

Microfacet models for refraction through rough surfaces

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Diffuse transmission

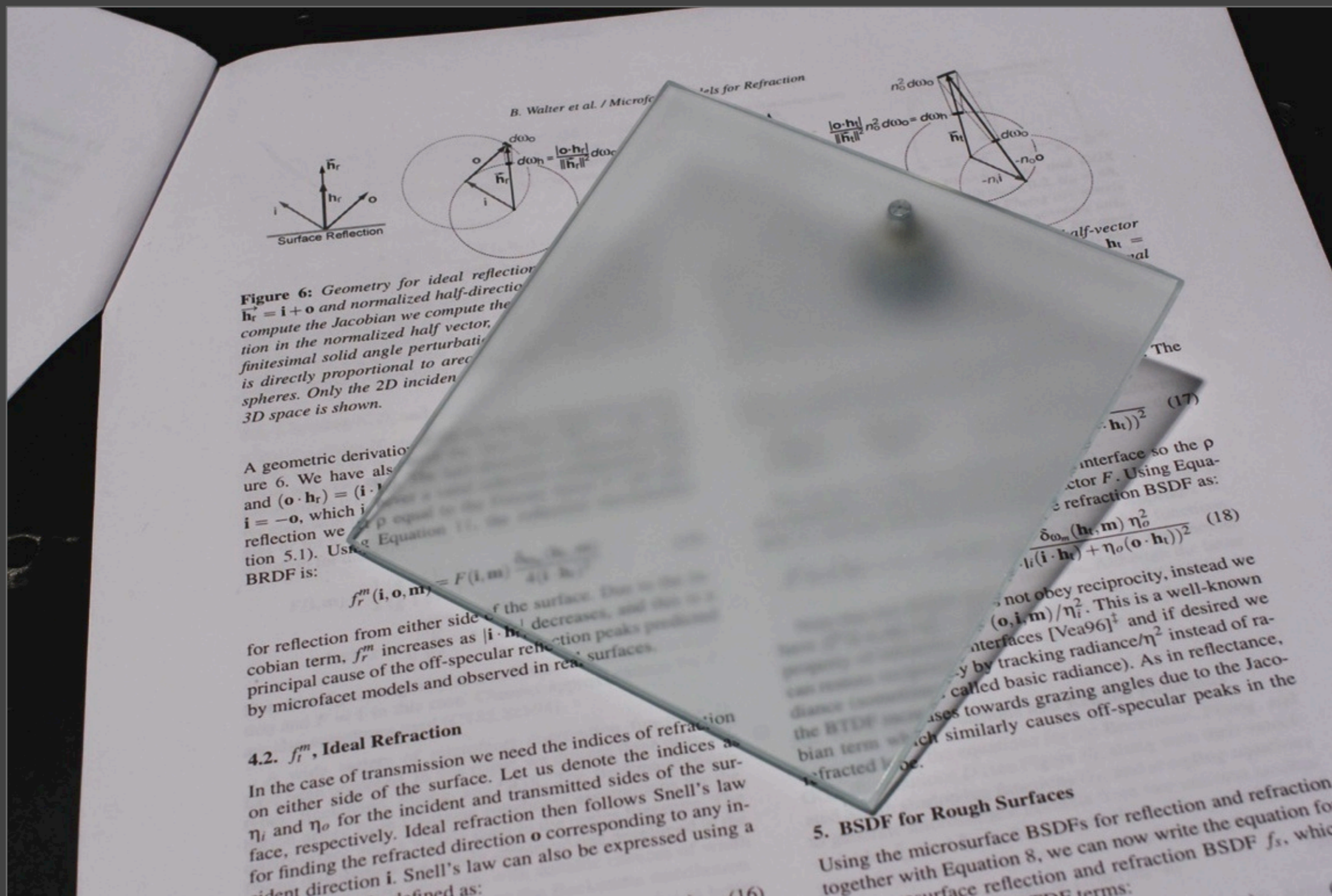


Figure 6: Geometry for ideal reflection. $\vec{h}_r = \vec{i} + \vec{o}$ and normalized half-direction \vec{h}_r . To compute the Jacobian we compute the perturbation in the normalized half vector, $d\vec{h}_r$. A finitesimal solid angle perturbation $d\omega_o$ is directly proportional to area dA on the sphere. Only the 2D incident plane in 3D space is shown.

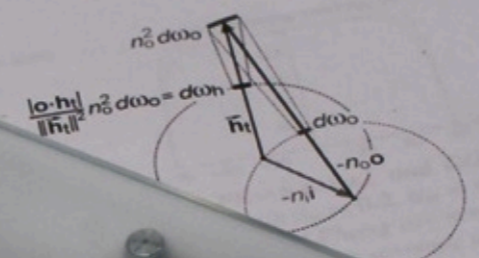
A geometric derivation of Equation 6. We have also shown that $(\vec{o} \cdot \vec{h}_r) = (\vec{i} \cdot \vec{h}_r)$ and $\vec{i} = -\vec{o}$, which is true for reflection where $\rho = 1$ (Equation 5.1). Using Equation 11, the reflection BRDF is:

$$f_r^m(\vec{i}, \vec{o}, \vec{m}) = F(\vec{i}, \vec{m}) \frac{\delta\omega_m(\vec{h}_r, \vec{m})}{4(\vec{i} \cdot \vec{h}_r)^2}$$

for reflection from either side of the surface. Due to the Jacobian term, f_r^m increases as $|\vec{i} \cdot \vec{h}_r|$ decreases, and this is a principal cause of the off-specular reflection peaks produced by microfacet models and observed in real surfaces.

4.2. f_t^m , Ideal Refraction

In the case of transmission we need the indices of refraction on either side of the surface. Let us denote the indices as η_i and η_o for the incident and transmitted sides of the surface, respectively. Ideal refraction then follows Snell's law for finding the refracted direction \vec{o} corresponding to any incident direction \vec{i} . Snell's law can also be expressed using a vector defined as:



$$\frac{\delta\omega_m(\vec{h}_t, \vec{m})}{4(\vec{i} \cdot \vec{h}_t)^2} \quad (17)$$

interface so the ρ factor F . Using Equation 11, the refraction BSDF is:

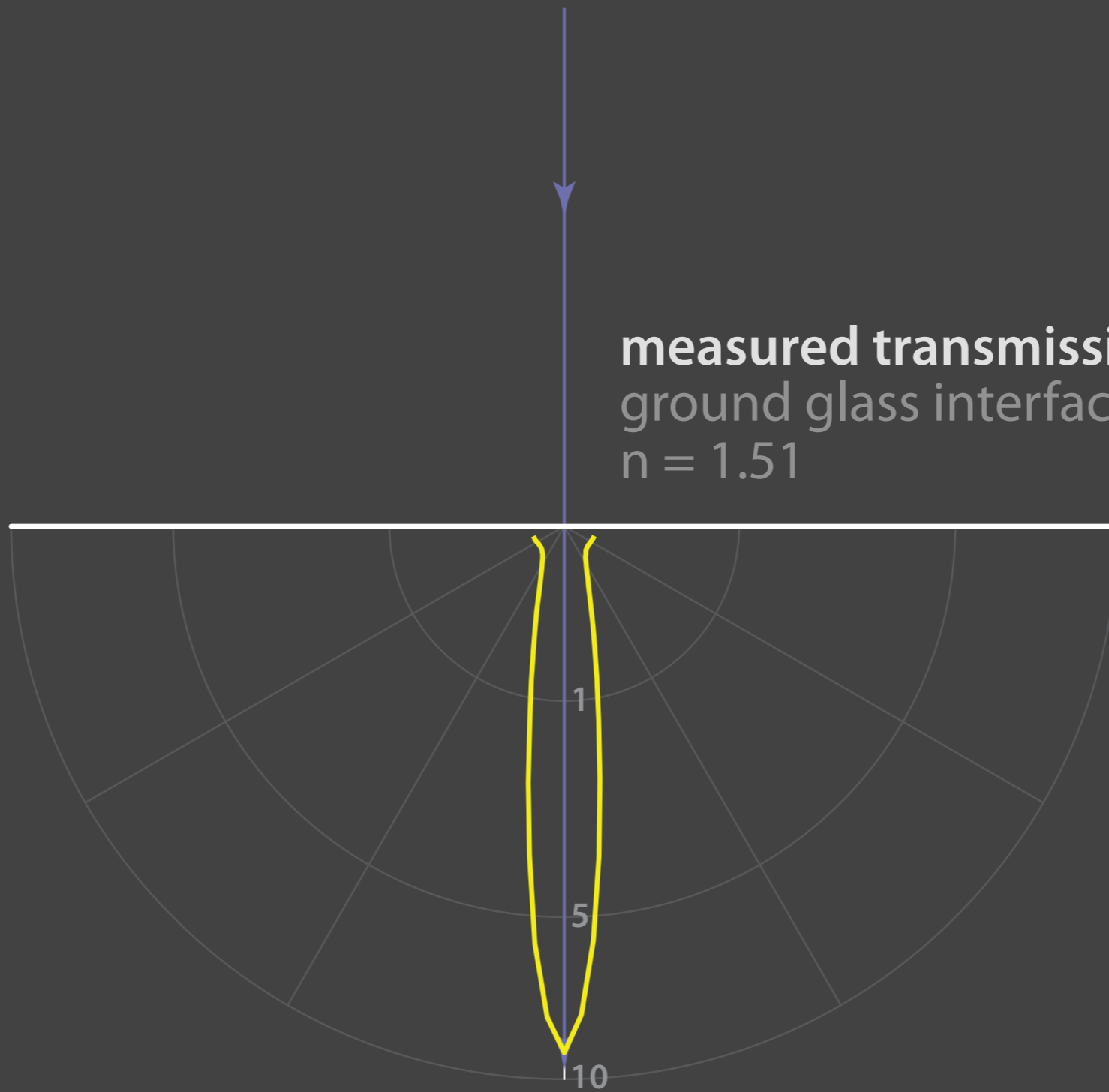
$$\frac{\delta\omega_m(\vec{h}_t, \vec{m}) \eta_o^2}{4(\vec{i} \cdot \vec{h}_t + \eta_o(\vec{o} \cdot \vec{h}_t))^2} \quad (18)$$

do not obey reciprocity, instead we use $(\vec{o}, \vec{i}, \vec{m})/\eta_i^2$. This is a well-known property of interfaces [Vea96]² and if desired we can remove reciprocity by tracking radiance/ η^2 instead of radiance (sometimes called basic radiance). As in reflection, the BSDF increases towards grazing angles due to the Jacobian term which similarly causes off-specular peaks in the refracted BSDF.

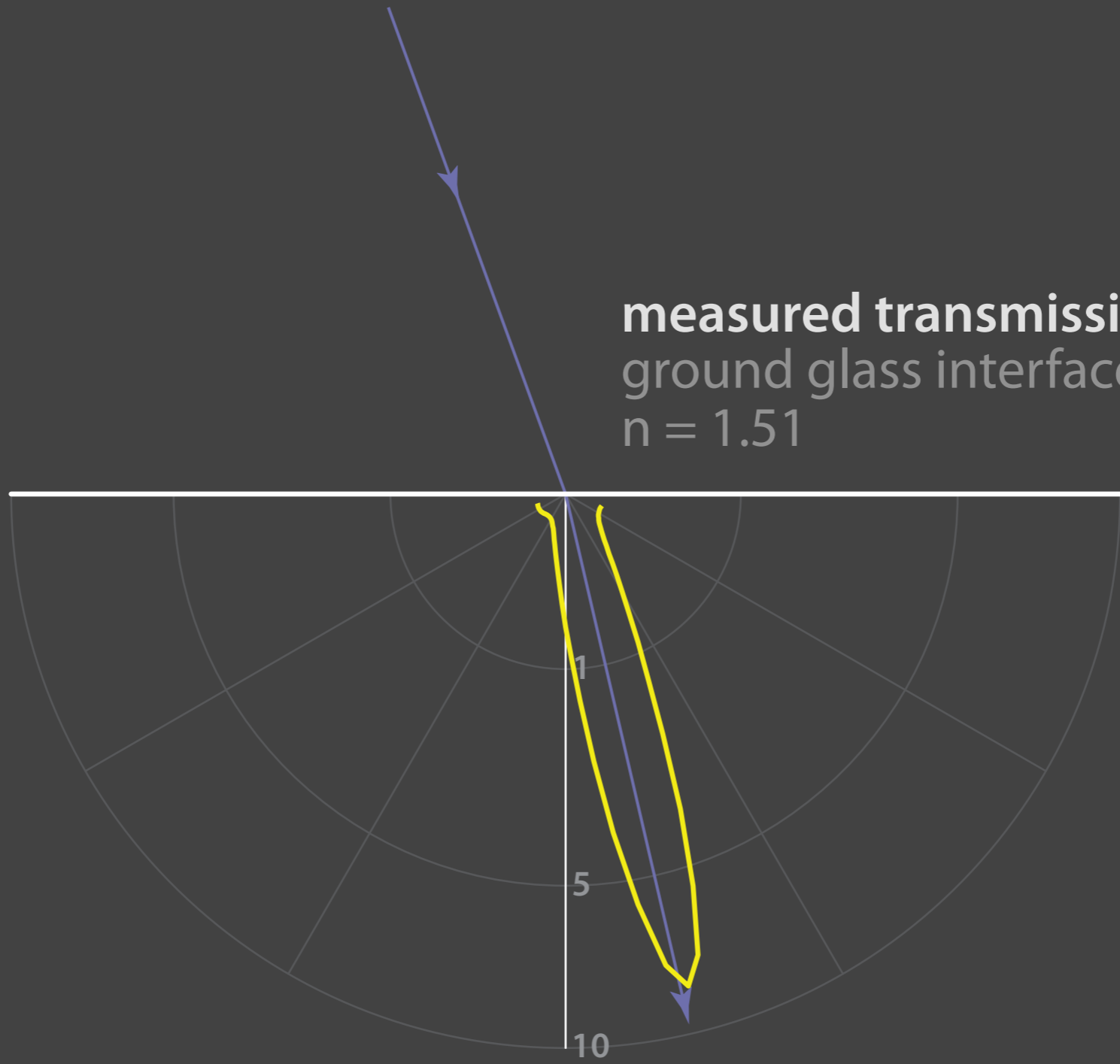
5. BSDF for Rough Surfaces

Using the microsurface BSDFs for reflection and refraction together with Equation 8, we can now write the equation for surface reflection and refraction BSDF f_s , which is defined in terms:

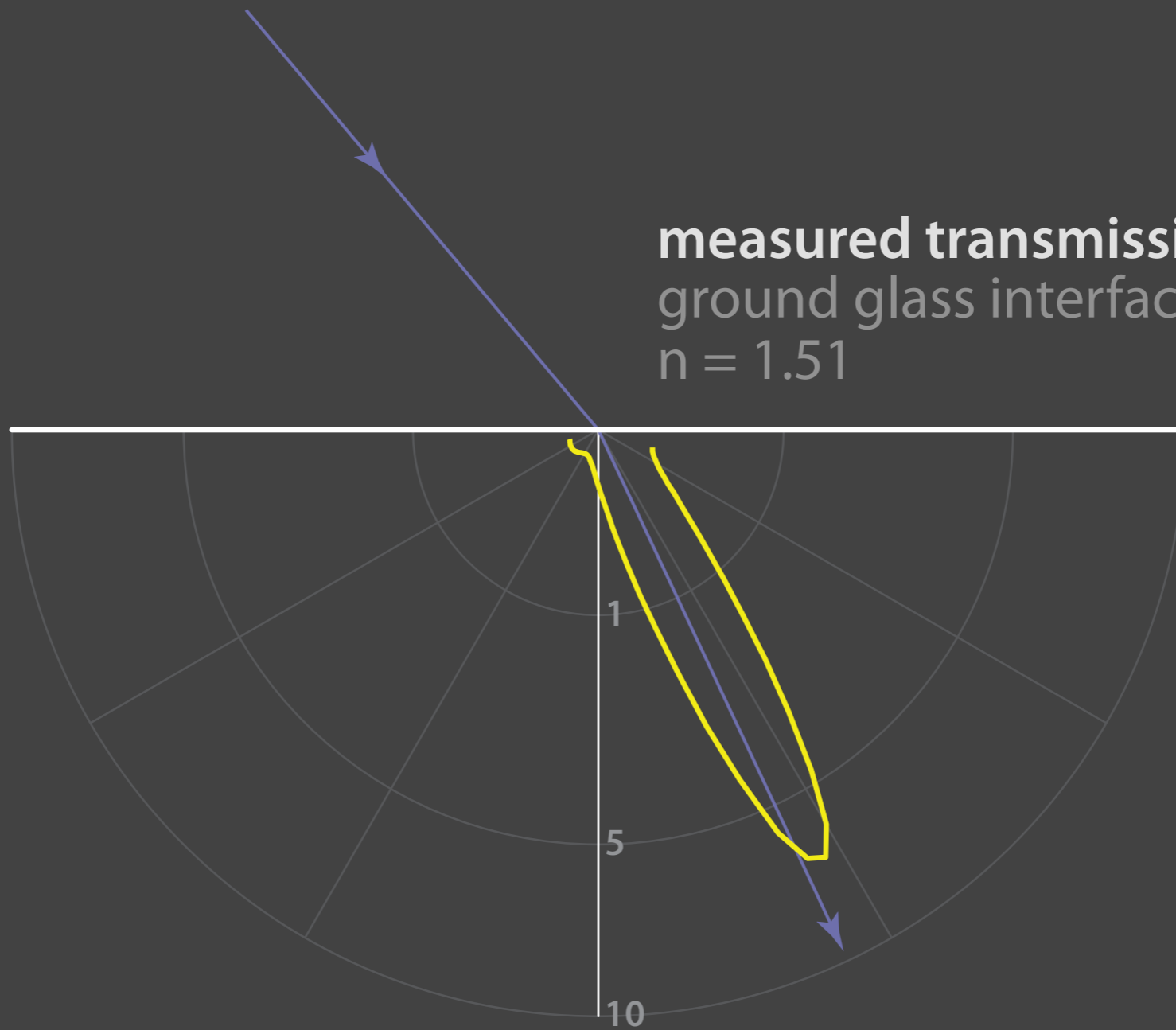
measured transmission
ground glass interface
 $n = 1.51$



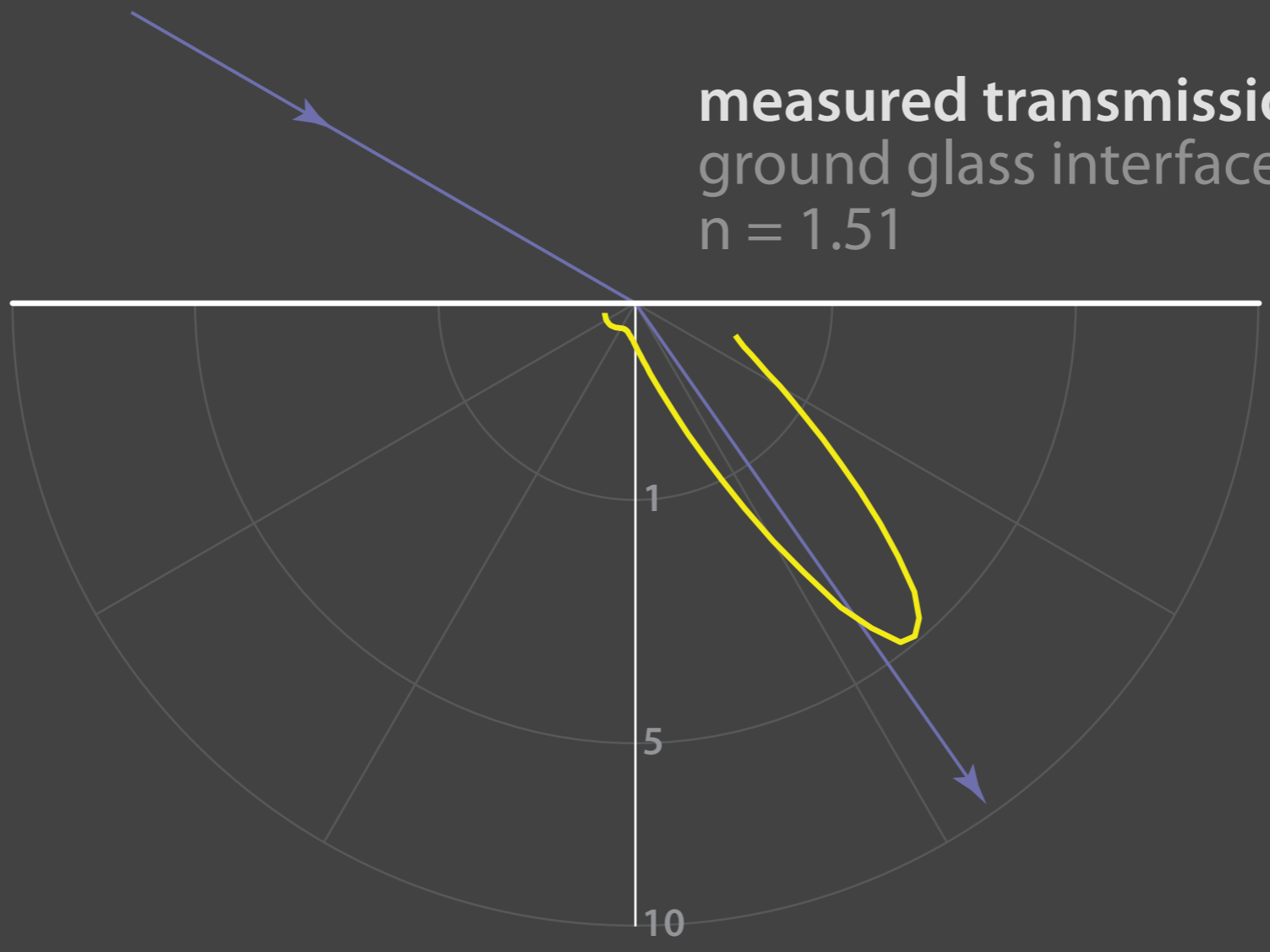
measured transmission
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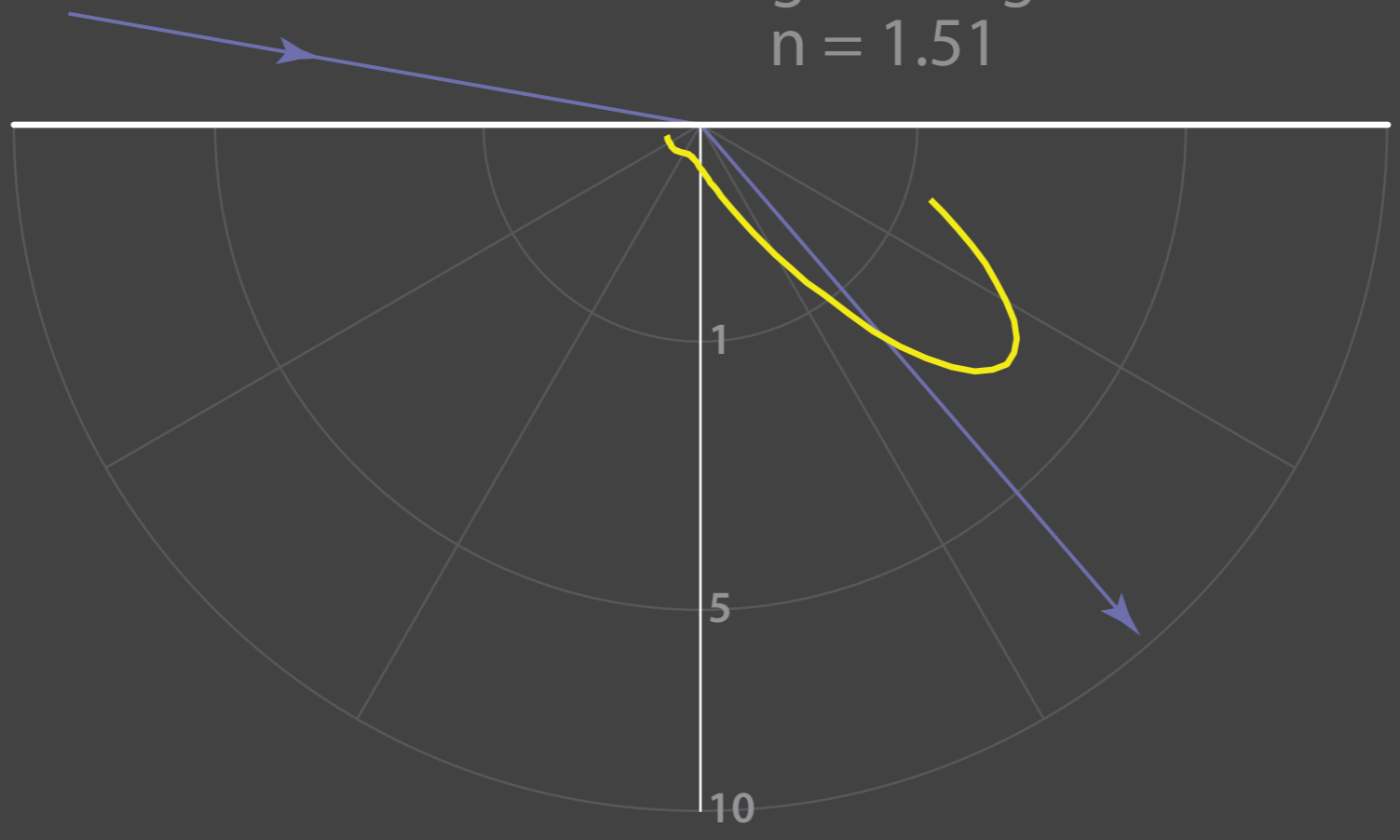
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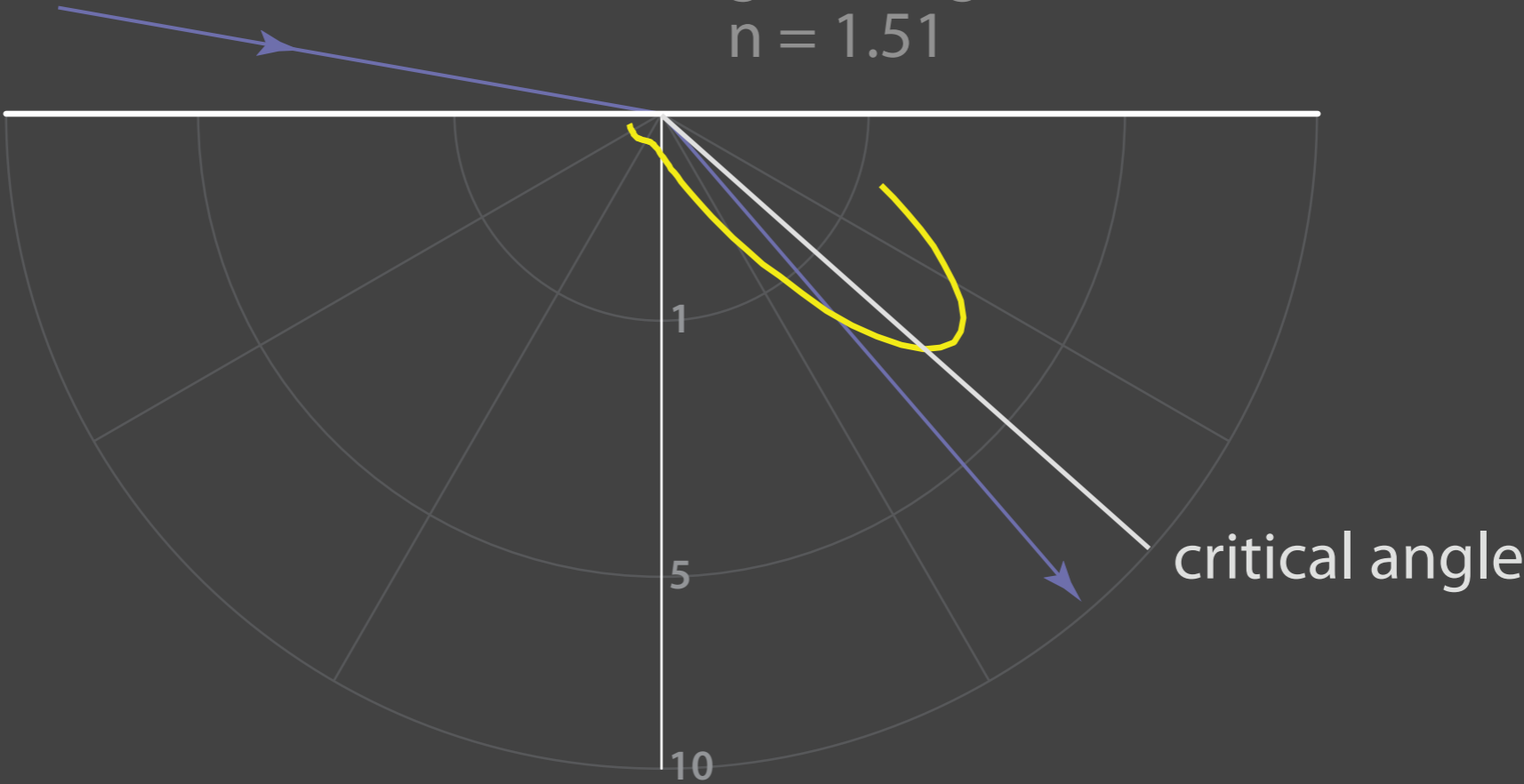
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measured transmission
ground glass interface
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Prior work

