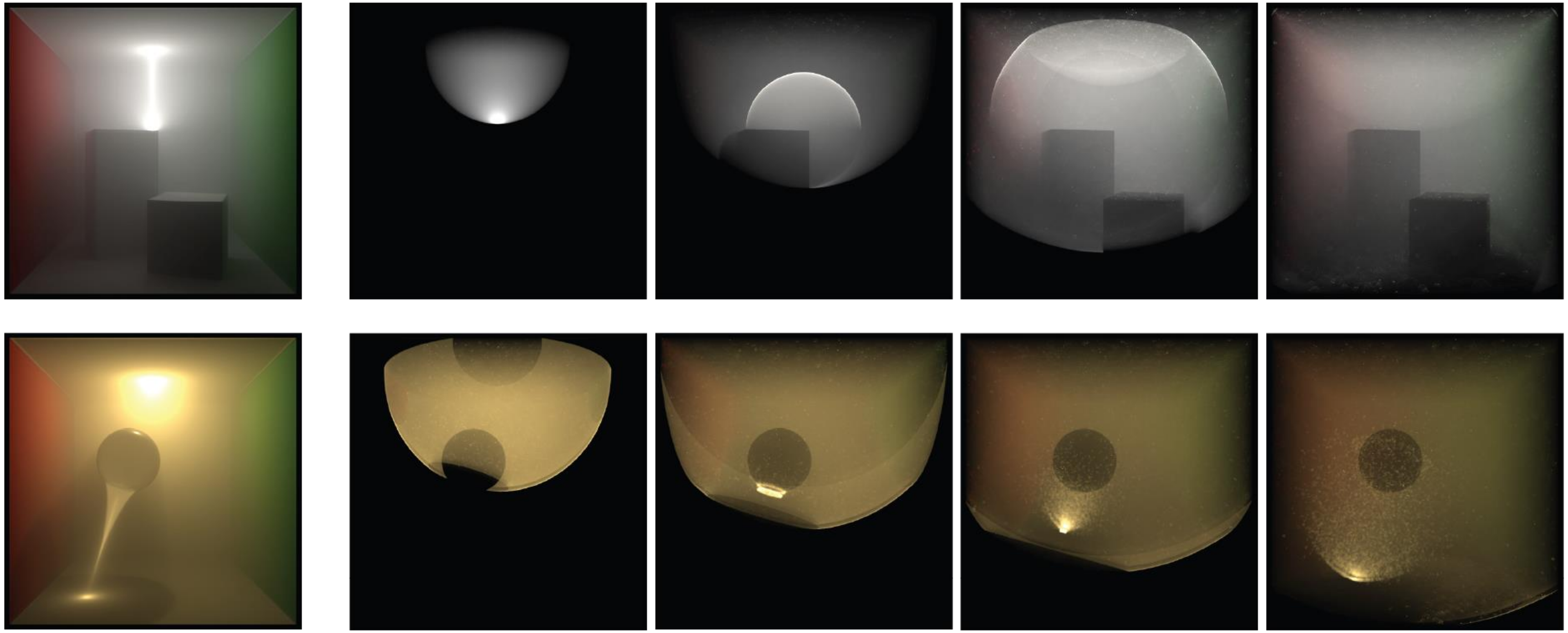
Temporally Sliced Photon Primitives for Time-of-flight Rendering



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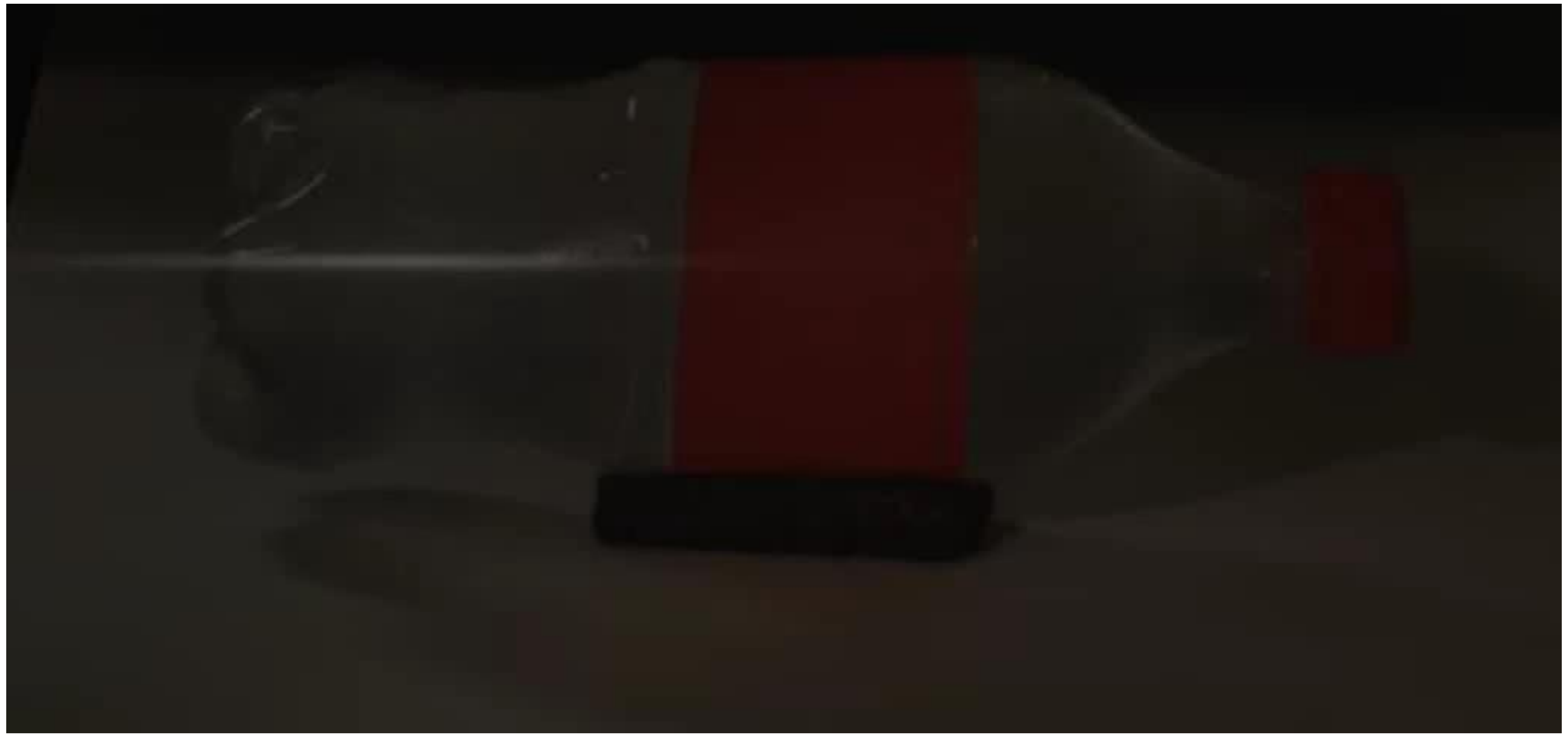
DARTMOUTH
VISUAL COMPUTING LAB

PRAGUE
EGSR 2022

Time-of-flight **Imaging**

Steady-state

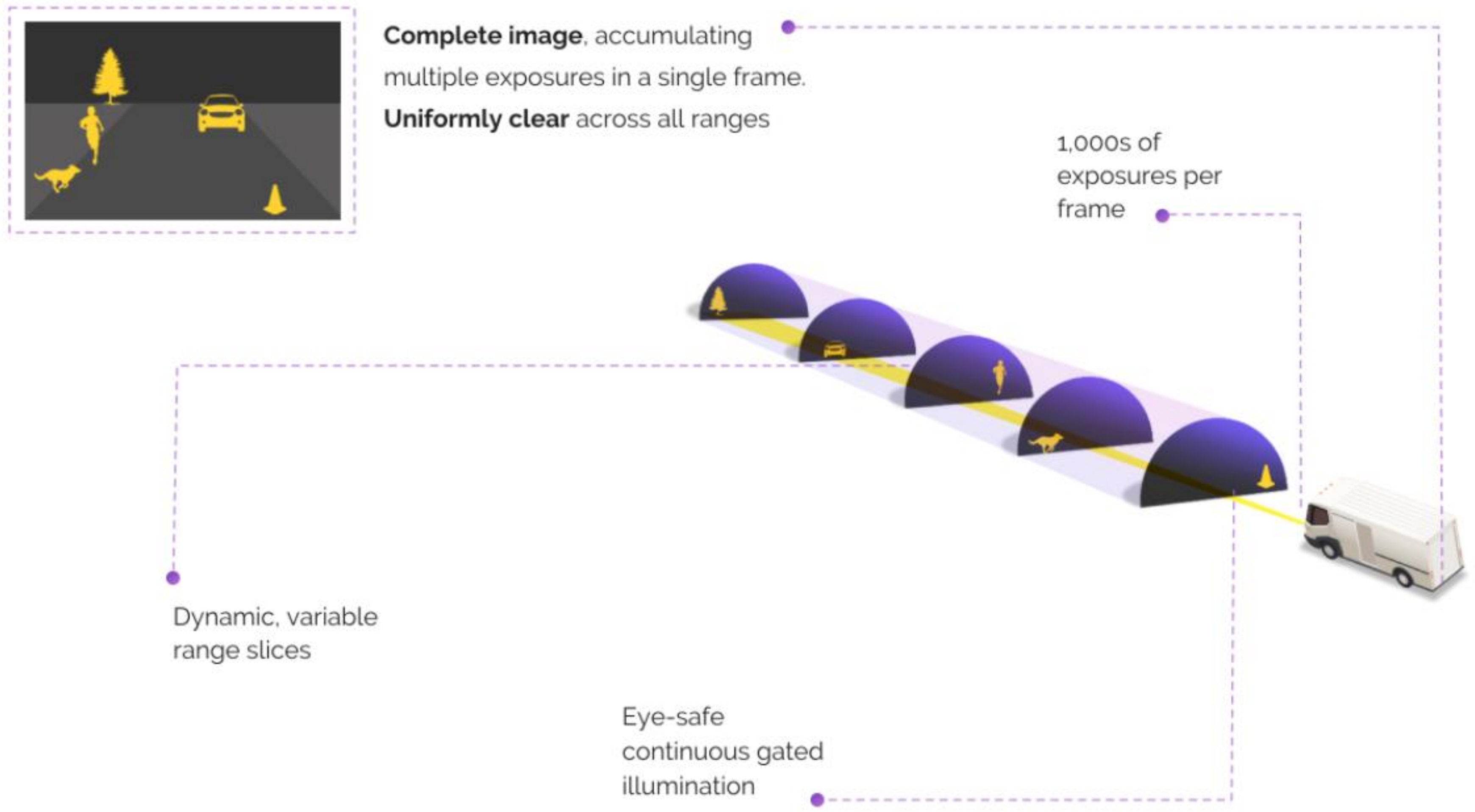
Time-of-flight



http://giga.cps.unizar.es/~ajarabo/pubs/femtoSIG2013/

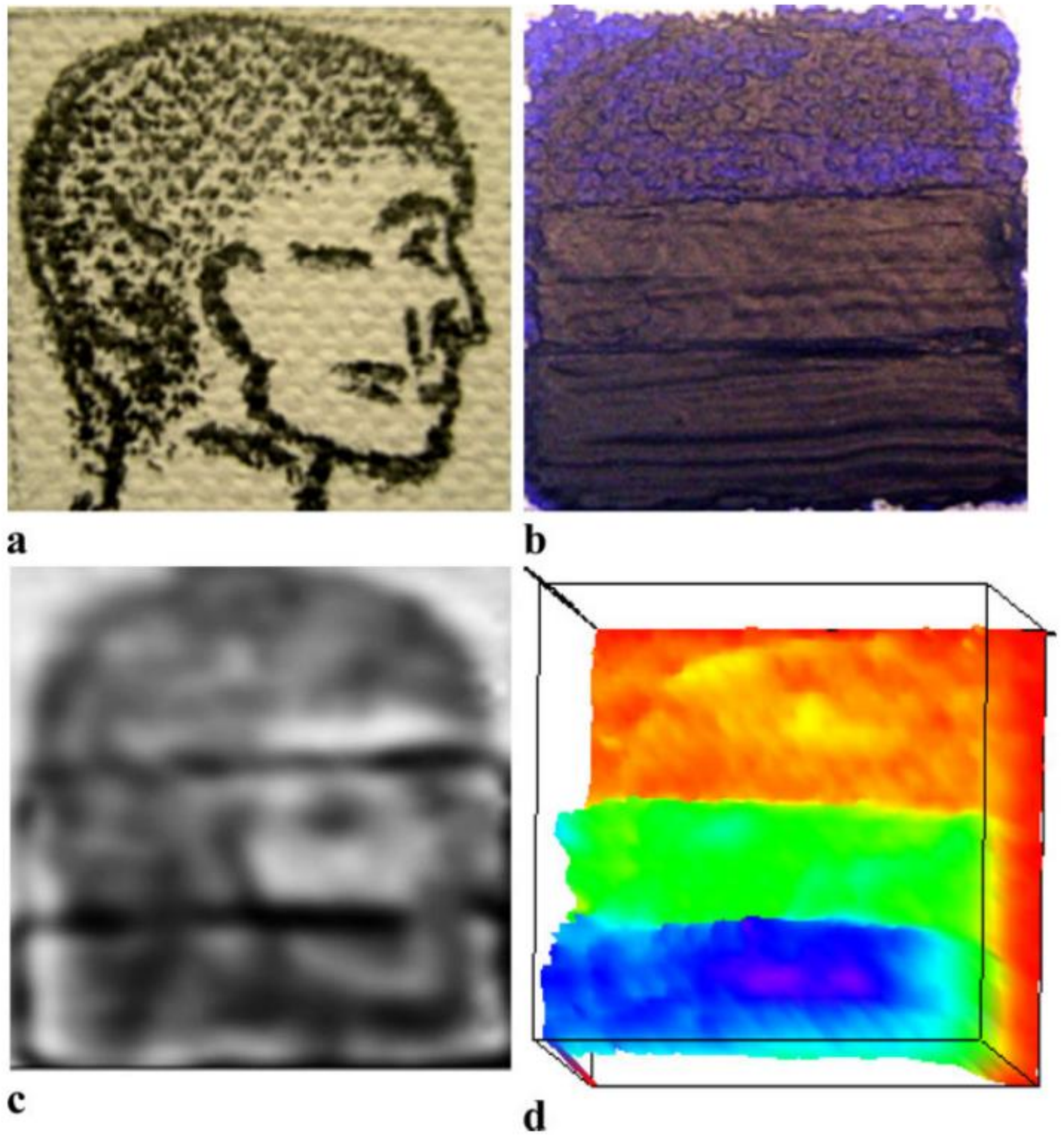
Sensing through **media**

- Seeing through fog



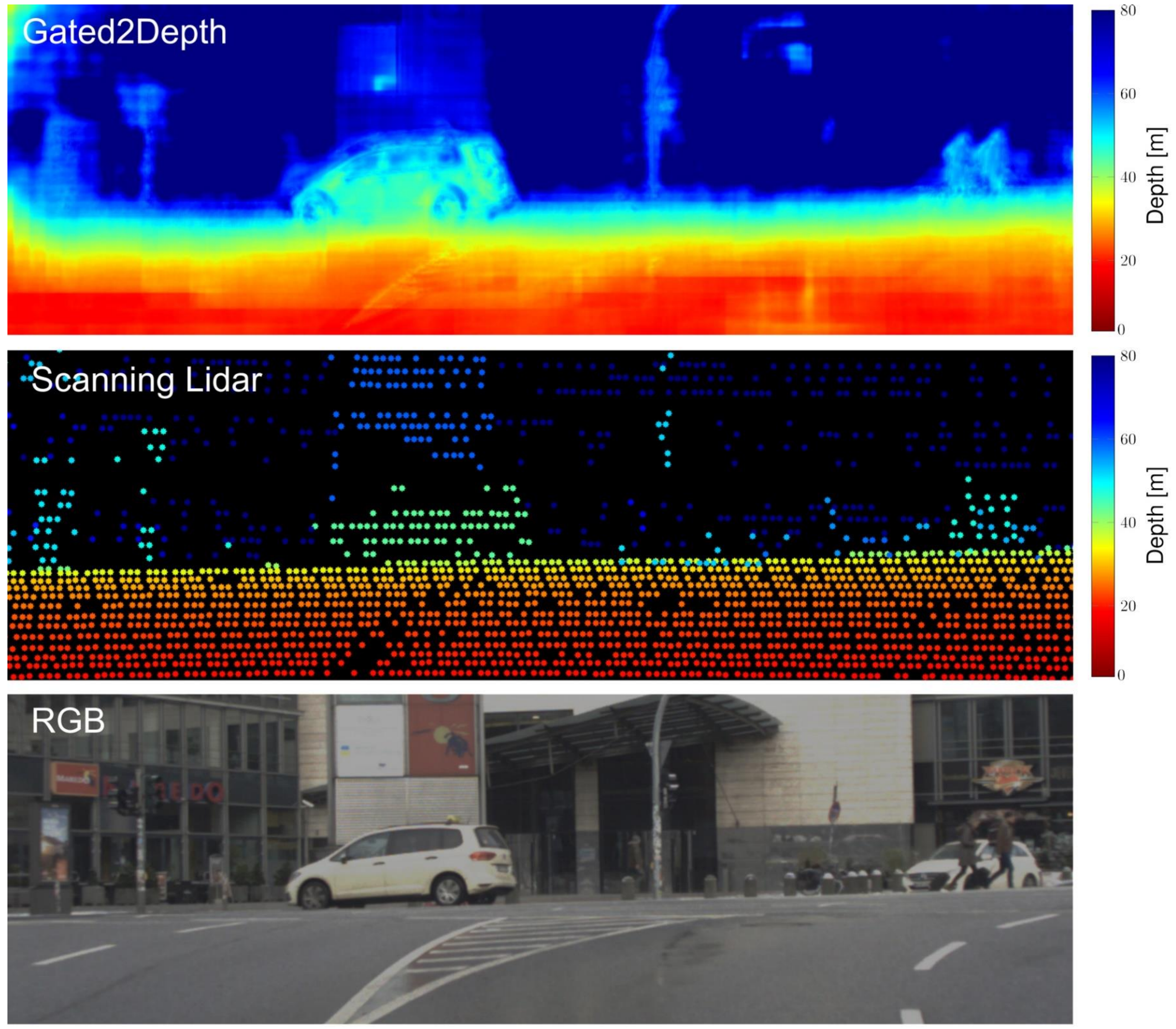
https://www.brightwayvision.com/technology

- Reveal buried sketch under painting



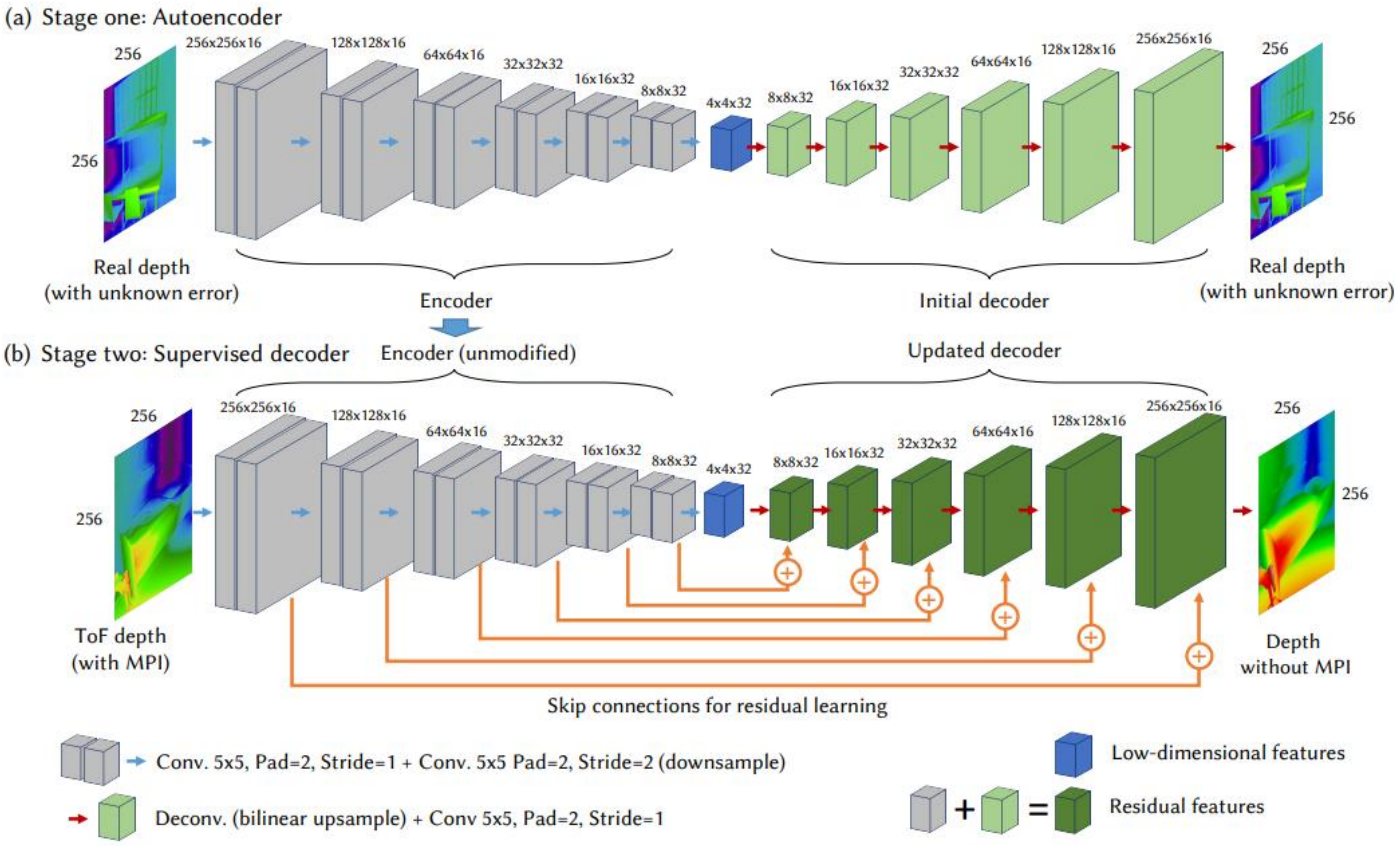
Abraham et al. (2010), ‘Non-Invasive Investigation of Art Paintings by Terahertz Imaging’

Why simulate time-of-flight imaging



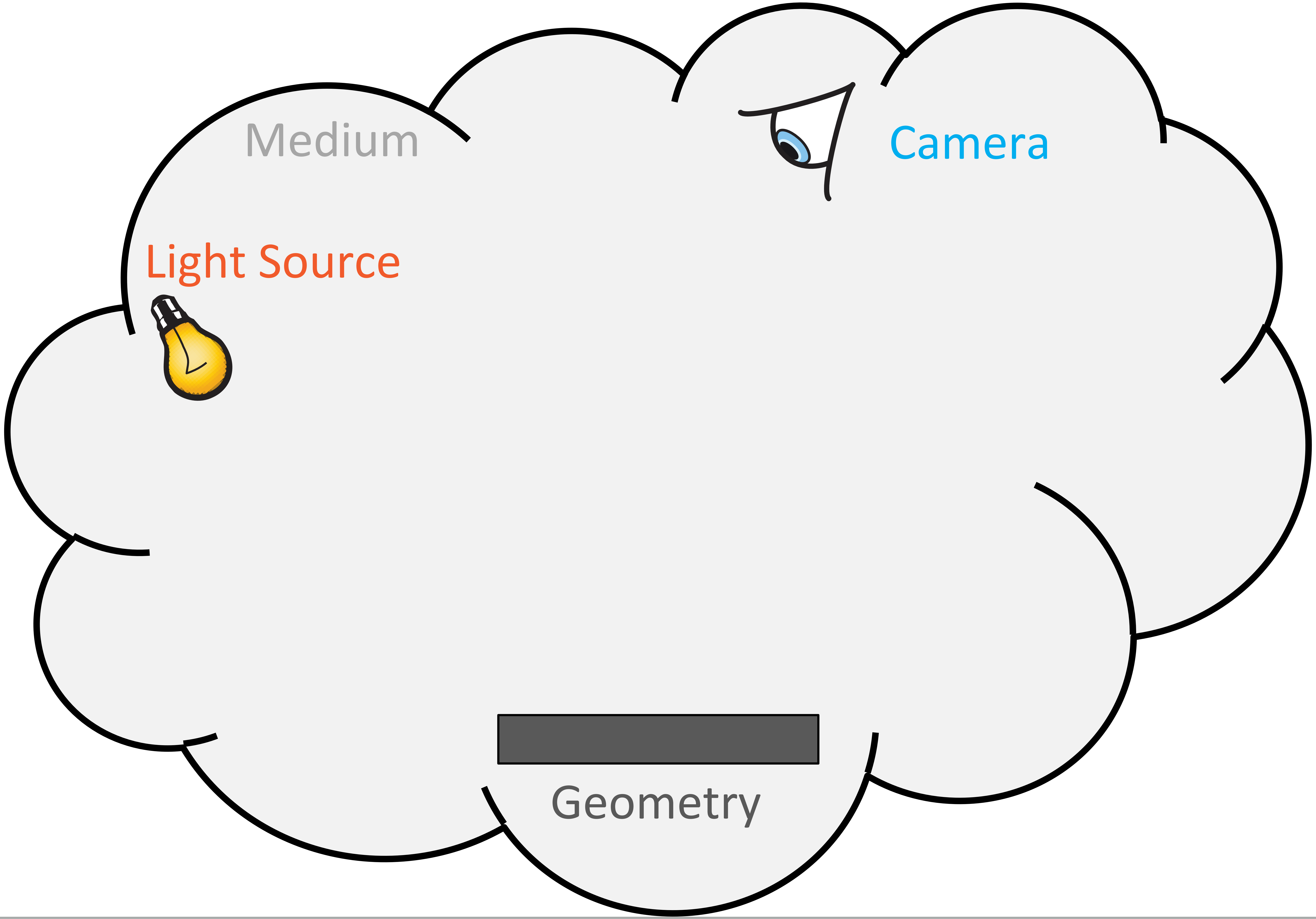
Gruber et al. used synthetic data from video game GTA V to train a gated sensor on generating depth.
Gruber et al. (2019), “Gated2Depth: Real-time Dense Lidar from Gated Images”

