A Comprehensive Theory of Volumetric Radiance Estimation Using Photon Points and Beams

Wojciech Jarosz[*†] Derek Nowrouzezahrai[*‡]
Iman Sadeghi[†] Henrik Wann Jensen[†]

[*] Disney Research, Zurich
[†] UC San Diego
[‡] University of Toronto

Association for Computing Machinery
ACM Transactions on Graphics
SIGGRAPH2011

Friday, 7 September 12

- Thanks for the introduction, and thank you all for coming to my talk
- In this paper we present a comprehensive theory of radiance estimation for volumetric photon mapping.
- Since this is a TOG paper, its long and necessarily has a very complicated title
- but in this talk, I'll try to distill our paper into its core ideas, which is the concept of photon beams.

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Photon Beams

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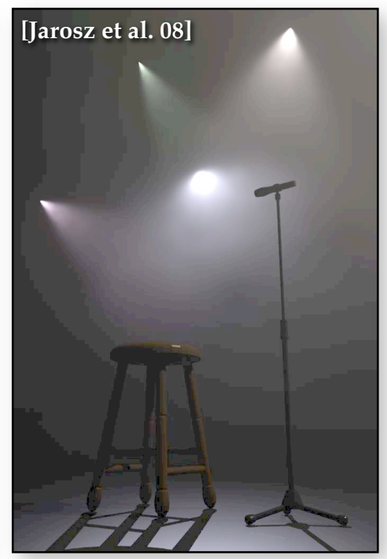
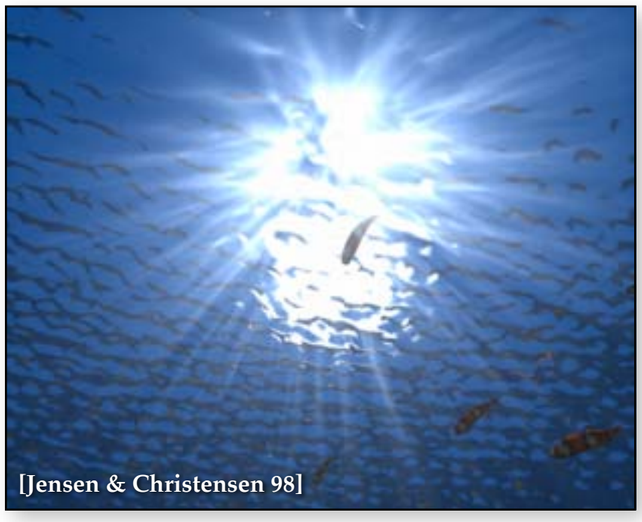
- In this talk we are interesting in rendering scenes like these
- The appearance of all of these photographs is due to light interacting with participating media

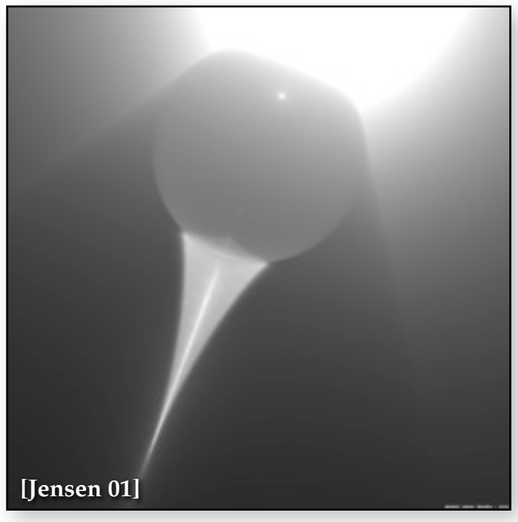
Volumetric Photon Mapping

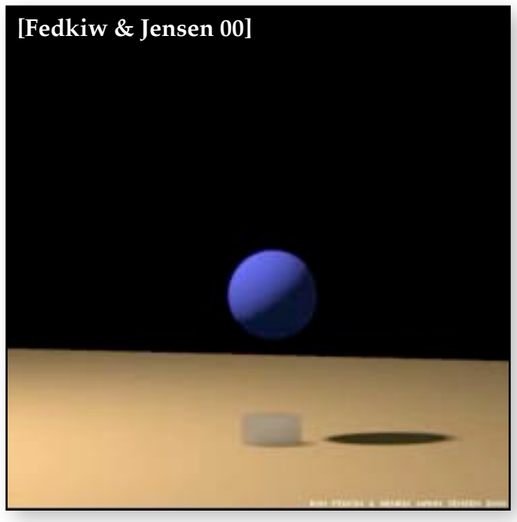
- A popular technique for simulating complex lighting in participating media is volumetric photon mapping
- This technique has been used both in academia and industry because it is relatively efficient, very general, and it is robust to complex light paths where other algorithms typically fail (such as volume caustics)

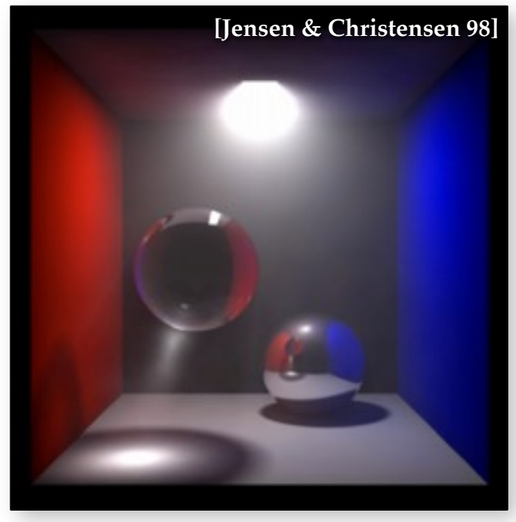
Volumetric Photon Mapping











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Previous Work (1)

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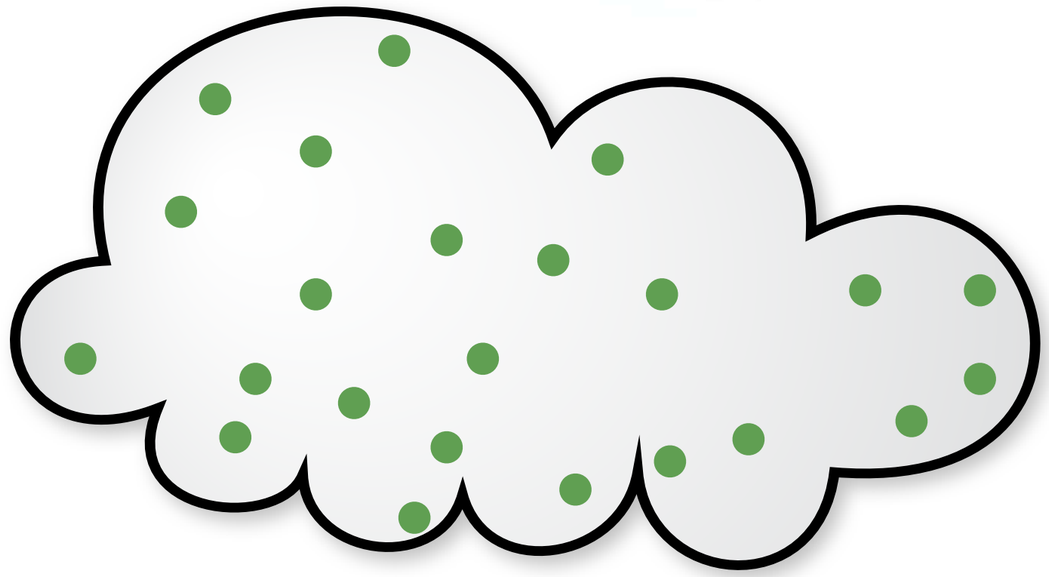
  [Jensen & Christensen 98]



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  [Jarosz et al. 08]

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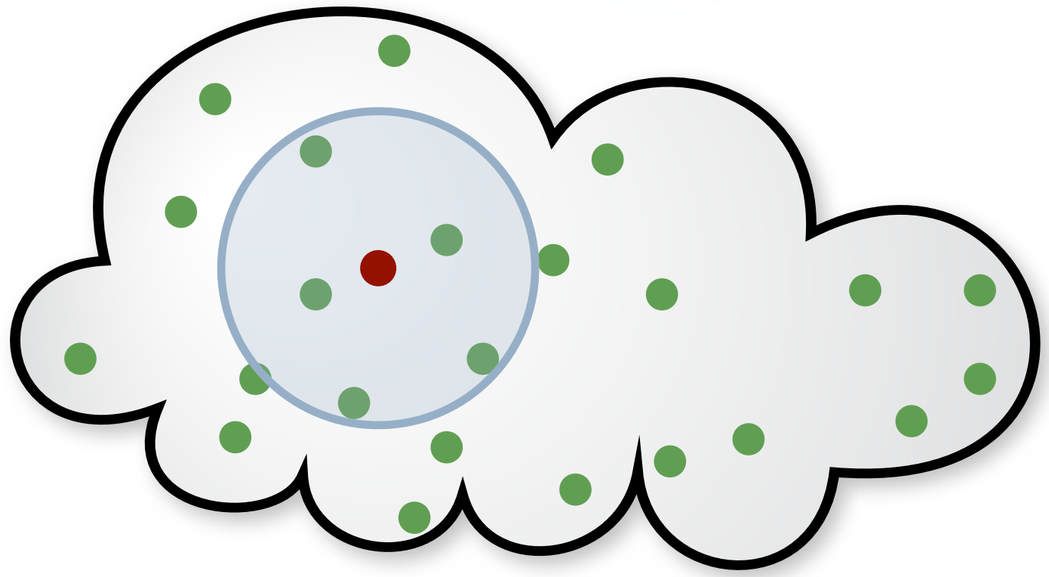

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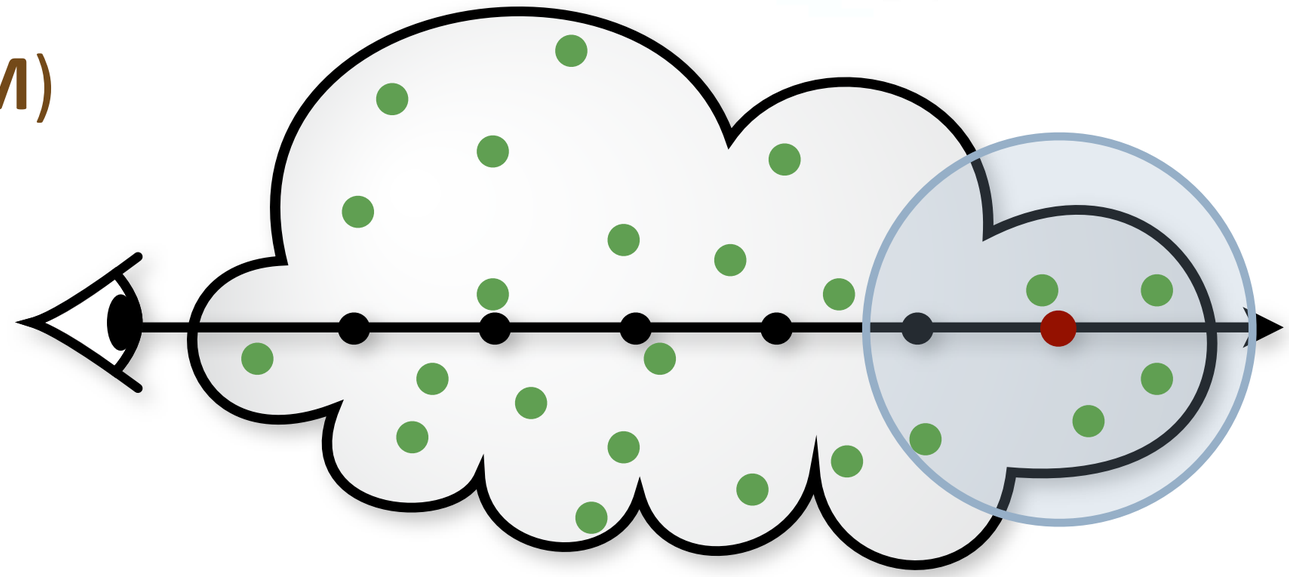

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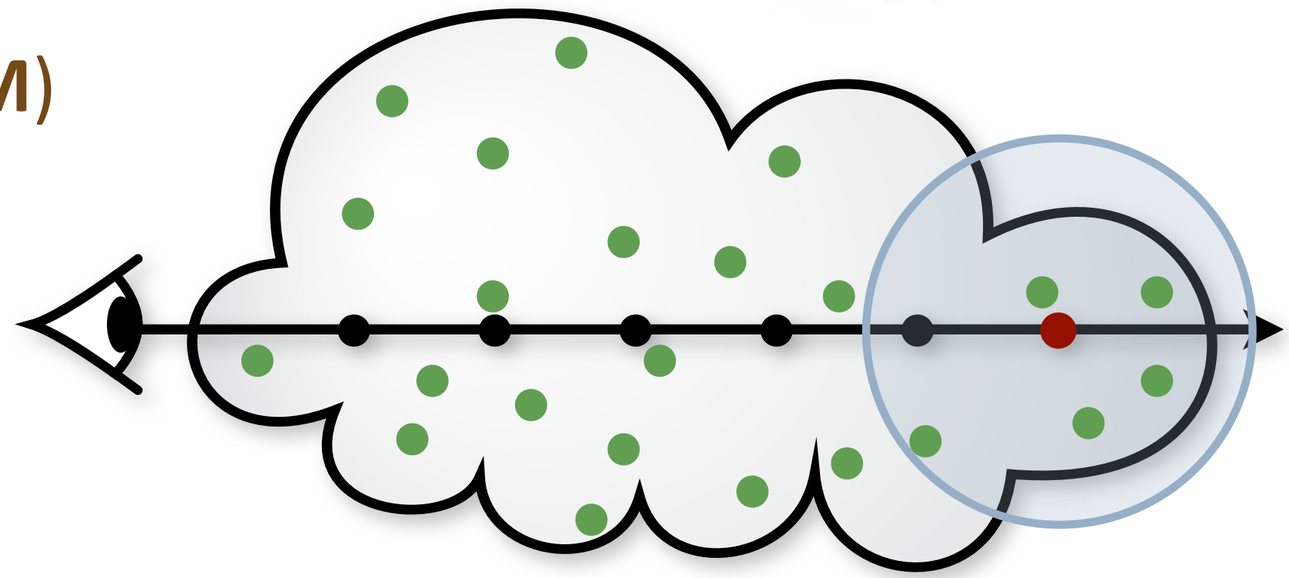

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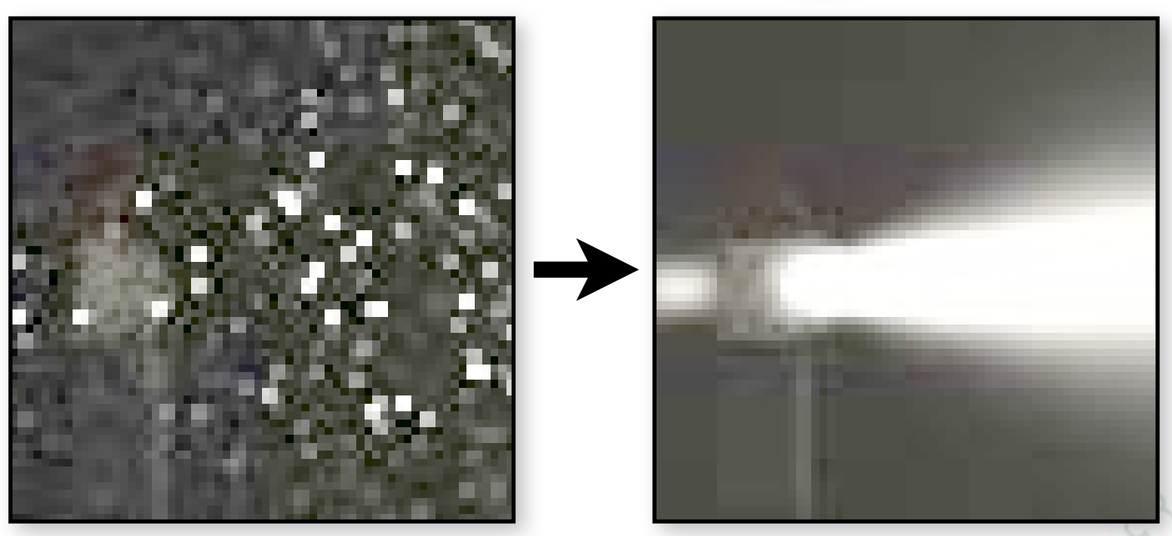

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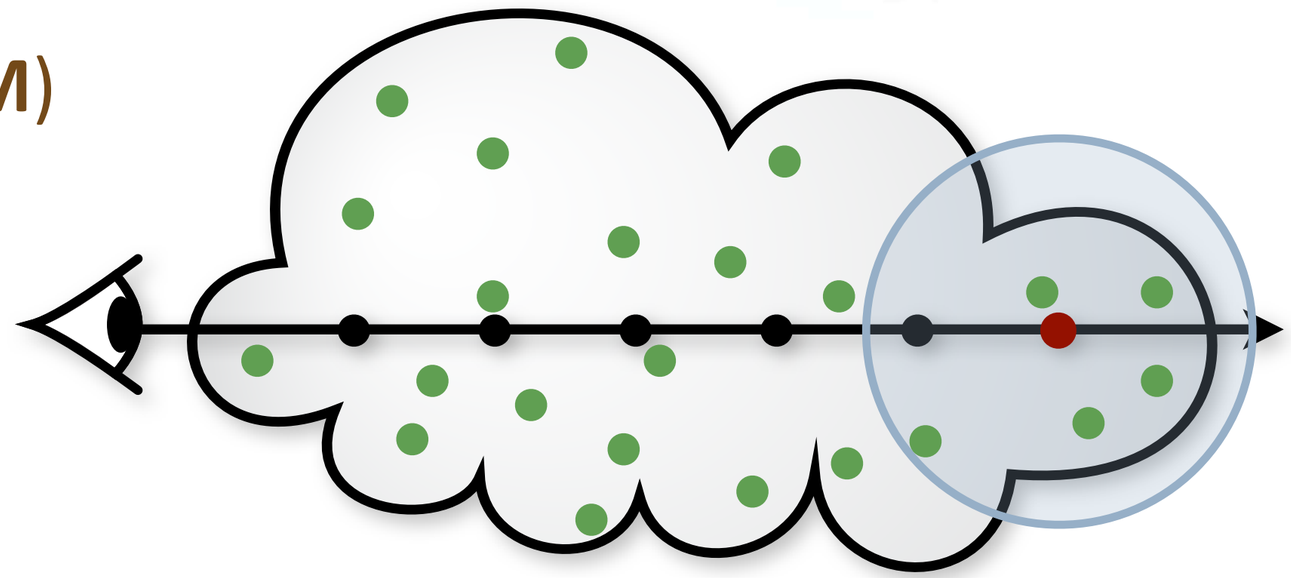

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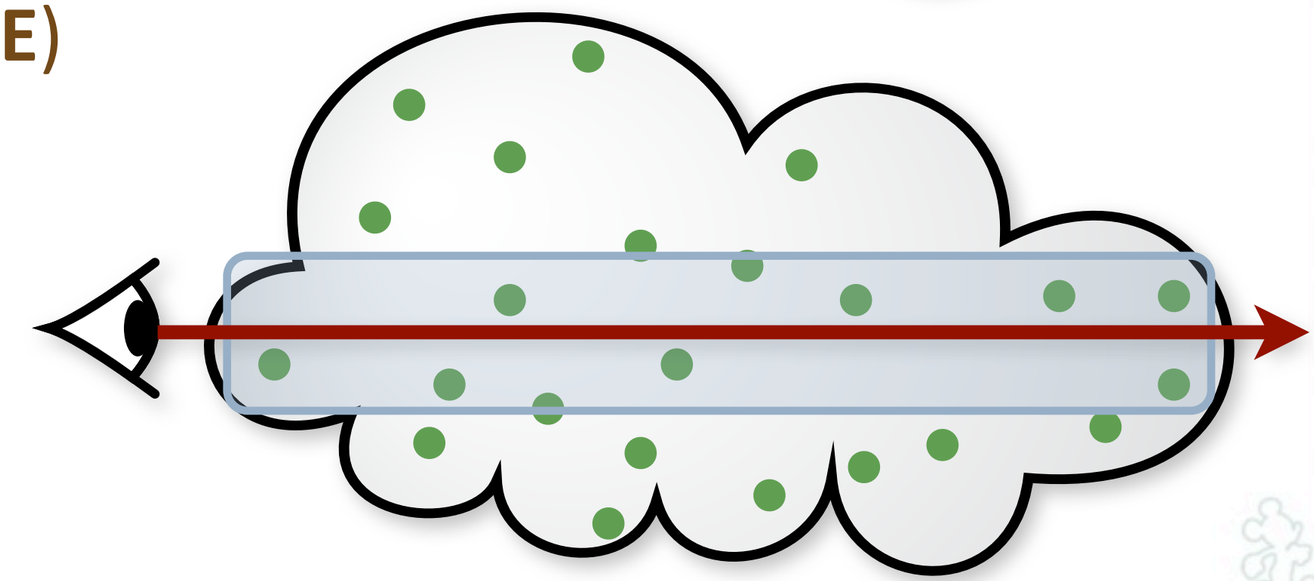

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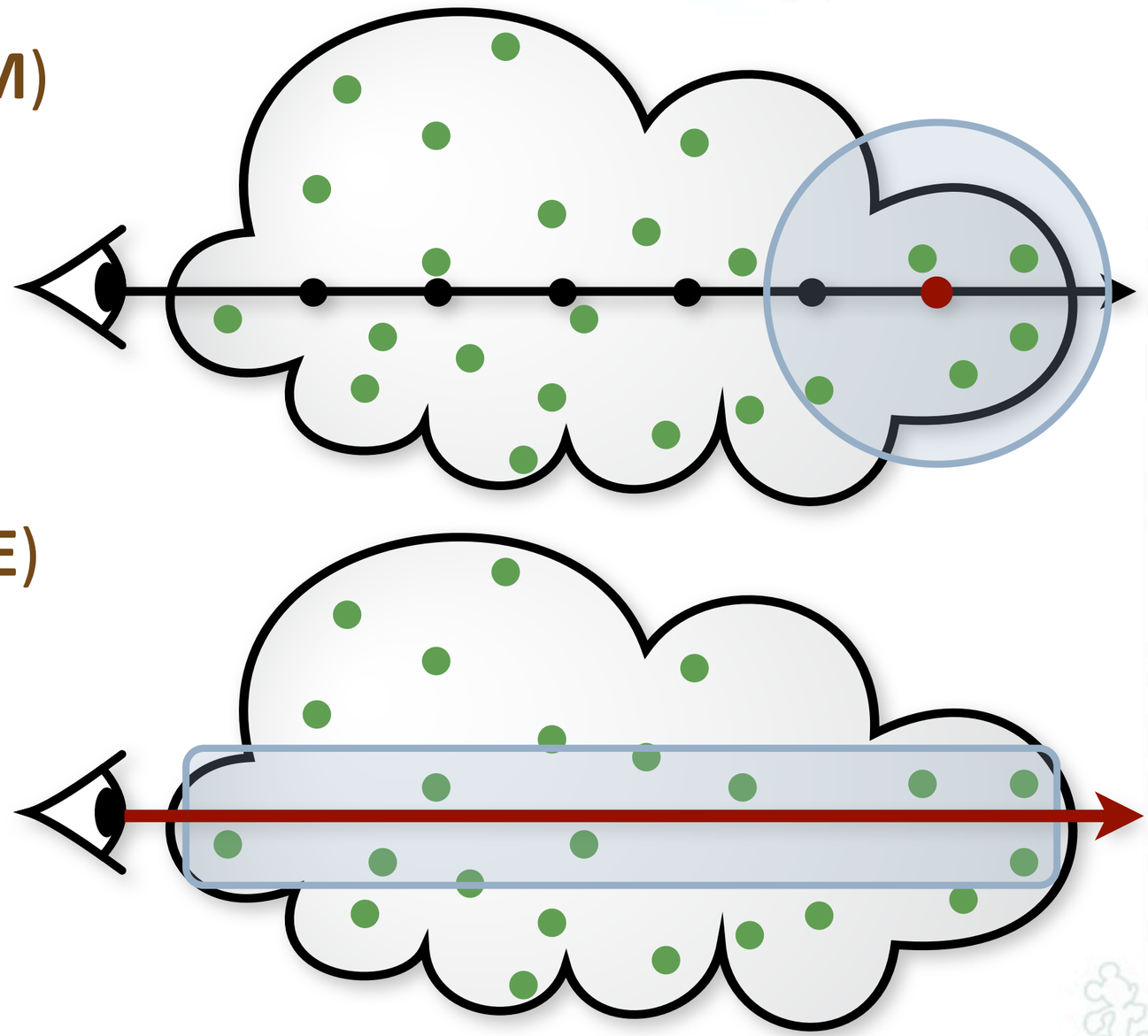
Query
Point



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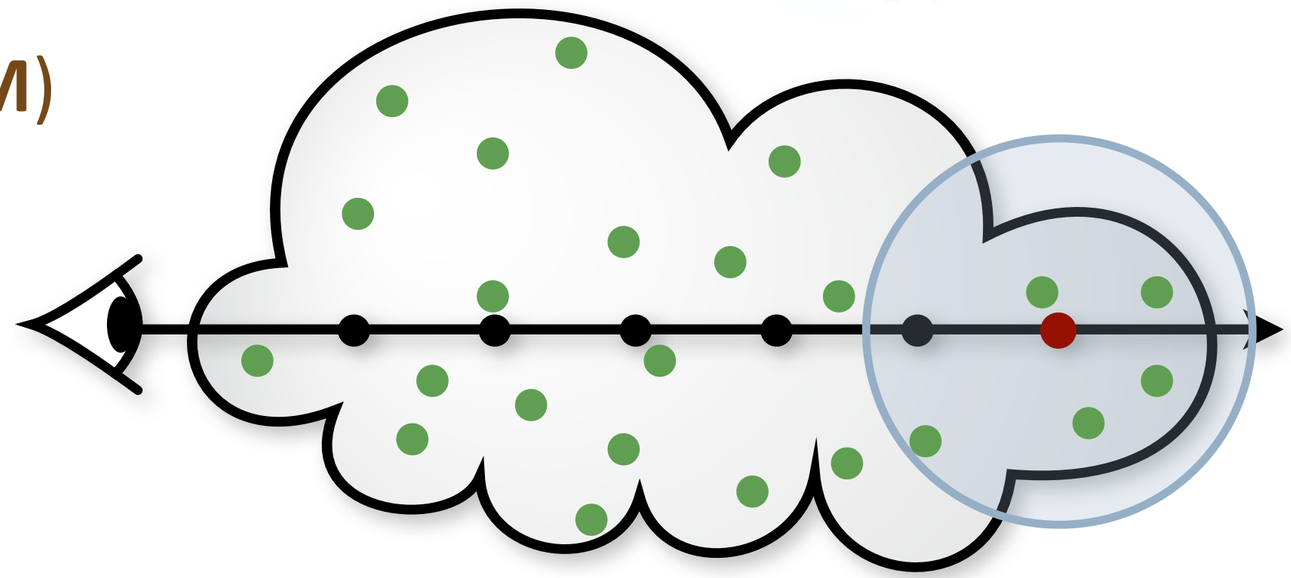
Point	x	Point



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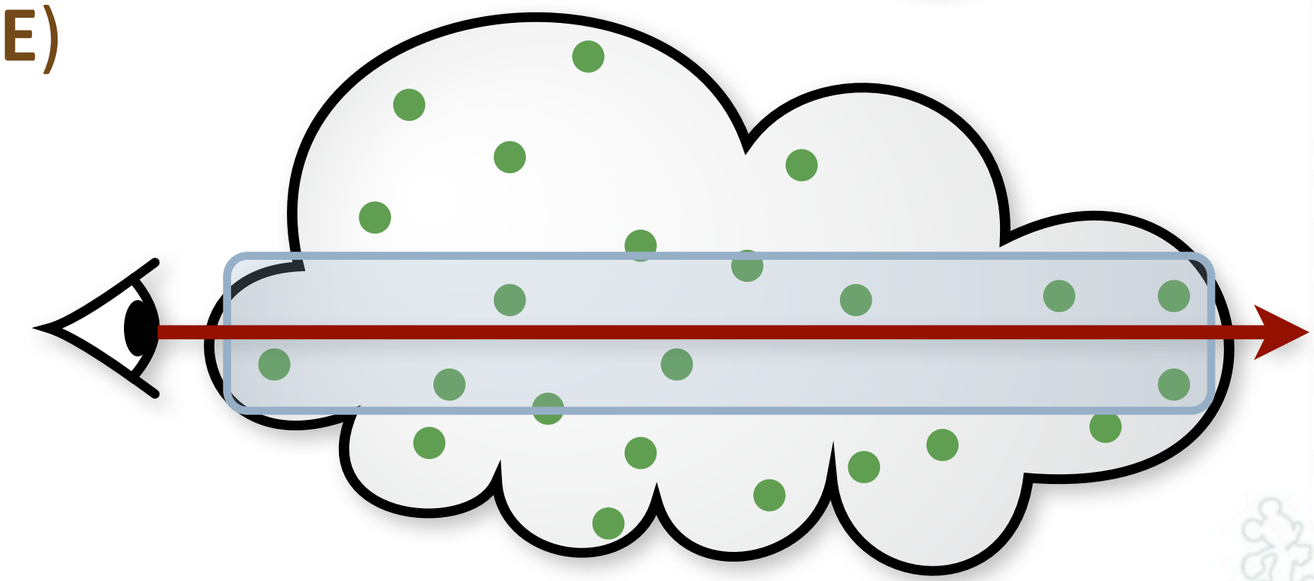

