Virtual light transport matrices for non-line-of-sight imaging

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2021 ICCV OCTOBER 11-17 VIRTUAL

What is NLOS imaging?

Seeing scenes behind a corner

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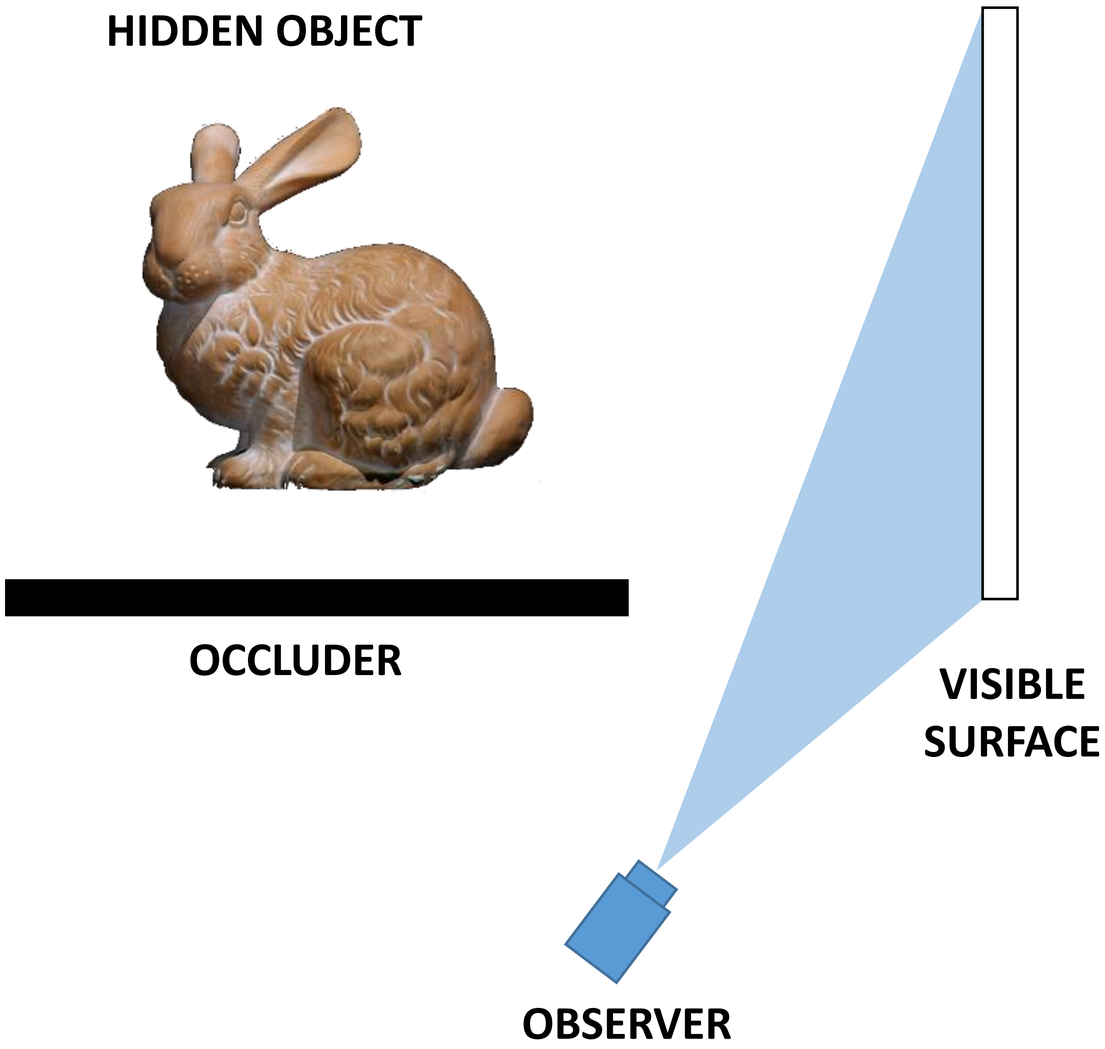
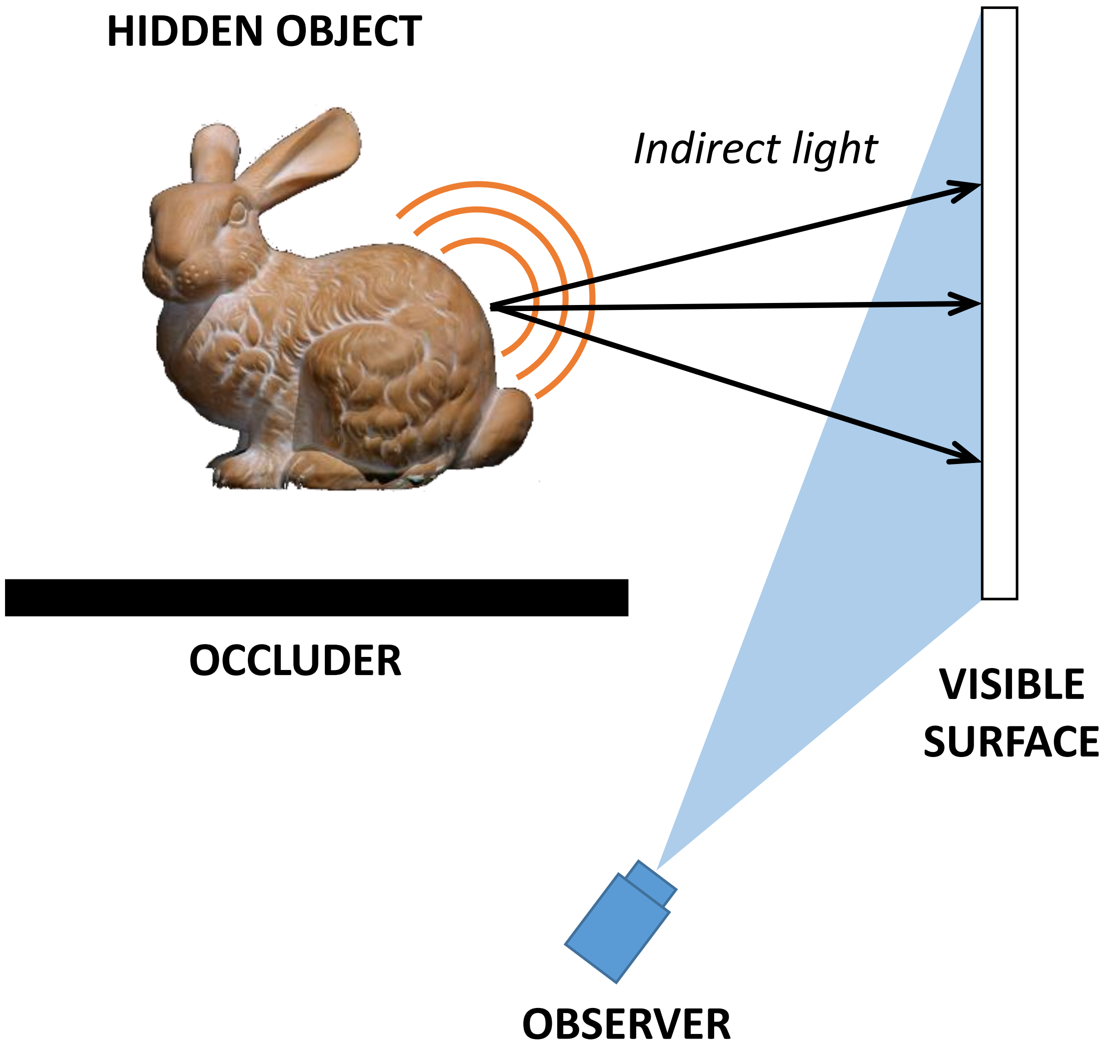
Seeing scenes behind a corner



What is NLOS imaging?

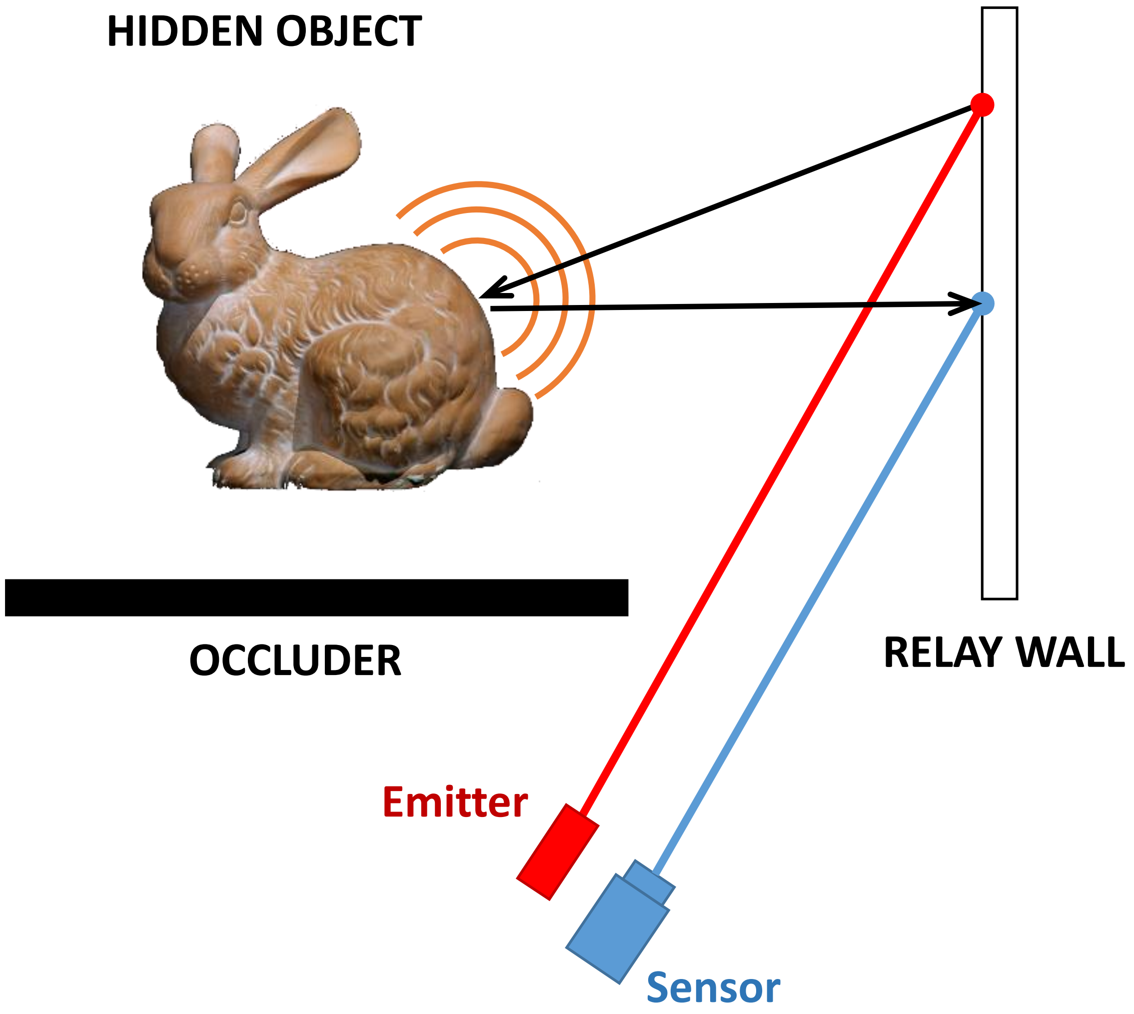
Seeing scenes behind a corner

*Analyze **indirect illumination***
in visible surfaces



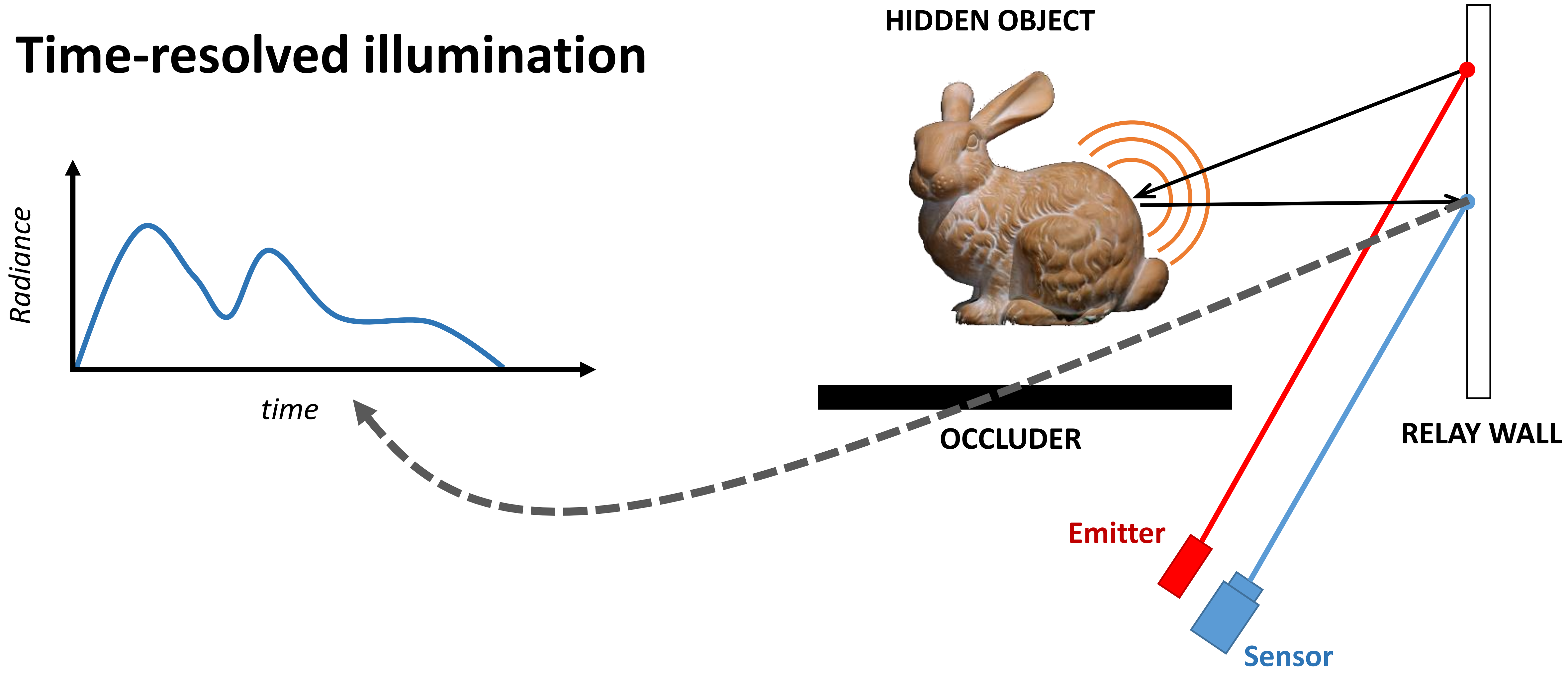
Active-light NLOS imaging

Time-resolved illumination



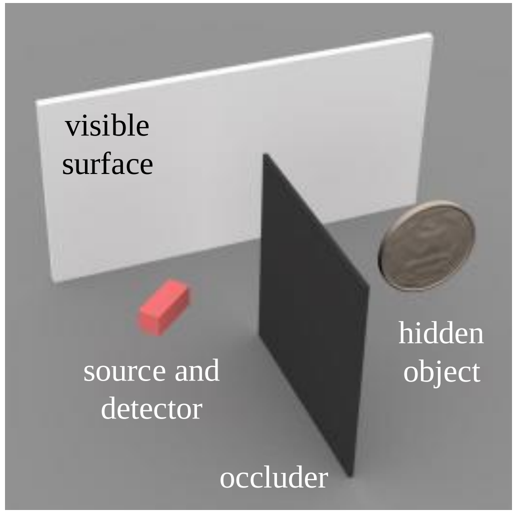
Active-light NLOS imaging

Time-resolved illumination



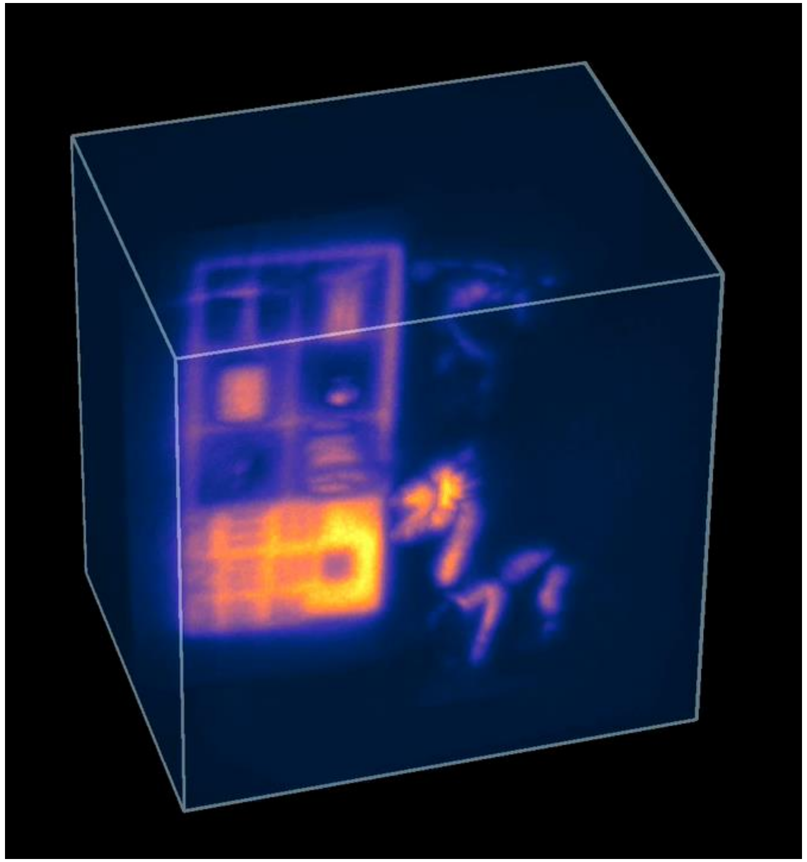
Active-light NLOS imaging

[Xin et al. 2019] Fermat paths



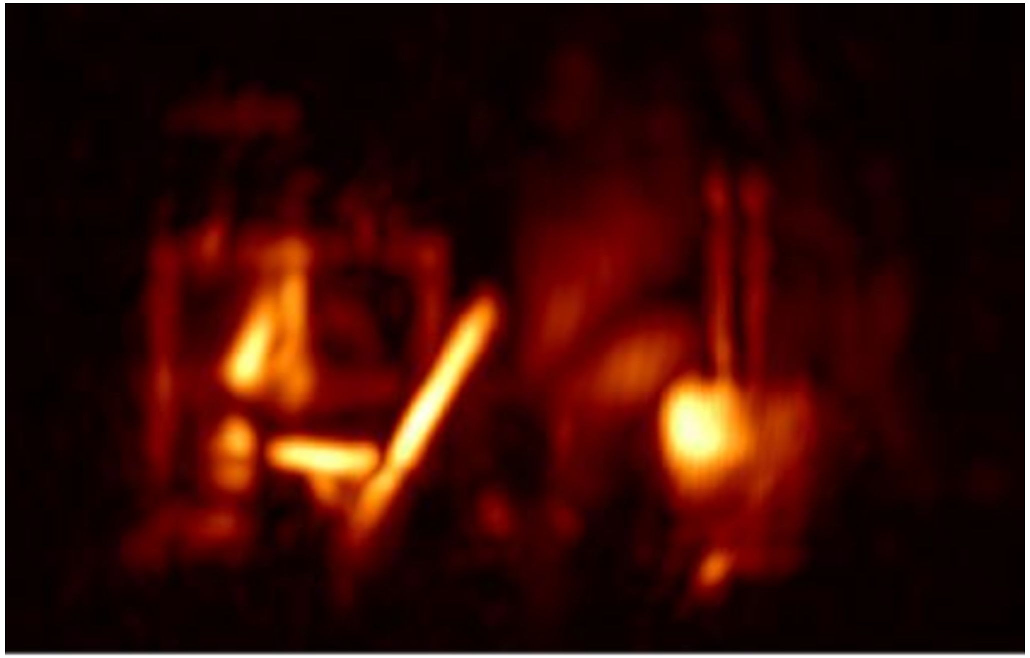
Active-light NLOS imaging

[Lindell et al. 2019] F-k migration



Active-light NLOS imaging

[Liu et al. 2019] Phasor fields



Active-light NLOS imaging

Current state: Mainly reconstruction of geometry

➔ Need general understanding:

- Light transport components
- Isolation of specific light paths
- Material analysis

Our goal

General understanding
of hidden scenes

Our goal

General understanding
of hidden scenes

⬇

Framework to compute light
transport in NLOS scenarios

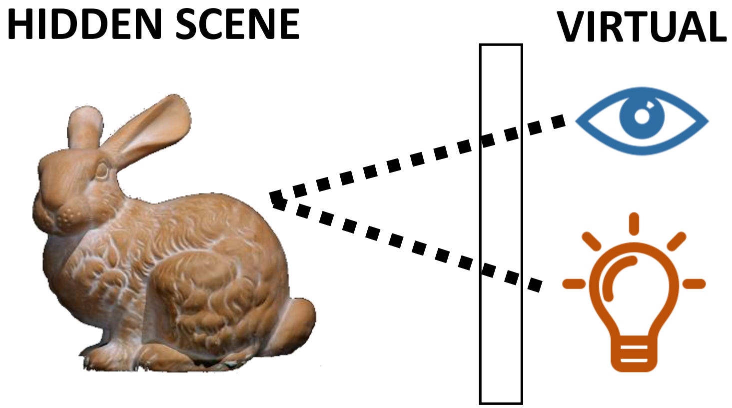
Our goal: General understanding of hidden scenes

How?

