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Carnegie Mellon University

THE ROBOTICS INSTITUTE

# Efficient Non-Line-of-Sight Imaging from Transient Sinograms

Carnegie Mellon University


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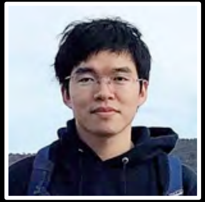
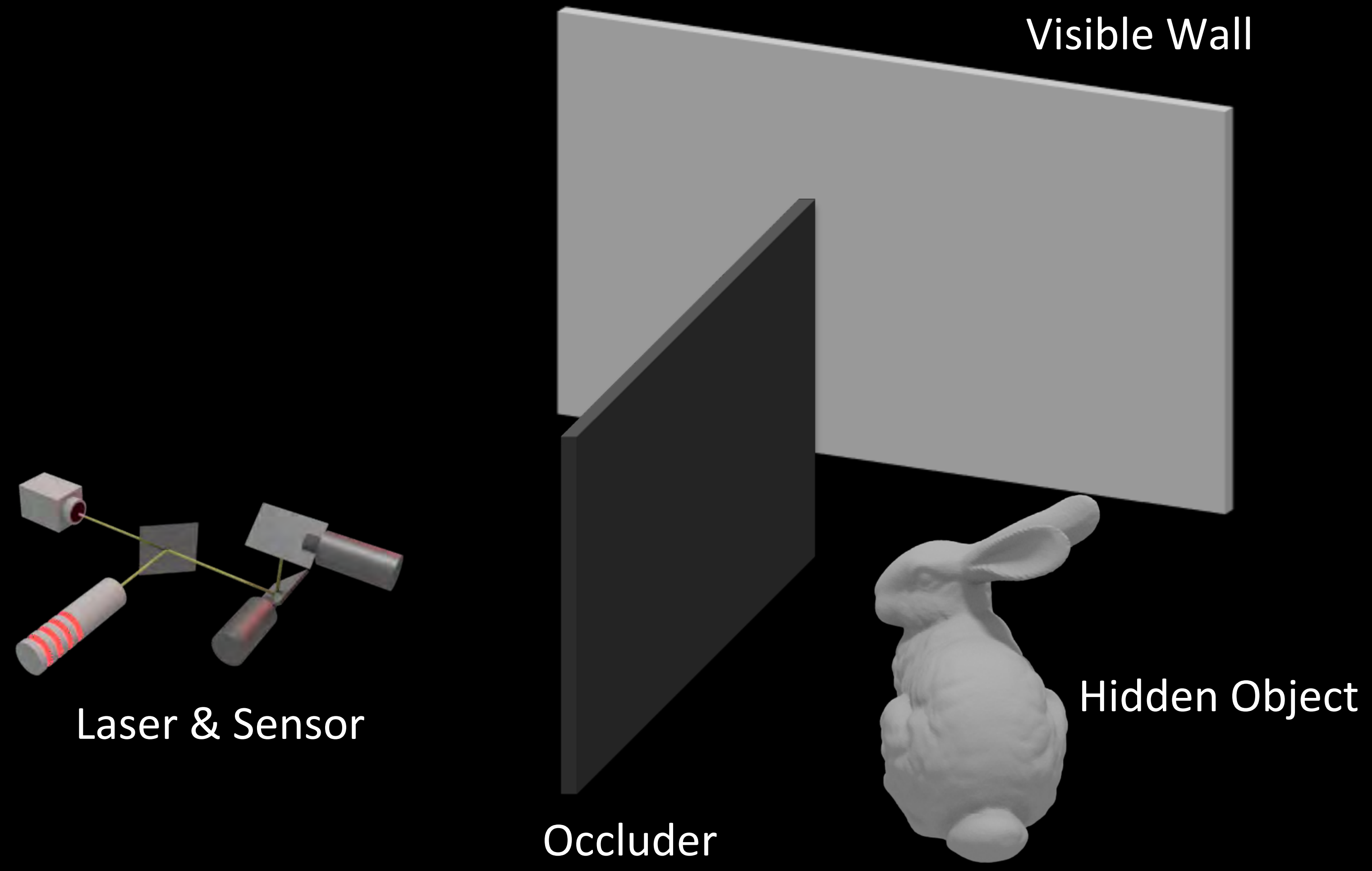
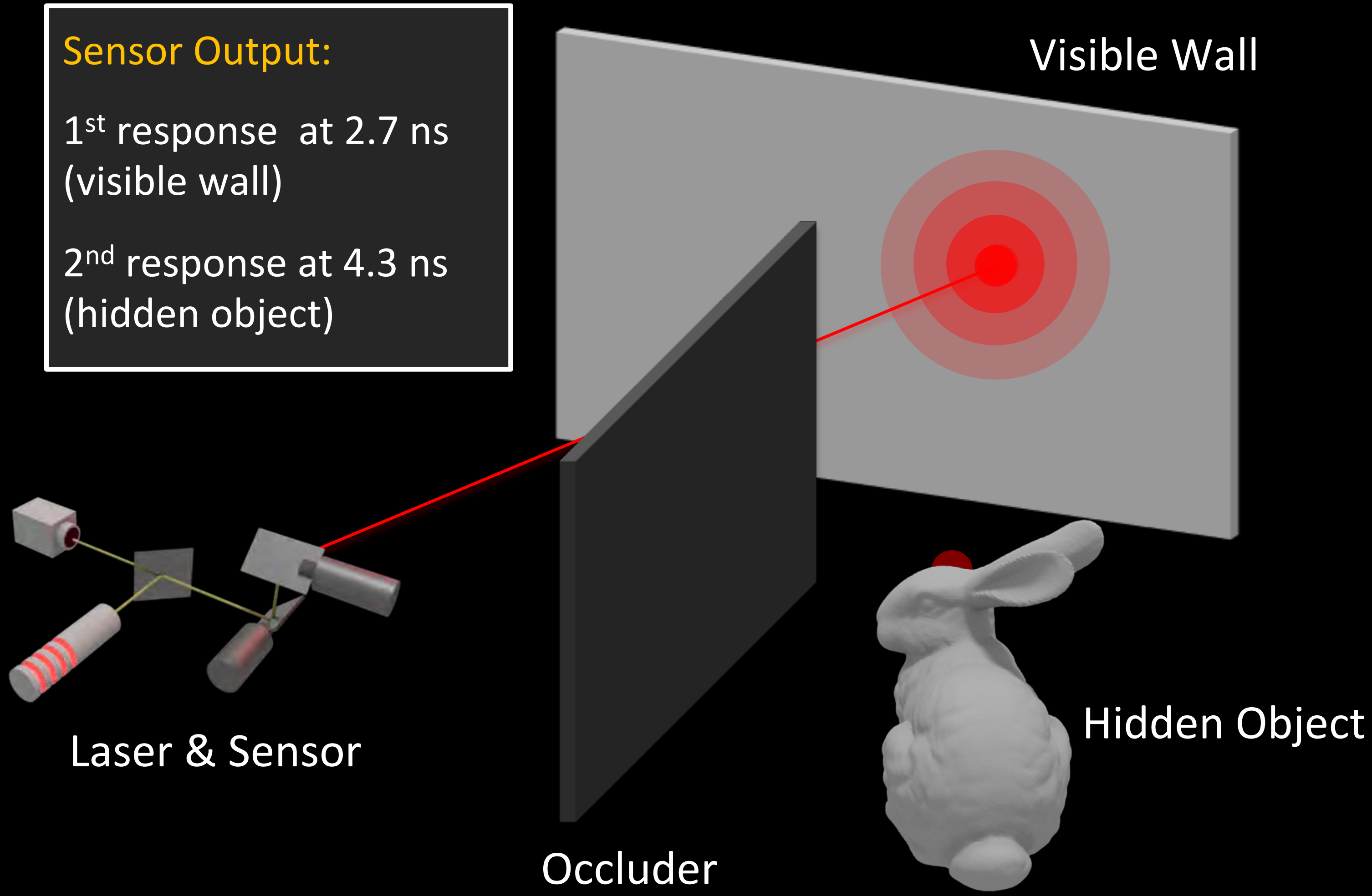
Dorian Chan


