State of the Art in Photon Density Estimation

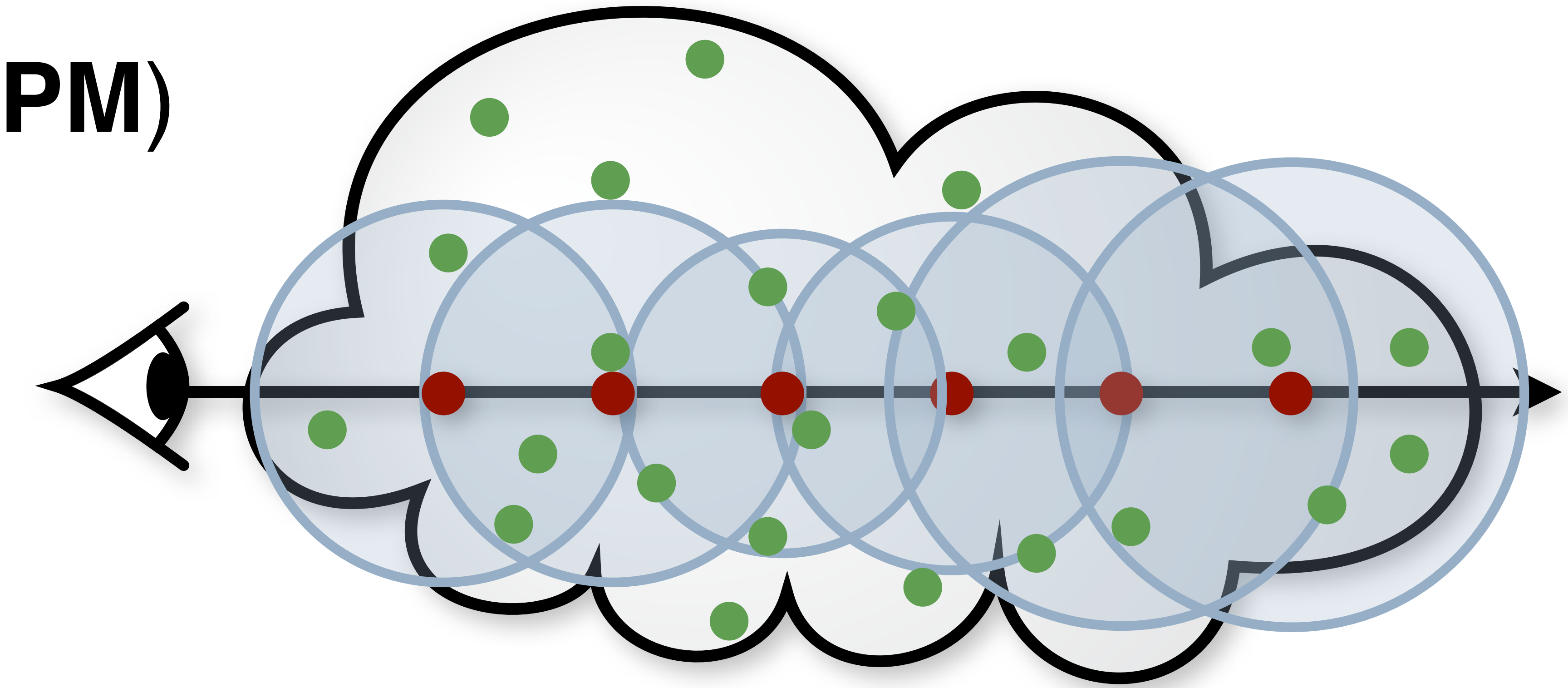
From Photons to Beams

Wojciech Jarosz

So Far...

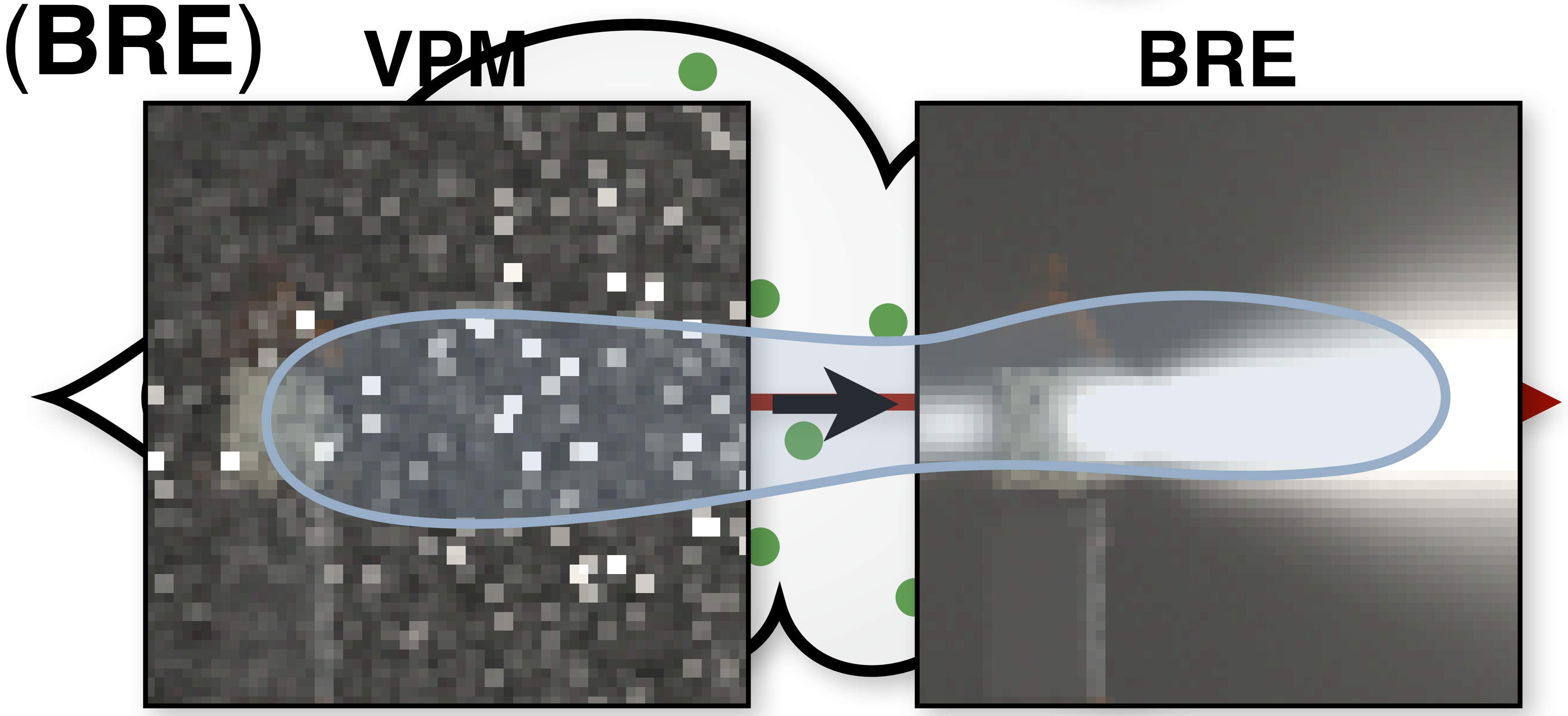
- Volumetric Photon Mapping (**VPM**) [Jensen & Christensen 98]

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)**



So Far...

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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)**

- Beyond Photon Points: [Jarosz et al. 11a]

Query	Data	Blur
Point/Beam	**Point/Beam**	**1D/2D/3D**

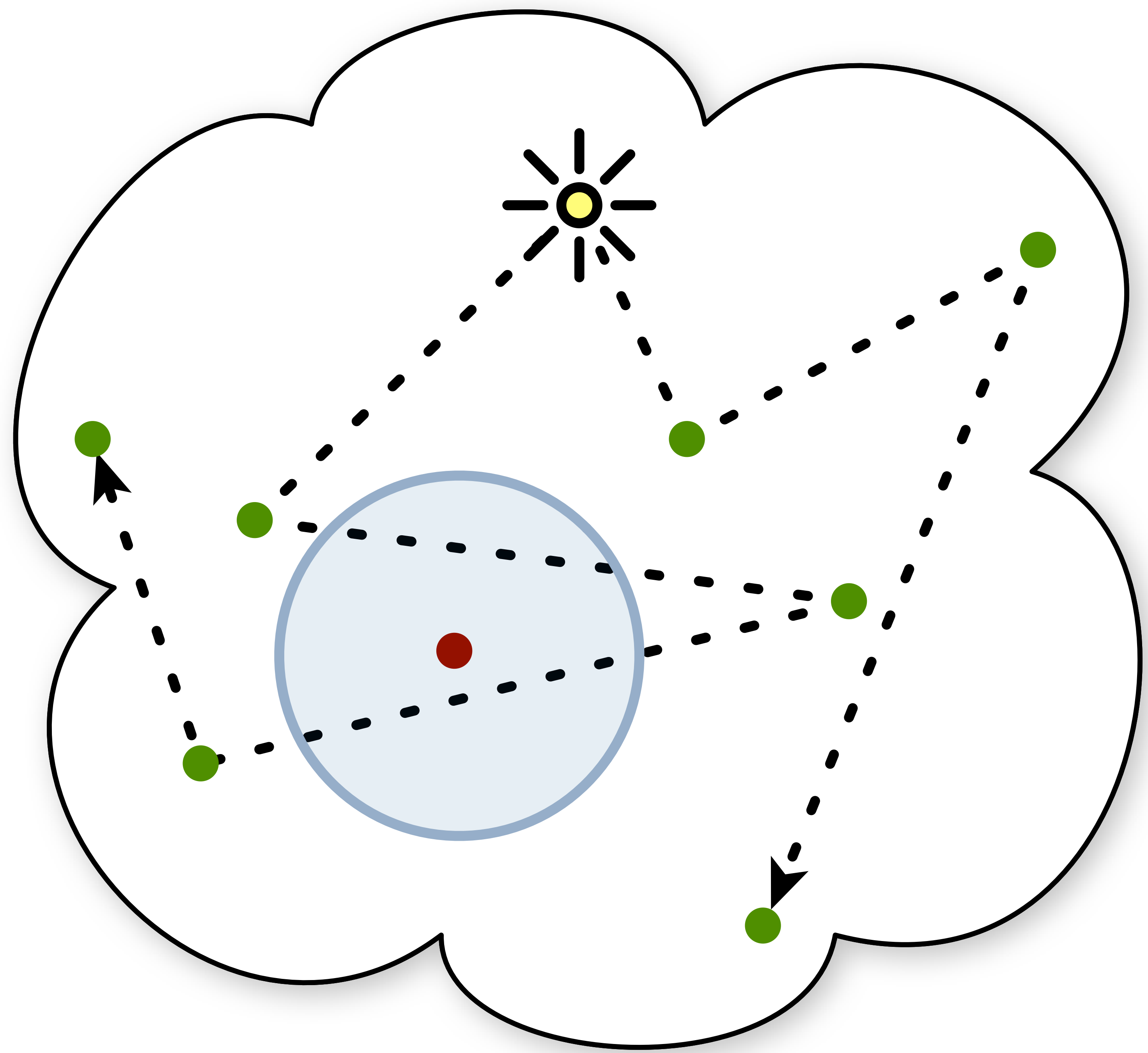
Density Estimator Options

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

Density Estimator Options

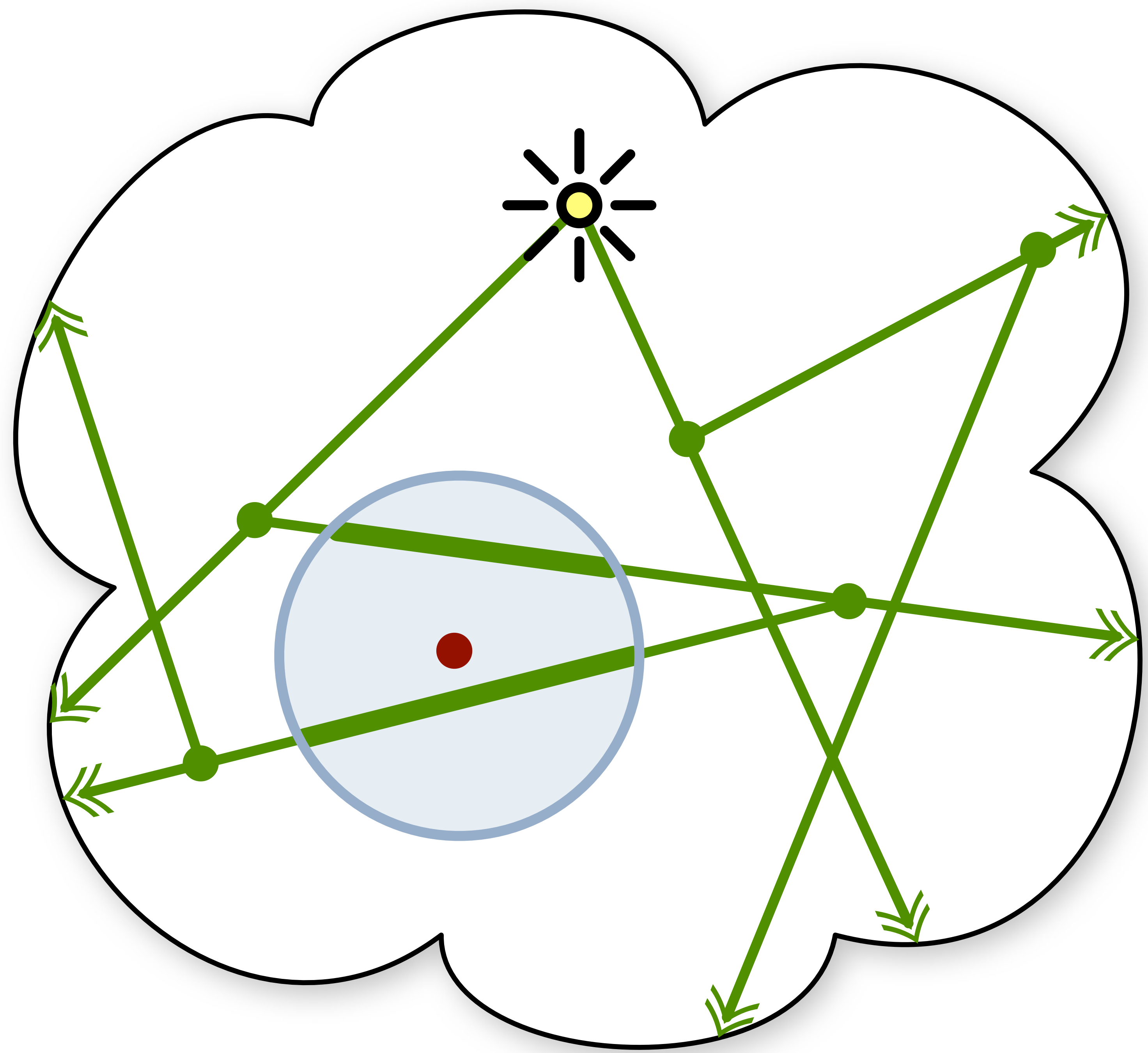
Query	x	Data	Blur
Point	x	Point	(3D)
Beam	x	Point	(2D)
Beam	**x**	**Point**	**(3D)**
Point	**x**	**Beam**	**(3D)**
Point	**x**	**Beam**	**(2D)**
Beam	**x**	**Beam**	**(3D)**
Beam	**x**	**Beam**	**$(2D)_1$**
Beam	**x**	**Beam**	**$(2D)_2$**
Beam	**x**	**Beam**	**(1D)**

Volumetric Photon Mapping



Photon Points

Volumetric Photon Mapping

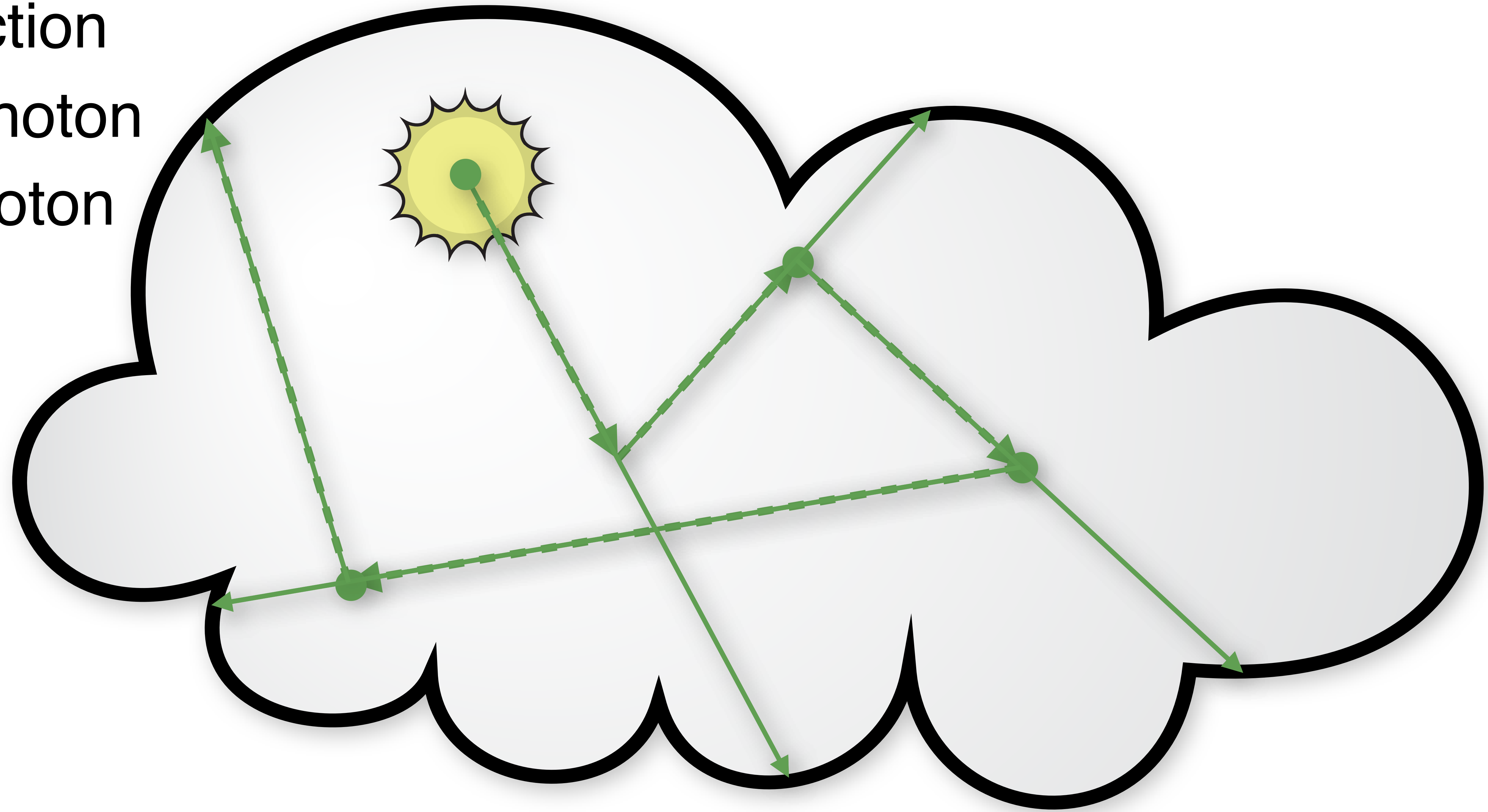


Photon Beams

Photon Beams

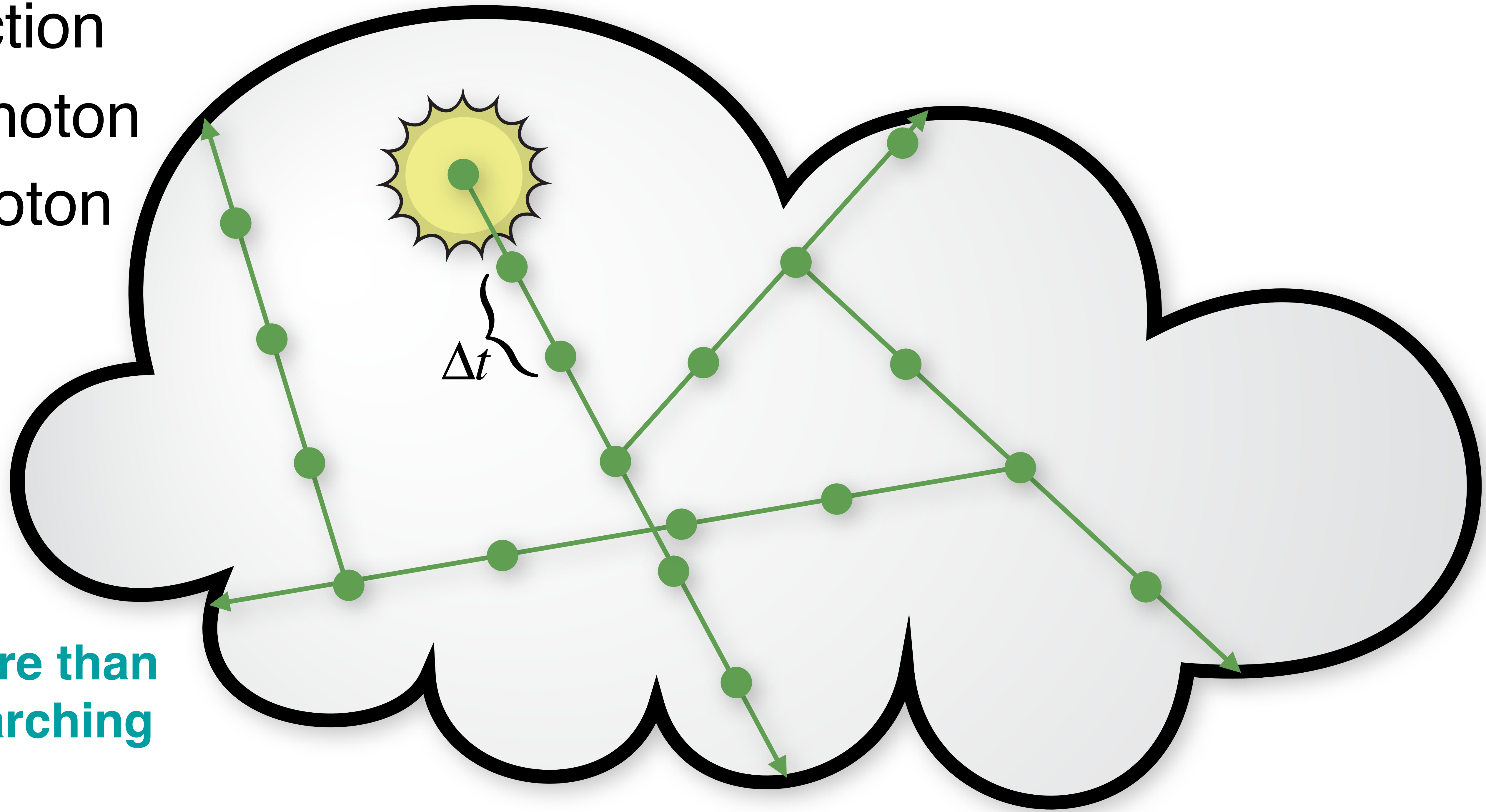
Traditional Photon Tracing

1) choose direction
2) propagate photon
3) deposit a photon
4) repeat



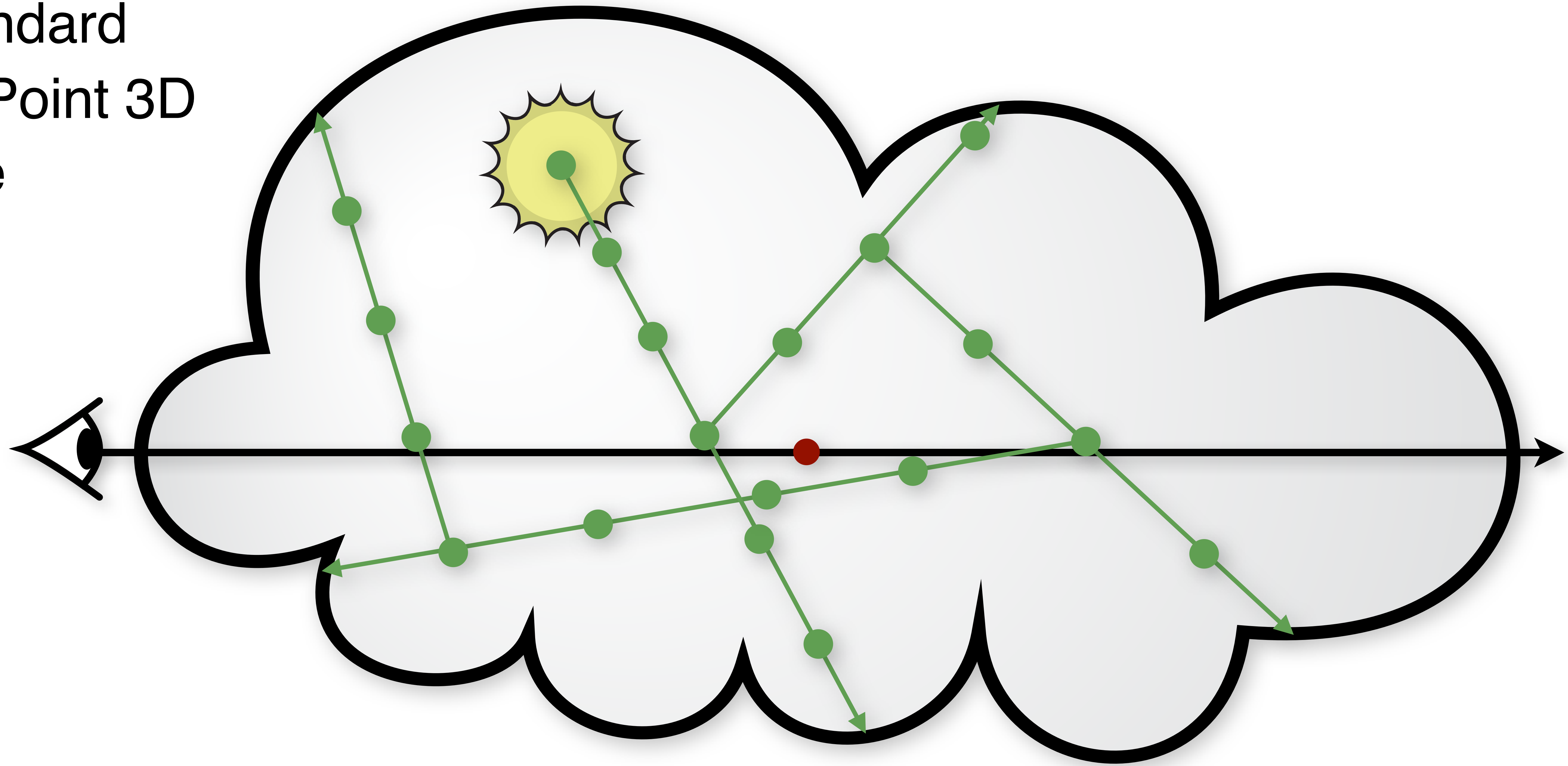
“Photon Marching”

1) choose direction
2) propagate photon
3) deposit a photon
4) repeat



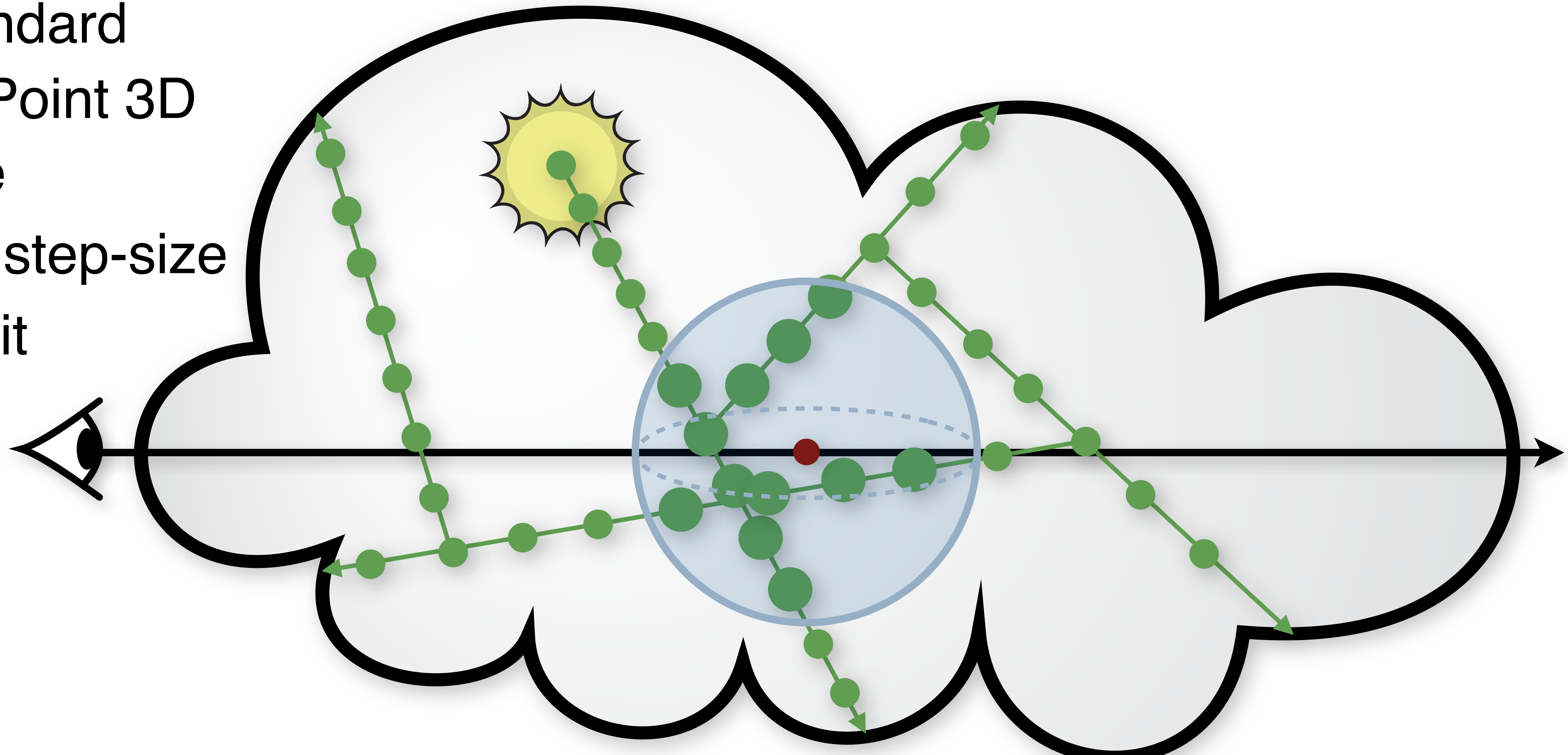
Could deposit more than one photon by marching along each ray

- Use standard Point x Point 3D estimate



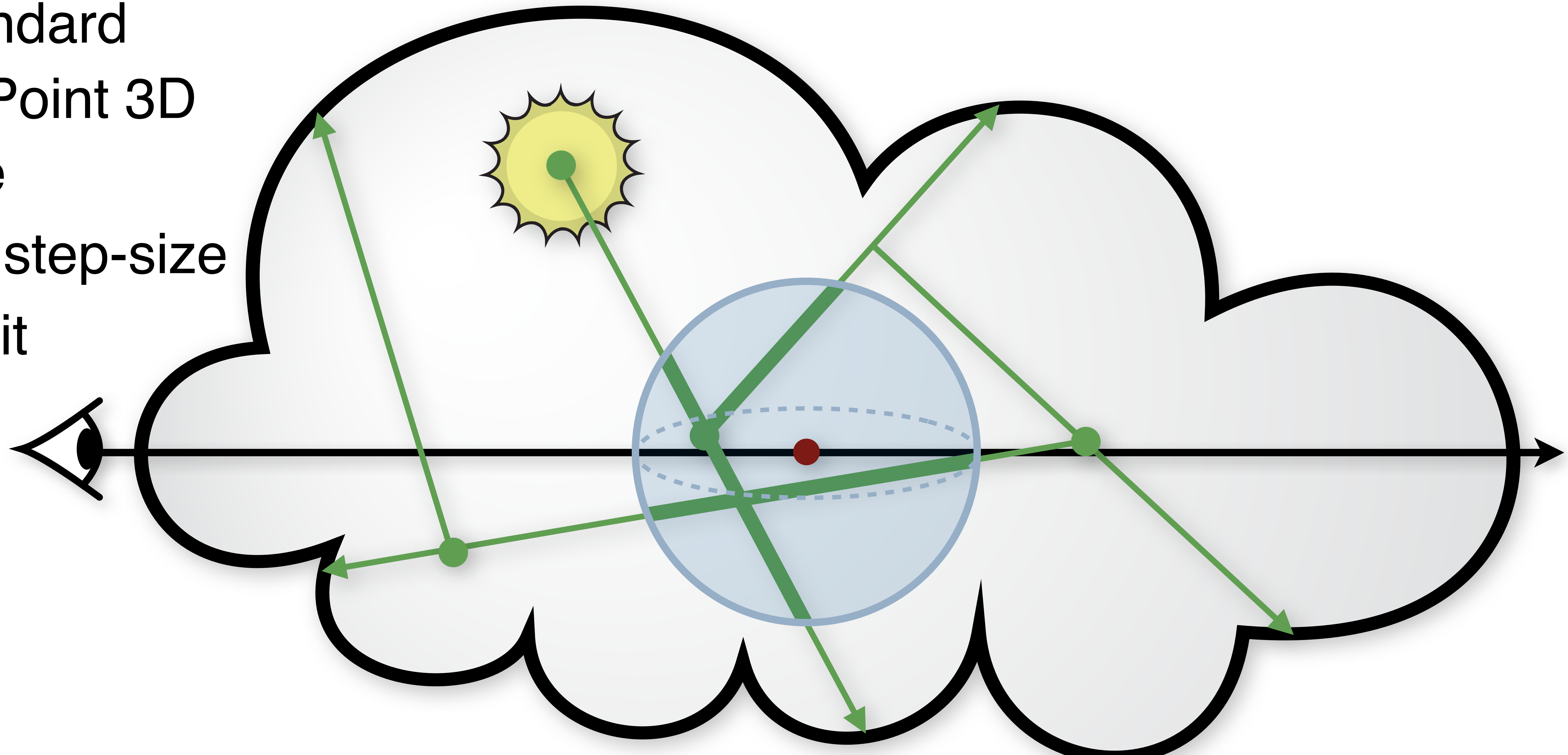
Radiance Estimation using “Discrete Photon Beams”

- Use standard Point x Point 3D estimate
- Reduce step-size
- Take limit

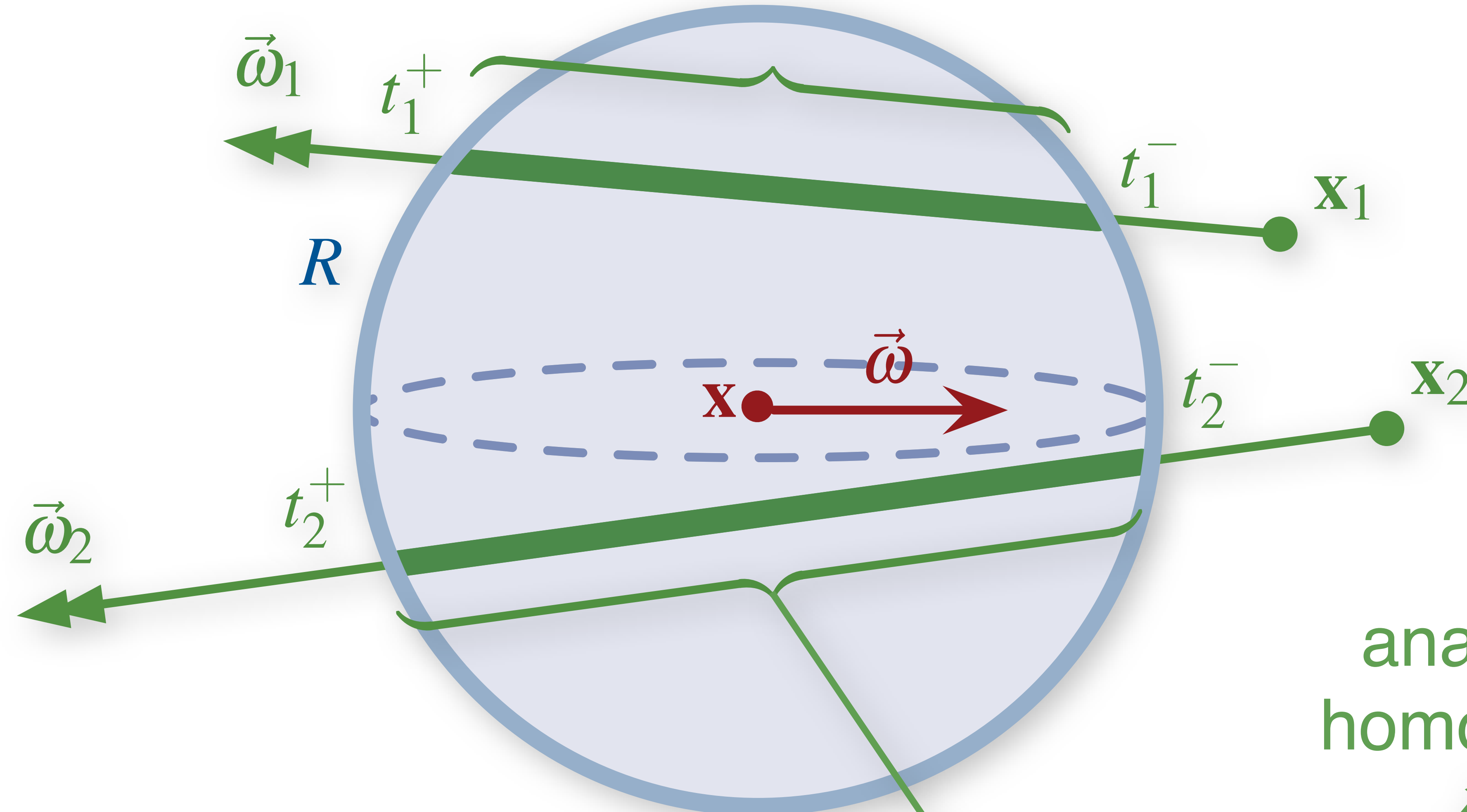


Radiance Estimation using "Continuous Photon Beams"

