Monte Carlo Methods for Physically Based Volume Rendering

Advanced methods

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DARTMOUTH
VISUAL COMPUTING LAB

Advanced methods

Photon tracing/mapping

Many-light methods

Radiance caching

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Photon tracing/mapping

Many-light methods

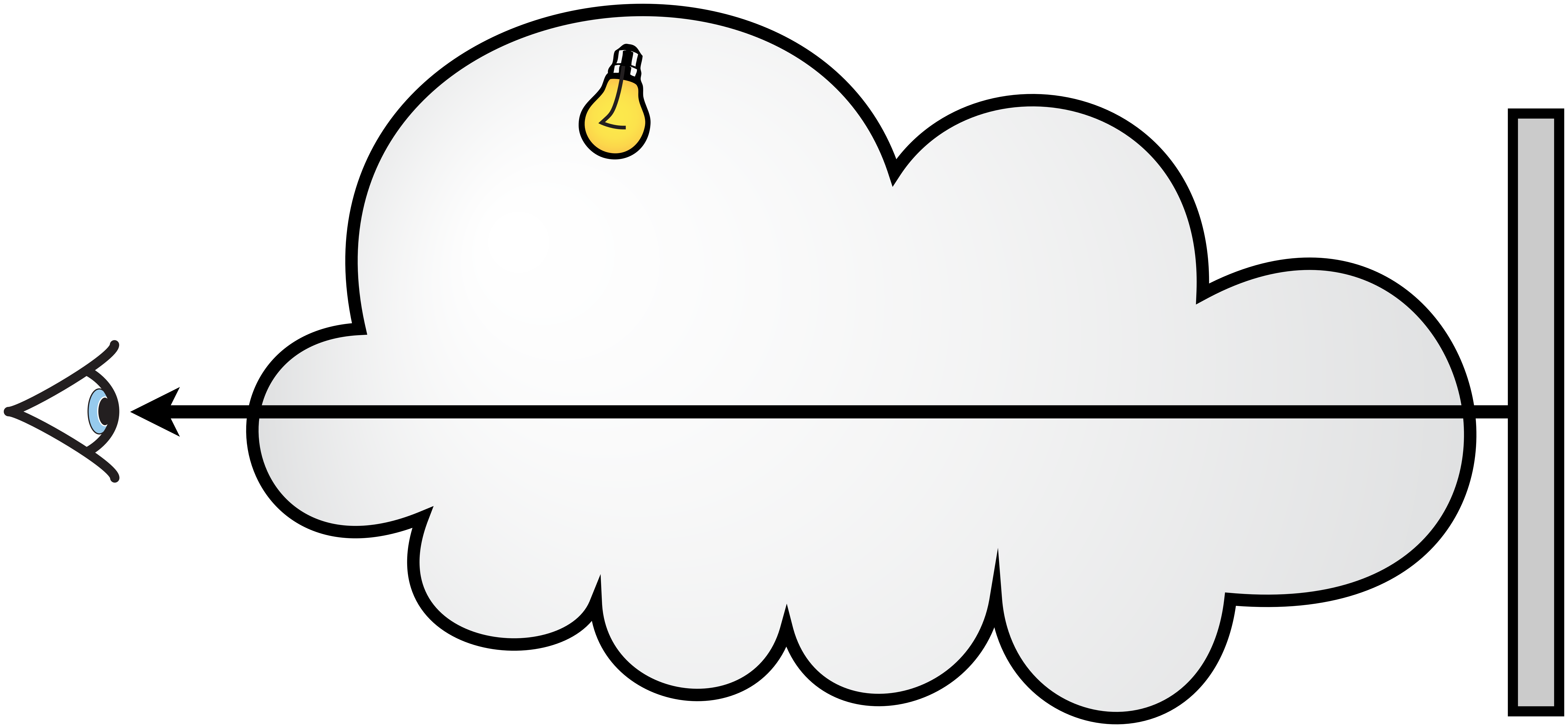
Radiance caching

More from Jaroslav & Johannes…

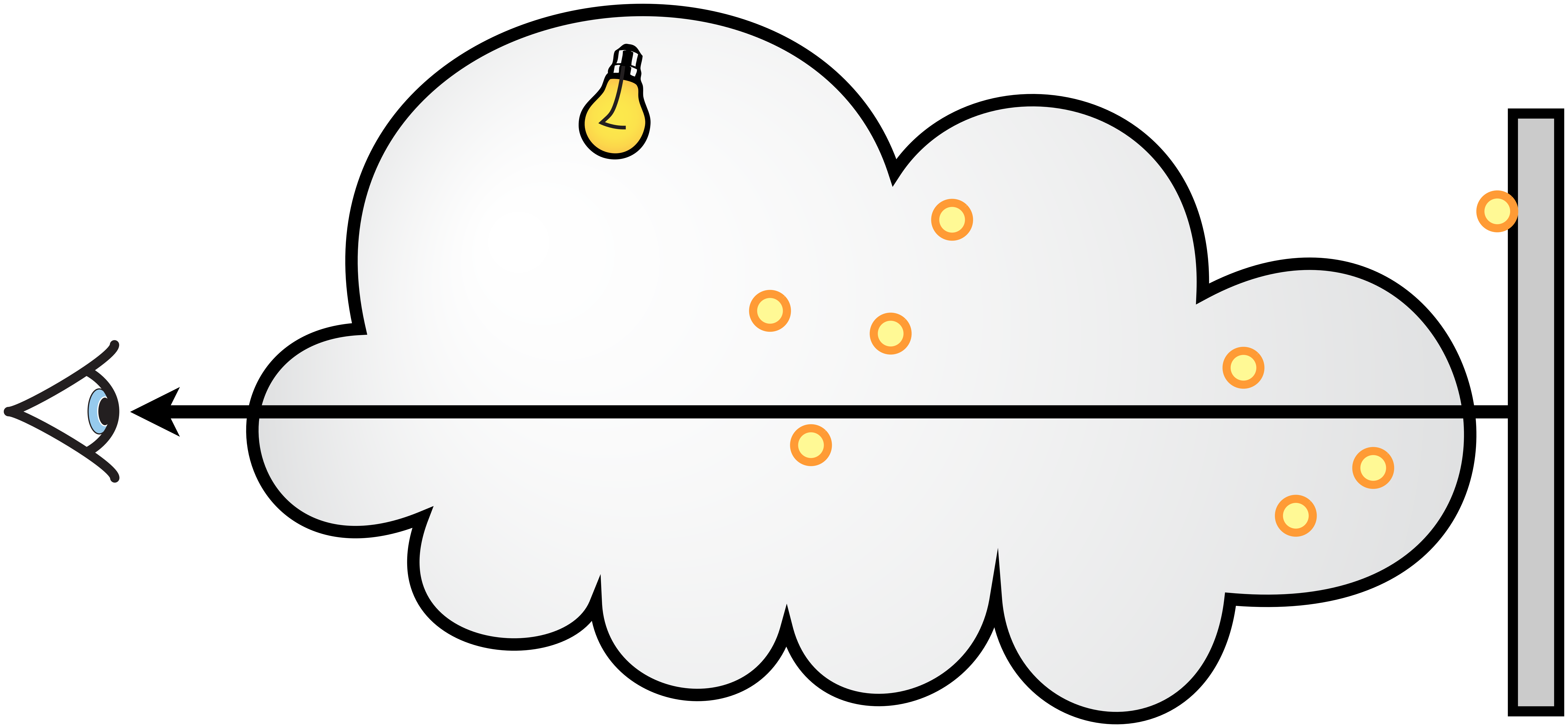
Volumetric photon mapping

1. Photon tracing
   - Simulate scattering of photons
2. Rendering
   - Reuse photons to estimate multiple scattering

Photon Tracing in Participating Media



Photon Tracing in Participating Media



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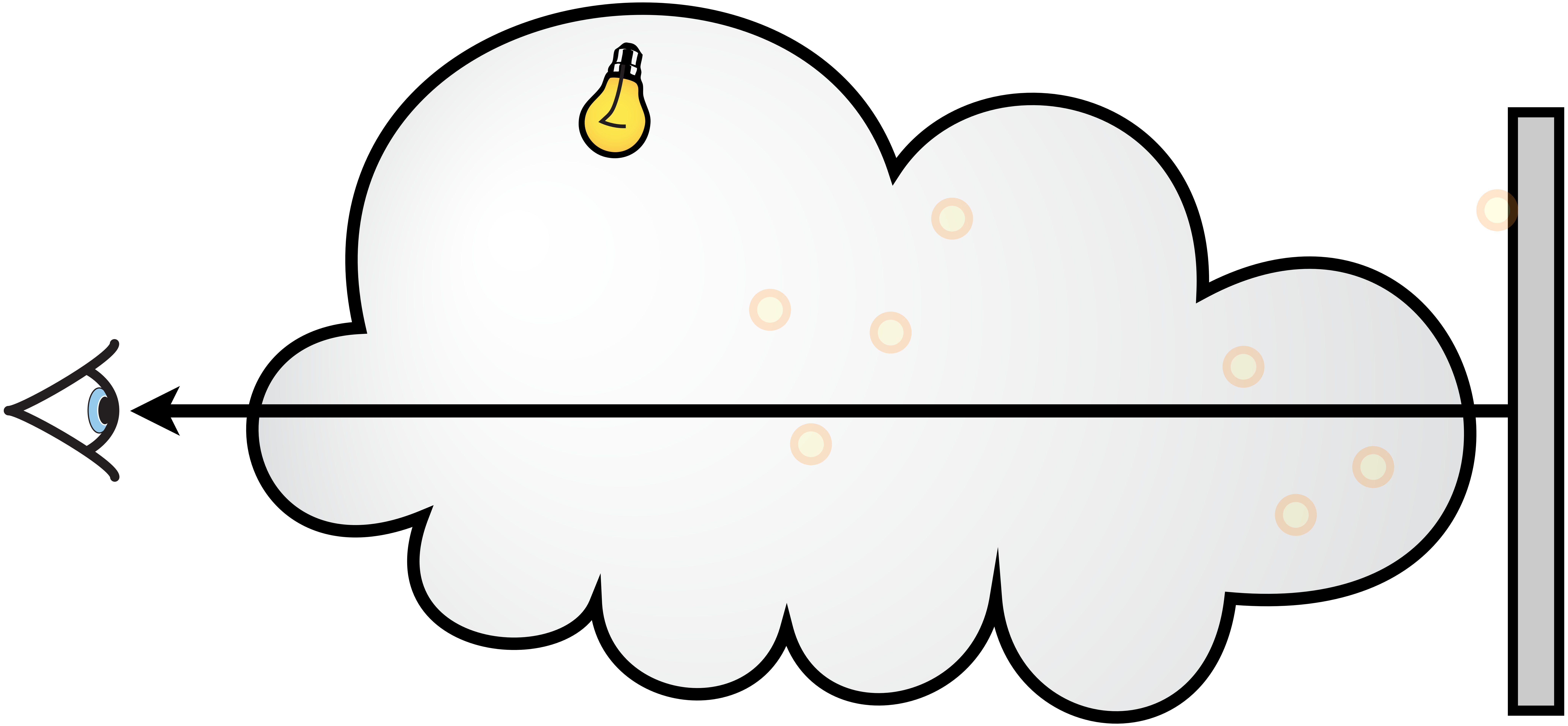

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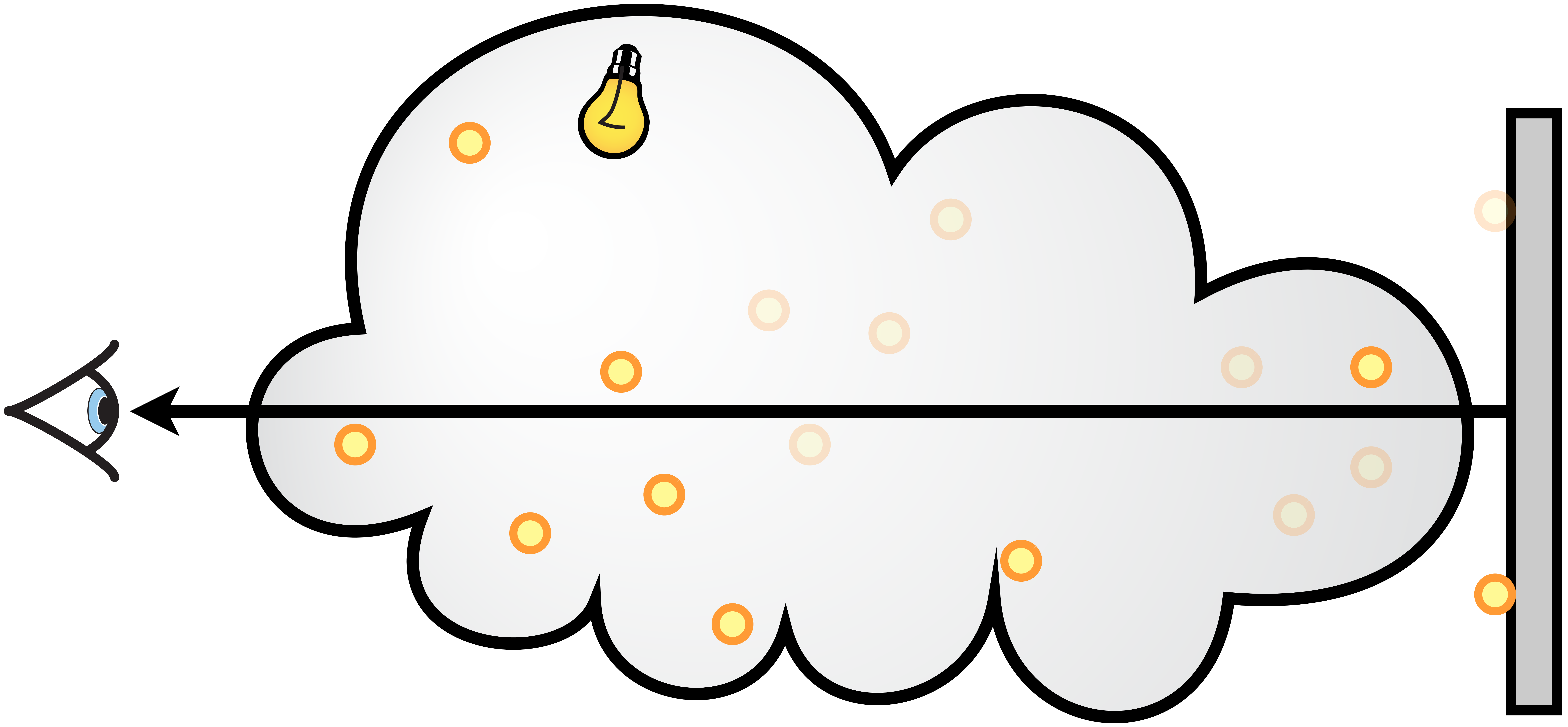
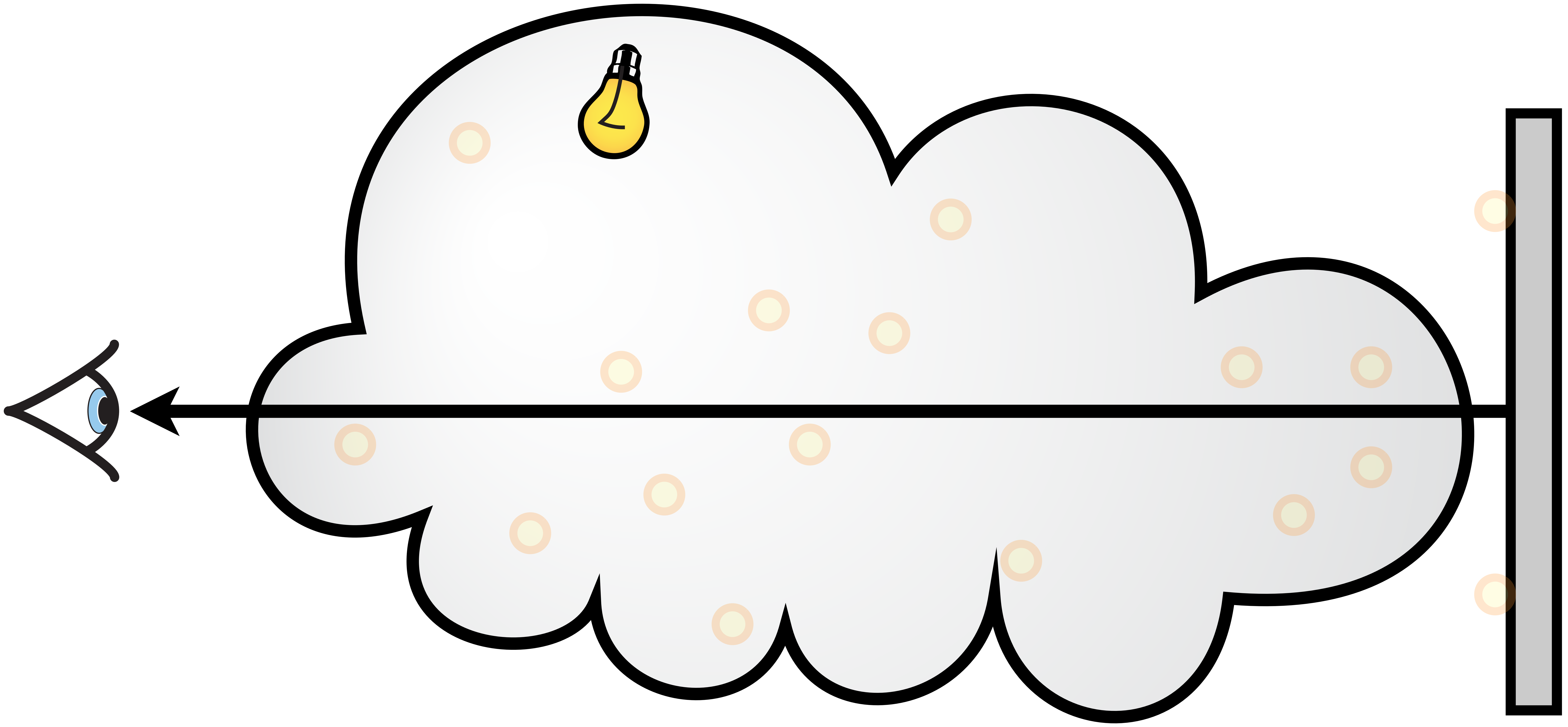


Photon Tracing in Participating Media



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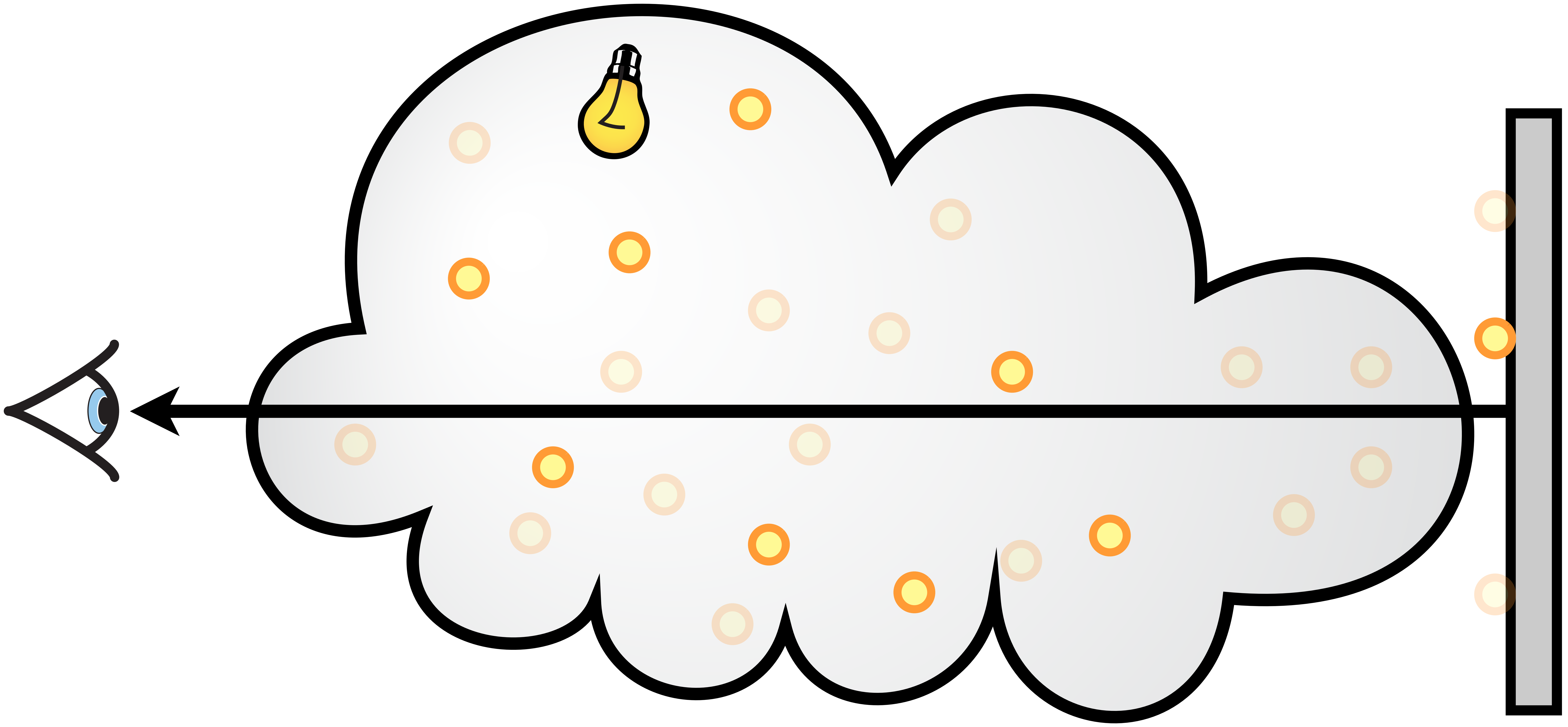
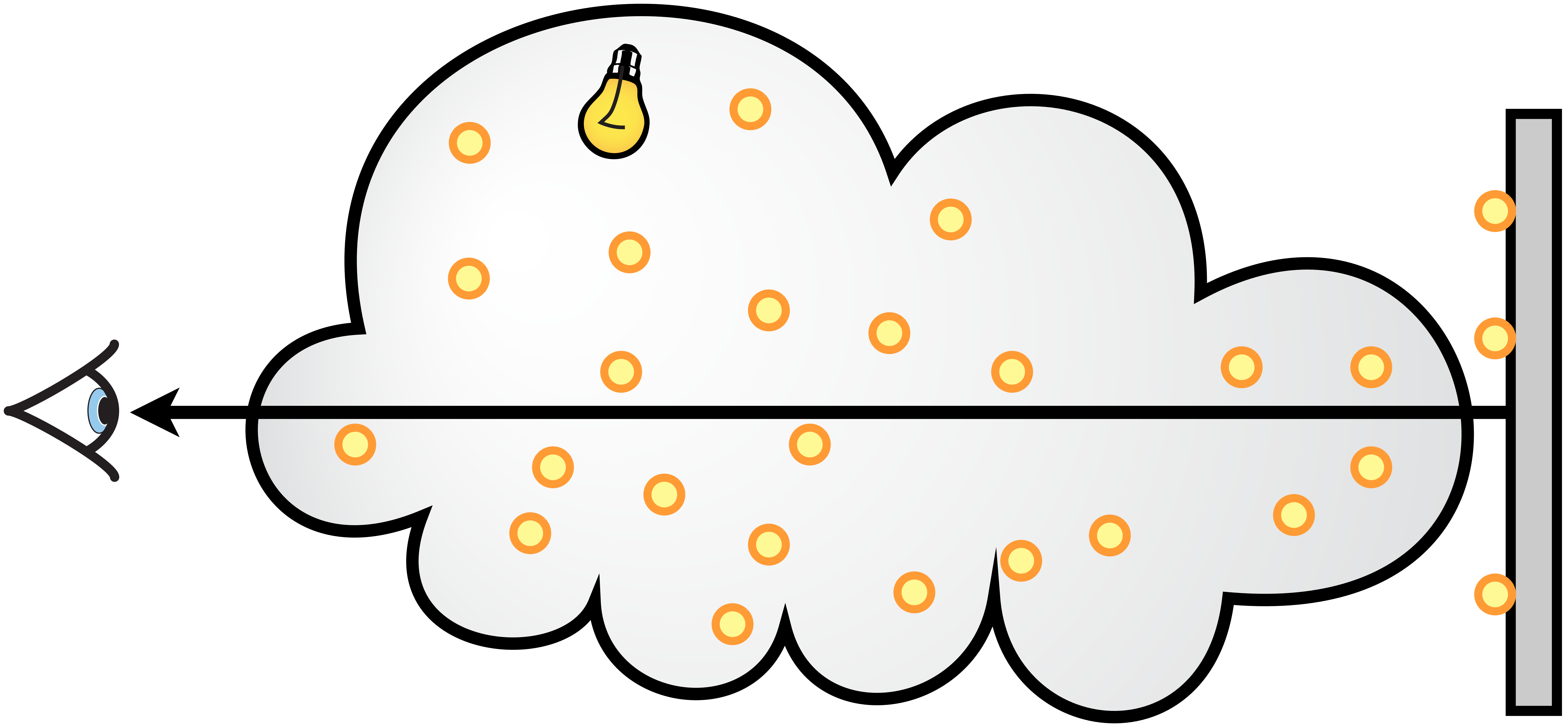


Photon Tracing in Participating Media



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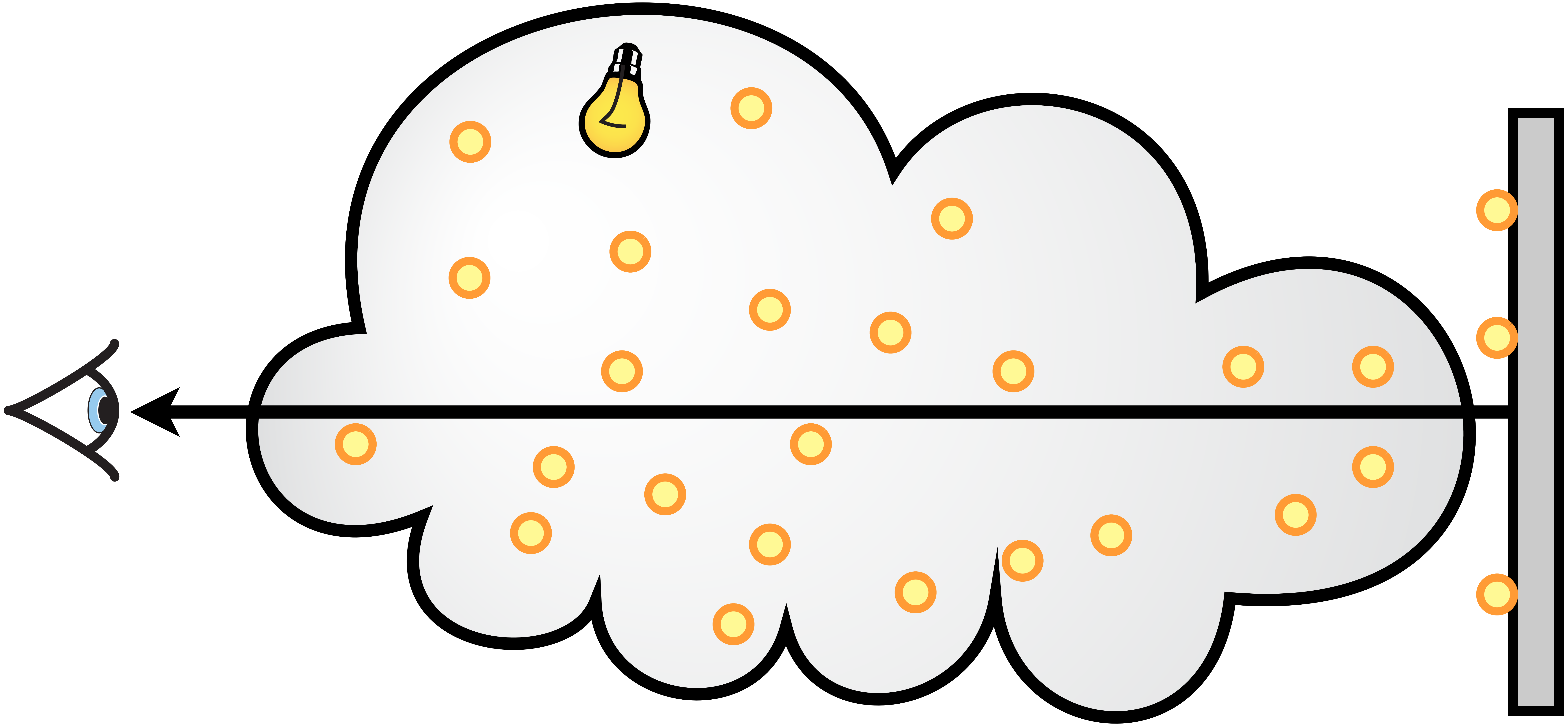
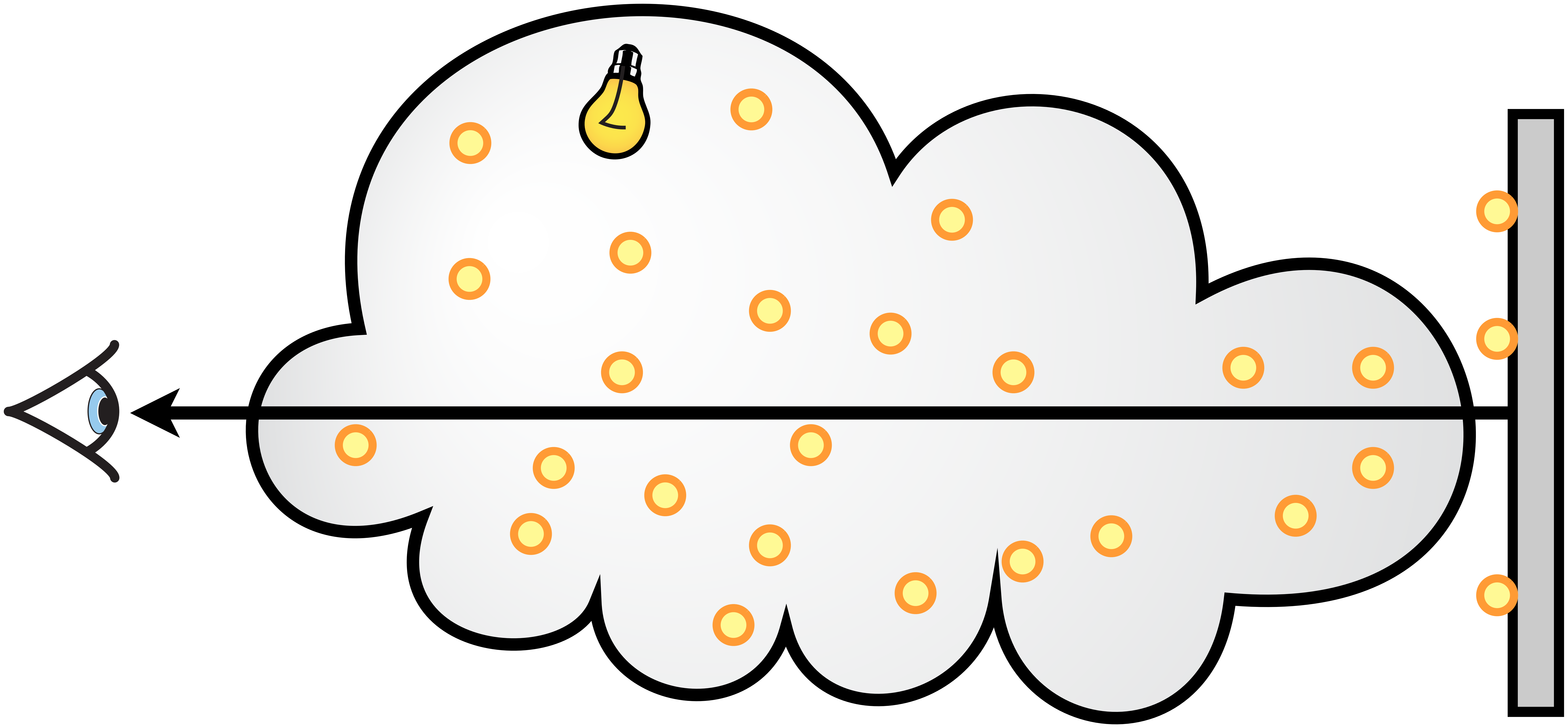


Photon Tracing in Participating Media

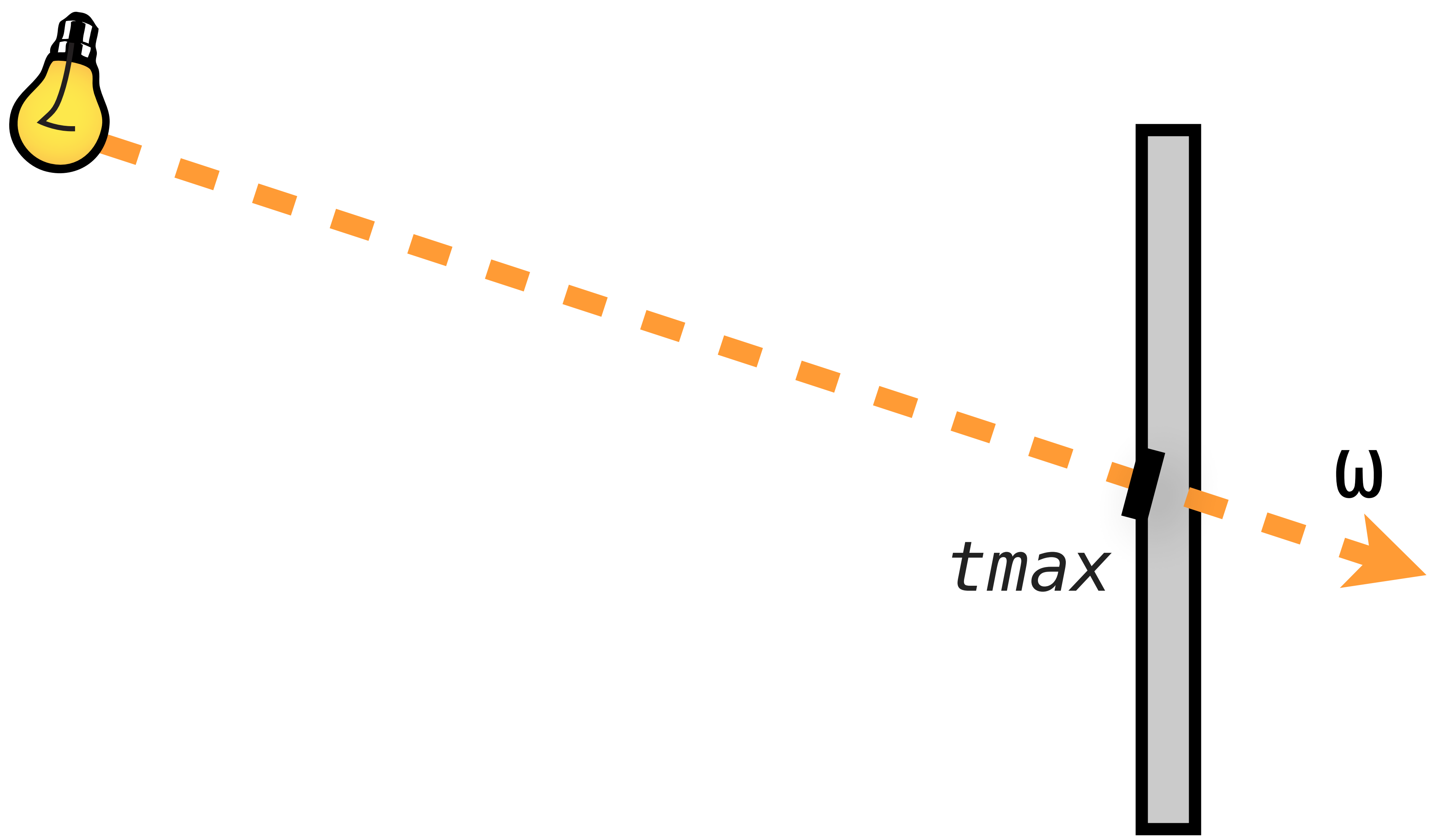


Basic Photon Tracer

```
void vPT(x, ω, Φ)
```

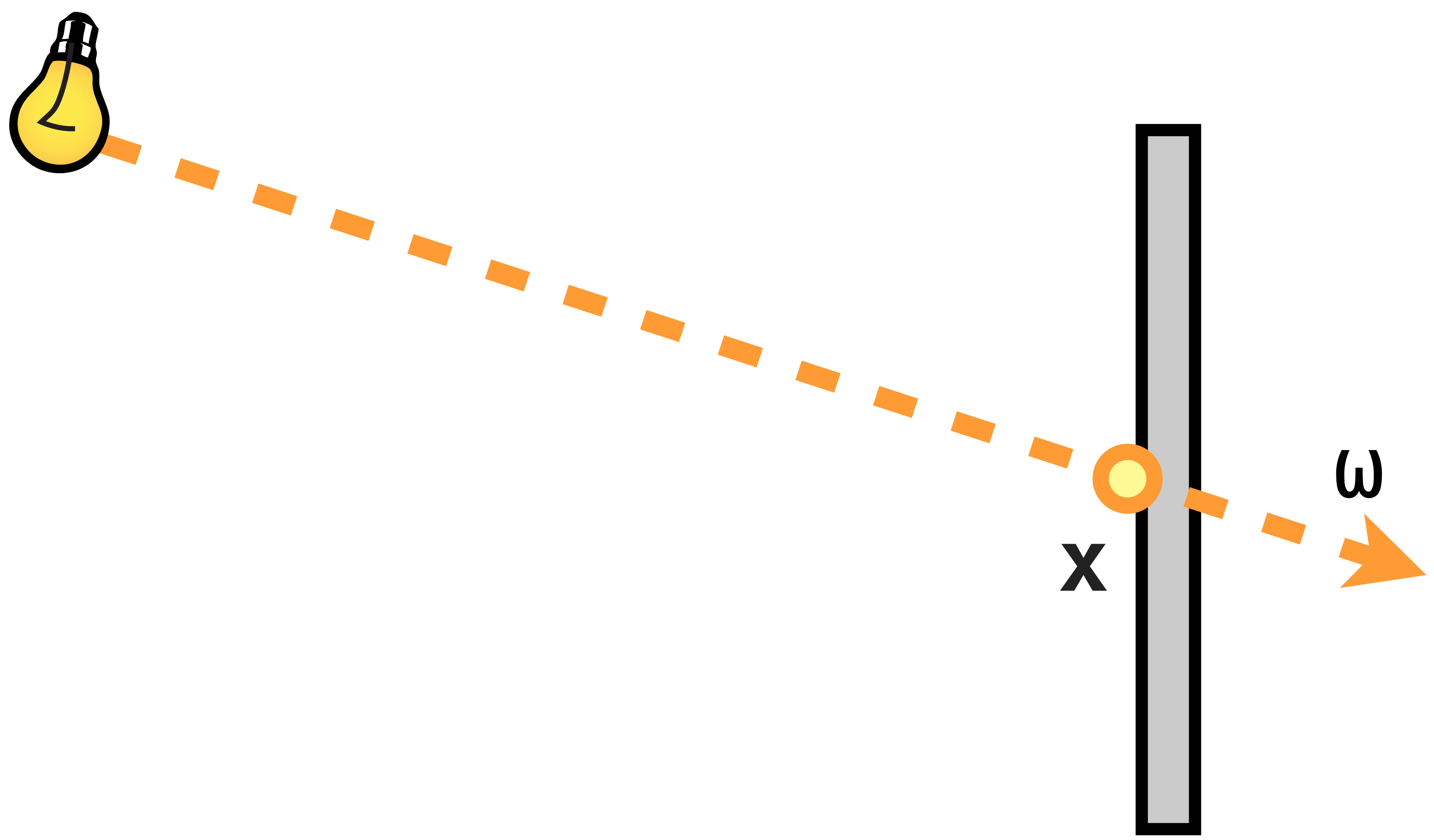
Basic Photon Tracer

```
void vPT(x, ω, Φ)
    tmax = nearestSurfaceHit(x, ω)
```



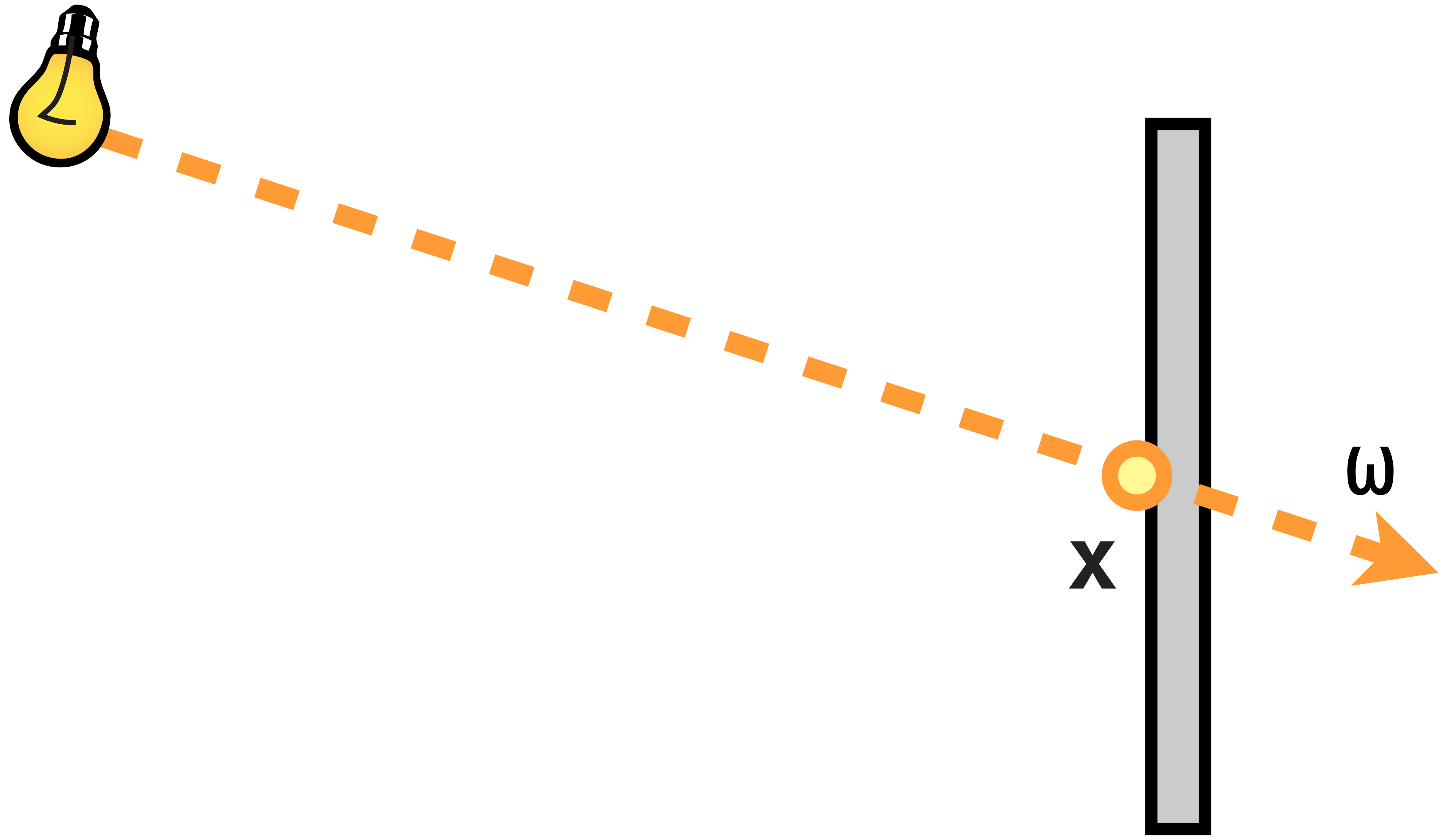
Basic Photon Tracer

```
void vPT(x, ω, Φ)
    tmax = nearestSurfaceHit(x, ω)
    x += tmax * ω // propagate photon
```



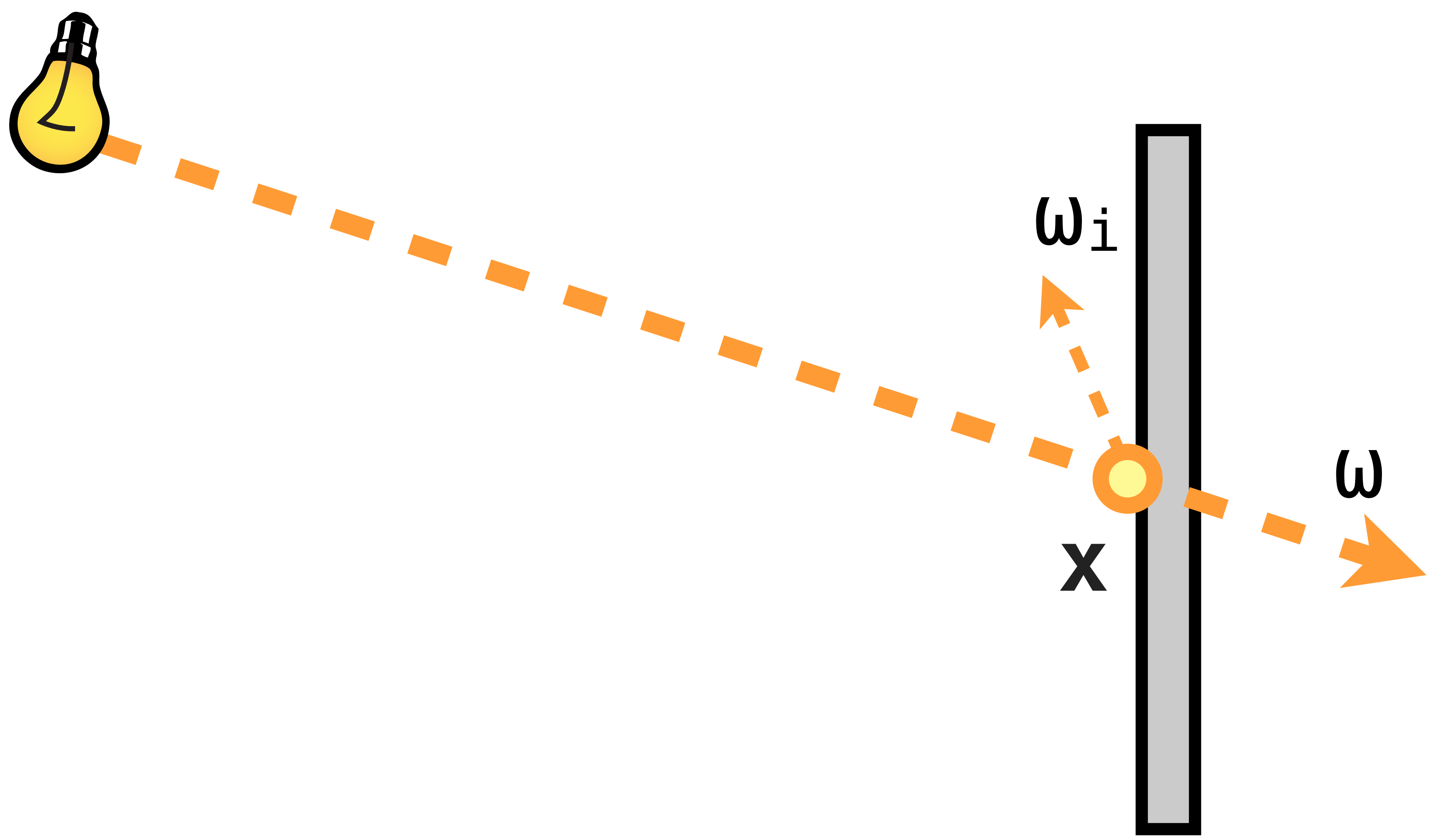
Basic Photon Tracer

```
void vPT(x, ω, Φ)
    tmax = nearestSurfaceHit(x, ω)
    x += tmax * ω // propagate photon
    storeSurfacePhoton(x, ω, Φ)
```



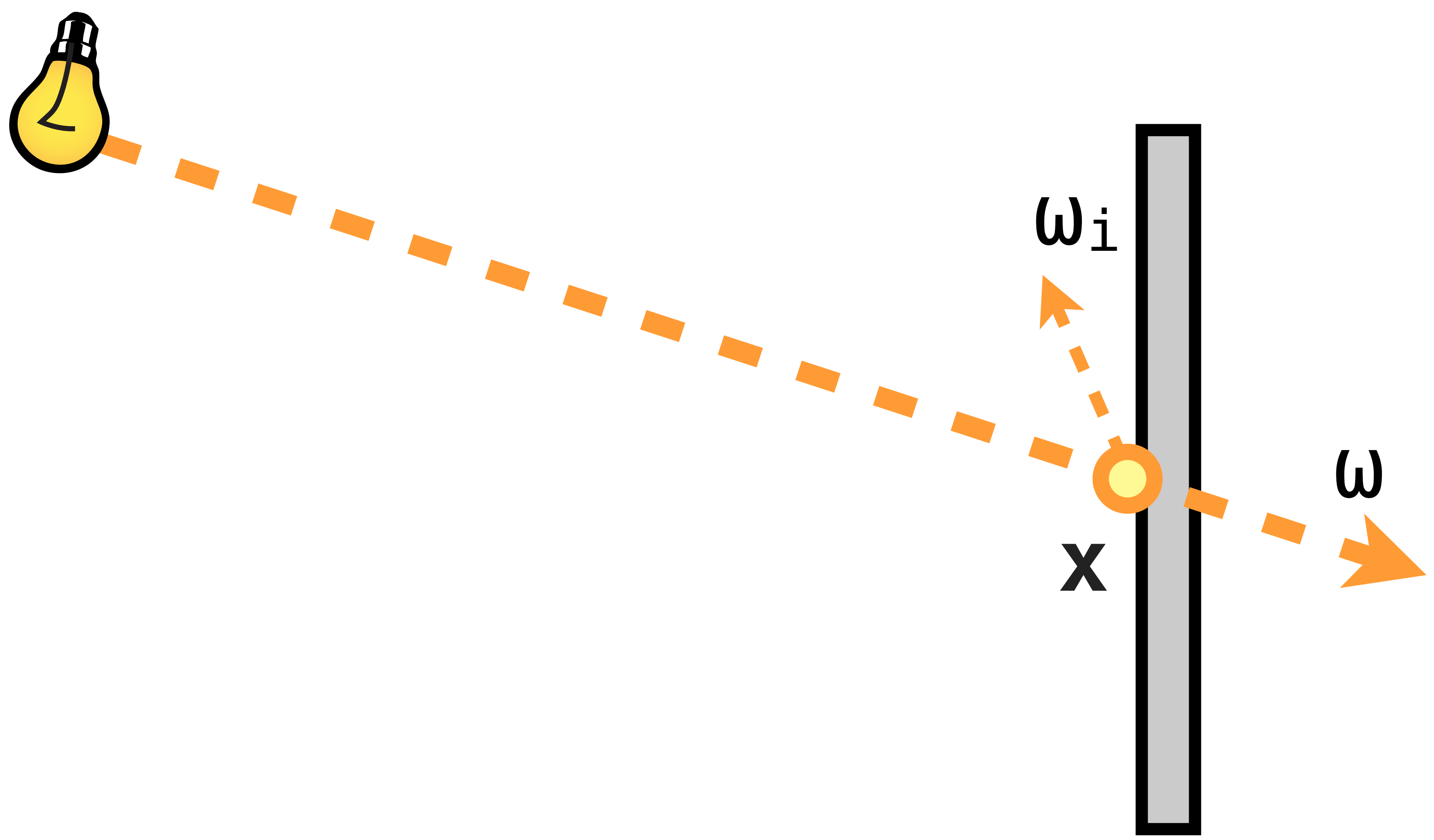
Basic Photon Tracer

```
void vPT(x, ω, Φ)
    tmax = nearestSurfaceHit(x, ω)
    x += tmax * ω // propagate photon
    storeSurfacePhoton(x, ω, Φ)
    (ωi, pdfi) = sampleBRDF(x, ω)
```



Basic Photon Tracer

```
void vPT(x, ω, Φ)
    tmax = nearestSurfaceHit(x, ω)
    x += tmax * ω // propagate photon
    storeSurfacePhoton(x, ω, Φ)
    (ωi, pdfi) = sampleBRDF(x, ω)
    return vPT(x, ωi, Φ * BRDF(x,ω,ωi) / pdfi)
```



Basic Photon Tracer

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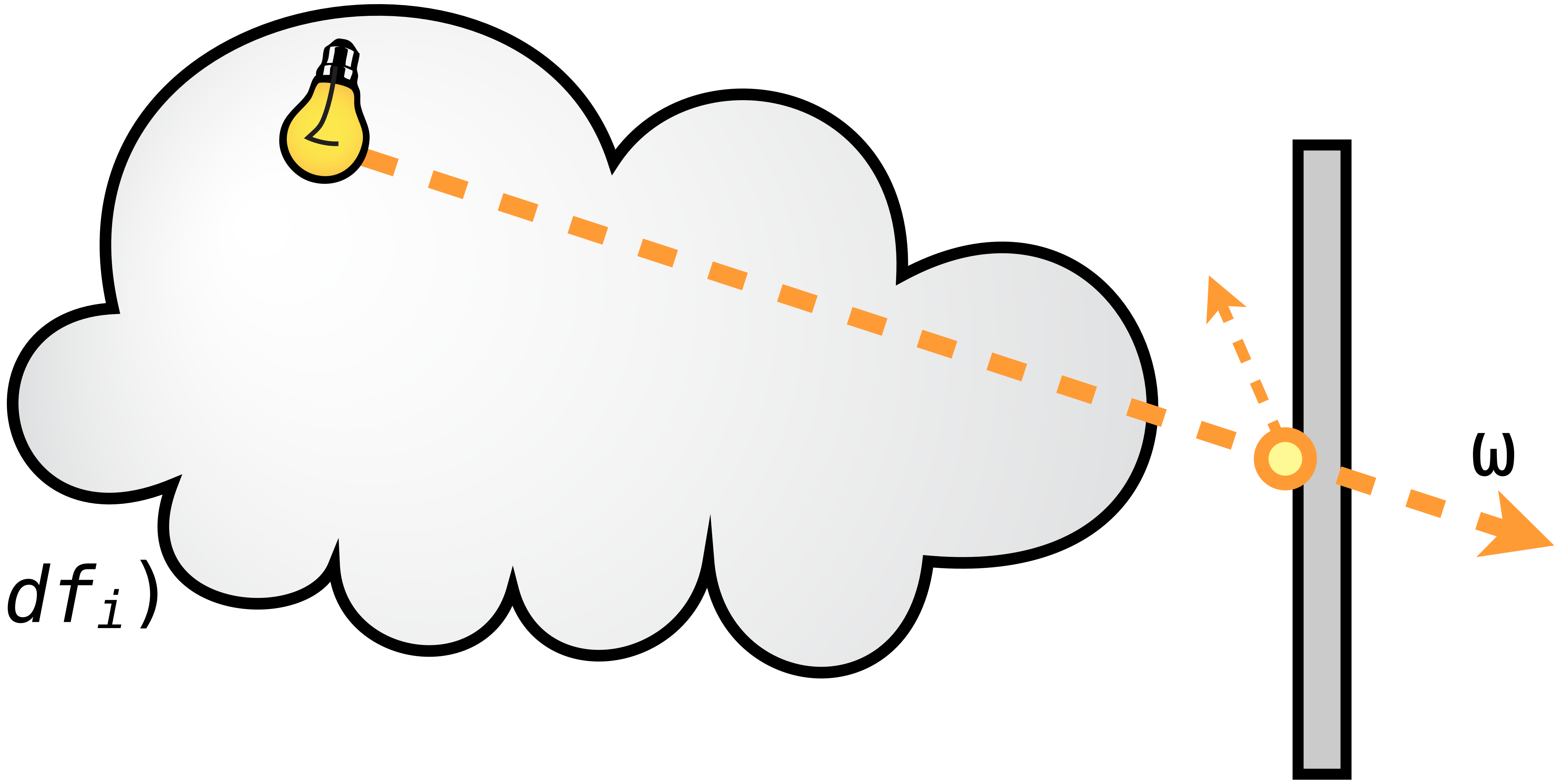
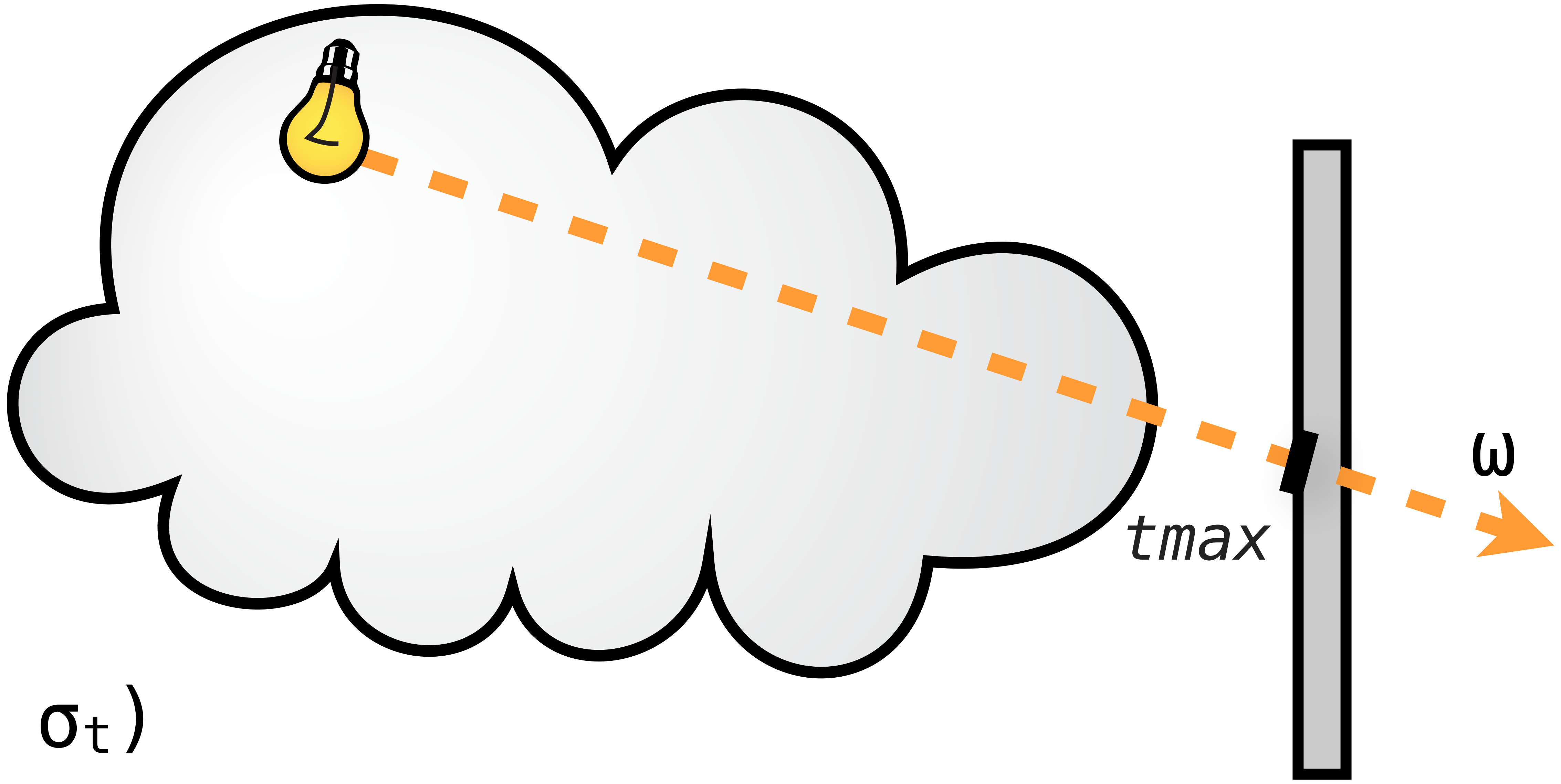


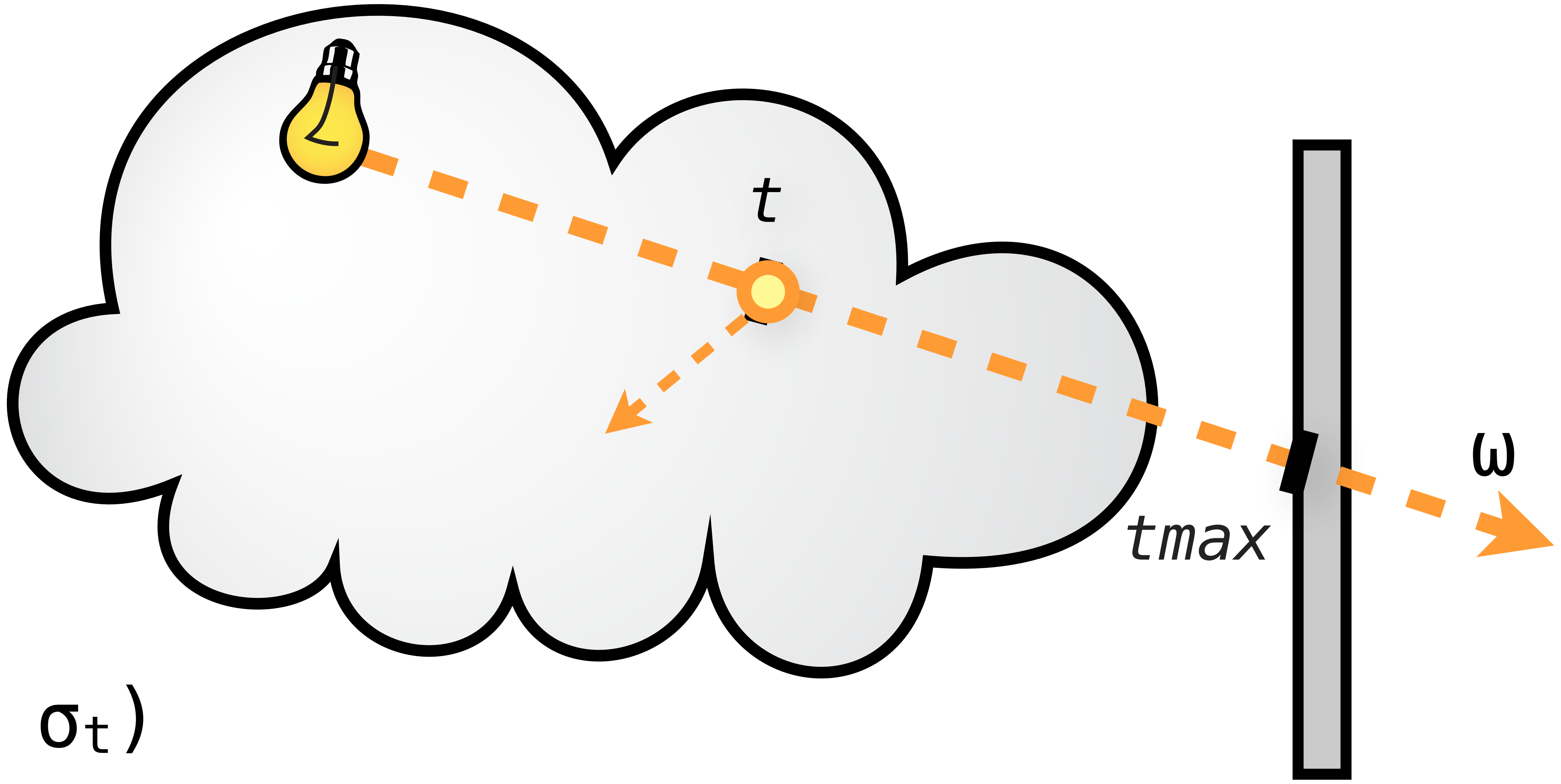
Basic Volumetric Photon Tracer

```
void vPT(x, ω, Φ)
    tmax = nearestSurfaceHit(x, ω)
    t = freeFlightDistance(x, ω)
    if (t < tmax)        // media scattering
        x += t * ω    // propagate photon
        storeVolumePhoton(x, ω, Φ)
        return vPT(x, samplePF(), Φ * σs / σt)
    else                  // surface scattering
        x += tmax * ω // propagate photon
        storeSurfacePhoton(x, ω, Φ)
        (ωi, pdfi) = sampleBRDF(x, ω)
        return vPT(x, ωi, Φ * BRDF(x,ω,ωi) / pdfi)
```



Basic Volumetric Photon Tracer

```
void vPT(x, ω, Φ)
    tmax = nearestSurfaceHit(x, ω)
    t = freeFlightDistance(x, ω)
    if (t < tmax)       // media scattering
        x += t * ω    // propagate photon
        storeVolumePhoton(x, ω, Φ)
        return vPT(x, samplePF(), Φ * σs / σt)
    else                    // surface scattering
        x += tmax * ω // propagate photon
        storeSurfacePhoton(x, ω, Φ)
        (ωi, pdfi) = sampleBRDF(x, ω)
        return vPT(x, ωi, Φ * BRDF(x,ω,ωi) / pdfi)
```

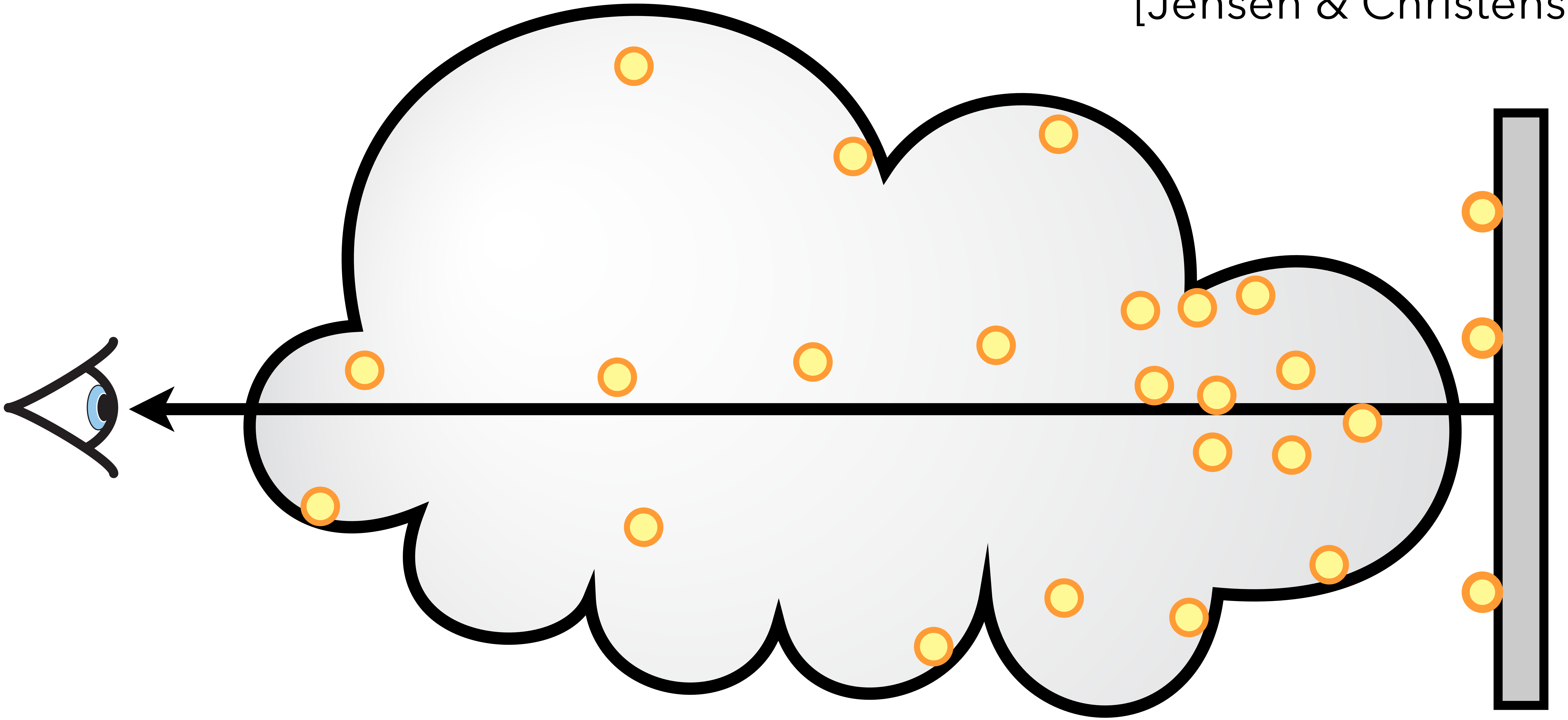


Two-pass Algorithm

1. Photon tracing
   - Simulate scattering of photons
2. Rendering
   - Reuse photons to estimate multiple scattering

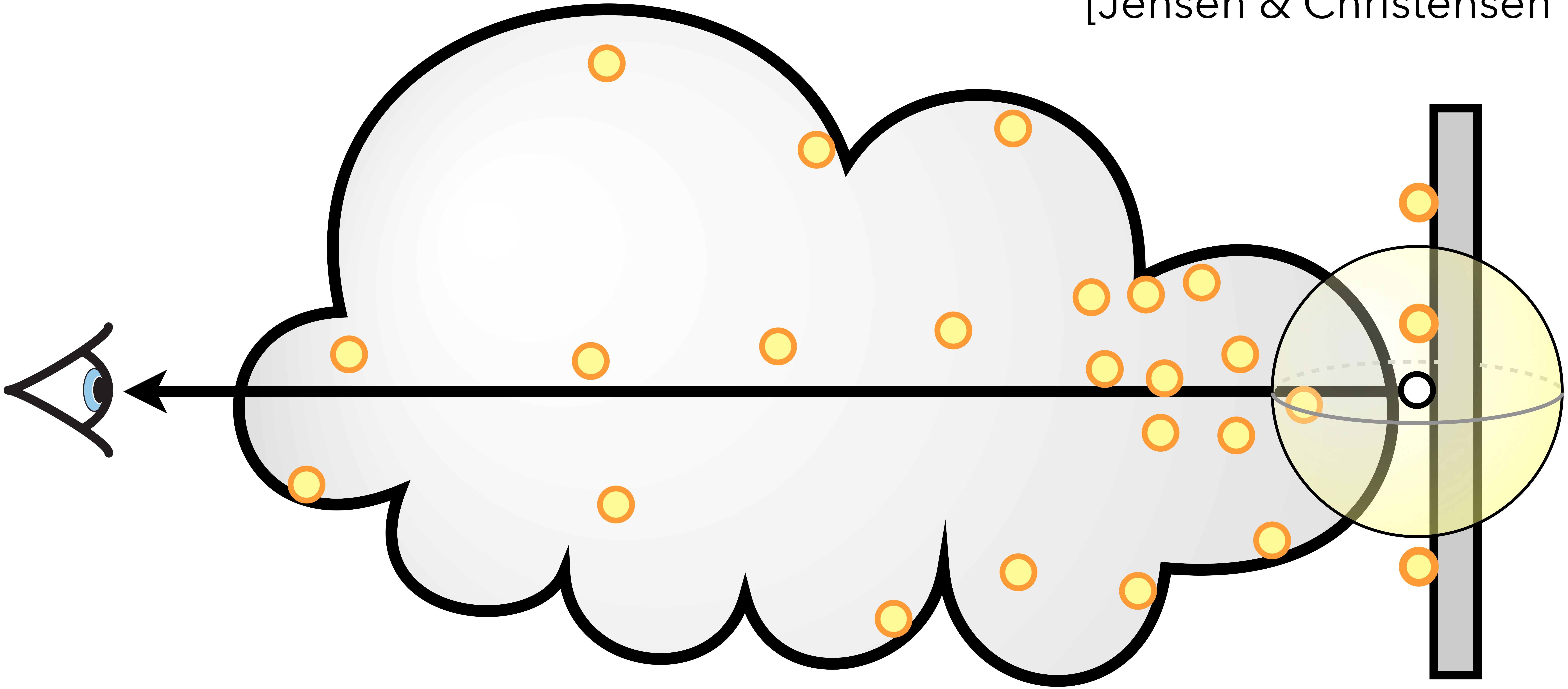
Radiance estimation

[Jensen & Christensen 98]



Radiance estimation

[Jensen & Christensen 98]



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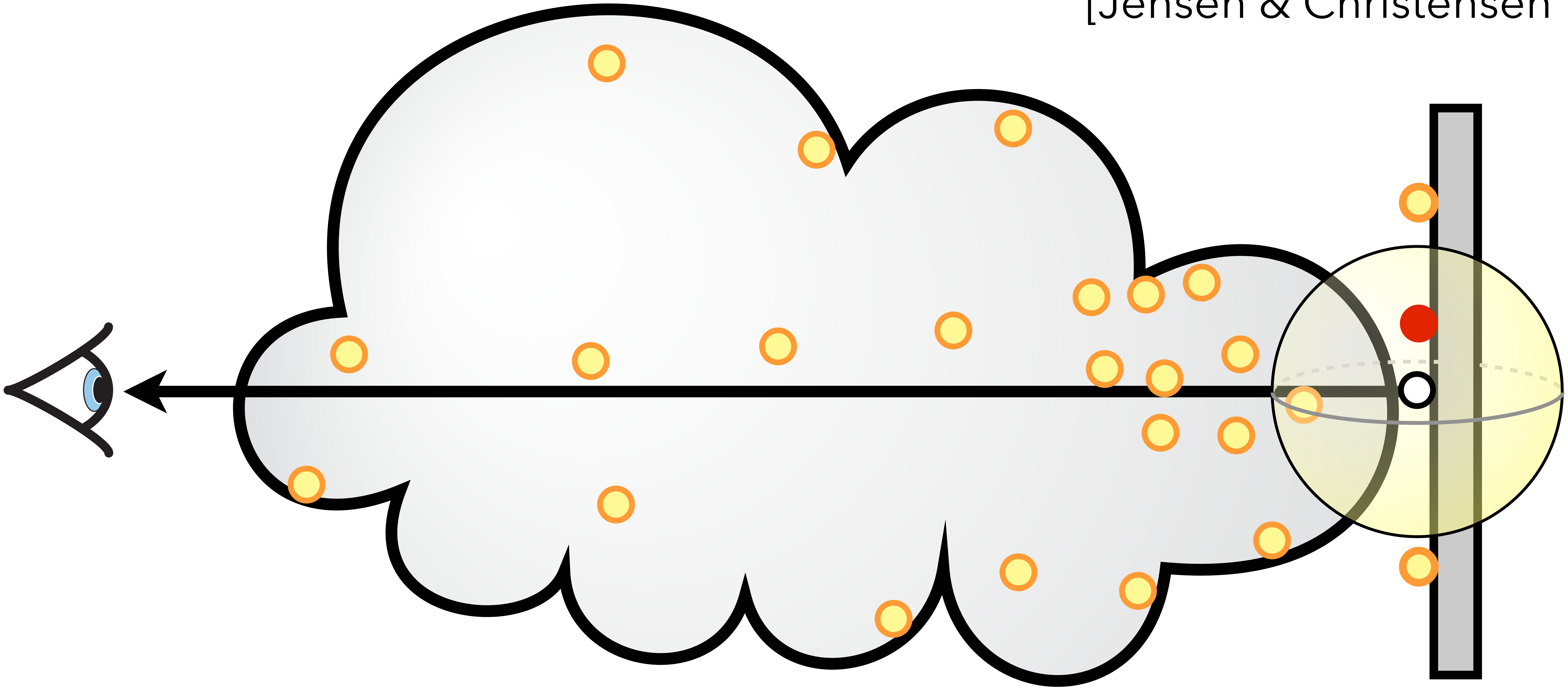
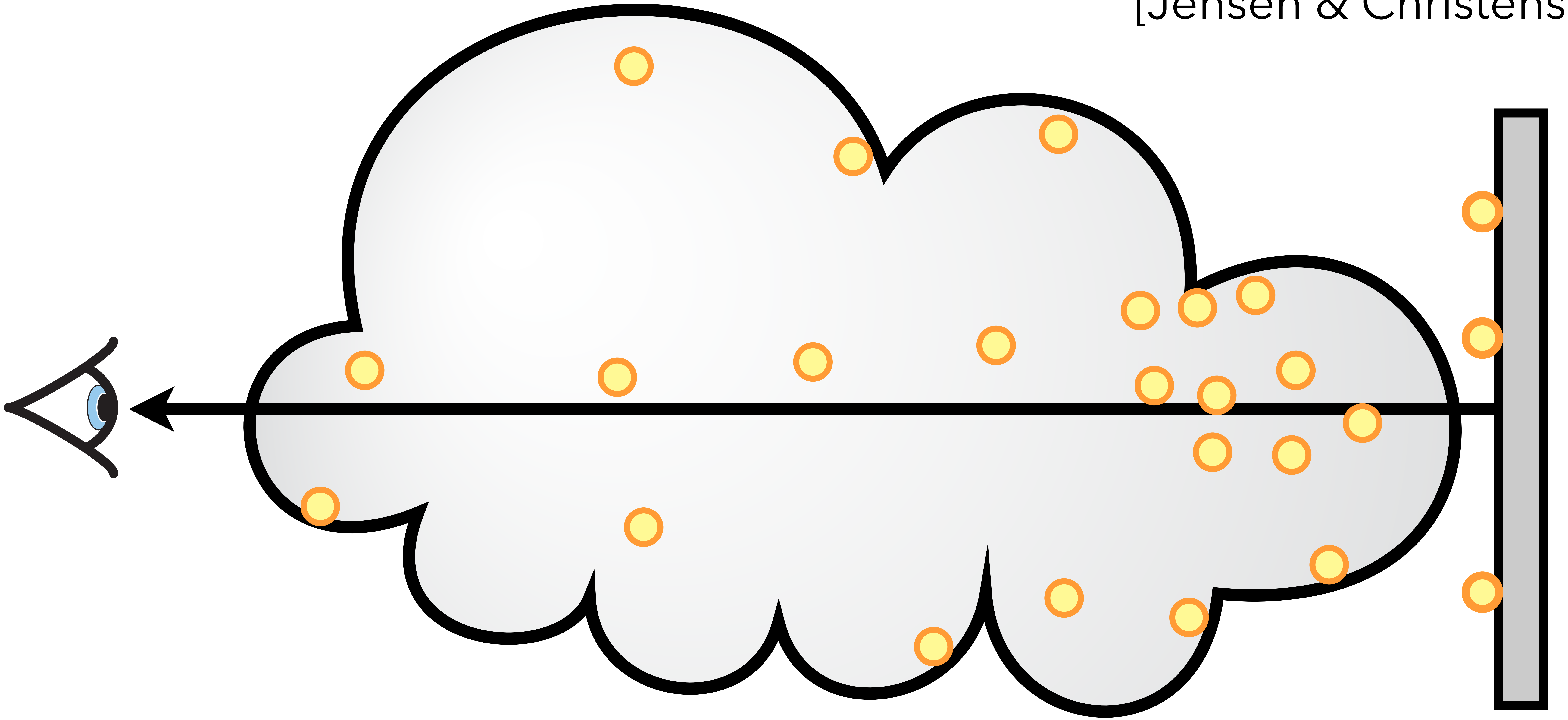