Ye Yuan


Kris Kitani


Matthew O'Toole


Visible Wall
Laser & Sensor
Occluder
Hidden Object

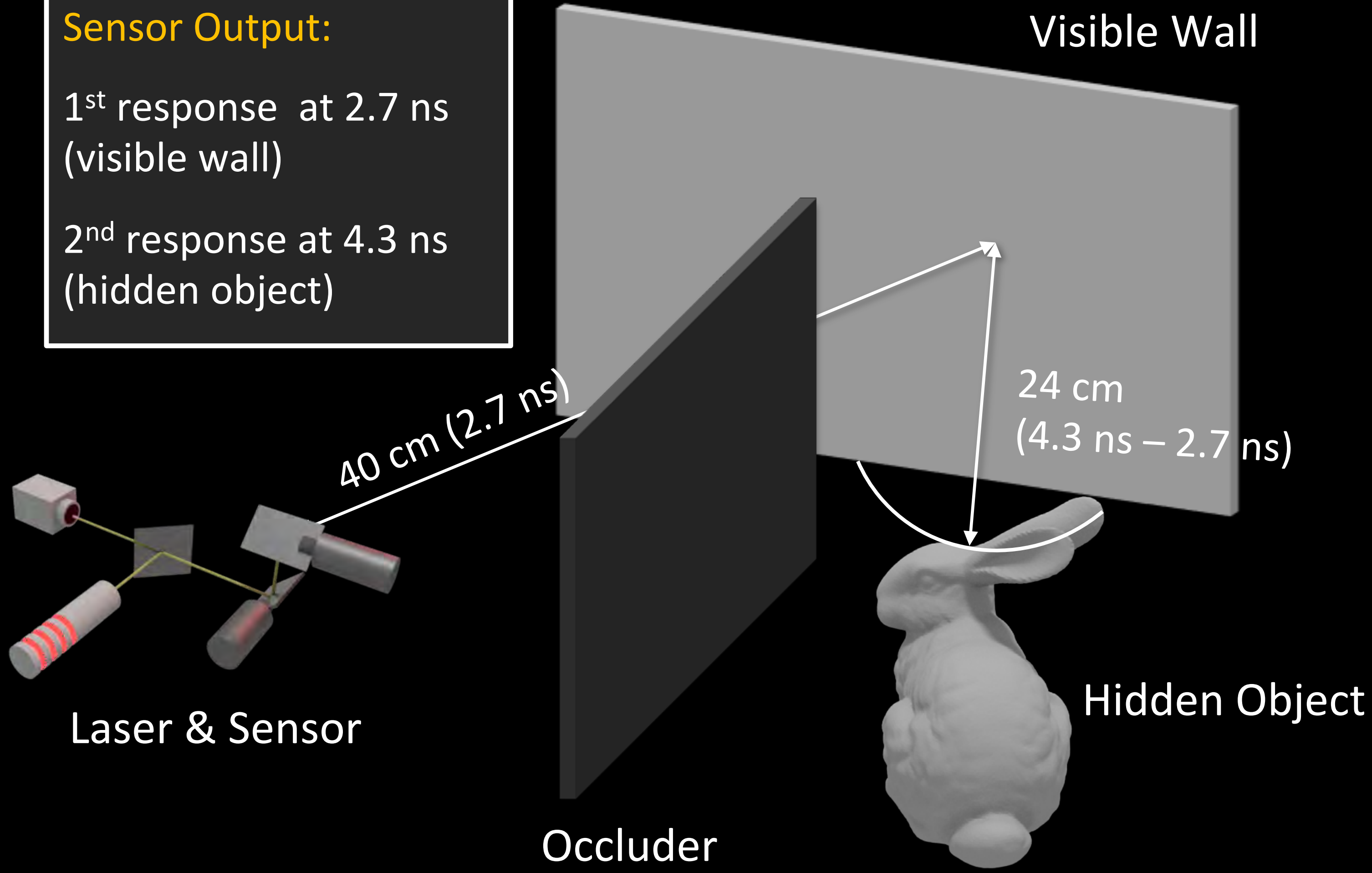


Sensor Output:
1st response at 2.7 ns (visible wall)
2nd response at 4.3 ns (hidden object)
Visible Wall
Laser & Sensor
Occluder
Hidden Object

Sensor Output:

1$^{st}$ response at 2.7 ns (visible wall)

2$^{nd}$ response at 4.3 ns (hidden object)



# Existing NLOS Imaging Techniques

Conventional approach is to raster scan a large 2D surface

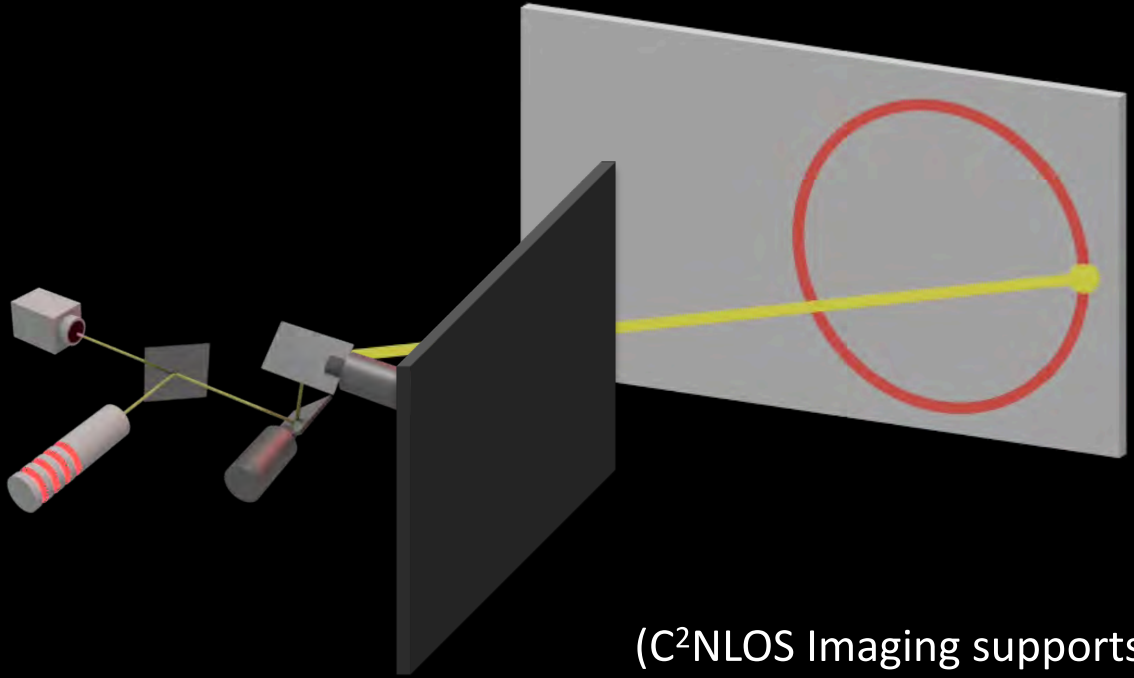
✗ Requires **long scanning times** and processing **large amounts of data**

# Key Questions

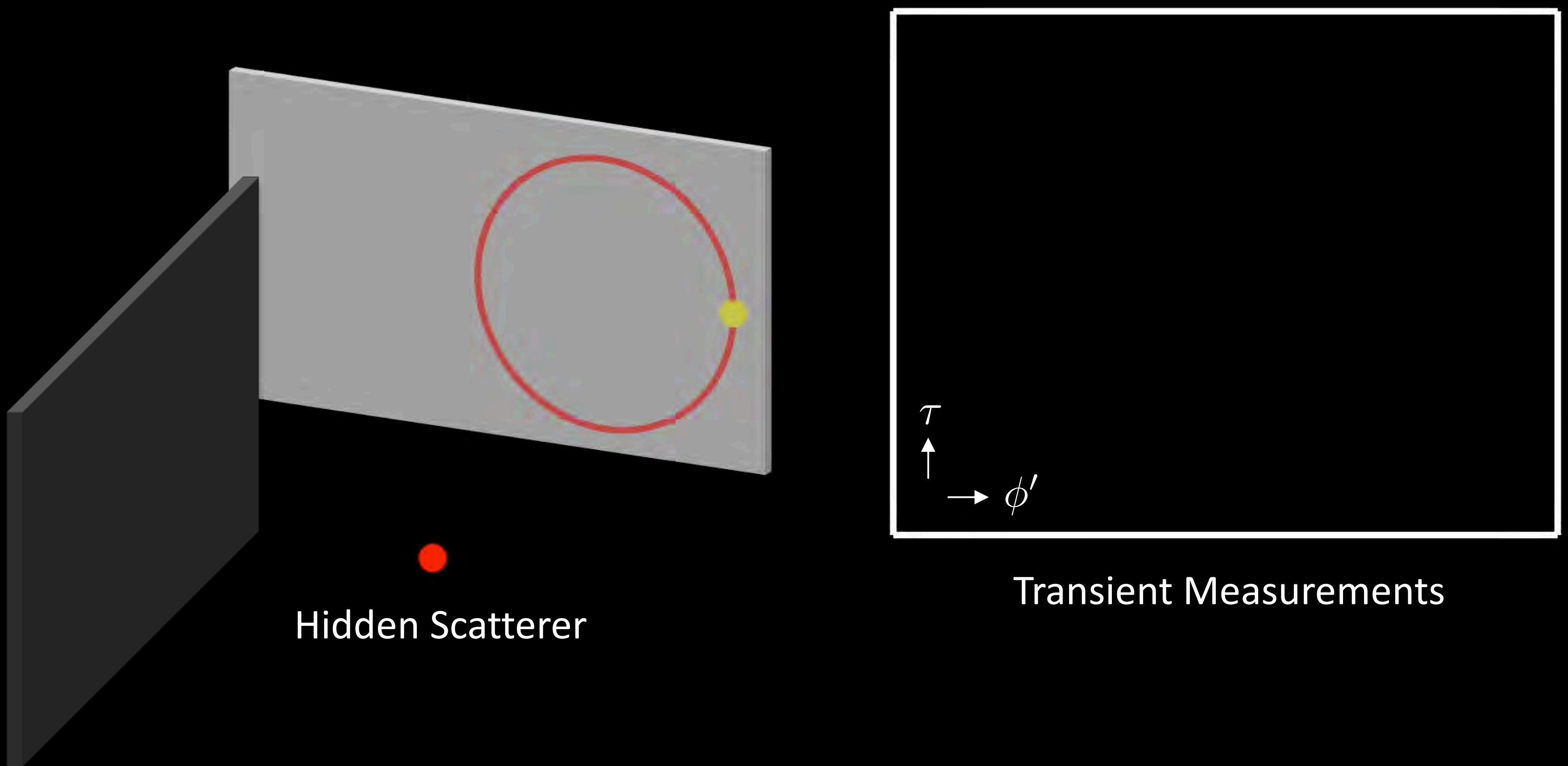
- Is it possible to reconstruct the hidden scene by scanning only a fraction of the wall?
- Do efficient reconstruction algorithms exist for processing such data?

