

Monte Carlo Methods for Volumetric Light Transport Simulation

Advanced methods



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DARTMOUTH
VISUAL COMPUTING LAB

Advanced methods

Photon tracing/mapping

Many-light methods

Combining techniques

Radiance caching

Advanced methods

Photon tracing/mapping

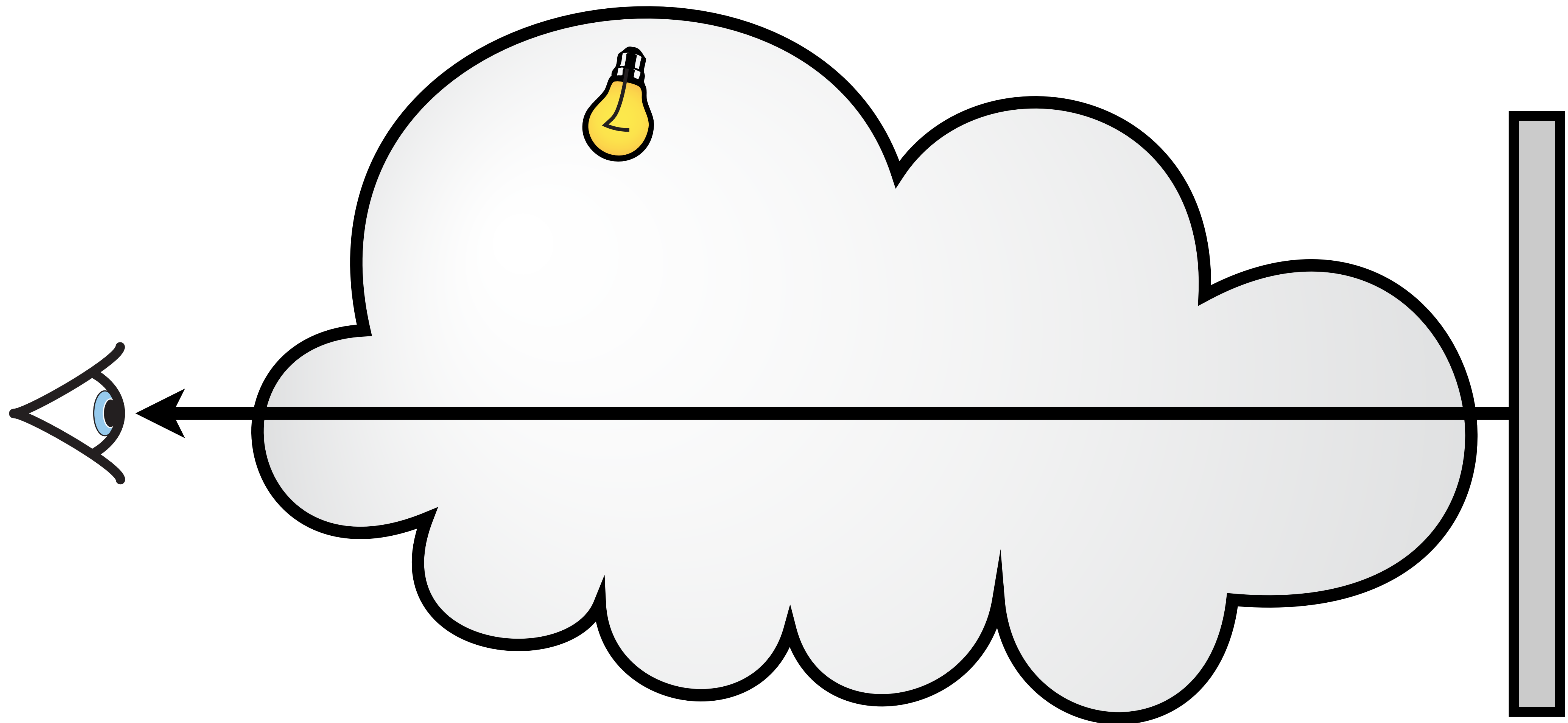
Many-light methods

Combining techniques

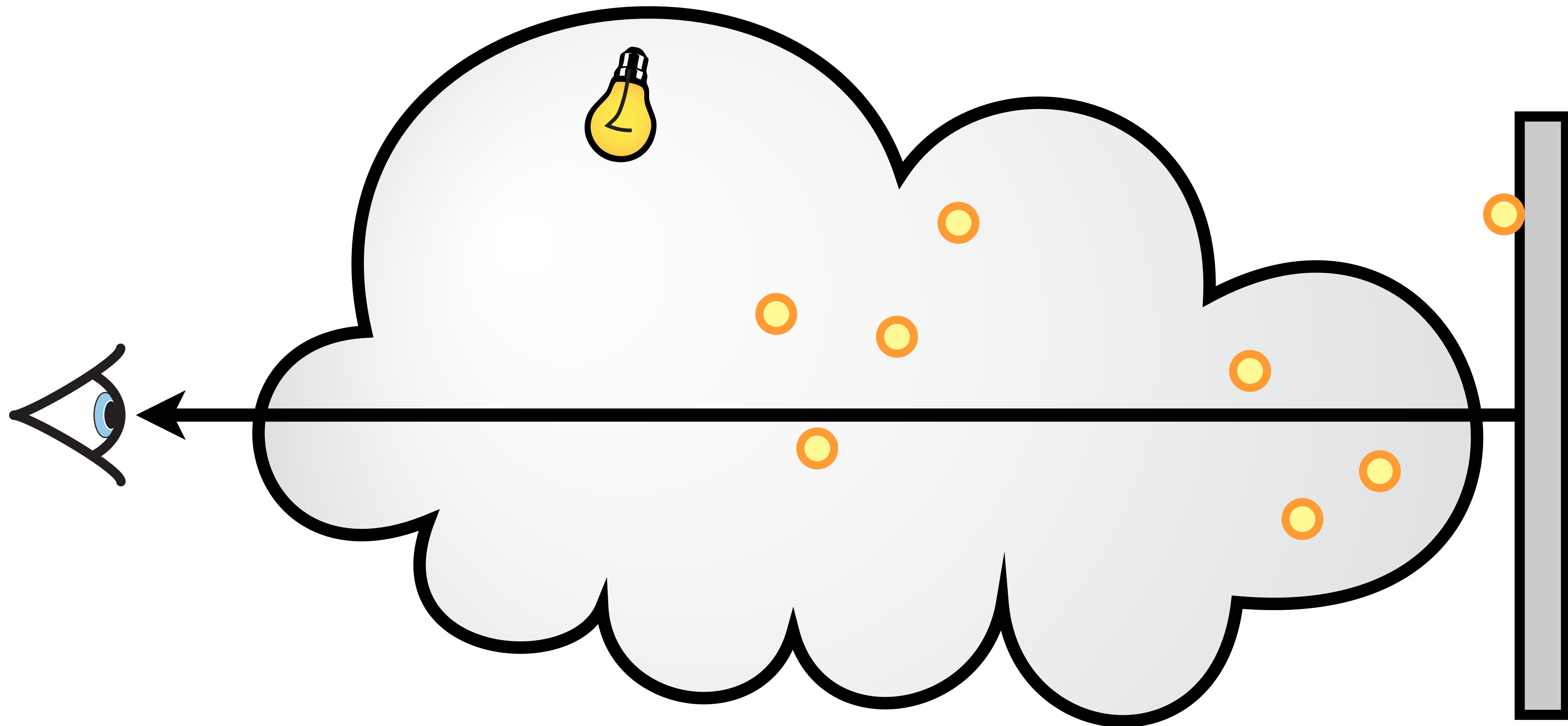
Radiance caching

More from Johannes...

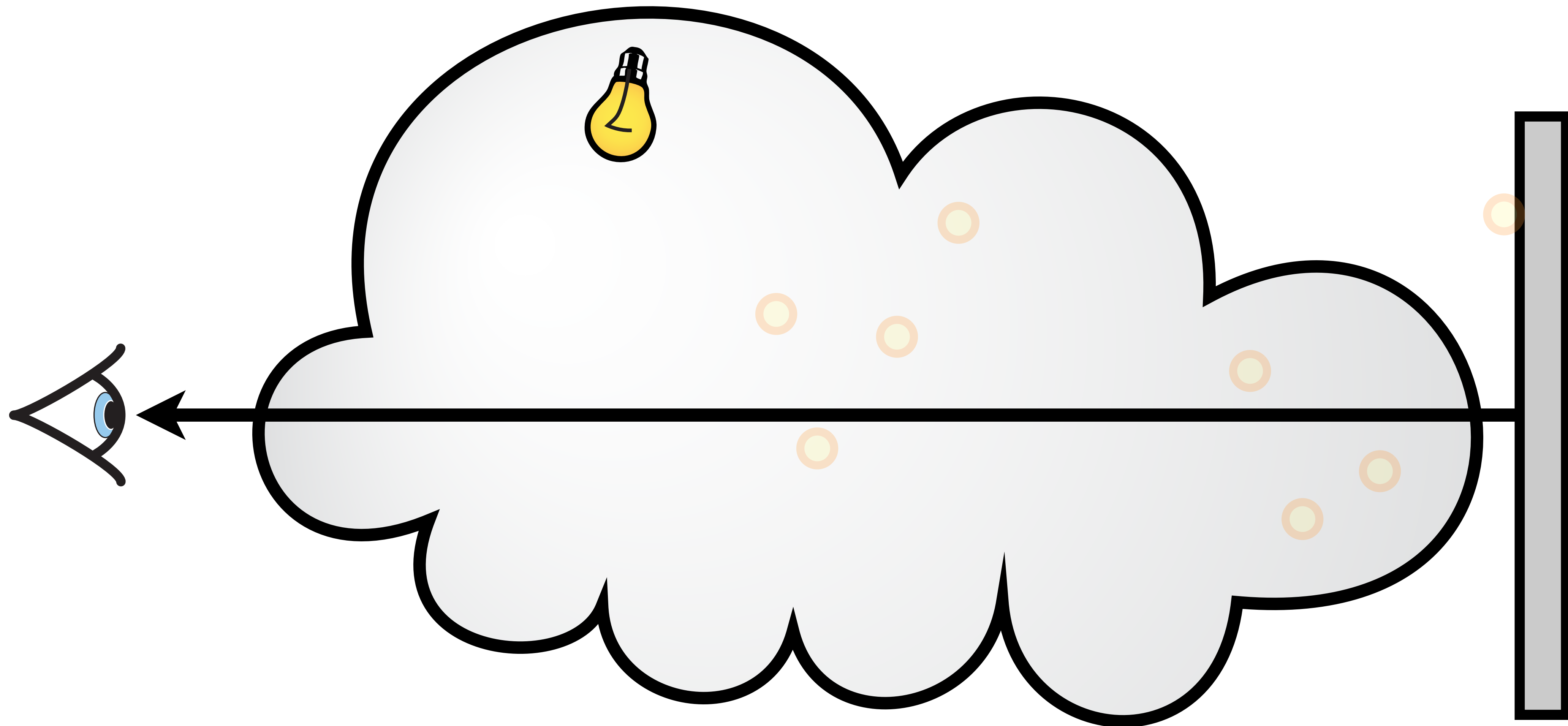
Photon Tracing in Participating Media



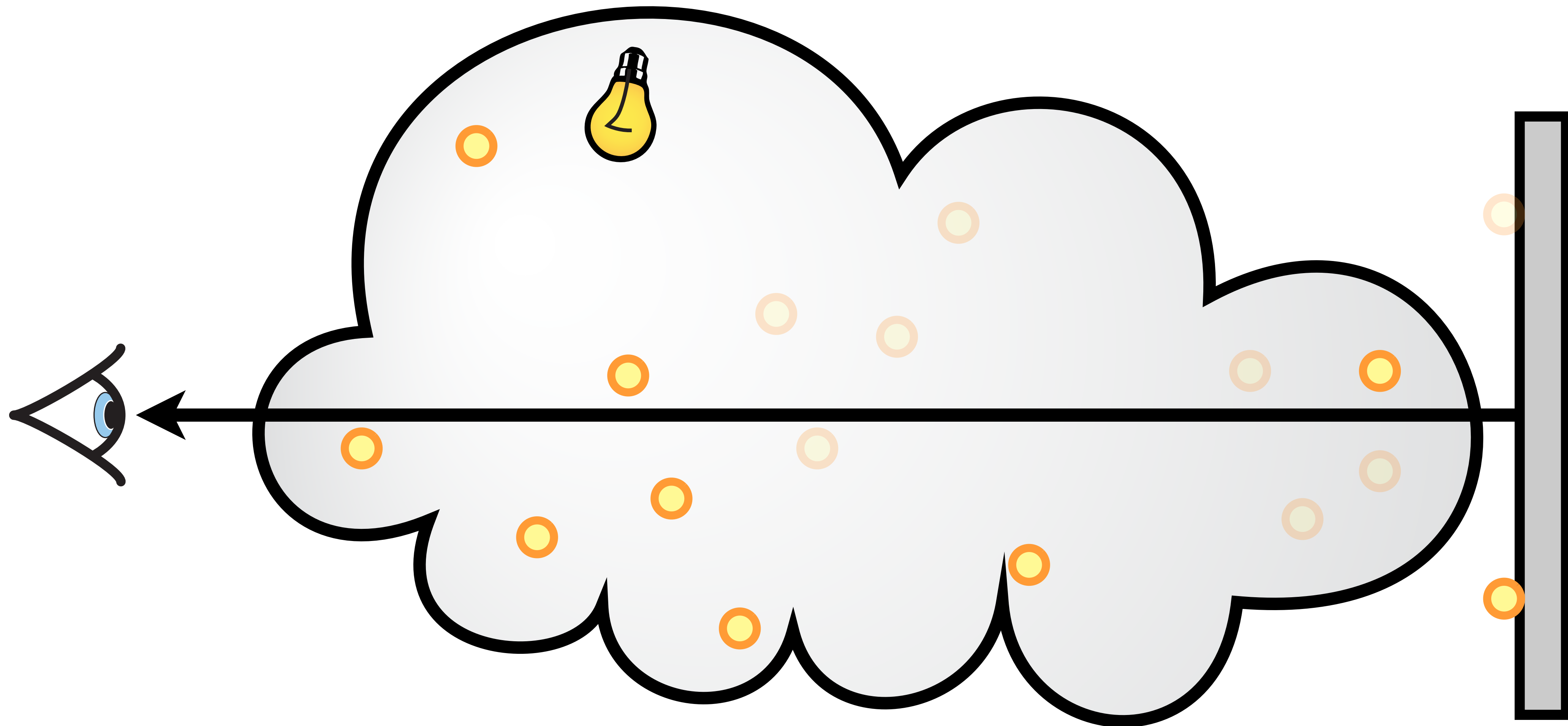
Photon Tracing in Participating Media



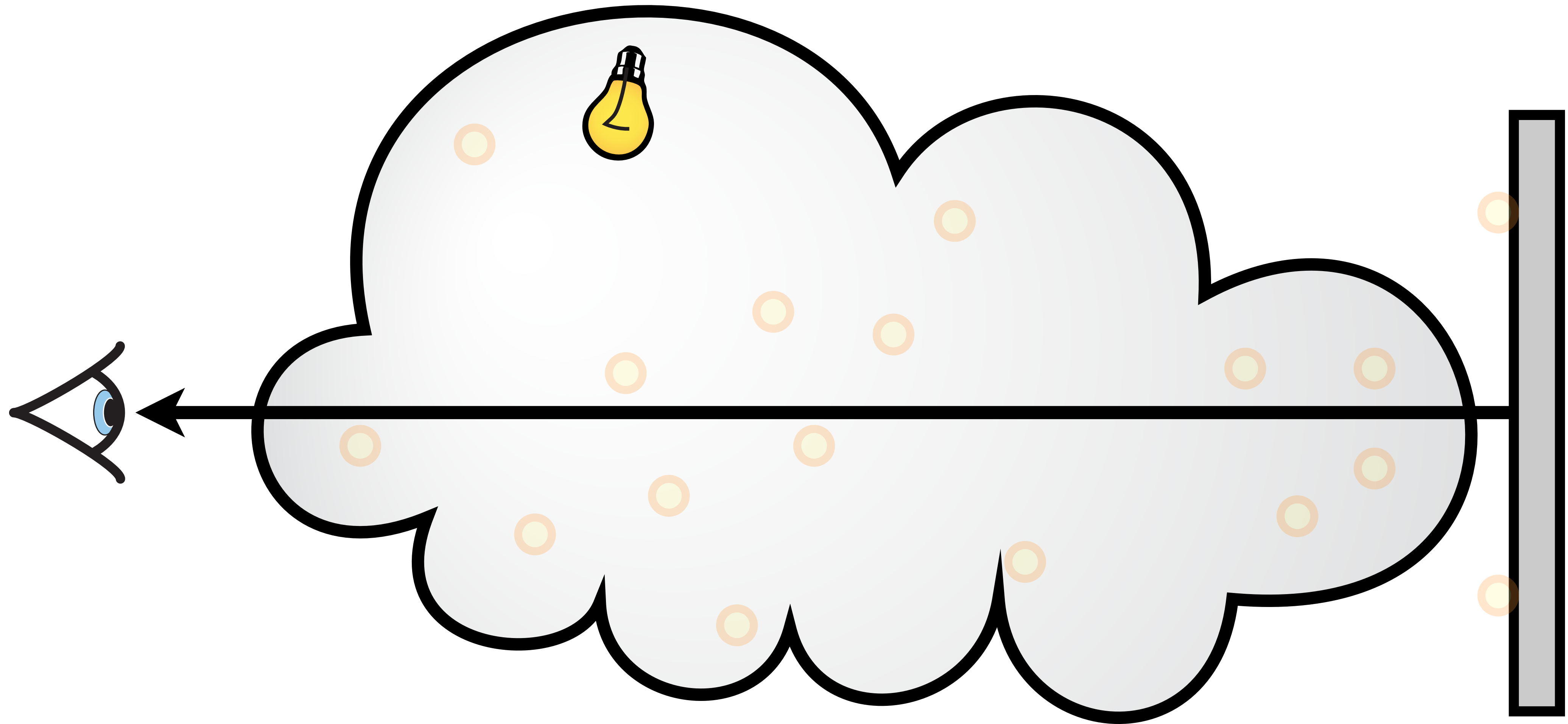
Photon Tracing in Participating Media



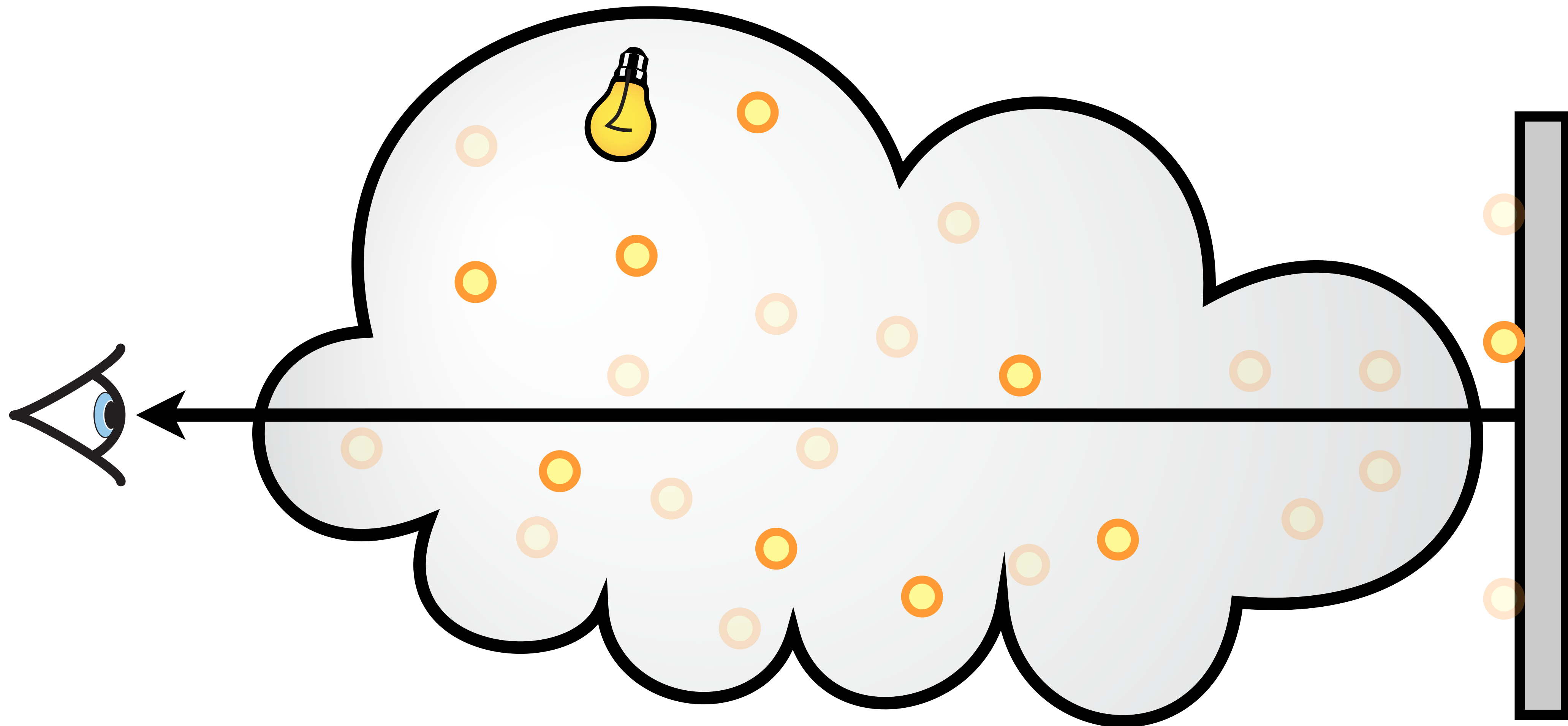
Photon Tracing in Participating Media



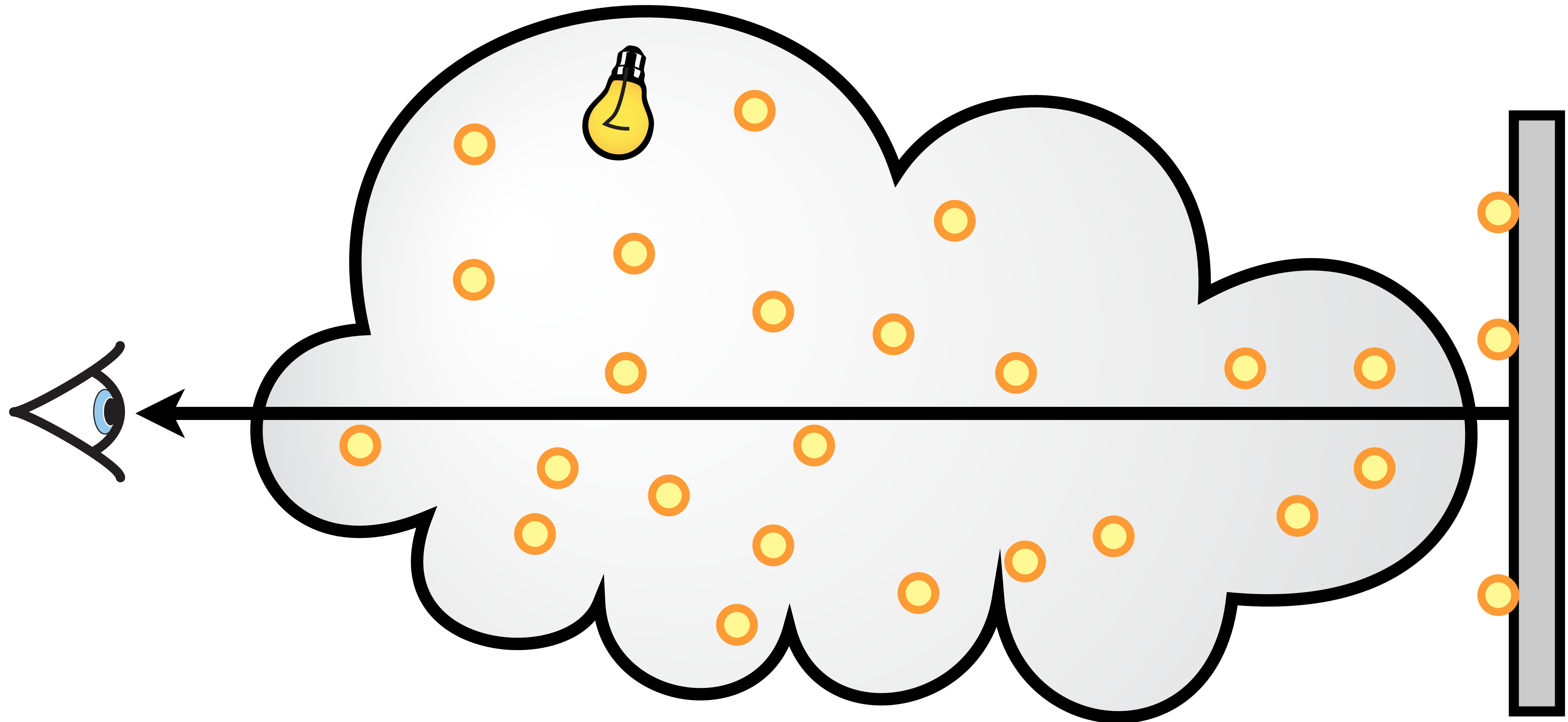
Photon Tracing in Participating Media



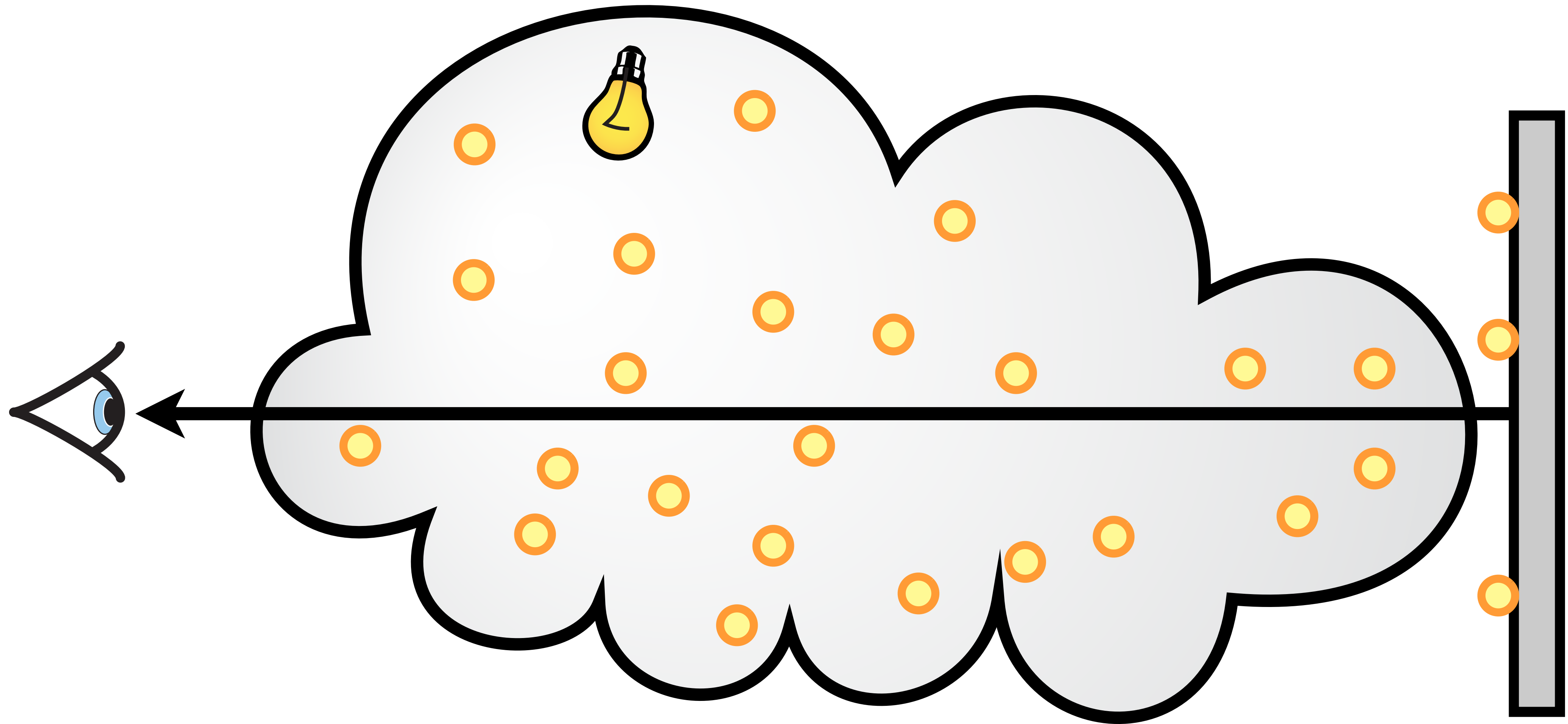
Photon Tracing in Participating Media



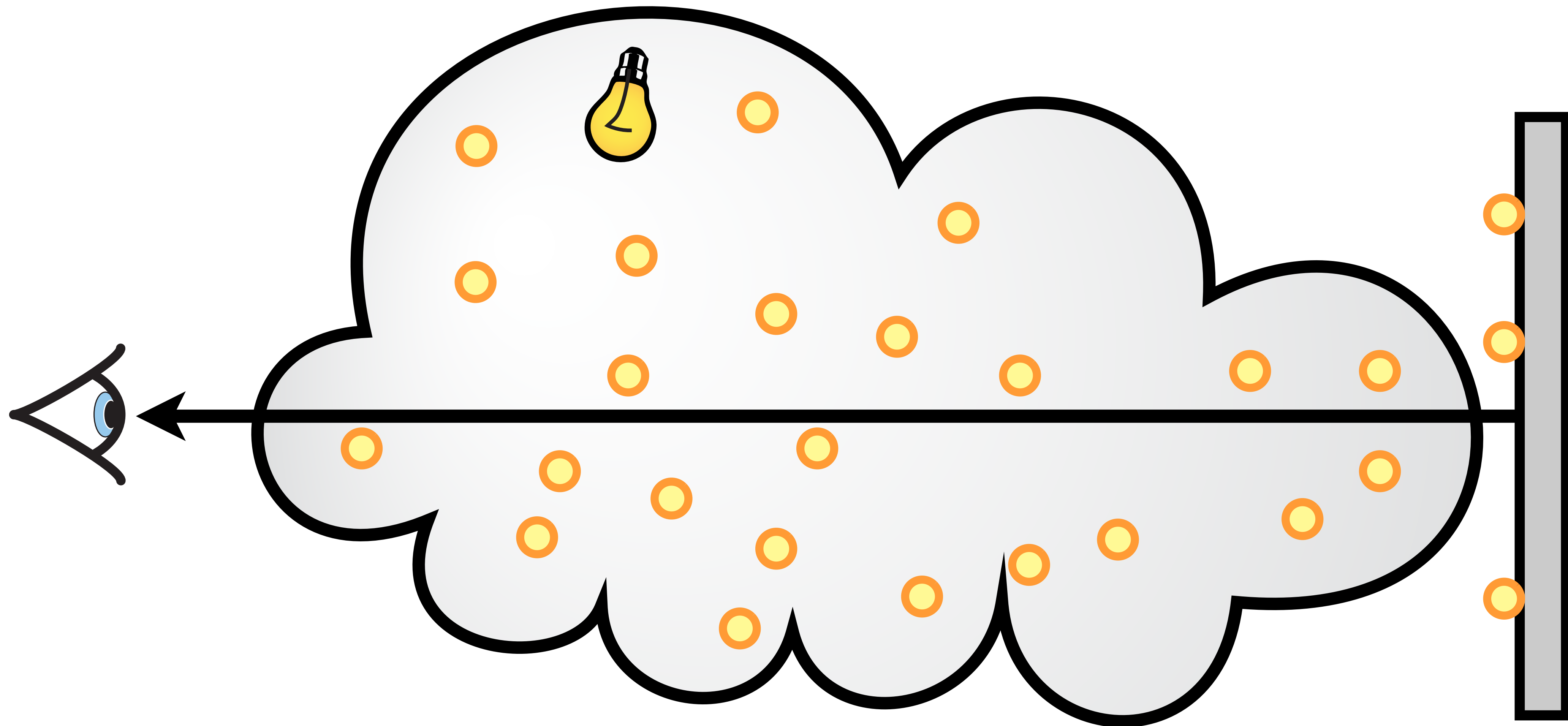
Photon Tracing in Participating Media



Photon Tracing in Participating Media

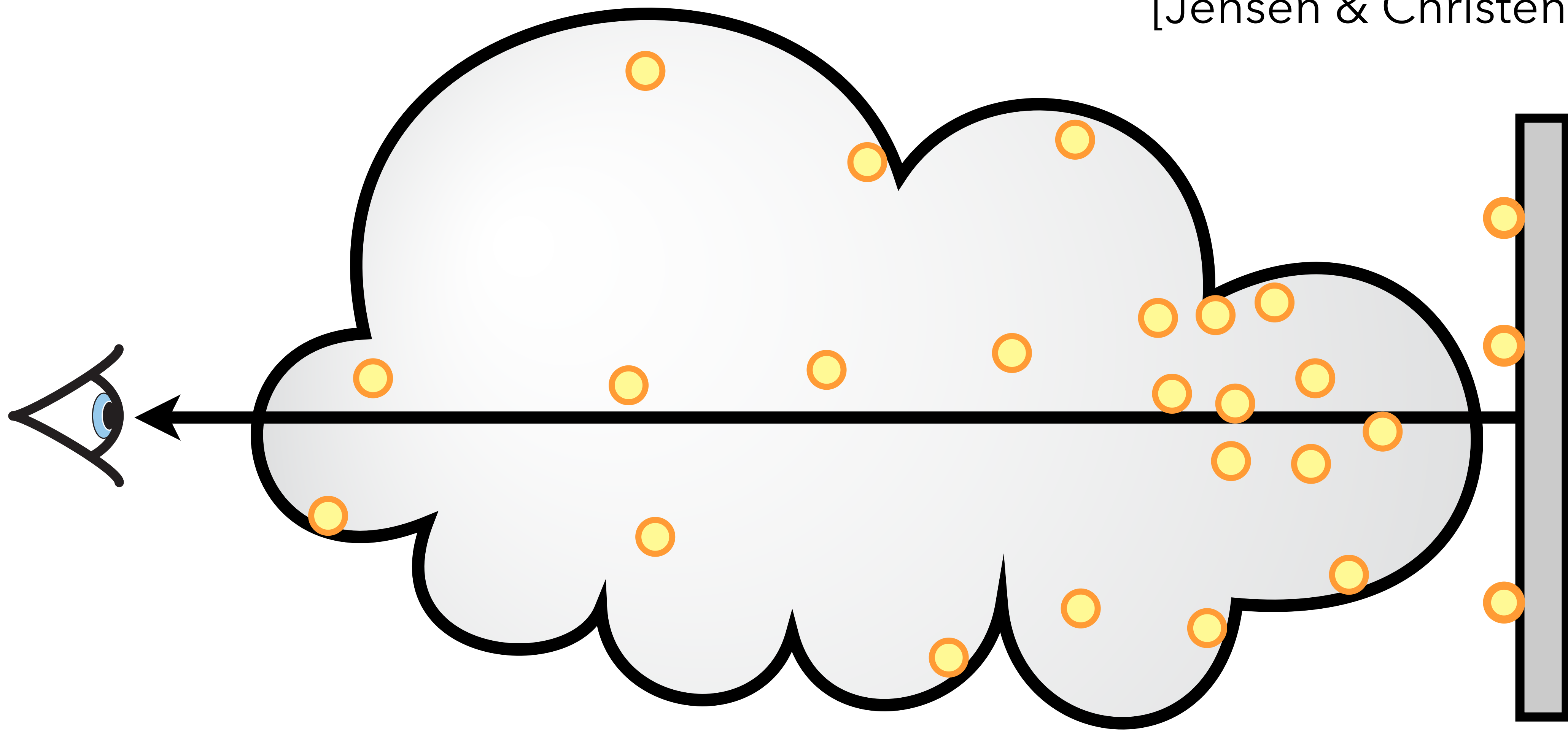


Photon Tracing in Participating Media



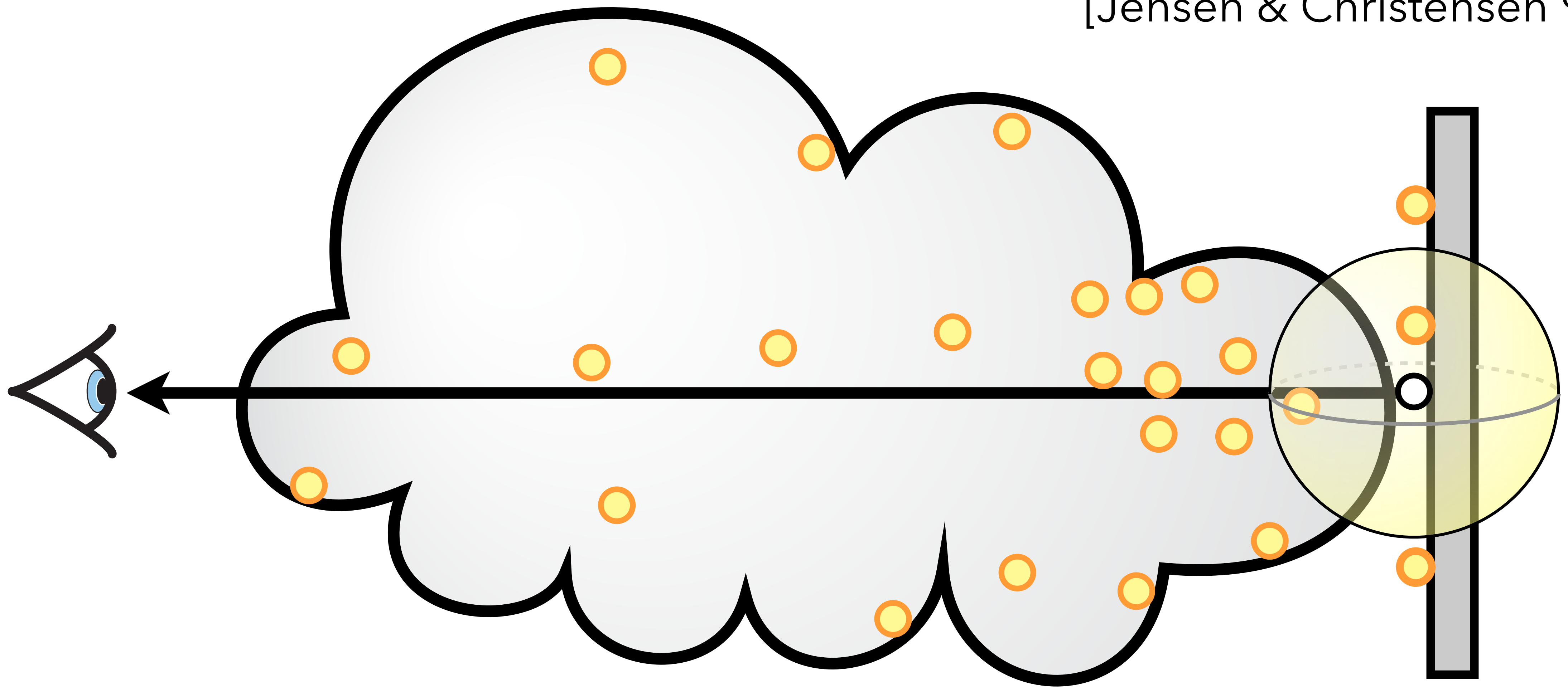
Radiance estimation

[Jensen & Christensen 98]



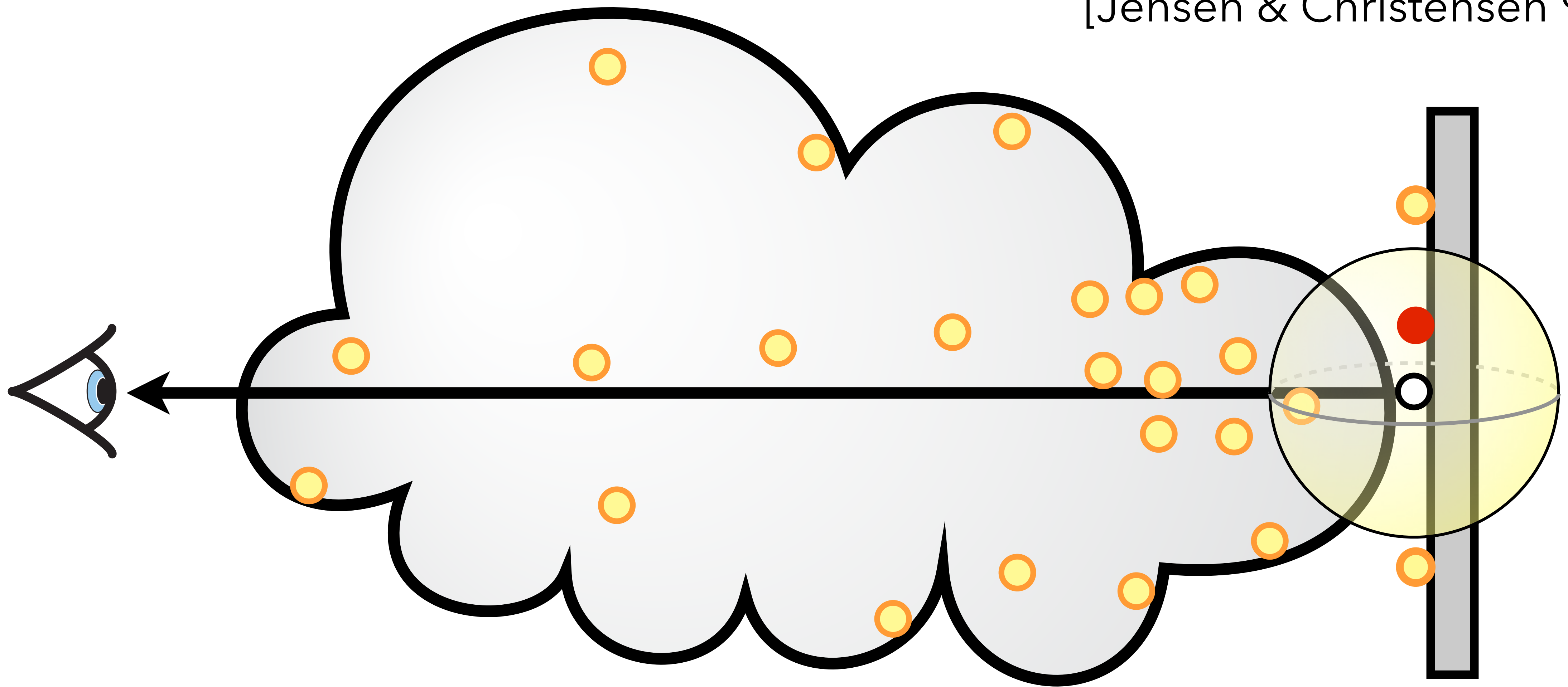
Radiance estimation

[Jensen & Christensen 98]



Radiance estimation

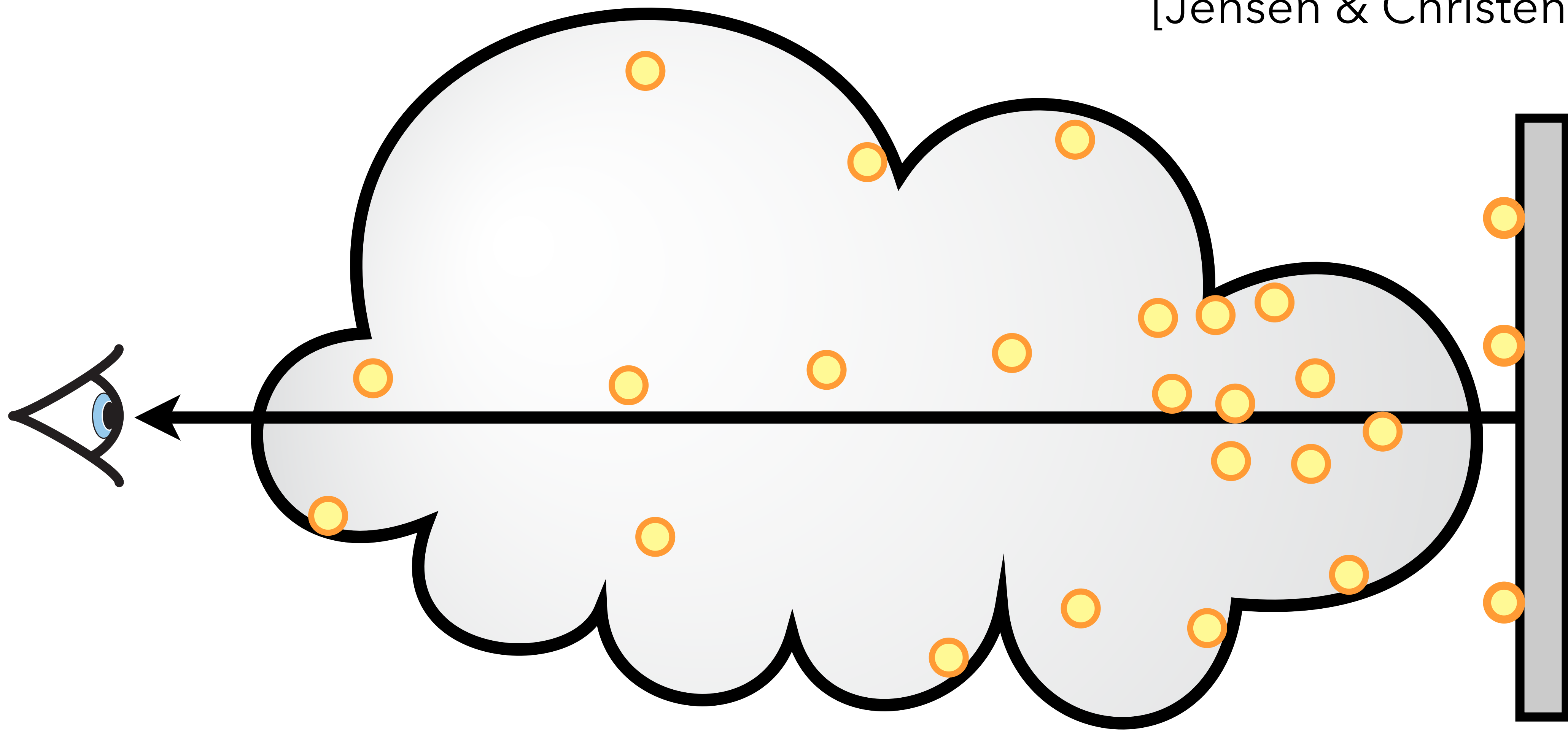
[Jensen & Christensen 98]



Density/radiance estimation on surface

Radiance estimation

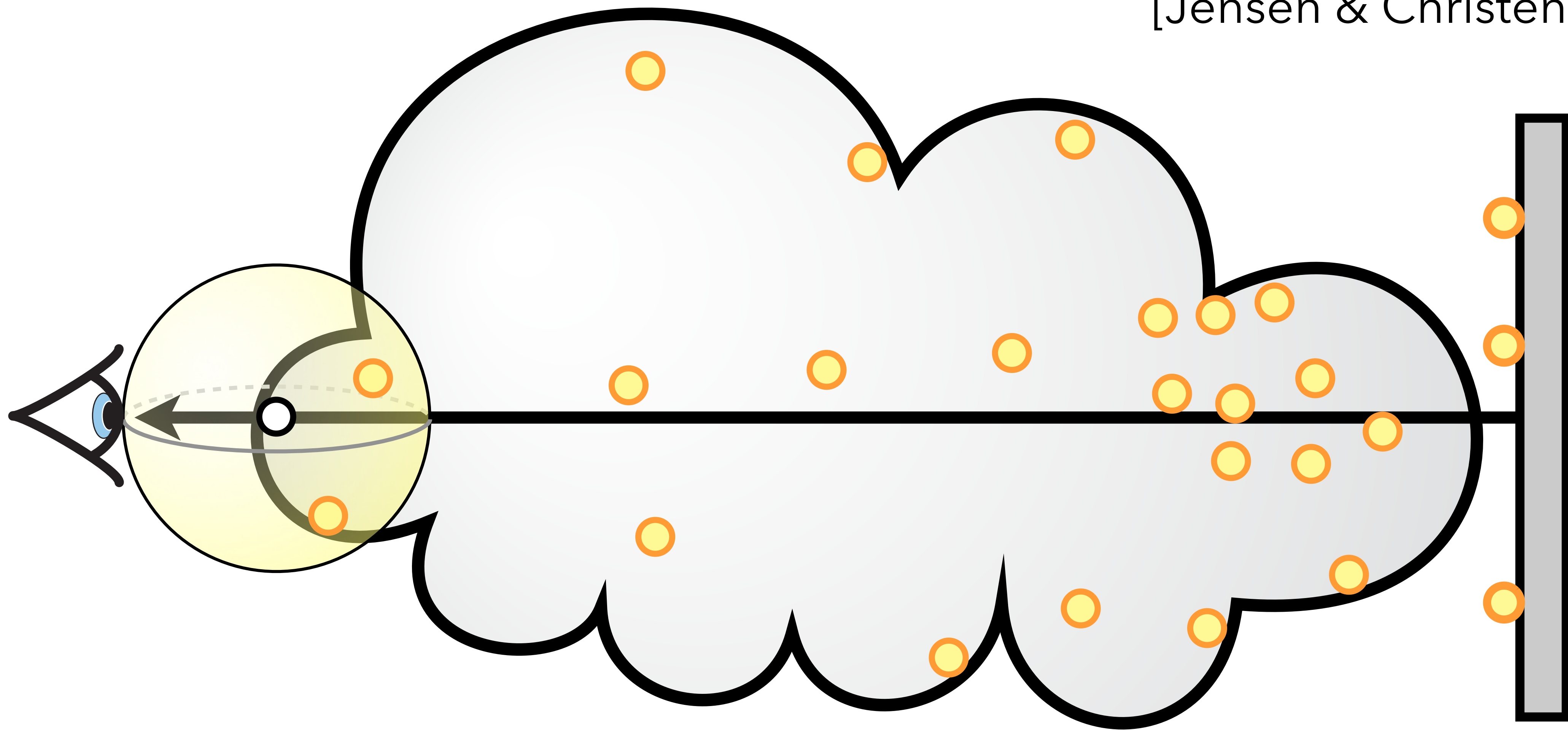
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

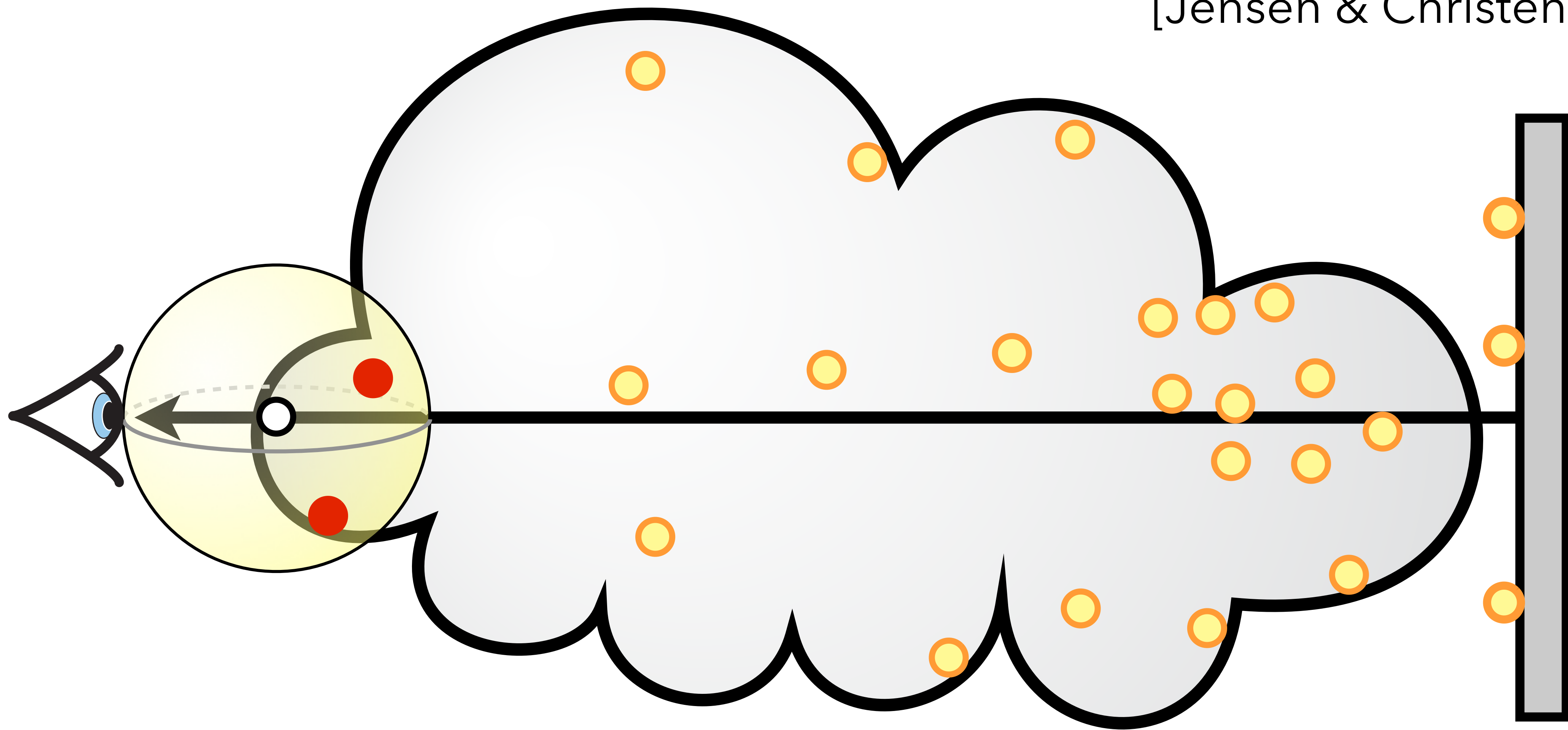
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

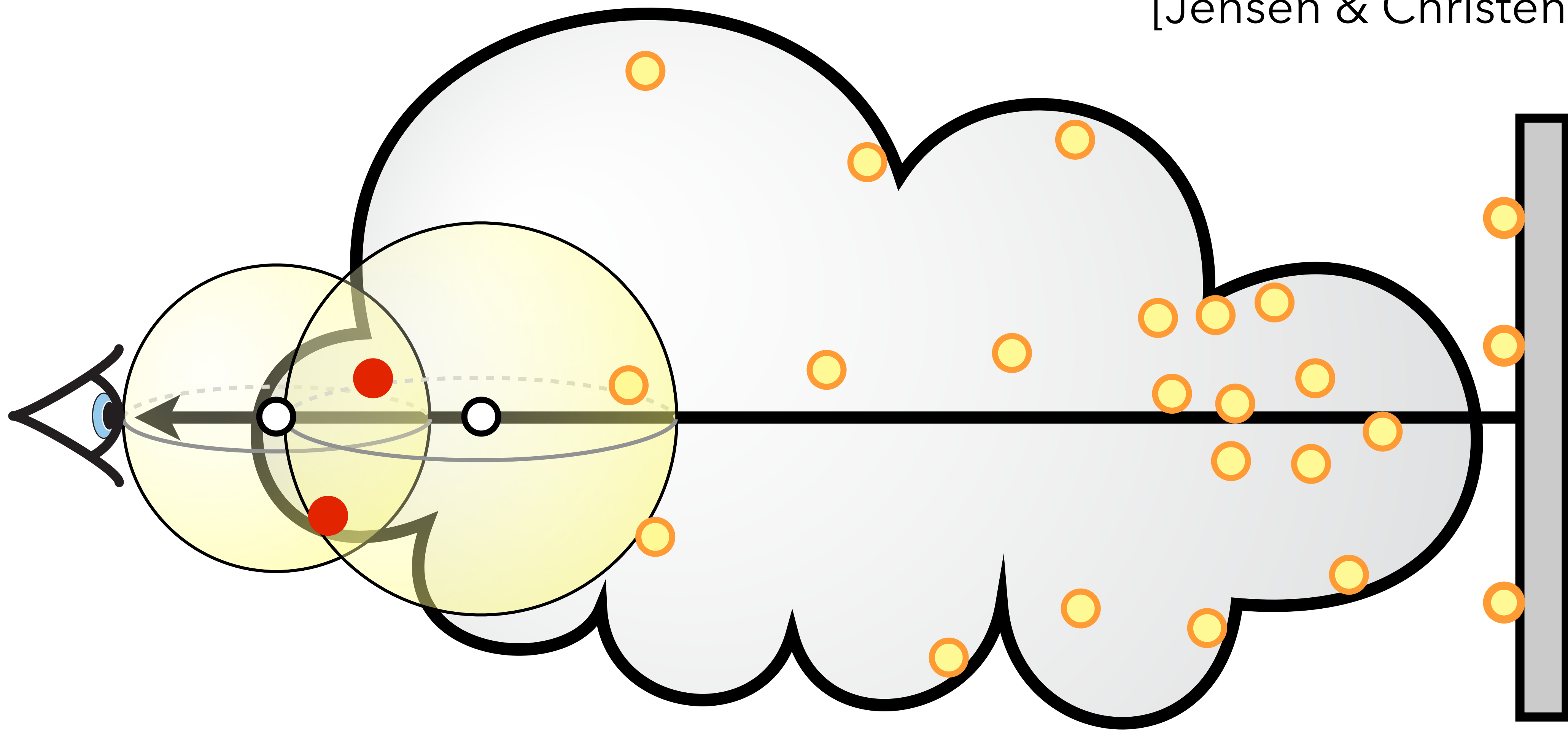
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

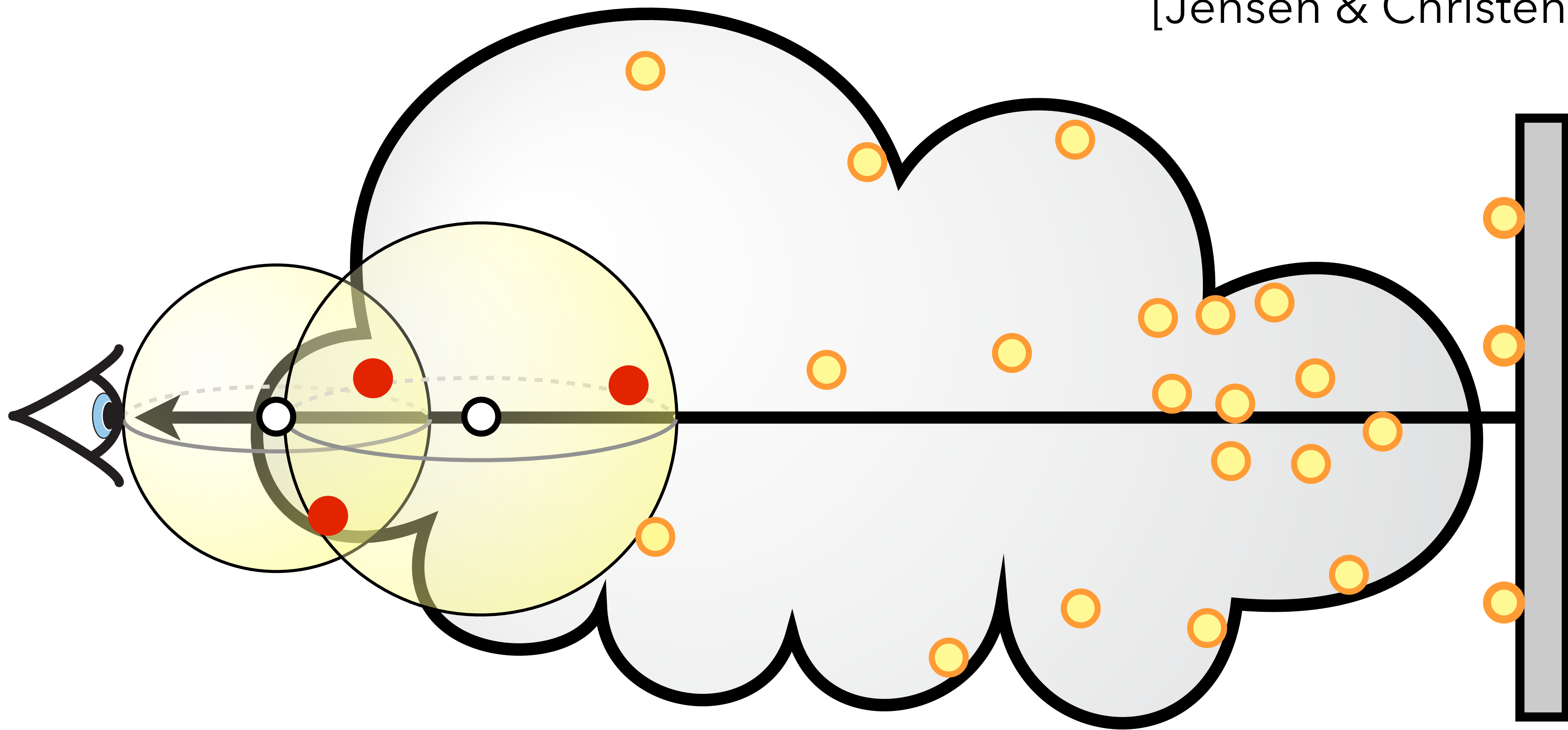
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

