Bidirectional Lightcuts

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SIGGRAPH2012

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Realistic Rendering Challenge

- Complex light sources
- Global illumination
- Wide range of materials

Images: **Autodesk® 360 Rendering** & **Autodesk® Homestyler®**

Realistic Rendering Challenge

- Complex light sources
- Global illumination
- Wide range of materials
  - Glossy, subsurface, volumetric

Equal Time Comparison

Probabilistic Photon Map

[Knaus & Zwicker 11]

Multidimensional Lightcuts (VPL)

[Walter et al. 06]

Bidirectional Path Trace

[Veach & Guibas 94,95]

Equal Time Comparison

Probabilistic Photon Map

Multidimensional Lightcuts (VPL)

Bidirectional Path Trace

Equal Time Comparison

Probabilistic Photon Map

Multidimensional Lightcuts (VPL)

Bidirectional Path Trace

Equal Time Comparison




Probabilistic Photon Map	Multidimensional Lightcuts (VPL)	Bidirectional Path Trace	New Method




Equal Time Comparison

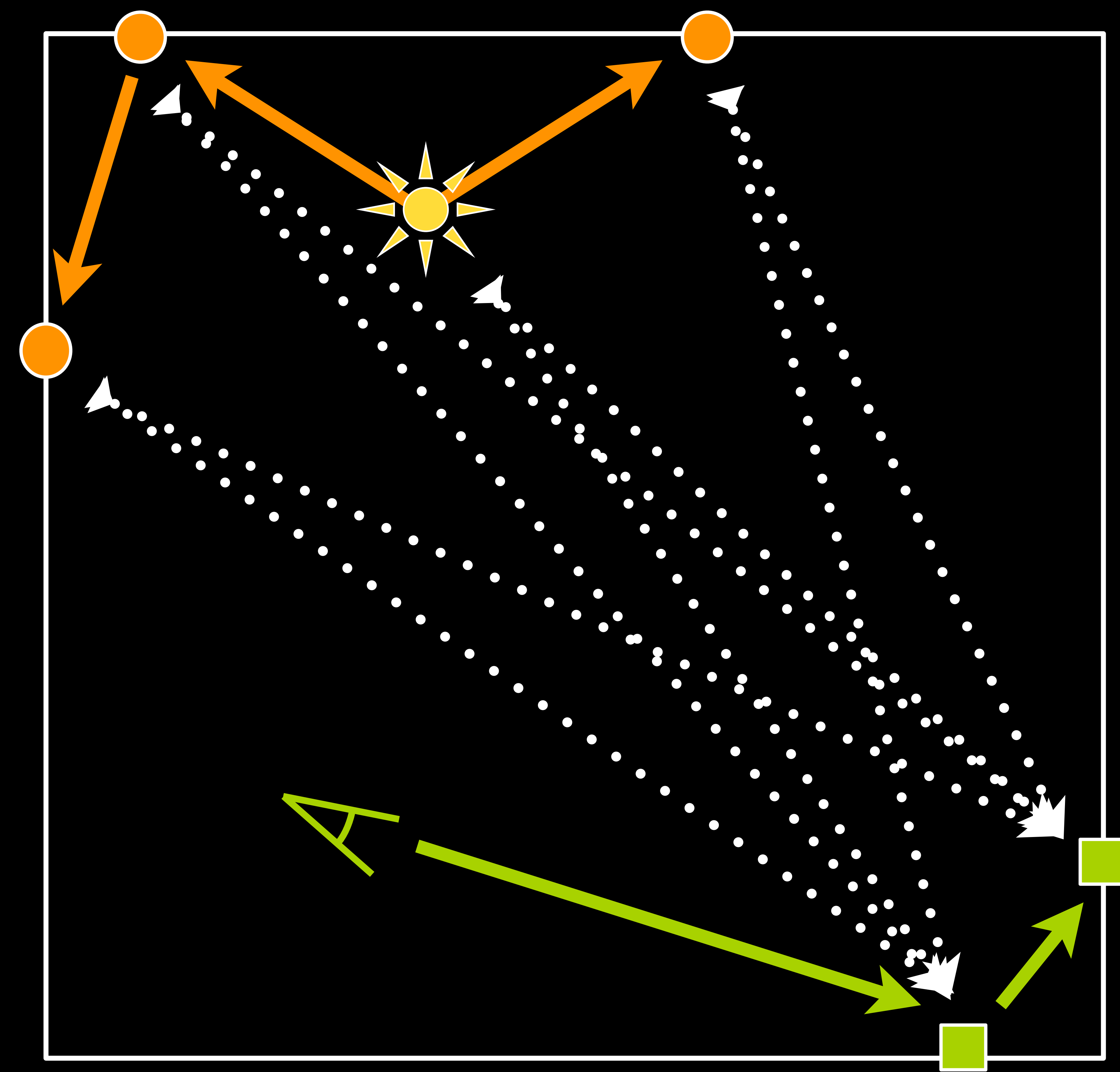
Probabilistic Photon Map	Multidimensional Lightcuts (VPL)	Bidirectional Path Trace	New Method

Goal: Combine Strengths

- Multidimensional Lightcuts
  - Biased virtual point light (VPL) method
  - ✓ Low noise and scalable performance
- Bidirectional Path Tracing
  - Noisy and slow to converge
  - ✓ Supports wide range of materials

Bidirectional Lightcuts

- Bidirectional VPL algorithm
  - Bidirectional estimators
  - Novel weighting scheme
    - Control bias vs. noise tradeoff
  - Scalable and low noise
    - Integrated with Lightcuts

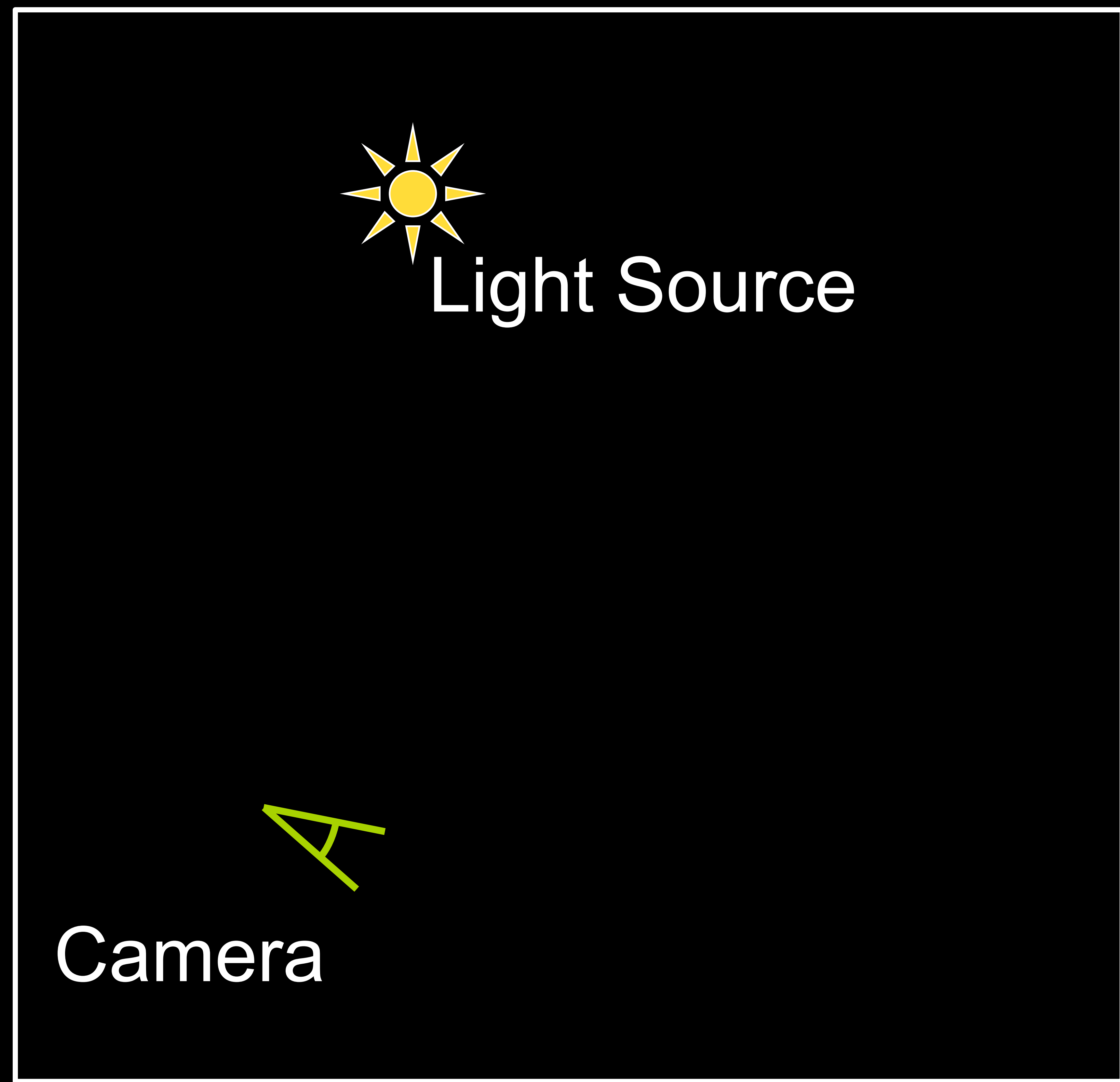


Outline

- Prior work: VPL and Bidirectional review
- New weighting strategy
- Integration with Multidimensional Lightcuts
- Results

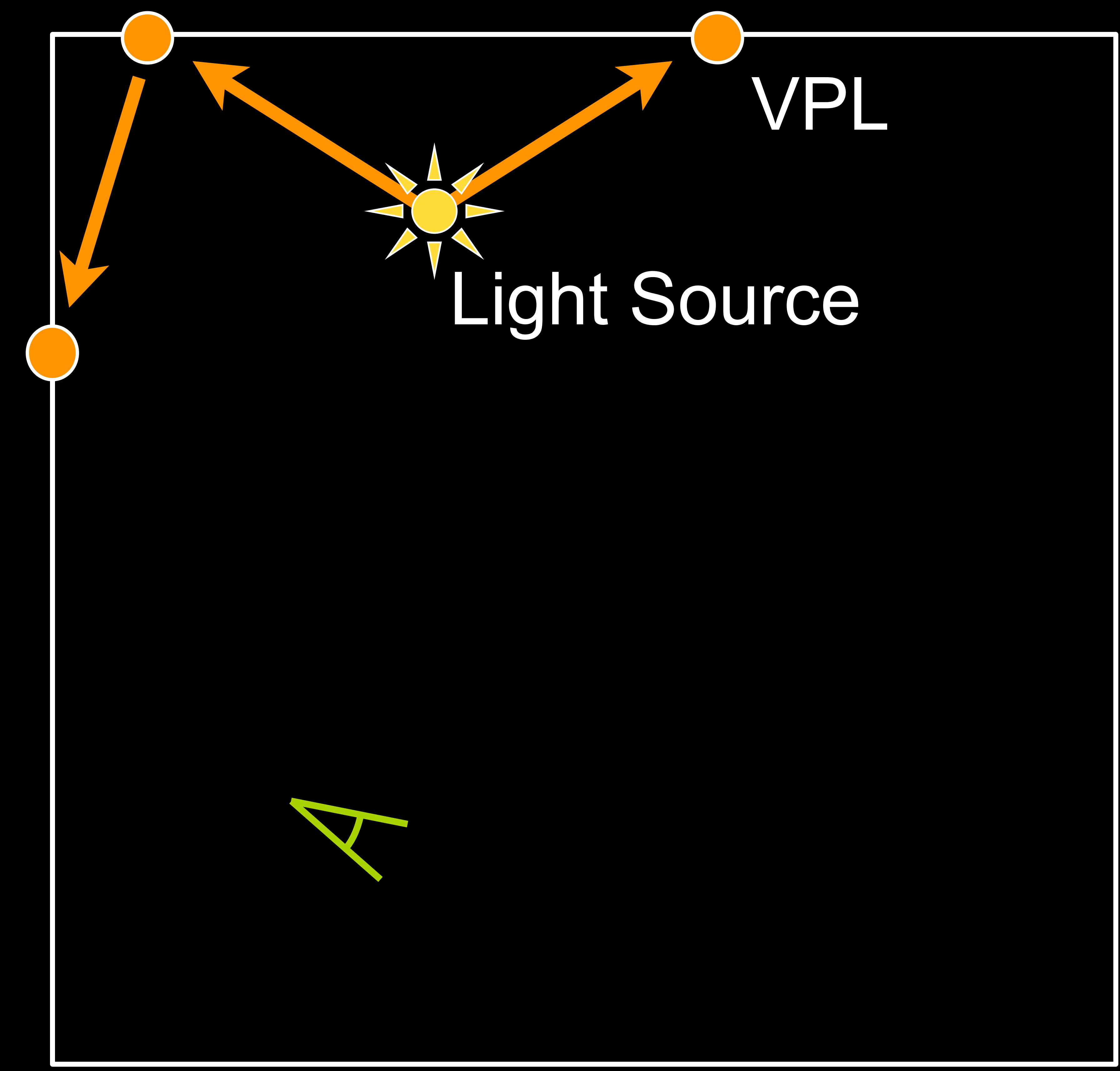
Virtual Point Light Methods

- Approximate global illumination using point lights



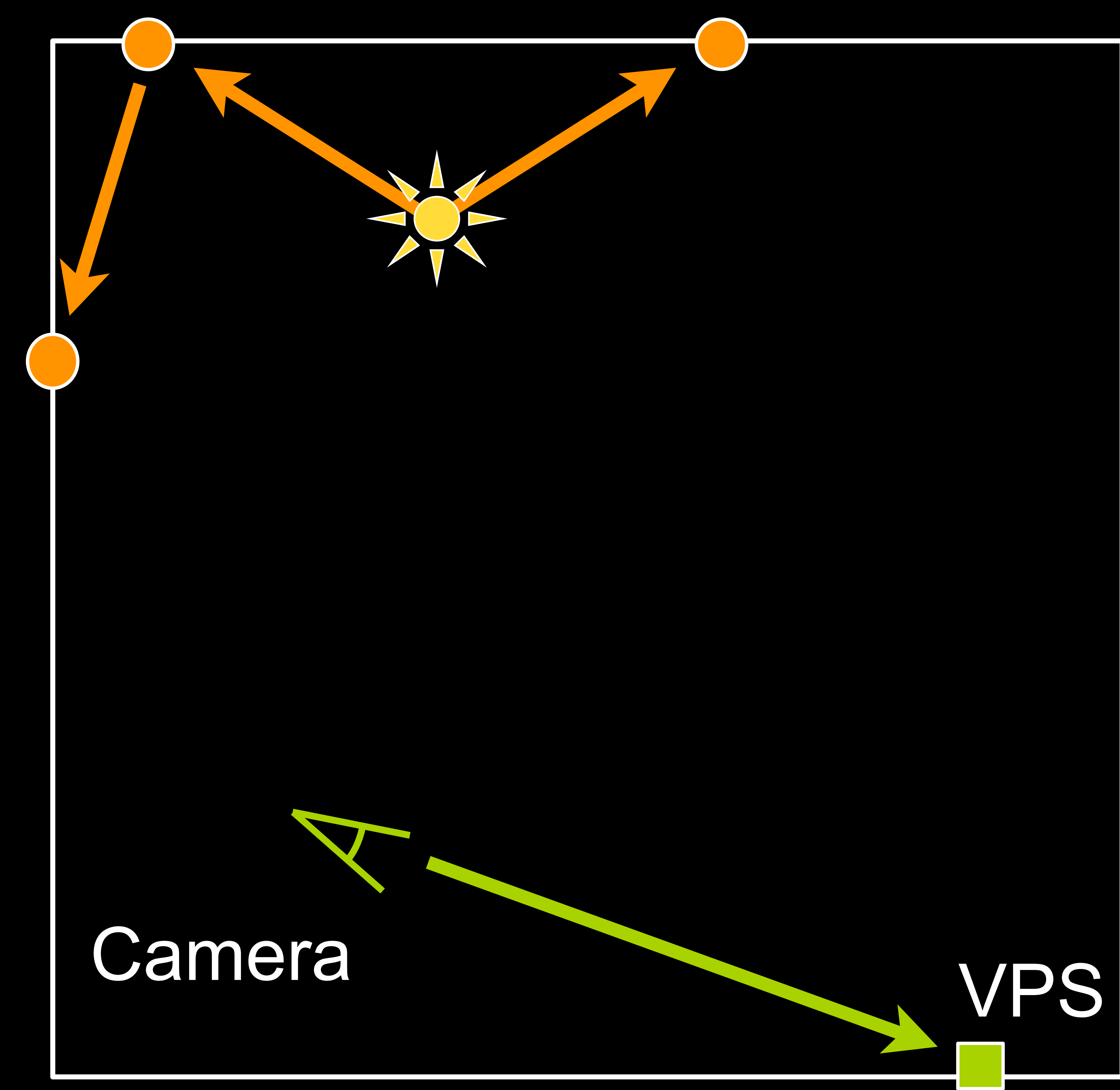
Virtual Point Light Methods

- Approximate global illumination using point lights
- Generate point lights (VPL)