Why simulate time-of-flight imaging

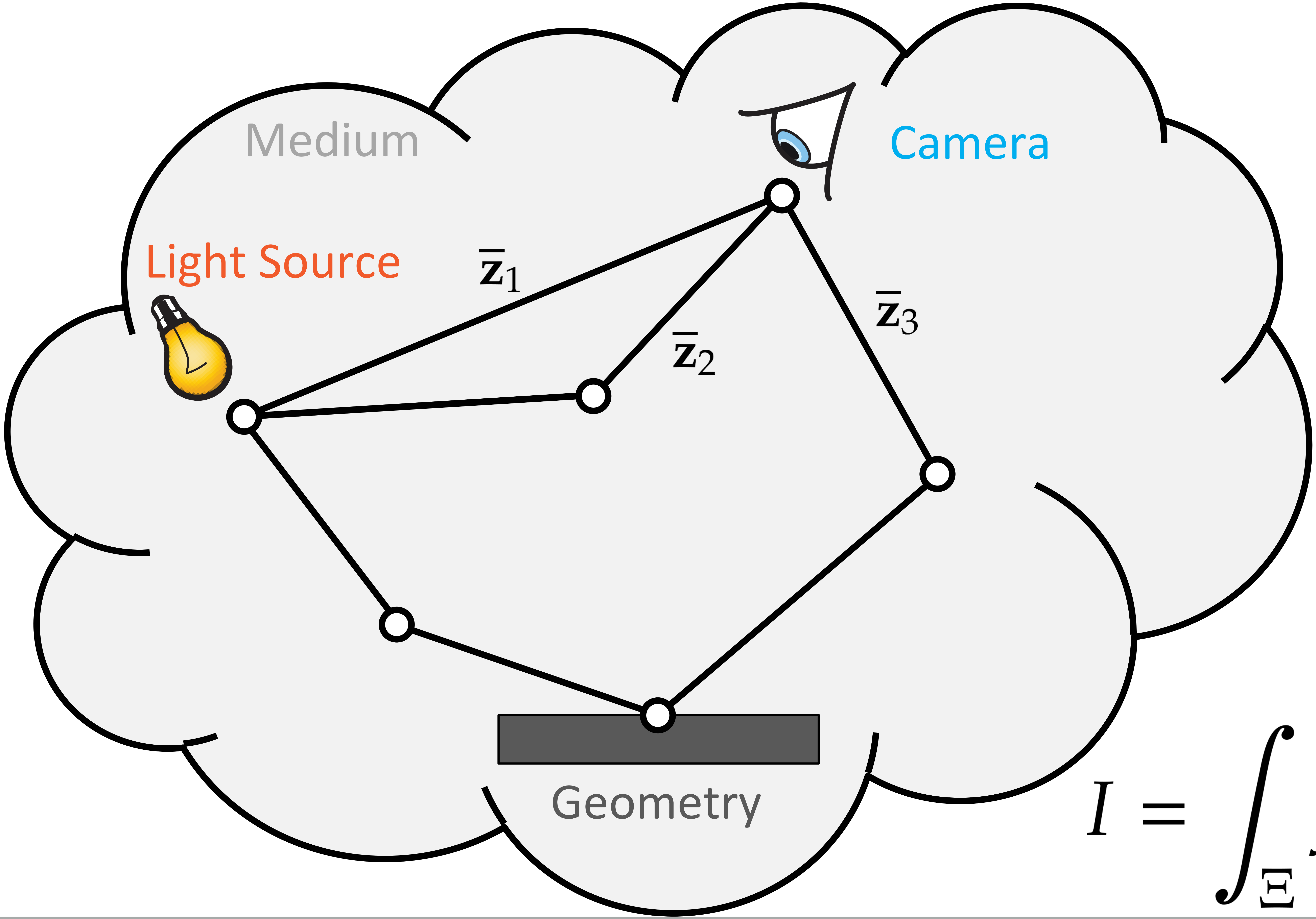


Marco et al. employed a neural network to correct multipath interference errors from time-of-flight cameras in depth reconstruction.
Marco et al. (2017), “DeepToF: Off-the-Shelf Real-Time Correction of Multipath Interference in Time-of-Flight Imaging”

Volumetric Rendering

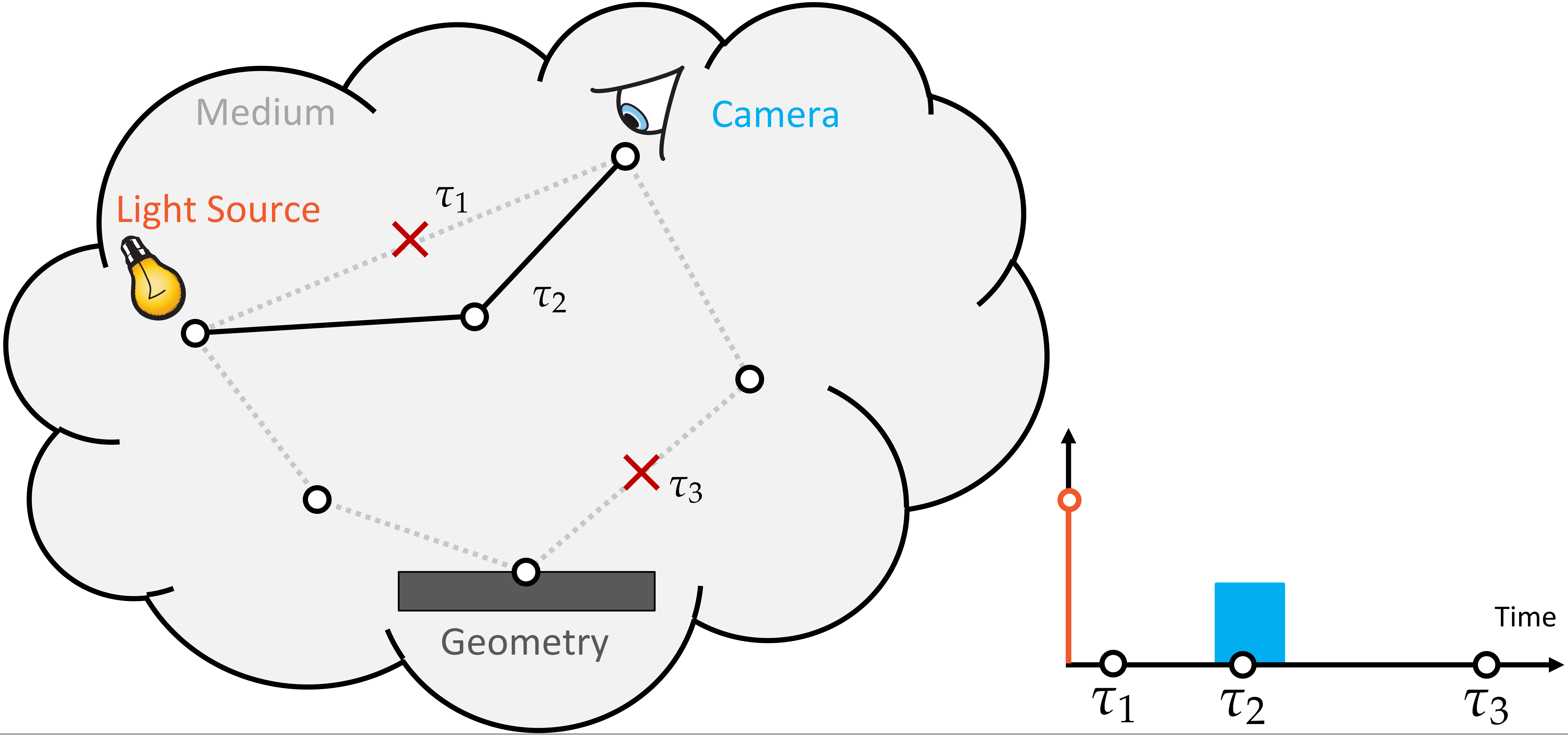


Volumetric Rendering



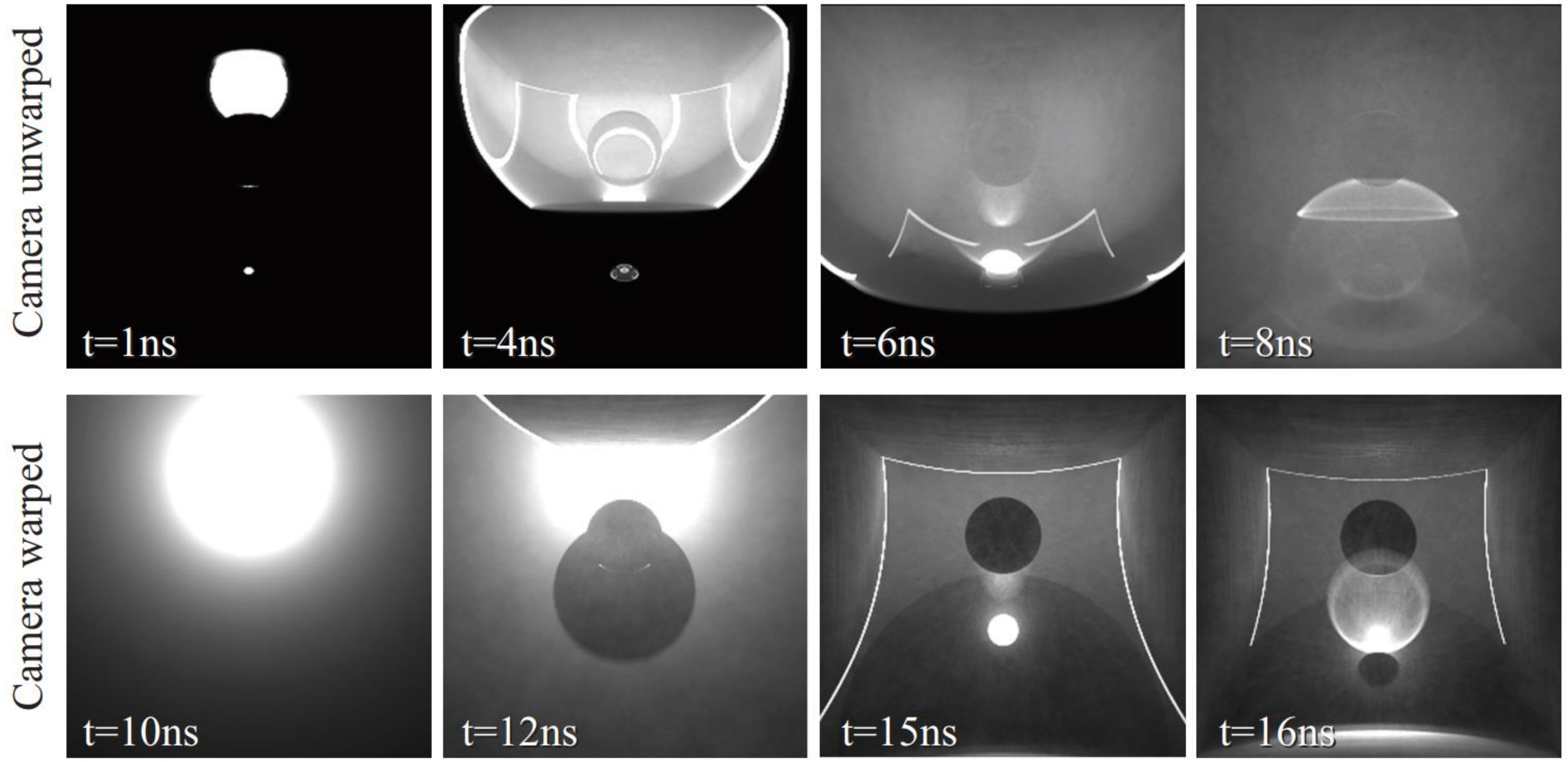
$$I = \int_{\Xi} f(\bar{\mathbf{z}})\, \mathrm{d}\mu(\bar{\mathbf{z}})$$

Time-of-flight Volumetric Rendering

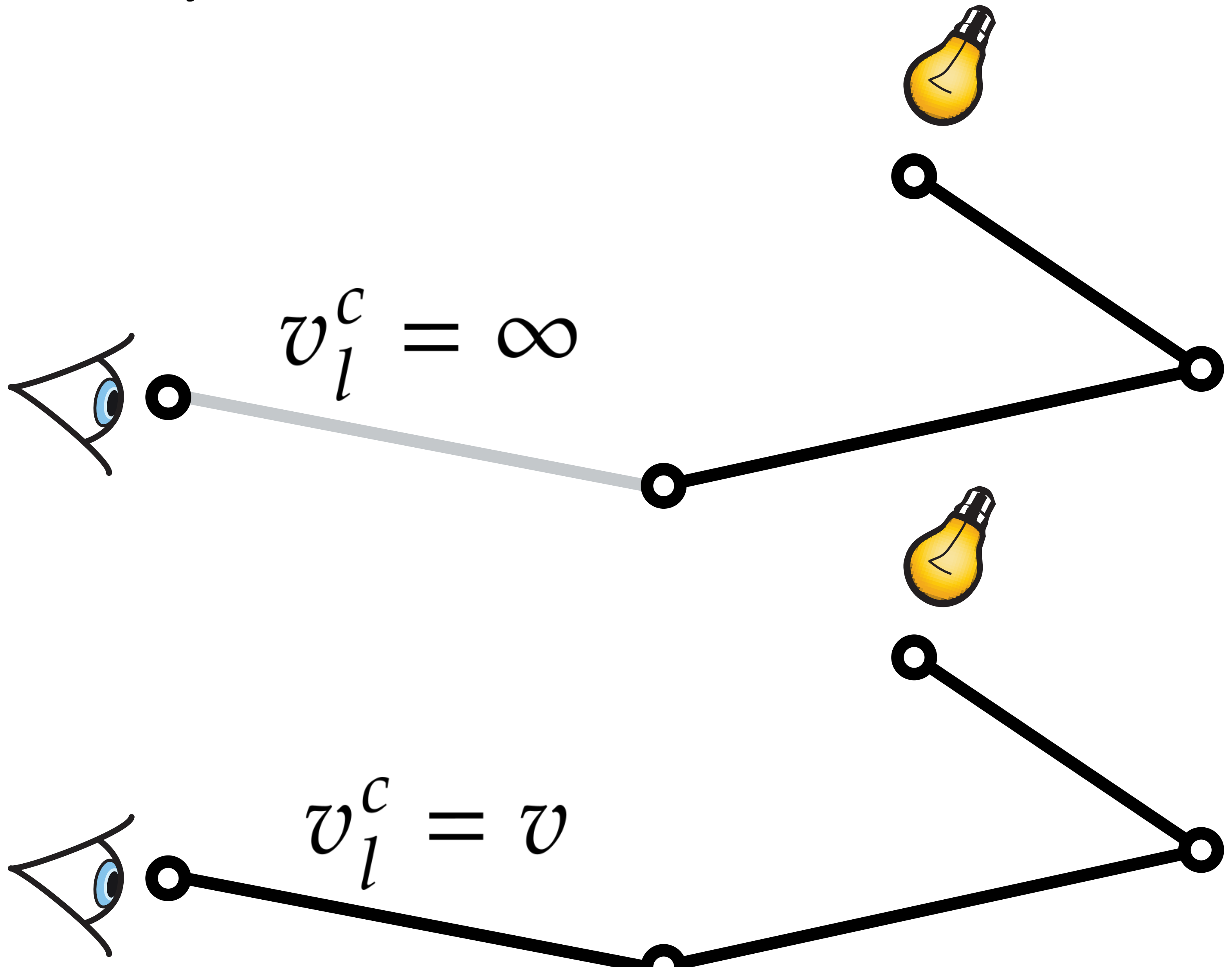


Camera-unwarped vs. warped

Camera-**unwarped** (**ignore** time delay in first cam segment)



Marco et al. (2019), 'Progressive Transient Photon Beams'



Camera-**warped** (**count** time delay in first cam segment)

Related Work

Apply photon mapping-based methods to volumetric time-of-flight rendering

- Jarabo et al. (2014)
  - Transient photon mapping
- Marco et al. (2019)
  - Progressive transient photon beams

A time-of-flight animation with many volumetric caustics.
Marco et al. (2019), “Progressive Transient Photon Beams”

Related Work

Deng et al. compare their method (left column) with previous work (right column).
Deng et al. (2019), "Photon surfaces for robust, unbiased volumetric density estimation"

Steady-state higher-order photon primitives

- Benedikt et al. (2017)
- Deng et al. (2019)

New benefits: unbiased, MIS

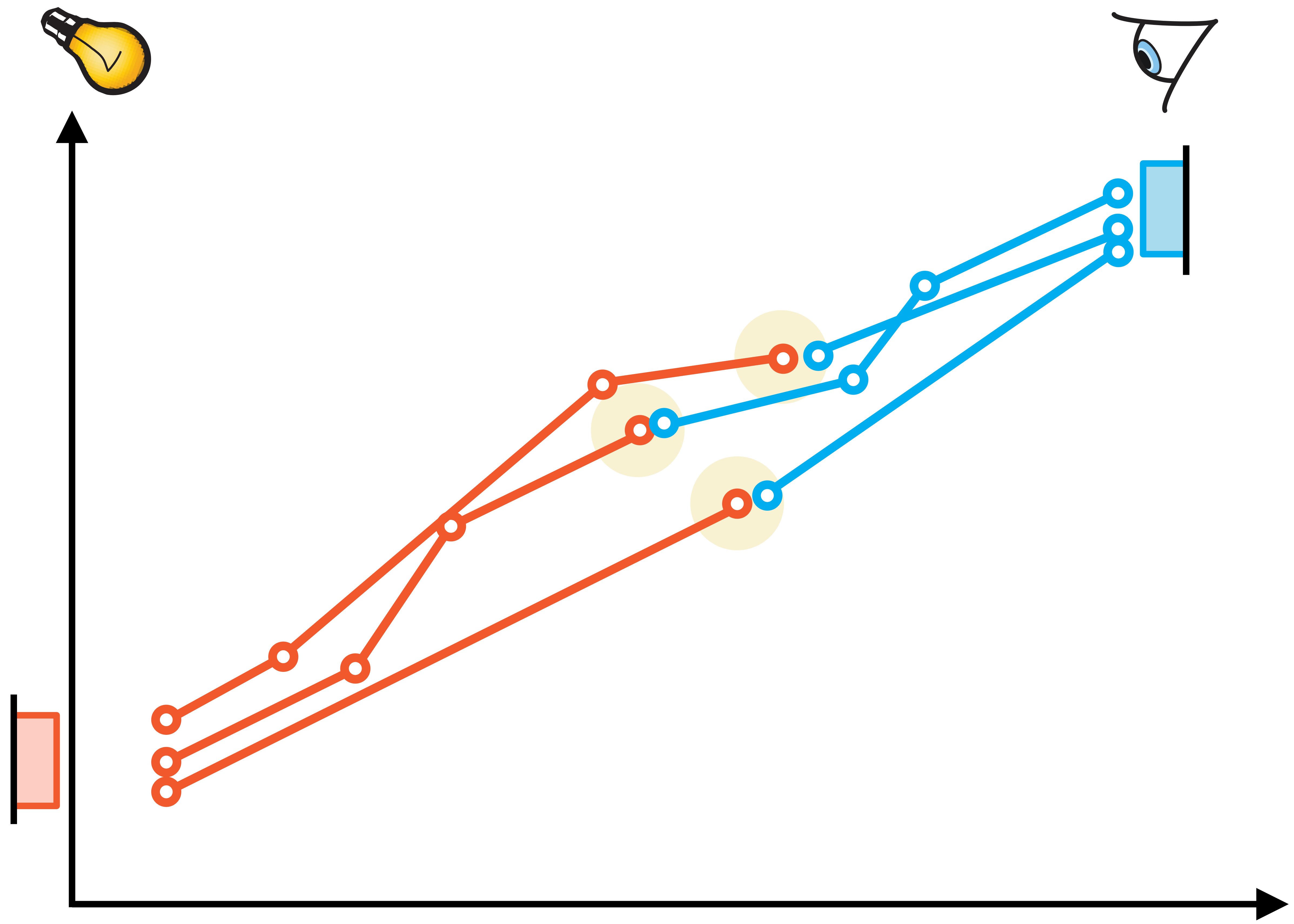
Goal

Apply the improvements from higher-order primitives to the time-of-flight setting.

- Unbiasedness
- Multiple Importance Sampling
- Increased Path Reuse

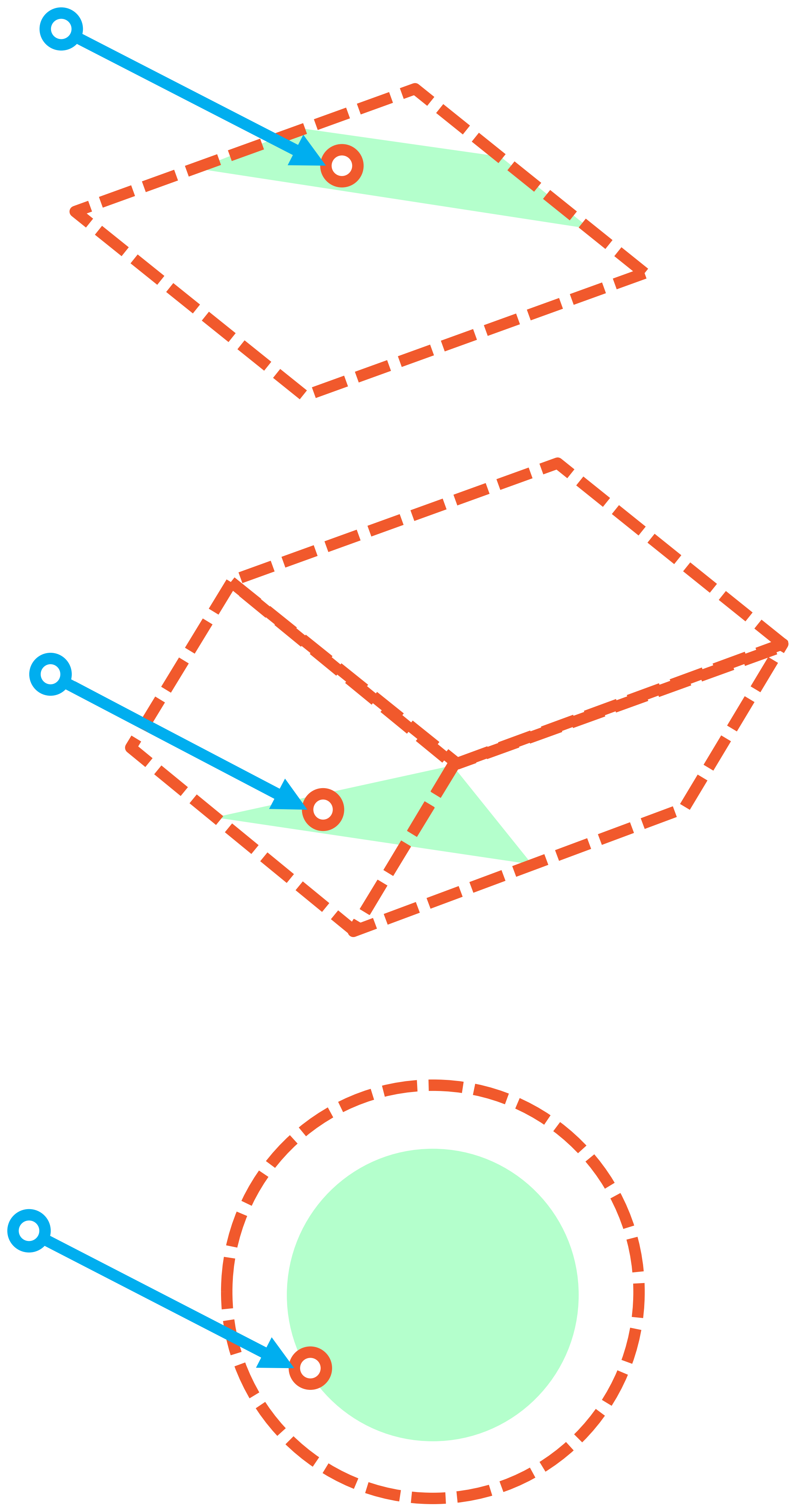
Contributions

- New formulation
- Recipe for sliced photon primitives

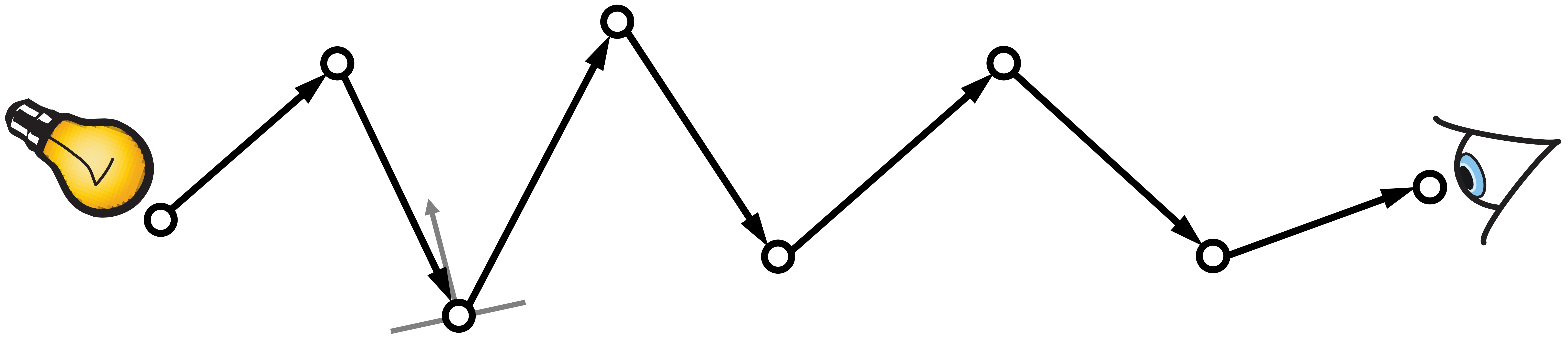


Contributions

- New formulation
- Recipe for sliced photon primitives

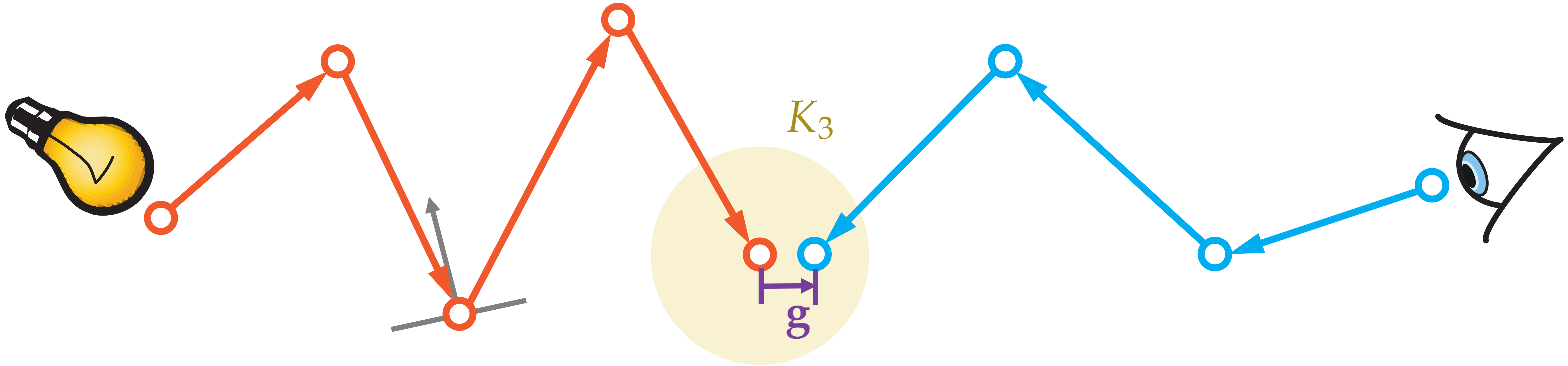


Path Space



$$I = \int_{\Xi} f(\overline{\mathbf{z}})\, \mathrm{d}\mu(\overline{\mathbf{z}})$$