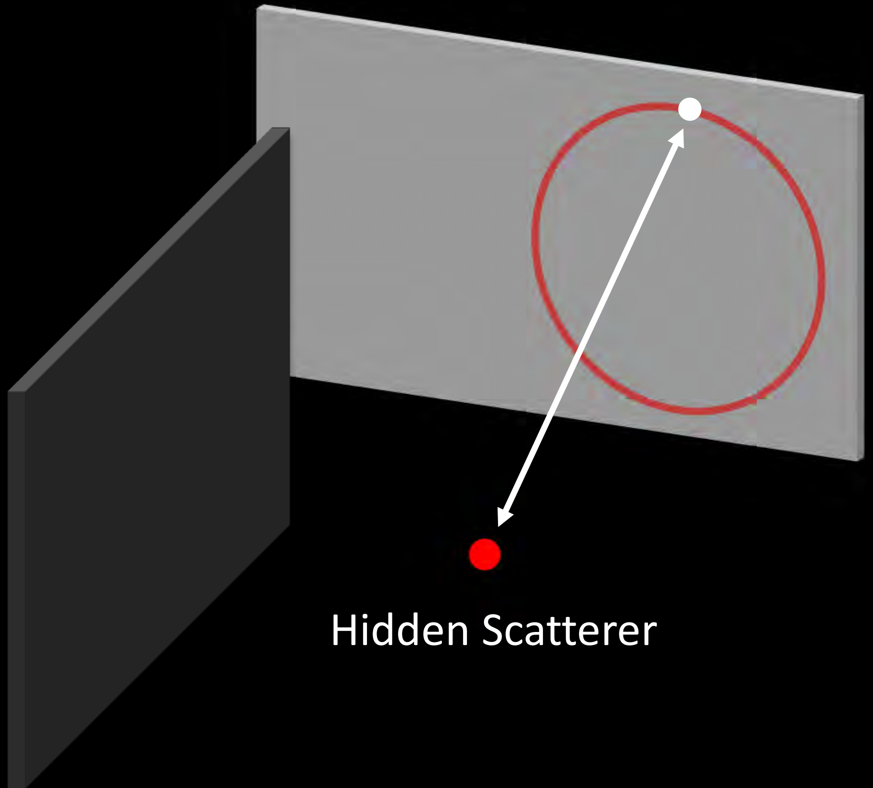
# Circular & Confocal NLOS (C²NLOS) Imaging

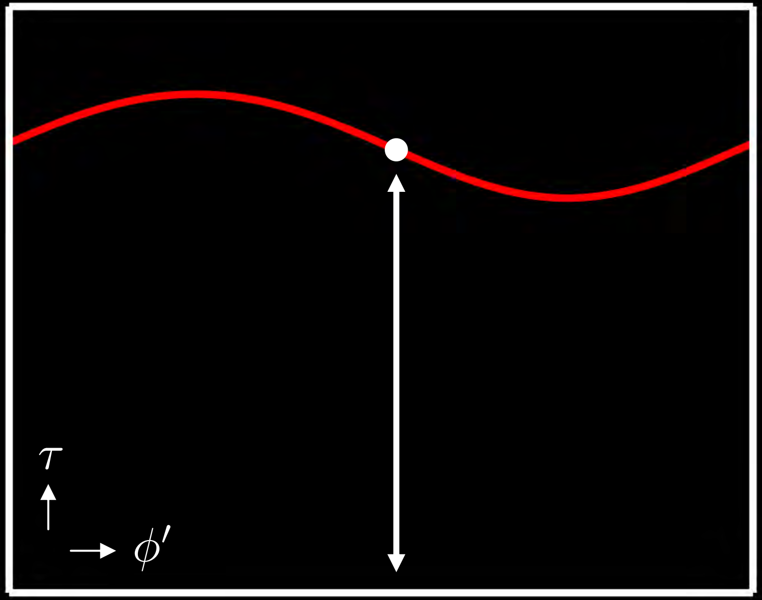
**Observation:** We identify a subset of measurements produced by **circular scanning** that yields important properties



(C²NLOS Imaging supports scanning rates of up to 130 Hz)

