Un modèle de BRDF bi-échelle combinant : Diffraction et Micro-facettes

Nicolas Holzschuch, Romain Pacanowski

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Journée "Tout sur les BRDF"
Poitiers 15 Juin 2017

Realistic Image Synthesis

Realistic Image Synthesis

Realistic Image Synthesis

Lots of BRDF Models

SGD [Bagher et al. 2012]

GGX [Walter et al .2007]

He et al. [1991]

Ashikmin et al. [2000]

Ashikmin & Shirley [2000]

Lafortune et al. [1997]

Neumann and Neumann [1996]

ABC [Löw et al. 2012]

Ward [1992]

Cook & Torrance [1982]

Hanrahan & Kruger [1993]

Blinn [1977]

Beard-Maxwel [1973]

Oren & Nayar [1994]

Granier & Heidrich [2003]

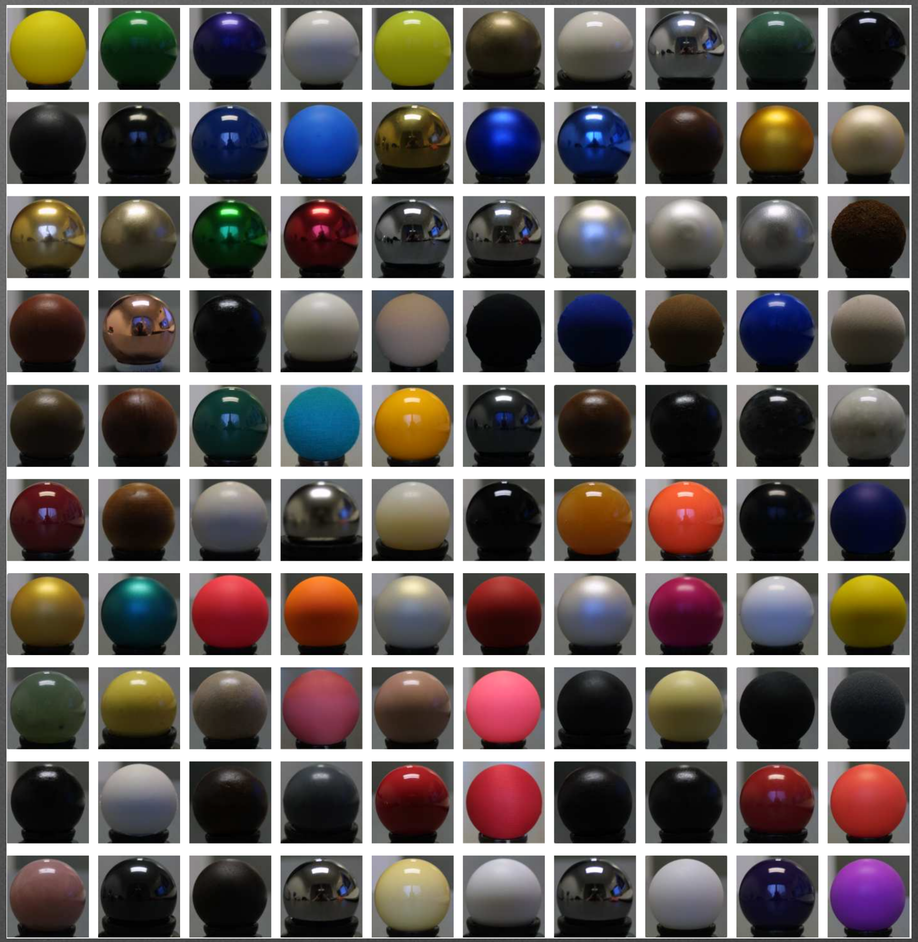
Schlick [1994]

Student-t [Ribardière et al. 2017]

AND MANY MORE !!!!!

Few BRDF Measurements Database

- MERL Data Base:
  - 100 materials
  - 2 versions: 2003 and 2006

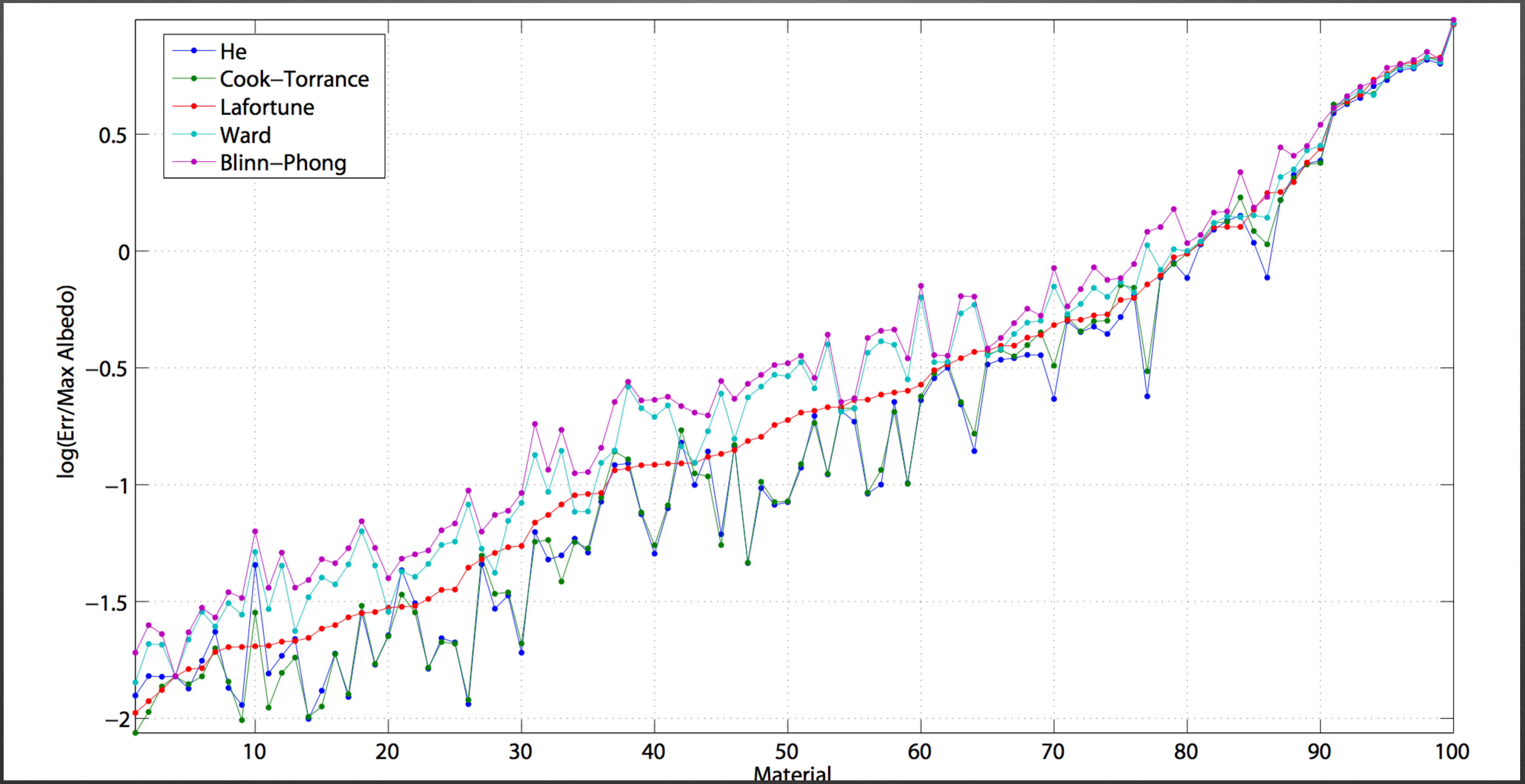


Cornell

Curet

BRDF Model comparisons

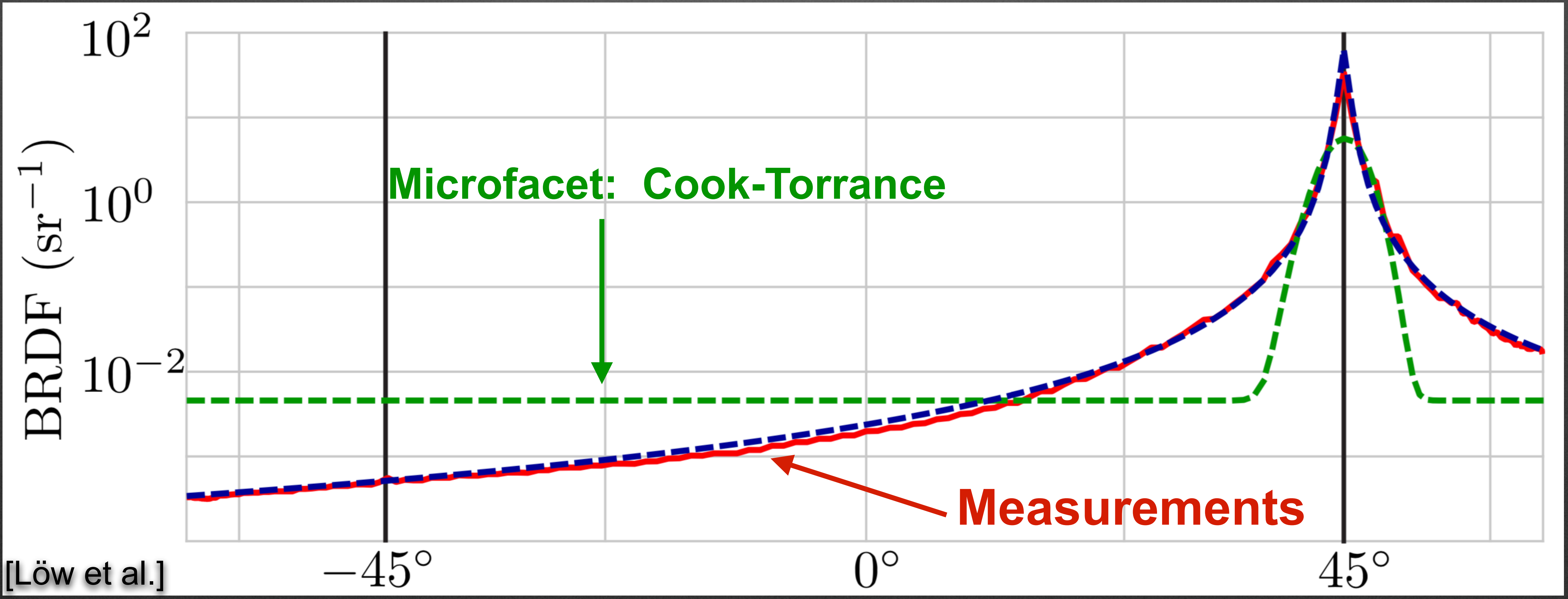
Study of fitting capabilities of BRDF Models [Ngan2005]



Winners: Cook-Torrance [1982] **and** A simplified version of He et al. [1991]

Closer Look on BRDF Measurements

- Microfacet Theory
  - Good prediction of Specular peak
  - Less Good for low values



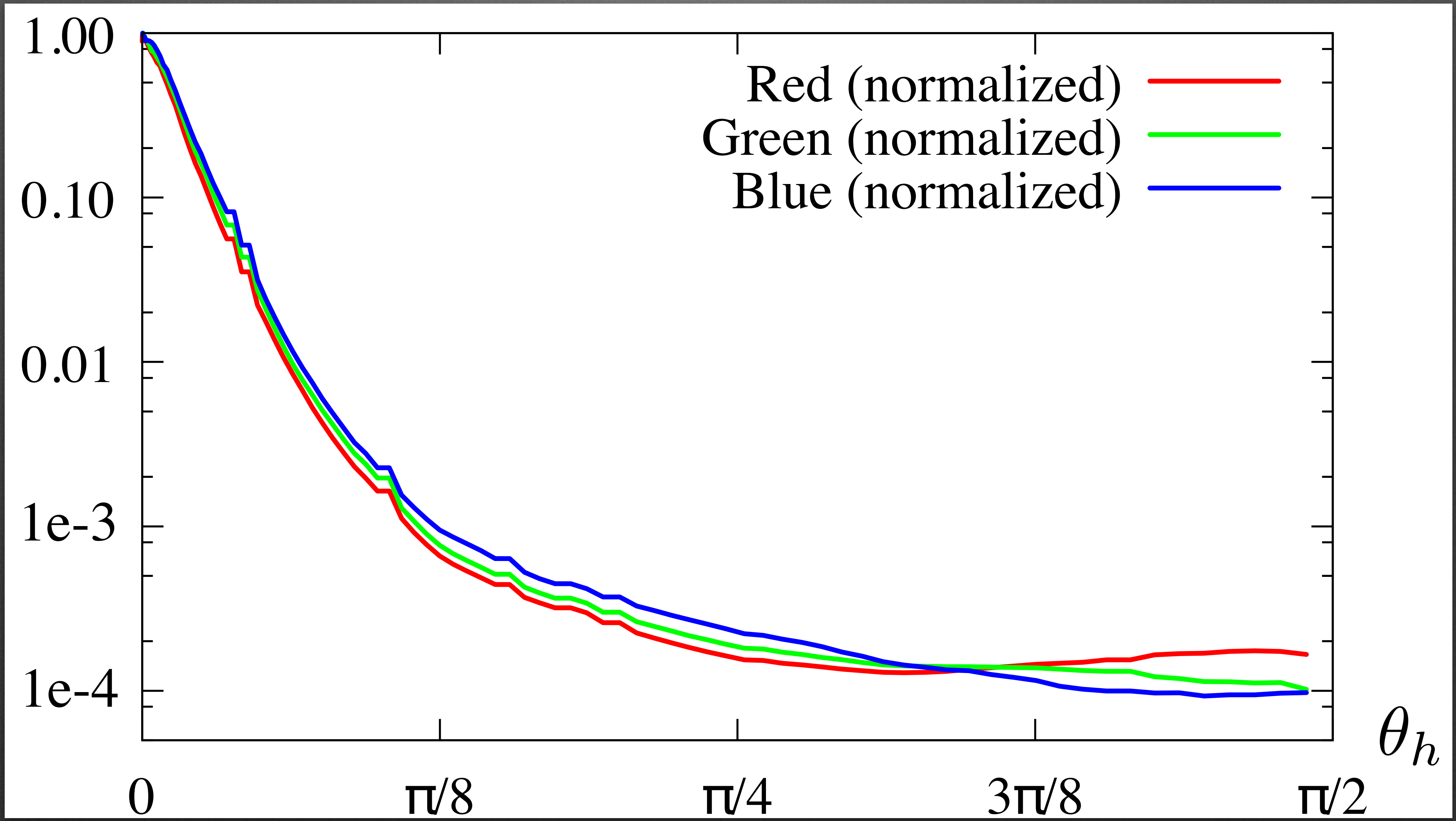
[Löw et al.]

Closer Look on BRDF Measurements

- Microfacet Theory
  - Good prediction of Specular peak
  - Less Good for low values
- Common solution:
  - To add a constant or diffuse term
    - For subsurface scattering behavior of the material
  - To add new lobes ==> No Physical Reality

Closer Look on BRDF Measurements

Nickel from MERL database

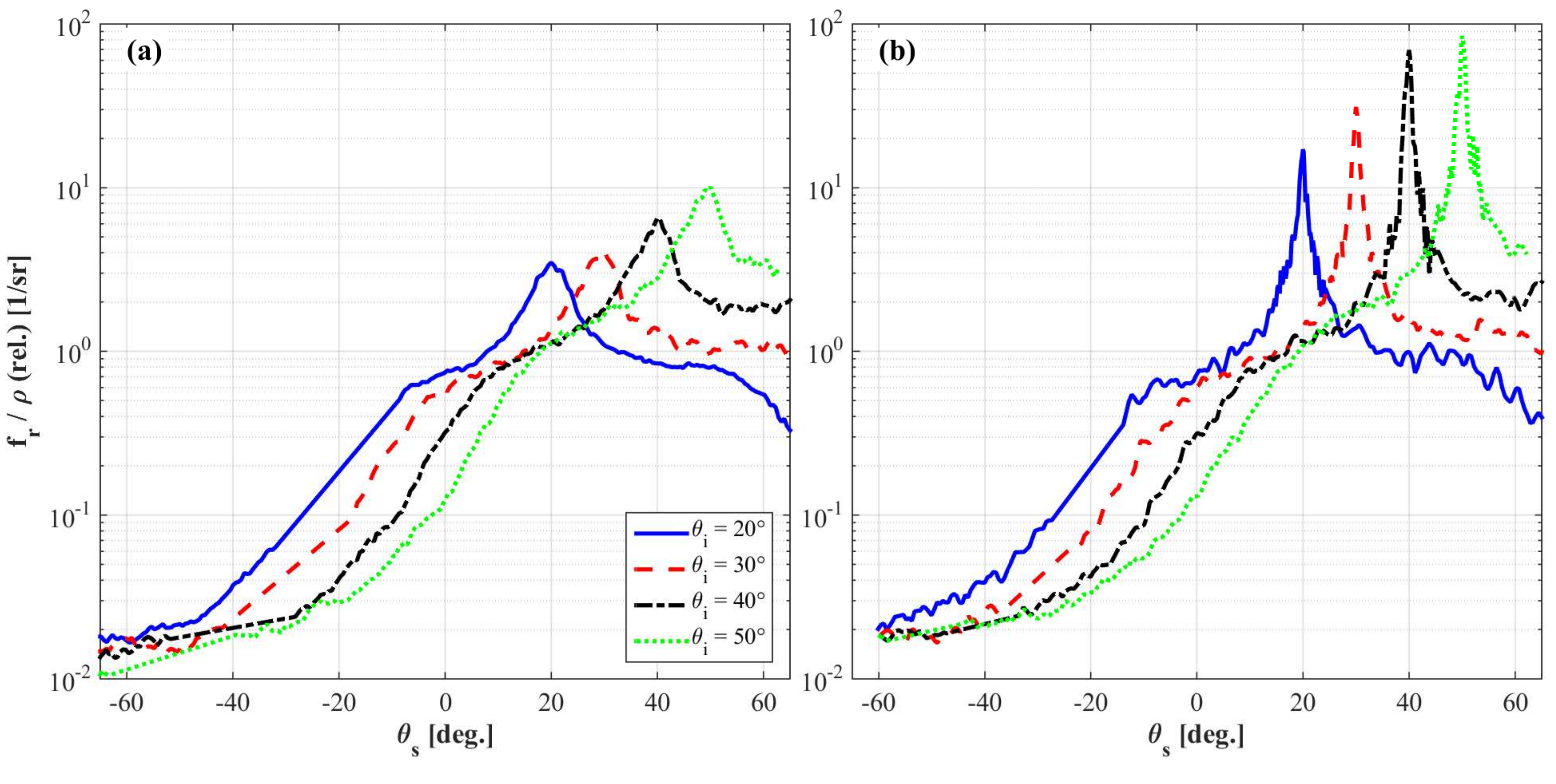


Lobe Size depends of the color

Closer Look on BRDF Measurements

λ = 3,39 microns

λ = 10,6 microns



Grit-Blasted Nickel

[Butler et al. 2015] (SPIE Imaging Spectrometry)

Observations on Measurements

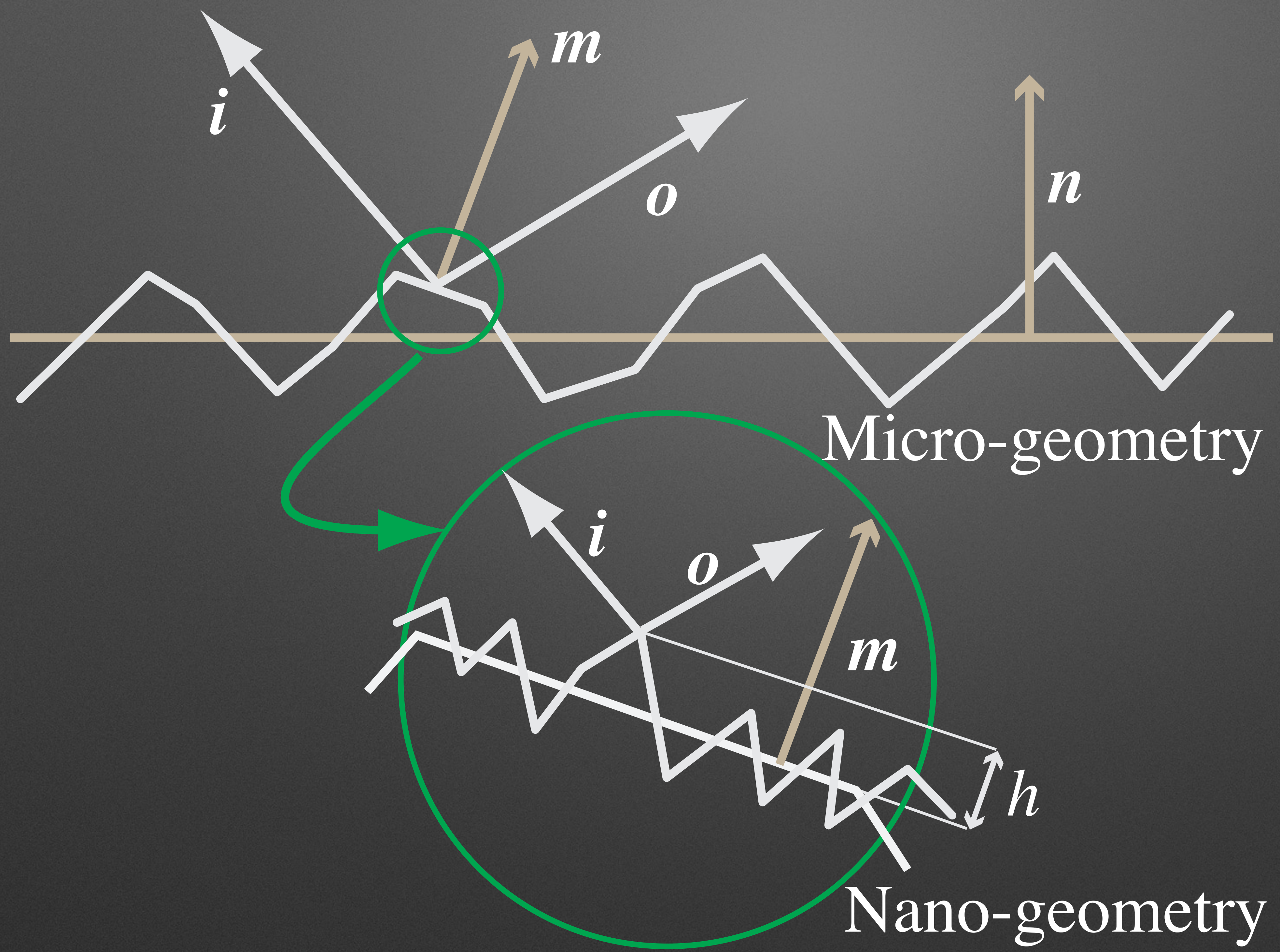
- Specular lobe
  - Wavelengths light Dependency

⇒ Contradicts Microfacet Theory

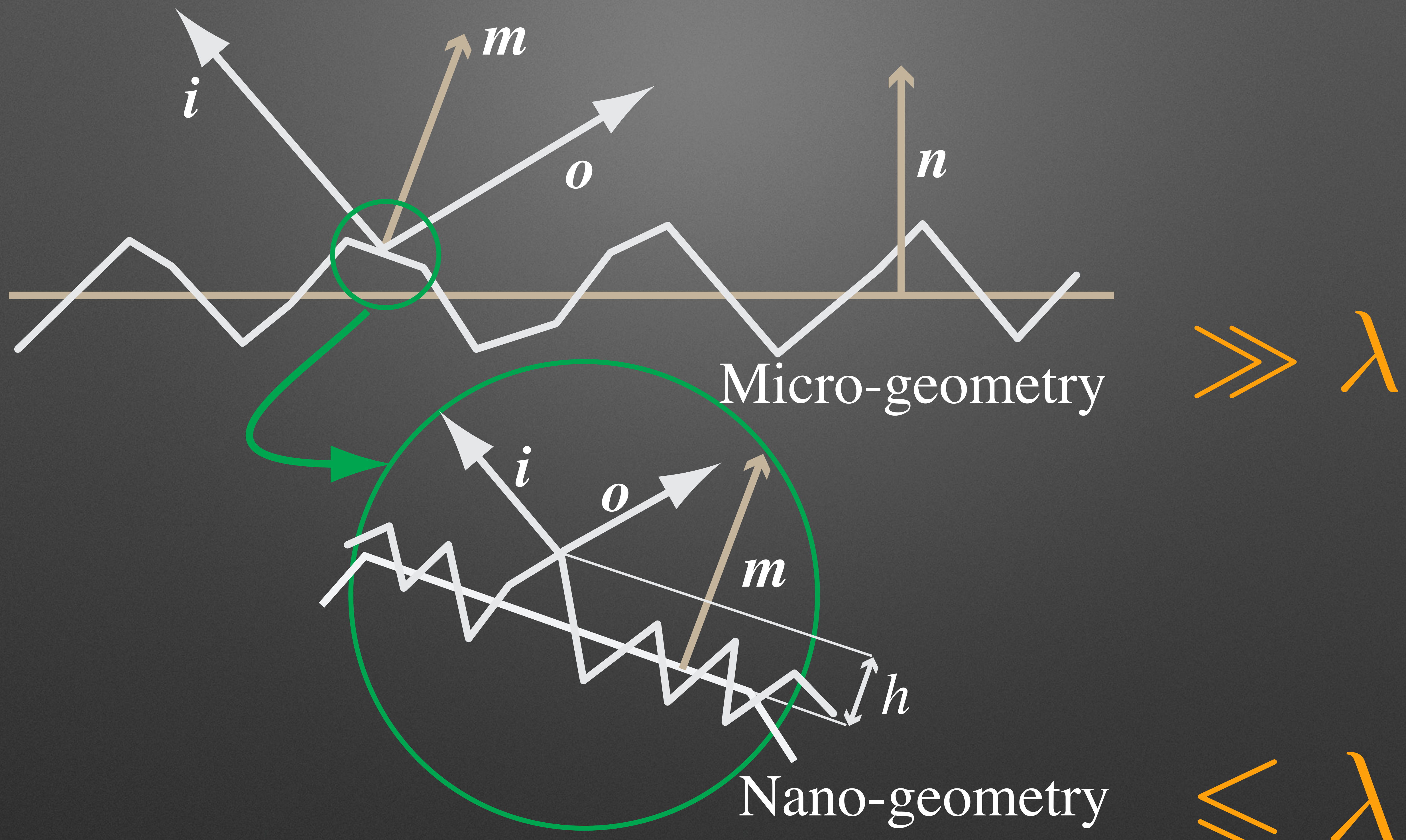
Microfacet Hypothesis

- Microfacet: Perfect Mirror with a Fresnel Coefficient
- Microfacet $\gg$ λ = light wavelength
  - Geometrical Optics
- Fresnel is the only wavelength dependent term
- How can we model this phenomenon?

