MULTIVERSAL RAY TRACING

JON SARGENT

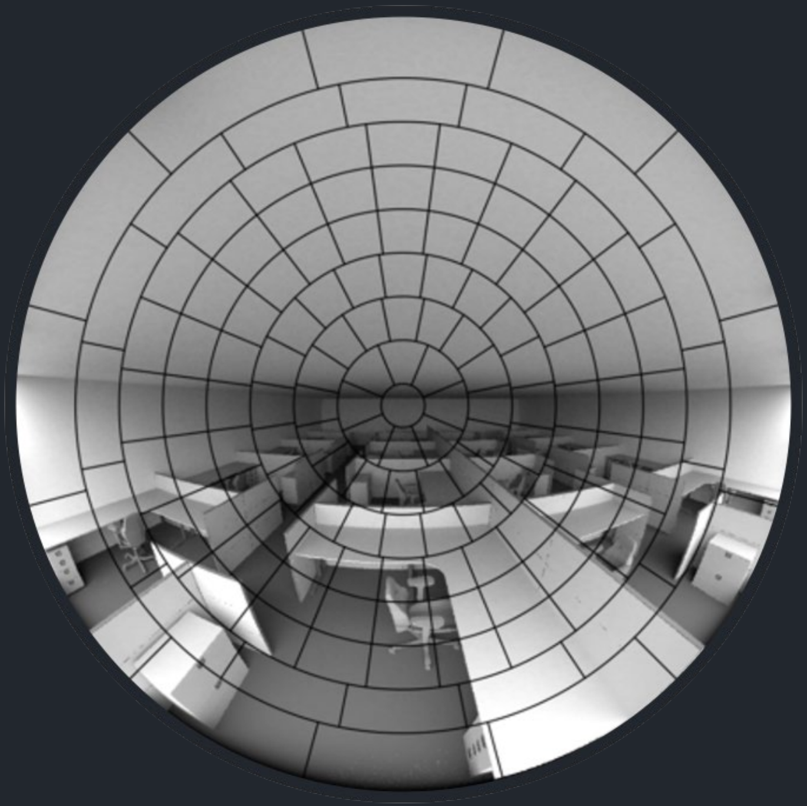
Environment

DYNAMISM

Environment

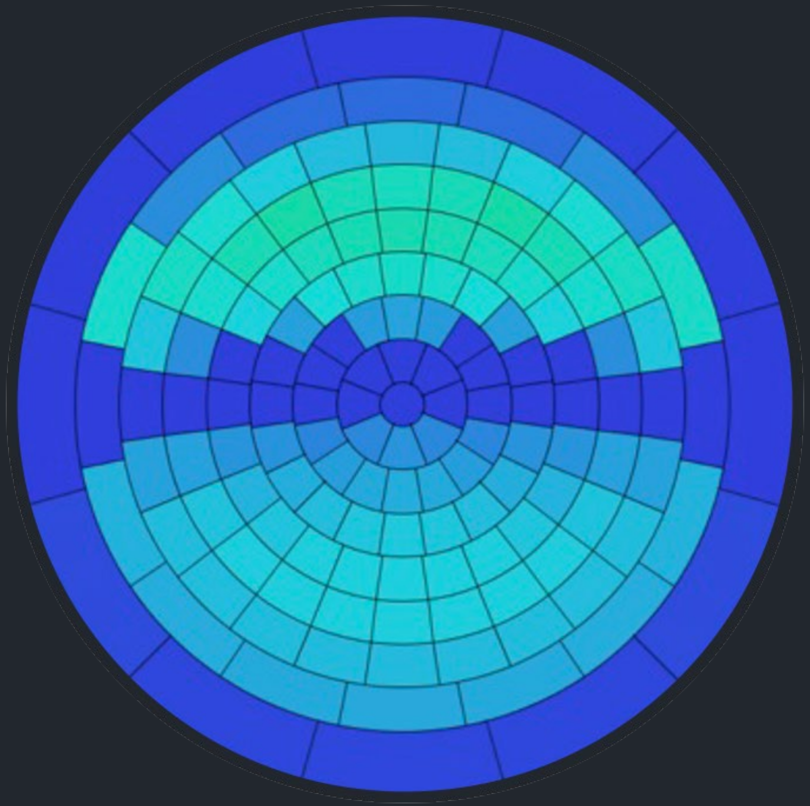
Scene

View



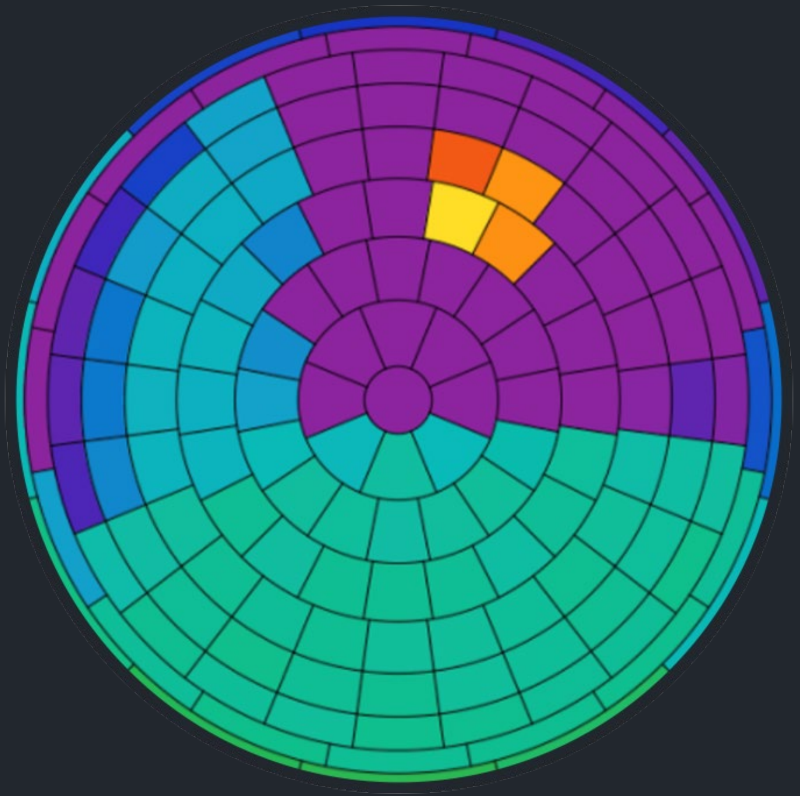
sensor-to-window

Transmission



through-window

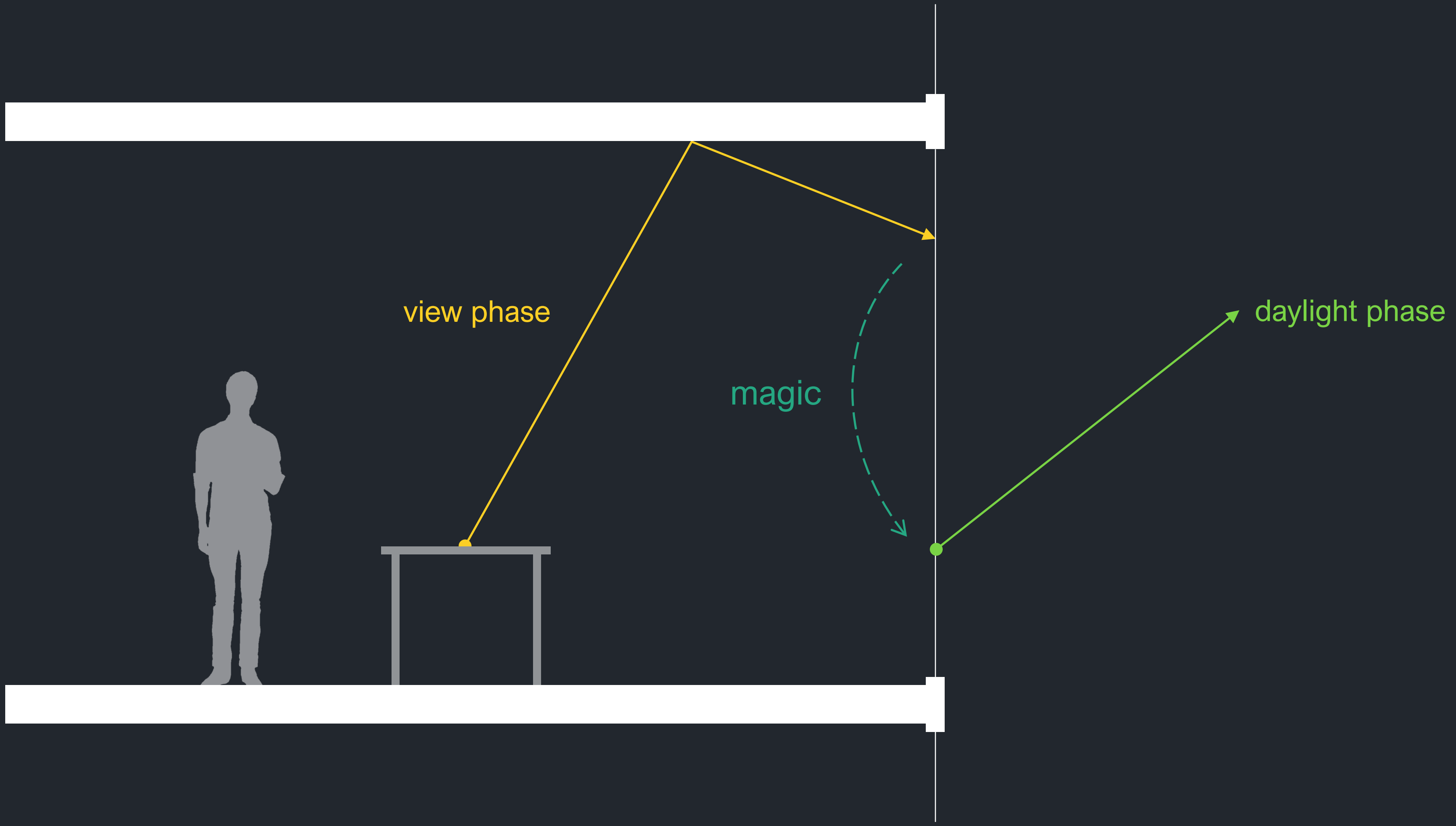
Daylight



window-to-sky

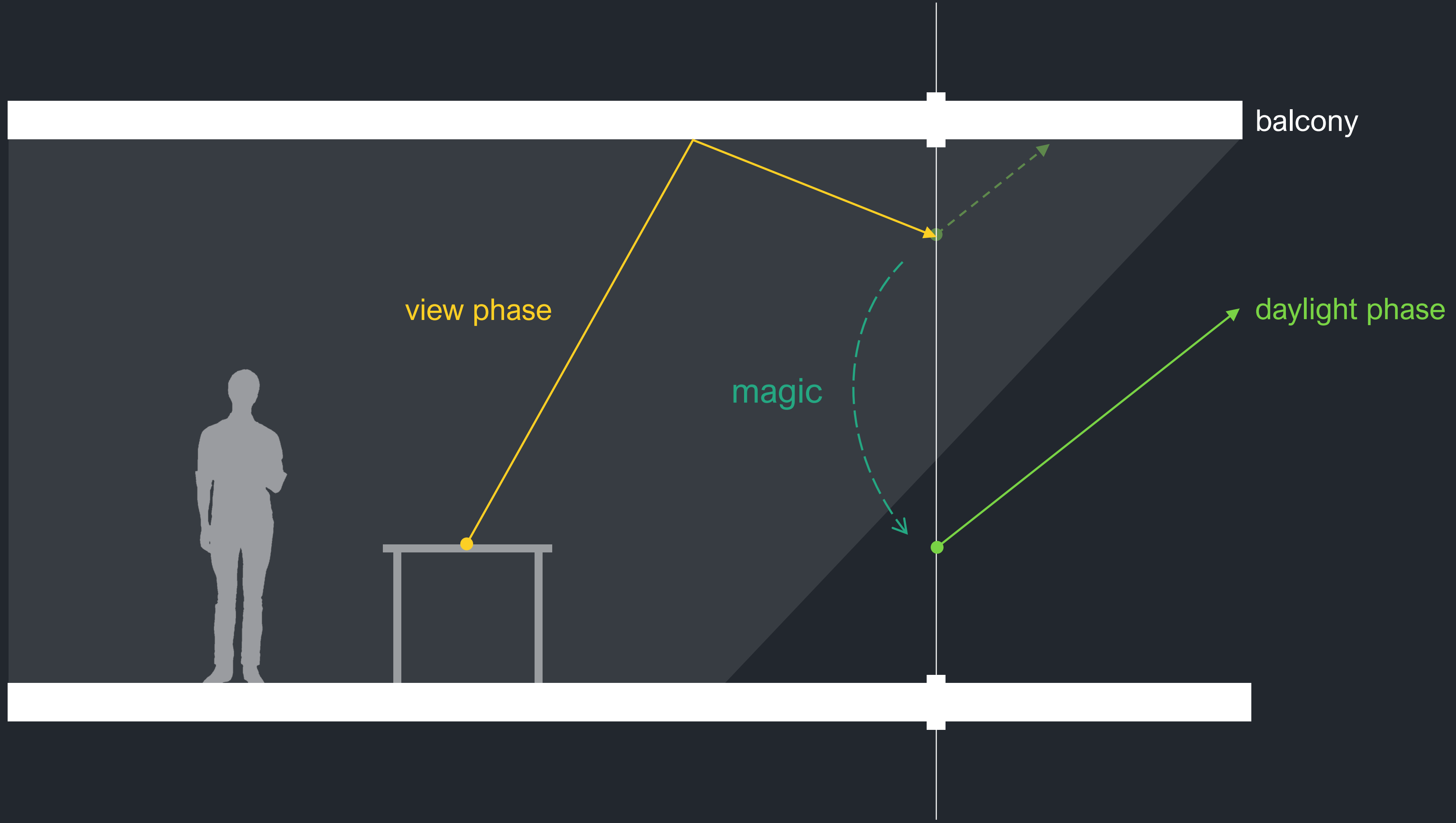
image credits: Andy McNeil, LBNL

The Teleportation Problem



SOLEMMA

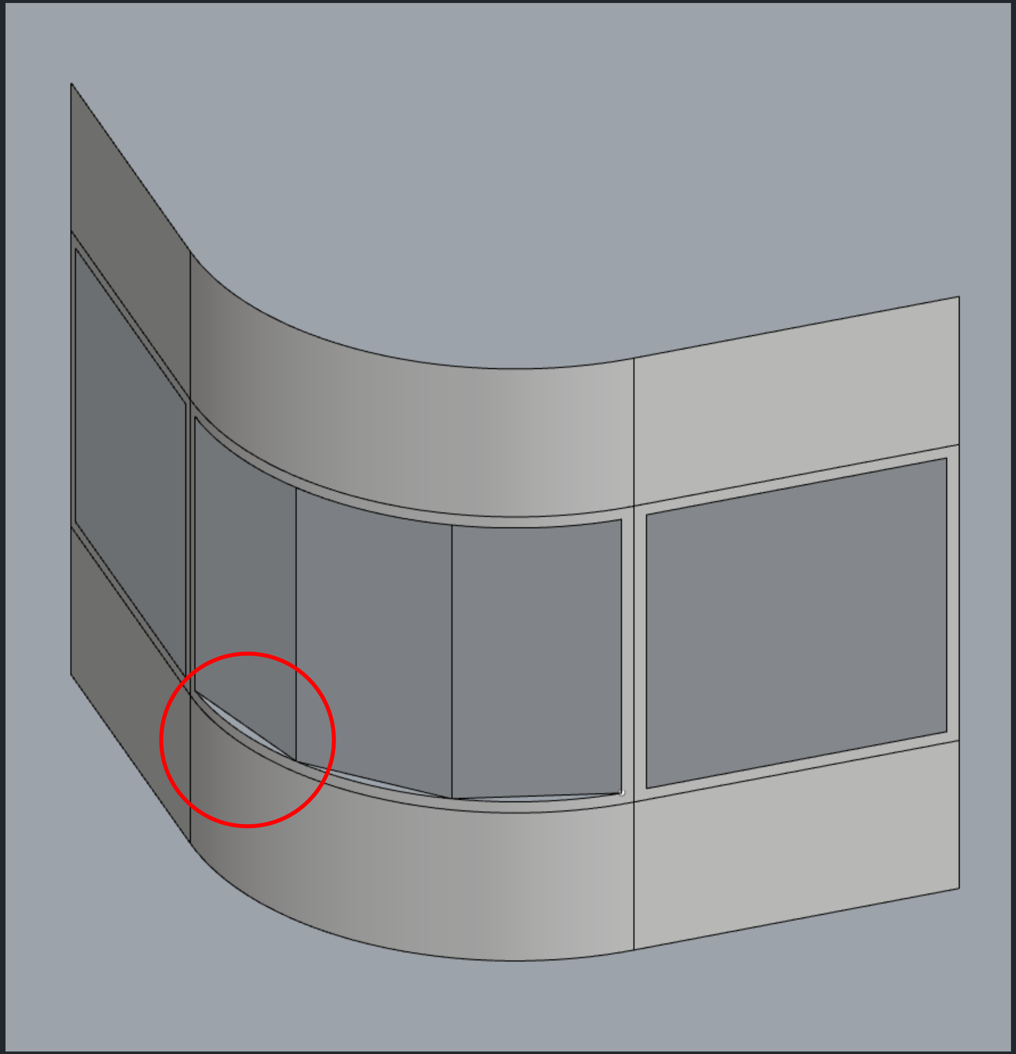
The Teleportation Problem



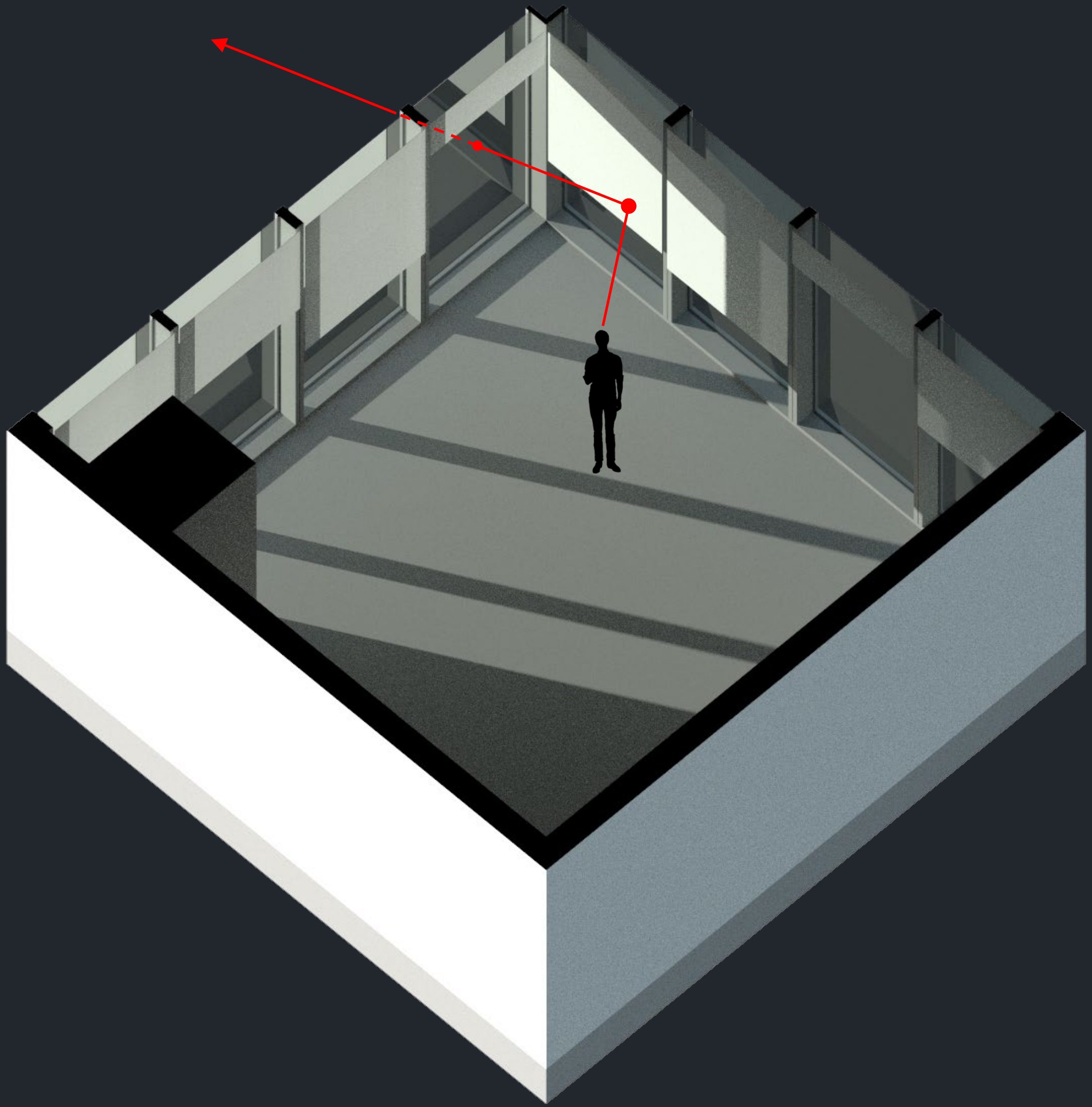
SOLEMMA

The Curvature Problem

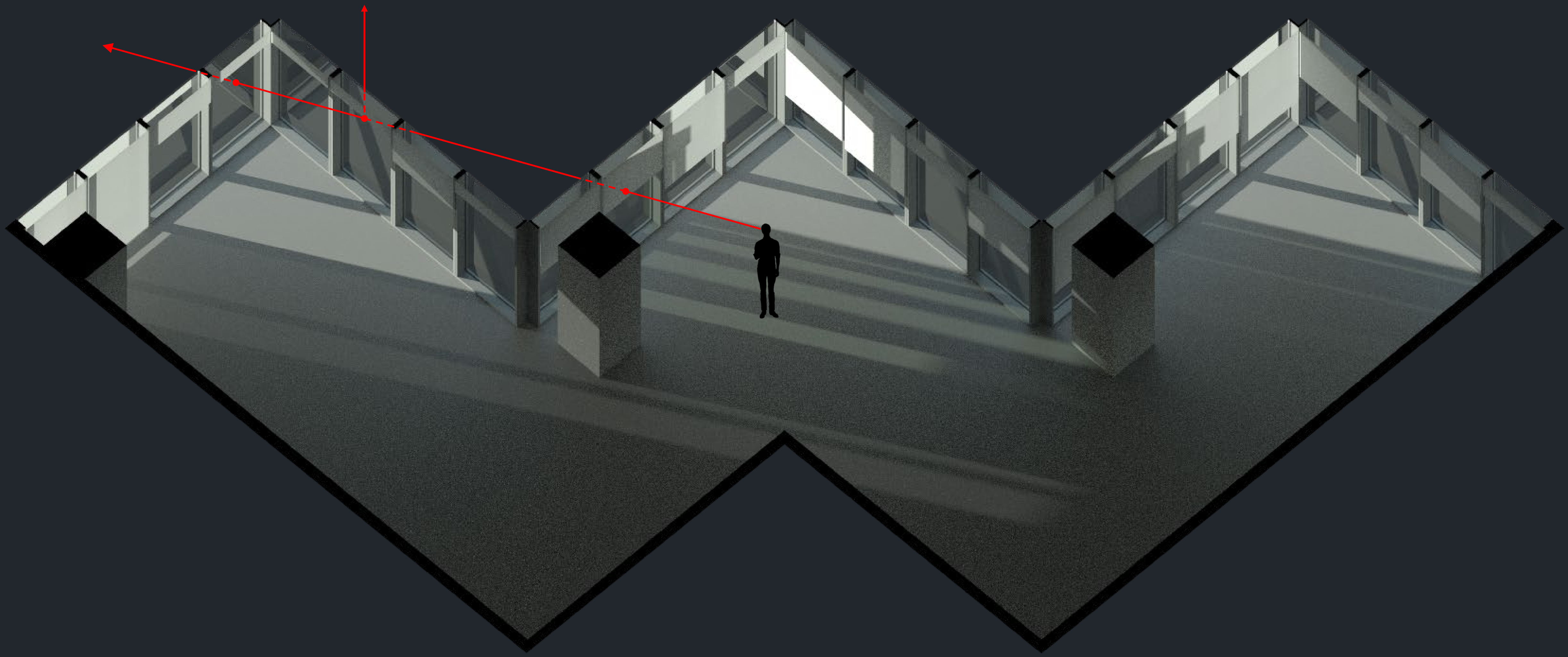
One Front Street, San Francisco [photo credit: Eric Hunt]



