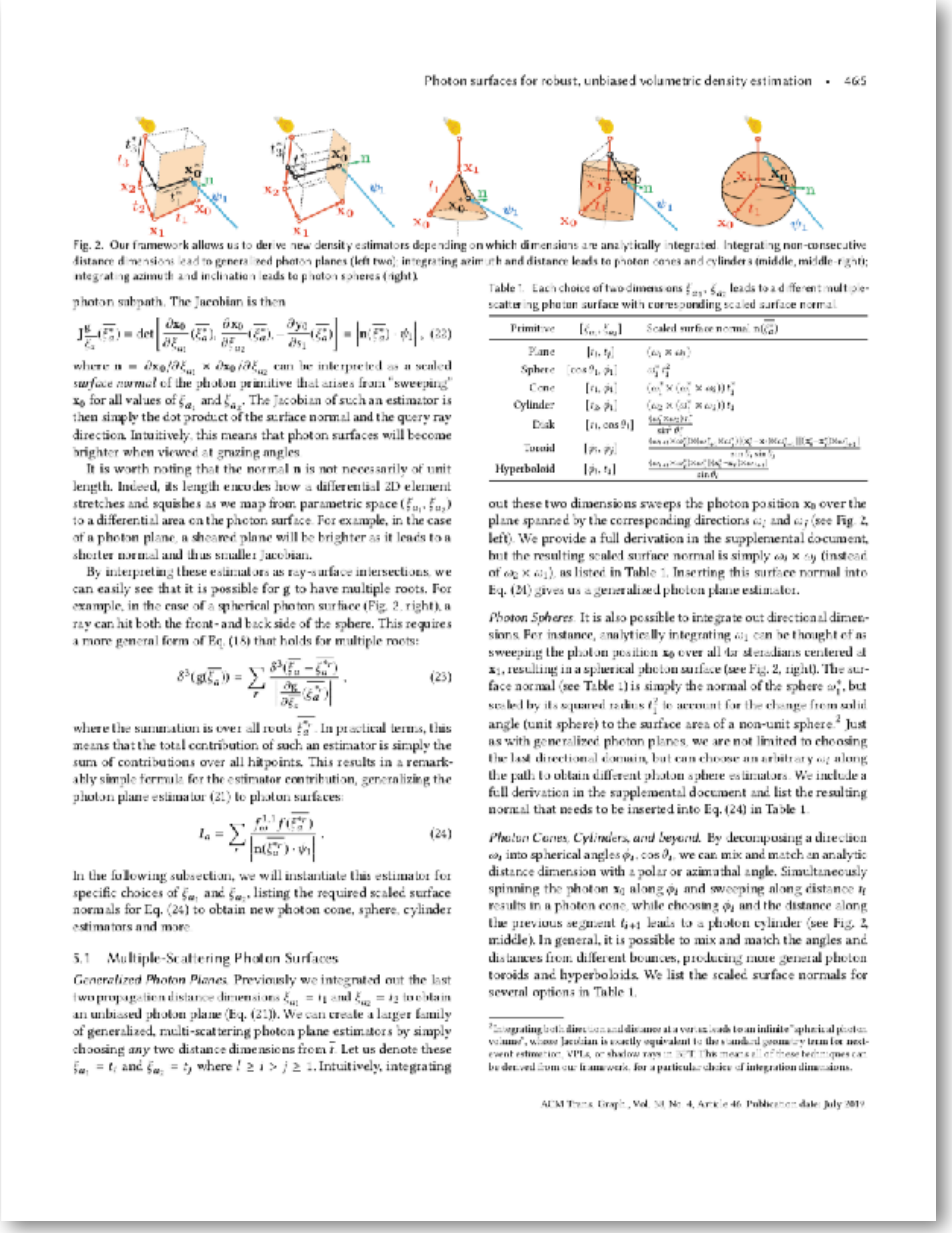


Fig. 2. Our framework allows us to derive new density estimators depending on which dimensions are analytically integrated. Integrating non-consecutive distance dimensions lead to generalized photon planes (left two); integrating azimuth and distance leads to photon cones and cylinders (middle, middle-right); integrating azimuth and inclination leads to photon spheres (right).

photon subpath. The Jacobian is then

$$J^{g}_{\bar{\xi}_a}(\overline{\xi^*_a}) = \det\left[\frac{\partial x_0}{\partial \xi_{a_1}}(\overline{\xi^*_a}), \frac{\partial x_0}{\partial \xi_{a_2}}(\overline{\xi^*_a}), -\frac{\partial y_0}{\partial s_1}(\overline{\xi^*_a})\right] = \left|n(\overline{\xi^*_a}) \cdot \psi_1\right|, \quad (22)$$

where $n = \partial x_0/\partial \xi_{a_1} \times \partial x_0/\partial \xi_{a_2}$ can be interpreted as a scaled *surface normal* of the photon primitive that arises from "sweeping" x_0 for all values of ξ_{a_1} and ξ_{a_2}. The Jacobian of such an estimator is then simply the dot product of the surface normal and the query ray direction. Intuitively, this means that photon surfaces will become brighter when viewed at grazing angles.

It is worth noting that the normal n is not necessarily of unit length. Indeed, its length encodes how a differential 2D element stretches and squishes as we map from parametric space (ξ_{a_1}, ξ_{a_2}) to a differential area on the photon surface. For example, in the case of a photon plane, a sheared plane will be brighter as it leads to a shorter normal and thus smaller Jacobian.

By interpreting these estimators as ray-surface intersections, we can easily see that it is possible for g to have multiple roots. For example, in the case of a spherical photon surface (Fig. 2, right), a ray can hit both the front- and back side of the sphere. This requires a more general form of Eq. (18) that holds for multiple roots:

$$\delta^3(g(\overline{\xi_a})) = \sum_r \frac{\delta^3(\overline{\xi_a} - \overline{\xi^{*r}_a})}{\left|\frac{\partial g}{\partial \xi_a}(\overline{\xi^{*r}_a})\right|}, \quad (23)$$

where the summation is over all roots $\overline{\xi^{*r}_a}$. In practical terms, this means that the total contribution of such an estimator is simply the sum of contributions over all hitpoints. This results in a remarkably simple formula for the estimator contribution, generalizing the photon plane estimator (21) to photon surfaces:

$$I_a = \sum_r \frac{f^{1,1}_{m} f(\overline{\xi^{*r}_a})}{\left|n(\overline{\xi^{*r}_a}) \cdot \psi_1\right|}. \quad (24)$$

In the following subsection, we will instantiate this estimator for specific choices of ξ_{a_1} and ξ_{a_2}, listing the required scaled surface normals for Eq. (24) to obtain new photon cone, sphere, cylinder estimators and more.

5.1 Multiple-Scattering Photon Surfaces

Generalized Photon Planes. Previously we integrated out the last two propagation distance dimensions $\xi_{a_1} = t_1$ and $\xi_{a_2} = t_2$ to obtain an unbiased photon plane (Eq. (21)). We can create a larger family of generalized, multi-scattering photon plane estimators by simply choosing *any* two distance dimensions from $\bar{t}$. Let us denote these $\xi_{a_1} = t_i$ and $\xi_{a_2} = t_j$ where $l \geq i > j \geq 1$. Intuitively, integrating out these two dimensions sweeps the photon position x_0 over the plane spanned by the corresponding directions ω_i and ω_j (see Fig. 2, left). We provide a full derivation in the supplemental document, but the resulting scaled surface normal is simply $\omega_i \times \omega_j$ (instead of $\omega_2 \times \omega_1$), as listed in Table 1. Inserting this surface normal into Eq. (24) gives us a generalized photon plane estimator.

Table 1. Each choice of two dimensions ξ_{a_1}, ξ_{a_2} leads to a different multiple-scattering photon surface with corresponding scaled surface normal.

Primitive	$[\xi_{a_1}, \xi_{a_2}]$	Scaled surface normal $n(\overline{\xi_a})$
Plane	$[t_i, t_j]$	$(\omega_i \times \omega_j)$
Sphere	$[\cos\theta_1, \phi_1]$	$\omega^+_1 t^2_1$
Cone	$[t_1, \phi_1]$	$(\omega^+_1 \times (\omega^+_1 \times \omega_2)) t^+_1$
Cylinder	$[t_2, \phi_1]$	$(\omega_2 \times (\omega^+_1 \times \omega_2)) t_1$
Disk	$[t_1, \cos\theta_1]$	[illegible]
Toroid	$[\phi_i, \phi_j]$	[illegible]
Hyperboloid	$[\phi_i, t_i]$	[illegible]

Photon Spheres. It is also possible to integrate out directional dimensions. For instance, analytically integrating ω_1 can be thought of as sweeping the photon position x_0 over all 4π steradians centered at x_1, resulting in a spherical photon surface (see Fig. 2, right). The surface normal (see Table 1) is simply the normal of the sphere ω^+_1, but scaled by its squared radius t^2_1 to account for the change from solid angle (unit sphere) to the surface area of a non-unit sphere.[2] Just as with generalized photon planes, we are not limited to choosing the last directional domain, but can choose an arbitrary ω_i along the path to obtain different photon sphere estimators. We include a full derivation in the supplemental document and list the resulting normal that needs to be inserted into Eq. (24) in Table 1.

Photon Cones, Cylinders, and beyond. By decomposing a direction ω_i into spherical angles ϕ_i, $\cos\theta_i$, we can mix and match an analytic distance dimension with a polar or azimuthal angle. Simultaneously spinning the photon x_0 along ϕ_i and sweeping along distance t_i results in a photon cone, while choosing ϕ_i and the distance along the previous segment t_{i+1} leads to a photon cylinder (see Fig. 2, middle). In general, it is possible to mix and match the angles and distances from different bounces, producing more general photon toroids and hyperboloids. We list the scaled surface normals for several options in Table 1.

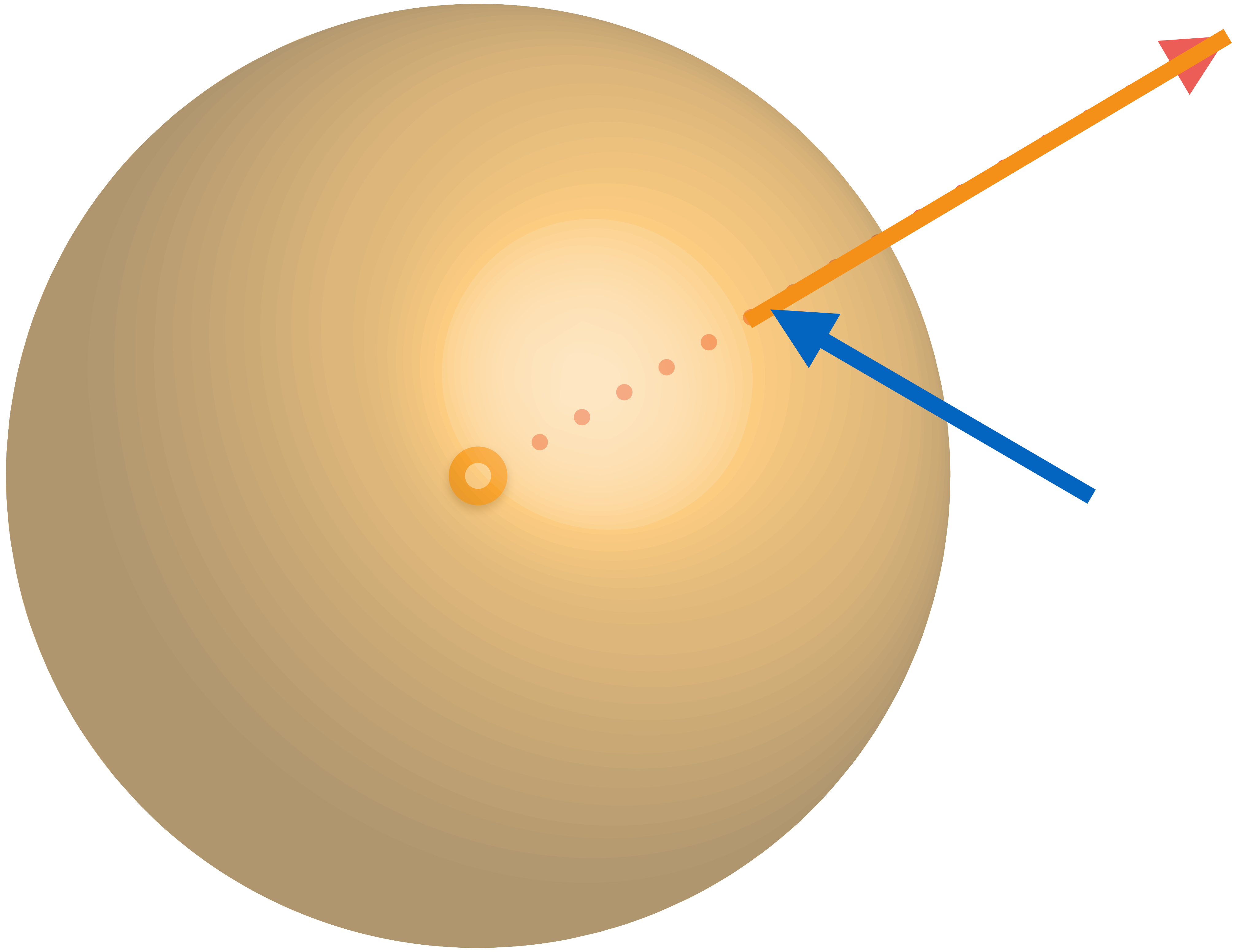
[2] Integrating both direction and distance at a vertex leads to an infinite "spherical photon volume", whose Jacobian is exactly equivalent to the standard geometry term for next-event estimation, VPLs, or shadow rays in BPT. This means all of these techniques can be derived from our framework, for a particular choice of integration dimensions.

Geometric interpretation

Theory

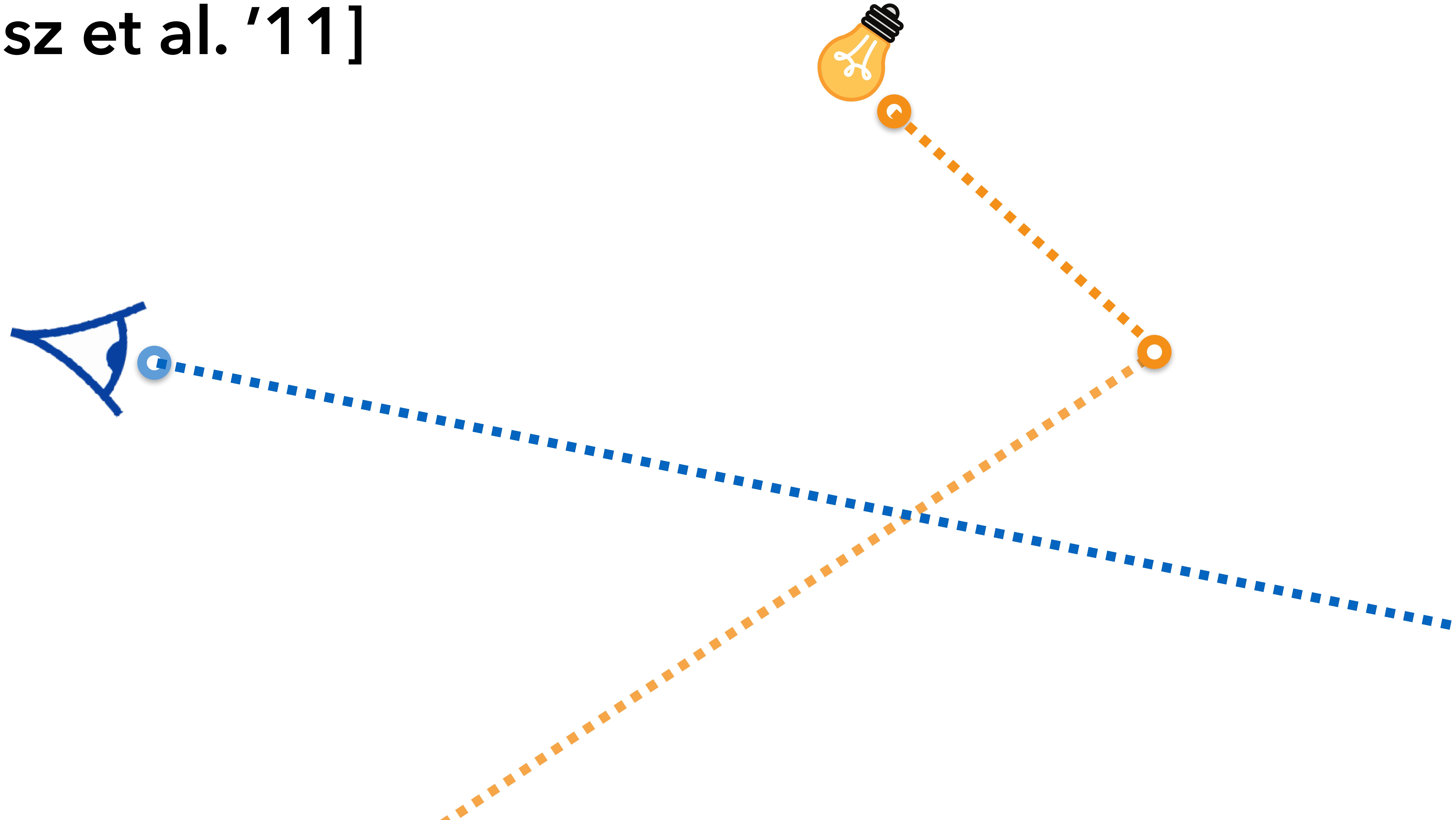
Fig. 2. Our framework allows us to derive new density estimators depending on which dimensions are analytically integrated. Integrating non-consecutive distance dimensions lead to generalized photon planes (left two); integrating azimuth and distance leads to photon cones and cylinders (middle, middle-right); integrating azimuth and inclination leads to photon spheres (right).

Geometric interpretation



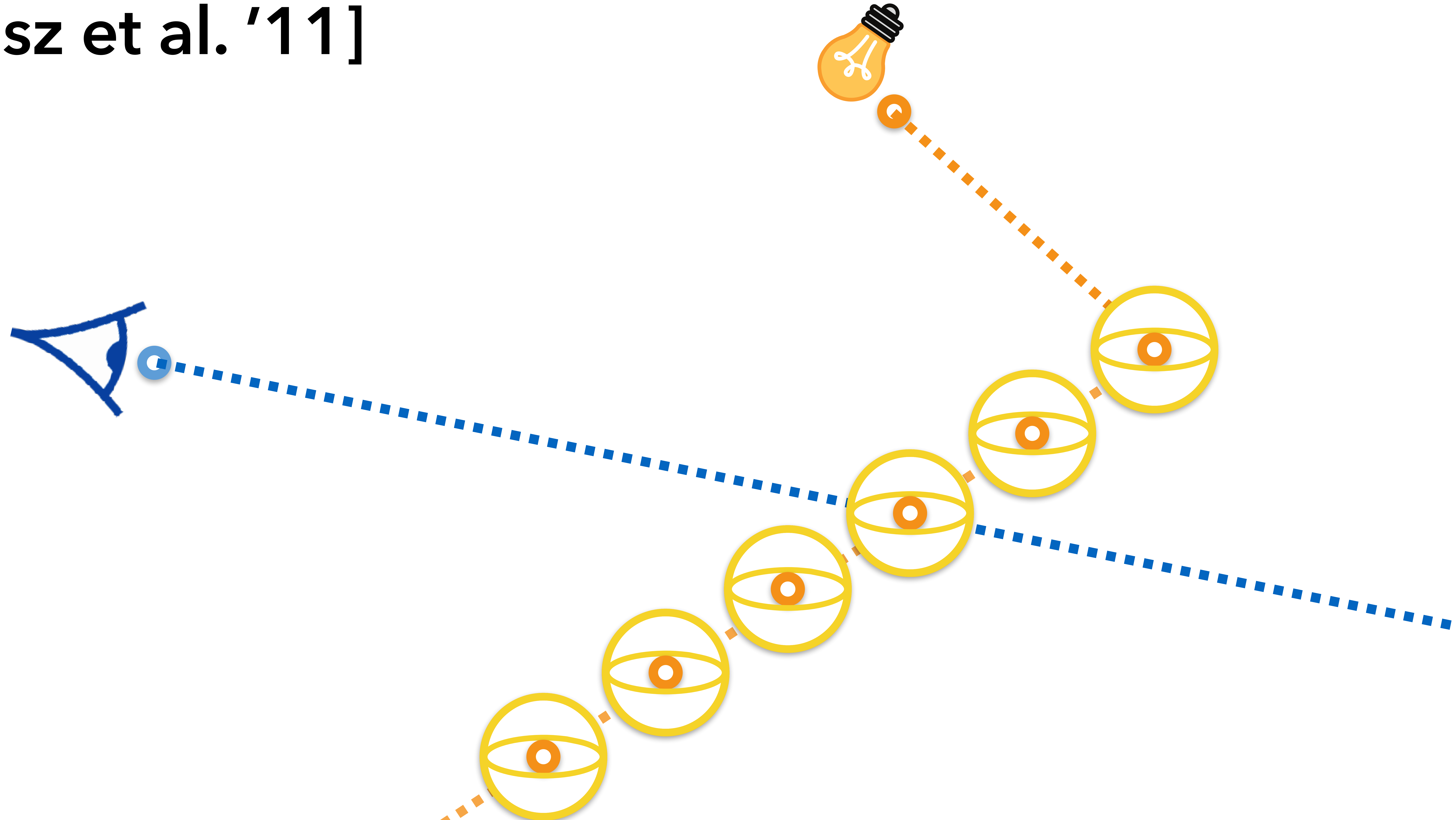
Derivation in previous work

[Jarosz et al. '11]



Derivation in previous work

[Jarosz et al. ’11]



Derivation in previous work

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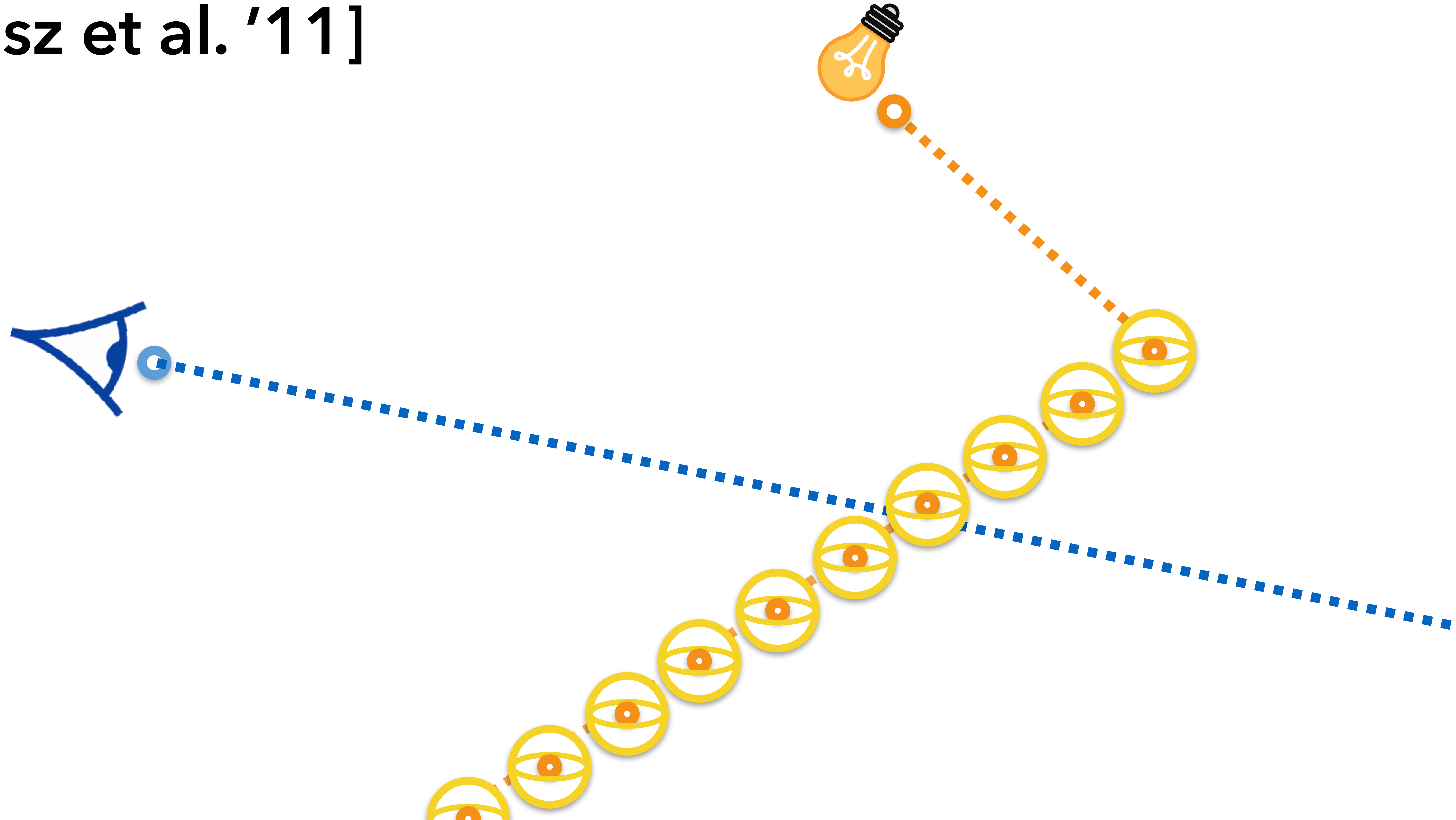

Derivation in previous work

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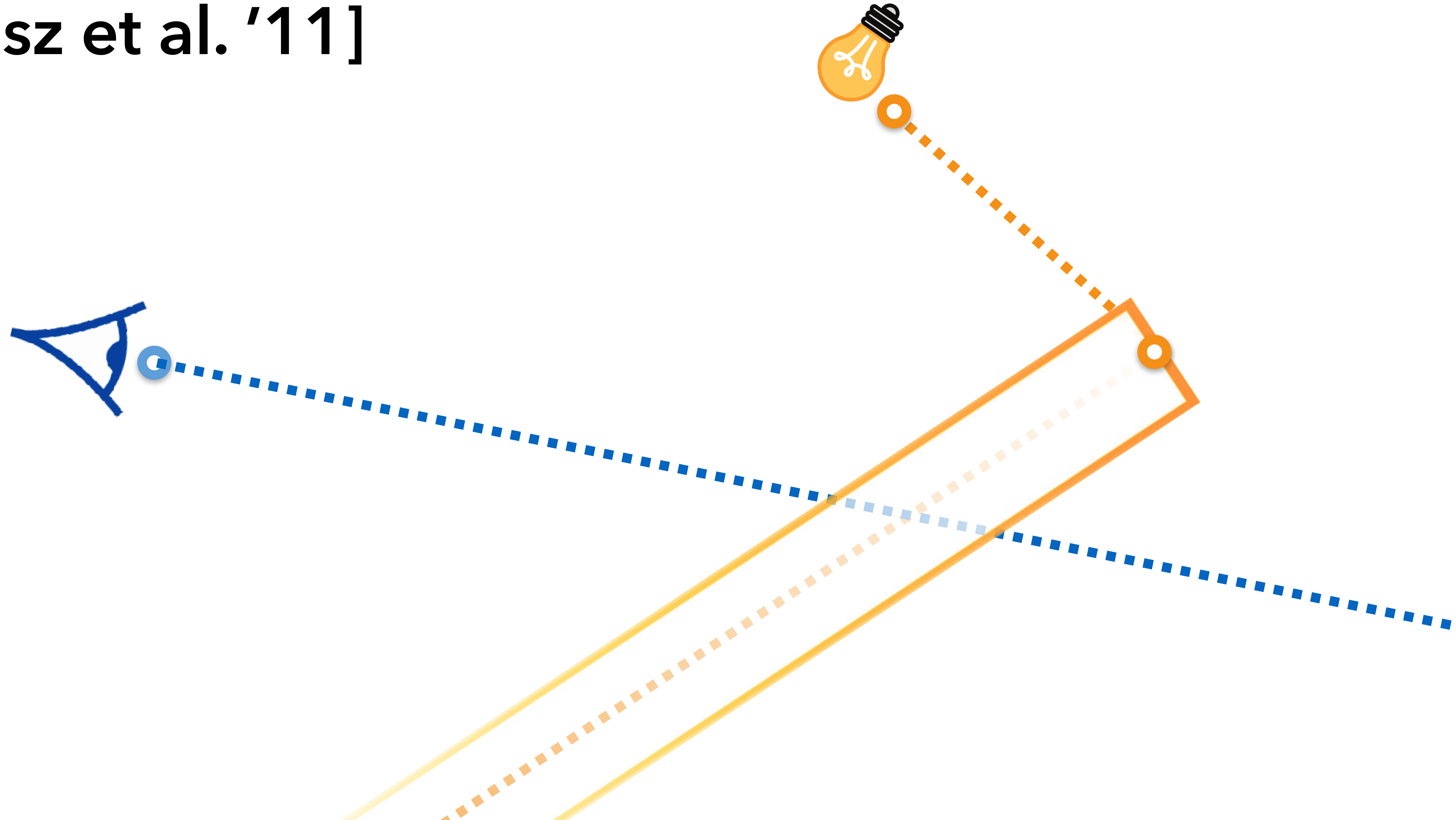
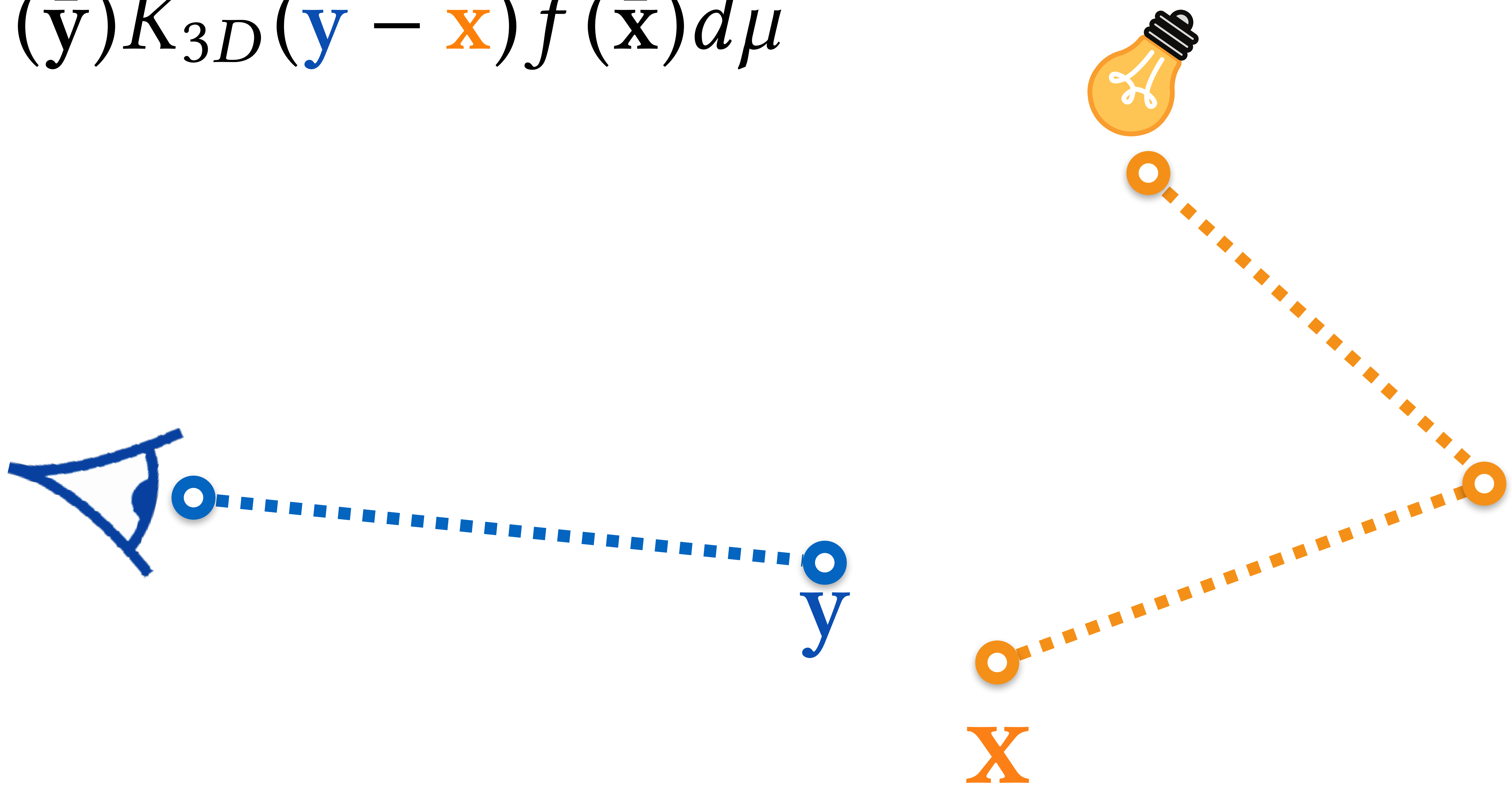


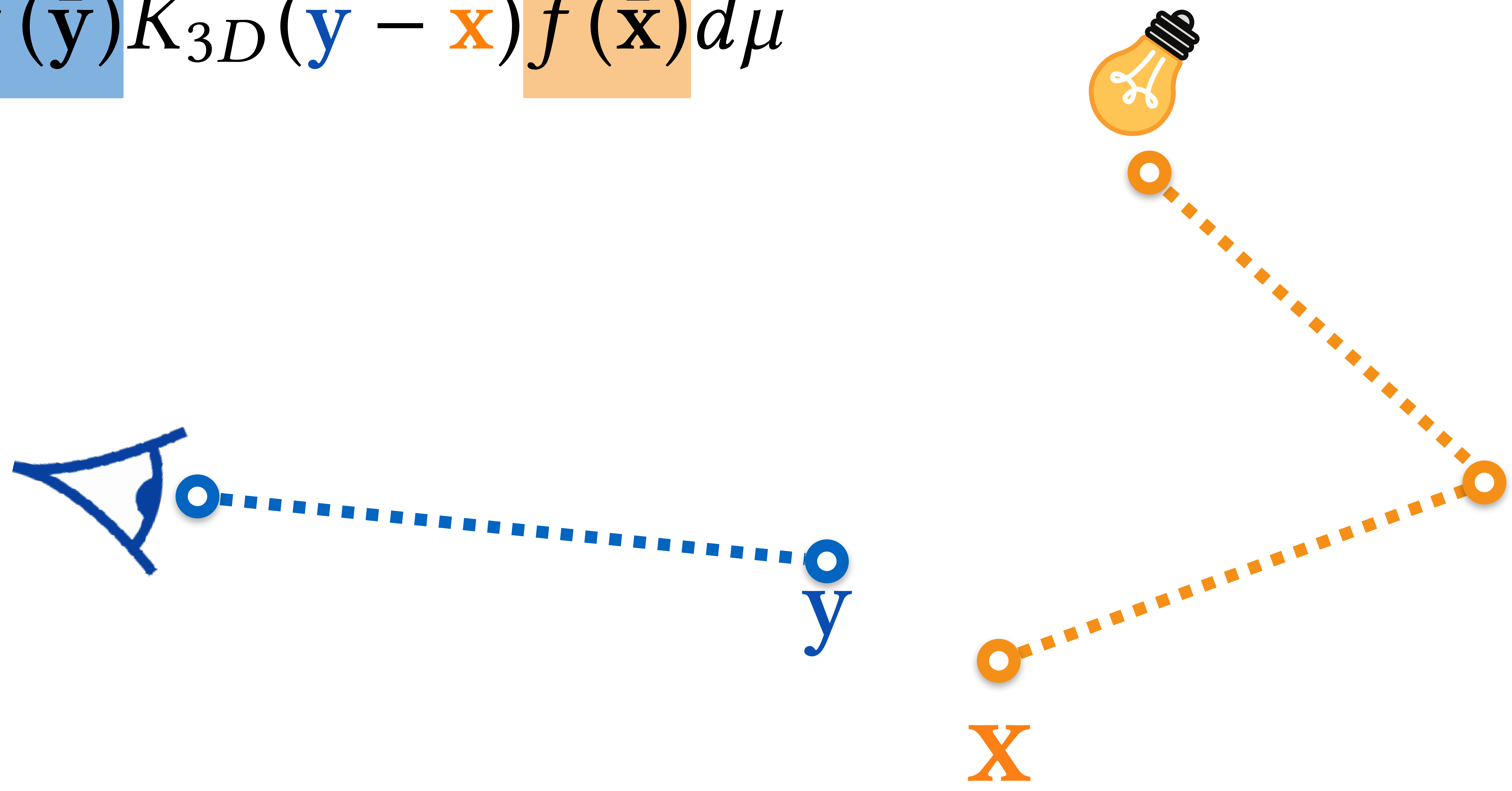
Our approach

$$I = \int f(\bar{\mathbf{y}})K_{3D}(\mathbf{y} - \mathbf{x})f(\bar{\mathbf{x}})d\mu$$



Our approach

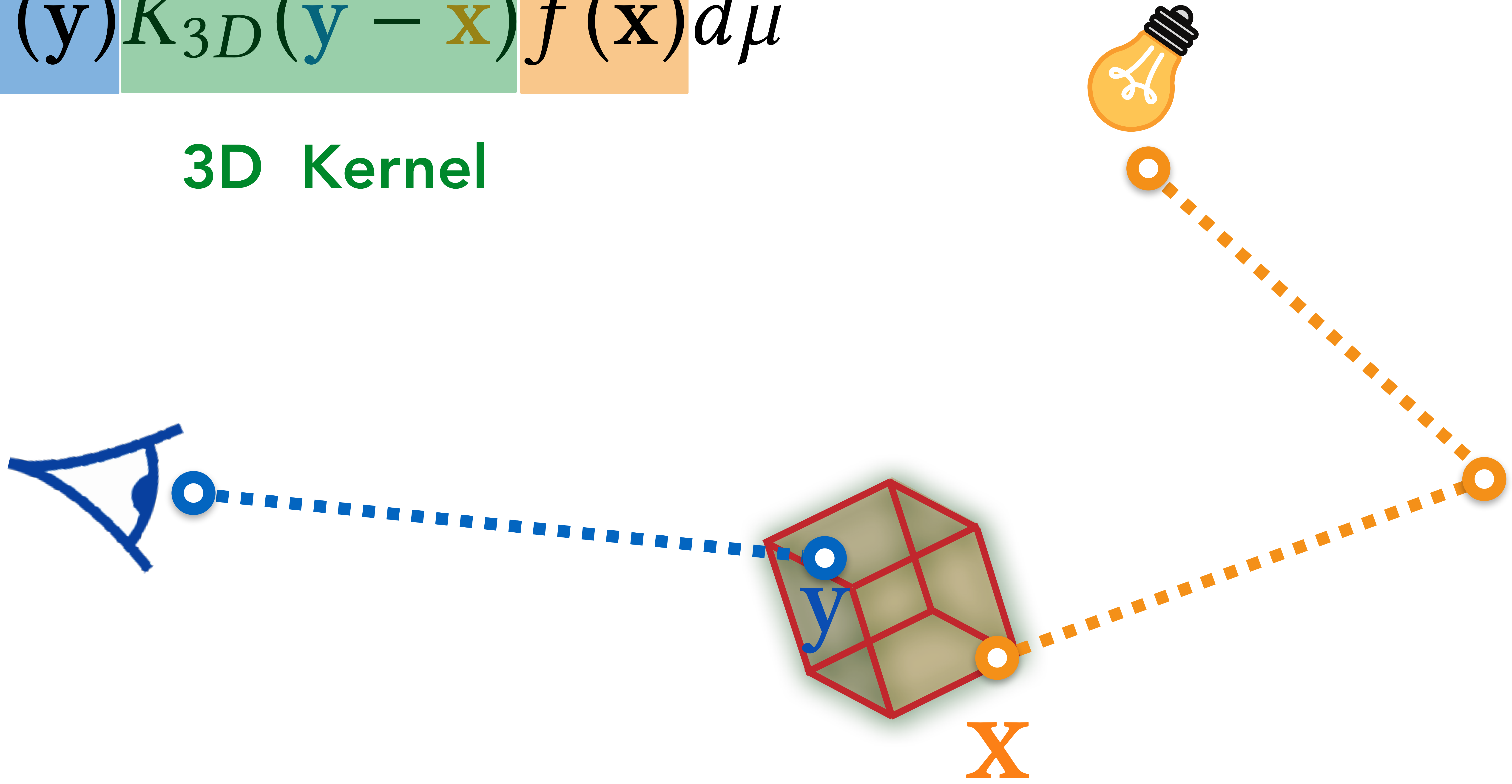
$$I = \int f(\bar{\mathbf{y}}) K_{3D}(\mathbf{y} - \mathbf{x}) f(\bar{\mathbf{x}}) d\mu$$



Our approach

$$I = \int f(\bar{\mathbf{y}}) K_{3D}(\mathbf{y} - \mathbf{x}) f(\bar{\mathbf{x}}) d\mu$$

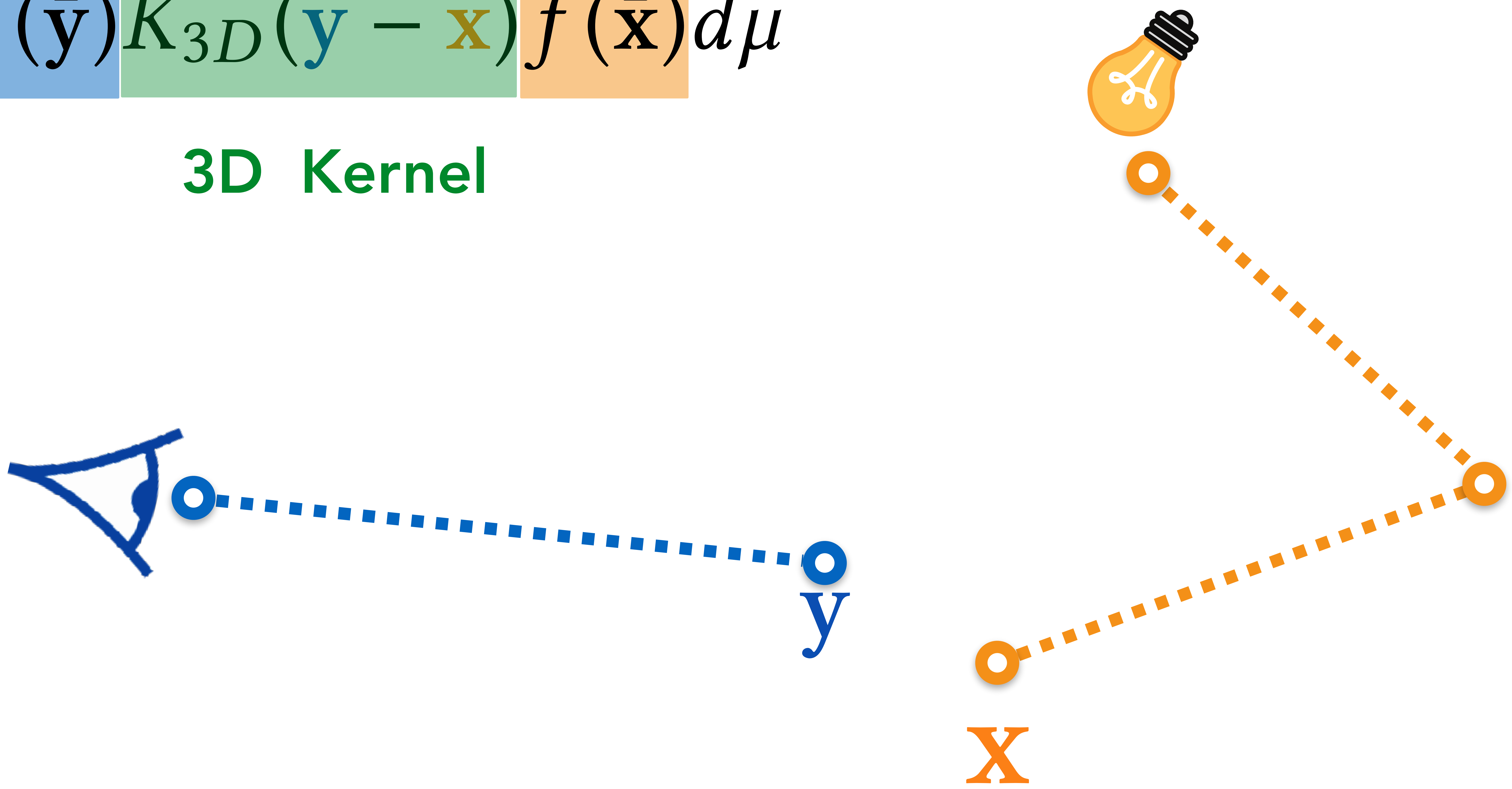
3D Kernel



Our approach

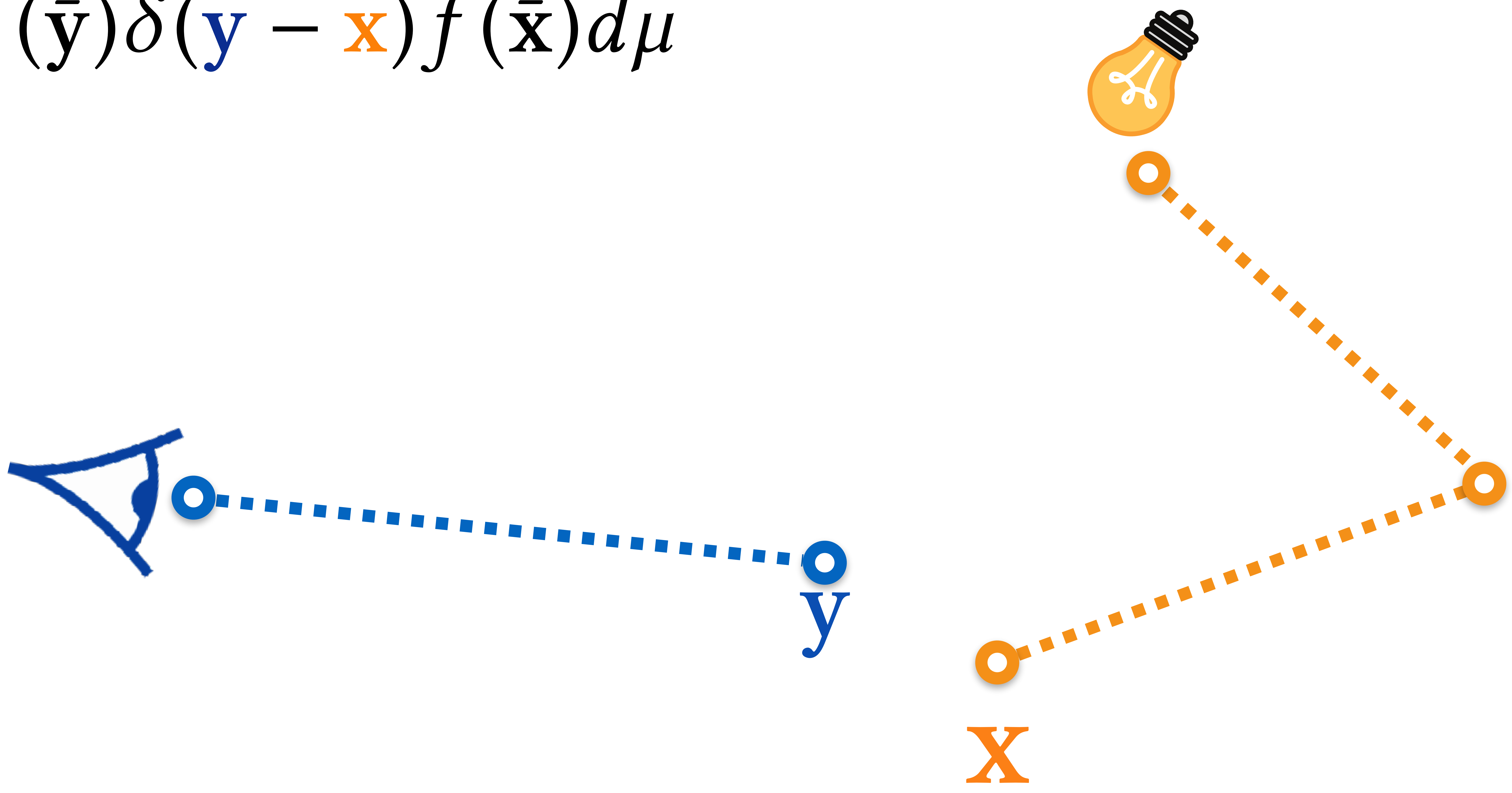
$$I = \int f(\bar{\mathbf{y}}) K_{3D}(\mathbf{y} - \mathbf{x}) f(\bar{\mathbf{x}}) d\mu$$