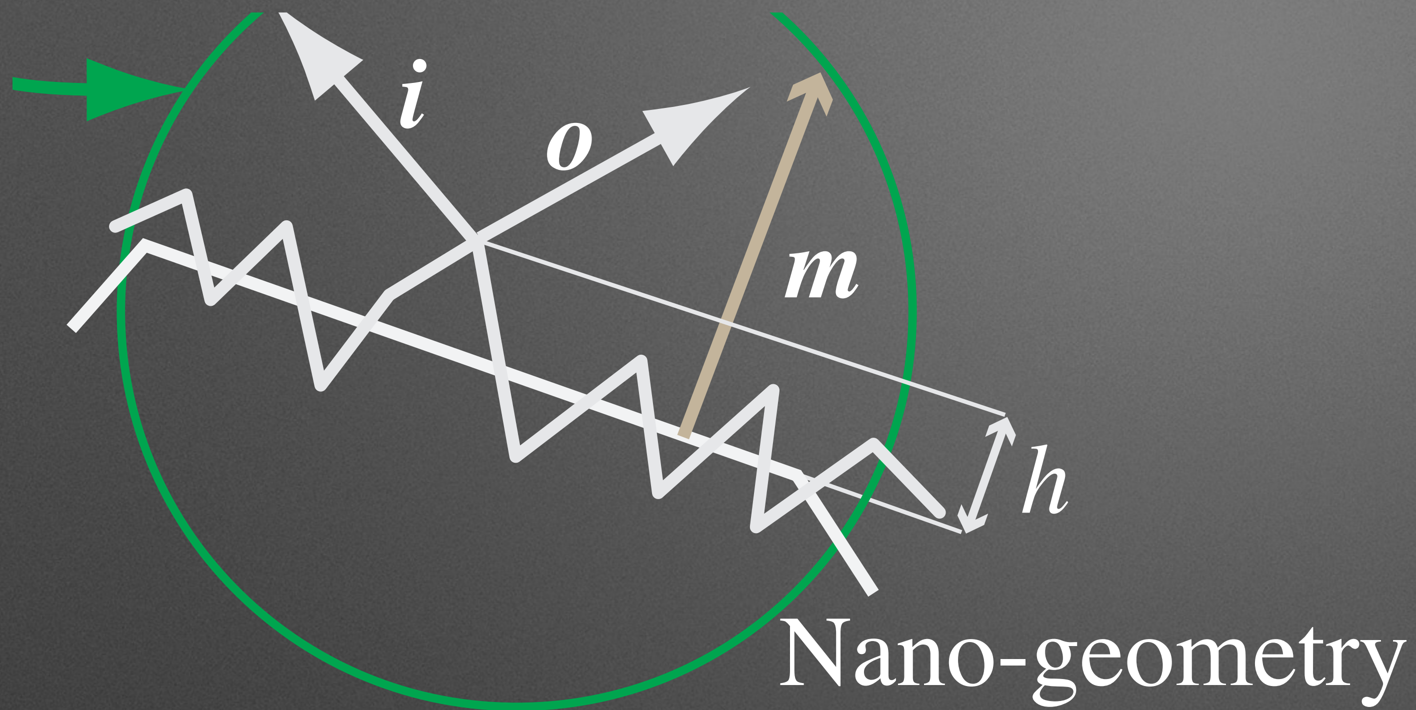
Two-Scale Reflectance Model



Two-Scale Reflectance Model



Two-Scale Reflectance Model

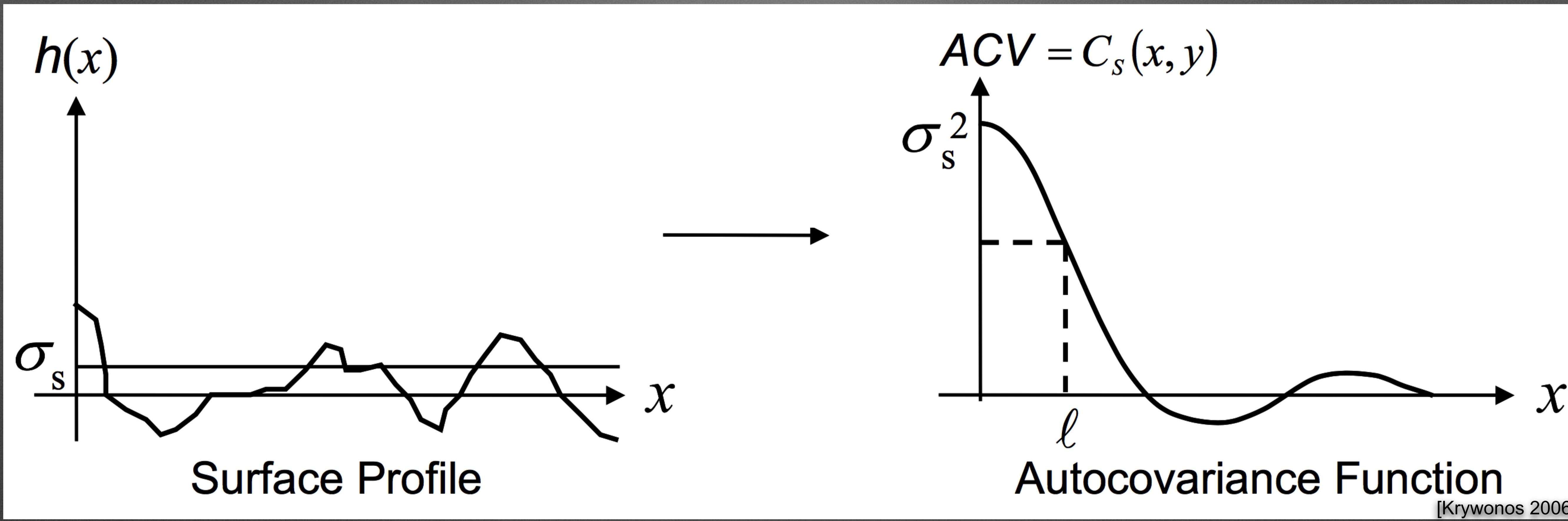


$\leqslant \lambda$

Wave Optics, Diffraction:

- Necessary to model Scattering of small scale surface
- Reflectance depends on wavelength

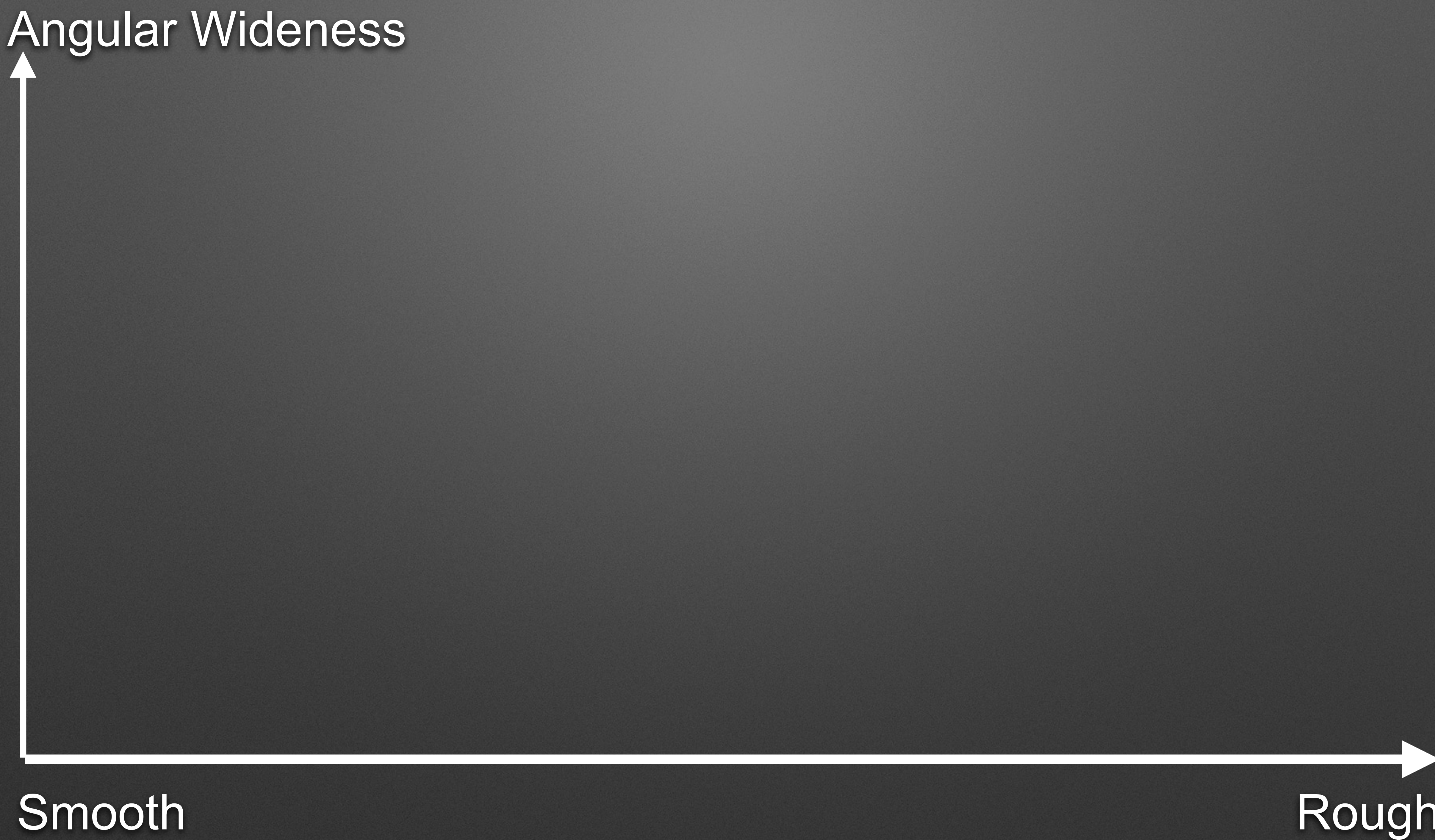
Surface Characteristics



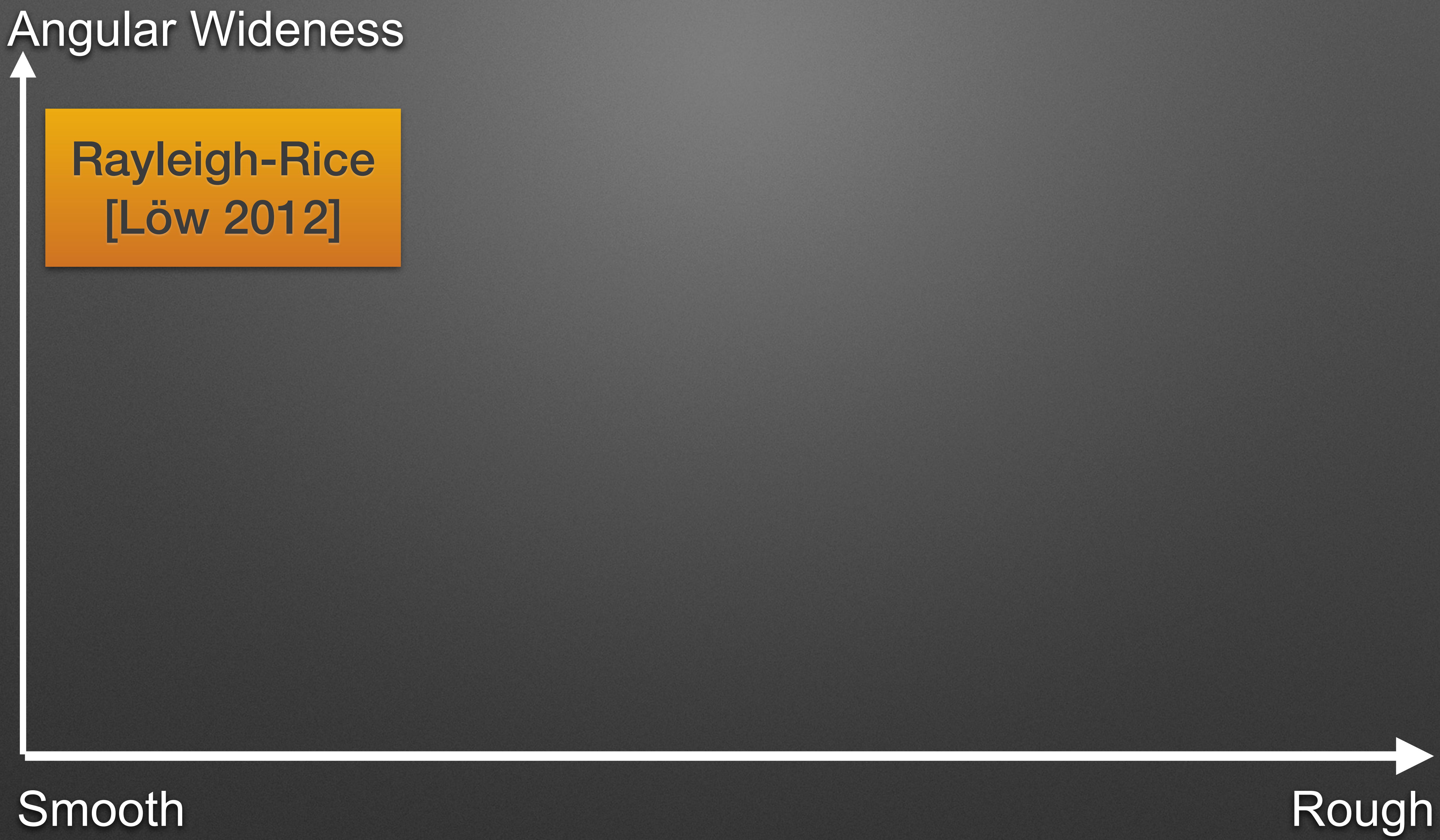
σ_s : RMS of the surface roughness

l : autocovariance length

Diffraction Theories for Scattering



Diffraction Theories for Scattering



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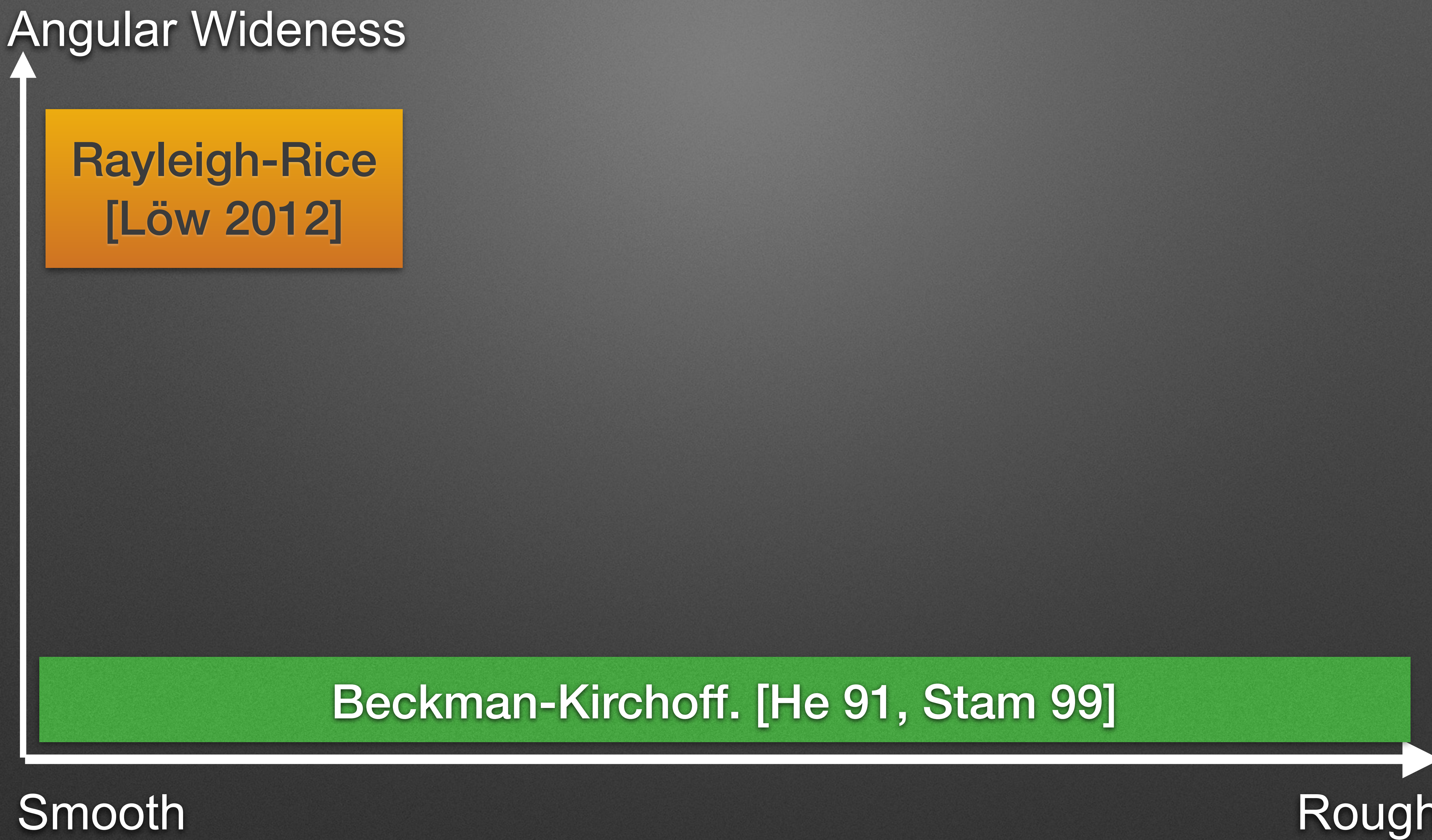

