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A Frequency Analysis of Light Transport

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Illumination effects

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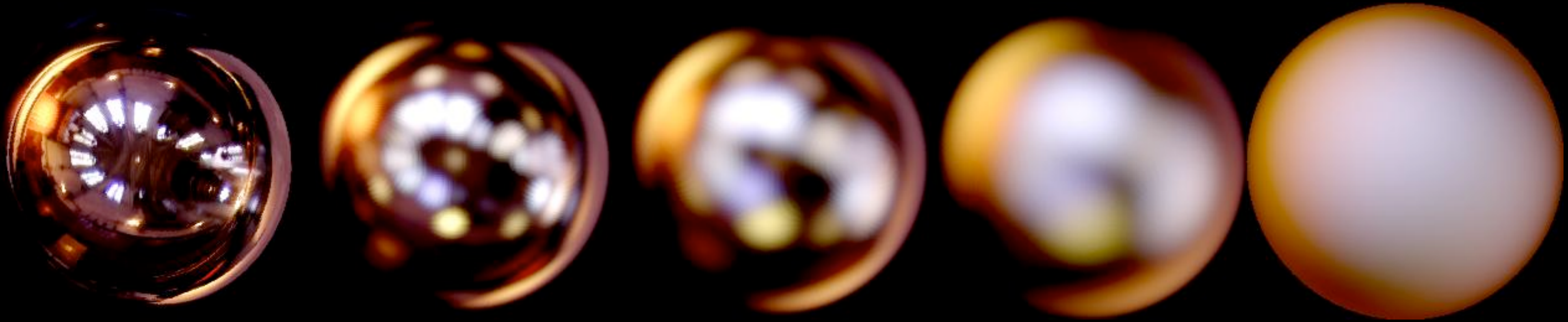
- Blurry reflections:



From [Ramamoorthi and Hanrahan 2001]

Illumination effects

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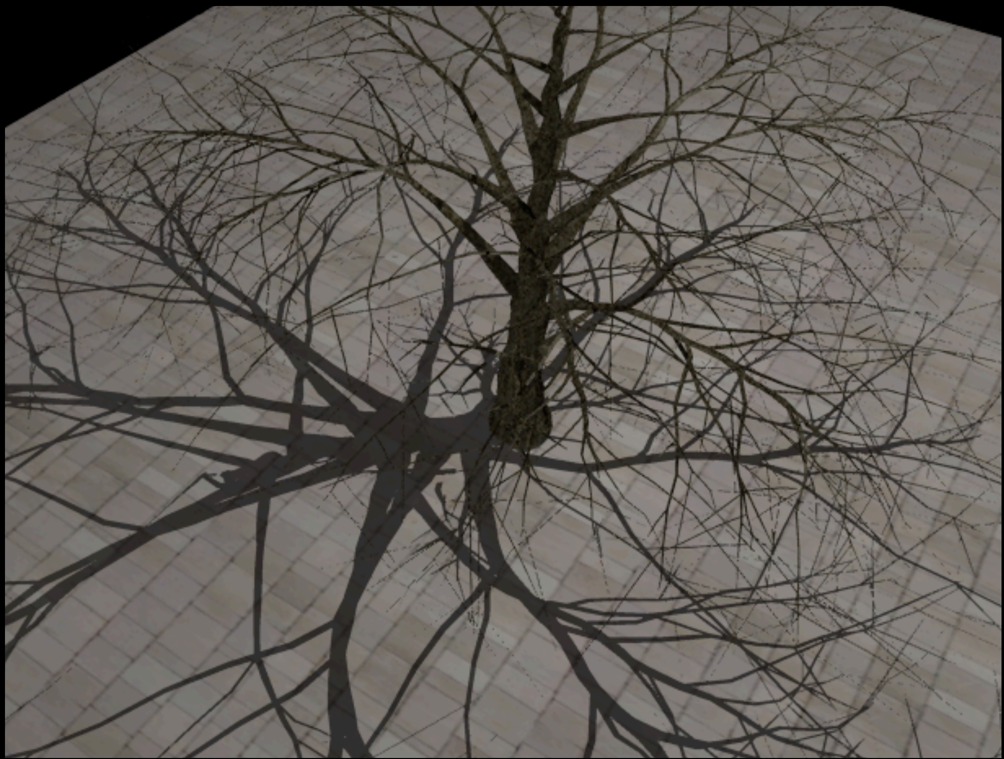
- Shadow boundaries:



Point light source

Area light source

Illumination effects

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- Indirect lighting is usually blurry:

Complete lighting

Illumination effects

- Indirect lighting is usually blurry:

Direct lighting only

Indirect lighting only

Frequency aspects of light transport

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- Blurriness = frequency content
  - Sharp variations: high frequency
  - Smooth variations: low frequency
- All effects are expressed as frequency content:
  - Diffuse shading: low frequency
  - Shadows: introduce high frequencies
  - Indirect lighting: tends to be low frequency

Problem statement

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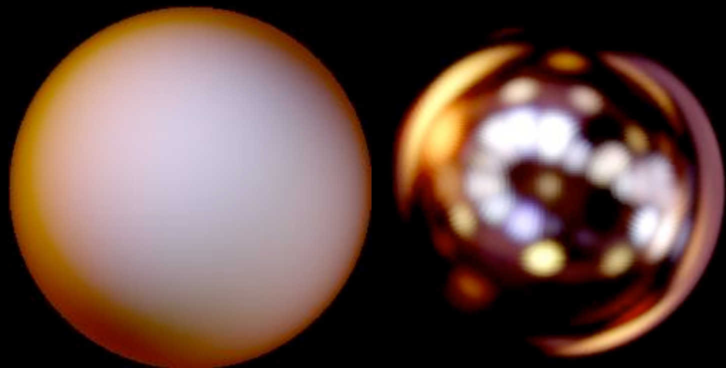
- How does light interaction in a scene explain the frequency content?
- Theoretical framework:
  – Understand the frequency spectrum of the radiance function
  – From equations of light transport

Unified framework:

- Spatial frequency
  (e.g. shadows, textures)

- Angular frequency
  (e.g. blurry highlight)



Disclaimer: not Fourier optics

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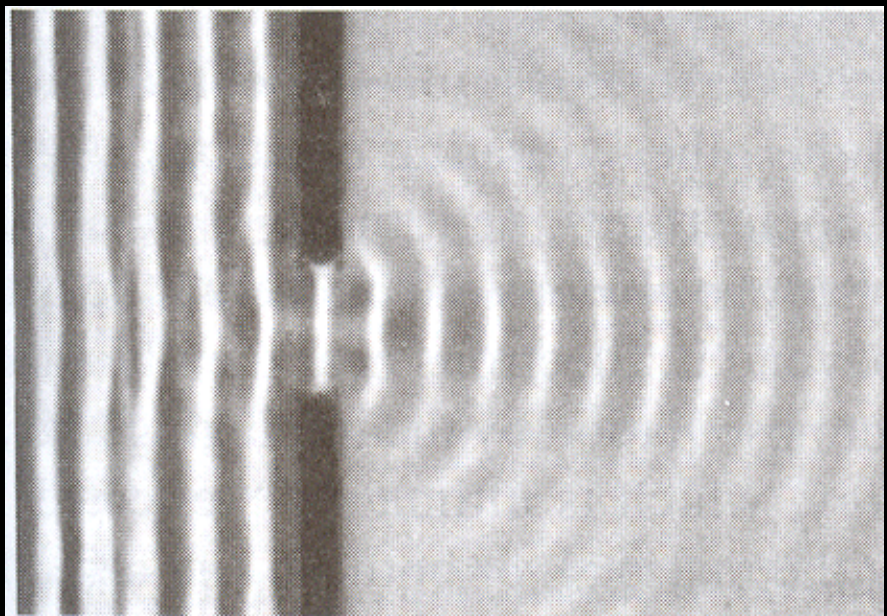
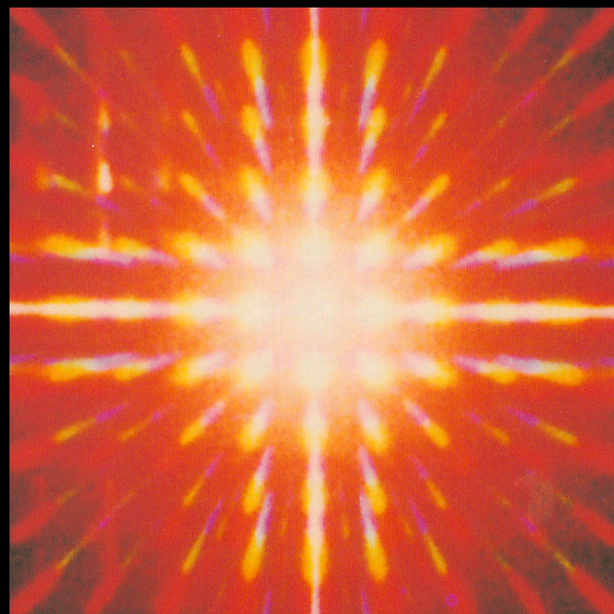
- We do **not** consider wave optics, interference, diffraction
- Only geometrical optics

From [Hecht]





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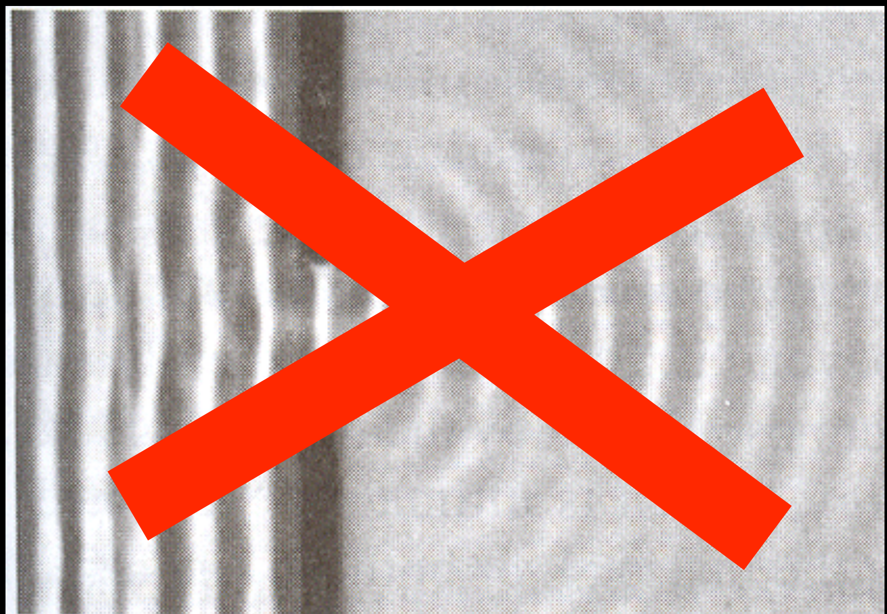

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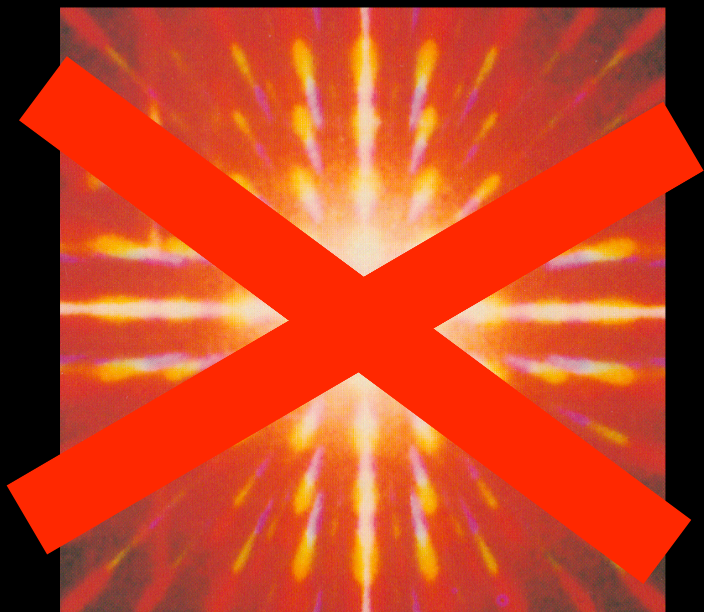

Overview

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- Previous work
- Our approach:
  - Local light field
  - Transformations on local light field
- Case studies:
  - Diffuse soft shadows
  - Adaptive shading sampling
- Conclusions and future directions

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Previous work

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- Vast body of literature:
  - Light field sampling
  - Perceptually-based rendering
  - Wavelets for Computer Graphics
  - Irradiance caching
  - Photon mapping
  - …
- We focus on frequency analysis in graphics:
  - Light field sampling
  - Reflection as a convolution

Light field sampling

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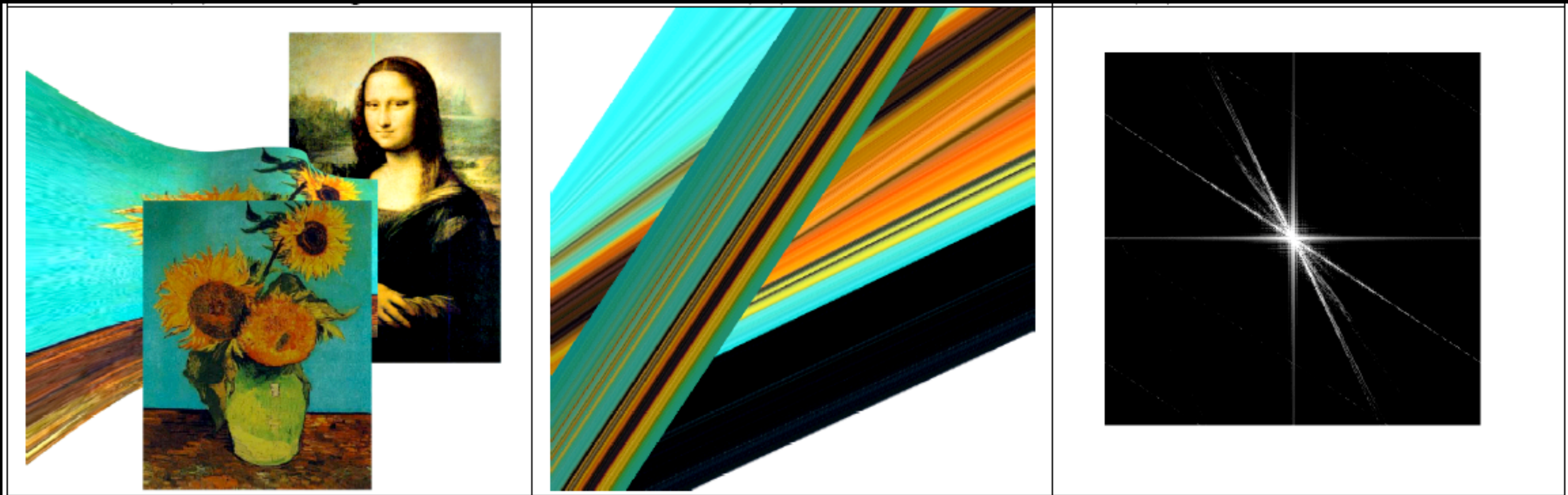
[Chai et al. 00, Isaksen et al. 00, Stewart et al. 03]

– Light field spectrum as a function of object distance
– No BRDF, occlusion ignored



(d1)Scene image | (d2) EPI | (d3) Fourier transform of EPI

From [Chai et al. 2000]

Signal processing for reflection

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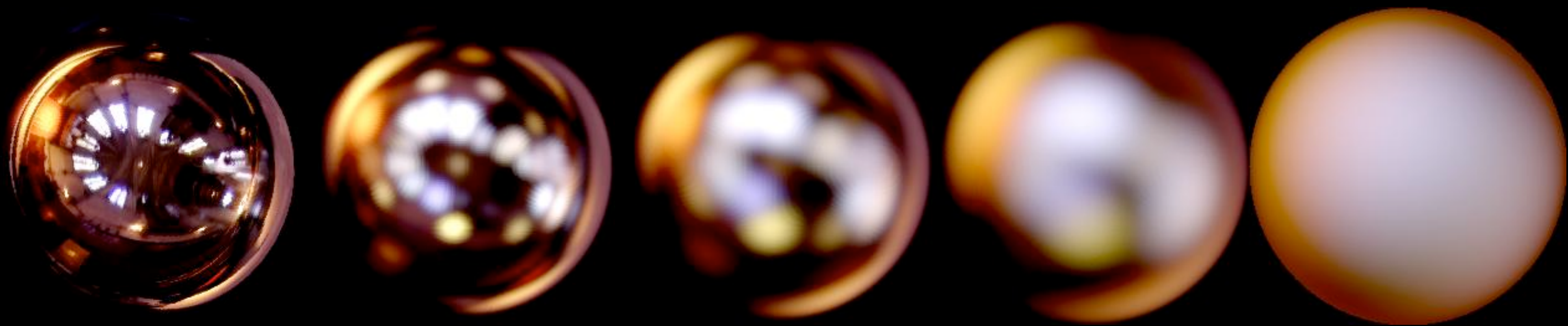
[Ramamoorthi & Hanrahan 01, Basri & Jacobs 03]

- Reflection on a curved surface is a convolution
- Direction only



From [Ramamoorthi and Hanrahan 2001]

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Our approach

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- Light sources are input signal
- Interactions are filters/transforms
  - Transport
  - Visibility
  - BRDF
  - Etc.