Our goal: General understanding of hidden scenes

How?

Phasor-field
NLOS imaging

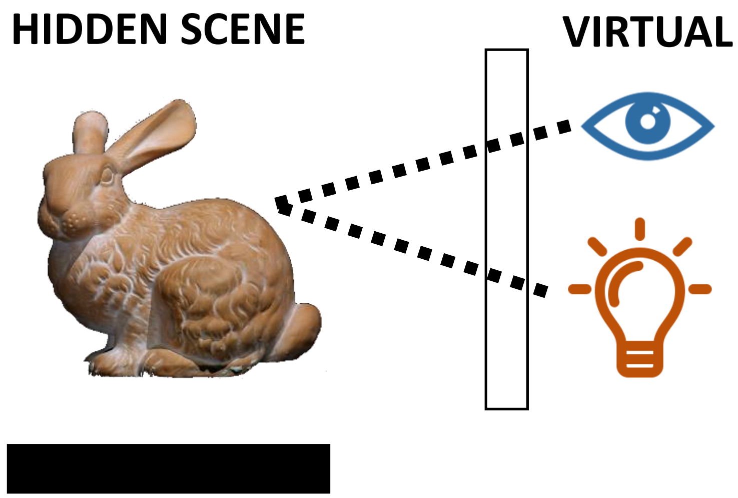


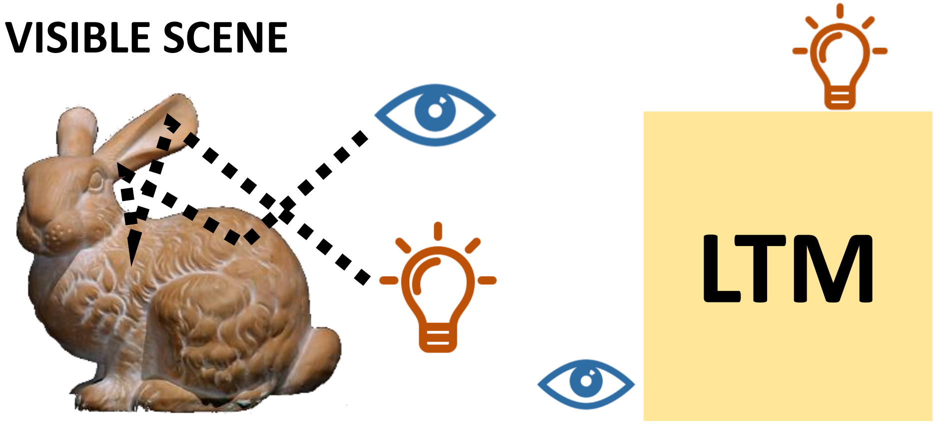
[redacted]

Our goal: General understanding of hidden scenes

How?

Phasor-field NLOS imaging **+** **LOS light transport matrices**

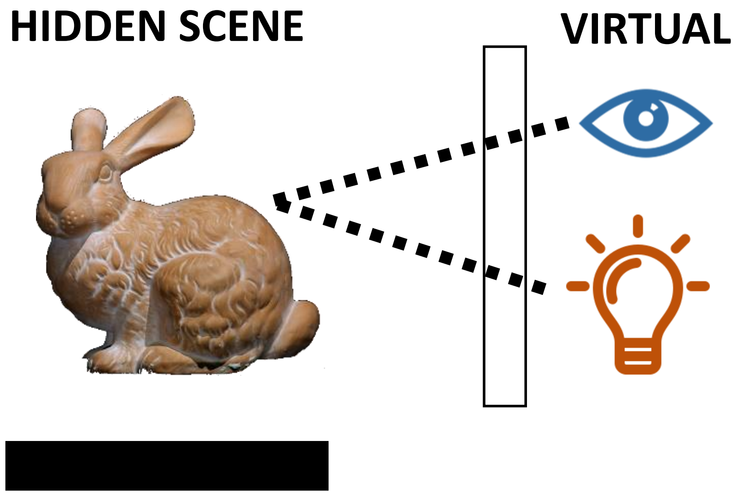




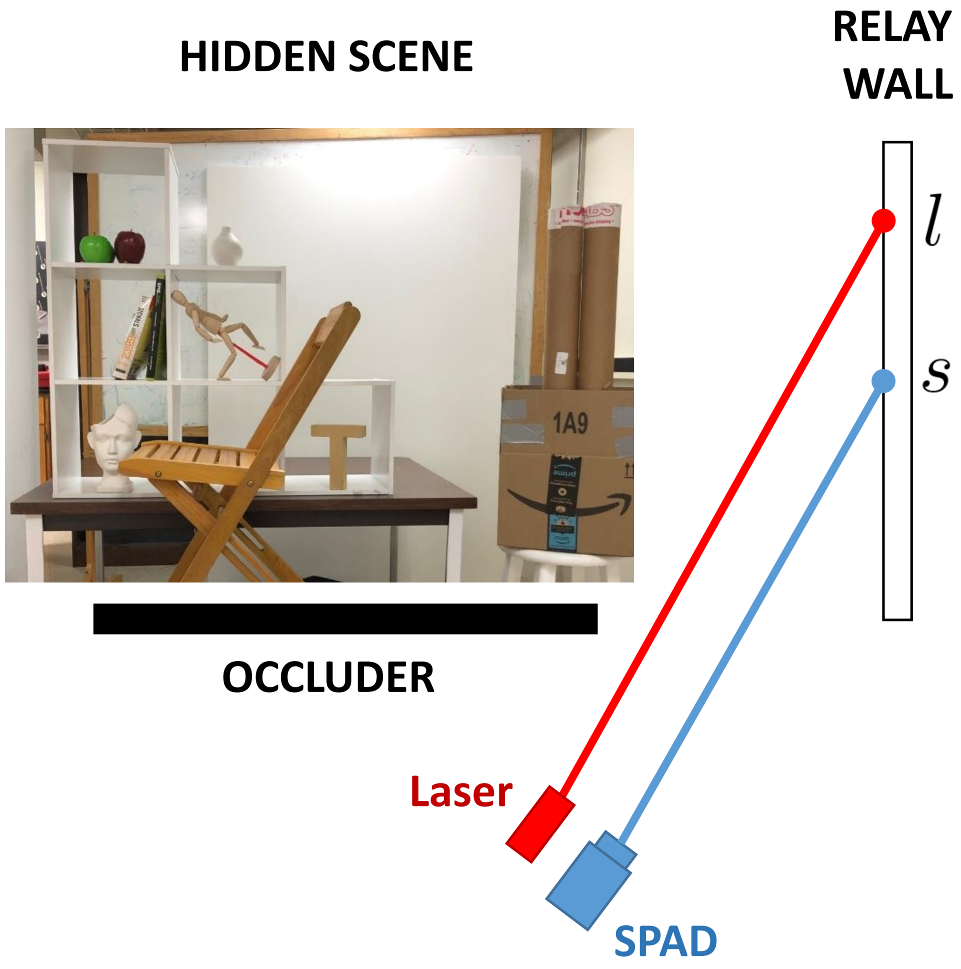
Our goal: General understanding of hidden scenes

How?

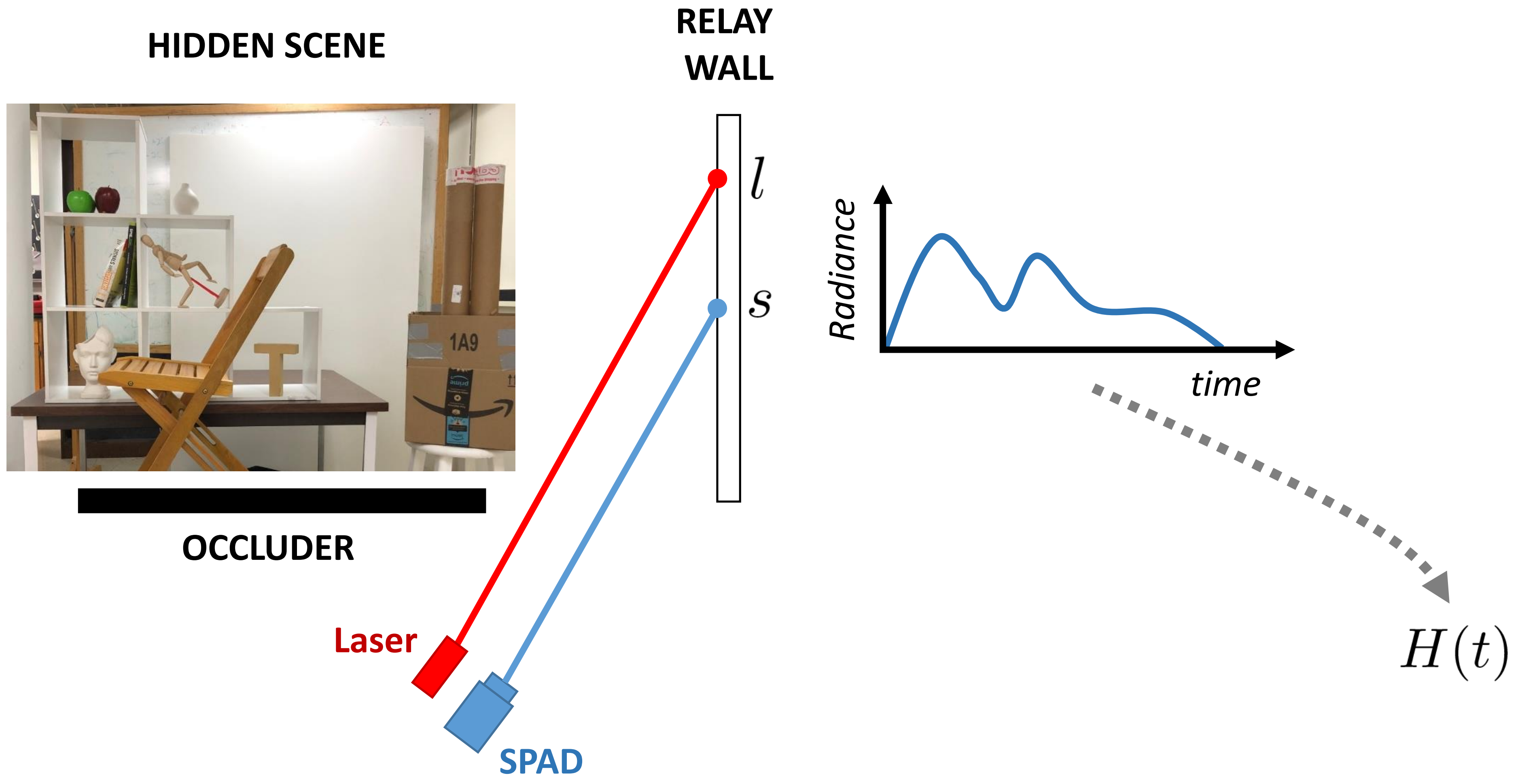
Phasor-field NLOS imaging + LOS light transport matrices



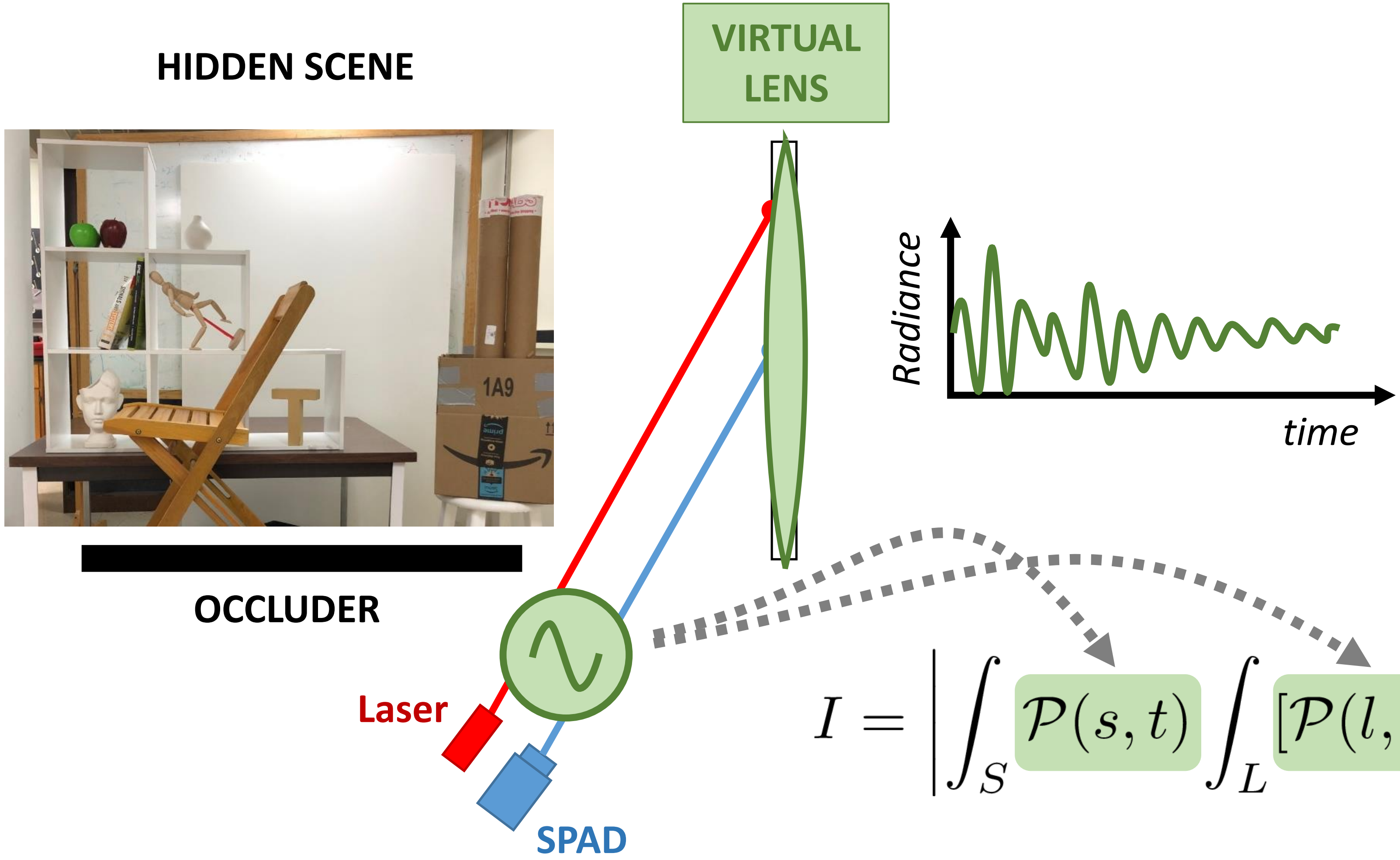
Phasor-field NLOS imaging [Liu et al. 2019, 2020]



Phasor-field NLOS imaging [Liu et al. 2019, 2020]

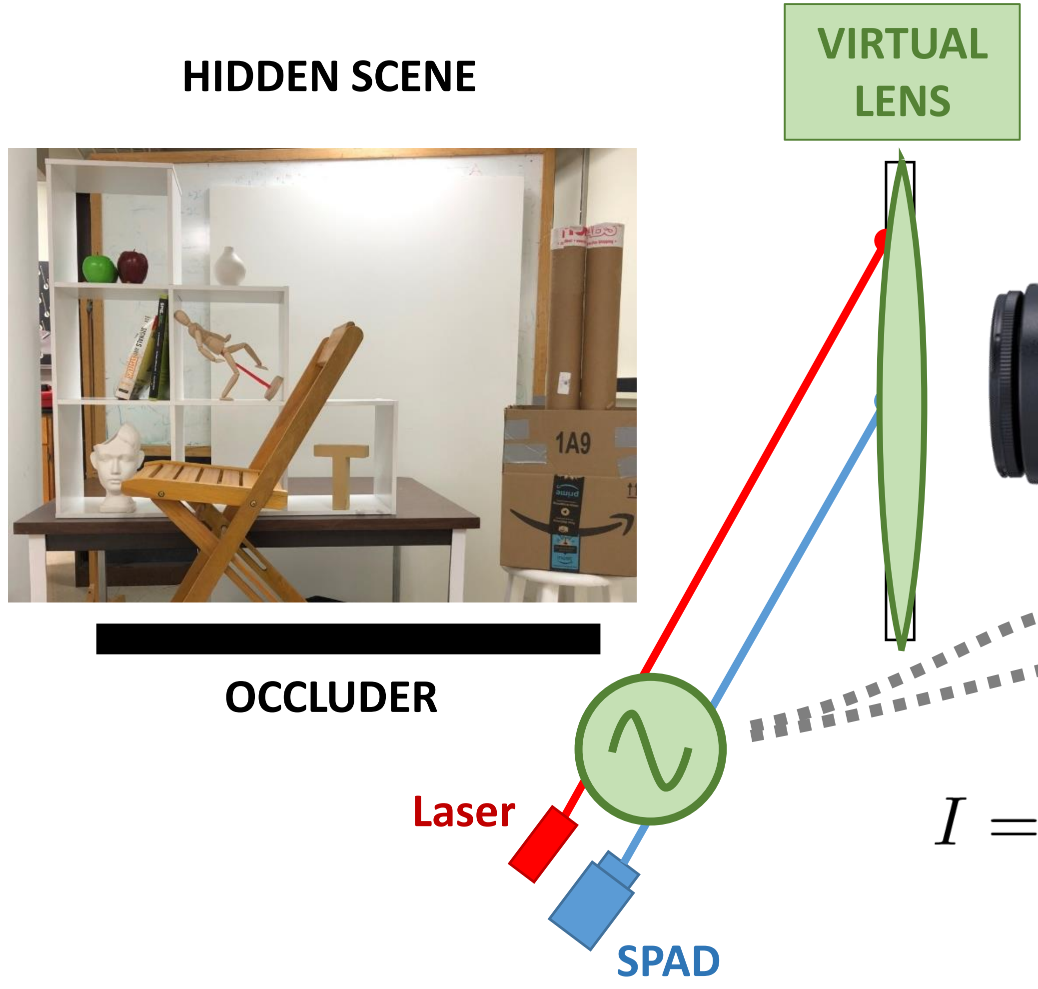


Phasor-field NLOS imaging [Liu et al. 2019, 2020]



$$I = \left| \int_S \mathcal{P}(s,t) \int_L [\mathcal{P}(l,t) * H(t)] \mathrm{d}l \, \mathrm{d}s \right|^2$$

Phasor-field NLOS imaging [Liu et al. 2019, 2020]

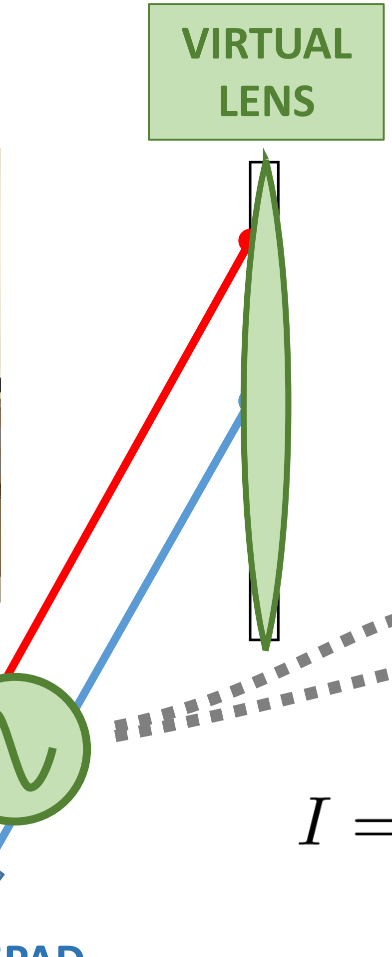


Transforms NLOS into virtual LOS (Line-of-Sight)

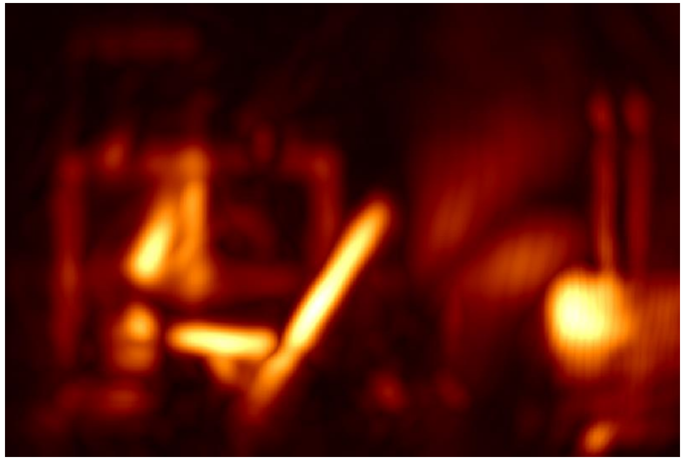
$$I = \left| \int_S \mathcal{P}(s,t) \int_L [\mathcal{P}(l,t) * H(t)] \mathrm{d}l \mathrm{d}s \right|^2$$

Phasor-field NLOS imaging [Liu et al. 2019, 2020]

