Microfacet models for refraction through rough surfaces

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Steve Marschner
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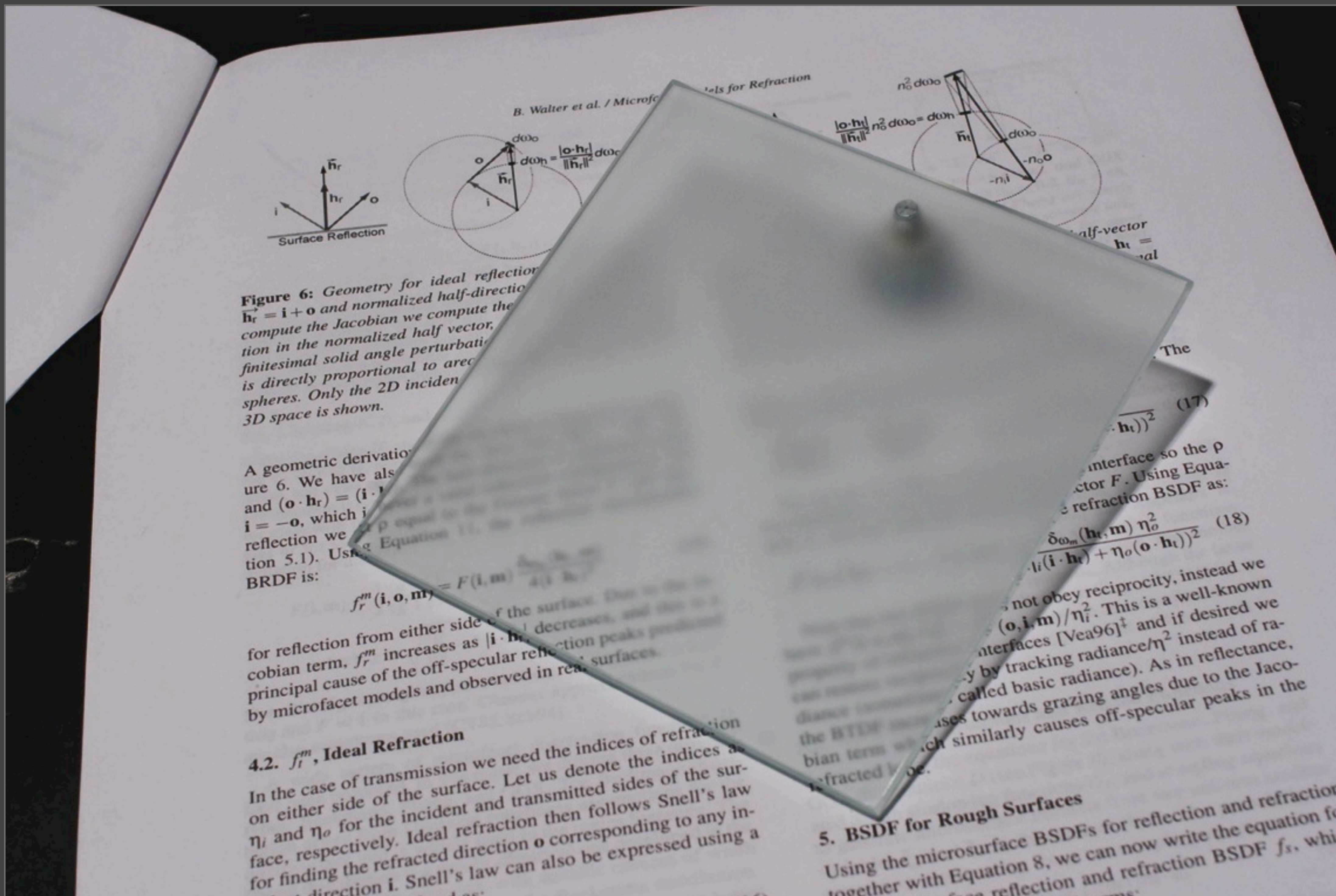
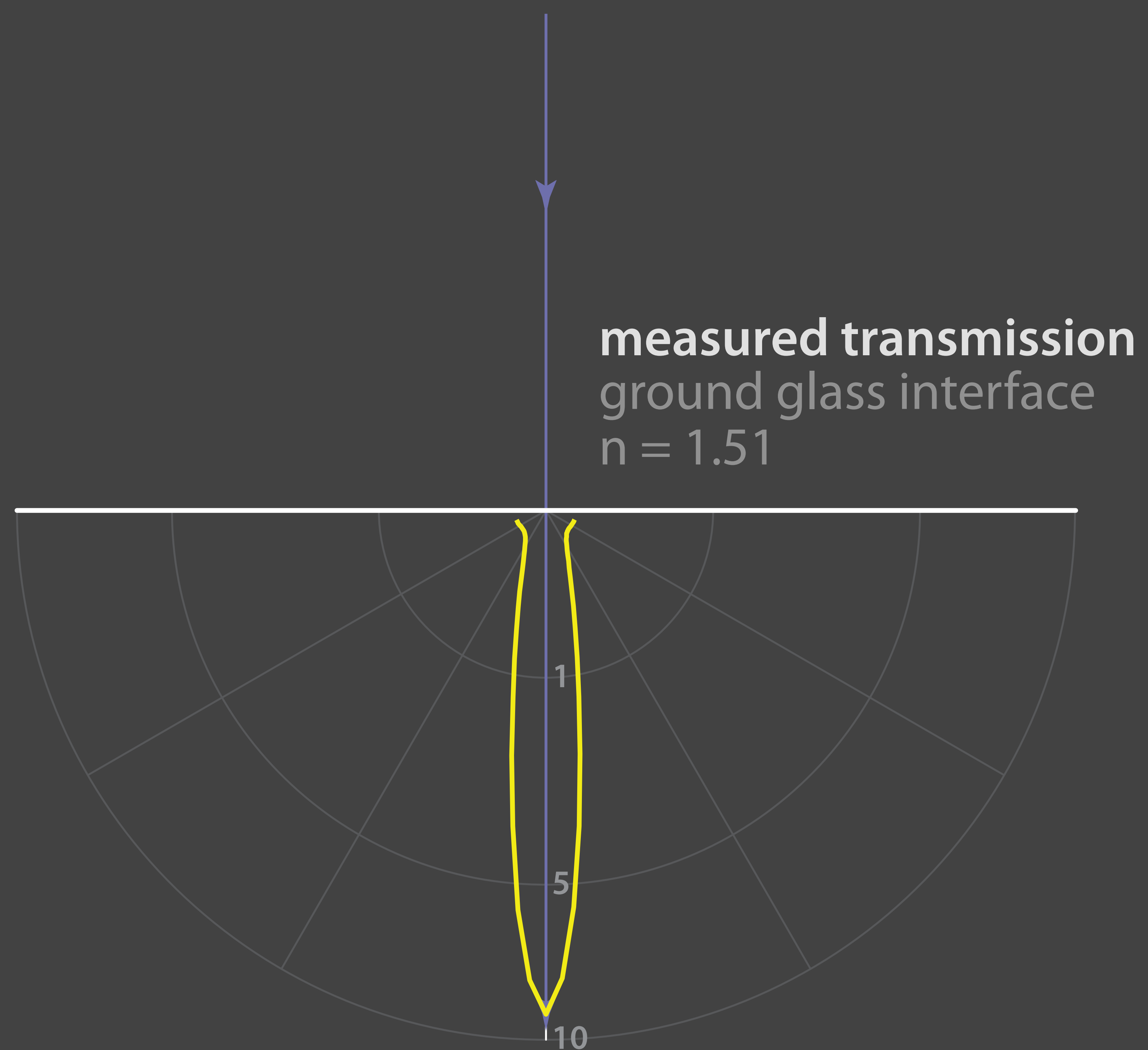
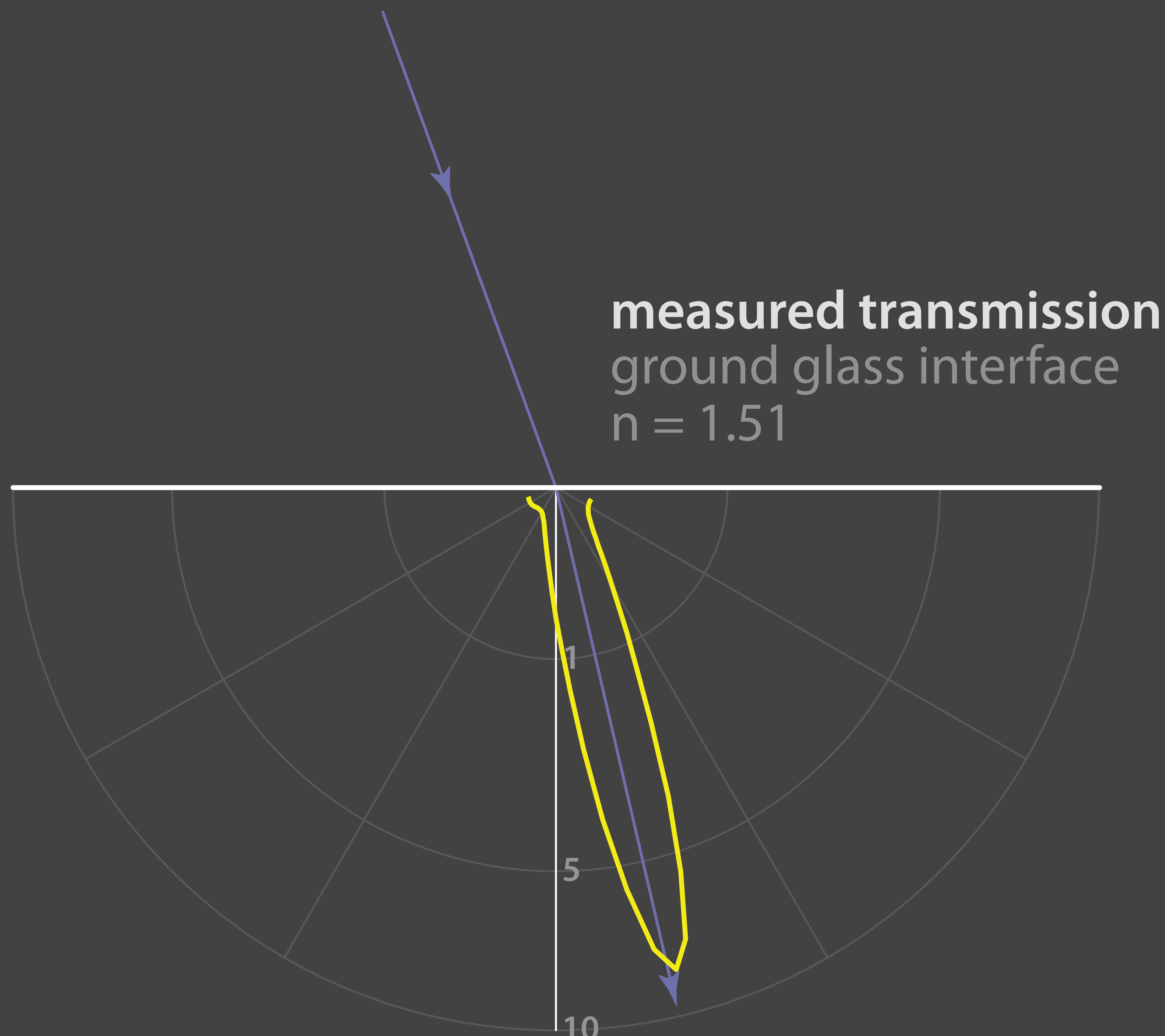
Diffuse transmission




measured transmission
ground glass interface
n = 1.51
1
5
10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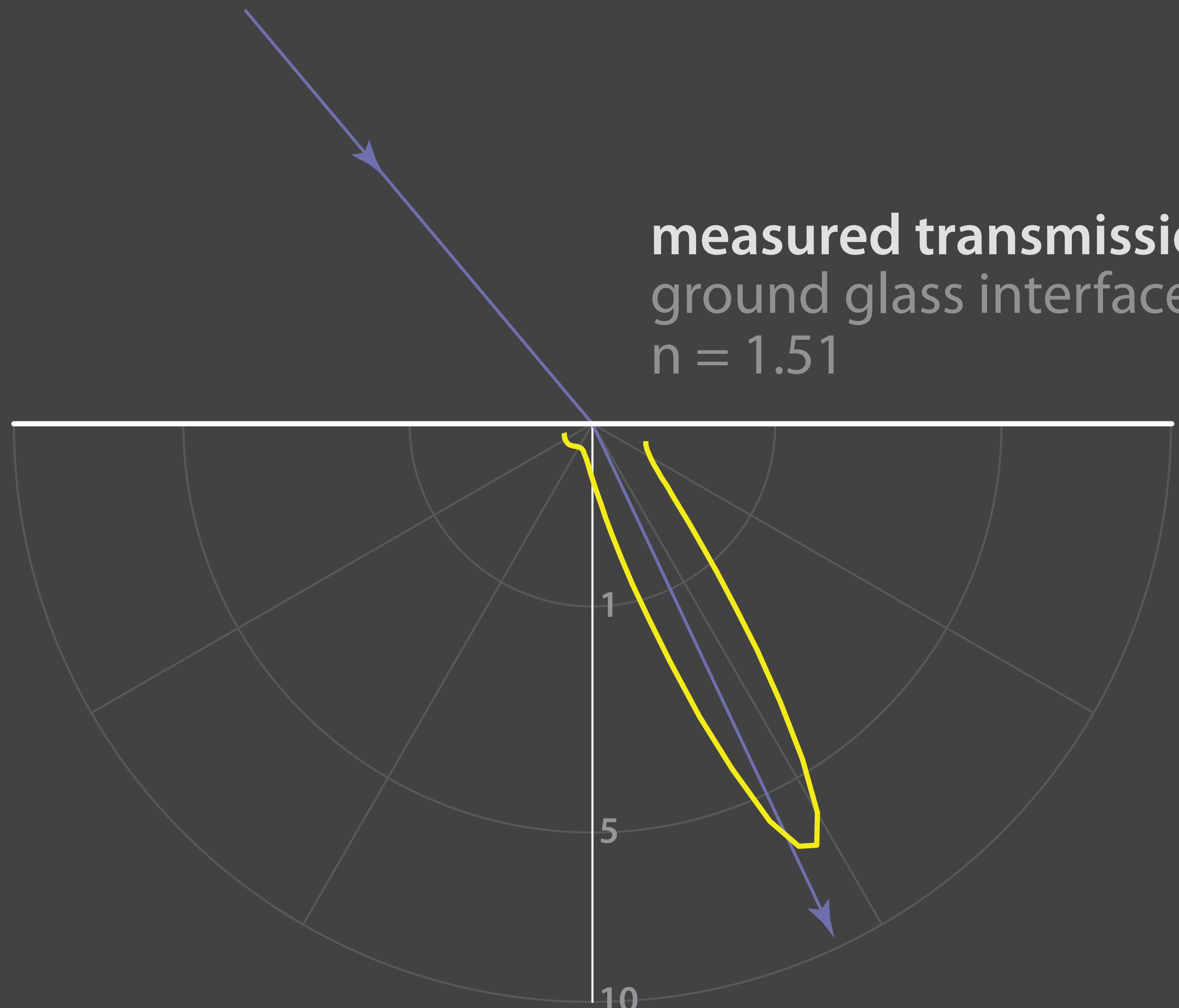

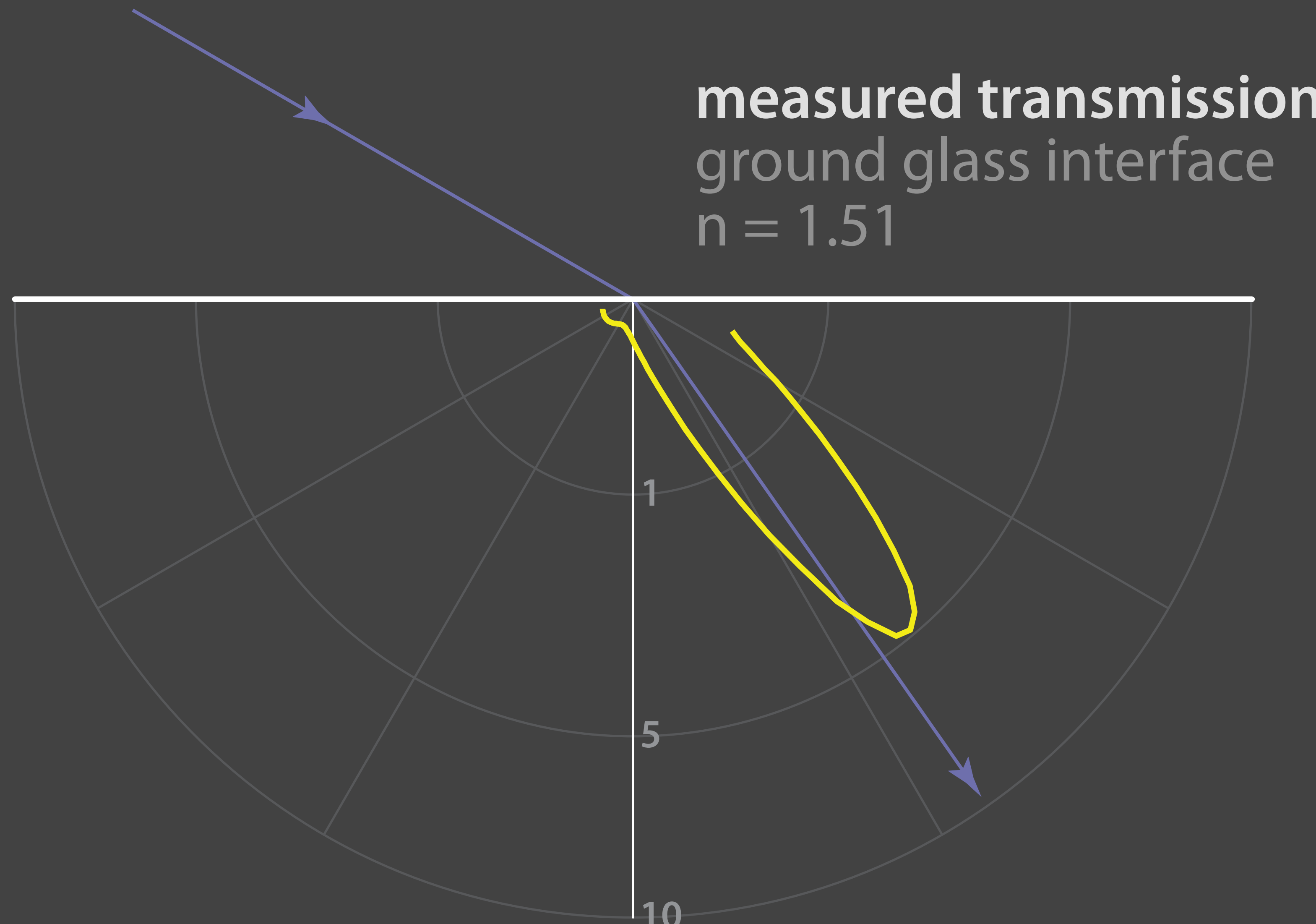
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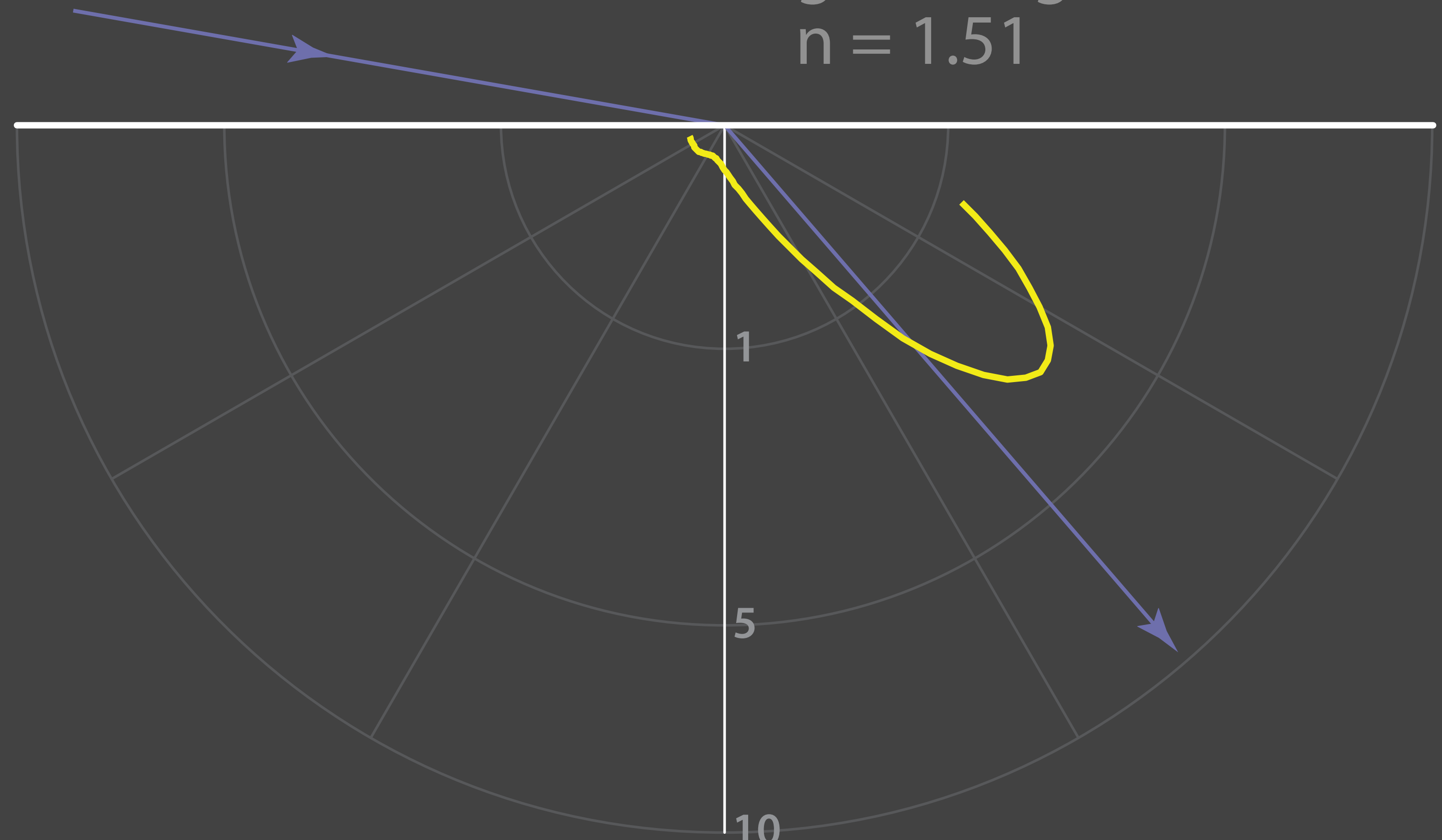