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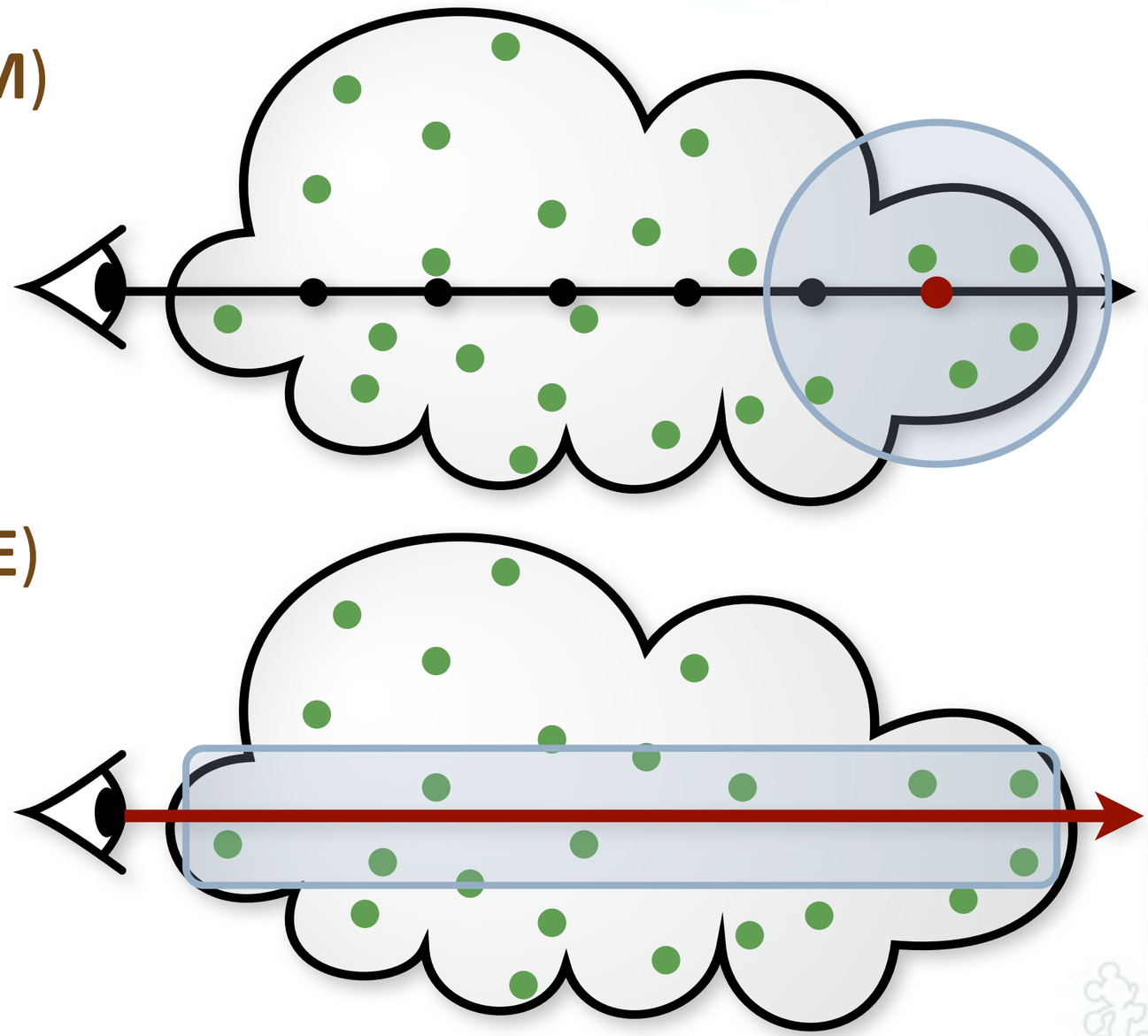

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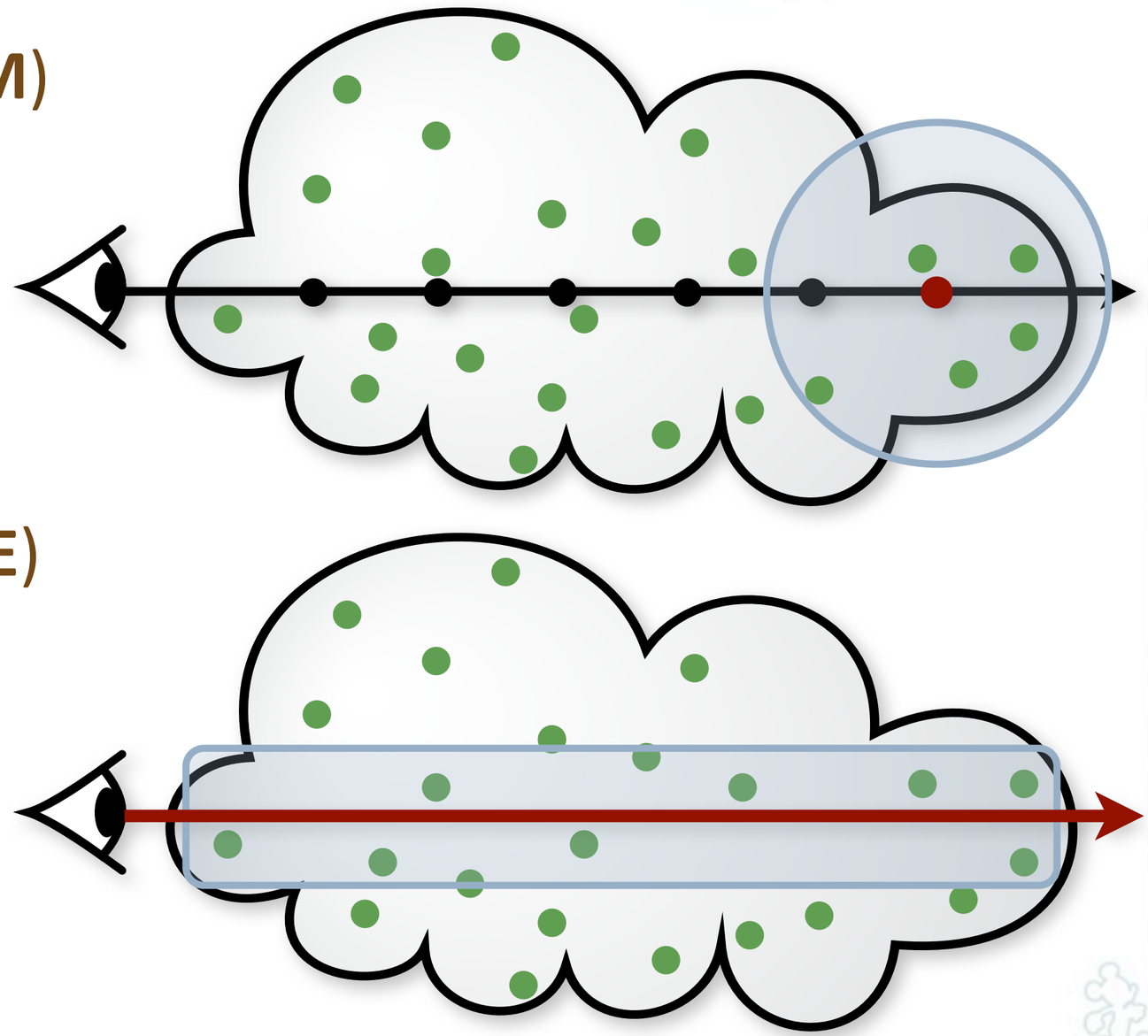

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Beam

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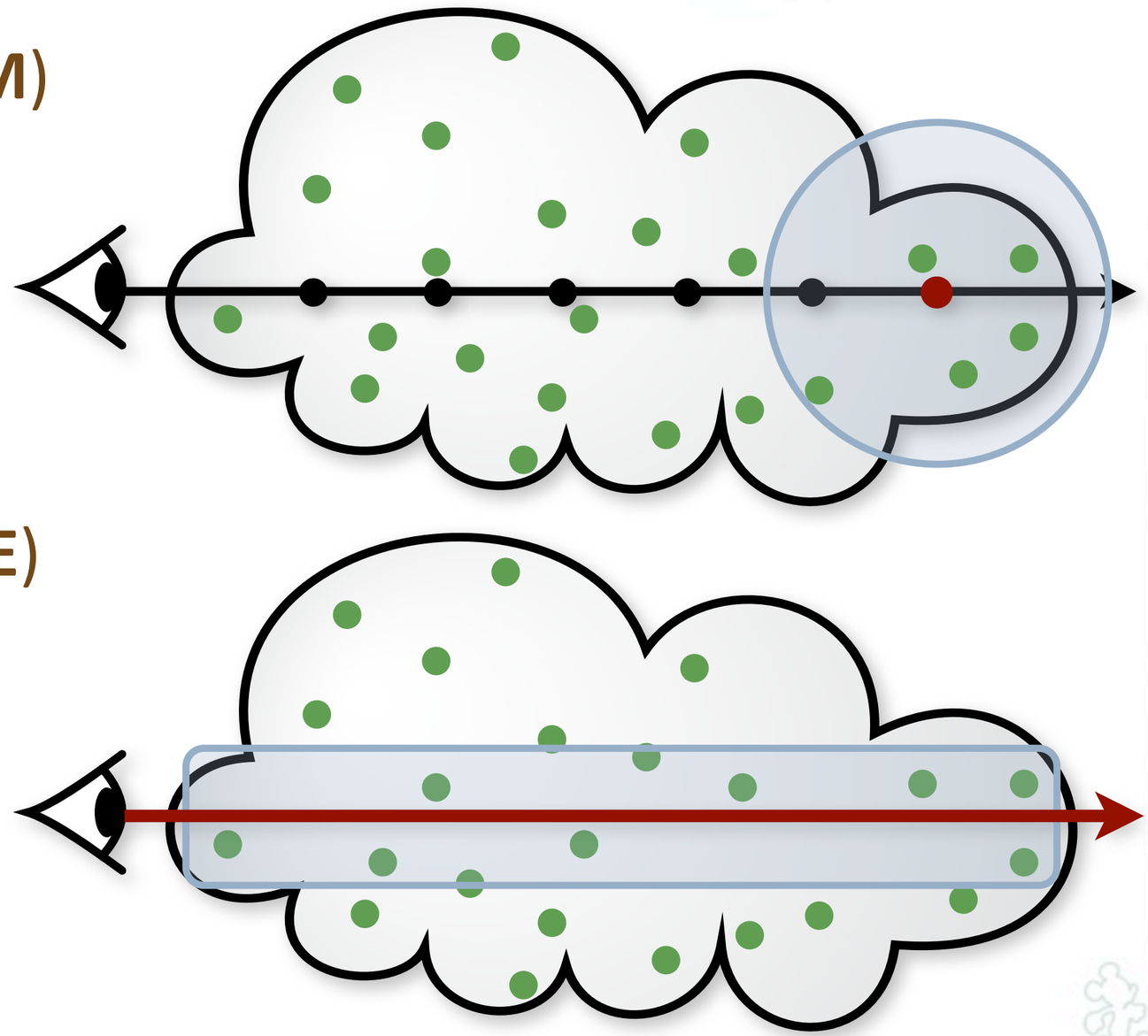

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Beam	x	Point

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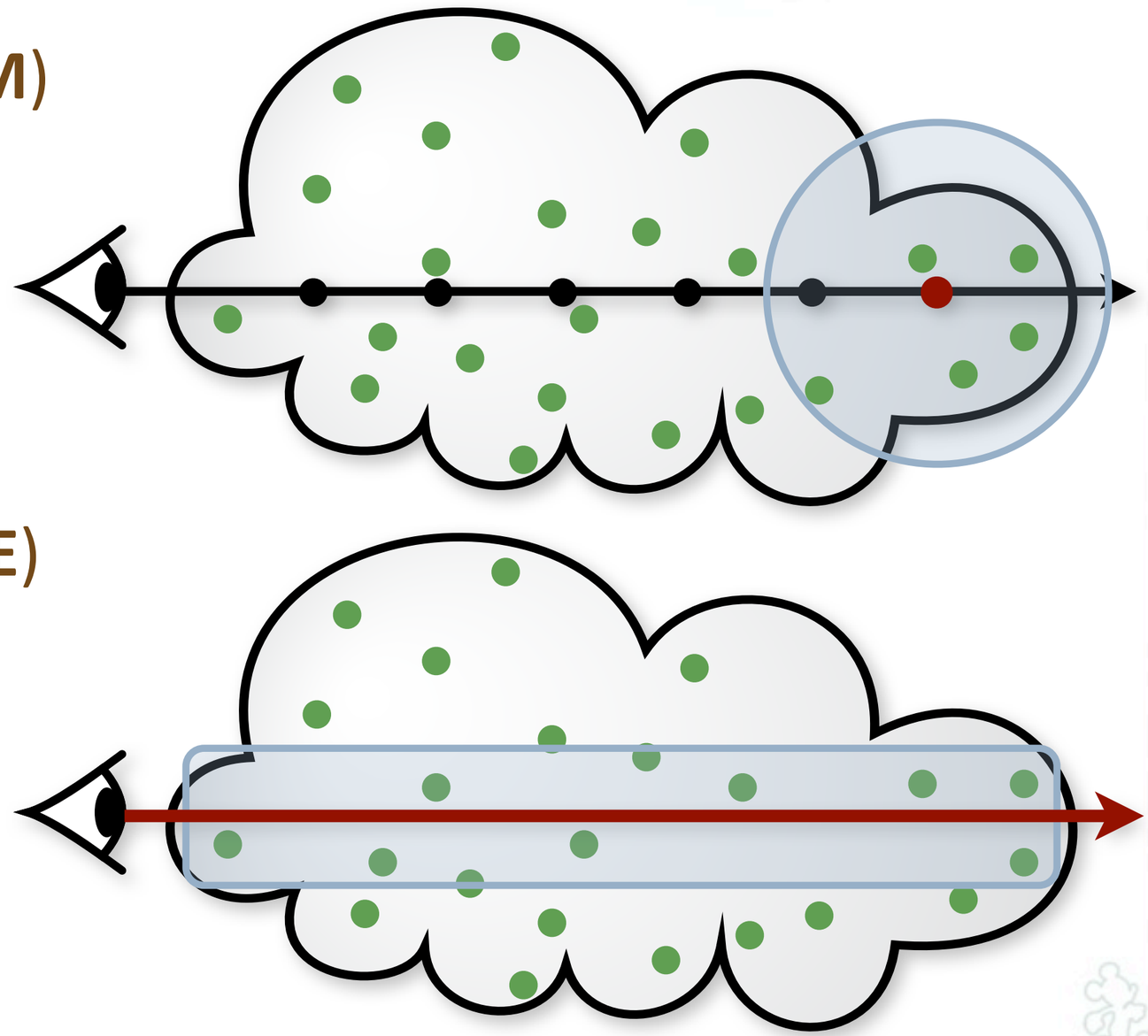

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Query	x	Data	Blur
Beam	x	Point	**(2D)**

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Point	x	Point	(3D)

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

- This Paper

Friday, 7 September 12

- In this paper we complete the circle and show that we can use this concept of beams not only for the query [click], but also for the data representation [click]. Additionally, we show that it is possible to obtain different flavors of density estimates by [click] modifying the dimentionality of the blur
- This results in a generalized theory which describes an entire family of density estimators.

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Query	x	Data	Blur
Point	x	Point	(3D)

- This Paper

Query
Point/Beam

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Point	x	Point	(3D)

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

- This Paper

Query	Data
Point/Beam	**Point/Beam**

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Point	x	Point	(3D)

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

- This Paper

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

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Our Contribution

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

- The derivation of our theory subsumes all previously published radiance estimators for participating media, and [CLICK] additionally adds several more ways to estimate radiance using the concept of photon beams.
- What results is a collection of 9 distinct estimators which have a number of interesting theoretical connections to existing work, and also allow for much more efficient rendering than previously possible

Our Contribution

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)**

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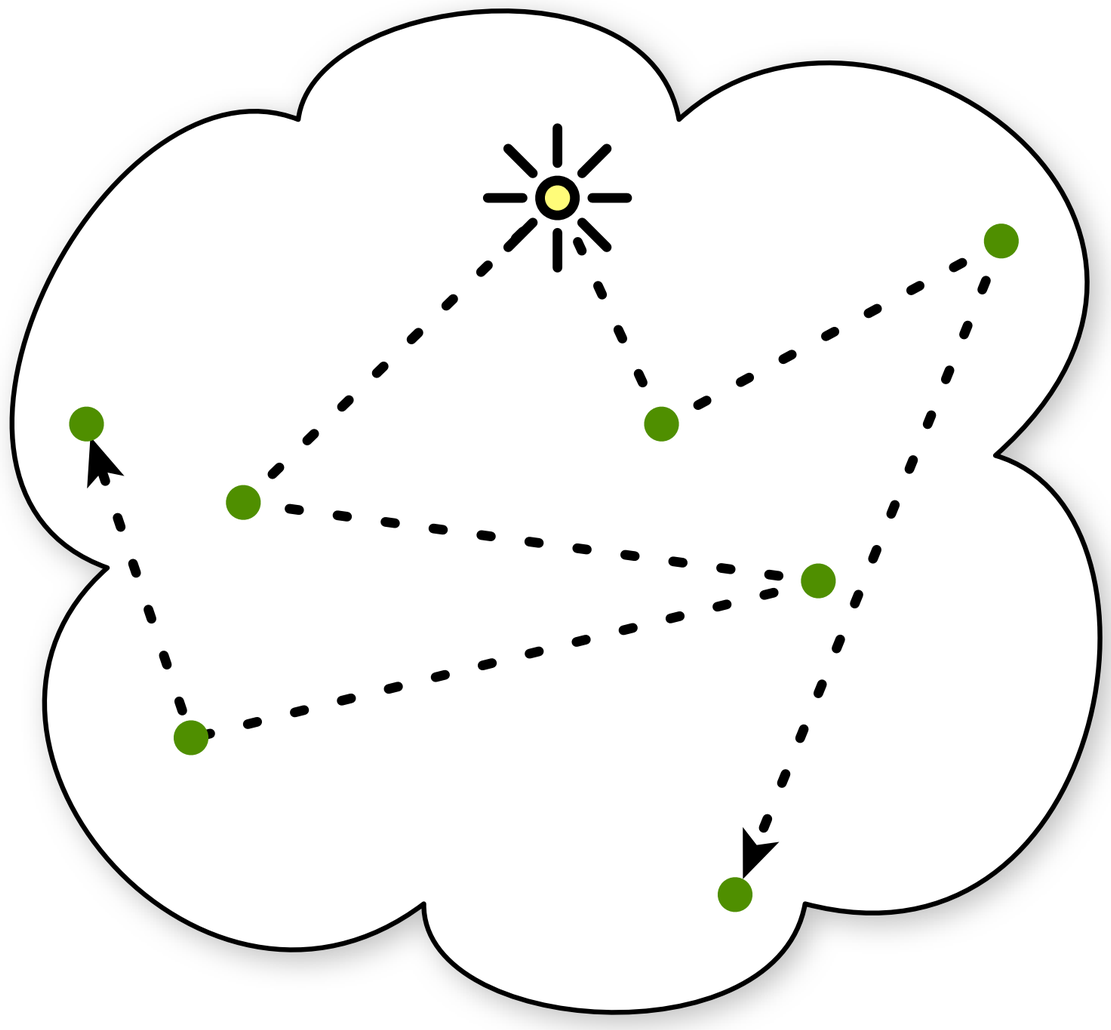
- What results is a collection of 9 distinct estimators which have a number of interesting theoretical connections to existing work, and also allow for much more efficient rendering than previously possible

Volumetric Photon Mapping



Photon Points

Friday, 7 September 12

- Volumetric photon mapping starts by shooting virtual photons from light sources.
- Each photon that is emitted from the light propagates through the medium and gets scattered into different directions, until the photon exits the medium or is absorbed.
- Volumetric photon mapping records the history of these scattering events and stores the vertices of these paths (the “photons”) into a volume photon map
- Now, in this particular case we have found 2 photons; however, at this location we are less lucky and find zero photons. One of the fundamental challenges here is that we do not know whether this location really should be very dark or whether we simply used too few photons in our simulation.
- Our only recourse is to either increase the search region (which blurs the result and introduces bias) or use more photons (which increases both memory usage and render time)
- The main idea behind this paper is that we can in fact do much better using only the information that is already available from the photon tracing pass. Standard photon mapping only considering the scattering locations, and this throwing away a lot of information that is present in the photon map
- In particular, if we instead considered the entire path of photons (and here I also extend each path segment to the end of the medium), at the same location we see that that two photons traveled nearby. If we could somehow use this information to compute the lighting, we would obtain a more accurate rendering.
- This is one of the core ideas behind our paper, and is what gives rise to a concept we call photon beams.

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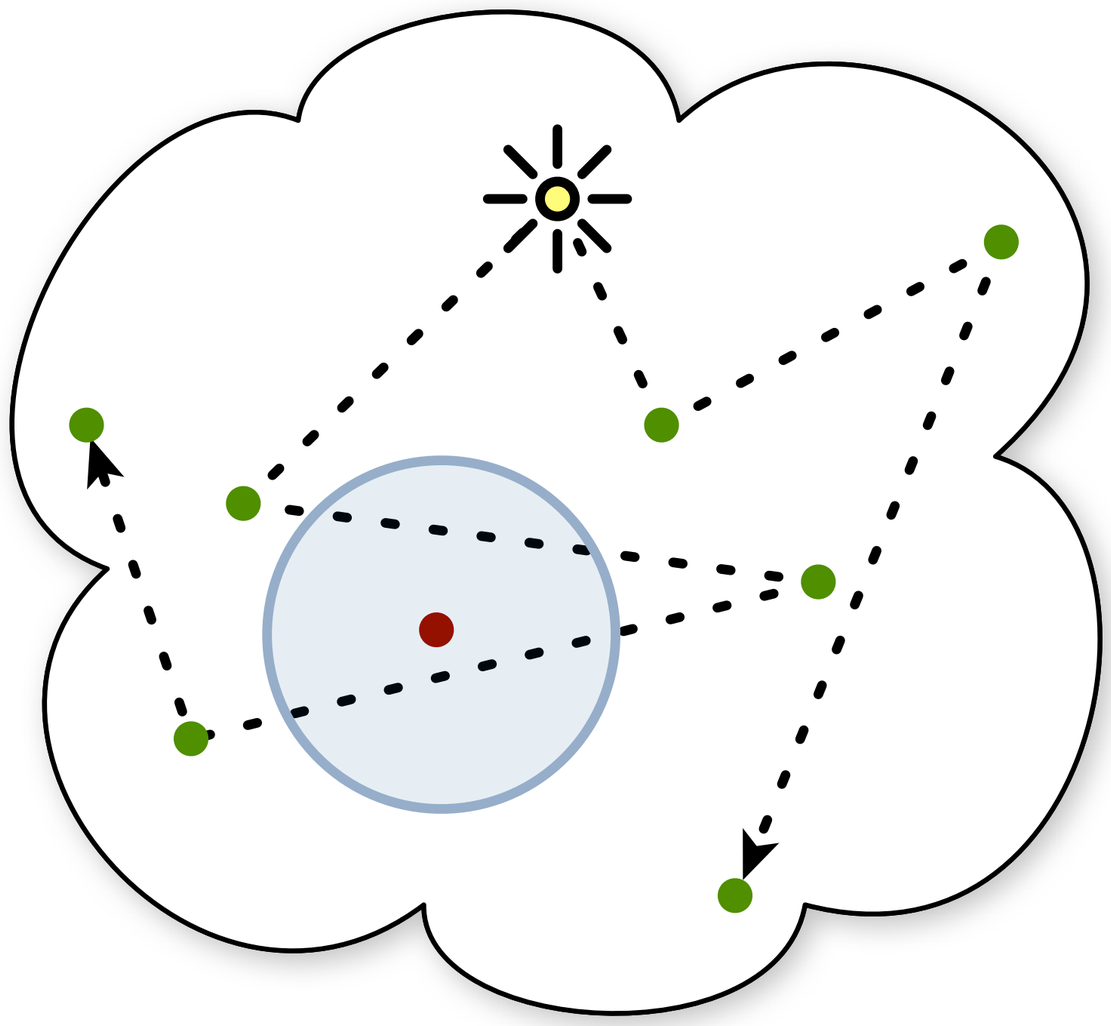

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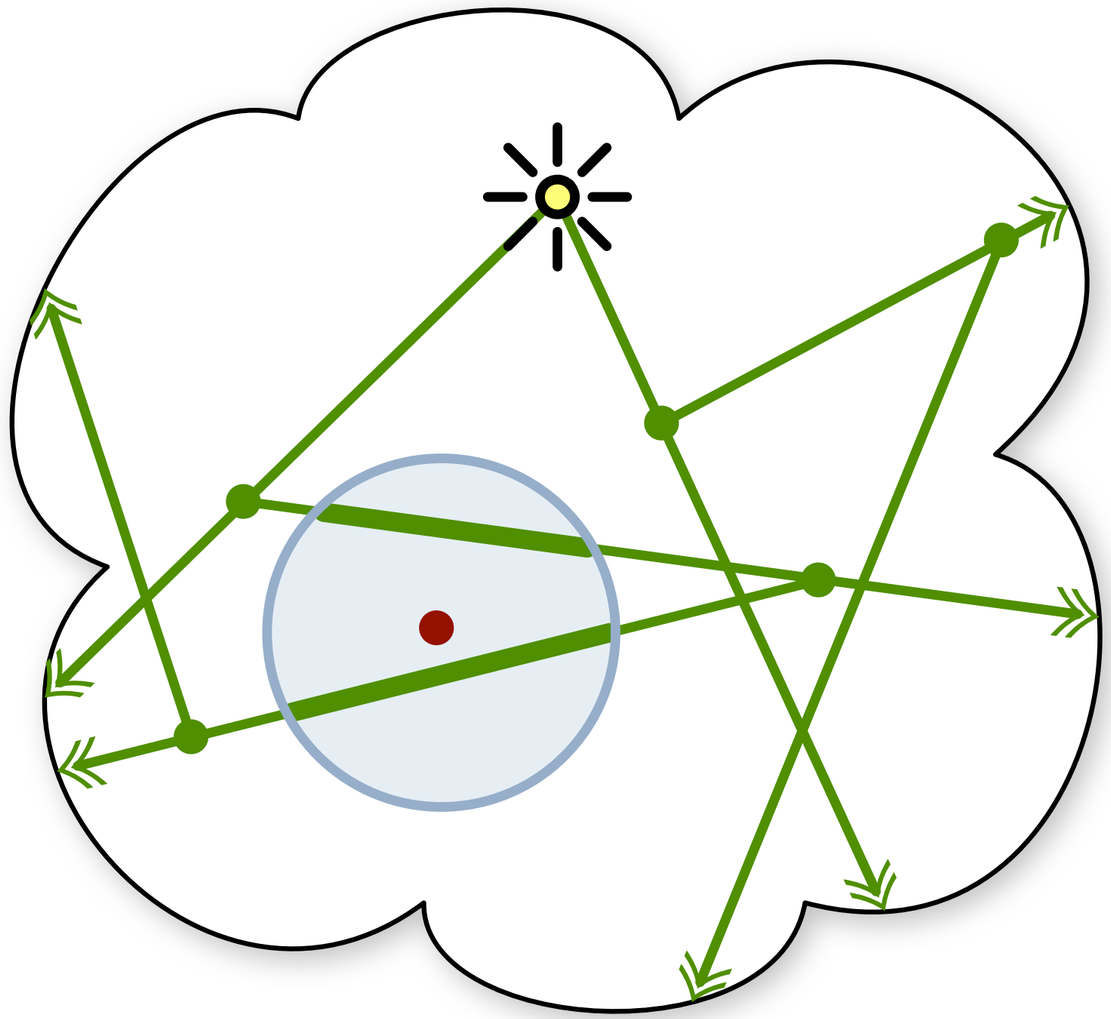

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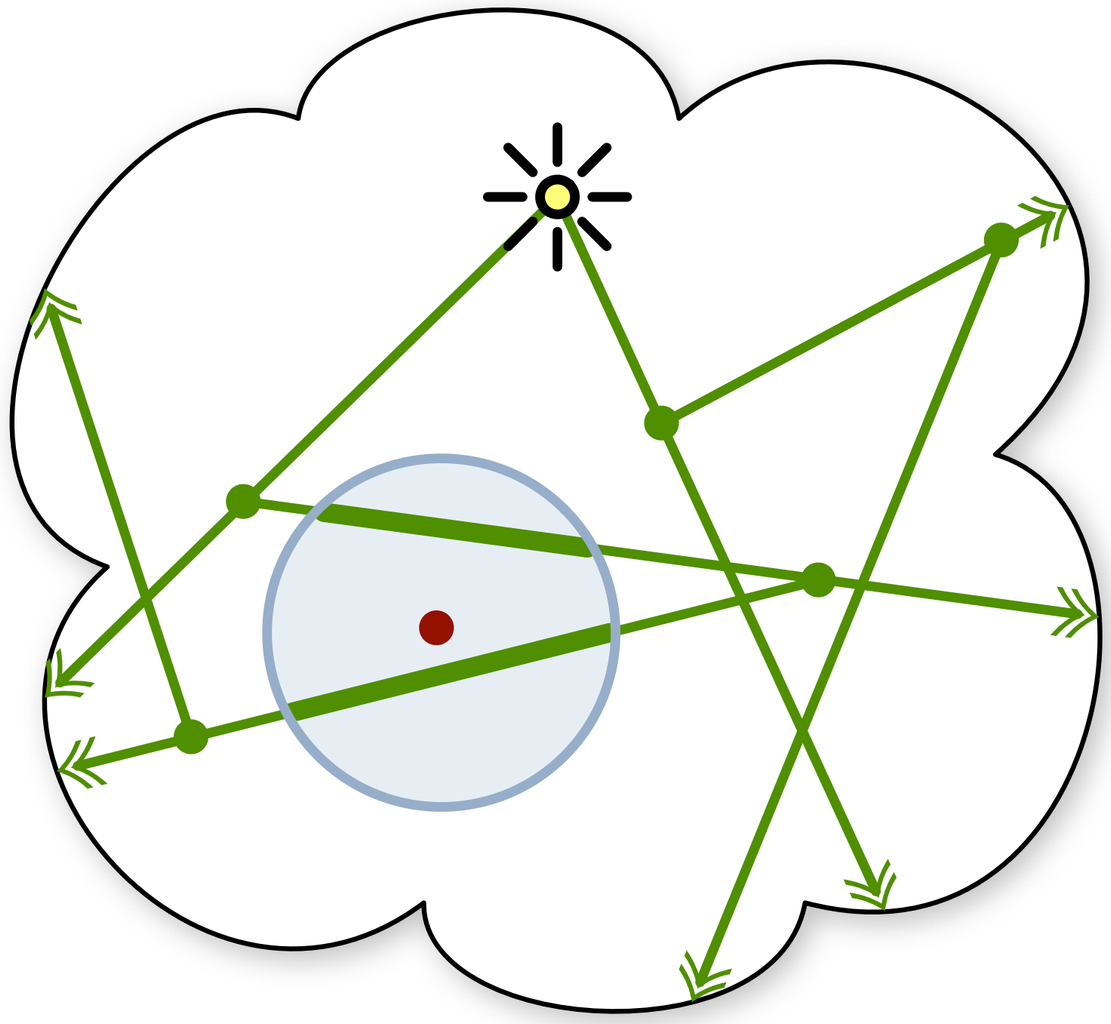