Density/radiance estimation on surface

Radiance estimation

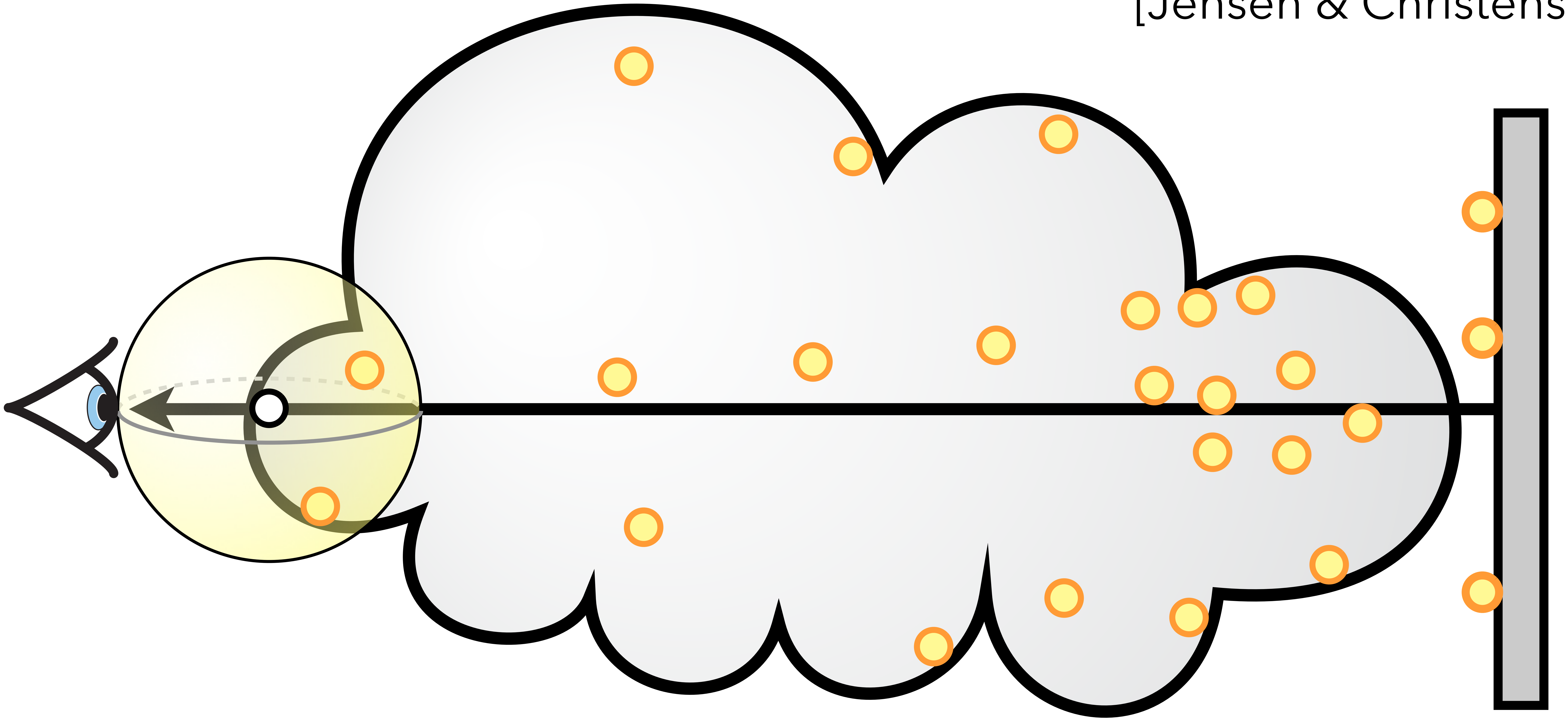
[Jensen & Christensen 98]



Density estimation as you ray march

Radiance estimation

[Jensen & Christensen 98]



Density estimation as you ray march

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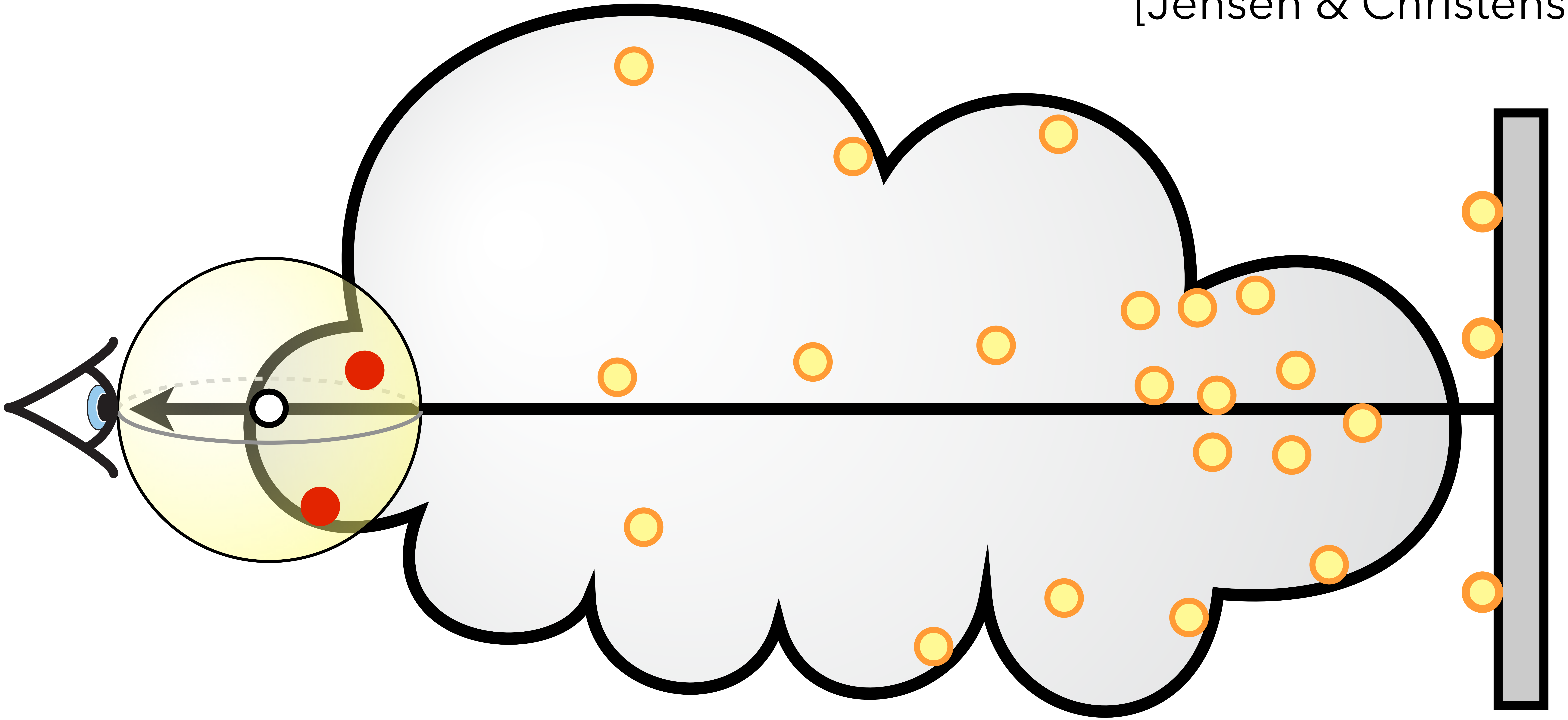

Density estimation as you ray march

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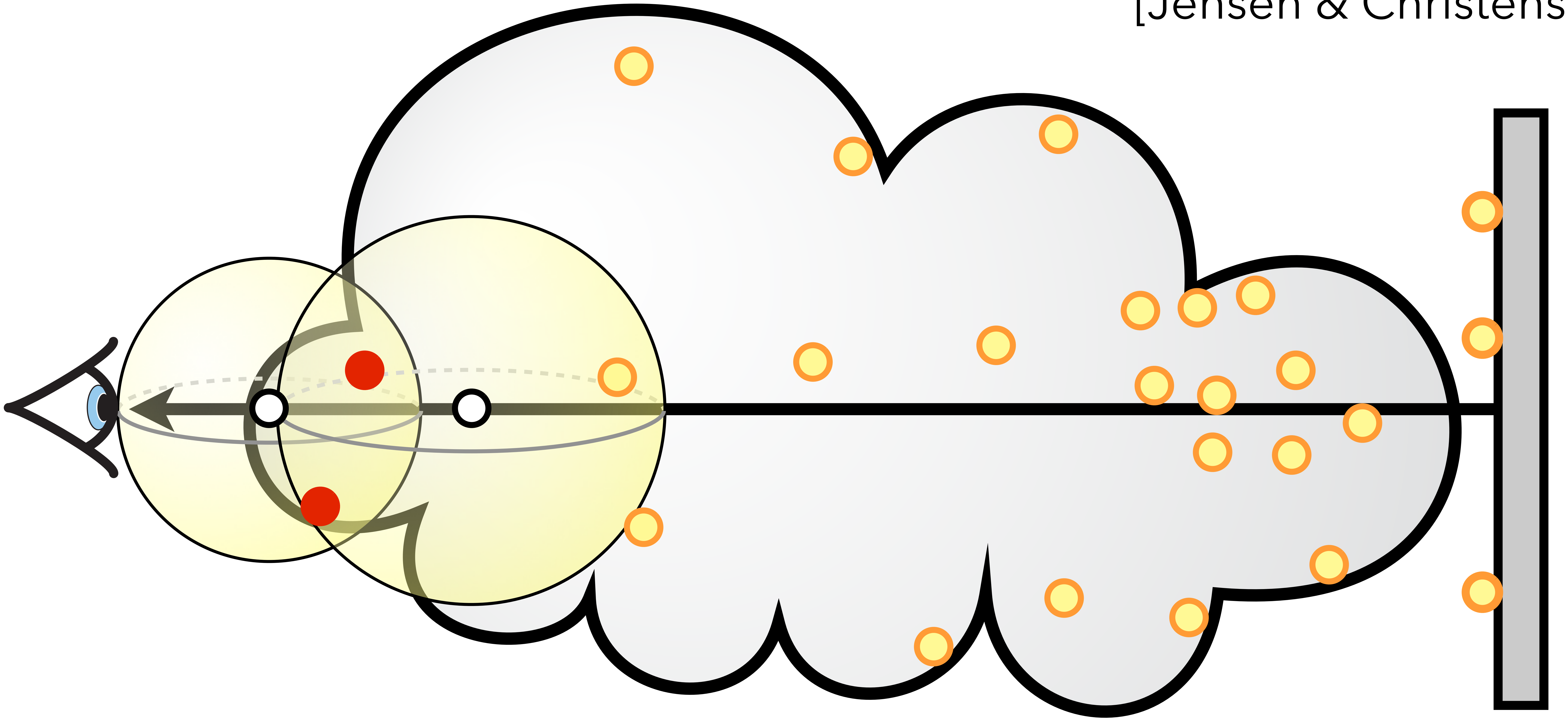

Density estimation as you ray march

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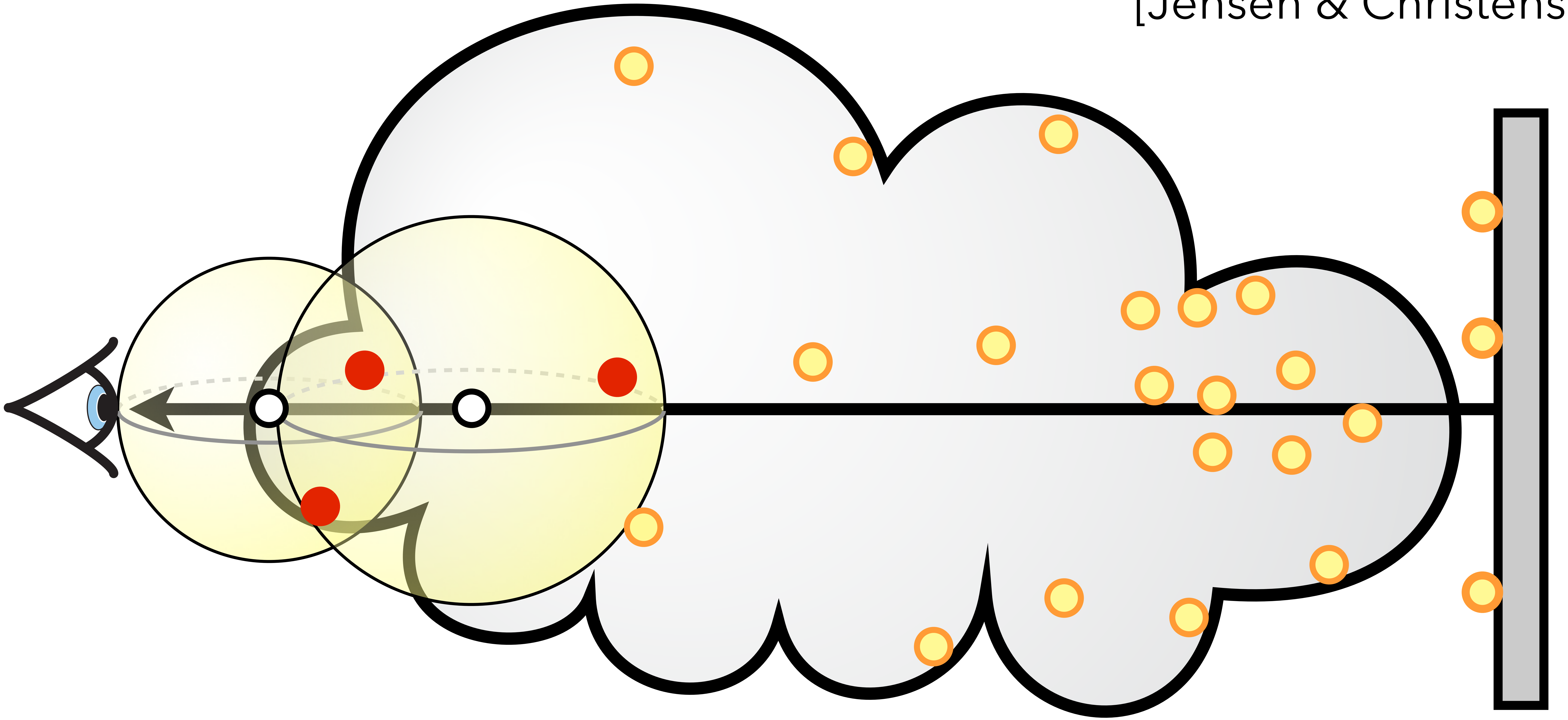

Density estimation as you ray march

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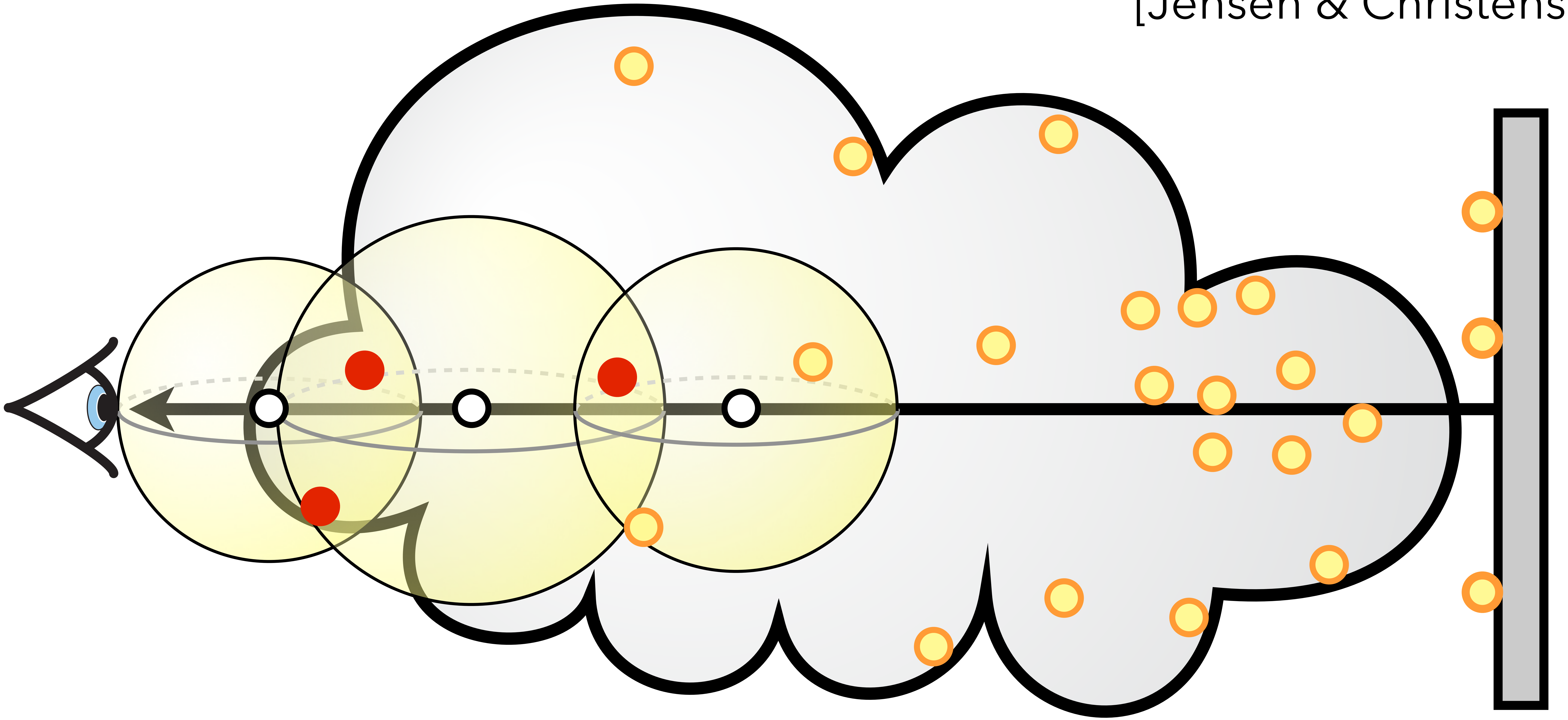

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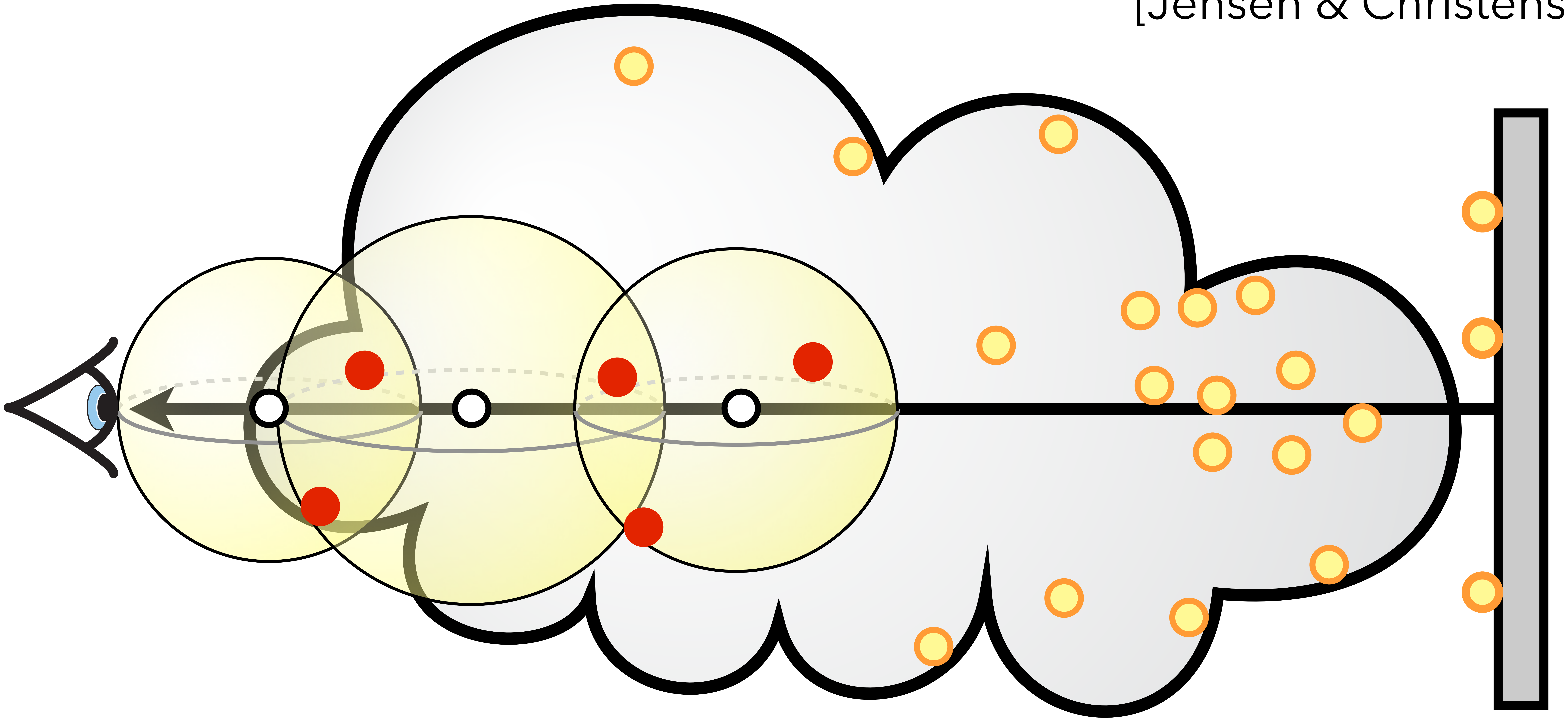

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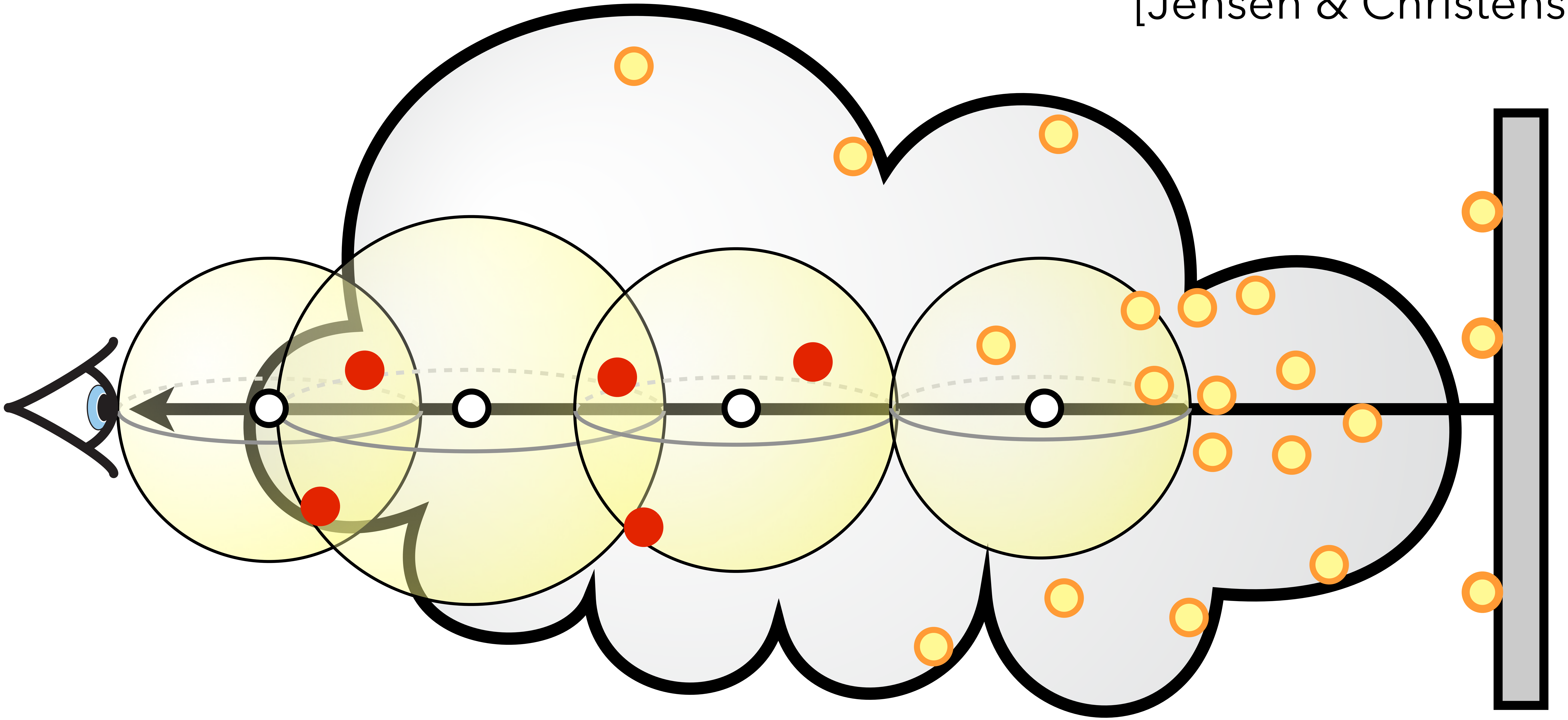

Density estimation as you ray march

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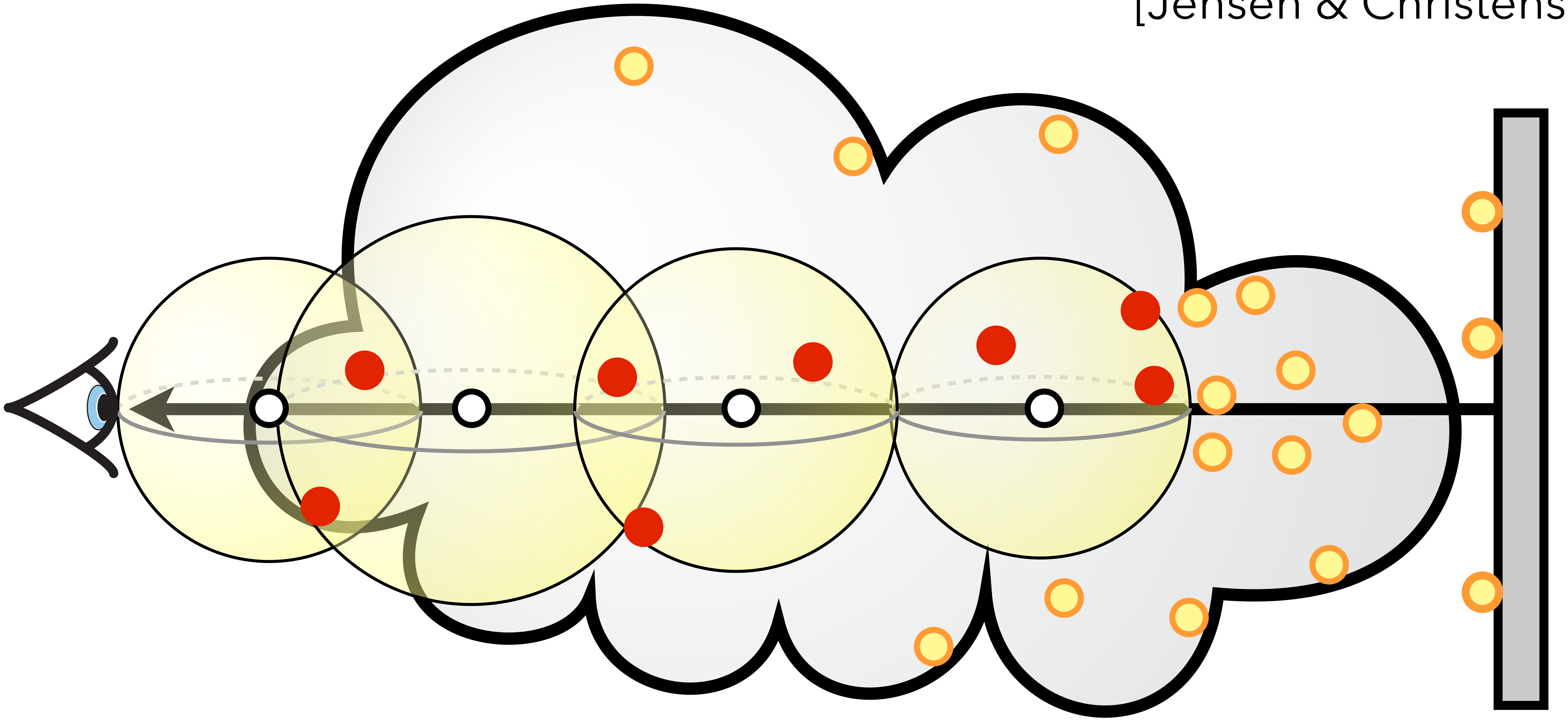

Density estimation as you ray march

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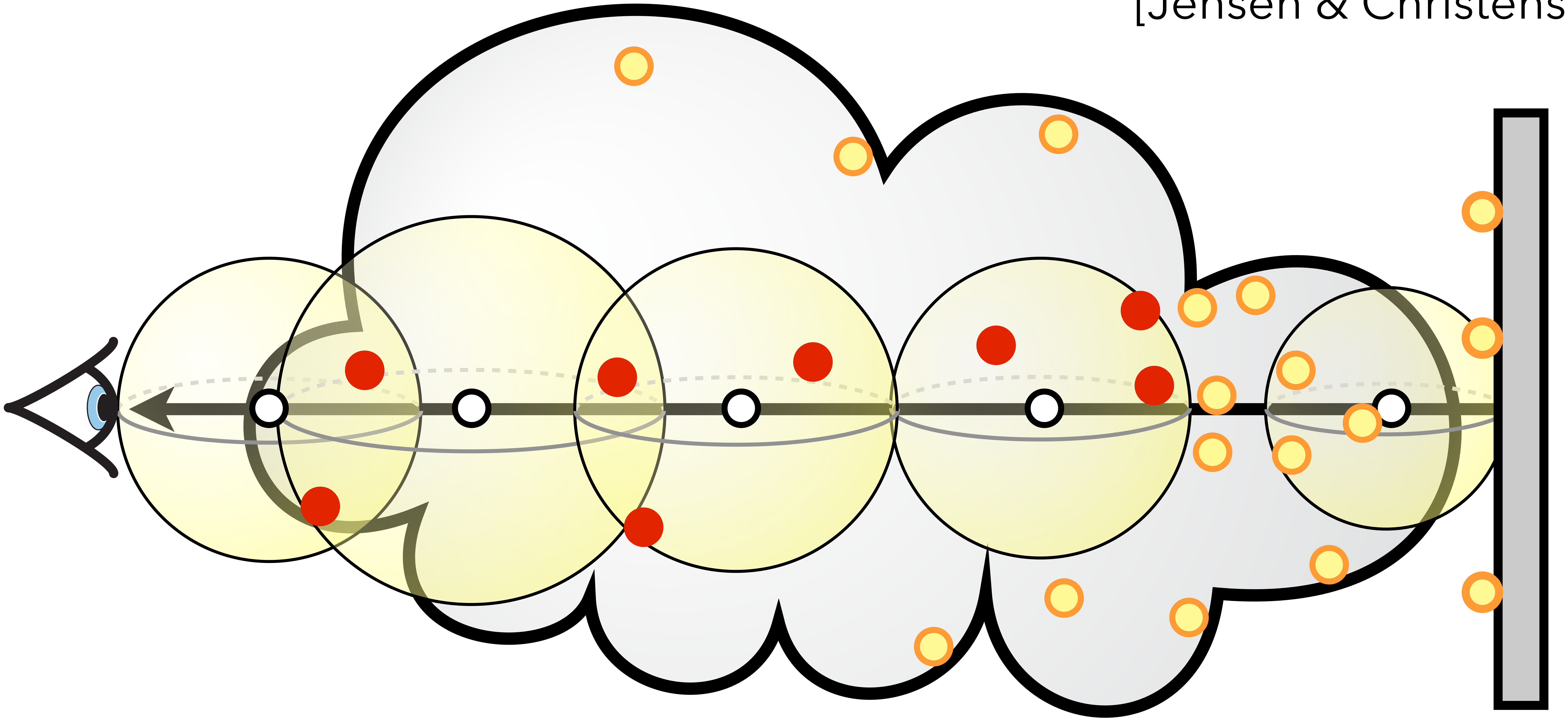

Density estimation as you ray march

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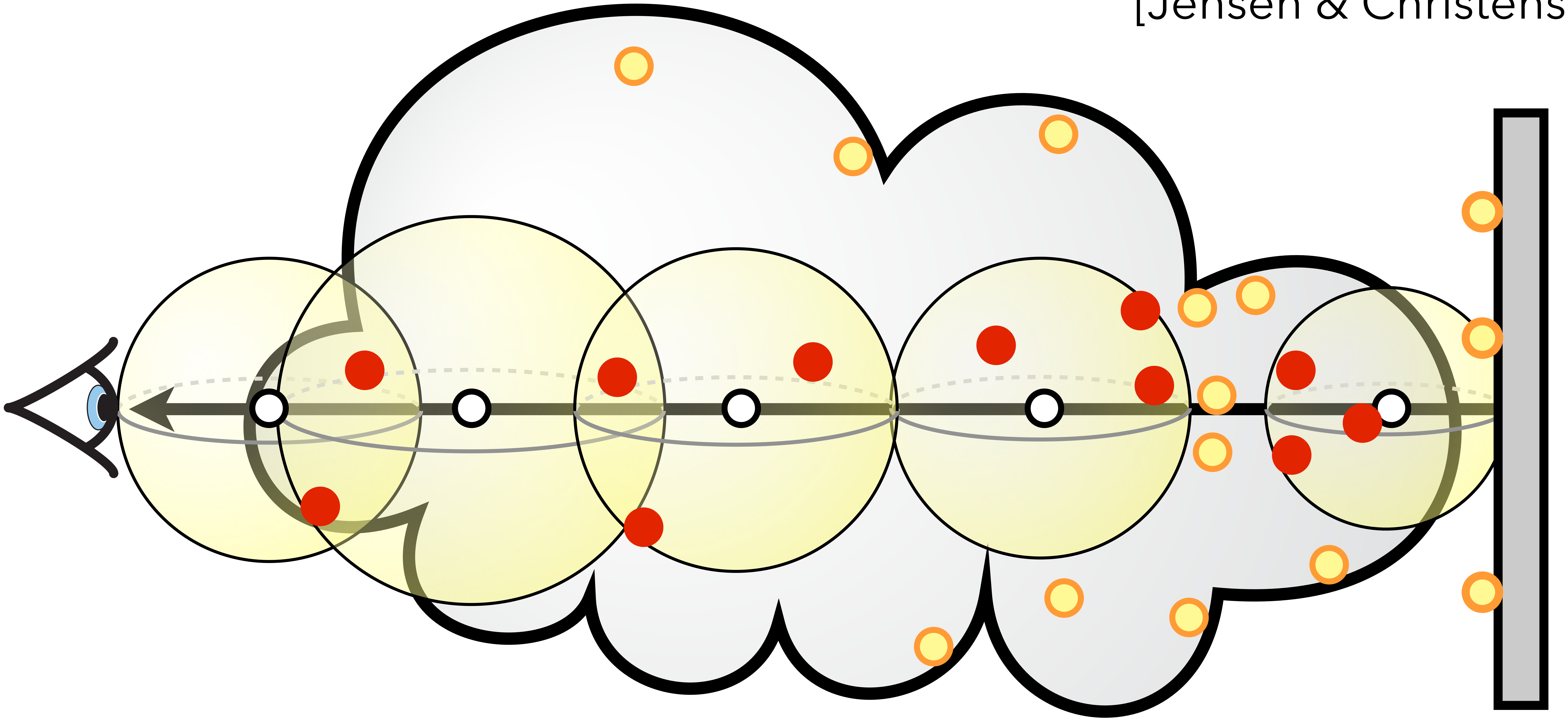
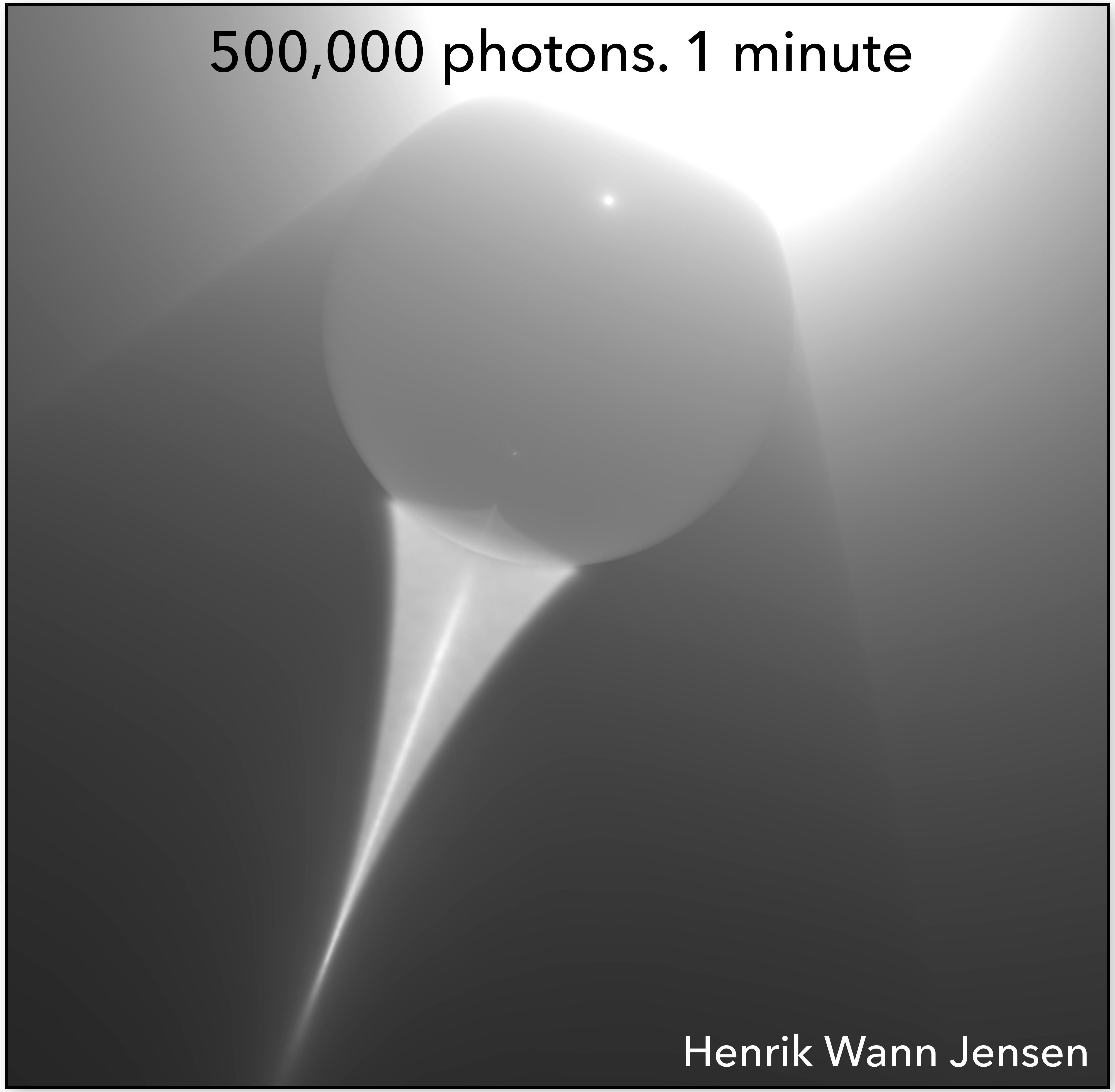
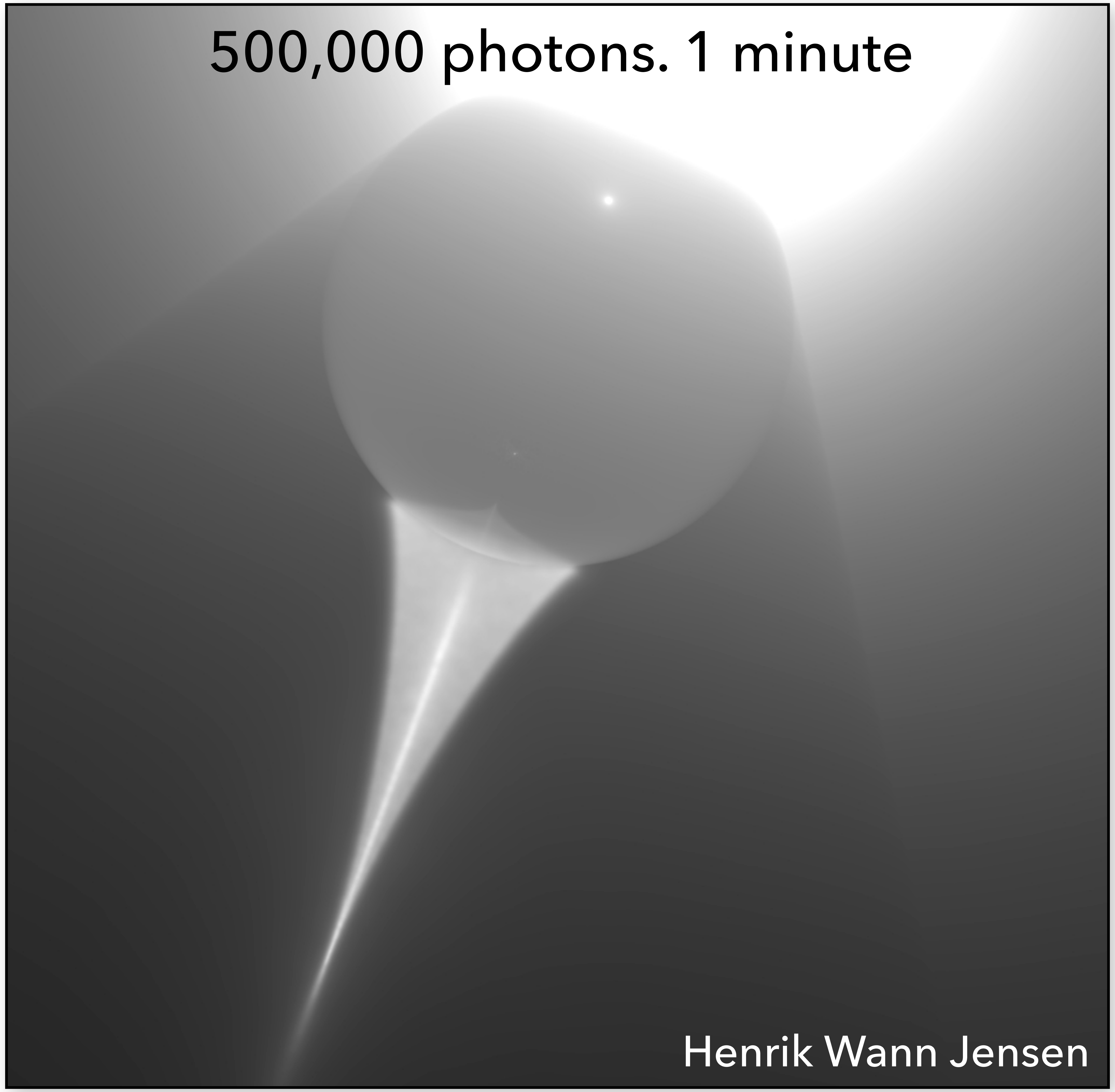


Density estimation as you ray march

A Volume Caustic

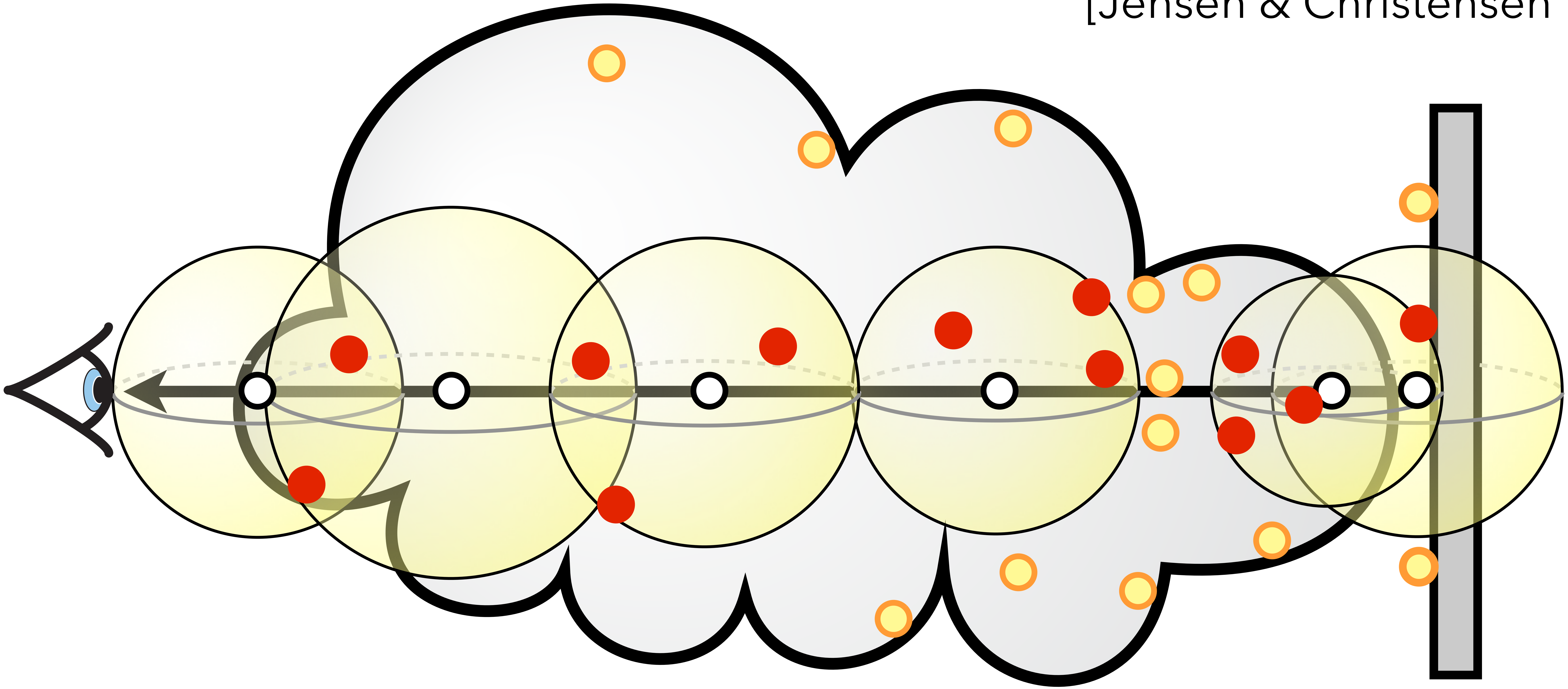


Subsurface Scattering



Radiance estimation

[Jensen & Christensen 98]



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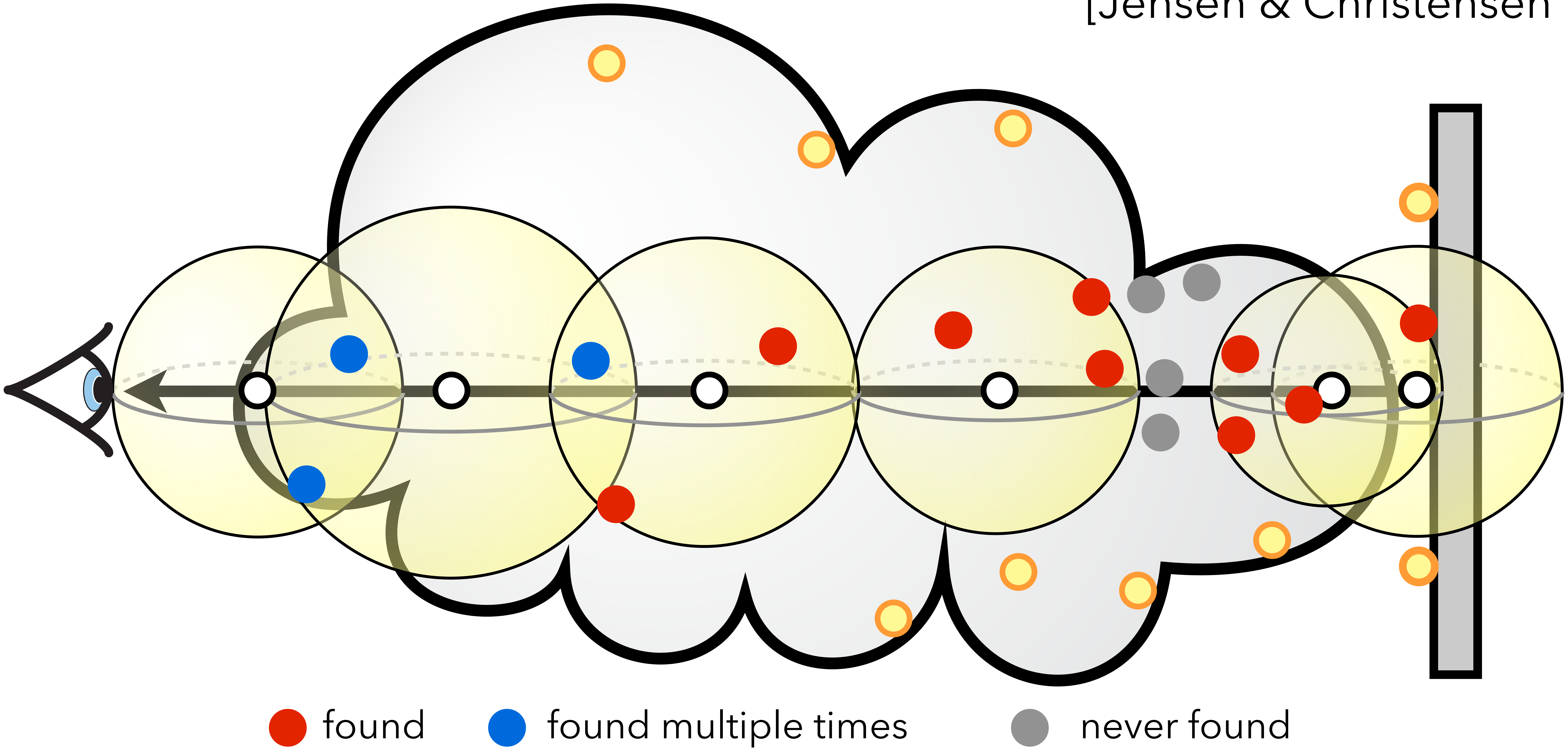
[Jensen & Christensen 98]



Drawbacks

[Jensen & Christensen 98]

Large Step-size

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[Jensen & Christensen 98]

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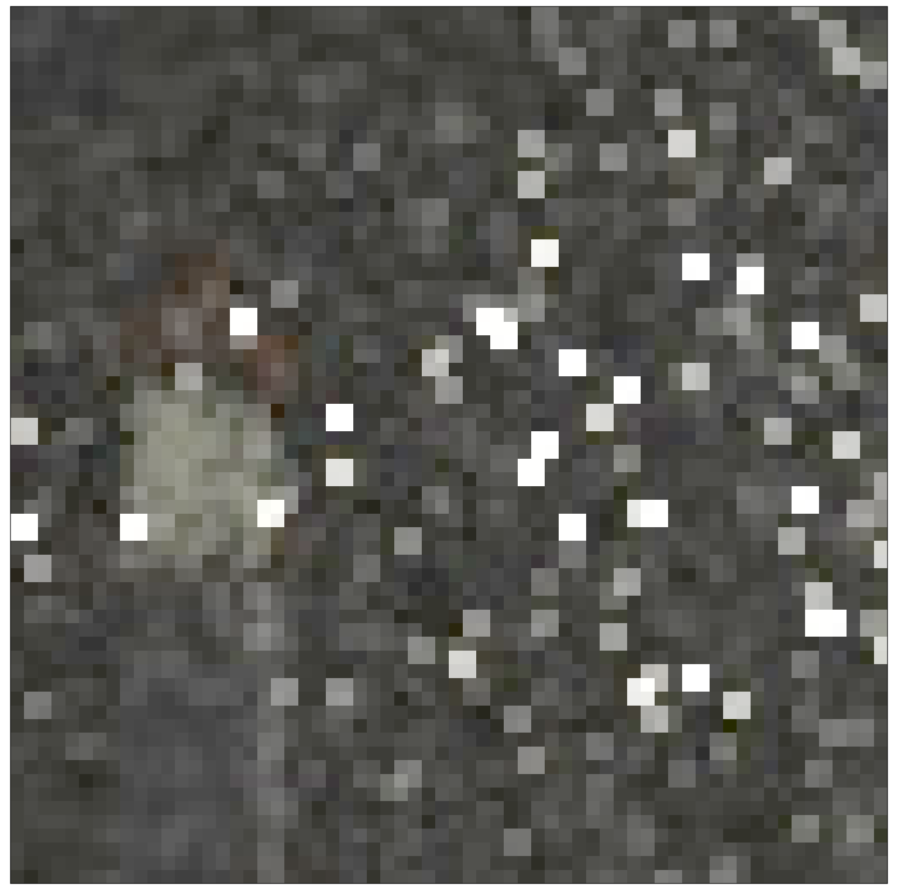
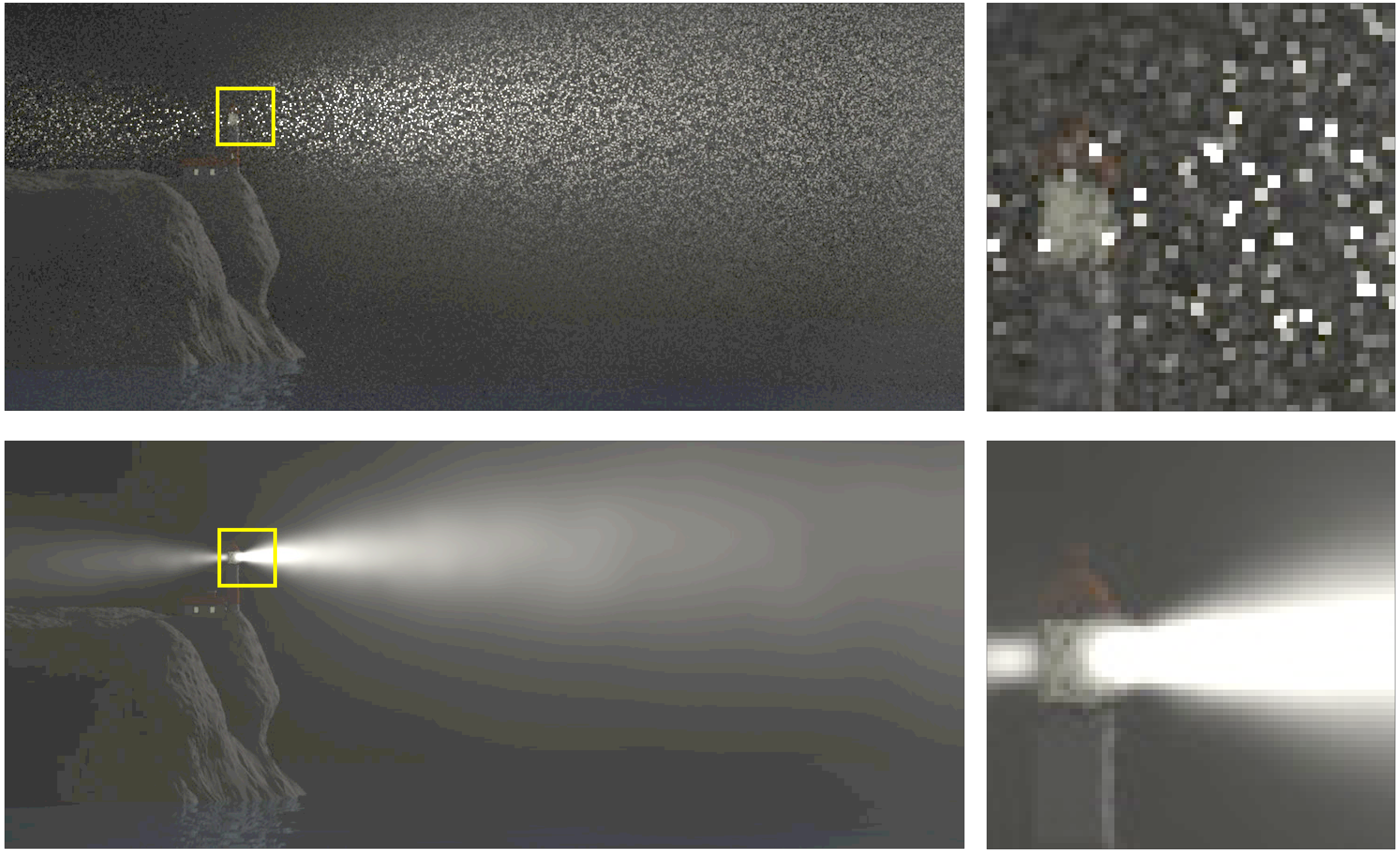


Drawbacks

[Jensen & Christensen 98]

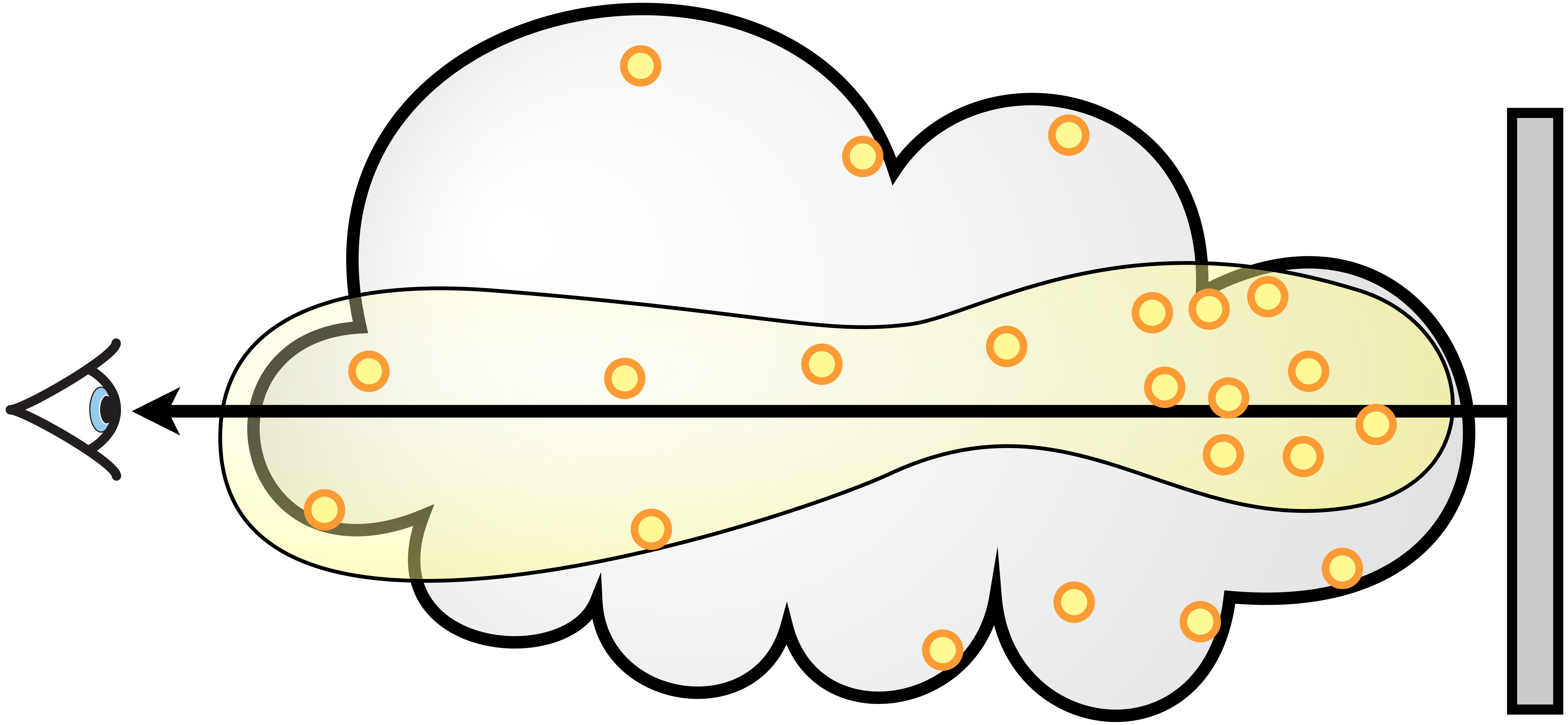
Large Step-size



Very Small Step-size

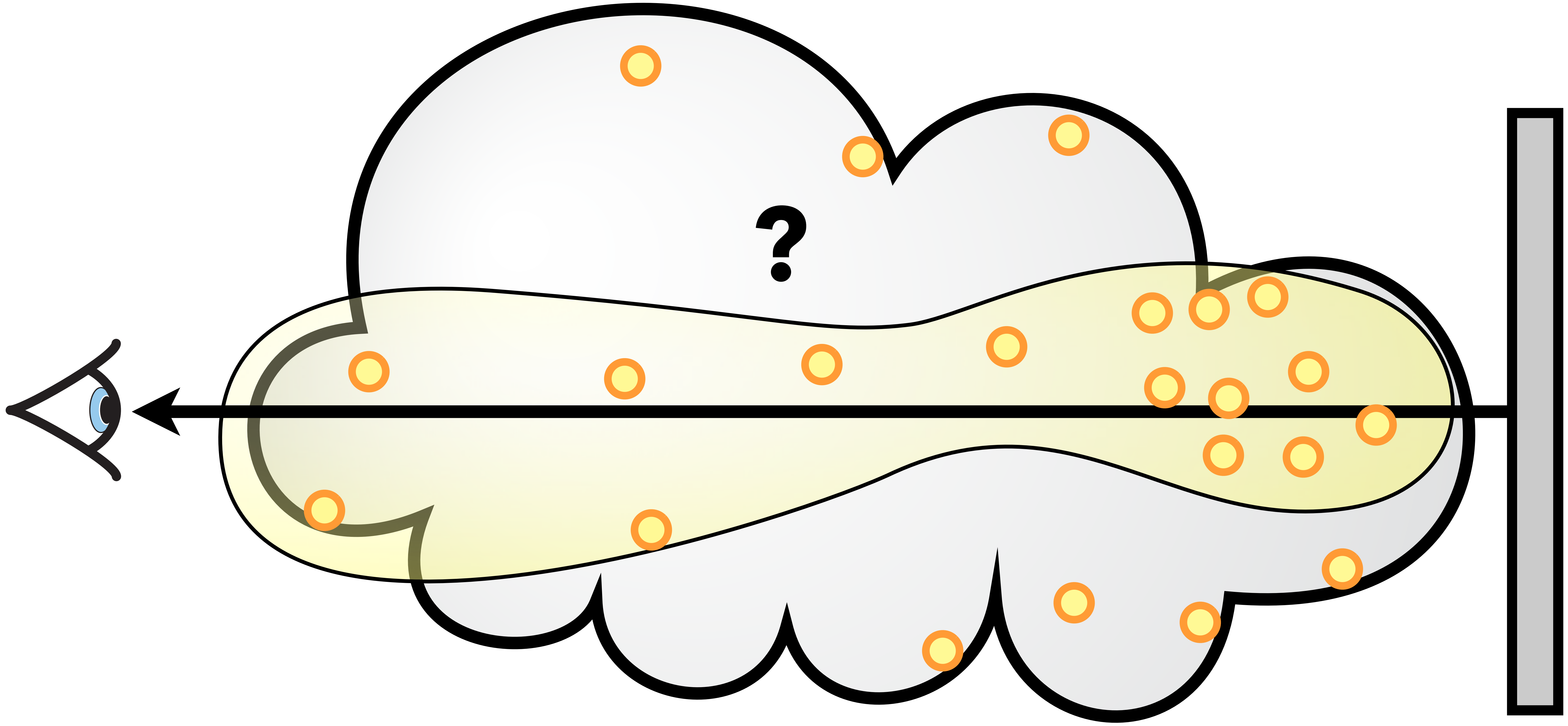
Radiance estimation

[Jarosz et al. 08]



Radiance estimation

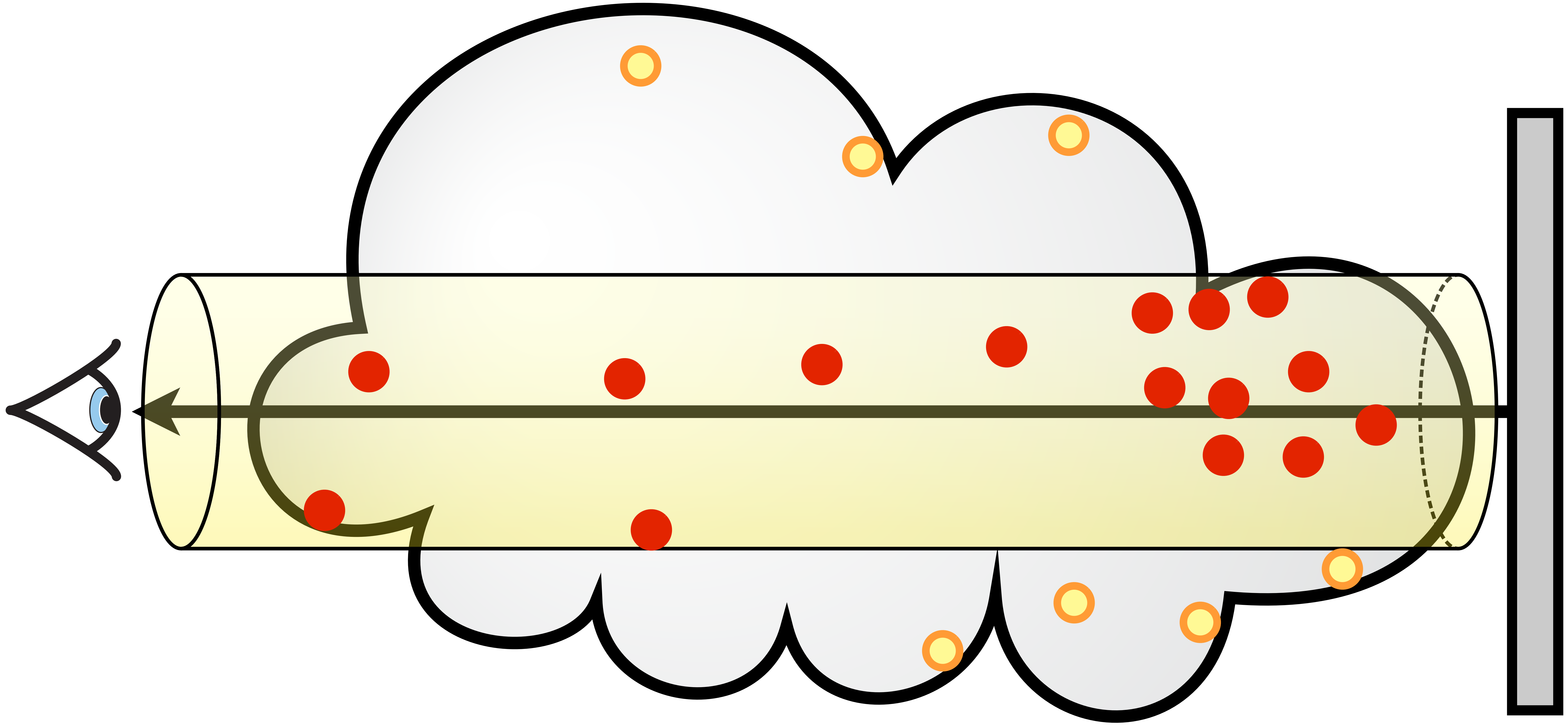
[Jarosz et al. 08]



How to find the photons?