Microfacet models in graphics

- Blinn 1977 introduced Torrance-Sparrow model
- Cook & Torrance 1982 Torrance-Sparrow specular
- Ashikhmin et al. 2000 microfacet BRDF generator
- Stam 2001 skin subsurface scattering model

Work outside graphics we build on

- Smith 1967 shadowing–masking framework
- Nee & Nee 2004 single-interface measurement idea

Contributions

Microfacet transmission model

- new geometric formulation
- clean, simple generalization of reflection

Microfacet distribution functions

- evaluate three choices against data
- new GGX distribution fits some surfaces better

Importance sampling

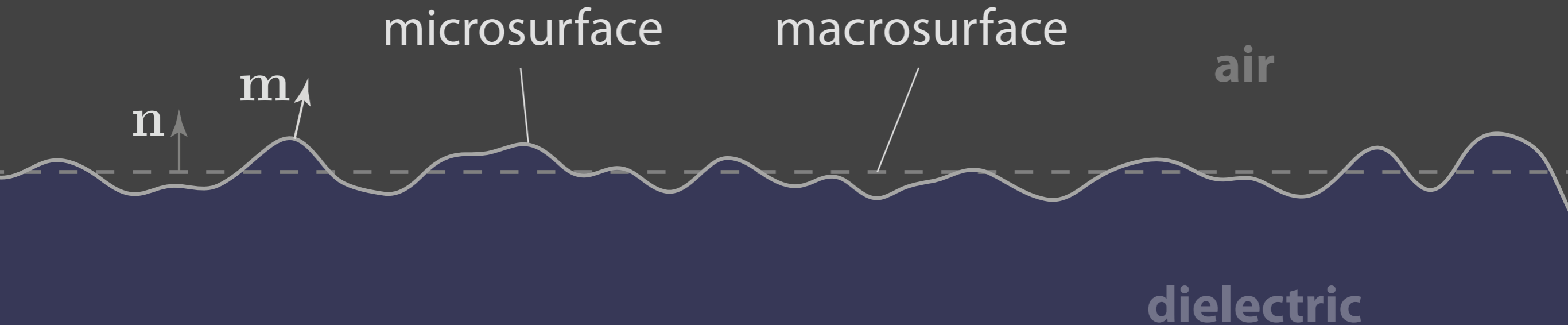
Measurement and validation

- single interface transmission

Microfacet scattering models

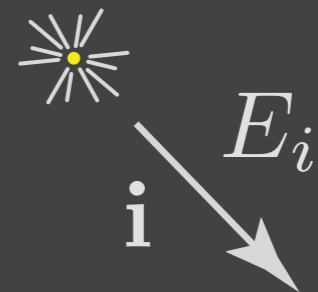
Assumptions

- rough dielectric surface
- single scattering

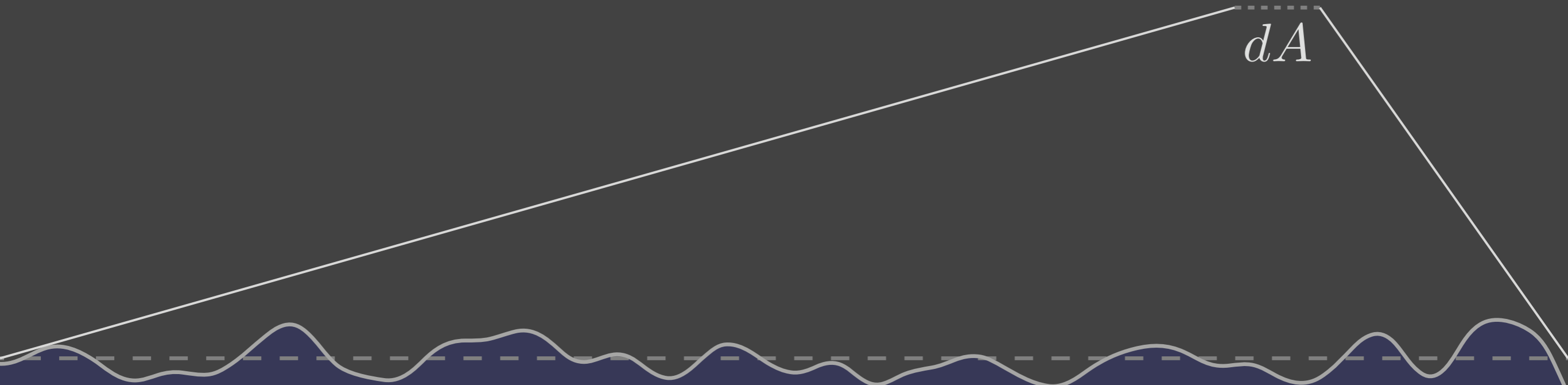


Microfacet reflection models

Incident irradiance E_i illuminates macrosurface area dA from direction \mathbf{i} .

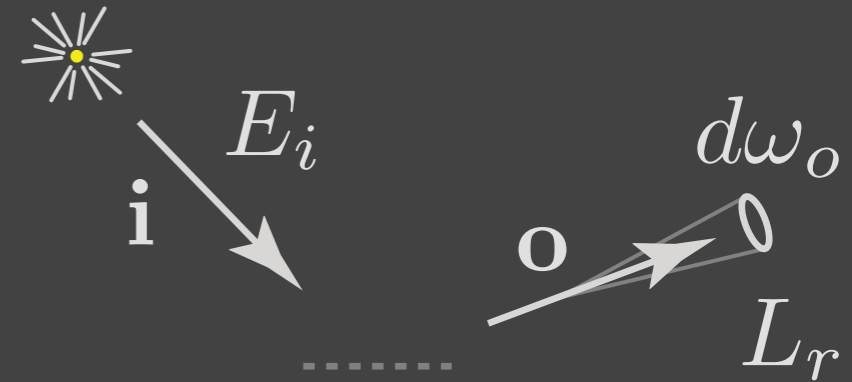


dA



Microfacet reflection models

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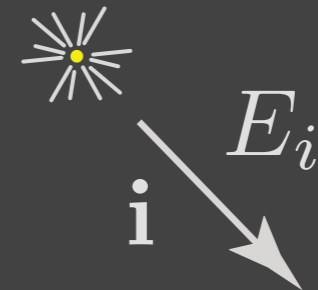


Reflected radiance L_r measured at direction \mathbf{o} in solid angle $d\omega_o$.

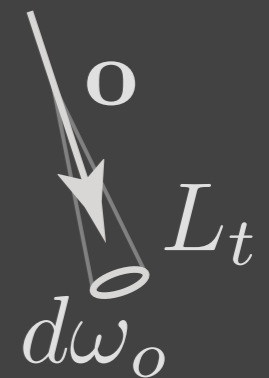
Bidirectional Reflectance Distribution Function: $f_r(\mathbf{i}, \mathbf{o}) = \frac{L_r}{E_i}$

Microfacet reflection models

Incident irradiance E_i illuminates macrosurface area dA from direction \mathbf{i} .



Reflected radiance L_r measured at direction \mathbf{o} in solid angle $d\omega_o$.



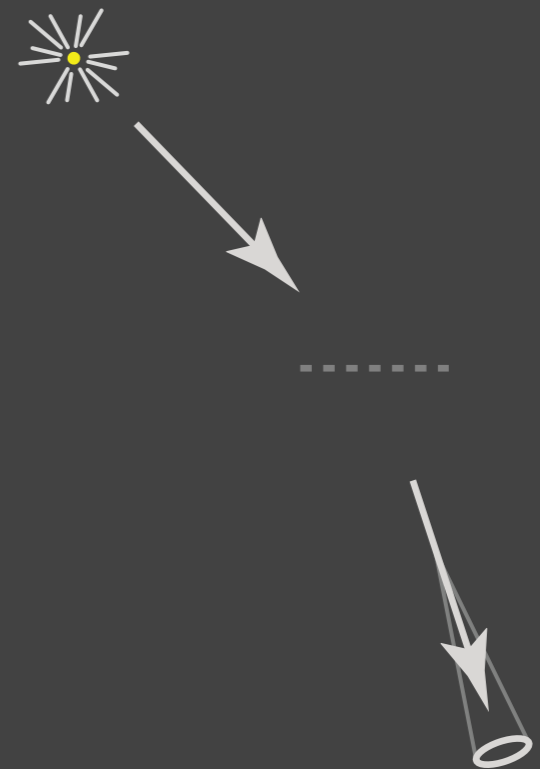
Bidirectional Reflectance Distribution Function: $f_r(\mathbf{i}, \mathbf{o}) = \frac{L_r}{E_i}$

Bidirectional Transmittance Distribution Function: $f_t(\mathbf{i}, \mathbf{o}) = \frac{L_t}{E_i}$

Reflection to transmission

Traditional microfacet reflection model:

$$f_r(\mathbf{i}, \mathbf{o}) = \frac{F(\mathbf{i}, \mathbf{m}) D(\mathbf{m}) G(\mathbf{i}, \mathbf{o}, \mathbf{m})}{4|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|}$$



Reflection to transmission

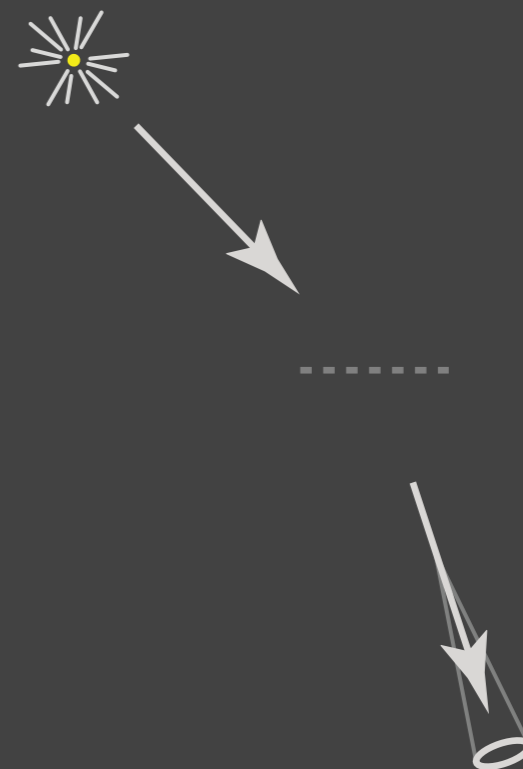
Traditional microfacet reflection model:

optical

geometric

$$f_r(\mathbf{i}, \mathbf{o}) = \frac{F(\mathbf{i}, \mathbf{m}) D(\mathbf{m}) G(\mathbf{i}, \mathbf{o}, \mathbf{m})}{4|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|}$$

We generalize the geometric analysis dealing with the **surface area** where scattering occurs.



“half-vector” function

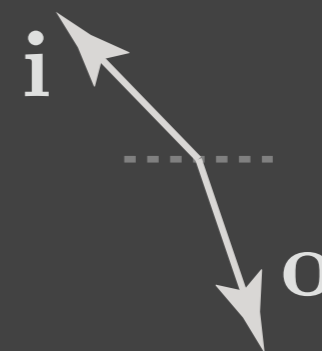
$$\mathbf{h}(\mathbf{i}, \mathbf{o})$$

normal distribution

$$D(\mathbf{m})$$

shadowing–masking

$$G(\mathbf{i}, \mathbf{o}, \mathbf{m})$$

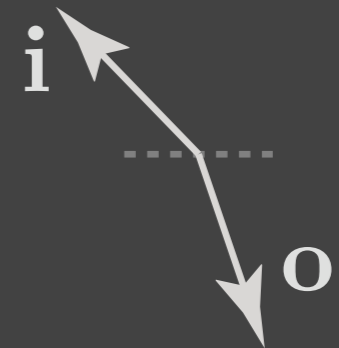


“half-vector” function
 $\mathbf{h}(\mathbf{i}, \mathbf{o})$

normal distribution
 $D(\mathbf{m})$

shadowing–masking
 $G(\mathbf{i}, \mathbf{o}, \mathbf{m})$

\mathbf{h} gives the one microsurface normal \mathbf{m} that will scatter light from \mathbf{i} to \mathbf{o} .



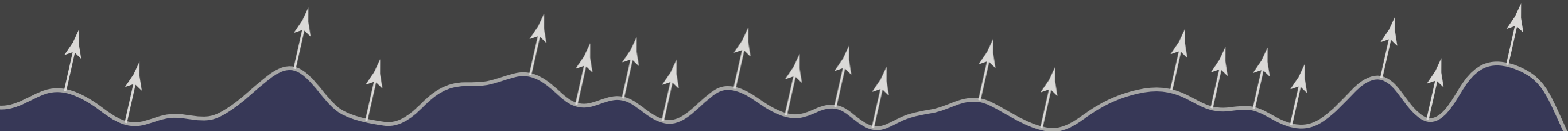
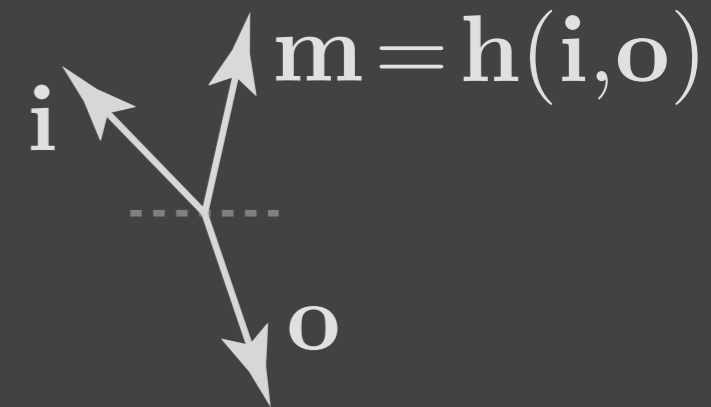
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- selects \mathbf{m}



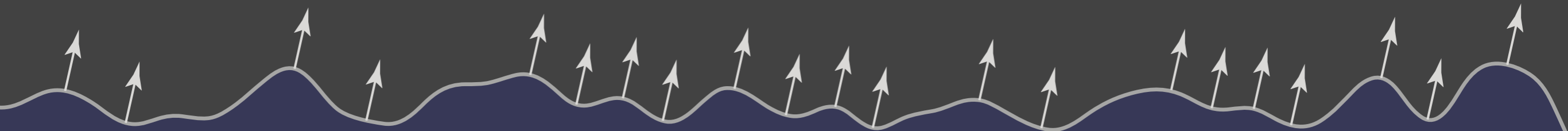
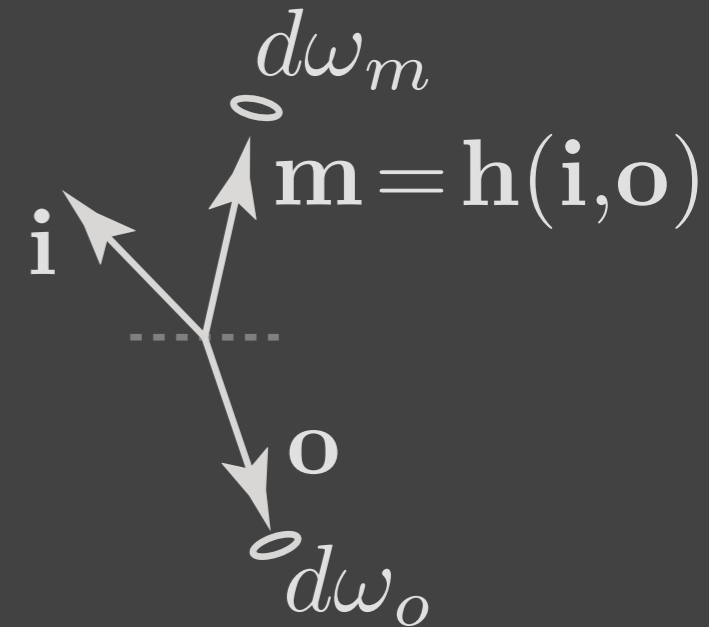
“half-vector” function
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\mathbf{h} gives the one microsurface normal \mathbf{m} that will scatter light from \mathbf{i} to \mathbf{o} .

- selects \mathbf{m}
- determines size of $d\omega_m$

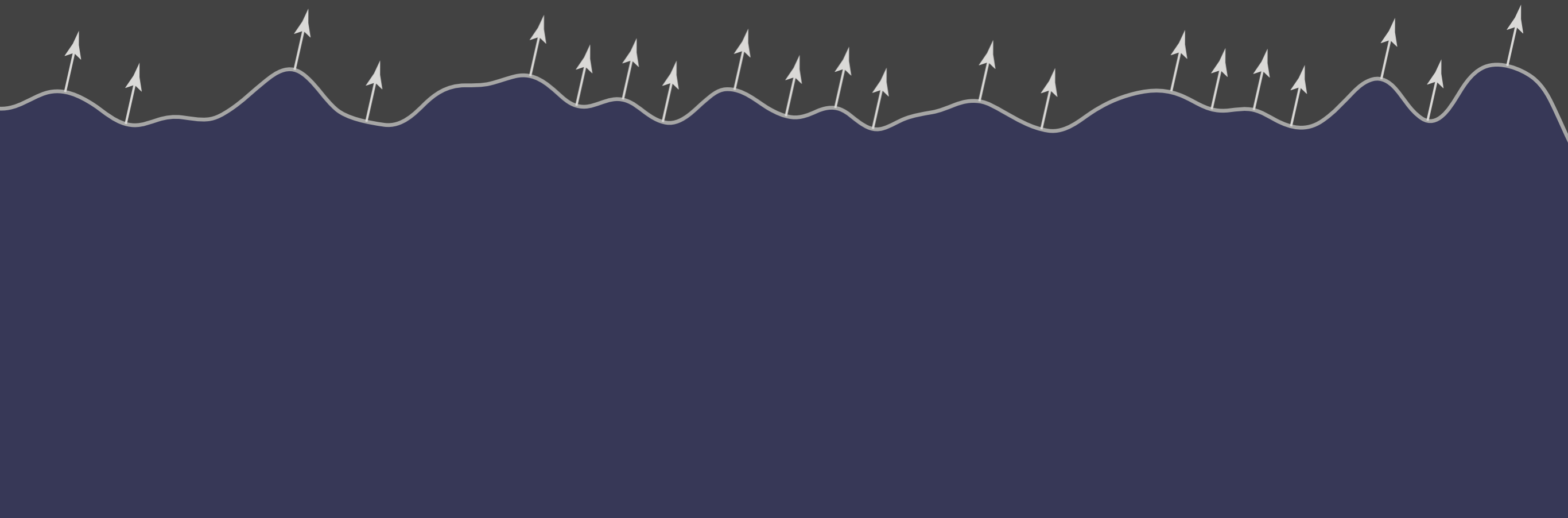
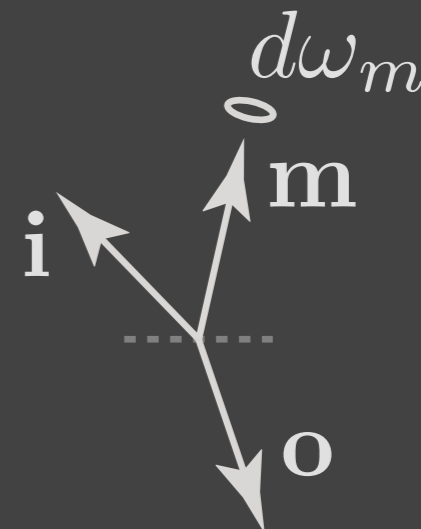


“half-vector” function
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shadowing–masking
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“half-vector” function

$$\mathbf{h}(\mathbf{i}, \mathbf{o})$$

normal distribution

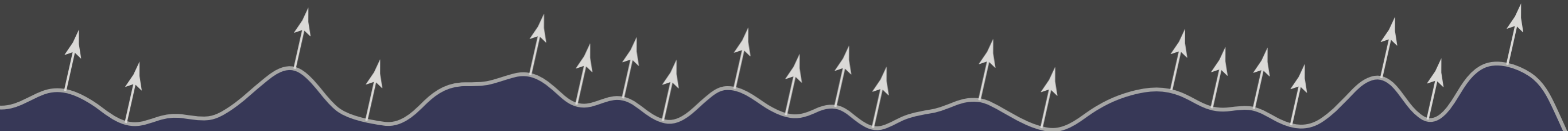
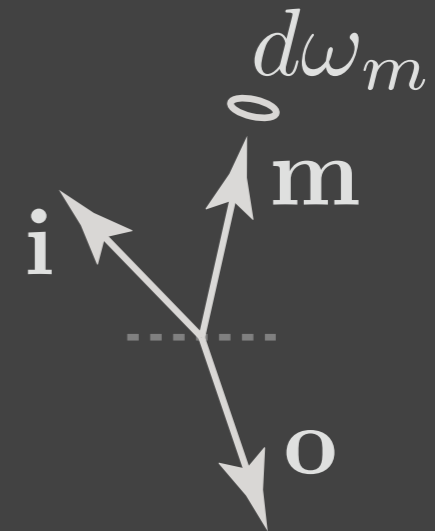
$$D(\mathbf{m})$$

shadowing–masking

$$G(\mathbf{i}, \mathbf{o}, \mathbf{m})$$

\mathbf{h} gives the one microsurface normal \mathbf{m} that will scatter light from \mathbf{i} to \mathbf{o} .