Virtual Point Light Methods

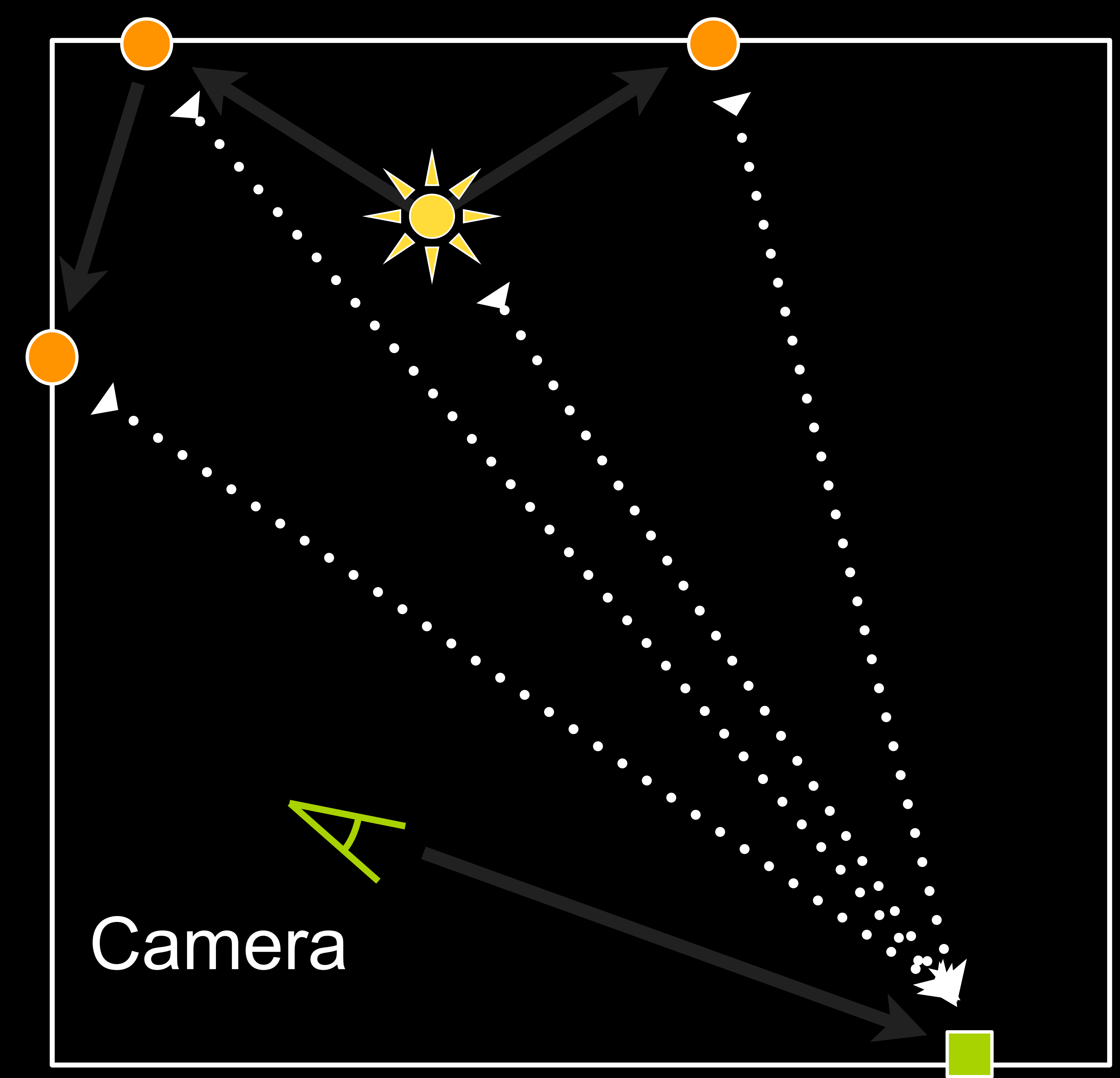
- Approximate global illumination using point lights
- Generate point lights (VPL)
- Generate point sensors (VPS)



Virtual Point Light Methods

- Approximate global illumination using point lights
- Generate point lights (VPL)
- Generate point sensors (VPS)
- Gather illumination

- More VPLs = more accurate



Material Appearance Problem

Naive VPL
(no clamping)

Material Appearance Problem

Naive VPL (no clamping)

Standard VPL (with clamping)

- Clamping distorts material appearance [Krivanek et al. 10]

Material Appearance Problem

Naive VPL (no clamping)

Standard VPL (with clamping)

Our Result

- Clamping distorts material appearance [Krivanek et al. 10]

Prior VPL Work

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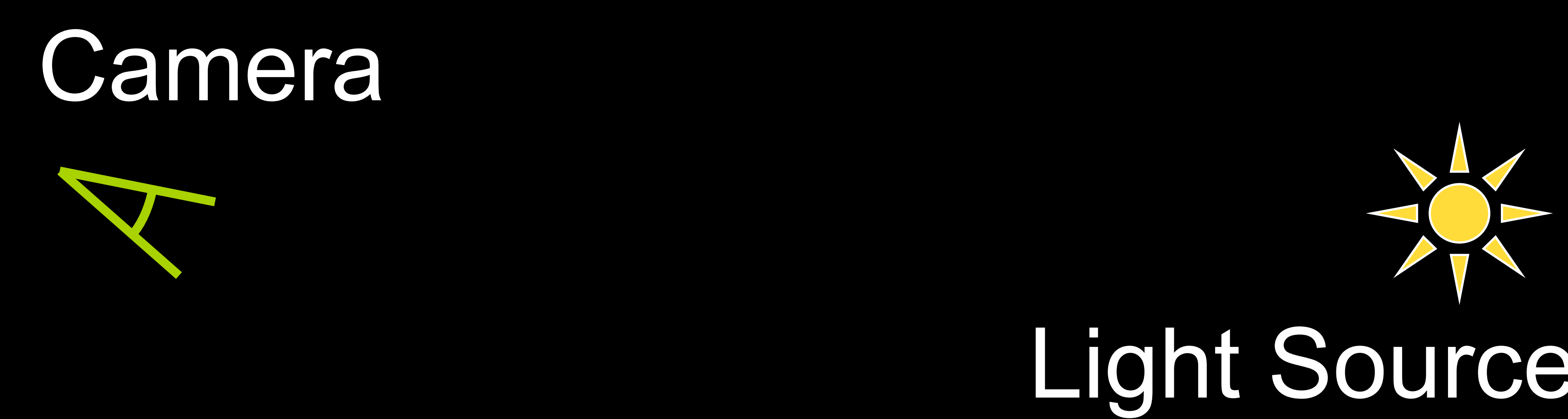
- Adaptive VPL generation
  - [Segovia et al. 06, Davidovic et al. 10]
- Modified VPLs
  - [Hasan et al. 09]
- VPL bias compensation
  - [Kollig & Keller 04, Engelhardt et al. 10, Novak et al. 11]
- Specialized BSSRDF extension
  - [Arbree et al. 08]
- Hybrid algorithms
  - [Dammertz et al. 10]

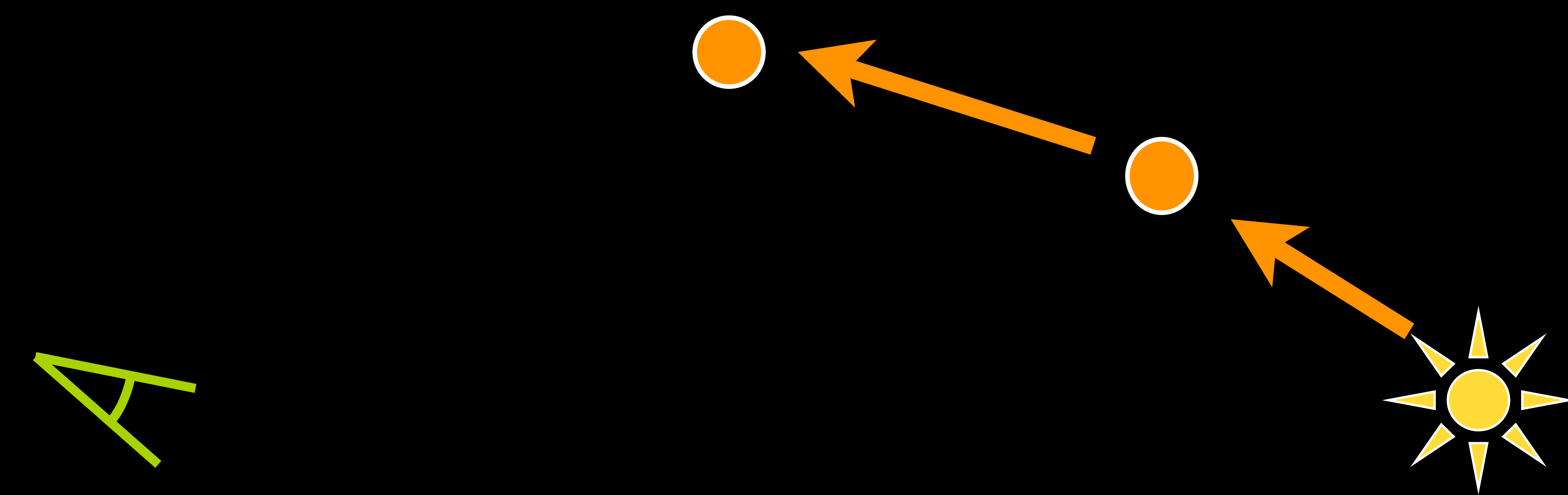
Bidirectional Path Tracing Review

- Bidirectional Path Tracing



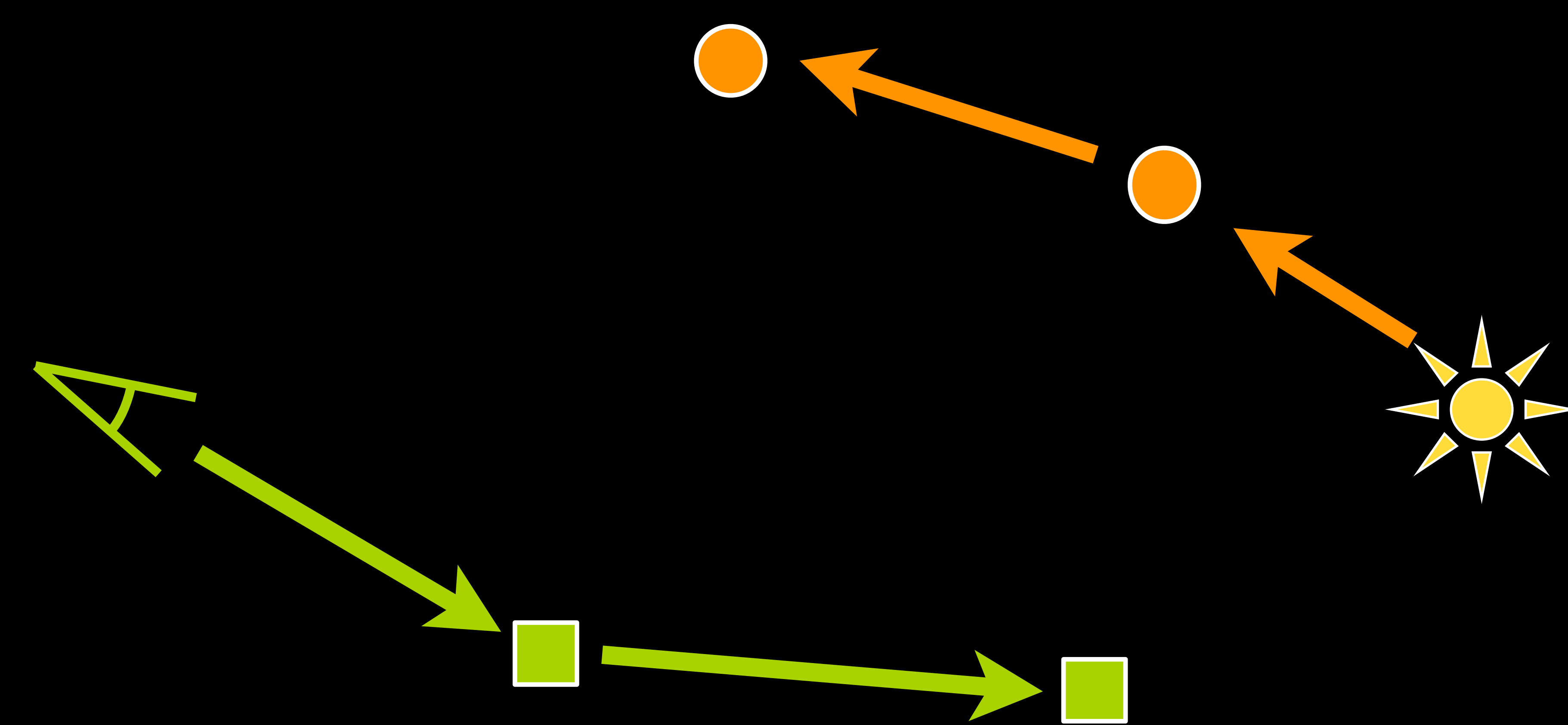
Bidirectional Path Tracing Review

- Bidirectional Path Tracing
  - Trace path from light



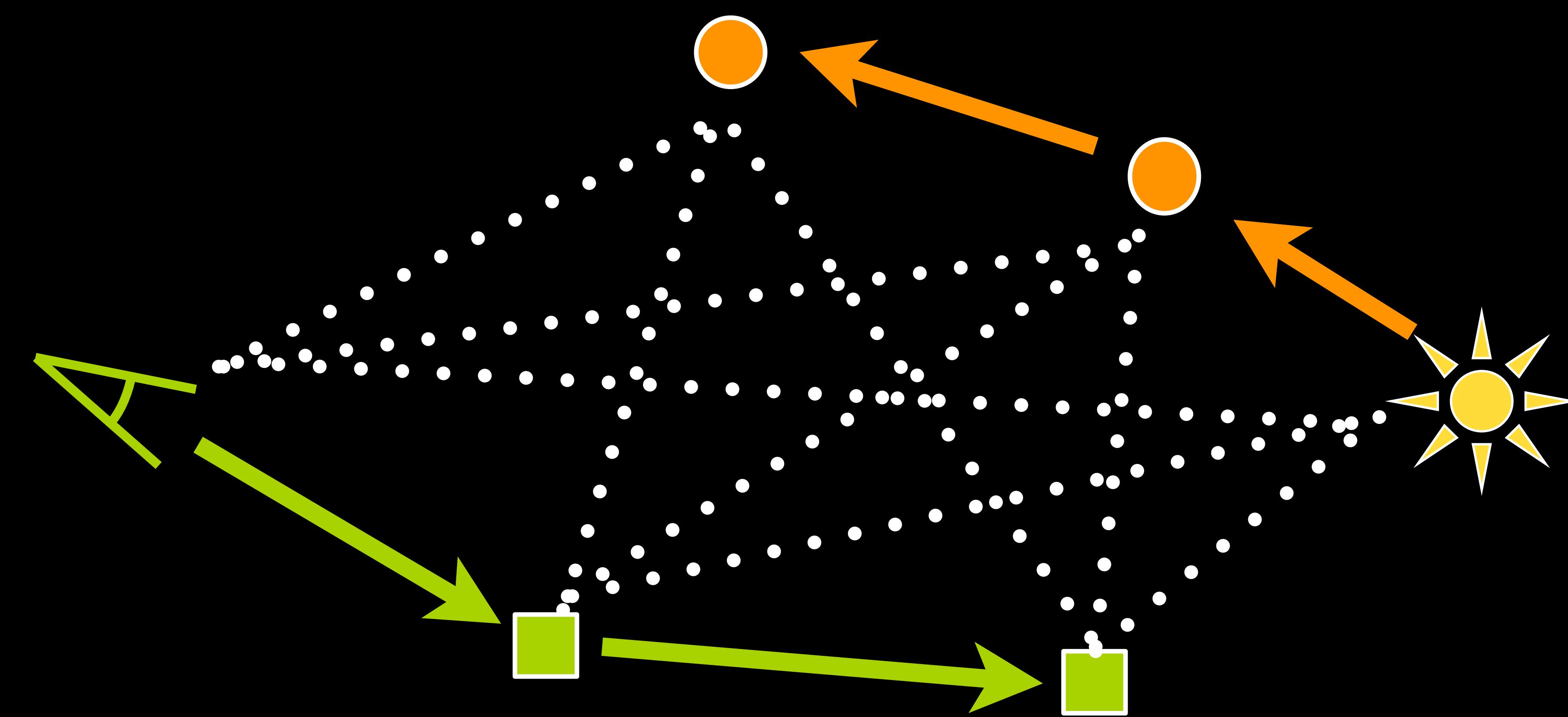
Bidirectional Path Tracing Review

- Bidirectional Path Tracing
  - Trace path from light
  - Trace path from camera