Extended Path Space

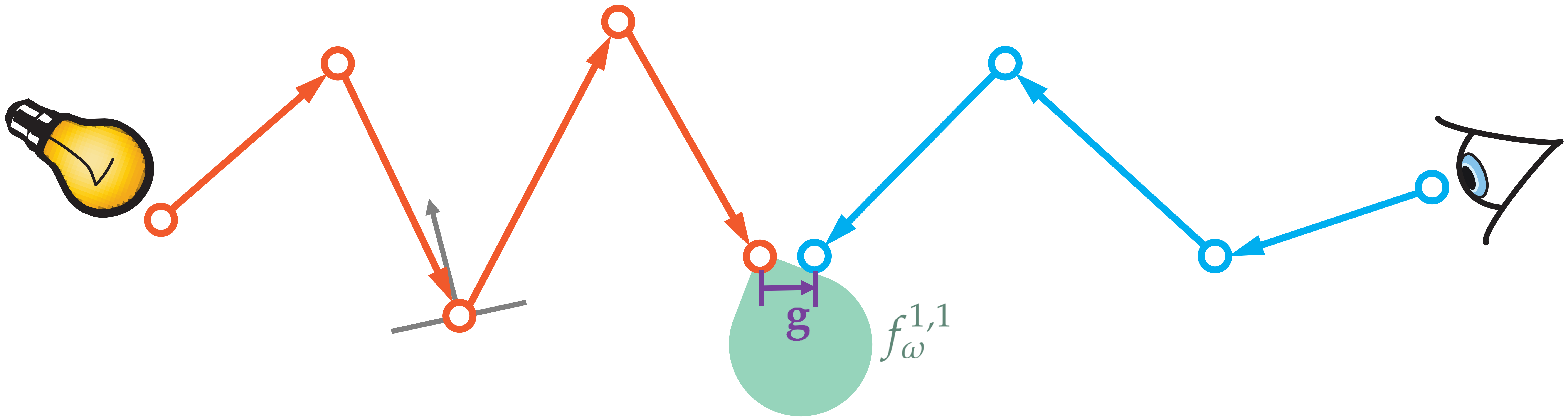


3D Blur   Offset vector

$$f(\bar{\mathbf{z}}) = f(\bar{\mathbf{x}}) f_{\omega}^{1,1} K_3(\mathbf{g}) f(\bar{\mathbf{y}})$$

Photon subpath contribution   Camera subpath contribution

Extended Path Space



Phase Function

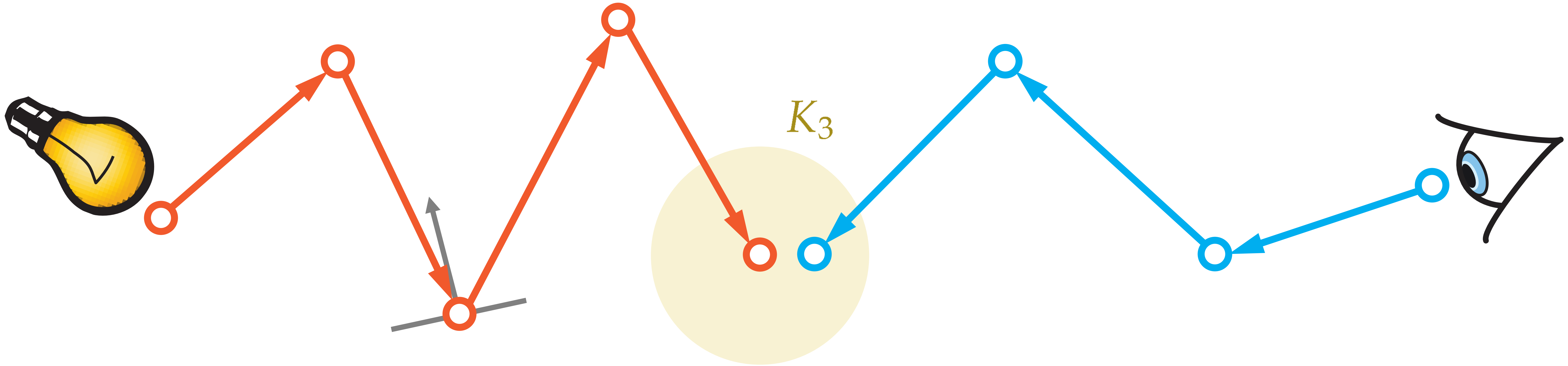
Offset vector

$$f(\bar{\mathbf{z}}) = f(\bar{\mathbf{x}})\, f_\omega^{1,1}\, K_3(\mathbf{g})\, f(\bar{\mathbf{y}})$$

Photon subpath contribution

Camera subpath contribution

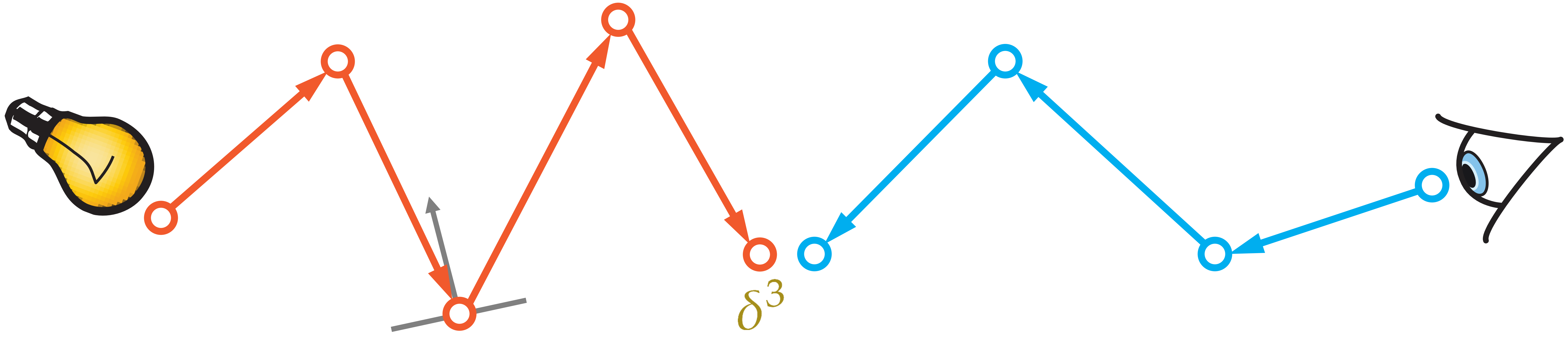
Extended Path Space



$$\int_{\Xi} f(\overline{\mathbf{x}}) f_{\omega}^{1,1} K_3(\mathbf{g}) f(\overline{\mathbf{y}}) \, \mathrm{d}\mu(\overline{\mathbf{x}\mathbf{y}})$$

Bias ☹

Extended Path Space



$$\int_{\Xi} f(\bar{\mathbf{x}}) f_{\omega}^{1,1} \delta^3(\mathbf{g}) f(\bar{\mathbf{y}}) \, \mathrm{d}\mu(\overline{\mathbf{xy}})$$

No bias ☺

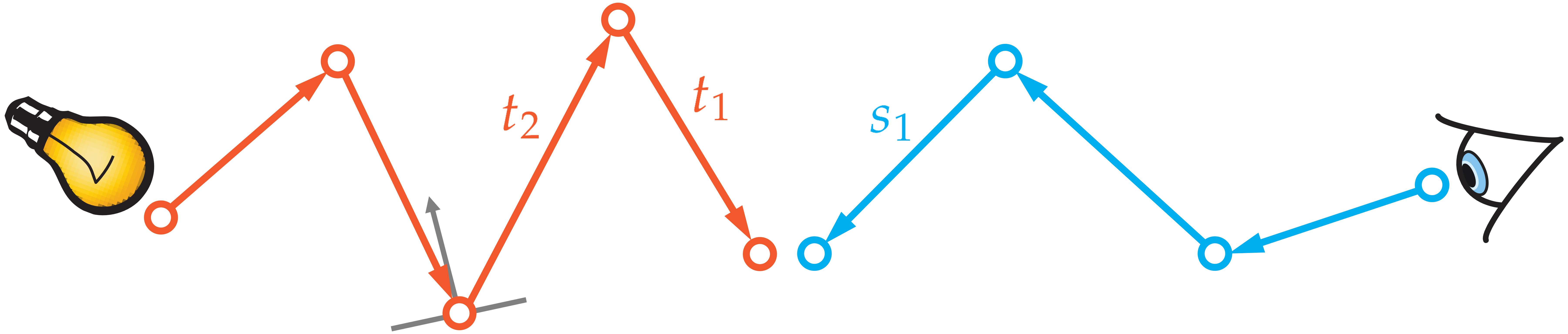
Cannot estimate with Monte Carlo ☹

Photon Primitives (Benedikt et al., Deng et al.)

$$\int_{\Xi_n} \int_{\Xi_a} f(\overline{\xi_a}) f_{\omega}^{1,1} \delta^3(\mathbf{g}) \, \mathrm{d}\overline{\xi_a} \, \mathrm{d}\overline{\xi_n}$$

Choose 3 dimensions to pre-integrate

Photon Primitives (Benedikt et al., Deng et al.)

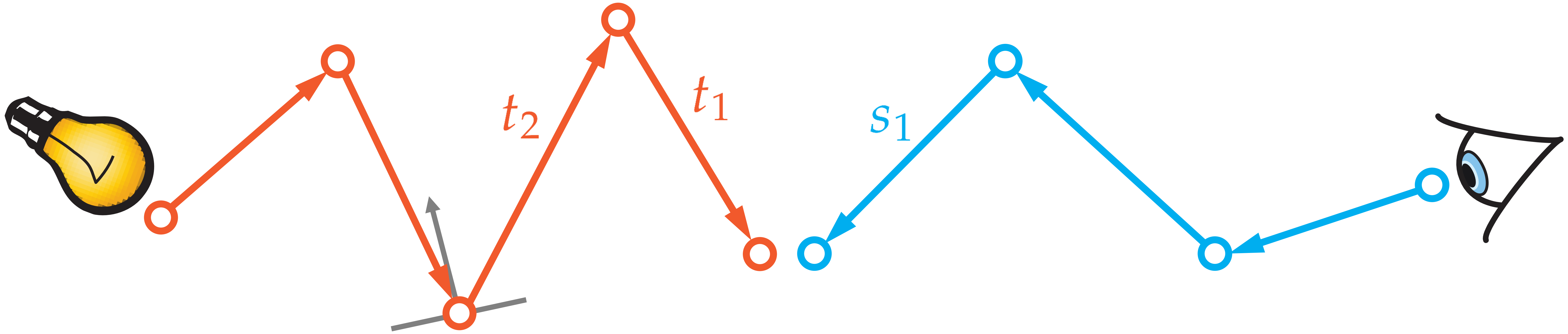


$$\overline{\xi_a} = \{t_2, t_1, s_1\}$$

$$\int_{\Xi_n} \int_{\Xi_a} f(\overline{\xi_a}) f_\omega^{1,1} \delta^3(\mathbf{g}) \, \mathrm{d}\overline{\xi_a} \, \mathrm{d}\overline{\xi_n}$$

Choose 3 dimensions to pre-integrate

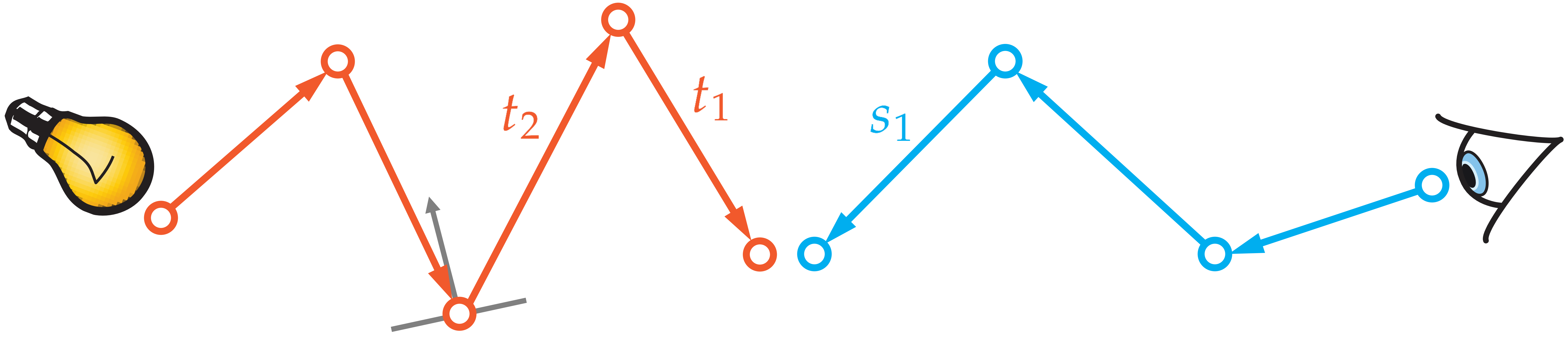
Photon Primitives (Benedikt et al., Deng et al.)



$$\int_{\Xi_n} f(\overline{\xi_a}) f_\omega^{1,1} \Big/ \left|\mathbf{J}^{\mathbf{g}}_{\overline{\xi_a}}\right| \, \mathrm{d}\overline{\xi_n}$$

Jacobian for change-of-variable

Photon Primitives (Benedikt et al., Deng et al.)

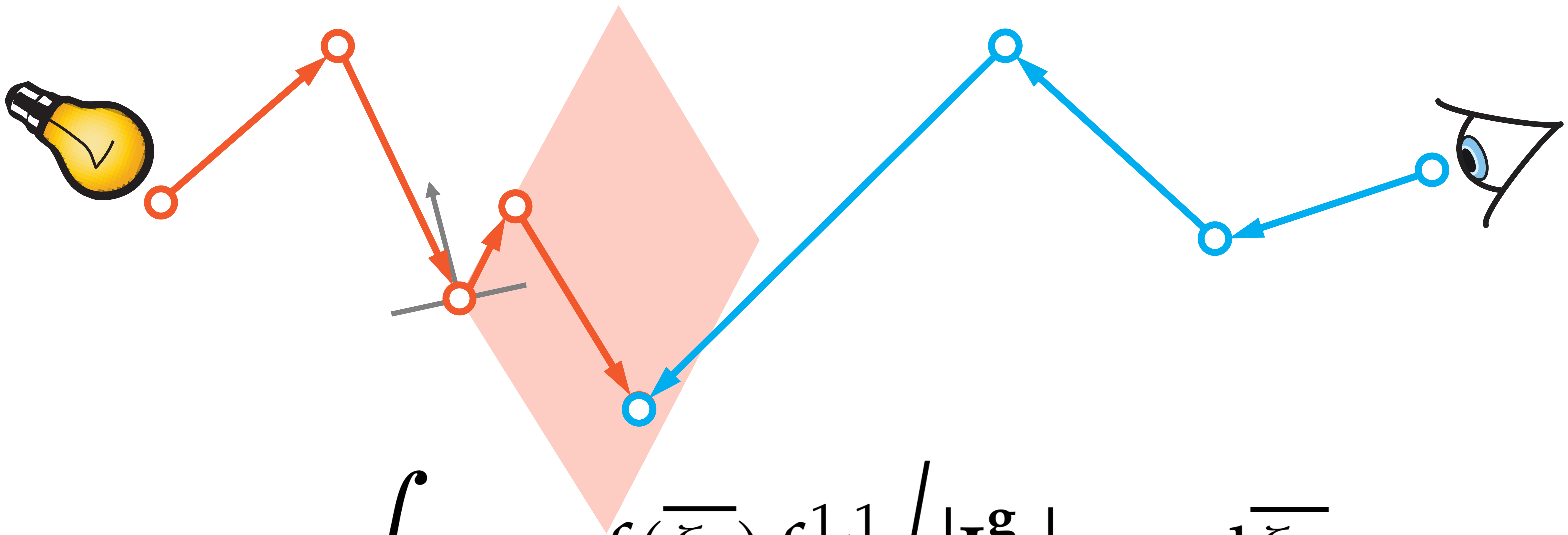


$$\int_{\Xi_n} f(\overline{\xi_a}) f_{\omega}^{1,1} \Big/ \left|\mathbf{J}^{\mathbf{g}}_{\overline{\xi_a}}\right| \, \mathrm{d}\overline{\xi_n}$$

No bias ☺

Can estimate ☺

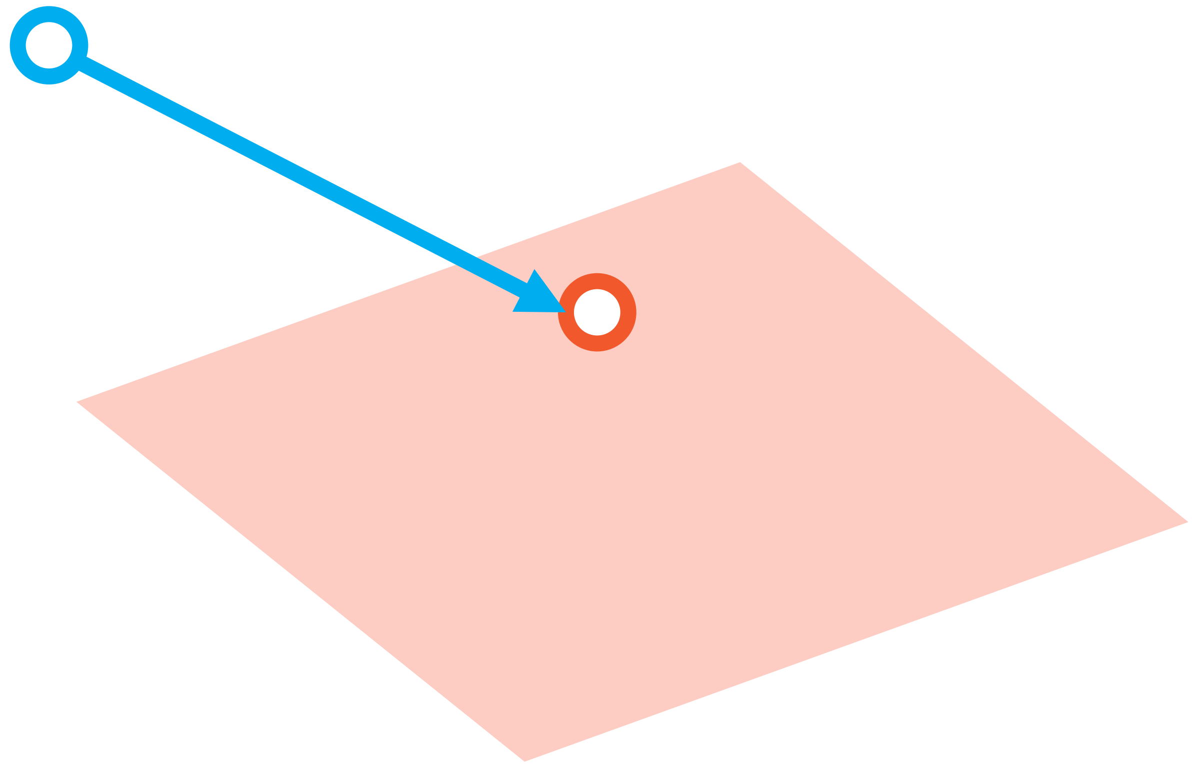
Photon Plane



$$\int_{\Xi_n} f(\overline{\xi_a}) f_{\omega}^{1,1} \Big/ \left|\mathbf{J}^{\mathbf{g}}_{\overline{\xi_a}}\right| \quad \mathrm{d}\overline{\xi_n}$$

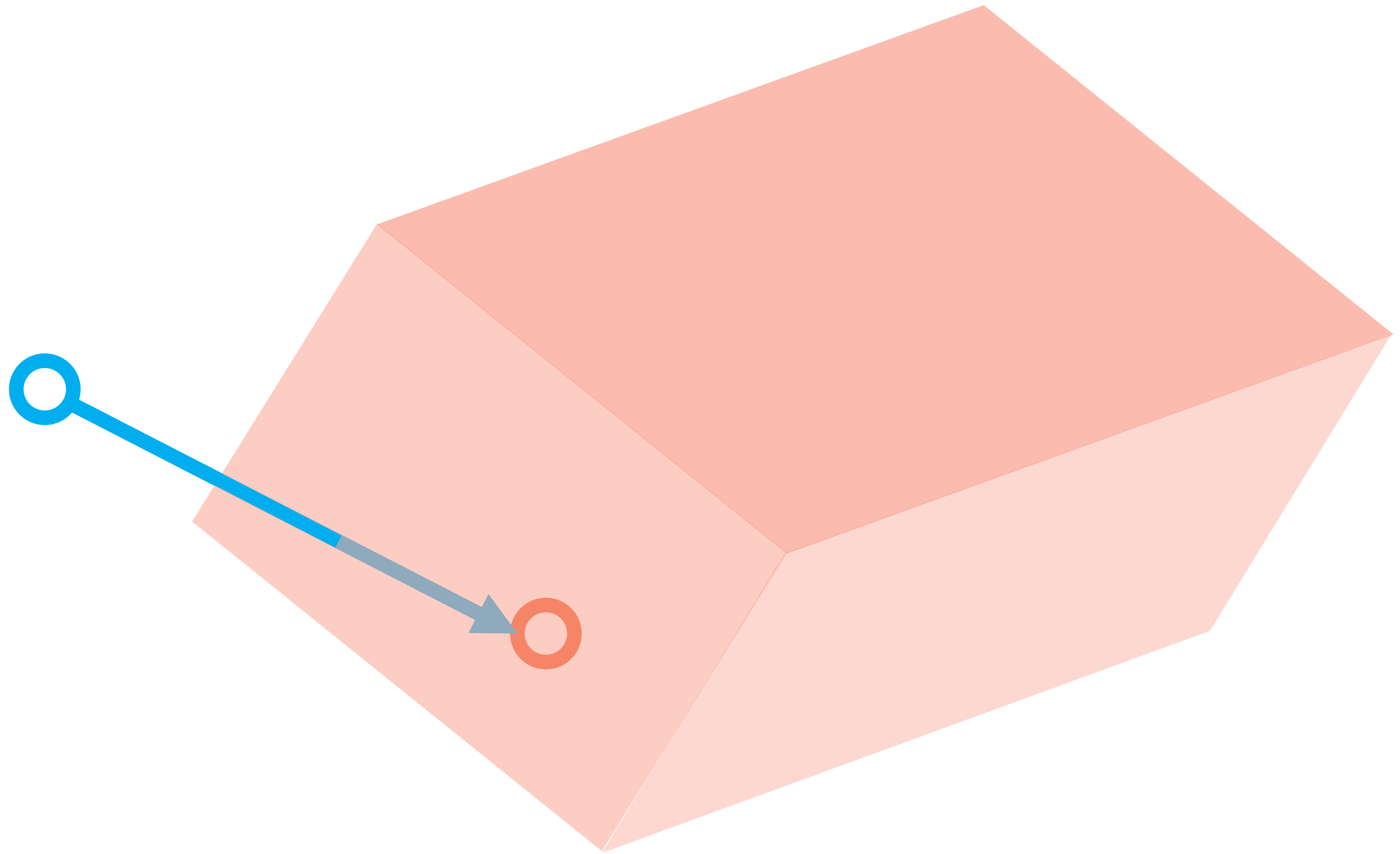
Photon Primitives (Benedikt et al., Deng et al.)