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Light source signal

Our approach

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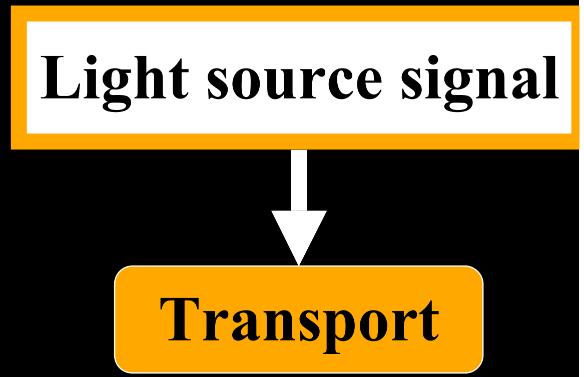

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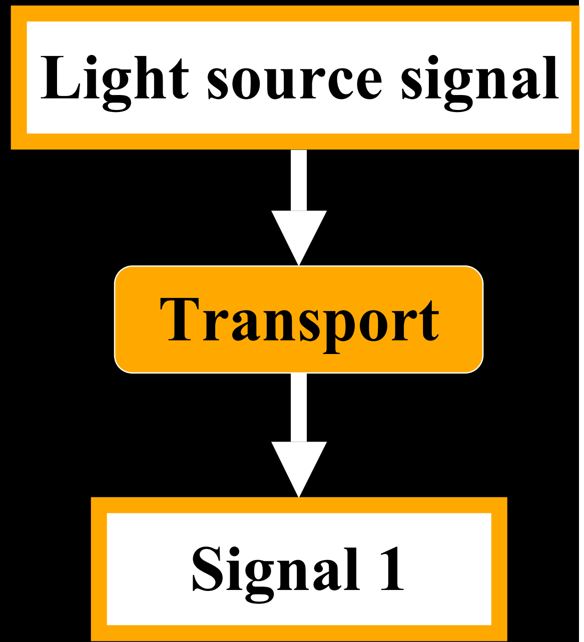

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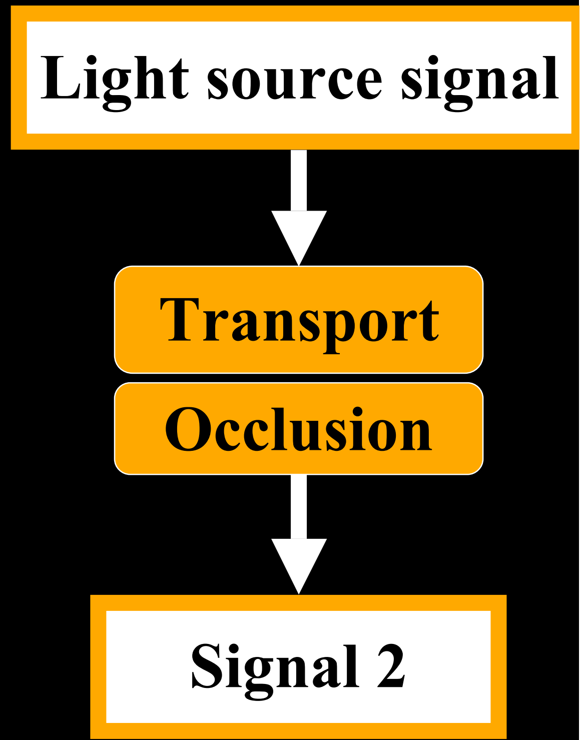

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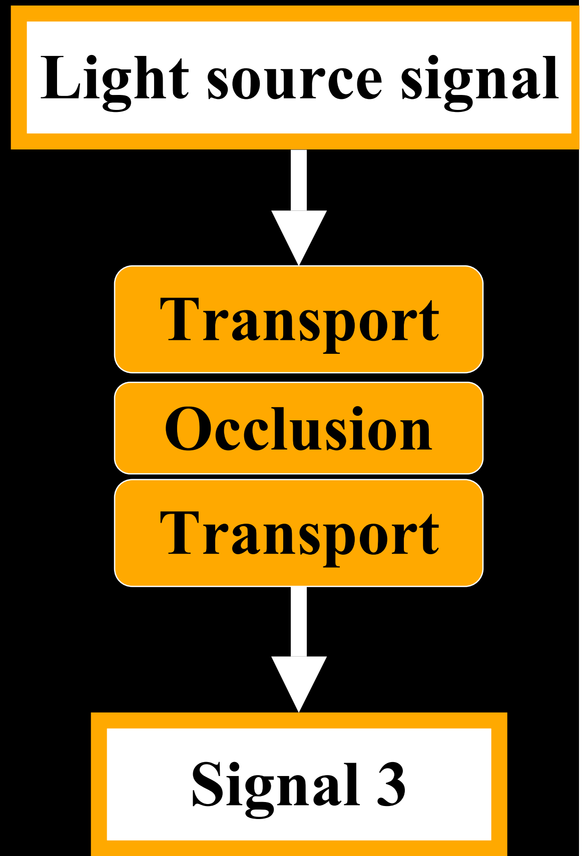

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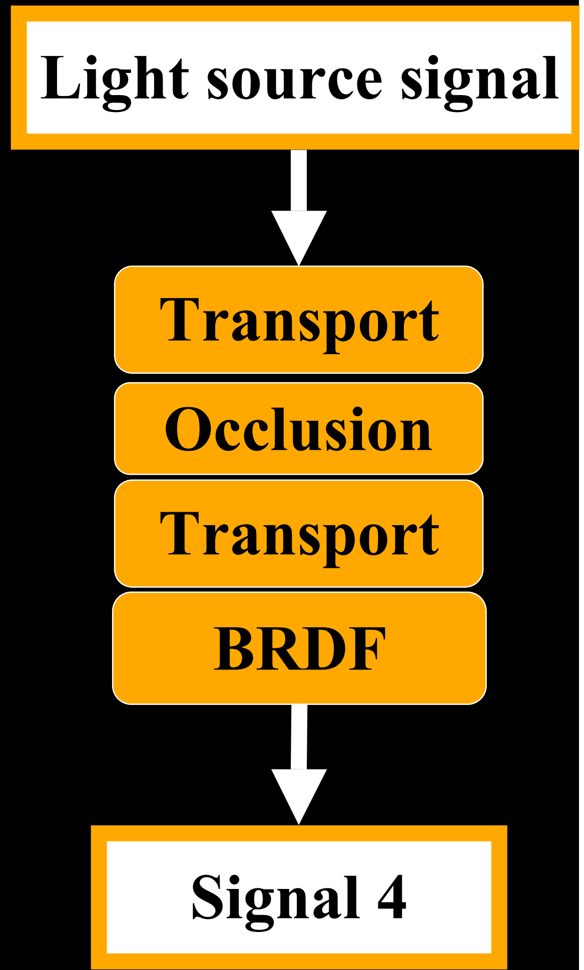

Local light field

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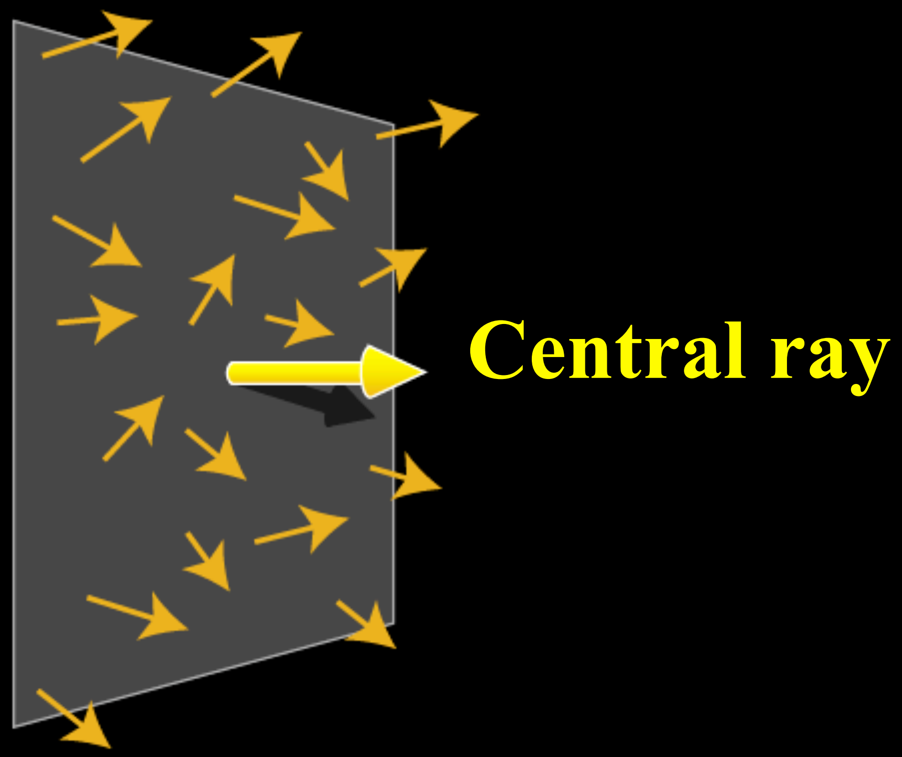
- 4D light field, around a *central ray*



Local light field

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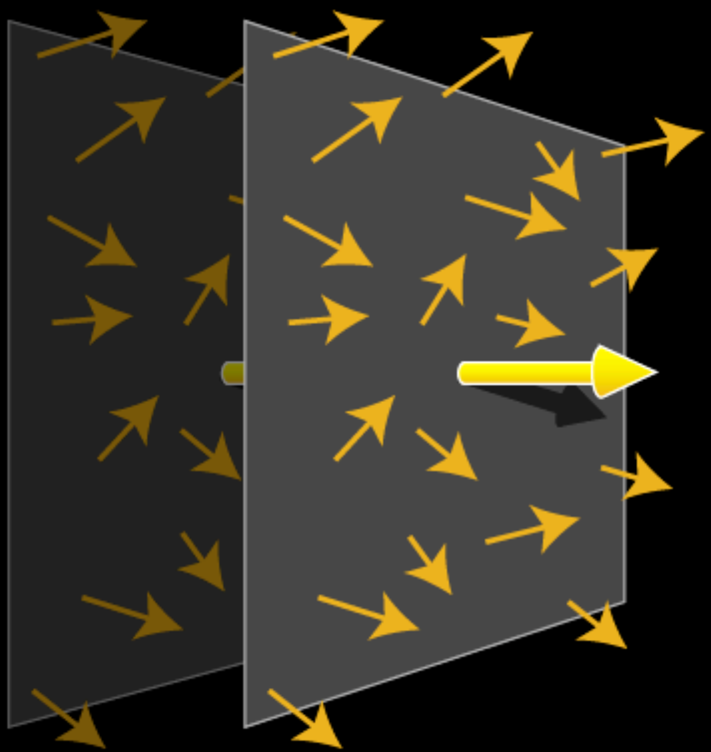
- 4D light field, around a *central ray*
- We study its spectrum during transport



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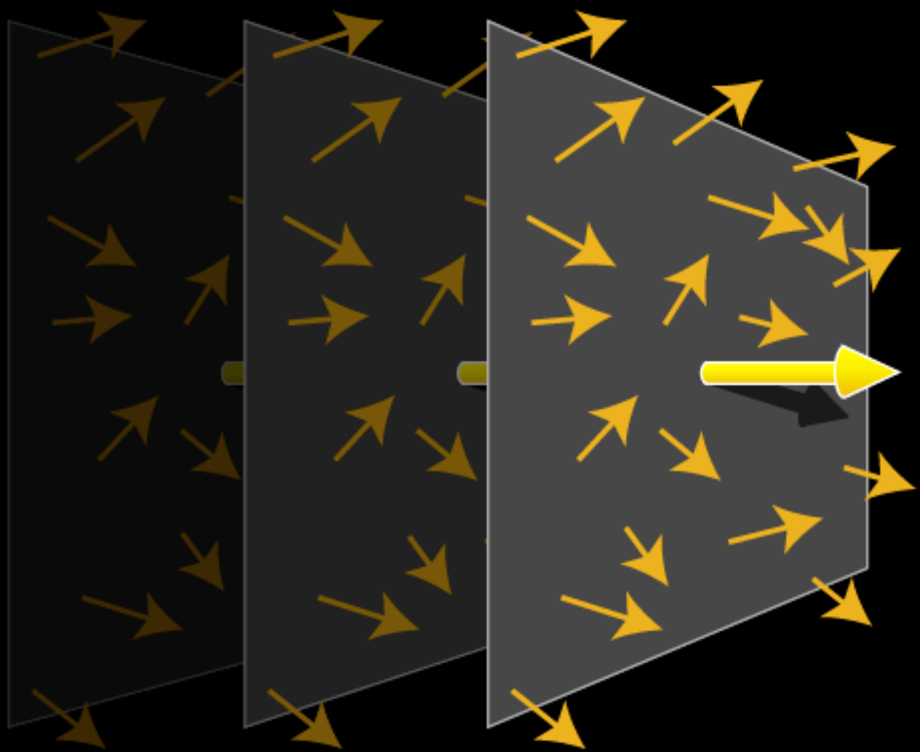