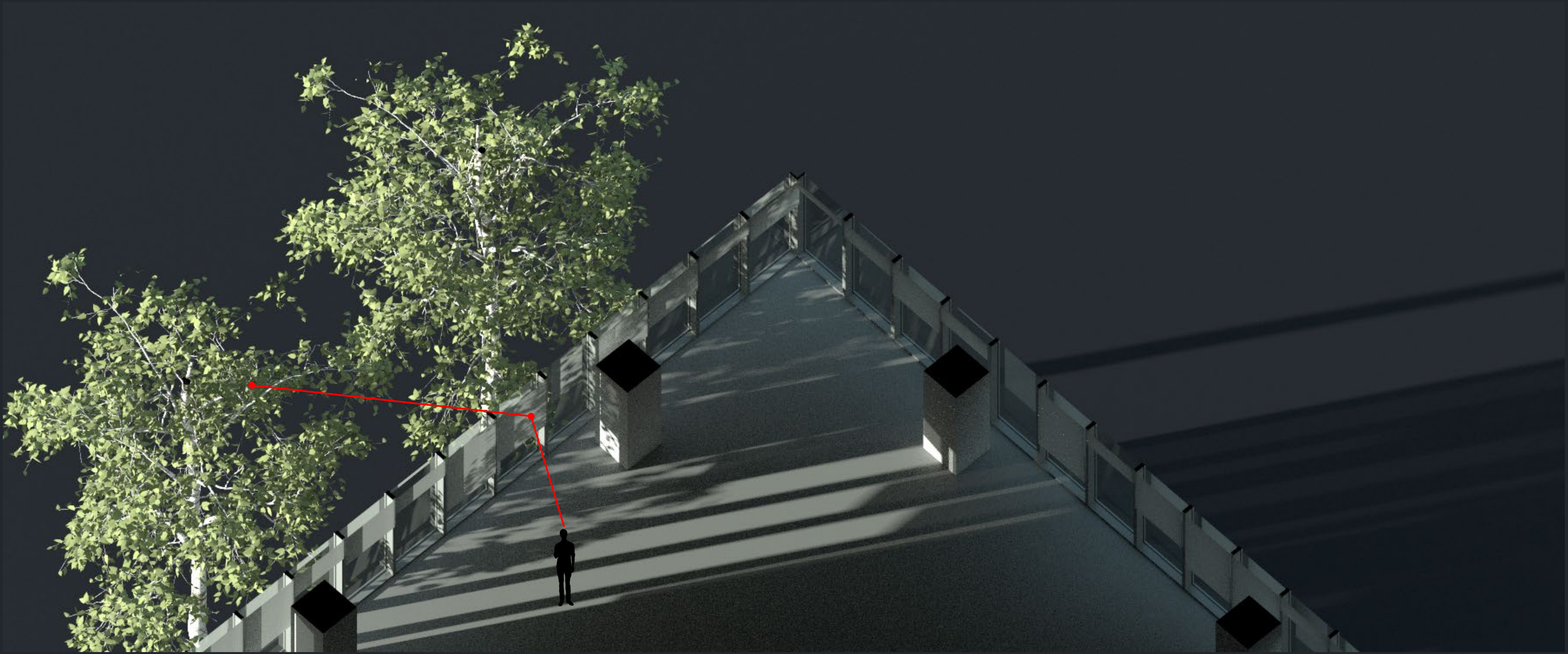
The Interaction Problem



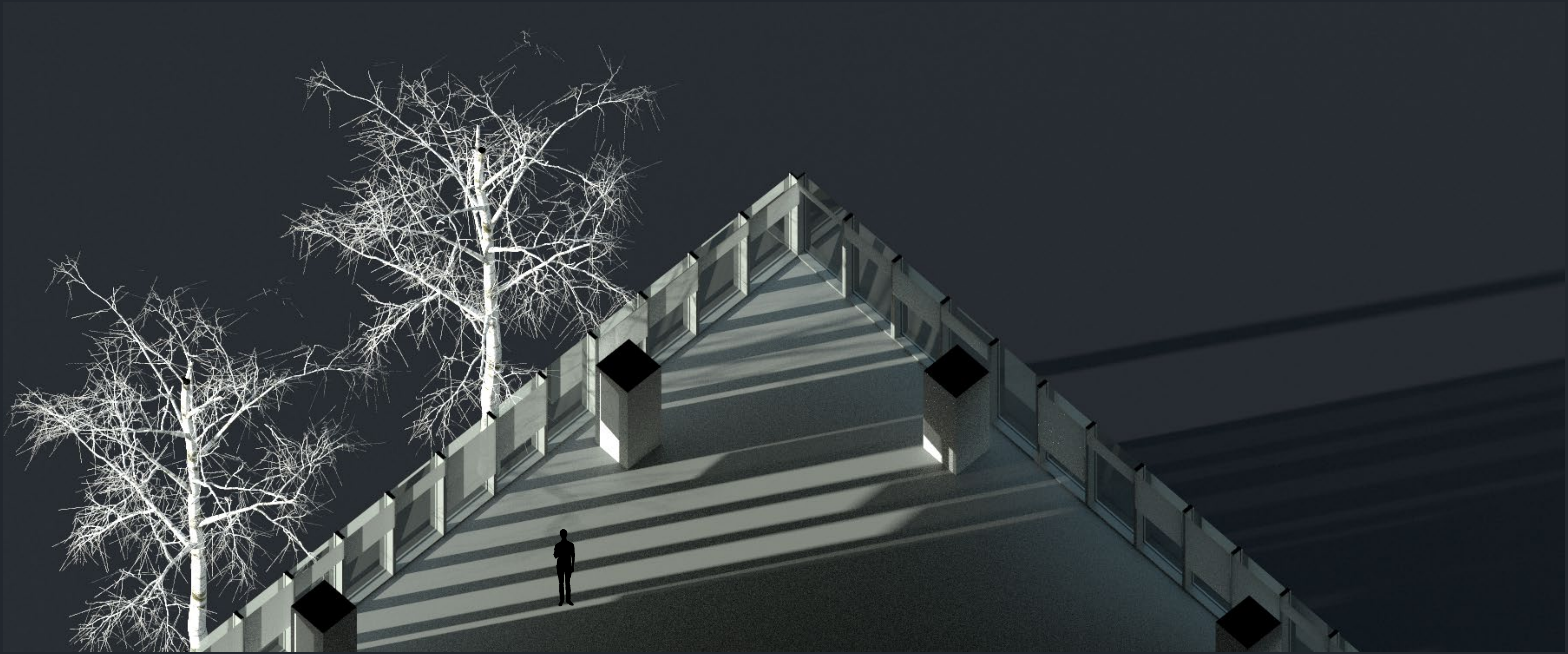
The Interaction Problem



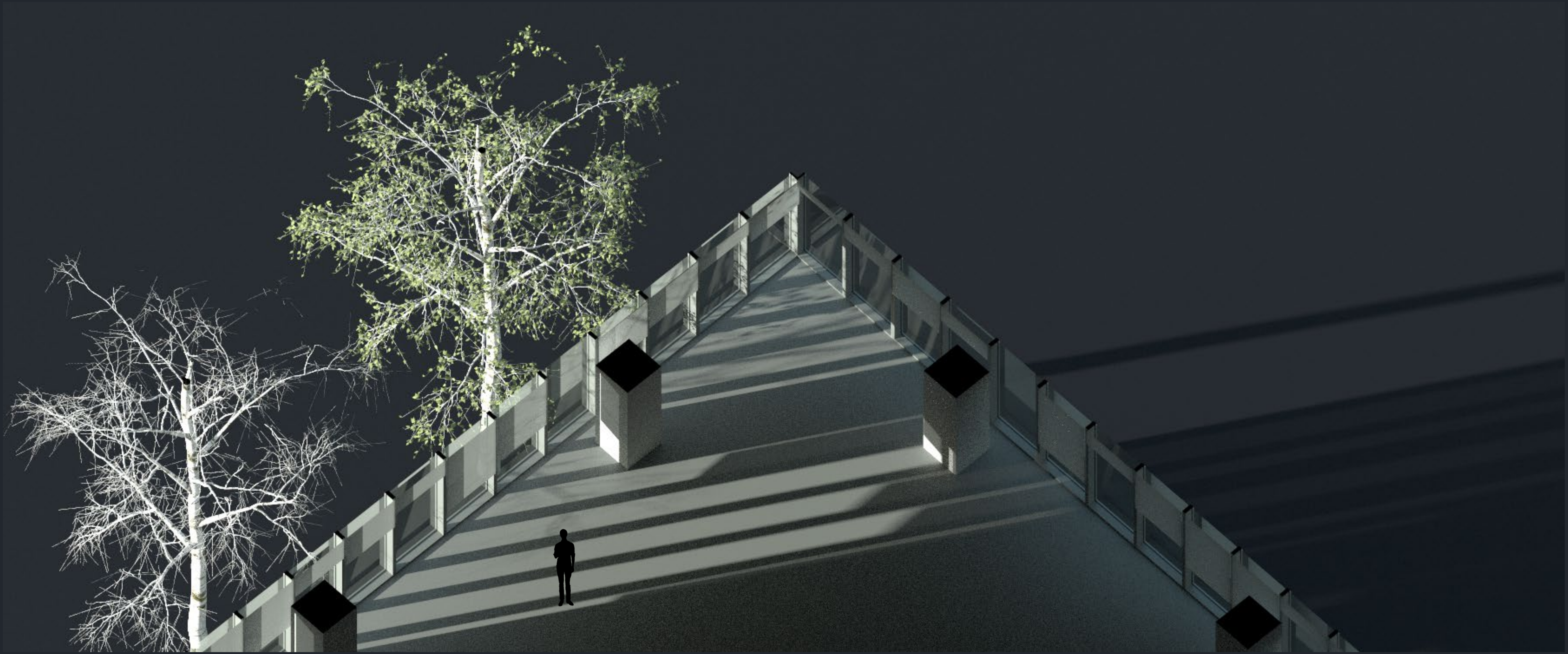
The Interaction Problem



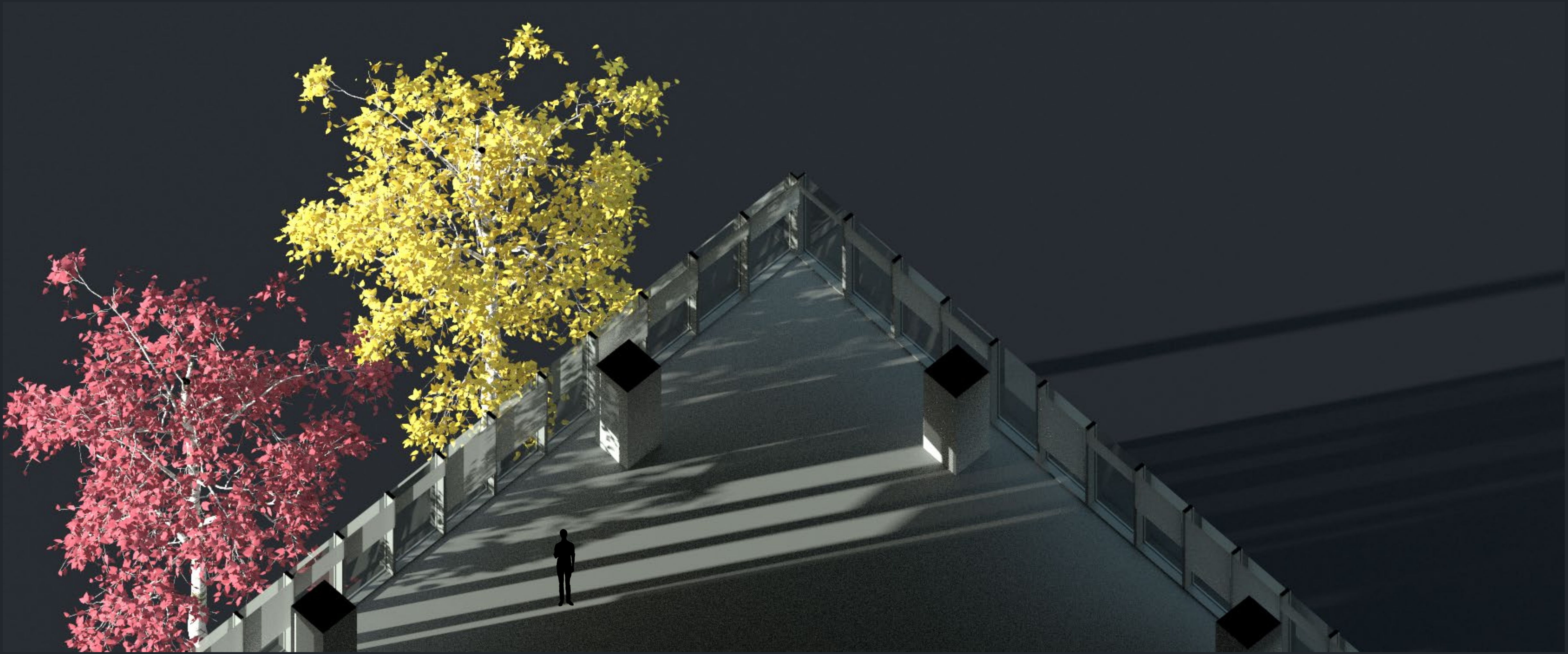
The Interaction Problem



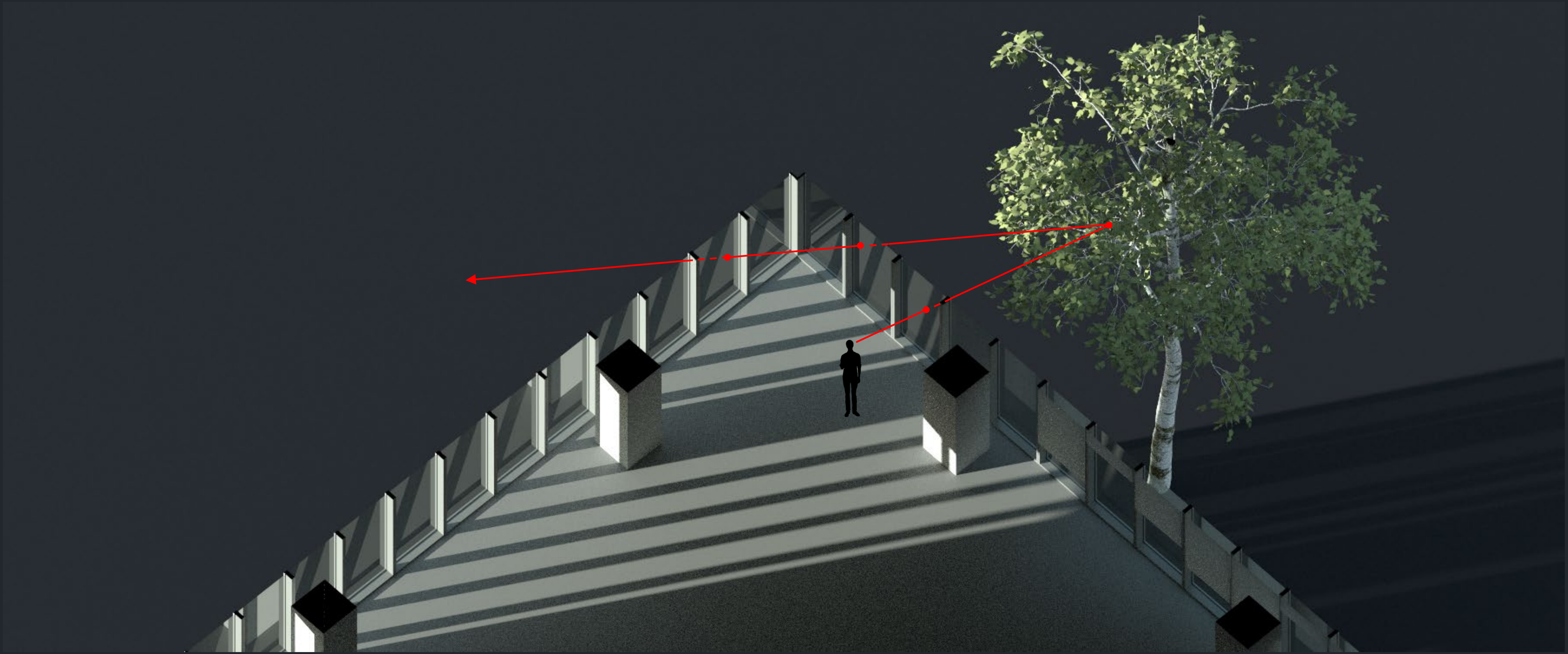
The Interaction Problem



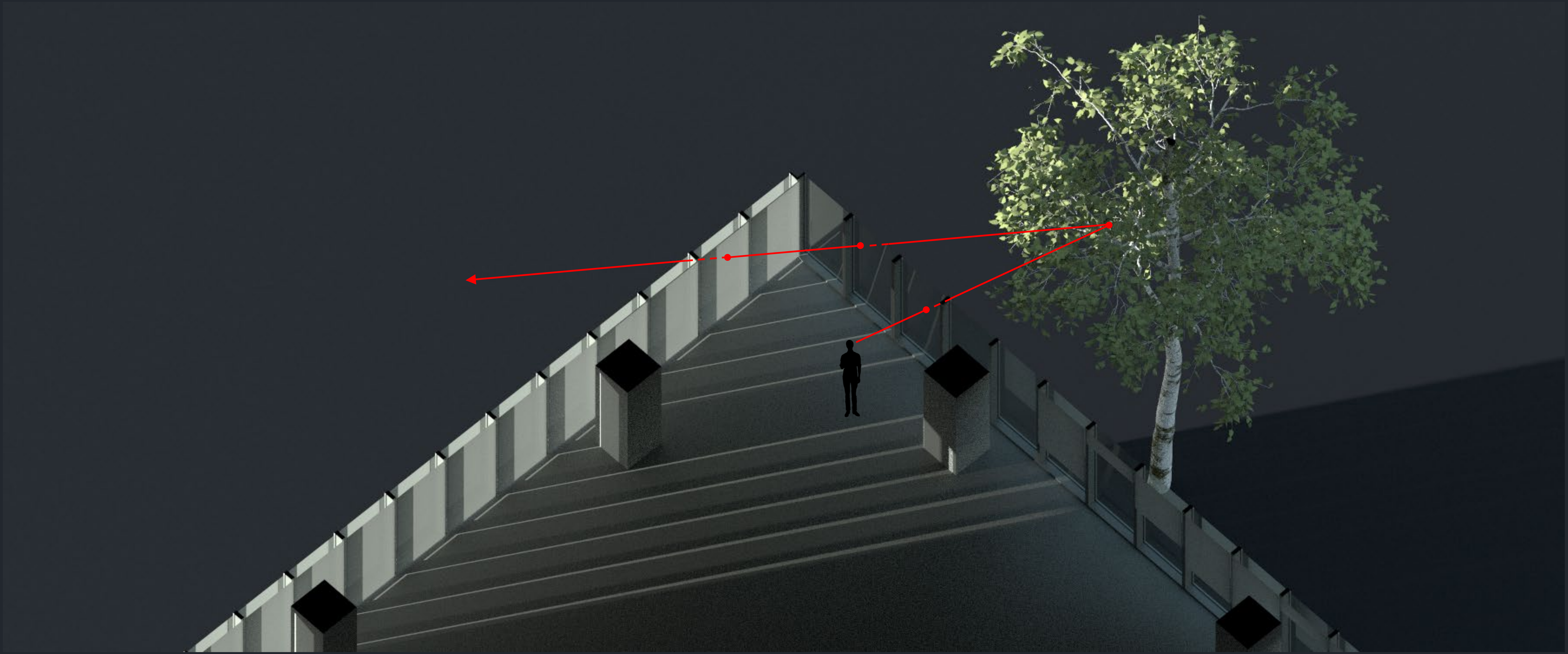
The Interaction Problem



The Interaction Problem



The Interaction Problem

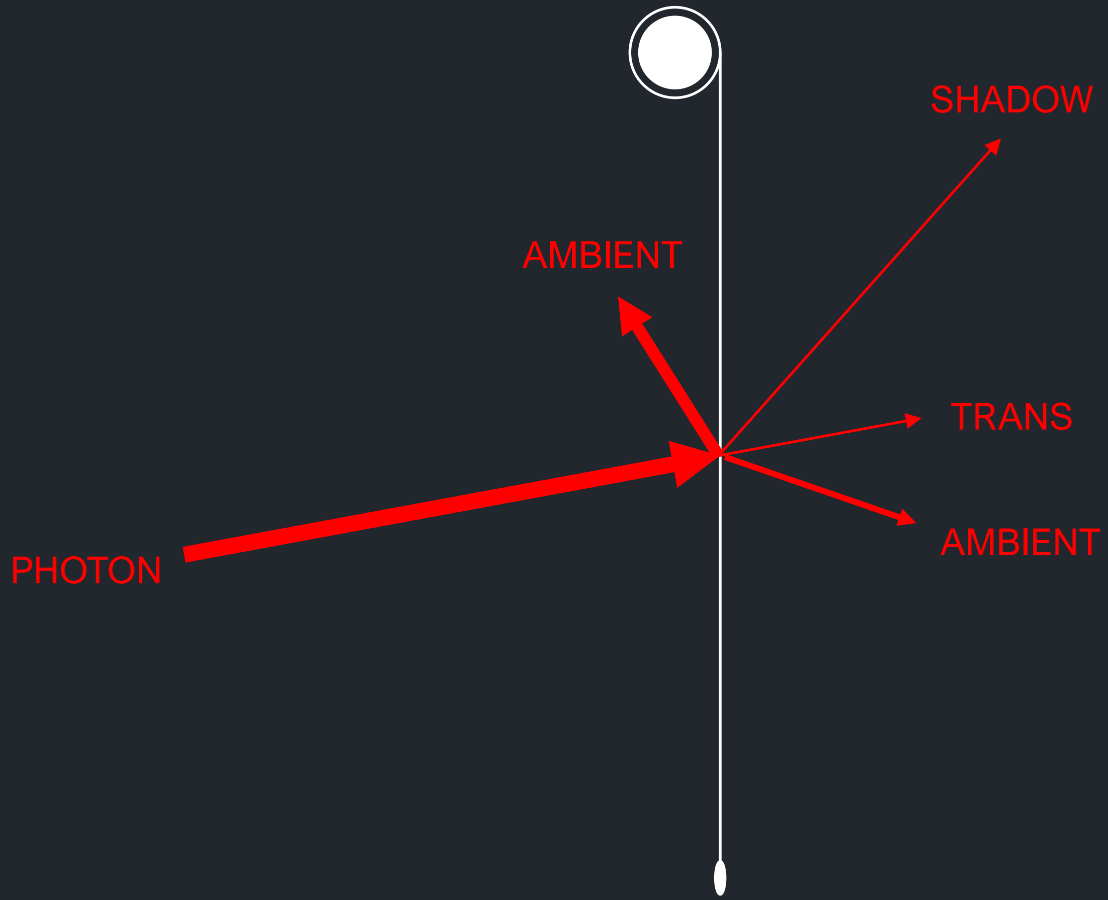


SOLEMMA

Tenants of Multiversal Ray Tracing

1. No binning of photons by location
2. No stopping and starting of photon paths
3. When a photon encounters a dynamic surface, *everything always happens*