D measures density of microsurface area with respect to microsurface normal \mathbf{m} .



“half-vector” function

$$\mathbf{h}(\mathbf{i}, \mathbf{o})$$

normal distribution

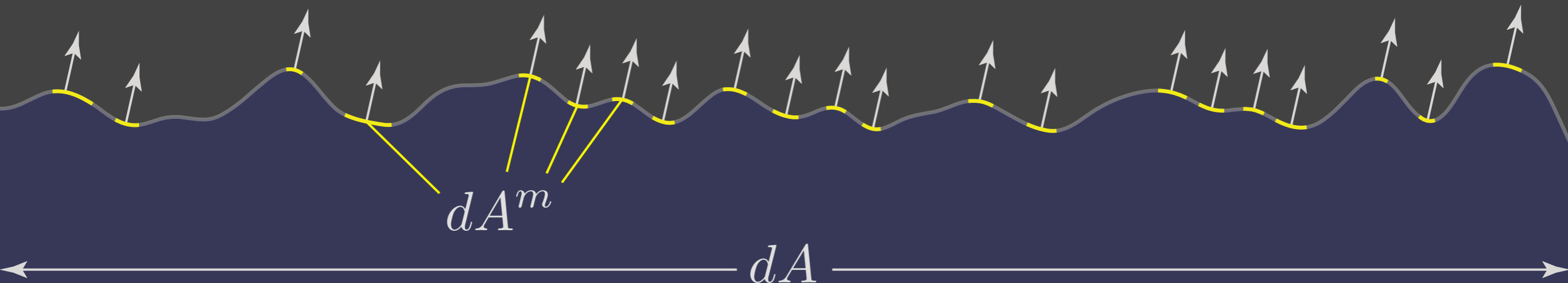
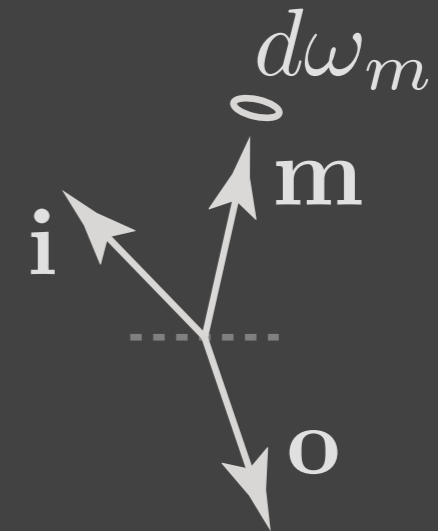
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$$dA^m = D(\mathbf{m}) d\omega_m dA$$

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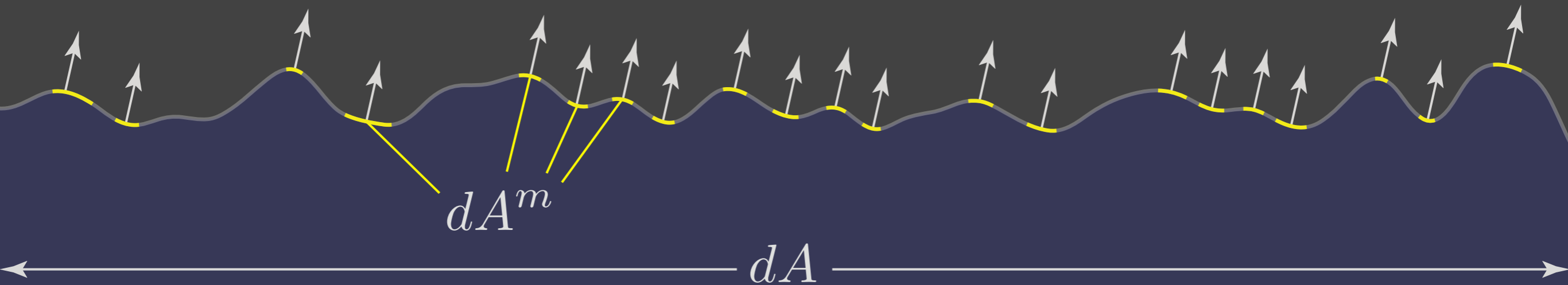
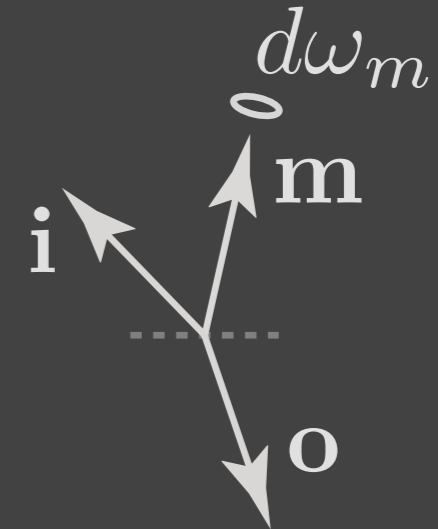
shadowing–masking

$$G(\mathbf{i}, \mathbf{o}, \mathbf{m})$$

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D measures density of microsurface area with respect to microsurface normal \mathbf{m} .

G measures the fraction of points with microsurface normal \mathbf{m} that are visible.



$$dA^m = D(\mathbf{m}) d\omega_m dA$$

“half-vector” function

$$\mathbf{h}(\mathbf{i}, \mathbf{o})$$

normal distribution

$$D(\mathbf{m})$$

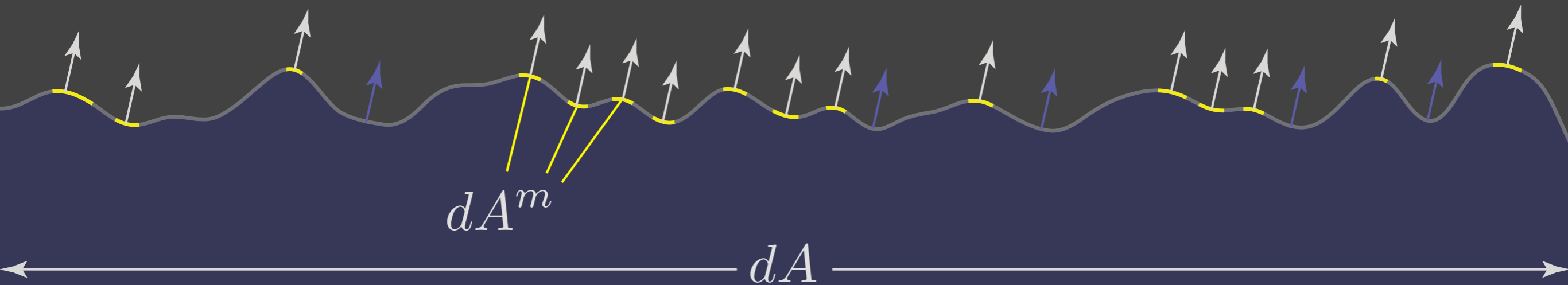
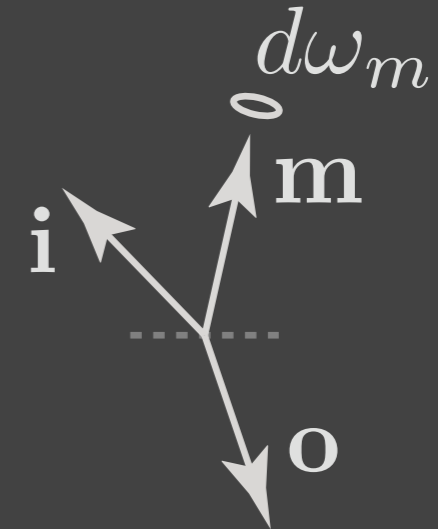
shadowing–masking

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$$dA^m = G(\mathbf{i}, \mathbf{o}, \mathbf{m}) D(\mathbf{m}) d\omega_m dA$$

“half-vector” function

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shadowing–masking

$$G(\mathbf{i}, \mathbf{o}, \mathbf{m})$$

For reflection or transmission:

$$f_s(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{m}|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \rho(\mathbf{i}, \mathbf{o}) \frac{dA^m}{dA d\omega_o}$$

$$dA^m = G(\mathbf{i}, \mathbf{o}, \mathbf{m}) D(\mathbf{m}) d\omega_m dA$$

“half-vector” function

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$$dA^m = G(\mathbf{i}, \mathbf{o}, \mathbf{m}) D(\mathbf{m}) d\omega_m dA$$

“half-vector” function

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For reflection or transmission:

easy to generalize

$$f_s(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{m}|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \rho(\mathbf{i}, \mathbf{o}) D(\mathbf{m}) G(\mathbf{i}, \mathbf{o}, \mathbf{m}) \frac{d\omega_m}{d\omega_o}$$

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For reflection or transmission:

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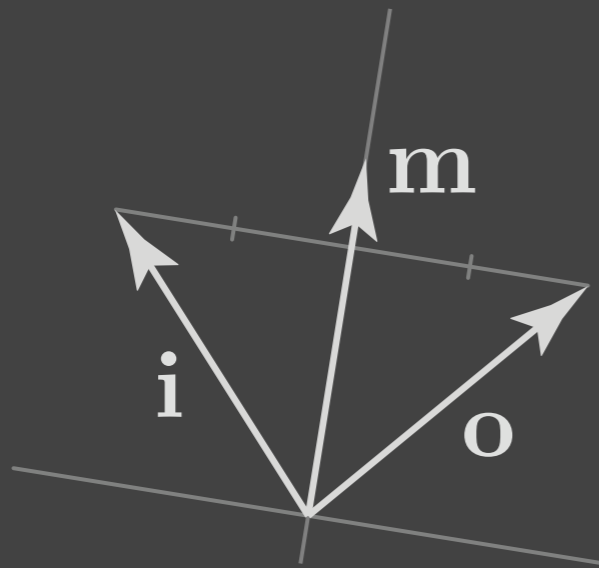
$$f_s(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{m}|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \rho(\mathbf{i}, \mathbf{o}) D(\mathbf{m}) G(\mathbf{i}, \mathbf{o}, \mathbf{m}) \frac{d\omega_m}{d\omega_o}$$

key contribution

$$dA^m = G(\mathbf{i}, \mathbf{o}, \mathbf{m}) D(\mathbf{m}) d\omega_m dA$$

Construction of half-vector

reflection



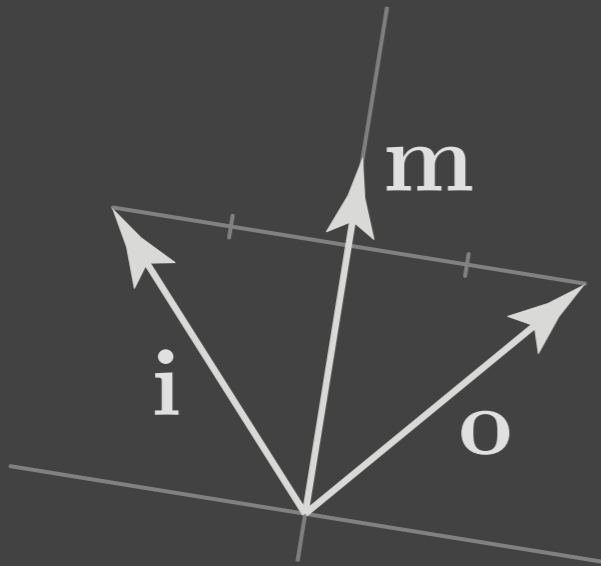
$\mathbf{i} + \mathbf{o}$ parallel to \mathbf{m}

refraction

Construction of half-vector

reflection

$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



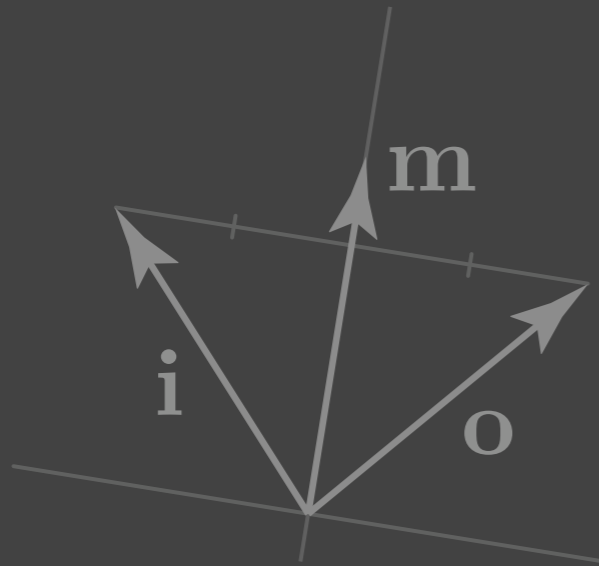
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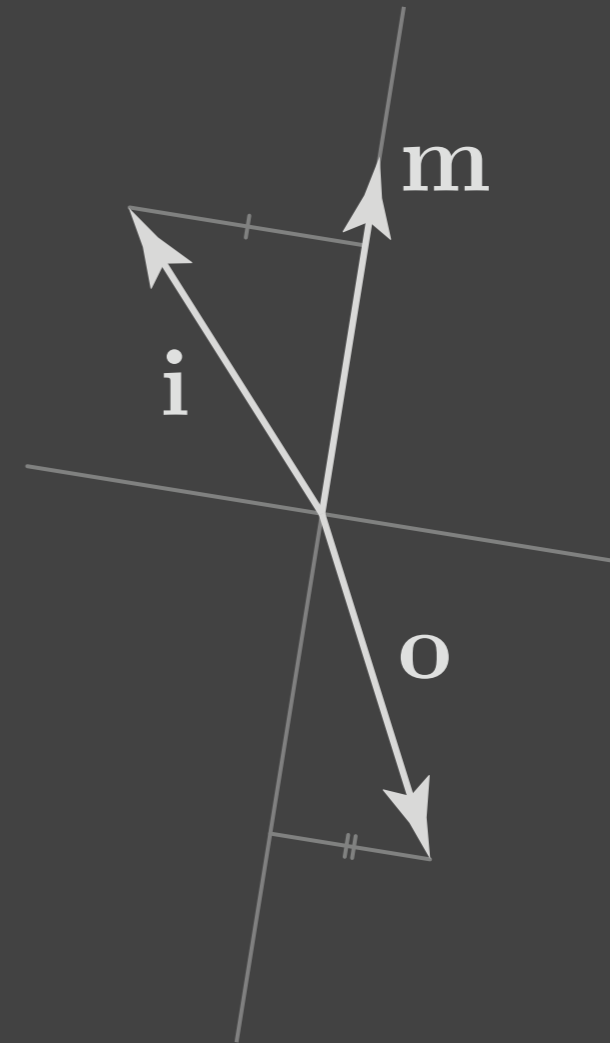
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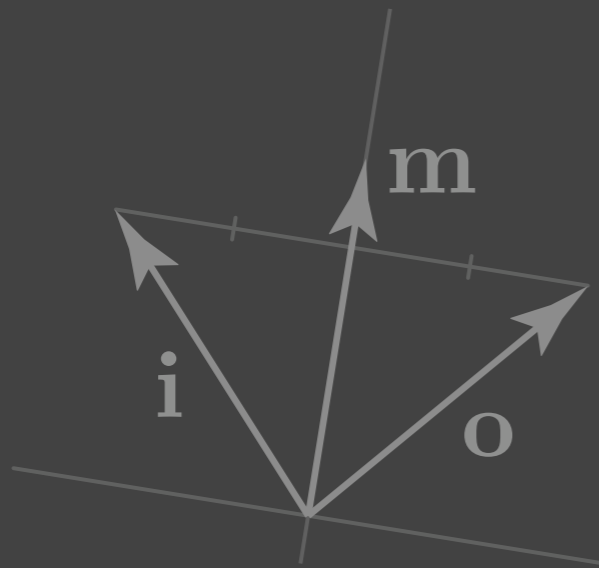
refraction



Construction of half-vector

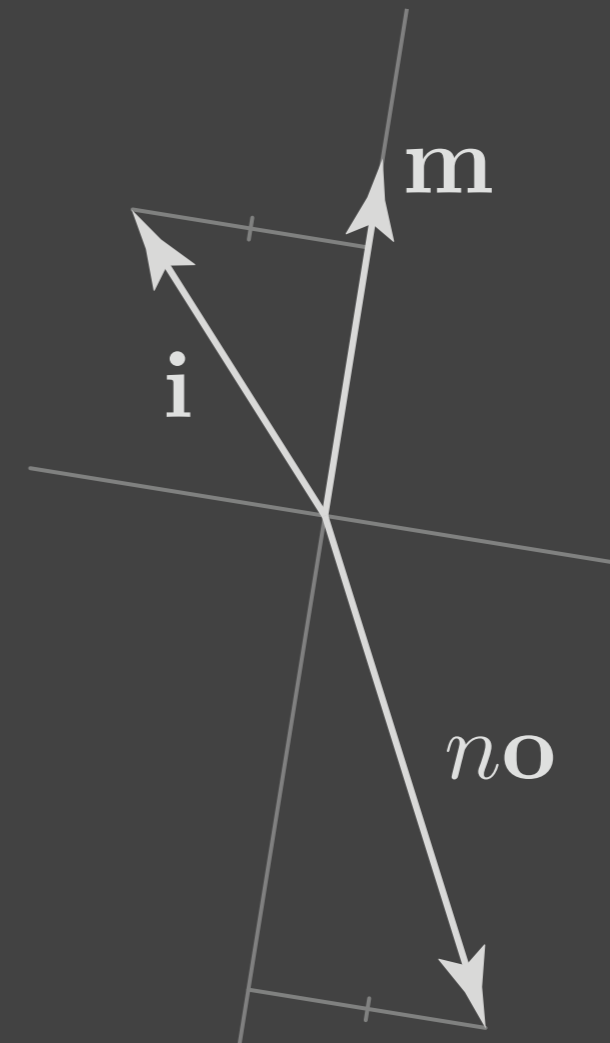
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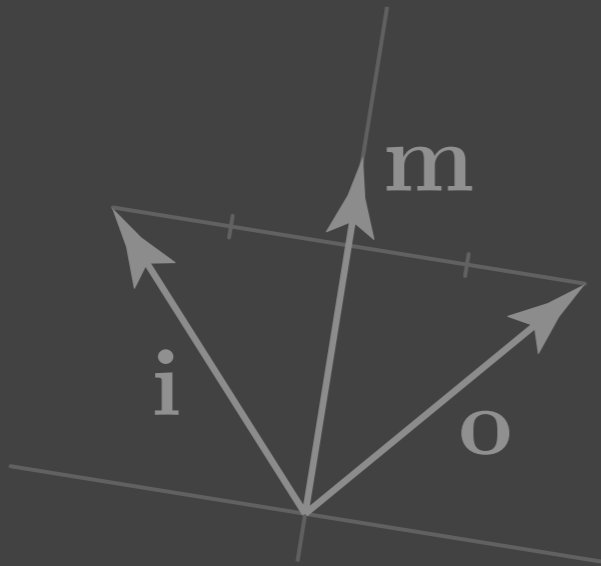


$\mathbf{i} + n\mathbf{o}$ parallel to \mathbf{m}

Construction of half-vector

reflection

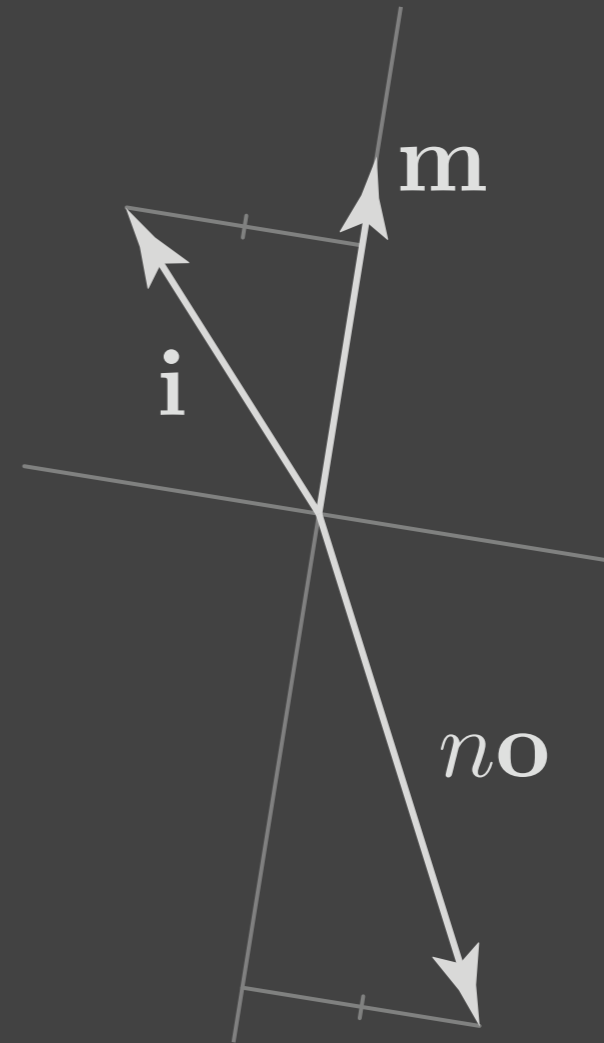
$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



$\mathbf{i} + \mathbf{o}$ parallel to \mathbf{m}

refraction

$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$



$\mathbf{i} + n\mathbf{o}$ parallel to \mathbf{m}

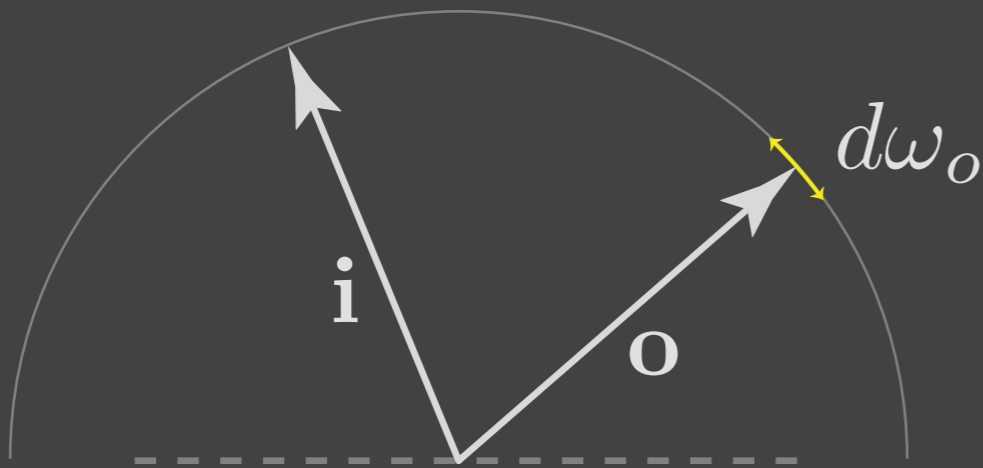
Construction of half-vector solid angle

reflection

$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$

refraction

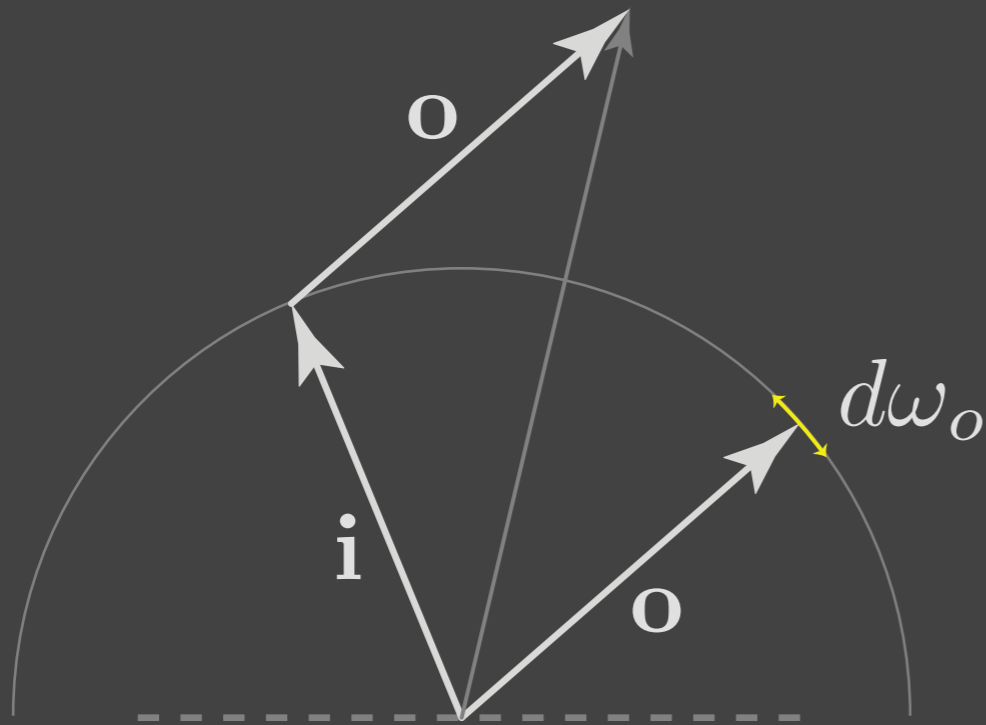
$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$