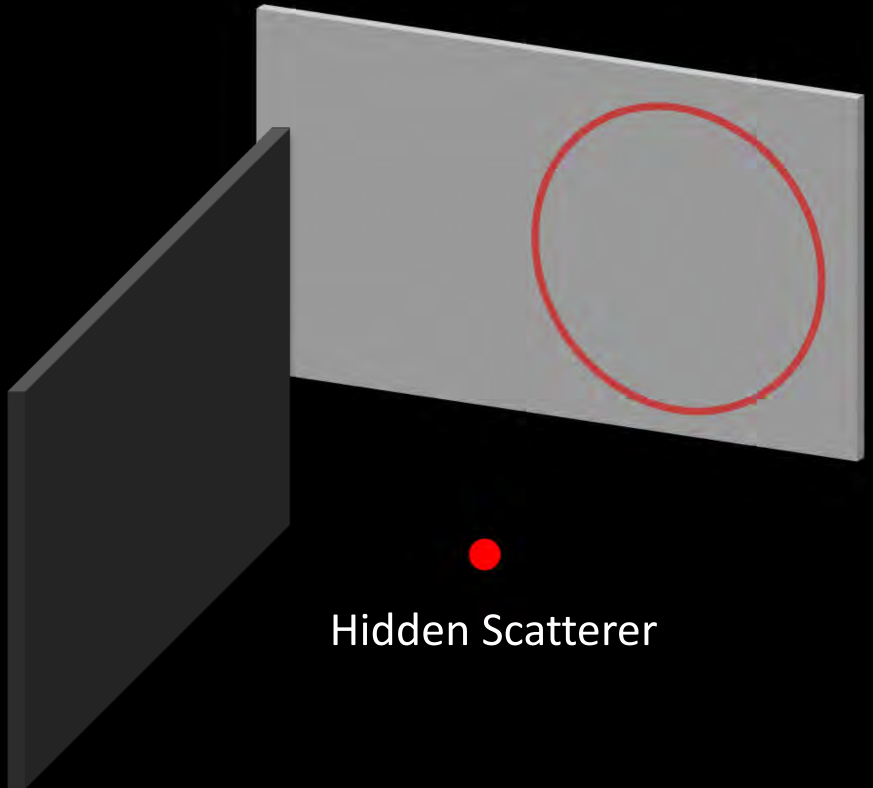

$\tau$
$\phi'$
Hidden Scatterer
Transient Measurements

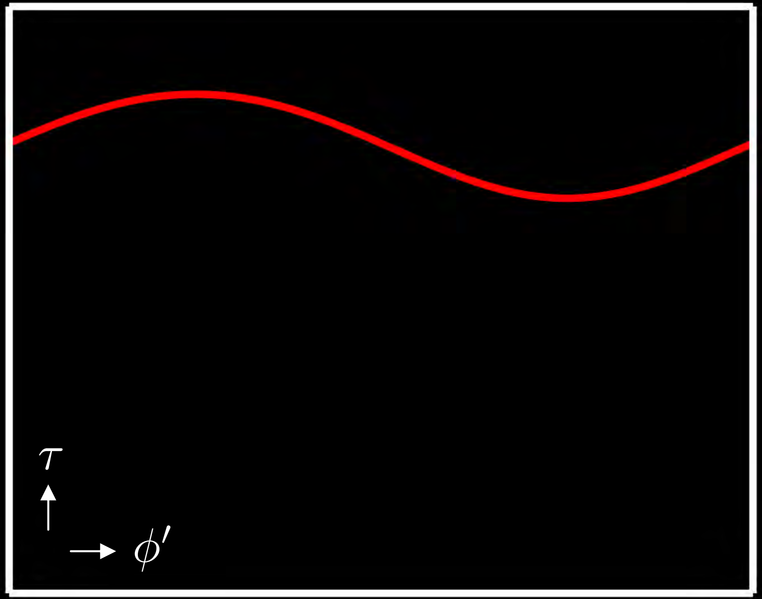


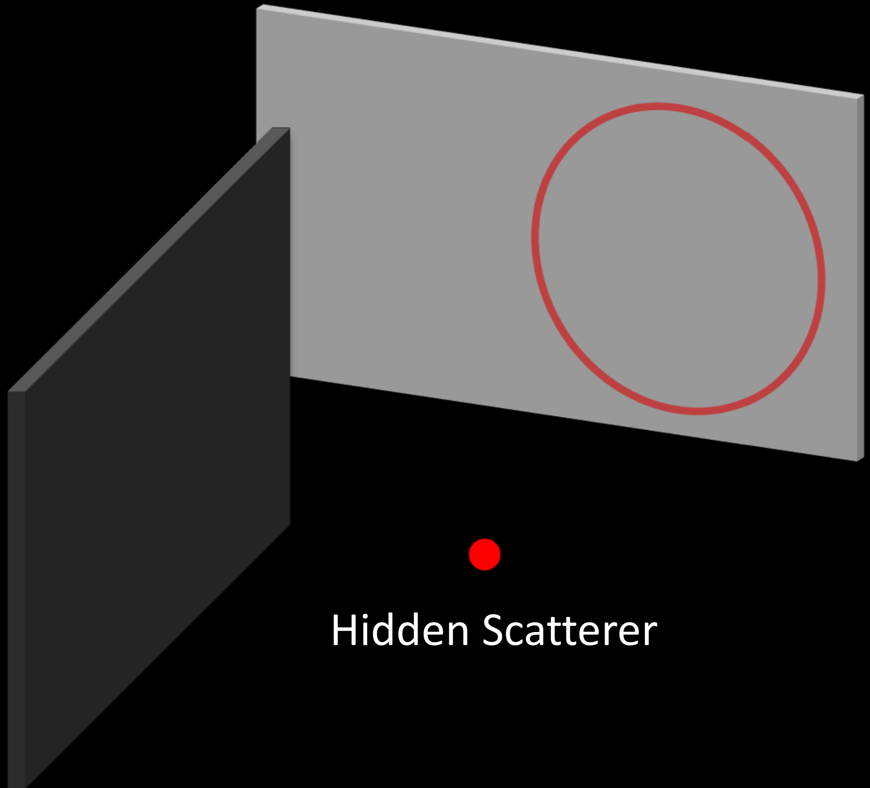

Transient Measurements

(Temporally Resample Measurements)




Transient Measurements

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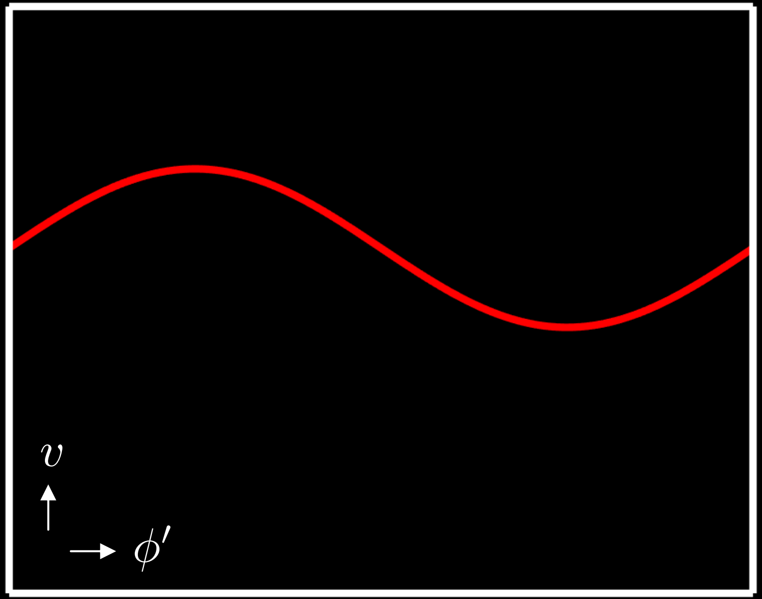
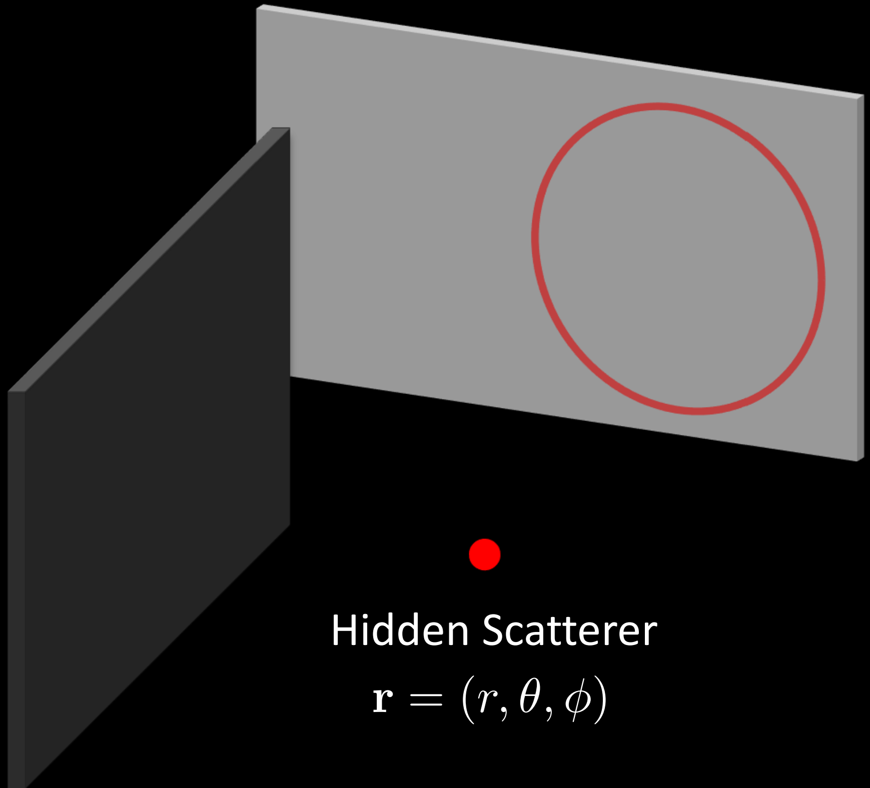