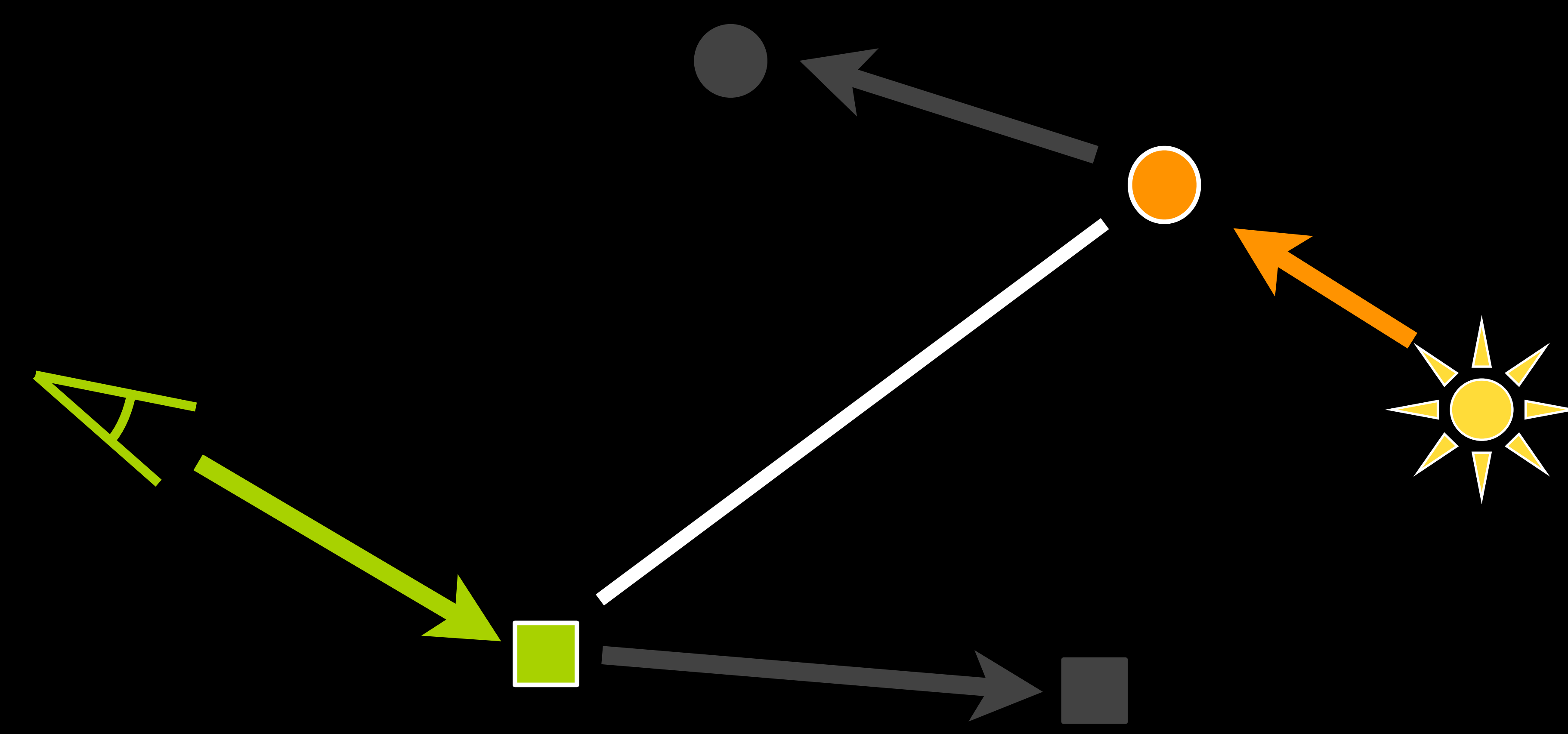
Bidirectional Path Tracing Review

- Bidirectional Path Tracing
  - Trace path from light
  - Trace path from camera
  - Sum over all connections



Bidirectional Path Tracing Review

- Multiple ways to generate each path



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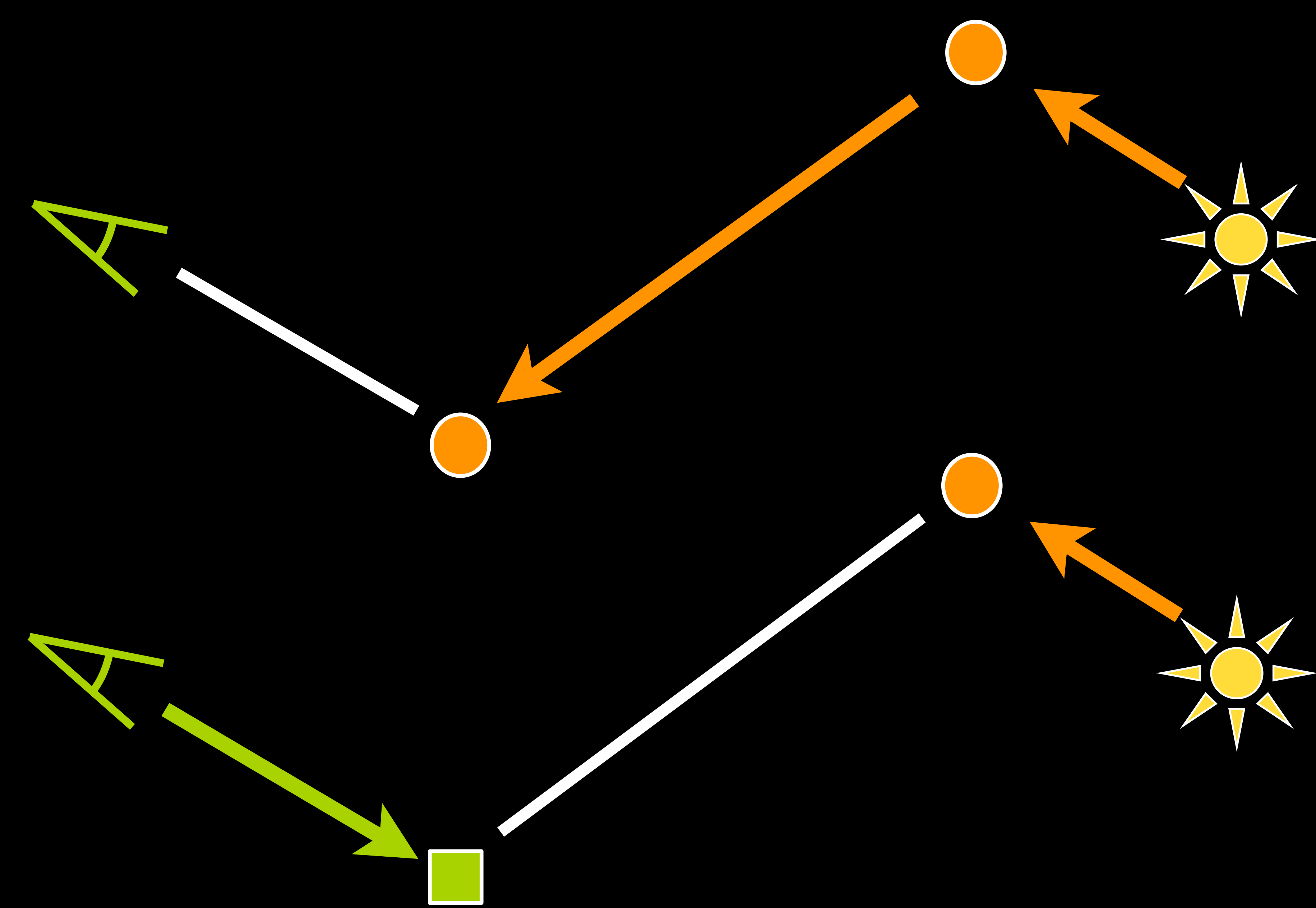

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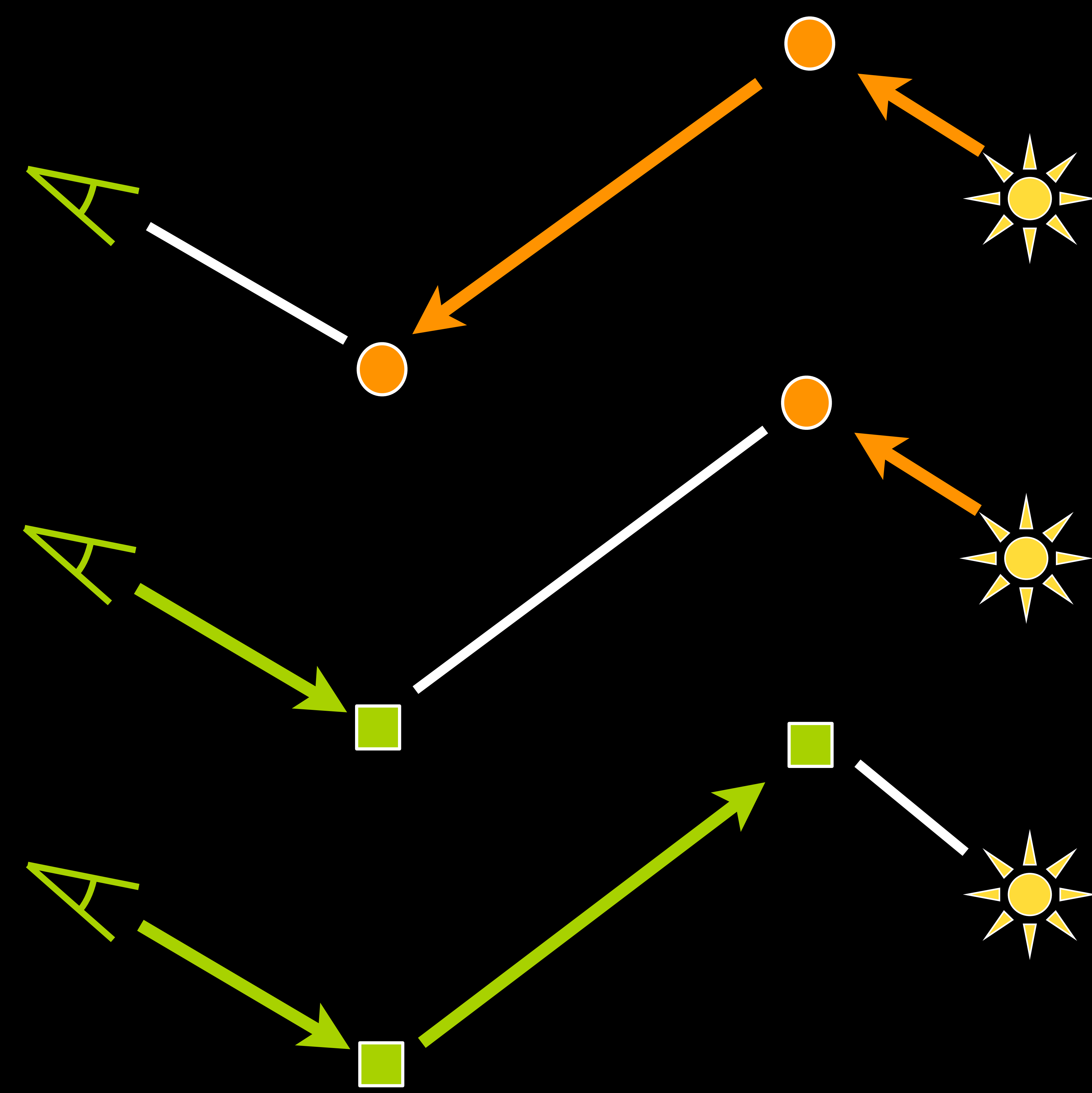

Bidirectional Path Tracing Review

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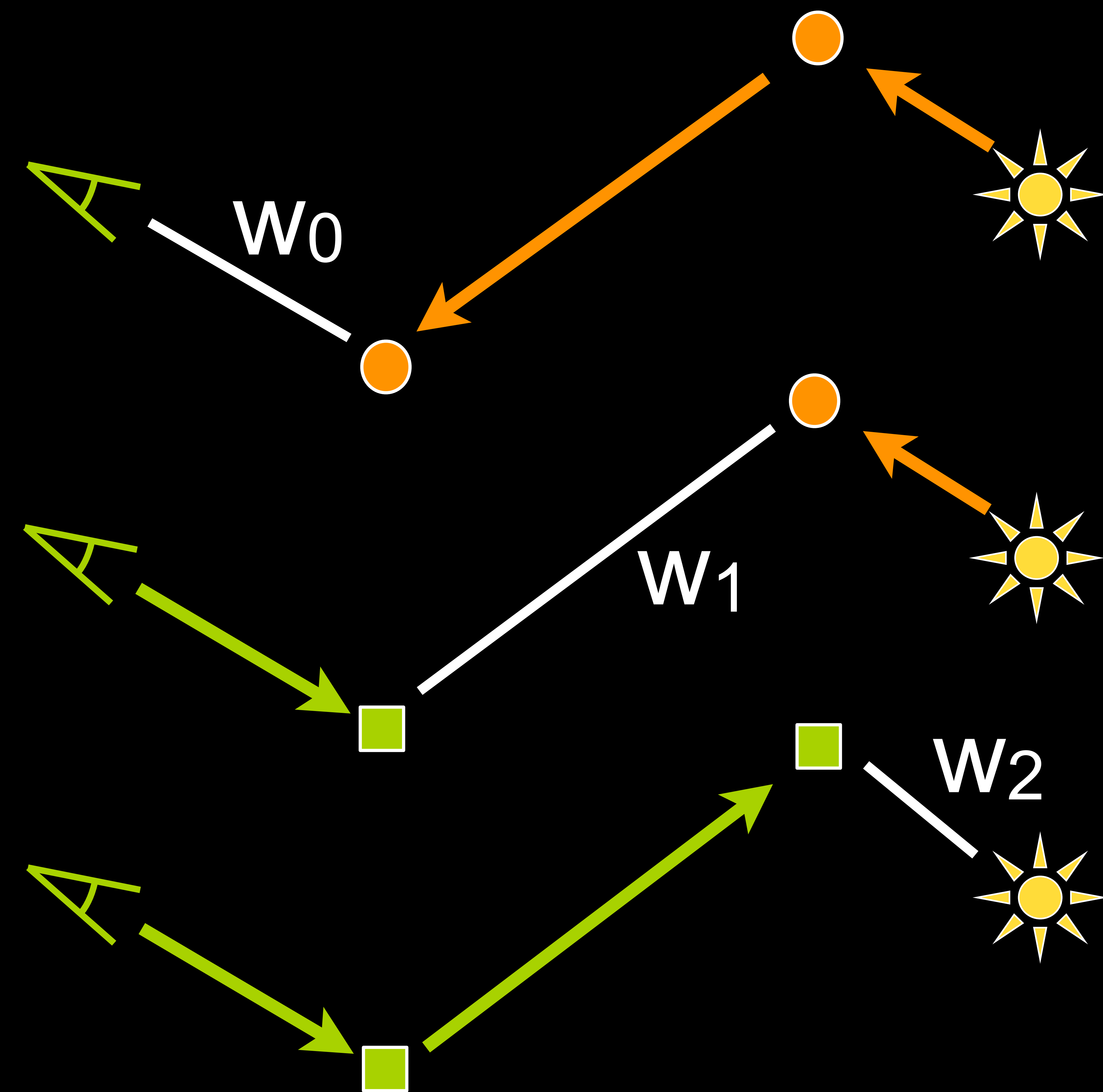
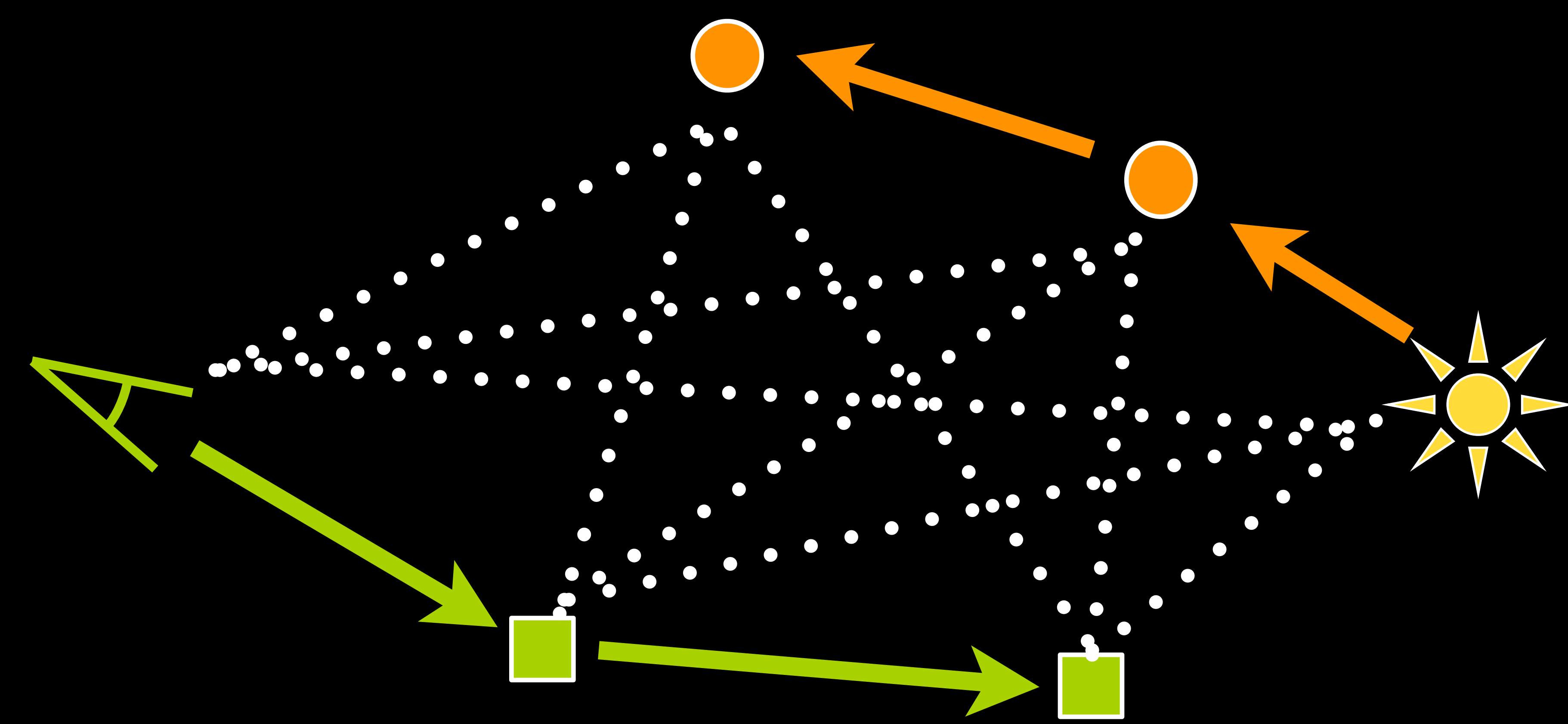
- Multiple ways to generate each path
  - Combine using weights: w_i
    - **e.g.,** Balance heuristic
  - Best connection depends on path
  - Unbiased if: $\sum w_i = 1$