- Use standard Point x Point 3D estimate
- Reduce step-size
- Take limit



Point Query × Beam Data (3D blur)

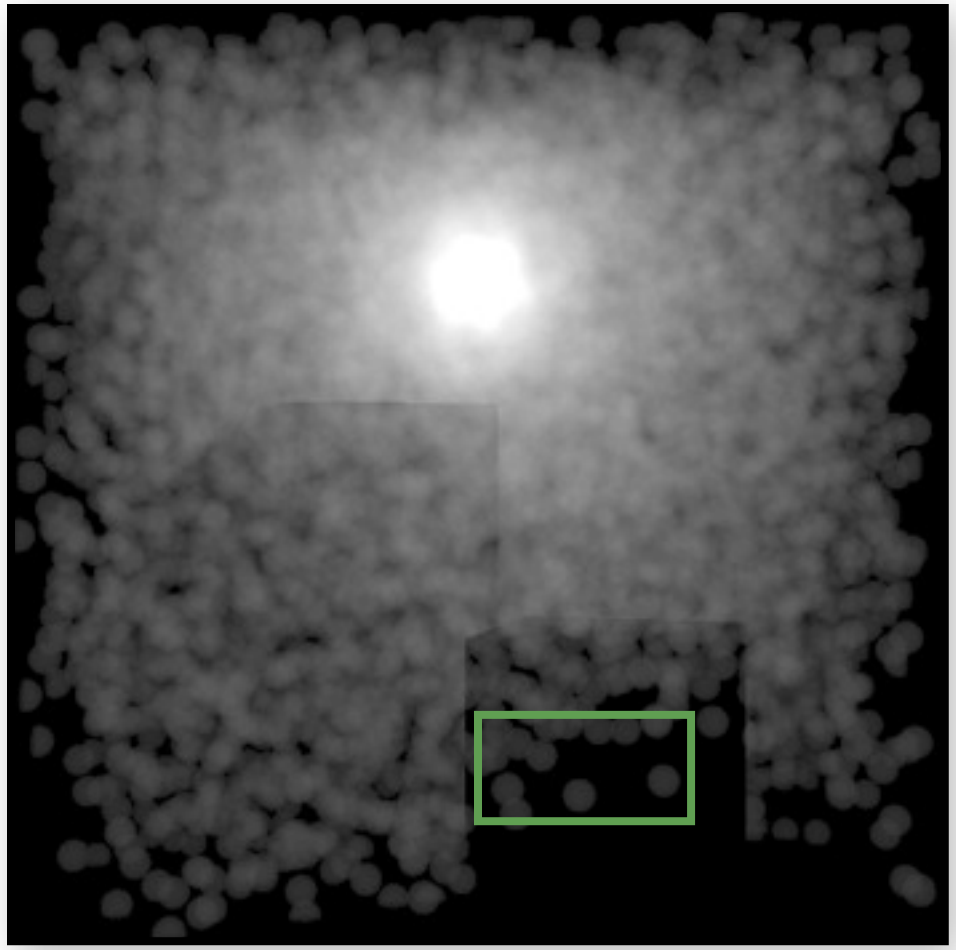


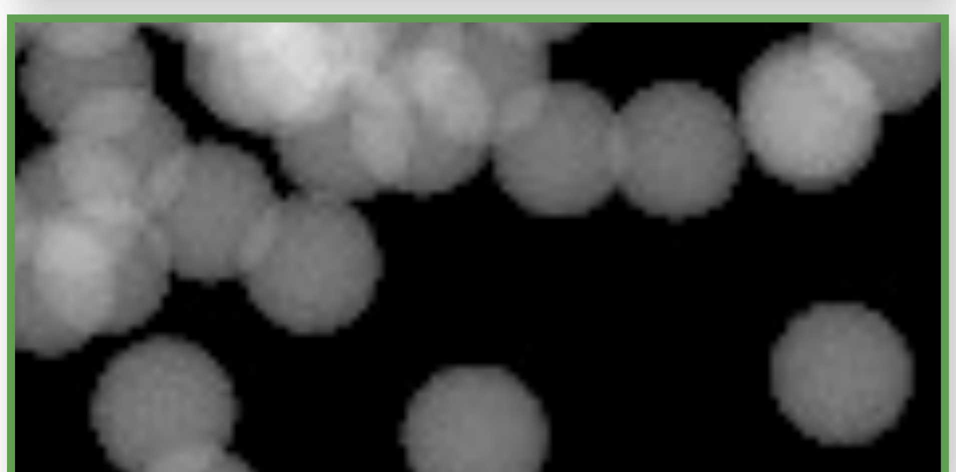
analytic solution in homogeneous media

$$L \approx \frac{1}{\boxed{\mu_R(r^3)}} \sum_i f(\theta_i) \boxed{\Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_t t}\, dt}$$

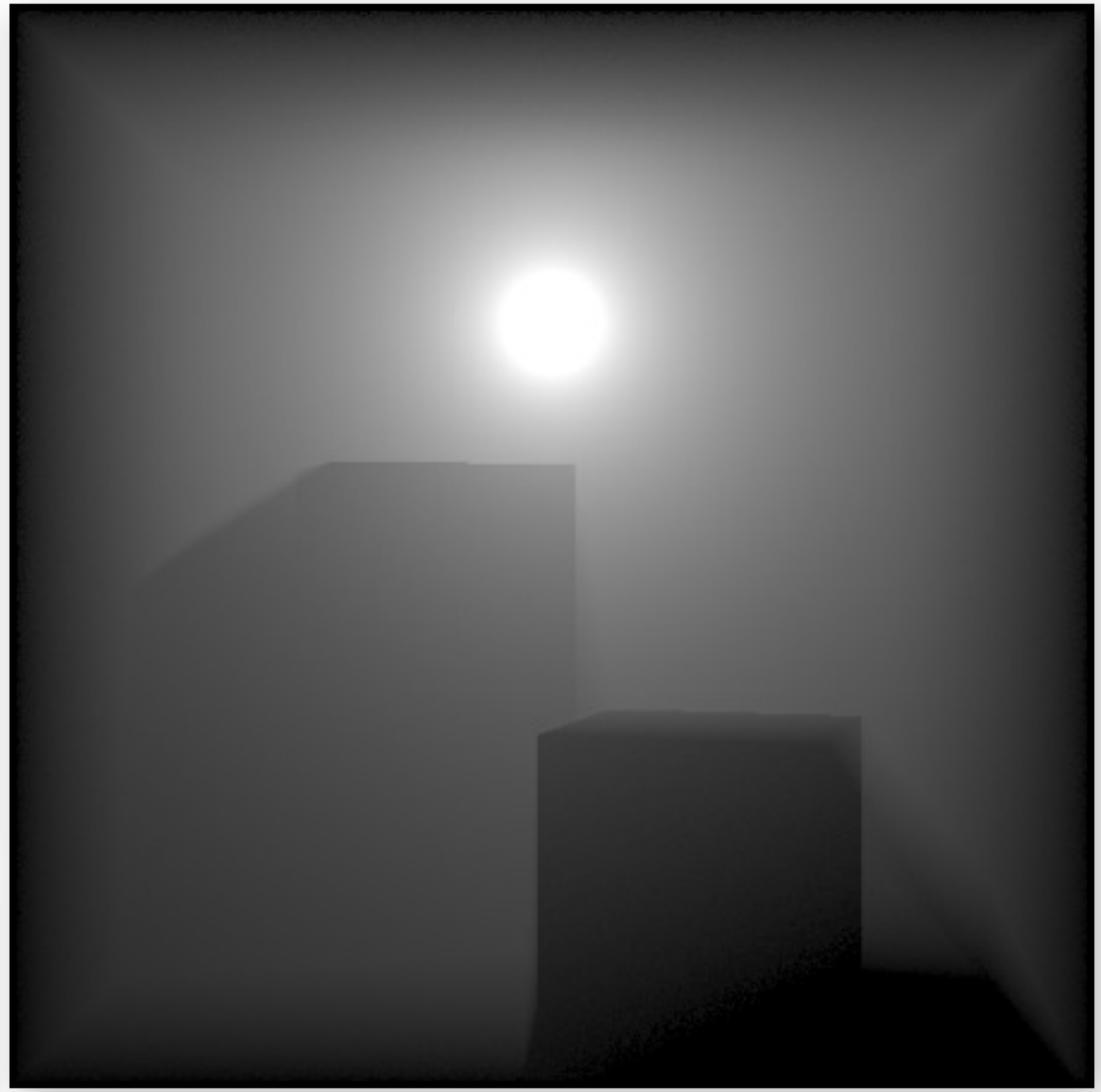
Photon Points vs. Photon Beams

100k Photon Points

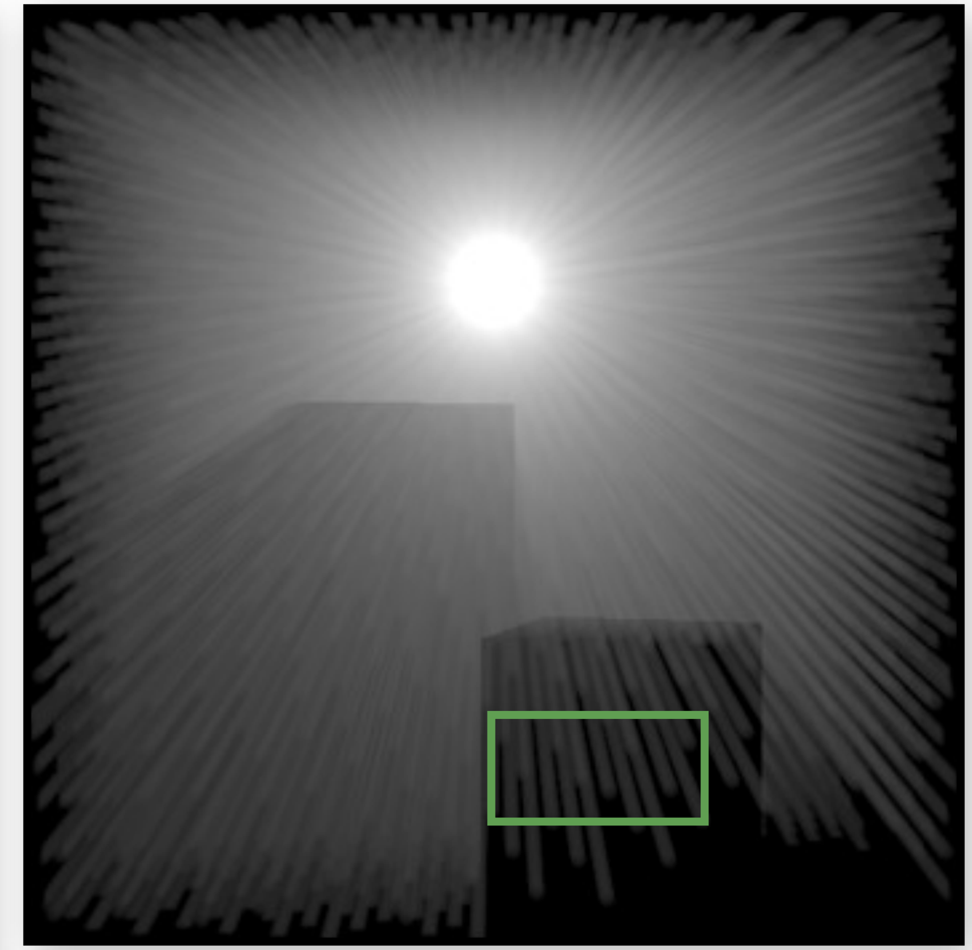


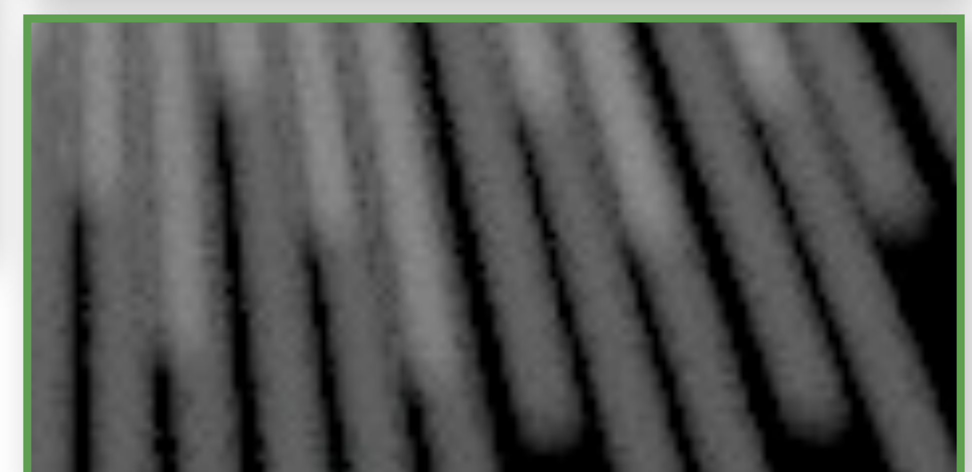


Ground Truth



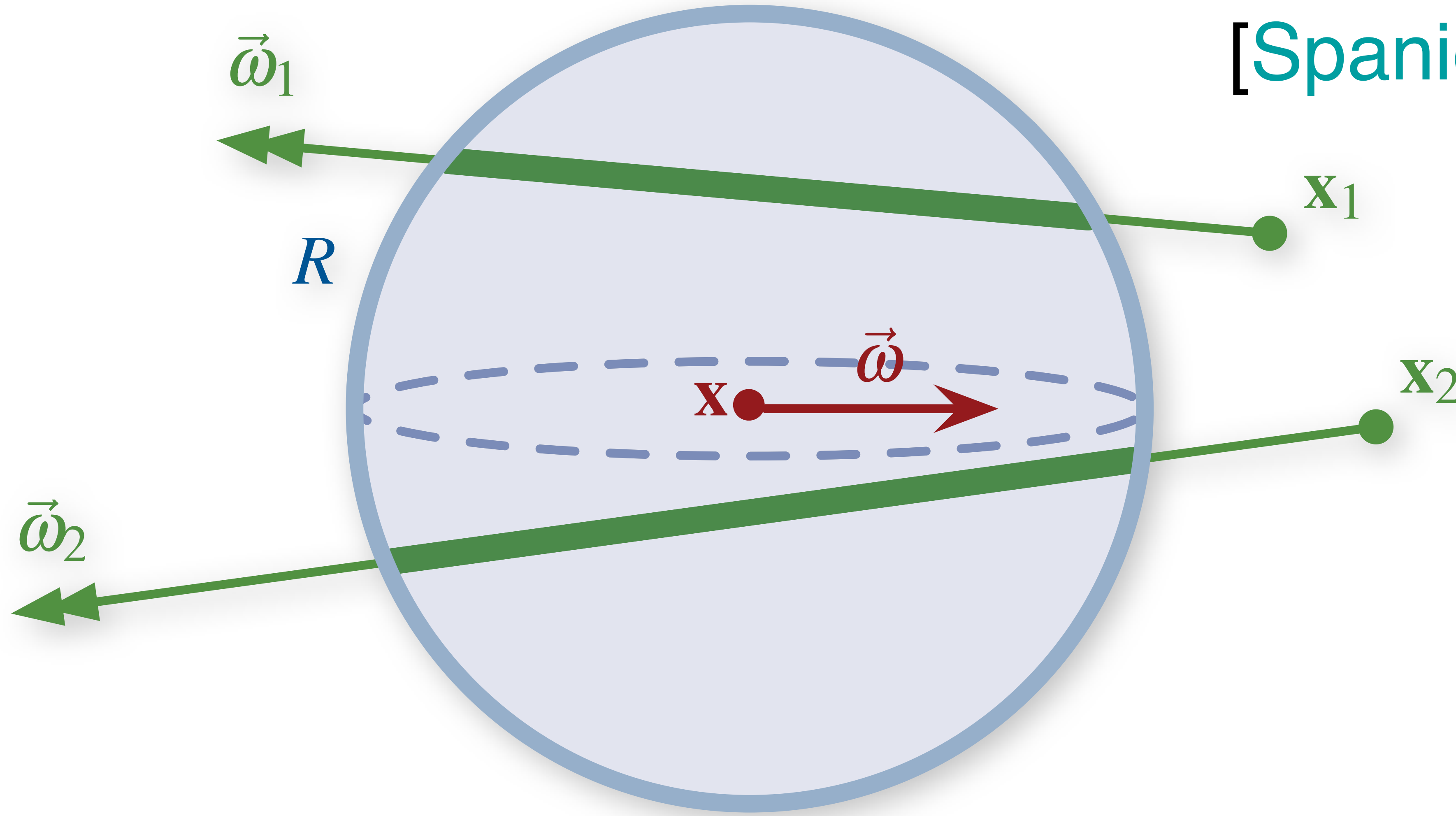
5k Photon Beams





Point Query × Beam Data (3D blur)

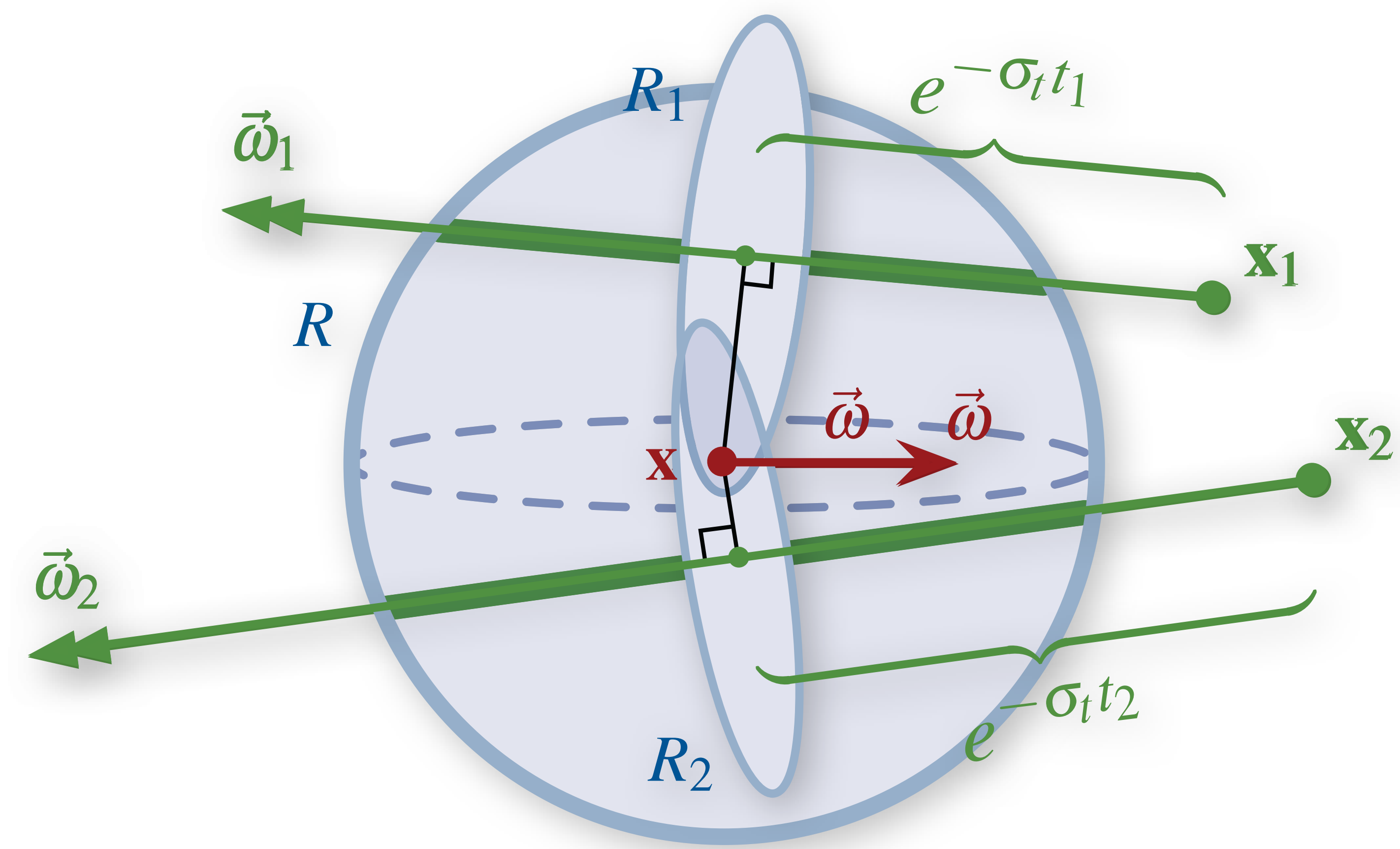
related to: “track length” estimators
[Spanier and Gelbard 69]



$$L \approx \frac{1}{\mu_R(r^3)} \sum_i f(\theta_i)\,\Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_t t}\,dt$$

Reducing Blur Dimensionality

Point Query x Beam Data (3D blur)

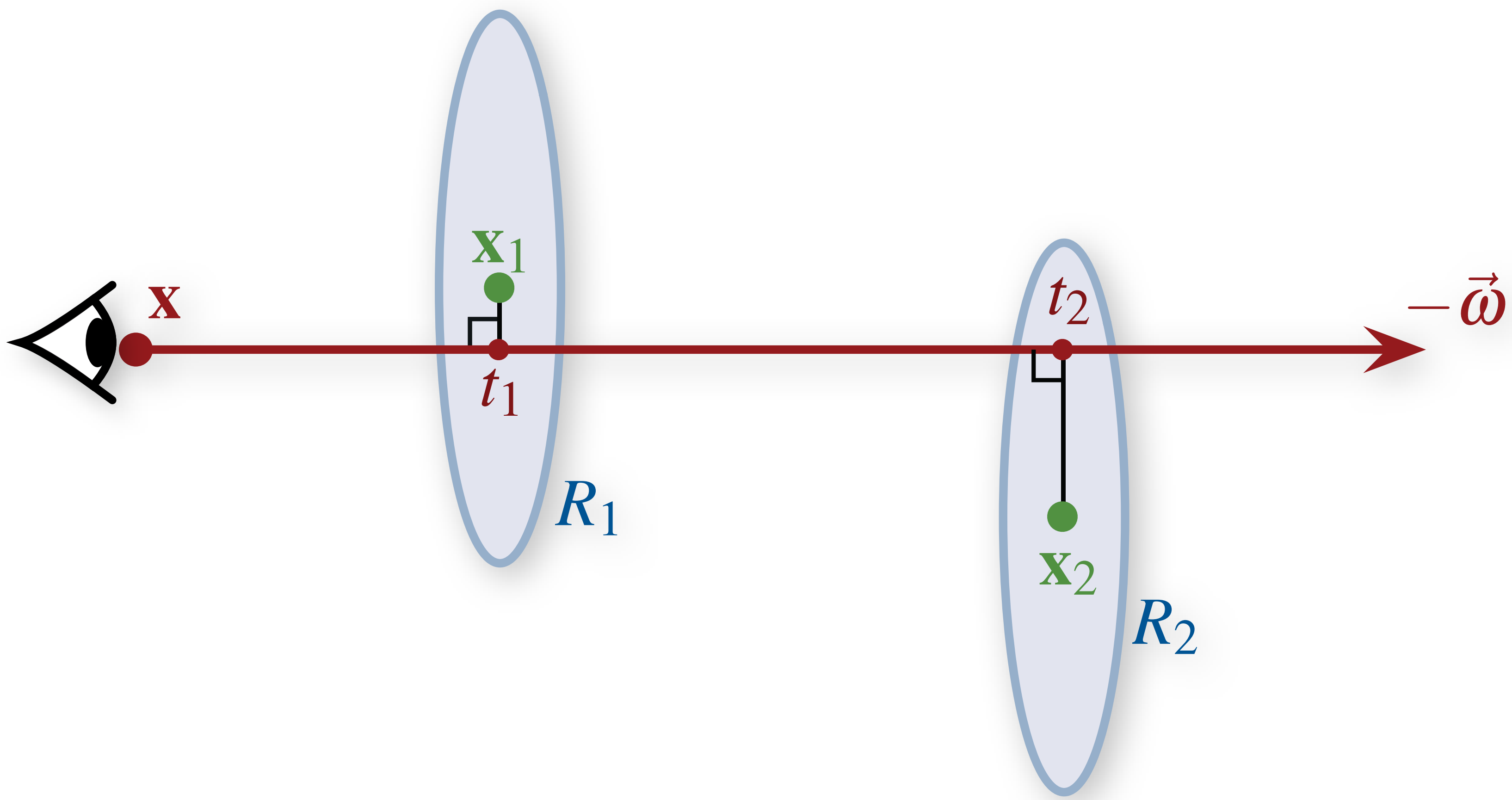


$$L \approx \frac{1}{\mu_R(r^3)} \sum_i f(\theta_i)\, \Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_t t}\, dt$$

$$L \approx \frac{1}{\mu_R(r^2)} \sum_i f(\theta_i)\, \Phi_i\, e^{-\sigma_t t_i}$$

Radiometric Duality

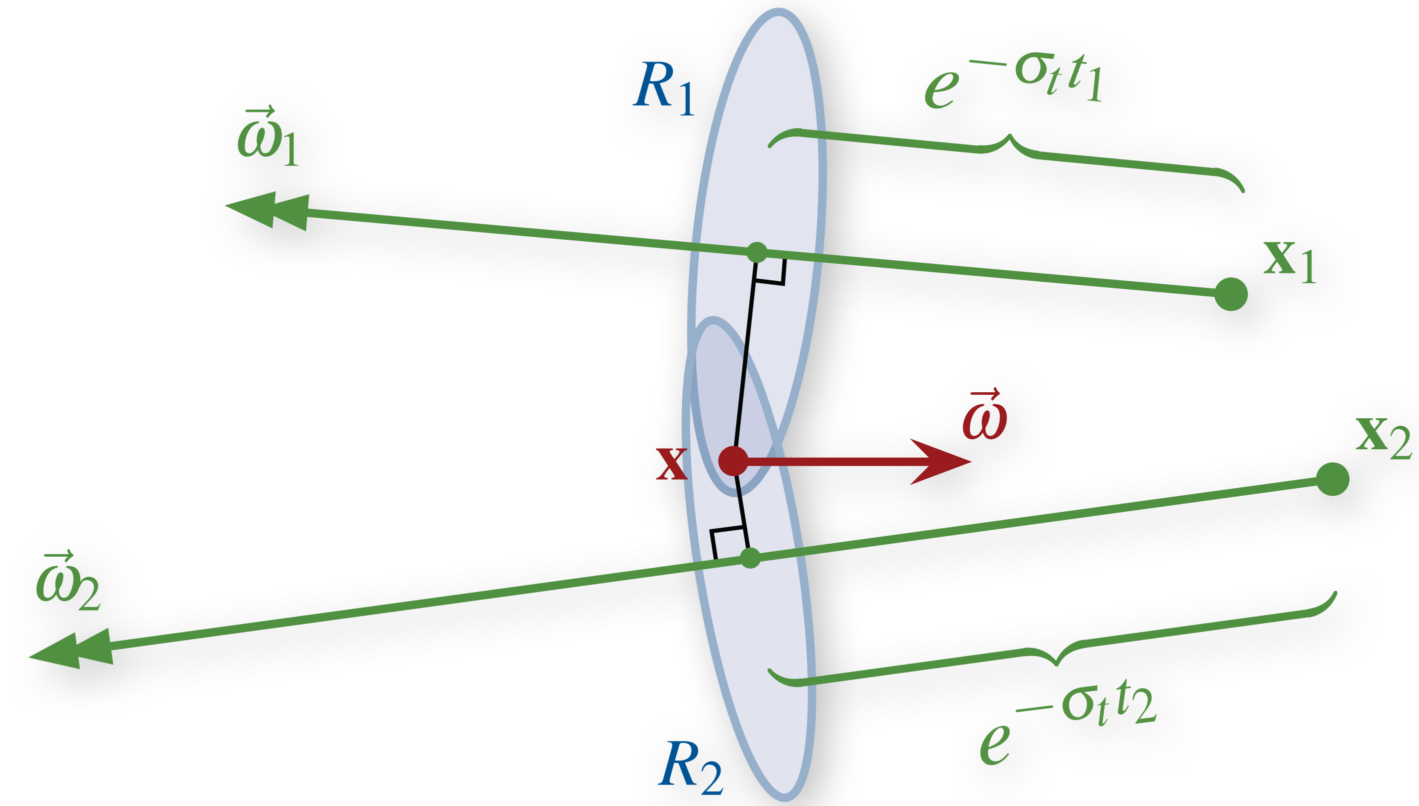
Beam Query x Point Data (2D blur)



$$L \approx \frac{1}{\mu_R(r^2)} \sum_i f(\theta_i)\,\Phi_i\,e^{-\sigma_t t_i}$$

"Beam Radiance Estimate"
[Jarosz et al. 08]

Point Query x Beam Data (2D blur)



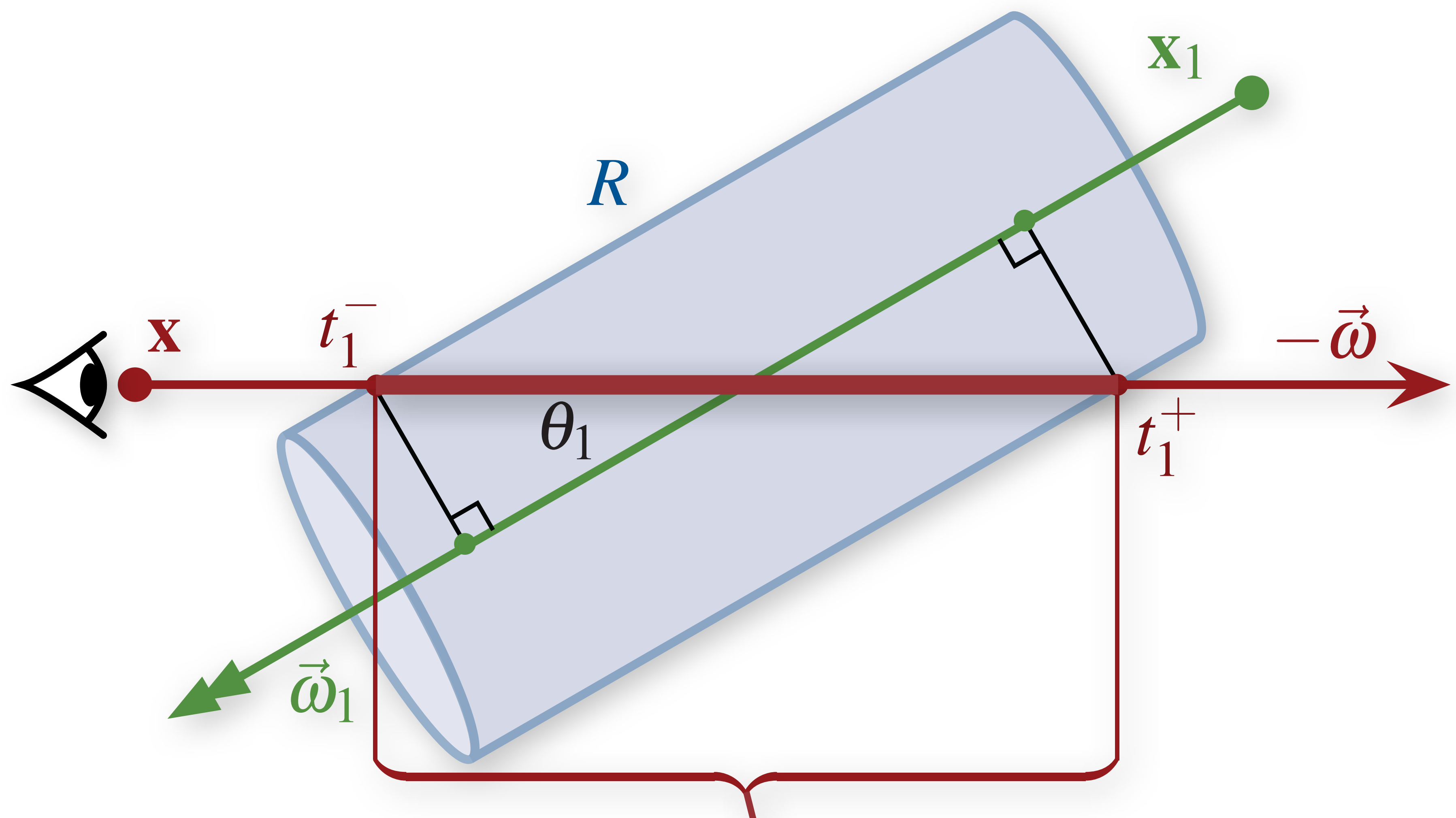
$$L \approx \frac{1}{\mu_R(r^2)} \sum_i f(\theta_i)\,\Phi_i\,e^{-\sigma_t t_i}$$

Beam Queries with Photon Beams

SIGGRAPHASIA2013

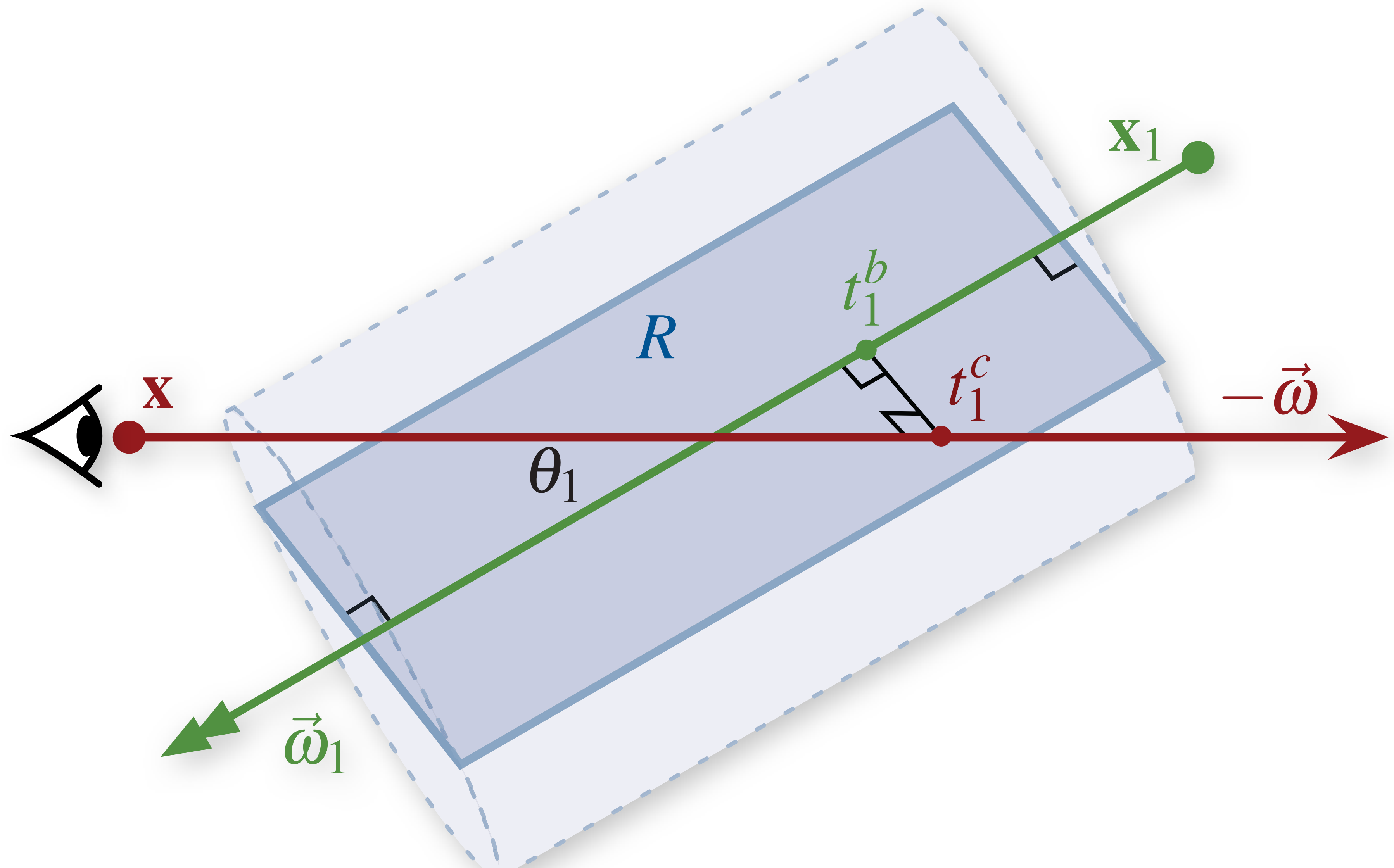
- Beam Query x Beam Data (3D)
- Beam Query x Beam Data $(2D)_1$
- Beam Query x Beam Data $(2D)_2$
- Beam Query x Beam Data (1D)

Beam Query × Beam Data (2D blur)



$$L \approx \frac{\sigma_s}{\mu_R(r^2)} \sum_i f(\theta_i) \Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_t t_c} e^{-\sigma_t t_b} \, dt_c$$

Beam Query × Beam Data (1D blur)