Fixed radius

[Jarosz et al. 08]



Fixed Radius Comparison

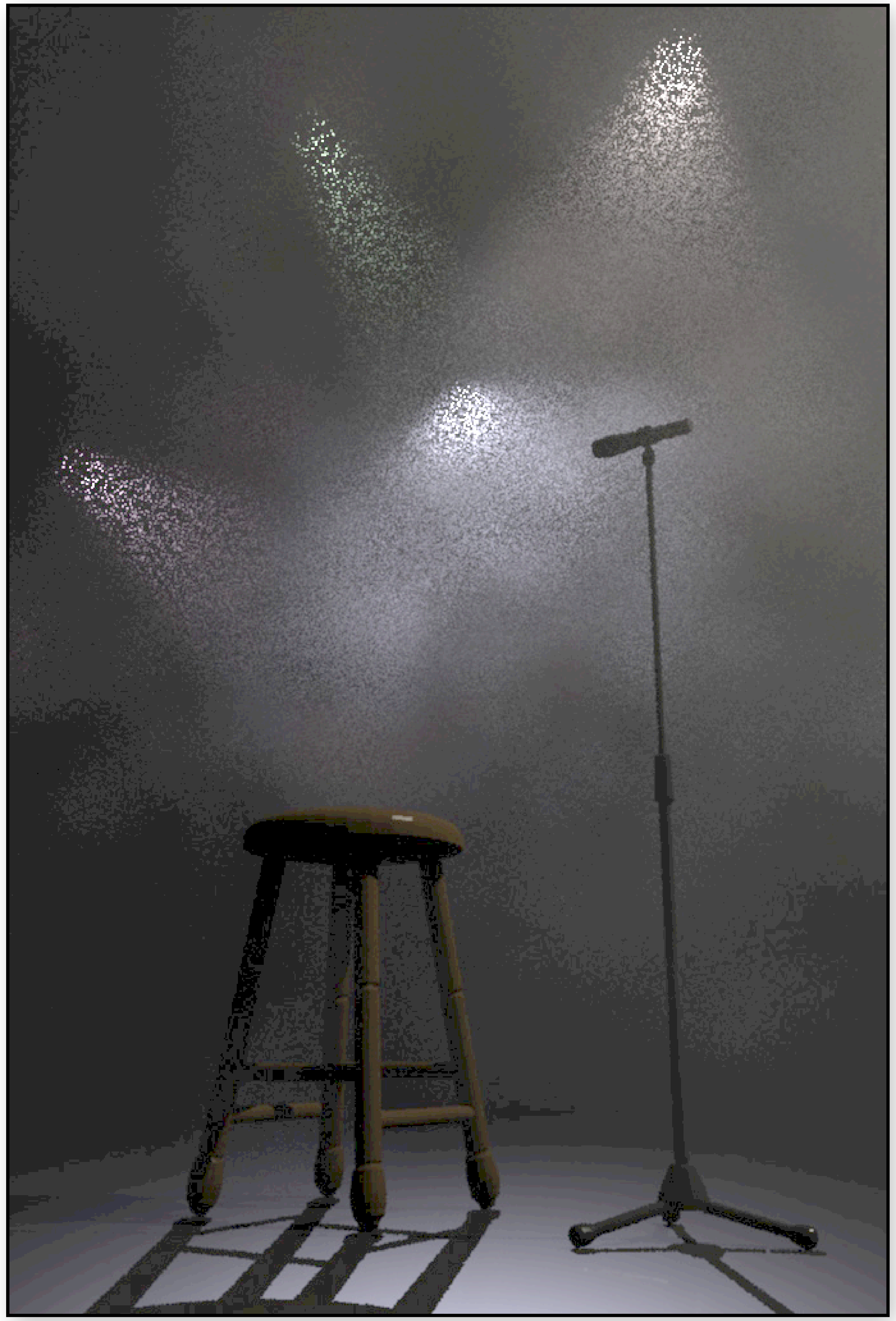
[Jarosz et al. 08]

Beam Estimate

Fixed Radius Comparison

[Jarosz et al. 08]

Traditional Estimate

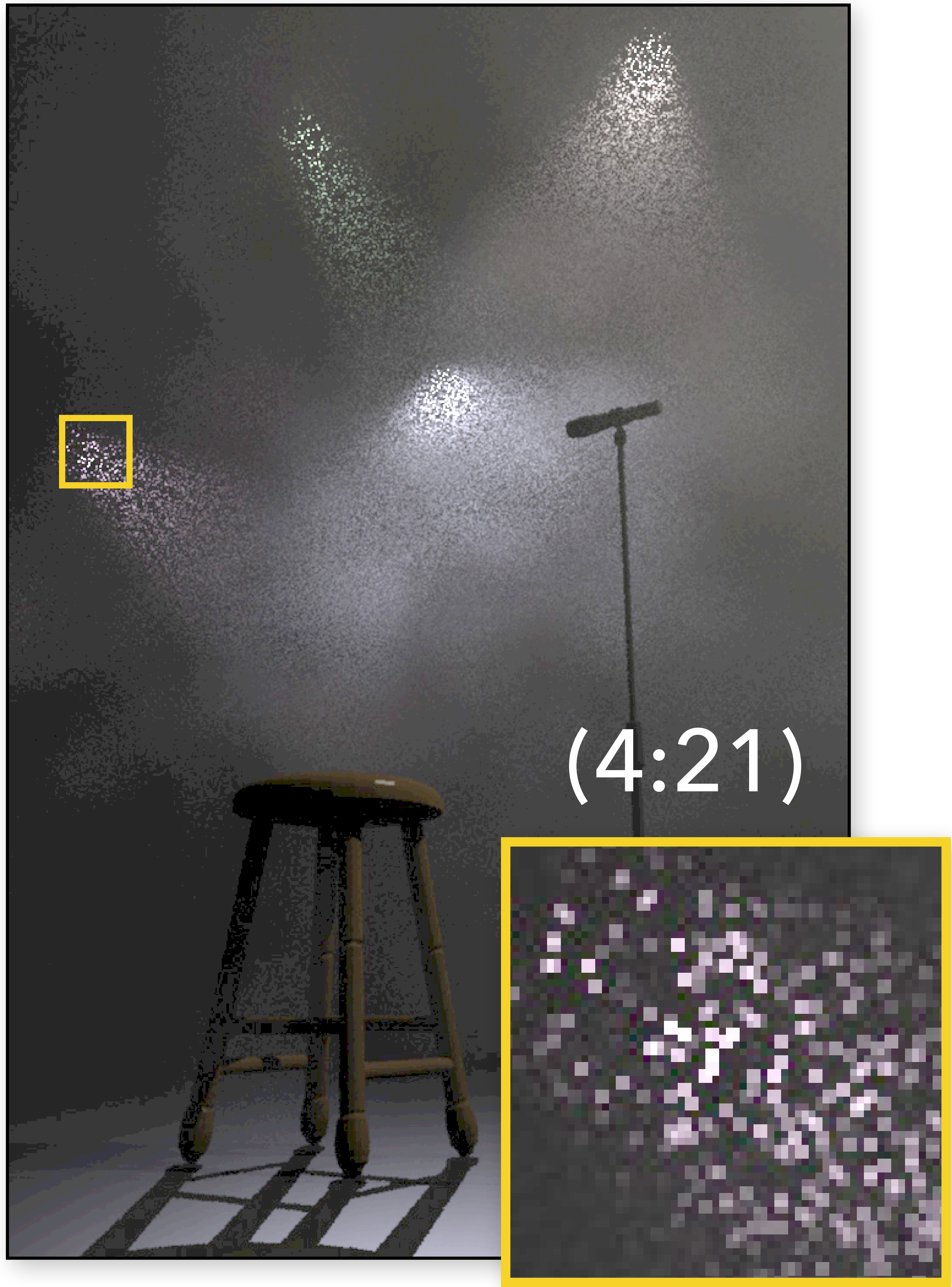


Beam Estimate

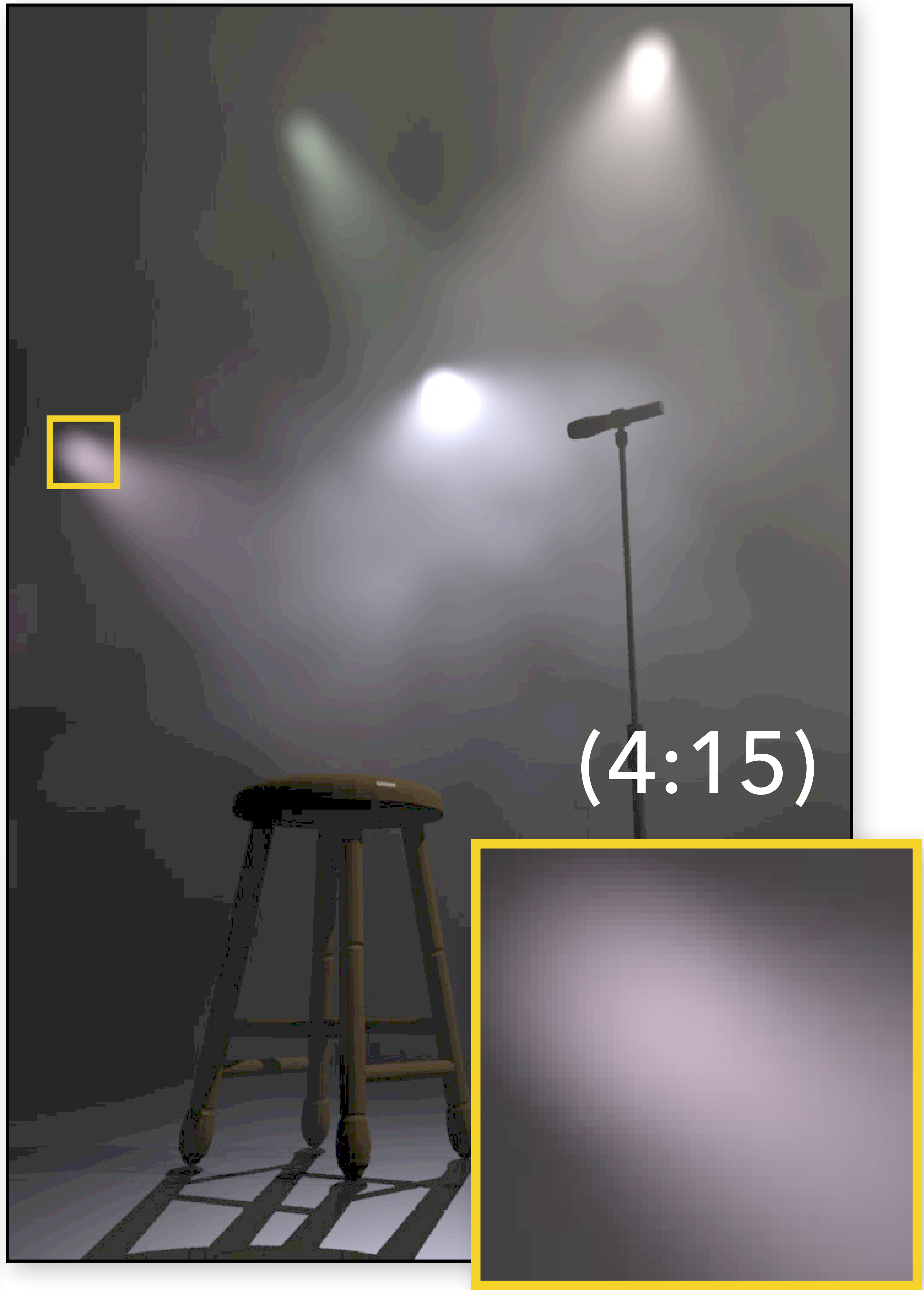
Fixed Radius Comparison

[Jarosz et al. 08]

Traditional Estimate



Beam Estimate



Fixed Radius Comparison

[Jarosz et al. 08]

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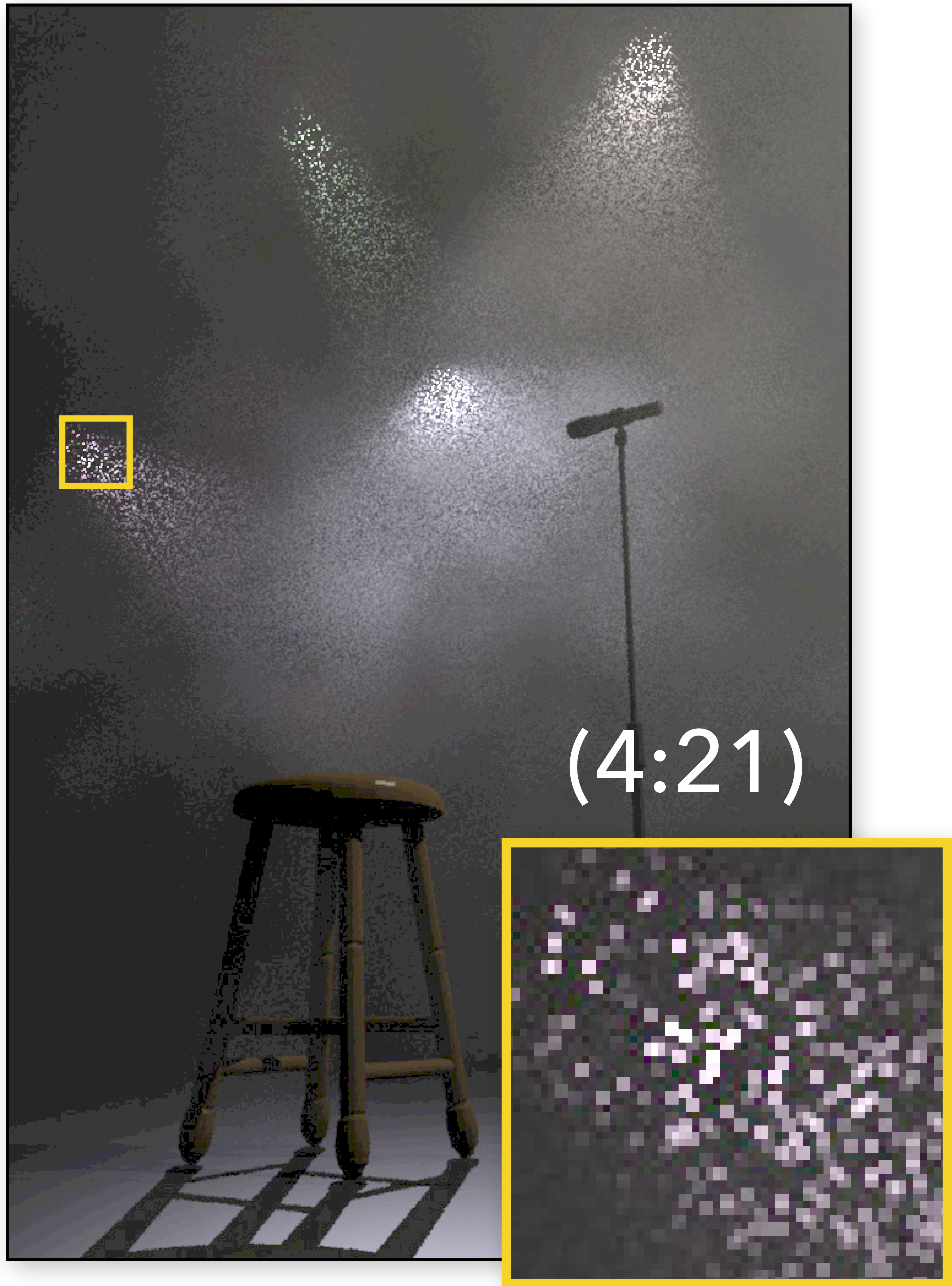
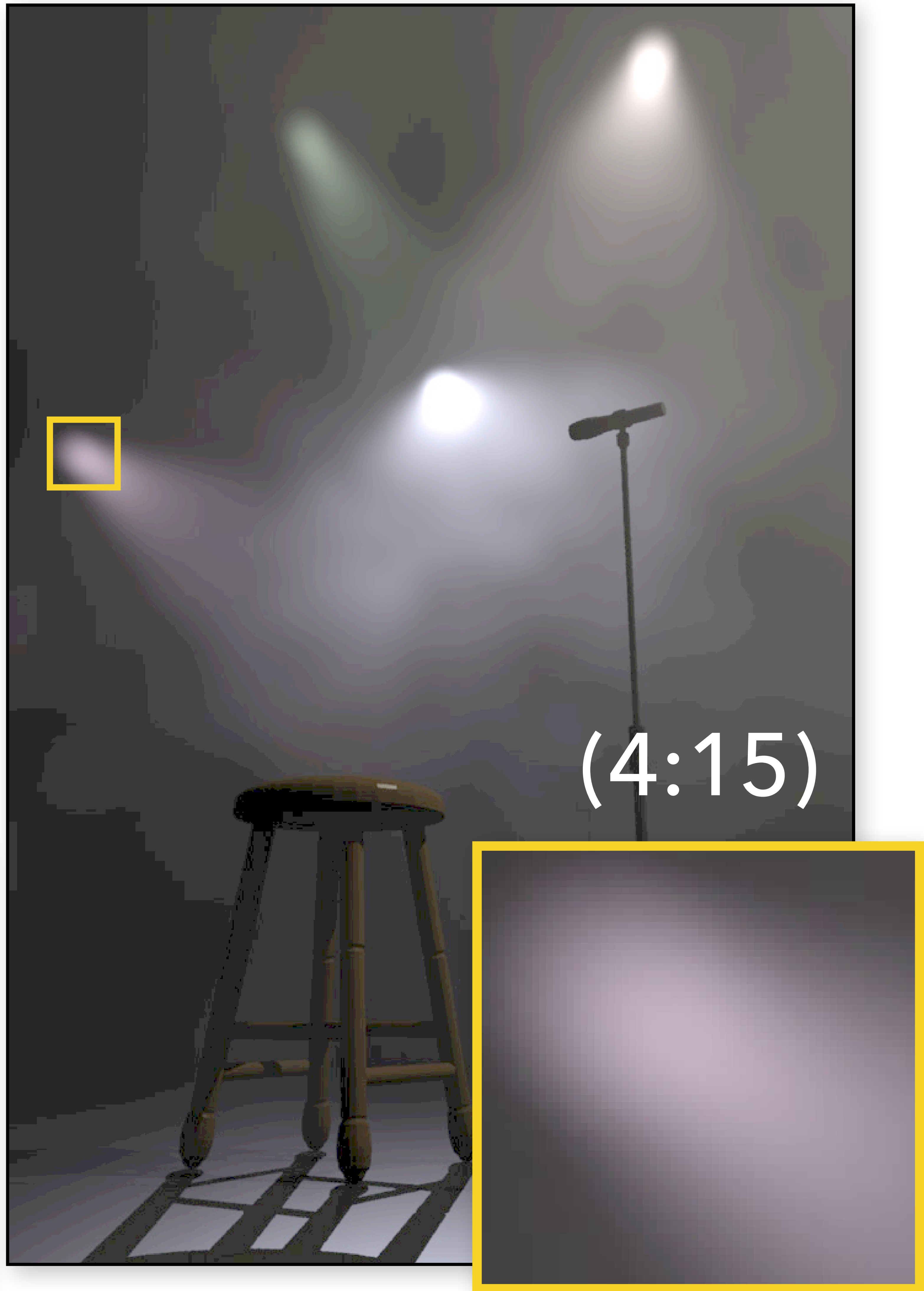


Beam Estimate



Volumetric Photon Mapping

[Jarosz et al. 08]

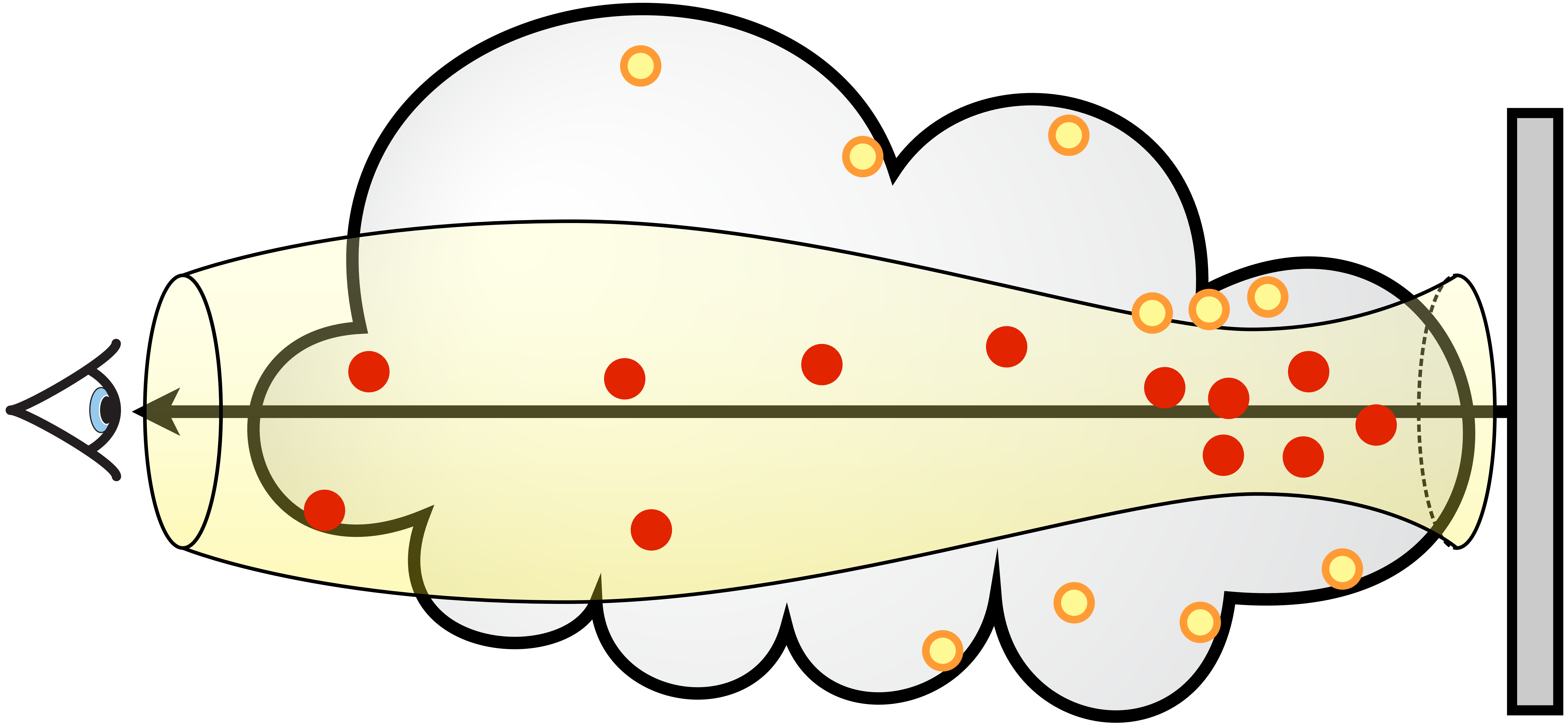
Fixed Radius

Nearest Neighbor

(Defining the kernel support by finding k nearest photons)

Varying Radius

[Jarosz et al. 08]



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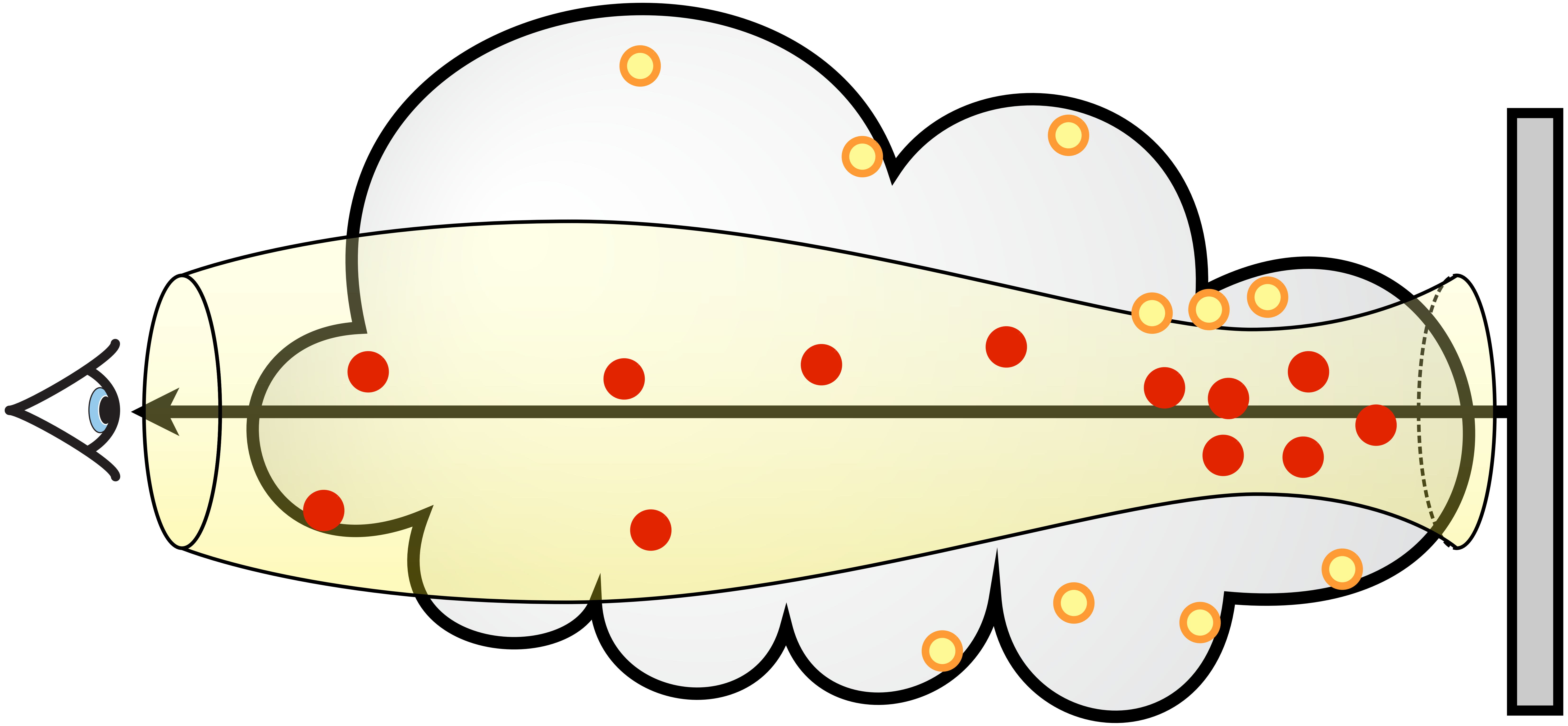
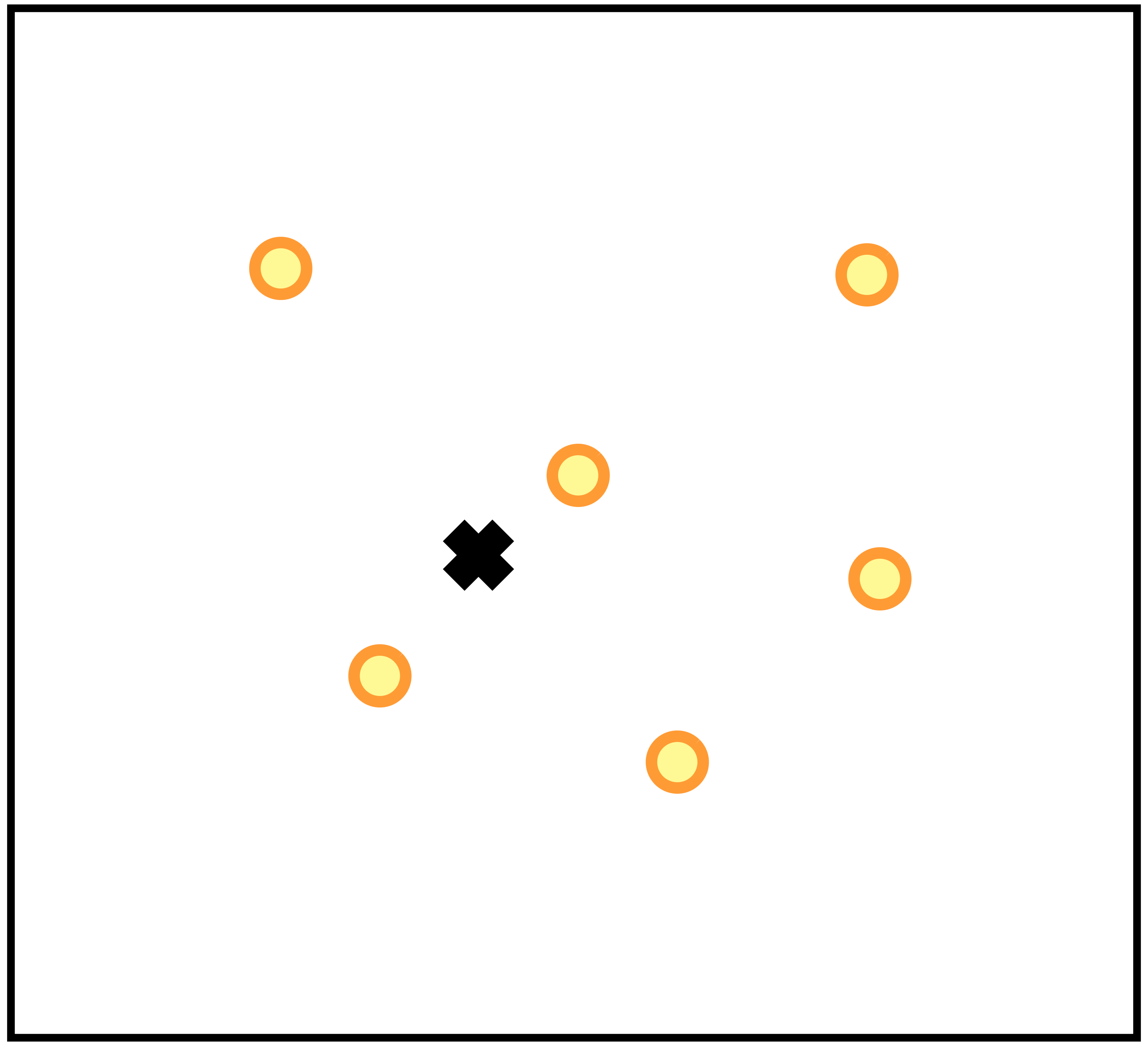
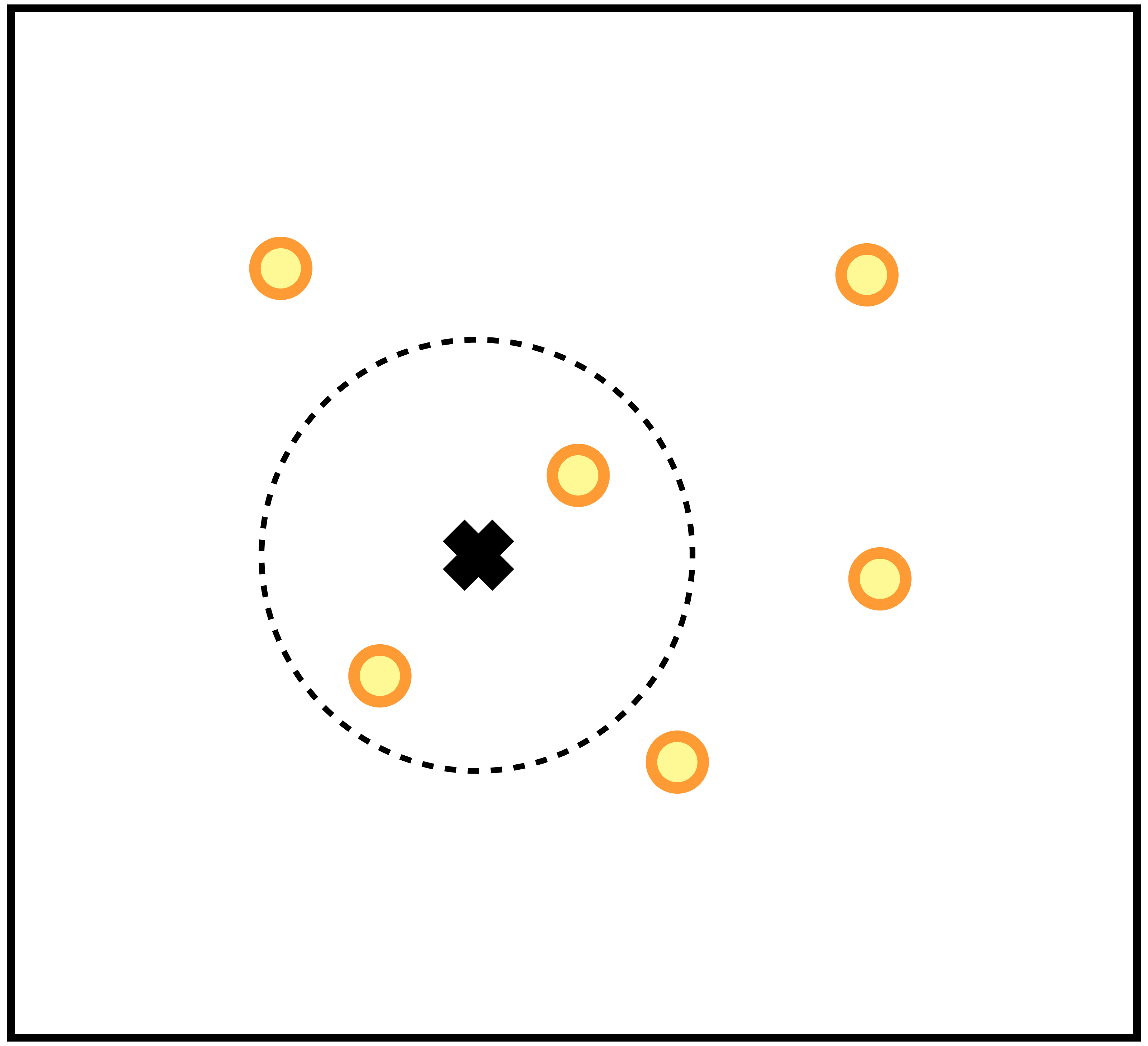


How to implement this efficiently?

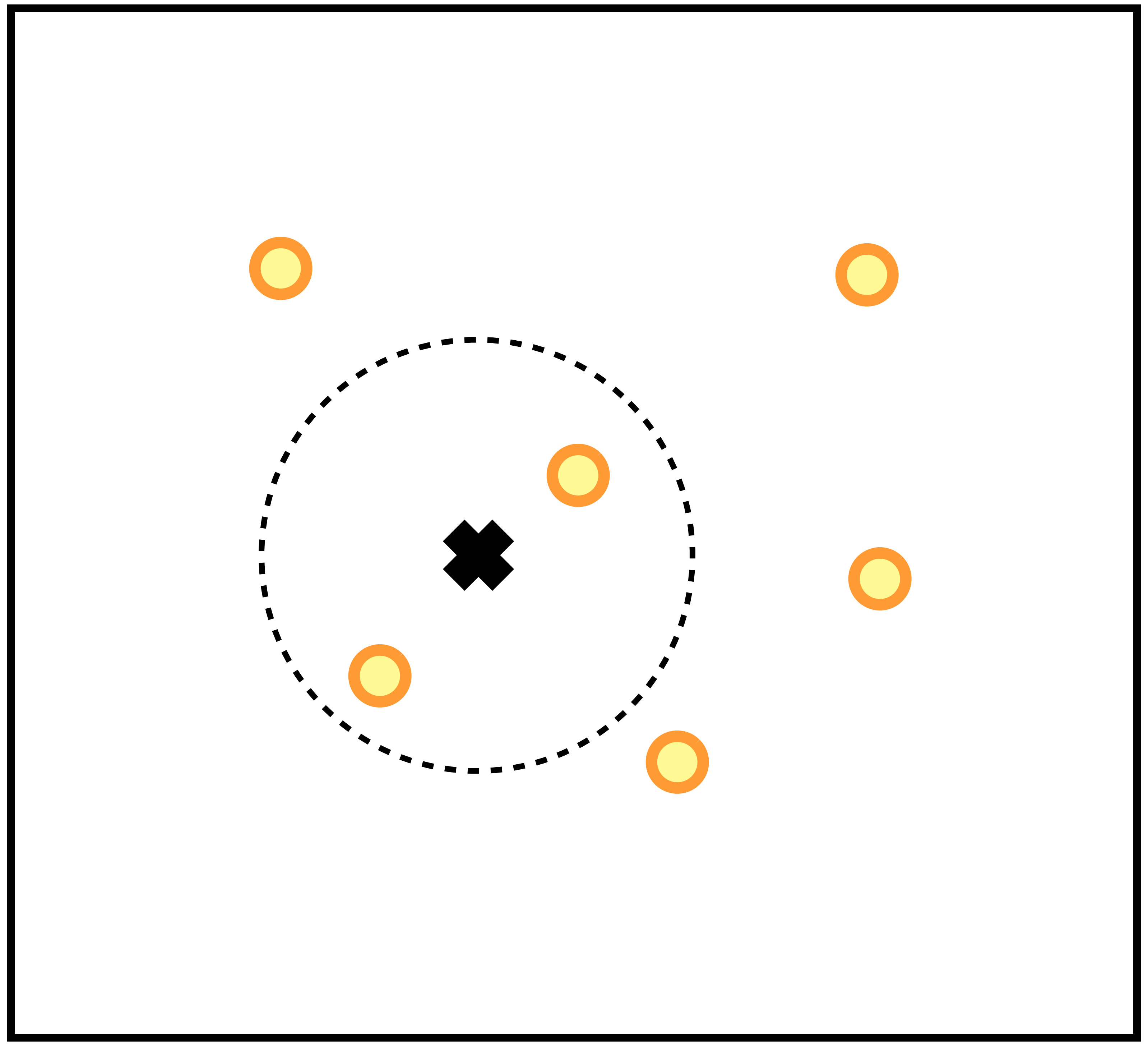
Primal vs Dual

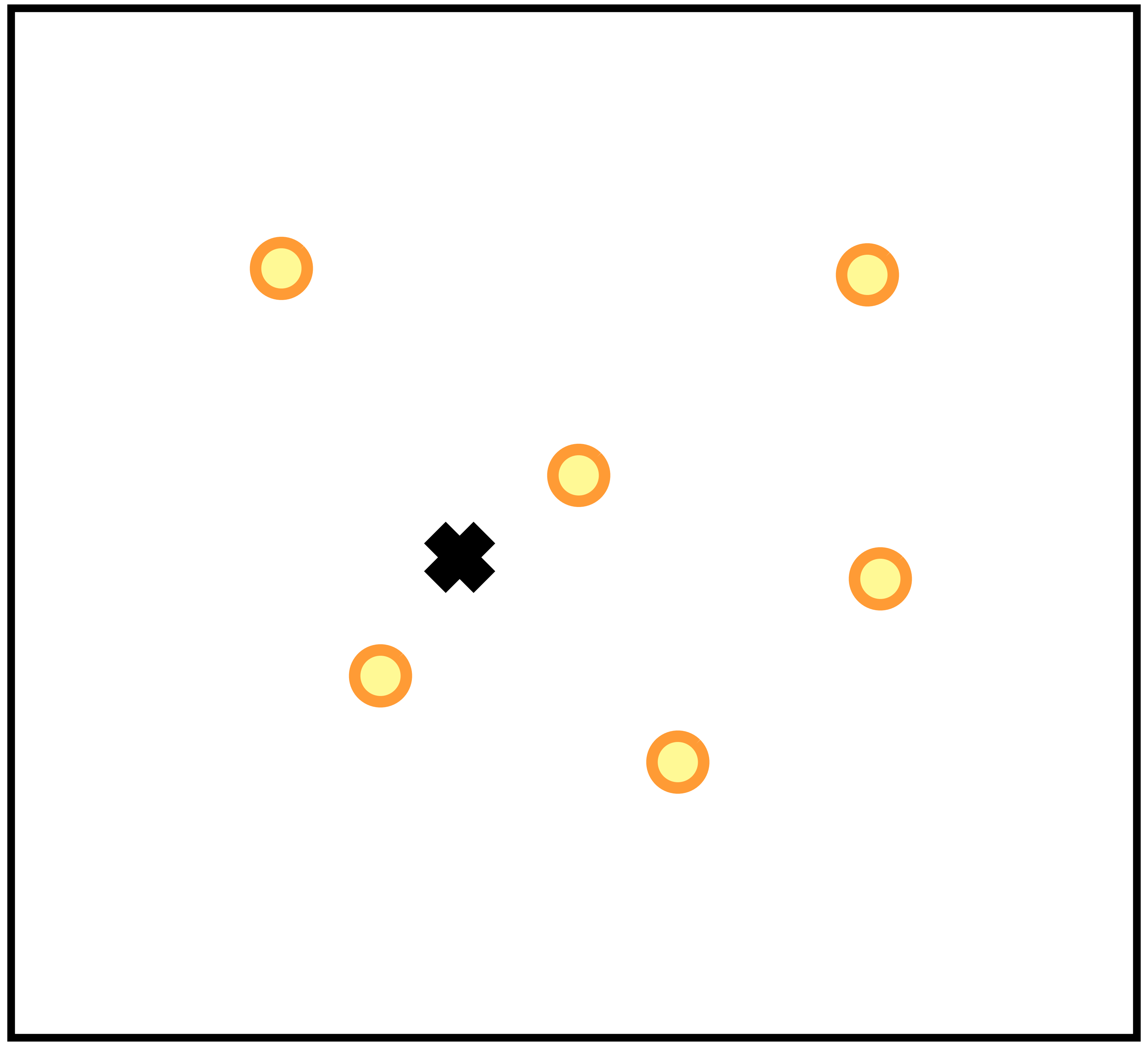


Primal vs Dual



Primal vs Dual





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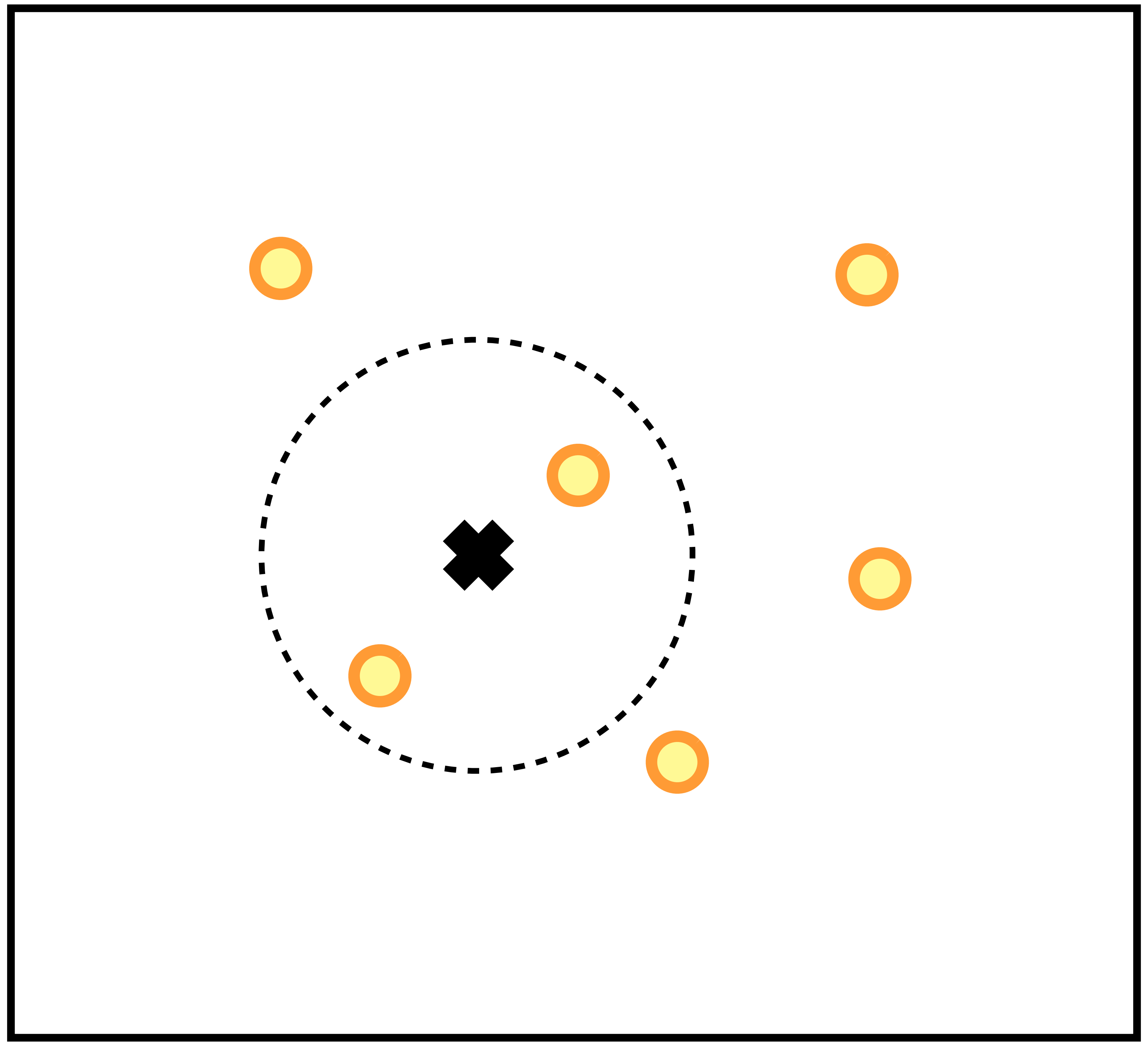
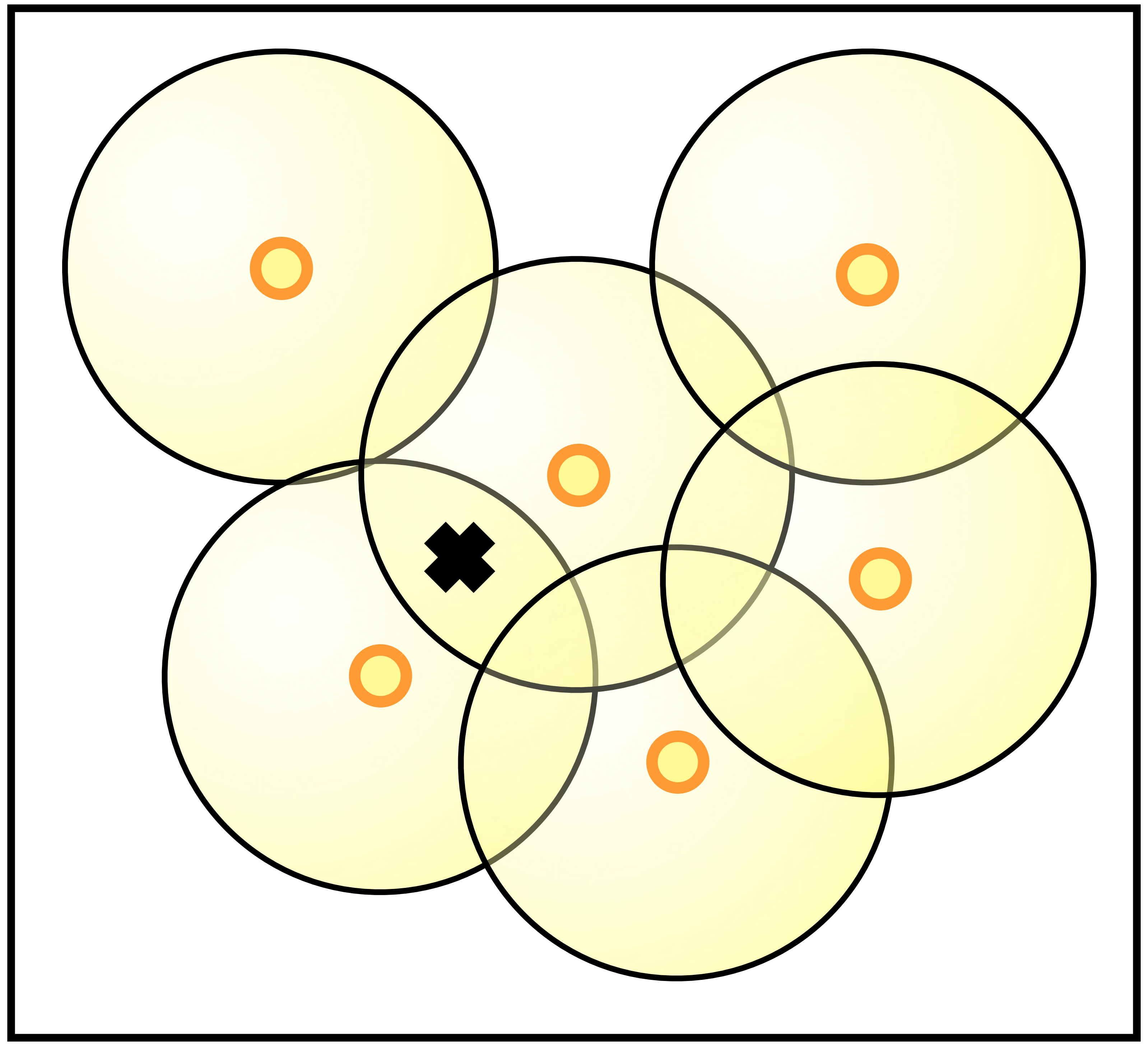
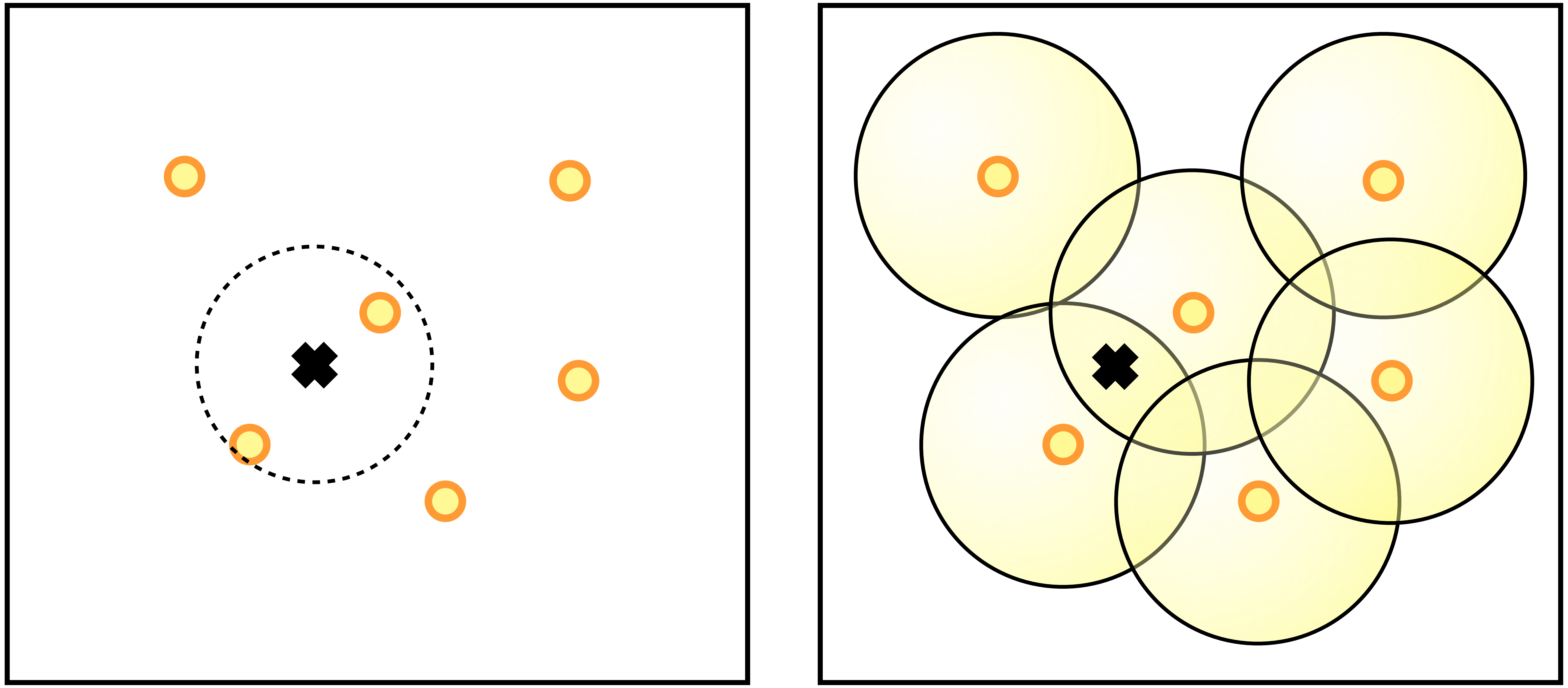


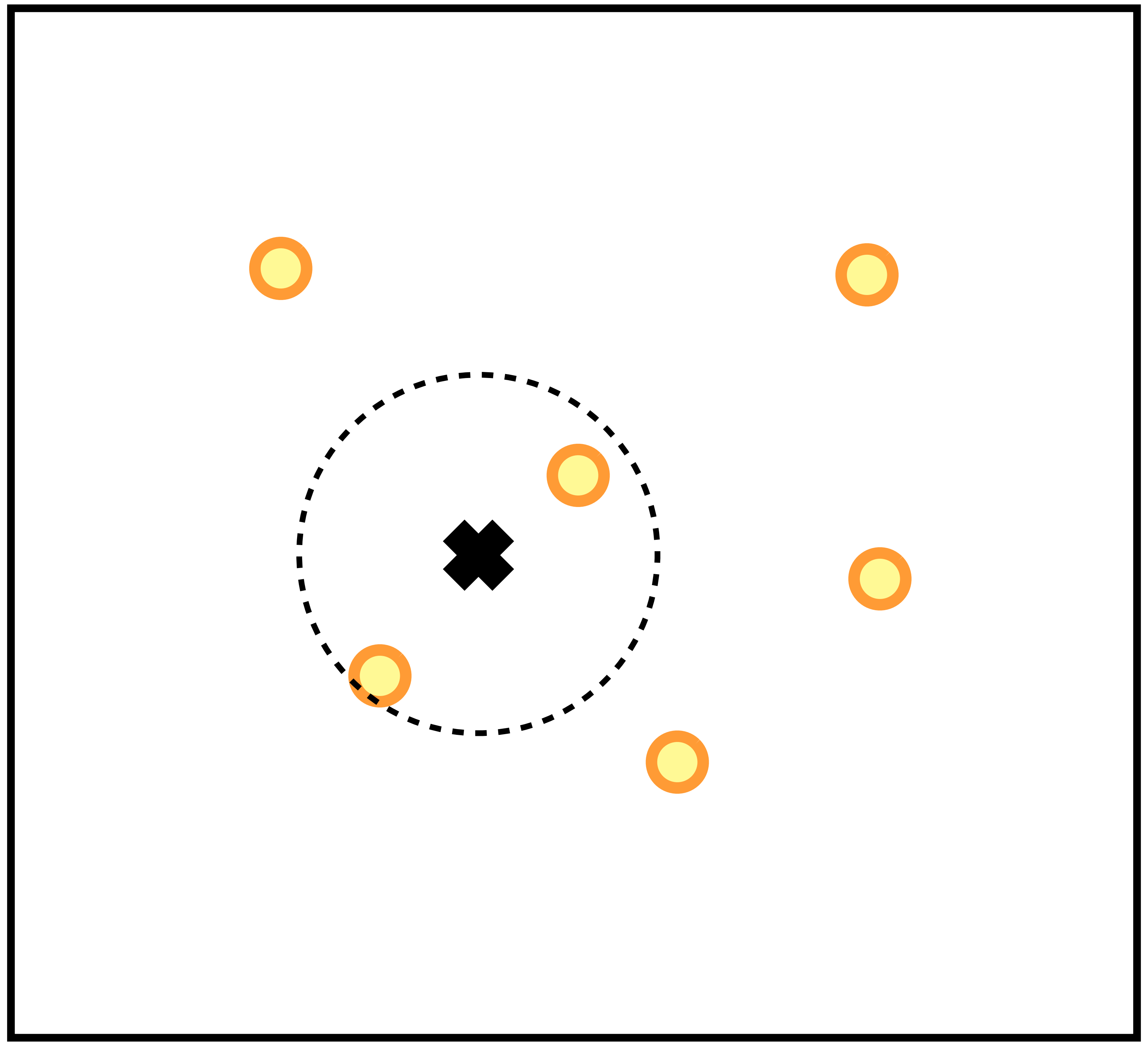


Primal vs Dual

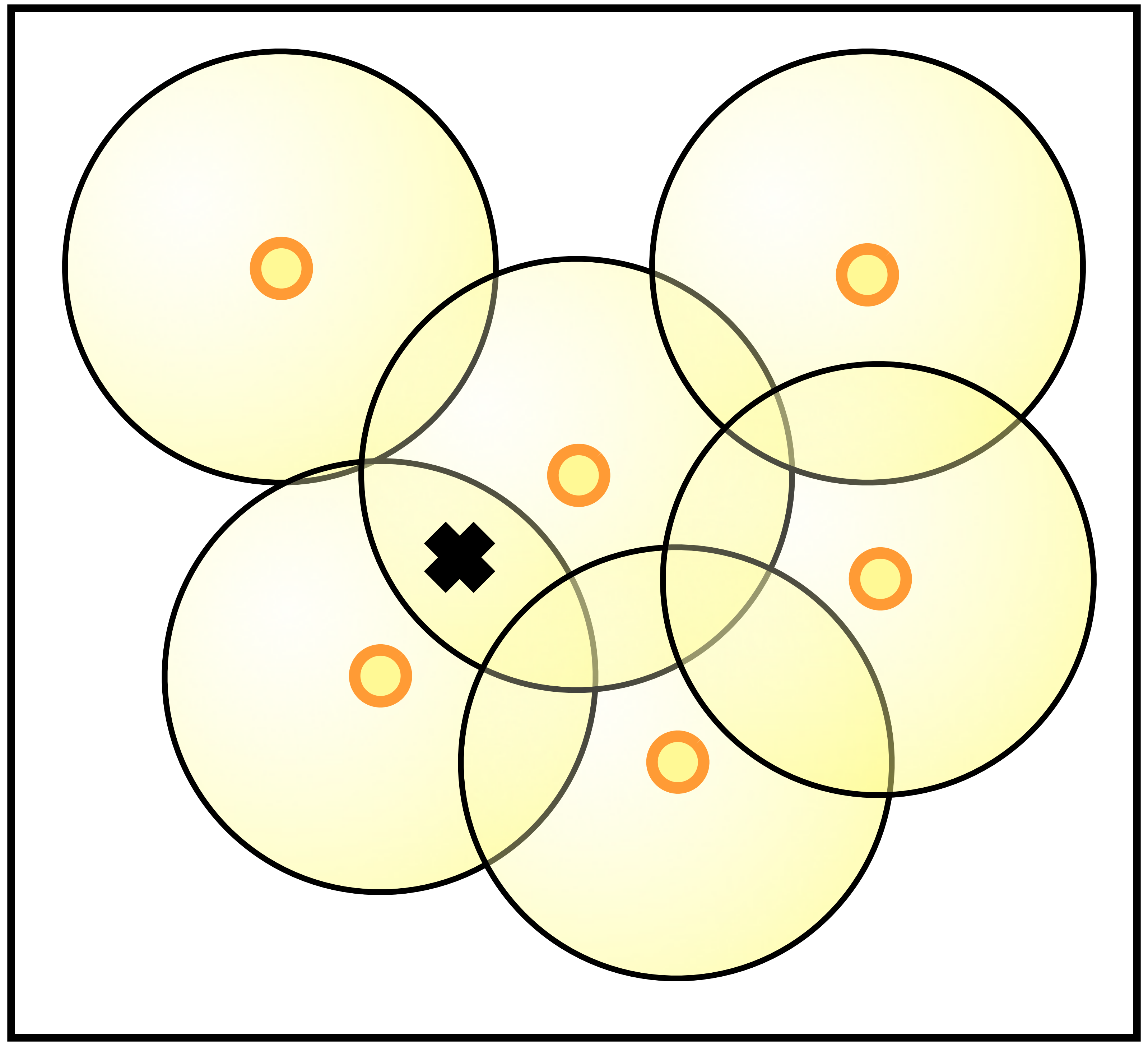


k-nearest neighbor

Primal vs Dual

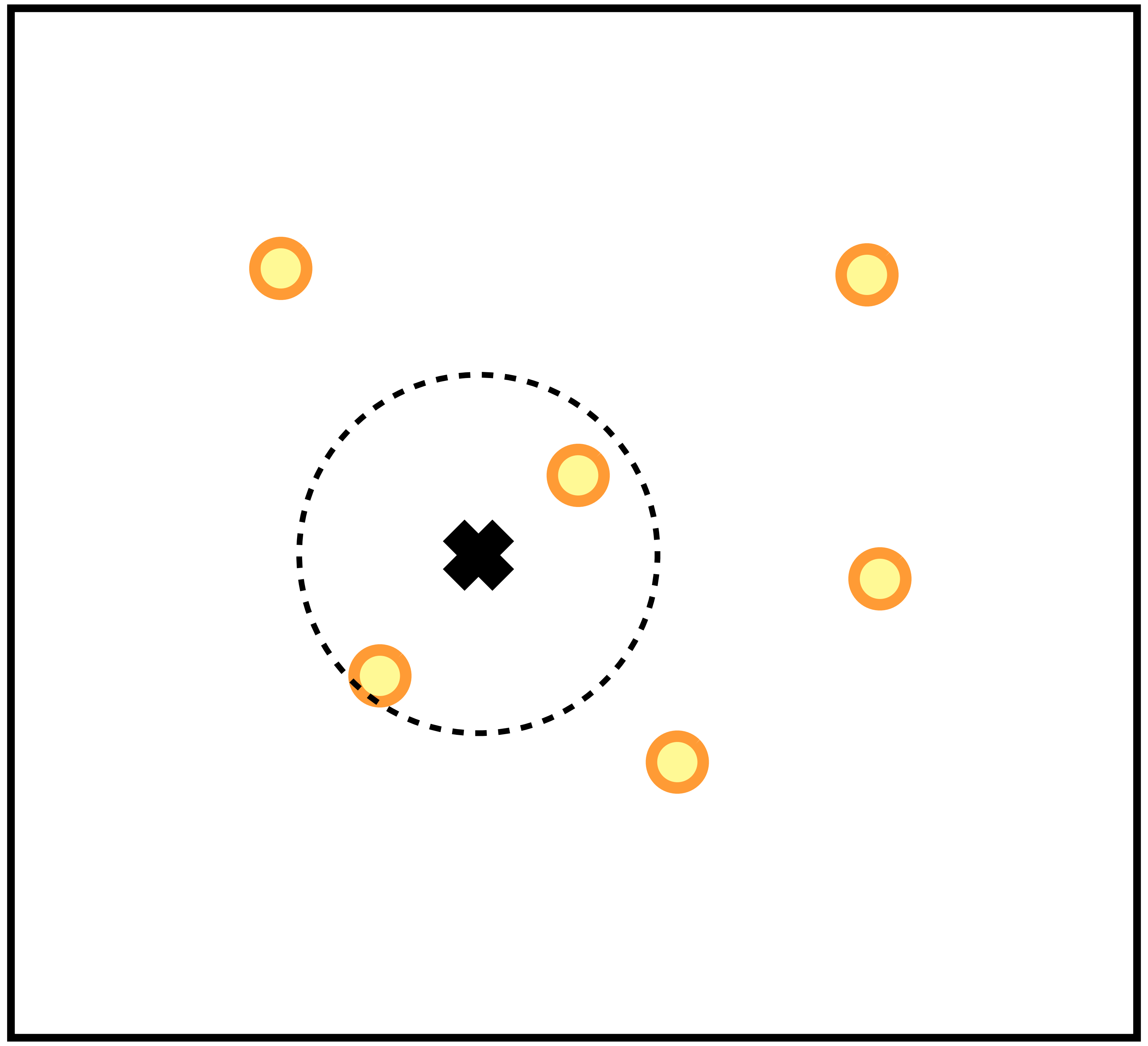


k-nearest neighbor

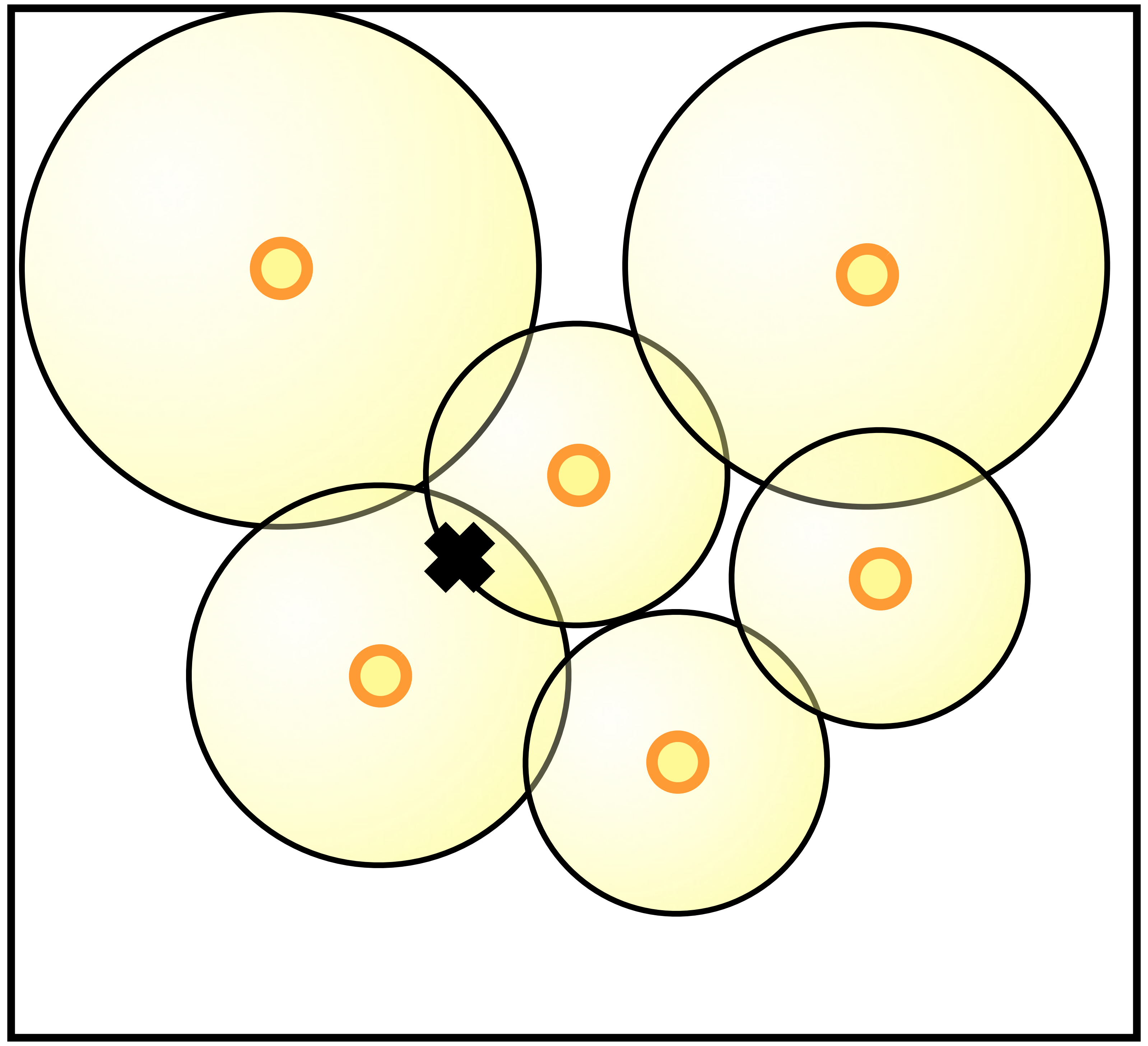


allow kernel radius to vary:
adaptive kernel method

Primal vs Dual



k-nearest neighbor



allow kernel radius to vary:
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Beam Radiance Estimate

[Jarosz et al. 08]

Beam Radiance Estimate

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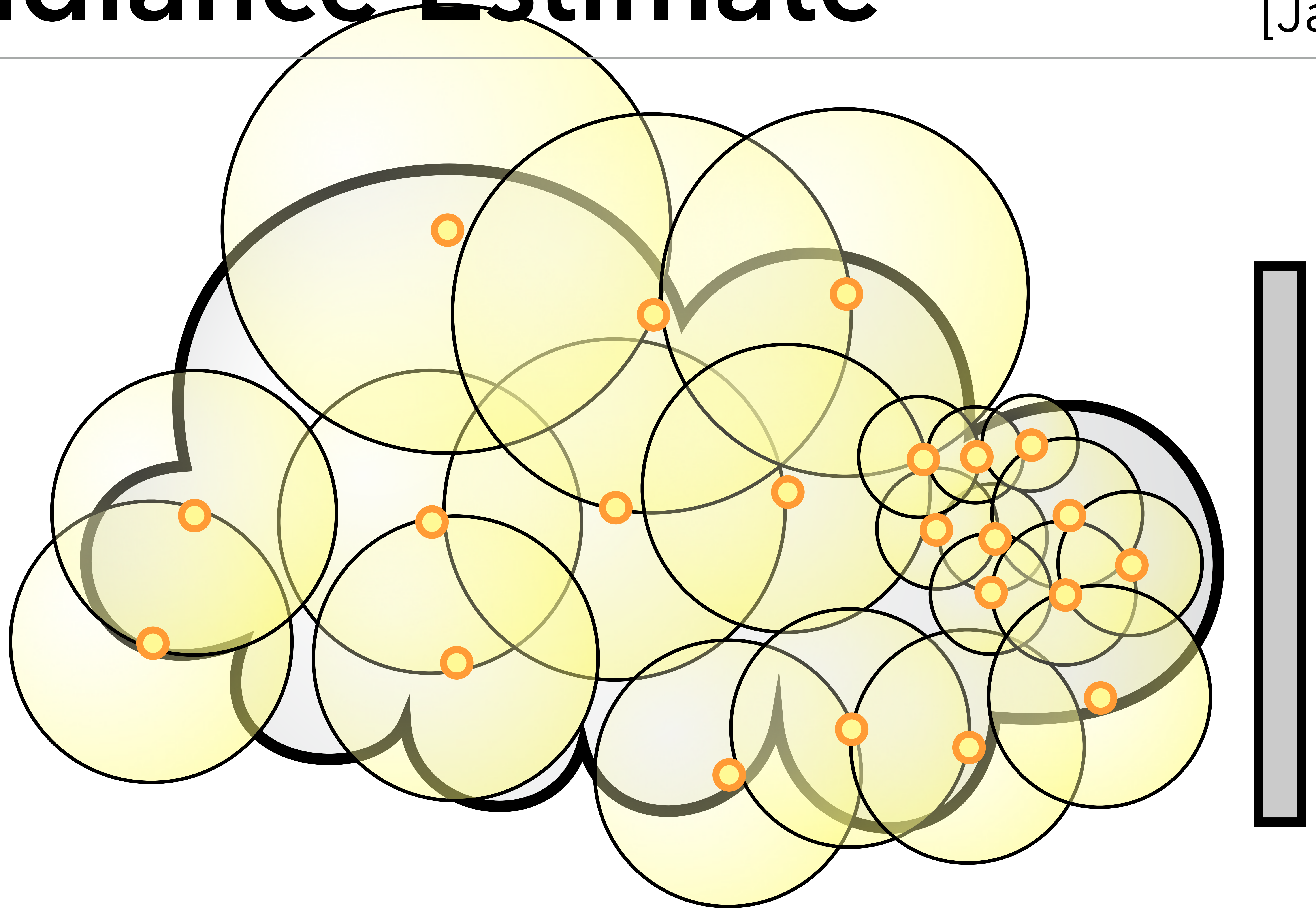
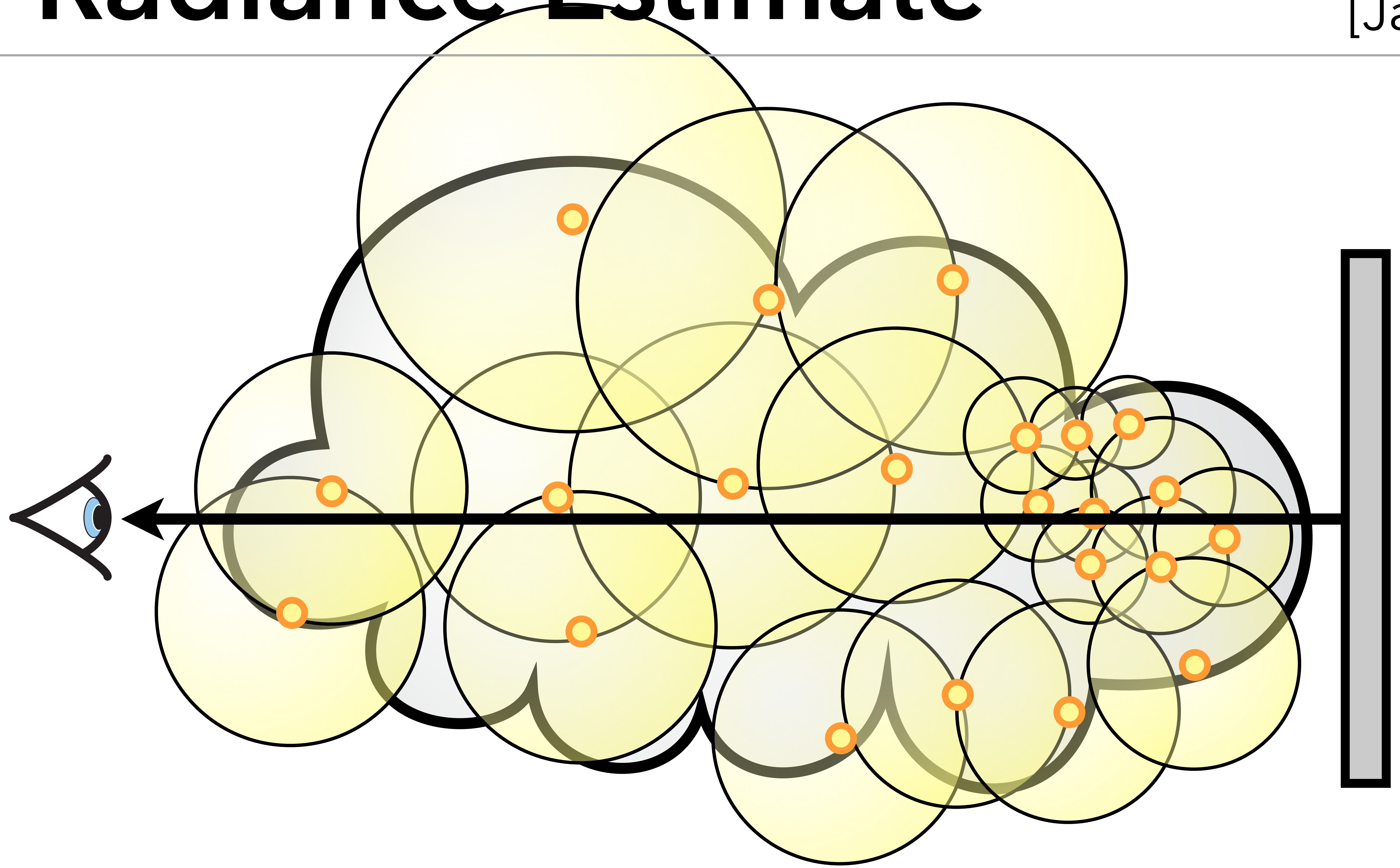


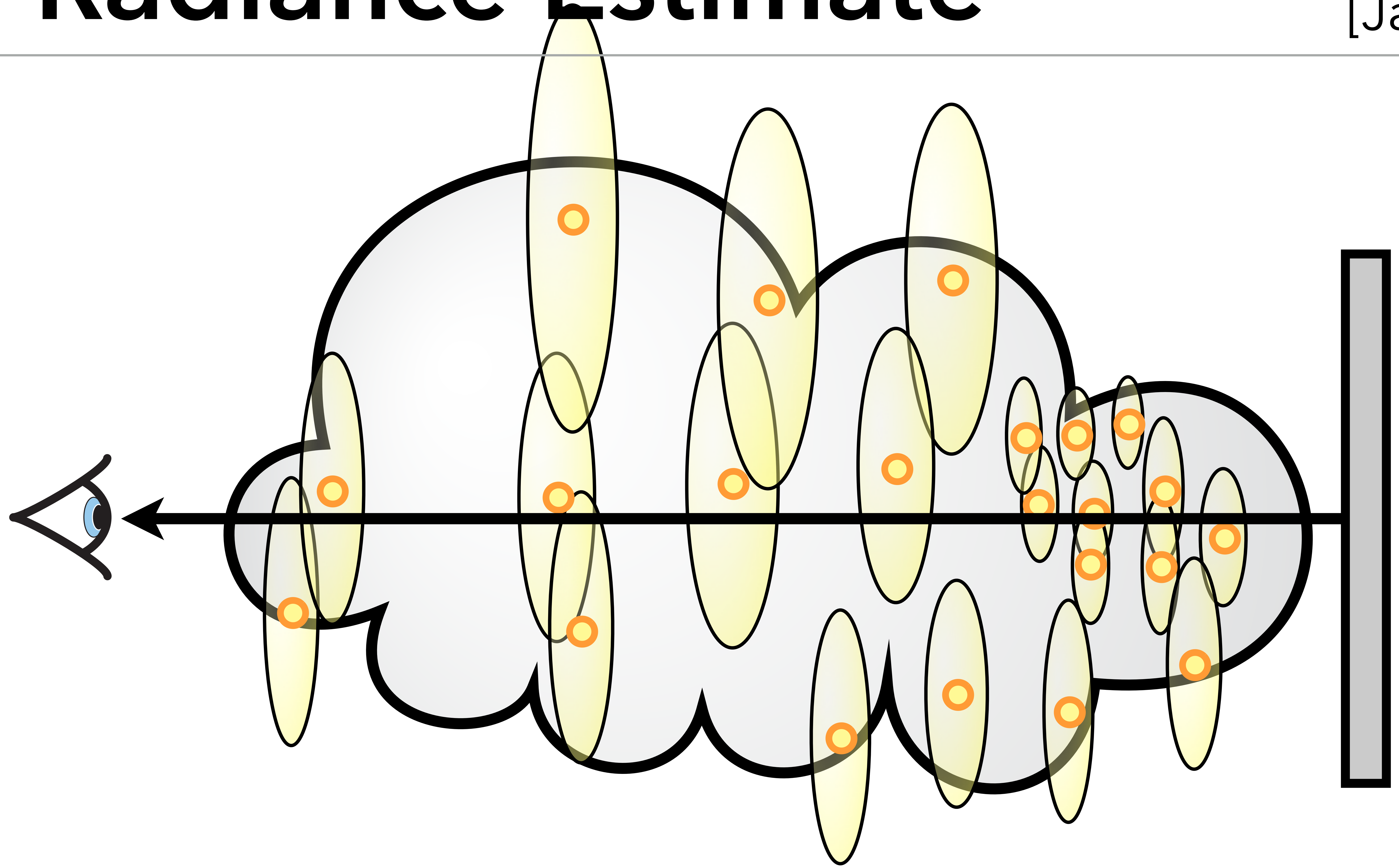
Beam Radiance Estimate

[Jarosz et al. 08]



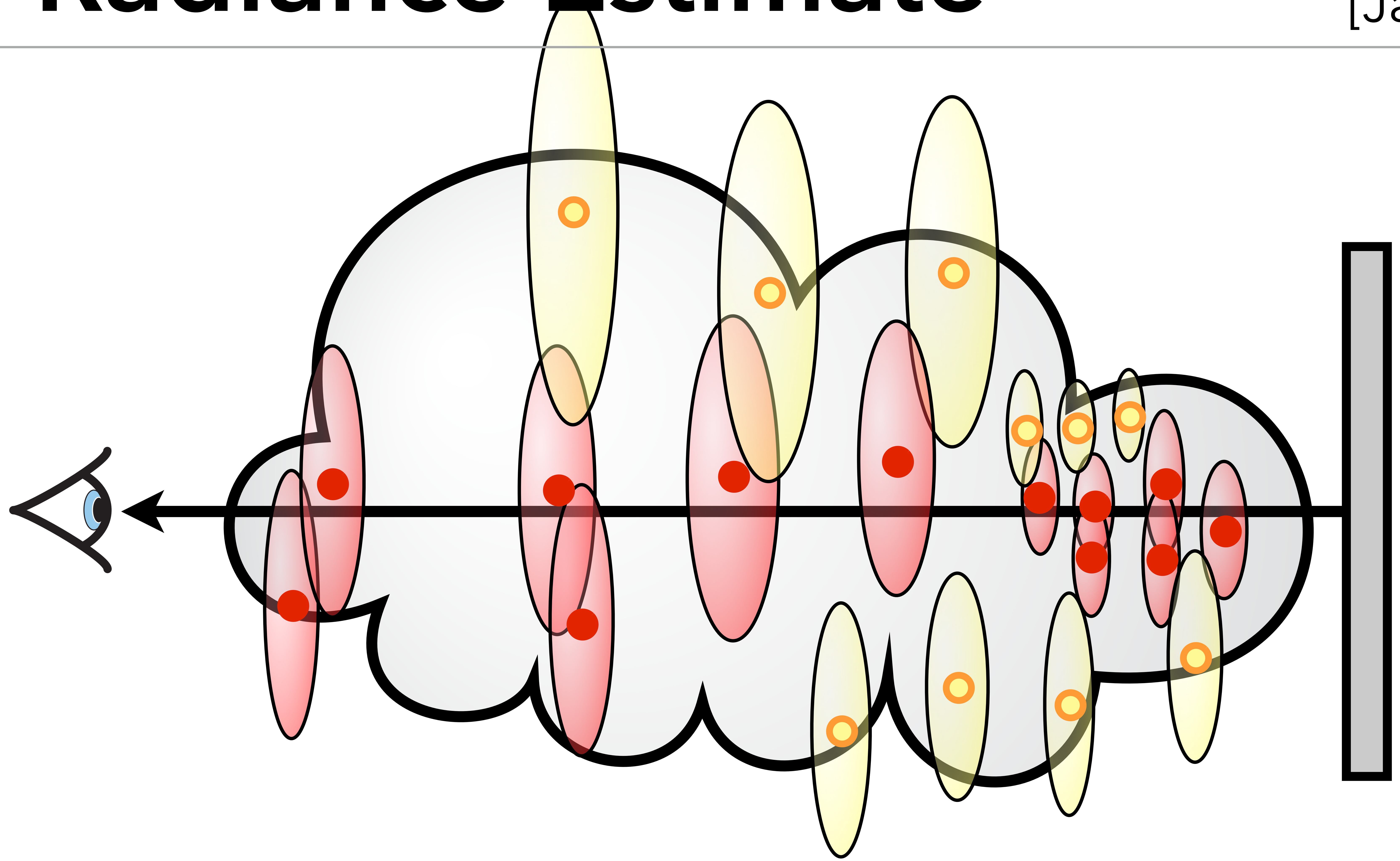
Beam Radiance Estimate

[Jarosz et al. 08]

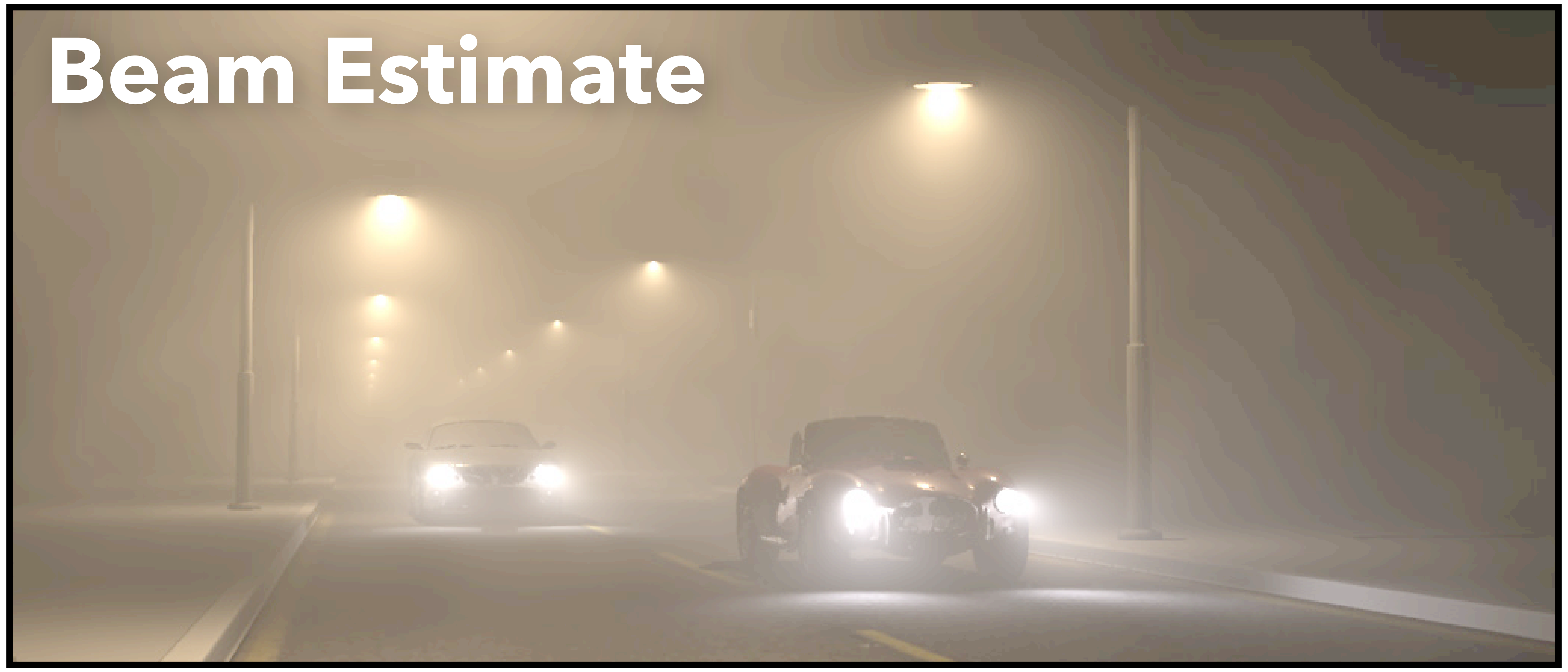


Beam Radiance Estimate

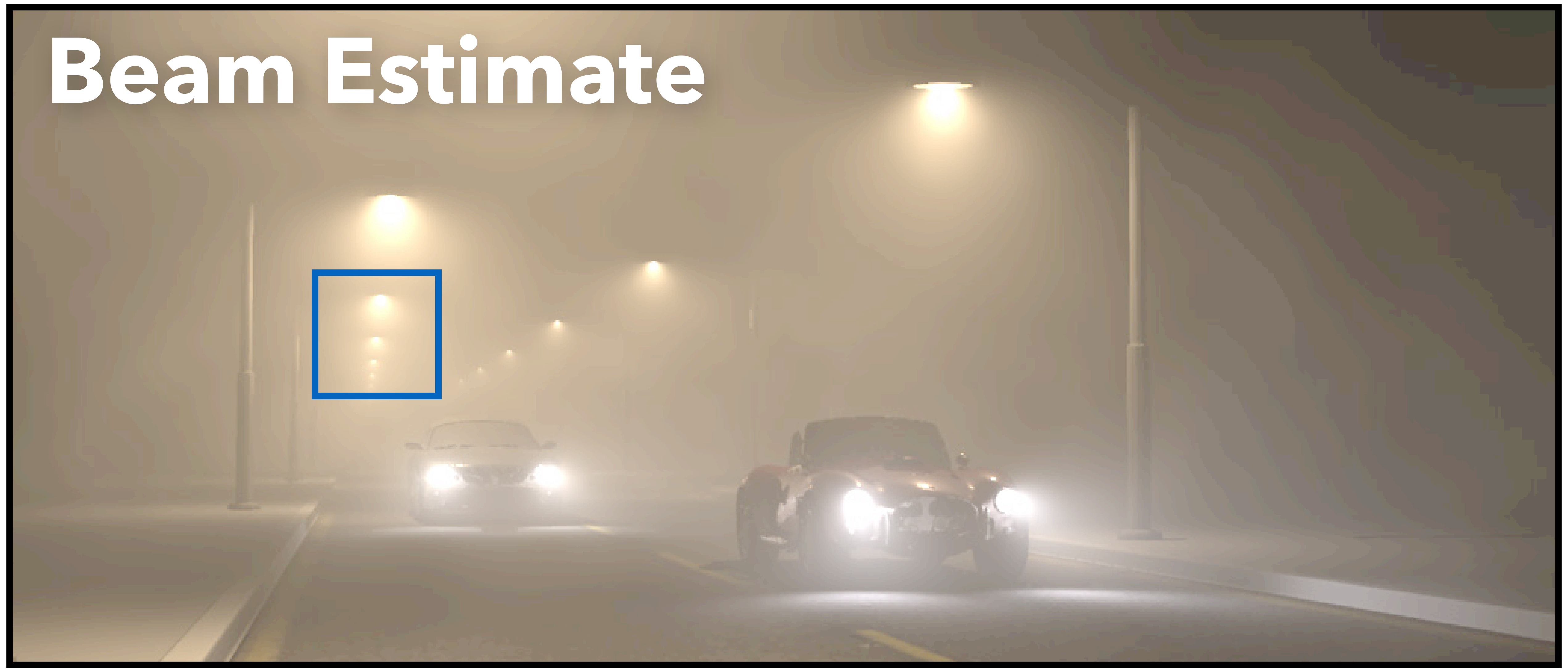
[Jarosz et al. 08]