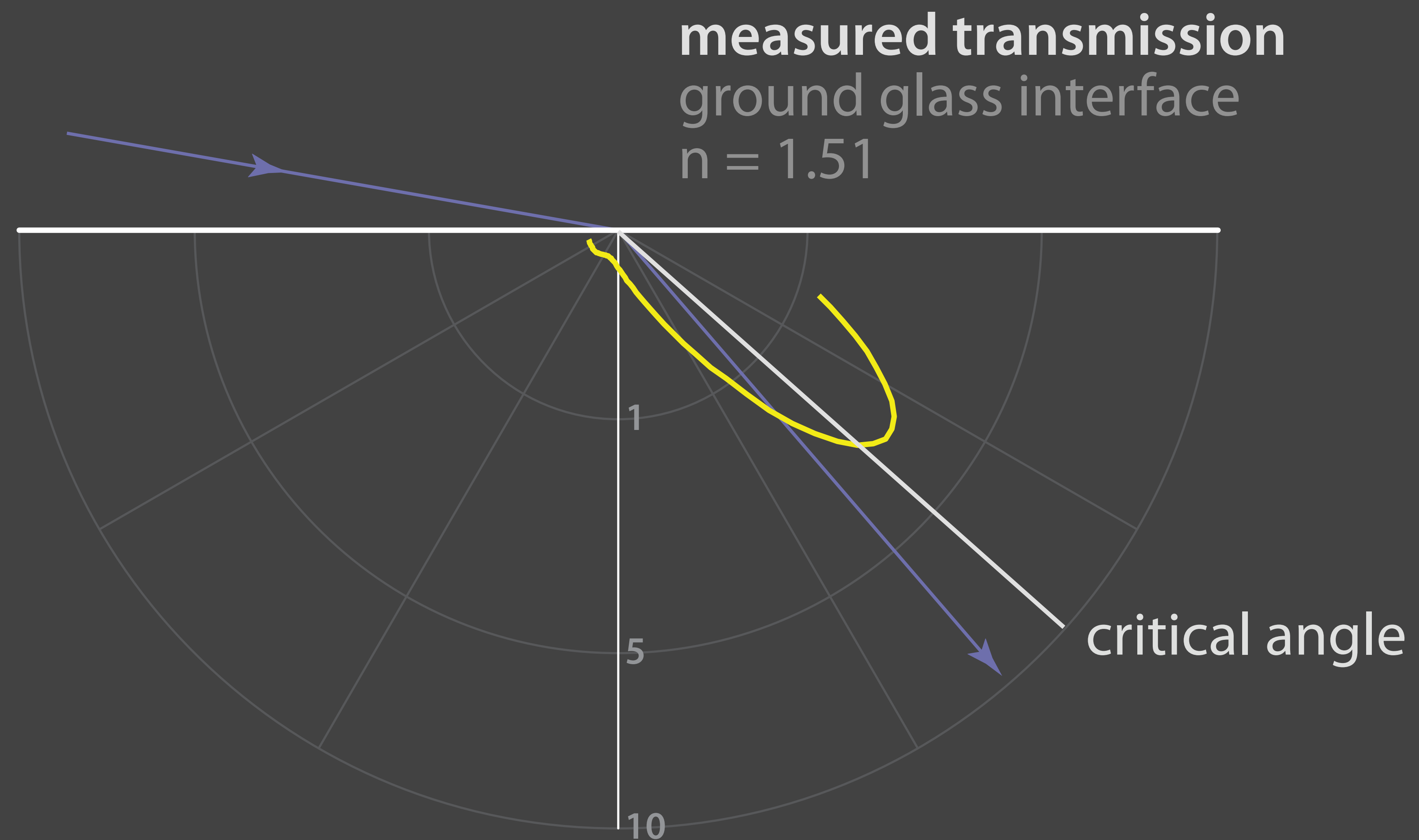

measured transmission
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critical angle

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

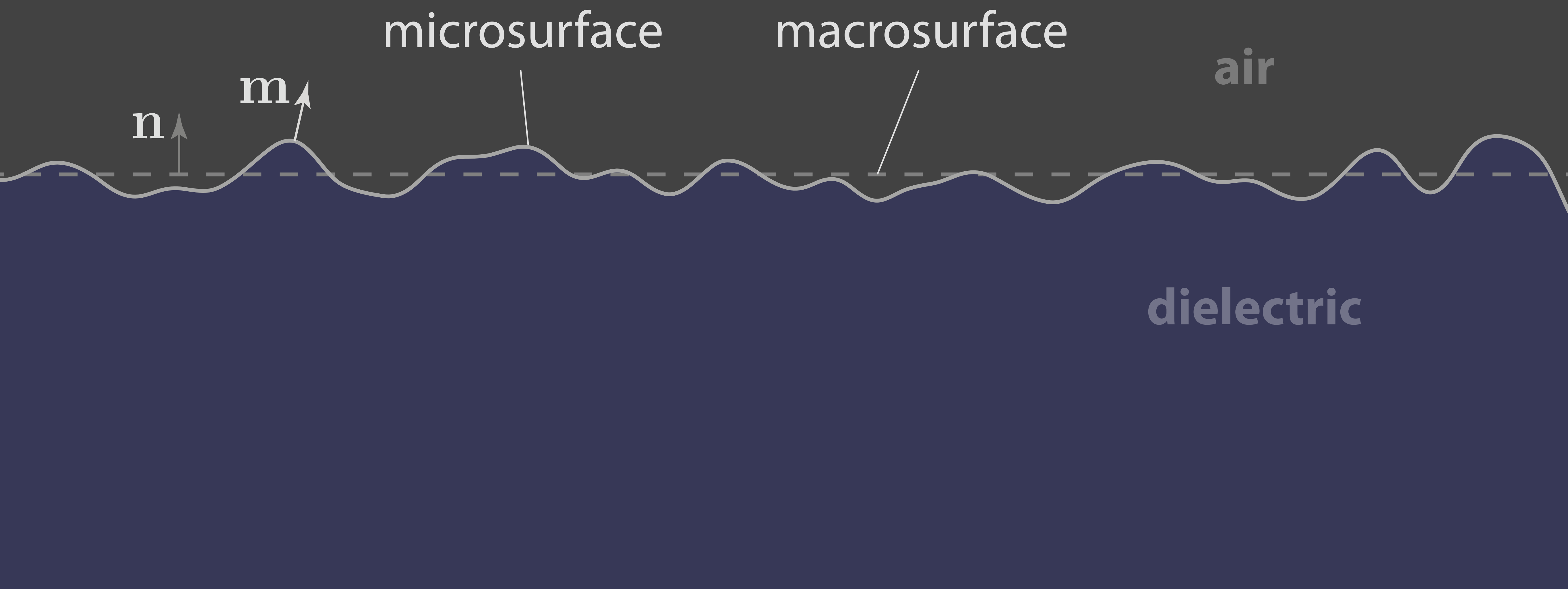
Measurement and validation

- single interface transmission

Microfacet scattering models

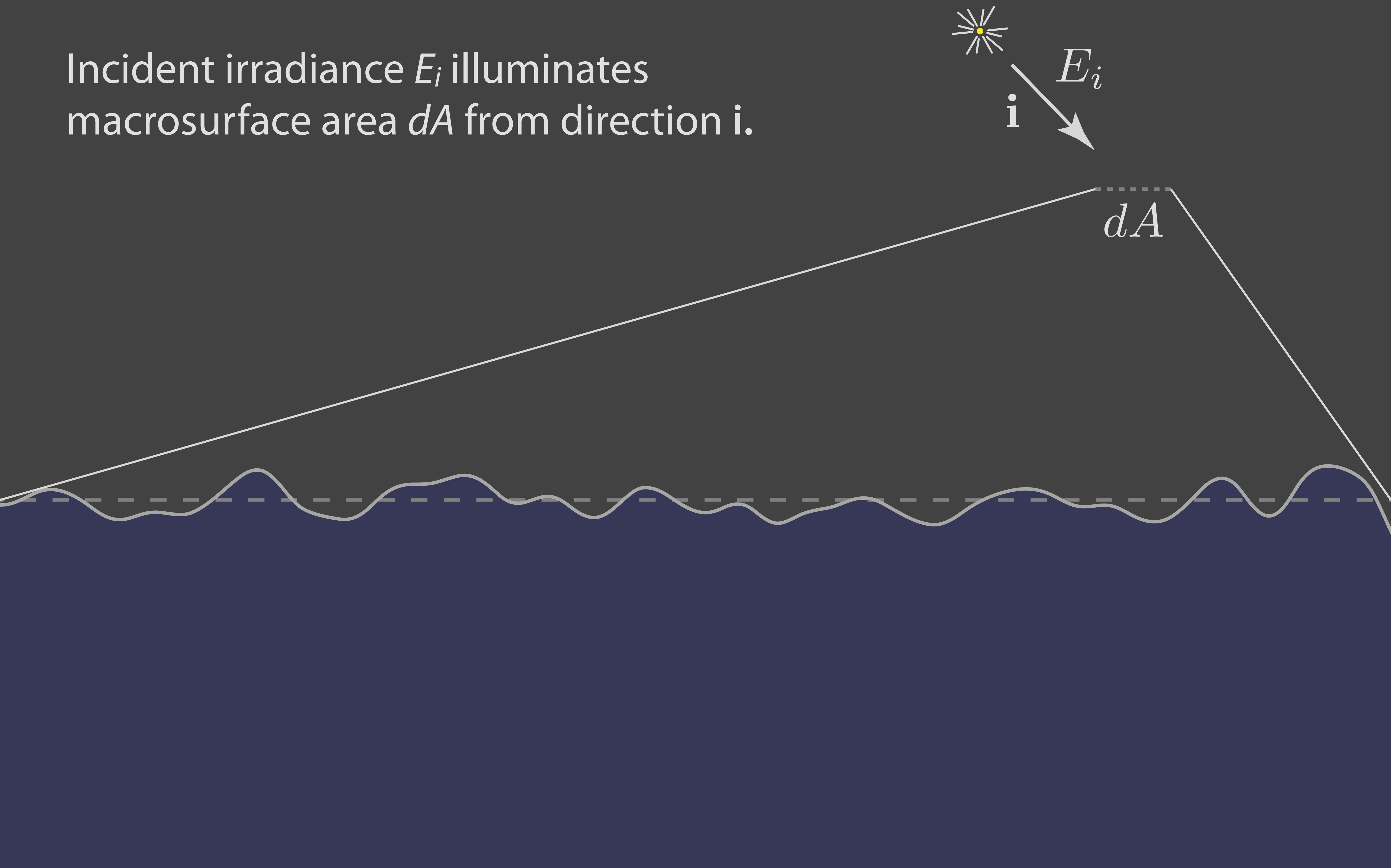
Assumptions

- rough dielectric surface
- single scattering



Microfacet reflection models

Incident irradiance E_i illuminates macrosurface area dA from direction **i**.



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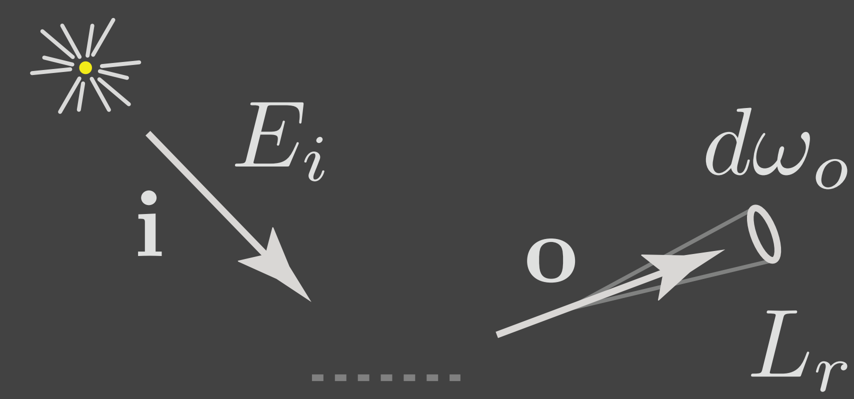
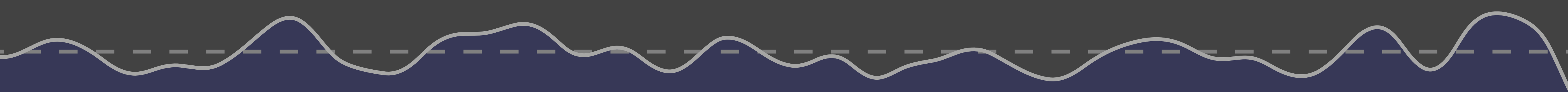
Reflected radiance L_r measured at direction **o** in solid angle $d\omega_o$.





Bidirectional **R**eflectance **D**istribution **F**unction: $f_r(\mathbf{i}, \mathbf{o}) = \dfrac{L_r}{E_i}$

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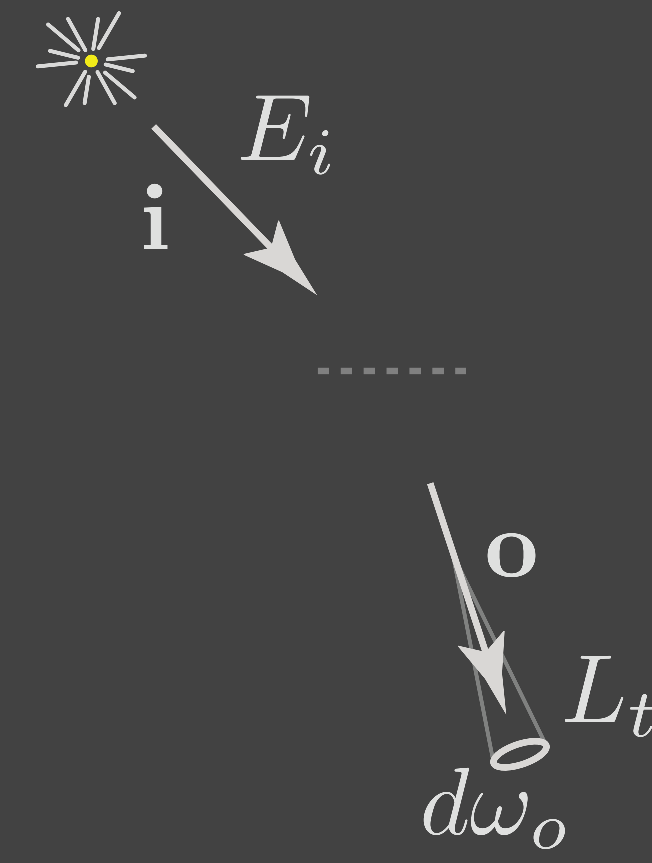

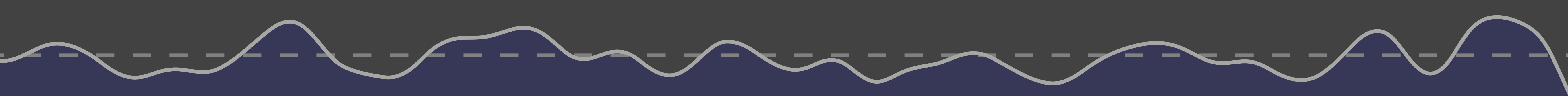

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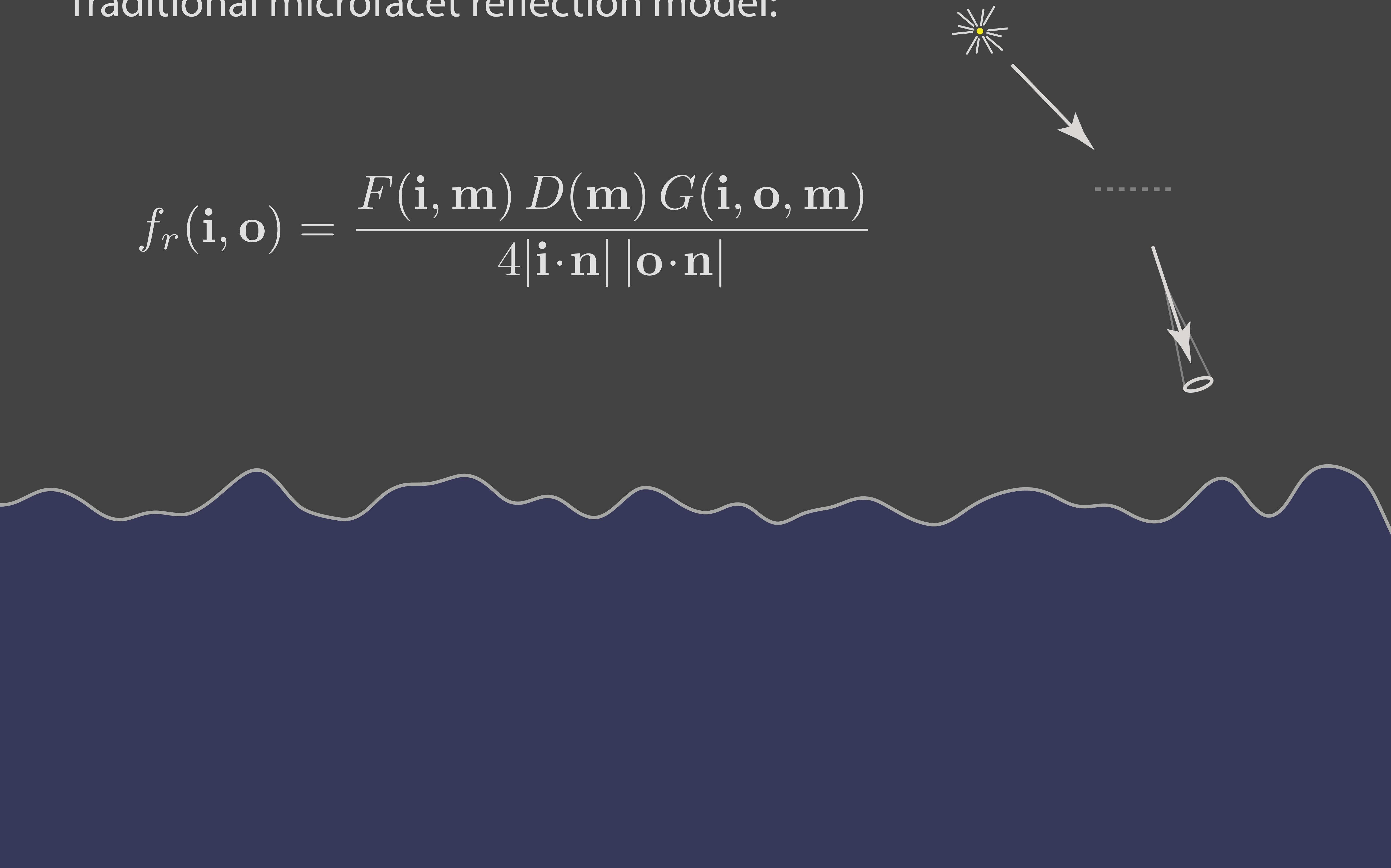
Bidirectional **T**ransmittance **D**istribution **F**unction: $f_t(\mathbf{i}, \mathbf{o}) = \frac{L_t}{E_i}$

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

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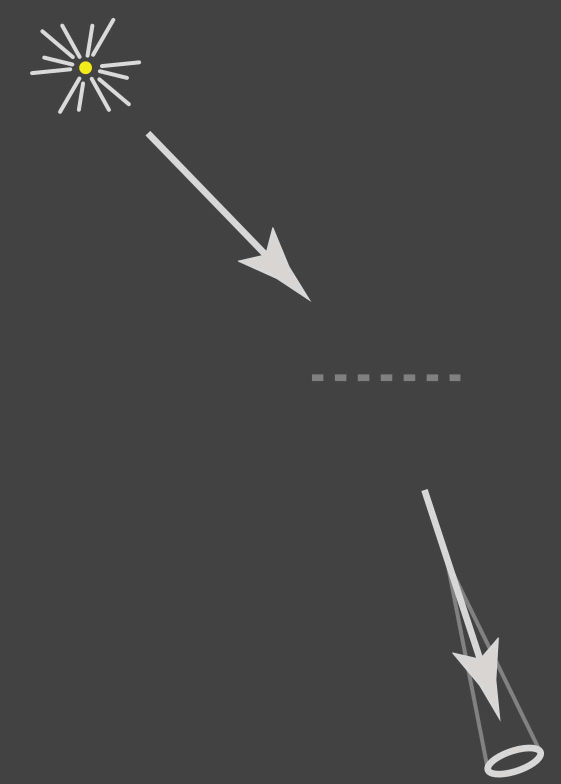
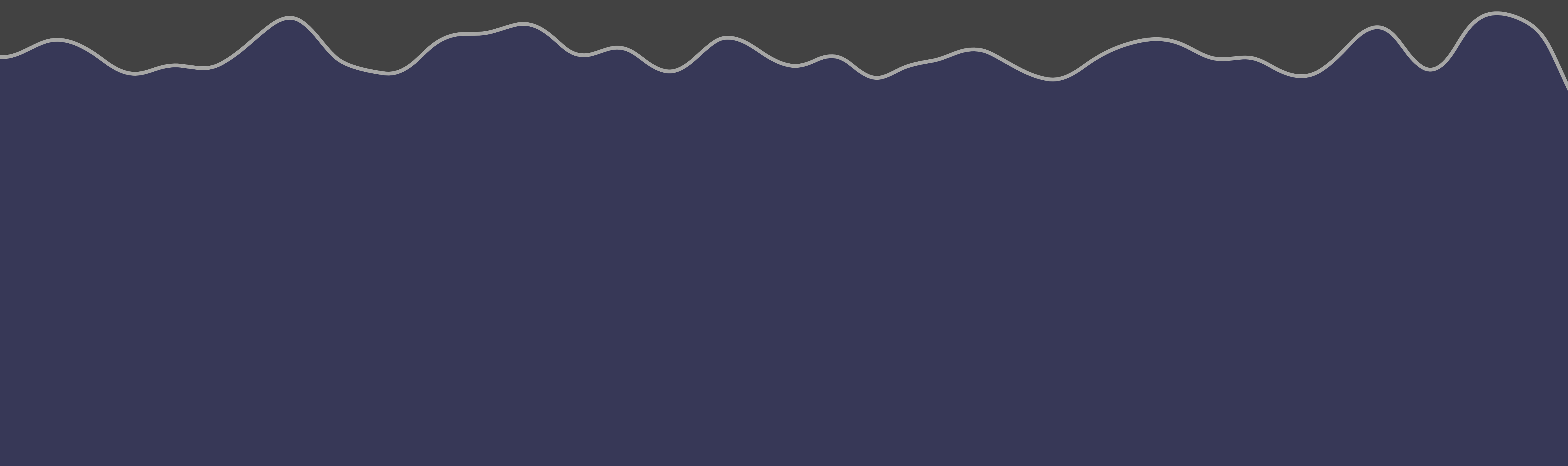


We generalize the geometric analysis dealing with the surface area where scattering occurs.