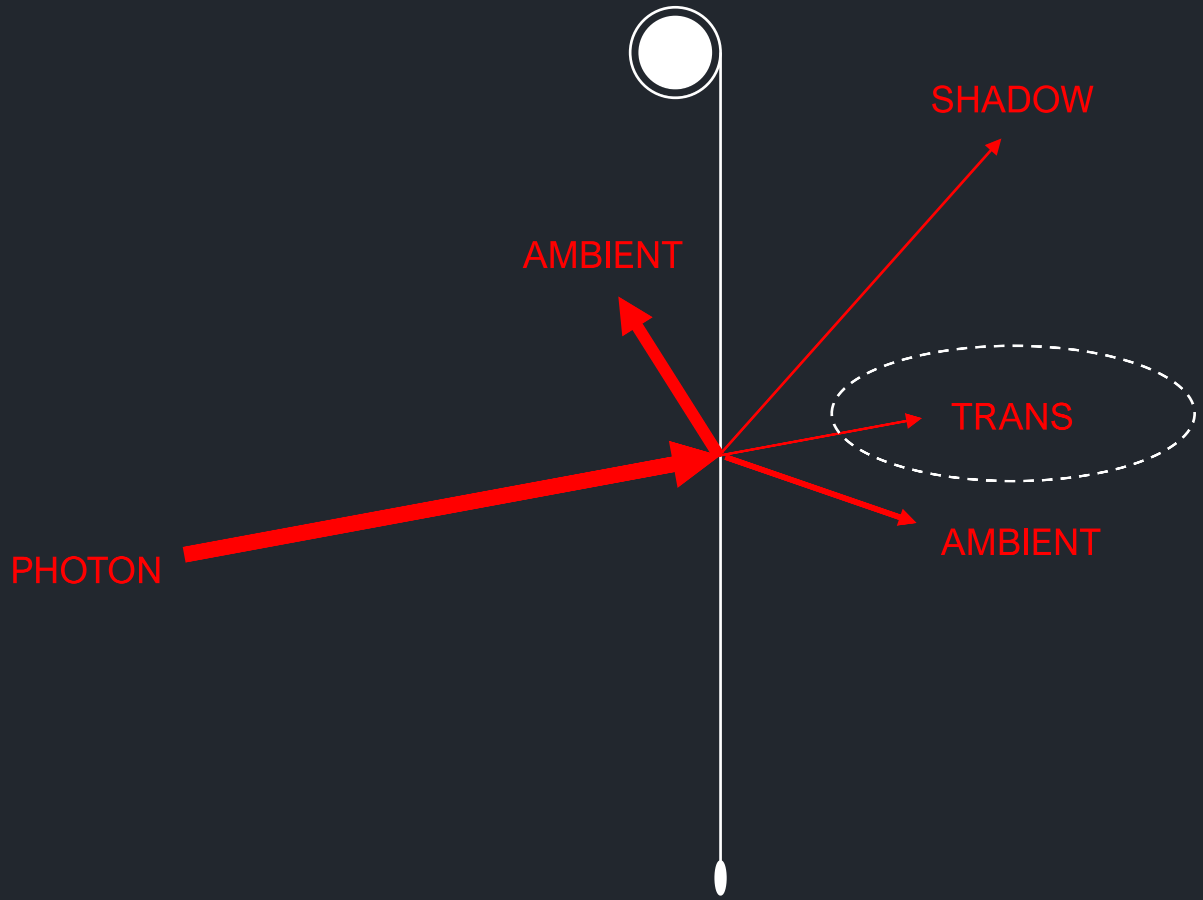
ROLLER SHADE



DECIDUOUS LEAF

SOLEMMA

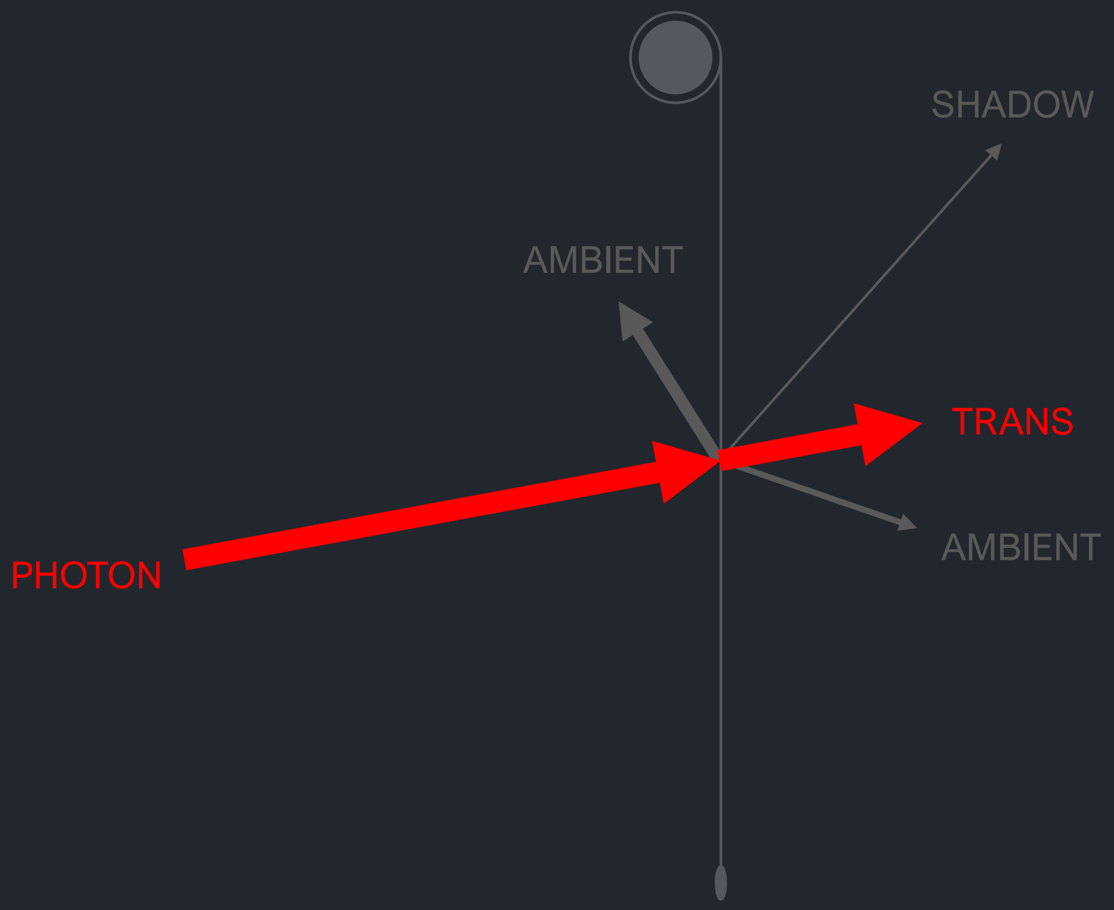
ROLLER SHADE



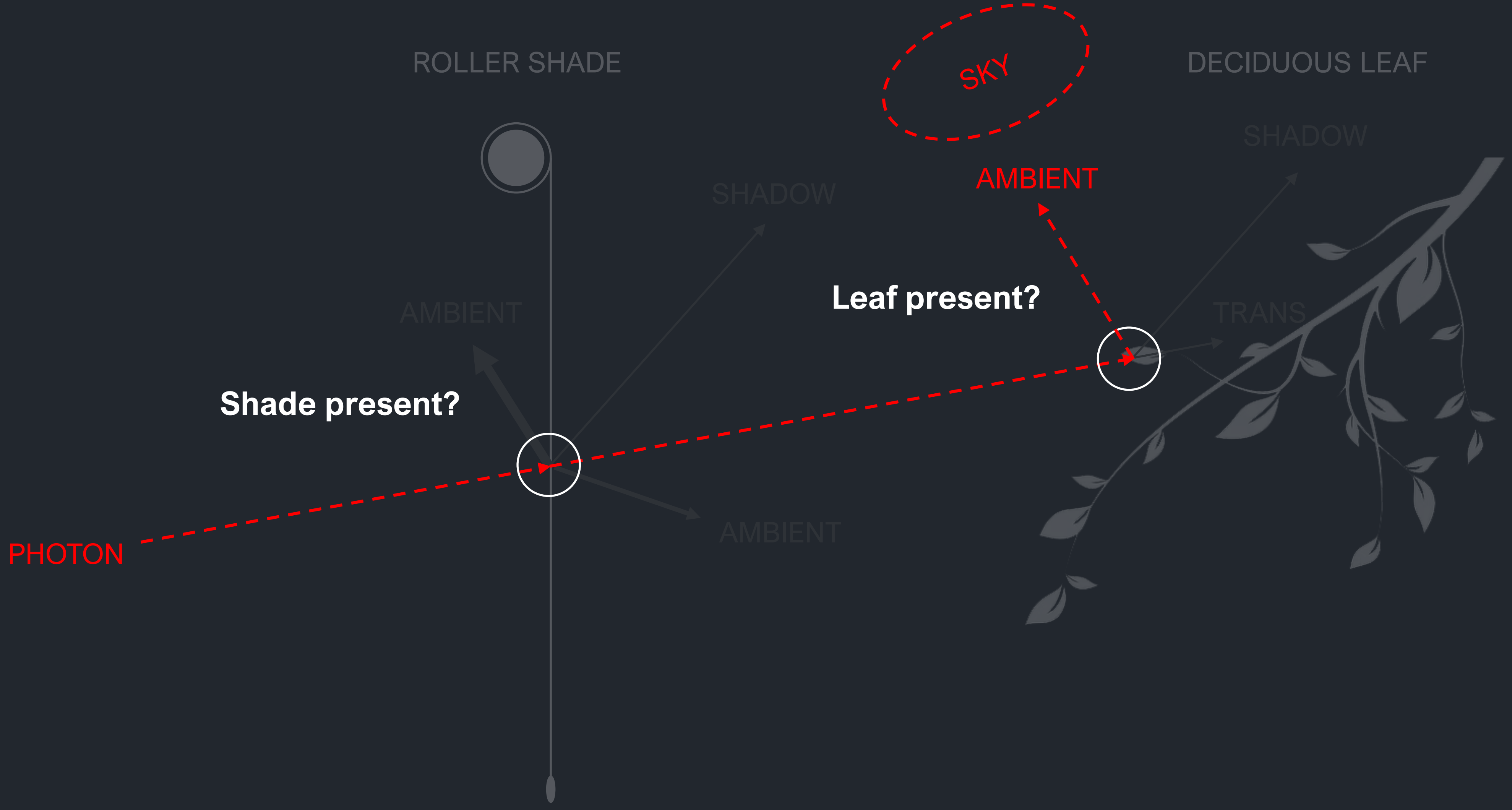
DECIDUOUS LEAF

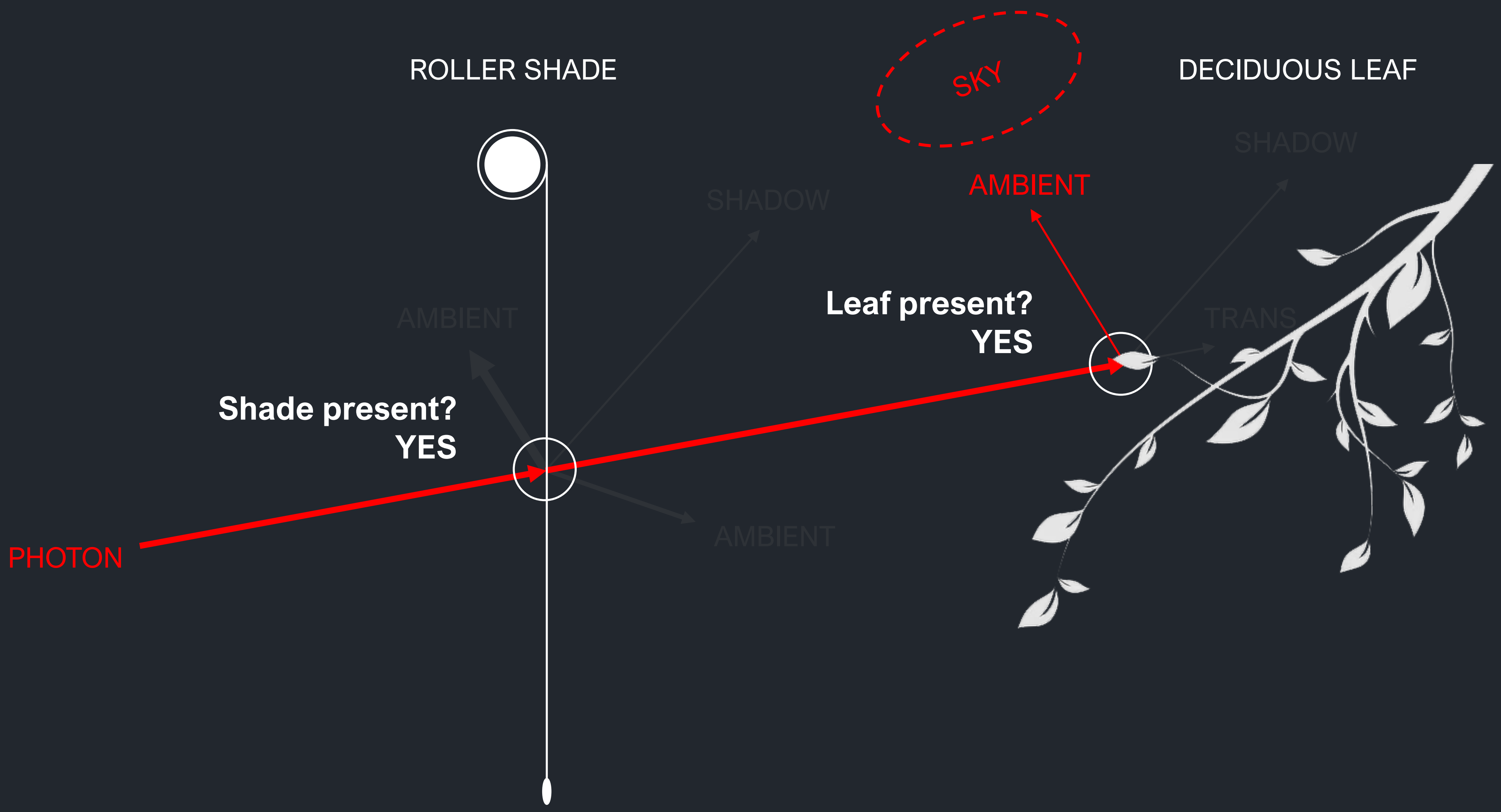
SOLEMMA

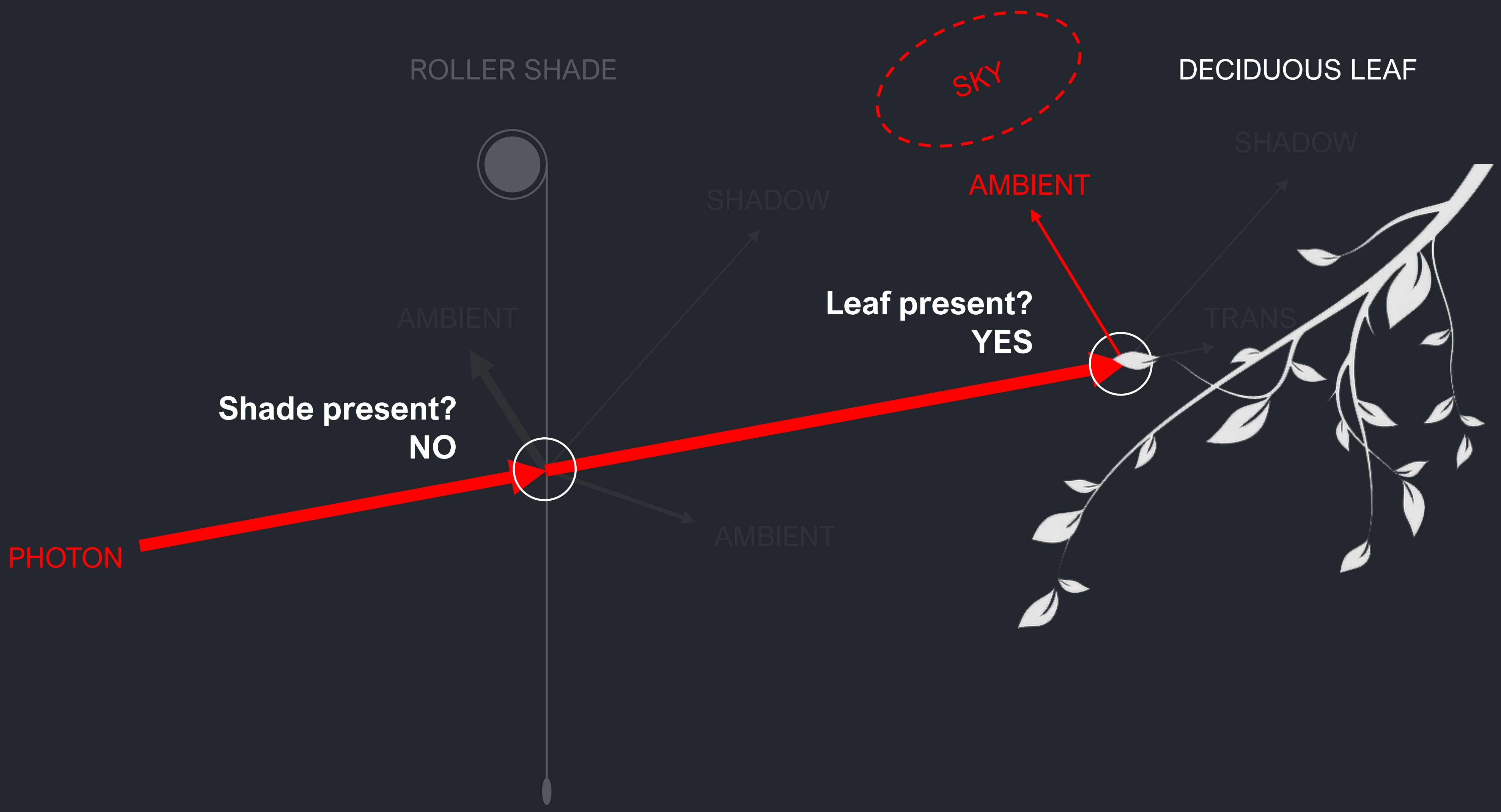
(NO) ROLLER SHADE



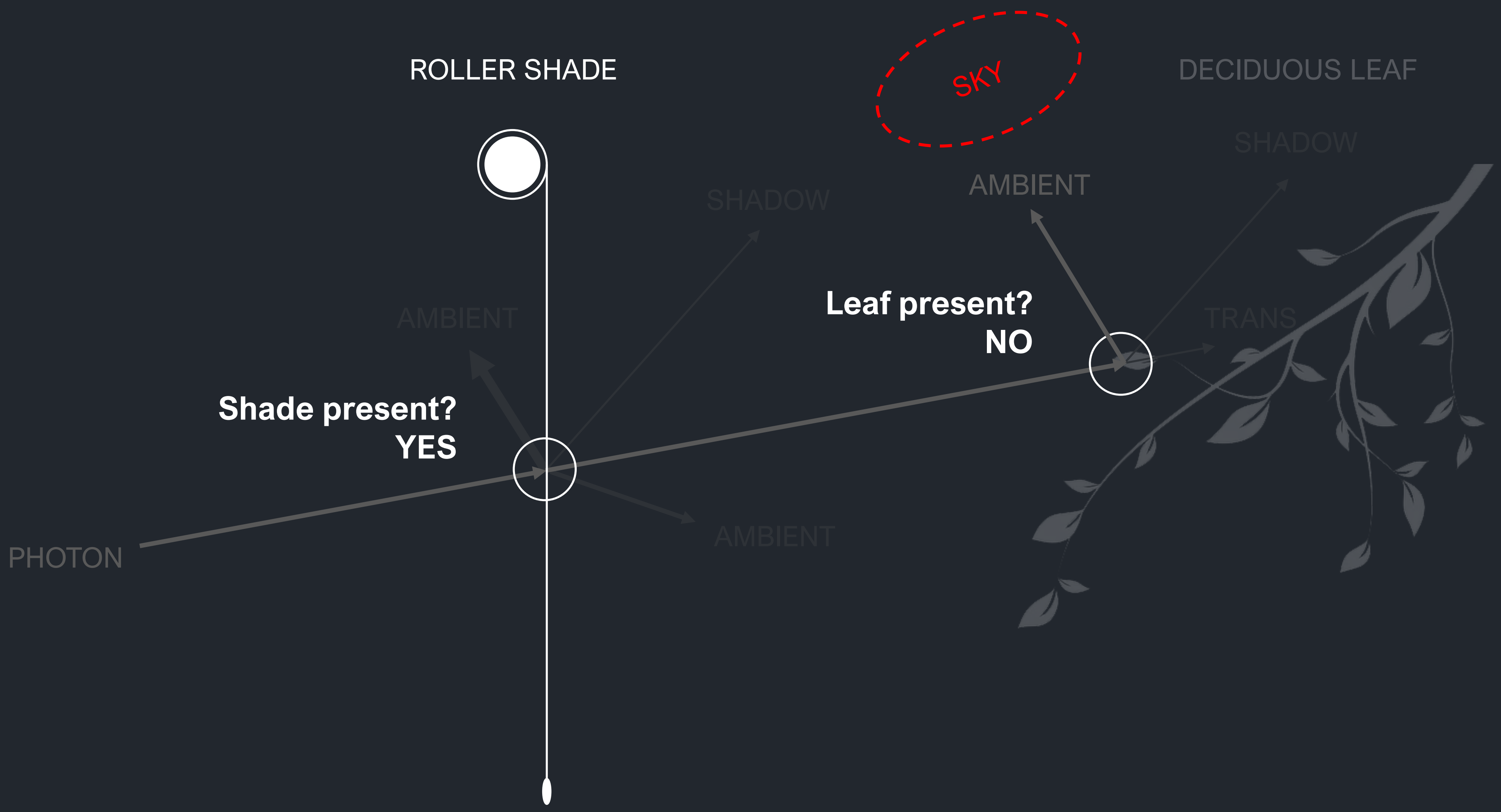
DECIDUOUS LEAF


ROLLER SHADE
SKY
DECIDUOUS LEAF
SHADOW
AMBIENT
SHADOW
Leaf present?
TRANS
AMBIENT
Shade present?
AMBIENT
PHOTON

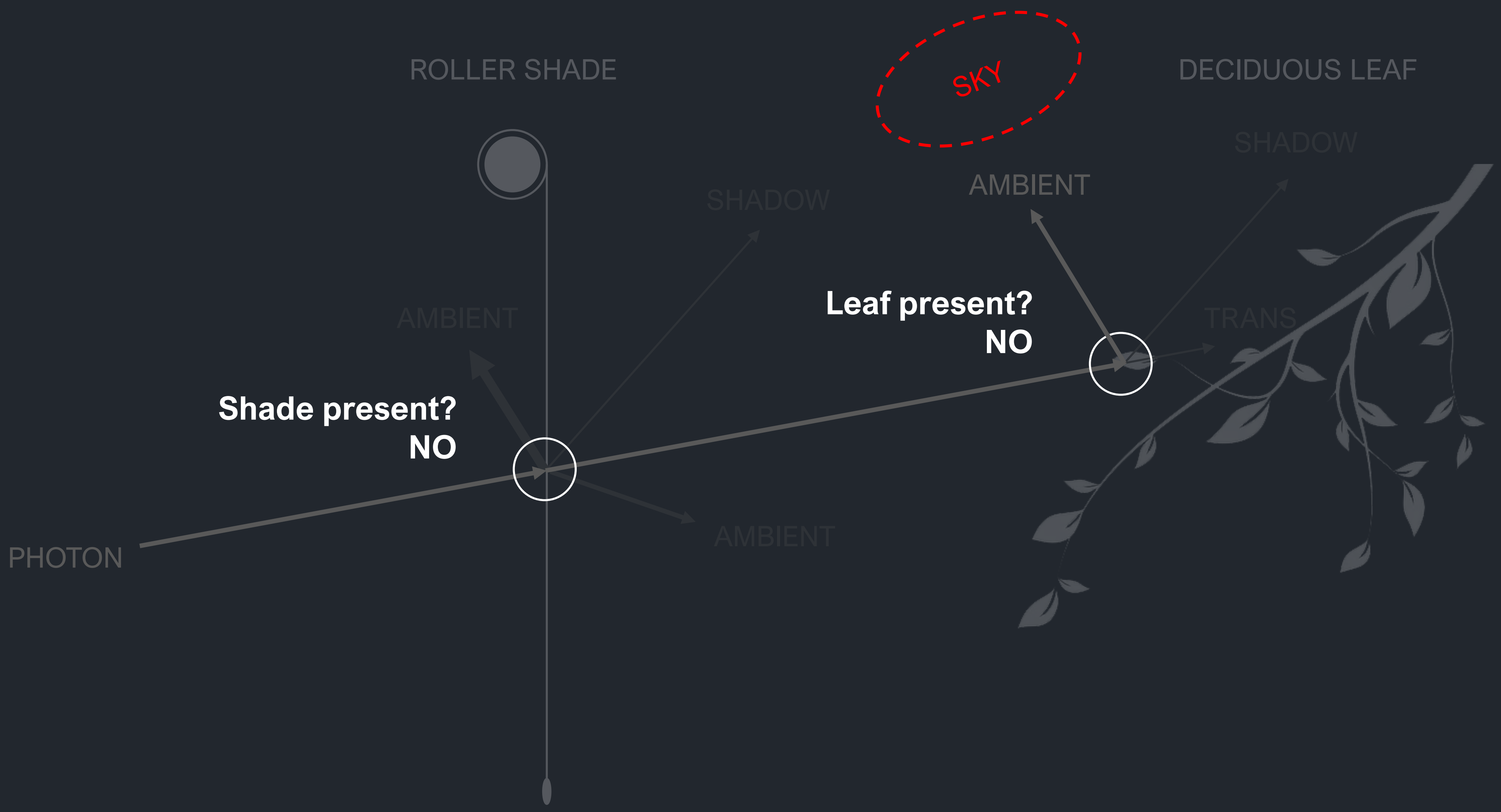

ROLLER SHADE
SKY
DECIDUOUS LEAF
SHADOW
AMBIENT
SHADOW
AMBIENT
Leaf present?
YES
TRANS
Shade present?
YES
AMBIENT
PHOTON


ROLLER SHADE
SKY
DECIDUOUS LEAF
SHADOW
AMBIENT
SHADOW
AMBIENT
Leaf present?
YES
TRANS
Shade present?
NO
AMBIENT
PHOTON

SOLEMMA

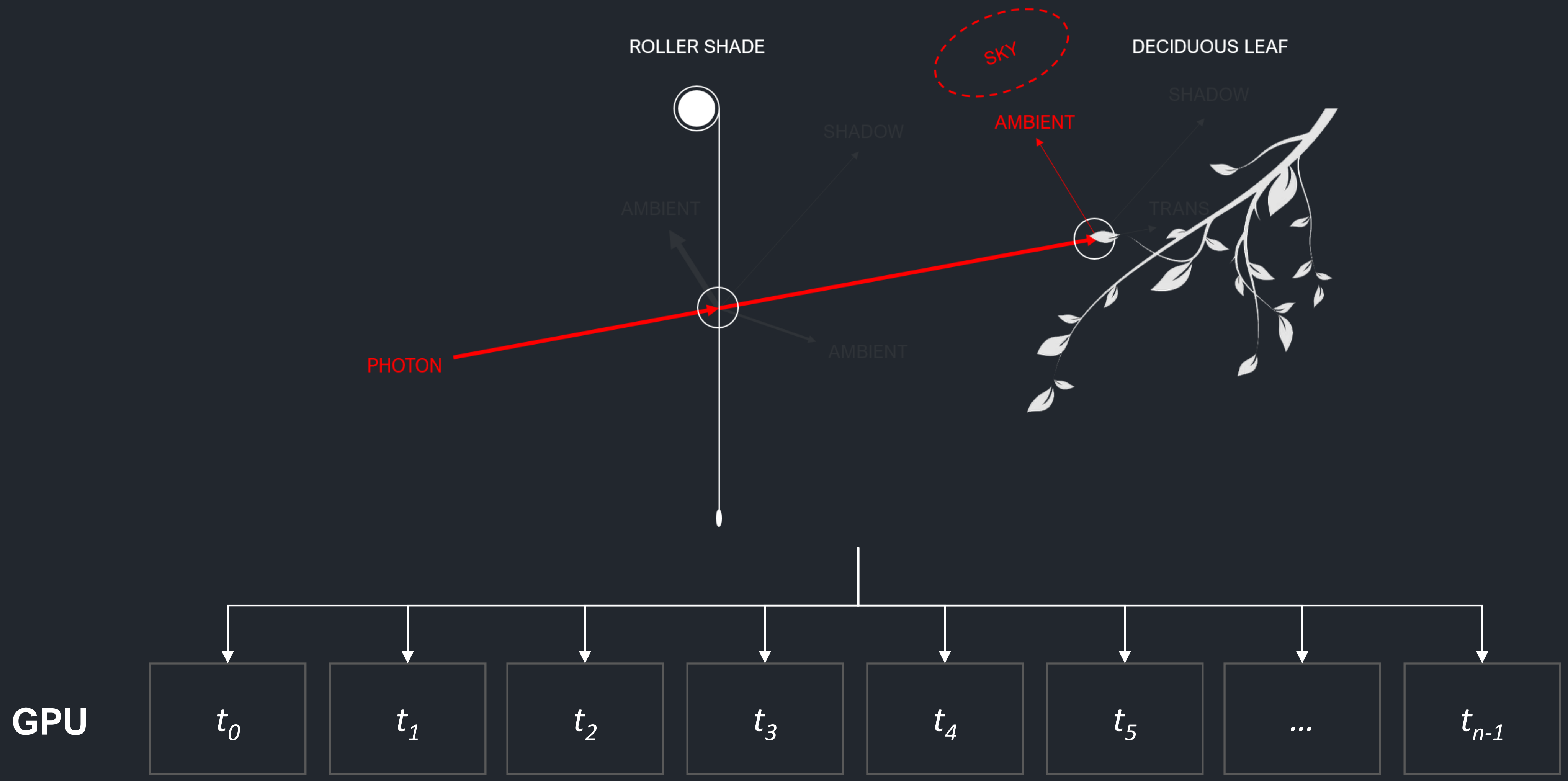

ROLLER SHADE
SKY
DECIDUOUS LEAF
SHADOW
AMBIENT
SHADOW
AMBIENT
Leaf present?
NO
TRANS
Shade present?
YES
AMBIENT
PHOTON

SOLEMMA


ROLLER SHADE
SKY
DECIDUOUS LEAF
SHADOW
AMBIENT
SHADOW
Leaf present?
NO
TRANS
AMBIENT
Shade present?
NO
AMBIENT
PHOTON

SOLEMMA

MULTIVERSE



SOLEMMA

MVRT (superposition of all states)

Placeholder shade material (there / not-there mix)

SHADES

MVRT

→ UNIVERSE 0: Shades open

SHADES

MVRT

- UNIVERSE 0: Shades open
- UNIVERSE 1: Shades closed

SHADES

MVRT

- UNIVERSE 0: Shades open
- UNIVERSE 1: Shades closed