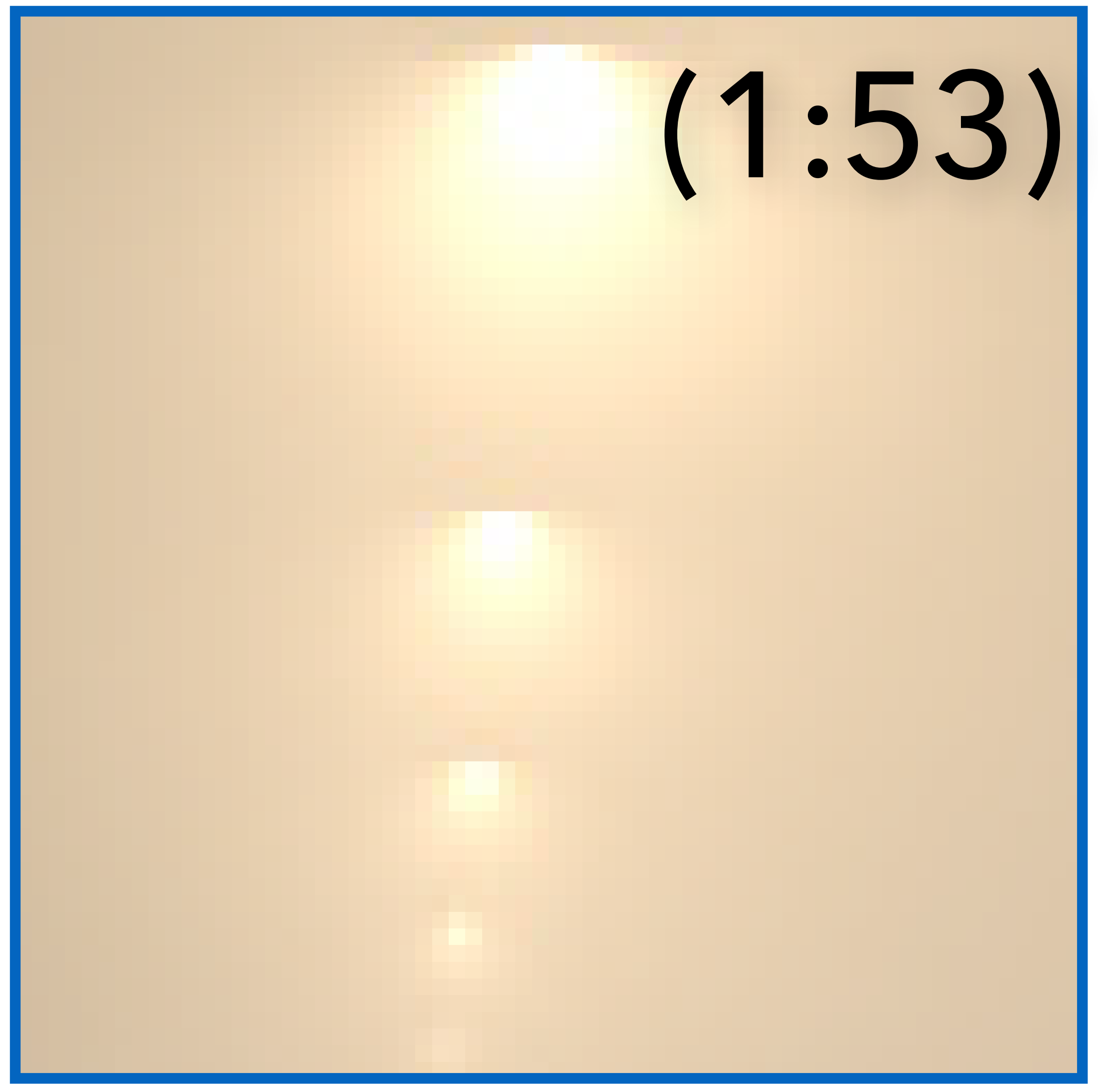


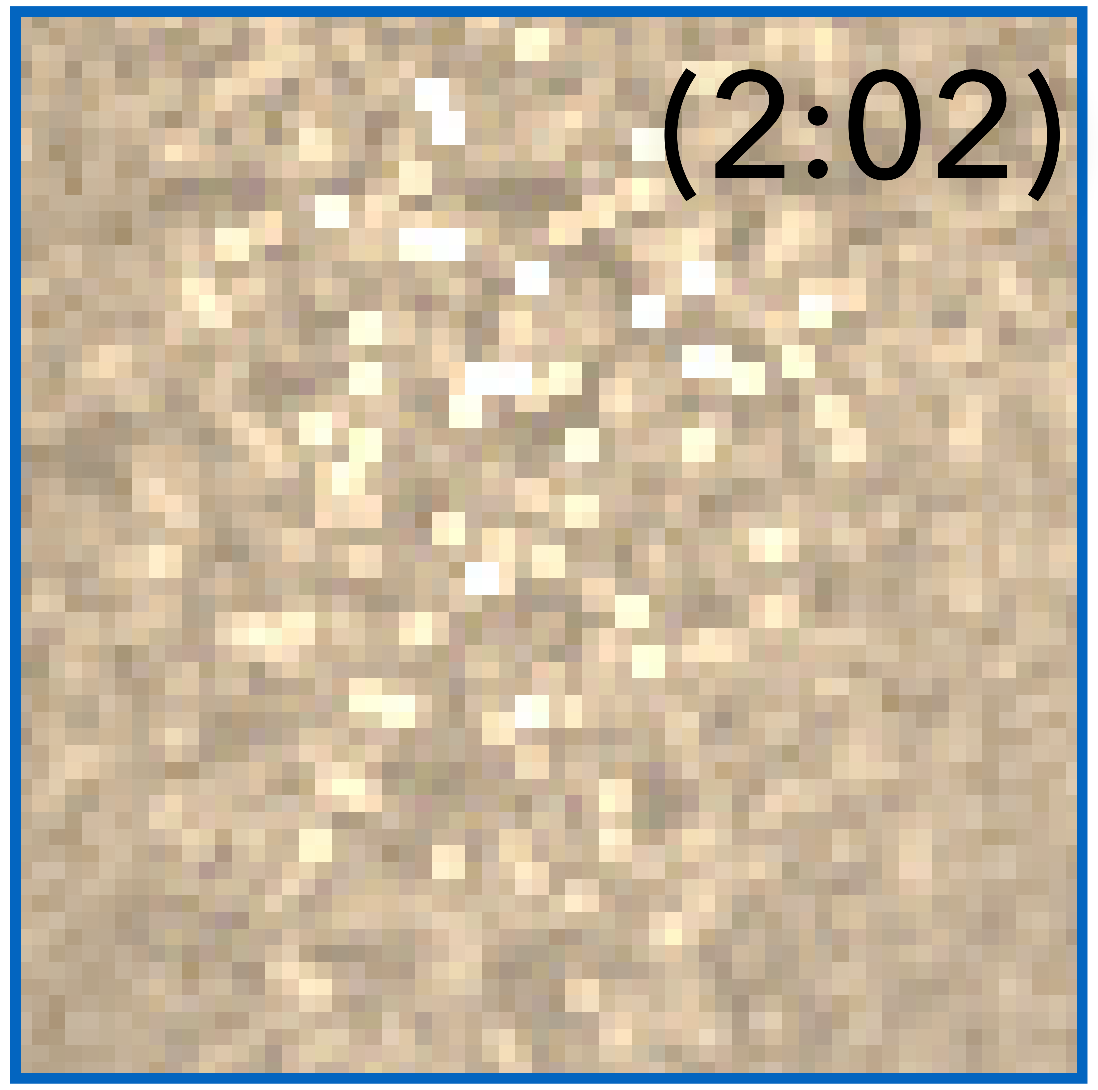
Cars on Foggy Street



Cars on Foggy Street

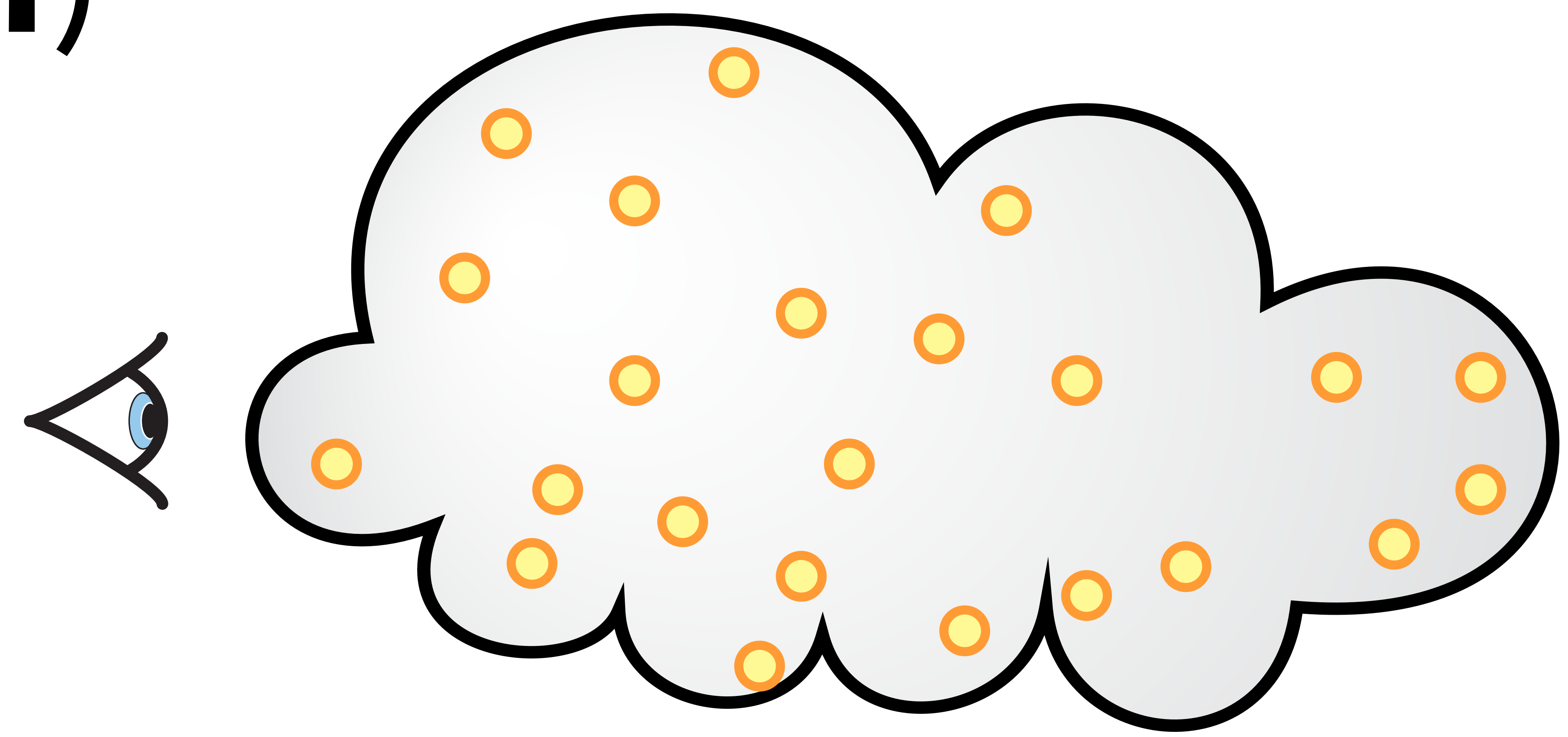






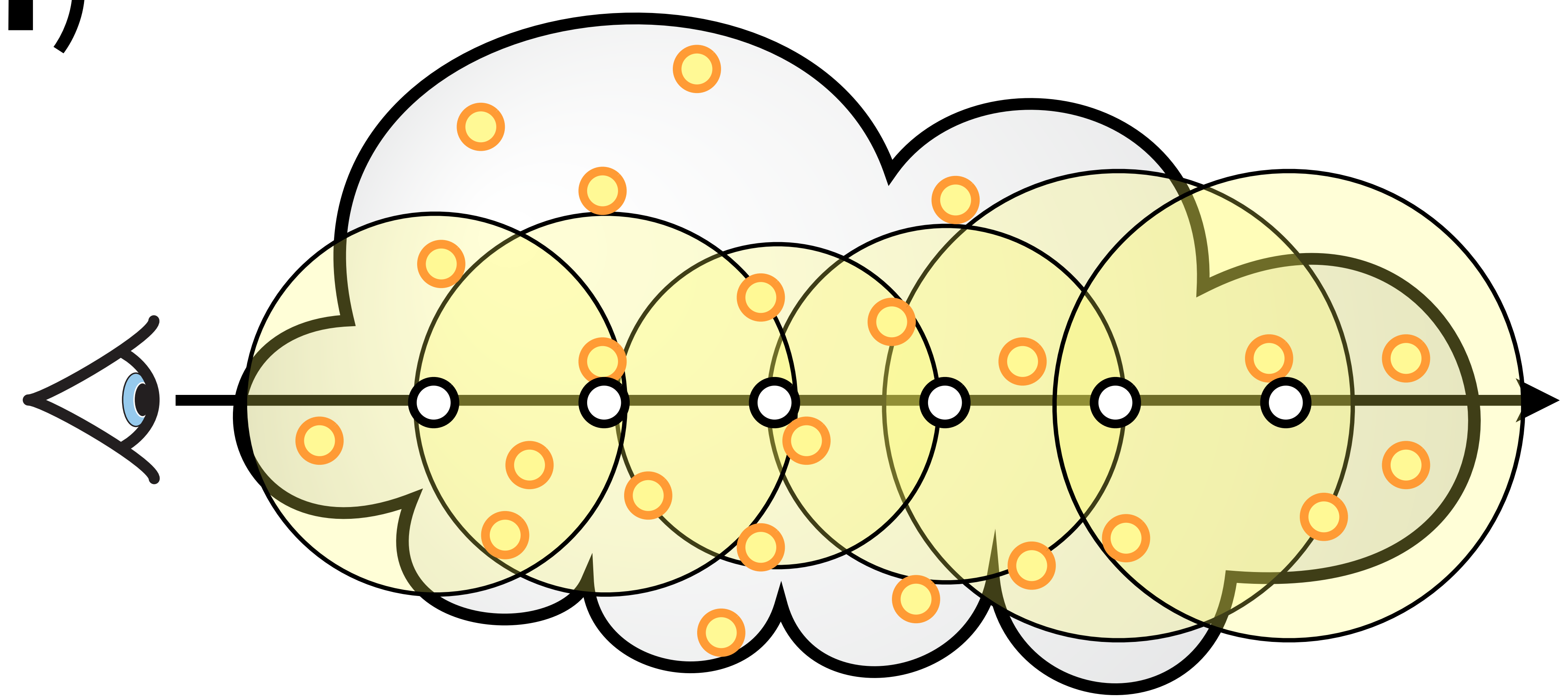
So Far...

Volumetric Photon Mapping (**VPM**)
[Jensen & Christensen 98]



So Far...

Volumetric Photon Mapping (**VPM**)
[Jensen & Christensen 98]

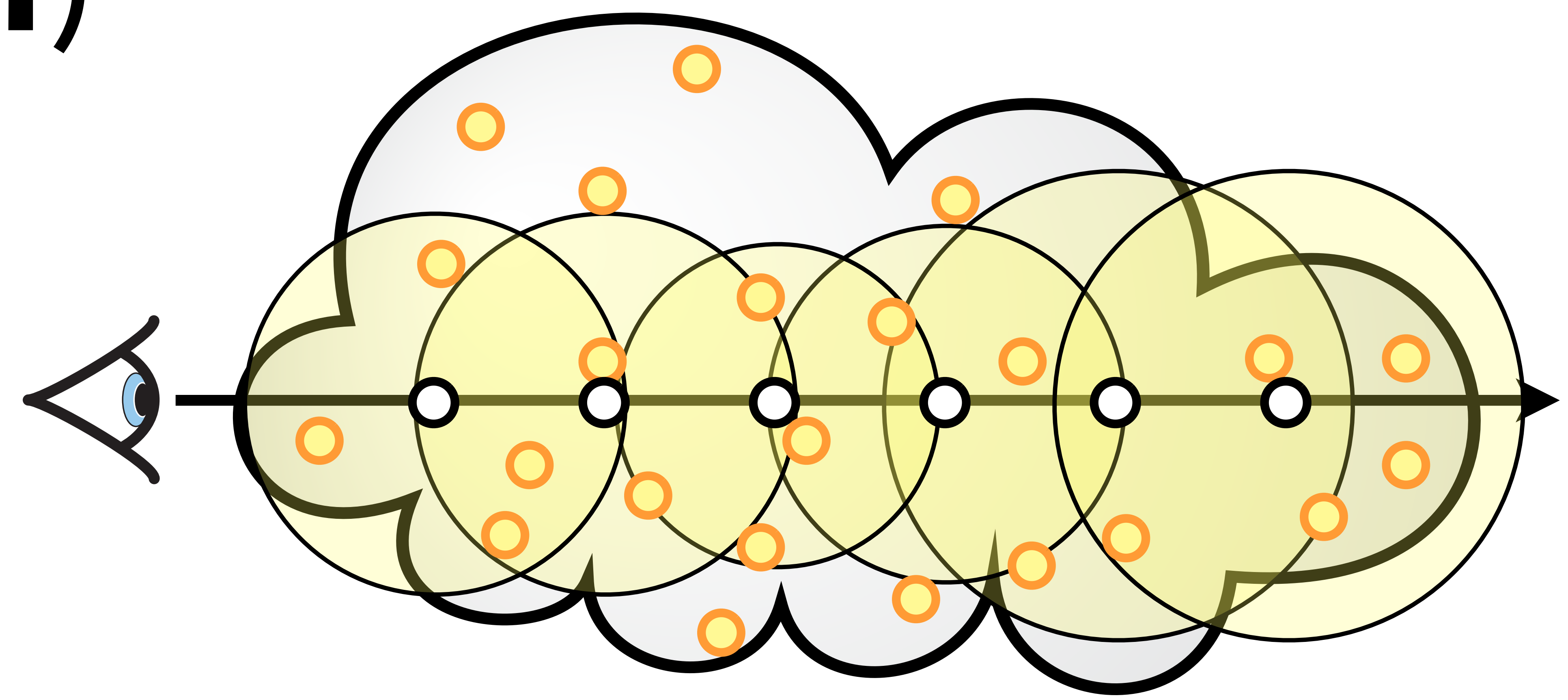


So Far...

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

Query
Point

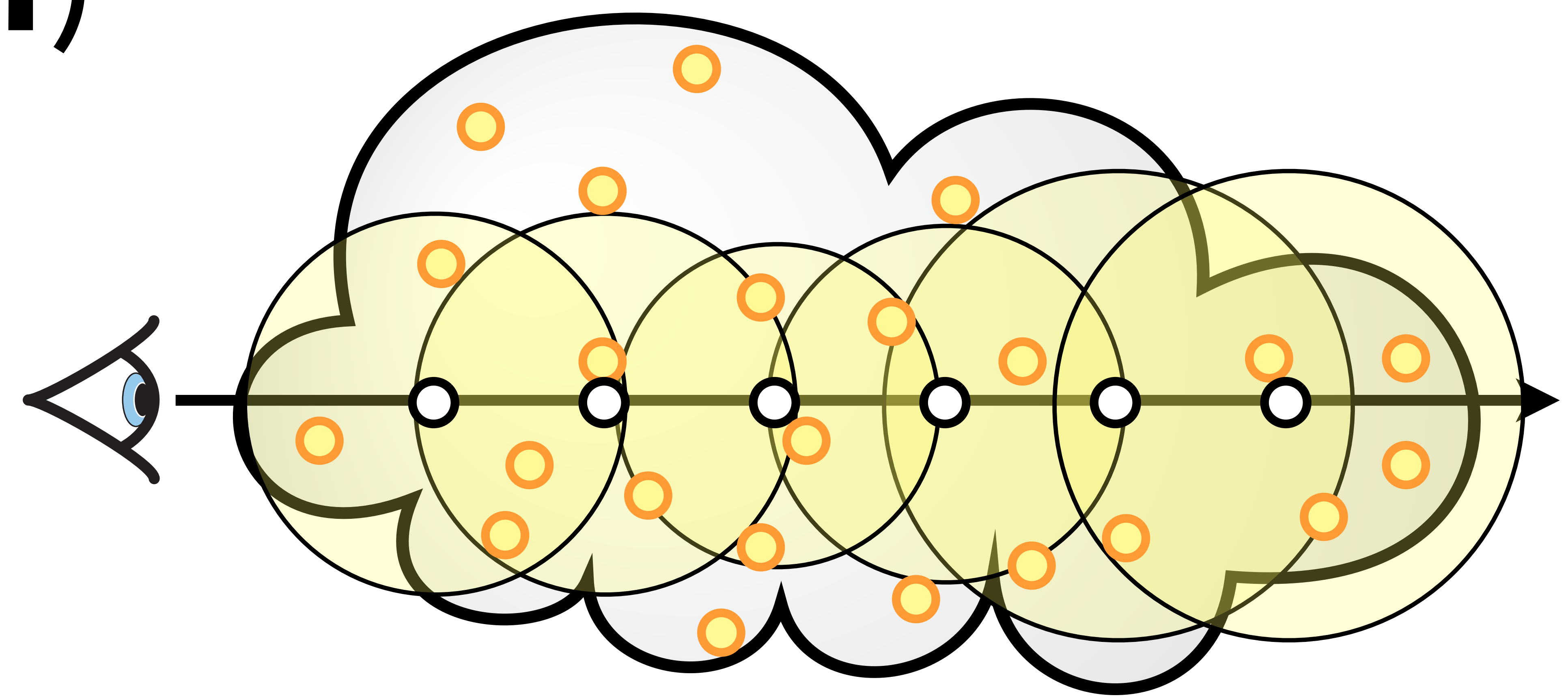


So Far...

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

Query	**x**	**Data**
Point	x	Point

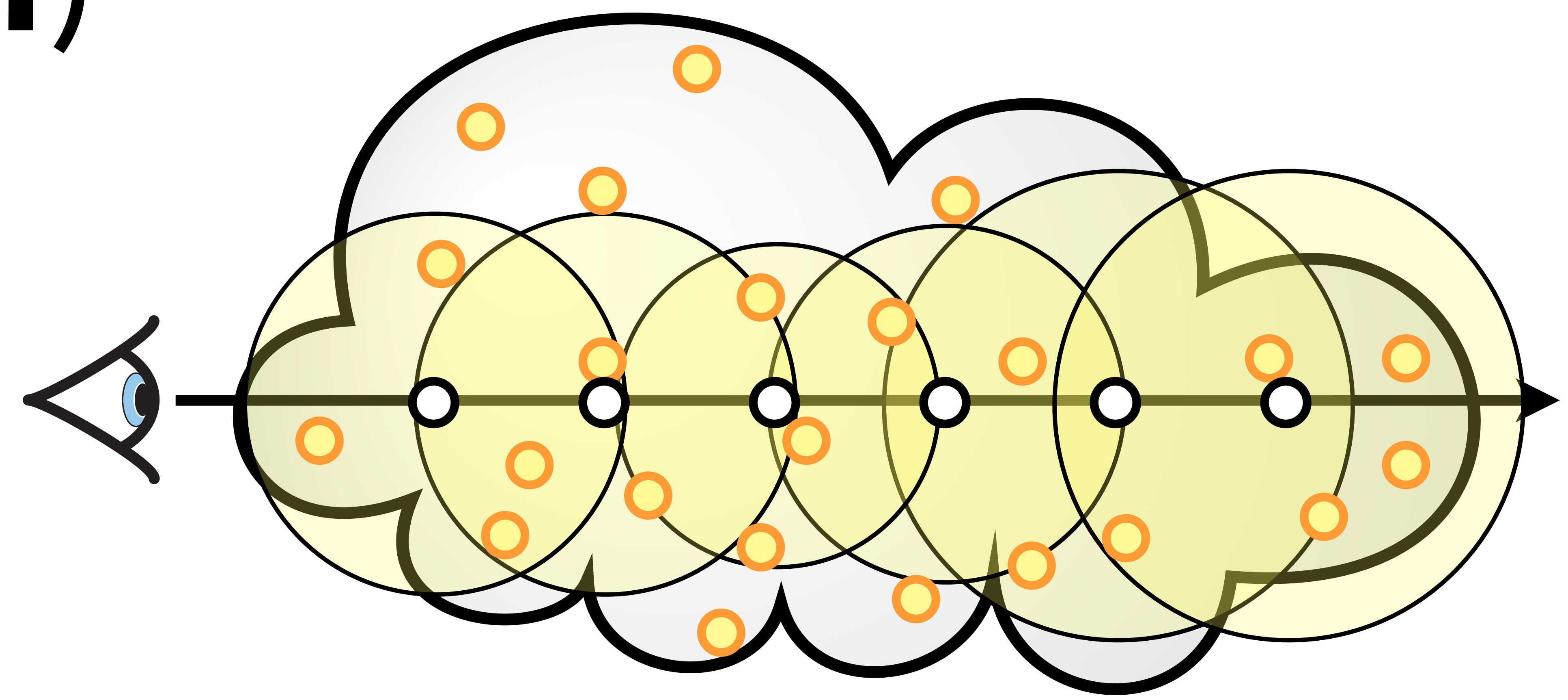


So Far...

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

Query	x	Data	Blur
Point	x	Point	(3D)

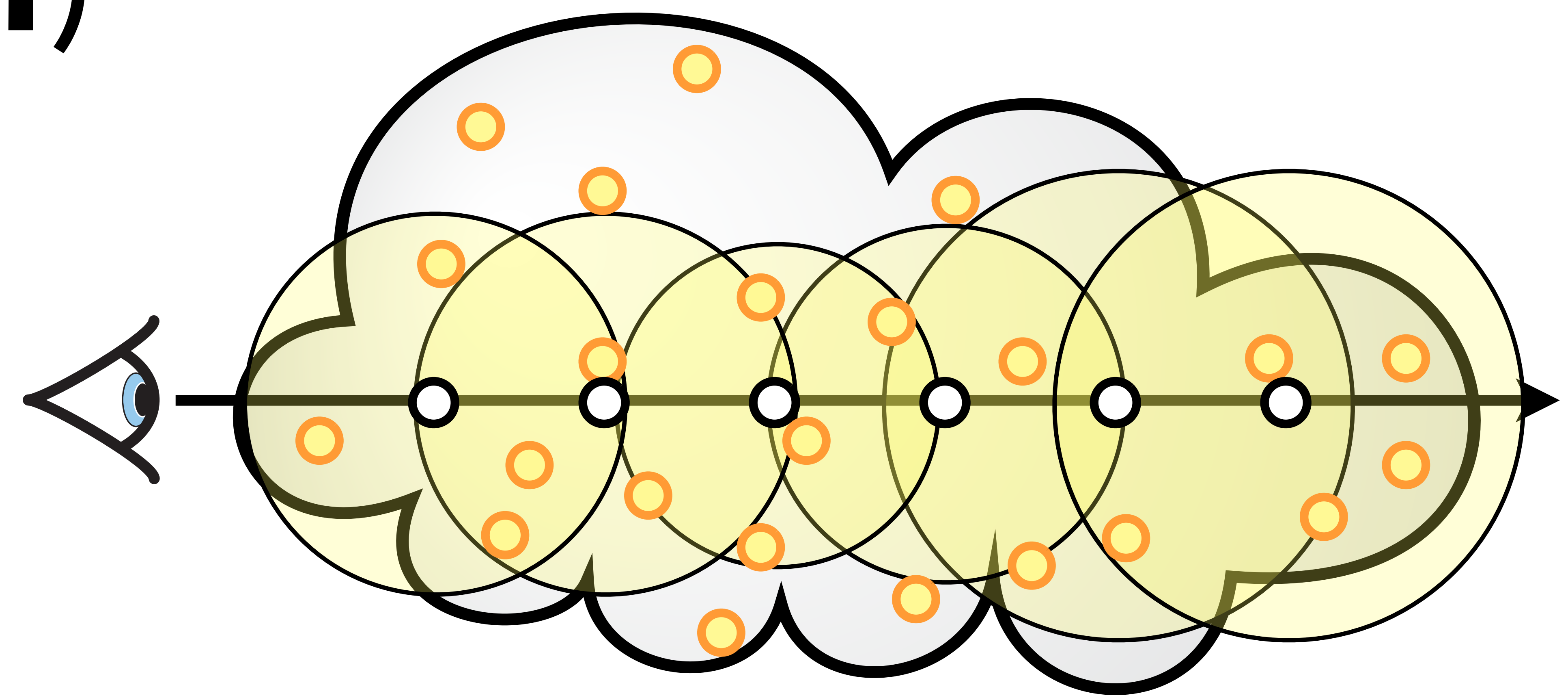


So Far...

Volumetric Photon Mapping (**VPM**)

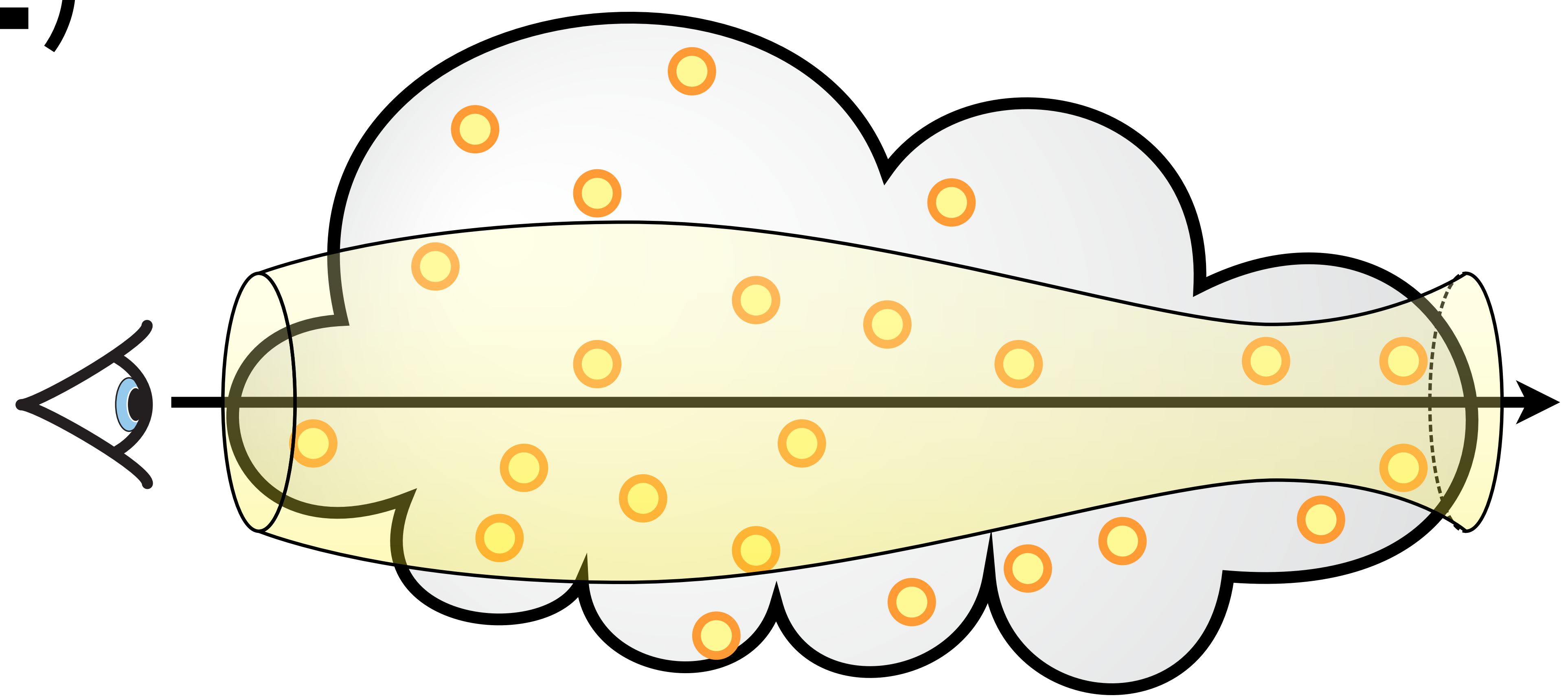
[Jensen & Christensen 98]

Query	**x**	**Data**	**Blur**
Point	x	Point	(3D)



The Beam Radiance Estimate (**BRE**)

[Jarosz et al. 08]

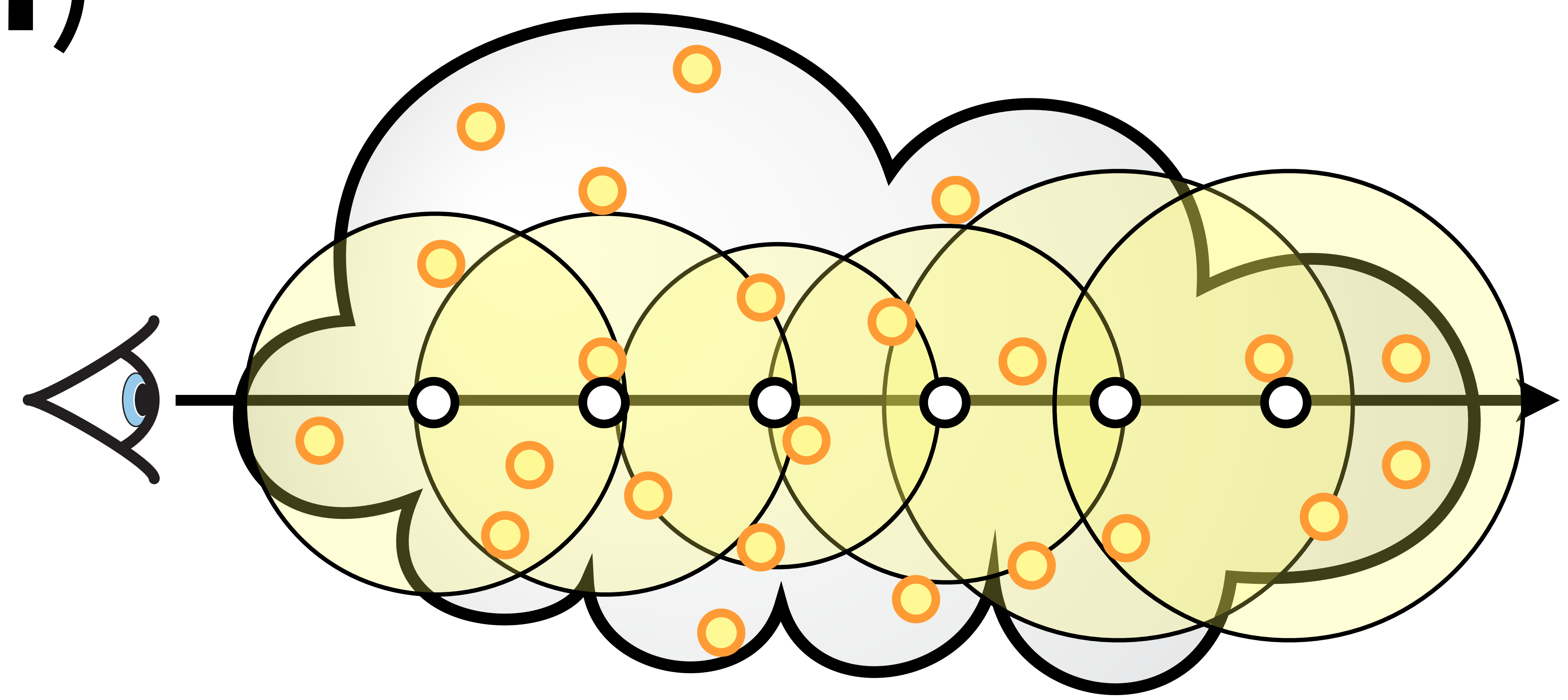


So Far...

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

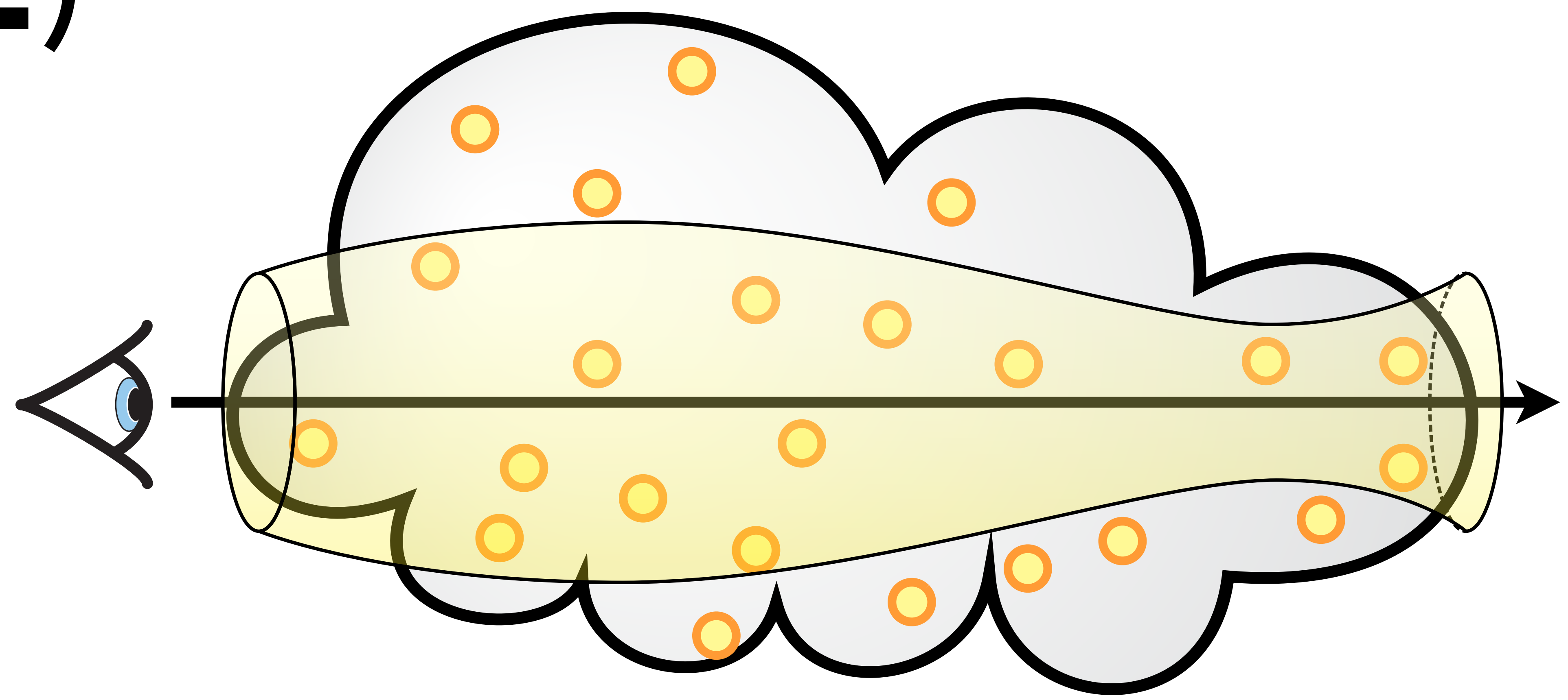
Query	x	Data	Blur
Point	x	Point	(3D)



The Beam Radiance Estimate (**BRE**)

[Jarosz et al. 08]

Query
Beam

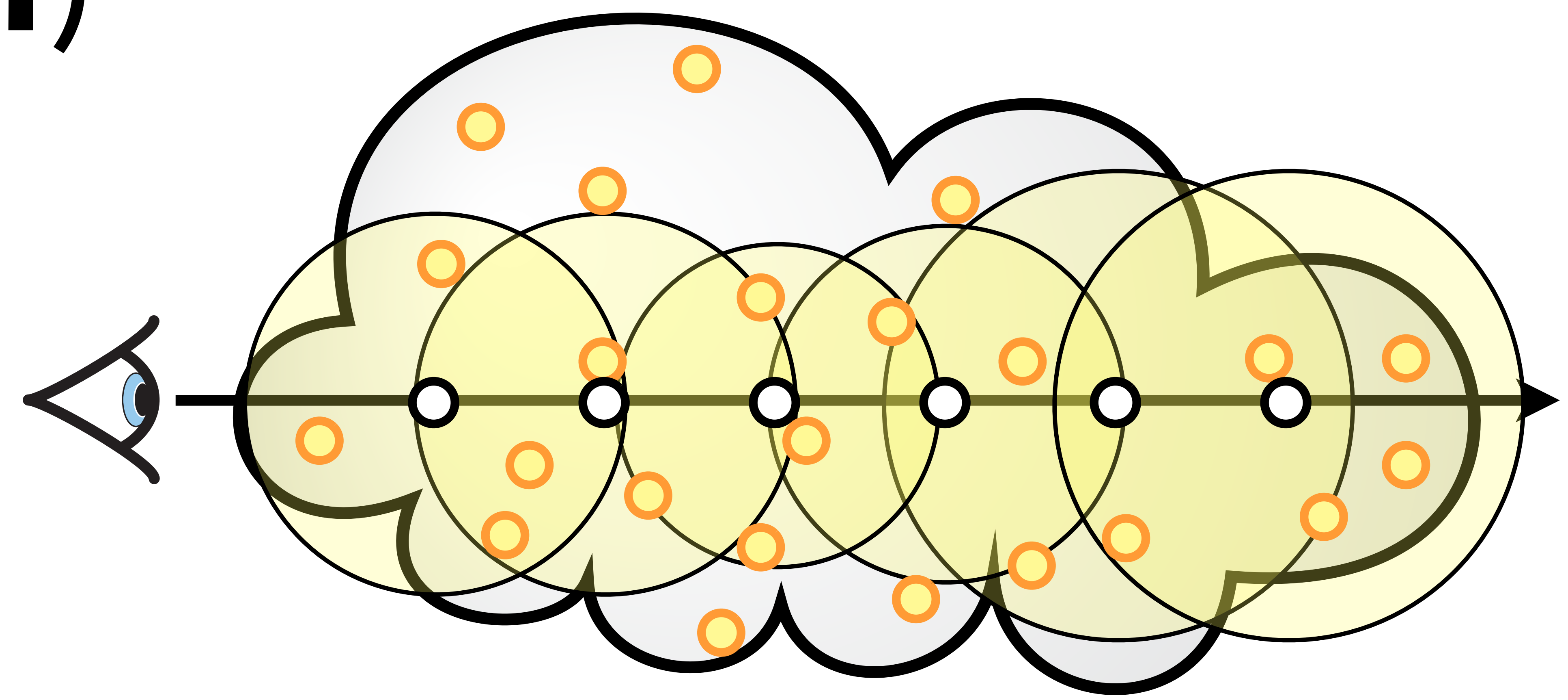


So Far…

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

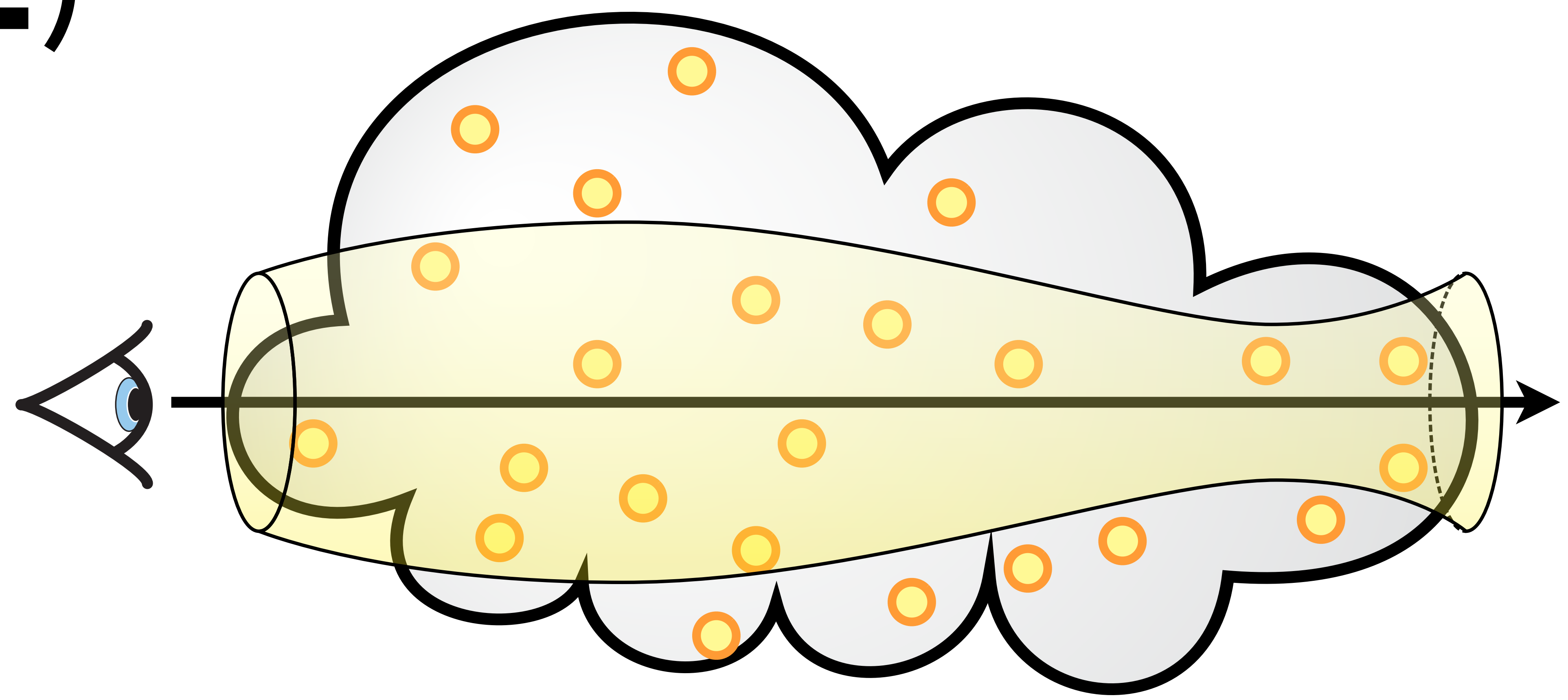
Query	x	Data	Blur
Point	x	Point	(3D)



The Beam Radiance Estimate (**BRE**)

[Jarosz et al. 08]

Query	x	Data
Beam	x	Point

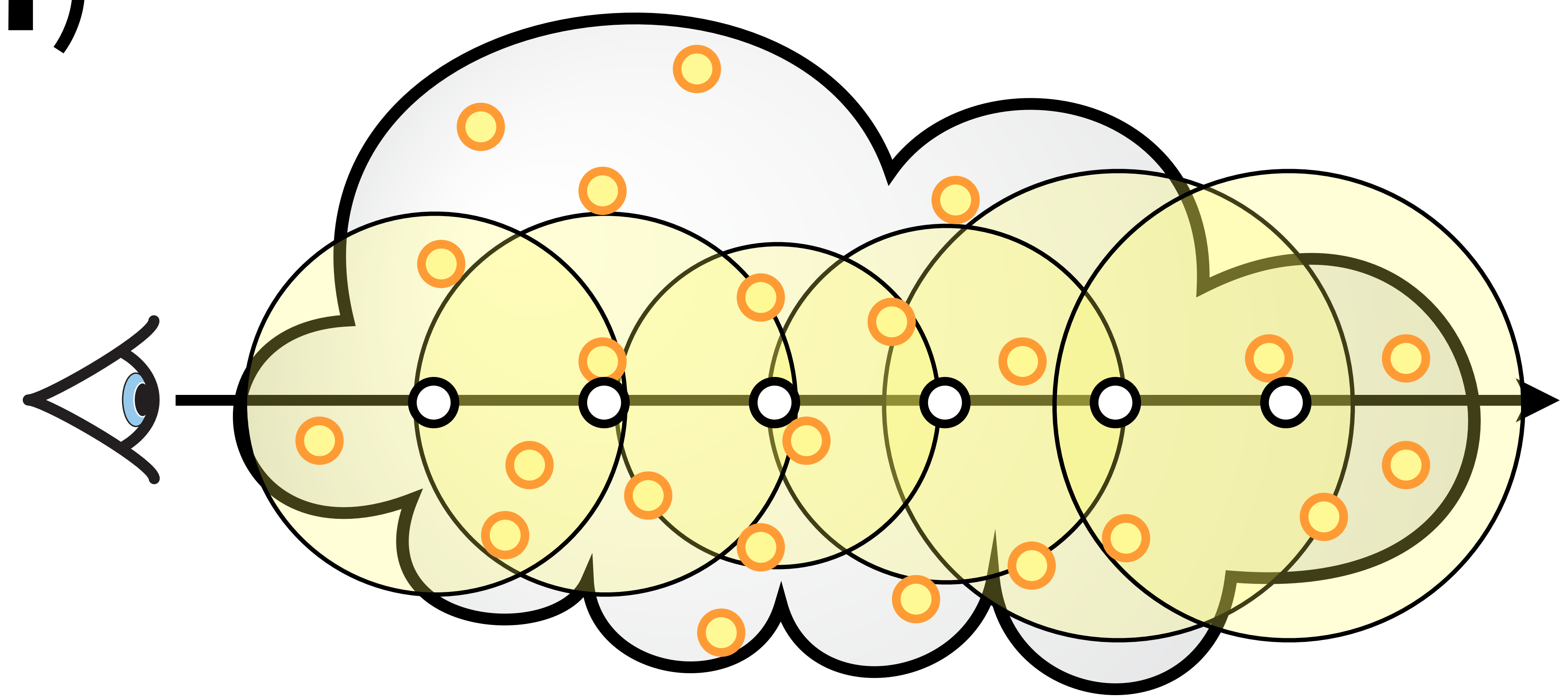


So Far...

Volumetric Photon Mapping (**VPM**)

[Jensen & Christensen 98]

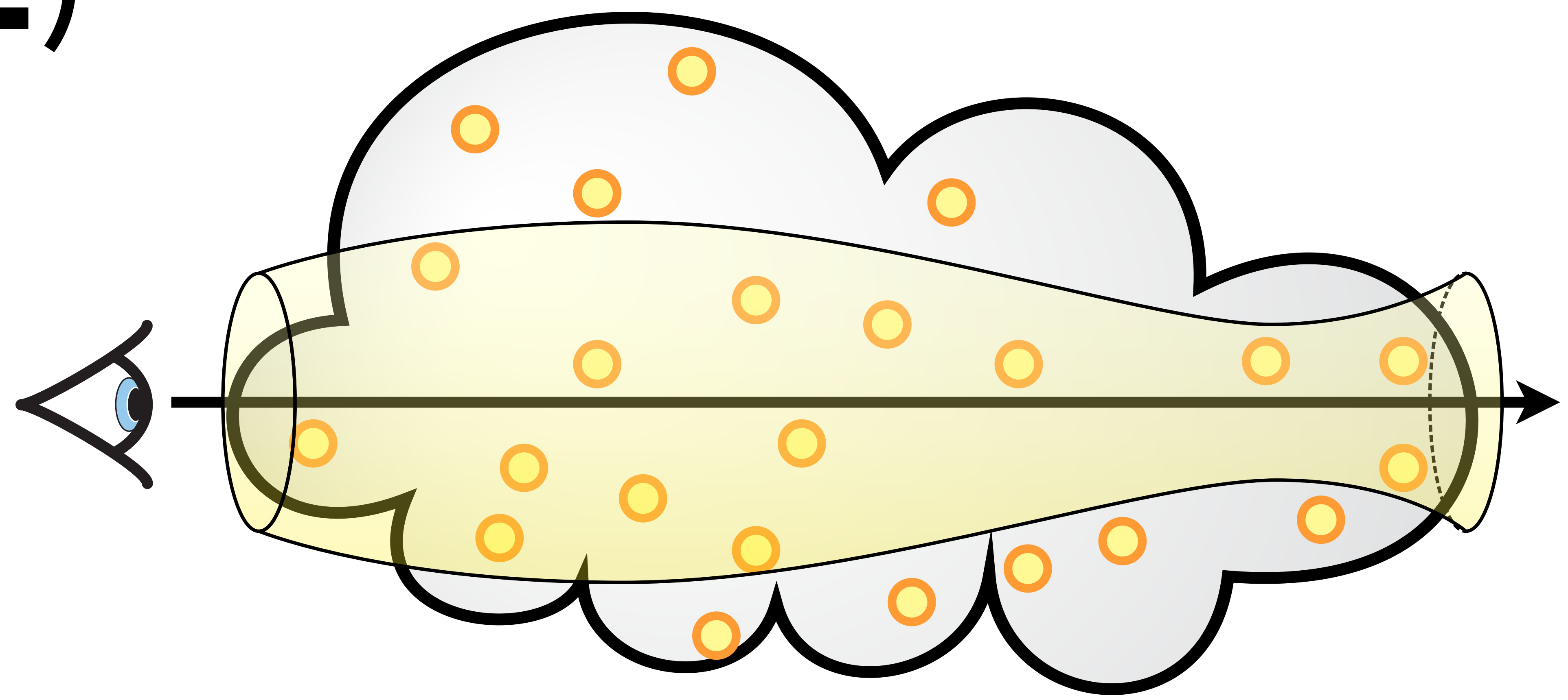
Query	x	Data	Blur
Point	x	Point	(3D)



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)

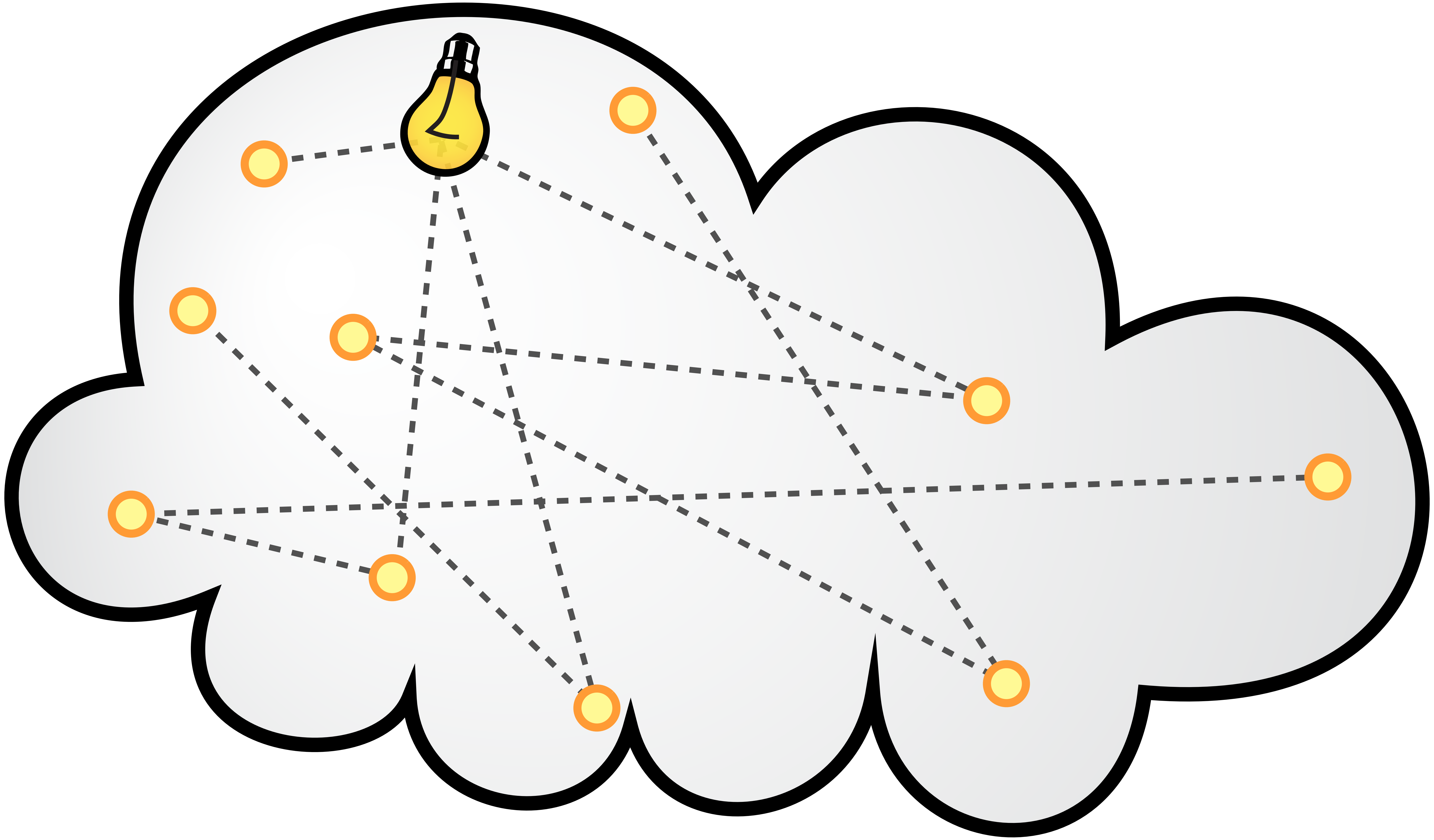
Other possibilities

[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

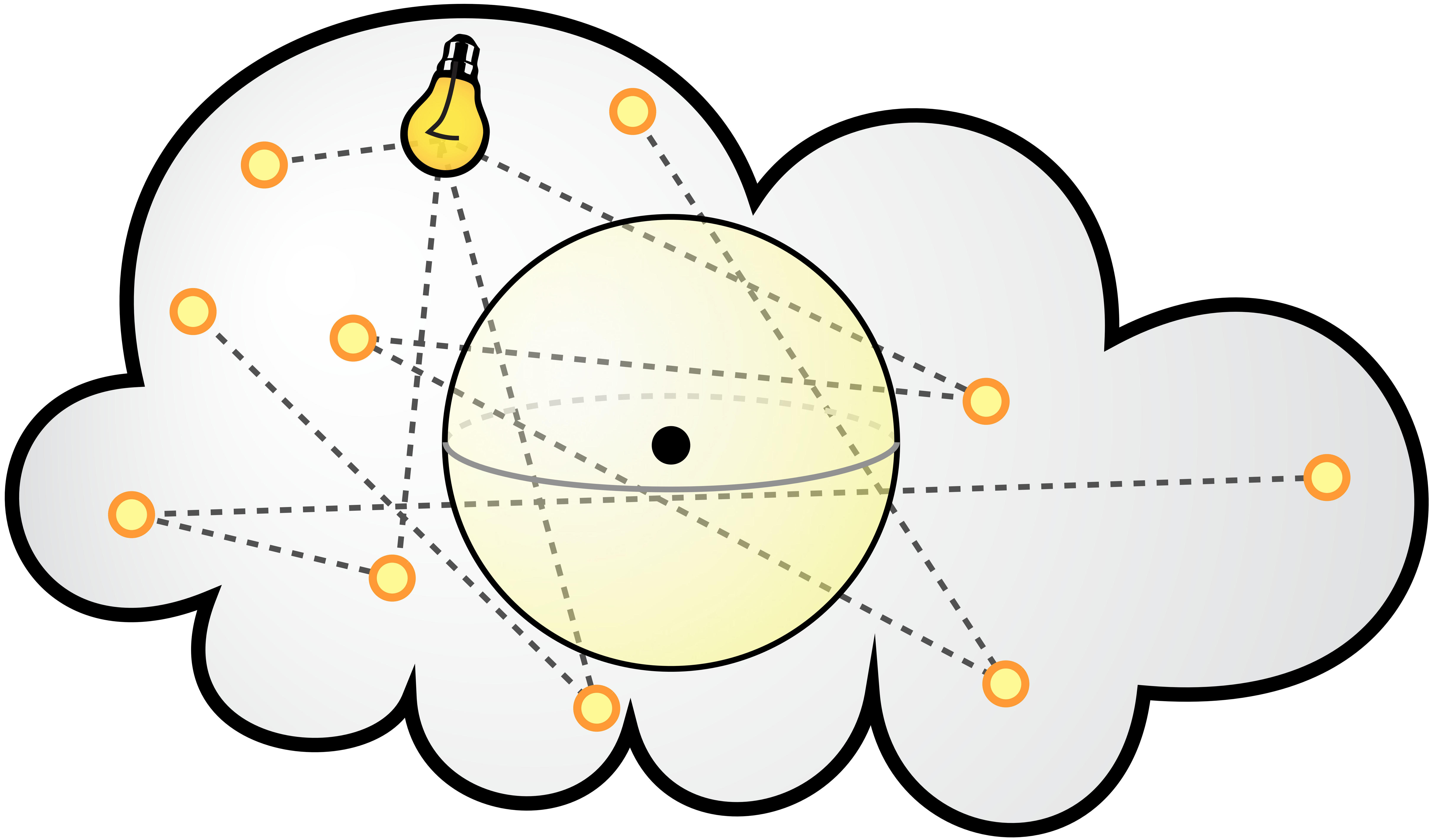
[Jarosz et al. 11]



Photon Points

Volumetric photon mapping

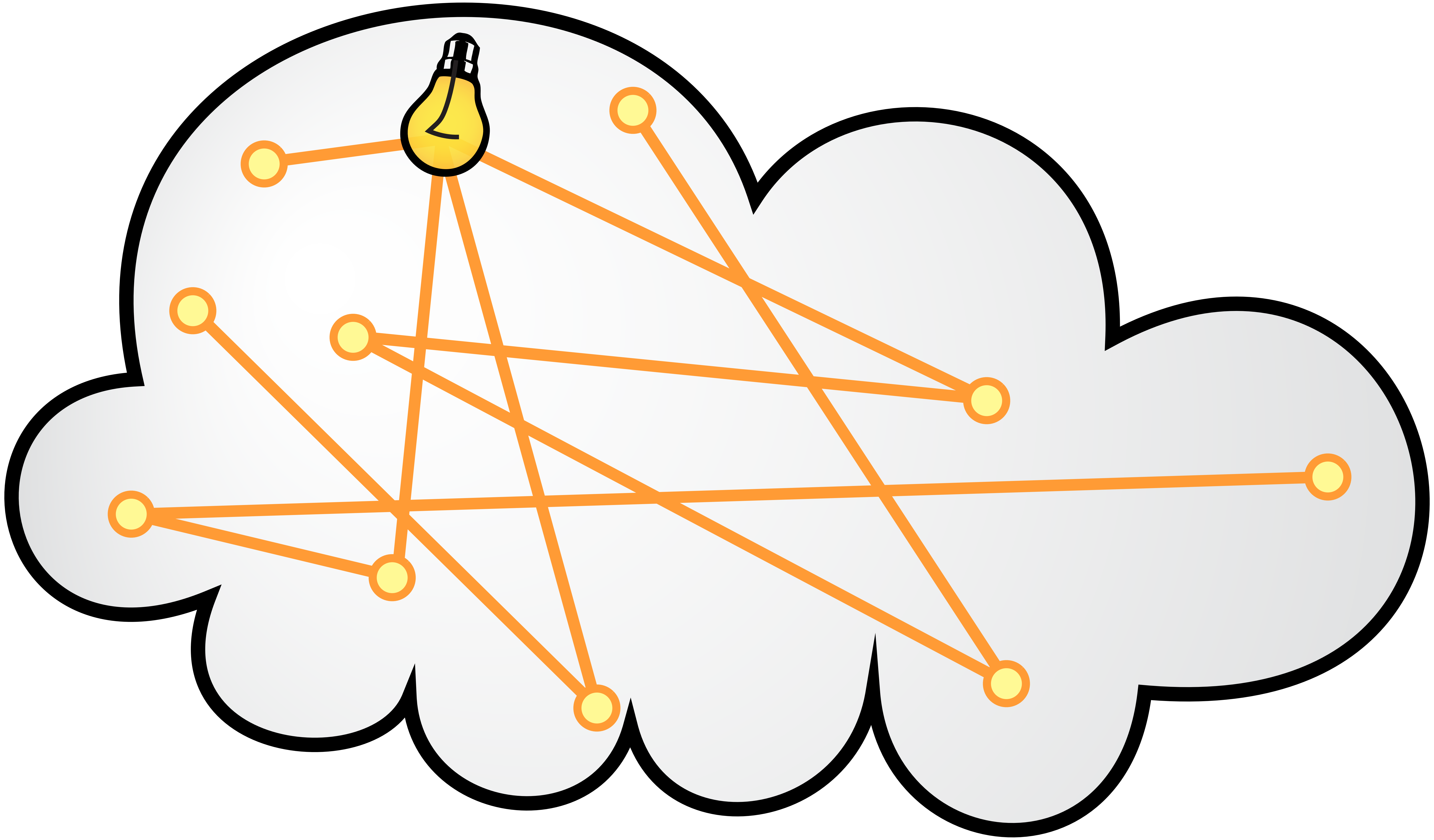
[Jarosz et al. 11]



Photon Points

Volumetric photon mapping

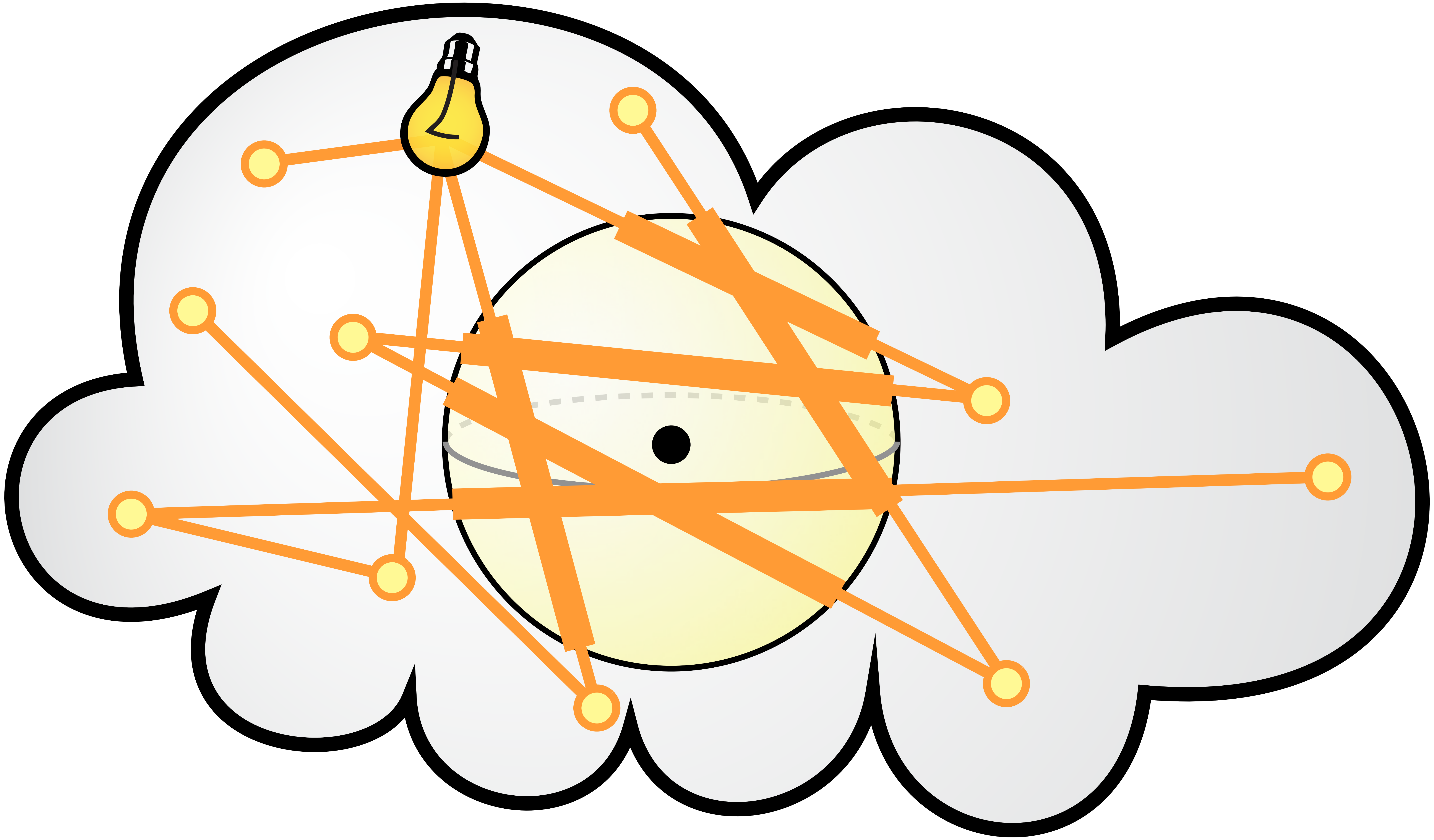
[Jarosz et al. 11]



Photon Beams

Volumetric photon mapping

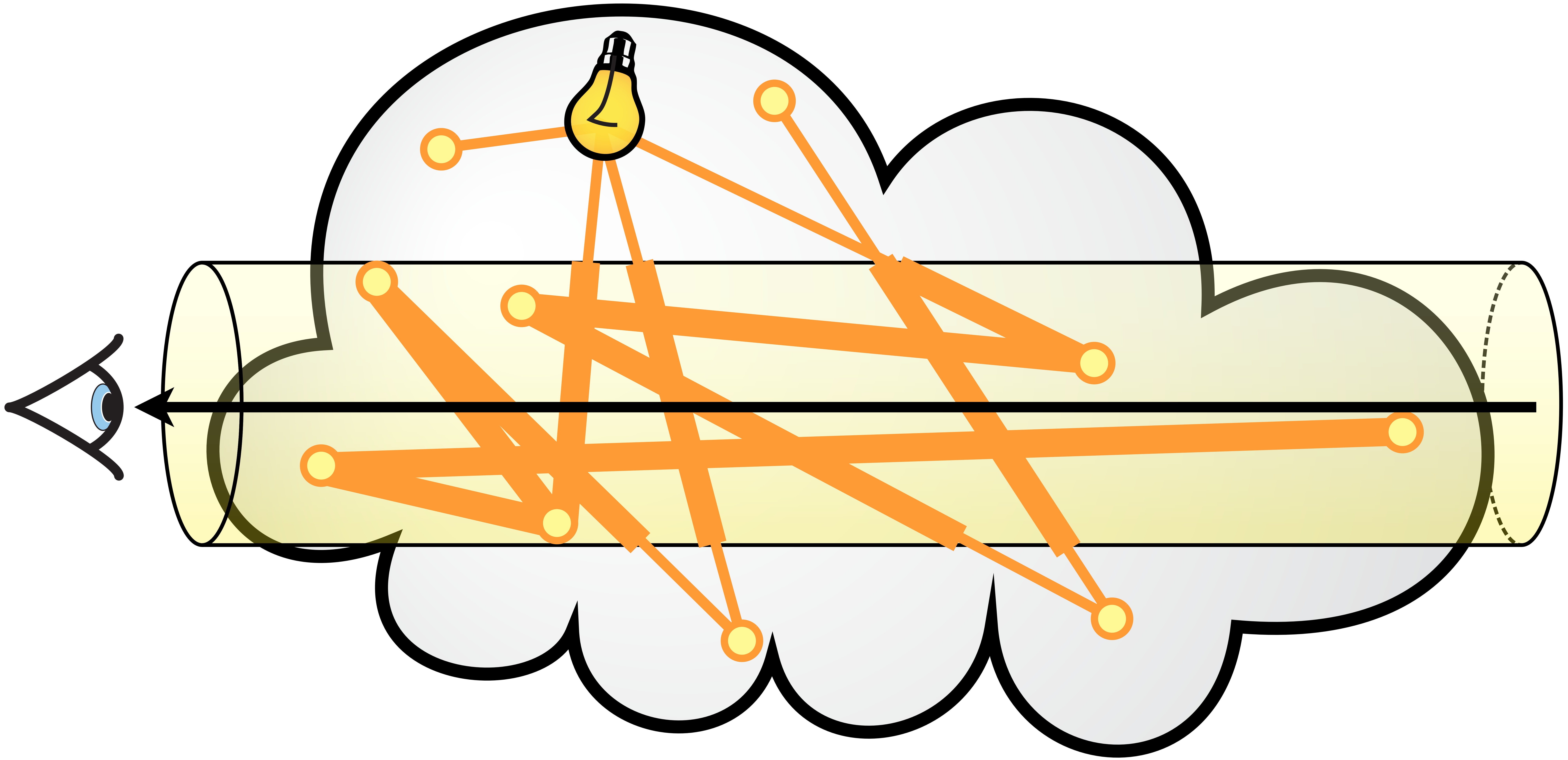
[Jarosz et al. 11]



Photon Beams **x** Point Query

Volumetric photon mapping

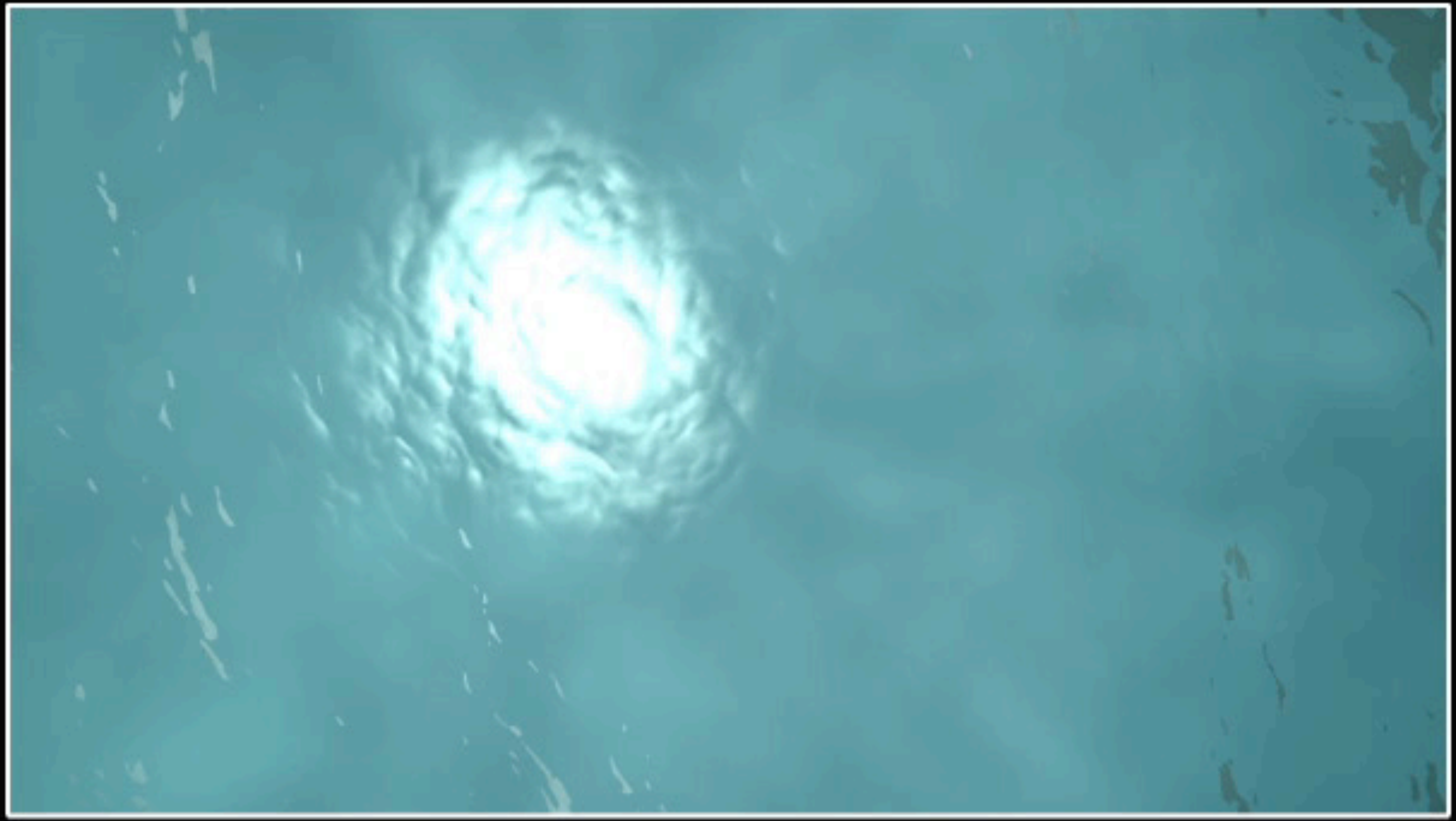
[Jarosz et al. 11]



