Decomposition and Acquisition of Light Transport under Spatially Varying Lighting

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Distant illumination

Light is distant and diffuse at the scene

- Angular variation at the scene
- Little/no spatial variation

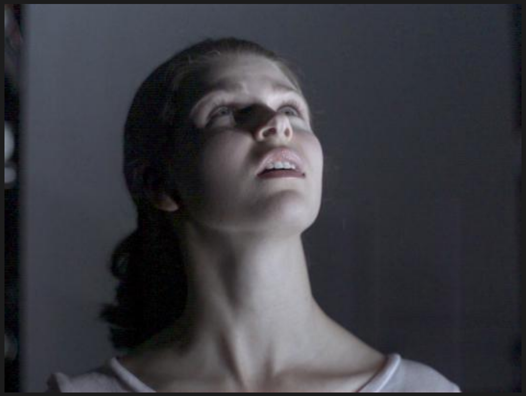


image credit: ict.usc.edu

Spatially varying illumination

Light focuses on the scene

- Spatial variation at the scene
- Small range of angles

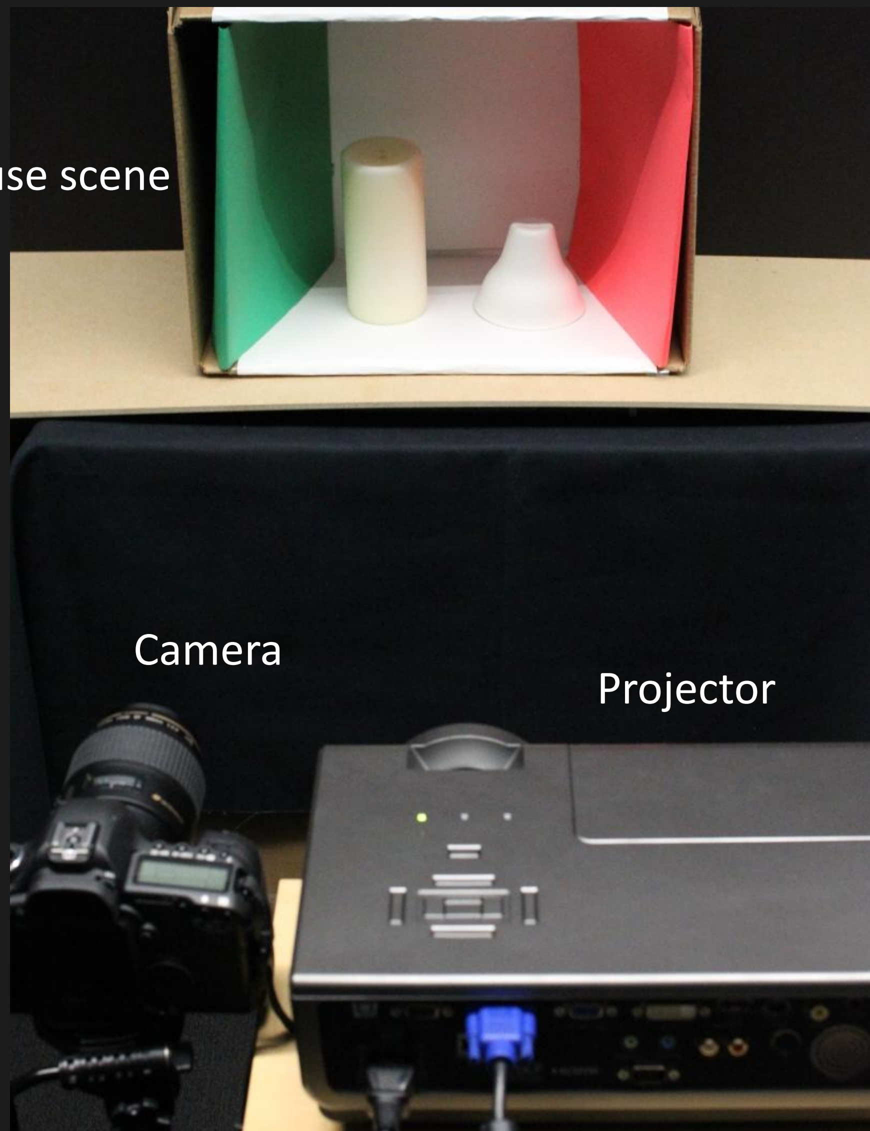
Examples

Many applications

- Structured light
- Image/video projection
- Augmented Reality

image credit: volkswagen

Projector-camera system



Light transport

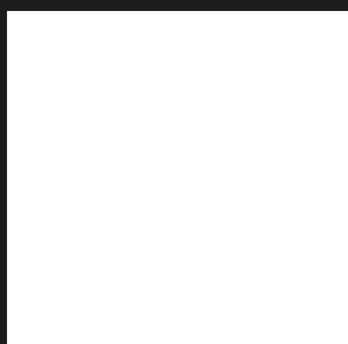
Input: projector pattern Output: camera image