Photon Plane



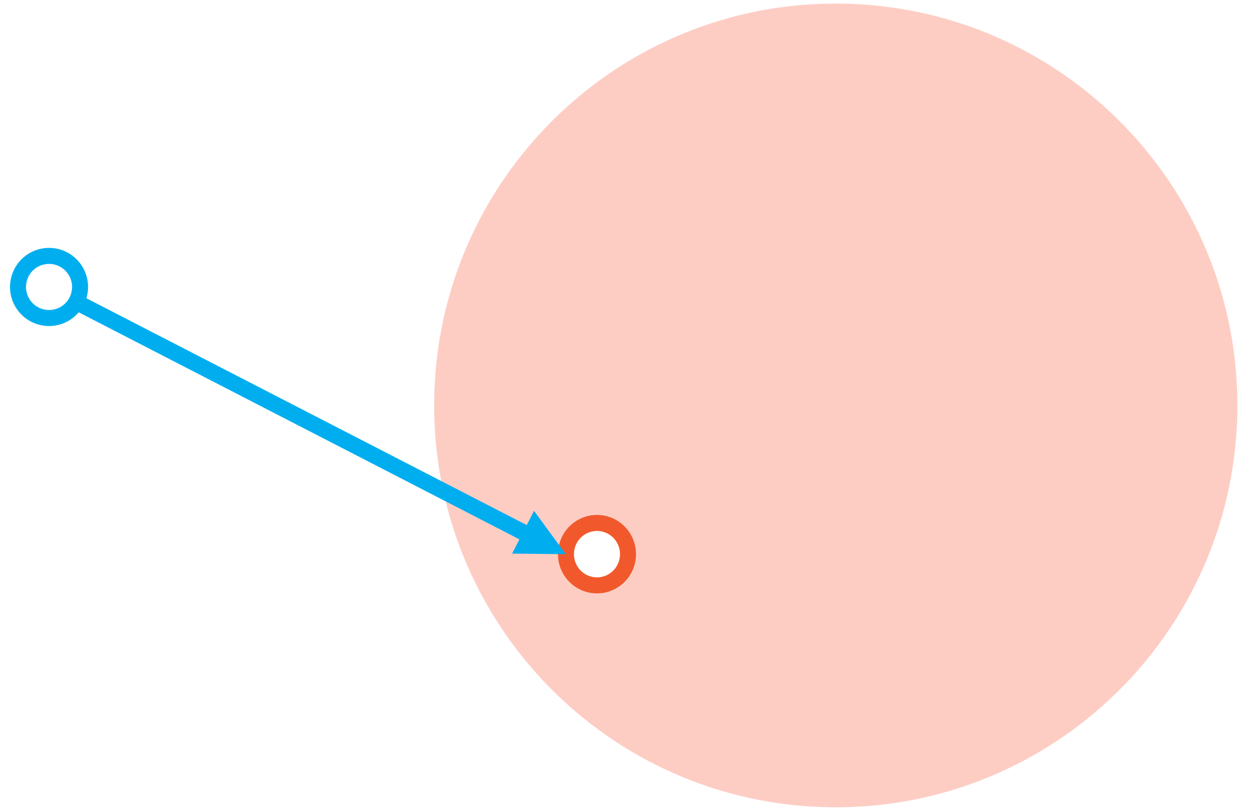
$$\overline{\xi_a} = \{t_2, t_1, s_1\}$$

Photon Parallelepiped



$$\overline{\xi_a} = \{t_3, t_2, t_1\}$$

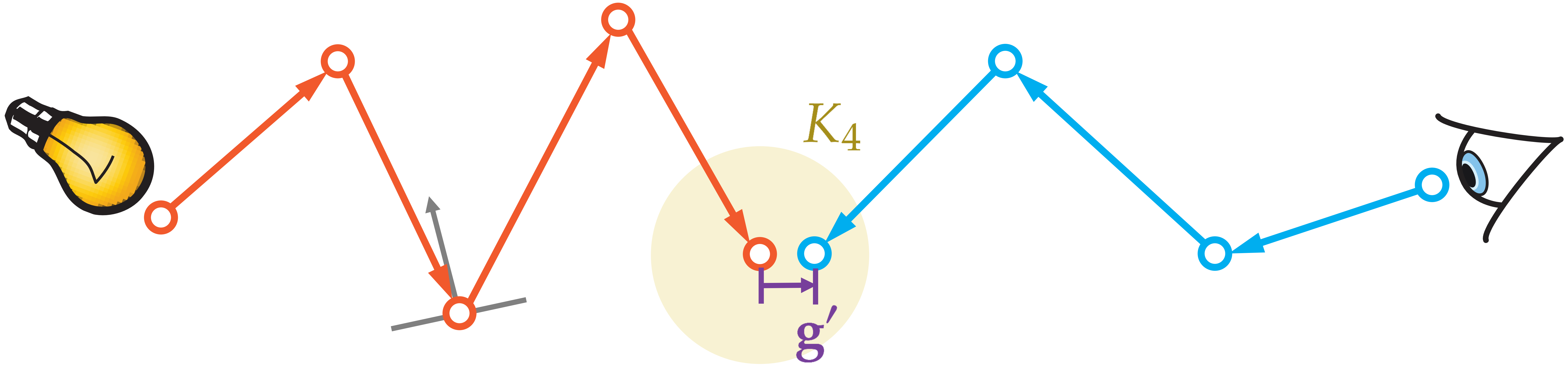
Photon Ball



$$\overline{\xi_a} = \{\cos\theta_1, \phi_1, t_1\}$$

Our Approach

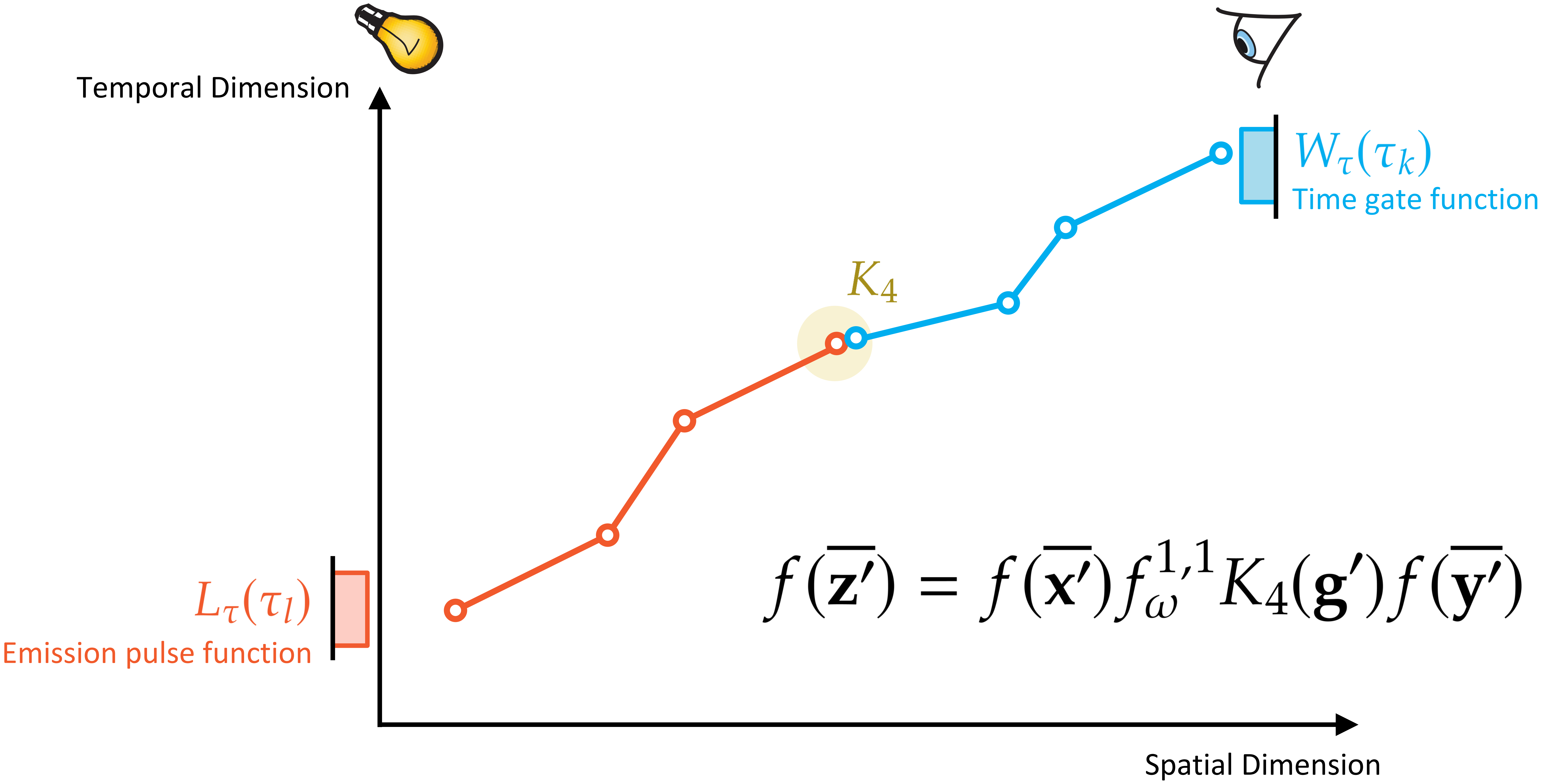
Spatio-temporal (4D) Extended Path Space



4D Blur **4D** offset vector

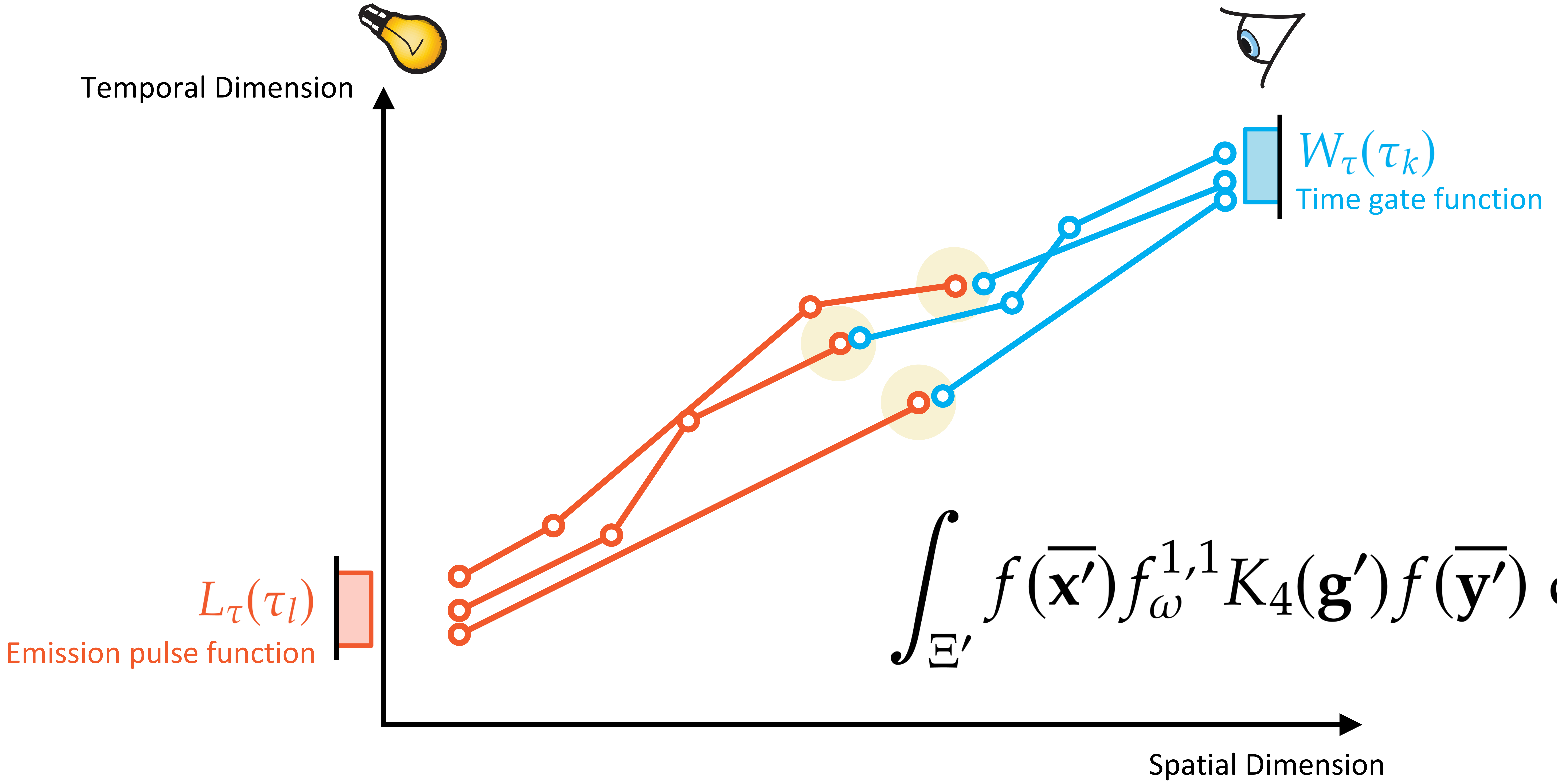
$$f(\overline{\mathbf{z}'}) = f(\overline{\mathbf{x}'}) f_{\omega}^{1,1'} K_4(\mathbf{g}') f(\overline{\mathbf{y}'})$$

Spatio-temporal (4D) Extended Path Space



$$f(\overline{\mathbf{z}'}) = f(\overline{\mathbf{x}'}) f_\omega^{1,1} K_4(\mathbf{g}') f(\overline{\mathbf{y}'})$$

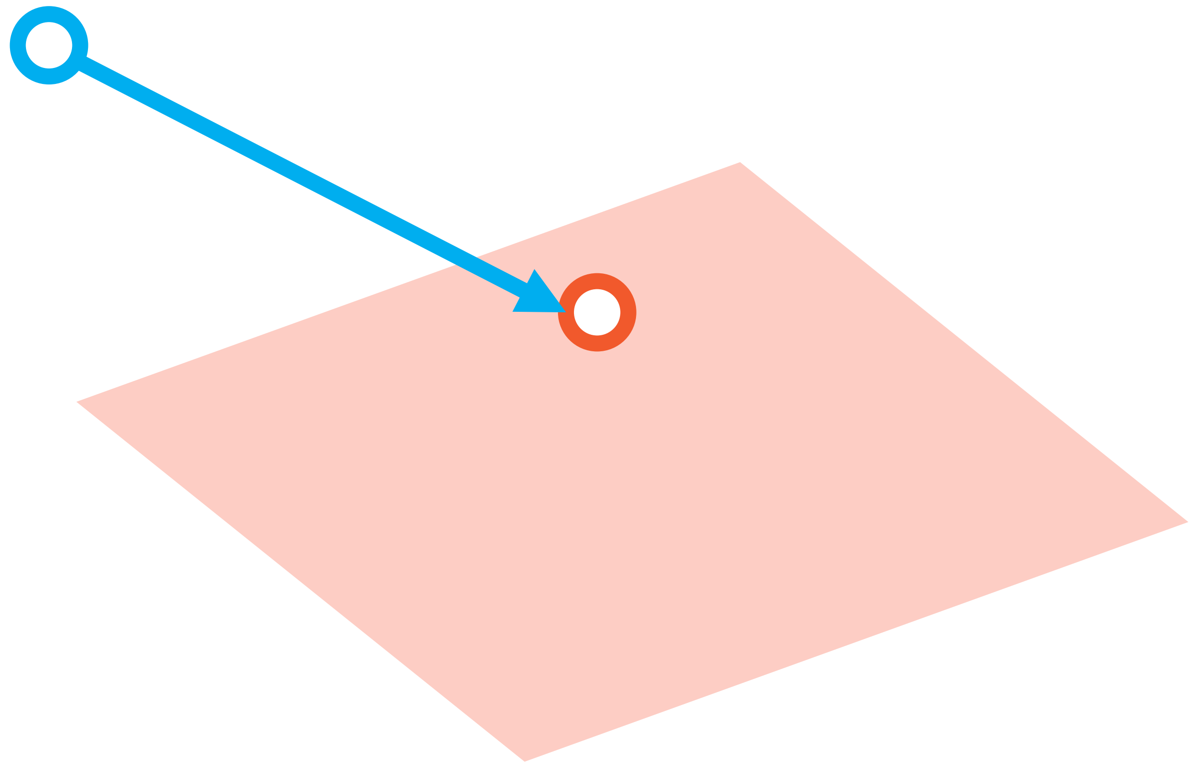
Spatio-temporal (4D) Extended Path Space



$$\int_{\Xi'} f(\overline{\mathbf{x}'}) f_{\omega}^{1,1} K_4(\mathbf{g}') f(\overline{\mathbf{y}'})\ \mathrm{d}\mu(\overline{\mathbf{x}'\mathbf{y}'})$$

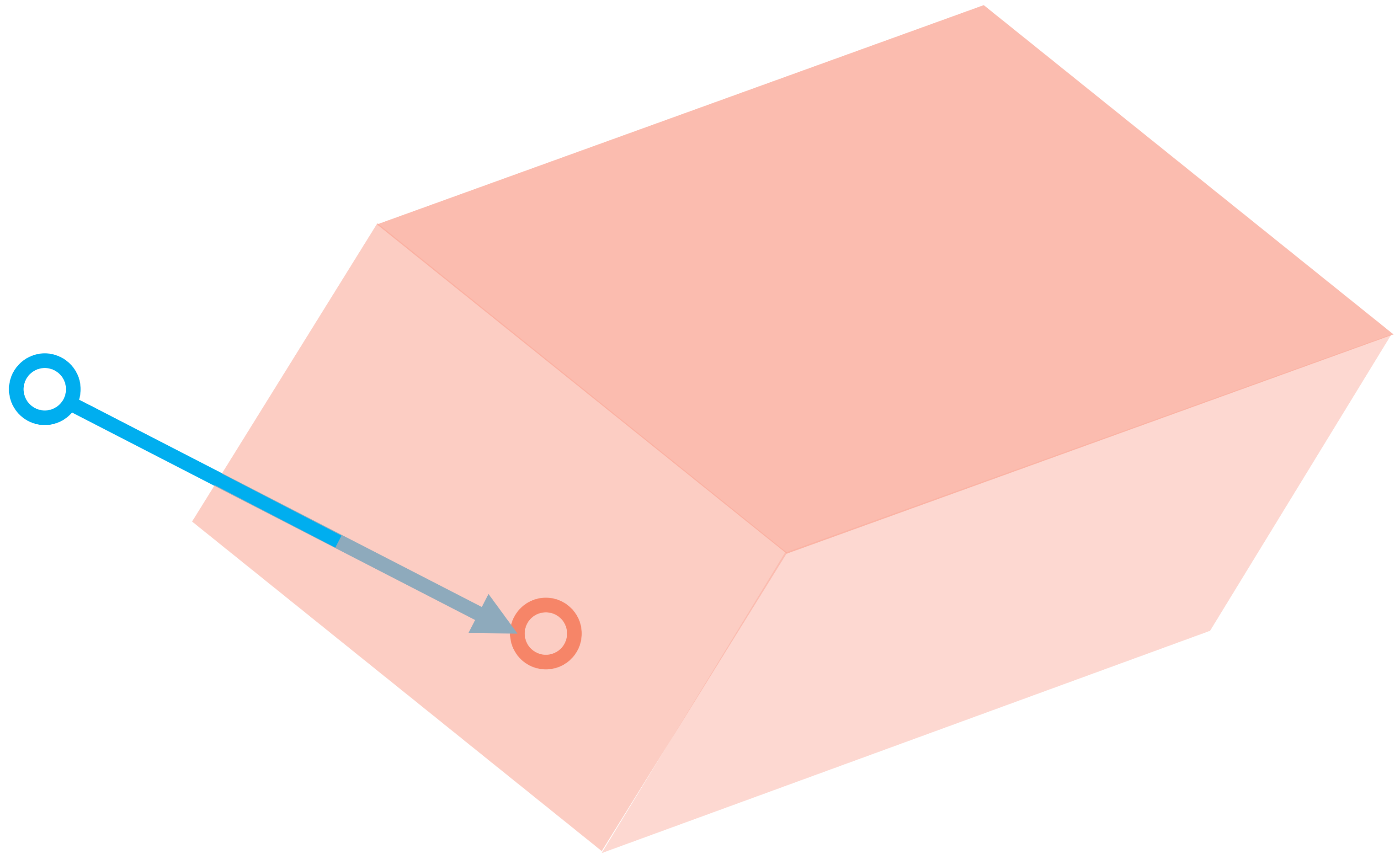
Photon Primitives (Benedikt et al., Deng et al.)

Photon Plane



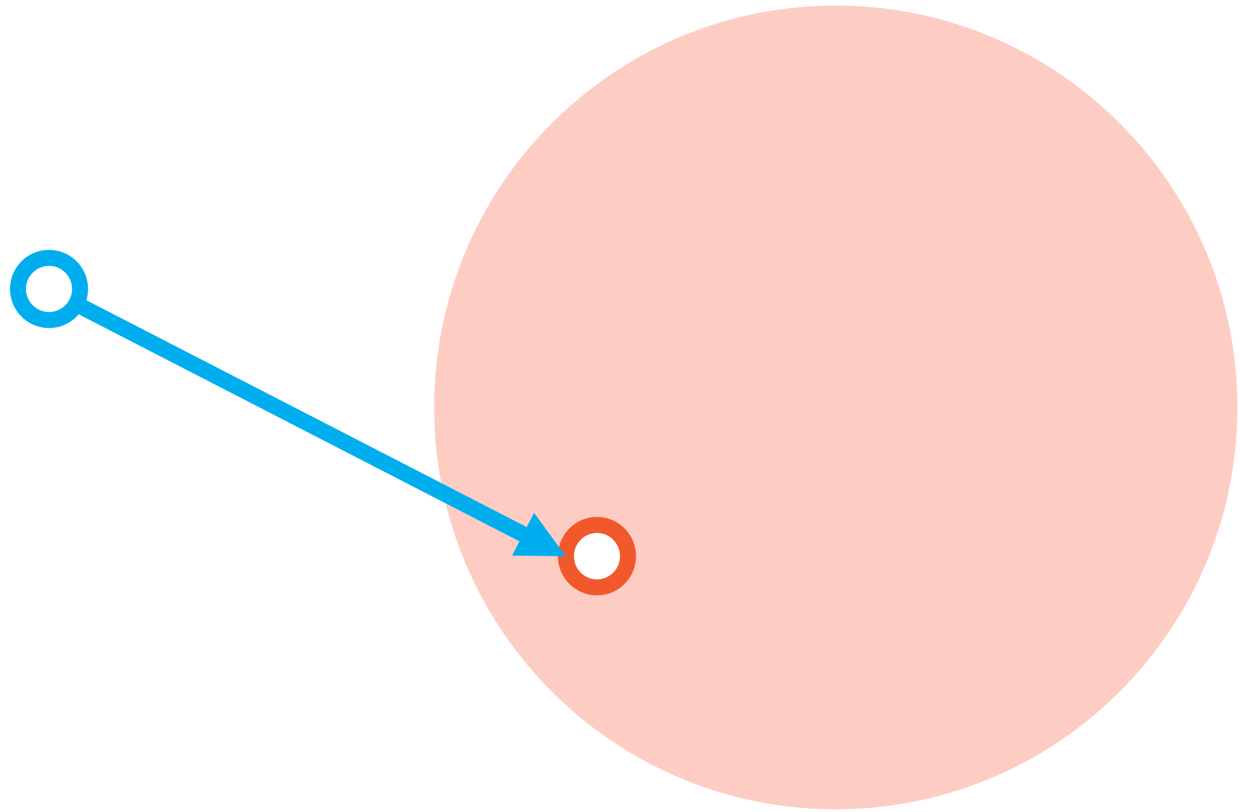
$$\overline{\xi_a} = \{t_2, t_1, s_1\}$$