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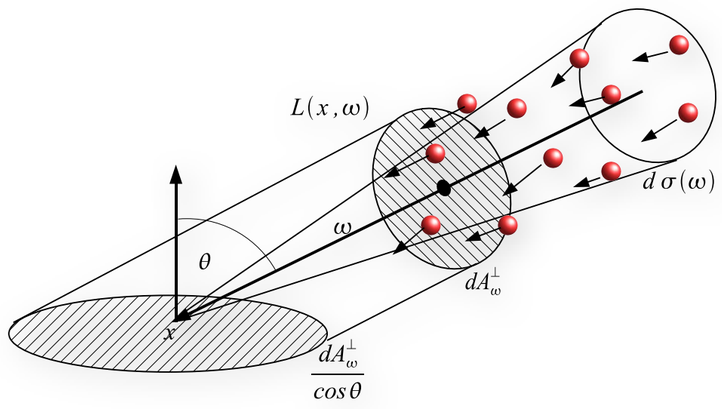
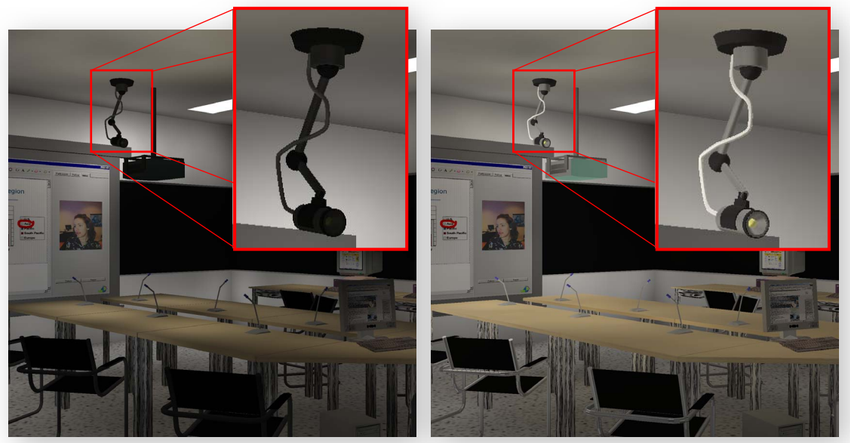
Previous Work (2)

- Ray Mapping
  [Havran et al. 05]
  [Herzog et al. 07]





Friday, 7 September 12

- The use of photon paths or beams of light has been explored by other researchers.
- Ray mapping techniques consider the trajectory of photons when performing density estimation at surfaces in order to reduce boundary bias in corners.
- One of our 9 estimators can be seen as a generalization of these algorithms to participating media, where using beams actually has a much greater benefit, as we will see
- Our estimators also have connections to beam tracing methods, but since we build off of photon mapping, we are geometry independent, and can easily incorporates multiple bounces of light

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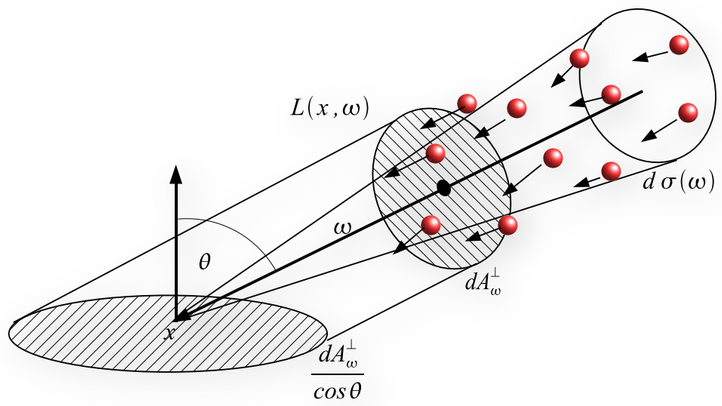
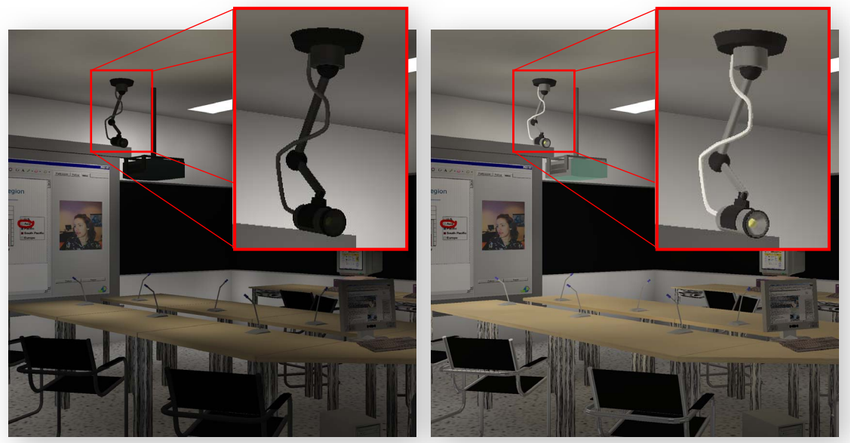
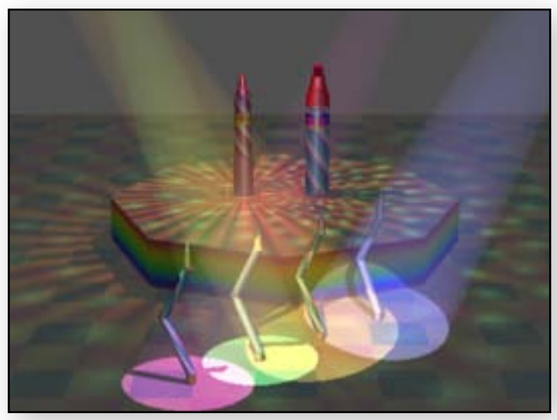




- Beam Tracing
  [Heckbert & Hanrahan 84]
  [Watt 90]
  [Nishita & Nakamae 94]
  [Iwasaki et al. 01]
  [Ernst et al. 05, Krüger et al. 06]



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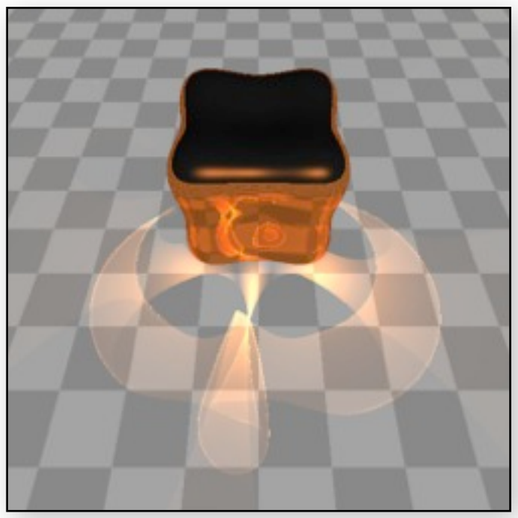
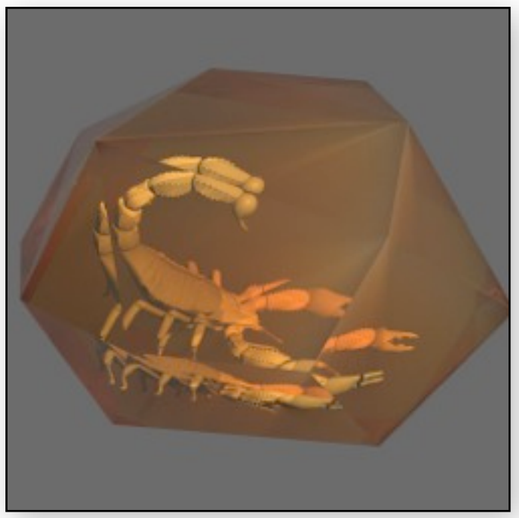
Previous Work (3)

- Root-finding methods
  [Mitchell and Hanrahan 92]
  [Walter et al. 09]





- Techniques which try to directly compute such volumetric effects using root finding produce results without the blurring artifacts present in photon mapping; however, they tend to only be applicable in restricted settings (e.g. a single bounce of light)
- With the improved density estimators we present, volumetric photon mapping can produce extremely crisp results that are competitive with these direct methods, but at a fraction of the cost

Notation/Assumptions

- homogeneous media

Friday, 7 September 12

- To make our derivations a bit more succinct, we will for now assume homogeneous media. We use sigma_s sigma_a and sigma_t to denote the scattering, absorption and extinction coefficients
- Additionally, we will assume that density estimation is performed using a global, fixed-size search region. Meaning, we don't use something like k-nearest neighbor density estimation
- Finally, all of these assumptions are just to make our lives a little easier, and can be lifted in an actual implementation as I will show later on.
- Using these assumptions, lets look at the various radiance estimators we can use in participating media

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Radiance Estimation using Photon Points

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

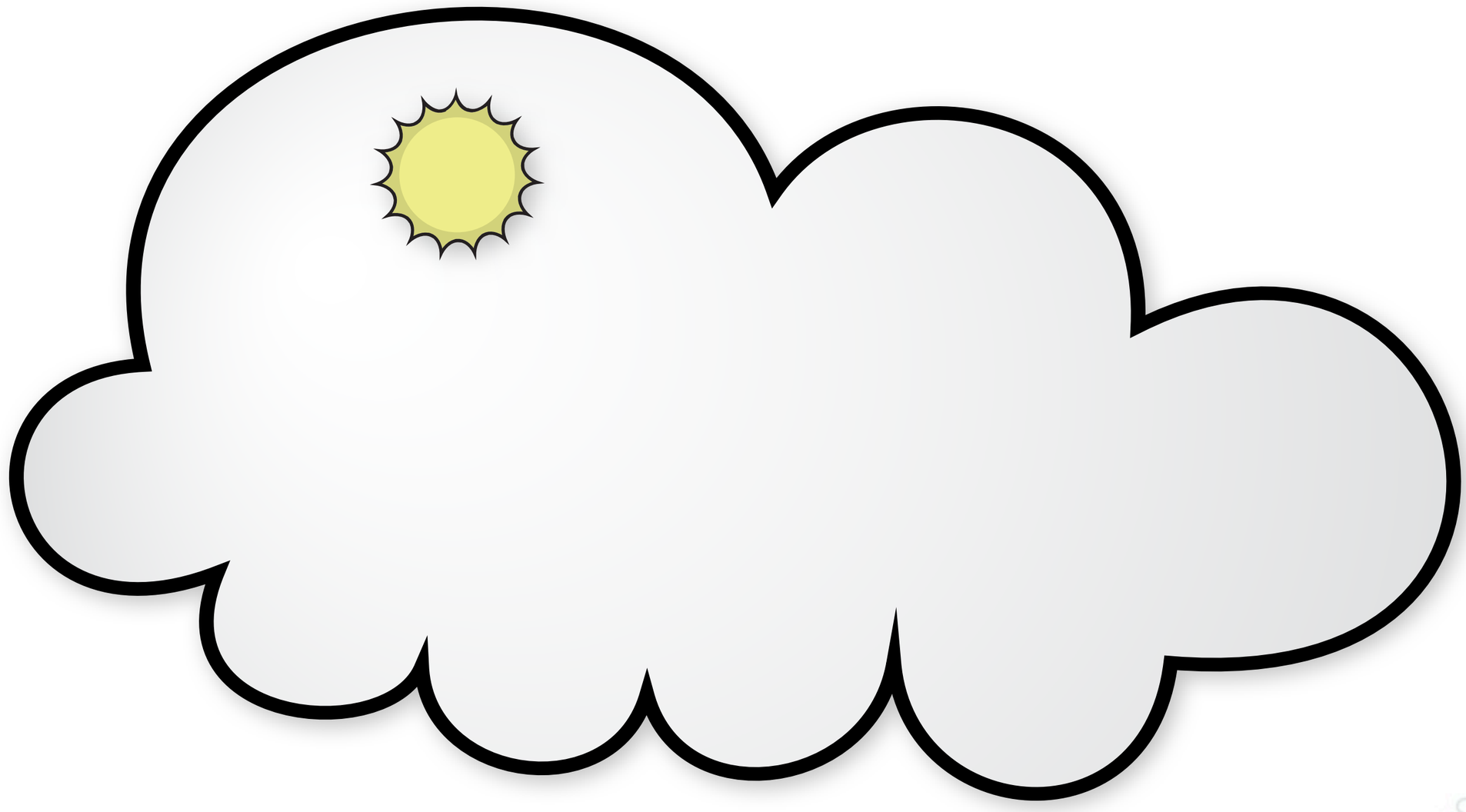
Radiance Estimation using Photon Points

- Point Query x Point Data (3D)
  - standard volumetric photon mapping [Jensen & Christensen 98]
- Beam Query x Point Data (2D)
  - splatting & beam radiance estimate [Boudet et al. 05], [Jarosz et al. 08]
- Beam Query x Point Data (3D)
  - new estimator

Photon Beams

- We can now turn to the new concept of photon beams
- But first we need to more precisely define how we can use photon paths for density estimation

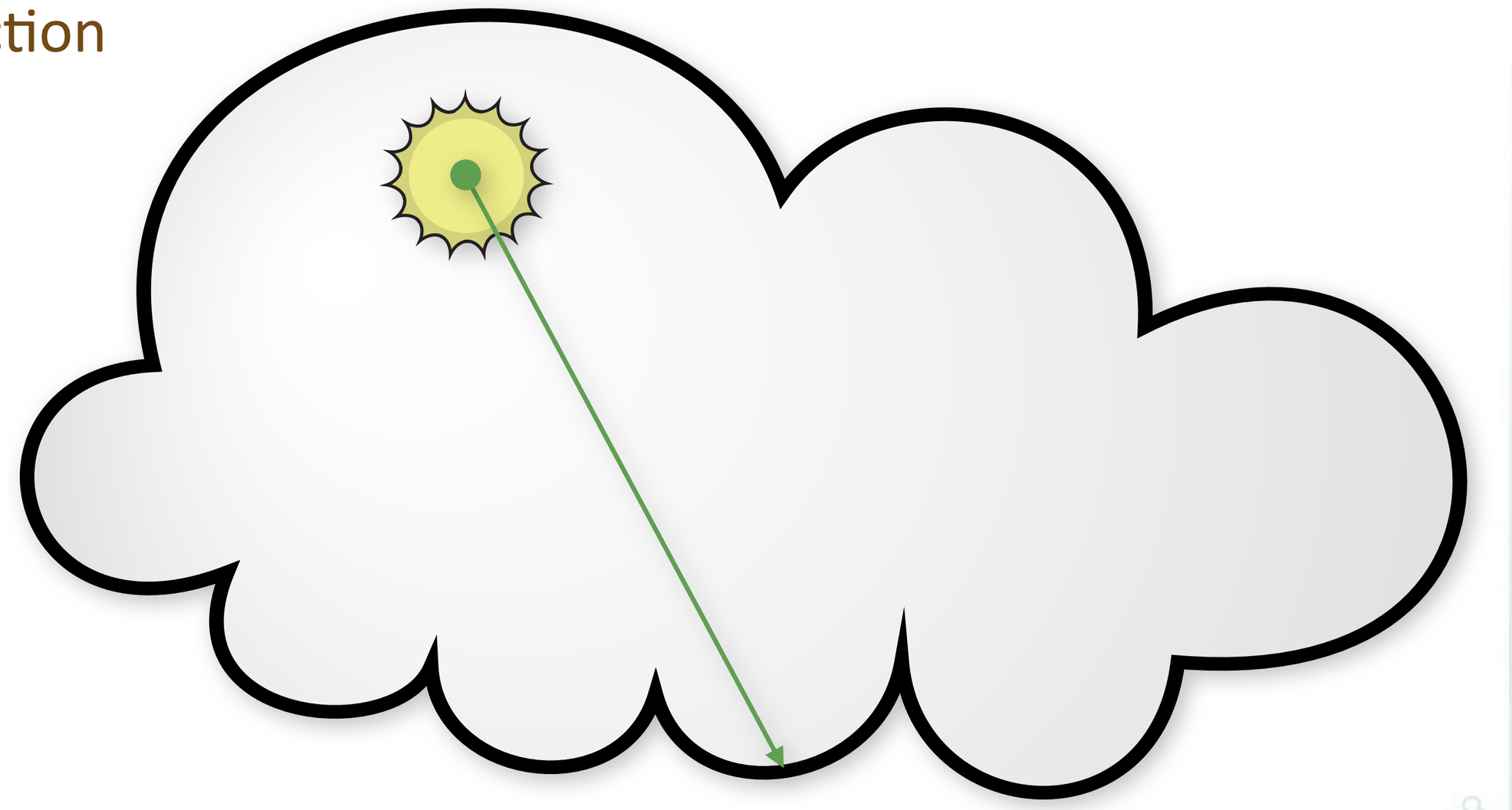
Traditional Photon Tracing



- The traditional procedure is quite simple:
  - [steps]
- For illustrative purposes let me superimpose the original rays that were shot during this process.
- We can see that we effectively placed one photon along each of these rays
- This is the standard approach, but it is possible to shoot photons in any number of ways
- In particular, we could instead deposit more than one photon along each of these rays, using a marching process analagous to ray marching, but for photons

Traditional Photon Tracing

1) choose direction



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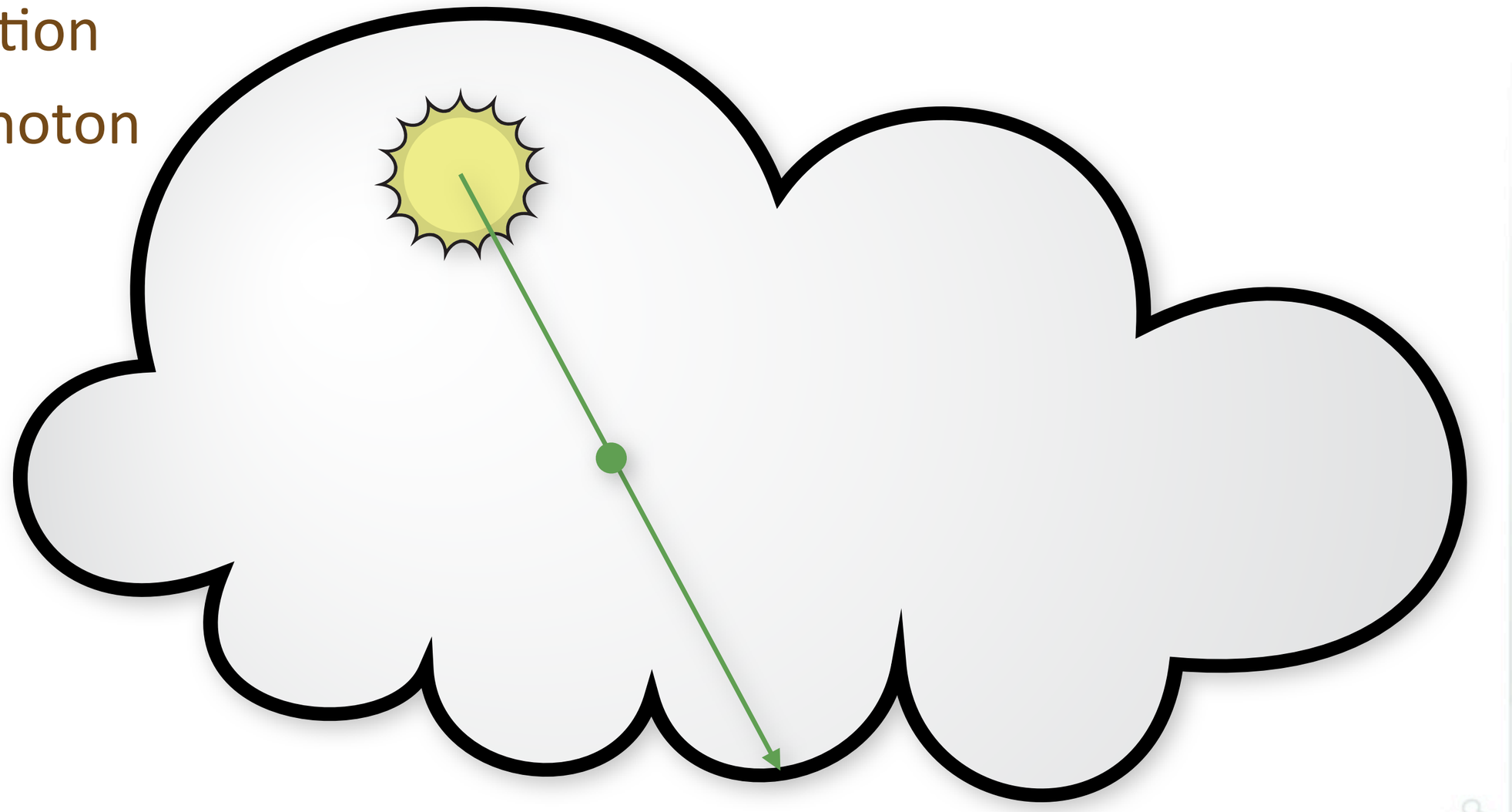

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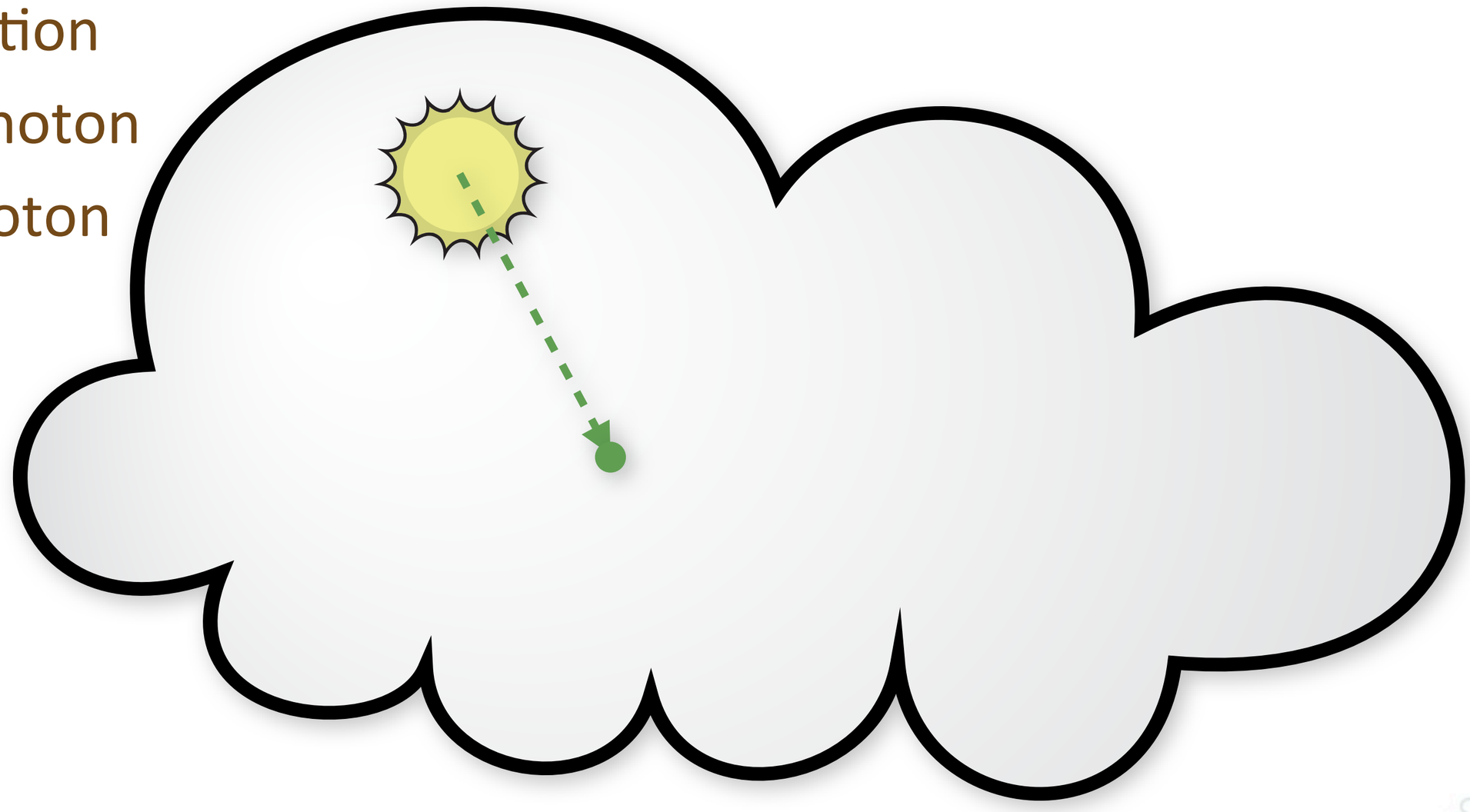

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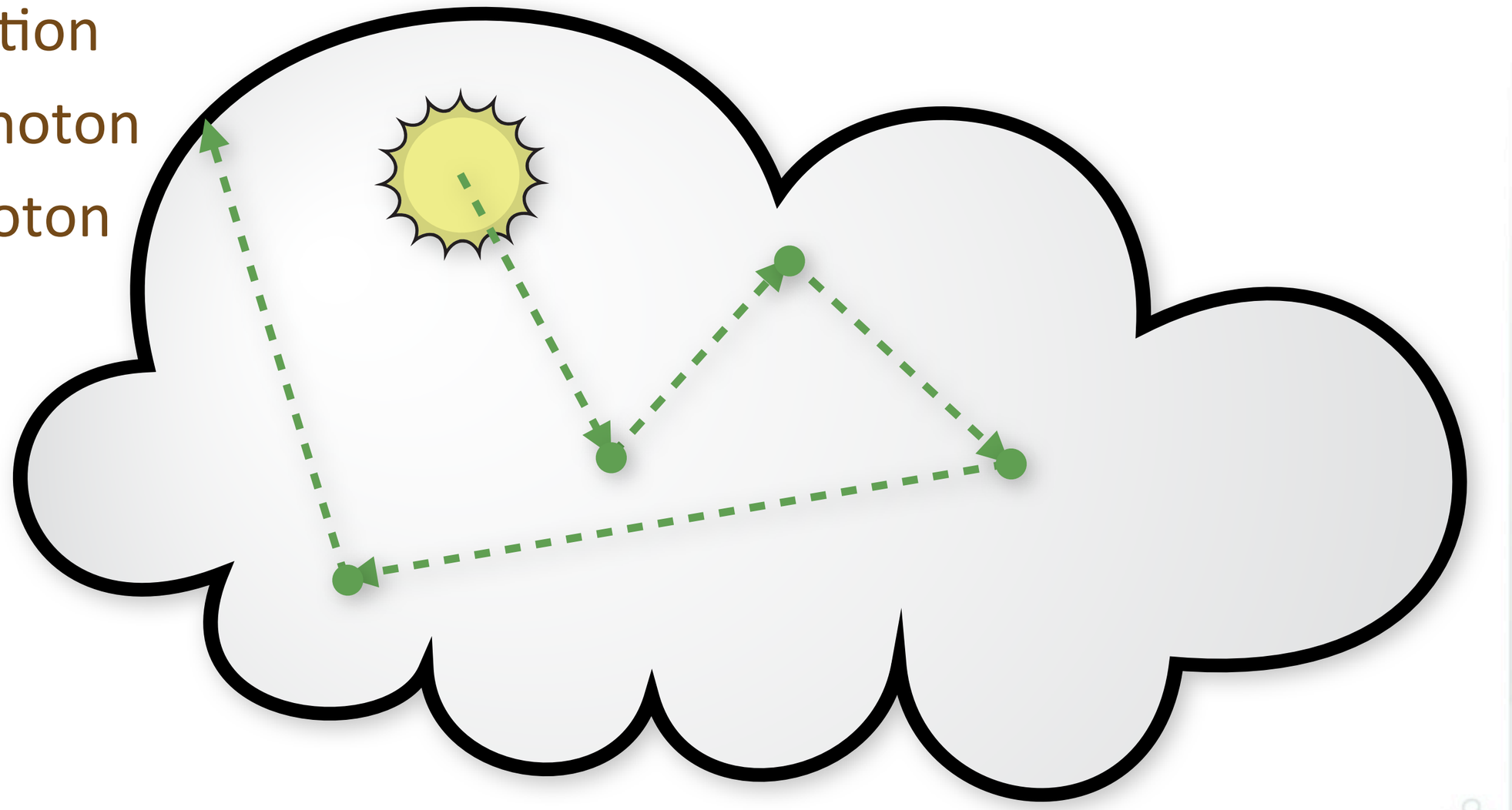

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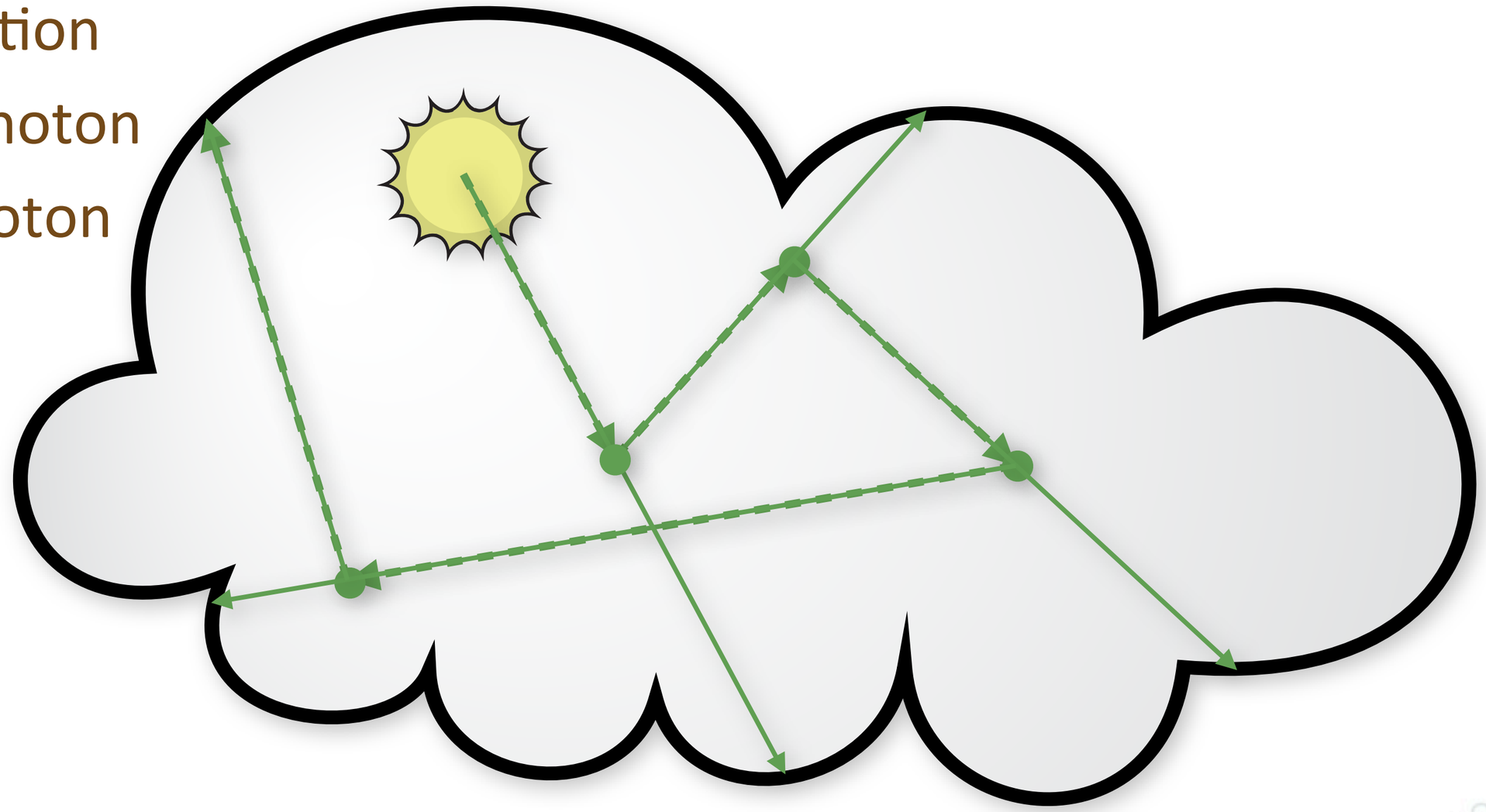