- UNIVERSE 2: Mix [0 1 0 0 1 1 1 0]

MVRT

- UNIVERSE 0: Shades open
- UNIVERSE 1: Shades closed
- UNIVERSE 2: Mix [0 1 0 0 1 1 1 0]
- UNIVERSE 3: Mix [0 .3 .6 .4 .8 .7 .2 0]

Storing **texture coordinate** lets us set on/off based on position!

MVRT

- UNIVERSE 0: Shades open
- UNIVERSE 1: Shades closed
- UNIVERSE 2: Mix [0 1 0 0 1 1 1 0]
- UNIVERSE 3: Mix [0 .3 .6 .4 .8 .7 .2 0]
- UNIVERSE 4: Mix [0 .2 .9 .3 .5 .3 0 0]

SHADES

MVRT

- UNIVERSE 0: Shades open
- UNIVERSE 1: Shades closed
- UNIVERSE 2: Mix [0 1 0 0 1 1 1 0]
- UNIVERSE 3: Mix [0 .3 .6 .4 .8 .7 .2 0]
- UNIVERSE 4: Mix [0 .2 .9 .3 .5 .3 0 0]
- UNIVERSE 5: Mix [.4 .5 .4 .6 .6 .8 .7 0]

MVRT

- UNIVERSE 0: Shades open
- UNIVERSE 1: Shades closed
- UNIVERSE 2: Mix [0 1 0 0 1 1 1 0]
- UNIVERSE 3: Mix [0 .3 .6 .4 .8 .7 .2 0]
- UNIVERSE 4: Mix [0 .2 .9 .3 .5 .3 0 0]
- UNIVERSE 5: Mix [.4 .5 .4 .6 .6 .8 .7 0]
- UNIVERSE 6: Mix [1 .1 .5 1 .5 .5 .5 .8]

… 256^8 – 7, or ~ 10^{19} other universes

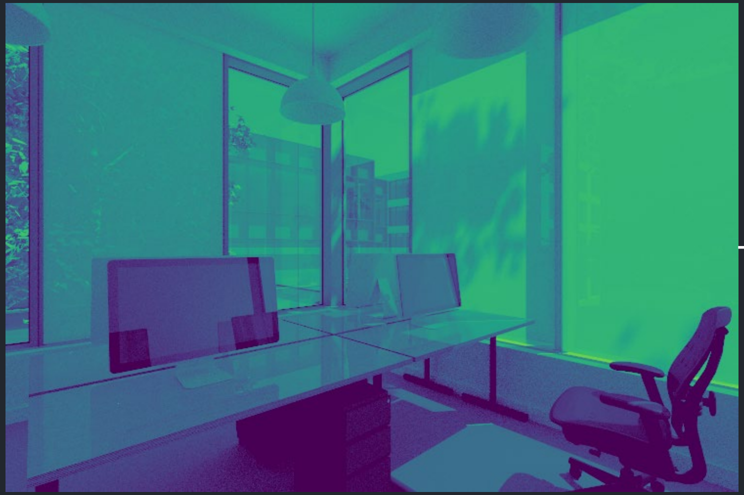
SOLEMMA

SHADES

UNIVERSE 2

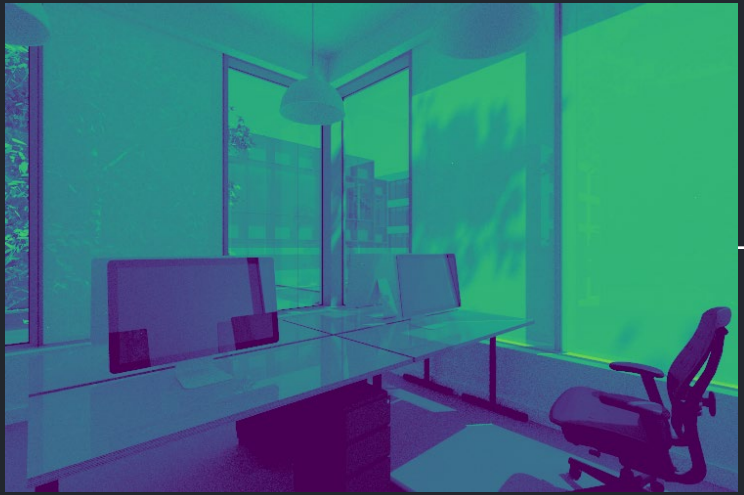
L_{avg} = 340 cd/m^2

-ab 5 -ad 256



REFERENCE

L_{avg} = 339 cd/m^2



DELTA (raw)

MSD (cd/m^2)	**MAE** (cd/m^2)
0.7	18

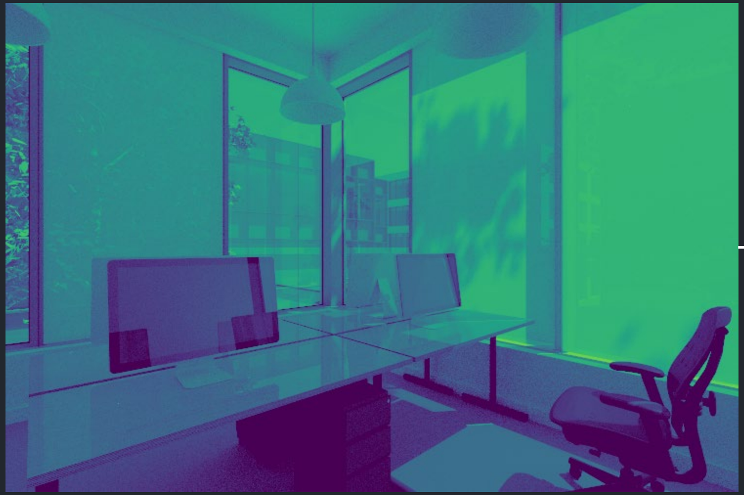
cd/m^2 1e1 1e2 1e3 1e4

SOLEMMA

SHADES

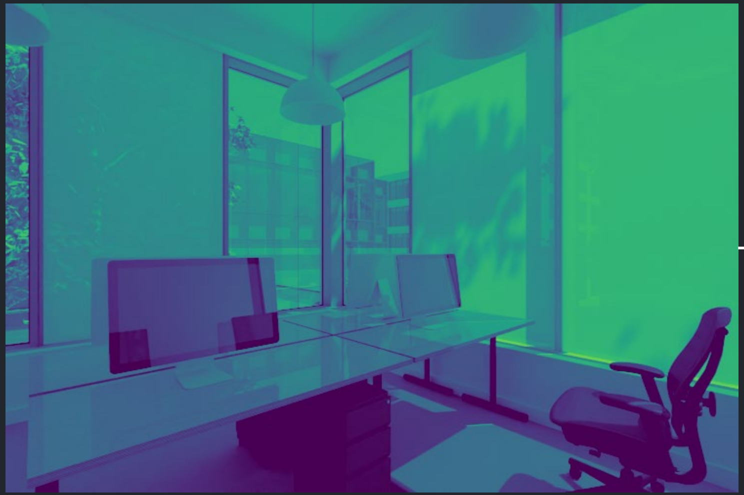
UNIVERSE 2 (denoised)