Photon Parallelepiped



$$\overline{\xi_a} = \{t_3, t_2, t_1\}$$

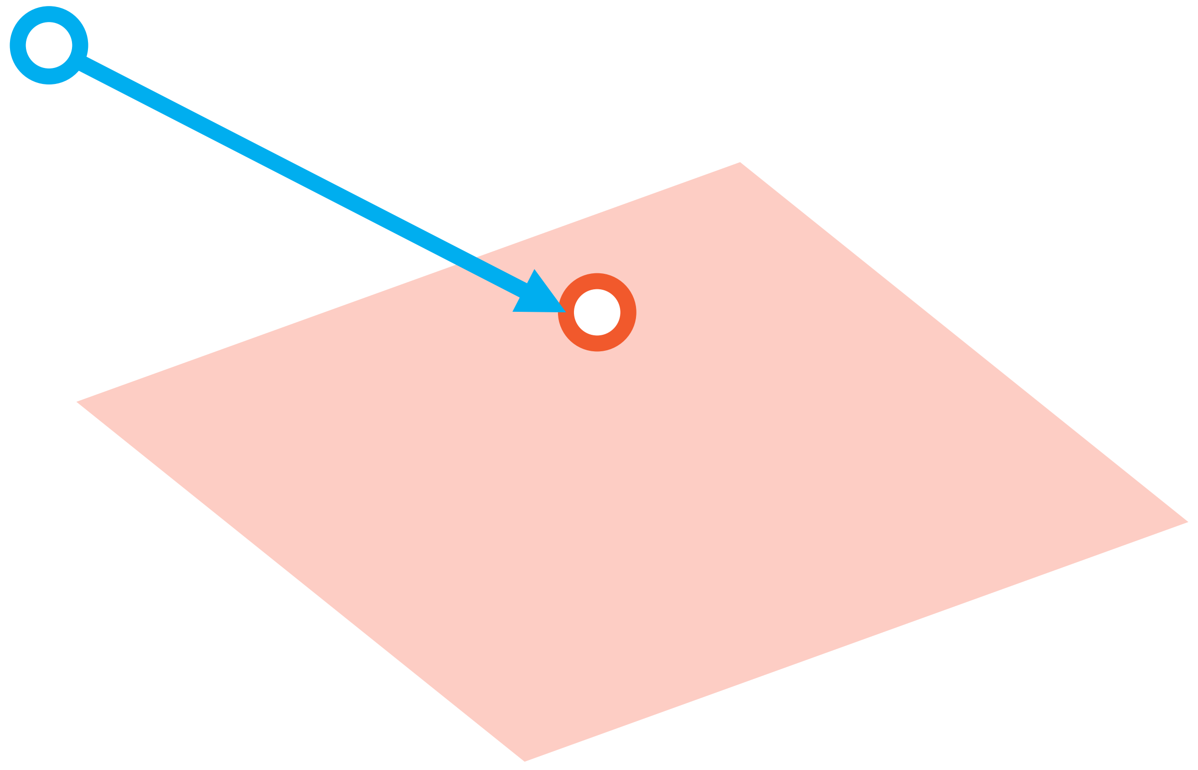
Photon Ball



$$\overline{\xi_a} = \{\cos\theta_1, \phi_1, t_1\}$$

Sliced Photon Primitives

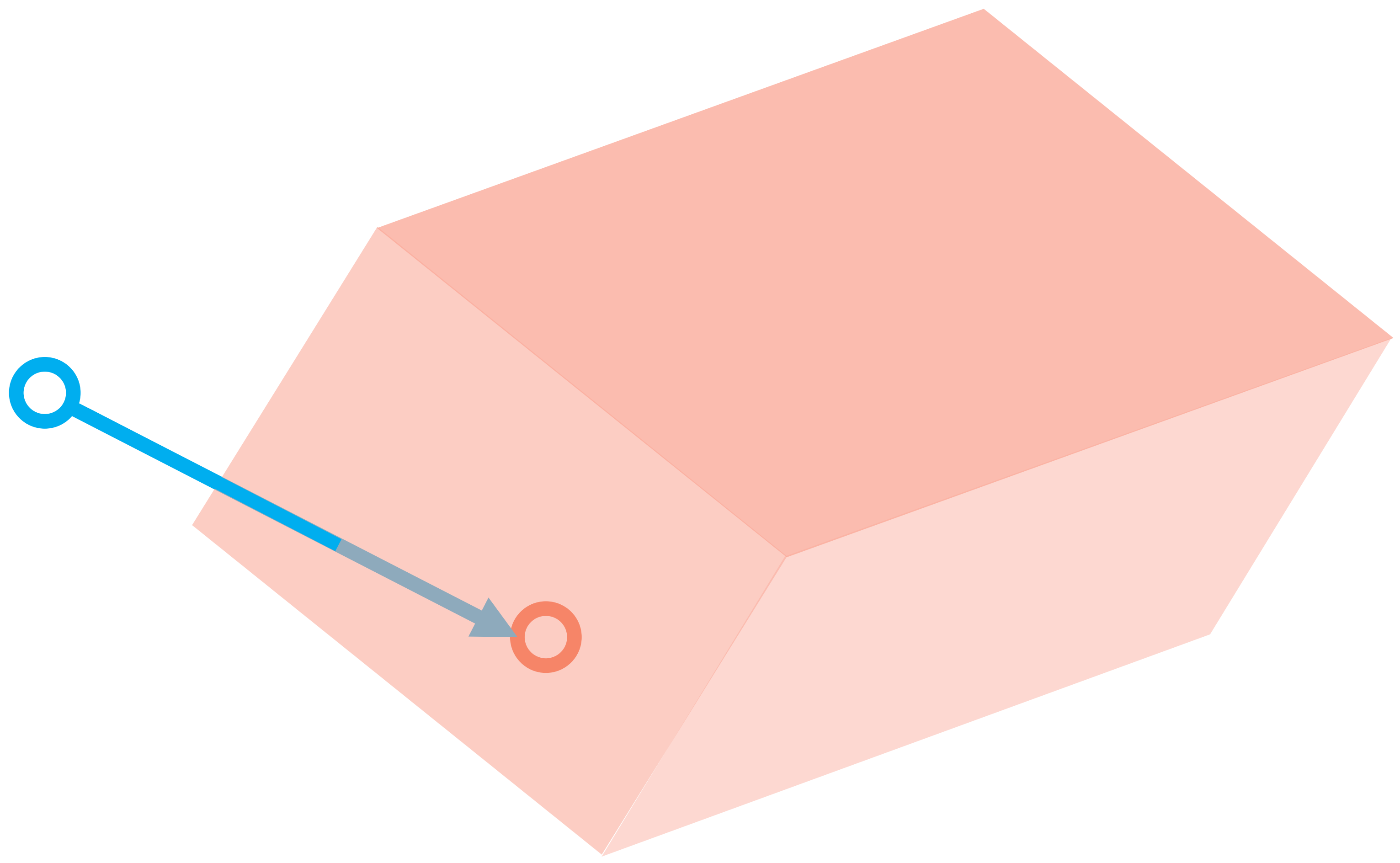
Photon Plane



$$\overline{\xi'_a} = \{t_2, t_1, s_1, \tau_k\}$$

Time gate

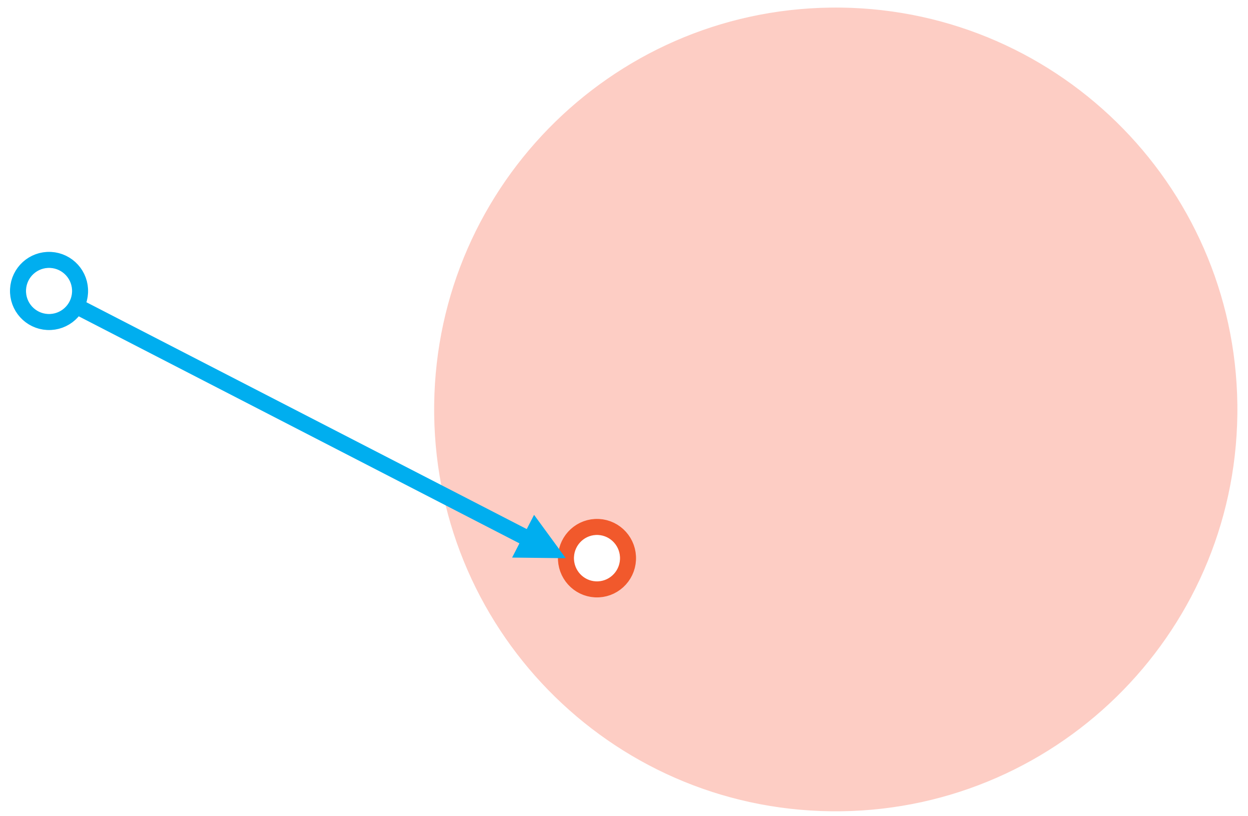
Photon Parallelepiped



$$\overline{\xi'_a} = \{t_3, t_2, t_1, s_1\}$$

Last camera distance

Photon Ball

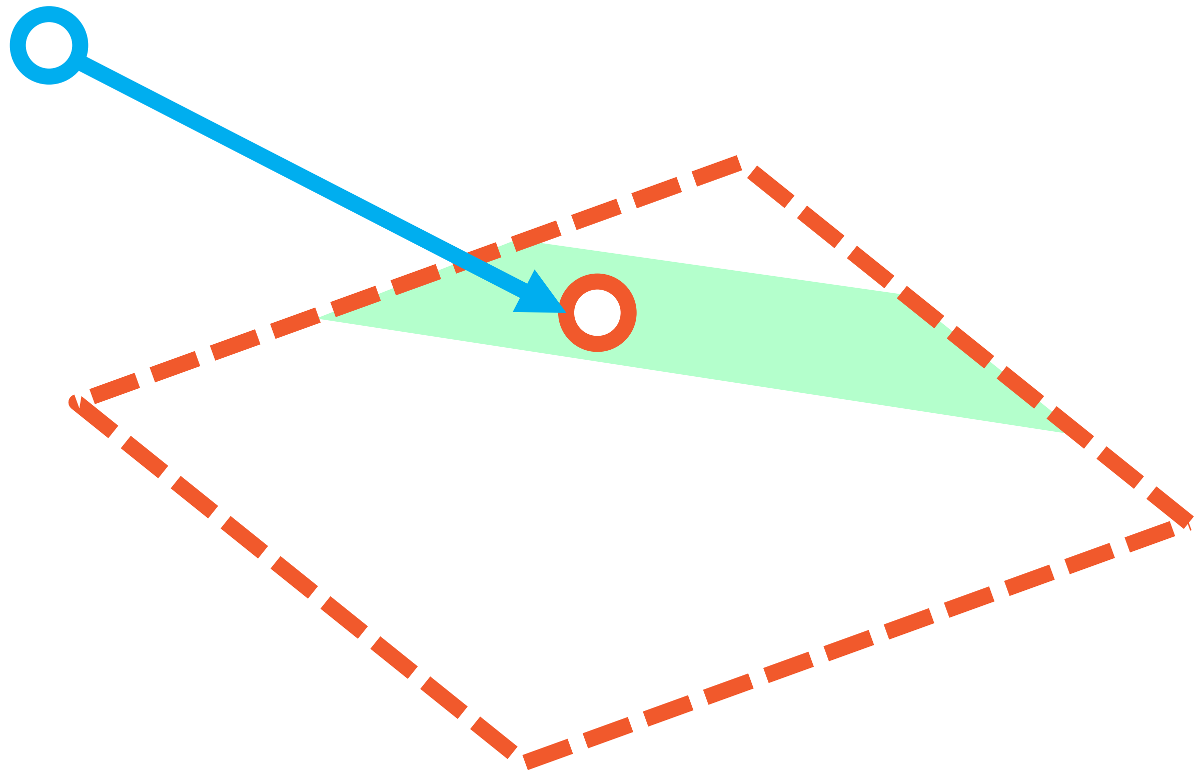


$$\overline{\xi'_a} = \{\cos\theta_1, \phi_1, t_1, s_1\}$$

Last camera distance

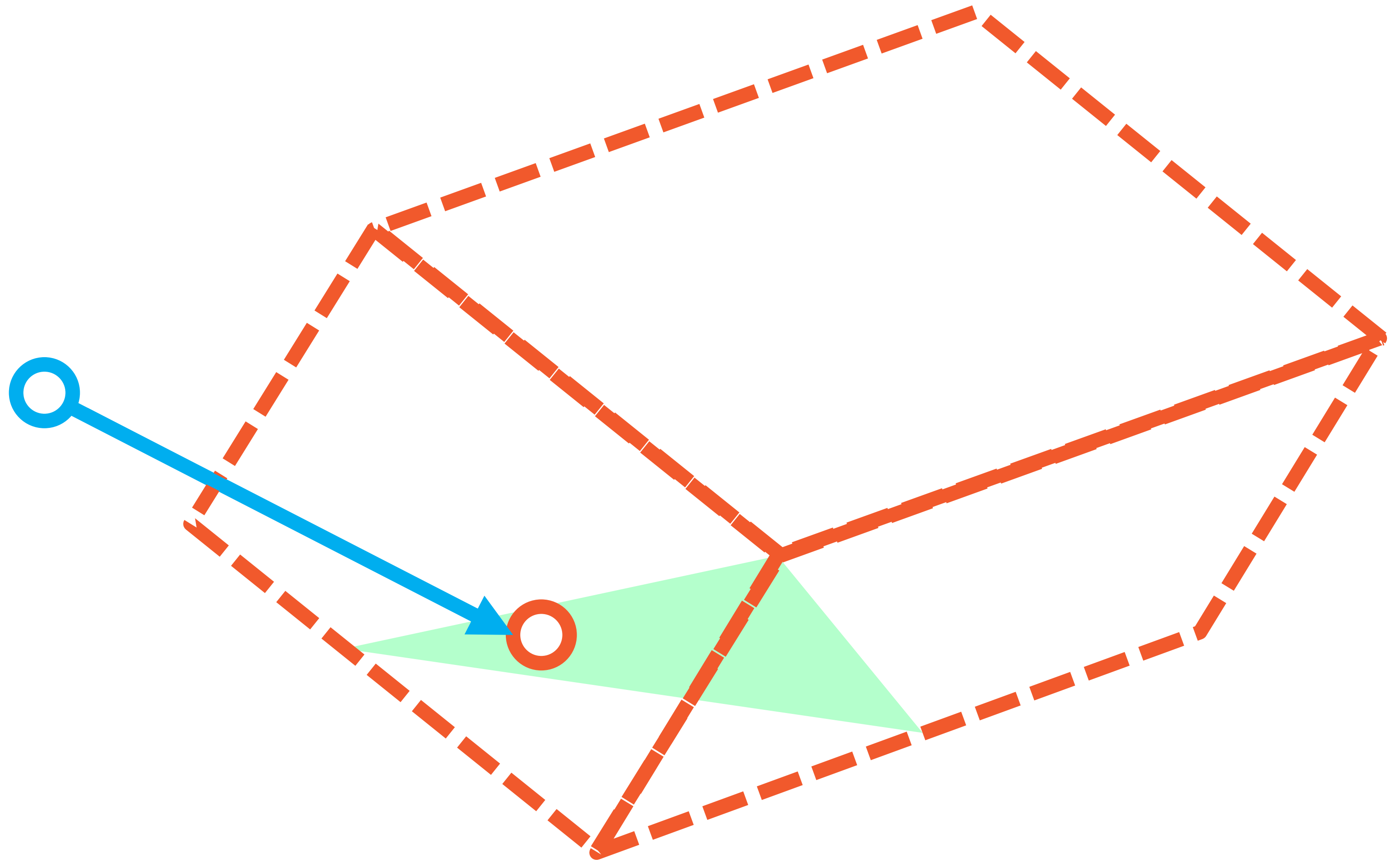
Sliced Photon Primitives

Sliced
Photon Plane



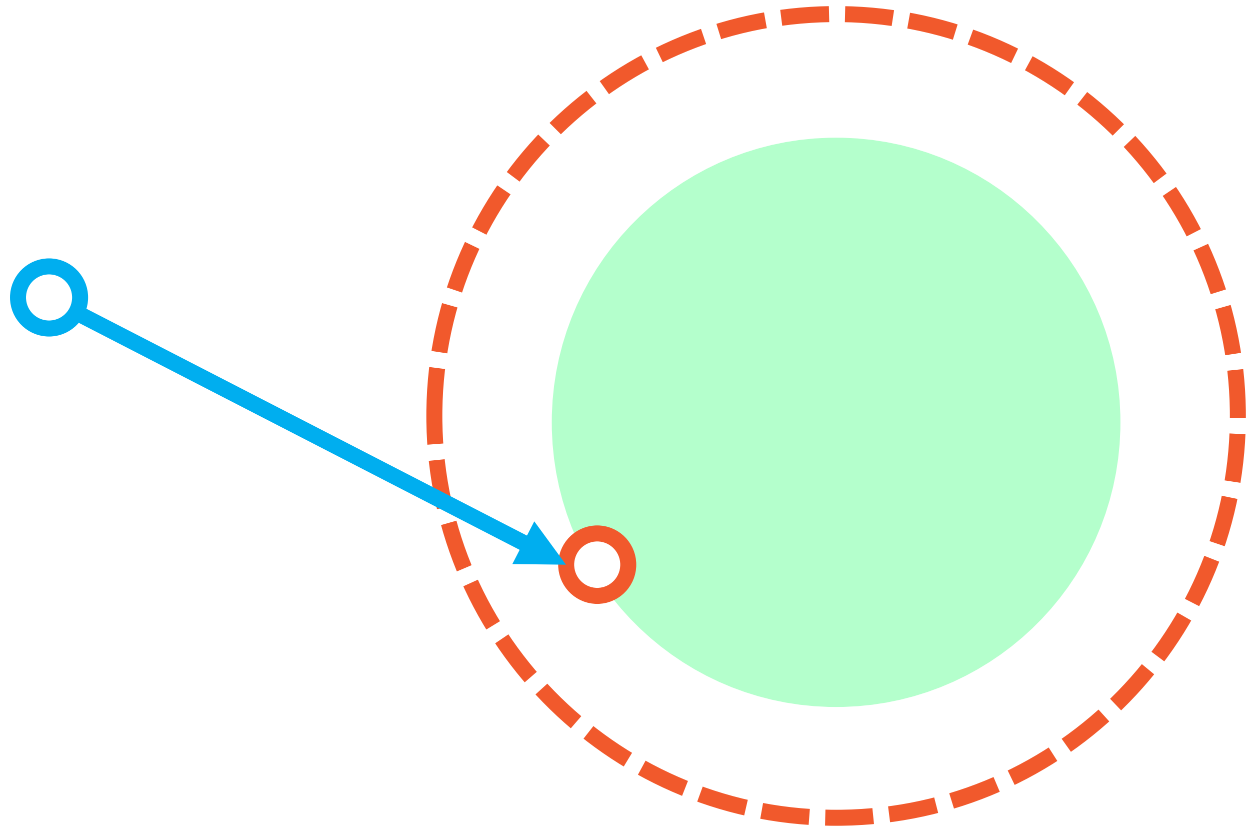
$$\overline{\xi'_a} = \{t_2, t_1, s_1, \tau_k\}$$

Sliced
Photon Parallelepiped



$$\overline{\xi'_a} = \{t_3, t_2, t_1, s_1\}$$

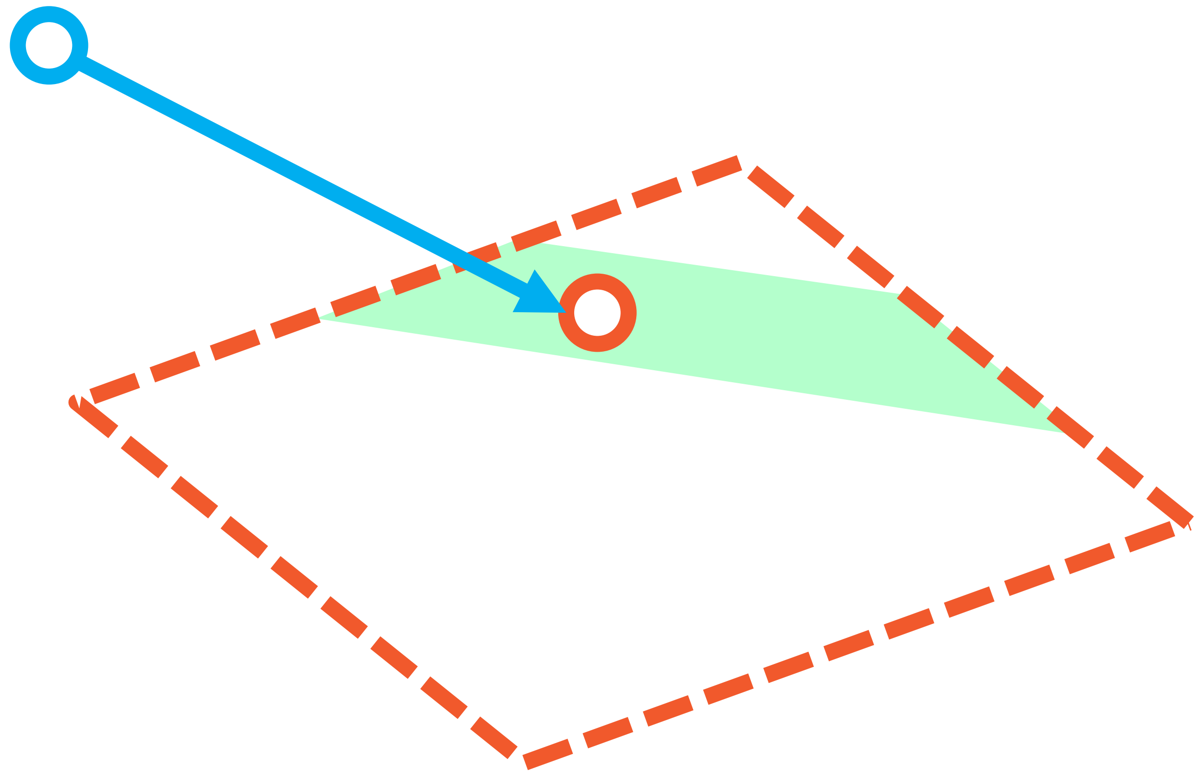
Sliced
Photon Ball



$$\overline{\xi'_a} = \{\cos\theta_1, \phi_1, t_1, s_1\}$$

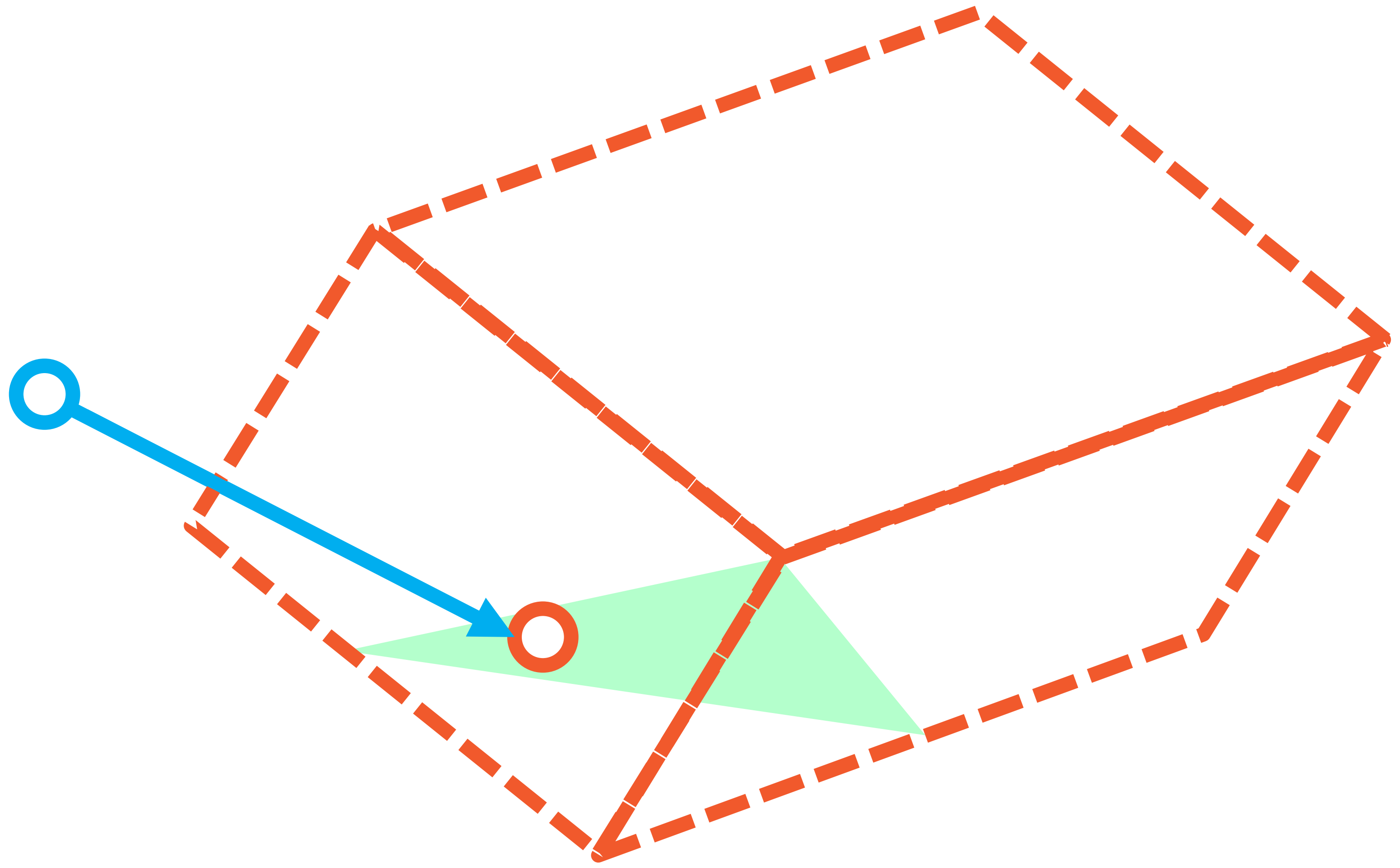
Sliced Photon Primitives

Sliced
Photon Plane



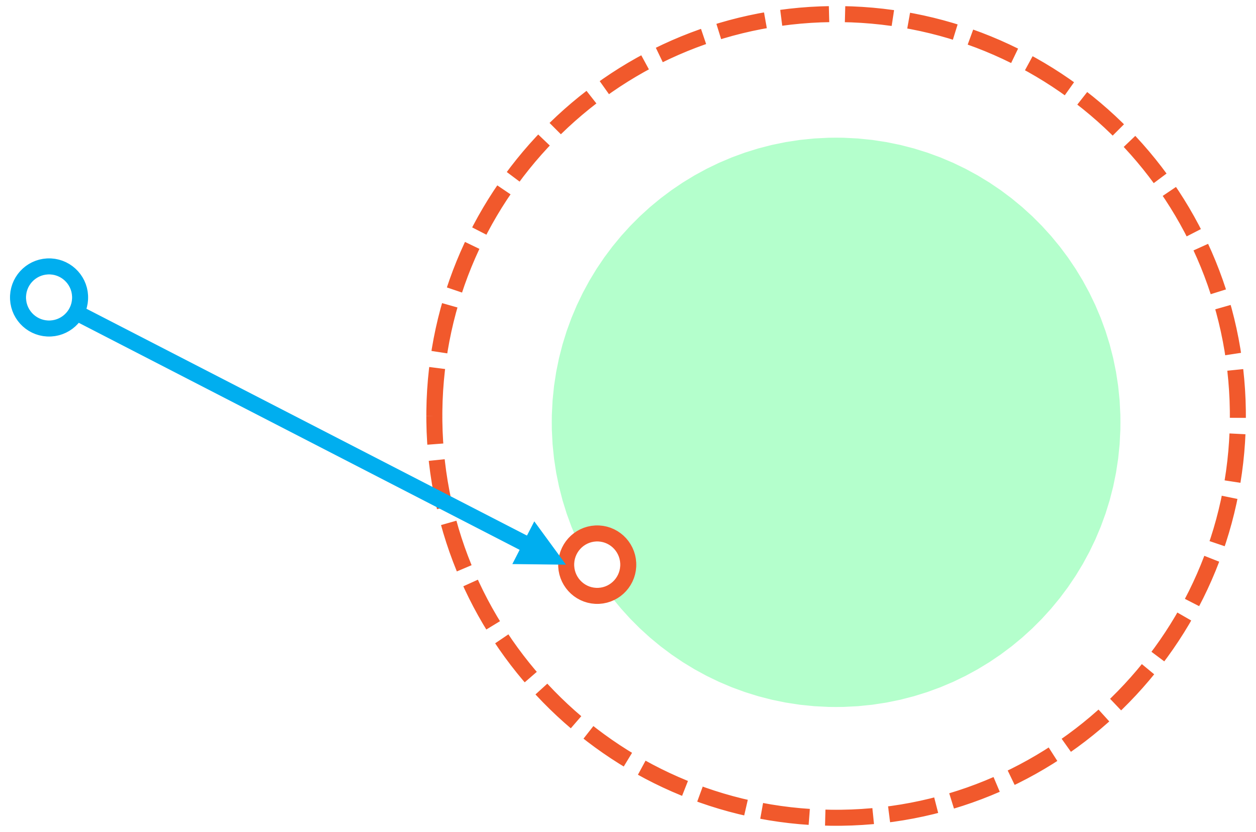
$$\mathbf{J} = \begin{bmatrix} | & | & | & | \\ \frac{\partial \mathbf{g}'}{\partial t_2} & \frac{\partial \mathbf{g}'}{\partial t_1} & \frac{\partial \mathbf{g}'}{\partial s_1} & \frac{\partial \mathbf{g}'}{\partial \tau_k} \\ | & | & | & | \end{bmatrix}$$