HIDDEN SCENE



RESULT

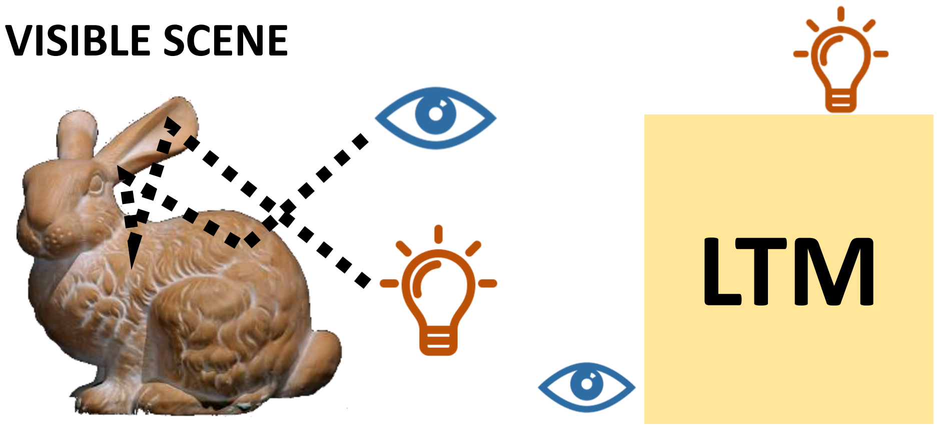


$$I = \left| \int_S \mathcal{P}(s,t) \int_L [\mathcal{P}(l,t) * H(t)] \mathrm{d}l \mathrm{d}s \right|^2$$

Our goal: General understanding of hidden scenes

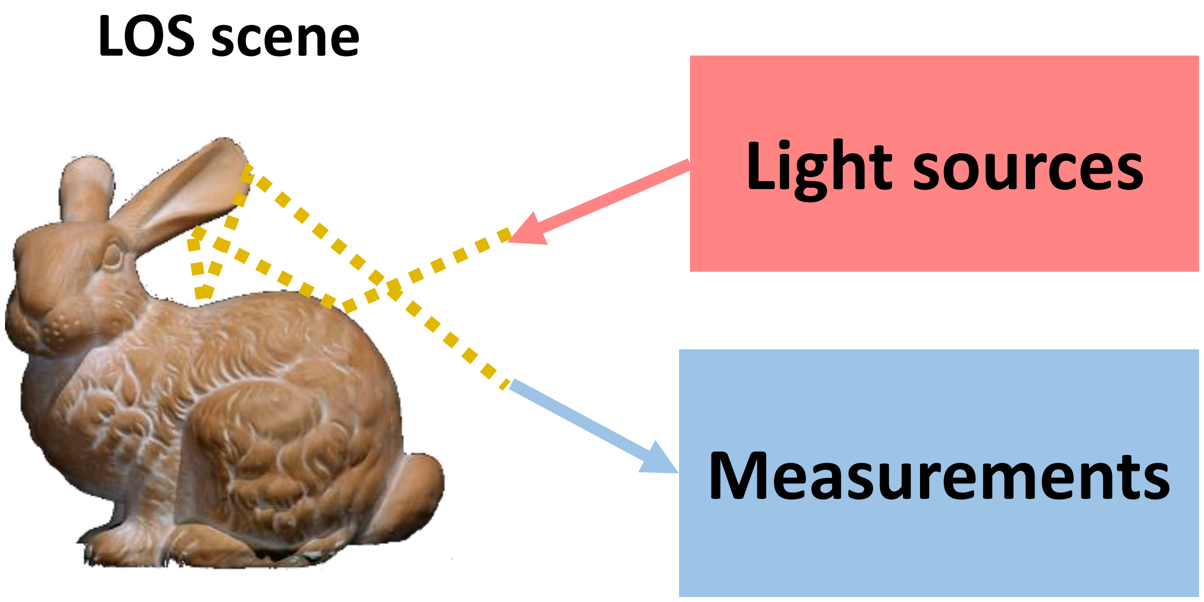
How?

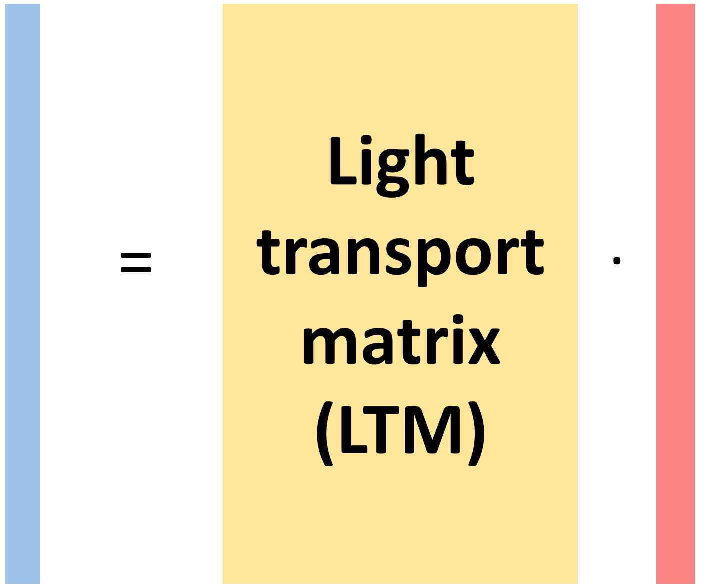
Phasor-field NLOS imaging + **LOS light transport matrices**



Light transport equation

LTMs are fundamental in scene understanding





$$\mathbf{i} = \mathbf{T} \cdot \mathbf{p}$$

Light transport matrix probing

[Nayar et al. 2006] Fast direct vs. global illumination separation

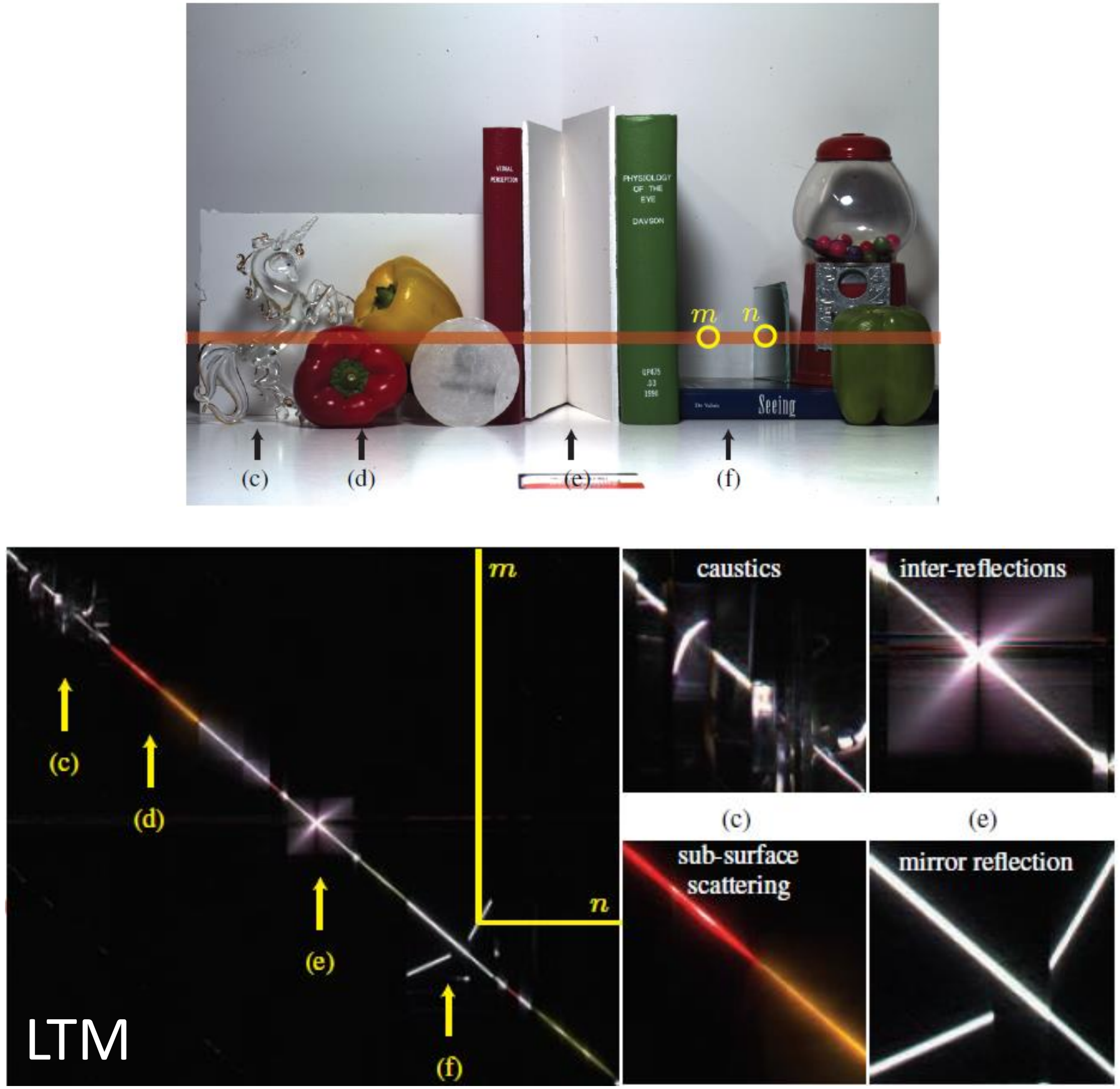
Direct

Global

Light transport matrix probing

[O'Toole et al. 2012]

LTM probing:
- Short vs long range separation
- De-scattering
- Masking specific paths
- Sub-surface scattering, caustics, interreflections

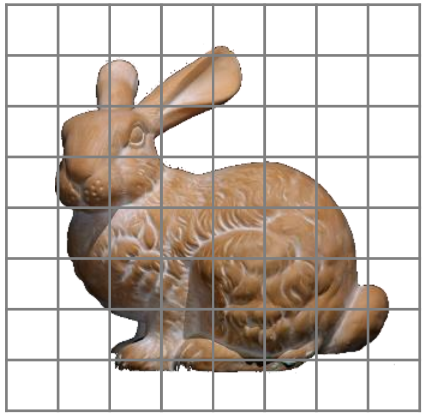


LOS light transport matrix probing

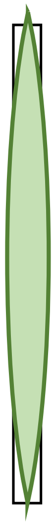
Virtual LTMs of hidden scenes

Phasor-field NLOS imaging + Light transport matrices

NLOS scene



OCCLUDER

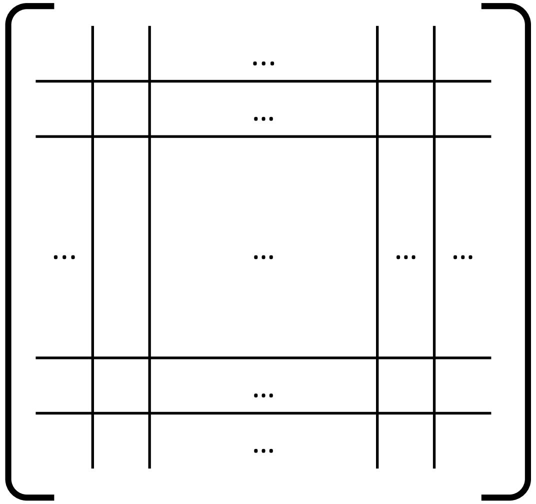


Virtual projector-camera

Virtual NLOS LTM

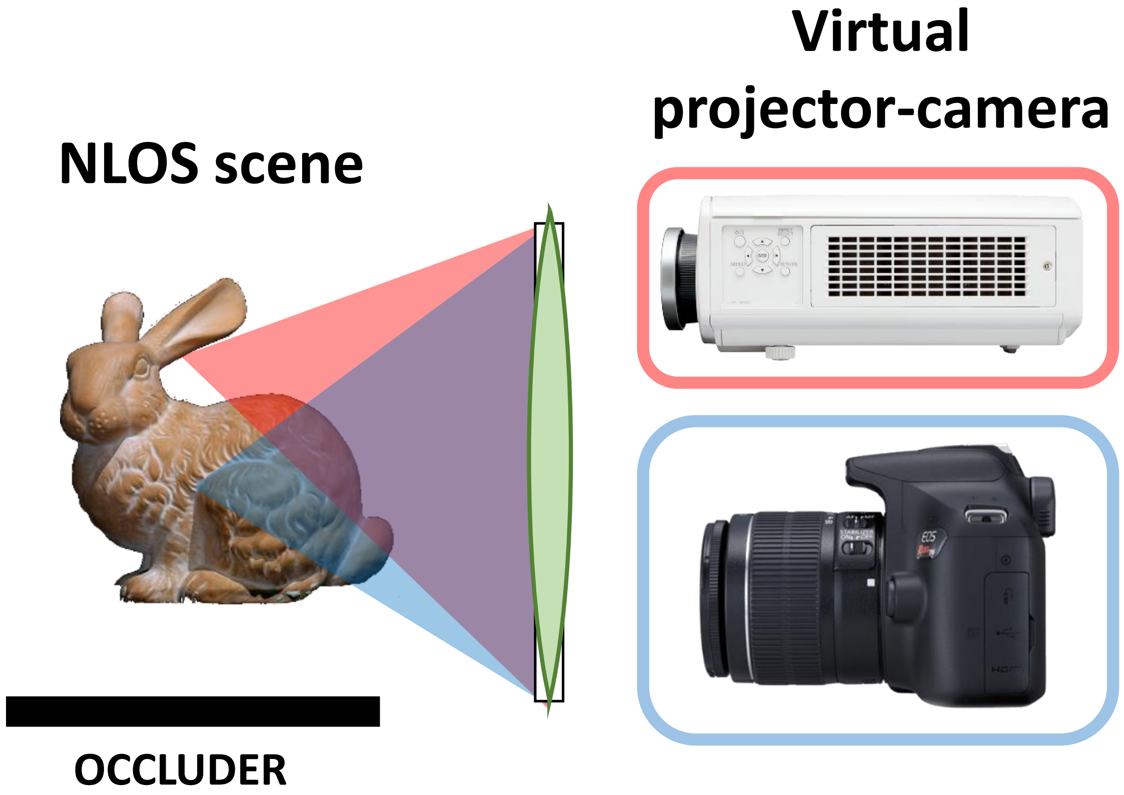
Projector pixels

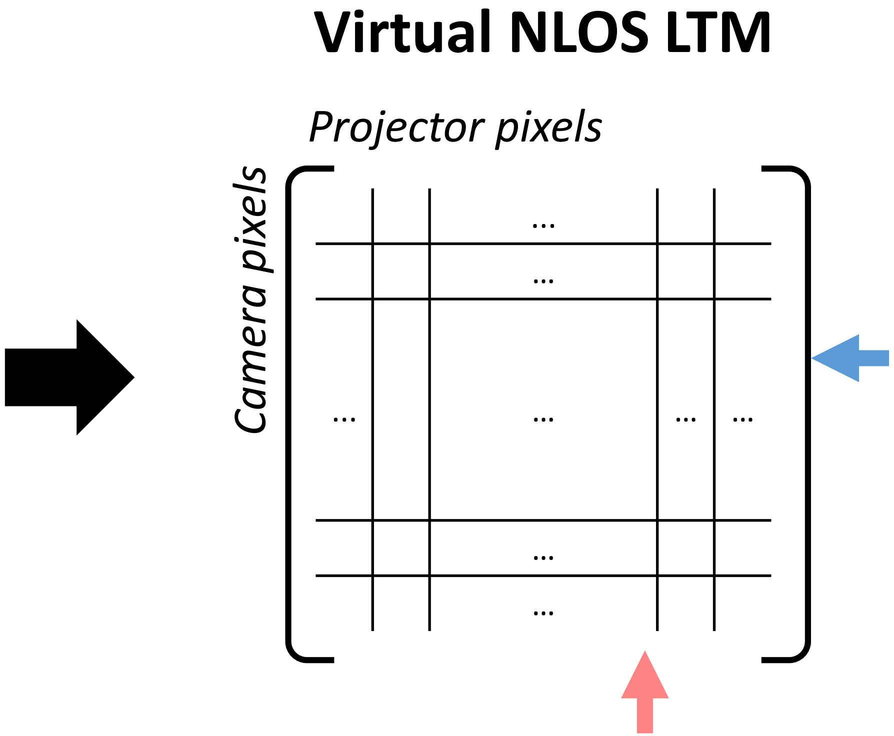
Camera pixels



Virtual LTMs of hidden scenes

Phasor-field NLOS imaging **+** **Light transport matrices**

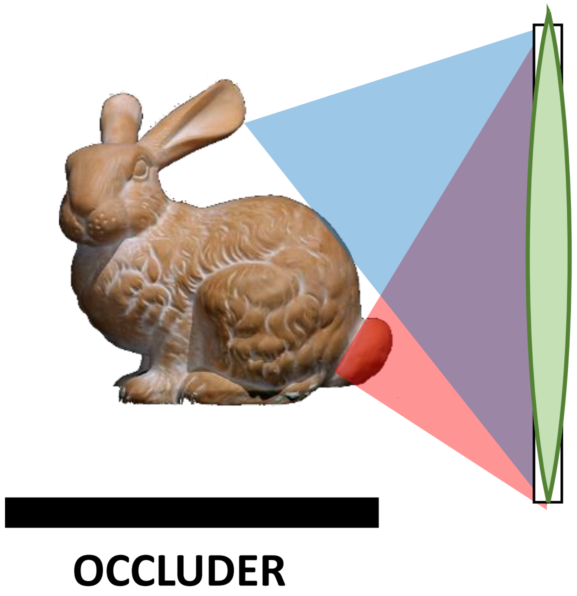




Virtual LTMs of hidden scenes

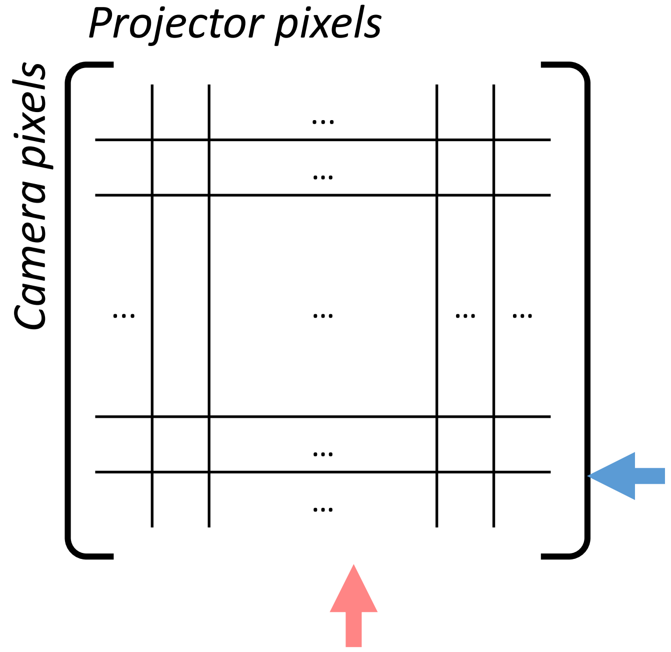
Phasor-field NLOS imaging + Light transport matrices