Projector pattern

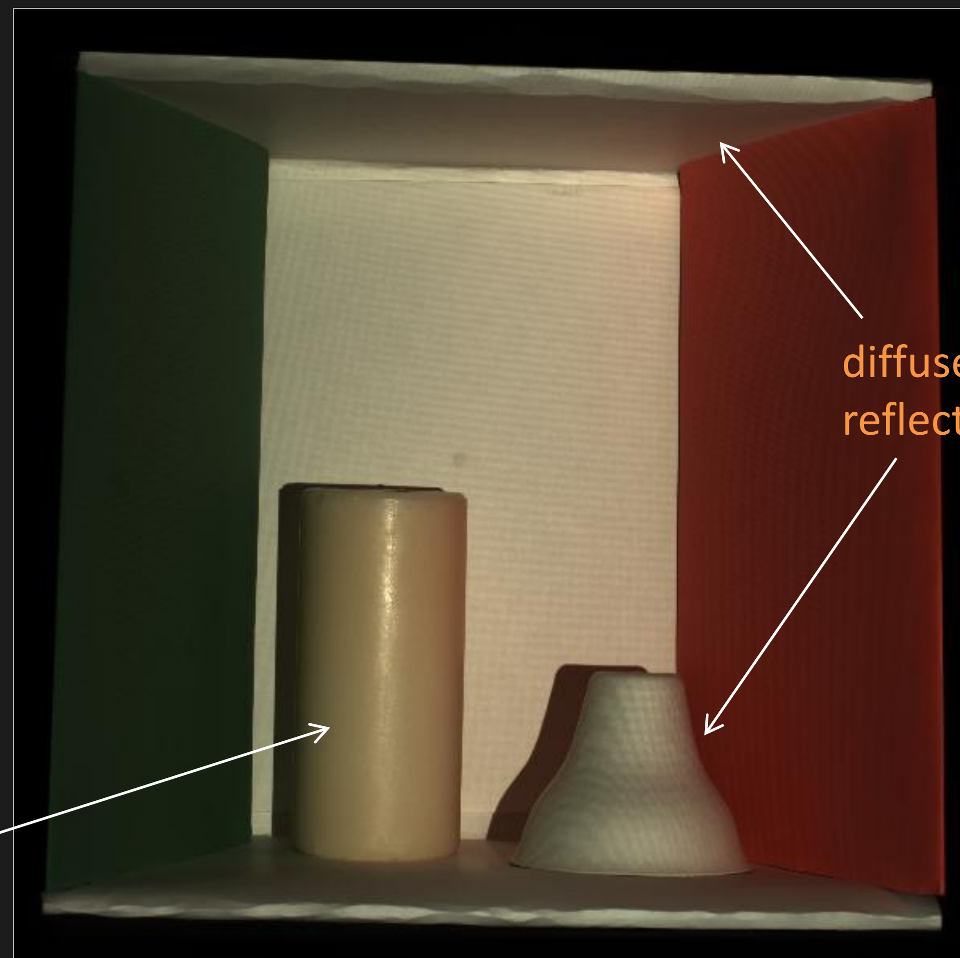
Camera image

Light transport

Diffuse scene: subsurface scattering, interreflection

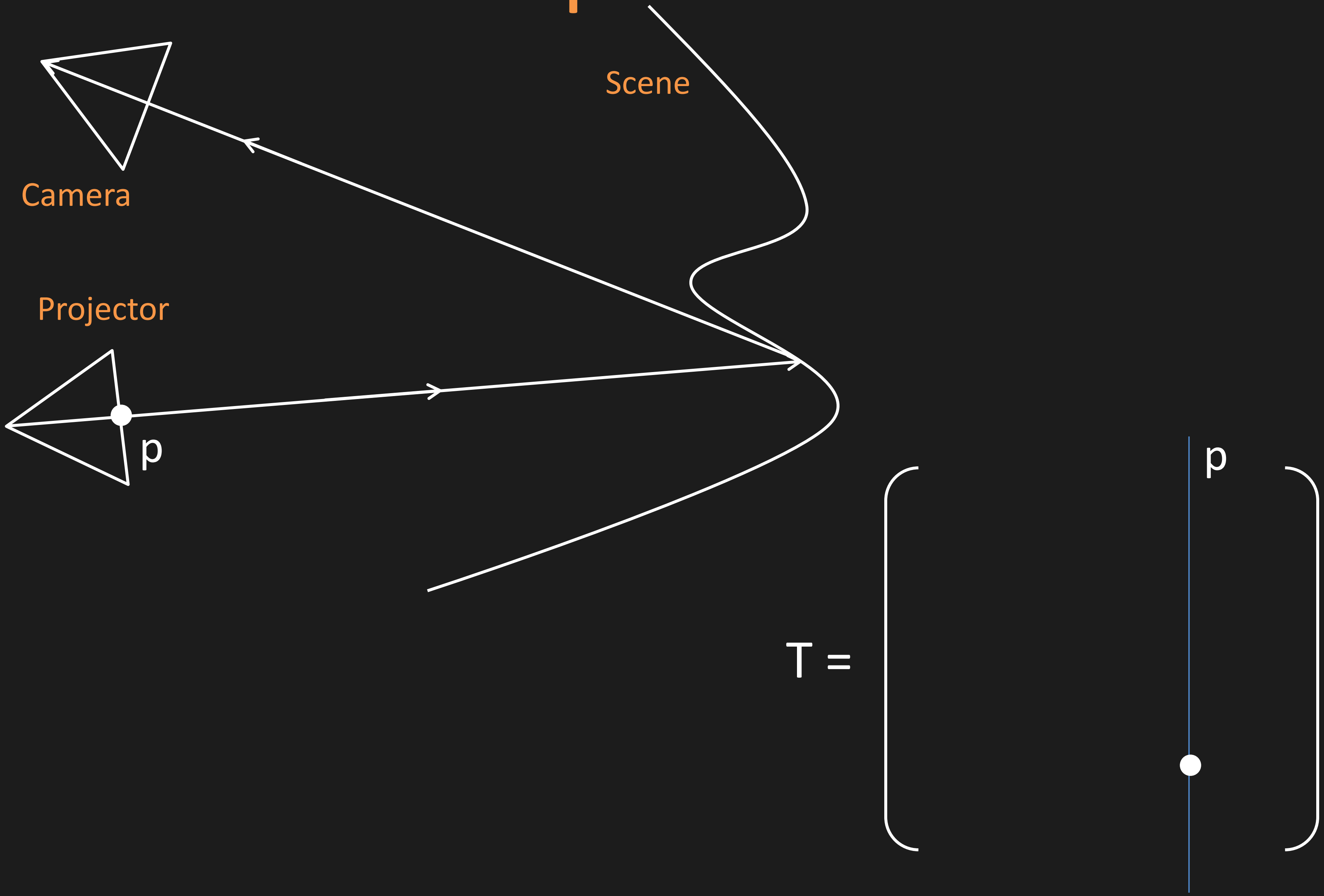


Projector pattern

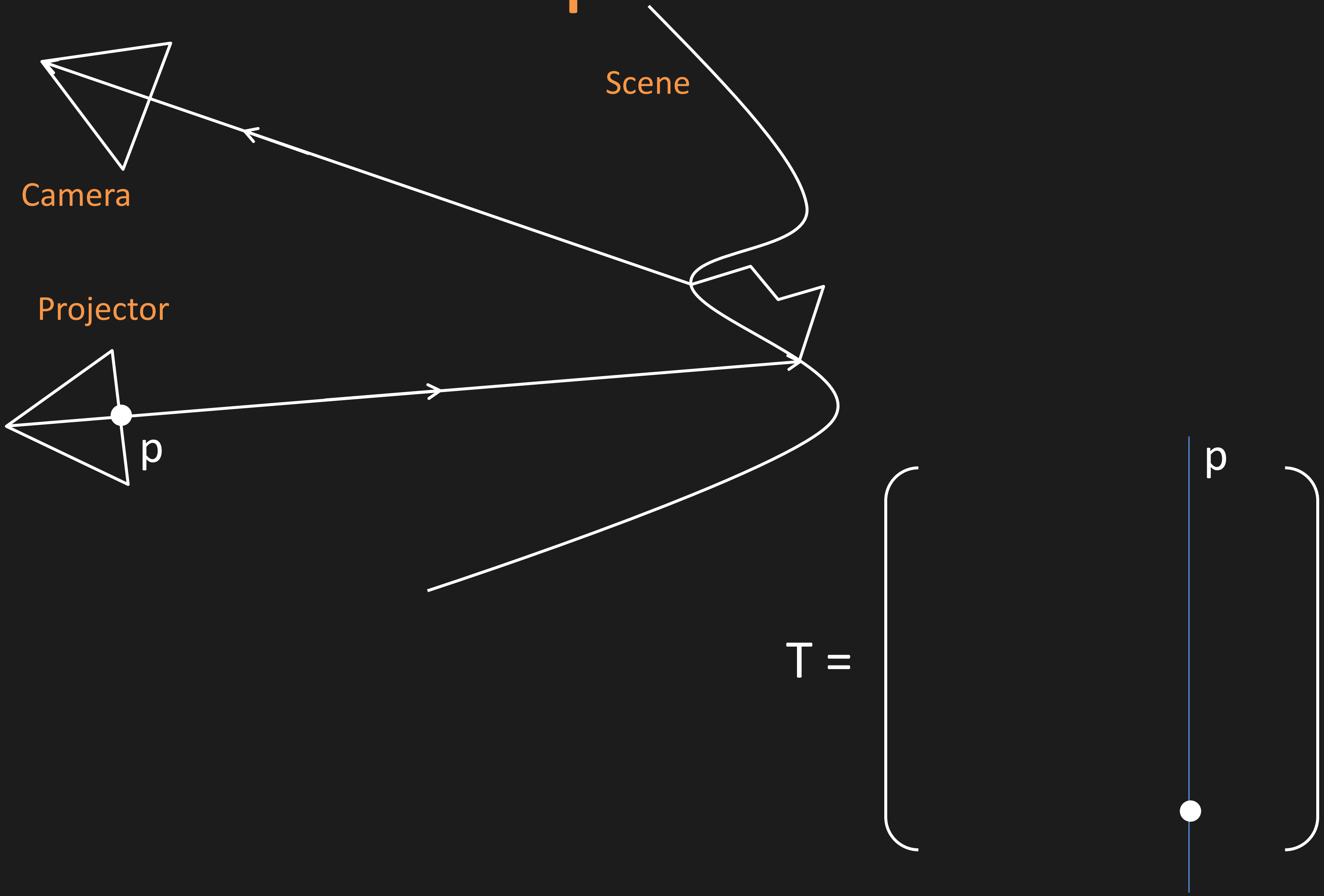


Camera image

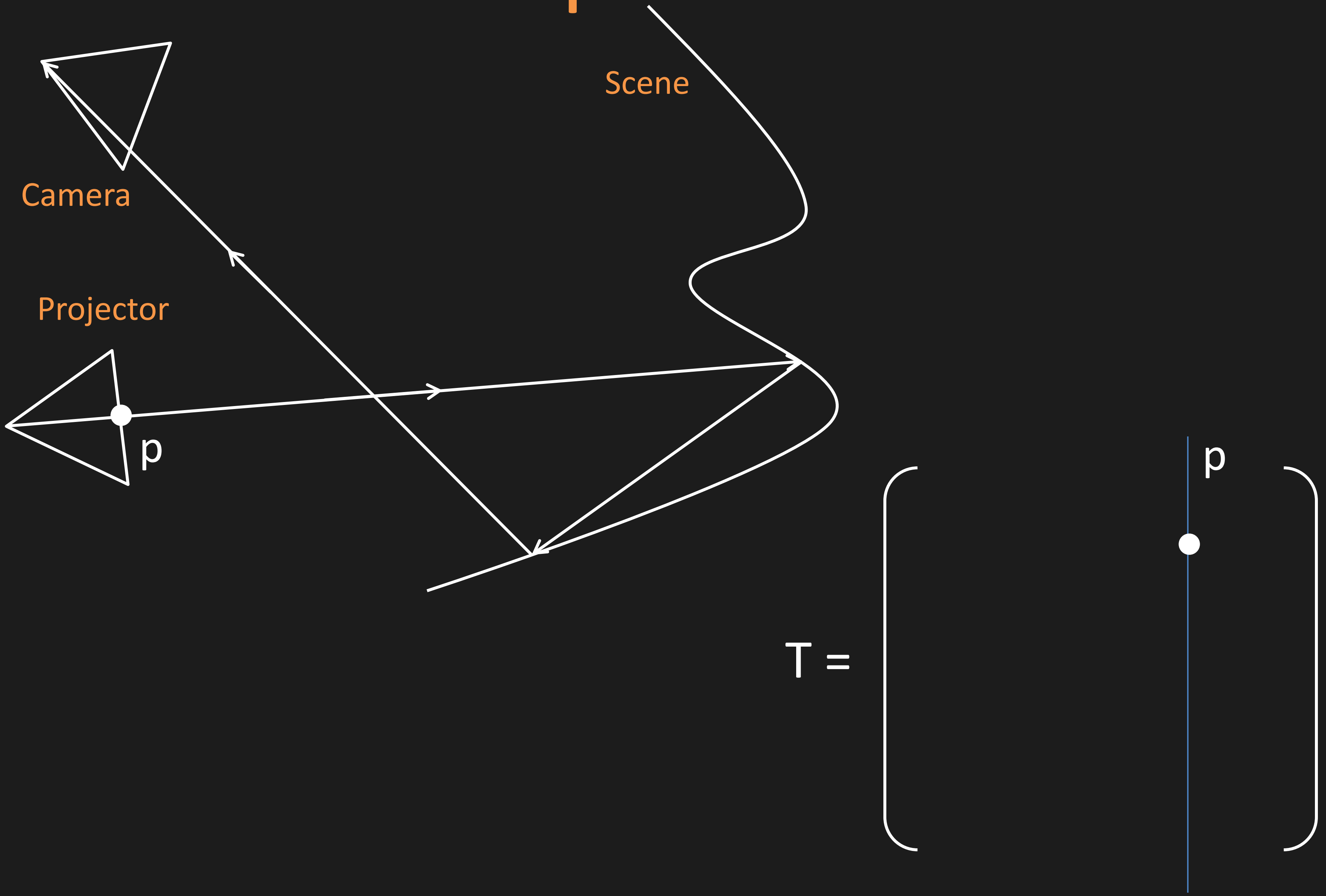
Transport matrix



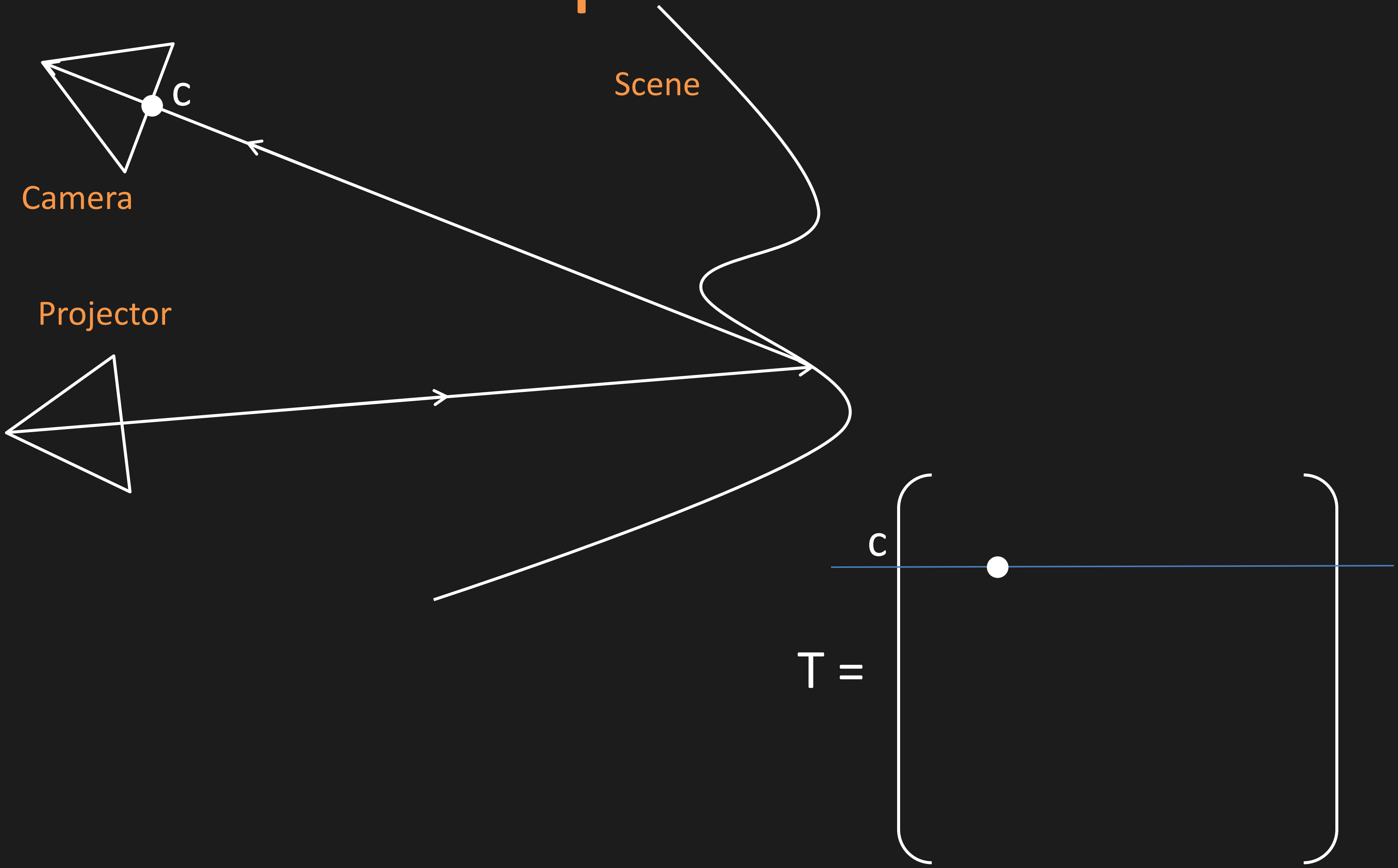
Transport matrix



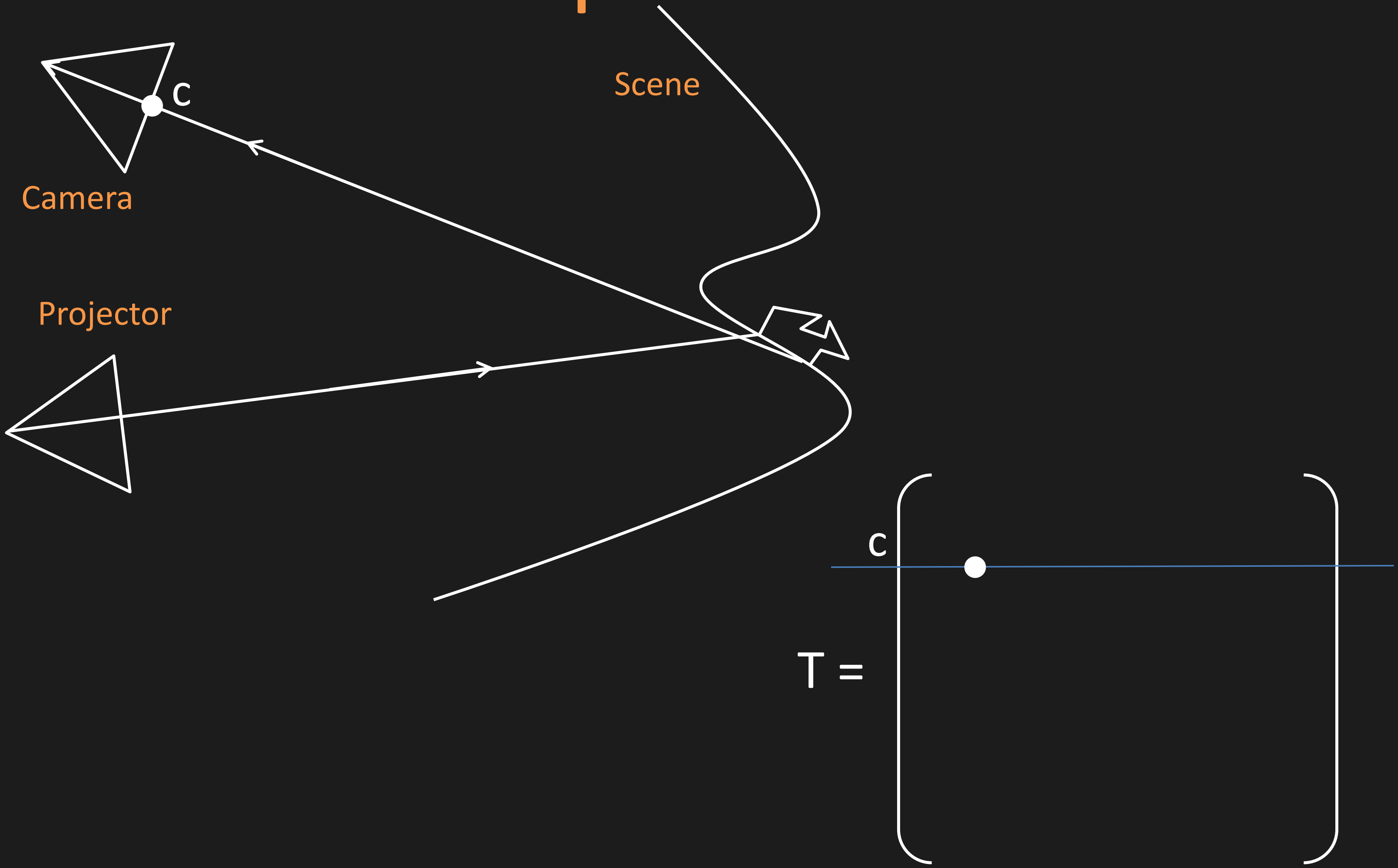
Transport matrix



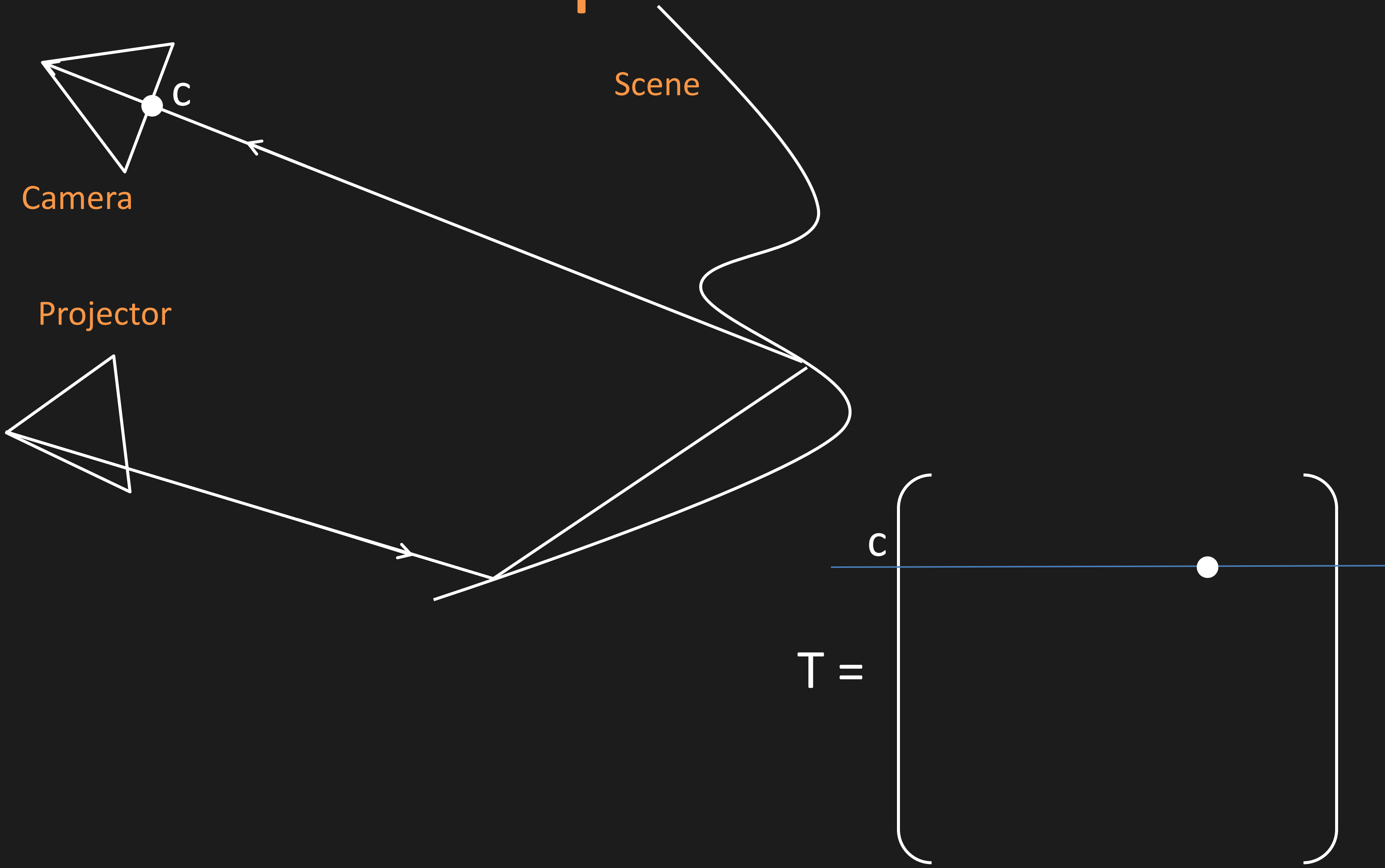
Transport matrix



Transport matrix

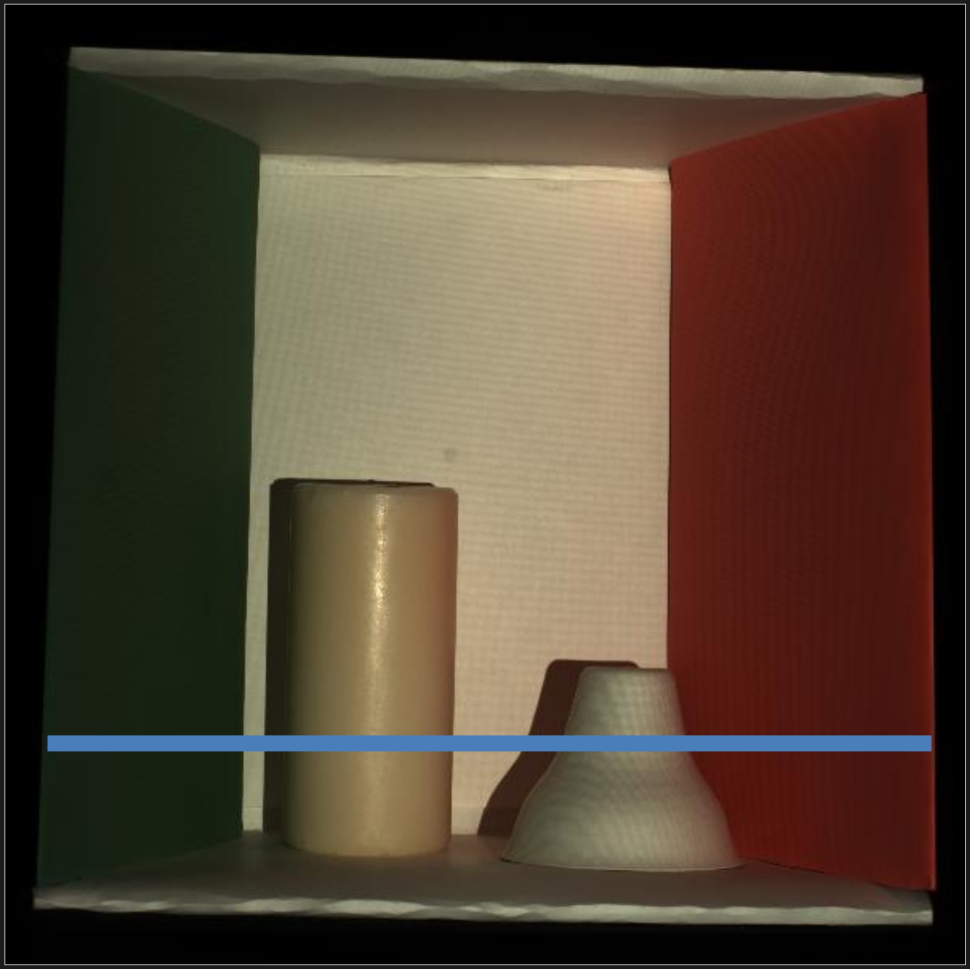


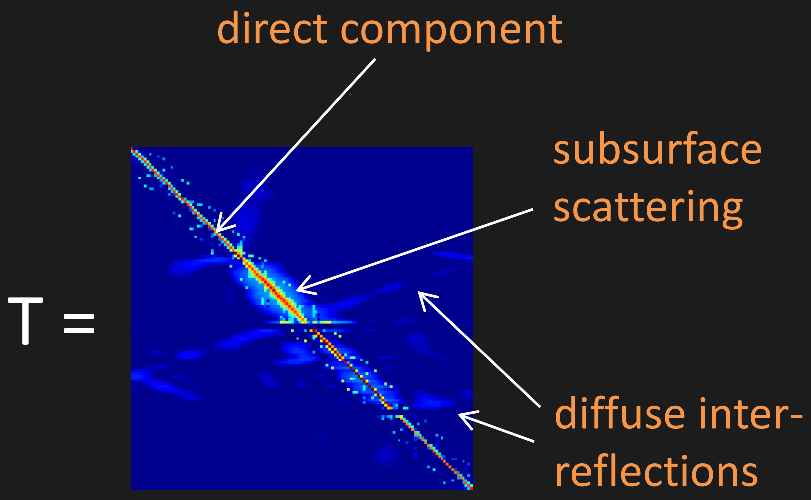
Transport matrix



Transport matrix

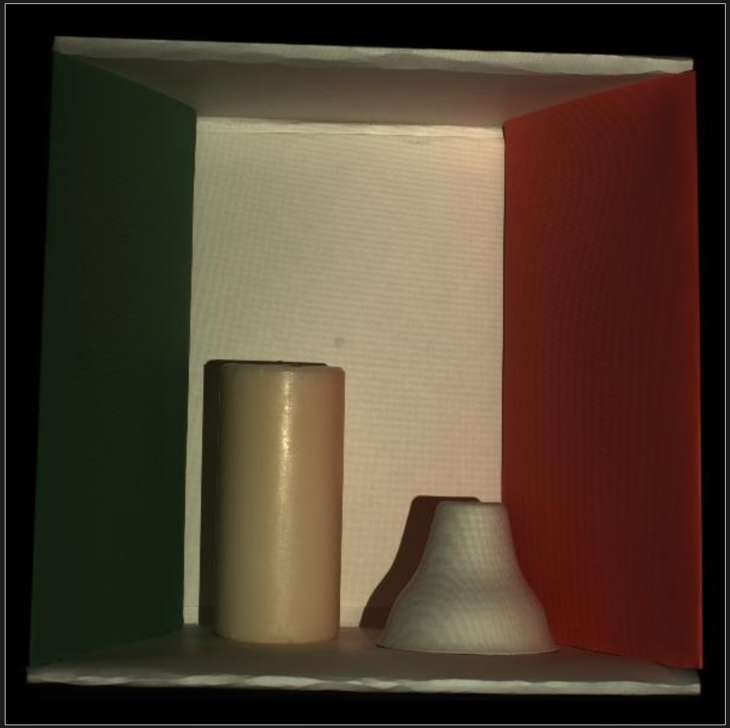
2D slice of the 4D light transport at the scanline



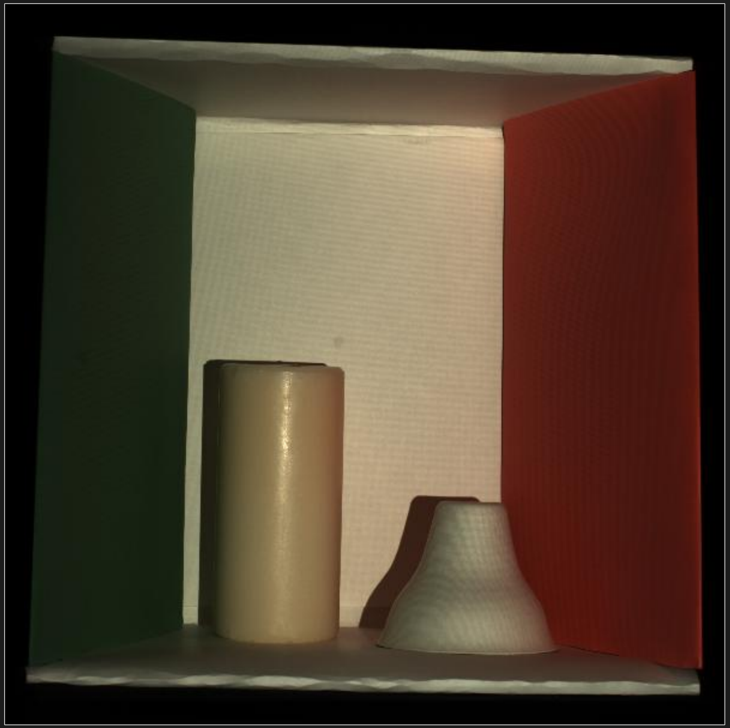


Acquisition

Acquire 360000 x 16384 matrix with 1060 patterns



Original



Reconstructed

SNR = 27.2 dB

Acquisition

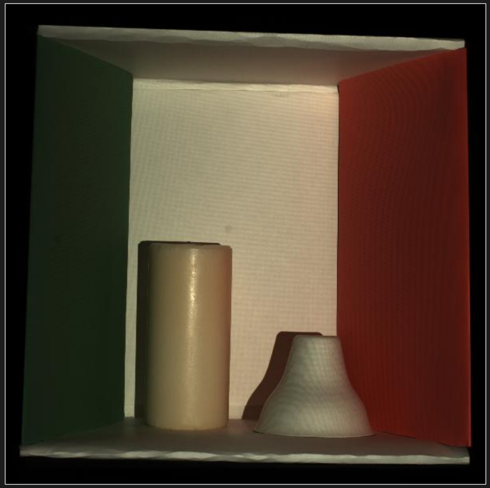
Acquire 360000 x 16384 matrix with 1060 patterns

Original

Reconstructed

SNR = 24.7 dB

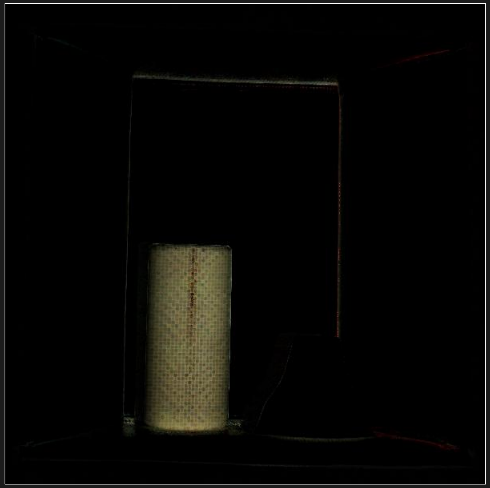