Photon Beams x Beam Query

Underwater Sun Beams

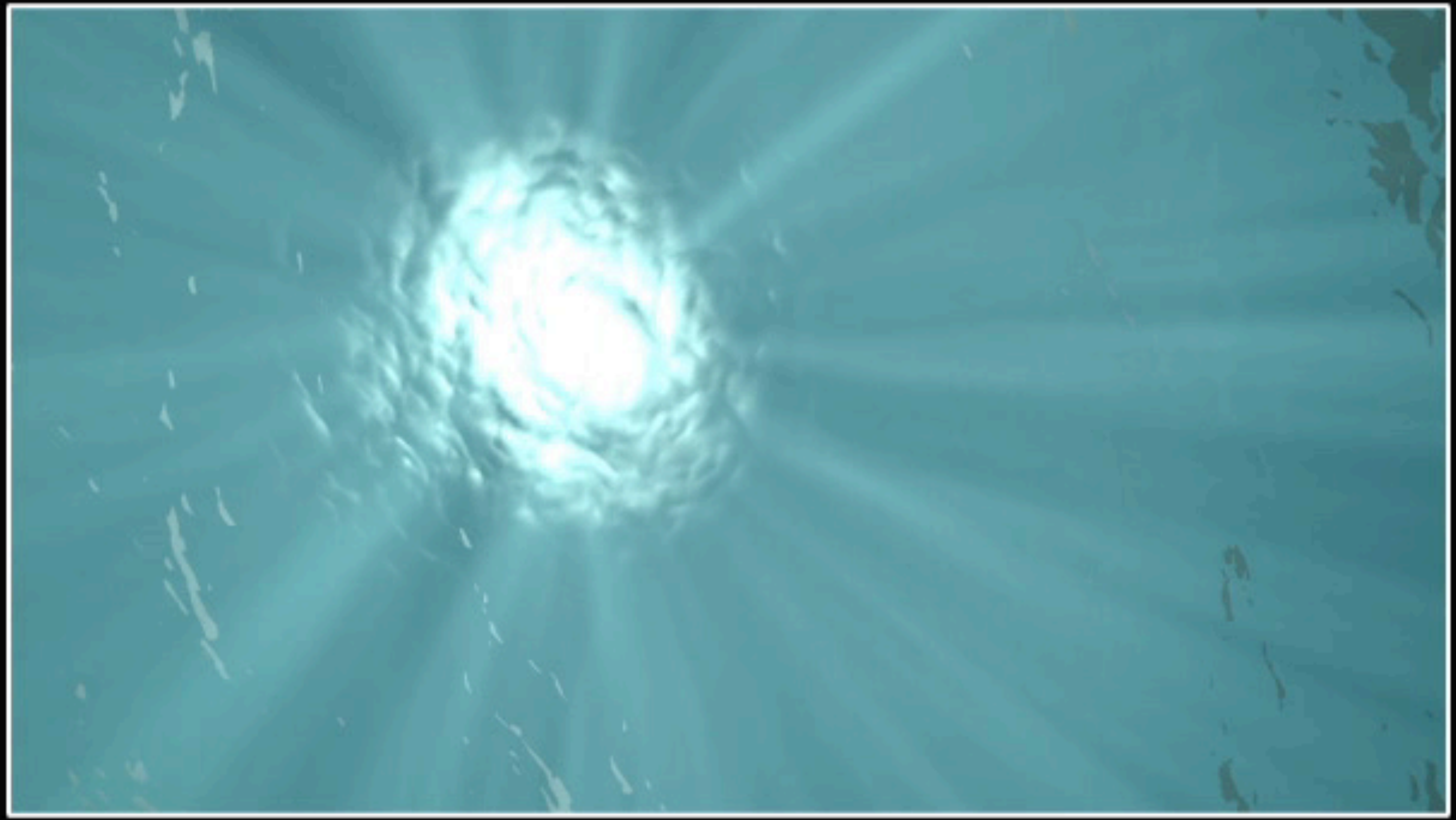
Photon Points



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

Roughly Equal Time

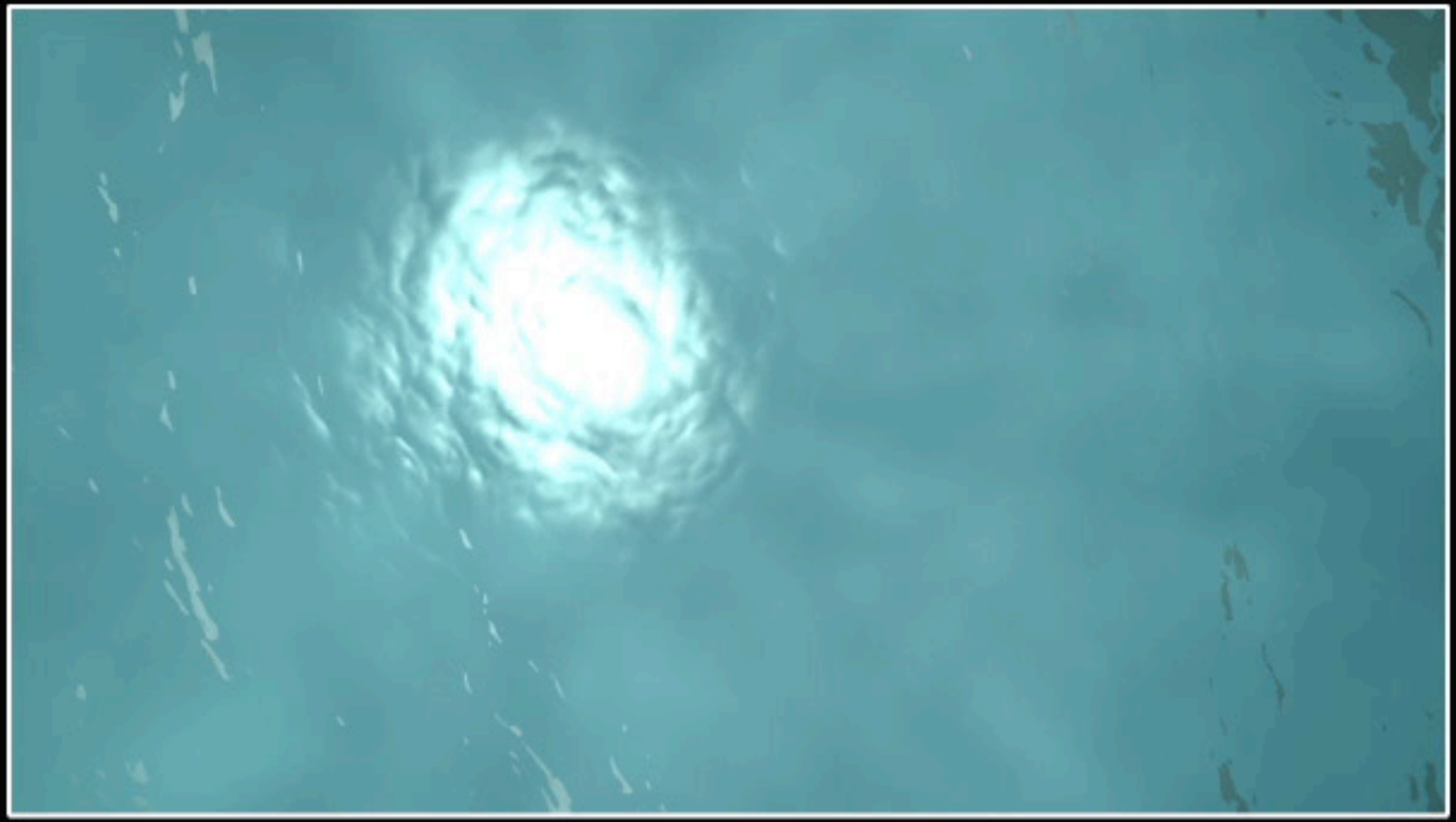
Photon Beams



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

Underwater Sun Beams

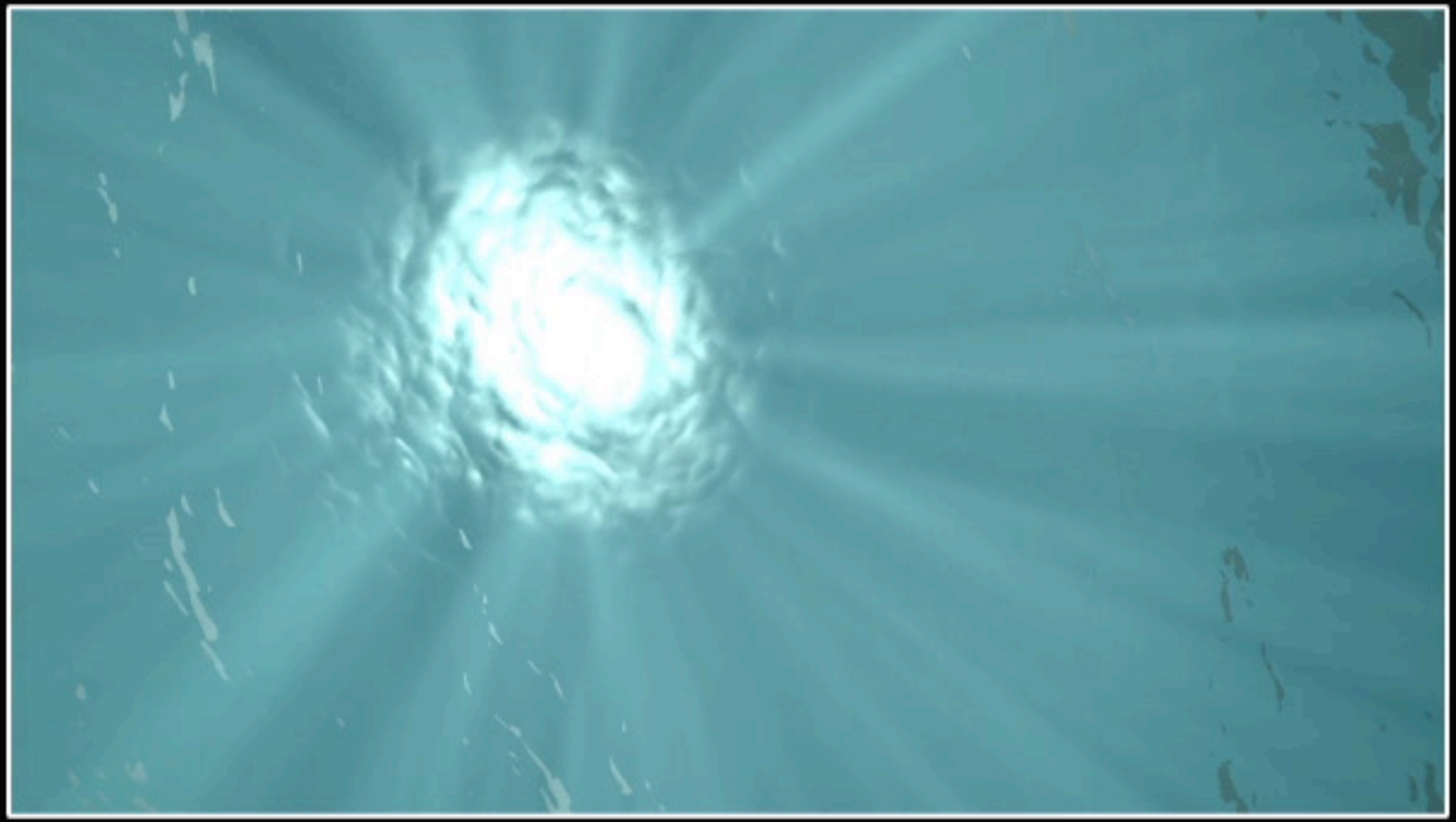
Photon Points



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

Roughly Equal Time

Photon Beams

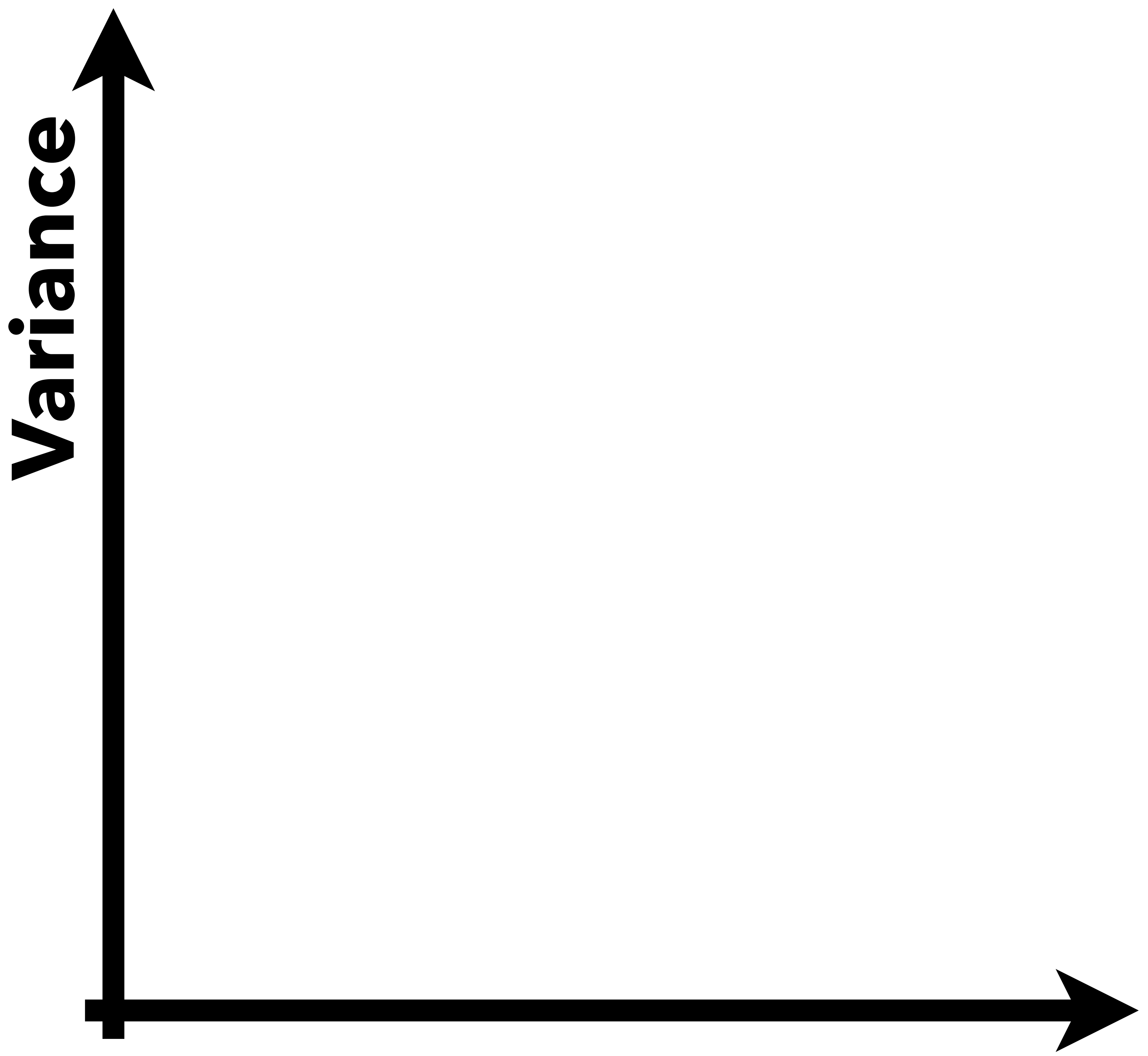


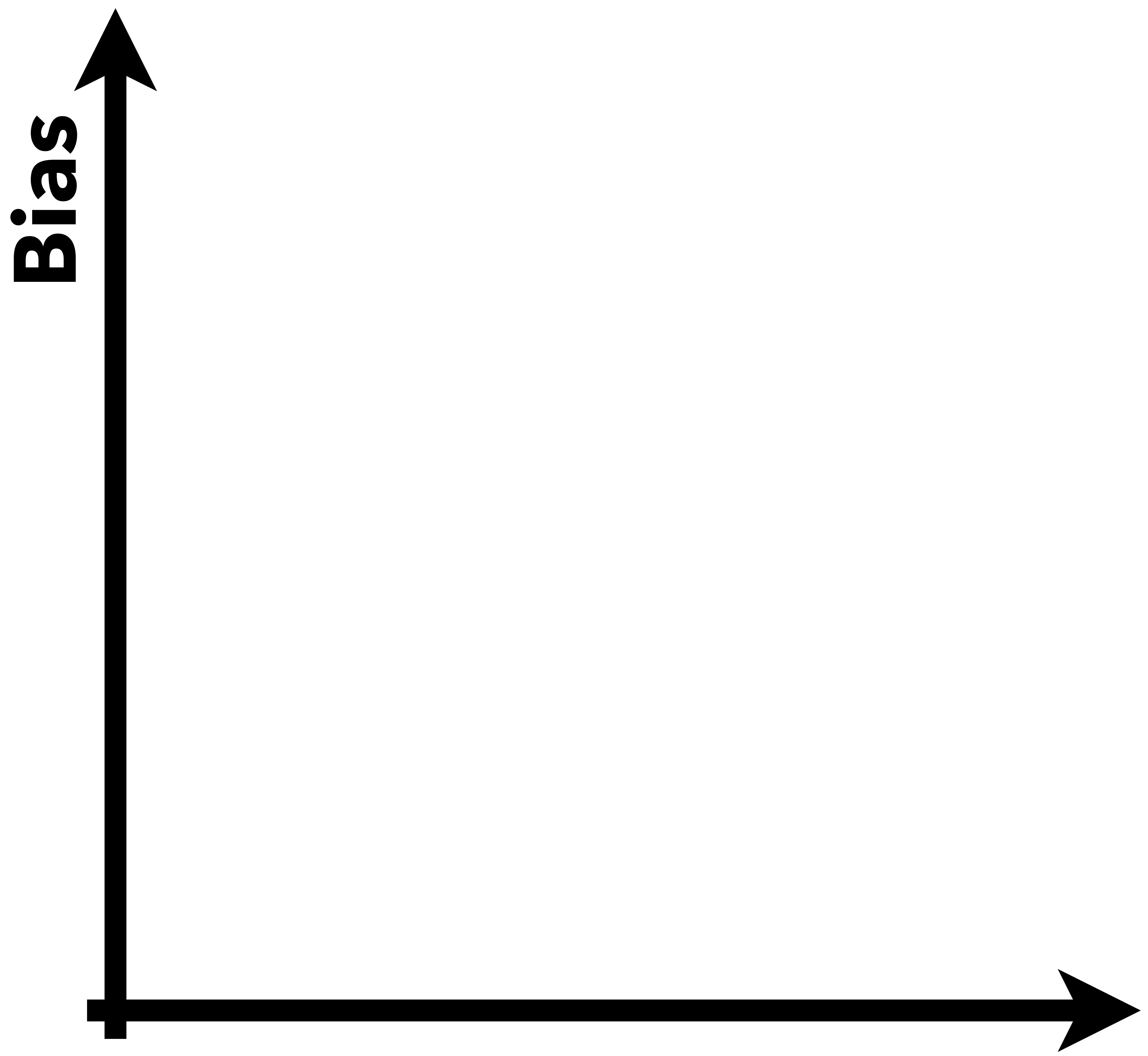
25K Photon **Beams**
~ 200 seconds/frame


[Jarosz et al. 11b]

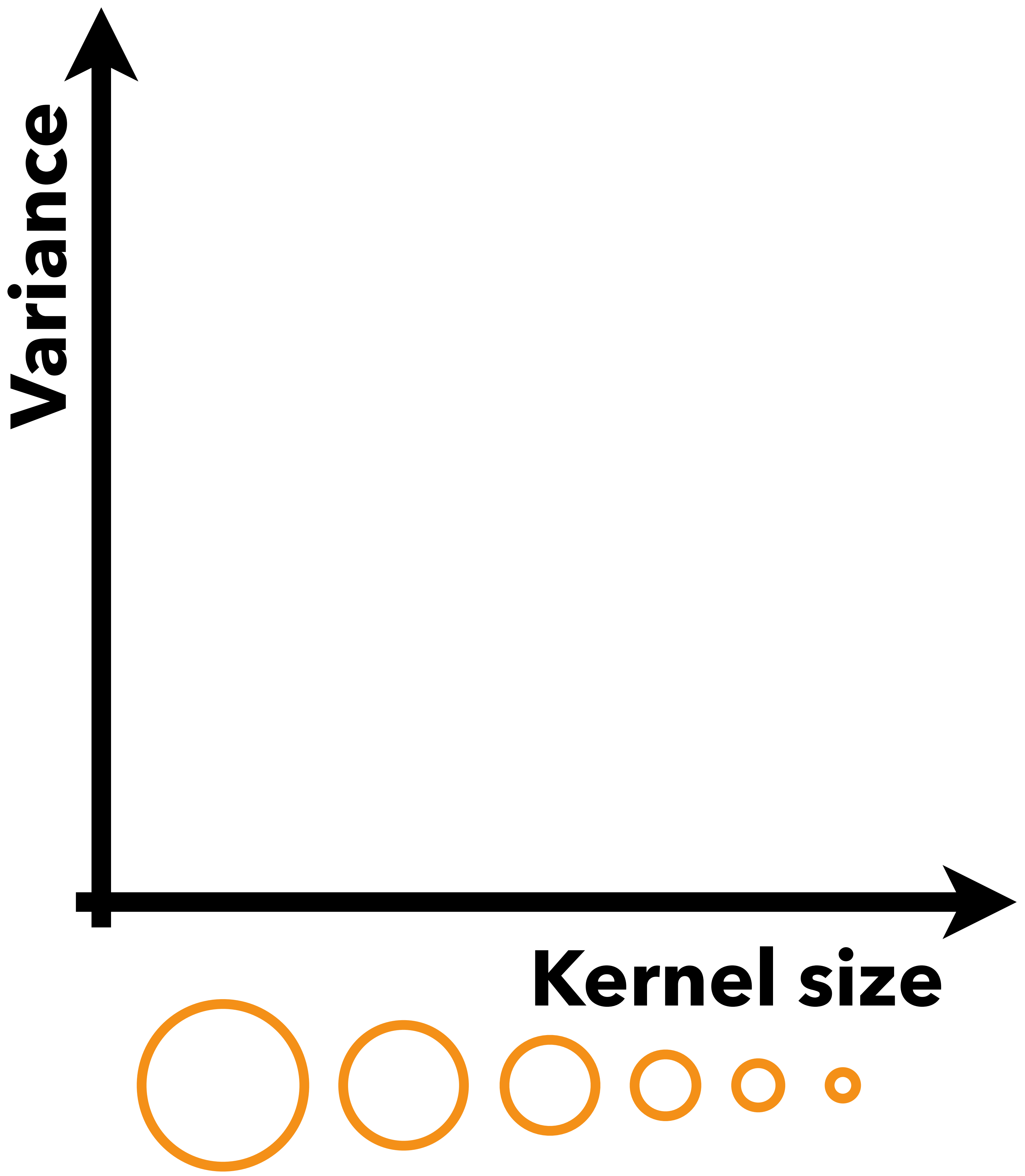

[Jarosz et al. 11b]

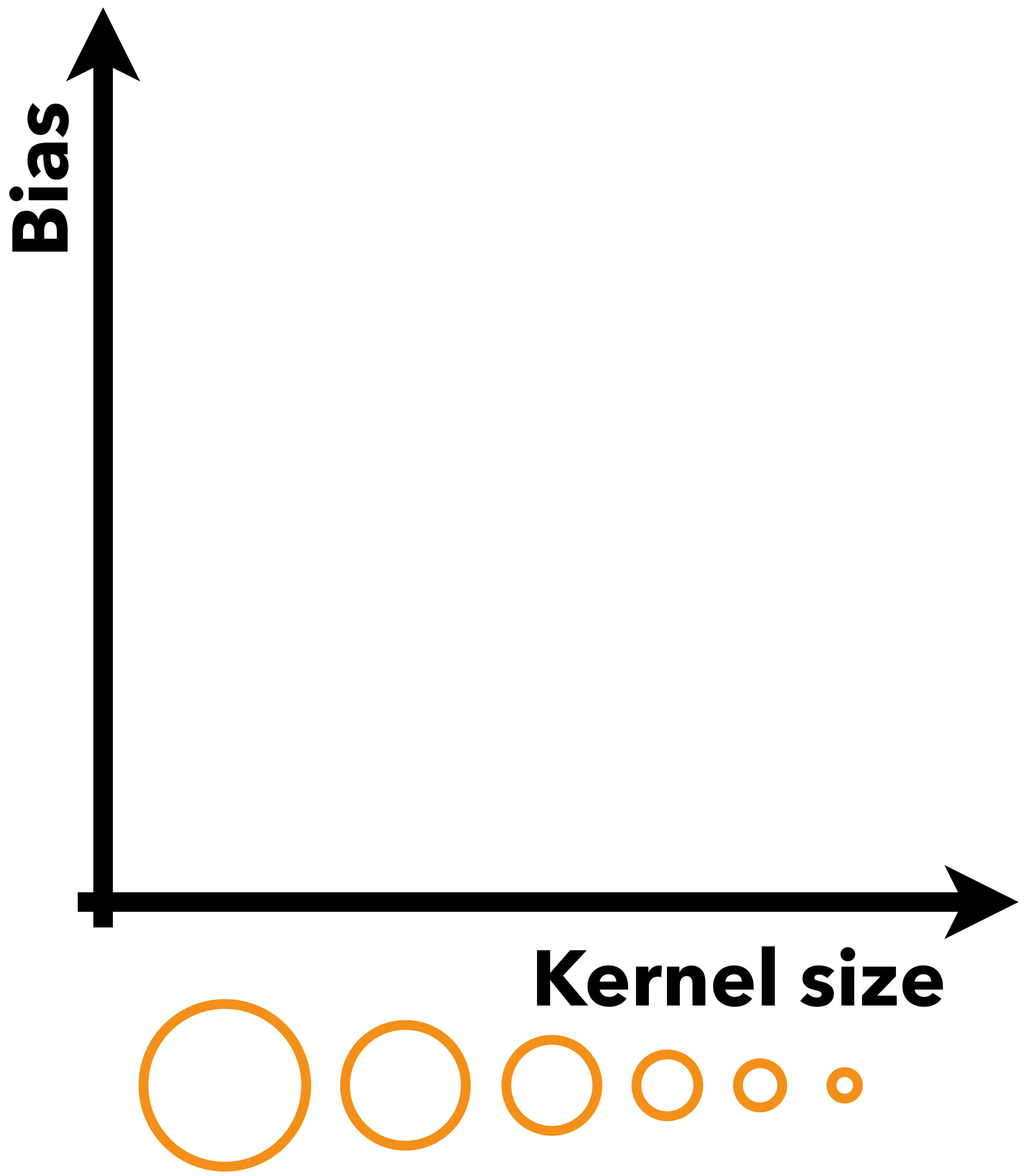
Convergence of Progressive Photon mapping



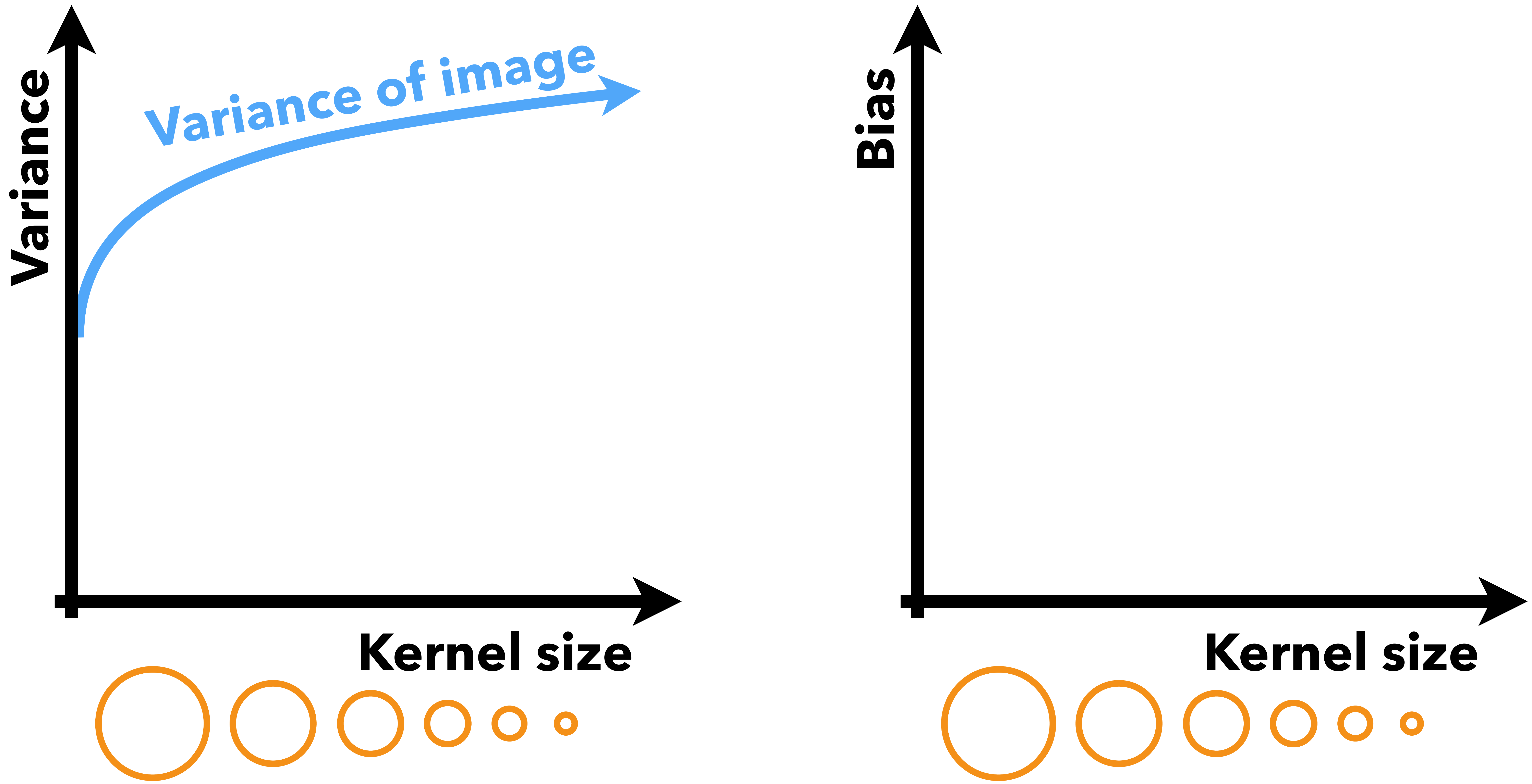


Convergence of Progressive Photon mapping

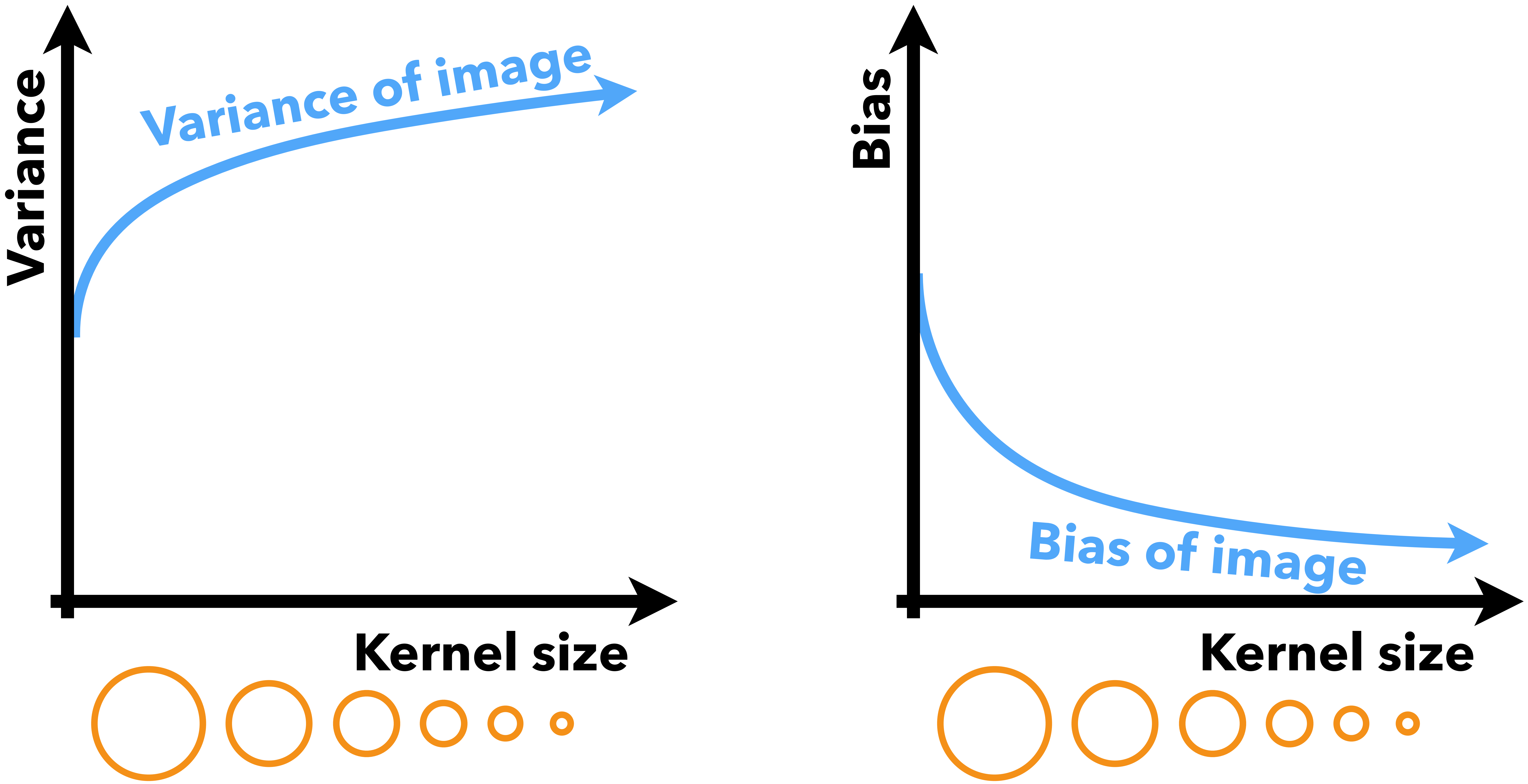




Convergence of Progressive Photon mapping

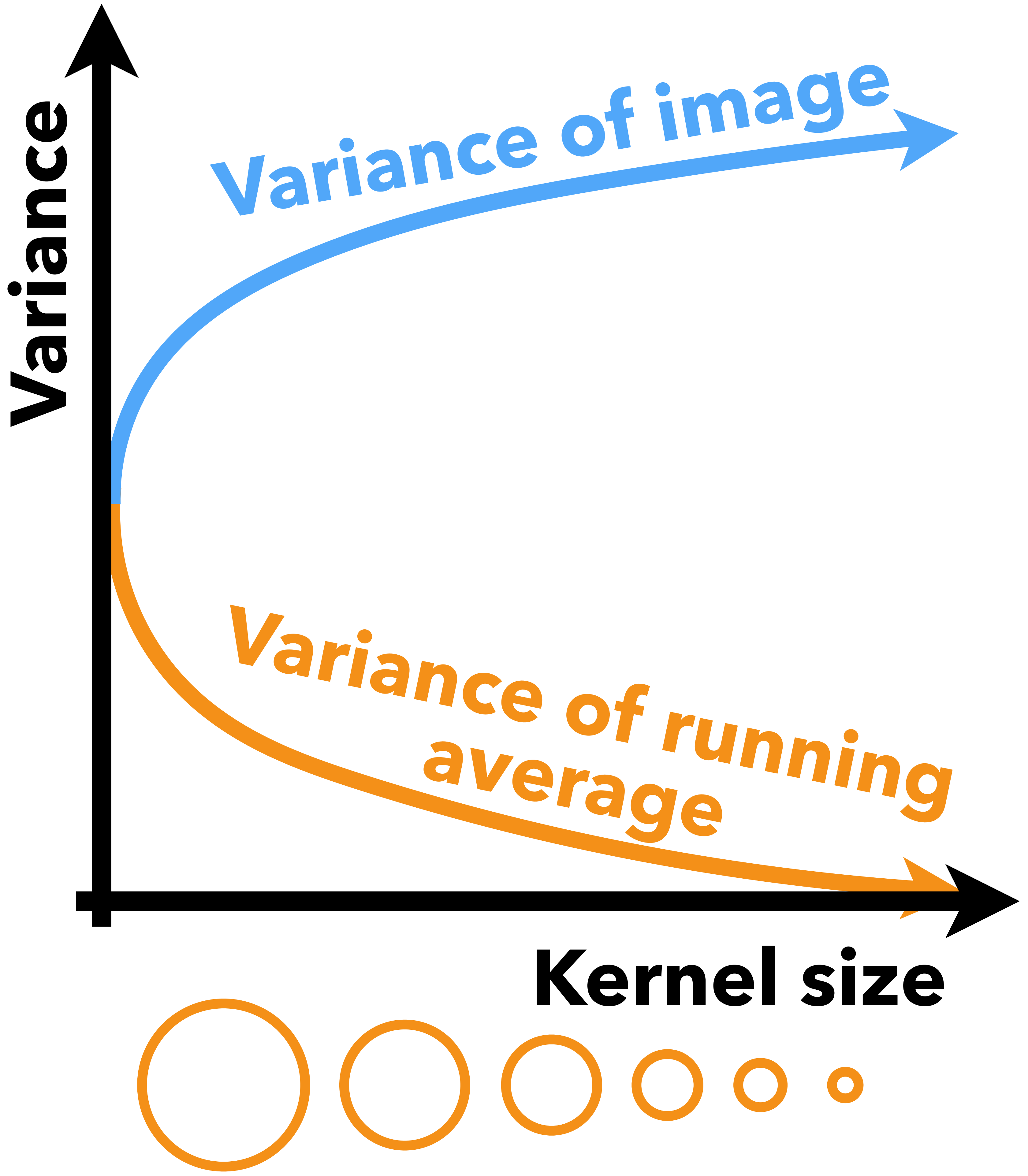


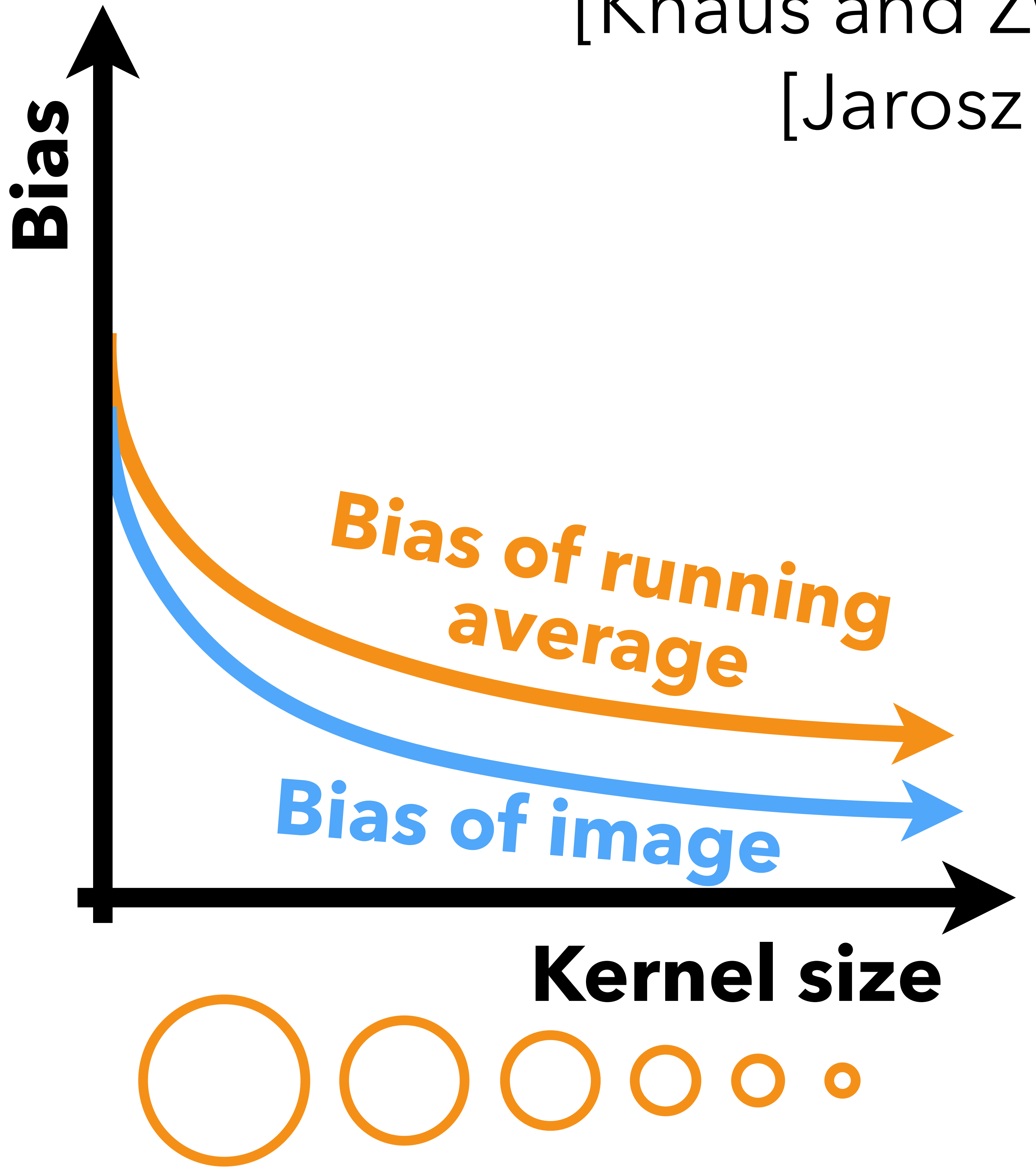
Convergence of Progressive Photon mapping



Convergence of Progressive Photon mapping

[Hachisuka and Jensen 09]
[Knaus and Zwicker 11]
[Jarosz et al. 11b]



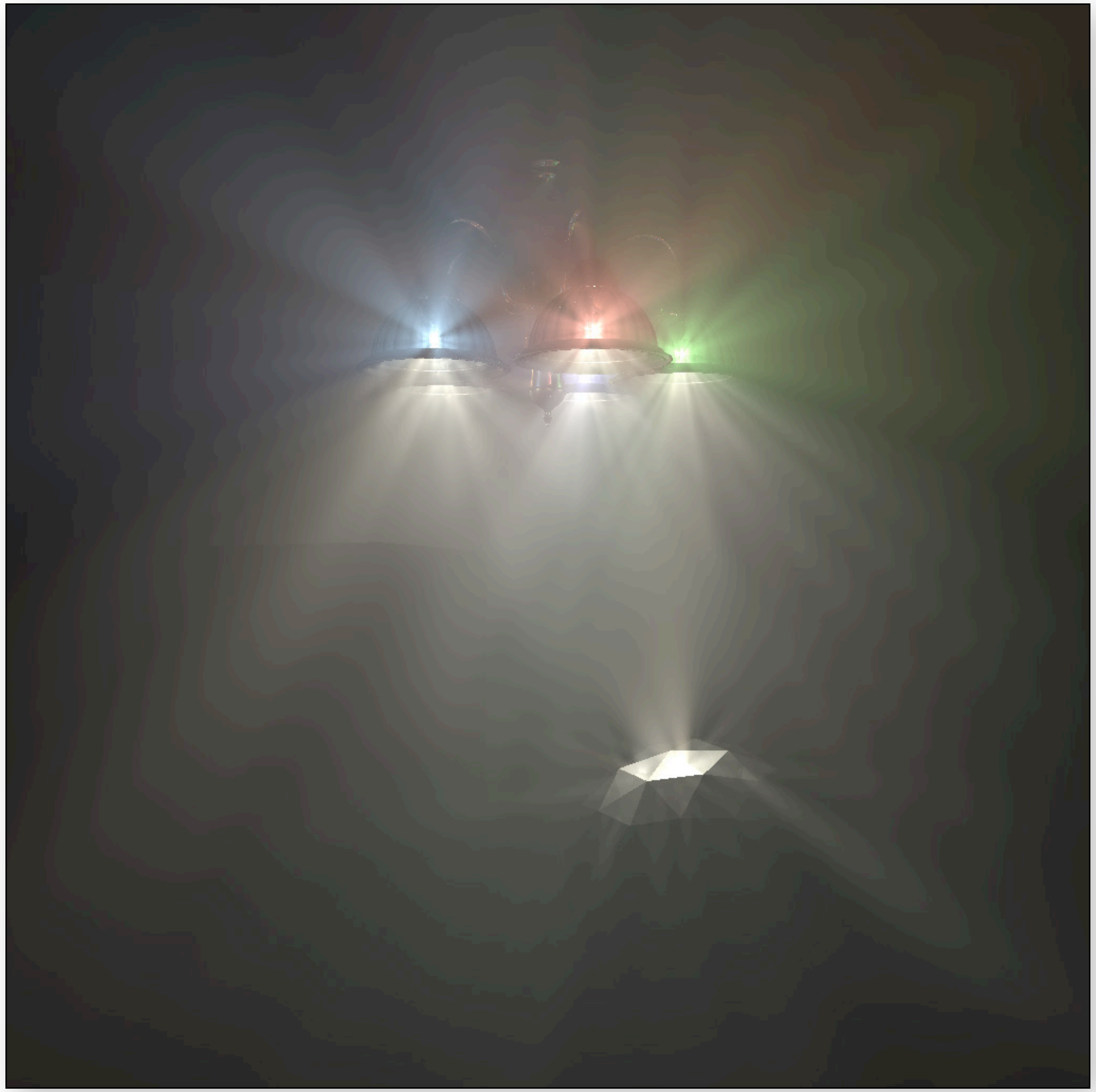


Progressive Photon Beams

[Jarosz et al. 11b]

Progressive Photon Beams

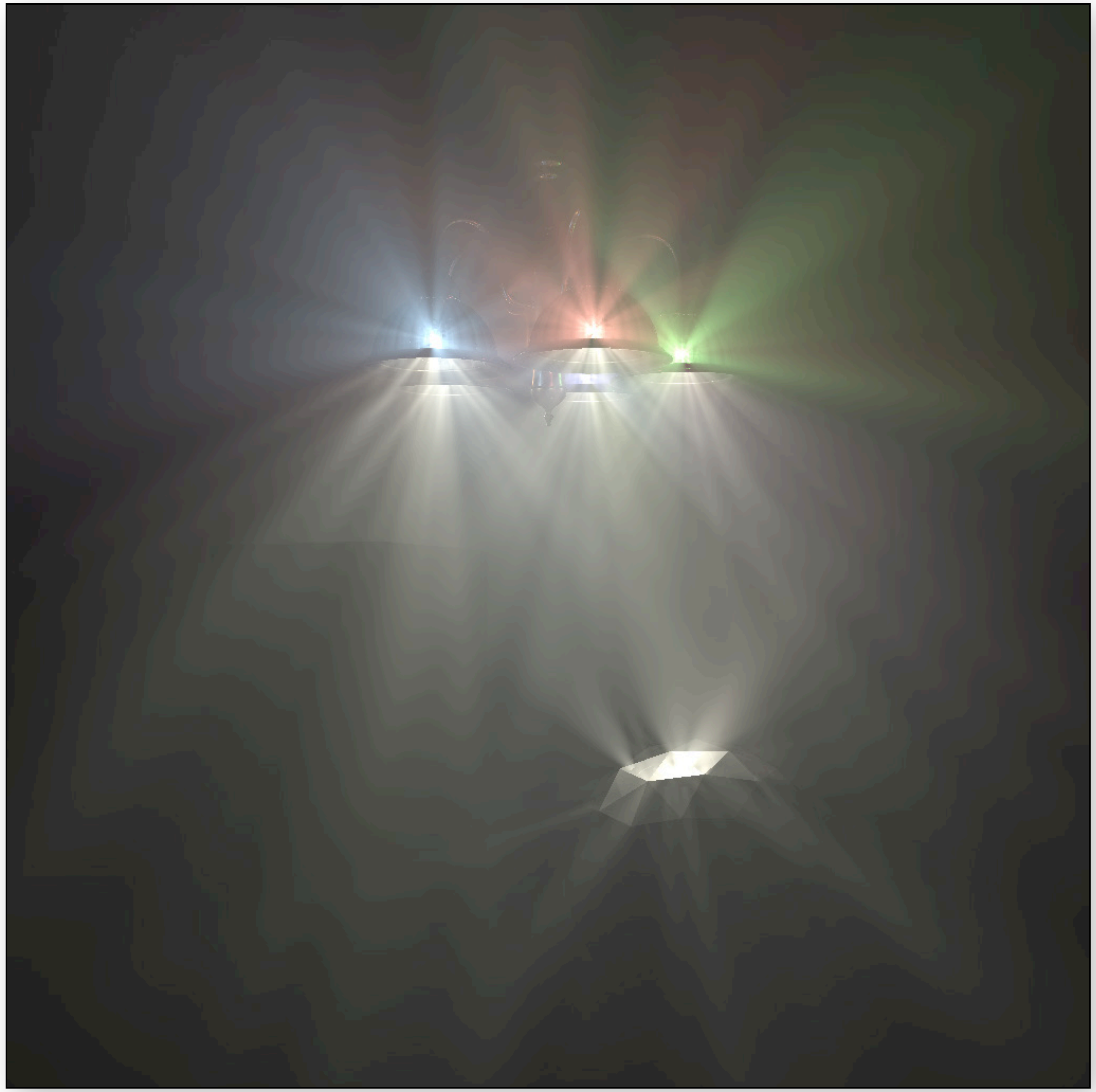
[Jarosz et al. 11b]



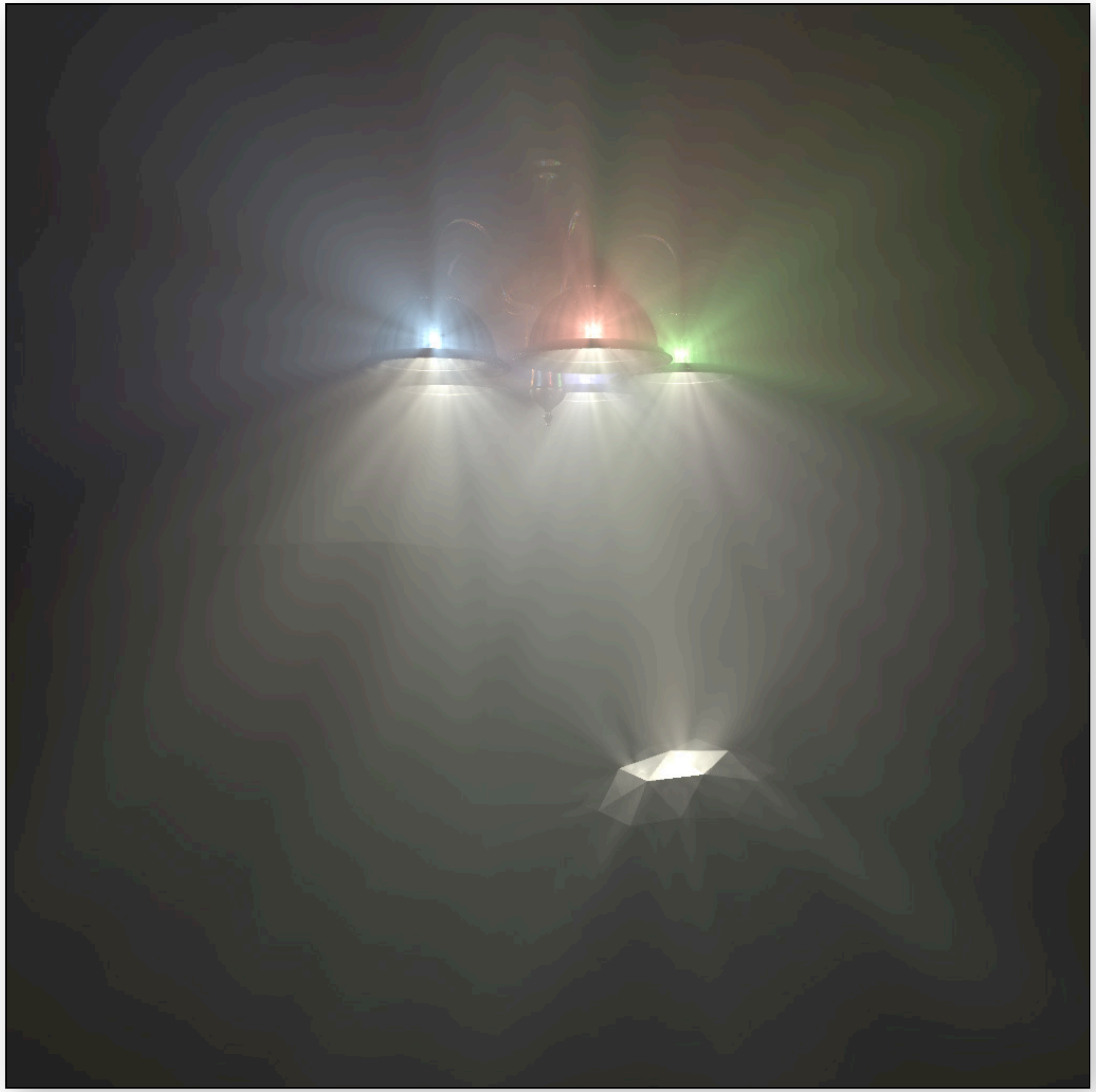
Pass 1

Progressive Photon Beams

[Jarosz et al. 11b]



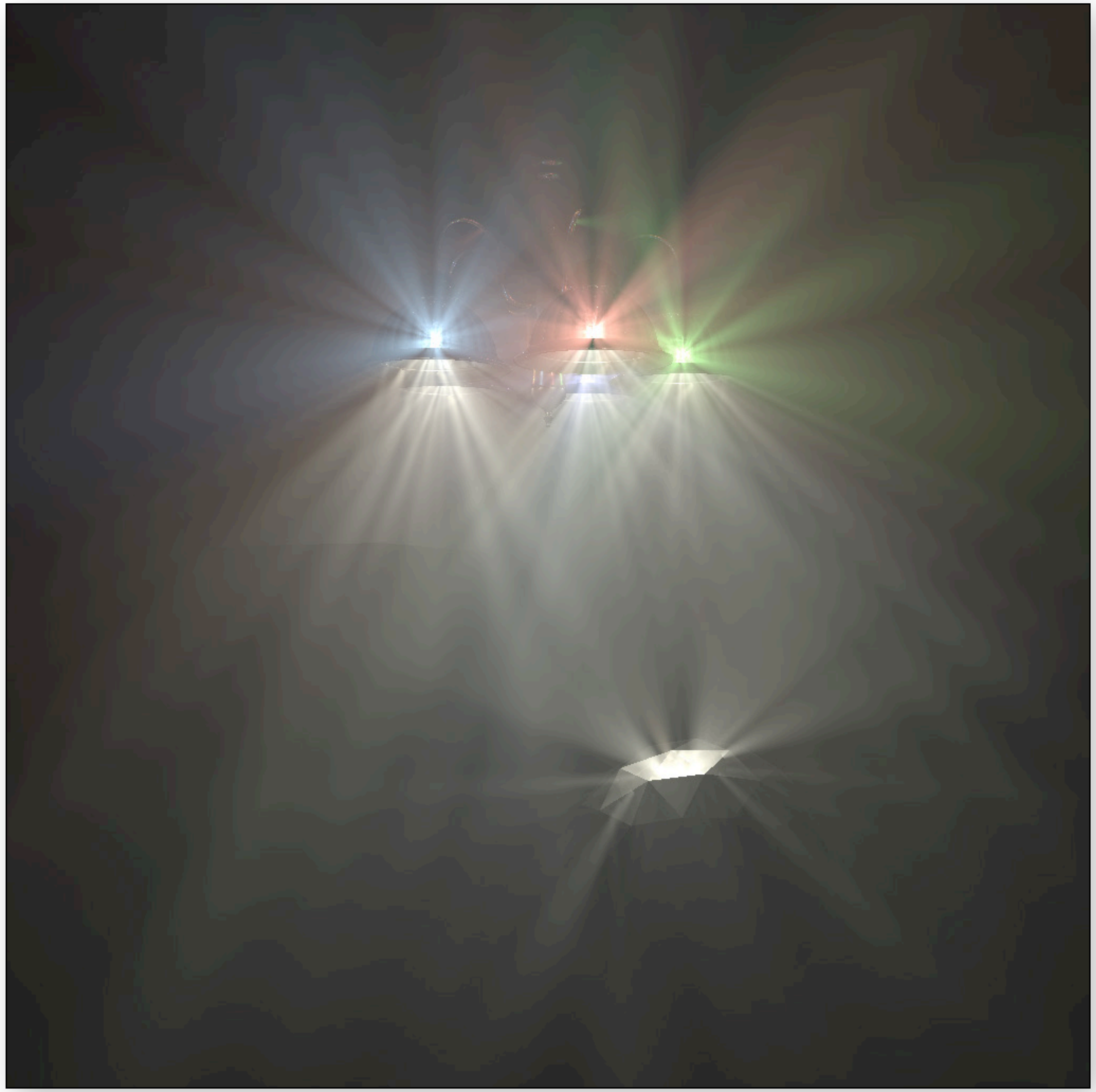
Pass 2



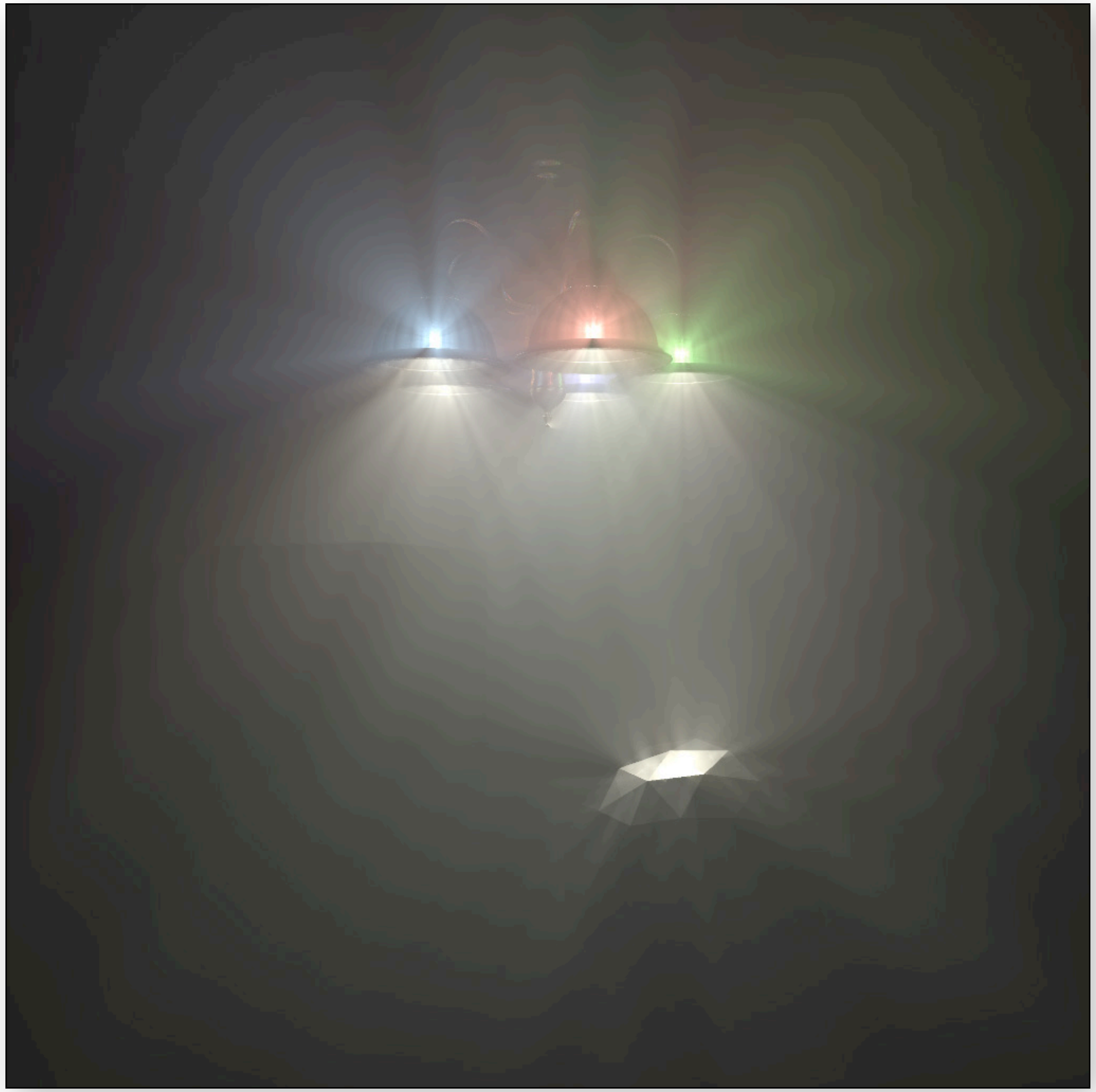
Average of Passes 1..2

Progressive Photon Beams

[Jarosz et al. 11b]



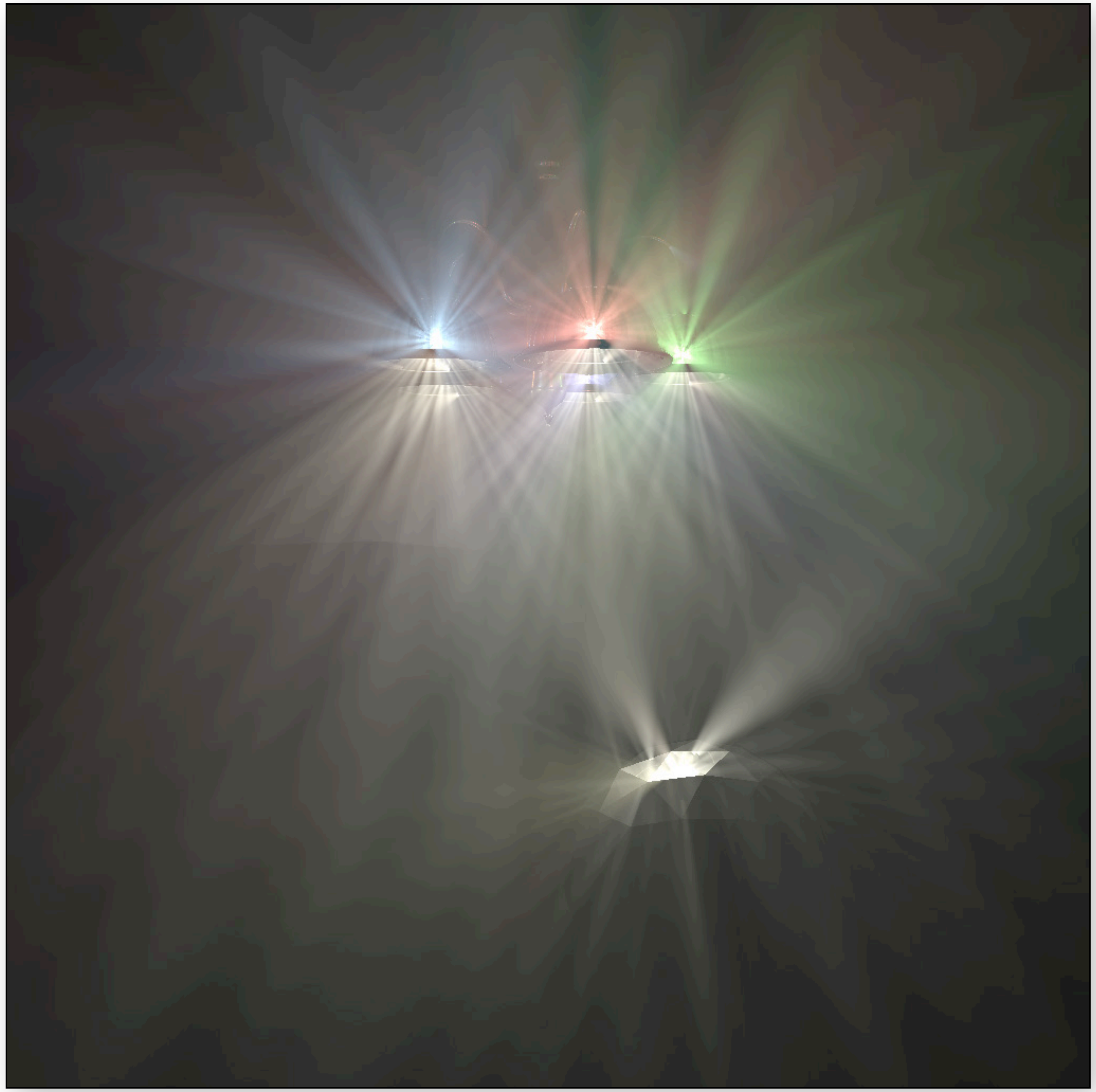
Pass 4



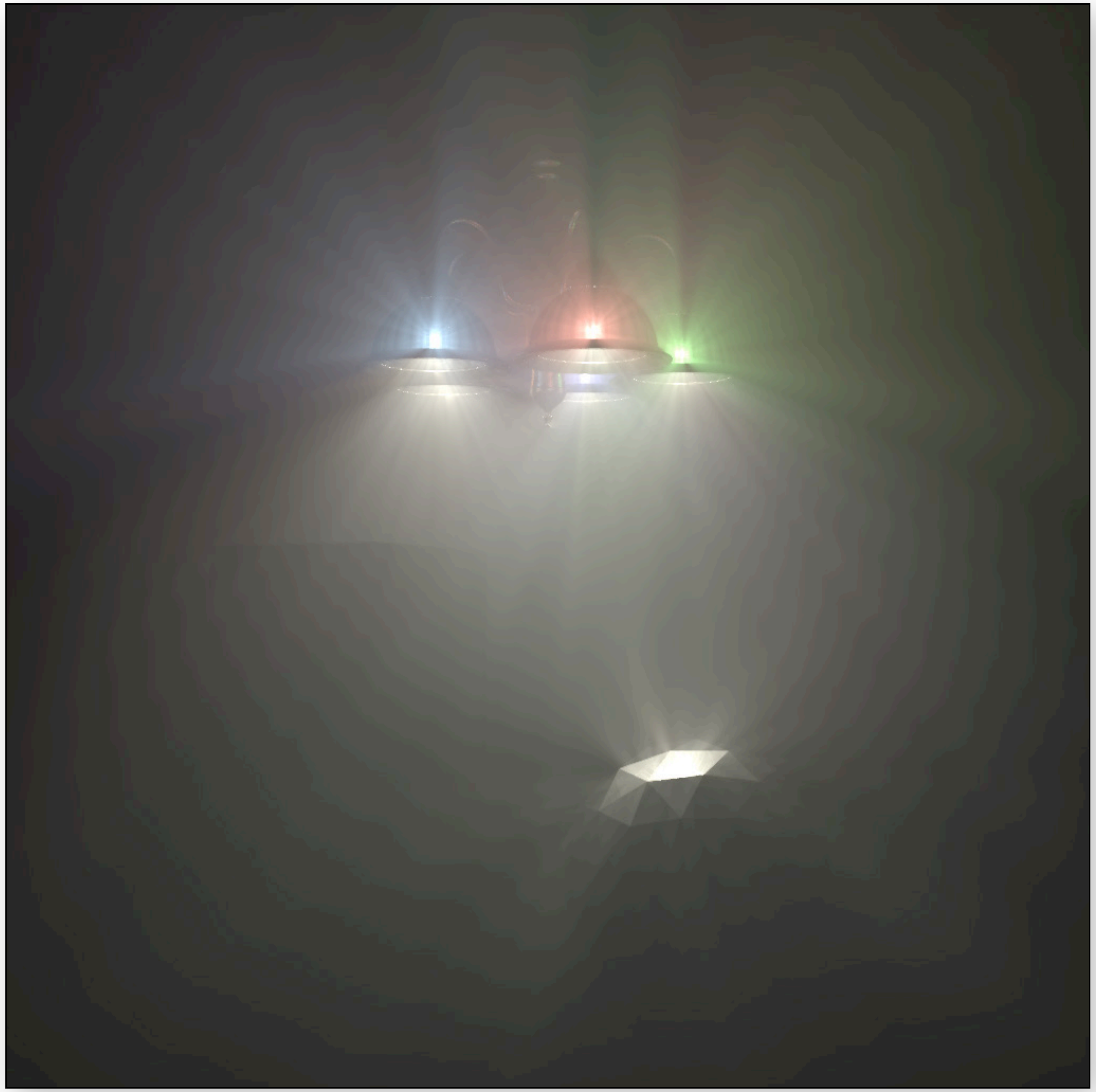
Average of Passes 1..4

Progressive Photon Beams

[Jarosz et al. 11b]



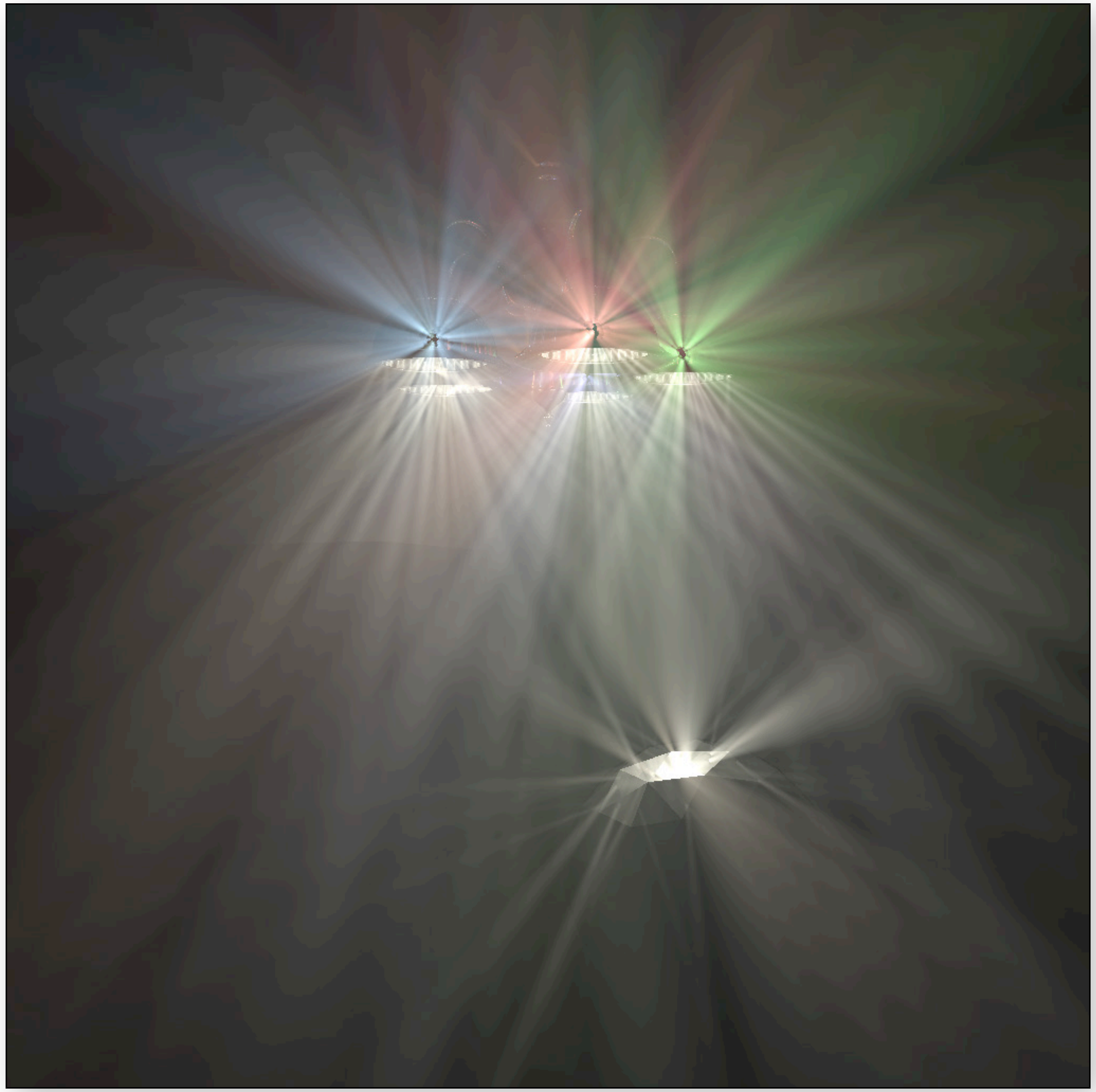
Pass 8



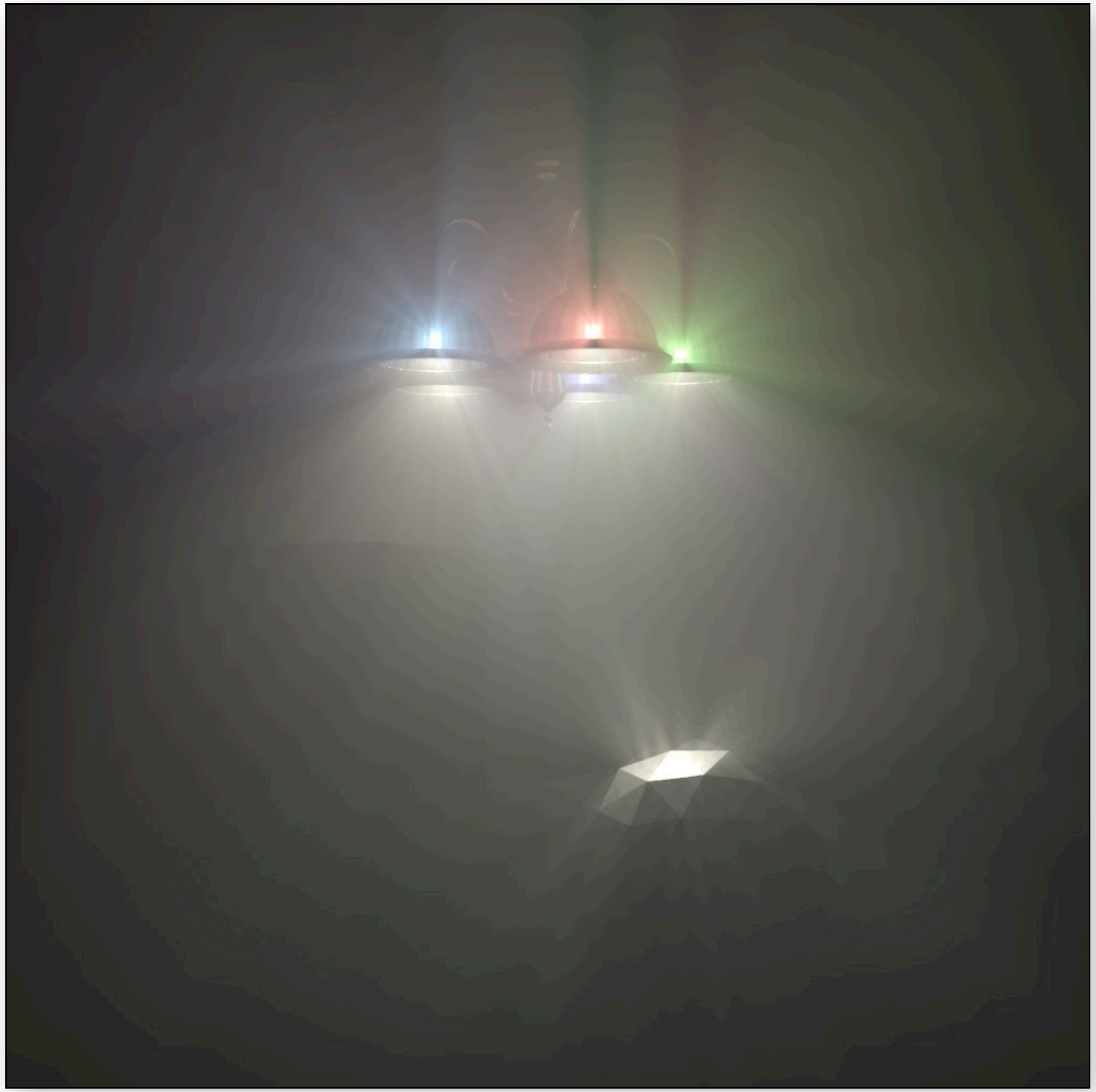
Average of Passes 1..8

Progressive Photon Beams

[Jarosz et al. 11b]



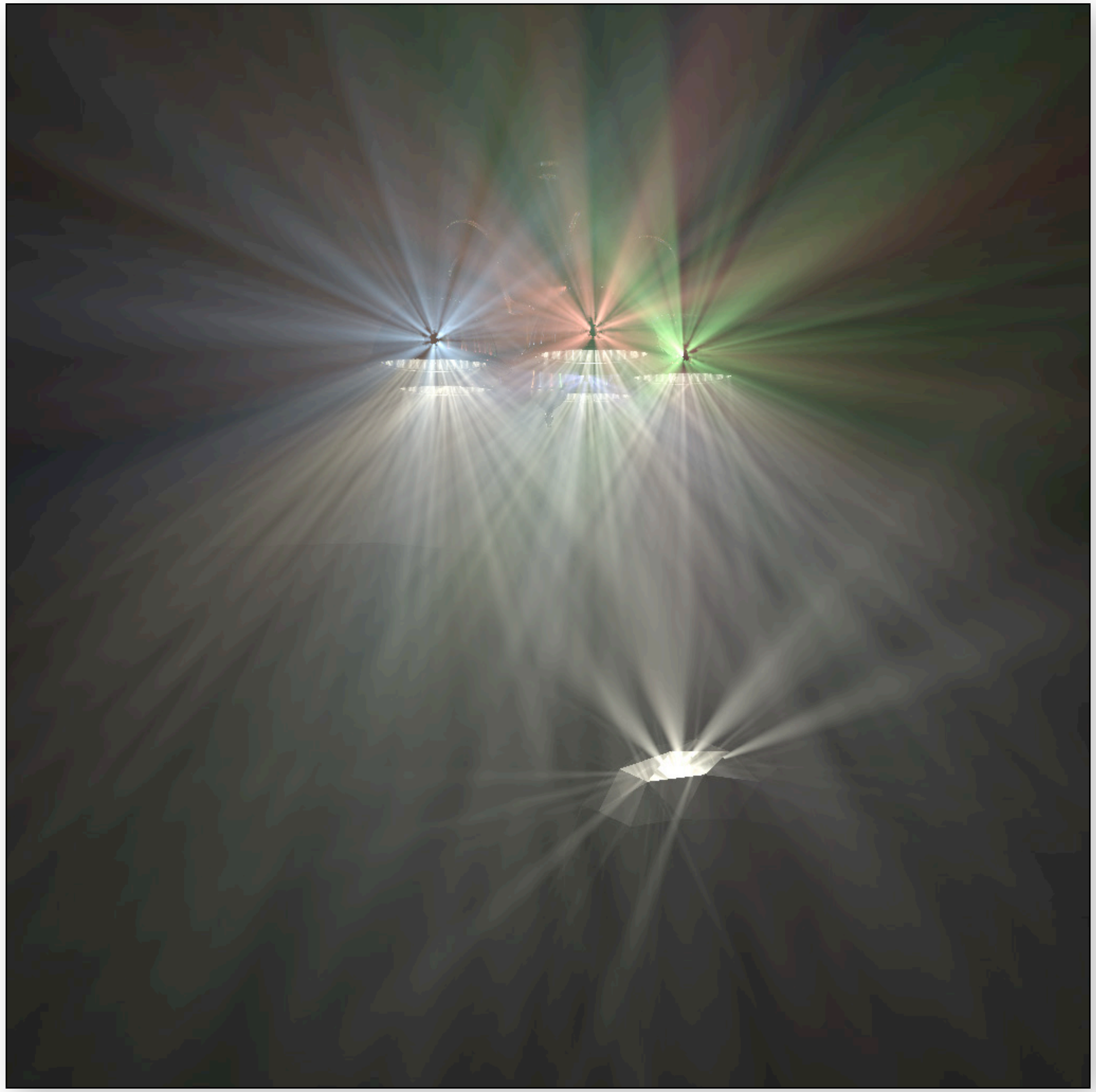
Pass 16



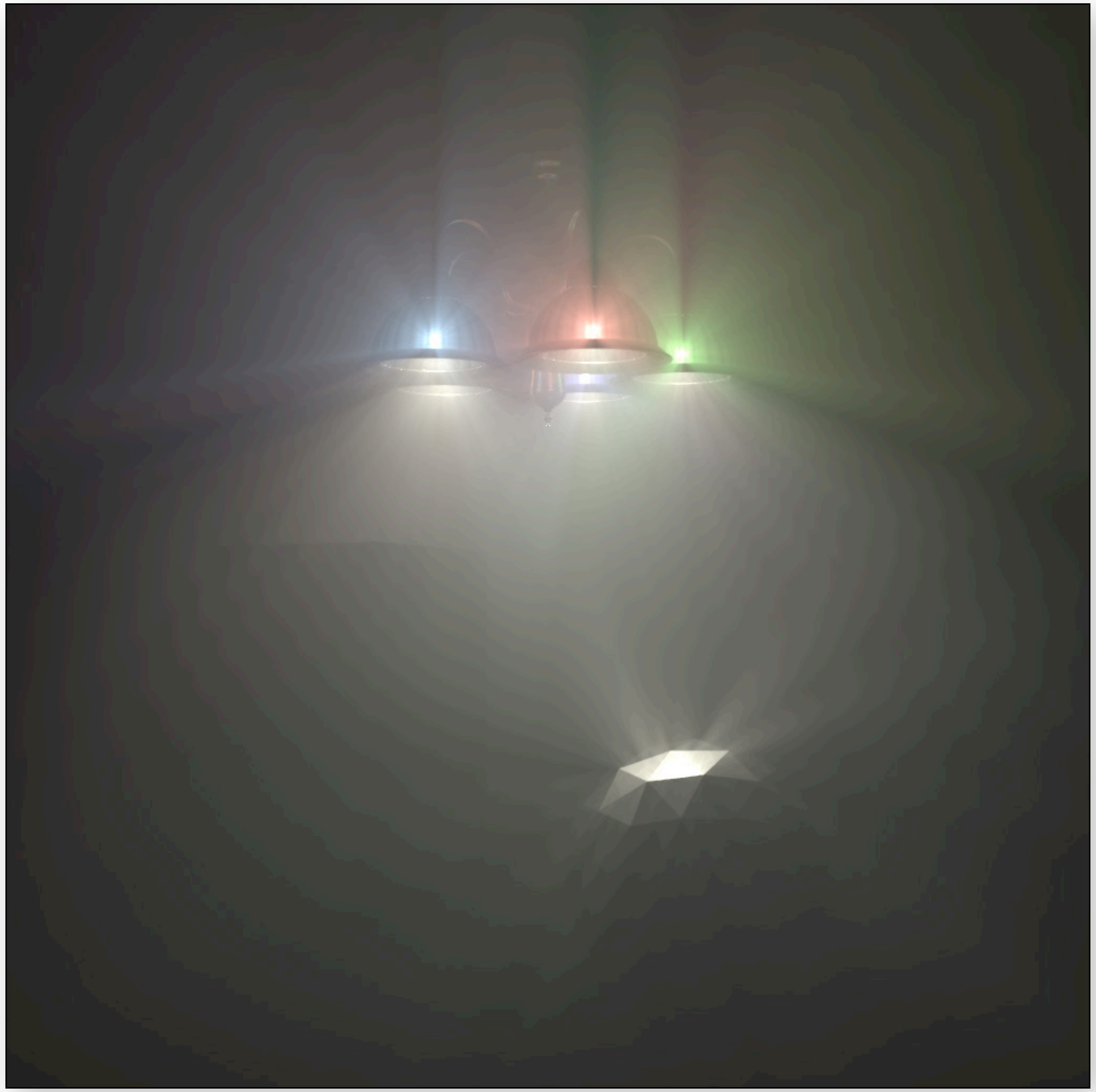
Average of Passes 1..16

Progressive Photon Beams

[Jarosz et al. 11b]