3D Kernel



Our approach

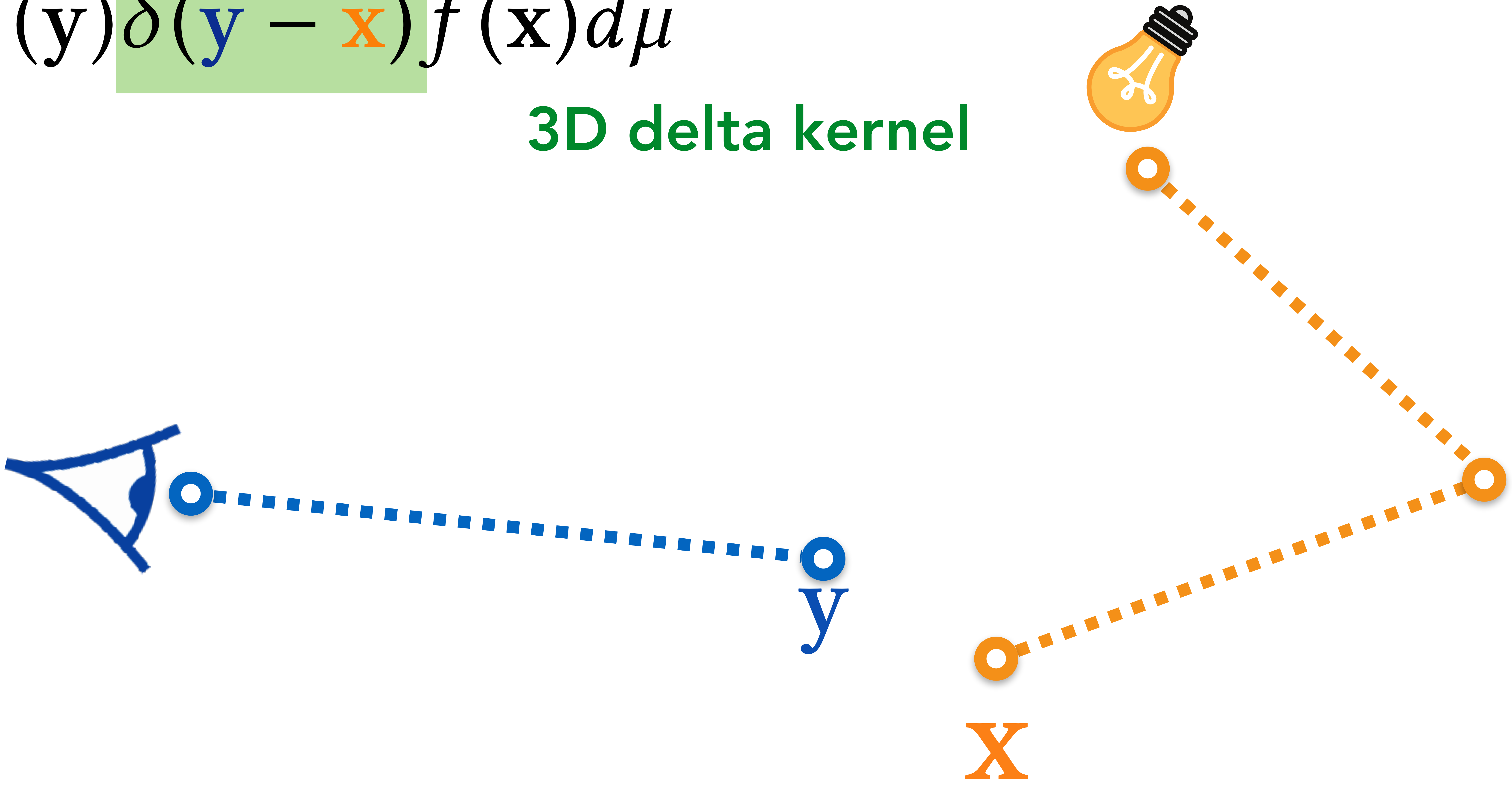
$$I = \int f(\bar{\mathbf{y}})\delta(\mathbf{y} - \mathbf{x})f(\bar{\mathbf{x}})d\mu$$



Our approach

$$I = \int f(\bar{\mathrm{y}})\delta(\mathbf{y} - \mathbf{x})f(\bar{\mathrm{x}})d\mu$$

3D delta kernel

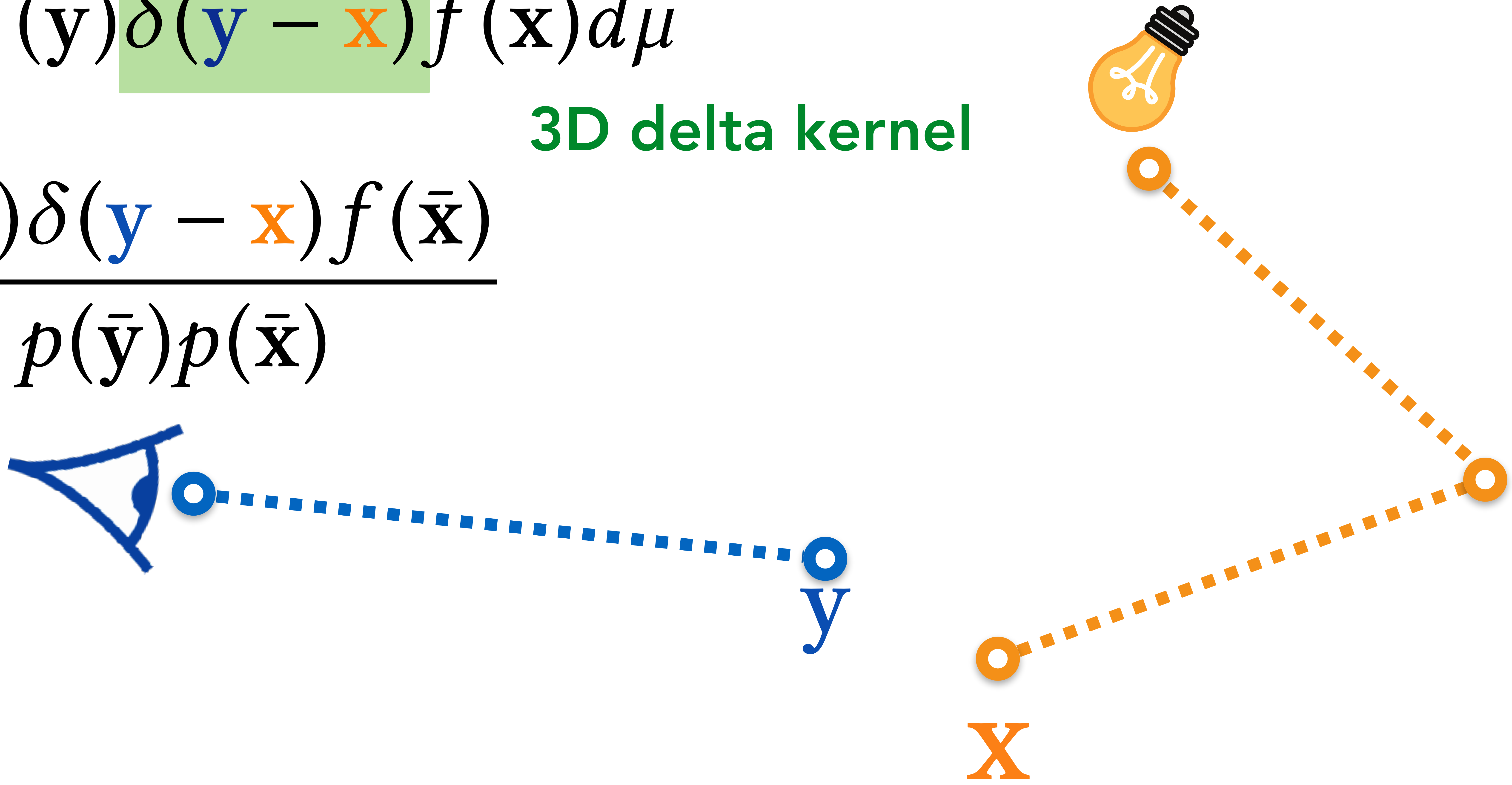


Our approach

$$I = \int f(\bar{\mathbf{y}})\delta(\mathbf{y} - \mathbf{x})f(\bar{\mathbf{x}})d\mu$$

3D delta kernel

$$\approx \frac{f(\bar{\mathbf{y}})\delta(\mathbf{y} - \mathbf{x})f(\bar{\mathbf{x}})}{p(\bar{\mathbf{y}})p(\bar{\mathbf{x}})}$$



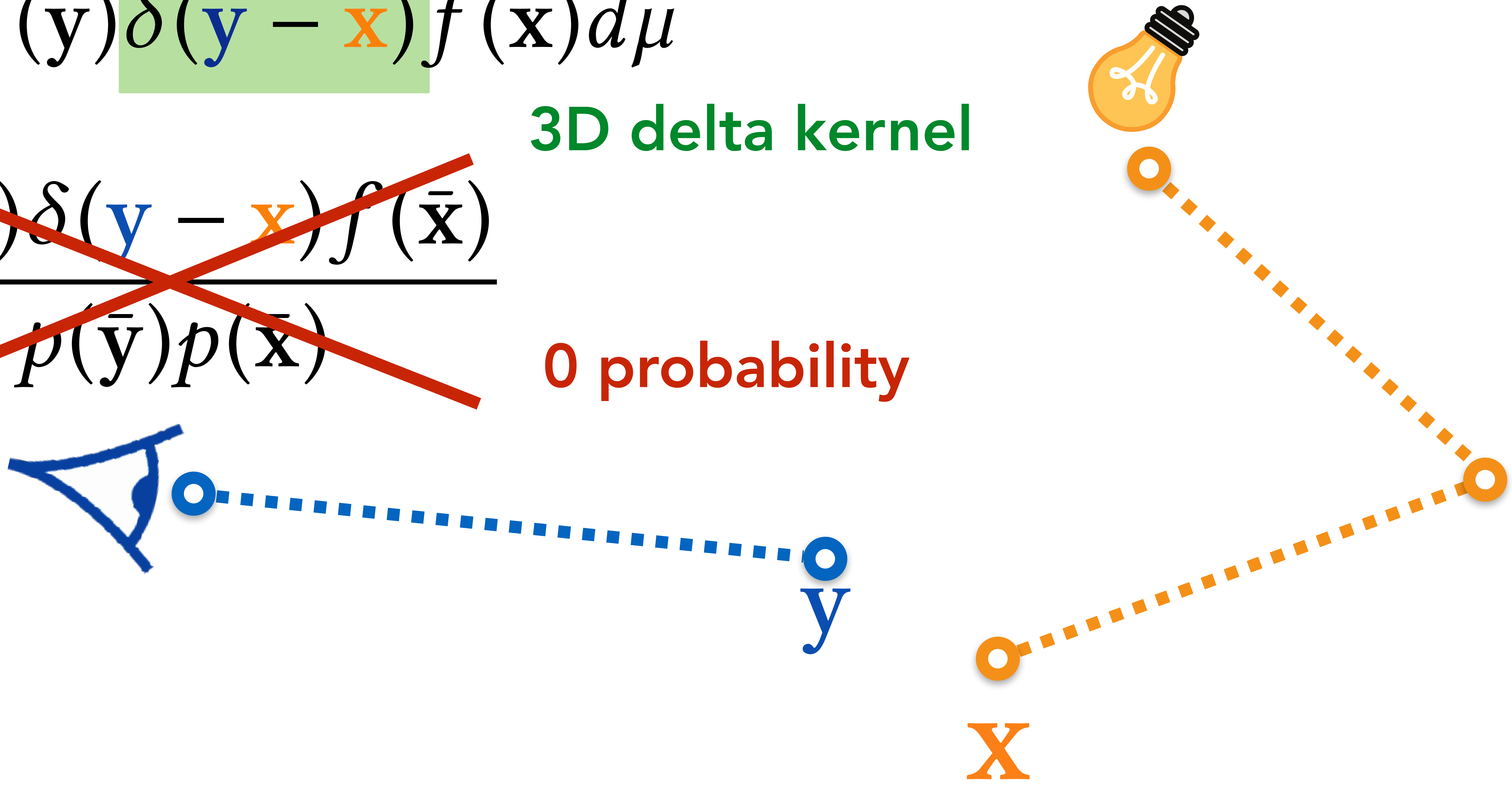
Our approach

$$I = \int f(\bar{\mathbf{y}})\delta(\mathbf{y} - \mathbf{x})f(\bar{\mathbf{x}})d\mu$$

3D delta kernel

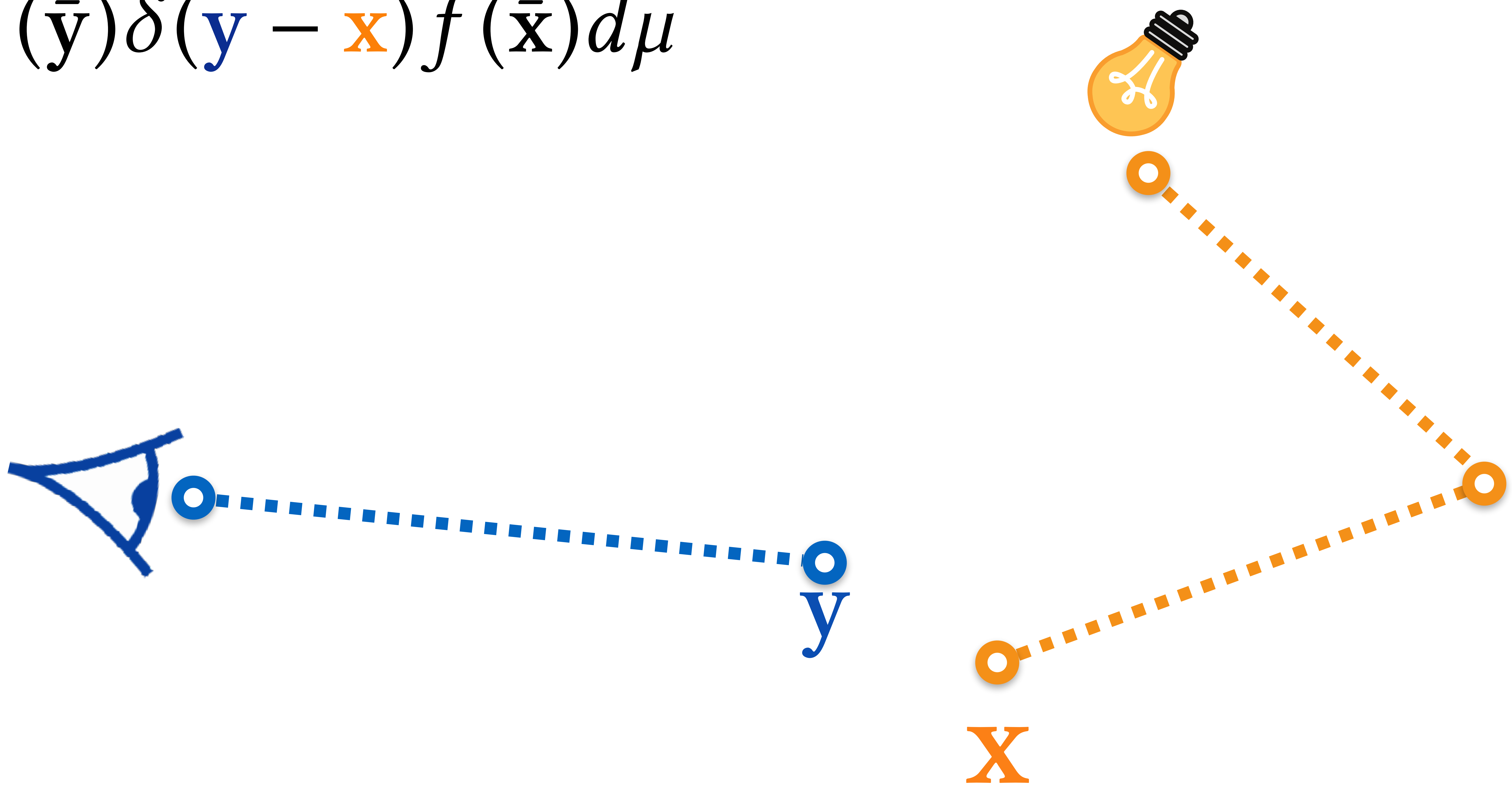
$$\approx \frac{f(\bar{\mathbf{y}})\delta(\mathbf{y} - \mathbf{x})f(\bar{\mathbf{x}})}{p(\bar{\mathbf{y}})p(\bar{\mathbf{x}})}$$

0 probability



Our approach

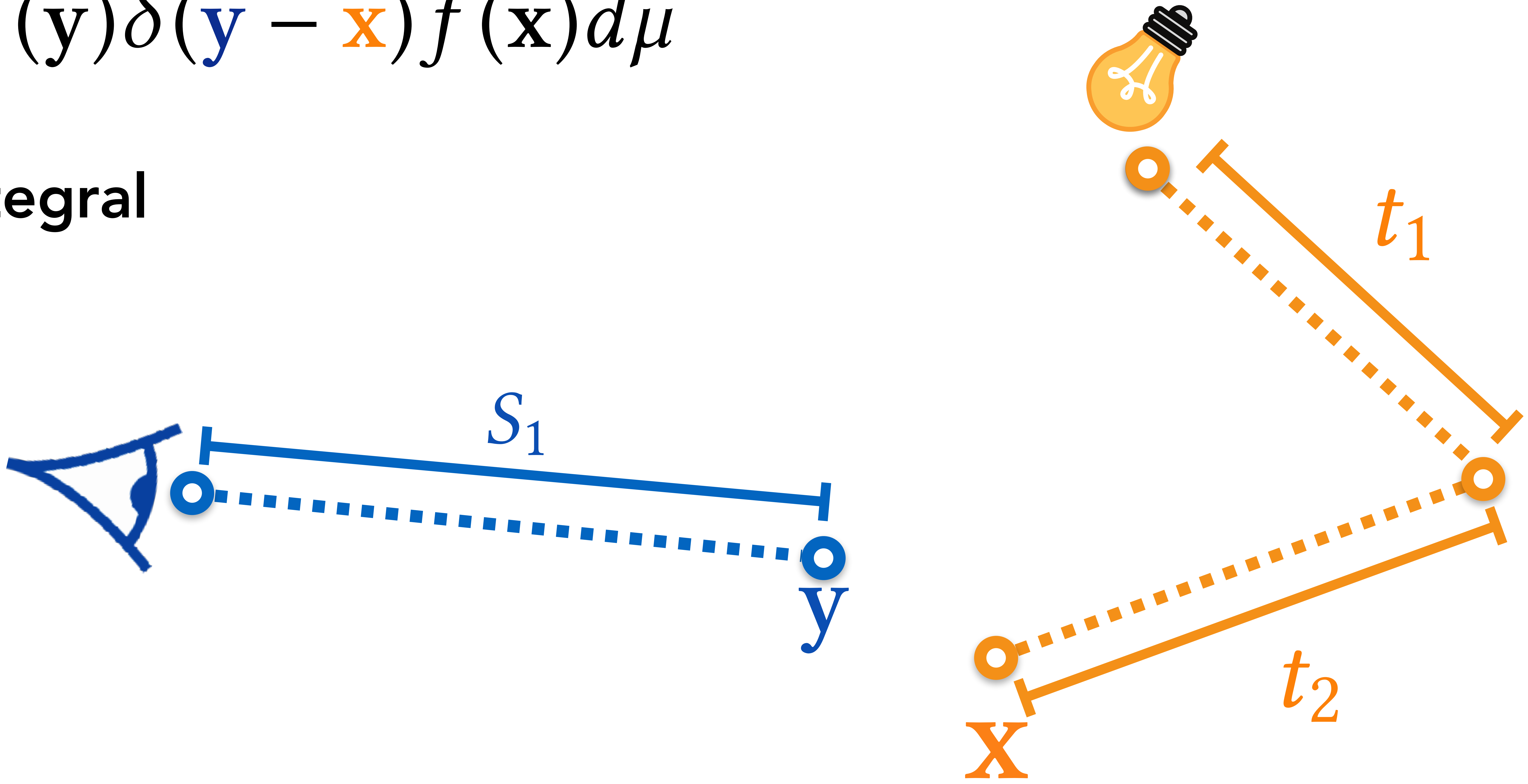
$$I = \int f(\bar{\mathbf{y}})\delta(\mathbf{y} - \mathbf{x})f(\bar{\mathbf{x}})d\mu$$



Our approach

$$I = \int f(\bar{\mathbf{y}})\delta(\mathbf{y} - \mathbf{x})f(\bar{\mathbf{x}})d\mu$$

split integral

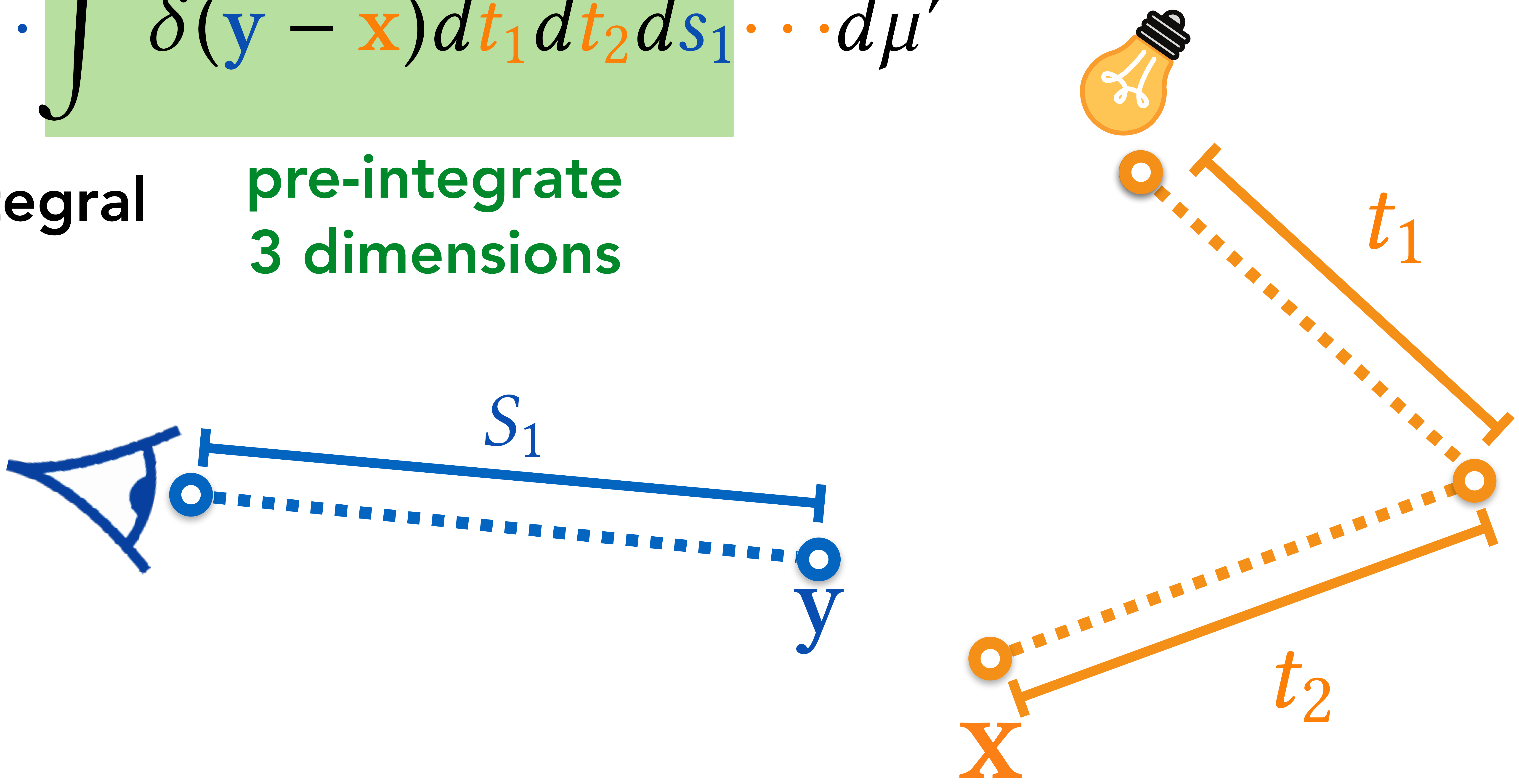


Our approach

$$I = \int \cdots \int \delta(\mathbf{y} - \mathbf{x})\, dt_1\, dt_2\, ds_1 \cdots d\mu'$$