Decomposition



Reconstructed

Direct

+



Near

+

Far

Decomposition

Reconstructed

Direct

+

Near

+

Far

Contributions

Decompose light transport into physical components

– Direct, Near Range (subsurface), Far (interreflections)

Efficiently acquire the component transports

- Varying bandwidth in projector's frequency-space
- Use minimal number proposed by the model

Acquisition and storage

- Distant illumination:
  - transport matrix is locally low-rank
  - Fuchs et al. 2007, Peers et al. 2009
  - Wang et al. 2009, O'Toole et al. 2010
- Spatially varying illumination
  - brute force, ignores diffuse inter-reflections
  - Masselus et al. 2003,
  - Sen et al. 2005, Garg et al. 2006

Decomposition

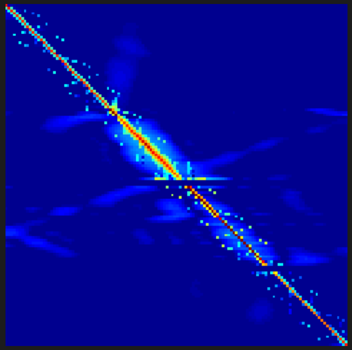
- Direct global separation
  - Nayar et al. 2006
  - separates floodlit images, not light transport
- Component separation
  - O' Toole et al. 2012
  - iterative process for a single image

Acquisition & Decomposition

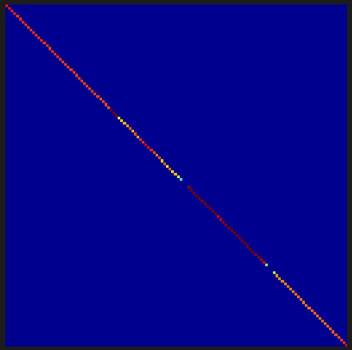
Transport model

Direct : single bounce (mainly)