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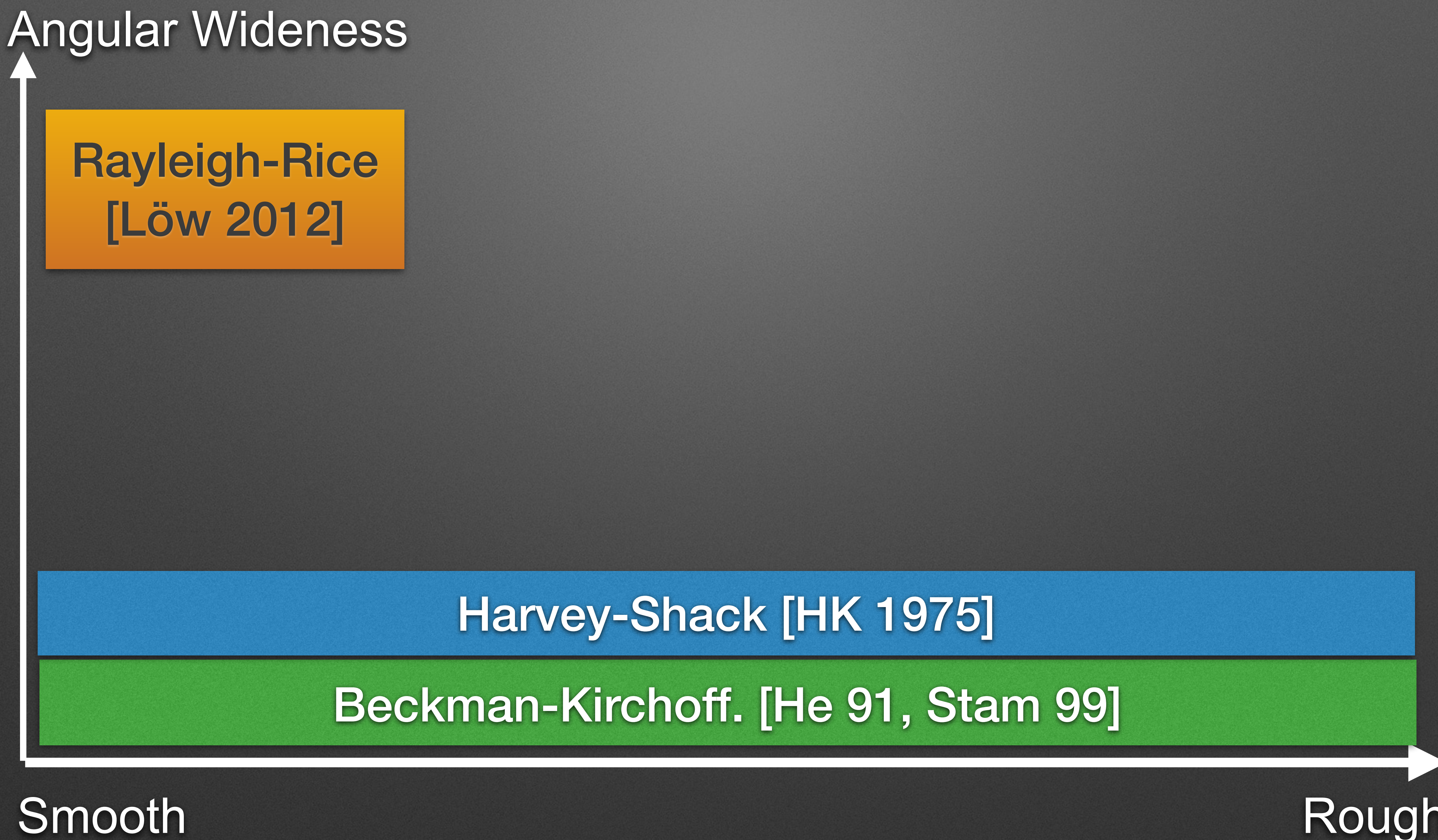
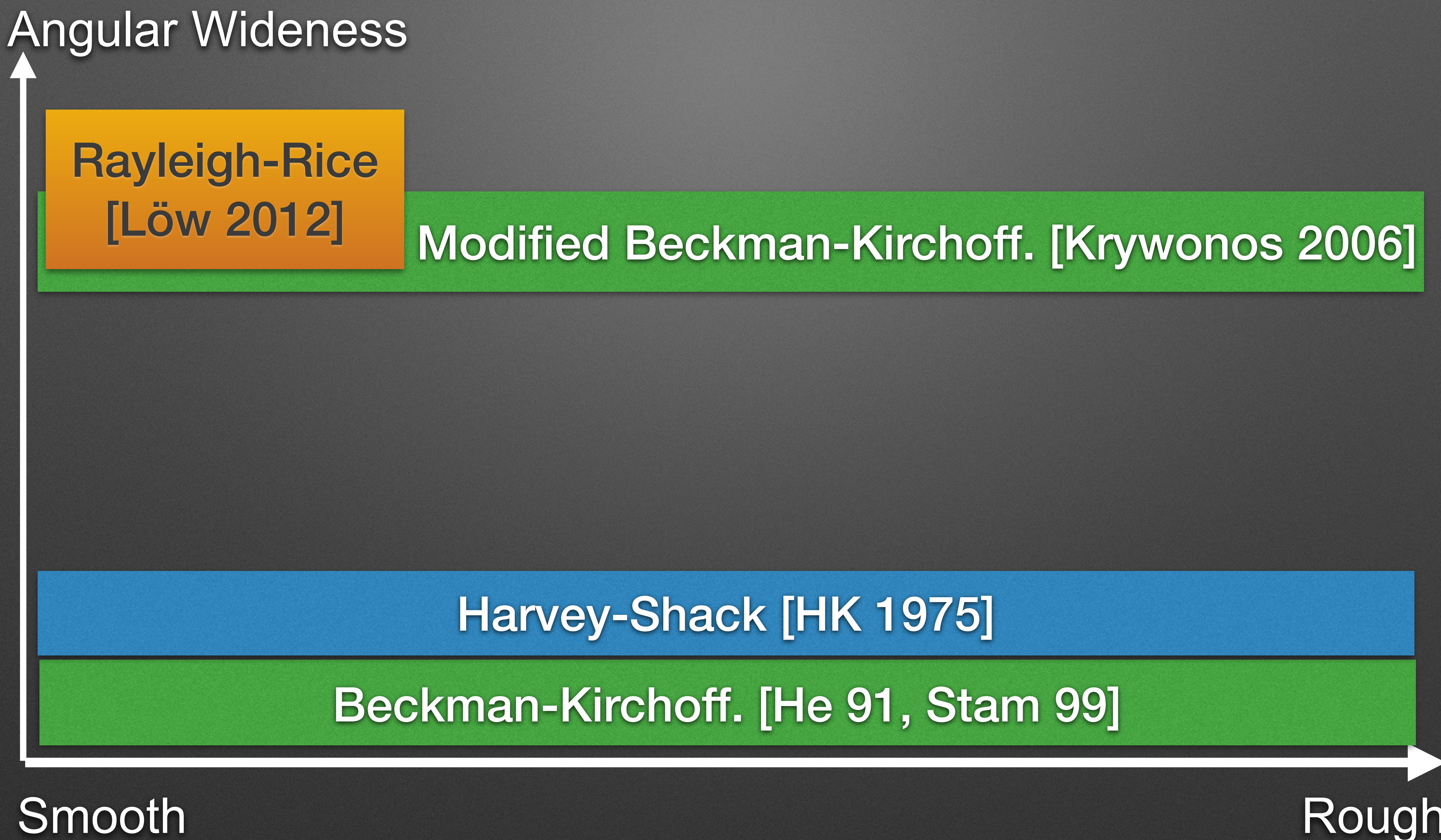


Diffraction Theories for Scattering



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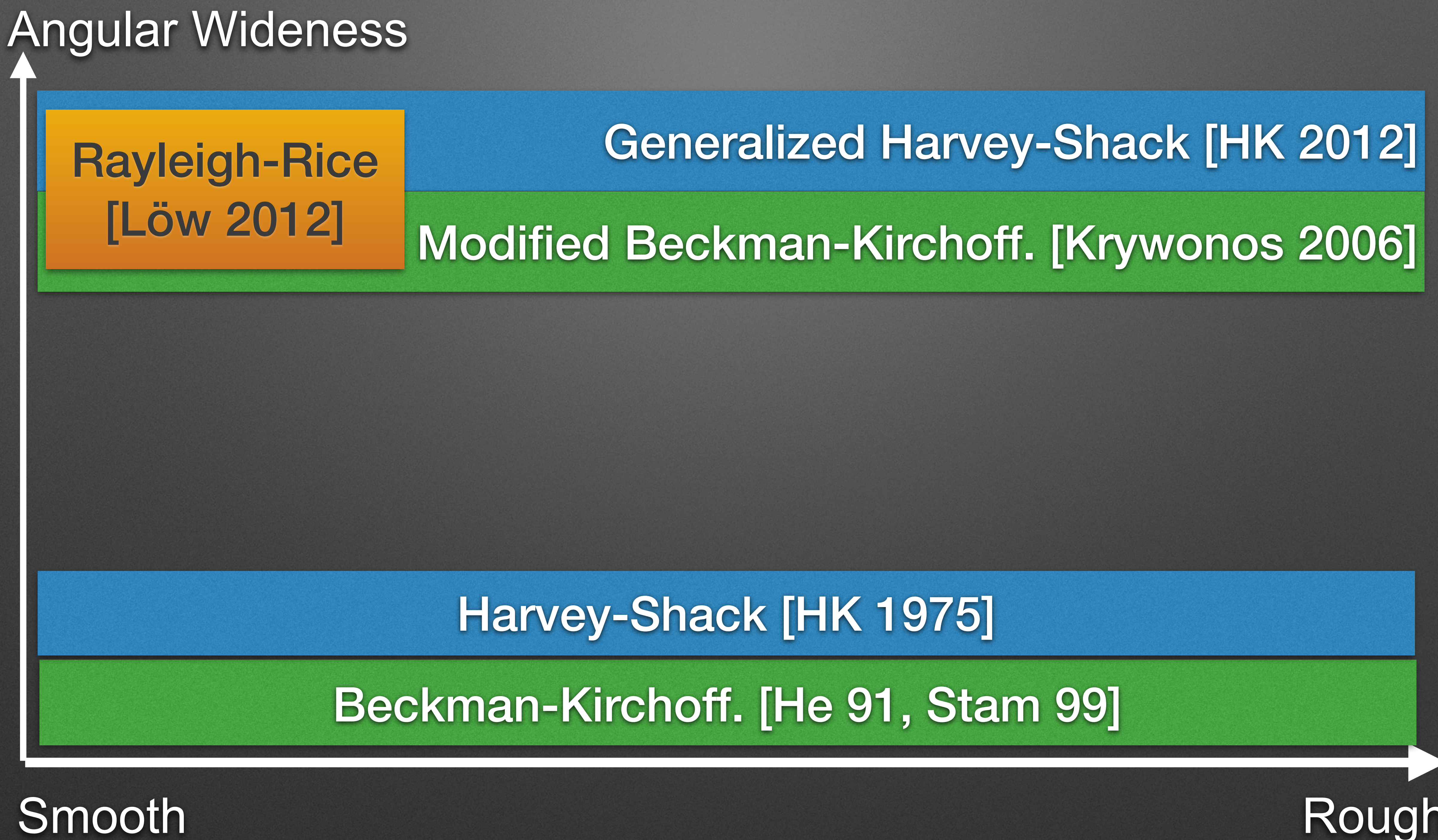
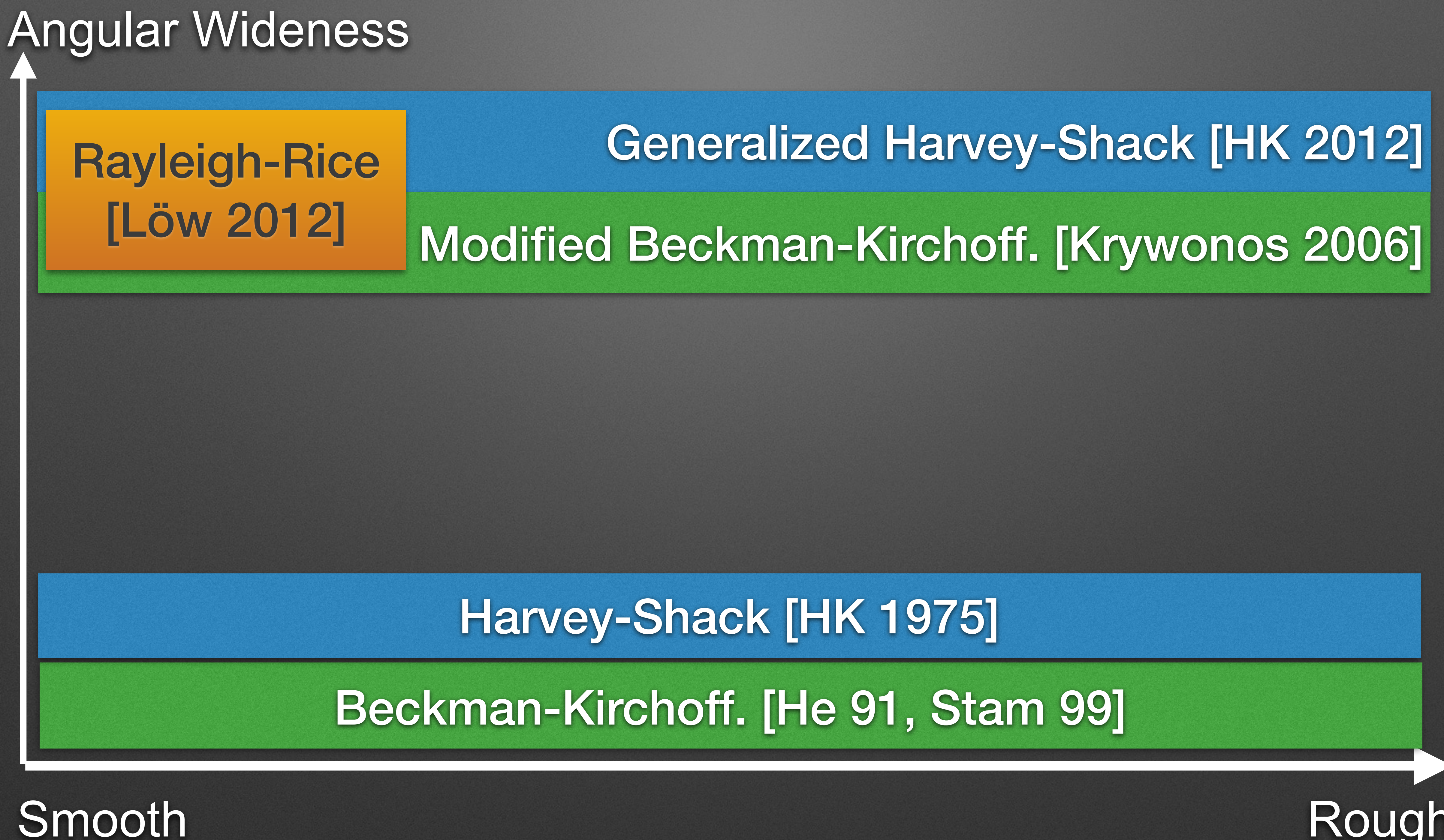


Diffraction Theories for Scattering



All Theories: SINGLE Scattering ONLY

Diffraction Theories for Scattering

Generalized Harvey-Shack

- Gaussian Surface Profile
- Arbitrary Autocovariance Function

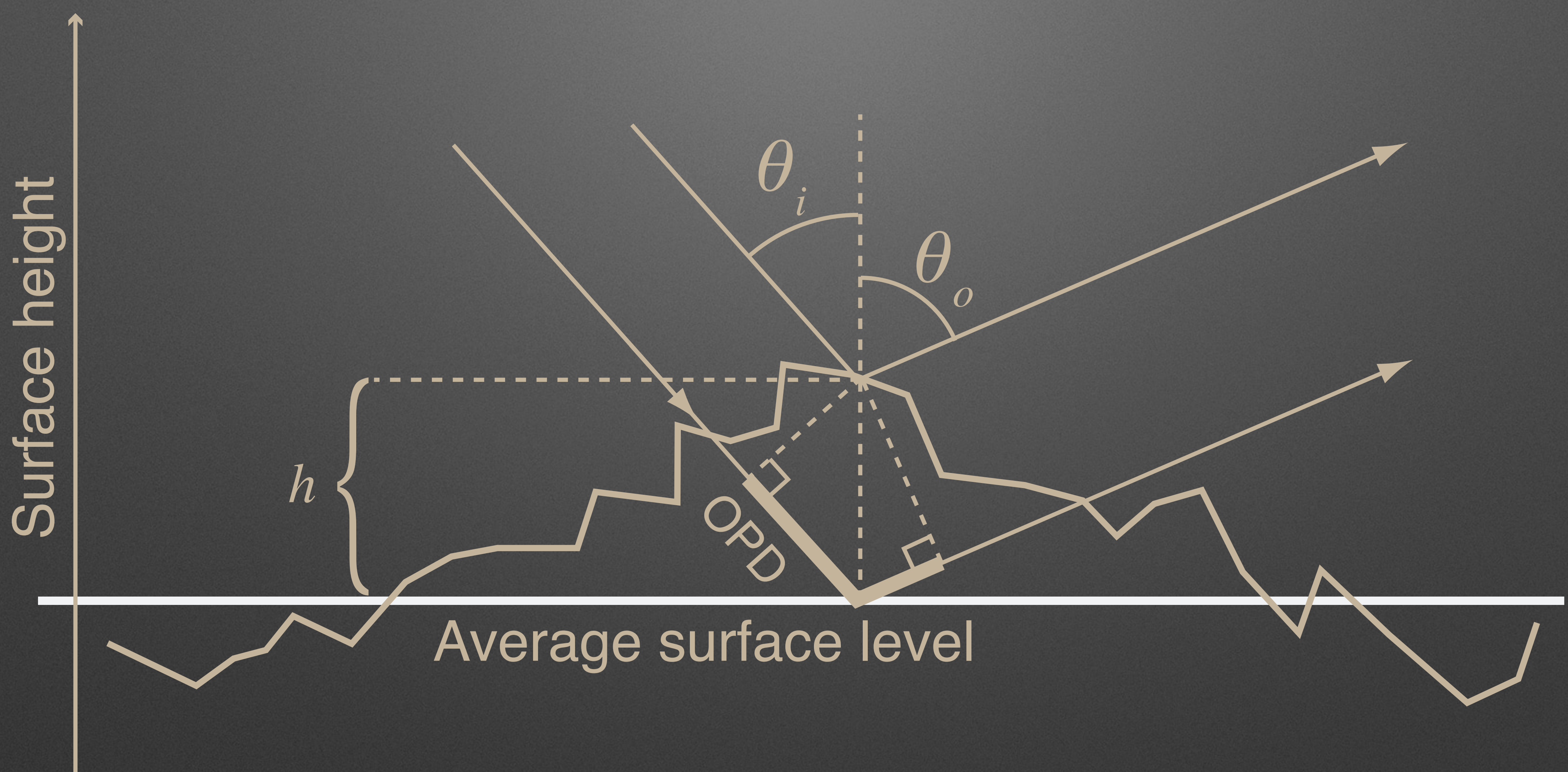
⇒ Our Model utilizes it

Modified Beckman-Kirchoff

- Gaussian Surface Profile
- Gaussian Autocovariance Function

Generalized Harvey-Shack

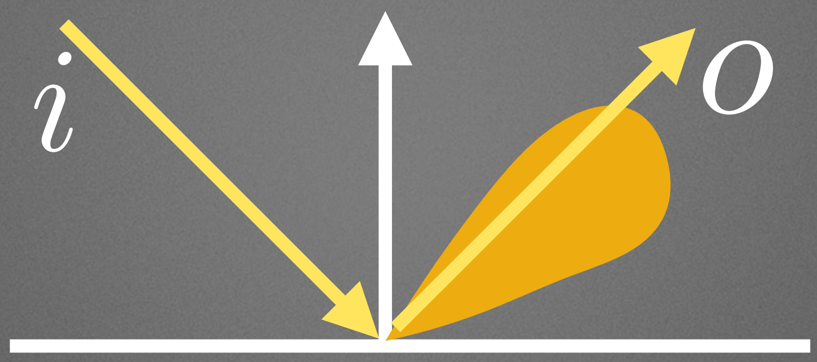
Main Idea: **Surface = Transfer Function** on the incident wave



$$\mathrm{OPD} = (cos\theta_i + cos\theta_o)h(x,y)$$

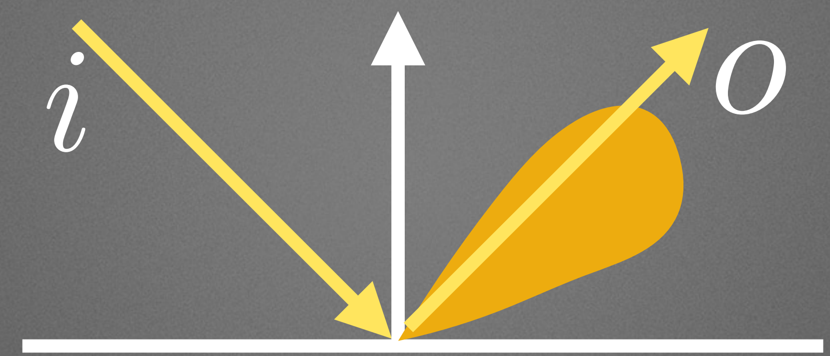
$$\mathrm{random\,phase} = \frac{2\pi}{\lambda}\mathrm{OPD}$$

Generalized Harvey-Shack



BRDF: Specular Peak (Dirac) + Diffraction Lobe

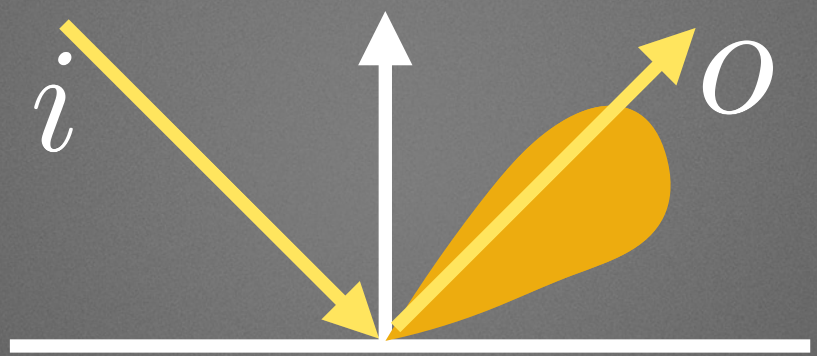
Generalized Harvey-Shack



BRDF: Specular Peak (Dirac) + Diffraction Lobe

$$\rho(i,o) = Fresnel(i,o)\left[A\delta(refl(i),o) + (1-A)\ \underbrace{\mathcal{F}_{|x,y}\{C(x,y,i,o)\}}_{\text{2D Fourier Transform}}\right]$$

Generalized Harvey-Shack



BRDF: Specular Peak (Dirac) + Diffraction Lobe

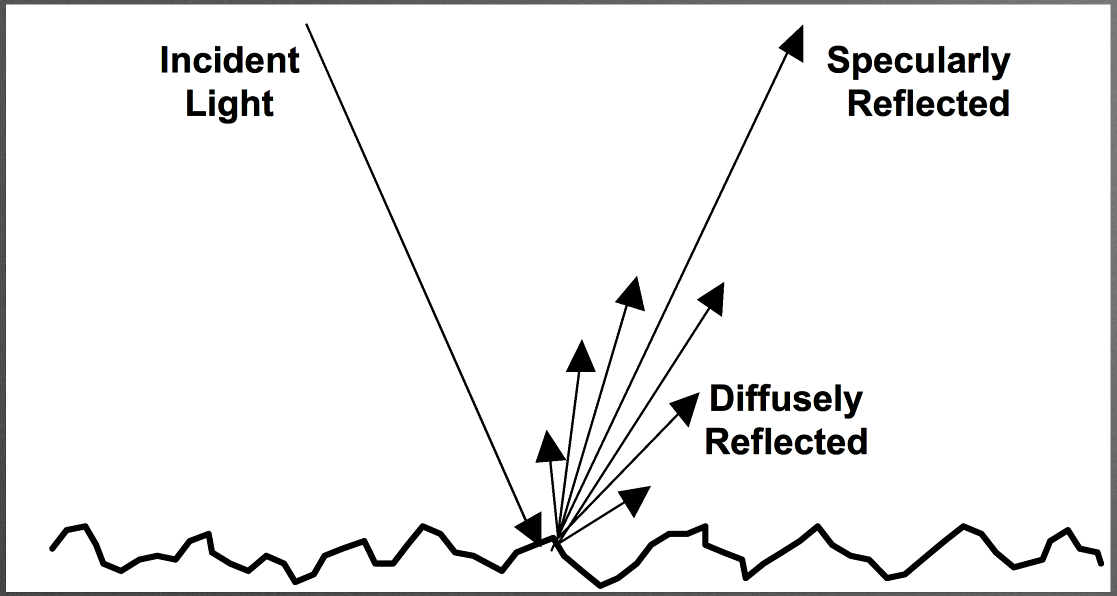
$$\rho(i,o) = Fresnel(i,o)\left[A\delta(refl(i),o) + (1-A)\underbrace{\mathcal{F}_{|x,y}\{C(x,y,i,o)\}}_{\text{2D Fourier Transform}}\right]$$