NLOS scene



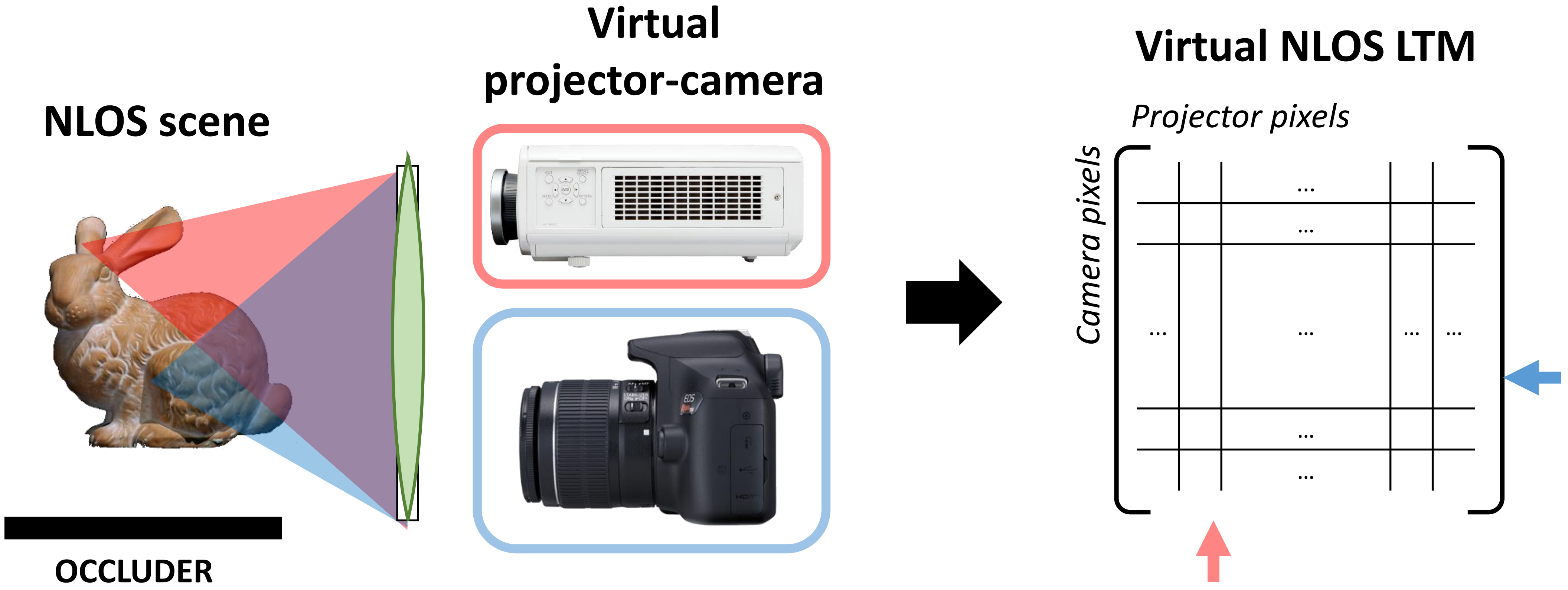
Virtual projector-camera

Virtual NLOS LTM



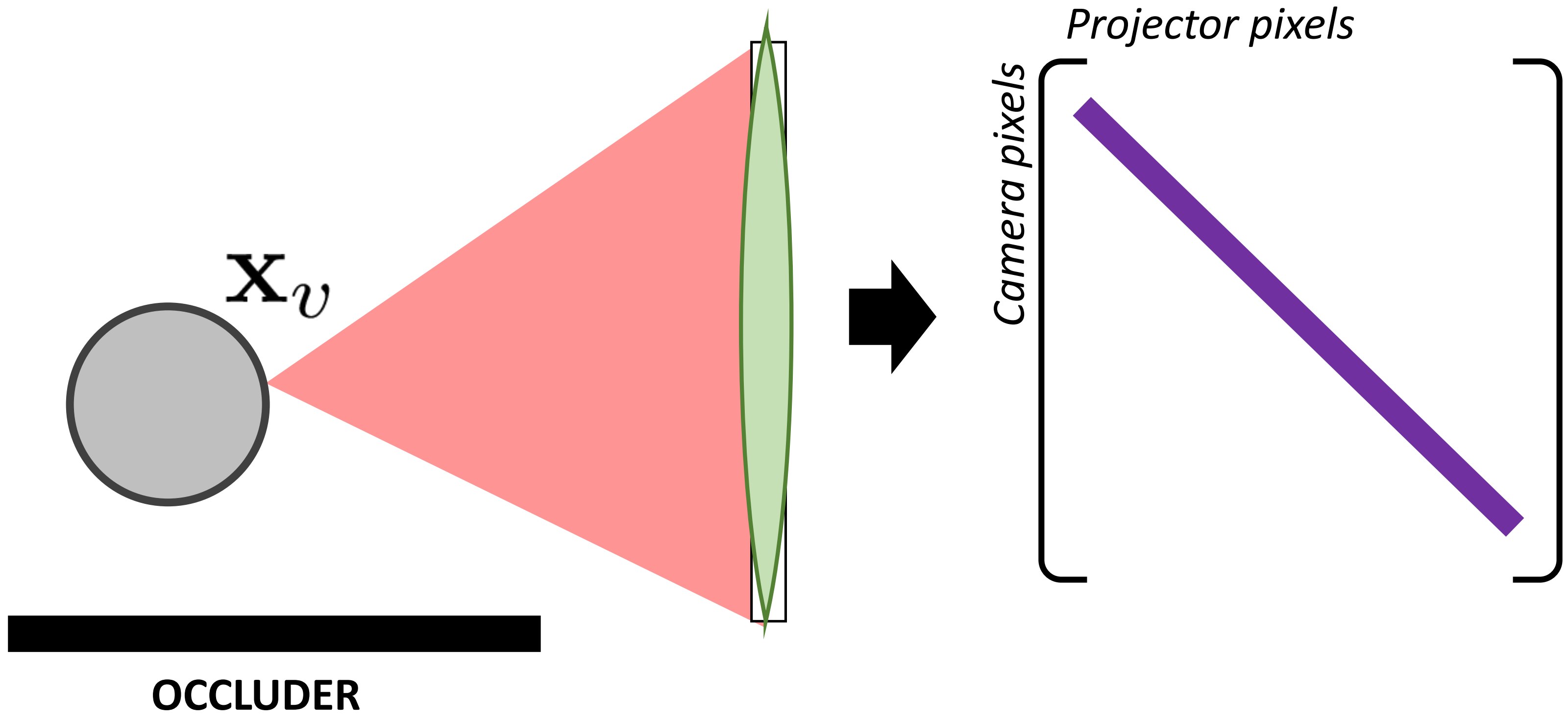
Virtual LTMs of hidden scenes

Phasor-field NLOS imaging + **Light transport matrices**



Virtual LTM computation

Diagonal: Confocal projector and camera pixels



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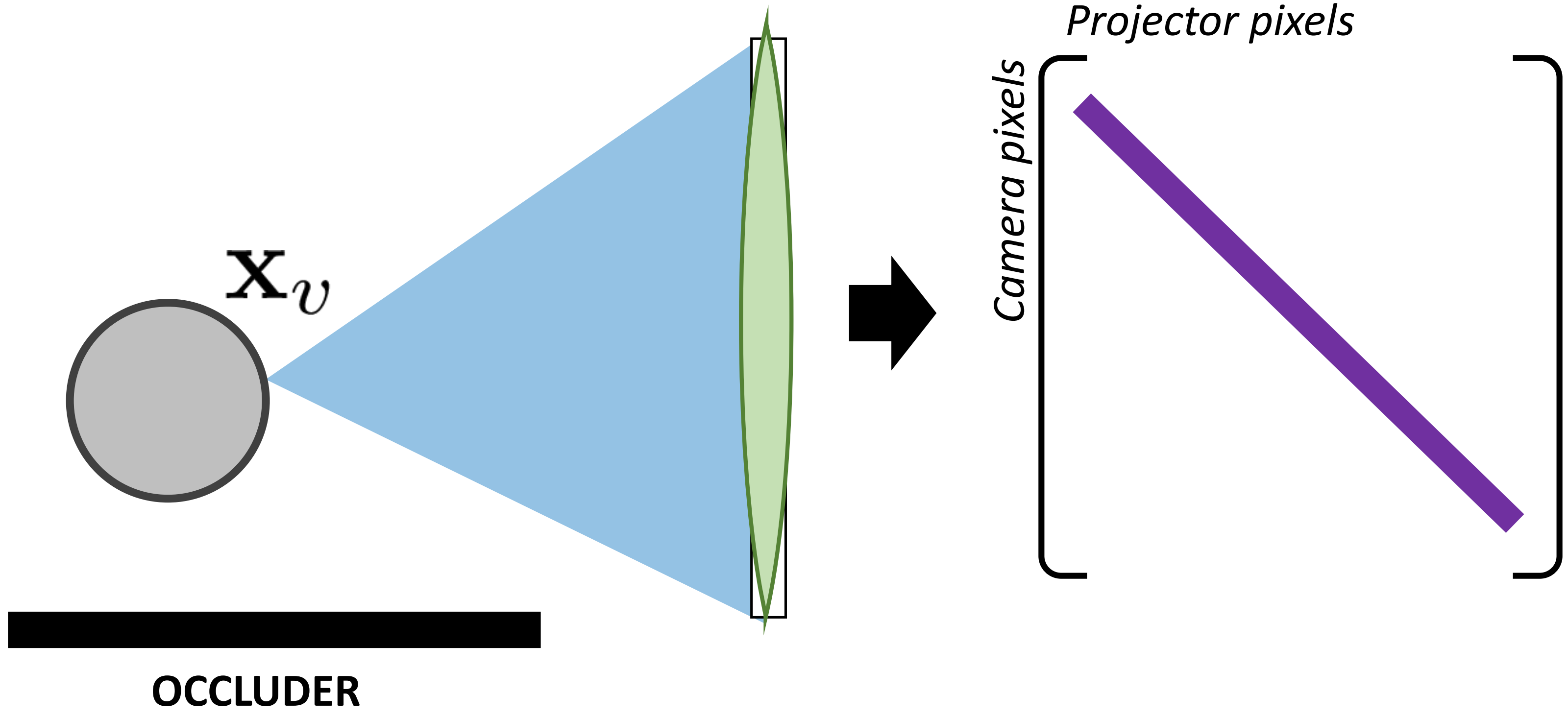

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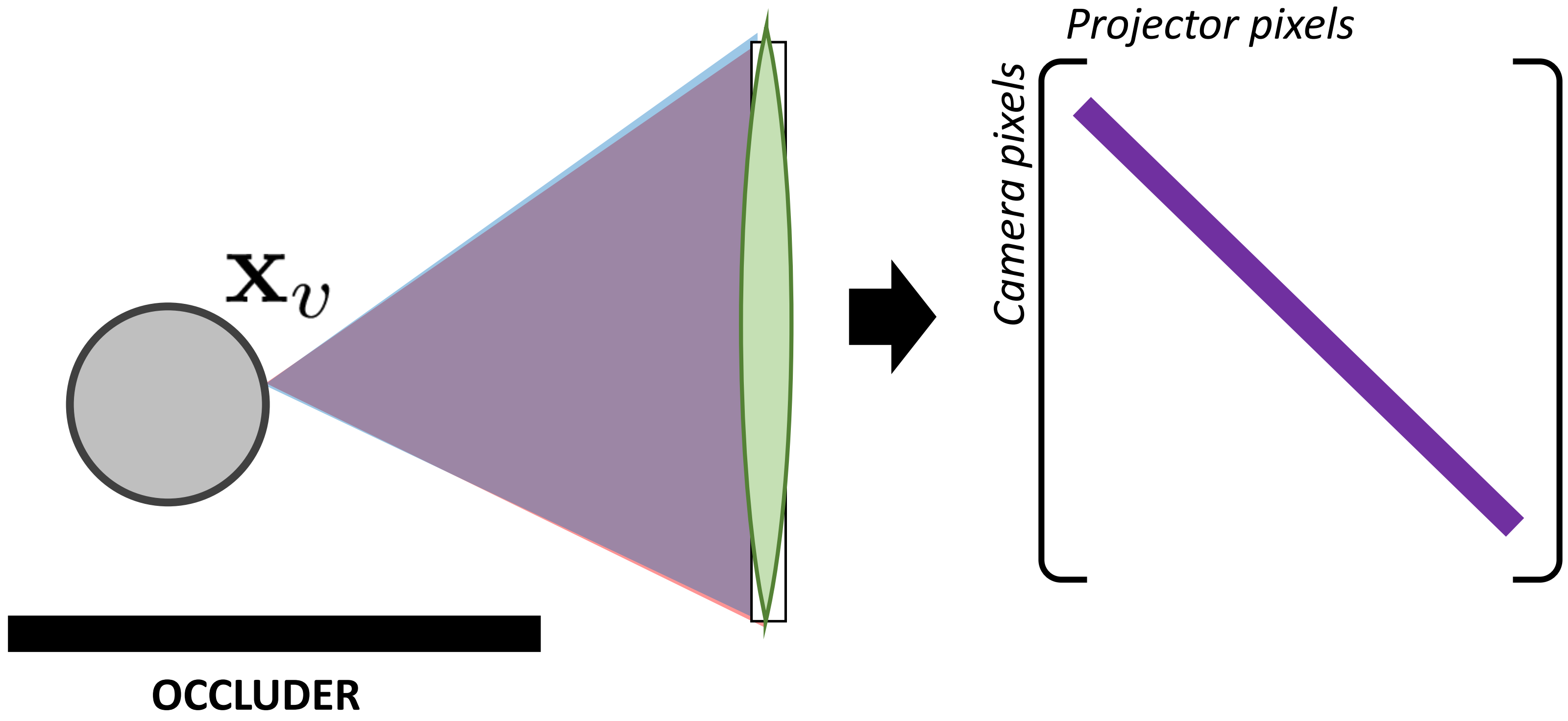

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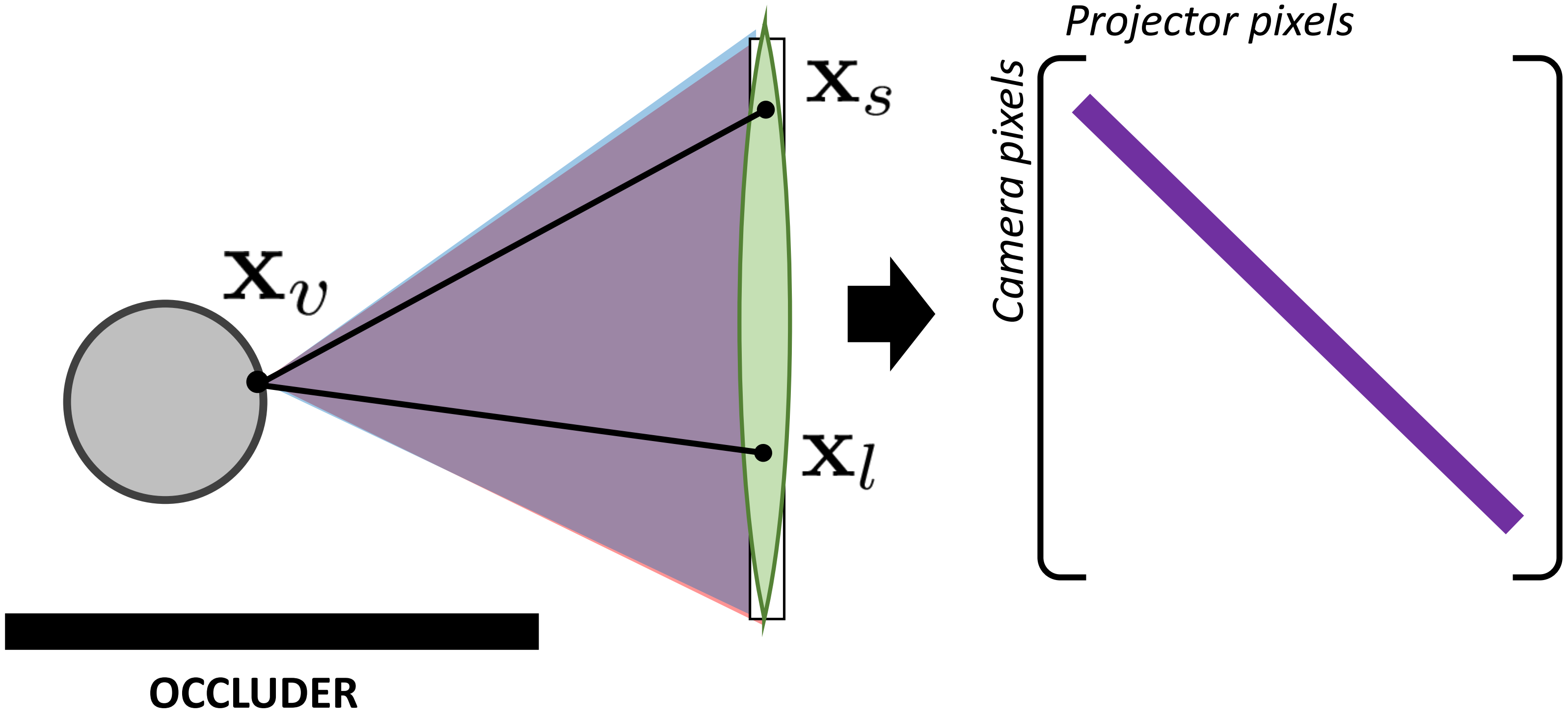


Shift phasor at

$$< \mathbf{x}_l, \mathbf{x}_s >$$

Thin lens operators

LASER

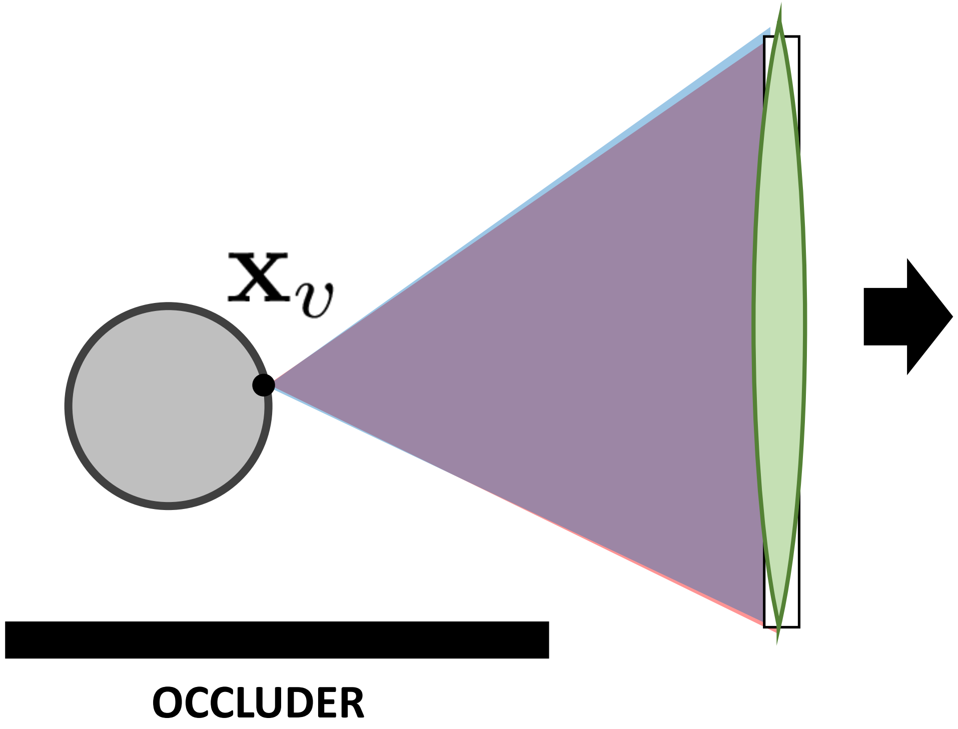
$$\frac{\mathcal{L}_\omega(\mathbf{x}_l, \mathbf{x}_v)}{|\mathbf{x}_l - \mathbf{x}_v|}$$

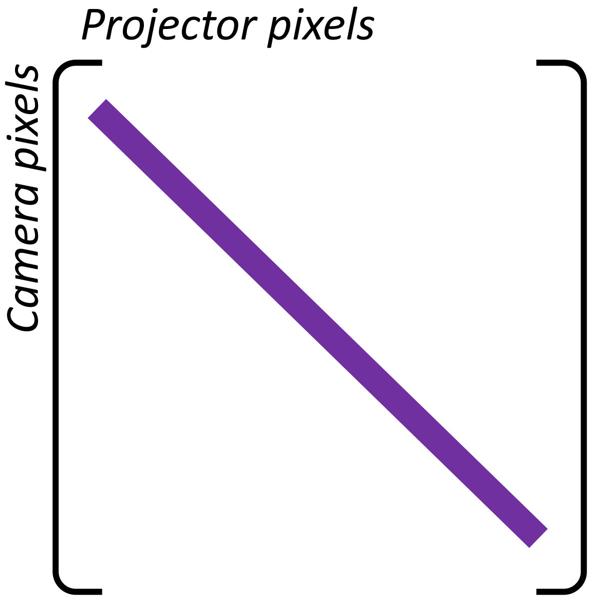
SPAD

$$\frac{\mathcal{L}_\omega(\mathbf{x}_s, \mathbf{x}_v)}{|\mathbf{x}_v - \mathbf{x}_s|}$$

Virtual LTM computation

Diagonal: Confocal projector and camera pixels

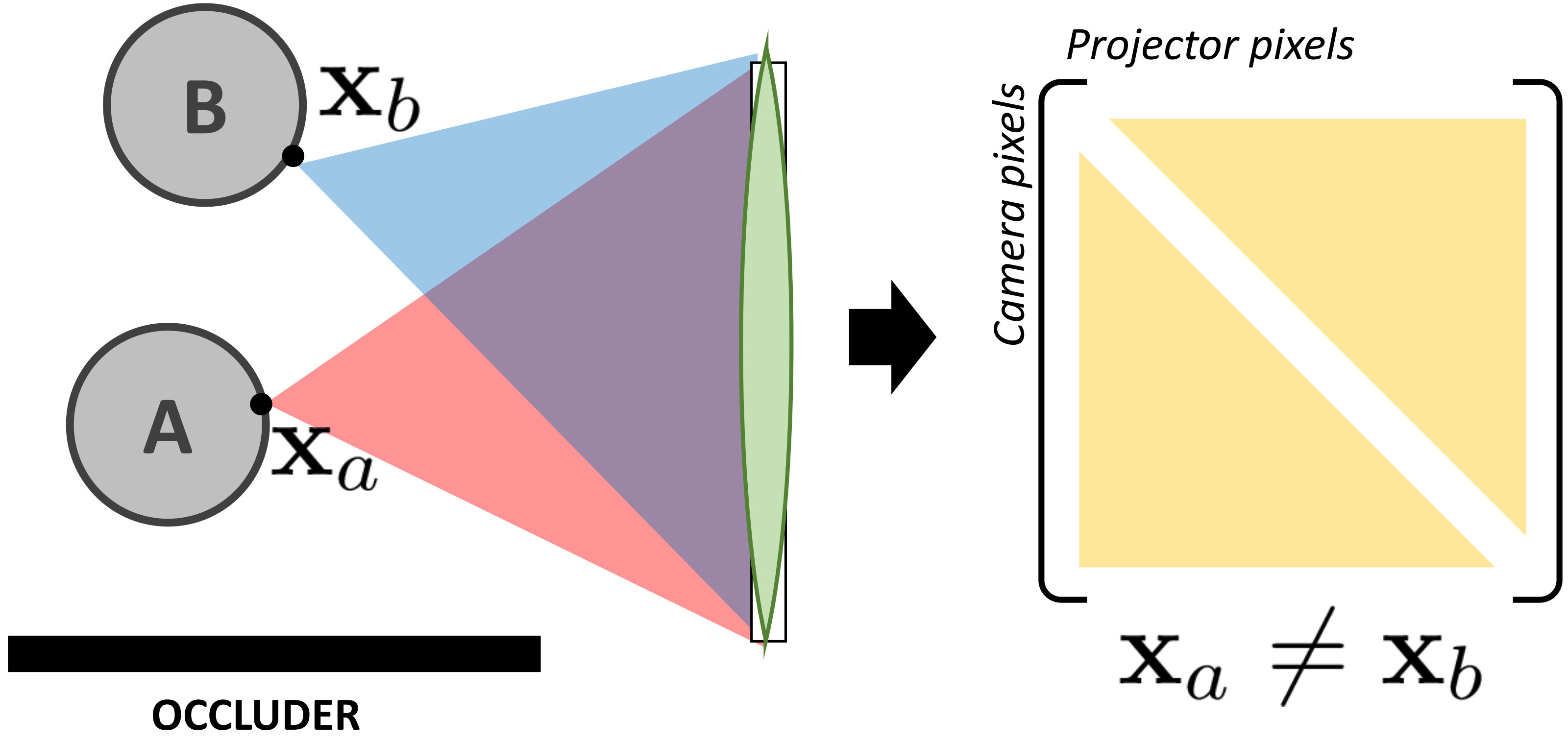




Direct illumination at $\mathbf{x}_v$.