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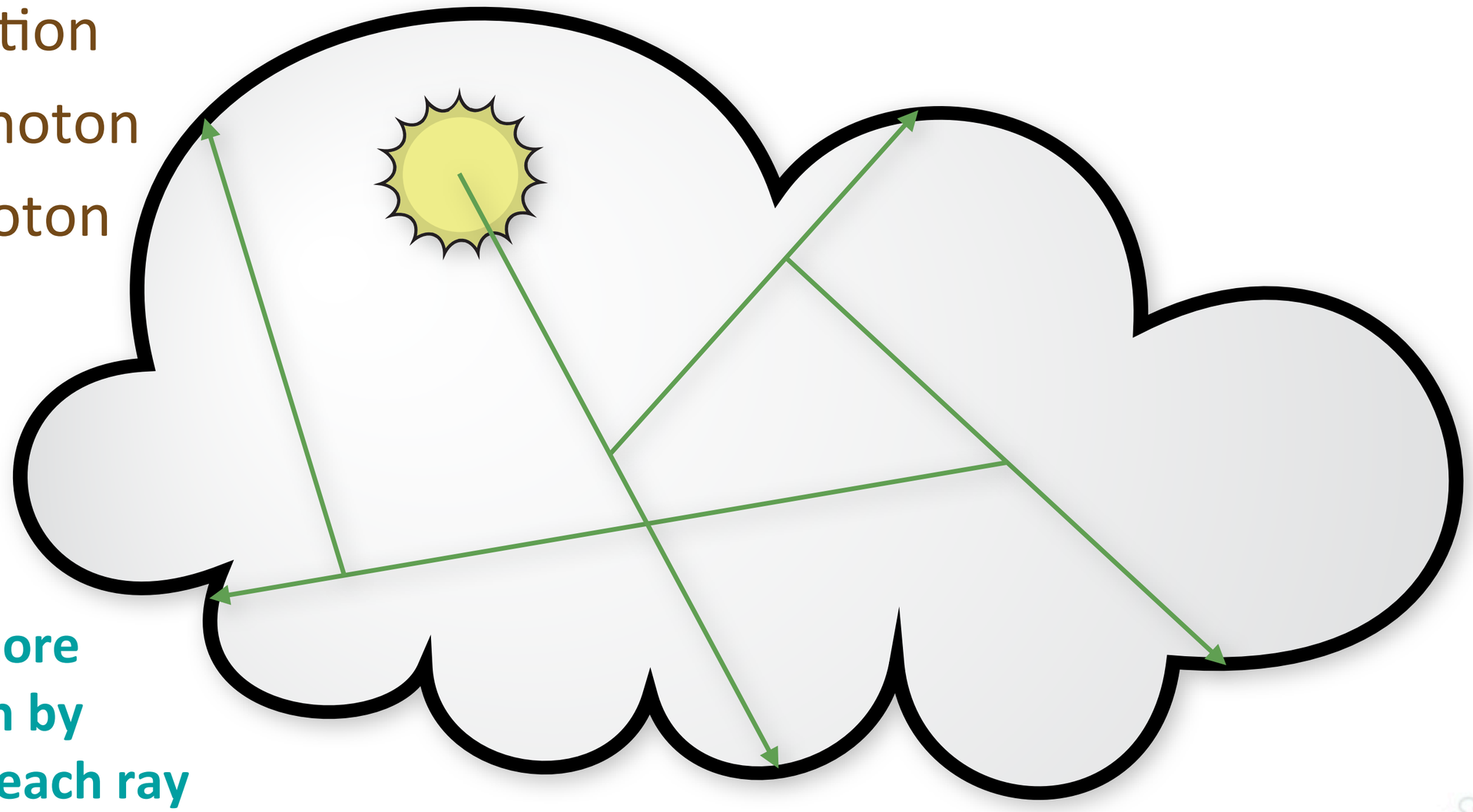
“Photon Marching”

1) choose direction

2) propagate photon

3) deposit a photon

4) repeat



Could deposit more than one photon by marching along each ray

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- We call this process photon marching.
- Since we deposited many photons instead of one, each photon will have less power. This will depend on the marching step size.
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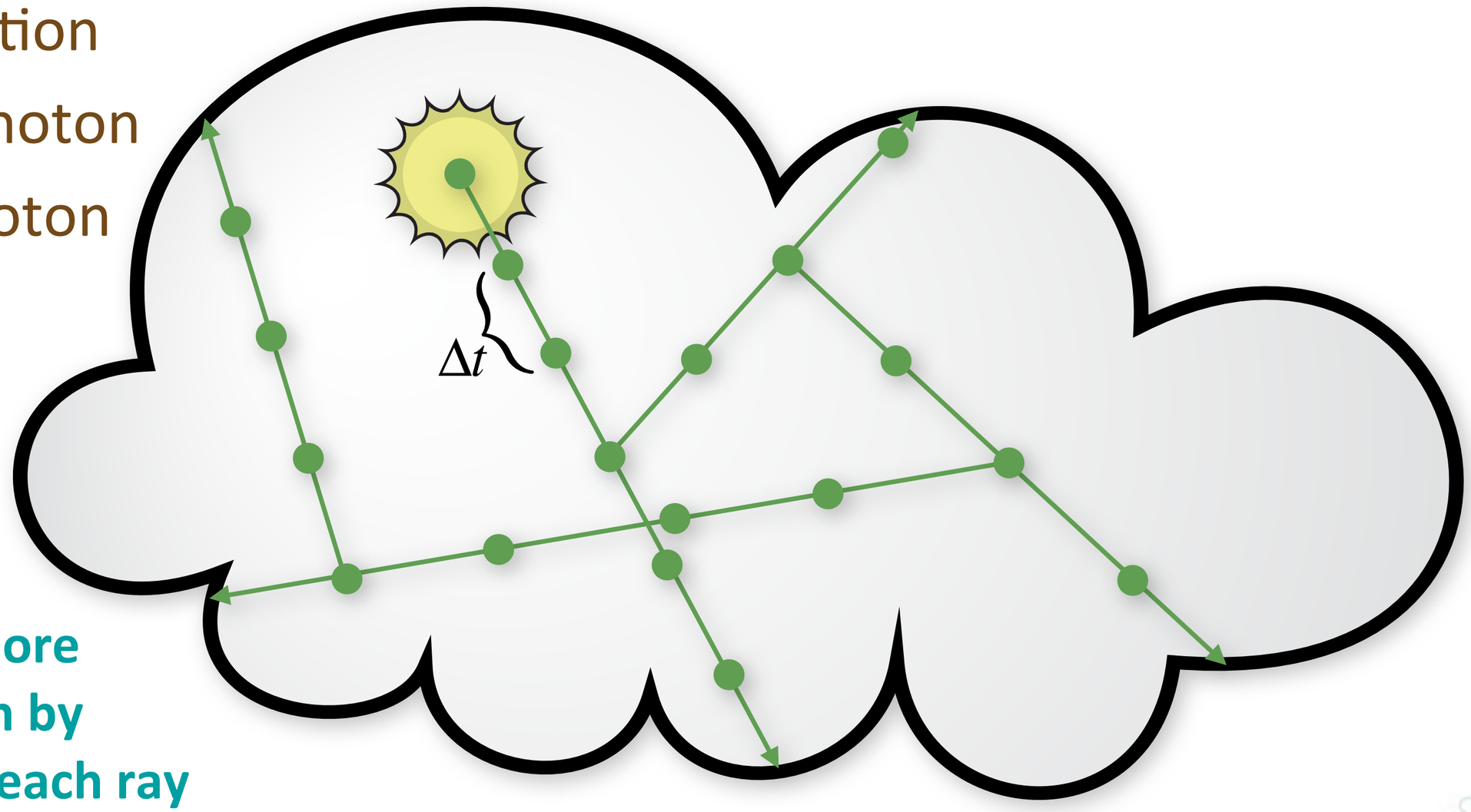

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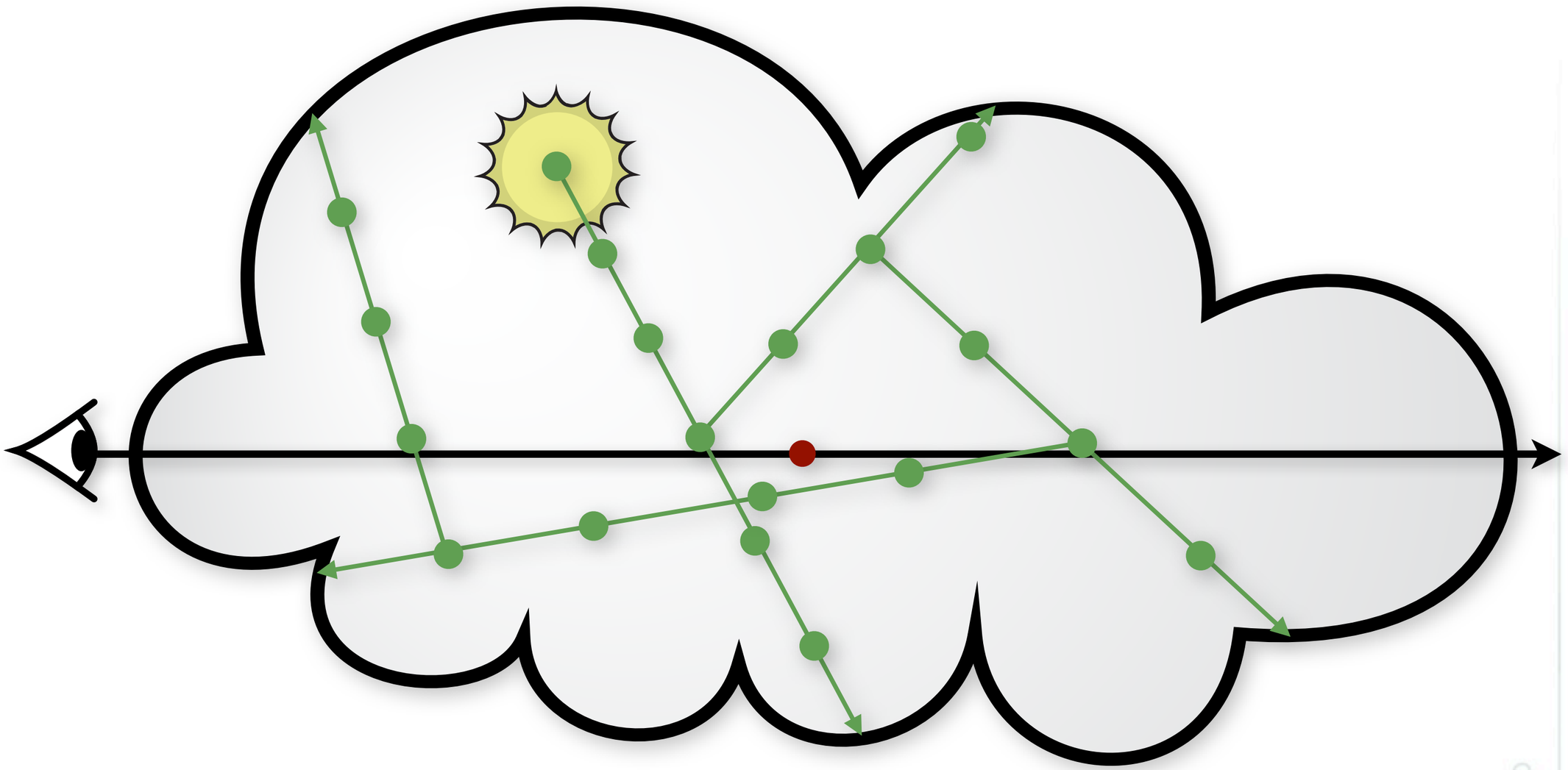
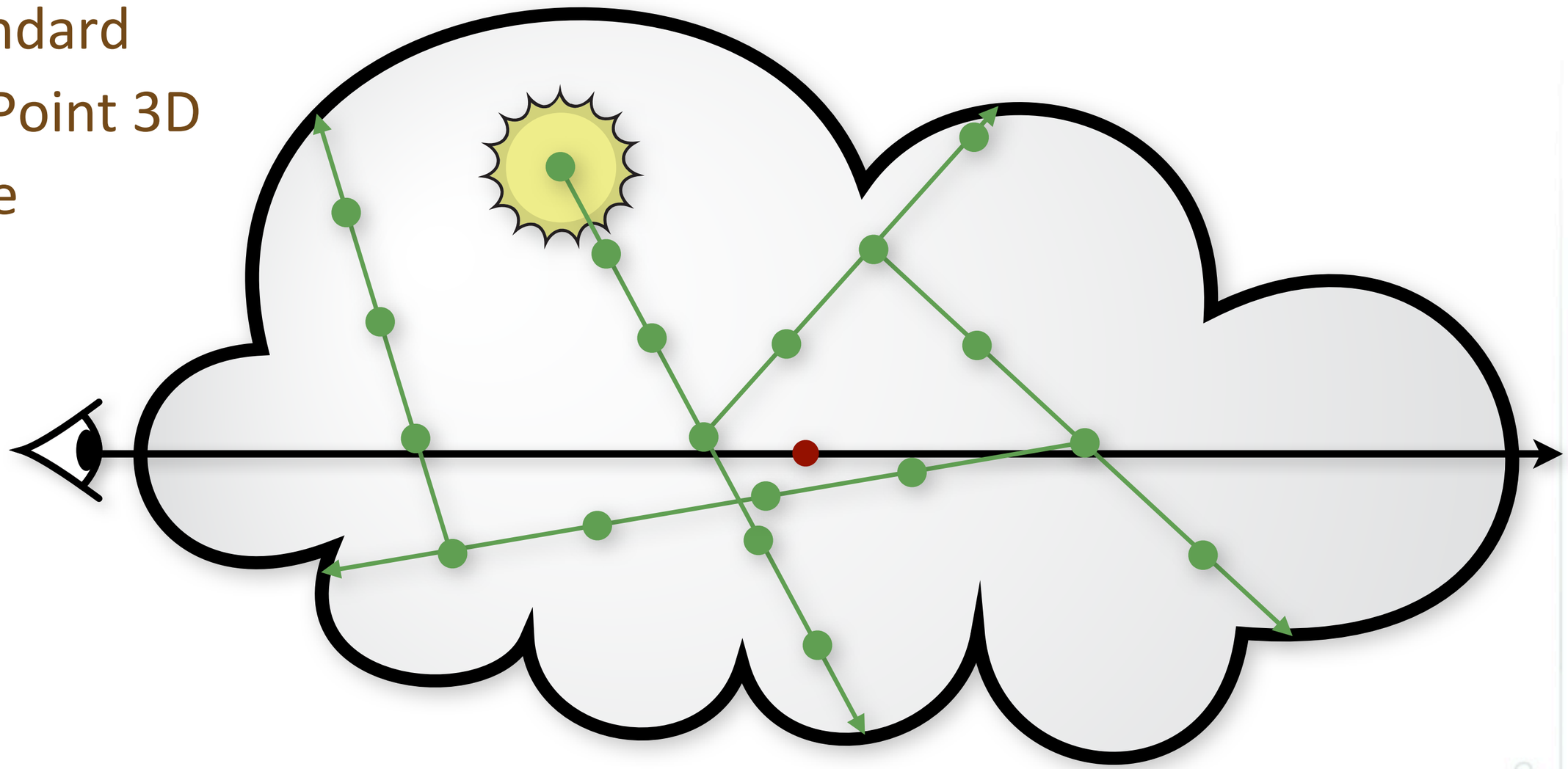


Radiance Estimation using “Discrete Photon Beams”

- Lets say we are interested in computing the inscattered radiance at this red point.
- Since we have a collection of photon points, we can accomplish this by simply using the standard Point Point 3D estimator
- We expand a search radius, and count all the photons that overlap the search region
- In order to derive the concept of photon beams, we consider what would happen as we decrease the photon marching step size. This will increase the number of photon points

Radiance Estimation using “Discrete Photon Beams”

- Use standard Point x Point 3D estimate



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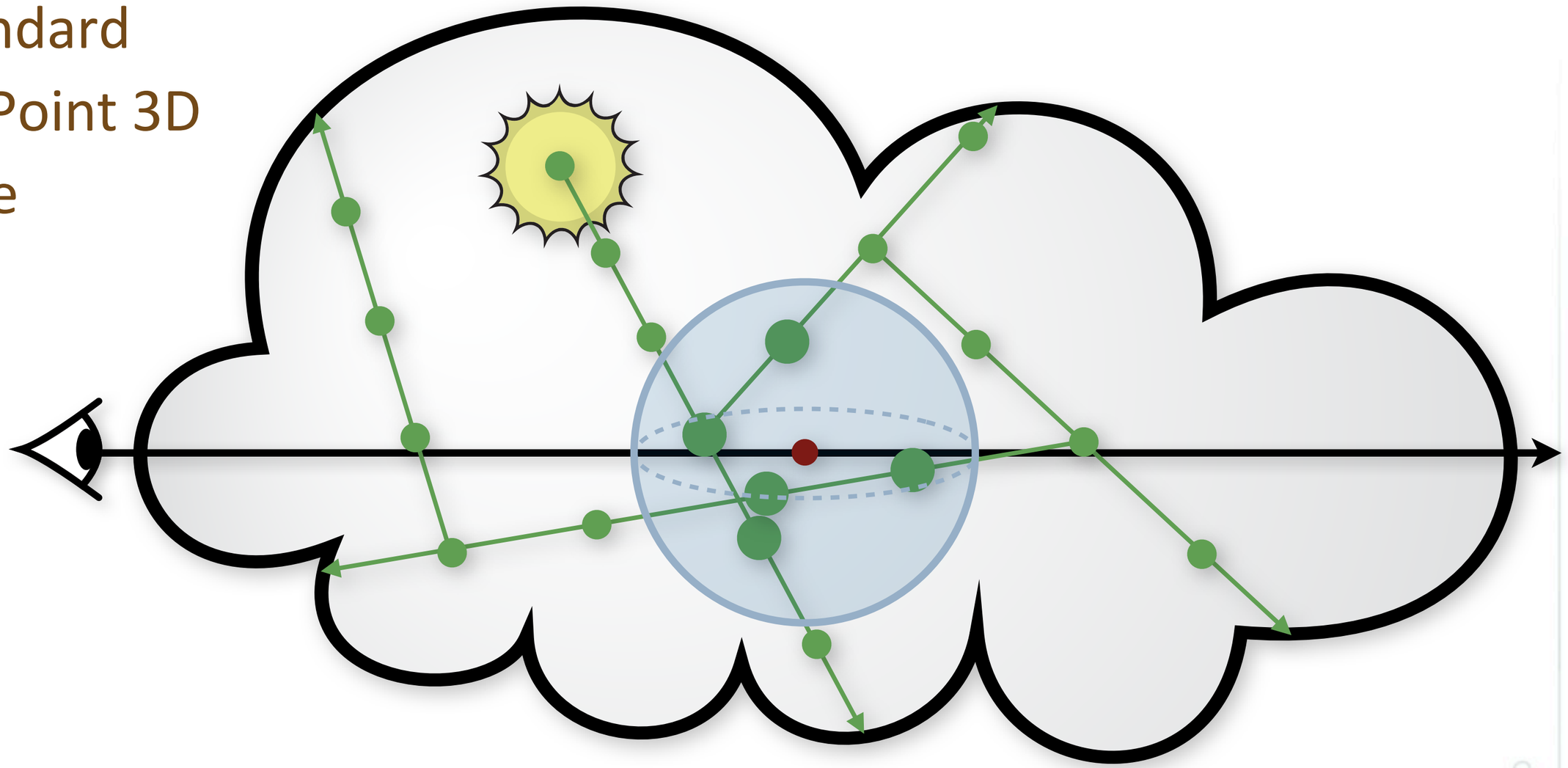

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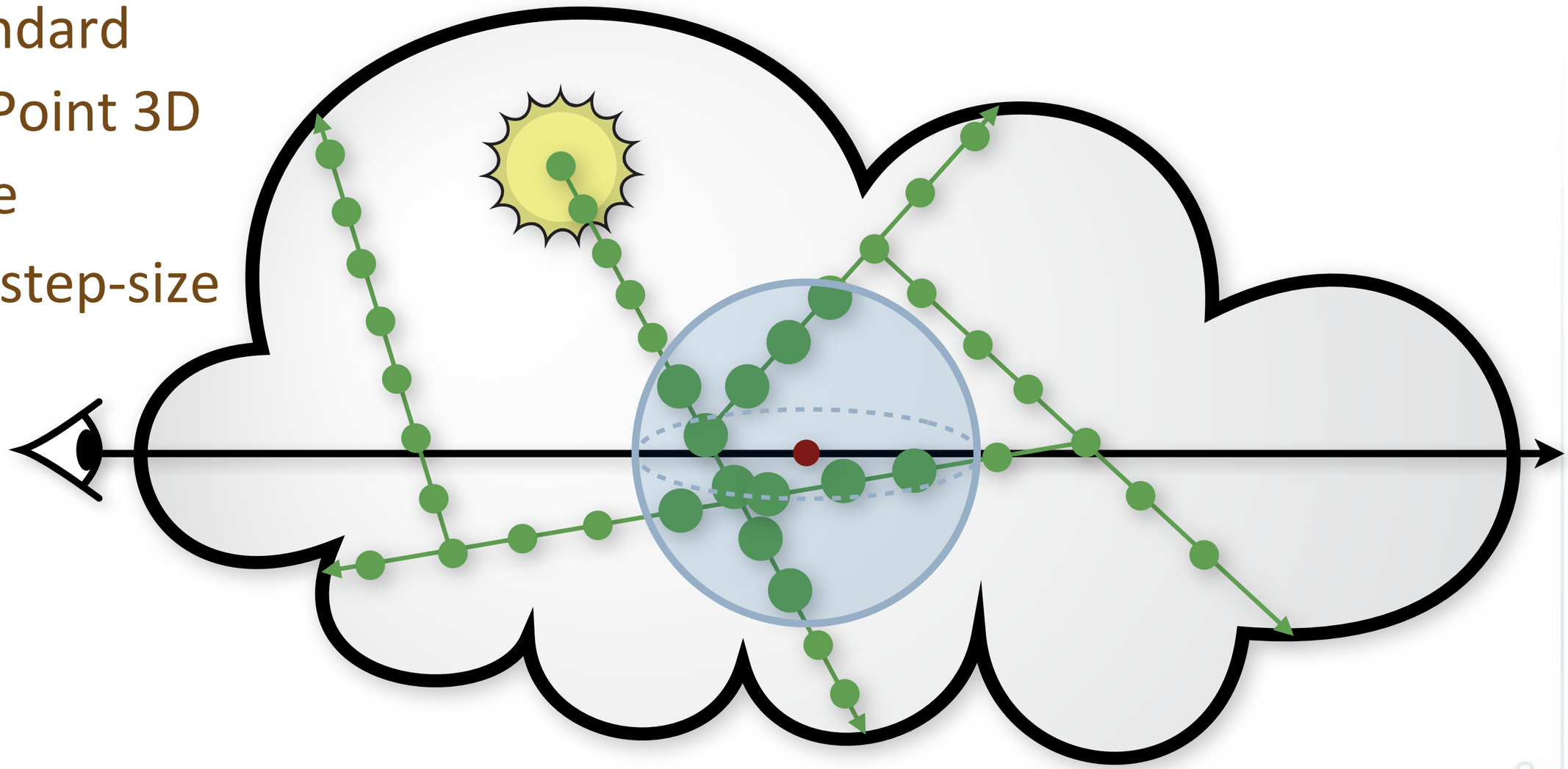

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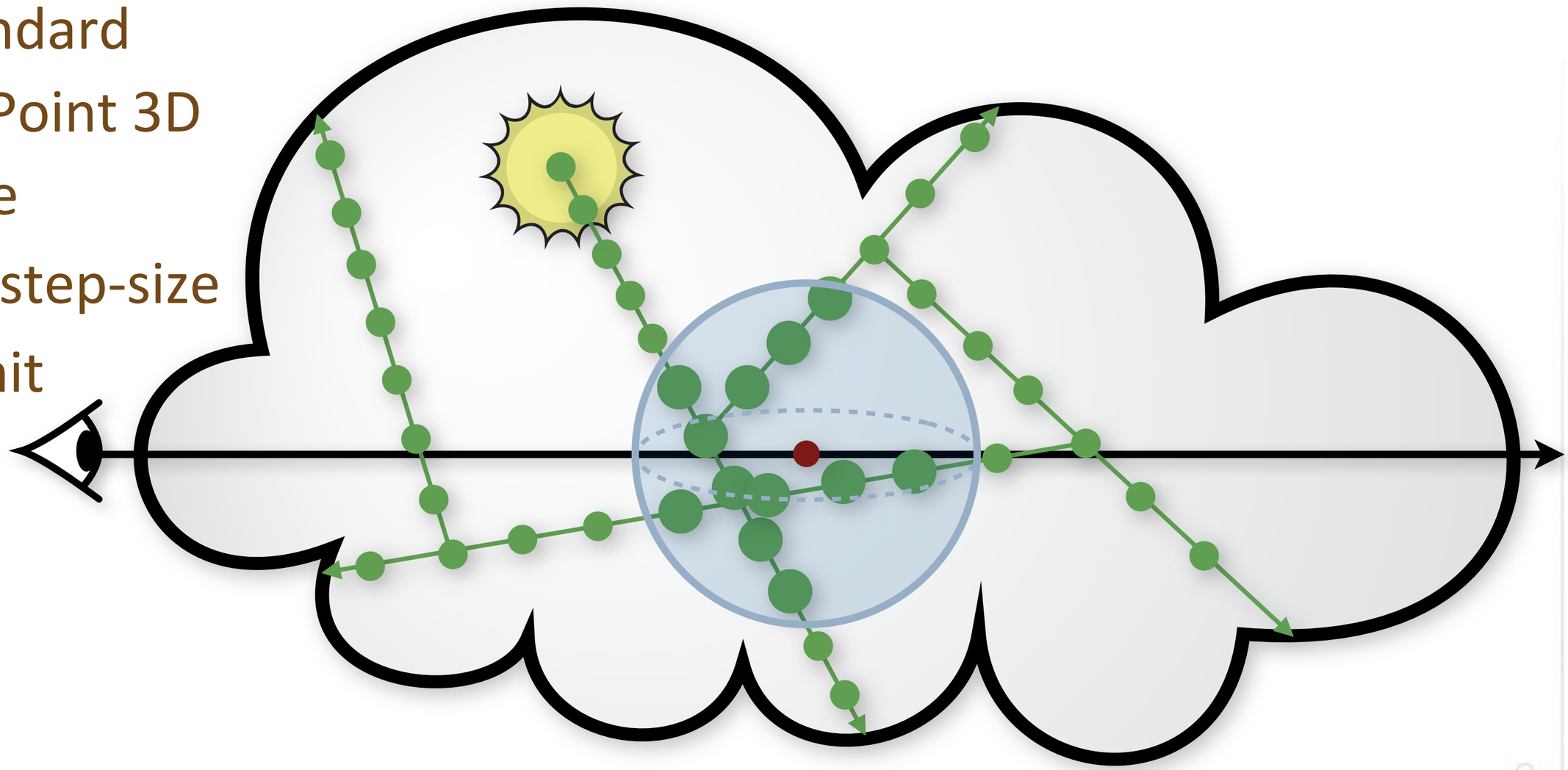
- Reduce step-size
- Take limit