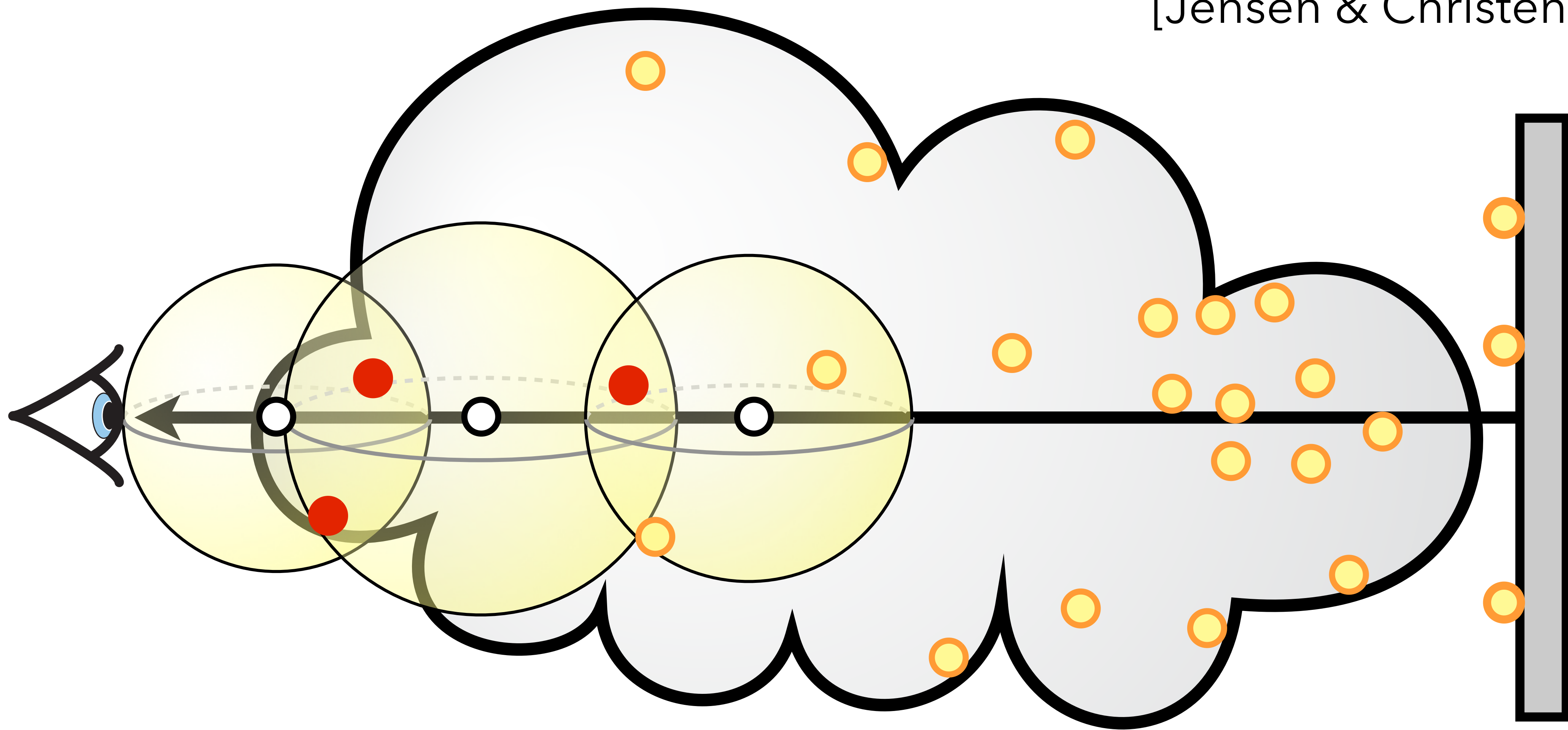
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

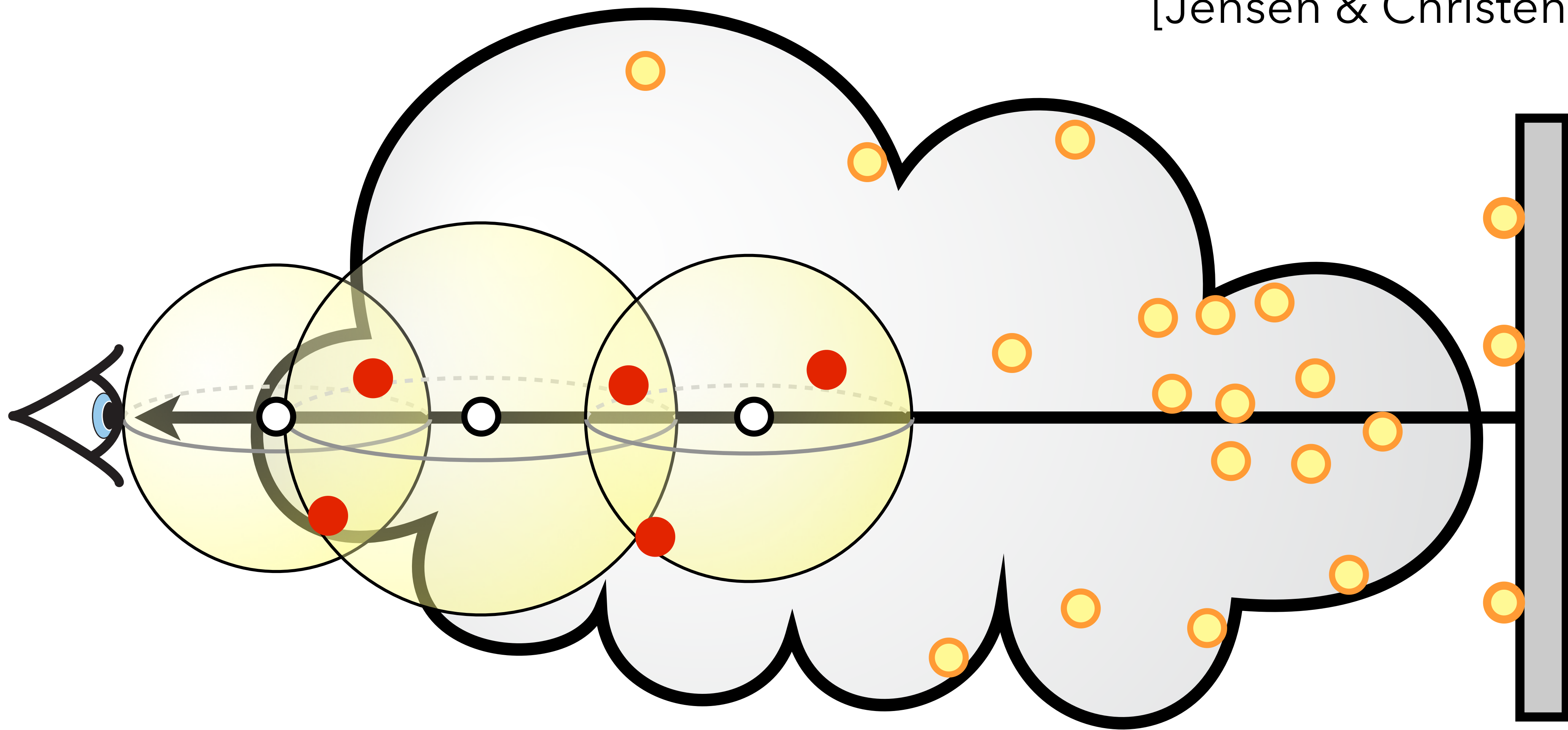
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

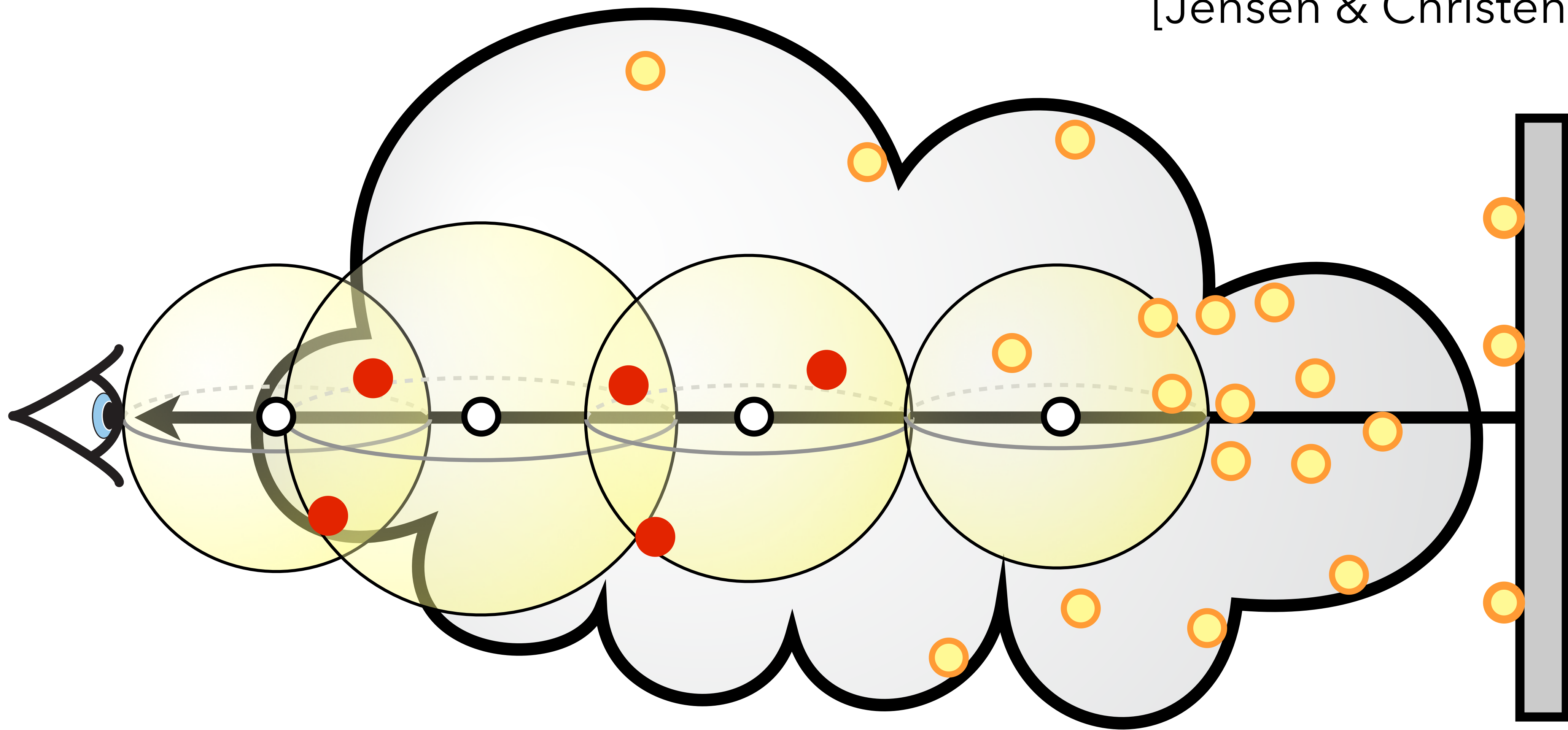
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

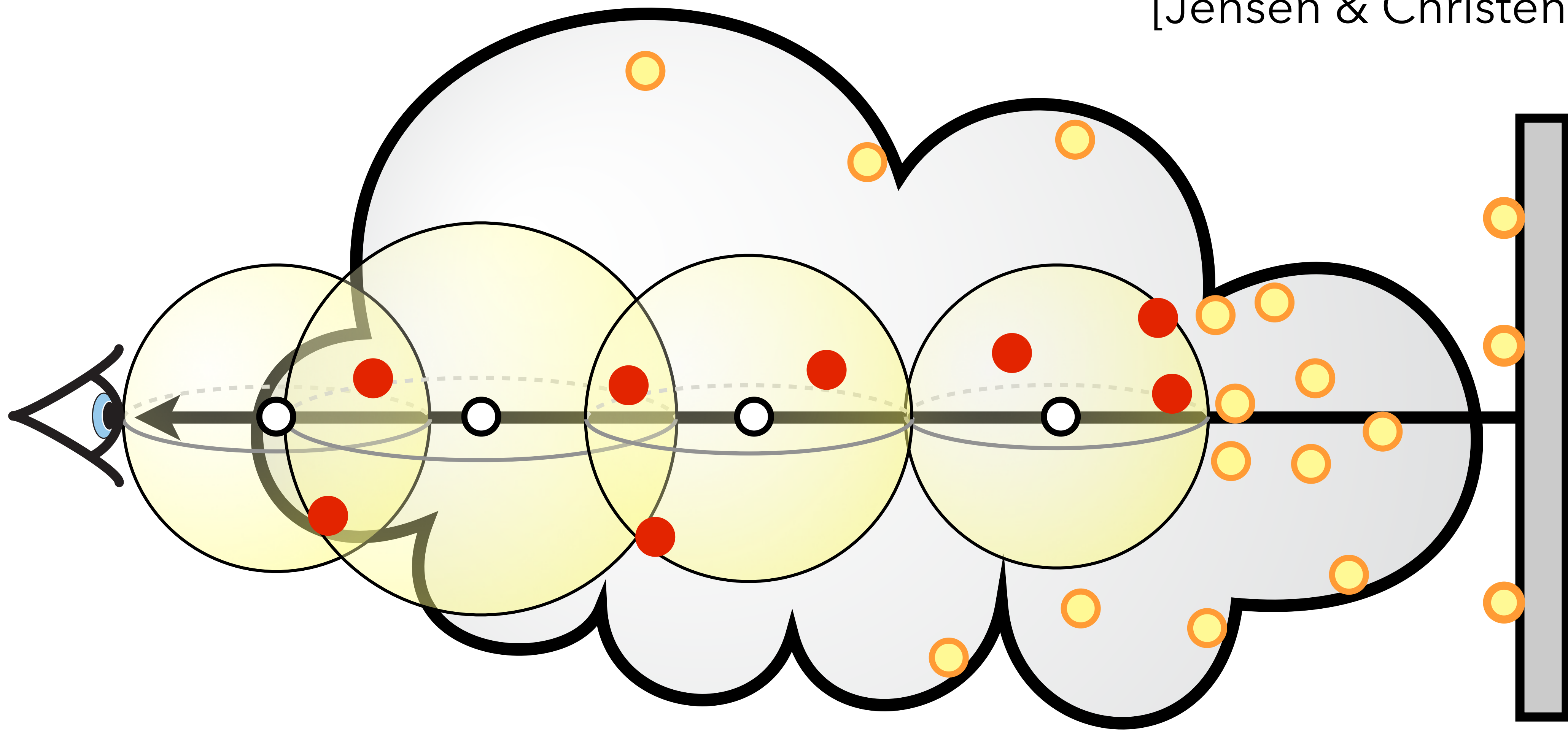
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

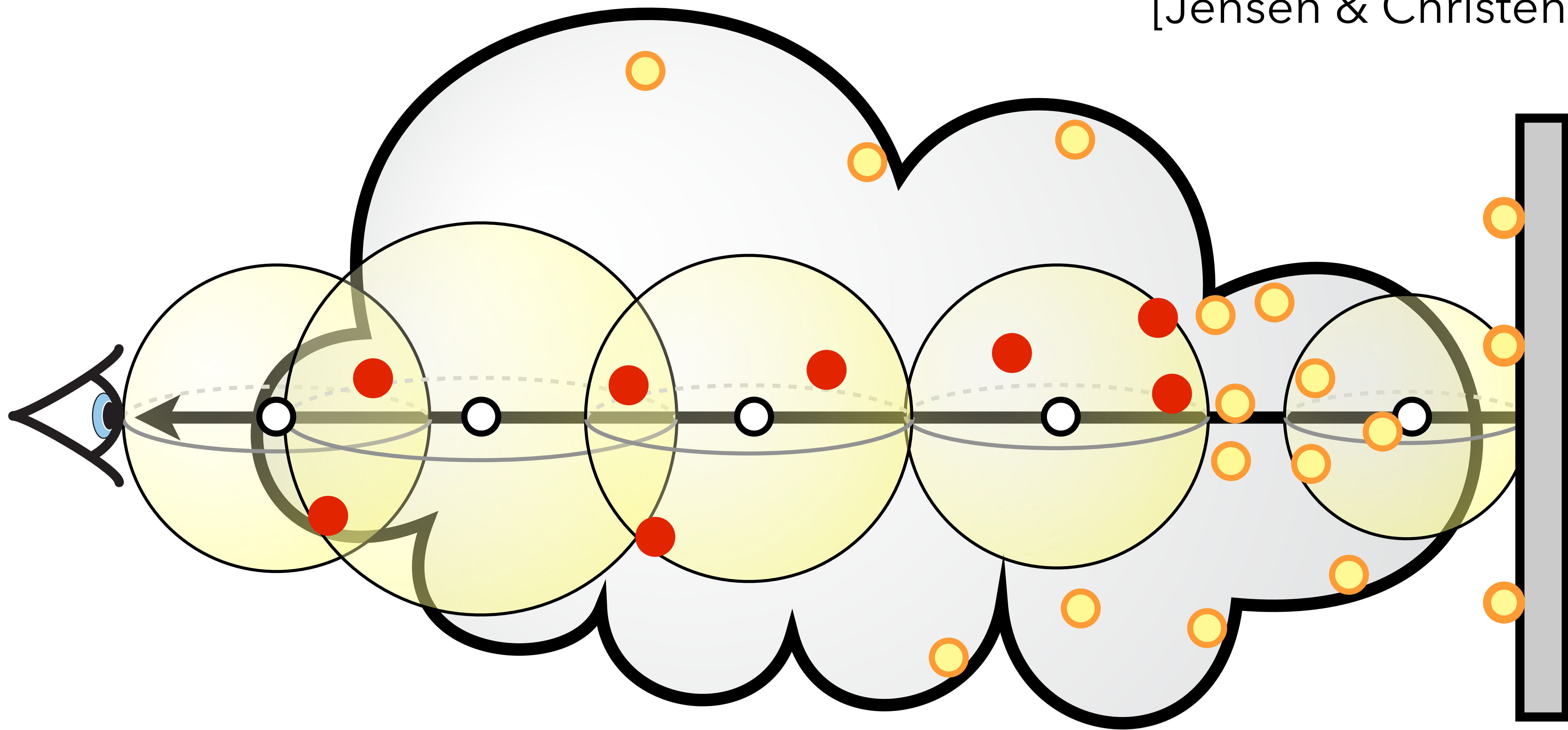
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

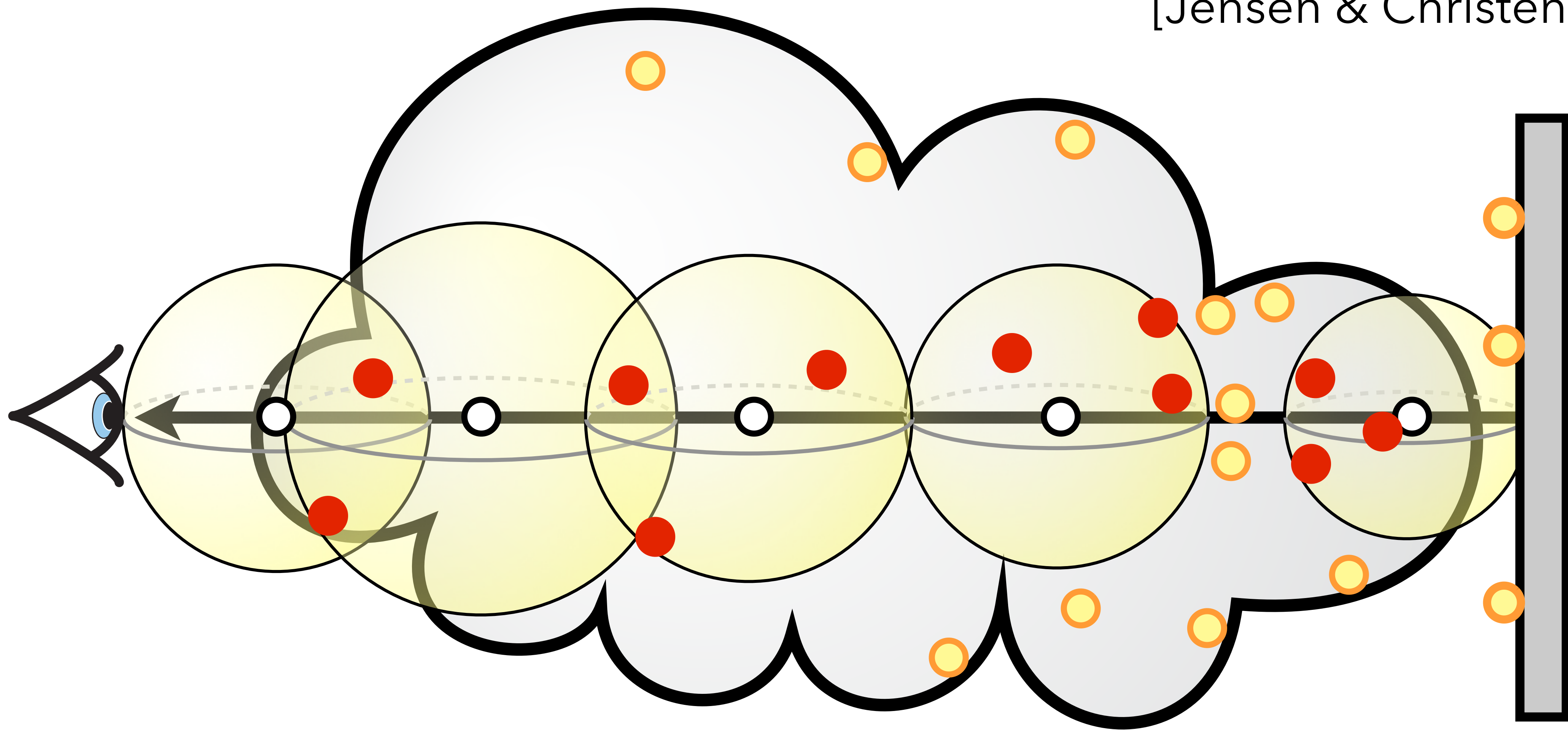
[Jensen & Christensen 98]



Density estimation as you ray march

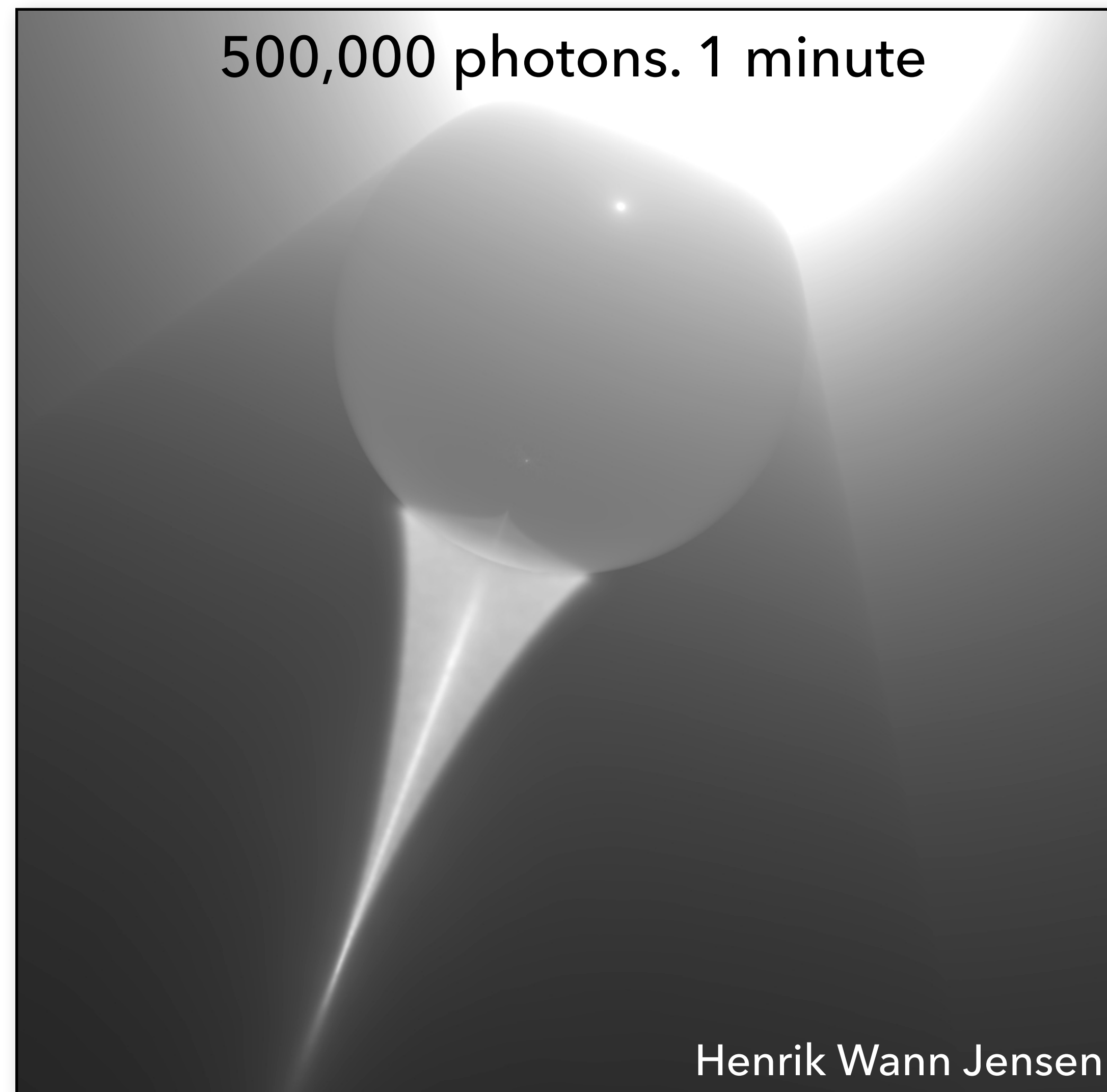
Radiance estimation

[Jensen & Christensen 98]



Density estimation as you ray march

A Volume Caustic

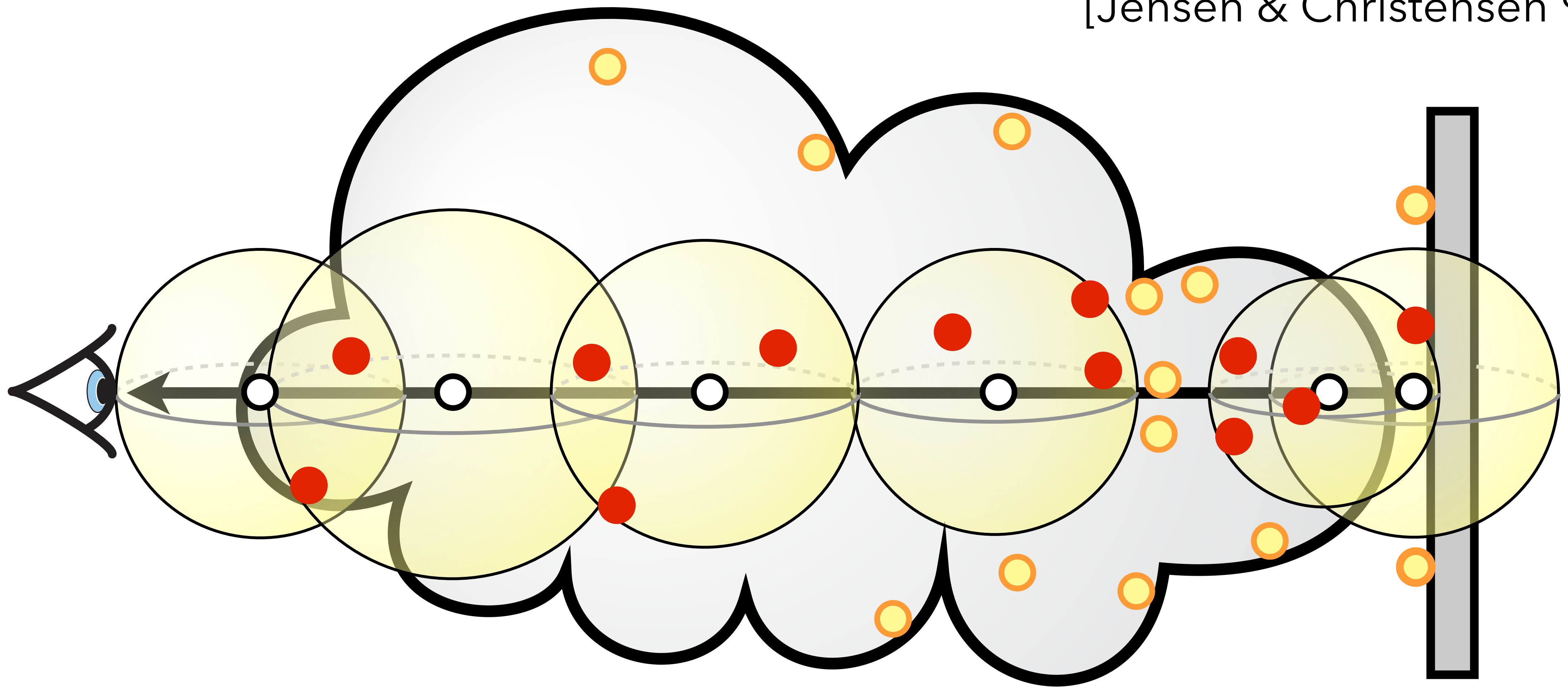


Subsurface Scattering



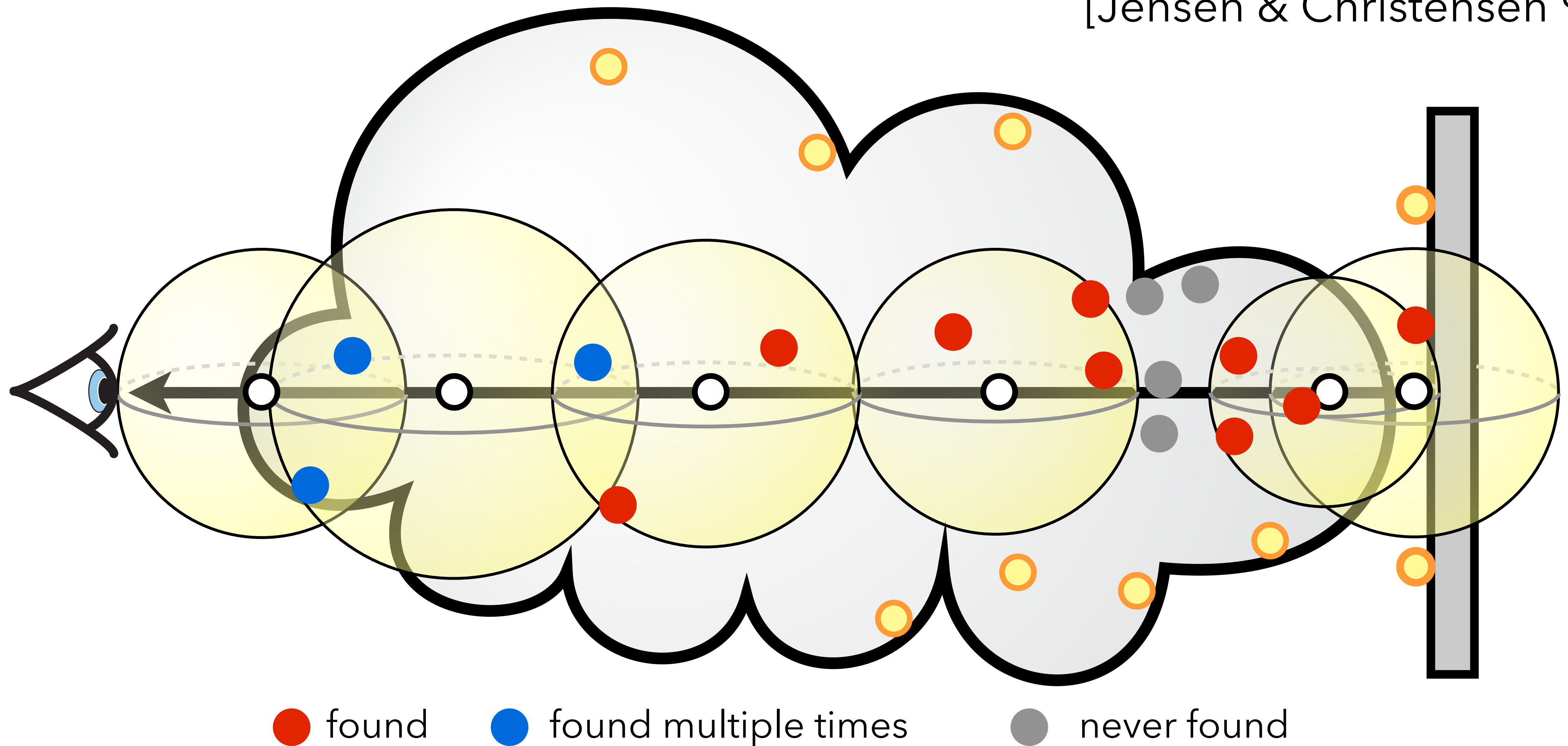
Radiance estimation

[Jensen & Christensen 98]



Radiance estimation

[Jensen & Christensen 98]



Drawbacks

[Jensen & Christensen 98]

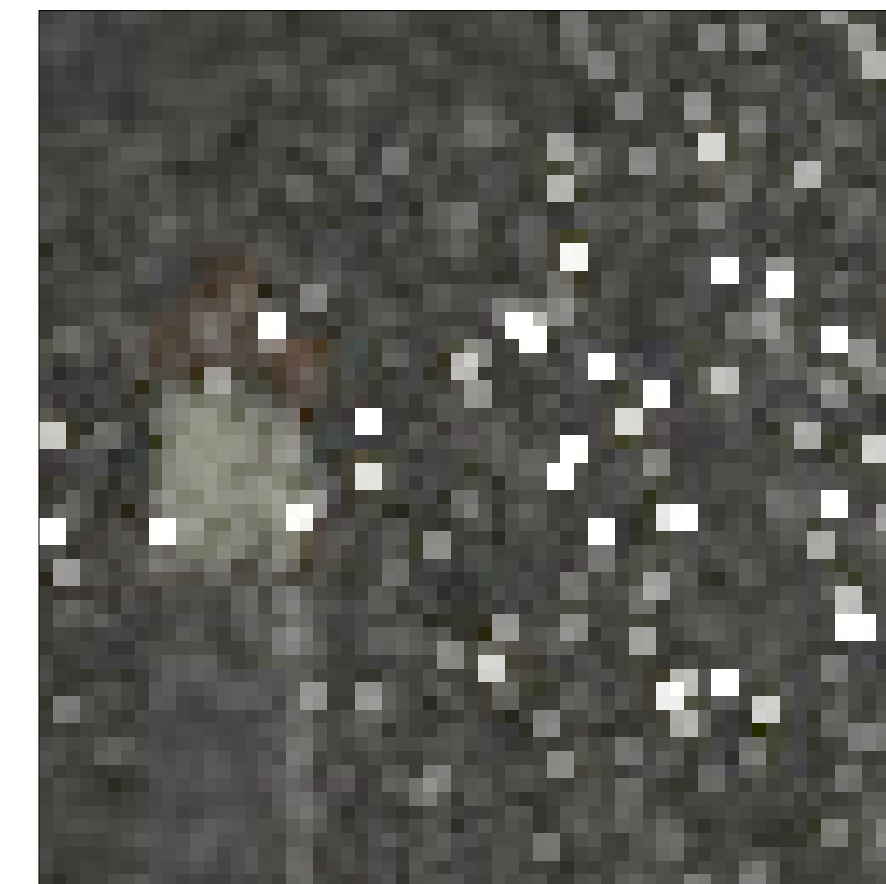
Large Step-size



Drawbacks

[Jensen & Christensen 98]

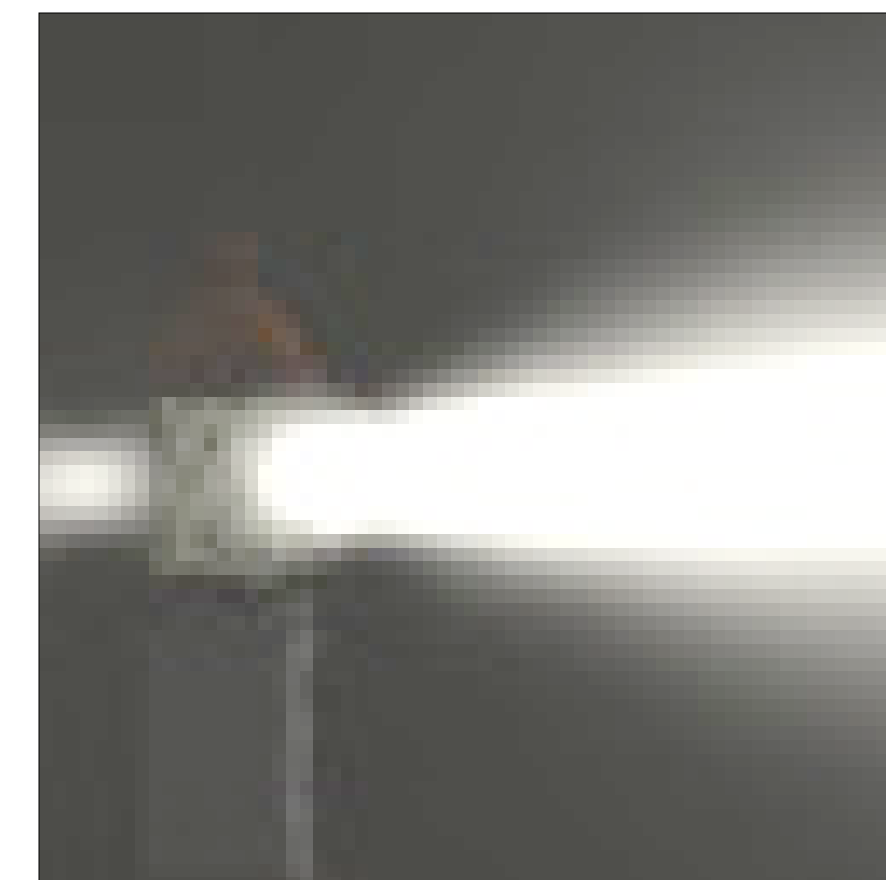
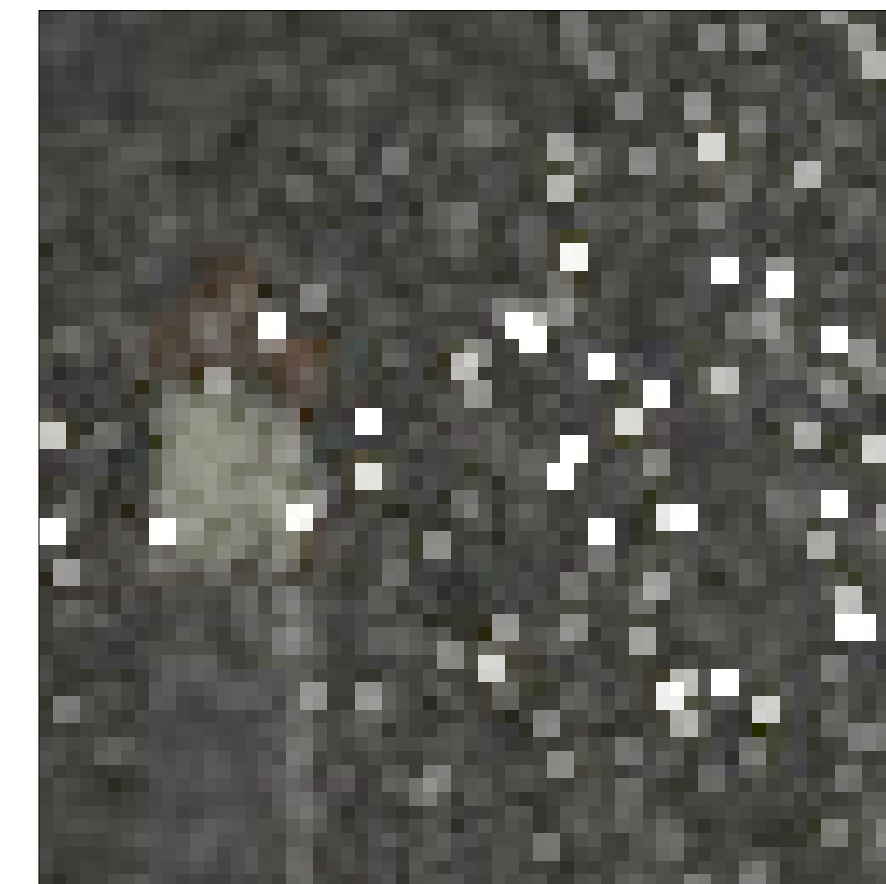
Large Step-size



Drawbacks

[Jensen & Christensen 98]

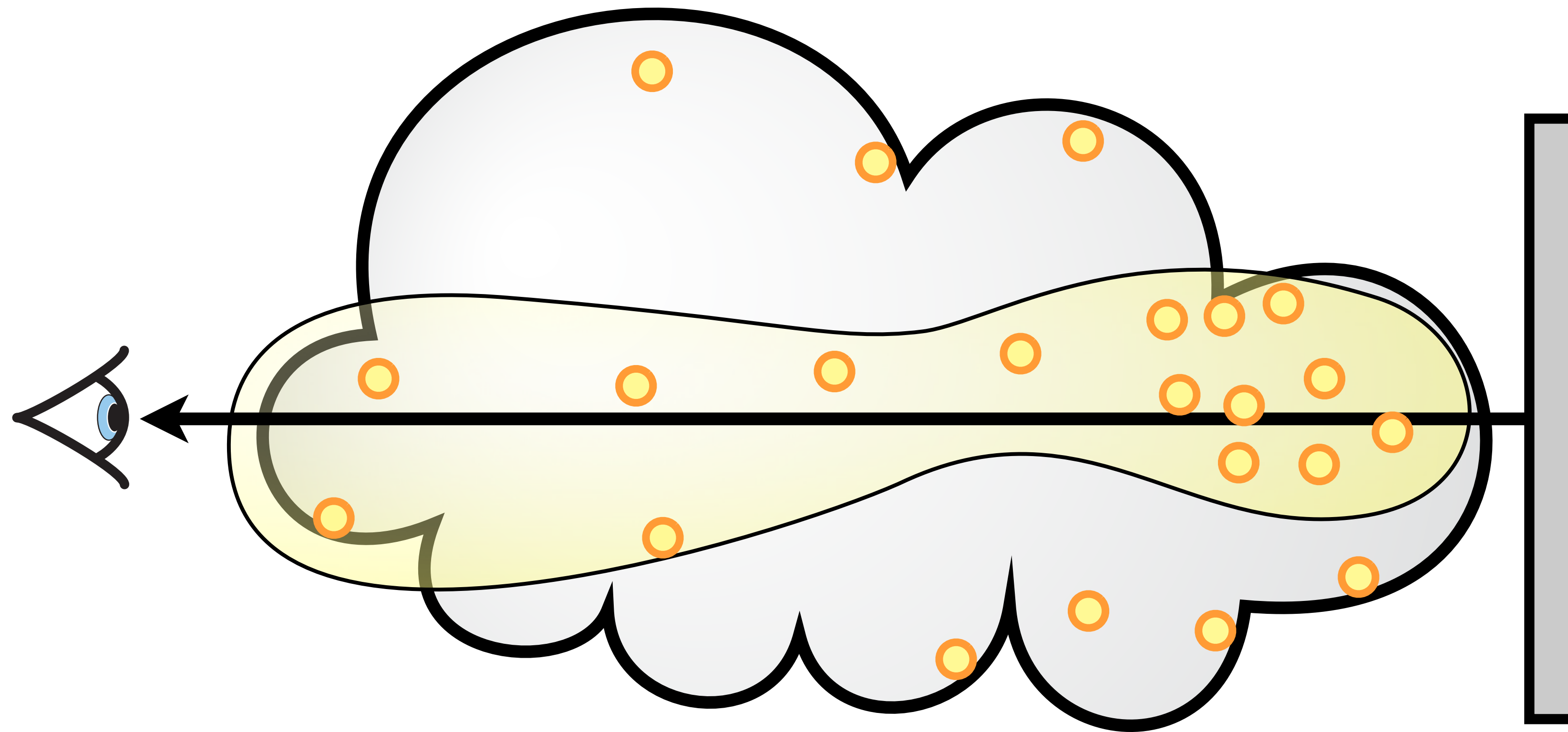
Large Step-size



Very Small Step-size

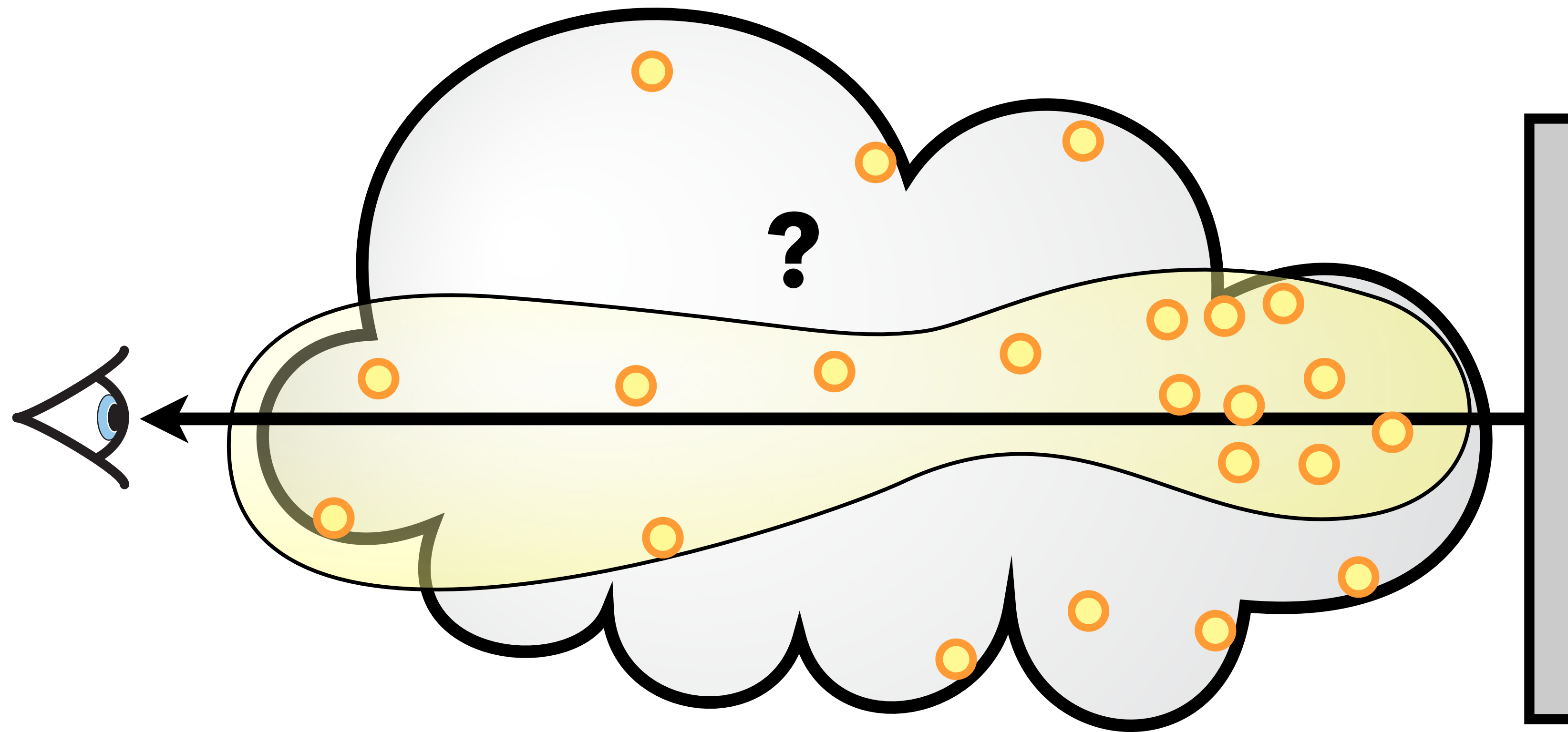
Radiance estimation

[Jarosz et al. 08]



Radiance estimation

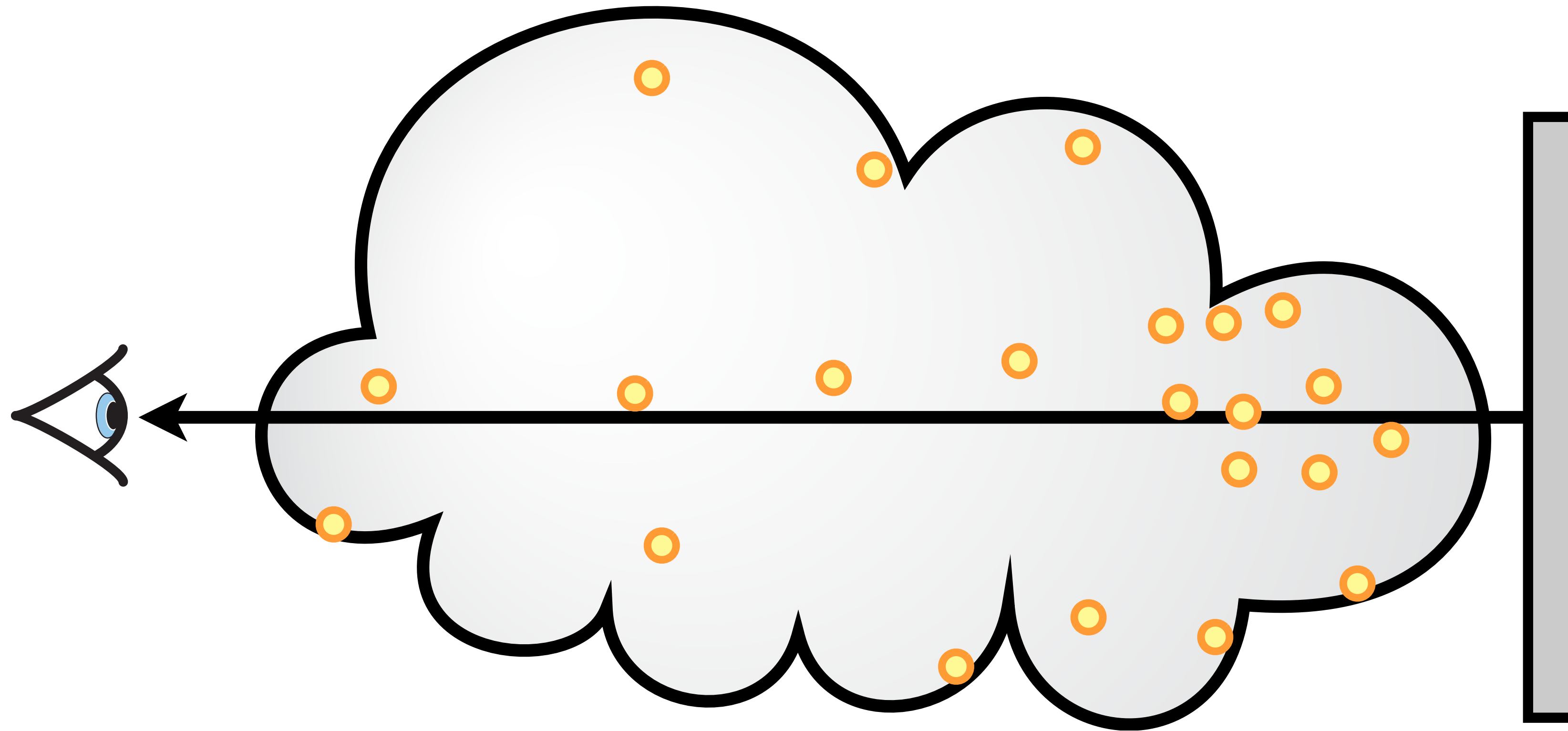
[Jarosz et al. 08]



How to find the photons?