split integral

pre-integrate
3 dimensions

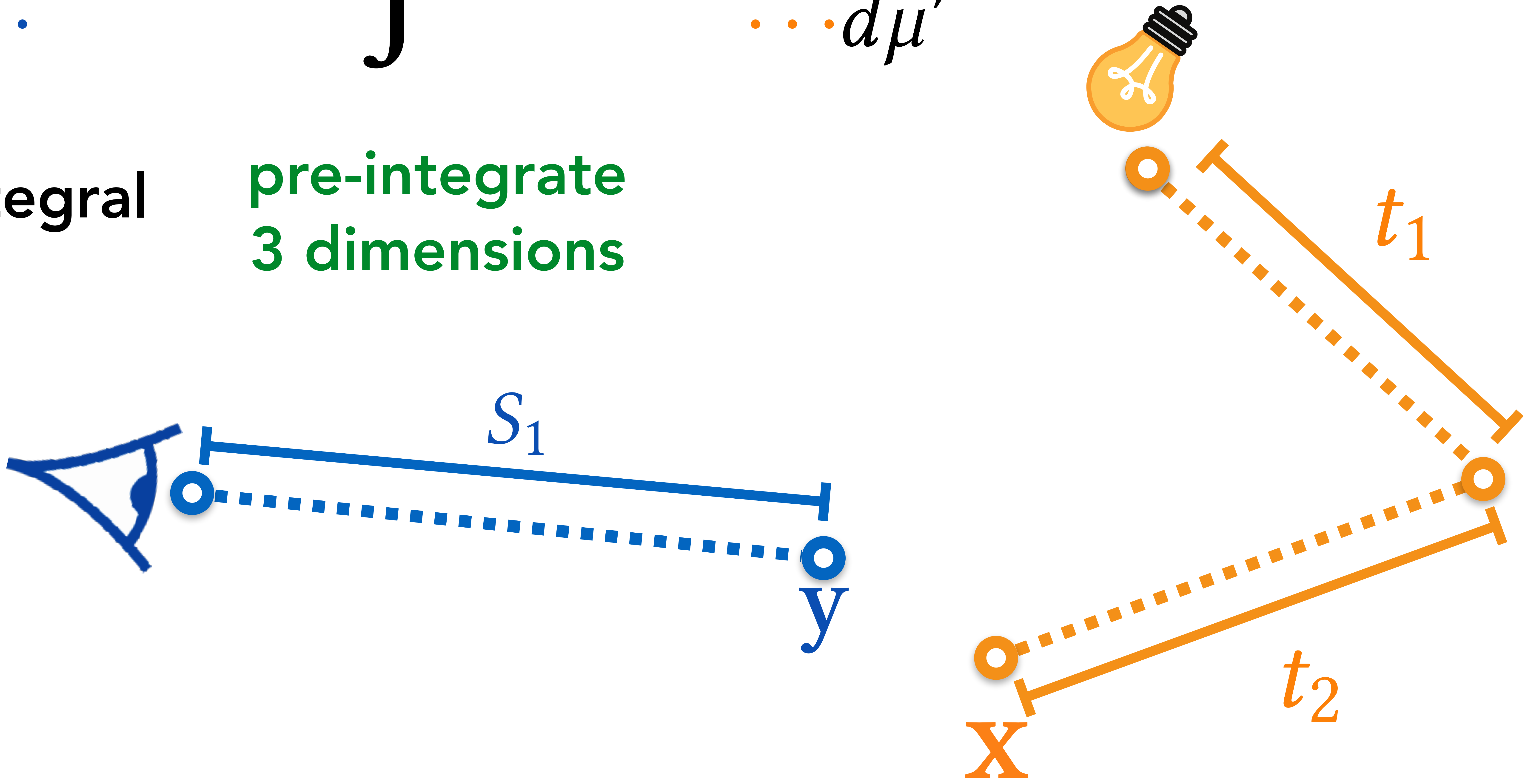


Our approach

$$I = \int \cdots \quad \mathbf{J} \quad \cdots d\mu'$$

split integral

pre-integrate
3 dimensions



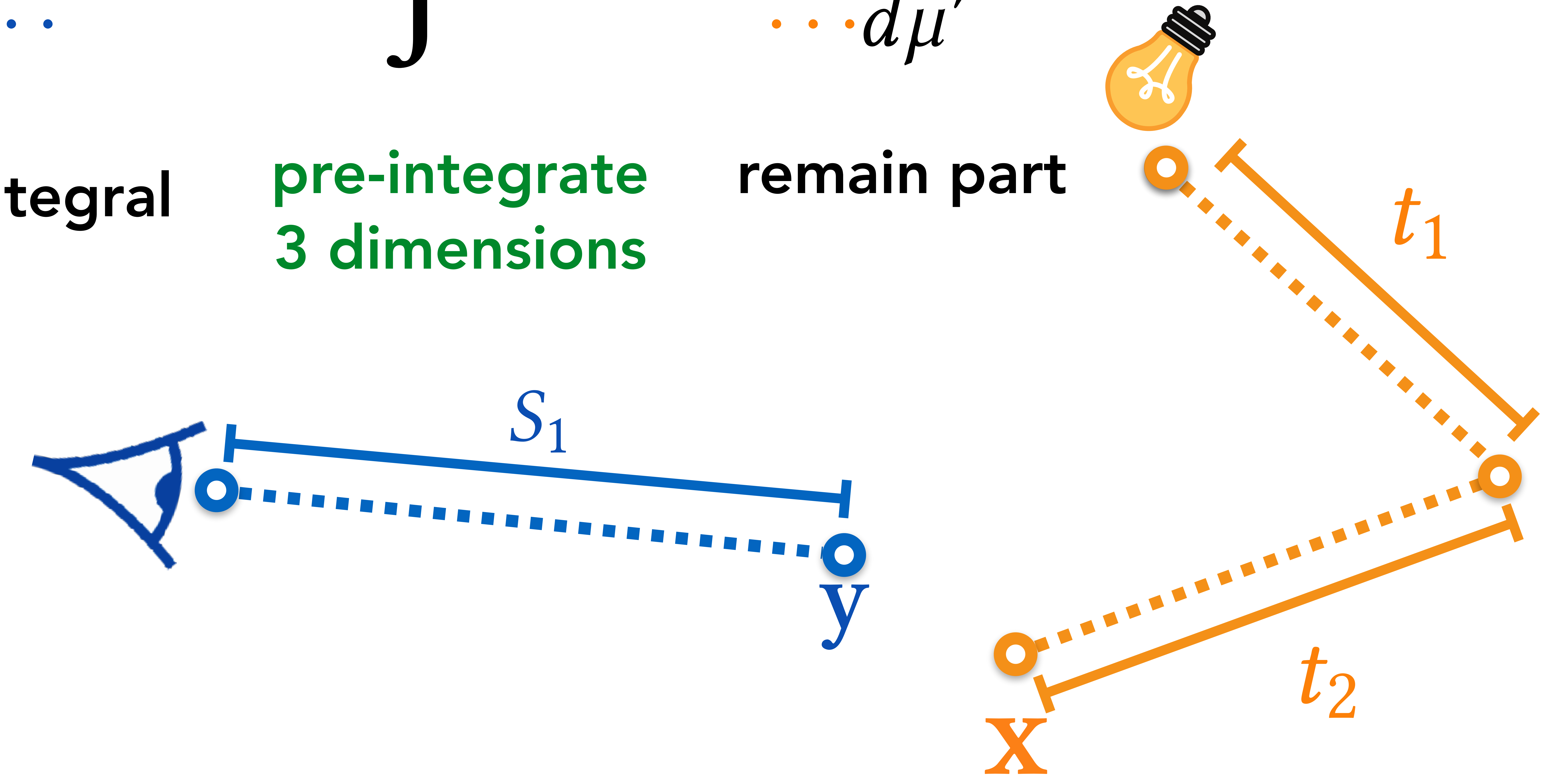
Our approach

$$I = \int \cdots \quad \mathbf{J} \quad \cdots d\mu'$$

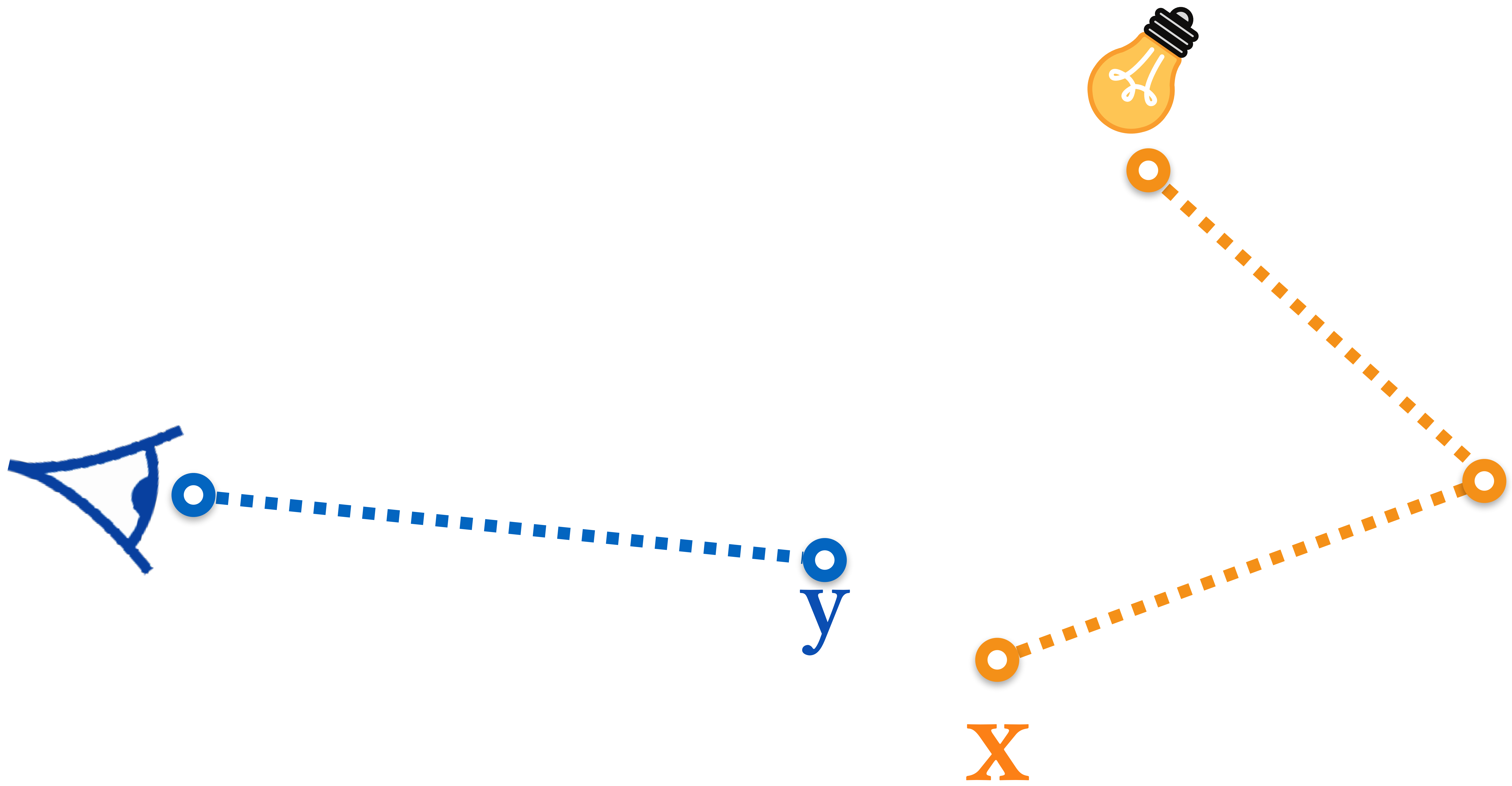
split integral

pre-integrate
3 dimensions

remain part

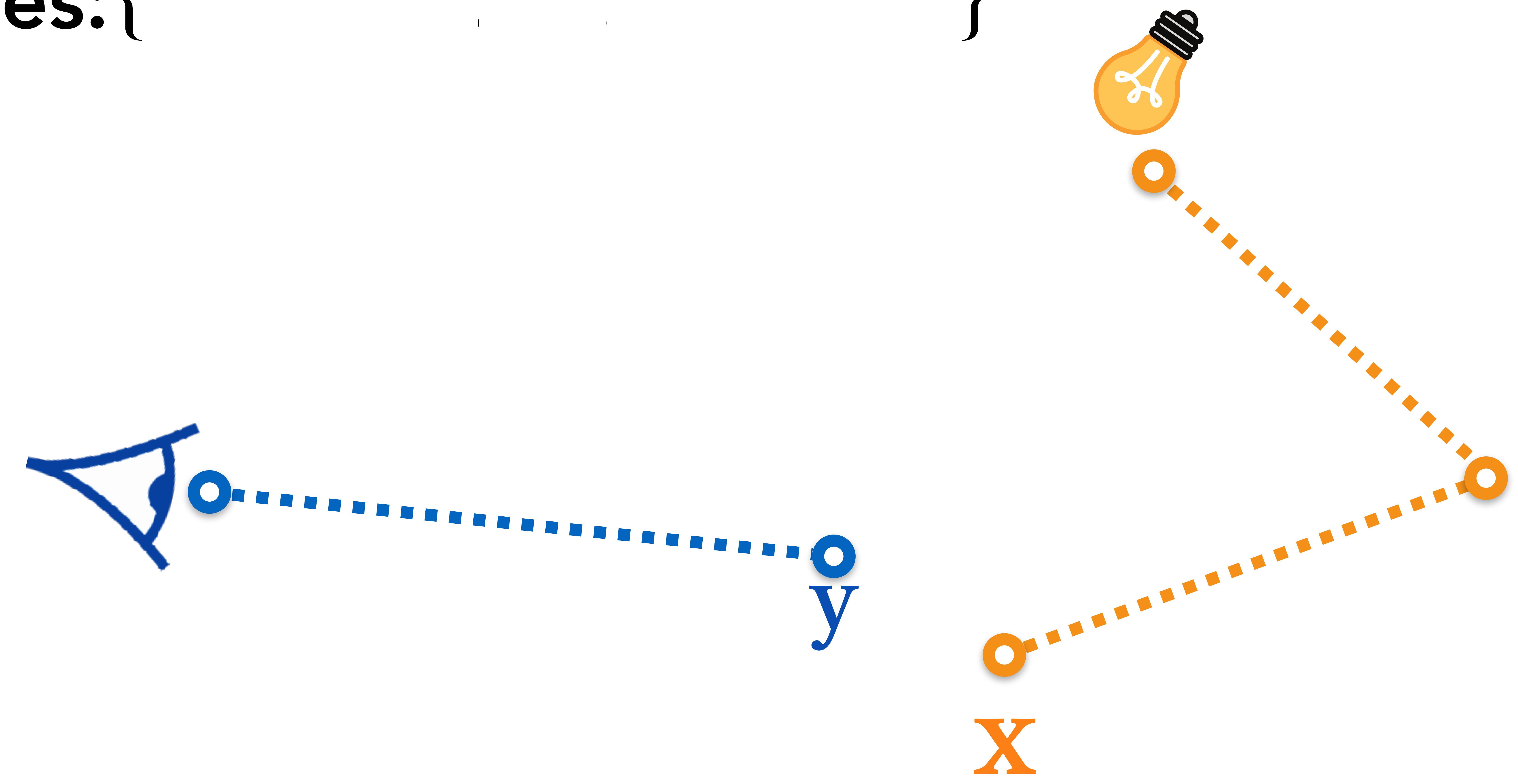


Our approach



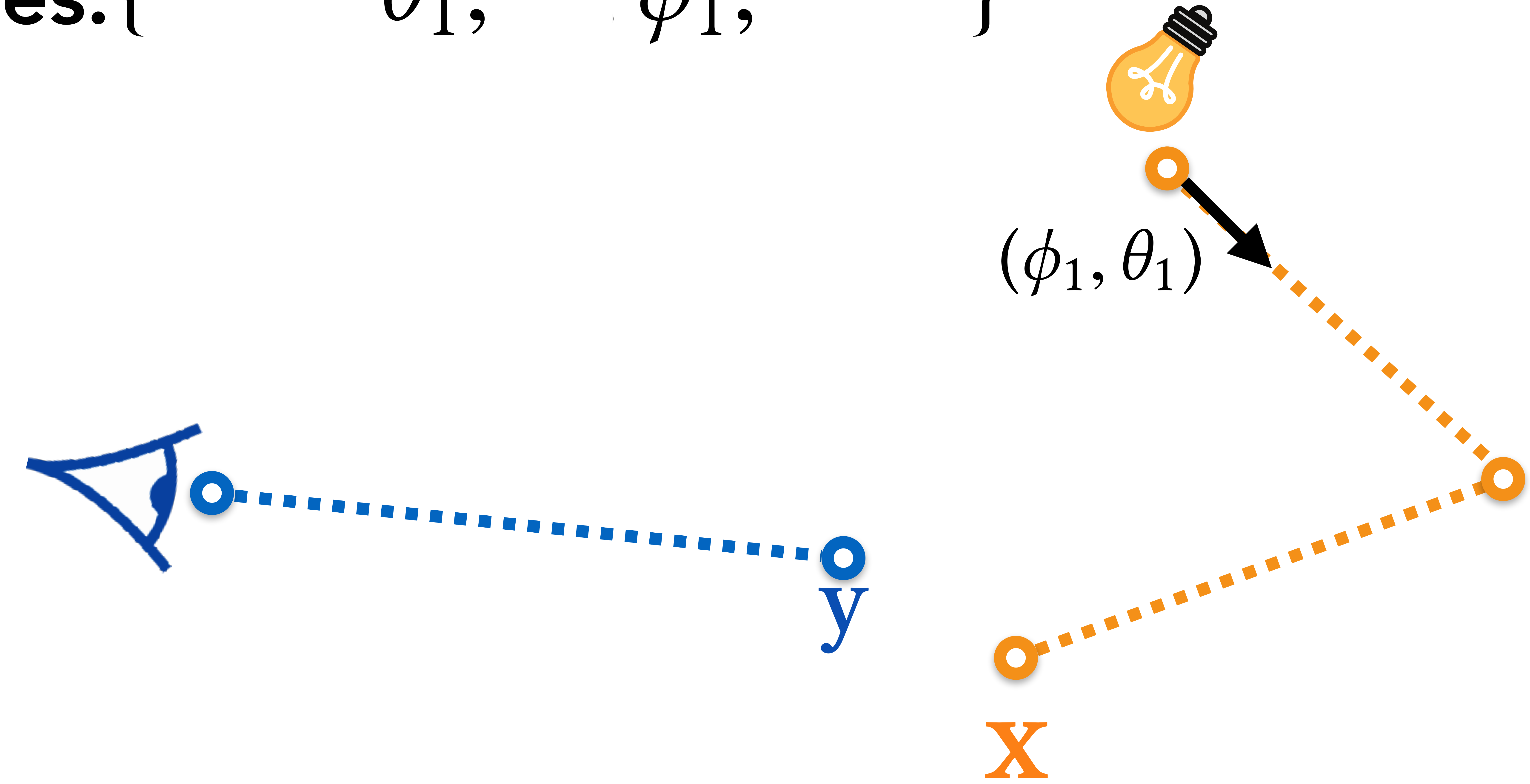
Our approach

Variables: { , , }



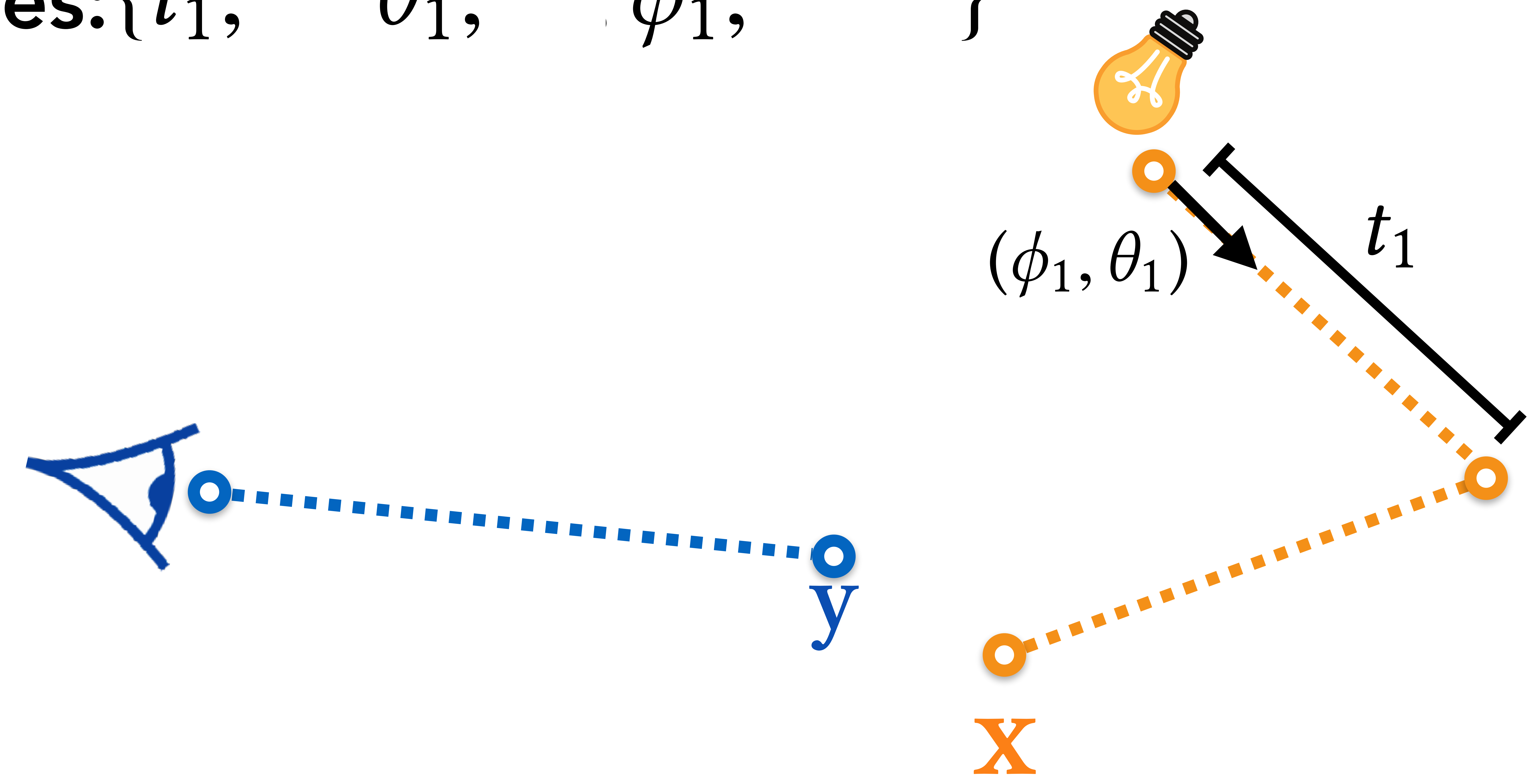
Our approach

Variables: $\{ \quad \theta_1, \quad \phi_1, \quad \}$



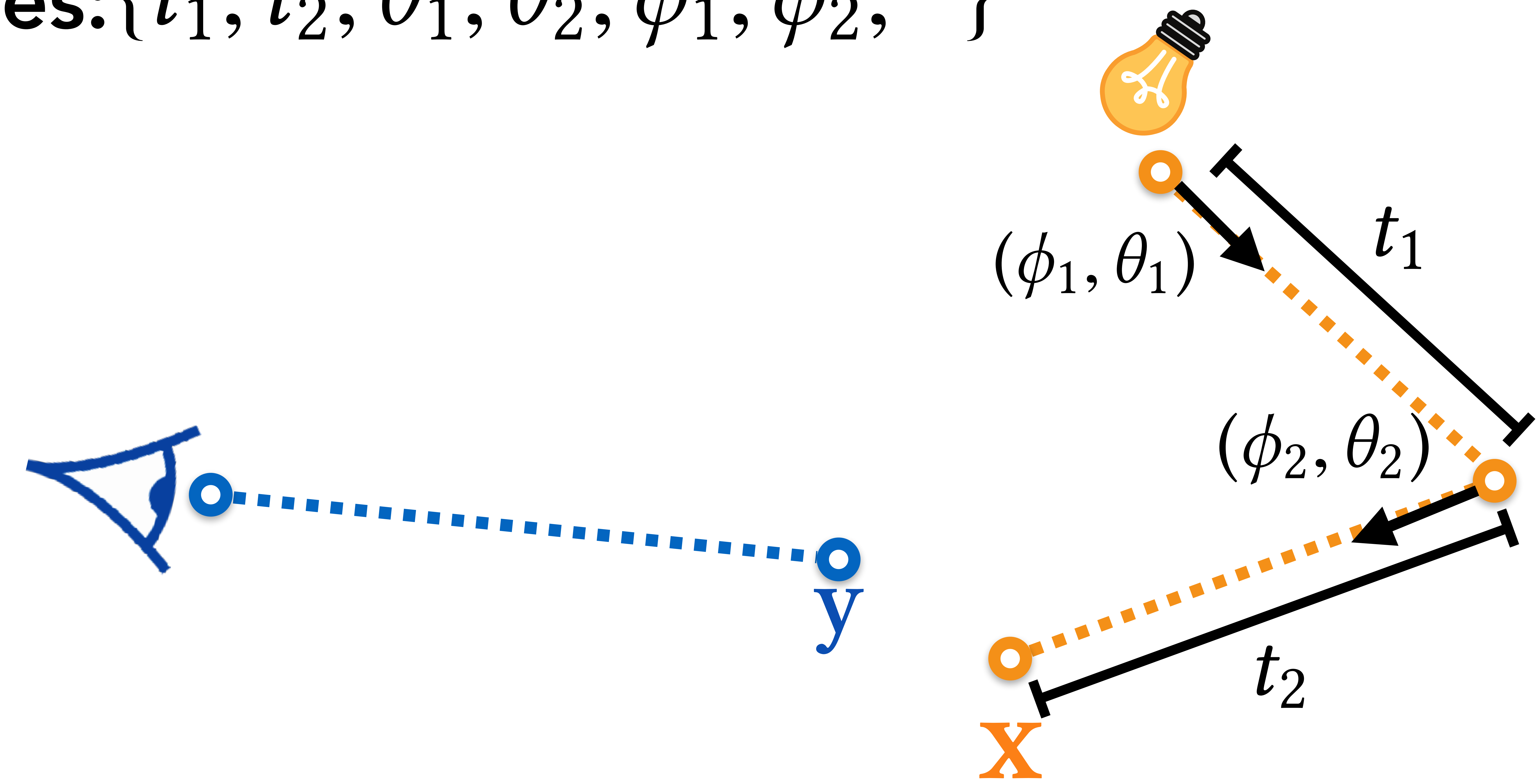
Our approach

Variables: $\{t_1, \quad \theta_1, \quad \phi_1, \quad \}$



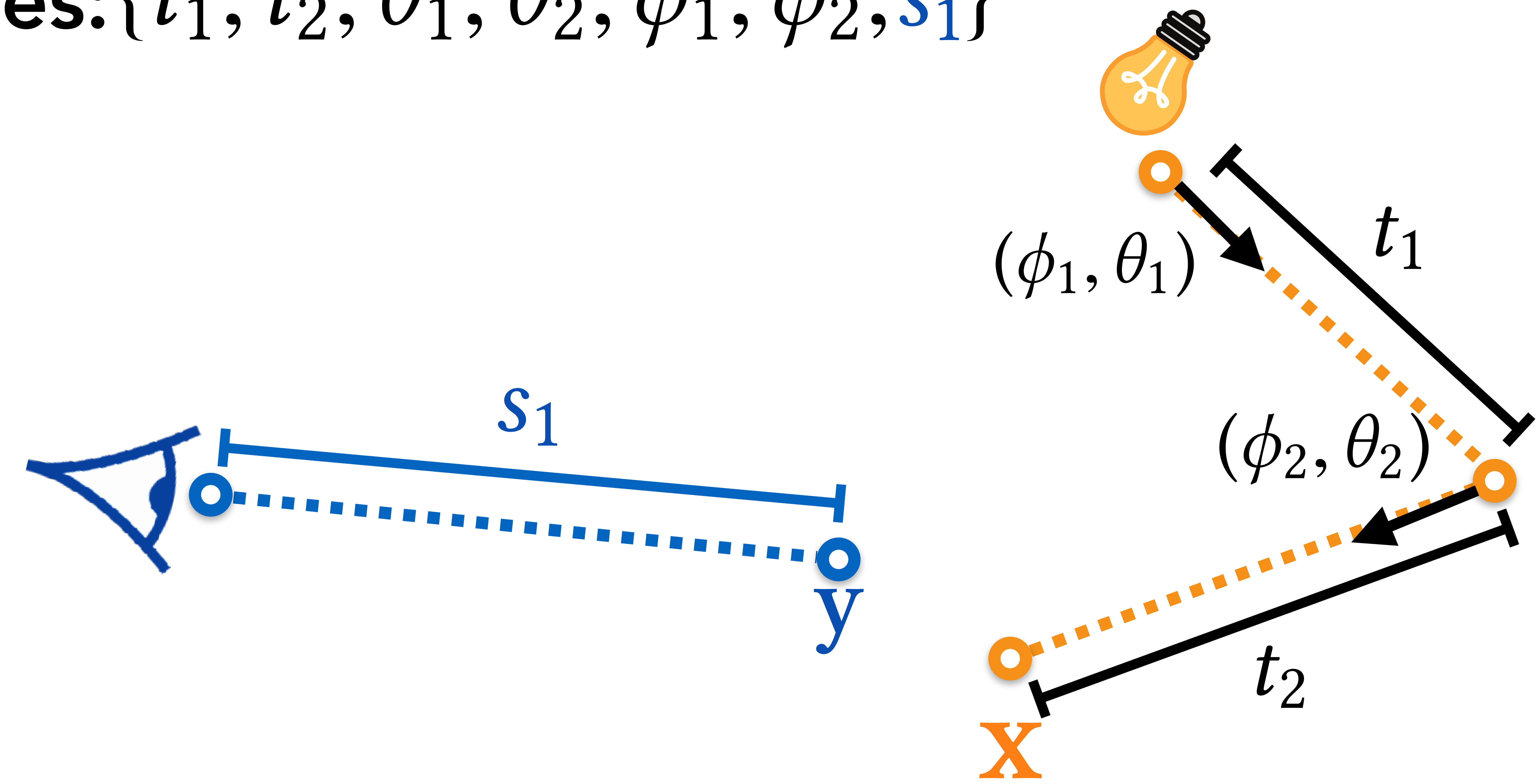
Our approach

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, \quad\}$



Our approach

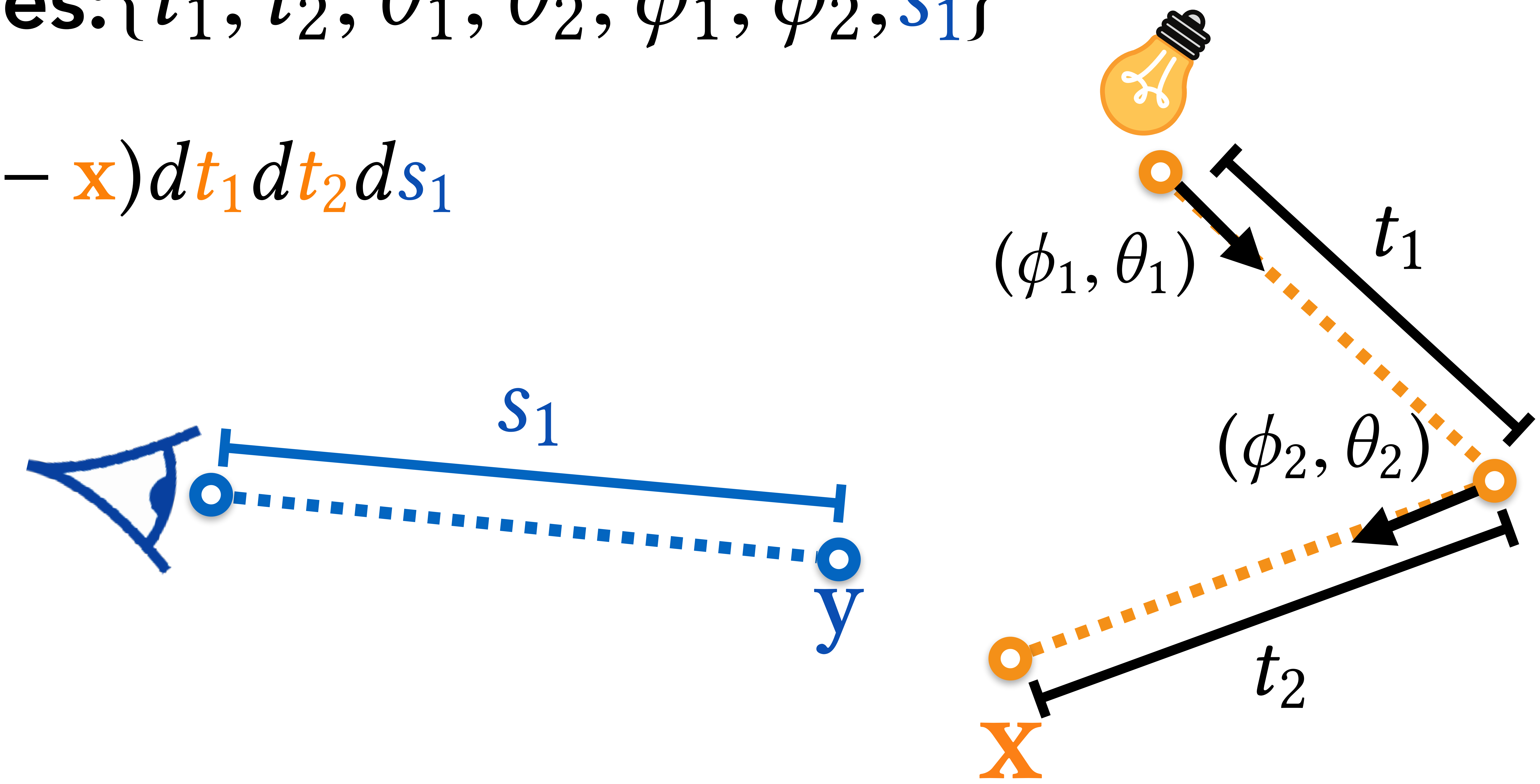
Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$



Our approach

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

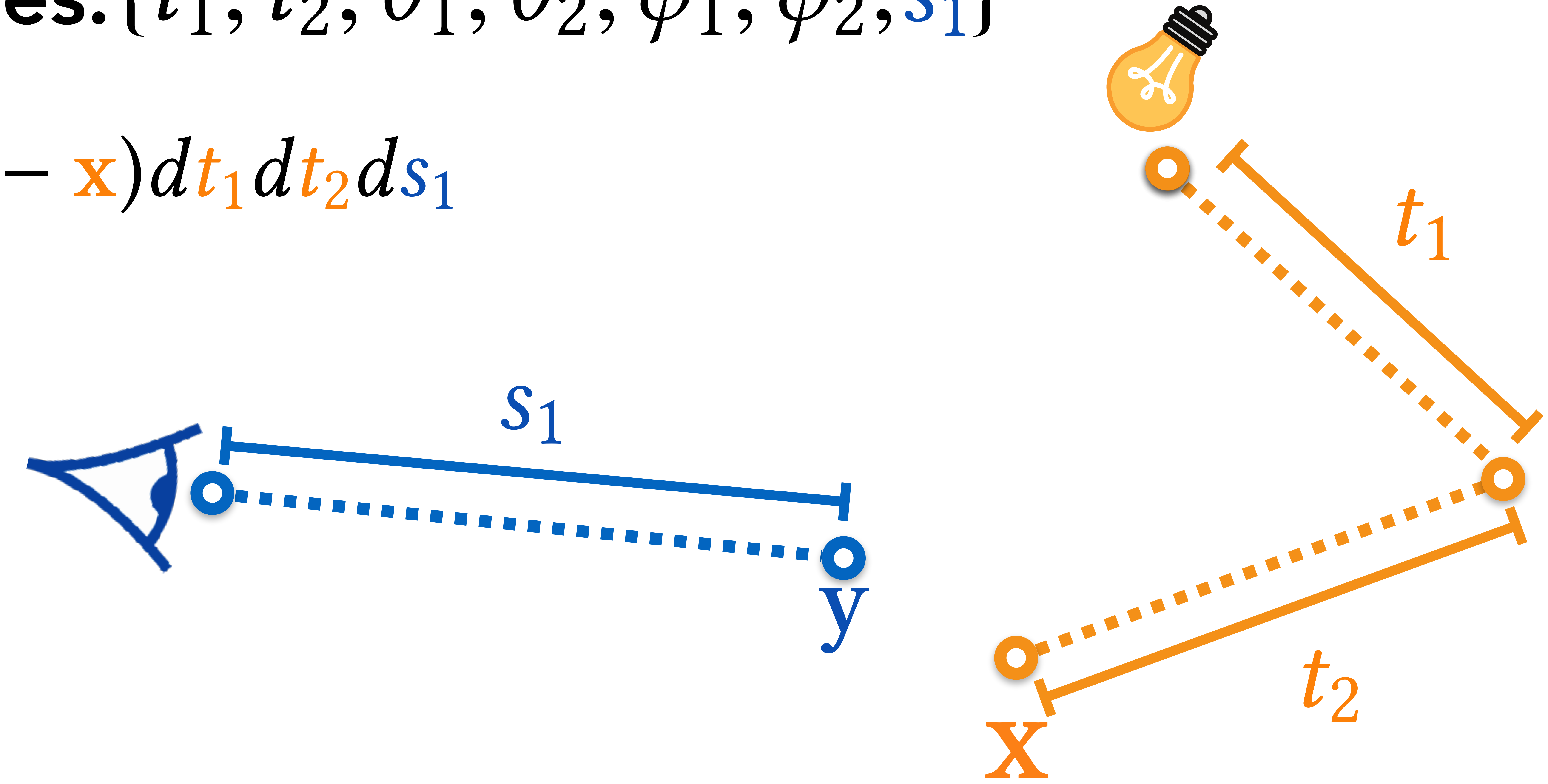
$$\int \delta(\mathbf{y} - \mathbf{x})\, dt_1\, dt_2\, ds_1$$



Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

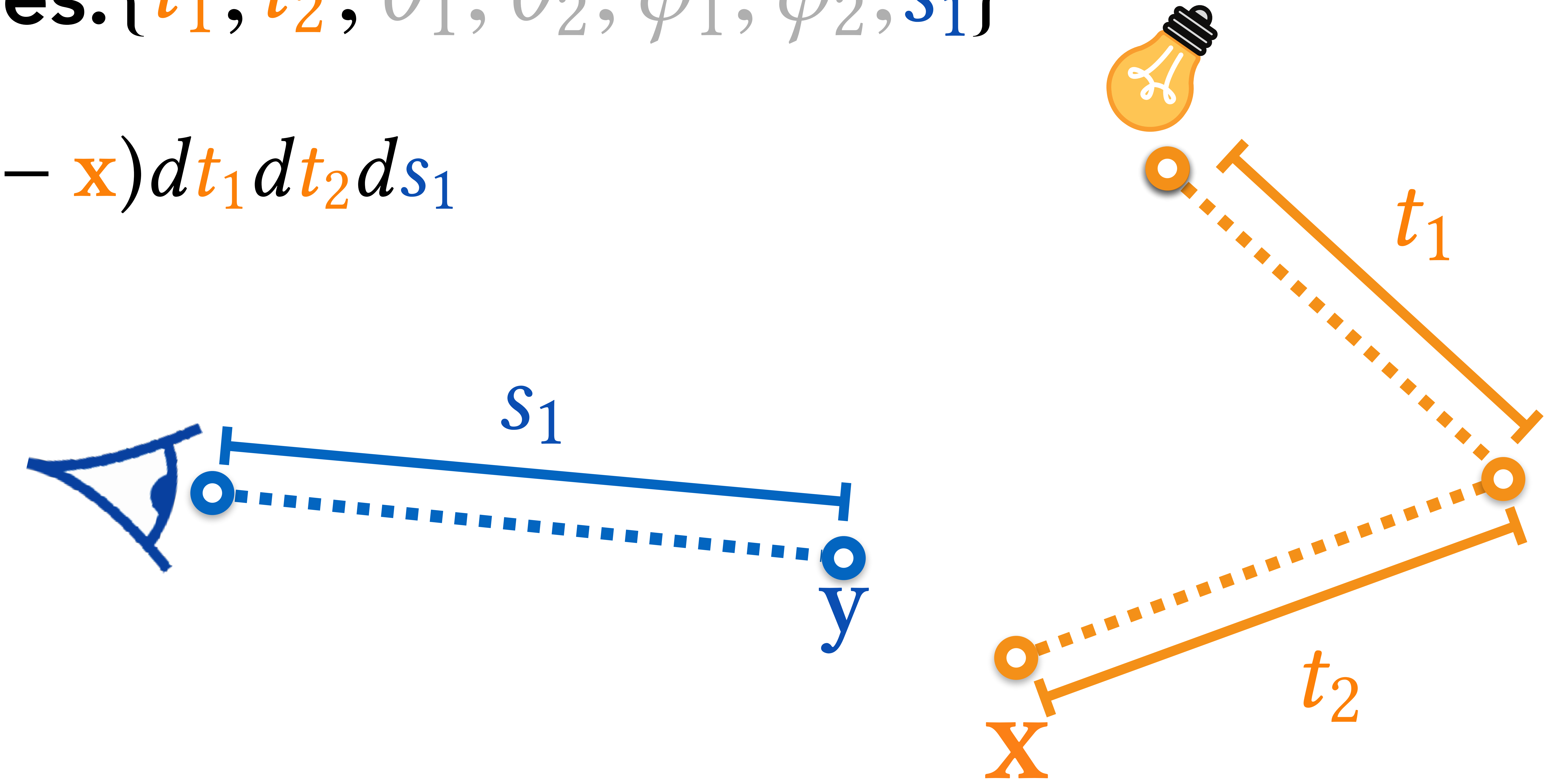
$$\int \delta(\mathbf{y} - \mathbf{x})\, dt_1\, dt_2\, ds_1$$



Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

$$\int \delta(\mathbf{y} - \mathbf{x})\,dt_1\,dt_2\,ds_1$$



Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

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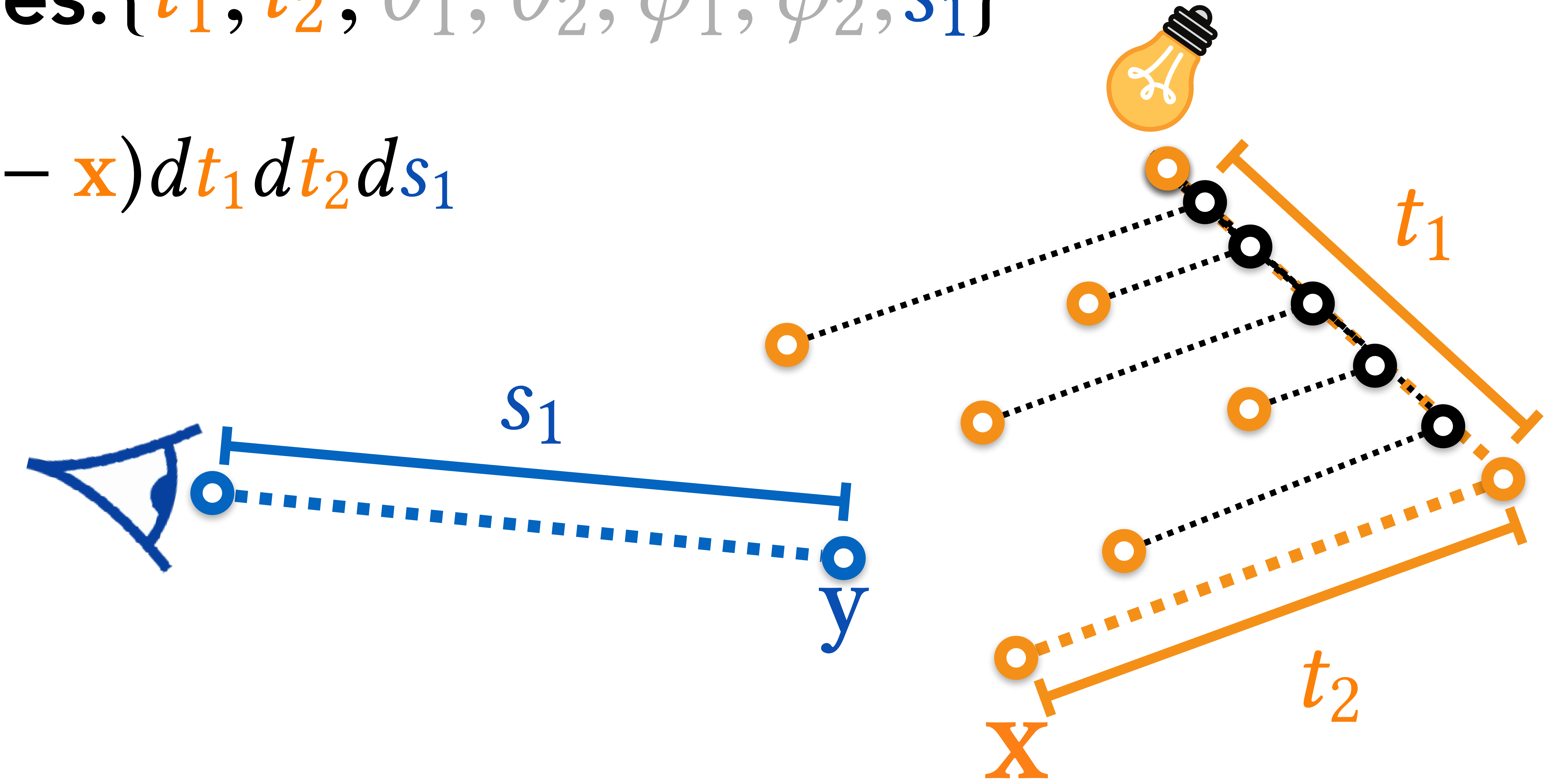

Photon surfaces

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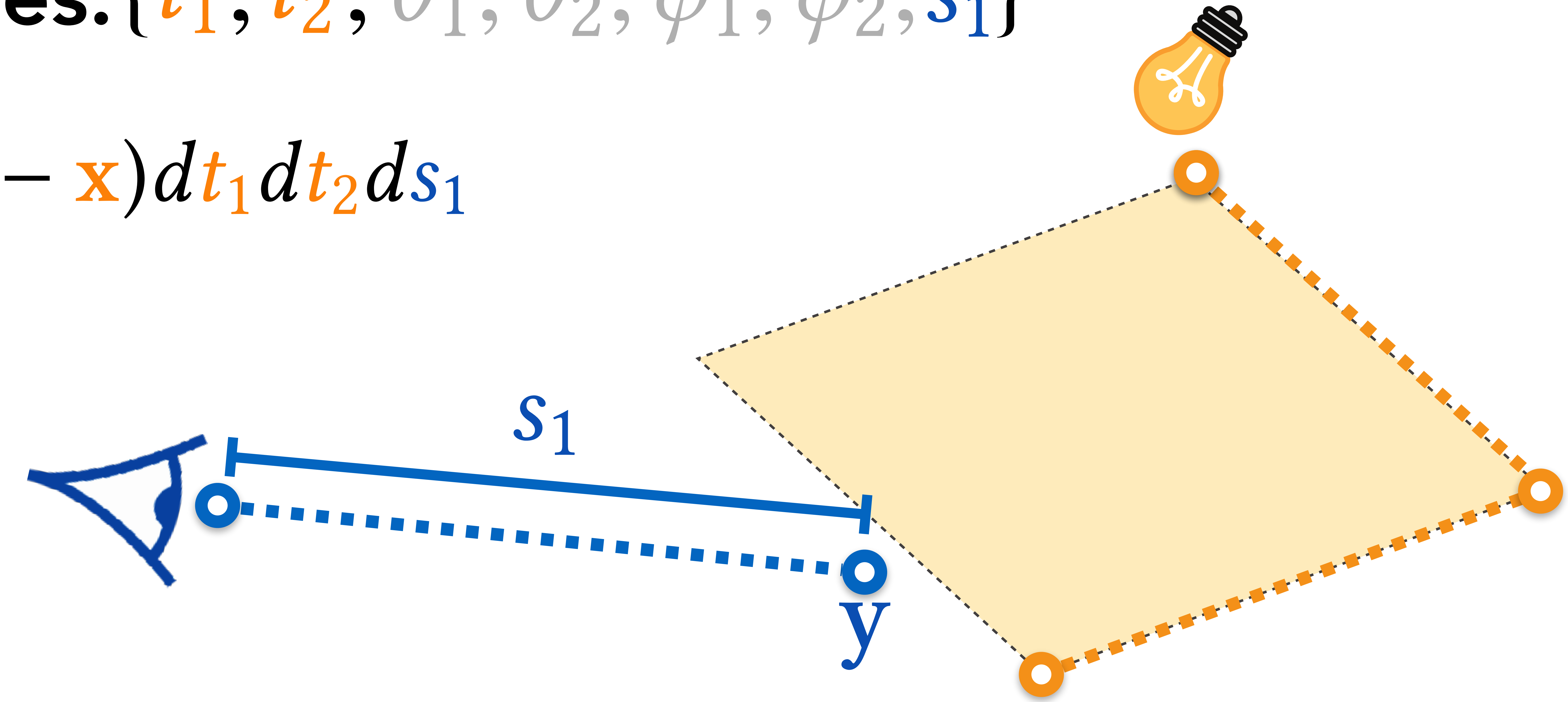
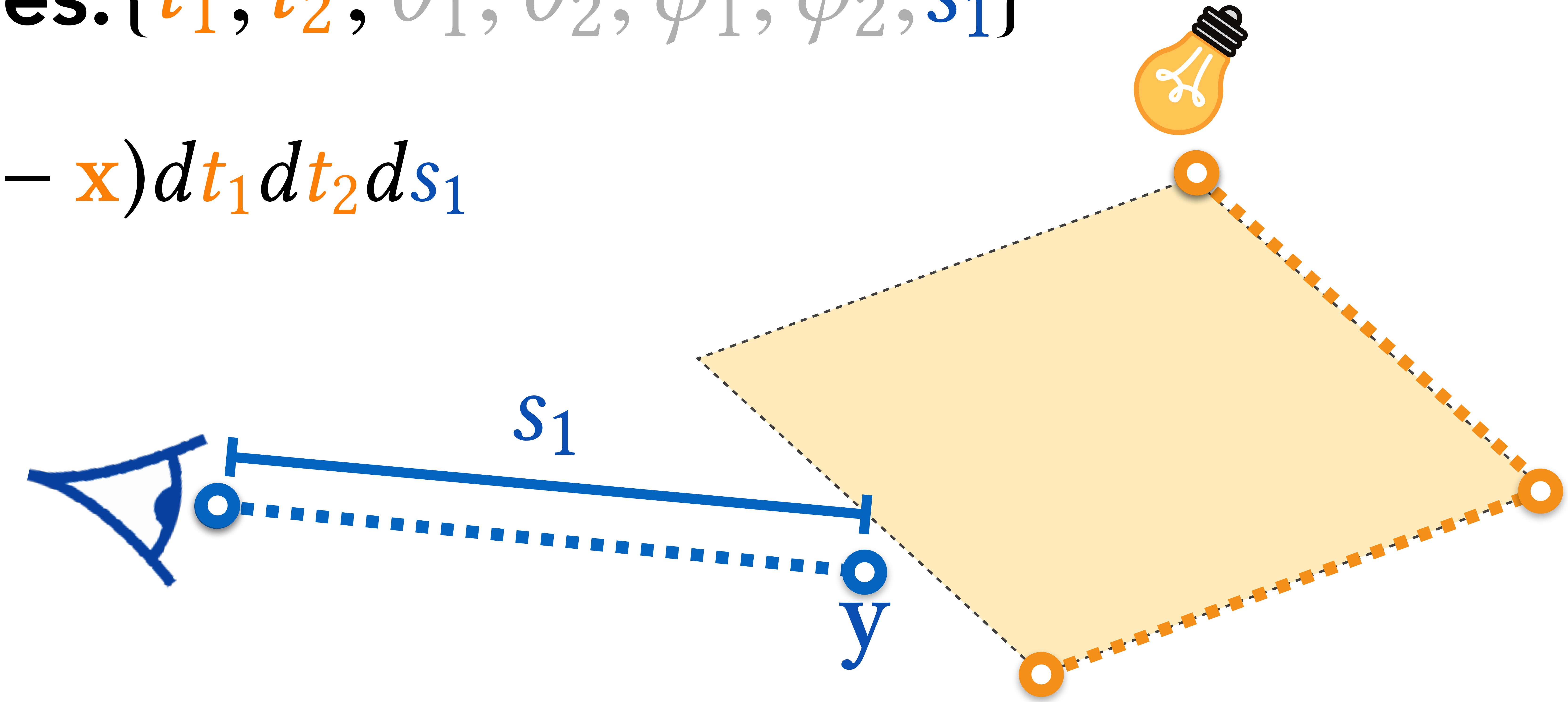


Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

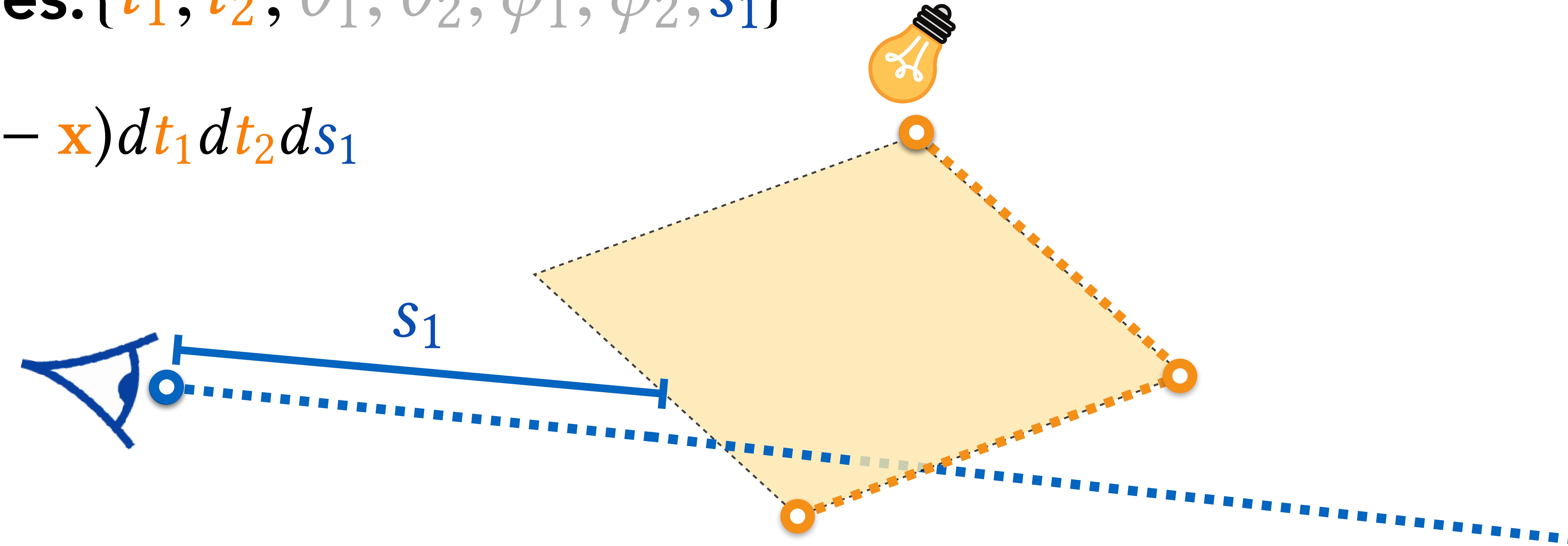
$$\int \delta(\mathbf{y} - \mathbf{x})\, dt_1\, dt_2\, ds_1$$



Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

$$\int \delta(\mathbf{y} - \mathbf{x})\, dt_1\, dt_2\, ds_1$$



Photon surfaces

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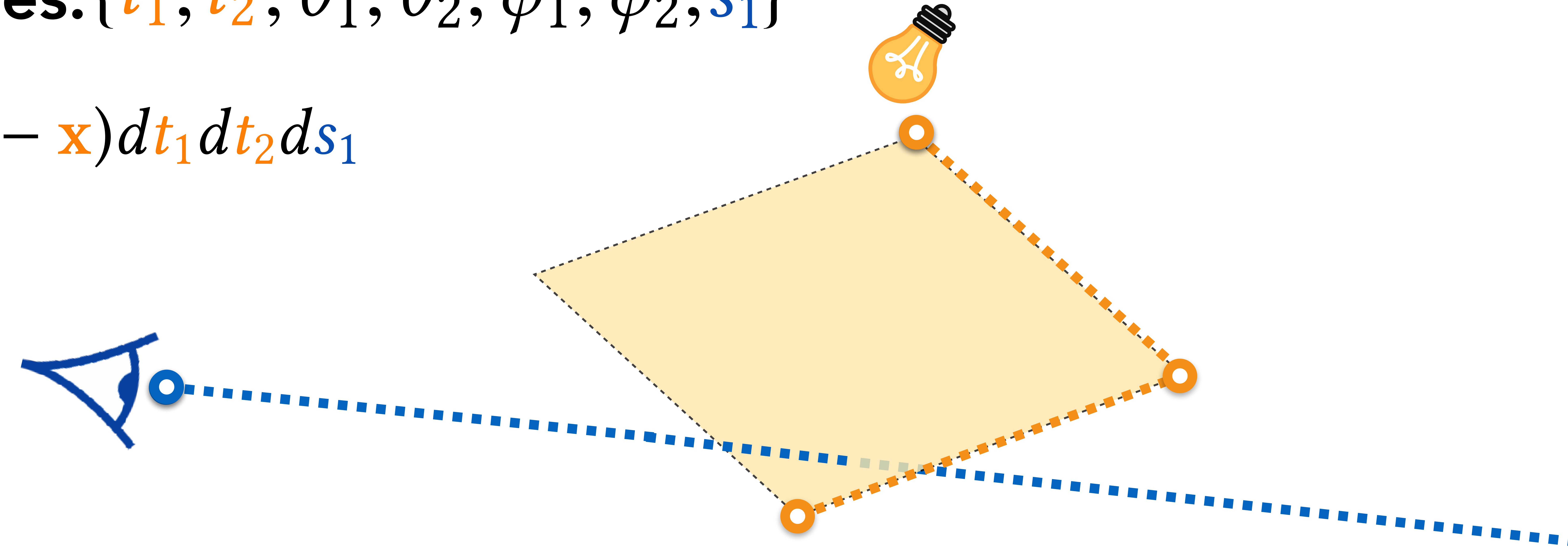
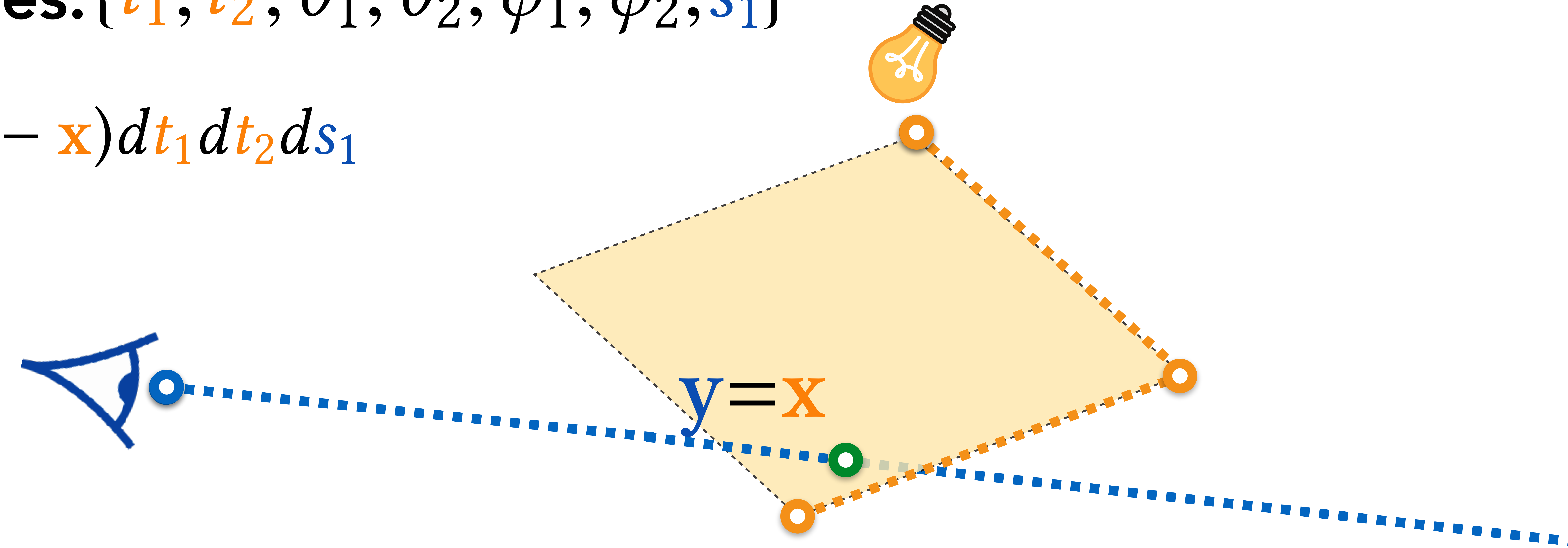


Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

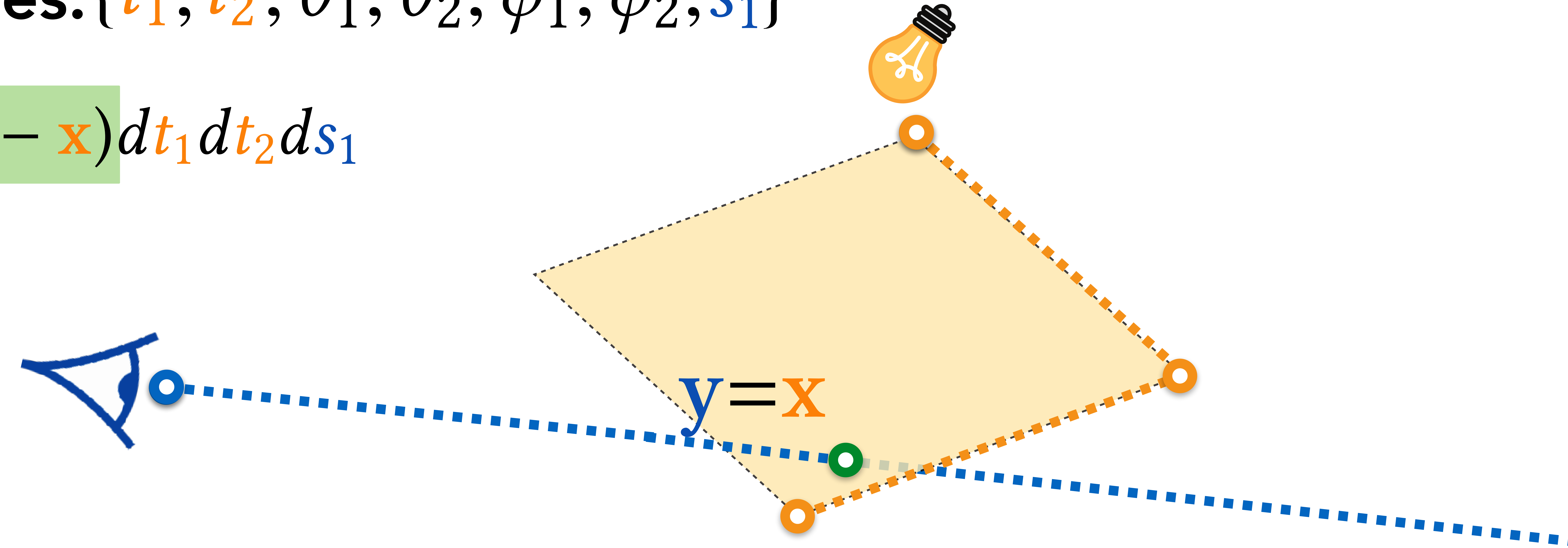
$$\int \delta(\mathbf{y} - \mathbf{x})\,dt_1\,dt_2\,ds_1$$



Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

$$\int \delta(\mathbf{y} - \mathbf{x}) dt_1 dt_2 ds_1$$



Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

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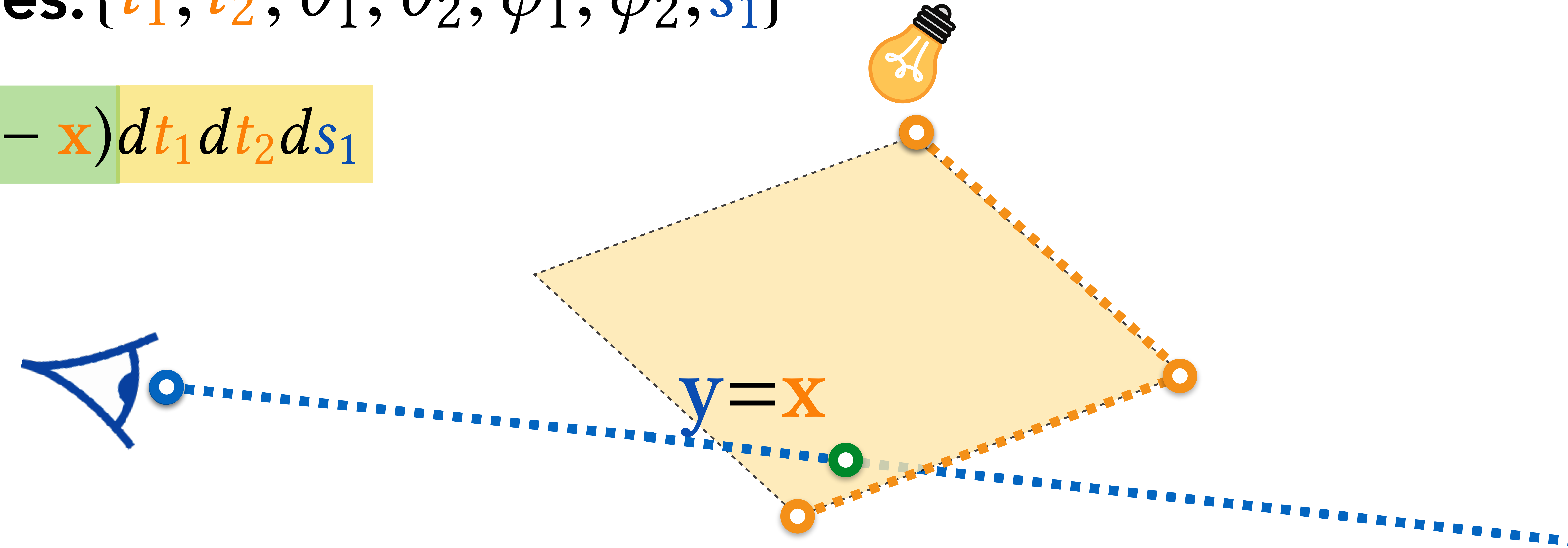
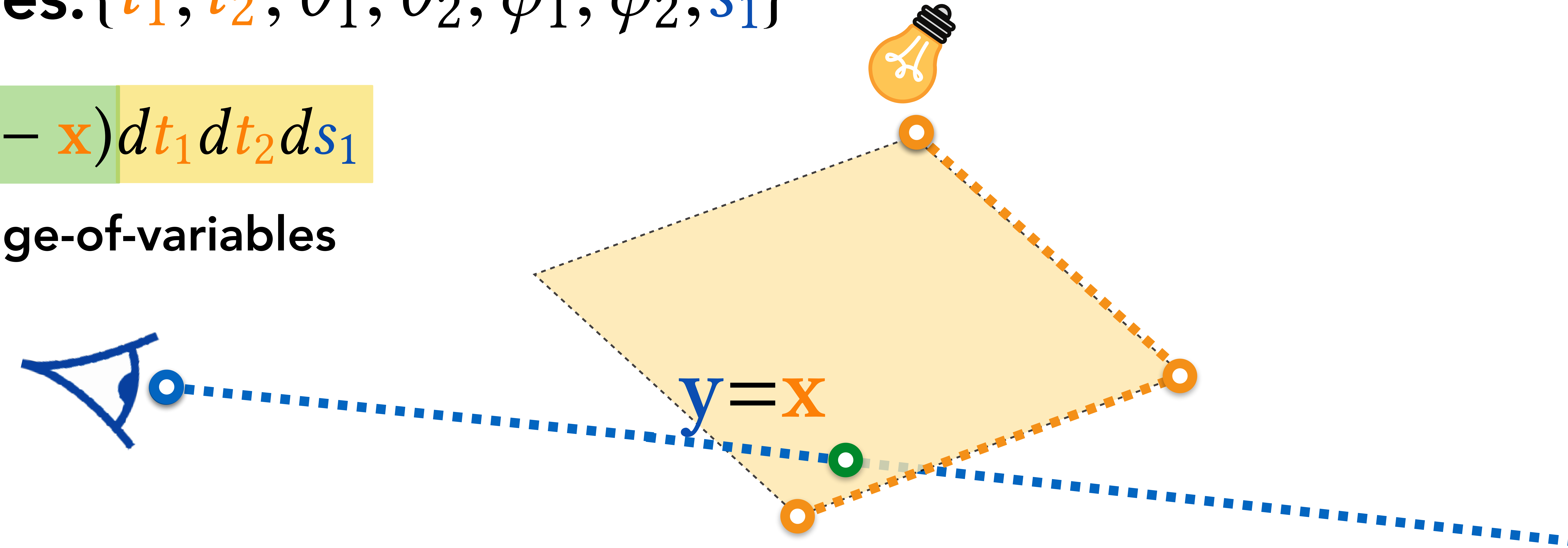


Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

$$\int \delta(\mathbf{y} - \mathbf{x})\, dt_1\, dt_2\, ds_1$$

change-of-variables

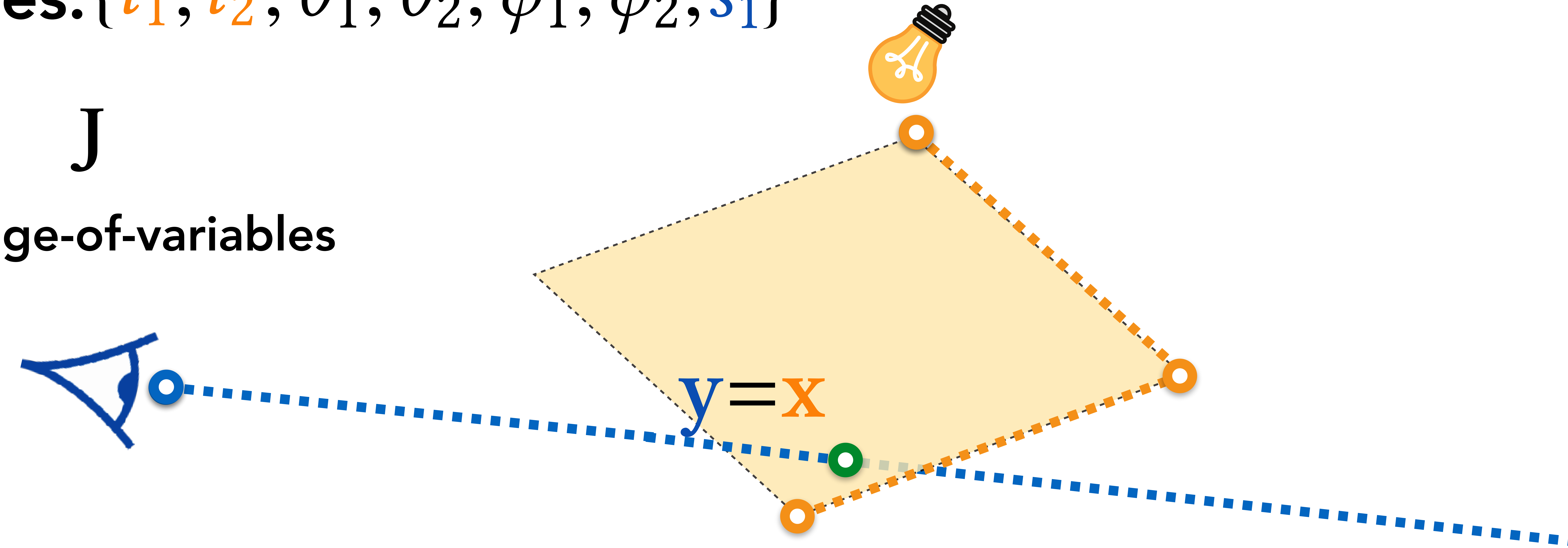


Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

J

change-of-variables

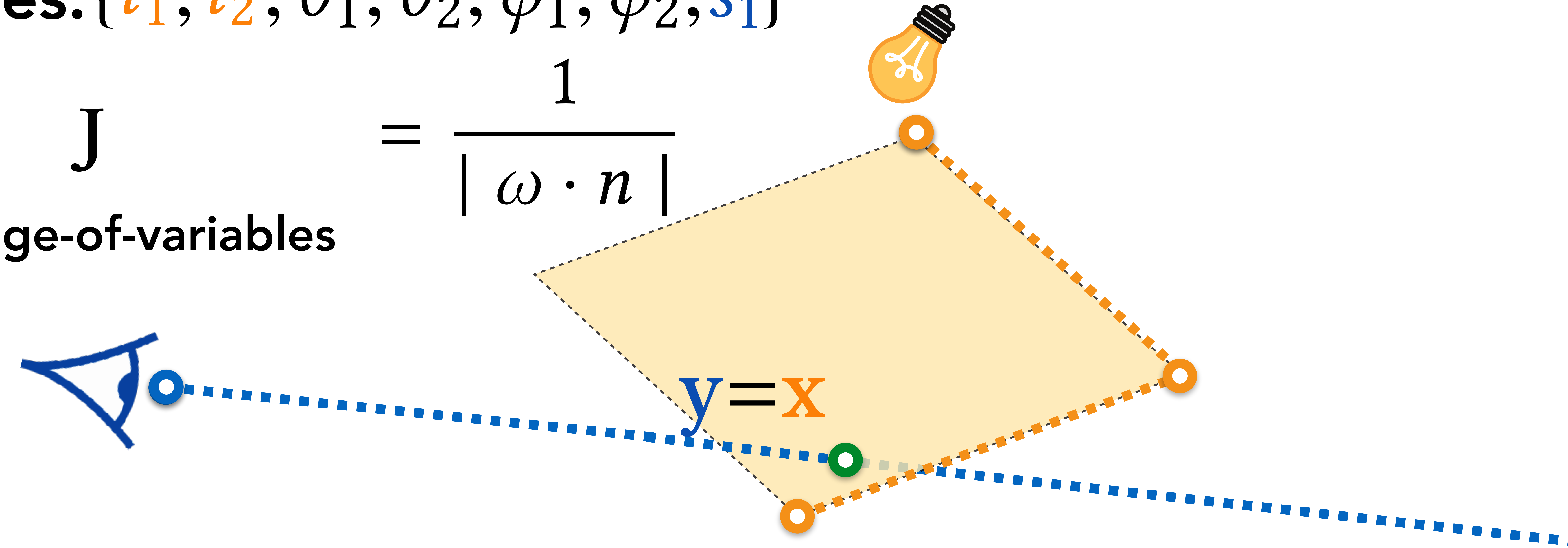


Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

$$\mathrm{J} = \frac{1}{|\,\omega \cdot n\,|}$$

change-of-variables

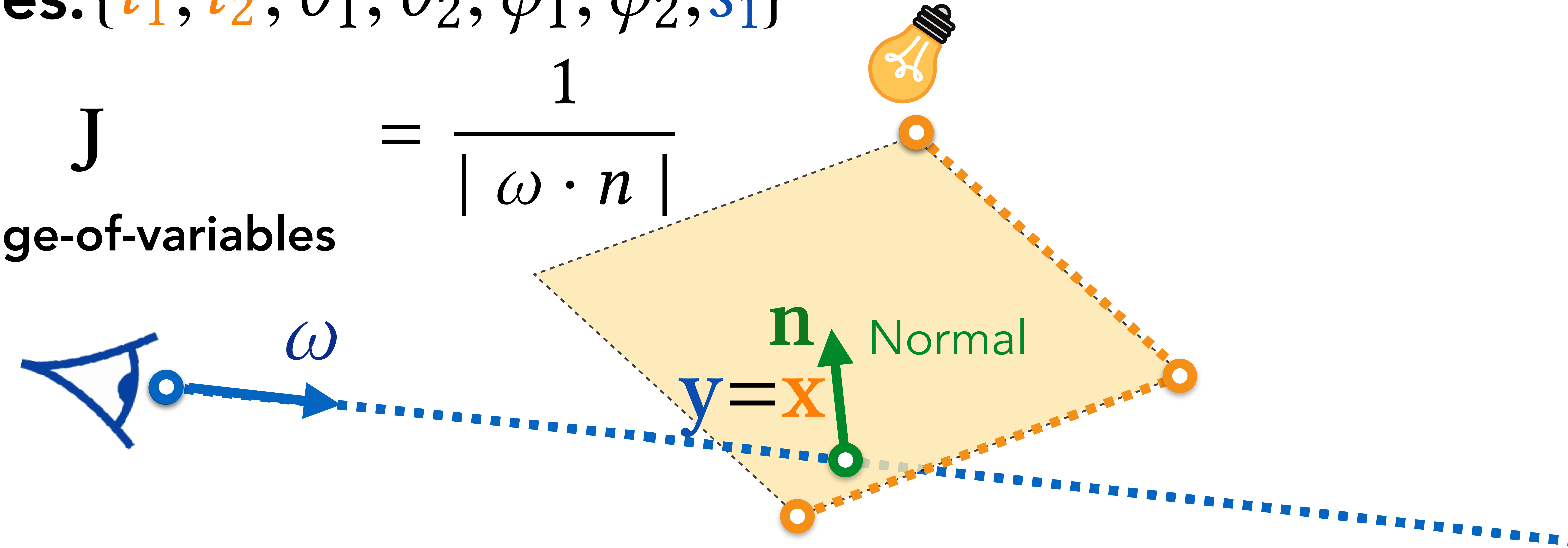


Photon surfaces

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

$$\mathrm{J} = \frac{1}{|\,\omega \cdot n\,|}$$

change-of-variables



Photon surfaces

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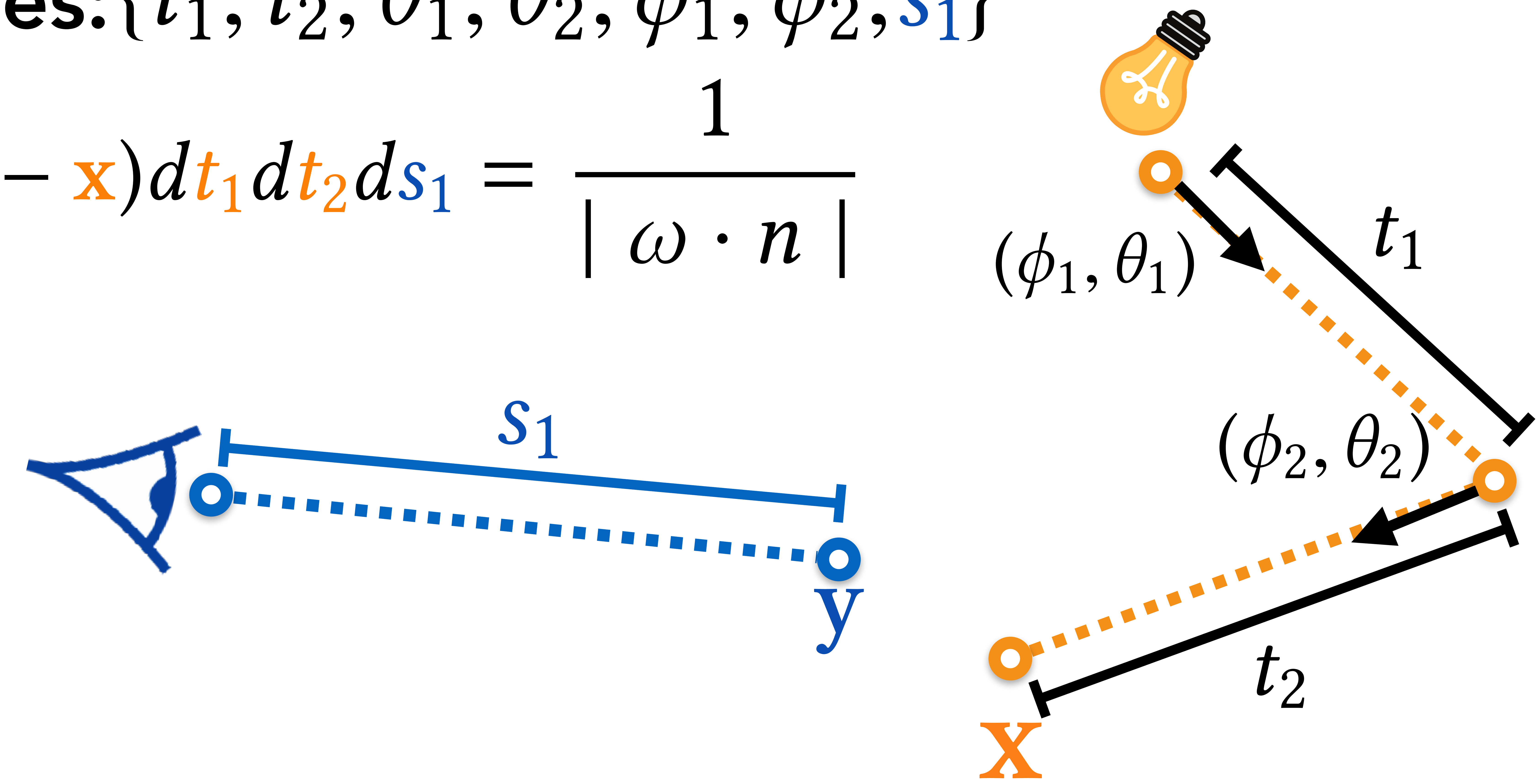
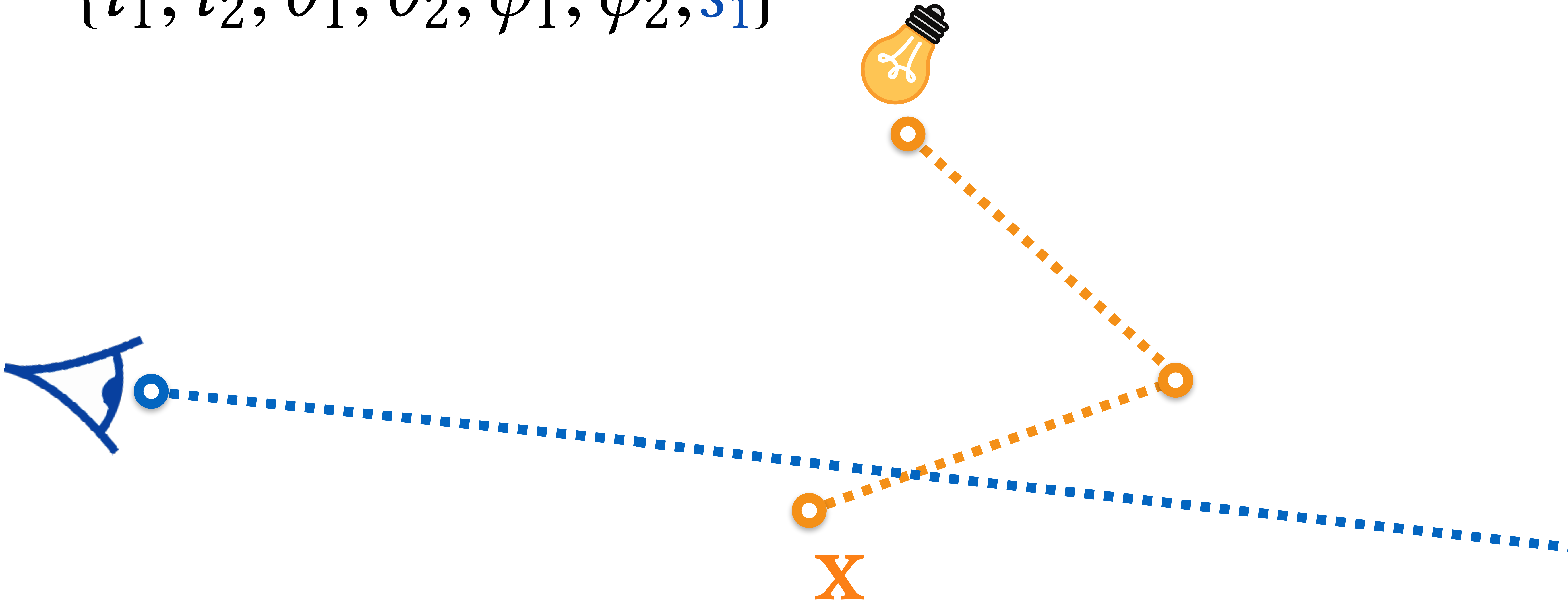
$$\int \delta(\mathbf{y} - \mathbf{x})\, dt_1\, dt_2\, ds_1 = \frac{1}{|\,\omega \cdot n\,|}$$



Some possible estimators

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$



Some possible estimators

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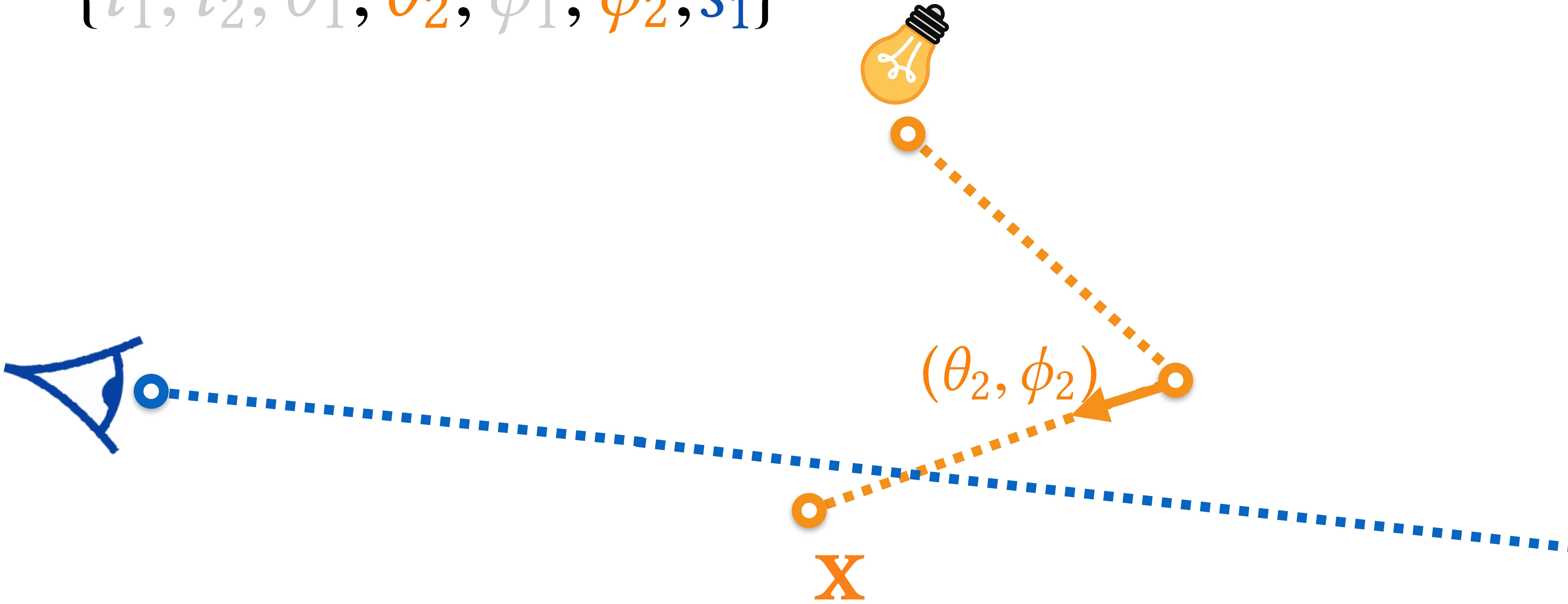
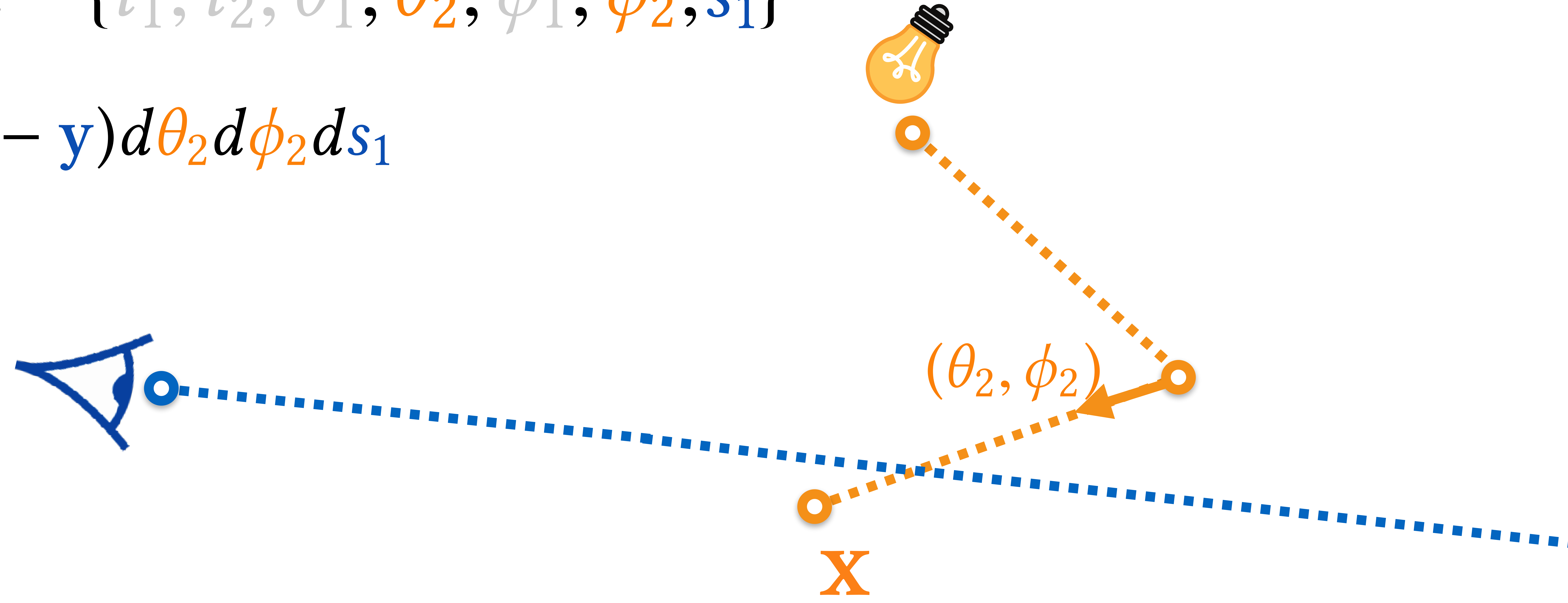


Some possible estimators

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

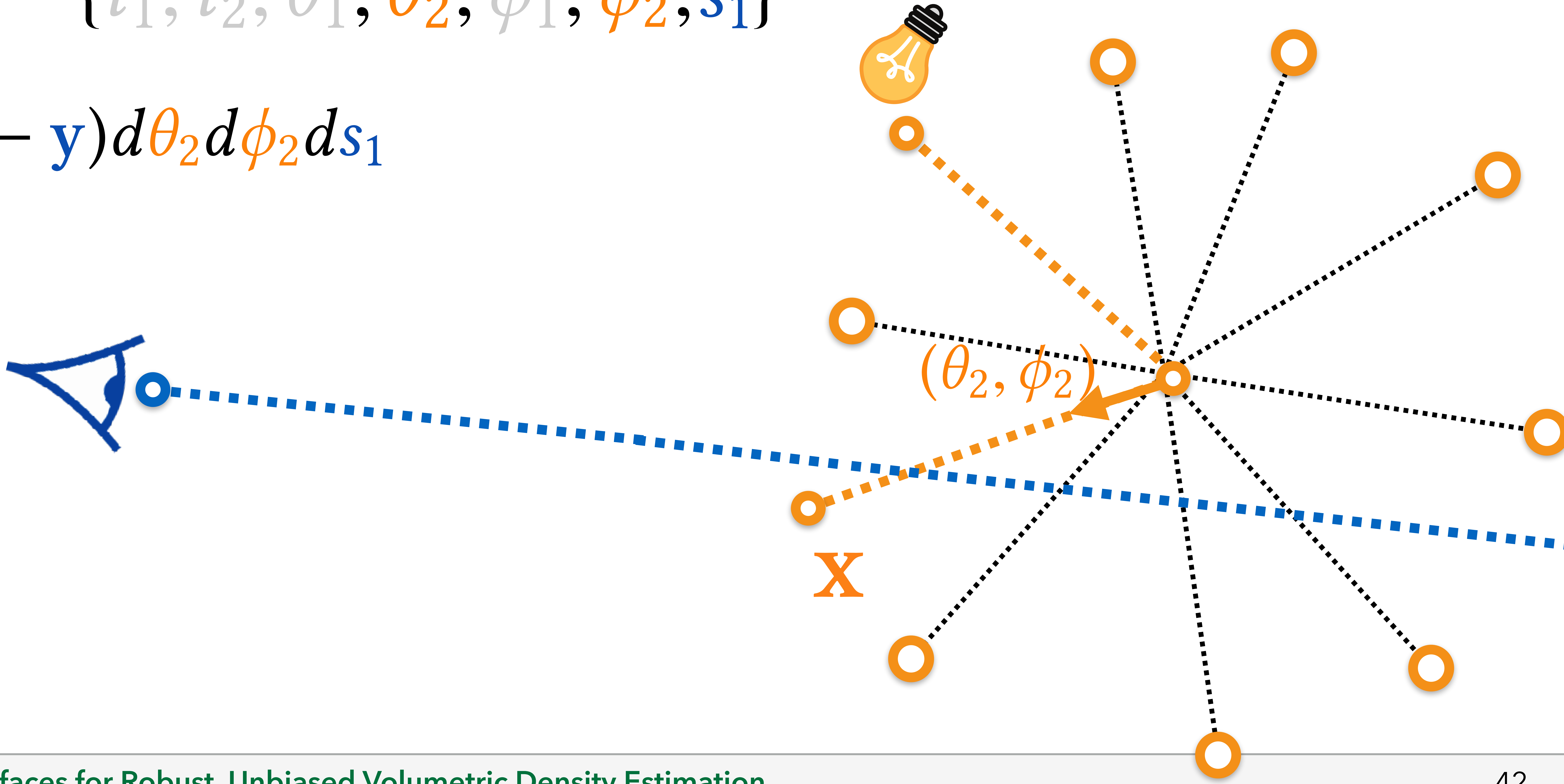
$$\int \delta(\mathbf{x} - \mathbf{y})\, d\theta_2\, d\phi_2\, ds_1$$



Some possible estimators

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

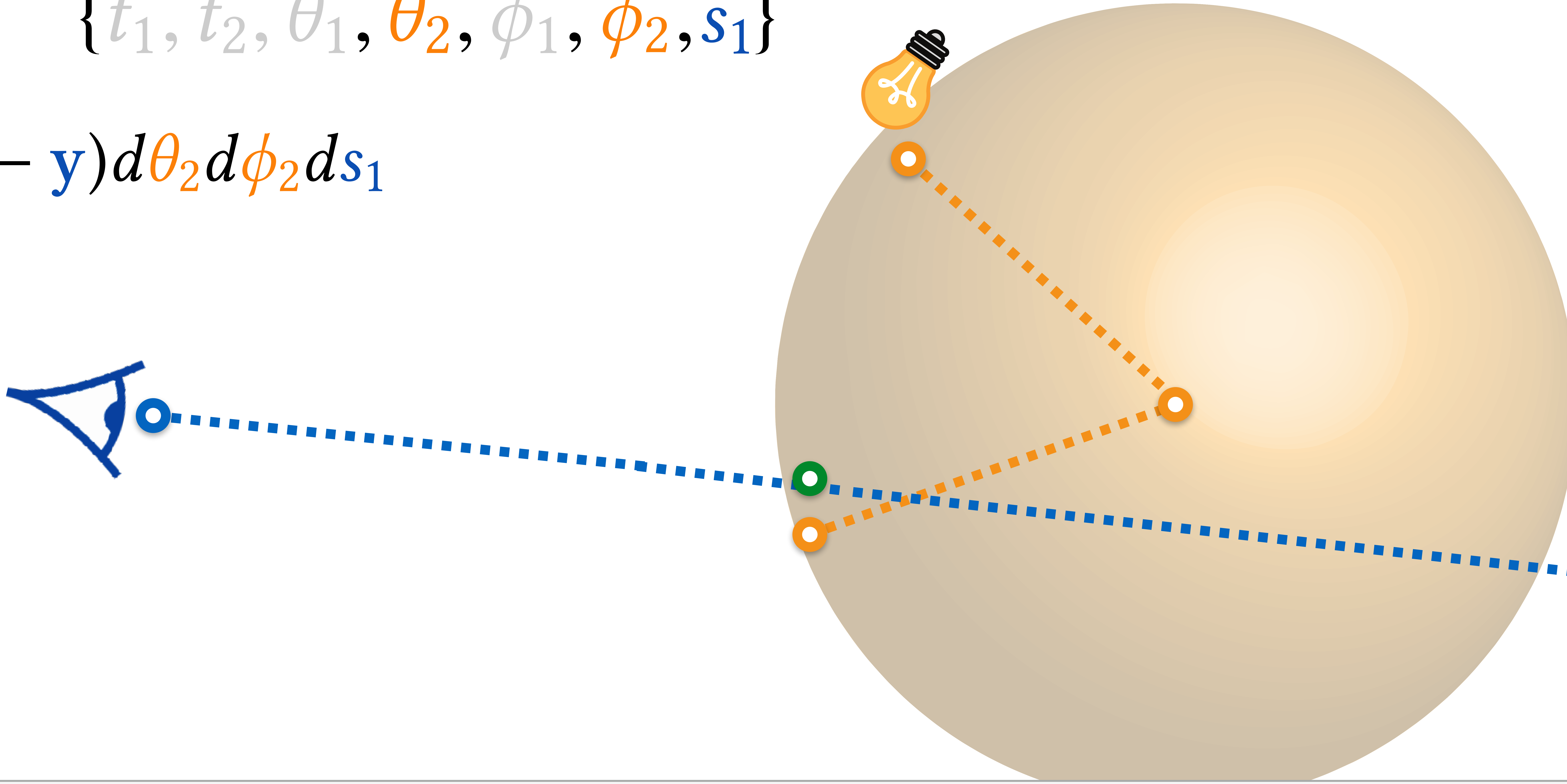
$$\int \delta(\mathbf{x} - \mathbf{y})\, d\theta_2\, d\phi_2\, ds_1$$



Some possible estimators

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

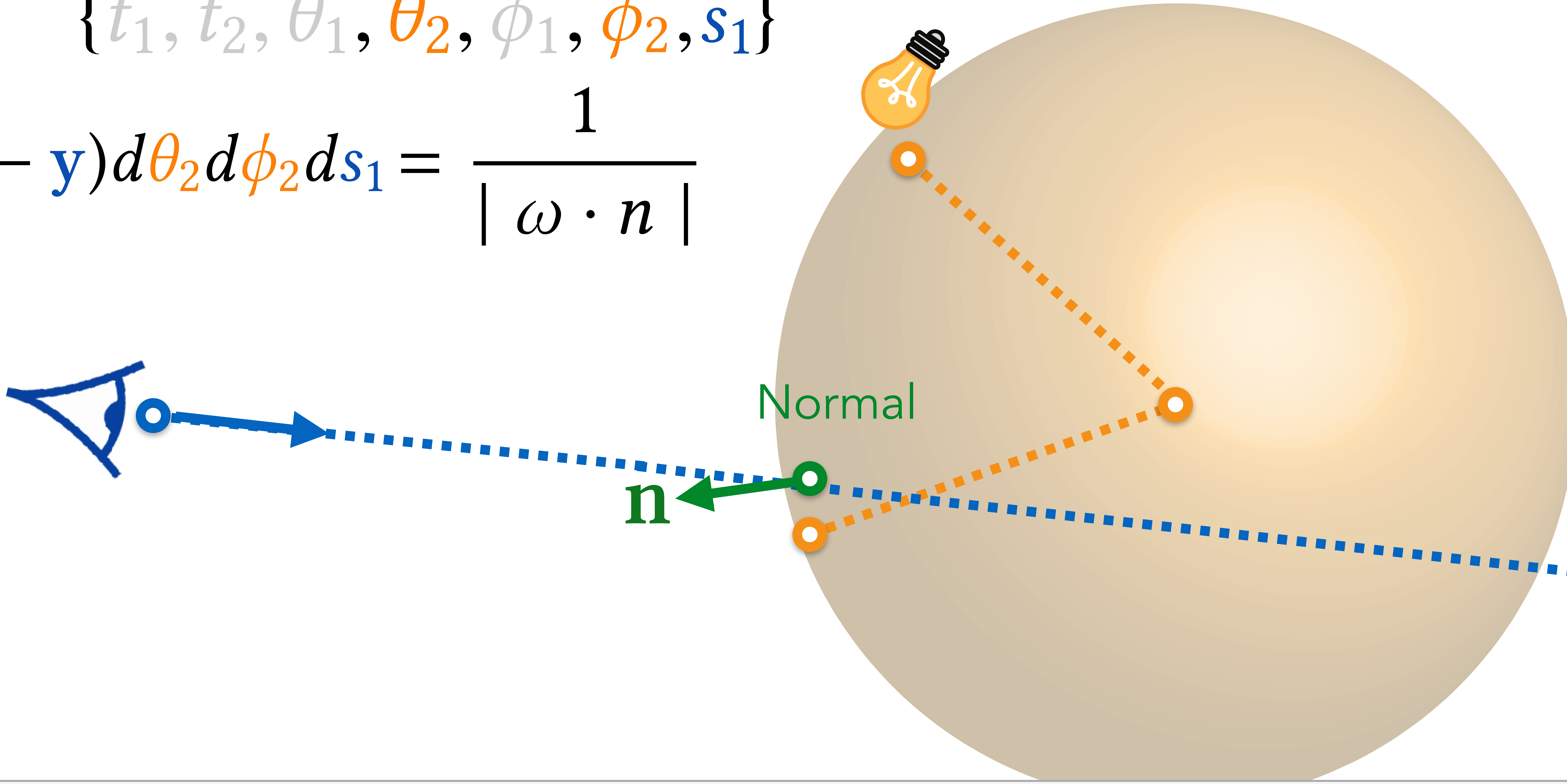
$$\int \delta(\mathbf{x} - \mathbf{y}) d\theta_2 d\phi_2 ds_1$$



Some possible estimators

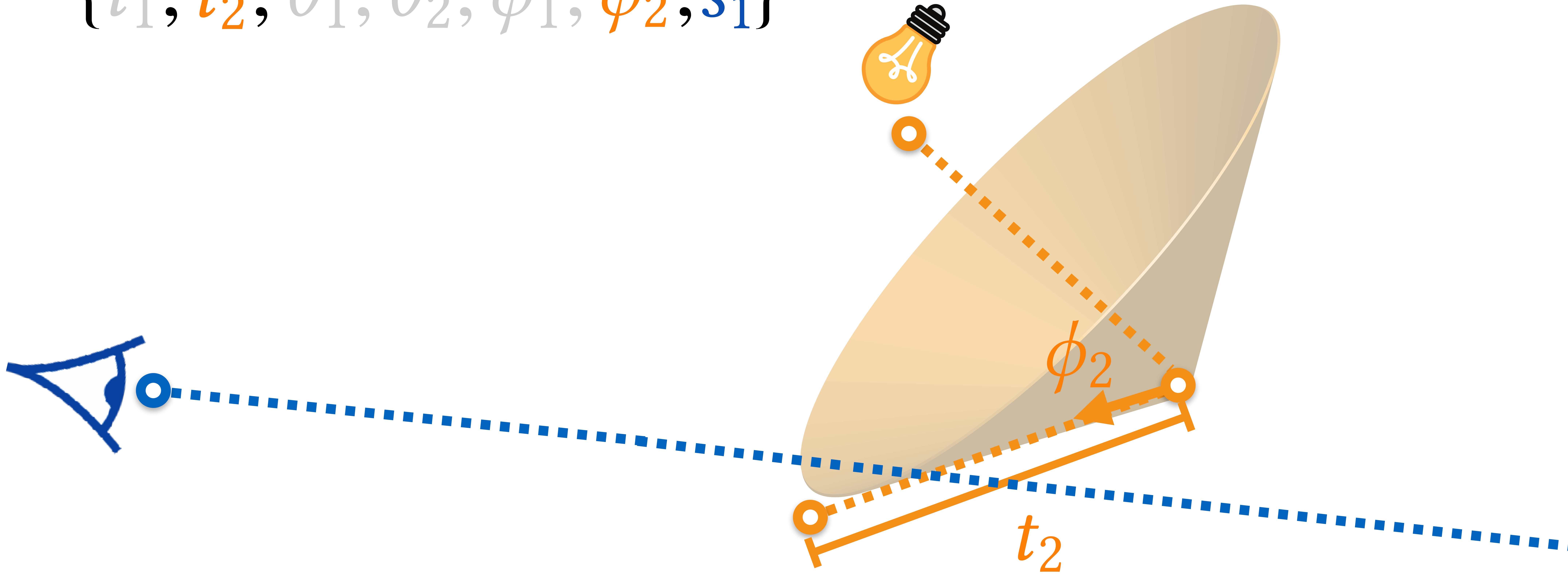
Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

$$\int \delta(\mathbf{x} - \mathbf{y})\, d\theta_2\, d\phi_2\, ds_1 = \frac{1}{|\,\omega \cdot n\,|}$$



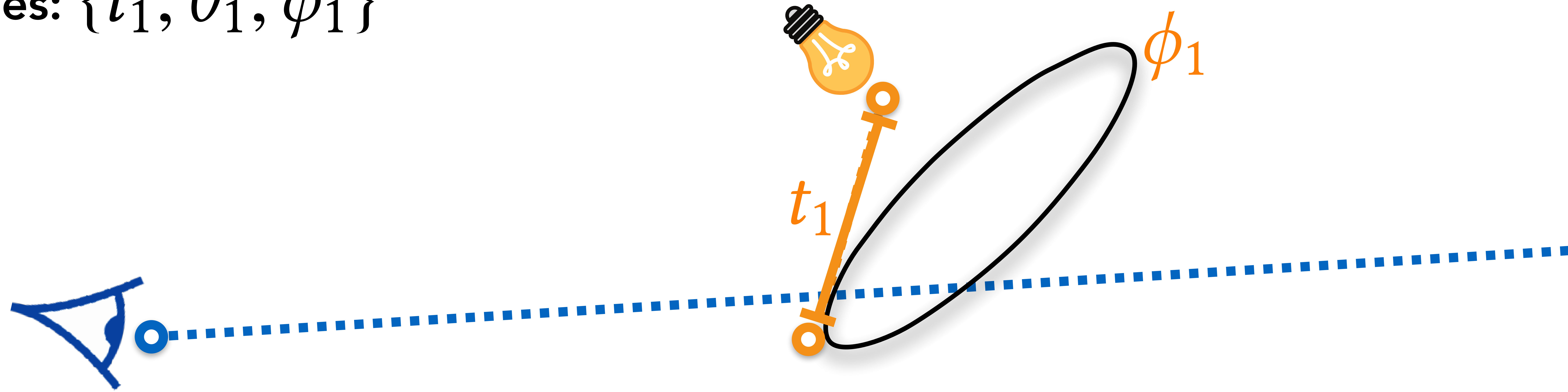
Some possible estimators

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$



What about single scattering?

Variables: $\{t_1, \theta_1, \phi_1\}$



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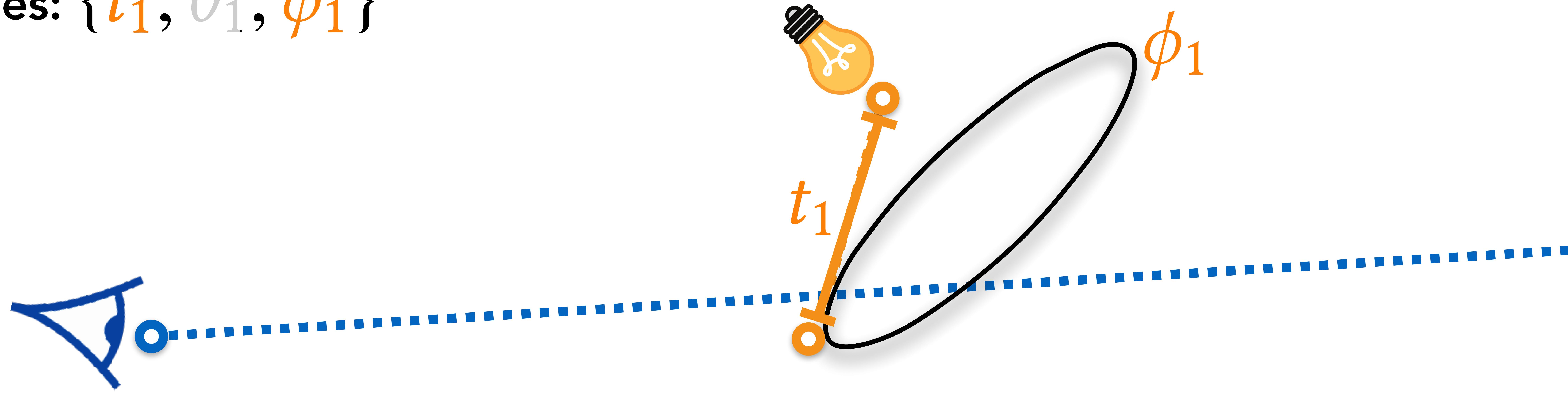

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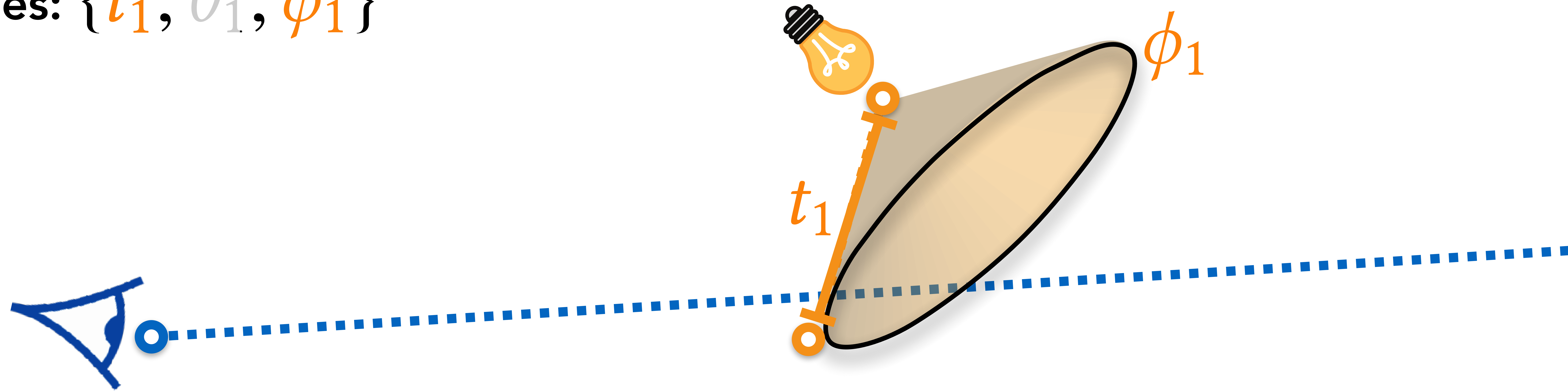
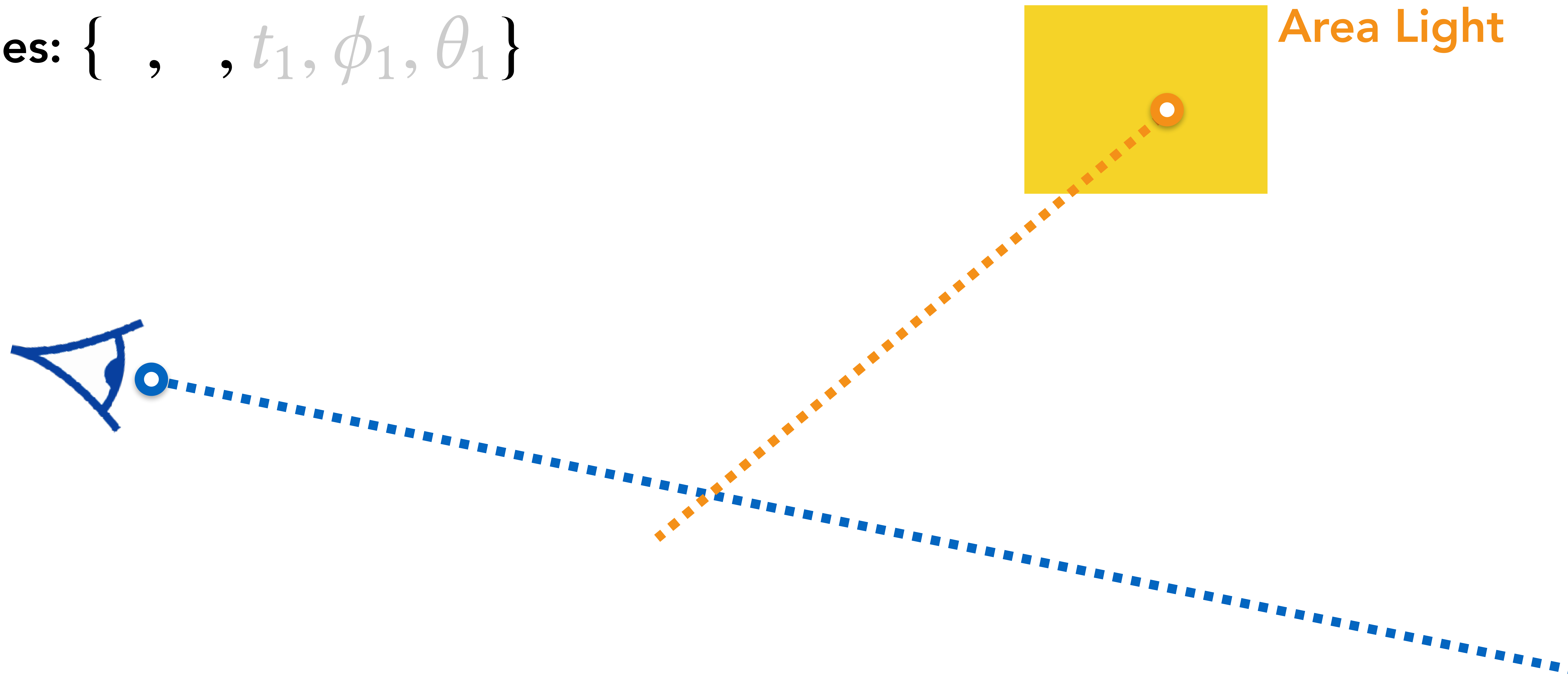


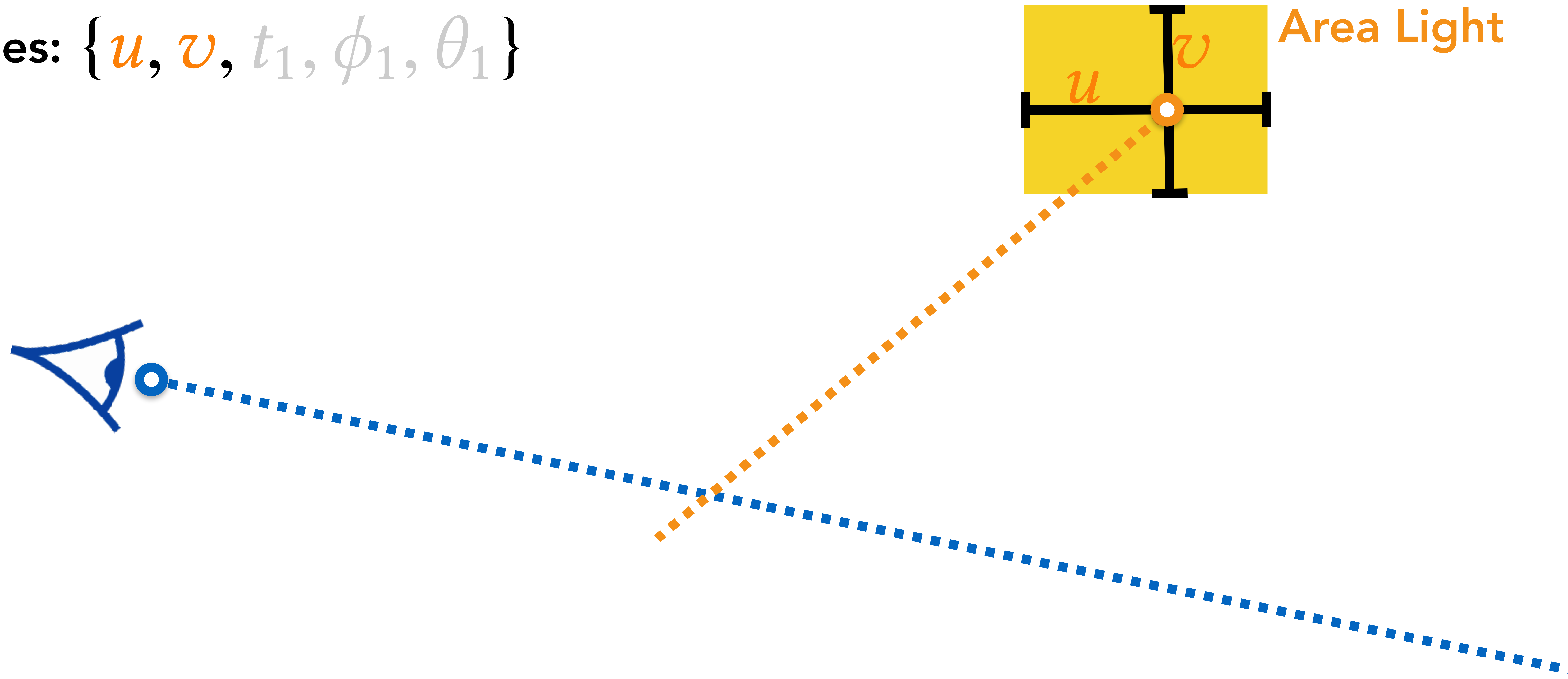
More possible estimators

Variables: $\{\ \ ,\ \ , t_1, \phi_1, \theta_1\}$



More possible estimators

Variables: $\{u, v, t_1, \phi_1, \theta_1\}$



More possible estimators

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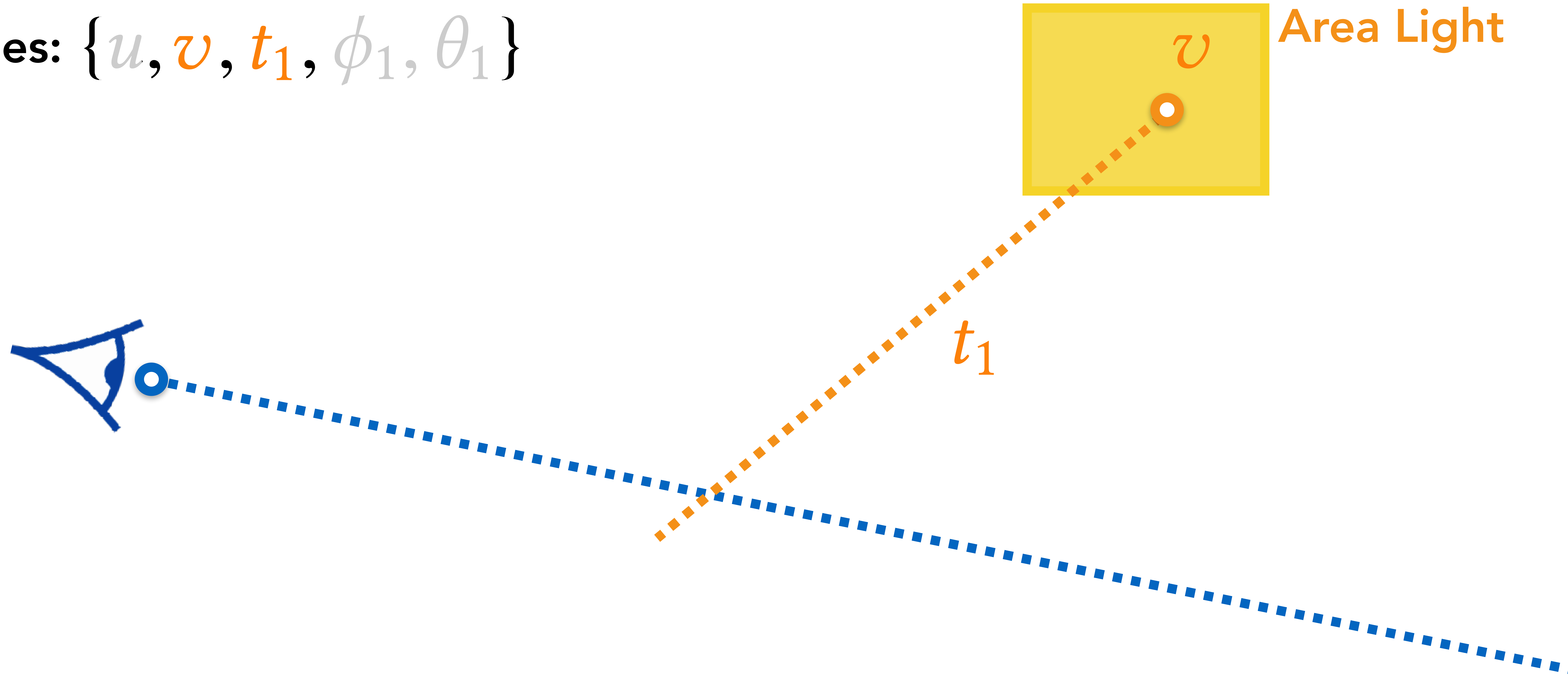

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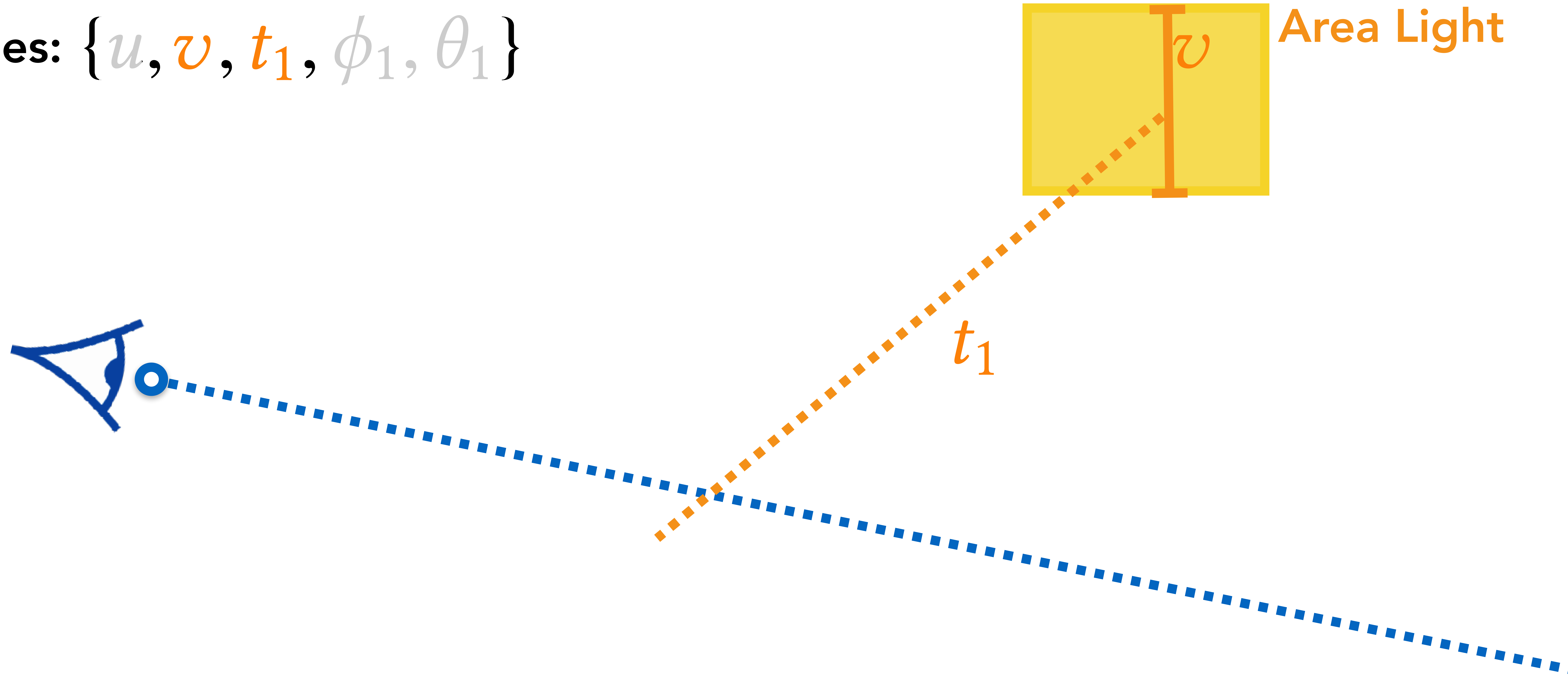