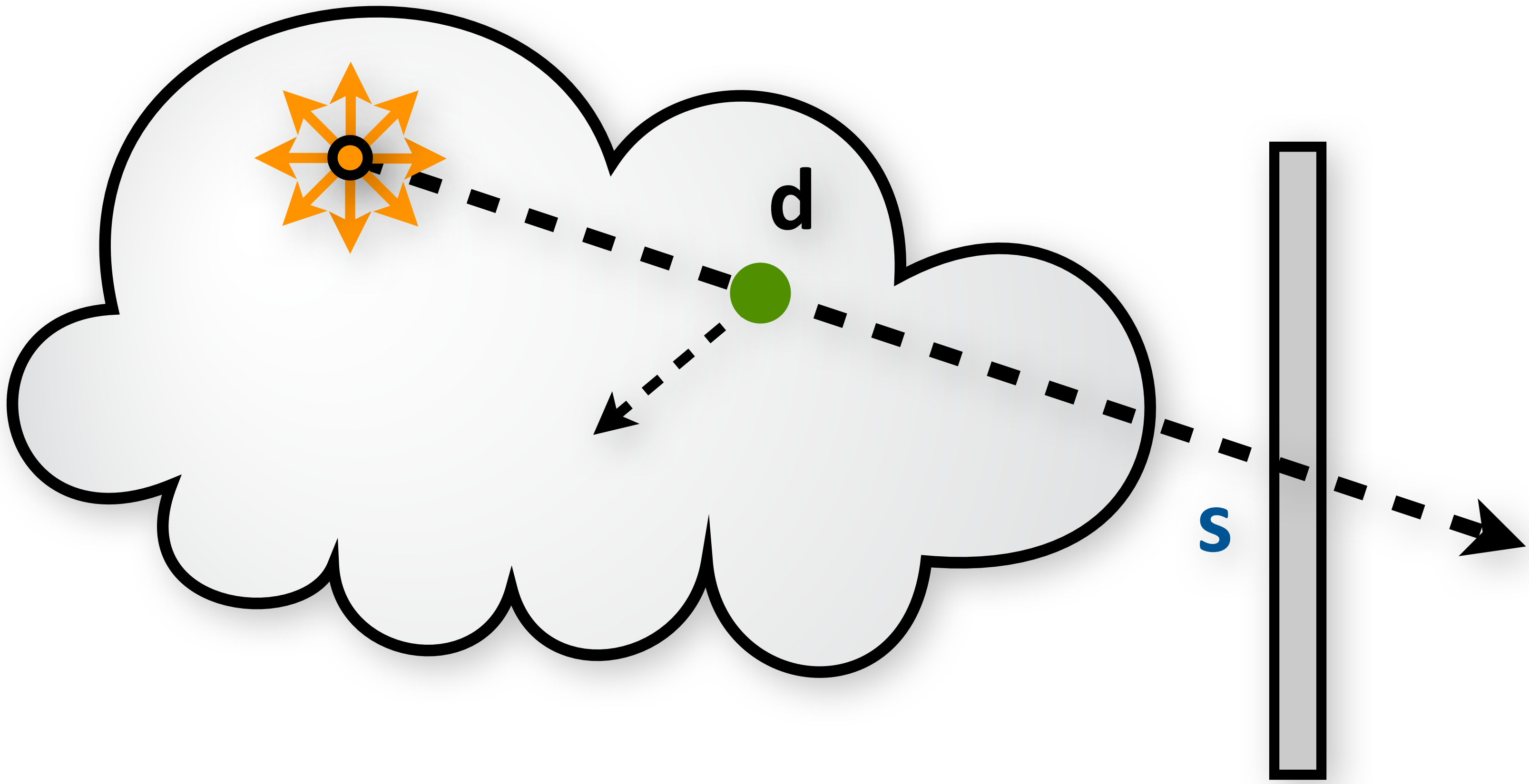
$$L \approx \frac{\sigma_s}{\mu_R(r)} \sum_i \frac{f(\theta_i)\, \Phi_i\, e^{-\sigma_t t_i^c}\, e^{-\sigma_t t_i^b}}{\sin \theta_i}$$

Radiance Estimator Summary

- Beam queries remove ray marching
- Beam data increases data density
- Lower blur dimension reduces bias and computation
- **use: Beam Query x Beam Data (1D)**

Basic Volumetric Photon Tracer

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



Basic Volumetric Photon Beam Tracer

```
void vPT(o, ω, Φ)
    s = nearestSurfaceHit(o, ω)
    storeVolumeBeam(o,ω,s,Φ)
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    if (d < s)          // media scattering
        o += d*ω        // propagate photon
        return vPT(o, samplePF(), Φ * σs / σt)
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        storeSurfacePhoton(o, ω, Φ)
        (ωi, pdfi) = sampleBRDF(o, ω)
        return vPT(o, ωi, Φ * BRDF(o,ω,ωi) / pdfi)
```
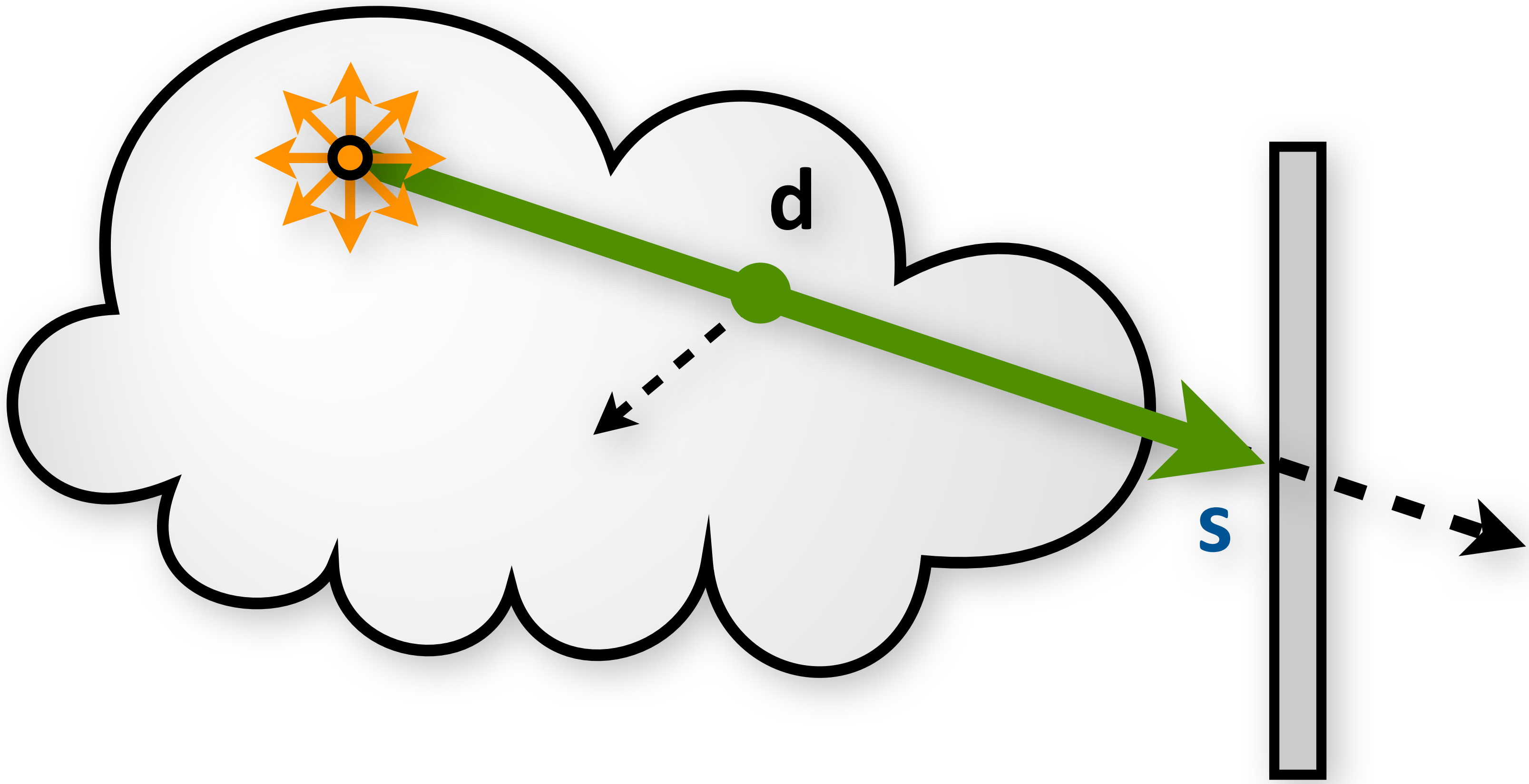
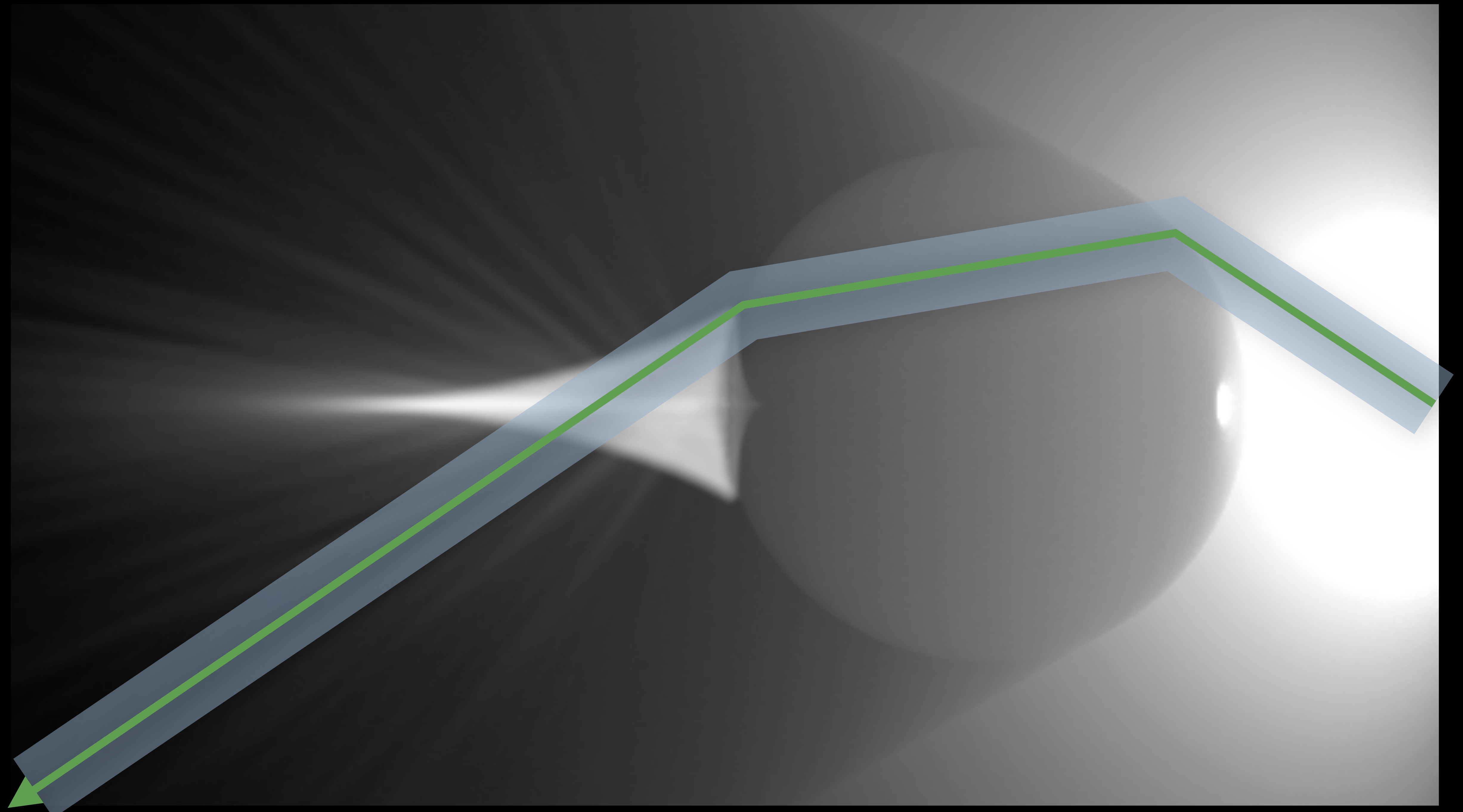
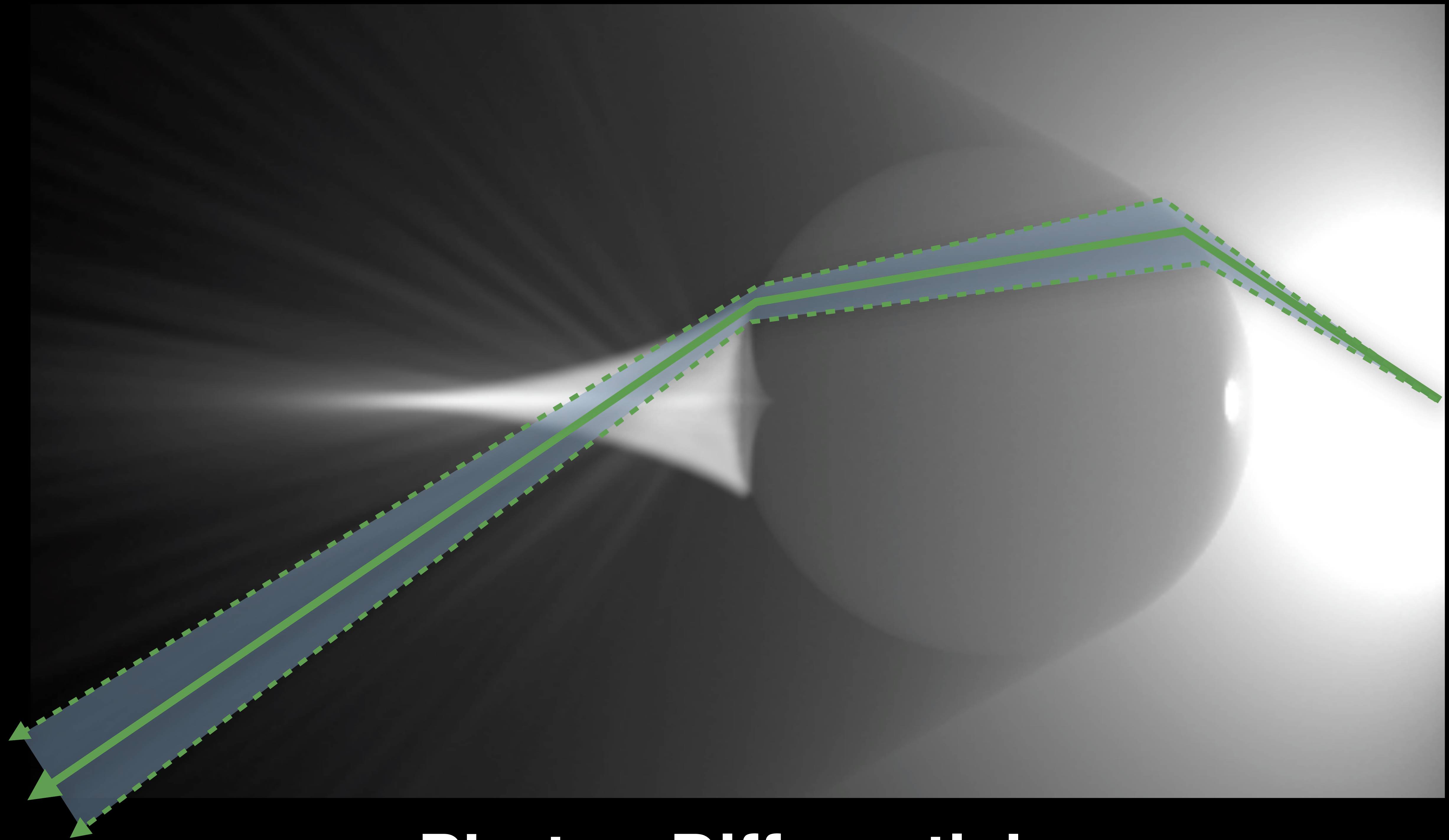



Fixed-width Beams



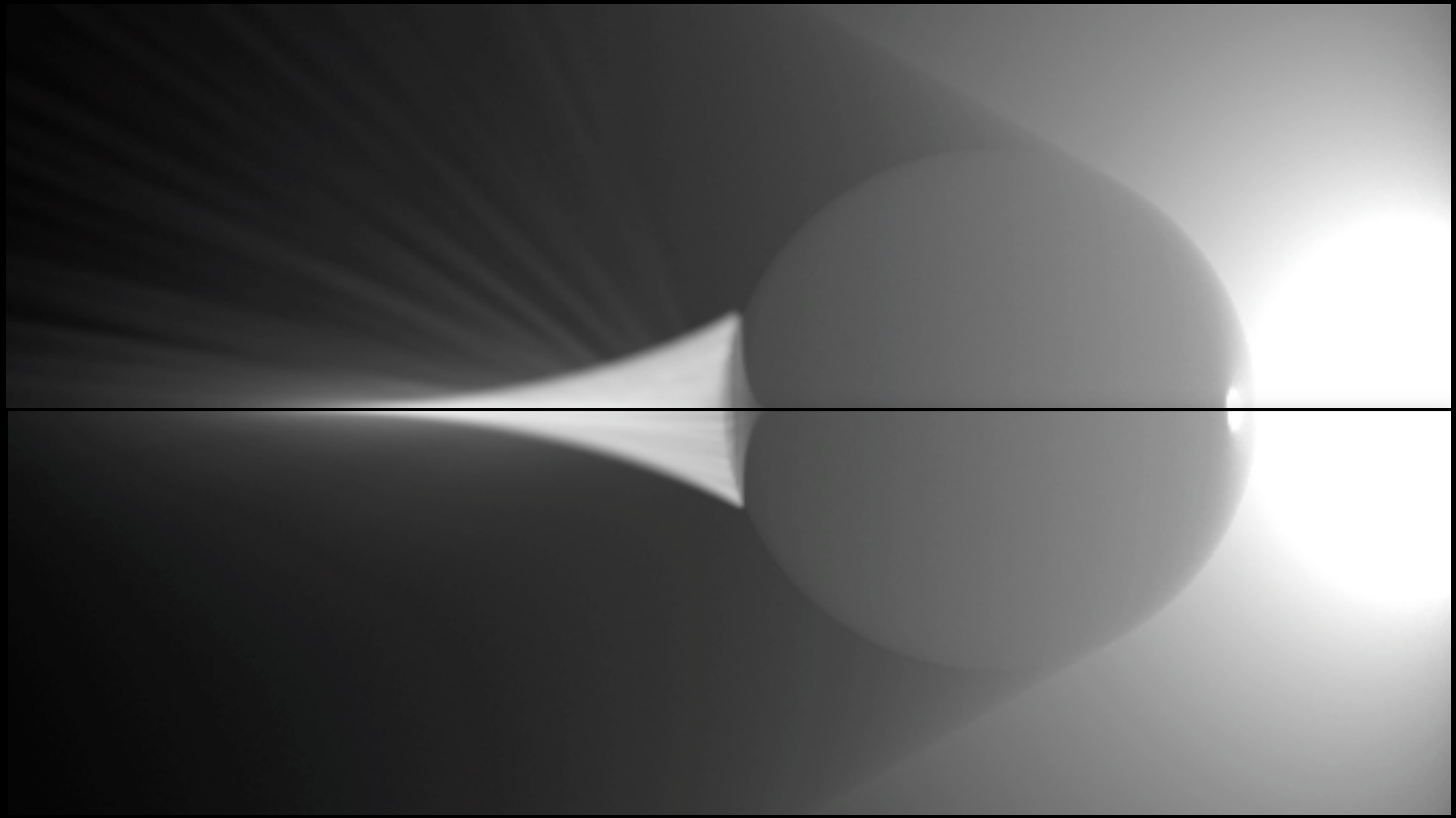
Fixed-width Beams



Photon Differentials

[Igehy 99, Schjøth et al. 07]

Fixed-width Beams



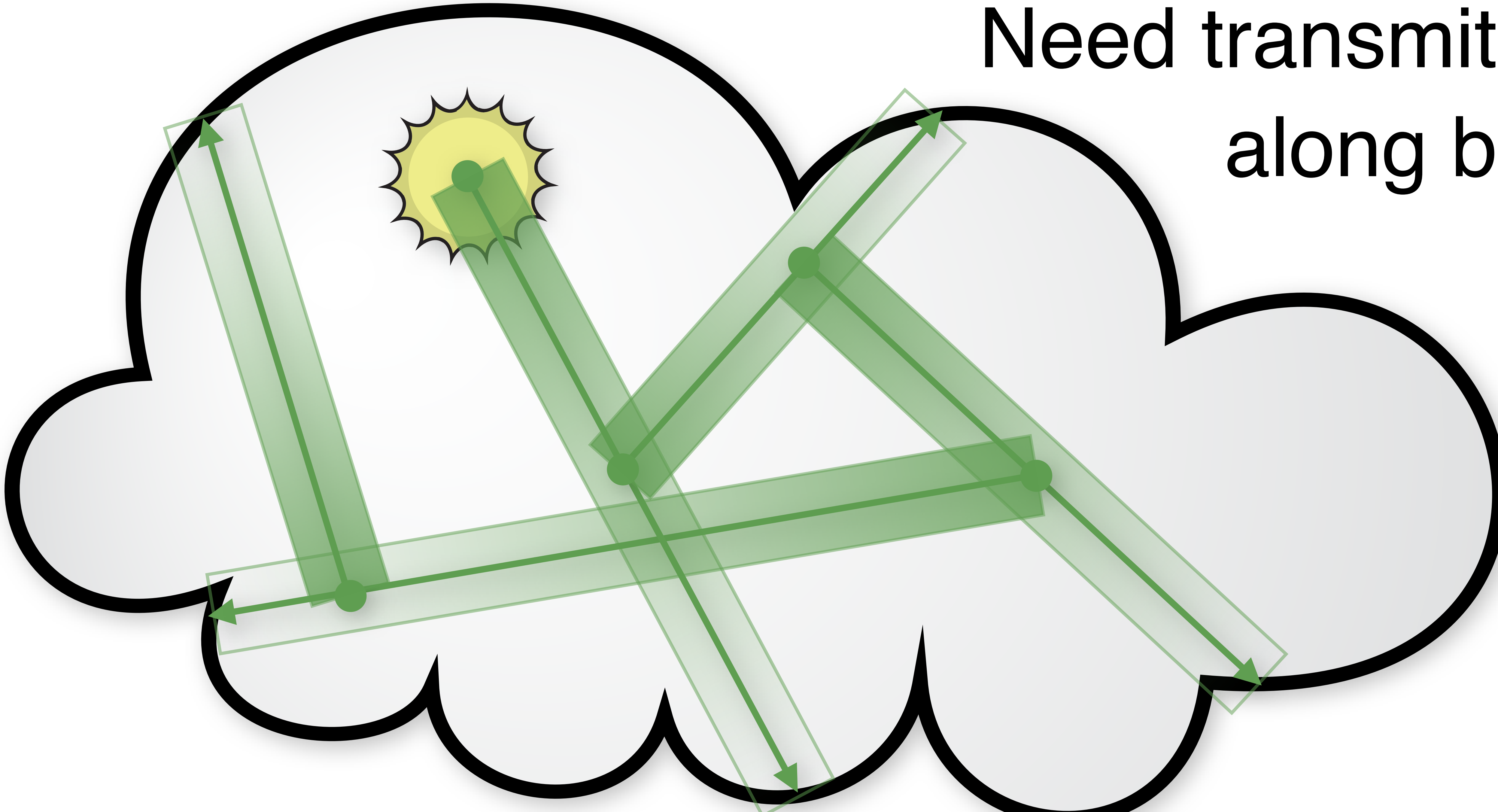
Adaptive-width Beams

Rendering

- Need to intersect each ray with all photon beams (expensive!)
- Place photon beams in an acceleration structure
- Rasterization (beams are just axial billboards!)
- Transmittance?

Evaluating Transmittance

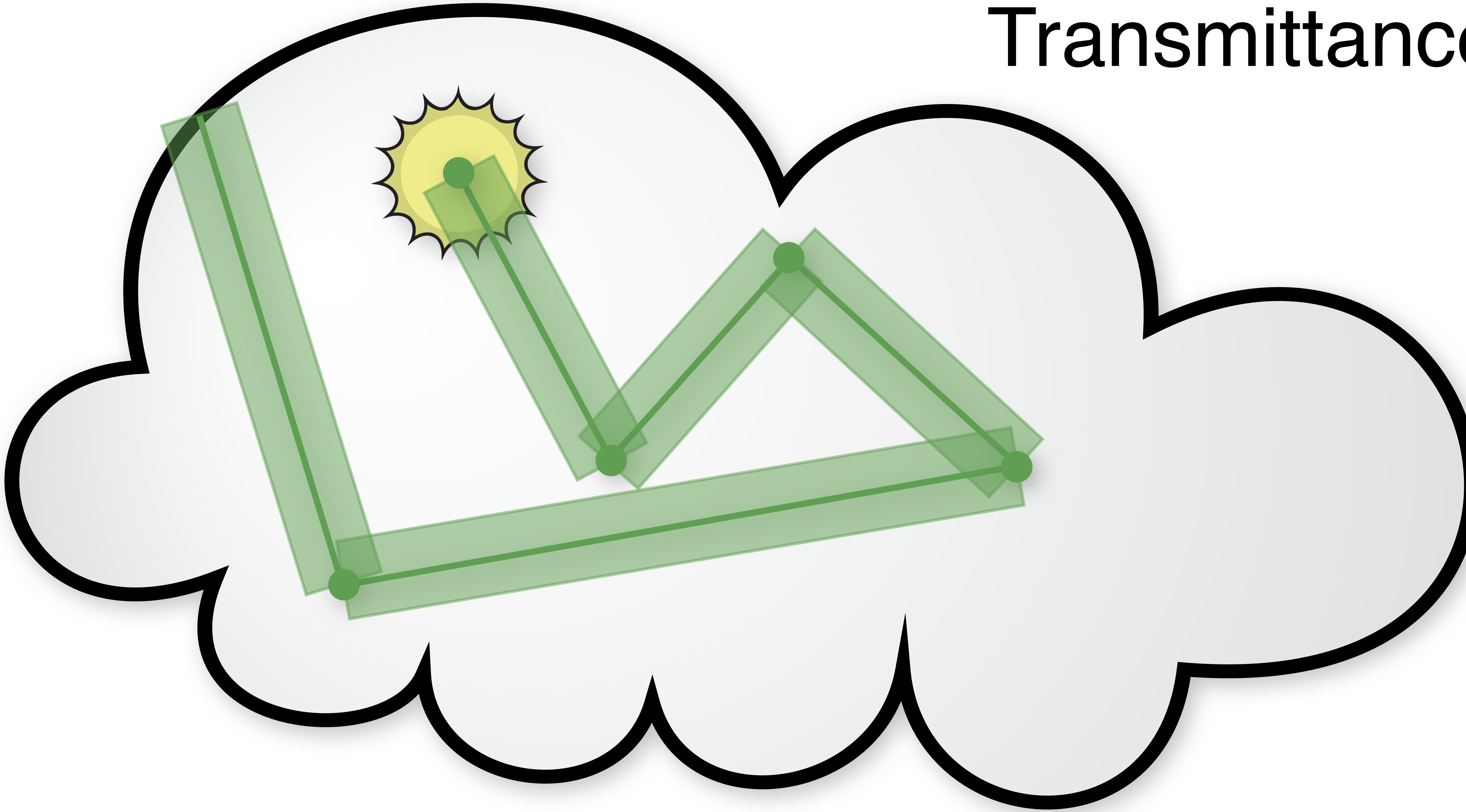
Need transmittance along beams



"Long Beams"

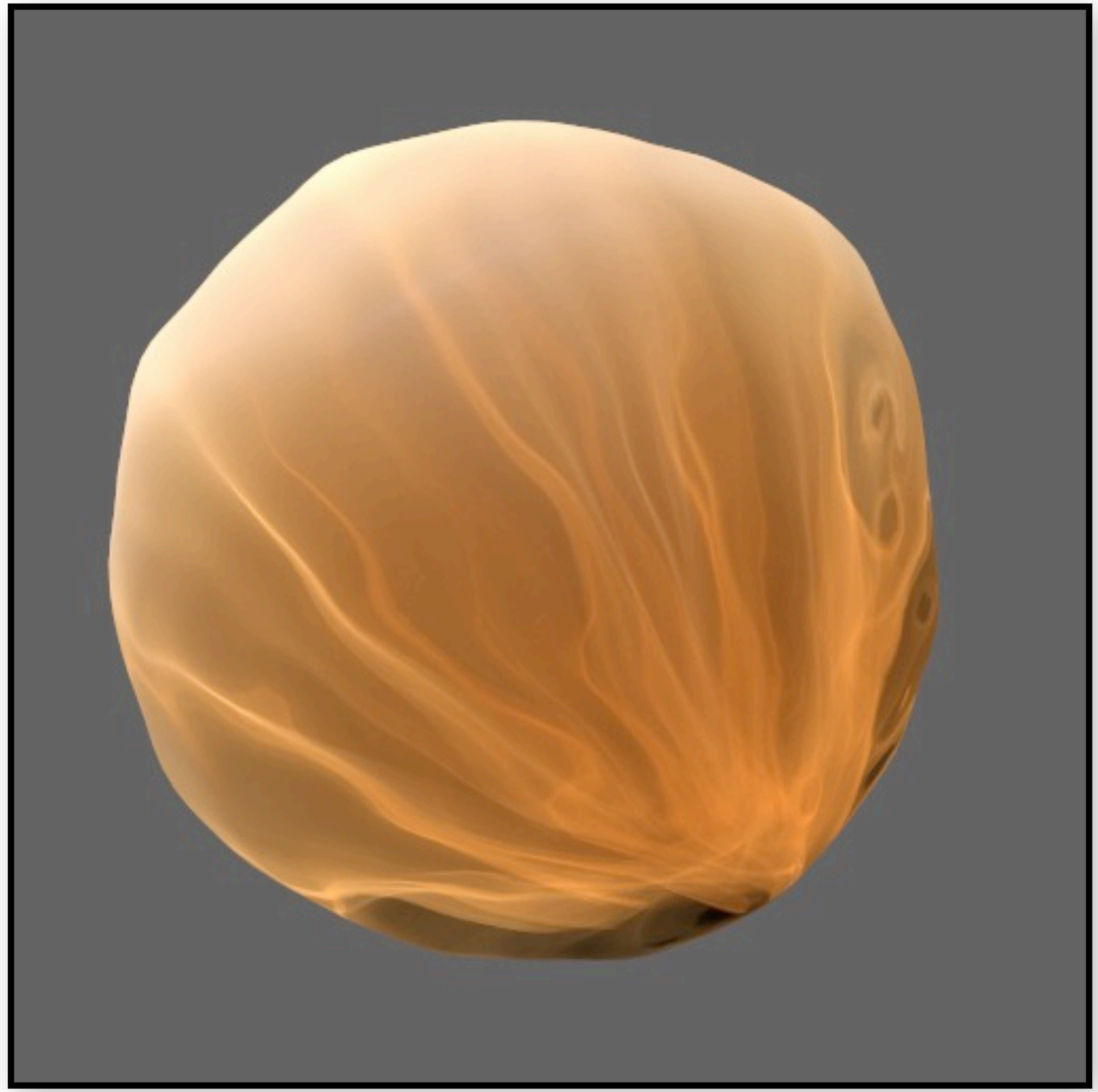
Evaluating Transmittance

Transmittance = 1!

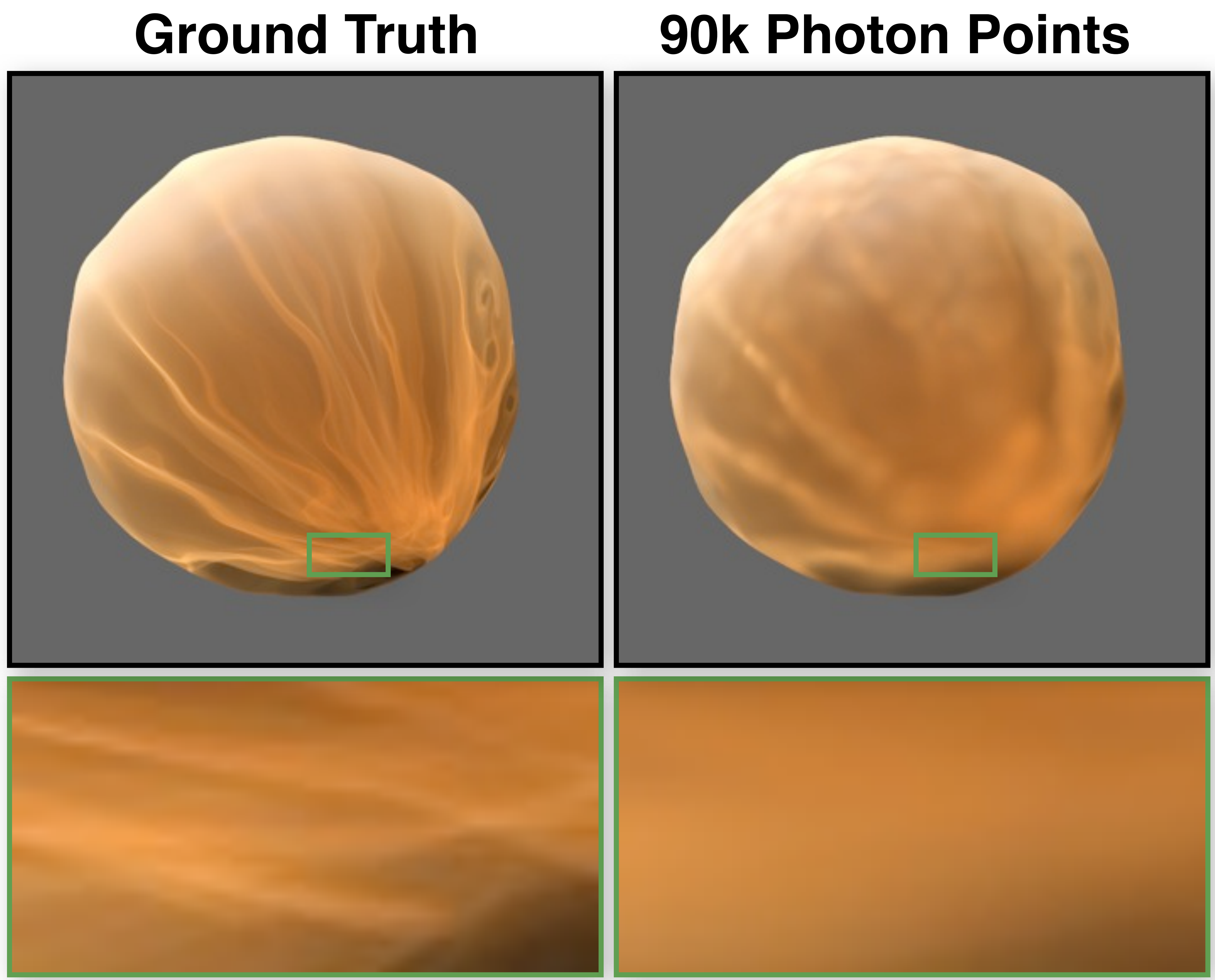


“Short Beams”