L_{avg} = 340 cd/m^2 -ab 5 -ad 256

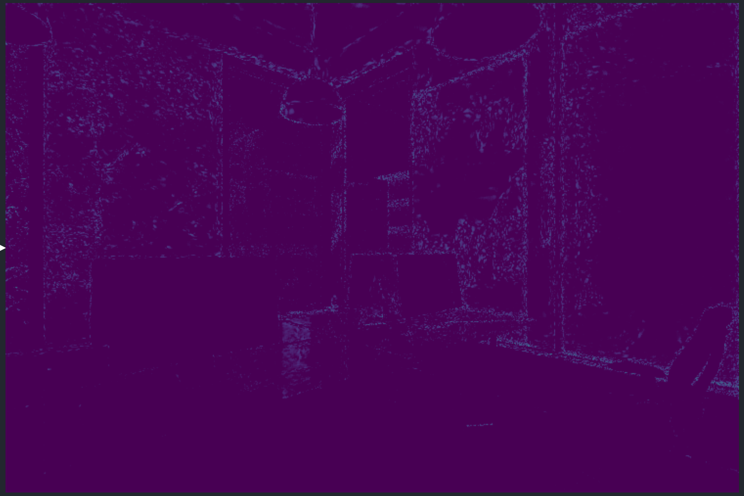


REFERENCE (denoised)

L_{avg} = 339 cd/m^2



DELTA (denoised)



MSD (cd/m^2)	**MAE** (cd/m^2)
0.7	4.4

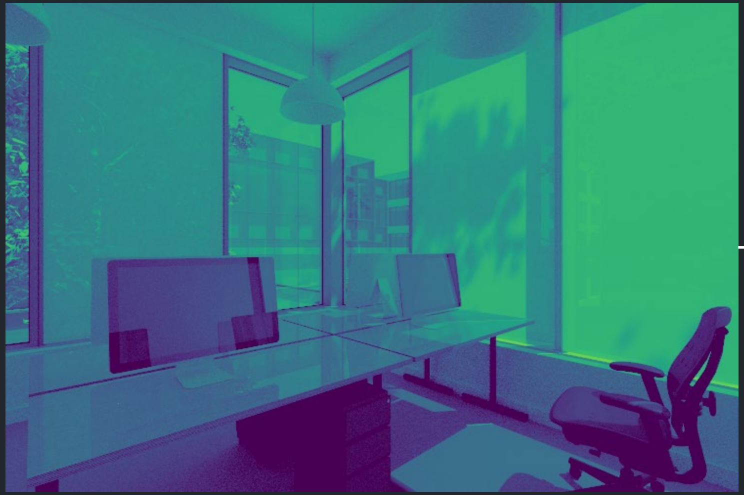
SOLEMMA

SHADES

UNIVERSE 2

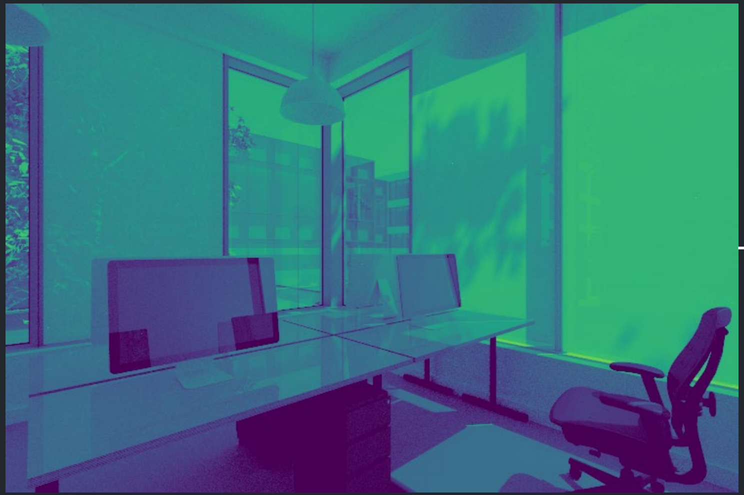
L_{avg} = 340 cd/m^2

-ab 5 -ad 256



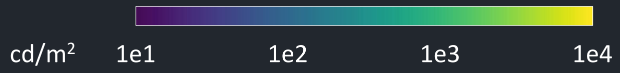
REFERENCE

L_{avg} = 339 cd/m^2



DELTA (25x25 pixel regions)

MSD (cd/m^2)	**MAE** (cd/m^2)
0.7	1.6

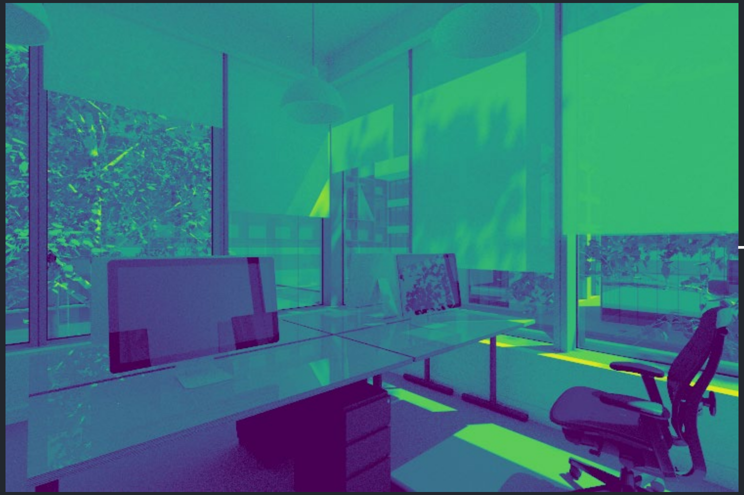


SOLEMMA

SHADES

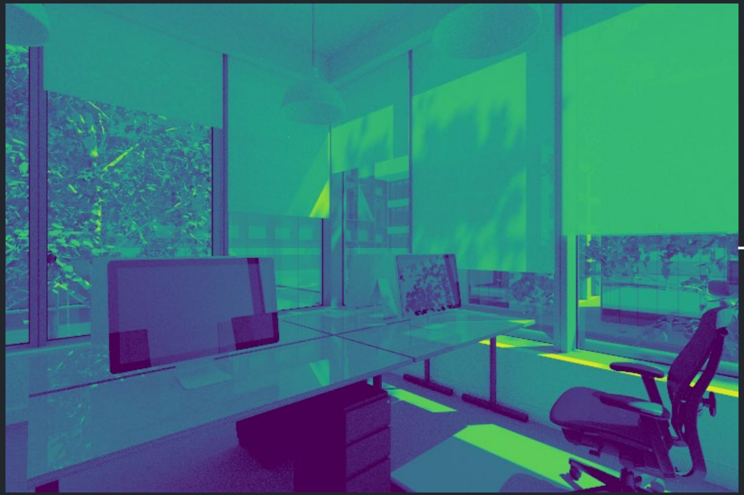
UNIVERSE 3

L_{avg} = 362 cd/m^2 -ab 5 -ad 256



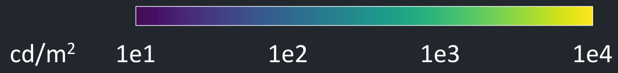
REFERENCE

L_{avg} = 362 cd/m^2



DELTA (25x25 pixel regions)

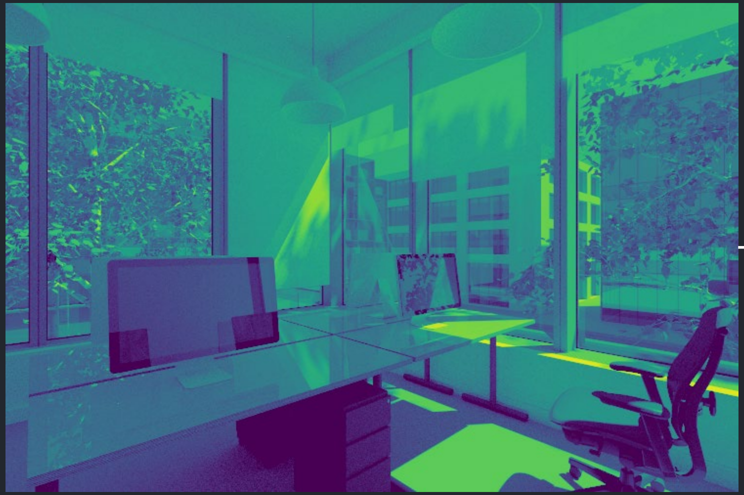
MSD (cd/m^2)	**MAE** (cd/m^2)
-0.4	2.0



UNIVERSE 4

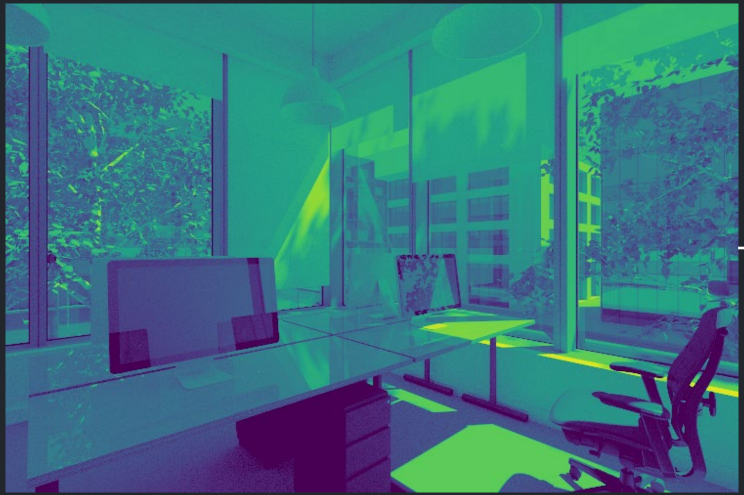
L_{avg} = 357 cd/m^2

-ab 5 -ad 256



REFERENCE

L_{avg} = 358 cd/m^2



DELTA (25x25 pixel regions)

MSD (cd/m^2)	**MAE** (cd/m^2)
-1.3	2.1

SOLEMMA

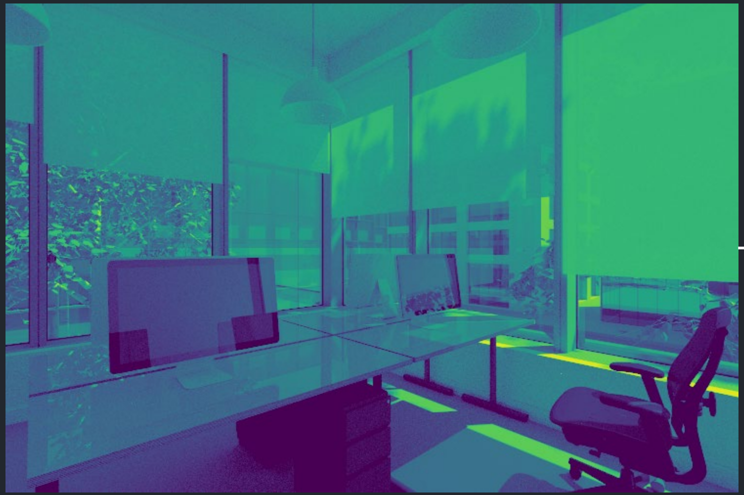
SHADES

UNIVERSE 5

L_{avg} = 350 cd/m^2 -ab 5 -ad 256

REFERENCE

L_{avg} = 350 cd/m^2



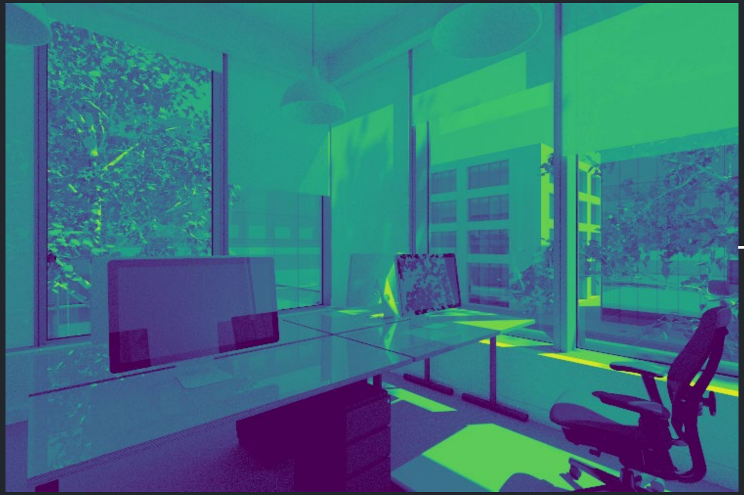
DELTA (25x25 pixel regions)

MSD (cd/m^2)	**MAE** (cd/m^2)
0.3	1.8

SHADES

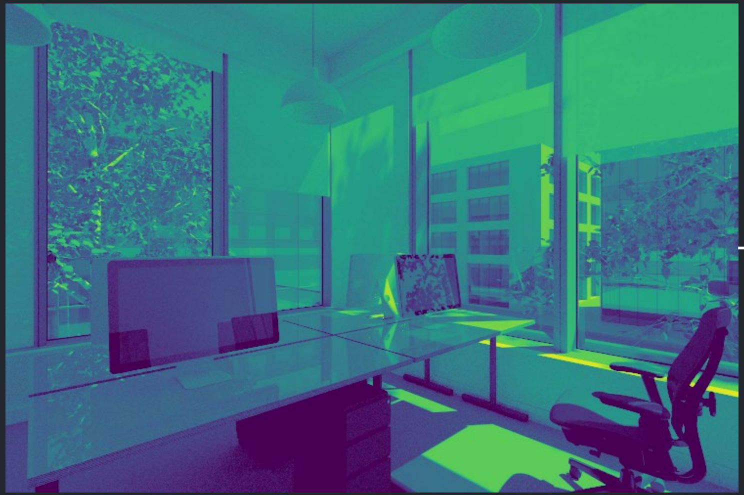
UNIVERSE 6

L_{avg} = 350 cd/m² -ab 5 -ad 256



REFERENCE

L_{avg} = 350 cd/m²

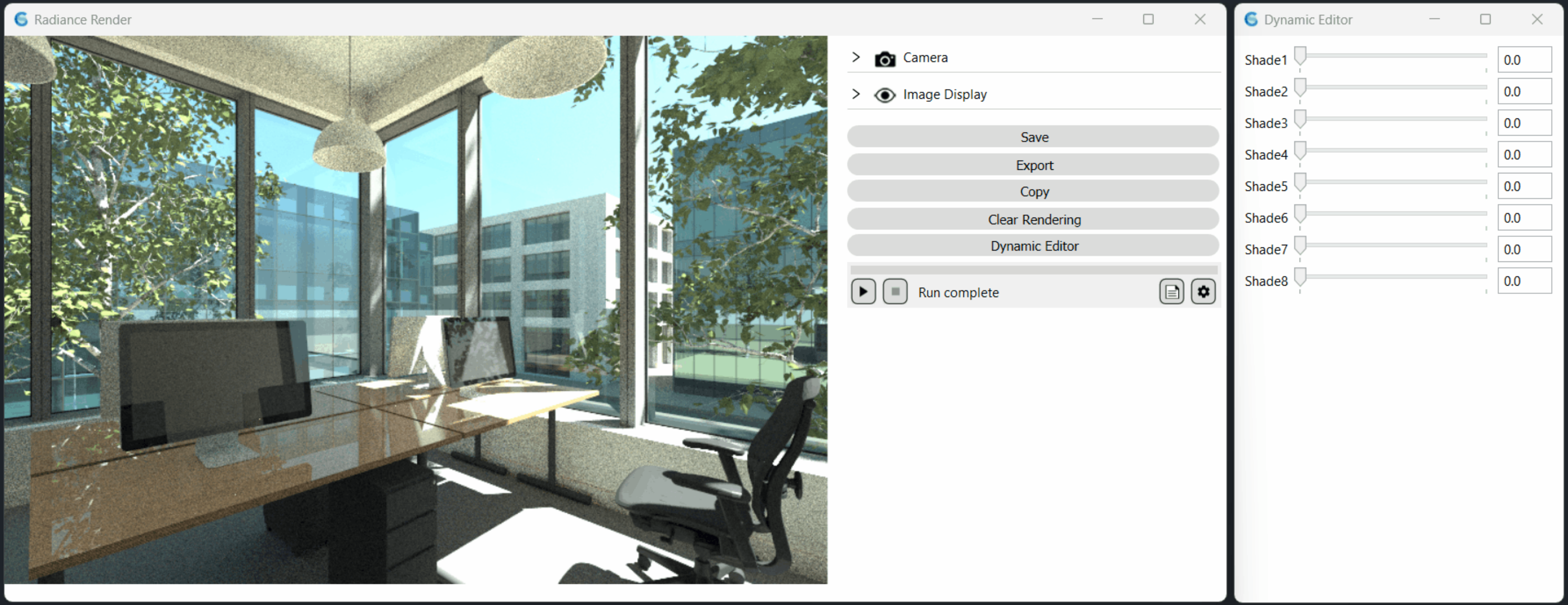


DELTA (25x25 pixel regions)

MSD (cd/m²)	**MAE** (cd/m²)
0.6	1.7

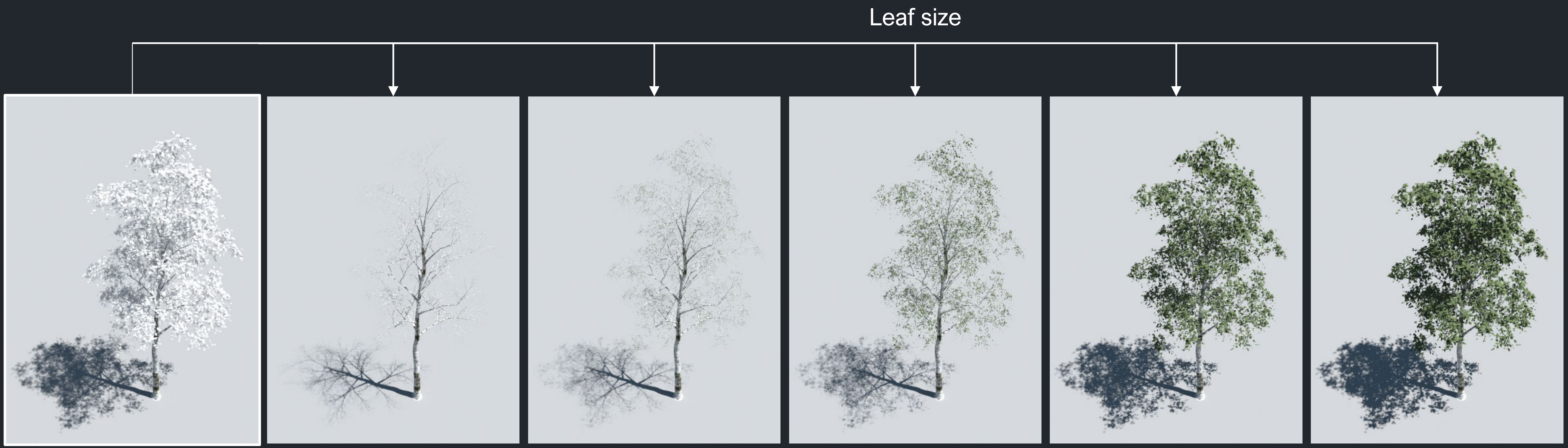
SOLEMMA

SHADES

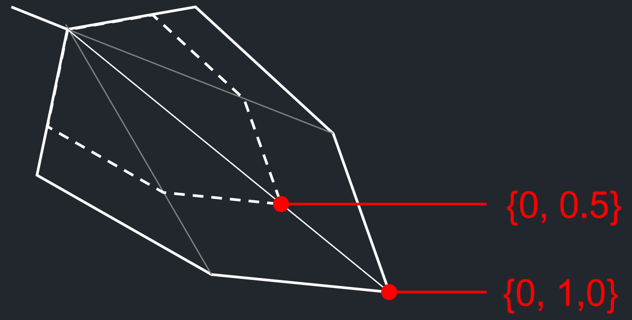

Radiance Render
Camera
Image Display
Save
Export
Copy
Clear Rendering
Dynamic Editor
Run complete
Dynamic Editor
Shade1 0.0
Shade2 0.0
Shade3 0.0
Shade4 0.0
Shade5 0.0
Shade6 0.0
Shade7 0.0
Shade8 0.0