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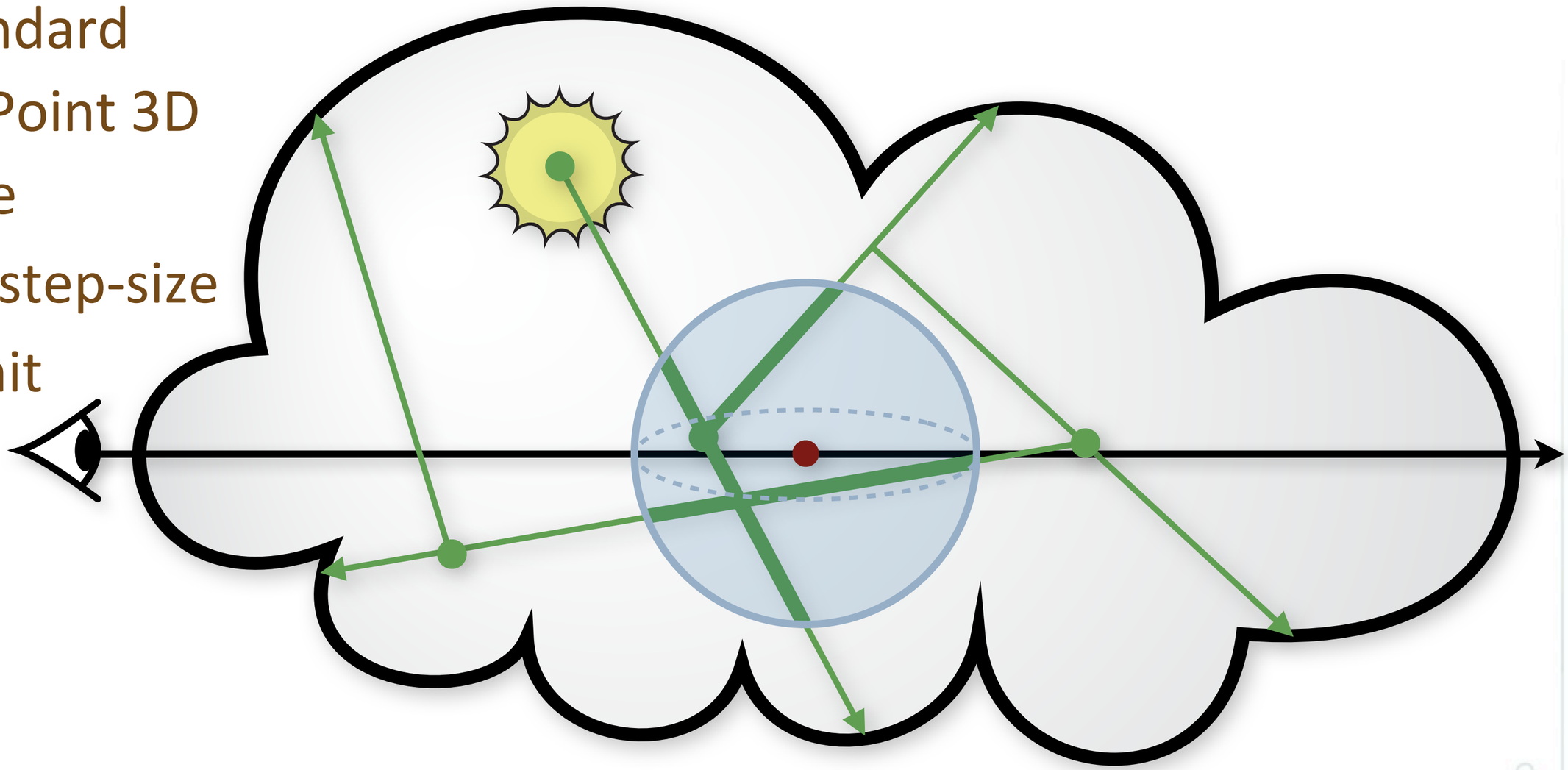
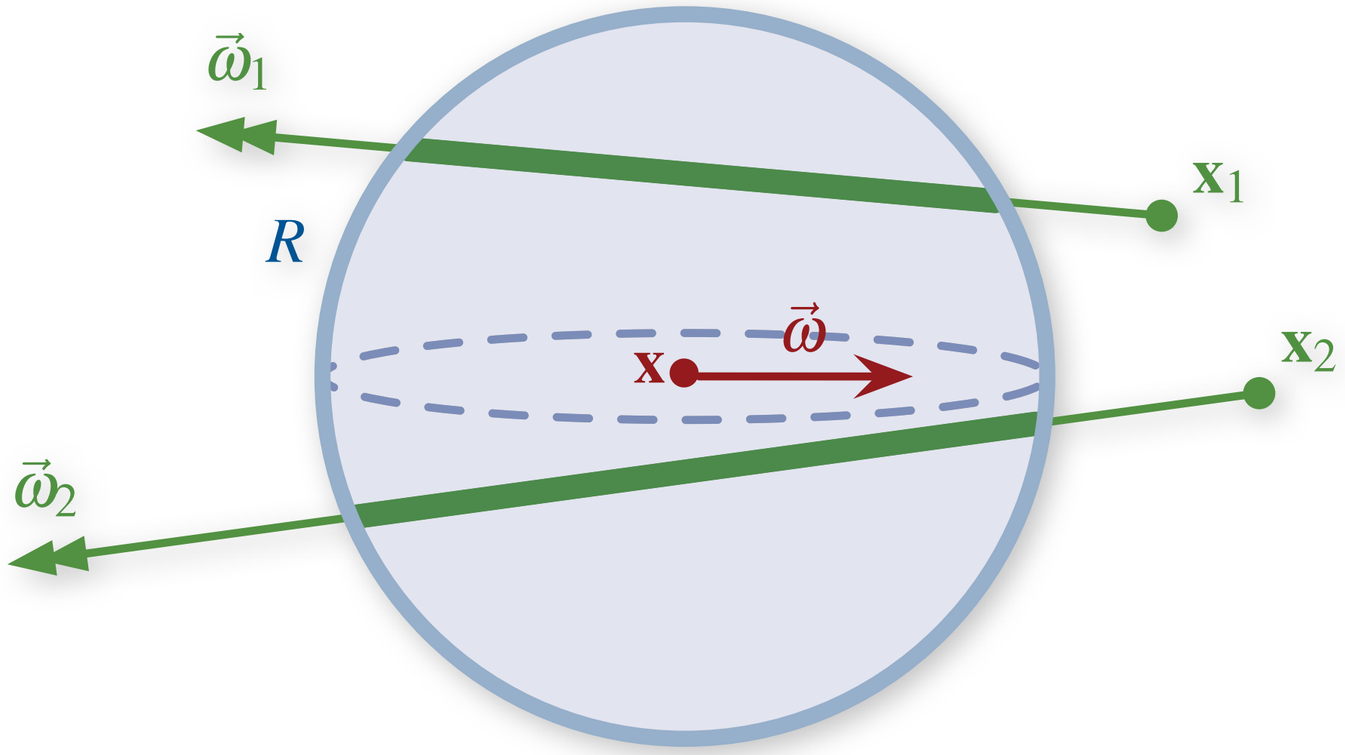


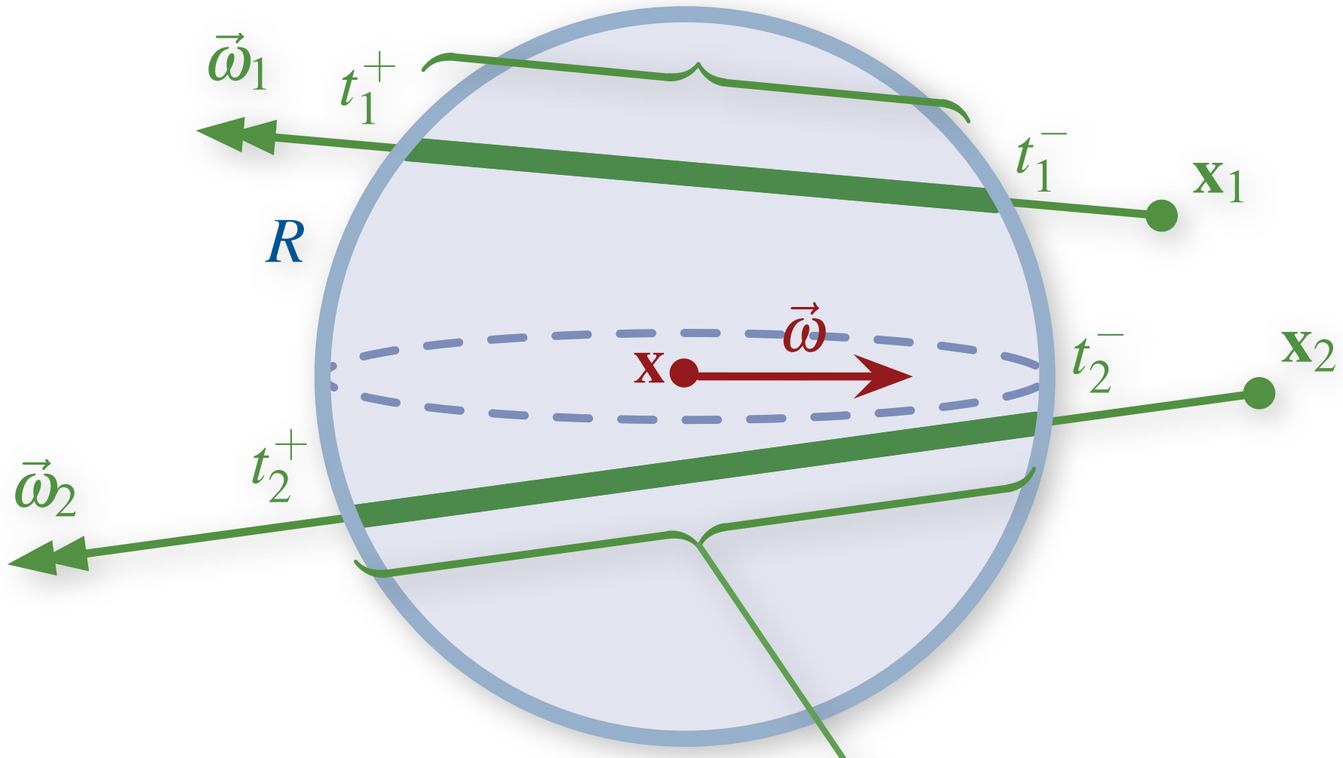
Point Query x Beam Data (3D blur)



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

- integral computable analytically

Point Query x Beam Data (3D blur)

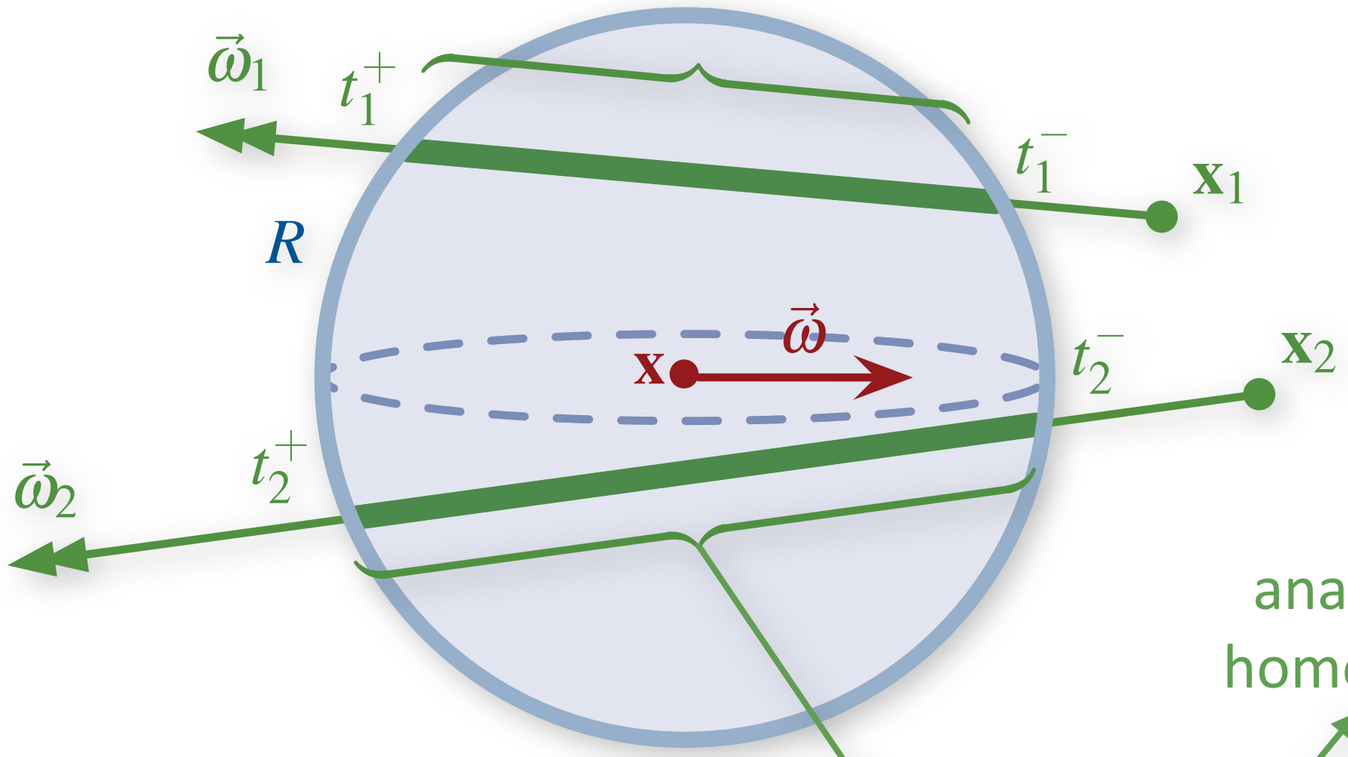


$$L \approx \frac{1}{\mu_R(r^3)} \sum_i f(\theta_i) \boxed{\Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_t t} dt}$$

Friday, 7 September 12

- integral computable analytically

Point Query x Beam Data (3D blur)



analytic solution in homogeneous media

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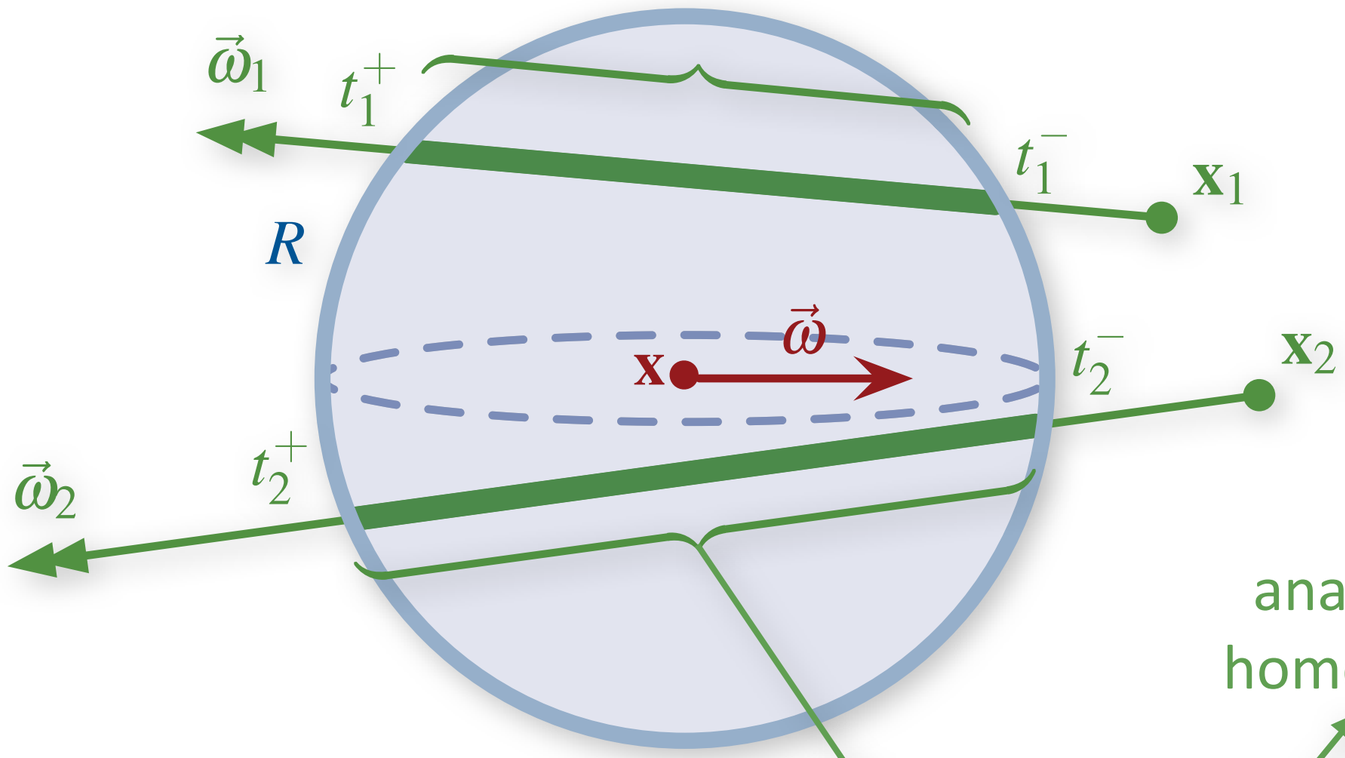

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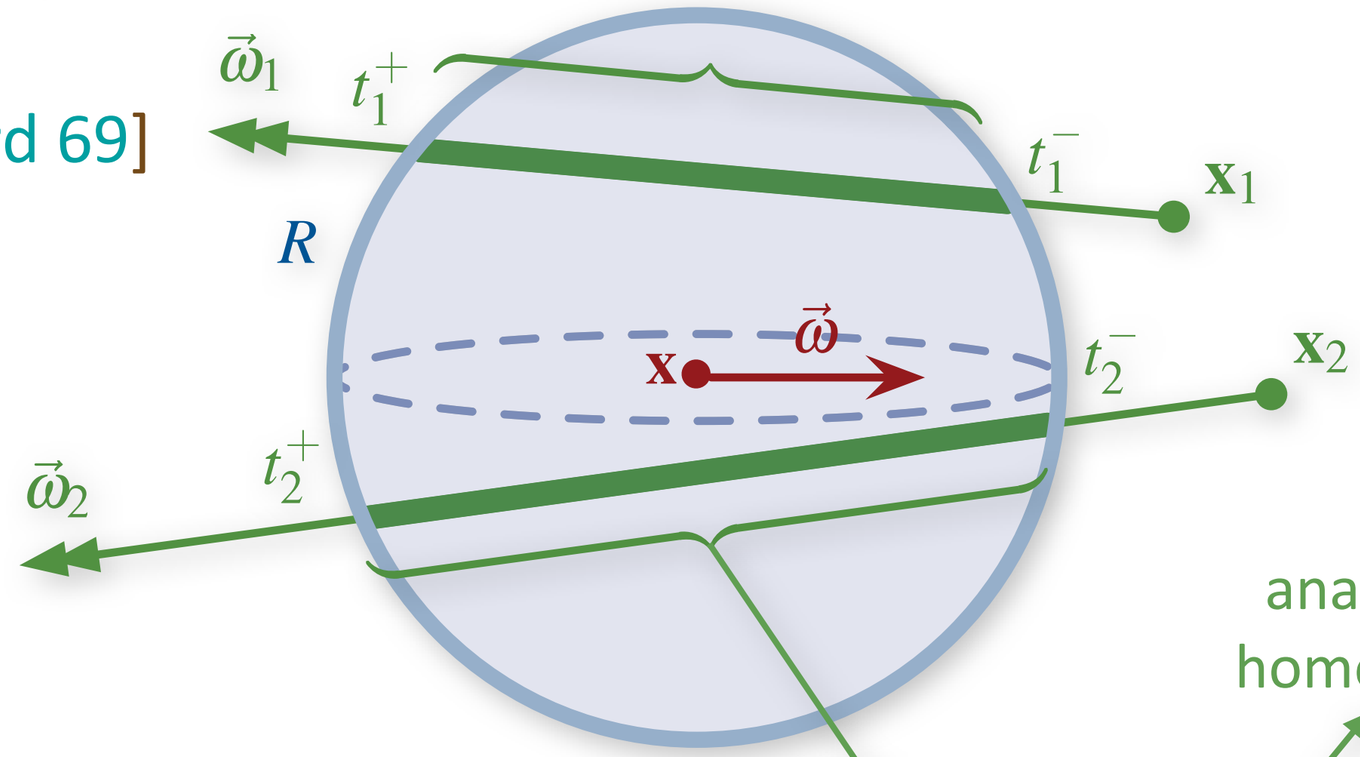
Point Query x Beam Data (3D blur)

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



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Radiometric Duality

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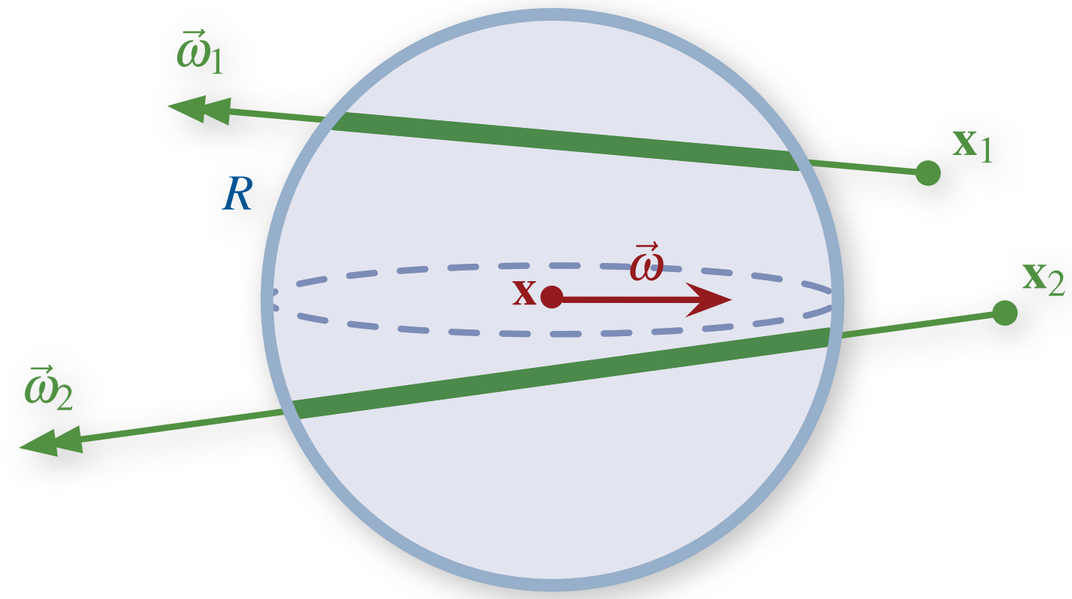

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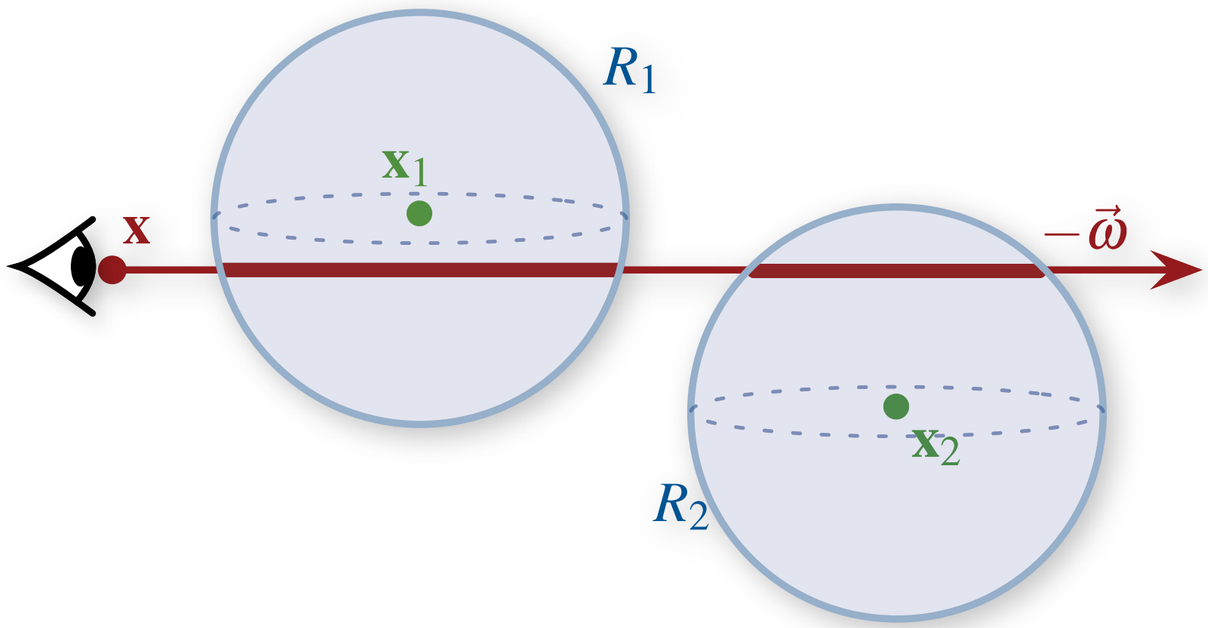

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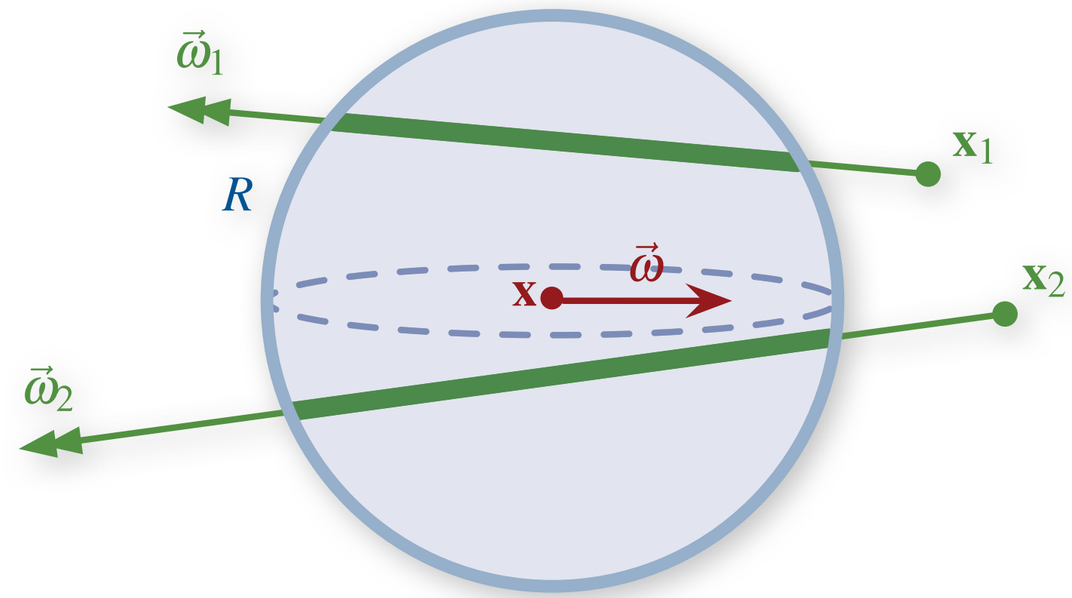

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Reducing Blur Dimensionality

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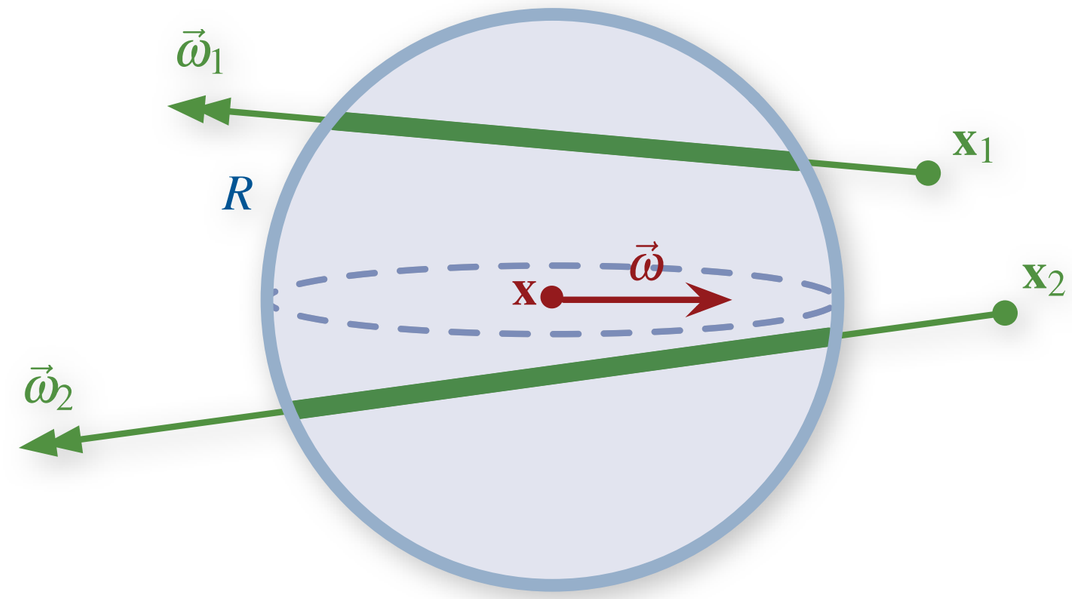

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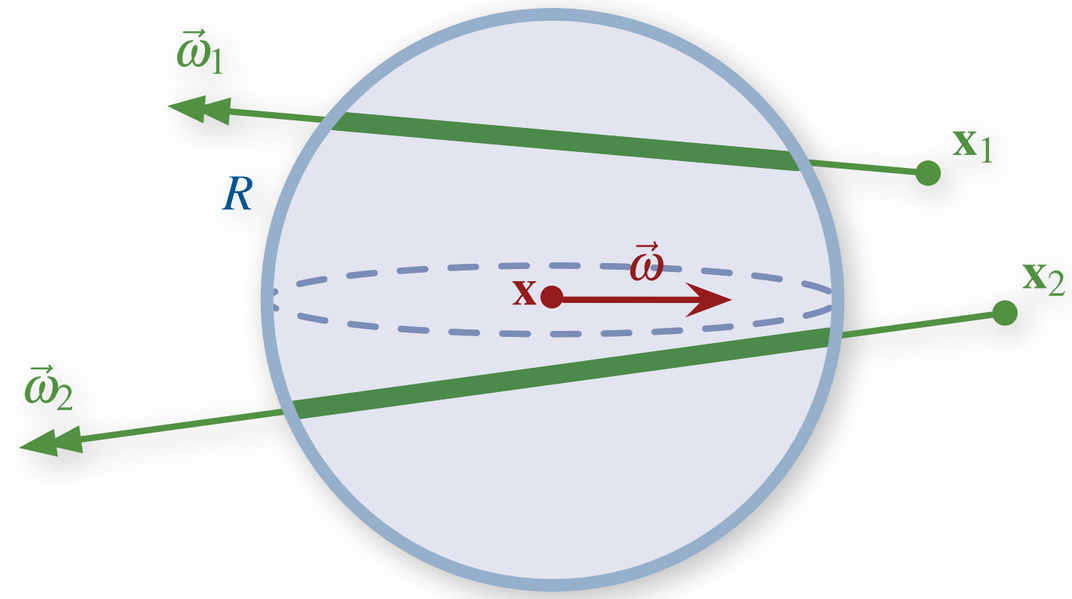