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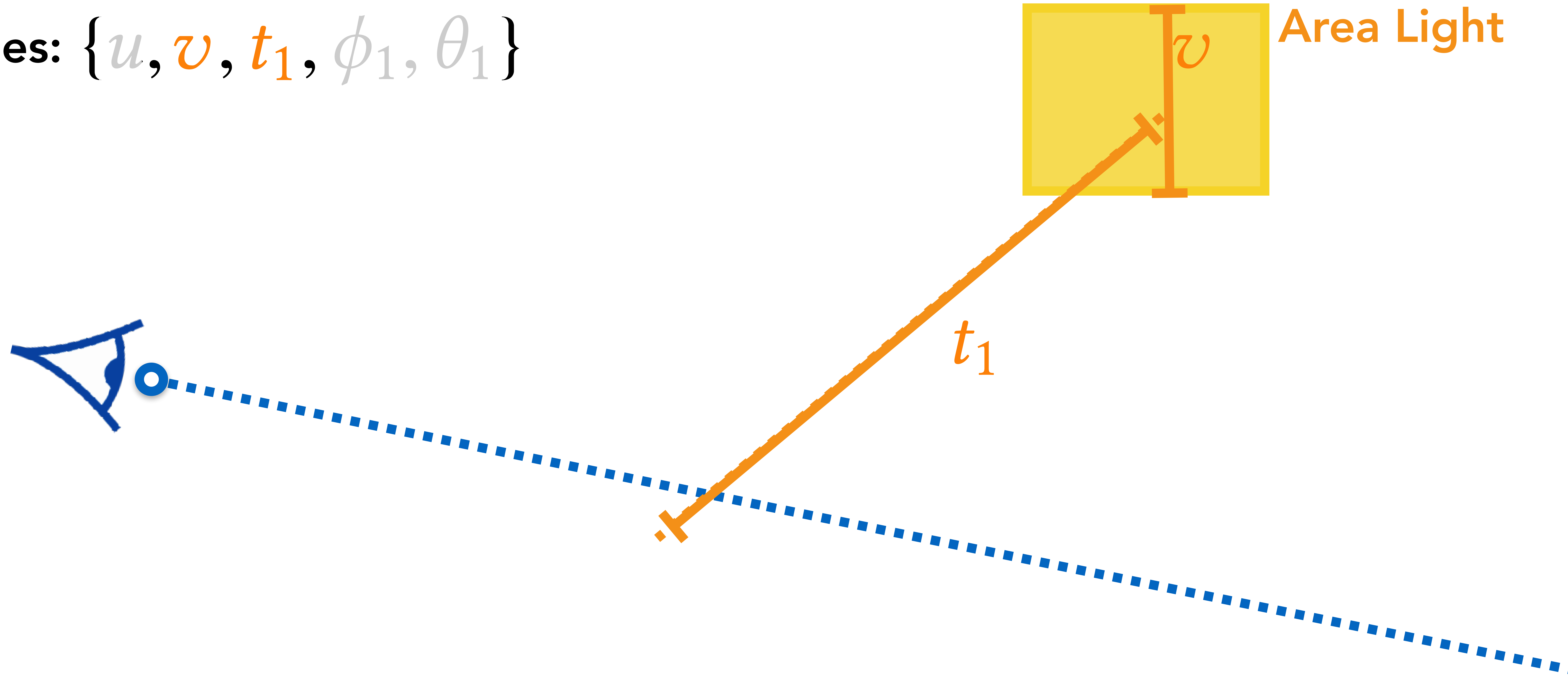

More possible estimators

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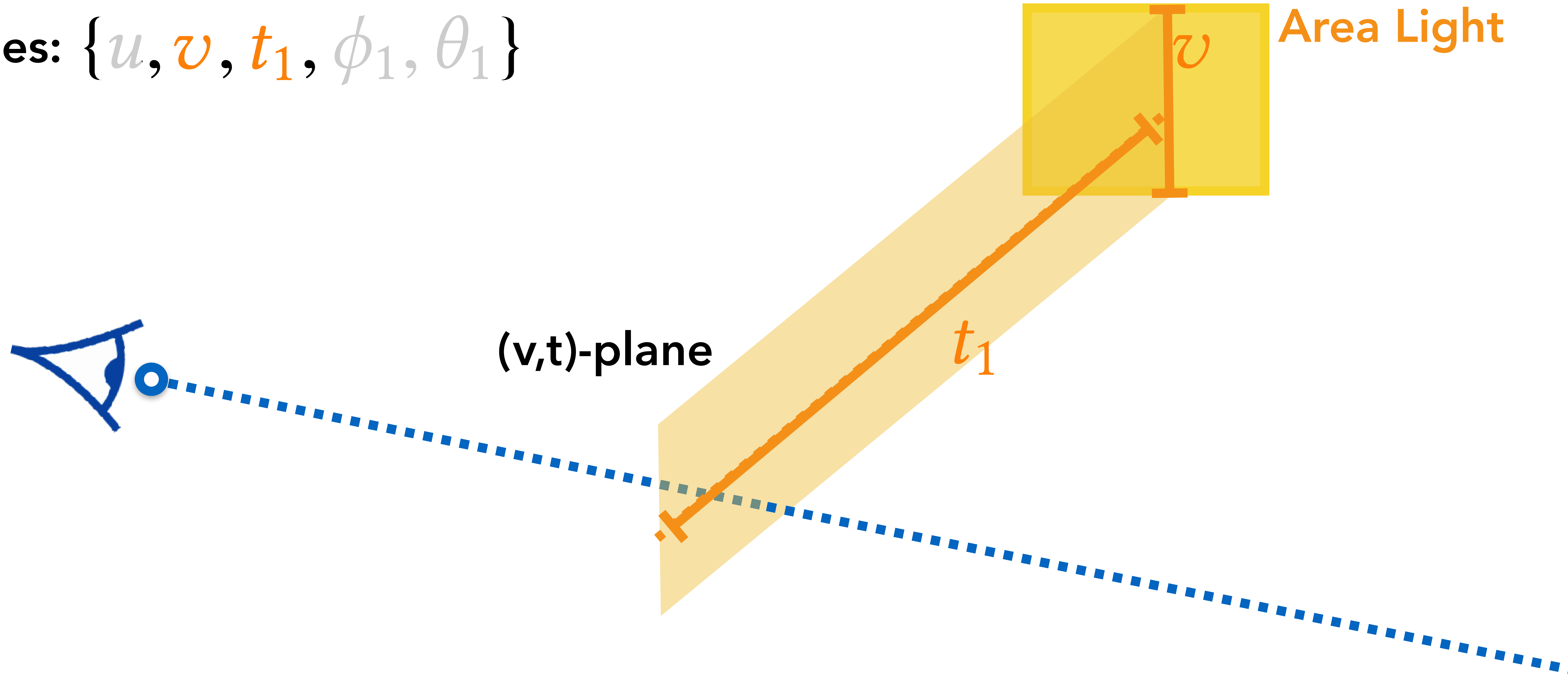

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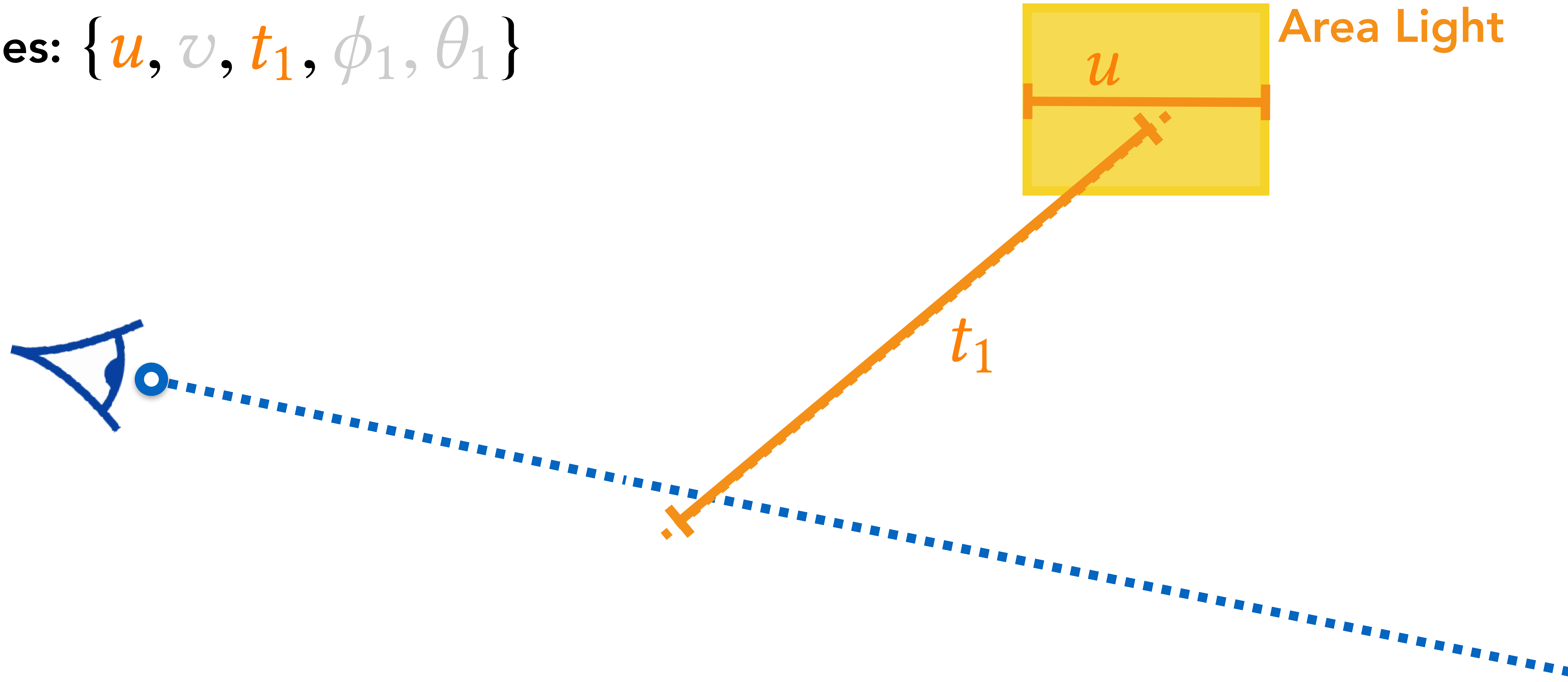

More possible estimators

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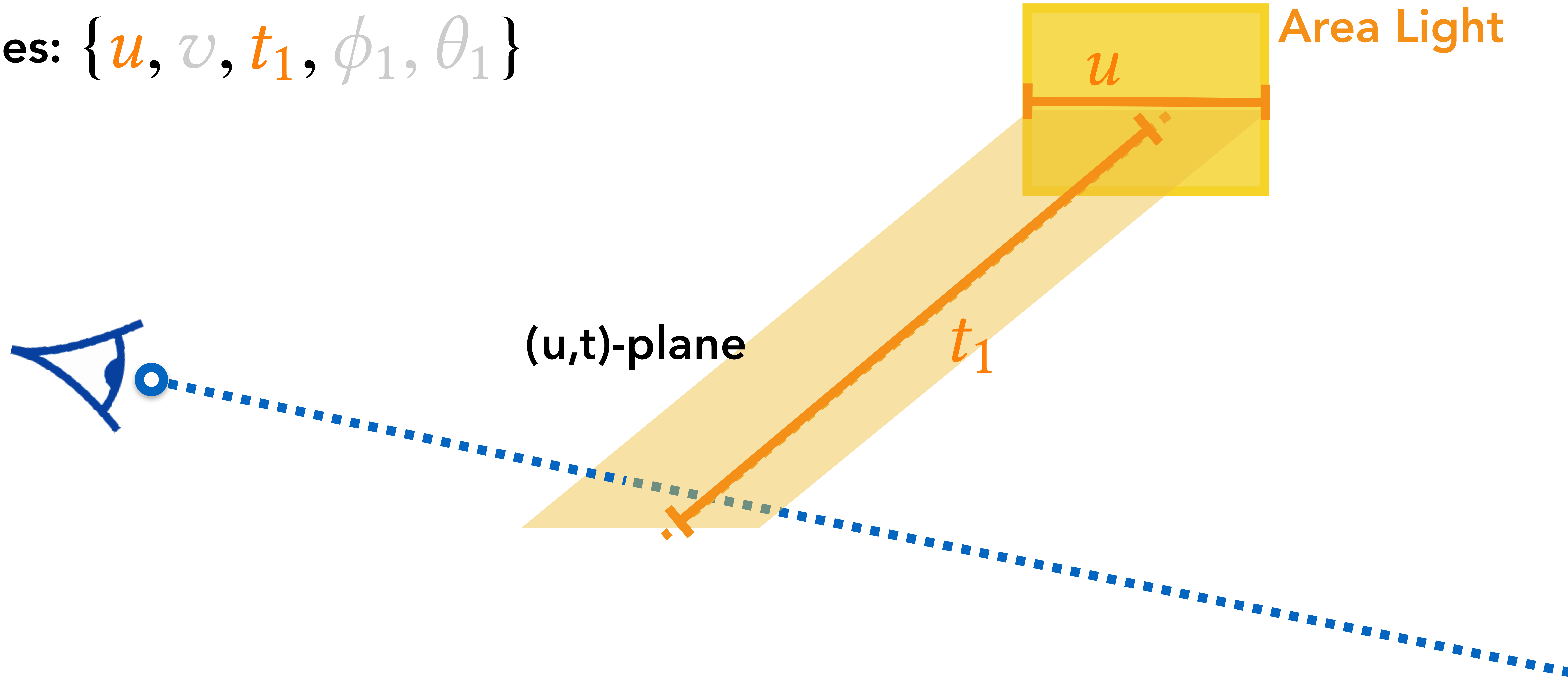

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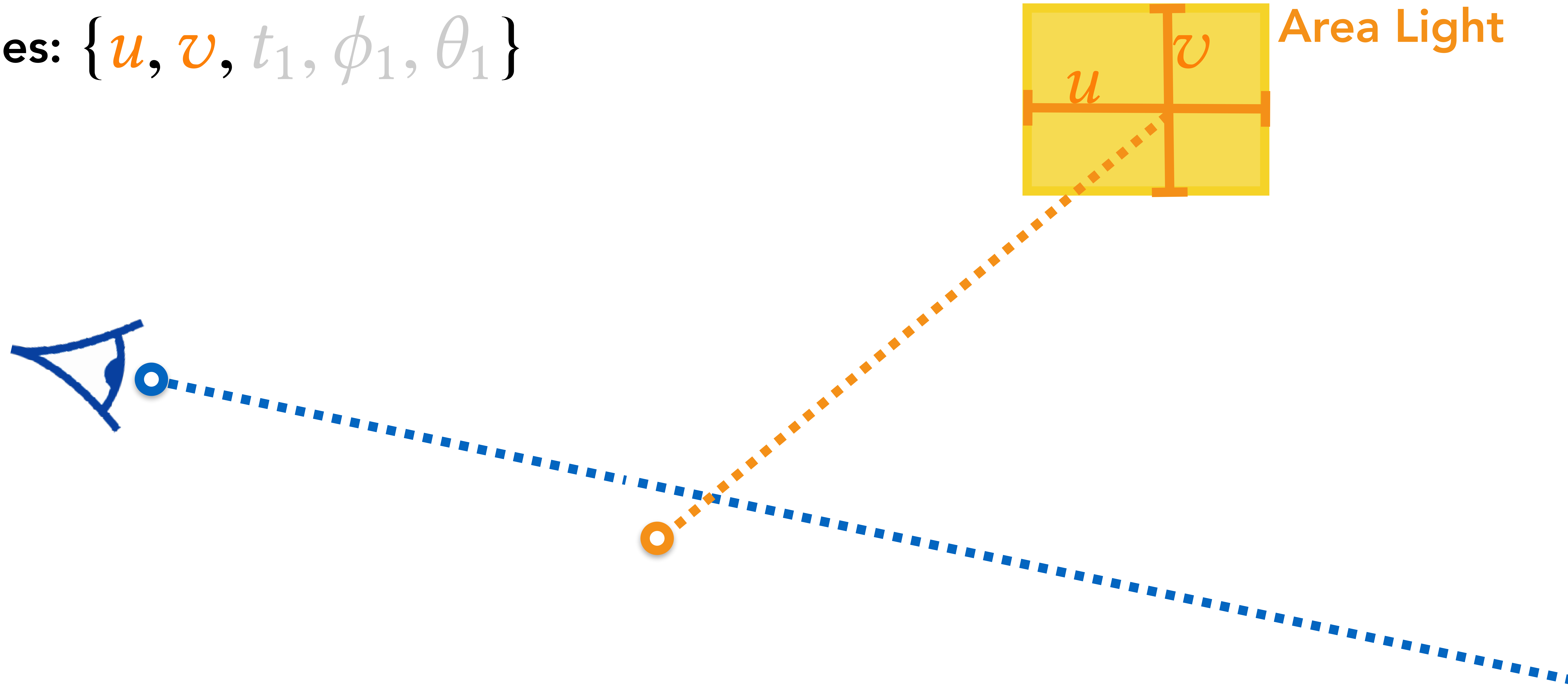
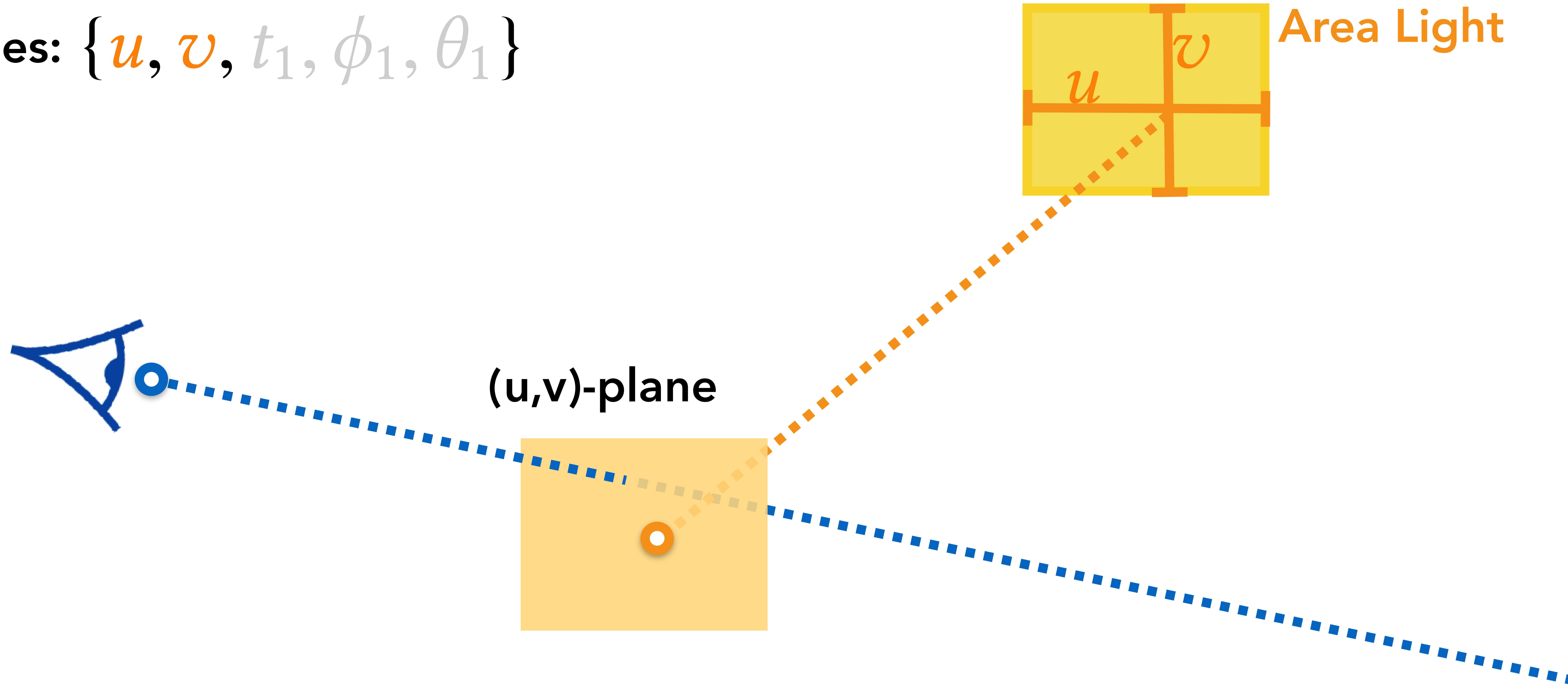


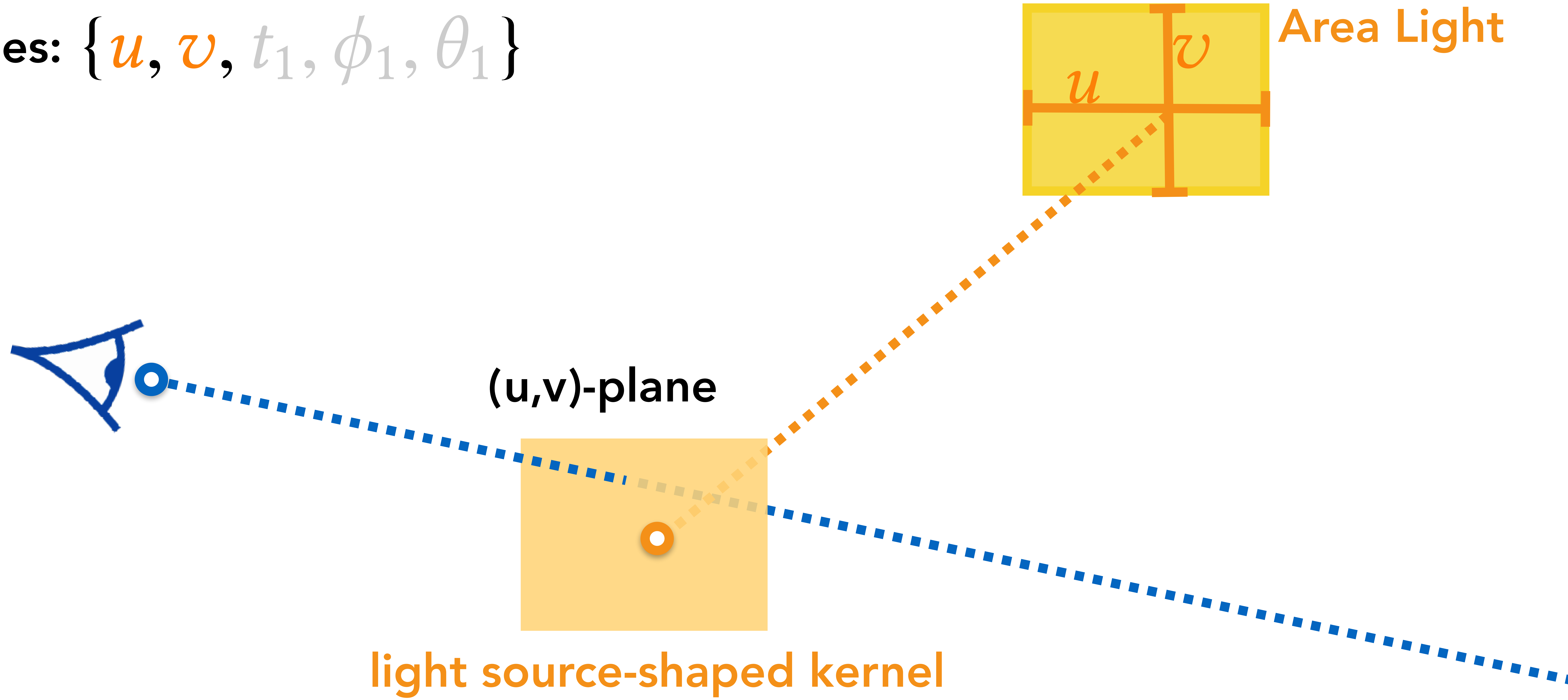
More possible estimators

Variables: $\{u, v, t_1, \phi_1, \theta_1\}$



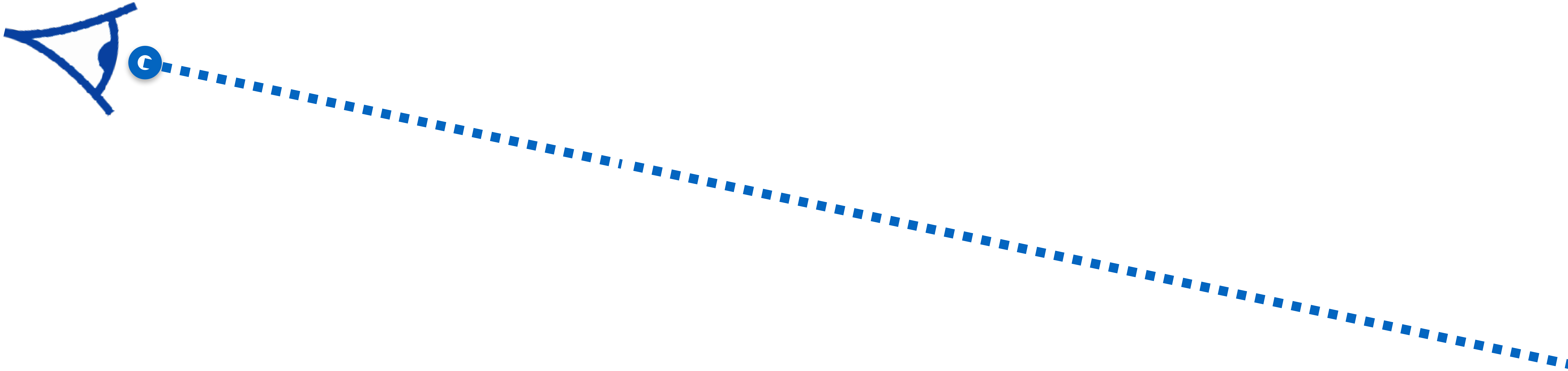
More possible estimators

Variables: $\{u, v, t_1, \phi_1, \theta_1\}$



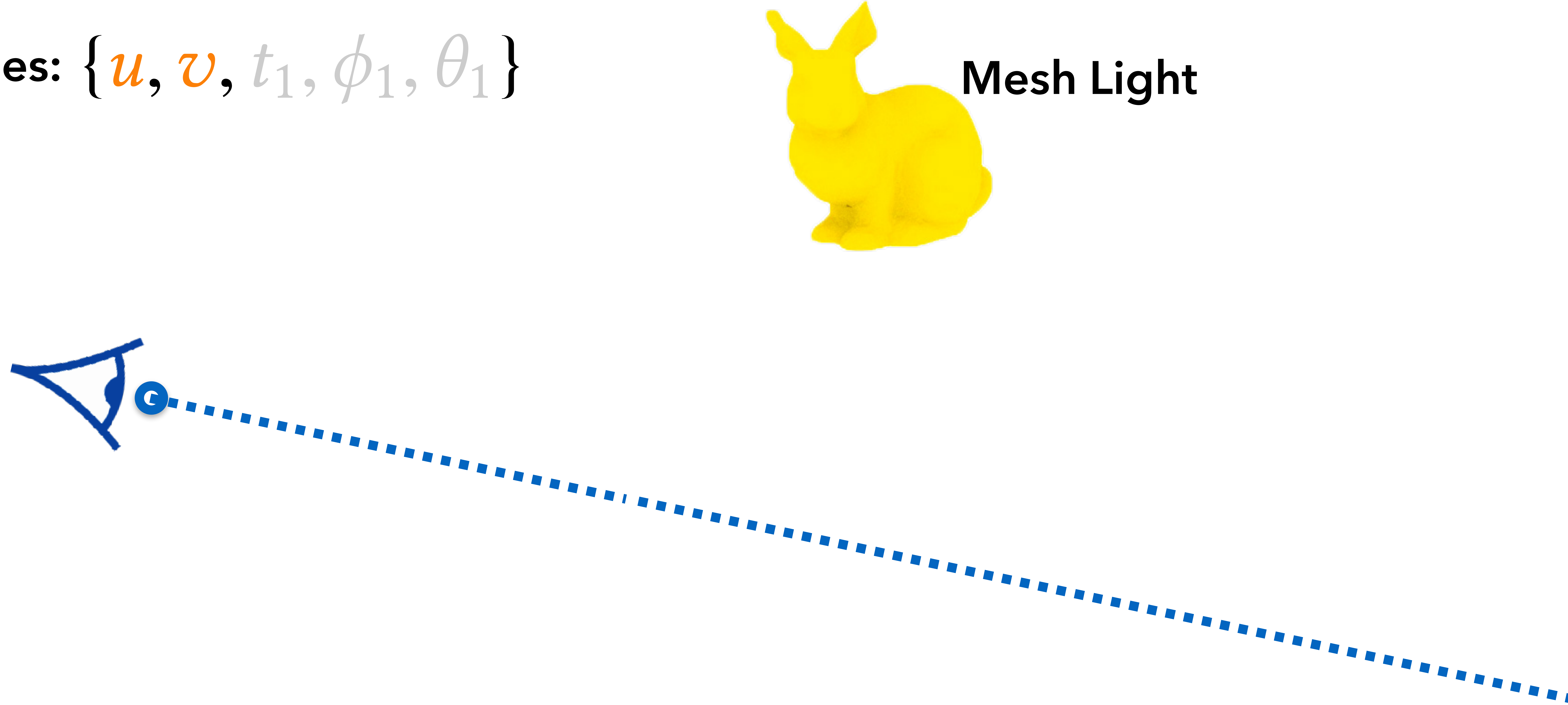
More possible estimators

Variables: $\{u, v, t_1, \phi_1, \theta_1\}$



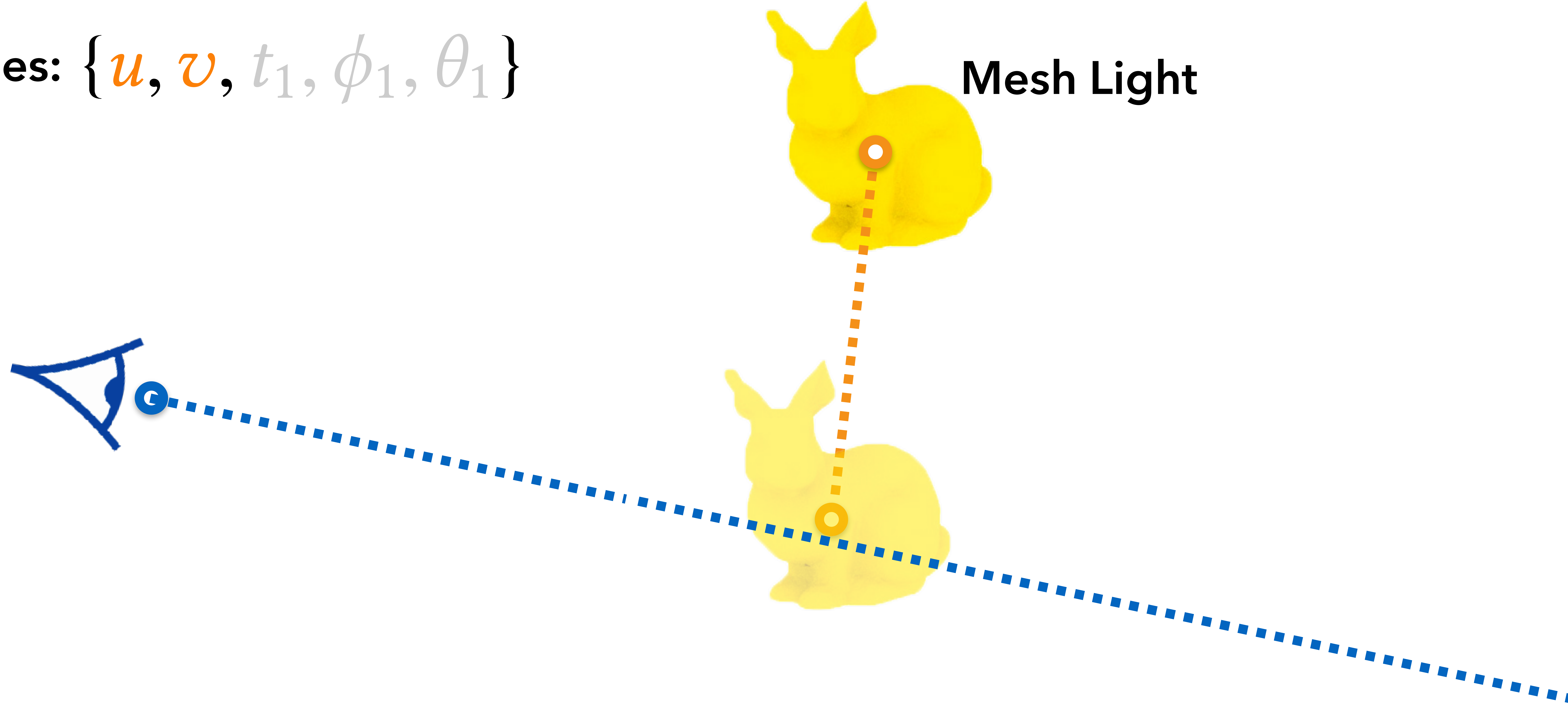
More possible estimators

Variables: $\{u, v, t_1, \phi_1, \theta_1\}$

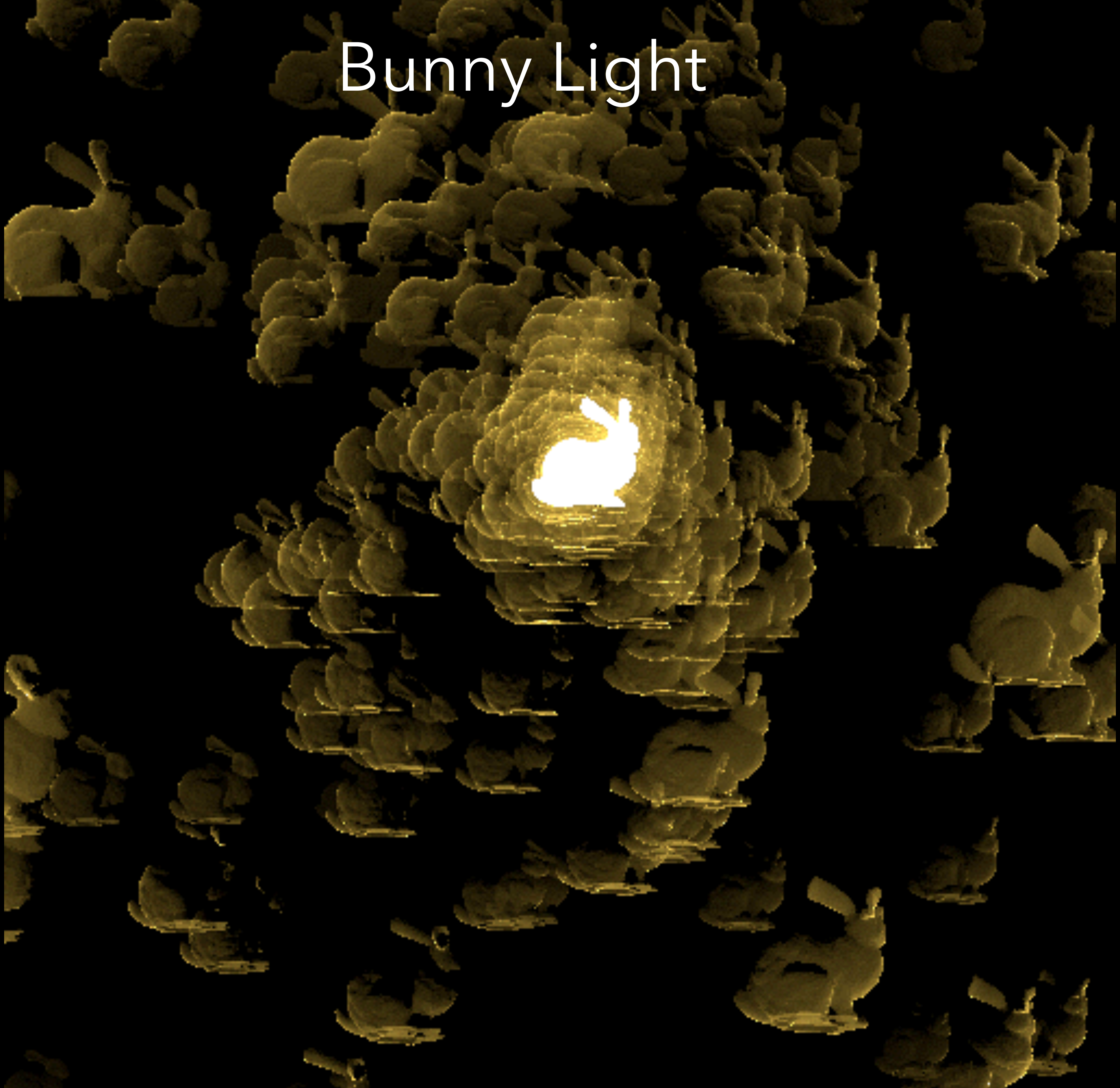


More possible estimators

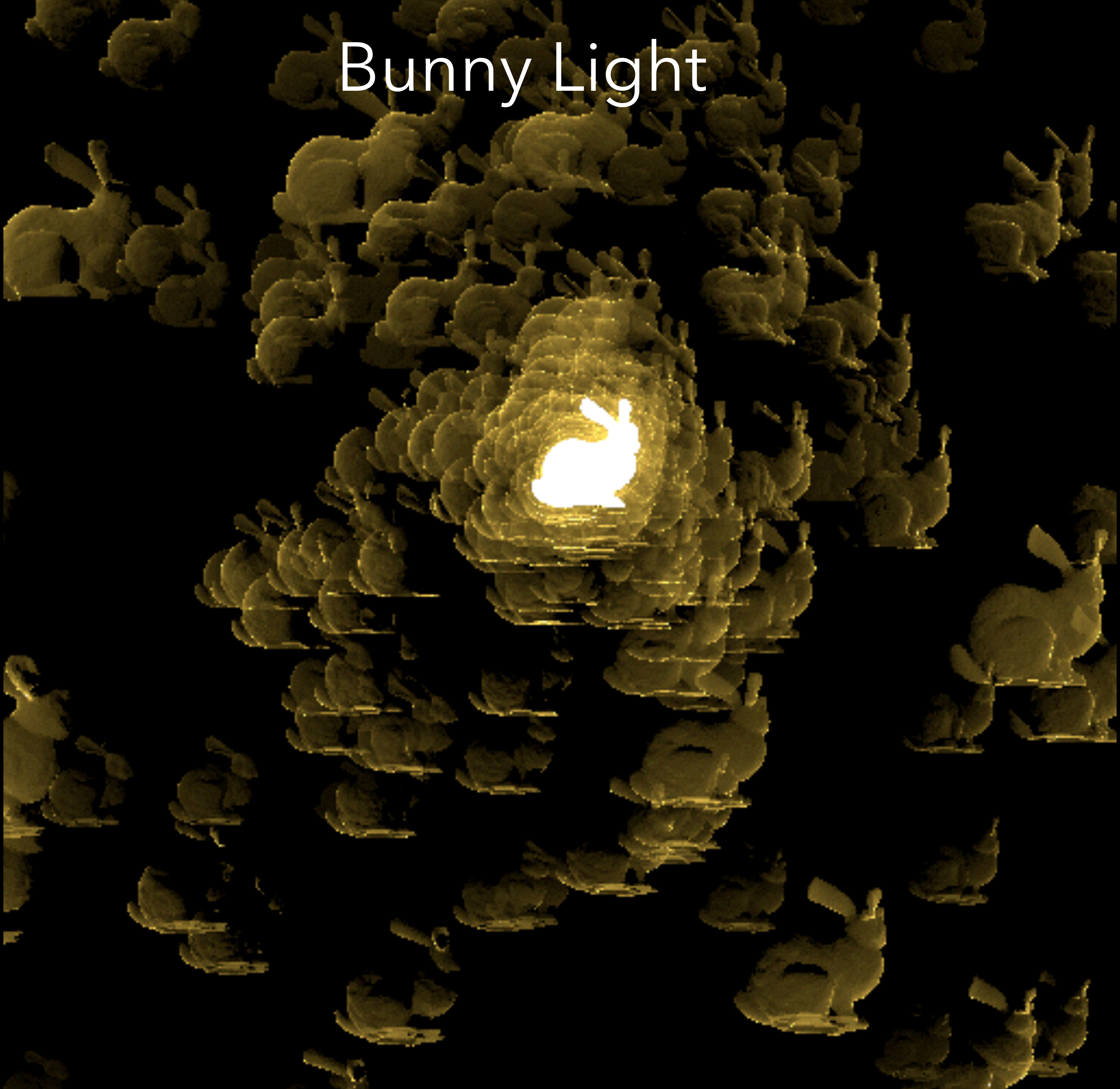
Variables: $\{u, v, t_1, \phi_1, \theta_1\}$



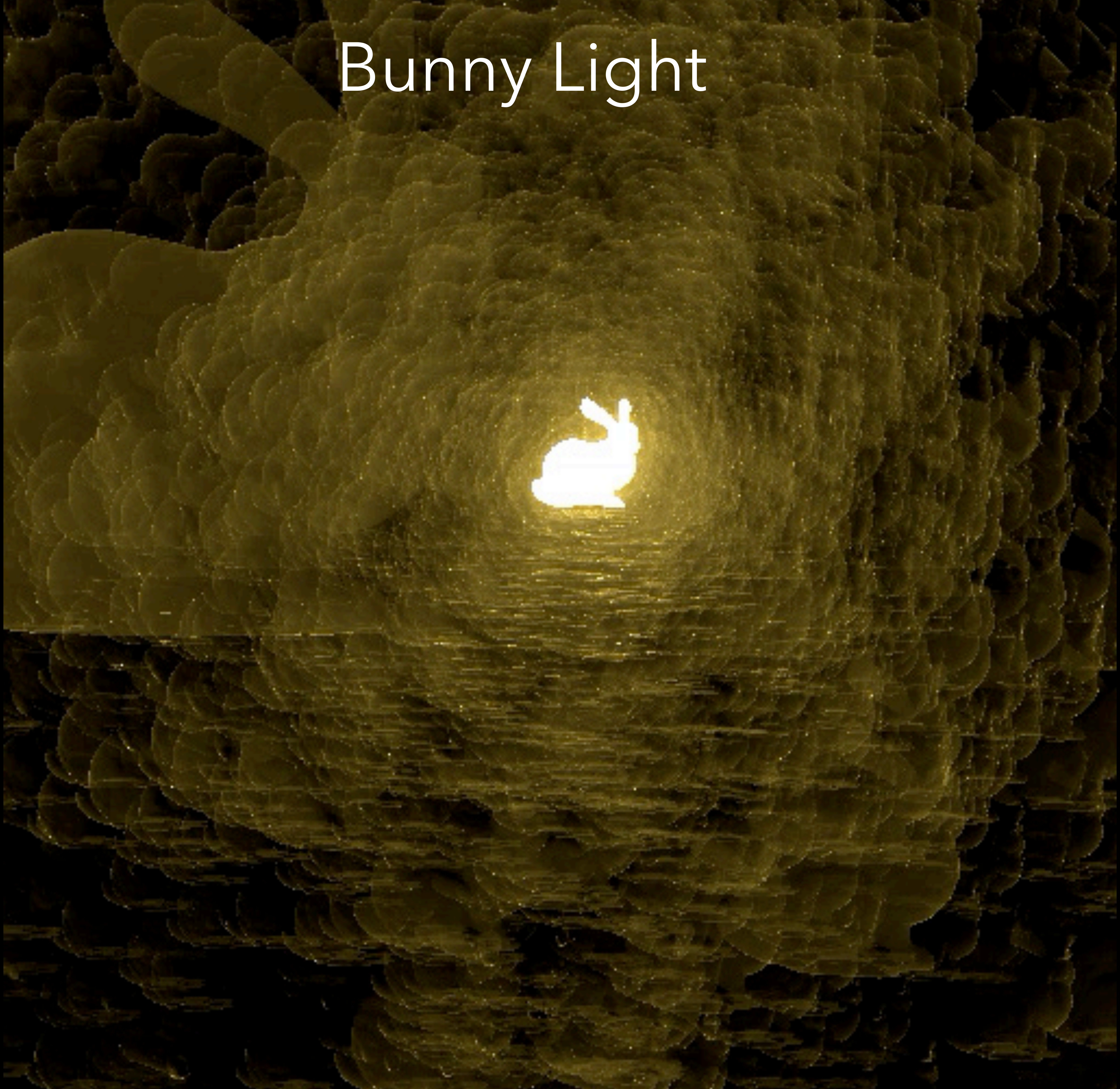
Bunny Light



Bunny Light



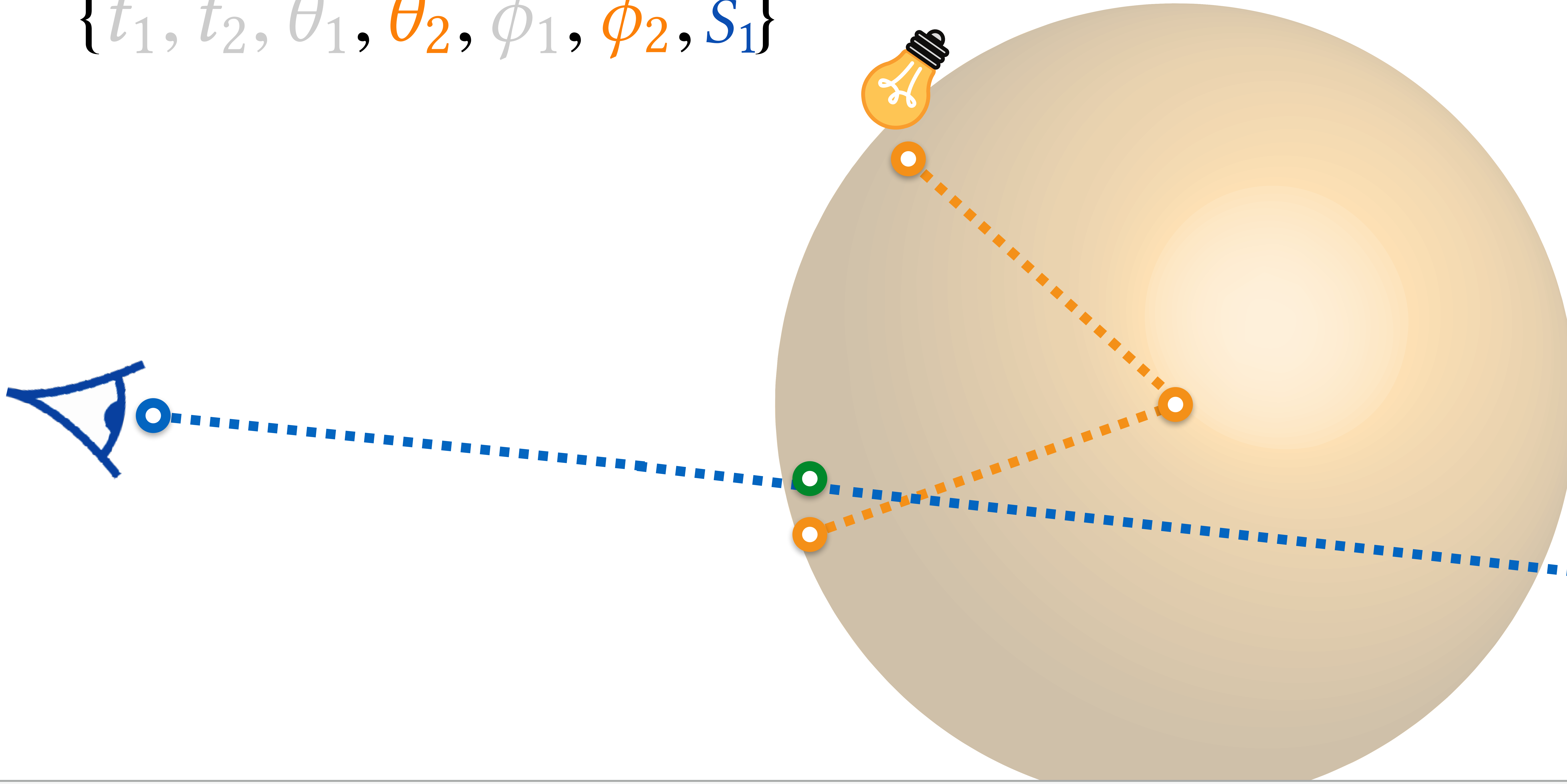
Bunny Light



Bunny Light

Some possible estimators

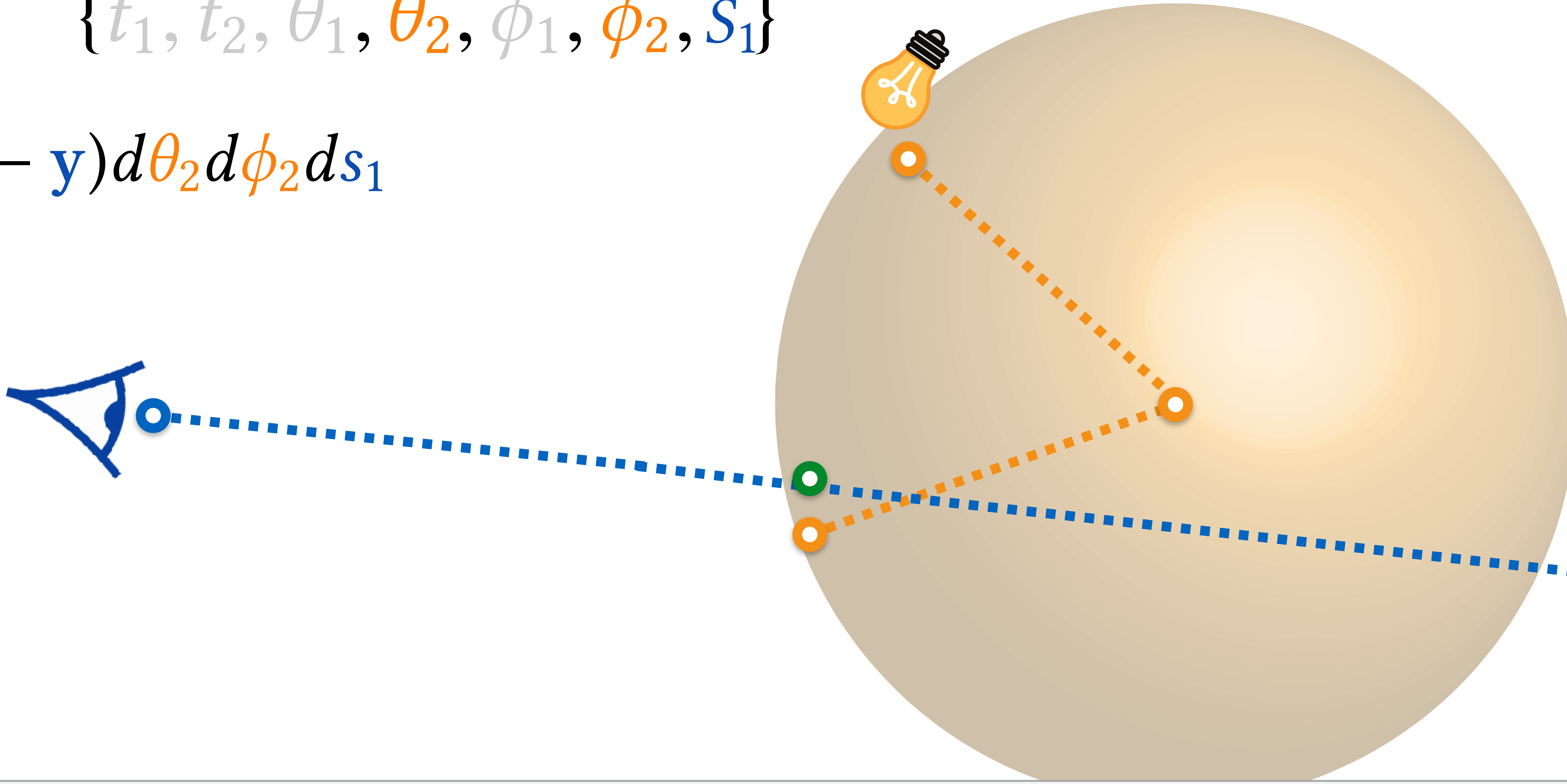
Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, S_1\}$