Sliced
Photon Parallelepiped



$$\mathbf{J} = \begin{bmatrix} | & | & | & | \\ \frac{\partial \mathbf{g}'}{\partial t_3} & \frac{\partial \mathbf{g}'}{\partial t_2} & \frac{\partial \mathbf{g}'}{\partial t_1} & \frac{\partial \mathbf{g}'}{\partial s_1} \\ | & | & | & | \end{bmatrix}$$

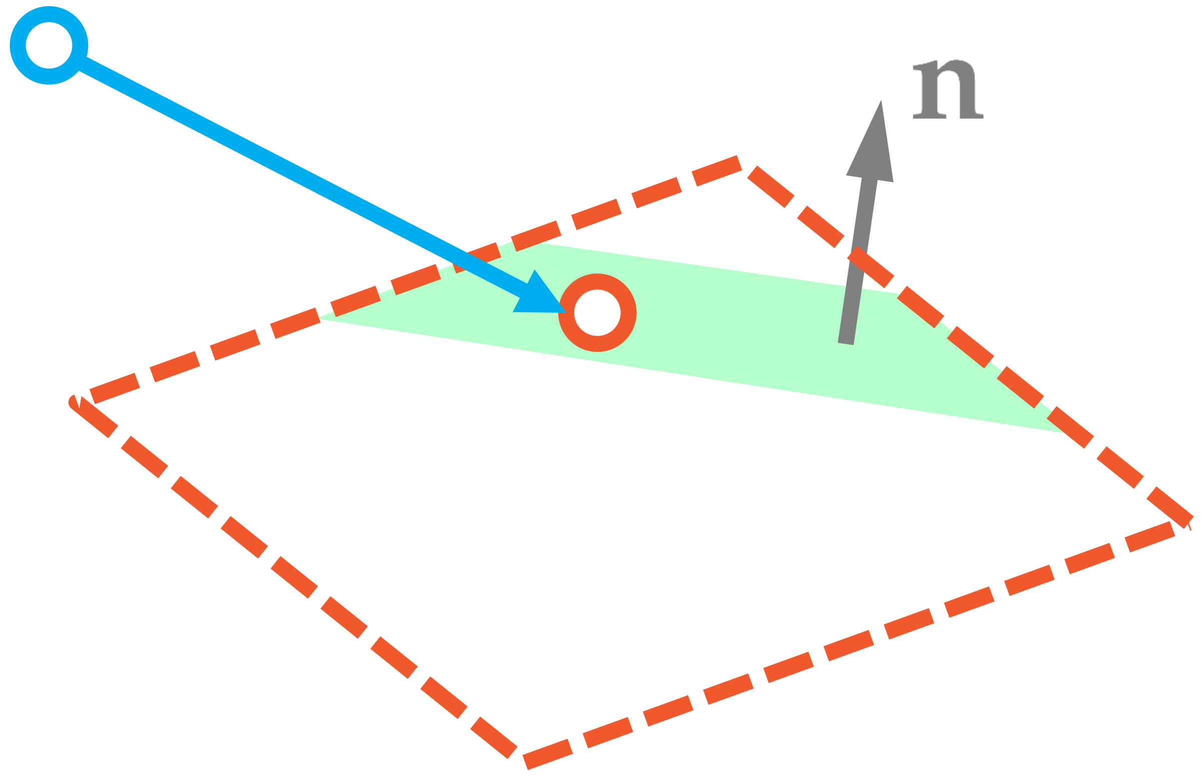
Sliced
Photon Ball



$$\mathbf{J} = \begin{bmatrix} | & | & | & | \\ \frac{\partial \mathbf{g}'}{\partial \cos\theta_1} & \frac{\partial \mathbf{g}'}{\phi_1} & \frac{\partial \mathbf{g}'}{\partial t_1} & \frac{\partial \mathbf{g}'}{\partial s_1} \\ | & | & | & | \end{bmatrix}$$

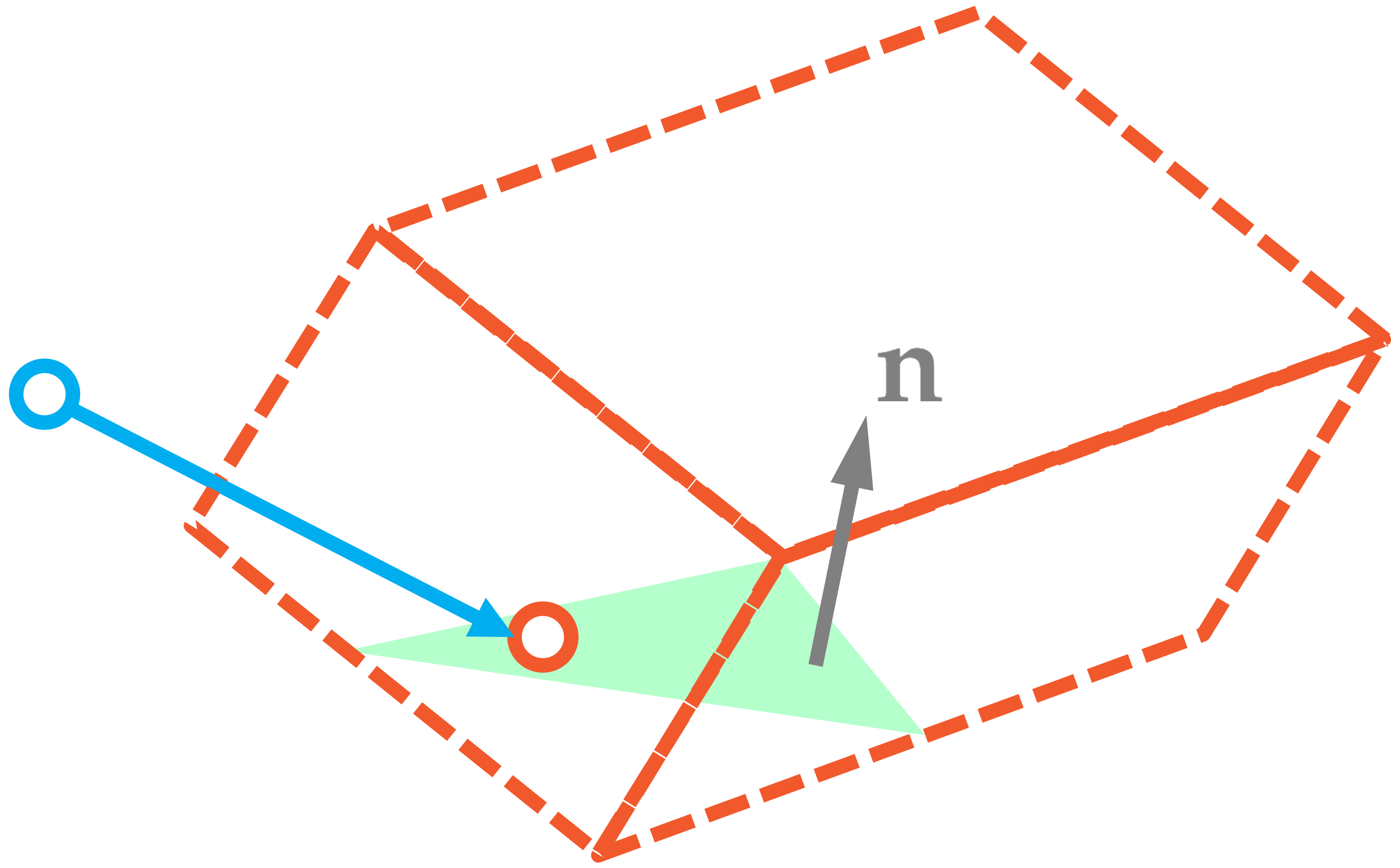
Sliced Photon Primitives

Sliced
Photon Plane



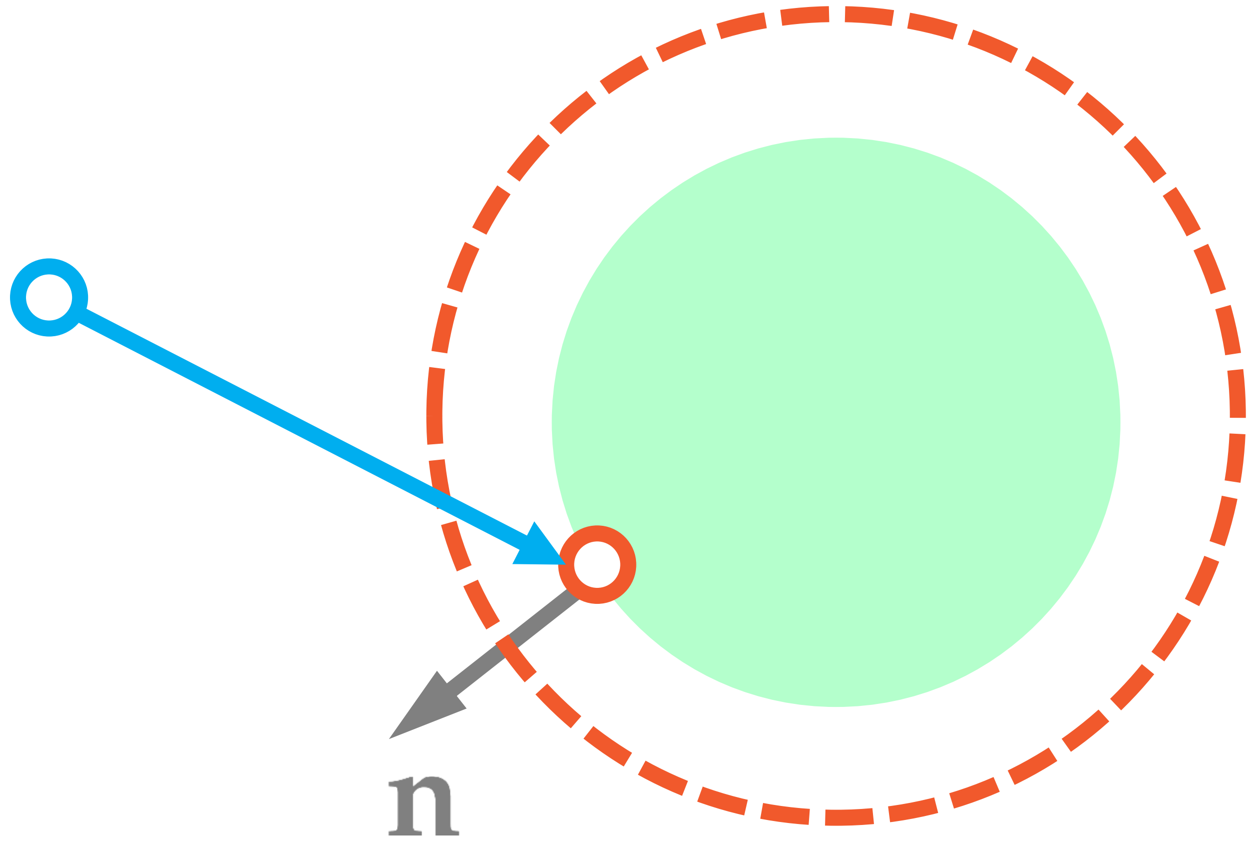
$$|\mathbf{J}| = |\psi_1 \cdot \mathbf{n}|$$

Sliced
Photon Parallelepiped



$$|\mathbf{J}| = |\psi_1 \cdot \mathbf{n}|$$

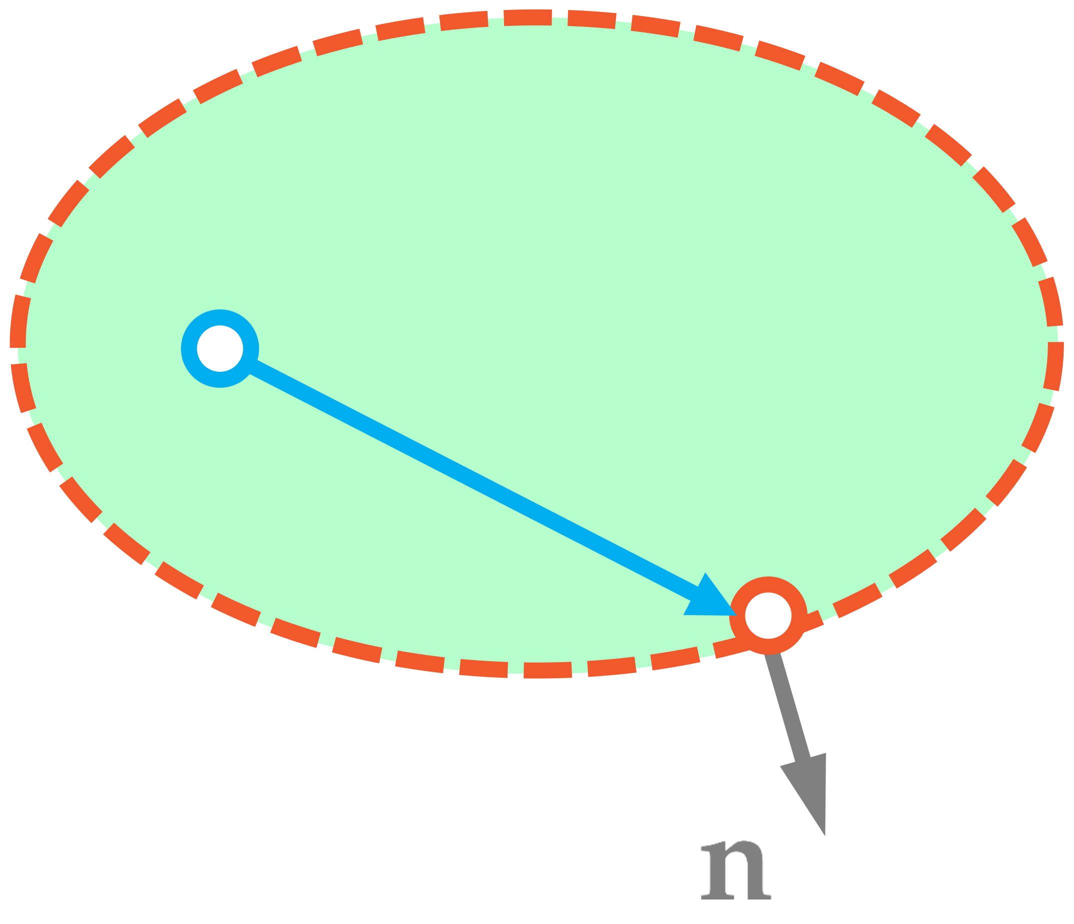
Sliced
Photon Ball



$$|\mathbf{J}| = |\psi_1 \cdot \mathbf{n}|$$

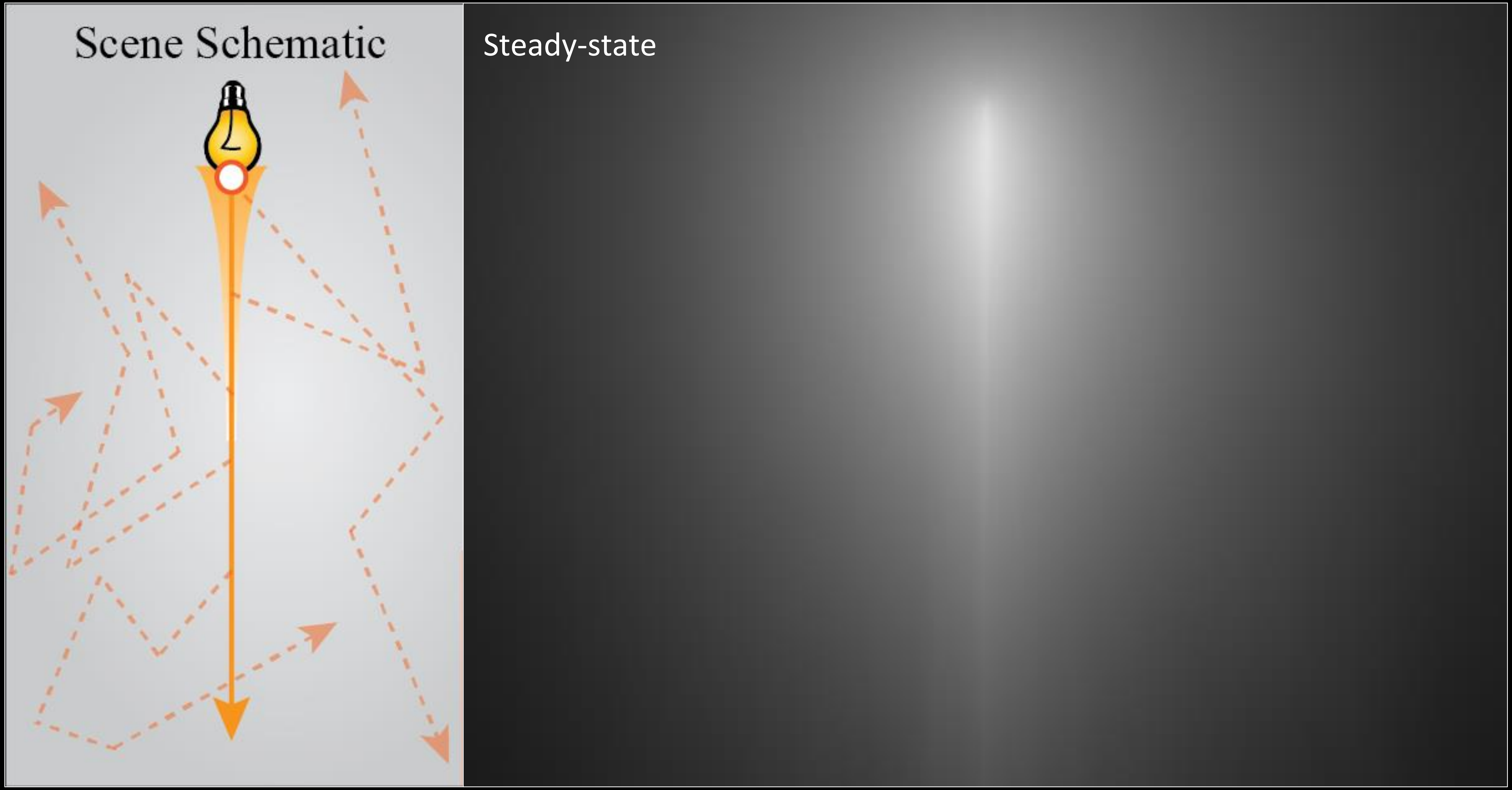
Sliced Photon Primitives

Sliced
Photon Ball
(camera-warped)