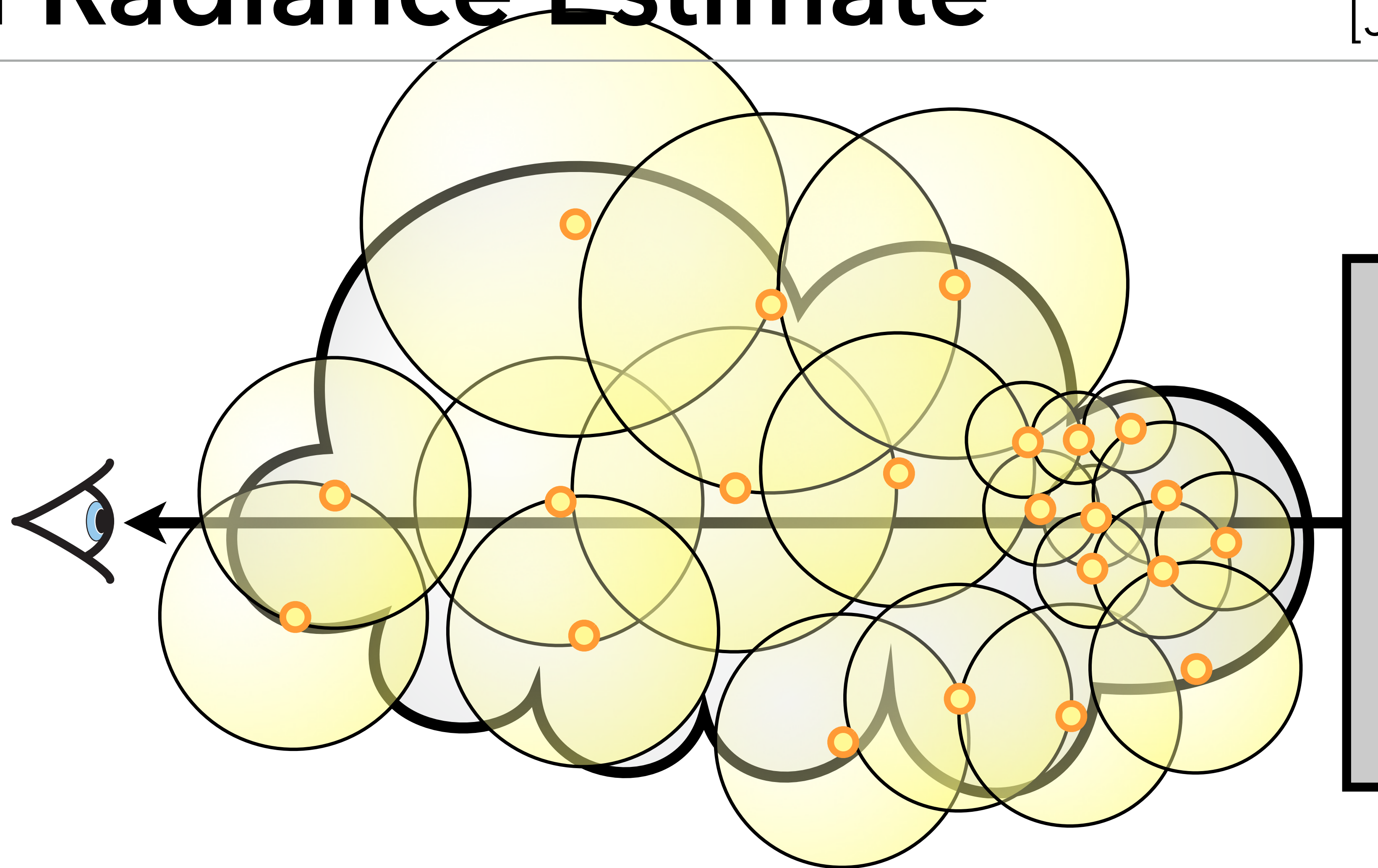
Beam Radiance Estimate

[Jarosz et al. 08]



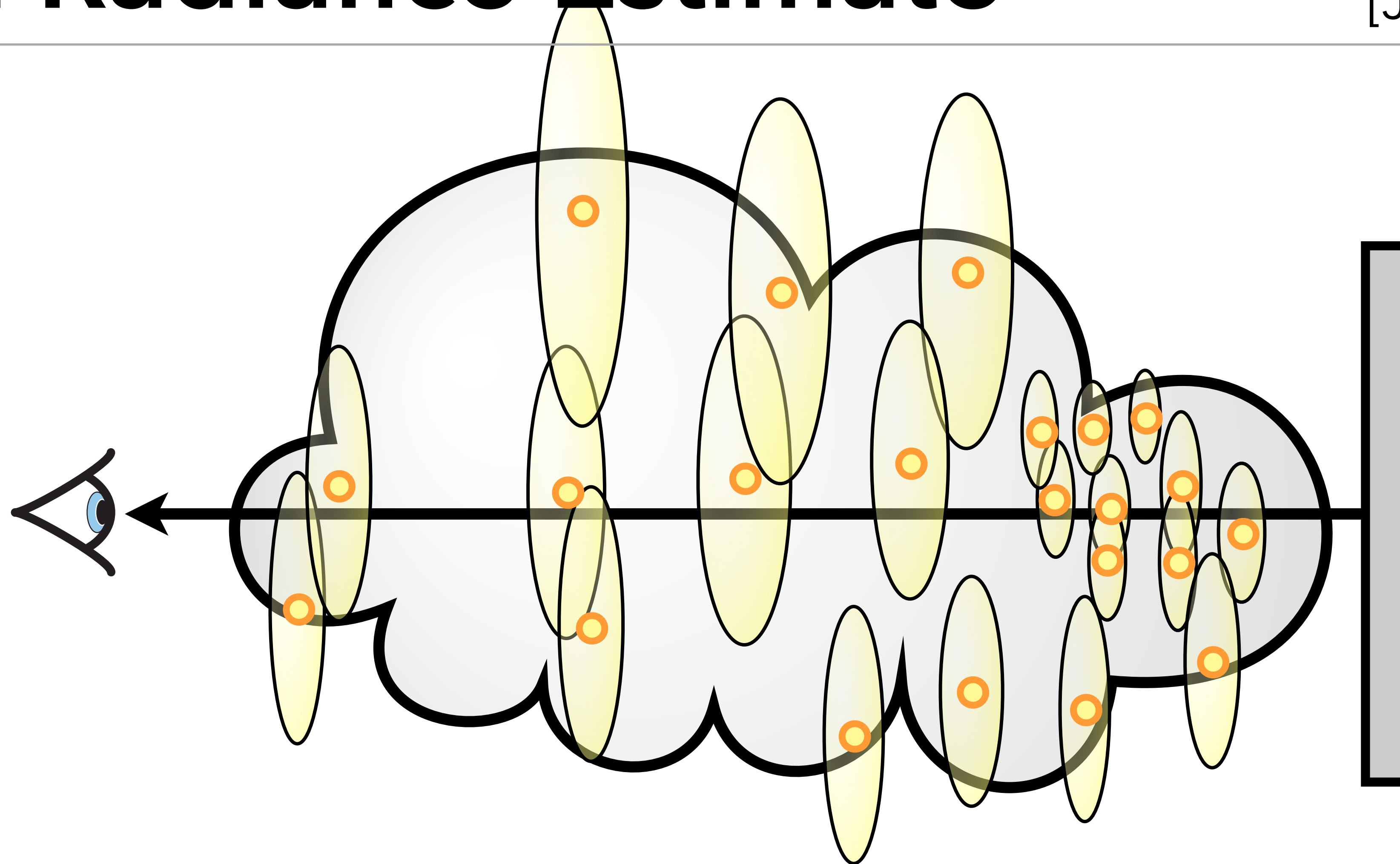
Beam Radiance Estimate

[Jarosz et al. 08]



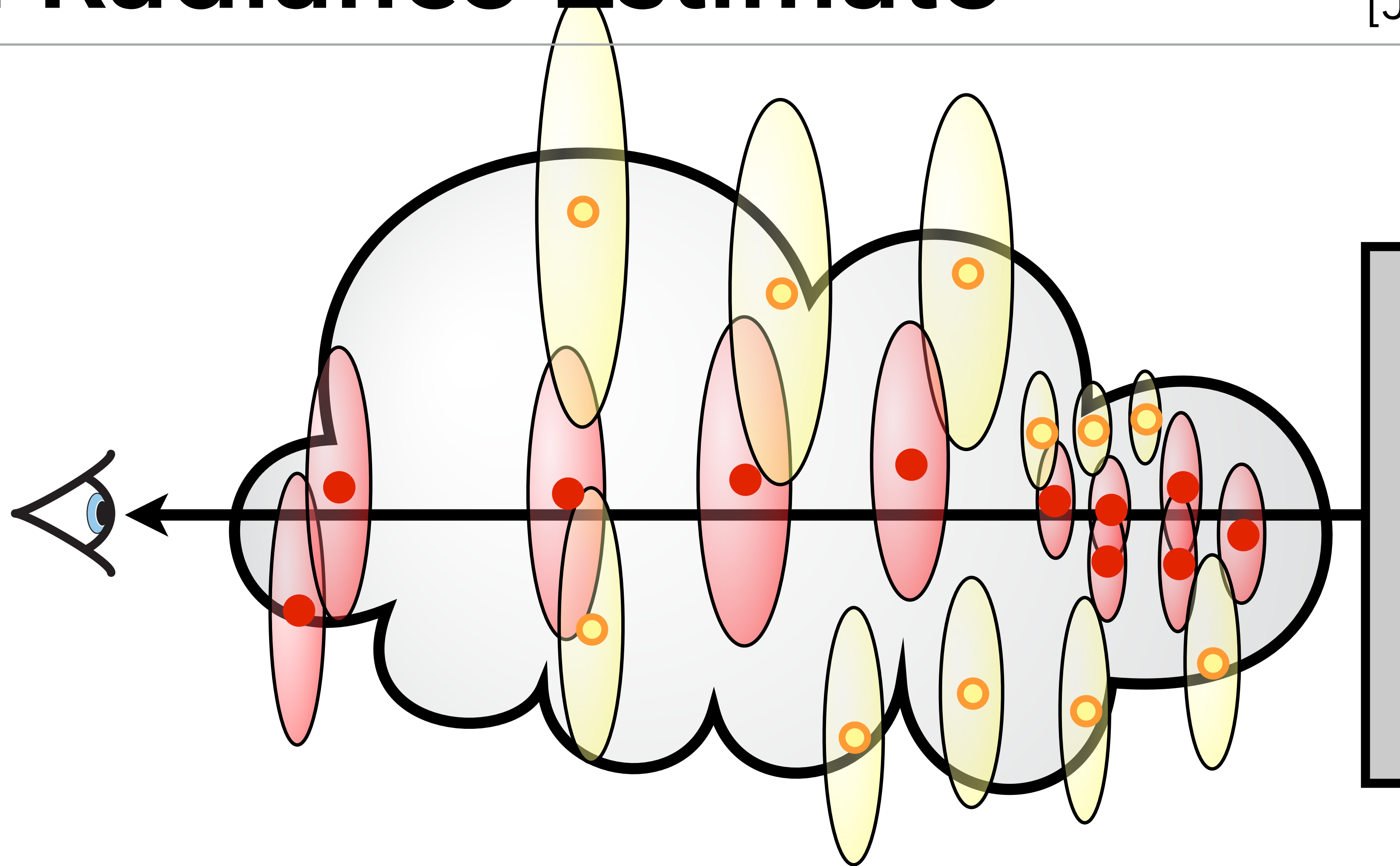
Beam Radiance Estimate

[Jarosz et al. 08]



Beam Radiance Estimate

[Jarosz et al. 08]

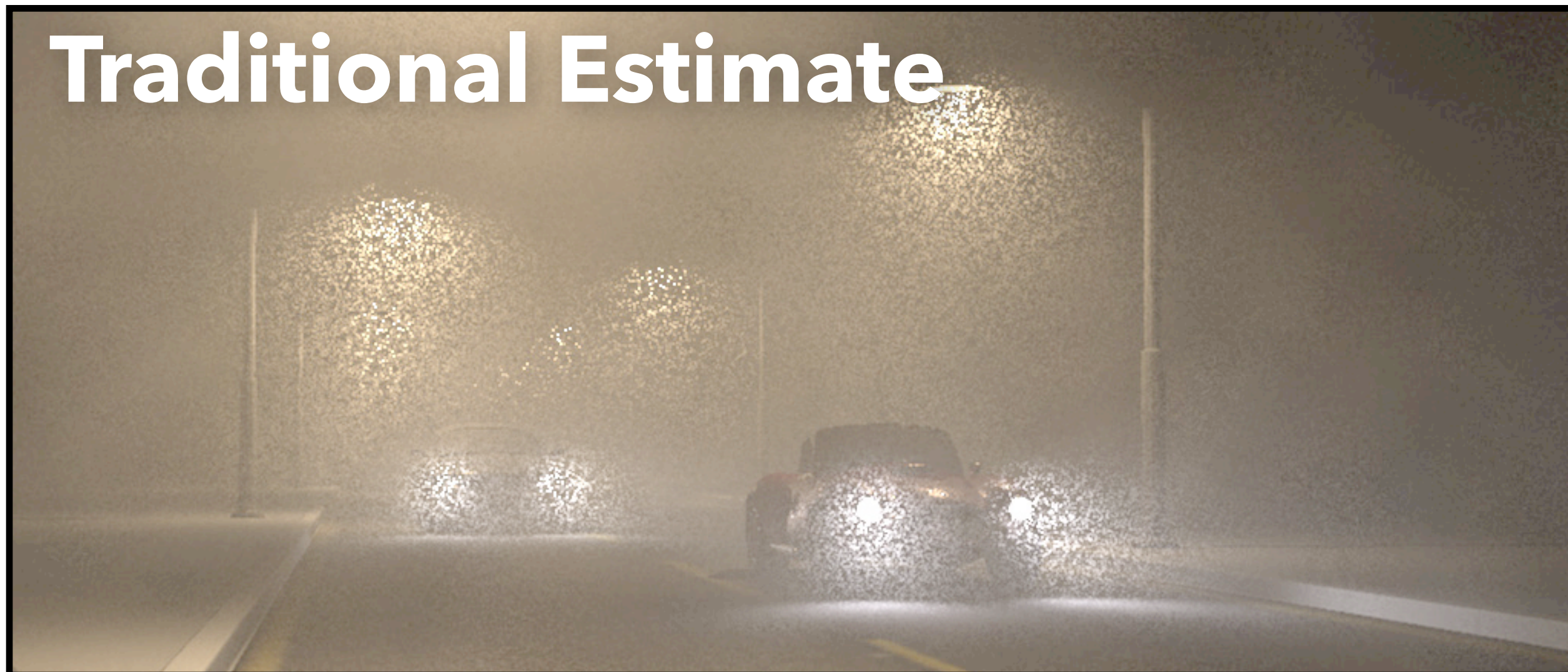


Cars on Foggy Street

Beam Estimate



Traditional Estimate

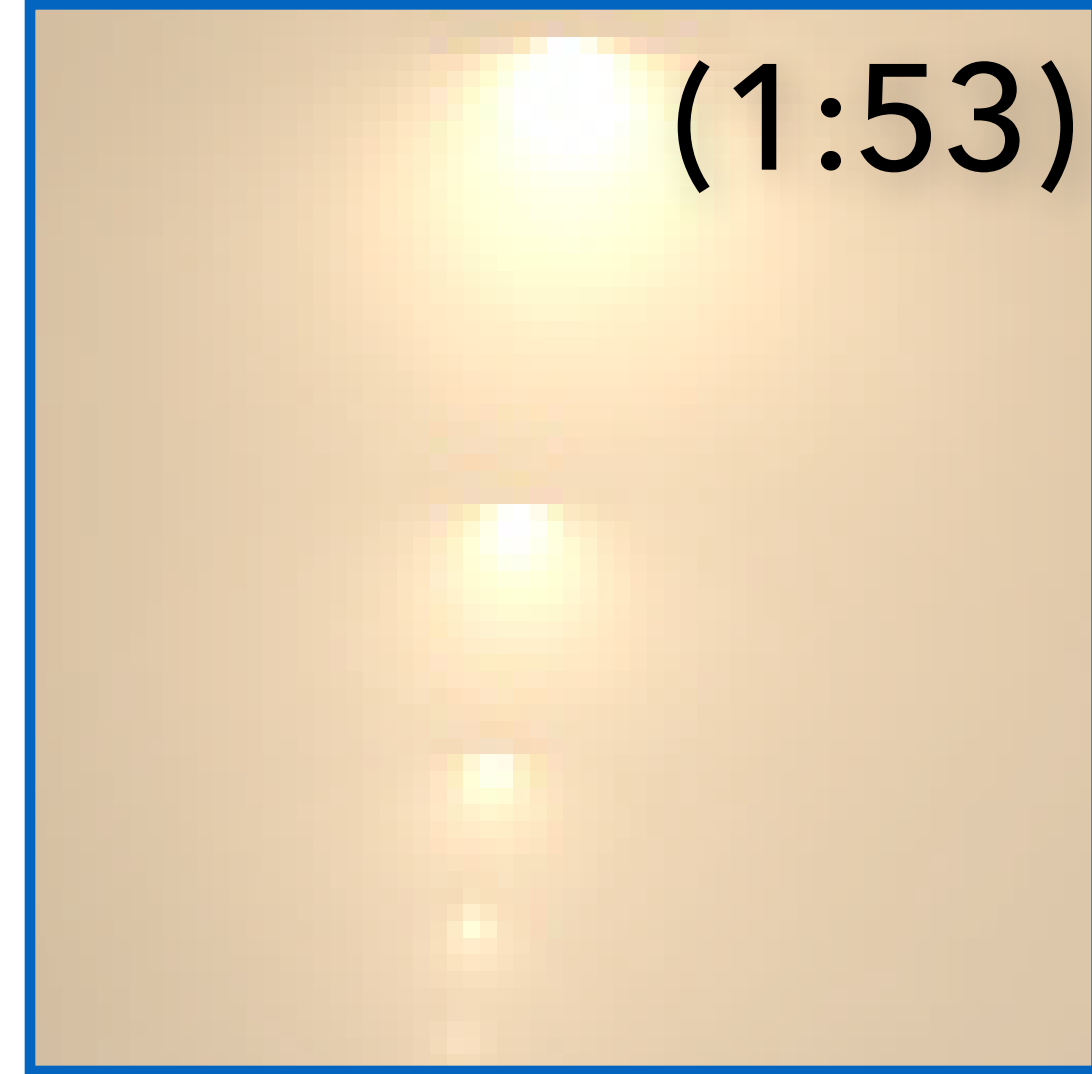


Cars on Foggy Street

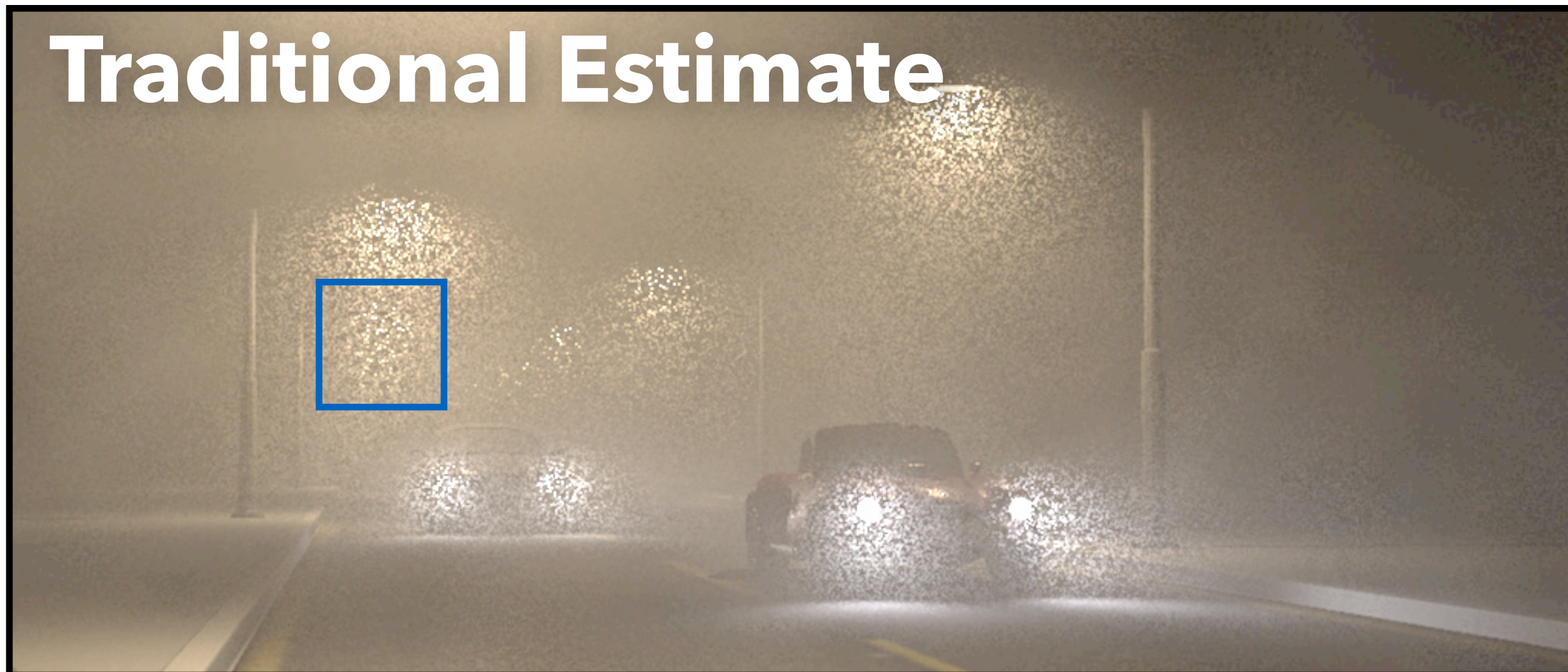
Beam Estimate



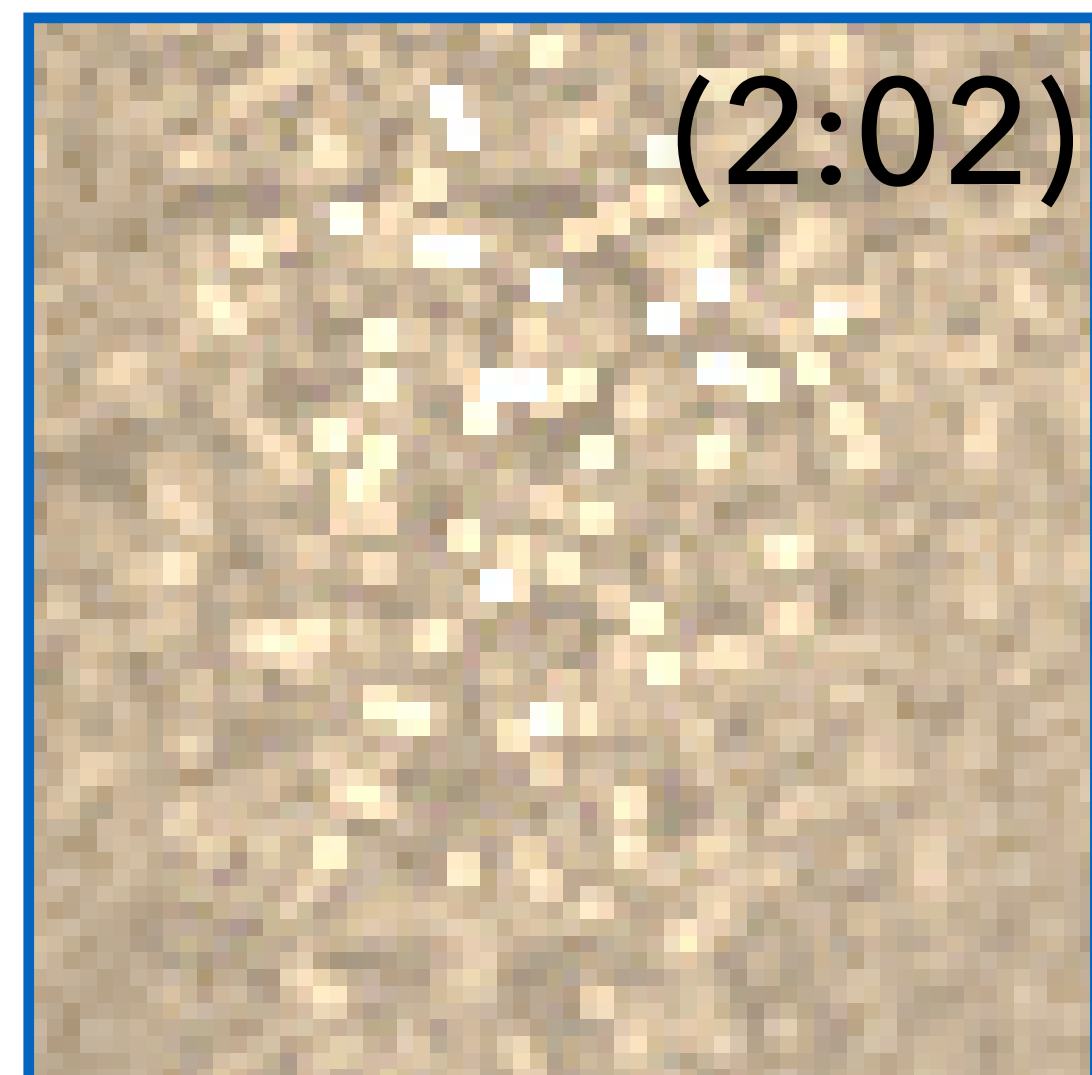
(1:53)



Traditional Estimate



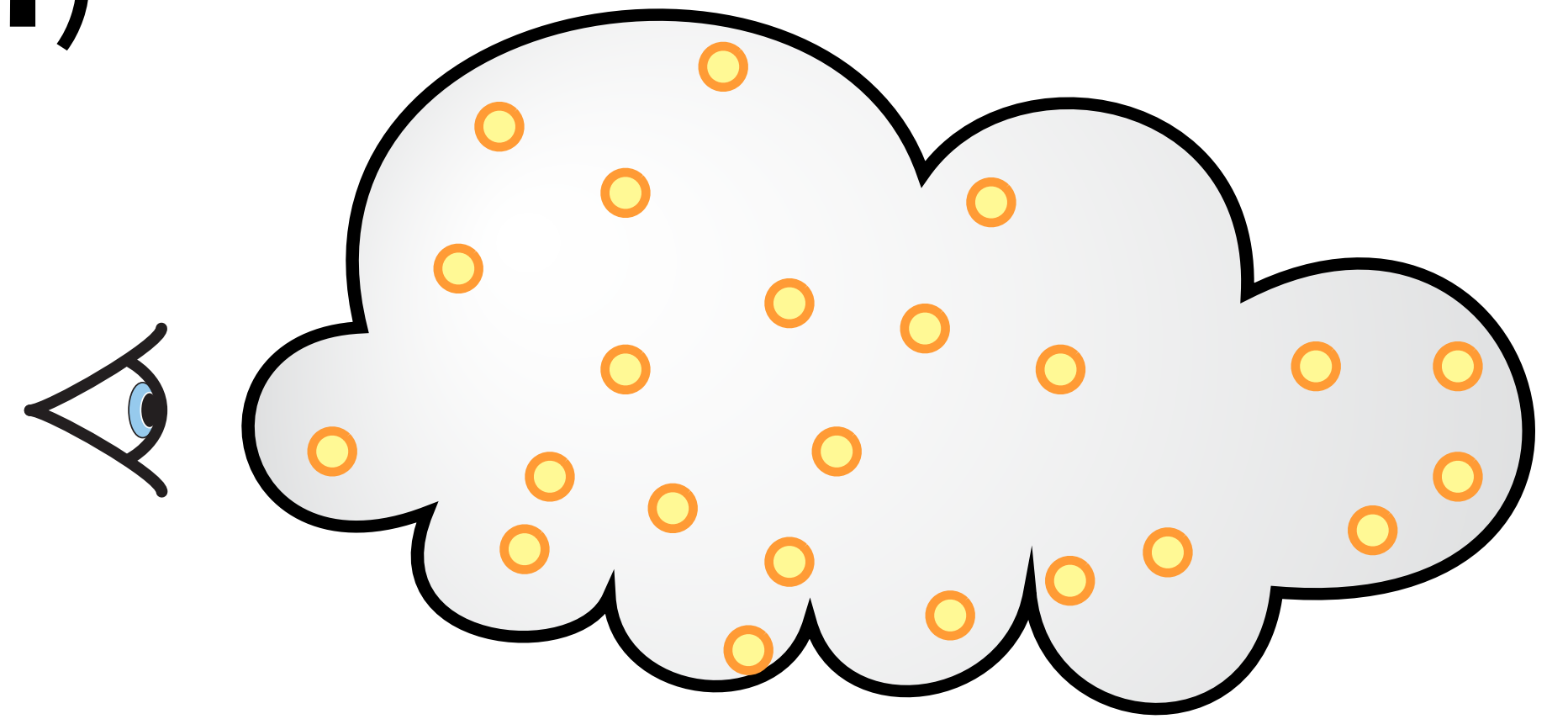
(2:02)



So Far...

Volumetric Photon Mapping (**VPM**)

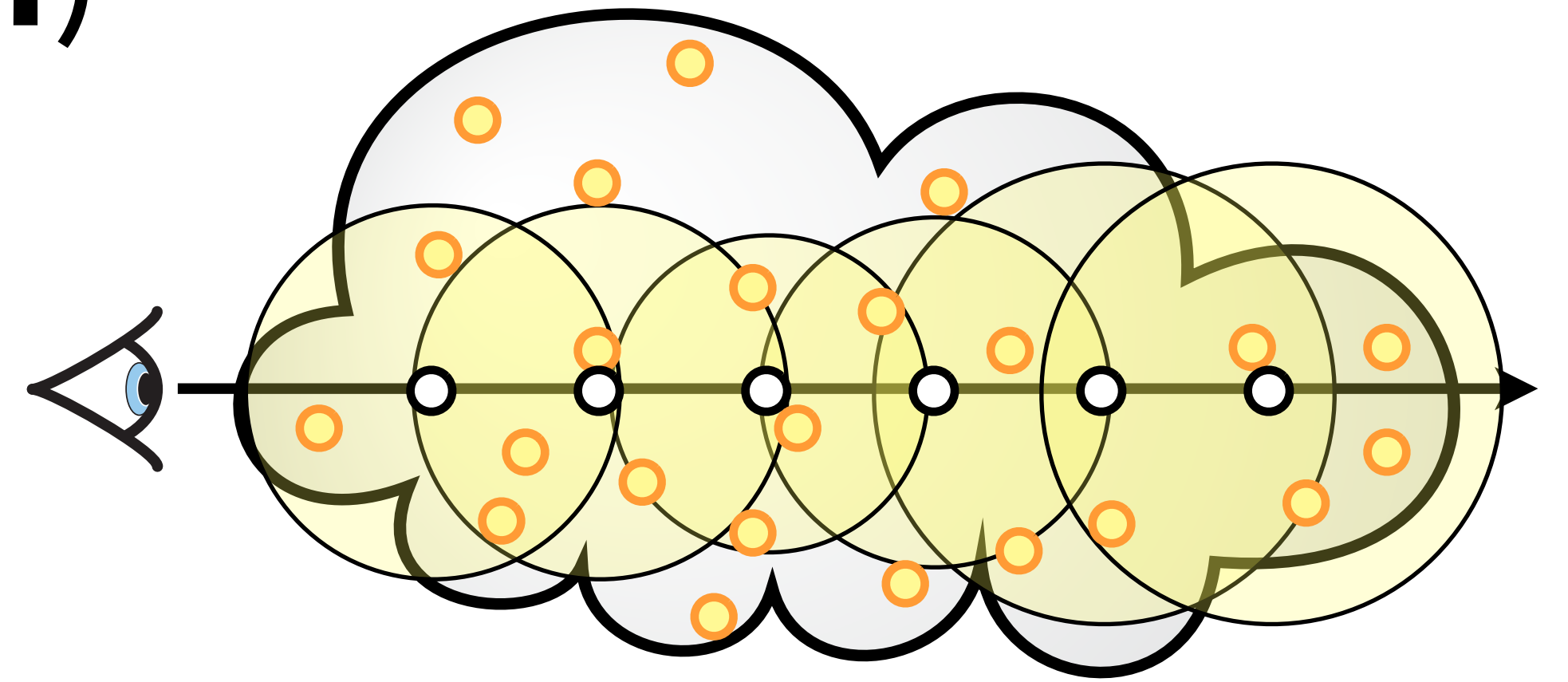
[Jensen & Christensen 98]



So Far...

Volumetric Photon Mapping (VPM)

[Jensen & Christensen 98]



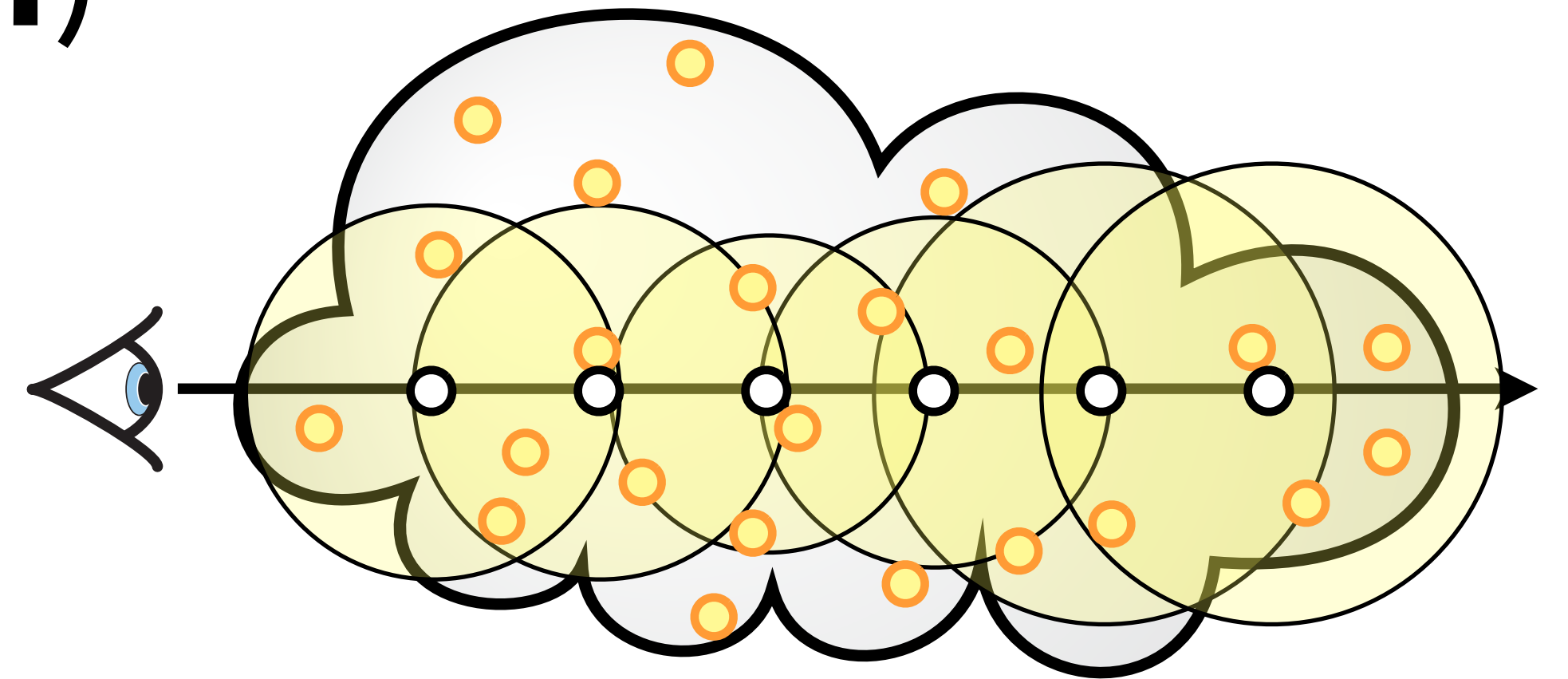
So Far...

Volumetric Photon Mapping (VPM)

[Jensen & Christensen 98]

Query

Point



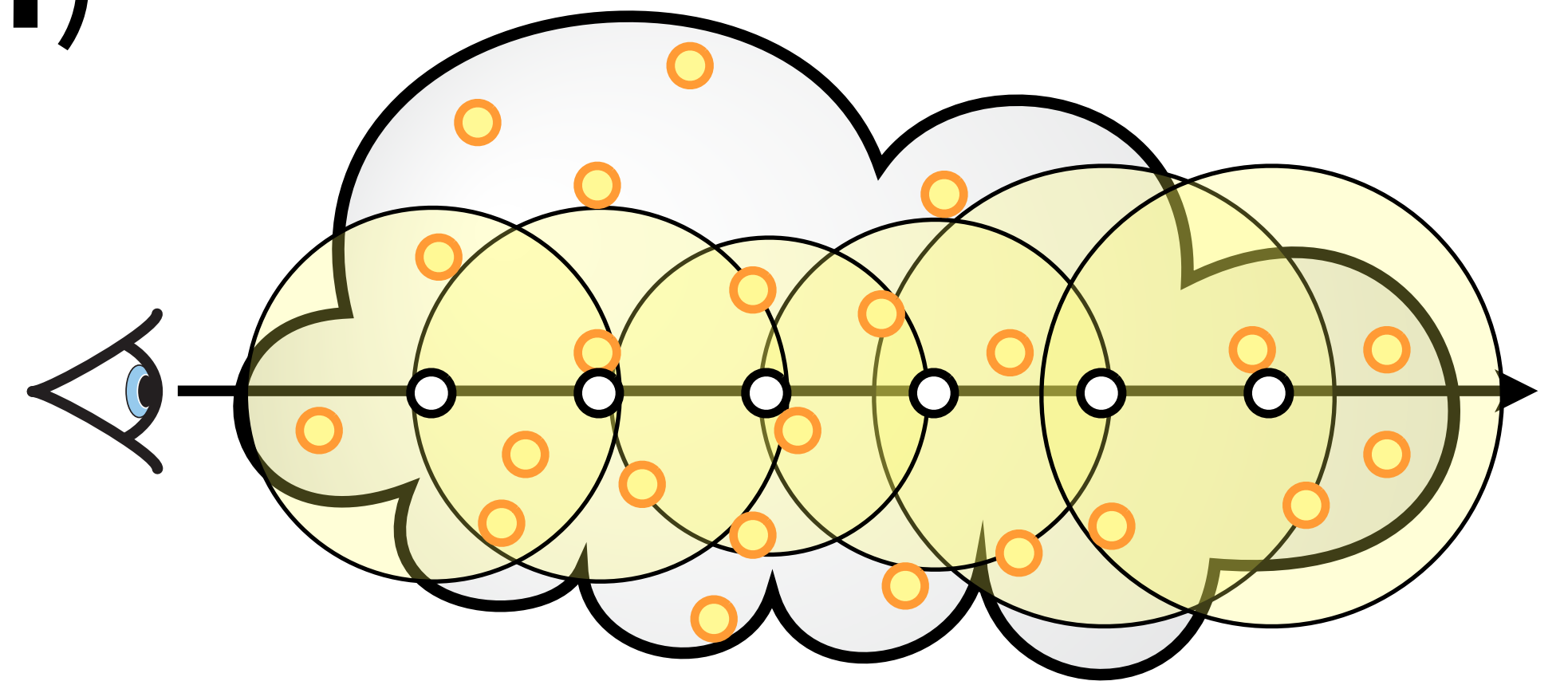
So Far...

Volumetric Photon Mapping (VPM)

[Jensen & Christensen 98]

Query	x	Data
--------------	----------	-------------

Point	x	Point
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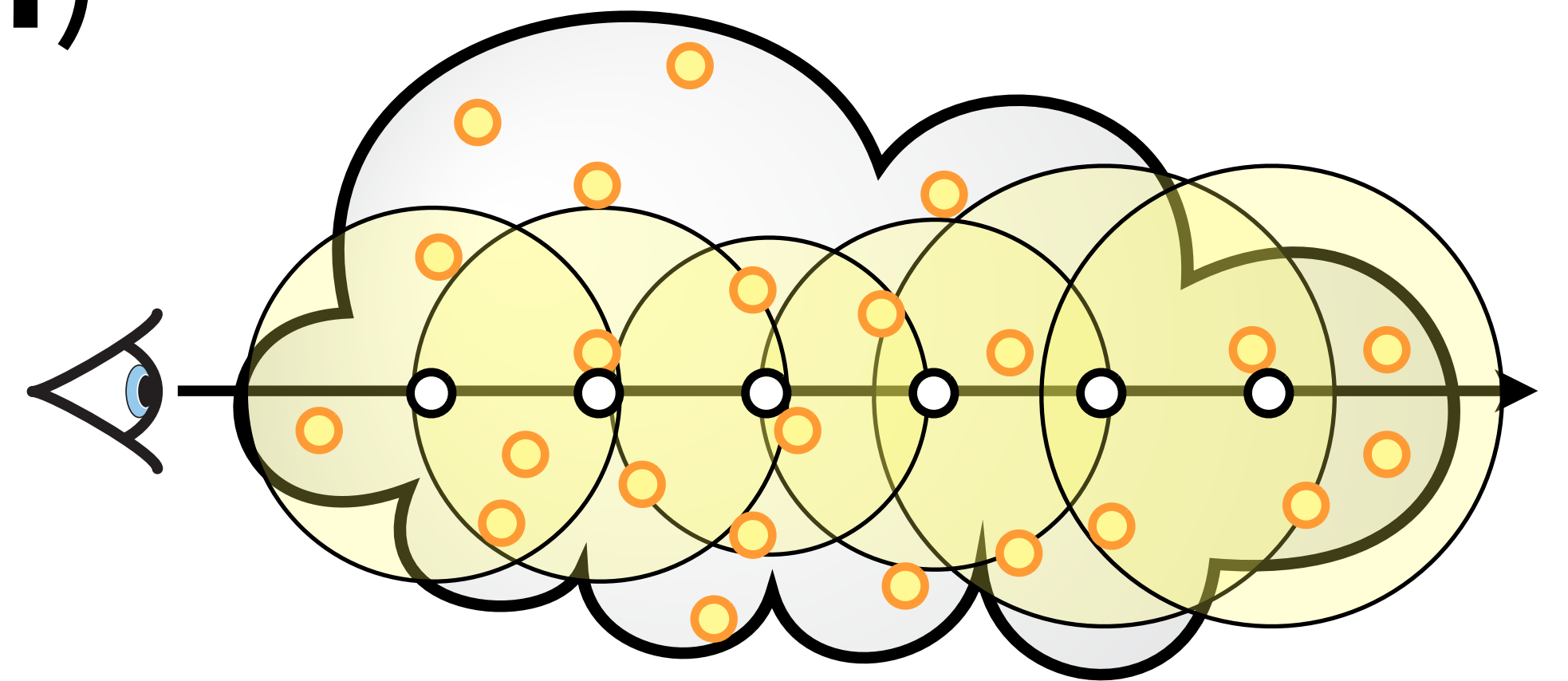
So Far...

Volumetric Photon Mapping (VPM)

[Jensen & Christensen 98]

Query	x	Data	Blur
-------	---	------	------

Point	x	Point	(3D)
-------	---	-------	------

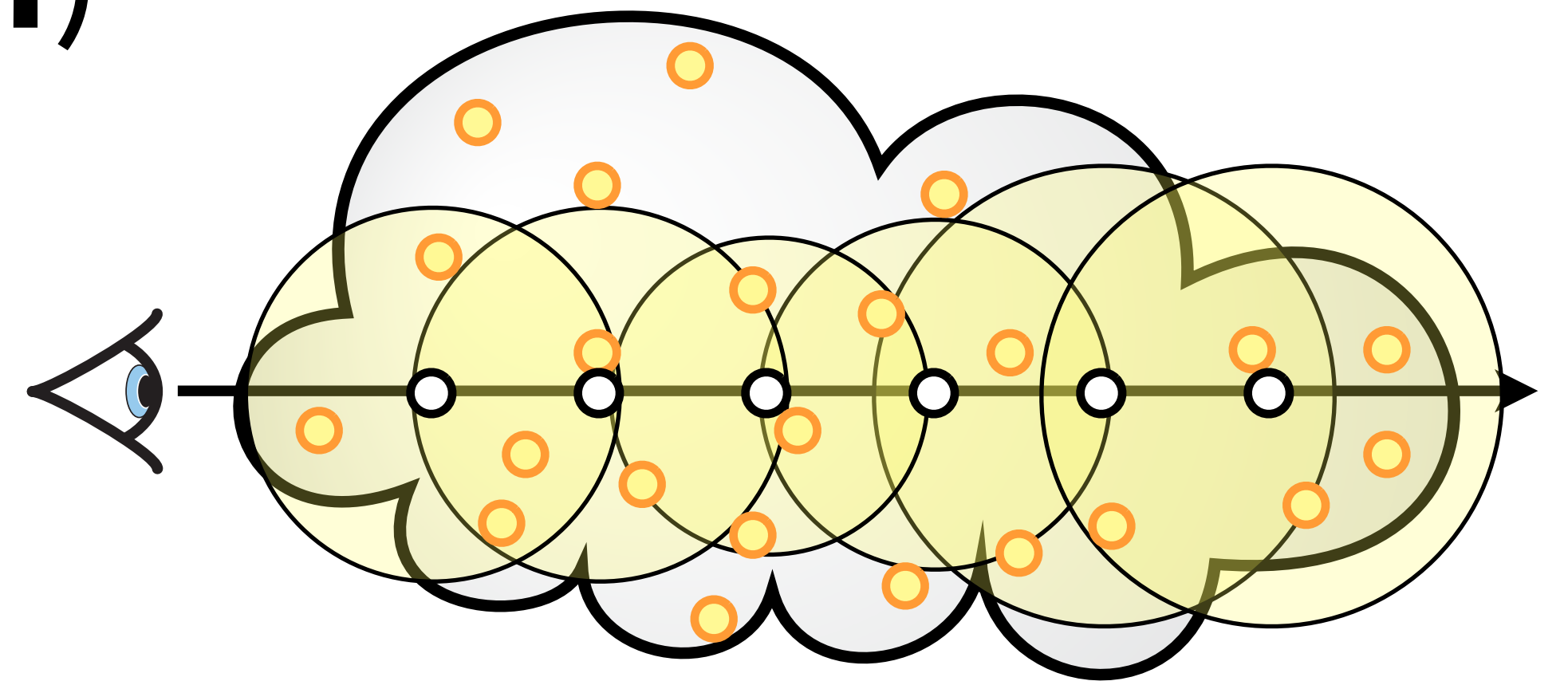


So Far...

Volumetric Photon Mapping (**VPM**)

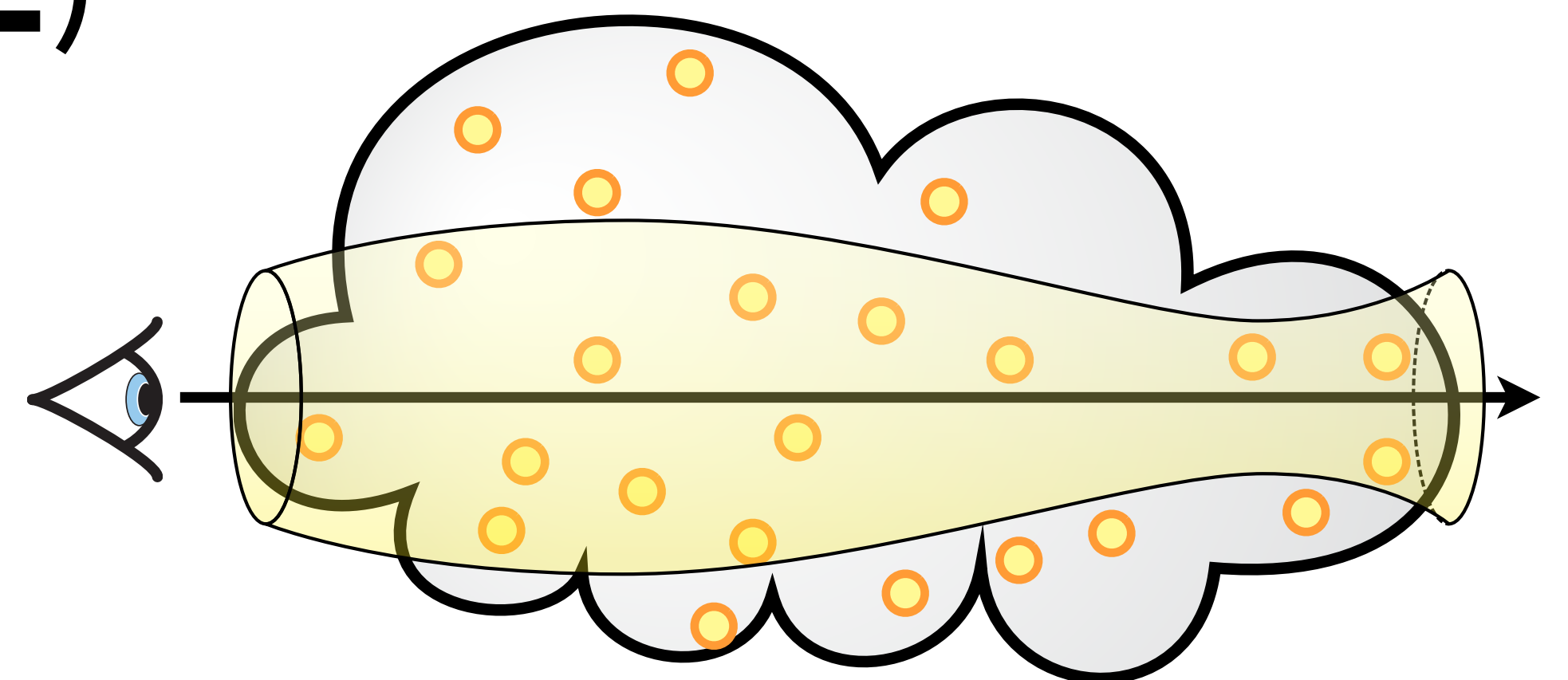
[Jensen & Christensen 98]

Query	x	Data	Blur
Point	x	Point	(3D)



The Beam Radiance Estimate (**BRE**)

[Jarosz et al. 08]



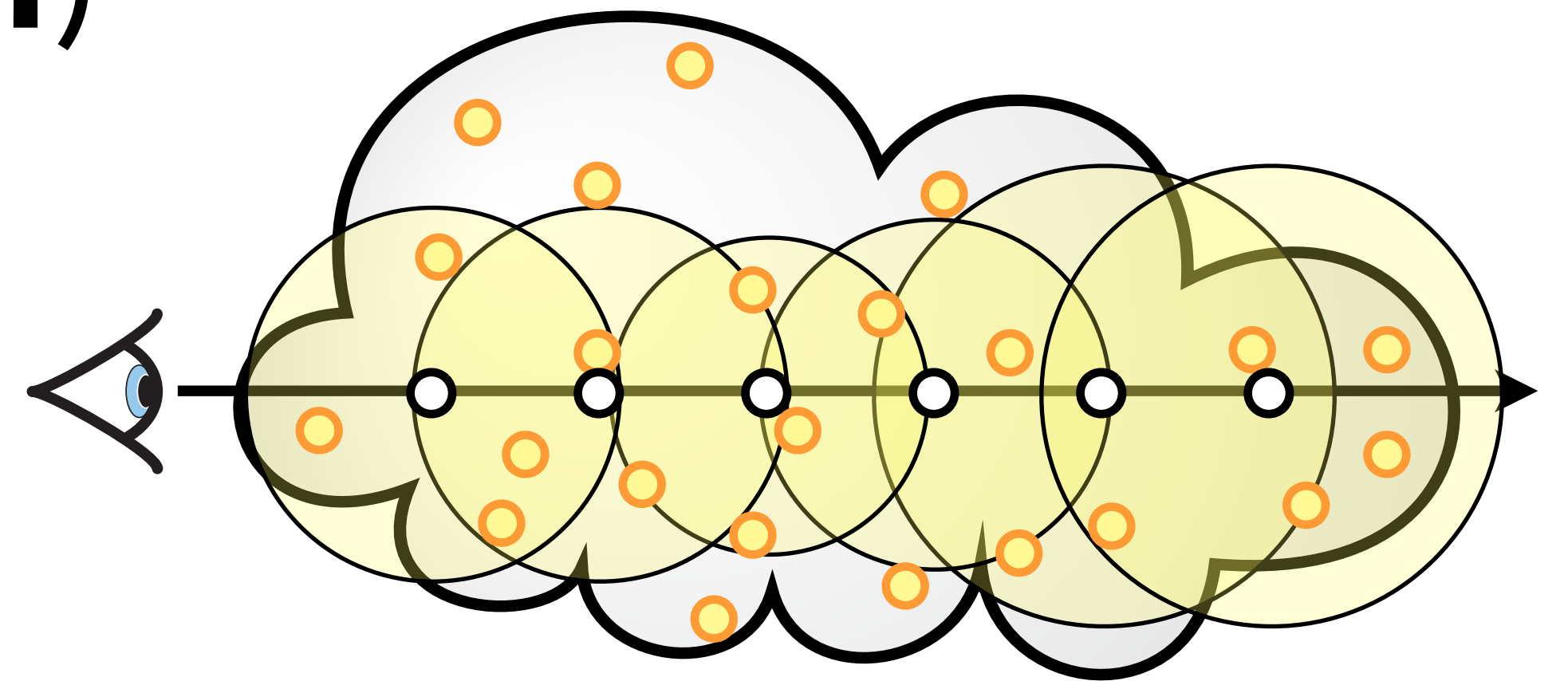
So Far...

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

Query	x	Data	Blur
--------------	----------	-------------	-------------

Point	x	Point	(3D)
-------	---	-------	------

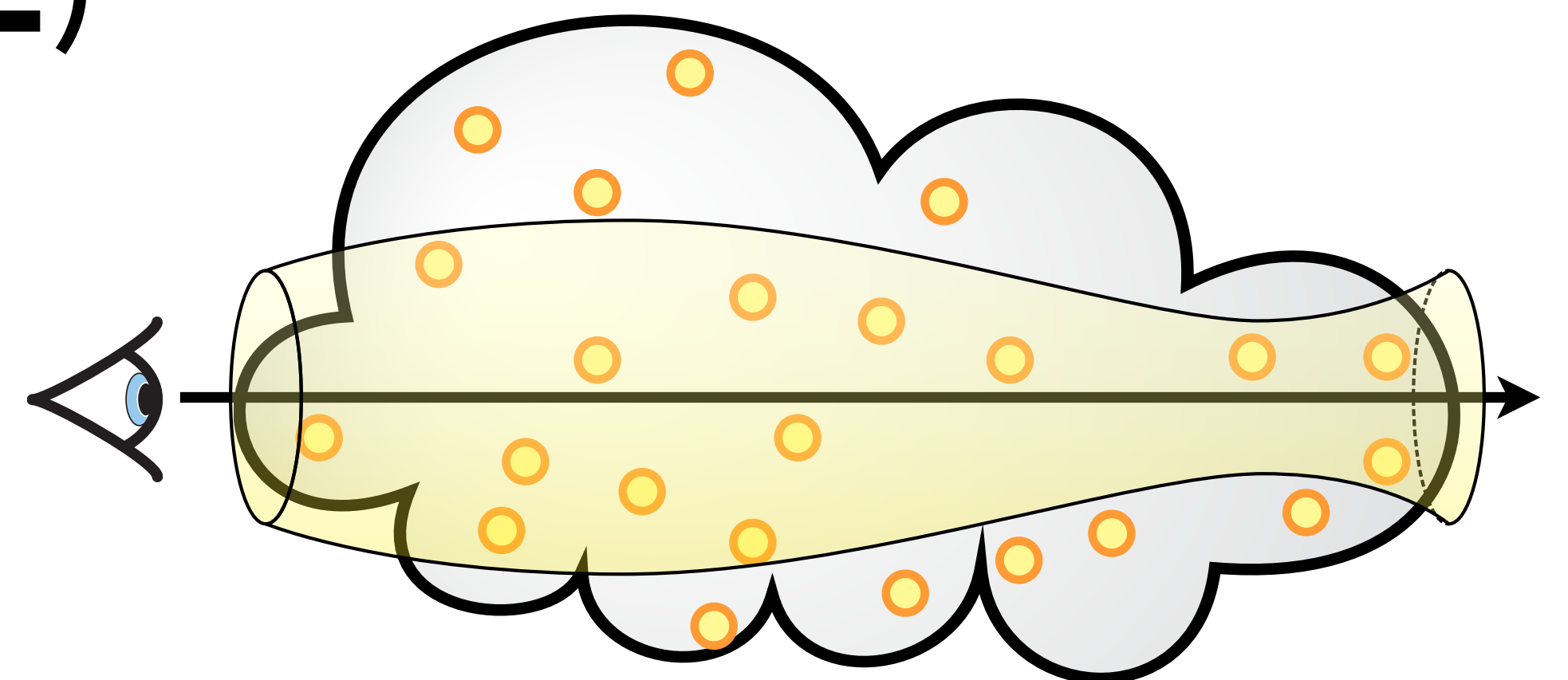


The Beam Radiance Estimate (**BRE**)

[Jarosz et al. 08]

Query

Beam



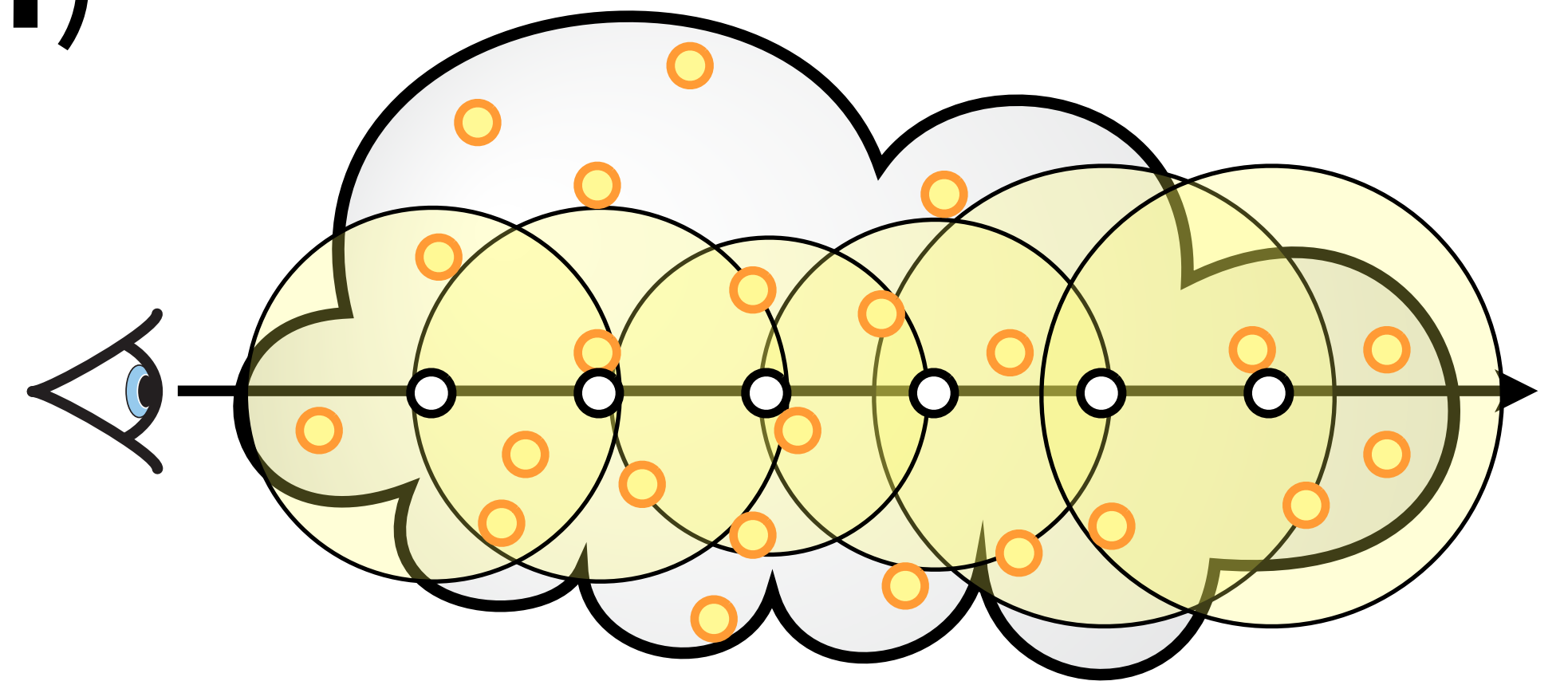
So Far...

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

Query	x	Data	Blur
--------------	----------	-------------	-------------

Point	x	Point (3D)
-------	---	------------

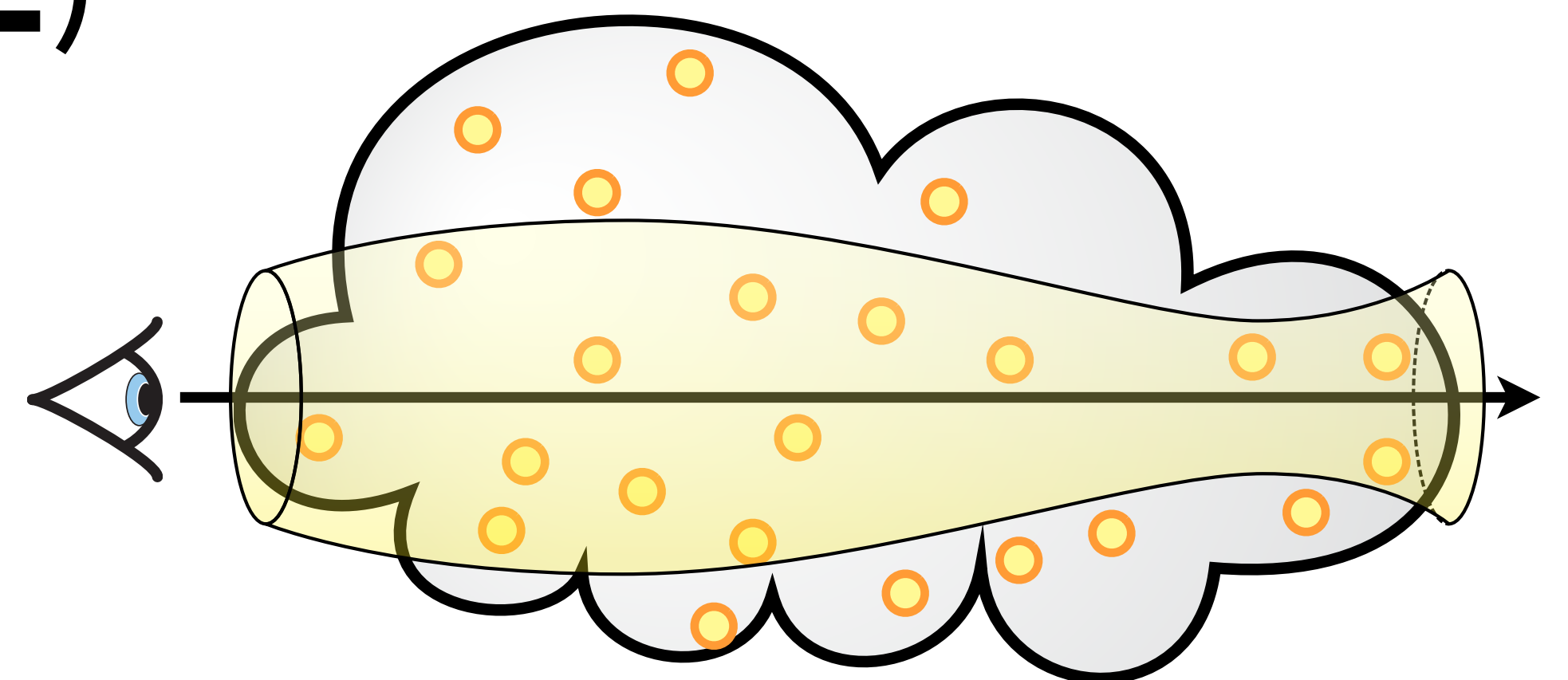


The Beam Radiance Estimate (**BRE**)

[Jarosz et al. 08]

Query	x	Data
--------------	----------	-------------

Beam	x	Point
-------------	---	-------

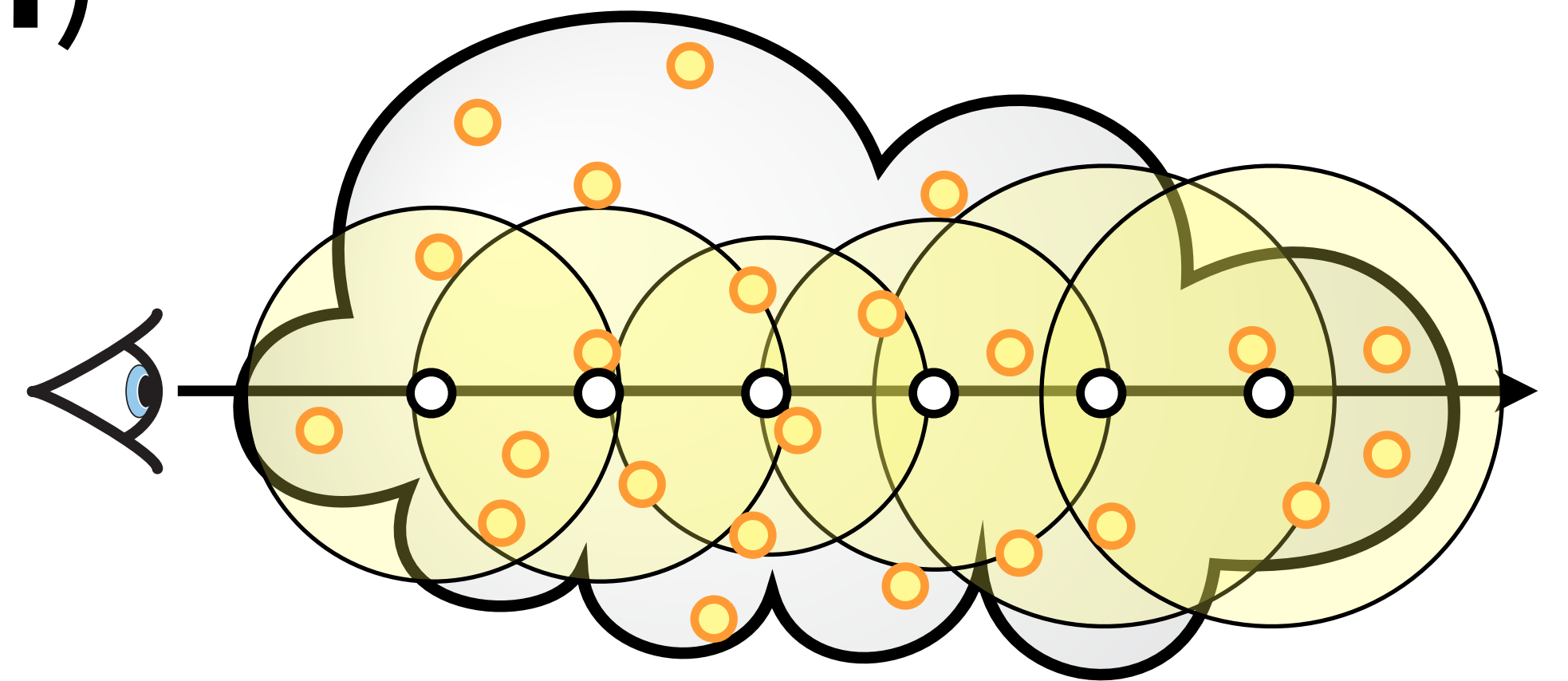


So Far...