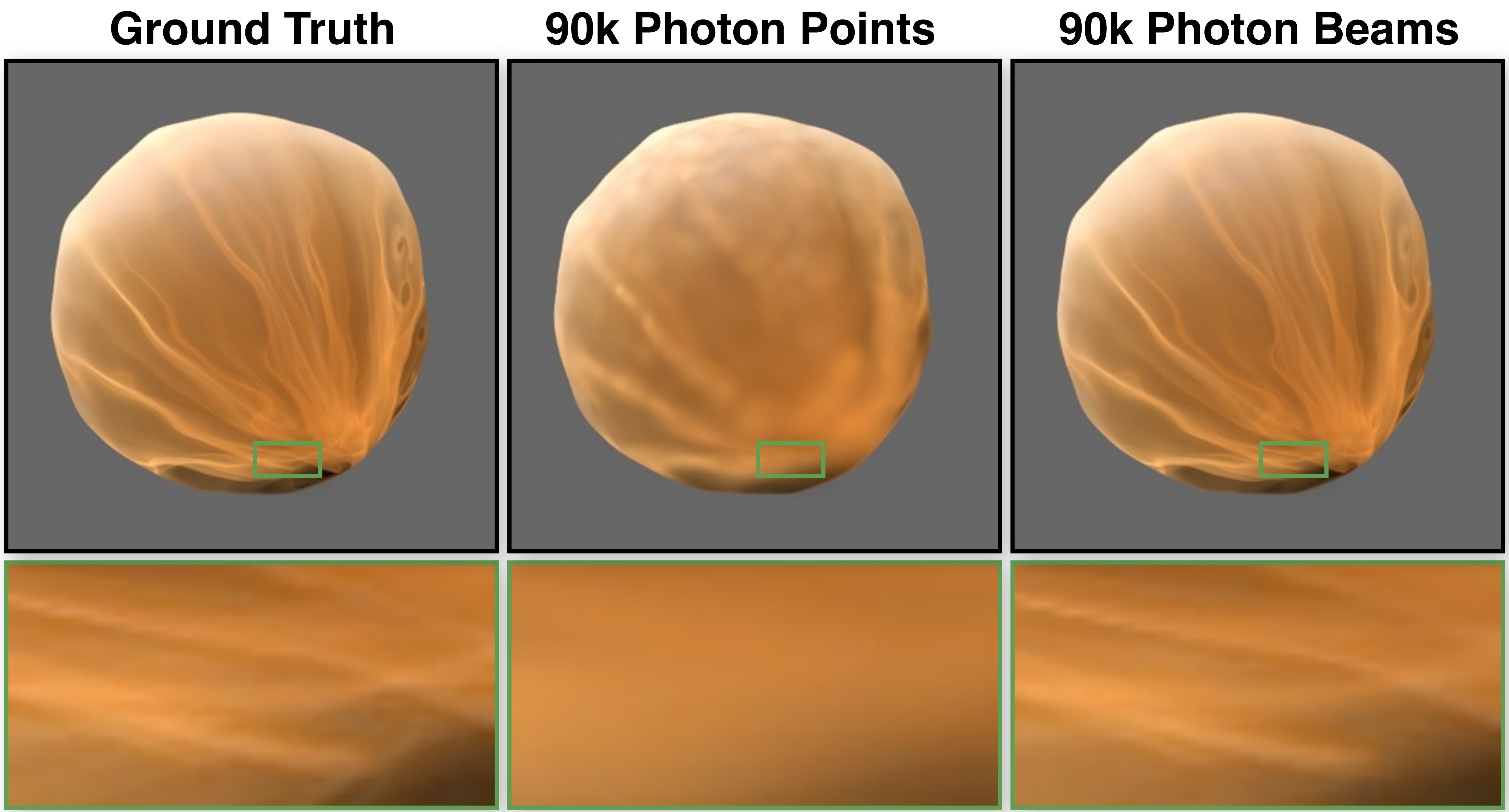
Bumpy Sphere



Bumpy Sphere



Bumpy Sphere

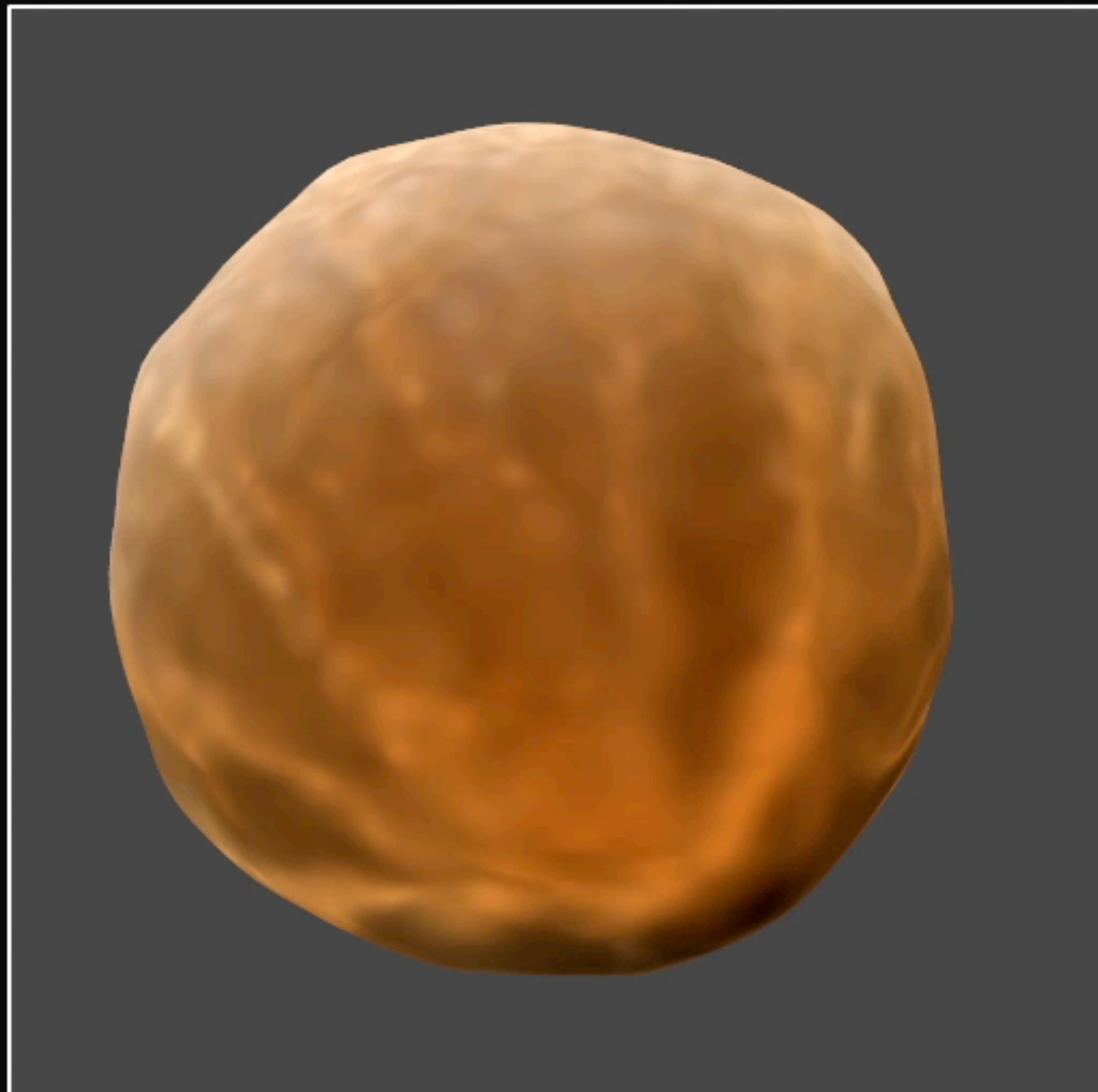


Bumpy Sphere

Rendered at 512x512 with up to 16 samples/pixel

Equal Photon Count

Photon Points



90K Photon **Points**
~ 40 seconds/frame

Photon Beams

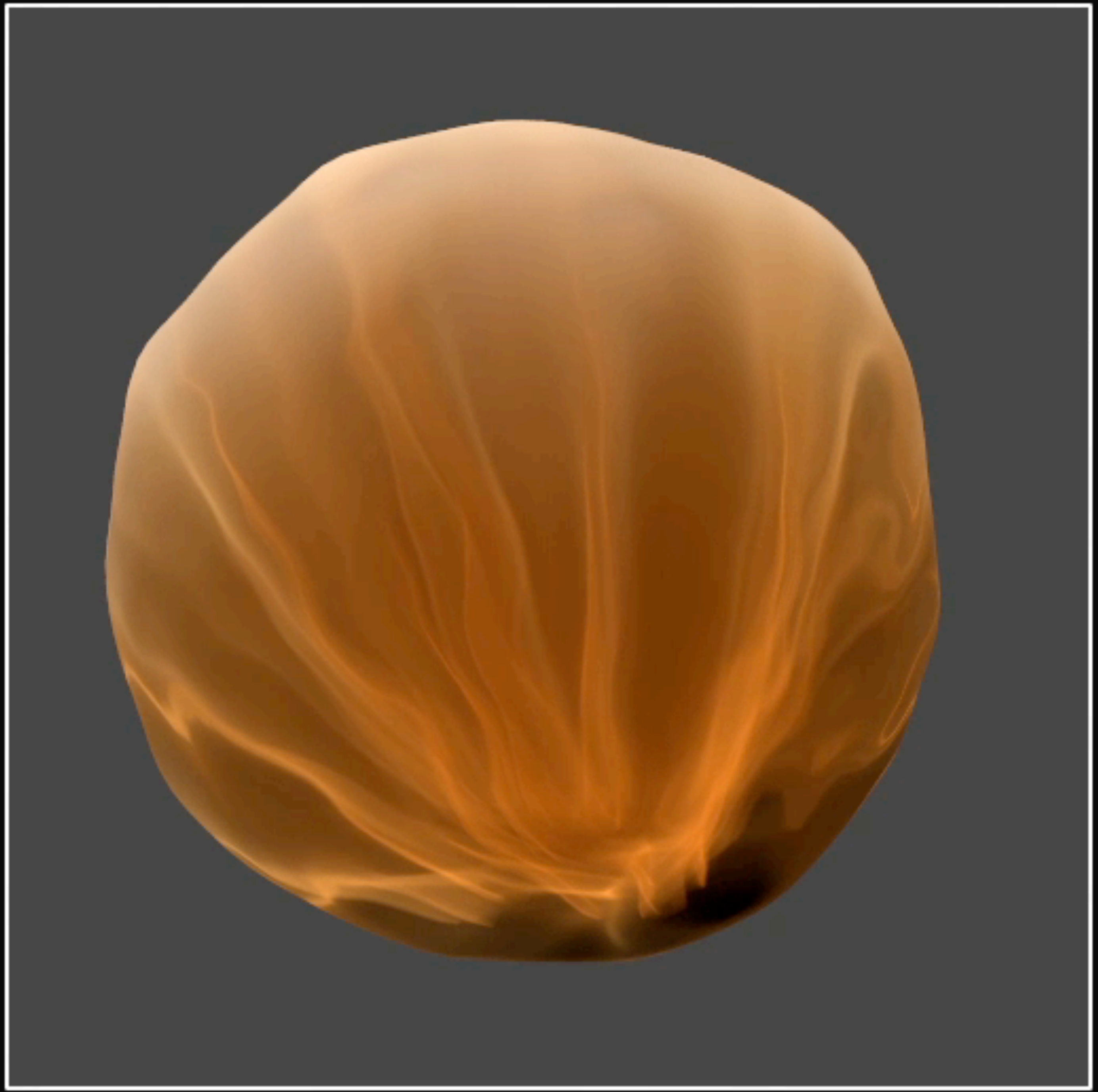
90K Photon **Beams**
~ 103 seconds/frame

Equal Render Time

Photon Points

Photon Beams

1.3M Photon **Points**
~ 101 seconds/frame



90K Photon **Beams**
~ 103 seconds/frame

Lighthouse

Photon Points

10K Photon **Points**
~ 31 seconds/frame

Roughly Equal Time

Photon Beams

700 Photon **Beams**
~ 25 seconds/frame

Underwater Sun Beams

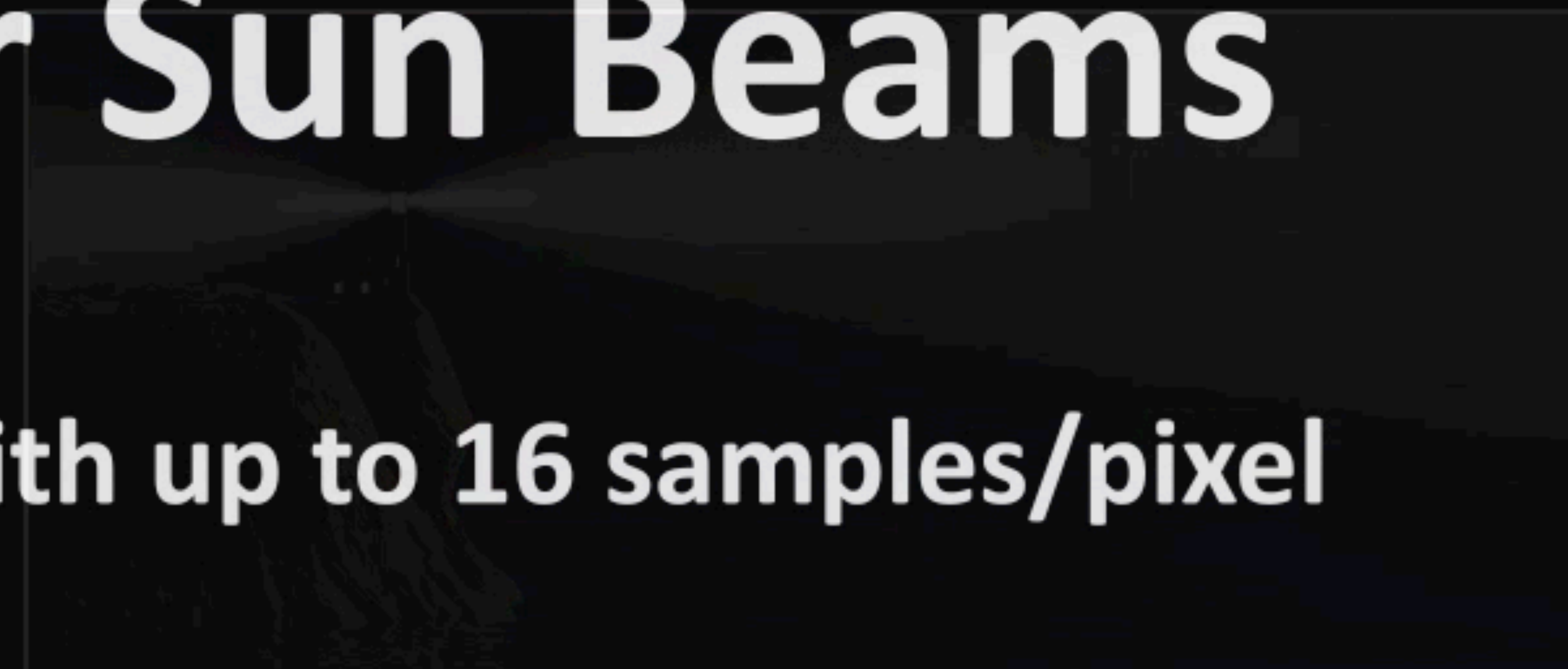
Rendered at 1024x576 with up to 16 samples/pixel

Lighthouse

Jarosz et al. ‘08

1M Photon **Points**
~ 226 seconds/frame
9x Render Time

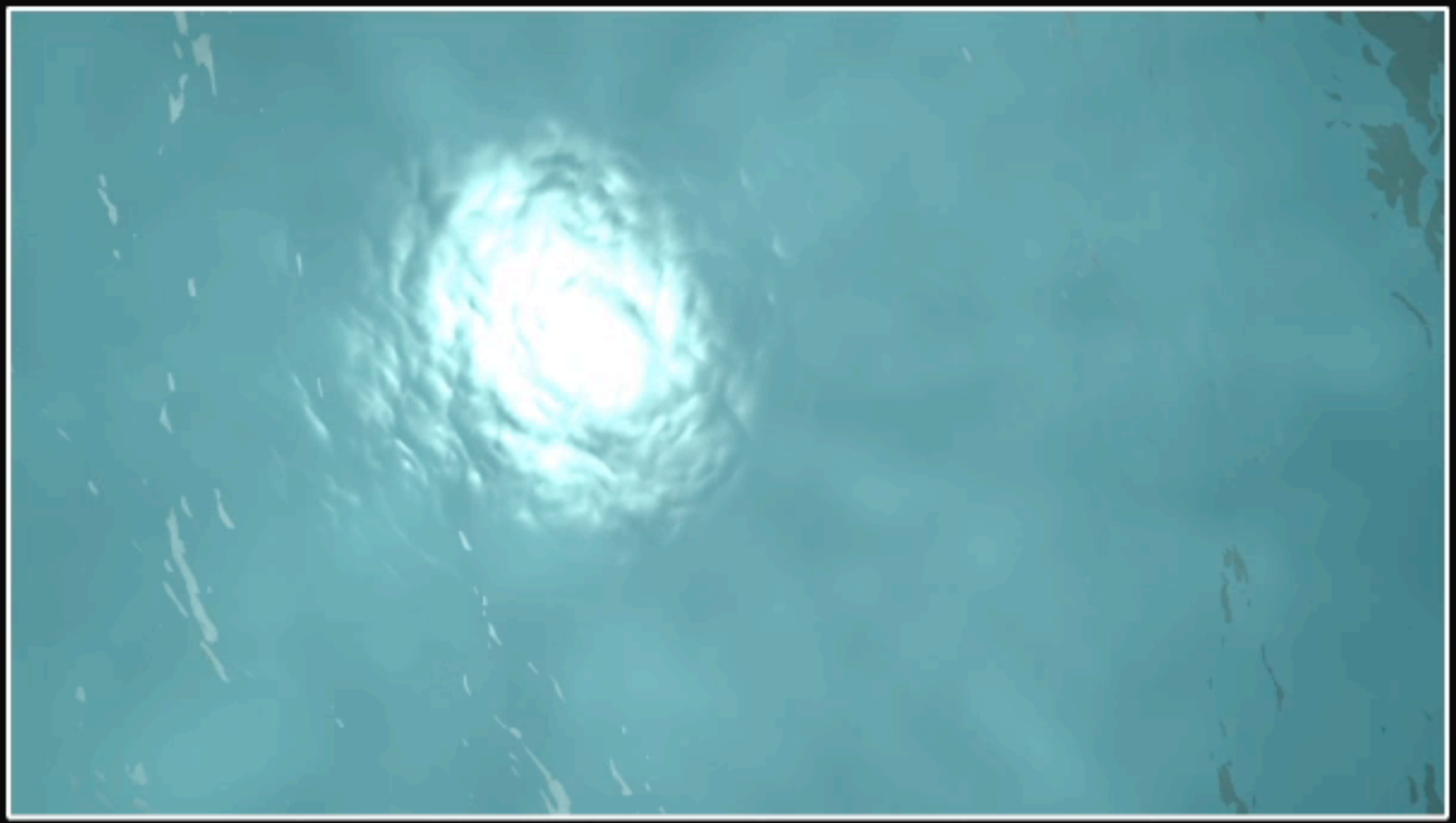
Our Method



700 Photon **Beams**
~ 25 seconds/frame

Underwater Sun Beams

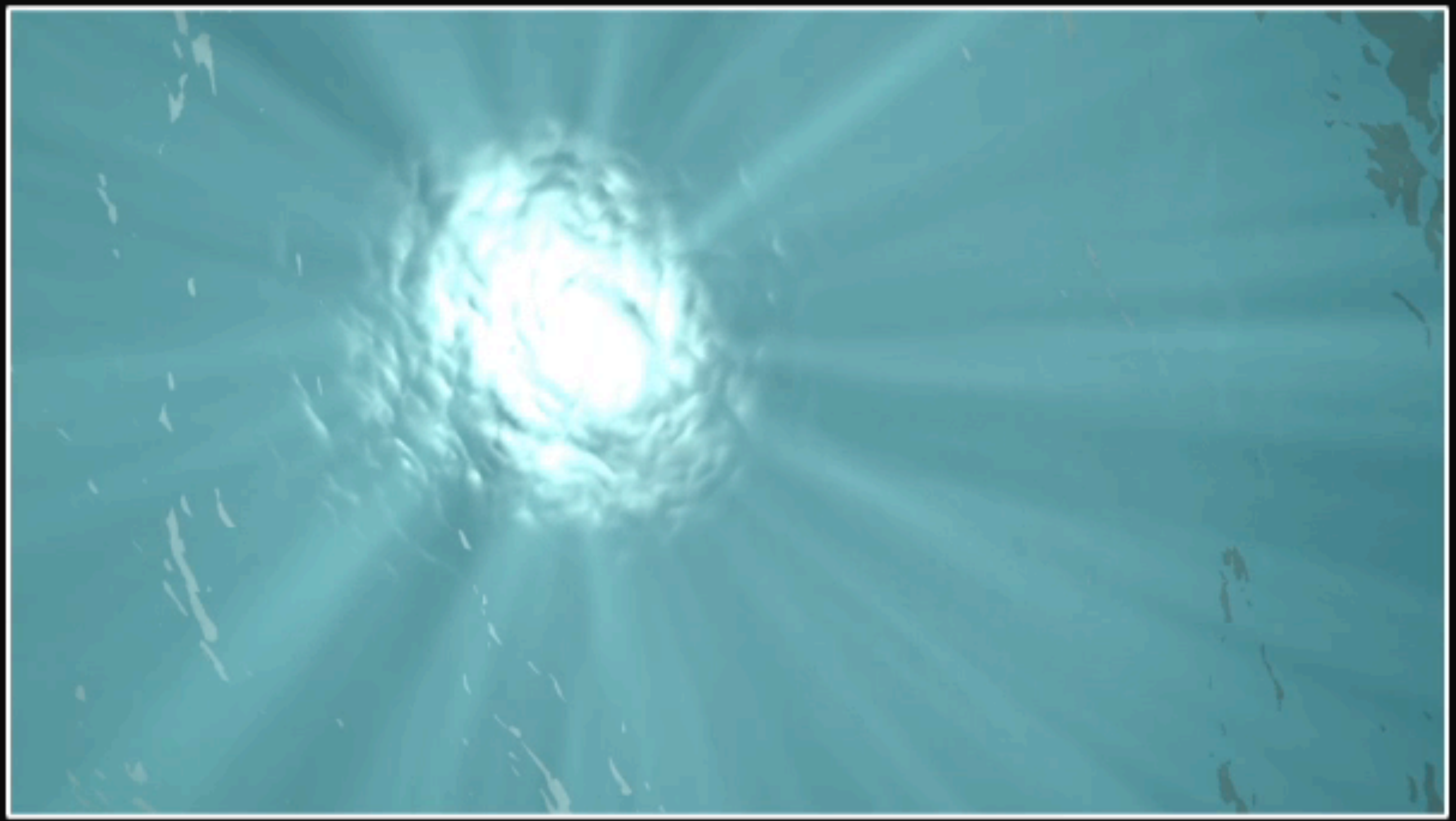
Photon Points



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

Roughly Equal Time

Photon Beams



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

Progressive Photon Beams [Jarosz et al. 11b]

- Combine benefits of:
  - photon beams
  - progressive photon mapping

Statistical Convergence

- Previous derivations not directly applicable
  - beam density vs. point density
- Reduction factor: $f_i = \dfrac{i+\alpha}{i+1}$
- *Application* of factor depends on blur dimensionality
  - Surfaces (2D): $r_{i+1}^2 = f_i \cdot r_i^2$
  - Volumetric photon mapping (3D): $r_{i+1}^3 = f_i \cdot r_i^3$
  - Beam × Beam (1D): $r_{i+1} = f_i \cdot r_i$

Algorithm

Step 1:

- Photon tracing: emit, scatter, store beams
- Scale beam widths by global factor r_i

Step 2:

- Tra[illegible] th, eva[illegible] ray using beams

- Display running average
- *Reduce* global factor r_i and *repeat*

Trivially Parallelizable

Results & Implementation

- 3 implementations:
  - GPU-only OptiX ray-tracer
  - GPU-only rasterization
  - General: Hybrid CPU/GPU

Results & Implementation

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  - GPU-only OptiX ray-tracer
  - GPU-only rasterization
  - General: Hybrid CPU/GPU

BumpySphere

OptiX Implementation

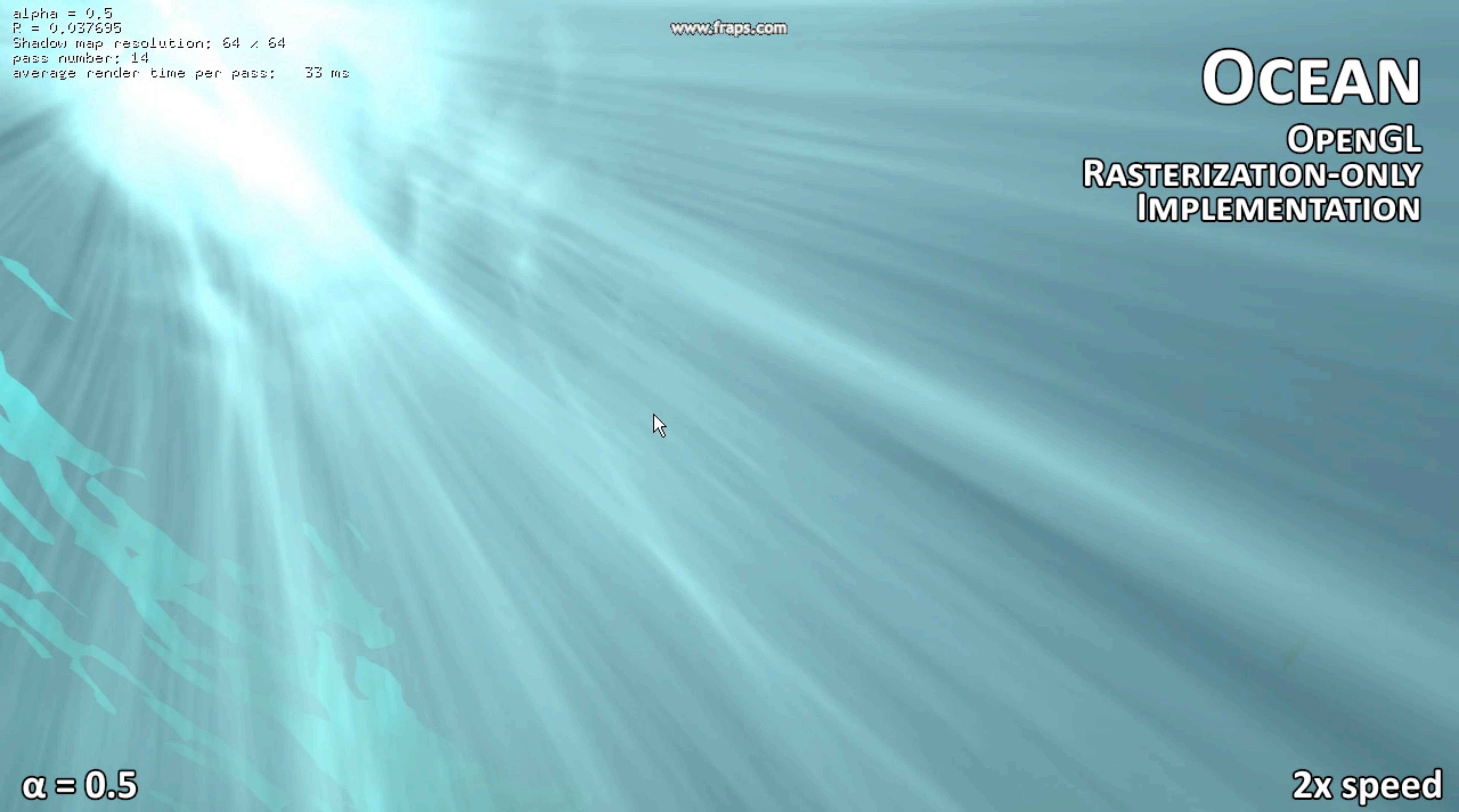
scene courtesy of Bruce Walter

alpha: 0.60 beams per pass: 1024 pass number: 1 render time per pass: 132.97 ms

2x speed

Results & Implementation

- 3 implementations:
  - GPU-only OptiX **ray-tracer**
  - GPU-only **rasterization**
  - General: Hybrid CPU/GPU


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

Results & Implementation

- 3 implementations:
  - GPU-only OptiX ray-tracer
  - GPU-only rasterization
  - General: Hybrid CPU/GPU

Cars

1280x720, Depth-of-Field

Pass 1

Homogeneous

Heterogeneous

Pass 1

Average of Passes 1..1

Pass 2 | Average of Passes 1..2

Pass 4	Average of Passes 1..4
	
	