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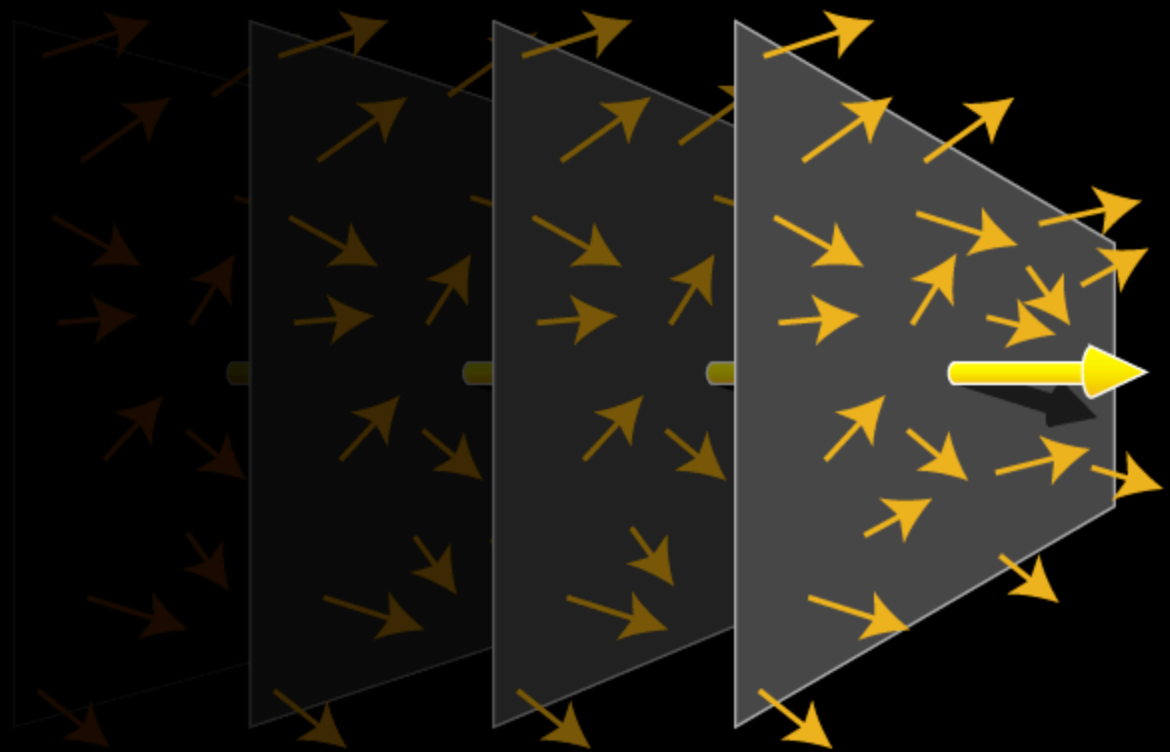

Local light field

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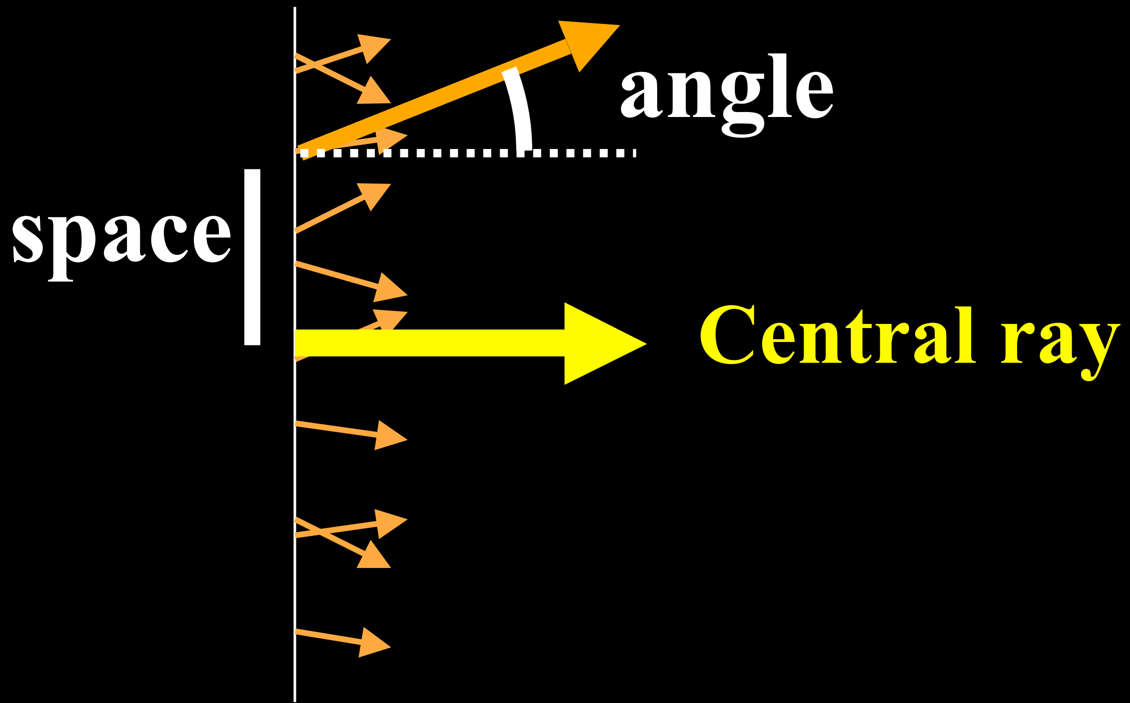
- We give explanations in 2D
  - Local light field is therefore 2D
- See paper for extension to 3D

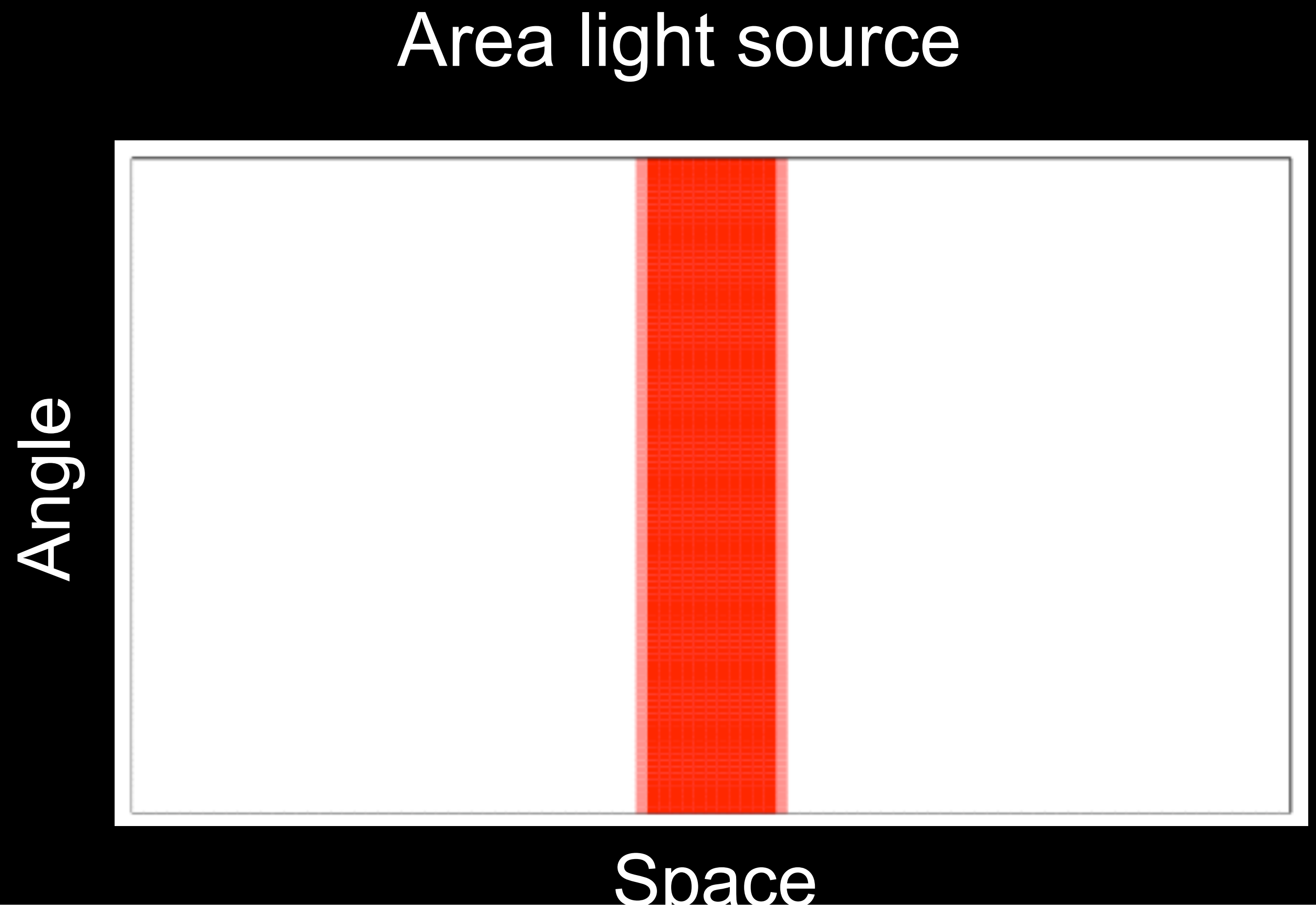
Local light field parameterization

- Space and angle



Local light field representation

- Density plot:



Local light field Fourier spectrum

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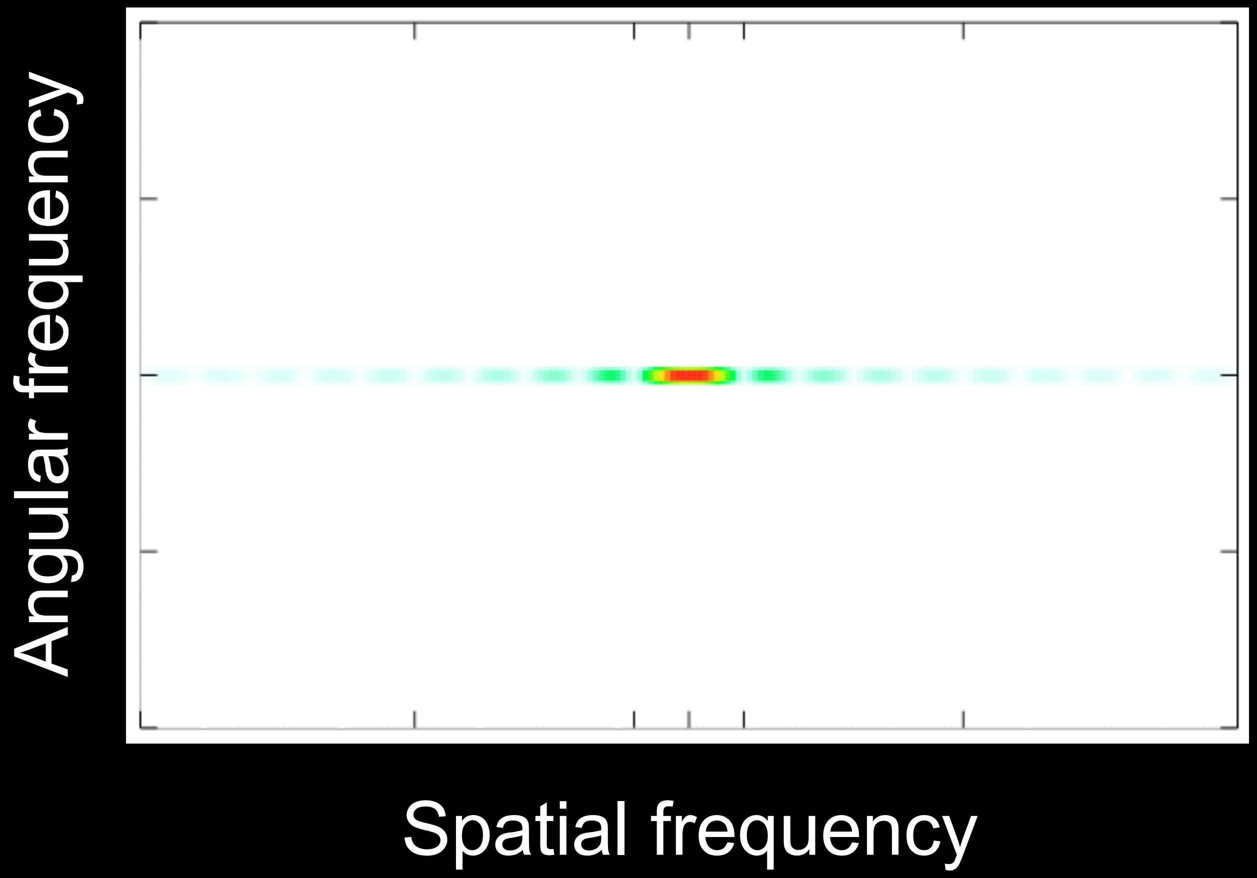
- We are interested in the Fourier spectrum of the local light field
- Also represented as a density plot

Local light field Fourier spectrum

Spectrum of an area light source:



Fourier analysis 101

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- Spectrum corresponds to blurriness:
  - Sharpest feature has size $1/F_{max}$
- Convolution theorem:
  - Multiplication ↔ convolution
- Classical spectra:
  - Box ↔ sinc
  - Dirac ↔ constant

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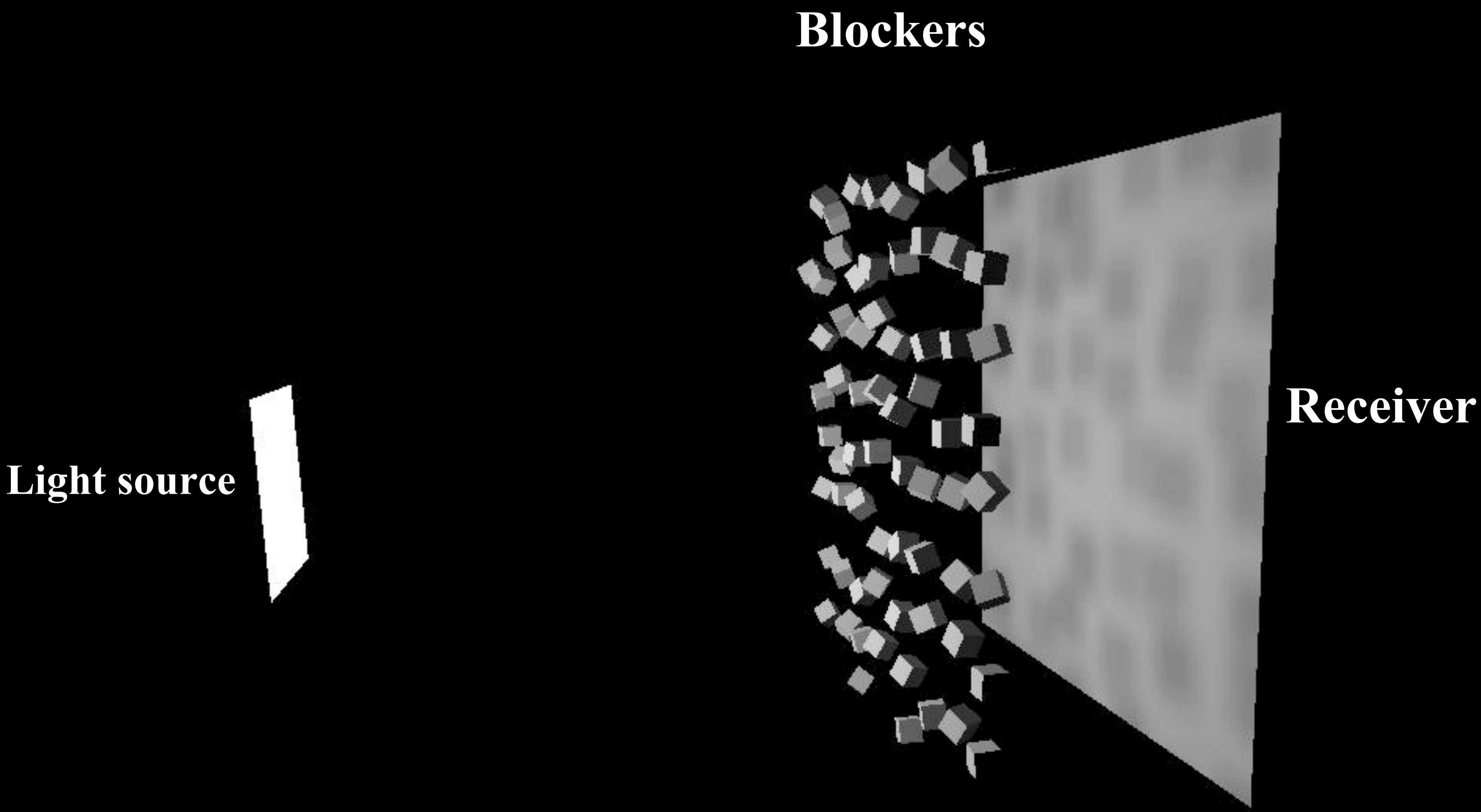
Example scene