Construction of half-vector solid angle

reflection

$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



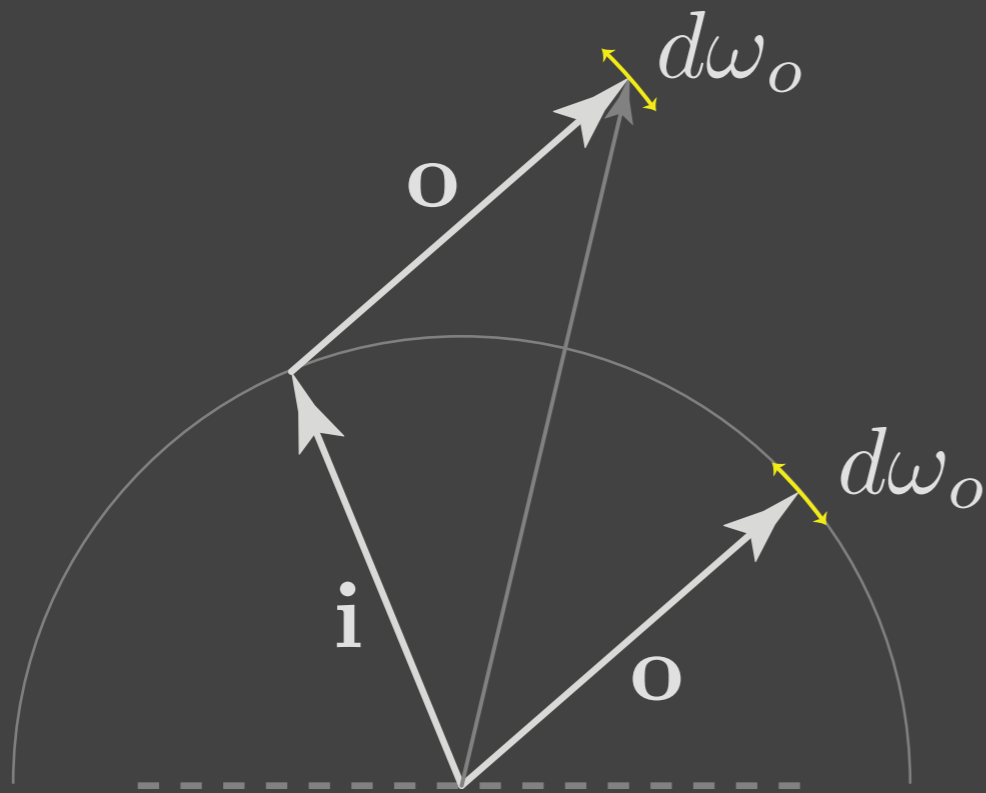
refraction

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Construction of half-vector solid angle

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$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



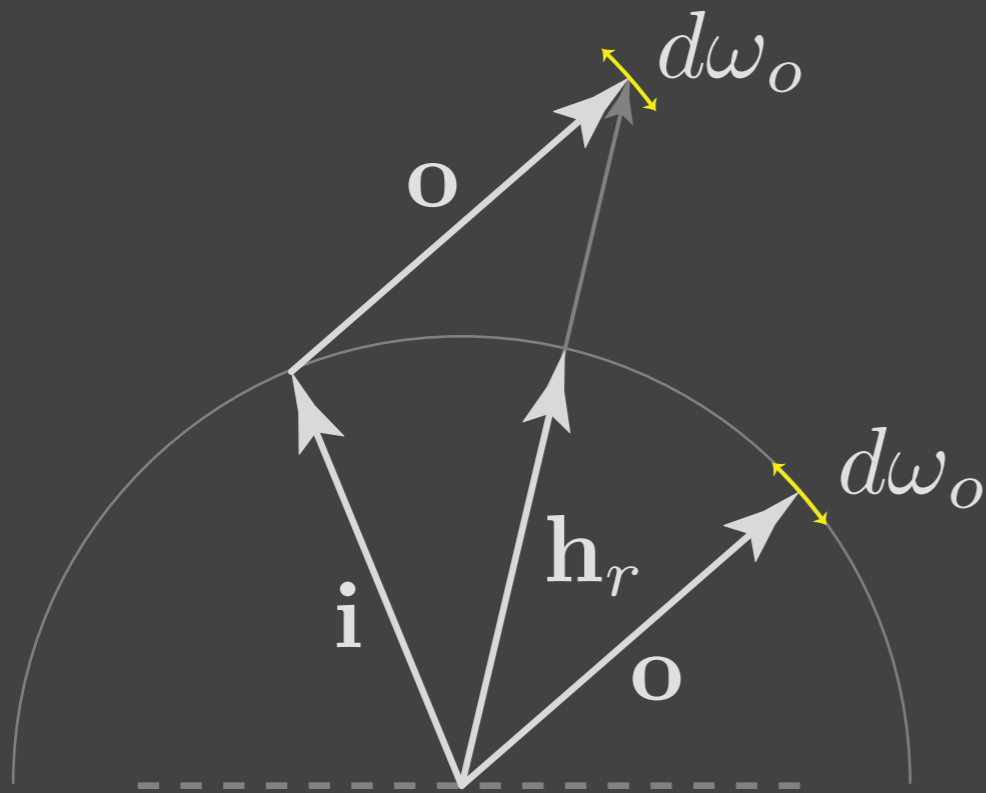
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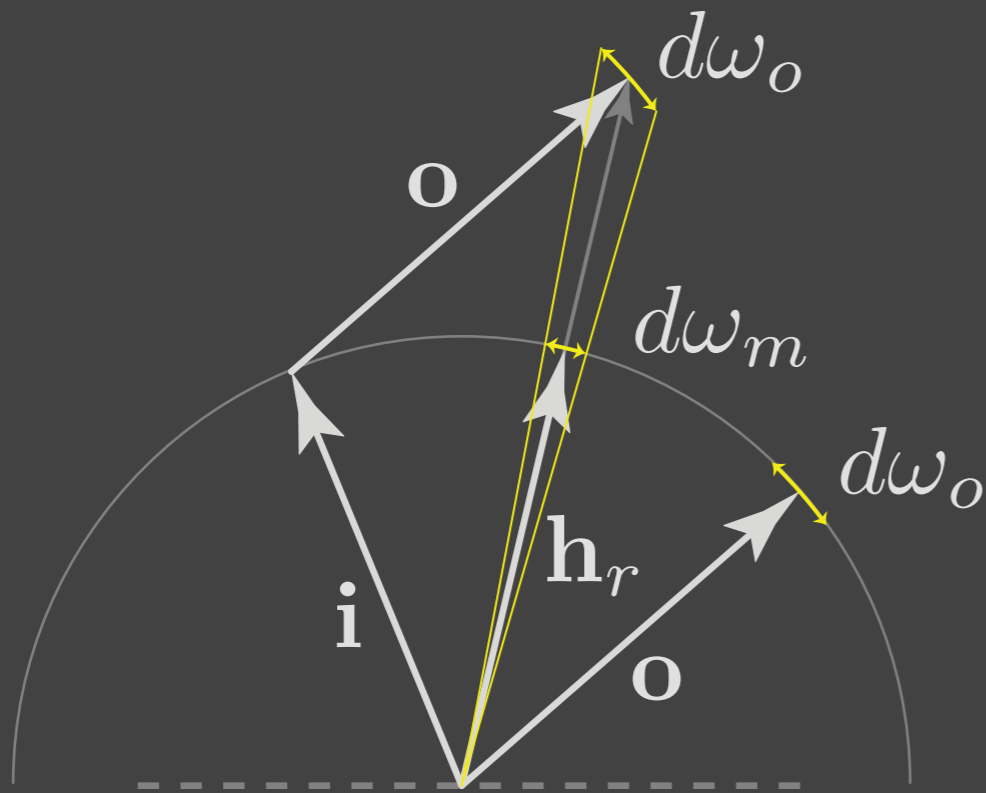
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refraction

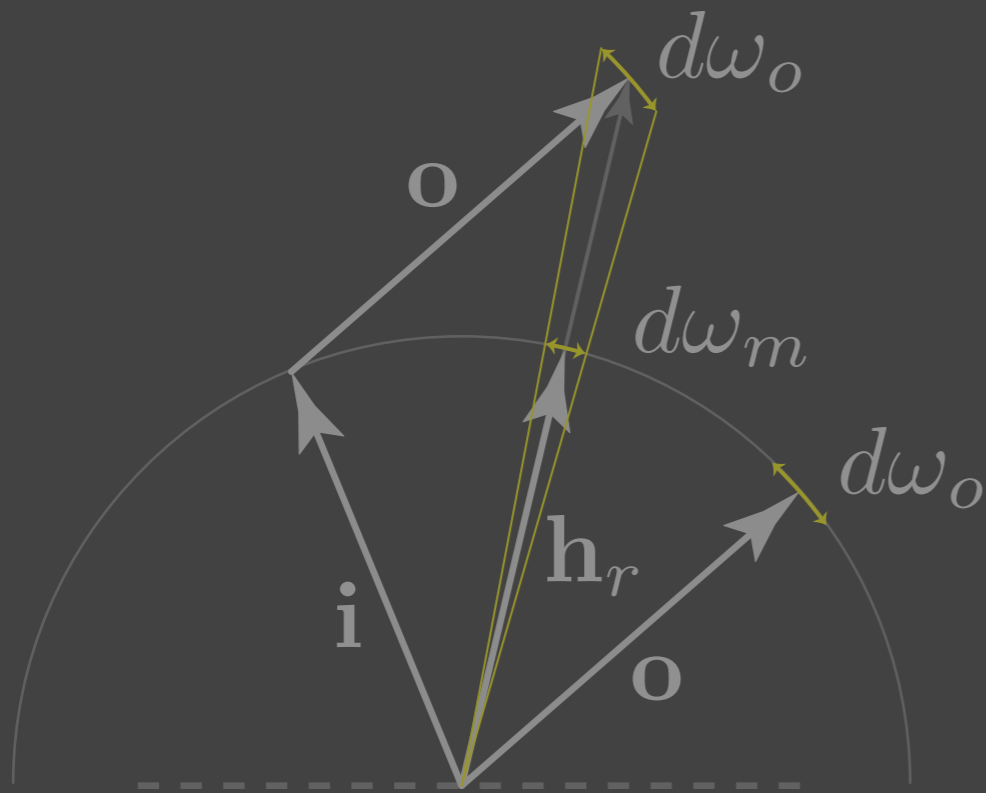
$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$

$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2} d\omega_o$$

Construction of half-vector solid angle

reflection

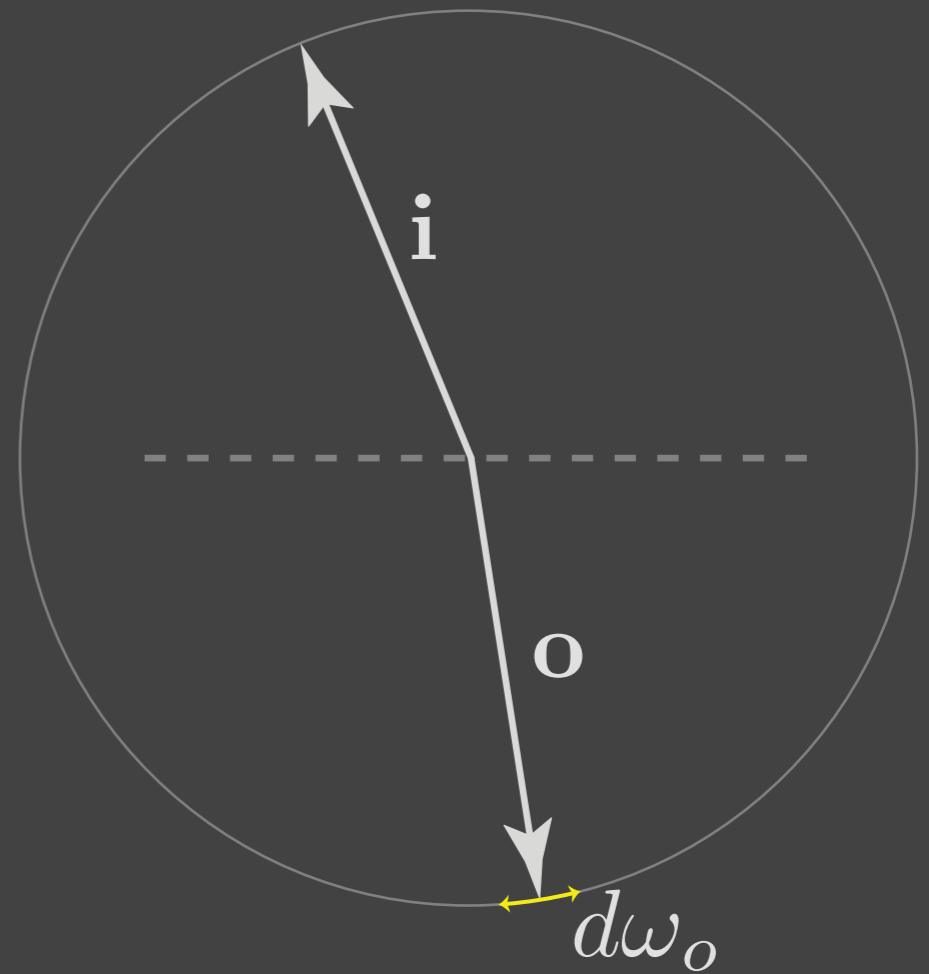
$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2} d\omega_o$$

refraction

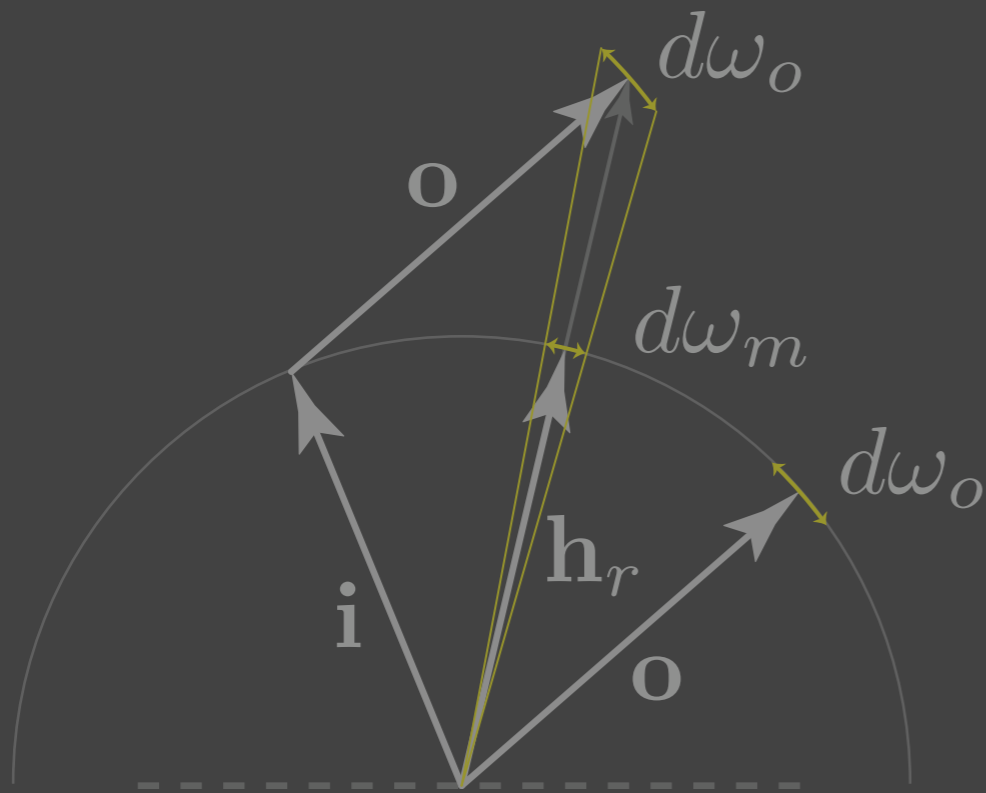
$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$



Construction of half-vector solid angle

reflection

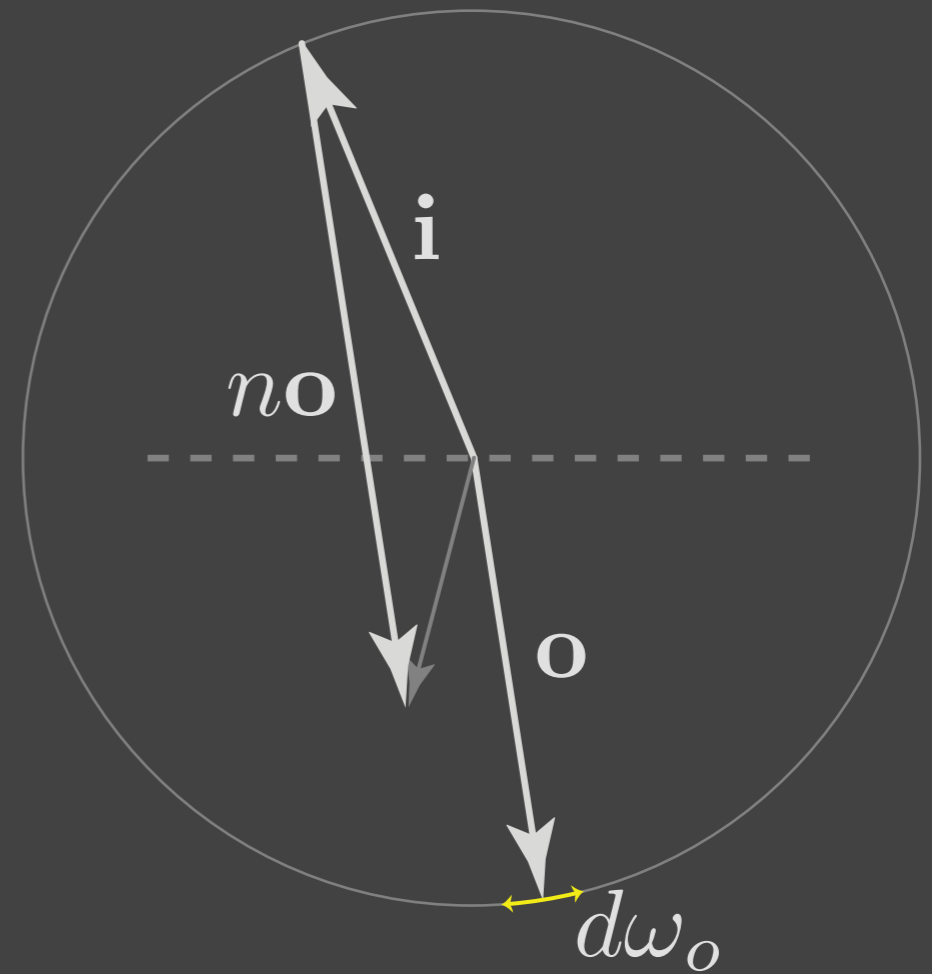
$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2} d\omega_o$$

refraction

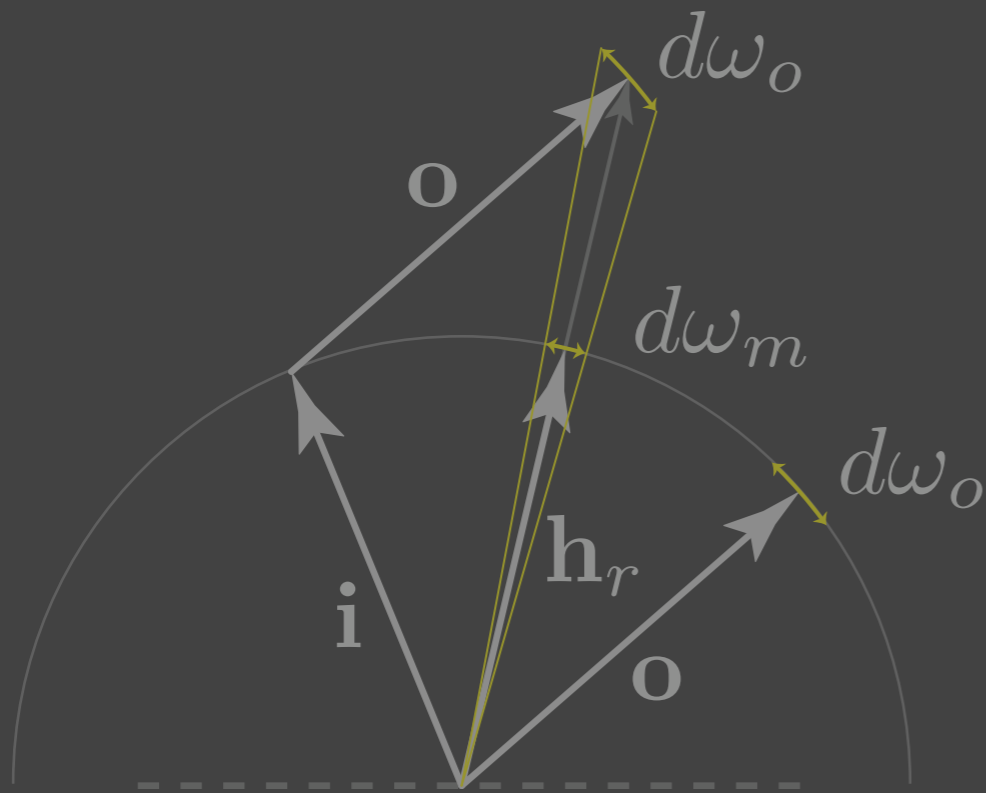
$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$