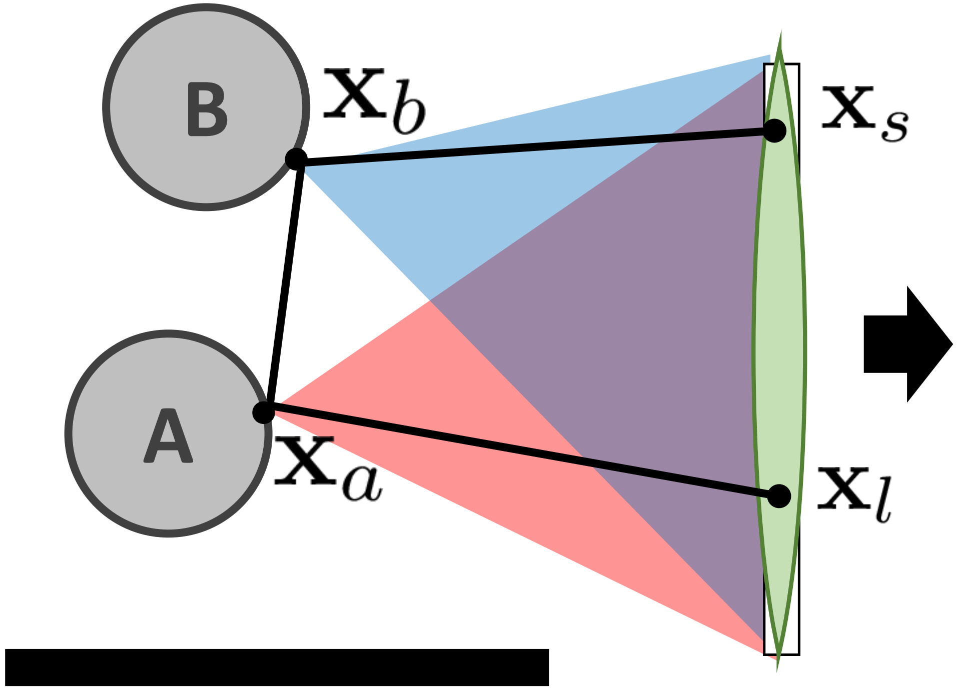
Virtual LTM computation

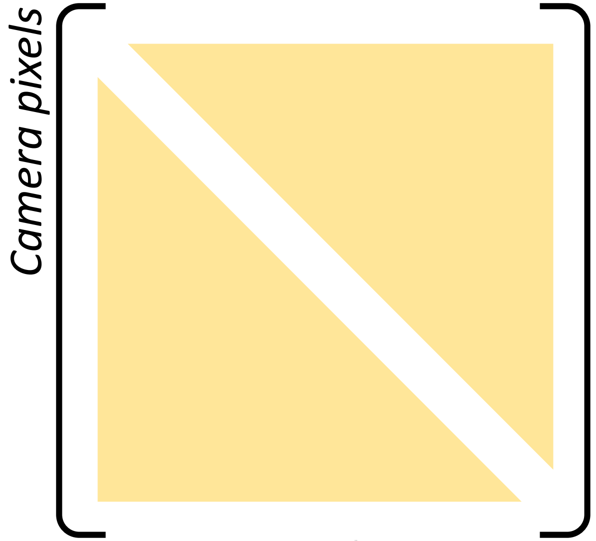
Off-diagonal: Different projector and camera pixels



Virtual LTM computation

Off-diagonal: Different projector and camera pixels





$$\mathbf{x}_a \neq \mathbf{x}_b$$

Shift phasor at

$$< \mathbf{x}_l, \mathbf{x}_s >$$

Thin lens operators

LASER

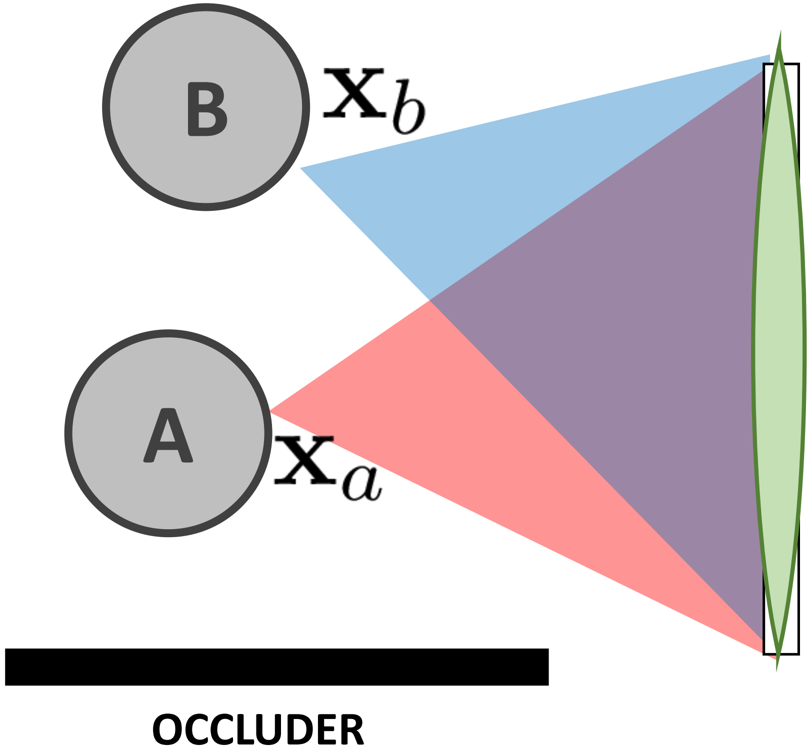
$$\frac{\mathcal{L}_\omega(\mathbf{x}_l, \mathbf{x}_a)}{|\mathbf{x}_l - \mathbf{x}_a|}$$

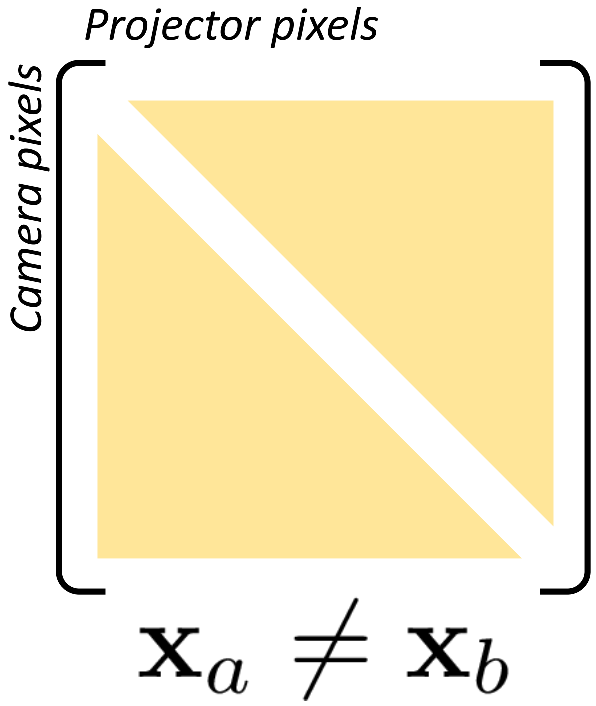
SPAD

$$\frac{\mathcal{L}_\omega(\mathbf{x}_s, \mathbf{x}_b)}{|\mathbf{x}_s - \mathbf{x}_b|}$$

Virtual LTM computation

Off-diagonal: Different projector and camera pixels

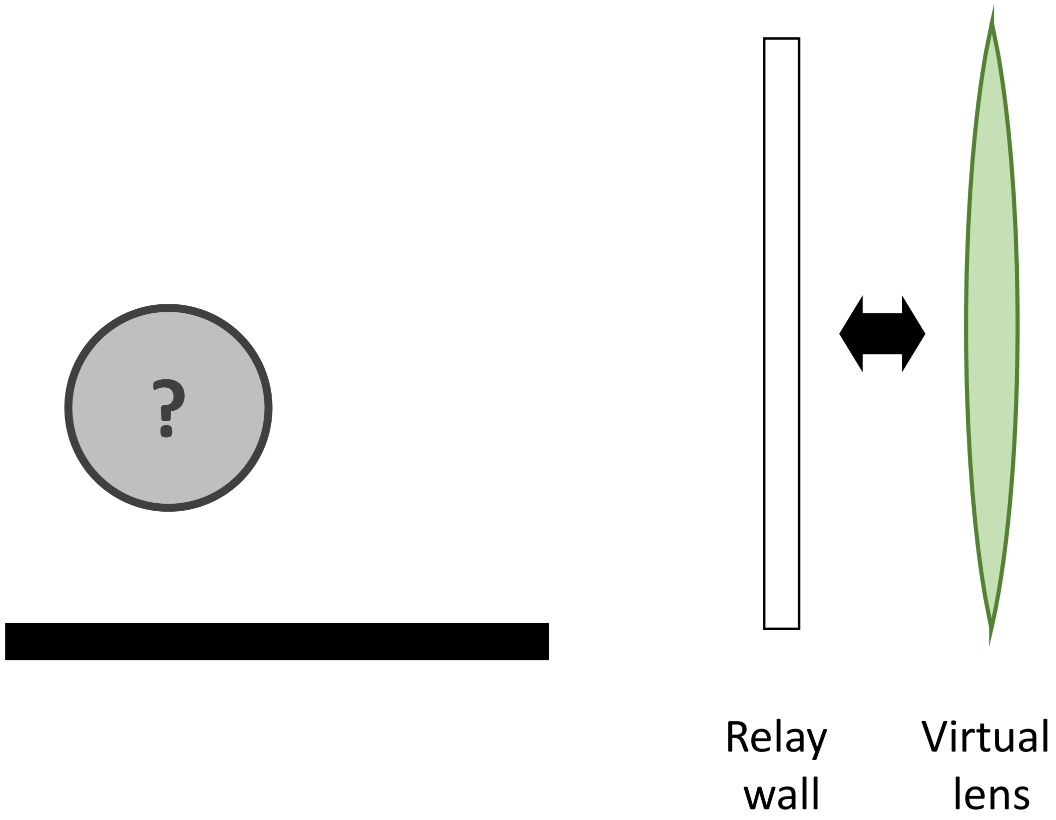




Indirect illumination from $\mathbf{x}_a$ to $\mathbf{x}_b$.

Virtual LTM: NLOS wide apertures

Size of relay wall = Size of lens aperture



Virtual LTM: NLOS wide apertures

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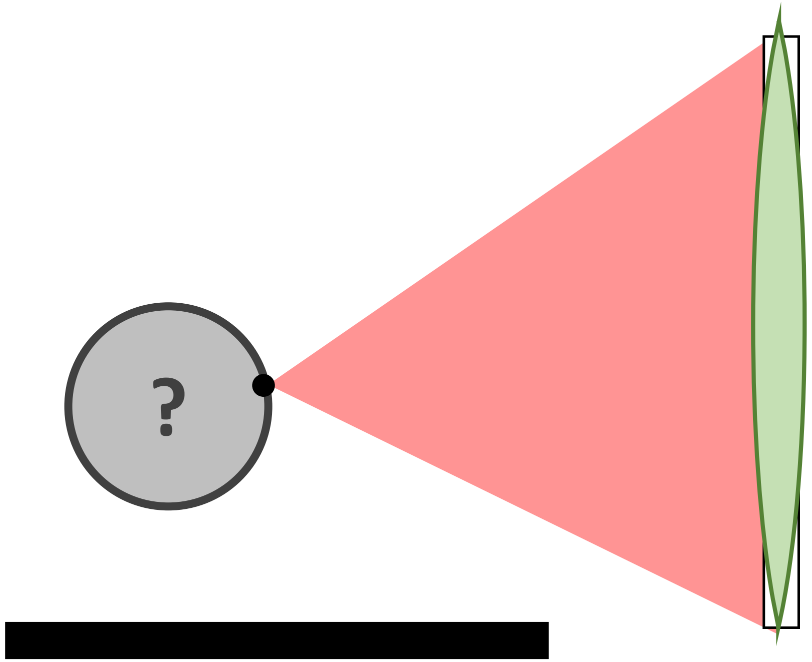

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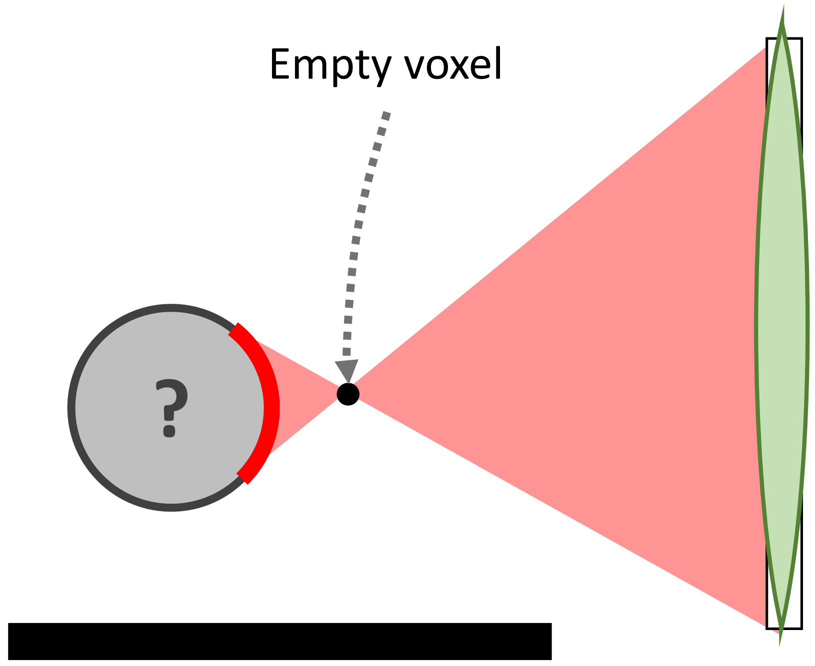
Virtual LTM: NLOS wide apertures

Size of relay wall = Size of lens aperture

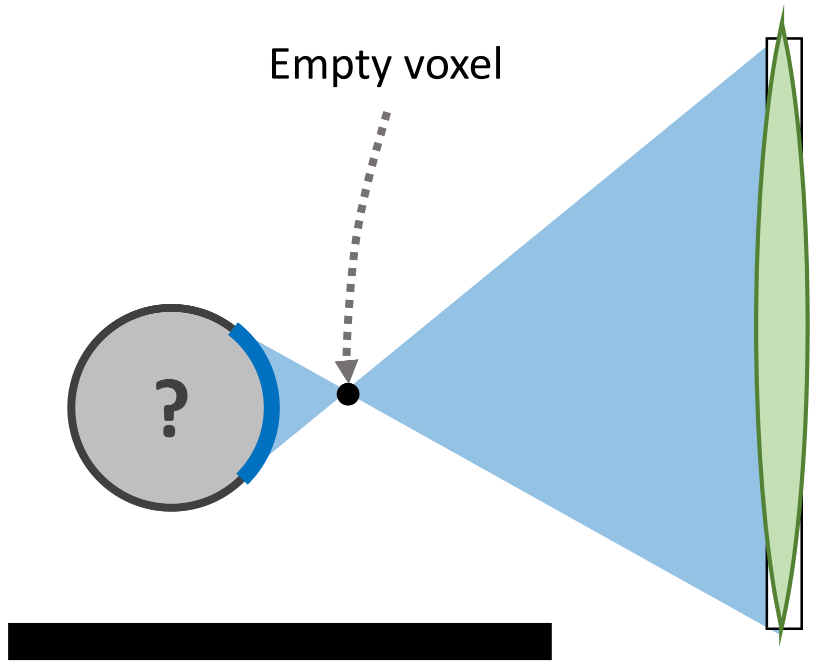


Out of focus light:

- Projector

Virtual LTM: NLOS wide apertures

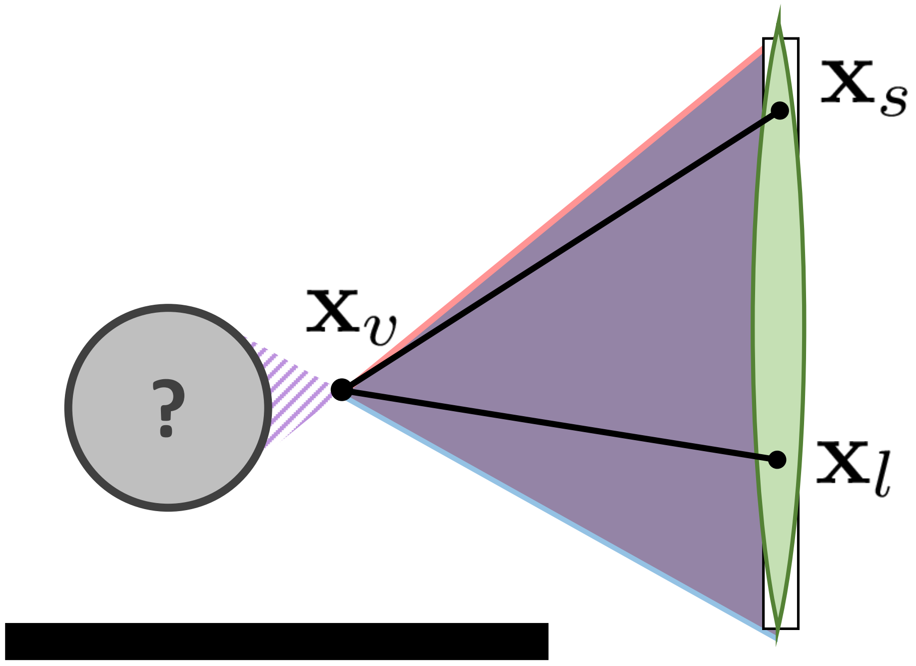
Size of relay wall = Size of lens aperture



Out of focus light:
- Projector
- Camera

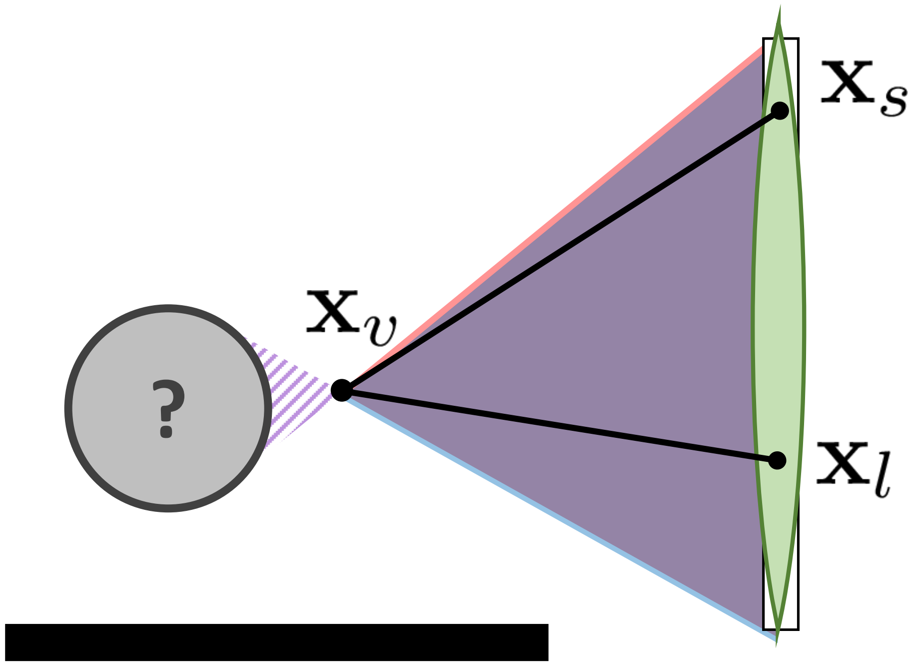
Virtual LTM: NLOS wide apertures

- Diagonal elements



Virtual LTM: NLOS wide apertures

- Diagonal elements



Gating single-bounce paths

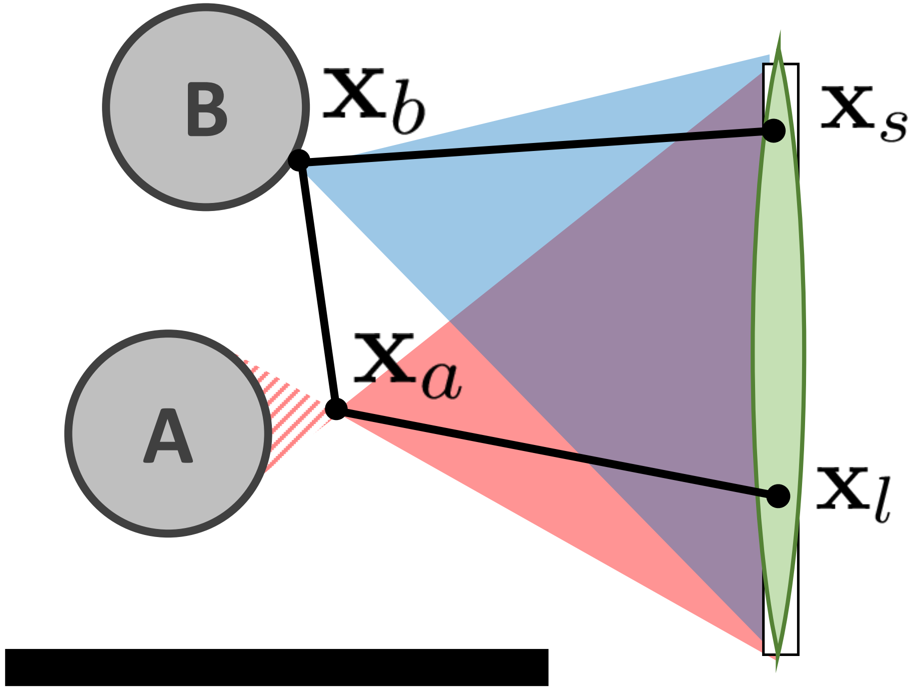
$$\mathbf{x}_l \rightarrow \mathbf{x}_v \rightarrow \mathbf{x}_s$$

at

$$t_d = \frac{|\mathbf{x}_l - \mathbf{x}_v| + |\mathbf{x}_s - \mathbf{x}_v|}{c}$$