$\mathcal{F}_{|x,y}\{C(x,y,i,o)\}$: Fourier Transform per light and view

$$C(x,y,i,o) \propto AutoCovariance(x,y)\,C'(i,o)$$

$$A = exp\{-(2\pi(\cos\theta_i + \cos\theta_o)\frac{\sigma_s}{\lambda})^2\}$$

Summary on Generalized Harvey-Shack



$$\rho(i,o) = \ldots(1-A)\,\mathcal{F}\{G(x,y,i,o)\}$$

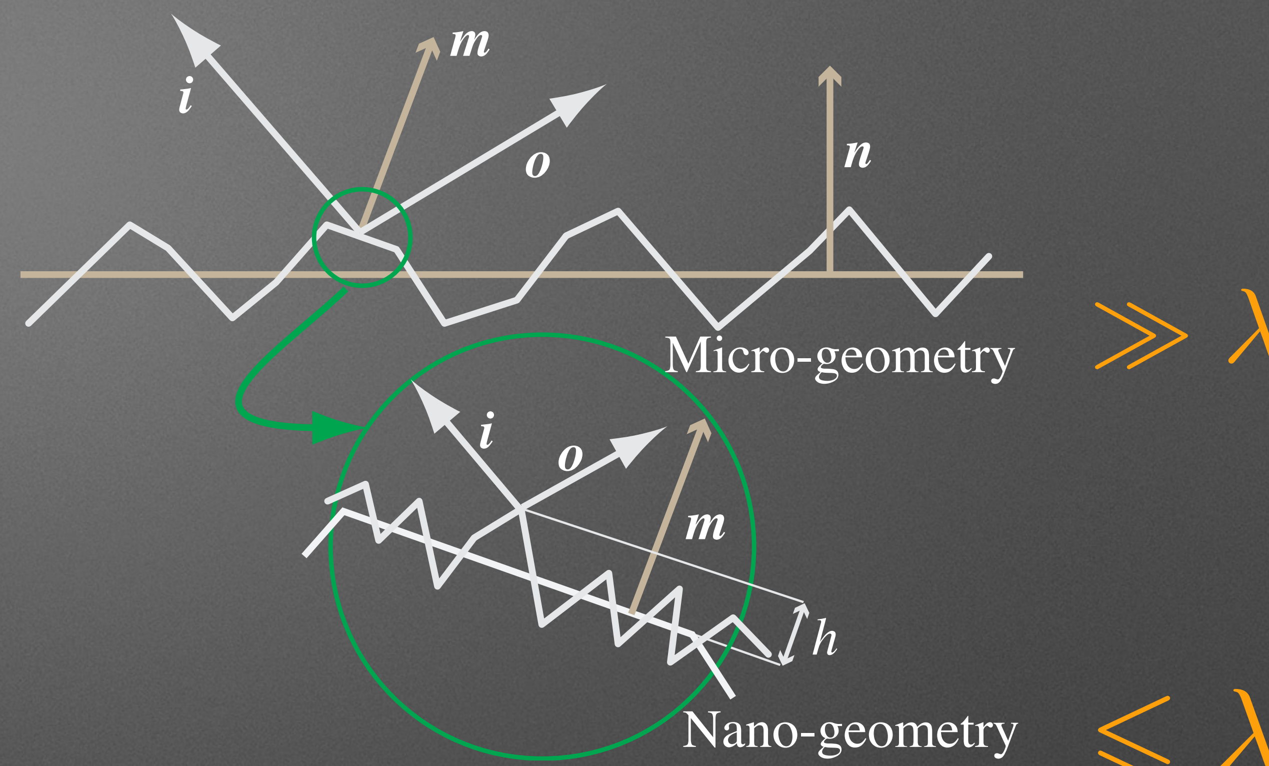
$$A = e^{-\left(2\pi(\cos\theta_i + \cos\theta_o)\frac{\sigma_s}{\lambda}\right)^2}$$

- Valid for all roughness and all angles
- Reflectance Depends on Wavelength
- BUT …
- Fourier Transform per directions

→ GHS is too expensive for CG

Diffraction into our Two-Scale Model

- Hypotheses
  - Micro-geometry: ROUGH
  - Nano-geometry: SMOOTH



⇒ GHS simplifies a bit

- Each Microfacet is a diffractive element
- Final BRDF :
  - Convolution of Diffractive Elements with Micro-geometry

Our Approach for Smooth Regime

$$\rho(i,o) = Fresnel\left[A\,\delta(refl(i),o) + (1-A)\,\mathcal{F}\{C(x,y,i,o)\}\right.$$

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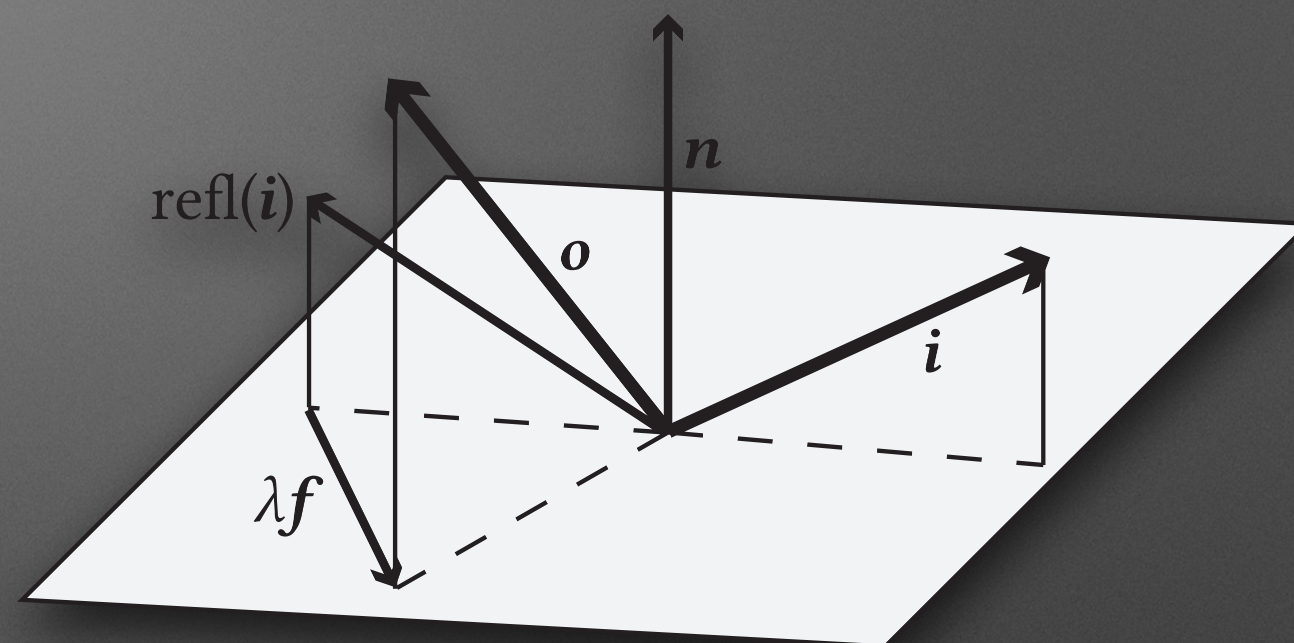
$$\rho(i, o) = Fresnel\left[A\,\delta(refl(i), o) + (1 - A)\,\mathcal{F}\{C(x, y, \cancel{i, o})\}\right.$$

- Fourier Transform depends **only** on the surface

Our Approach for Smooth Regime

$$\rho(i,o) = Fresnel\left[A\,\delta(refl(i),o) + (1-A)\,\mathcal{F}\{C(x,y,\sout{i,o})\}\right.$$

- Fourier Transform depends **only** on the surface



$$\mathcal{F}\{C(x,y)\} : PSD(Surface) \approx \text{K-Correlation}(\sigma_s, f)$$

$$||\mathbf{f}|| = \frac{2}{\lambda}\sin\theta_h\cos\theta_d$$

Our Approach for Smooth Regime

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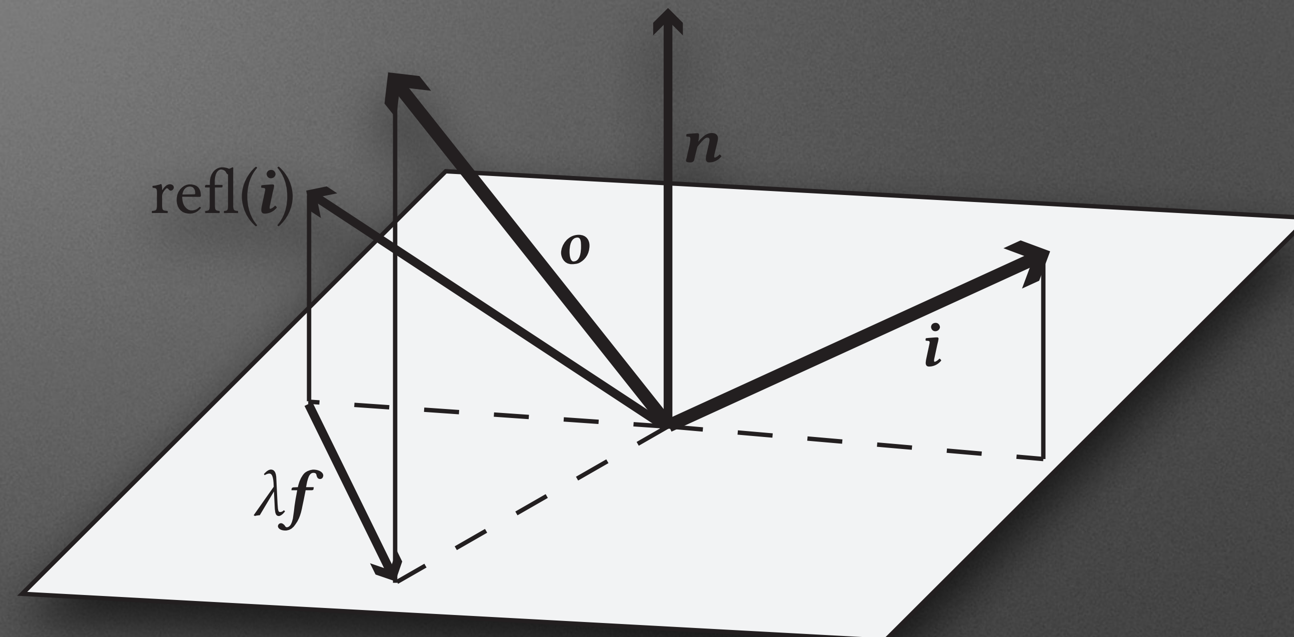


$$\mathcal{F}\{C(x,y)\} : PSD(Surface) \approx \text{K-Correlation}(\sigma_s, f)$$

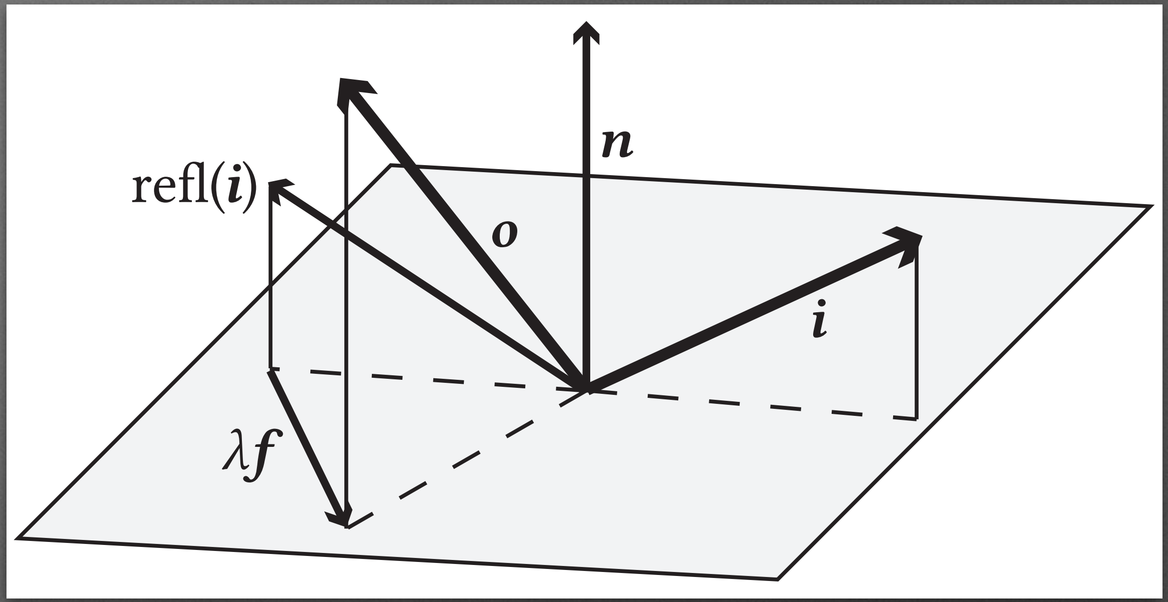
$$||\mathbf{f}|| = \frac{2}{\lambda}\sin\theta_h\cos\theta_d$$

- f ⟺ Alternative Parametrization [Barla et al. Mam 2015]

Renormalization of the Diffraction Lobe

$$\mathcal{F}\{C(x,y)\} \approx \text{K-Correlation}(\sigma_s, \mathbf{f})$$

$$\sigma_s^2 = \iint \text{K-Correlation}(\sigma_s, \mathbf{f})\, df$$

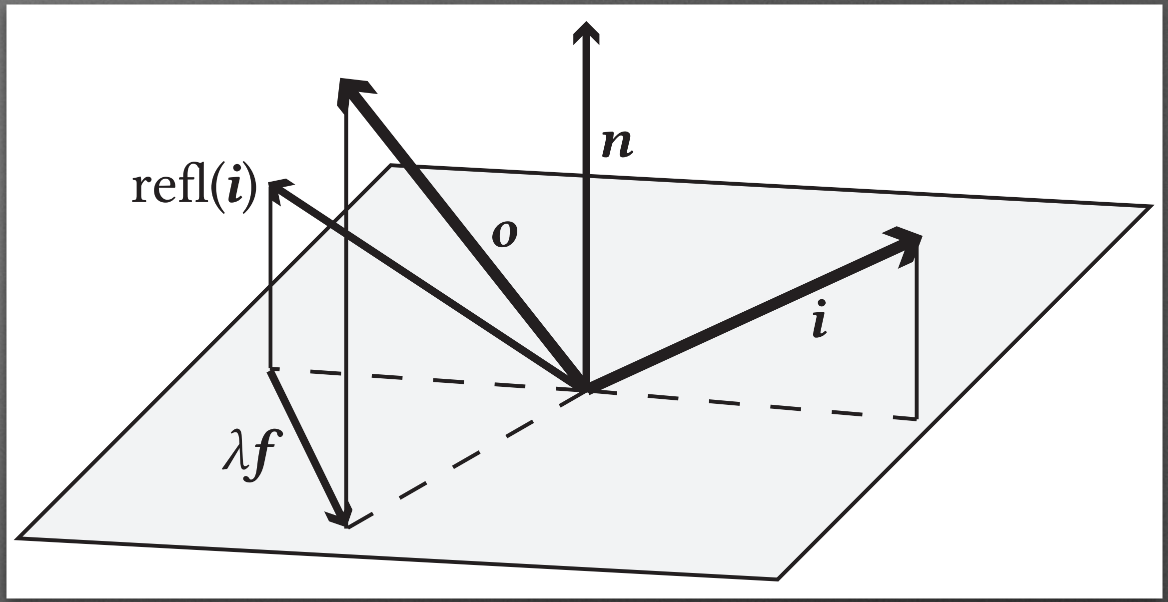


Renormalization of the Diffraction Lobe

$$\mathcal{F}\{C(x,y)\} \approx \text{K-Correlation}(\sigma_s, \mathbf{f})$$

- Renormalization

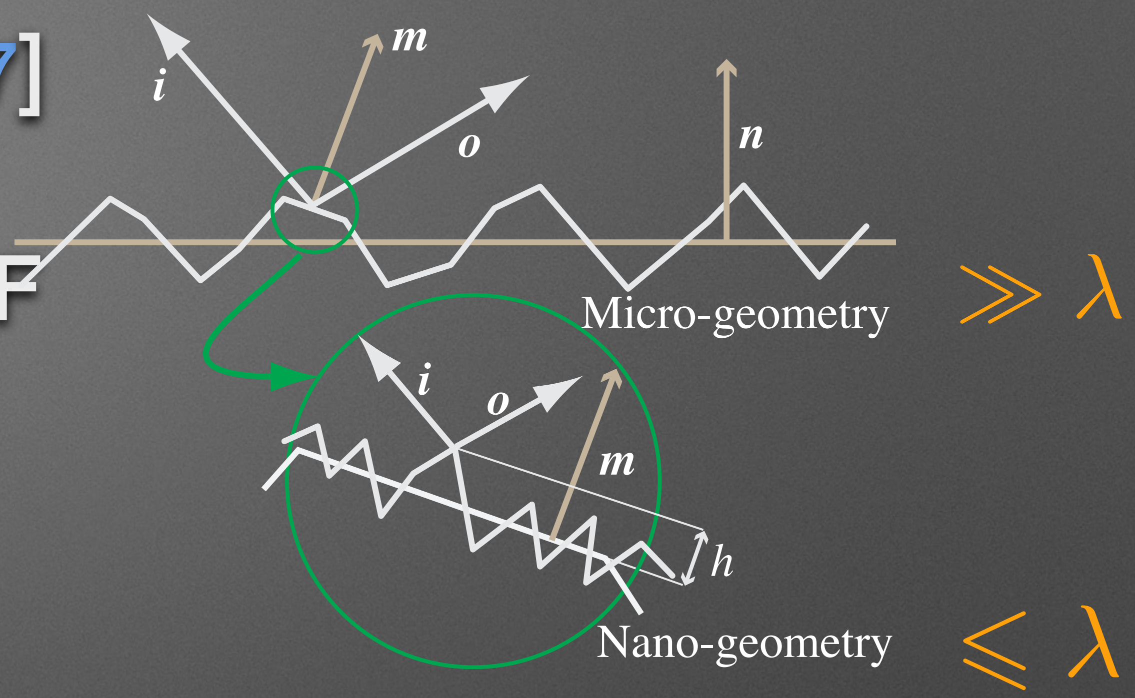
$$\sigma_s^2 = \iint \text{K-Correlation}(\sigma_s, \mathbf{f})\, df$$



- Enforce Energy repartition between dirac and diffraction [Harvey2012]
- Comes from the Autocovariance Function Property
- Precomputed for a large range of values: 8.9MB

Diffraction into our Two-Scale Model

- Microfacet Framework [Walter2007]
- Convolution of a Microfacet BRDF



Diffraction into our Two-Scale Model

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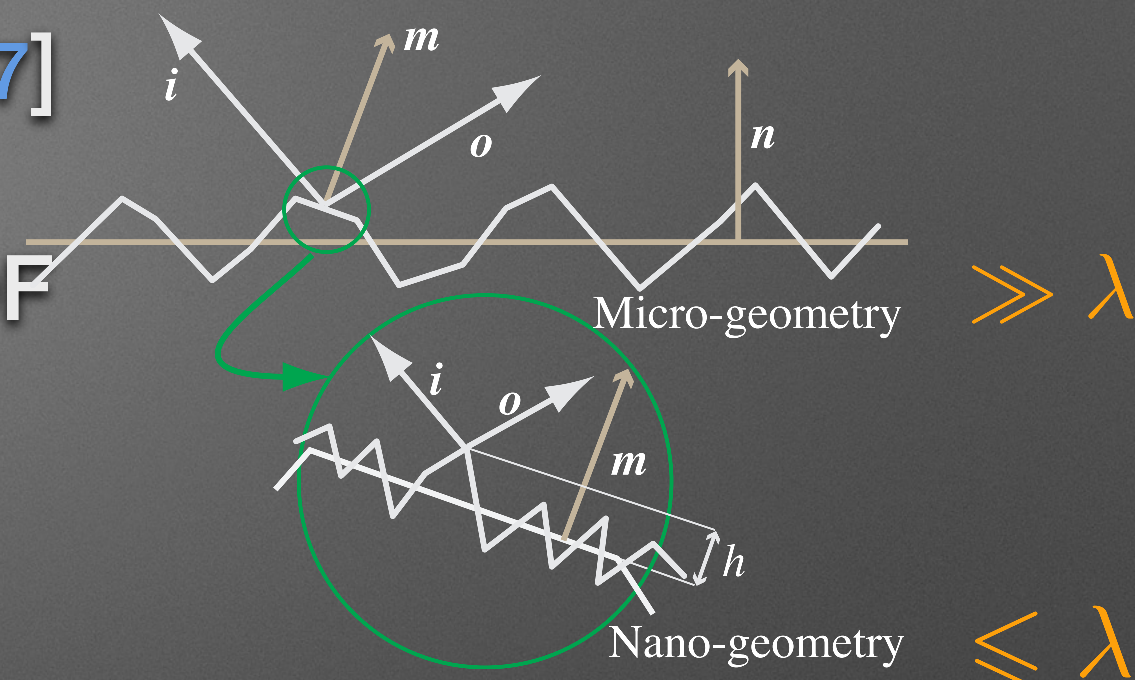

$$\rho(i,o) = \int_{\Omega_m} \underbrace{\rho_m(i,o,m)}_{Microfacet\,BRDF} \; G(i,o)D(m)\,d\omega_m$$

Diffraction into our Two-Scale Model

- Microfacet Framework [Walter2007]
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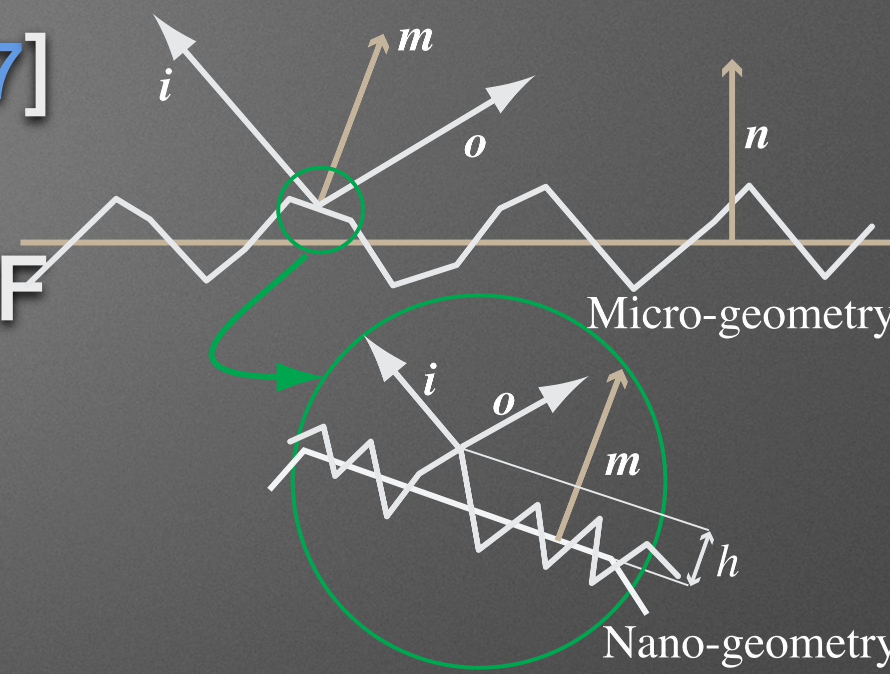

$\gg \lambda$

$\leqslant \lambda$

$$\rho(i,o) = \int_{\Omega_m} \underbrace{\rho_m(i,o,m)}_{Microfacet\,BRDF} \; G(i,o)D(m)\,d\omega_m$$

- In Our Case, Smooth Diffractive Microfacet:

$$\rho_m(i,o,m) = Fresnel\left[A\,\delta(refl(i),o) + (1-A)\,K_{\sigma_s}(f)\right]$$

Convolution of a Diffractive Microfacet

$$\rho(i,o) = \int_{\Omega_m} Fresnel(i,o)\Big[A\,\delta(refl(i),o) + (1-A)\,K_{\sigma_s}(f)\Big]G(i,o)D(m)\,d\omega_m$$

Convolution of a Diffractive Microfacet

$$\rho(i,o) = \int_{\Omega_m} Fresnel(i,o)\Big[A\,\delta(refl(i),o) + (1-A)\,K_{\sigma_s}(f)\Big]G(i,o)D(m)\,d\omega_m$$

$$\rho(i,o) = \underbrace{\int_{\Omega_m} Fresnel(i,o)\,A\,\delta(refl(i),o)\,G(i,o)\,D(m)\,d\omega_m}_{\text{Microfacet-based BRDF}}$$

$$+ \underbrace{\int_{\Omega_m} Fresnel(i,o)\,(1-A)\,K_{\sigma_s}(f)G(i,o)D(m)\,d\omega_m}_{\text{Diffraction Part}}$$

Convolution of a Diffractive Microfacet

$$\rho(i,o) = \int_{\Omega_m} Fresnel(i,o)\Big[A\,\delta(refl(i),o) + (1-A)\,K_{\sigma_s}(f)\Big]G(i,o)D(m)\,d\omega_m$$

$$\rho(i,o) = \frac{Fresnel(i,o)D(\theta_h)G(i,o)}{4\,\pi\,\cos\theta_i\,\cos\theta_o}$$

$$+ \underbrace{\int_{\Omega_m} Fresnel(i,o)\,(1-A)\,K_{\sigma_s}(f)G(i,o)D(m)\,d\omega_m}_{\text{Diffraction Part}}$$