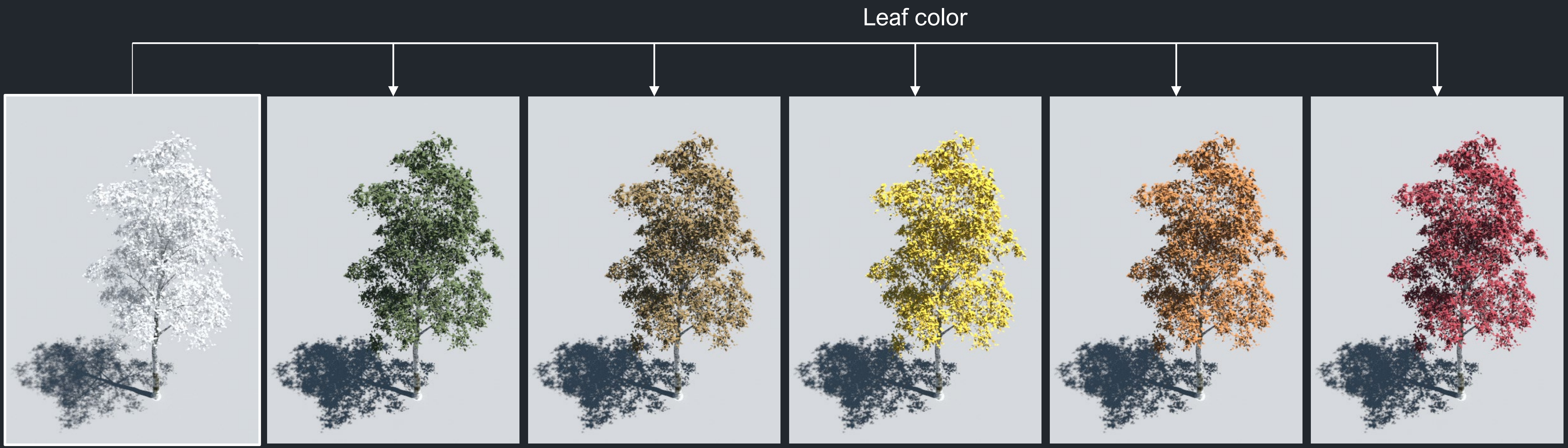
TREES

Leaves on/off (same ray trace)



(one) ray trace

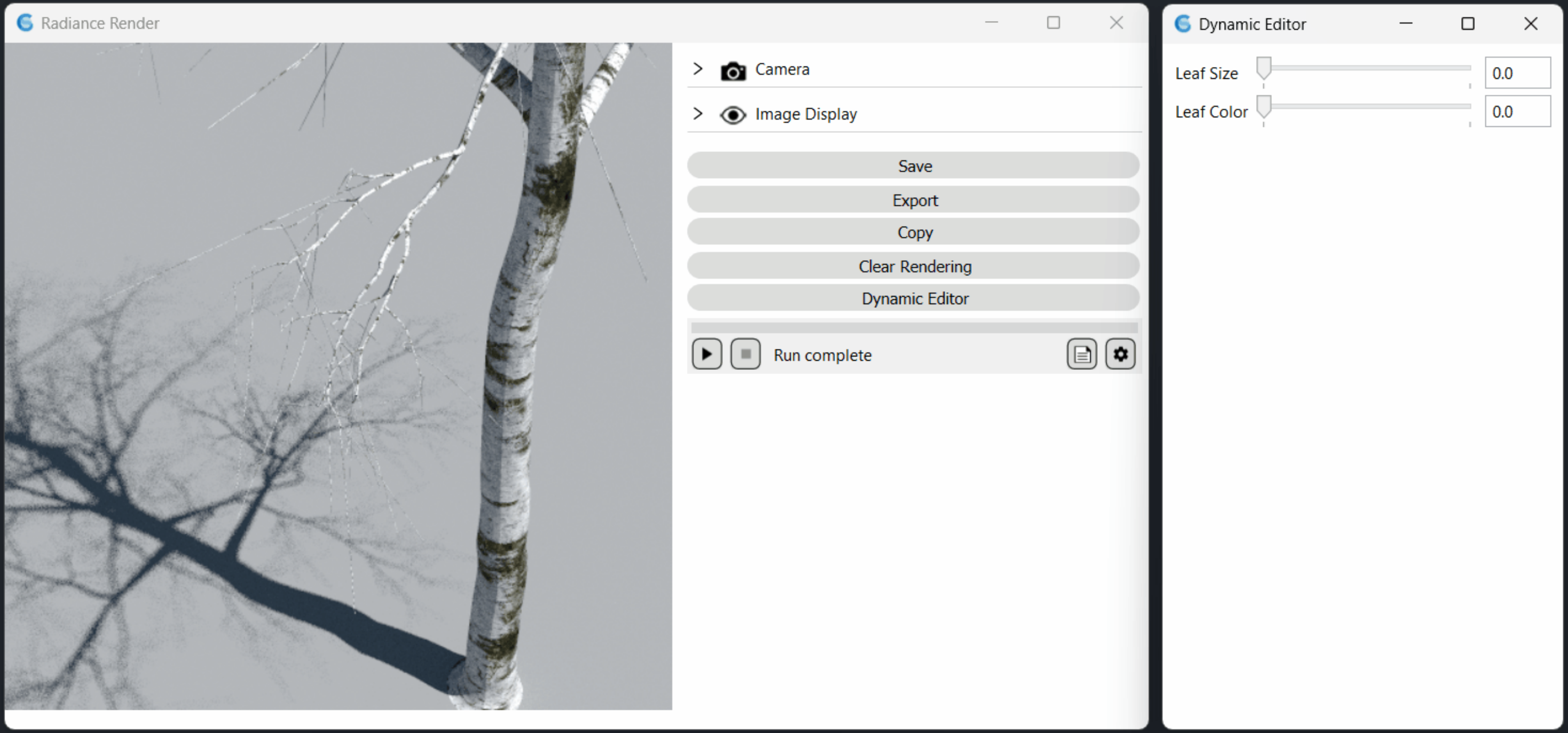




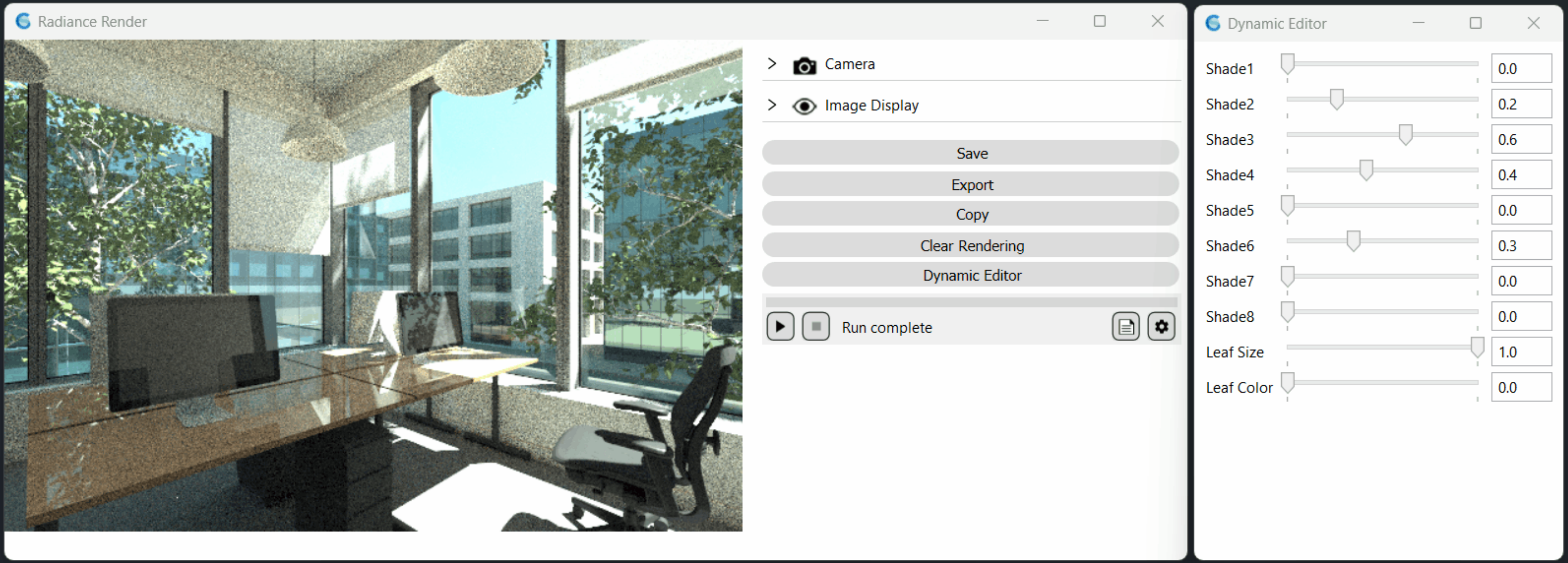
(one) ray trace

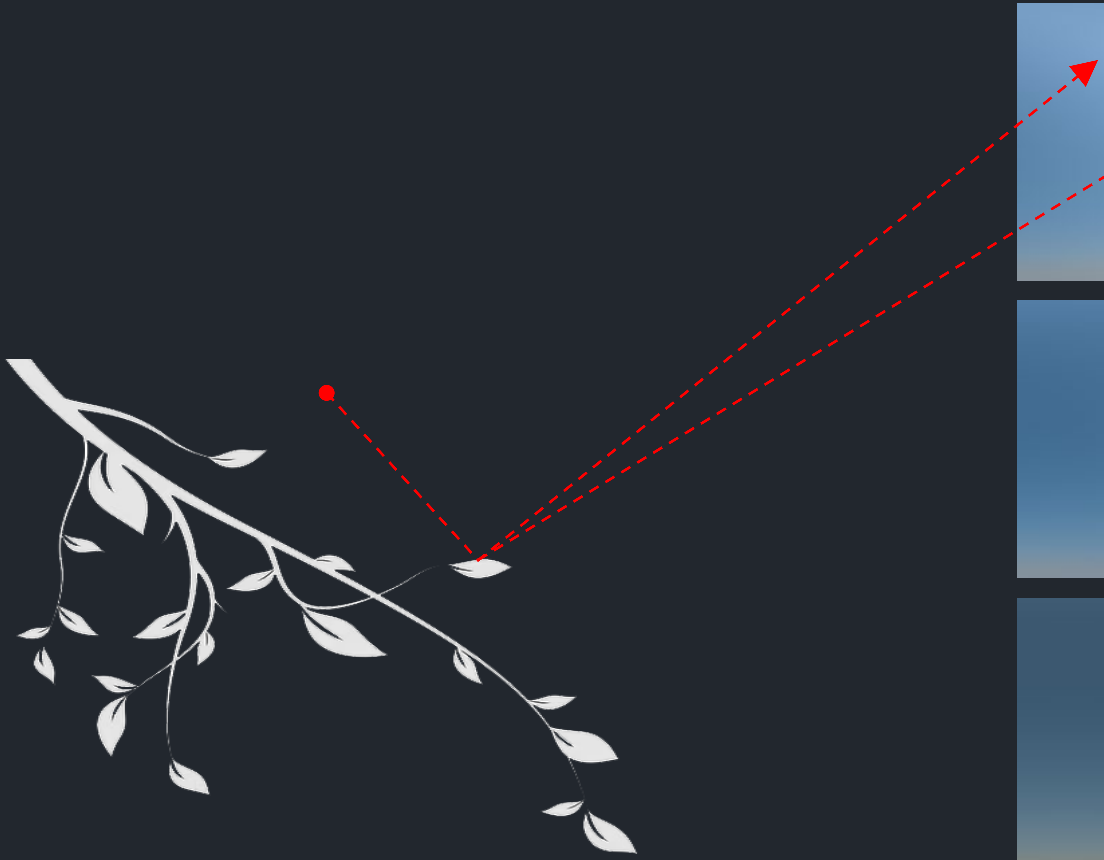
SOLEMMA

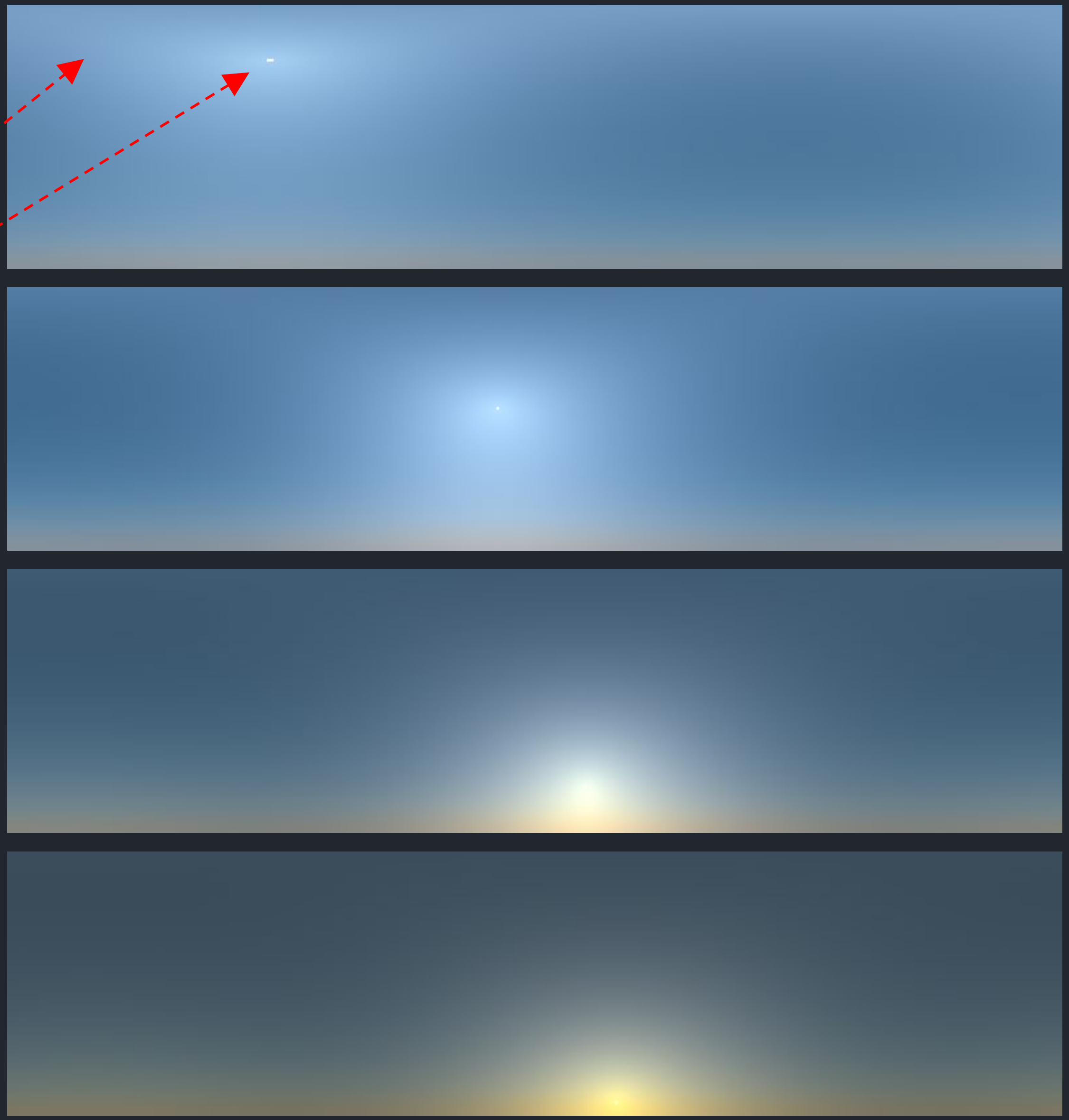
TREES



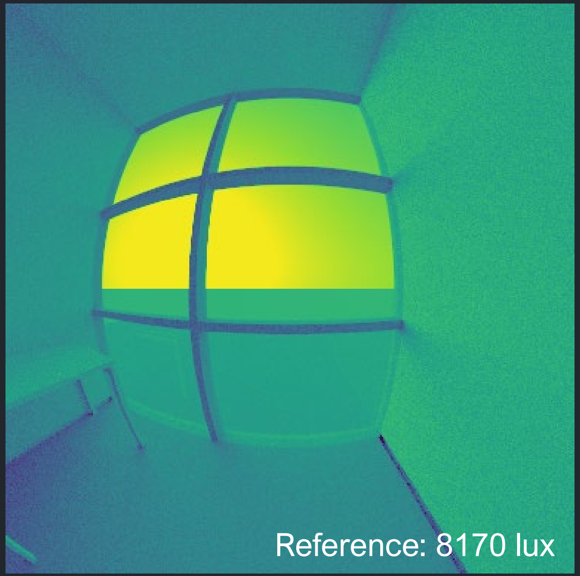
Radiance Render
Camera
Image Display
Save
Export
Copy
Clear Rendering
Dynamic Editor
Run complete
Dynamic Editor
Leaf Size
0.0
Leaf Color
0.0

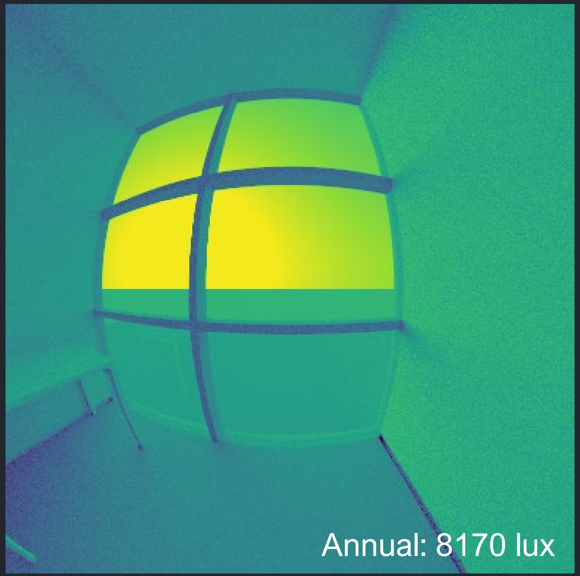

Radiance Render
Camera
Image Display
Save
Export
Copy
Clear Rendering
Dynamic Editor
Run complete
Dynamic Editor
Shade1 0.0
Shade2 0.2
Shade3 0.6
Shade4 0.4
Shade5 0.0
Shade6 0.3
Shade7 0.0
Shade8 0.0
Leaf Size 1.0
Leaf Color 0.0