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Transport in free space

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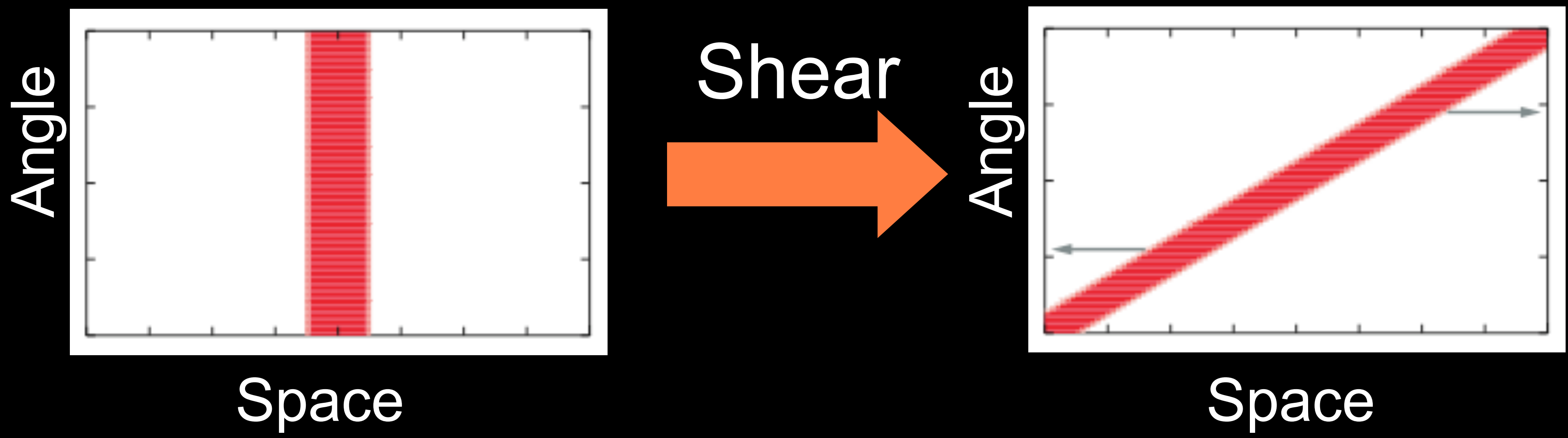
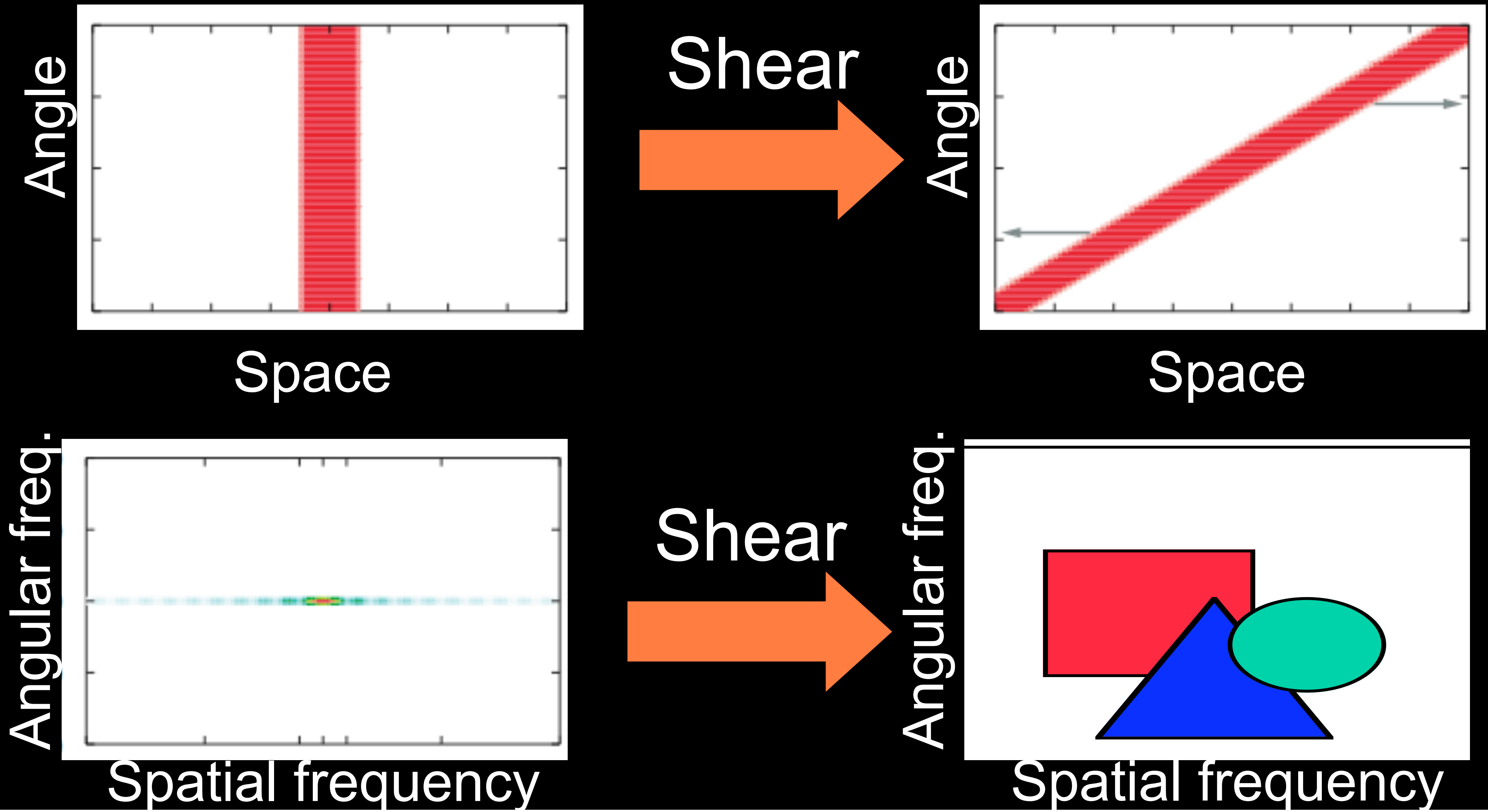
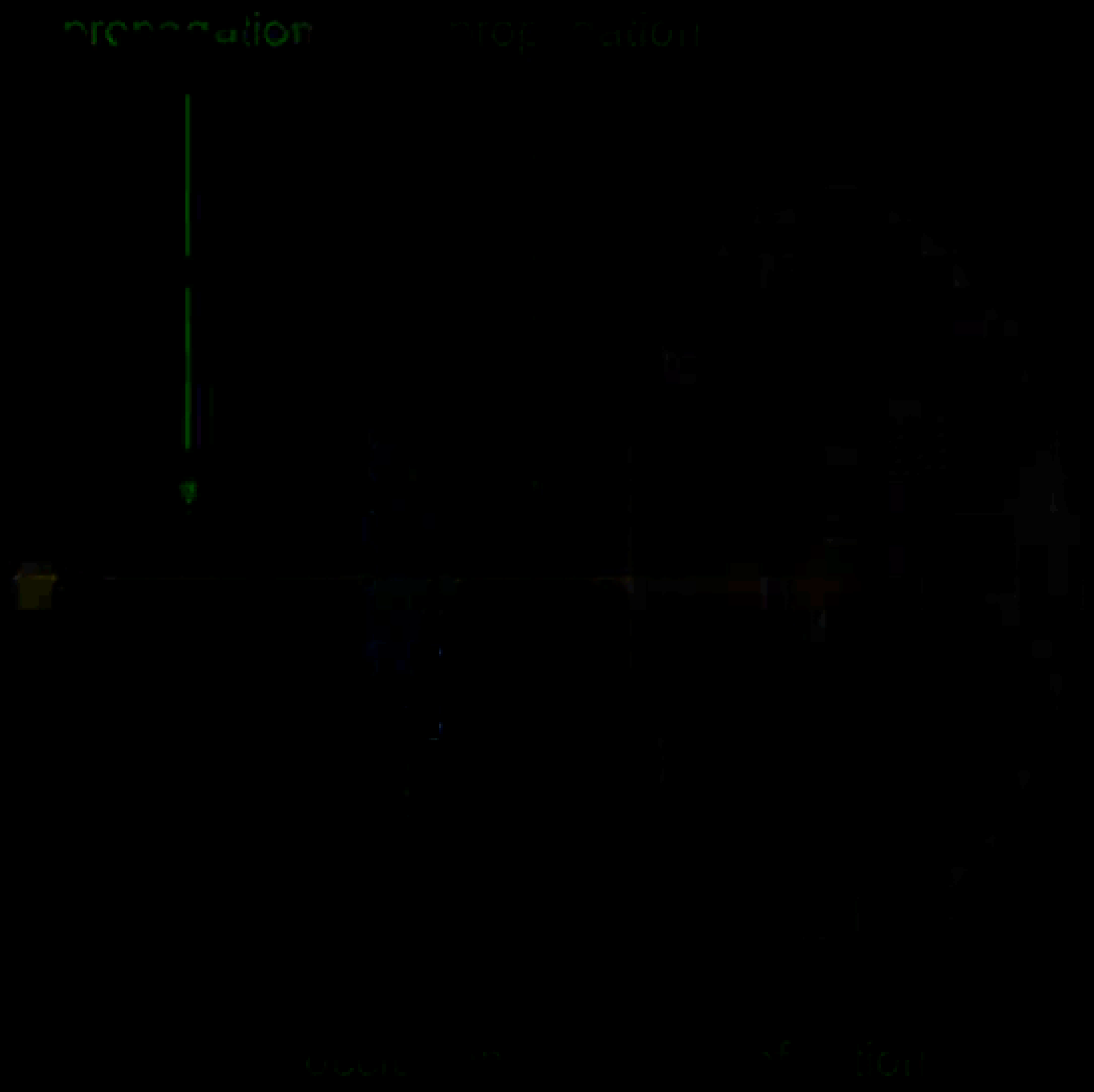


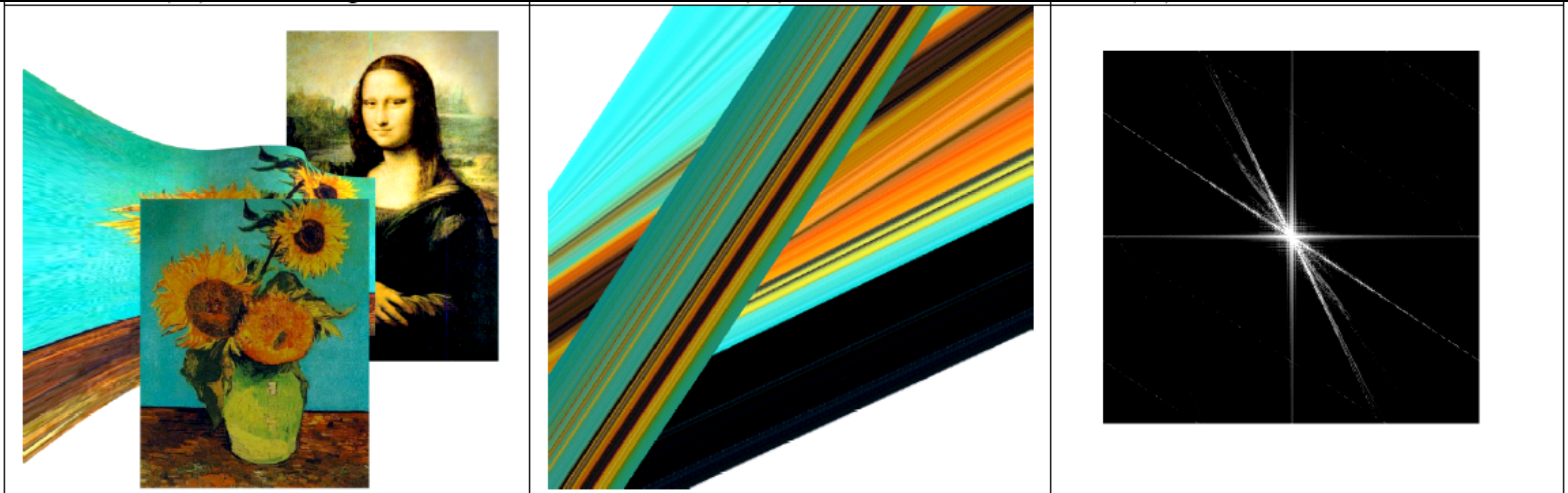
Transport in free space




propagation

Transport → Shear

- This is consistent with light field spectra [Chai et al. 00, Isaksen et al. 00]



(d1)Scene image | (d2) EPI | (d3) Fourier transform of EPI

From [Chai et al. 2000]

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Occlusion: multiplication

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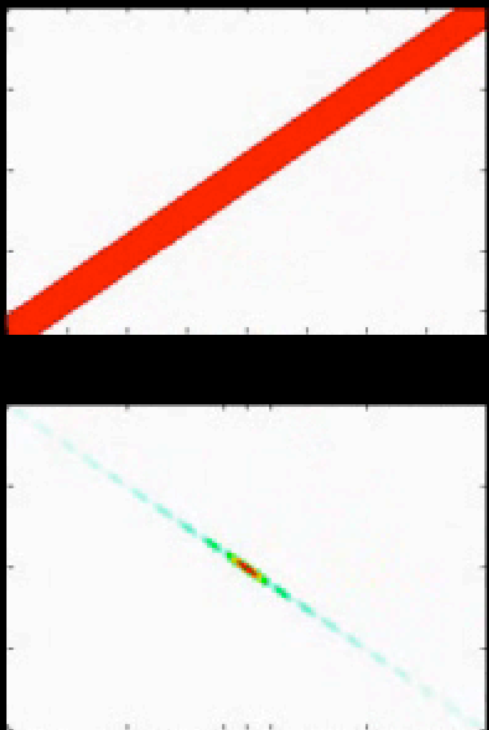
- Occlusion is a multiplication in ray space
  - Convolution in Fourier space
- Creates new spatial frequency content
  - Related to the spectrum of the blockers