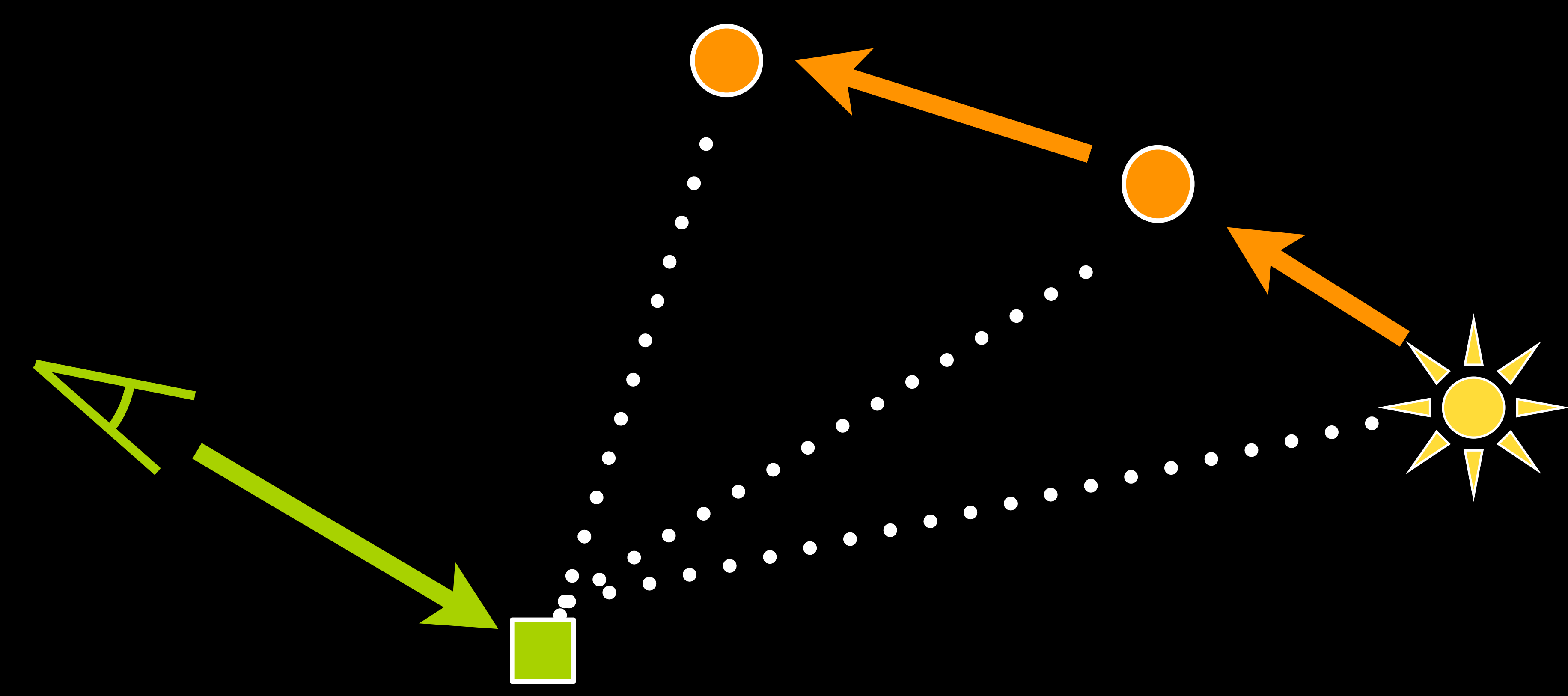
Bidirectional Path Tracing Review

- Advantages
  - Wider range of paths handled efficiently
- Disadvantages
  - Increased cost per sample
  - Some paths are still hard to find
    - May be noisy or slow to converge



Bidirectional VPL Rendering

- Standard VPL rendering
  - Limited subset of bidirectional methods
  - Clamping causes weight sum < 1



Bidirectional VPL Rendering

- Standard VPL rendering
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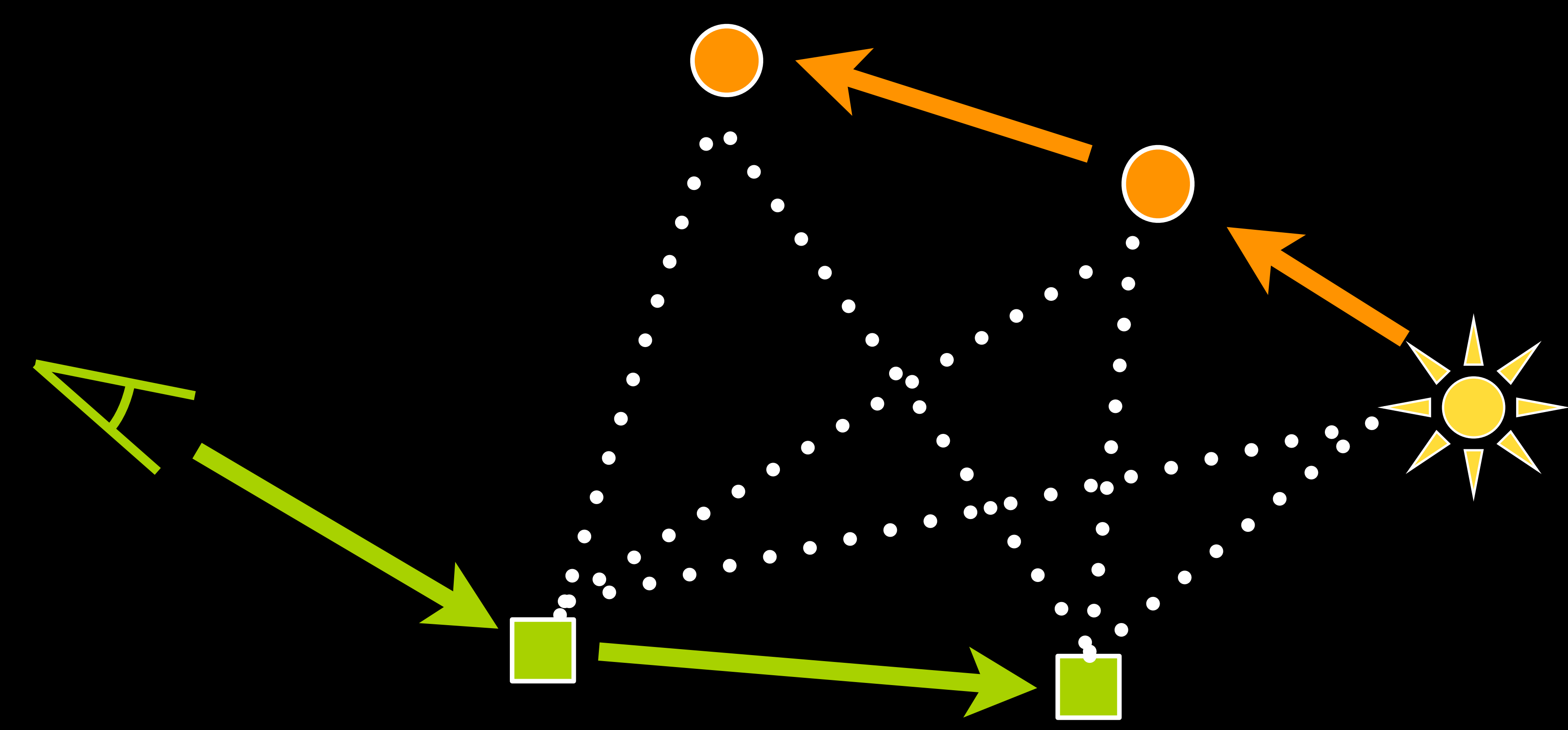
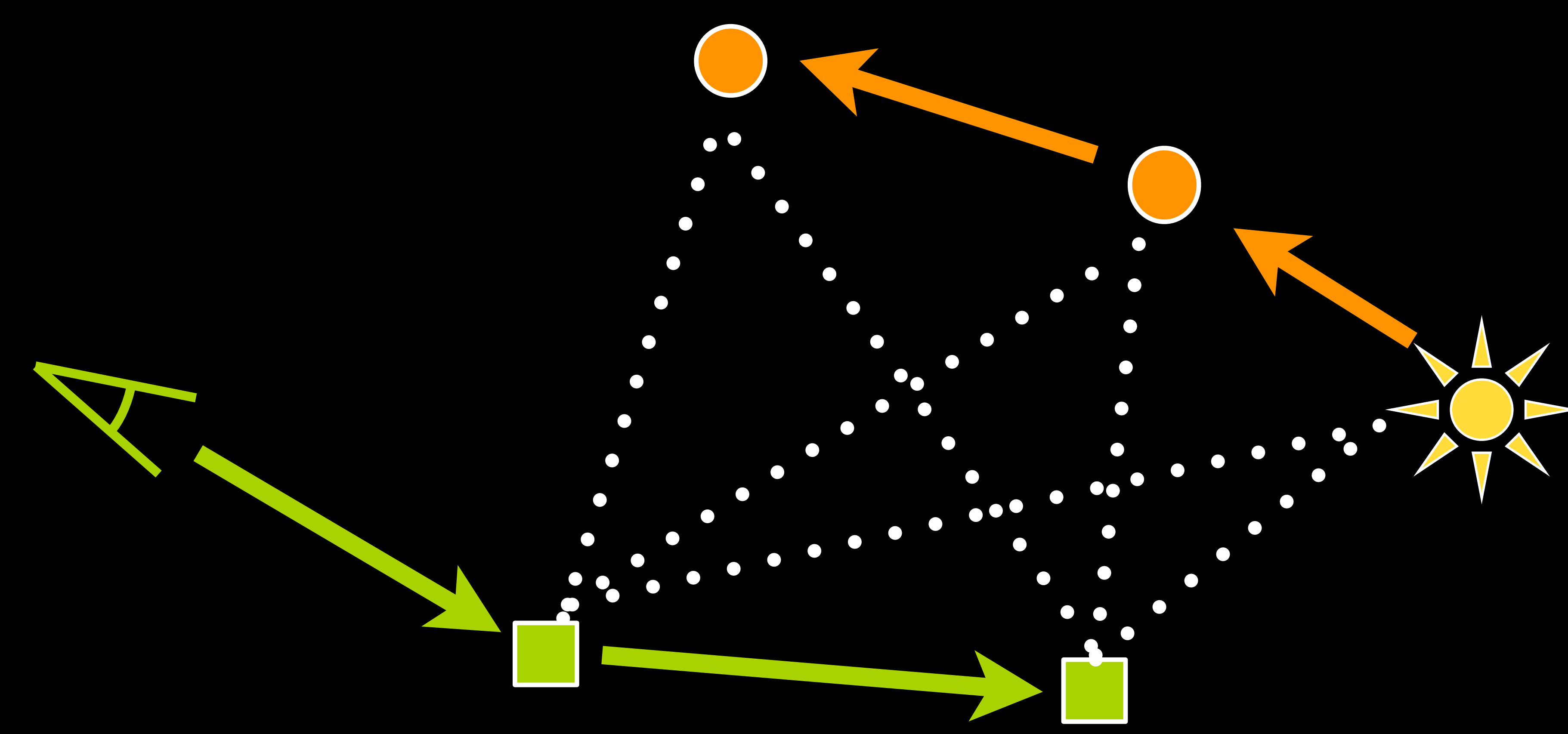
  - Clamping causes weight sum < 1
- Bidirectional extension



Bidirectional VPL Rendering

- Standard VPL rendering
  - Limited subset of bidirectional methods
  - Clamping causes weight sum < 1
- Bidirectional extension
  - Unbiased weighting [Kollig & Keller 04]
    - Low noise properties of VPL rendering is lost



Outline

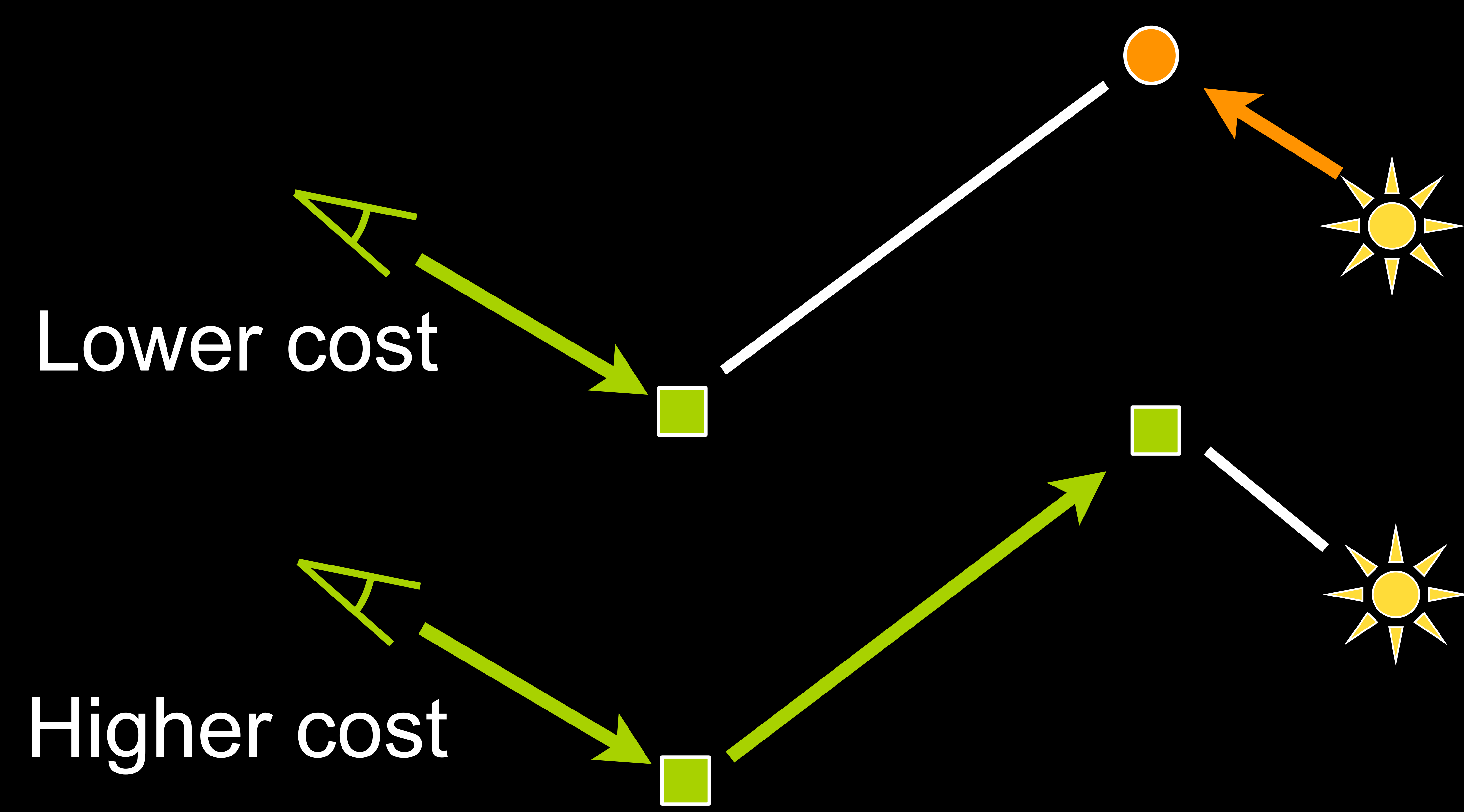
- Prior work: VPL and Bidirectional review
- New weighting strategy
- Integration with Multidimensional Lightcuts
- Results

New Weighting Strategy

- Designed for low noise while minimizing bias
- Four weight constraints
  - 1) Energy conservation
  - 2) Clamping
  - 3) Diffuse VPLs
  - 4) Exclude high variance eye paths
- Actual weight is the minimum of constraints

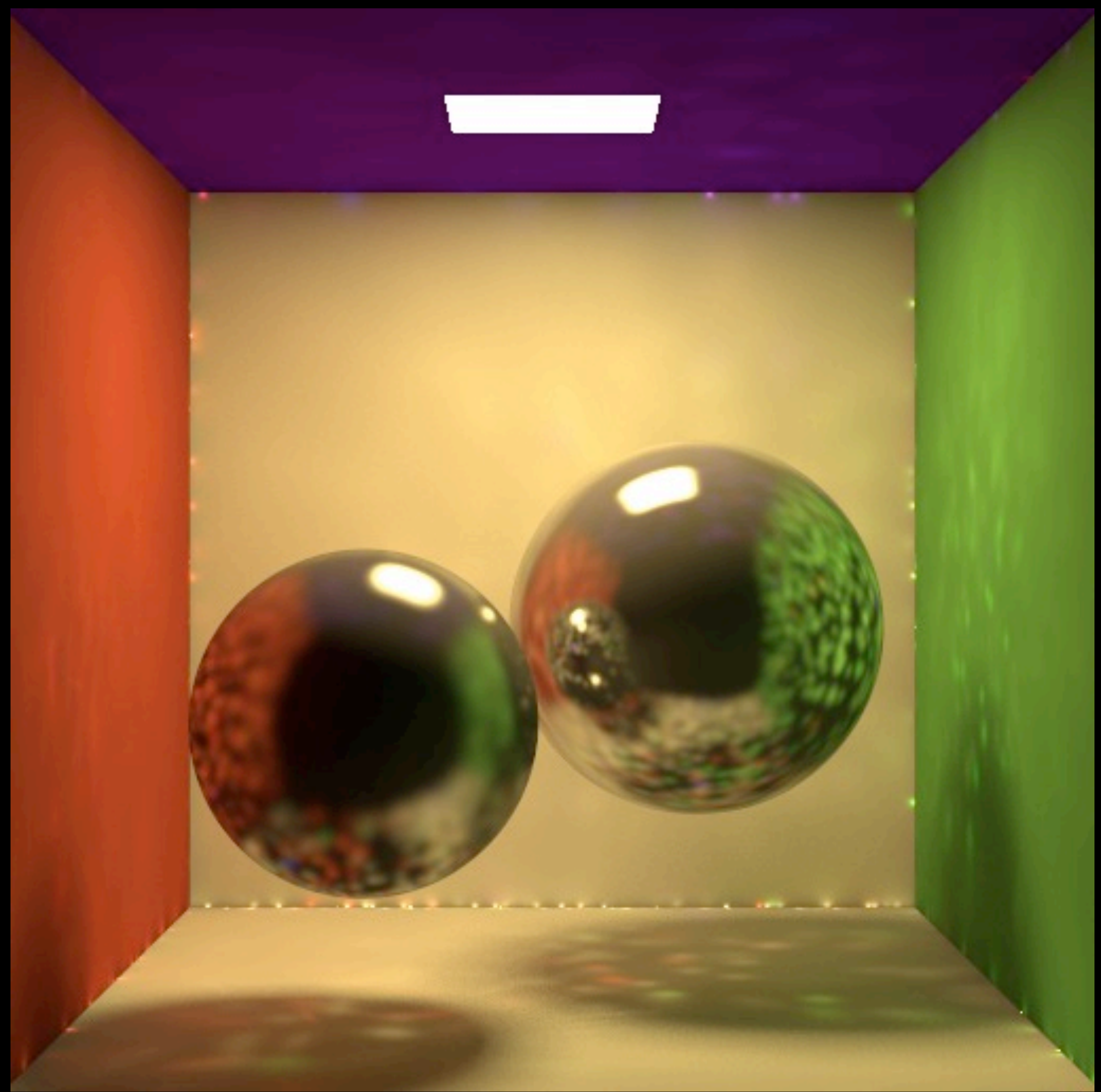
First Weight Constraint

- 1) Energy conservation
  - Weight sum ≤ 1
  - Reduce amortized cost
    - Prefer shorter eye paths