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

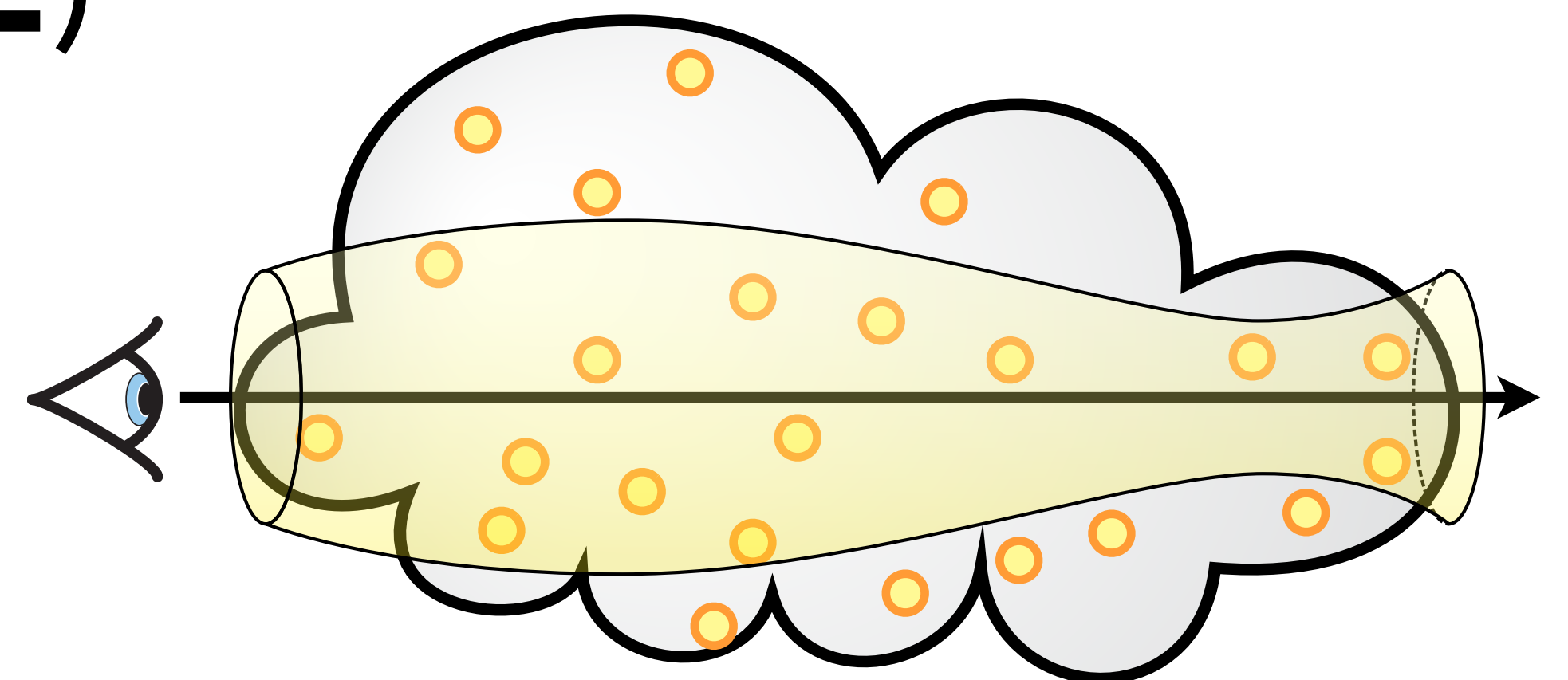
Query	x Data	Blur
Point	x Point	(3D)



The Beam Radiance Estimate (**BRE**)

[Jarosz et al. 08]

Query	x Data	Blur
Beam	x Point	(2D)



Other possibilities

Query	x	Data	Blur
Point	x	Point	(3D)
Beam	x	Point	(2D)

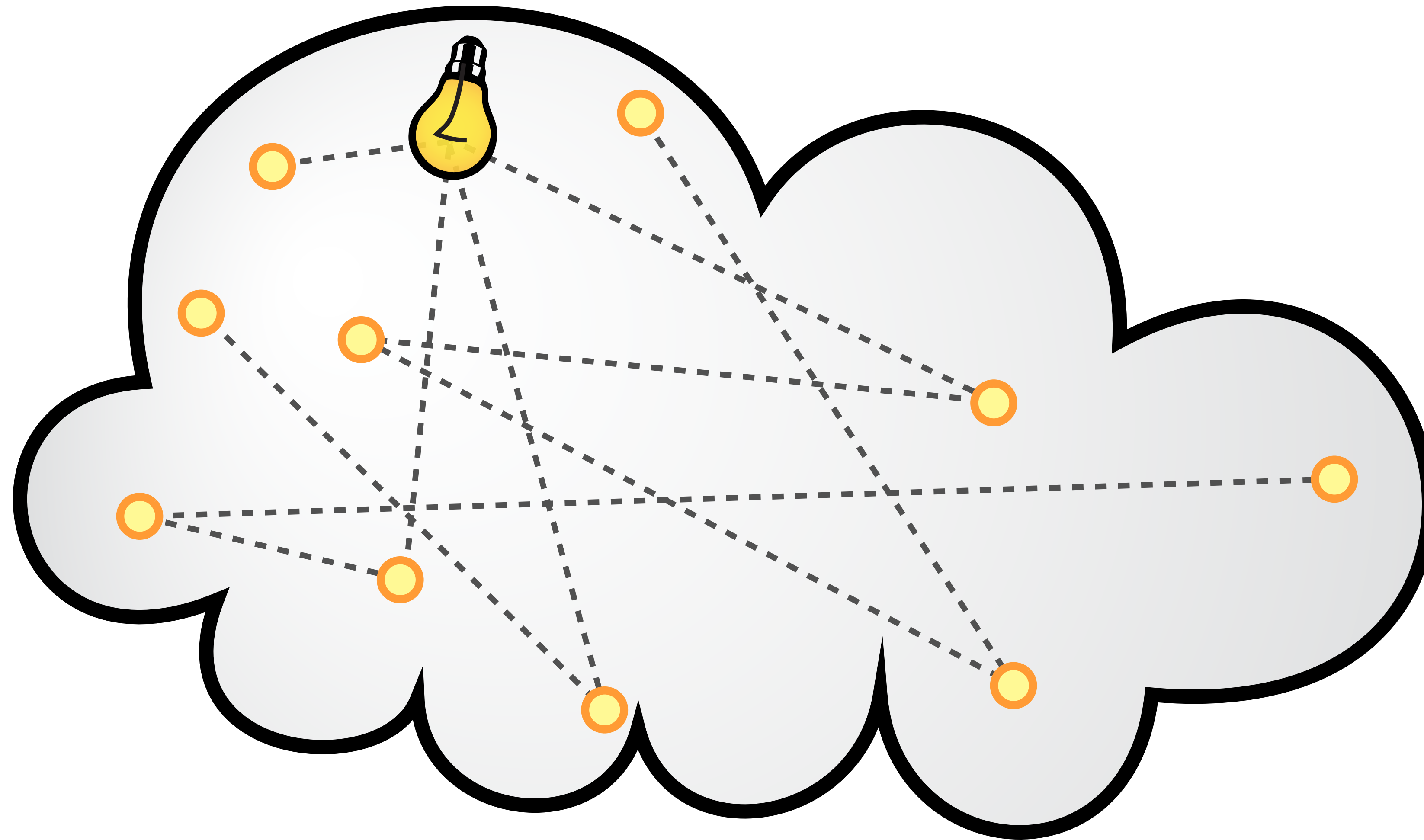
Other possibilities

[Jarosz et al. 11]

Query	x	Data	Blur
Point	x	Point	(3D)
Beam	x	Point	(2D)
Beam	x	Point	(3D)
Point	x	Beam	(3D)
Point	x	Beam	(2D)
Beam	x	Beam	(3D)
Beam	x	Beam	(2D)
Beam	x	Beam	(2D)
Beam	x	Beam	(1D)

Volumetric photon mapping

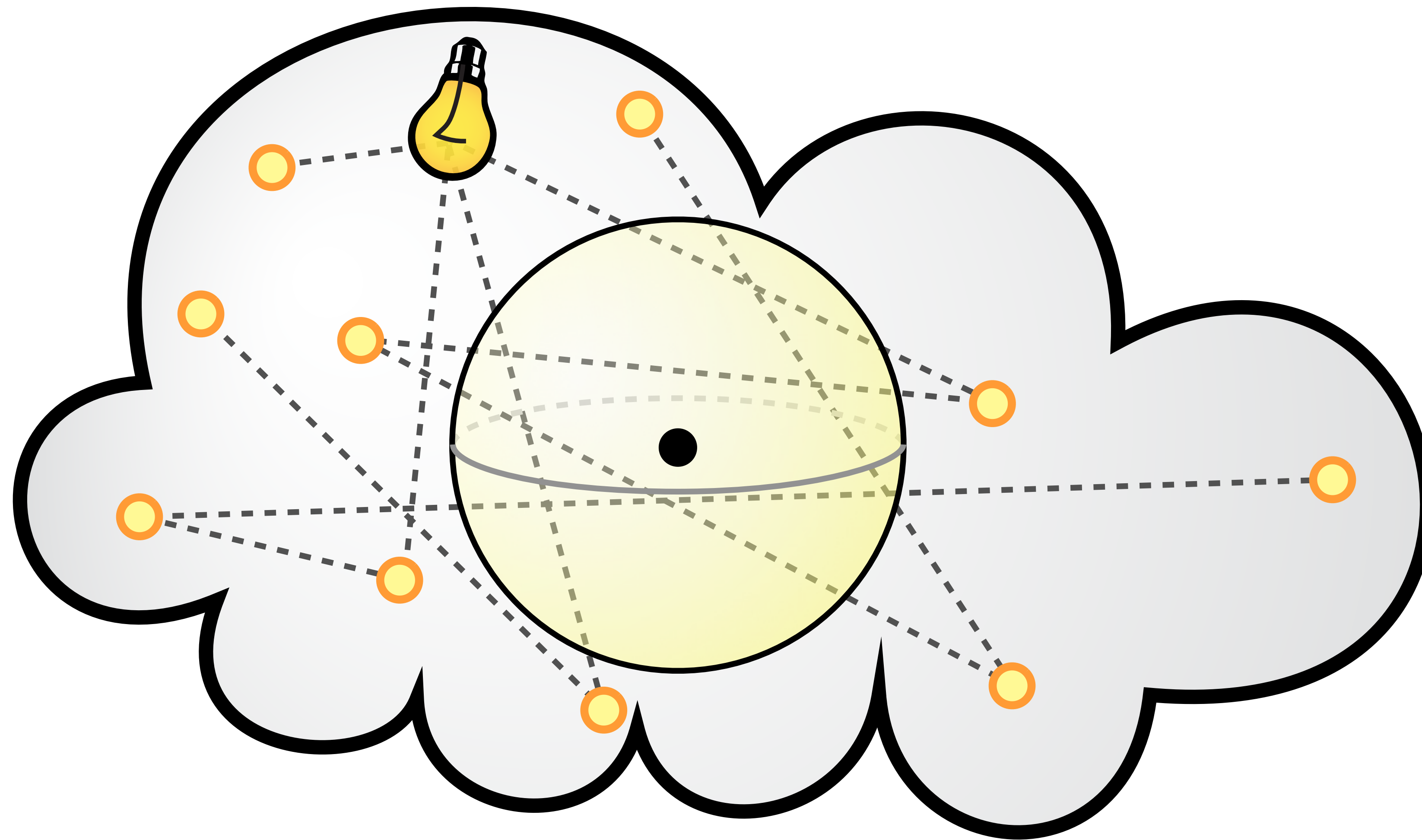
[Jarosz et al. 11]



Photon Points

Volumetric photon mapping

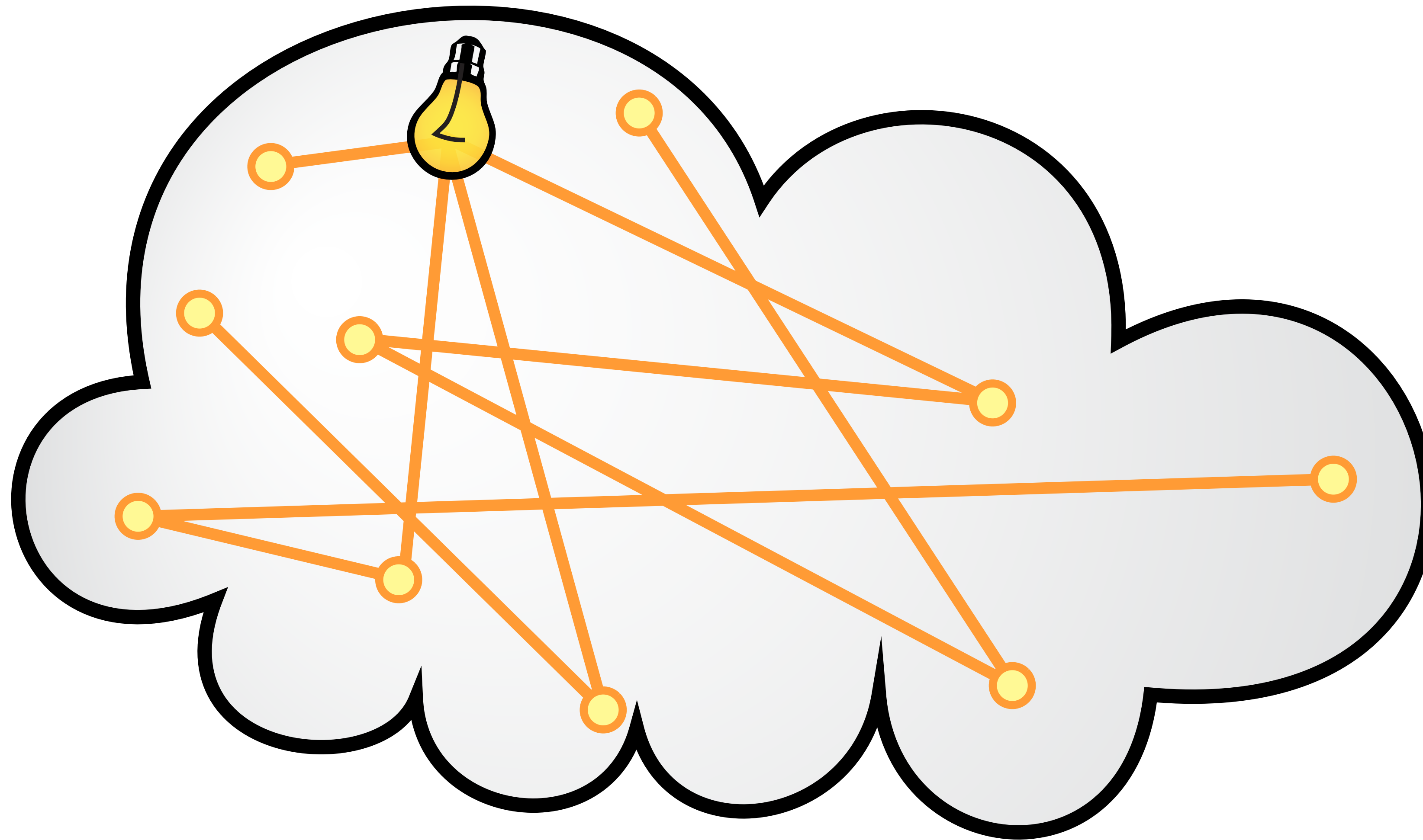
[Jarosz et al. 11]



Photon Points

Volumetric photon mapping

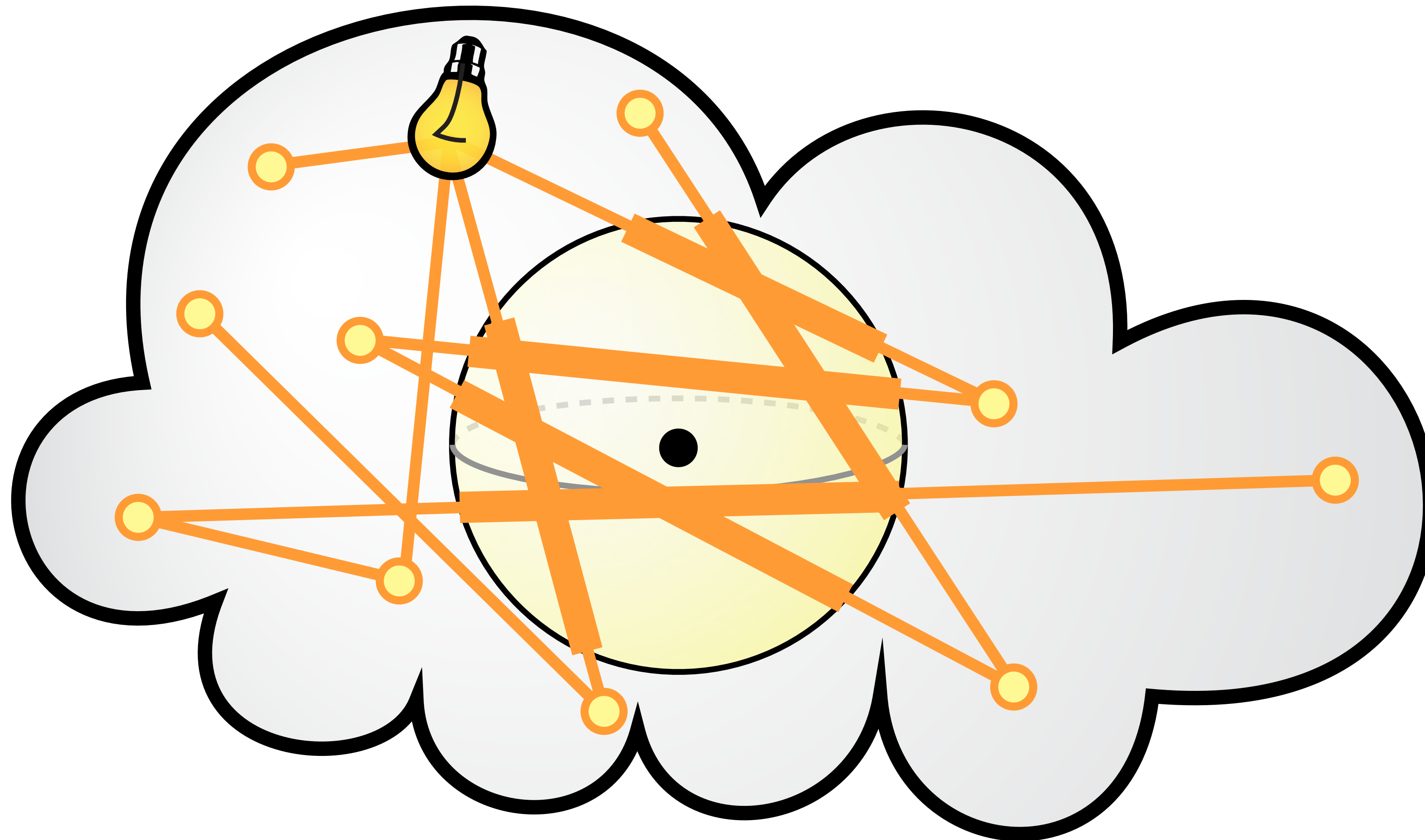
[Jarosz et al. 11]



Photon Beams

Volumetric photon mapping

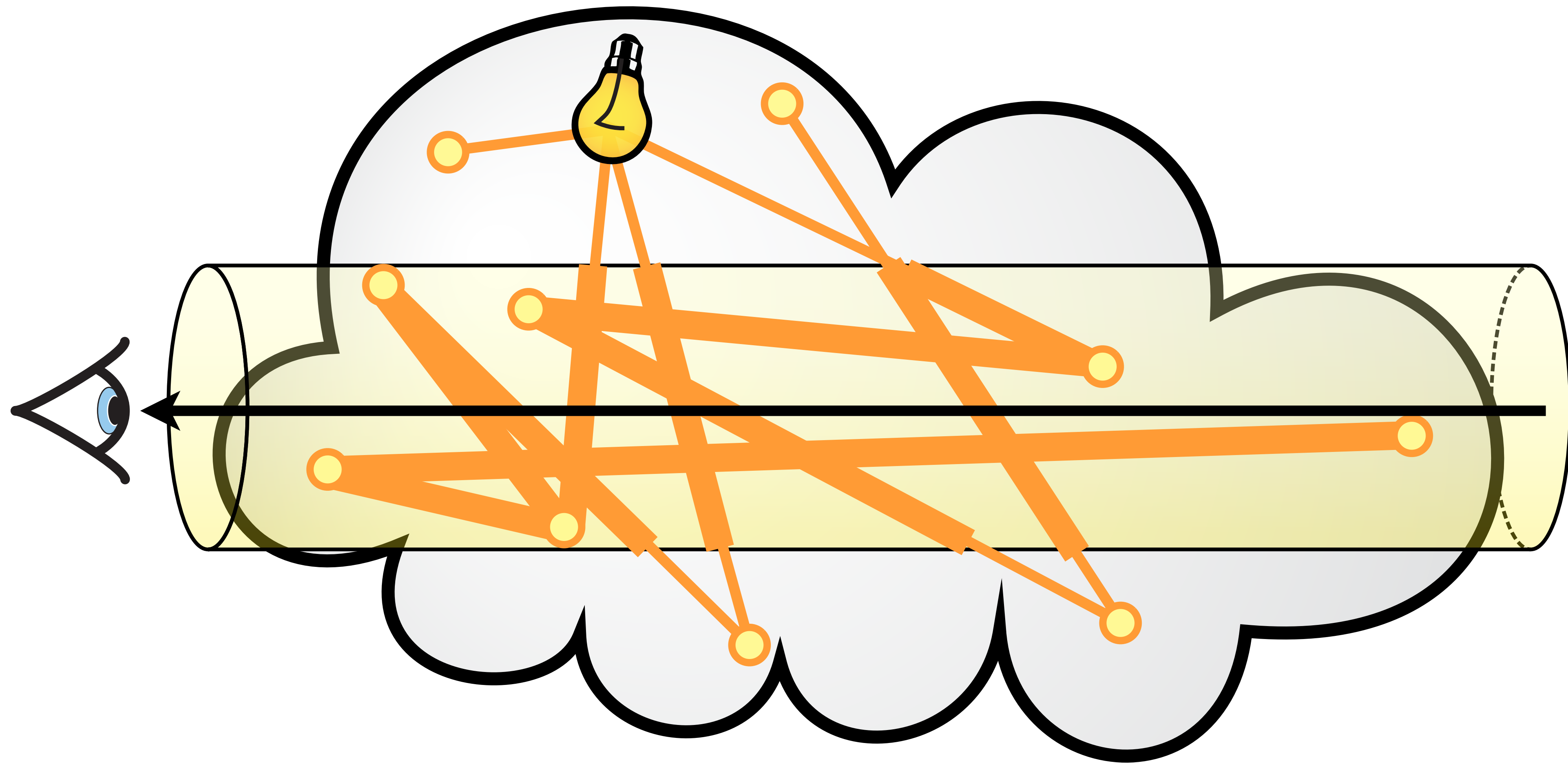
[Jarosz et al. 11]



Photon Beams x Point Query

Volumetric photon mapping

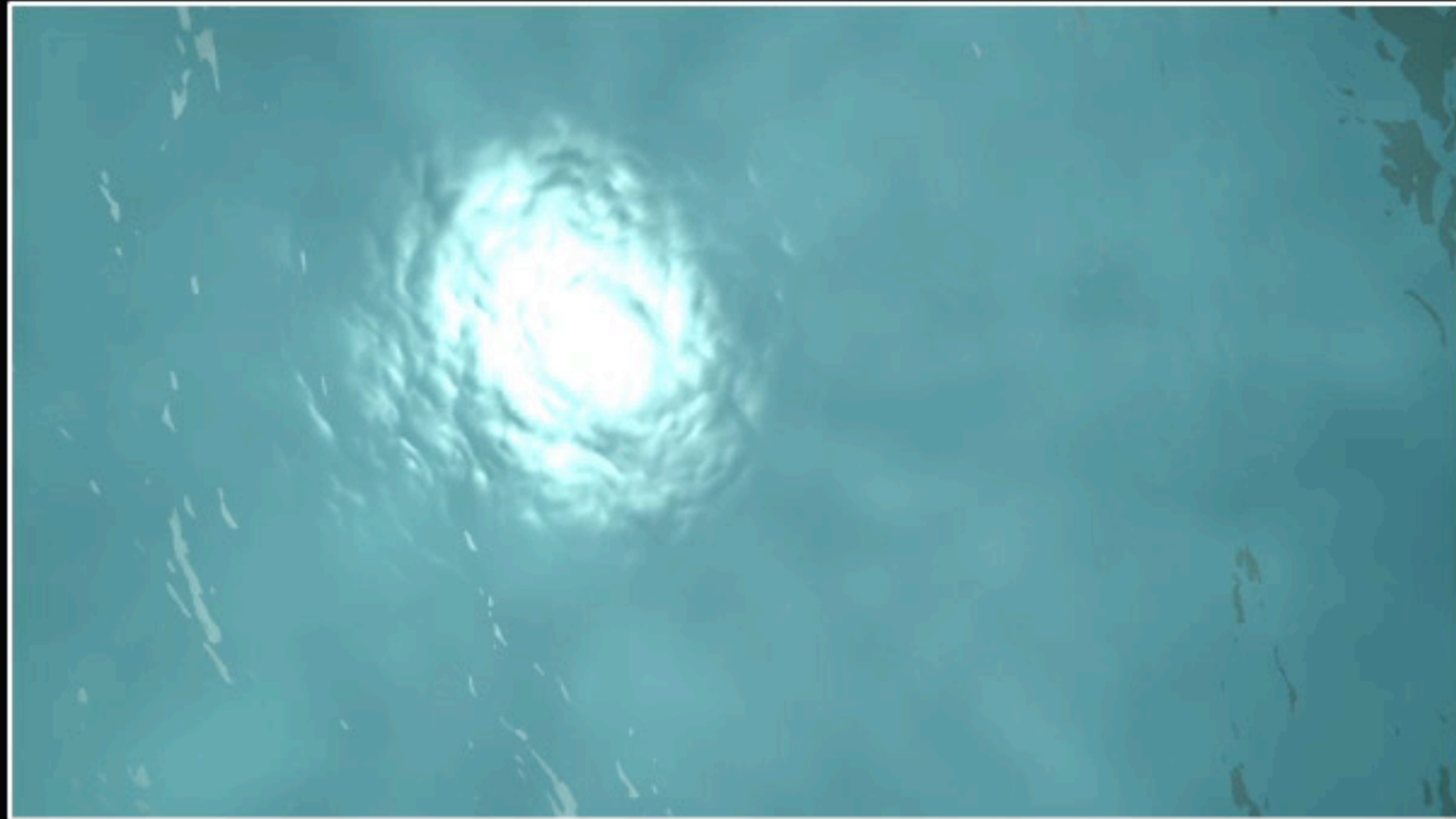
[Jarosz et al. 11]



Photon Beams \times Beam Query

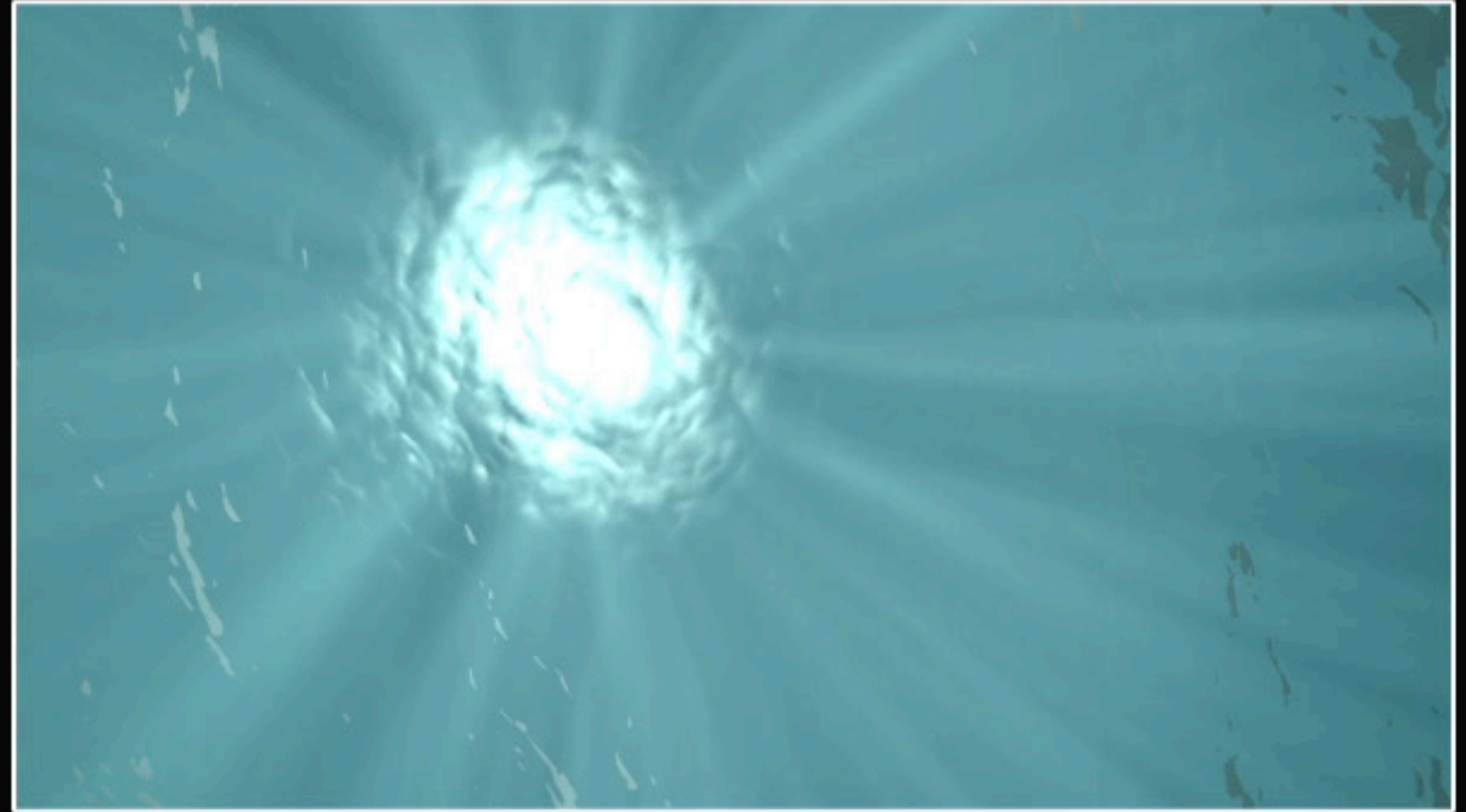
Underwater Sun Beams

Photon Points



100K Photon **Points**
~ 204 seconds/frame

Photon Beams

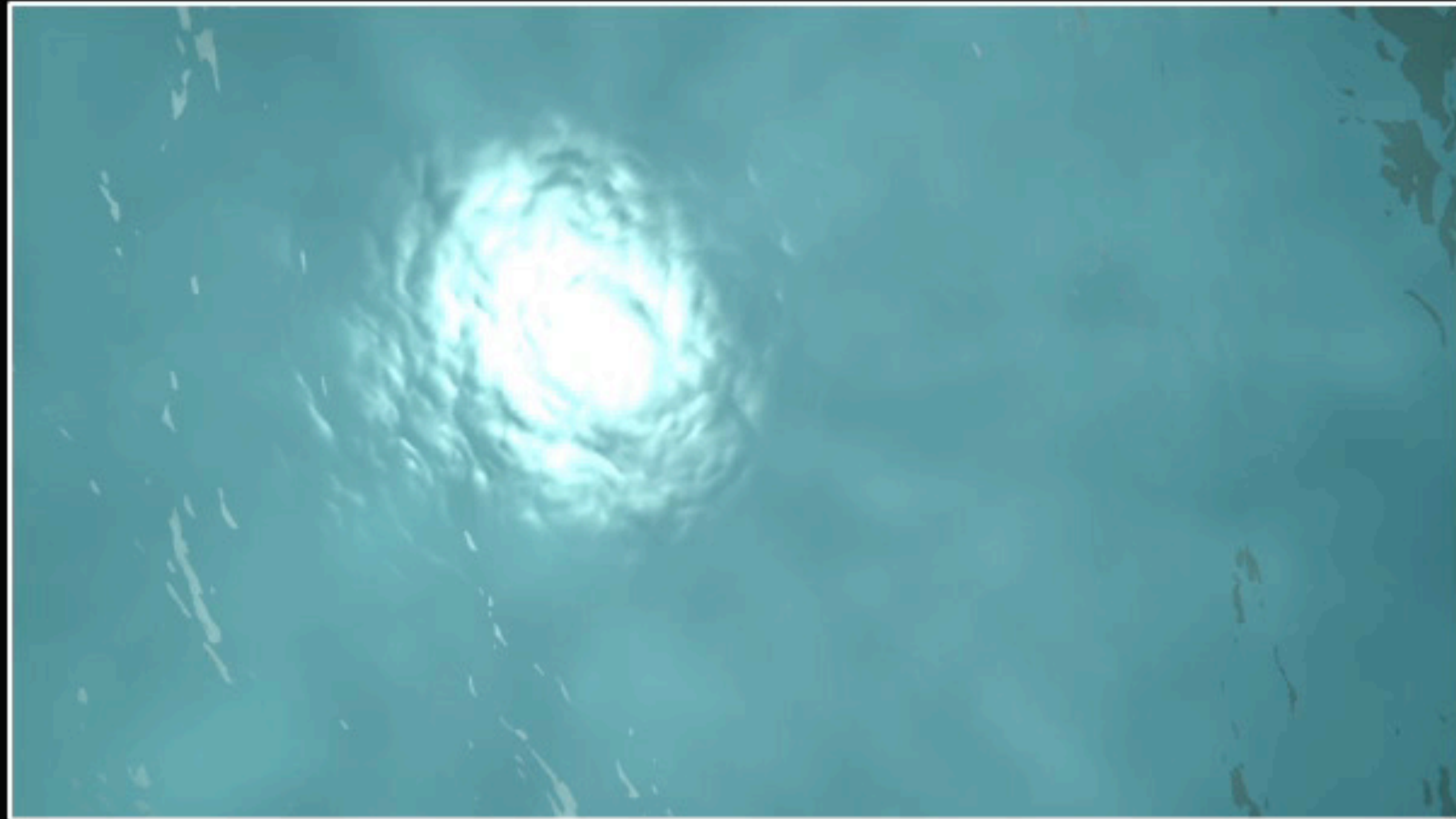


25K Photon **Beams**
~ 200 seconds/frame

Roughly Equal Time

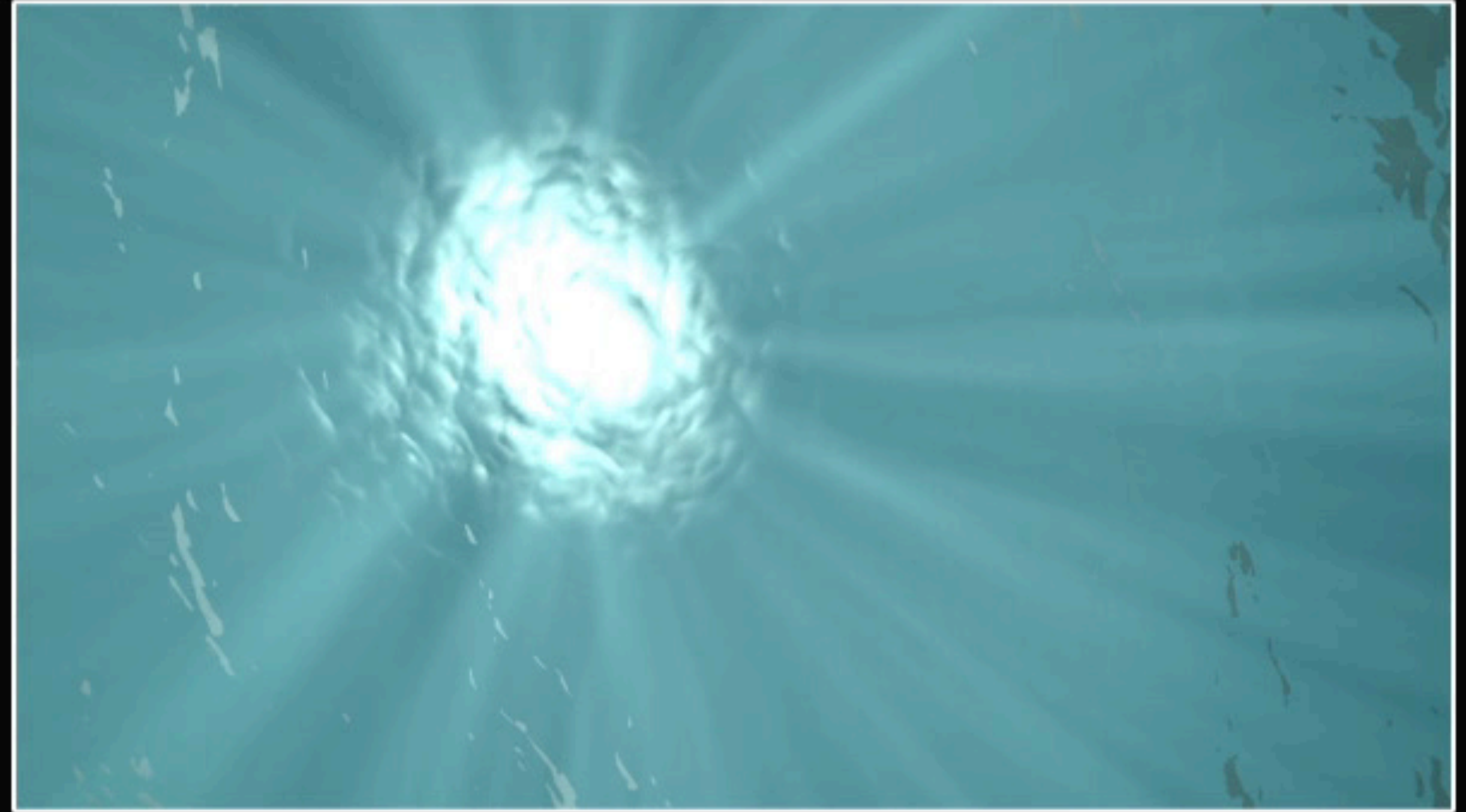
Underwater Sun Beams

Photon Points



100K Photon **Points**
~ 204 seconds/frame

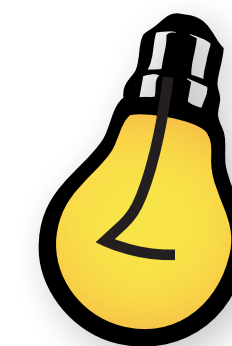
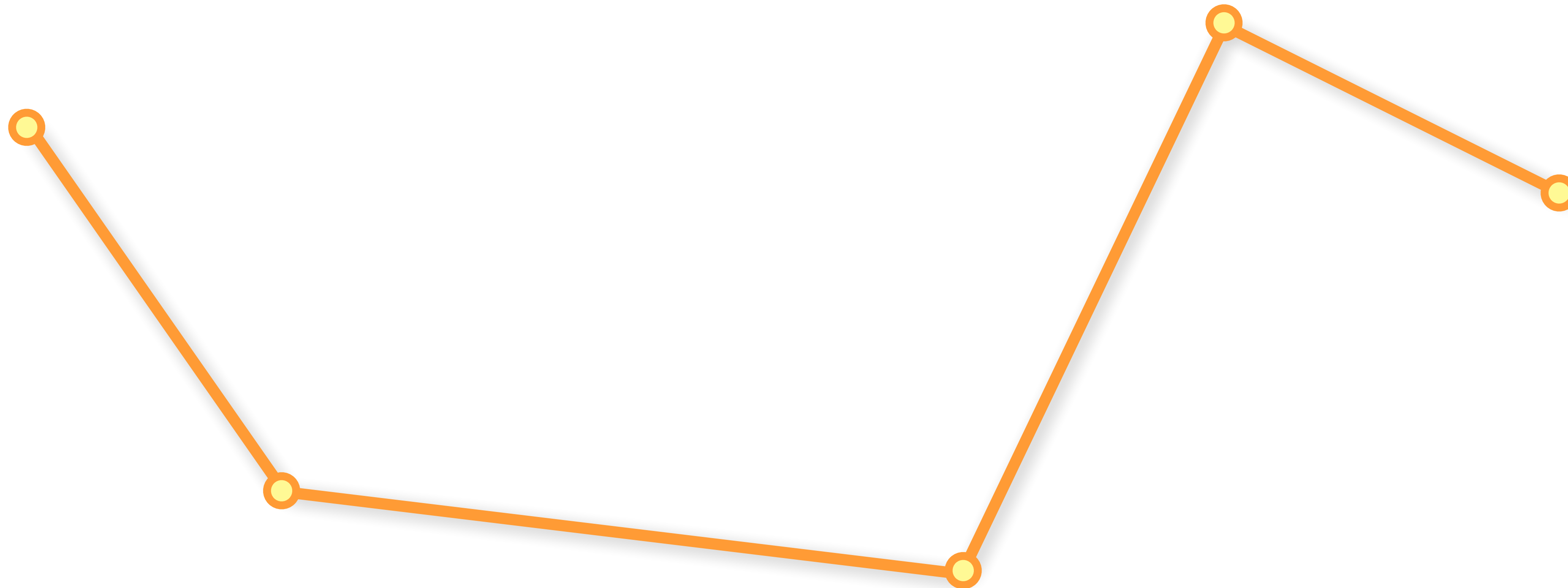
Photon Beams



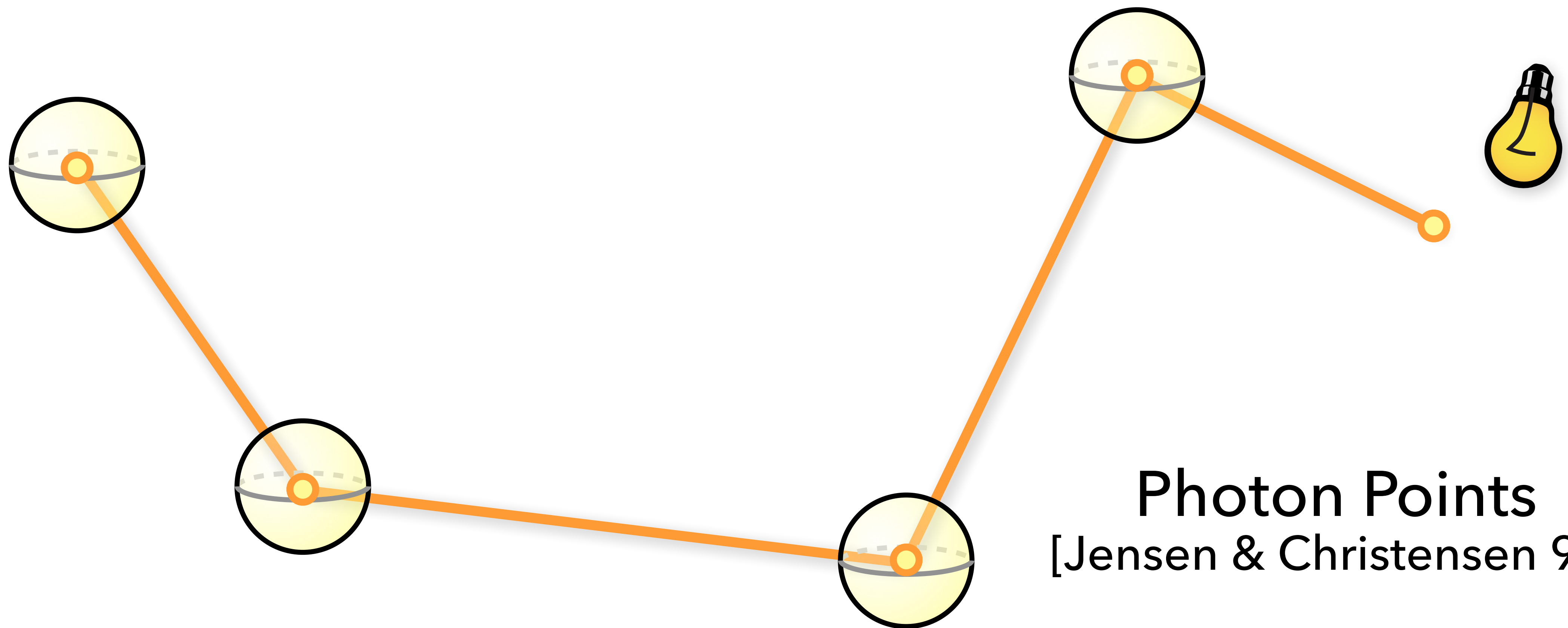
25K Photon **Beams**
~ 200 seconds/frame

Roughly Equal Time

Photon Points

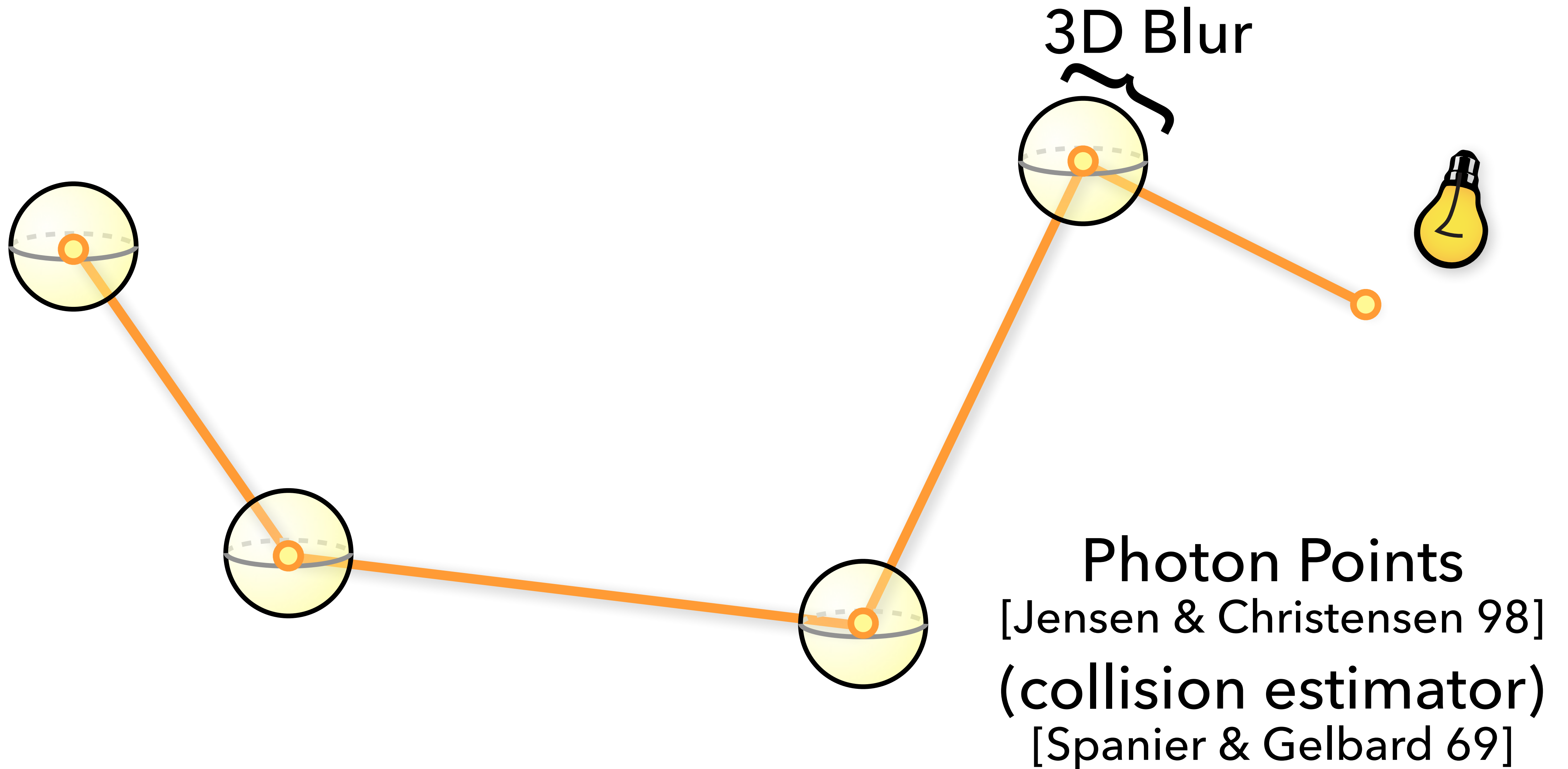


Photon Points

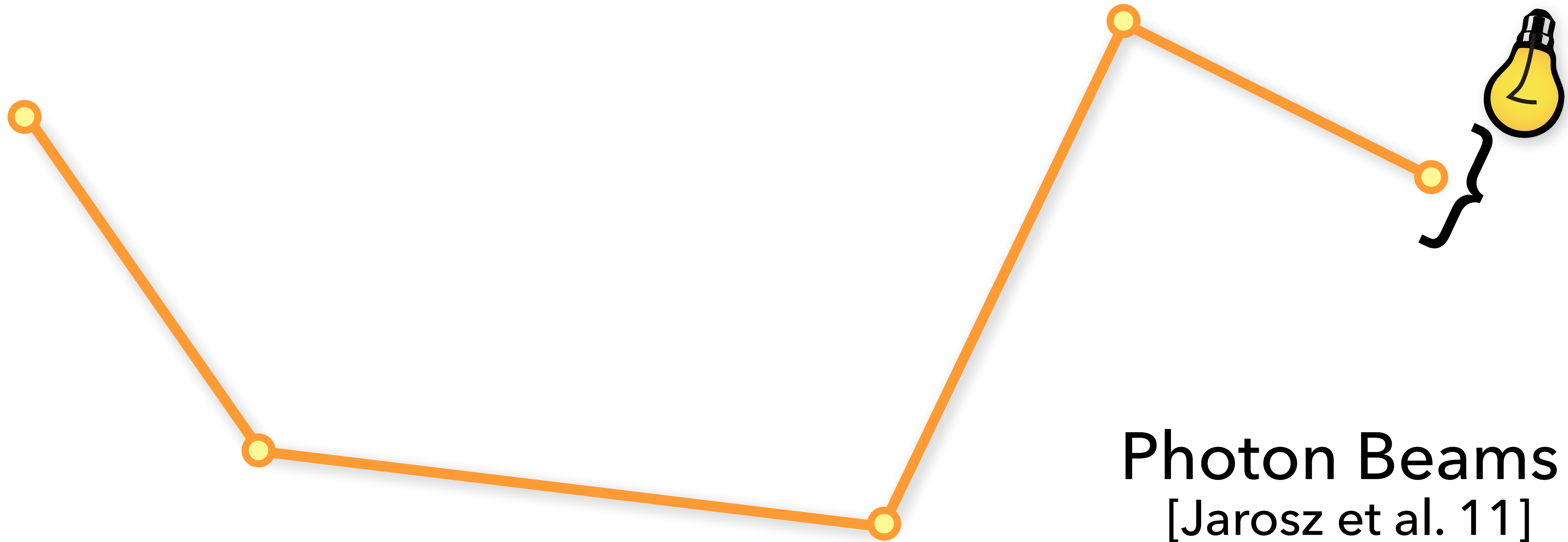


Photon Points
[Jensen & Christensen 98]

Photon Points

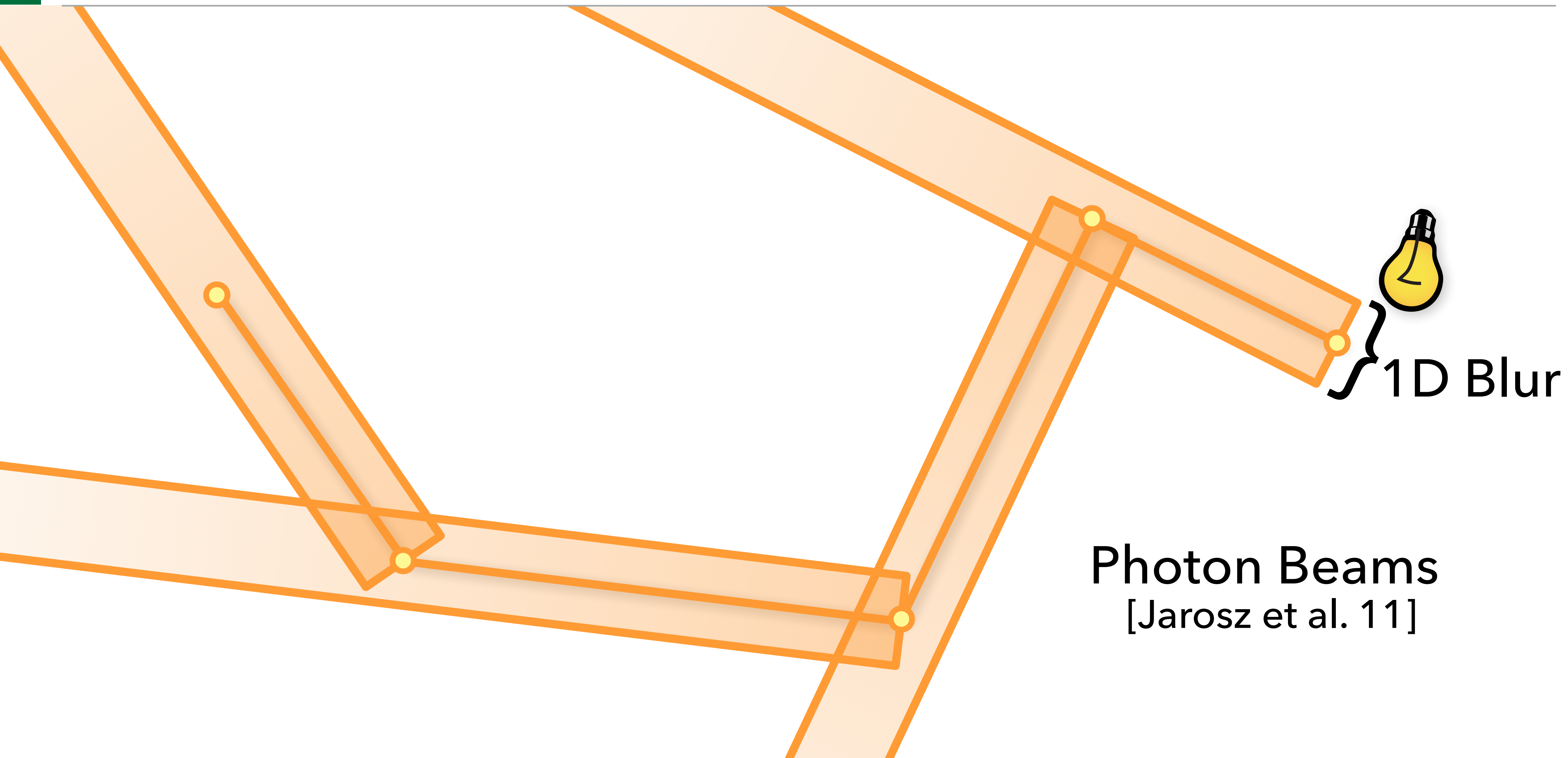


Photon Beams



Photon Beams
[Jarosz et al. 11]

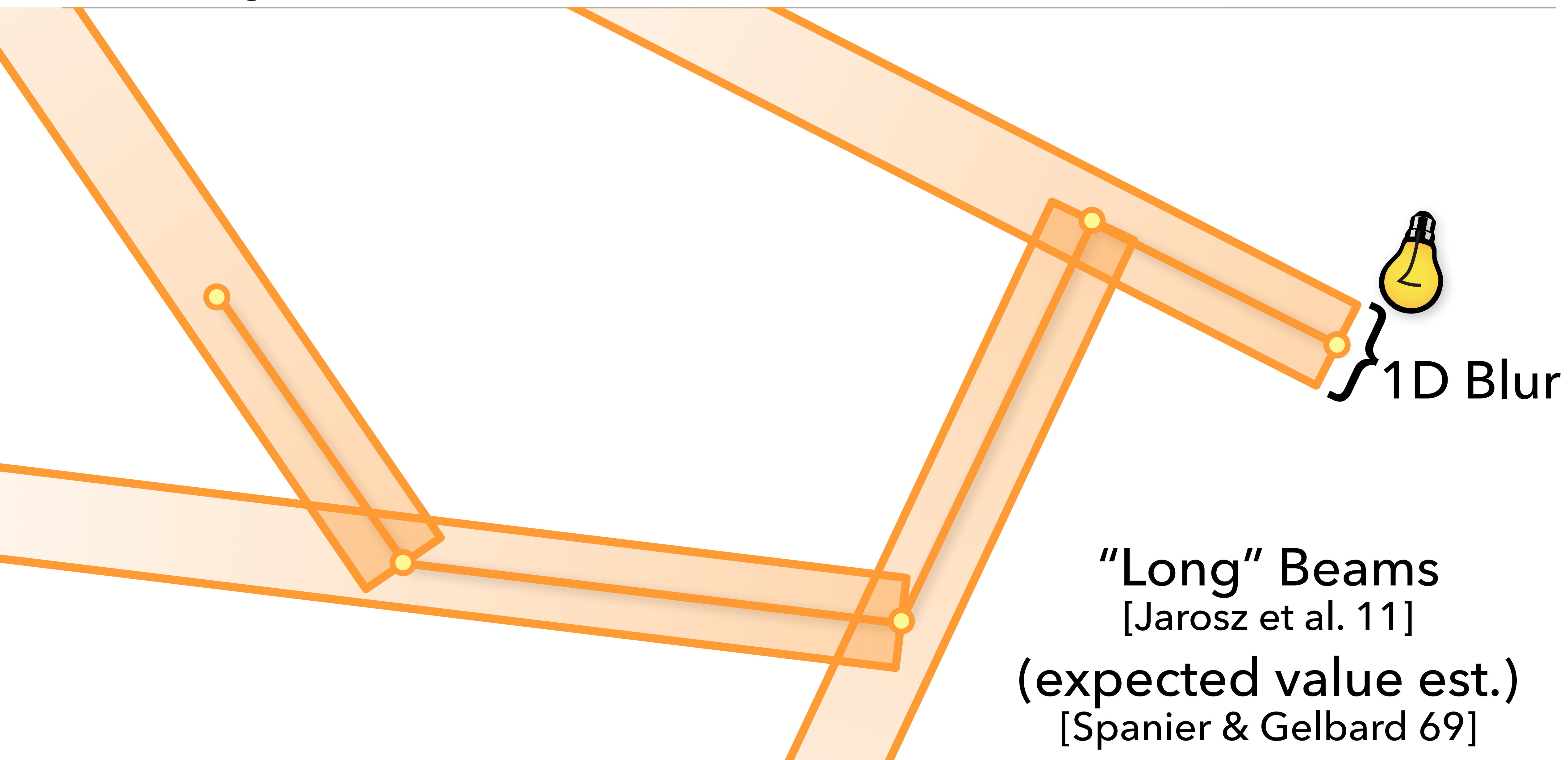
Photon Beams



1D Blur

Photon Beams
[Jarosz et al. 11]