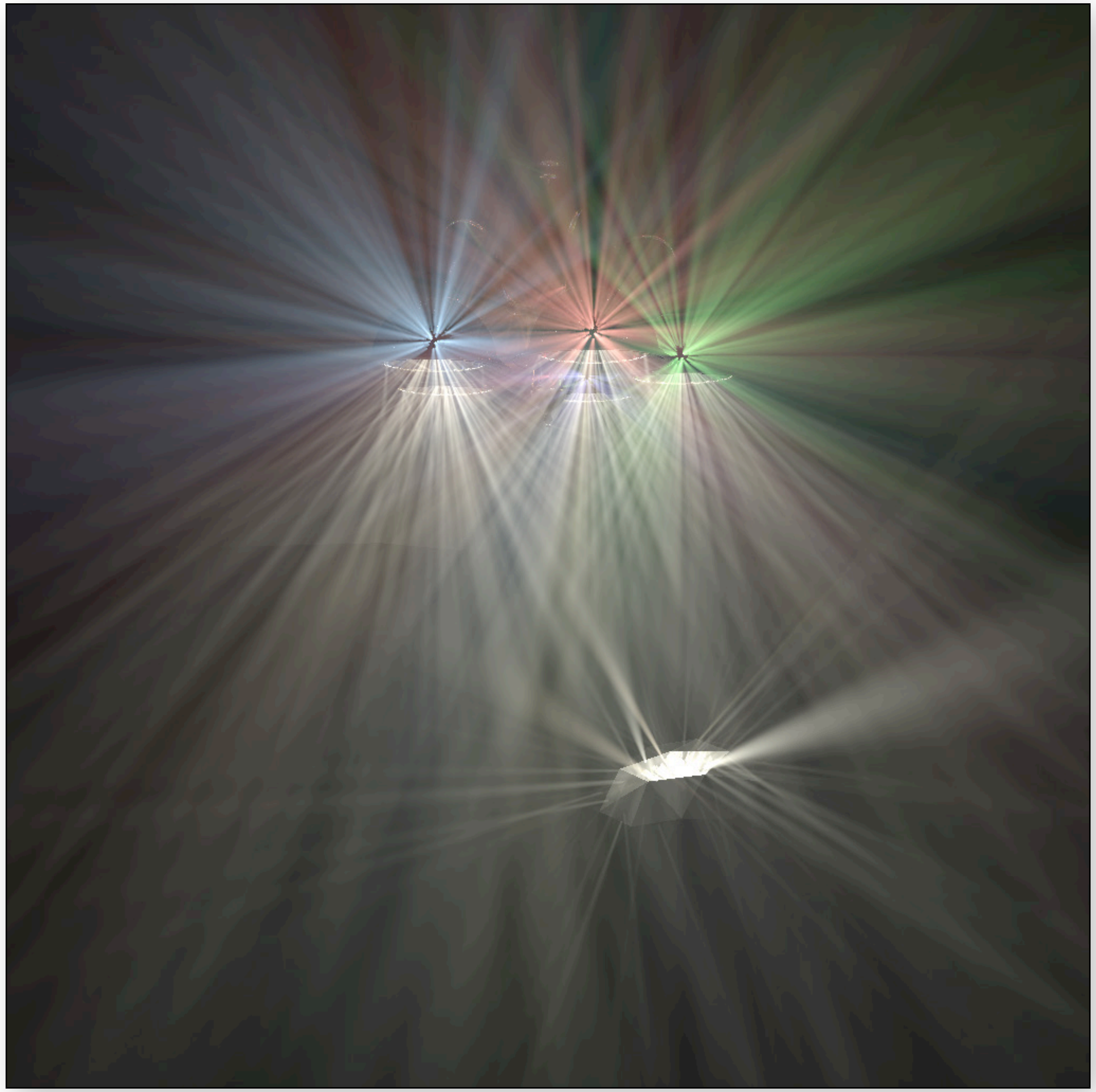
Pass 32



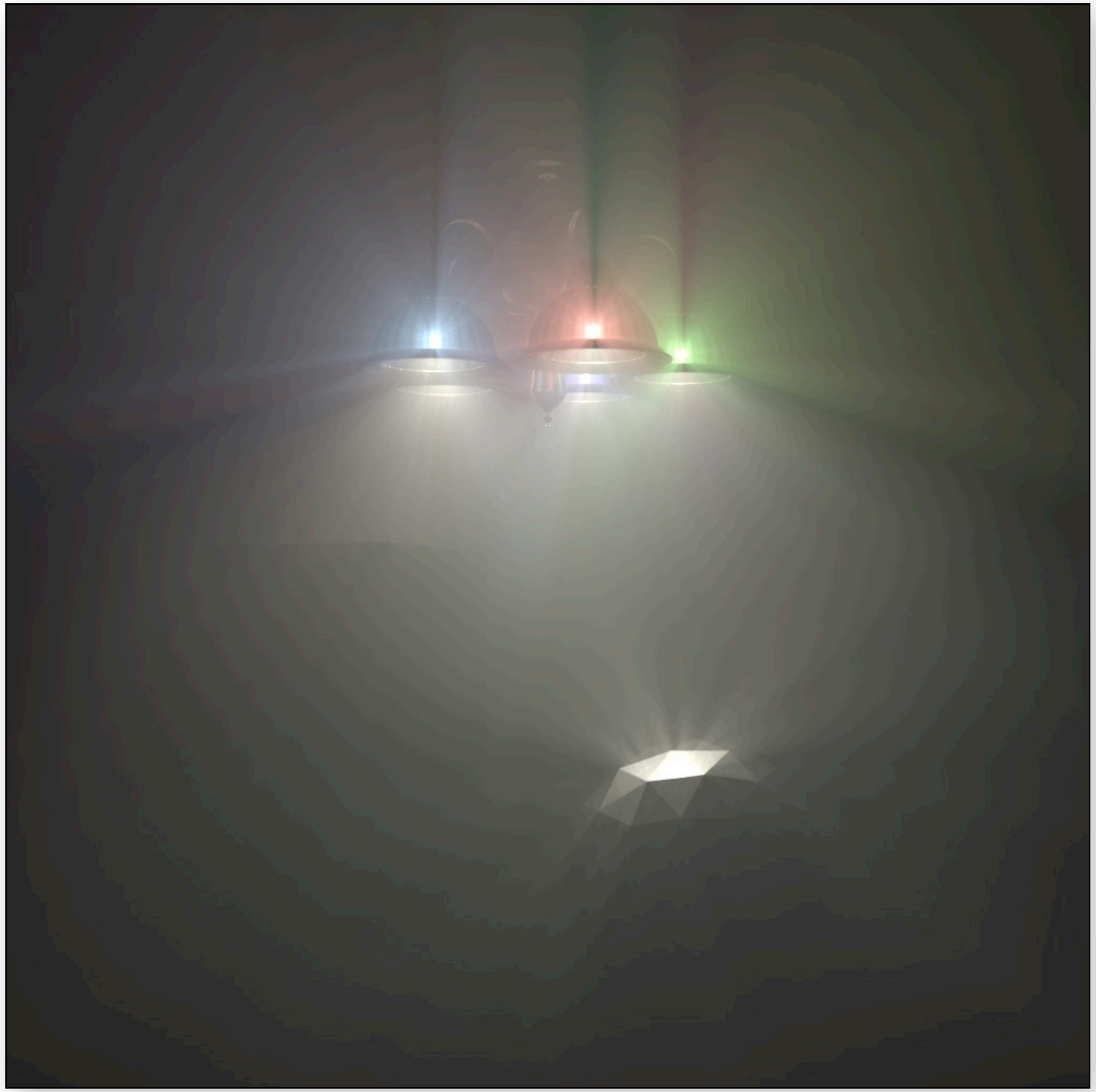
Average of Passes 1..32

Progressive Photon Beams

[Jarosz et al. 11b]



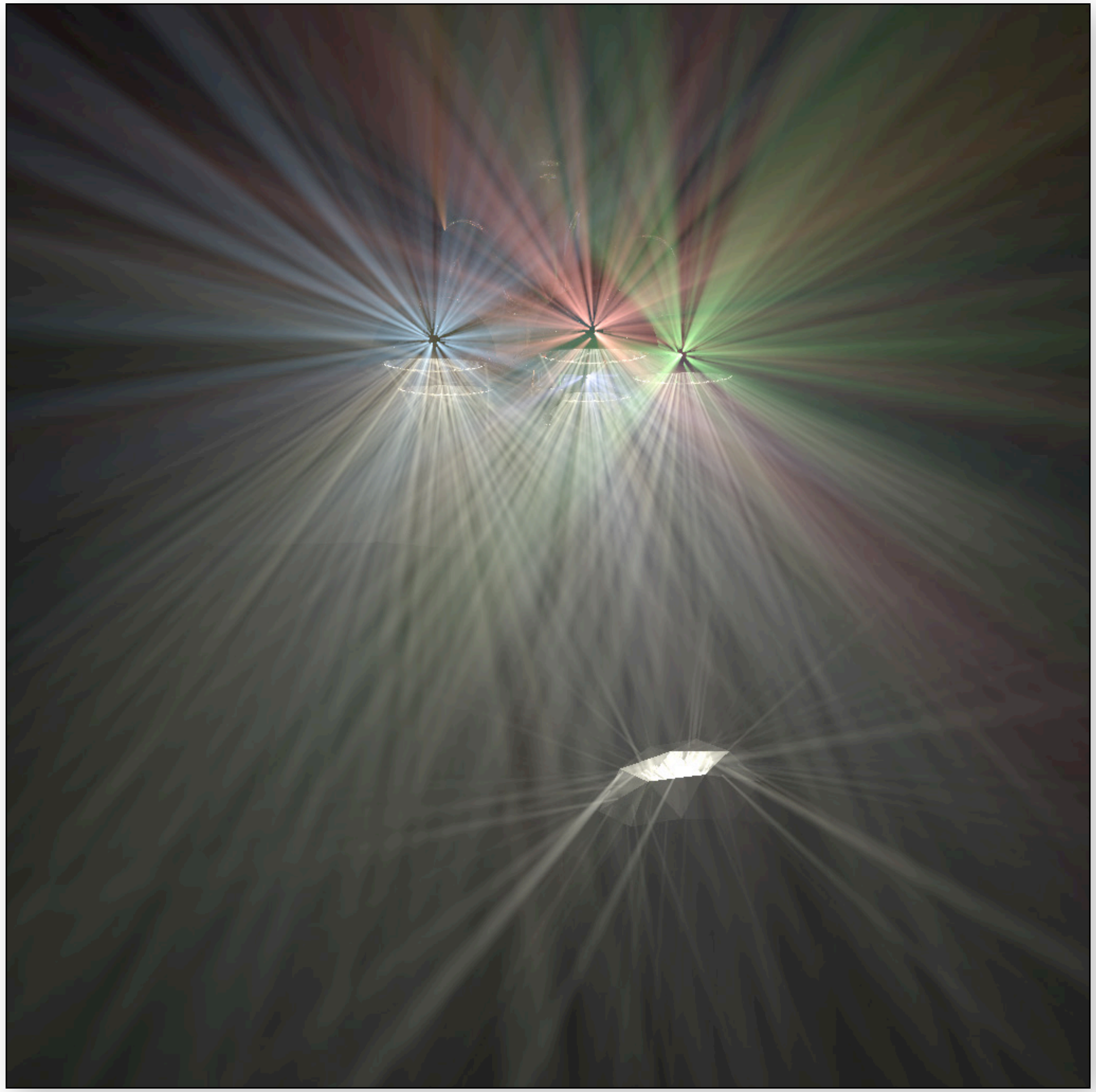
Pass 64



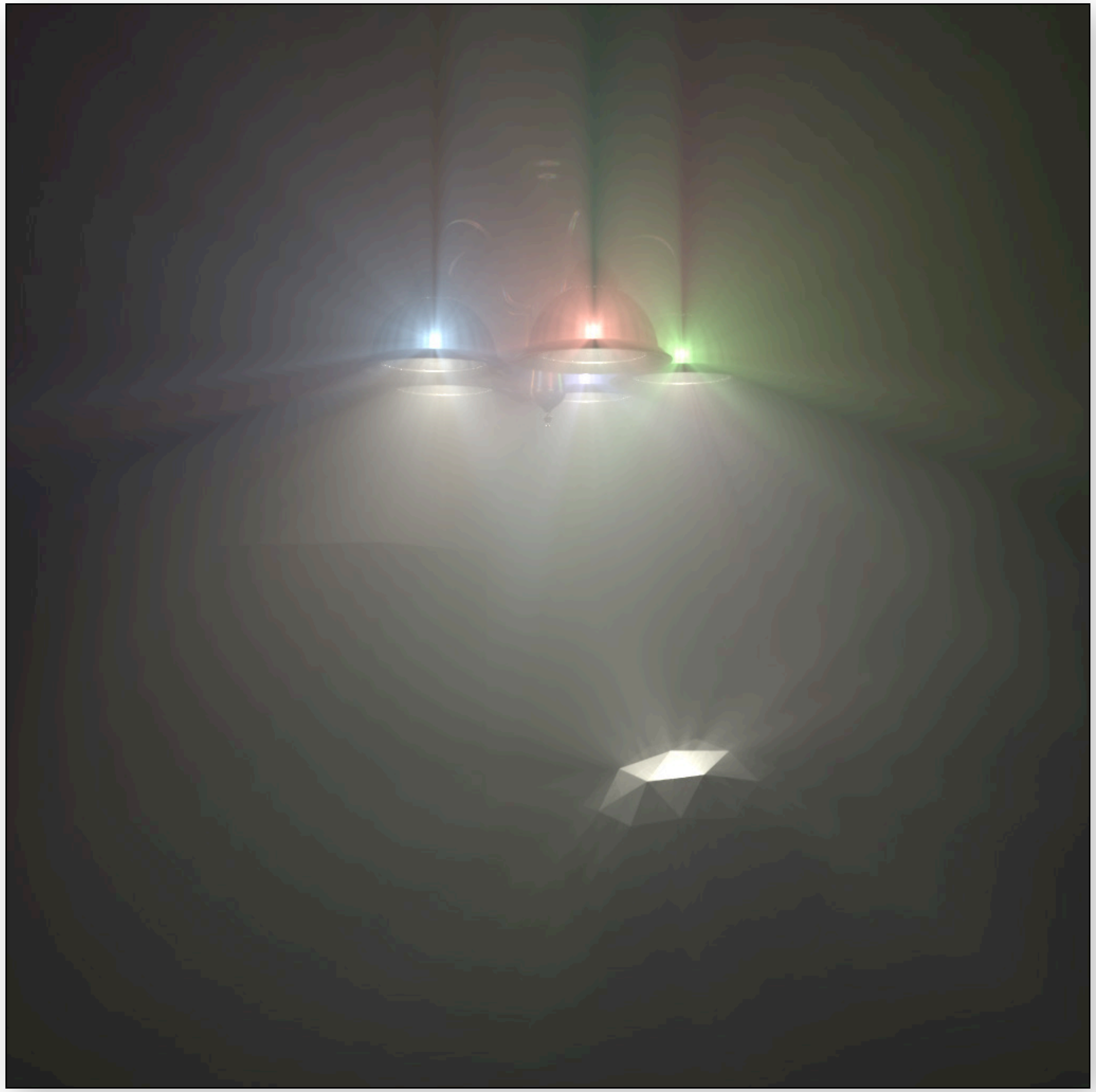
Average of Passes 1..64

Progressive Photon Beams

[Jarosz et al. 11b]



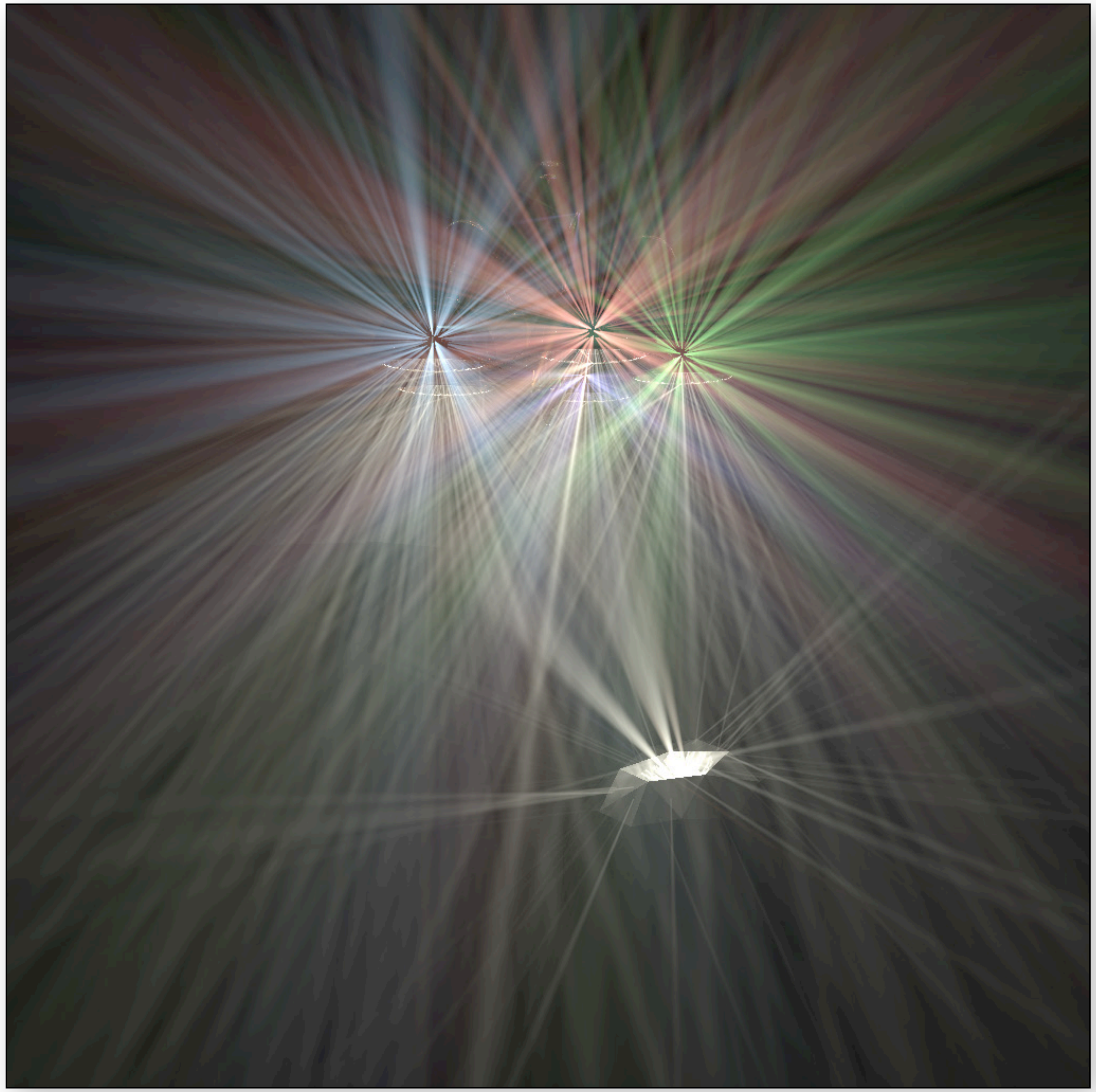
Pass 128



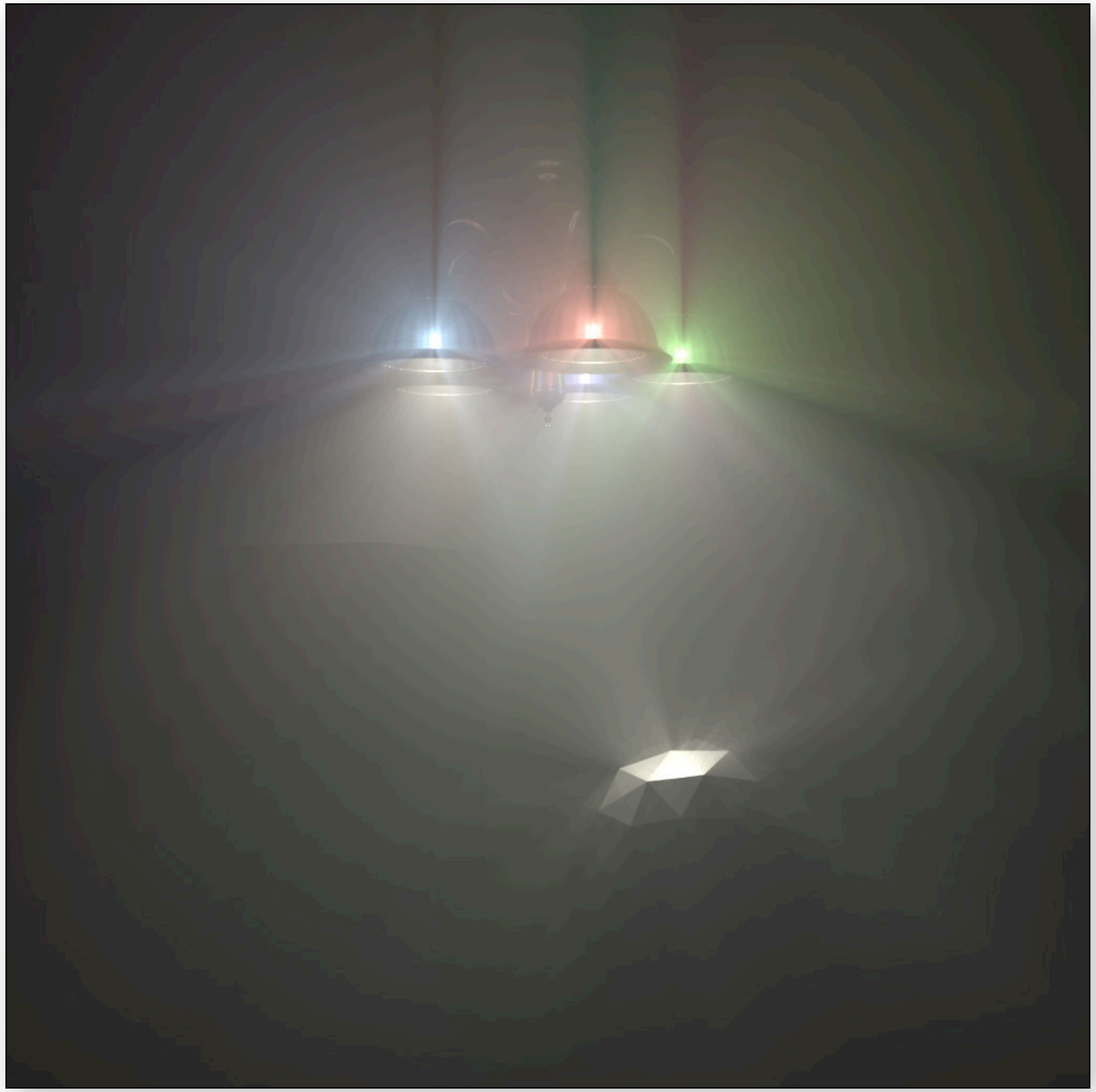
Average of Passes 1..128

Progressive Photon Beams

[Jarosz et al. 11b]



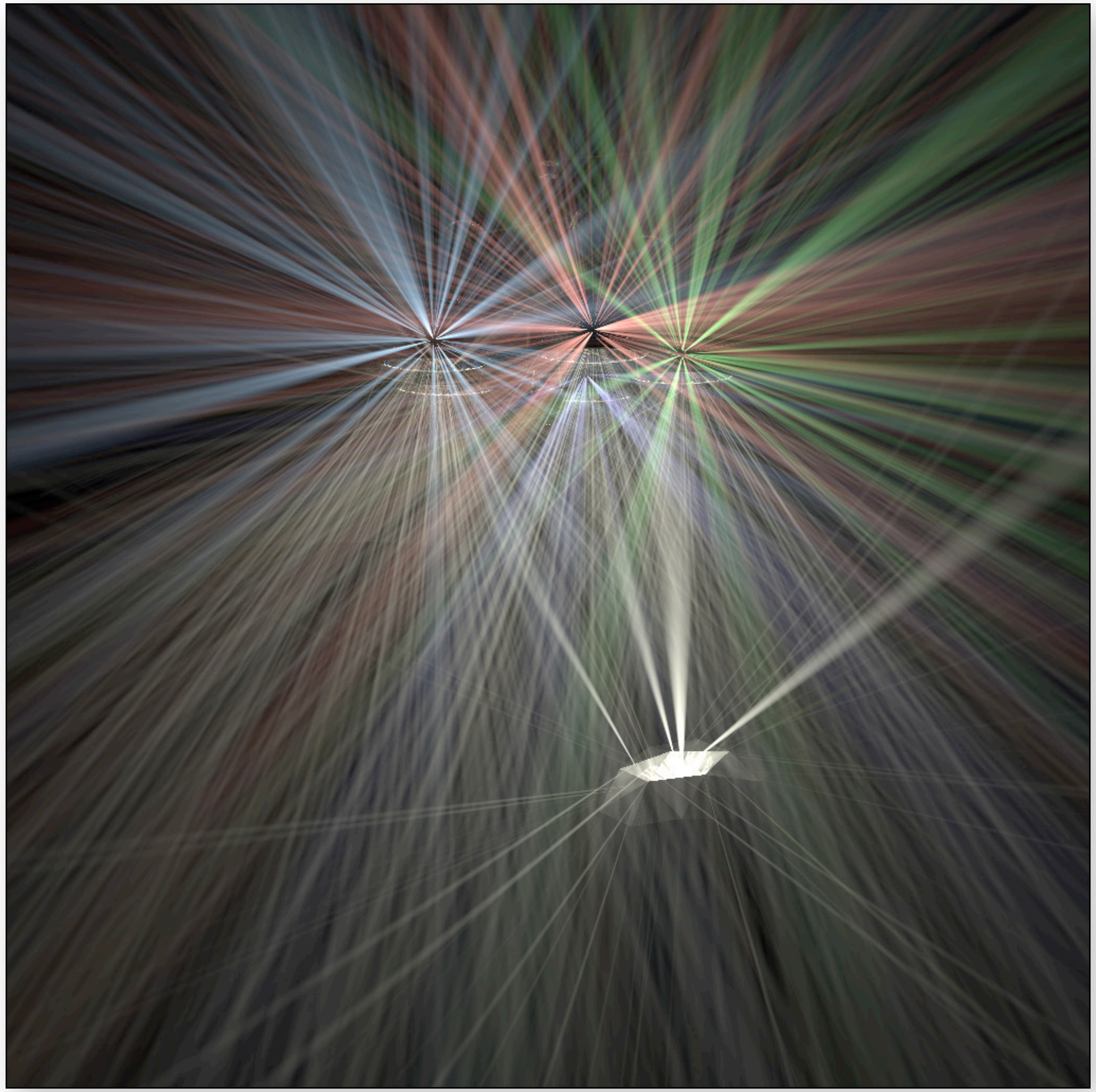
Pass 256



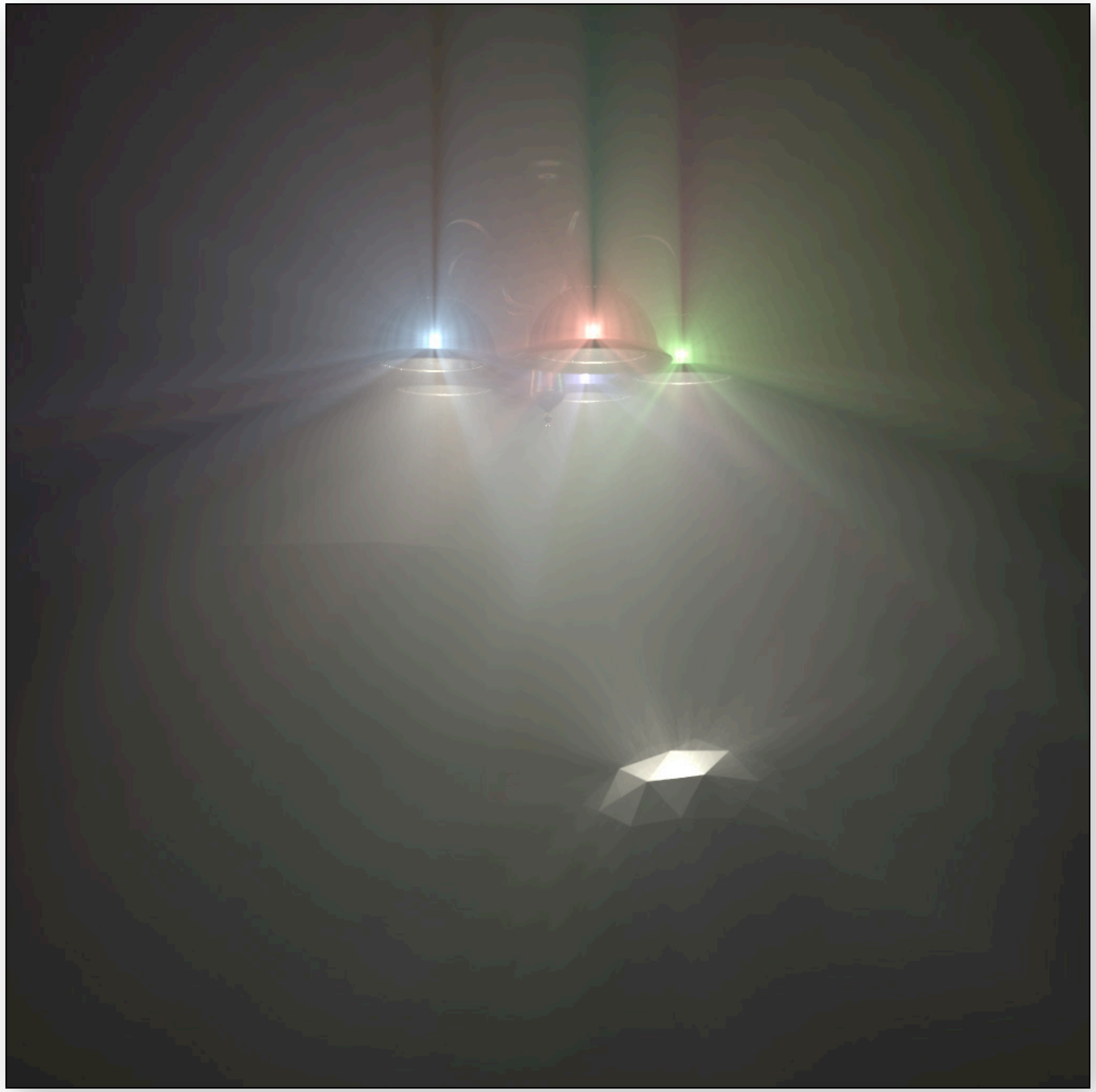
Average of Passes 1..256

Progressive Photon Beams

[Jarosz et al. 11b]



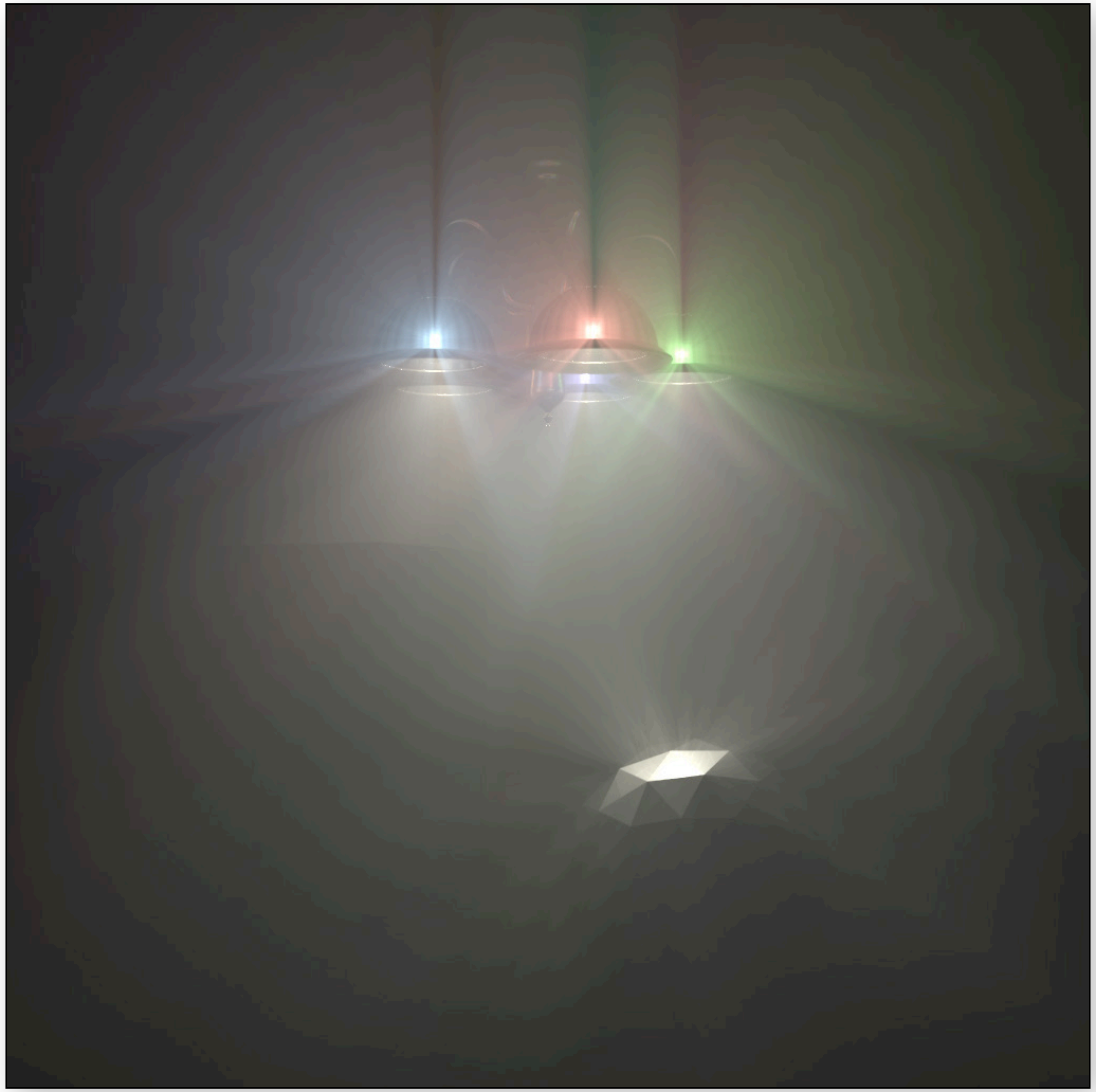
Pass 512



Average of Passes 1..512

Progressive Photon Beams

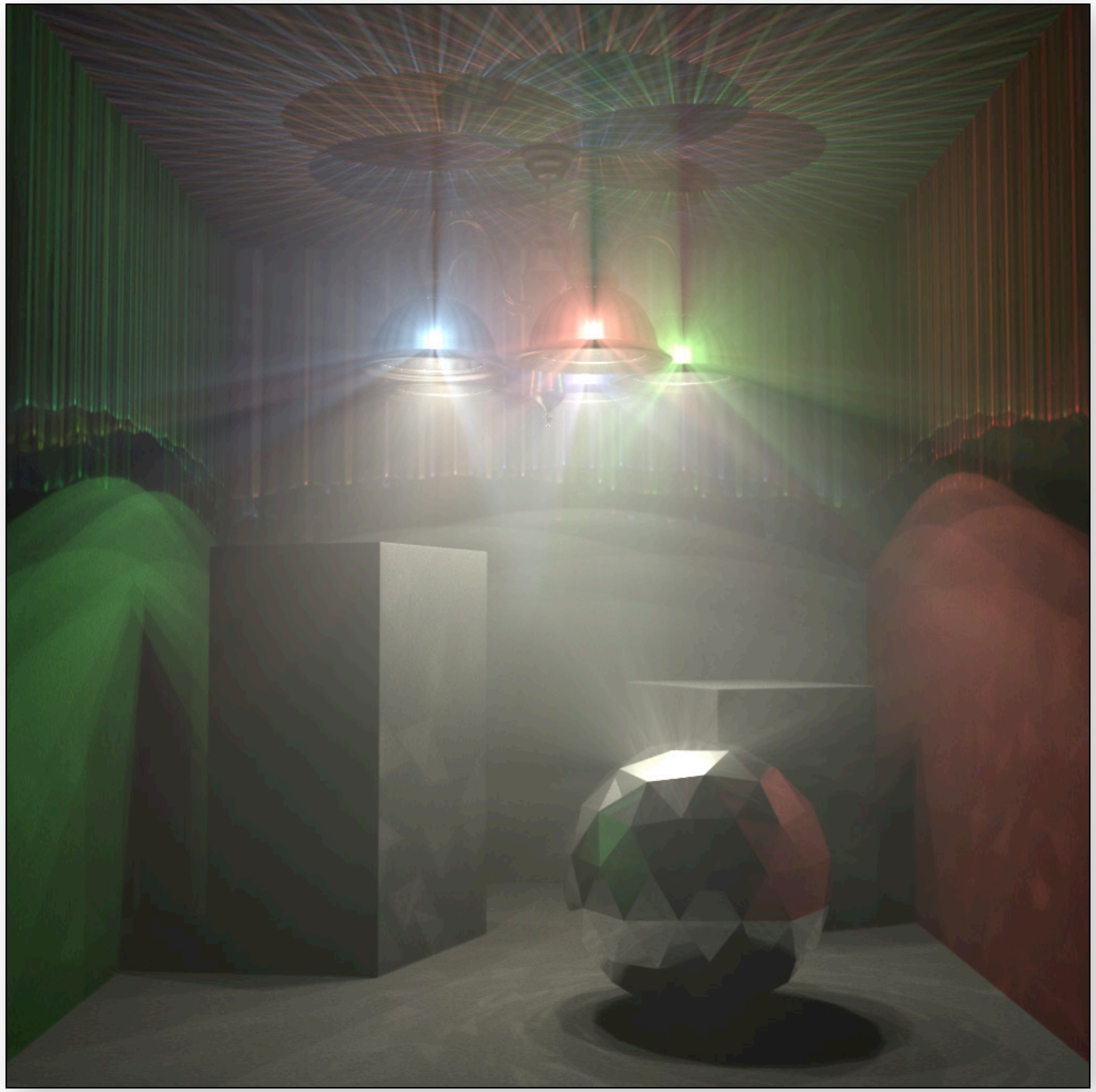
[Jarosz et al. 11b]



100K beams per pass
51.2M beams total

Progressive Photon Beams

[Jarosz et al. 11b]



100K beams per pass
51.2M beams total
+ progressive surface photon mapping

Cars

1280x720, Depth-of-Field

Pass 1

Homogeneous

Heterogeneous

Cars

1280x720, Depth-of-Field

Pass 2	Average of Passes 1..2
	
	

Cars

1280x720, Depth-of-Field

Pass 4 | Average of Passes 1..4

Cars

1280x720, Depth-of-Field

Pass 8 | Average of Passes 1..8

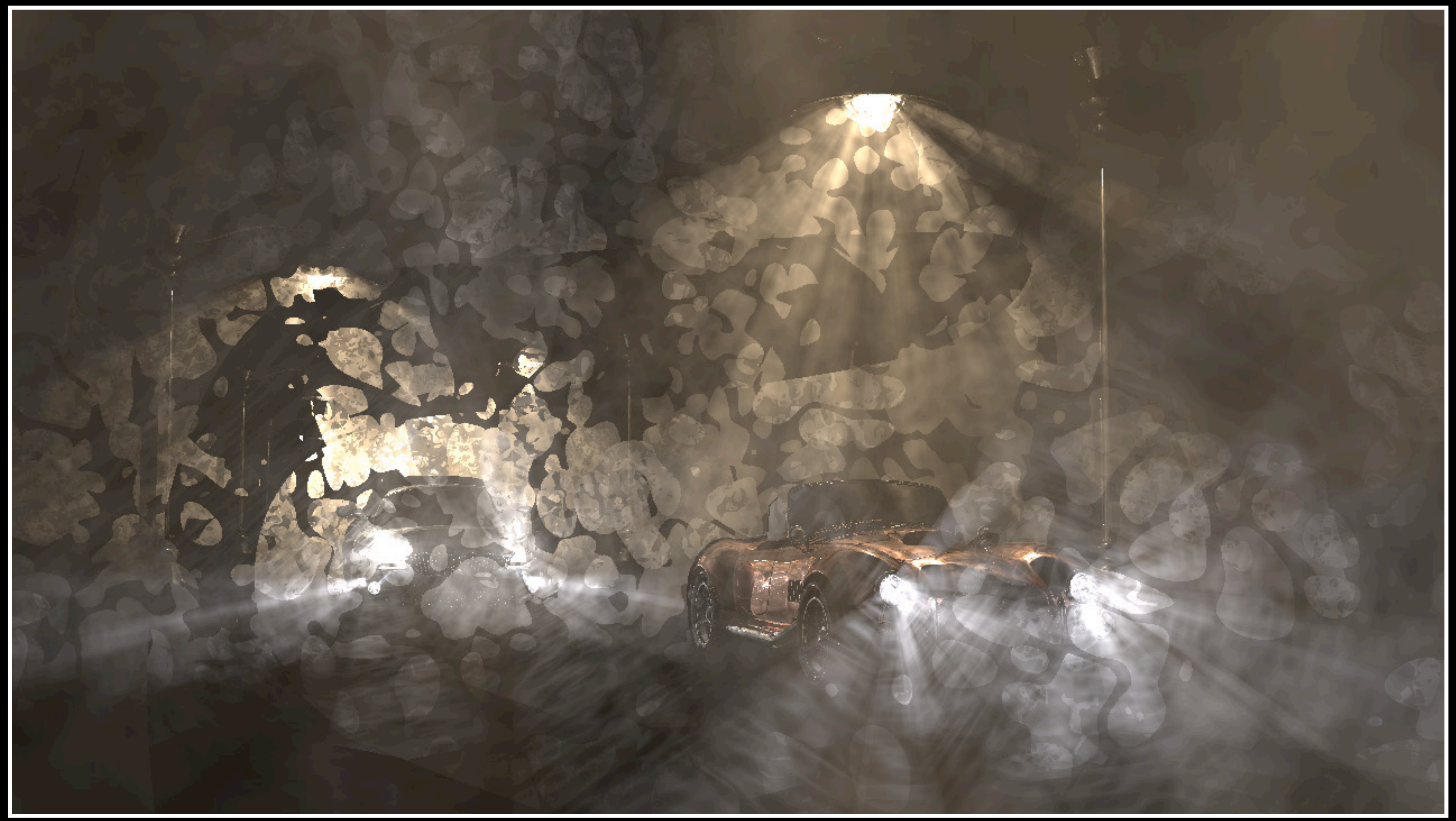
Cars

1280x720, Depth-of-Field

Pass 16	Average of Passes 1..16
	
	

Cars

1280x720, Depth-of-Field

Pass 32	Average of Passes 1..32
	
	

Cars

1280x720, Depth-of-Field

Pass 64	Average of Passes 1..64
	
	

CARS

1280x720, Depth-of-Field

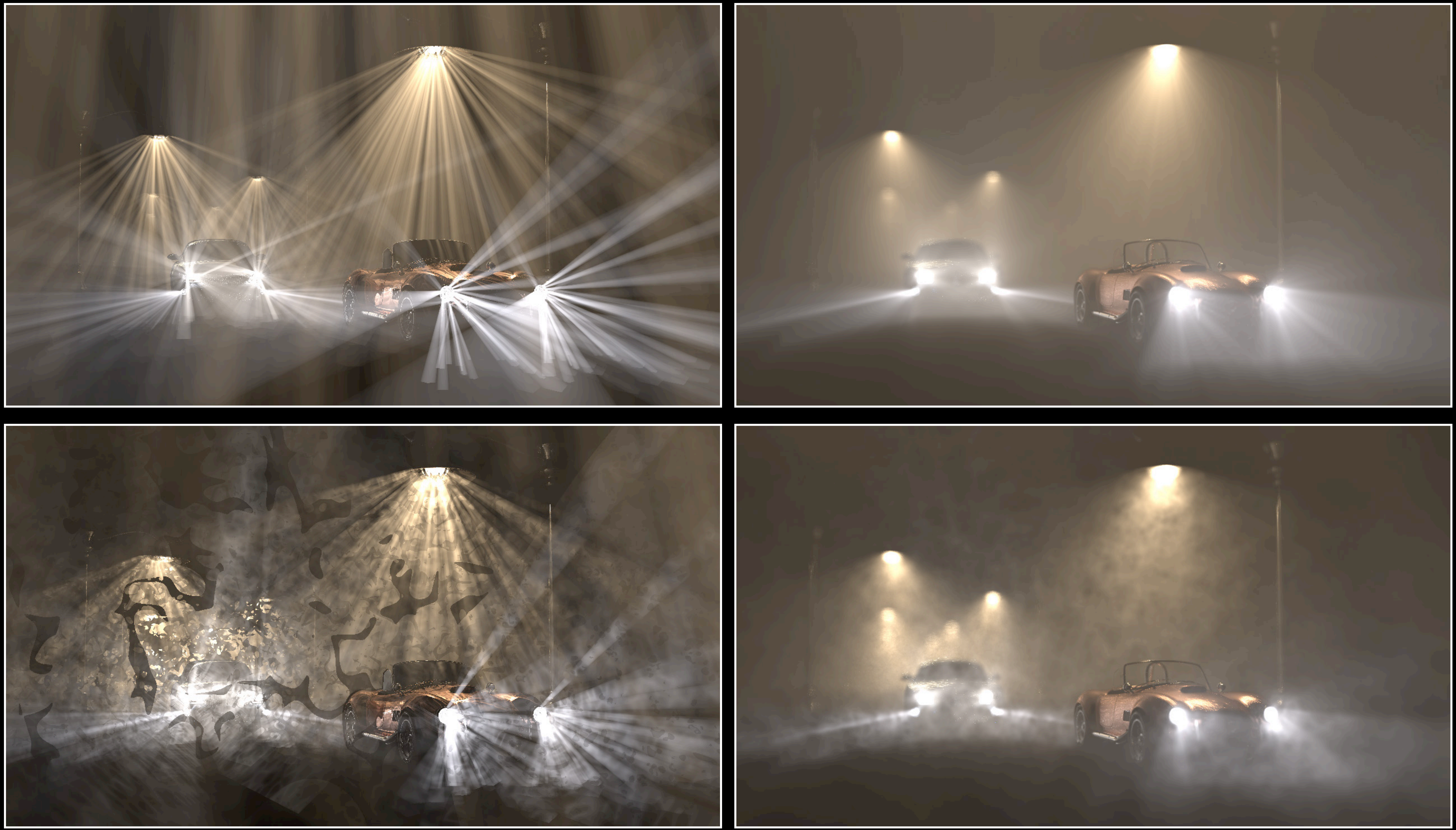
Pass 128

Average of Passes 1..128

Cars

1280x720, Depth-of-Field

Pass 256 | Average of Passes 1..256



Cars

1280x720, Depth-of-Field

Pass 512	Average of Passes 1..512
	
	

CARS

1280x720, Depth-of-Field

Pass 1024

Average of Passes 1..1024

Cars

1280x720, Depth-of-Field

Homogeneous

14.55M Photon Beams

9.5 minutes

Heterogeneous

15.04M Photon Beams

16.8 minutes

Cars

1280x720, Depth-of-Field

Homogeneous

14.55M Photon Beams

9.5 minutes

Heterogeneous

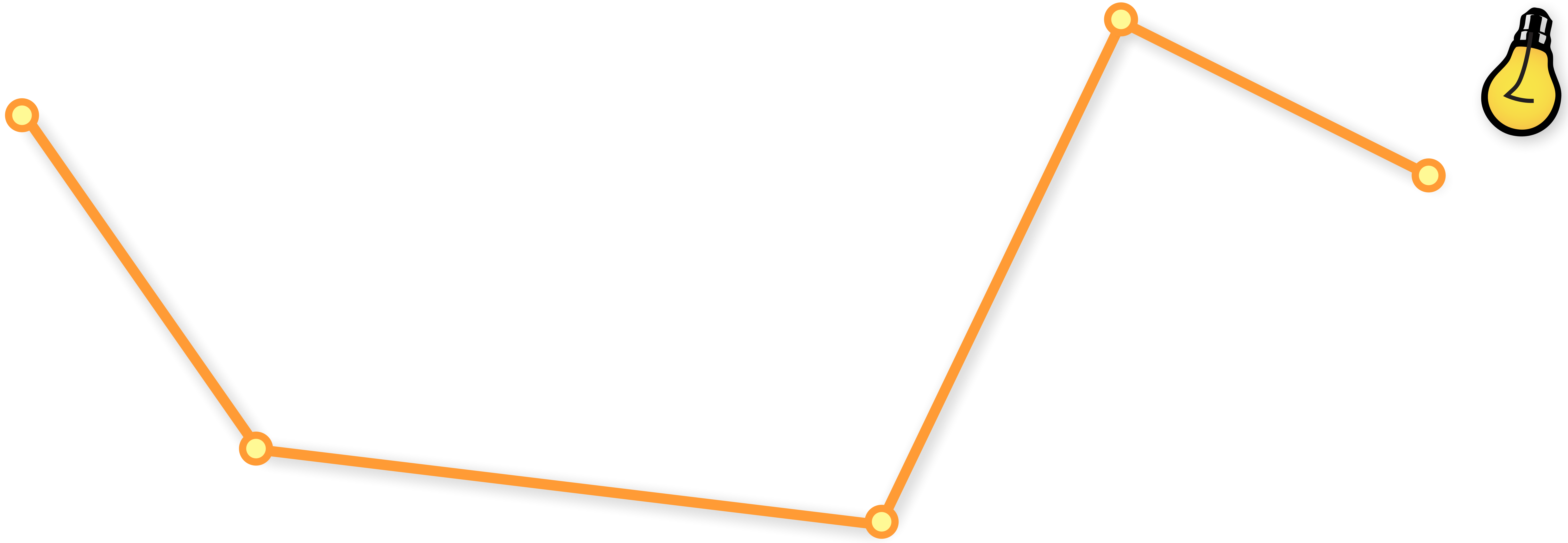
15.04M Photon Beams

16.8 minutes

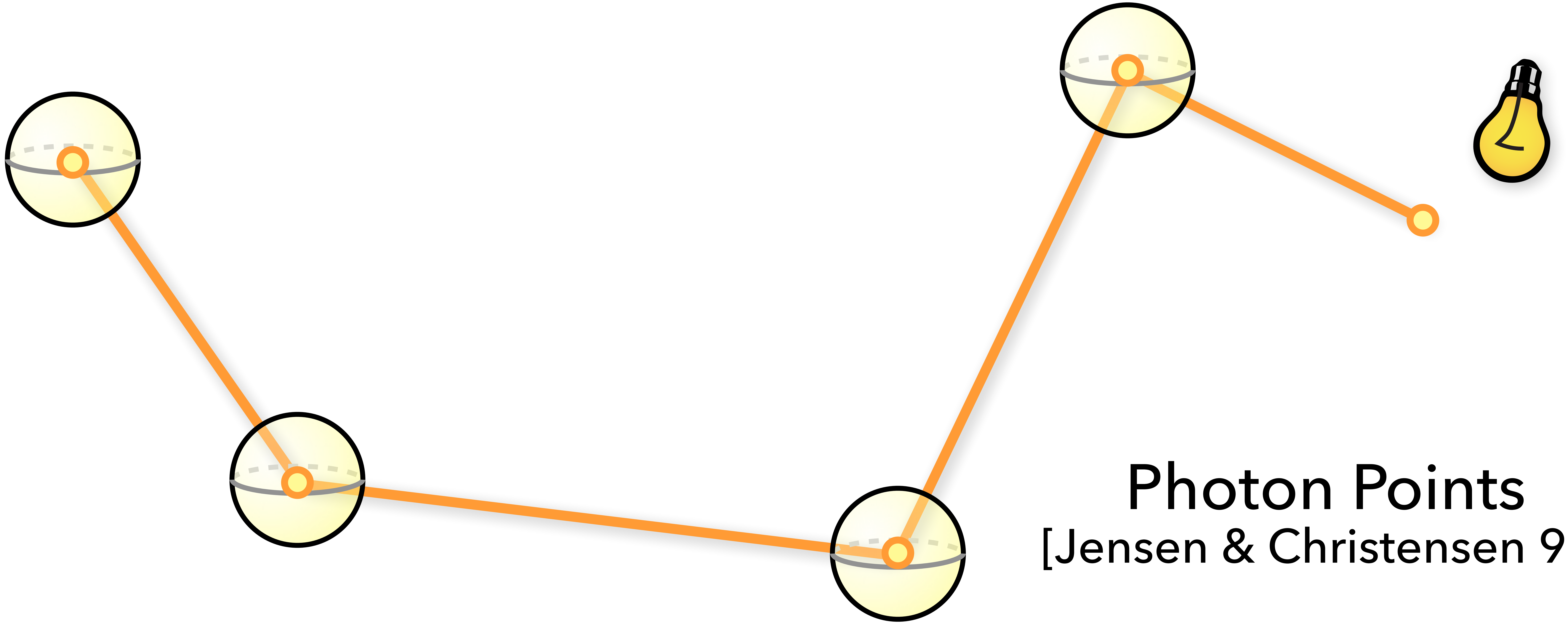
alpha = 0.5
R = 0.037695
Shadow map resolution: 64 x 64
pass number: 14
average render time per pass: 33 ms
www.fraps.com
OCEAN
OPENGL
RASTERIZATION-ONLY
IMPLEMENTATION
α = 0.5
2x speed


alpha = 0.5
R = 0.037695
Shadow map resolution: 64 x 64
pass number: 14
average render time per pass: 33 ms
www.fraps.com
OCEAN
OPENGL
RASTERIZATION-ONLY
IMPLEMENTATION
α = 0.5
2x speed

Photon Points

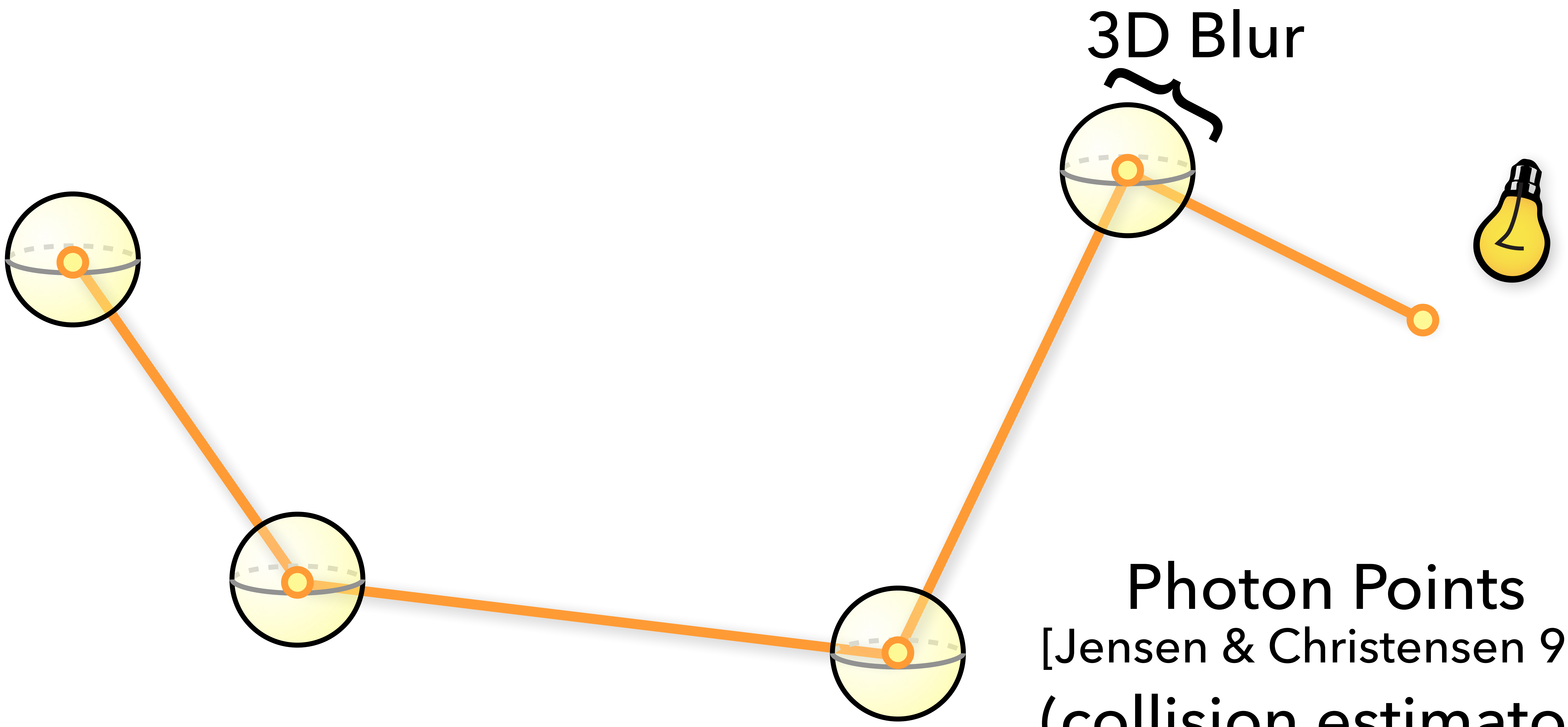


Photon Points



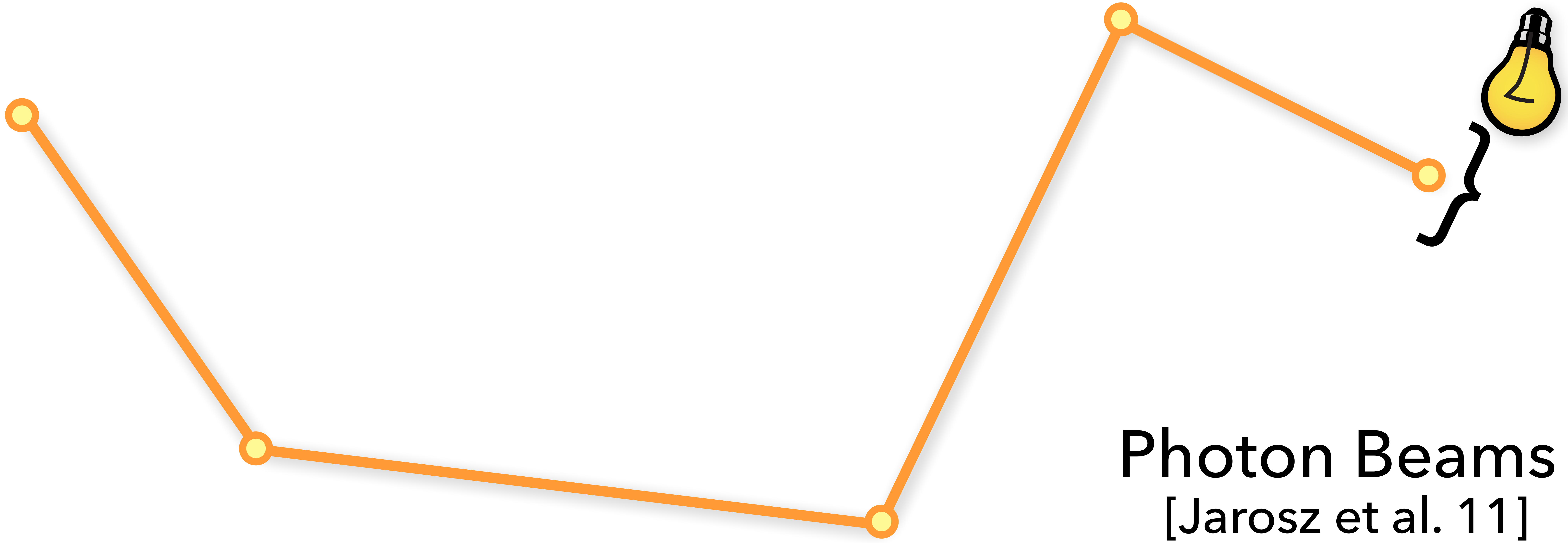
Photon Points
[Jensen & Christensen 98]

Photon Points



Photon Points
[Jensen & Christensen 98]
(collision estimator)
[Spanier & Gelbard 69]

Photon Beams



Photon Beams
[Jarosz et al. 11]

Photon Beams

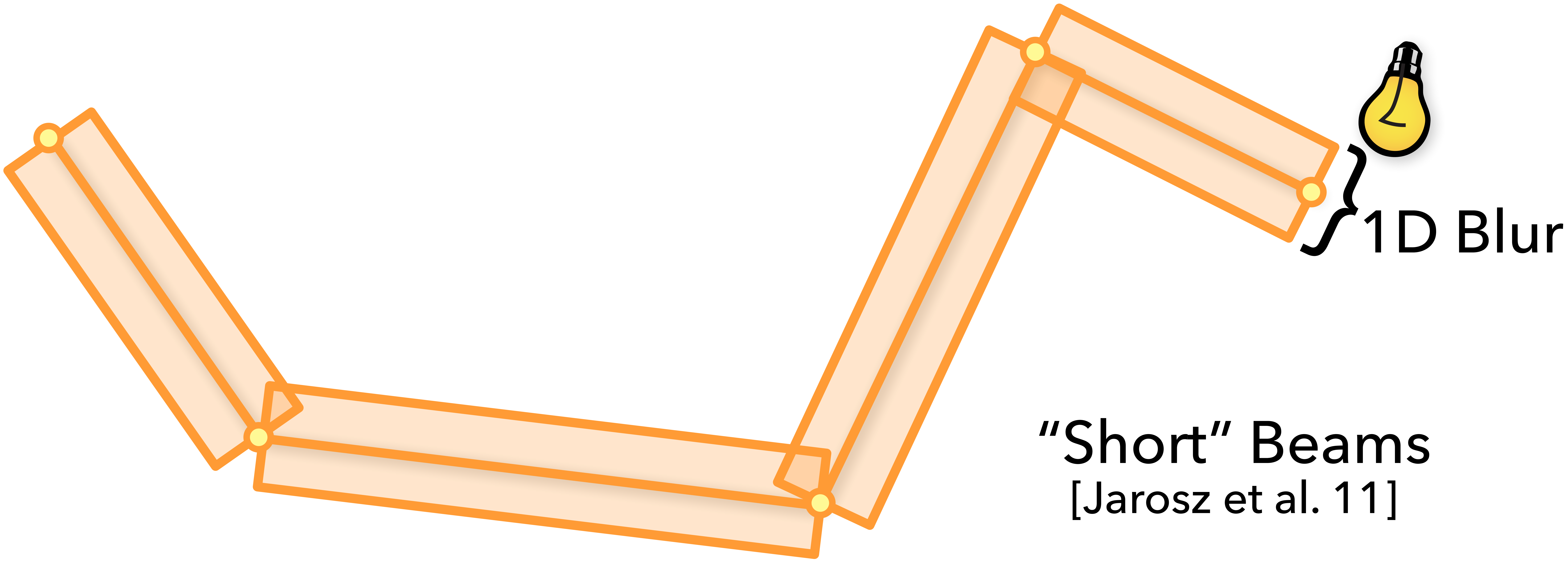
Photon Beams
[Jarosz et al. 11]

(Long) Photon Beams

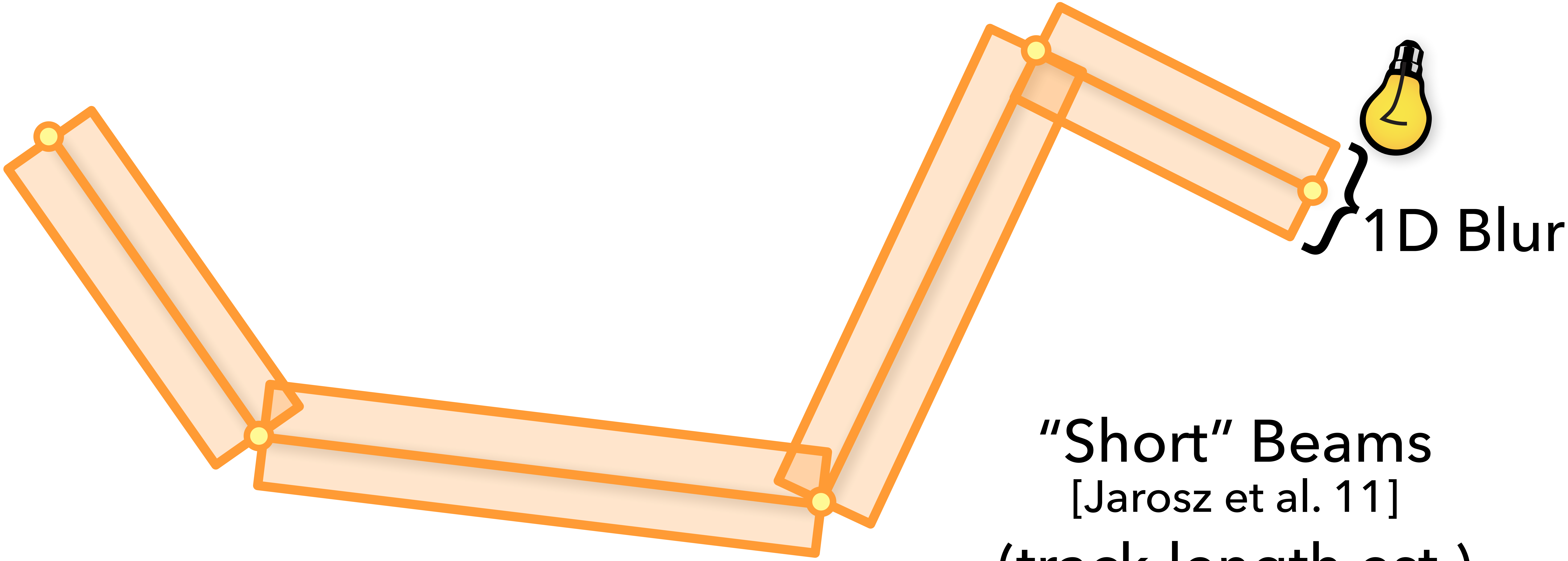
"Long" Beams
[Jarosz et al. 11]

(expected value est.)
[Spanier & Gelbard 69]

(Short) Photon Beams



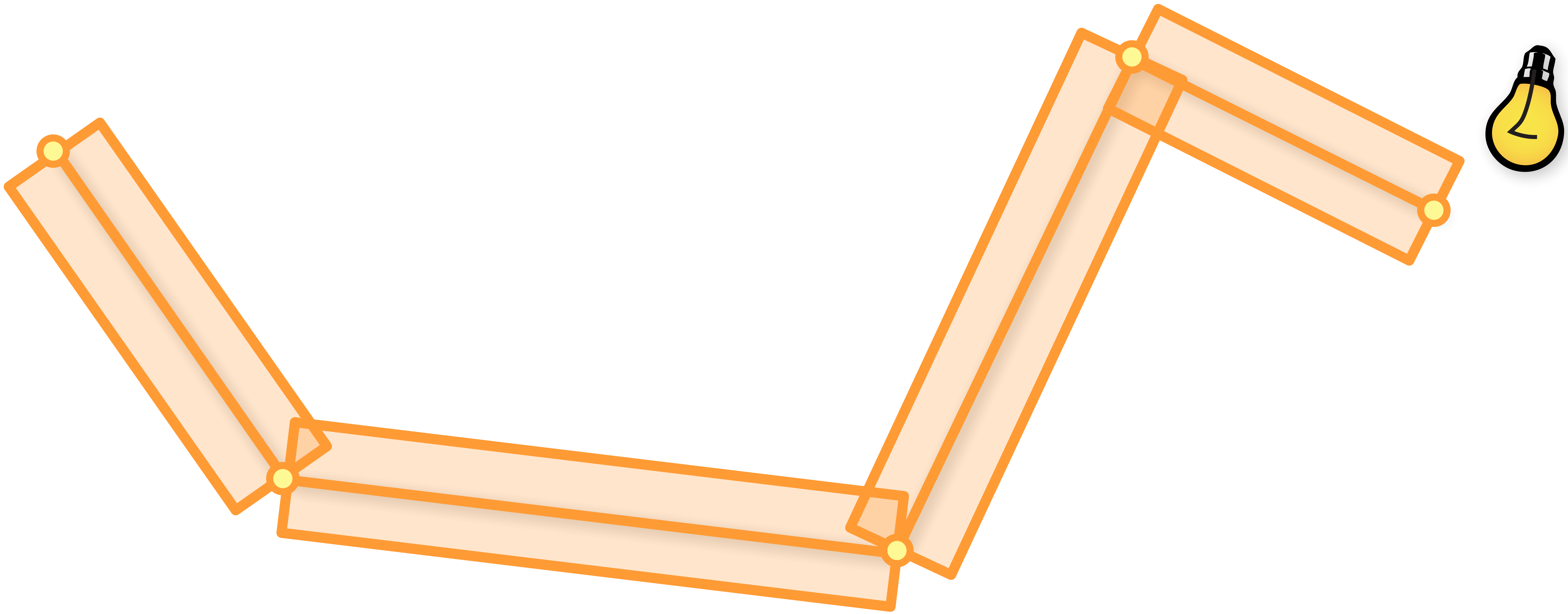
(Short) Photon Beams



"Short" Beams
[Jarosz et al. 11]

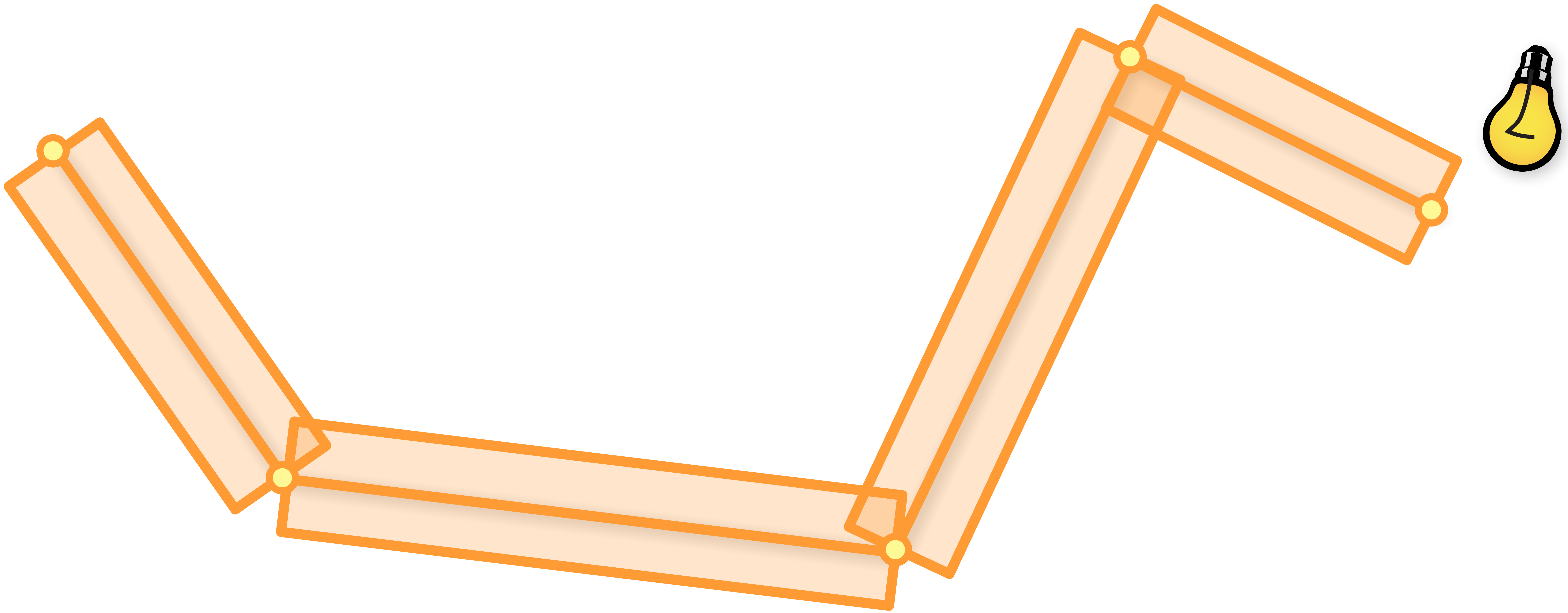
(track-length est.)
[Spanier & Gelbard 69]

Beyond Photon Beams?

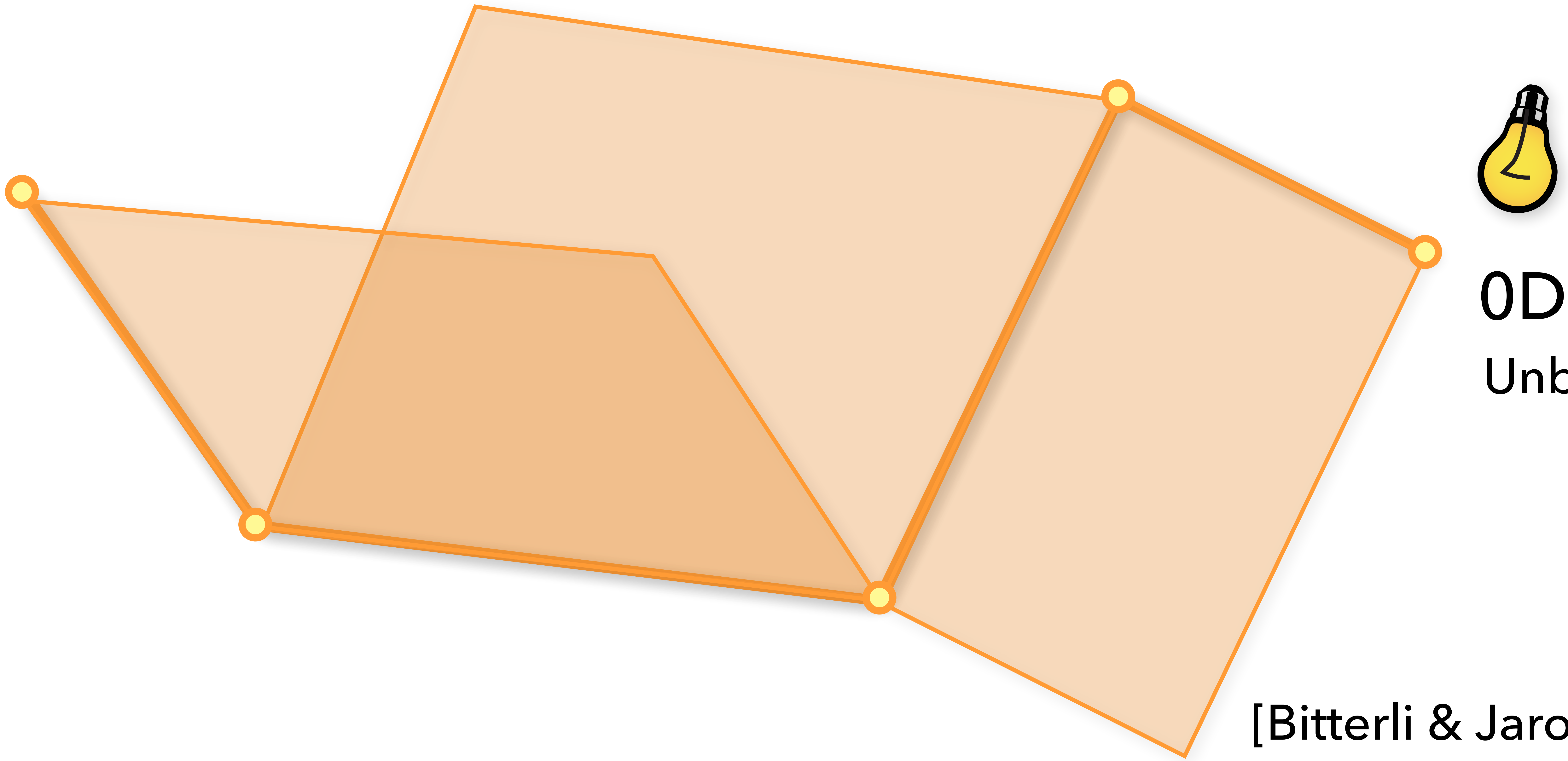


Beyond Photon Beams?

We can keep going to higher dimensional "photons"!