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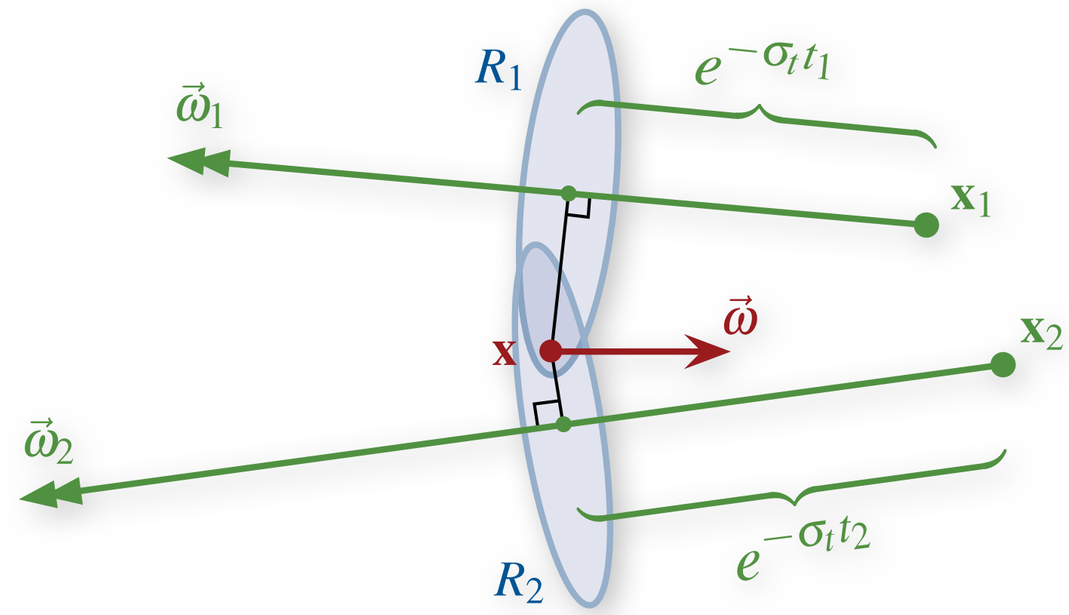
Reducing Blur Dimensionality

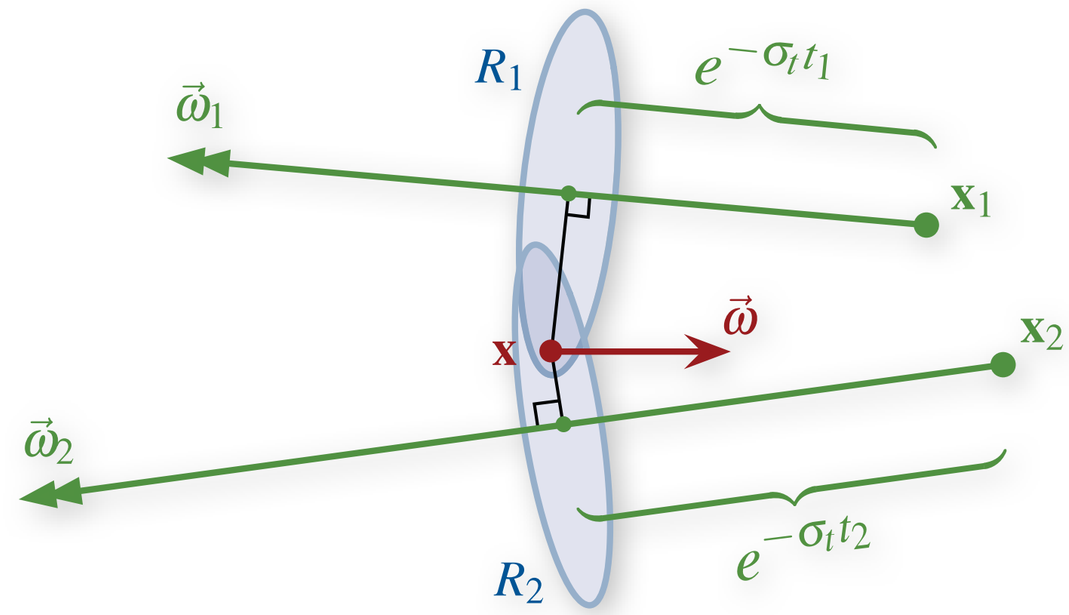
Point Query x Beam Data (2D blur)



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

Reducing Blur Dimensionality

Point Query x Beam Data (2D blur)



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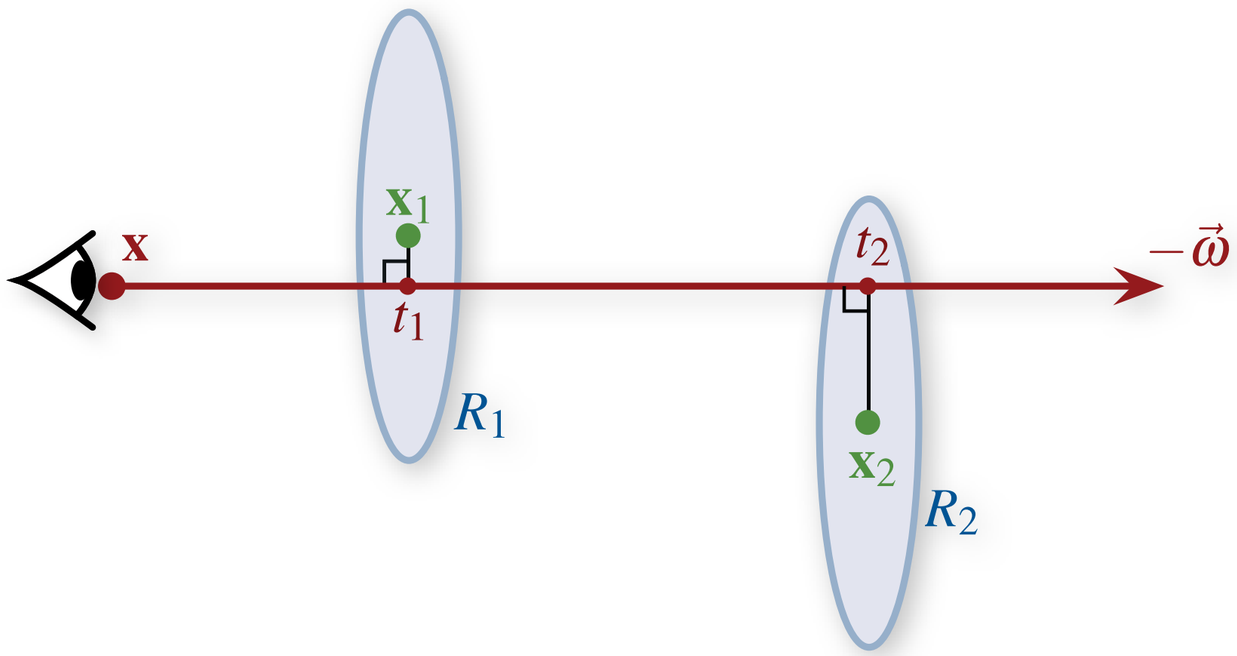
generalization of photon ray splatting [Herzog et al. 07]

Radiometric Duality

Beam Query x Point Data (2D blur)



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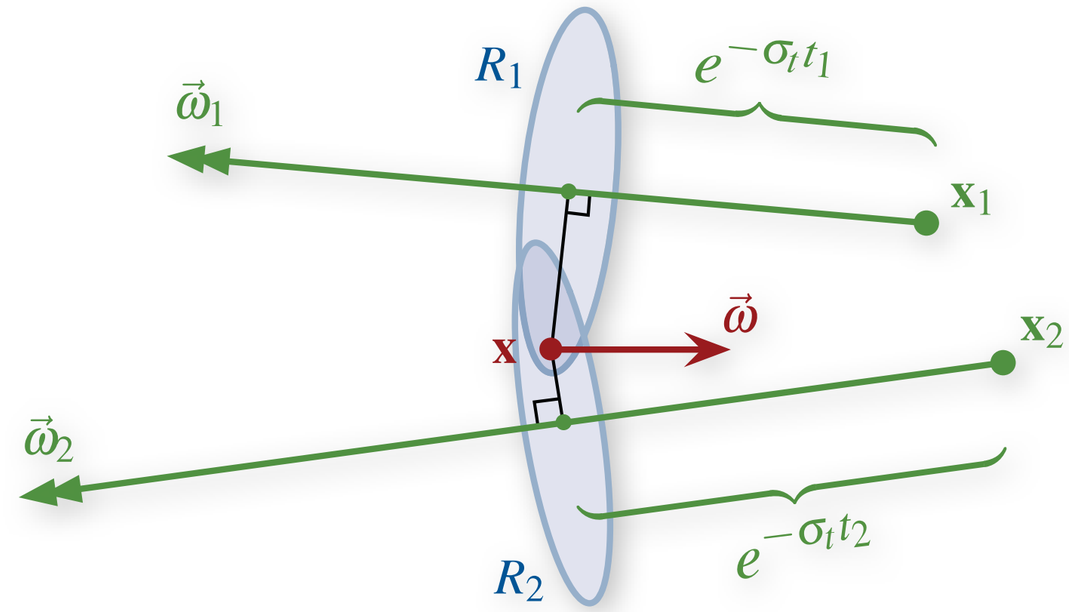
[Jarosz et al. 08]

Point Query x Beam Data (2D blur)



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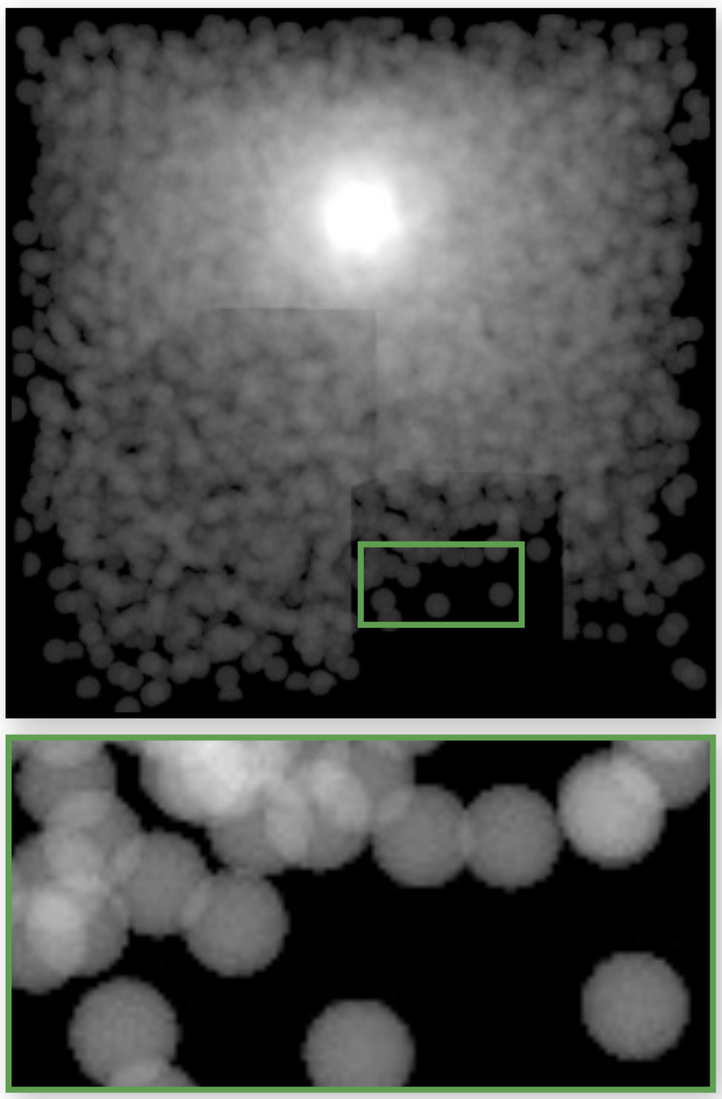
generalization of photon ray splatting [Herzog et al. 07]

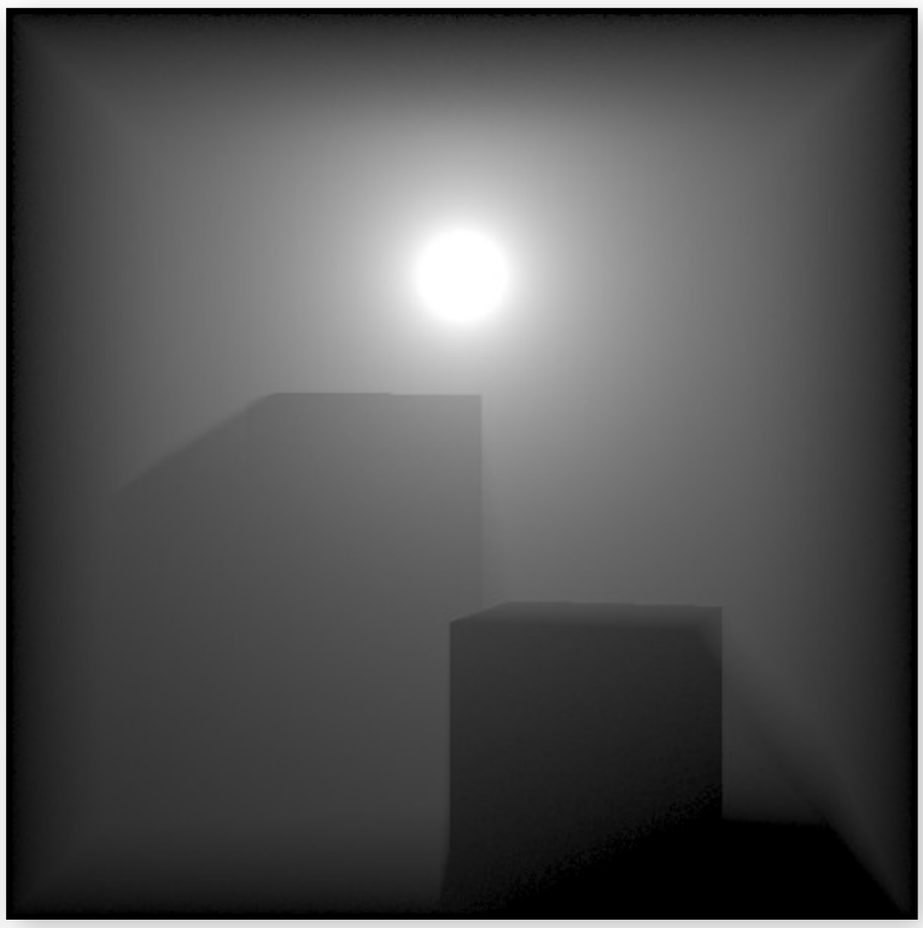
Photon Points vs. Photon Beams

Ground Truth

- Simple scene with a point light
- With 100k photons points the type of artifacts you get look something like this
- And using only 5 thousand photon beams, each photon path looks like a thick line on the screen, leading to much higher density and coverage

Photon Points vs. Photon Beams





Friday, 7 September 12

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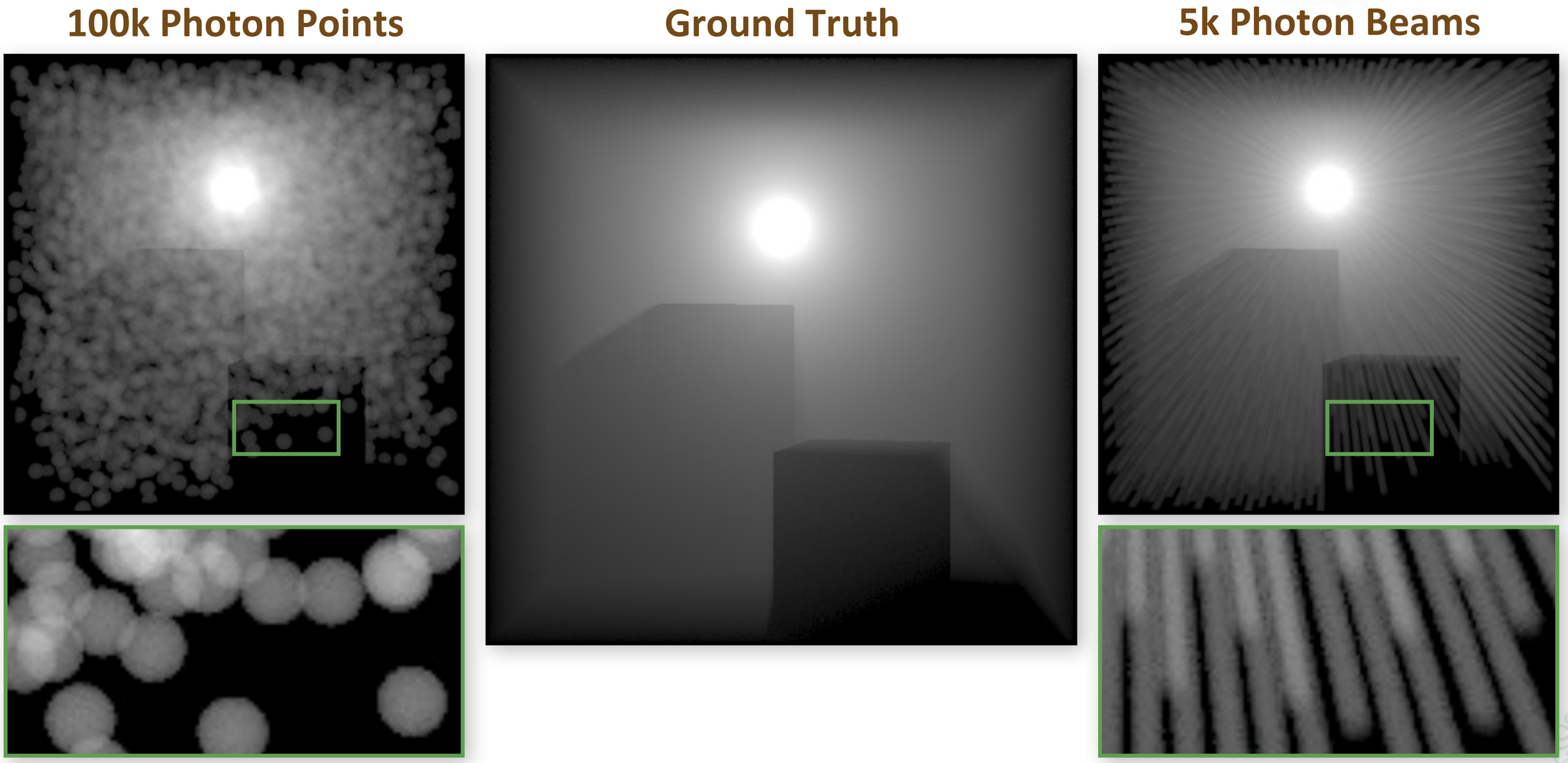

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Estimating Beam Radiance with Photon Beams

- 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 x Beam Data (2D blur)

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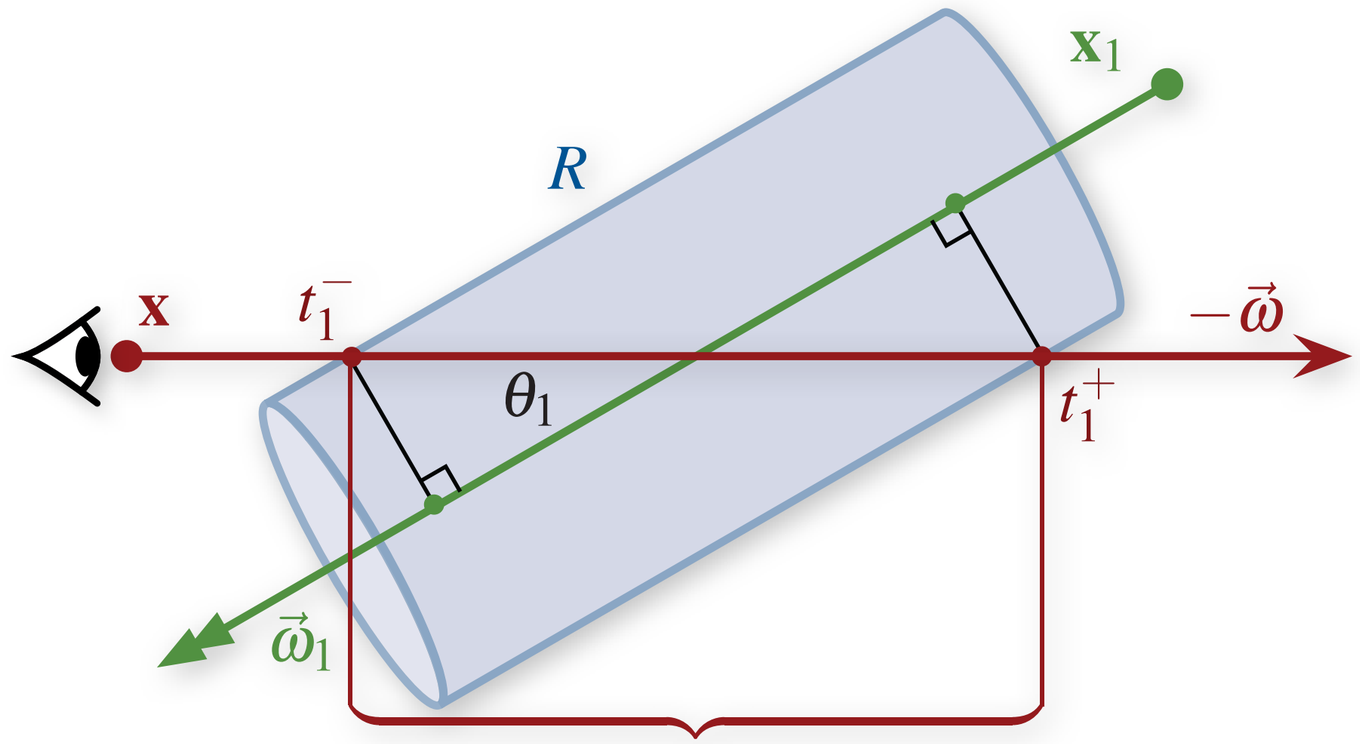
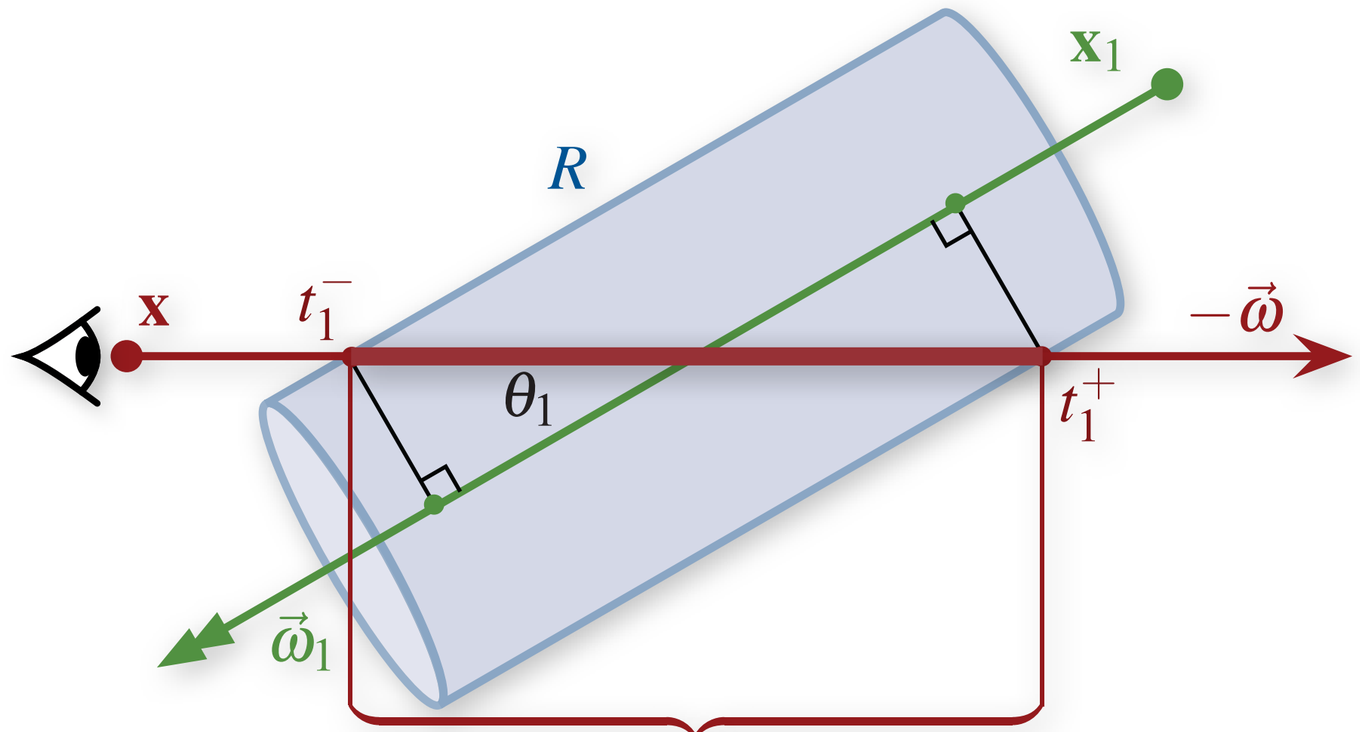


$$L \approx \frac{\sigma_s}{\mu_R(r^2)} \sum_i f(\theta_i)\, \Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_t t_c}\, e^{-\sigma_t t_b}\, dt_c$$

Beam Query x Beam Data (2D blur)



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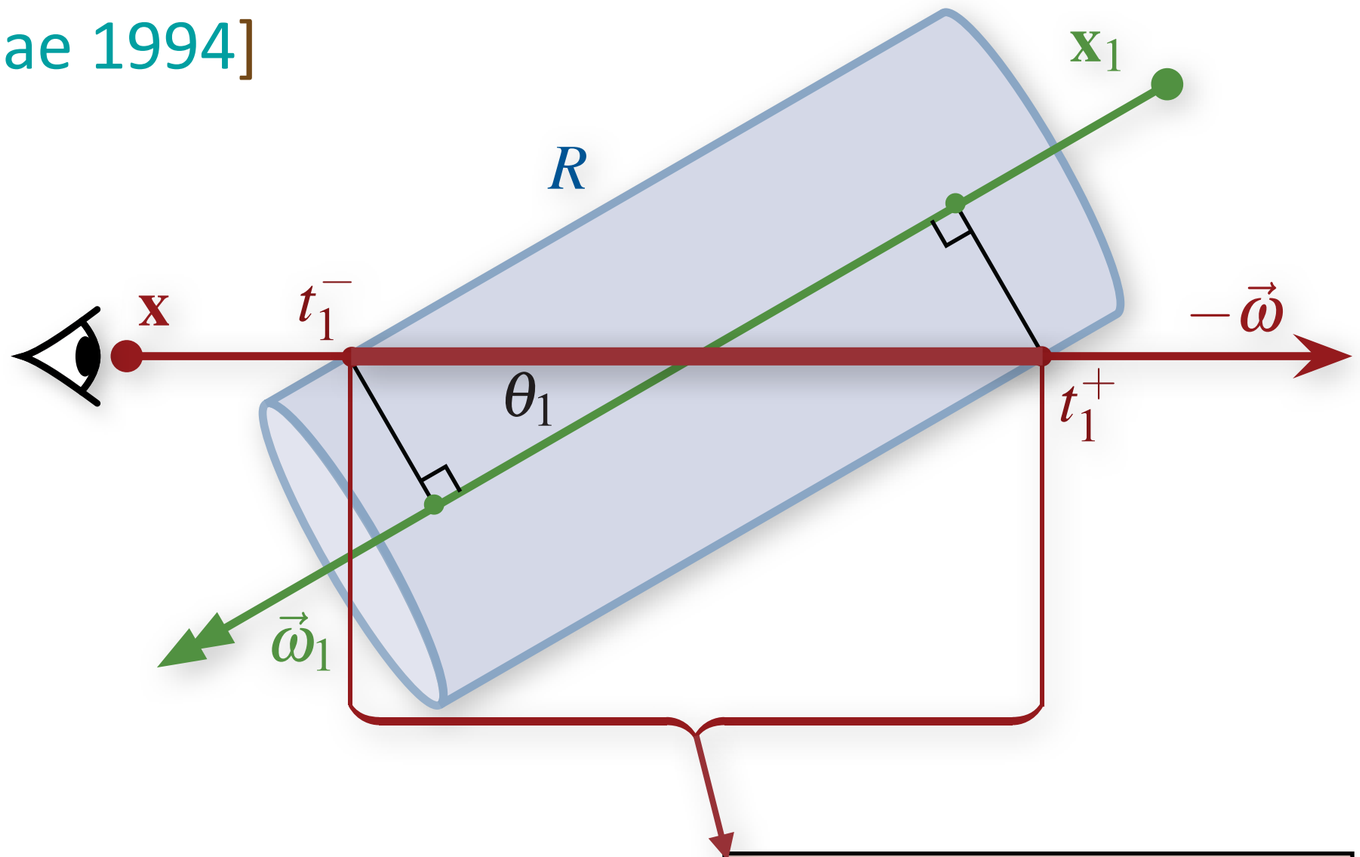
Beam Query x Beam Data (2D blur)

related to beam tracing
[Nishita and Nakamae 1994]