Convolution of a Diffractive Microfacet

$$\rho_{ghs}(i,o) = \int\limits_{\Omega_m} Fr(i,o)\,(1 - A_{\sigma_s}(i,o))\,K_{\sigma_s}(f)G(i,o)D(m)\,d\omega_m$$

Convolution of a Diffractive Microfacet

$$\rho_{ghs}(i,o) = \int_{\Omega_m} Fr(i,o)\,(1 - A_{\sigma_s}(i,o))\,K_{\sigma_s}(f) G(i,o) D(m)\,d\omega_m$$

$$\rho_{ghs}(i,o) \approx Fr(i,o)\,G(i,o)\,(1 - A_{\sigma_s}(\theta_d)) \underbrace{\int_{\Omega_m} K_{\sigma_s}(f)\; D(m)\,(h \cdot m)^2\,d\omega_m}_{Convolution \approx K'_{\sigma_s}(f)}$$

$$f = 2\,\cos\theta_d\,\sqrt{(1 - (h \cdot m)^2}$$

Convolution of a Diffractive Microfacet

$$\rho_{ghs}(i,o) = \int_{\Omega_m} Fr(i,o)\,(1 - A_{\sigma_s}(i,o))\,K_{\sigma_s}(f)G(i,o)D(m)\,d\omega_m$$

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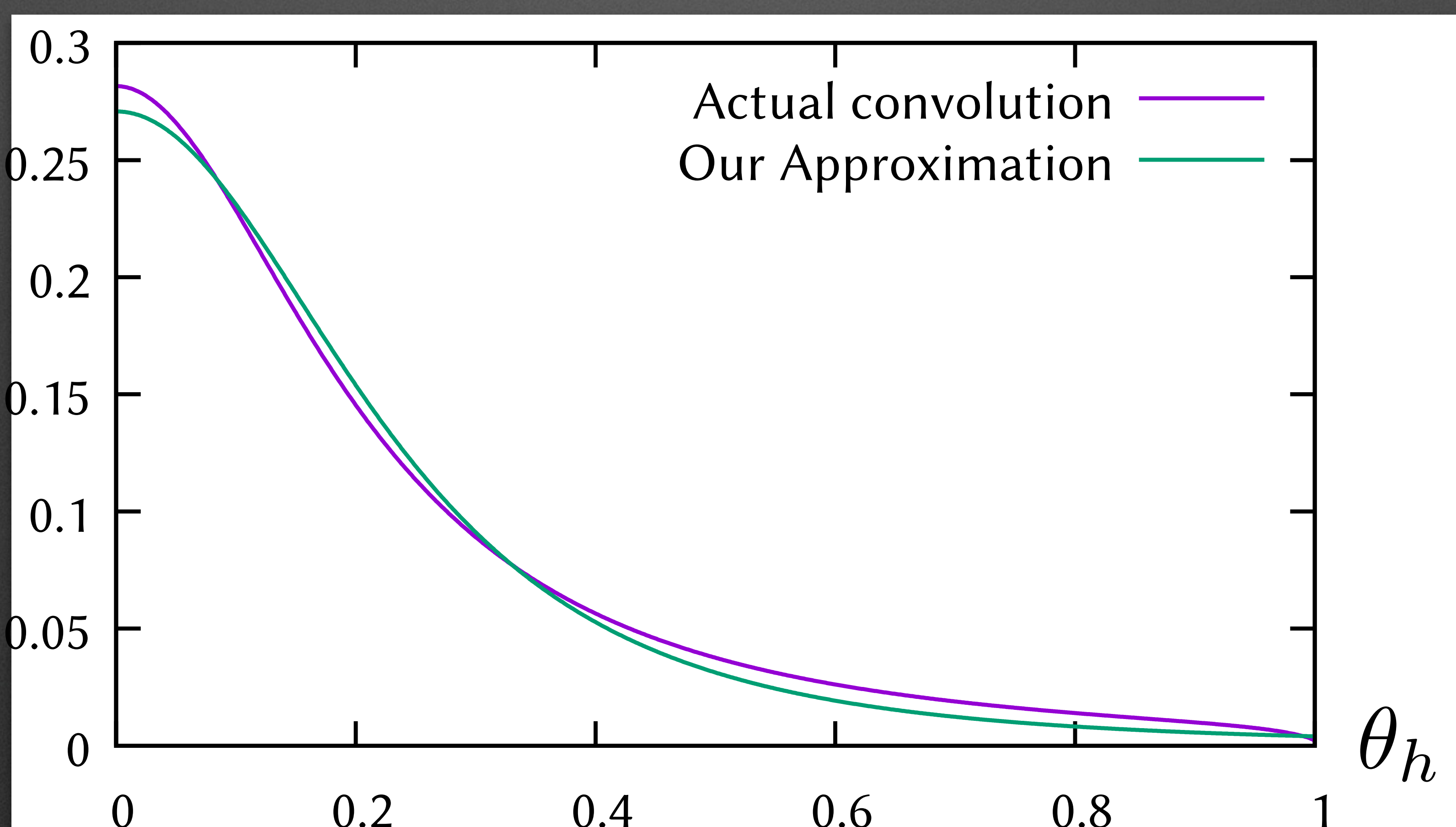


Convolution of a Diffractive Microfacet

$$\rho_{ghs}(i,o) \approx Fr\,(1-A)\,G(i,o)\int_{\Omega_m} K_{\sigma_s}(f)\; D(m)\,(h\cdot m)^2\,d\omega_m$$

$$f = 2\,\cos\theta_d\,\sqrt{(1-(h\cdot m)^2}$$

$$\underbrace{\qquad\qquad}_{Convolution \approx K'_{\sigma_s}(f)}$$

Convolution Computation

- Product of Zonal Harmonics. 100 Coefficients
- Result is a new K-Correlation Function
- 4D Table Precomputed
- Parameters : $\frac{\cos\theta_d}{\lambda}$, $D(m)$ and K-Correlation Model

Our Model for Conductor

- Combination of a Specular Lobe and Diffractive Lobe

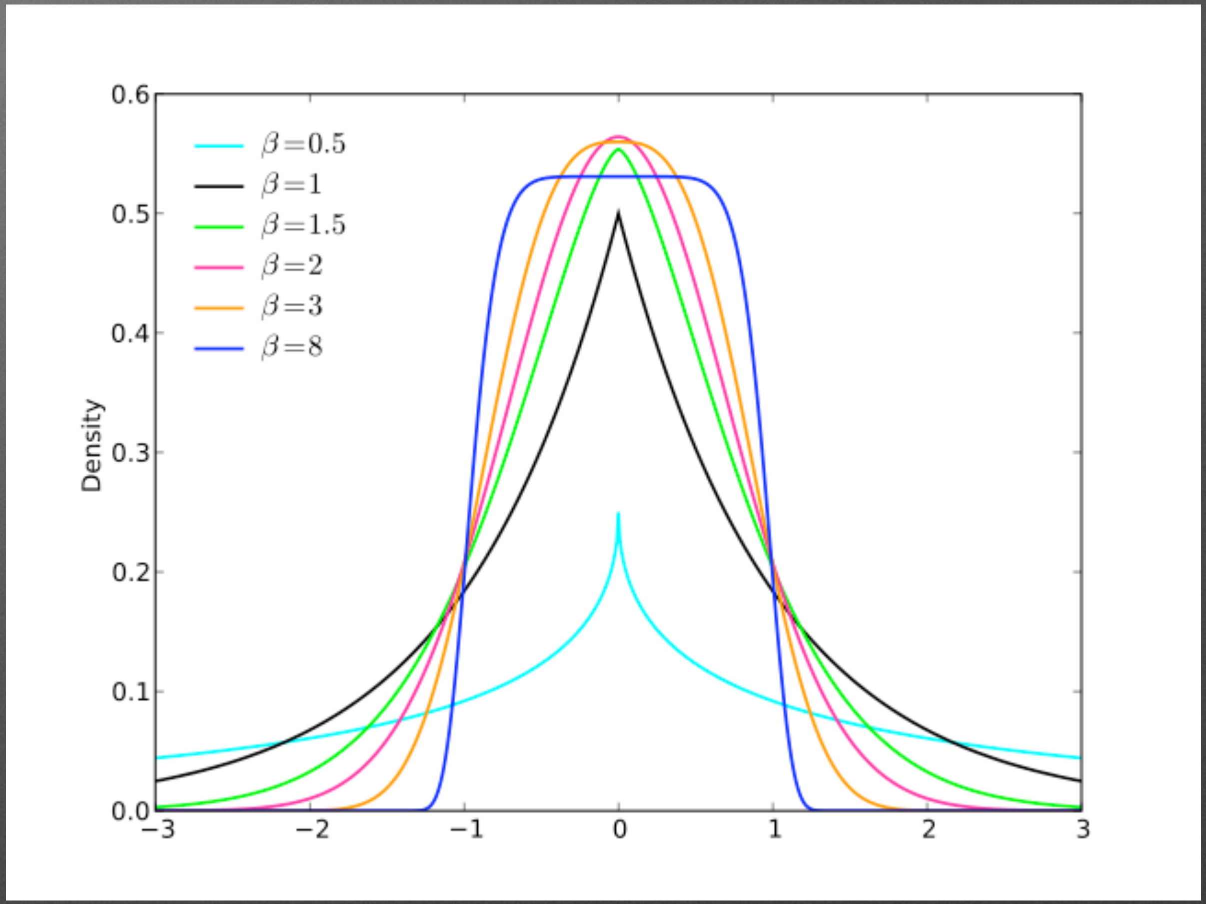
$$\rho(i,o) = A_{\sigma_s}(\theta_d)\,\underbrace{\rho_{epd}(i,o)}_{specular} + \underbrace{\rho_{ghs}(i,o)}_{diffraction}$$

- Specular Lobe: Exponential Power Disbribution (EPD)

$$epd(x) = \frac{p}{\pi\beta^2\Gamma(1/p)}\,e^{-(x/\beta^2)^p}$$

Exponential Power Distribution NDF

- Generalization of Gaussian Distribution
    - Kurtosis control
    - Similar to [Brady2014]
- Analytical Importance Sampling
    - Distribution only
- Shadowing Term
    - Precomputed for large range of possible values for the parameters
    - 390 KB 2D Array



Parameters of the Model

- Diffraction Lobe

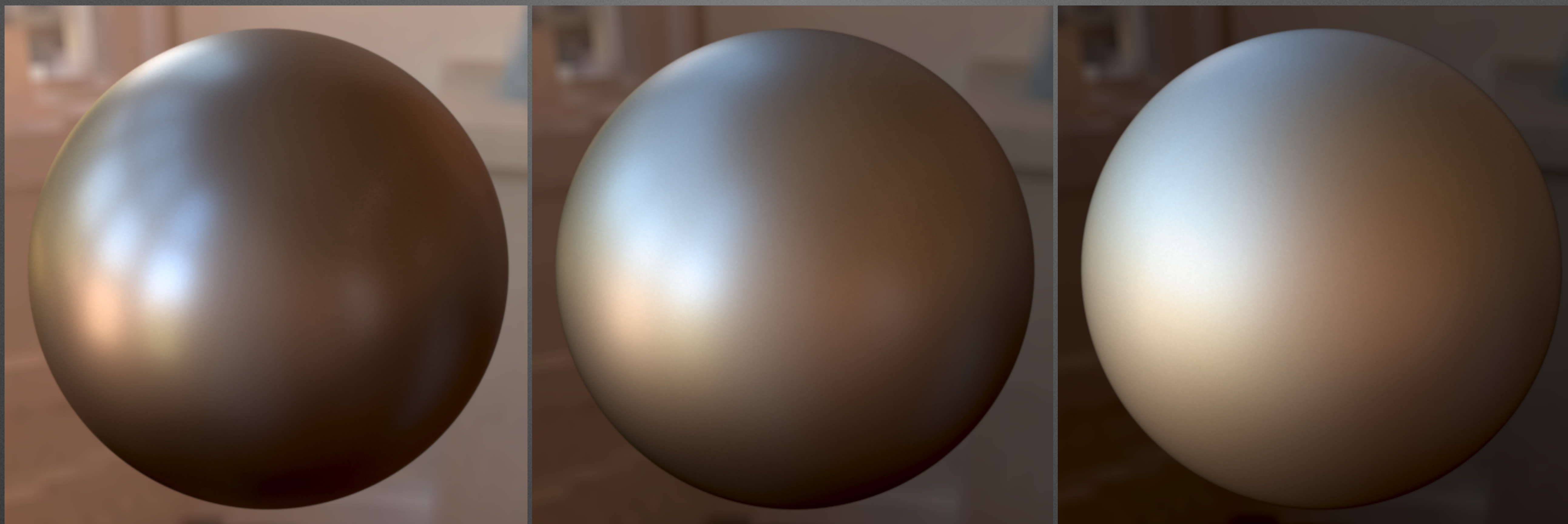
RMS of Surface Roughness : 1
Index of Refraction : 2 per wavelength
K-correlation Model : 2 parameters

- Specular Lobe

$$\beta : \text{Width}$$

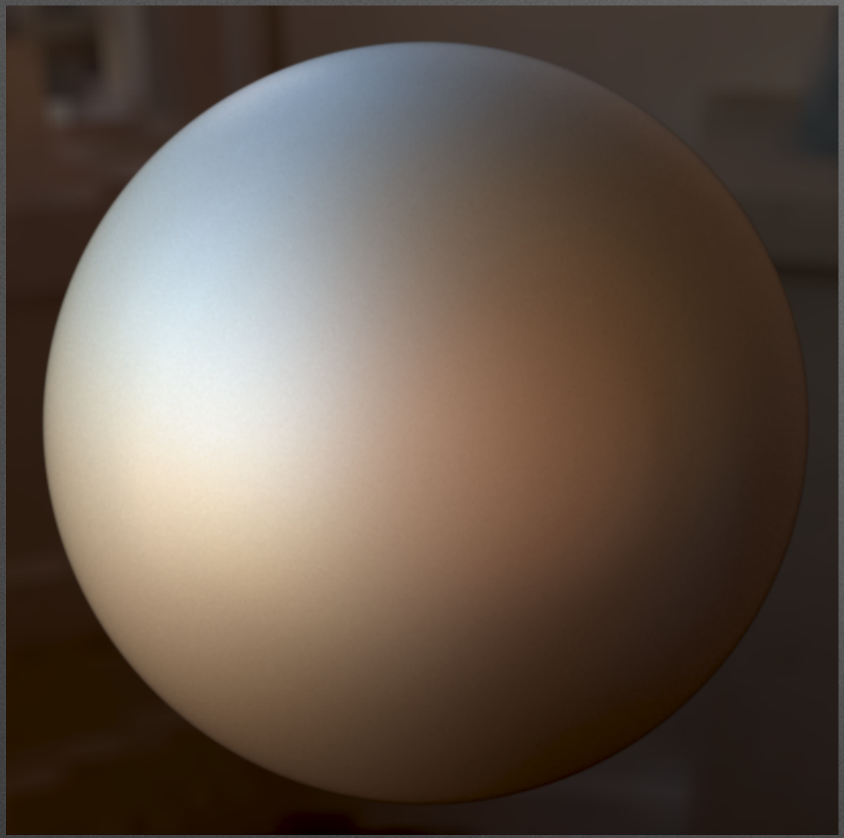
$$p : \text{Kurtosis}$$

Diffraction Parameters Behaviour

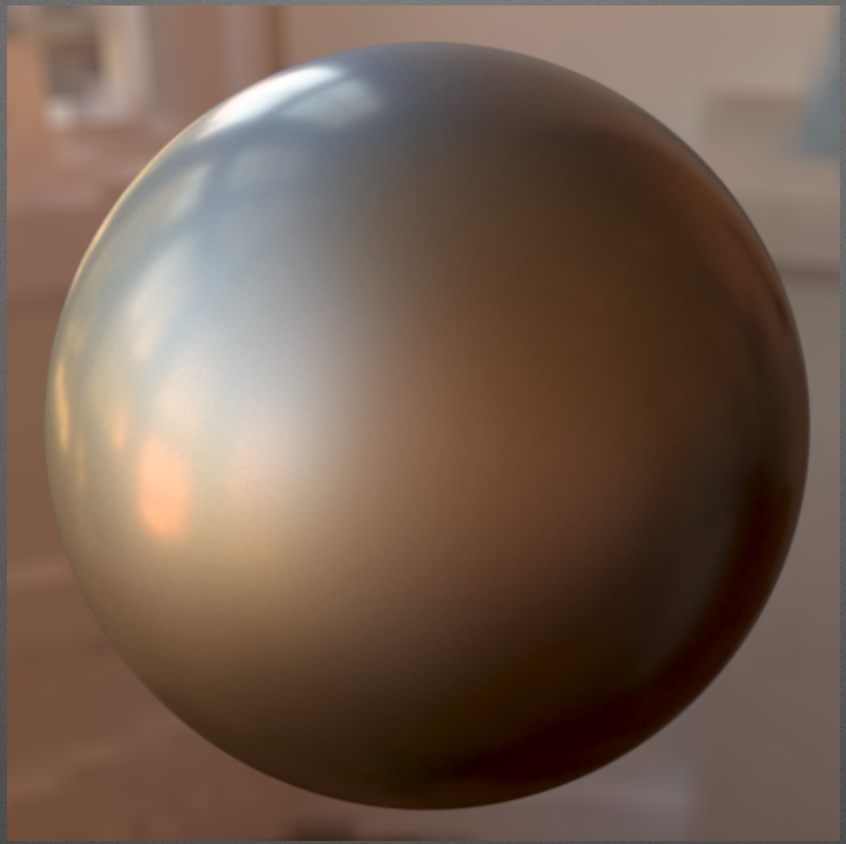


$\sigma_s \times 3, b/3$ $\sigma_s \times 1, b \times 1$ $\sigma_s \times 4, b \times 4$