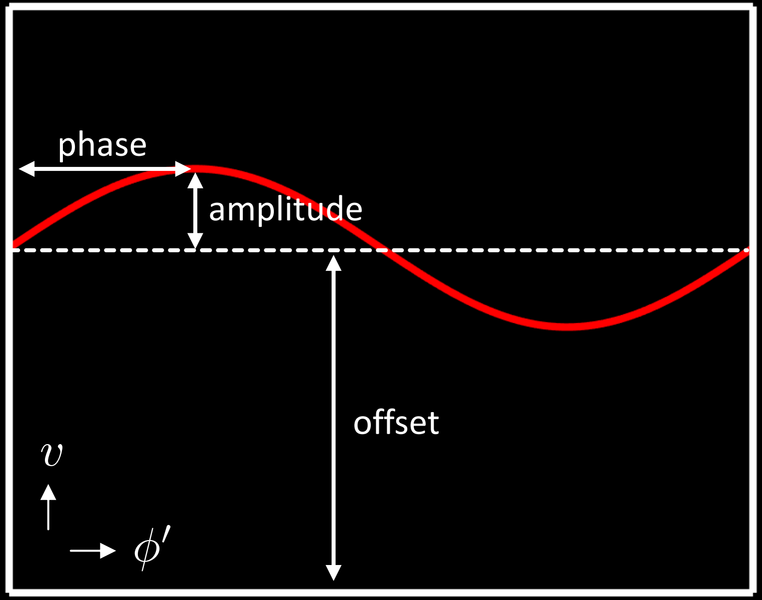

Transient Measurements

# C²NLOS measurements consist of a superposition of sinusoids (*i.e.*, a *transient sinogram*)



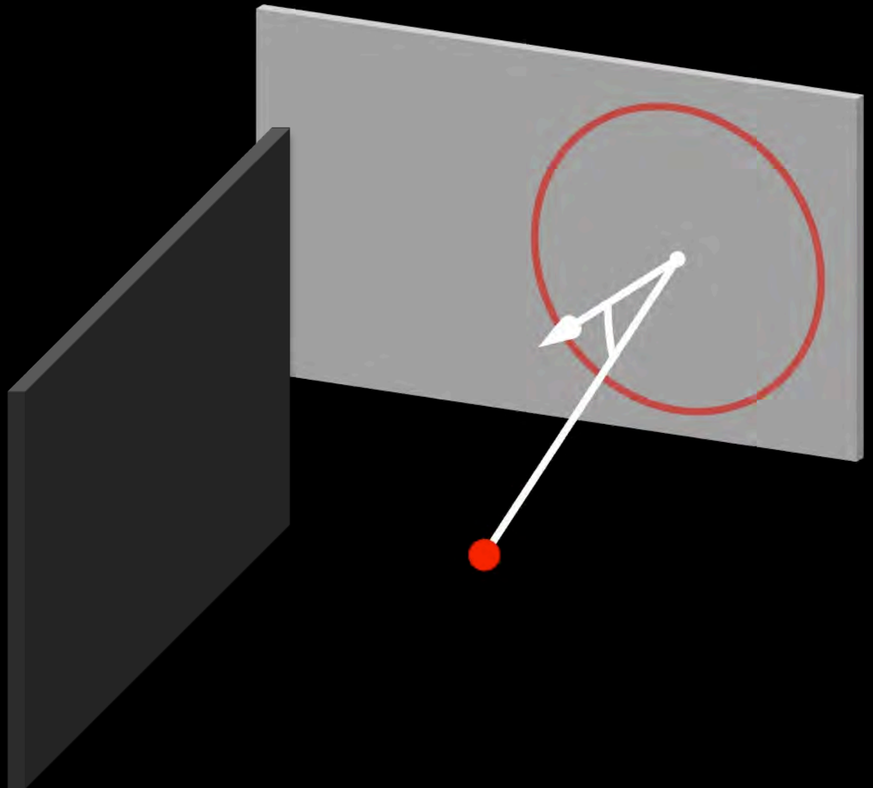
Hidden Scatterer

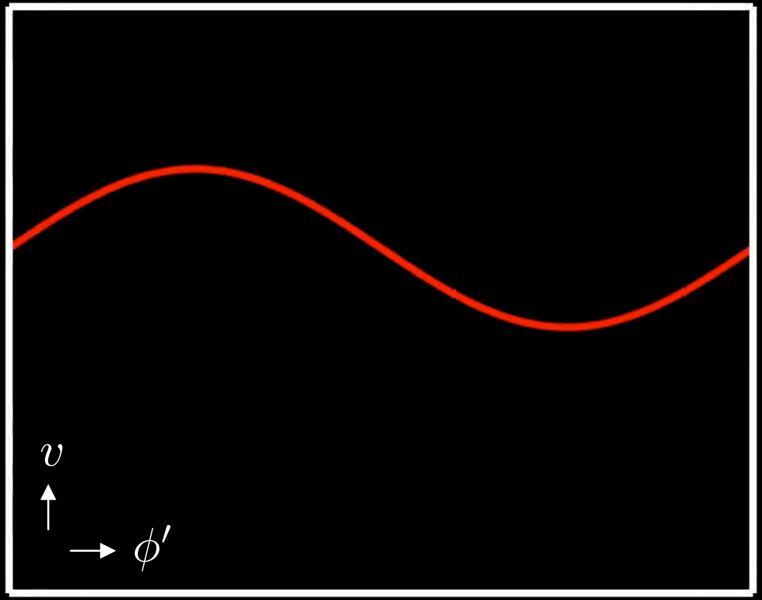
$\mathbf{r} = (r, \theta, \phi)$




Transient Sinogram

# $C^2$NLOS measurements consist of a superposition of sinusoids (*i.e.*, a *transient sinogram*)



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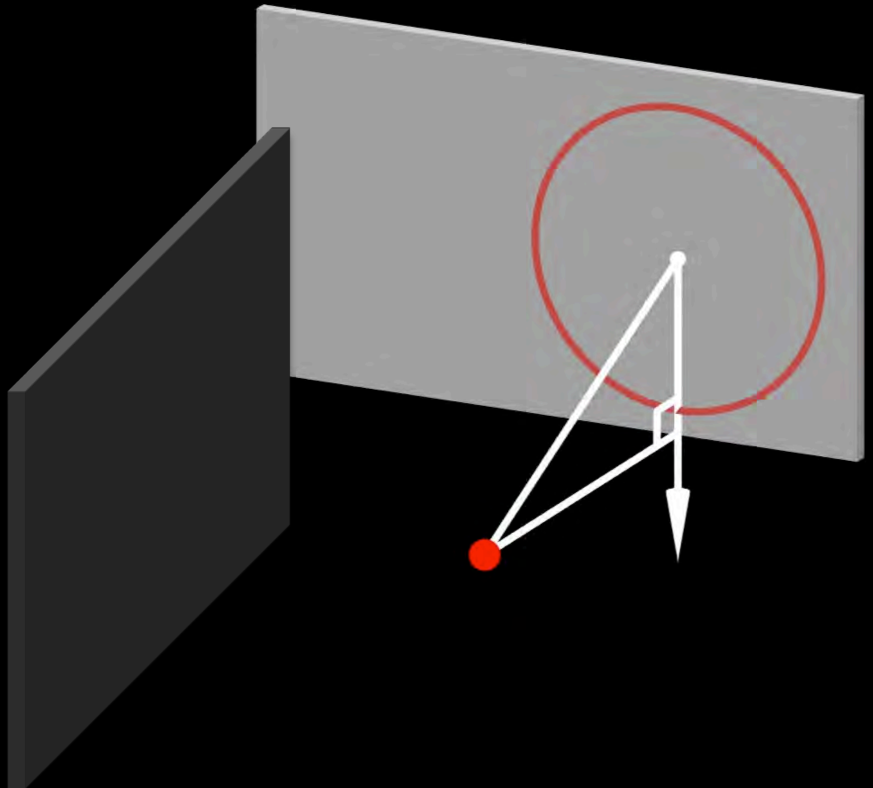

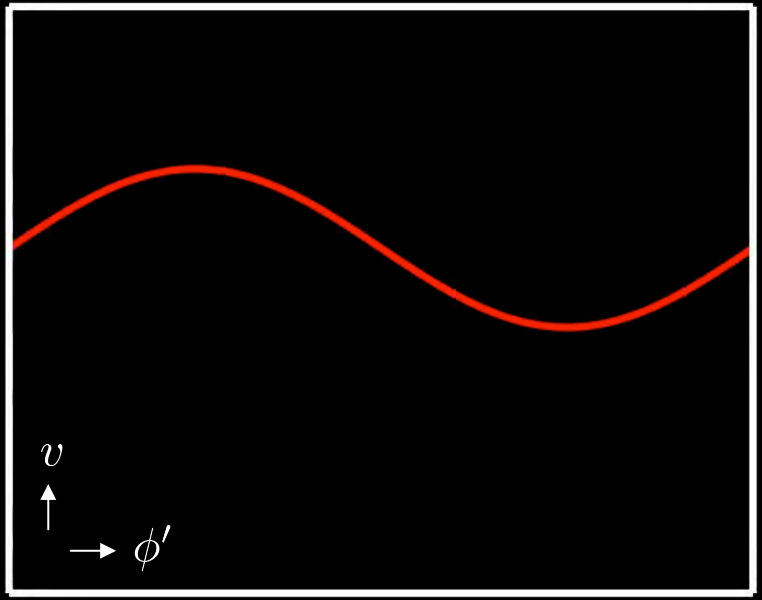


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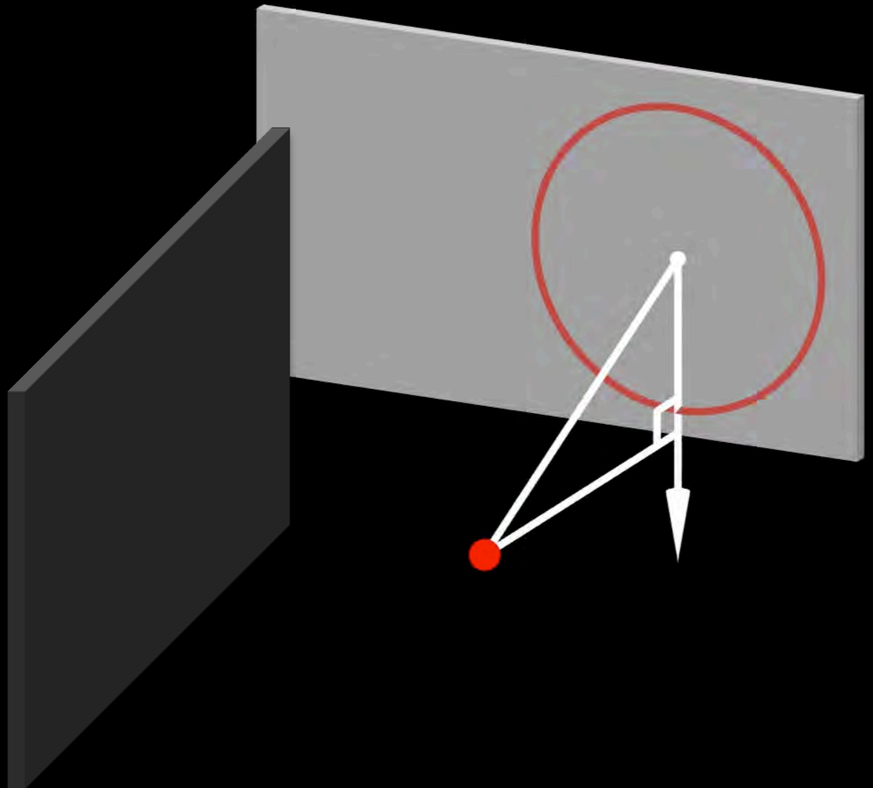