“half-vector” function

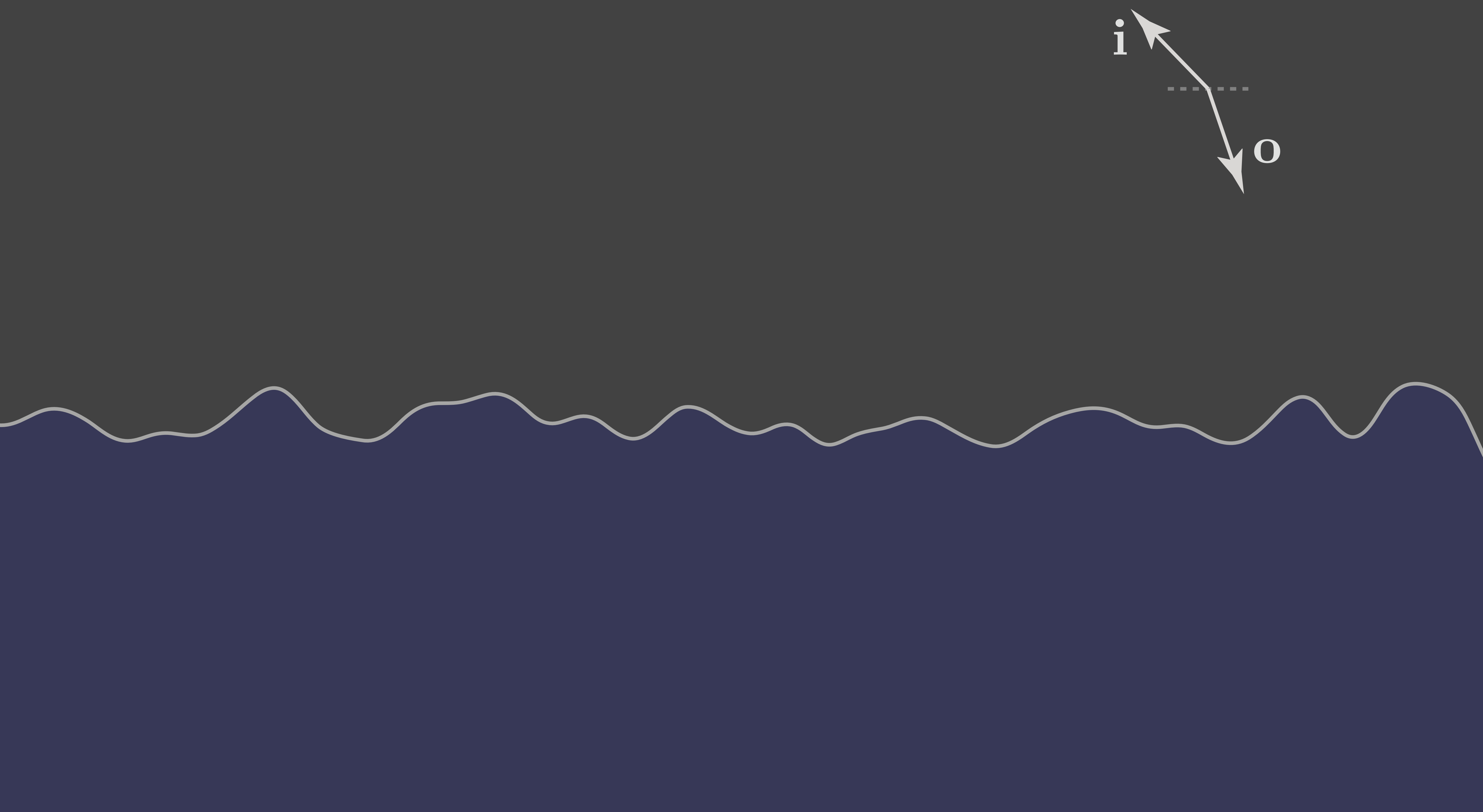
$\mathbf{h}(\mathbf{i}, \mathbf{o})$

normal distribution

$D(\mathbf{m})$

shadowing–masking

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



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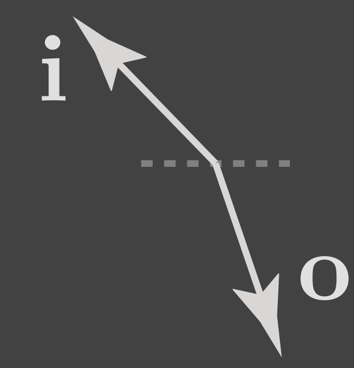

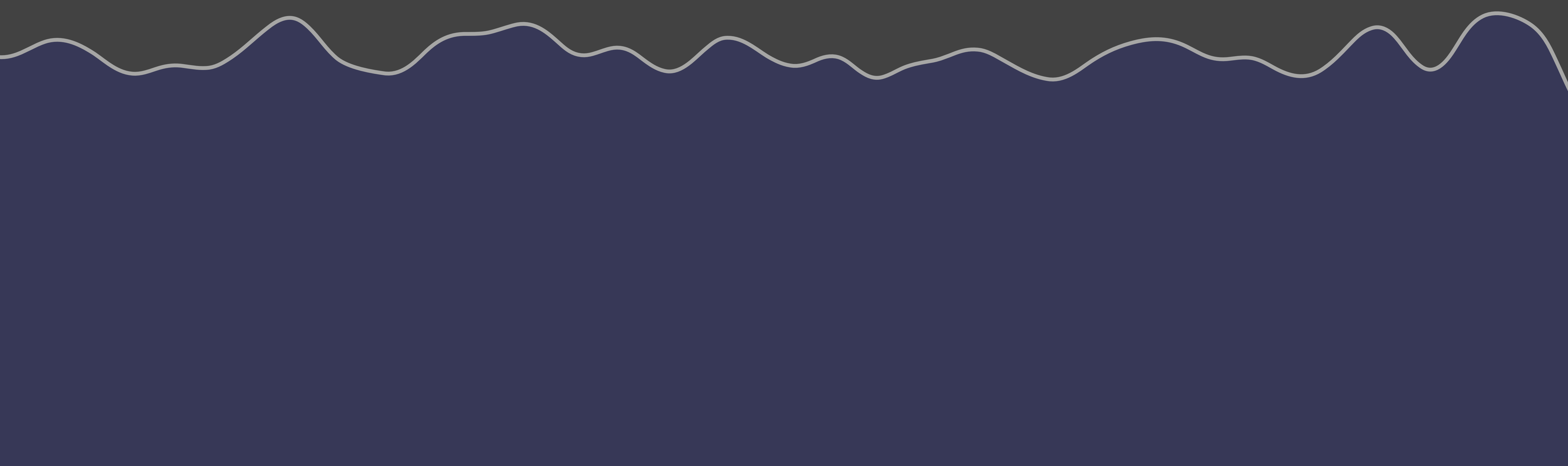

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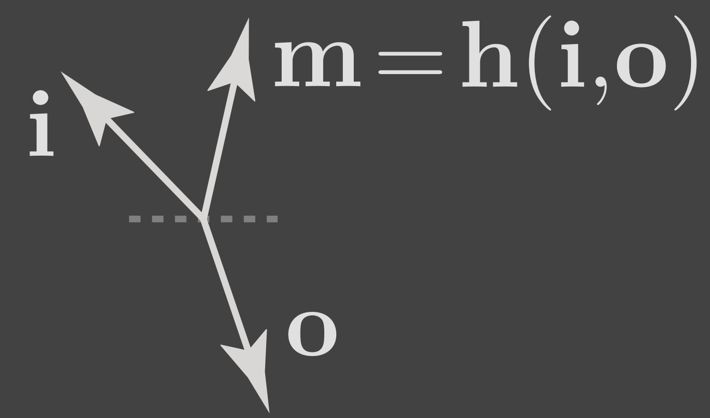

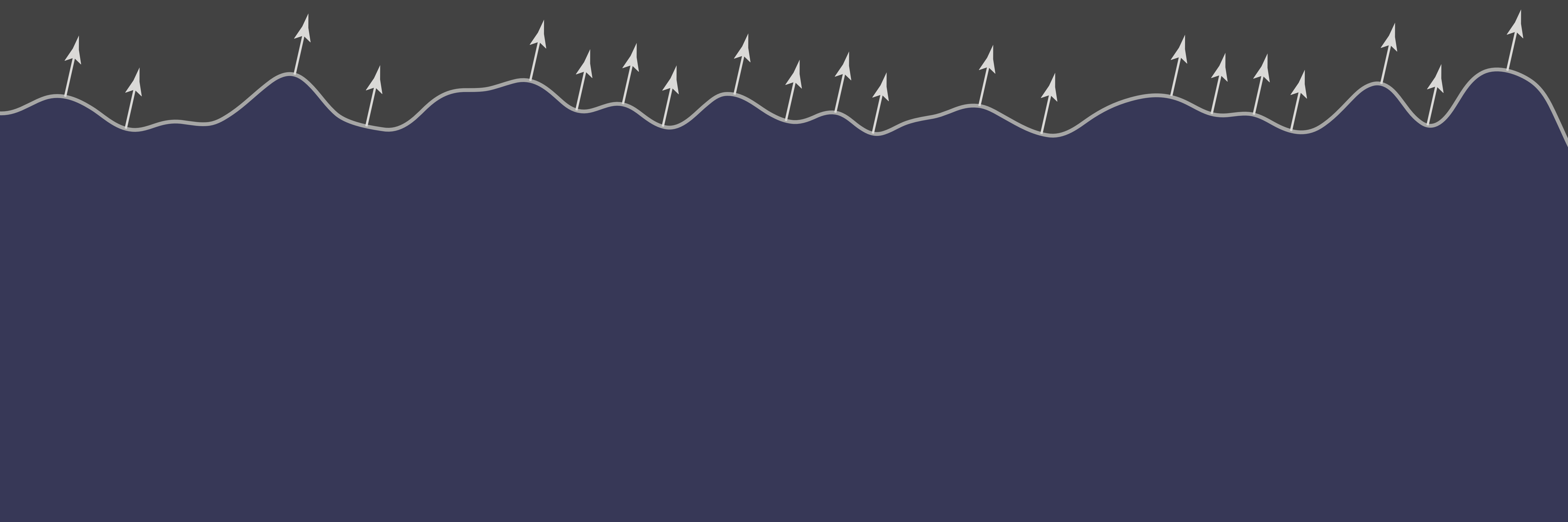

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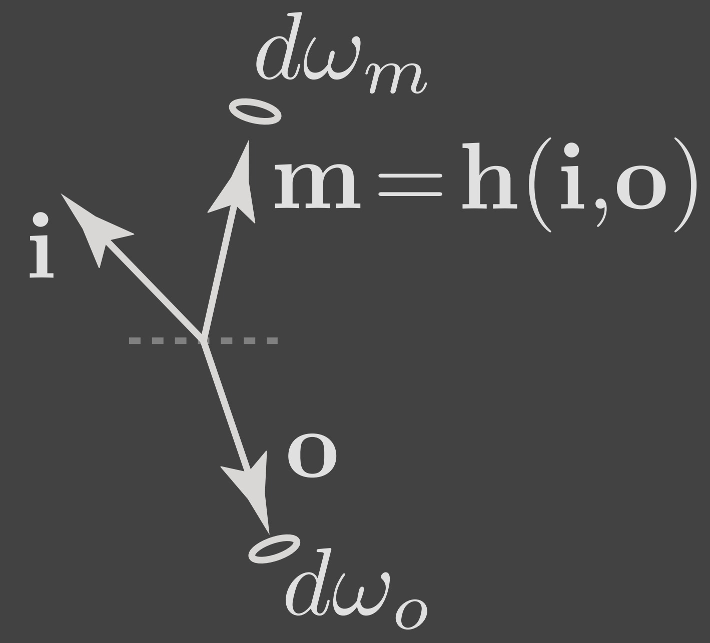
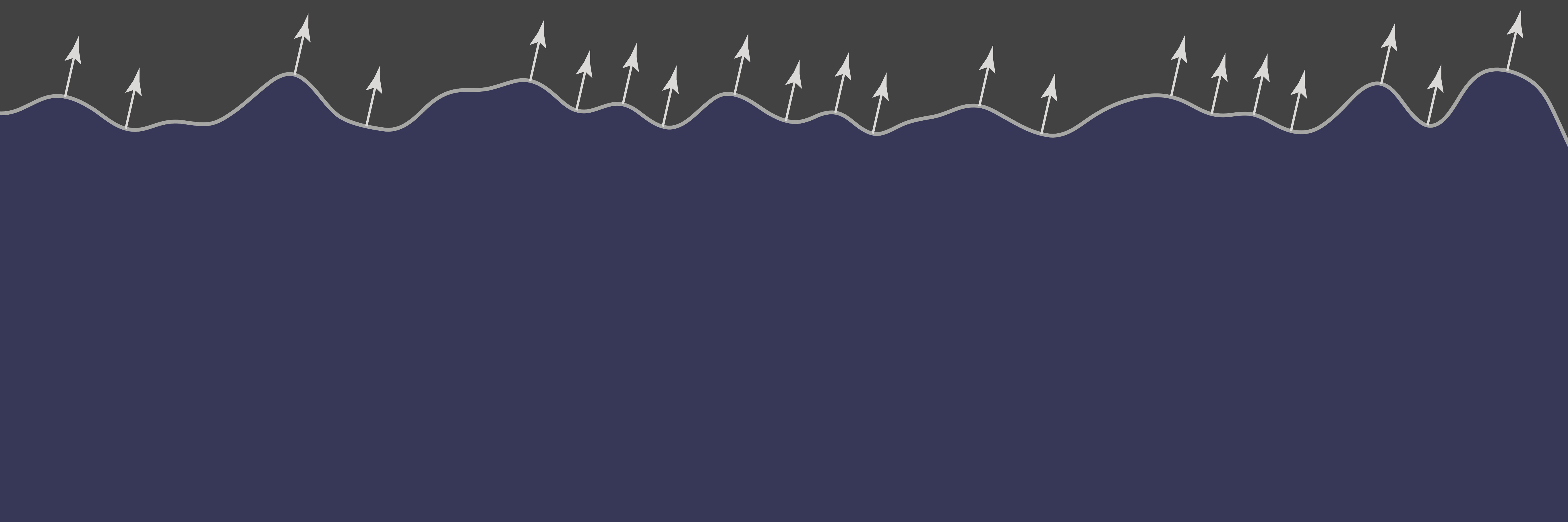
- selects **m**
- determines size of $d\omega_m$





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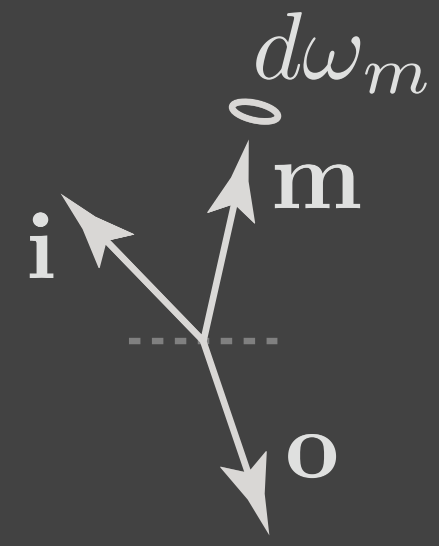

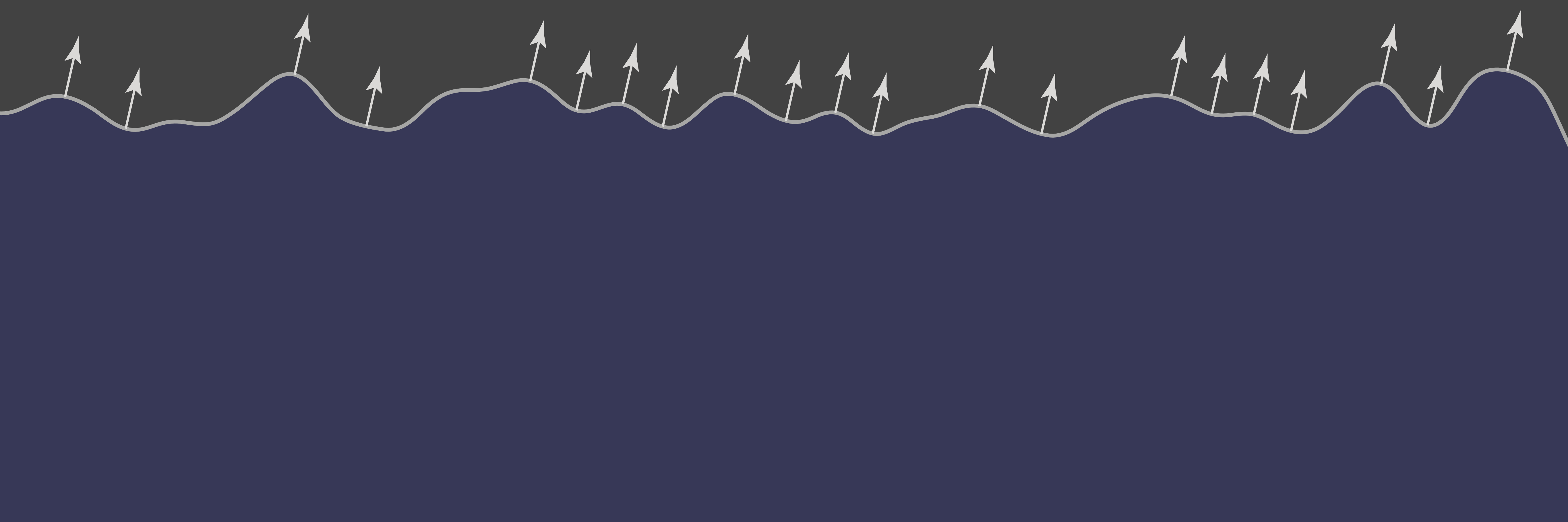

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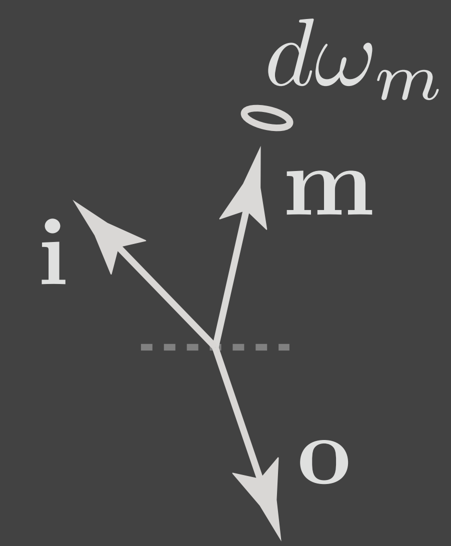
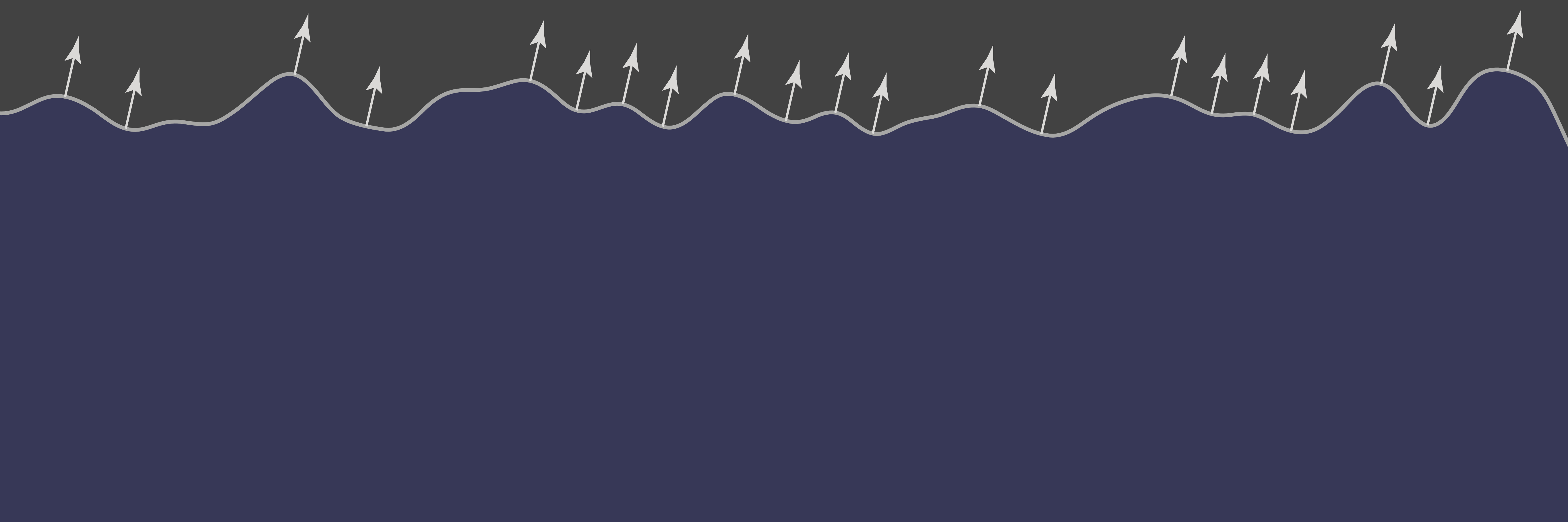


D measures density of microsurface area with respect to microsurface normal **m**.



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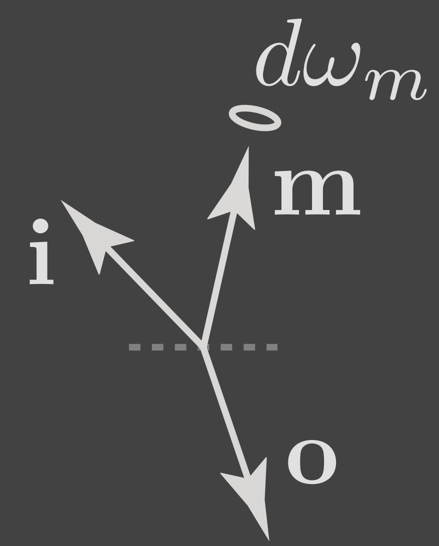

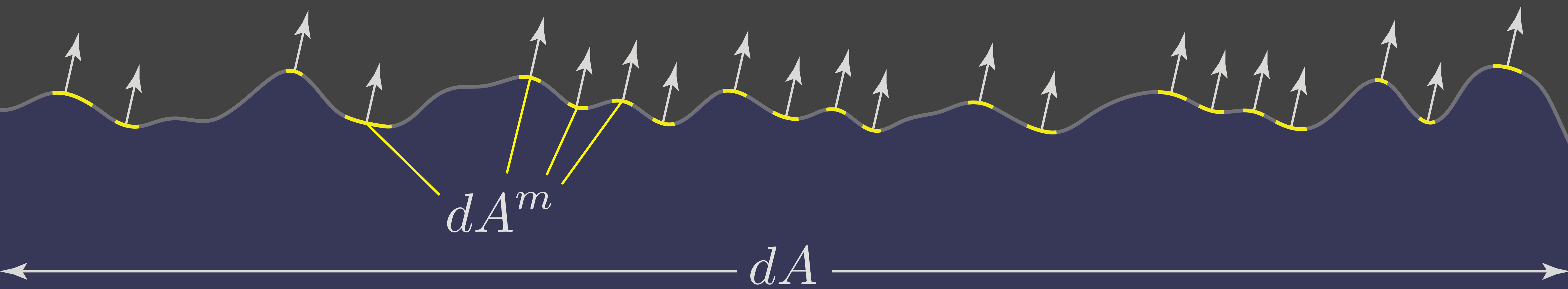

$$dA^m = D(\mathbf{m})\, d\omega_m\, dA$$

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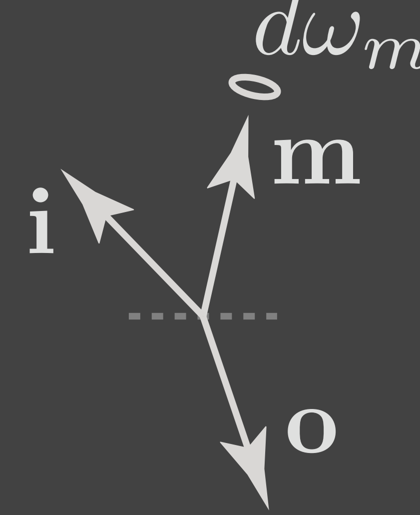

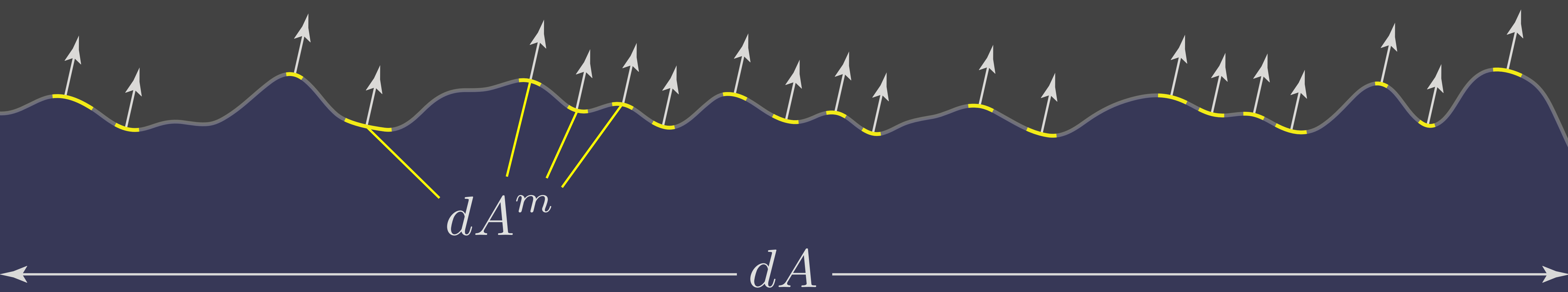

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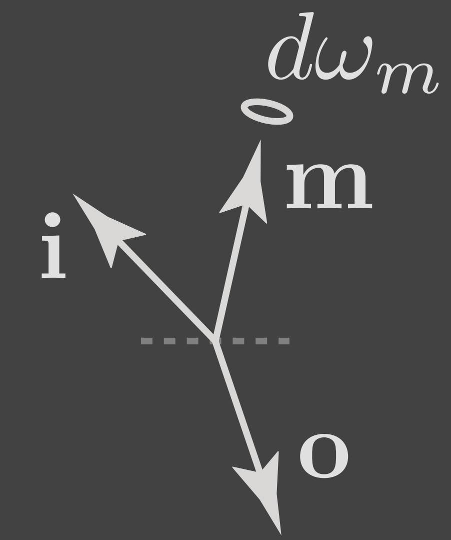