Occlusion



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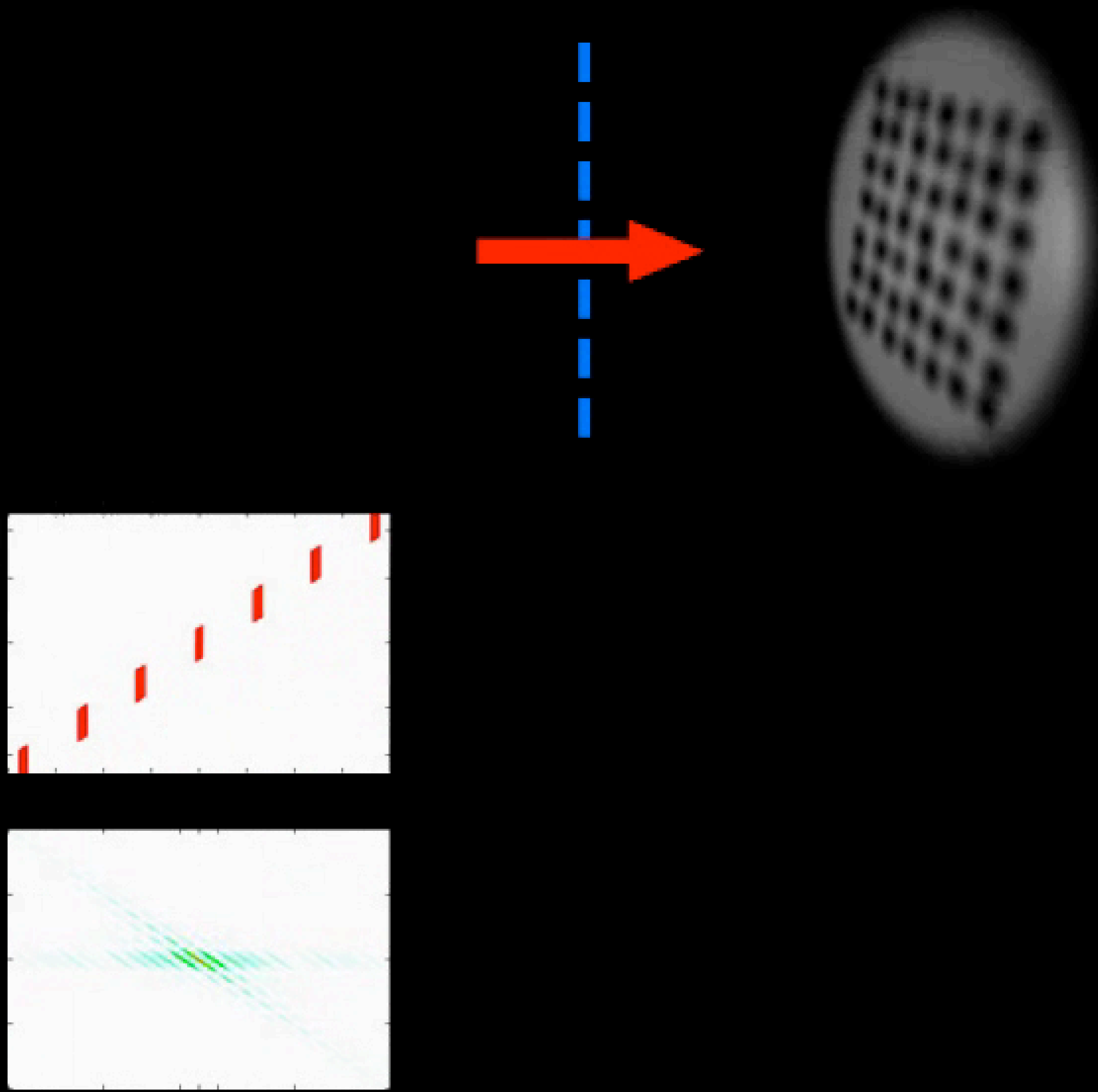
Light Propagation



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BRDF integration

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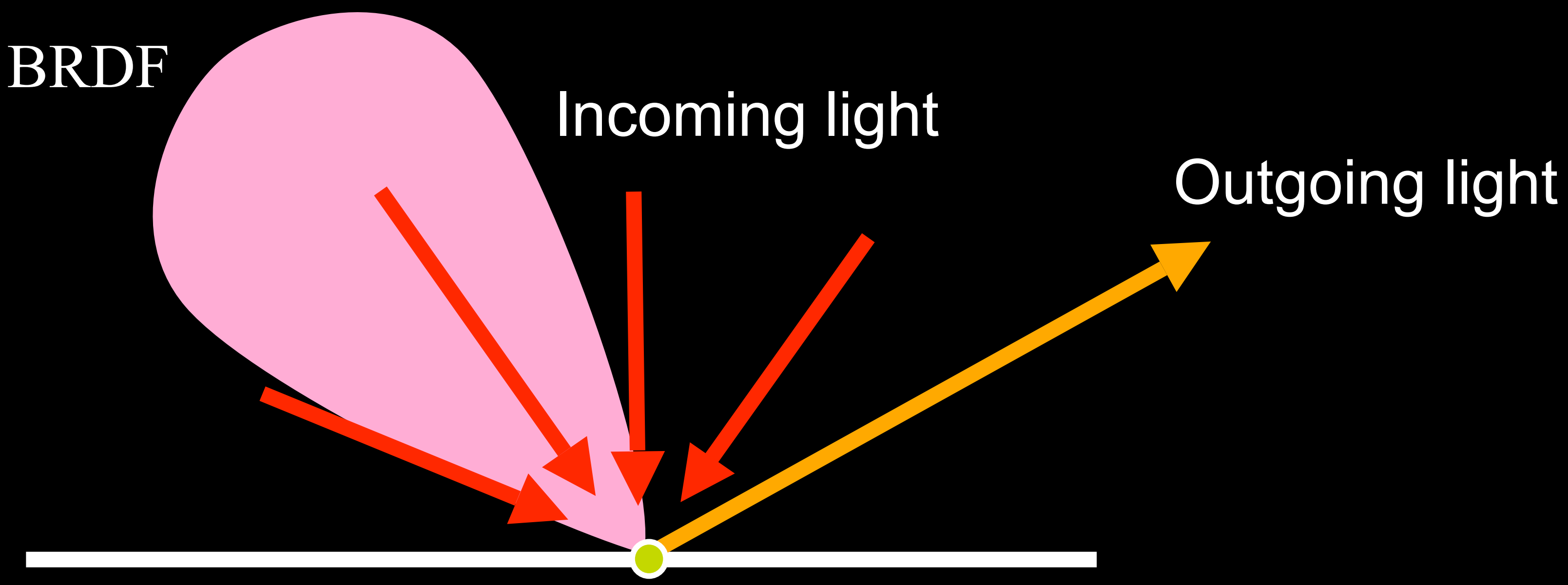
- Outgoing light:
  - Integration of incoming light times BRDF



BRDF integration

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- Ray-space: **convolution**
  - Outgoing light: convolution of incoming light and BRDF
  - For rotationally-invariant BRDFs
- Fourier domain: **multiplication**
  - Outgoing spectrum: multiplication of incoming spectrum and BRDF spectrum

BRDF in Fourier: multiplication

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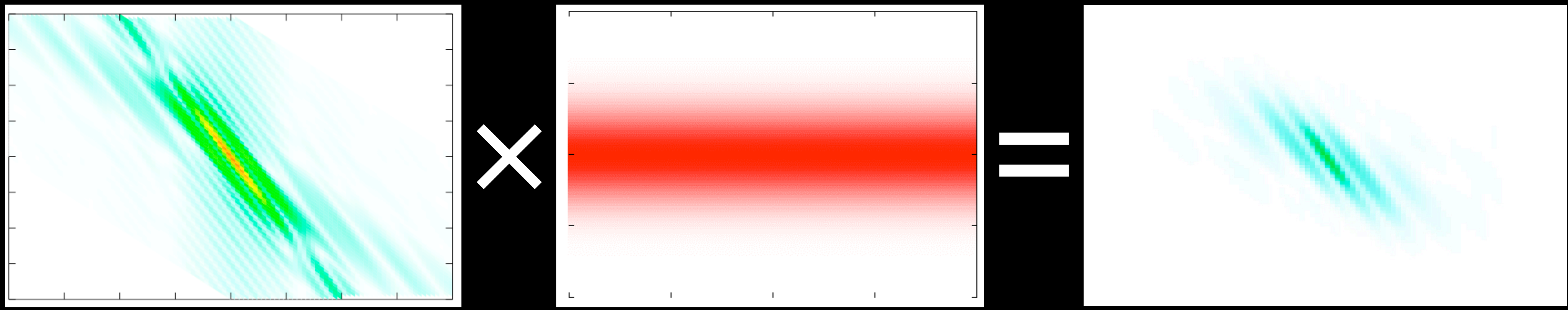

- BRDF is bandwidth-limiting in angle

Example: diffuse BRDF

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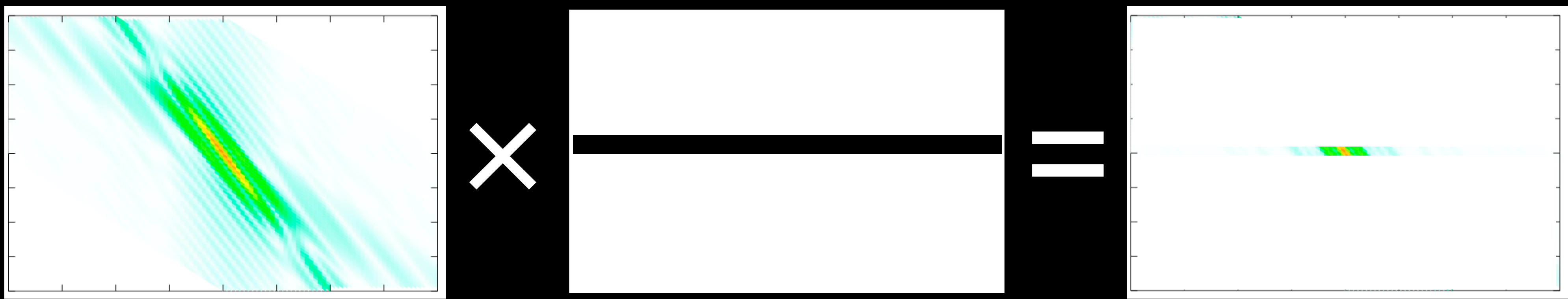
- Convolve by constant:
  - multiply by Dirac
  - Only spatial frequencies remain



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Curved receiver

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- Reduce to the case of a planar surface:
  - "Unroll" the curved receiver
- Equivalent to changing angular content:
  - Linear effect on angular dimension
  - No effect on spatial dimension
- Shear in the angular dimension

[redacted]

Transforms: summary

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	Radiance/Fourier	Effect
Transport	Shear	
Occlusion	Multiplication/Convolution	Adds spatial frequencies
BRDF	Convolution/Multiplication	Removes angular frequencies
Curvature	Shear	

More effects in paper

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- Cosine term (multiplication/convolution)
- Fresnel term (multiplication/convolution)
- Texture mapping (multiplication/convolution)
- Central incidence angle (scaling)
- Separable BRDF
- Spatially varying BRDF (semi-convolution)

- …and extension to 3D

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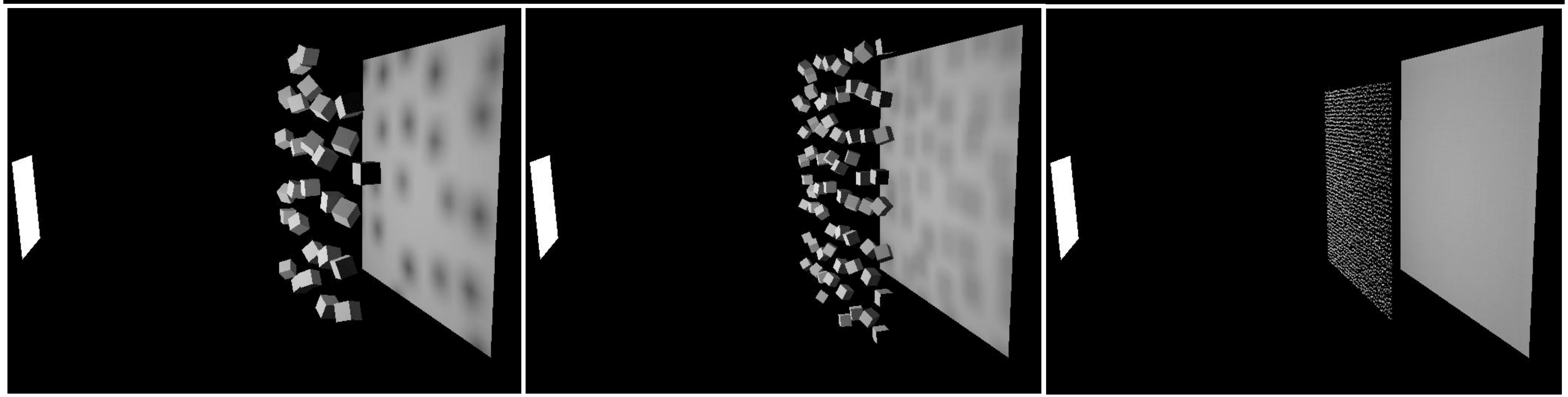
Diffuse soft shadows

- Decreasing blockers size:
  - First high-frequencies increase
  - Then only low frequency
  - Non-monotonic behavior



Diffuse soft shadows (2)

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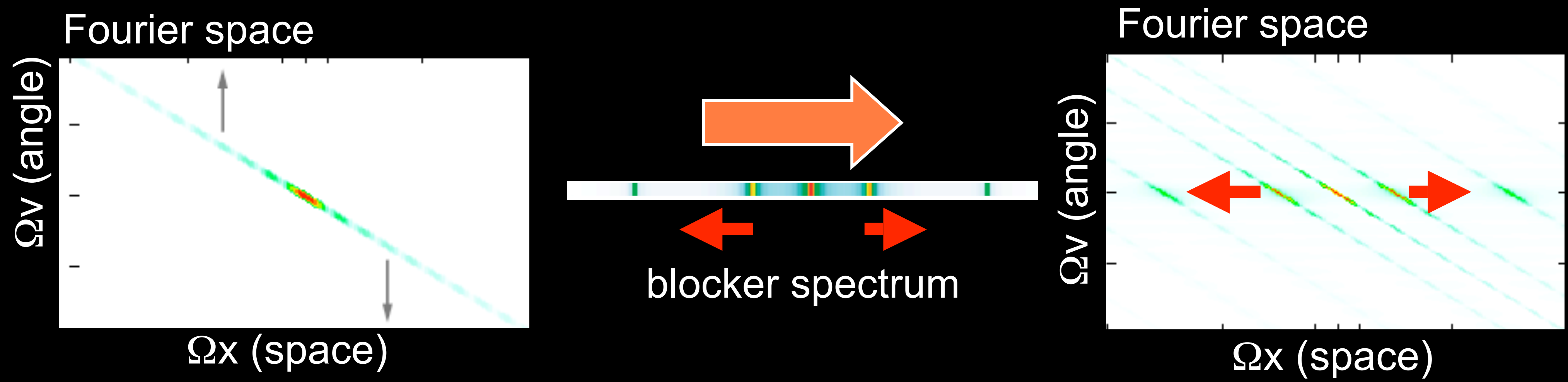
- Occlusion : convolution in Fourier
  - creates high frequencies
  - Blockers scaled down → spectrum scaled up



Diffuse soft shadows (3)