Construction of half-vector solid angle

reflection

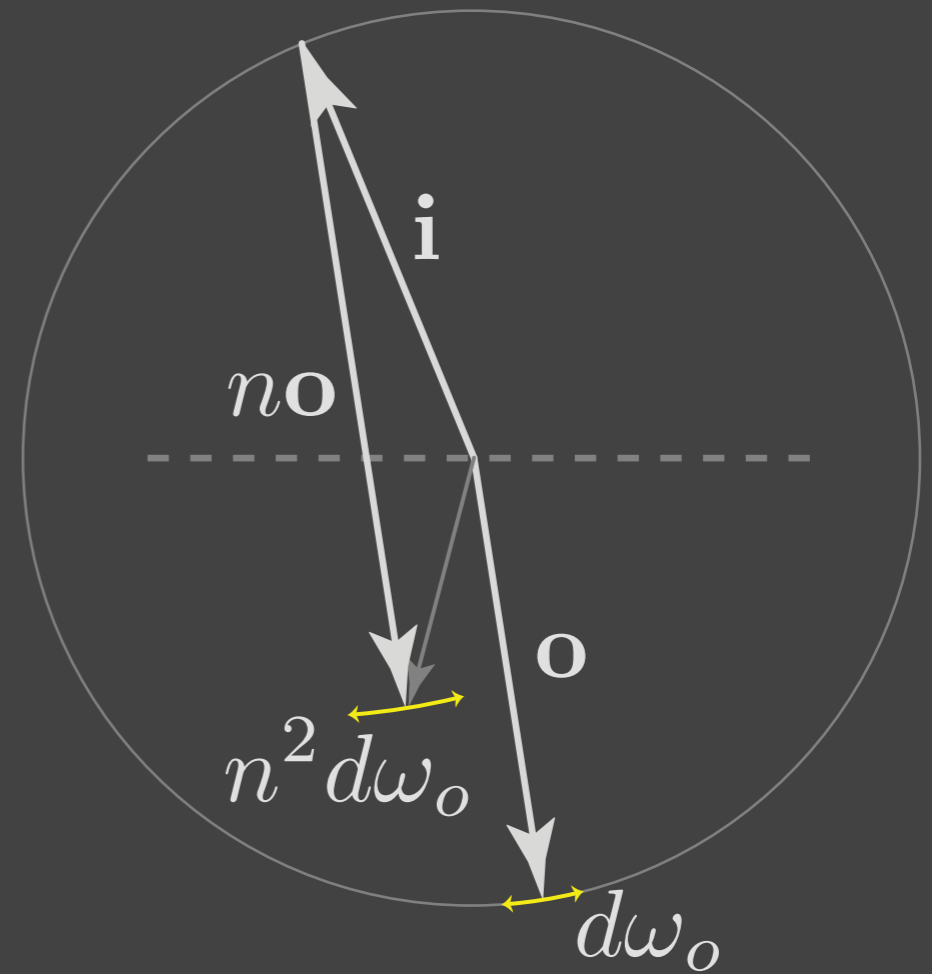
$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2} d\omega_o$$

refraction

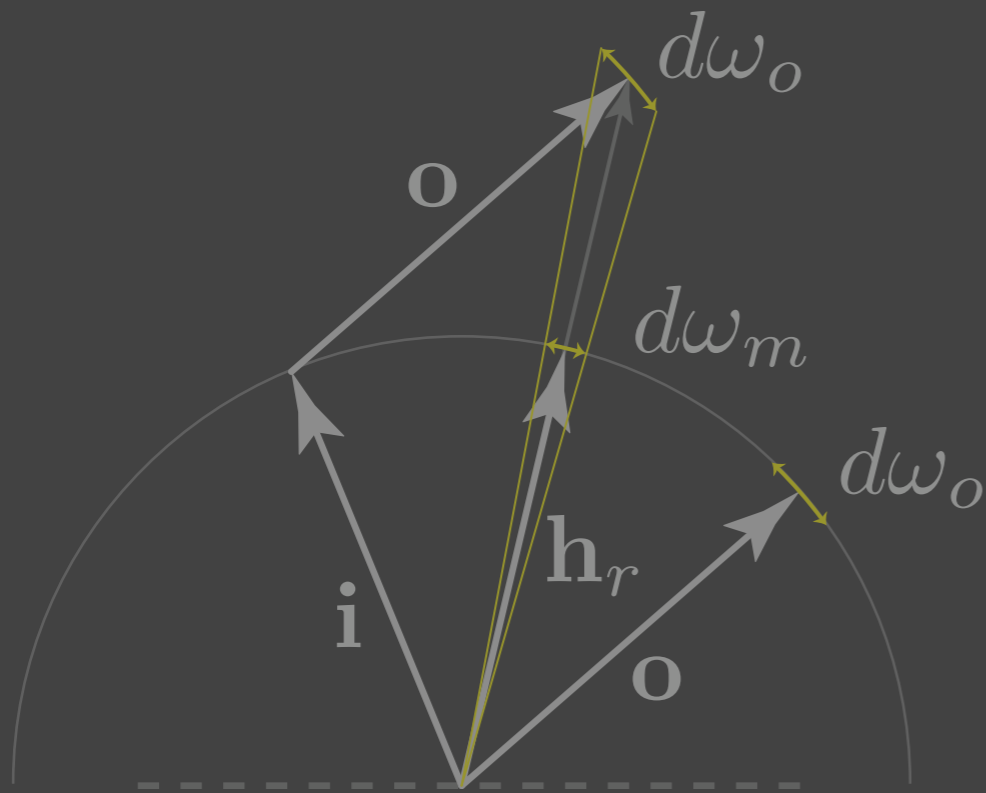
$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$



Construction of half-vector solid angle

reflection

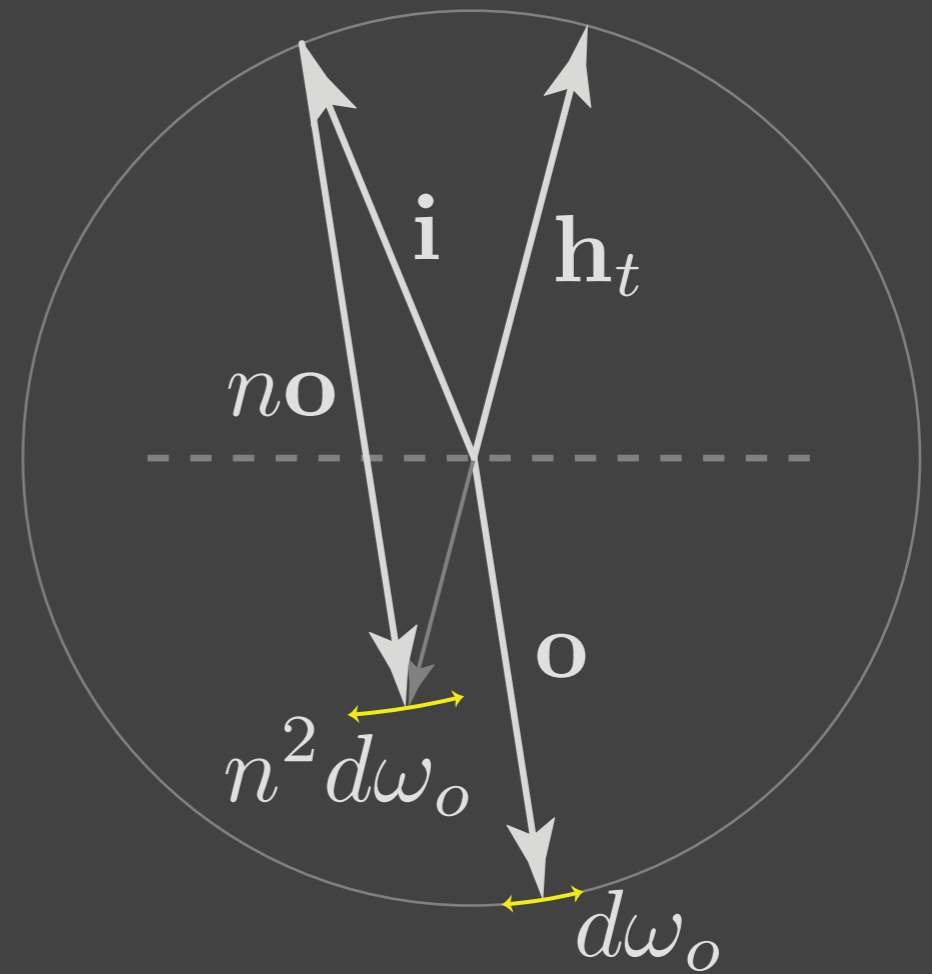
$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2} d\omega_o$$

refraction

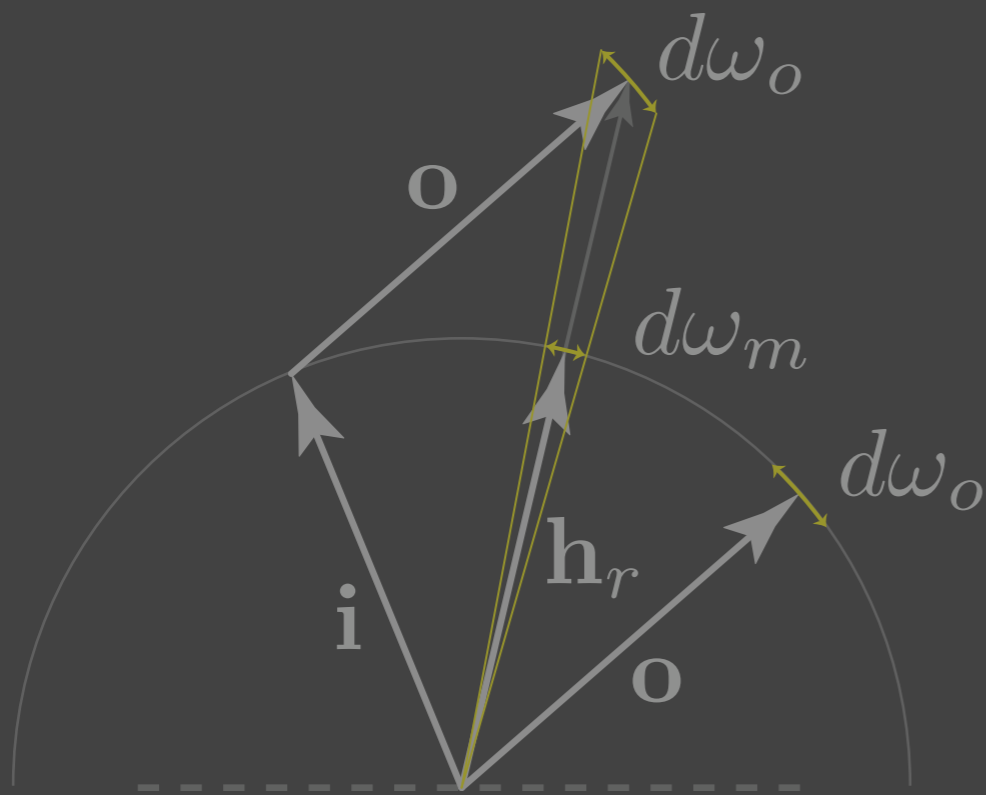
$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$



Construction of half-vector solid angle

reflection

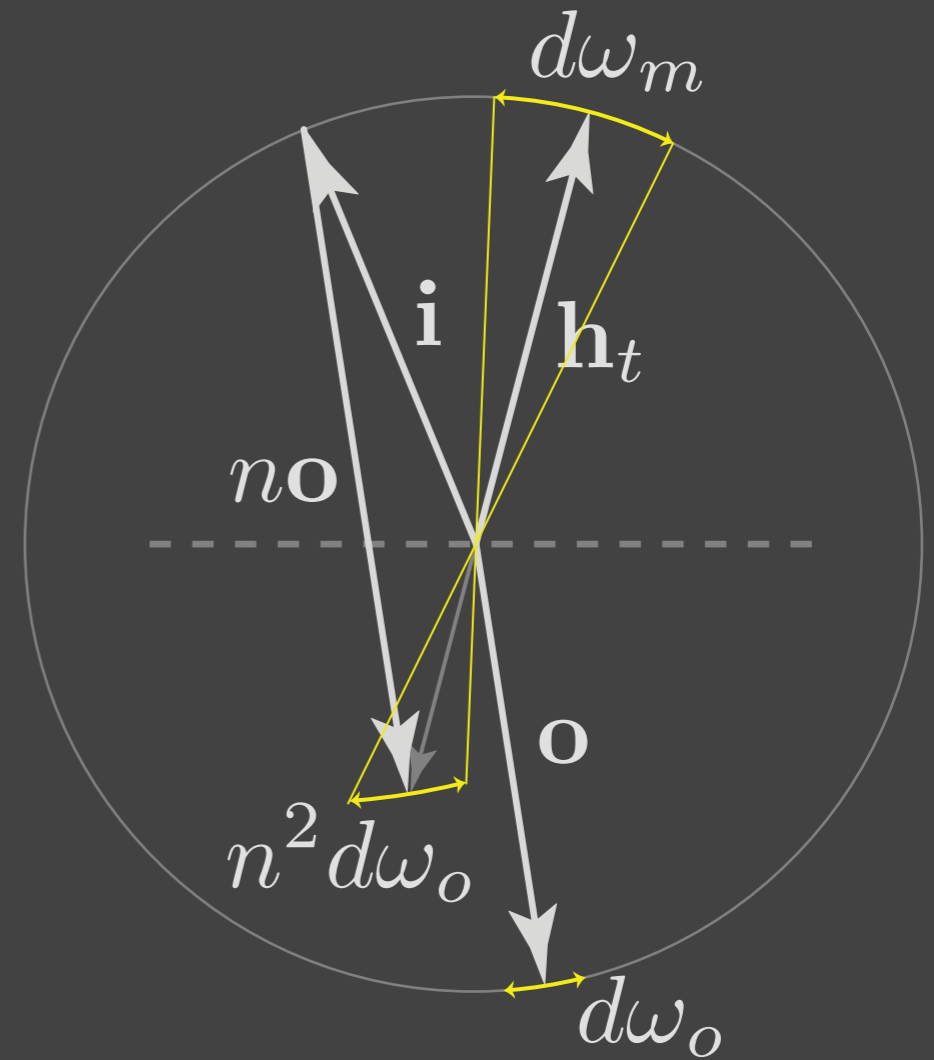
$$\mathbf{h}_r = \text{normalize}(\mathbf{i} + \mathbf{o})$$



$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2} d\omega_o$$

refraction

$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$



$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_t|}{\|\mathbf{i} + n\mathbf{o}\|^2} n^2 d\omega_o$$

Result: scattering functions

reflection

$$f_s(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{m}|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \rho(\mathbf{i}, \mathbf{o}) D(\mathbf{m}) G(\mathbf{i}, \mathbf{o}, \mathbf{m}) \frac{d\omega_m}{d\omega_o}$$

transmission

$$f_s(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{m}|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \rho(\mathbf{i}, \mathbf{o}) D(\mathbf{m}) G(\mathbf{i}, \mathbf{o}, \mathbf{m}) \frac{d\omega_m}{d\omega_o}$$

Result: scattering functions

reflection

$$f_r(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{h}_r|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} F(\mathbf{i}, \mathbf{h}_r) D(\mathbf{h}_r) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_r) \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2}$$

transmission

$$f_s(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{m}|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \rho(\mathbf{i}, \mathbf{o}) D(\mathbf{m}) G(\mathbf{i}, \mathbf{o}, \mathbf{m}) \frac{d\omega_m}{d\omega_o}$$

Result: scattering functions

reflection

$$f_r(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{h}_r|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} F(\mathbf{i}, \mathbf{h}_r) D(\mathbf{h}_r) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_r) \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2}$$

transmission

$$f_t(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{h}_t|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} (1 - F(\mathbf{i}, \mathbf{h}_t)) D(\mathbf{h}_t) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_t) \frac{n^2 |\mathbf{o} \cdot \mathbf{h}_t|}{\|\mathbf{i} + n\mathbf{o}\|^2}$$

Result: scattering functions

reflection

$$f_r(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{h}_r| |\mathbf{o} \cdot \mathbf{h}_r|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \frac{F(\mathbf{i}, \mathbf{h}_r) D(\mathbf{h}_r) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_r)}{\|\mathbf{i} + \mathbf{o}\|^2}$$

transmission

$$f_t(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{h}_t|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} (1 - F(\mathbf{i}, \mathbf{h}_t)) D(\mathbf{h}_t) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_t) \frac{n^2 |\mathbf{o} \cdot \mathbf{h}_t|}{\|\mathbf{i} + n\mathbf{o}\|^2}$$

Result: scattering functions

reflection

$$f_r(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{h}_r| |\mathbf{o} \cdot \mathbf{h}_r|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \frac{F(\mathbf{i}, \mathbf{h}_r) D(\mathbf{h}_r) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_r)}{\|\mathbf{i} + \mathbf{o}\|^2}$$

transmission

$$f_t(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{h}_t| |\mathbf{o} \cdot \mathbf{h}_t|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \frac{n^2 (1 - F(\mathbf{i}, \mathbf{h}_t)) D(\mathbf{h}_t) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_t)}{\|\mathbf{i} + n\mathbf{o}\|^2}$$

Result: scattering functions

reflection

$$f_r(\mathbf{i}, \mathbf{o}) = \frac{F(\mathbf{i}, \mathbf{h}_r) D(\mathbf{h}_r) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_r)}{4|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|}$$

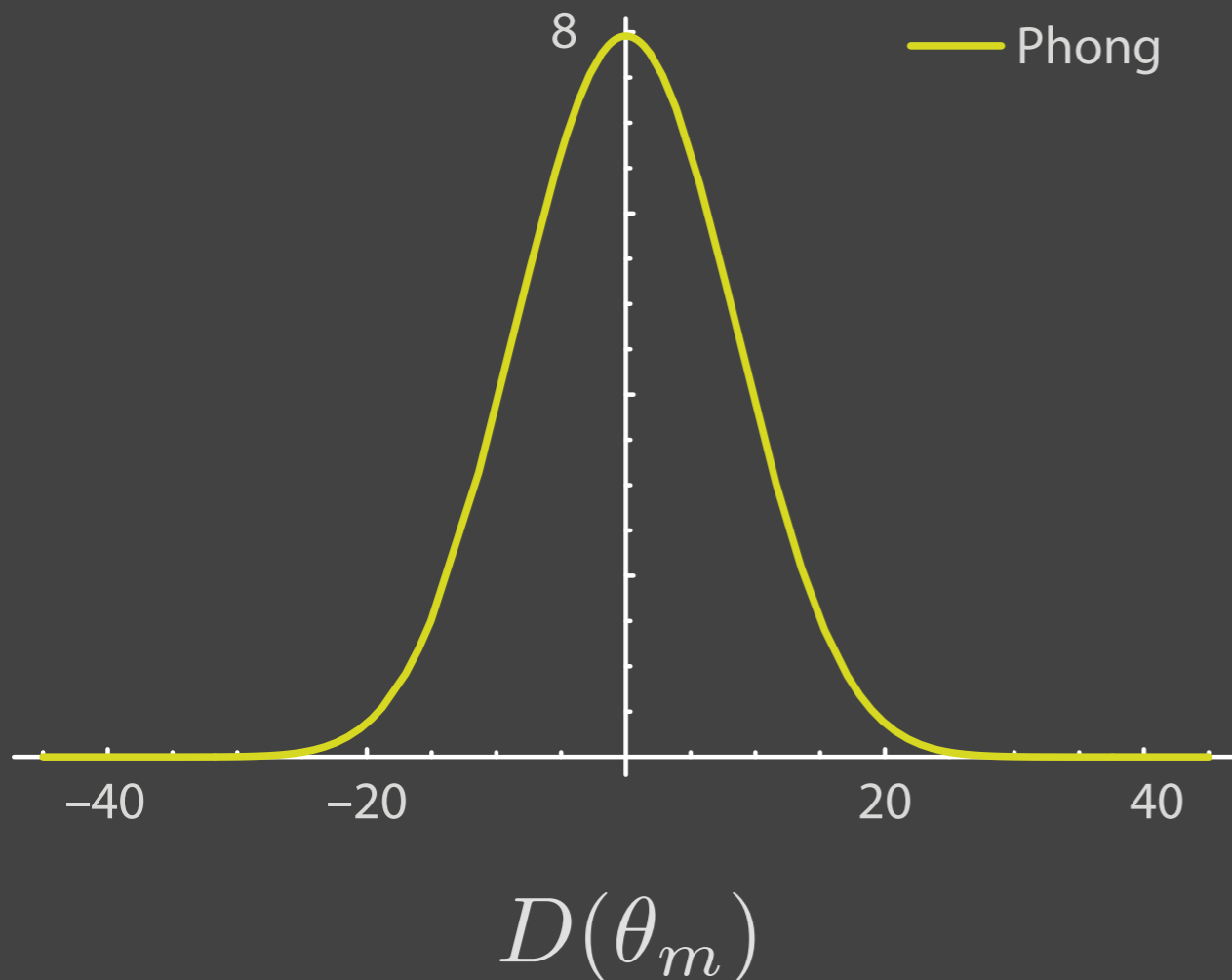
transmission

$$f_t(\mathbf{i}, \mathbf{o}) = \frac{|\mathbf{i} \cdot \mathbf{h}_t| |\mathbf{o} \cdot \mathbf{h}_t|}{|\mathbf{i} \cdot \mathbf{n}| |\mathbf{o} \cdot \mathbf{n}|} \frac{n^2 (1 - F(\mathbf{i}, \mathbf{h}_t)) D(\mathbf{h}_t) G(\mathbf{i}, \mathbf{o}, \mathbf{h}_t)}{\|\mathbf{i} + n\mathbf{o}\|^2}$$

Normal distributions

Choice of distribution is determined by surface

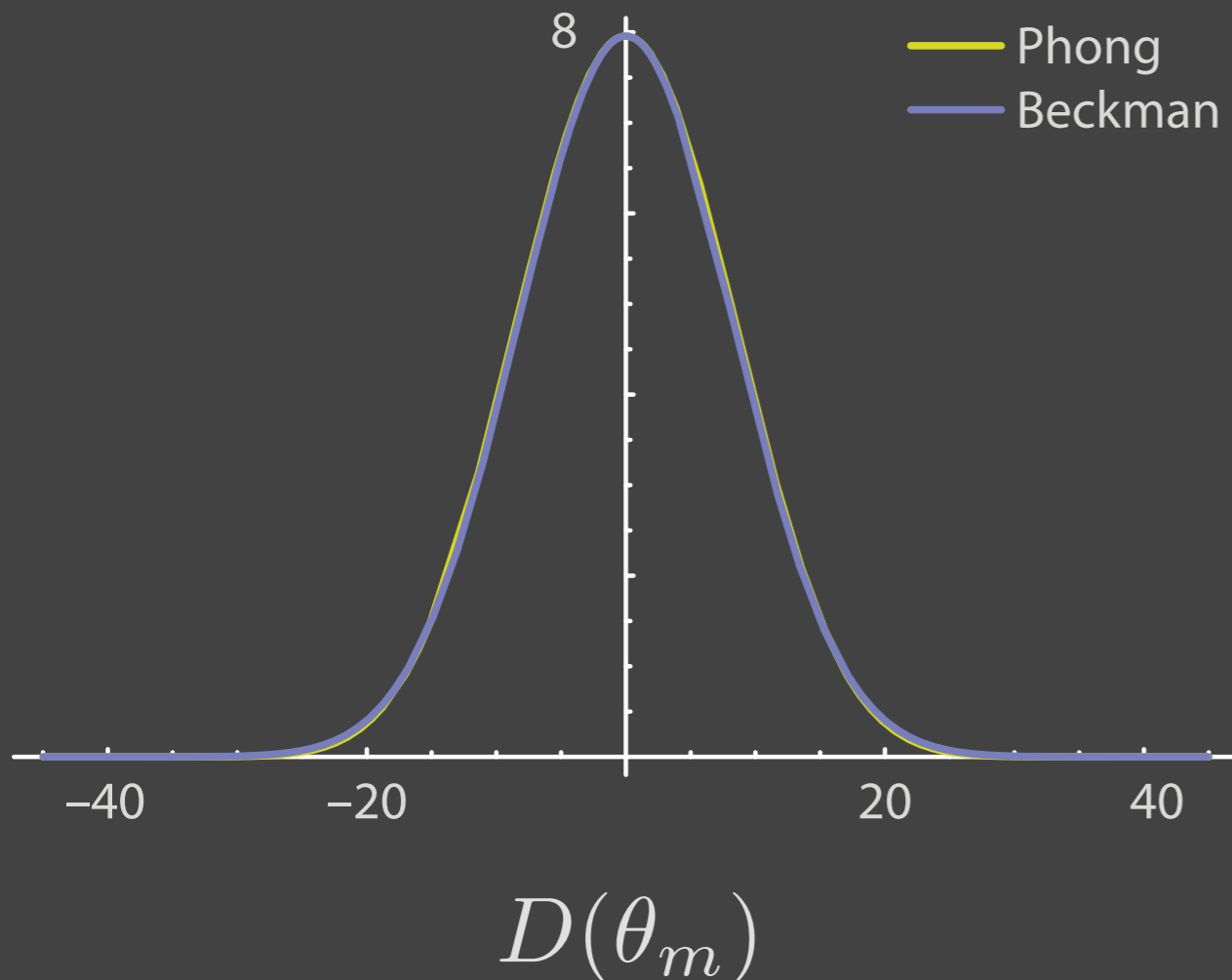
- Phong describes same surfaces as Beckman
- new GGX distribution fits some surfaces better
- analytical Smith shadowing–masking