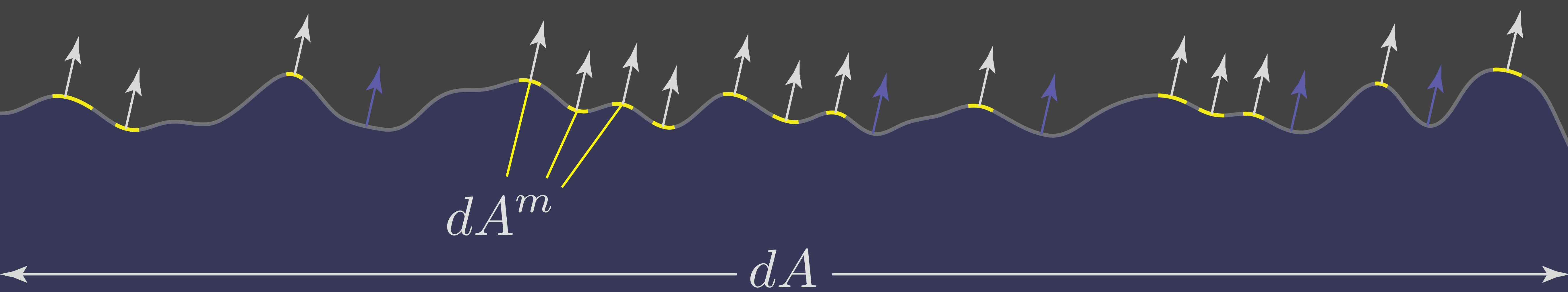

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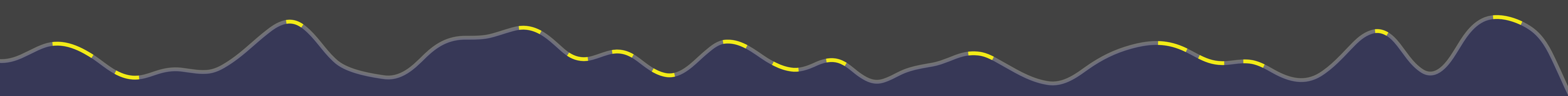
For reflection or transmission:

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



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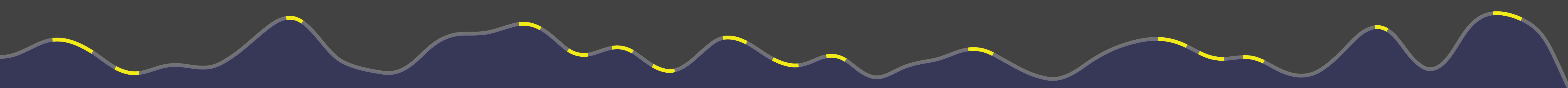

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easy to generalize

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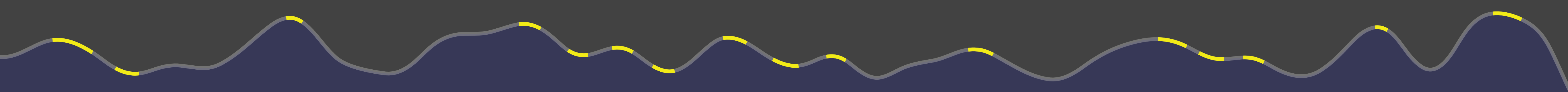

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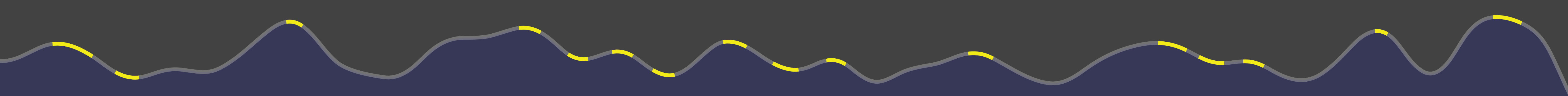
key contribution



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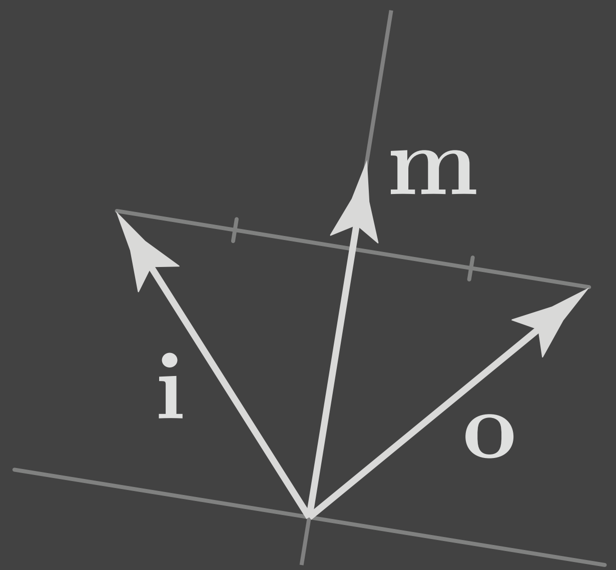
Construction of half-vector

reflection



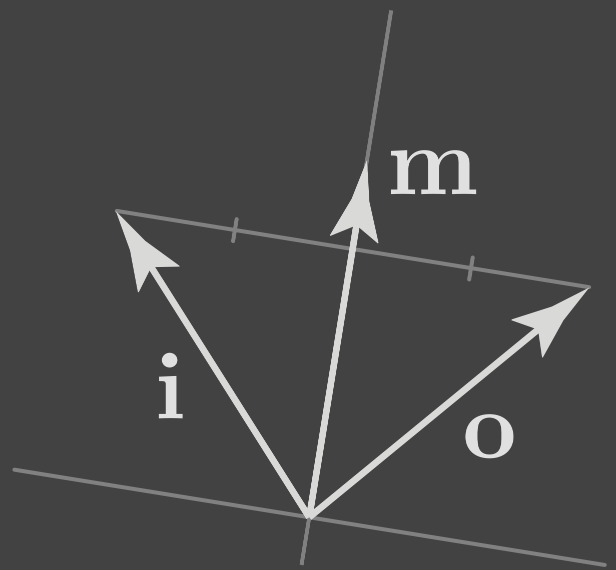
$\mathbf{i} + \mathbf{o}$ parallel to $\mathbf{m}$

refraction

Construction of half-vector

reflection

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



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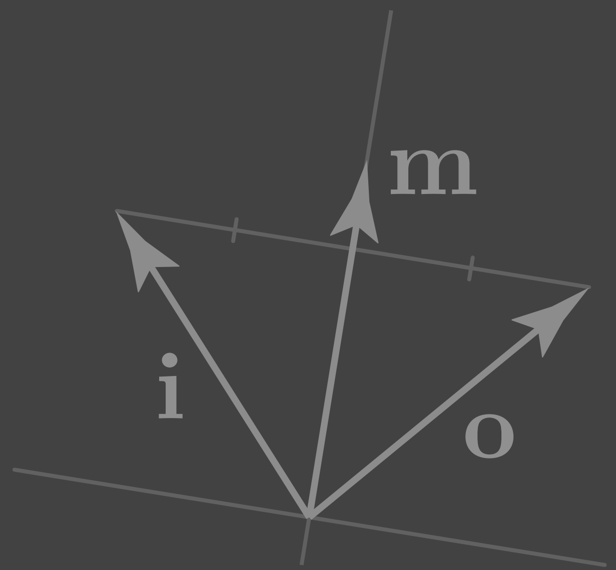

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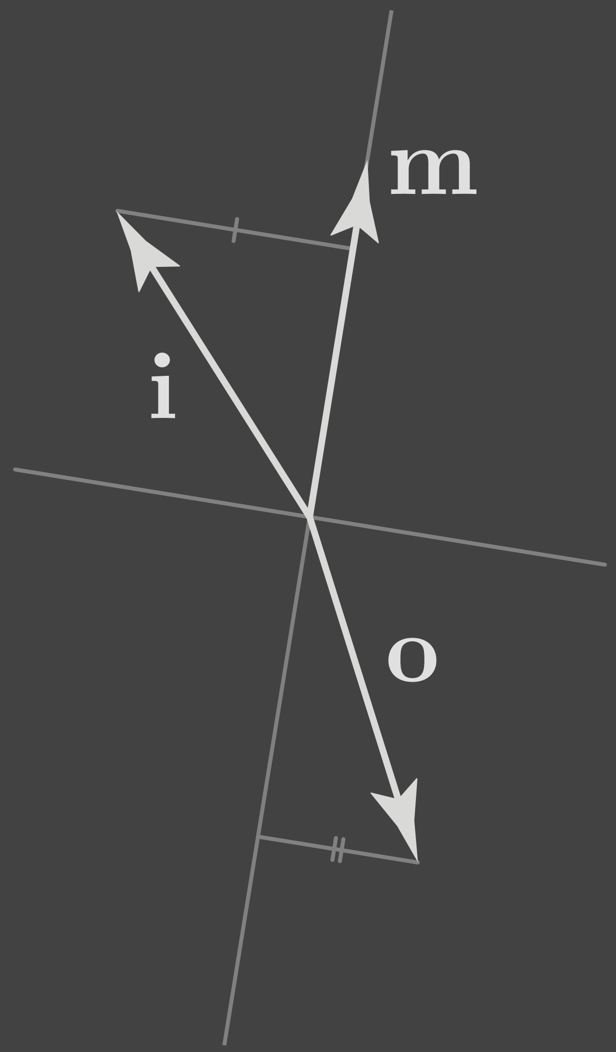

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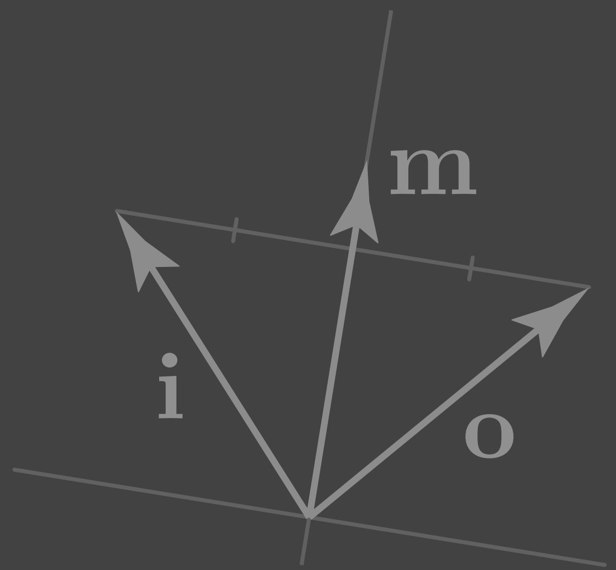

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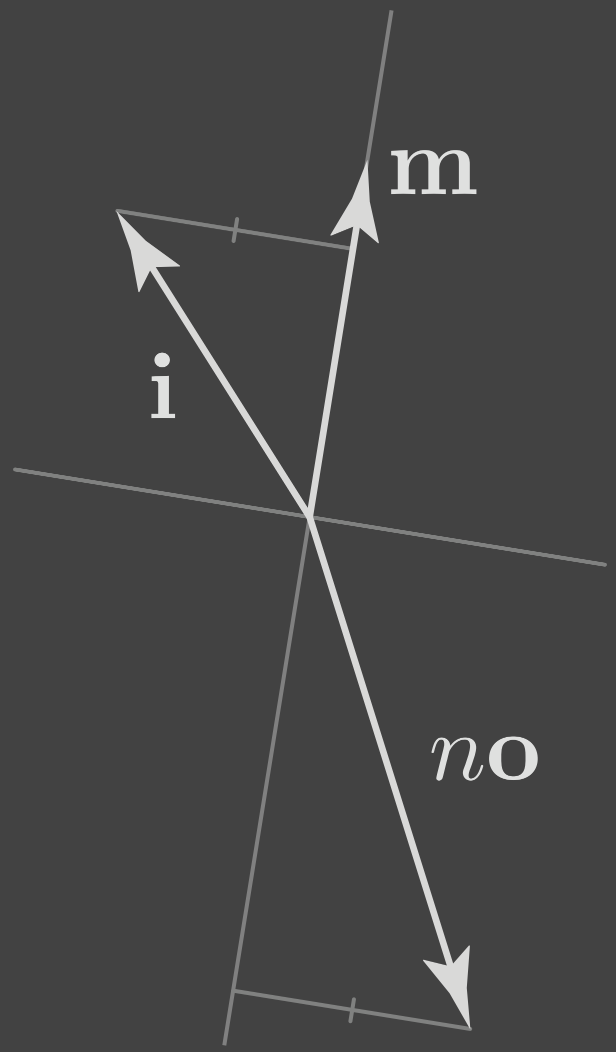

$\mathbf{i} + n\mathbf{o}$ parallel to $\mathbf{m}$

Construction of half-vector

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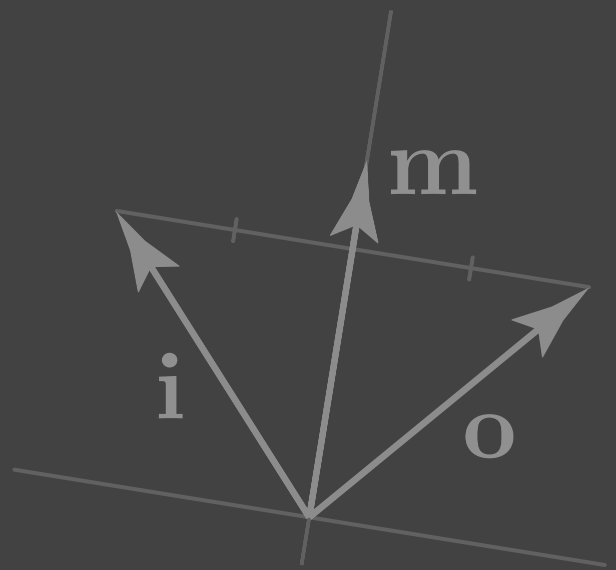
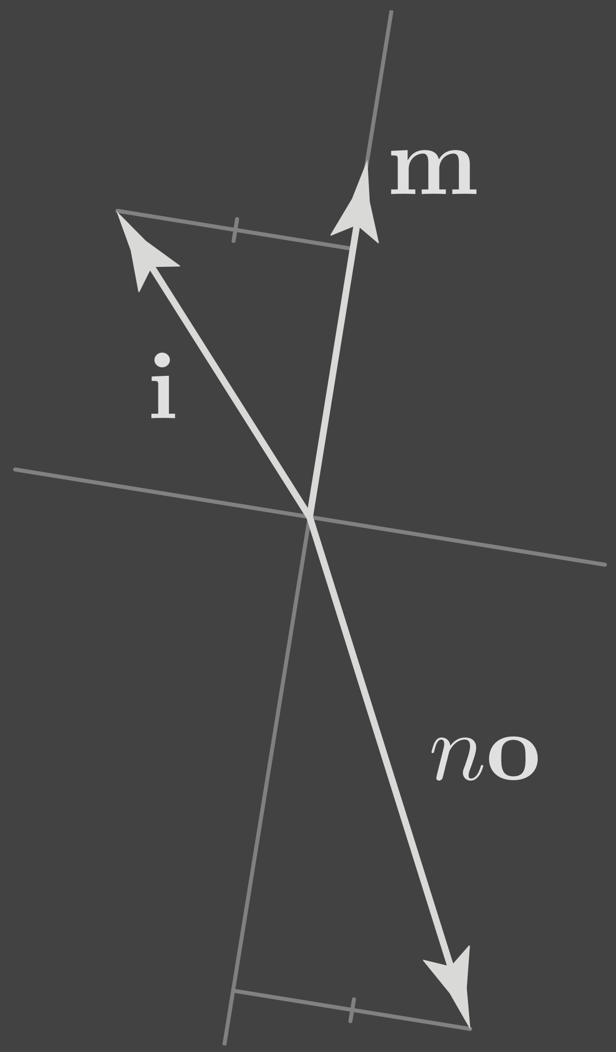


$\mathbf{i} + \mathbf{o}$ parallel to $\mathbf{m}$

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

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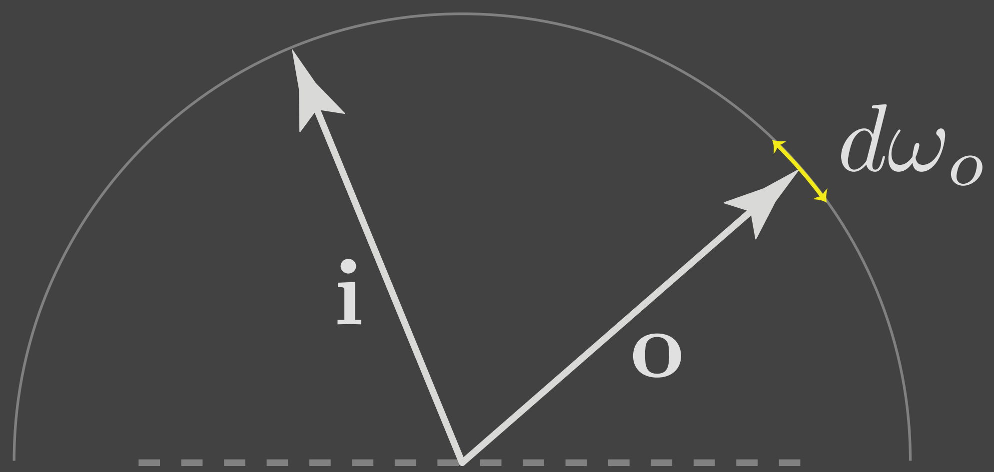

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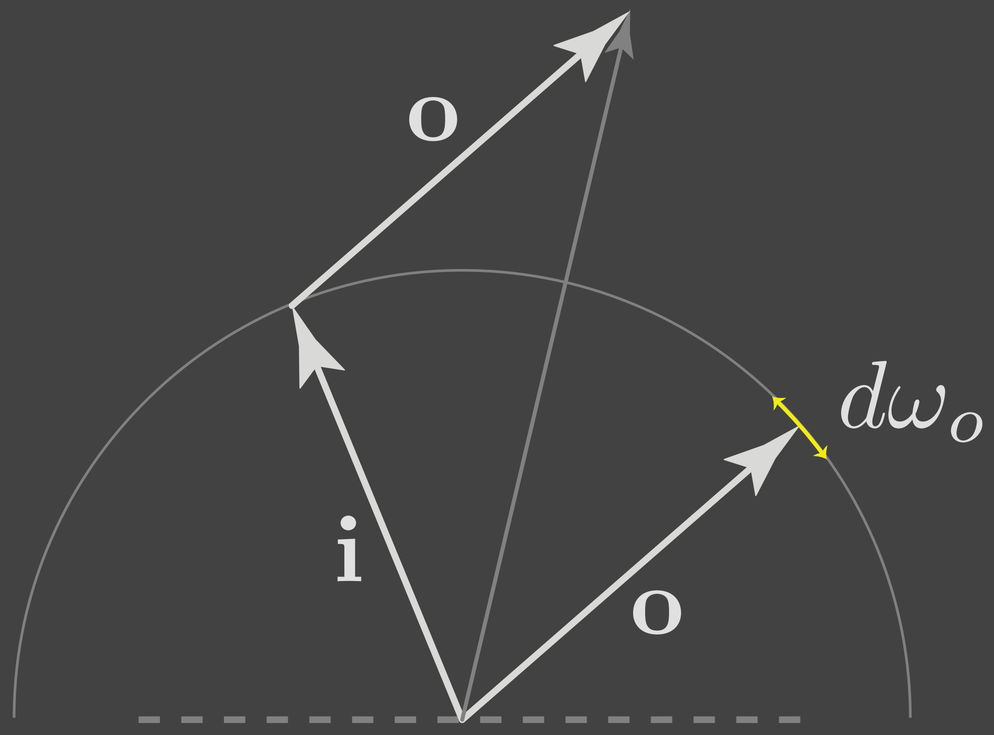

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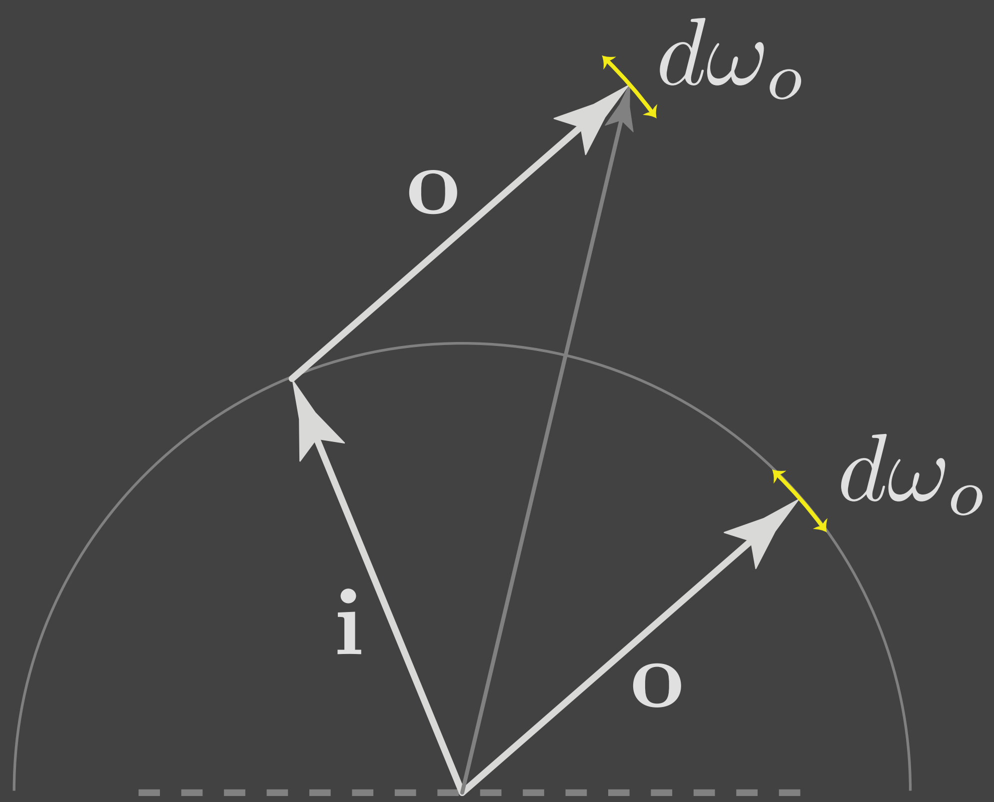