Photon Planes

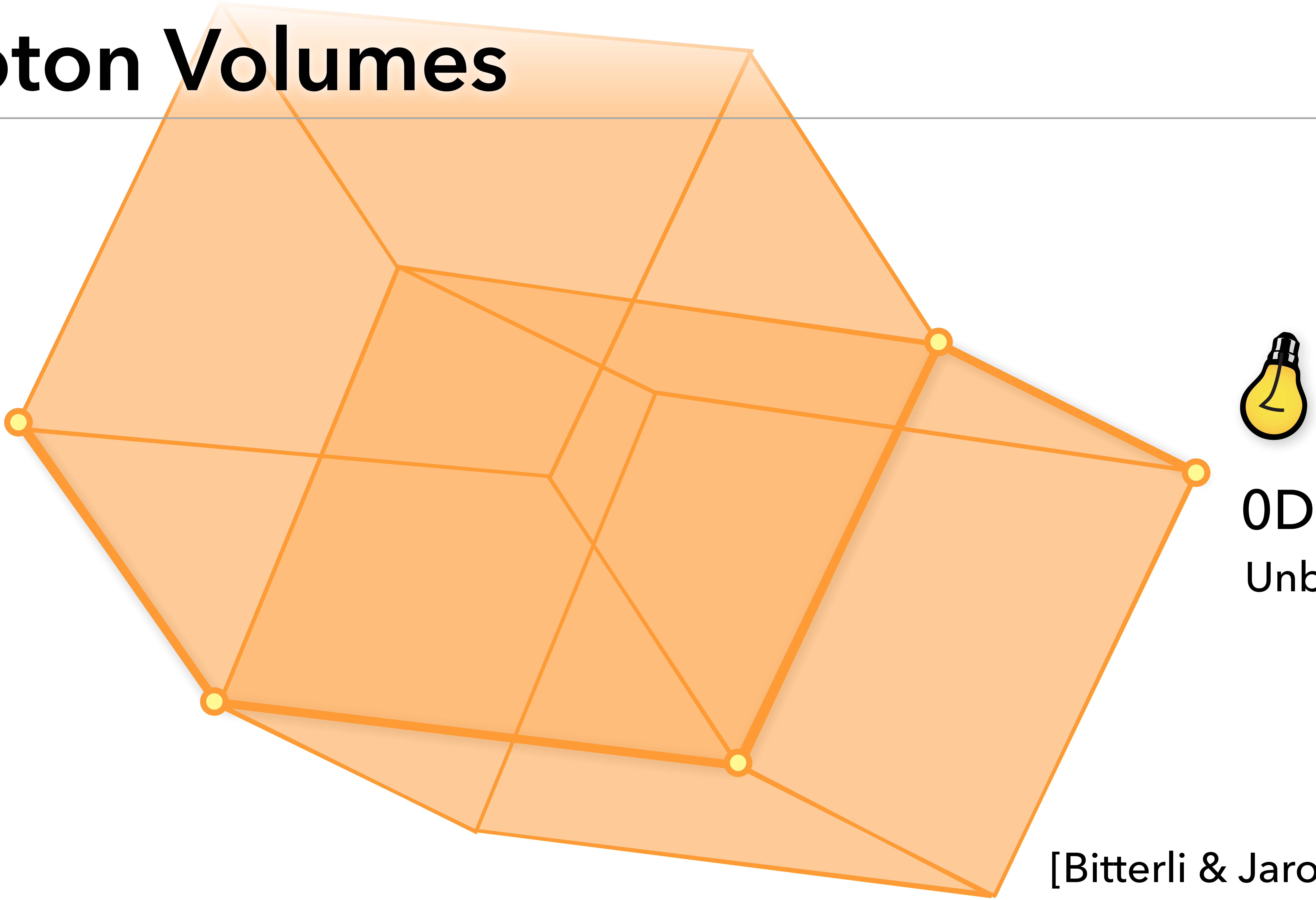


0D Blur

Unbiased

[Bitterli & Jarosz 17]

Photon Volumes



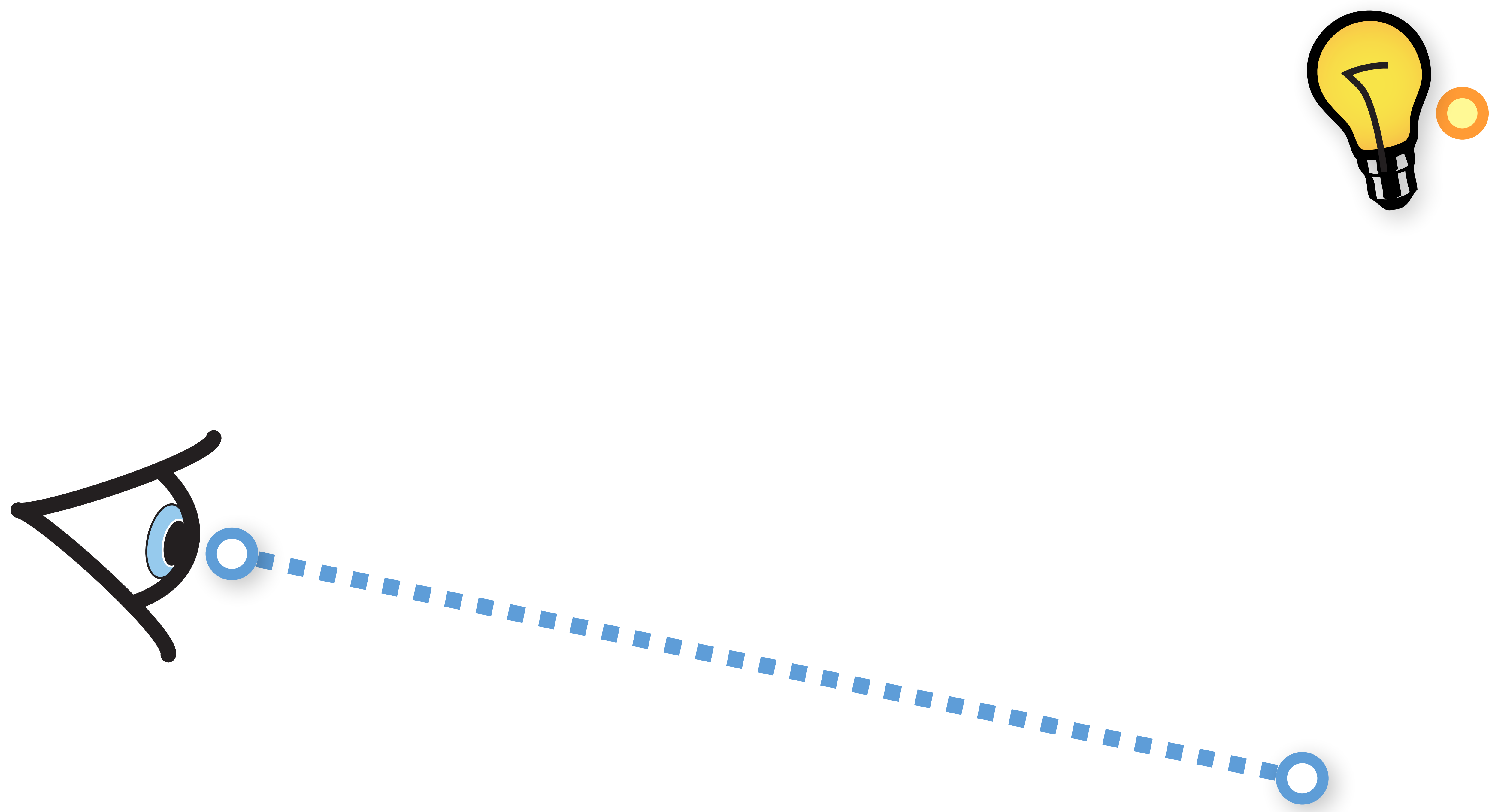
0D Blur

Unbiased

[Bitterli & Jarosz 17]

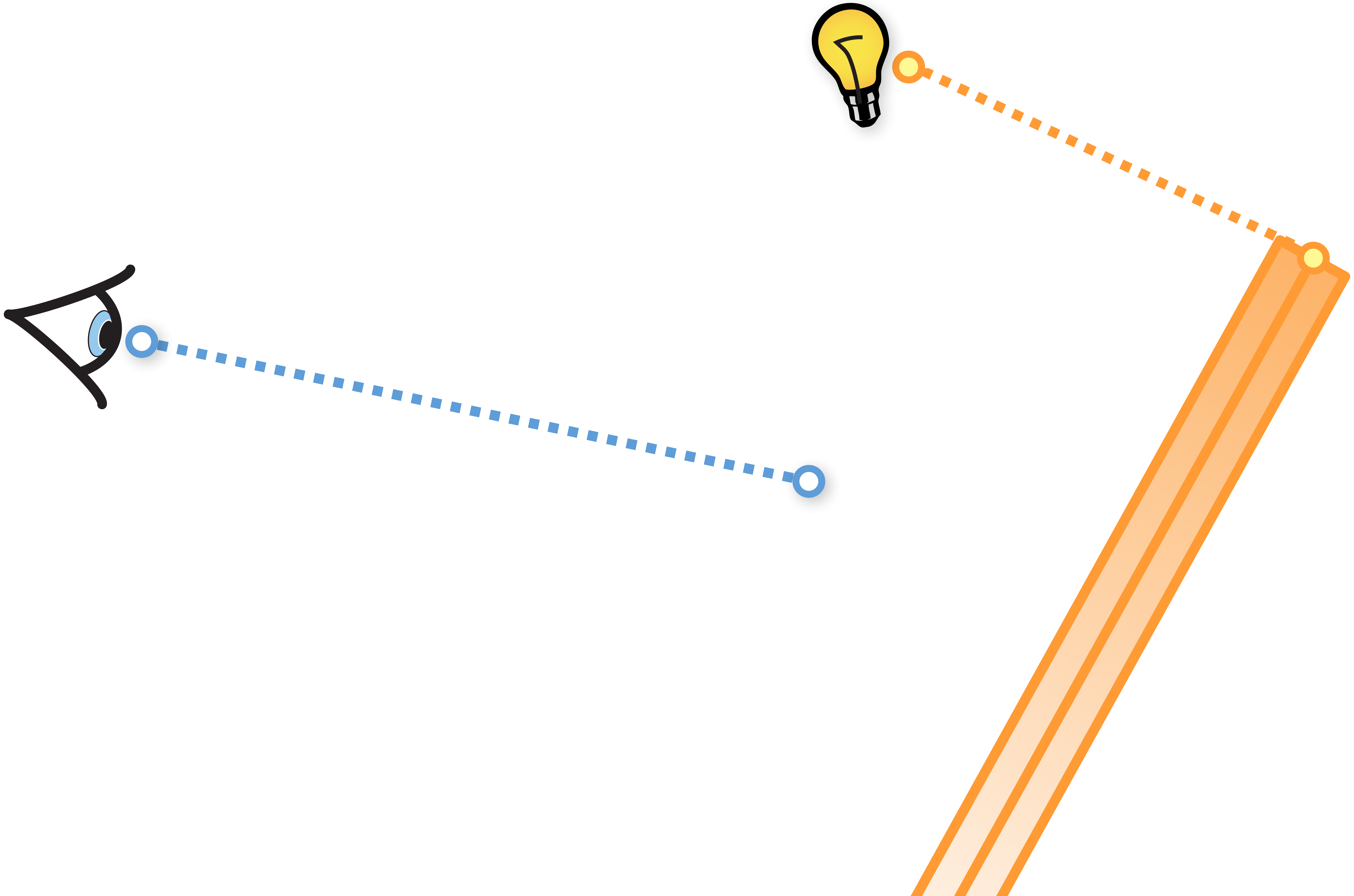
Photon Beams

[Bitterli & Jarosz 17]



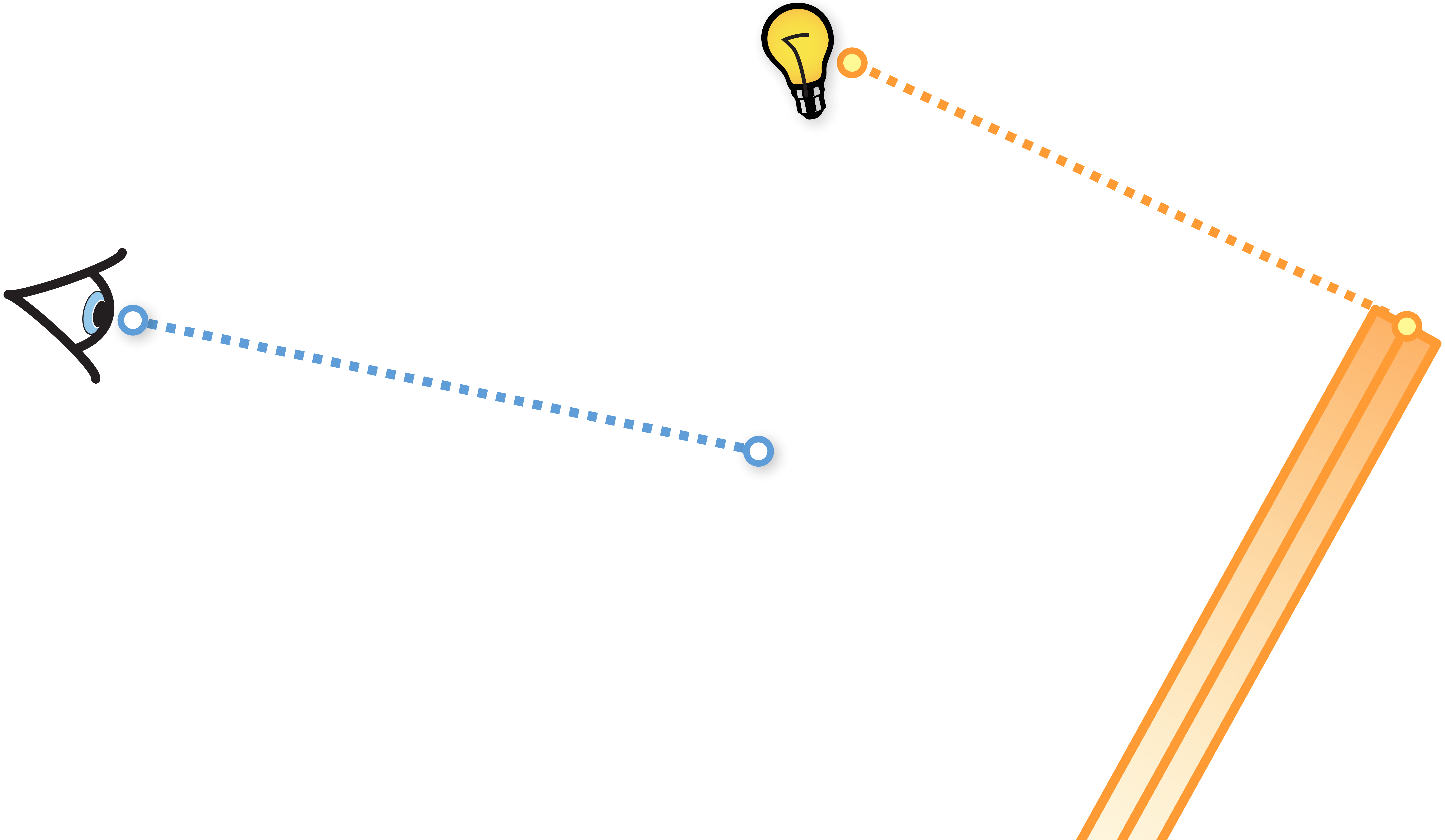
Photon Beams

[Bitterli & Jarosz 17]



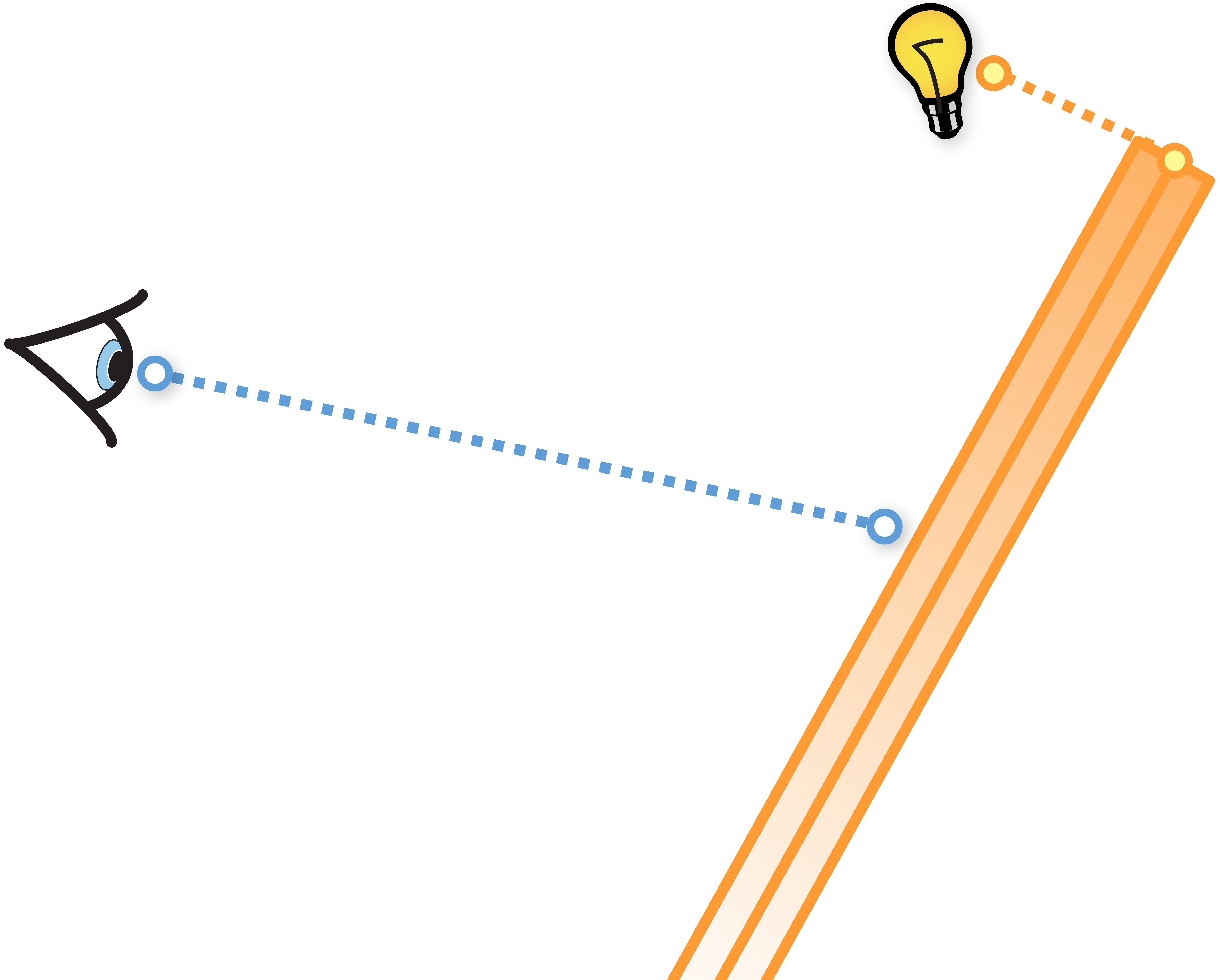
Photon Beams

[Bitterli & Jarosz 17]



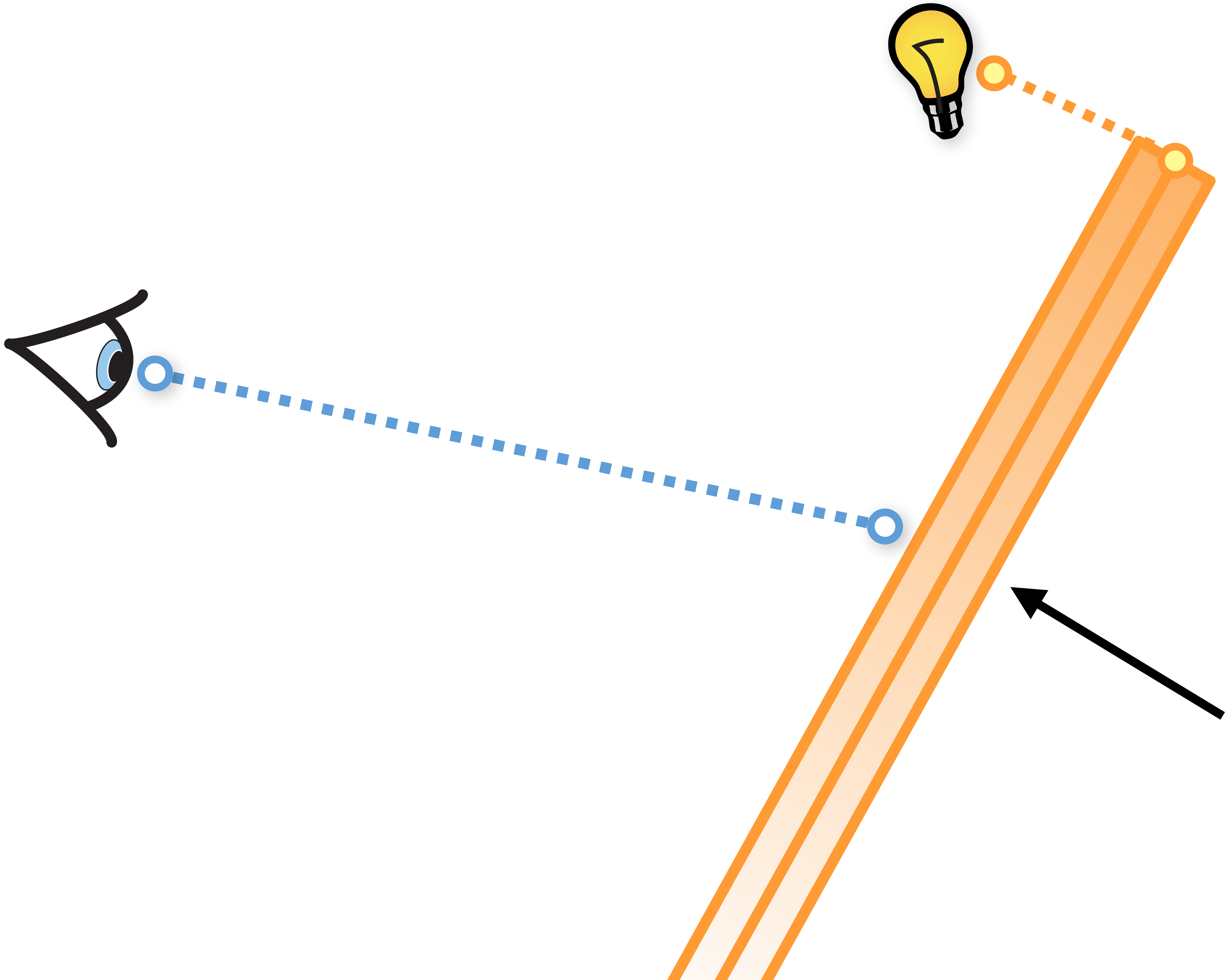
Photon Beams

[Bitterli & Jarosz 17]



Photon Beams

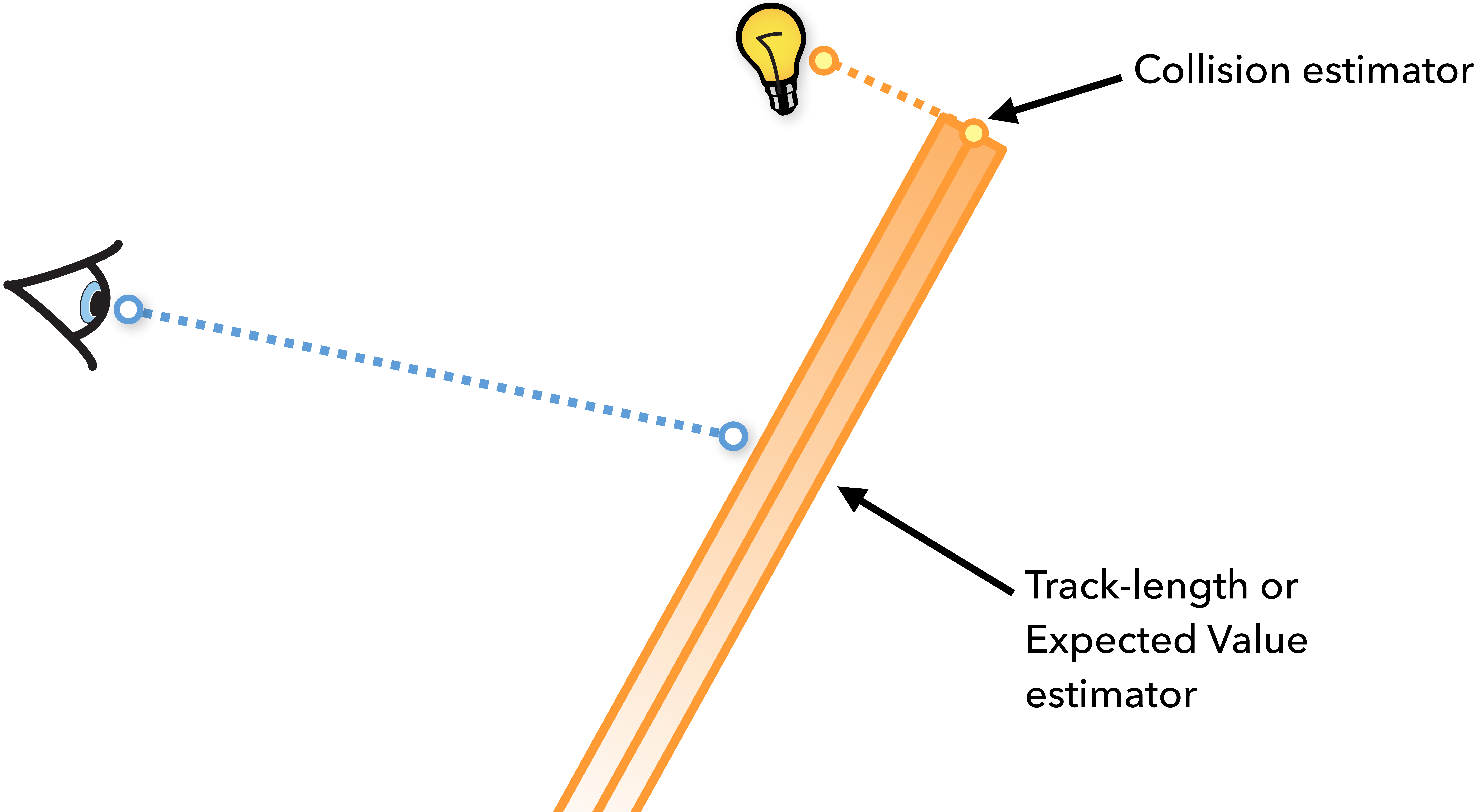
[Bitterli & Jarosz 17]



Track-length or Expected Value estimator

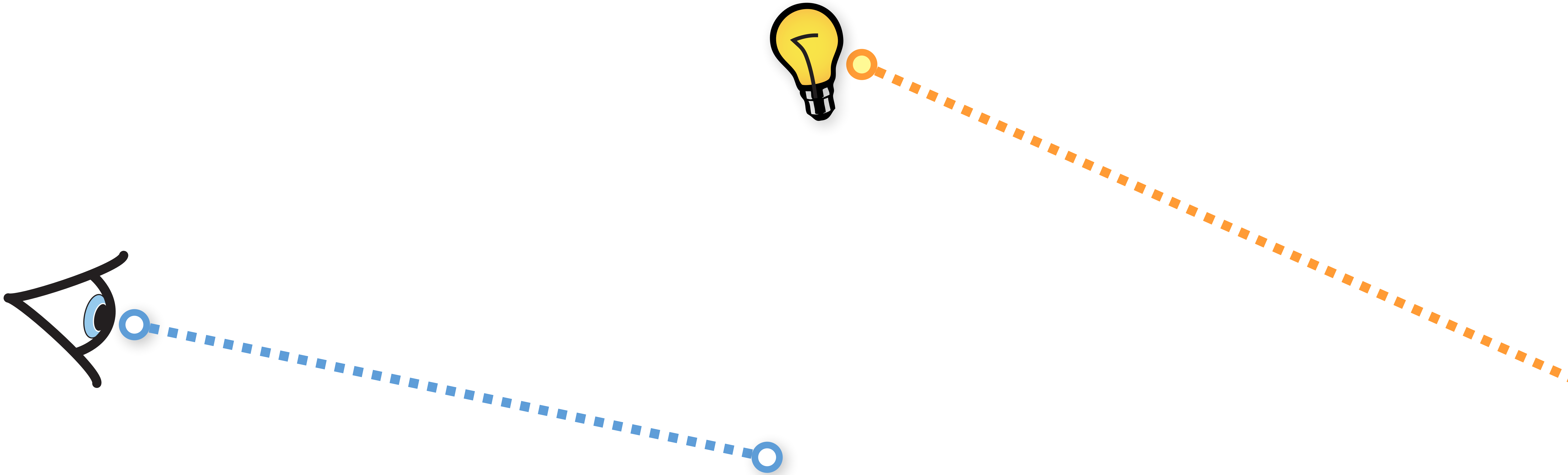
Photon Beams

[Bitterli & Jarosz 17]



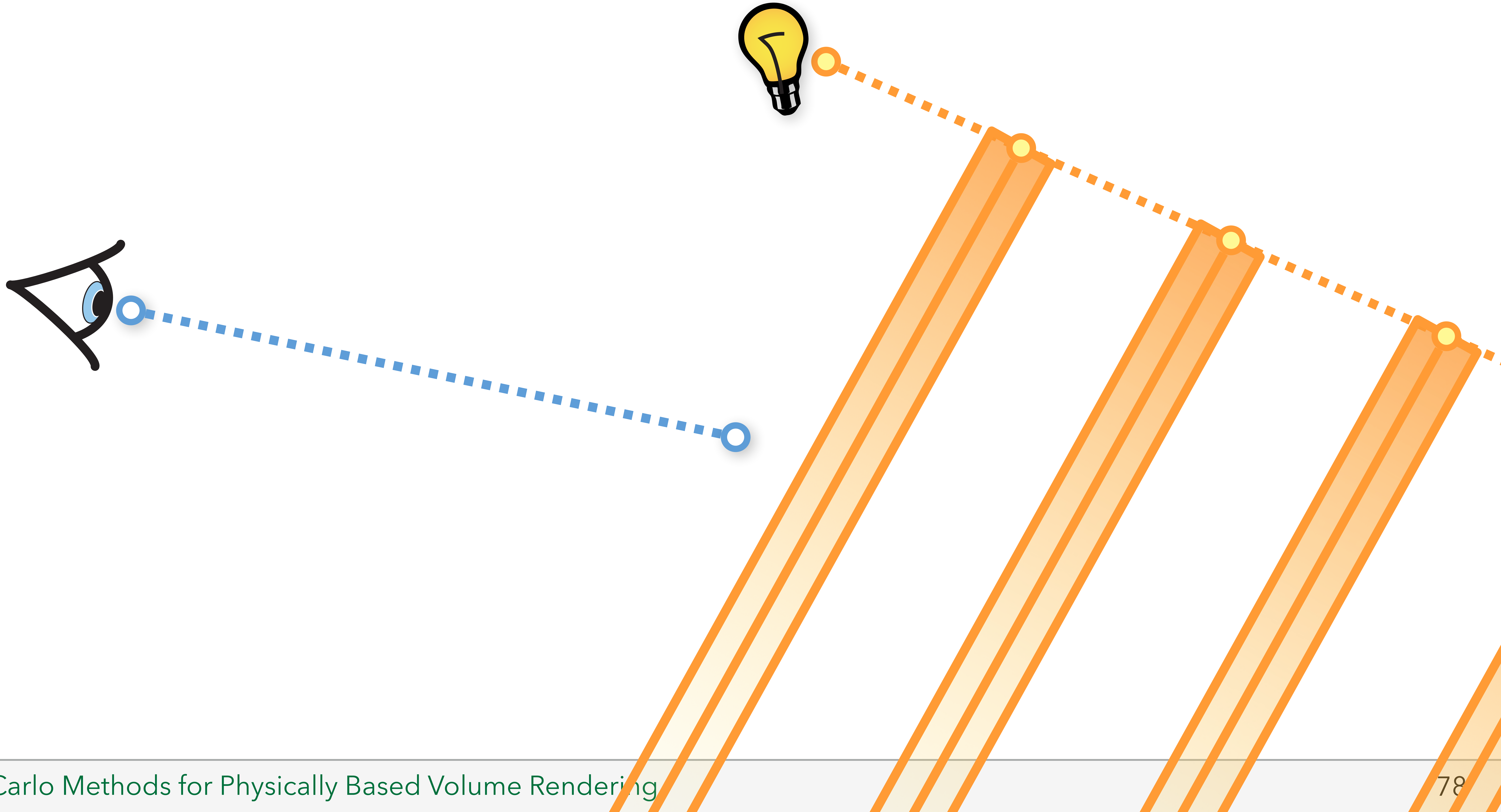
Beam Marching

[Bitterli & Jarosz 17]



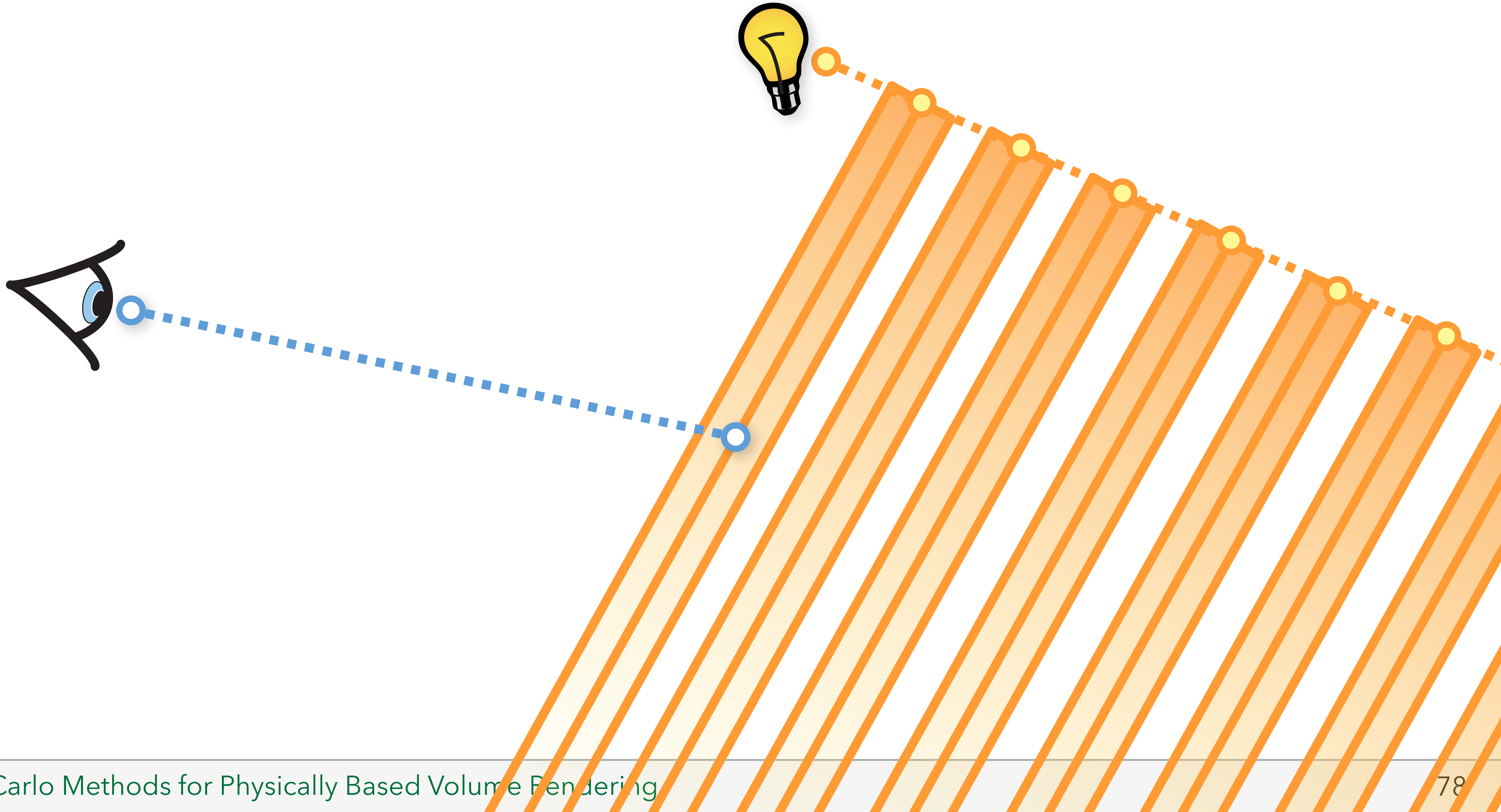
Beam Marching

[Bitterli & Jarosz 17]



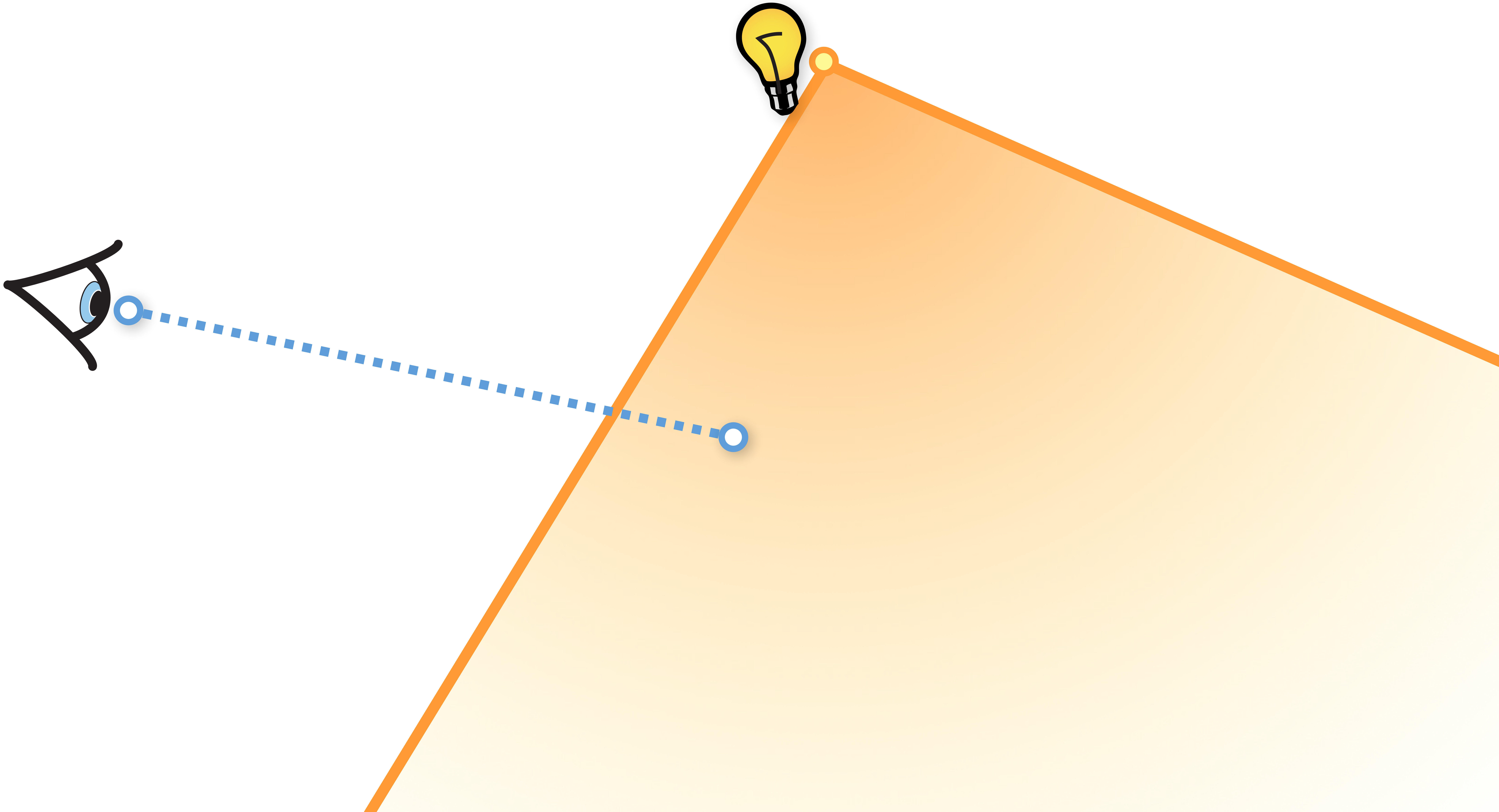
Beam Marching

[Bitterli & Jarosz 17]



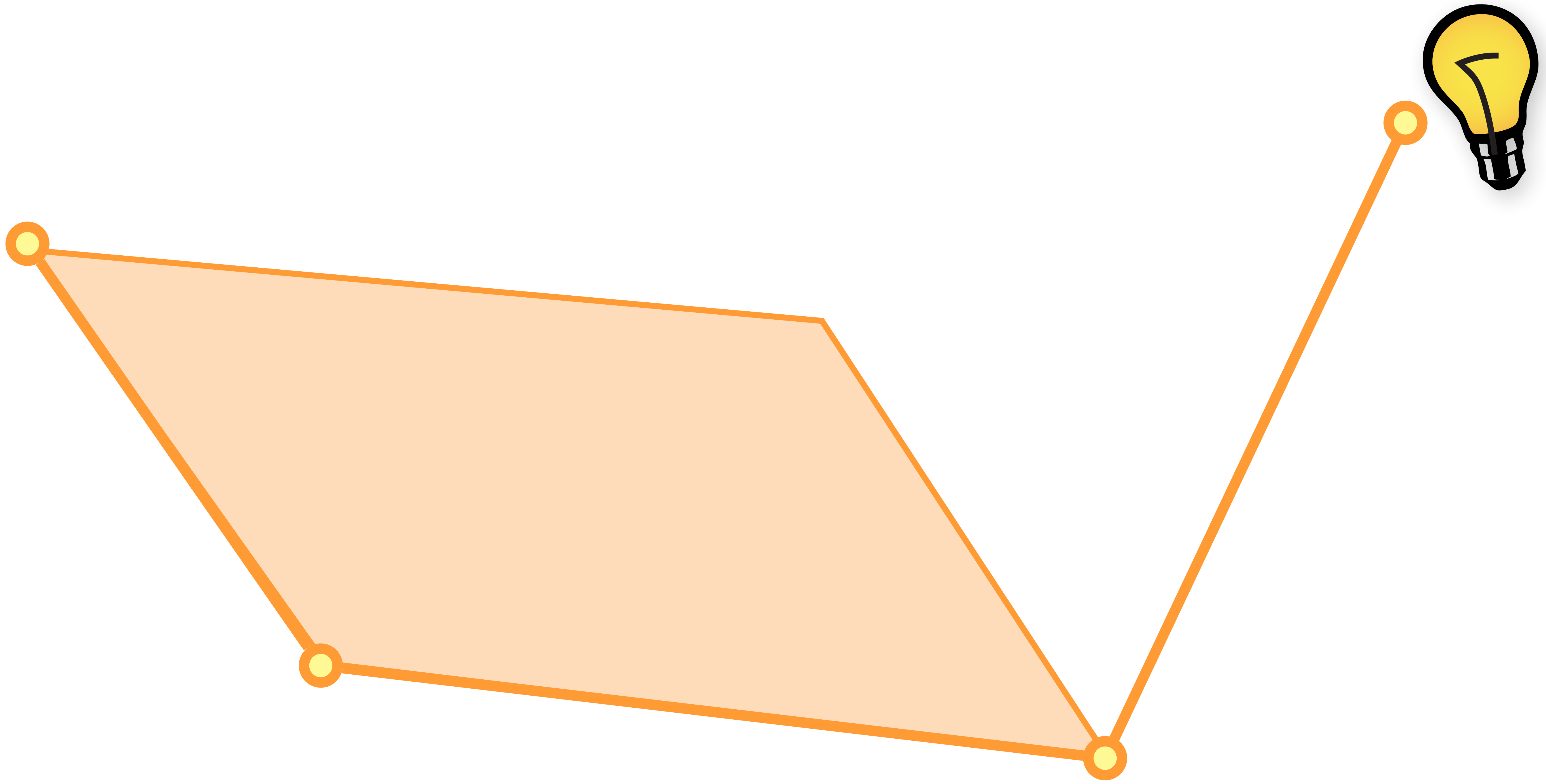
Photon Plane

[Bitterli & Jarosz 17]



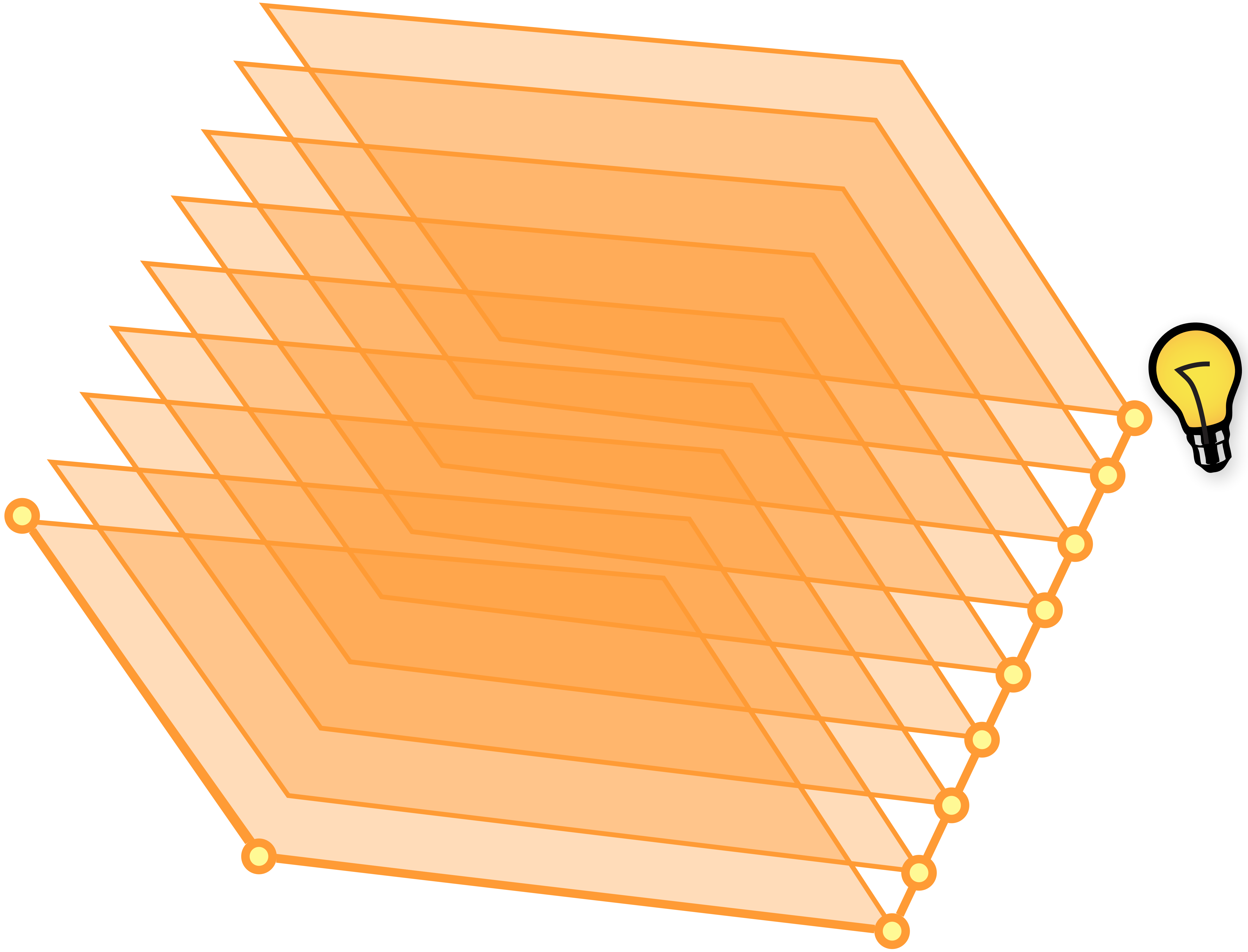
Plane Marching

[Bitterli & Jarosz 17]



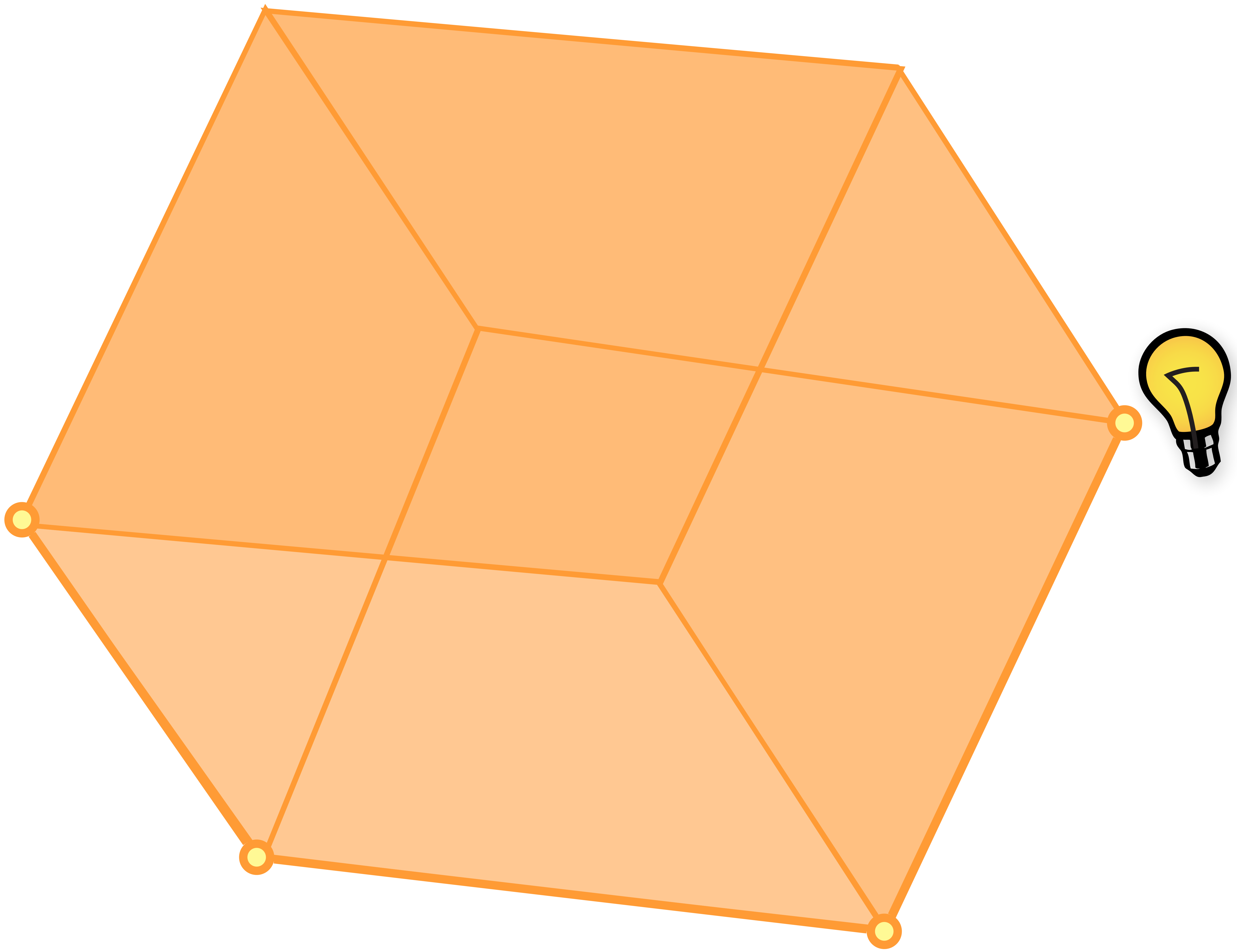
Plane Marching

[Bitterli & Jarosz 17]



Photon Volume

[Bitterli & Jarosz 17]




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

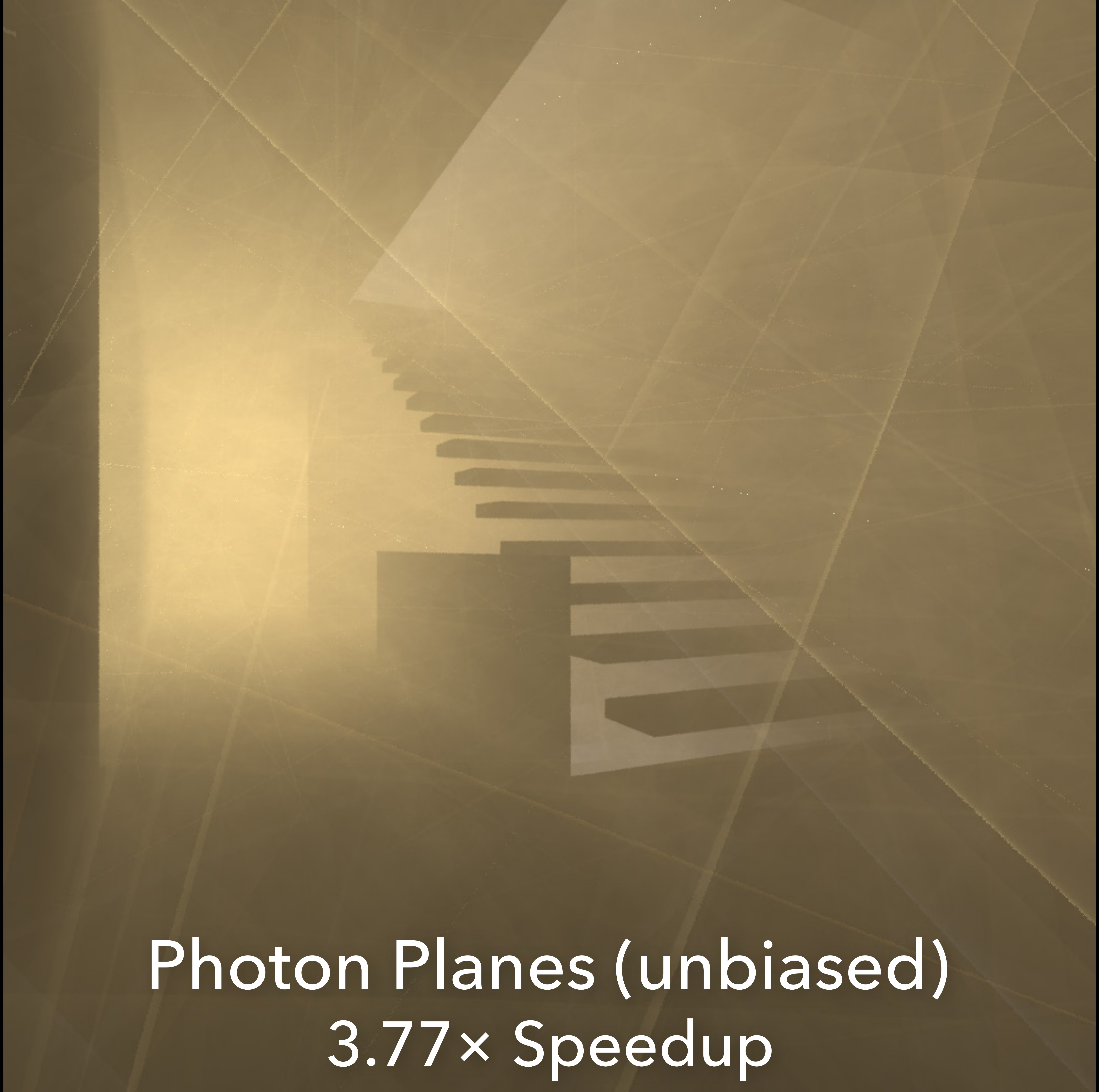

Photon Points
(biased)
Photon Beams
(biased)
Photon Planes
(unbiased)
Photon Volumes
(unbiased)


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


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


Full Light Transport


Photon Beams (1D blur)

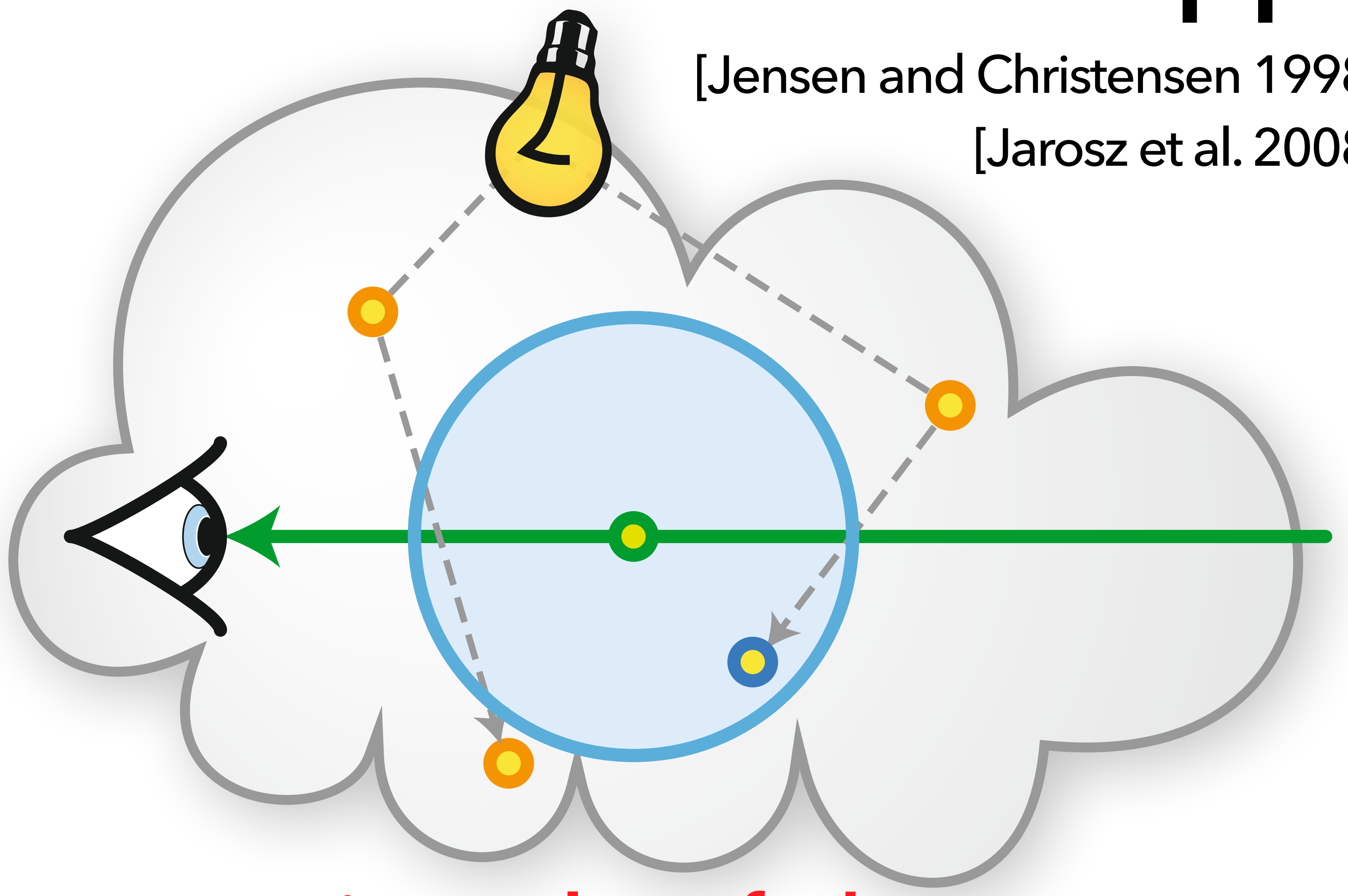

Photon Planes (unbiased)
3.77× Speedup

Photon Planes (1D blur)
14.14× Speedup


Photon Beams (1D blur)

Volumetric Photon Mapping

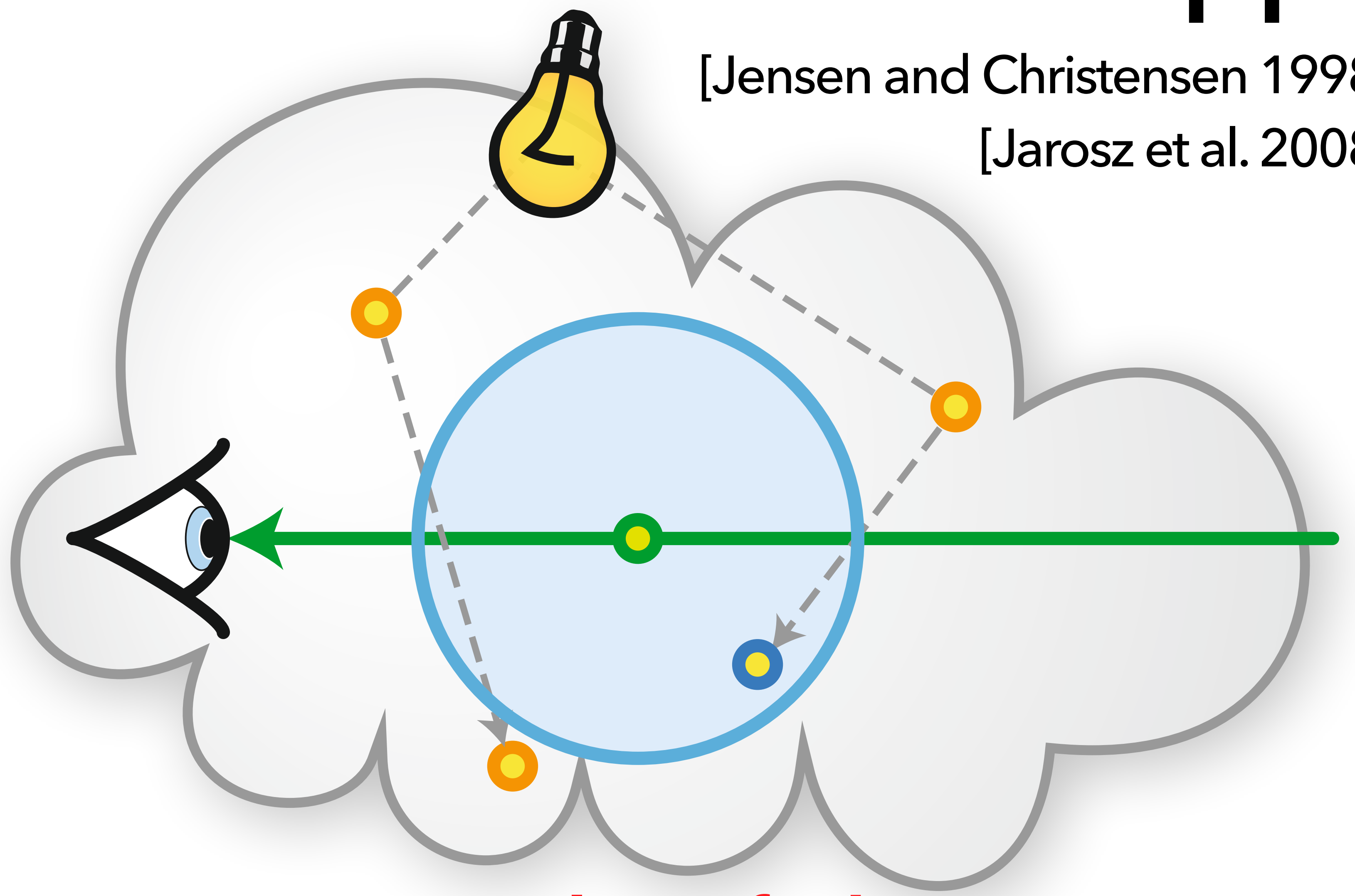
[Jensen and Christensen 1998]
[Jarosz et al. 2008]



requires a lot of photons

Volumetric Photon Mapping

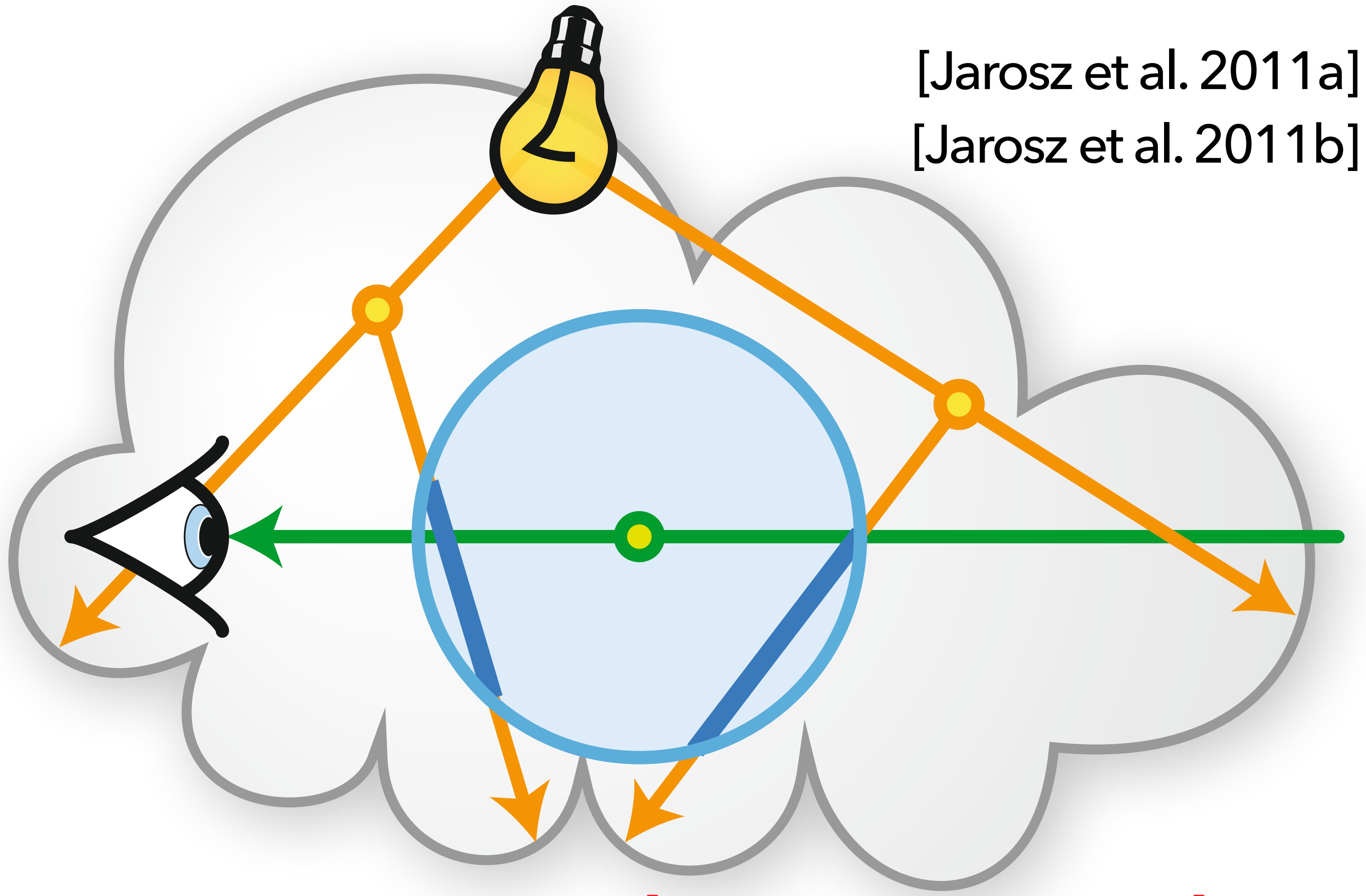
[Jensen and Christensen 1998]
[Jarosz et al. 2008]



requires a lot of photons

Photon Beams

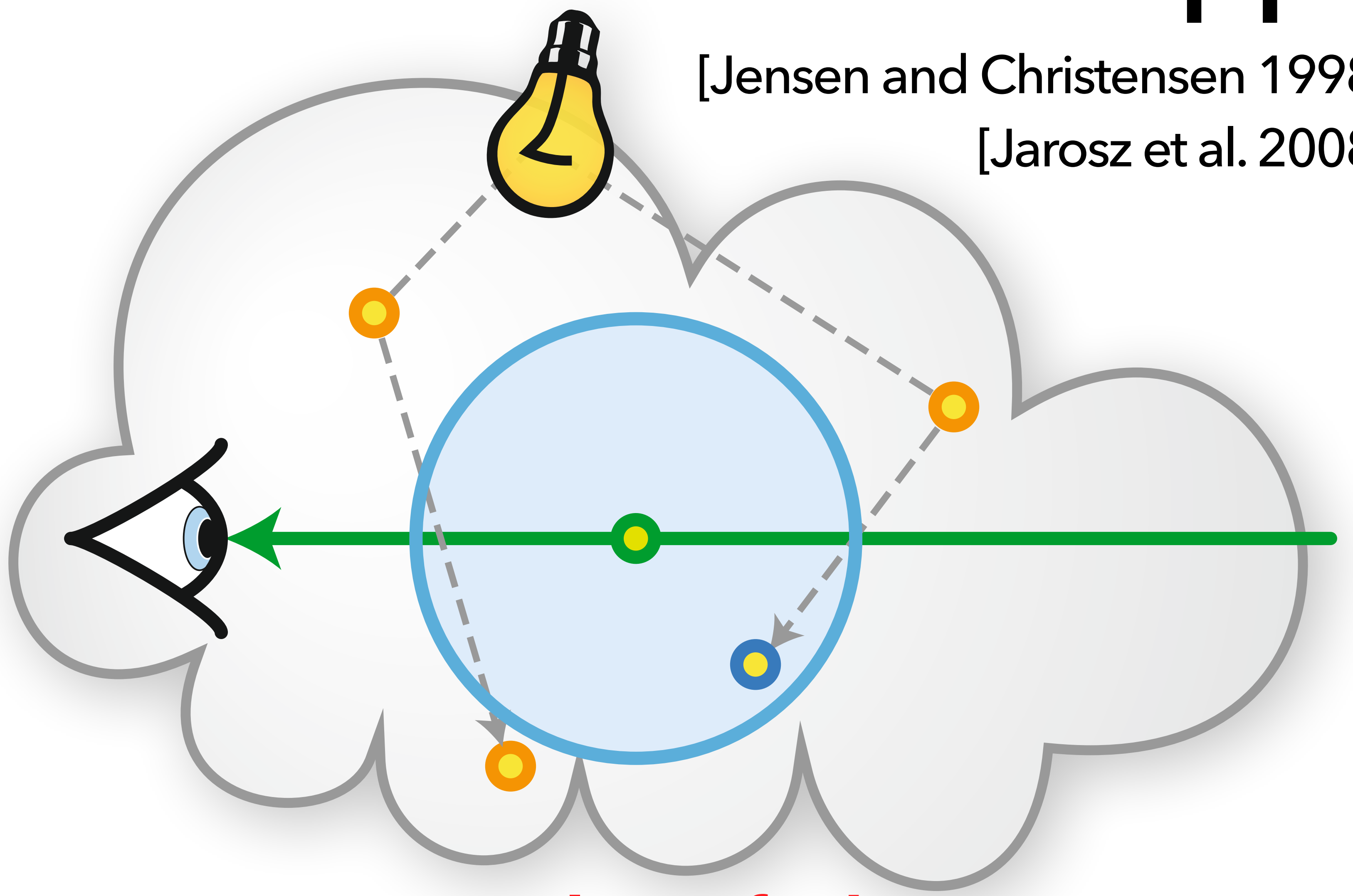
[Jarosz et al. 2011a]
[Jarosz et al. 2011b]



great caustics, multi-scattering slow

Volumetric Photon Mapping

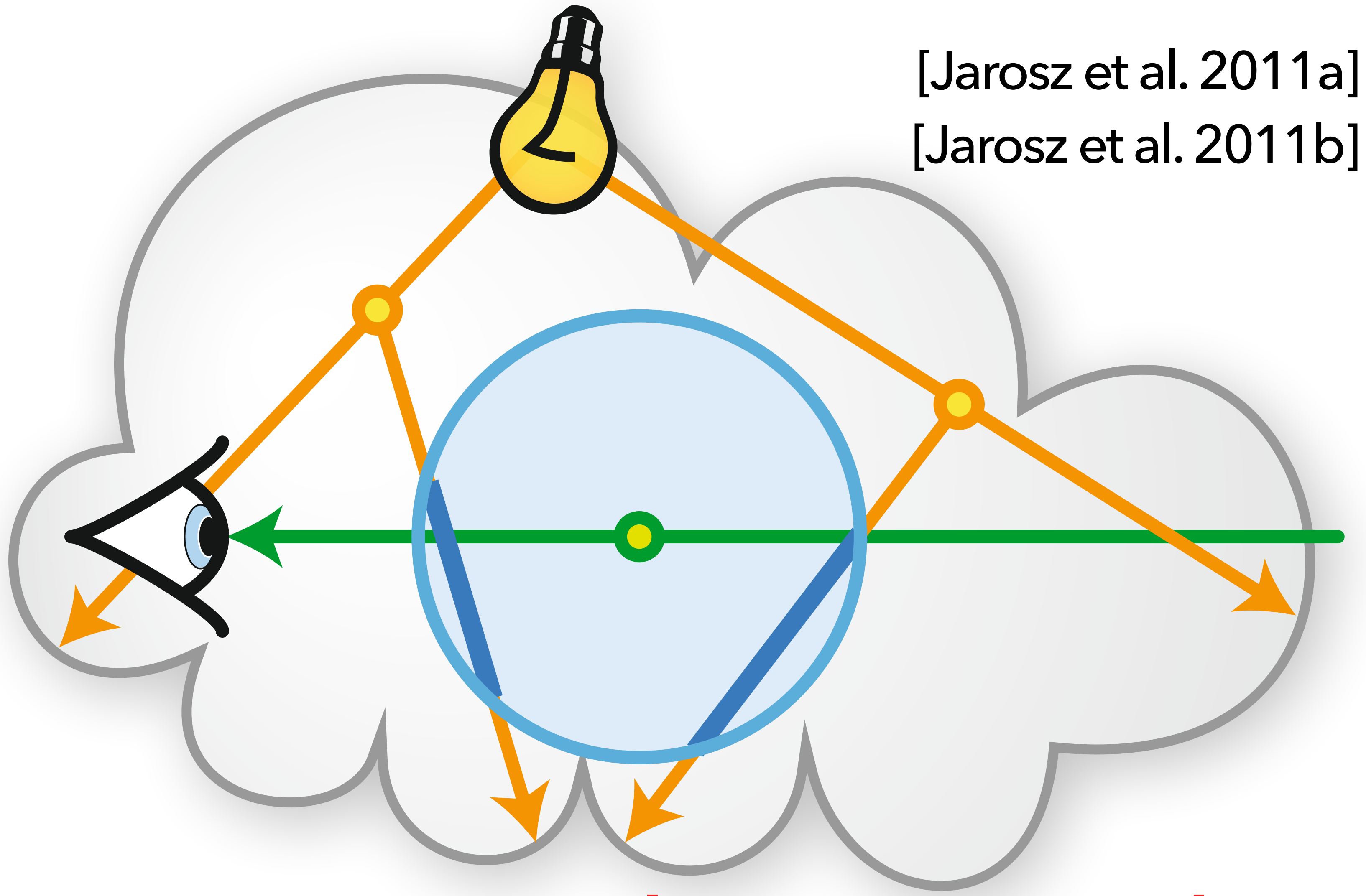
[Jensen and Christensen 1998]
[Jarosz et al. 2008]



requires a lot of photons

Photon Beams

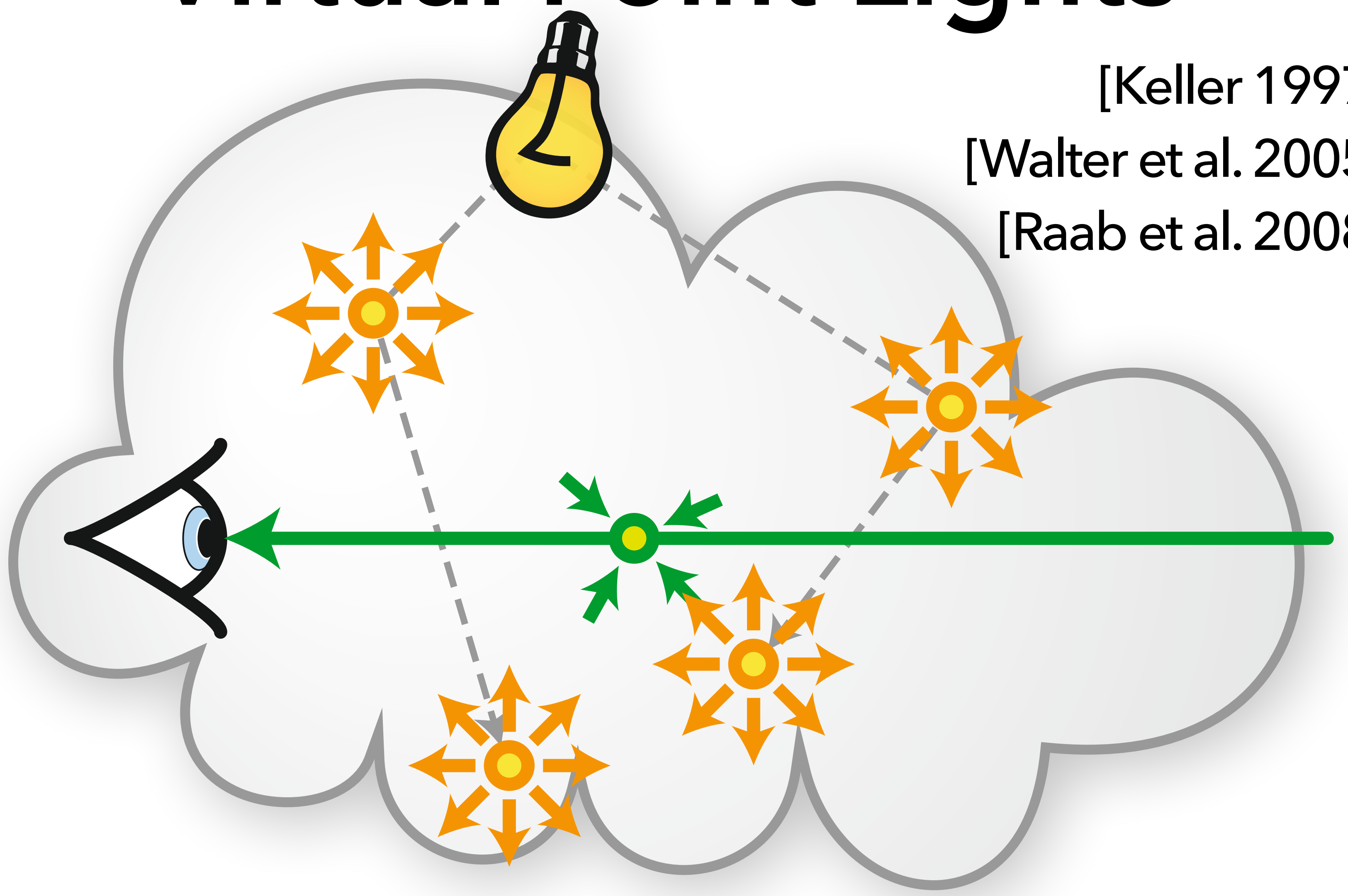
[Jarosz et al. 2011a]
[Jarosz et al. 2011b]