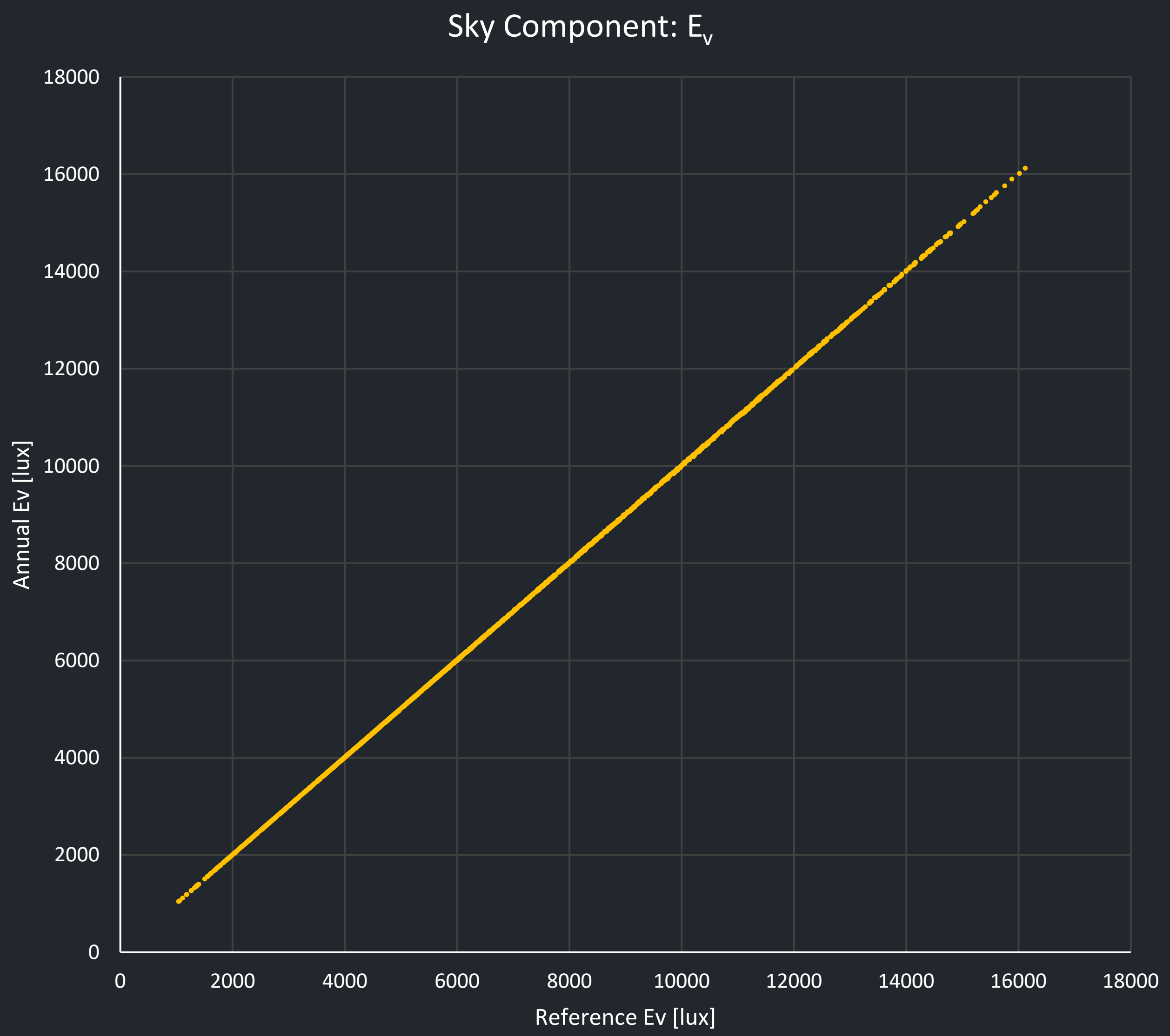




SKY



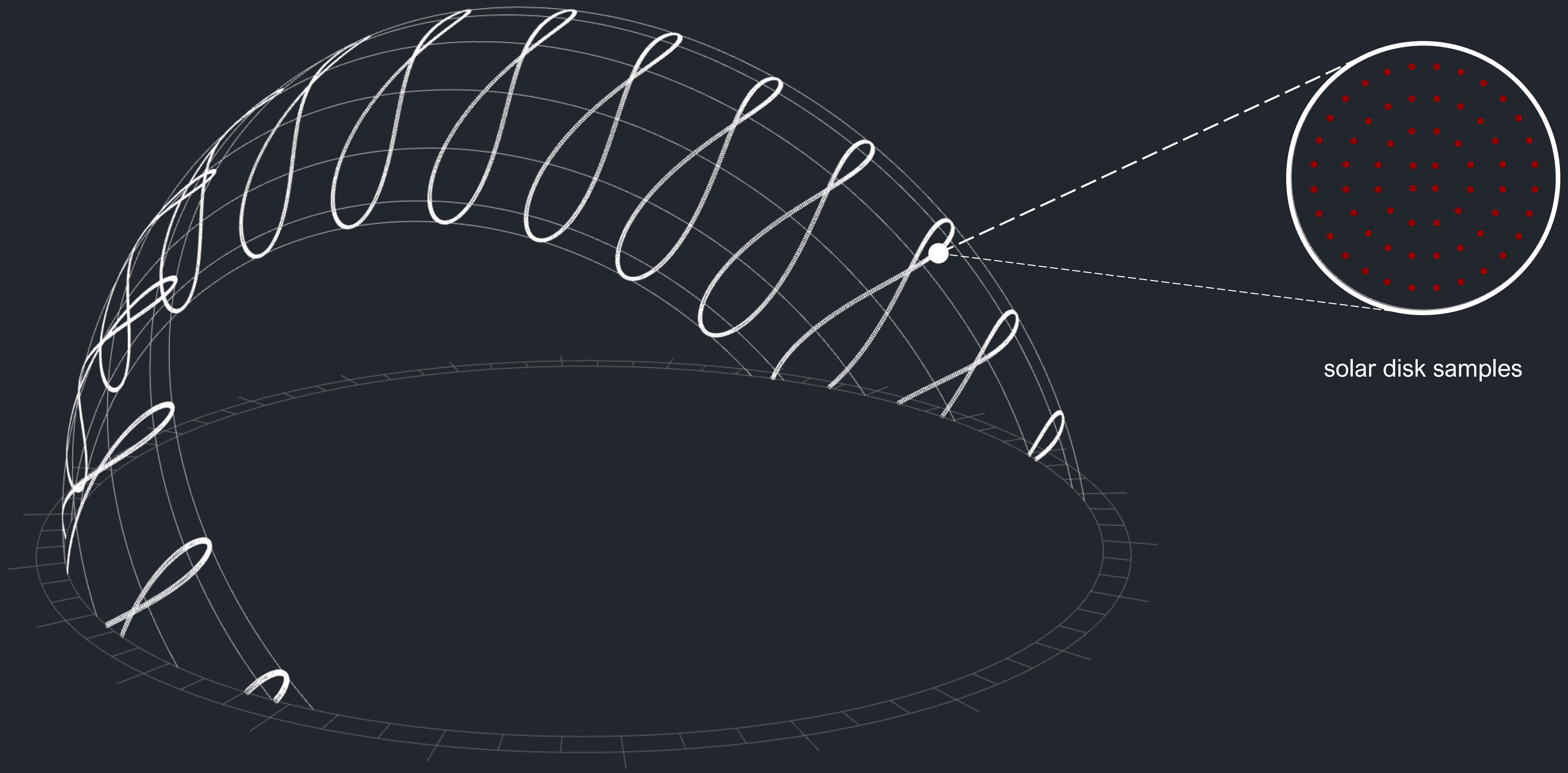




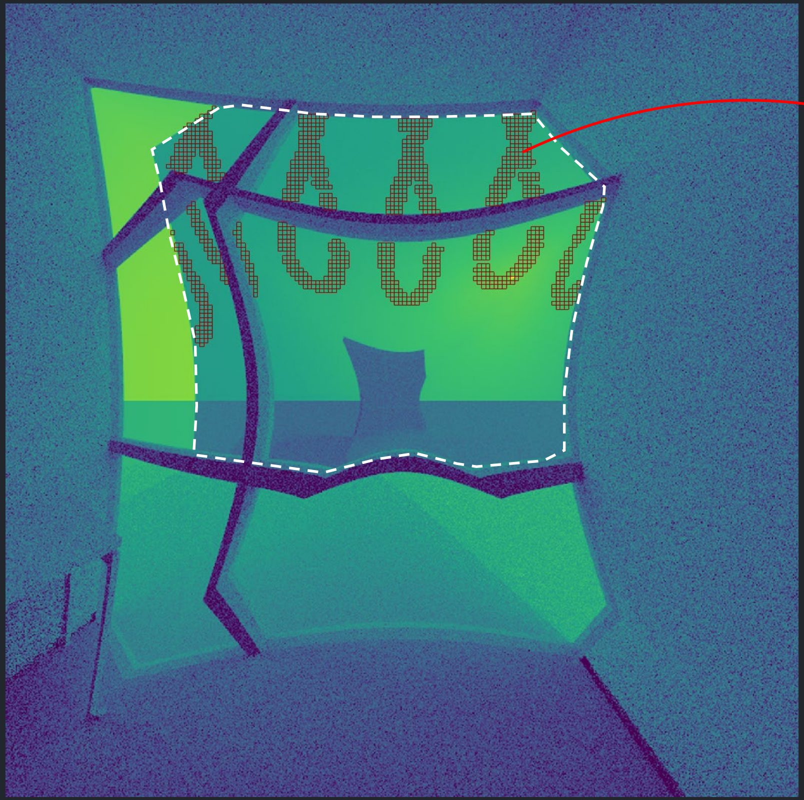
100 ms

SOLEMMA

Direct view



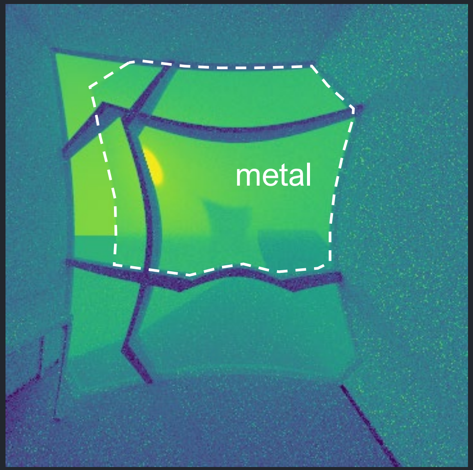
Reflected view

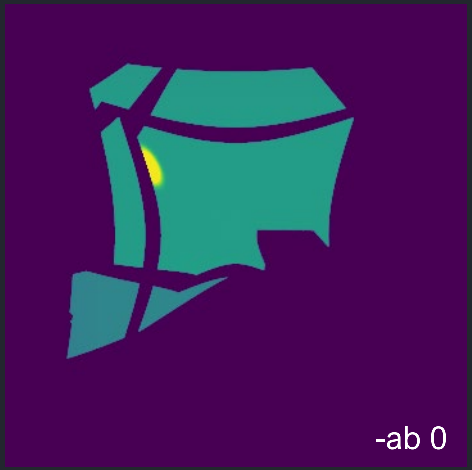


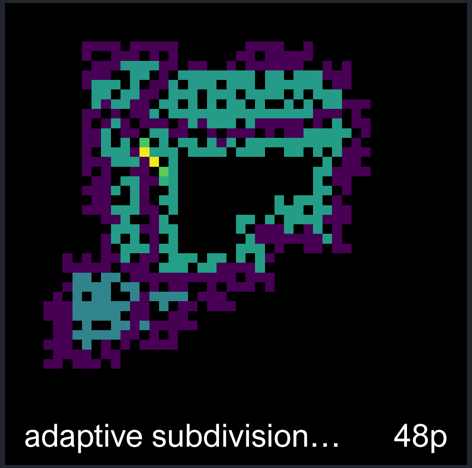
Super samples (glass reflector)

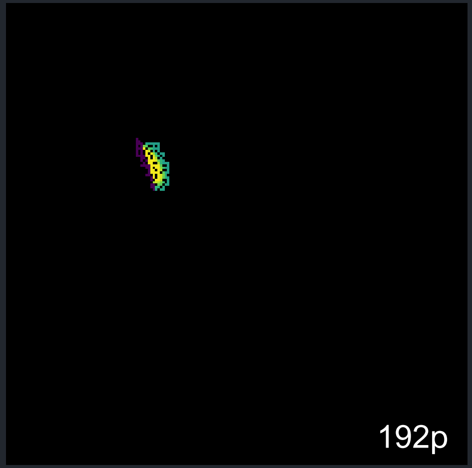
Distance-to-disk look up (θ, φ)

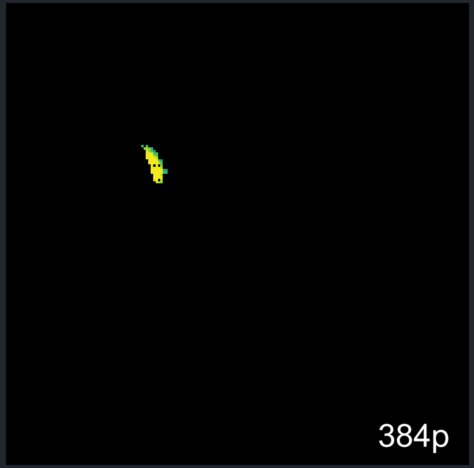
First-bounce (shadow test)





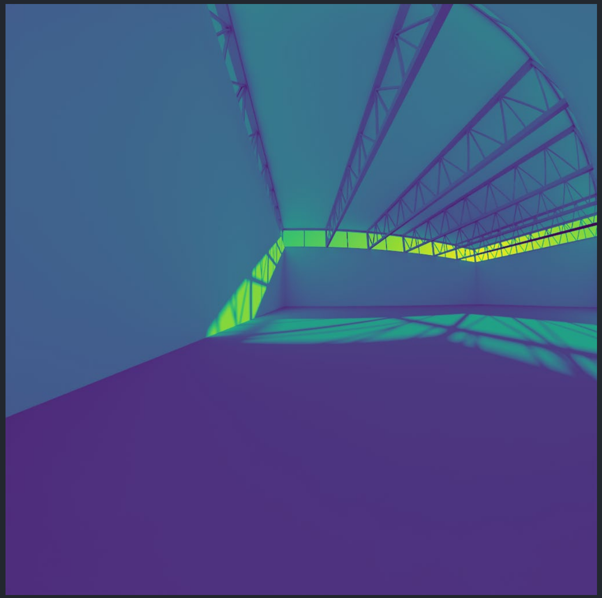






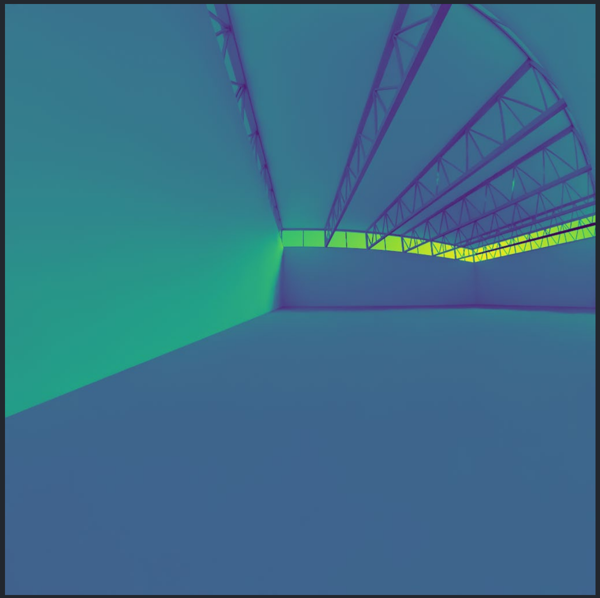
SOLEMMA

Patch problems



Gymnasium model (reference)