- Diagonal matrix, large magnitude



T



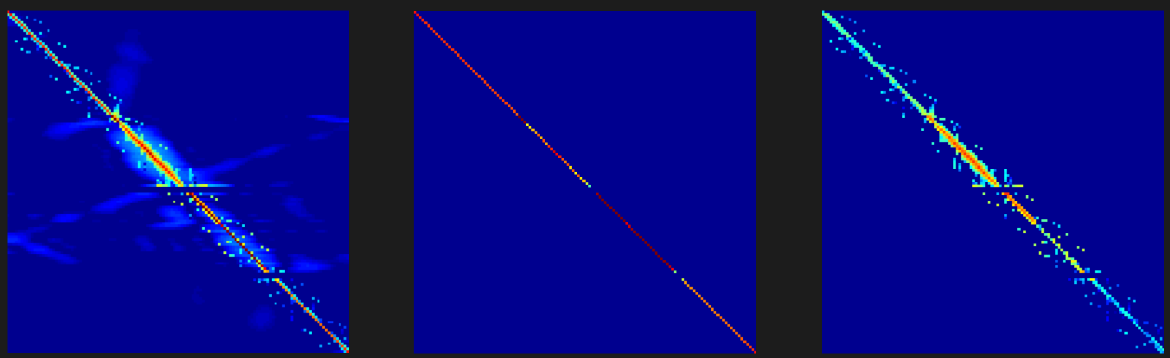
Direct

D

Transport model

Near-range: subsurface effects, local interreflection

- Banded diagonal matrix, sparse



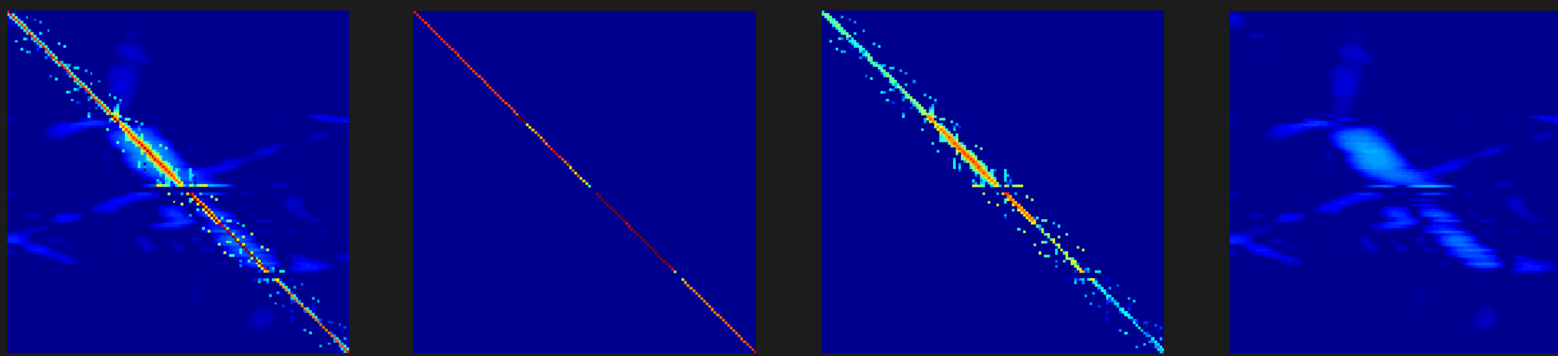
Direct Near-range

T D + N

Transport model

Far-range: diffuse interreflection

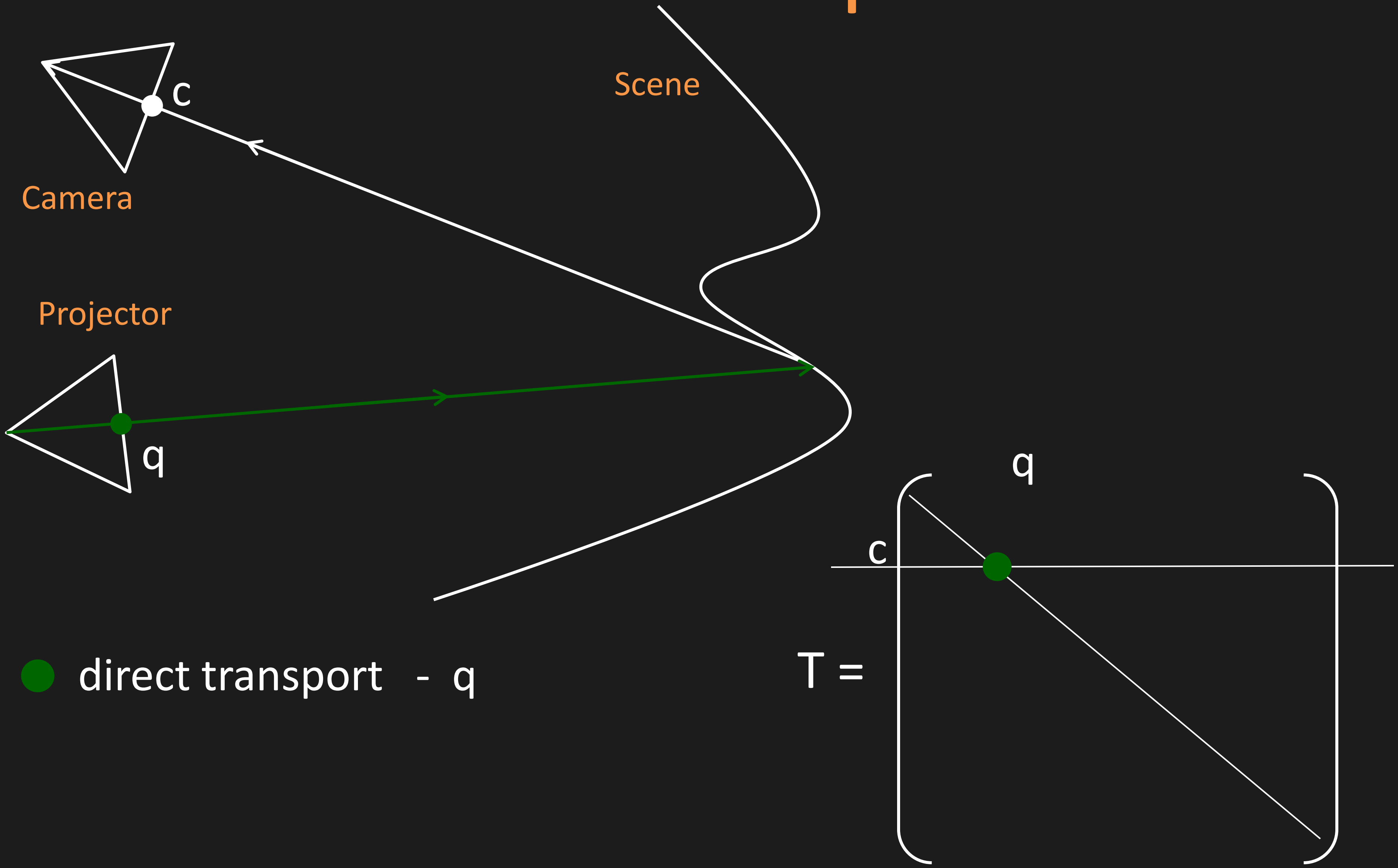
- Dense, small magnitude, low frequency



Direct Near-range Far-range

$$T = D + N + F$$

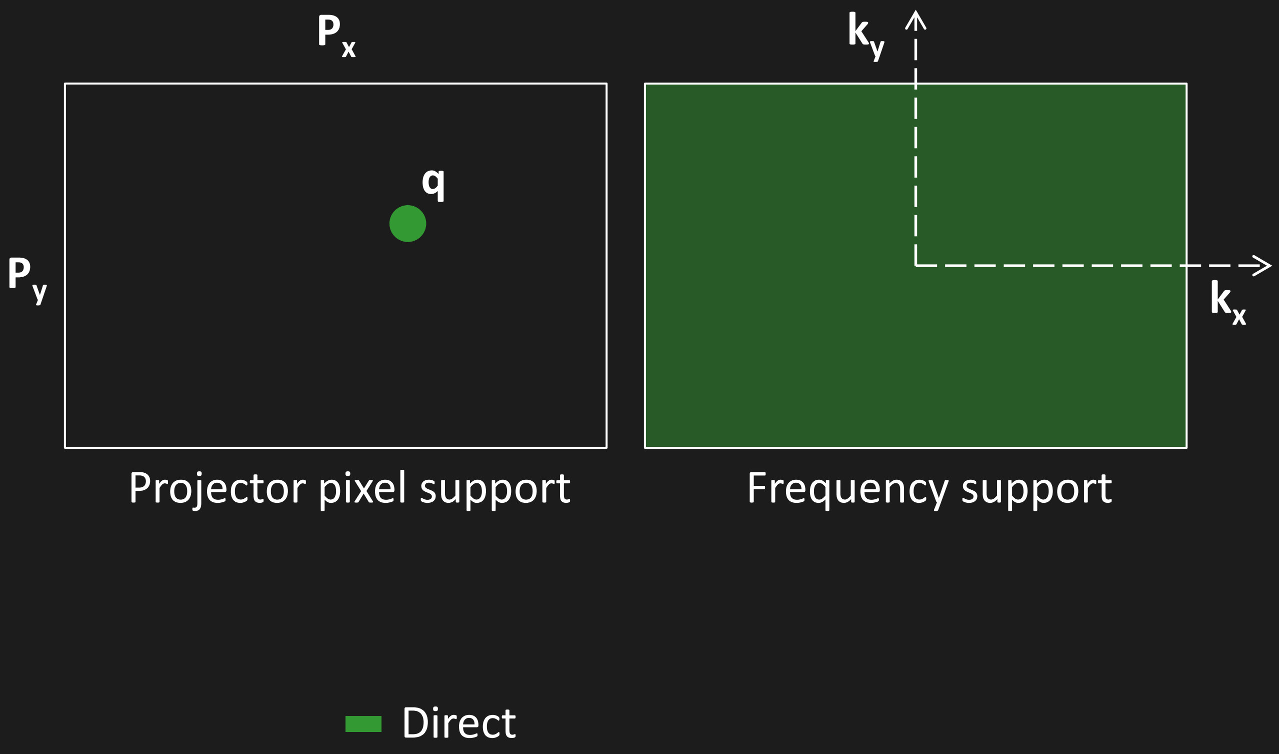
Direct transport



direct transport - q

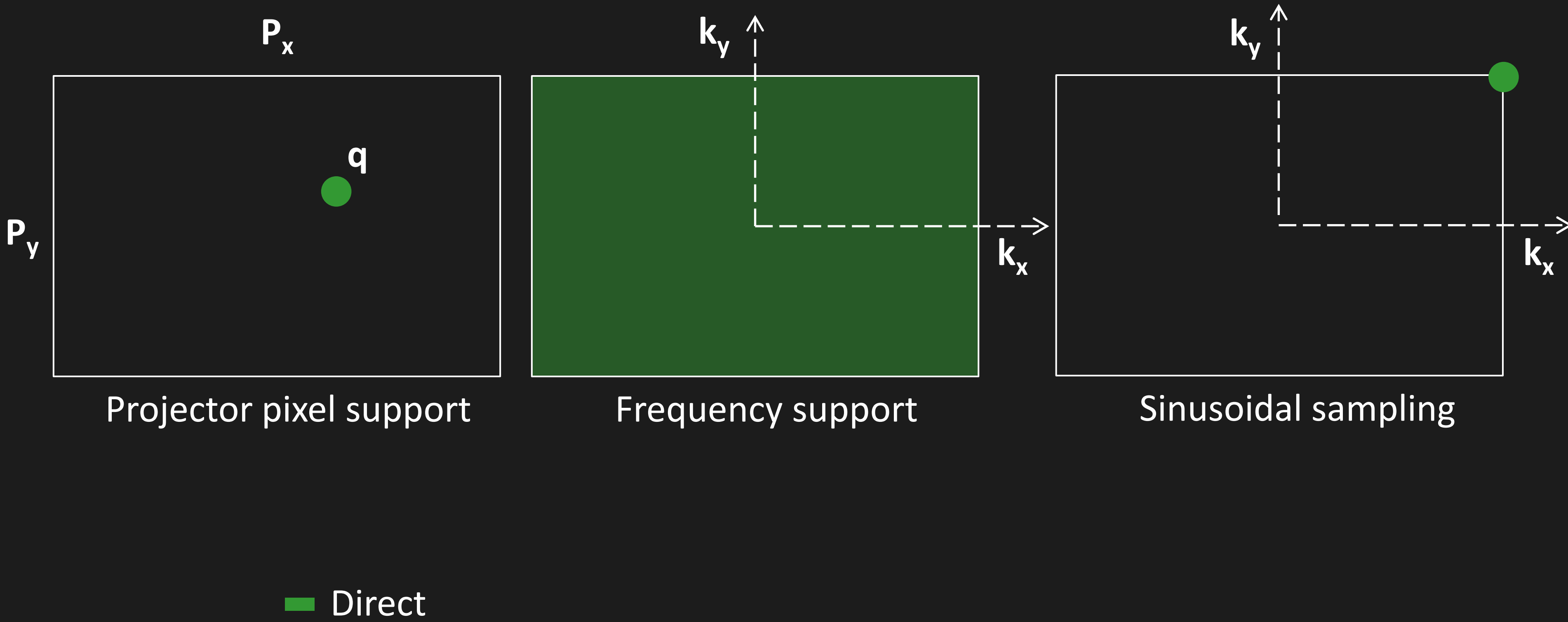
Direct transport

Localized in space – 1 unknown at each camera pixel



Direct transport