$$|\mathbf{J}| = |\psi_1 \cdot \mathbf{n}|$$

The searchlight scene



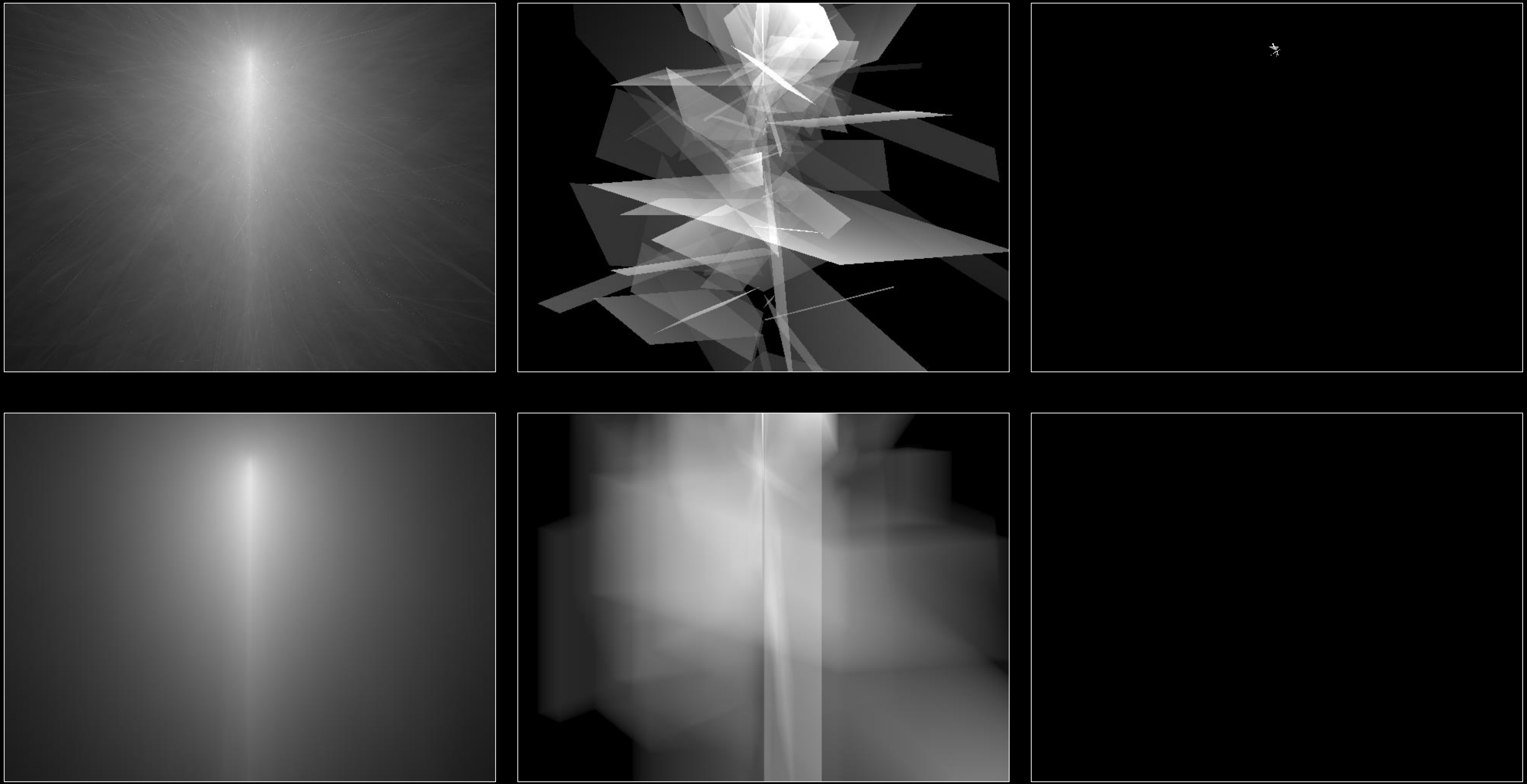
Steady State 300k paths

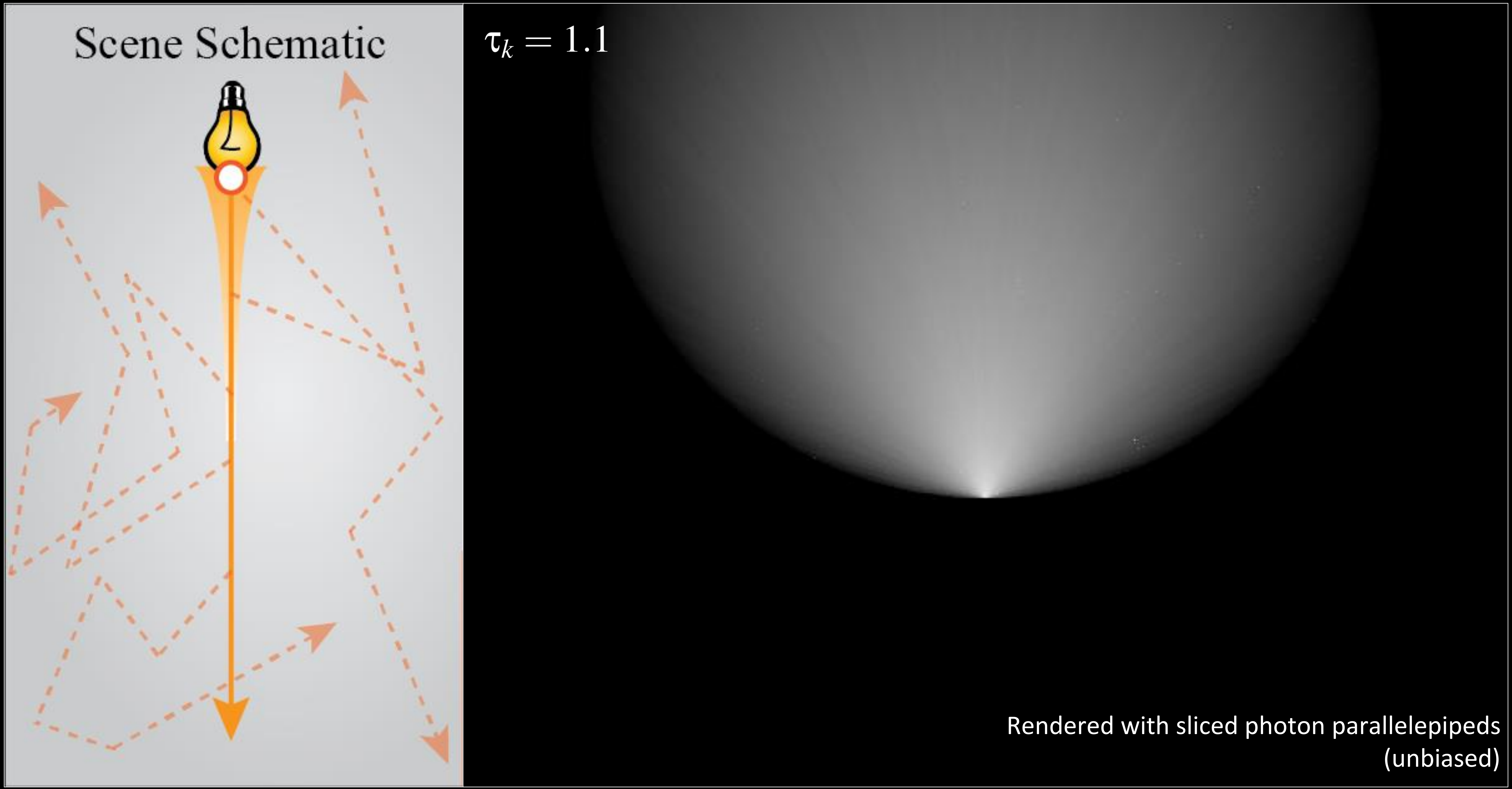
Steady State 100 paths

Sliced Primitive 100 paths

Plane

Parallelepiped



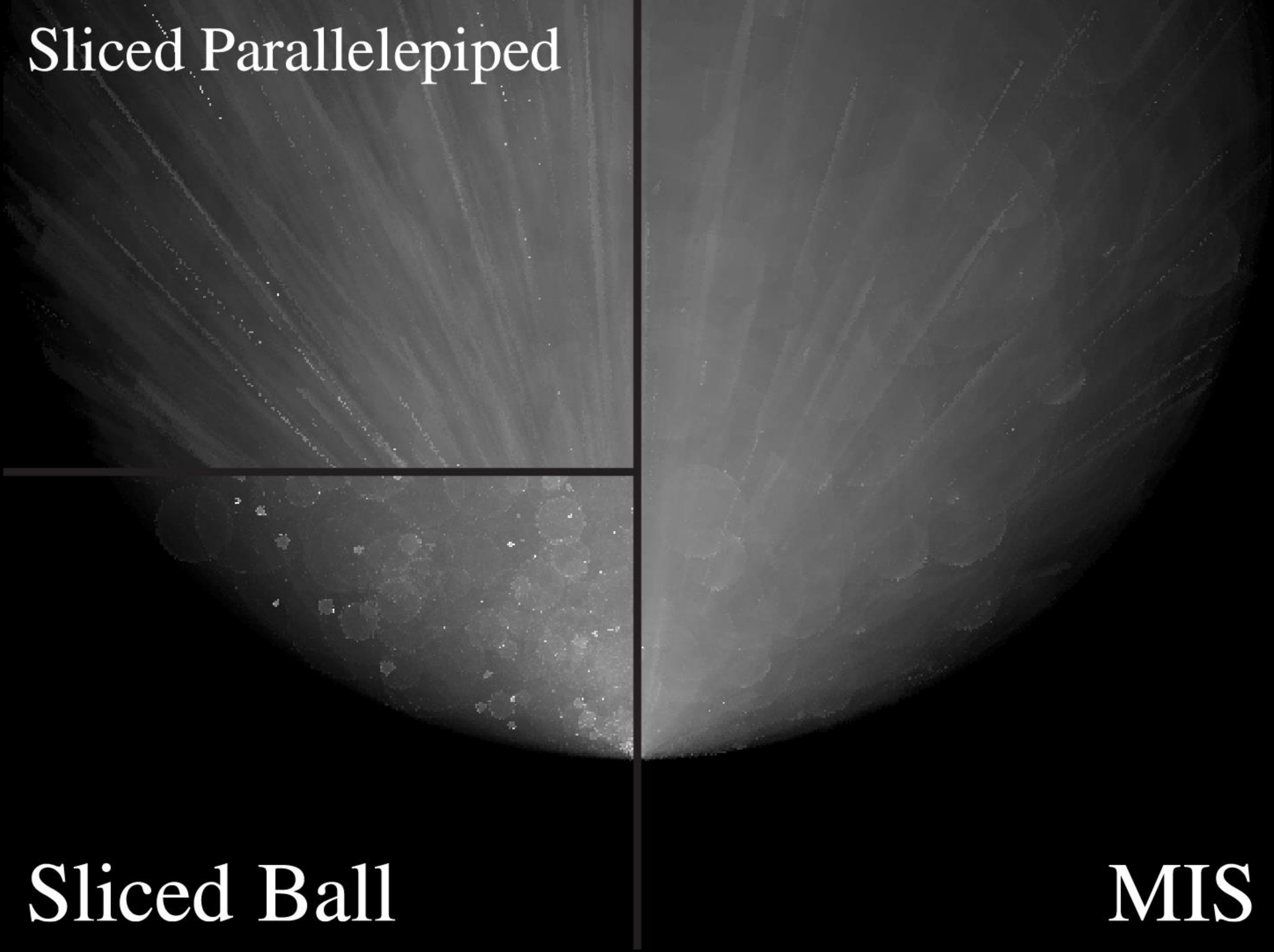

Scene Schematic
$\tau_k = 1.1$
Rendered with sliced photon parallelepipeds
(unbiased)

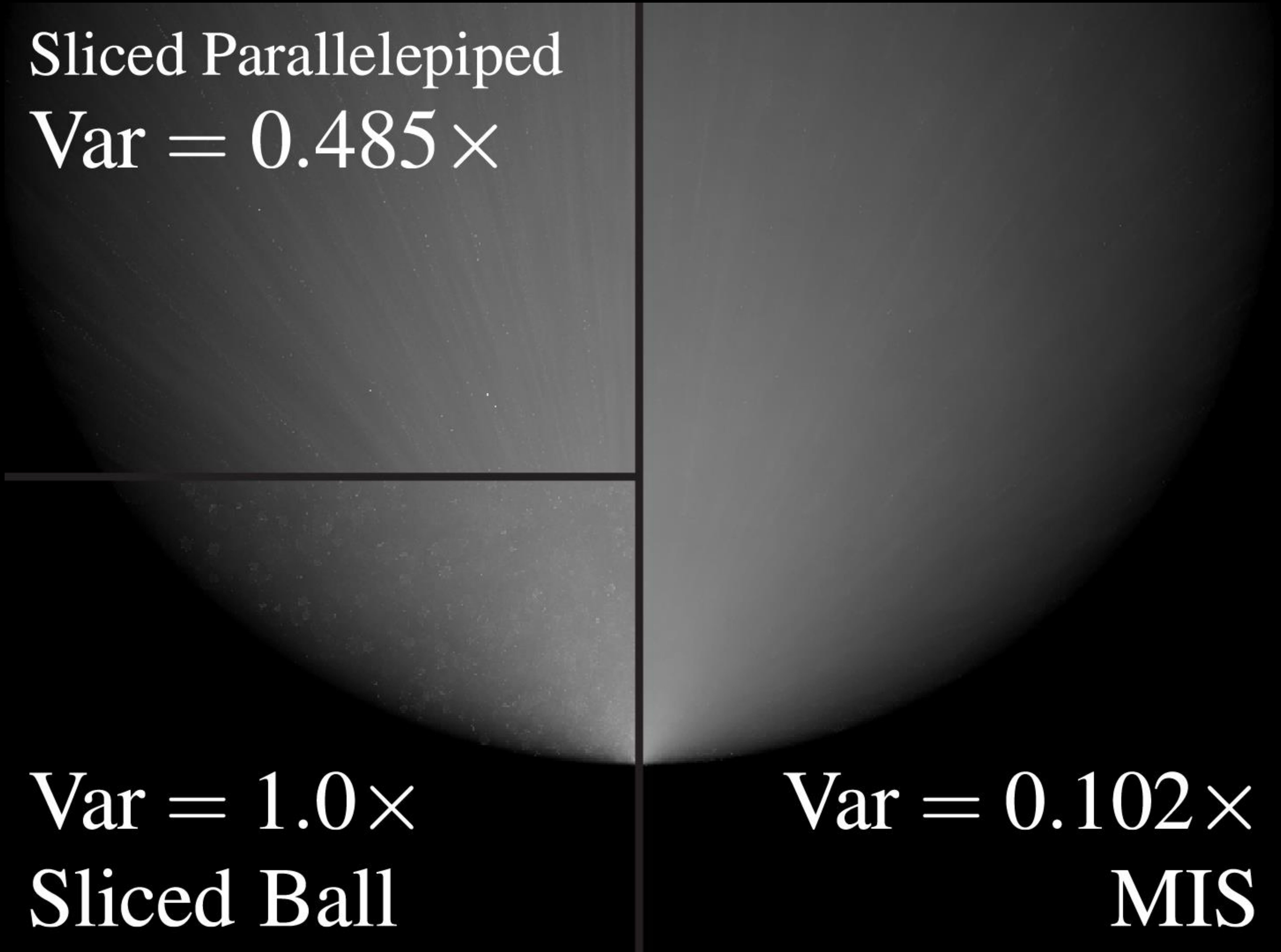
Warped and unwarped primitives

Multiple Importance Sampling

- **Combine** the **strengths** of different estimators (and avoid their weaknesses)
  - Smart weighted average of the estimators
  - We use the score-based variant [Jendersie18]

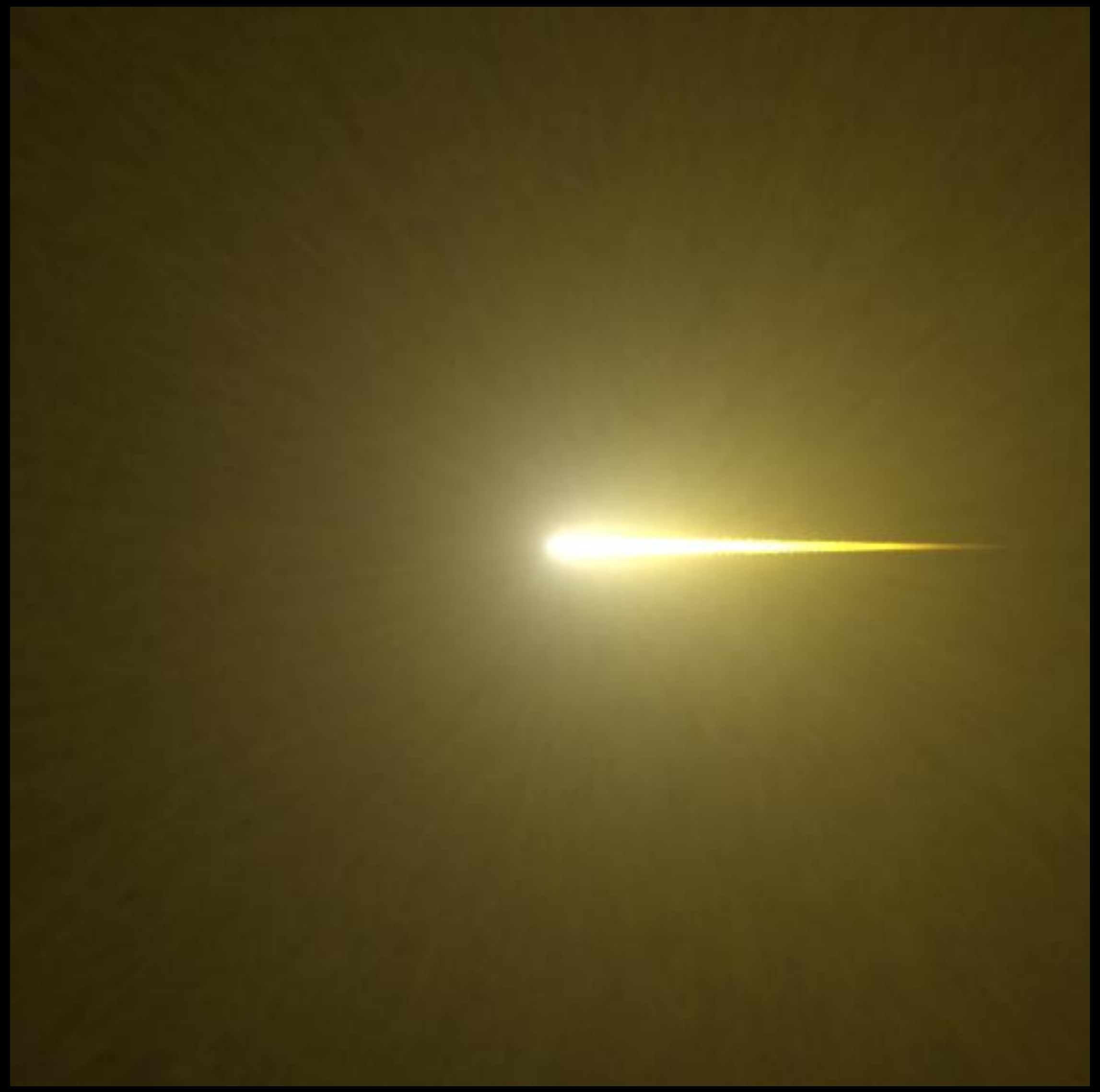
$$w_a(\bar{\mathbf{z}}) = \langle I \rangle_a^{-\beta}(\bar{\mathbf{z}}) / \sum_{k=1}^{m} \langle I \rangle_k^{-\beta}(\bar{\mathbf{z}})$$


Sliced Parallelepiped
Sliced Ball
MIS

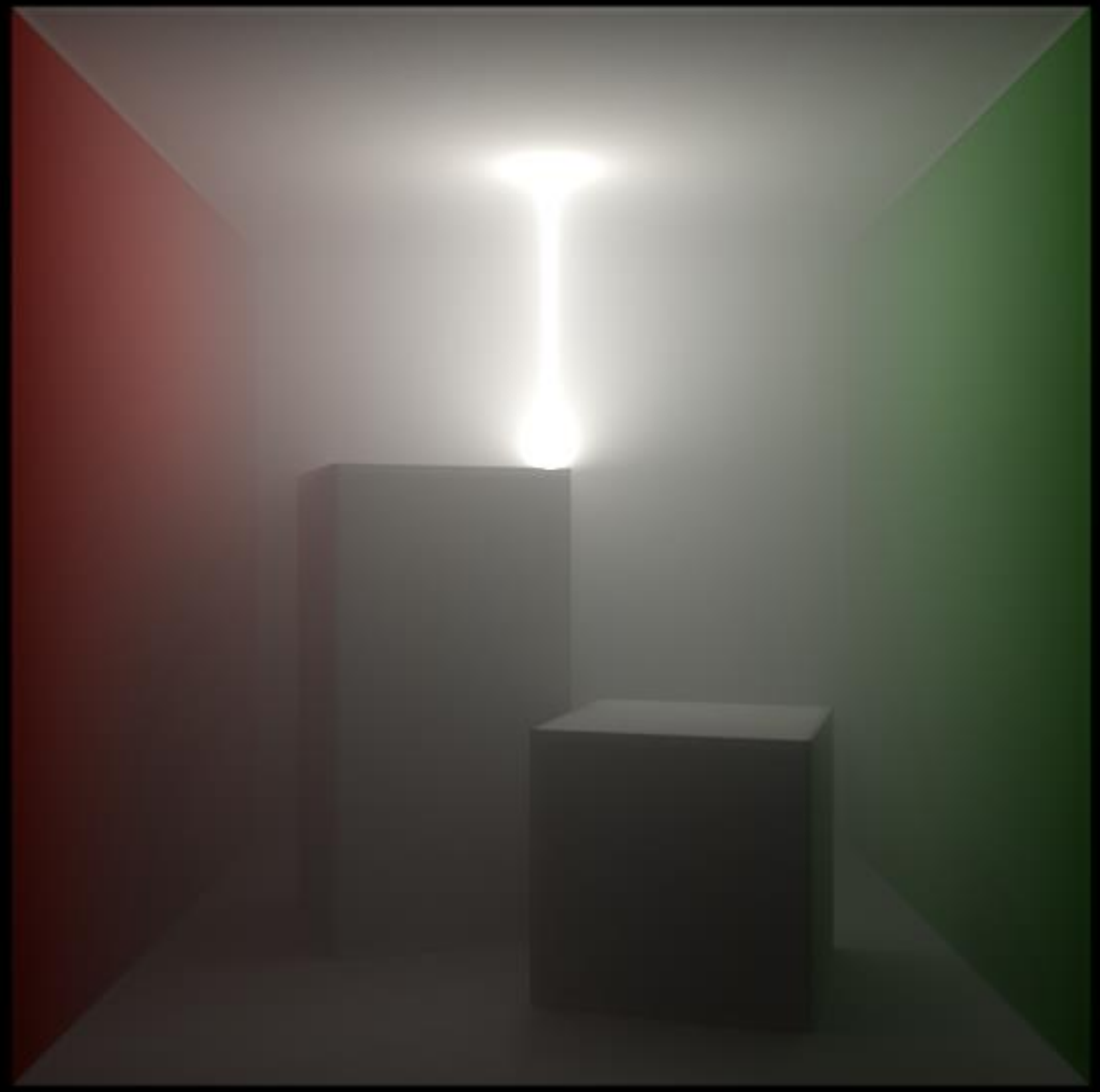

Sliced Parallelepiped
Var = 0.485×
Var = 1.0×
Sliced Ball
Var = 0.102×
MIS

Results from General Ray Tracer

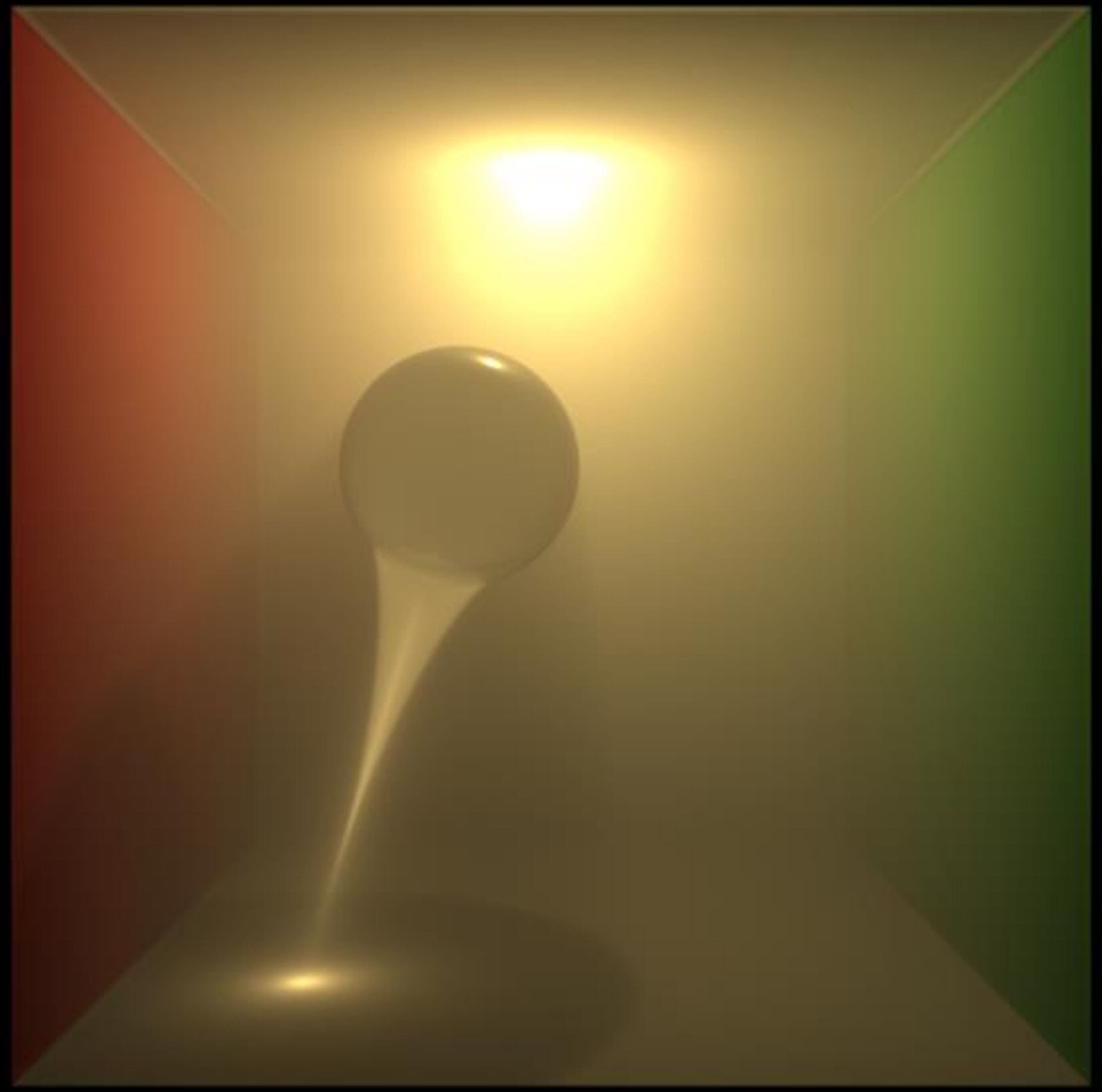
Subsurface Scattering



Cornell Box

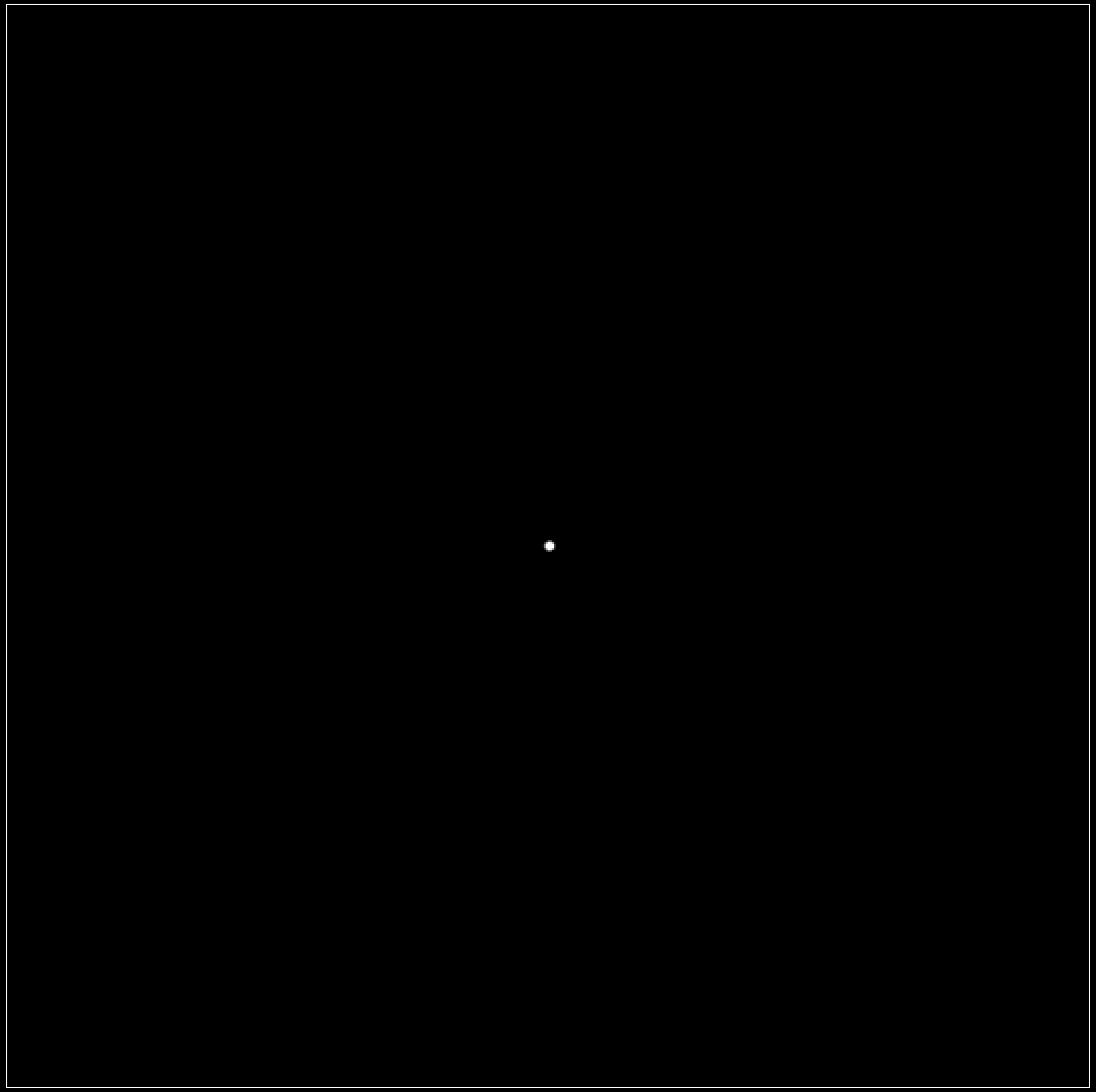


Volumetric Caustic

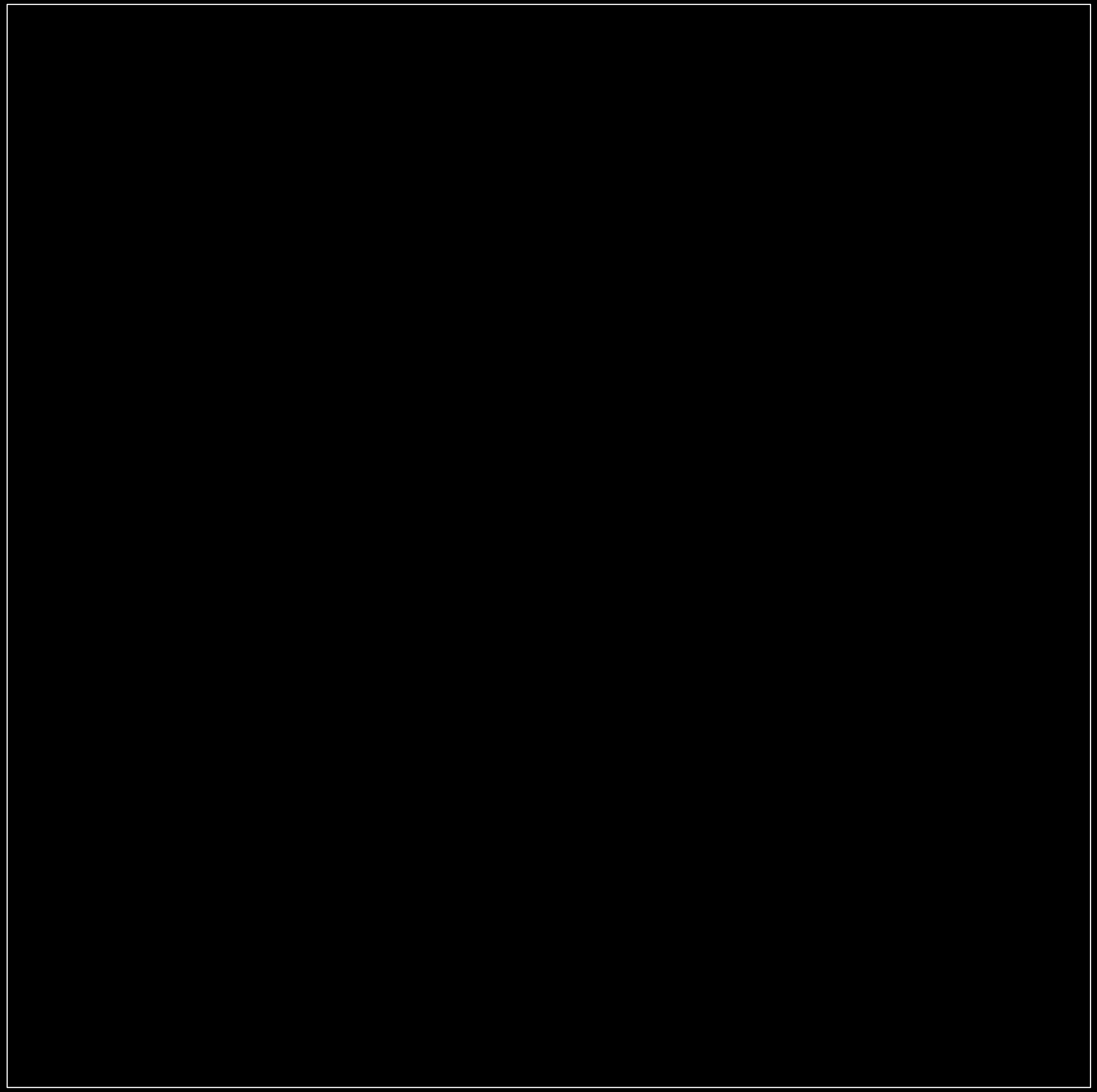


Subsurface Scattering

Progressive Transient Photon Beam
(**Prev**)