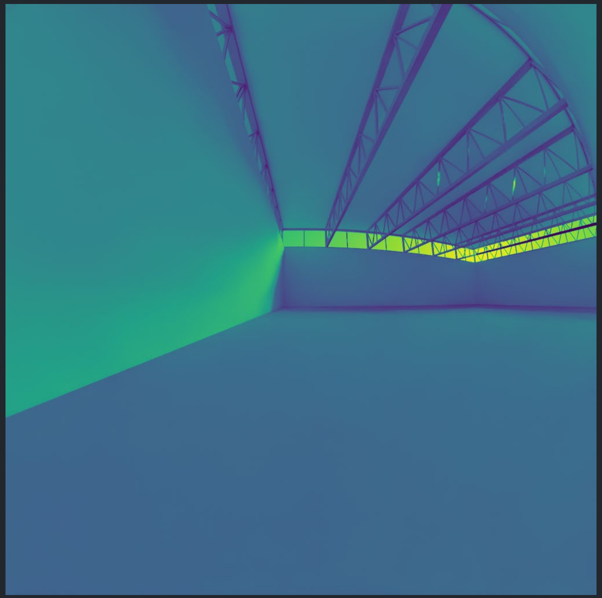
588 lux



145 patches
with direct-view correction

725 lux

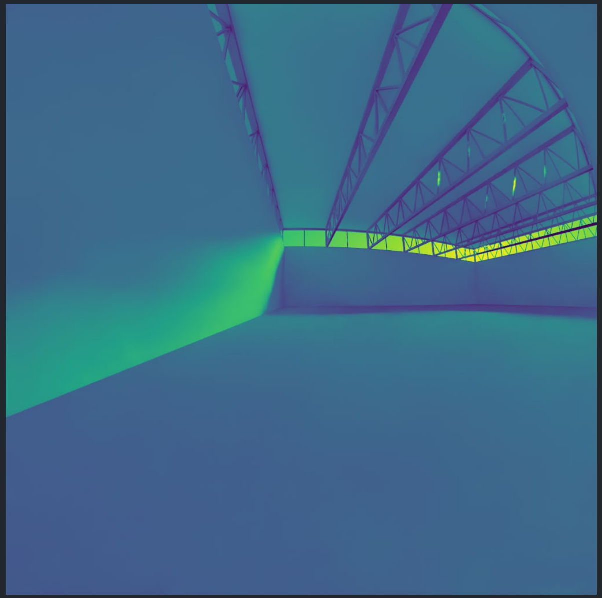
+22%



577 patches
with direct-view correction

768 lux

+31%

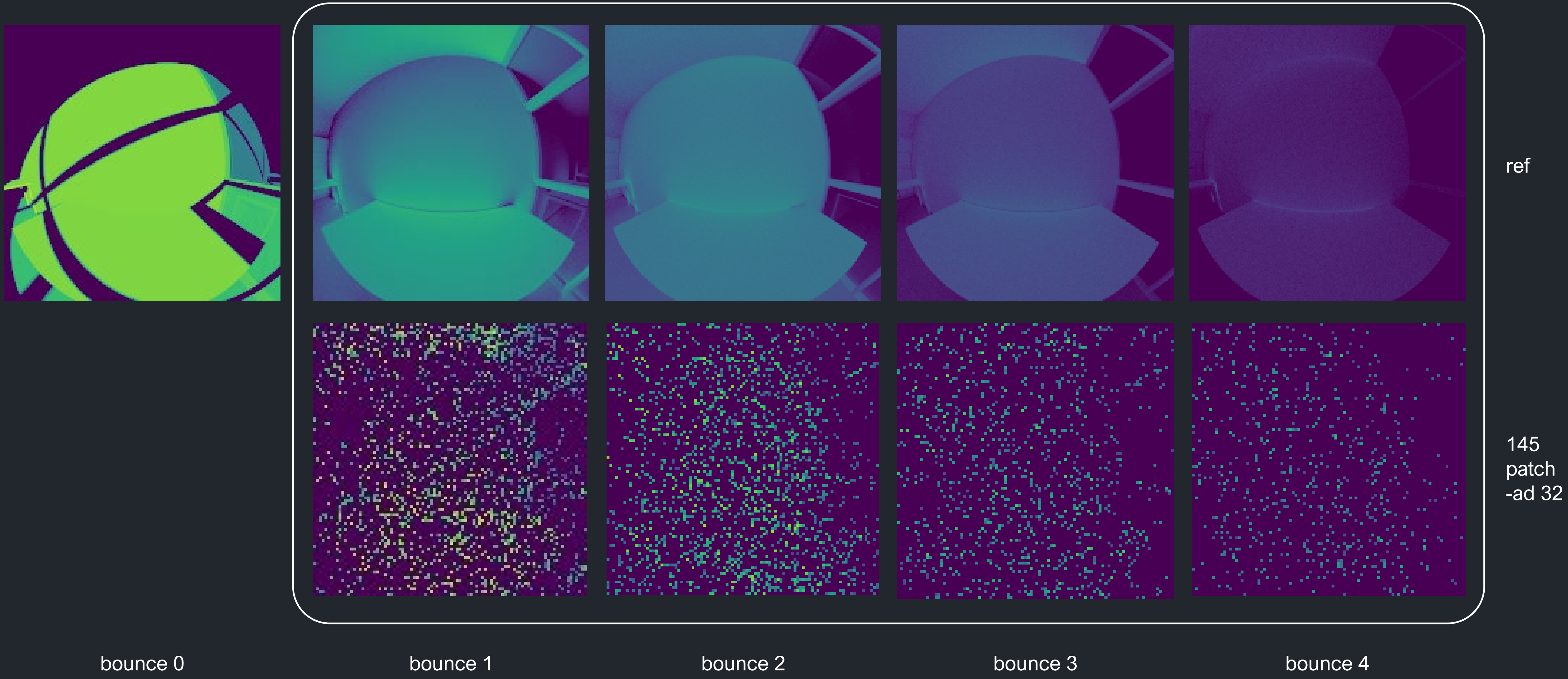


2305 patches
with direct-view correction

717 lux

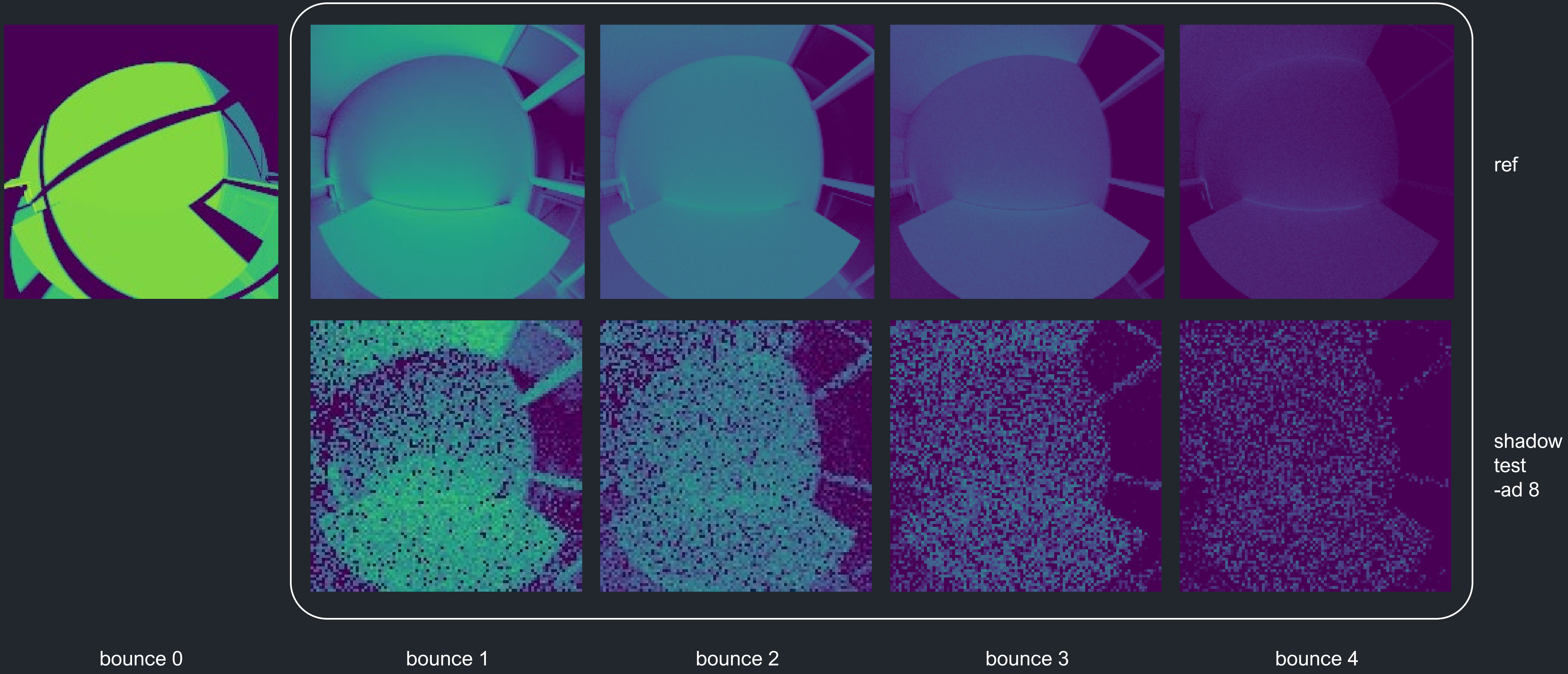
+22%

Secondary-bounces

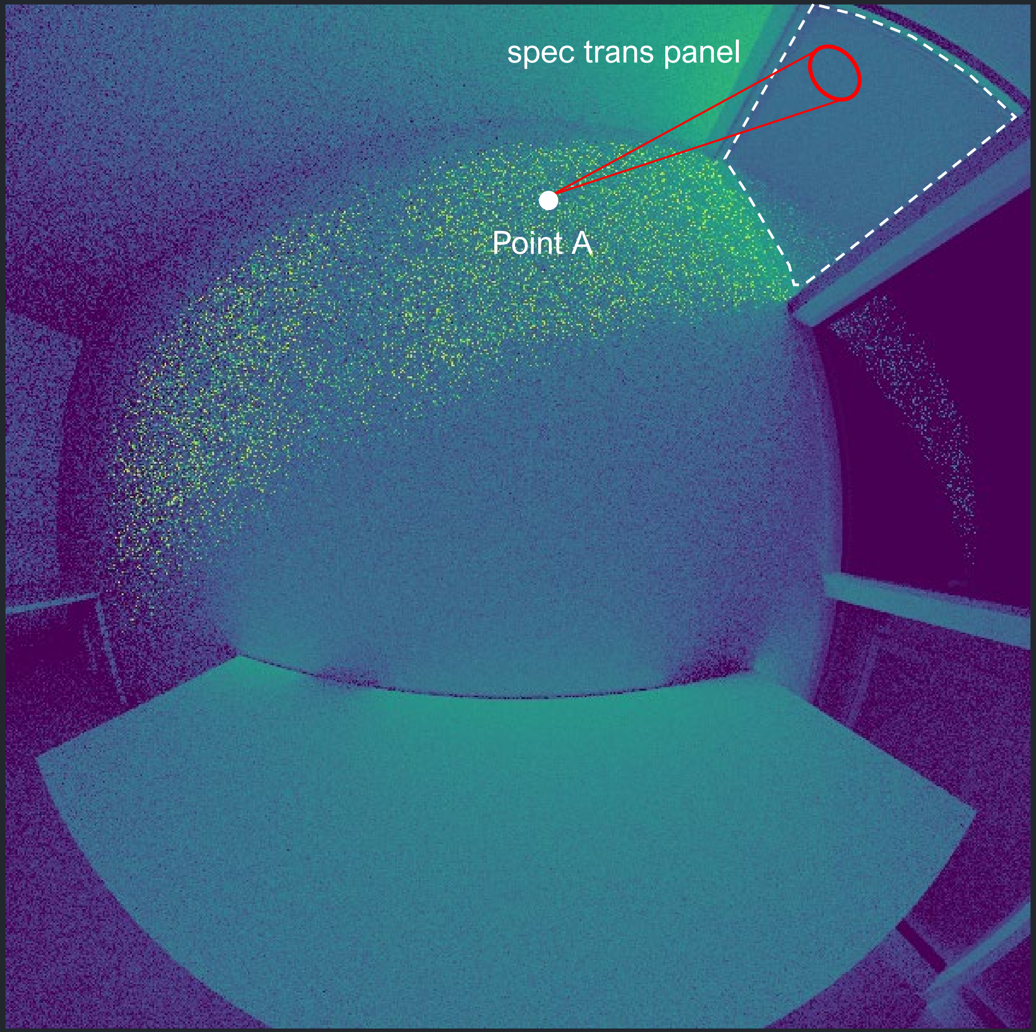


SOLEMMA

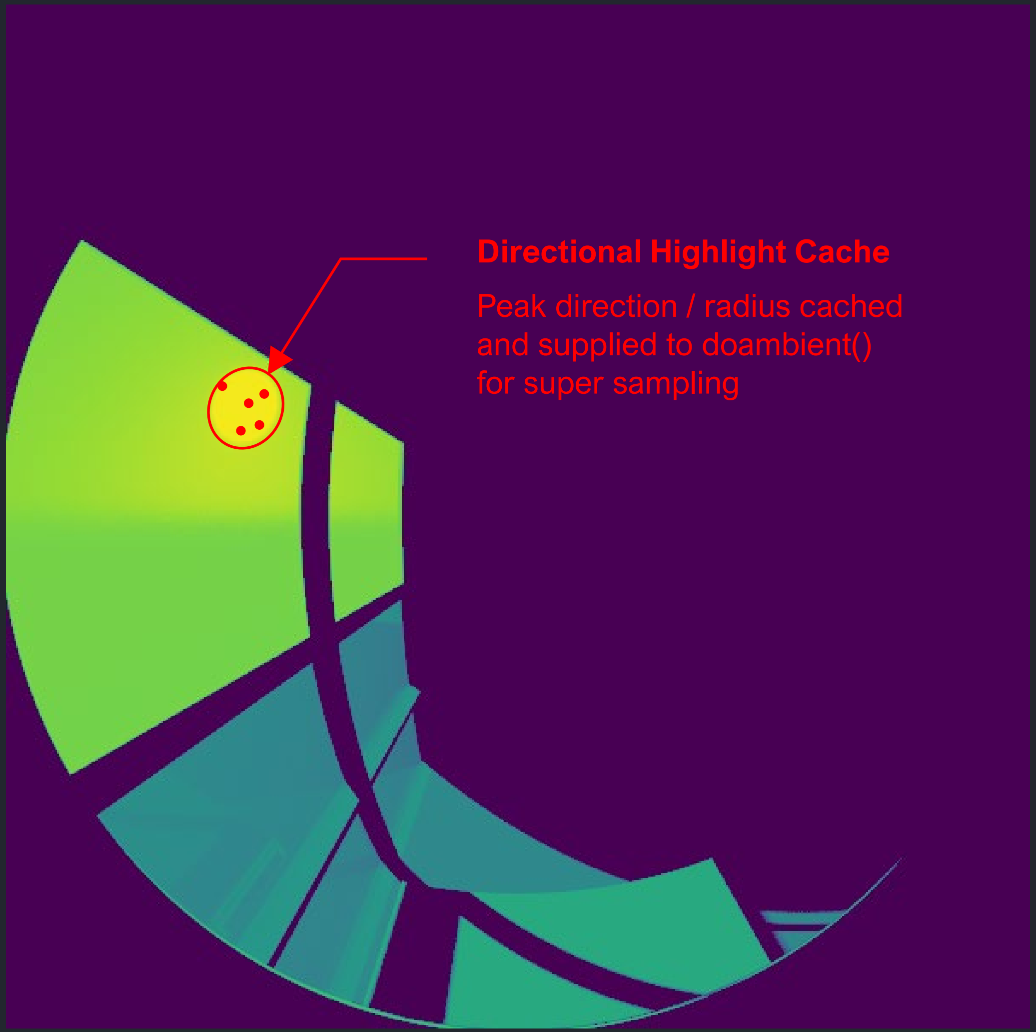
Secondary-bounces



Rough caustics



Sun contribution, second bounce



Ambient hemisphere from point A

SOLEMMA

TEST CASES

01 GLZ Clear Glazing

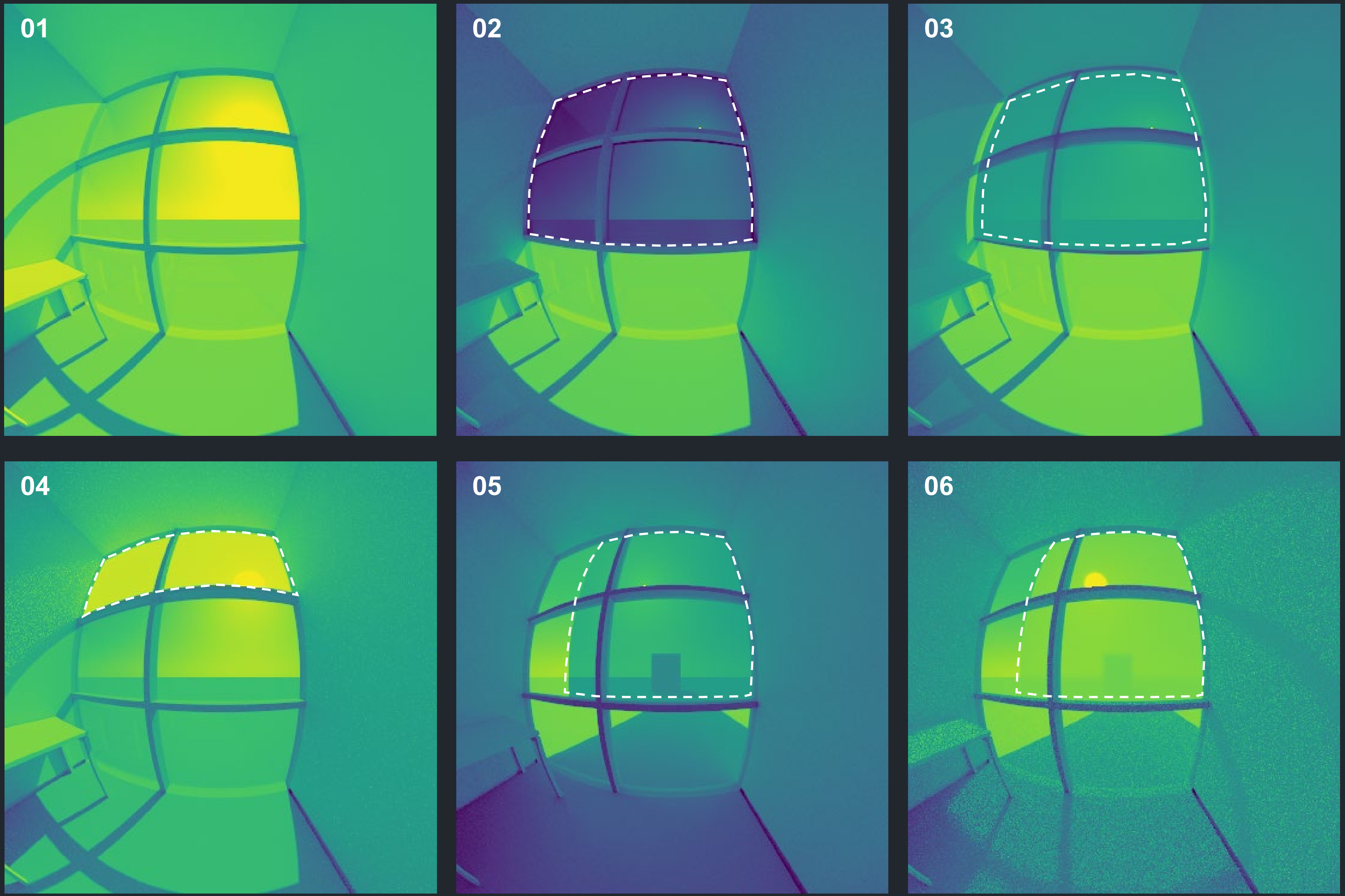
02 ECG Electrochromic Glazing

03 SHD Fabric Shade

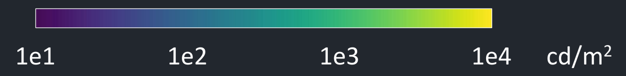
04 TRN Translucent Clerestory

05 NGL North Glass Reflector

06 NMT North Metal Reflector



Reference models:
Wasilewski, S., J. Wienold, and M. Andersen (2022) “A Critical Comparison of Annual Glare Simulation Methods” in *BuildSIM-Nordic.*

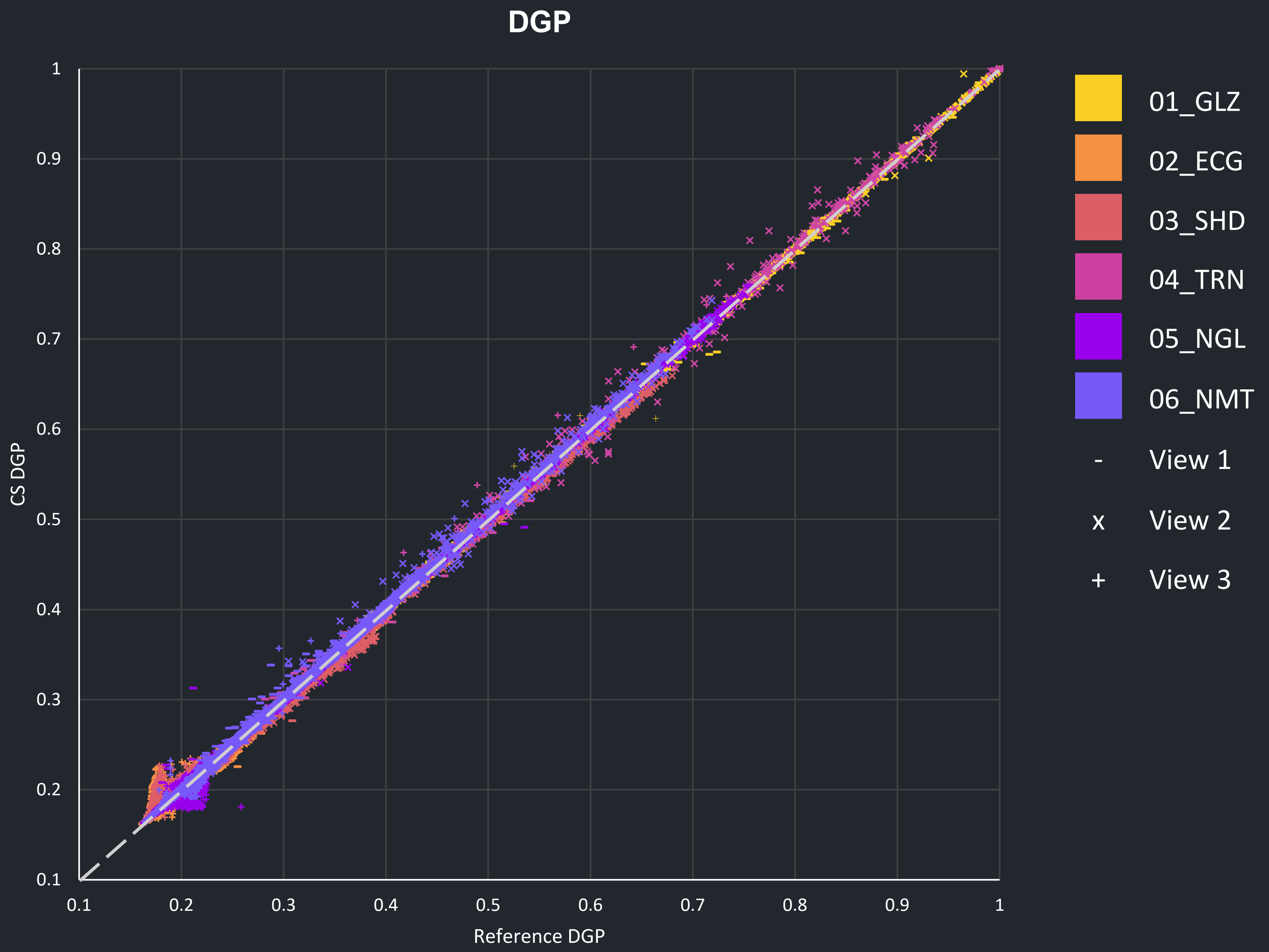


SOLEMMA

TEST CASES

	MSD	rMSE	MAE
GLZ	0.000	0.002	0.001
ECG	0.001	0.007	0.003
SHD	0.000	0.007	0.004
TRN	0.001	0.004	0.002
NGL	-0.001	0.005	0.002
NMT	0.001	0.004	0.002

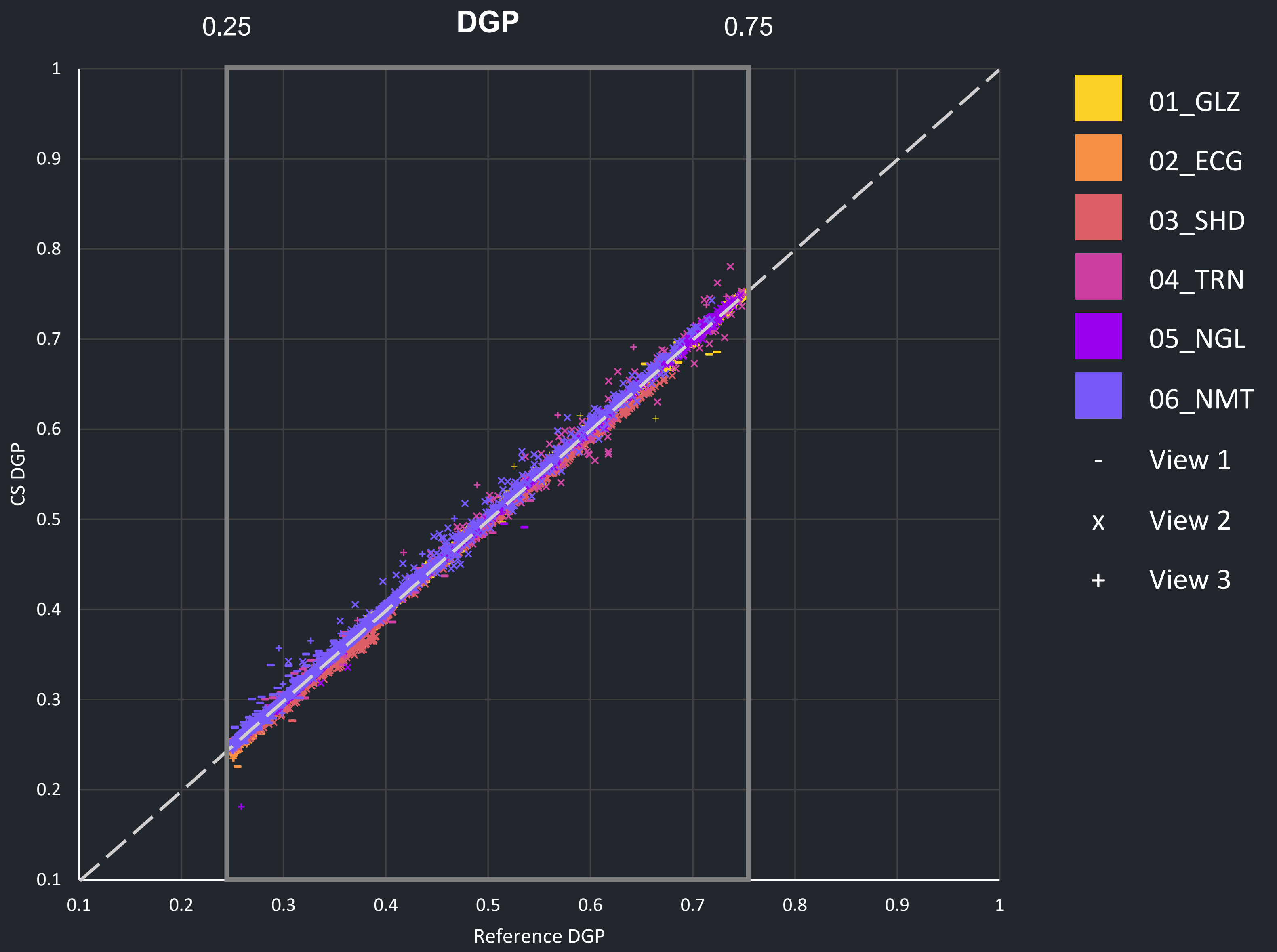
*Test and reference DGP values both computed without glare-source grouping



TEST CASES

	MSD	rMSE	MAE
GLZ	0.000	0.002	0.001
ECG	-0.001	0.003	0.002
SHD	-0.002	0.006	0.004
TRN	0.001	0.004	0.002
NGL	0.000	0.003	0.001
NMT	0.002	0.005	0.003

*Test and reference DGP values both computed without glare-source grouping



ClimateStudio v2 WIP

Average Run Time
1.8 sec*

*using 8 processes on
AMD Ryzen Threadripper 2950X 16-Core 3.50 GHz
NVIDIA RTX 2080 Ti

Table 4.10: *Simulation times for the test methods. Base time is with initial settings. High Settings are those specified in the Convergence Properties Section.*

	time* (base)	time* (high)	computer
DGPs	9.8	19.0	A
eDGPs (1)	6170	-	A, D
imageless DGP	3.8	12.5	A
ClimateStudio (2)	2.3	16.2	B
raytraverse	15.5	-	A
AGC	31.8	-	A,C

* *times given are real time in average seconds per point and scene.*

A. *2018 MacBook Pro with Intel 2.9 GHz Core i9 processor, 16 GB RAM, and a solid-state hard drive. Using 12 processes.*
B. *Windows 10 Virtual Machine with Intel Xeon Gold 6248R CPU @ 3.00GHz, 8 GB RAM, Nvidia GRID RTX8000P-2Q GPU*
C. *2022 MacBook Pro M1max. Using 3 processes.*
D. *Dell PowerEdge R6515 Server AMD EPYC 7413 with Ubuntu 20.04.3 LTS, using 1 process.*

1. *ClimateStudio requires simulating a grid of points, so six points were simulated instead of three. Reported times are pro-rated.*
2. *Illuminance calculations done on computer A.*

Wasilewski, S., J. Wienold, and M. Andersen (2022)
"A Critical Comparison of Annual Glare Simulation Methods" in *BuildSIM-Nordic.*

Next steps

- More test models!
- Dynamic reference cases
- Shadow cache
- Pure caustics

When will all this be available?

- ClimateStudio 2.0 public release date TBD
- WIP version should be ready this fall
- To request early access, email **jon@solemma.com**