1 high-freq. sinusoidal pattern



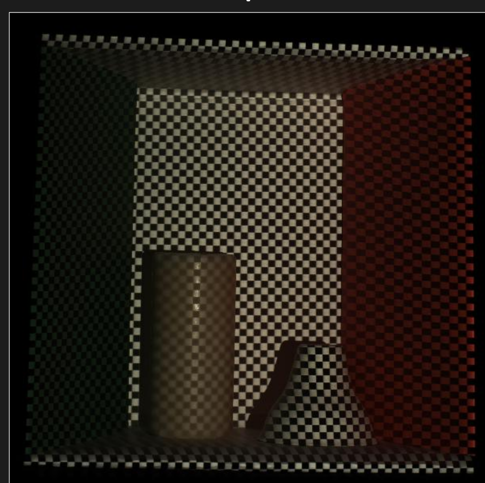
Direct transport

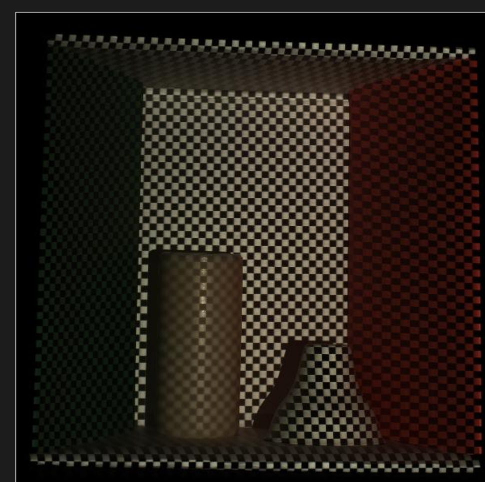
I_+ I_-

Projector pattern

b_+ b_-

Camera image





Direct transport

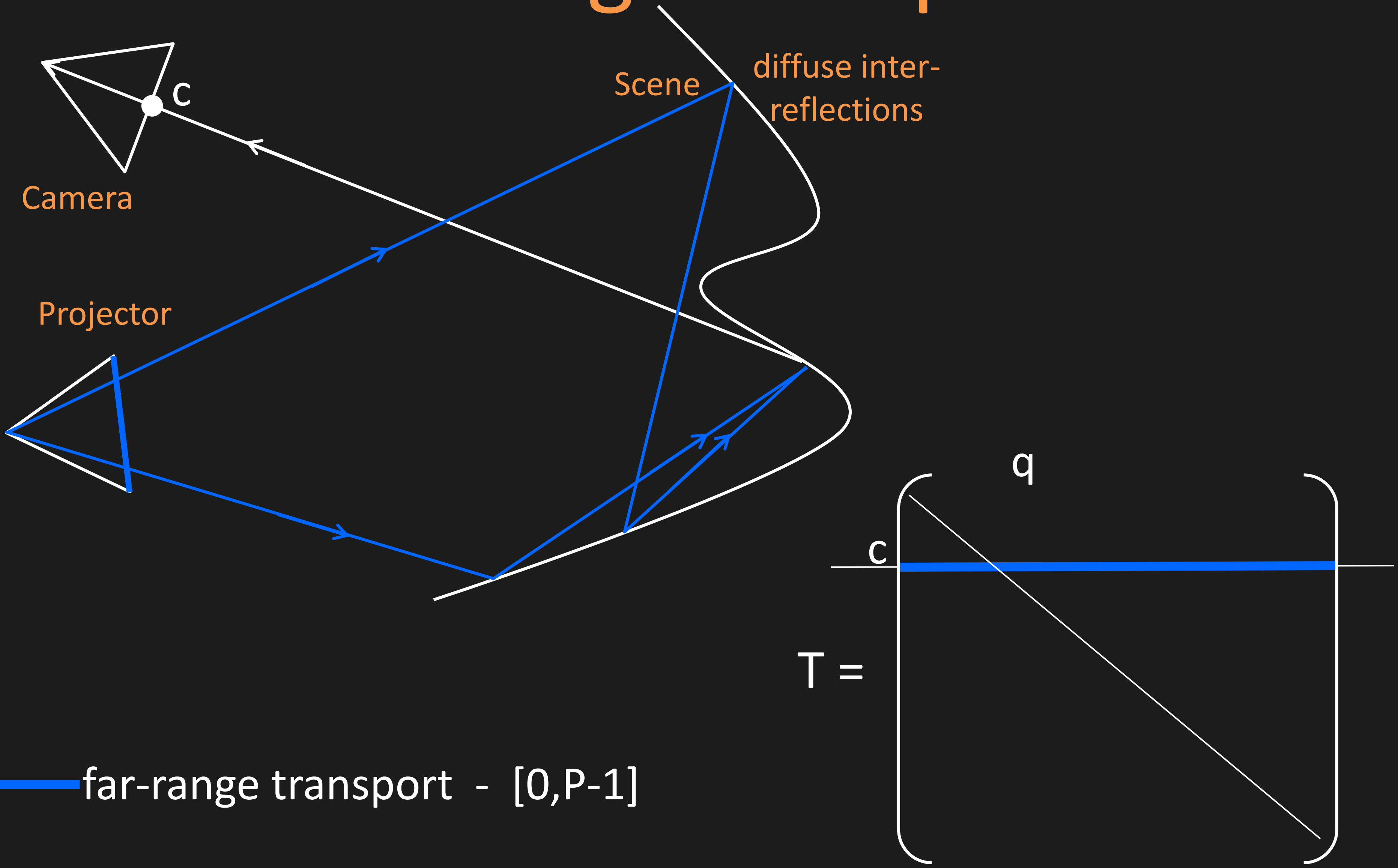
$$\frac{b_+ - b_-}{l_+ - l_-}$$

Compute

Direct

Global

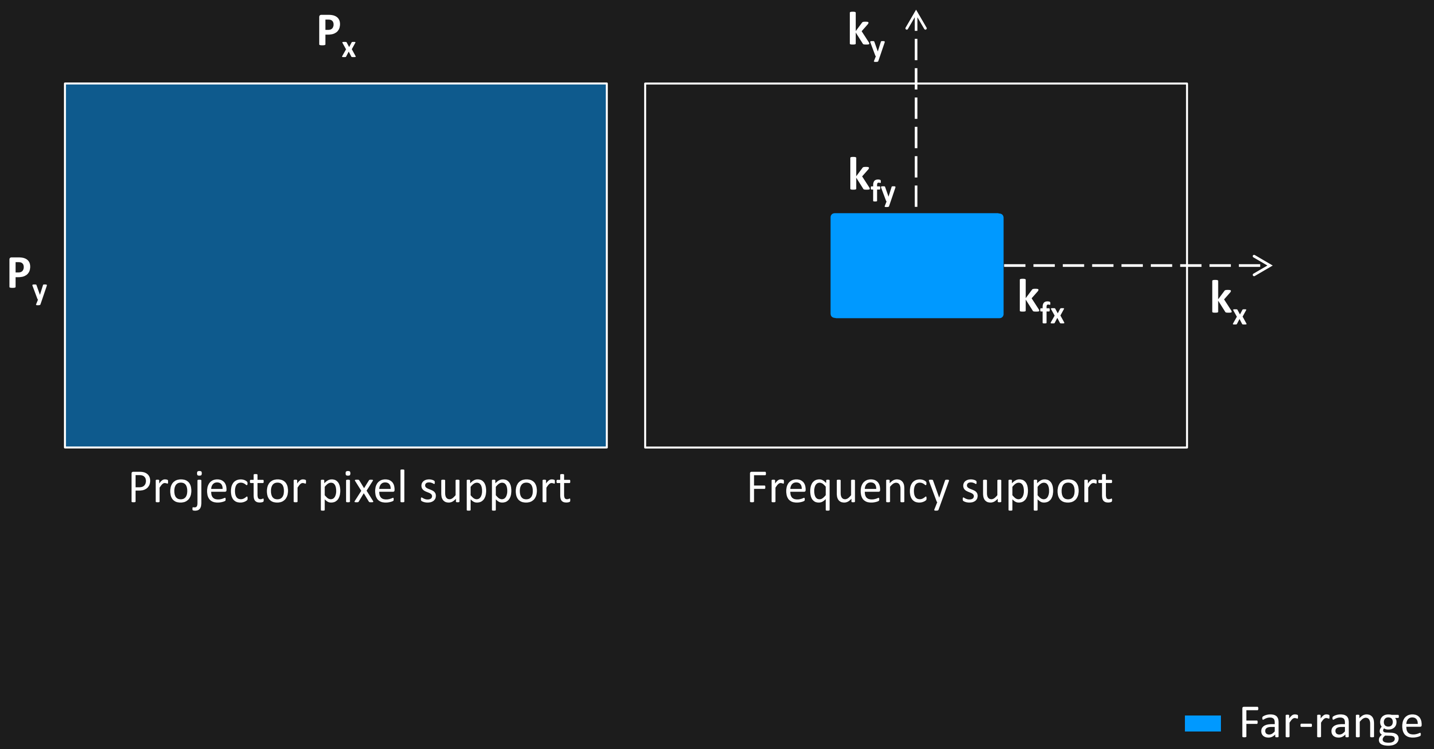
Far-range transport



far-range transport - [0,P-1]

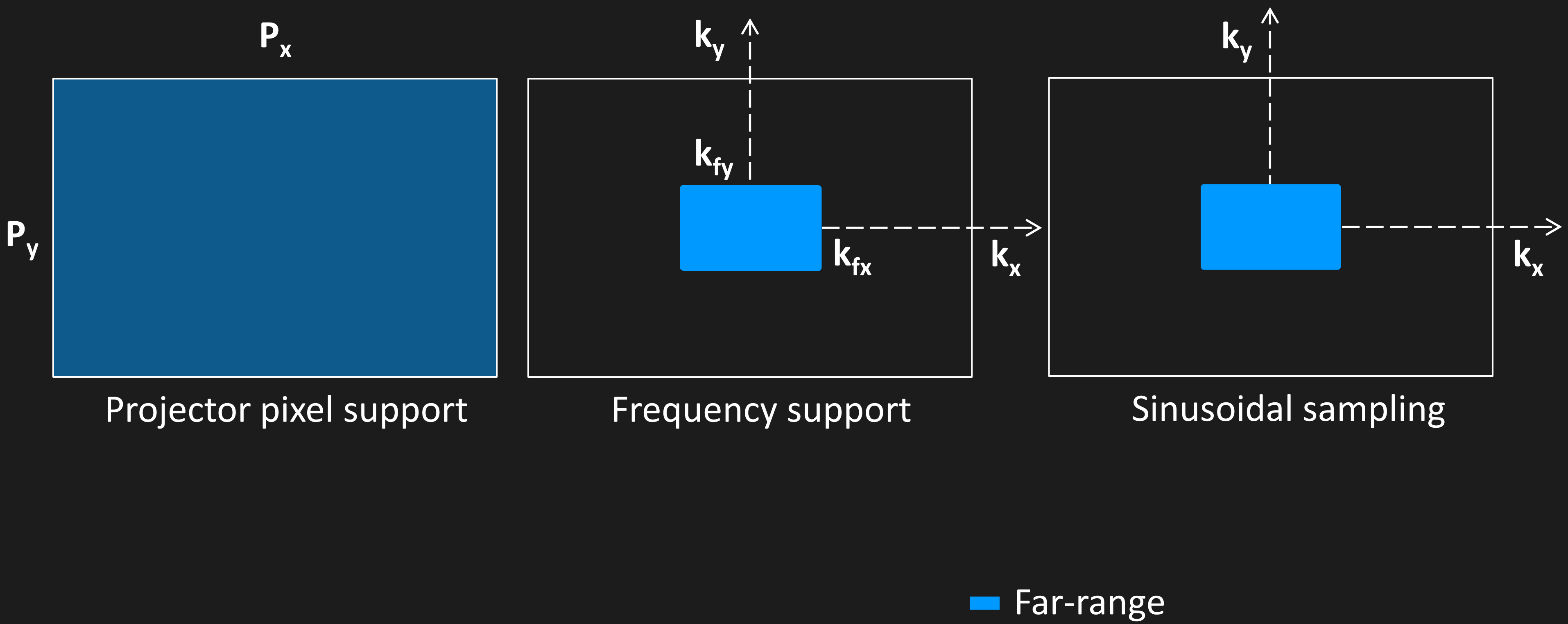
Far-range transport

Localized in frequency – $4k_{fx}k_{fy}$ unknowns



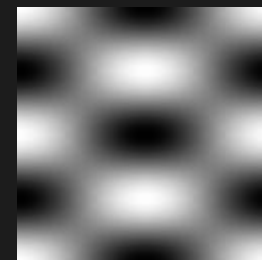
Far-range transport

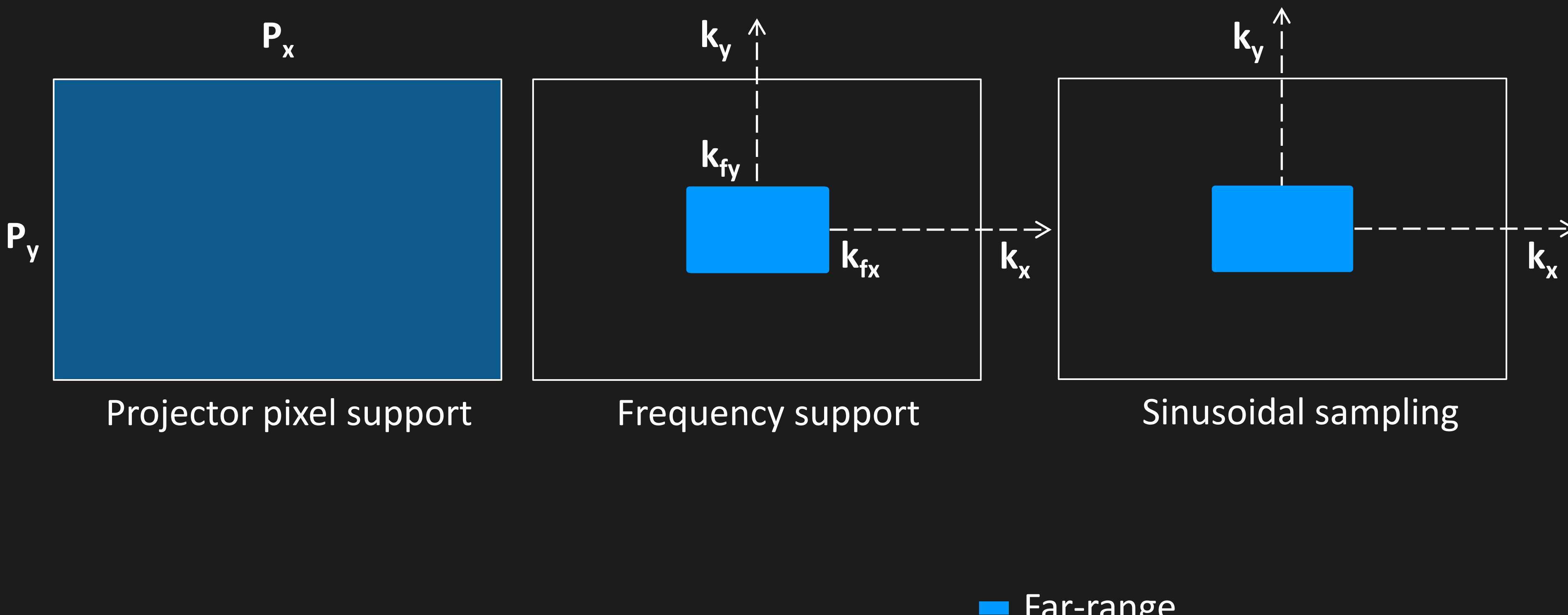
Use all $4k_{fx}k_{fy}$ sinusoidal patterns for measurement