Pass 8 | Average of Passes 1..8

Pass 16 | Average of Passes 1..16

Pass 32

Average of Passes 1..32

Pass 64 | Average of Passes 1..64

Pass 128

Average of Passes 1..128

Pass 256

Average of Passes 1..256

Pass 512

Average of Passes 1..512

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

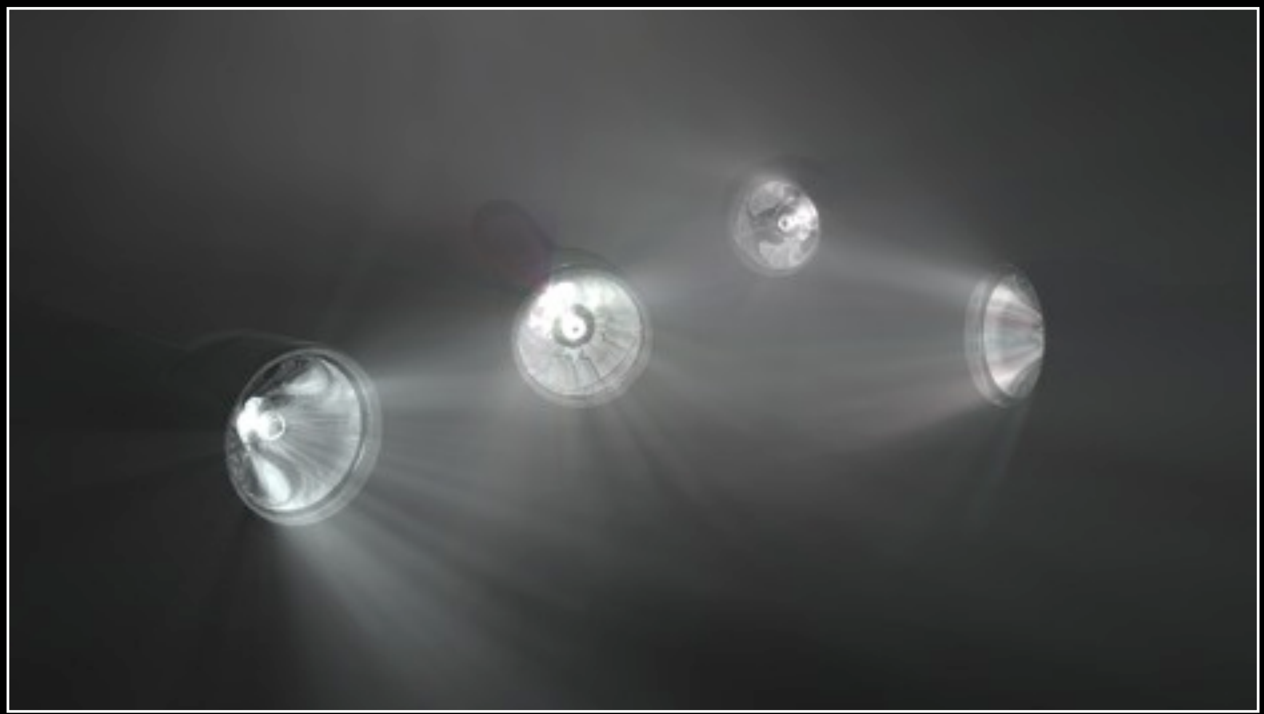
16.8 minutes

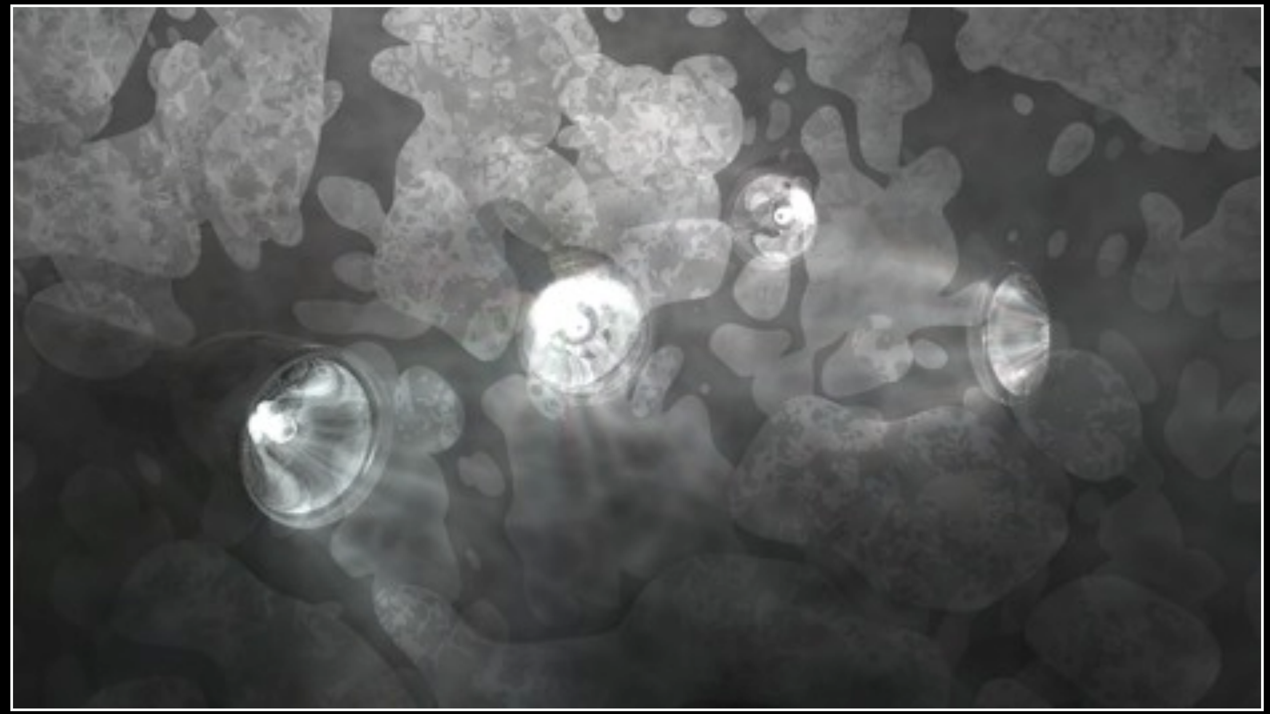
FlashLights

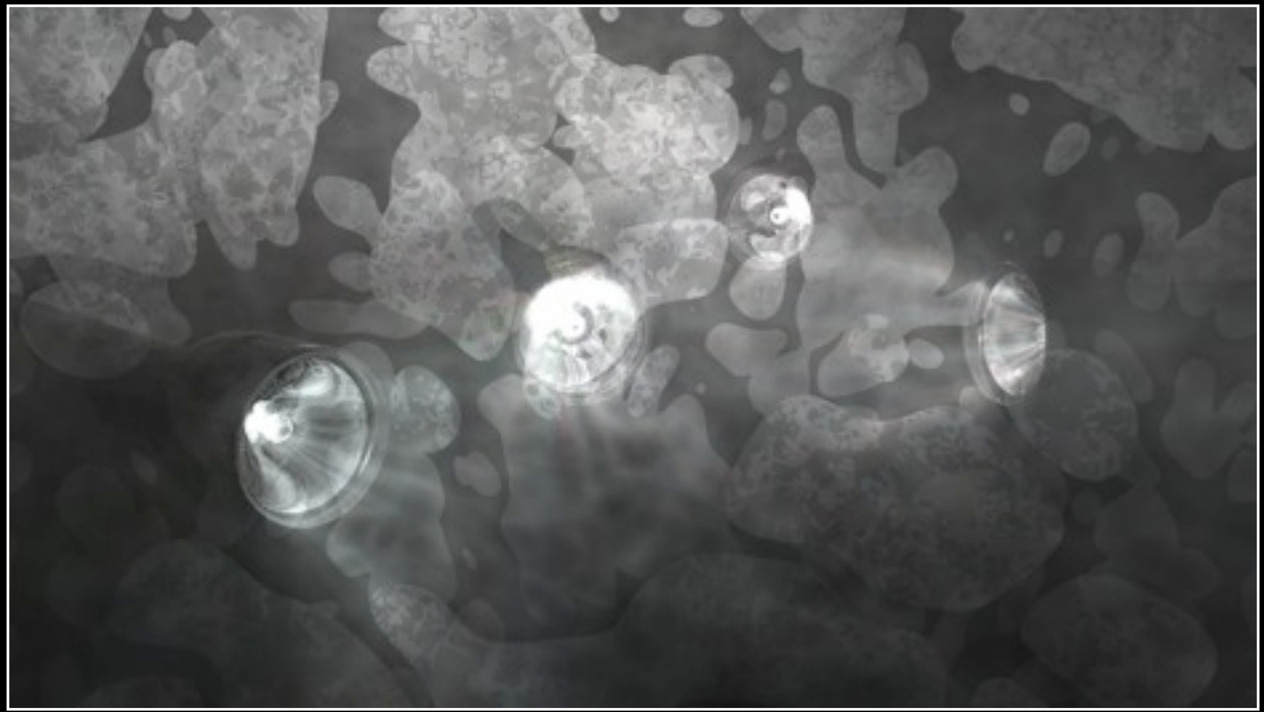
1280x720, Depth-of-Field

Pass 1

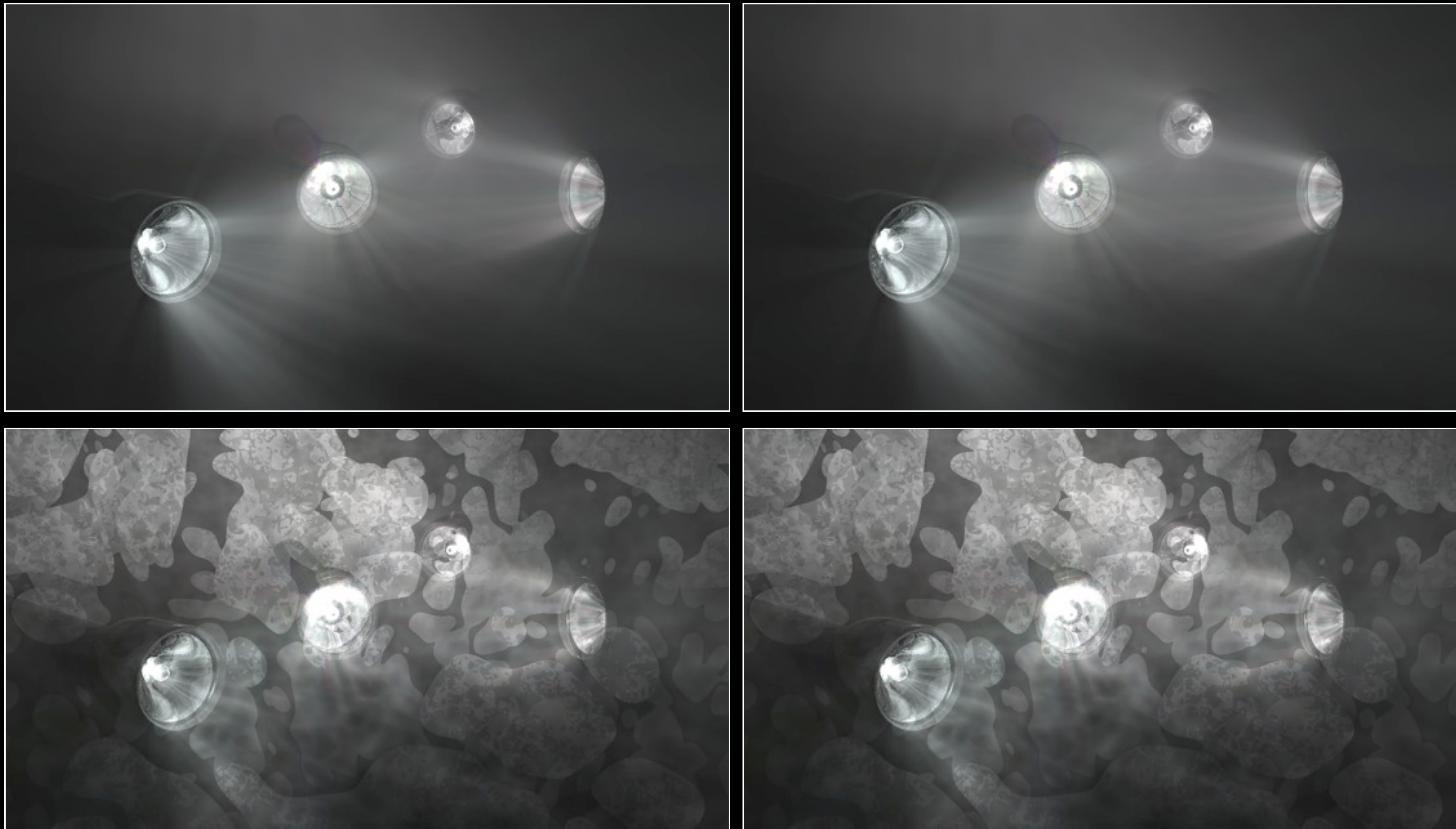
Average of Passes 1..1





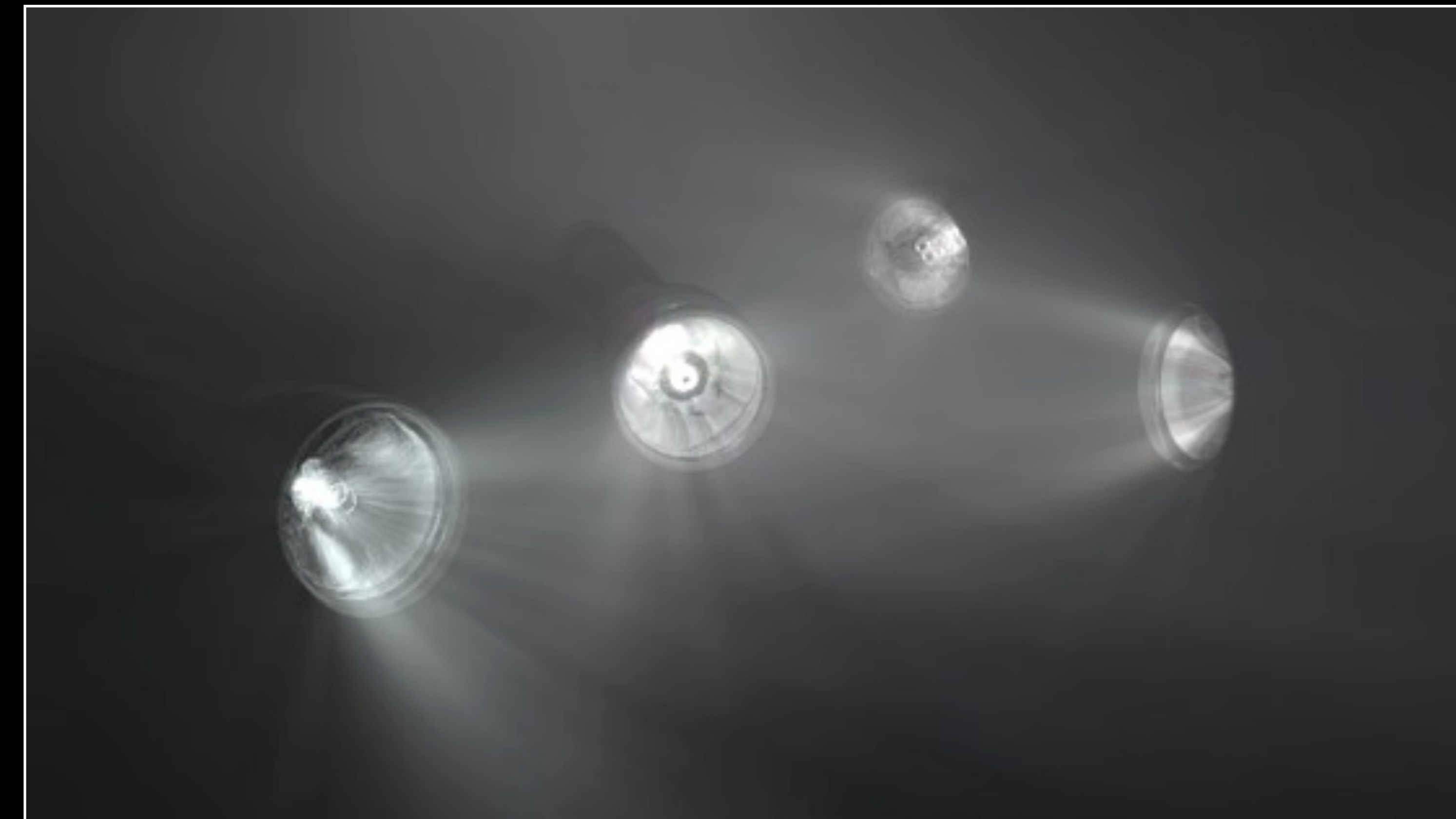


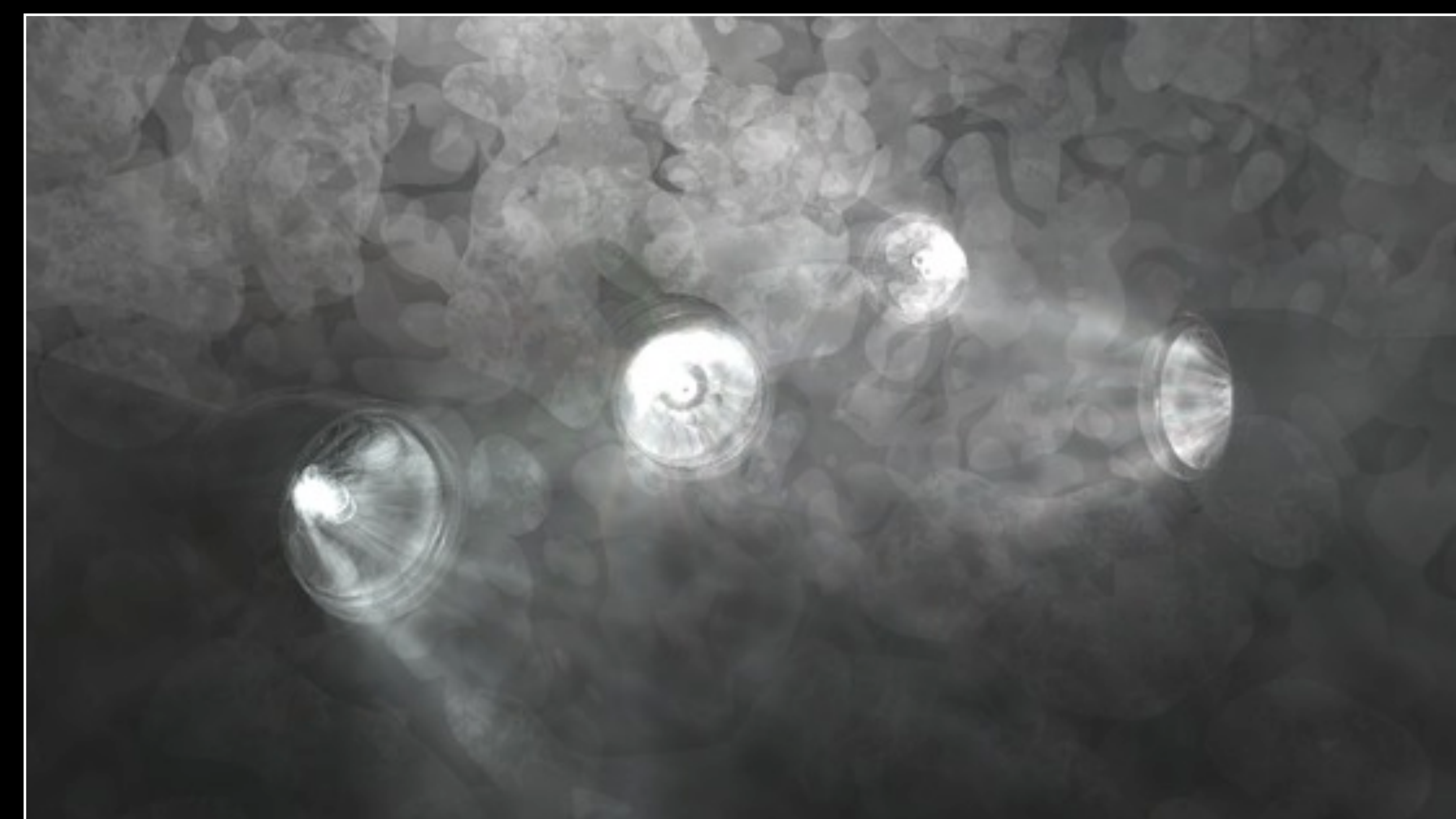
Pass 1 | Average of Passes 1..1



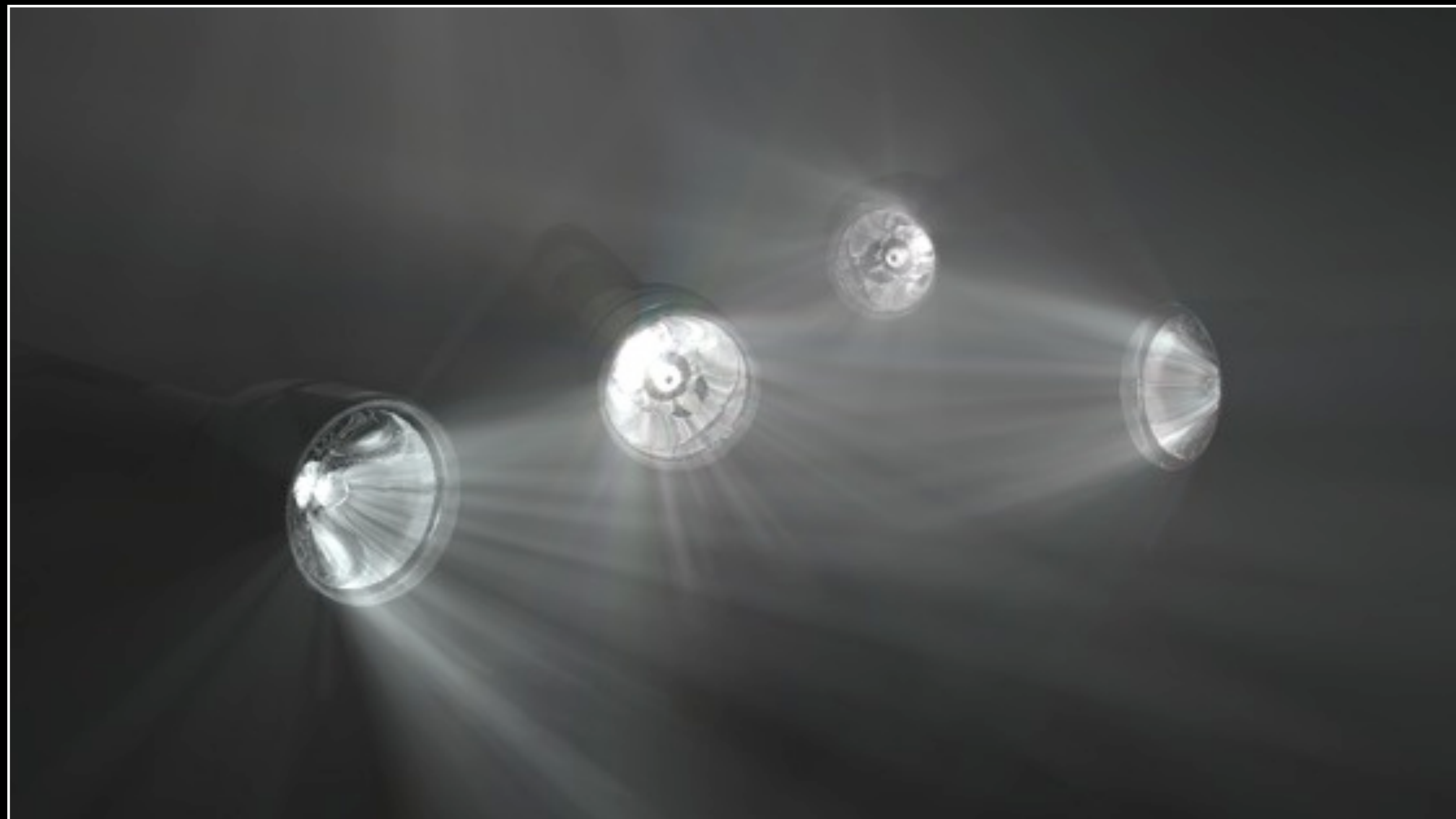
Pass 2

Average of Passes 1..2

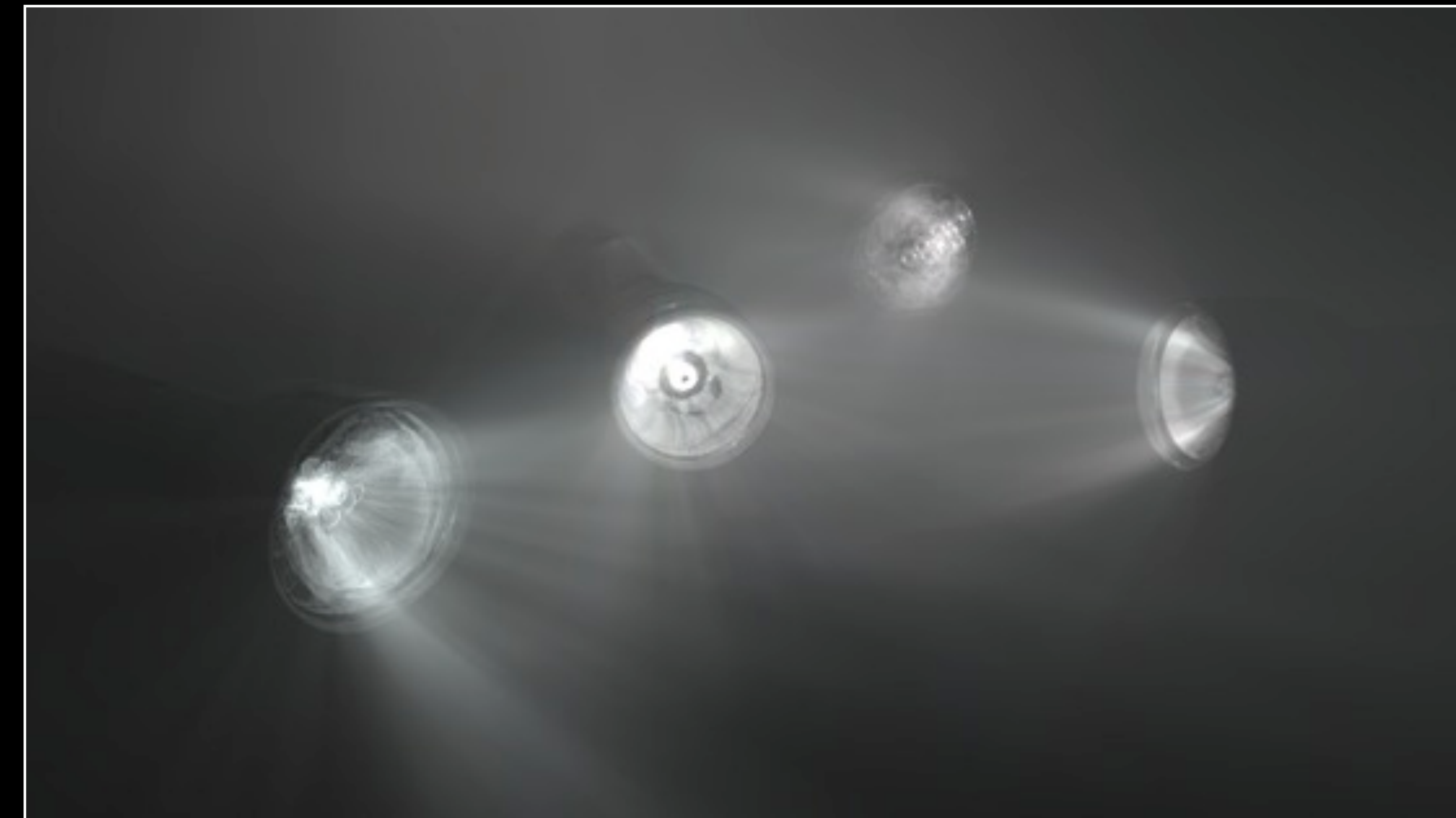


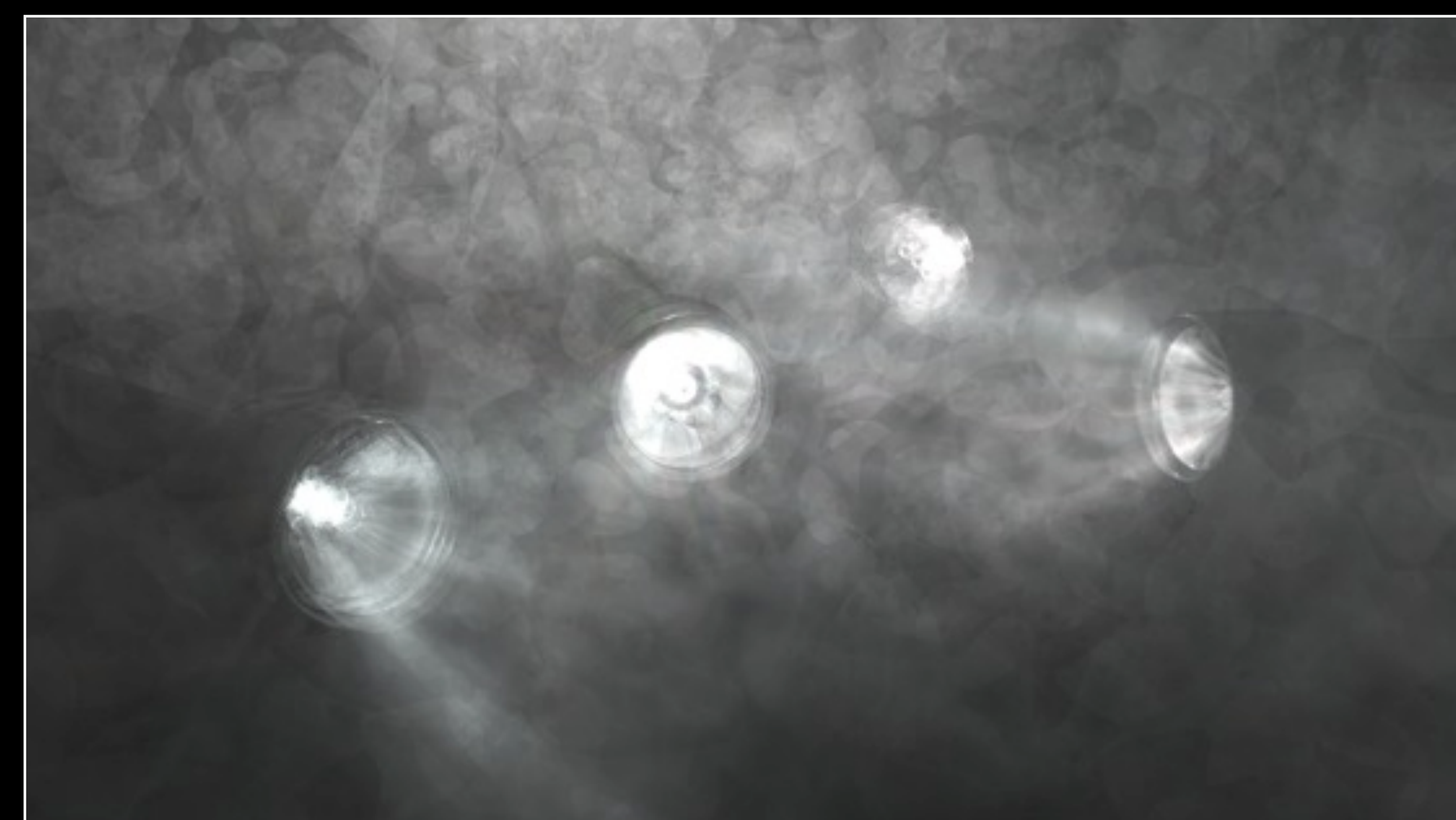


Pass 4