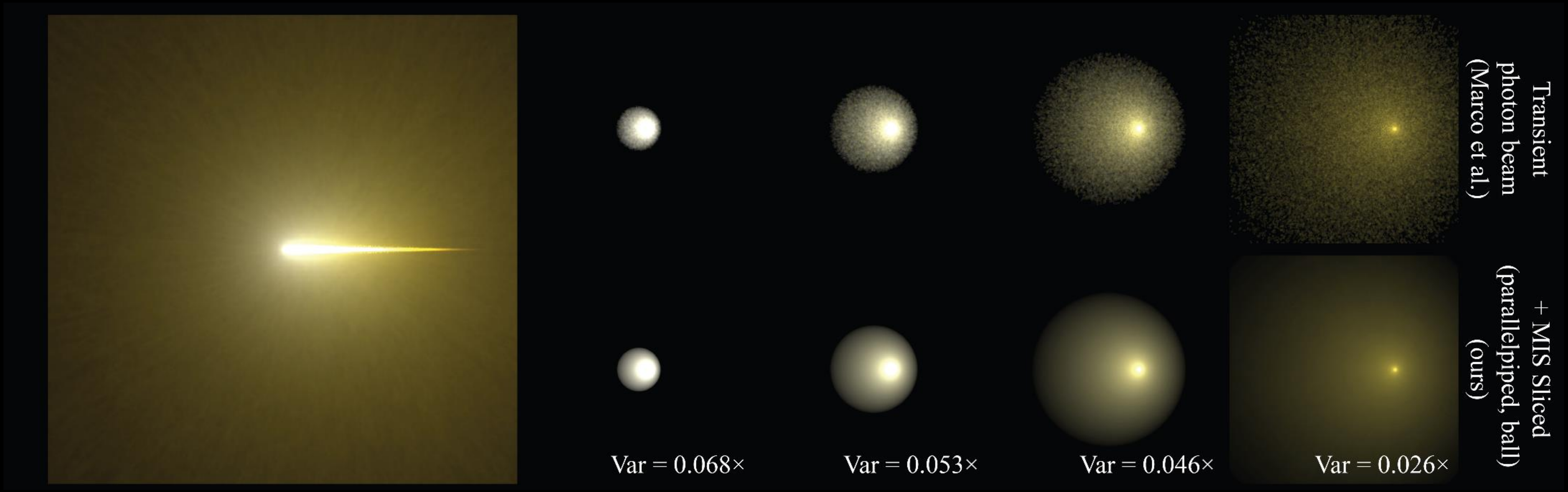


MIS Sliced (Parallelepiped, Ball)
(**Ours**)



Subsurface Scattering

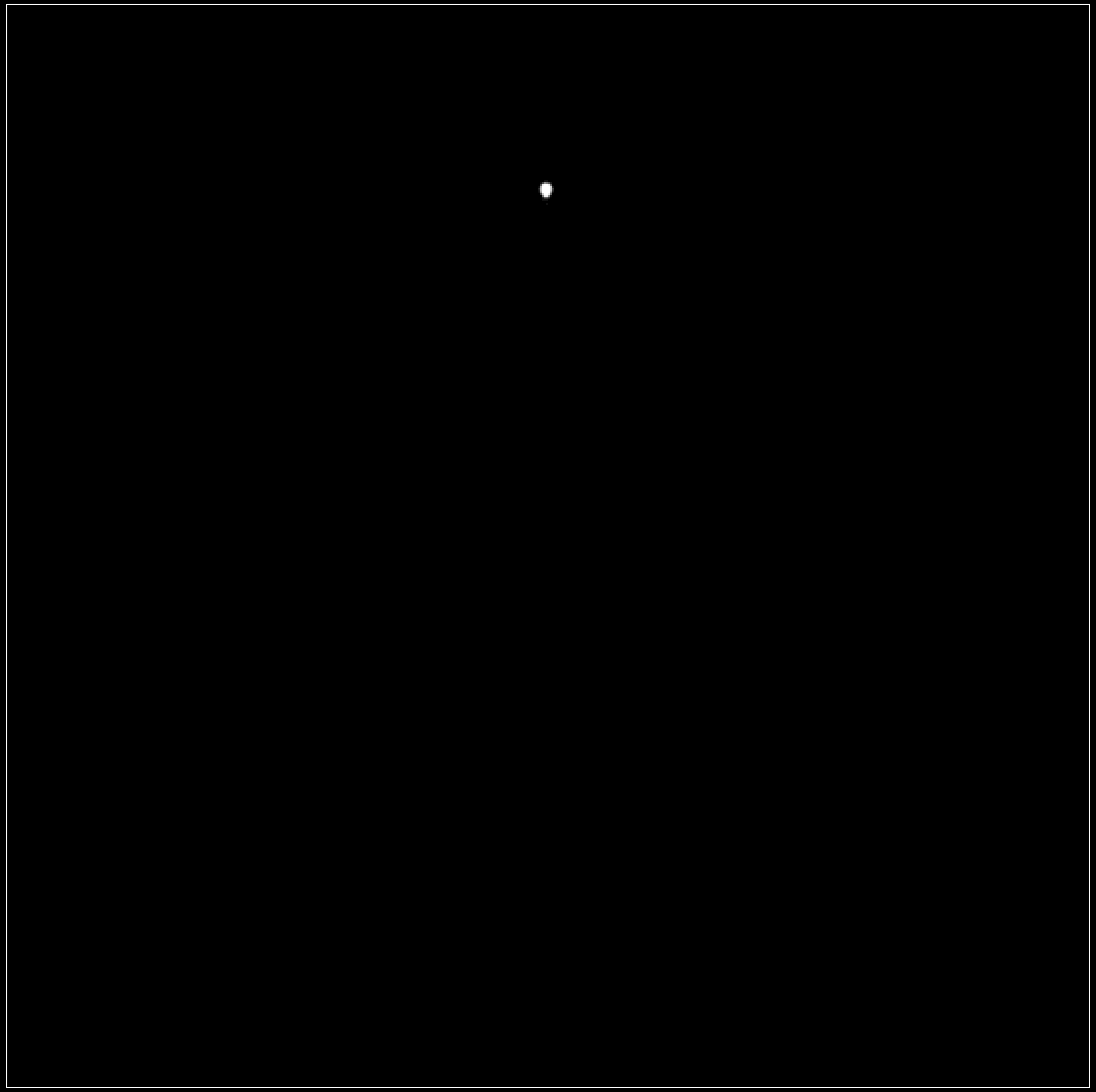
(Prev)



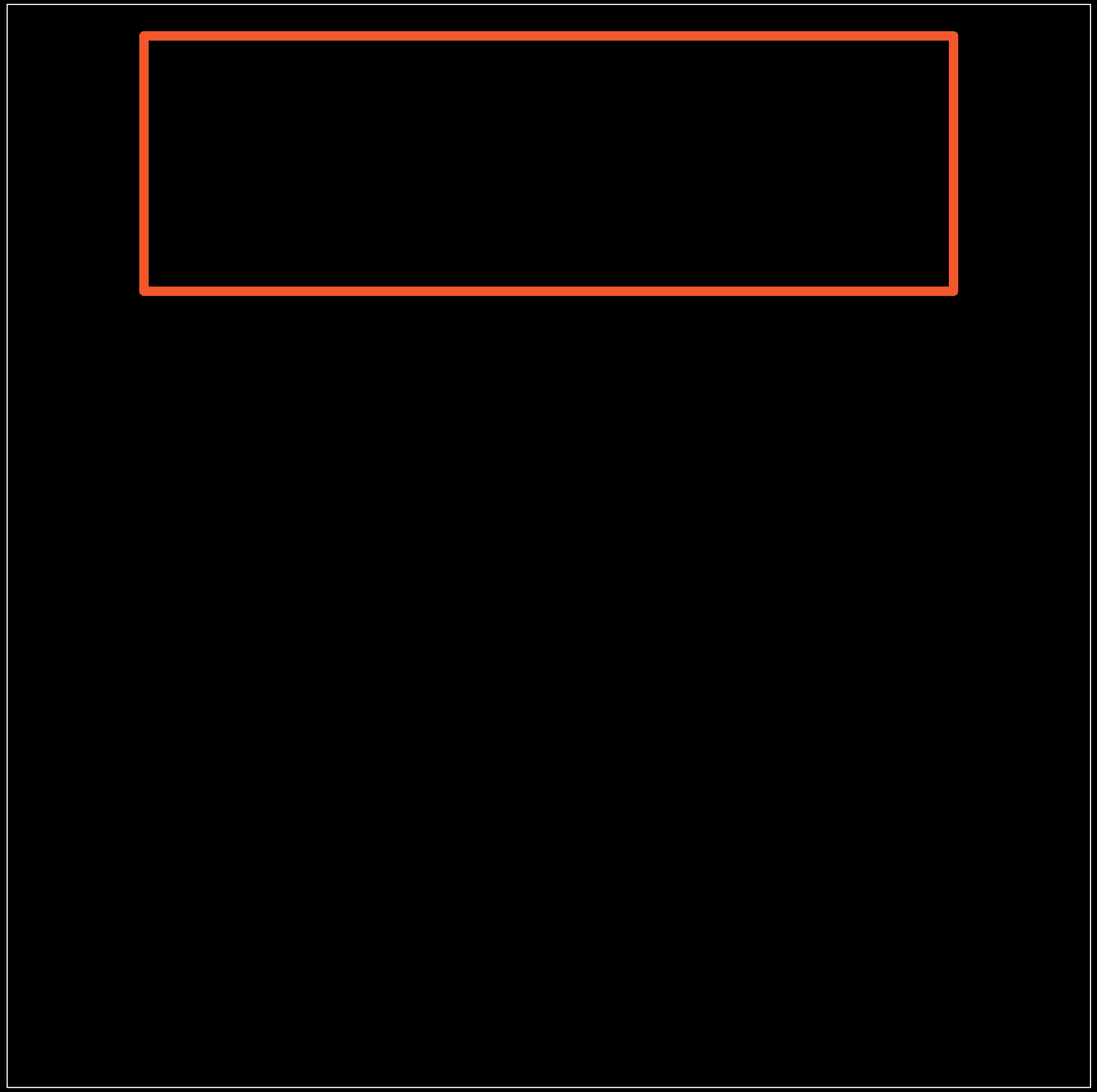
(Ours)

Cornell Box

Progressive Transient Photon Beam
(Prev)

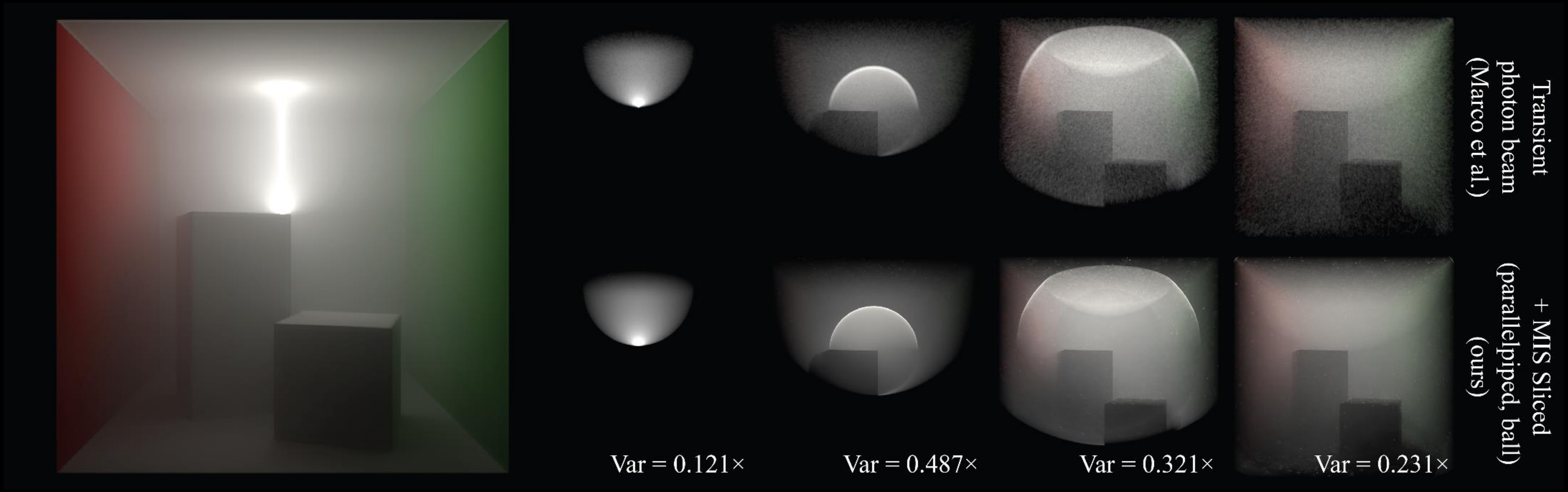


MIS Sliced (Parallelepiped, Ball)
(Ours)



Cornell Box

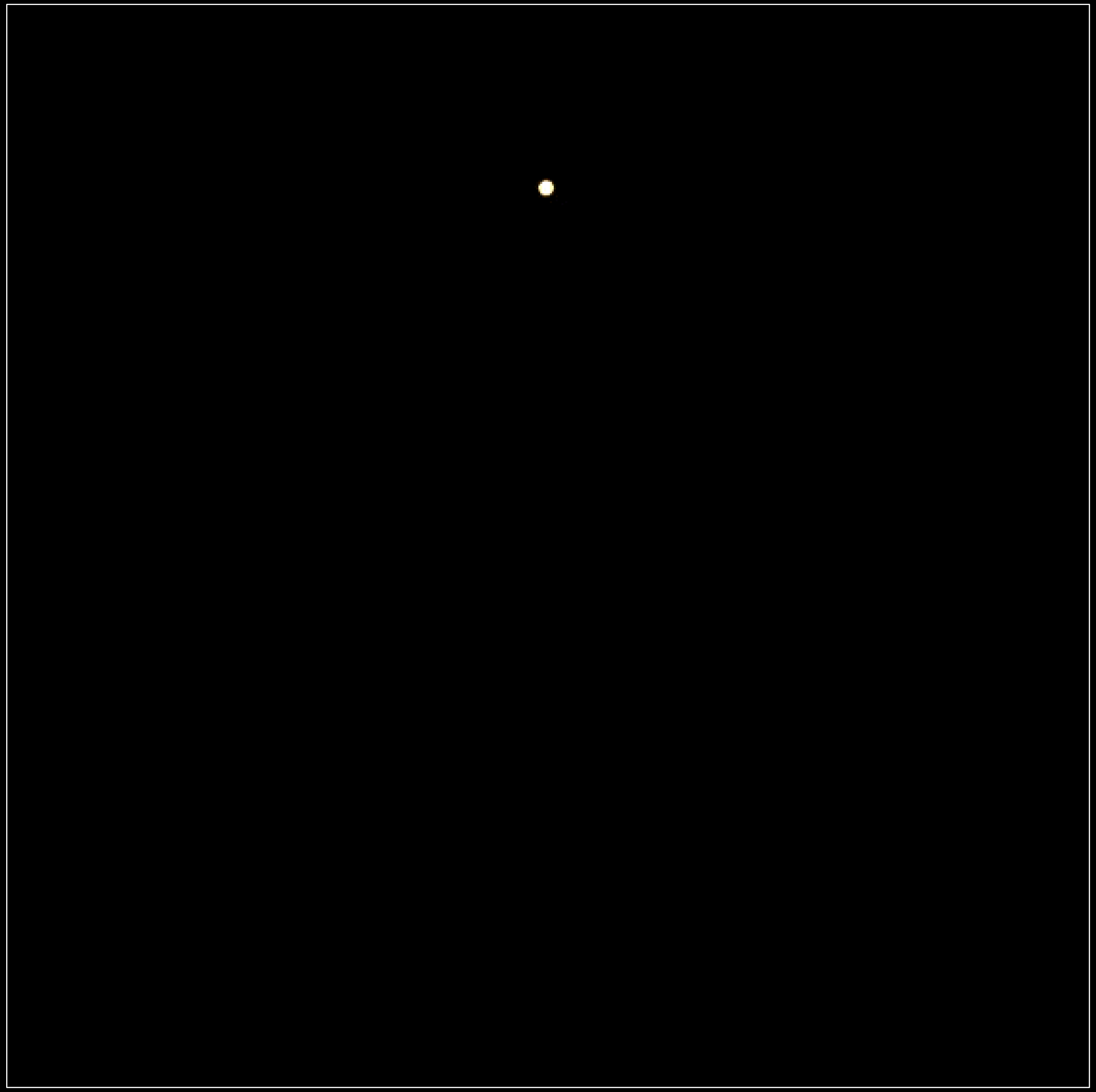
(Prev)



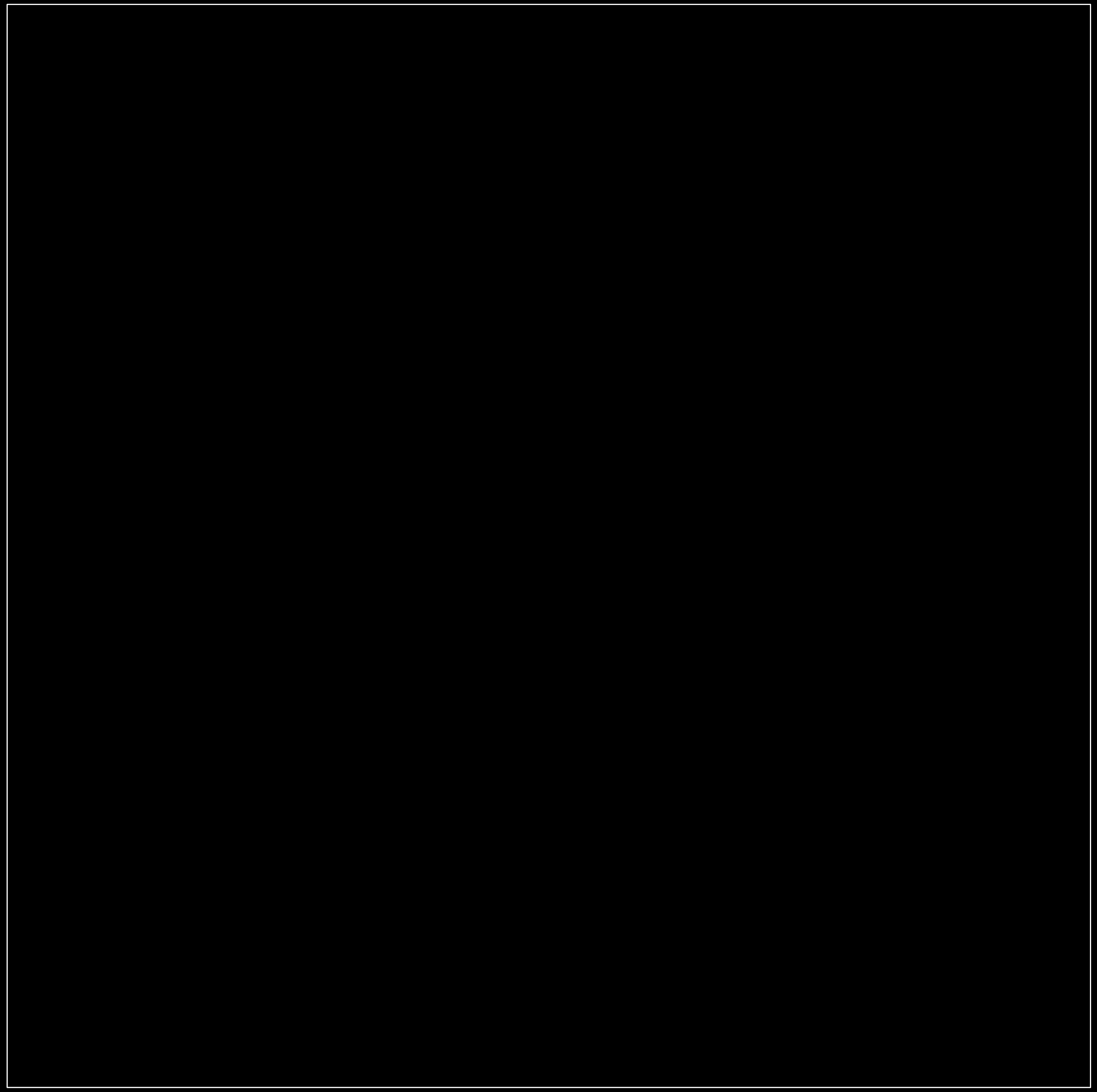
(Ours)

Volumetric Caustic

Progressive Transient Photon Beam
(**Prev**)

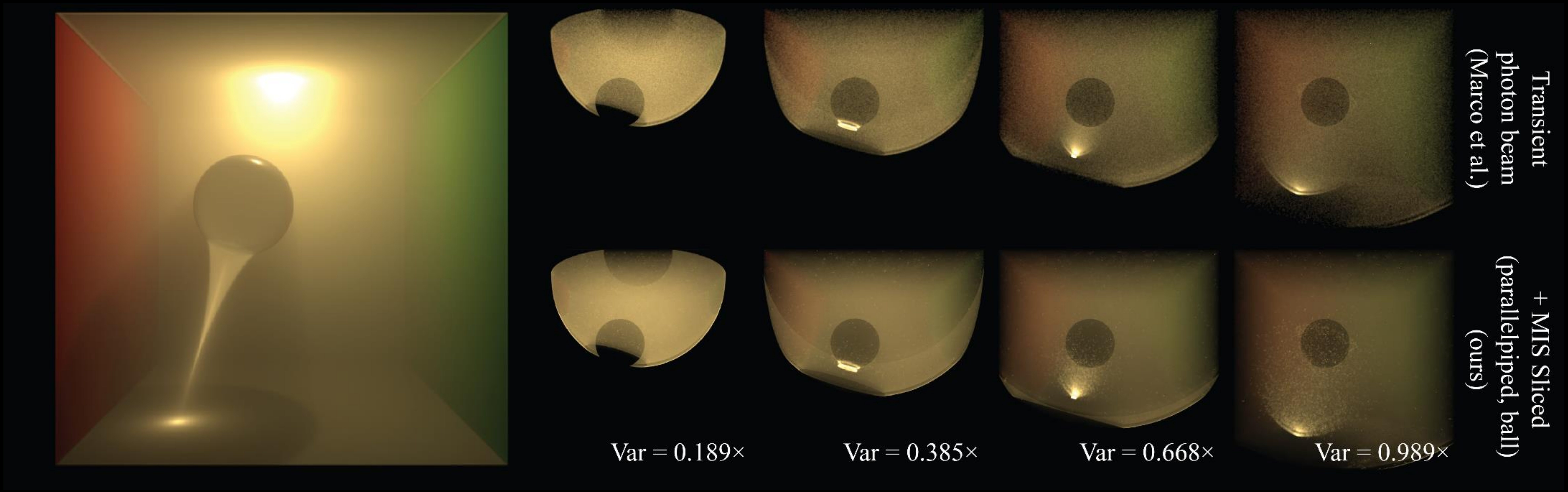


+ MIS Sliced (Parallelepiped, Ball)
(**Ours**)



Volumetric Caustic

(Prev)



(Ours)

Conclusion

- We lay the foundation for **accelerating volumetric time-of-flight rendering** by introducing:
  - A novel extended spatio-temporal path space **formulation** of the problem
  - A **recipe** for deriving and combining a new family of estimators

Thank you!