Virtual LTM: NLOS wide apertures

- Off-diagonal elements



Virtual LTM: NLOS wide apertures

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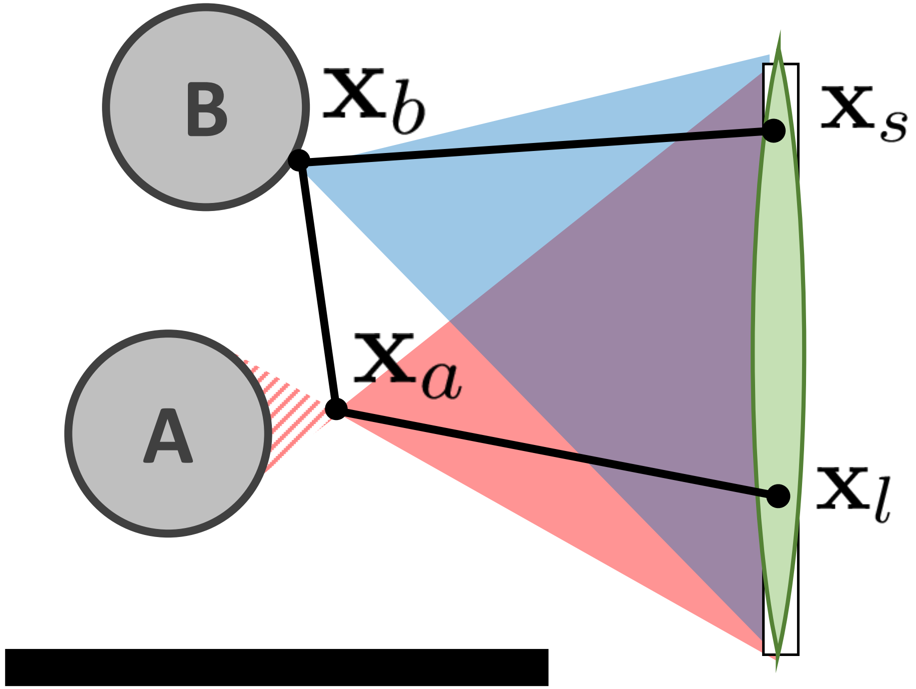
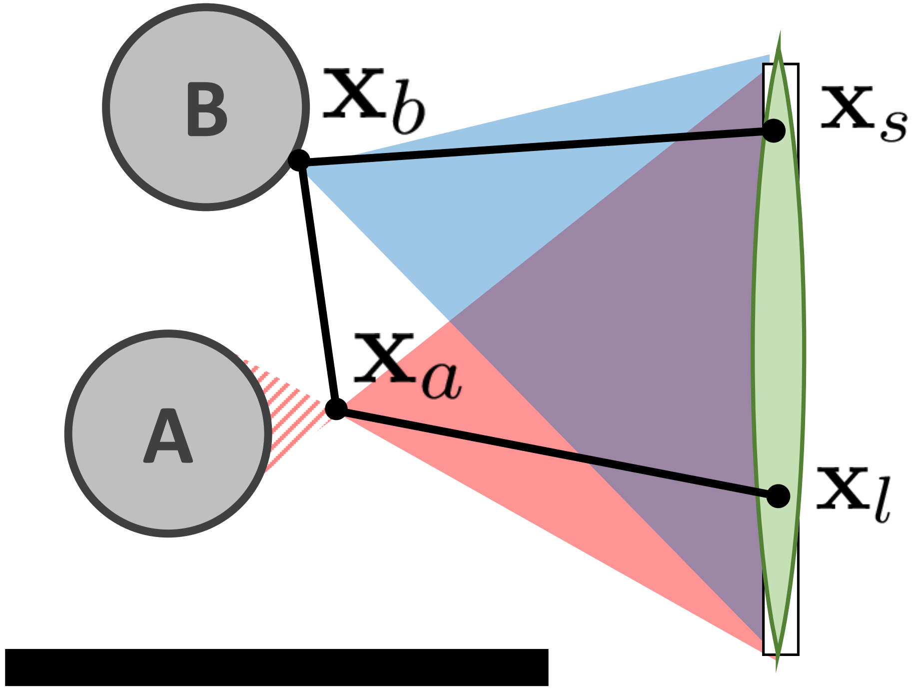


Gating two-bounce paths?

$$\mathbf{x}_l \rightarrow \mathbf{x}_a \rightarrow \mathbf{x}_b \rightarrow \mathbf{x}_s$$

Virtual LTM: NLOS wide apertures

- Off-diagonal elements



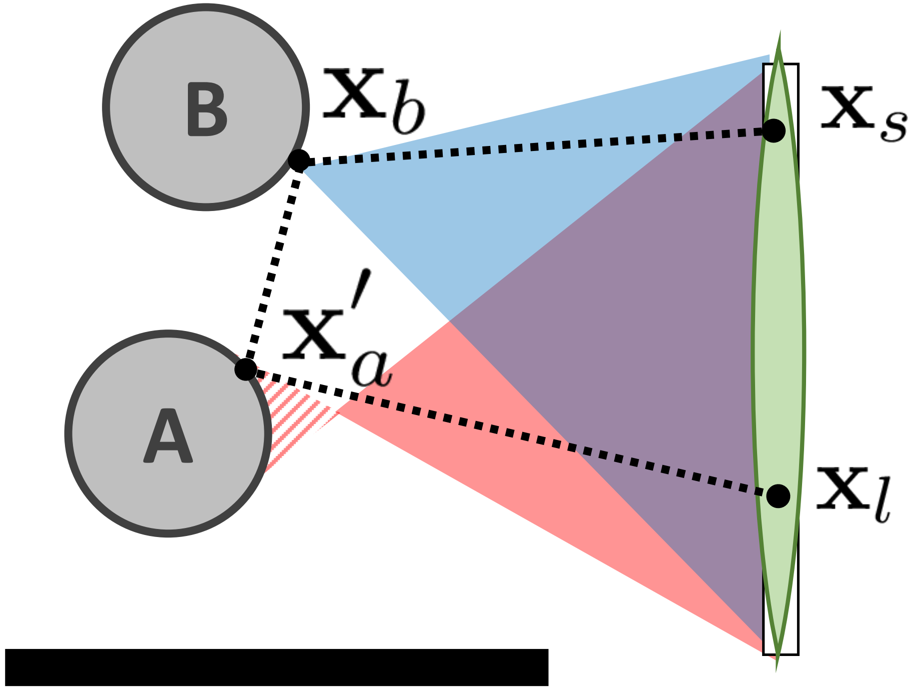
Gating two-bounce paths?

$$\mathbf{x}_l \rightarrow \mathbf{x}_a \rightarrow \mathbf{x}_b \rightarrow \mathbf{x}_s$$

But… out-of-focus paths of same length

Virtual LTM: NLOS wide apertures

- Off-diagonal elements



Gating two-bounce paths?

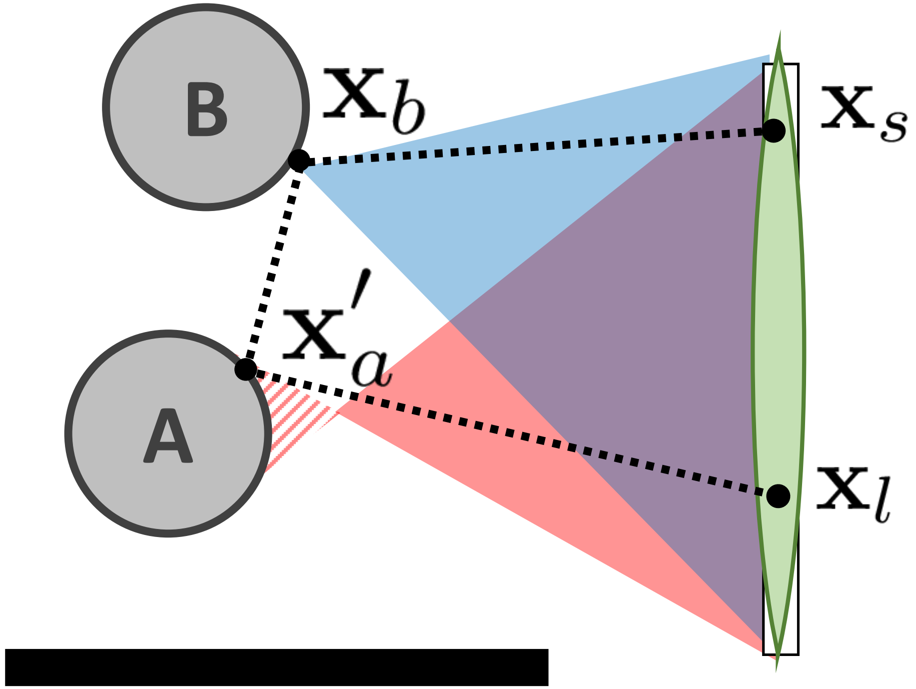
$$\mathbf{x}_l \rightarrow \mathbf{x}_a \rightarrow \mathbf{x}_b \rightarrow \mathbf{x}_s$$

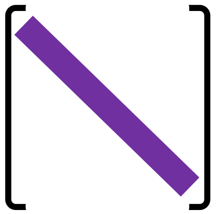
But… out-of-focus paths of same length

$$\mathbf{x}_l \rightarrow \mathbf{x}'_a \rightarrow \mathbf{x}_b \rightarrow \mathbf{x}_s$$

Virtual LTM: NLOS wide apertures

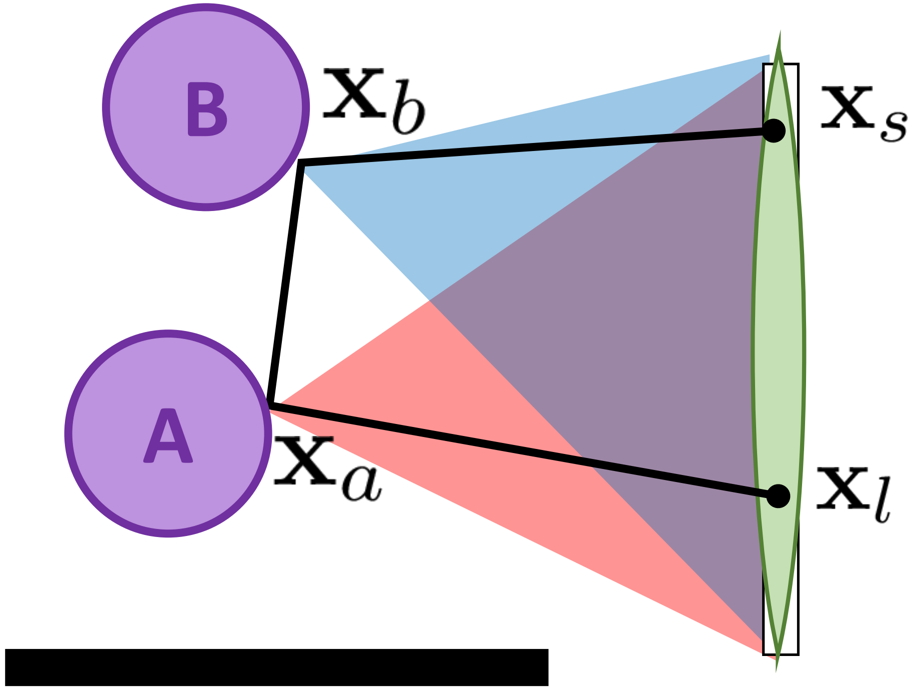
- Off-diagonal elements

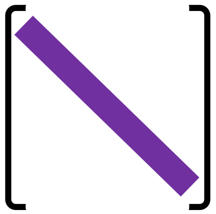


Diagonal  $\approx$ Geometry

Virtual LTM: NLOS wide apertures

- Off-diagonal elements



Diagonal  $\approx$ Geometry

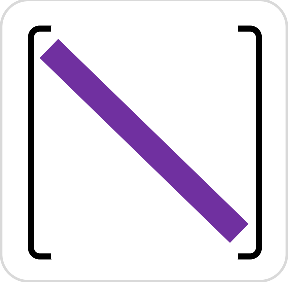
- Focus only at non-empty voxels

- Gate two-bounce paths:

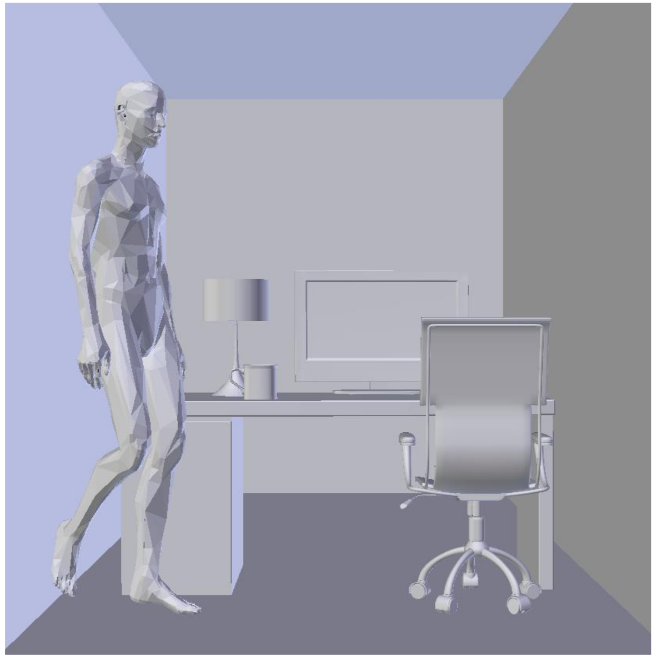
$$t_i = \frac{|\mathbf{x}_l - \mathbf{x}_a| + |\mathbf{x}_a - \mathbf{x}_b| + |\mathbf{x}_s - \mathbf{x}_b|}{c}$$

Results: Direct illumination

LTM diagonal



- Diagonal computation and gating



Results: Direct illumination

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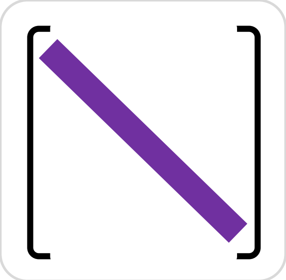
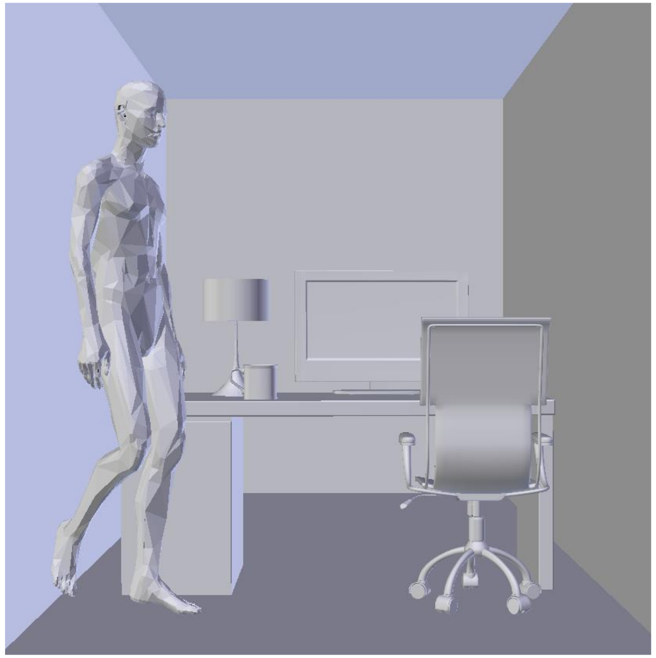
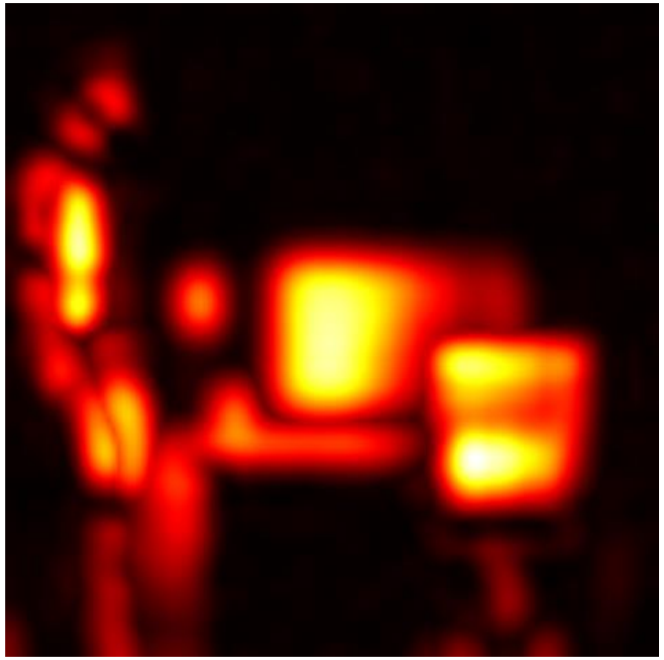
LTM diagonal