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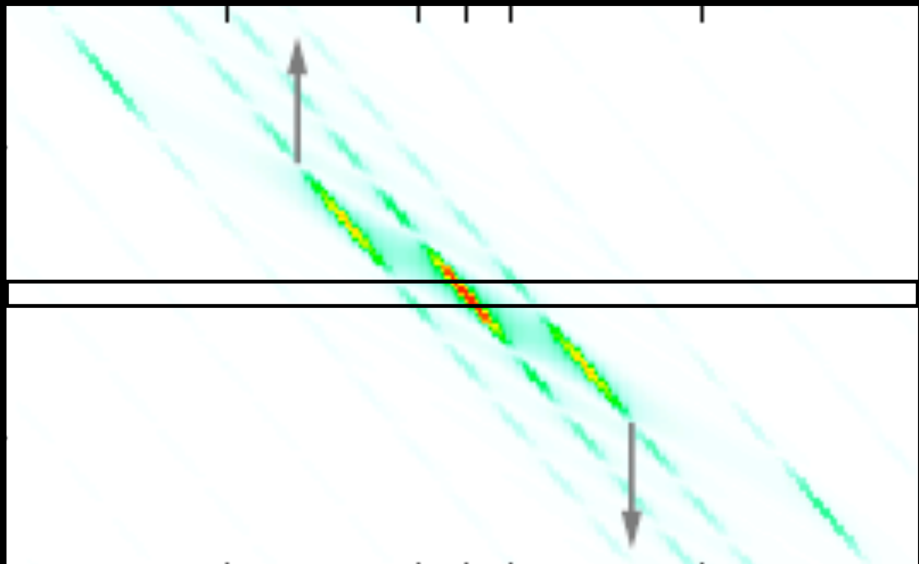
- Transport after occlusion:
  - Spatial frequencies moved to angular dimension
- Diffuse reflector:
  - Angular frequencies are cancelled



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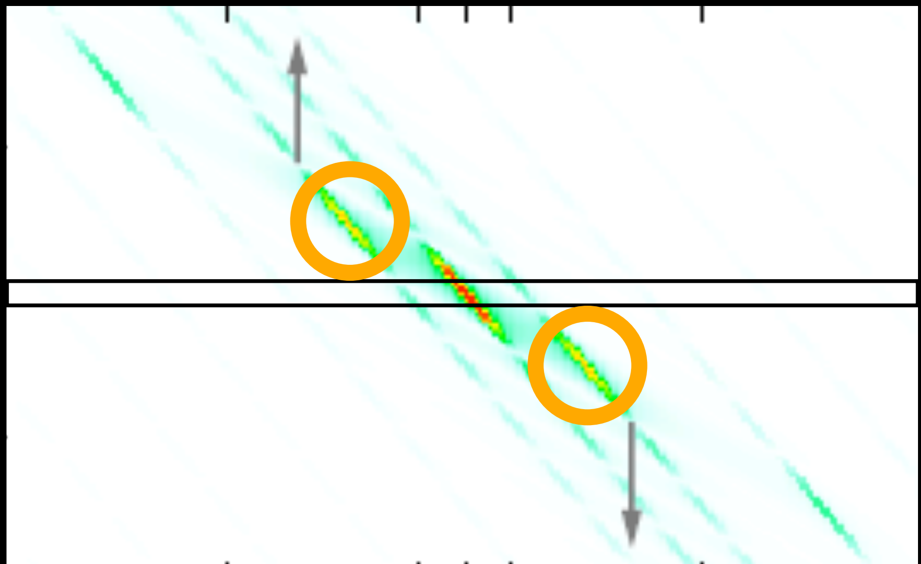

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Adaptive shading sampling

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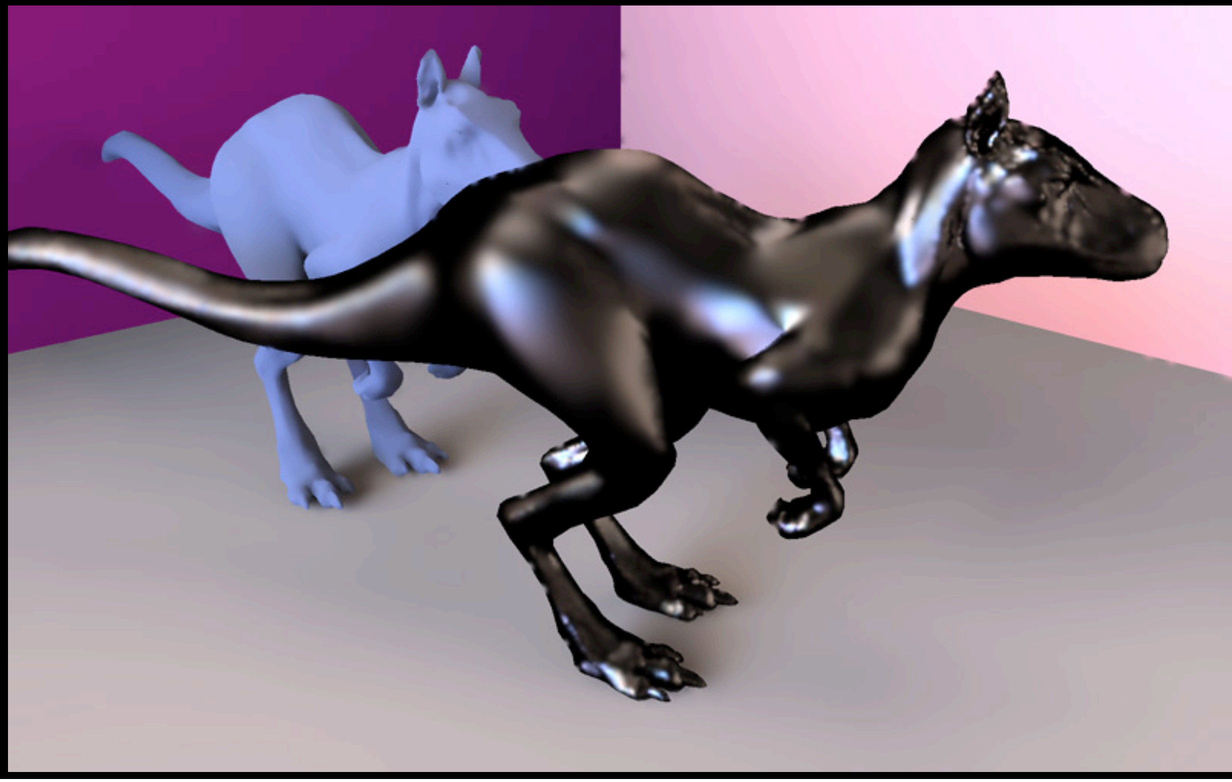
- Monte-Carlo ray tracing
- Blurry regions need fewer shading samples



Adaptive shading sampling

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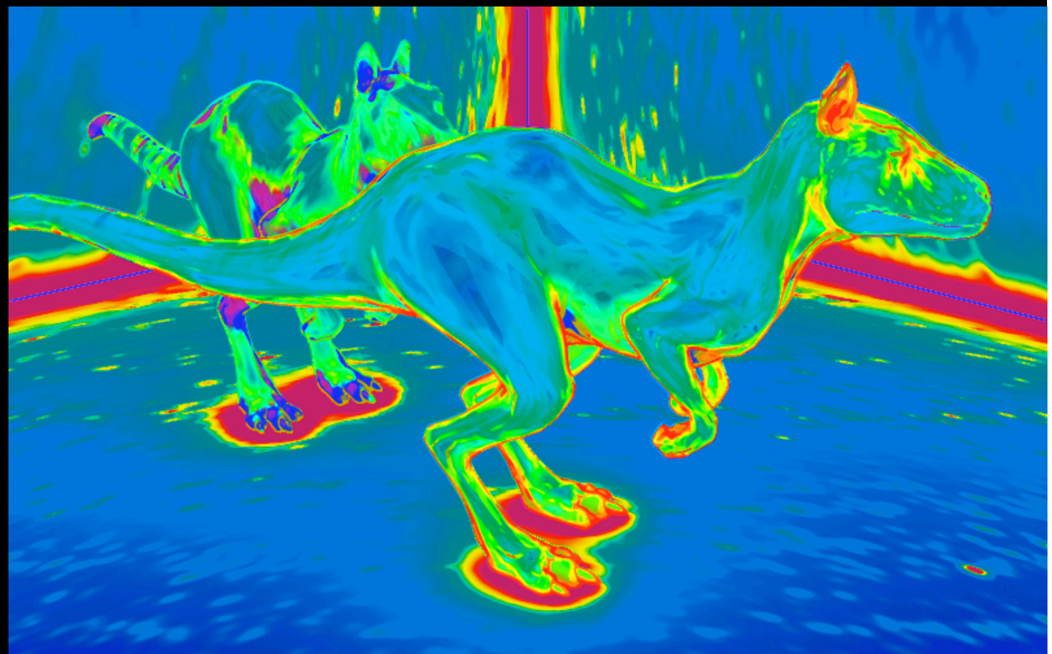
- Per-pixel prediction of max. frequency (bandwidth)
  - Based on curvature, BRDF, distance to occluder, etc.
  - No spectrum computed, just estimate max frequency



Per-pixel bandwidth criterion

Adaptive shading sampling

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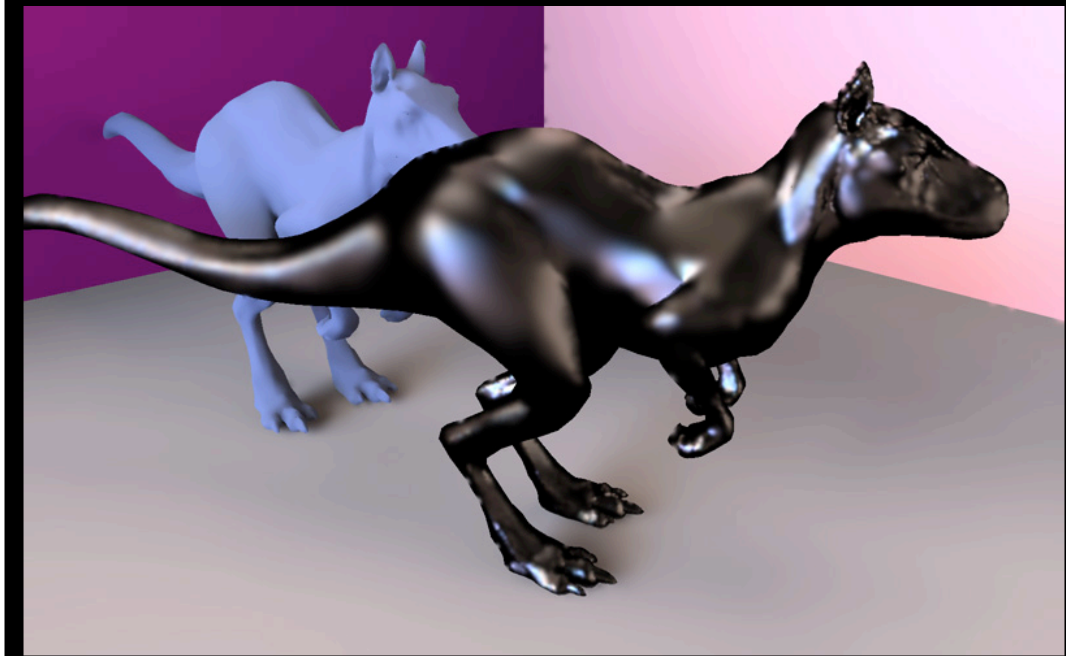
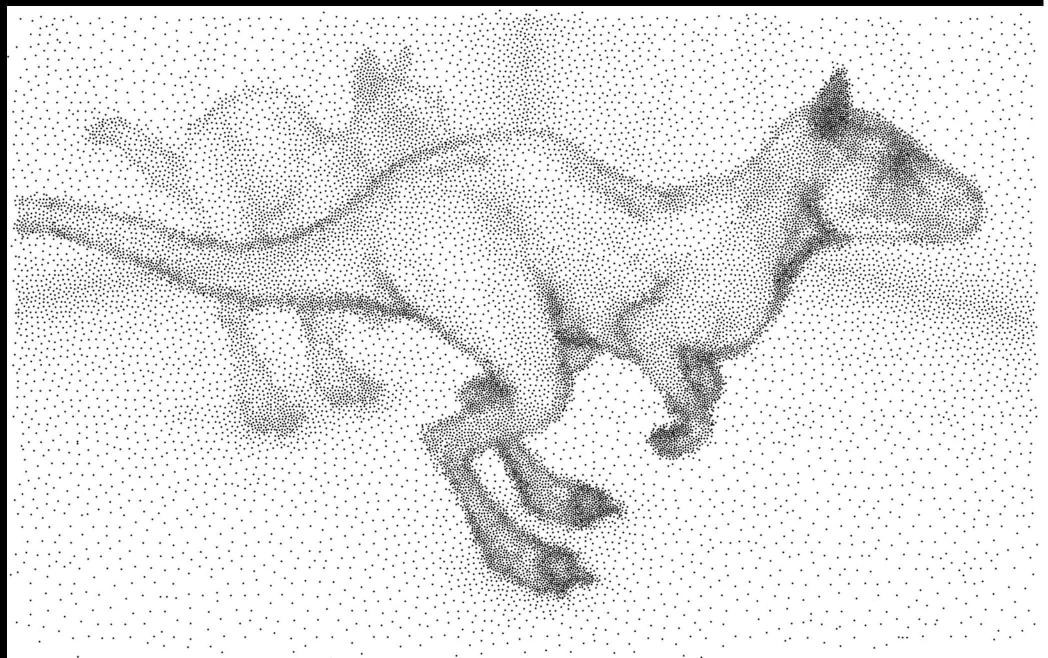
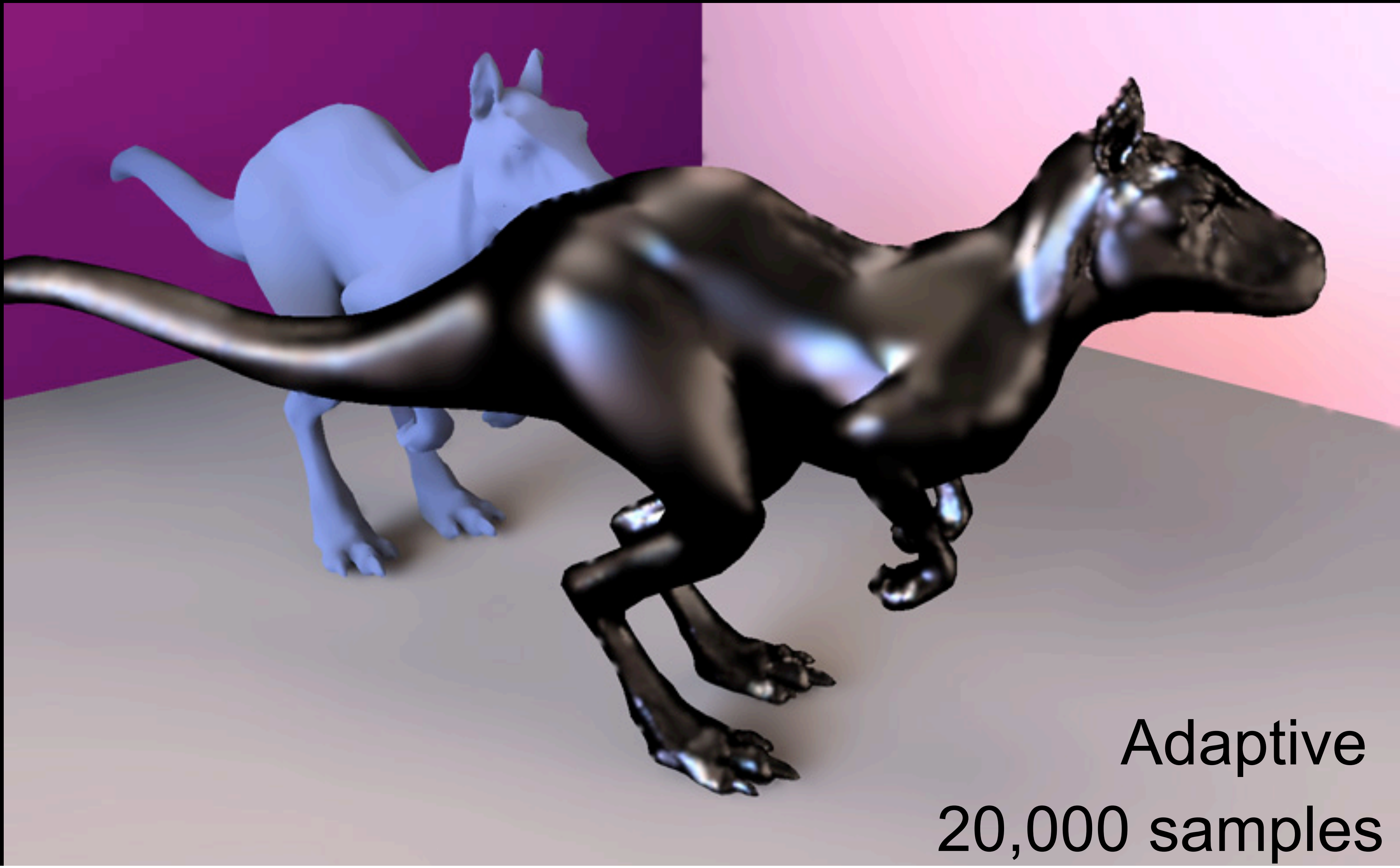