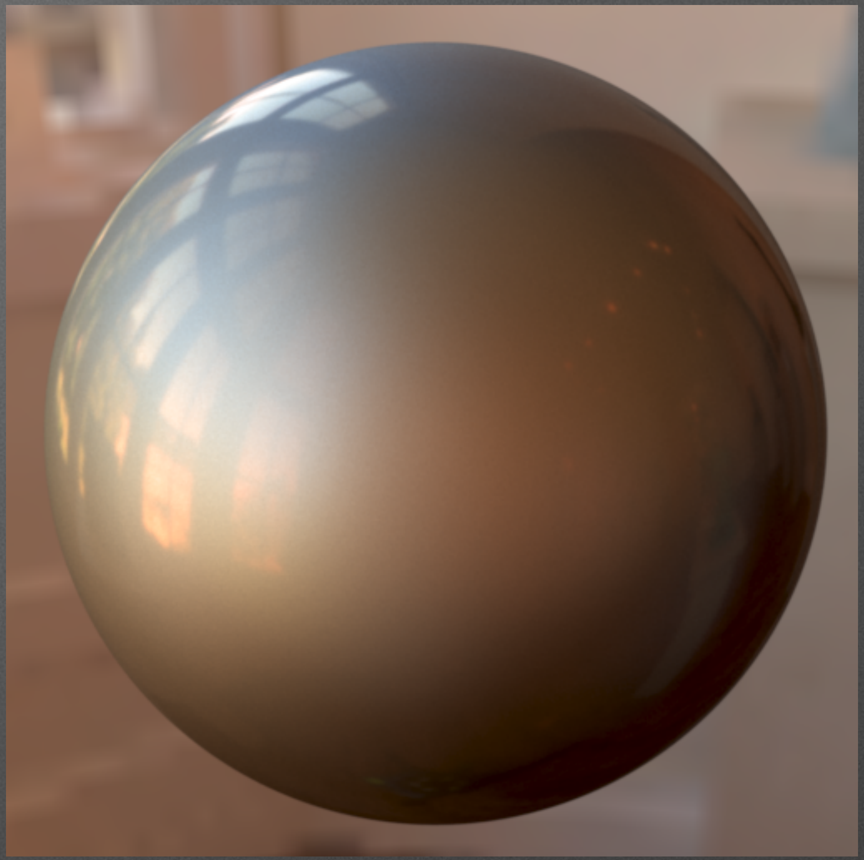
Specular Lobe Behavior



$\beta \times 4$



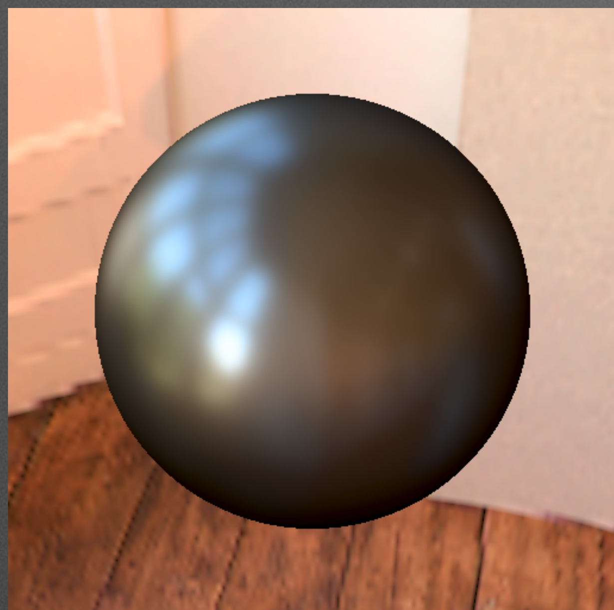
$\beta \times 1$



$\beta / 4$

Diffraction parameters remain unchanged

Comparison for Nickel



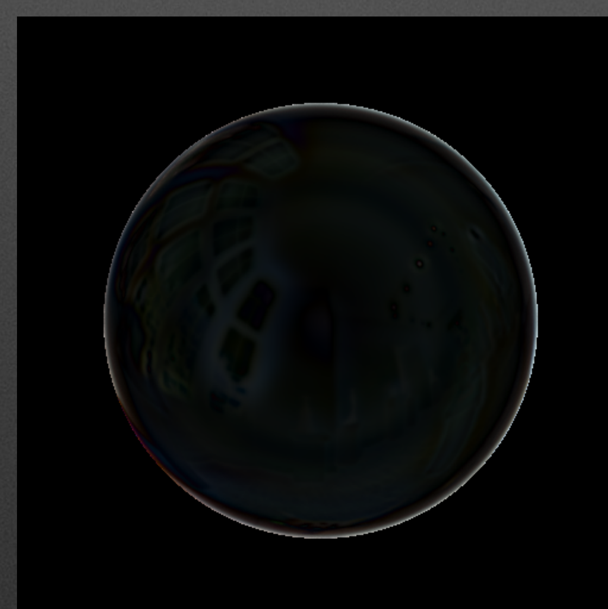
Diffraction

+

Microfacet

=

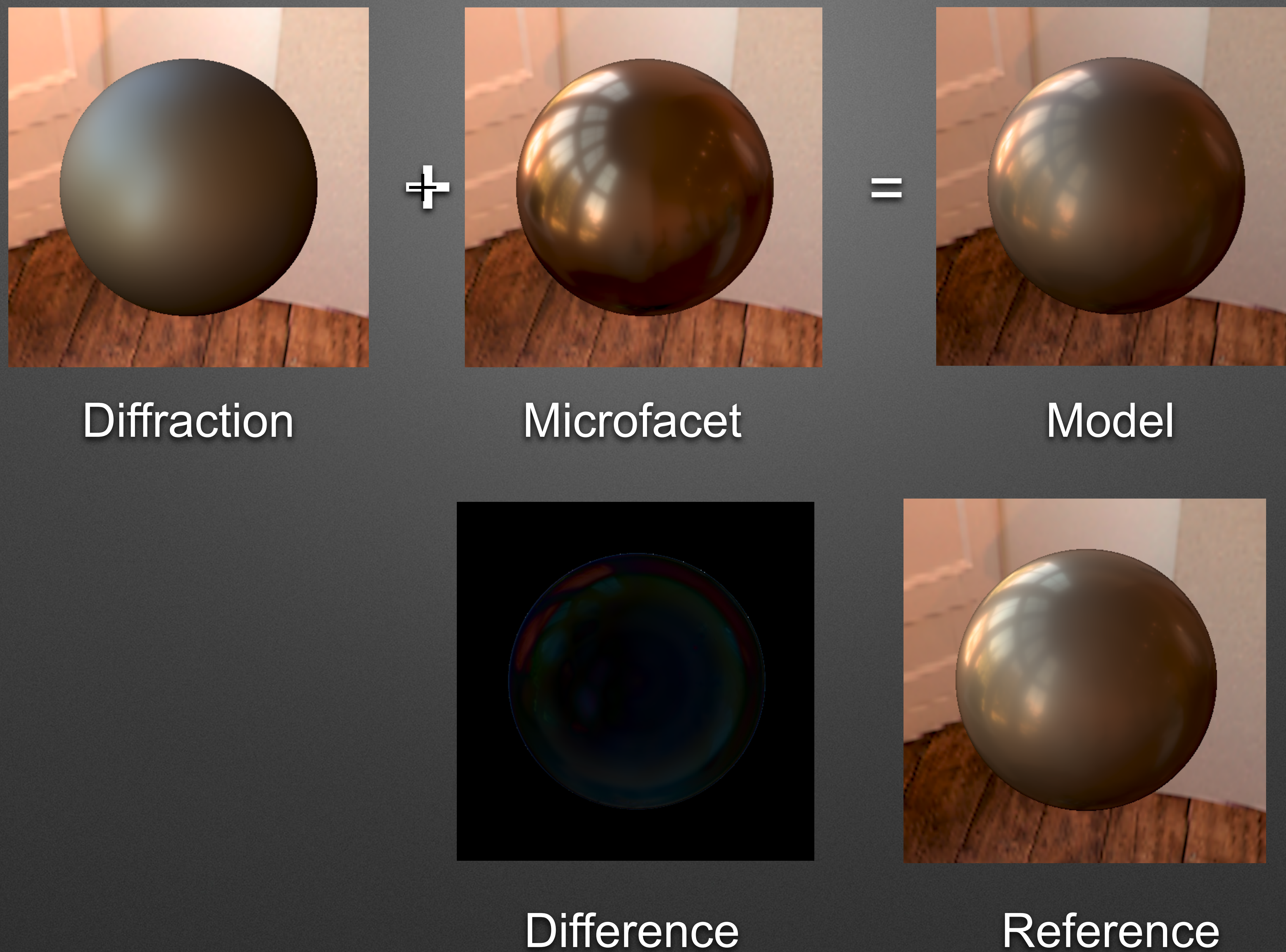
Model



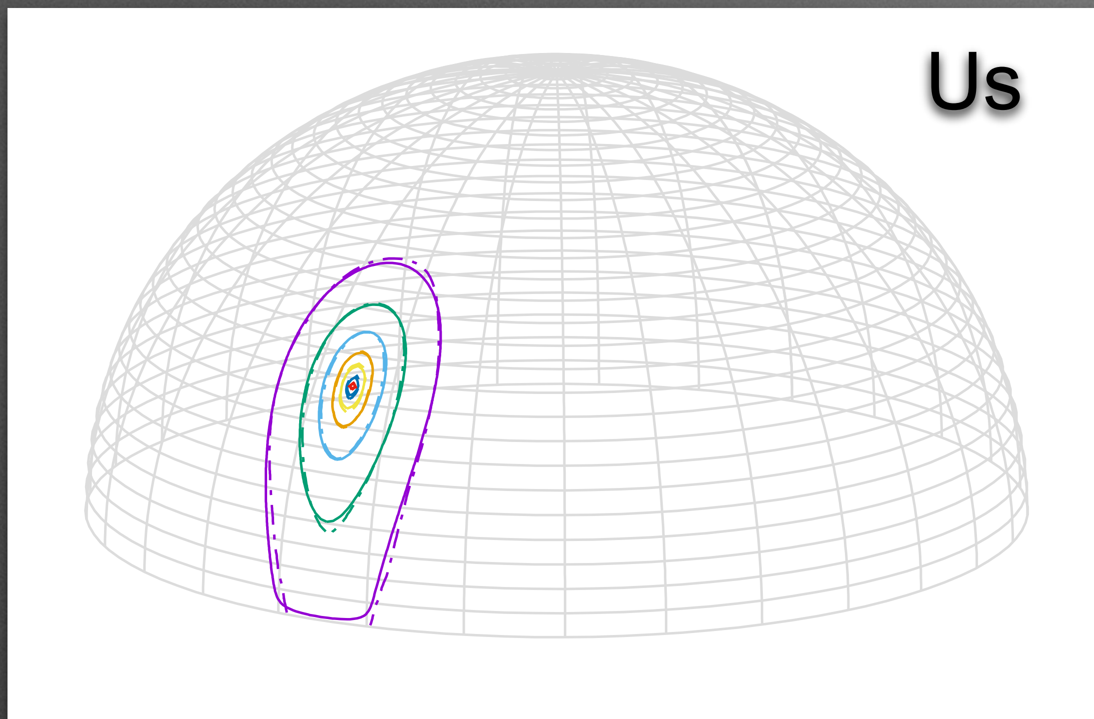
Difference

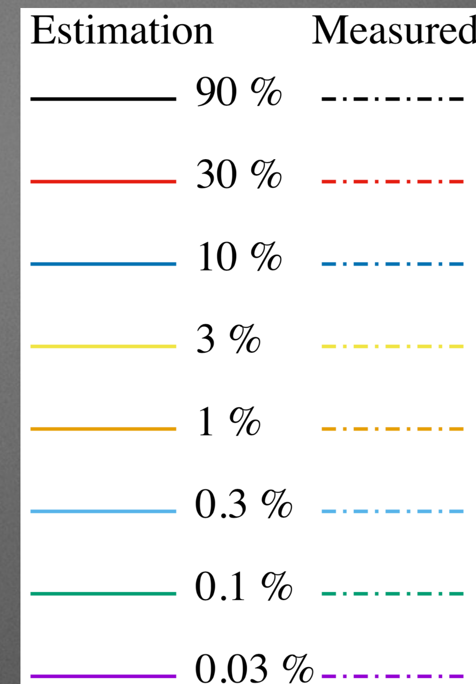
Reference

Comparison for Alum-Bronze

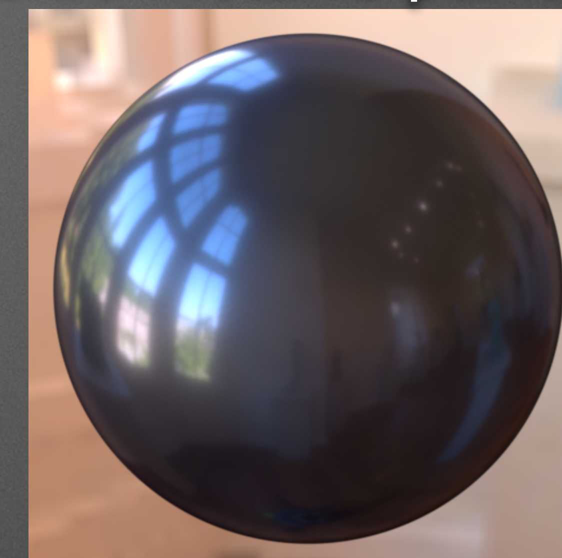


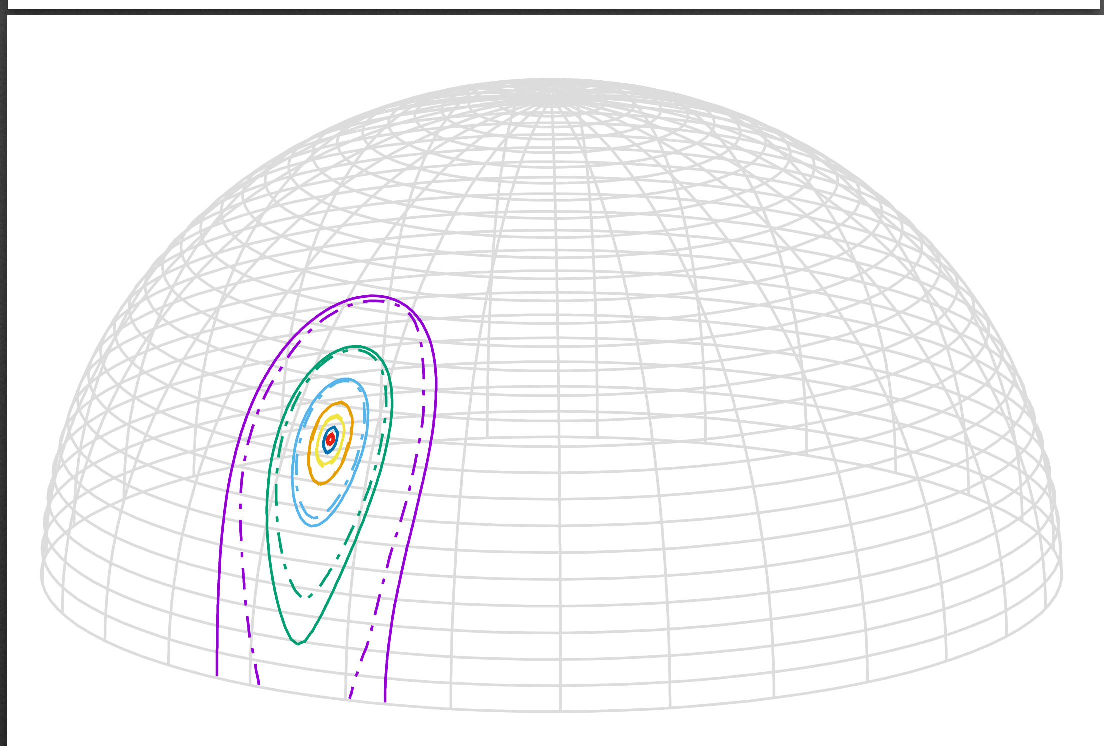
Fitting Results outside the Incident Plane



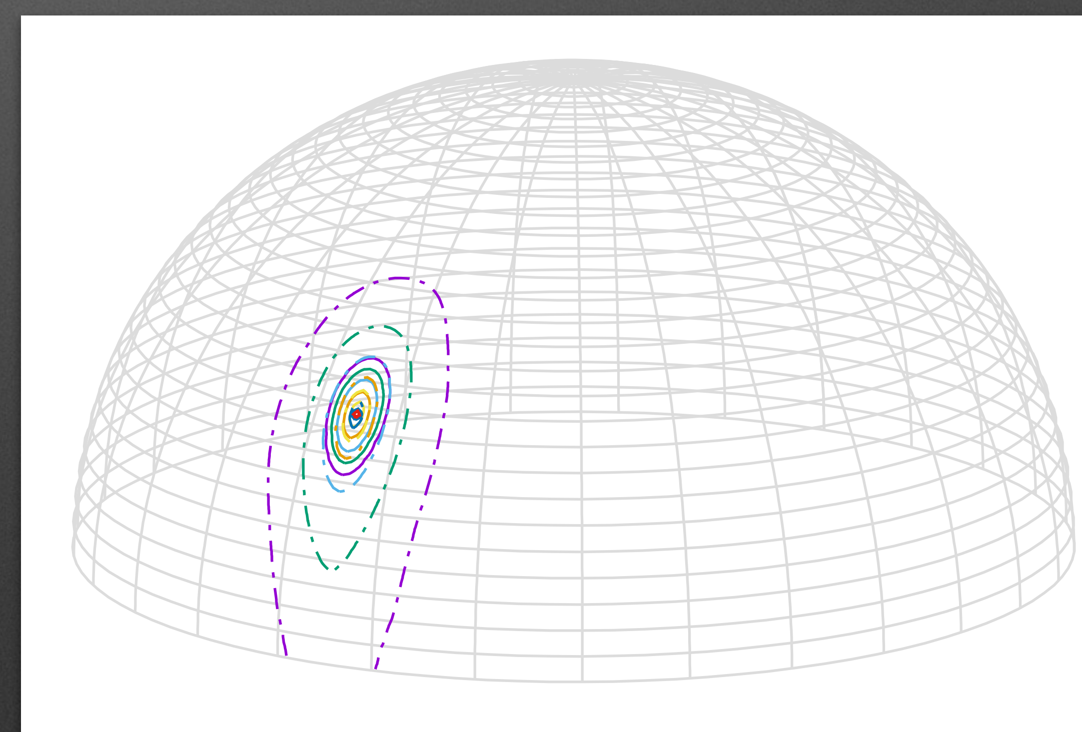


blue-metallic-paint2



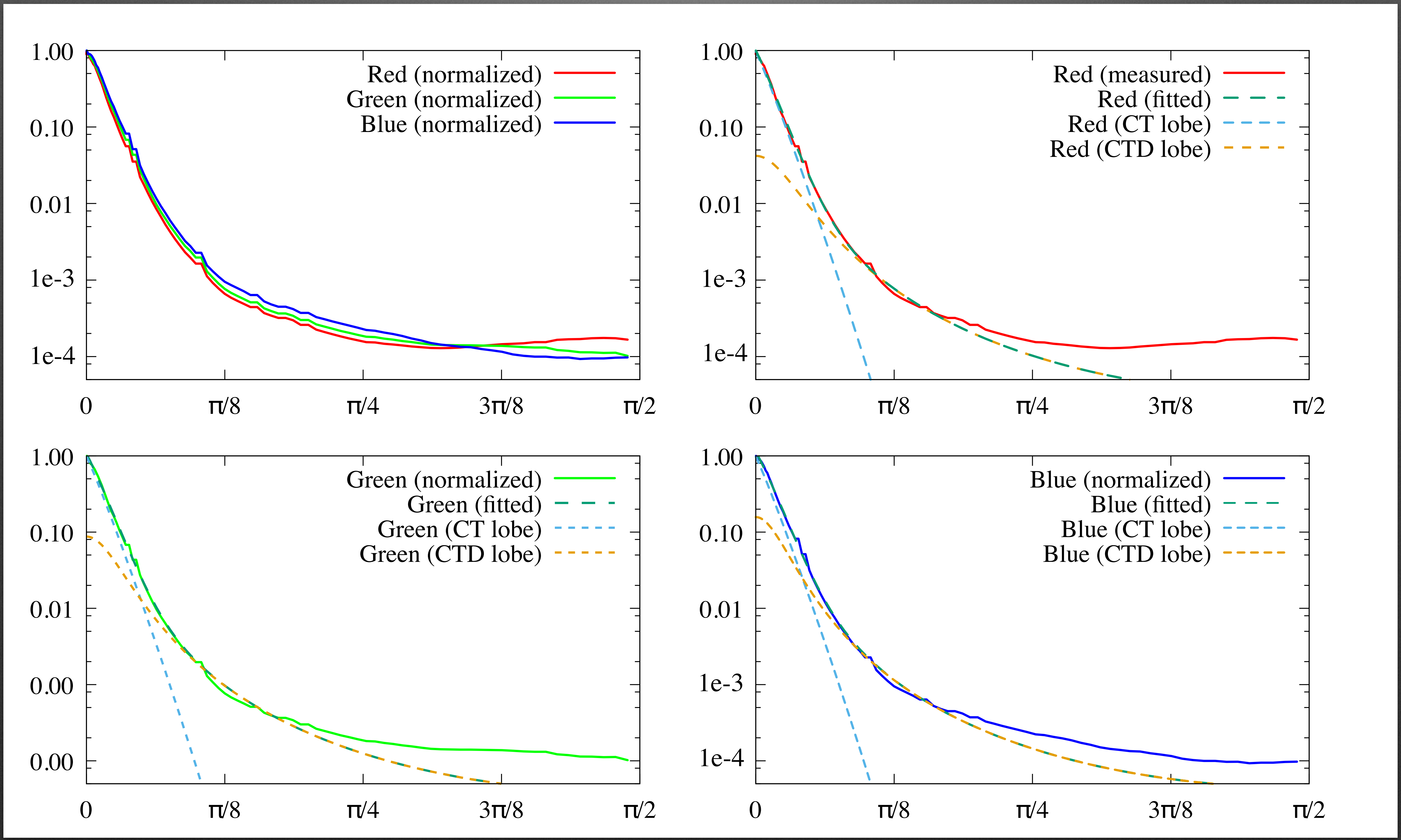


Löw et al. (diffraction only)



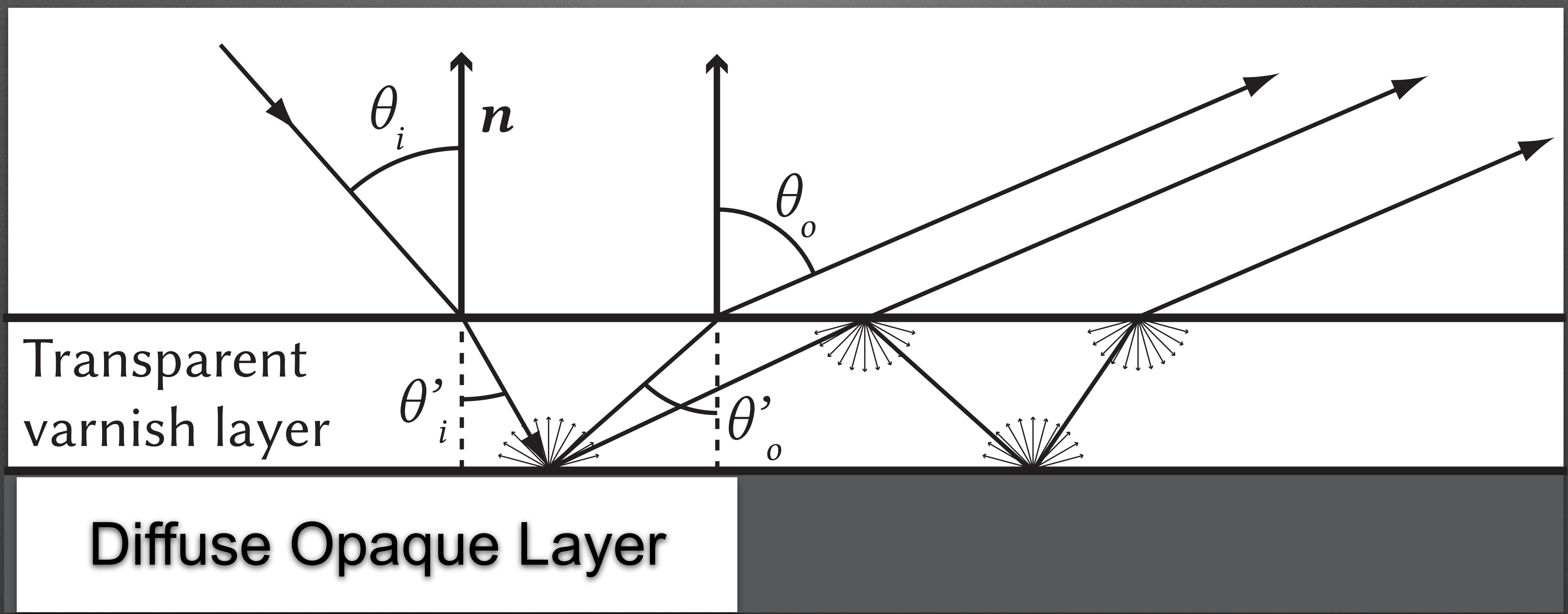
SGD (microfacet only)

Lobe width variation



Extension for Plastic Material

$$\rho_{plastic}(\mathbf{i}, \mathbf{o}) = \rho_{conductor}(\mathbf{i}, \mathbf{o}) + \rho_{diffuse}(\mathbf{i}, \mathbf{o})$$



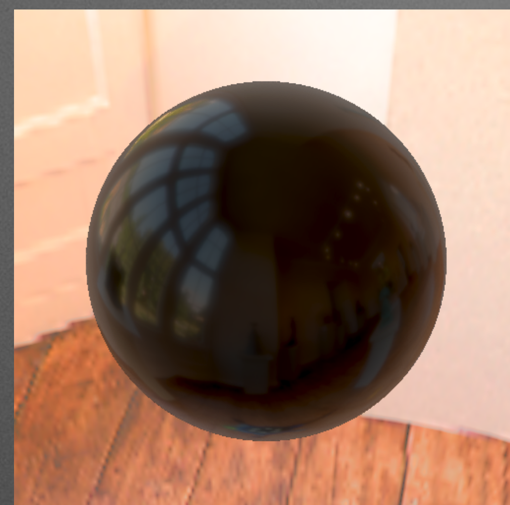
- Diffuse Part: Model from [Weidlich et Wilkie 2007]
- Conductor Part: Real Index of Refraction

Results for Plastic Model

- Varnish on a diffuse surface:

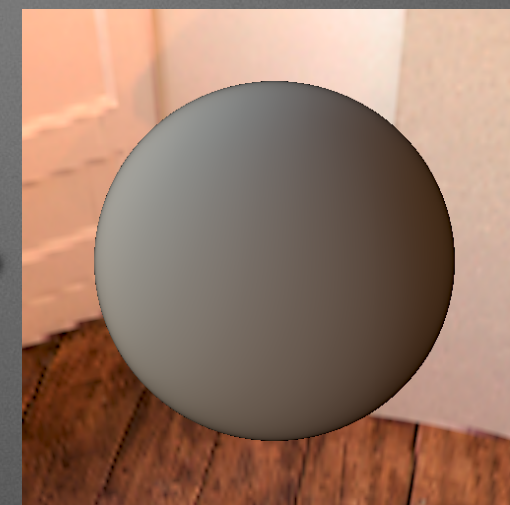
Diffraction

+



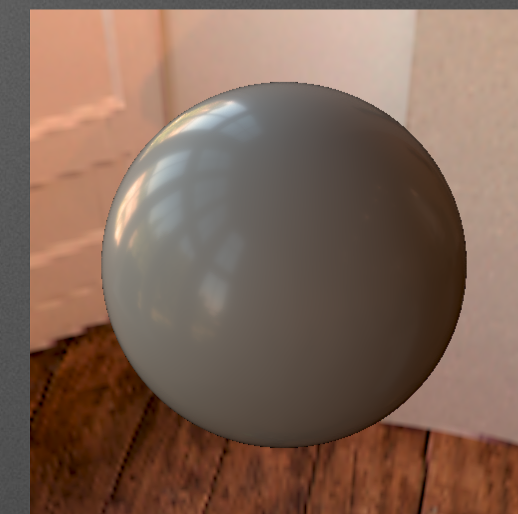
Microfacet

+



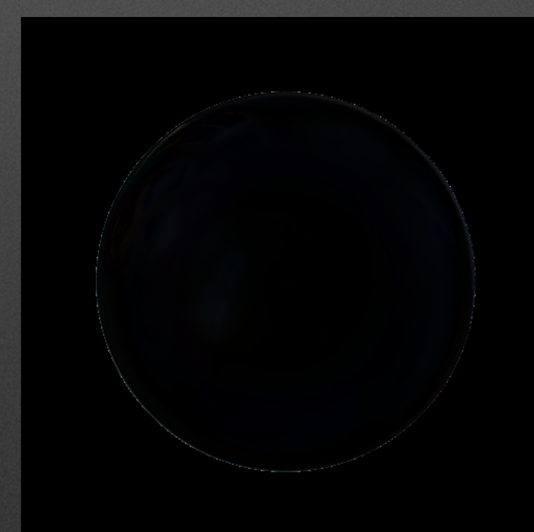
Diffuse

=

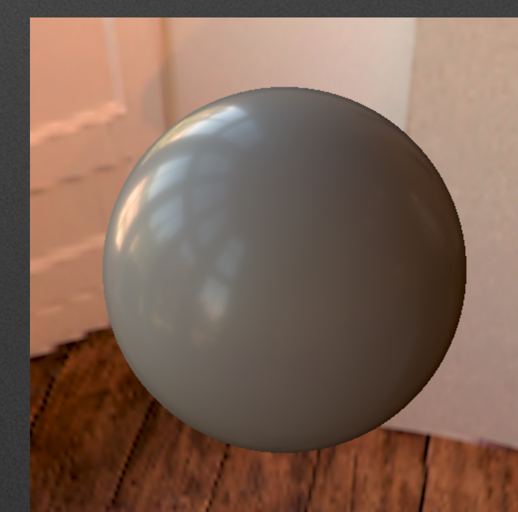


Model

Gray-Plastic Material

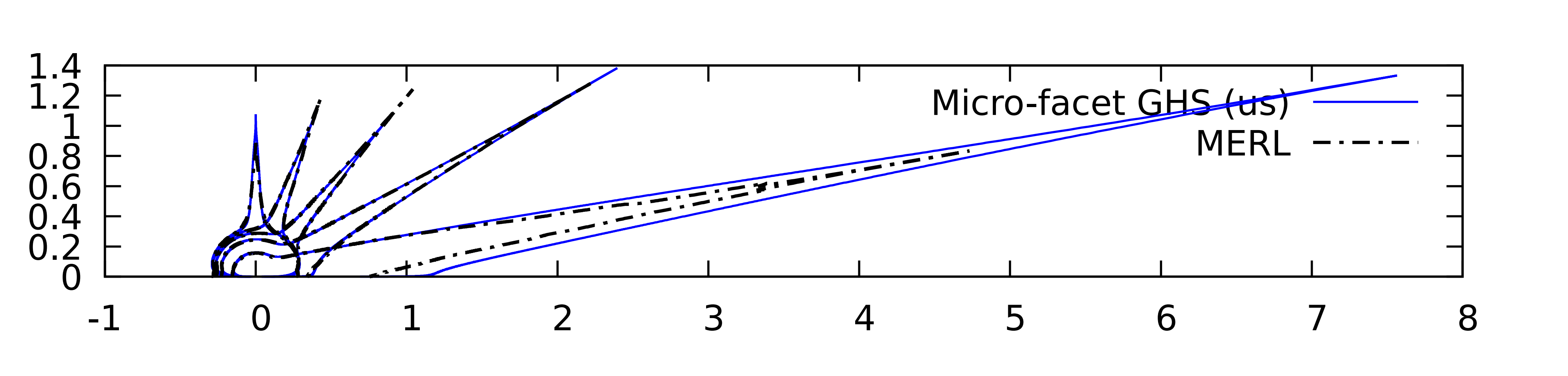


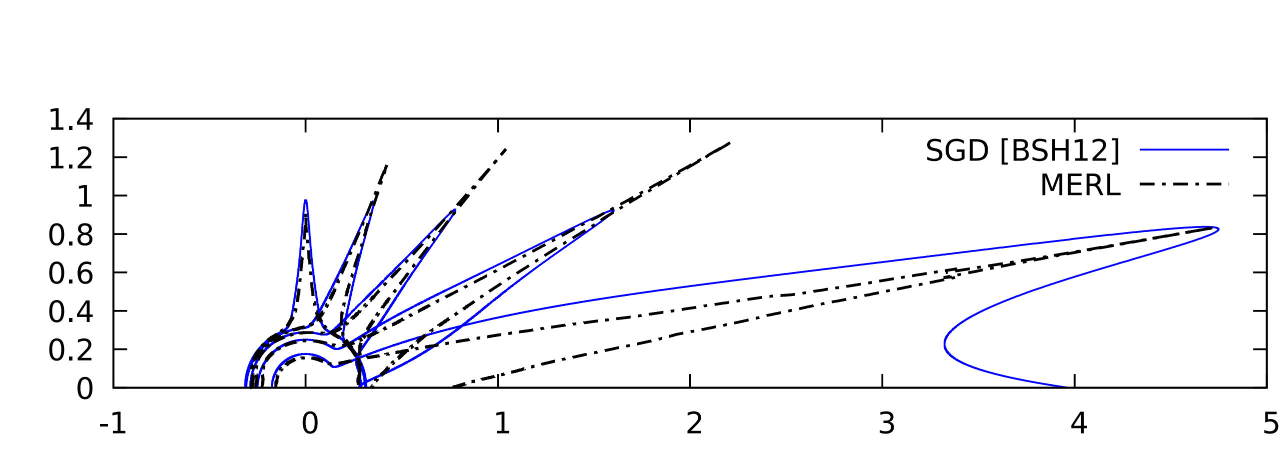
Difference

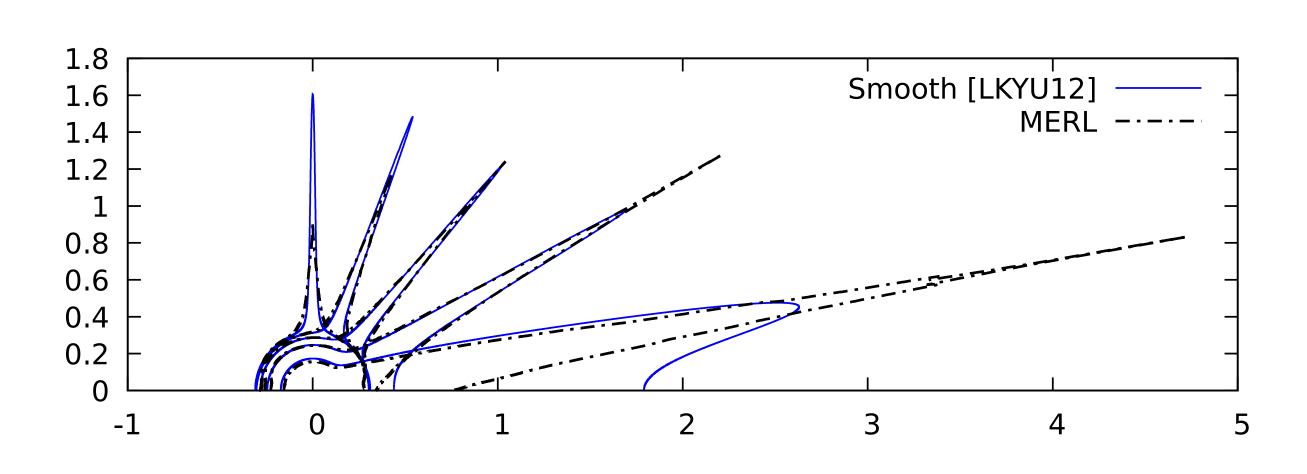


Reference

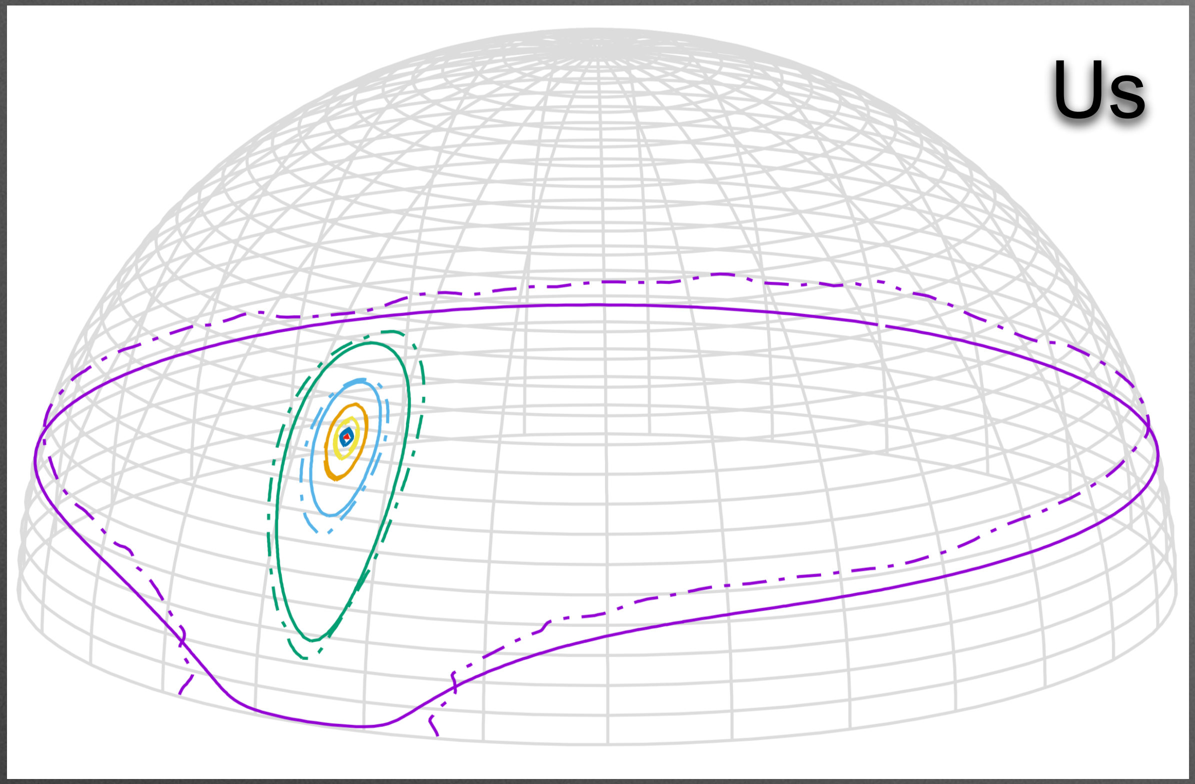
Fitting Results in Incident Plane



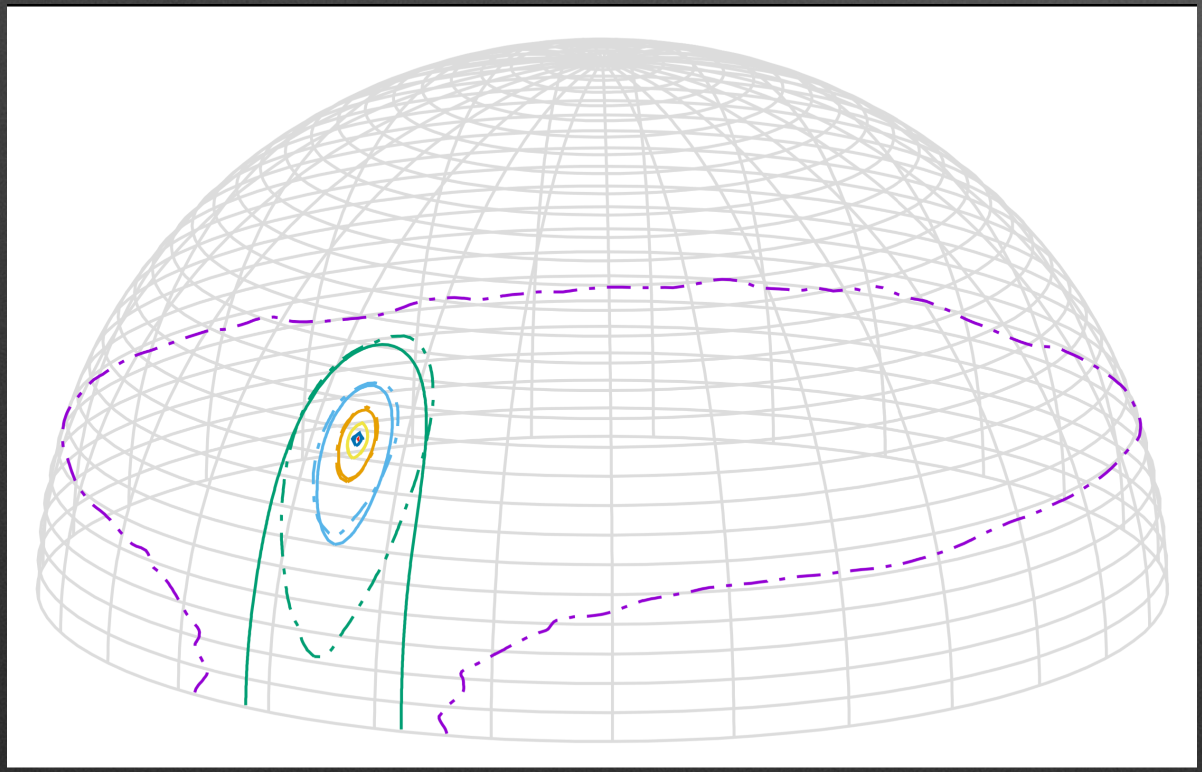




Fitting Results outside Incident Plane

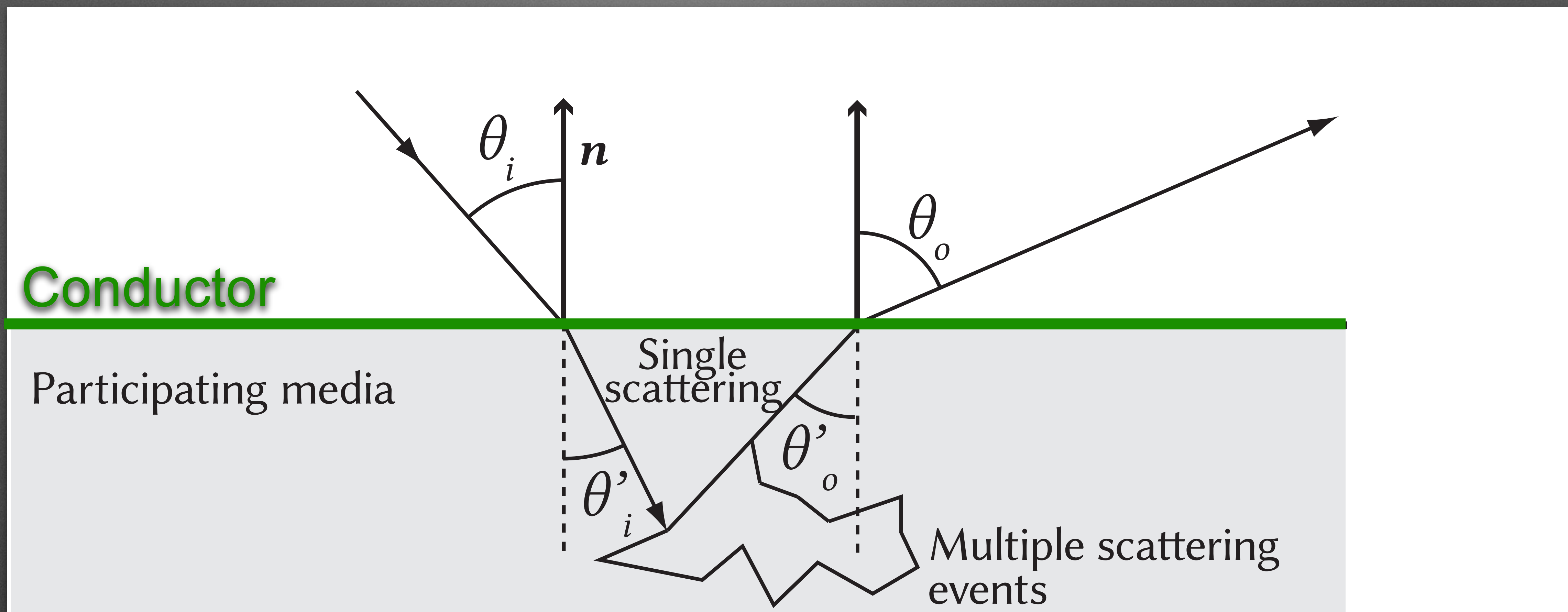


Our Model



Löw et al. (diffraction only)

Two-Layer Model for Subsurface



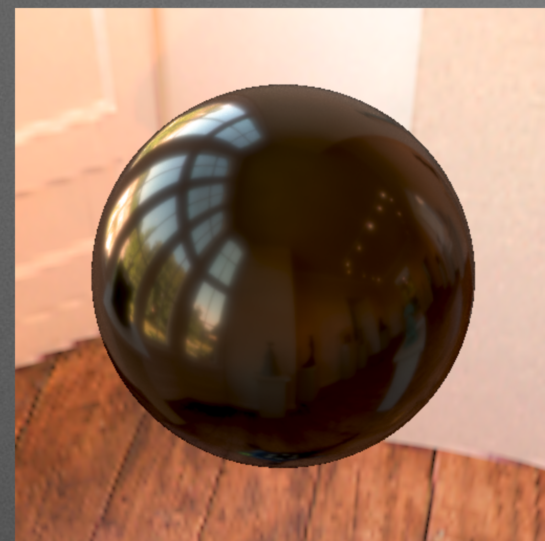
$$\rho_{subsurface}(i,o) = \rho_{conductor}(i,o) + \underbrace{\rho_{single}(i,o) + \rho_{multi}(i,o)}$$