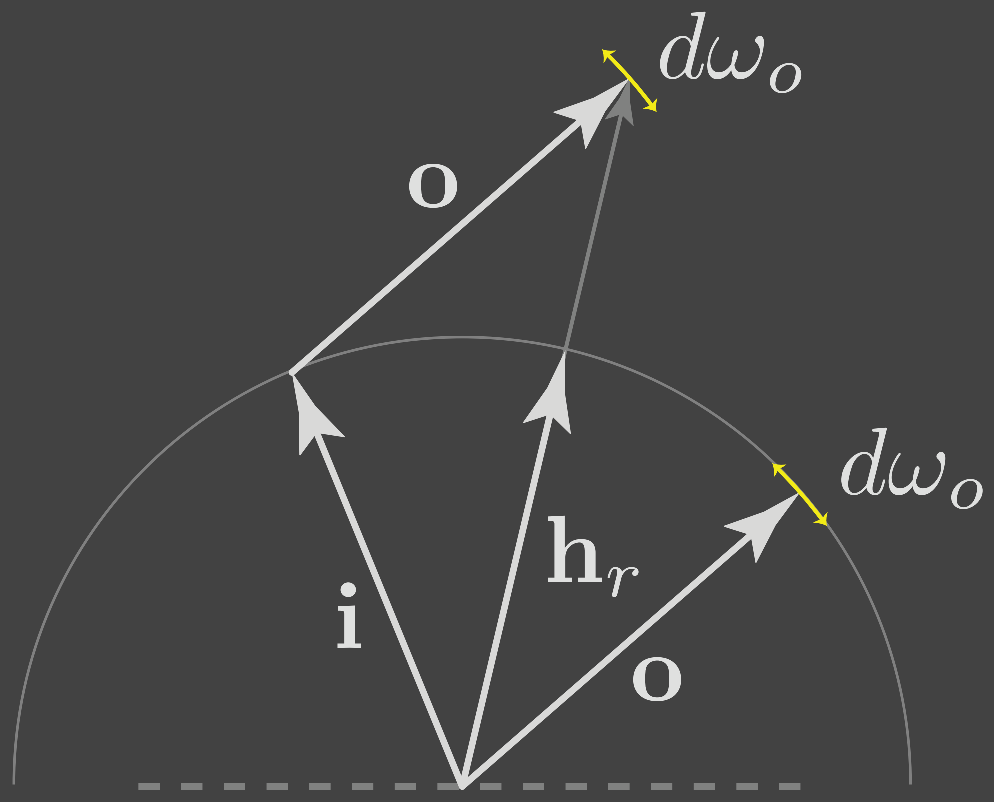
refraction

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

Construction of half-vector solid angle

reflection

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



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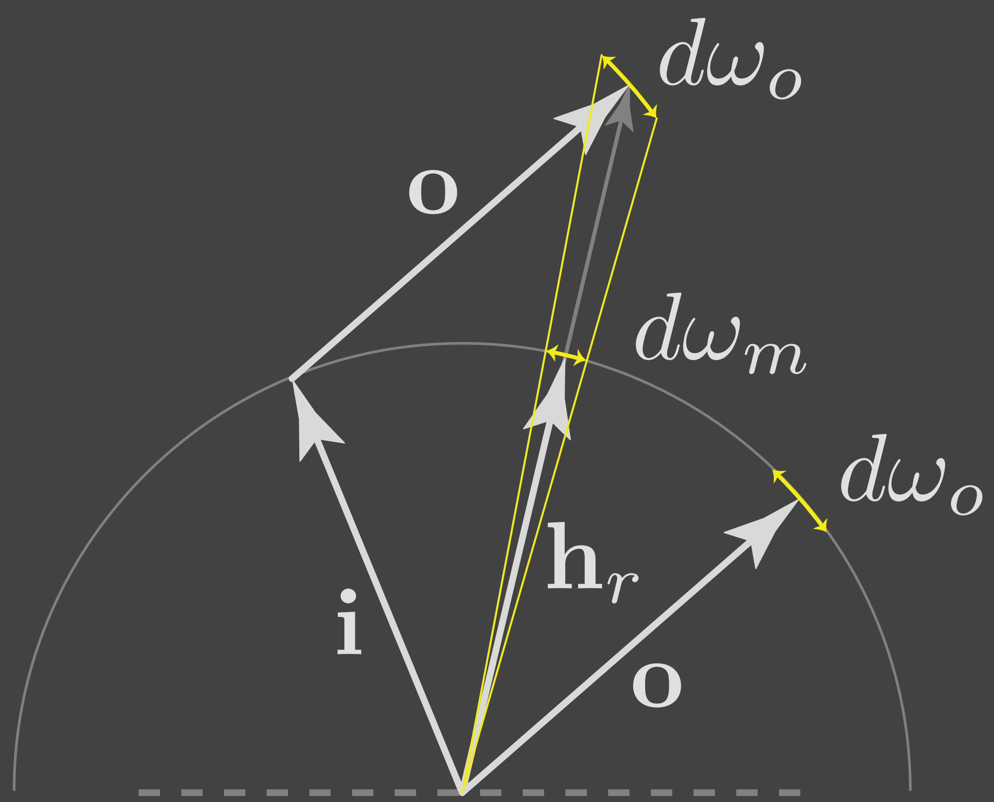

$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2} \, d\omega_o$$

refraction

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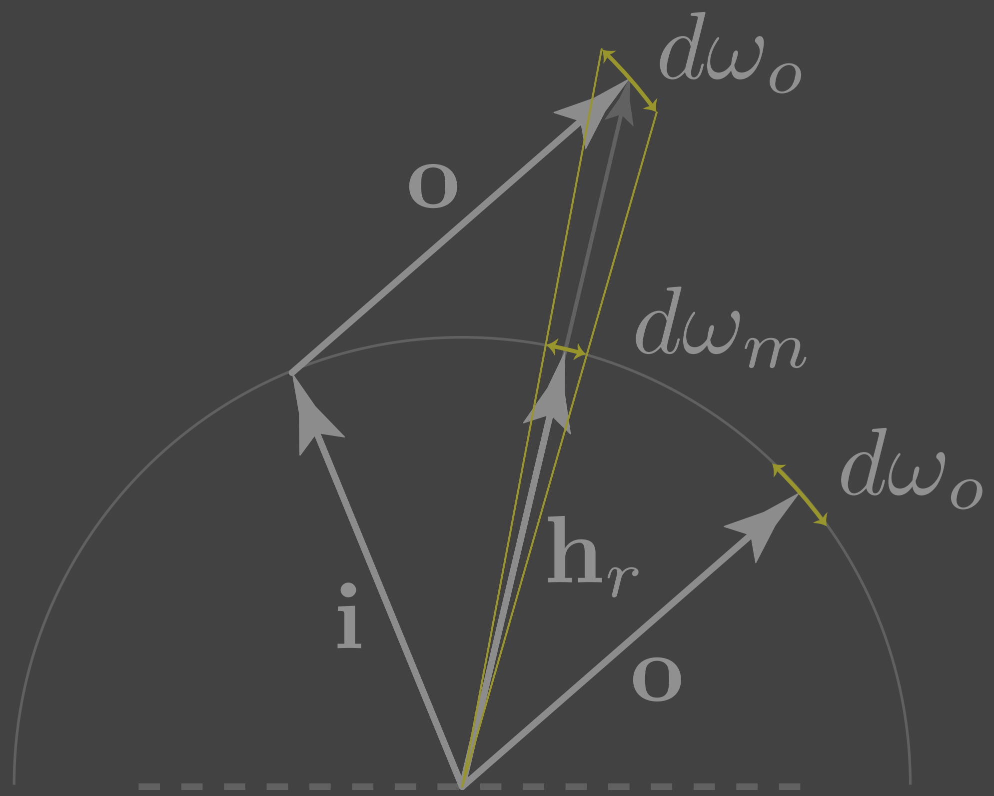

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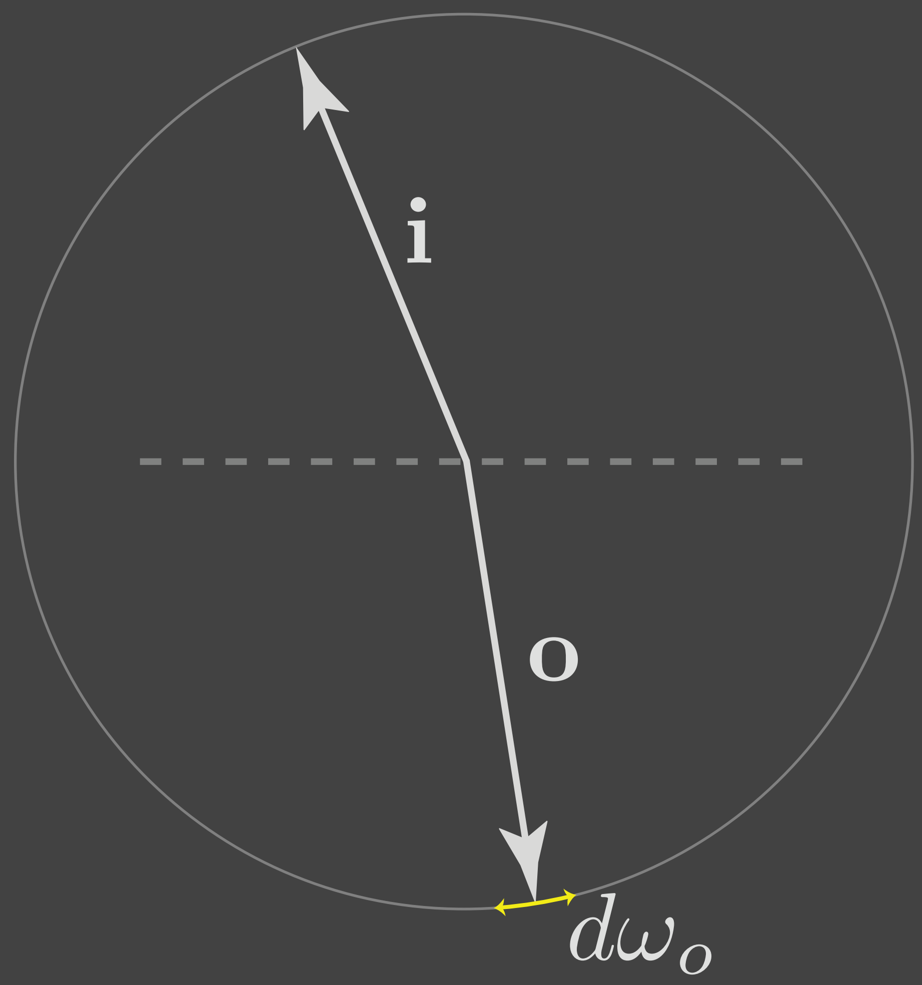

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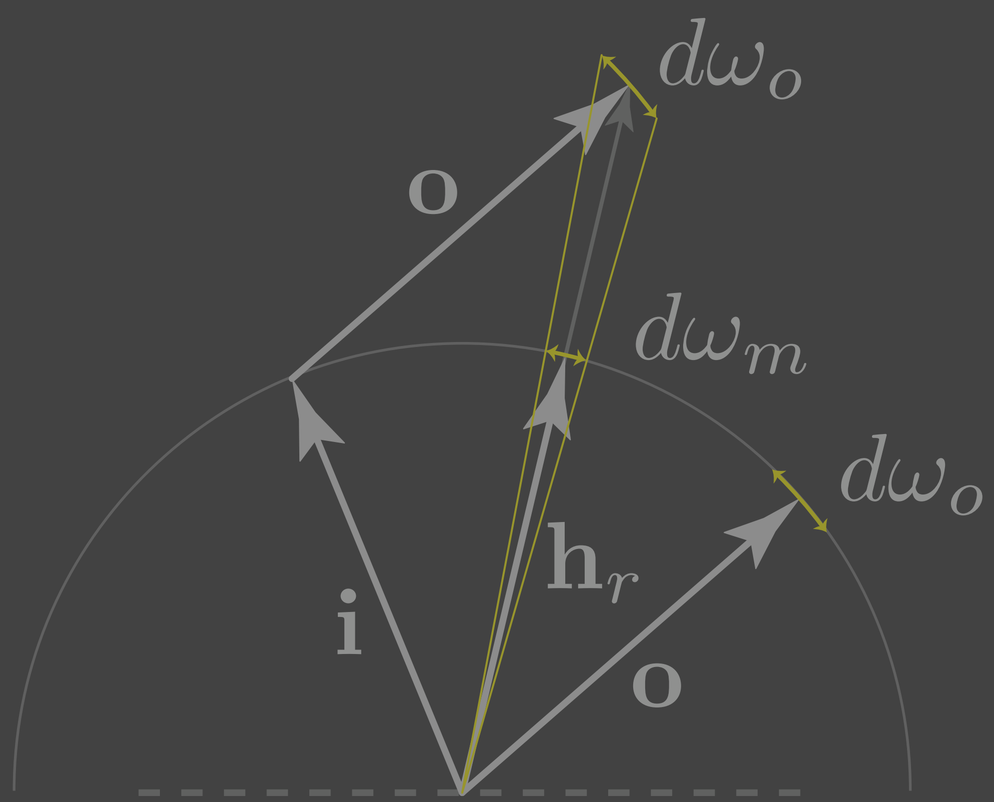

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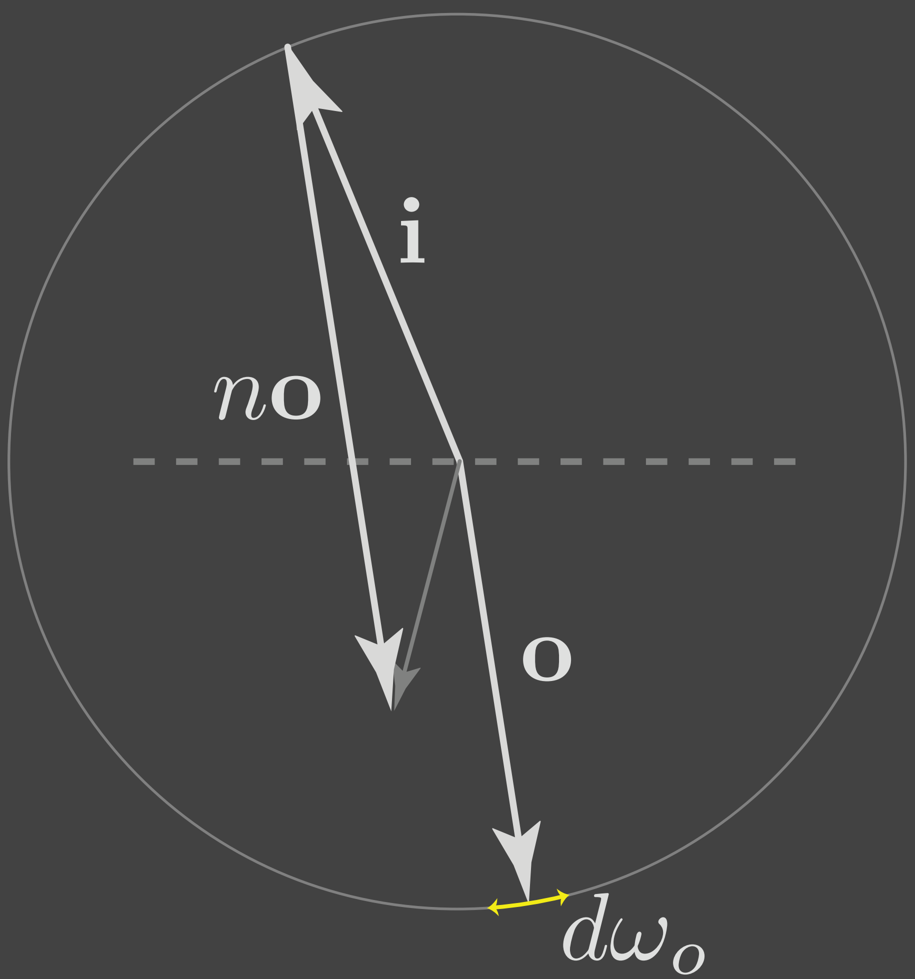

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reflection

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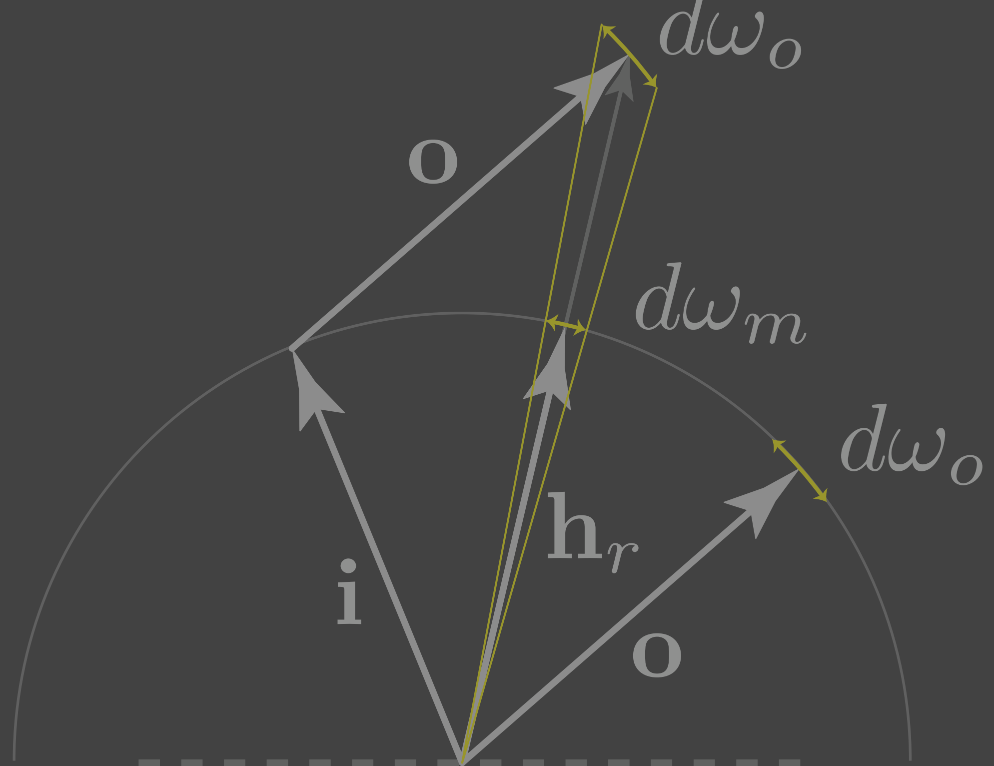
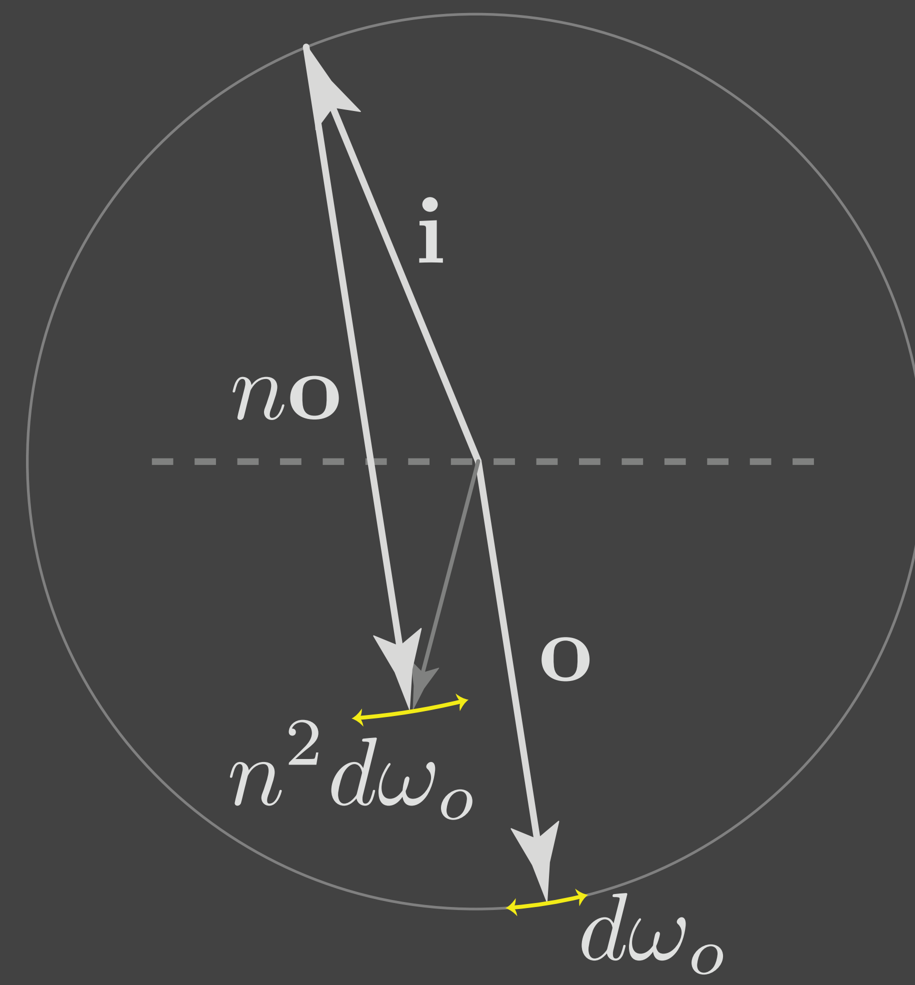


$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_r|}{\|\mathbf{i} + \mathbf{o}\|^2} \, d\omega_o$$

refraction

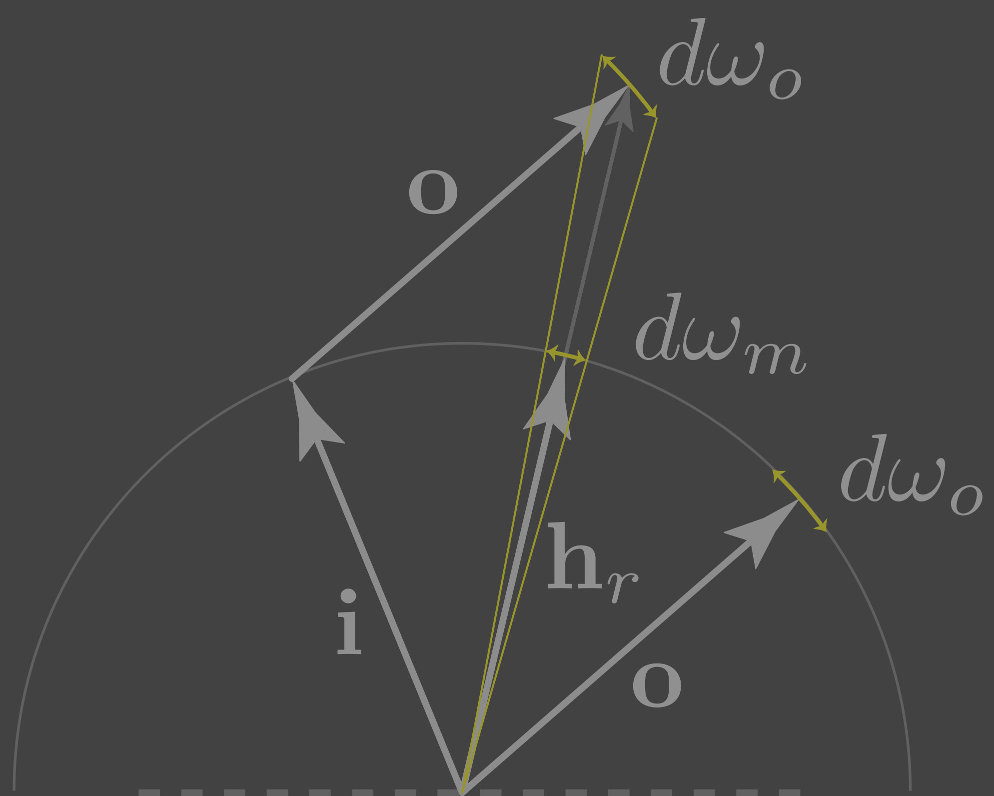
$$\mathbf{h}_t = -\text{normalize}(\mathbf{i} + n\mathbf{o})$$



Construction of half-vector solid angle

reflection

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



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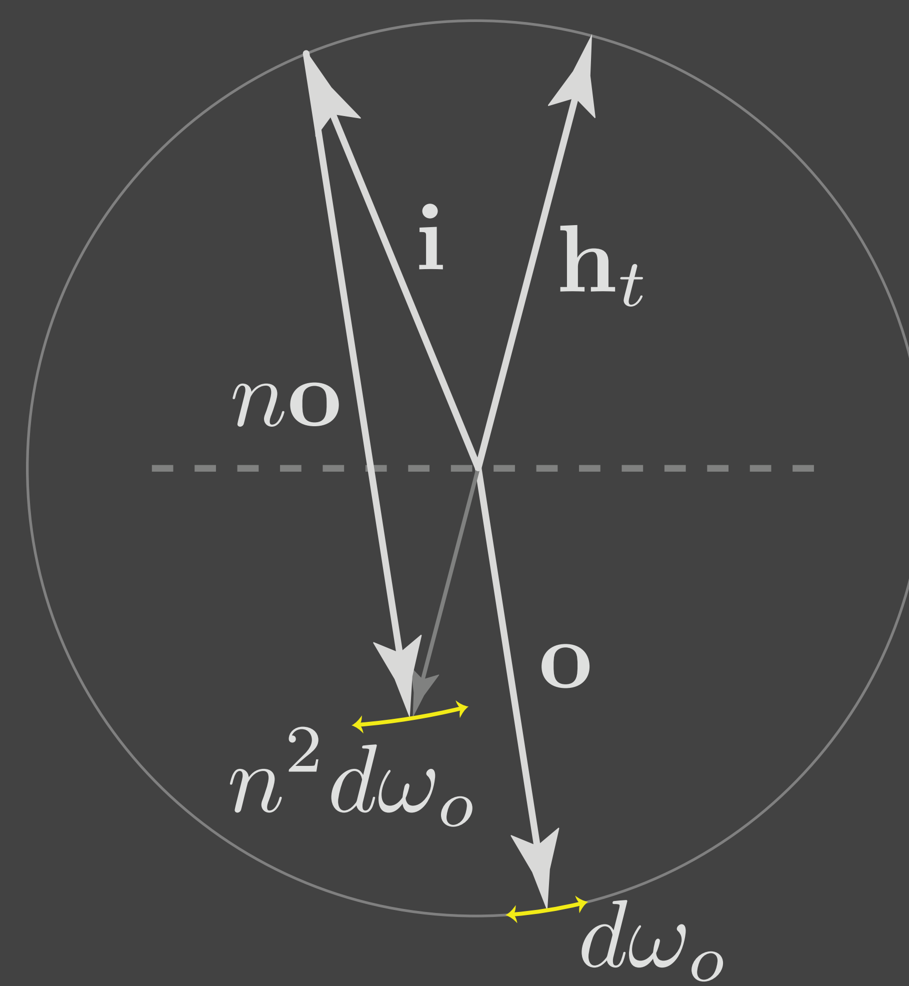