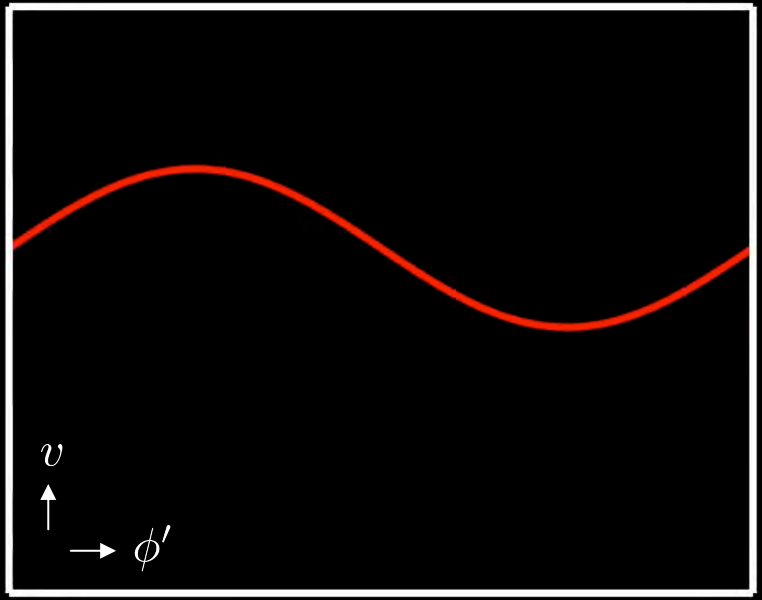


Transient Sinogram

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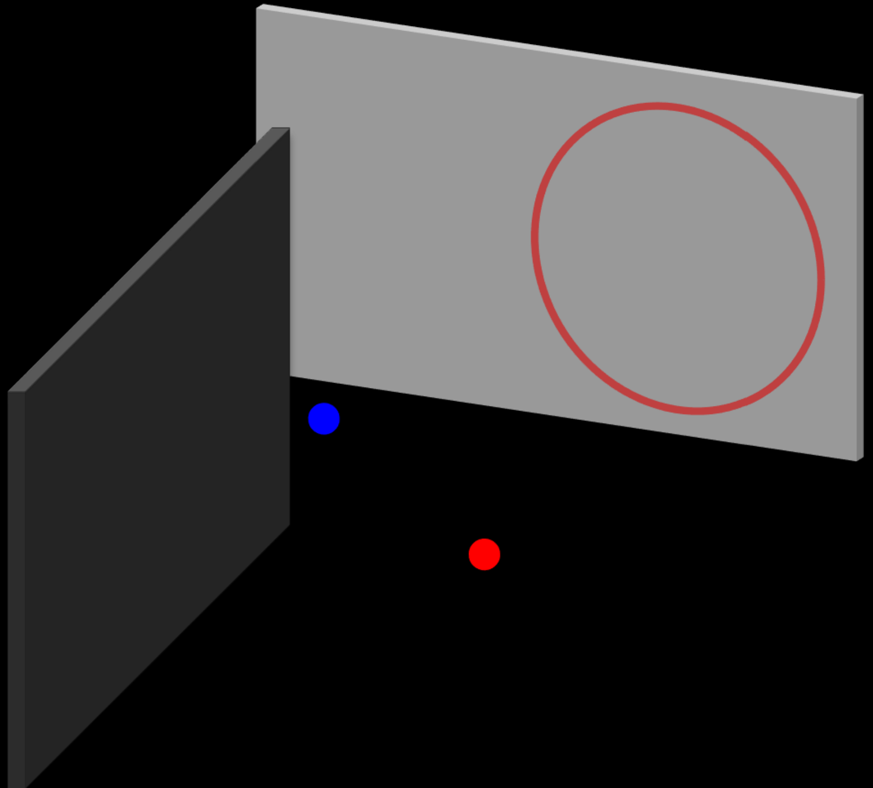
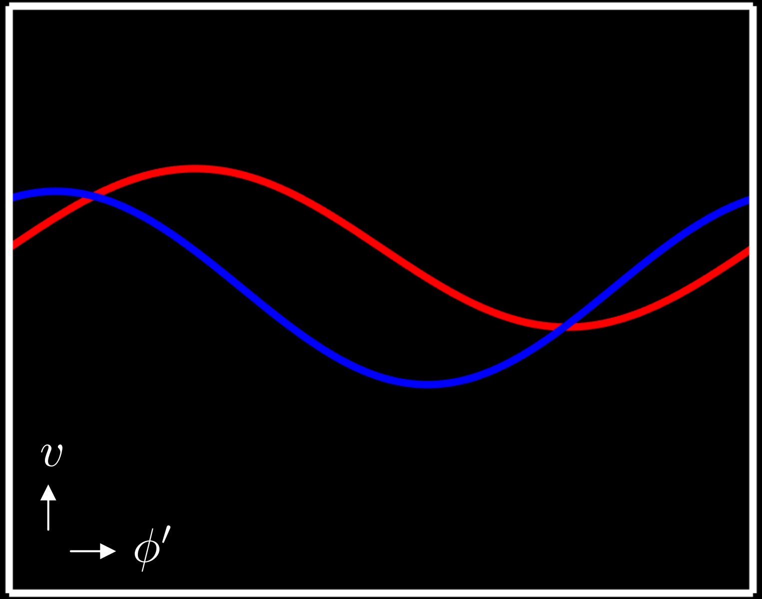


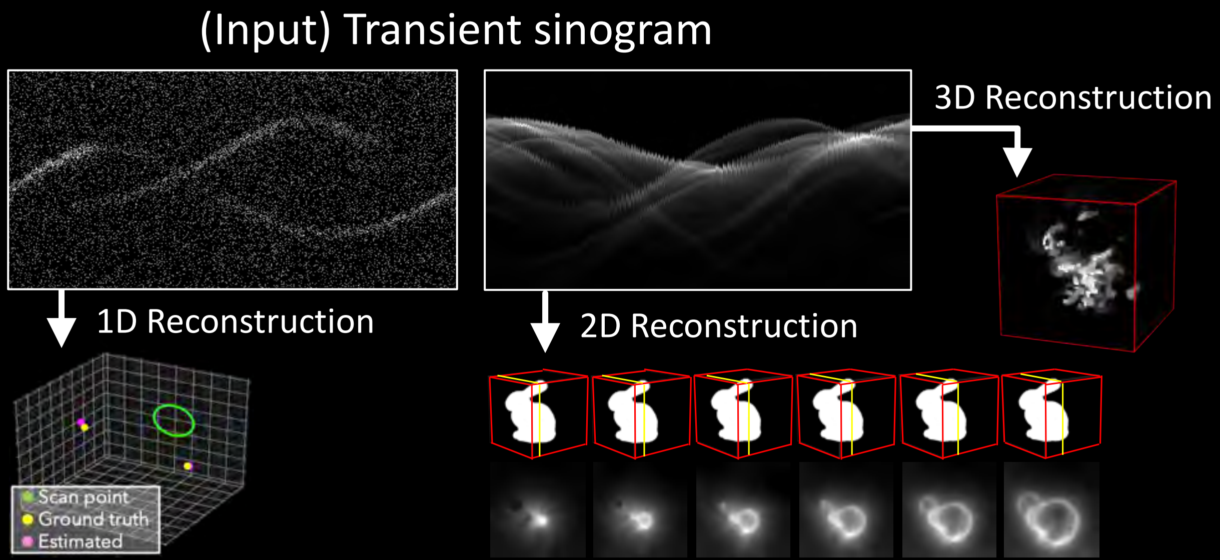



Transient Sinogram

# Reconstructions from Transient Sinograms

A single transient sinogram can be used for the

- "1D" reconstruction of N scatterers (*i.e.*, positional tracking)
- 2D reconstruction of the hidden scene at a given distance
- 3D reconstruction of the full volumetric representation of the hidden scene



# Comparisons

## Baseline Algorithms:

Light Cone Transform (LCT) [O'Toole et al., 2018] & F-K Migration [Lindell et al., 2019]