Some possible estimators

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

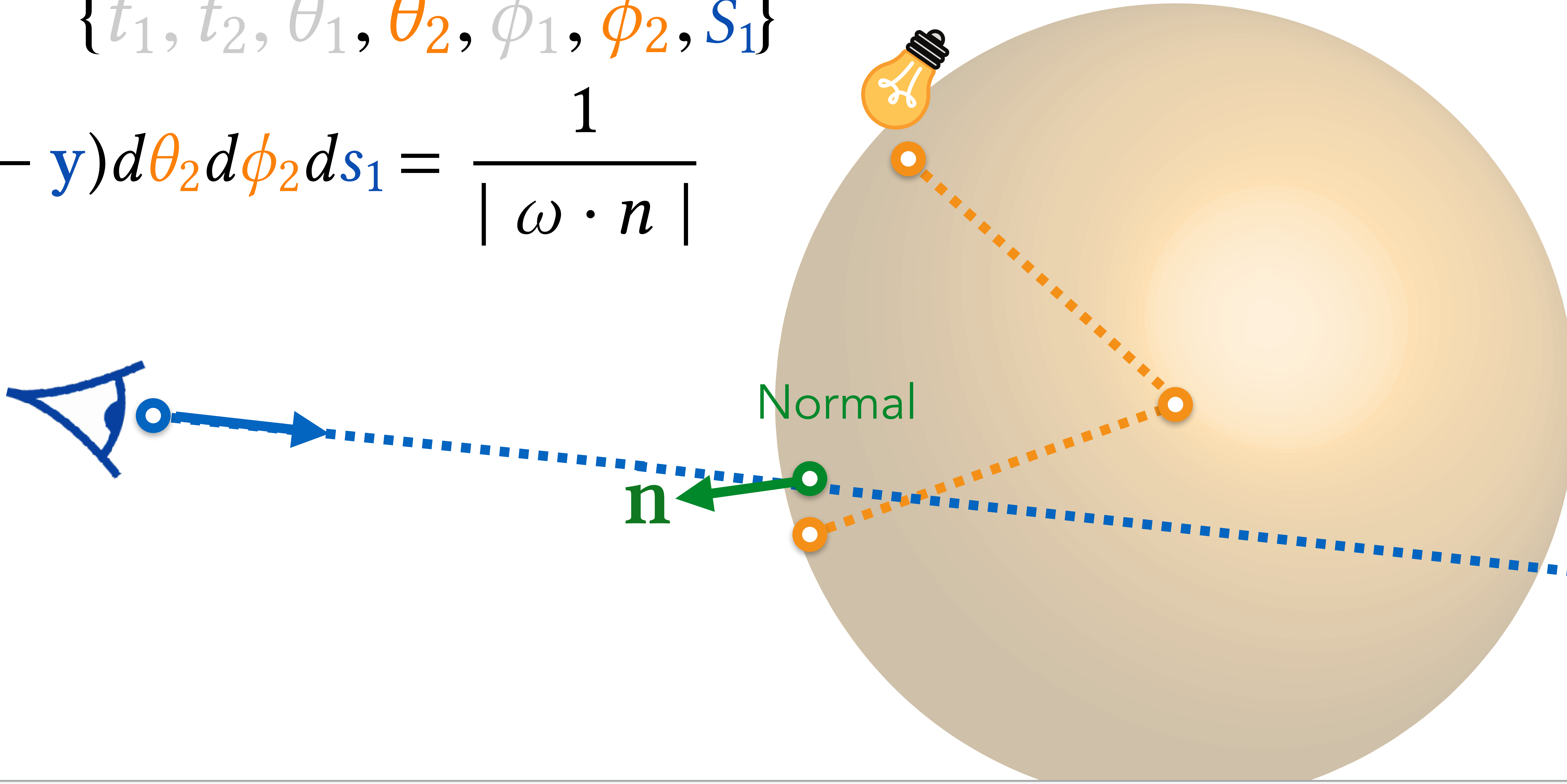
$$\int \delta(\mathbf{x} - \mathbf{y})\, d\theta_2\, d\phi_2\, ds_1$$



Some possible estimators

Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

$$\int \delta(\mathbf{x} - \mathbf{y})\, d\theta_2\, d\phi_2\, ds_1 = \frac{1}{|\,\omega \cdot n\,|}$$