Far-range transport

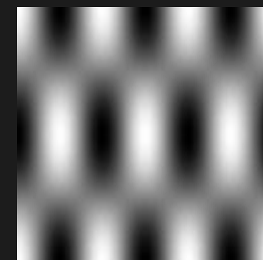
Example pattern

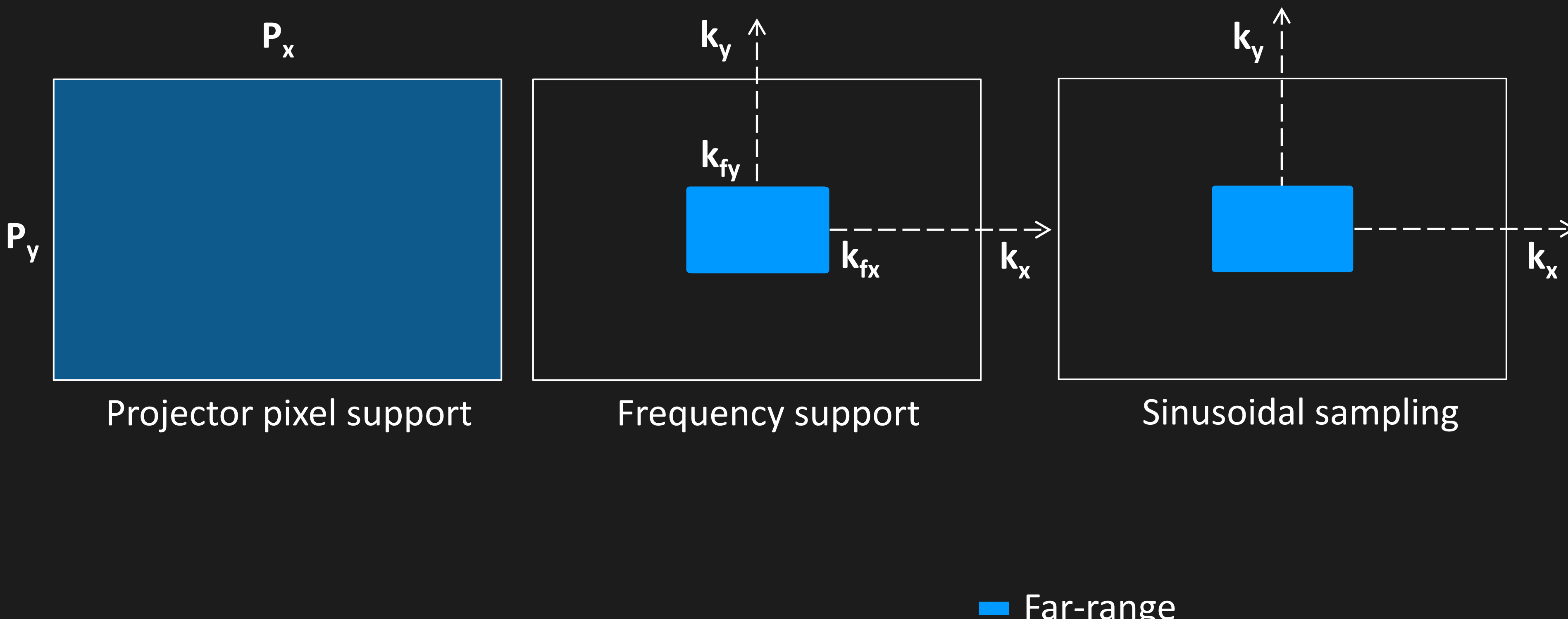




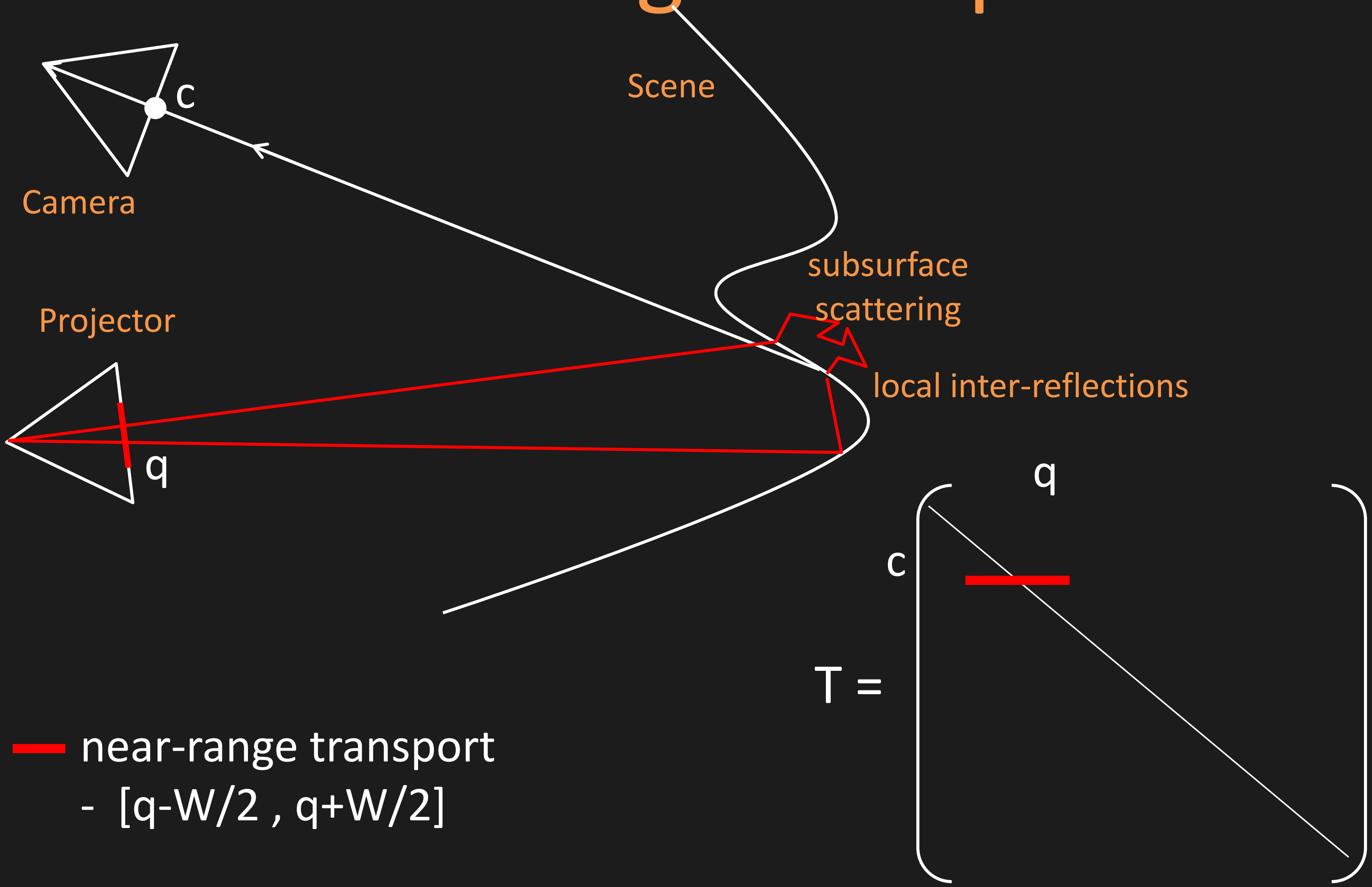
Far-range transport

Example pattern





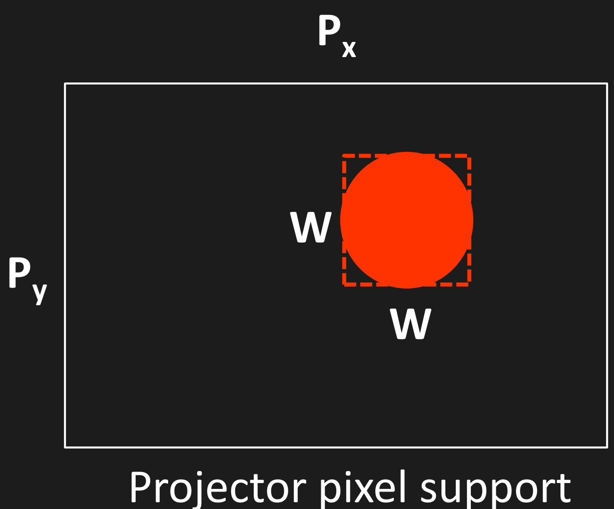
Near-range transport

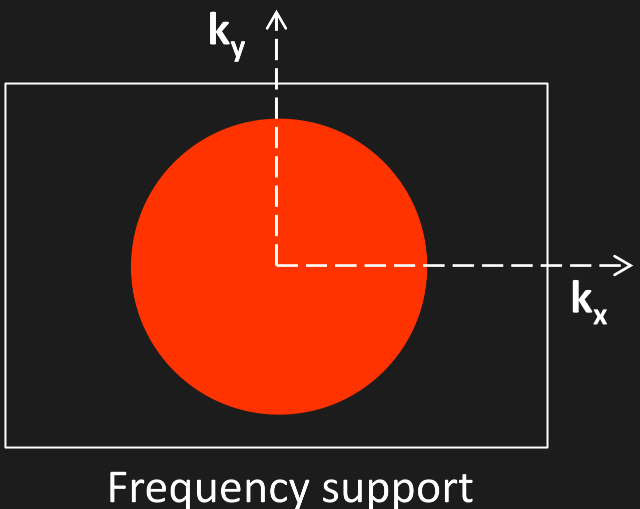


near-range transport
- [q-W/2 , q+W/2]