Shading samples

Adaptive sampling



Uniform sampling

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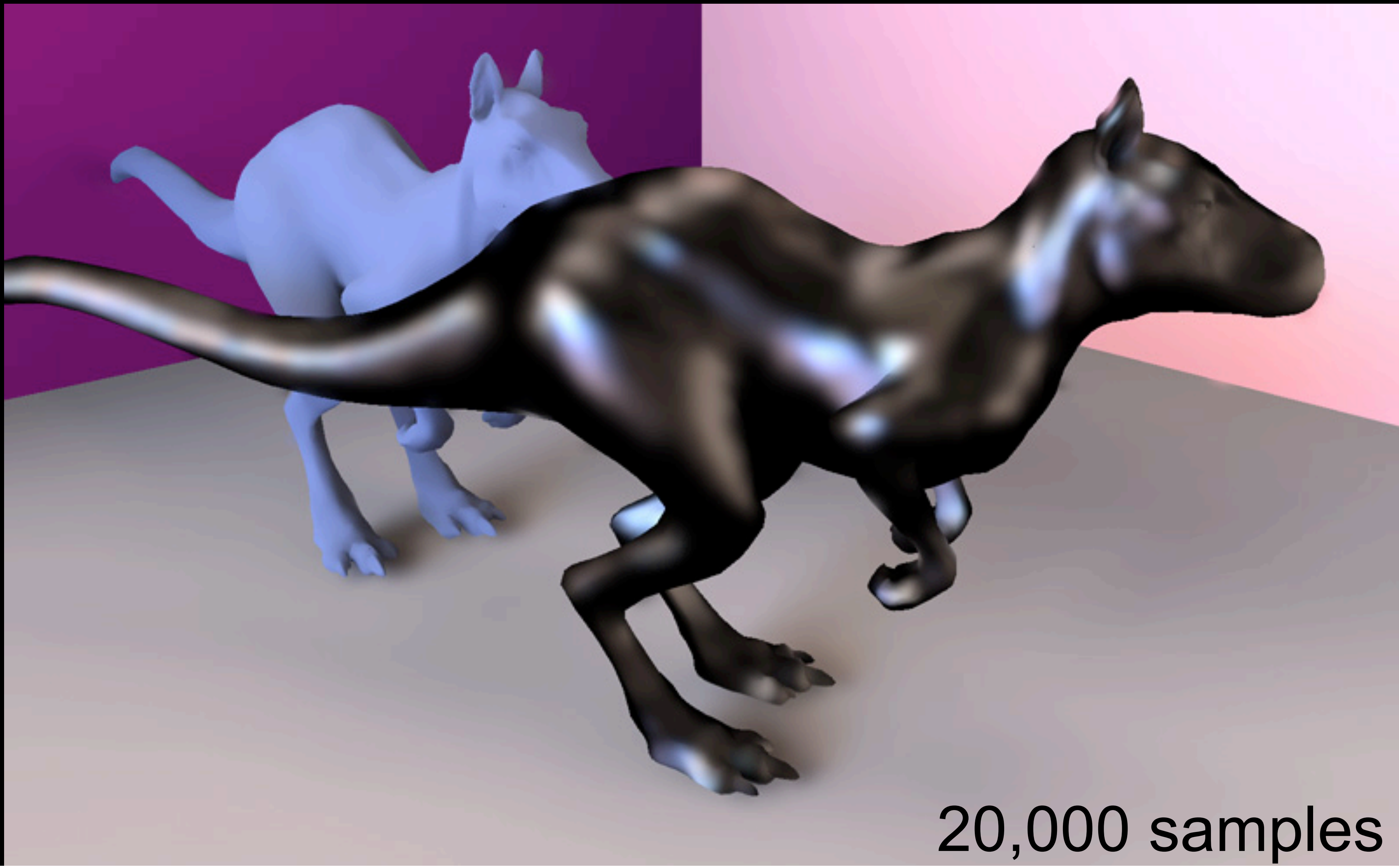

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Conclusions

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- Unified framework:
  - For frequency analysis of radiance
  - In both space and angle
  - Simple mathematical operators
  - Extends previous analyses
- Explains interesting lighting effects:
  - Soft shadows, caustics
- Proof-of-concept:
  - Adaptive sampling

Future work

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- More experimental validation on synthetic scenes
- Extend the theory:
  - Bump mapping, microfacet BRDFs, sub-surface scattering…
  - Participating media
- Applications to rendering:
  - Photon mapping
  - Spatial sampling for PRT
  - Revisit traditional techniques
- Applications to vision and shape from shading

Acknowledgments

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- Jaakko Lehtinen
- Reviewers of the MIT and ARTIS graphics groups
- Siggraph reviewers
- This work was supported in part by:
  - NSF CAREER award 0447561 Transient Signal Processing for Realistic Imagery
  - NSF CISE Research Infrastructure Award (EIA9802220)
  - ASEE National Defense Science and Engineering Graduate fellowship
  - INRIA Équipe associée
  - Realreflect EU IST project
  - MIT-France

Solar oven

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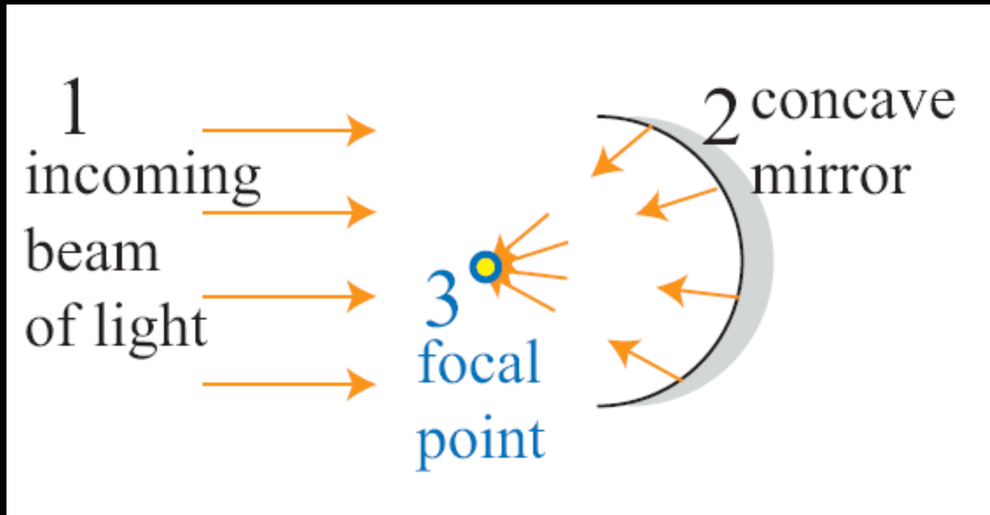
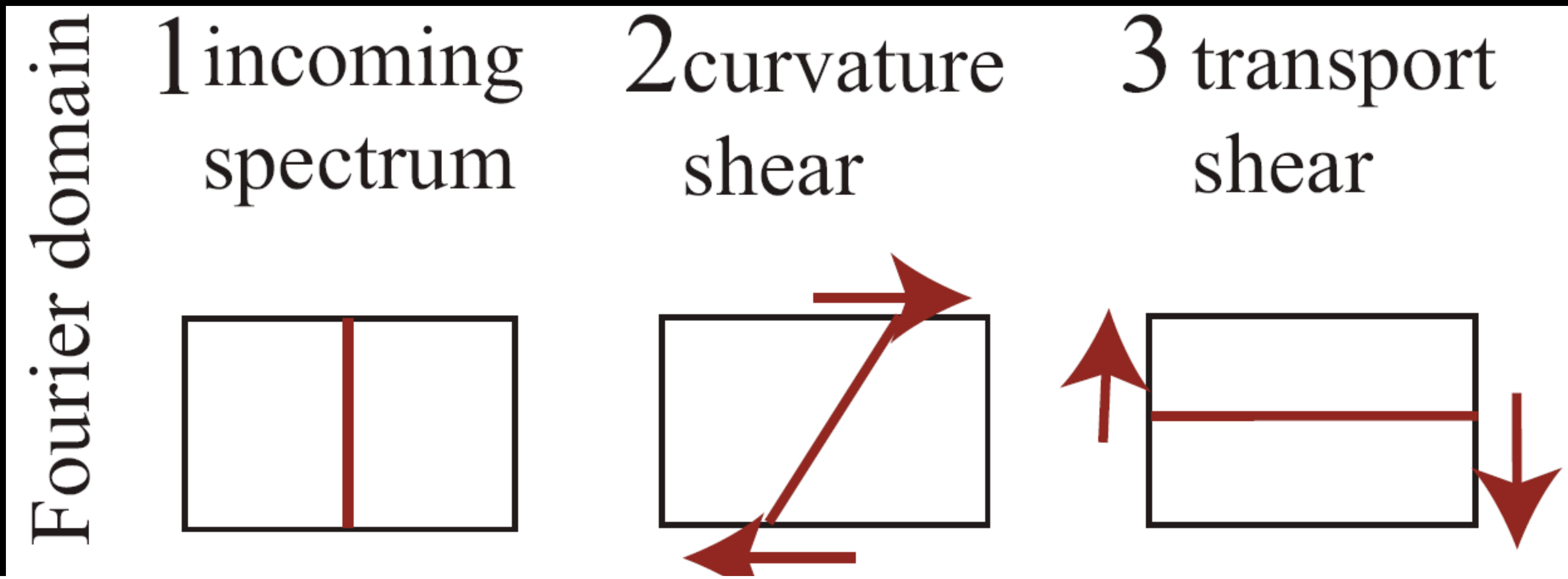
- Curved surface
- In: parallel light rays
- Out: focal point





Other bases?

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- We're not using Fourier as a function basis
  - Don't recommend it, actually
  - Just used for analysis, understanding, predictions
- Results are useable with any other base:
  - Wavelets, Spherical Harmonics, point sampling, etc
  - Max. frequency translates in sampling rate
- Analysis relies on Fourier properties:
  - Especially the convolution theorem

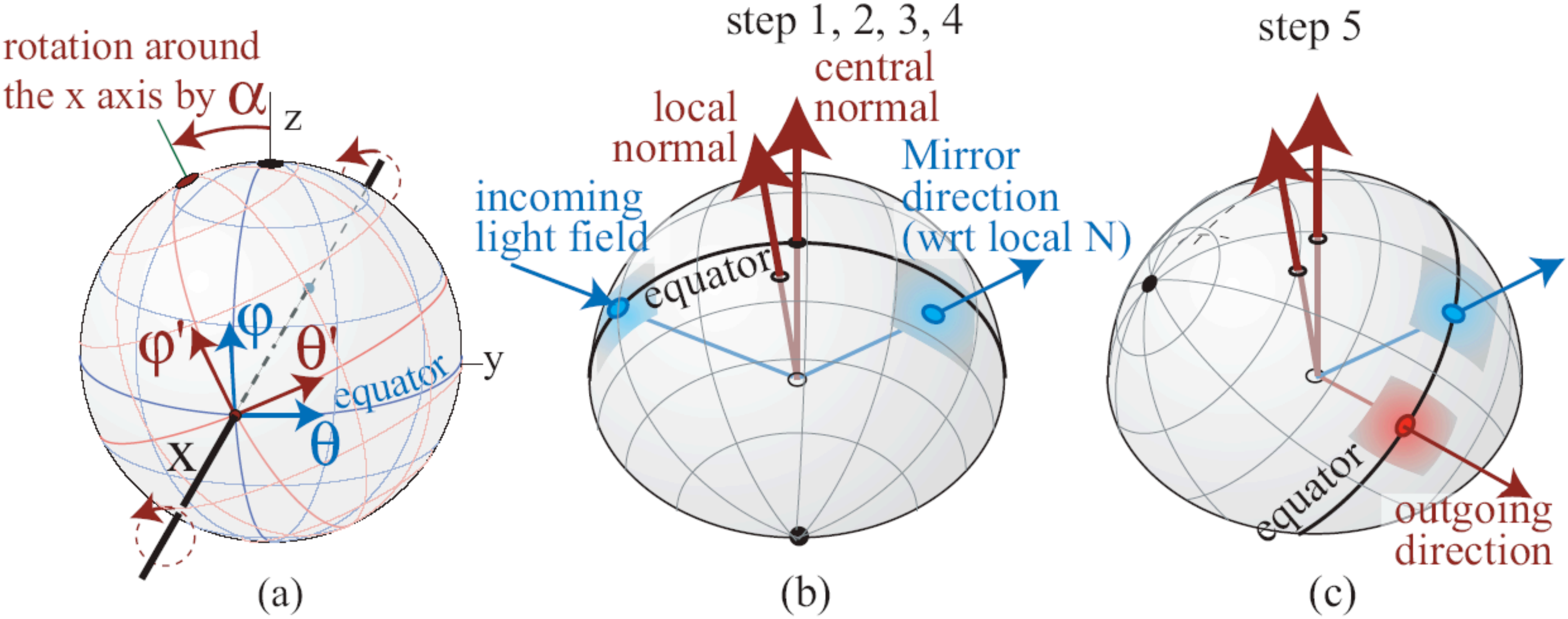
Why *Local* Light Field?

SIGGRAPH2005

- Linearization:
  - $\theta \approx \tan\theta$
  - Curvature
- Local information is what we need:
  - Local frequency content, for local sampling
  - Local properties of the scene (occluders, curv.)