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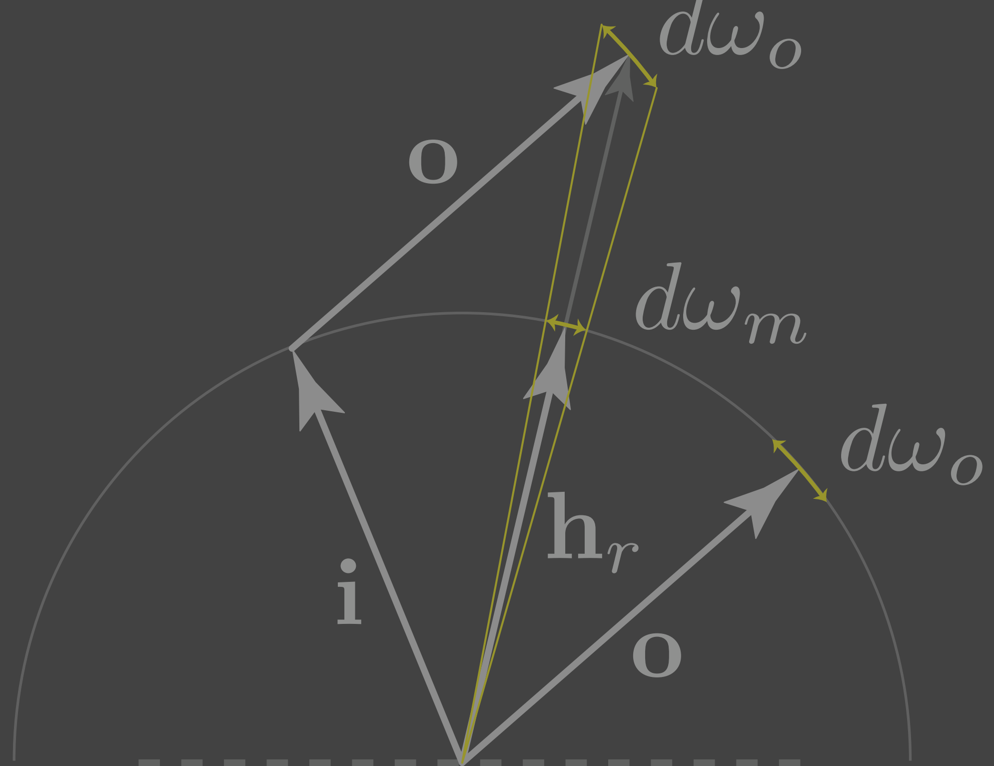

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refraction

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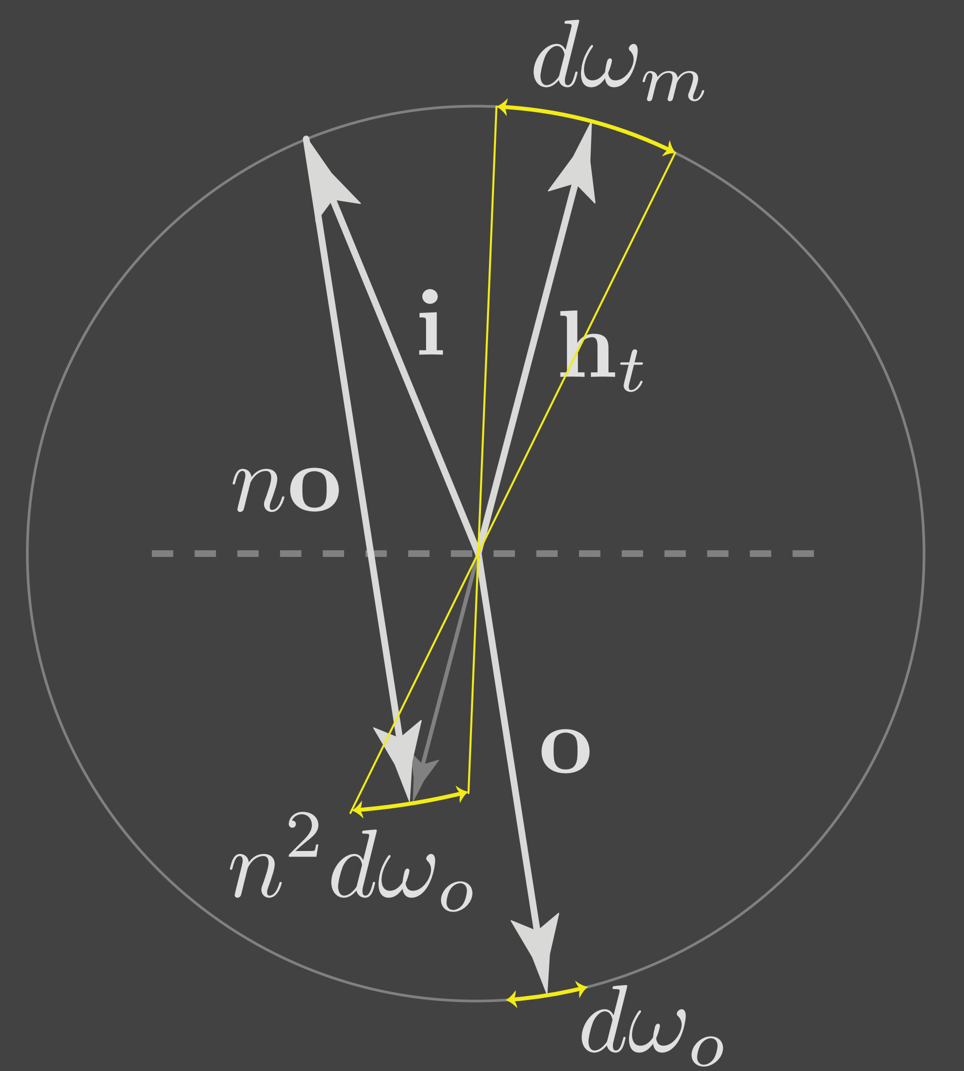

$$d\omega_m = \frac{|\mathbf{o} \cdot \mathbf{h}_t|}{\|\mathbf{i} + n\mathbf{o}\|^2} \, n^2 d\omega_o$$

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

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

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

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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

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

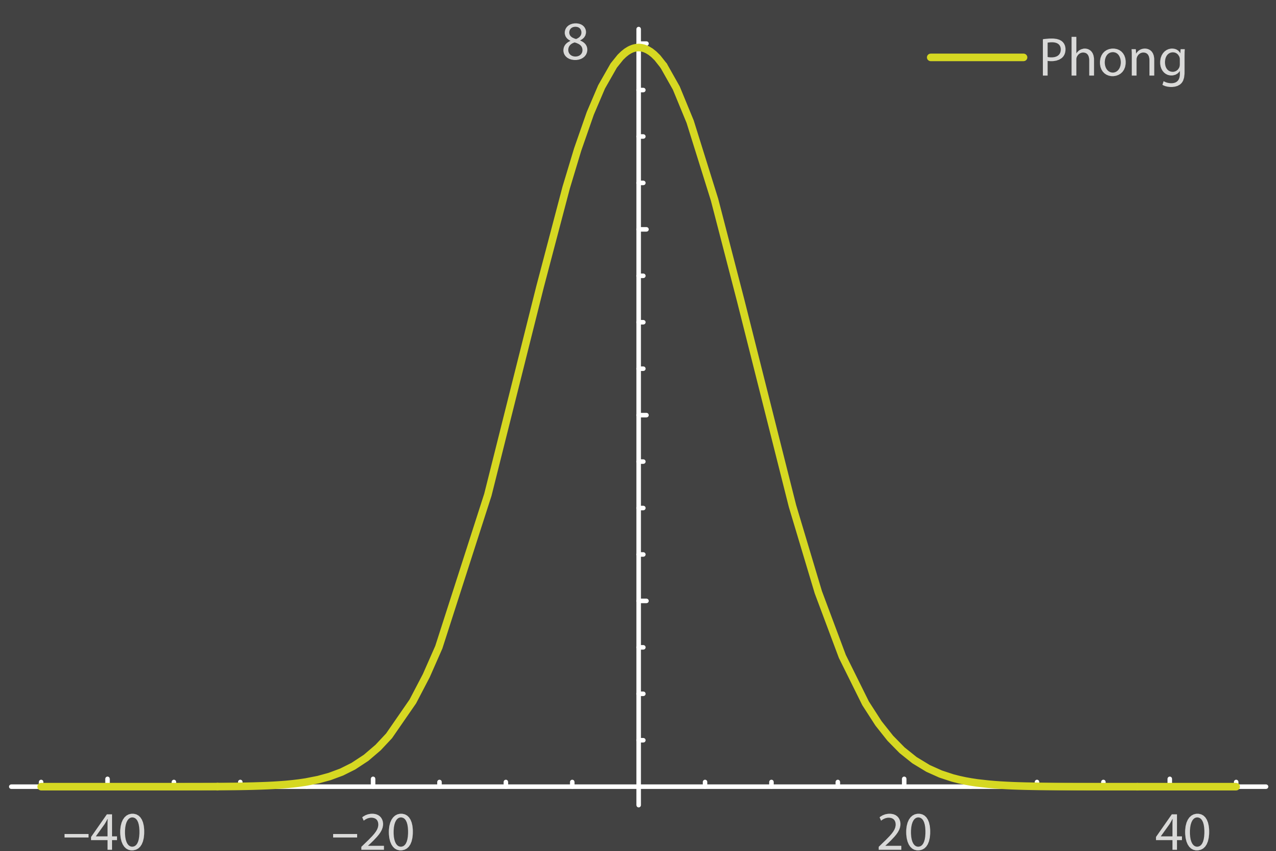
transmission

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

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



$D(\theta_m)$

Normal distributions

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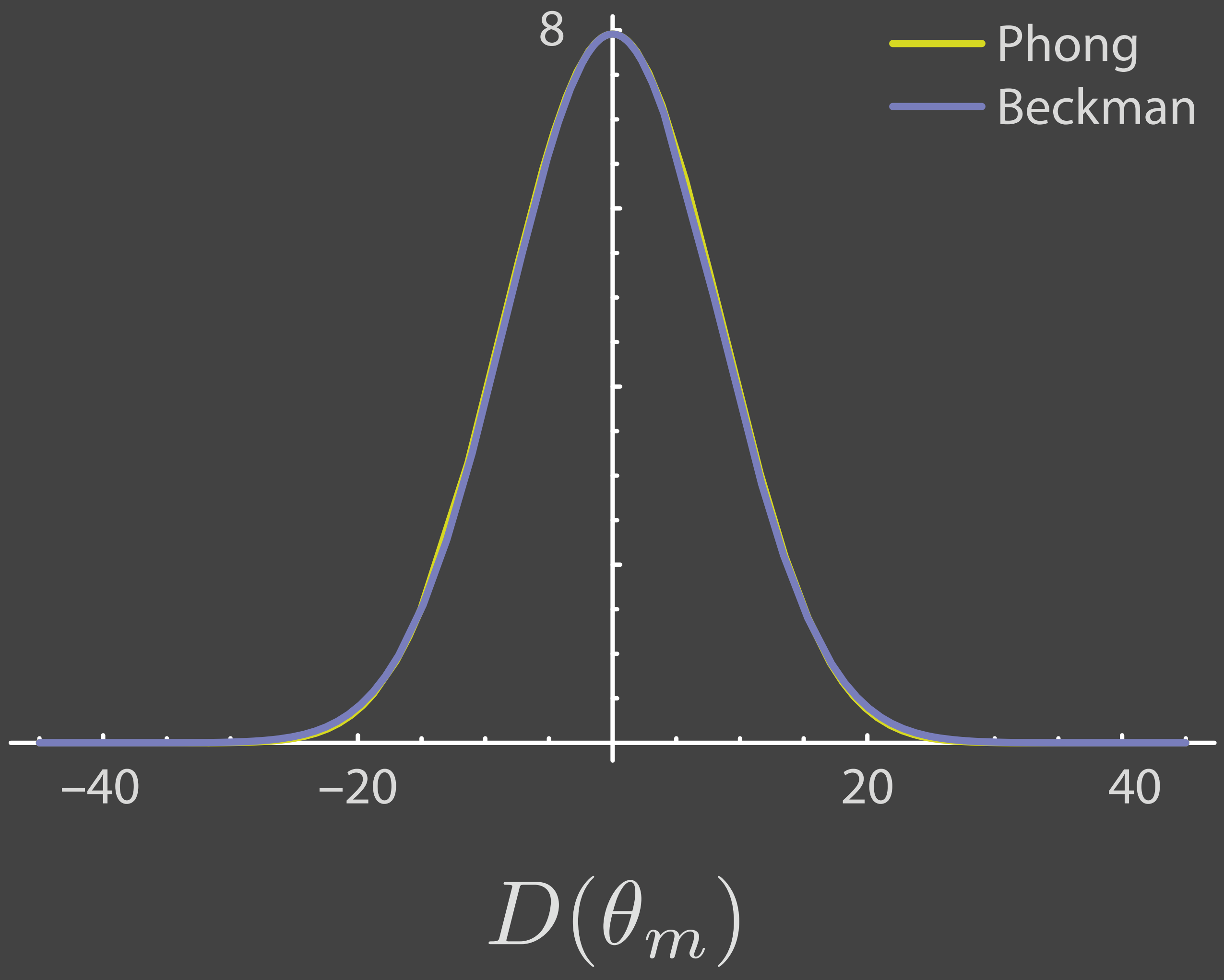

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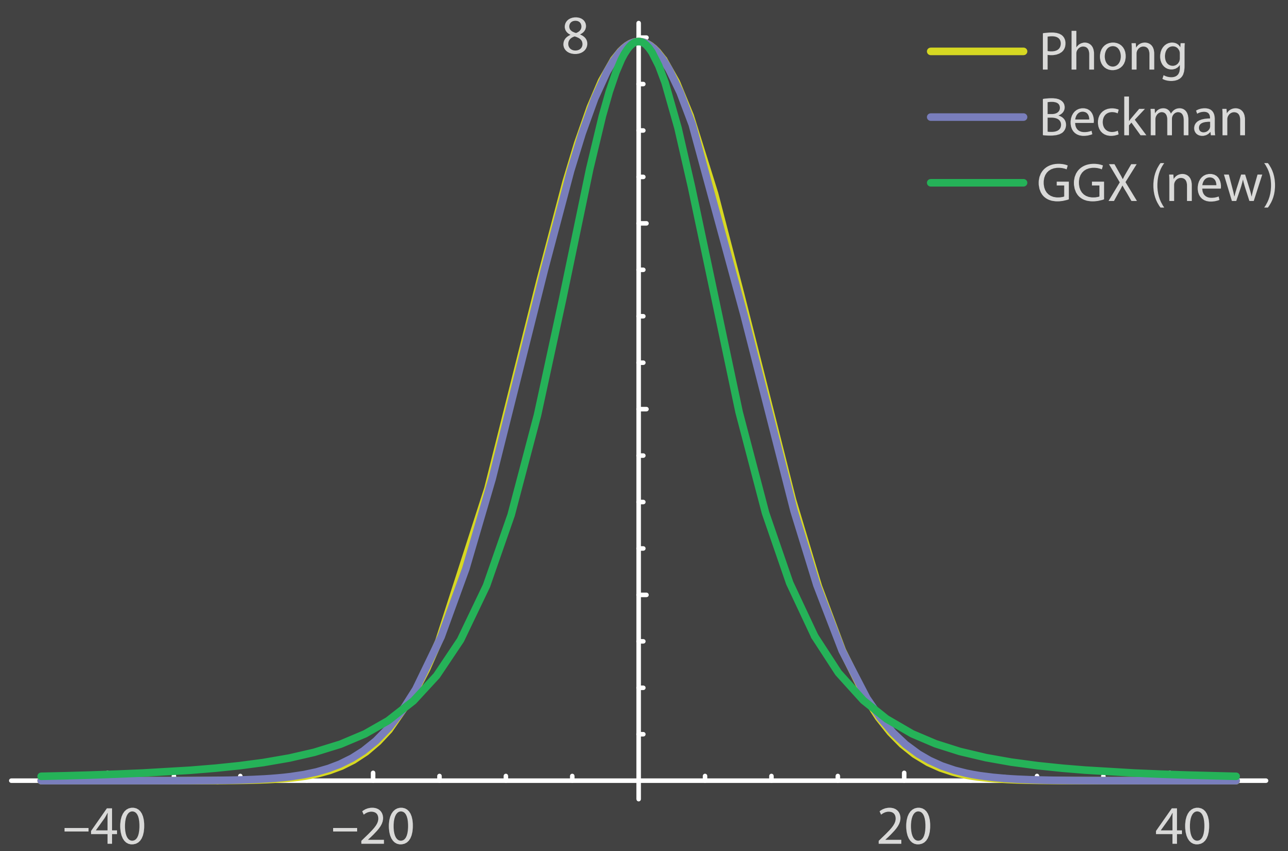

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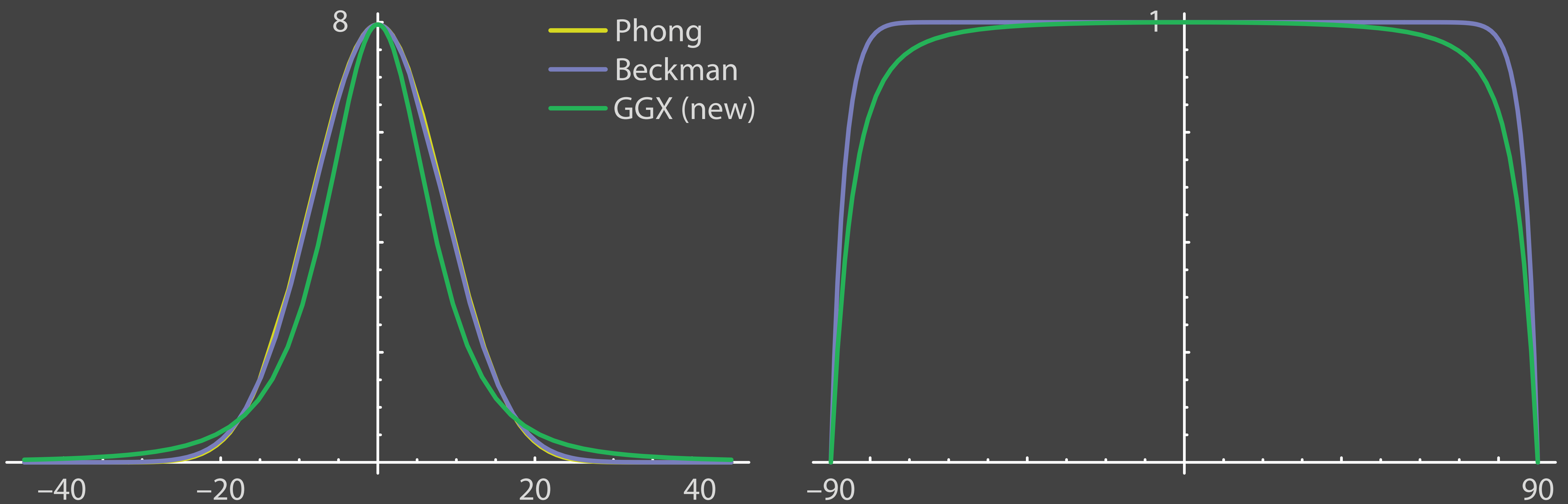


$D(\theta_m)$ $G_1(\theta_{i,o})$

Importance sampling

Sampling procedure

- choose normal according to $D(\mathbf{m})\ |\mathbf{m} \cdot \mathbf{n}|$

  explicit formulas in paper

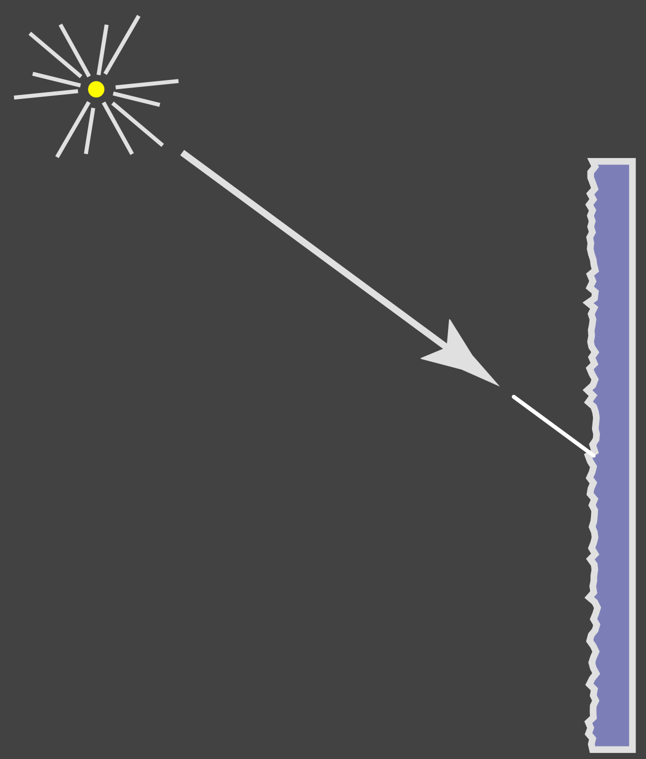
- compute **o** by reflection or refraction
- compute pdf of **o** using $d\omega_m / d\omega_o$

  leaves G and some cosines for the weight

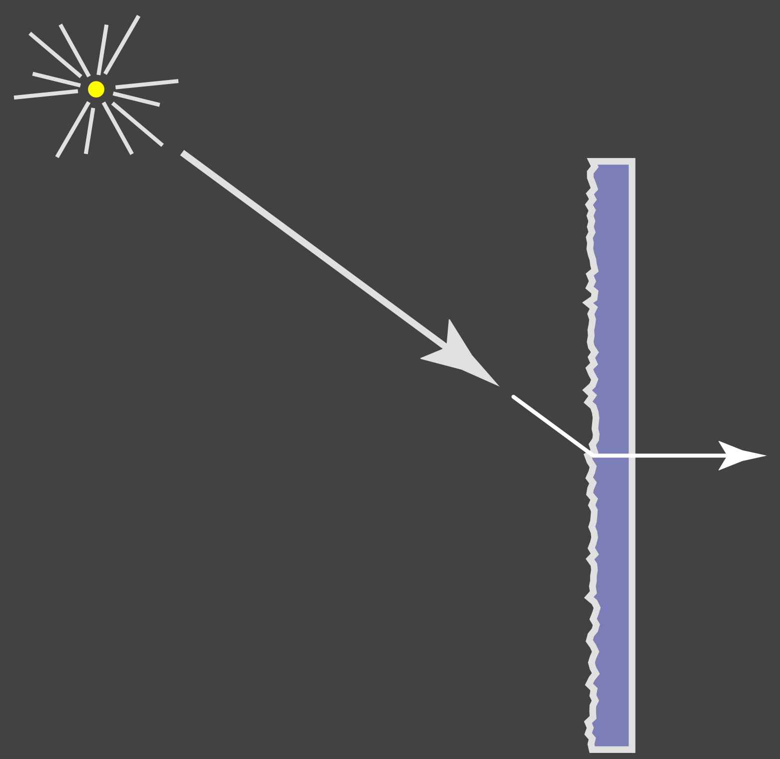
- can adjust sampling roughness to control weight