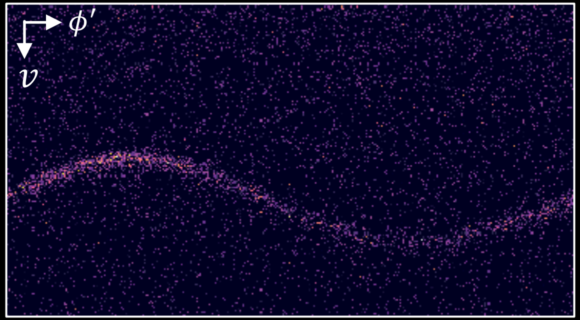
- Requires confocal NLOS scan of a full 2D surface

3-Points (for positional tracking results only)

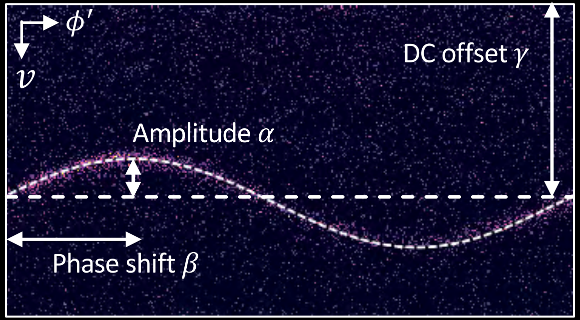
- Trilateration-based position estimation requires sampling only three samples
- Limited to positional tracking a single scatterer

# Positional Tracking

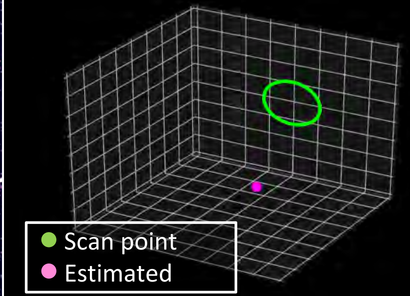
- Estimate corresponding sinusoid parameters of the input transient sinogram
- Our Hough Transform based approach achieves this quickly, accurately, and robustly




Transient sinogram
(Input)



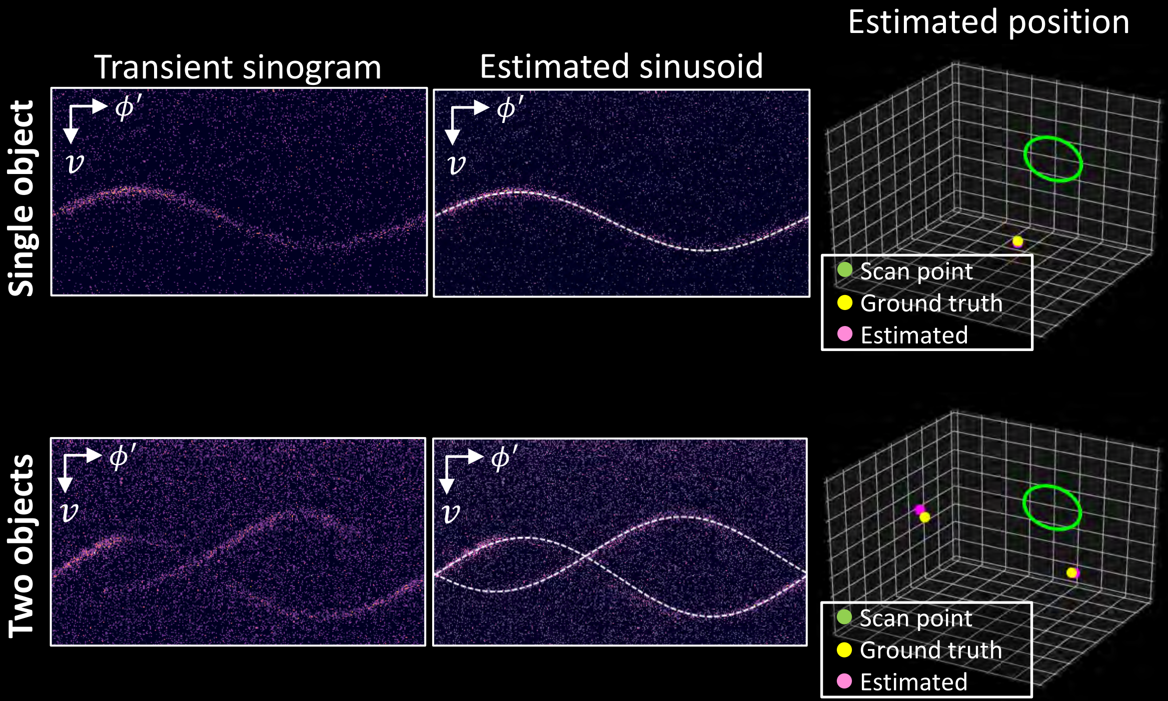

Sinusoid parameters estimated
by Hough Transform




Estimated position
(Output)

# Positional Tracking Results

- Despite using fewer samples, our solution achieves similar accuracy to LCT & FK
- Our method is, however, **faster** than both LCT & FK in terms of both acquisition and computation time



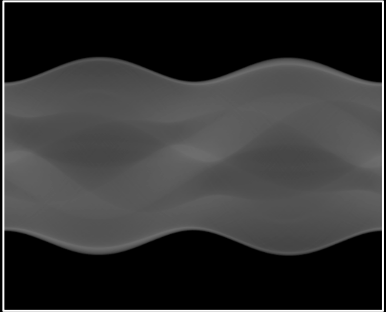

| Method | Time [sec] | Mean Error x-axis | Mean Error y-axis | Mean Error z-axis |
|---|---|---|---|---|
| LCT | 6.86 | 0.84 | 0.89 | 0.19 |
| FK | 25.45 | 0.31 | 0.31 | 0.17 |
| 3Points | **0.20** | 0.56 | 0.65 | 0.22 |
| C²NLOS(Ours) | 0.50 | 0.44 | 0.42 | 0.93 |

| Method | Time [sec] | Mean Error x-axis | Mean Error y-axis | Mean Error z-axis |
|---|---|---|---|---|
| LCT | 6.92 | 1.34 | 1.47 | 1.40 |
| FK | 26.65 | 0.29 | 0.39 | 0.07 |
| 3Points | — | — | — | — |
| C²NLOS(Ours) | **0.52** | 2.20 | 1.30 | 7.37 |

# 2D Reconstruction

- Efficient reconstruction with the inverse Radon transform: an integral transform used to solve the CT reconstruction problem from a sinogram
- Radon transform can be directly applied to a transient sinogram to reconstruct 2D images