Extension to 3D

- It works. See paper:



Reflection on a surface: Full summary

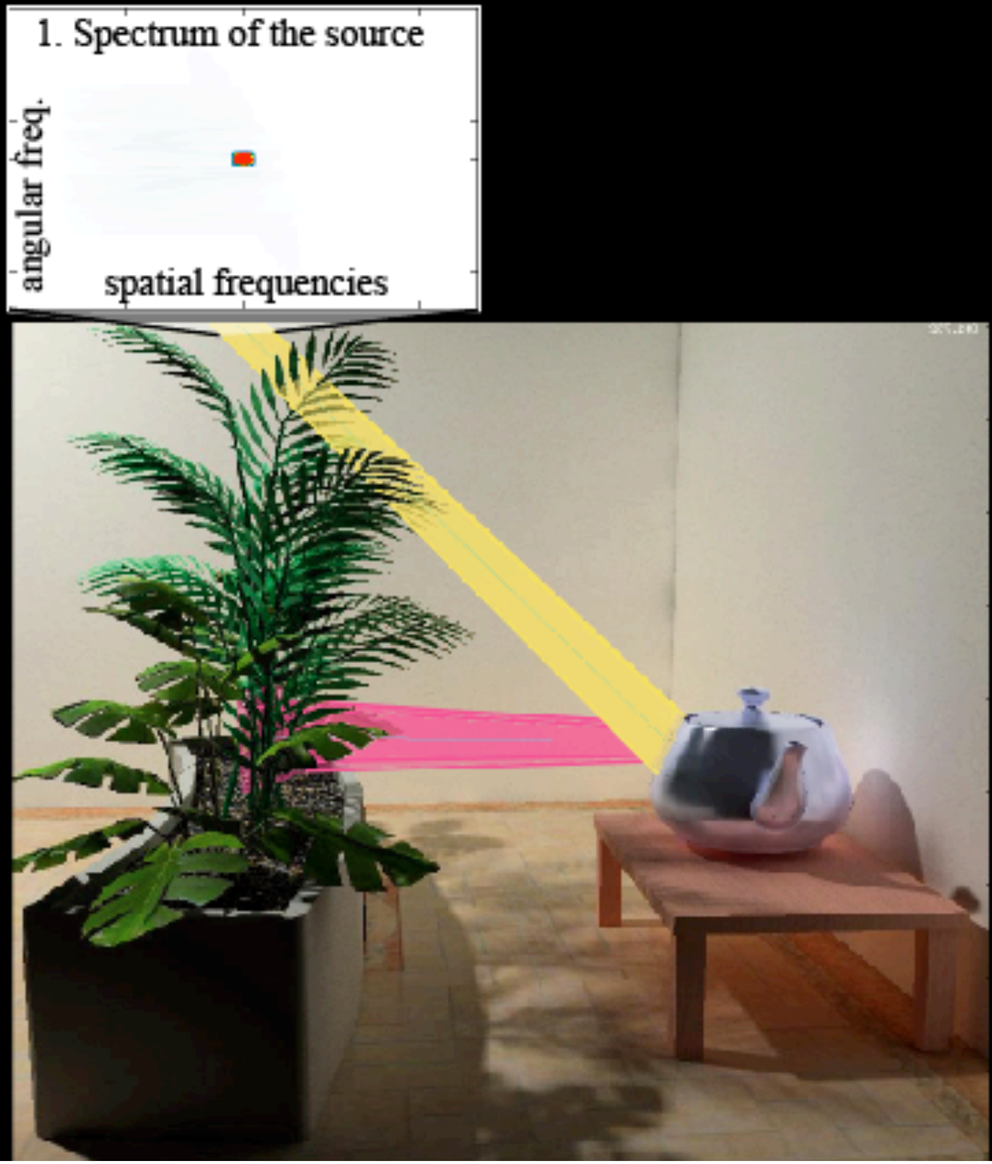
- Angle of incidence
- Curvature
- Cosine/Fresnel term
- Mirror re-parameterization
- BRDF
- Curvature

Reflection on a surface: Full summary

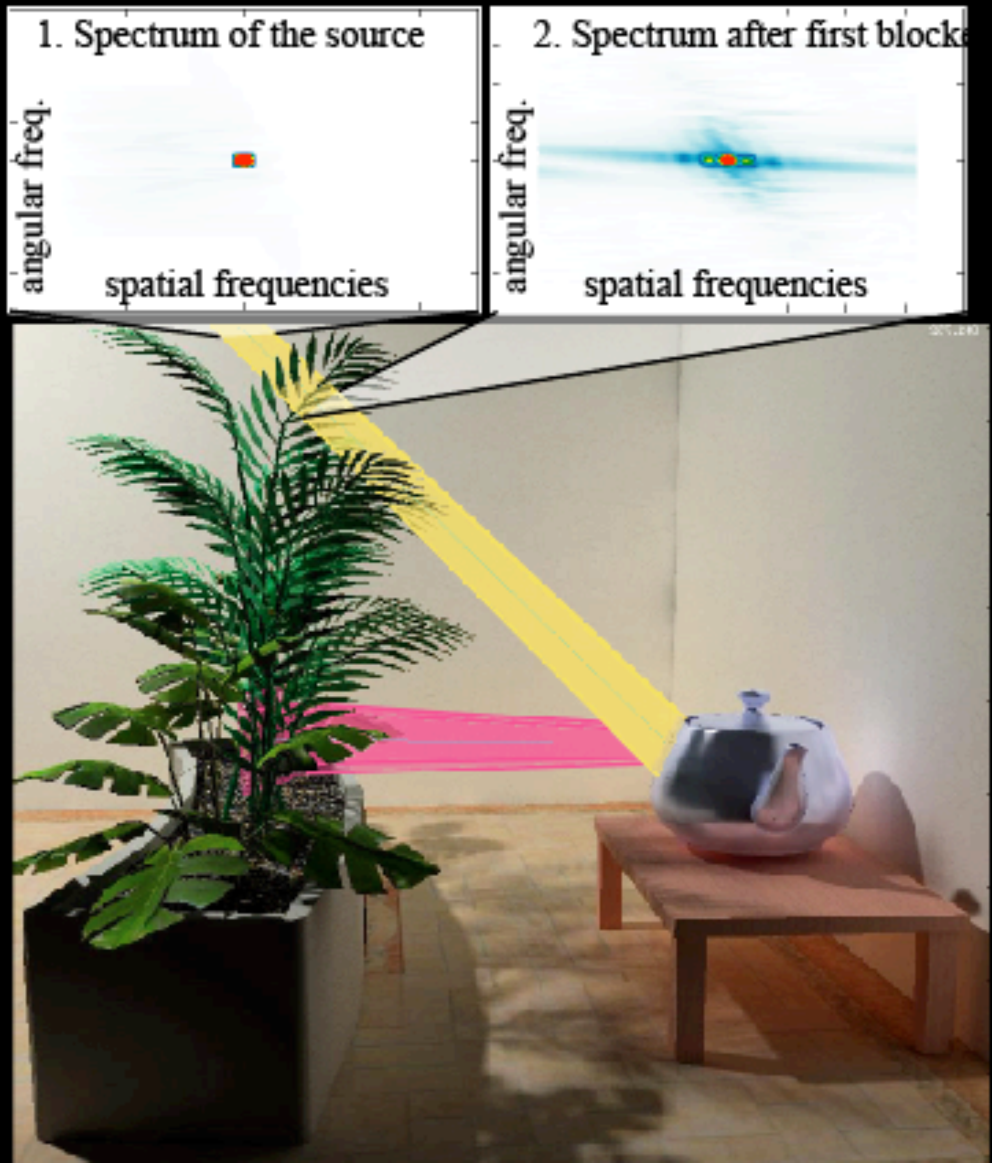
SIGGRAPH2005

- Angle of incidence: scaling
- Curvature: shear in angle
- Cosine/Fresnel term: multiplication/convolution
- Mirror re-parameterization
- BRDF: convolution/multiplication
- Curvature: shear in angle

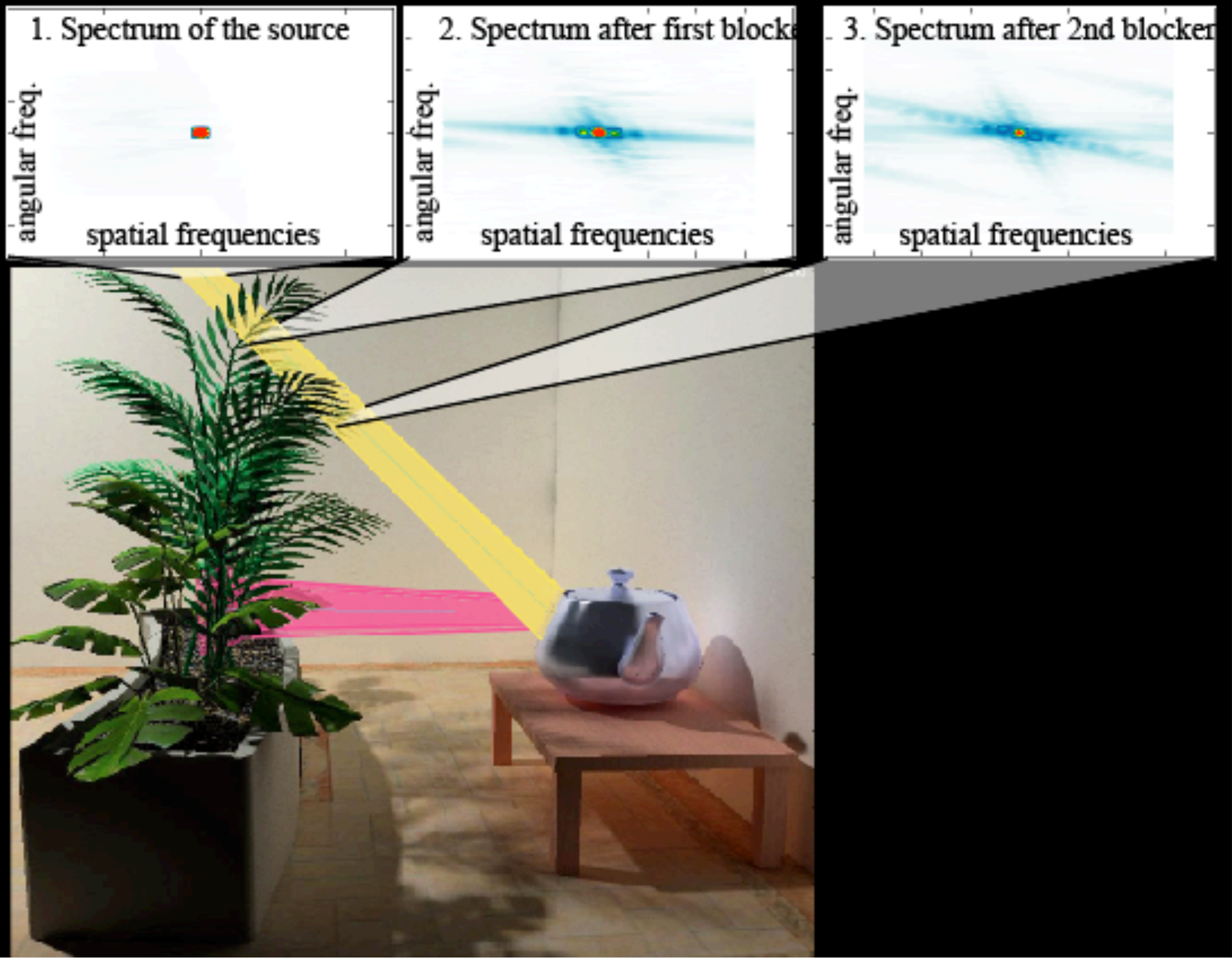
Application: 3D scene



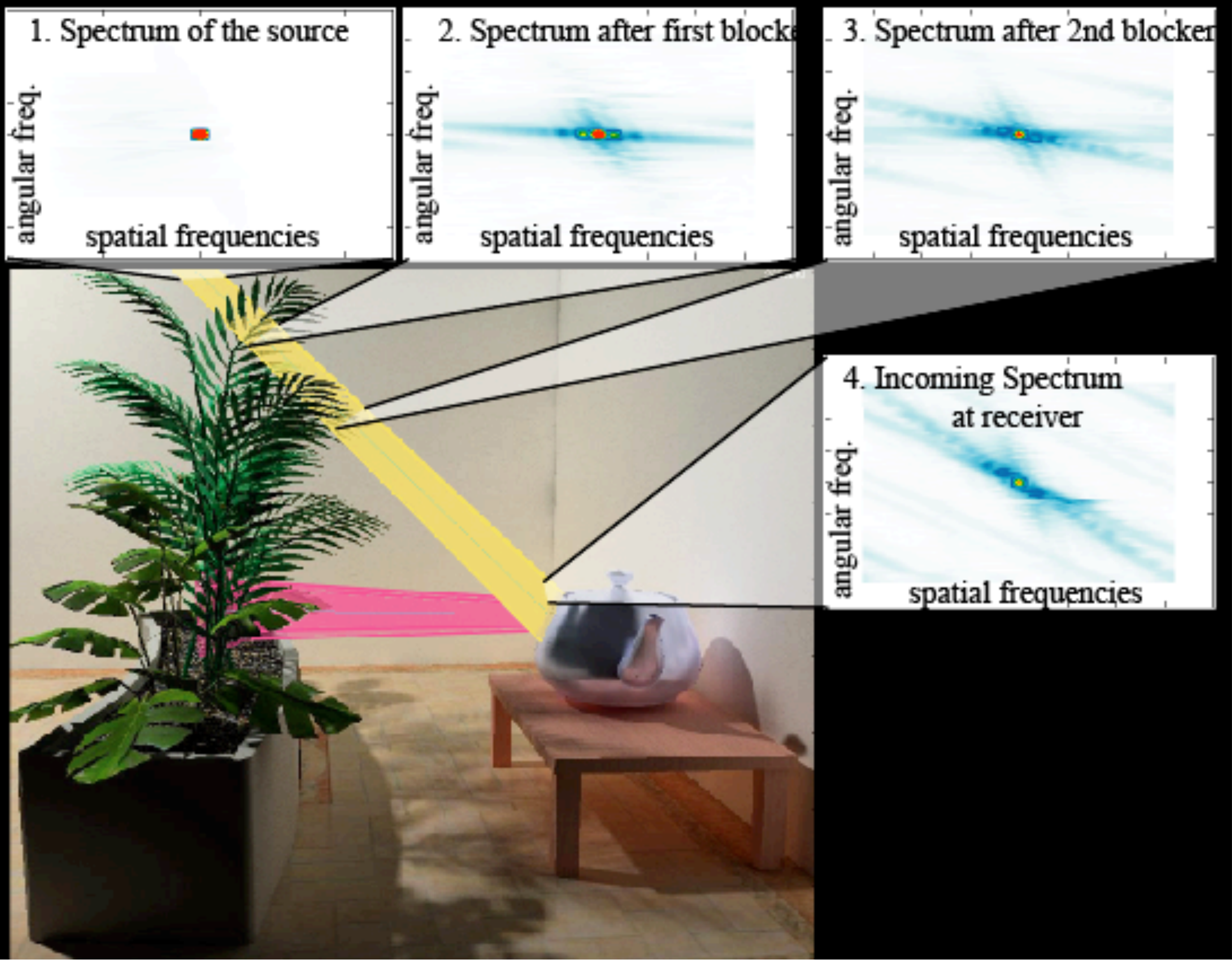
Application: 3D scene



Application: 3D scene



Application: 3D scene



Application: 3D scene