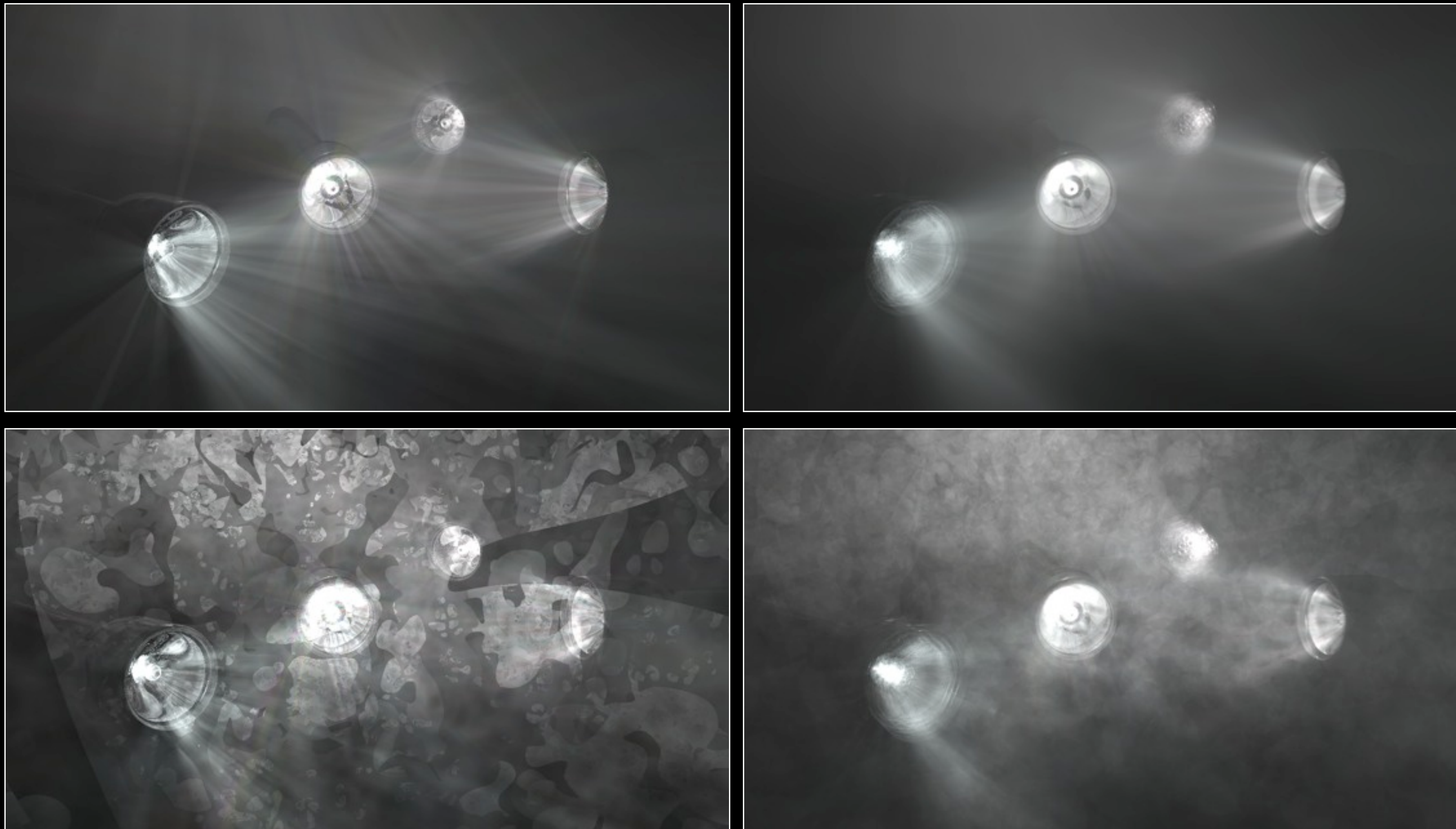


Average of Passes 1..4



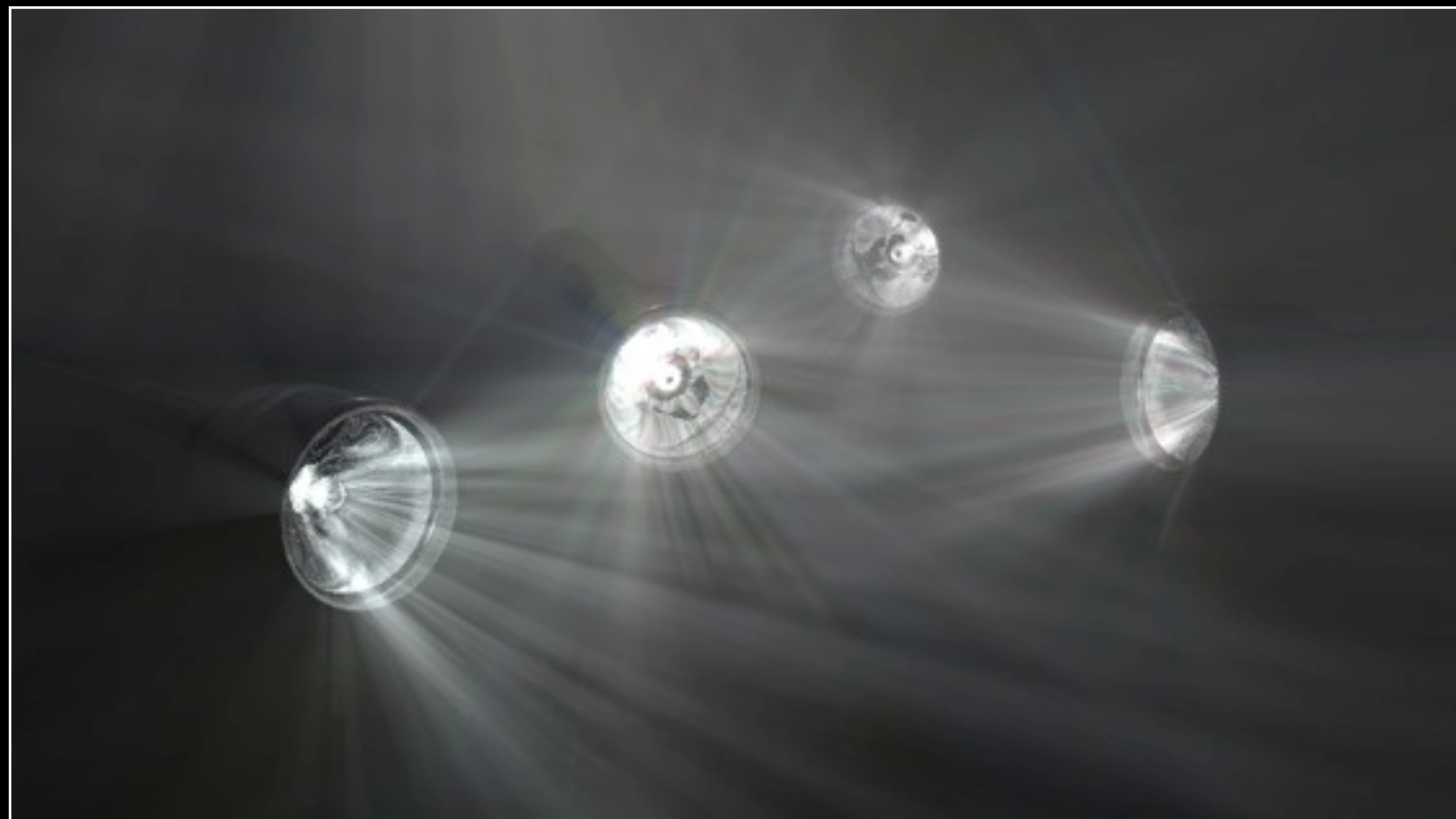


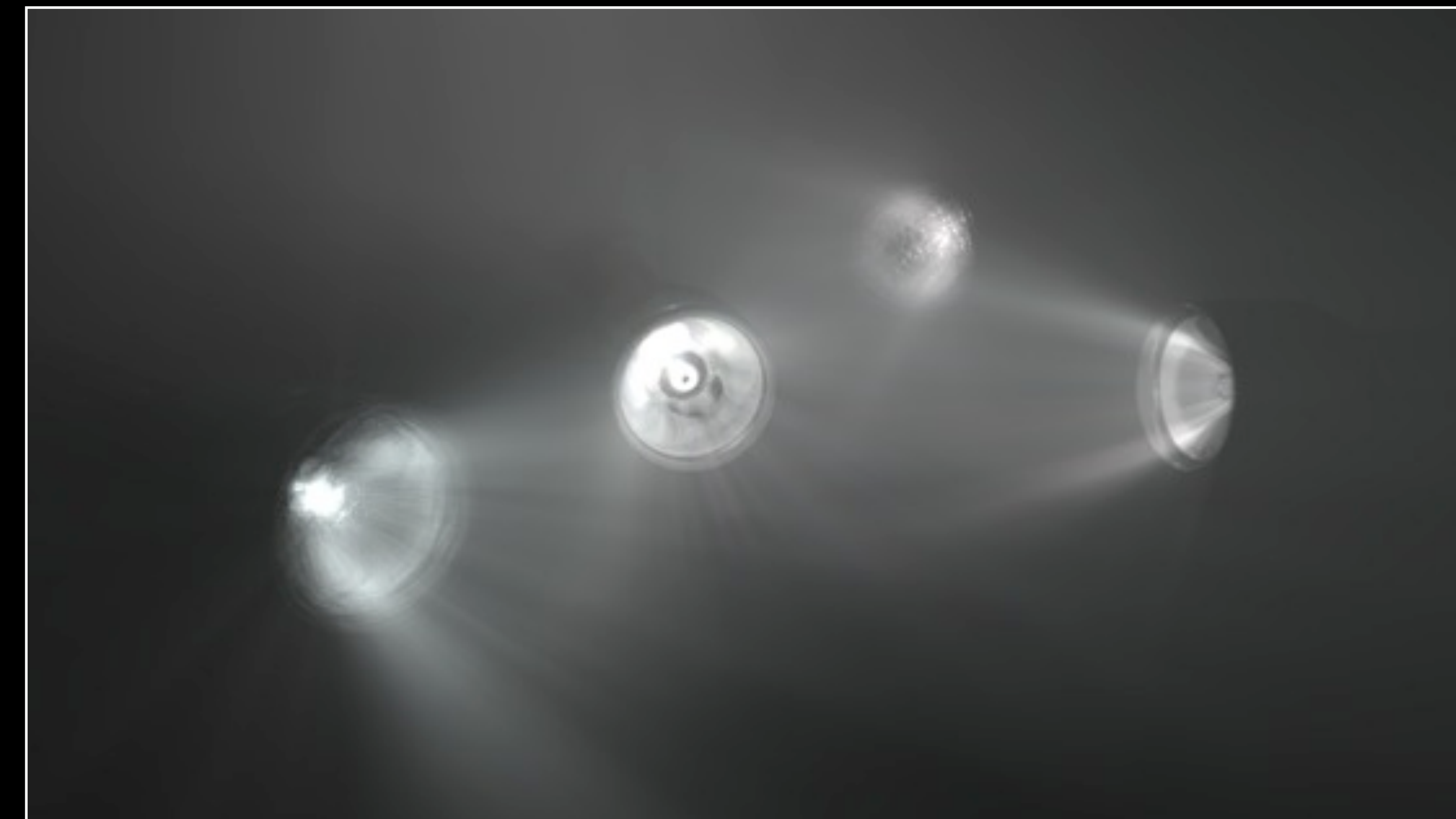
Pass 8 | Average of Passes 1..8



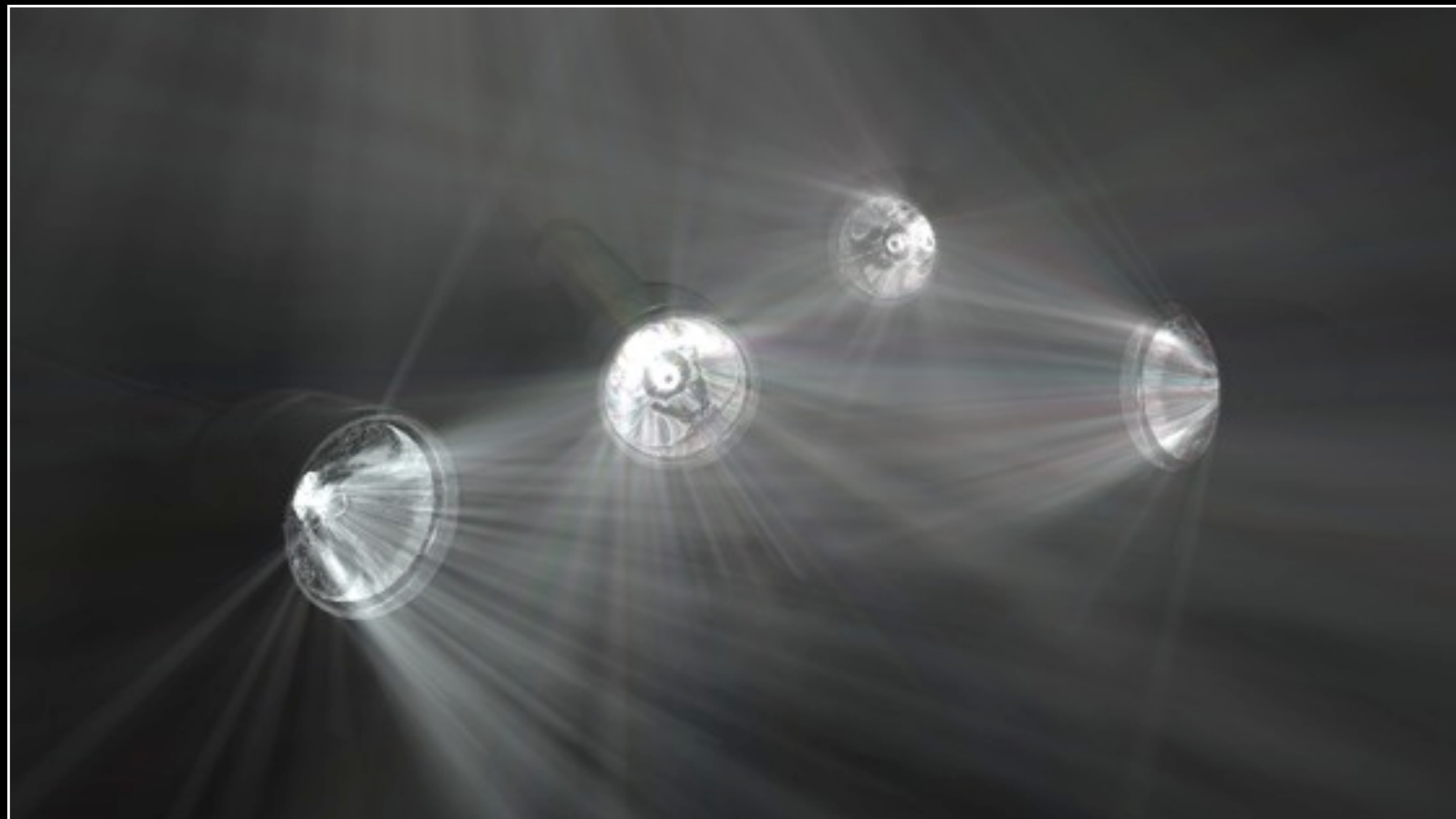
Pass 16

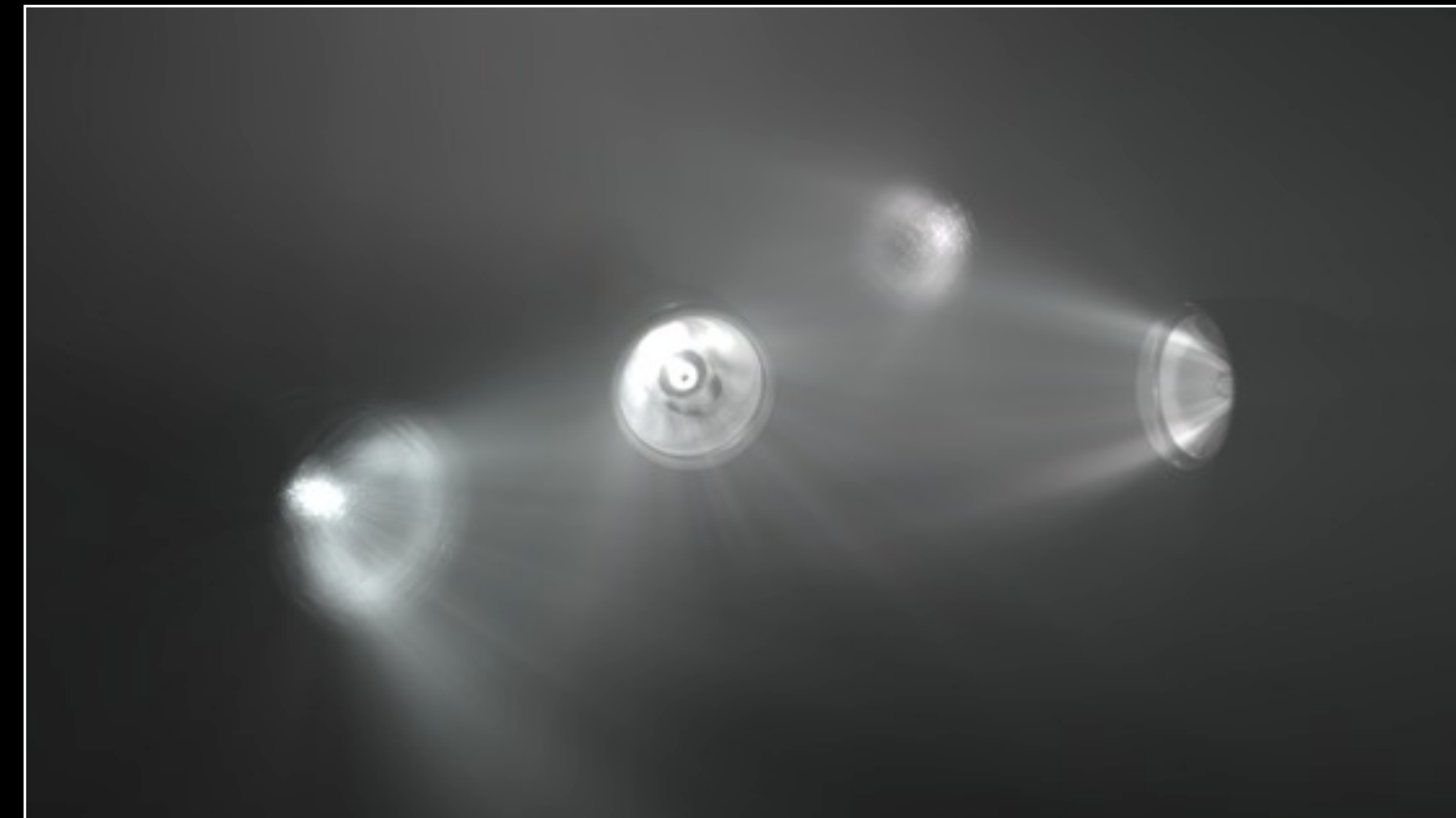
Average of Passes 1..16



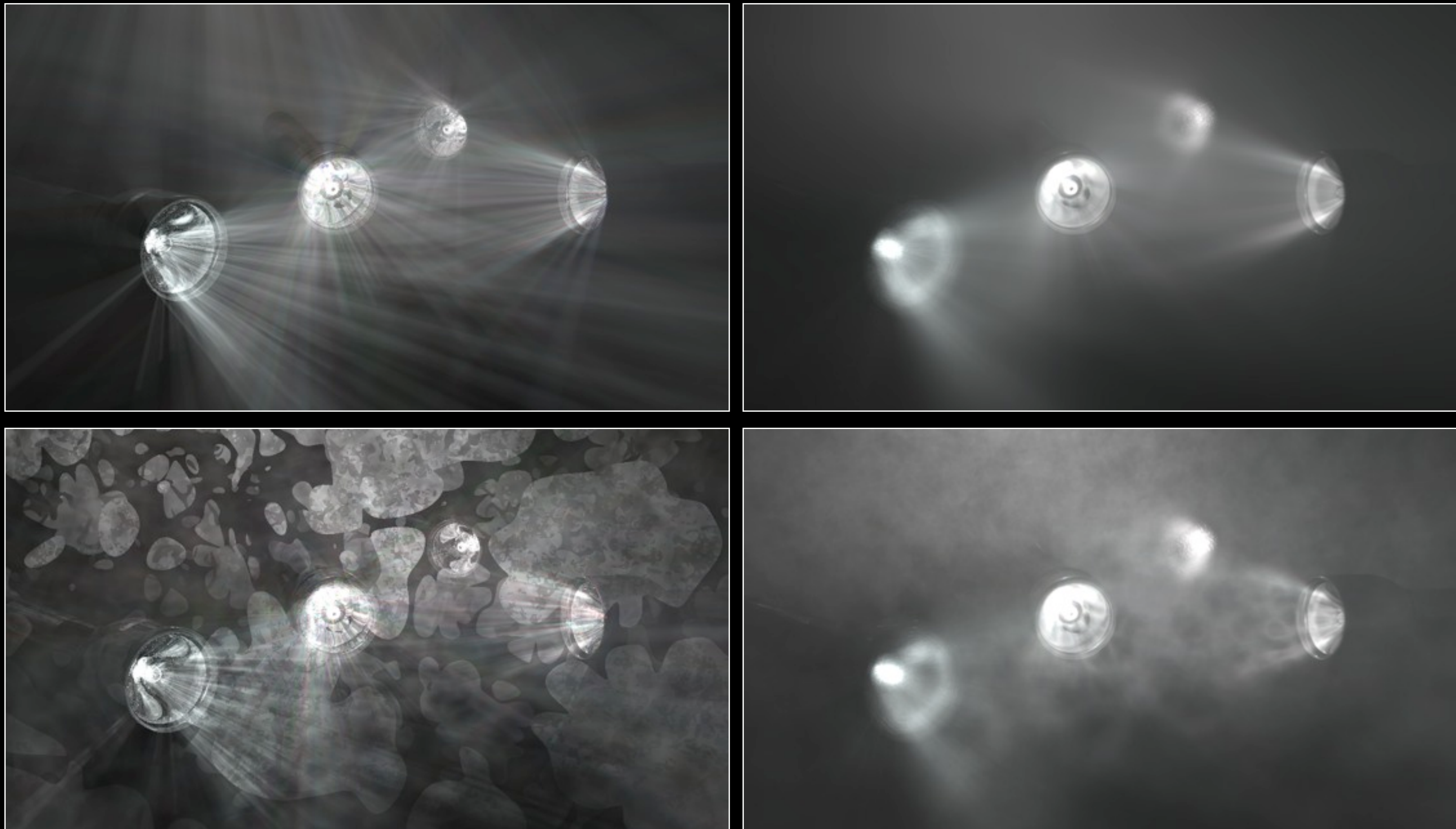


Pass 32 | Average of Passes 1..32



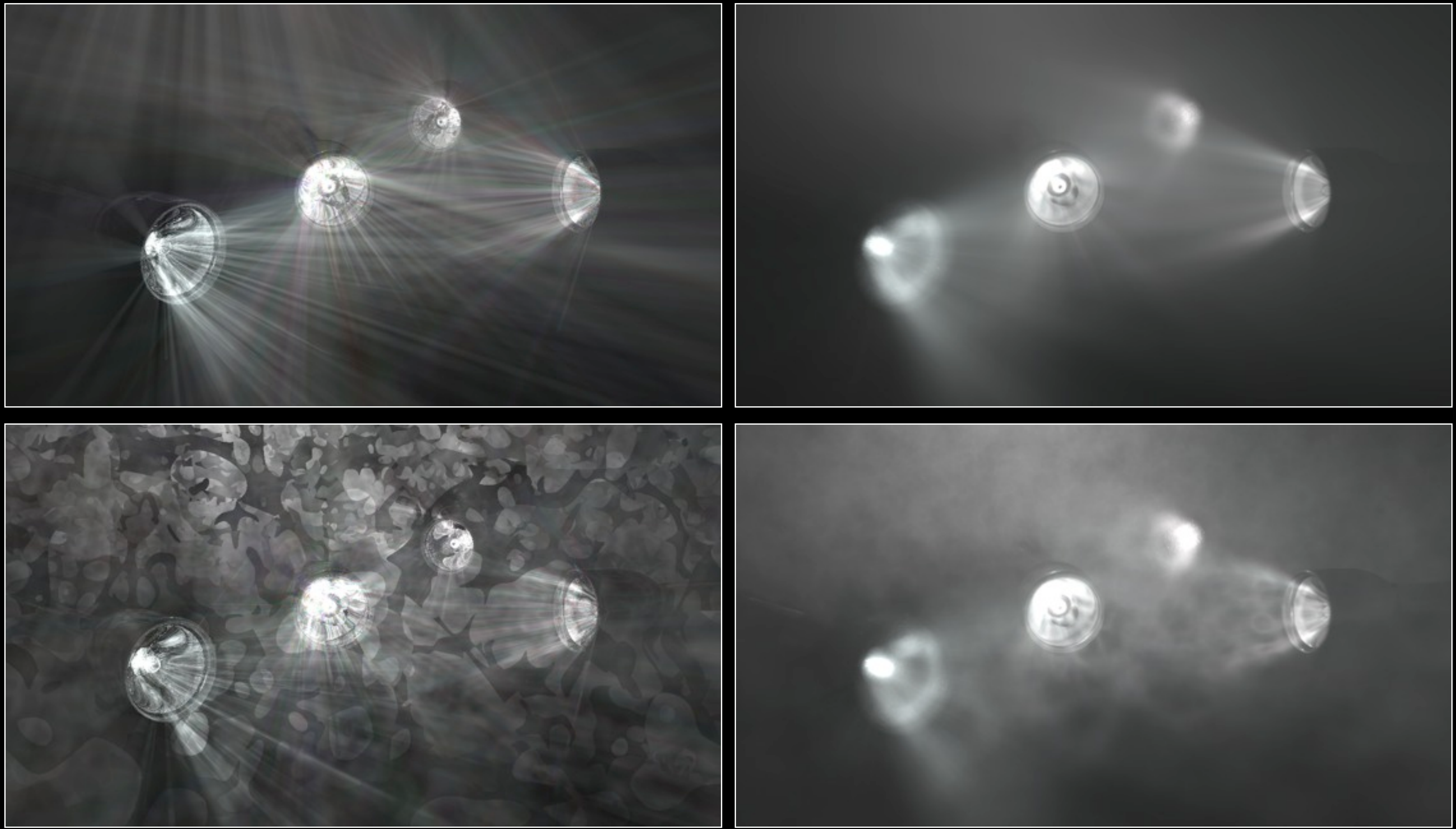


Pass 64 | Average of Passes 1..64

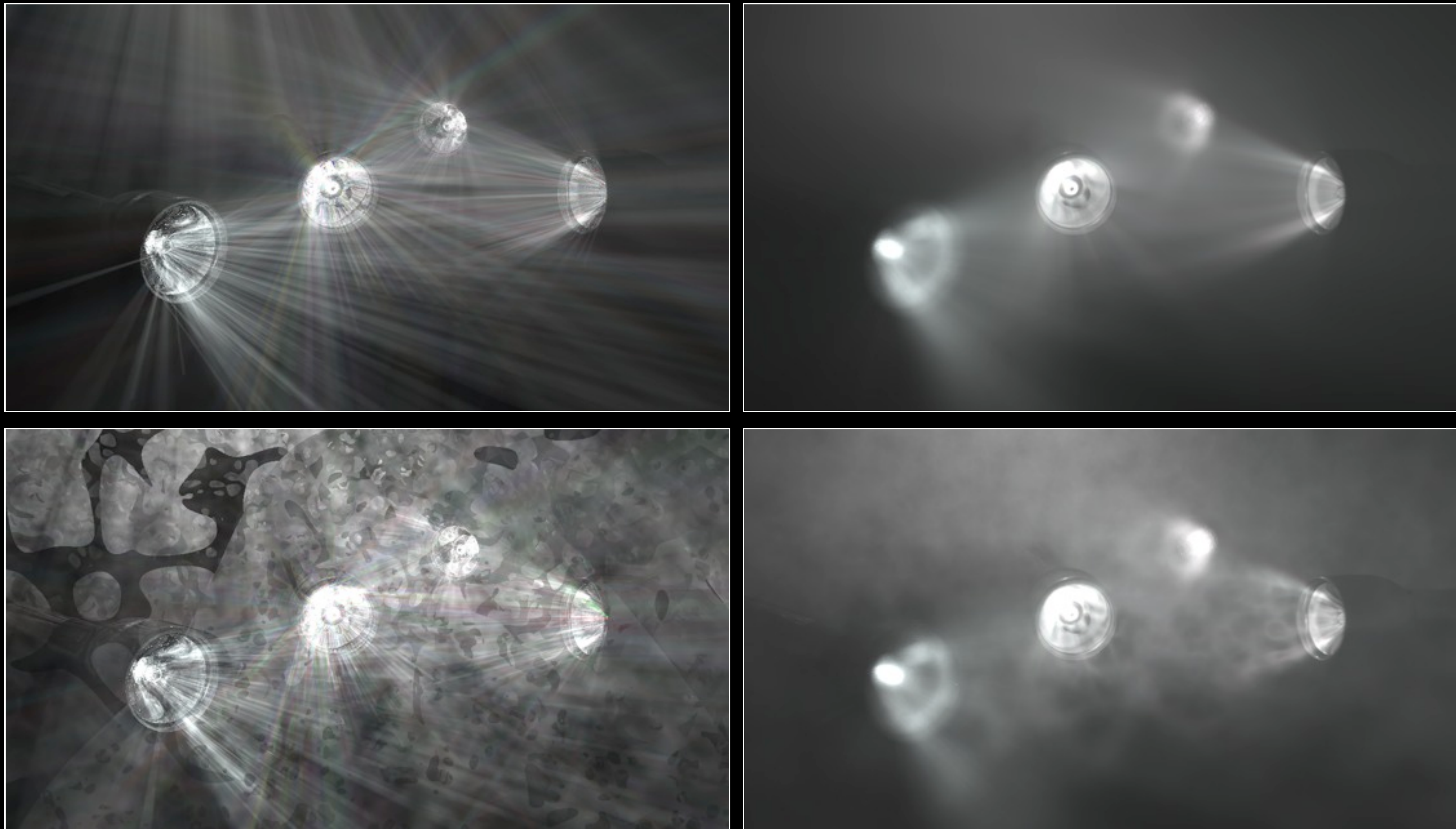


Pass 128

Average of Passes 1..128

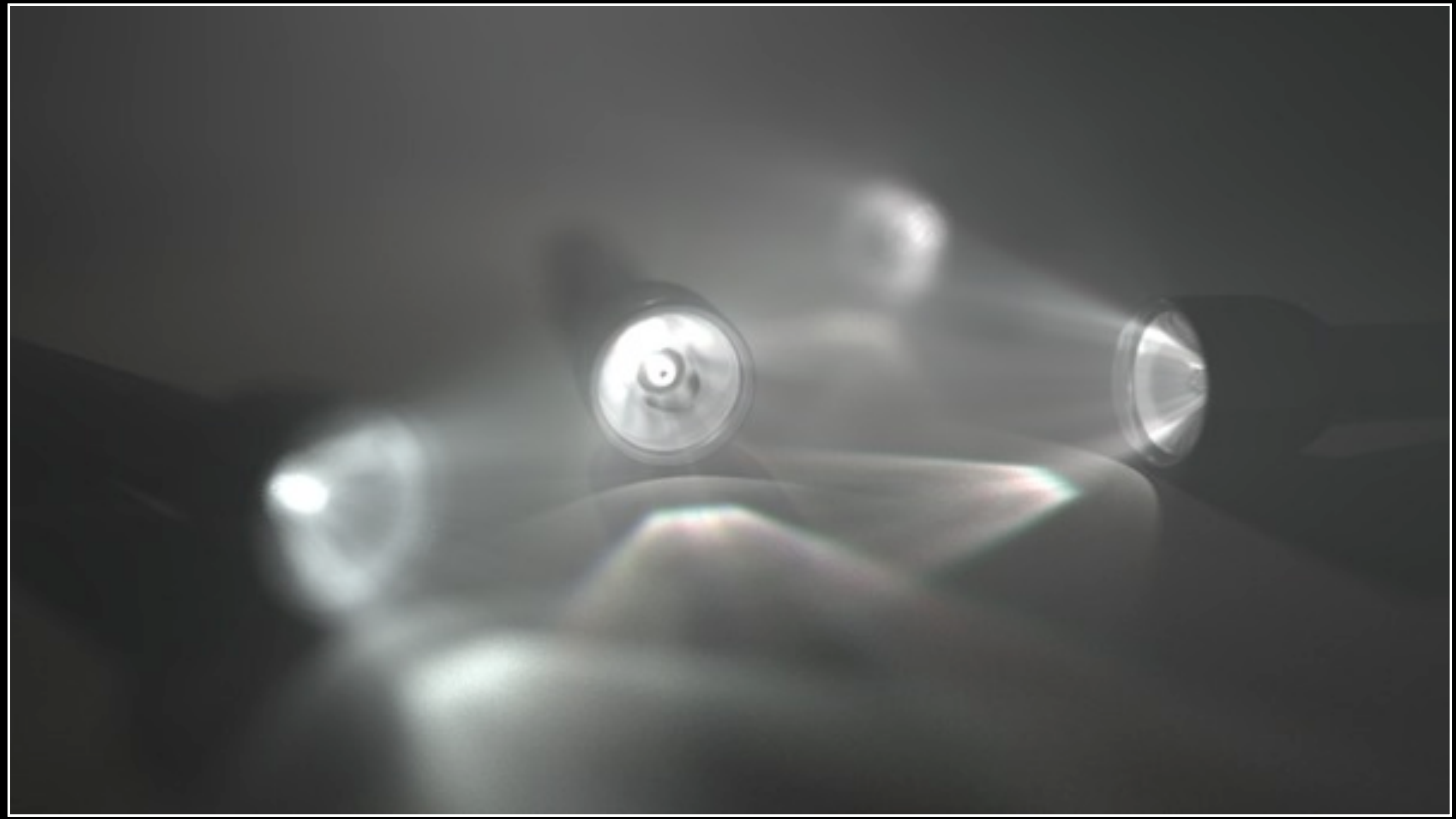


Pass 256 | Average of Passes 1..256



FLASHLIGHTS

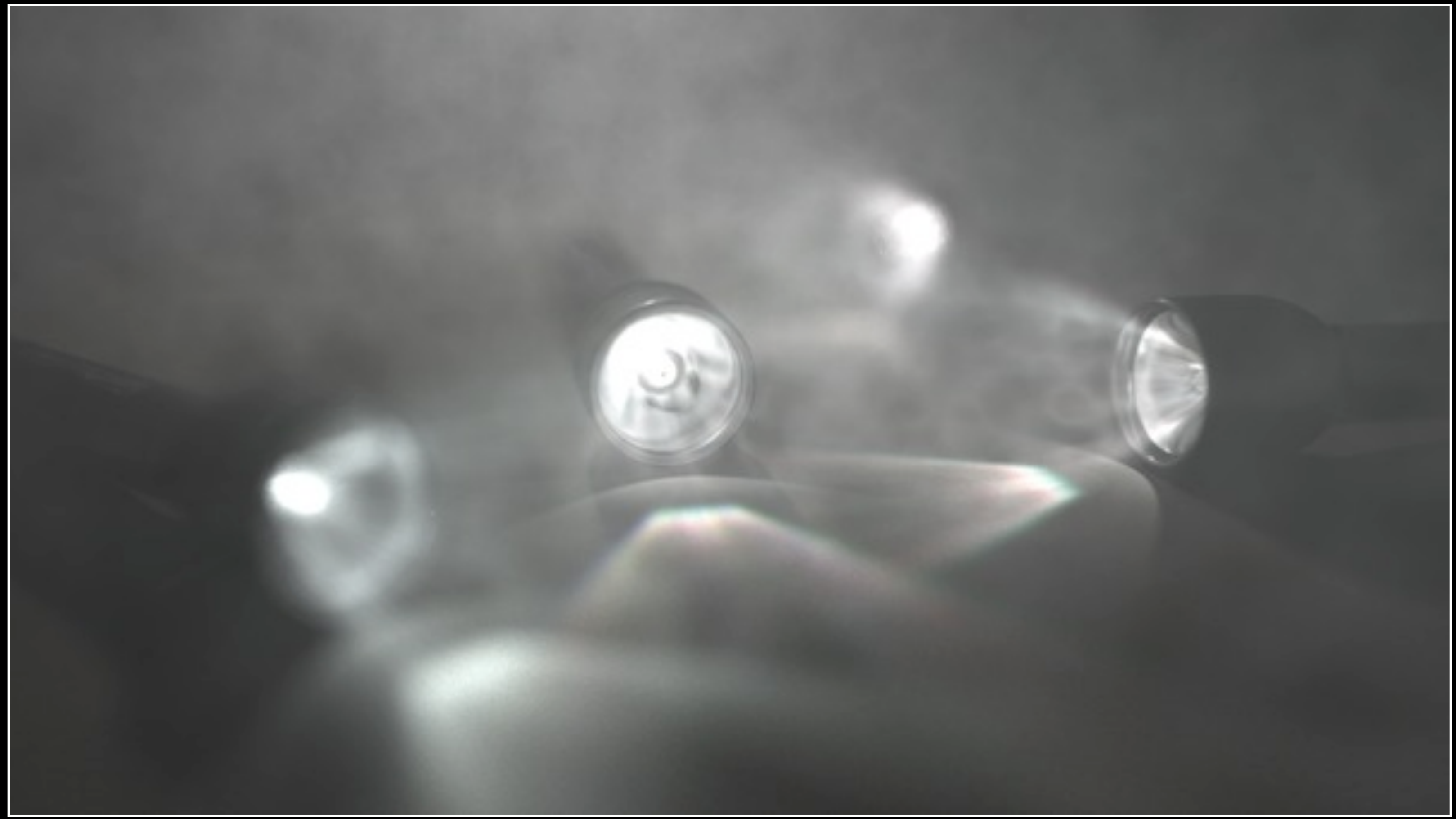
1280x720, Depth-of-Field



Homogeneous

2.1M Photon Beams

8 minutes



Heterogeneous

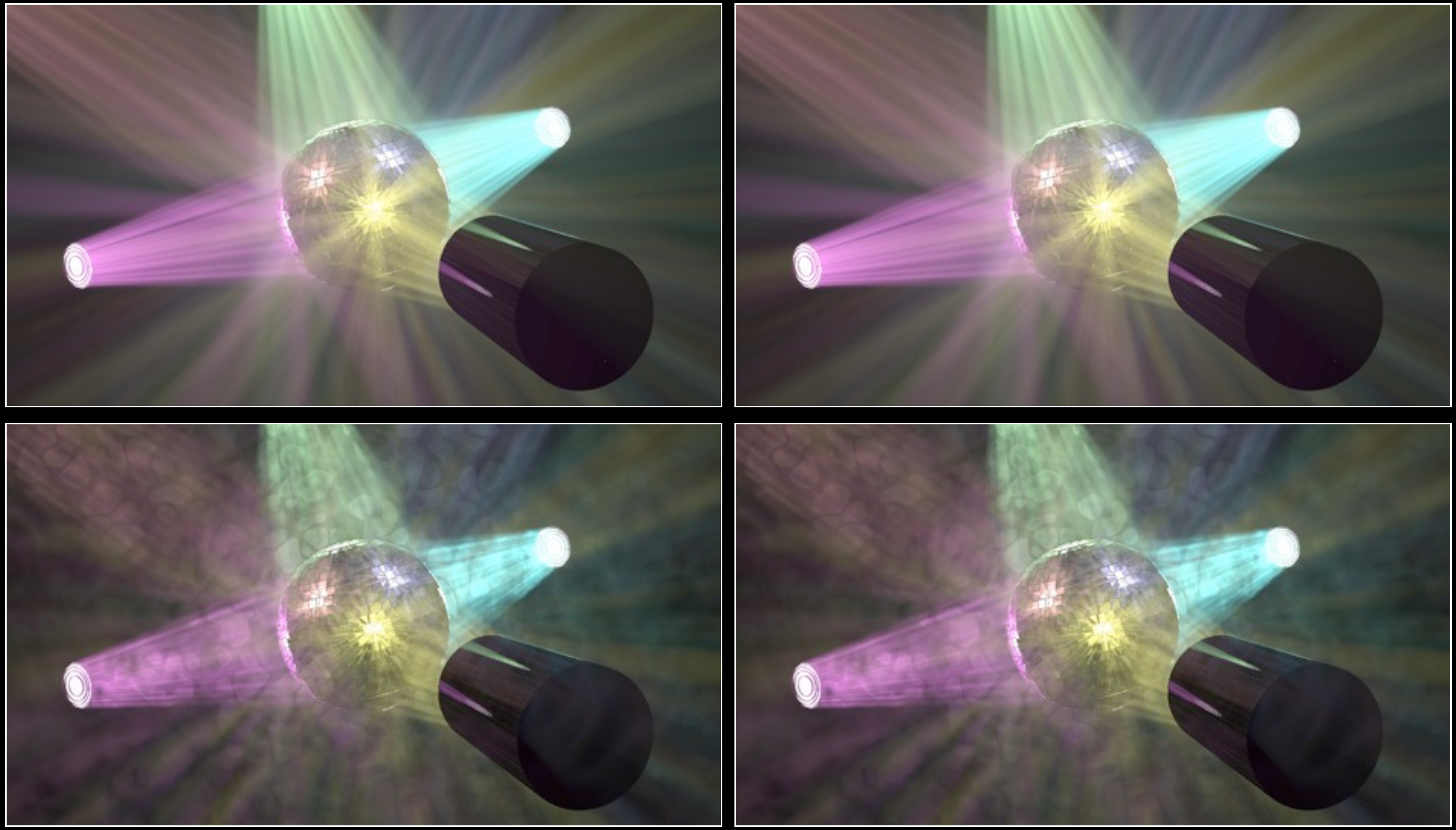
2.1M Photon Beams

10.8 minutes