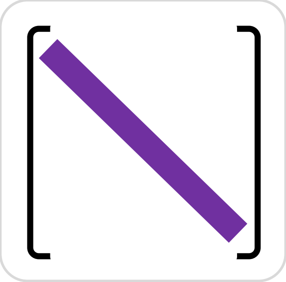


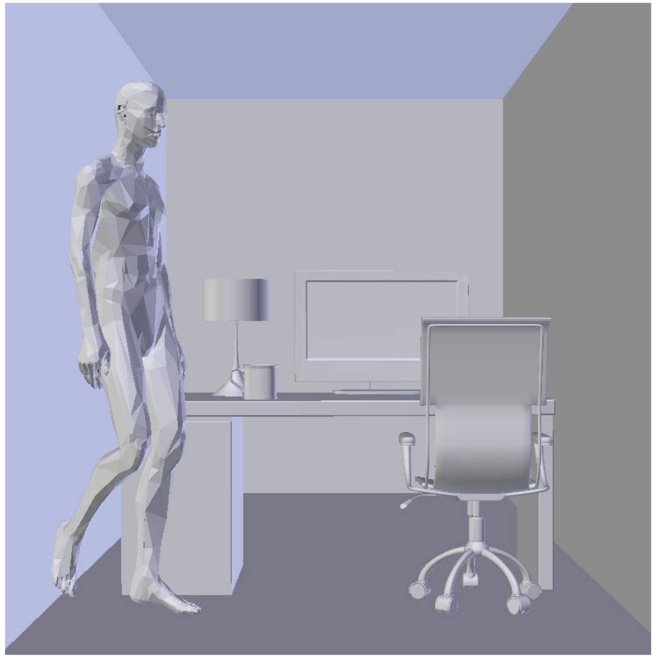
Single-bounce gating

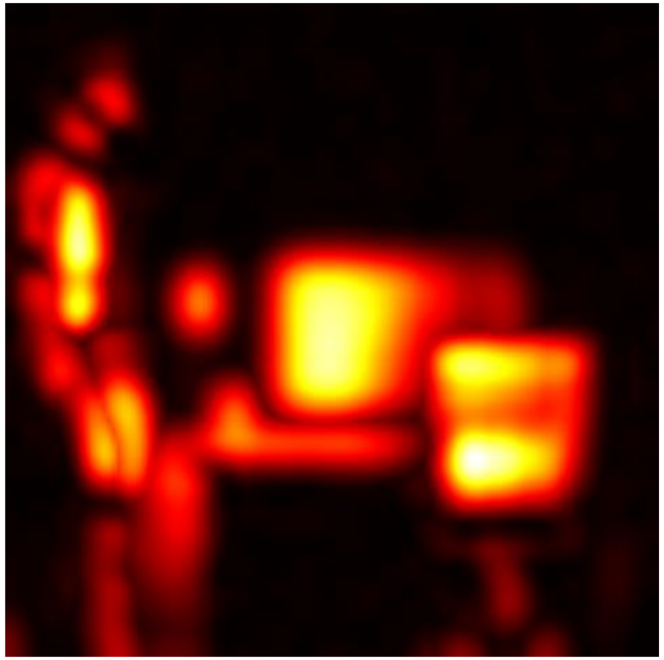
Results: Direct illumination

- Diagonal computation and gating

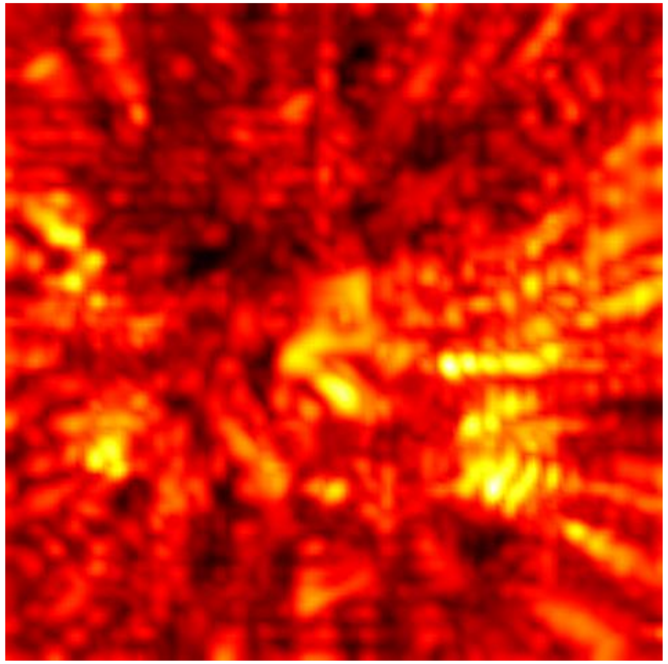
LTM diagonal







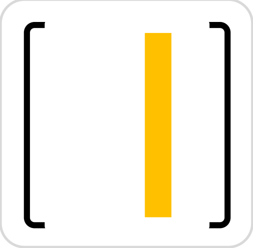
Single-bounce gating



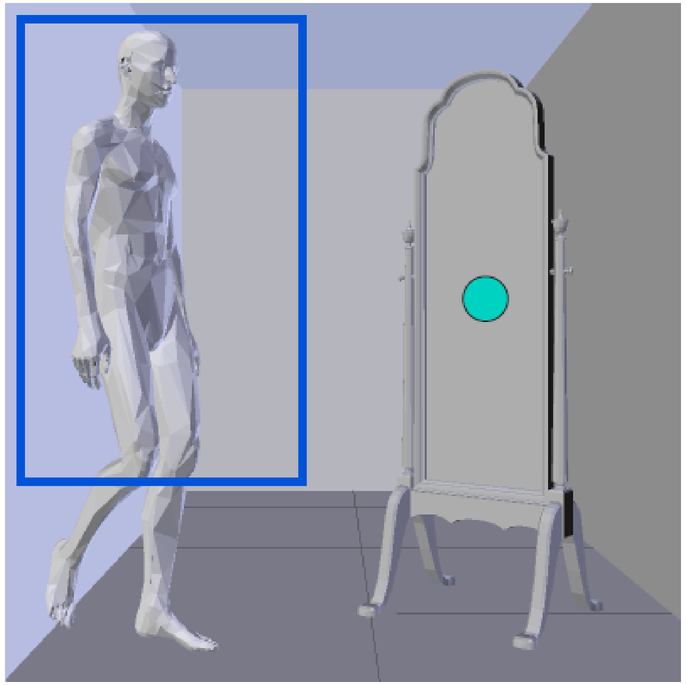
No gating

Results: Indirect illumination

LTM off-diagonal at

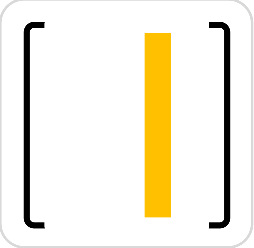


- Off-diagonal under material changes

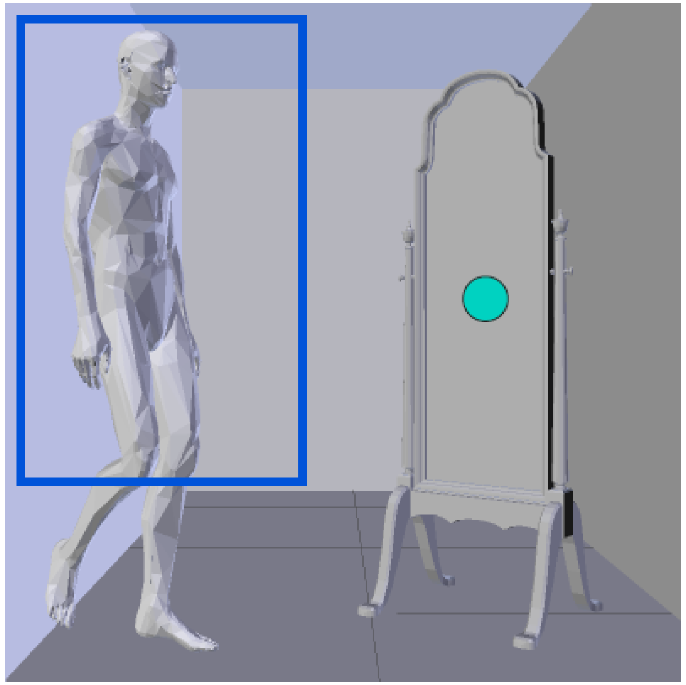


Results: Indirect illumination

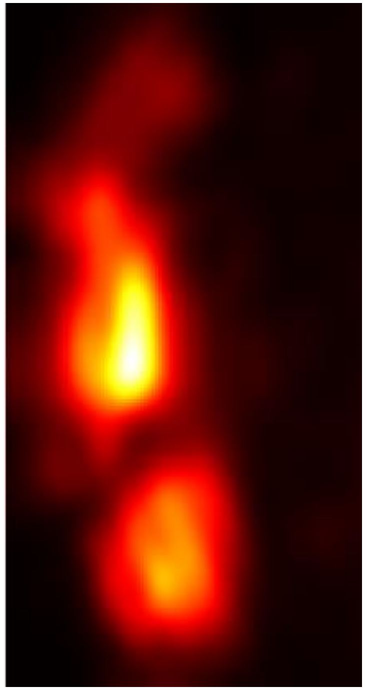
LTM off-diagonal at



- Off-diagonal under material changes



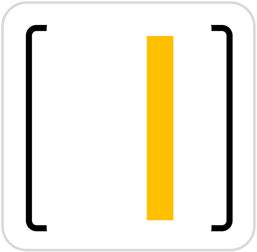
Low reflector specularity

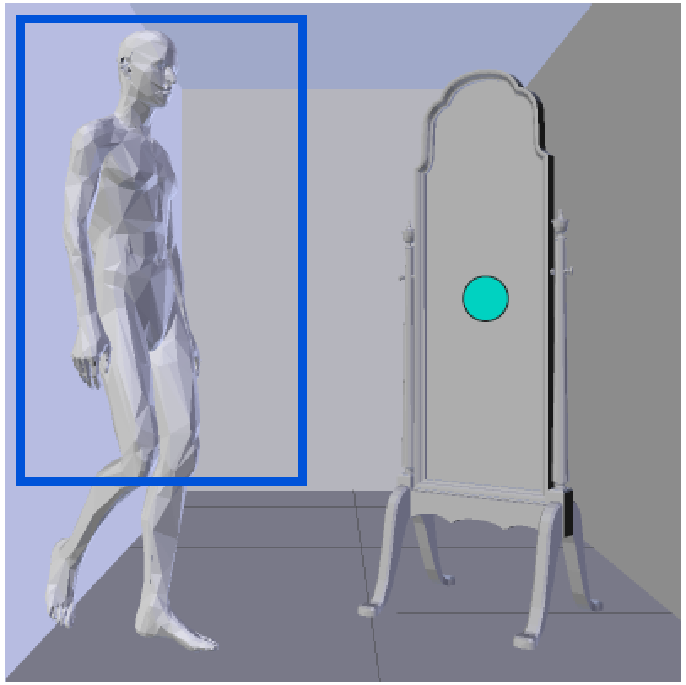


Results: Indirect illumination

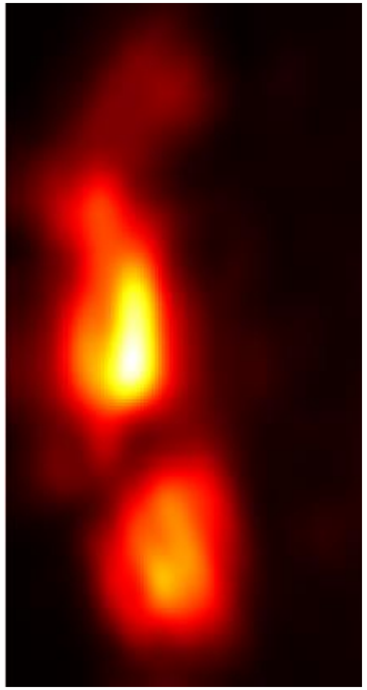
- Off-diagonal under material changes

LTM off-diagonal at 

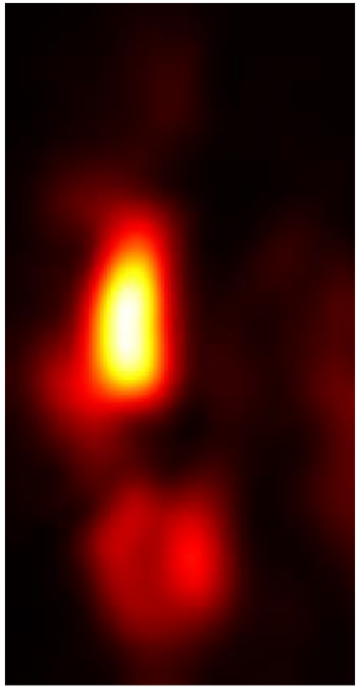




Low reflector specularity

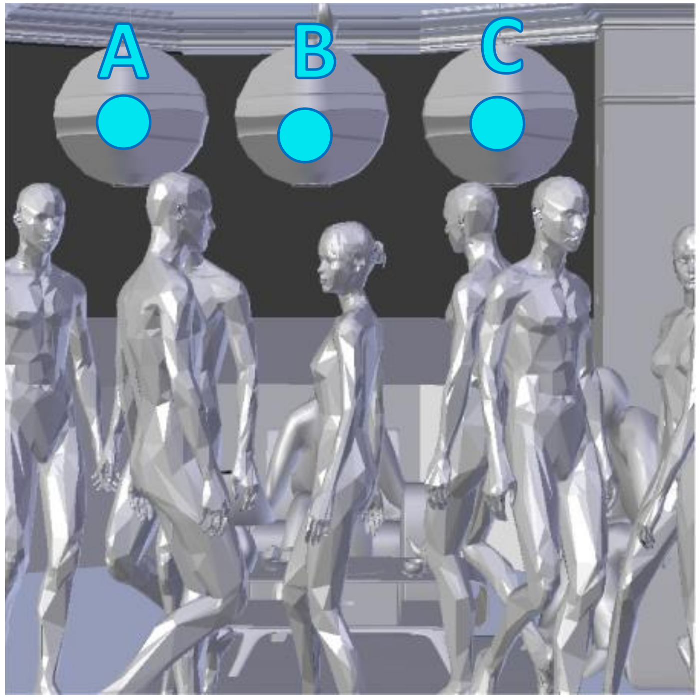


High reflector specularity

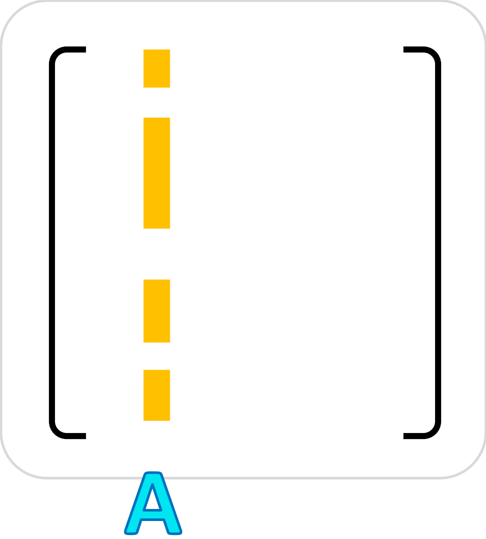


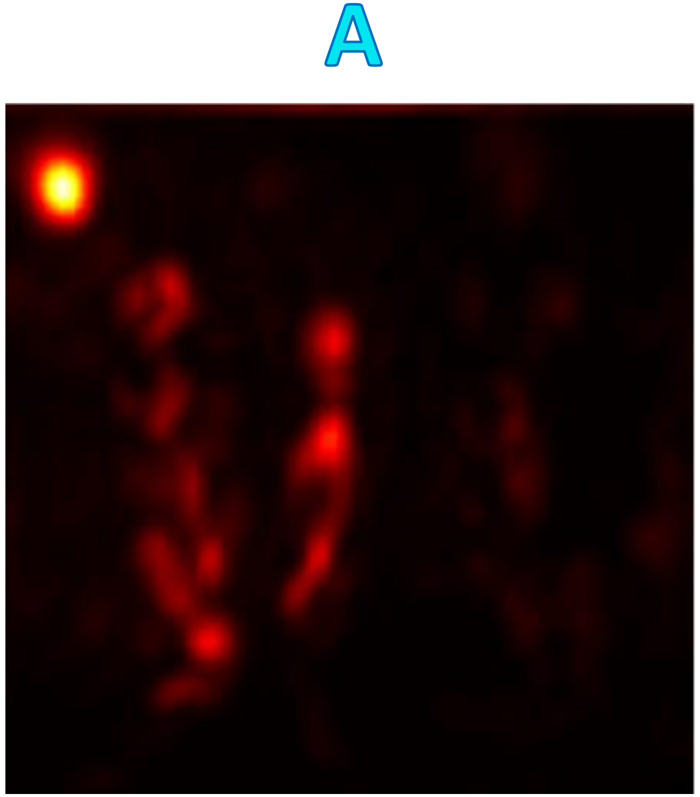
Results: LTM probing

- Off-diagonal, indirect light



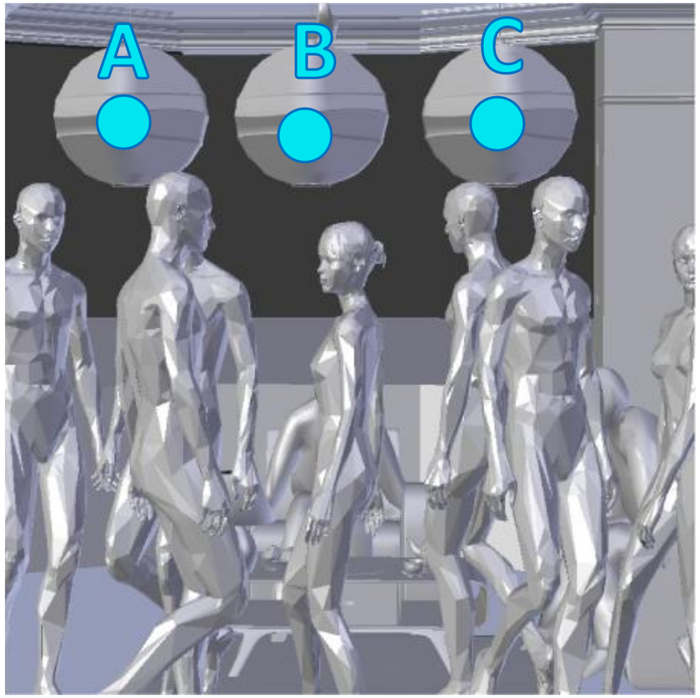
LTM off-diagonal



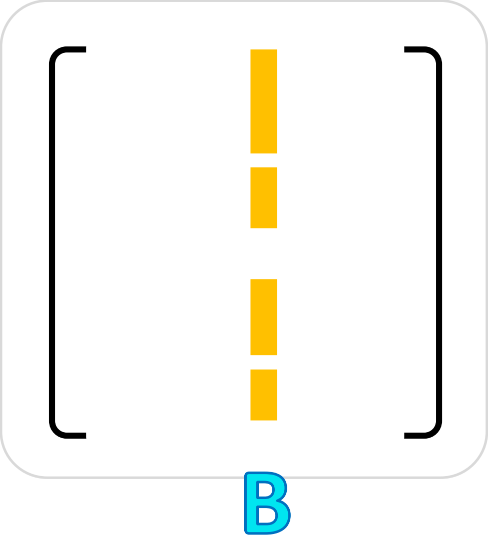


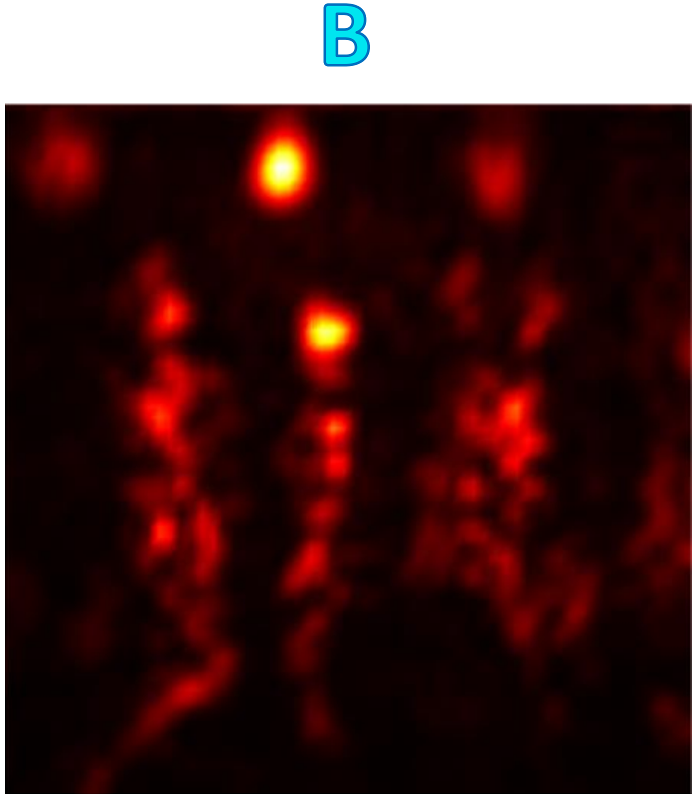
Results: LTM probing

- Off-diagonal, indirect light



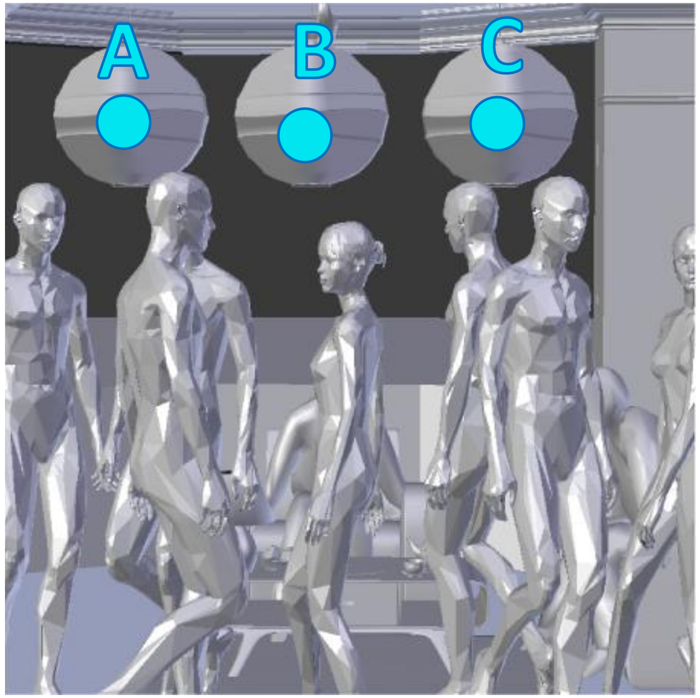
LTM off-diagonal



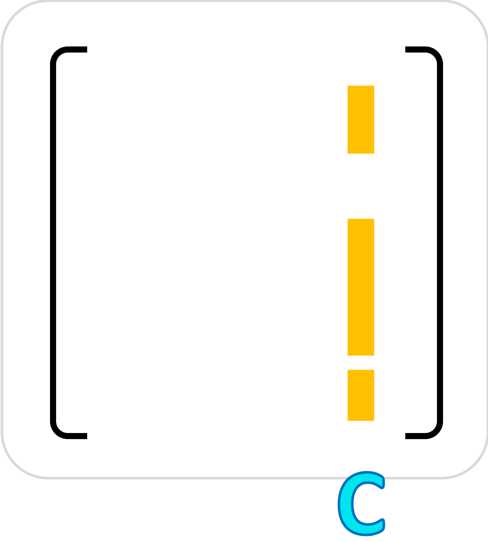


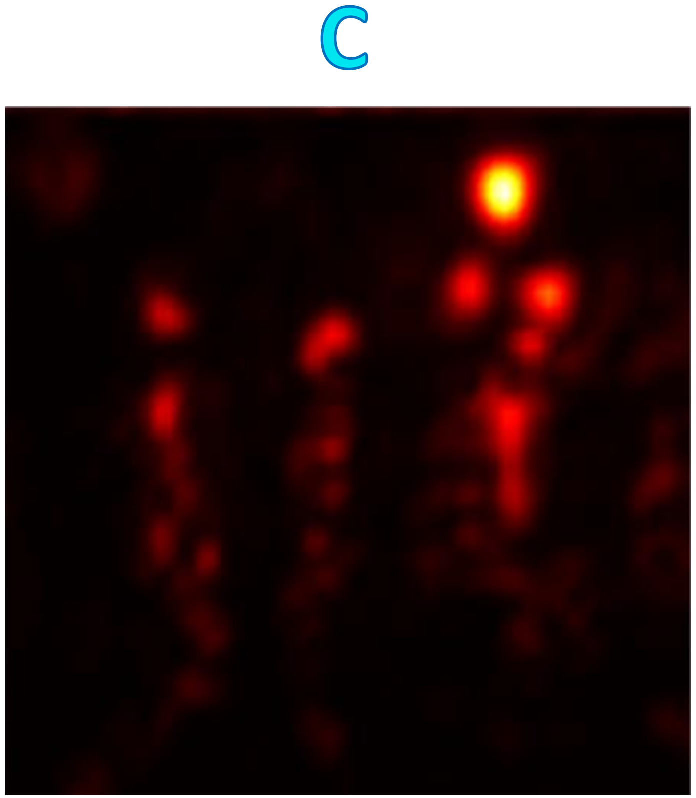
Results: LTM probing

- Off-diagonal, indirect light