Normal distributions

Choice of distribution is determined by surface

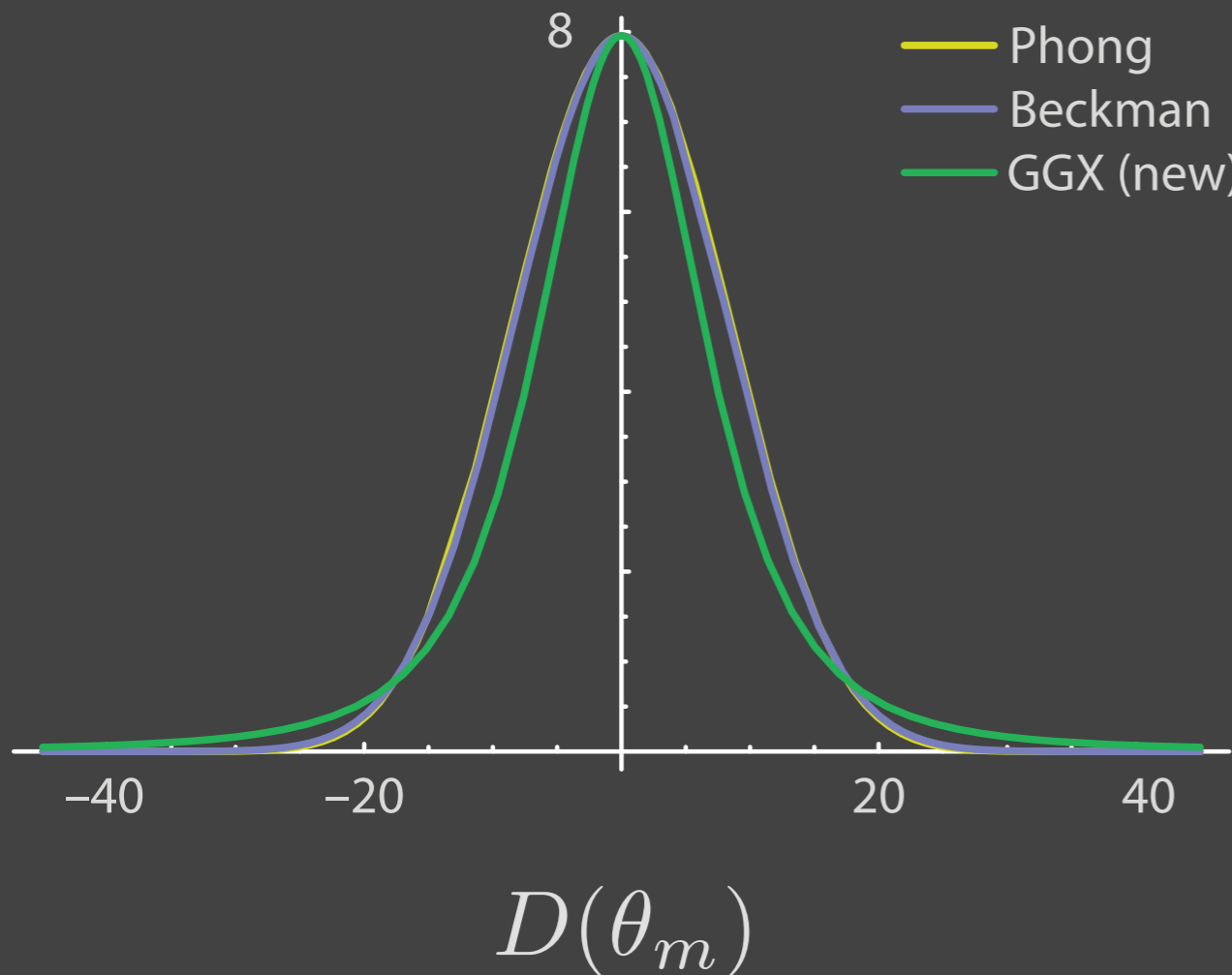
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Normal distributions

Choice of distribution is determined by surface

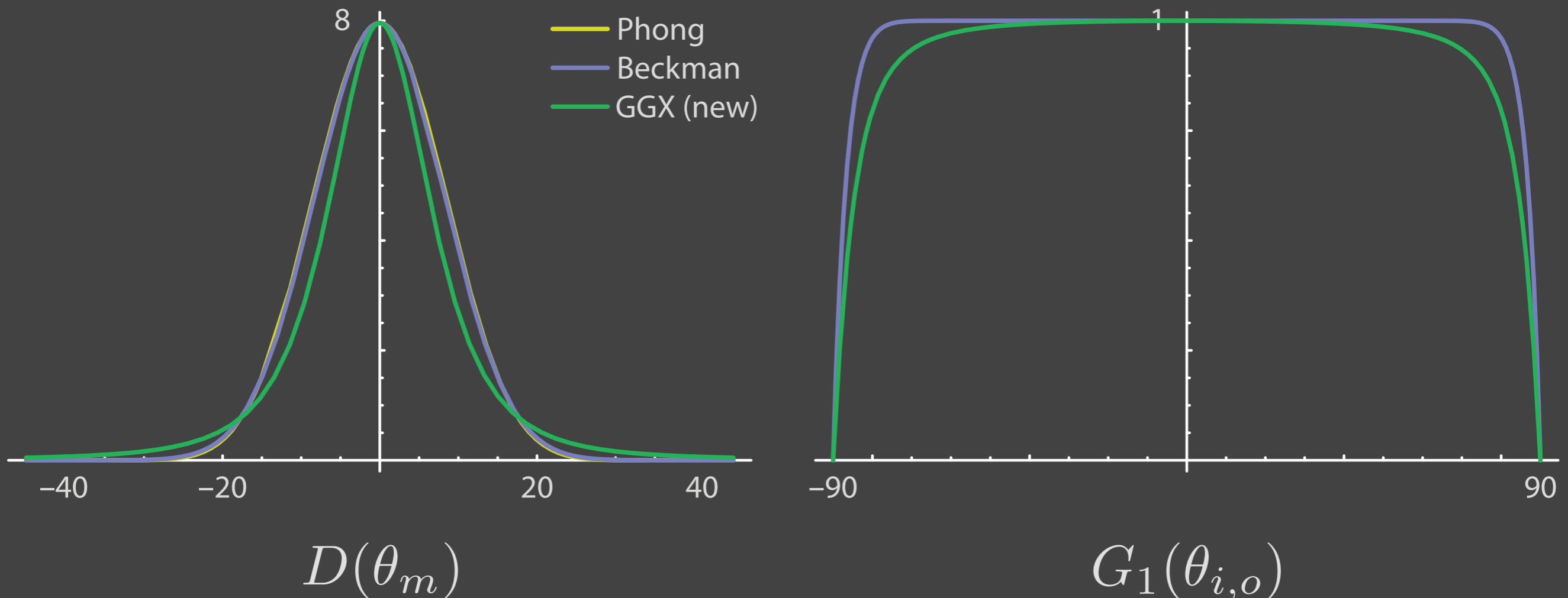
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Normal distributions

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Importance sampling

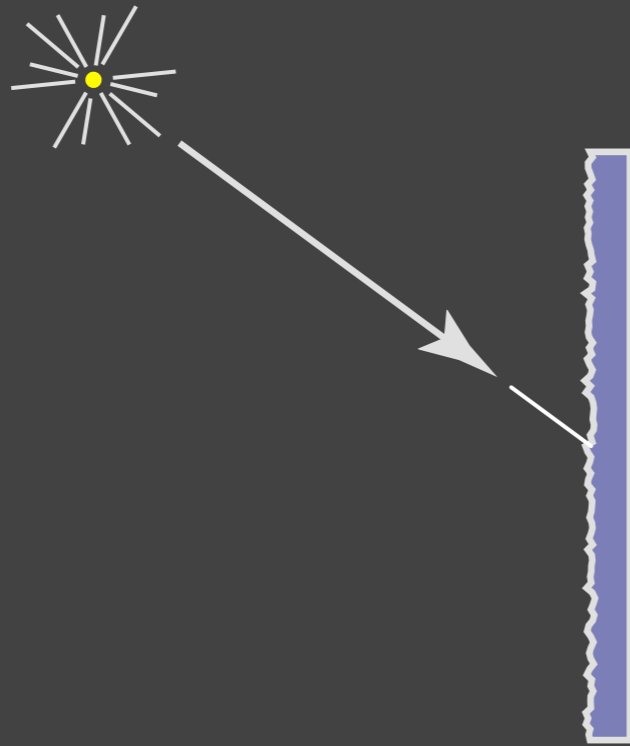
Sampling procedure

- choose normal according to $D(\mathbf{m}) |\mathbf{m} \cdot \mathbf{n}|$
explicit formulas in paper
- compute \mathbf{o} by reflection or refraction
- compute pdf of \mathbf{o} using $d\omega_m/d\omega_o$
leaves G and some cosines for the weight
- can adjust sampling roughness to control weight