Near-range transport

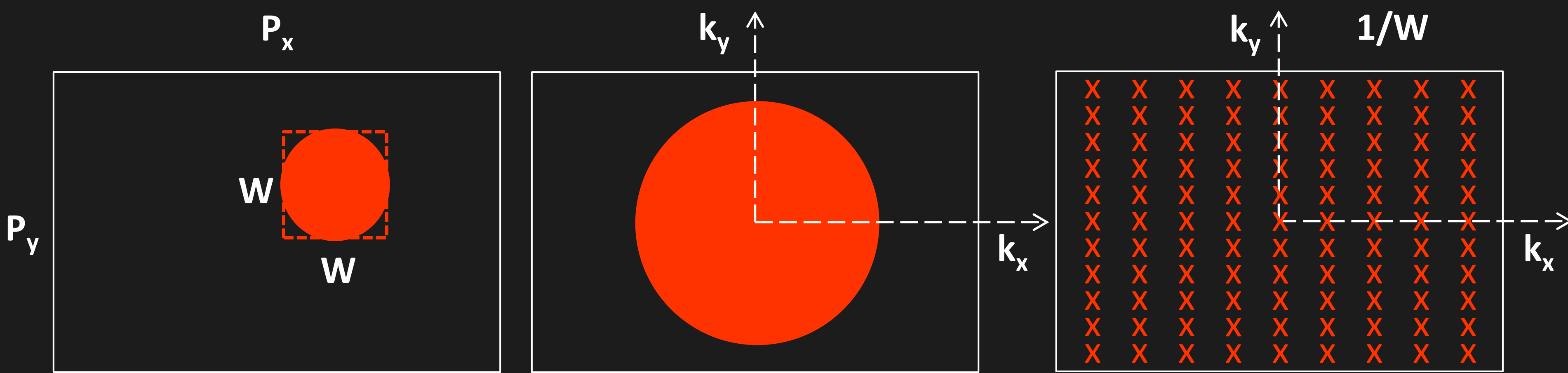
W^2 unknowns at each camera pixel





Near-range transport

W^2 sinusoidal patterns placed 1/W apart



Projector pixel support

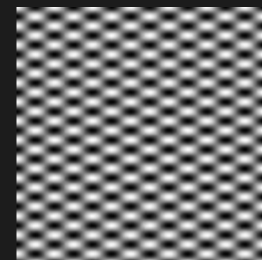
Frequency support

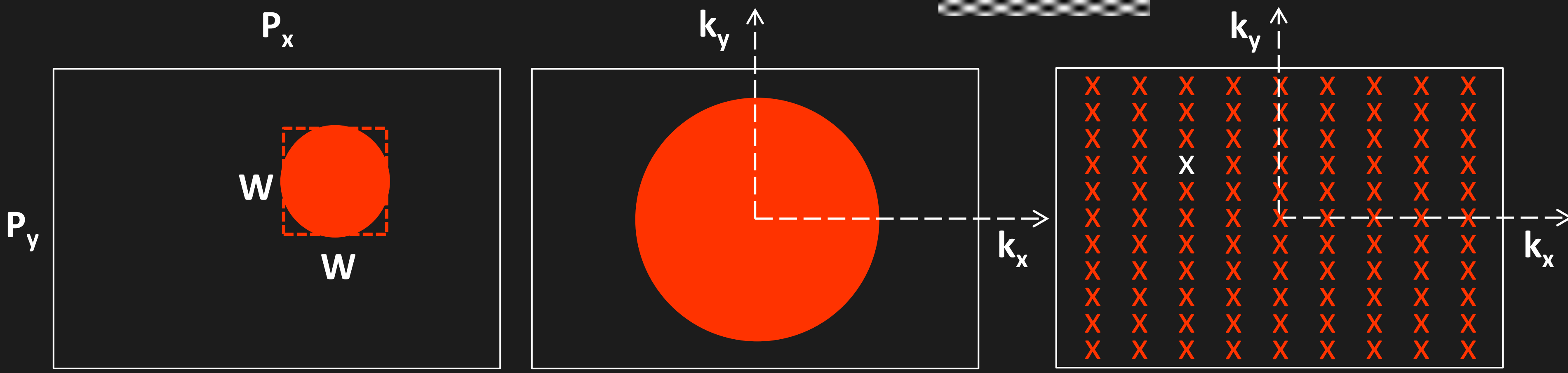
Sinusoidal sampling

Near-range

Near-range transport

Example pattern





Projector pixel support

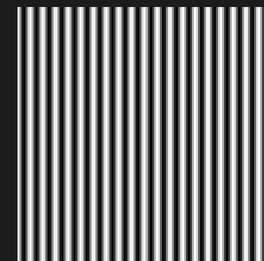
Frequency support

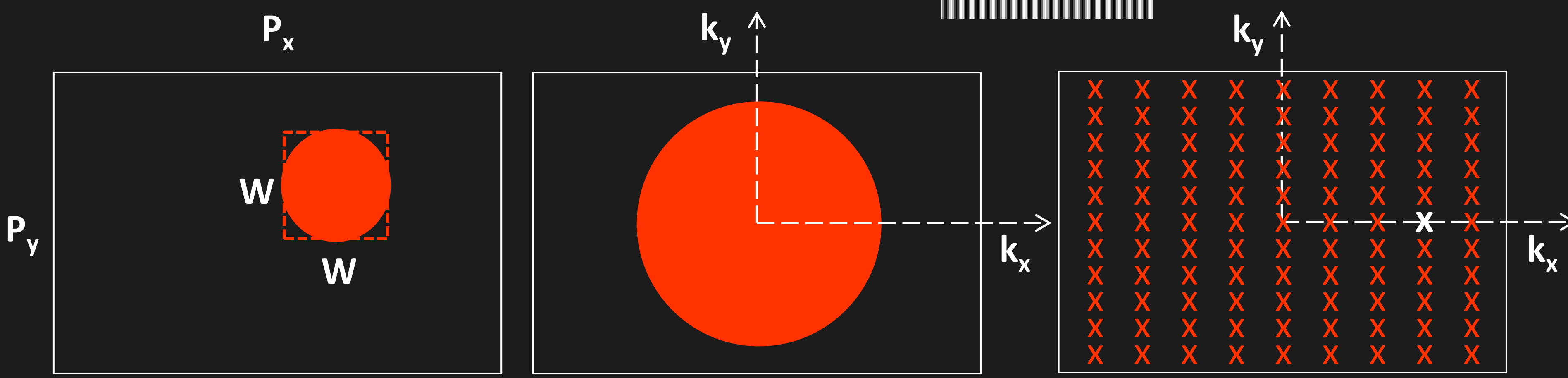
Sinusoidal sampling

Near-range

Near-range transport

Example pattern





Projector pixel support

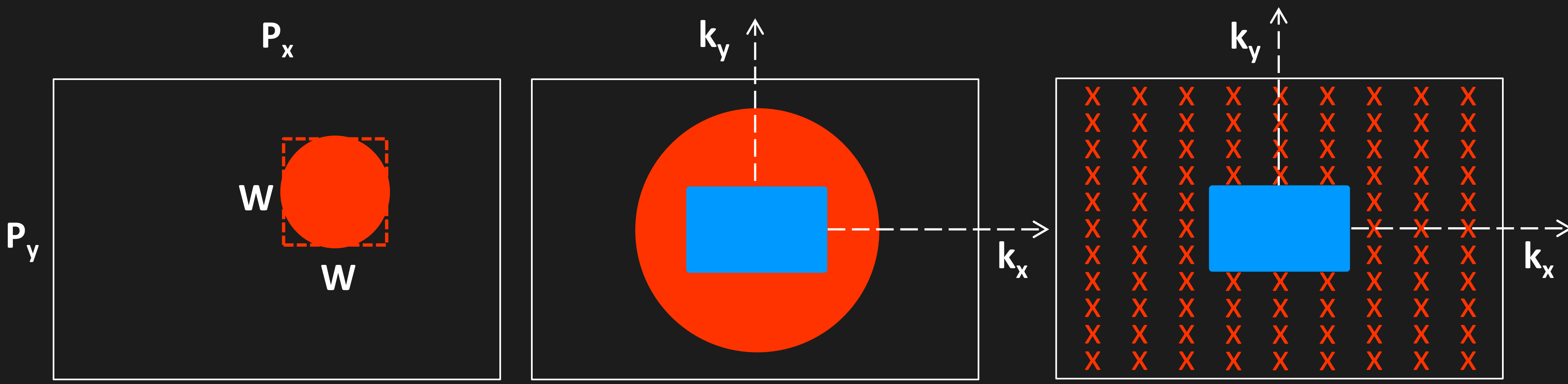
Frequency support

Sinusoidal sampling

Near-range

Far-range interference

Overlap of few patterns with far-range bandwidth



Projector pixel support

Frequency support

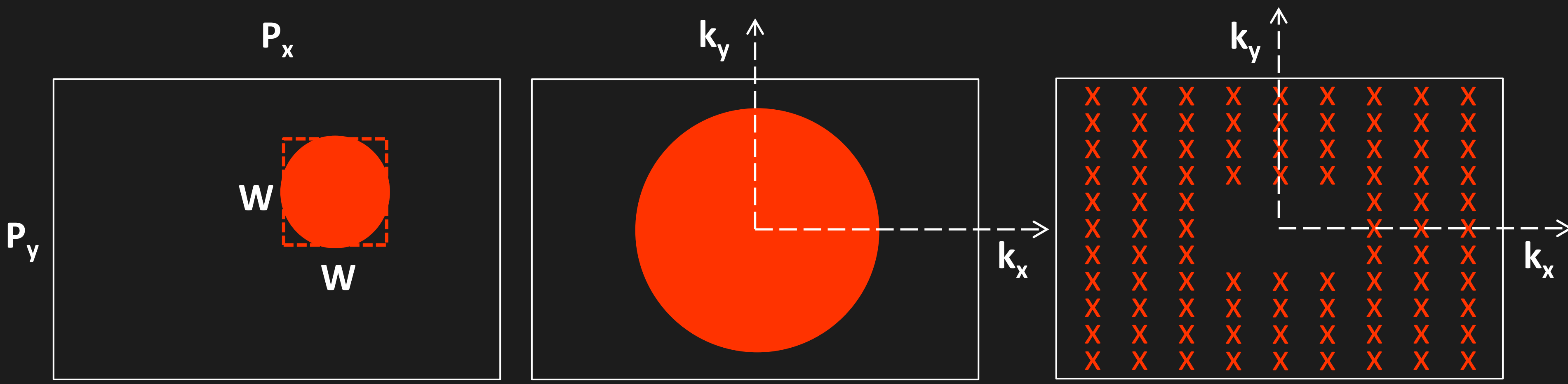
Sinusoidal sampling

Near-range

Far-range

Near-range measurements

Drop such sinusoidal patterns

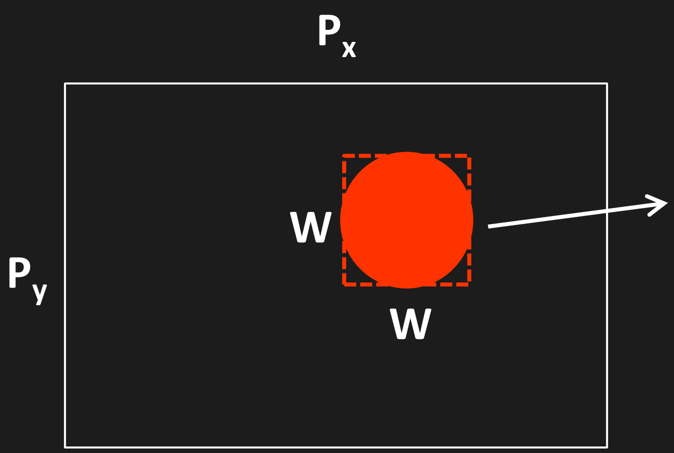


Projector pixel support   Frequency support   Sinusoidal sampling

Near-range

Sparsity prior

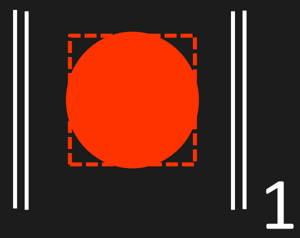
System of equations is underdetermined



Projector pixel support

sparse and has a long tail distribution

min

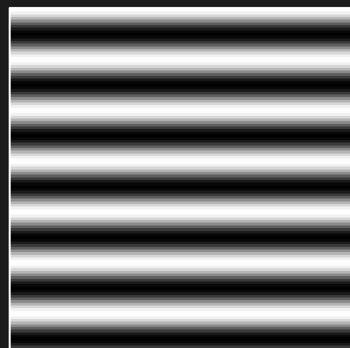


Near-range

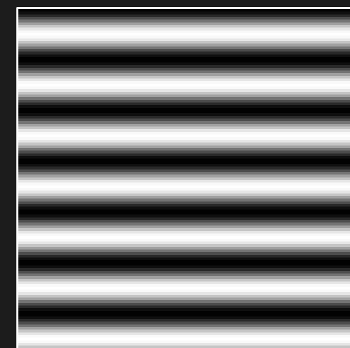
Near-range transport

Projector pattern

I_+



I_-

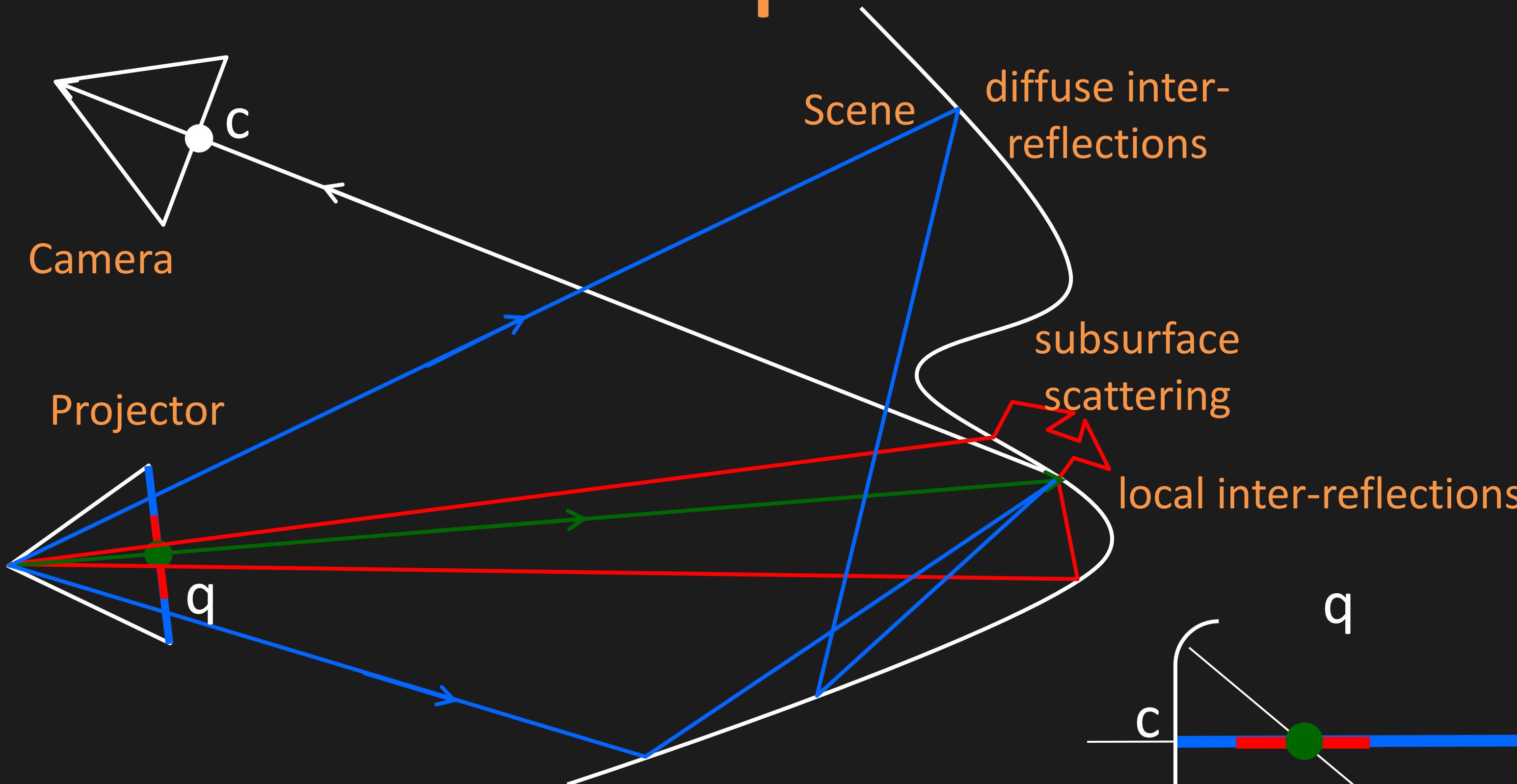


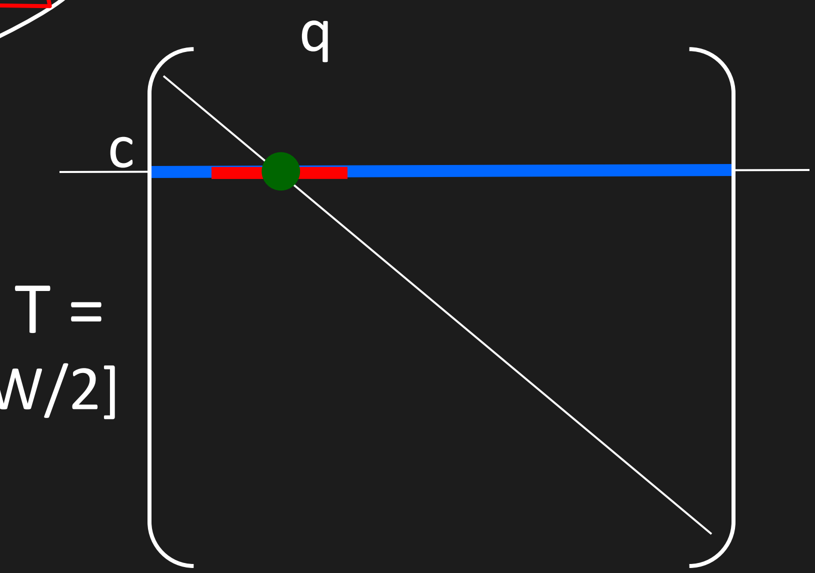
Camera image

b_+

b_-

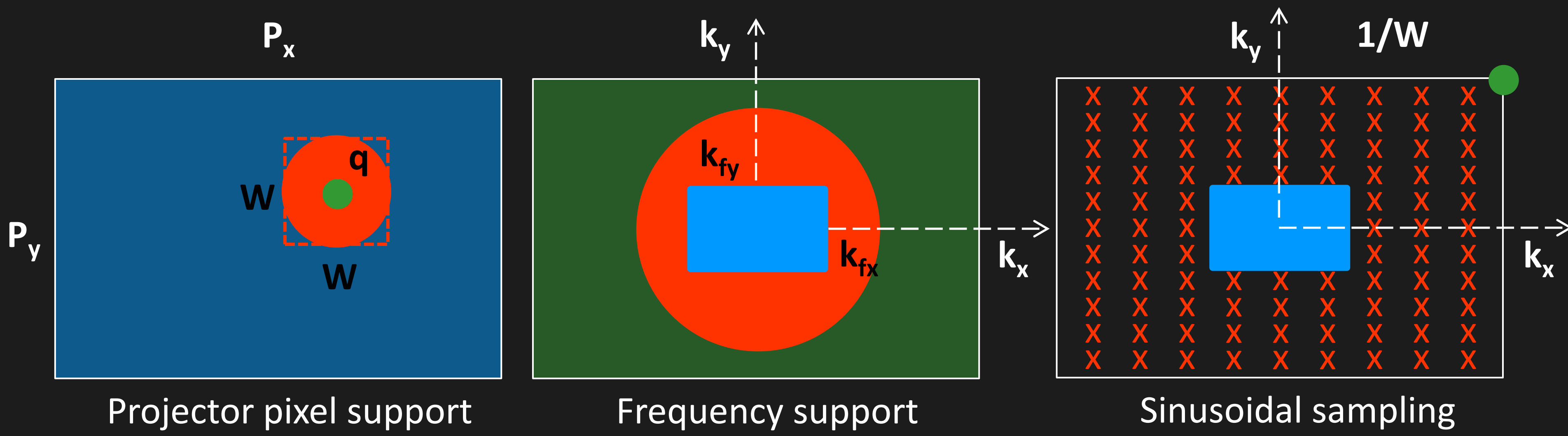
Transport model





- direct transport - q
- near-range transport - [q-W/2 , q+W/2]
- far-range transport - [0,P-1]

Frequency-space

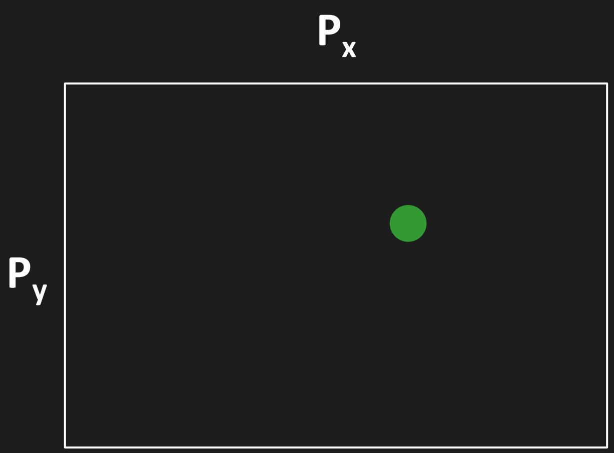


Direct   Near-range   Far-range

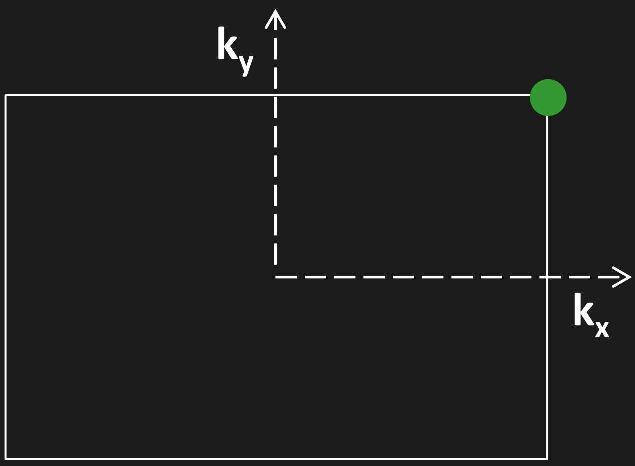
Number of measurements: Direct

1 unknown

1 pattern sufficient



Projector pixel support



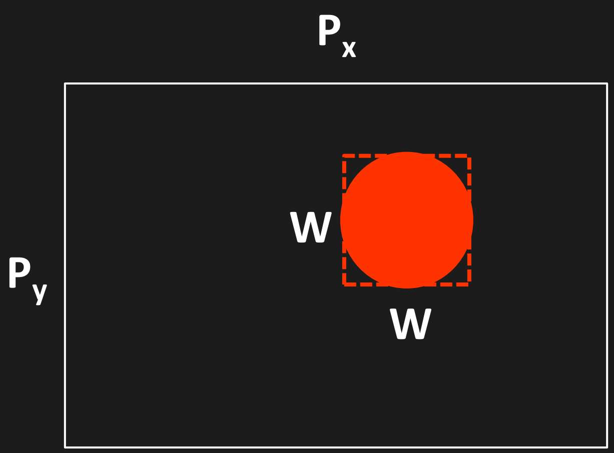
Sinusoidal sampling

Direct

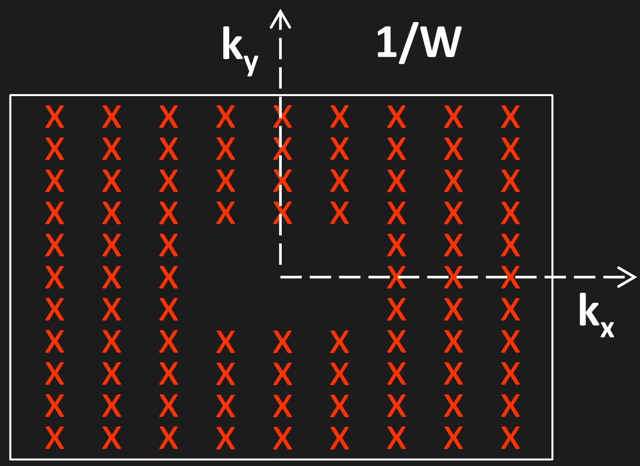
Number of measurements: Near

W^2 unknowns.