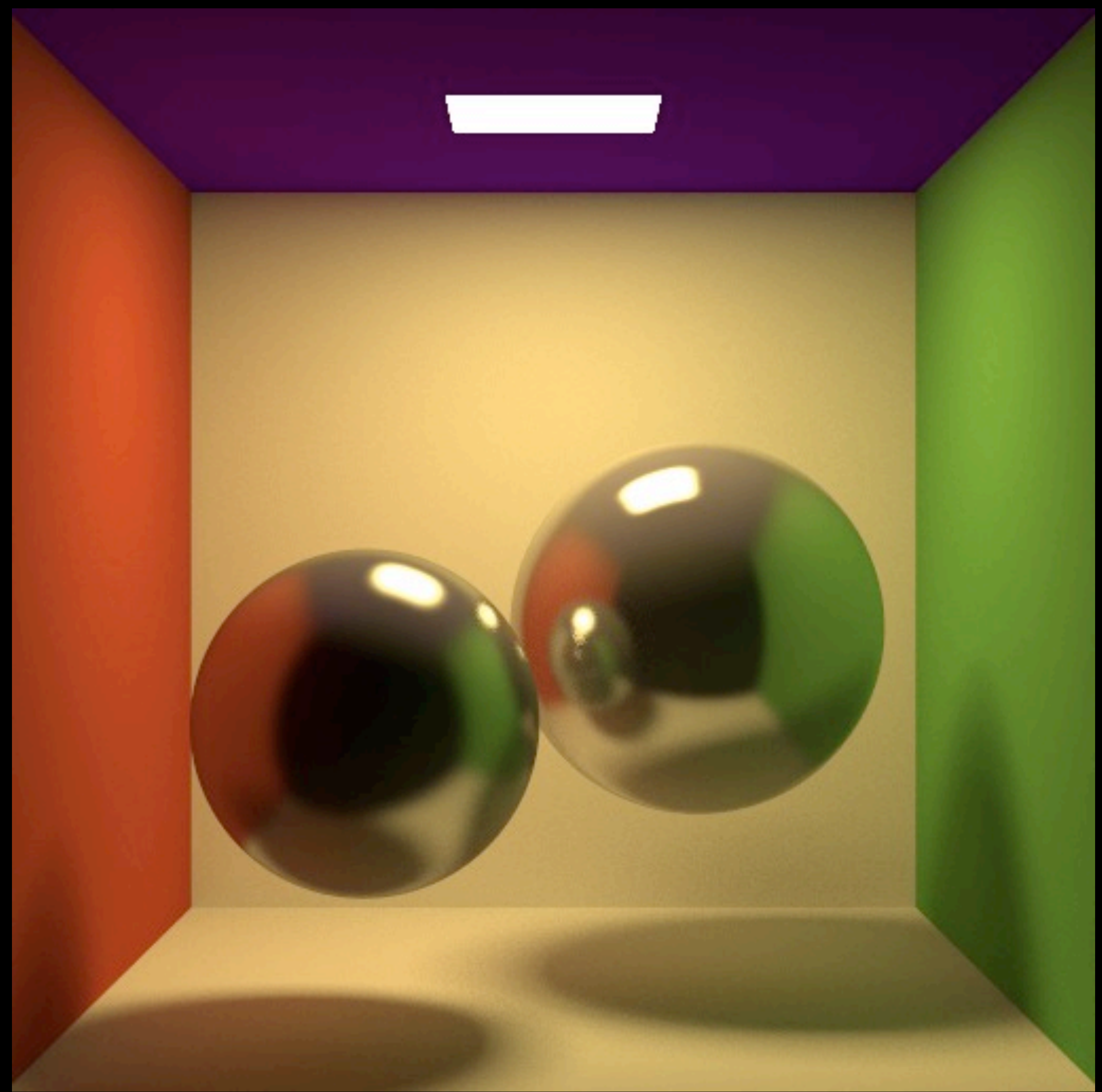


Second Weight Constraint

- 2) Clamping
  - Control VPL noise
    - Matches previous clamping [Walter et al. 06]



No clamping



With clamping

Third Weight Constraint

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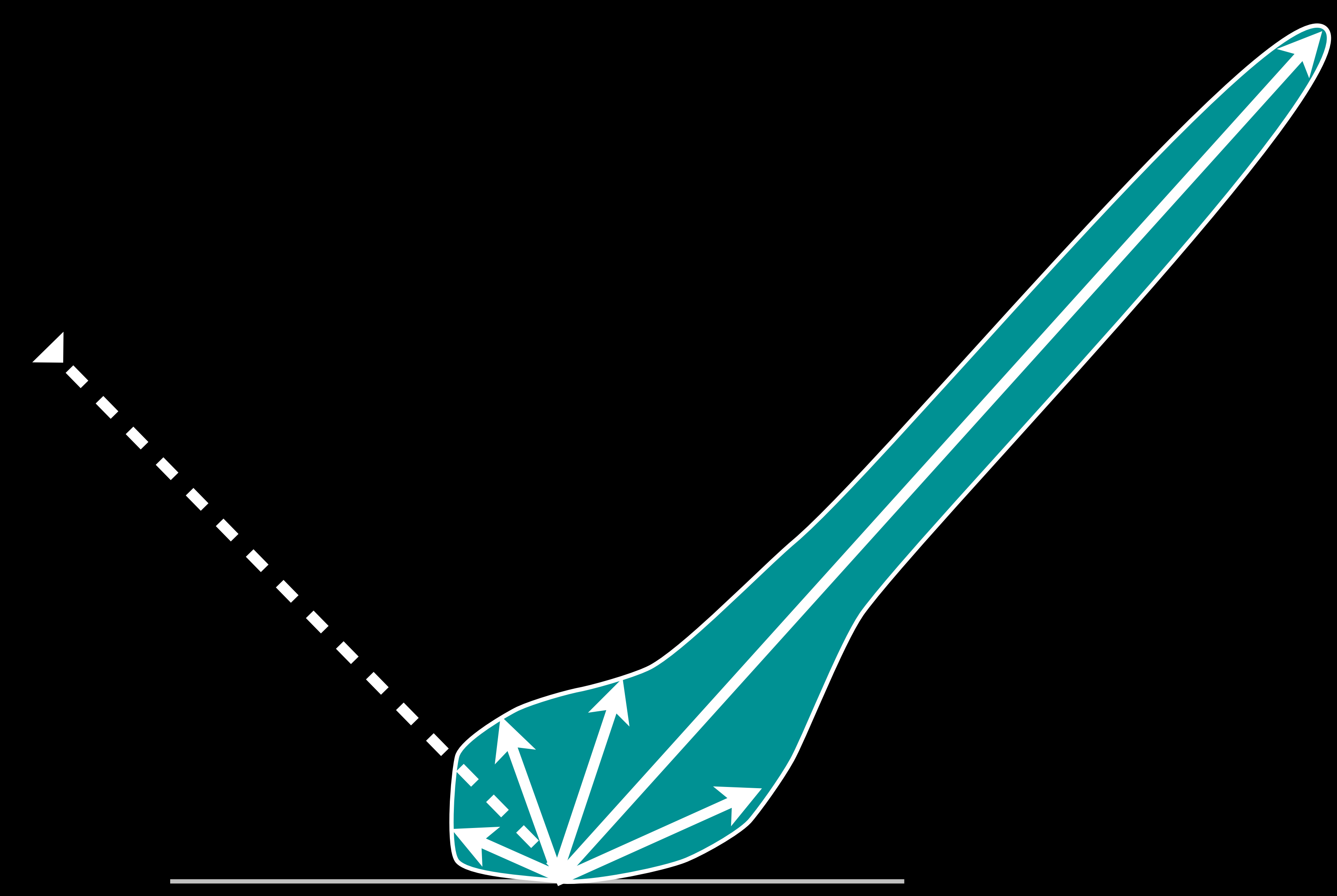
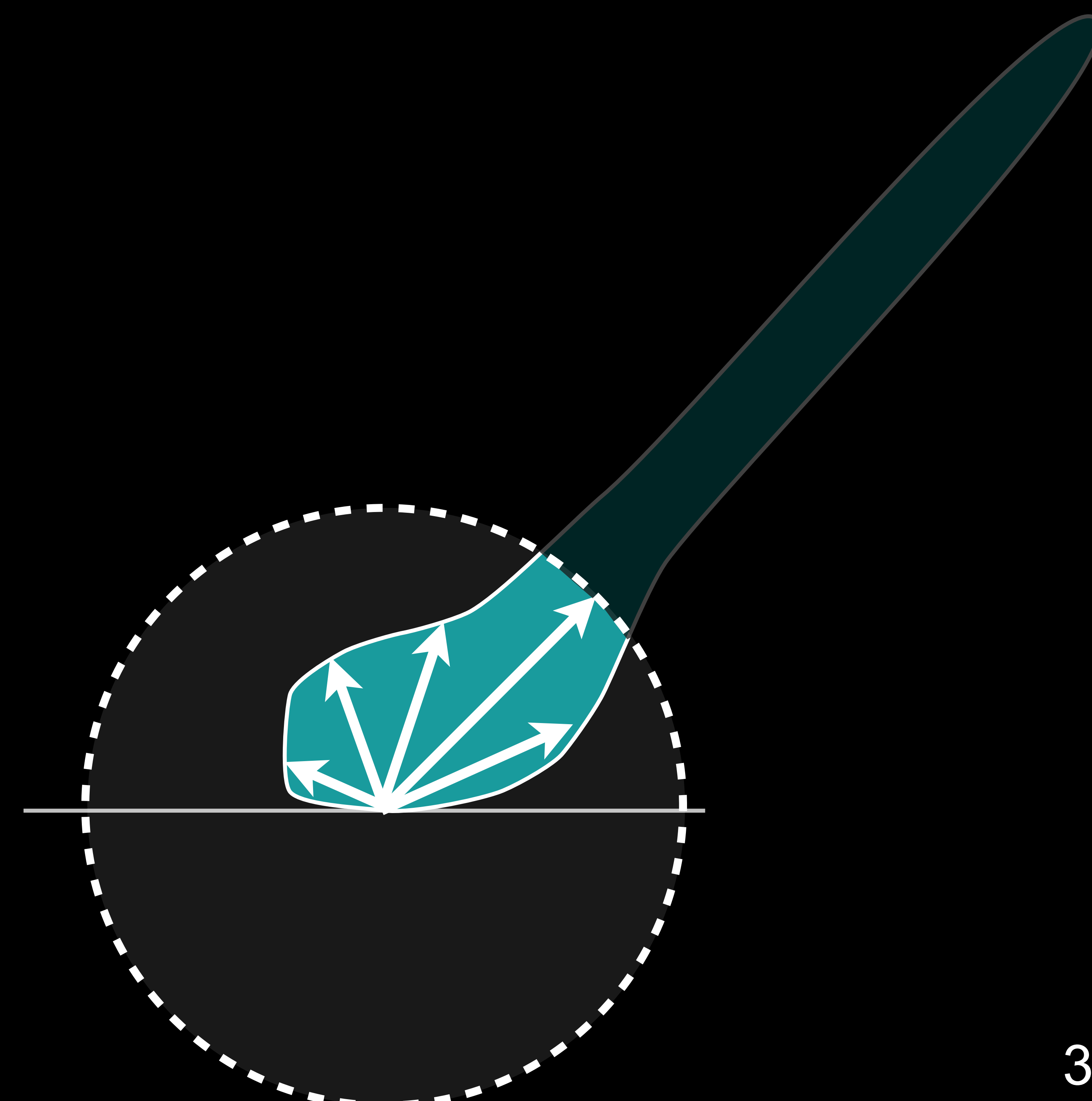
- 3) Diffuse VPLs:
  - Primarily a cost optimization
    - Narrowly directional VPLs are inefficient
    - Typically expensive with little effect



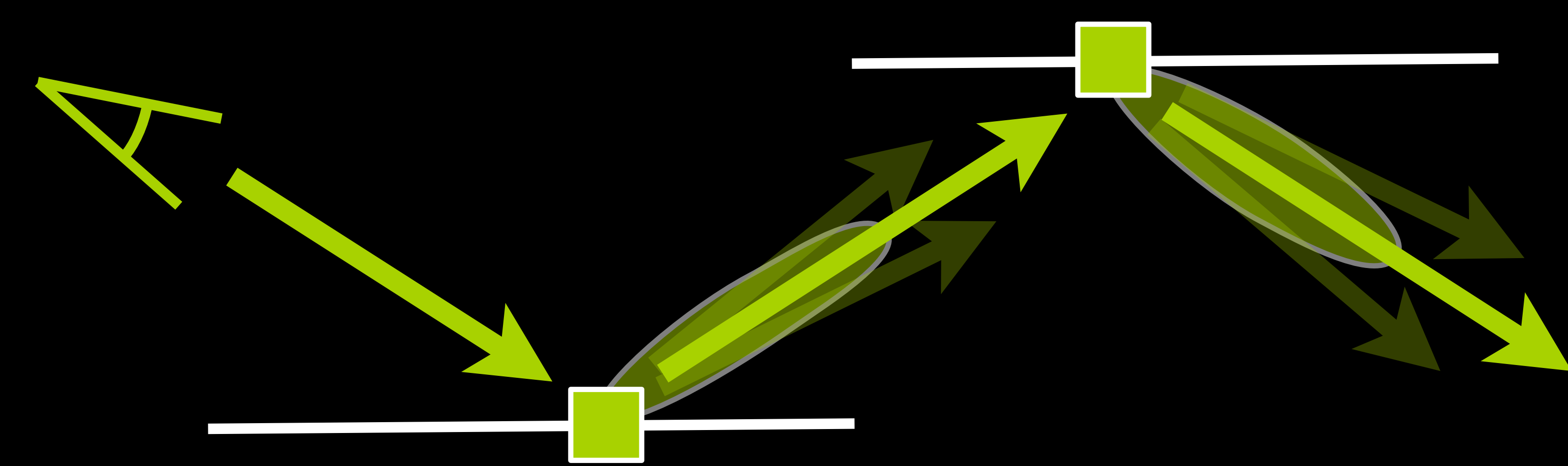
Third Weight Constraint

- 3) Diffuse VPLs:
  - Primarily a cost optimization
    - Narrowly directional VPLs are inefficient
    - Typically expensive with little effect
  - New diffuse vs. glossy classifier
    - Independent of material model
    - Preserves Lambertian, isotropic, etc.
    - Applicable to other rendering algorithms

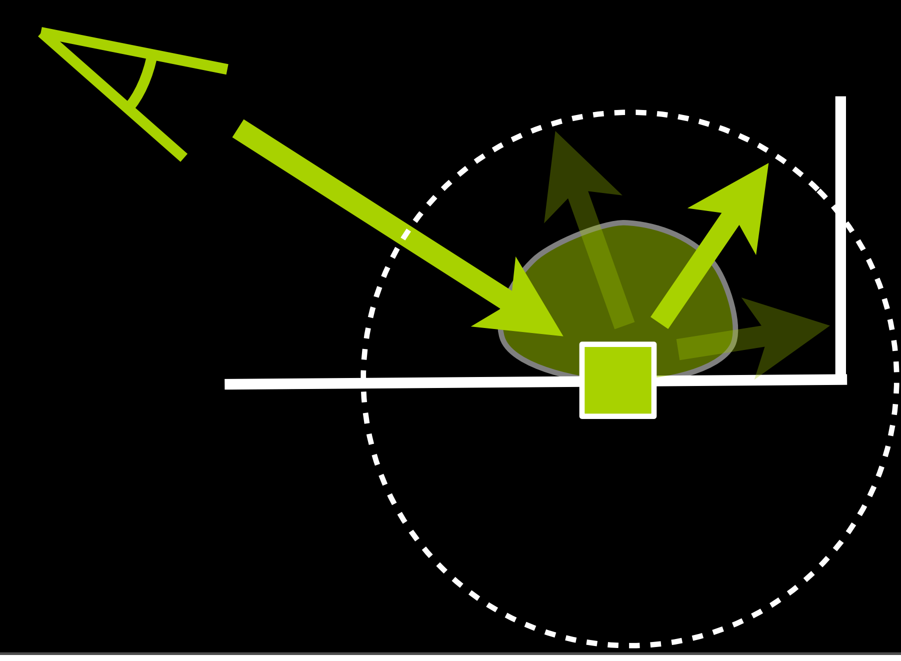


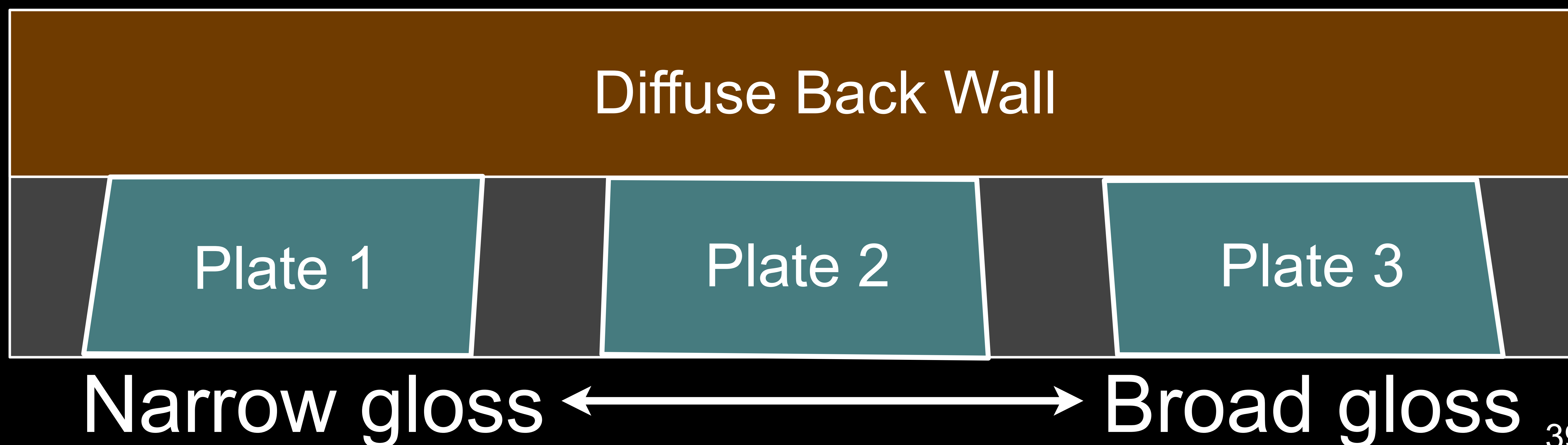
Fourth Weight Constraint

- 4) Exclude high variance eye paths:
  - Control VPS noise
  - Based on directional spread heuristic
    - 4a) Narrow eye ray spread
      - E.g., sharp glossy reflections
      - Unrestricted recursion