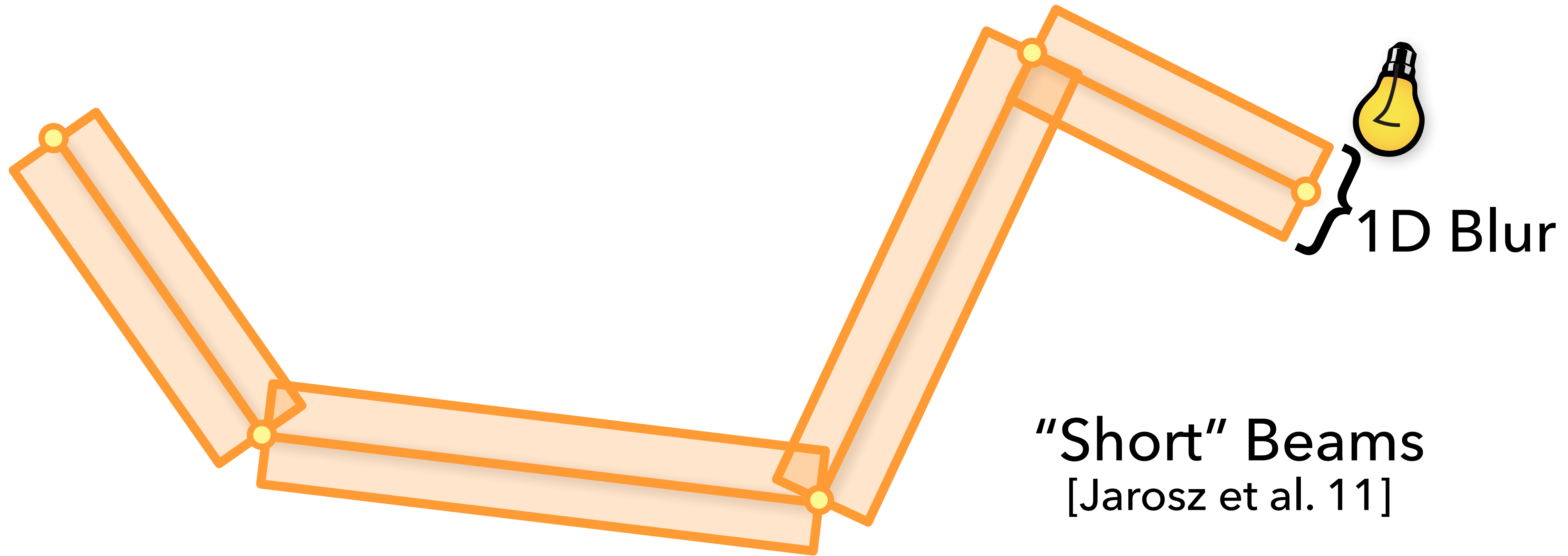
(Long) Photon Beams



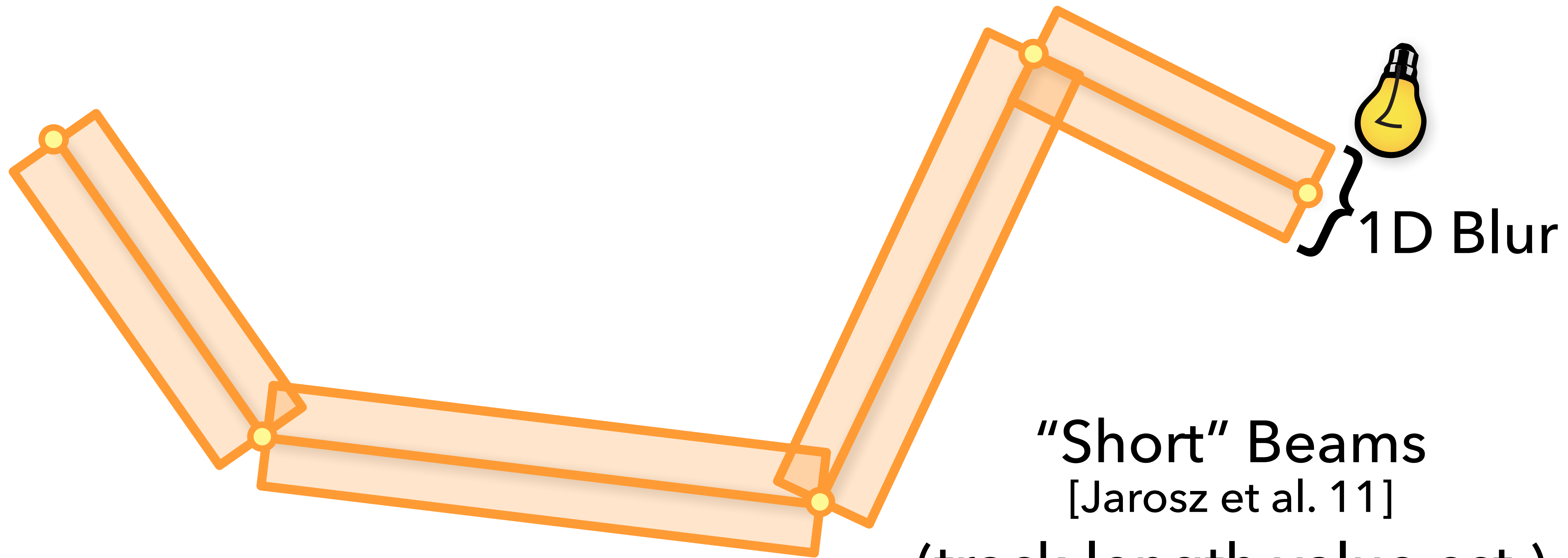
1D Blur

"Long" Beams
[Jarosz et al. 11]
(expected value est.)
[Spanier & Gelbard 69]

(Short) Photon Beams



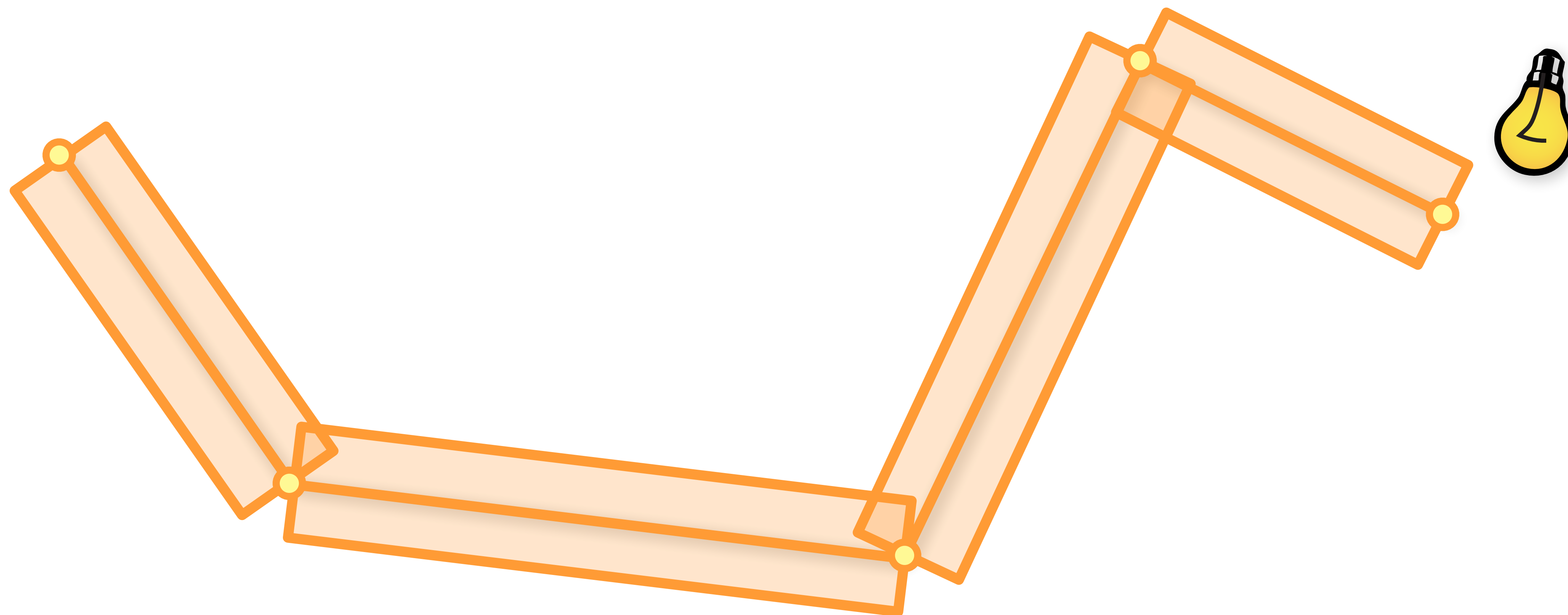
(Short) Photon Beams



"Short" Beams
[Jarosz et al. 11]

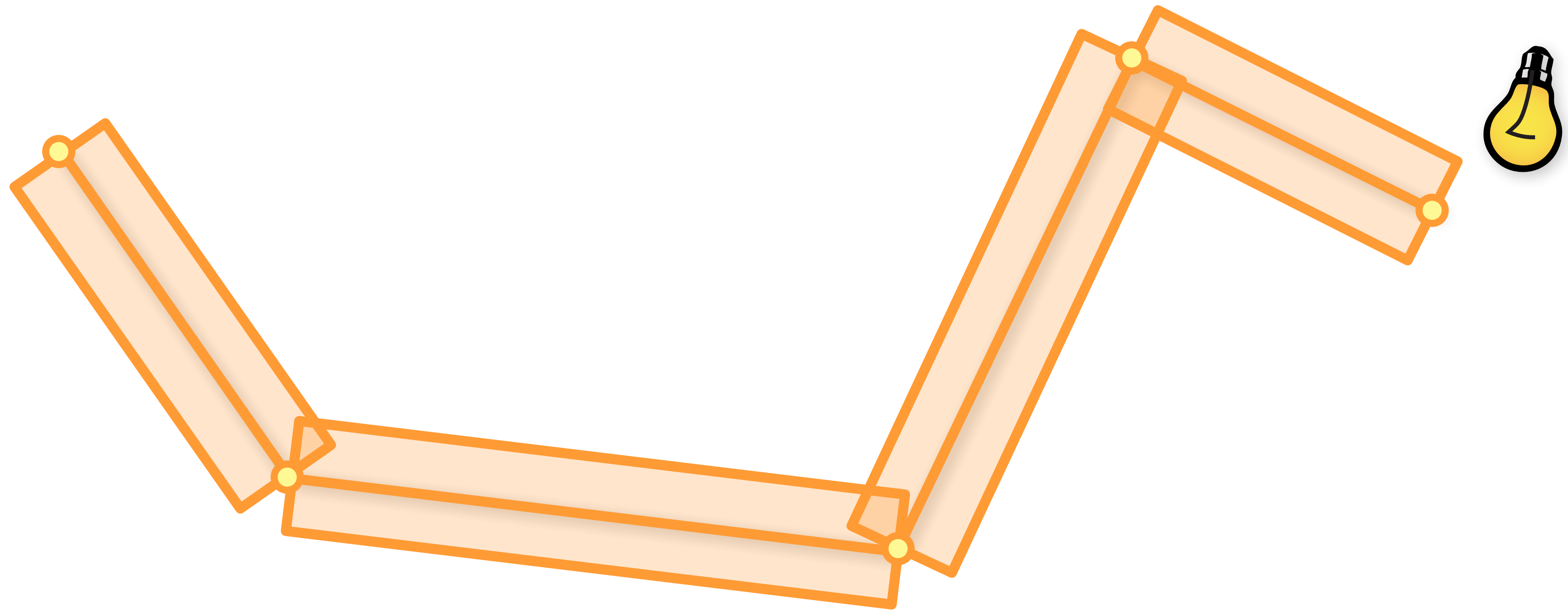
(track-length value est.)
[Spanier & Gelbard 69]

Beyond Photon Beams?

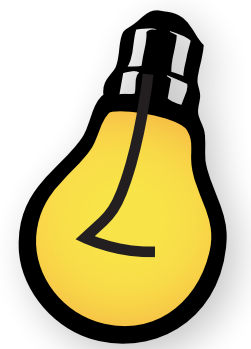
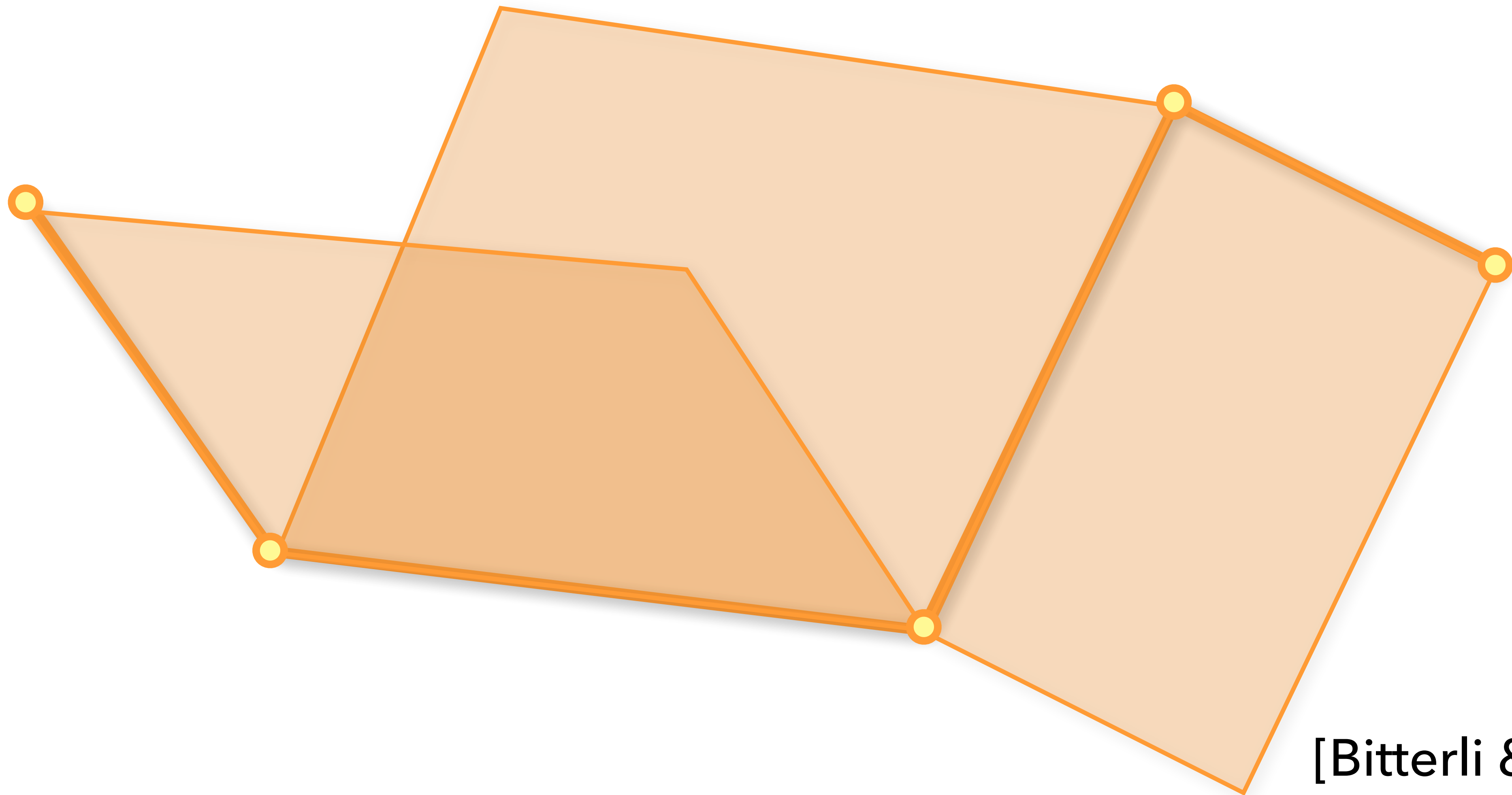


Beyond Photon Beams?

We can keep going to higher dimensional "photons"!



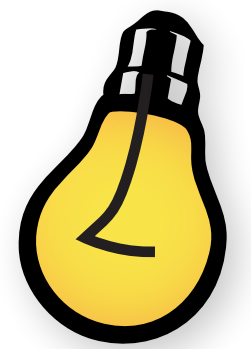
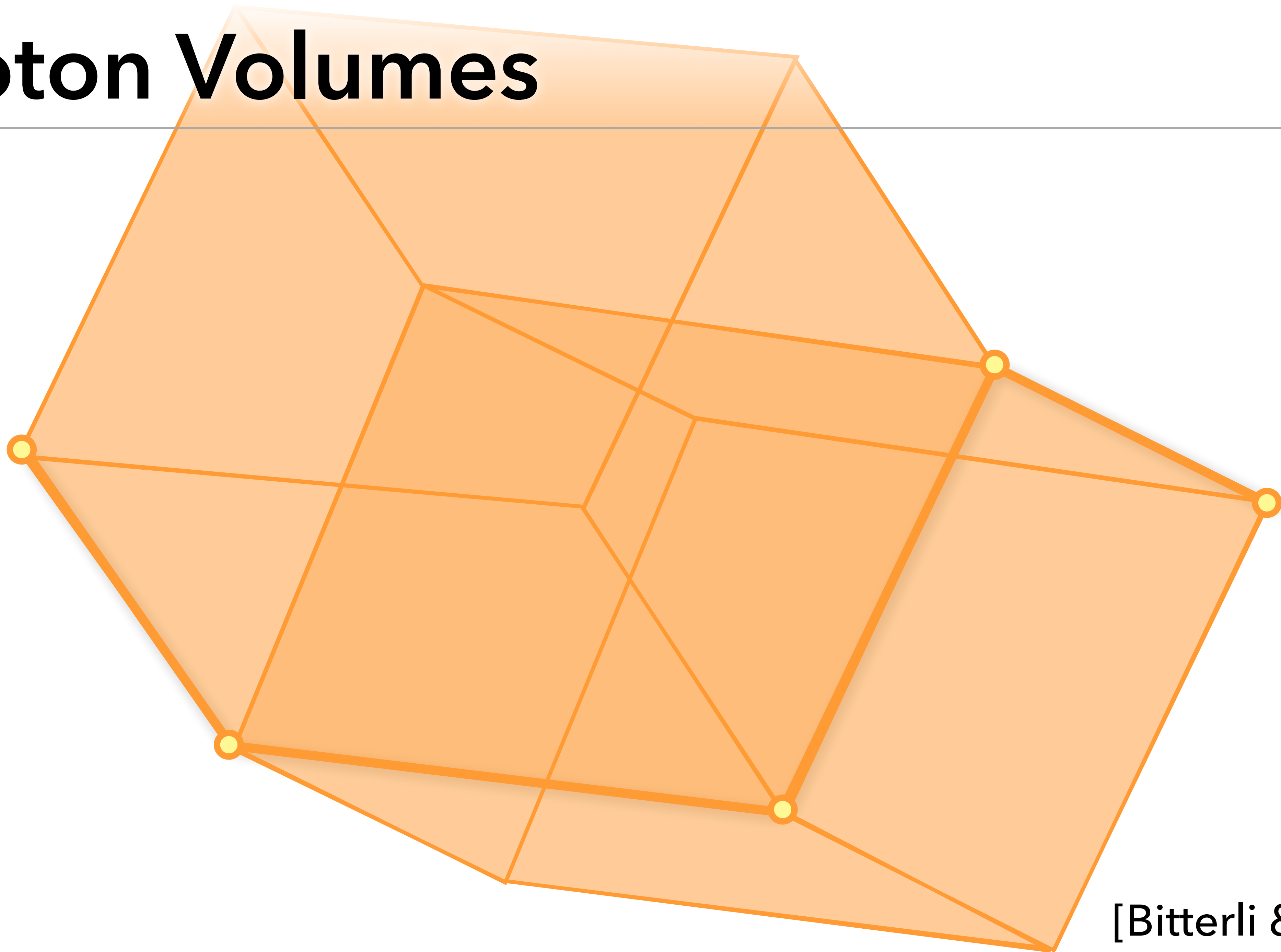
Photon Planes



0D Blur
Unbiased

[Bitterli & Jarosz 17]

Photon Volumes

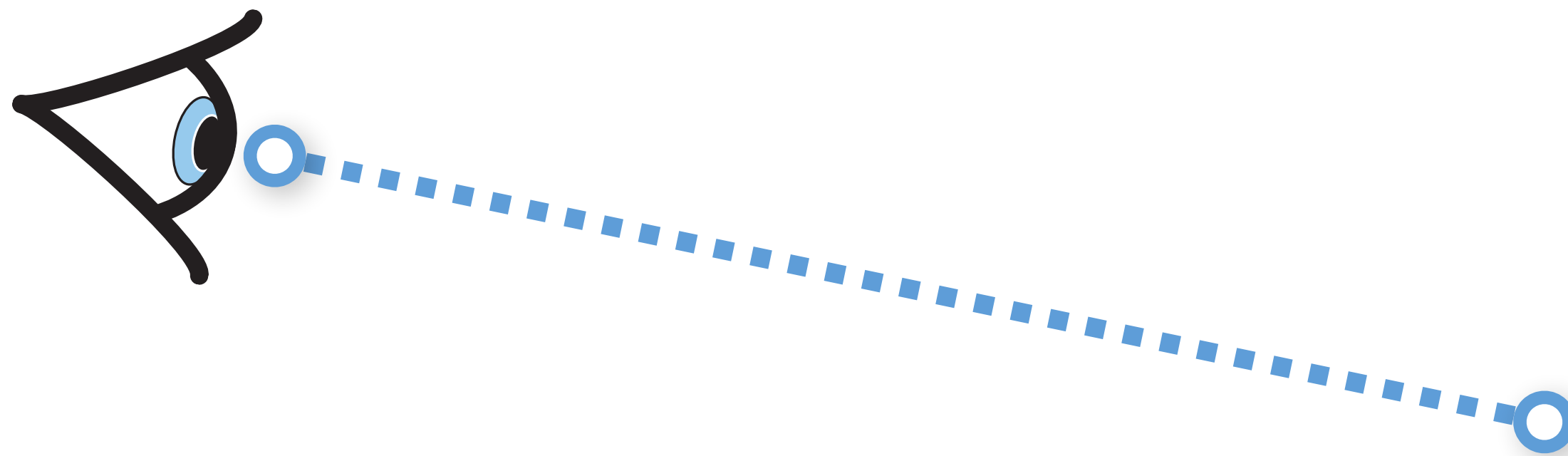
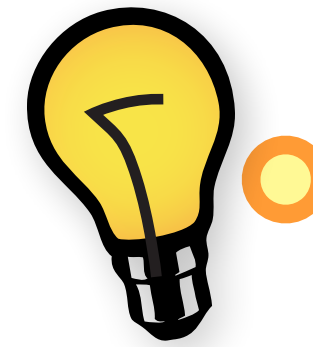


0D Blur
Unbiased

[Bitterli & Jarosz 17]

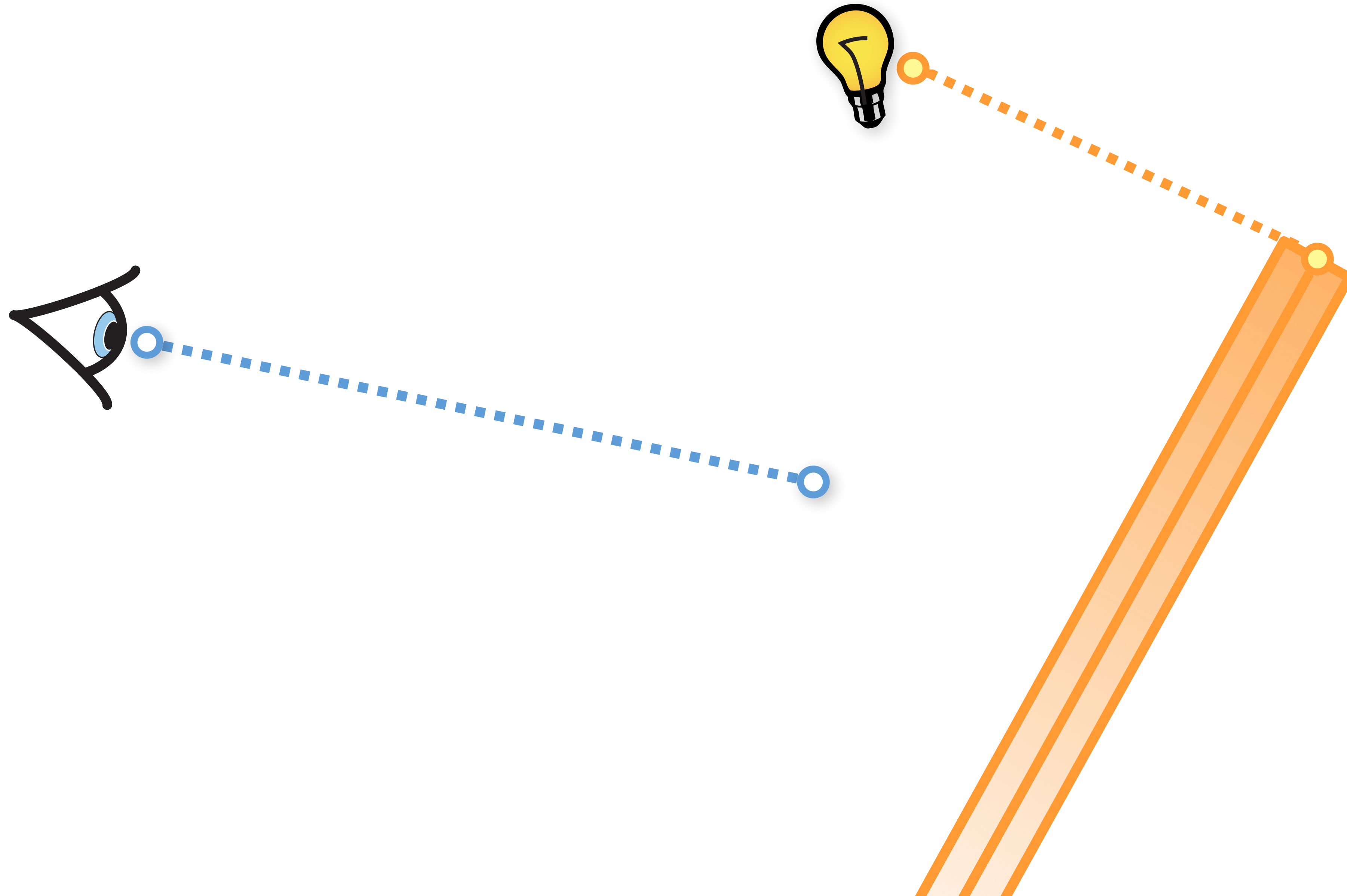
Photon Beams

[Bitterli & Jarosz 17]



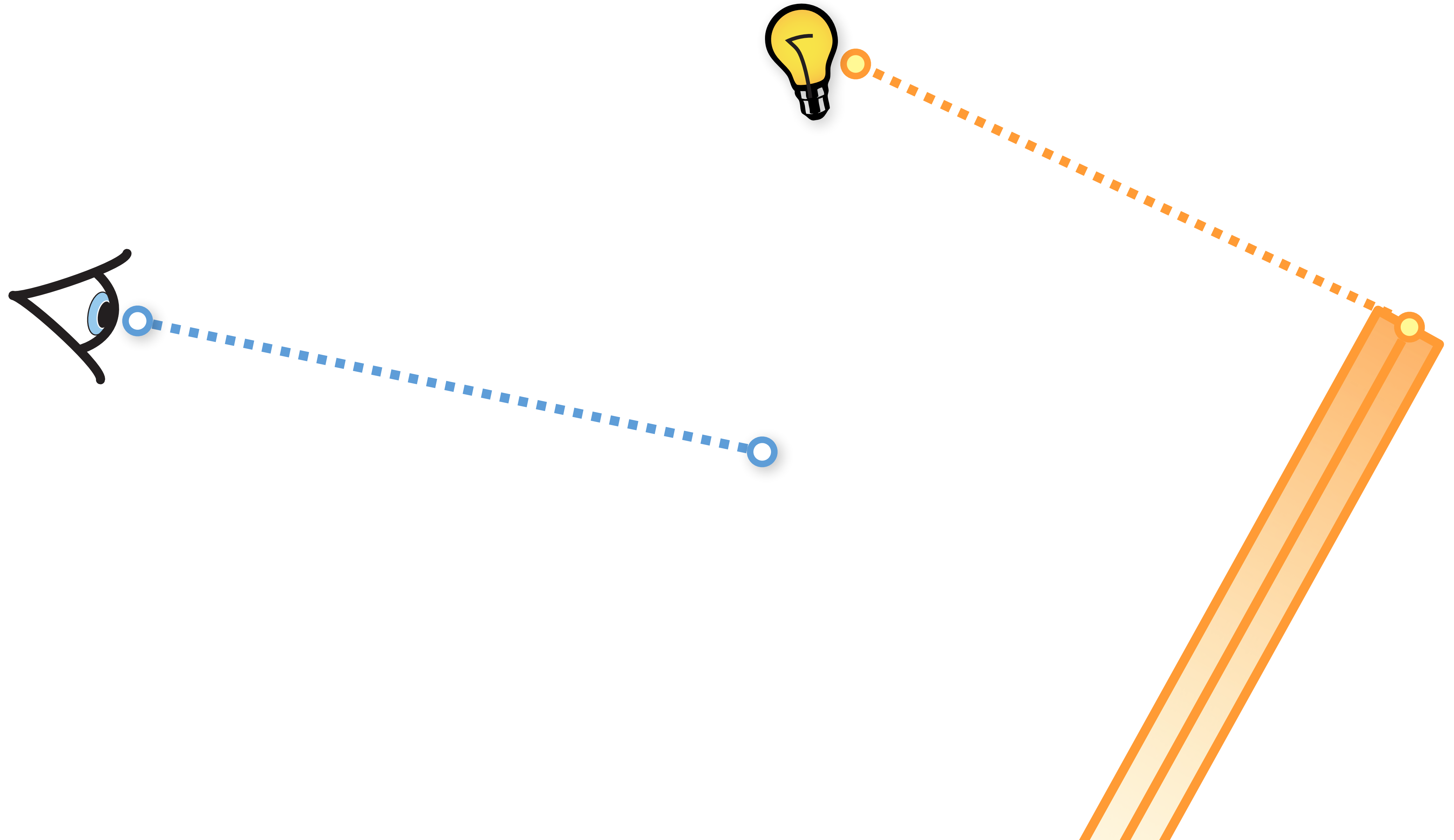
Photon Beams

[Bitterli & Jarosz 17]



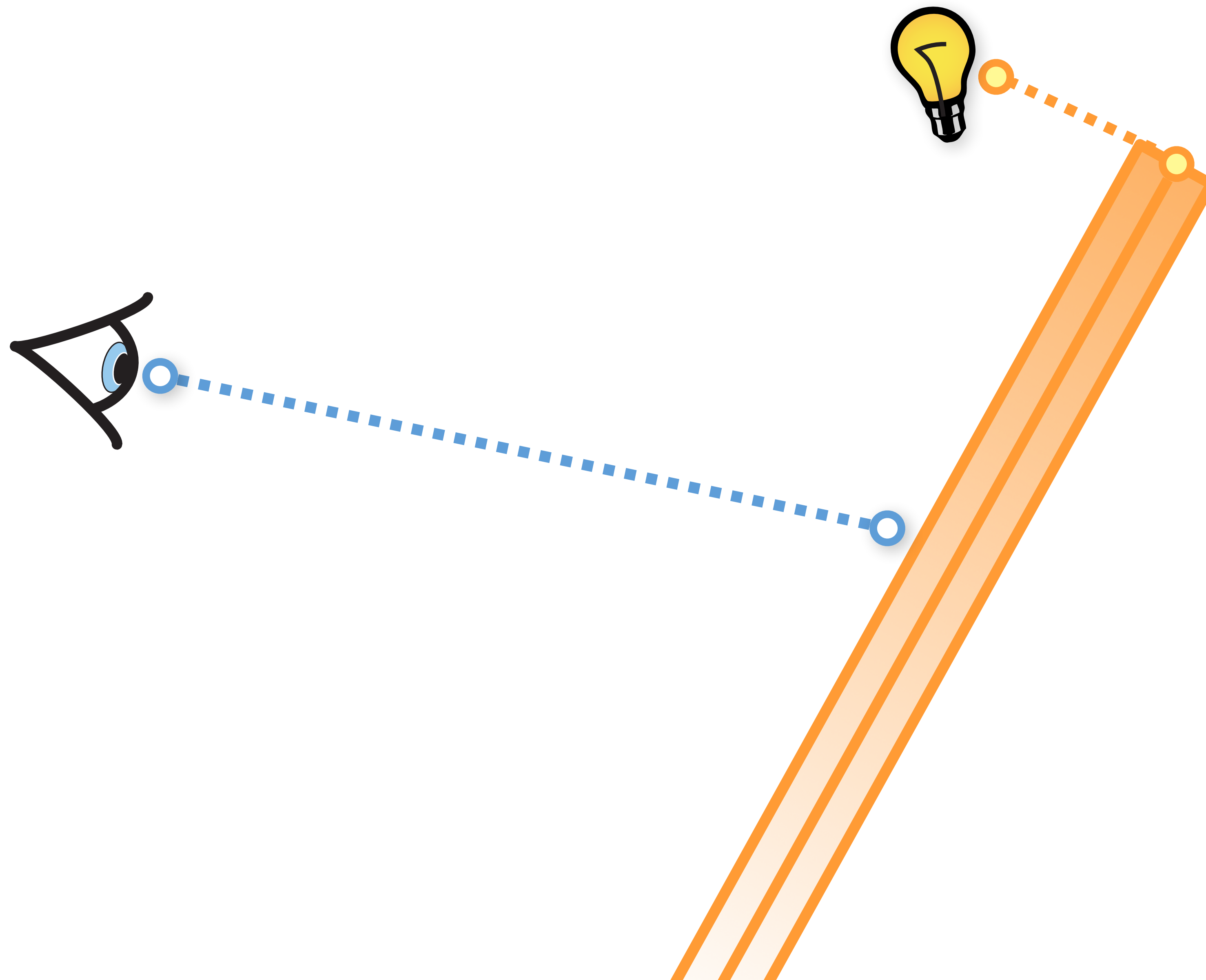
Photon Beams

[Bitterli & Jarosz 17]



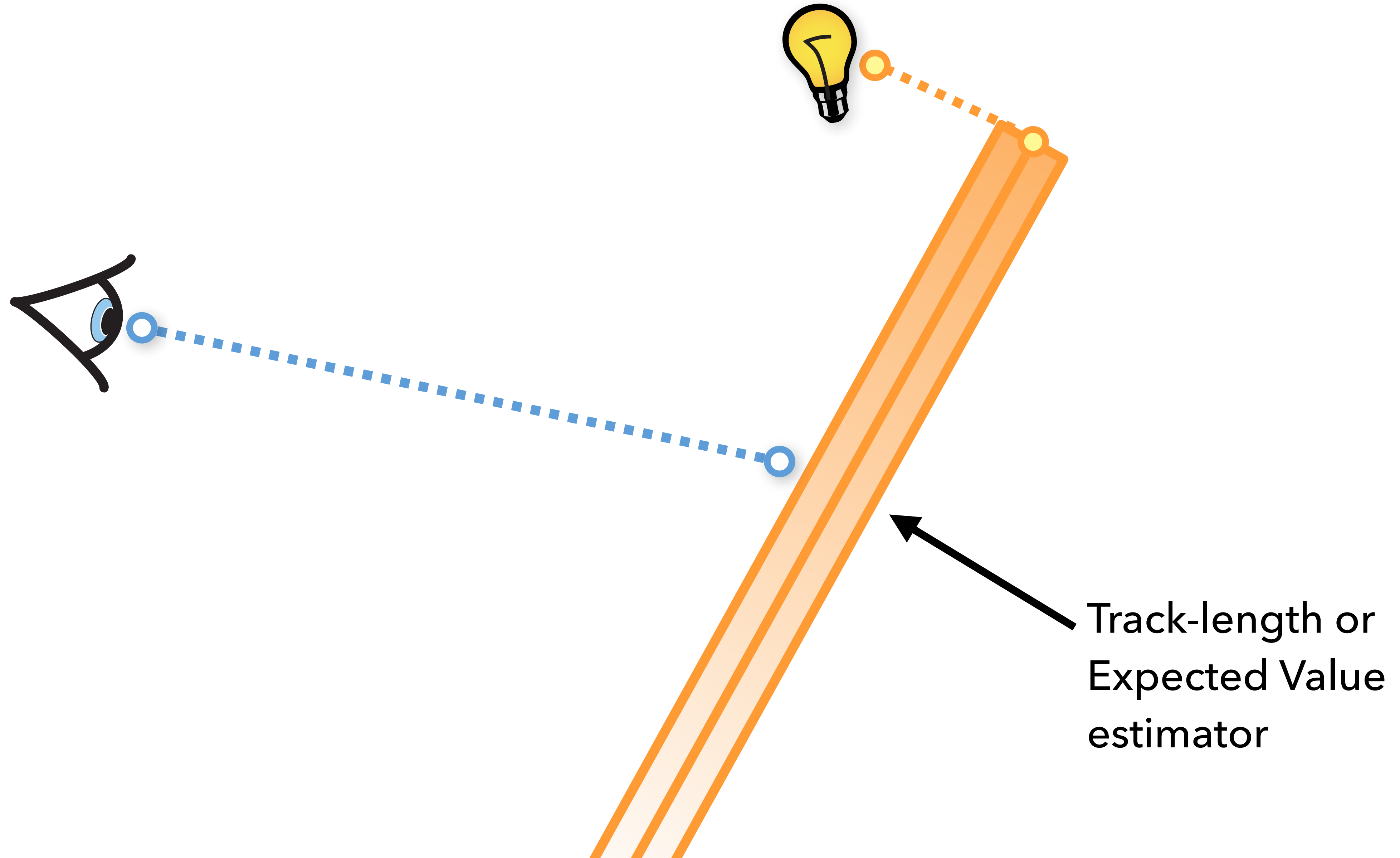
Photon Beams

[Bitterli & Jarosz 17]



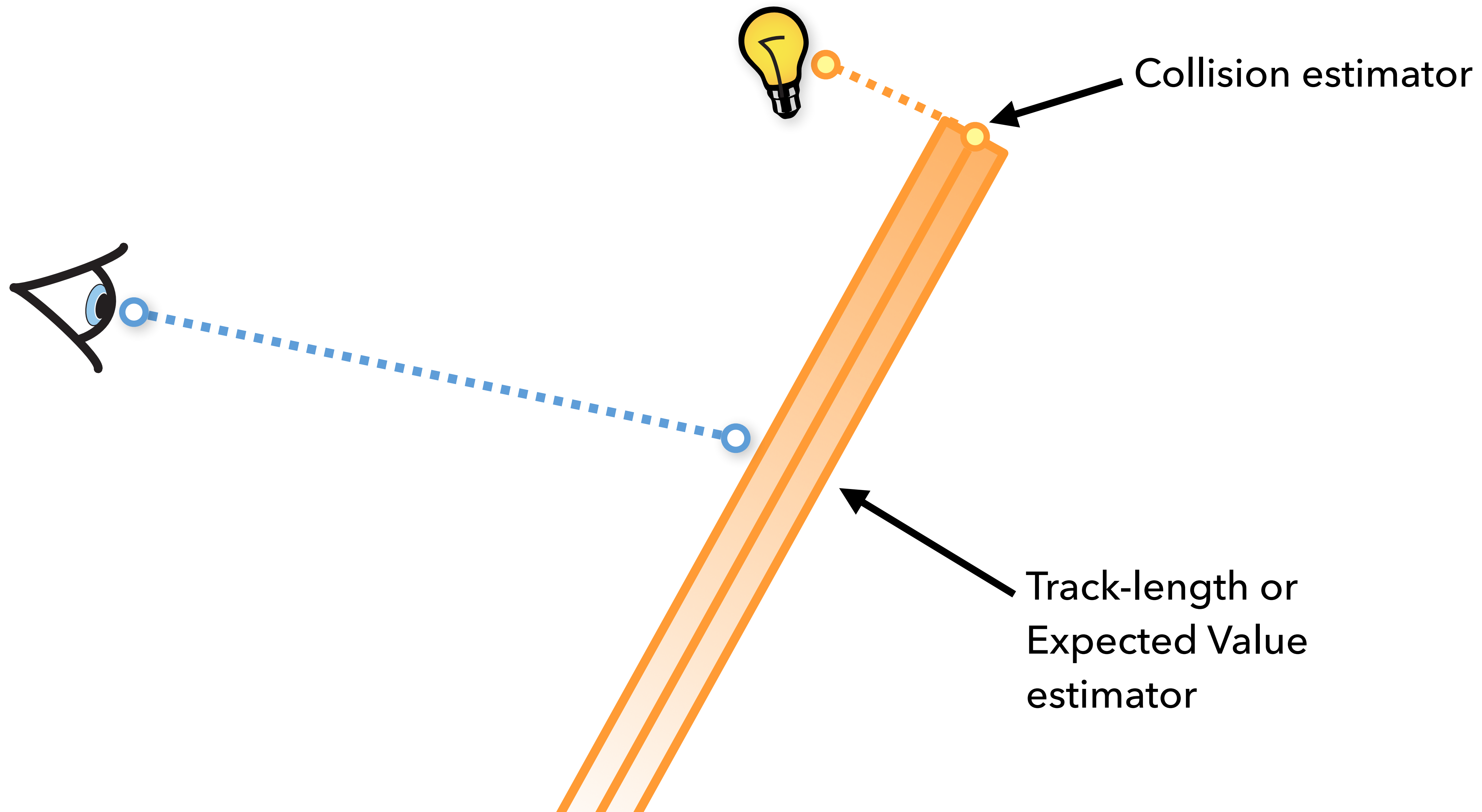
Photon Beams

[Bitterli & Jarosz 17]



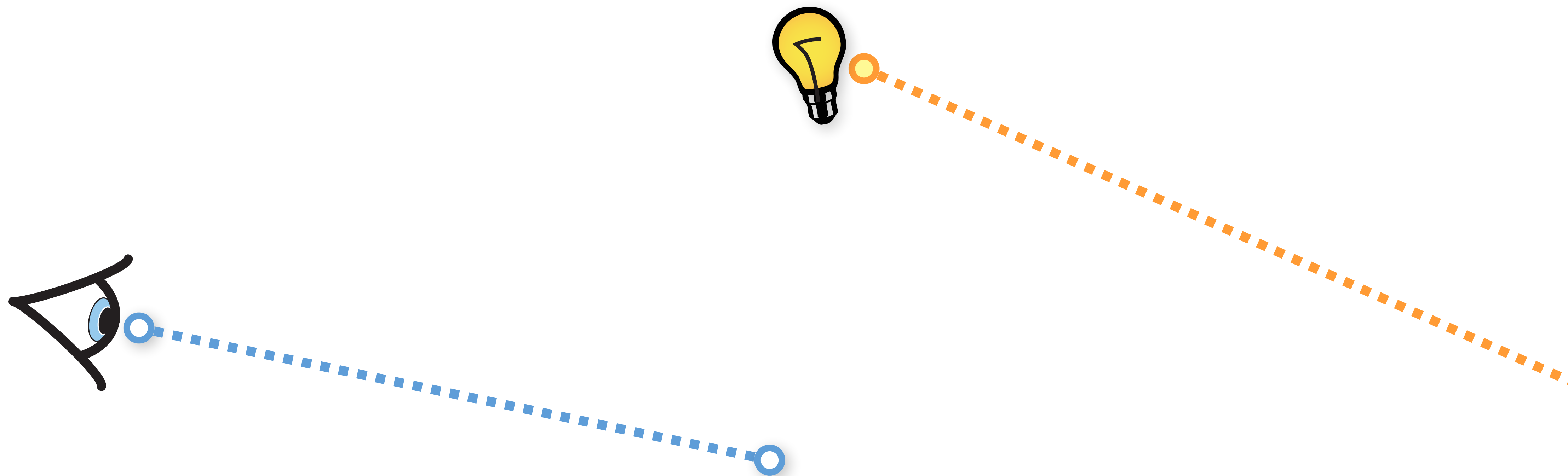
Photon Beams

[Bitterli & Jarosz 17]



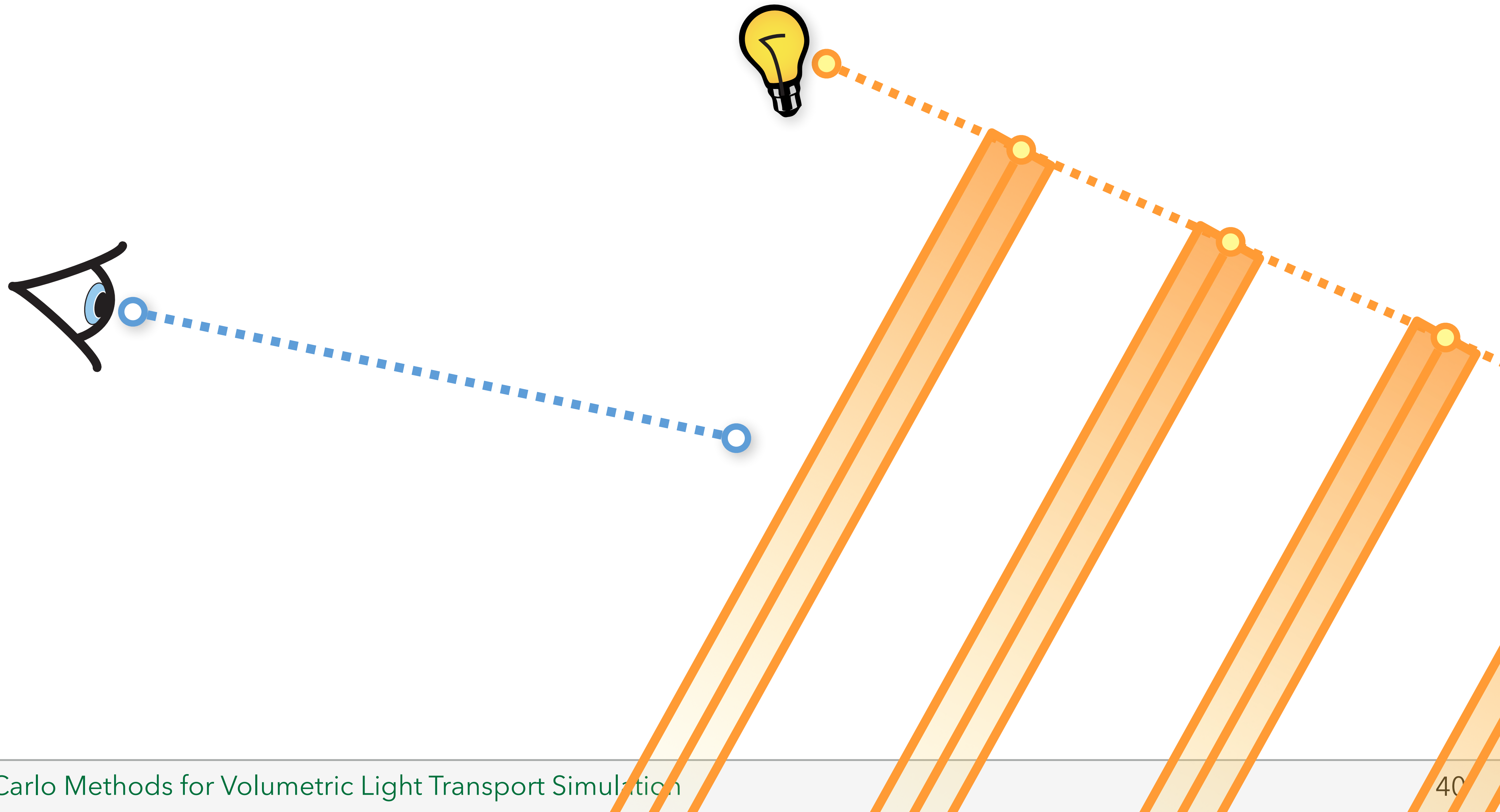
Beam Marching

[Bitterli & Jarosz 17]



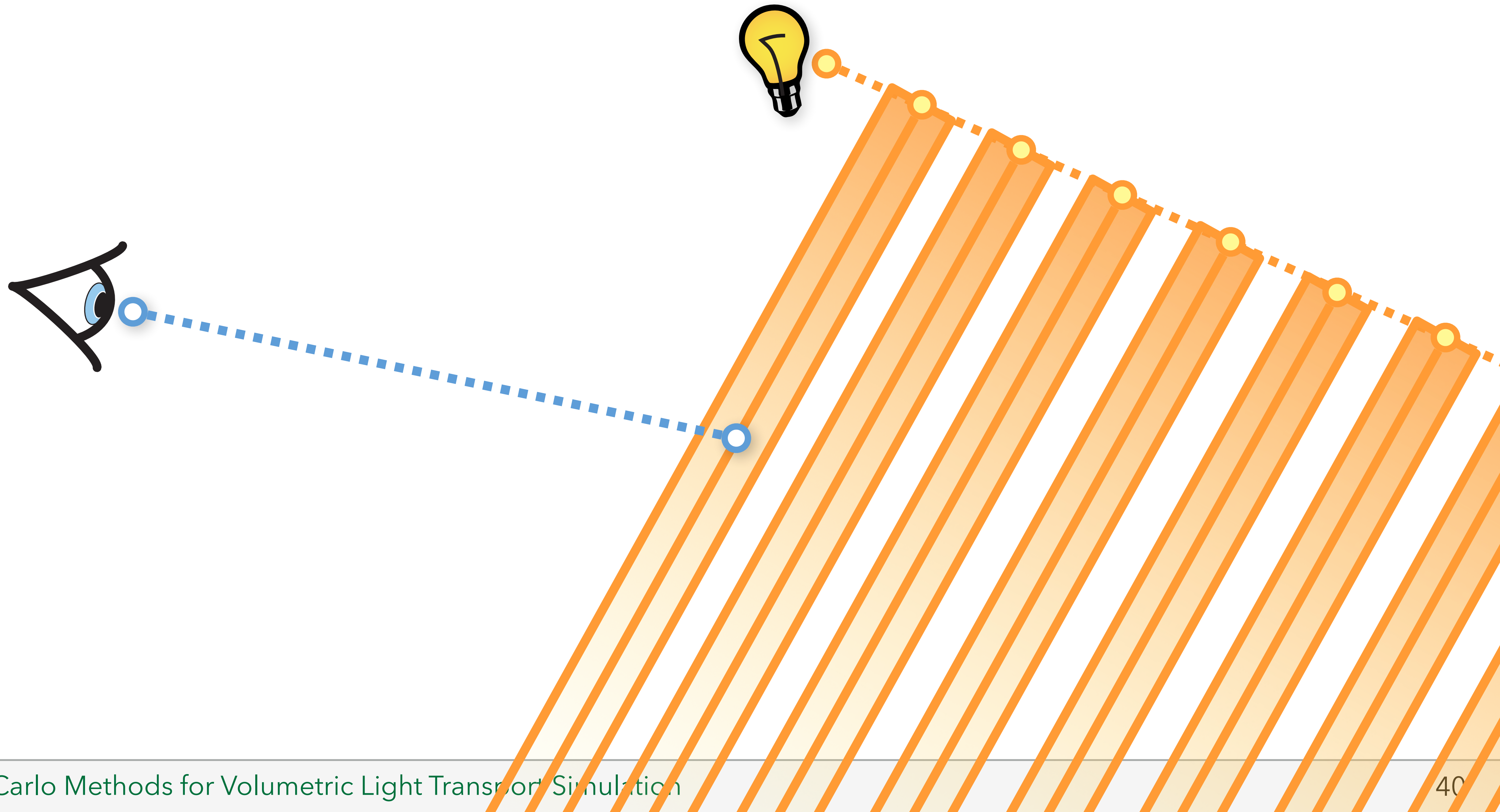
Beam Marching

[Bitterli & Jarosz 17]



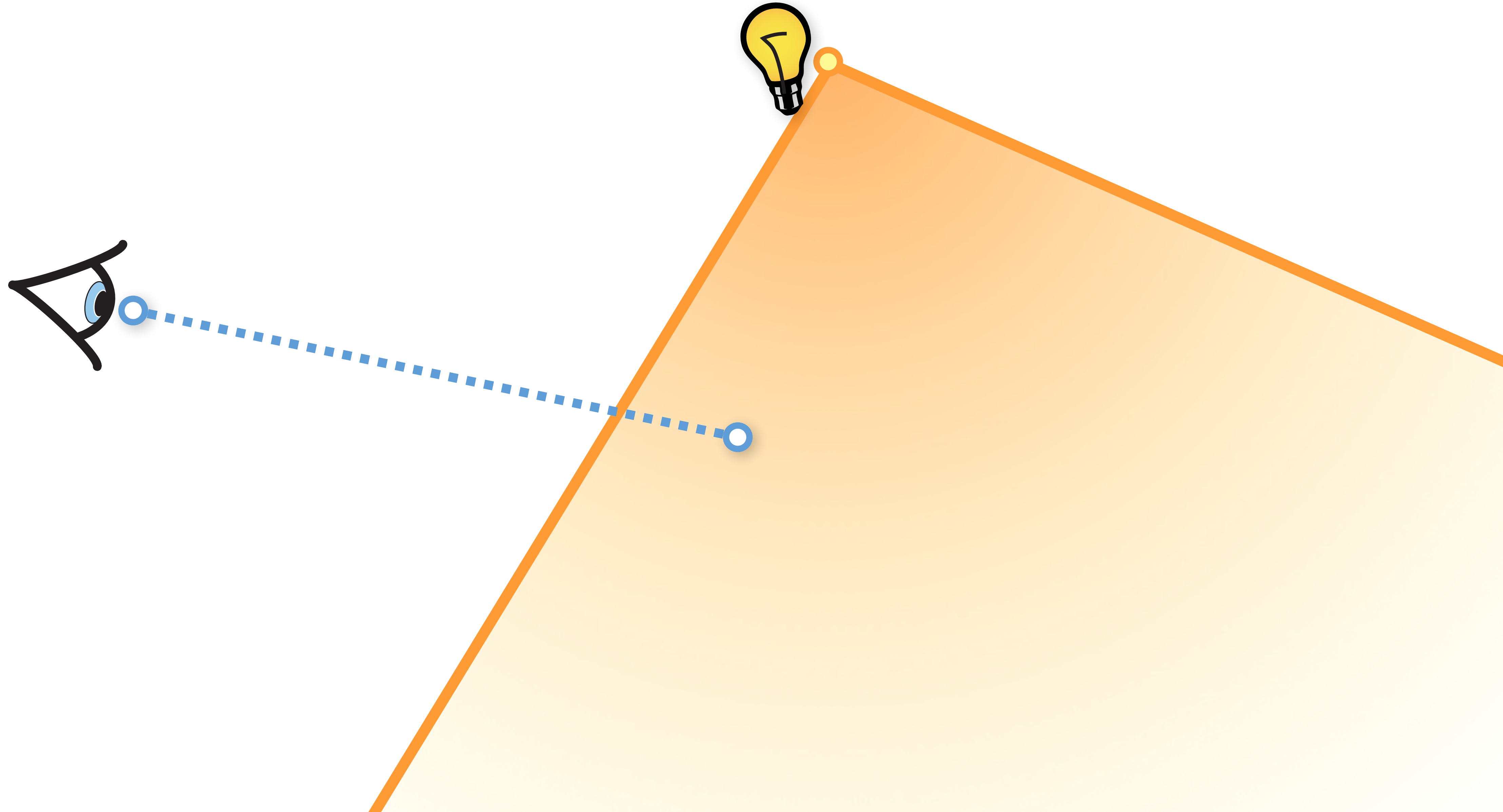
Beam Marching

[Bitterli & Jarosz 17]



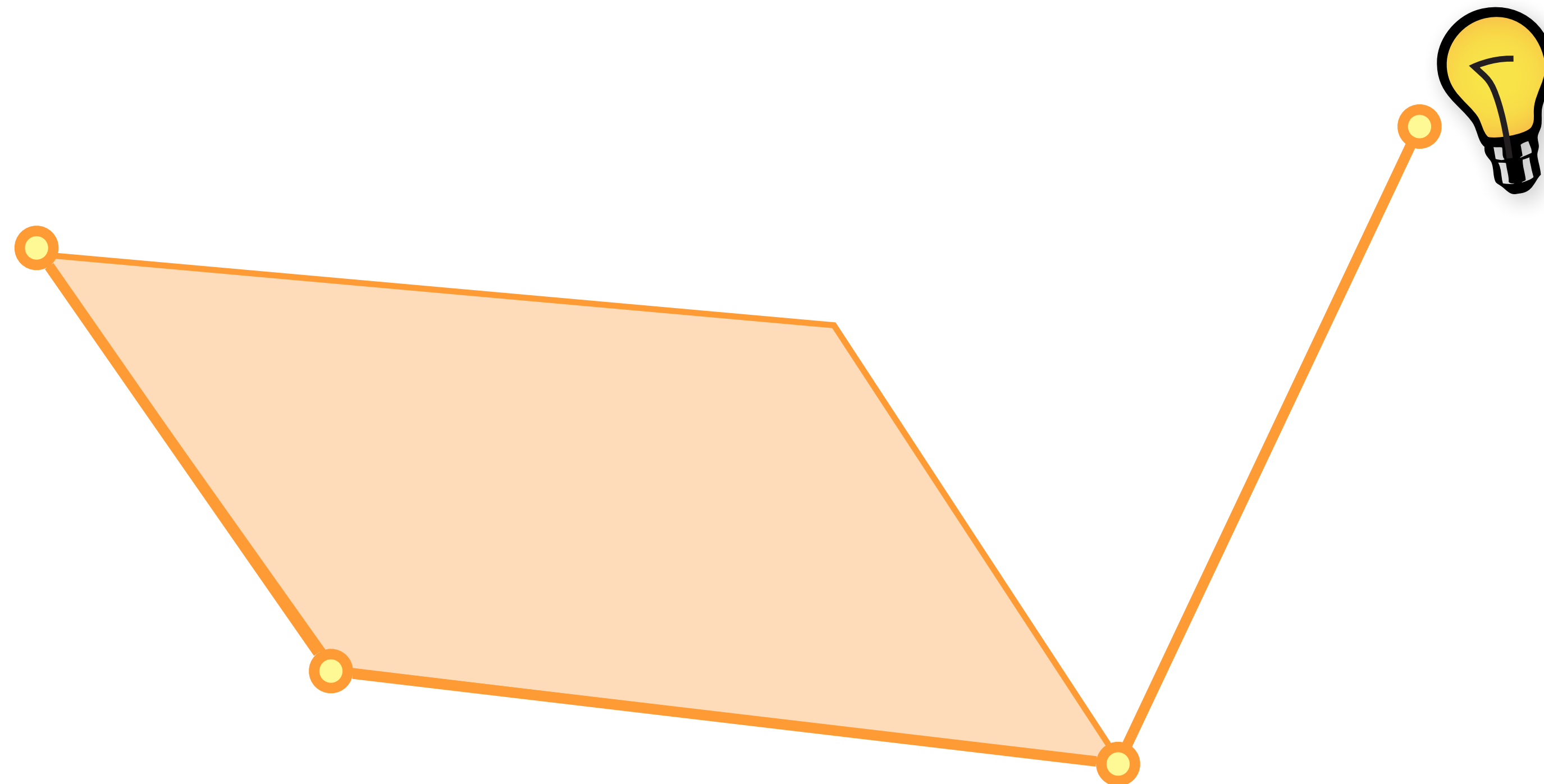
Photon Plane

[Bitterli & Jarosz 17]