Measuring transmission

Measuring transmission



Measuring transmission



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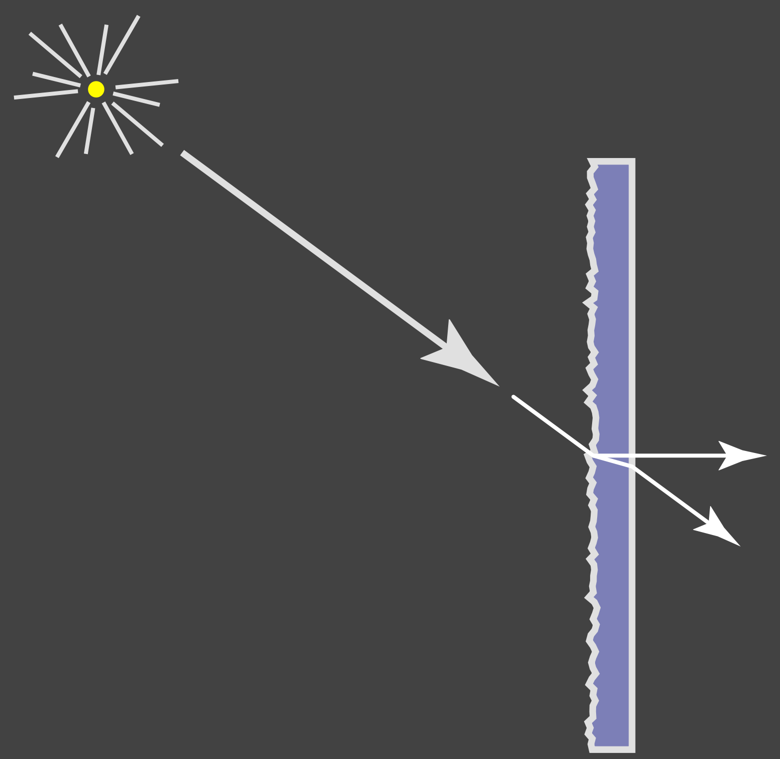

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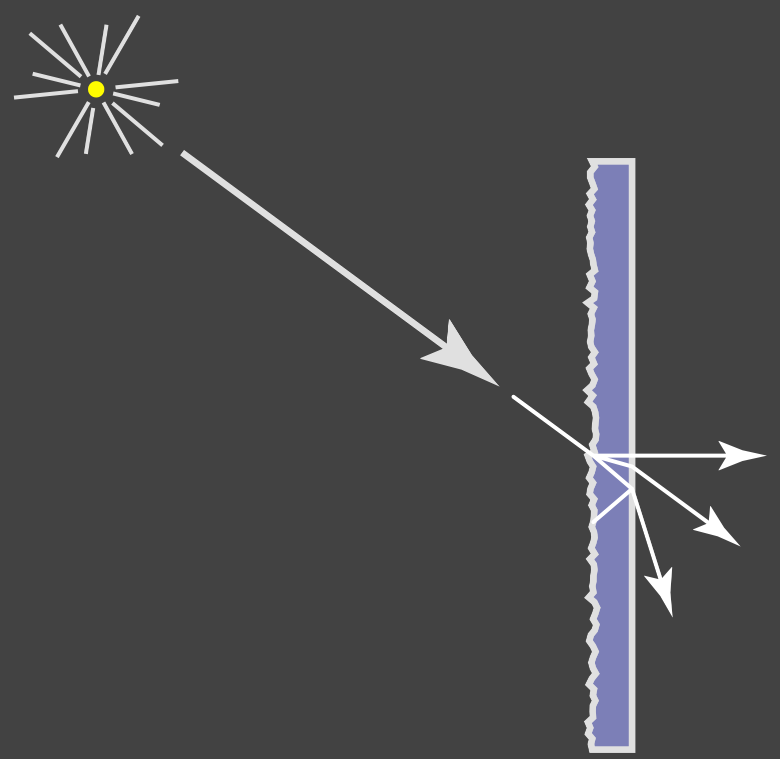

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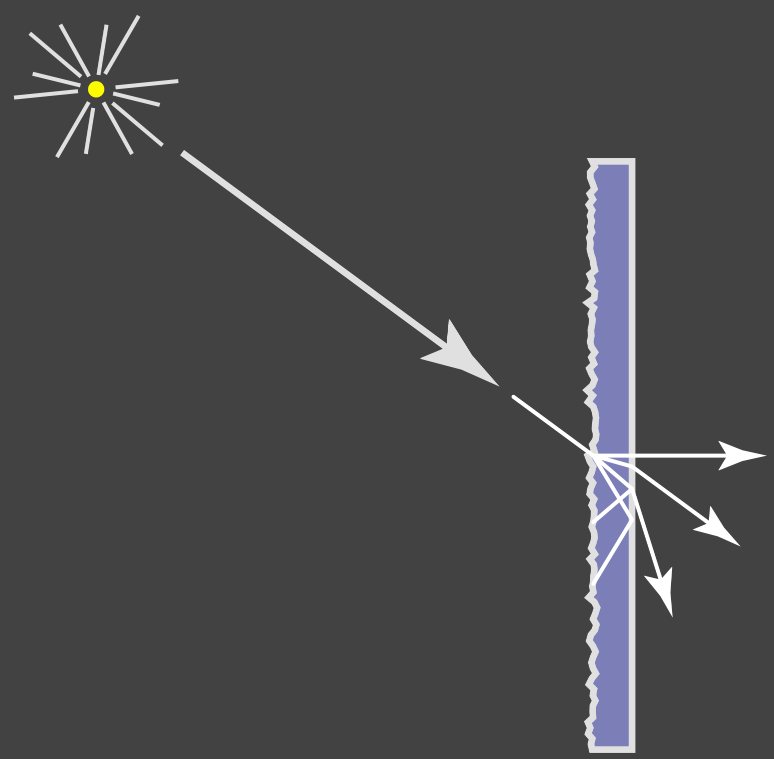
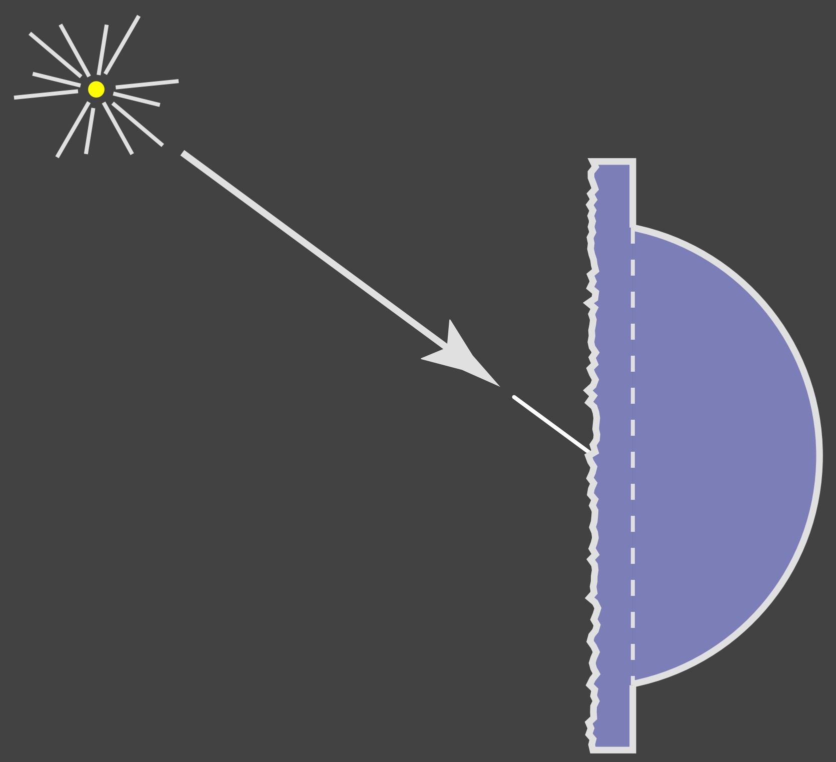
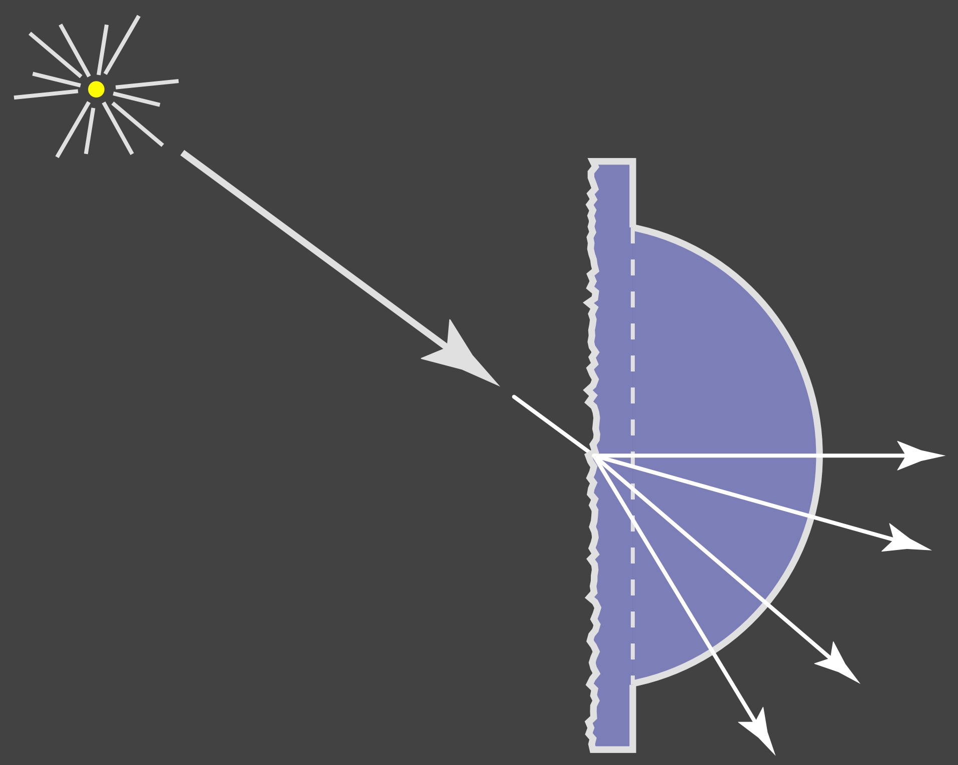