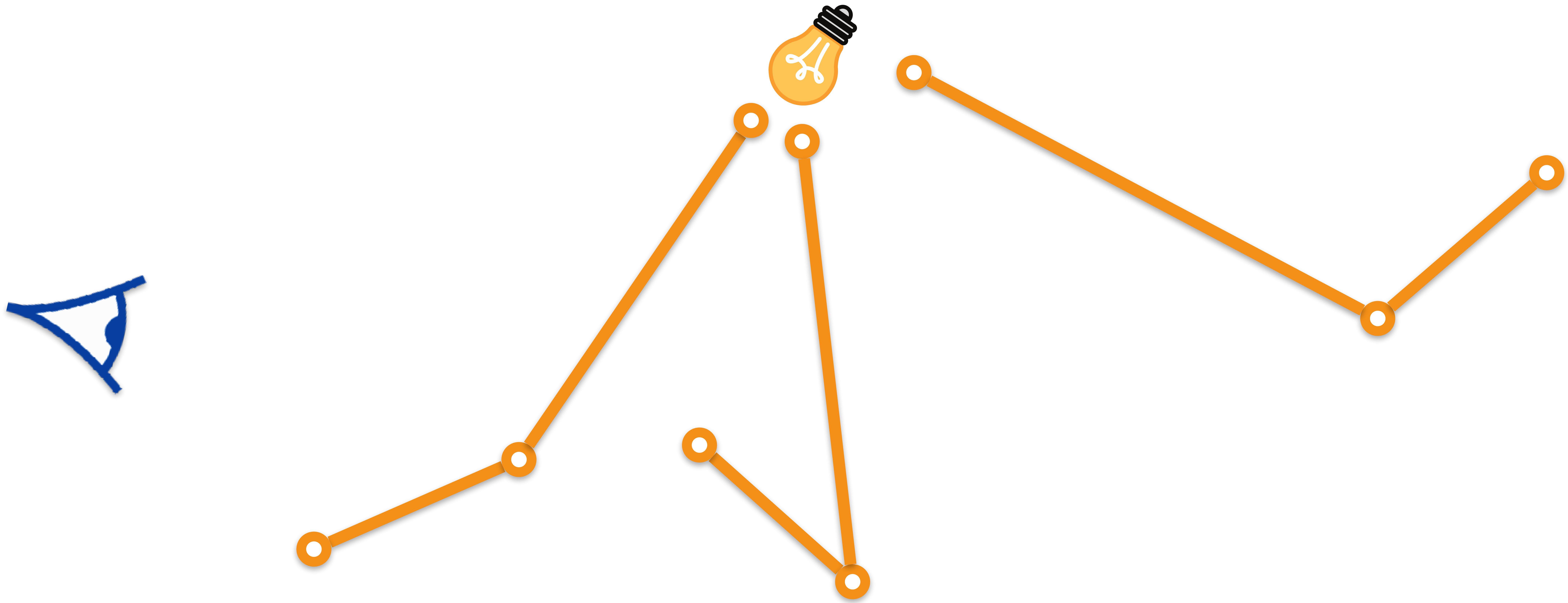


PROCEDURE

How we render with photon surfaces

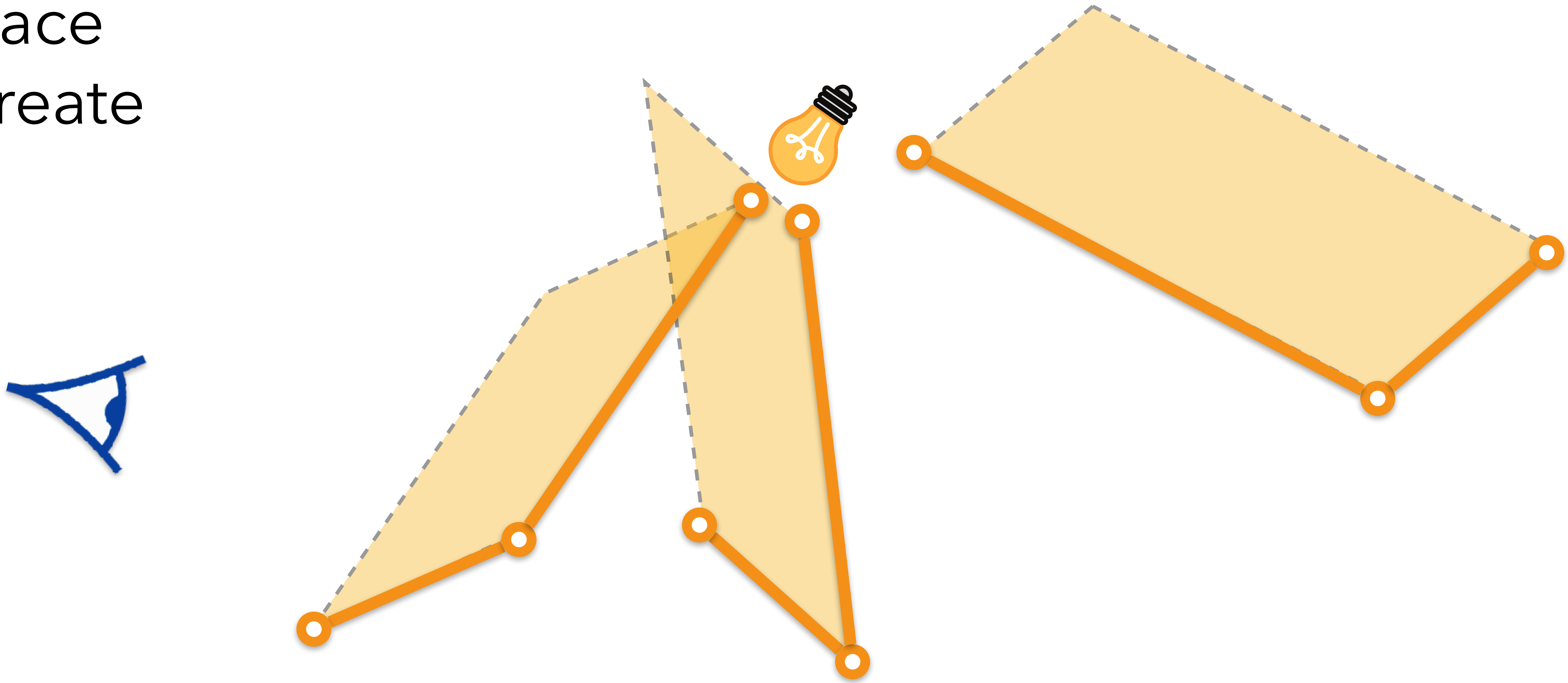
How we render with photon surfaces

1: Trace



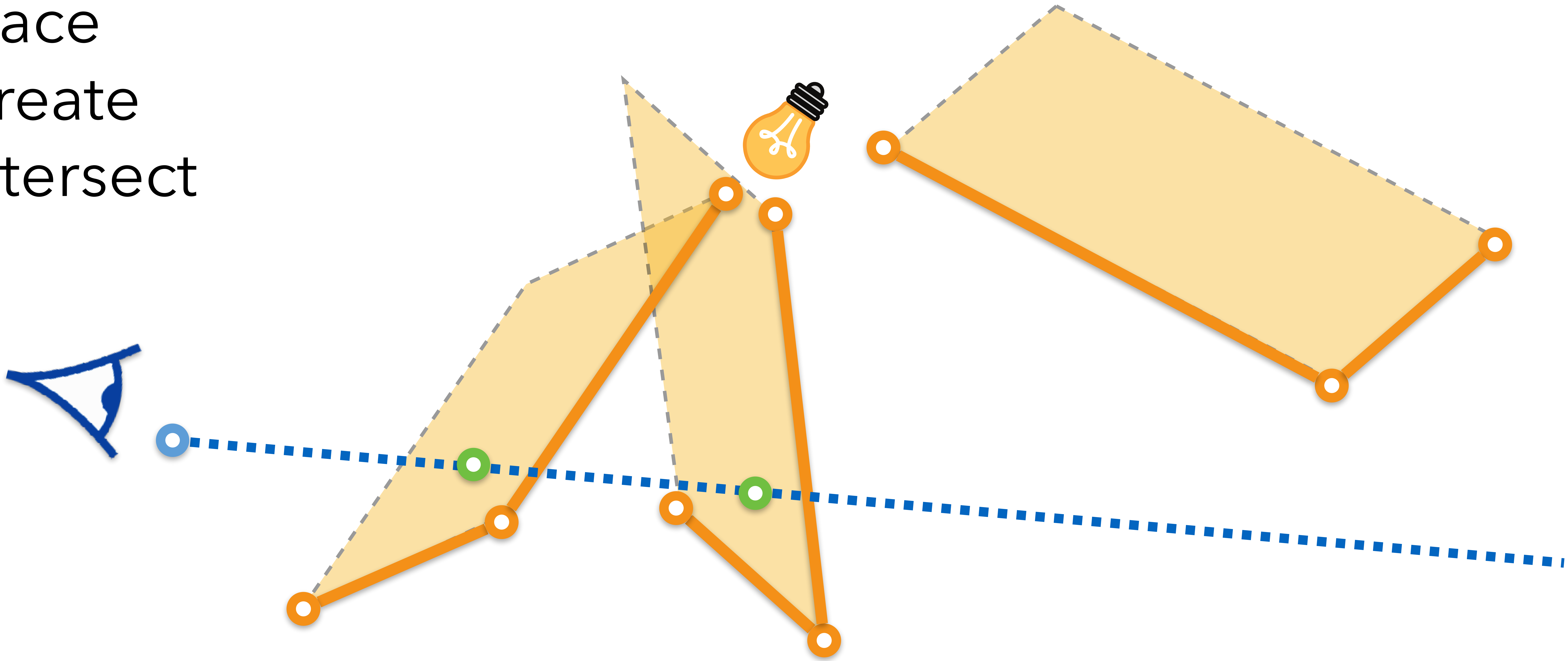
How we render with photon surfaces

1: Trace
2: Create



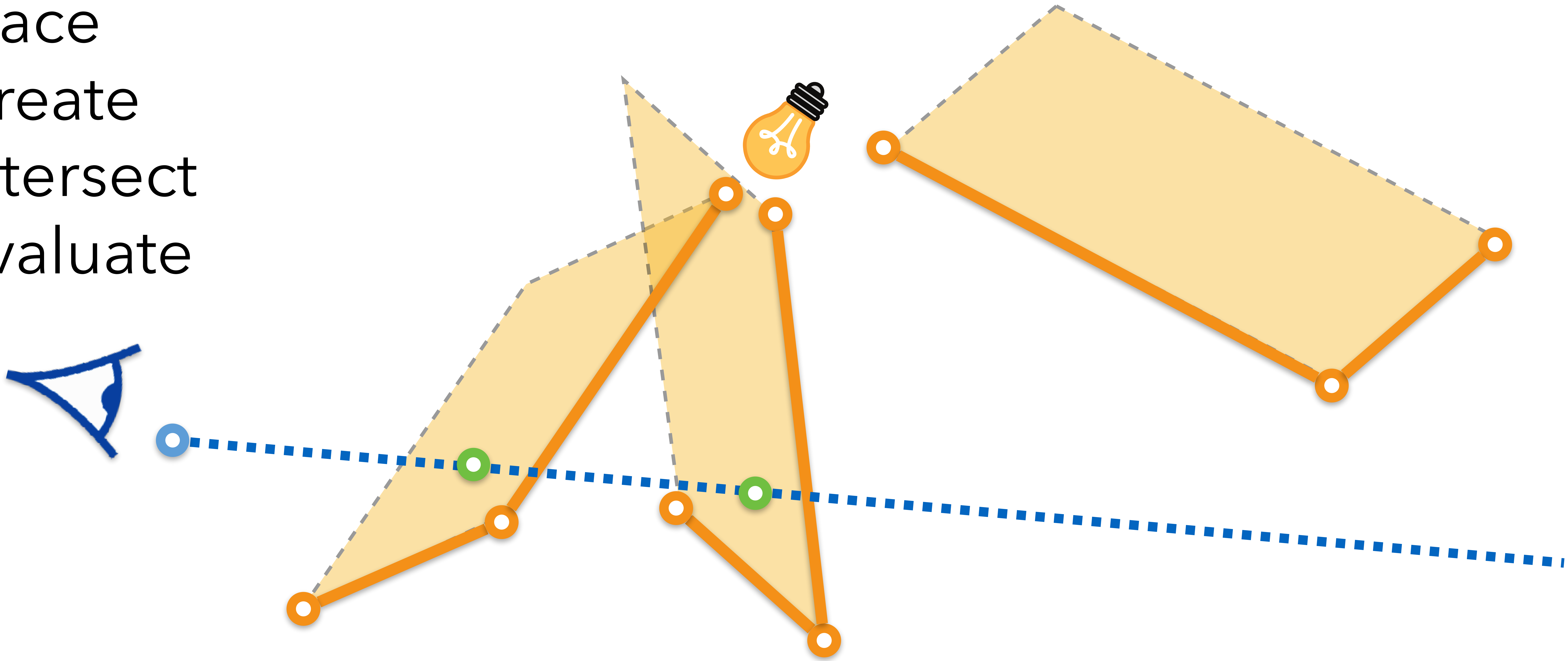
How we render with photon surfaces

1: Trace
2: Create
3: Intersect



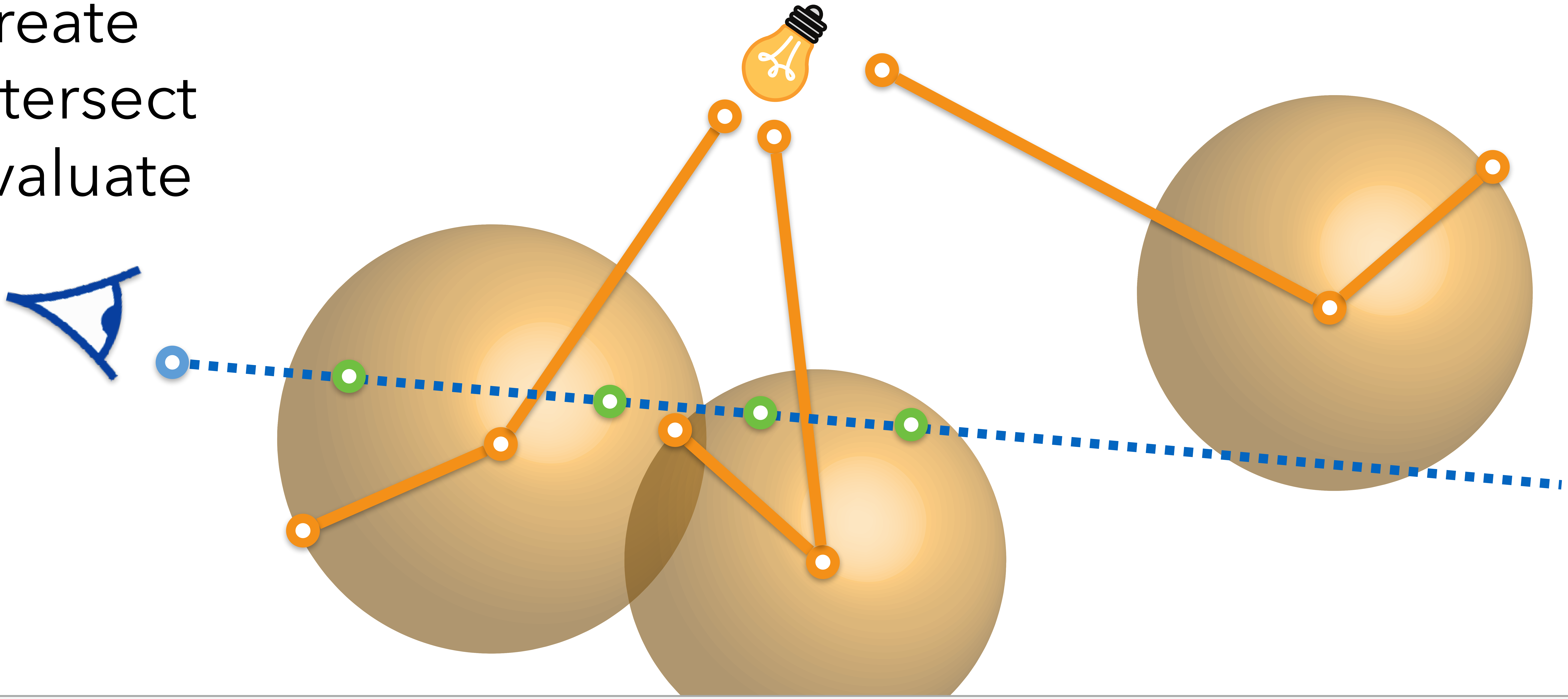
How we render with photon surfaces

1: Trace
2: Create
3: Intersect
4: Evaluate



How we render with photon surfaces

1: Trace
2: Create
3: Intersect
4: Evaluate



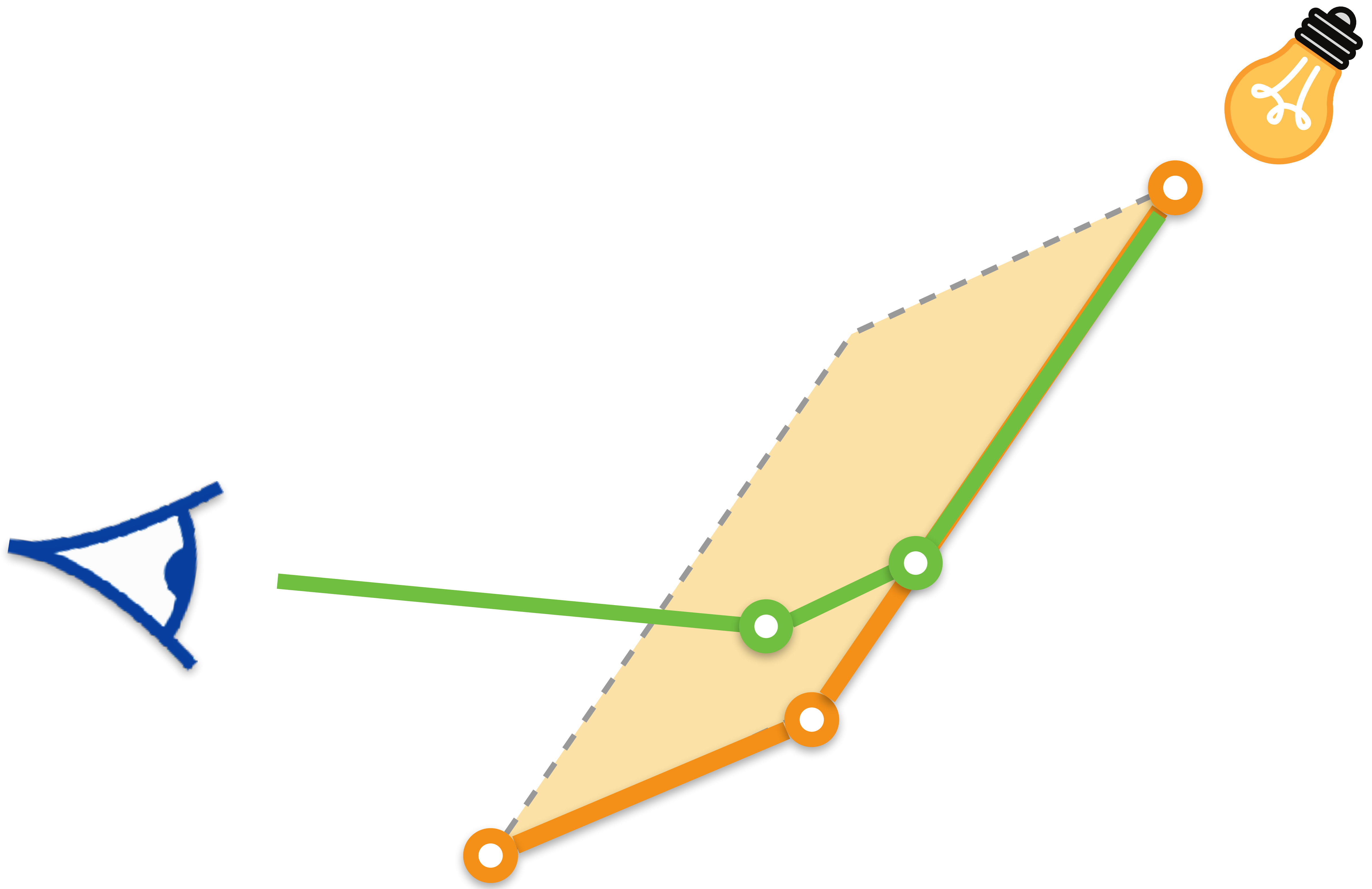

Plane
N
Sphere
N
Cylinder
N
Cone
N


Plane
N
Sphere
N
Cylinder
N
Cone
N

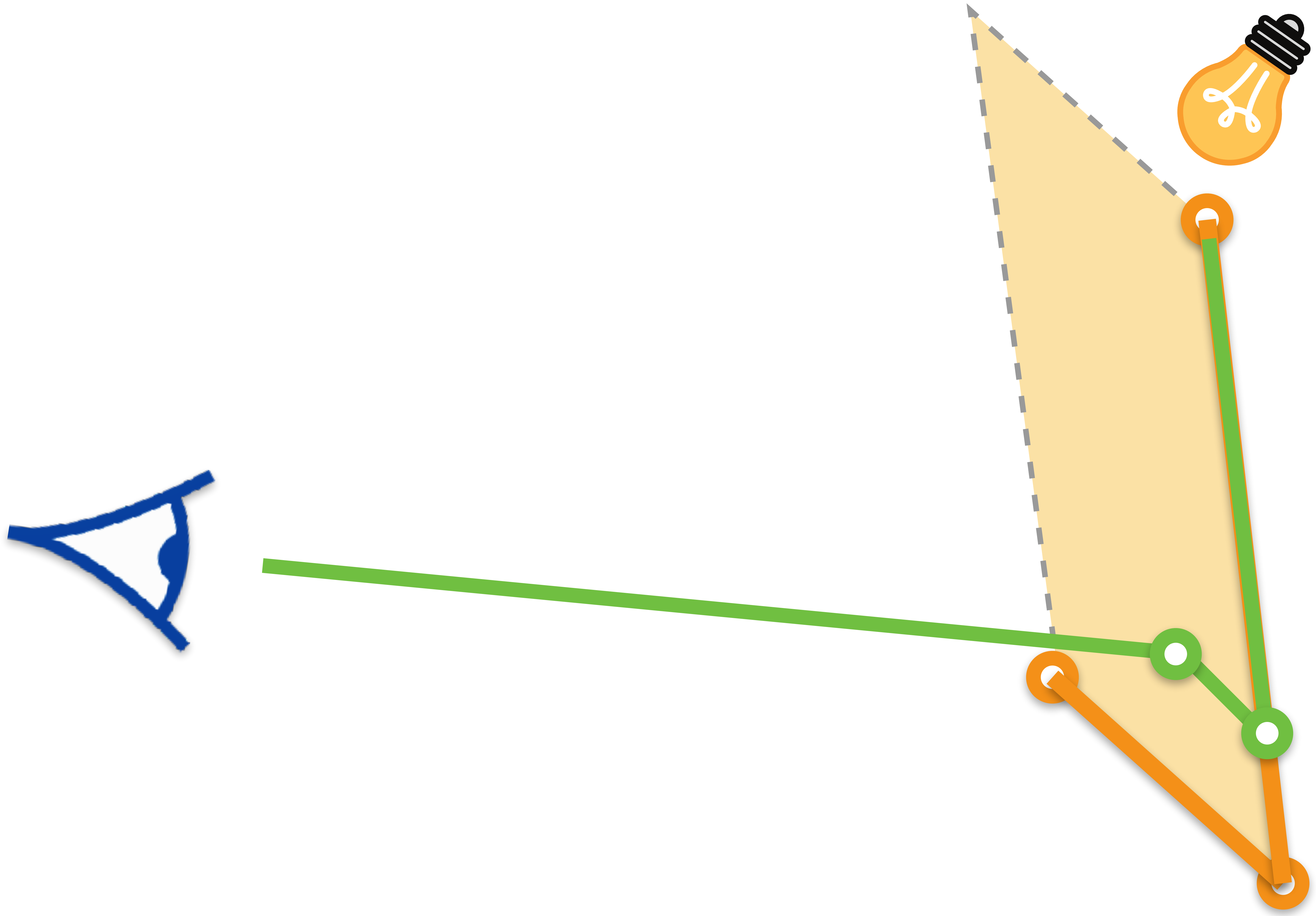

Plane
N
Sphere
N
Cylinder
N
Cone
N

Photon surfaces as sampling strategies

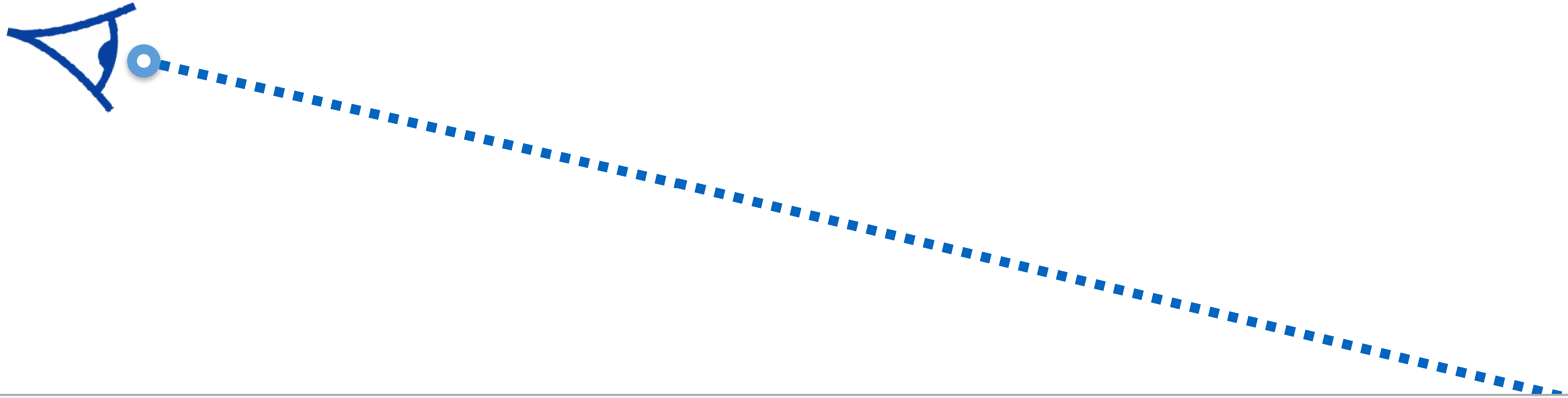
Photon surfaces as sampling strategies



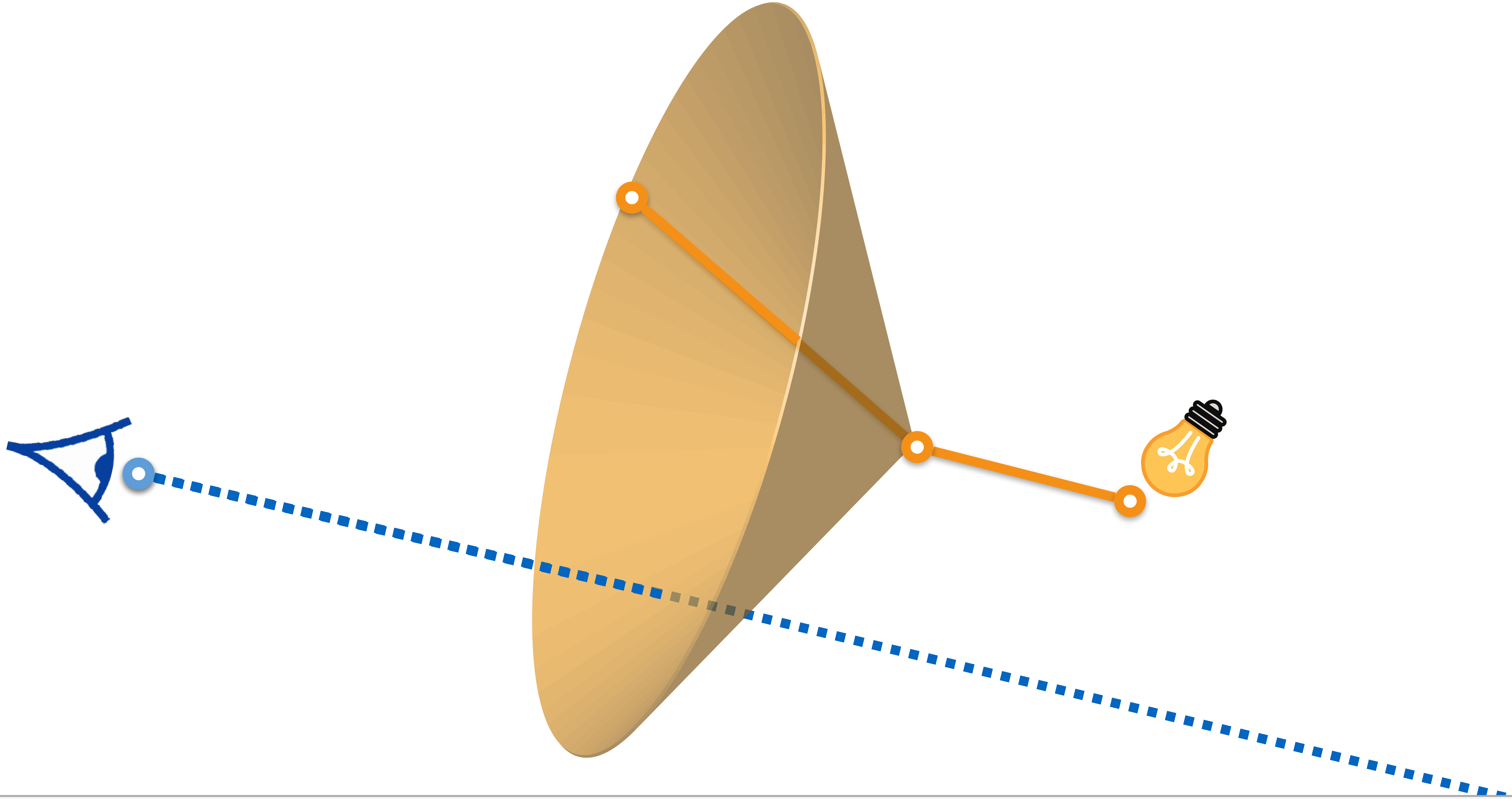
Photon surfaces as sampling strategies



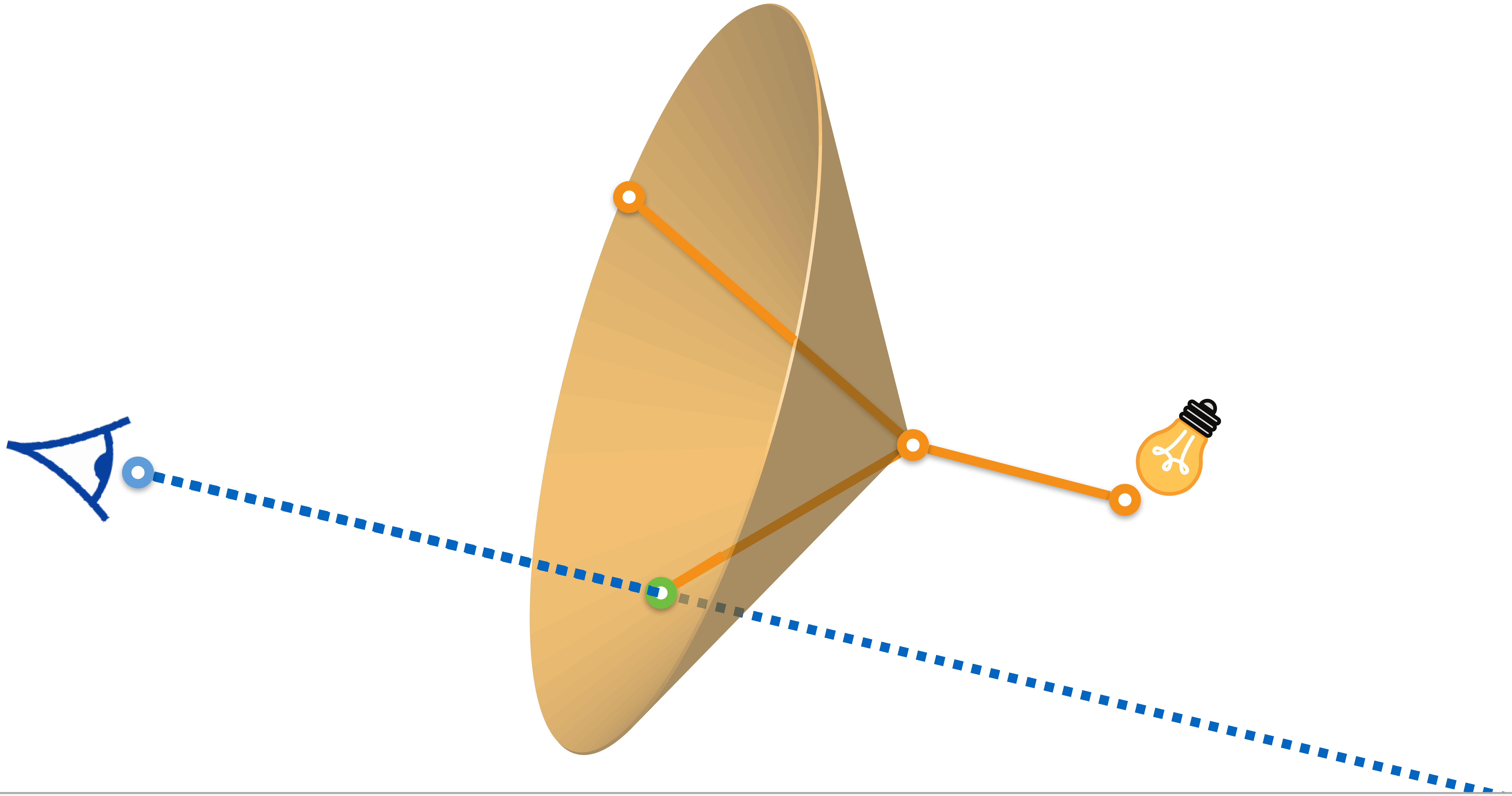
Photon surfaces as sampling strategies



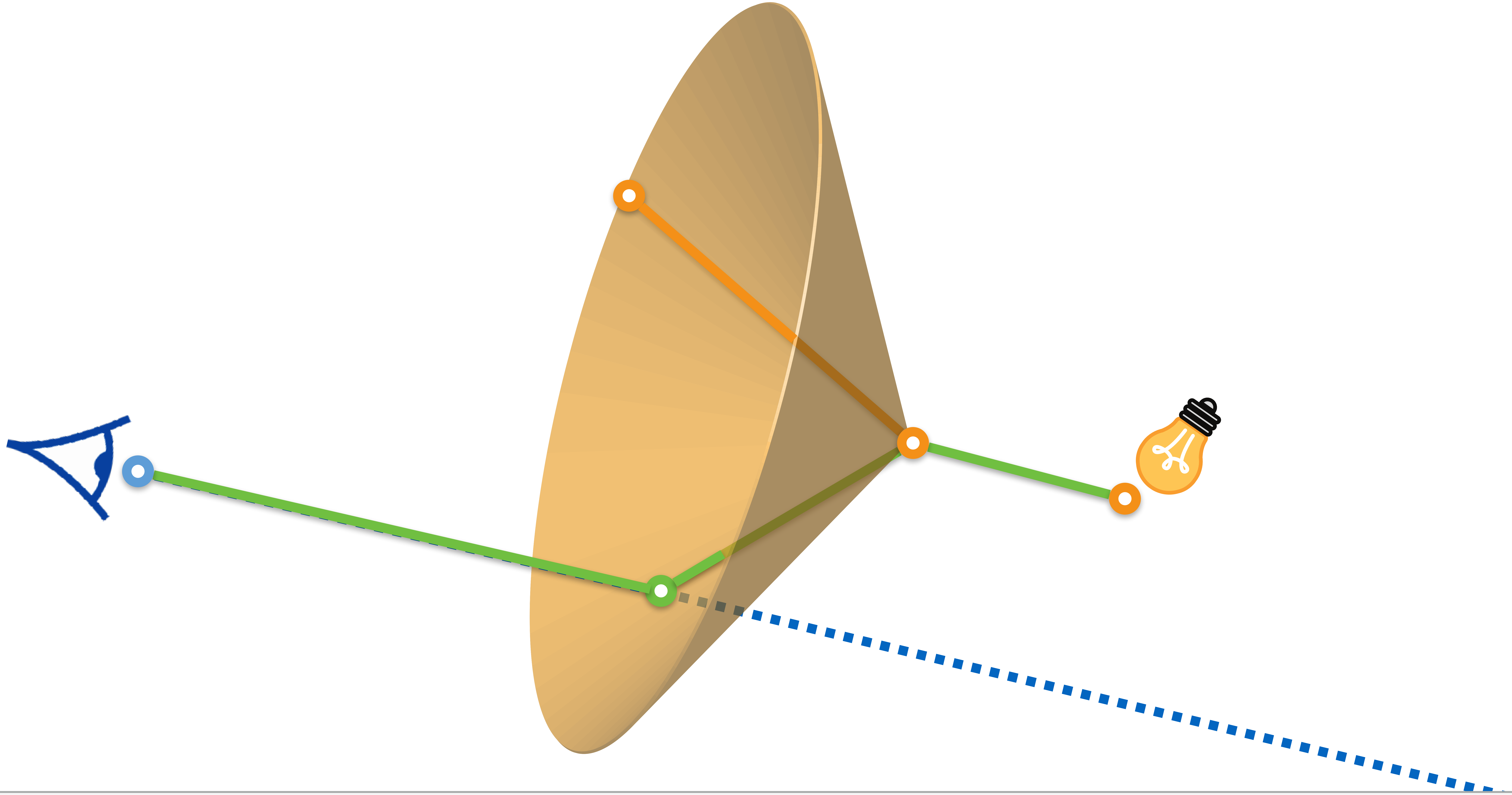
Photon surfaces as sampling strategies



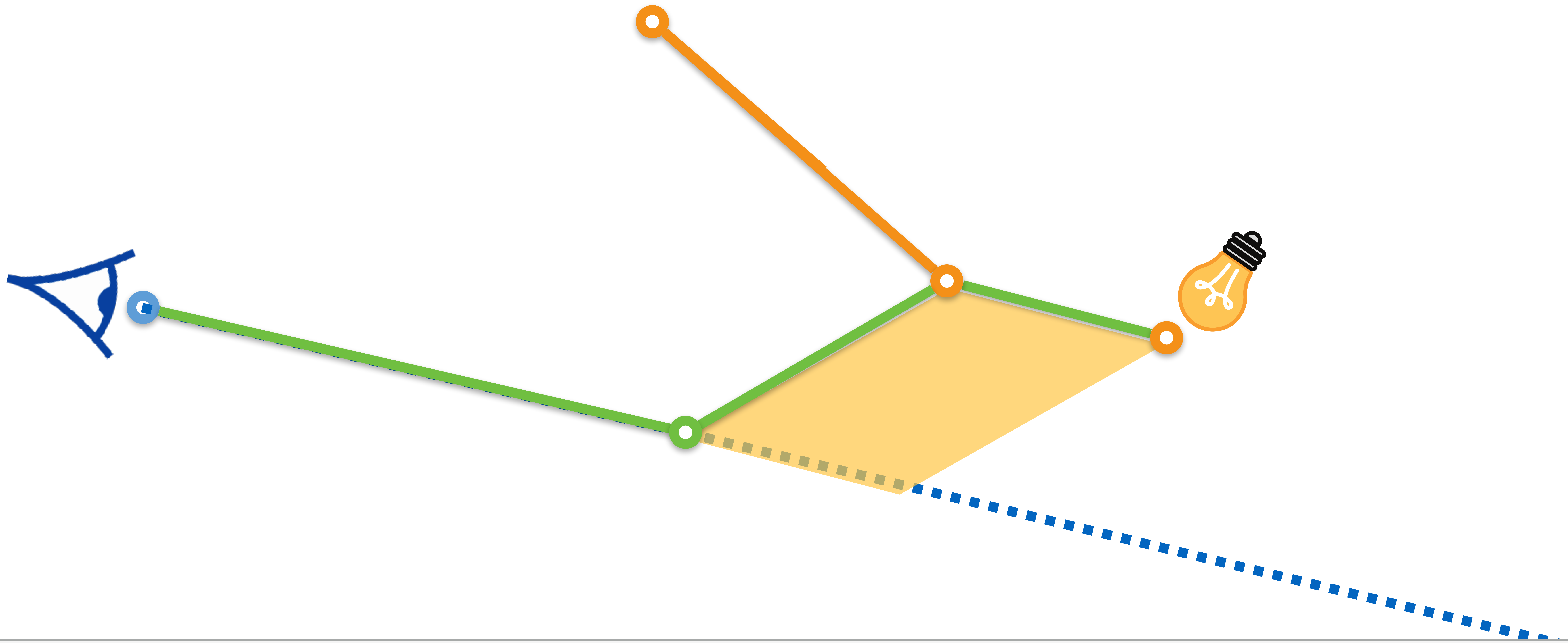
Photon surfaces as sampling strategies



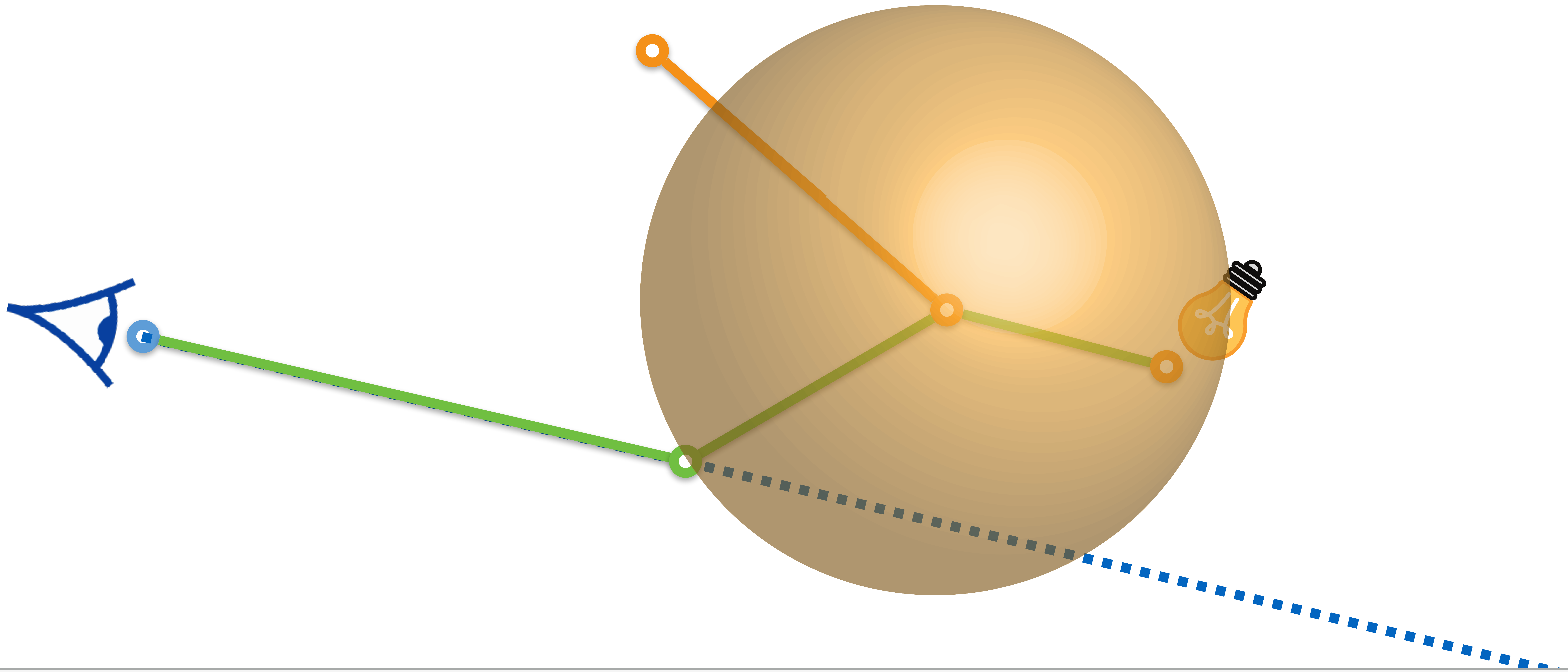
Photon surfaces as sampling strategies



Photon surfaces as sampling strategies

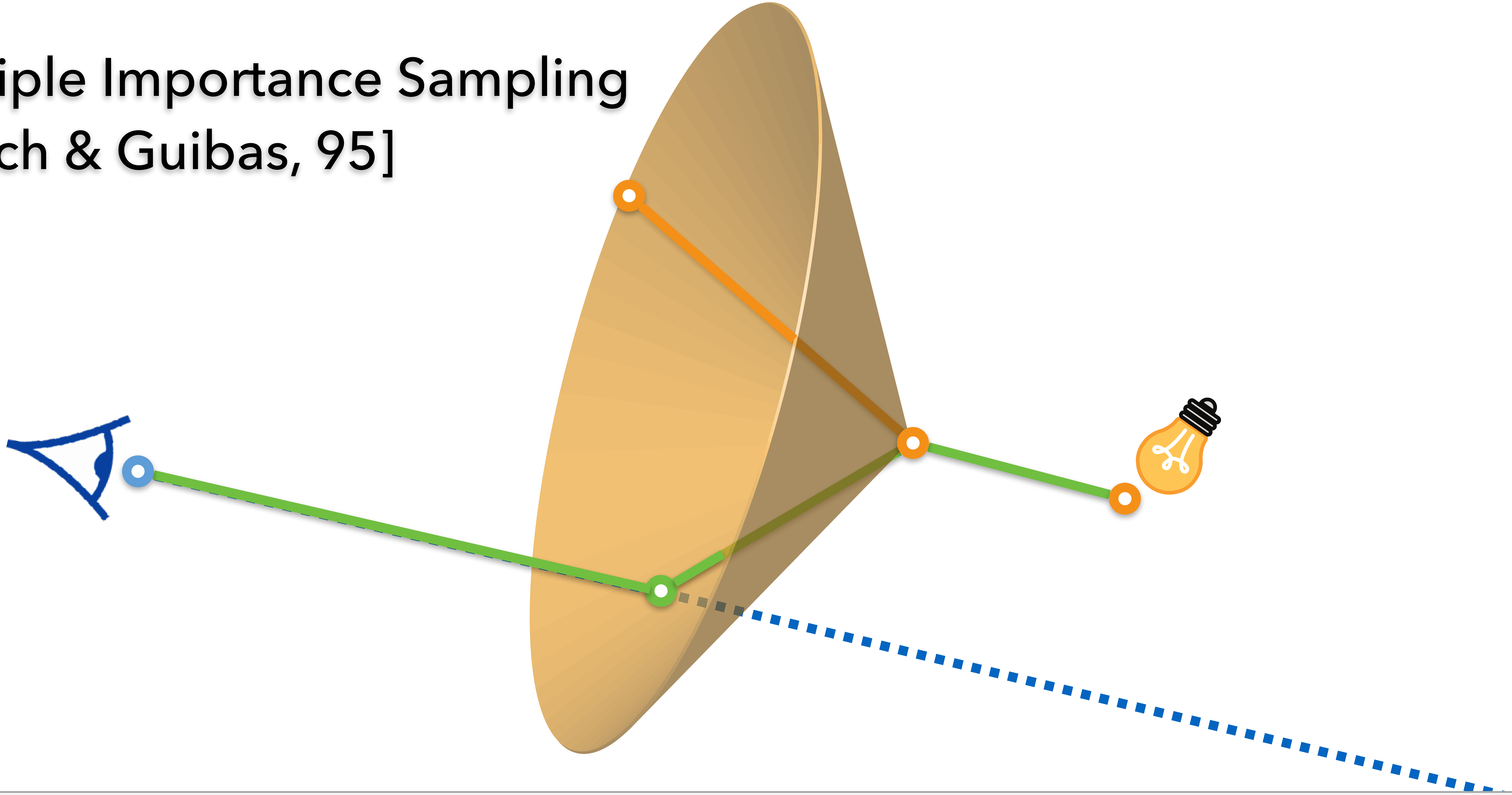


Photon surfaces as sampling strategies

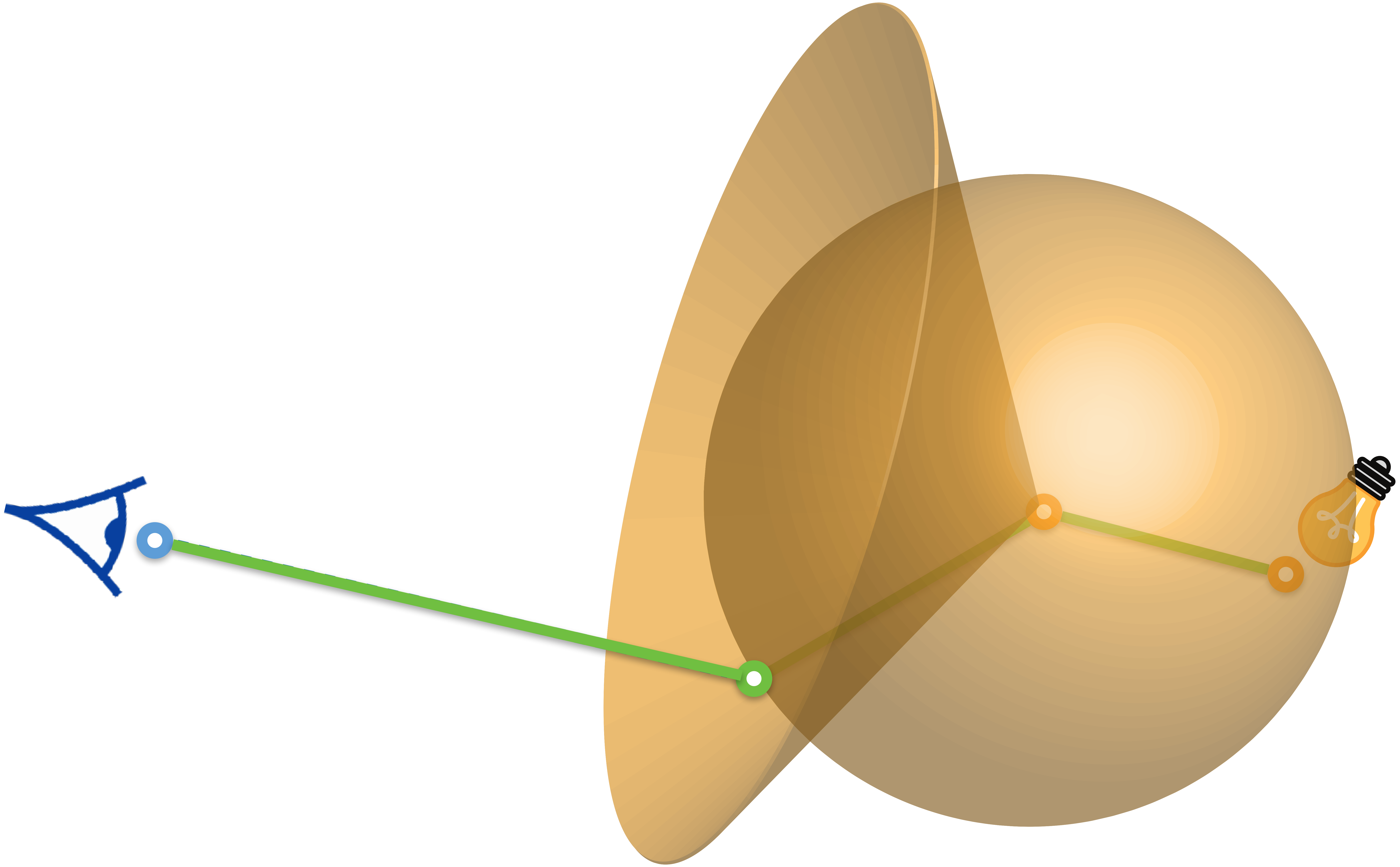


Photon surfaces as sampling strategies

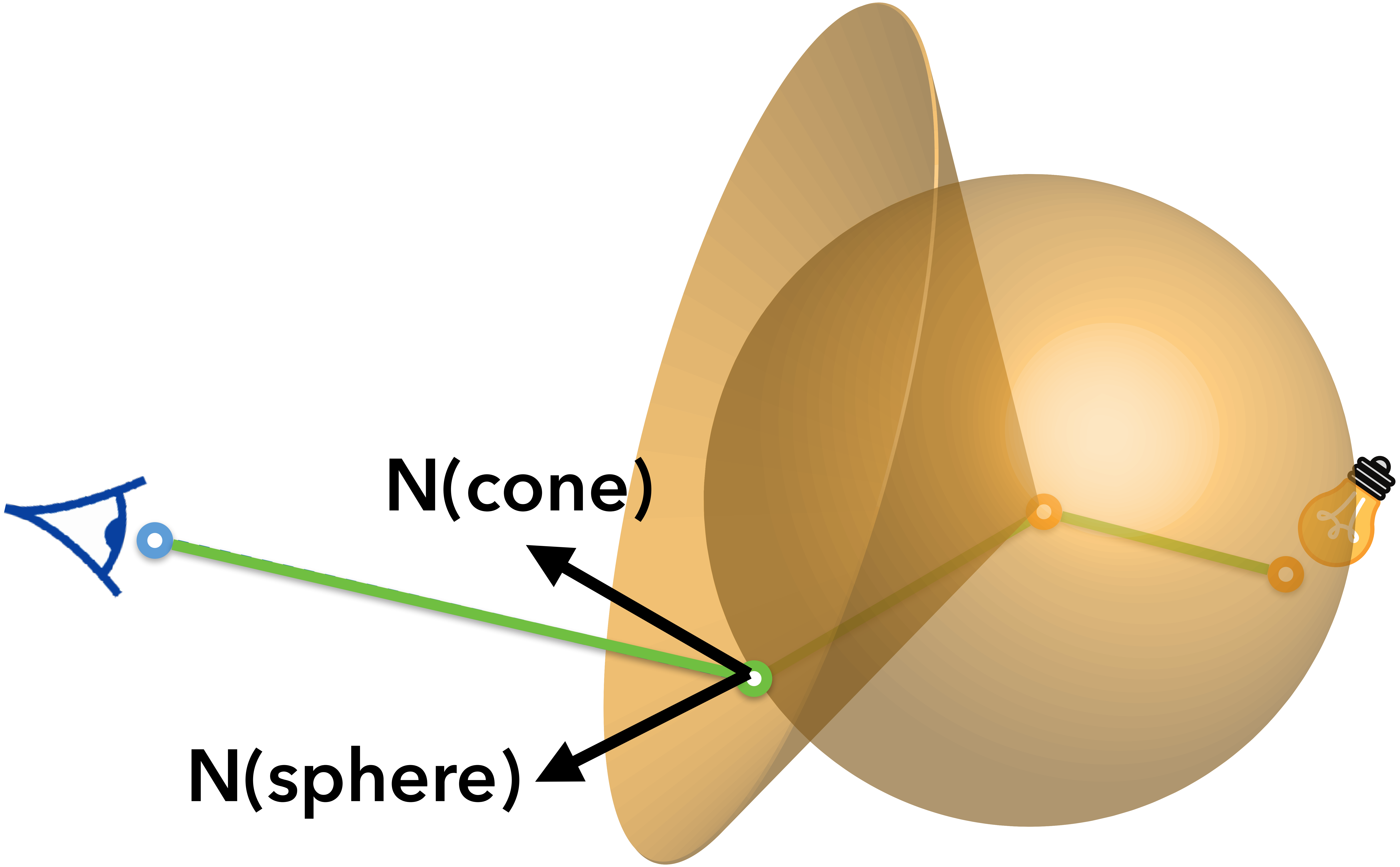
Multiple Importance Sampling
[Veach & Guibas, 95]



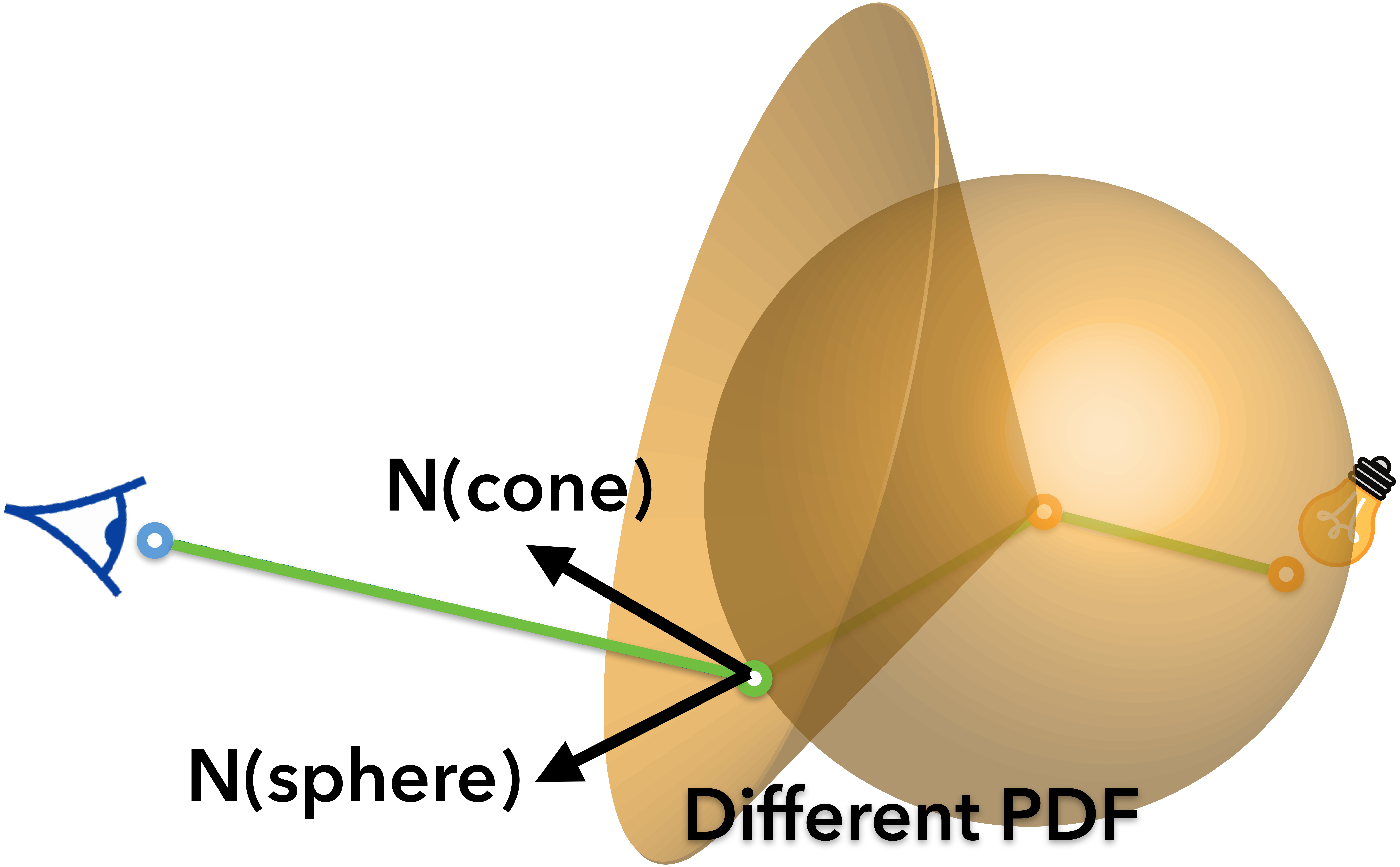
Photon surfaces as sampling strategies



Photon surfaces as sampling strategies



Photon surfaces as sampling strategies




Full light transport

2nd bounce


Unweighted

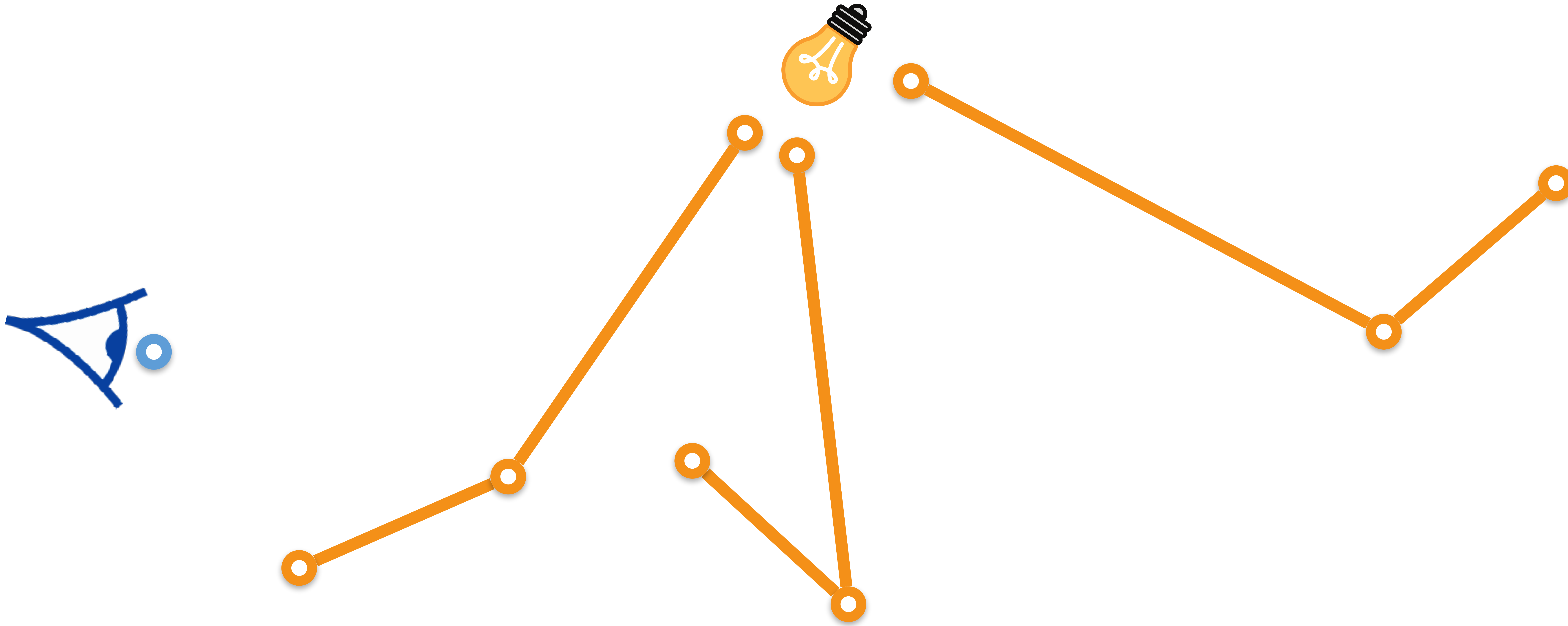

Weighted

PROCEDURE (WITH MIS)

Combining different estimators

Combining different estimators

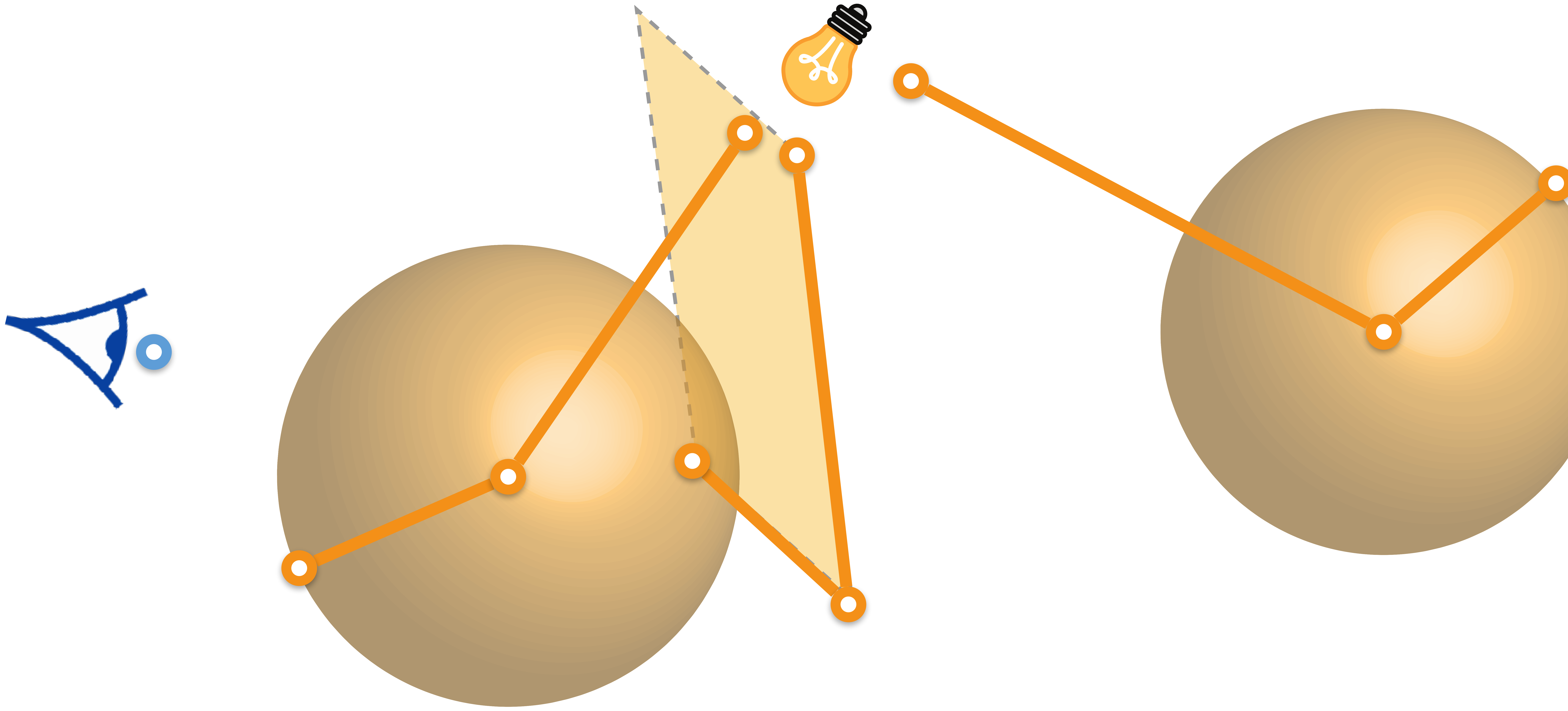
1: Trace



Combining different estimators

1: Trace

2: Create

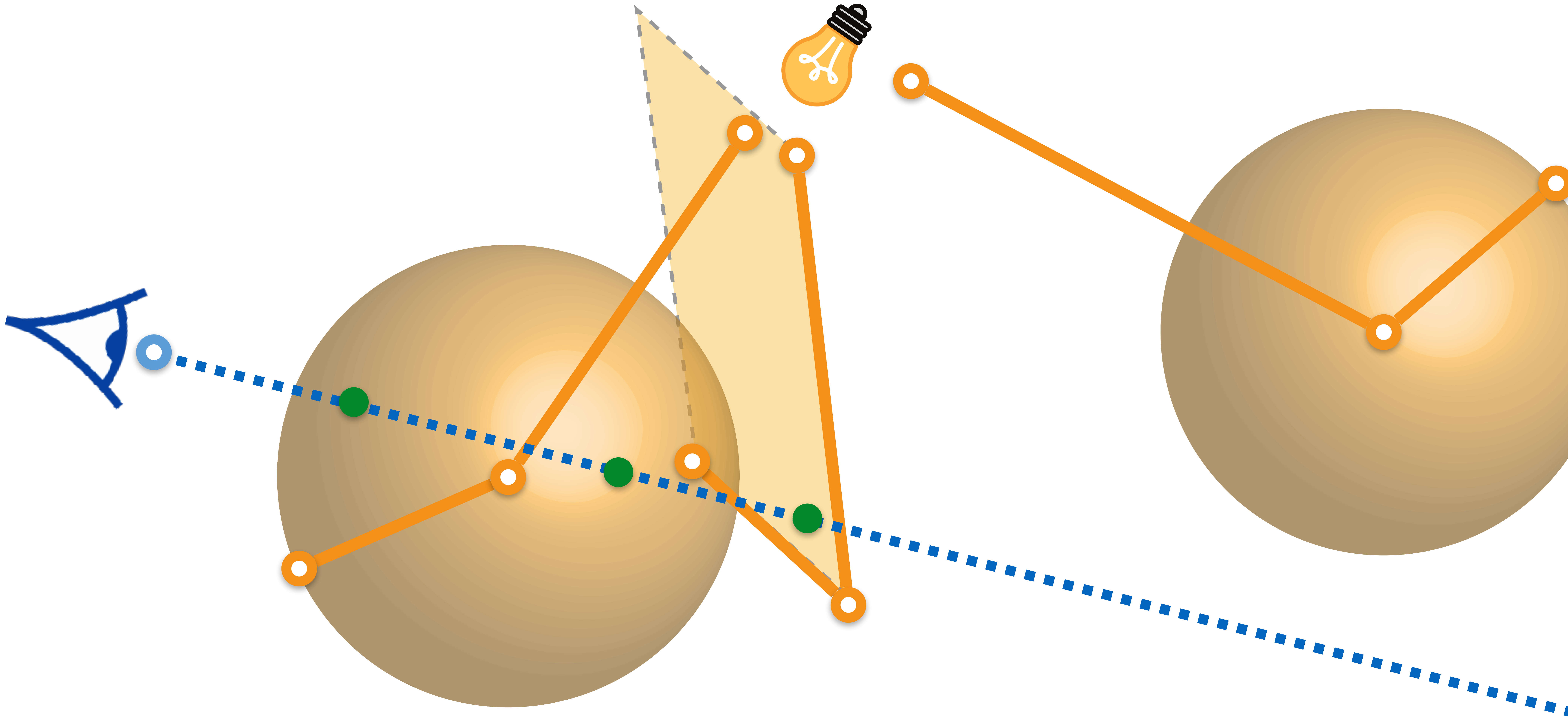


Combining different estimators

1: Trace

2: Create

3: Intersect



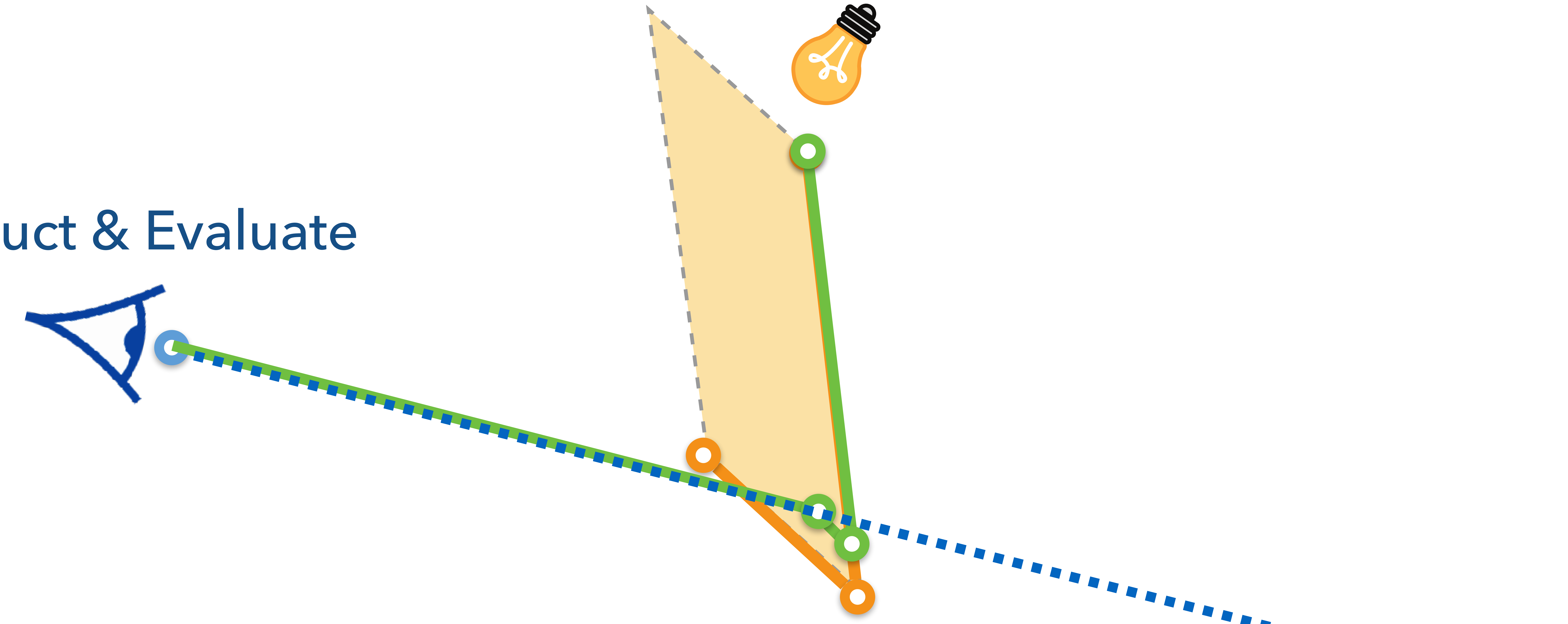
Combining different estimators

1: Trace

2: Create

3: Intersect

4: Reconstruct & Evaluate



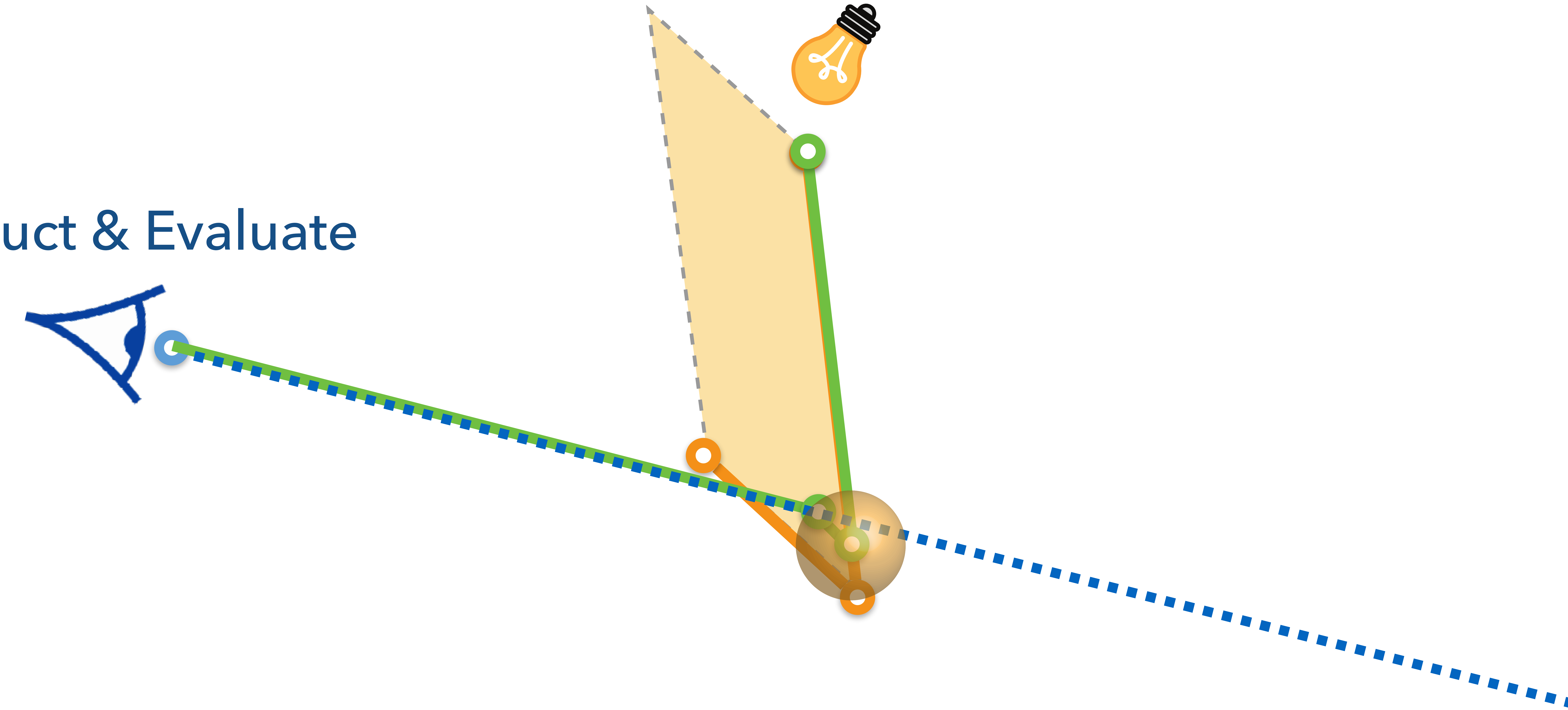
Combining different estimators

1: Trace

2: Create

3: Intersect

4: Reconstruct & Evaluate



RESULTS

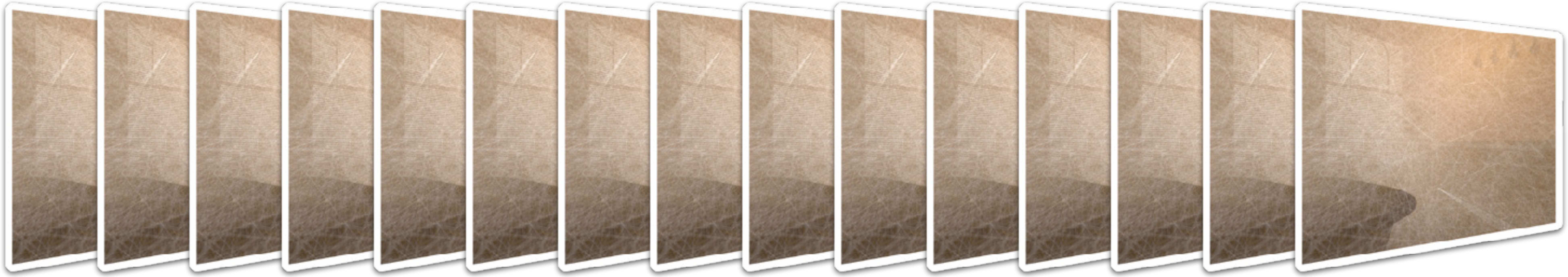
Performance analysis

Quantative performance analysis

5min / image

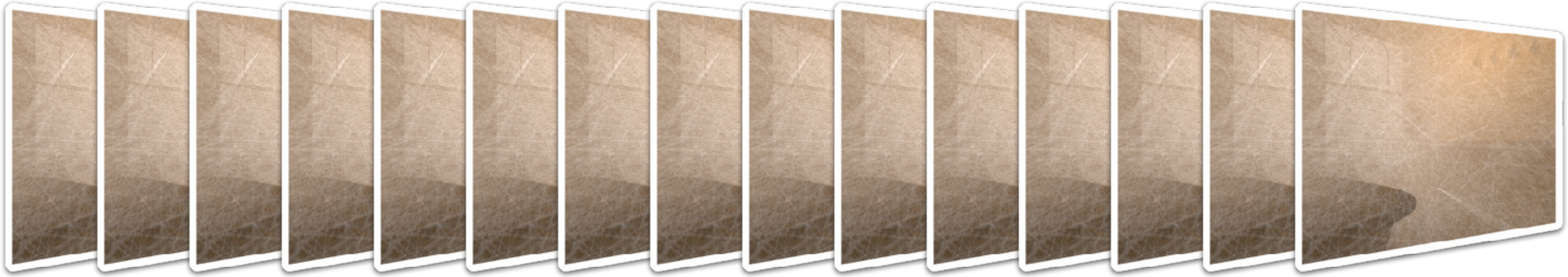
Quantative performance analysis

5min / image



Quantative performance analysis

5min / image

Var []

Scene 1

Medium only


Photon beam
Var:1x
(Single-scattering)
Equal time


Ours, MIS
(3 single-scattering planes, cone, sphere)
Var:0.129x
(Single-scattering)
Equal time

Photon plane

Ours, MIS (3 planes + cone + cylinder)

Var:0.229x

(Multi-scattering)

Equal time

Scene 2


Photon beam
Var:1x
(Single-scattering)
Equal time


Ours (3 single-scattering planes)
Var:0.389x
(Single-scattering)
Equal time

Scene 3

Photon plane

Var:1x

(Multi-scattering)

Equal time

Ours, MIS (3 planes + cone + cylinder)

Var:0.483x

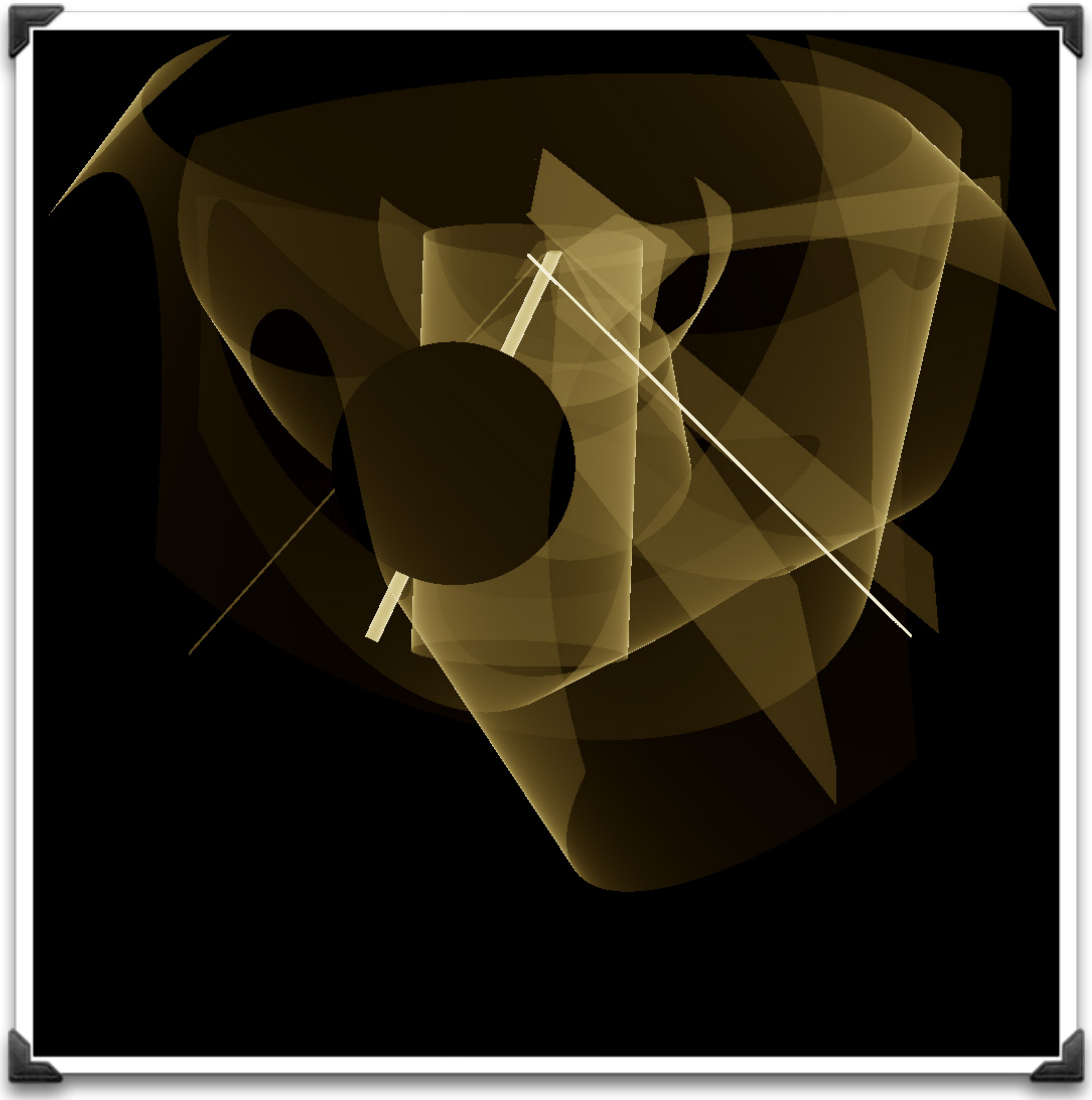
(Multi-scattering)

Equal time

Conclusions

We've improved **unbiased** photon density estimation:

Photon surface

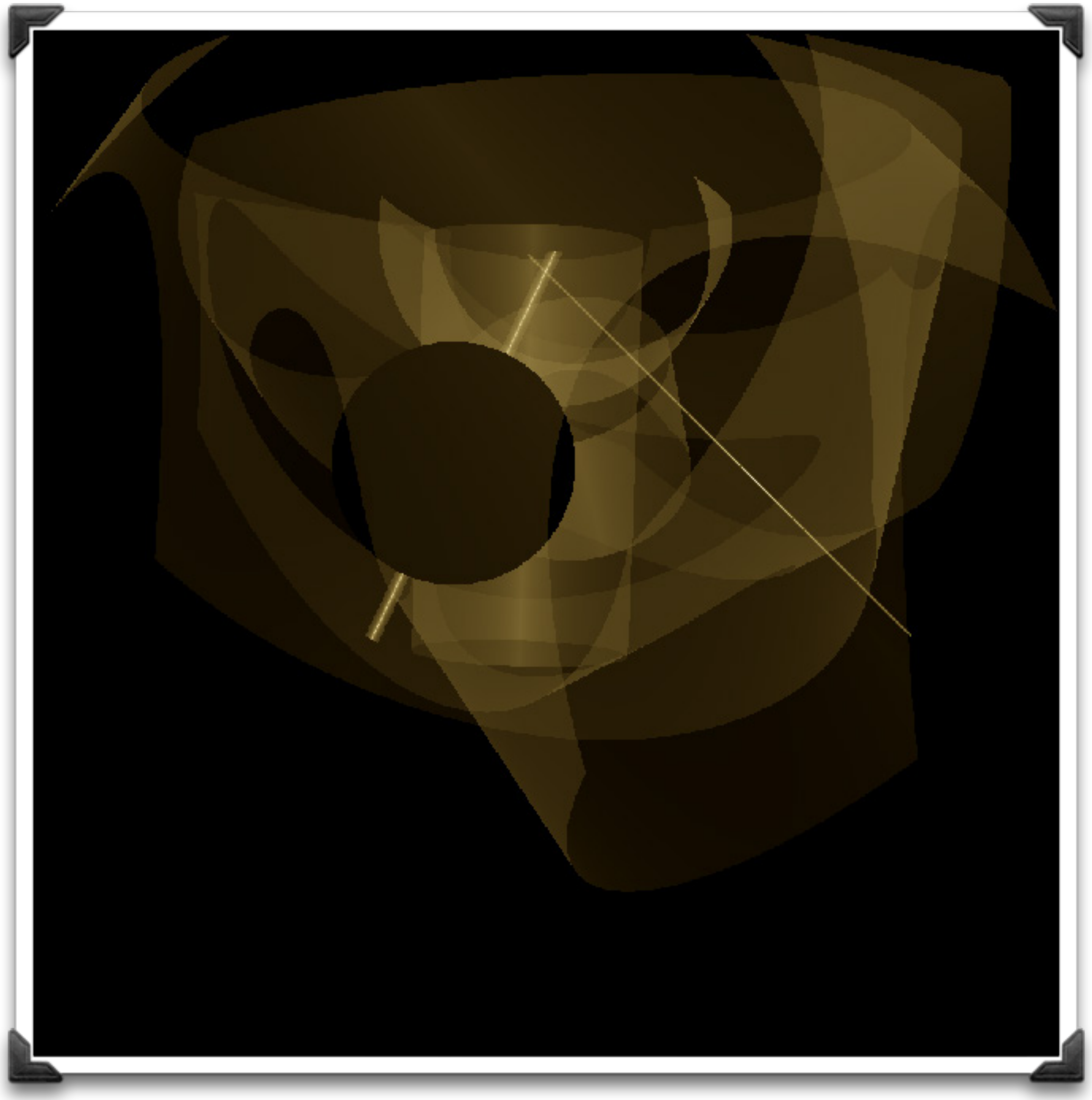


Conclusions

We've improved **unbiased** photon density estimation:

Photon surface

Combination using MIS



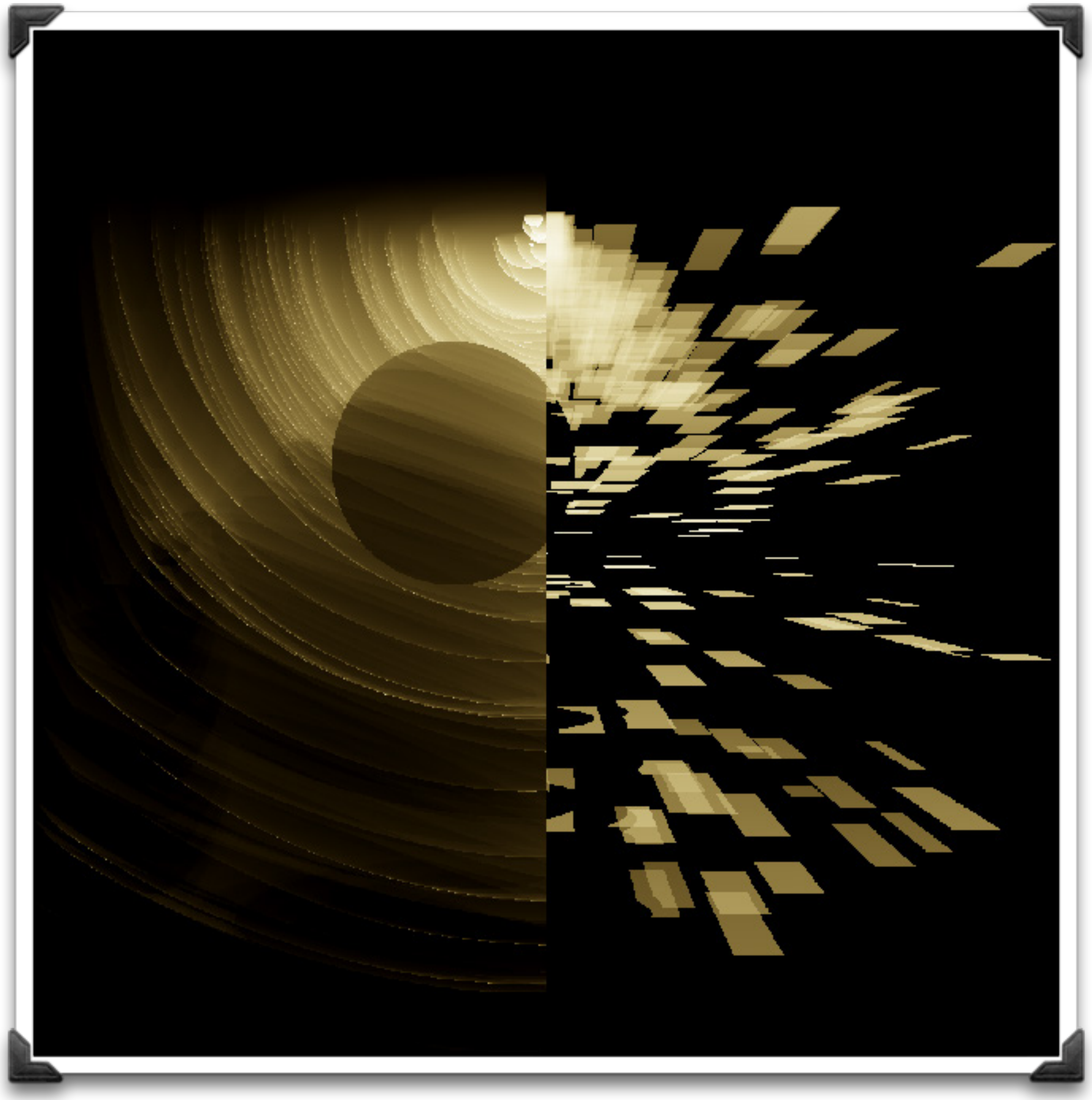
Conclusions

We've improved **unbiased** photon density estimation:

Photon surface

Combination using MIS

Single-scattering



Limitations

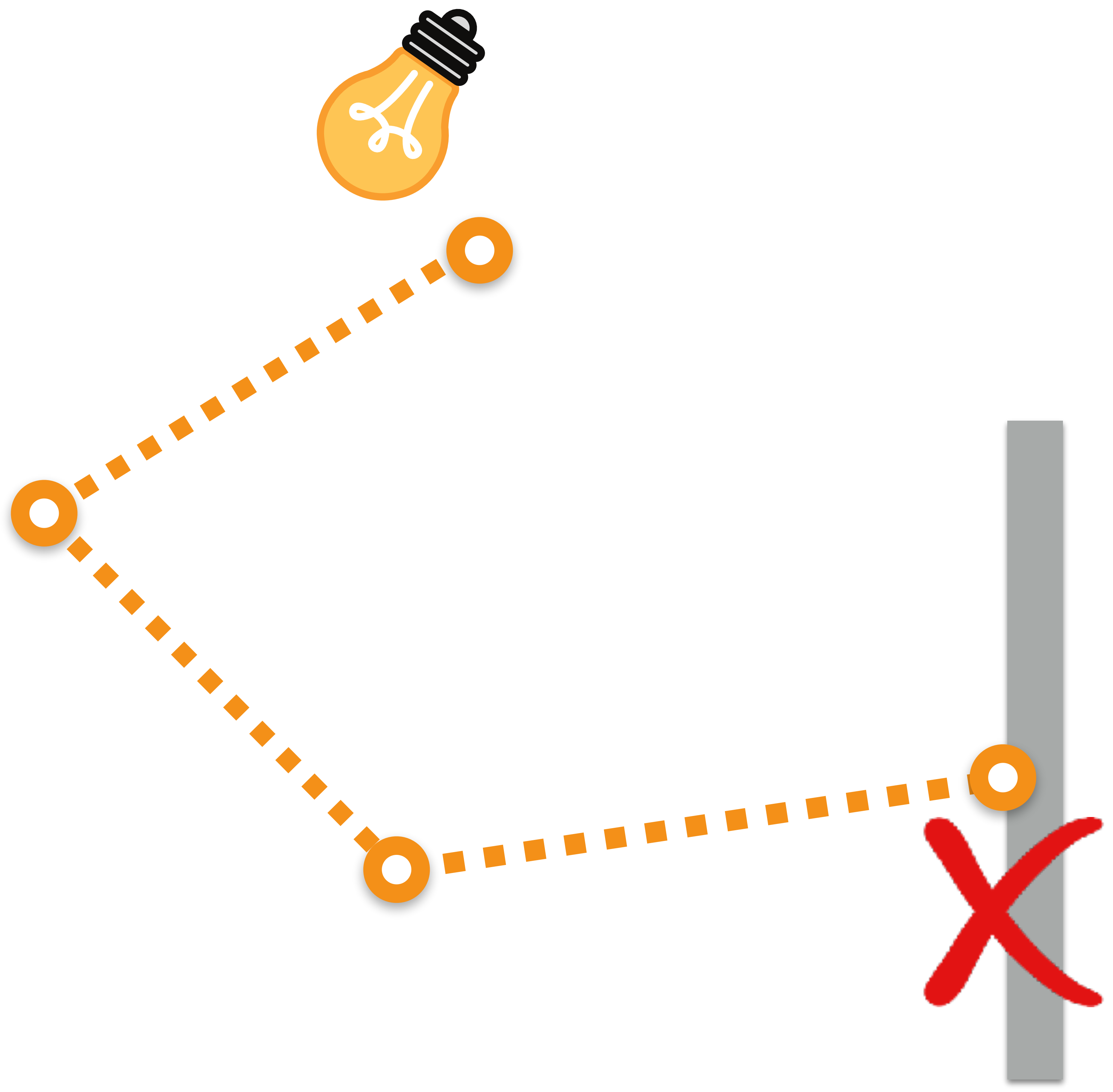
Heterogeneity is still too slow to be practical.