Disco

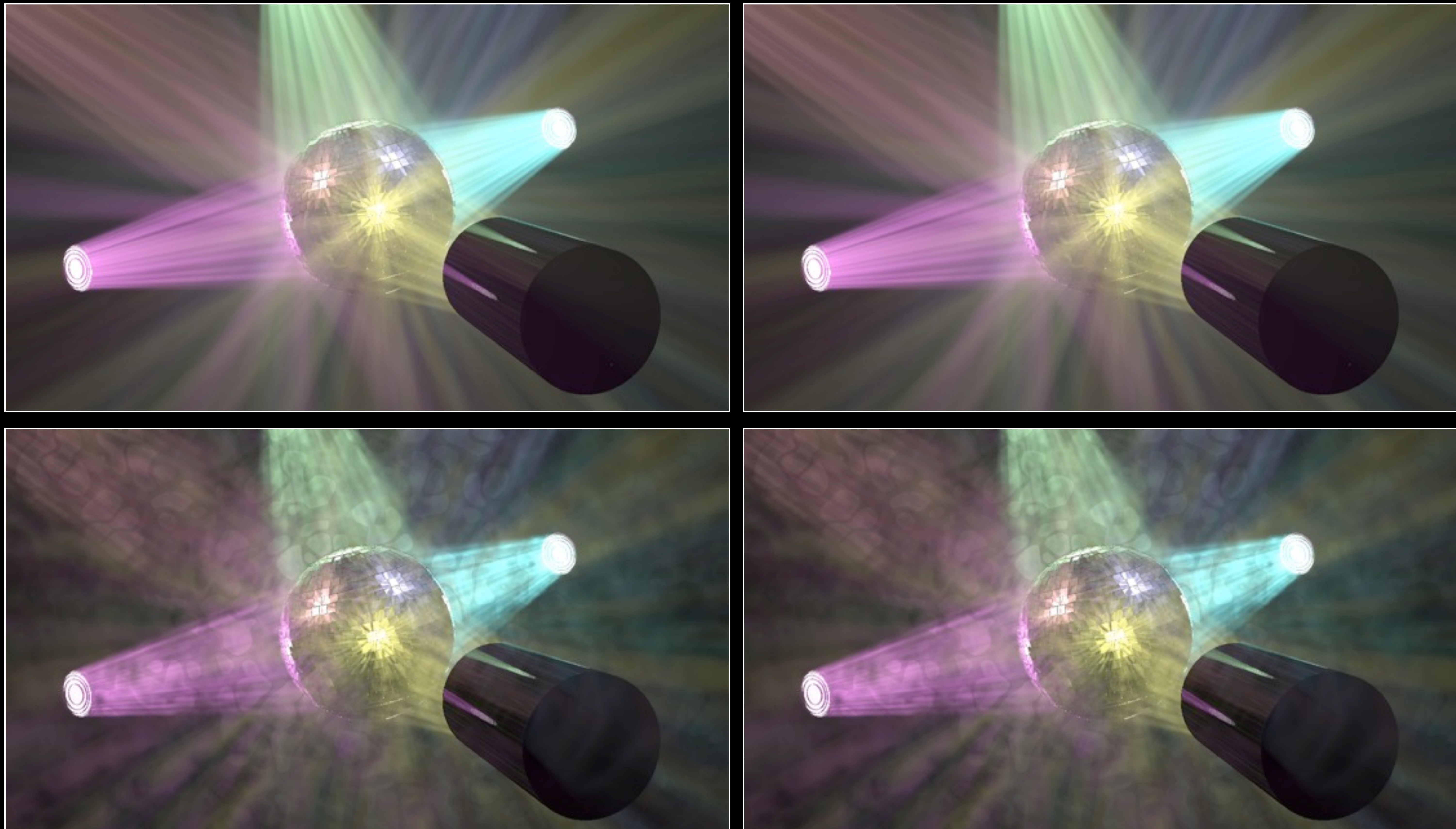
1280x720, Depth-of-Field

Pass 1 | Average of Passes 1..1

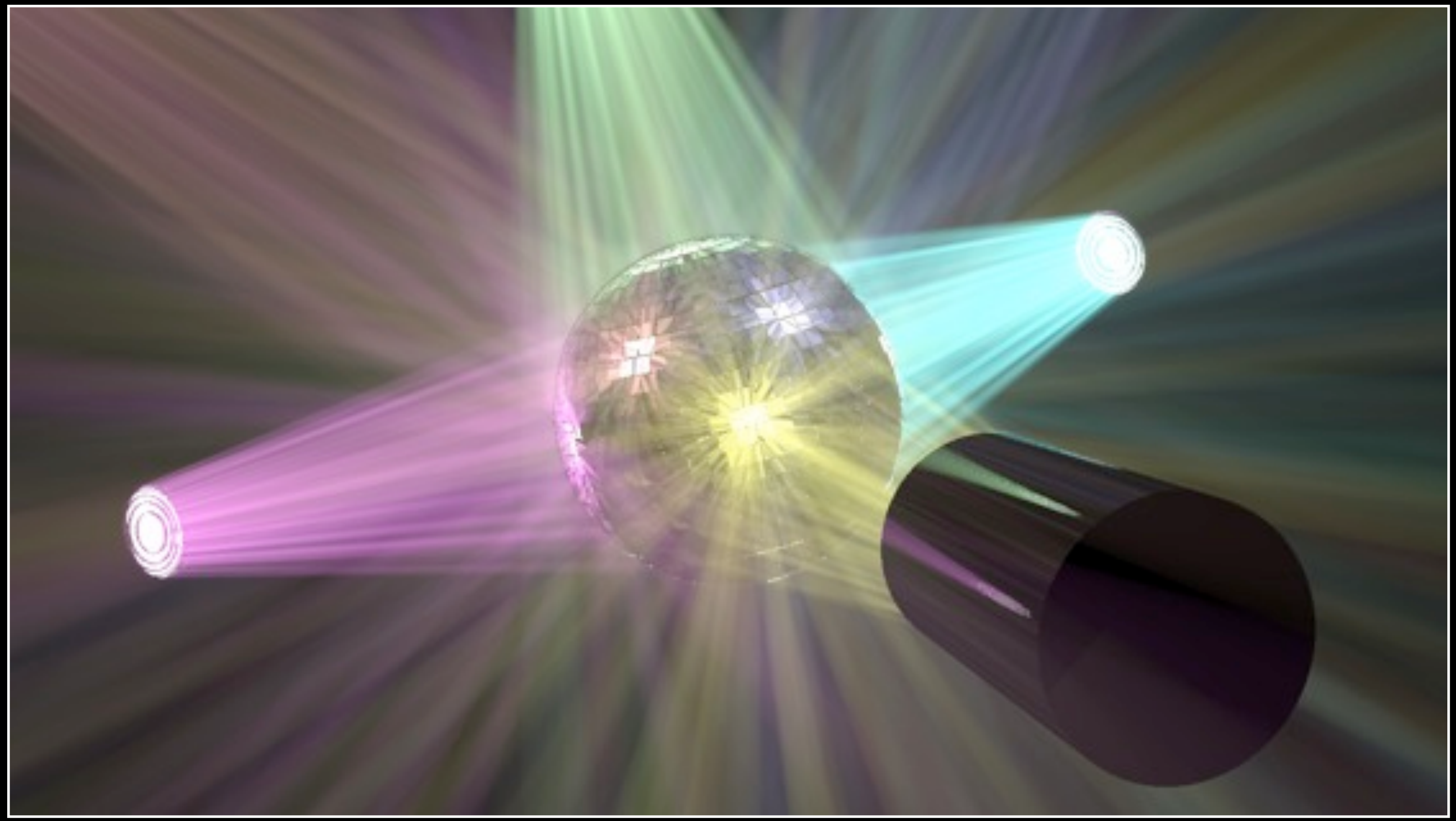


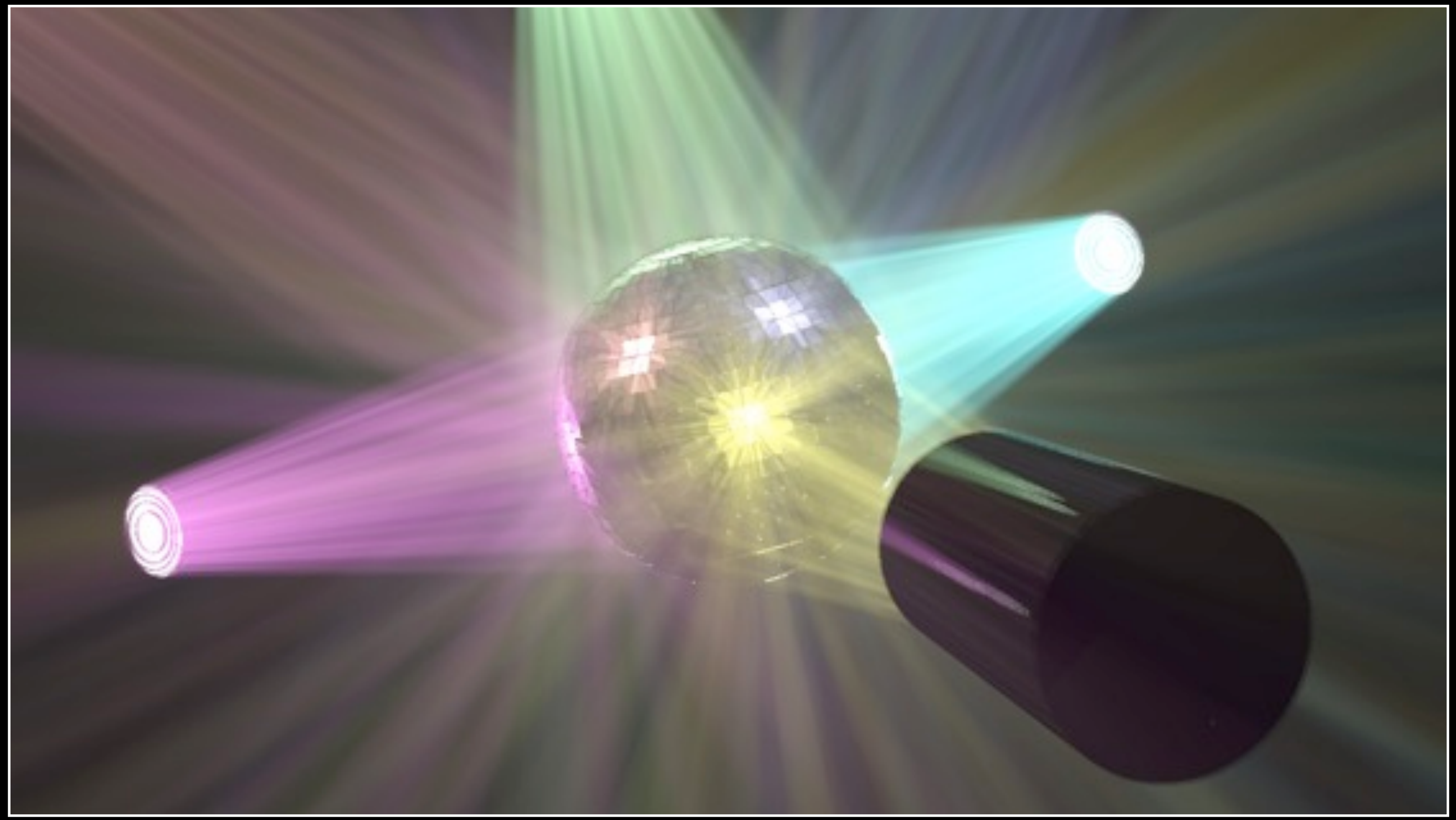
Pass 1

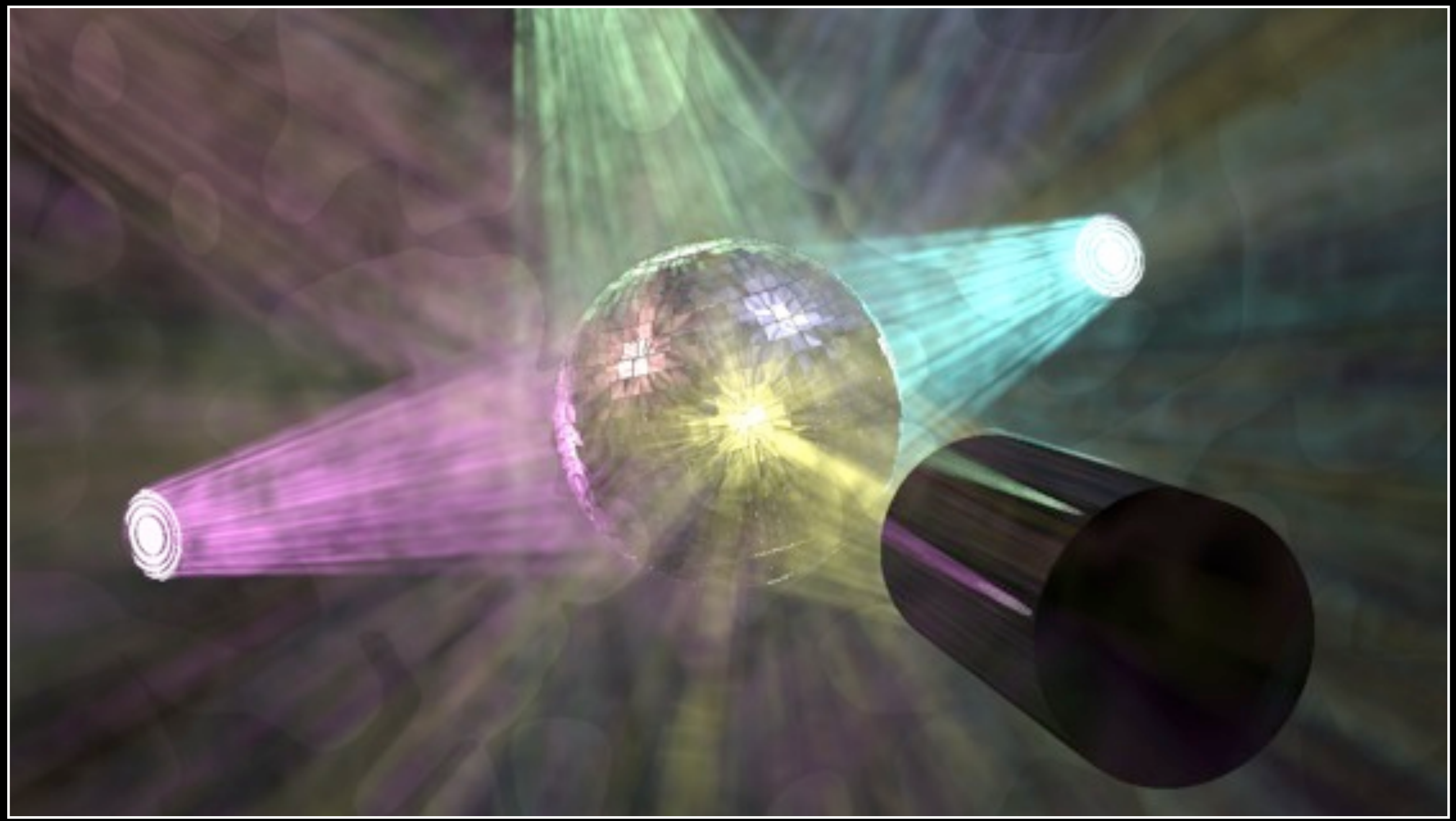
Average of Passes 1..1

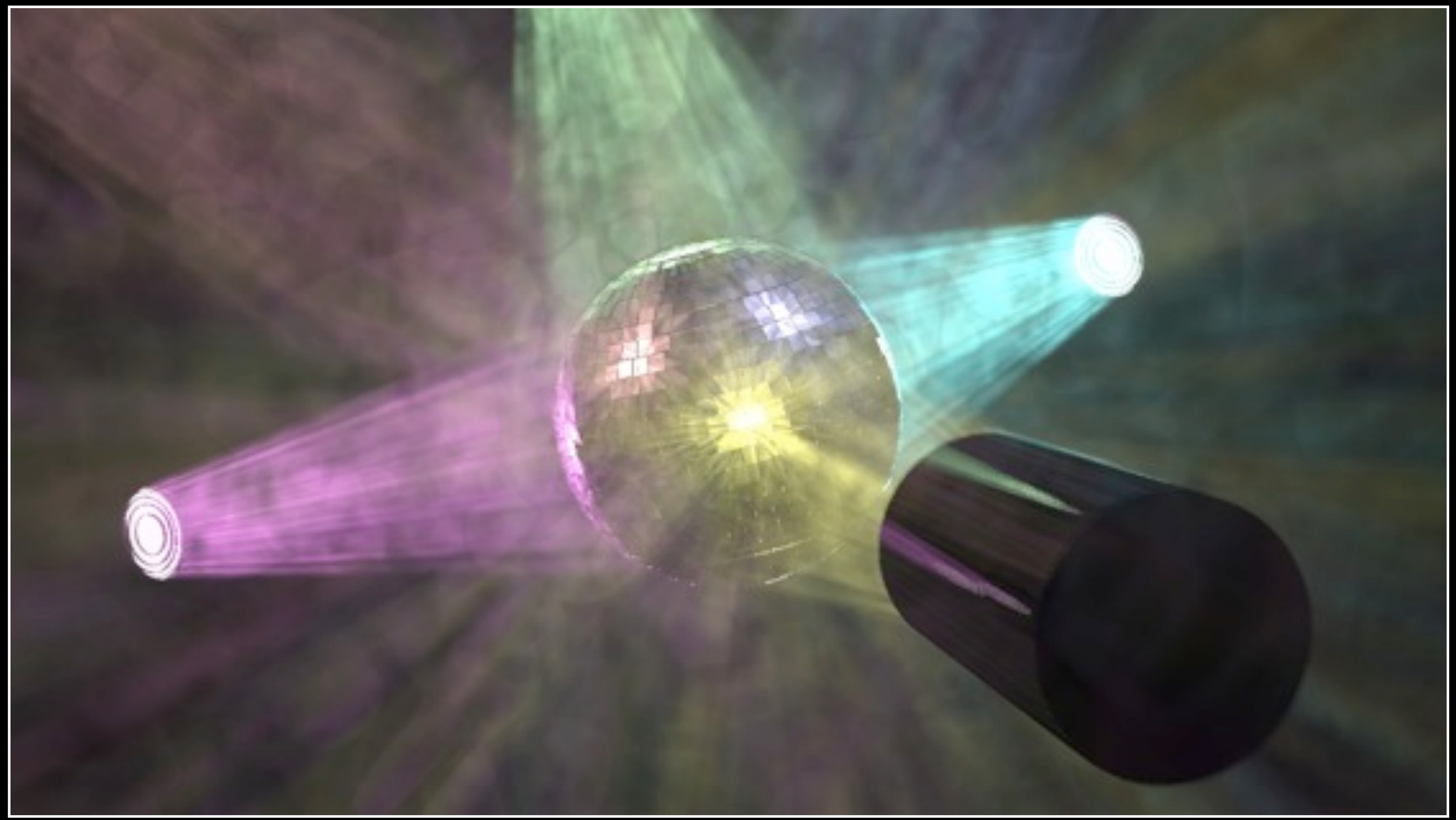


Pass 2 | Average of Passes 1..2



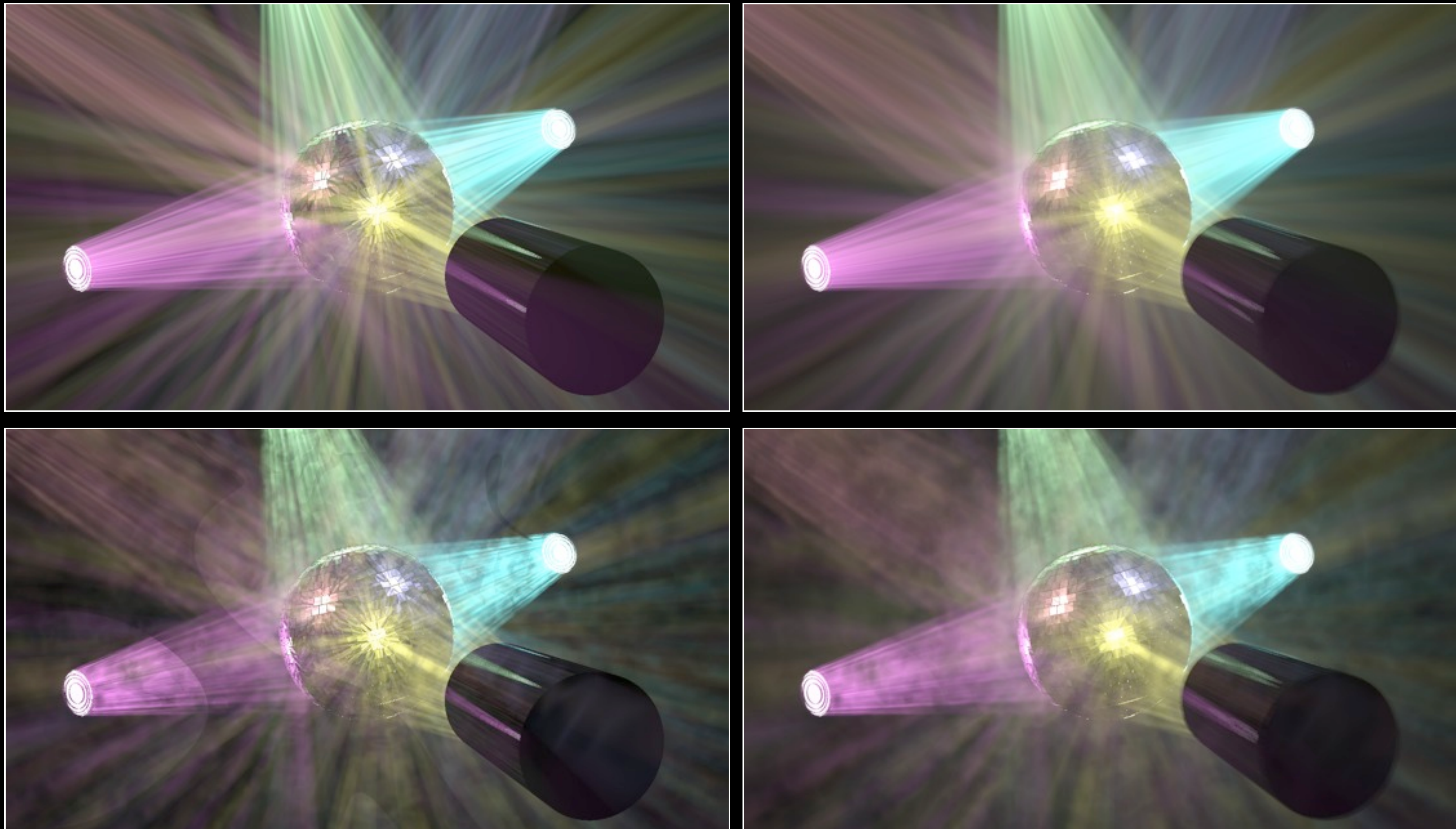




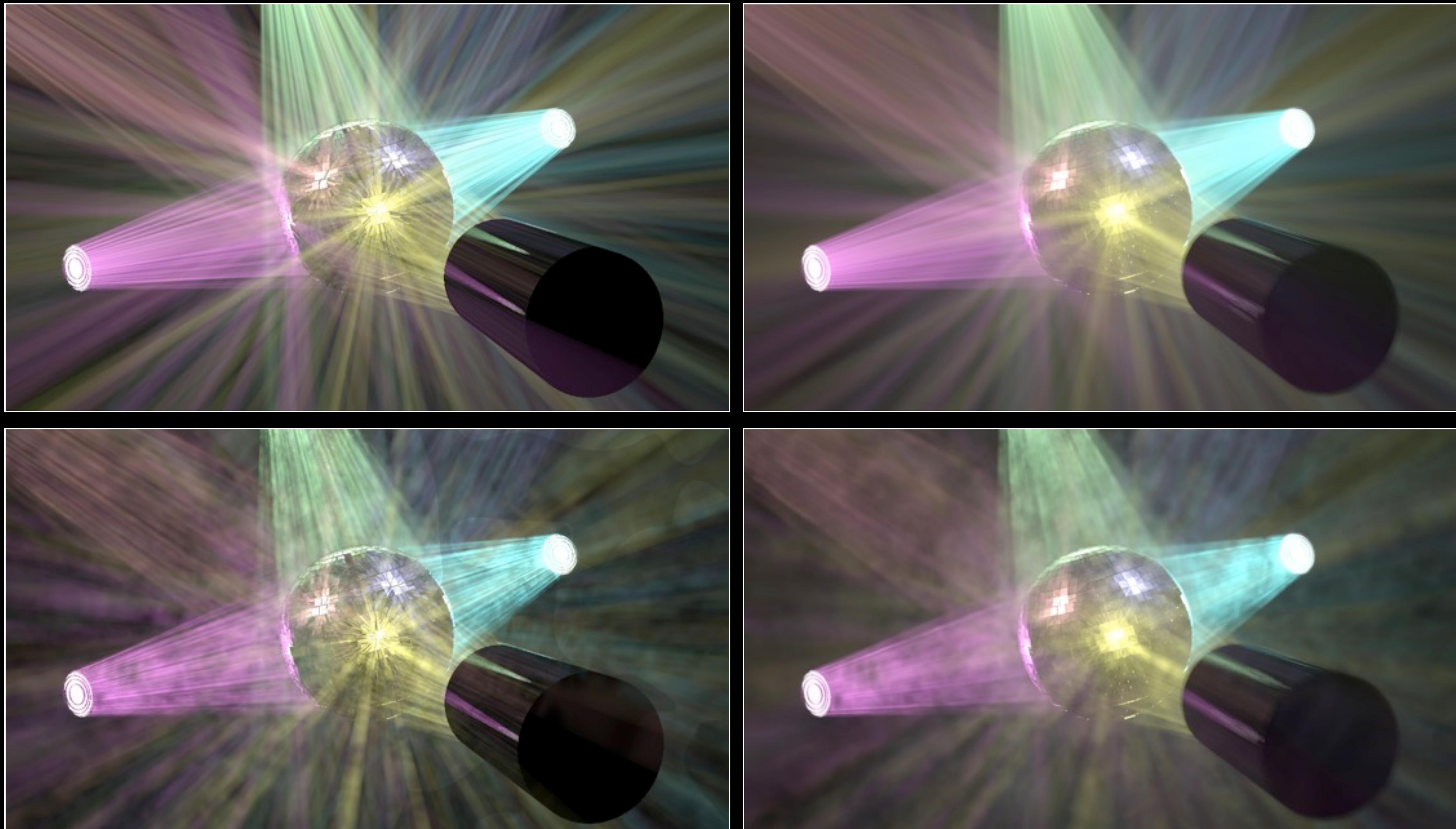


Pass 4

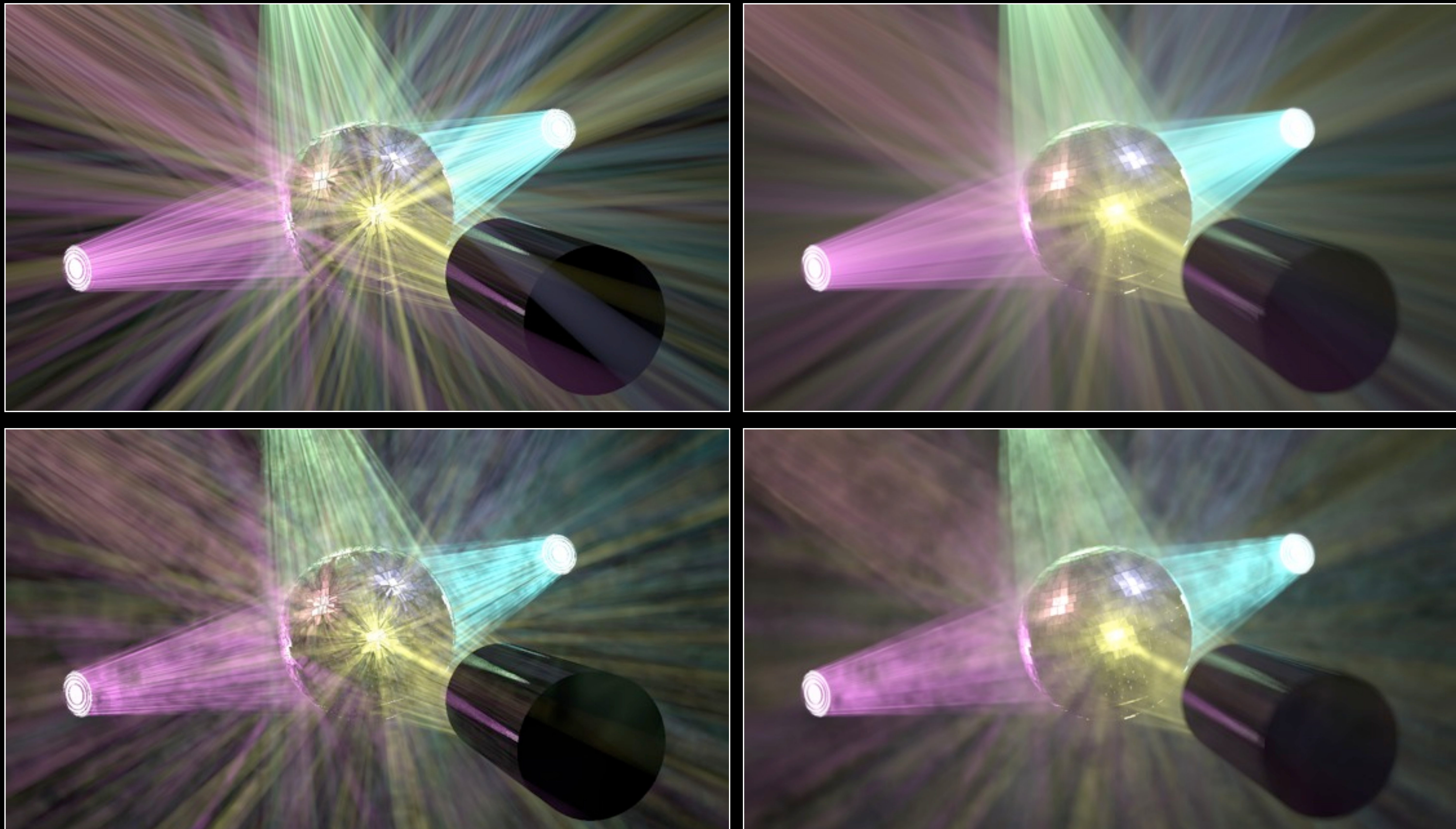
Average of Passes 1..4



Pass 8 | Average of Passes 1..8

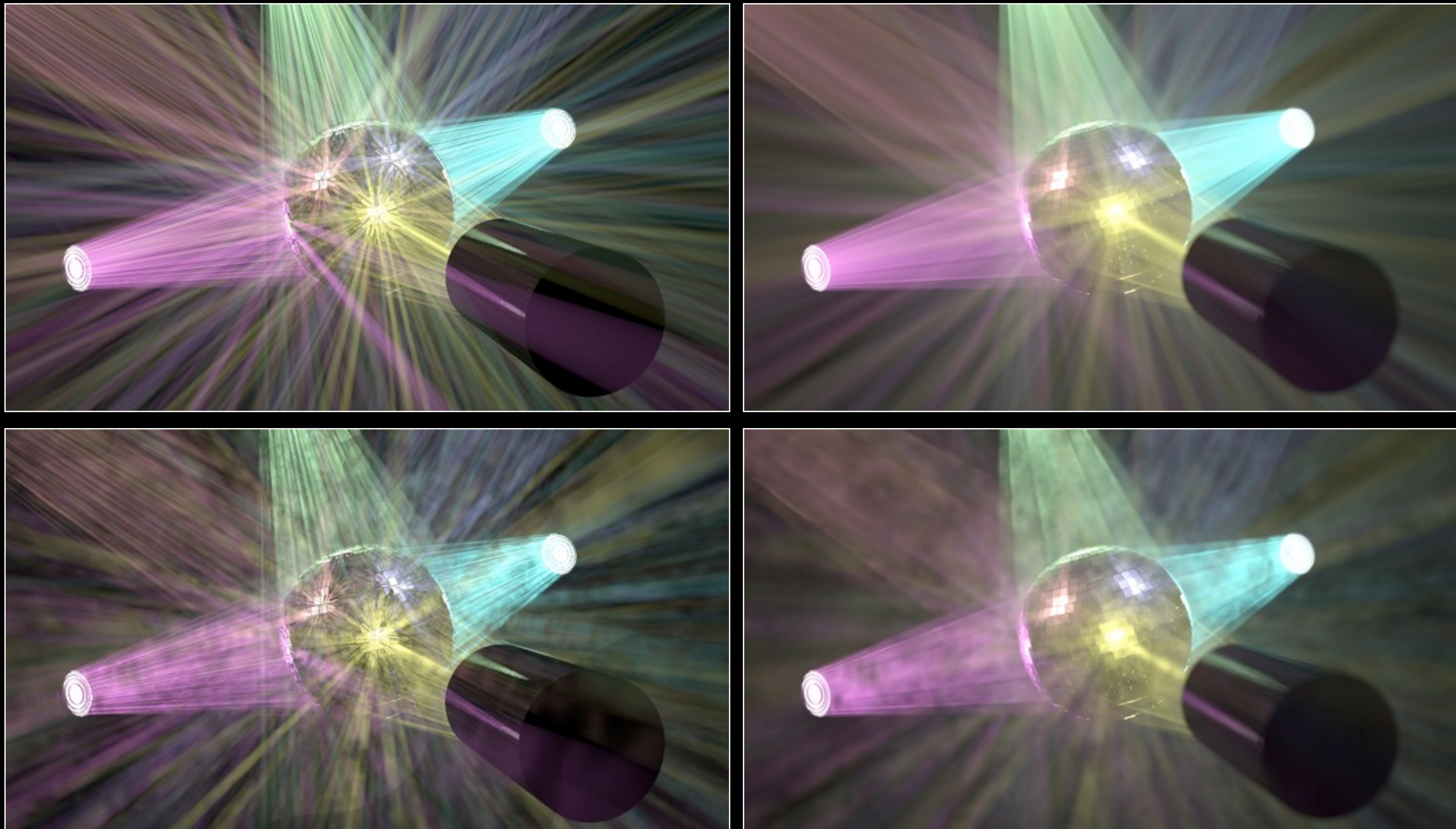


Pass 16 | Average of Passes 1..16

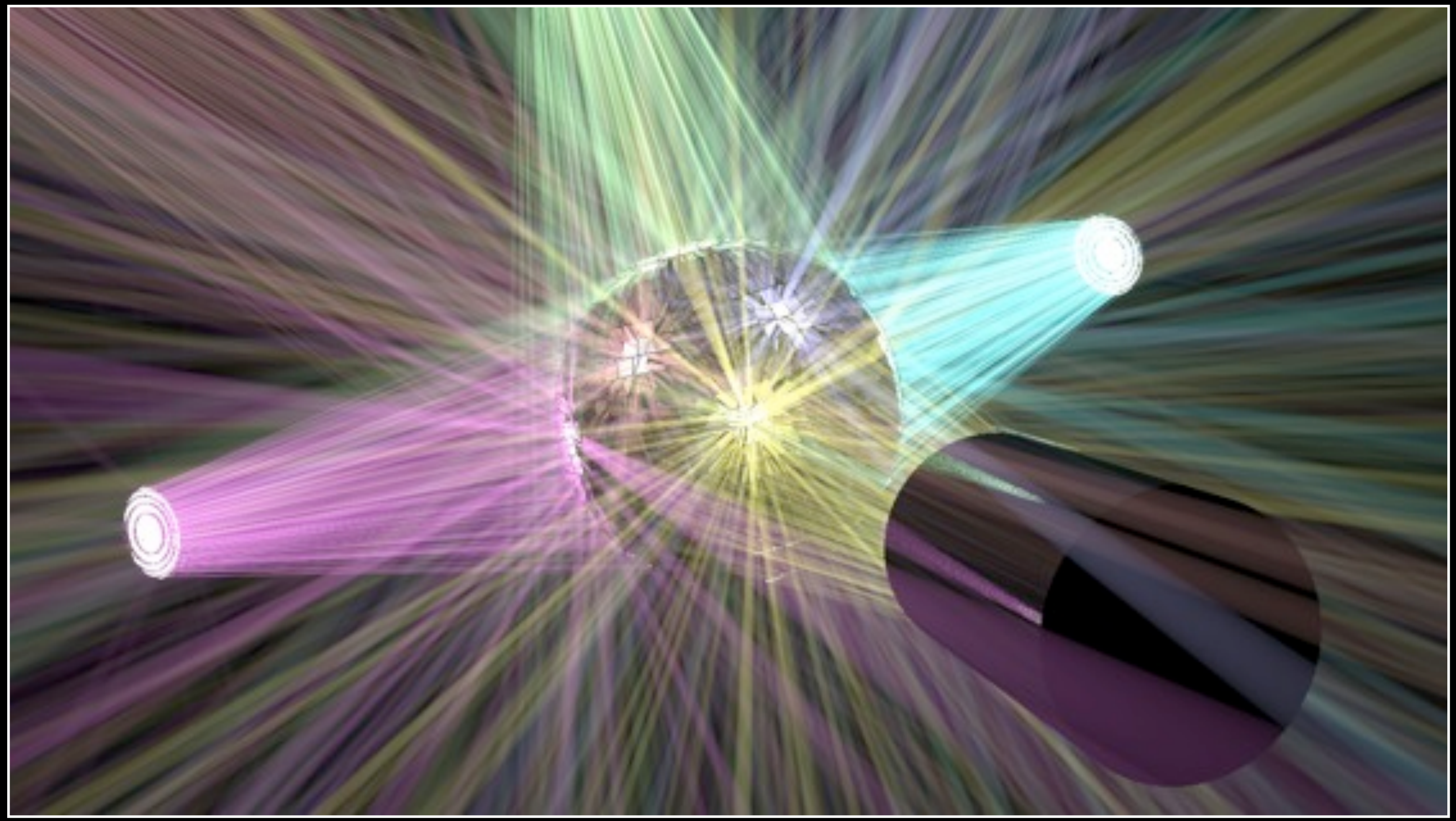


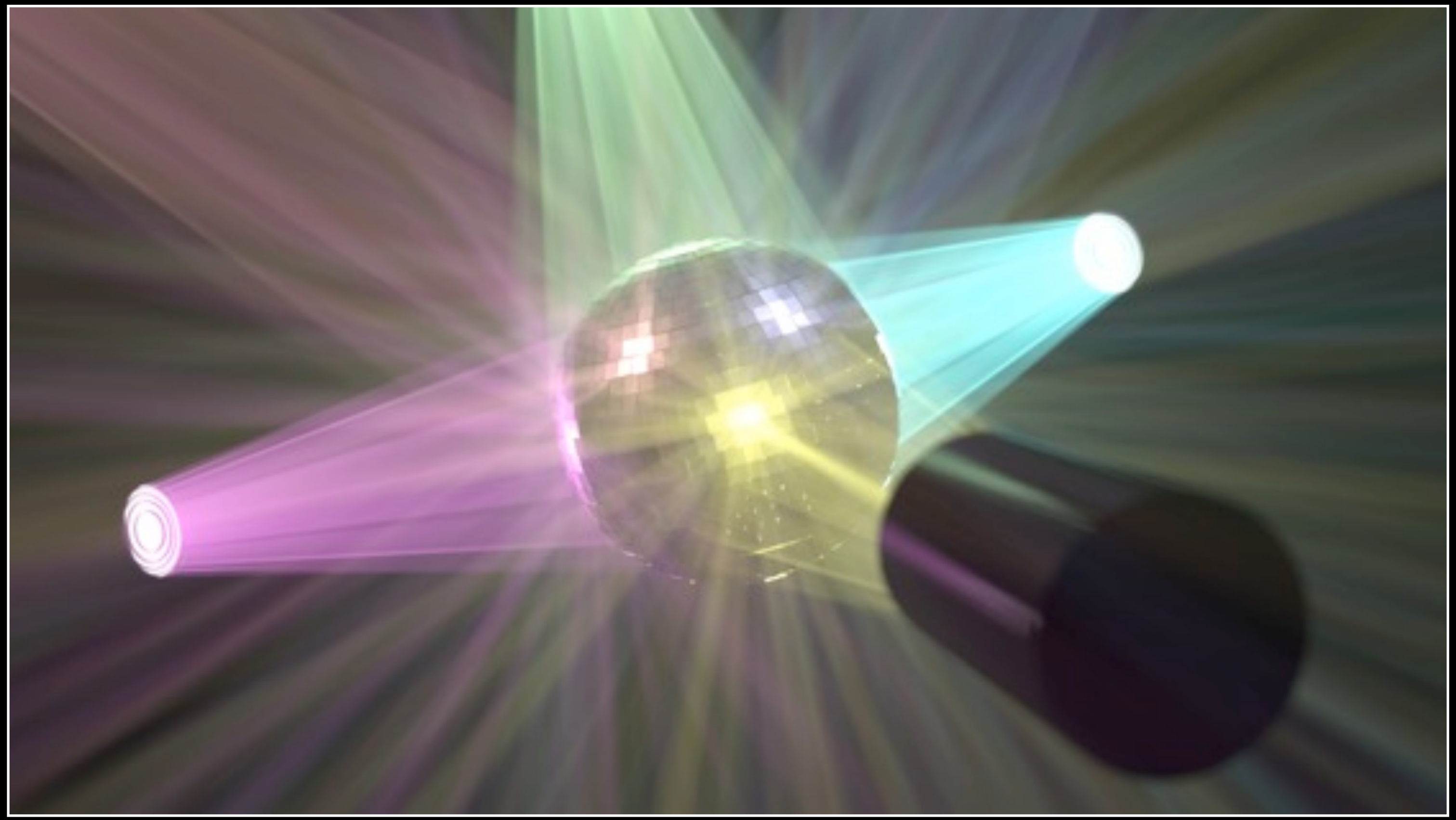
Pass 32

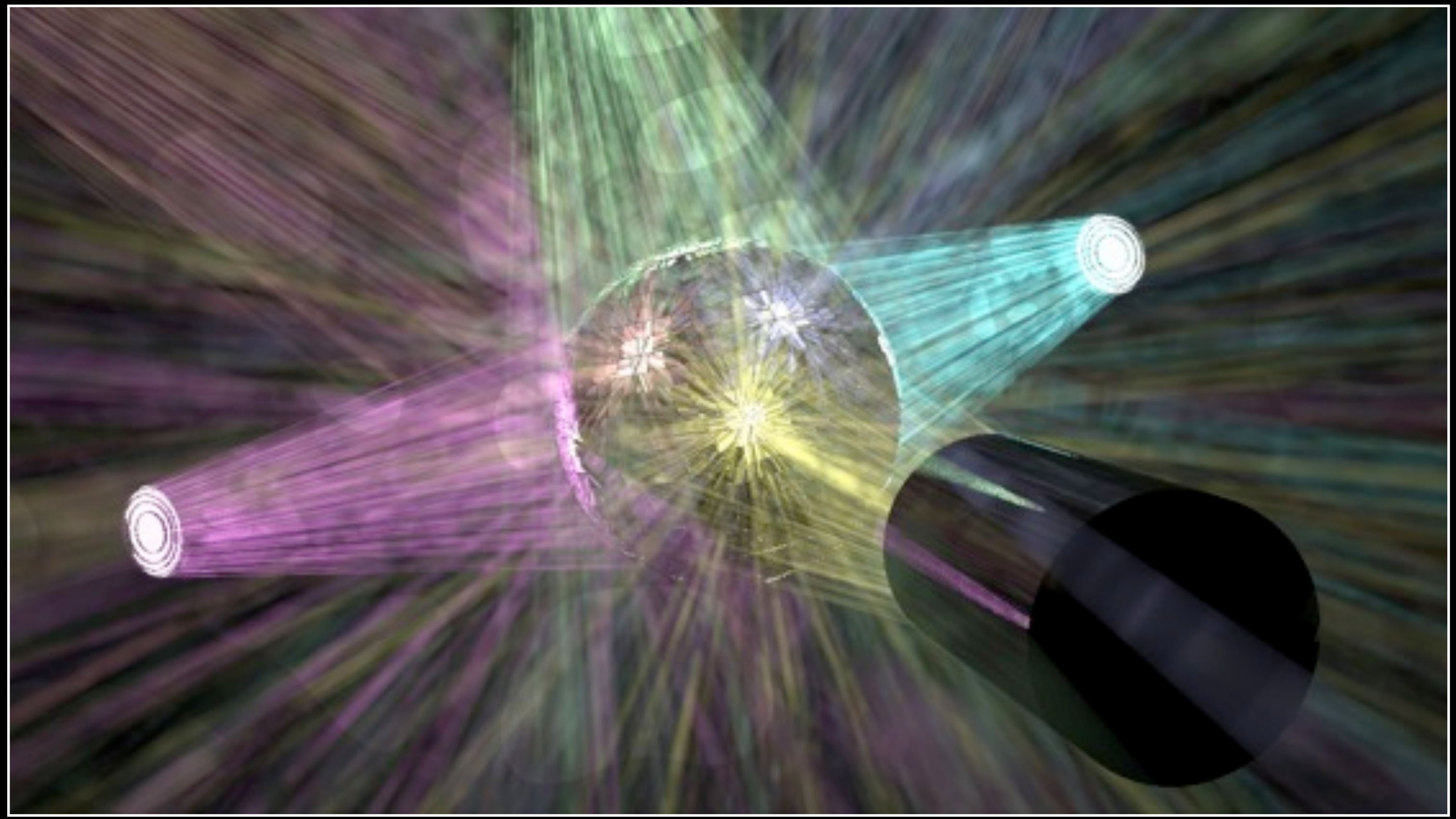
Average of Passes 1..32

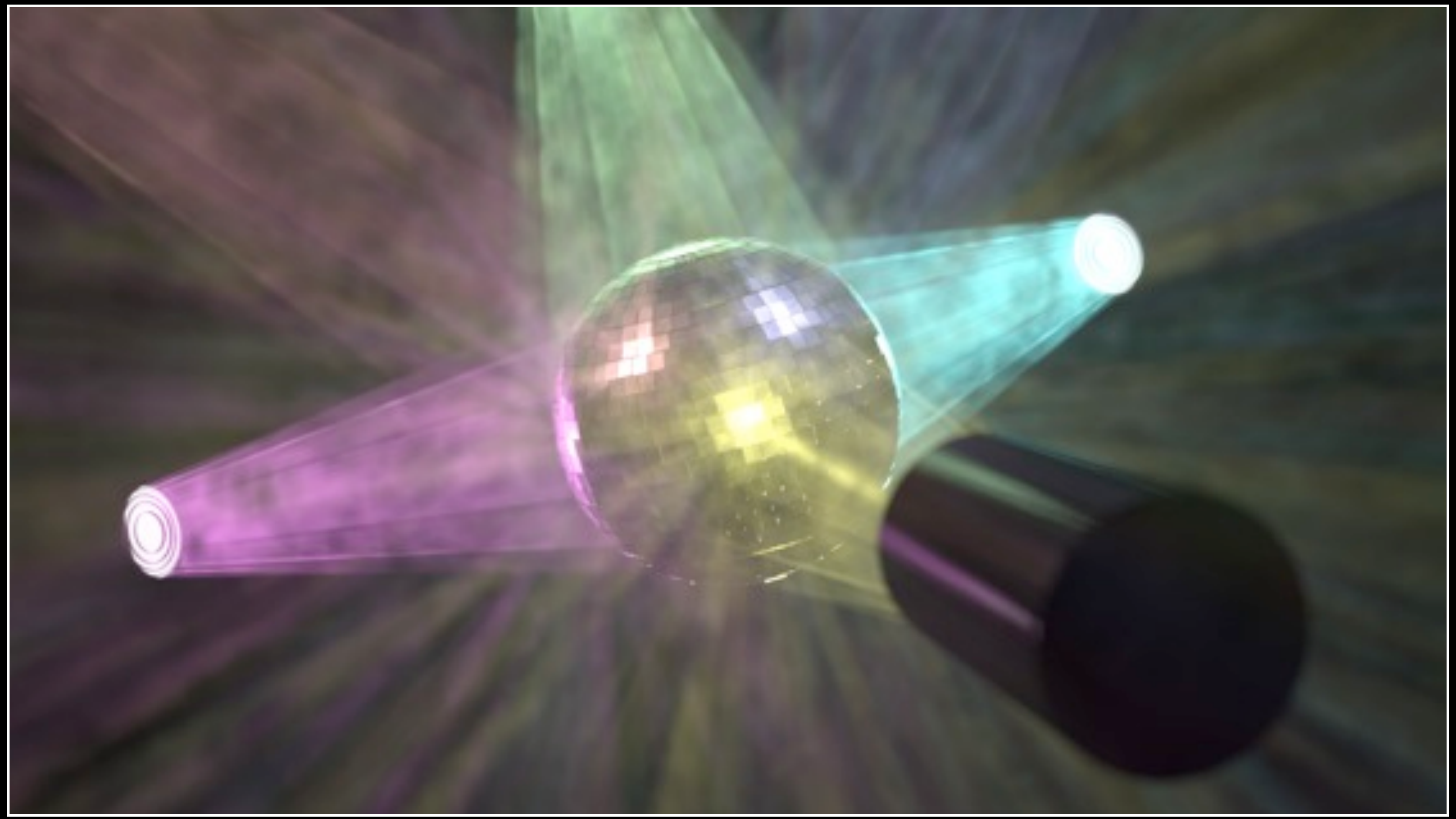