Less than W^2 patterns sufficient



Projector pixel support



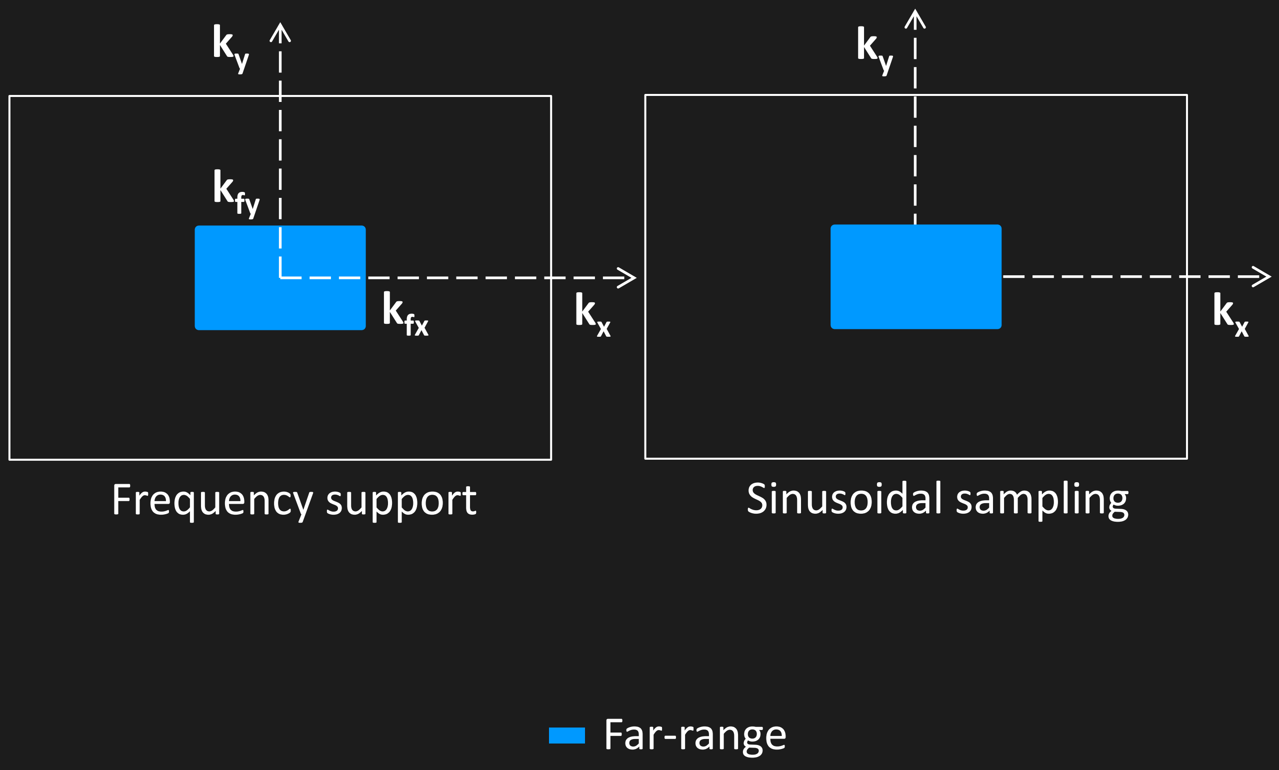
Sinusoidal sampling

Near-range

Number of measurements: Far

$4k_{fx}k_{fy}$ unknowns.

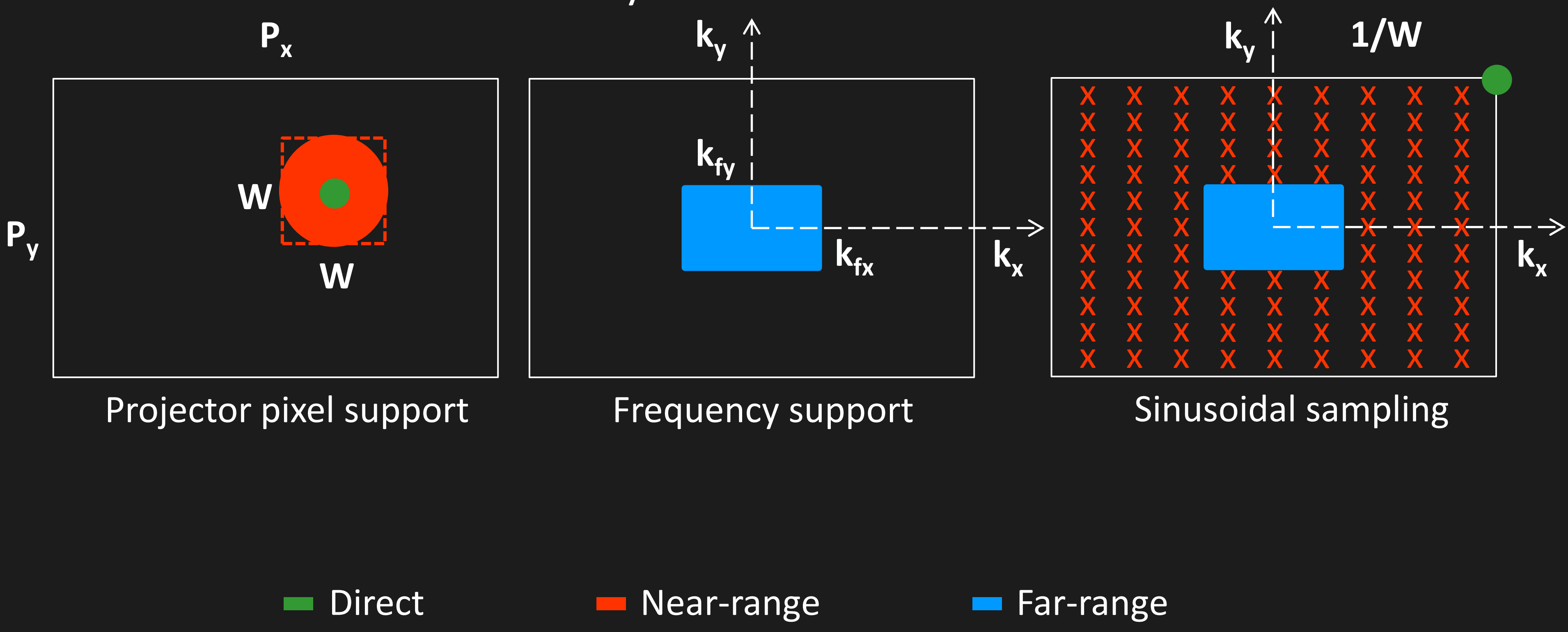
$4k_{fx}k_{fy}$ patterns sufficient



Number of measurements: All

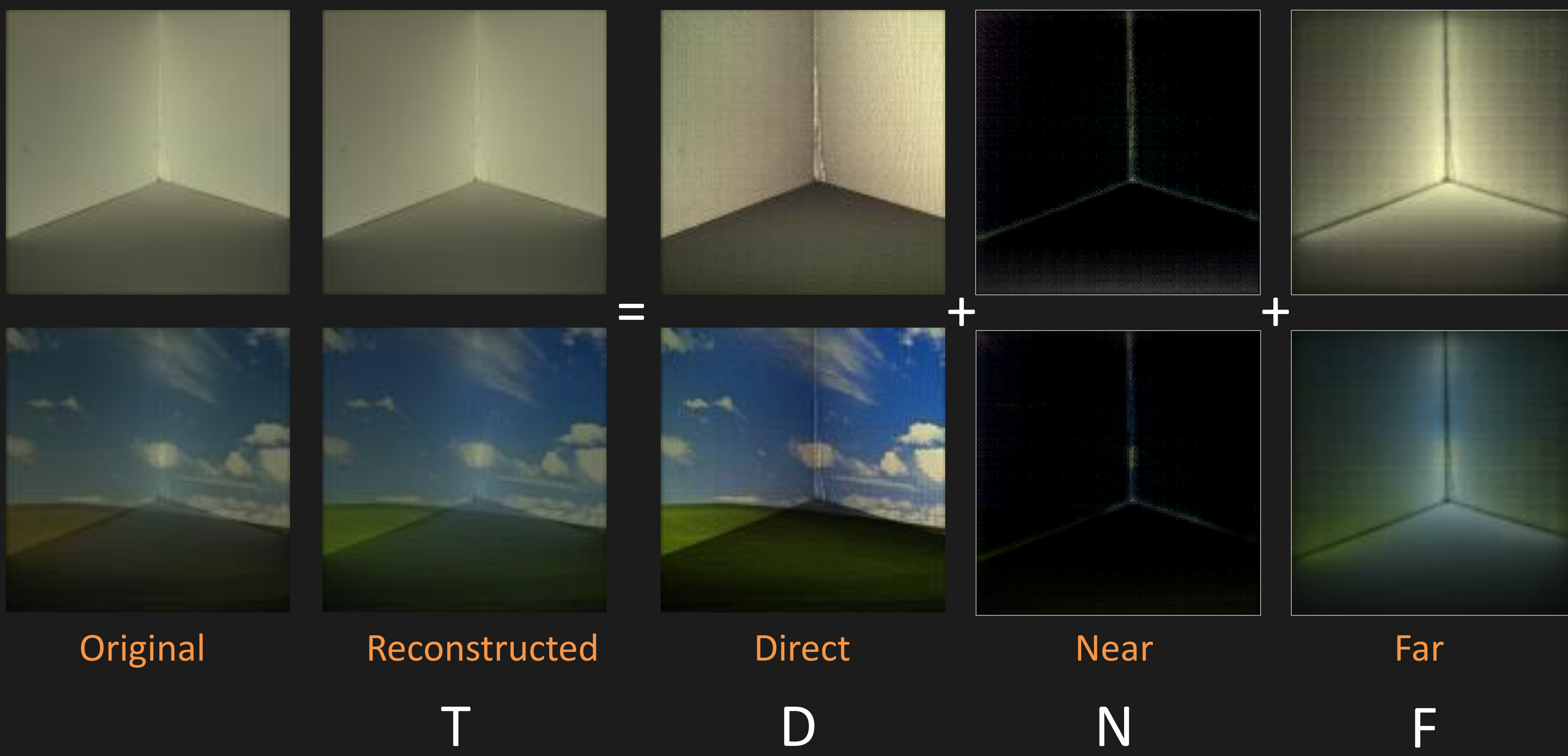
$1 + 4k_{fx}k_{fy} + W^2$ unknowns.

Less than $1 + 4k_{fx}k_{fy} + W^2$ patterns sufficient

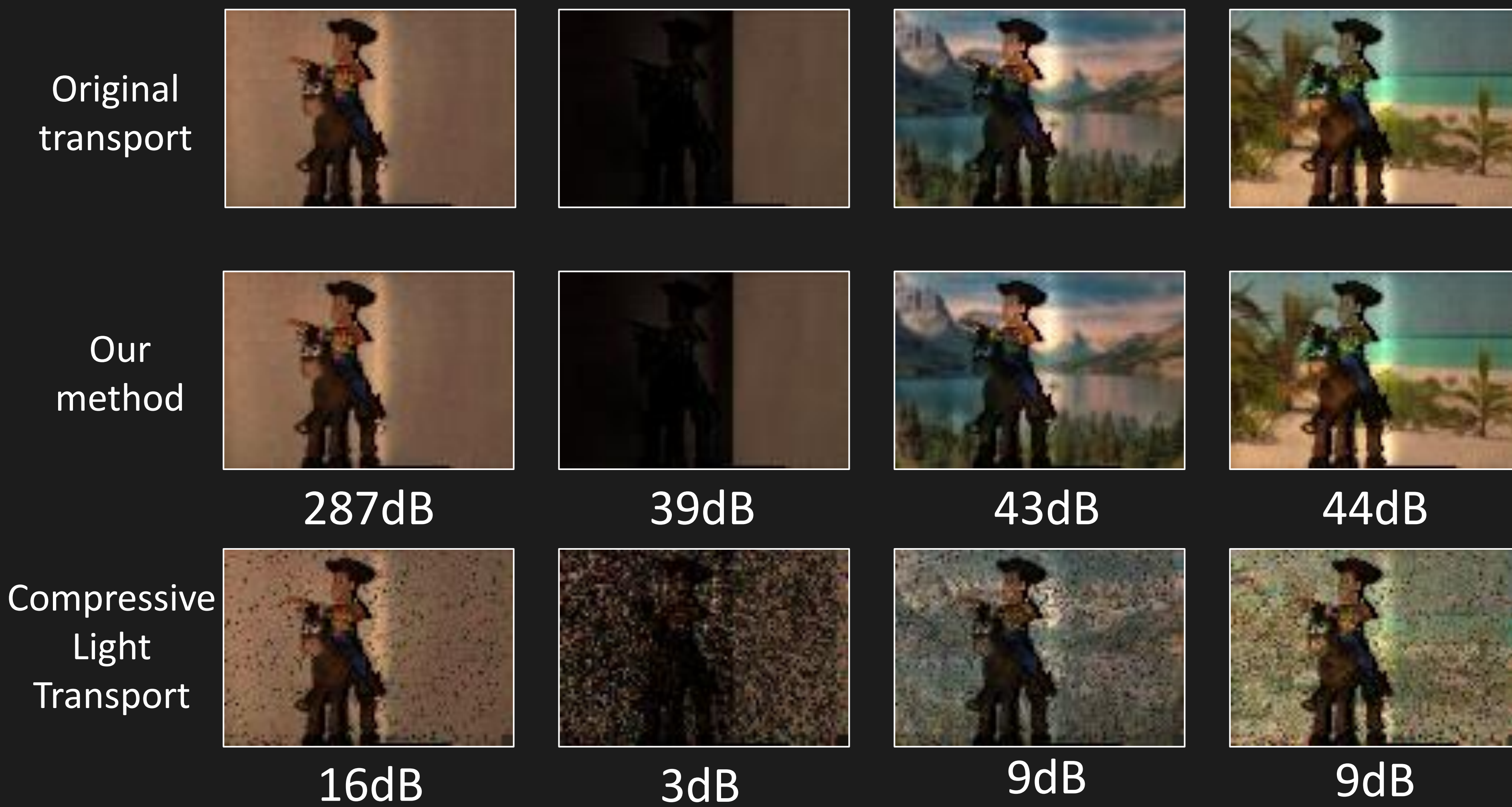


Results

Acquire 16384 x 16384 matrix with 788 patterns



Comparisons



Limitations

Projector-camera correspondence

- Currently a preprocessing step
- Joint correspondence and transport estimation
- Tough for specular objects

Diffuse scenes

- Works well for diffuse scenes
- Specular and transparent scenes don't follow low-frequency interreflections

Conclusions

Decomposition of transport

- Separates physically meaningful components
- Simple compact model for direct, near, far

Efficient acquisition of transport

- Simple projector-camera setup
- Close to optimal number of patterns

Thank you