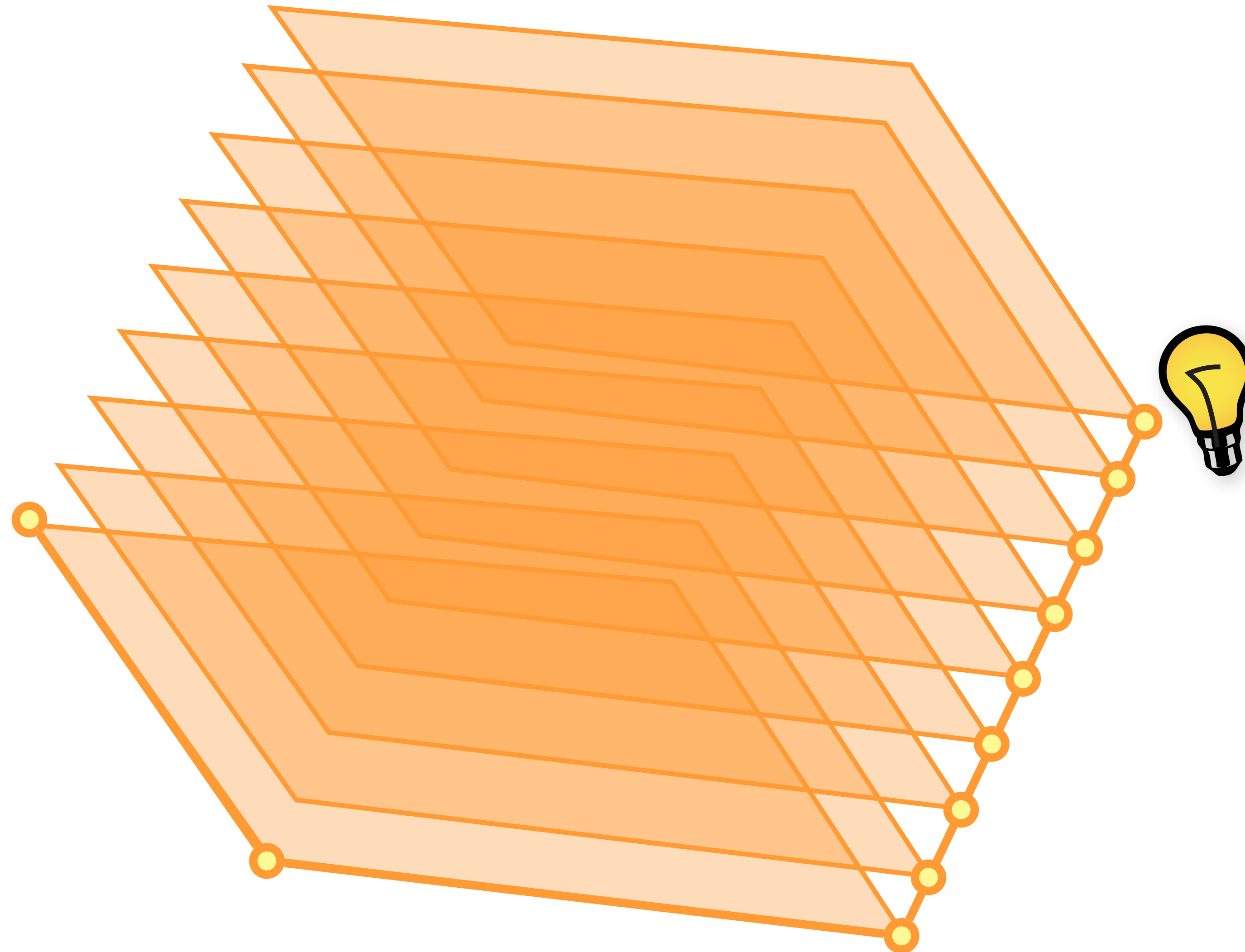
Plane Marching

[Bitterli & Jarosz 17]



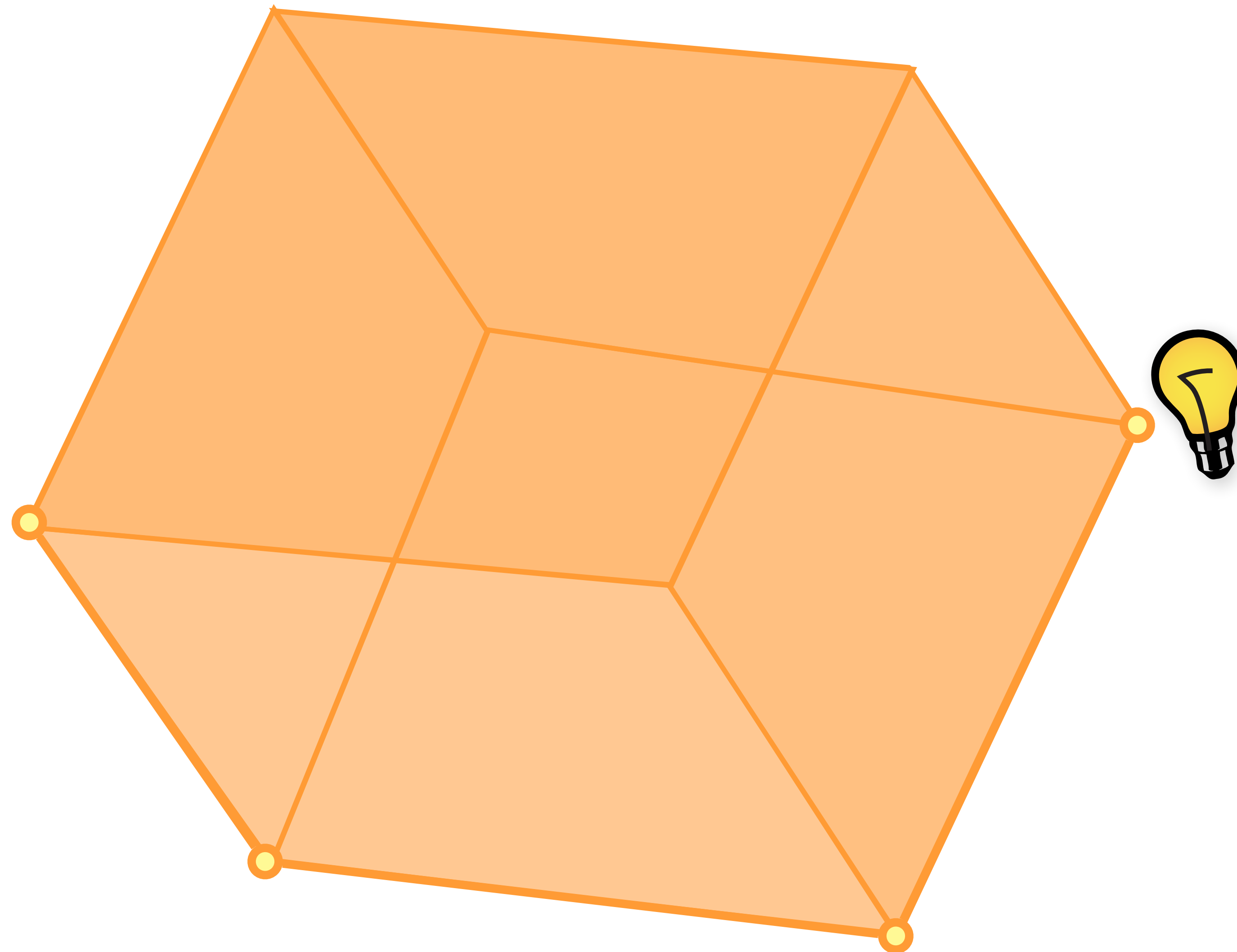
Plane Marching

[Bitterli & Jarosz 17]



Photon Volume

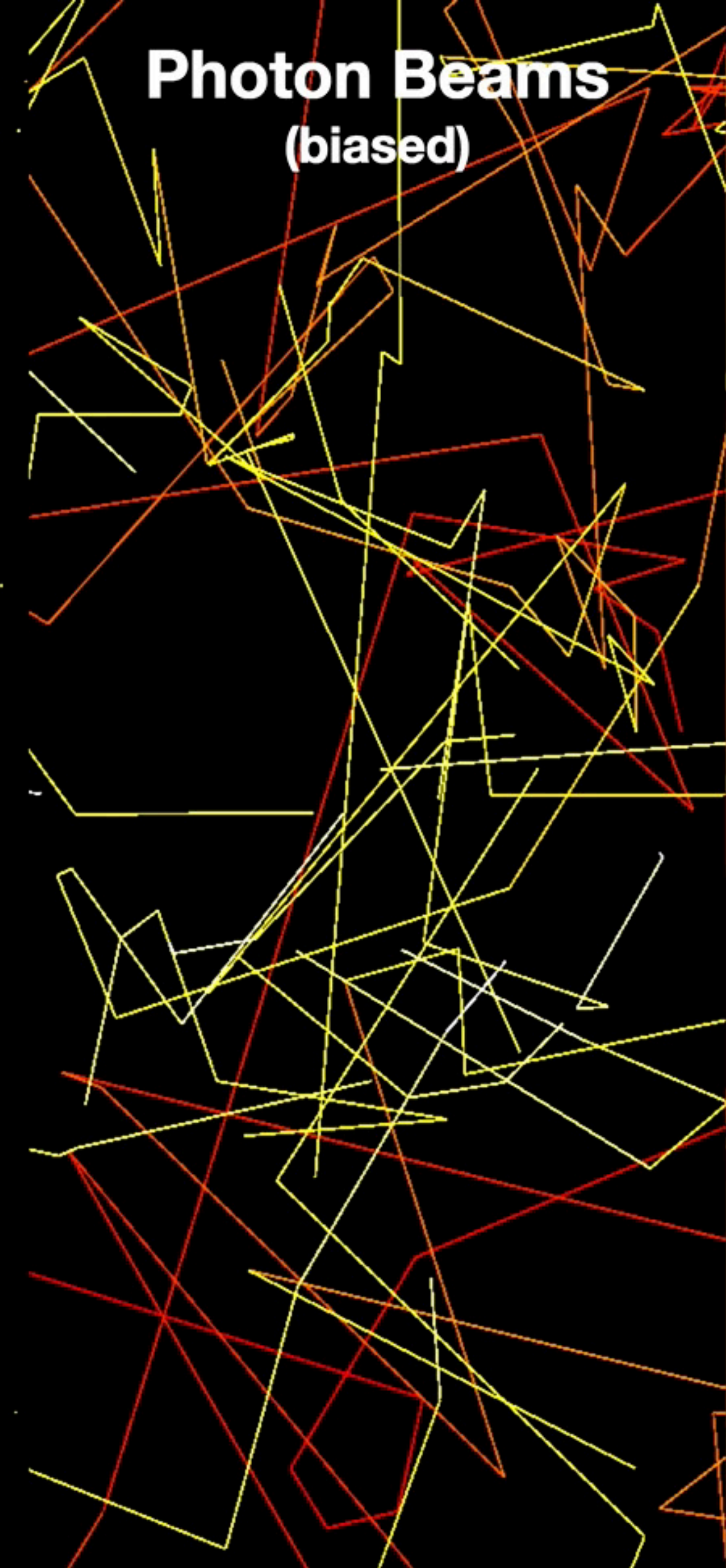
[Bitterli & Jarosz 17]



Photon Points
(biased)



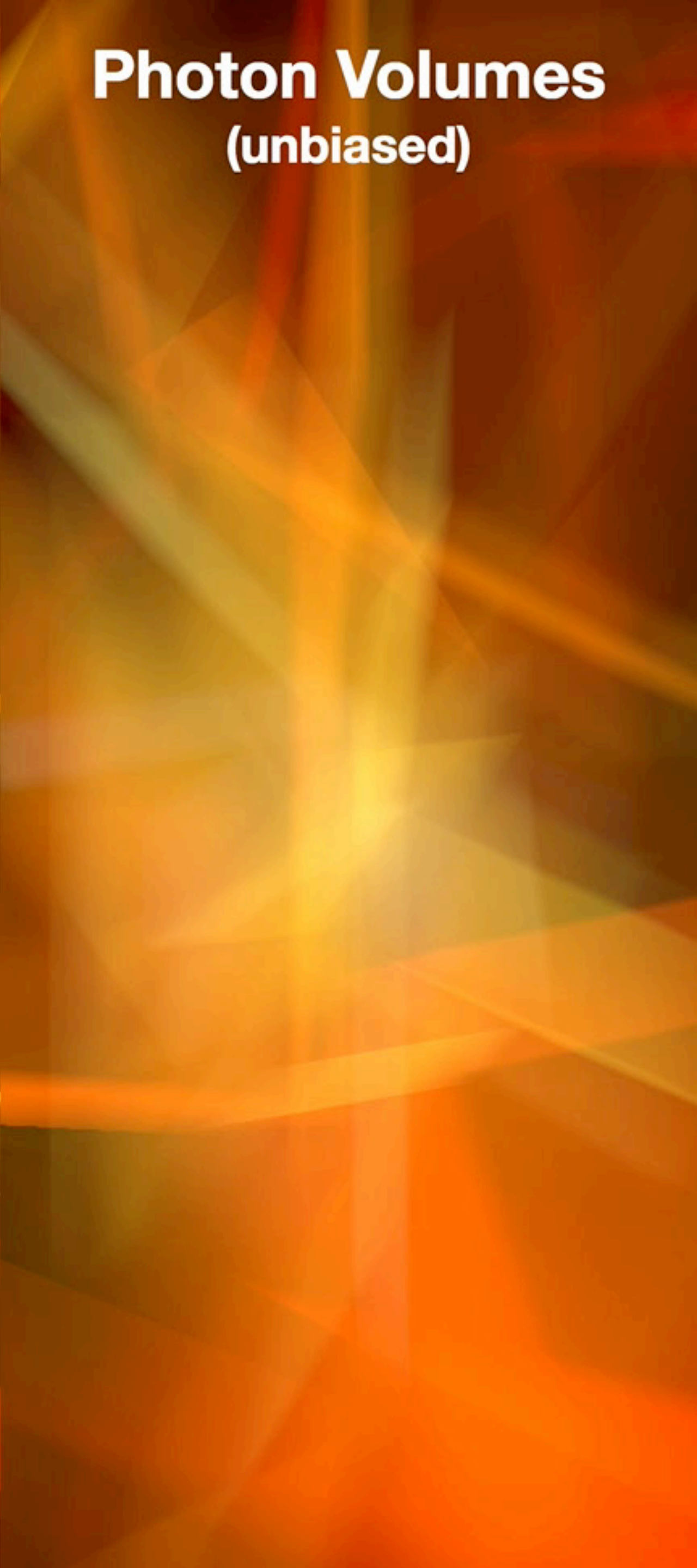
Photon Beams
(biased)



Photon Planes
(unbiased)



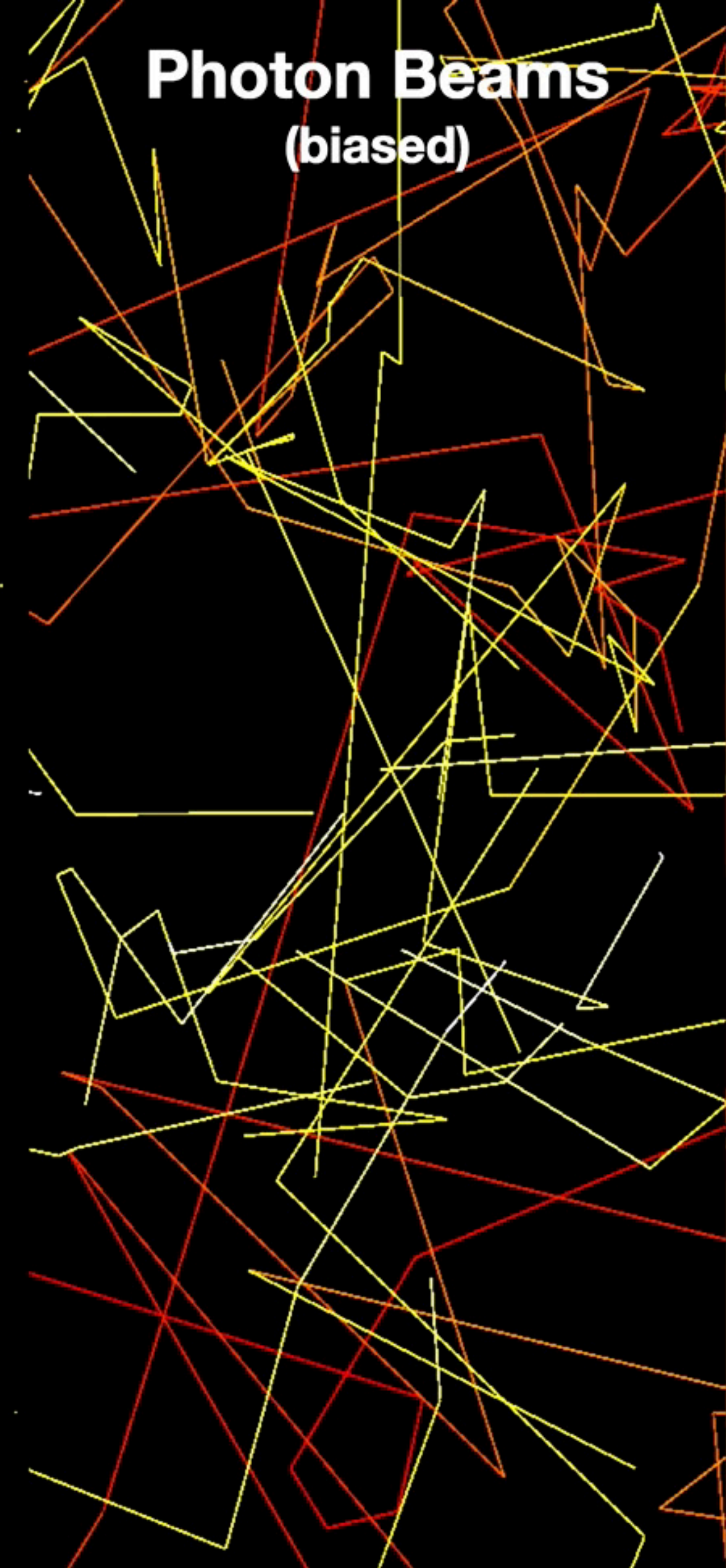
Photon Volumes
(unbiased)



Photon Points
(biased)



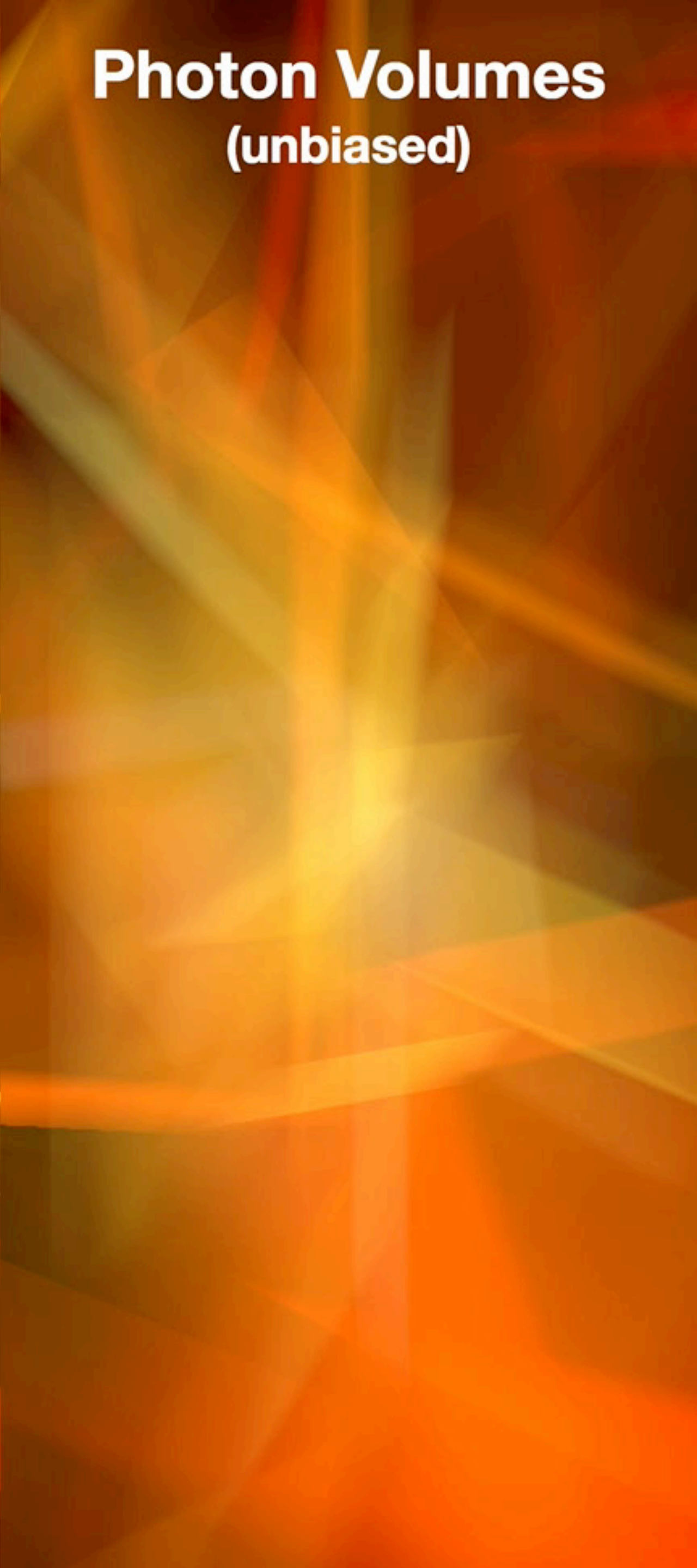
Photon Beams
(biased)

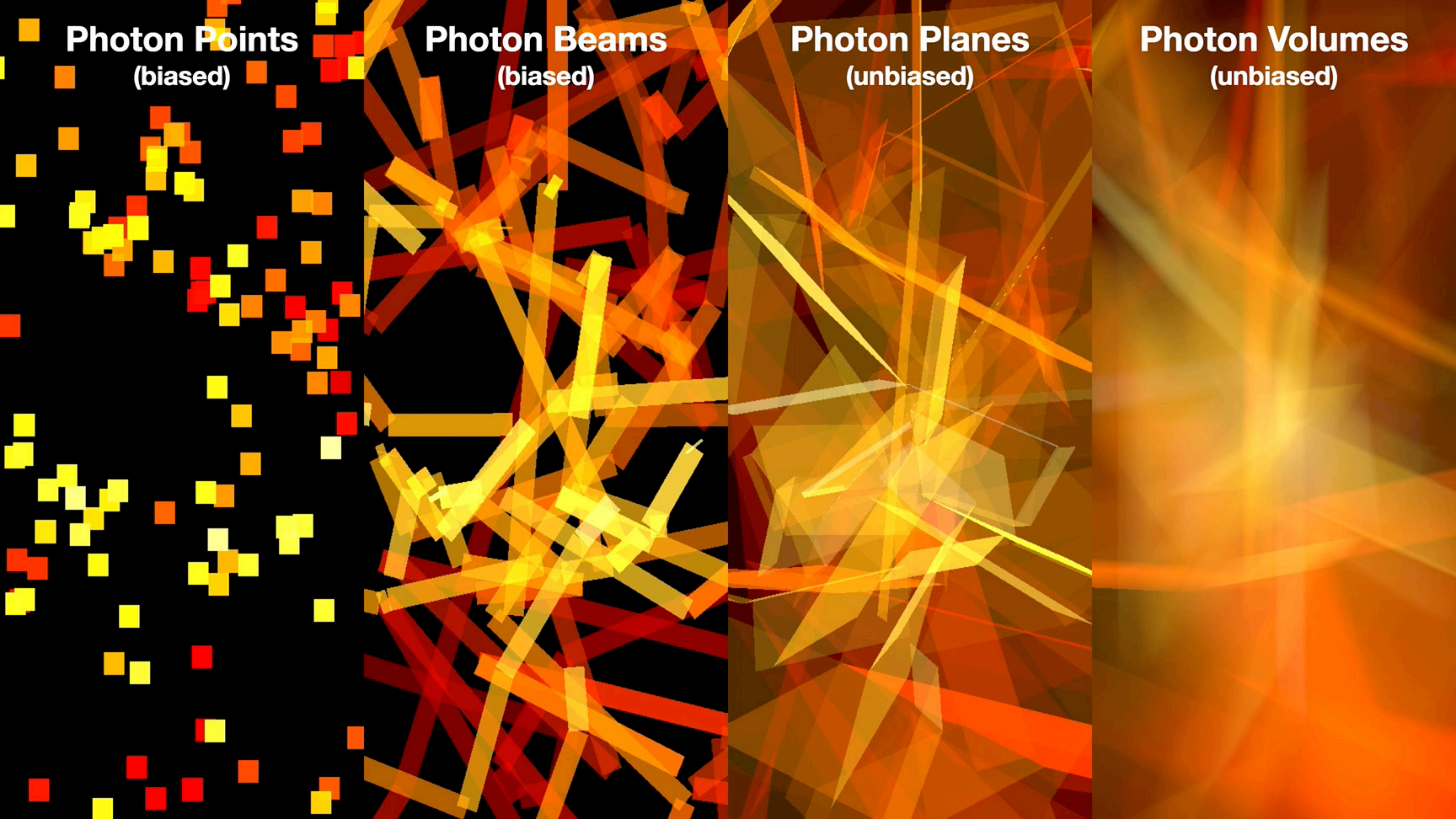


Photon Planes
(unbiased)



Photon Volumes
(unbiased)



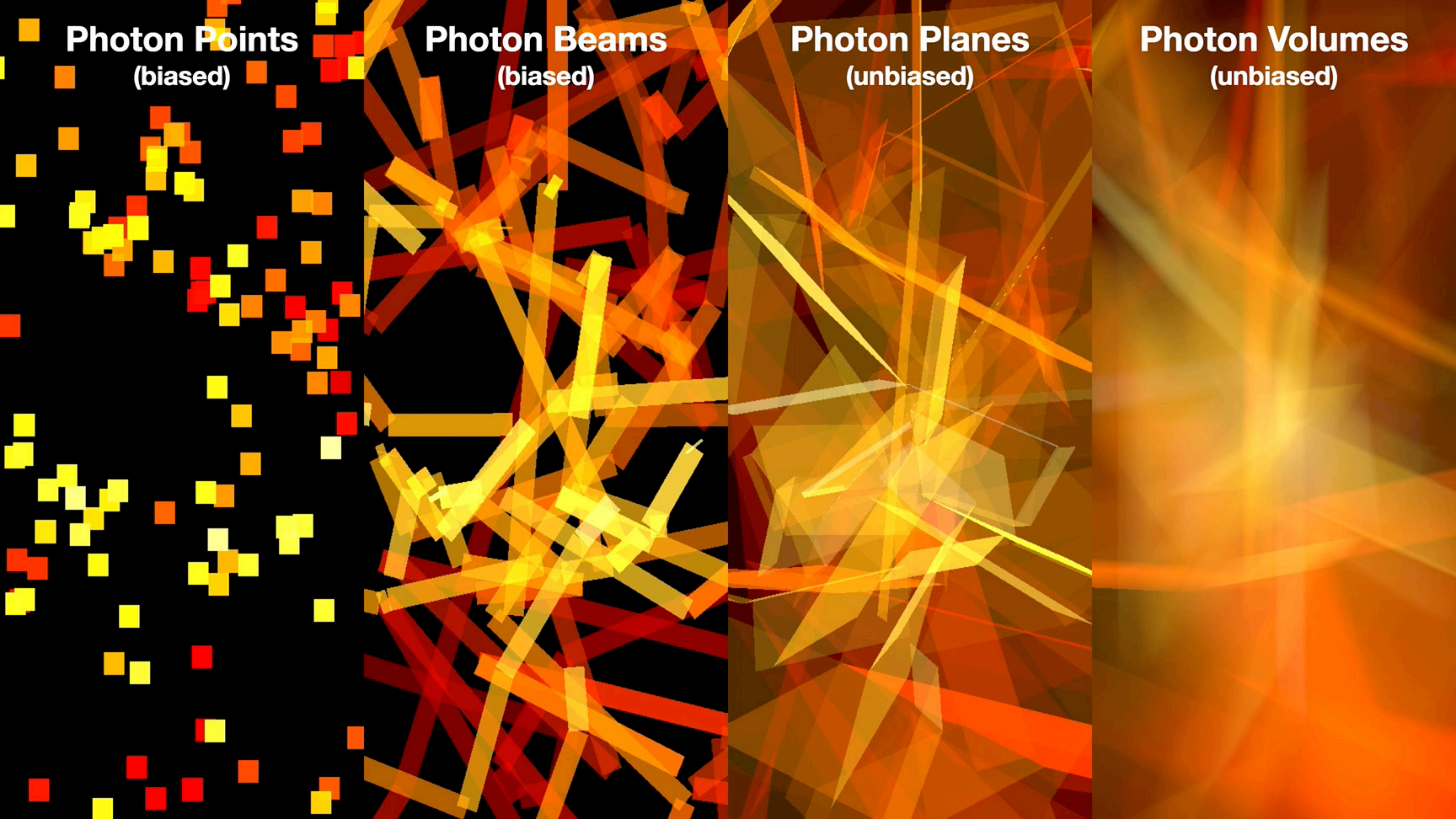


Photon Points
(biased)

Photon Beams
(biased)

Photon Planes
(unbiased)

Photon Volumes
(unbiased)



Photon Points
(biased)

Photon Beams
(biased)

Photon Planes
(unbiased)


Photon Volumes
(unbiased)

A photograph of a modern staircase in a bright, minimalist interior. The staircase features wooden treads and a glass railing supported by a single vertical post. The floor is made of large, light-colored square tiles. The walls are white, and the ceiling has recessed lighting. The overall atmosphere is clean and bright.

Full Light Transport



Photon Beams (1D blur)



Photon Planes (unbiased)
3.77× Speedup



Photon Planes (1D blur)
14.14× Speedup

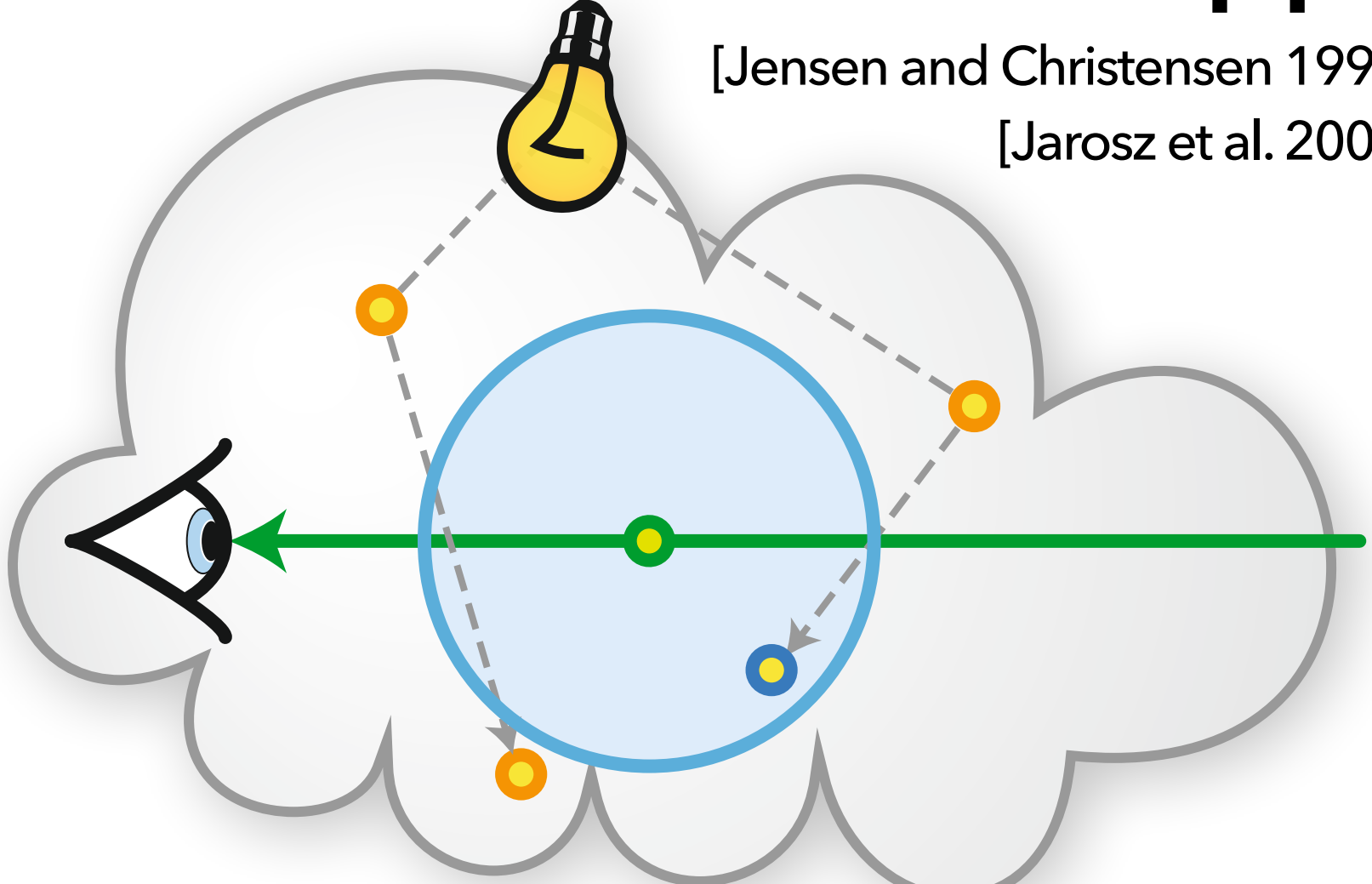


Photon Beams (1D blur)

Volumetric Photon Mapping

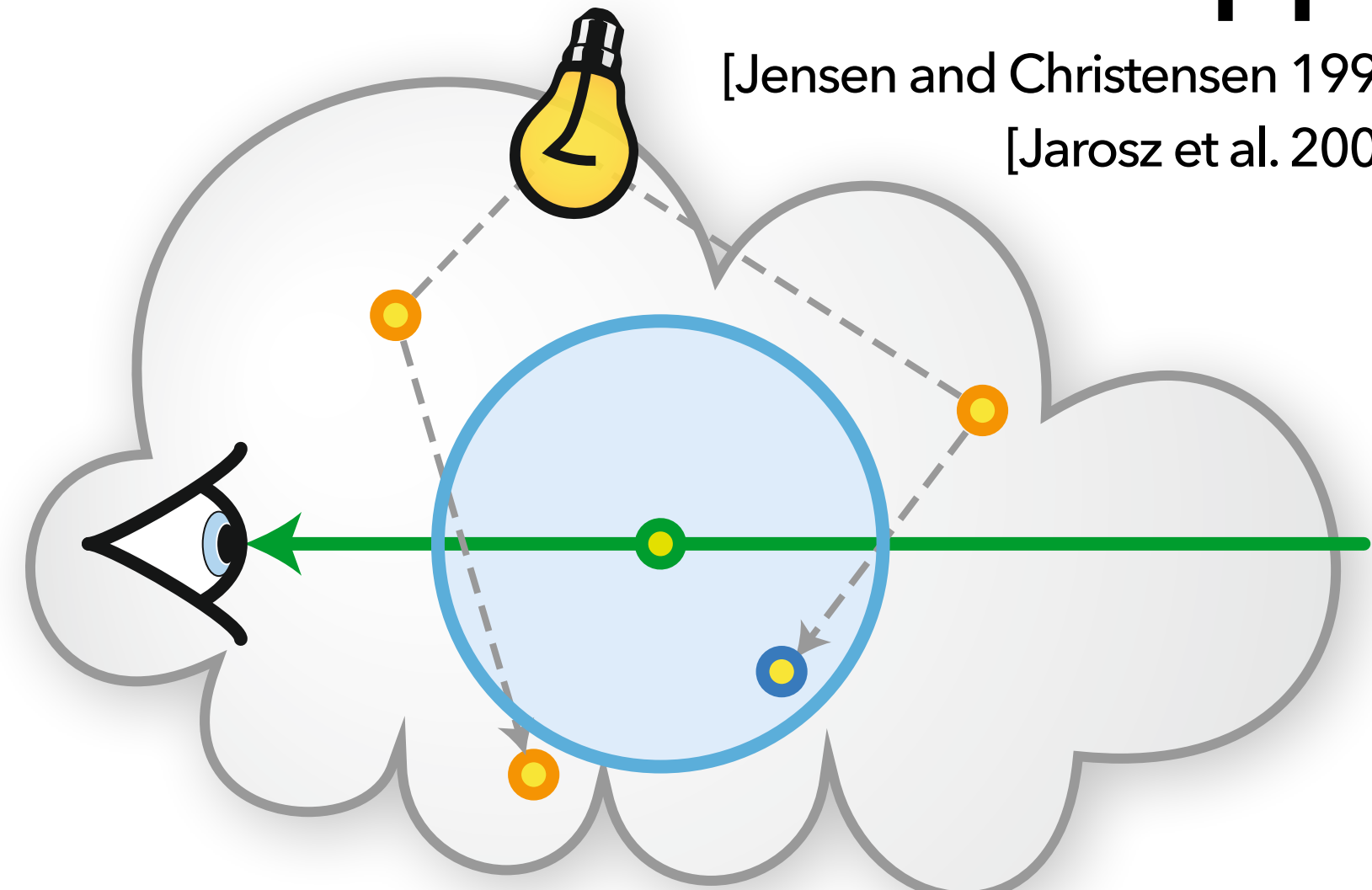
[Jensen and Christensen 1998]

[Jarosz et al. 2008]



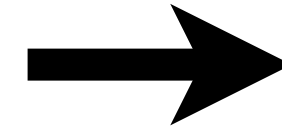
requires a lot of photons

Volumetric Photon Mapping

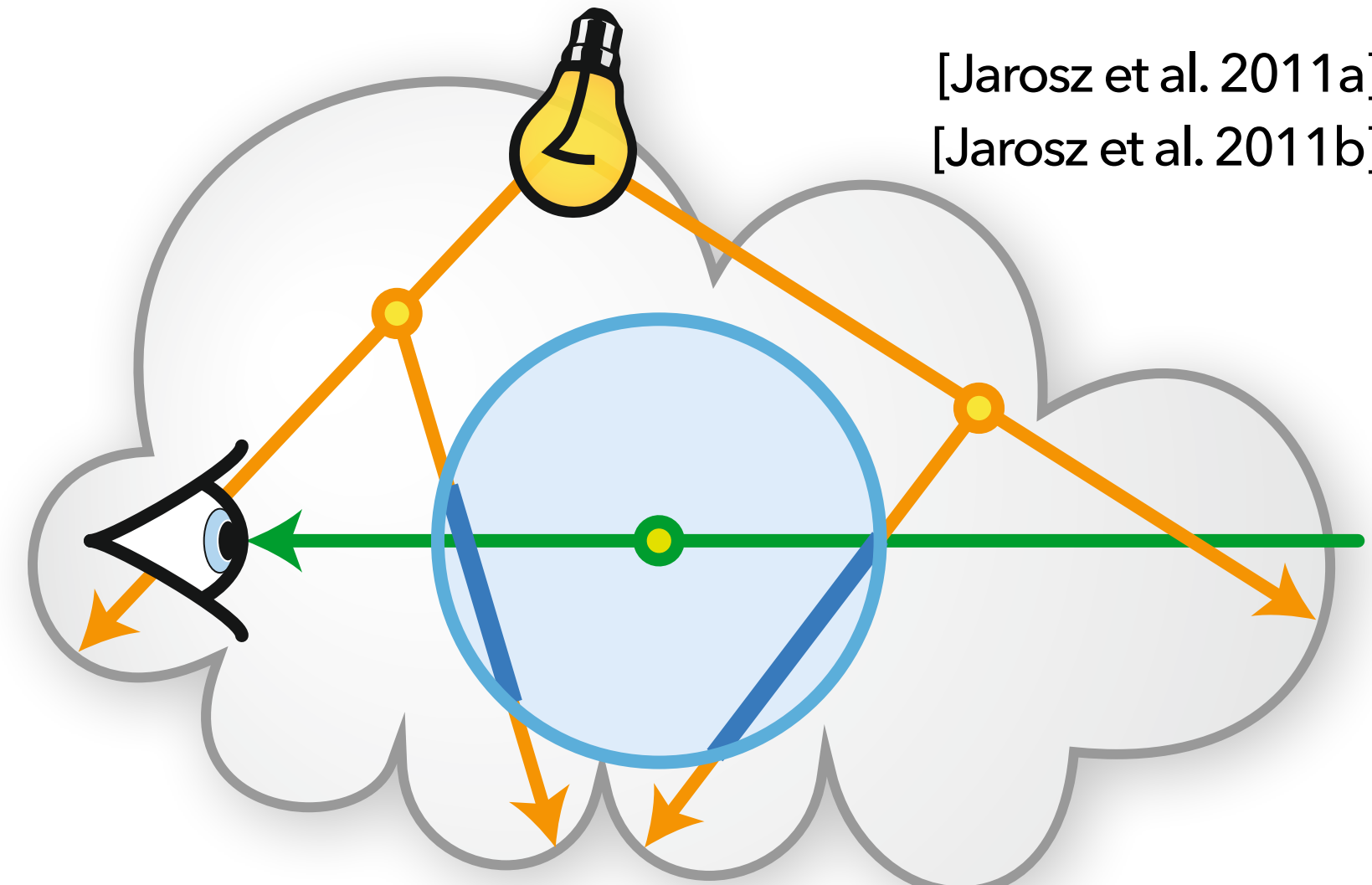


[Jensen and Christensen 1998]
[Jarosz et al. 2008]

requires a lot of photons



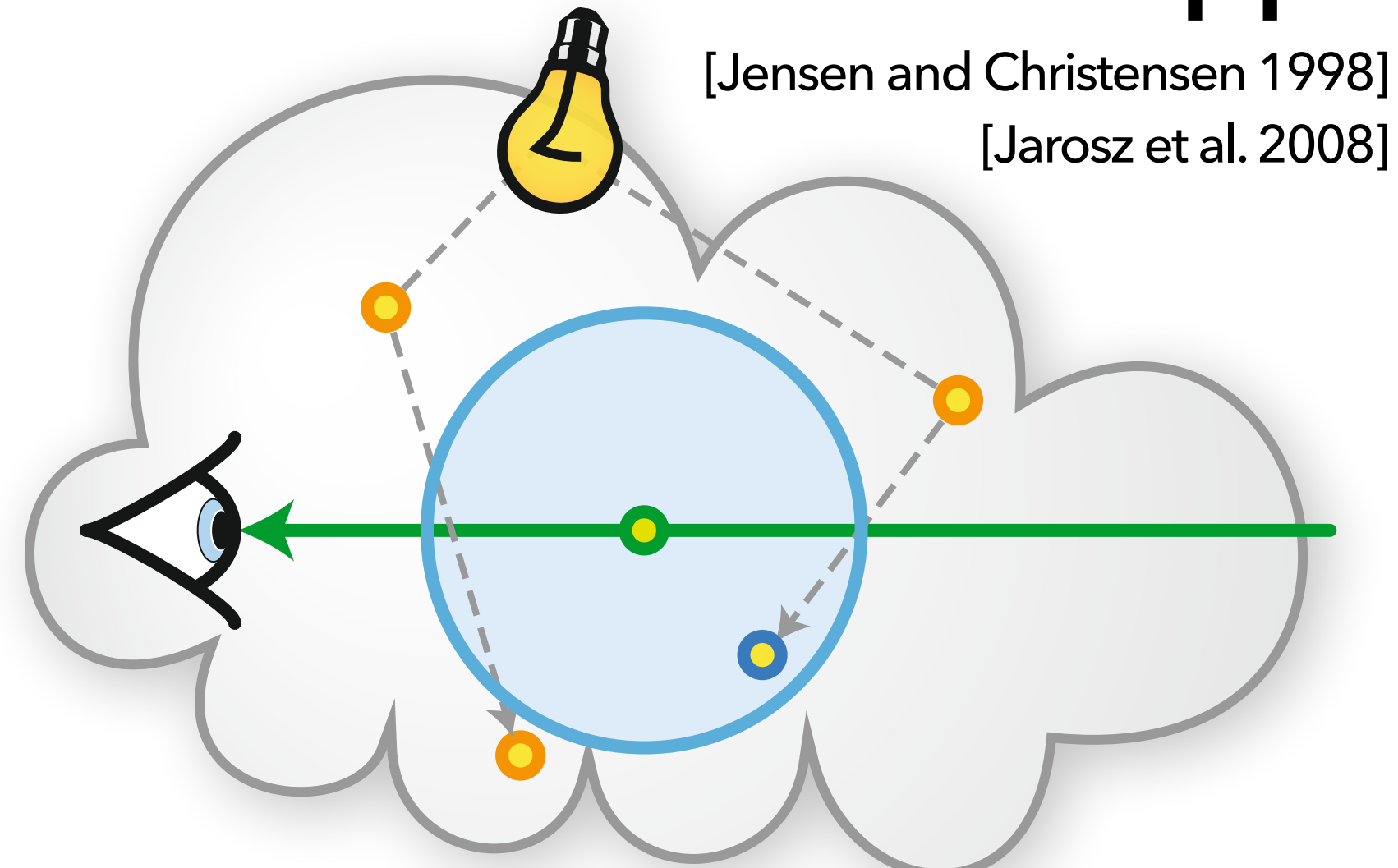
Photon Beams



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

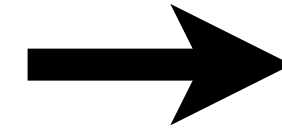
great caustics, multi-scattering slow

Volumetric Photon Mapping

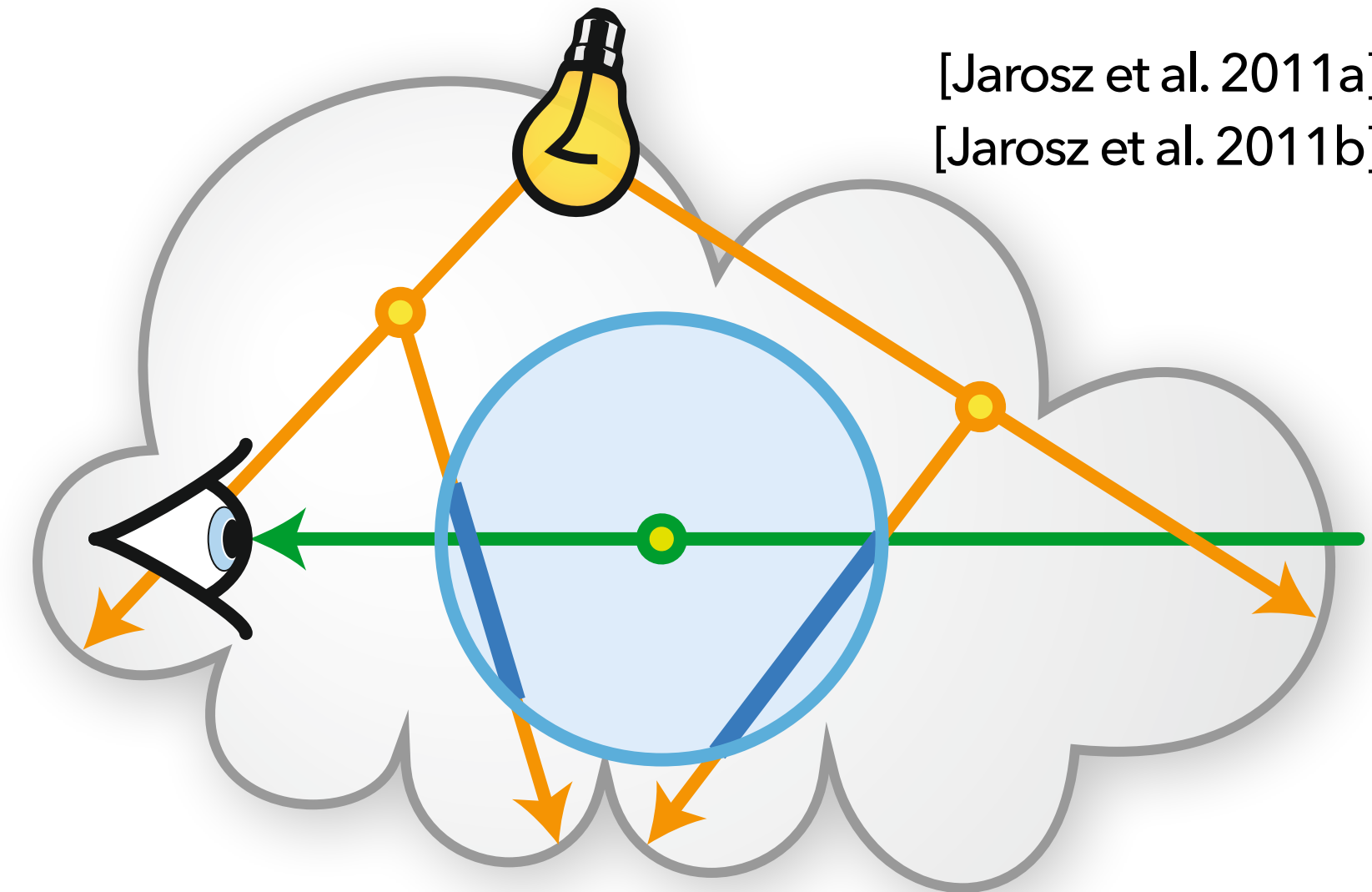


[Jensen and Christensen 1998]
[Jarosz et al. 2008]