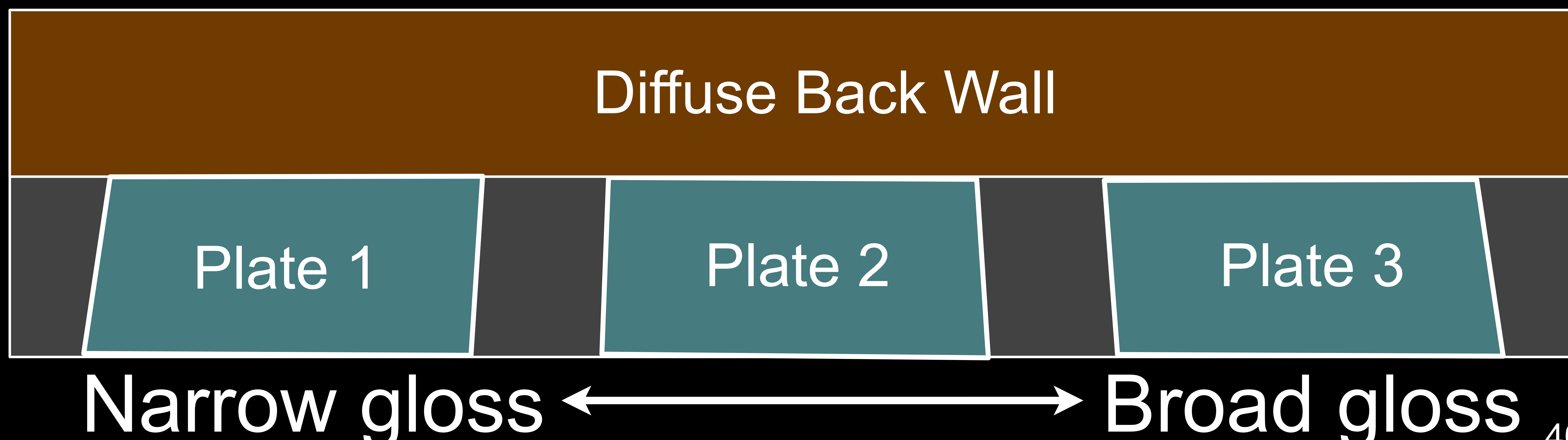


    - 4b) Wide eye ray spread
      - E.g., Subsurface, diffuse indirect
      - Restrict to short range effects only



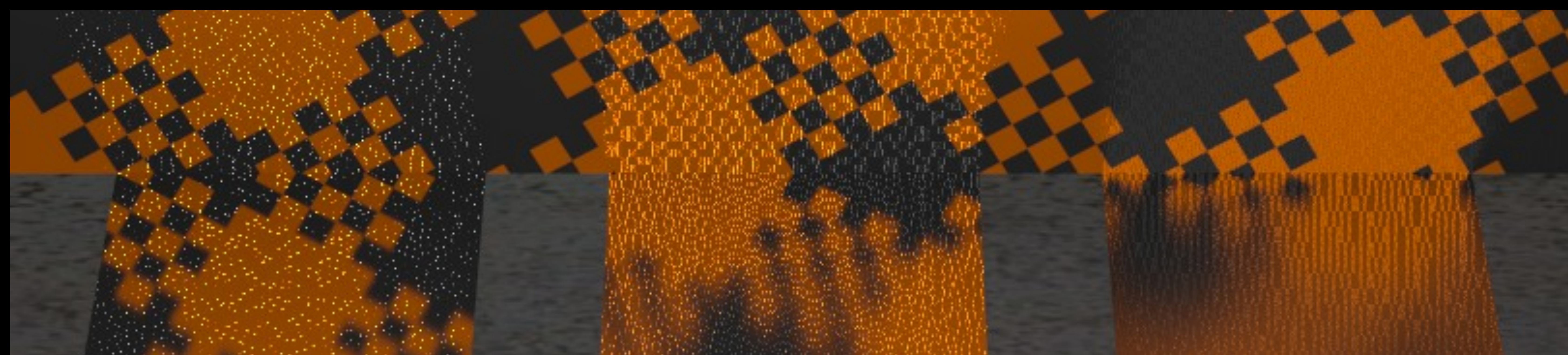

Diffuse Back Wall
Plate 1
Plate 2
Plate 3
Narrow gloss
Broad gloss

Standard VPL (not bidirectional)



Standard VPL
(not bidirectional)

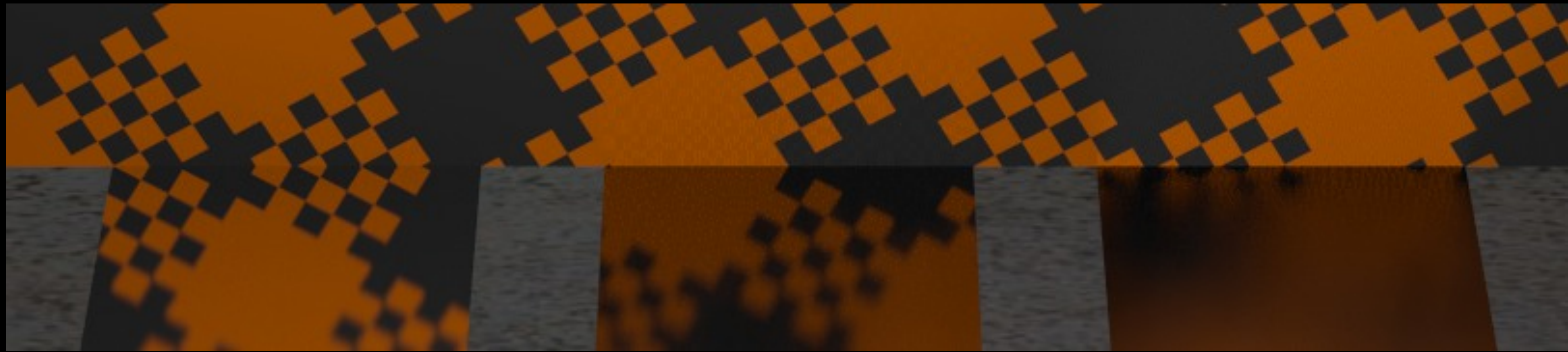
Without constraint 4
(unbiased)



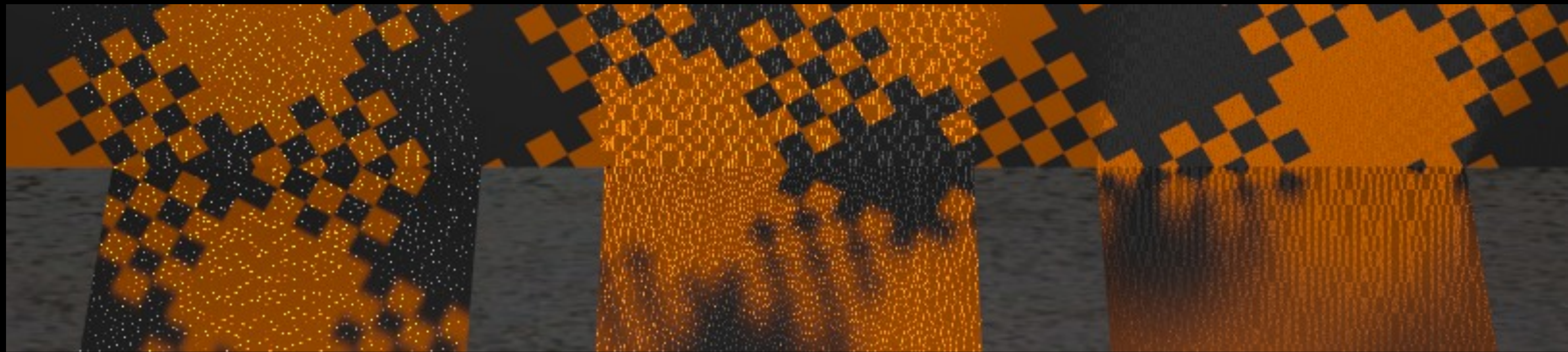
Narrow gloss ⟷ Broad gloss

Standard VPL
(not bidirectional)

With Constraint 4



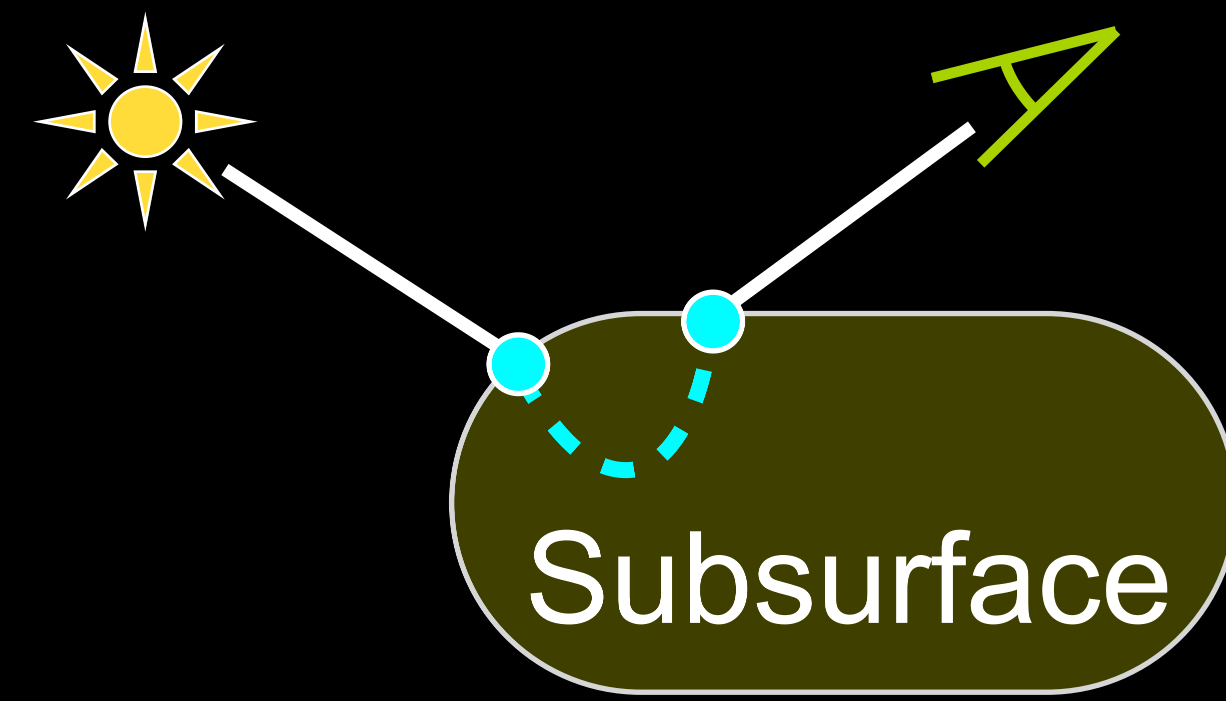
Without constraint 4
(unbiased)



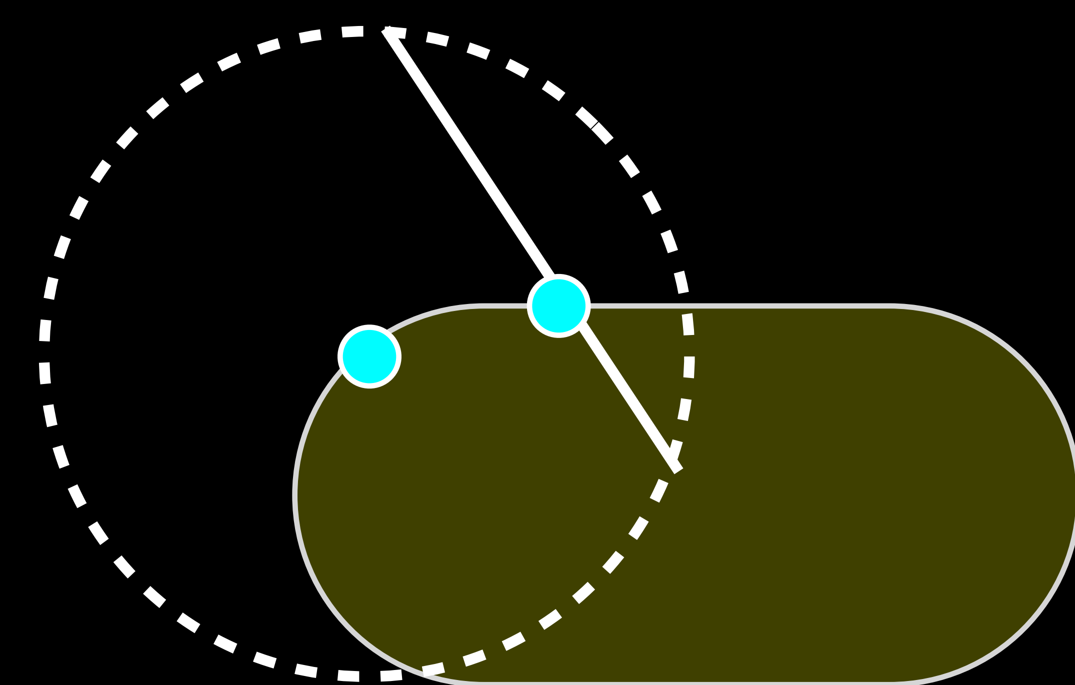
Narrow gloss ⟷ Broad gloss

Subsurface Extensions

- Path-based representation
  - 2 vertices plus special segment



- New BSSRDF sampling method
  - Ray tracing random chords on spheres



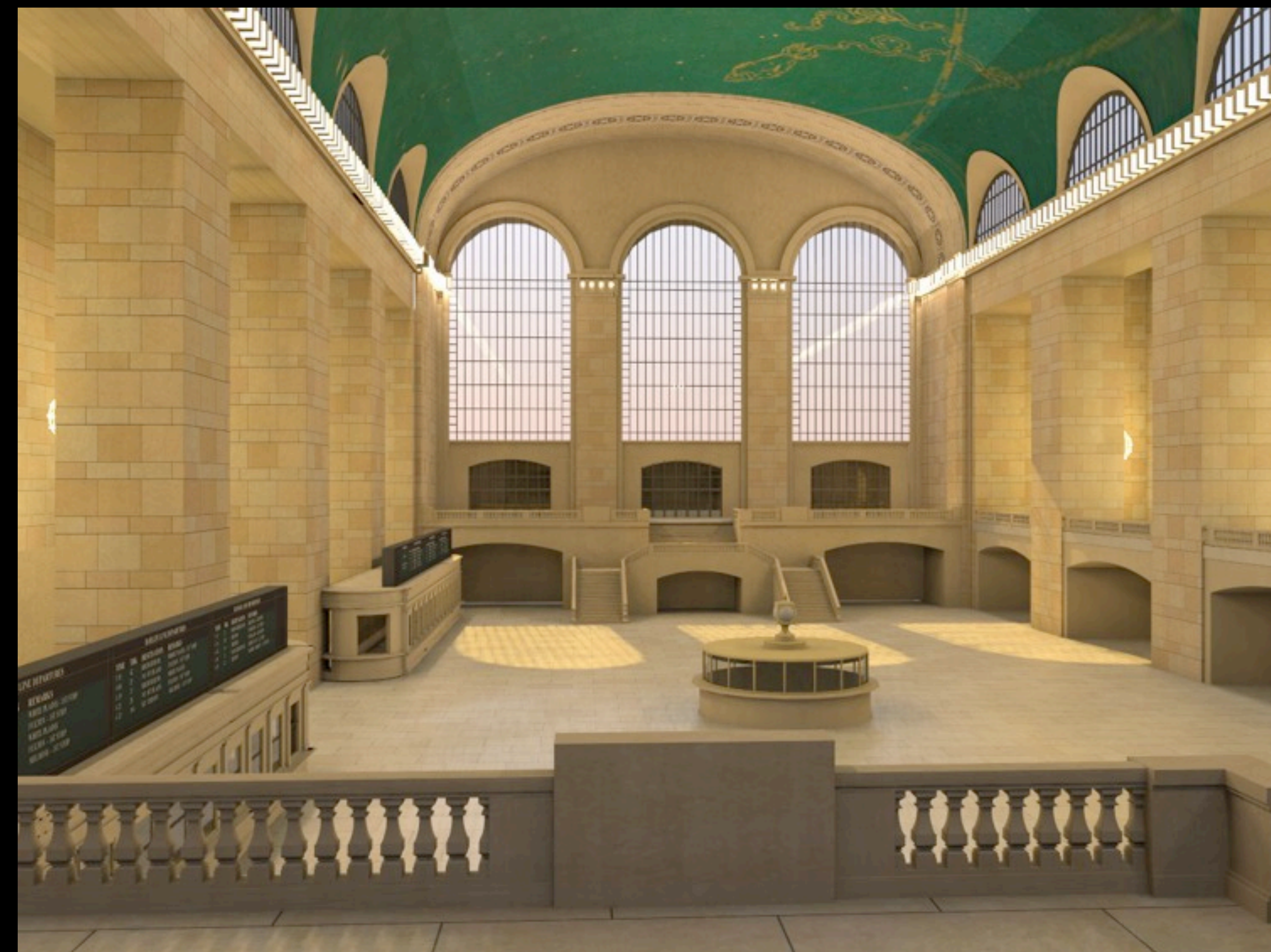
- Applicable to other path-based algorithms