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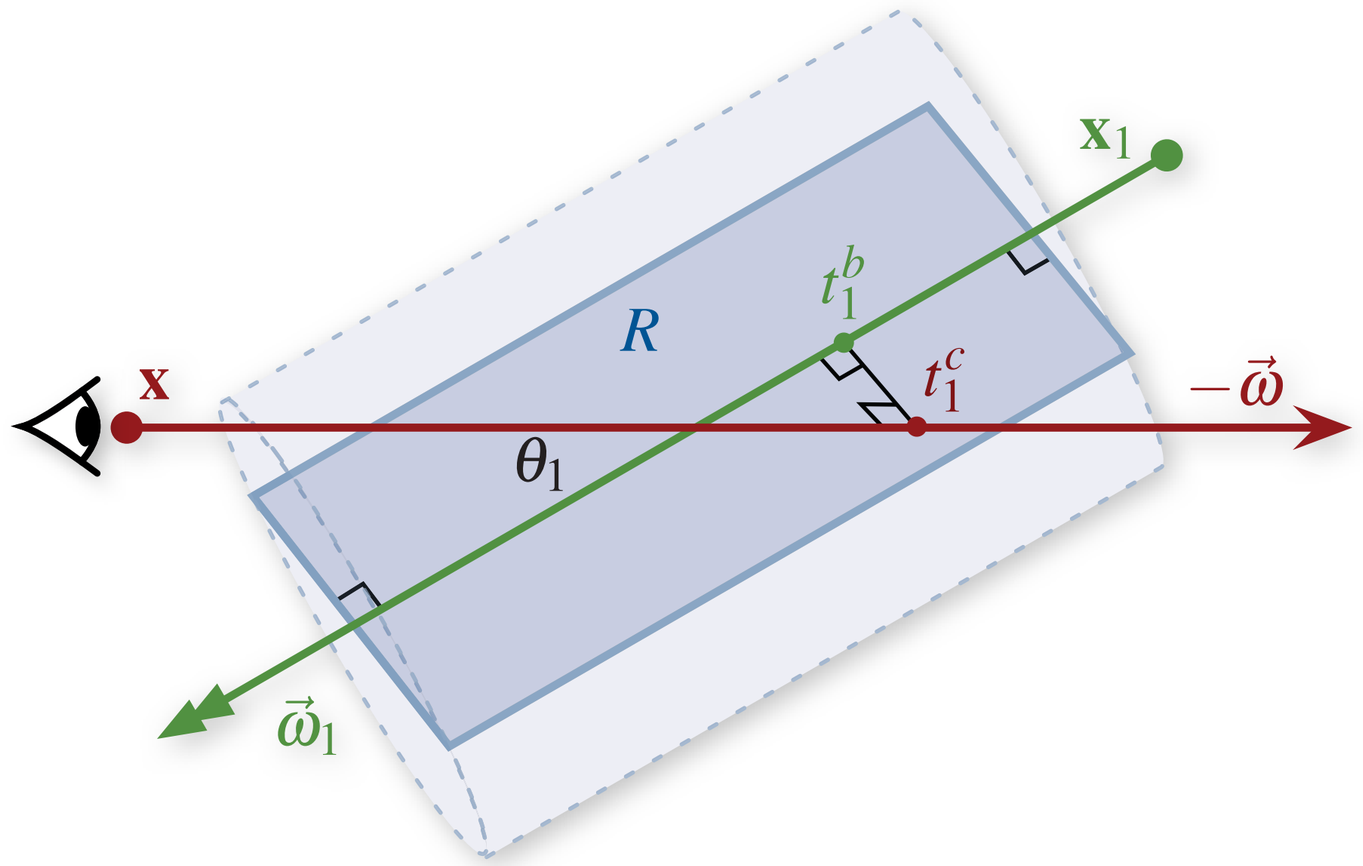
Beam Query x Beam Data (1D blur)



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

Radiance Estimator Summary

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- **use: Beam Query x Beam Data (1D)**

Implementation Details

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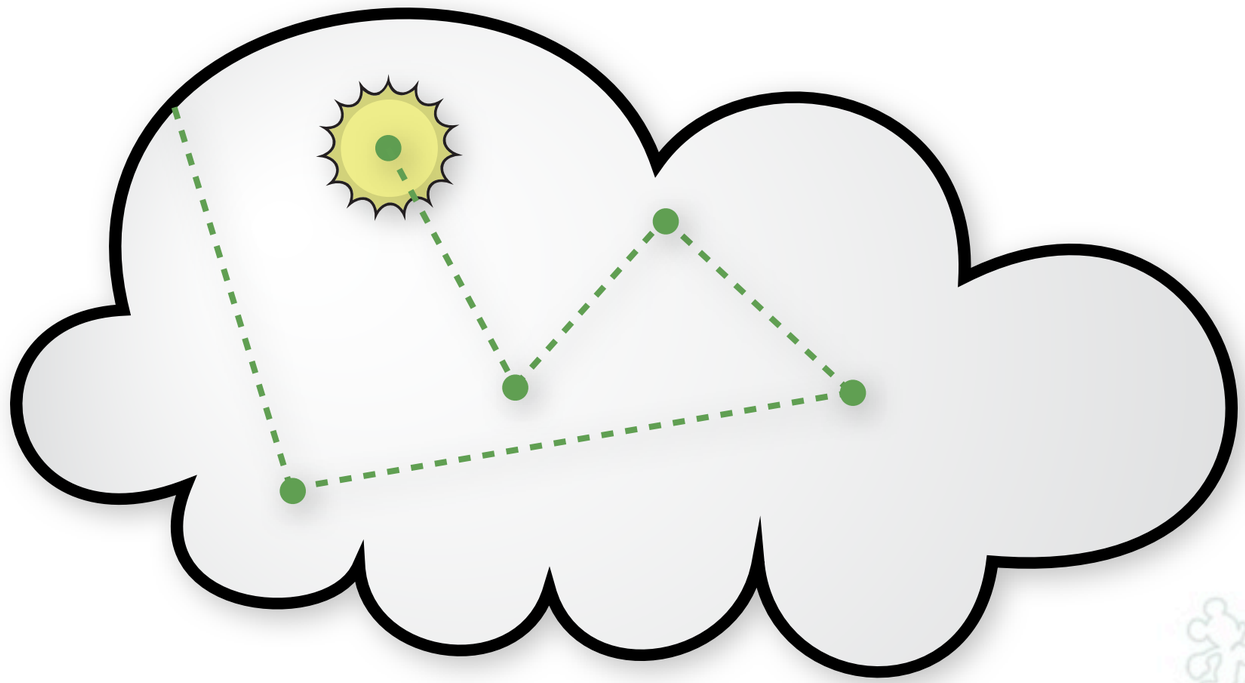
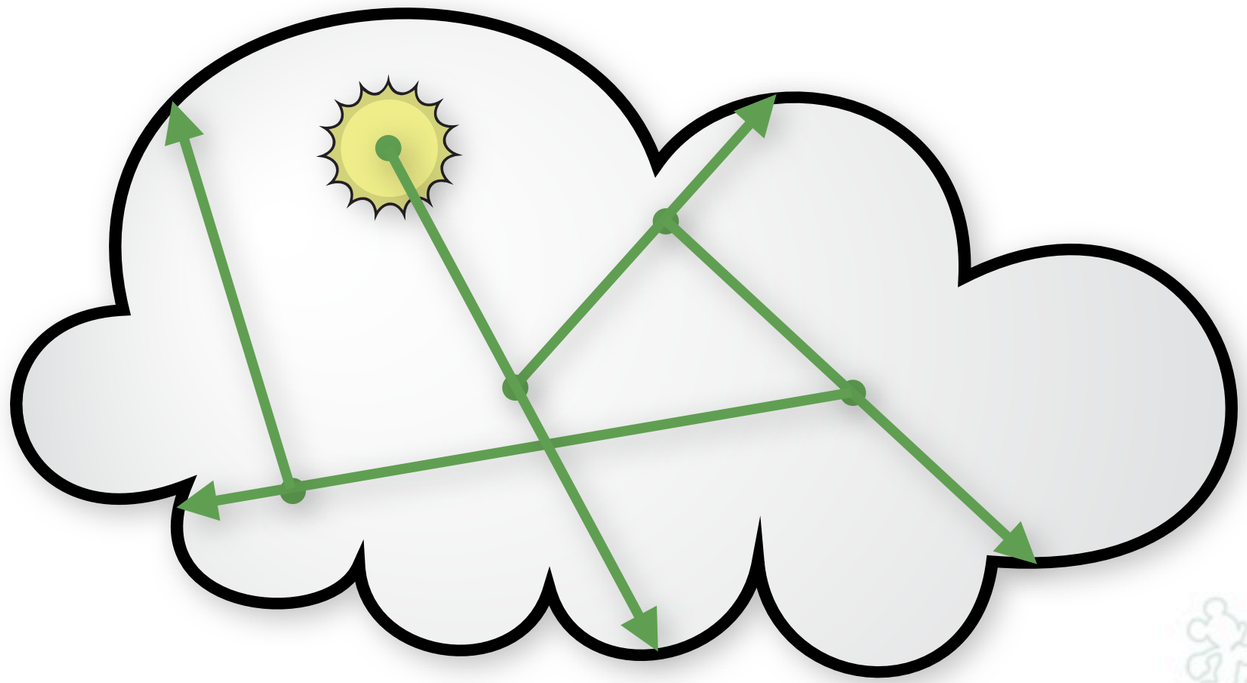
- Standard photon shooting/tracing
- Store:
  - start power/position/direction (standard)



Implementation Details

- Standard photon shooting/tracing
- Store:
  - start power/position/direction (standard)
  - also:
    - length of beam
    - some book keeping



Rendering

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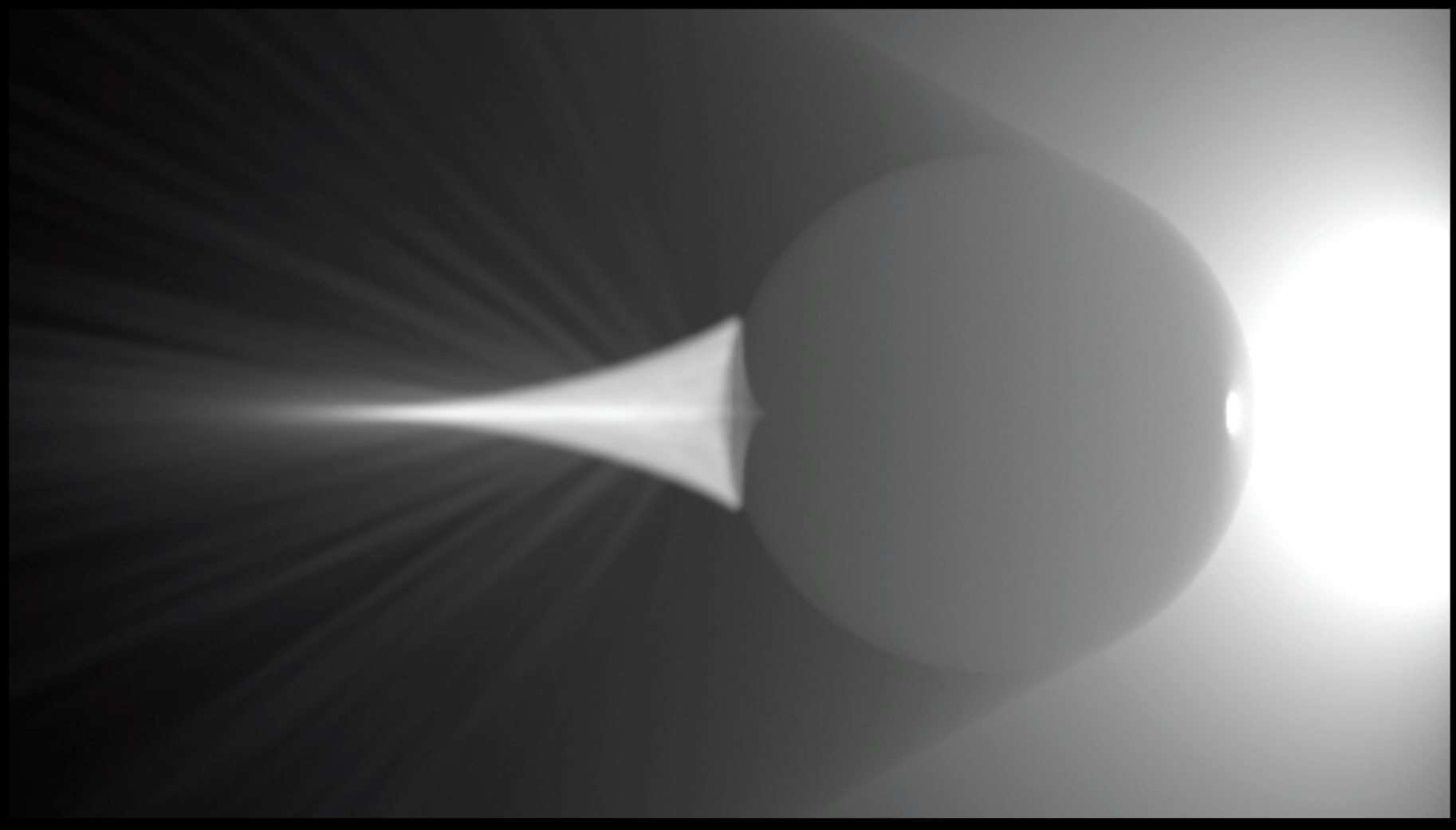
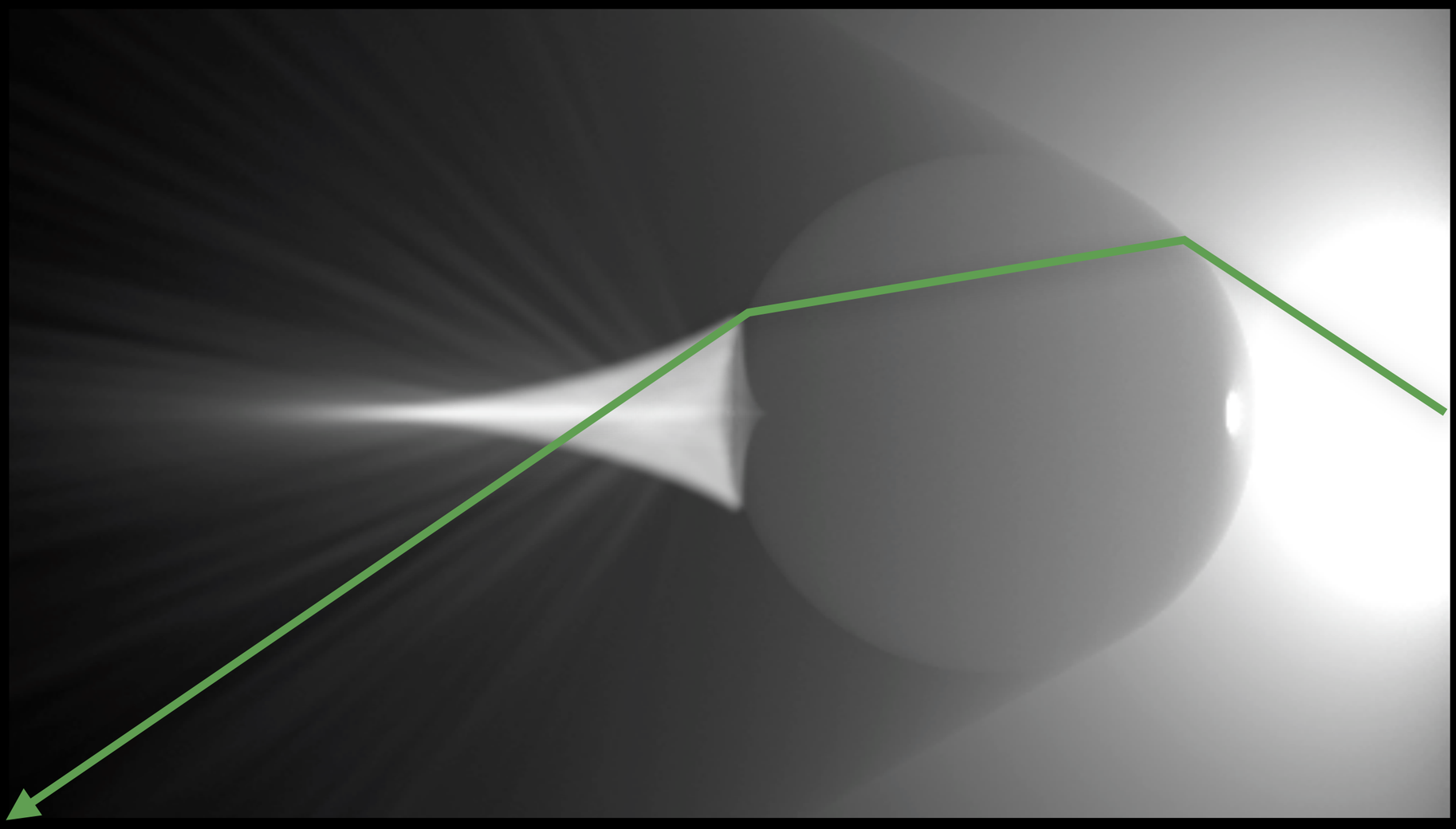
- Place photon beams in a BVH
  - split into sub-beams to reduce spatial overlap



- So with this algorithm, you could very easily produce images like this volume caustic
- We [click] shoot a photon path through the scene, and by [click] applying a fixed-width blur, each beam gets rendered as a cylindrical billboard
- However, you can see that there are some banding artifacts here, and this is because the blur does not adapt to the local density of beams. In certain regions we end up overblurring, and in other regions we underblur, and see the individual beams
- Standard photon mapping solves this by using k-nearest neighbor density estimation



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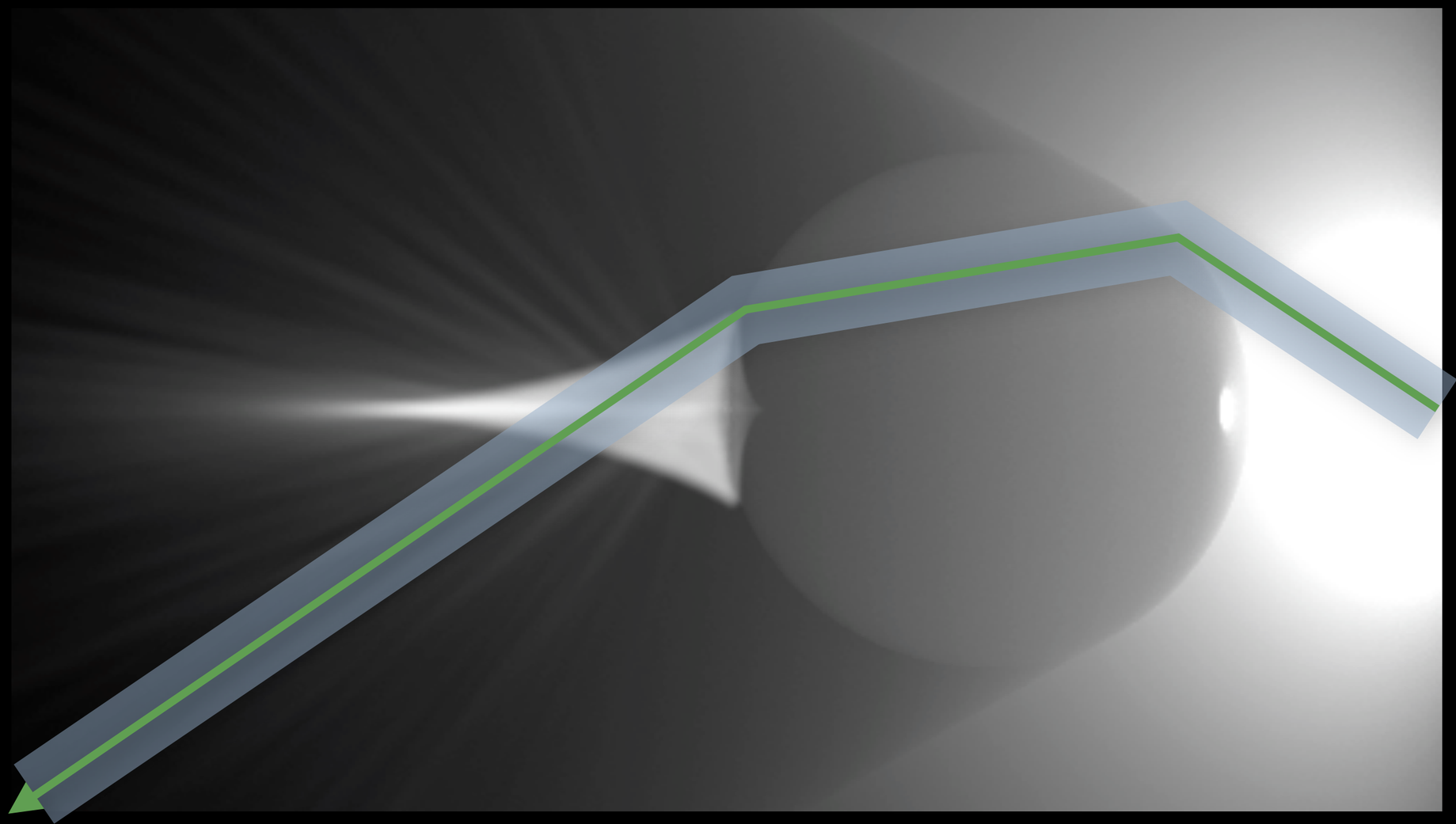
Fixed-width Beams



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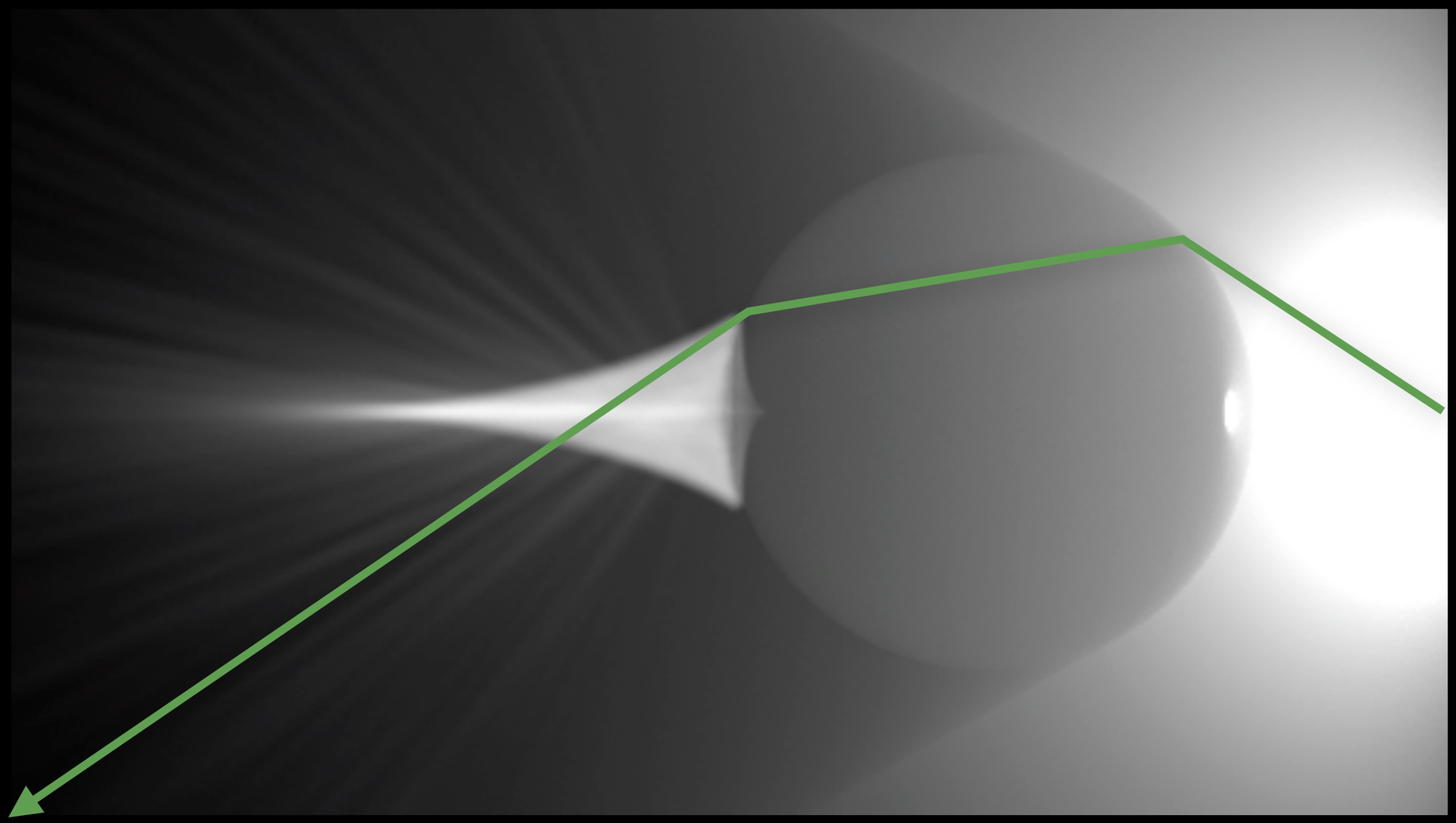
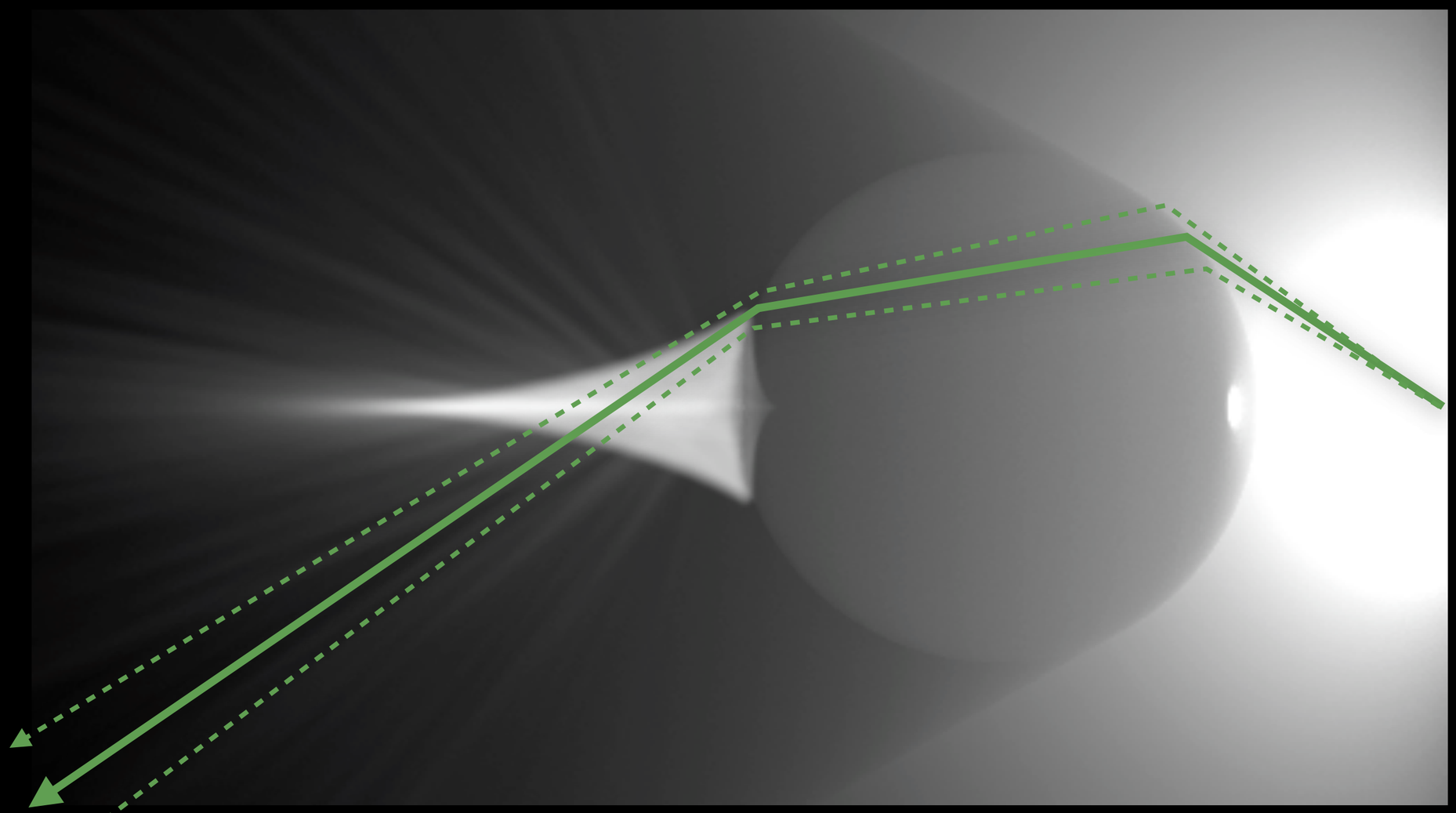


Photon Differentials
[Igehy 99, Schjøth et al. 07]

Friday, 7 September 12

- We solve this problem by using photon differentials
- We not only trace the beam itself, but also trace two differential rays. These additional rays are propagated through specular bounces and determine how the light locally converges and diverges.
- In the paper we also show how we extend this idea to handle area light sources and multiple scattering.
- We use this information differential information to change the blur width along the length of each beam [click]

Fixed-width Beams



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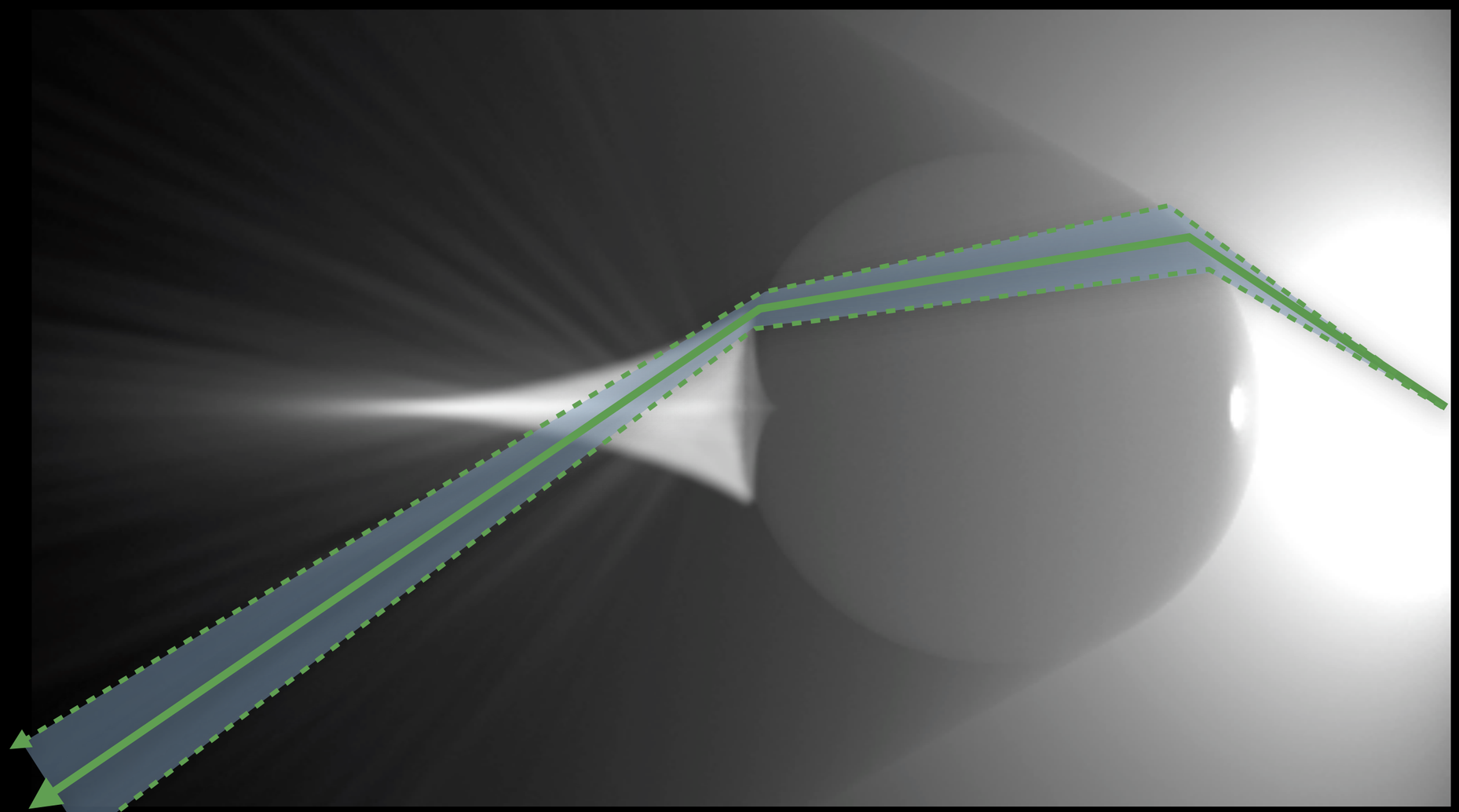