Radon Transform for Computed Tomography

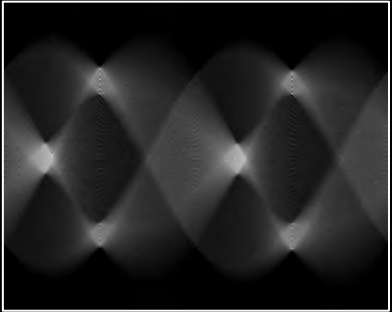


Sinogram

Inverse Radon Transform

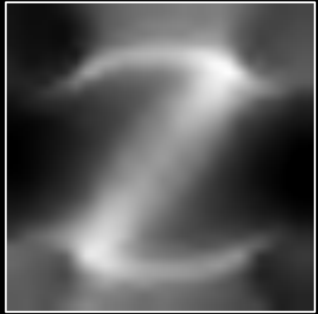
Reconstructed CT image

Radon transform for $C^2$NLOS Imaging



Transient sinogram

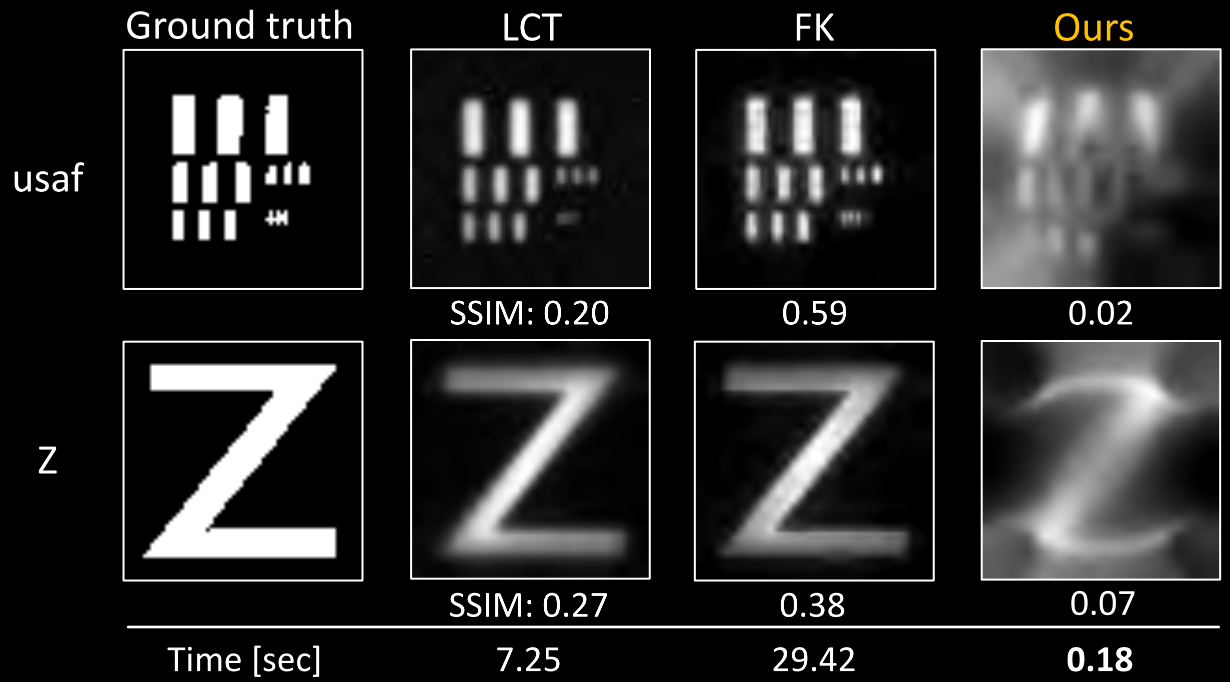
Inverse Radon Transform



Reconstructed 2D image

# 2D Reconstruction Results

Despite working with far fewer measurements, our inverse Radon based 2D reconstruction from $C^2$NLOS measurement produces a reasonable reconstruction of the 2D scene, and is significantly faster than LCT and FK



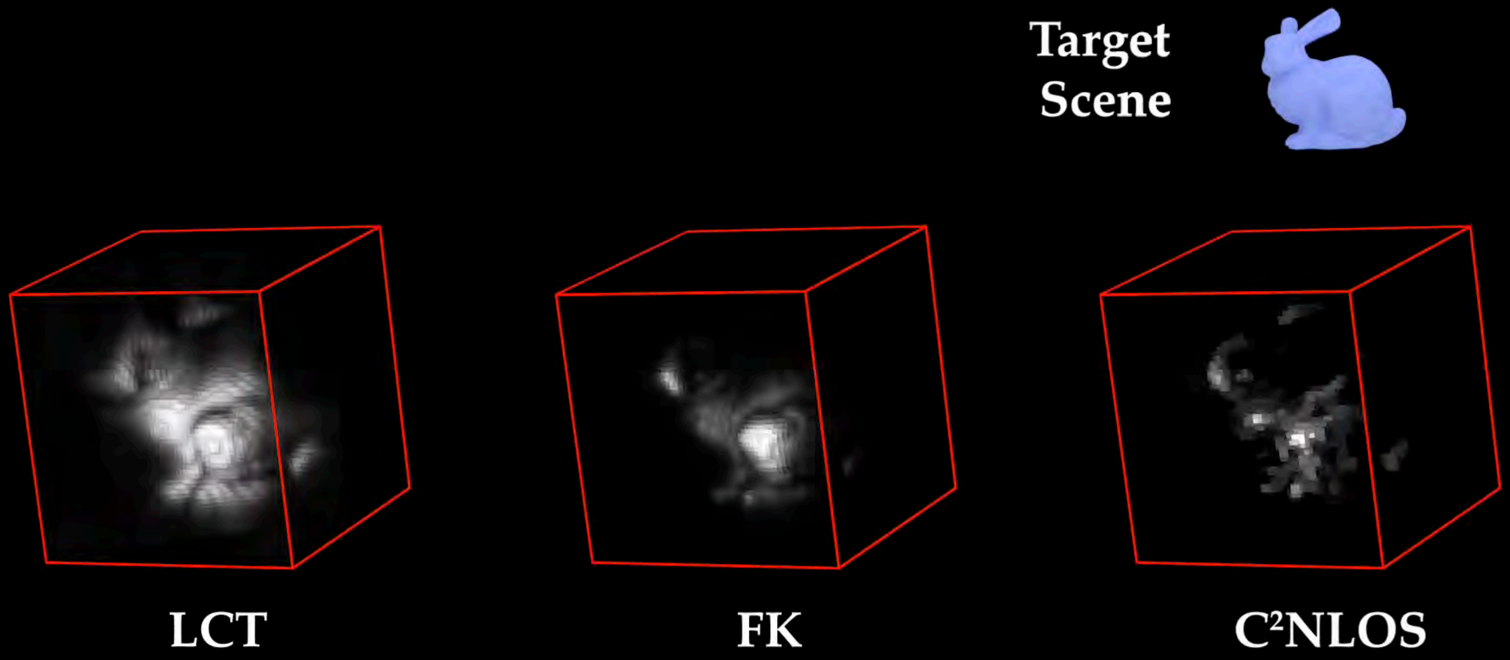
# 3D Reconstruction Algorithm

We implemented a modified version of the iterative light cone transform (LCT) procedure proposed in confocal NLOS imaging [O'Toole et al., 2018] to recover 3D volumes from transient sinograms

$$\boldsymbol{\rho}_{3D} = \underset{\rho}{argmin}\frac{1}{2}\|\underbrace{\boldsymbol{\tau}_{circ}}_{\text{C}^2\text{NLOS measurement}} - \underbrace{\boldsymbol{M}\boldsymbol{A}}_{\text{Subsampling \& mapping matrix}}\underbrace{\boldsymbol{\rho}}_{\text{Albedo}}\|_2^2 + \underbrace{\Gamma(\boldsymbol{\rho})}_{\text{Prior term}}$$

# 3D Reconstruction Results

Even though C$^2$NLOS imaging only uses 9% of data utilized by the LCT or FK, it still generates an approximate reconstruction of the hidden scene



# Concluding Remarks

- Proposed circular and confocal non-line-of-sight ($C^2$NLOS) imaging that reduces both acquisition times and computational requirements
- Analyzed $C^2$NLOS measurements, which consist of a superposition of sinusoids (*i.e.*, transient sinogram)
- Developed efficient reconstruction procedures that leverage the geometric properties of transient sinograms
- Empirically showed that our measurements are sufficient for reconstructing NLOS scenes

# Efficient Non-Line-of-Sight Imaging from Transient Sinograms

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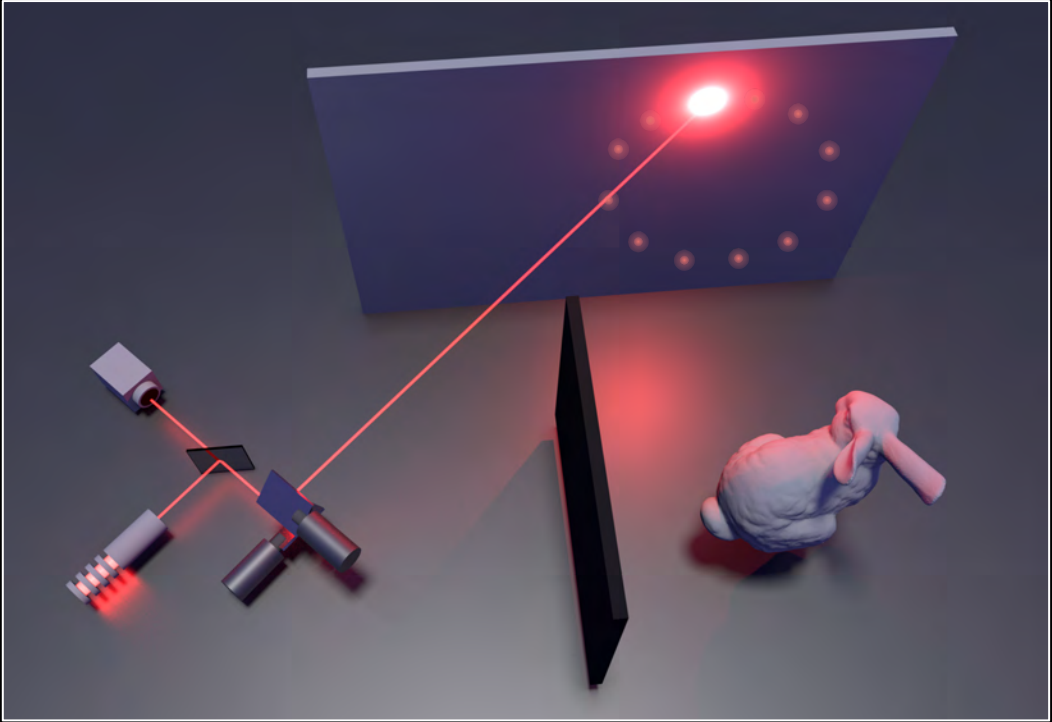

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Project page: https://marikoisogawa.github.io/project/c2nlos.html