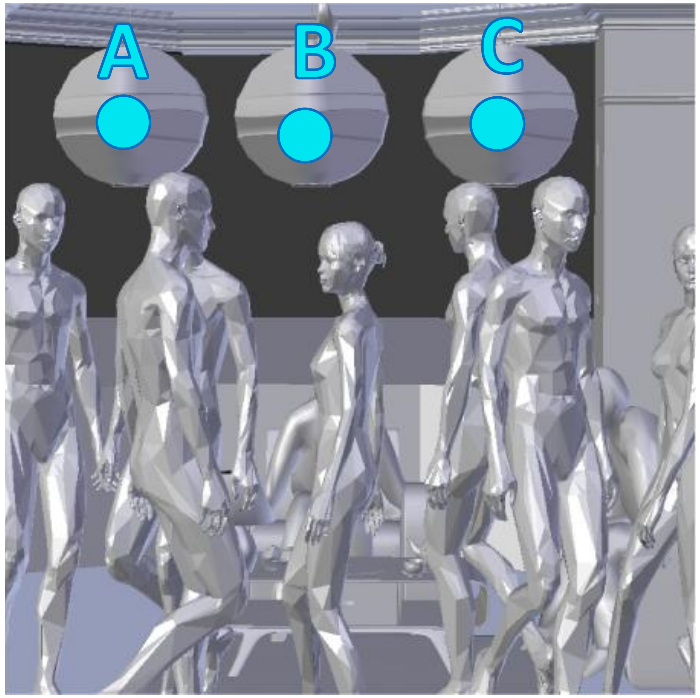
LTM off-diagonal

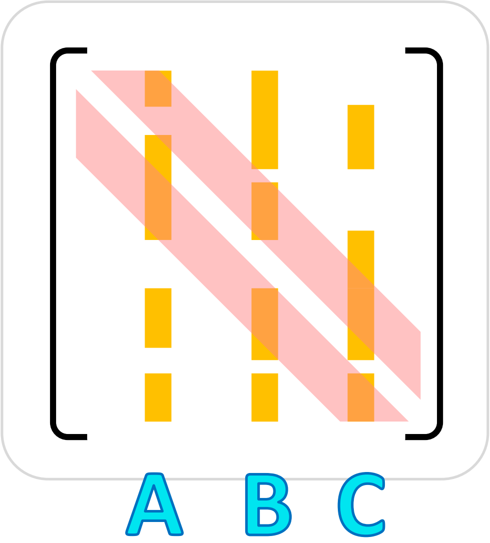


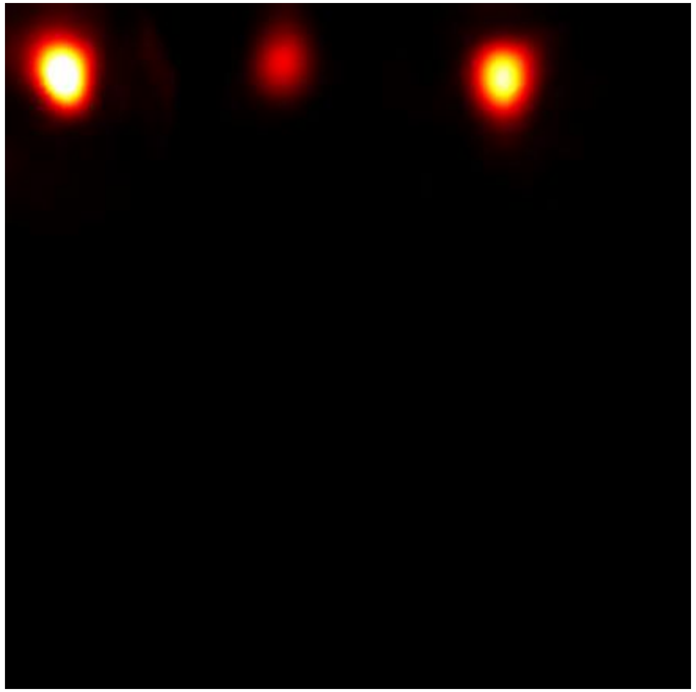


Results: LTM probing

- Off-diagonal, near-range



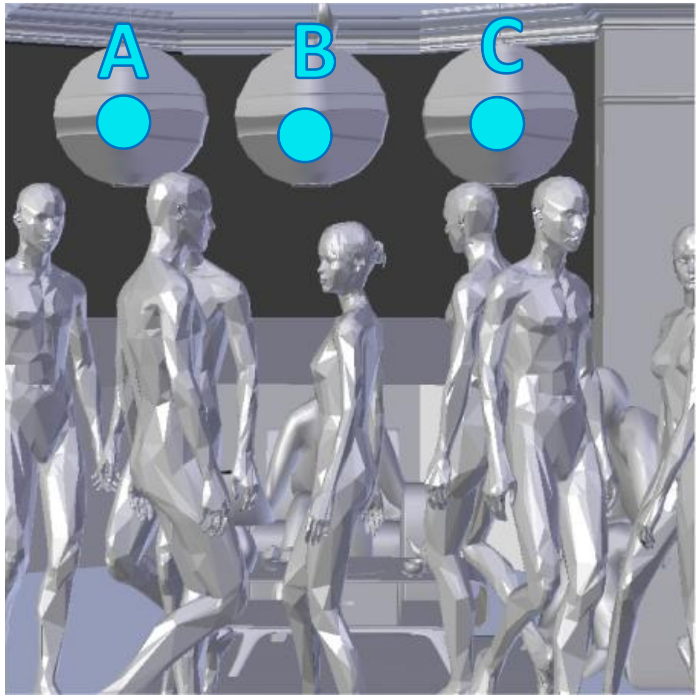




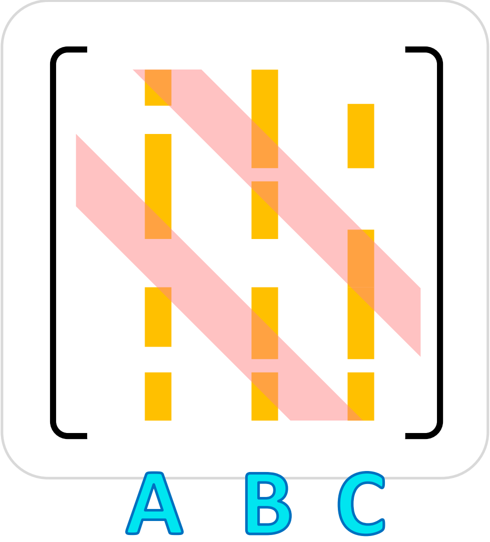
0.1m to 0.4m

Results: LTM probing

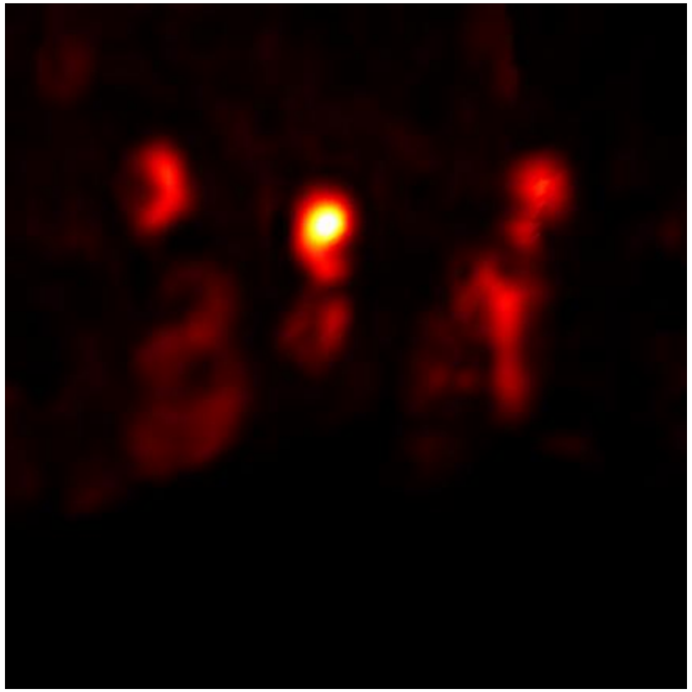
- Off-diagonal, mid-range



LTM off-diagonal



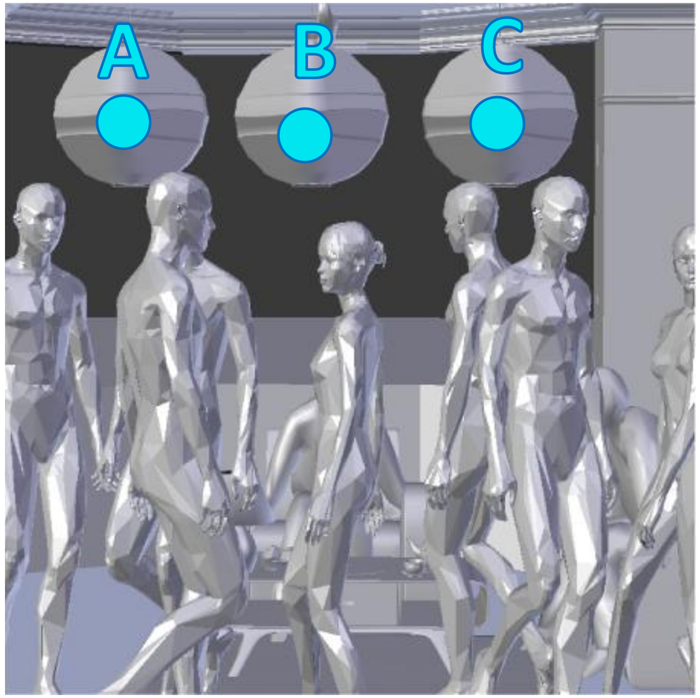
A, B, C

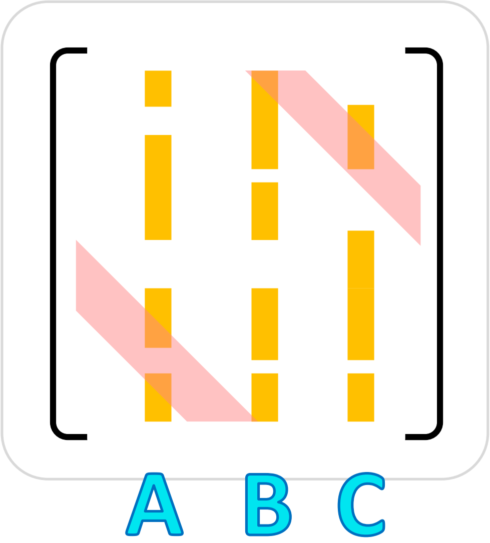


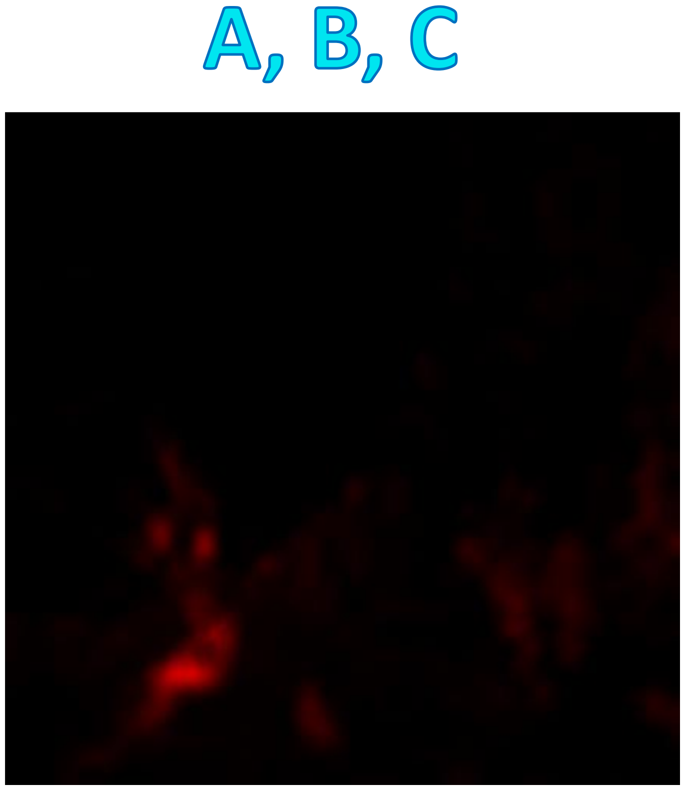
1.1m to 1.4m

Results: LTM probing

- Off-diagonal, far-range

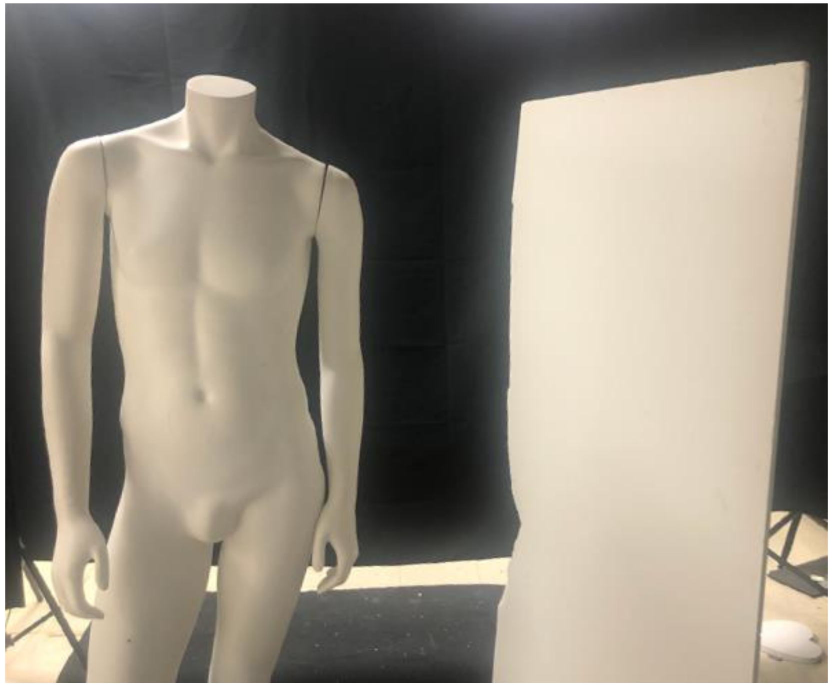




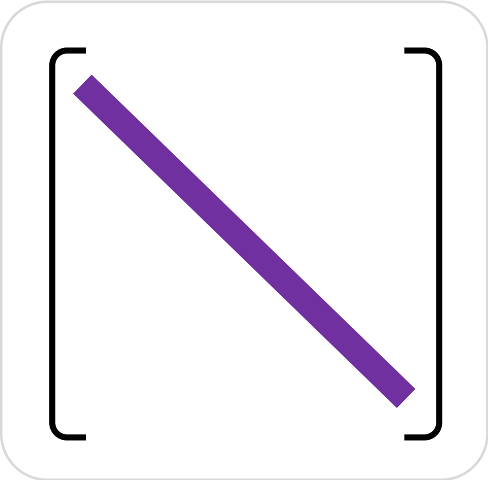


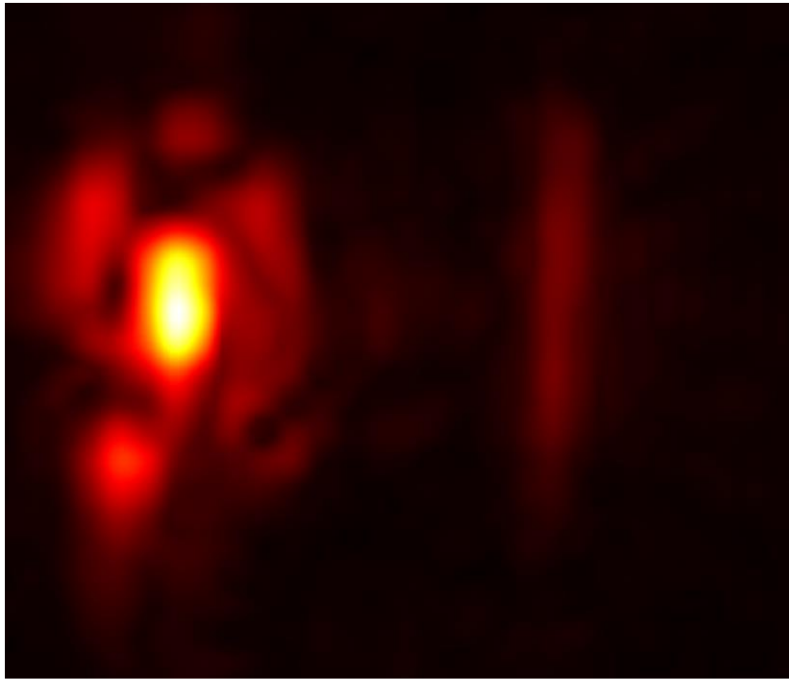
Results: Real scenarios

- Horizontal 1D SPAD ➔ Focus light on vertical line



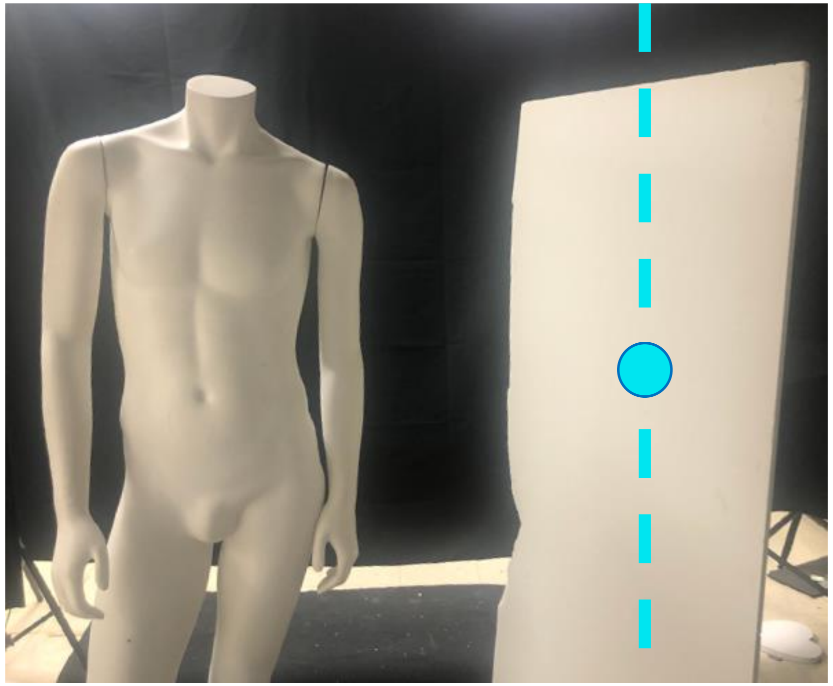
LTM diagonal



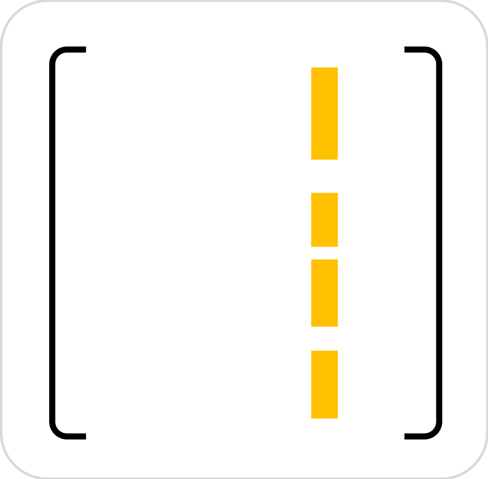


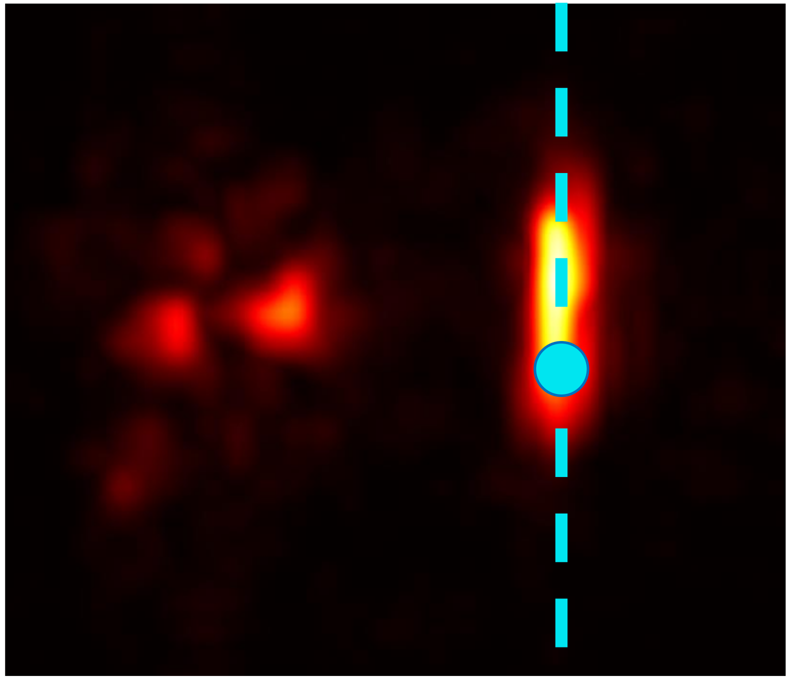
Results: Real scenarios

- Horizontal 1D SPAD ➔ Focus light on vertical line



LTM off-diagonal





Summary

- Coupled LTM with NLOS forward propagation
- Specific imaging functions for virtual LTM
- Mitigate large-aperture issues
- Probing the LTM: direct-indirect, specific path lengths

Future work

- Apply existing LOS techniques for deeper LTM analysis
- Improve separation higher-order bounces
- Applications: 2-corner setups, de-scattering

Virtual light transport matrices for non-line-of-sight imaging

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Miguel Ángel Cosculluela[1] Andreas Velten[2] Diego Gutierrez[1]

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