Limitations

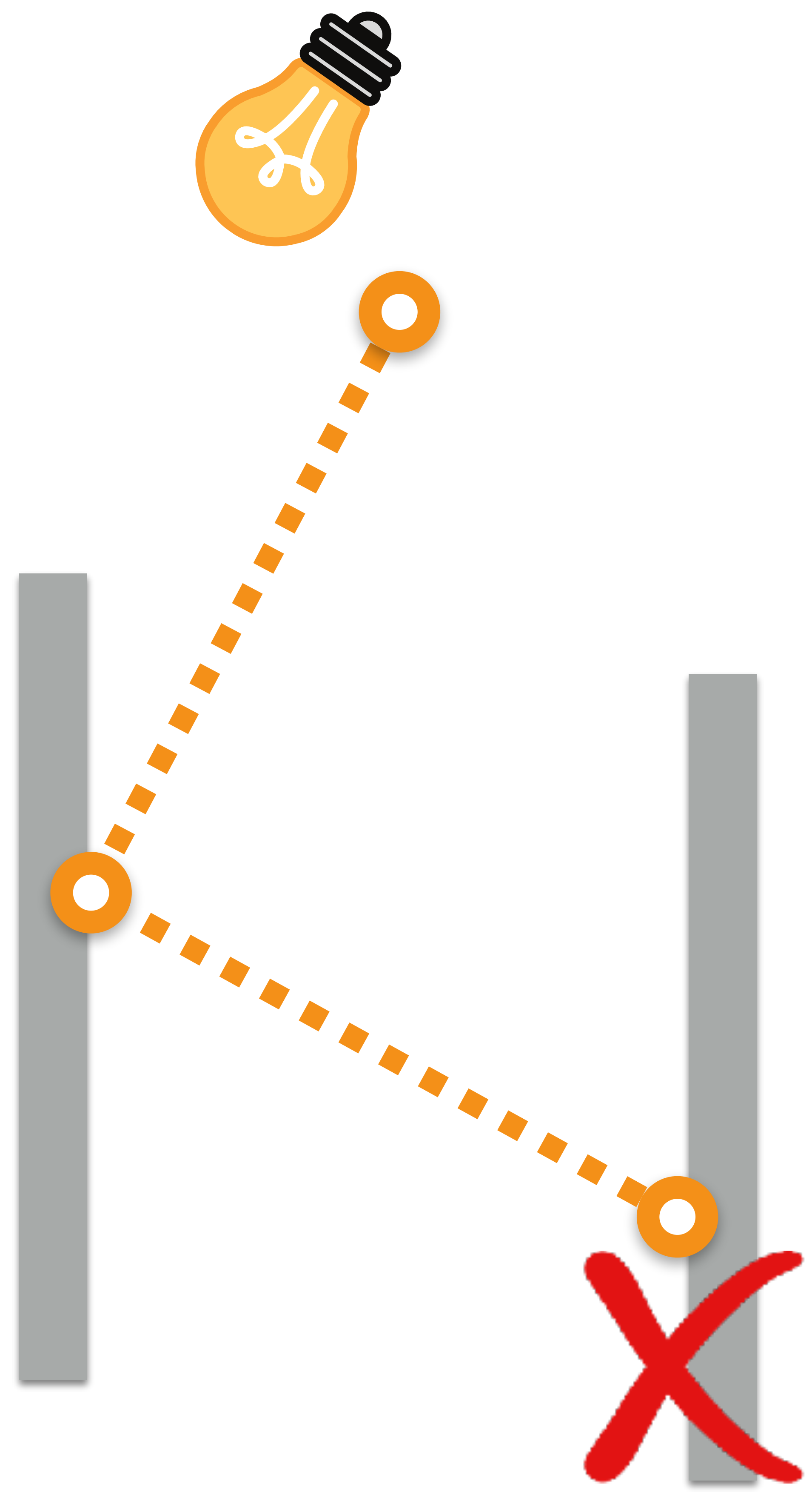
Some types of **light transport** cannot be handled efficiently

Future Work

Medium-to-**surface**



Surface-to-**surface**

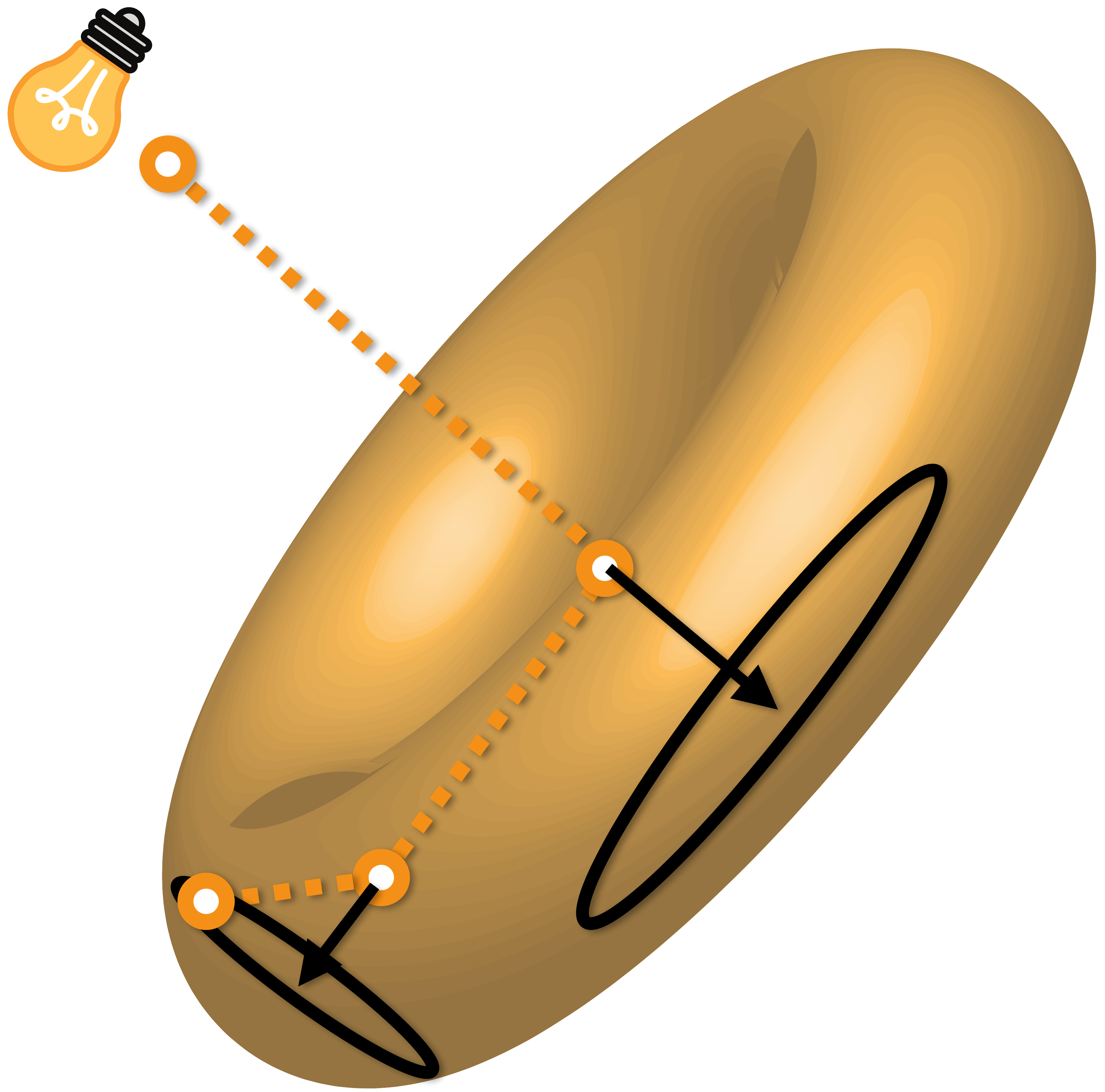


Future Work

More possible **base estimators**

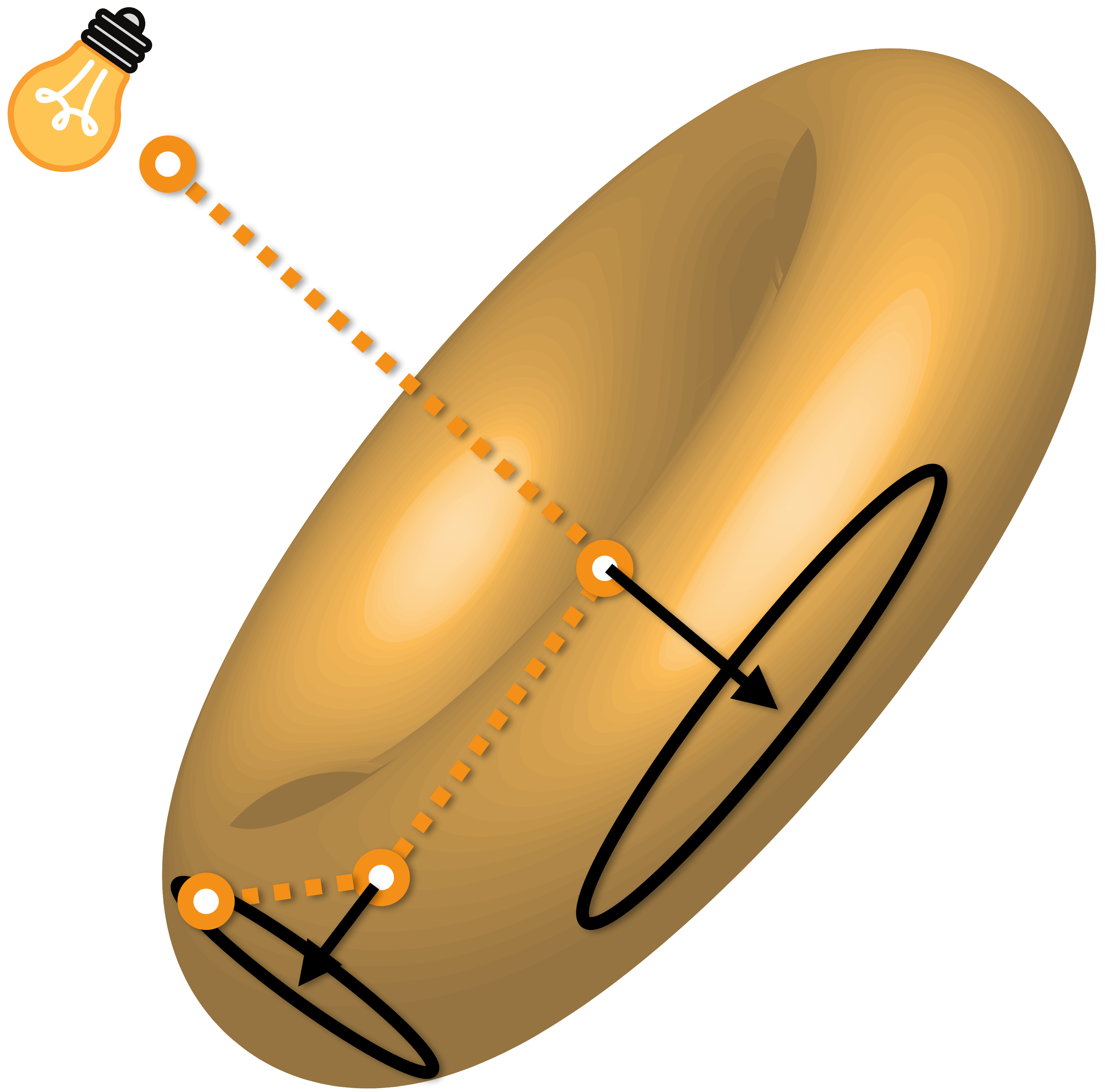
Future Work

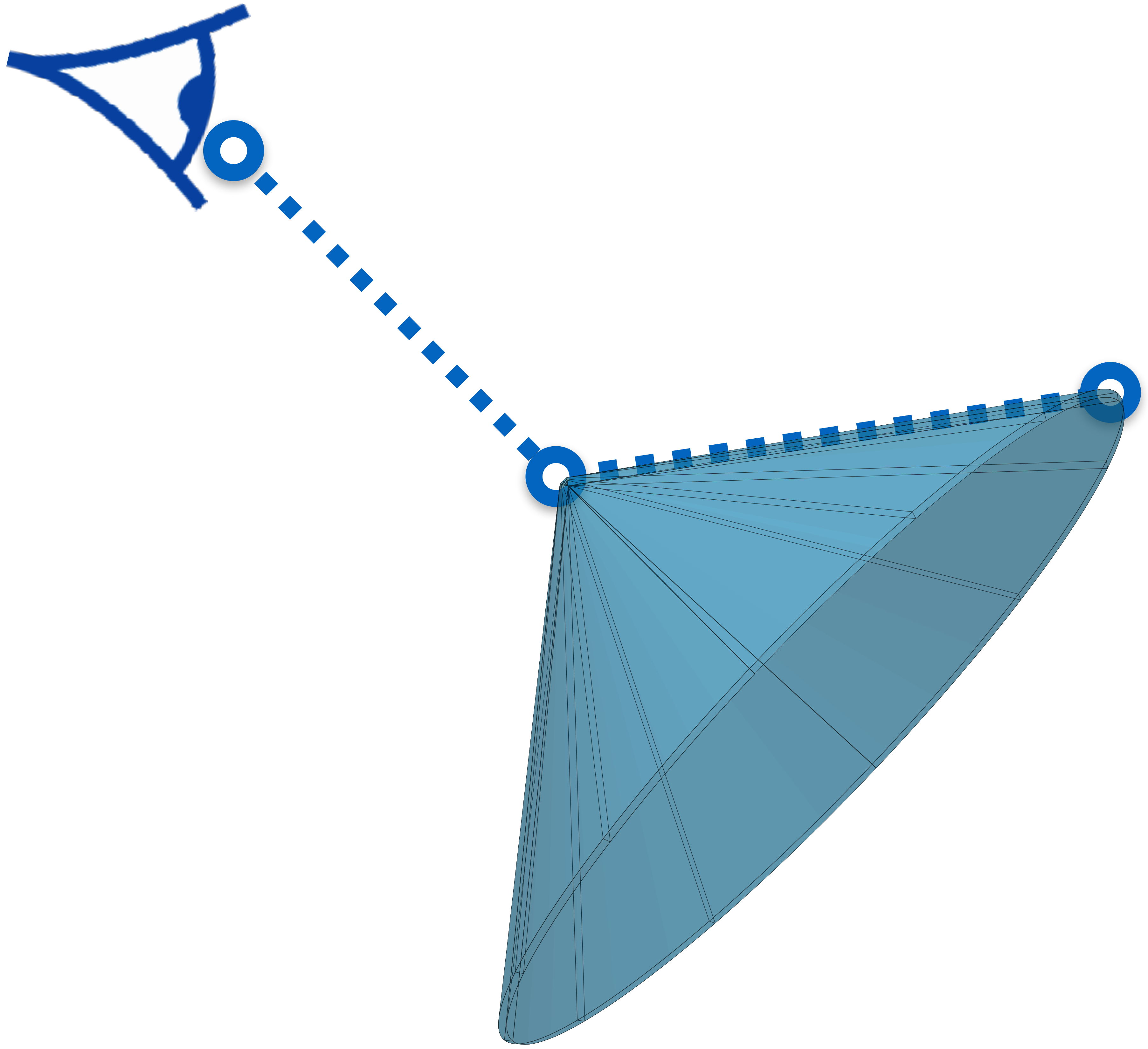
More possible **base estimators**



Future Work

More possible **base estimators**



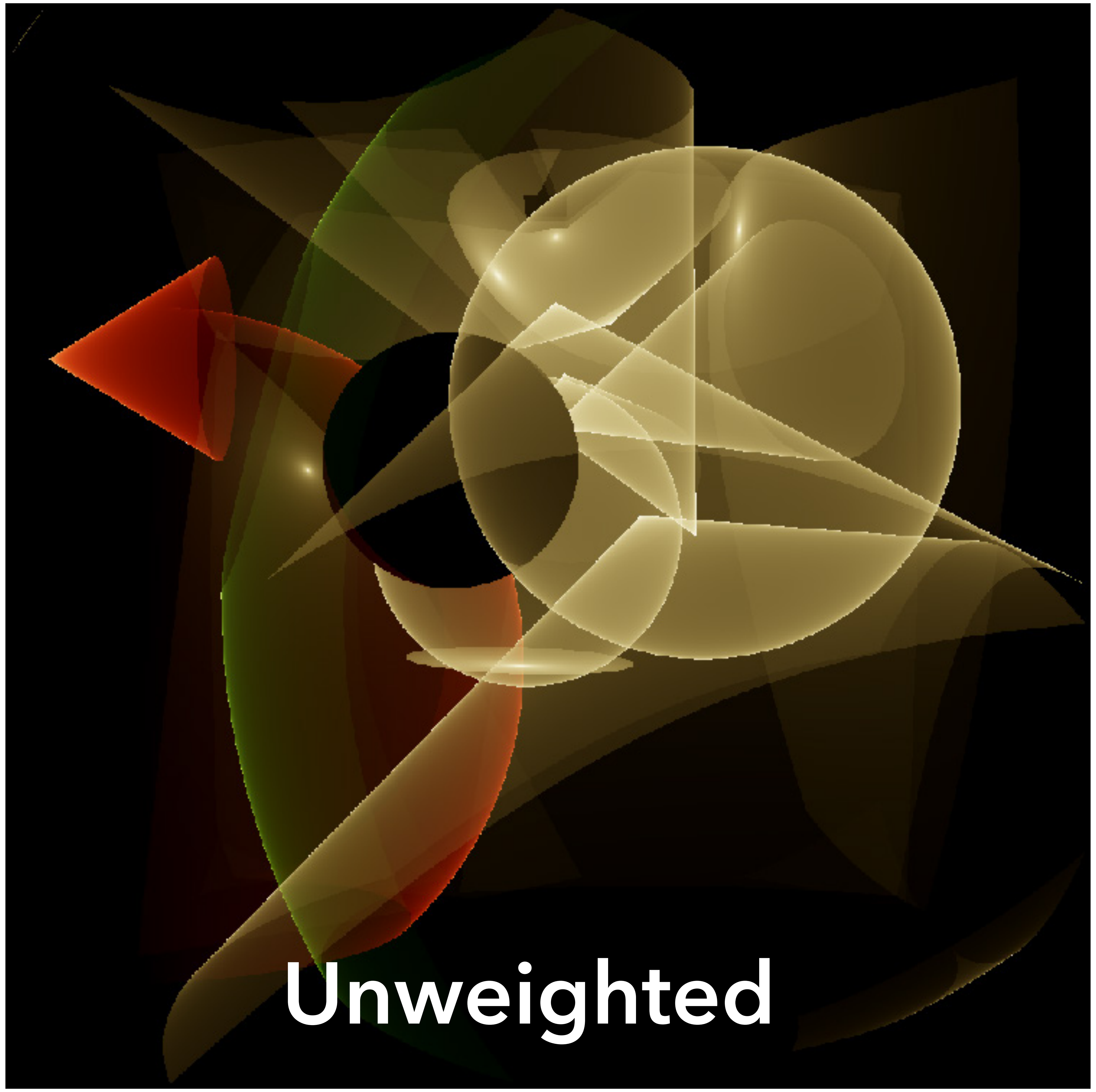


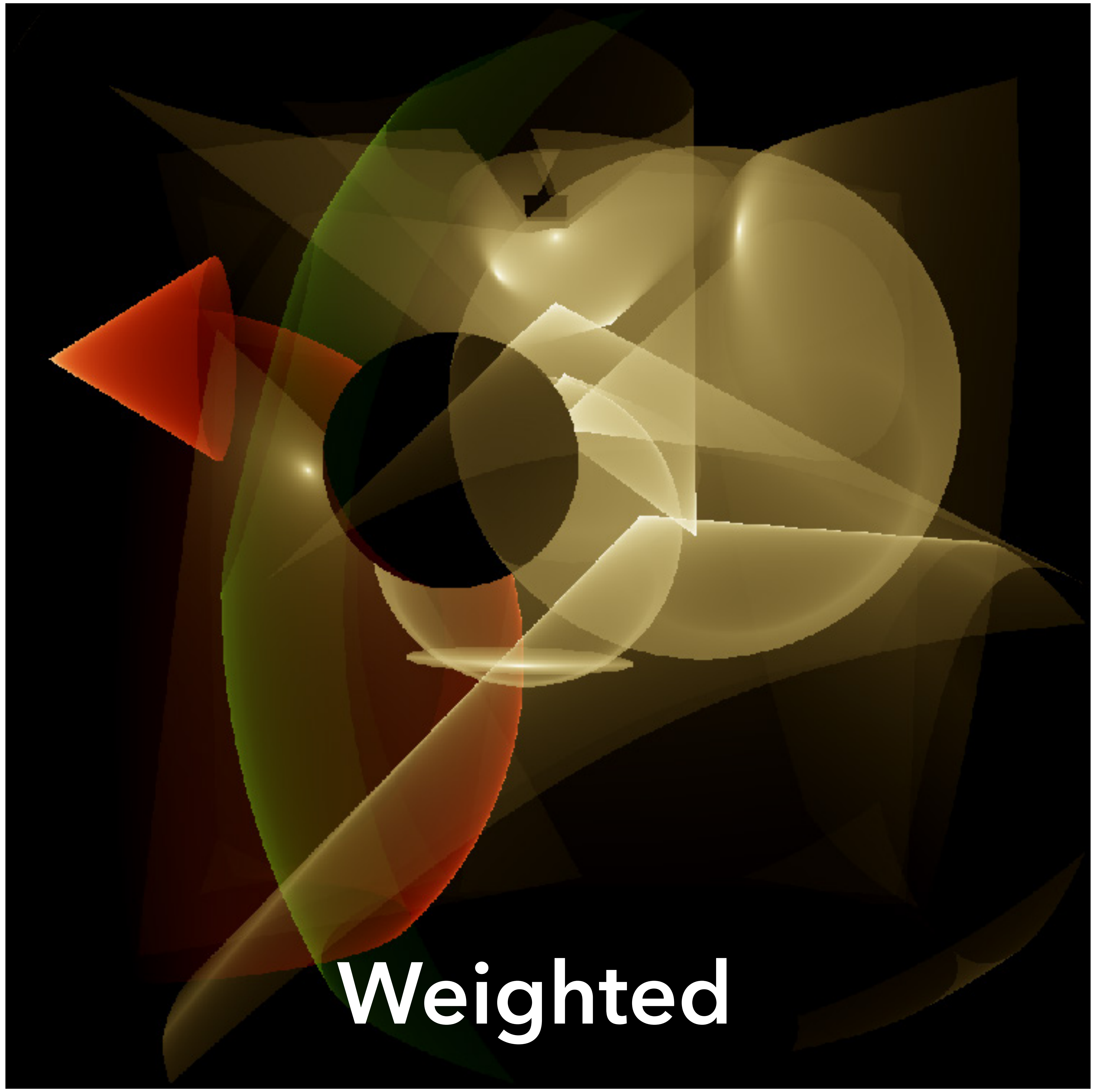
Future Work

Implementing in a **path tracer**

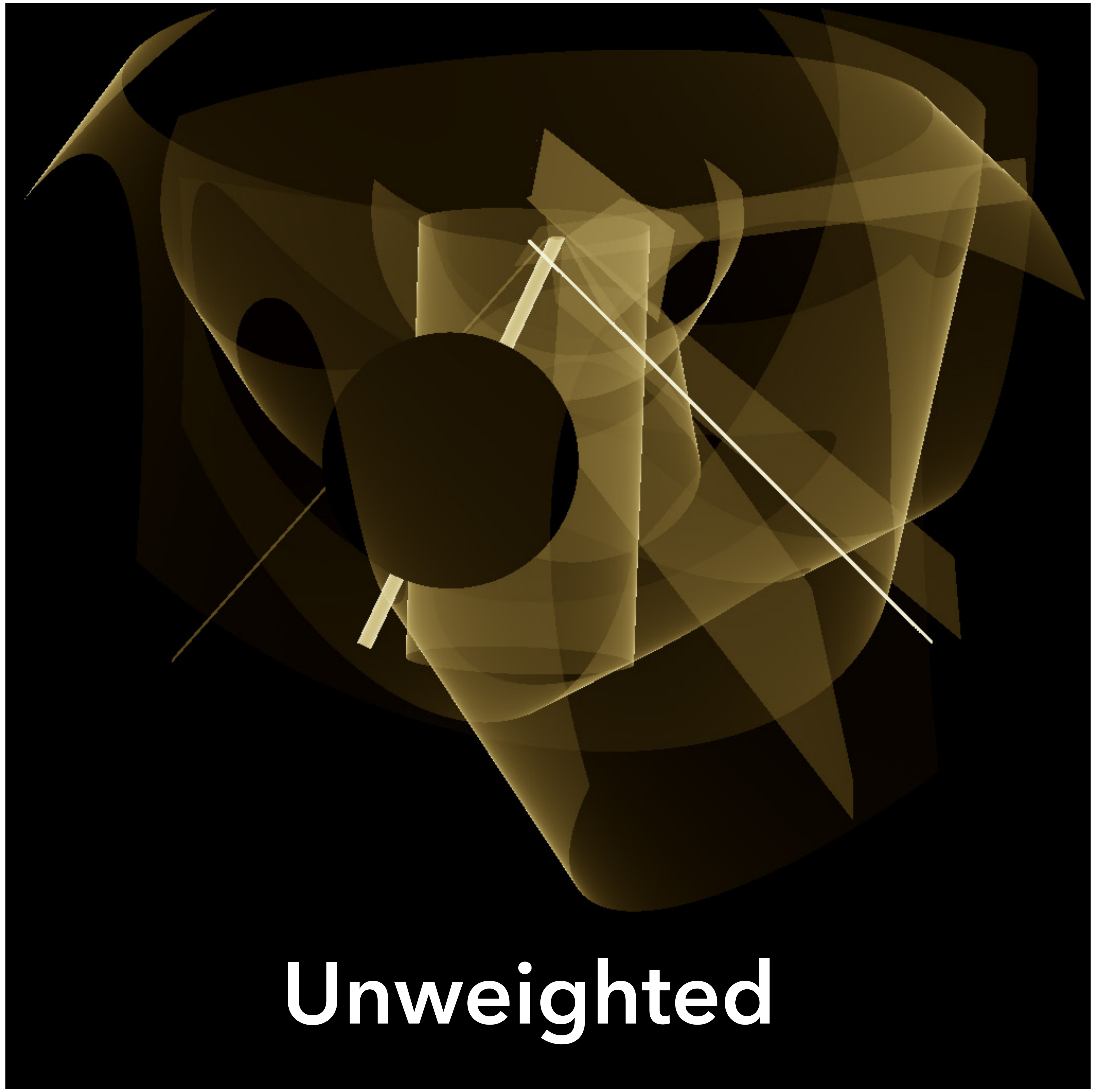
Thank you!

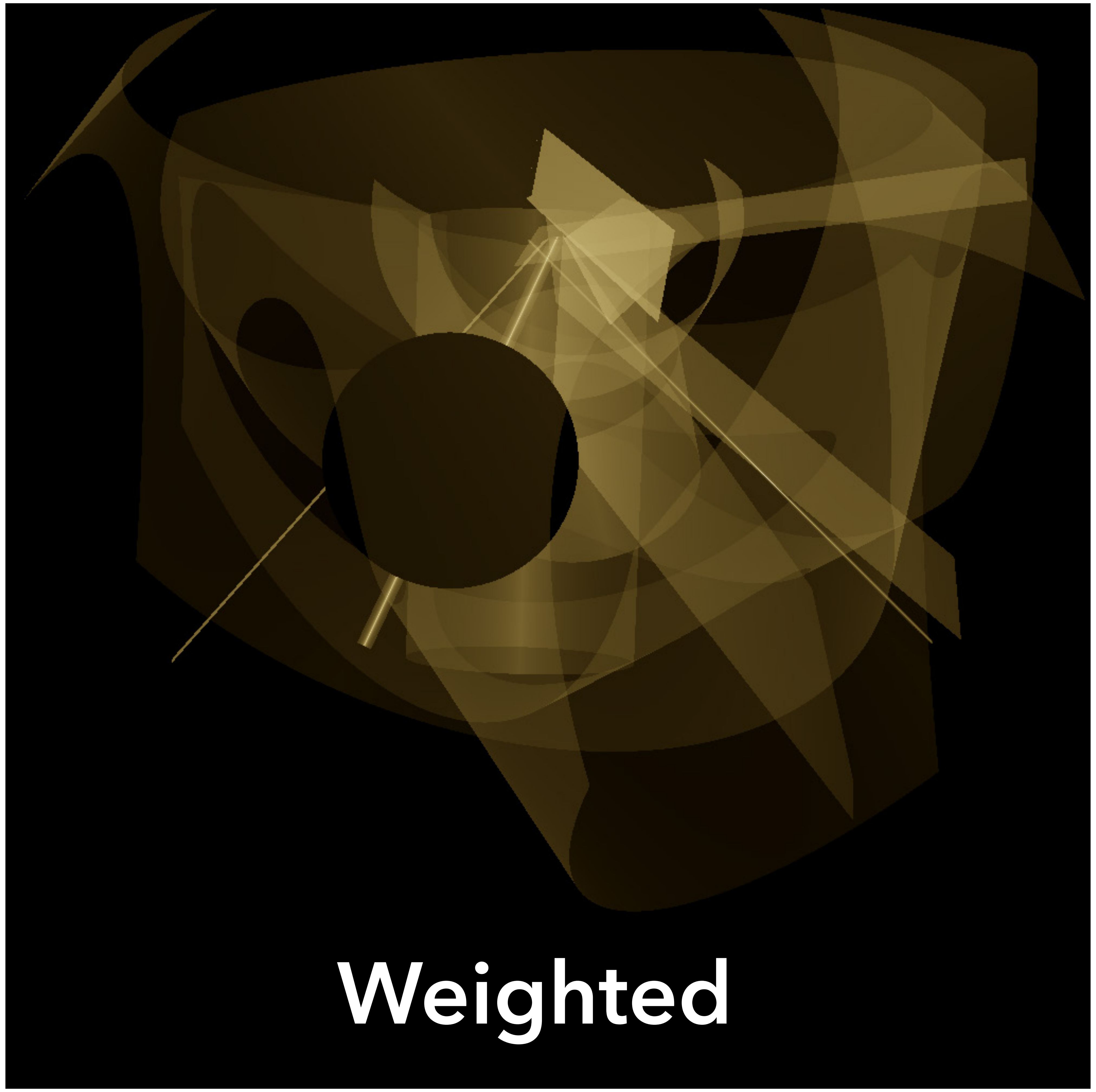
Some combinations are much worse



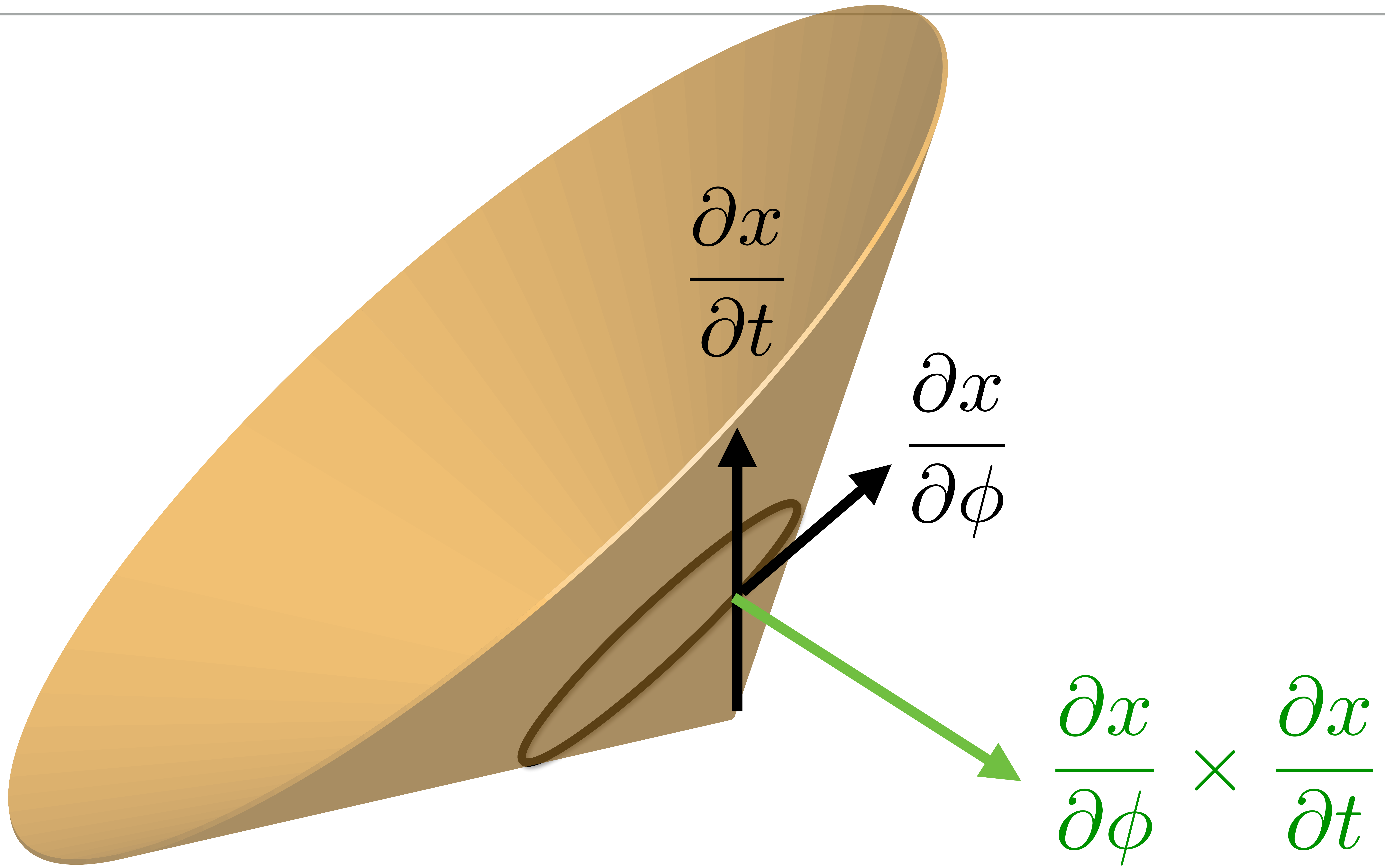


Some combinations are much better





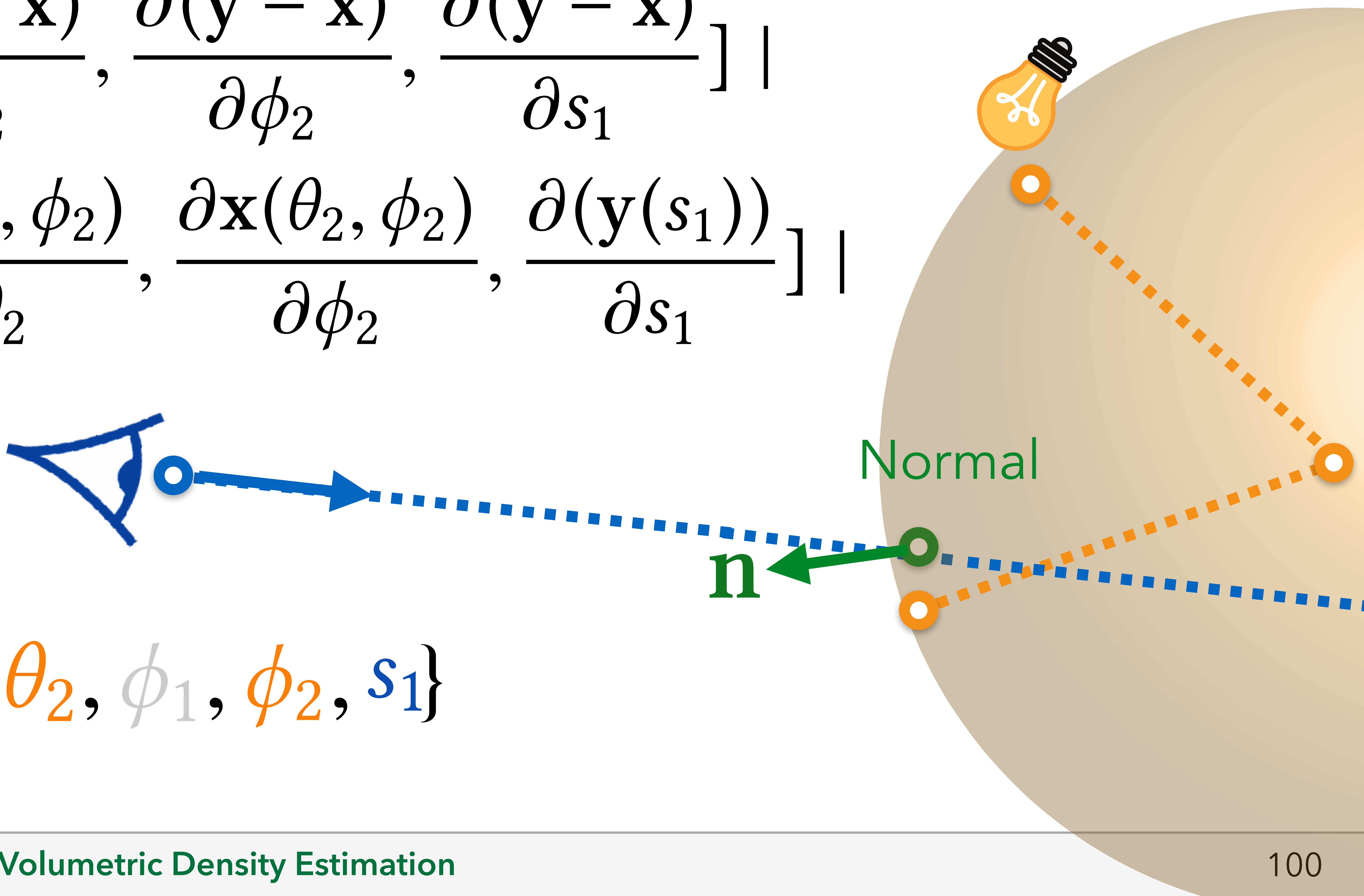
Surface differential



Surface differential

$$| \omega \cdot n | = | \det [\frac{\partial(\mathbf{y}-\mathbf{x})}{\partial \theta_2}, \frac{\partial(\mathbf{y}-\mathbf{x})}{\partial \phi_2}, \frac{\partial(\mathbf{y}-\mathbf{x})}{\partial s_1}] |$$

$$= | \det [\frac{\partial \mathbf{x}(\theta_2, \phi_2)}{\partial \theta_2}, \frac{\partial \mathbf{x}(\theta_2, \phi_2)}{\partial \phi_2}, \frac{\partial(\mathbf{y}(s_1))}{\partial s_1}] |$$



Variables: $\{t_1, t_2, \theta_1, \theta_2, \phi_1, \phi_2, s_1\}$

Long Beam and Short Beam

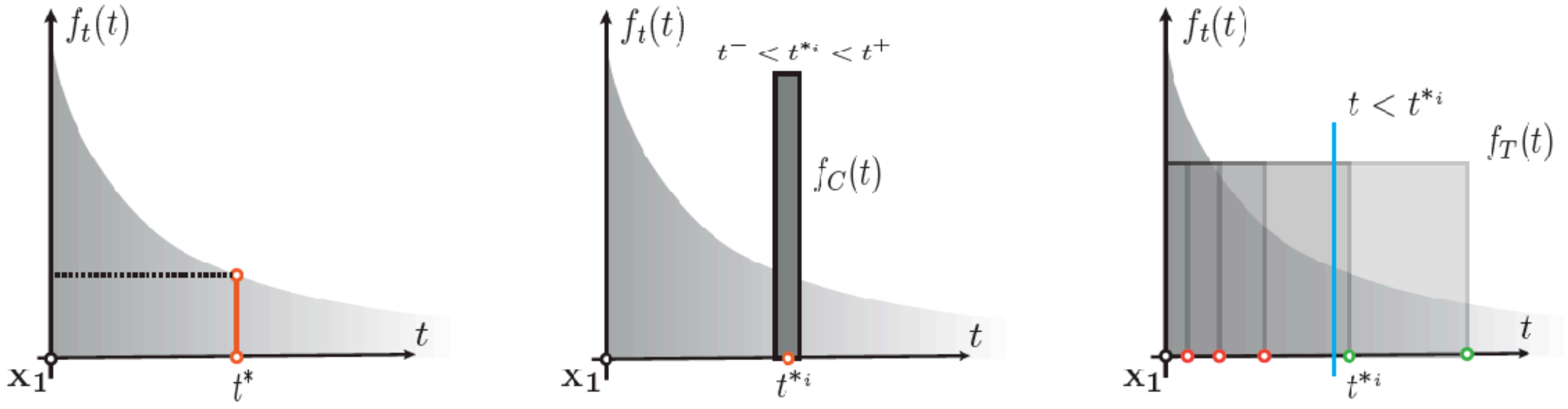


Figure 5.2: Expected value (right), collision estimator (middle) and tracklength estimator (left): Expected value directly compute the transmittance; collision estimator check if the sample t^{*i} falls in the interval $[t^-, t^+]$; track-length estimator check if the sample go beyond some distance t.

Long Beam and Short Beam

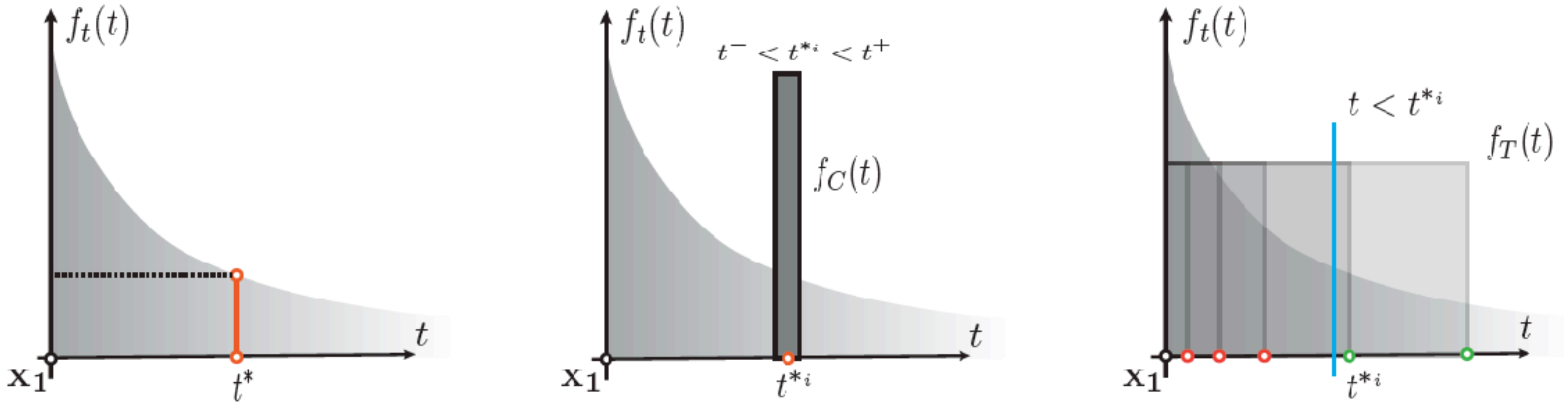
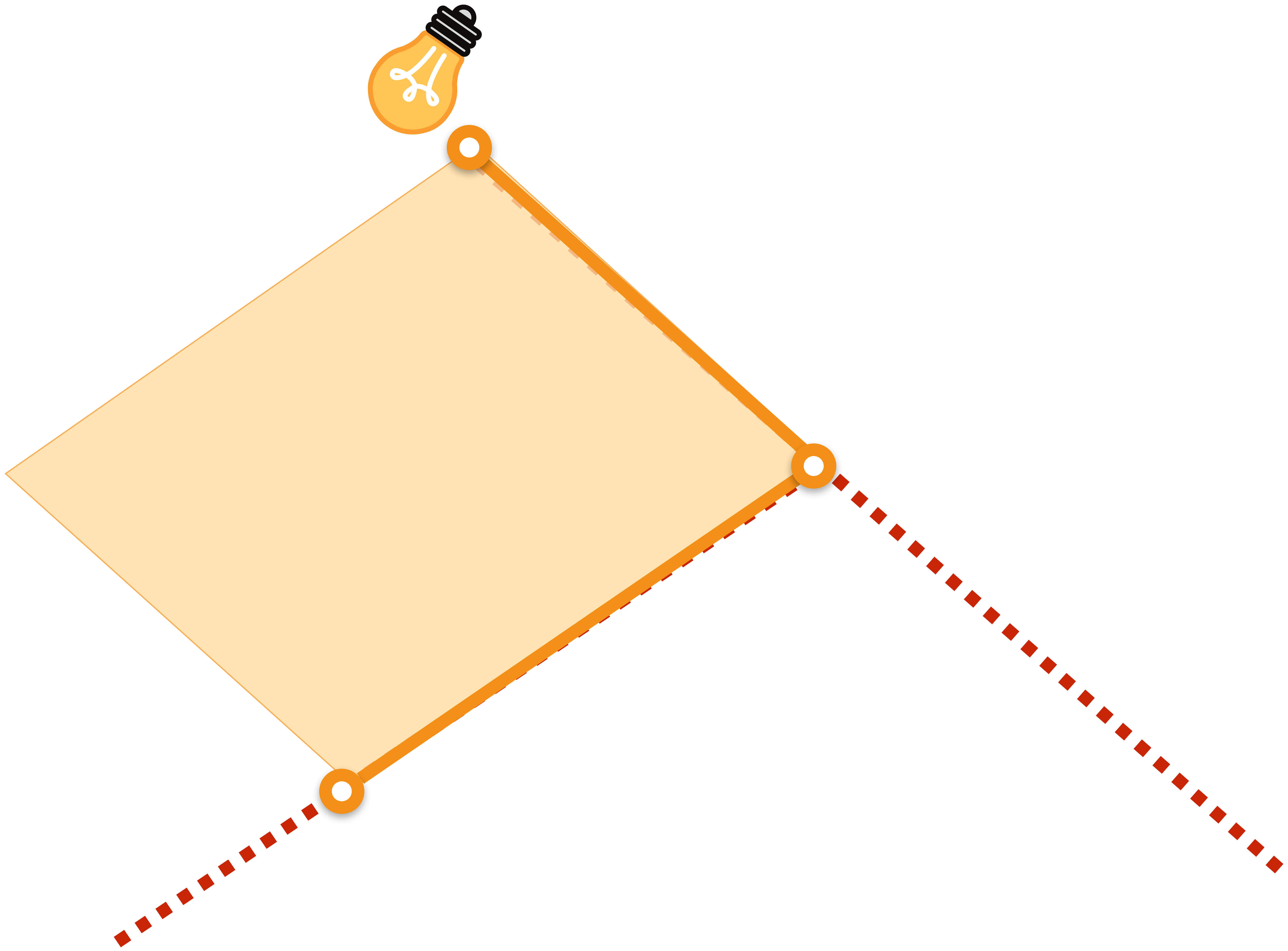


Figure 5.2: Expected value (right), collision estimator (middle) and tracklength estimator (left): Expected value directly compute the transmittance; collision estimator check if the sample t^{*i} falls in the interval $[t^-, t^+]$; track-length estimator check if the sample go beyond some distance t.

Long & short surfaces



Expense of each estimator