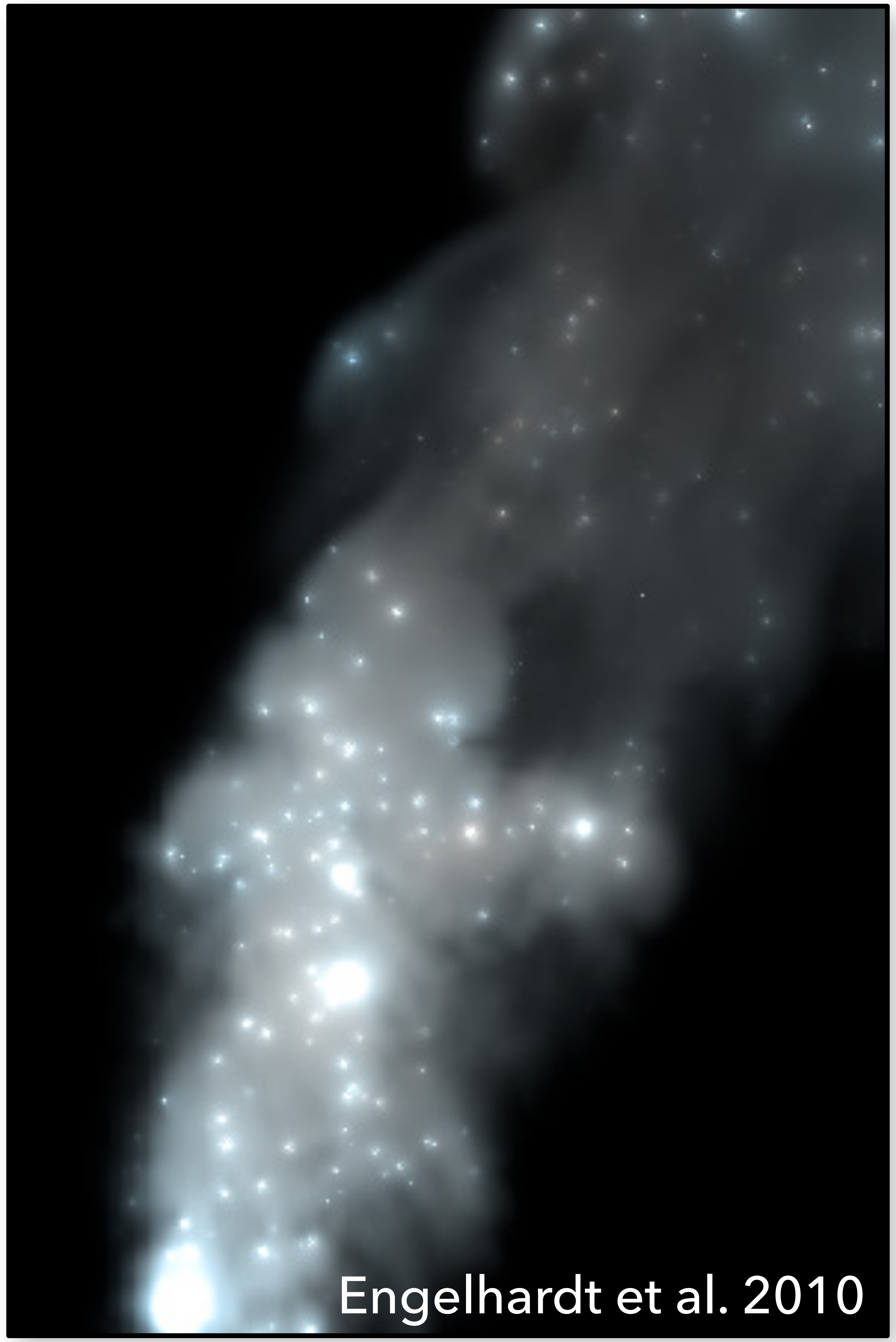
great caustics, multi-scattering slow

Virtual Point Lights

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

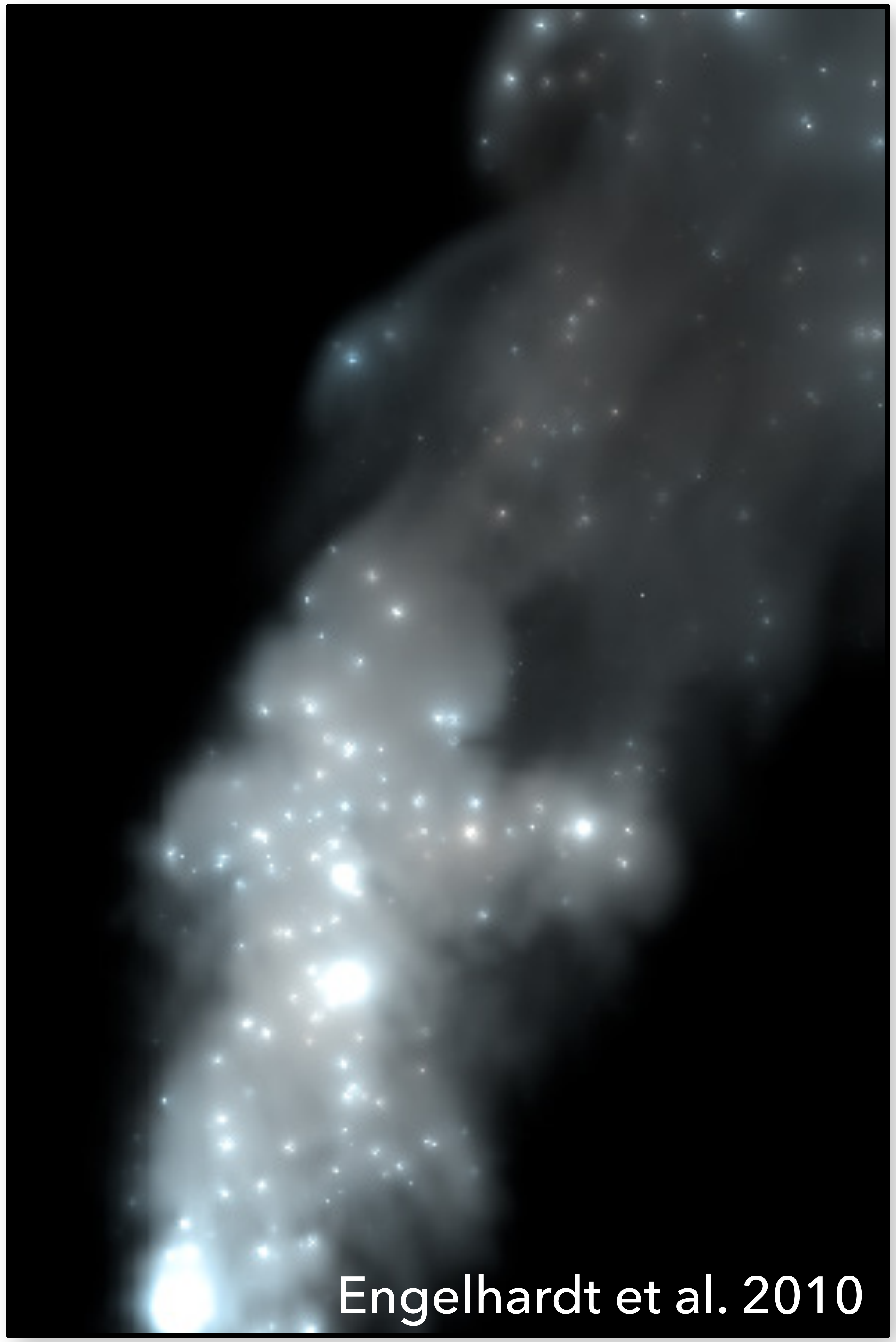


Singularities or Energy Loss



VPLs - no clamping

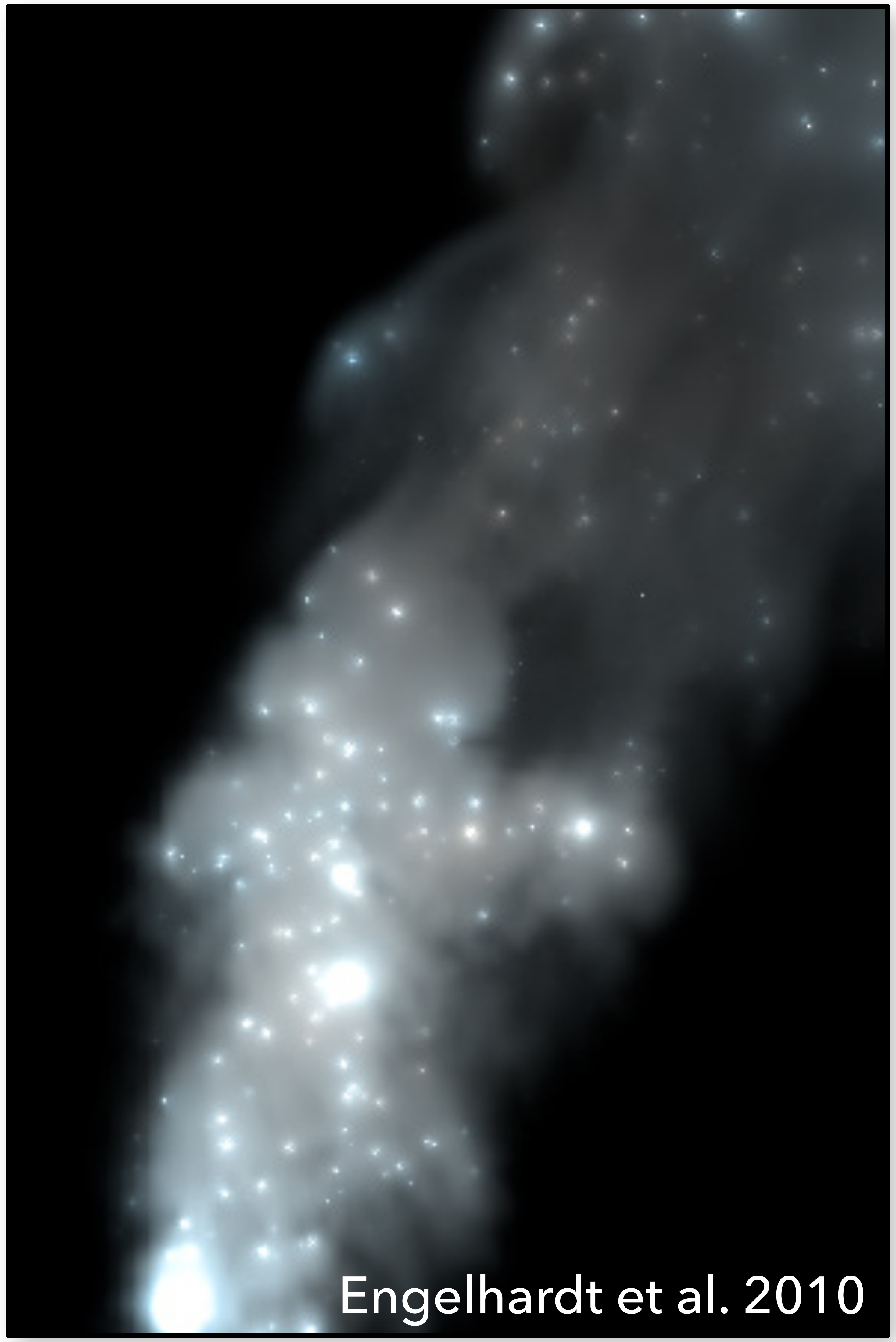
Singularities or Energy Loss



VPLs - no clamping

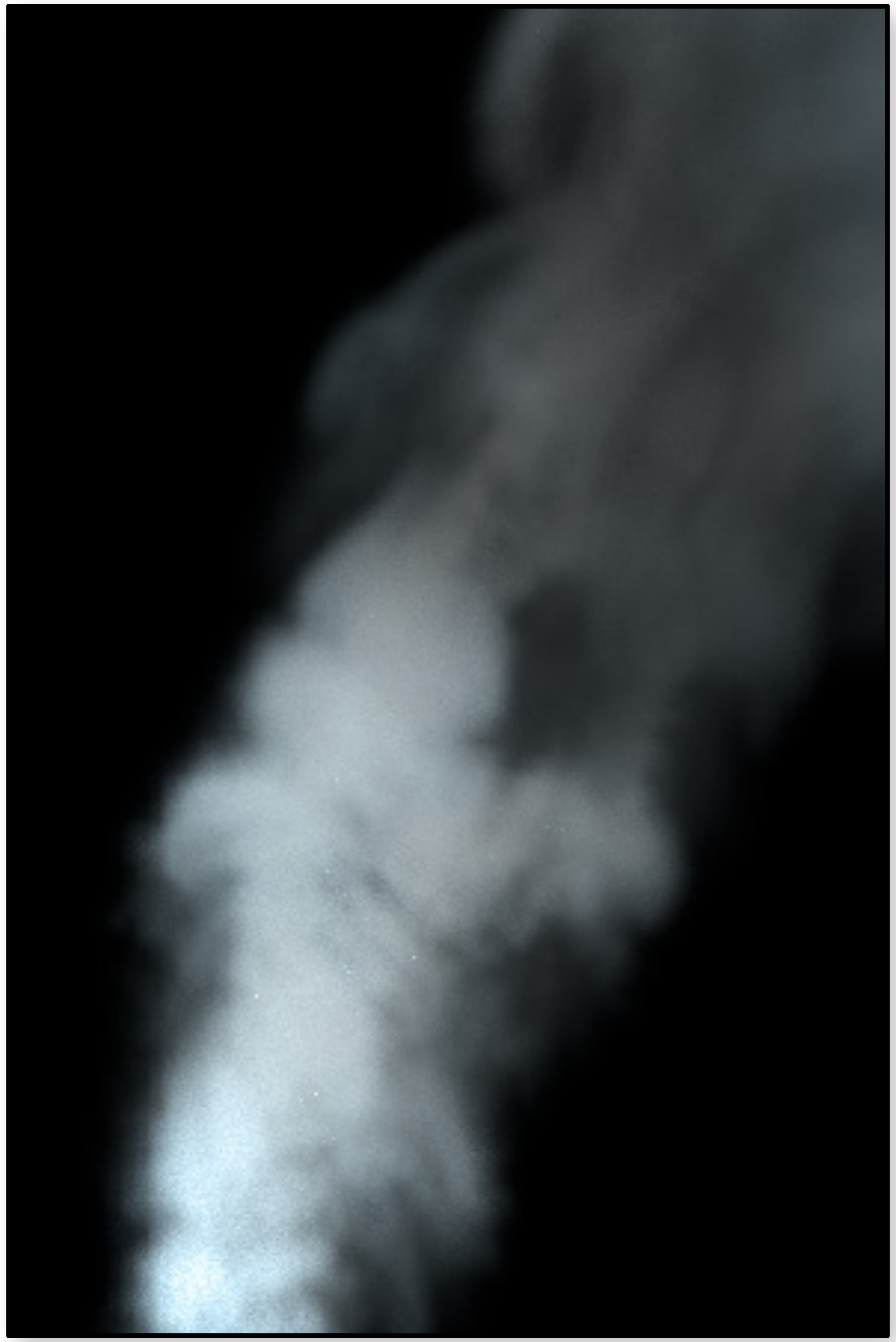
VPLs - clamping

Singularities or Energy Loss

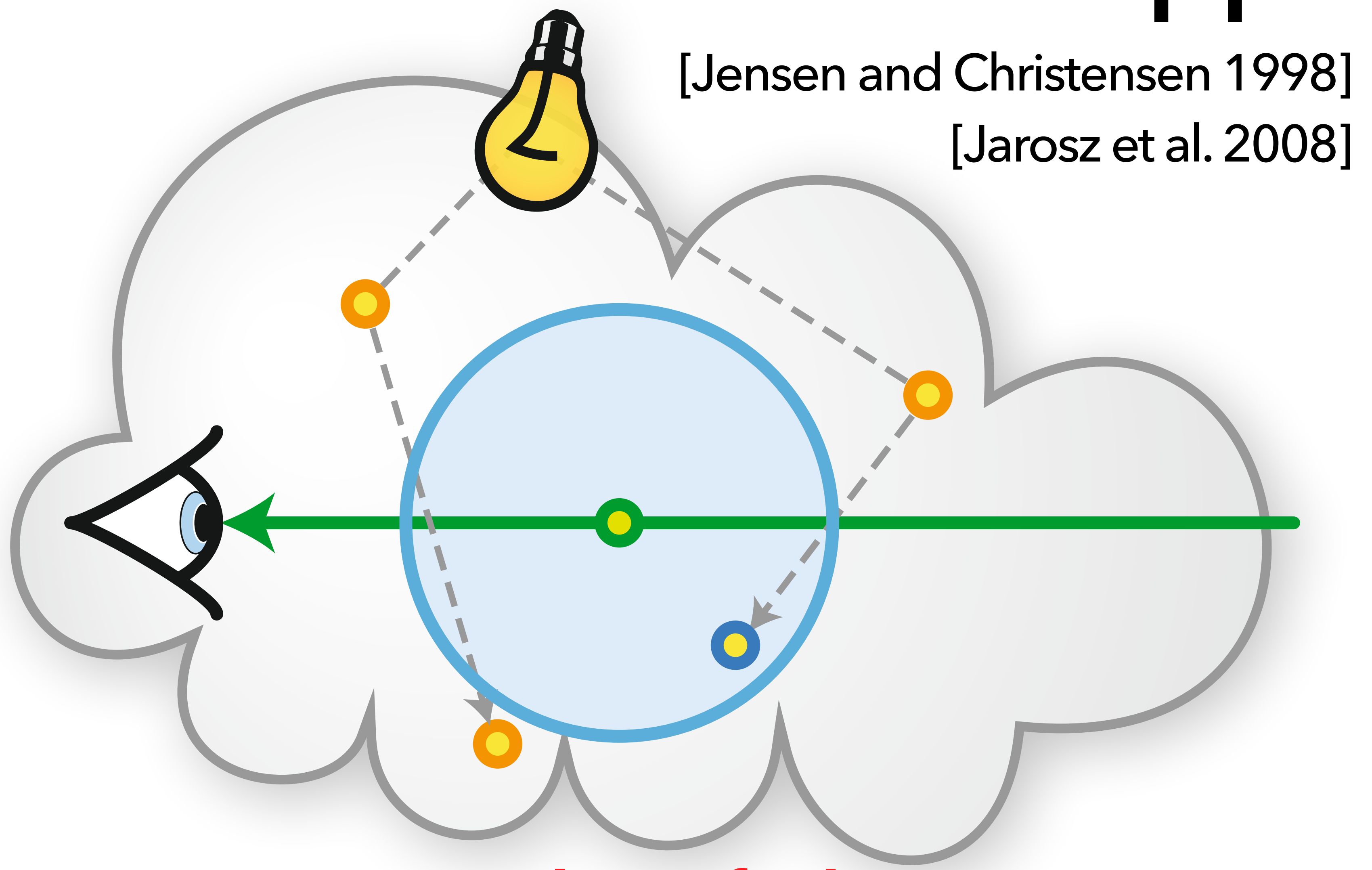


VPLs - no clamping

VPLs - clamping

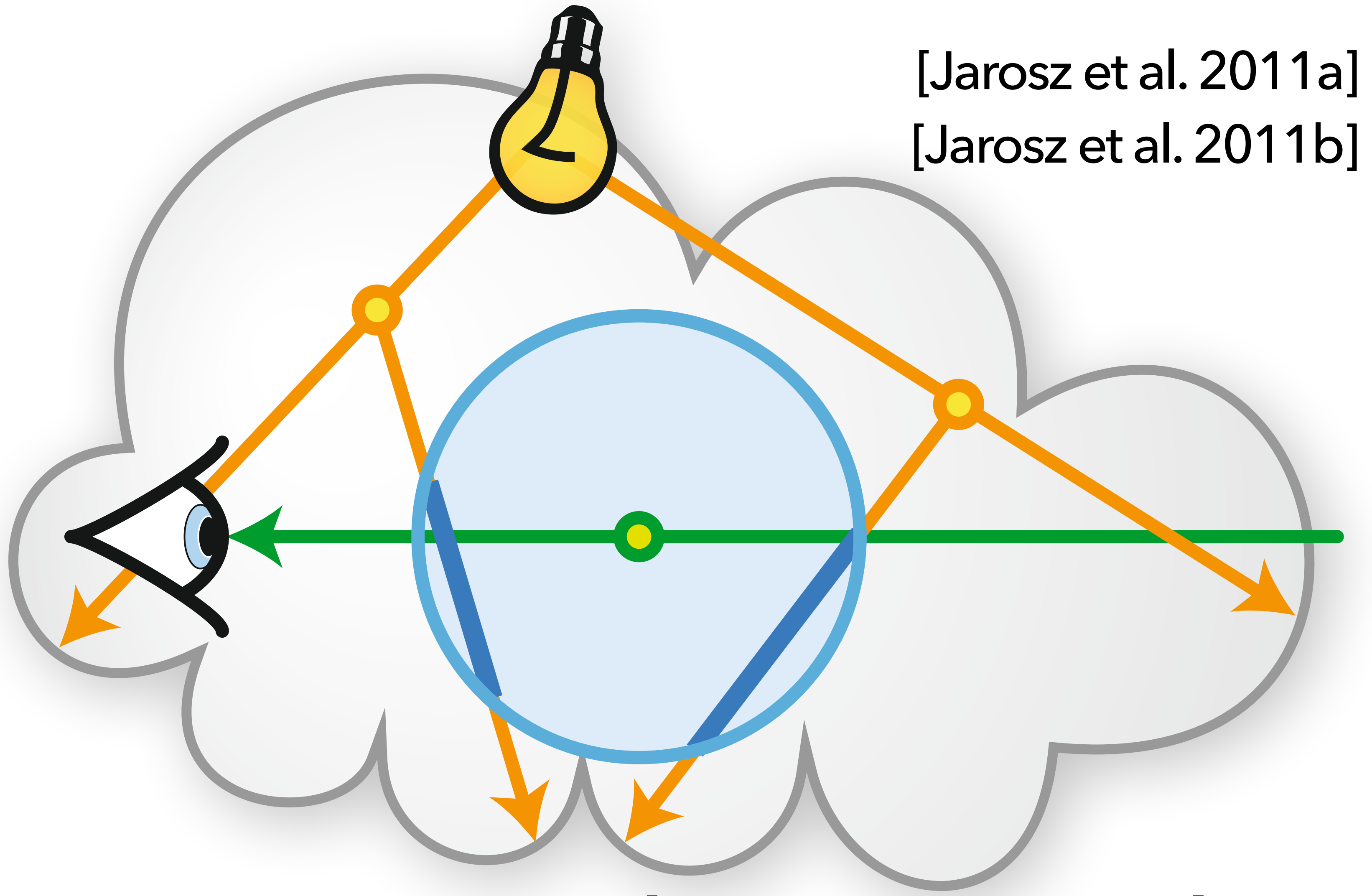

Reference

Volumetric Photon Mapping



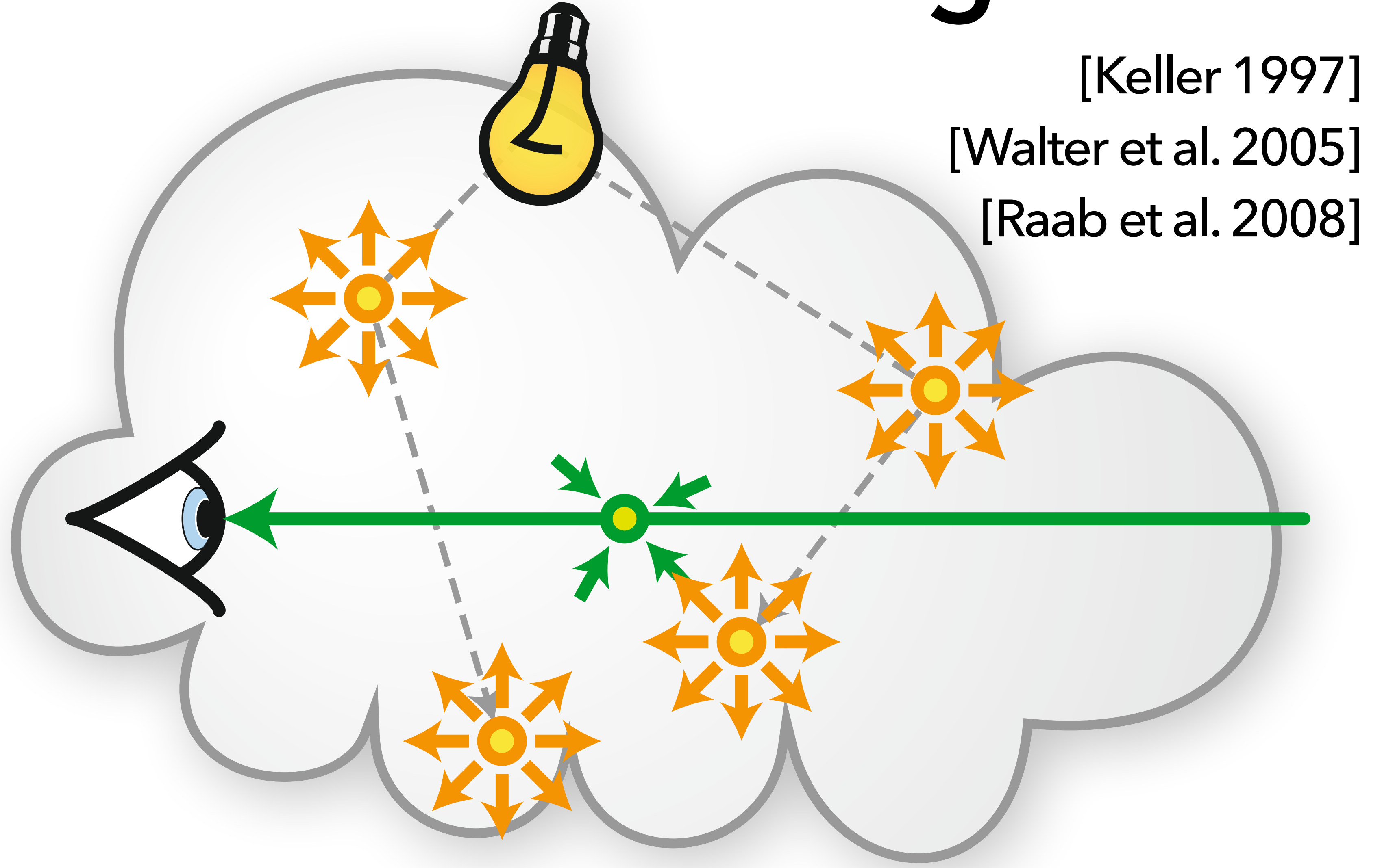
requires a lot of photons

Photon Beams

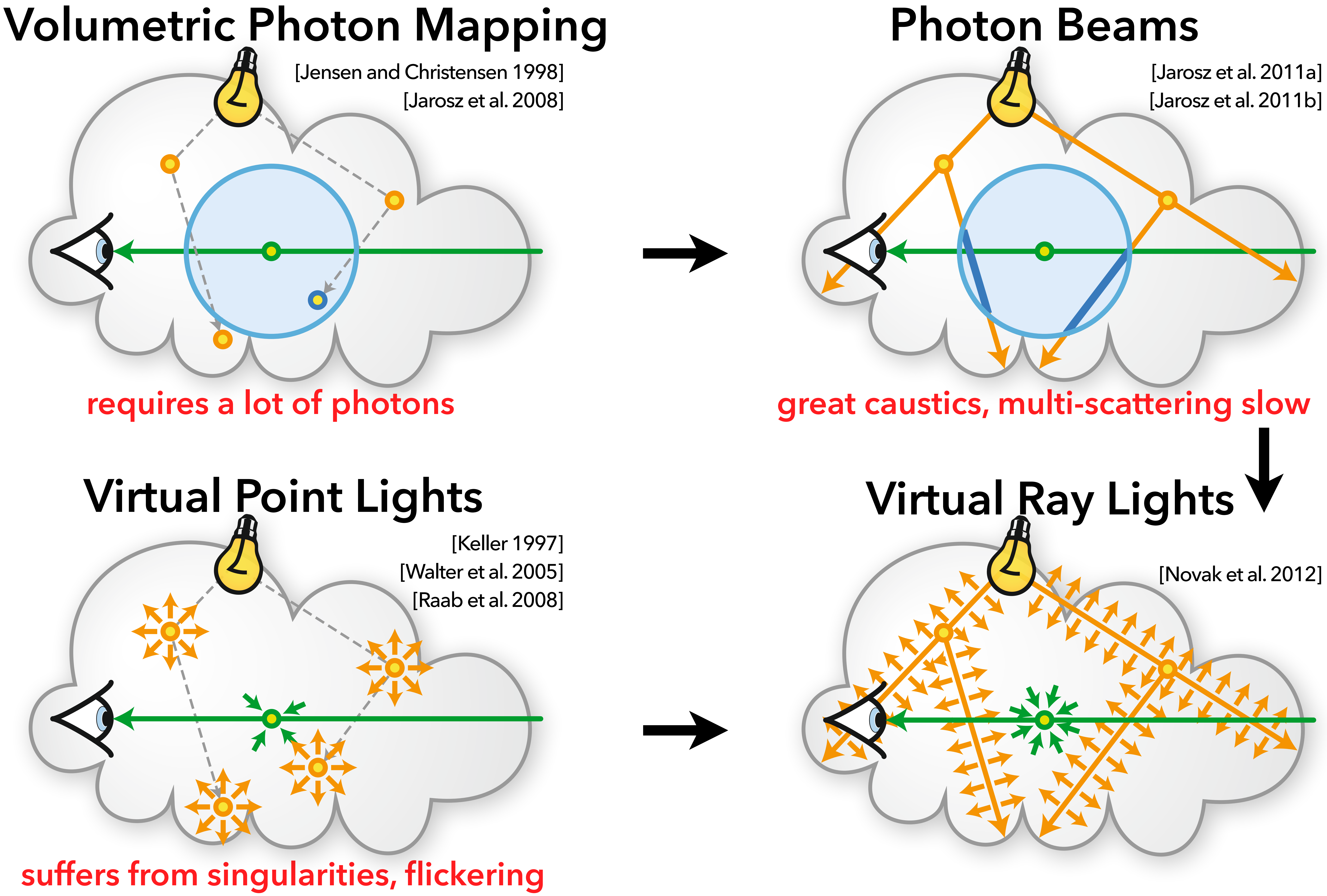


great caustics, multi-scattering slow

Virtual Point Lights



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

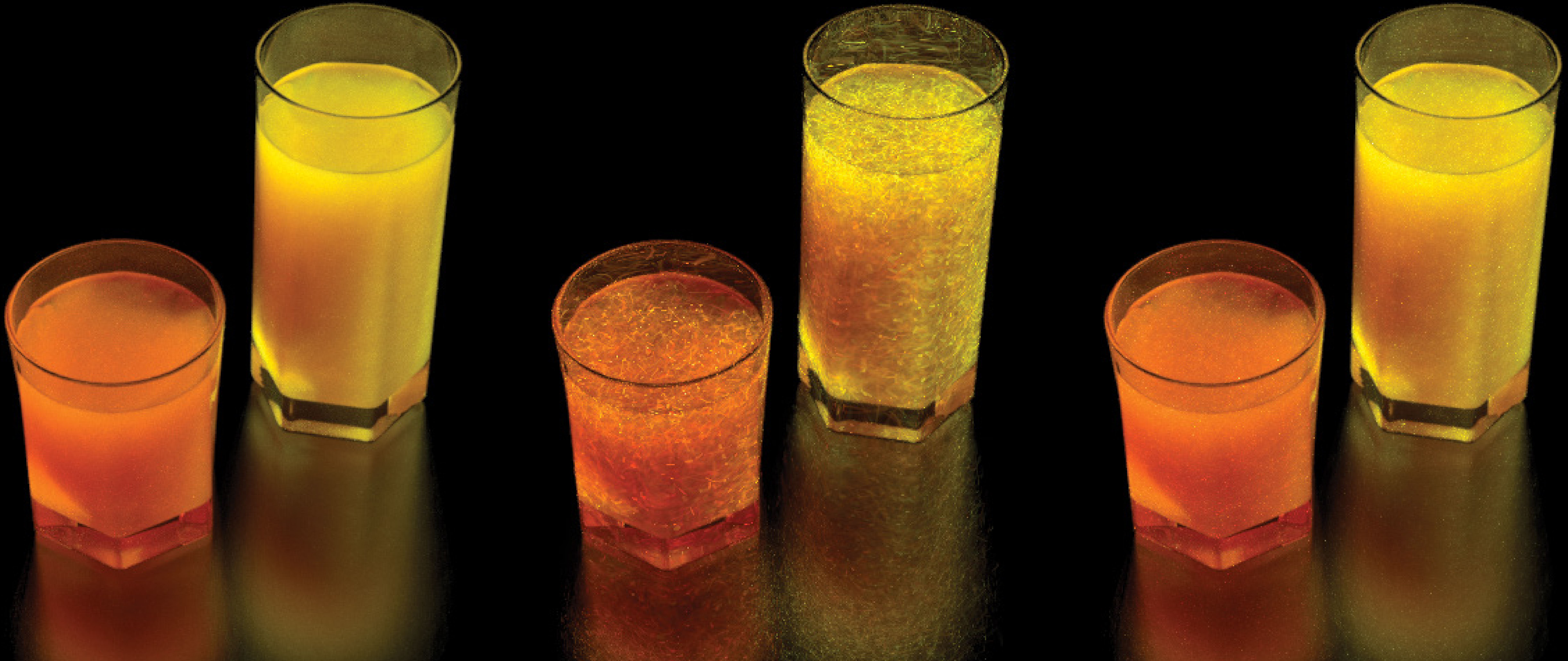
(Photon Beams)

Multiple scattering

Comparison

Multiple scattering

Multiple Scattering Only



Multiple Scattering Only

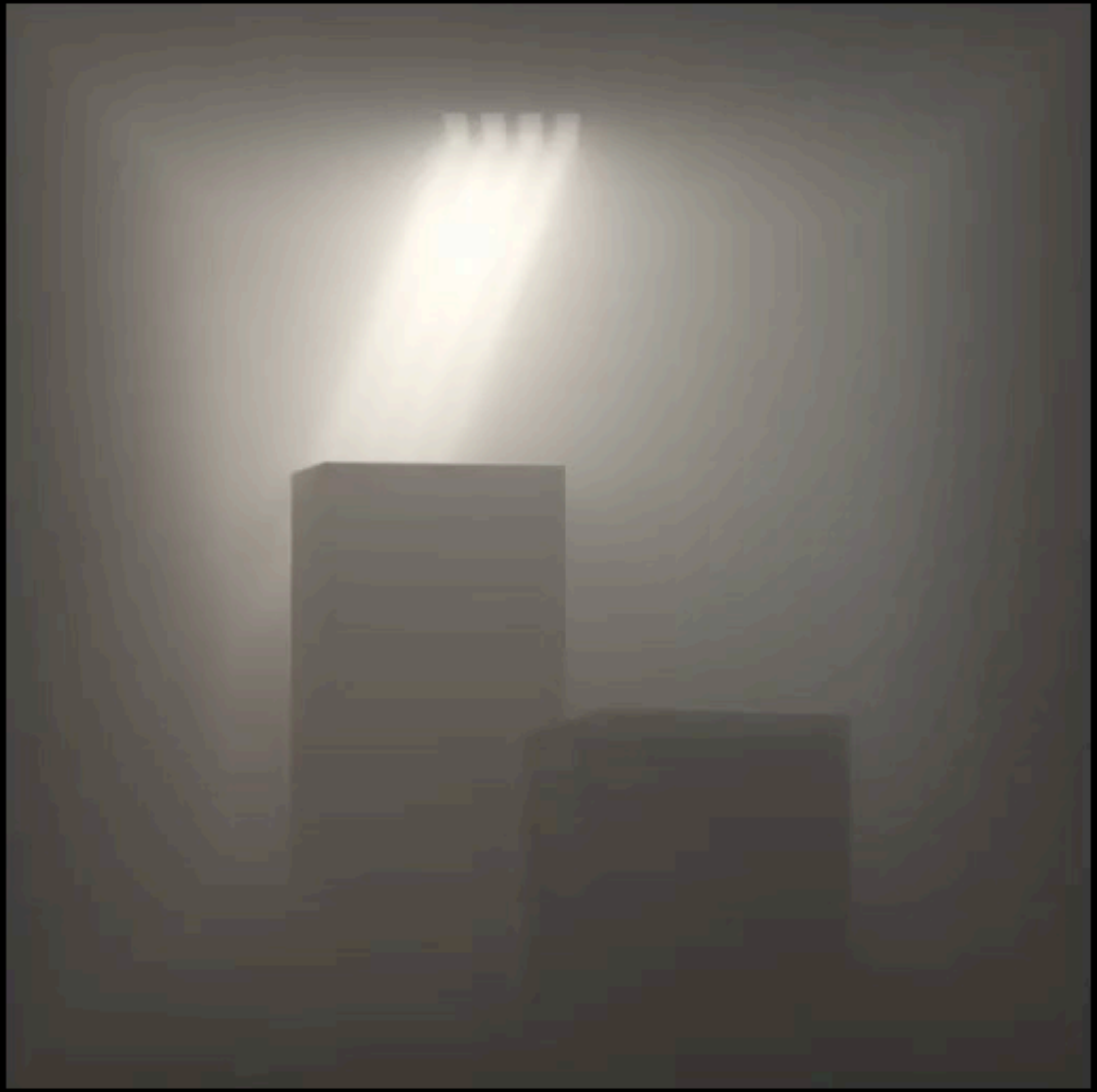
Virtual Ray Lights

Progressive Photon Beams

Virtual Point Lights

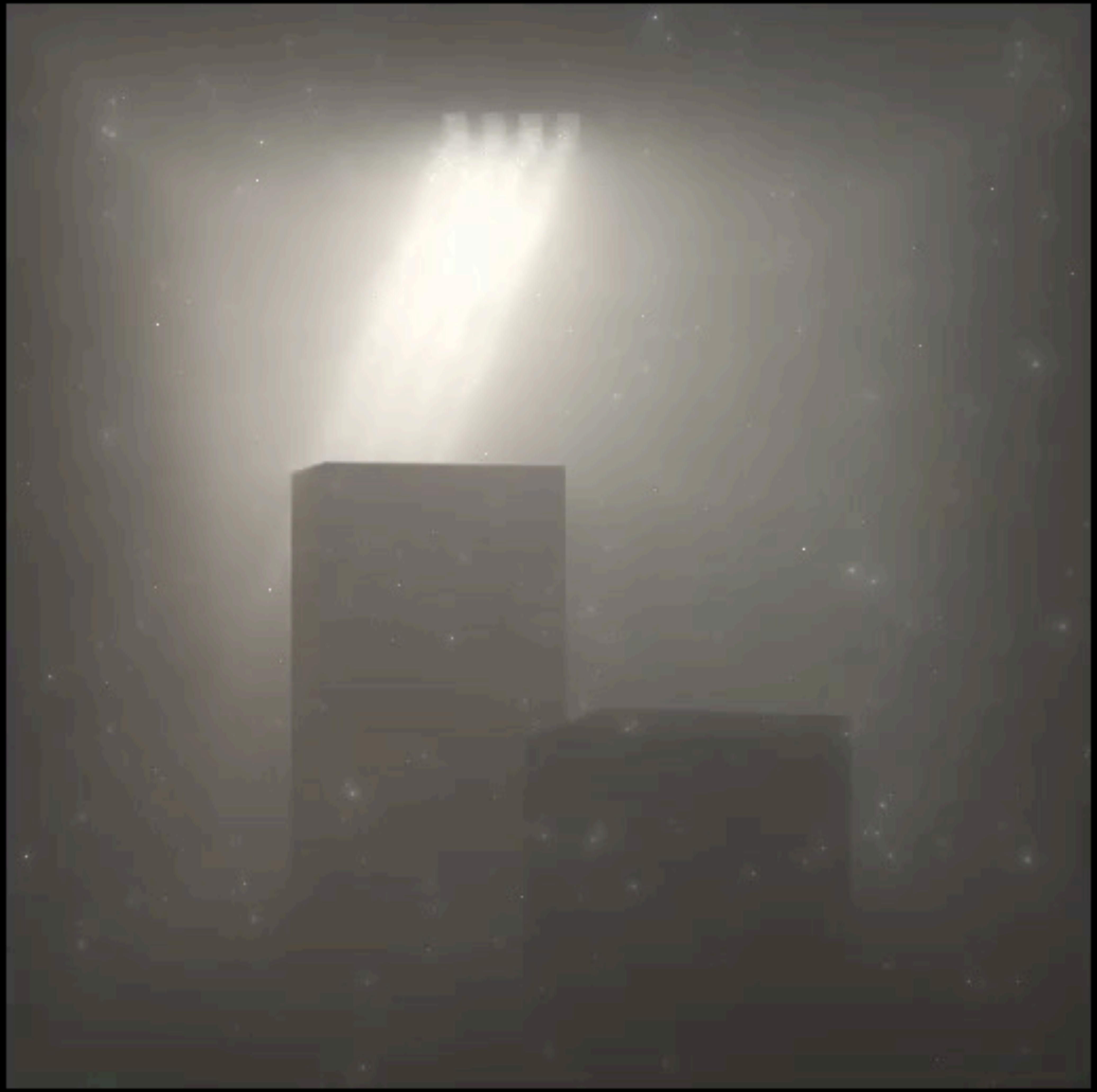
Temporal Stability

Virtual Ray Lights



1 minute/frame

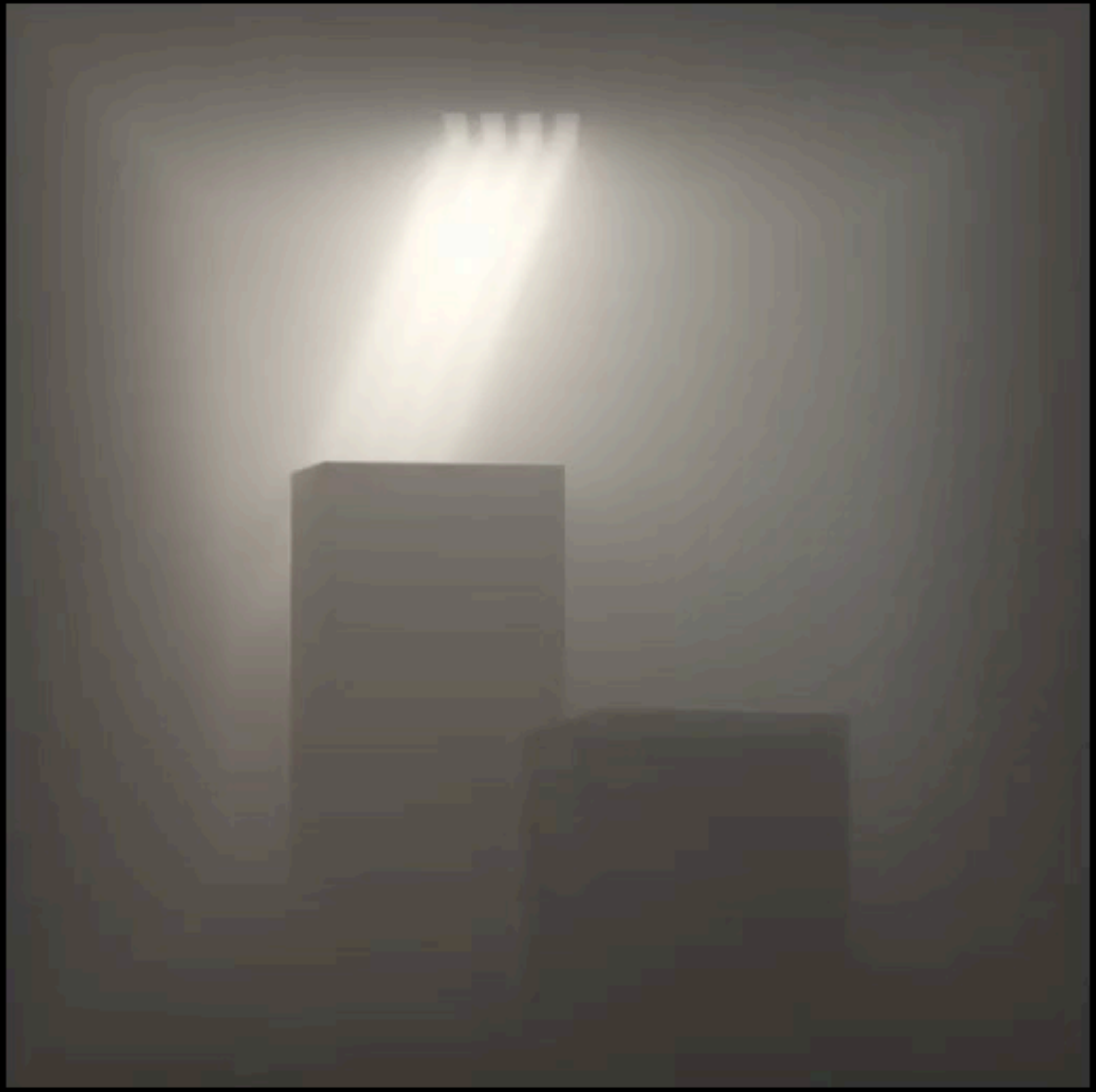
Virtual Point Lights



1 minute/frame

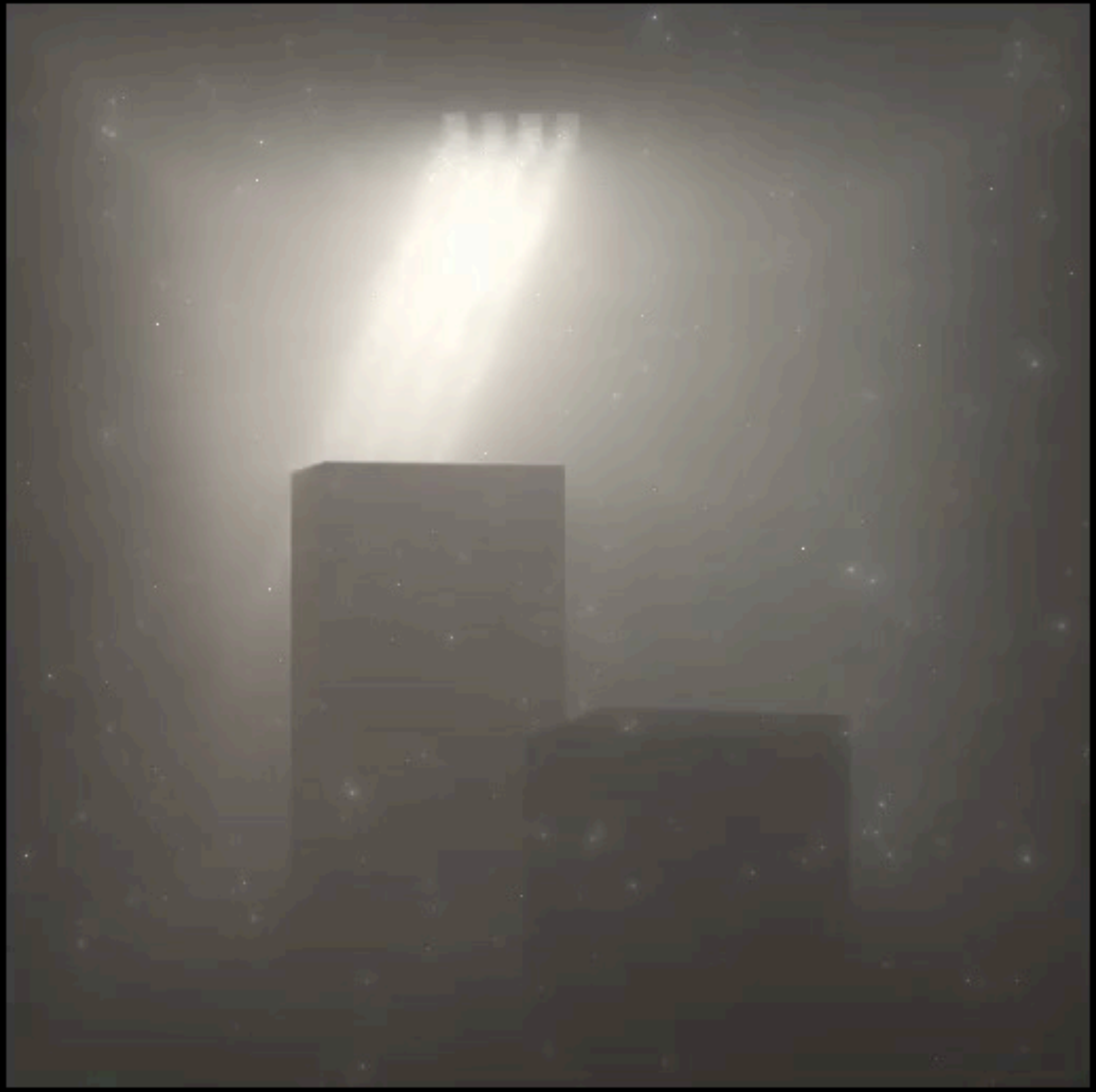
Temporal Stability

Virtual Ray Lights



1 minute/frame

Virtual Point Lights

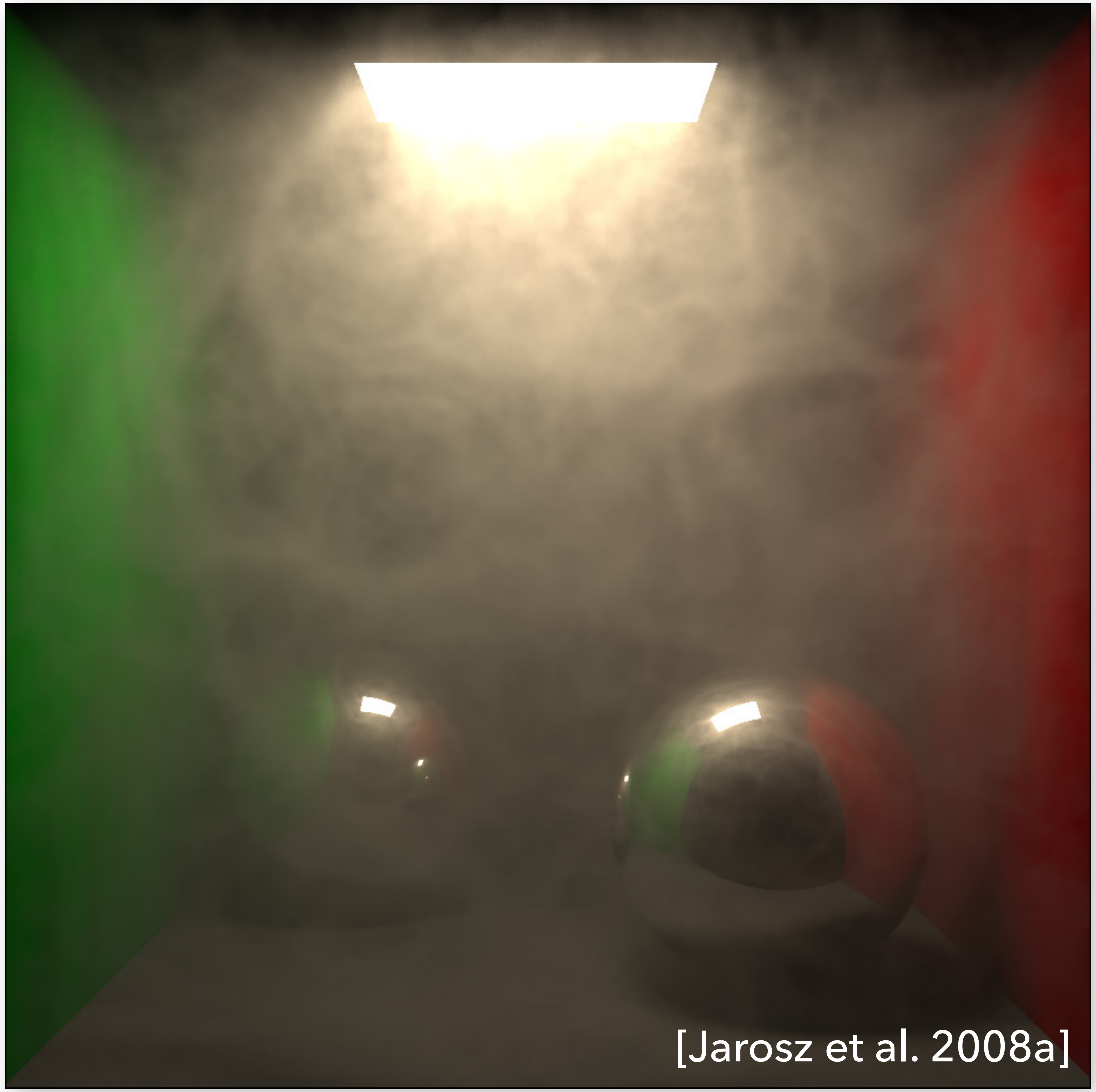


1 minute/frame

Radiance caching

Illumination changes slowly

- Compute lighting and cache for reuse by nearby rays



[Jarosz et al. 2008a]

Radiance caching

Illumination changes slowly

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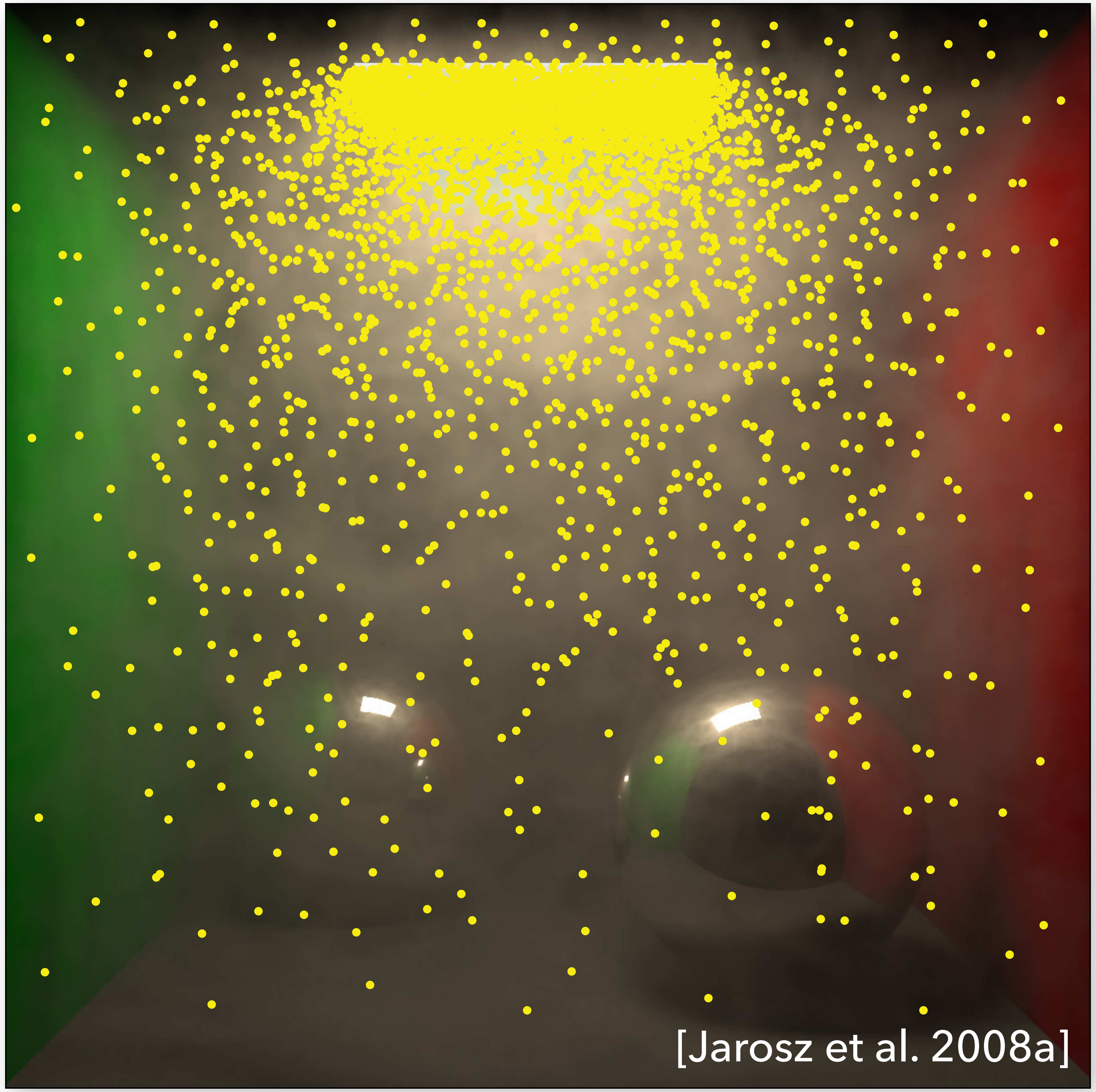

[Jarosz et al. 2008a]

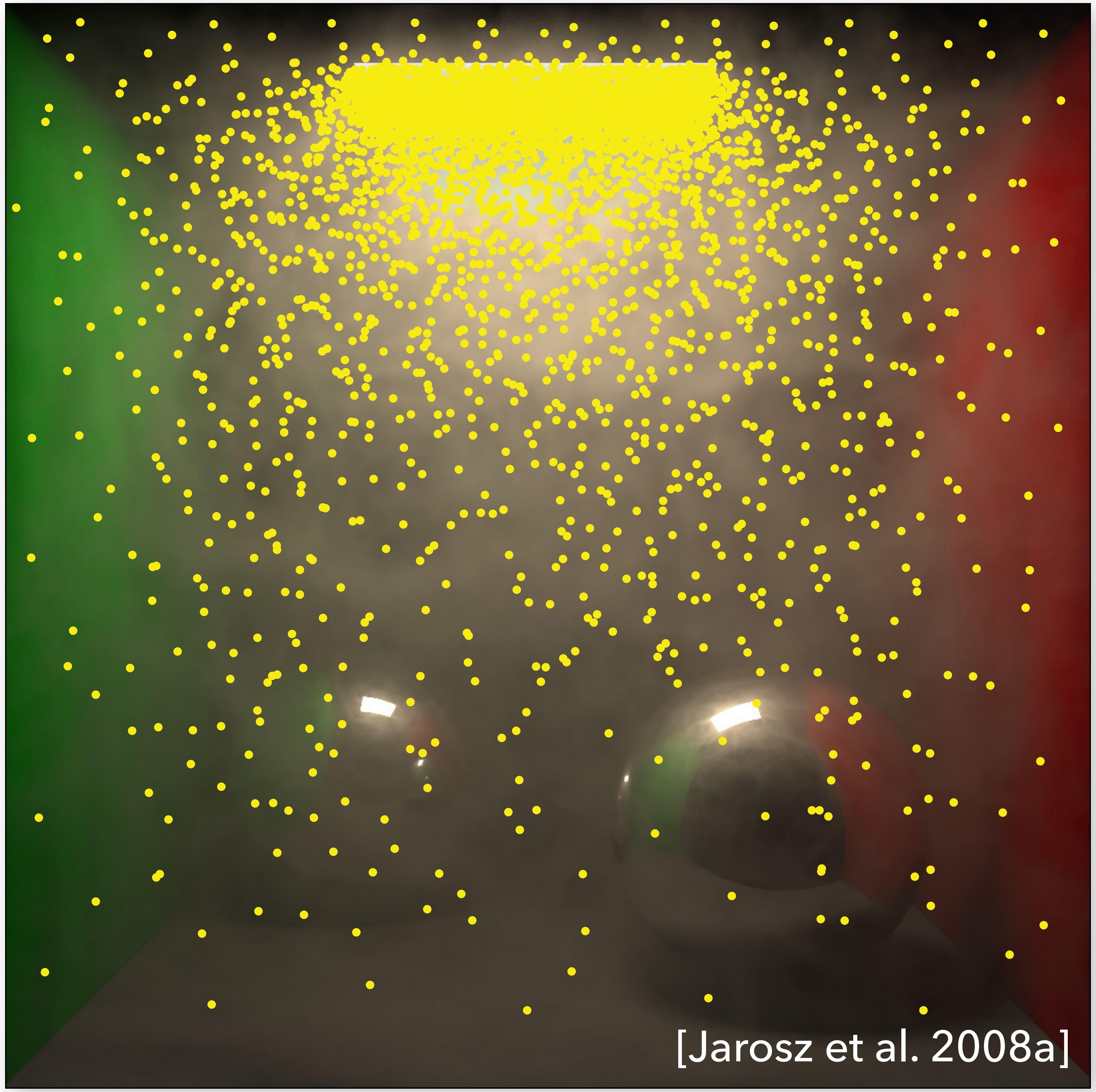
Radiance caching

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]



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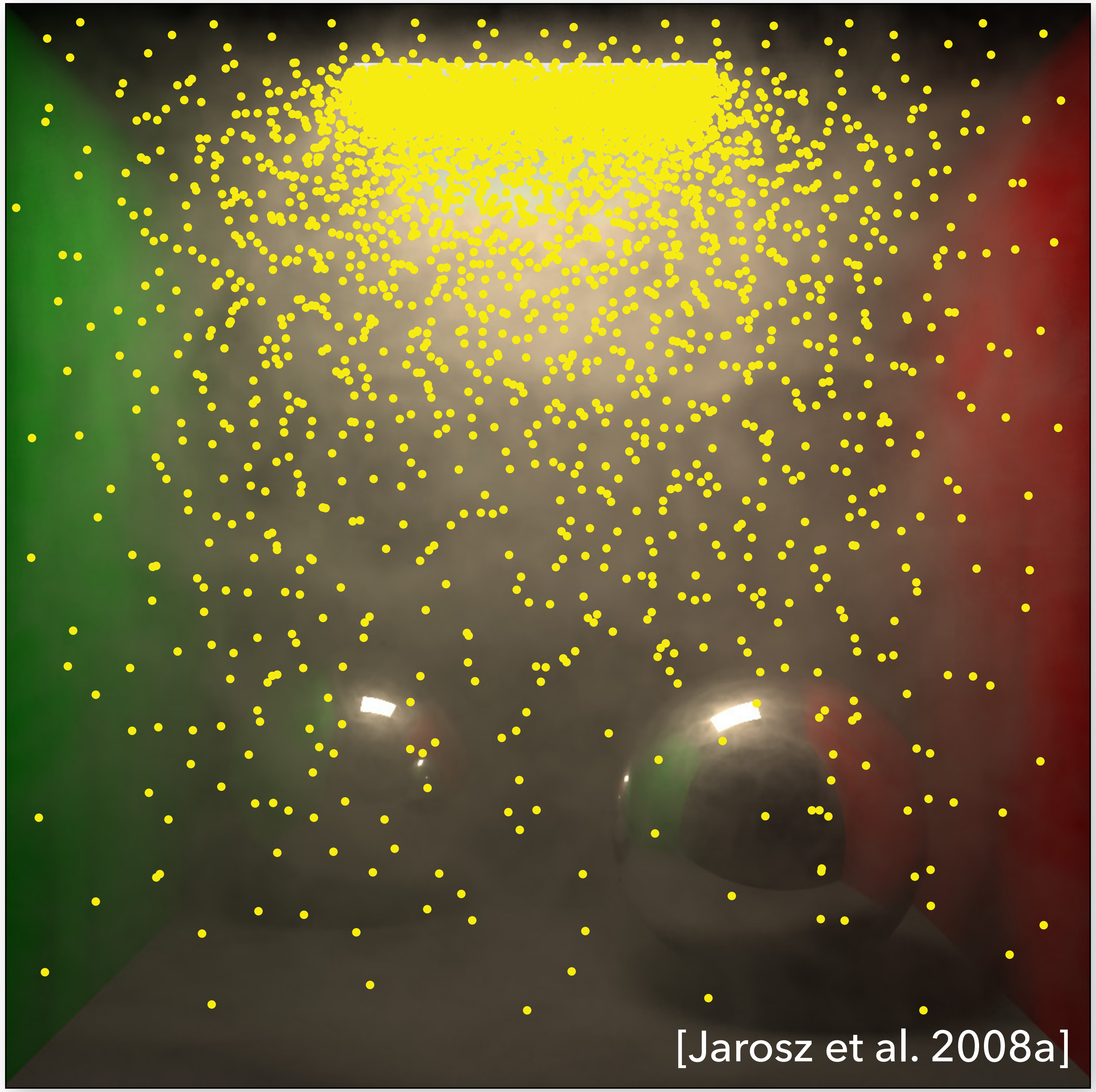
[Jarosz et al. 08a, b]


[Jarosz et al. 2008a]

Radiance caching

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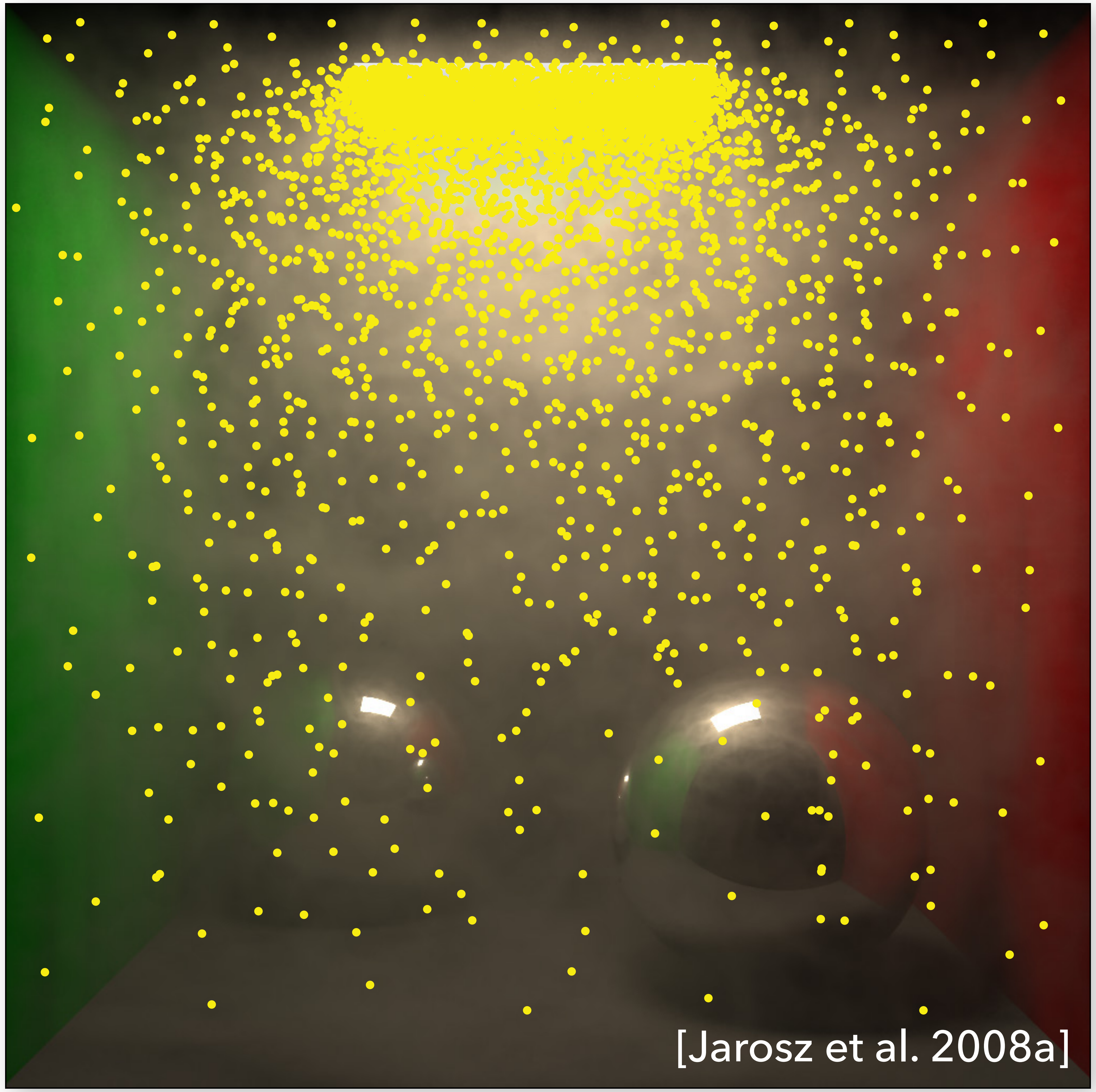
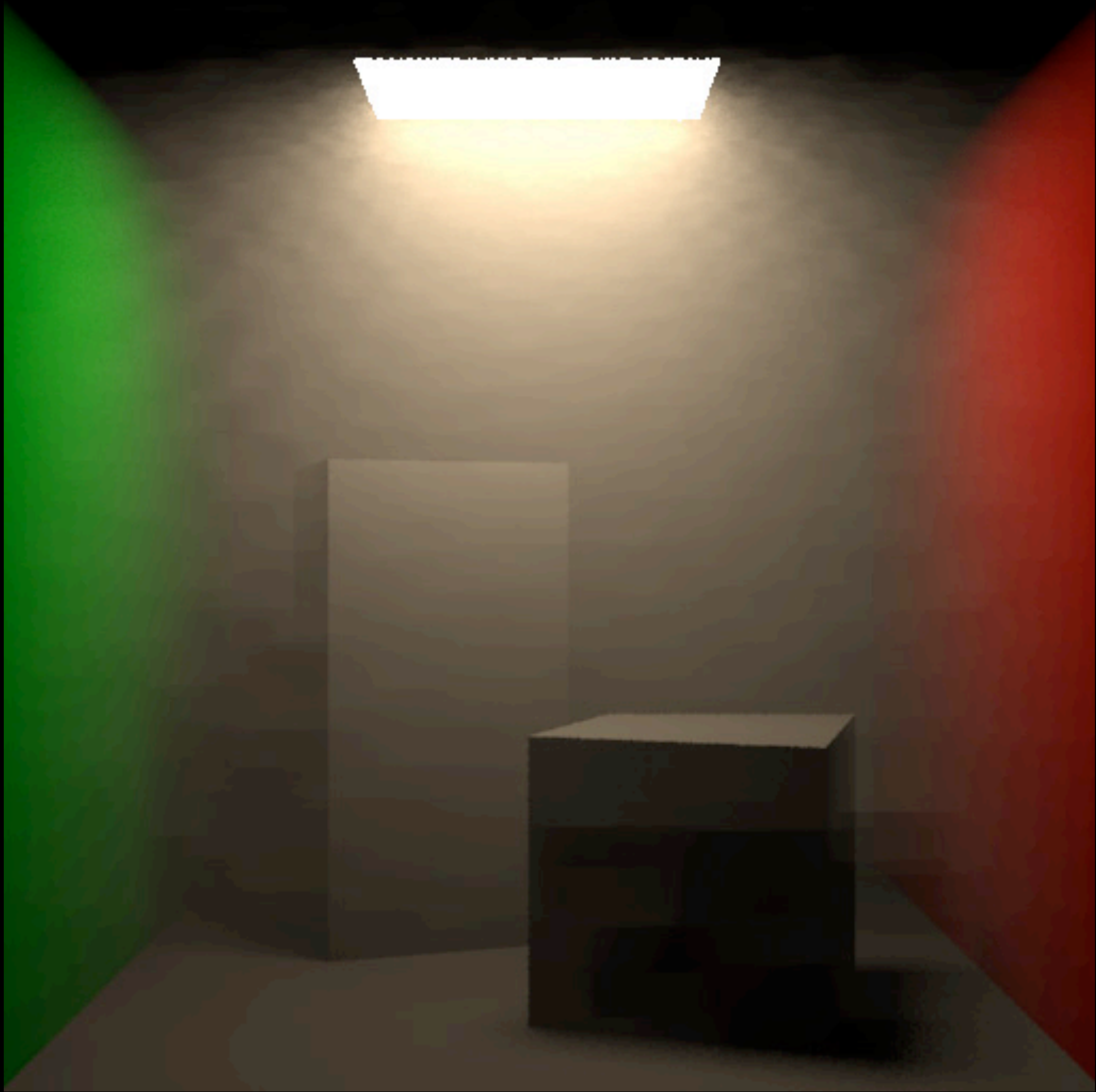
[Jarosz et al. 08a, b]

[Marco et al. 18]

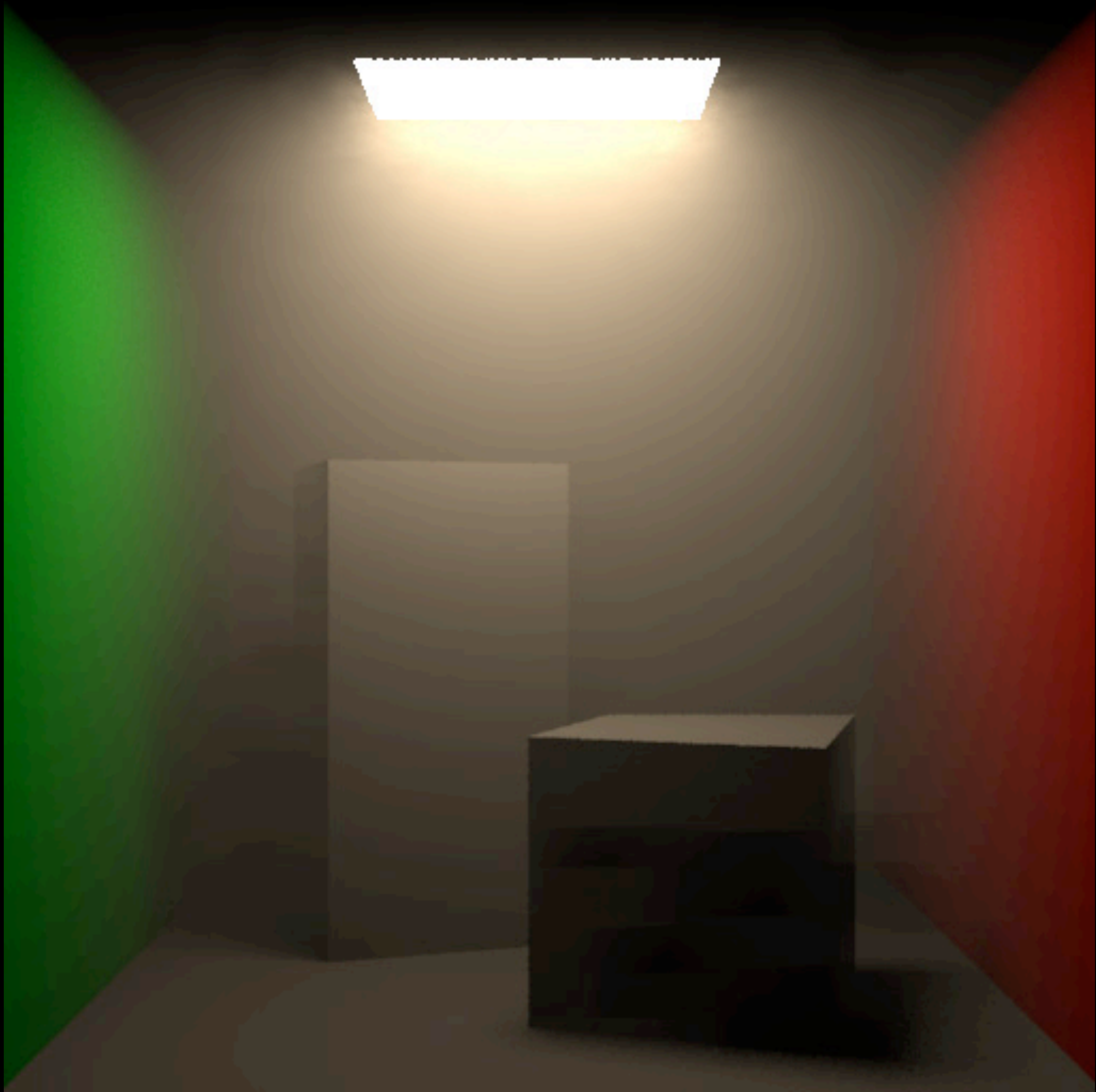


No gradients

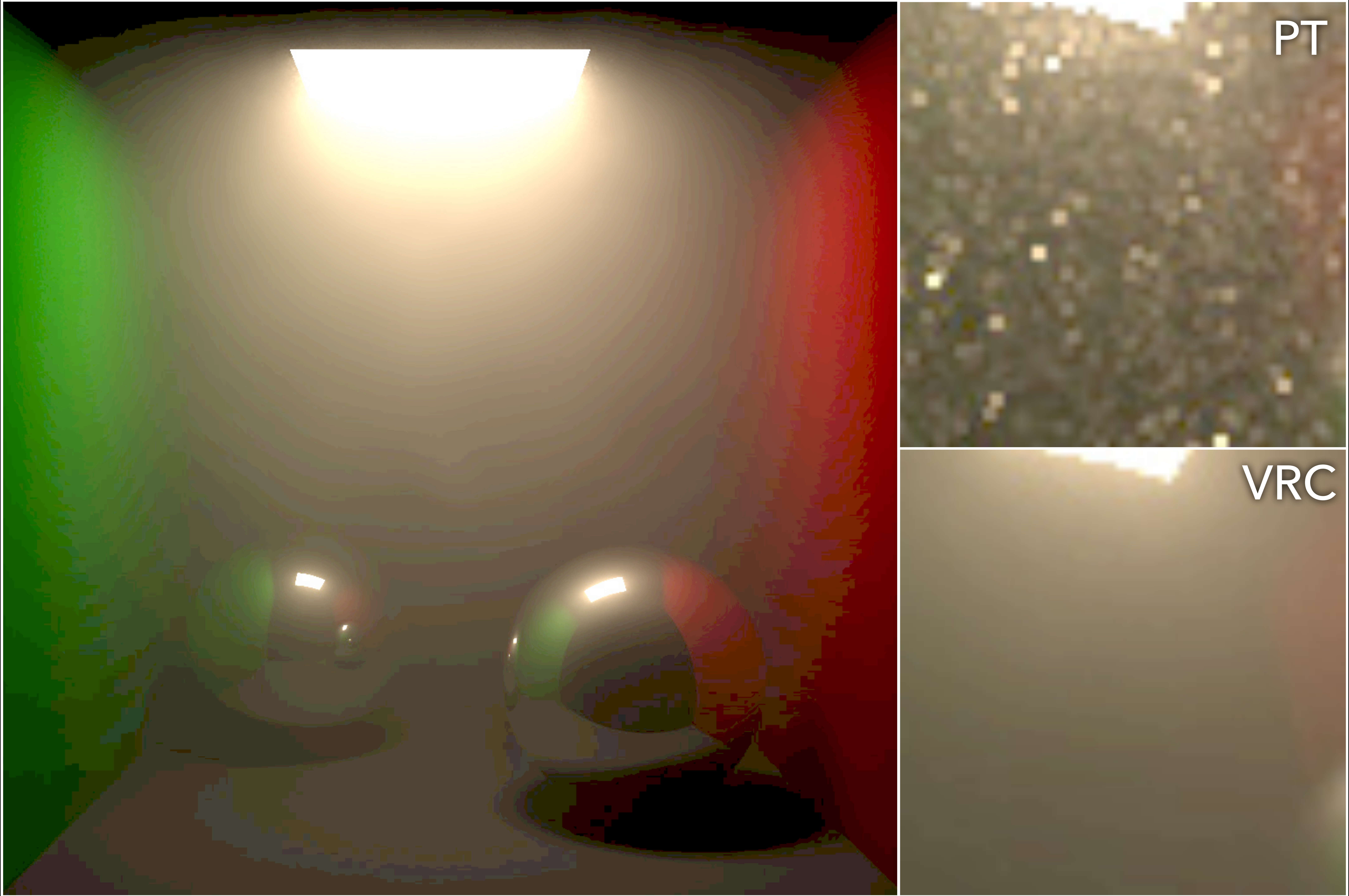


[Jarosz et al. 2008a]

With gradients



[Jarosz et al. 2008a]



[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

Radiance caching

Advanced methods

Photon tracing/mapping

Many-light methods

Radiance caching

More from Jaroslav & Johannes…