requires a lot of photons



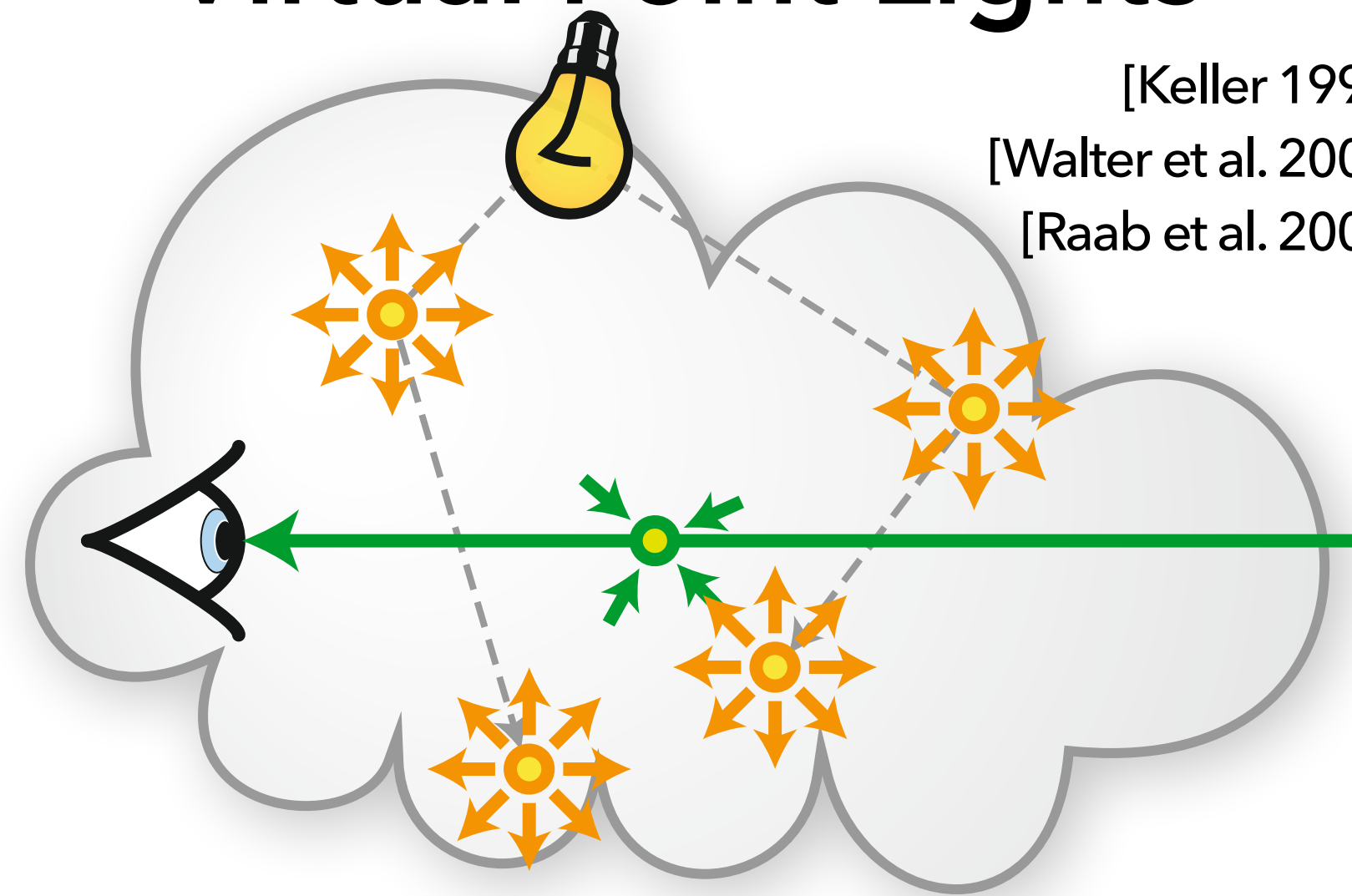
Photon Beams



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

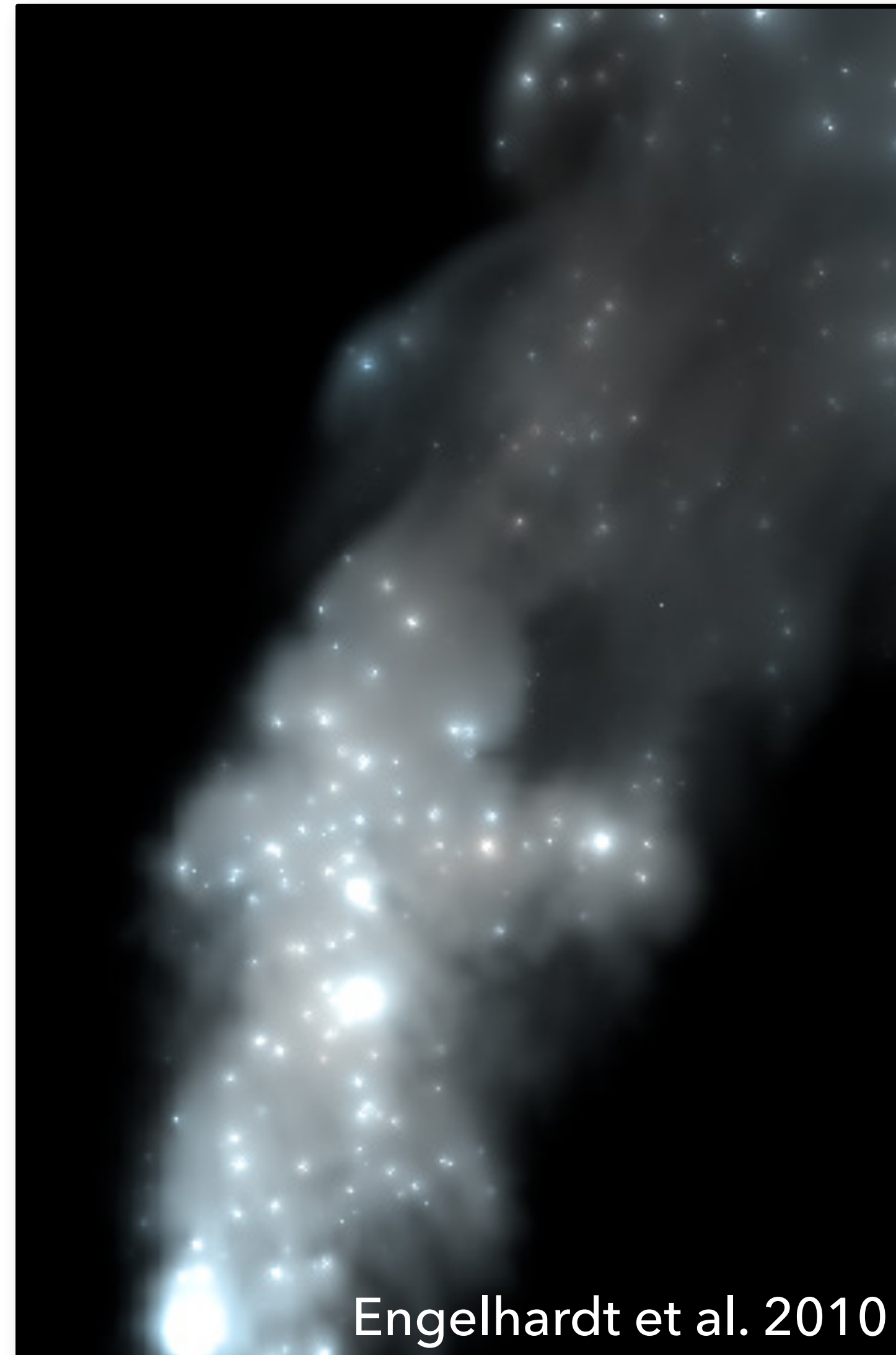
great caustics, multi-scattering slow

Virtual Point Lights



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

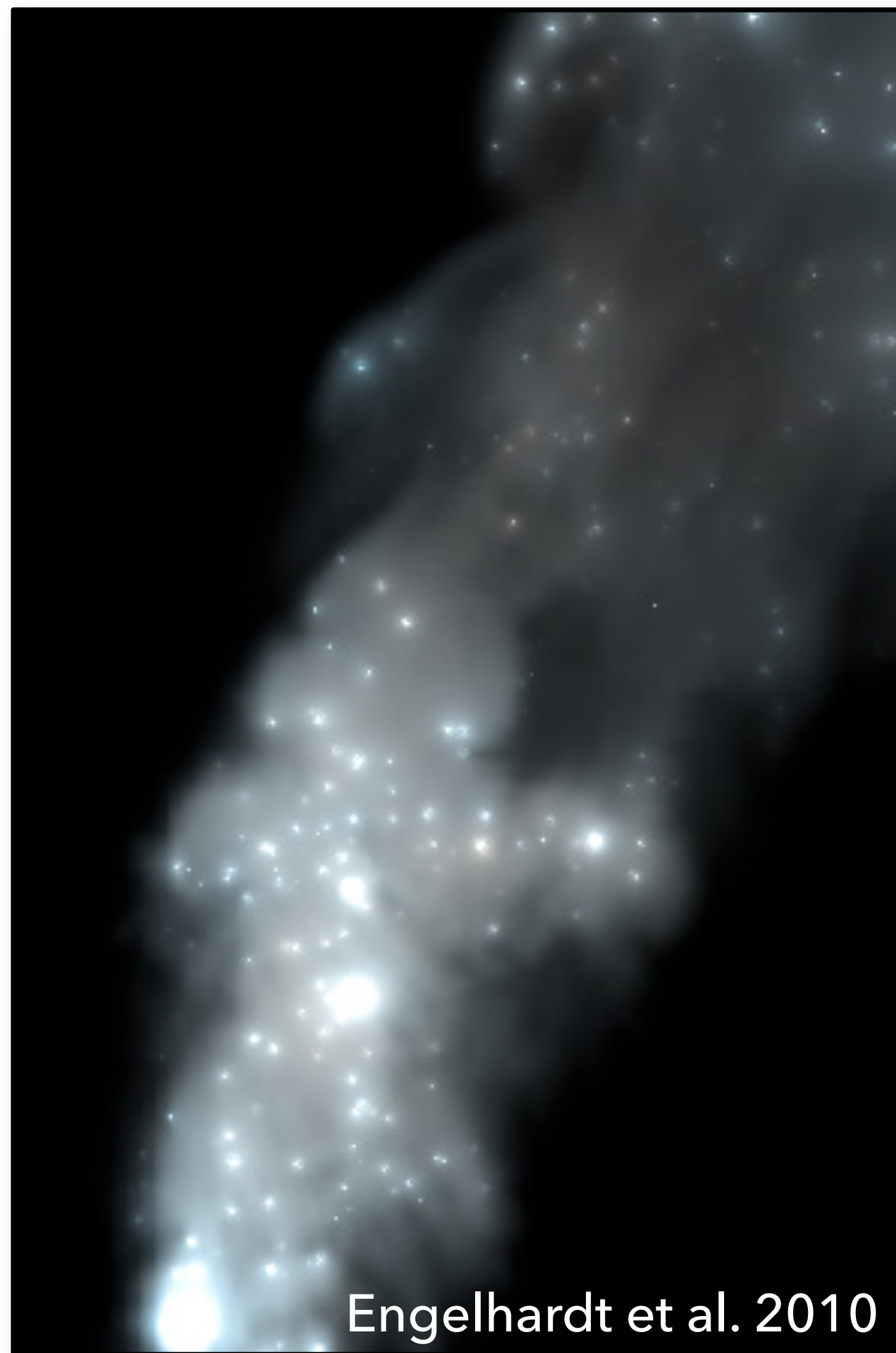
Singularities or Energy Loss



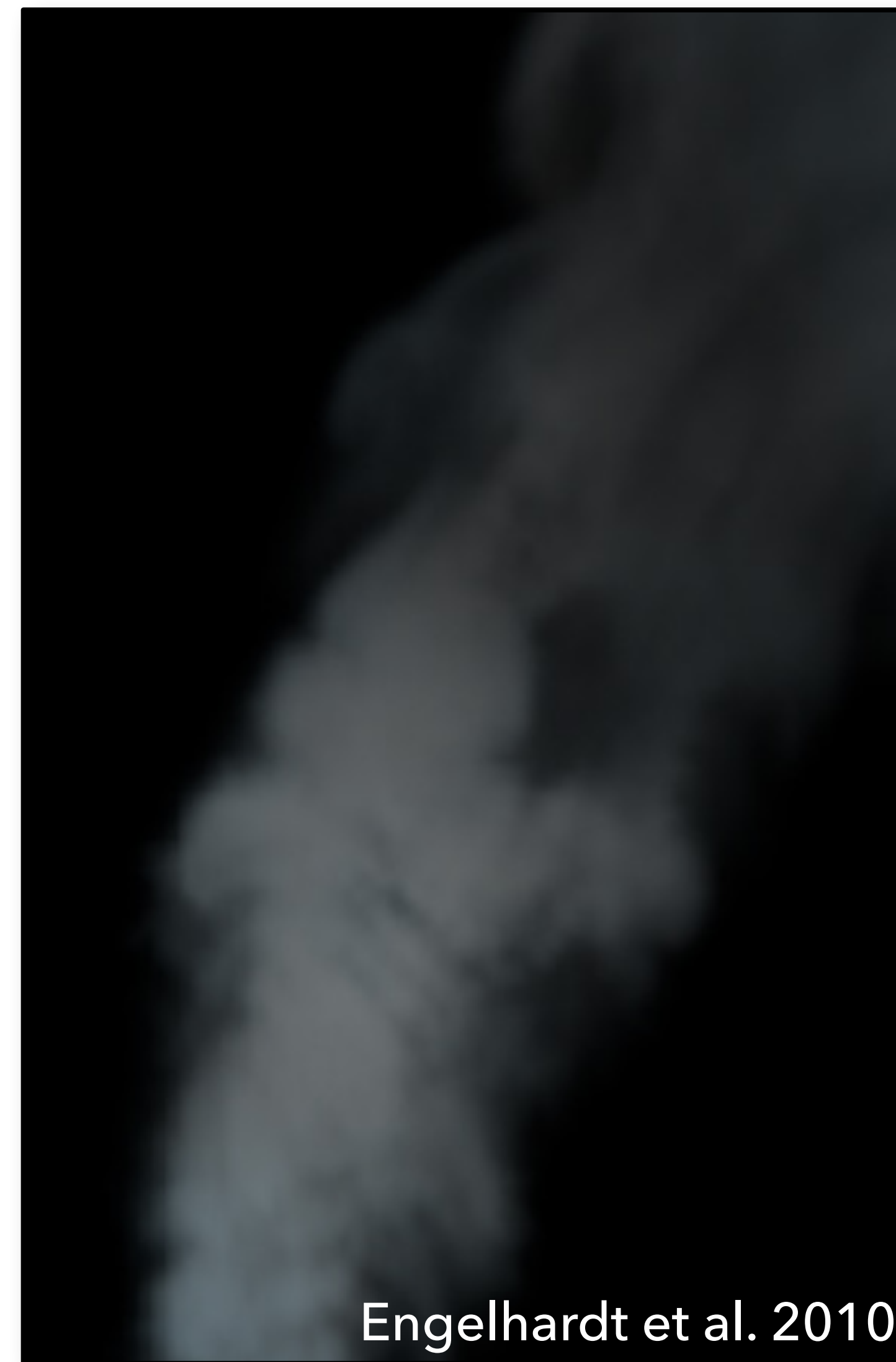
Engelhardt et al. 2010

VPLs - no clamping

Singularities or Energy Loss

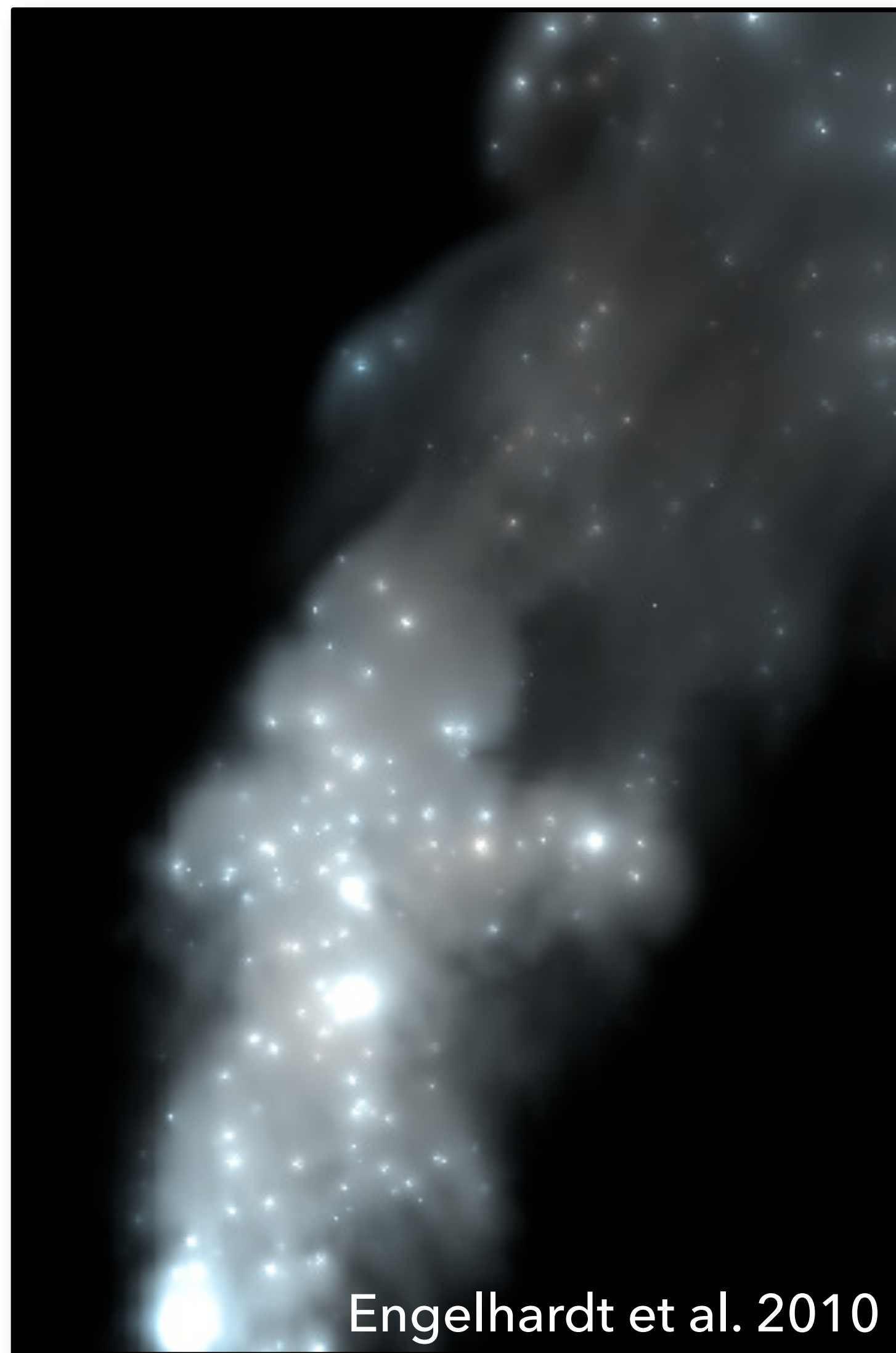


VPLs - no clamping



VPLs - clamping

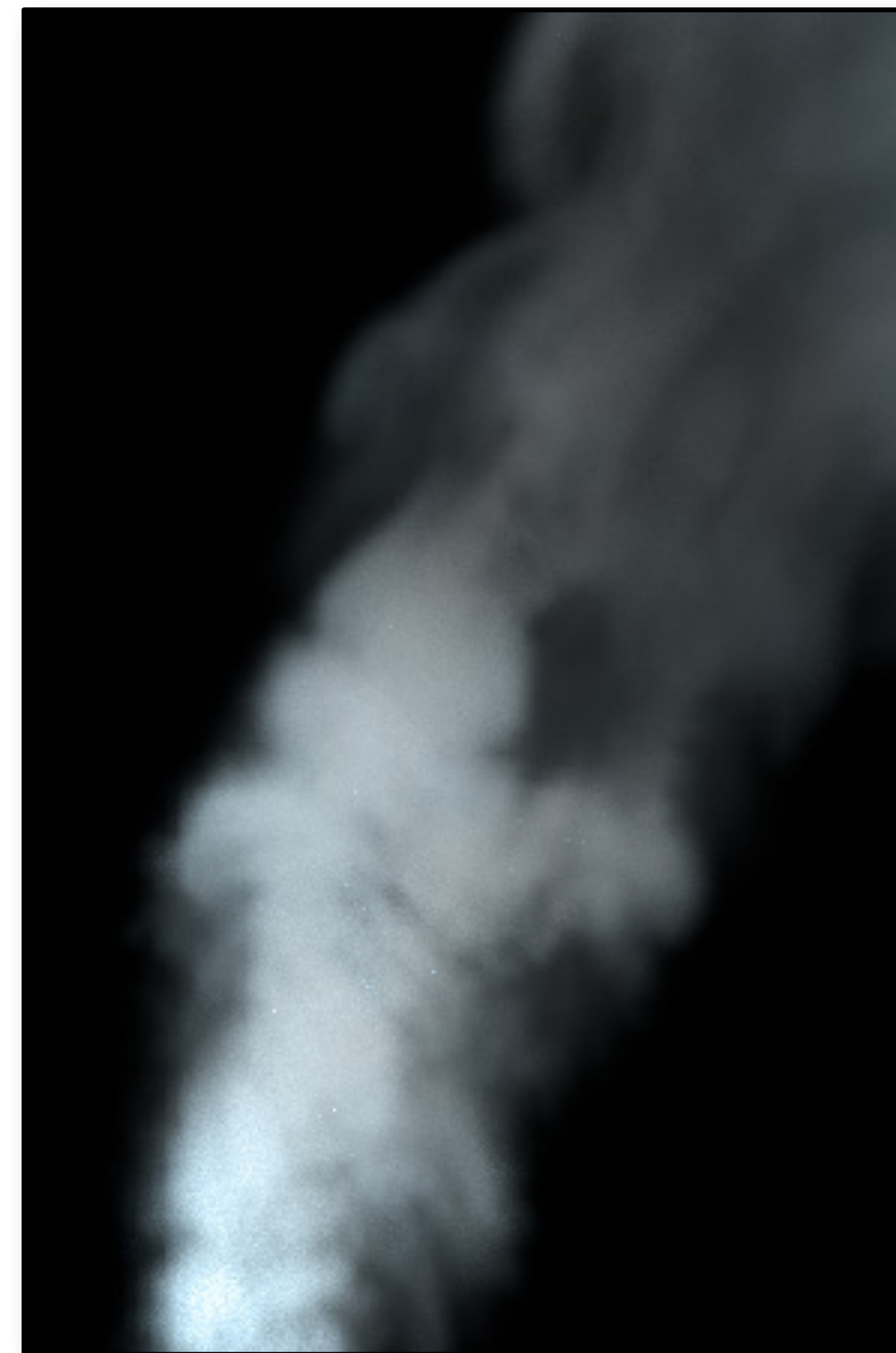
Singularities or Energy Loss



VPLs - no clamping

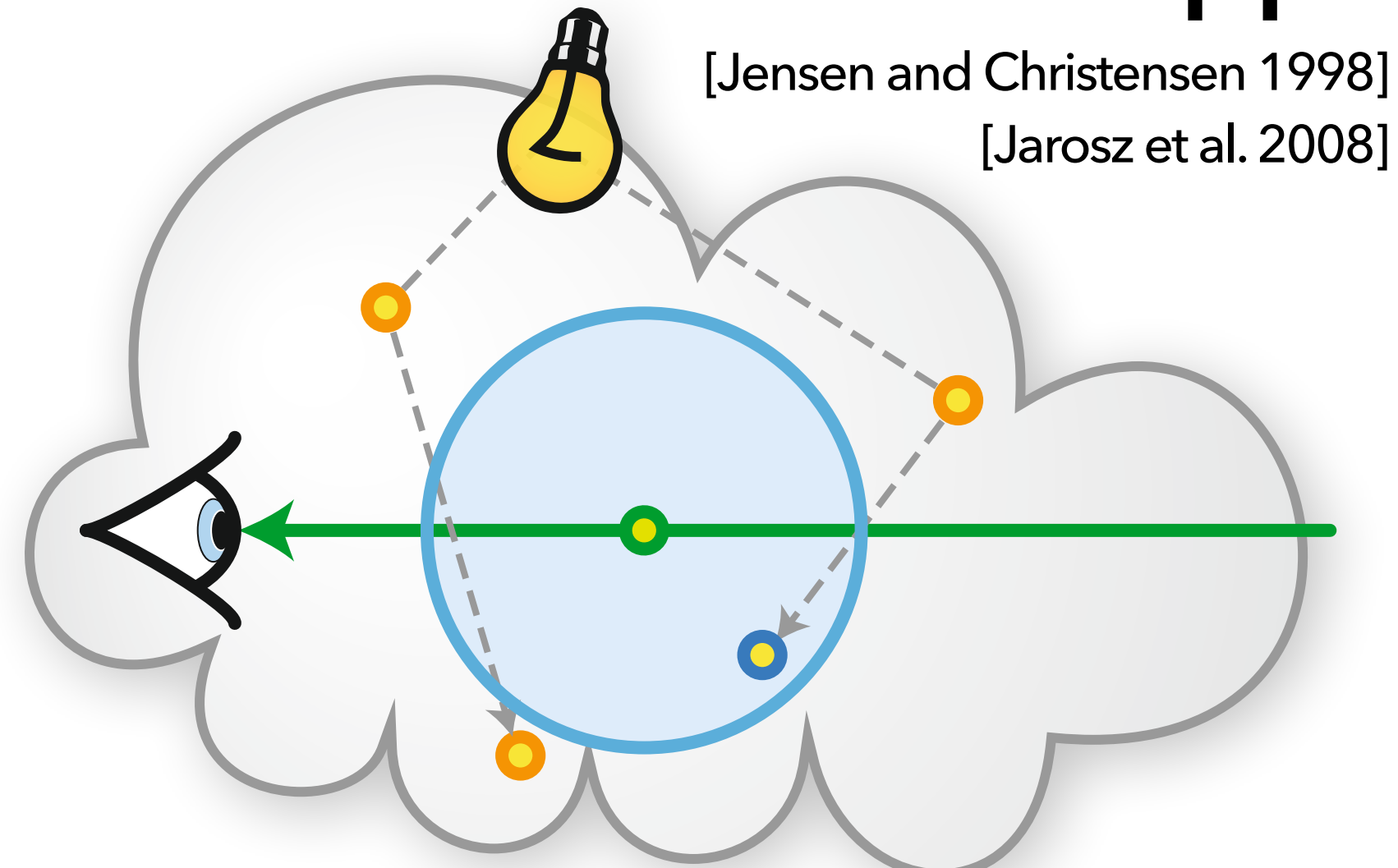


VPLs - clamping



Reference

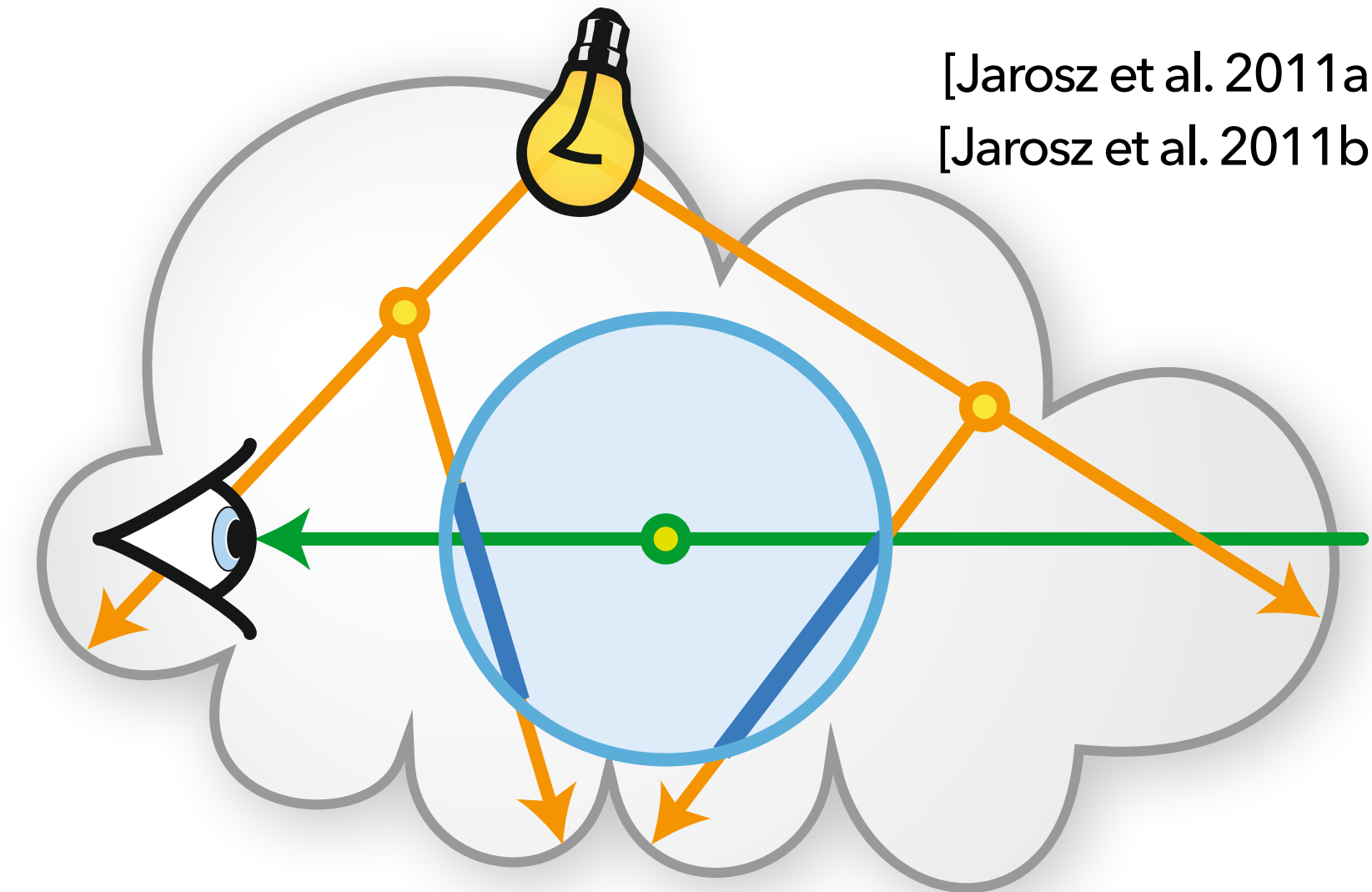
Volumetric Photon Mapping



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

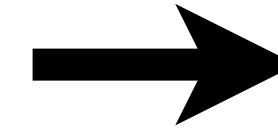
requires a lot of photons

Photon Beams

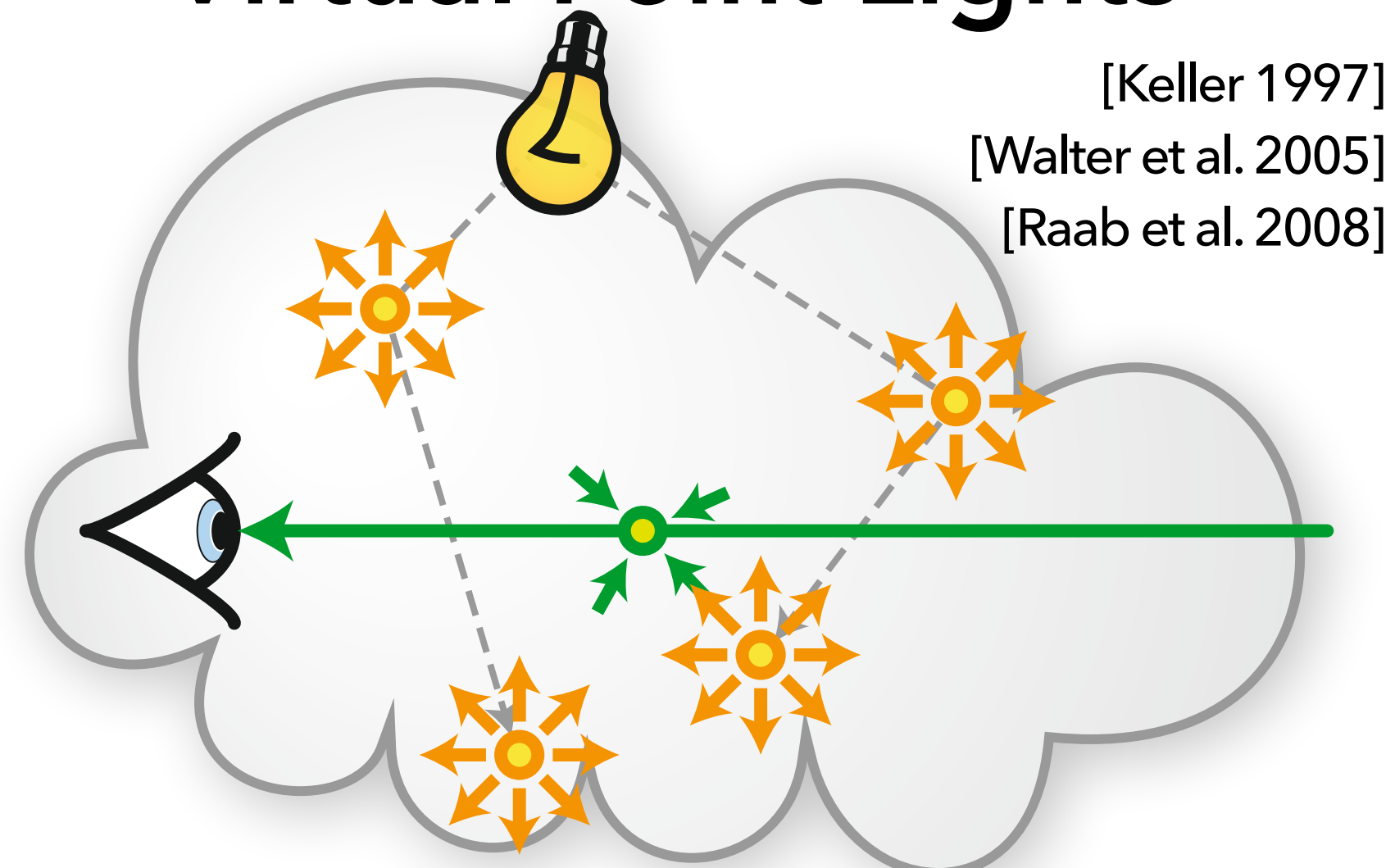


[Jarosz et al. 2011a]
[Jarosz et al. 2011b]

great caustics, multi-scattering slow



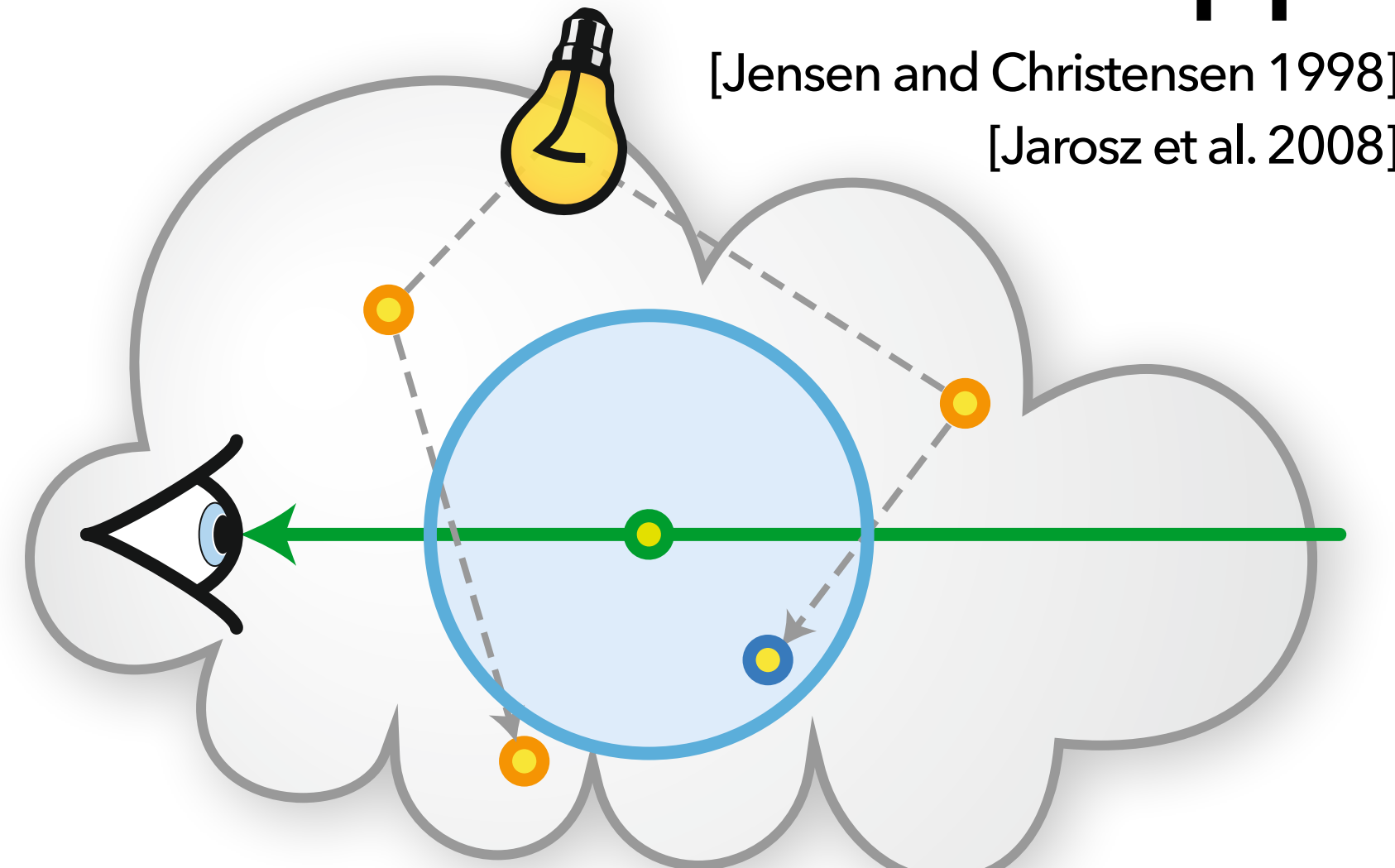
Virtual Point Lights



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

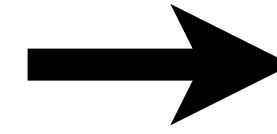
suffers from singularities, flickering

Volumetric Photon Mapping

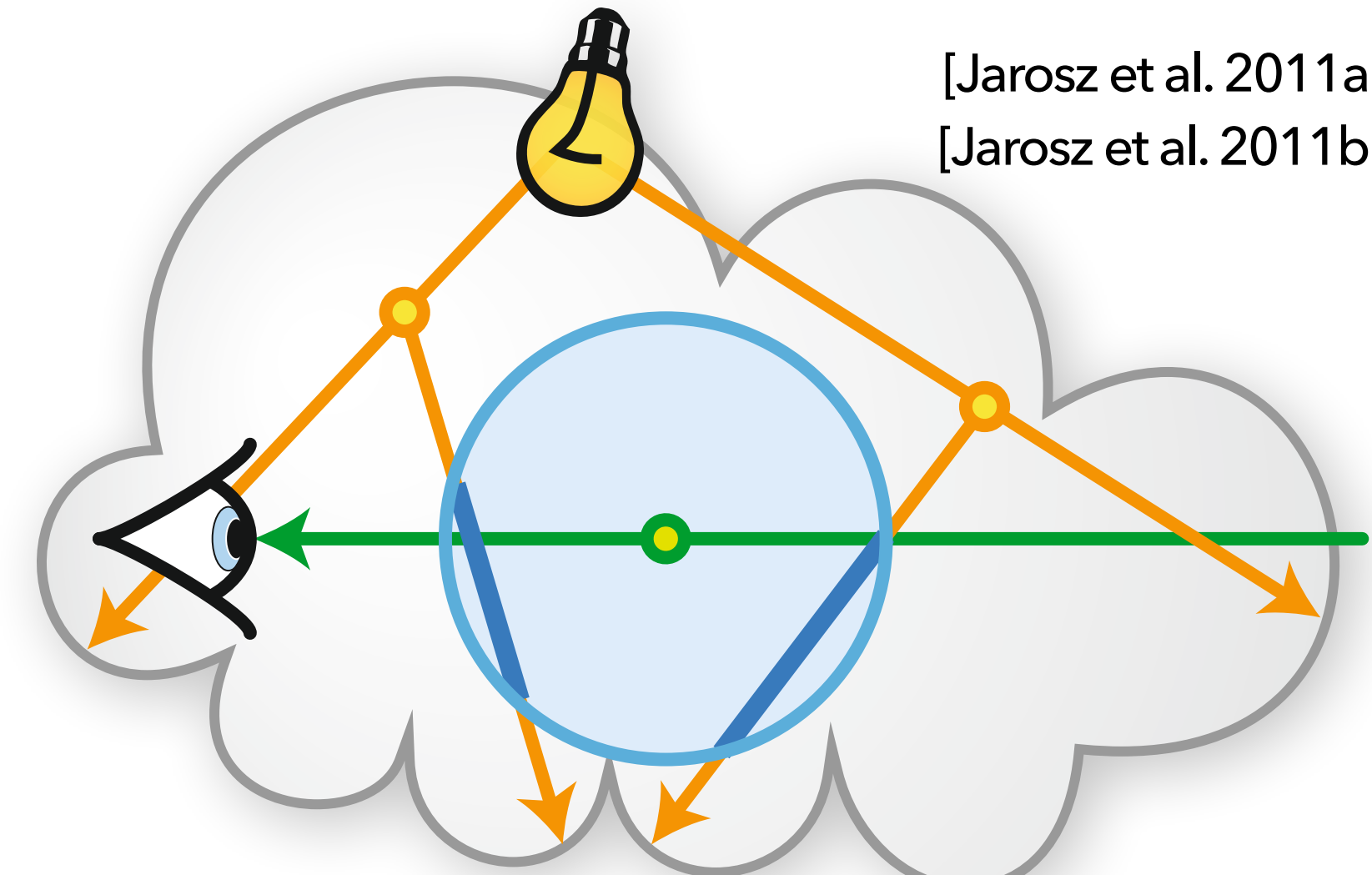


[Jensen and Christensen 1998]
[Jarosz et al. 2008]

requires a lot of photons

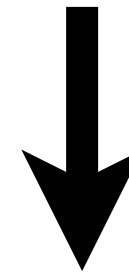


Photon Beams

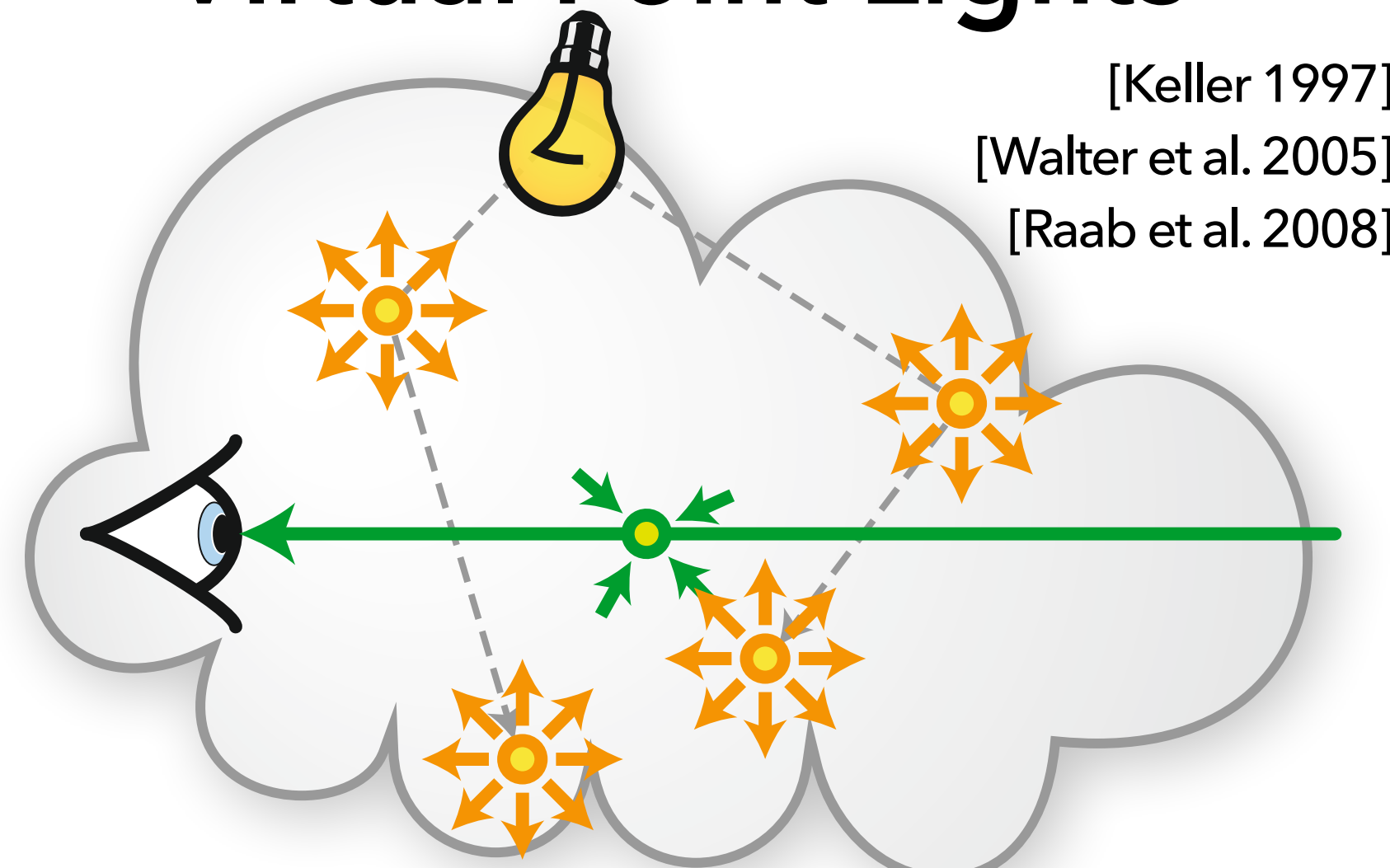


[Jarosz et al. 2011a]
[Jarosz et al. 2011b]

great caustics, multi-scattering slow

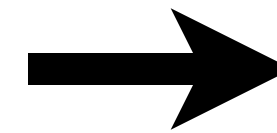


Virtual Point Lights

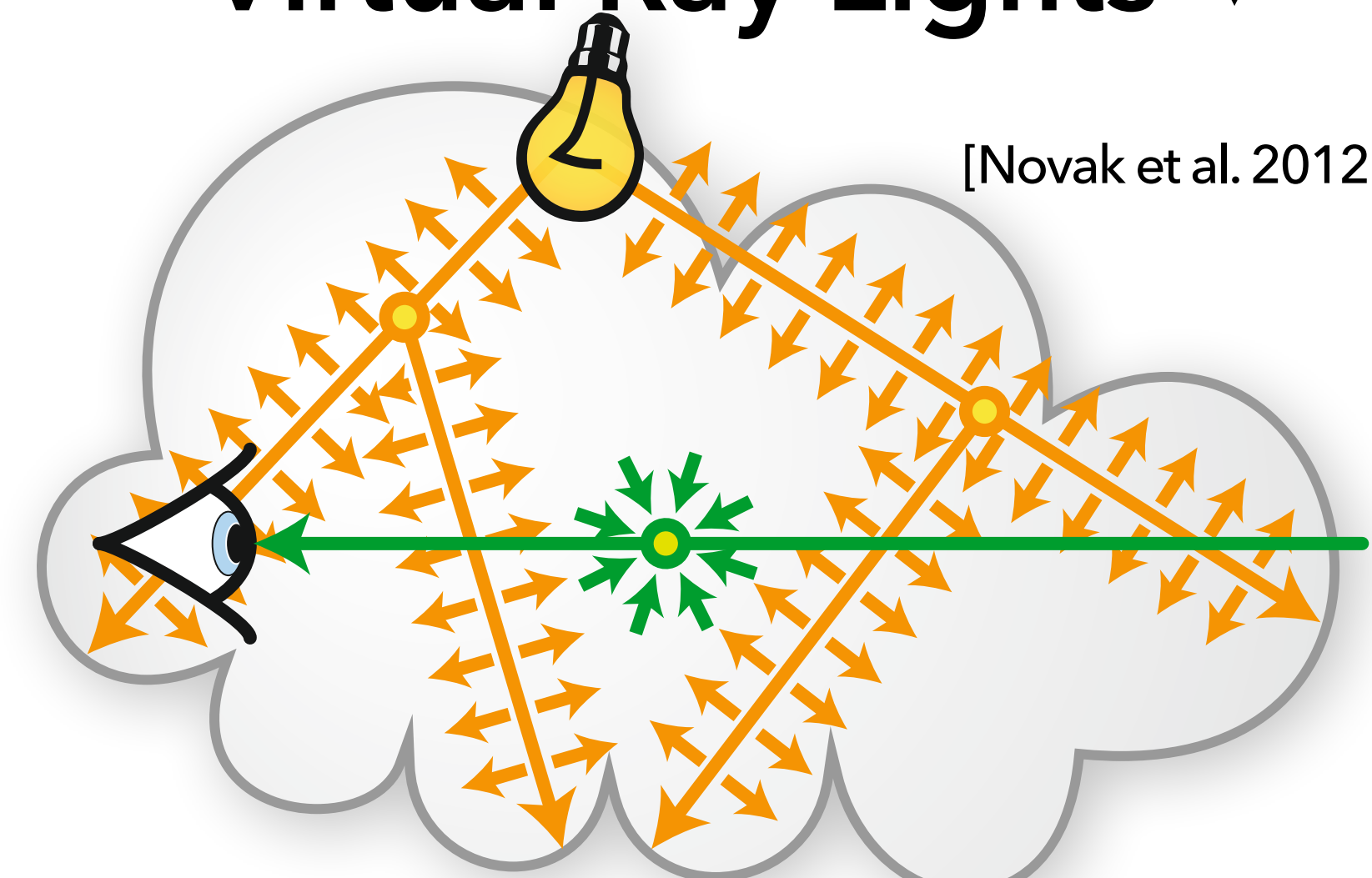


[Keller 1997]
[Walter et al. 2005]
[Raab et al. 2008]

suffers from singularities, flickering



Virtual Ray Lights



[Novak et al. 2012]

Comparison

Fruit Juice

homogeneous

anisotropic (HG $g = 0.55$)

512x512



Comparison



Surface illumination
(Photon Mapping)



Single scattering
(Photon Beams)



Multiple scattering

Comparison



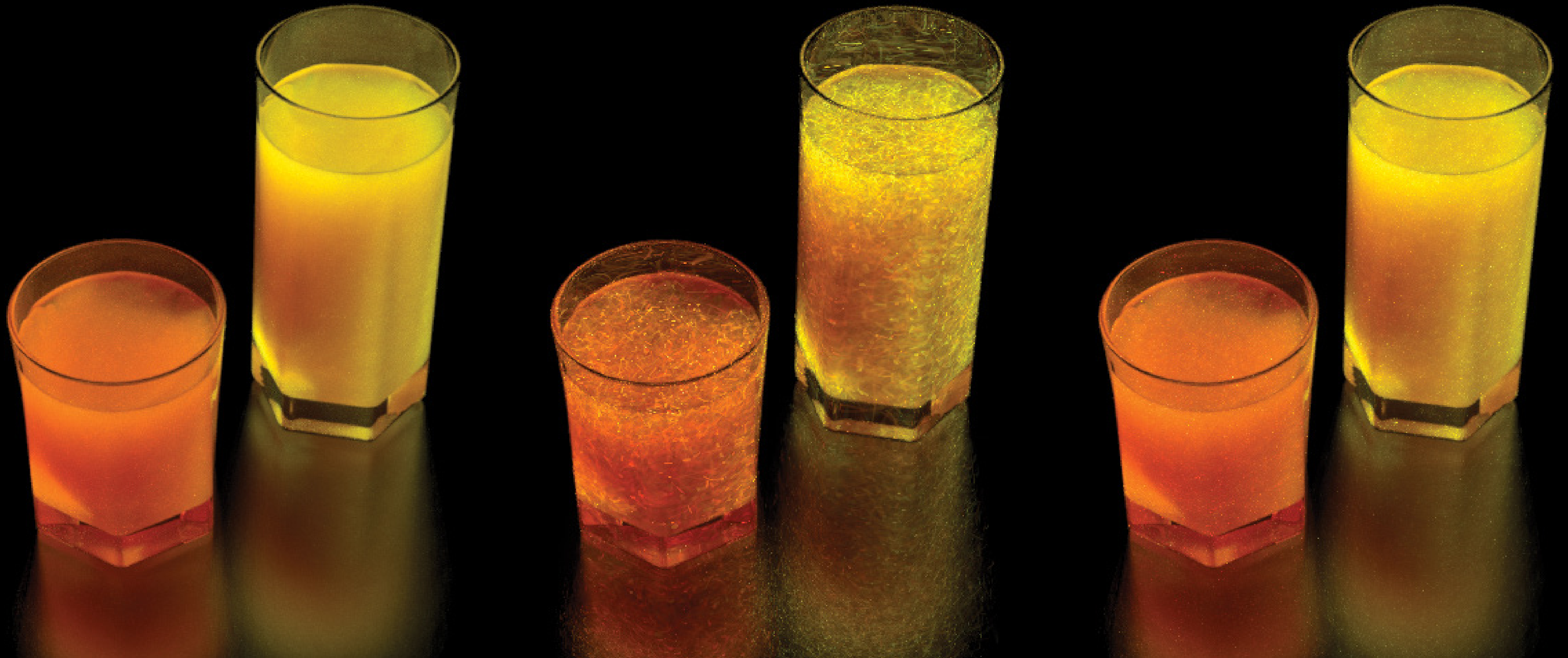
Multiple scattering

Multiple Scattering Only

Virtual Ray Lights

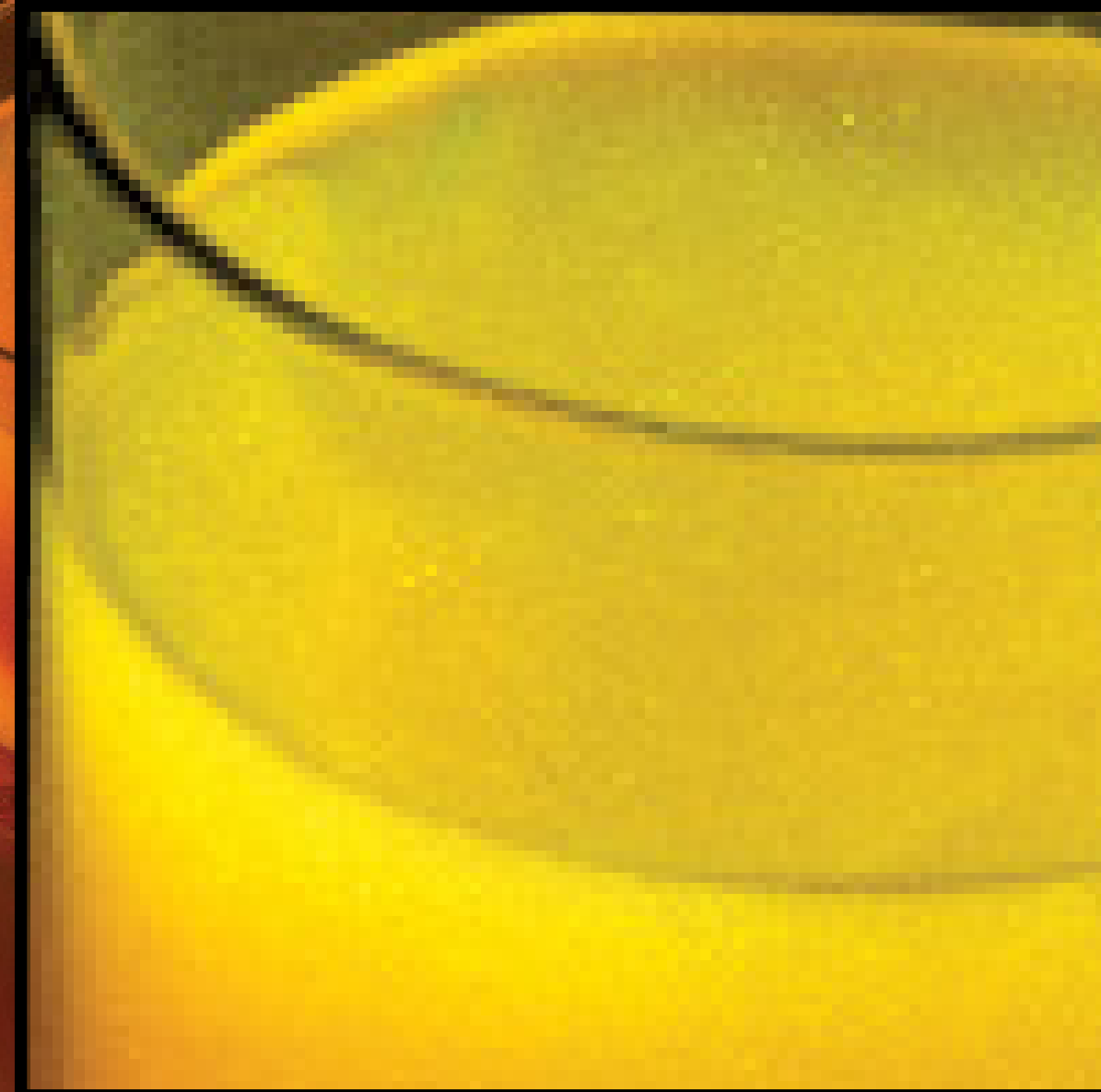
Progressive Photon Beams

Virtual Point Lights

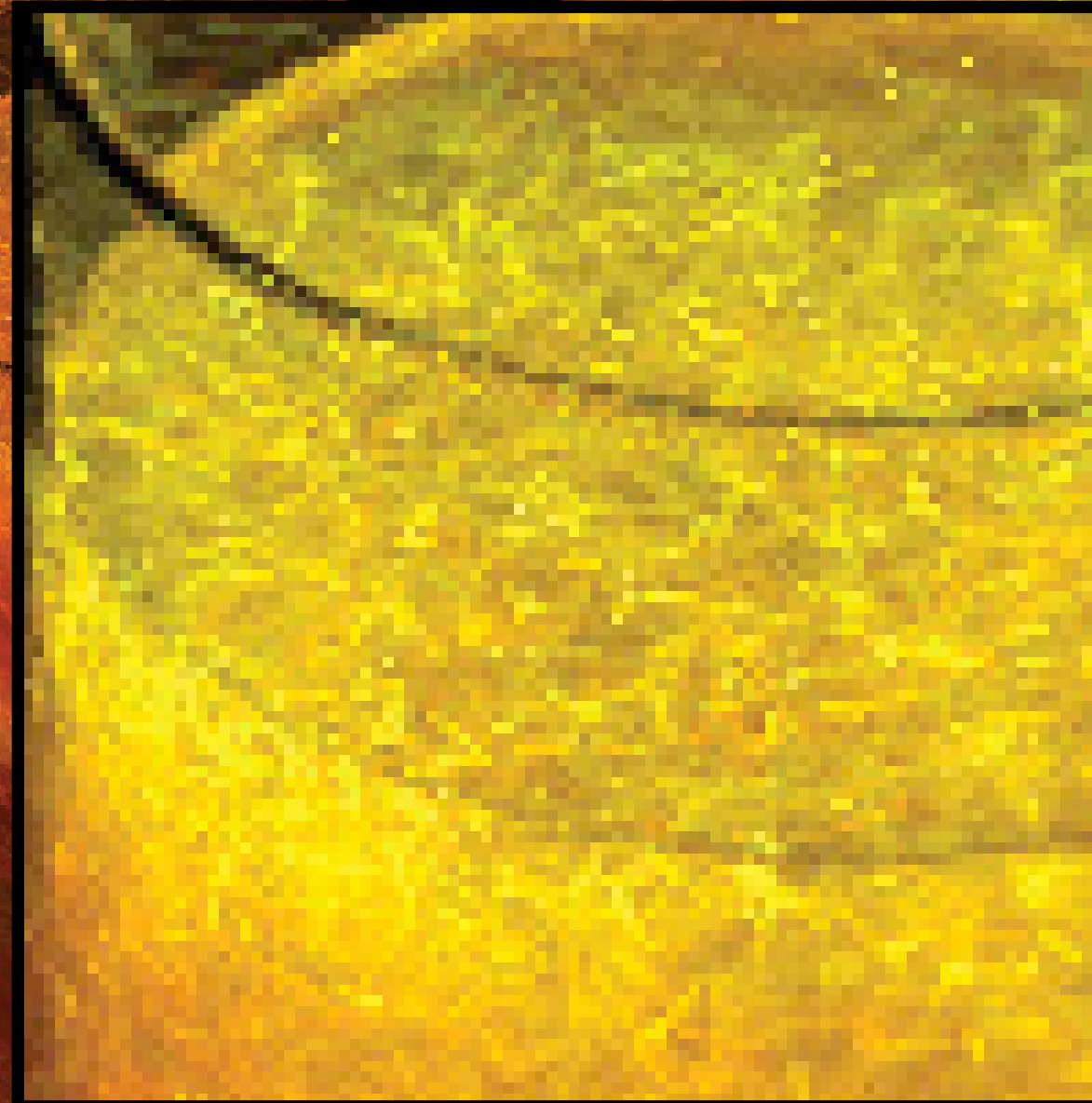


Multiple Scattering Only

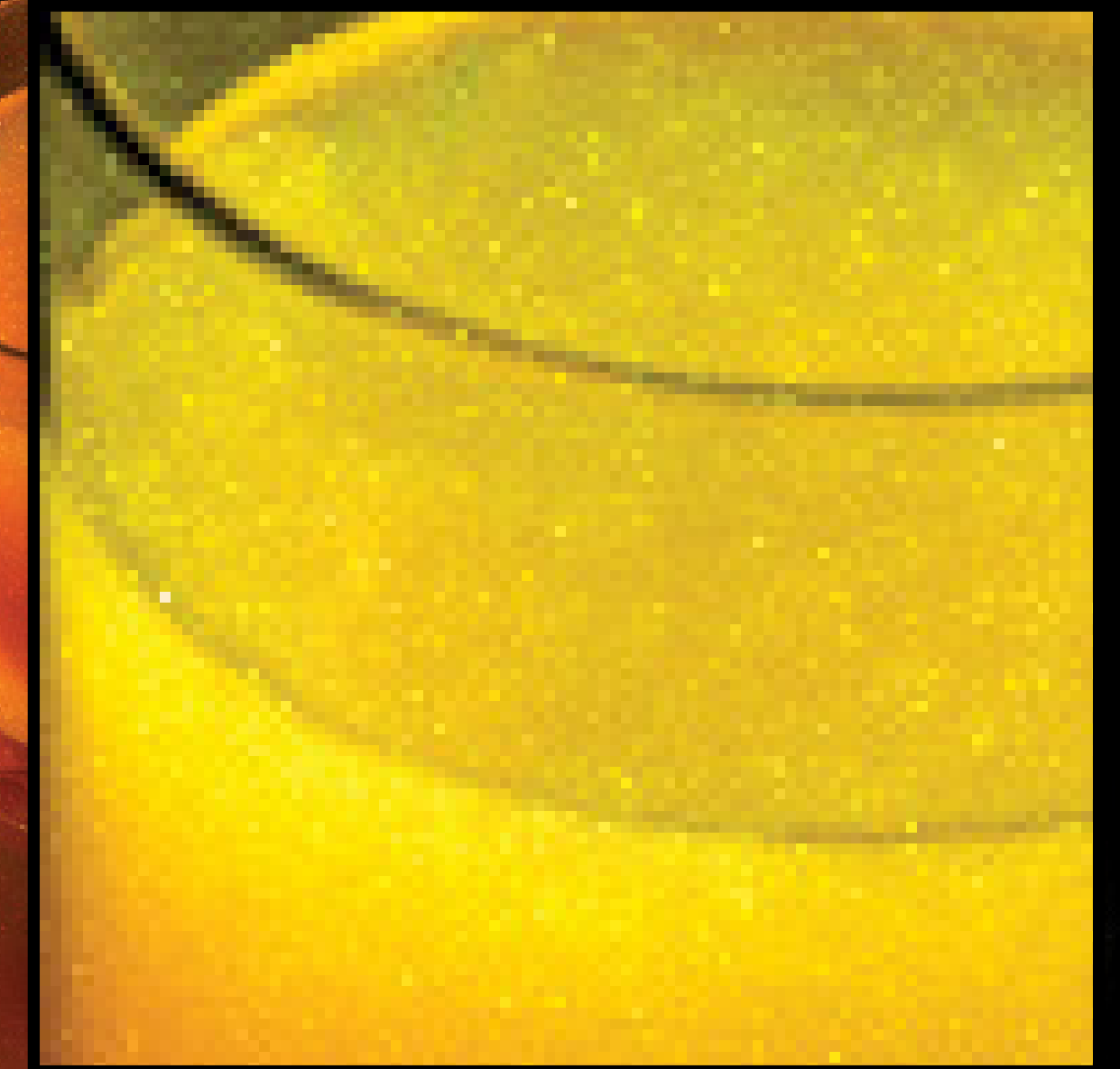
Virtual Ray Lights



Progressive Photon Beams

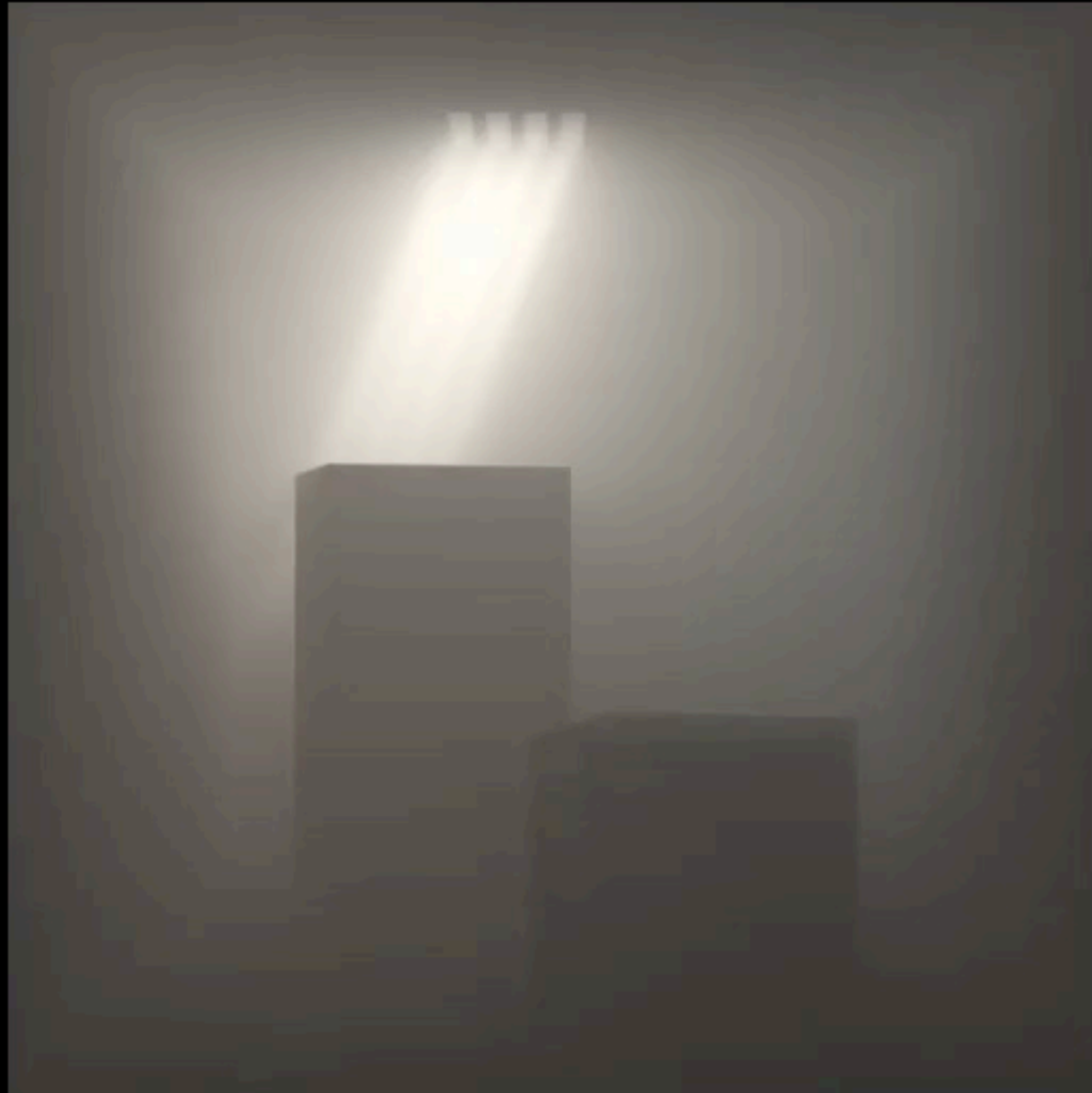


Virtual Point Lights



Temporal Stability

Virtual Ray Lights



1 minute/frame

Virtual Point Lights

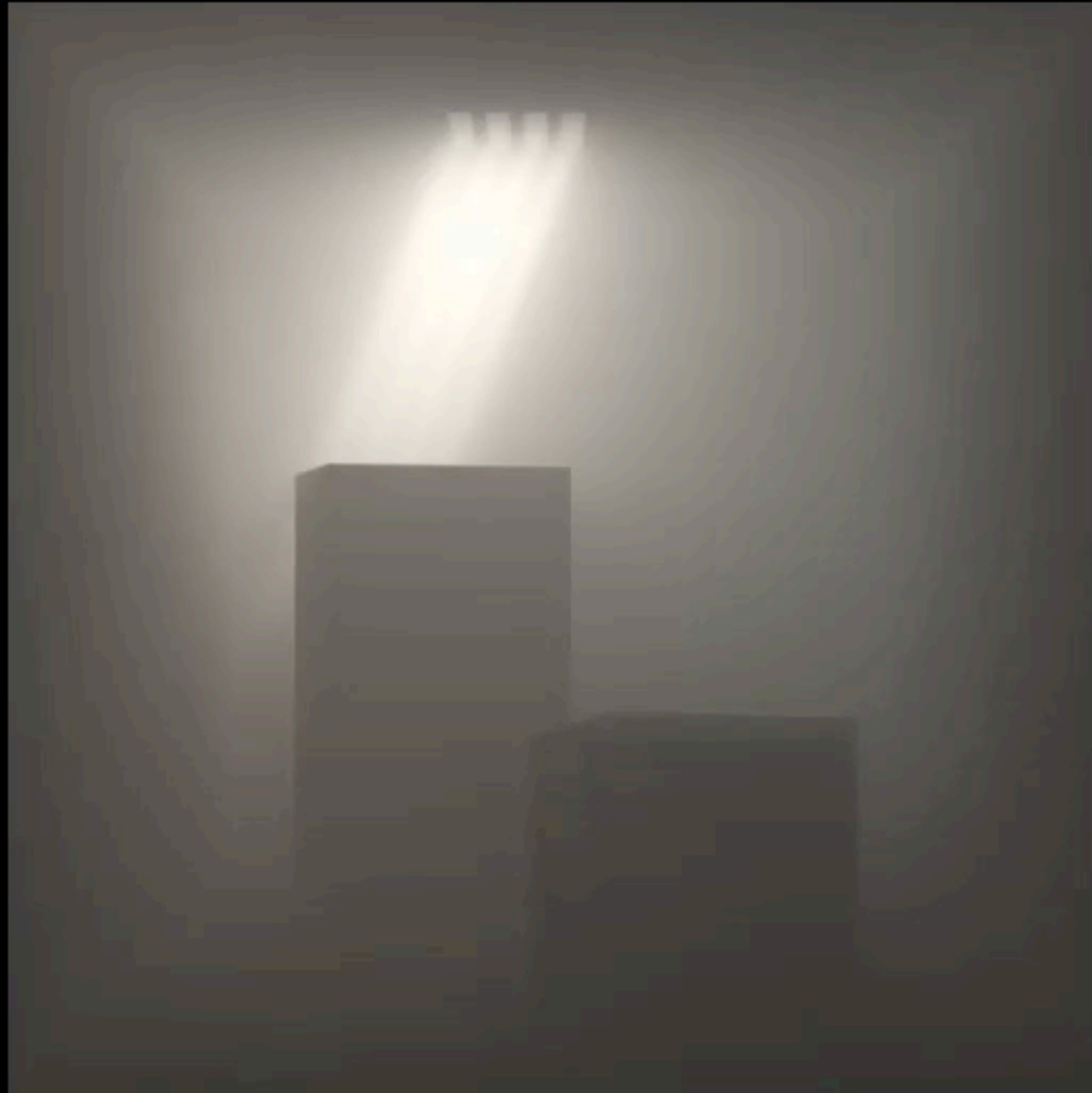


1 minute/frame

Temporal Stability

Virtual Ray Lights

Virtual Point Lights



1 minute/frame



1 minute/frame

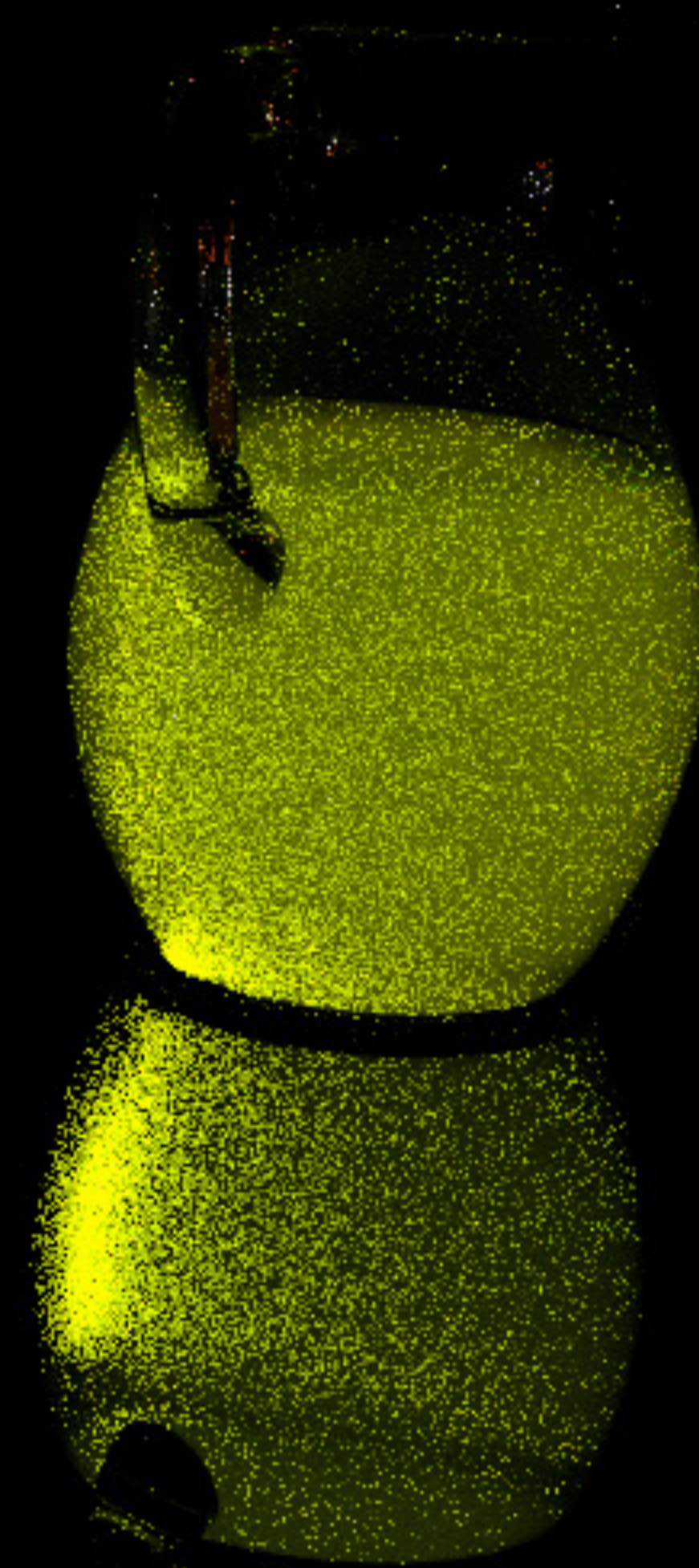
Combining techniques

UPBP (Unified Points, Beams, and Paths)
[Křivánek et al. 14]