Outline

- Prior work: VPL and Bidirectional review
- New weighting strategy
- Integration with Multidimensional Lightcuts
- Results

Multidimensional Lightcuts

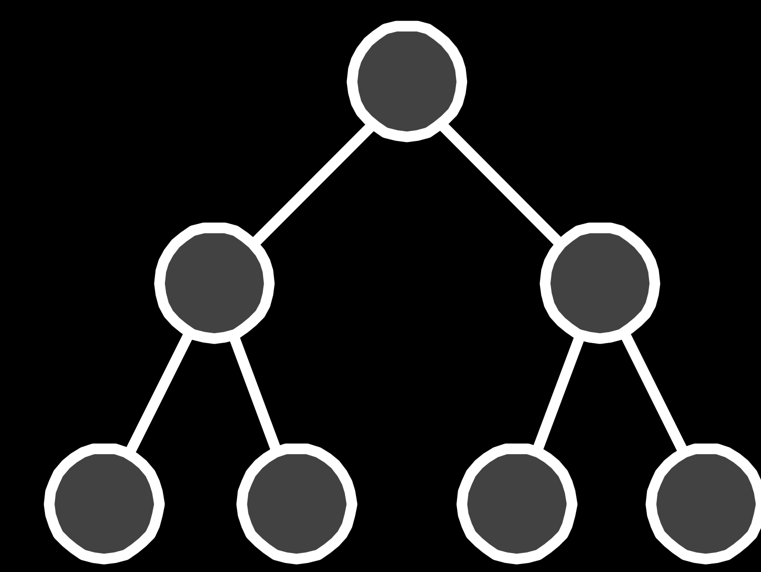
- Millions of sensor/light pairs per pixel
  - Brute force → expensive
- Multidimensional Lightcuts
  - Evaluate small subset of pairs



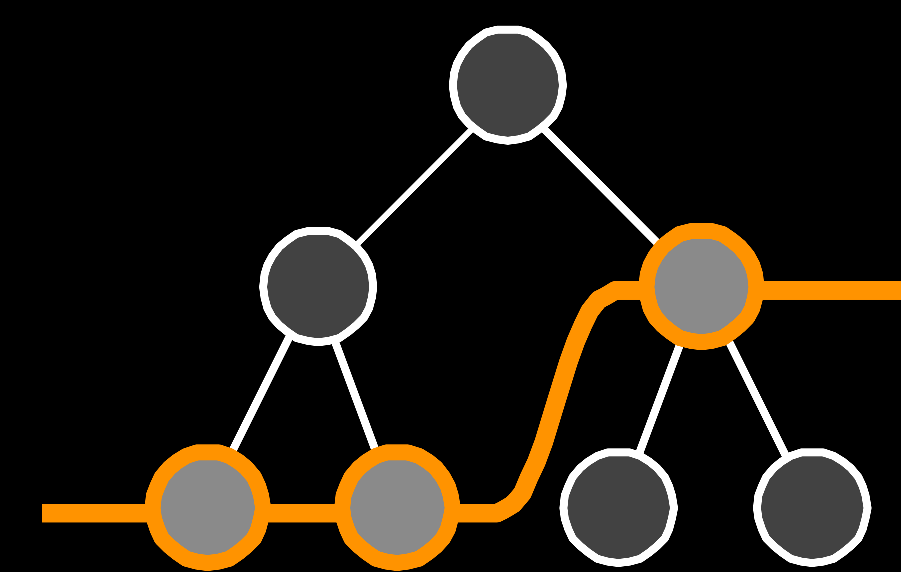
Grand Central [Walter et al. 05]
0.03% of sensor/light pairs evaluated

Multidimensional Lightcuts

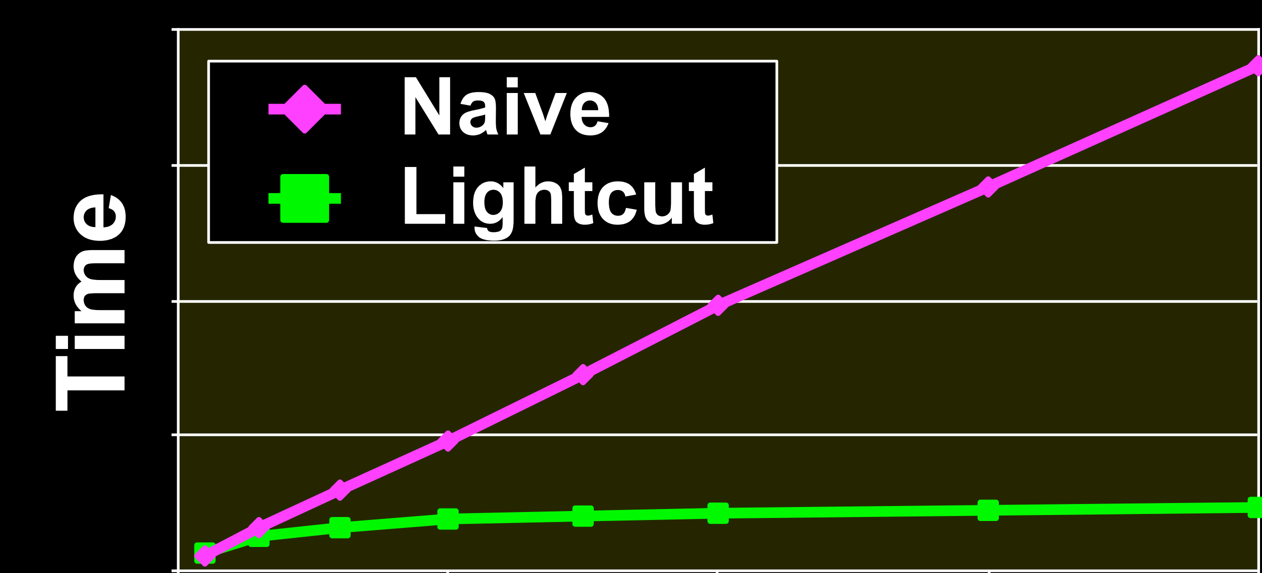
- Cluster points into hierarchies



- Adaptive select cut (partition)
  - Bound max error per cluster
  - Refine until below perceptual threshold

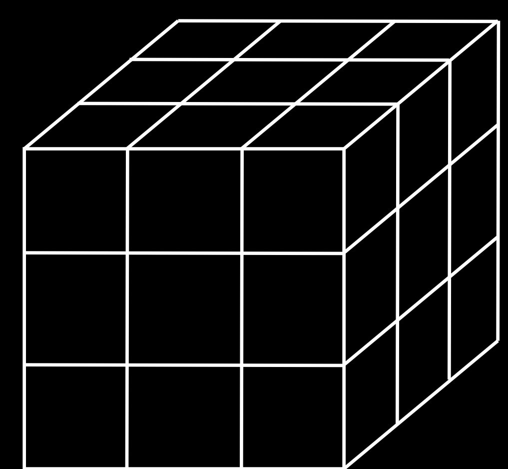


- Sublinear cost per point
  - Used in Autodesk® 360 Rendering
    - A million images this year

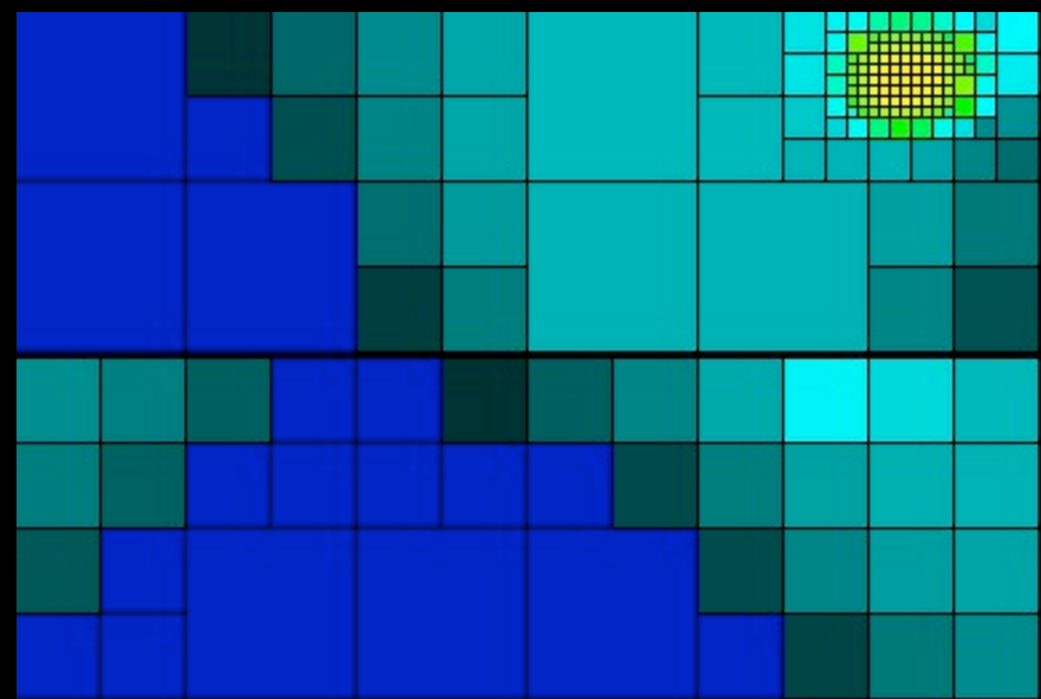


Lightcuts Integration

- Lightcut extensions
  - New material types
  - Added weighting terms to bounding and evaluation
  - Quad-tree cubemaps representation for bounds



Cubemap



Unfolded quad-tree cubemap

Outline

- Prior work: VPL and Bidirectional review
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- Results

Results: Accurate Materials

Glossy

Standard VPL

Our Method

Results: Accurate Materials

Glossy

Subsurface

Standard VPL

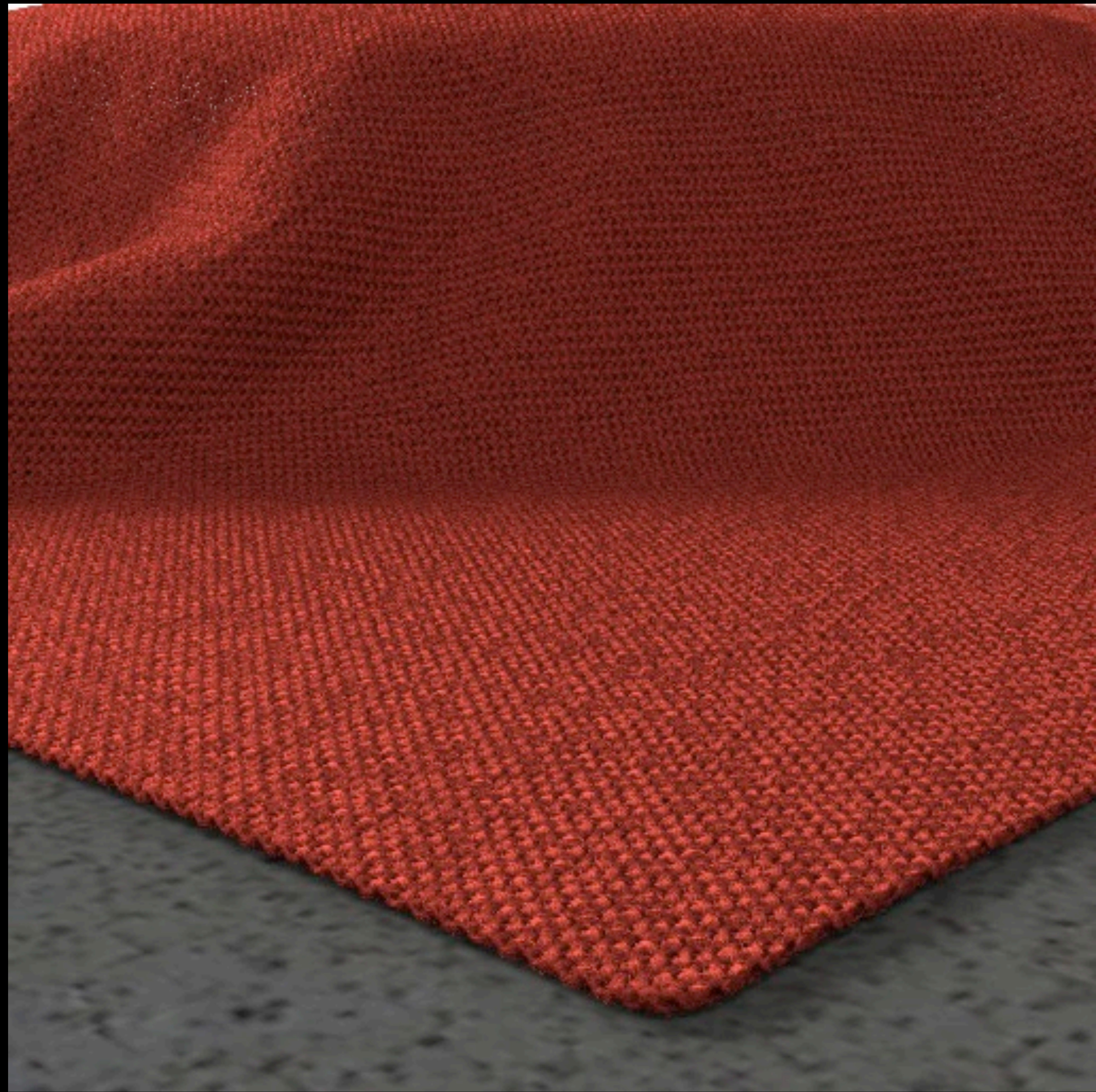
Our Method

Results: Accurate Materials

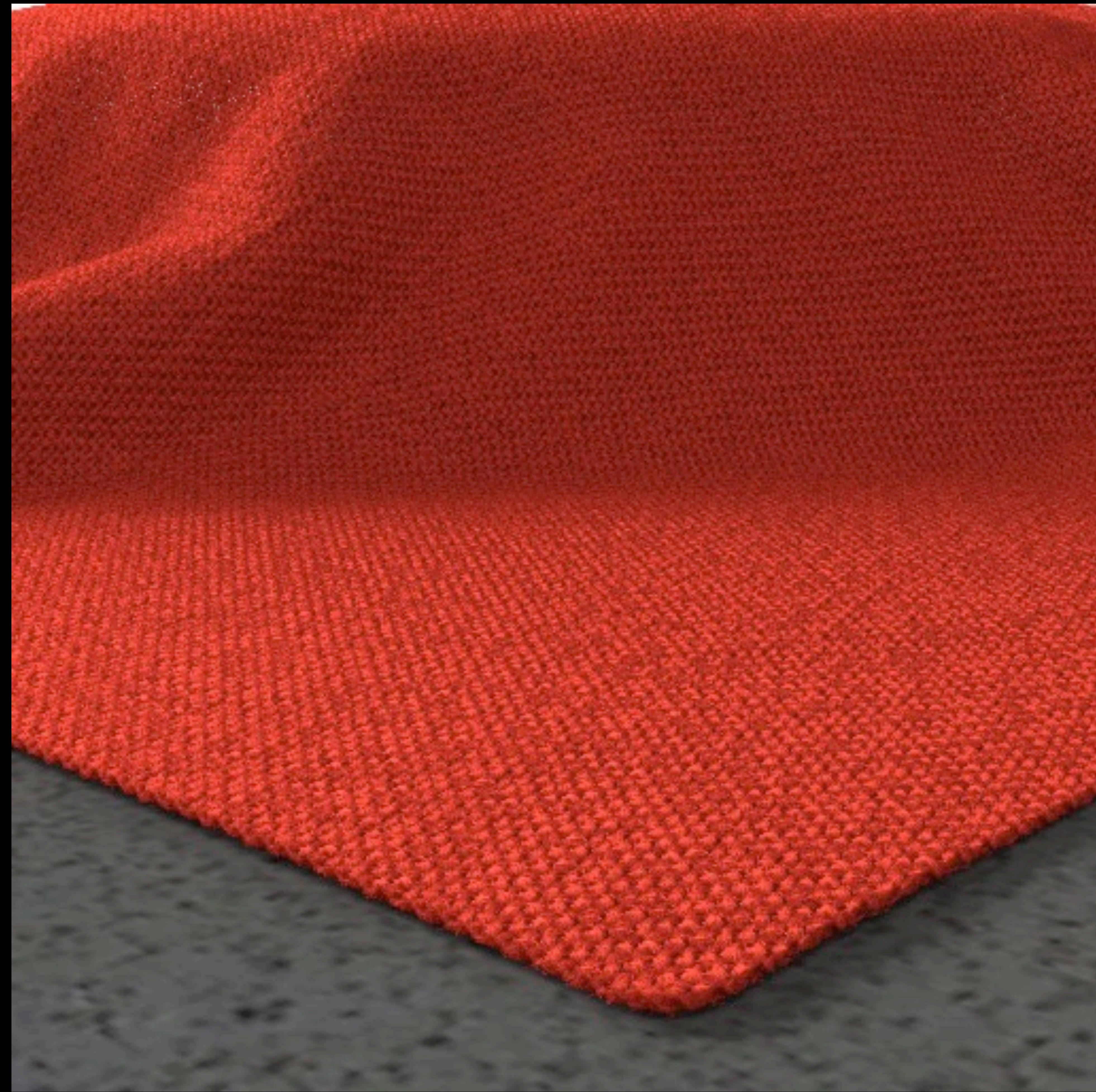
Glossy

Subsurface

Volumetric



Standard VPL



Our Method

Anisotropic volumetric fiber model (giga-voxel resolution)