Pass 64 | Average of Passes 1..64

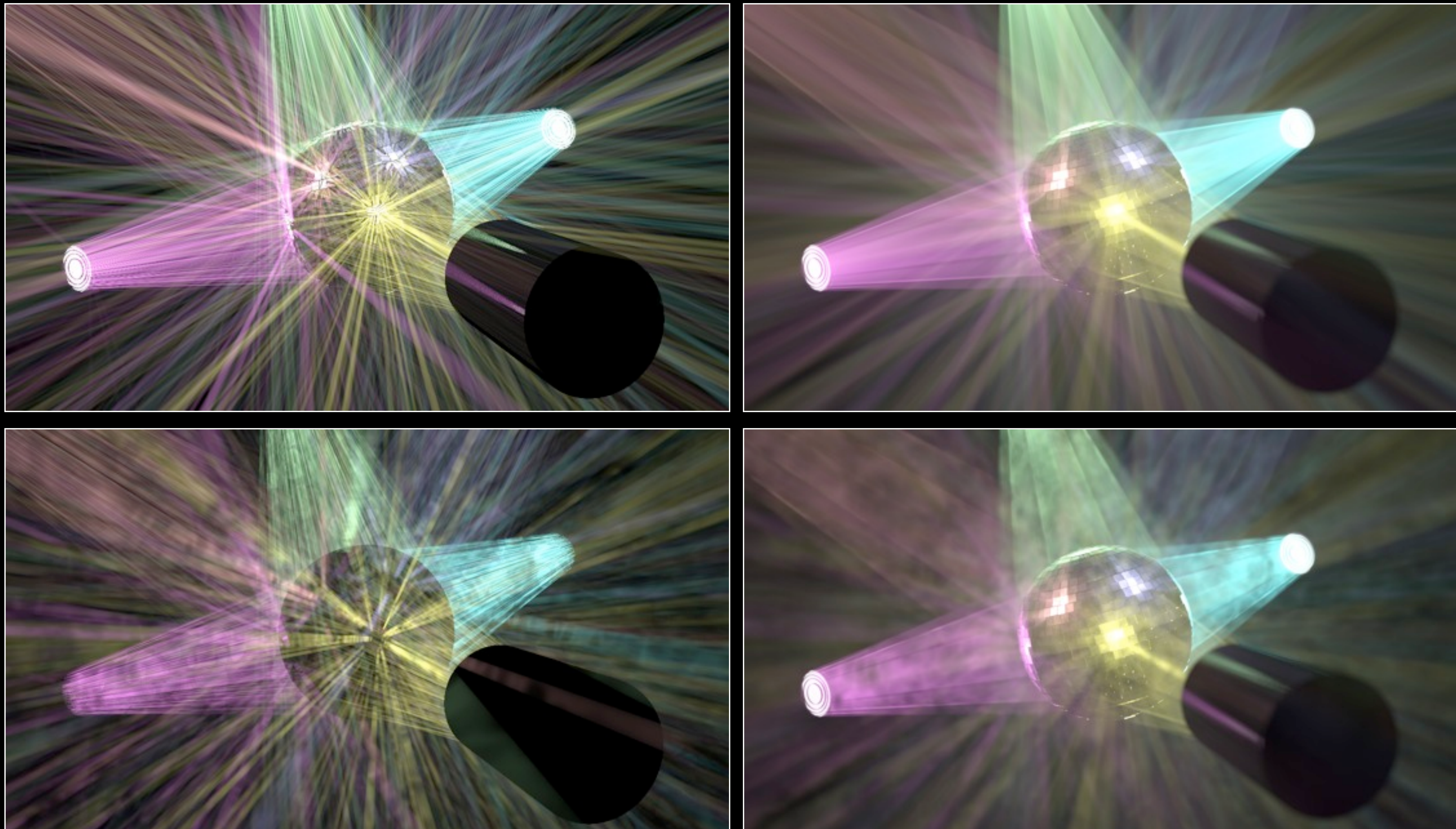




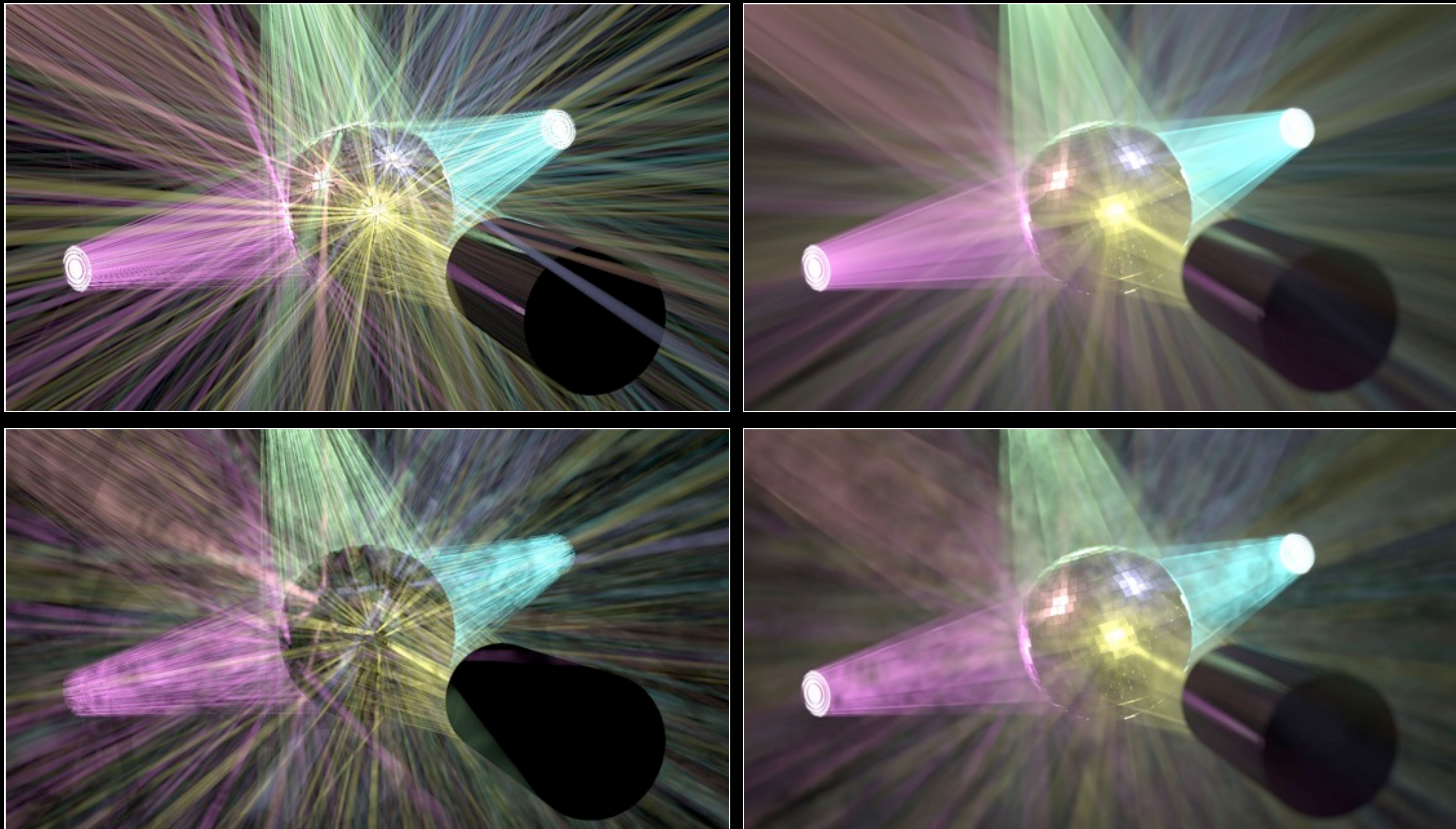




Pass 128 | Average of Passes 1..128

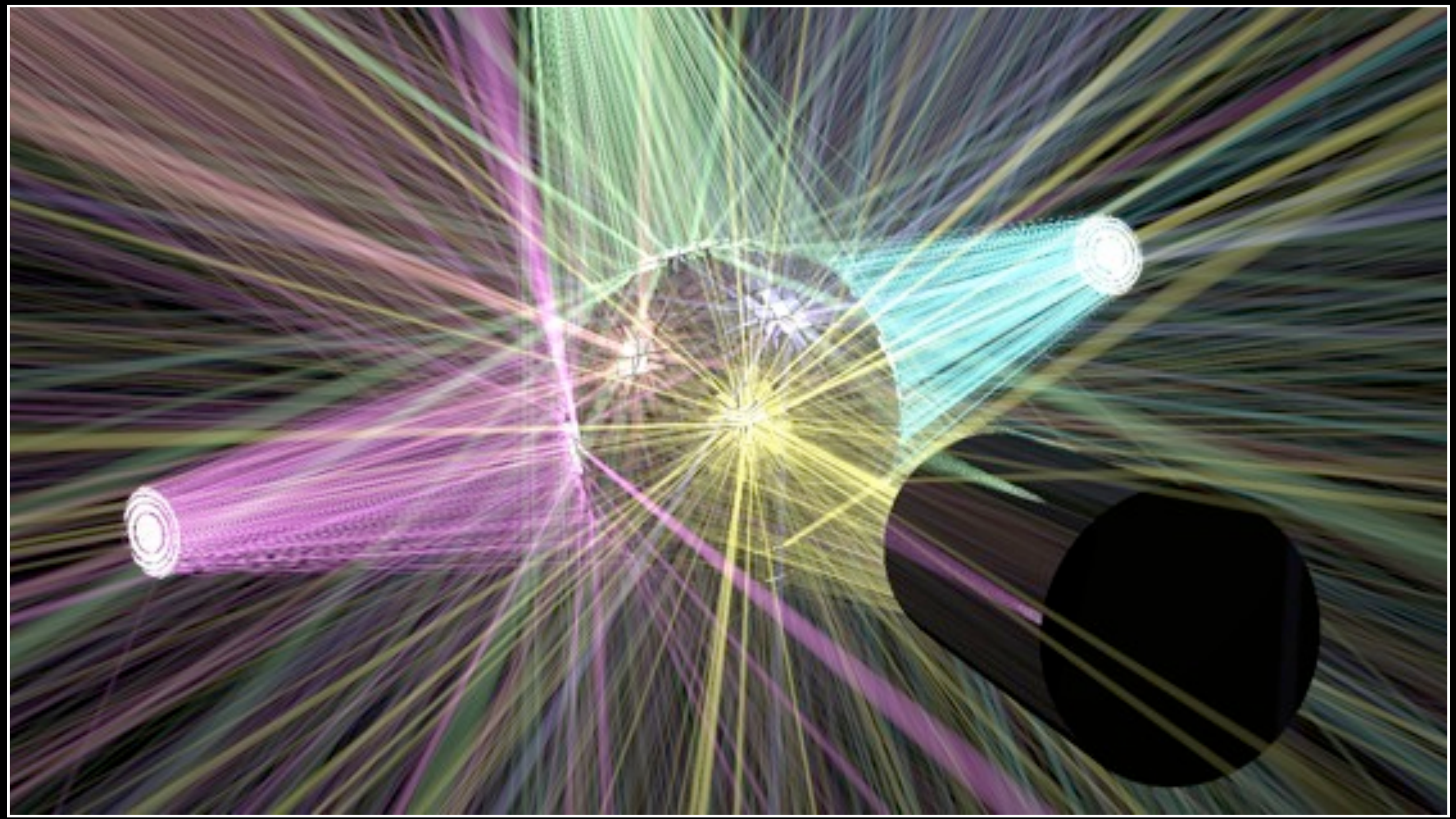


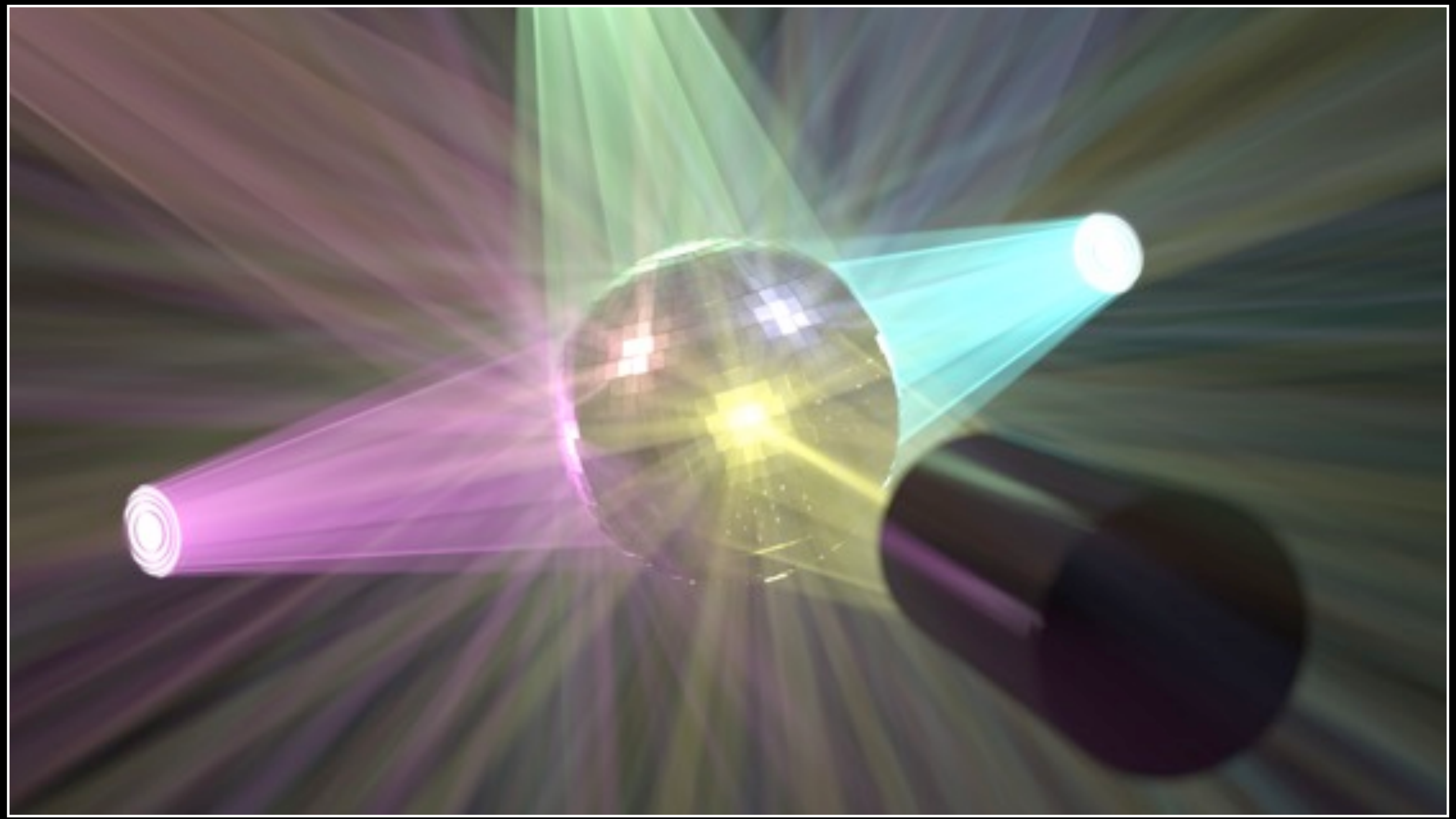
Pass 256 | Average of Passes 1..256

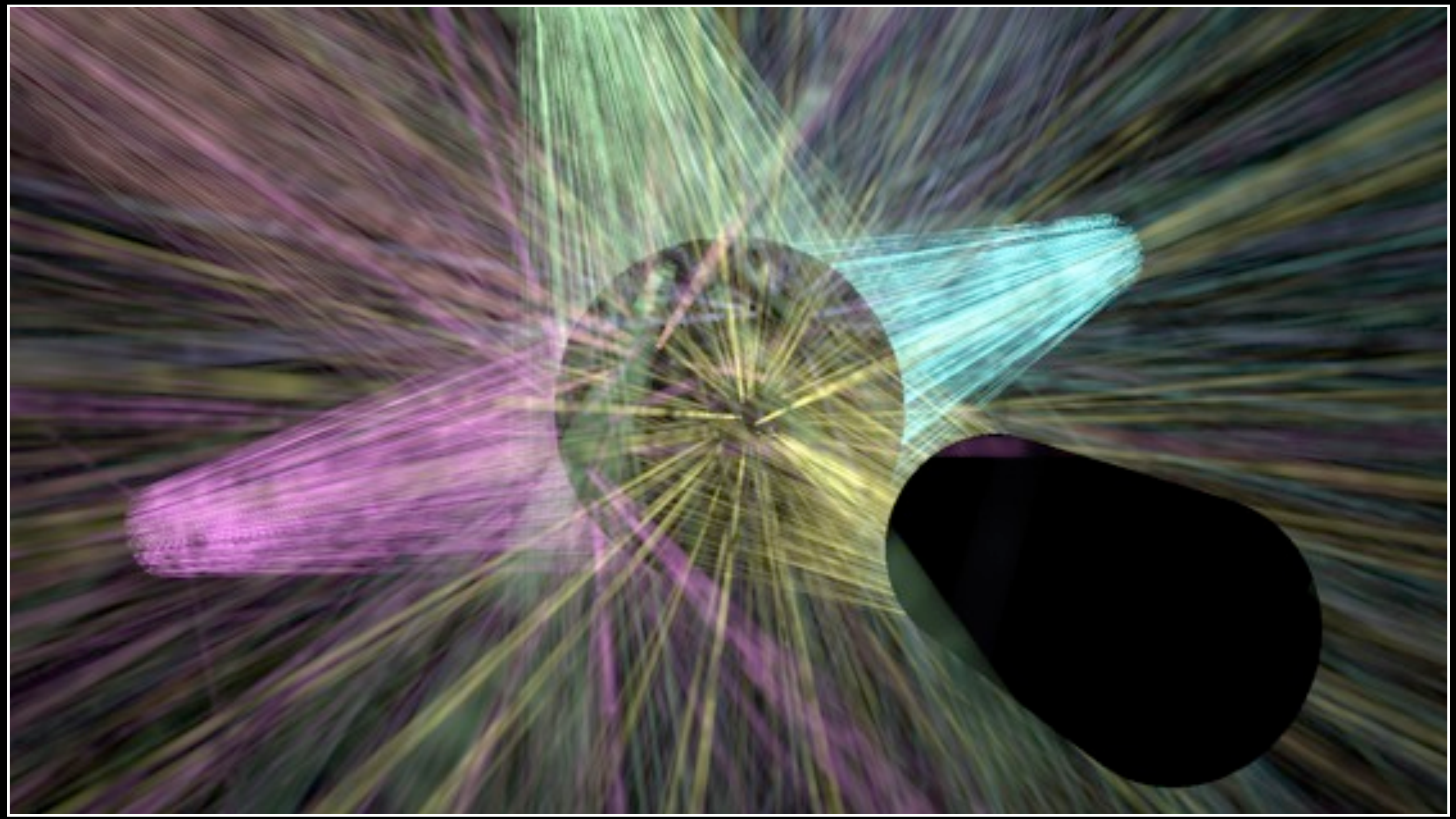


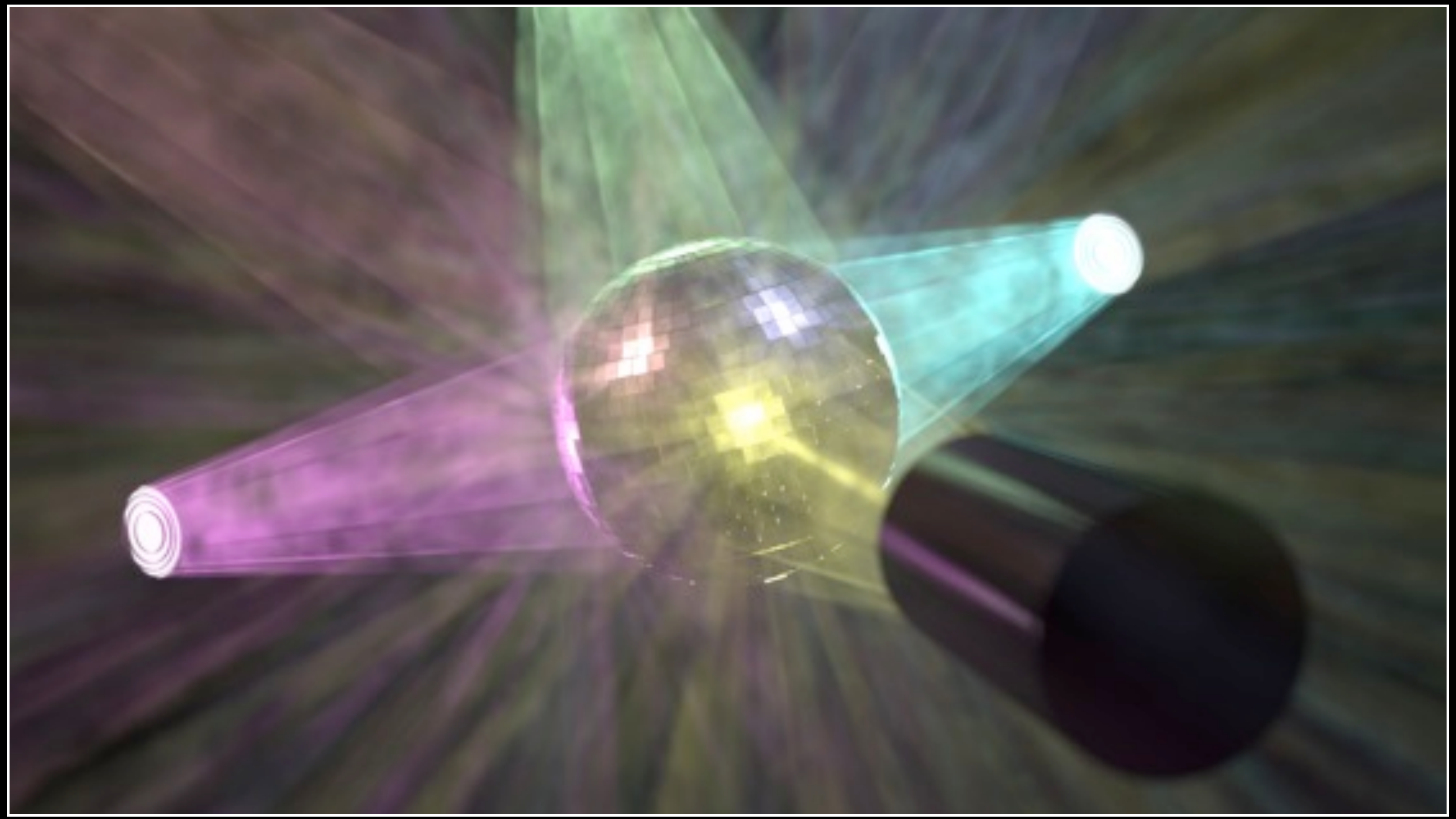
Pass 512

Average of Passes 1..512

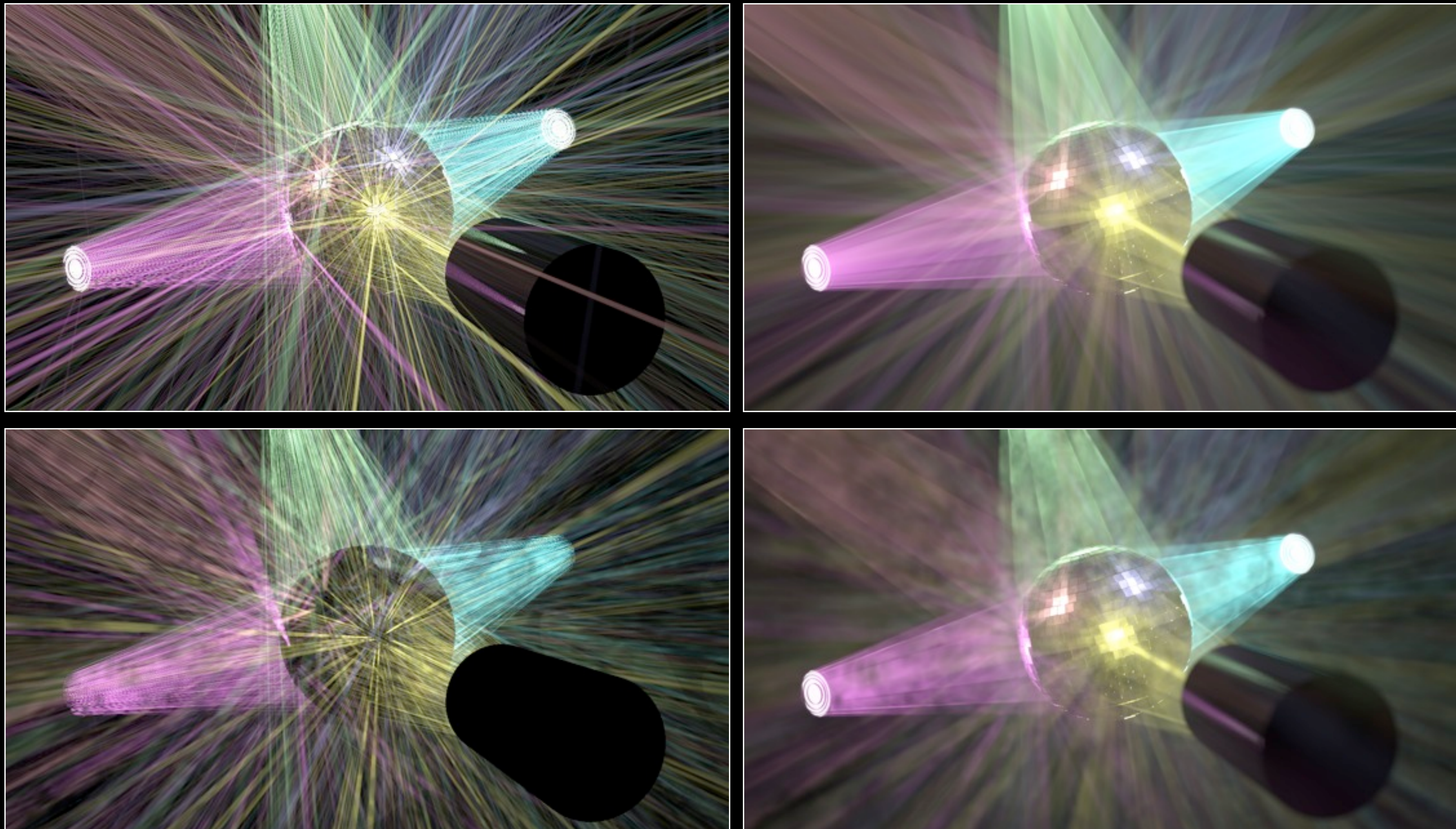






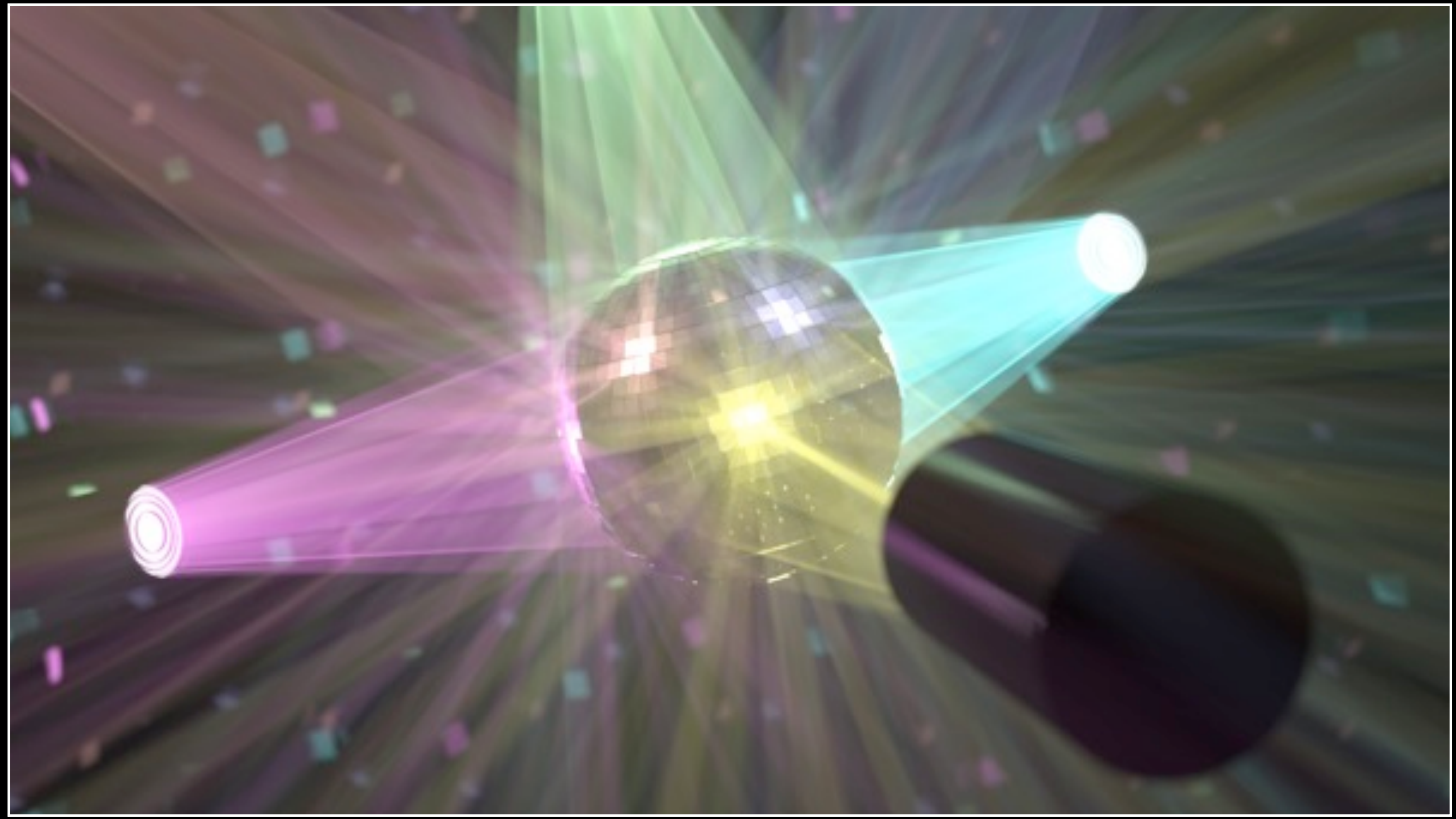


Pass 1024 | Average of Passes 1..1024



Disco

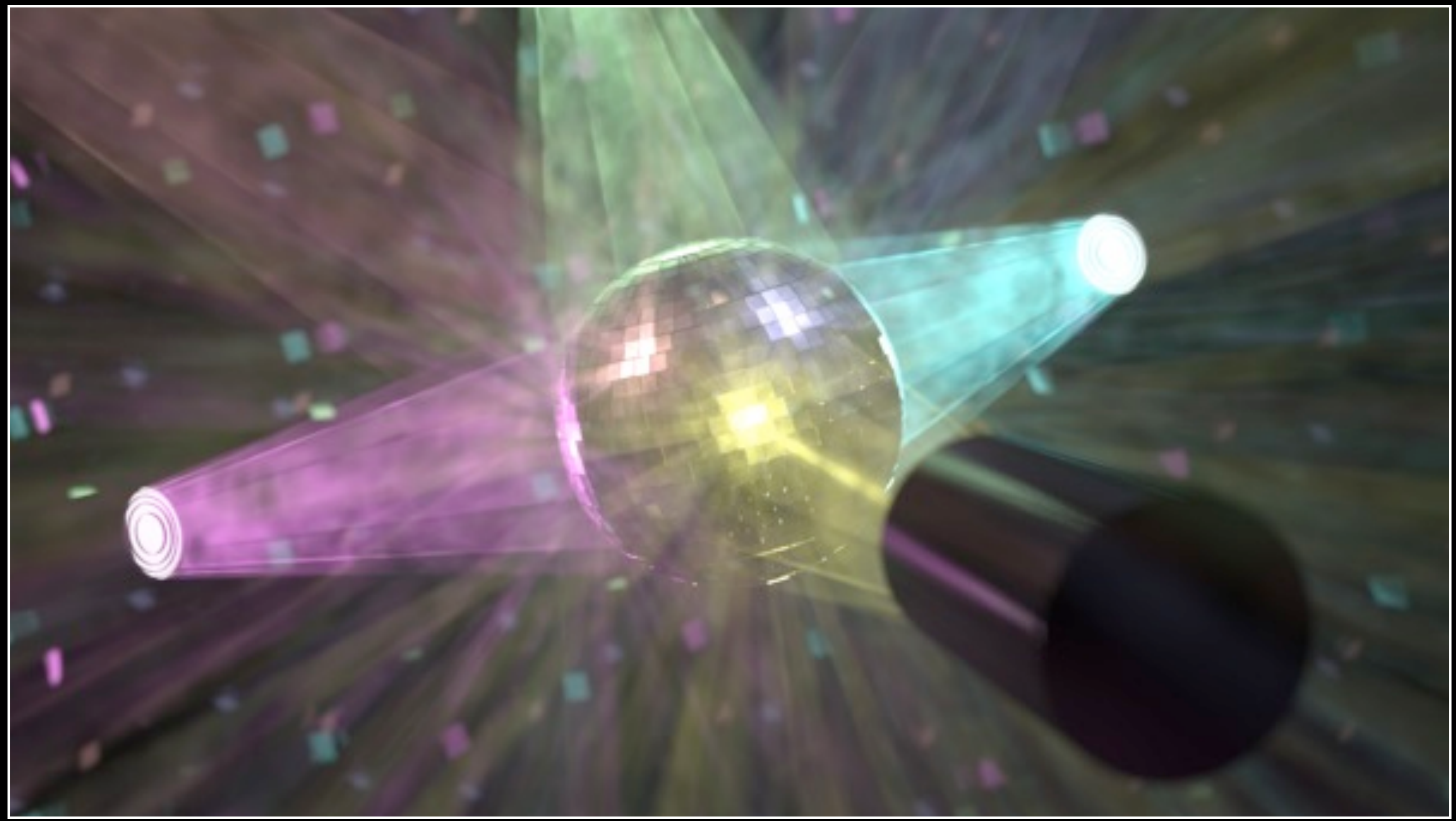
1280x720, Depth-of-Field



Homogeneous

19.67M Photon Beams

3 minutes



Heterogeneous

16.19M Photon Beams

5.7 minutes

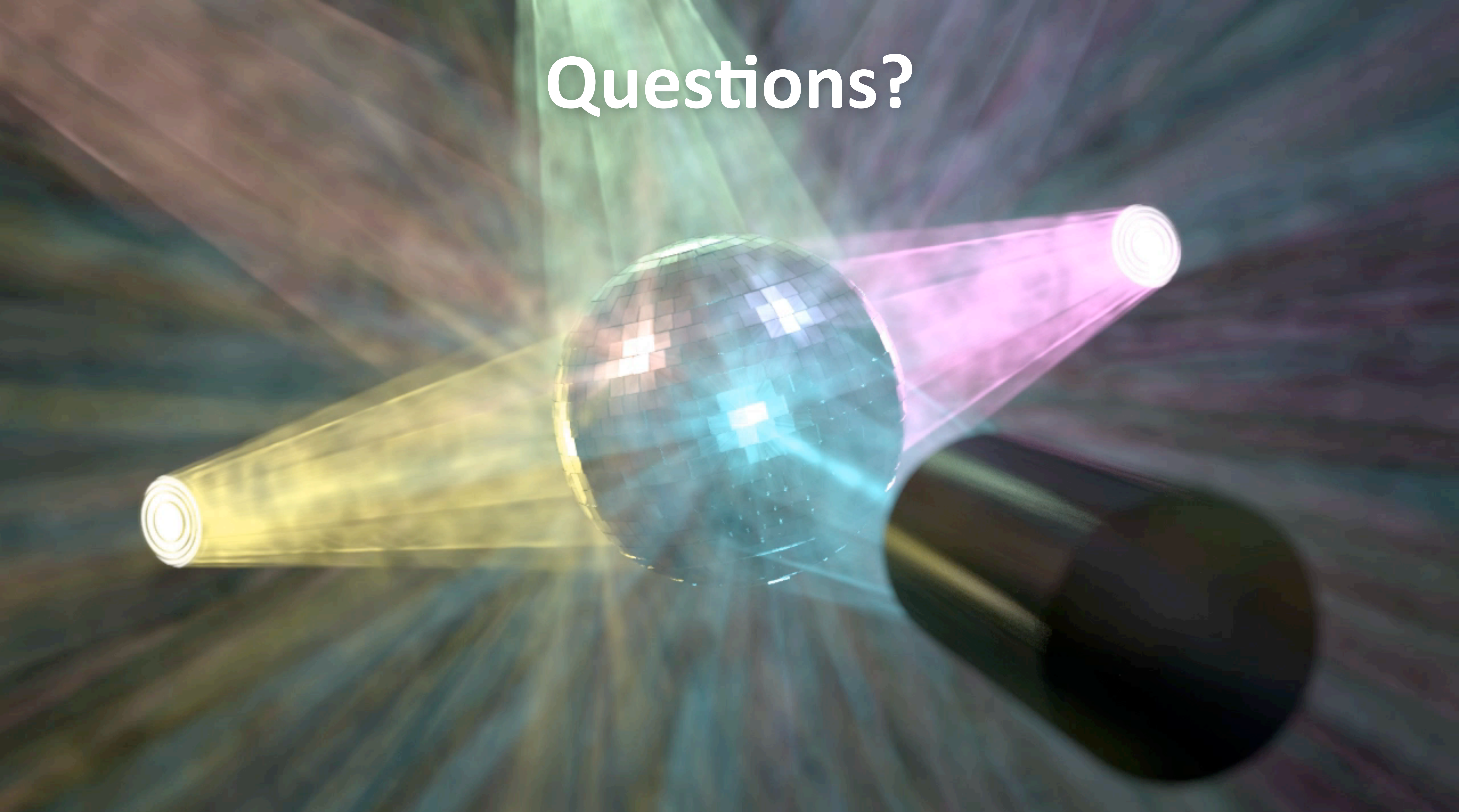
USER INTERACTION

Hybrid CPU/GPU Implementation

Homogeneous

Heterogeneous

Real-time capture


Questions?