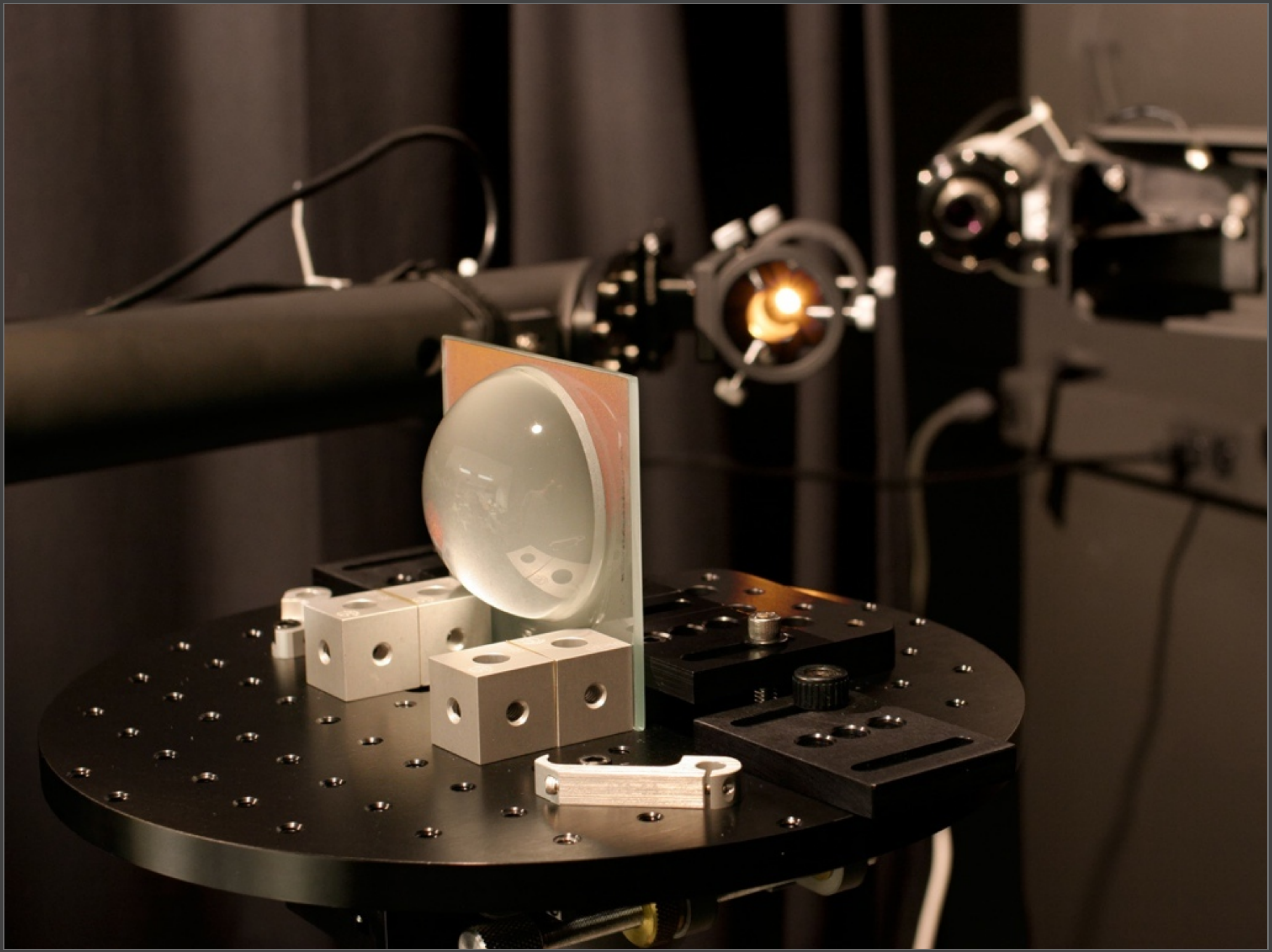
Measuring transmission



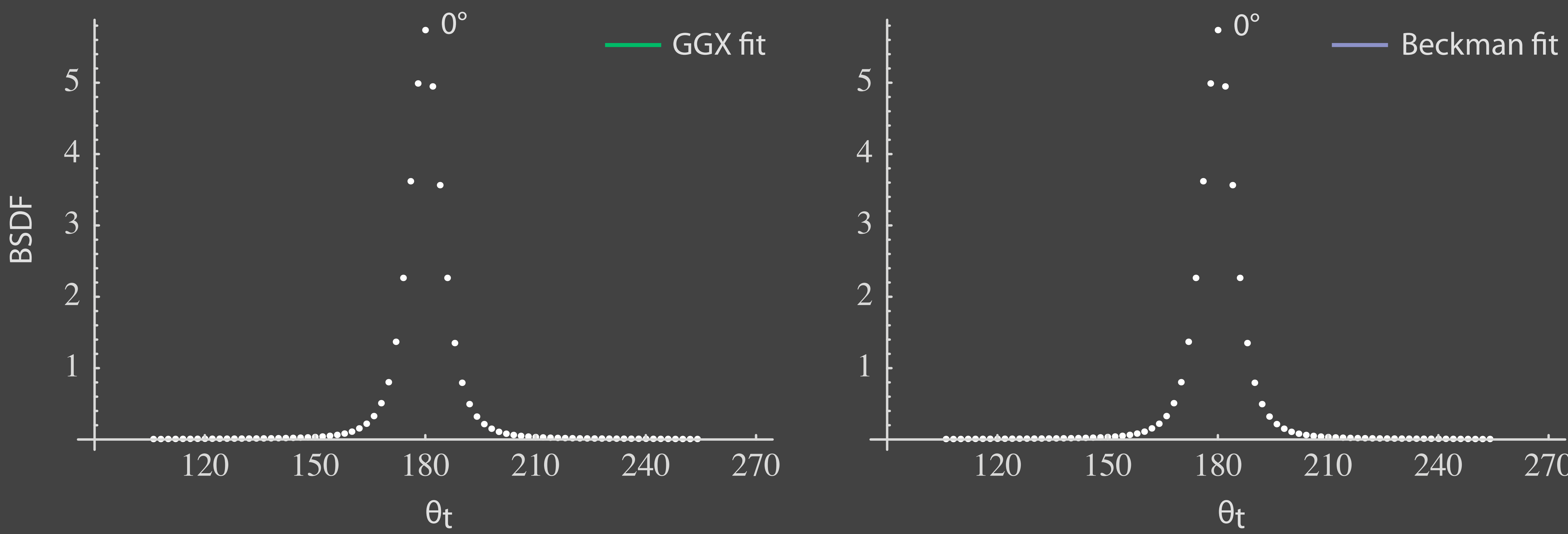
Measuring transmission



Measurement setup

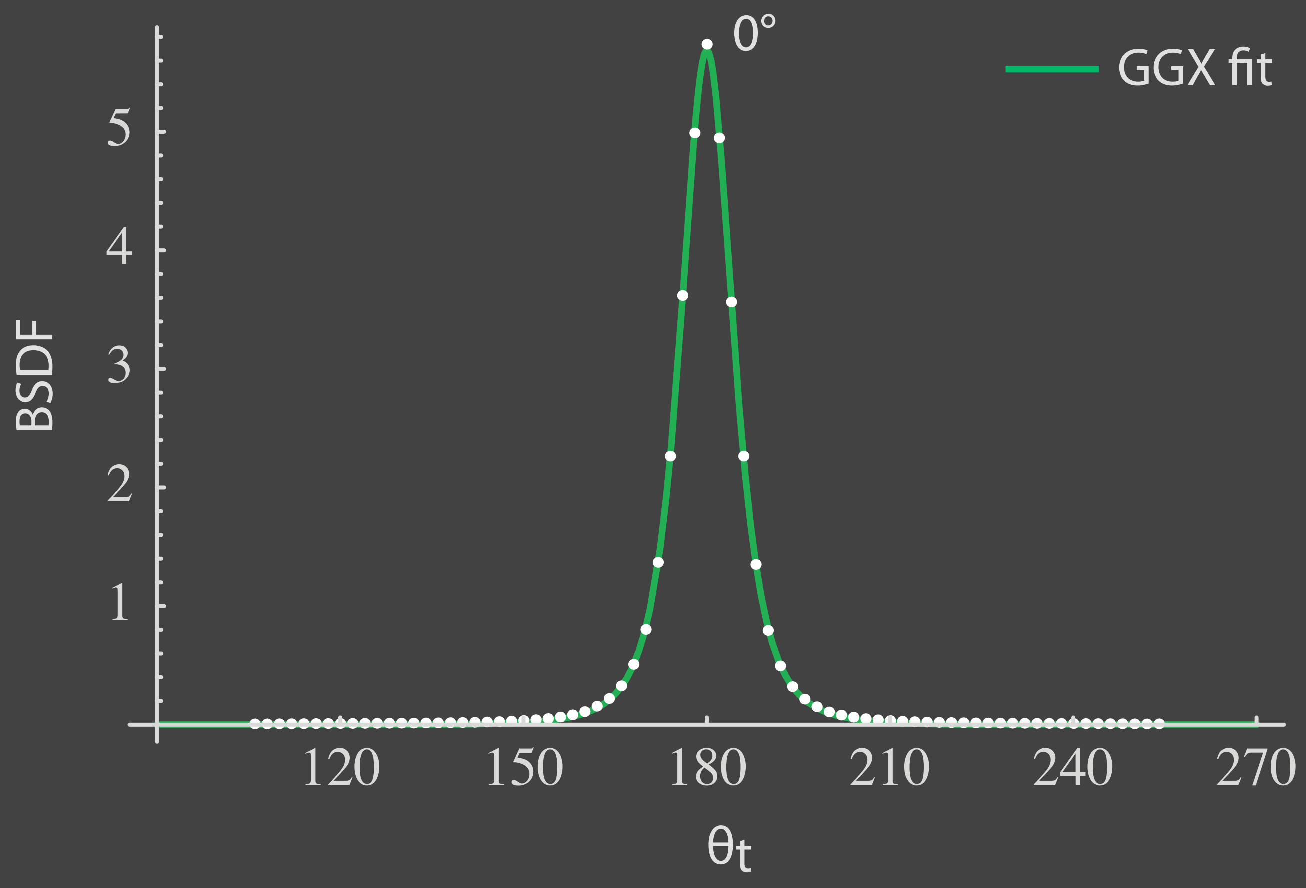


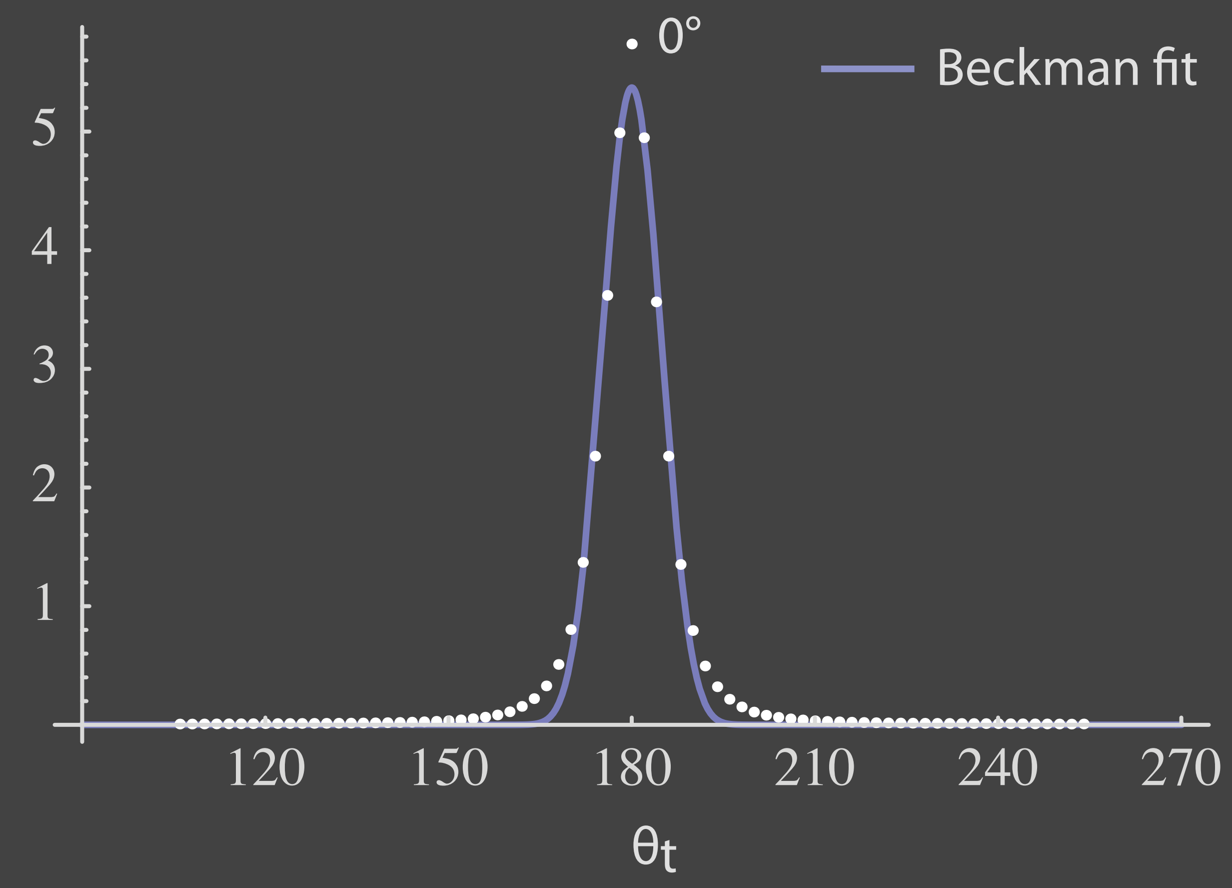
Validation: ground glass



Fit is to normal incidence data only

Validation: ground glass





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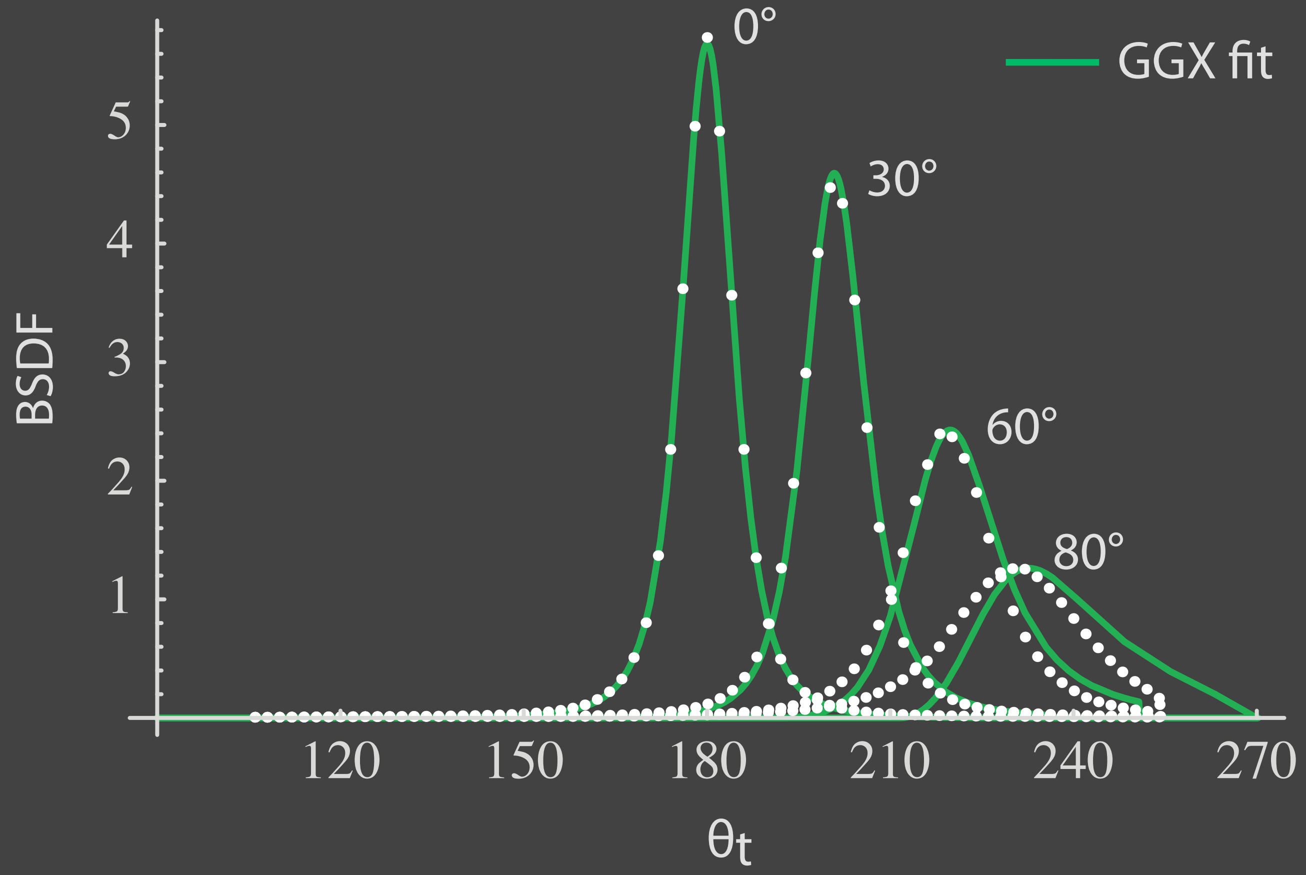
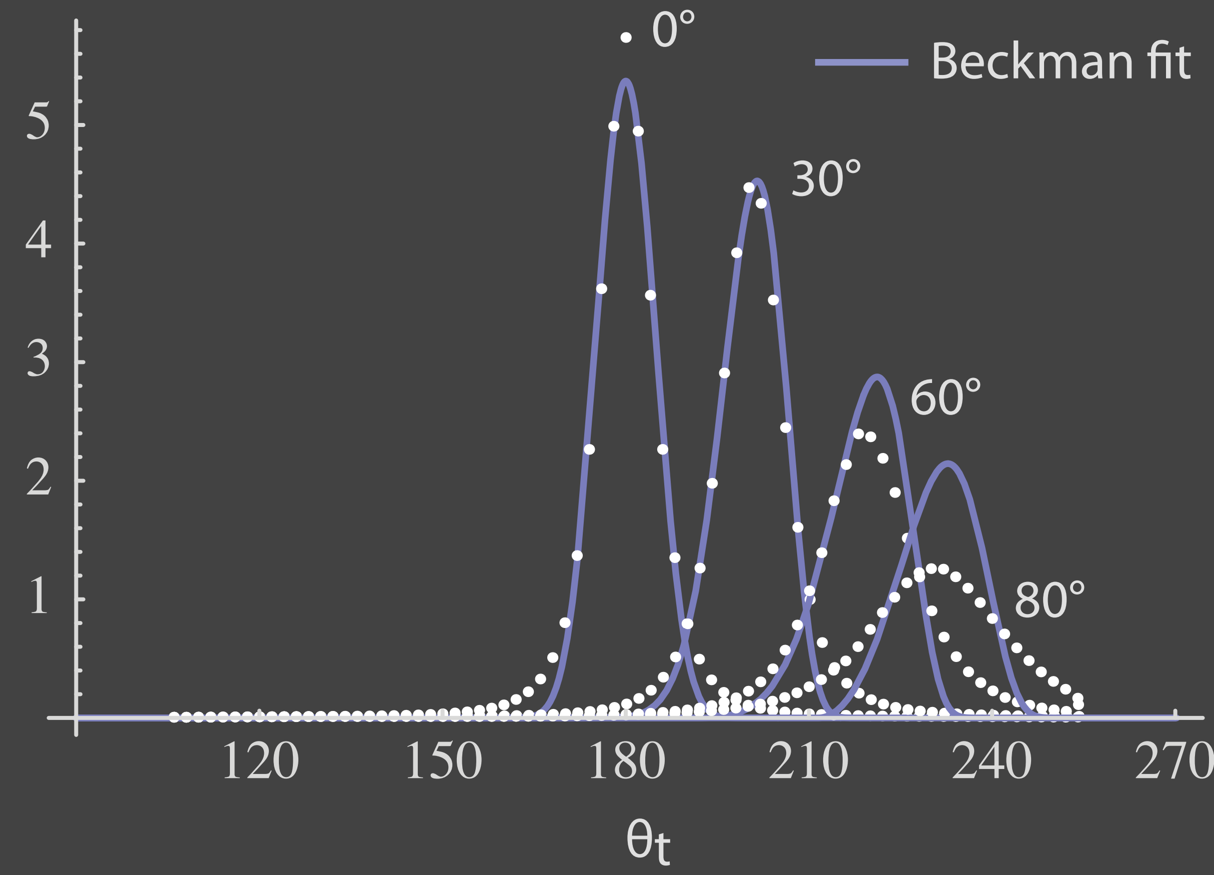
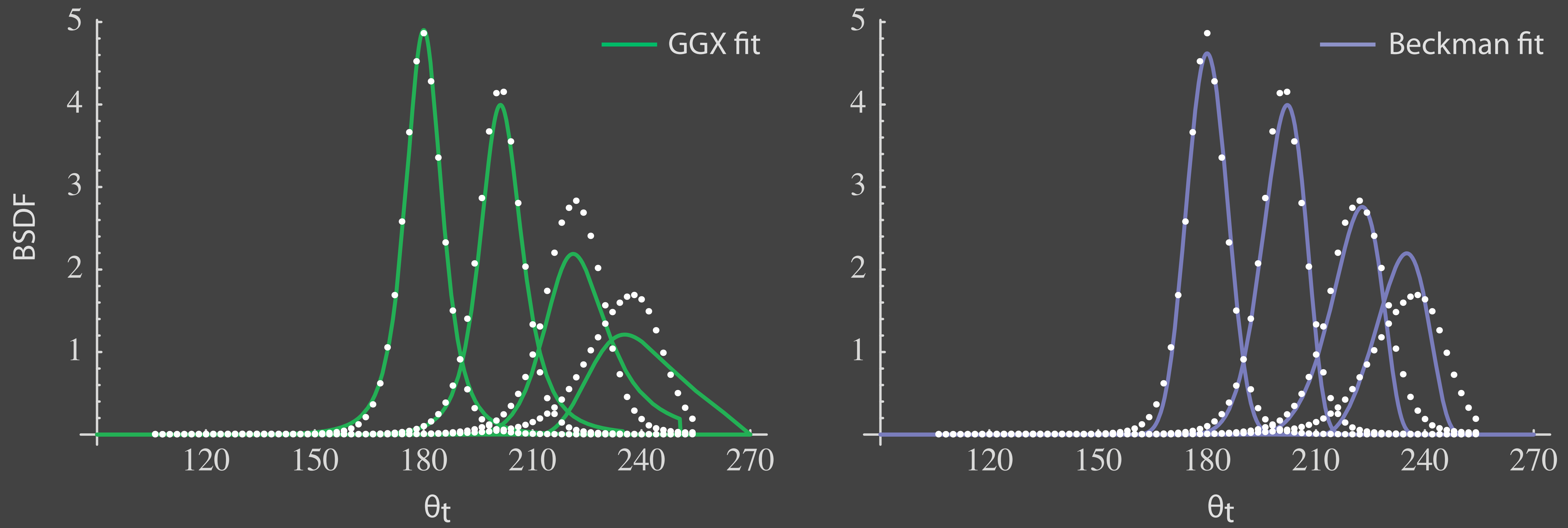




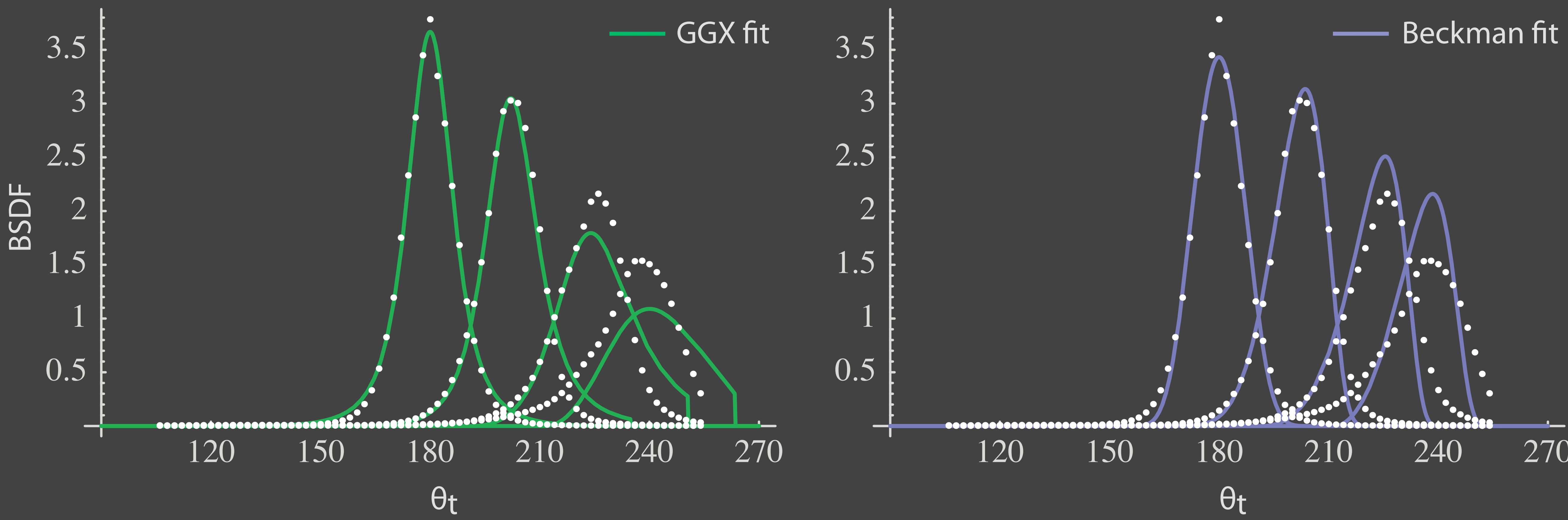
Fit is to normal incidence data only

Validation: “frosted” glass



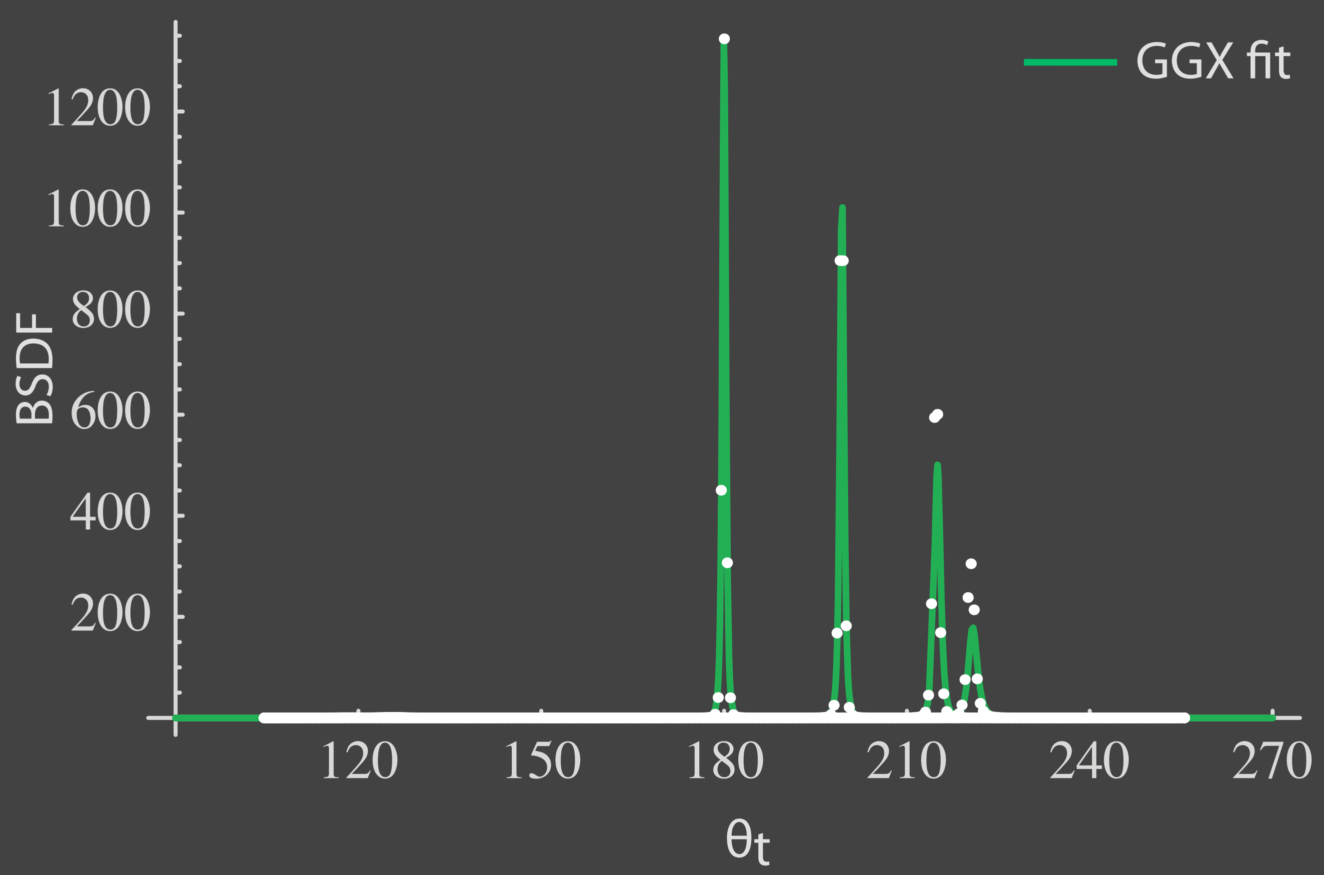
Fit is to normal incidence data only

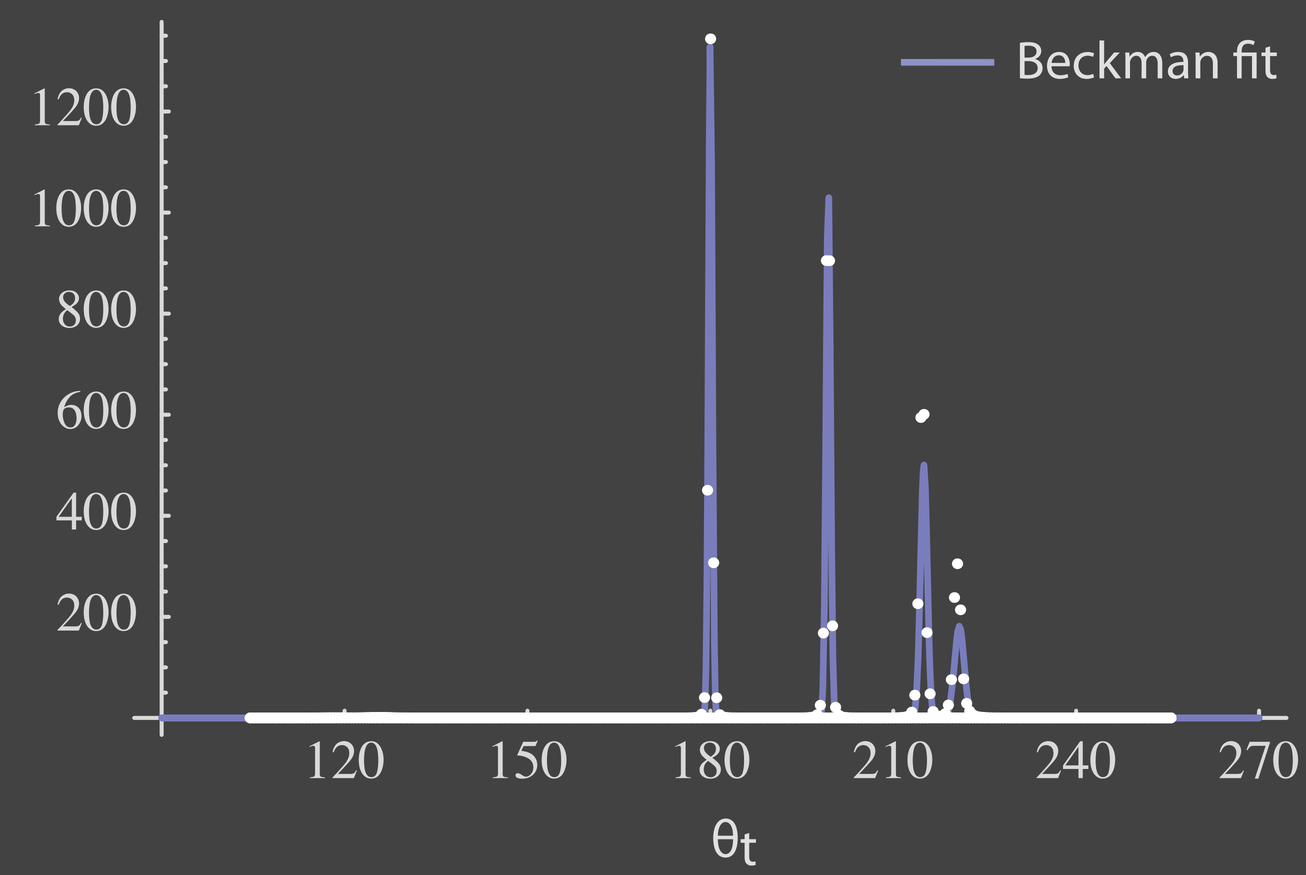
Validation: acid-etched glass



Fit is to normal incidence data only

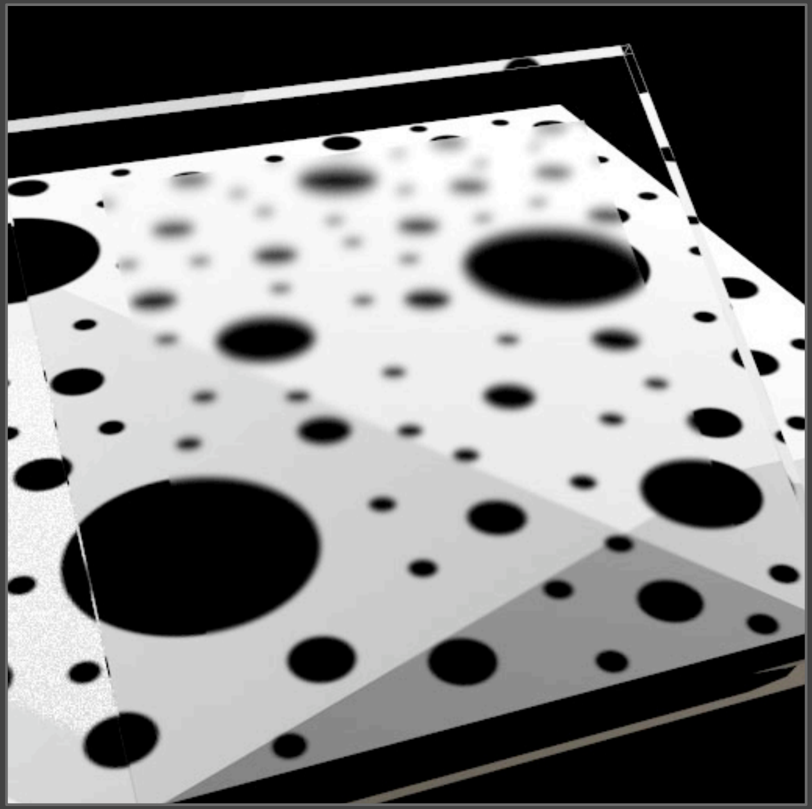
Validation: antiglare glass





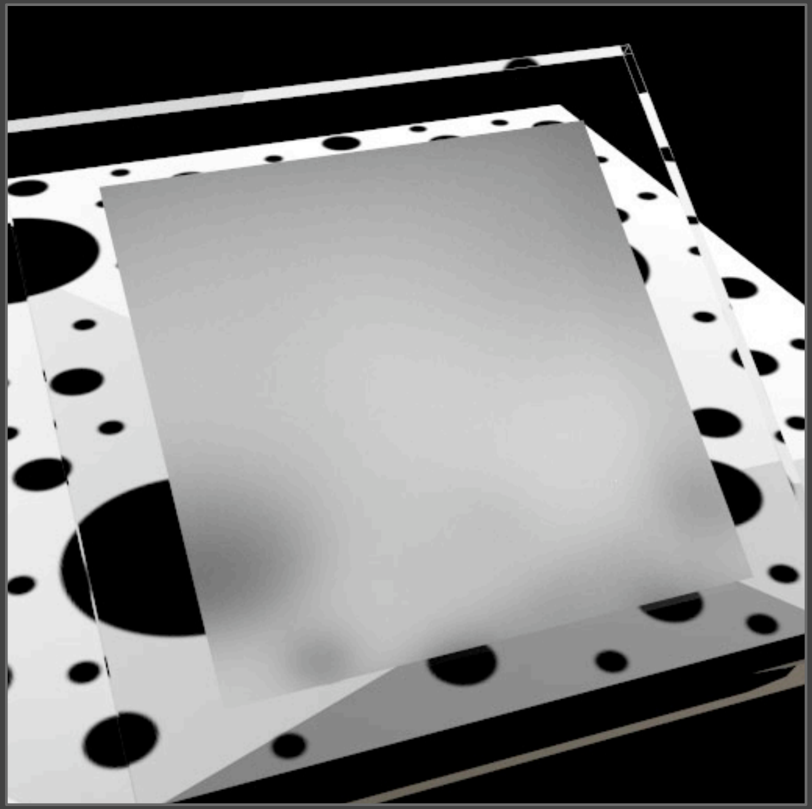
Fit is to normal incidence data only

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

NSF grants ACI-0205438, CNS-0615240

NSF CAREER CCF-0347303

Alfred P. Sloan Research Fellowship

Intel Corporation equipment donation