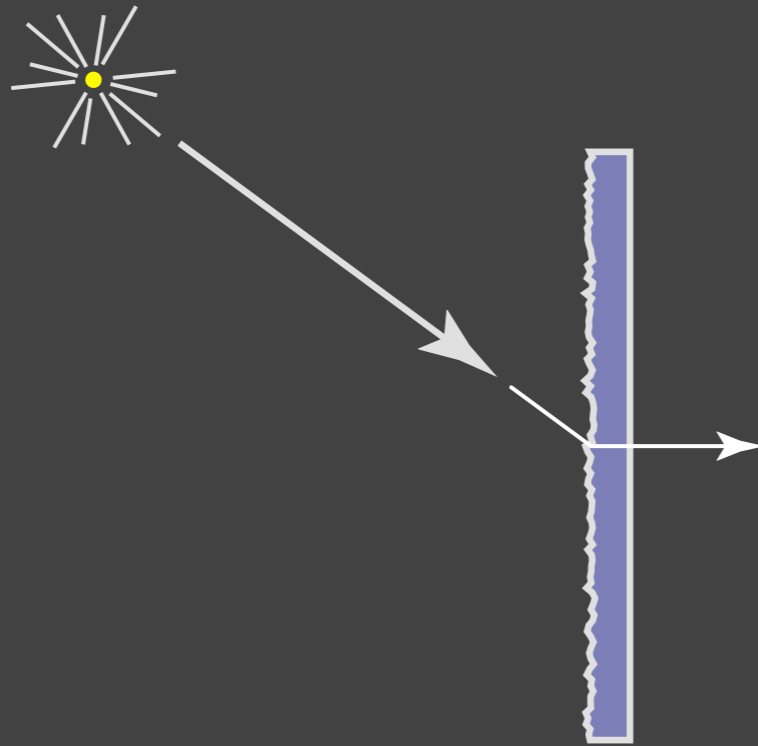
Measuring transmission



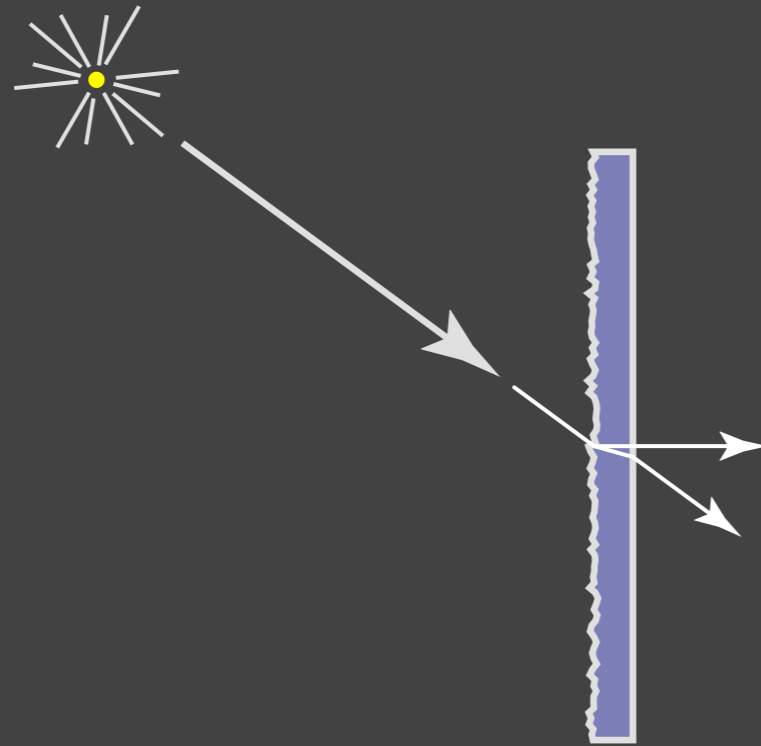
Measuring transmission



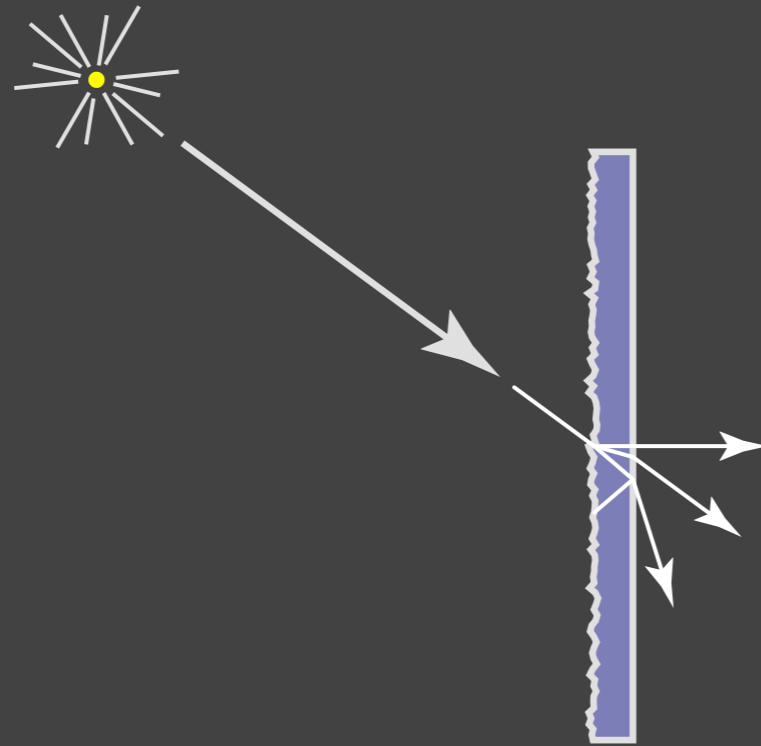
Measuring transmission



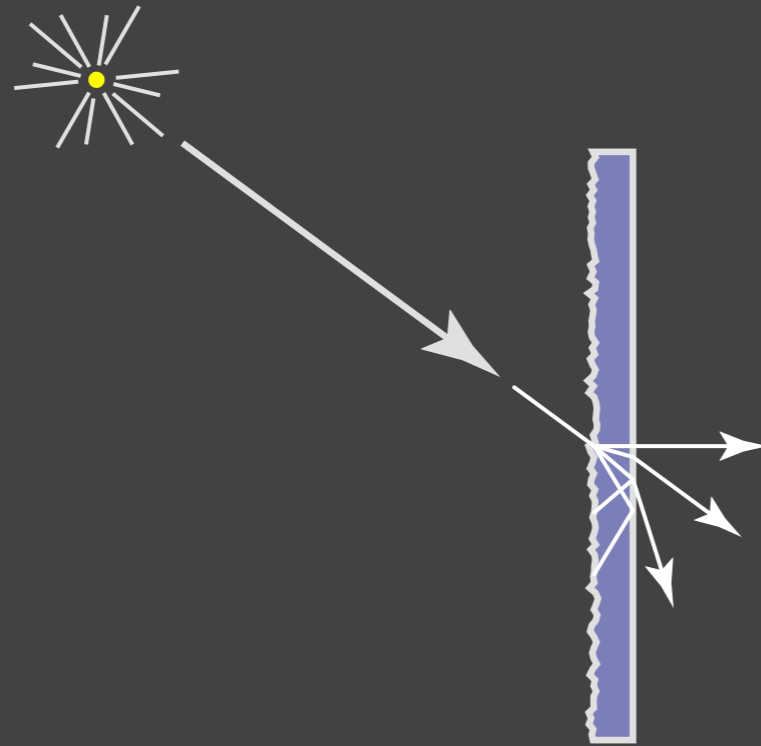
Measuring transmission



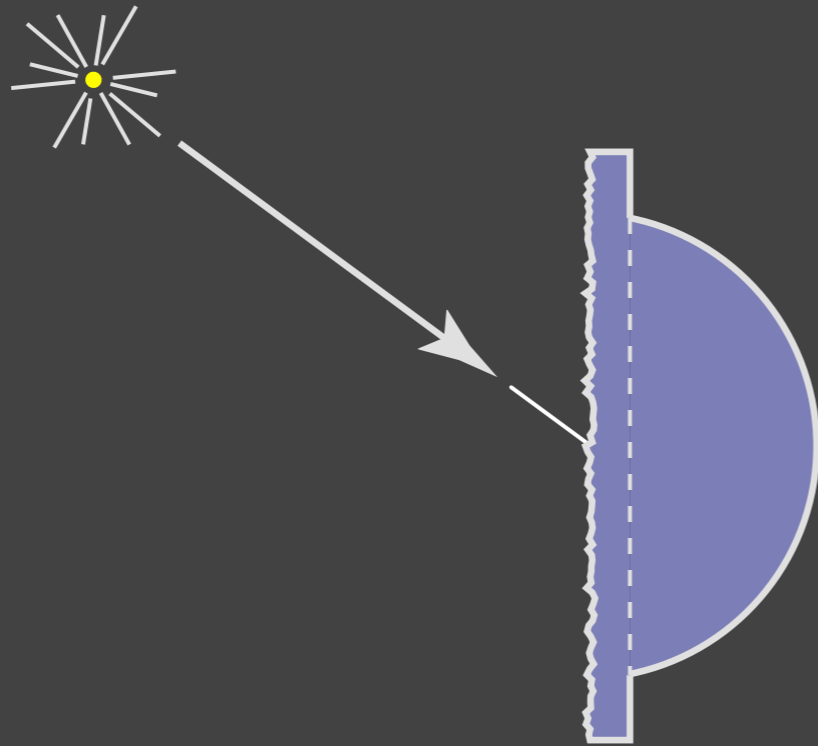
Measuring transmission



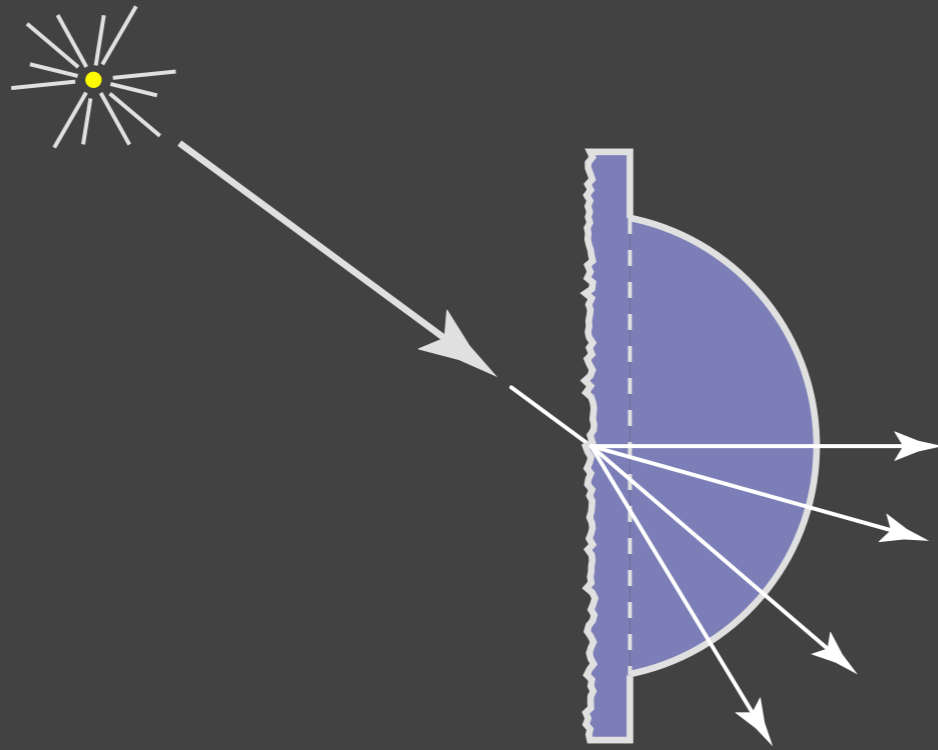
Measuring transmission



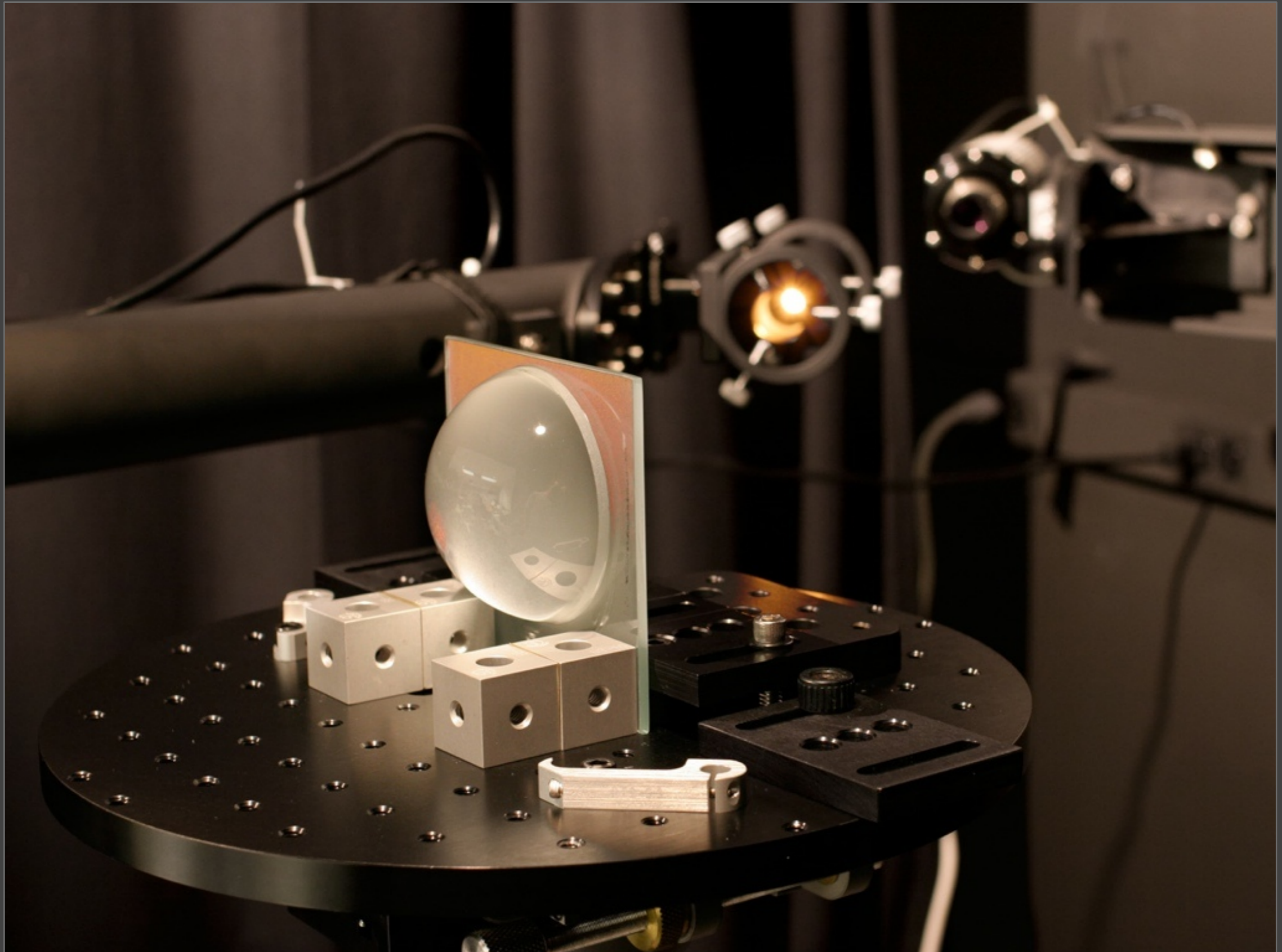
Measuring transmission



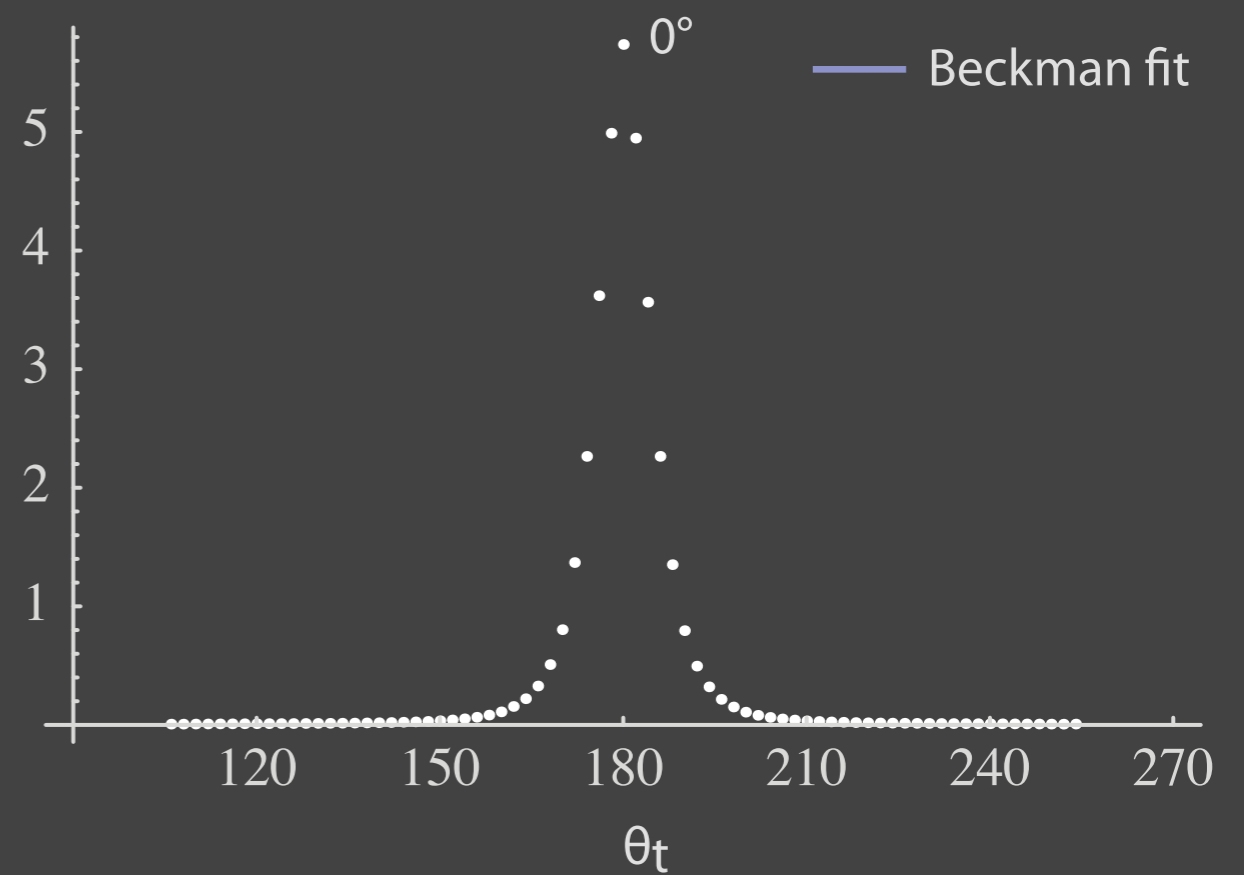
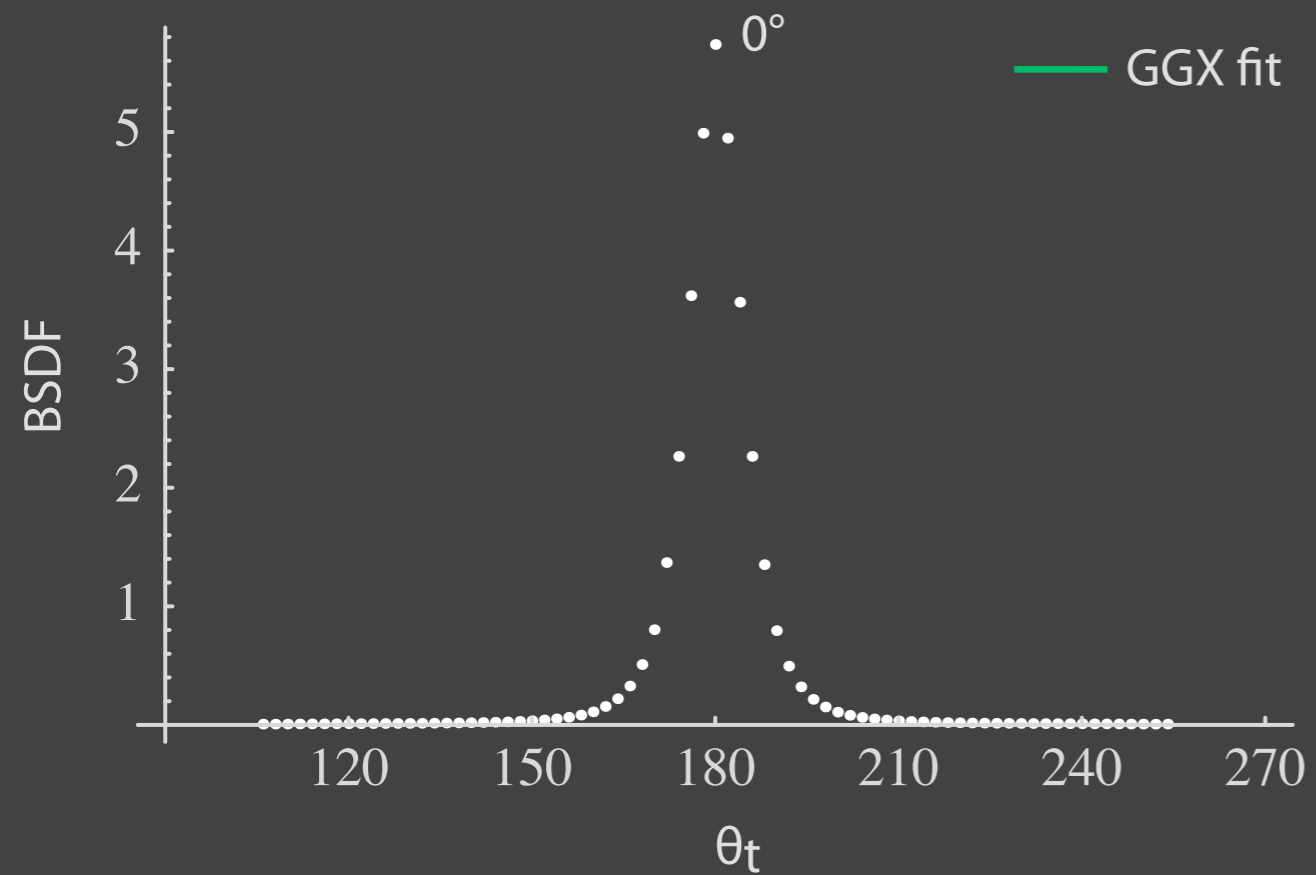
Measuring transmission



Measurement setup

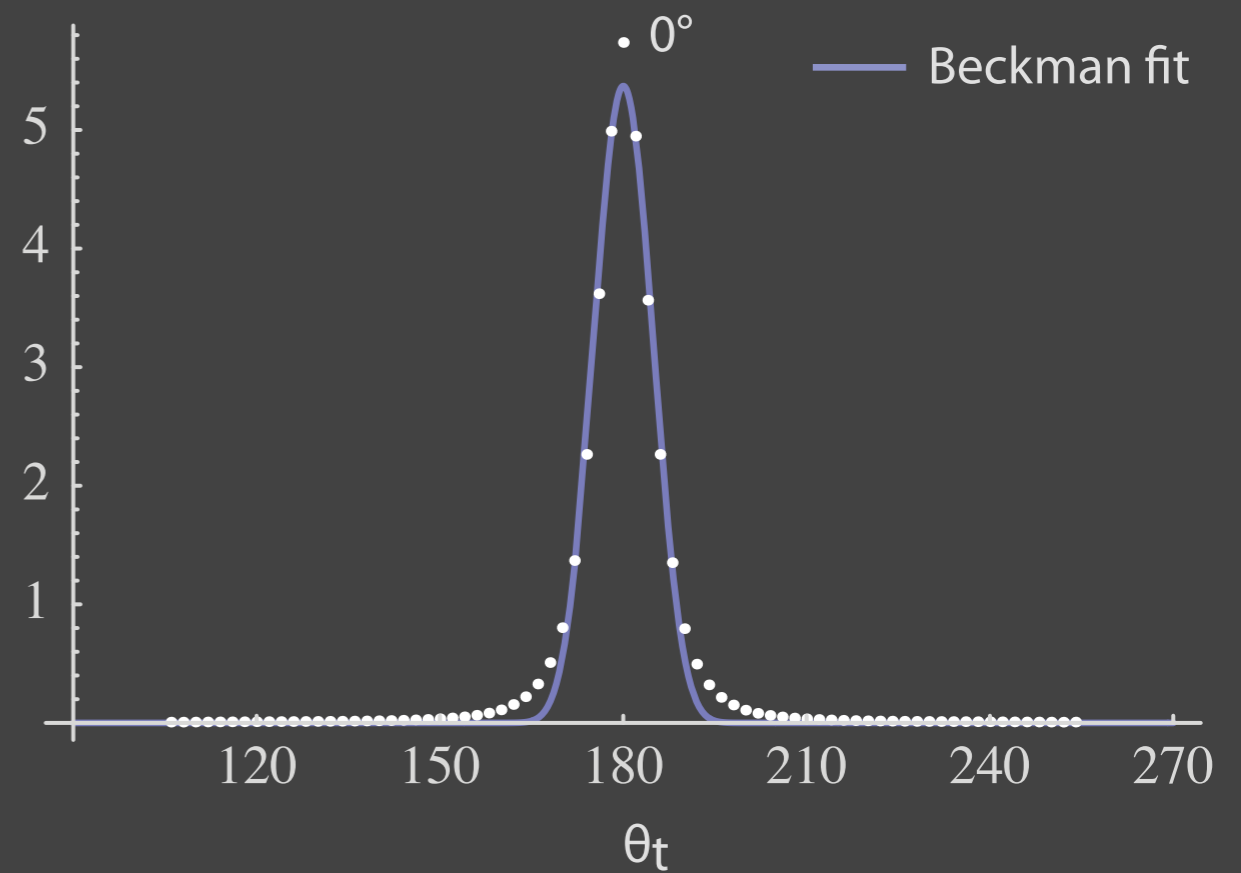
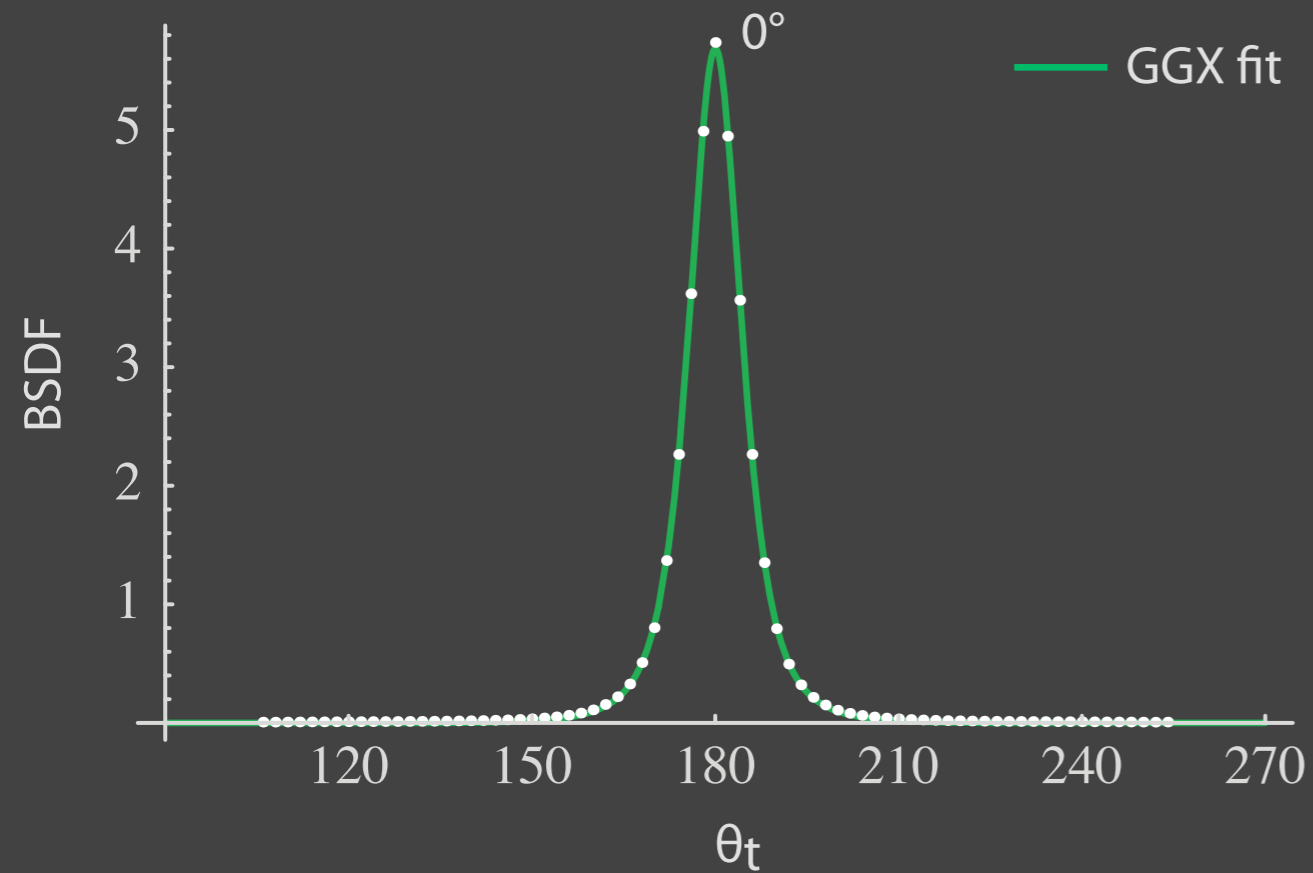


Validation: ground glass



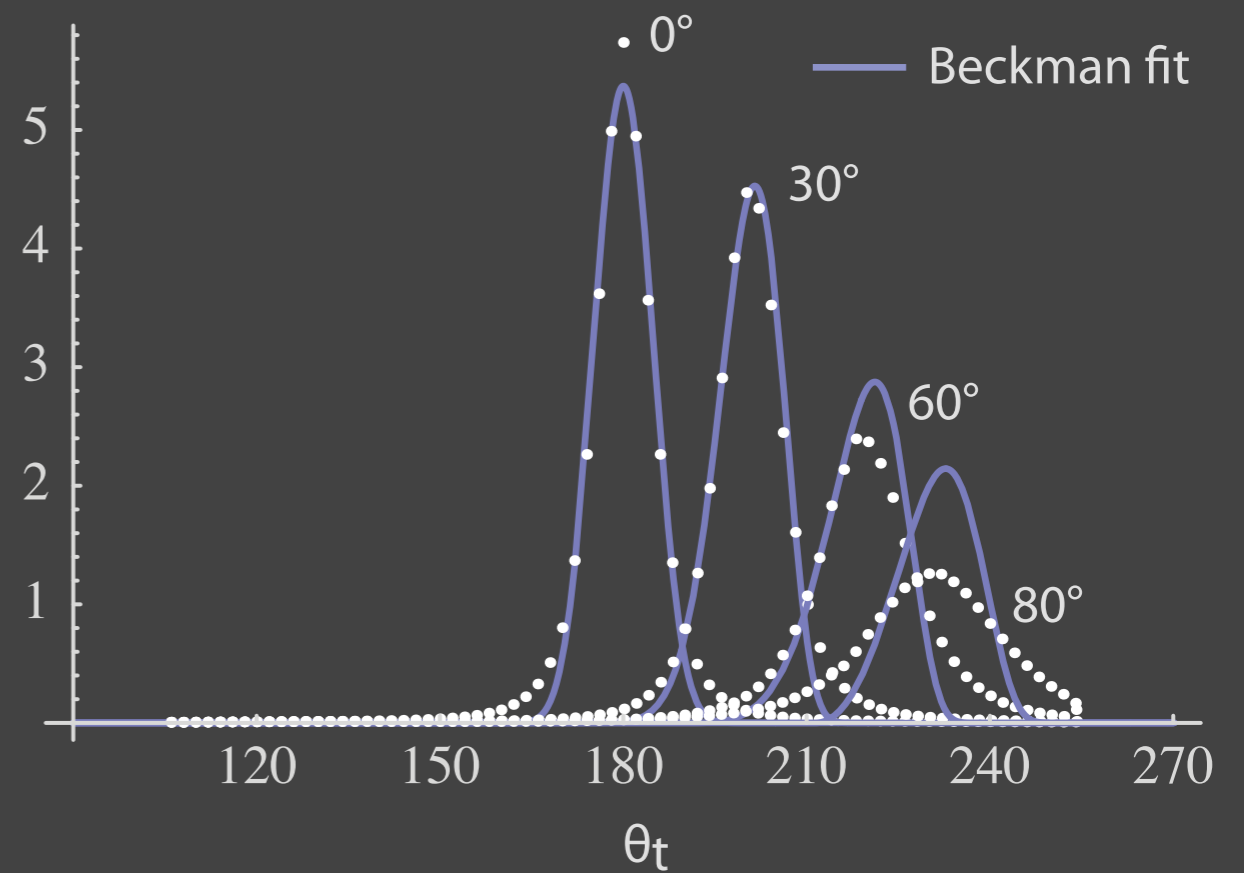
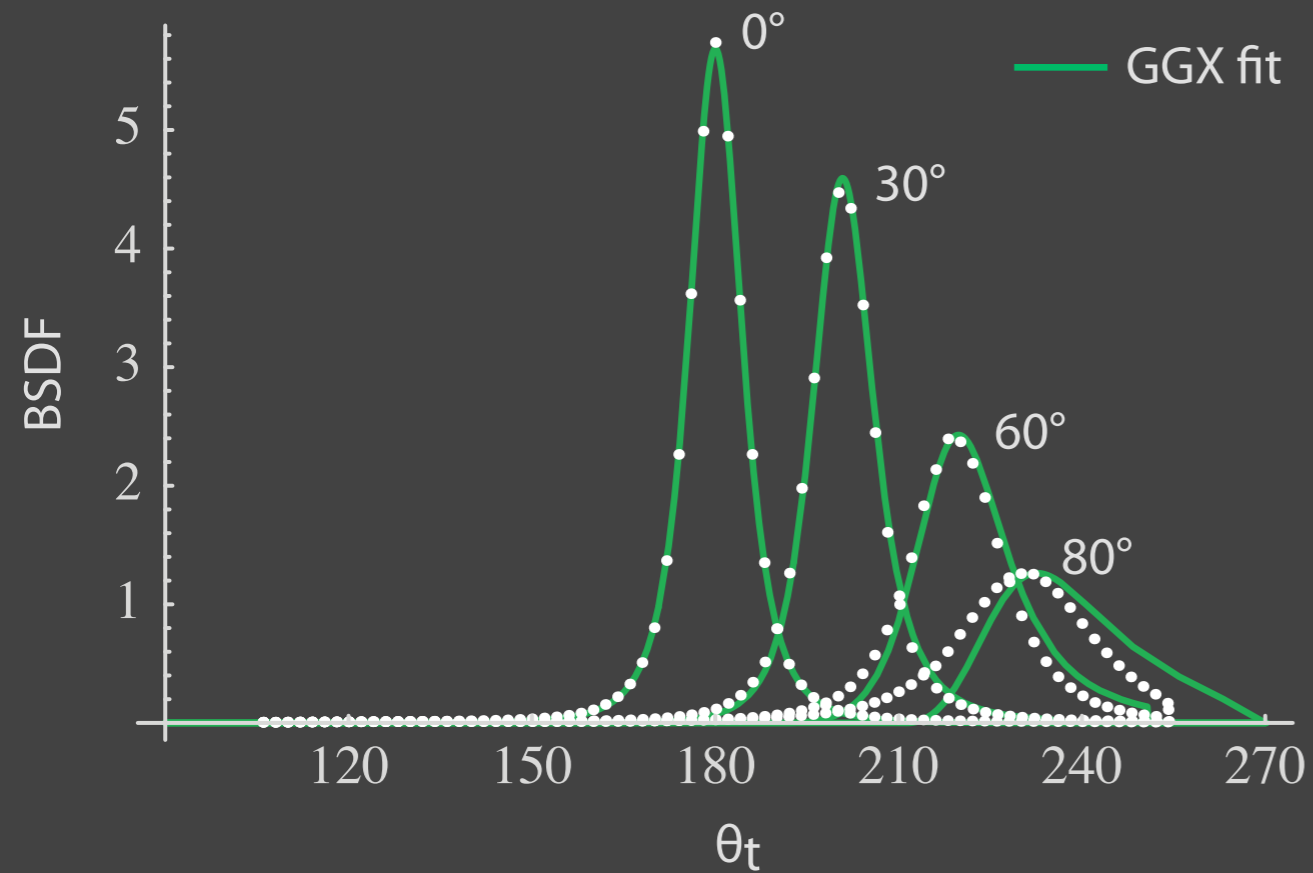
Fit is to normal incidence data only

Validation: ground glass



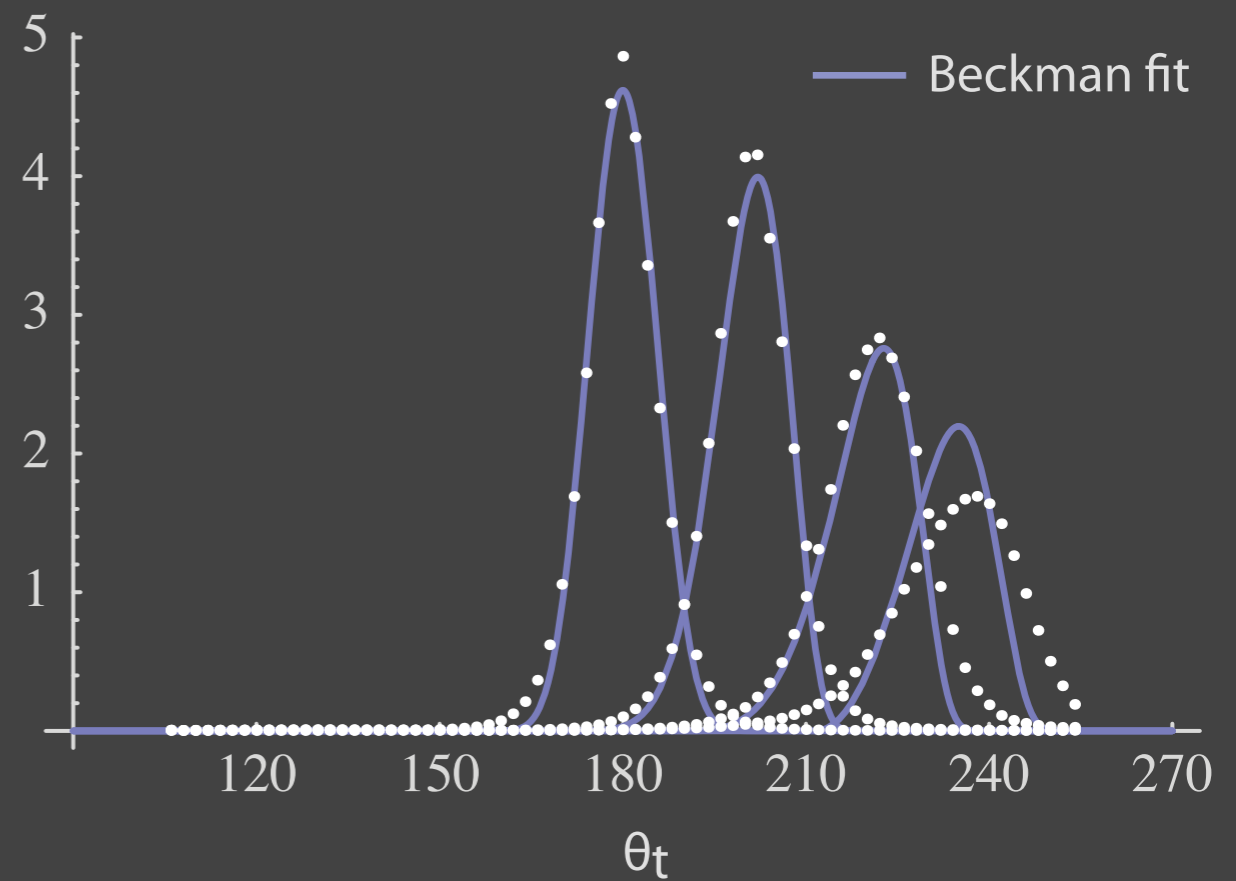
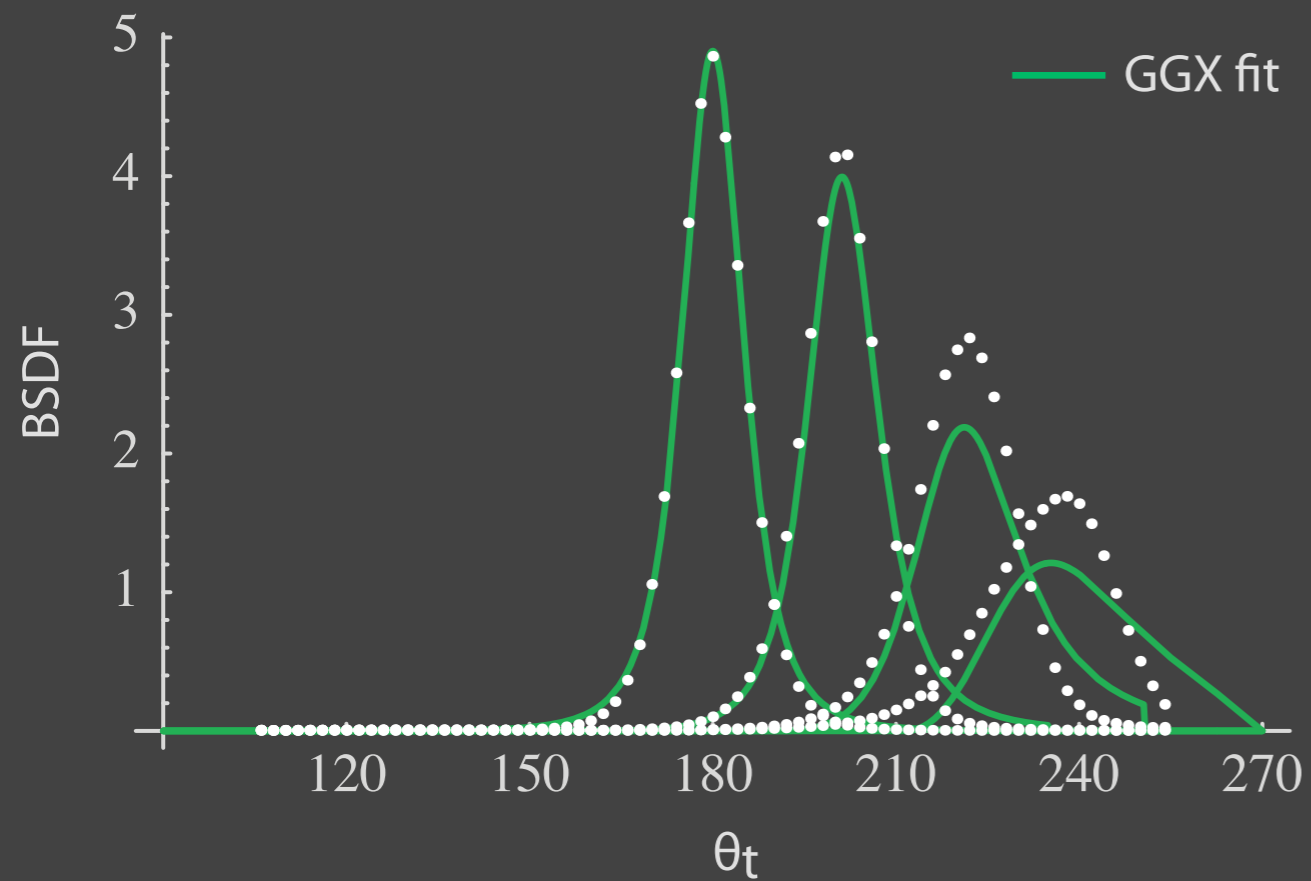
Fit is to normal incidence data only