Bidirectional Lightcuts

Standard VPL

Bidirectional Lightcuts

Standard VPL

+

Bidirectional Estimators

Bidirectional Lightcuts

Standard VPL | Bidirectional Estimators | Our Method

- Accurate rendering of complex materials
  - e.g., glossy counter, subsurface milk, volumetric cloth

Timing Results

Standard VPL

Ball

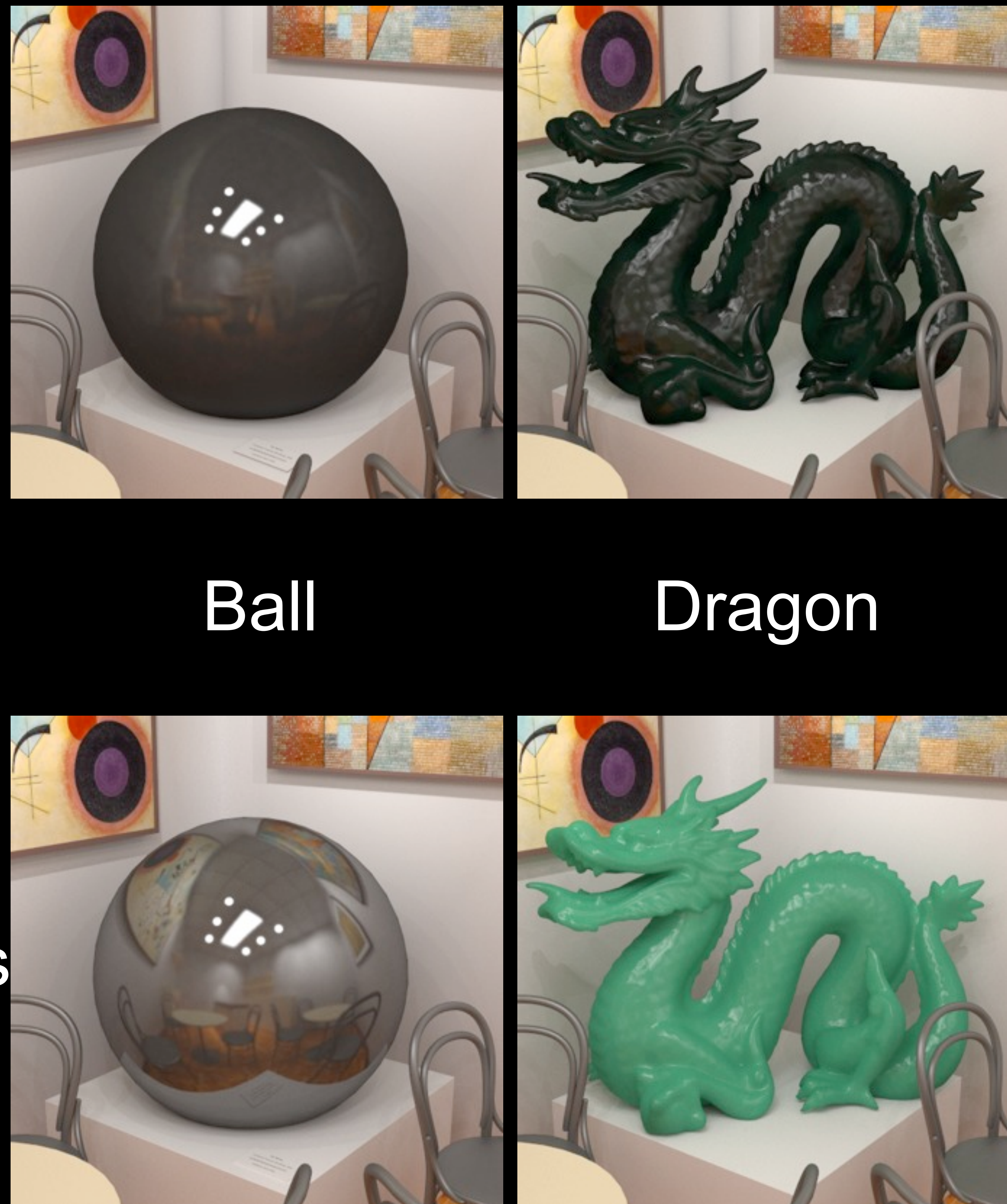
Bidirectional Lightcuts

Images 512x512, 1 million VPLs, 64 eye rays per pixel, 4 cores at 3.4GHz

Timing Results

Standard VPL

Bidirectional Lightcuts



Ball

Dragon

Images 512x512, 1 million VPLs, 64 eye rays per pixel, 4 cores at 3.4GHz

Timing Results

Standard VPL

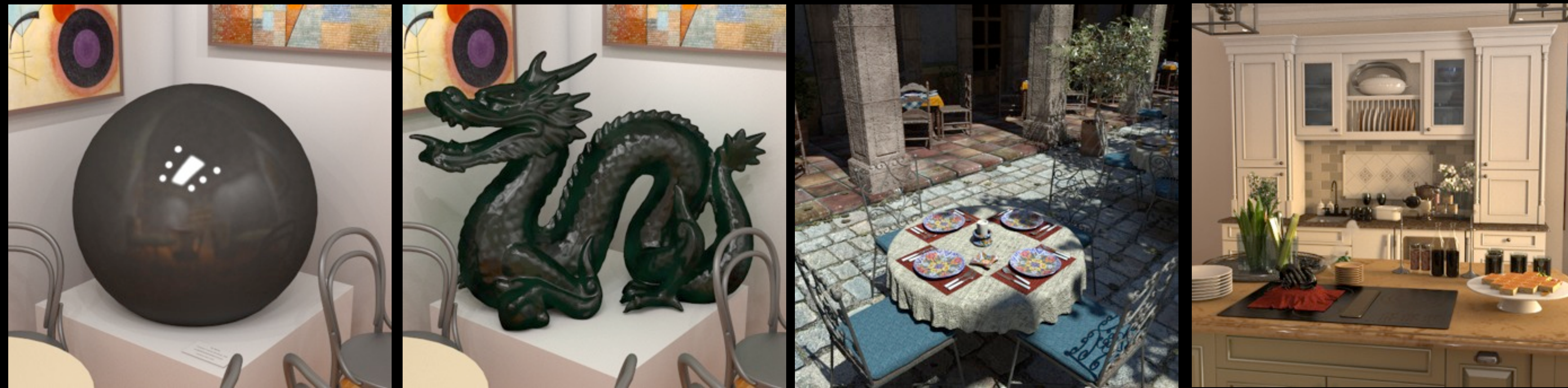
Ball | Dragon | SanMiguel

Bidirectional Lightcuts

Images 512x512, 1 million VPLs, 64 eye rays per pixel, 4 cores at 3.4GHz

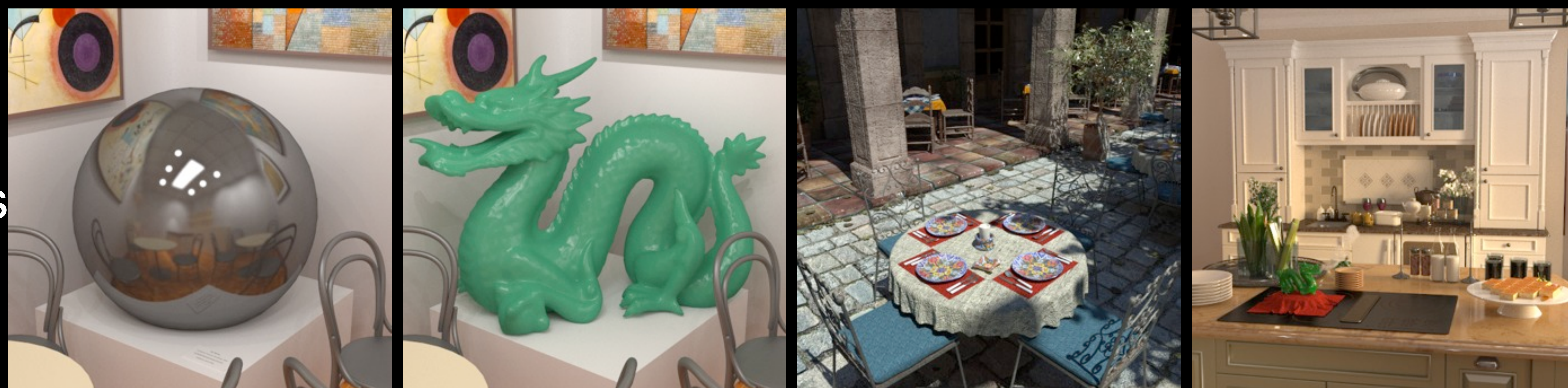
Timing Results

Standard VPL



Ball | Dragon | SanMiguel | Kitchen

Bidirectional Lightcuts



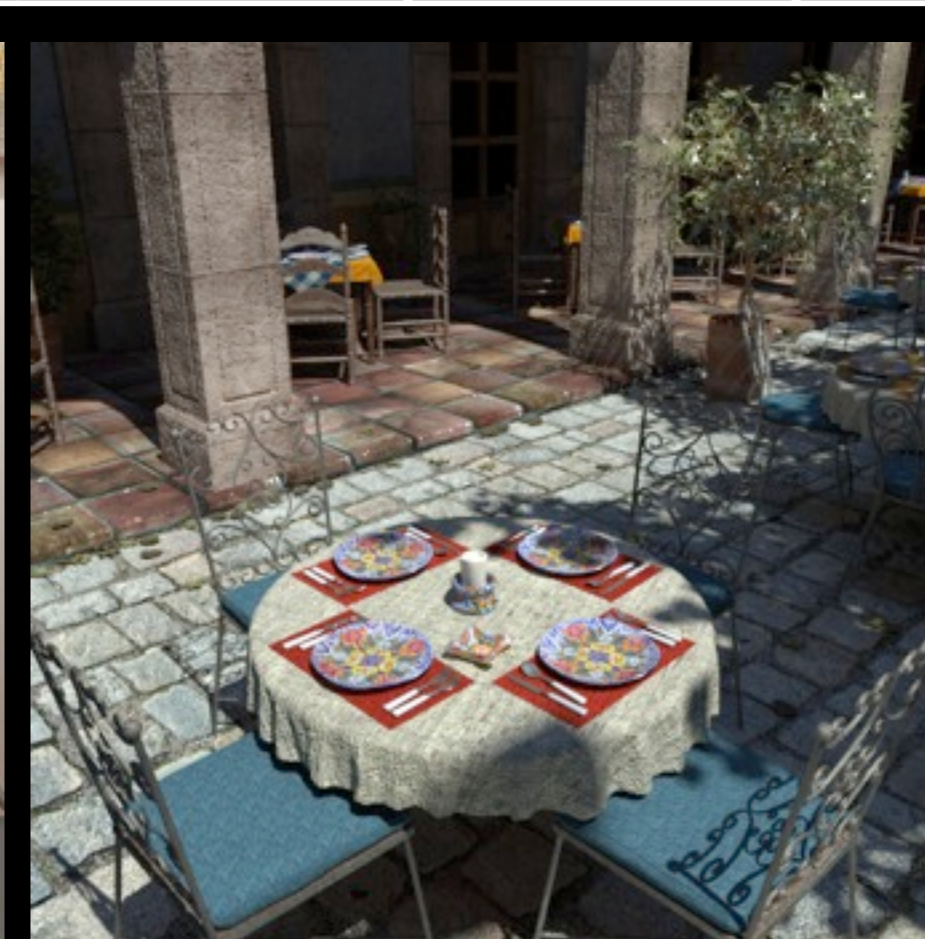
Images 512x512, 1 million VPLs, 64 eye rays per pixel, 4 cores at 3.4GHz

Timing Results




Lightcuts (standard)	346s	359s	434s	1076s
Bidirectional	479s (**+38%**)	745s (**+107%**)	618s (**+42%**)	1803s (**+67%**)






Images 512x512, 1 million VPLs, 64 eye rays per pixel, 4 cores at 3.4GHz

Limitations and Future Work

- Noise control relies on heuristics
  - Effective in our tests but without guarantees
- Cannot handle some phenomena (e.g., caustics)
  - VPL methods are ill-suited to such paths
  - Combine with specialized algorithms

Conclusion

- VPL-based rendering has many advantages
  - Low noise
  - Scalable performance
  - Limited in materials and effects

- Bidirectional extension
  - Wider range of materials
  - Enable new applications

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The End

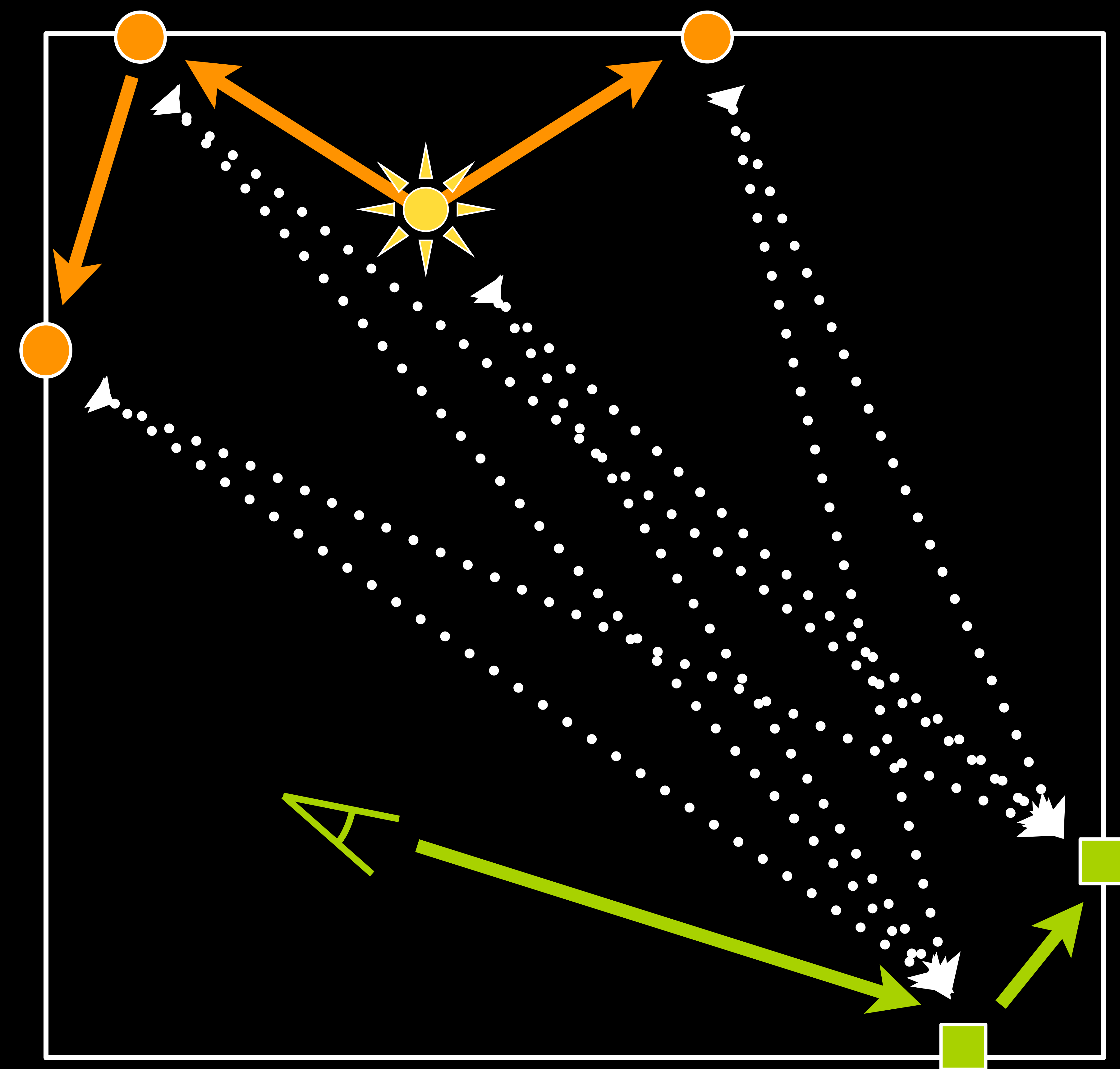
- Acknowledgements
  - Models and assistance:

    Edgar Velazquez-Armendariz, Shuang Zhao, Adam Arbree, John Hutchinson, Jaroslav Krivanek, Guillermo M. Leal Llaguno, Stanford Graphics Lab

  - Funded by:
    - National Science Foundation
    - Autodesk
    - Intel Science and Technology Center - Visual Computing

Summary

- Bidirectional VPL algorithm
  - Recursive sensor generation
  - Novel weighting scheme
    - Control bias vs. noise tradeoff
  - Scalable and low noise
    - Integrated with Lightcuts



- General techniques
  - New BSSRDF sampling
  - Model independent diffuse classifier

Equal Time Comparison

Progressive Photon Map

Our Method

Bidirectional Path Trace

Enlarged