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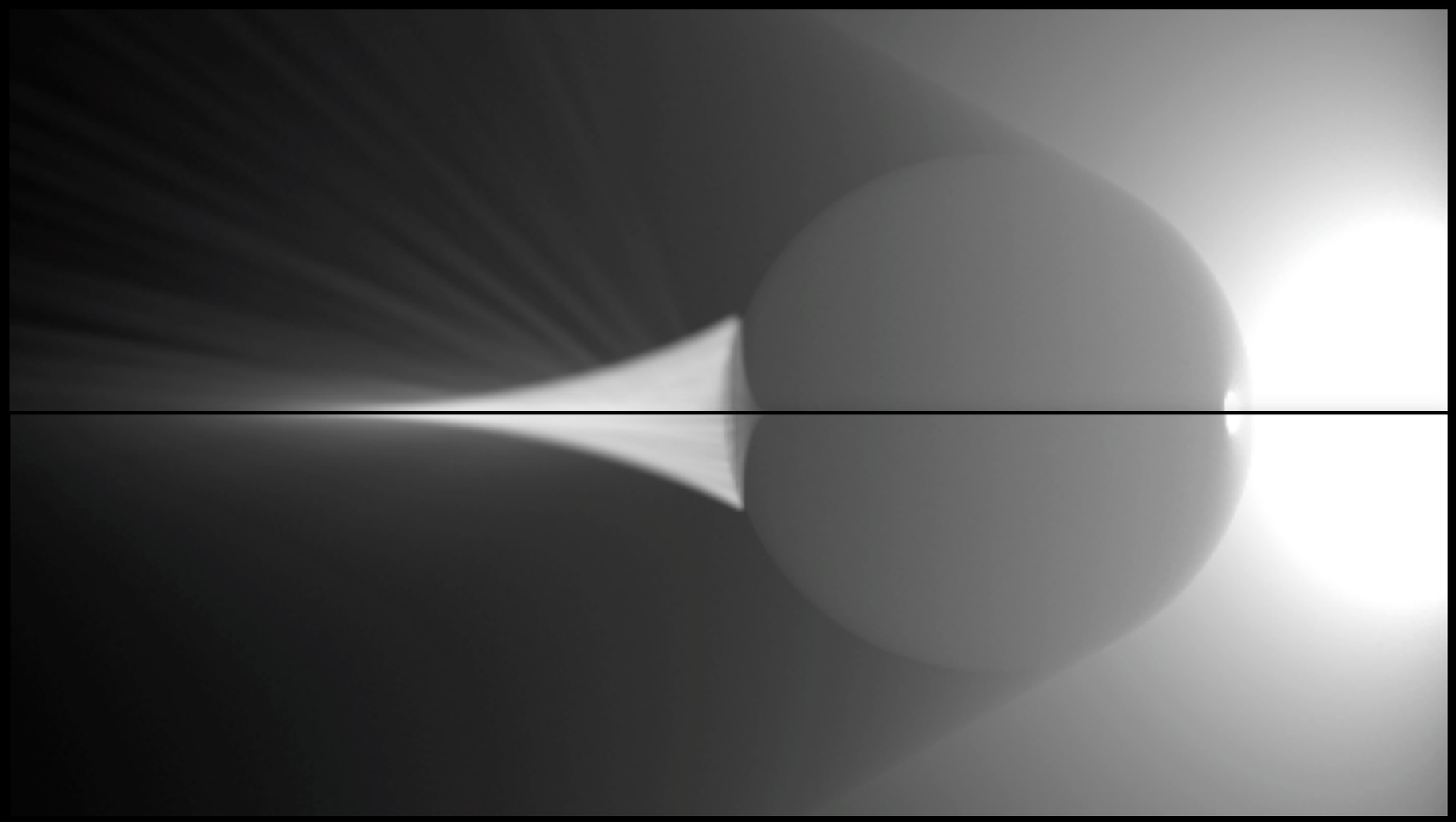


Adaptive-width Beams

- Which eliminates the banding artifacts in sparse regions, while avoiding overblur in dense regions

Results

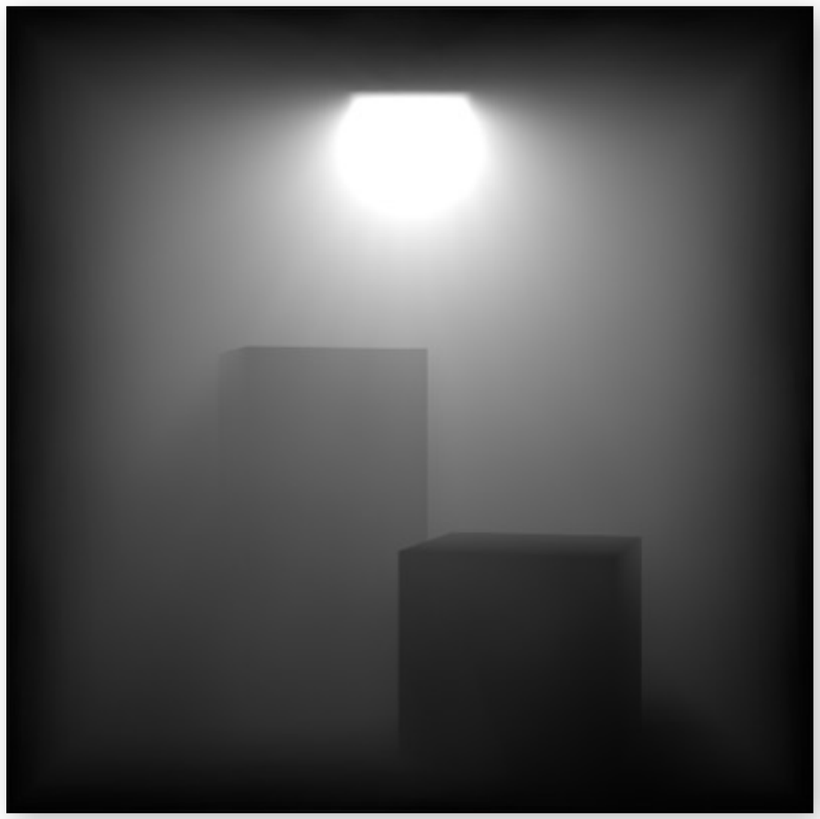
- MacBook Pro 3.06 GHz Intel Core 2 Duo

Results

- MacBook Pro 3.06 GHz Intel Core 2 Duo
- Previous photon mapping state-of-the-art:
  - Beam Query x Point Data (2D) [Jarosz et al. 08]

Cornell Box

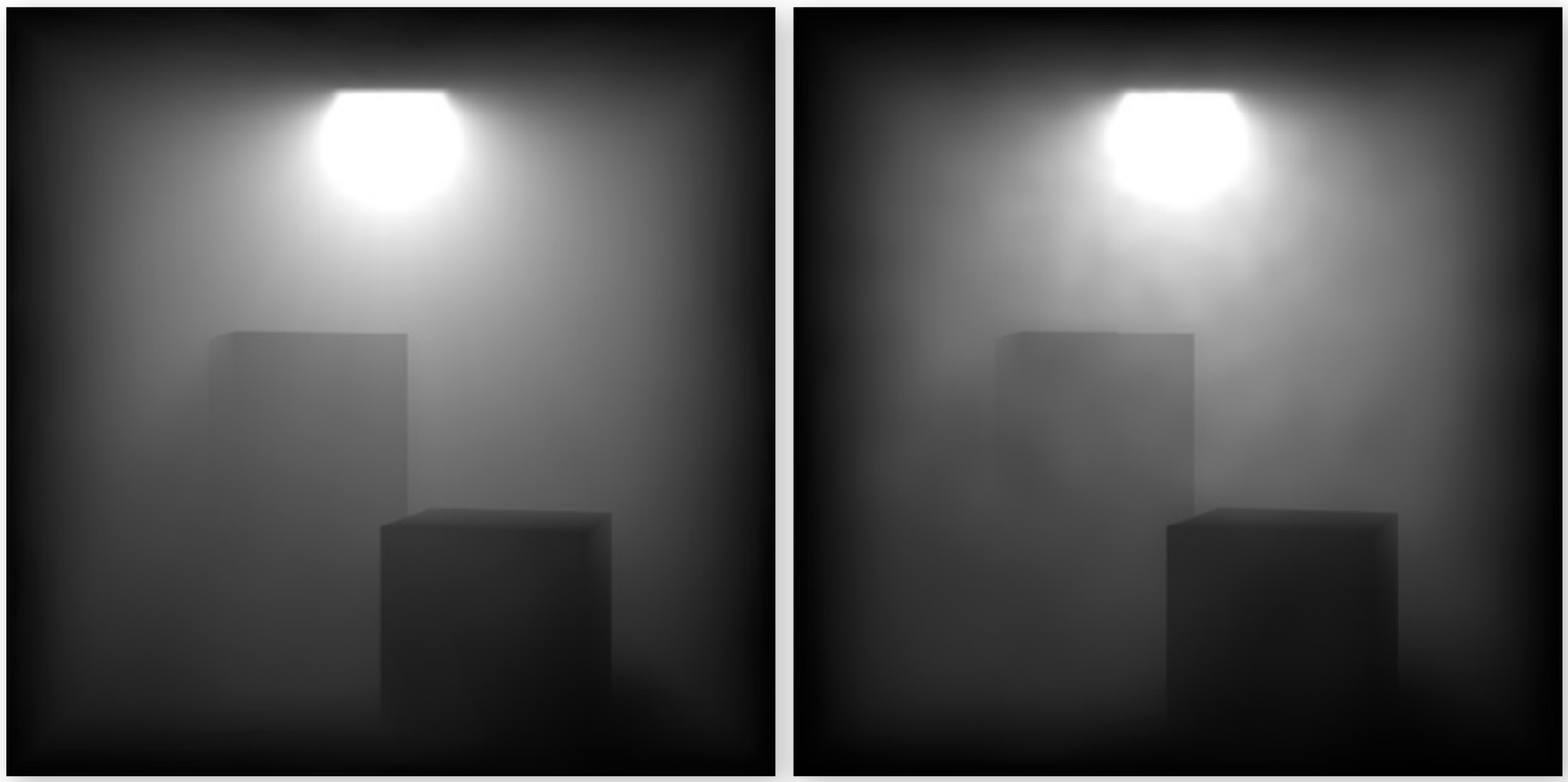
Area light, single + multiple scattering



Photon Beams
17.3k Beams - 1:48

Cornell Box

Area light, single + multiple scattering



Photon Beams
17.3k Beams - 1:48

Photon Points
280k Points - 1:49

Equal time

Cornell Box

Area light, single + multiple scattering

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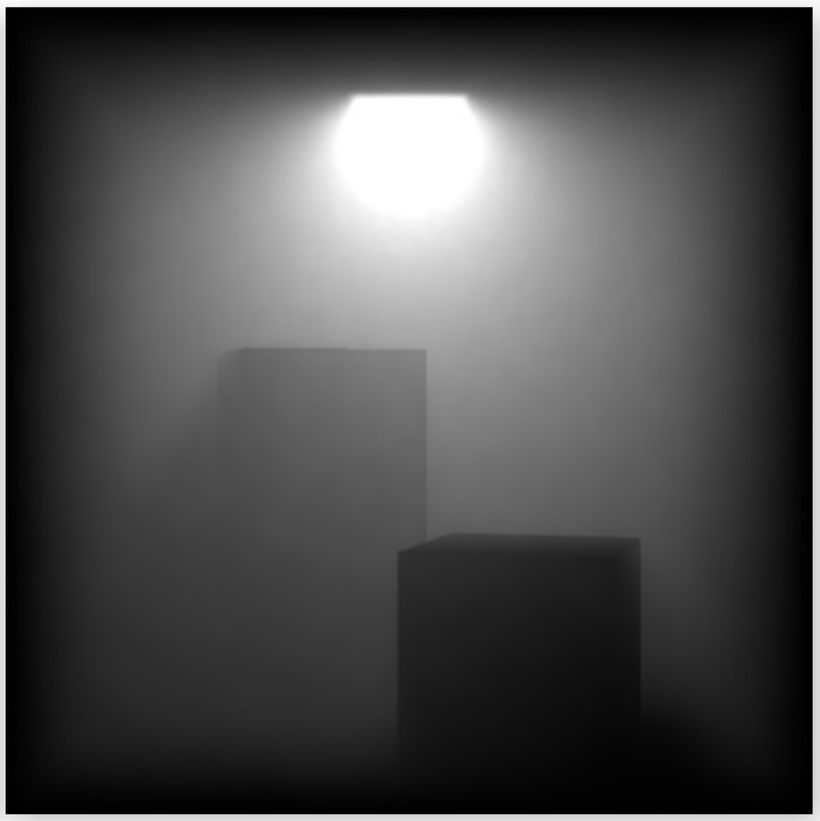
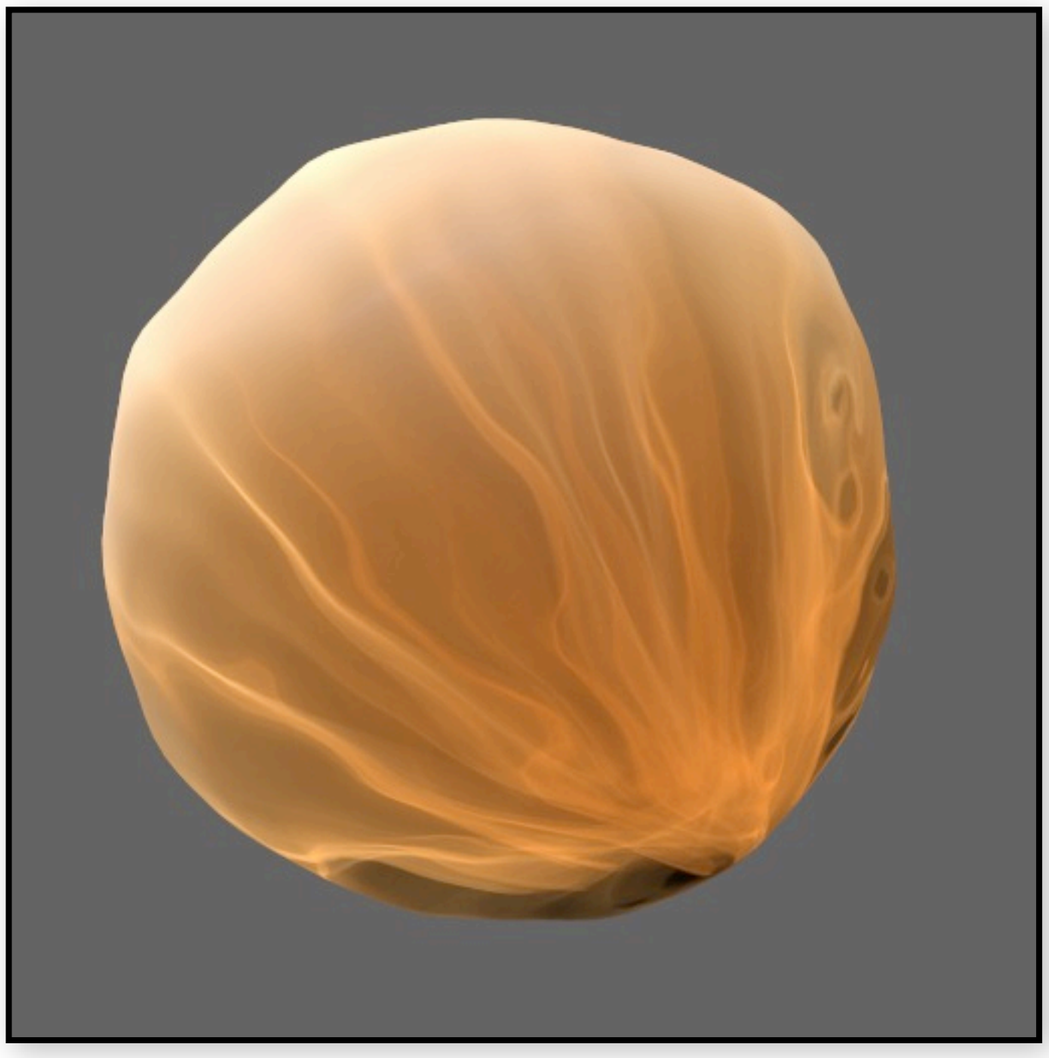


Photon Points
9.3M Points 17:34
“Equal” Quality

Bumpy Sphere

courtesy of Bruce Walter



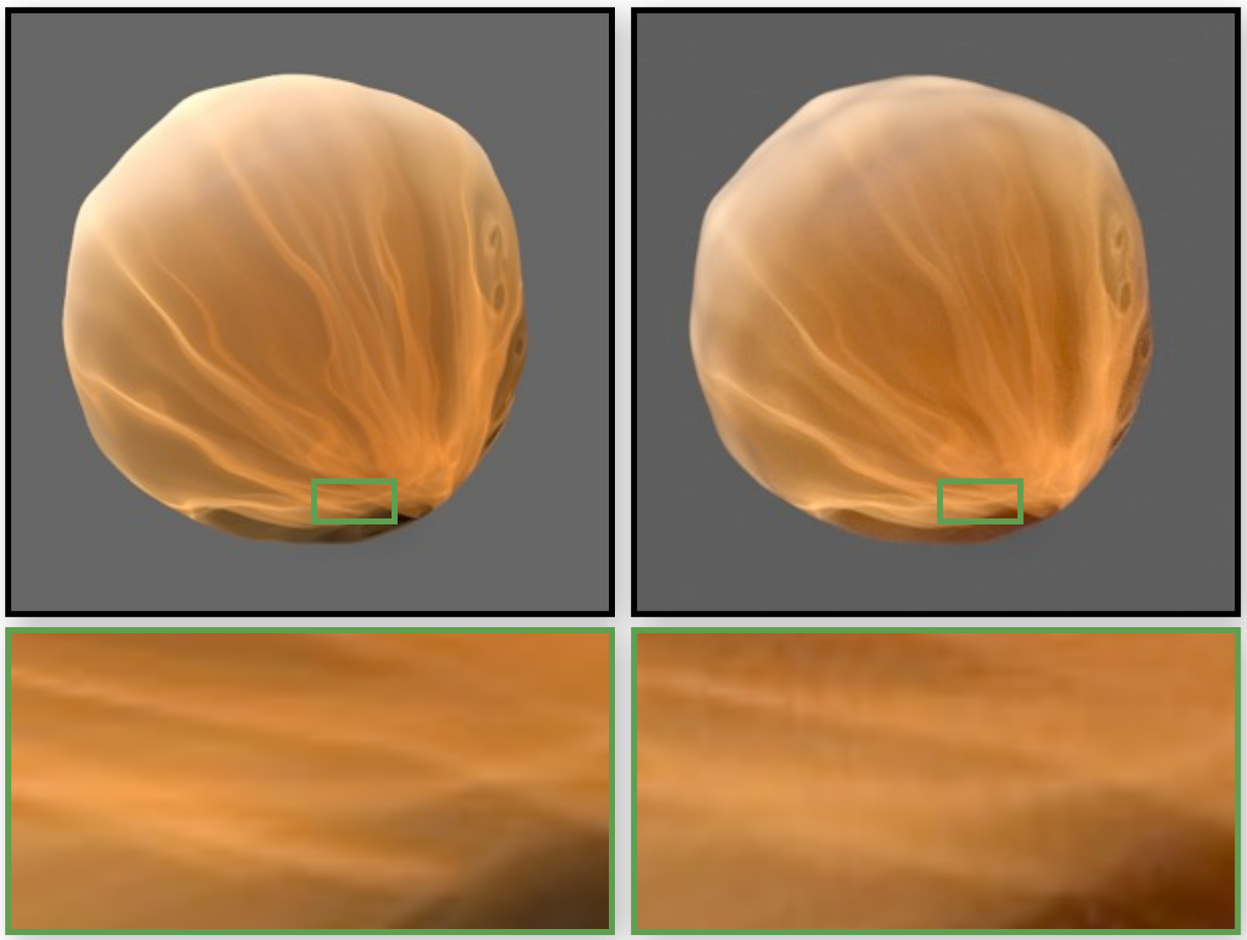
- Our second scene is this Bumpy Sphere scene courtesy of Bruce Walter
- This is effectively a dielectric interface filled with a scattering medium, and you can think of this as a ball of amber, and as light refracts through the deformed boundary it produces these intricate volume caustics inside the sphere.

Bumpy Sphere

courtesy of Bruce Walter

Ground Truth

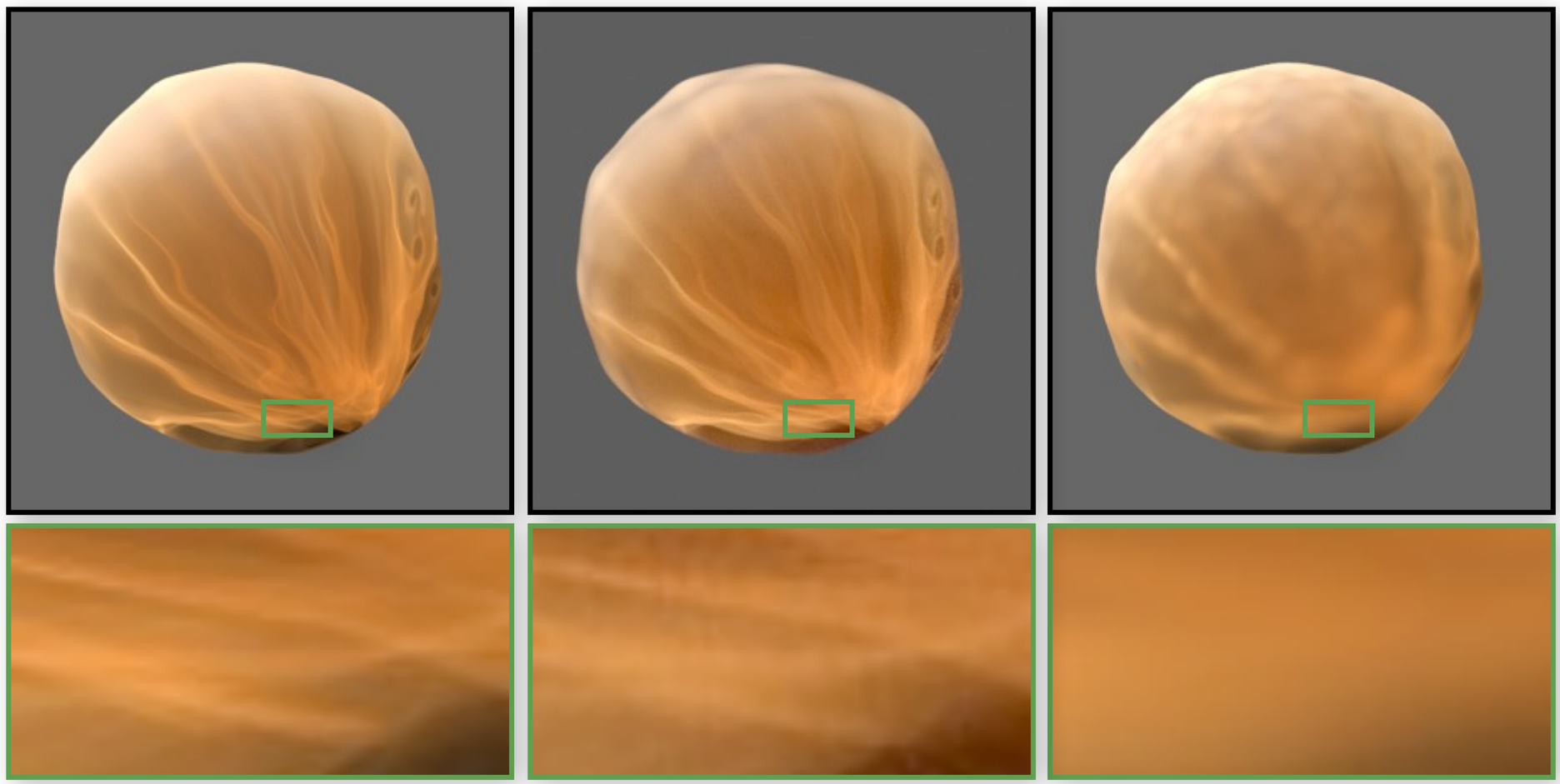
[Walter et al. 09]



- Walter and collegues developed a direct root-finding method to compute the amount of light that reaches a point within a triangular boundary.
- The benefit of such a direct approach is that you can get extremely crisp results [click].
- In comparison, standard photon mapping results in extremely blurred features unless you use a very large number of photons

Bumpy Sphere

courtesy of Bruce Walter



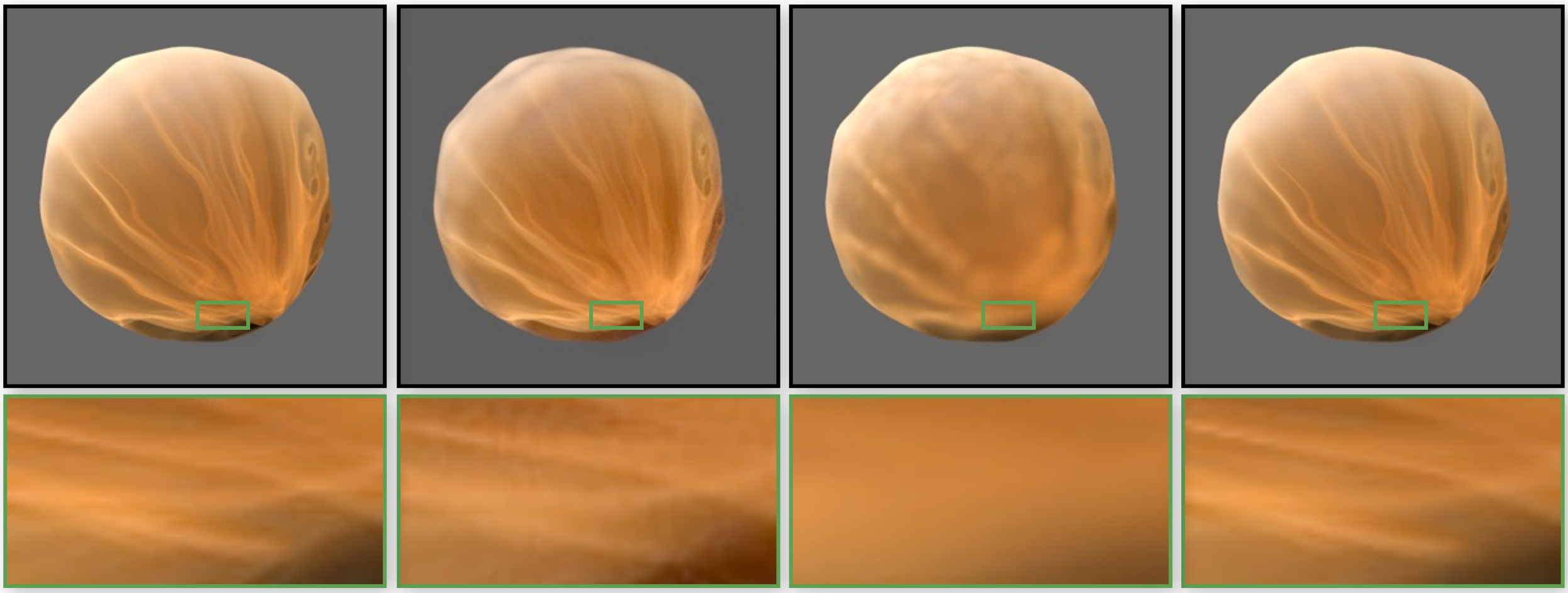
Friday, 7 September 12

- In comparison, standard photon mapping results in extremely blurred features unless you use a very large number of photons
- However [click], we can get an incredible increase in resolution if we simply use the same exact photon simulation but store the results as beams instead of points.

Bumpy Sphere

courtesy of Bruce Walter

Ground Truth	[Walter et al. 09]	90k Photon Points	90k Photon Beams



Friday, 7 September 12

- However [click], we can get an incredible increase in resolution if we simply use the same exact photon simulation but store the results as beams instead of points.
- In contrast to Walter's method, it is easy to incorporate total internal reflection, and multiple scattering
- Also, you can see that in Walter's method there is a bit of high-frequency noise. This is because it is still necessary to ray march within the medium. On the other hand, with a beam query, we obtain the entire integral through the medium in one lookup without the need for ray marching.

Bumpy Sphere

Rendered at 512x512 with up to 16 samples/pixel

- The benefits of photon beams also applies to animations.
- Here we show a comparison using point on the left and beams on the right, using the exact same photon simulation with 90k photons
- We can see that photon beams not only resolve these fine details much more faithfully, they also reduce temporal flickering
- Estimating radiance using beams is a bit more expensive, so we see that with the same number of points as beams the left animation renders faster

- However, even if we shot 1.3M photons to equal time, photon beams still provides a significant quality improvement

Lighthouse

Rendered at 1024x435 with up to 16 samples/pixel

- Our next example is this animated lighthouse scene.
- The remarkable thing here is that we are able to resolve this lighting using only 700 beams, whereas at equal time (with 10k photon points) significant artifacts are present
- Even if we shot 1M photons (at 9 times the render time) these artifacts remain

Underwater Sun Beams

Rendered at 1024x576 with up to 16 samples/pixel

- Finally, in this example we are looking up at the sun from beneath ocean waves.
- The standard approach effectively point-samples these beams of refracted light, and this introduces flickering and undersampling, so the results are extremely blurry
- On the other hand, with photon beams, each beam of light is represented much more naturally as a photon beam, sampling the lighting much more density
- Even with 10M photons and 7.5X the render time, this looks worse than using just 25K photon beams

Summary

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- photon beams:
  - “up-res’ing” # of photons along paths

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- photon beams:
  - “up-res’ing” # of photons along paths
- thousands of beams vs. millions of photons
- for volumetric photon mapping:
  - store *photon beams*, and *query* with a *beam*

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