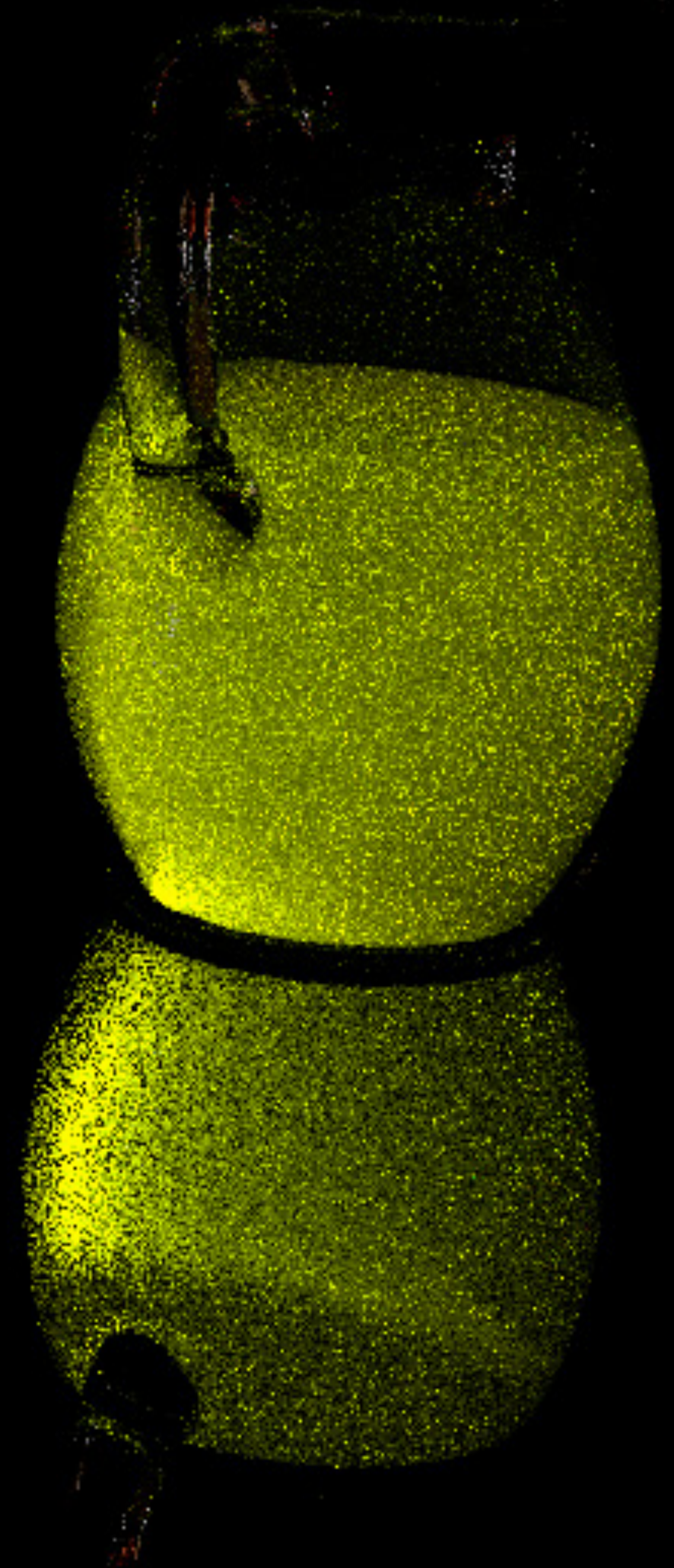
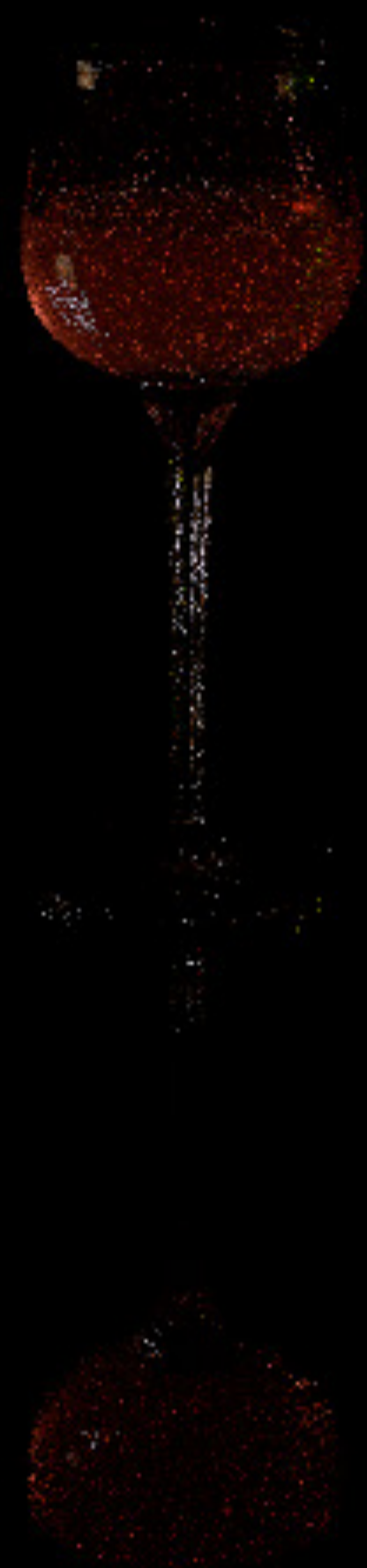
A simple, yet difficult scene



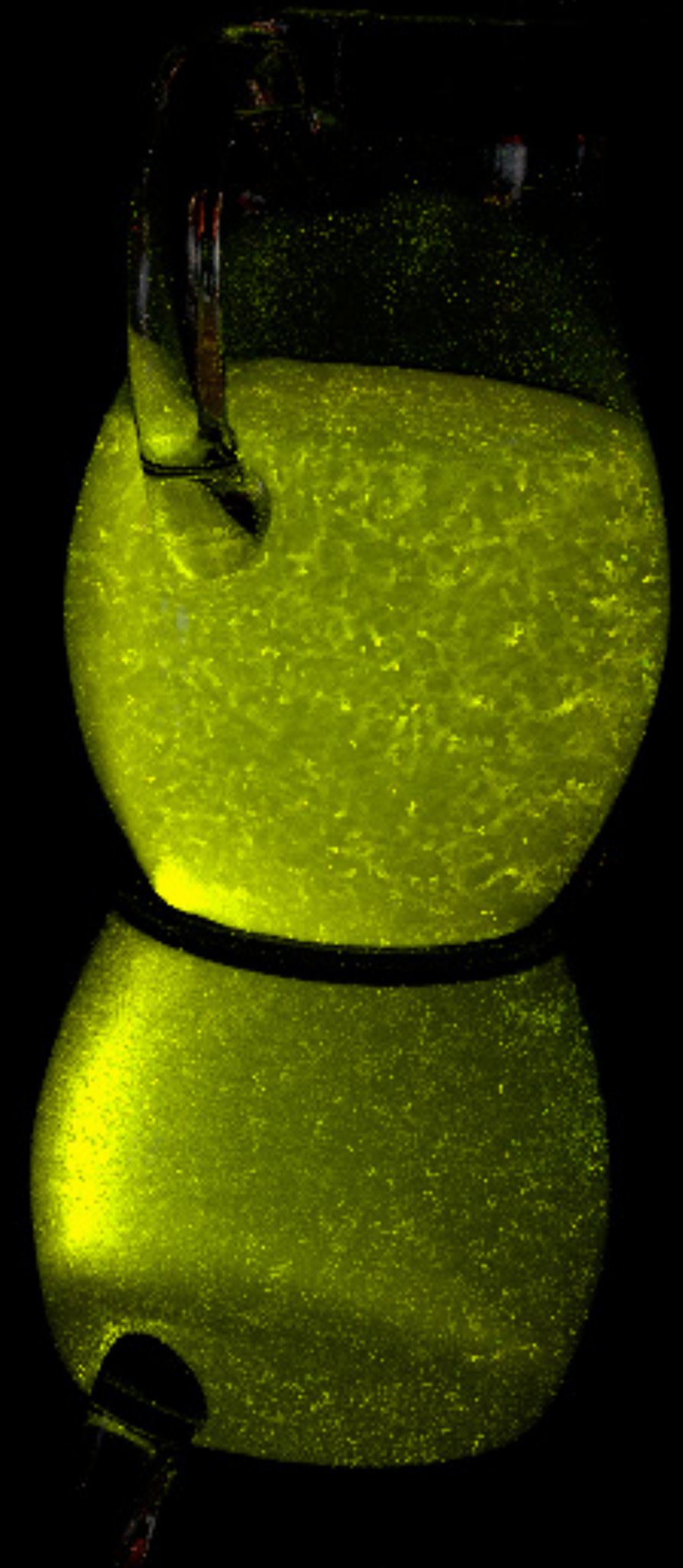
Bidirectional Path Tracing



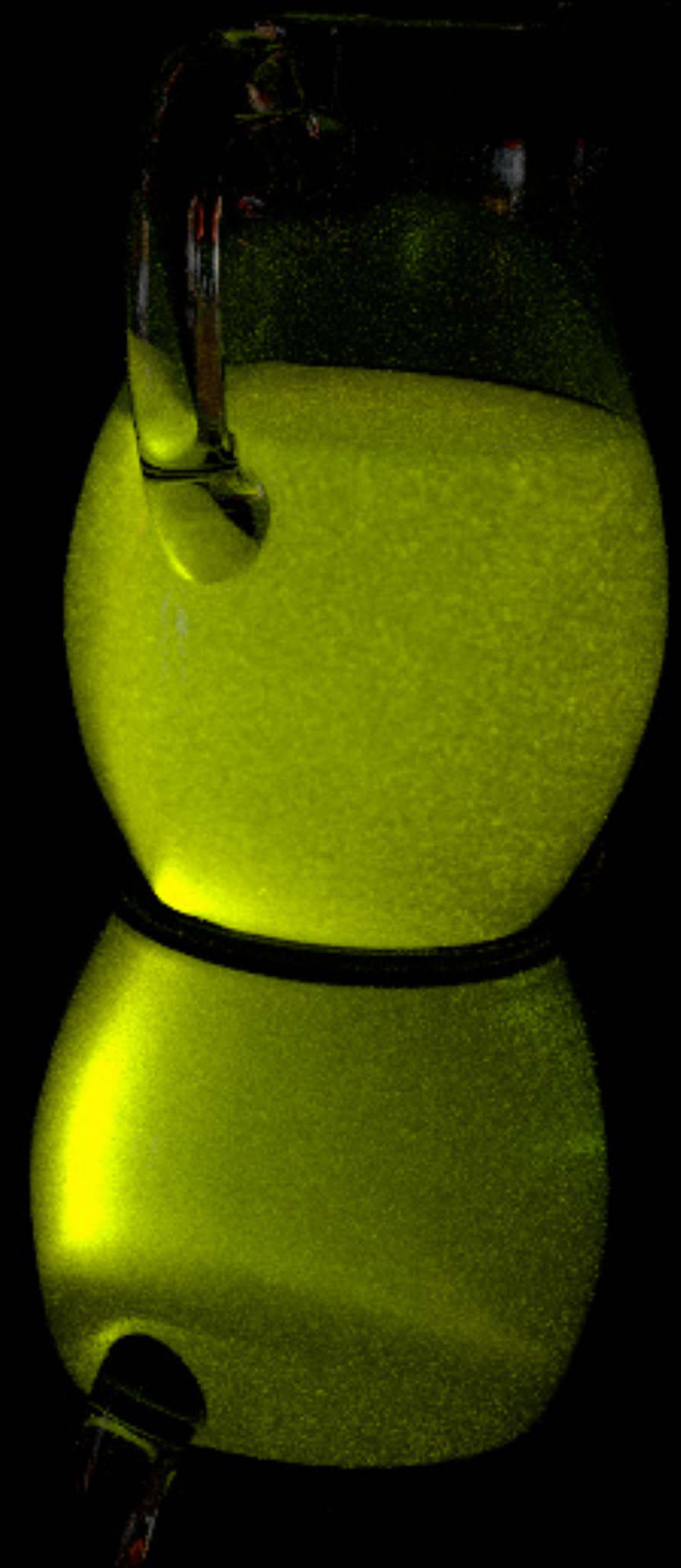
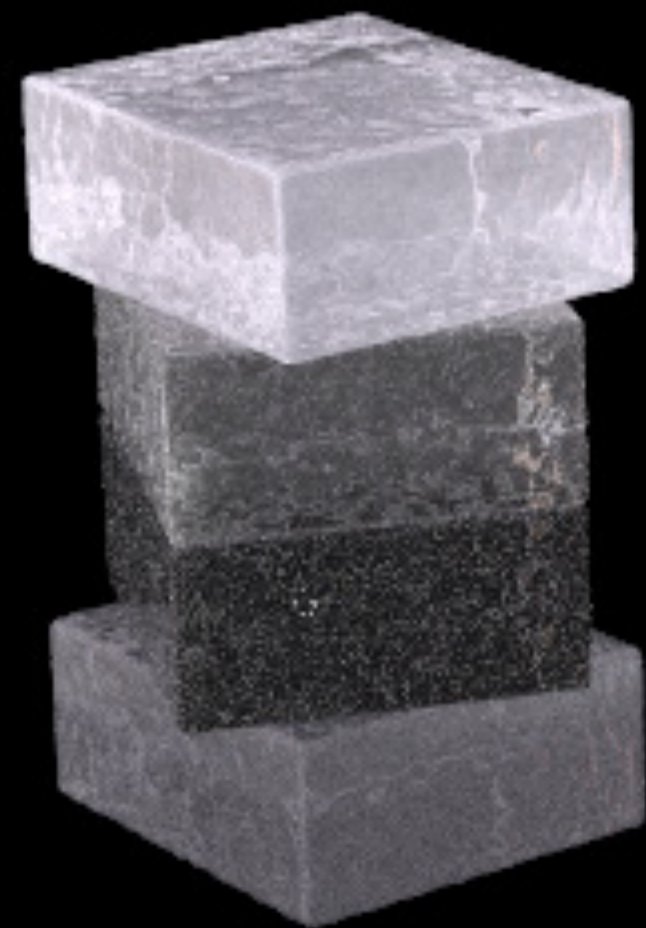
Bidirectional Photon Mapping



Bidirectional Photon Beams



Bidirectional Beam Radiance Estimate



Automatic combination



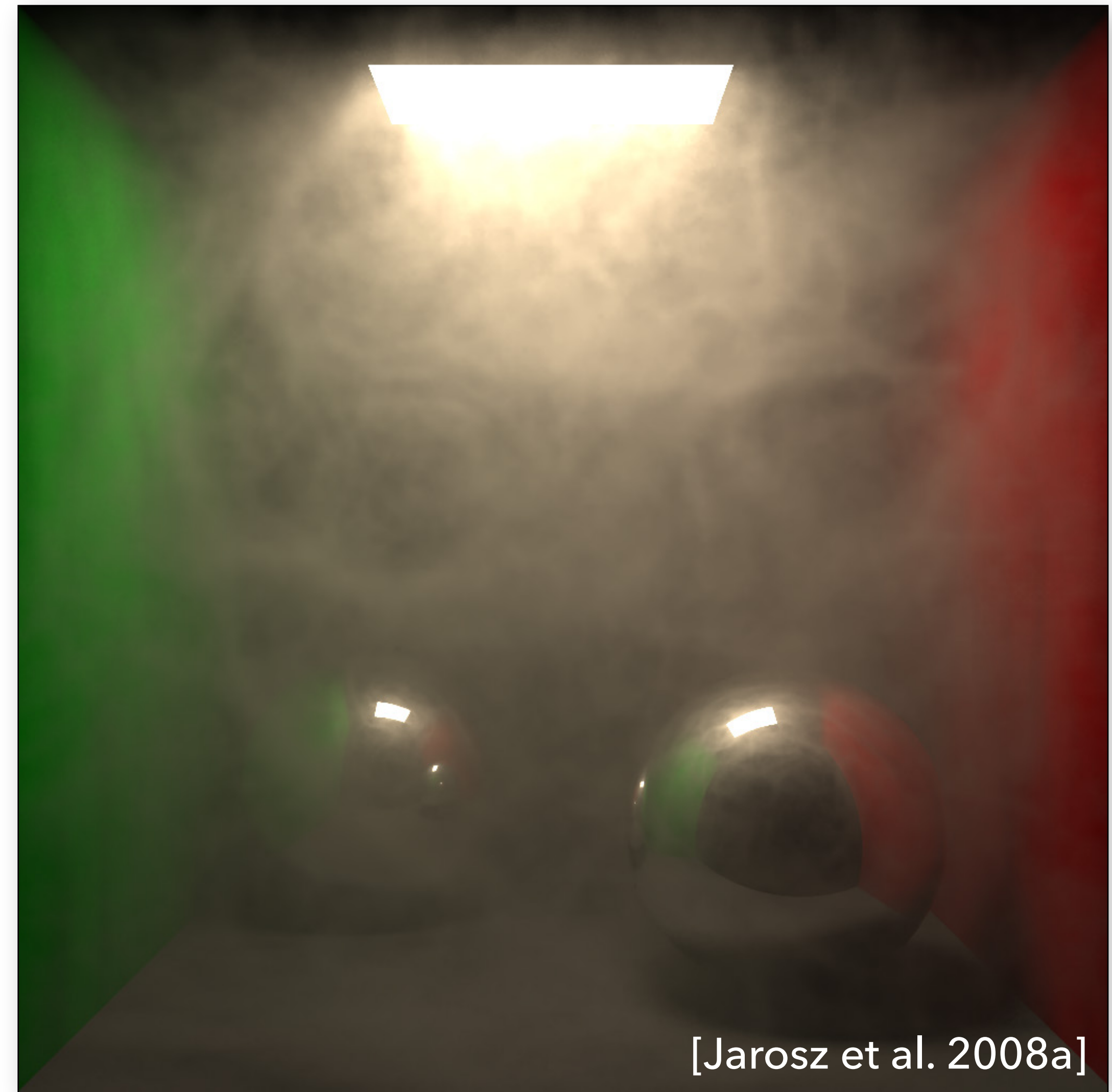
UPBP (Unified Points, Beams, and Paths)

[Křivánek et al. 14]

Radiance caching

Illumination changes slowly

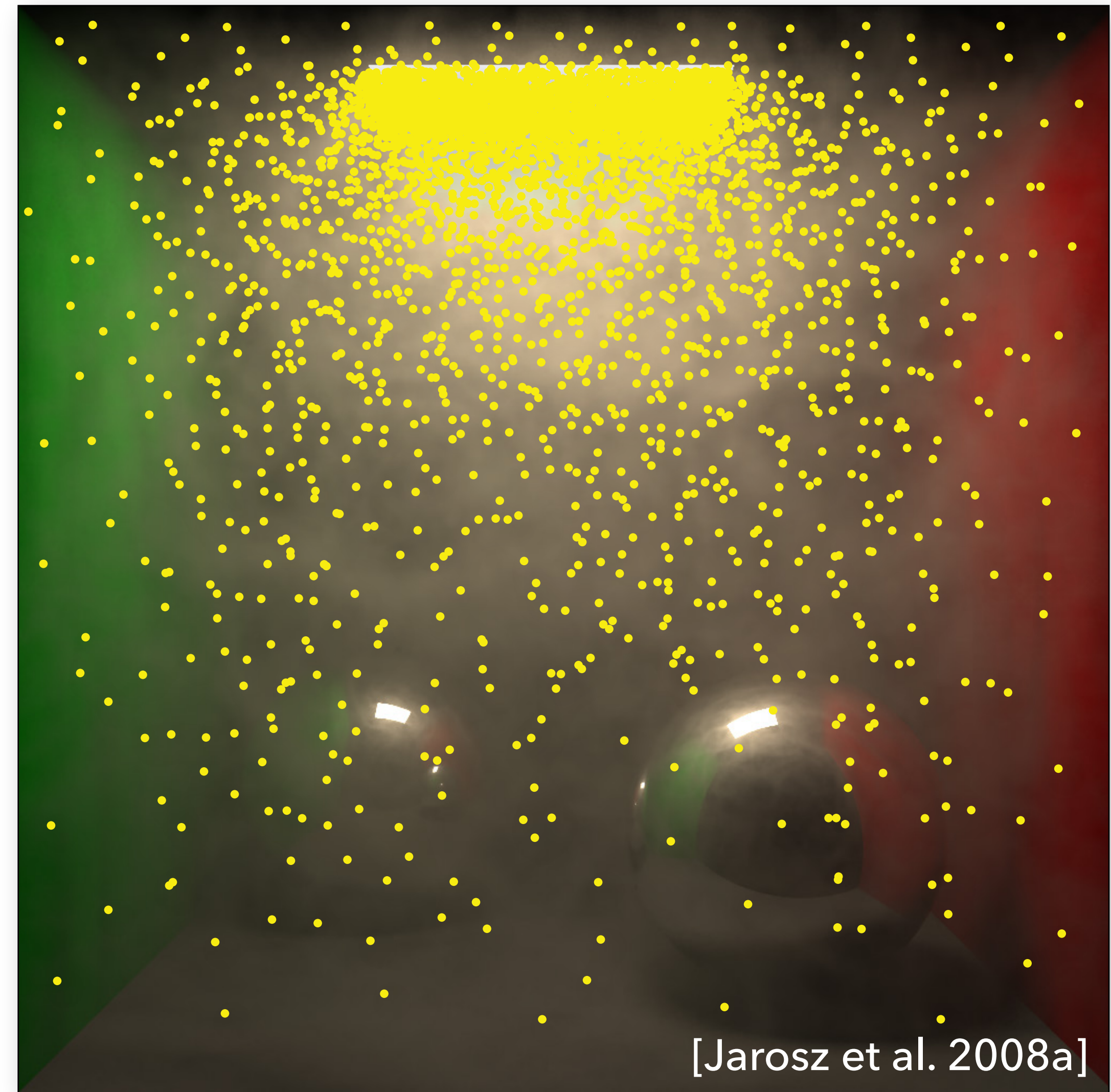
- Compute lighting and cache for reuse by nearby rays



Radiance caching

Illumination changes slowly

- Compute lighting and cache for reuse by nearby rays



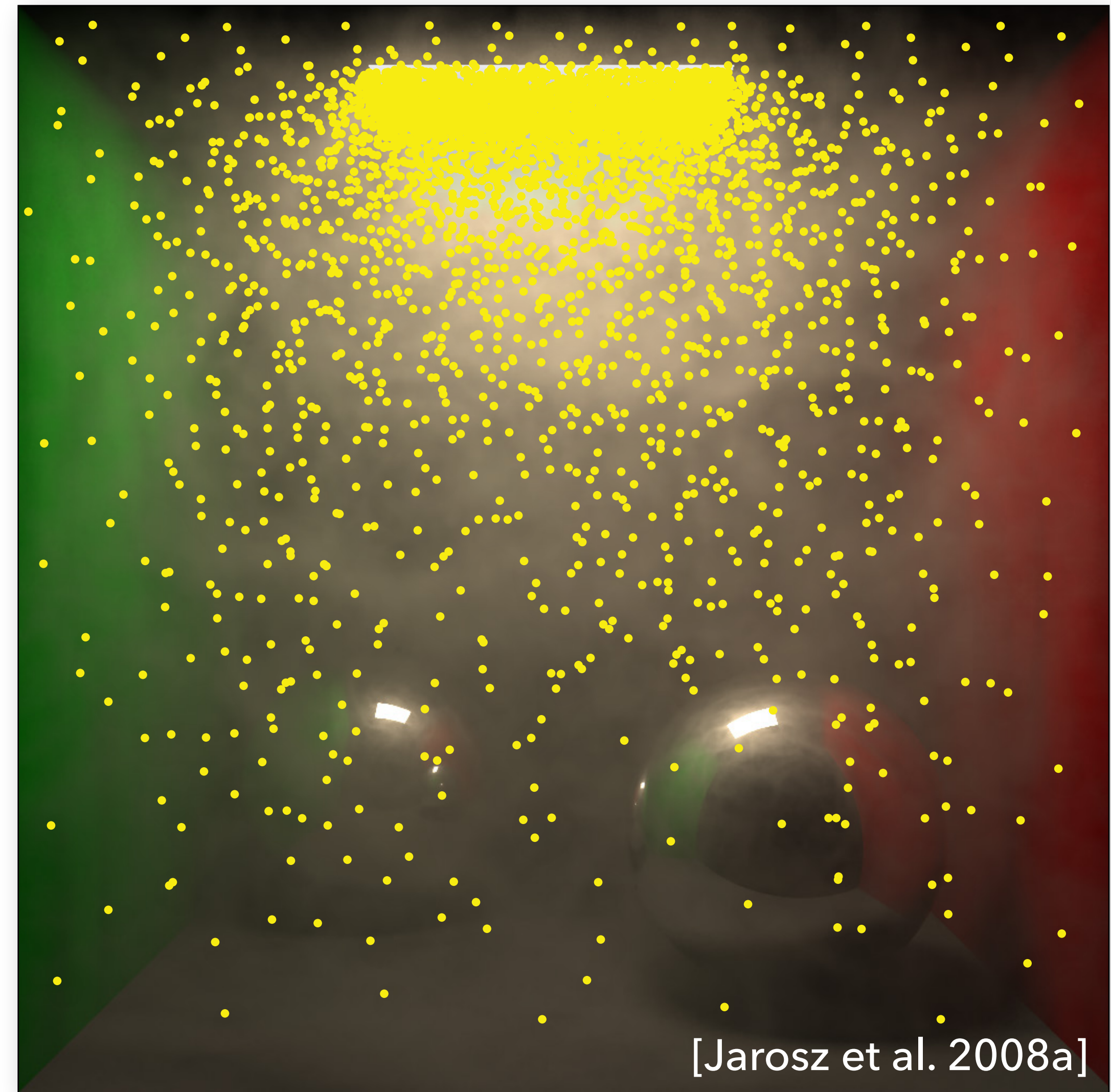
Radiance caching

Illumination changes slowly

- Compute lighting and cache for reuse by nearby rays

Extension of (ir)radiance caching

- [Ward 88, Ward & Heckbert 92]
- [Křivánek 05a, b]
- [Jarosz et al. 12, Schwarzhaupt et al. 12]



Radiance caching

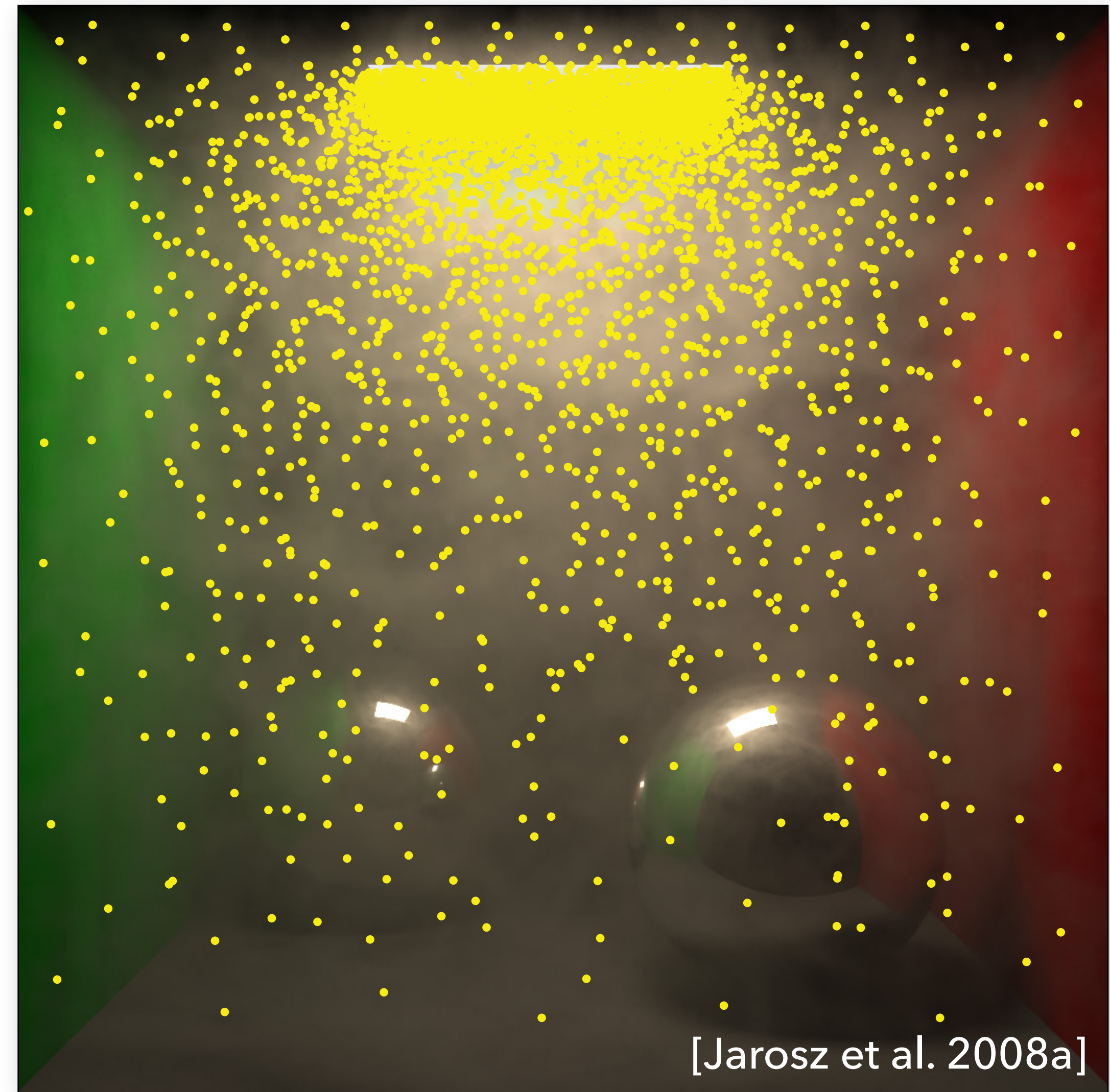
Illumination changes slowly

- Compute lighting and cache for reuse by nearby rays

Extension of (ir)radiance caching

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- [Křivánek 05a, b]
- [Jarosz et al. 12, Schwarzhaupt et al. 12]

[Jarosz et al. 08a, b]



Radiance caching

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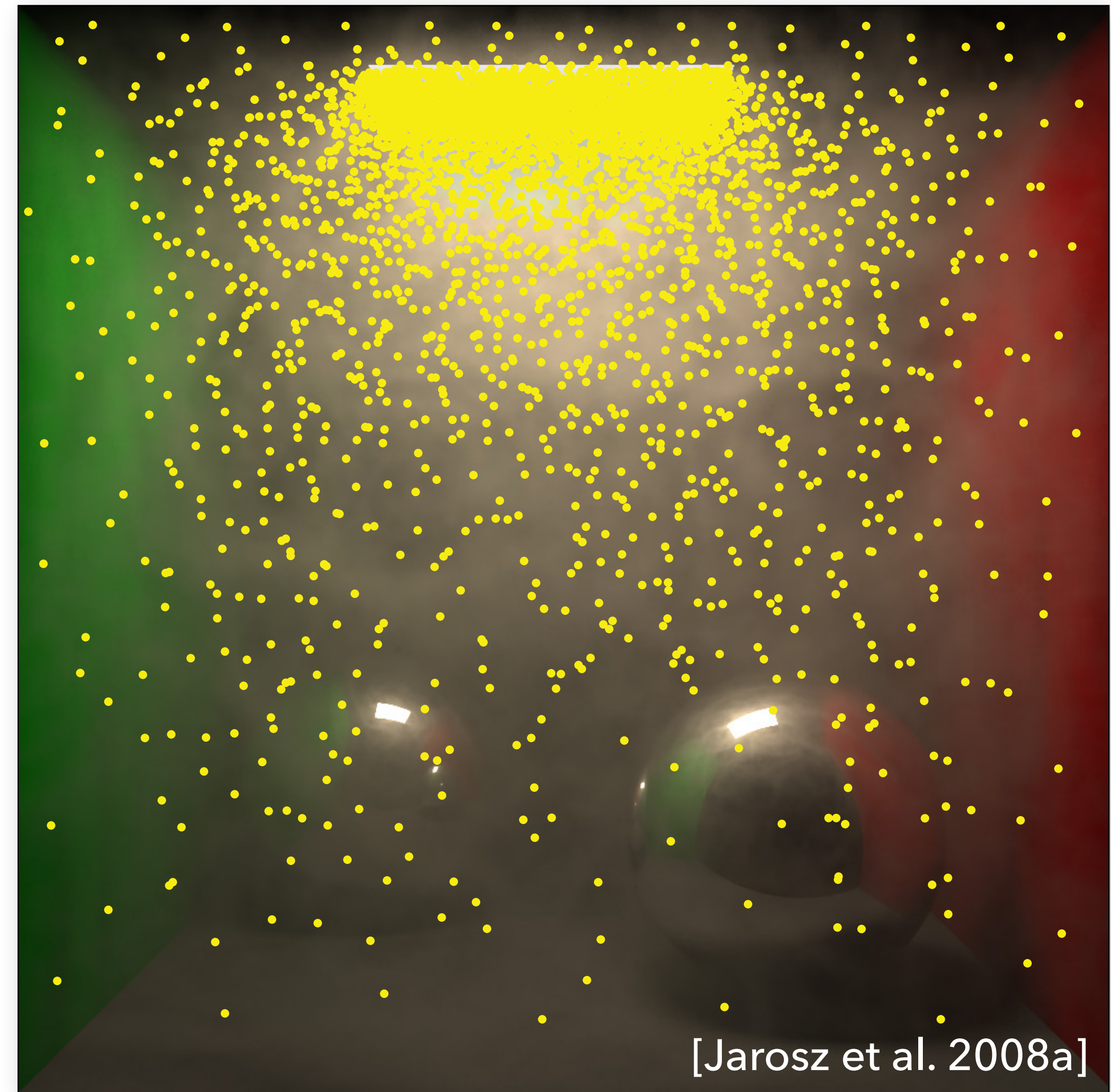
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Extension of (ir)radiance caching

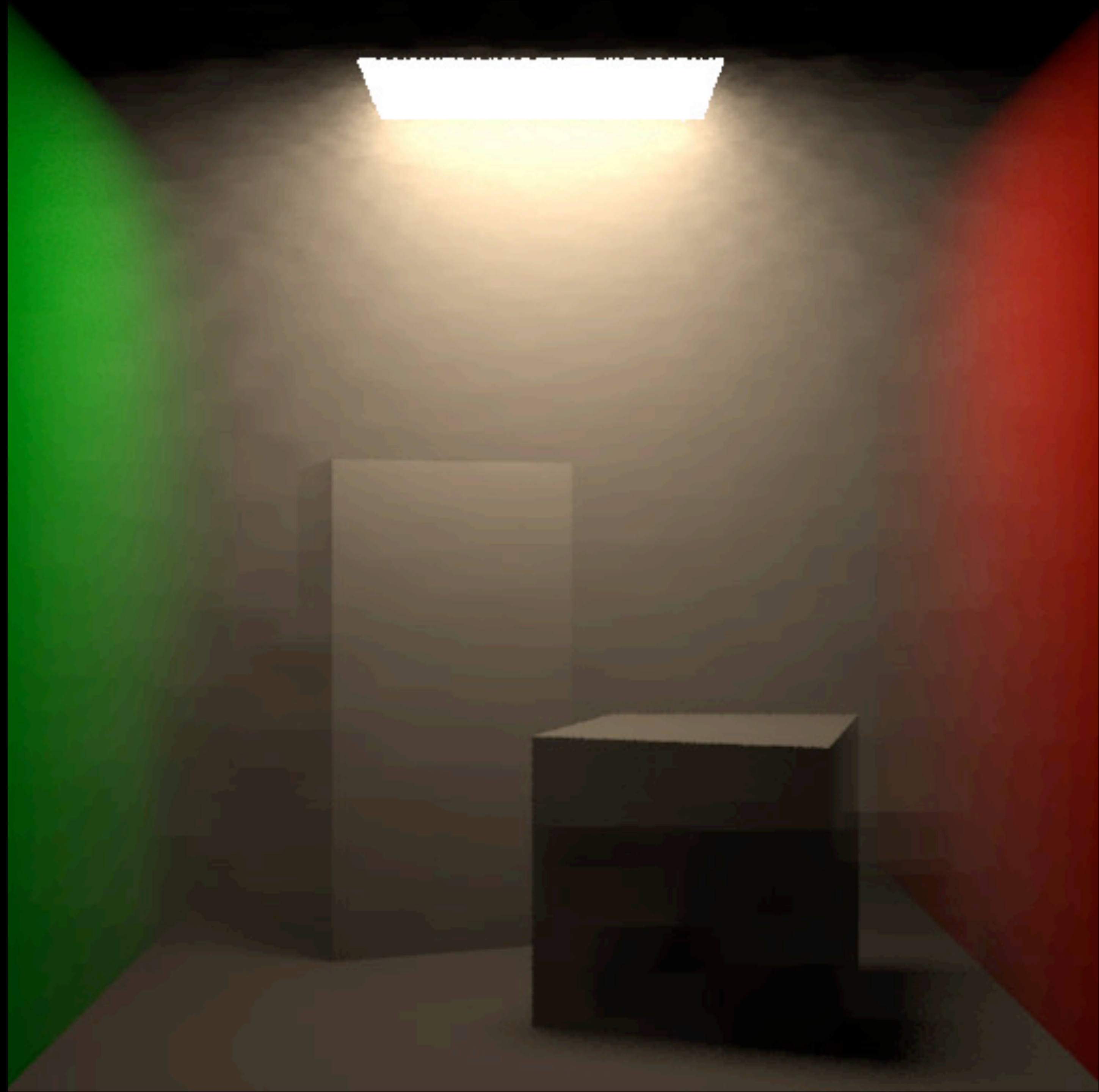
- [Ward 88, Ward & Heckbert 92]
- [Křivánek 05a, b]
- [Jarosz et al. 12, Schwarzhaupt et al. 12]

[Jarosz et al. 08a, b]

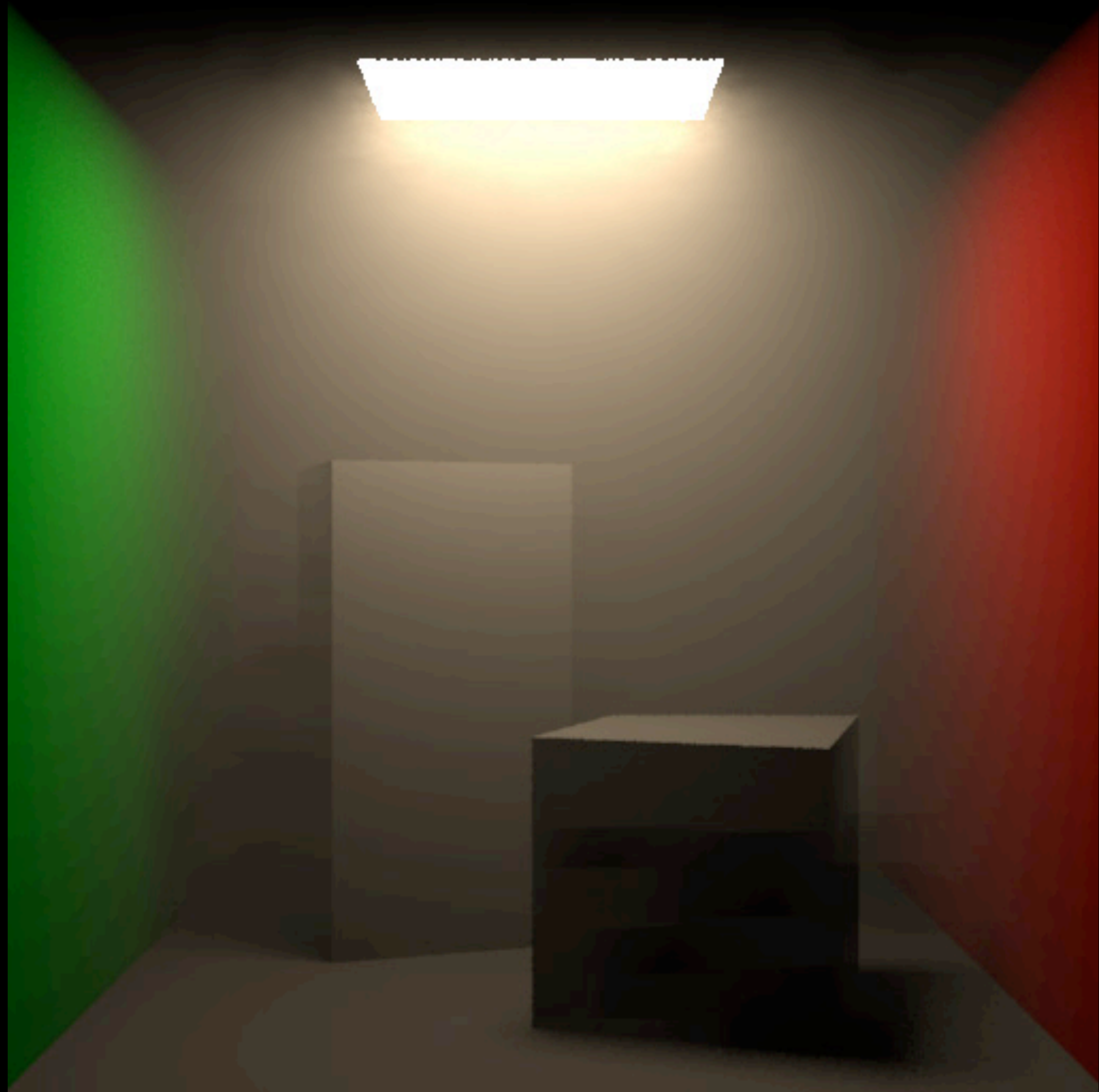
[Marco et al. 18]



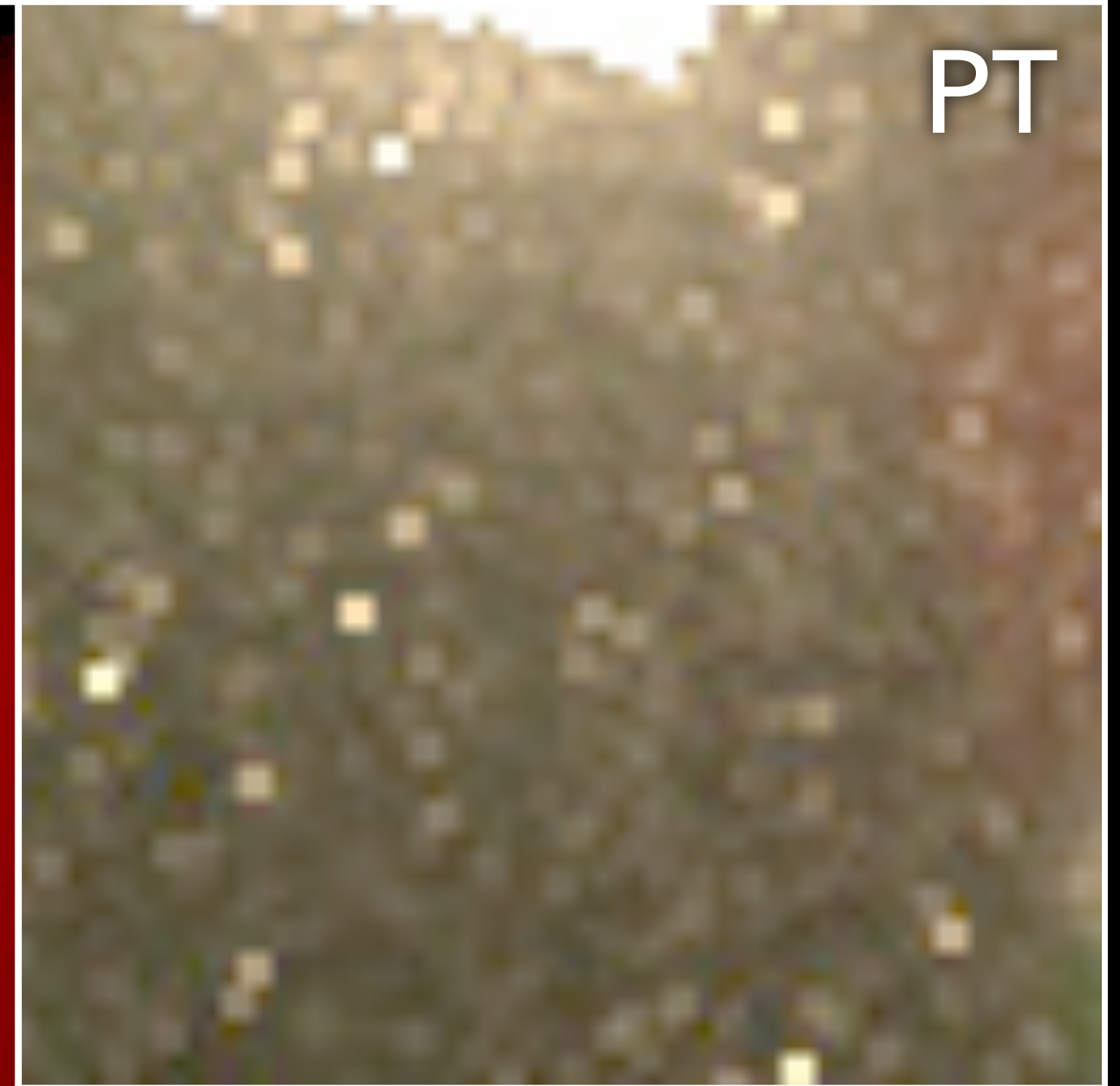
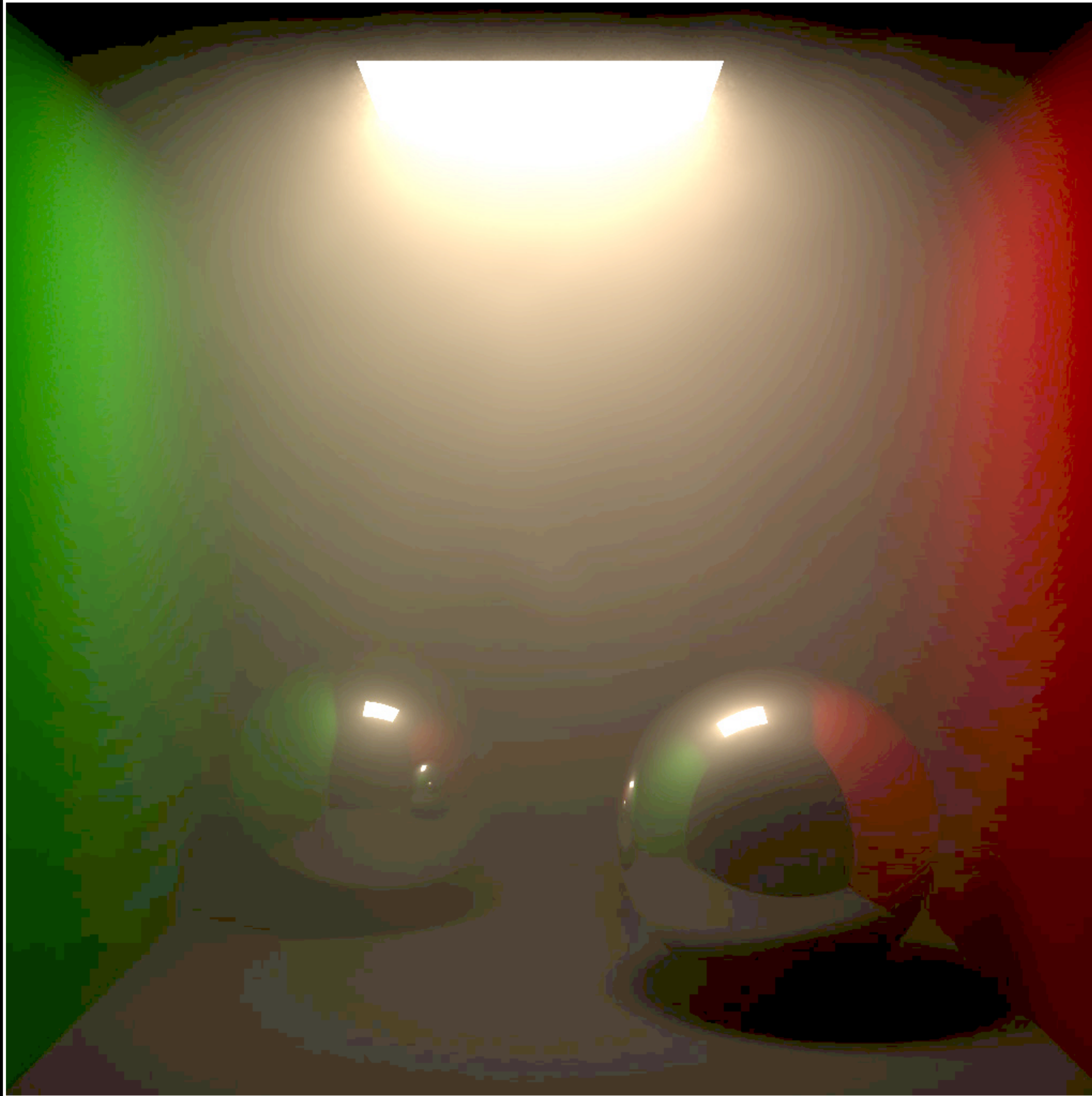
No gradients

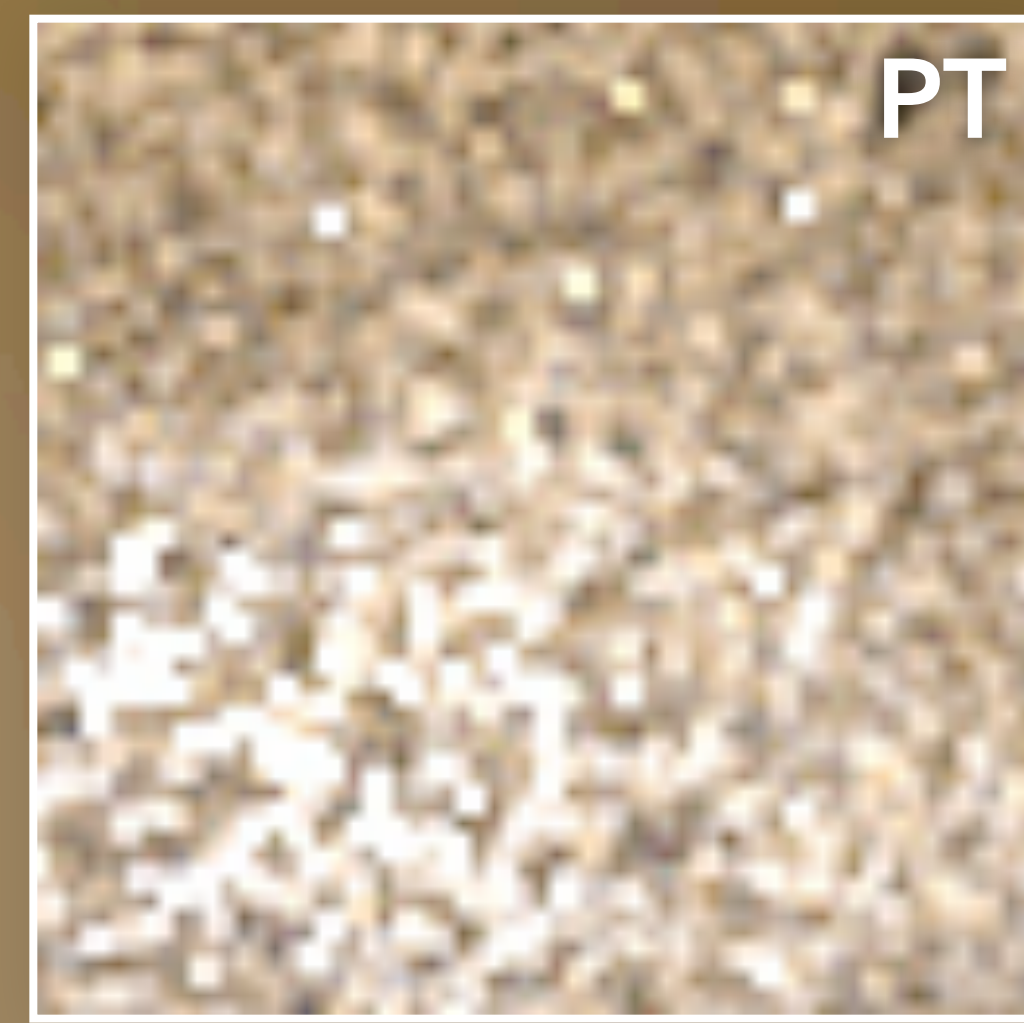


With gradients



[Jarosz et al. 2008a]





[Jarosz et al. 2008a]



Path tracing



1st order radiance caching

[Jarosz et al. 2008a]



(occlusion-unaware gradient)
1st order radiance caching

[Jarosz et al. 2008a]



(occlusion-aware gradient + hessian)
2nd order radiance caching

[Marco et al. 2018]



Reference

Advanced methods

Photon tracing/mapping

Many-light methods

Combining techniques

Radiance caching

Advanced methods

Photon tracing/mapping

Many-light methods

Combining techniques

Radiance caching

More from Johannes...