Validation: ground glass



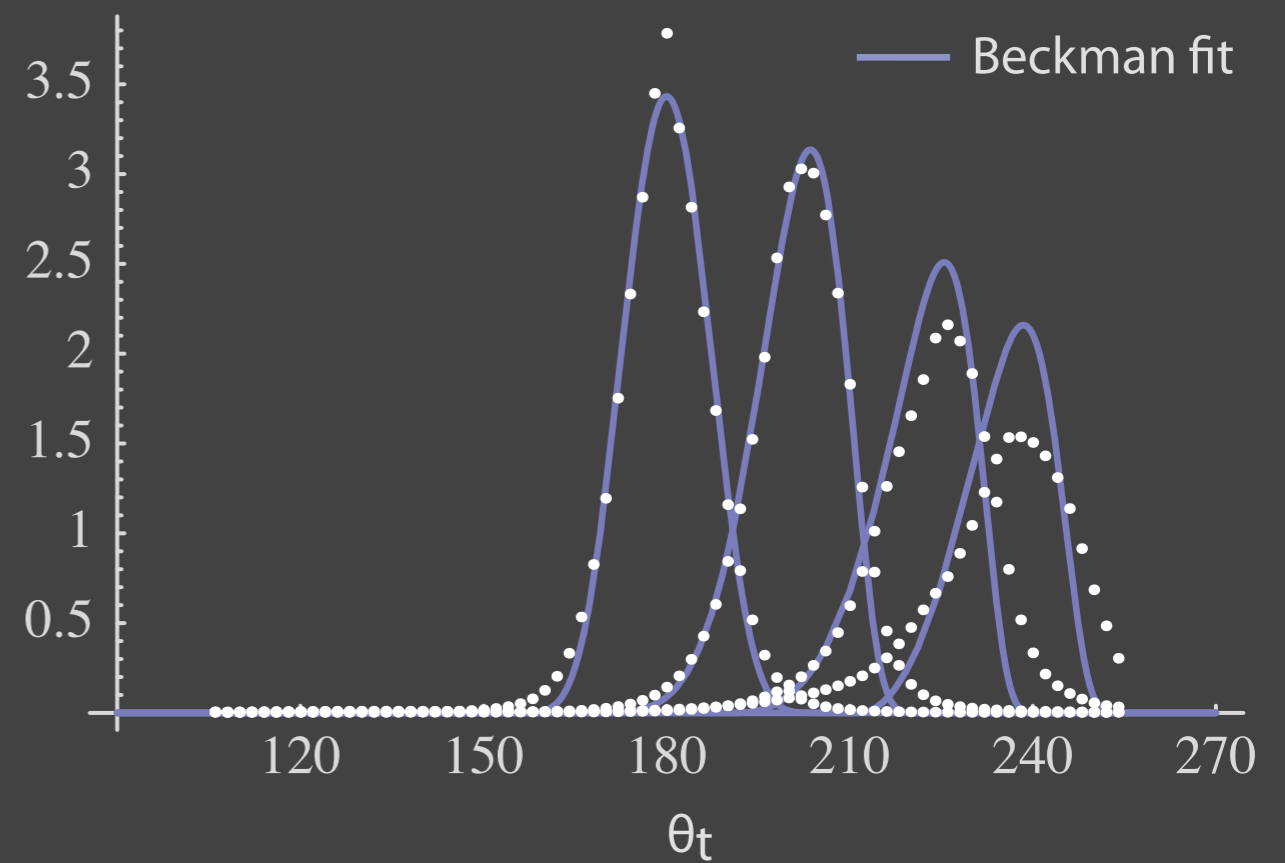
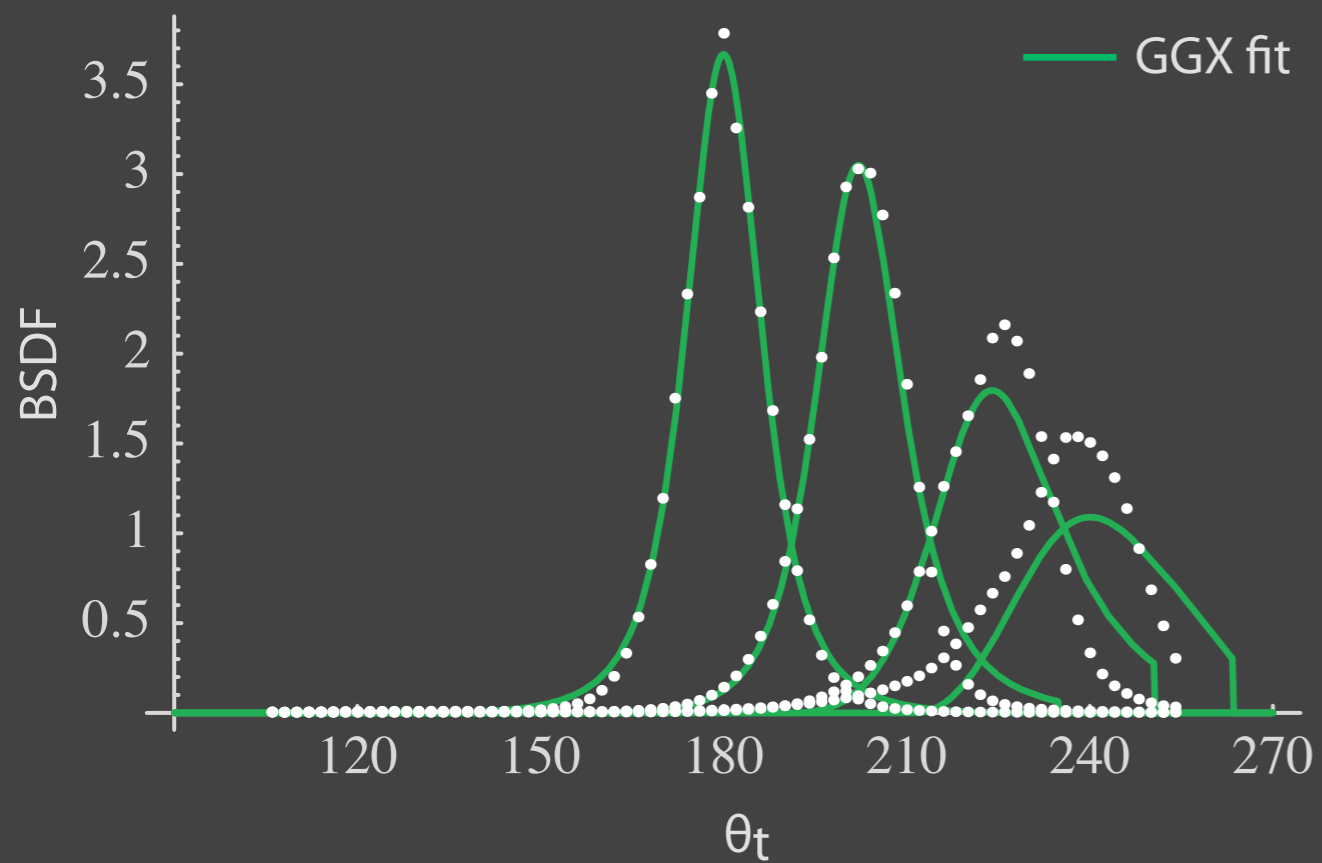
Fit is to normal incidence data only

Validation: "frosted" glass



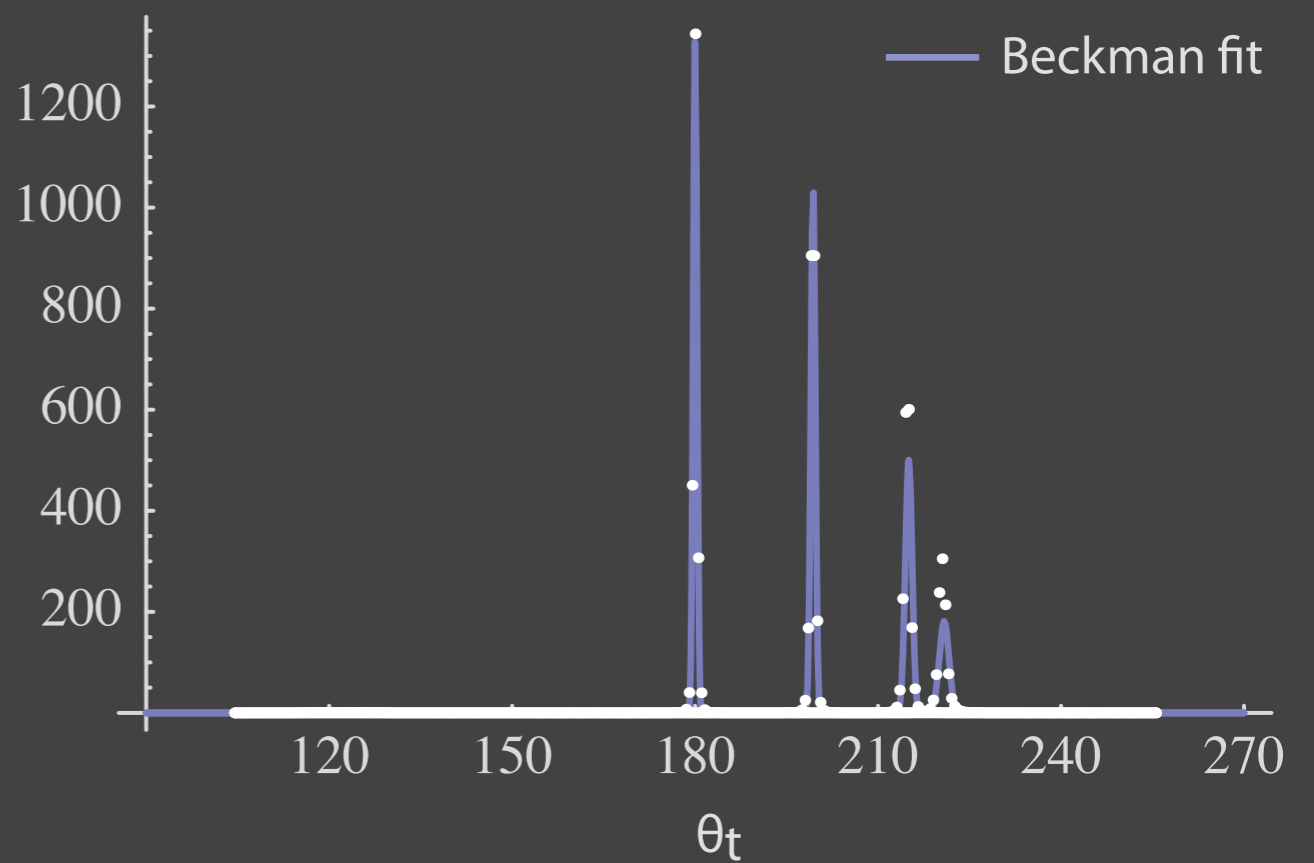
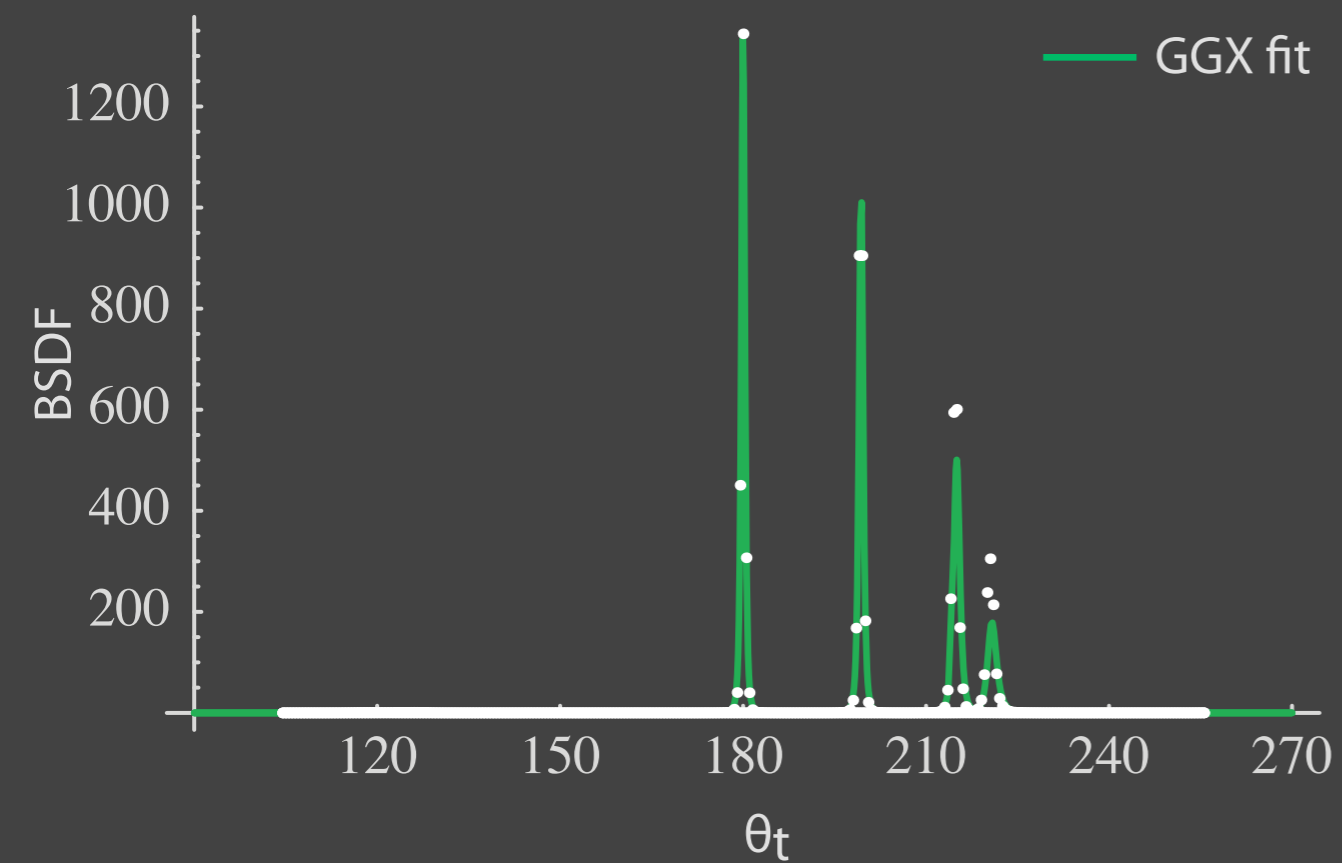
Fit is to normal incidence data only

Validation: acid-etched glass



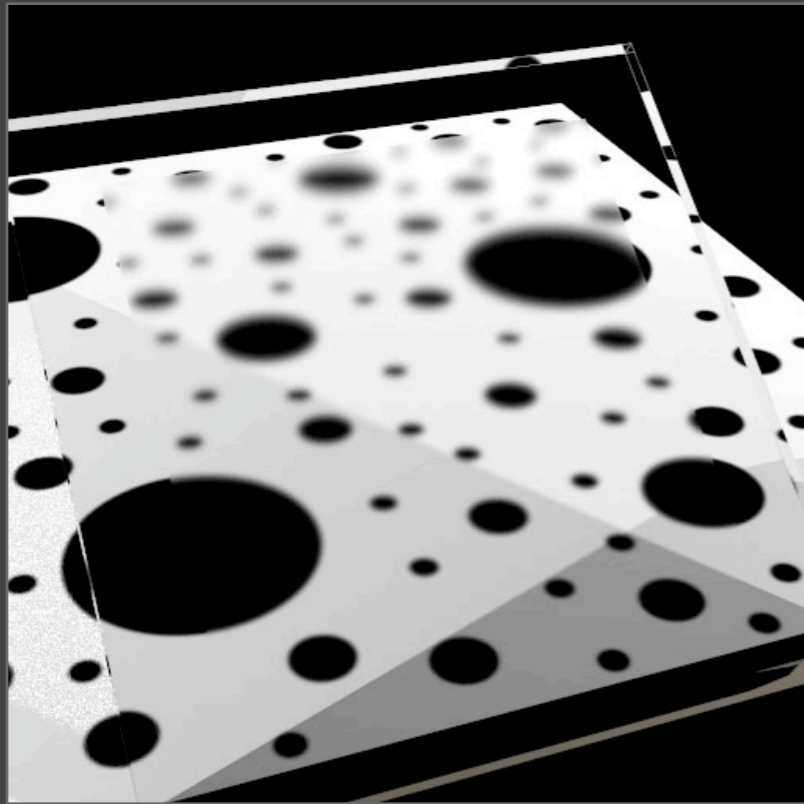
Fit is to normal incidence data only

Validation: antiglare glass

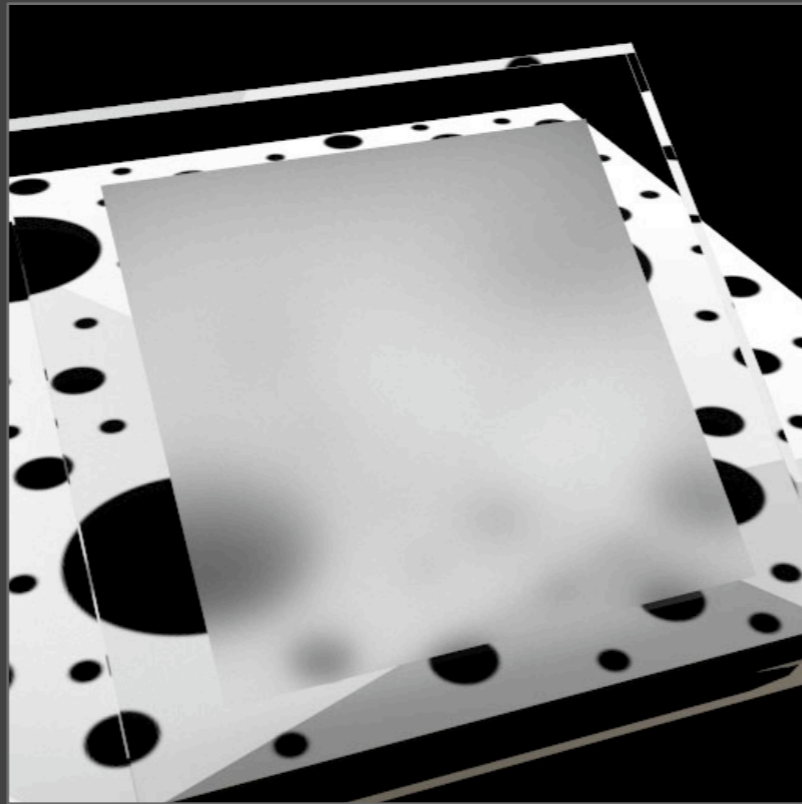


Fit is to normal incidence data only

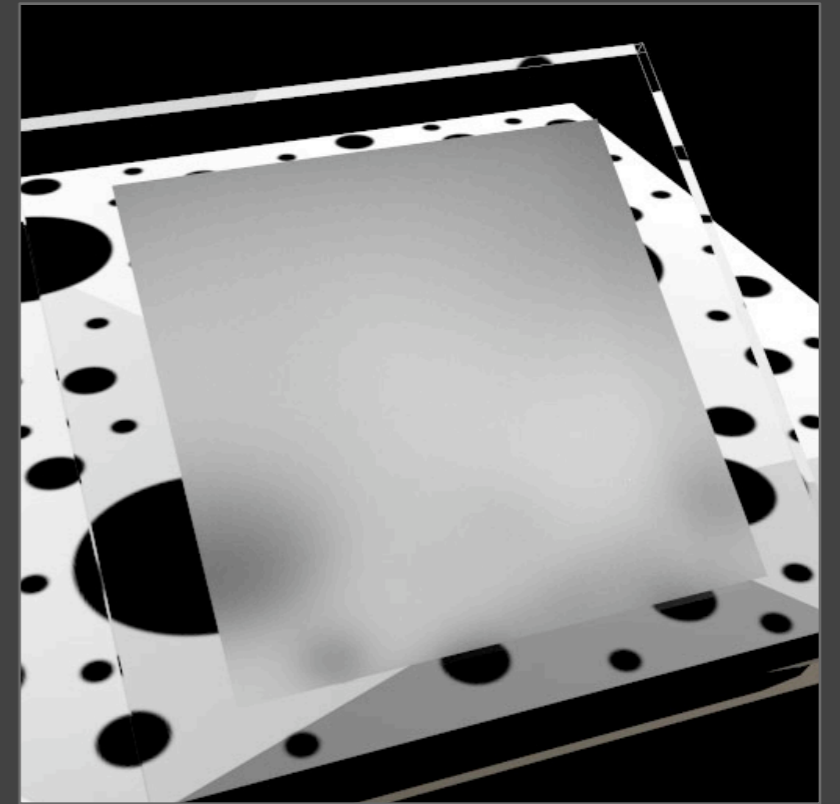
Transmission through rough glass



anti-glare glass
Beckman, $\alpha_b = 0.023$



ground glass
GGX, $\alpha_g = 0.394$



acid-etched glass
GGX, $\alpha_g = 0.553$

Etched globe



Contributions

Microfacet transmission model

- new geometric formulation
- clean, simple generalization of reflection

Microfacet distribution functions

- evaluate three choices against data
- new GGX distribution fits some surfaces better

Importance sampling

Measurement and validation

- single interface transmission

Acknowledgments

Steve Westin initial measurement idea

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