Subsurface Model from Jensen et al. Sigg. 2001

Result for Subsurface Model

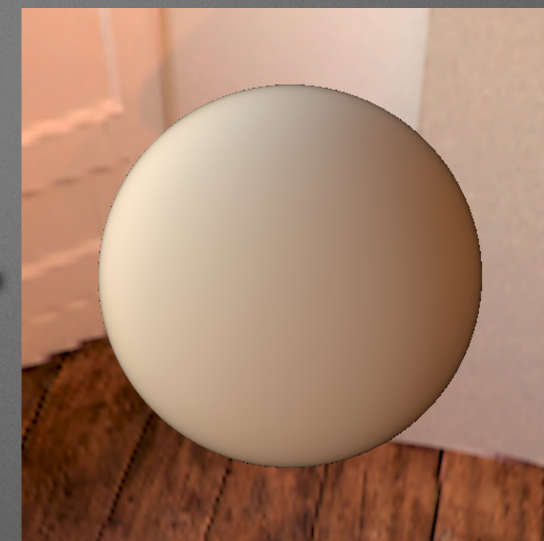
Diffraction

+



Microfacet

+

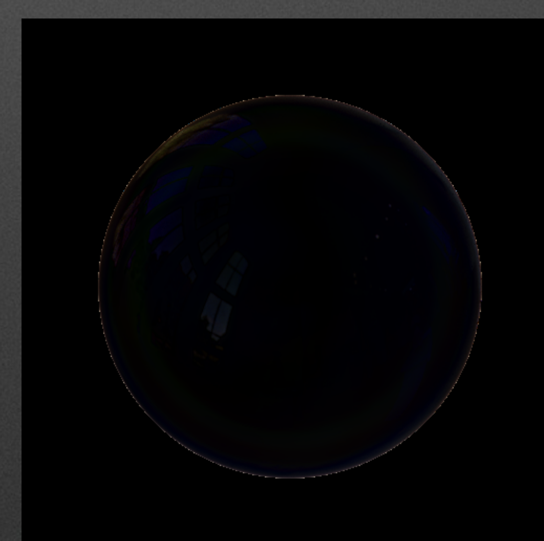


Diffuse

=

Model

Alumina-oxide Material

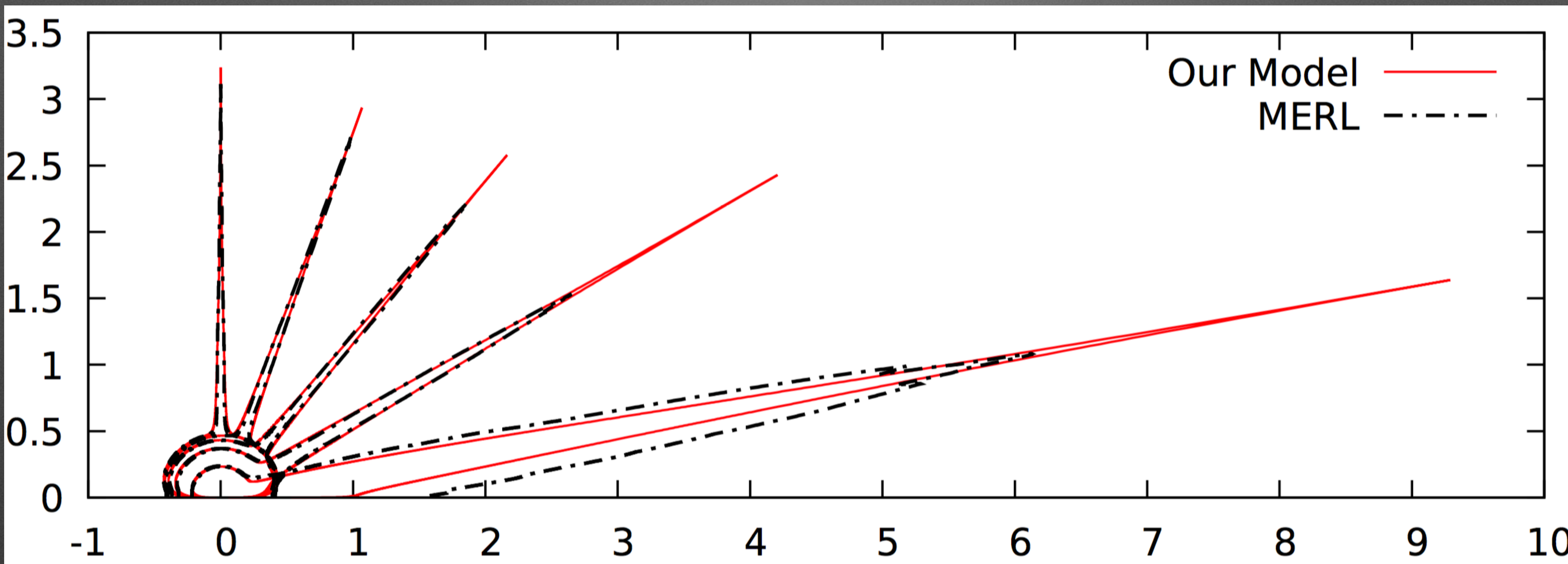


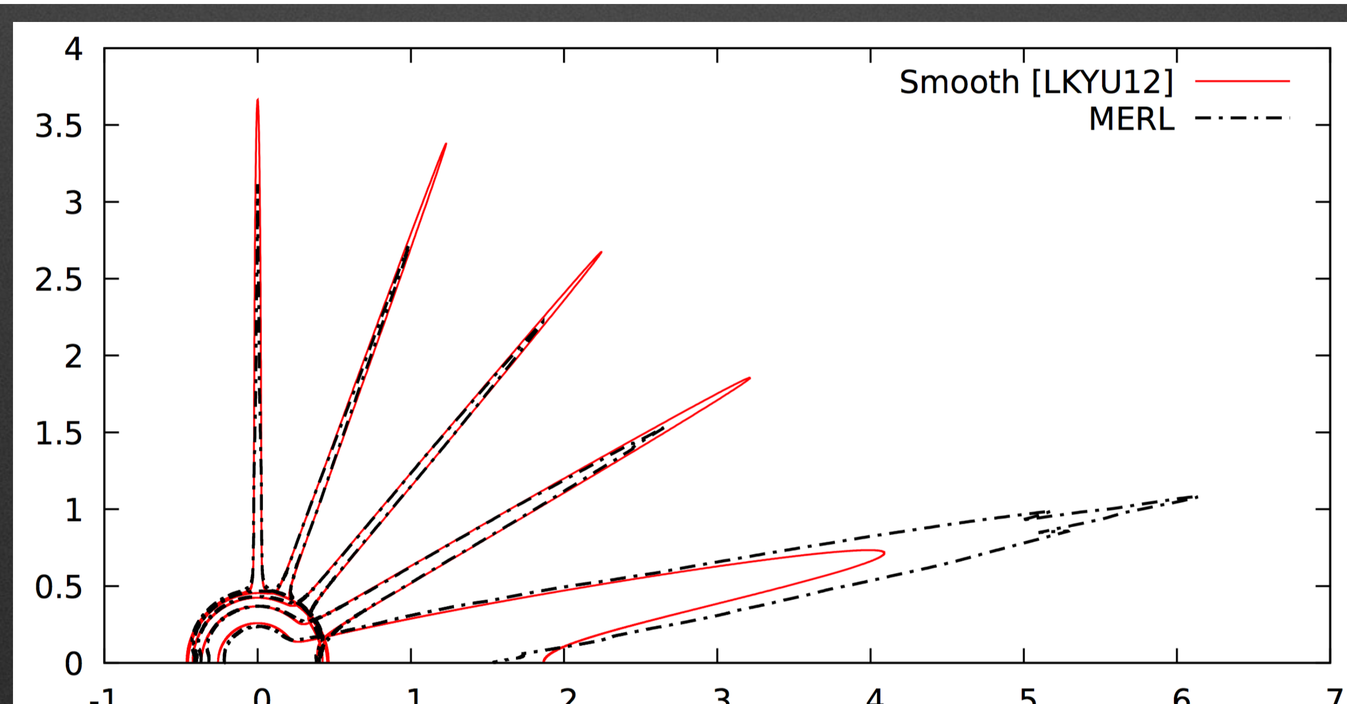
Difference

Reference

Result for Subsurface Model

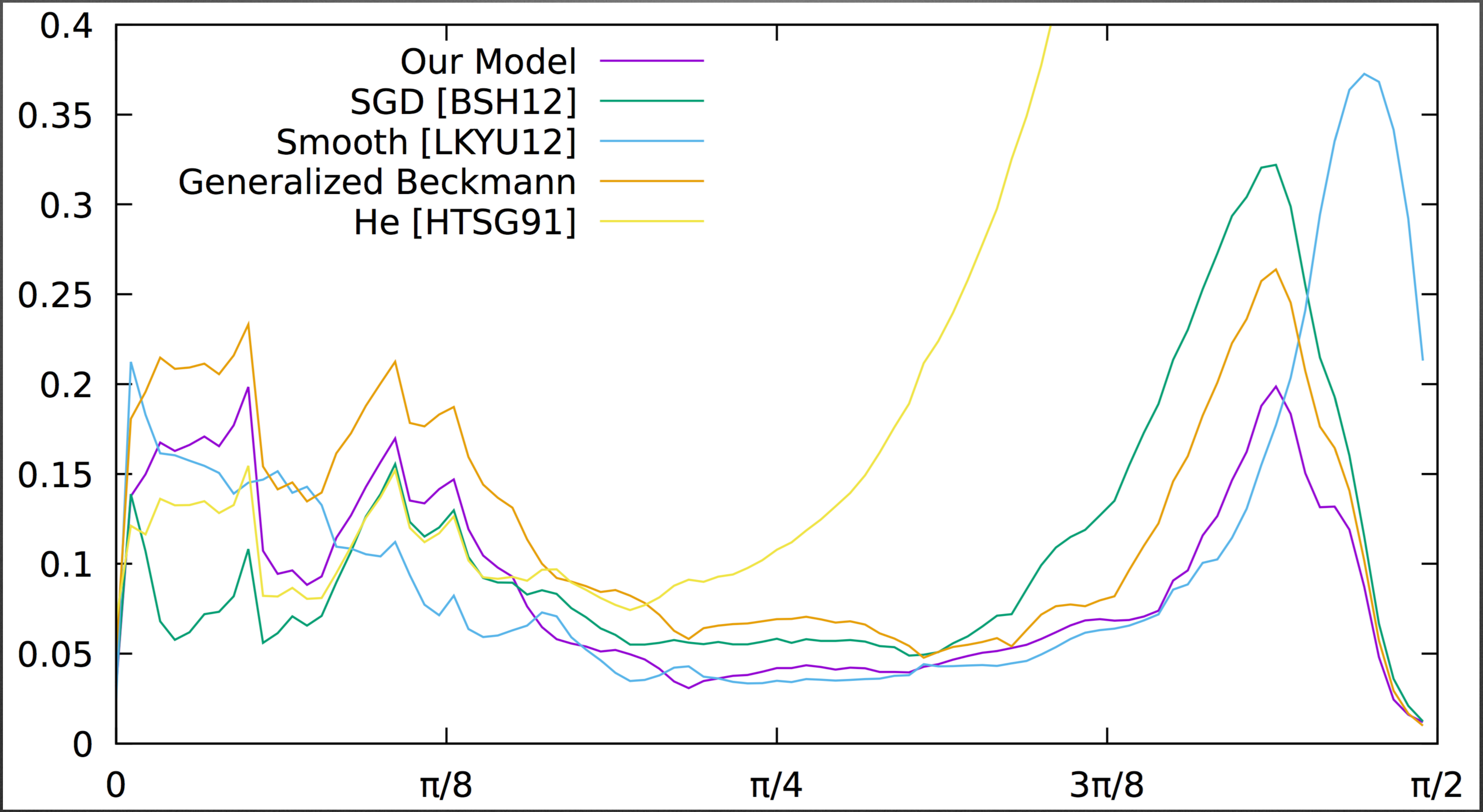
ALUMINA-OXYDE





Result for Subsurface Model

ALUMINA-OXYDE

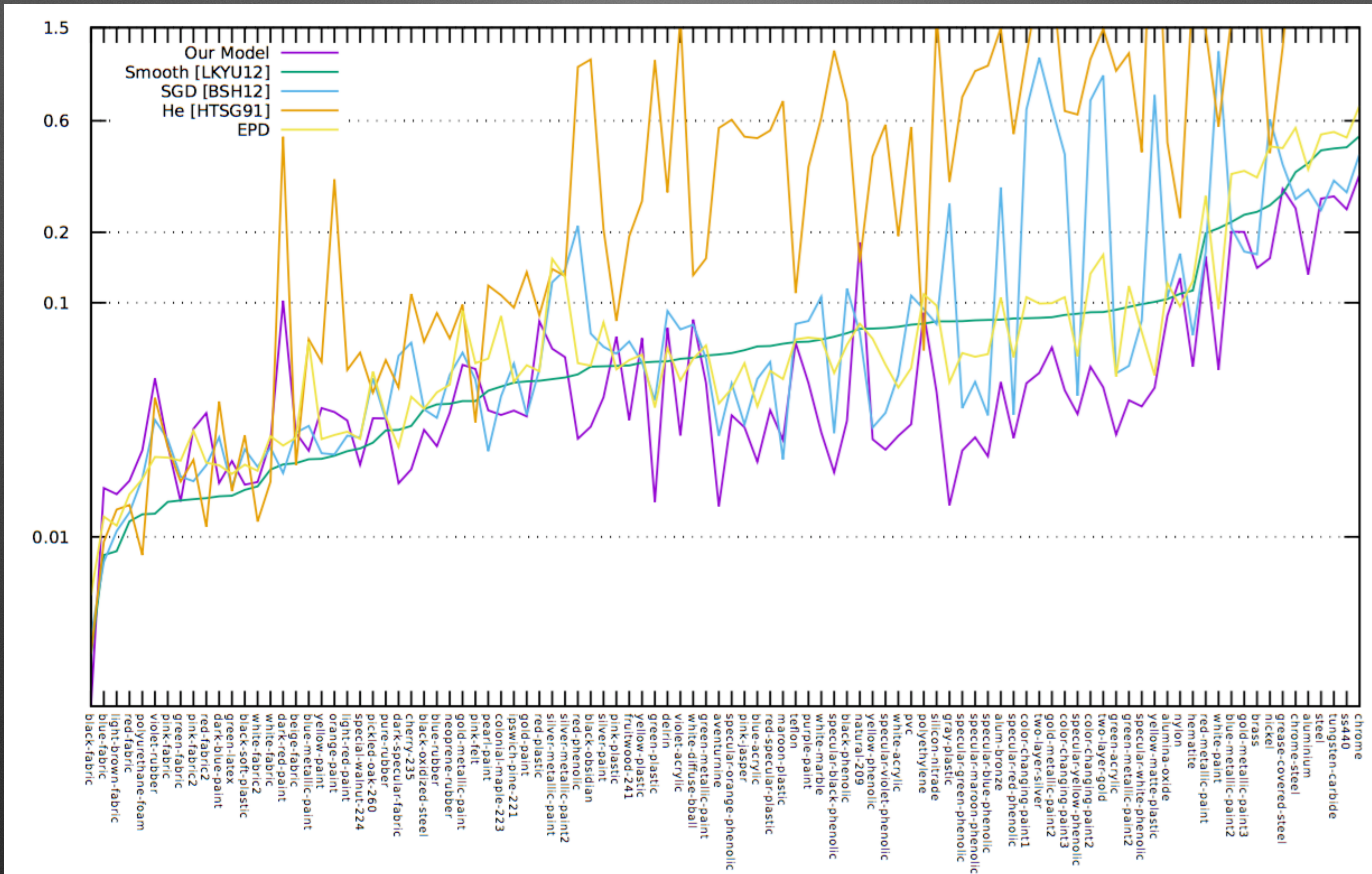


RMS Error of BRDF * cosine

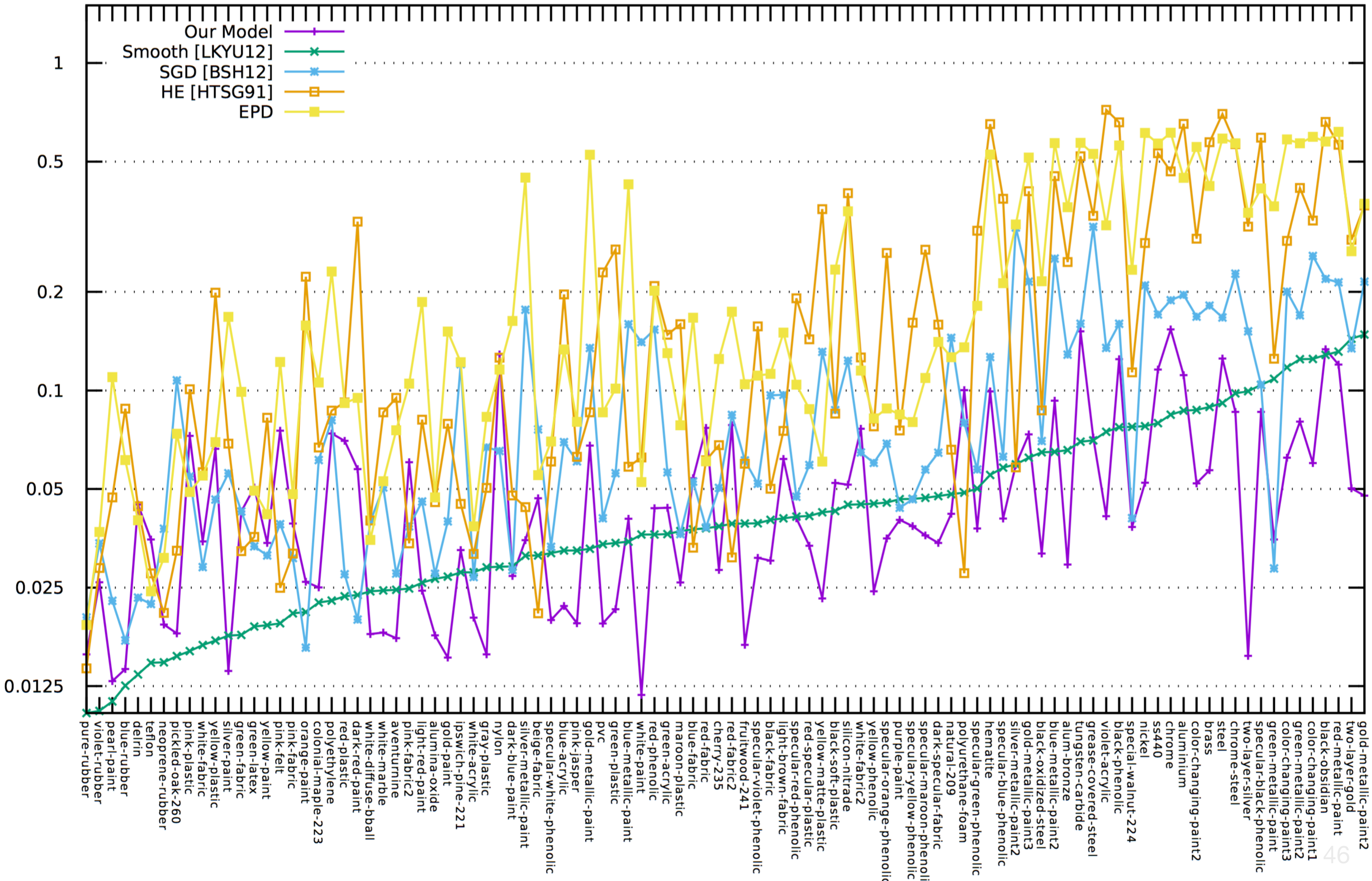
Fitting Strategy

- Similar to Bagher et al. 2016
  - Compressive Weights ⇔ less weight on high values
  - Measurement Apparatus Compensation
- One Pass of all parameters
- Approx. 10 minutes on 2.6 GHz Intel i7
  - C++. Levenberg-Marquardt impl. Lourakis

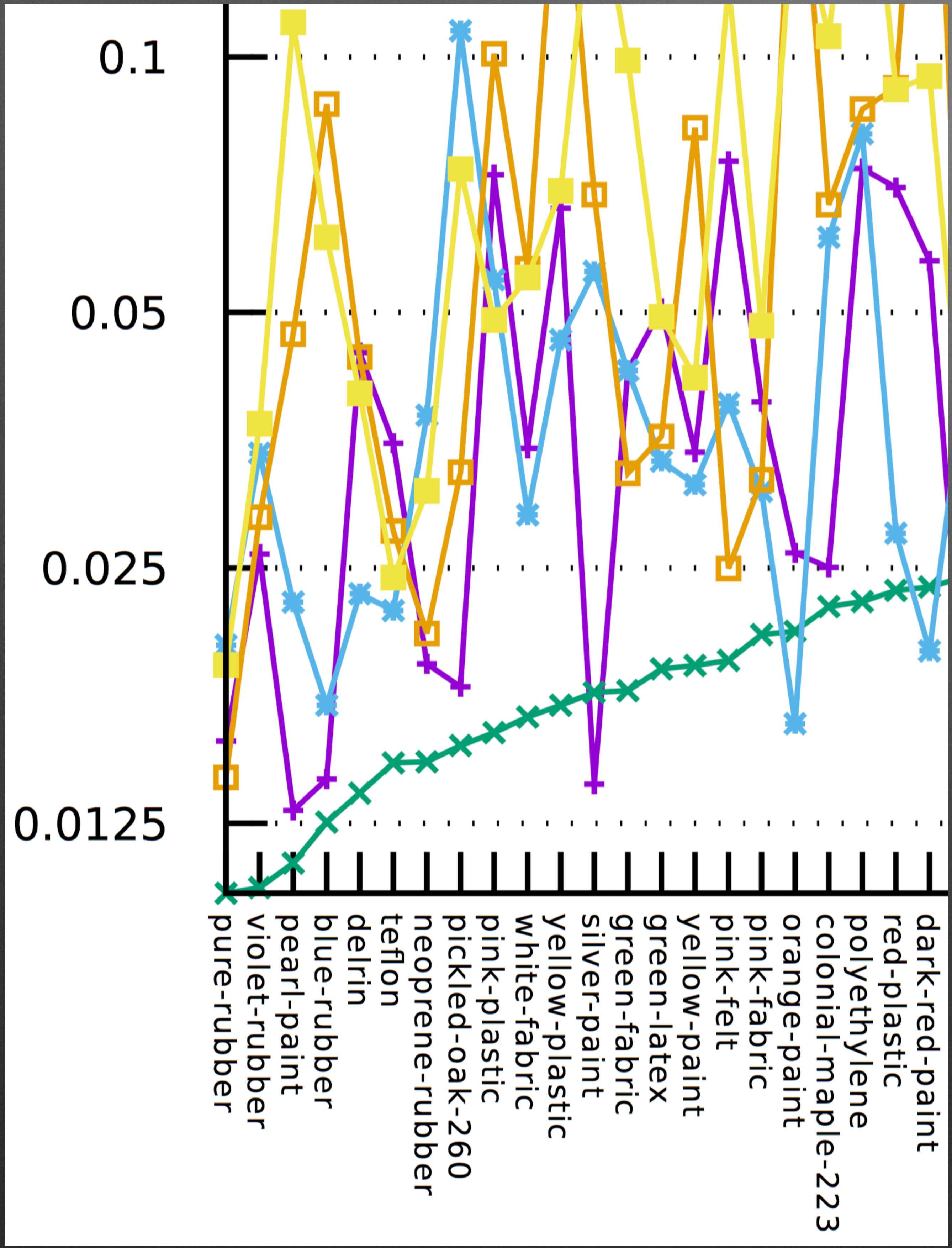
General Fitting Comparisons



Rendering Comparions : SMAPE Metric



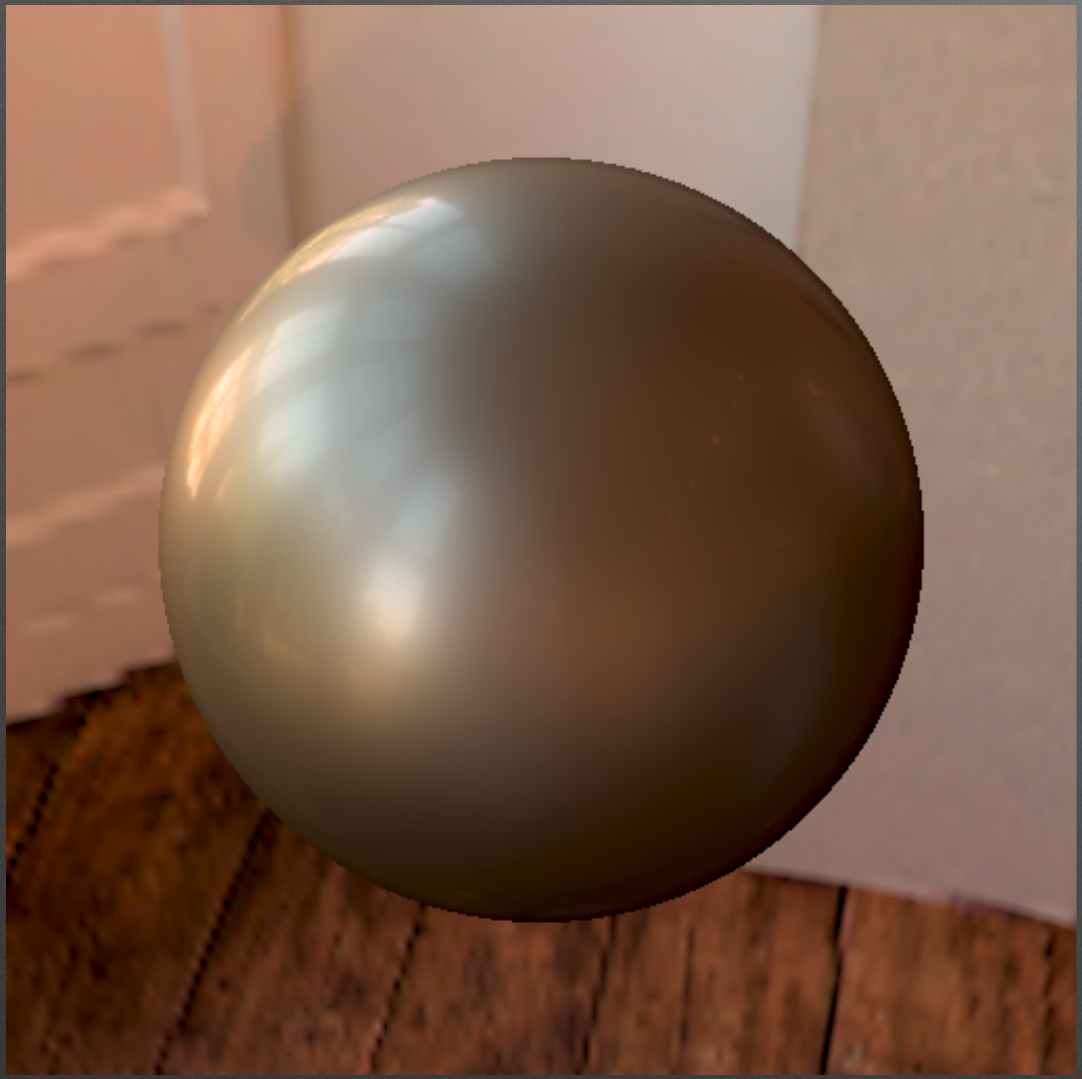
Rendering Comparions : SMAPE Metric



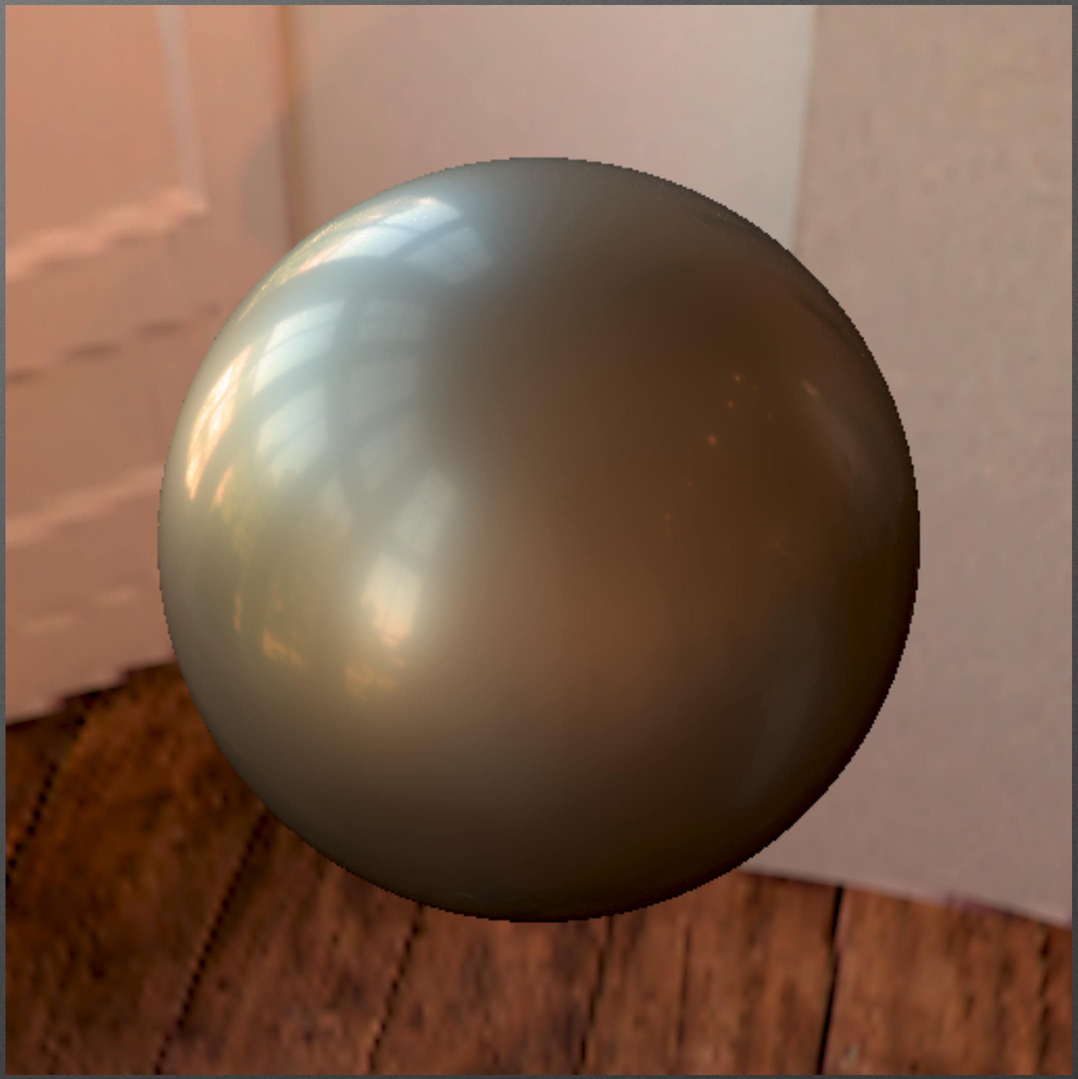
Bad Fits:

- Pink Plastic
- Pink Felt

Gold-Metallic Paint 2

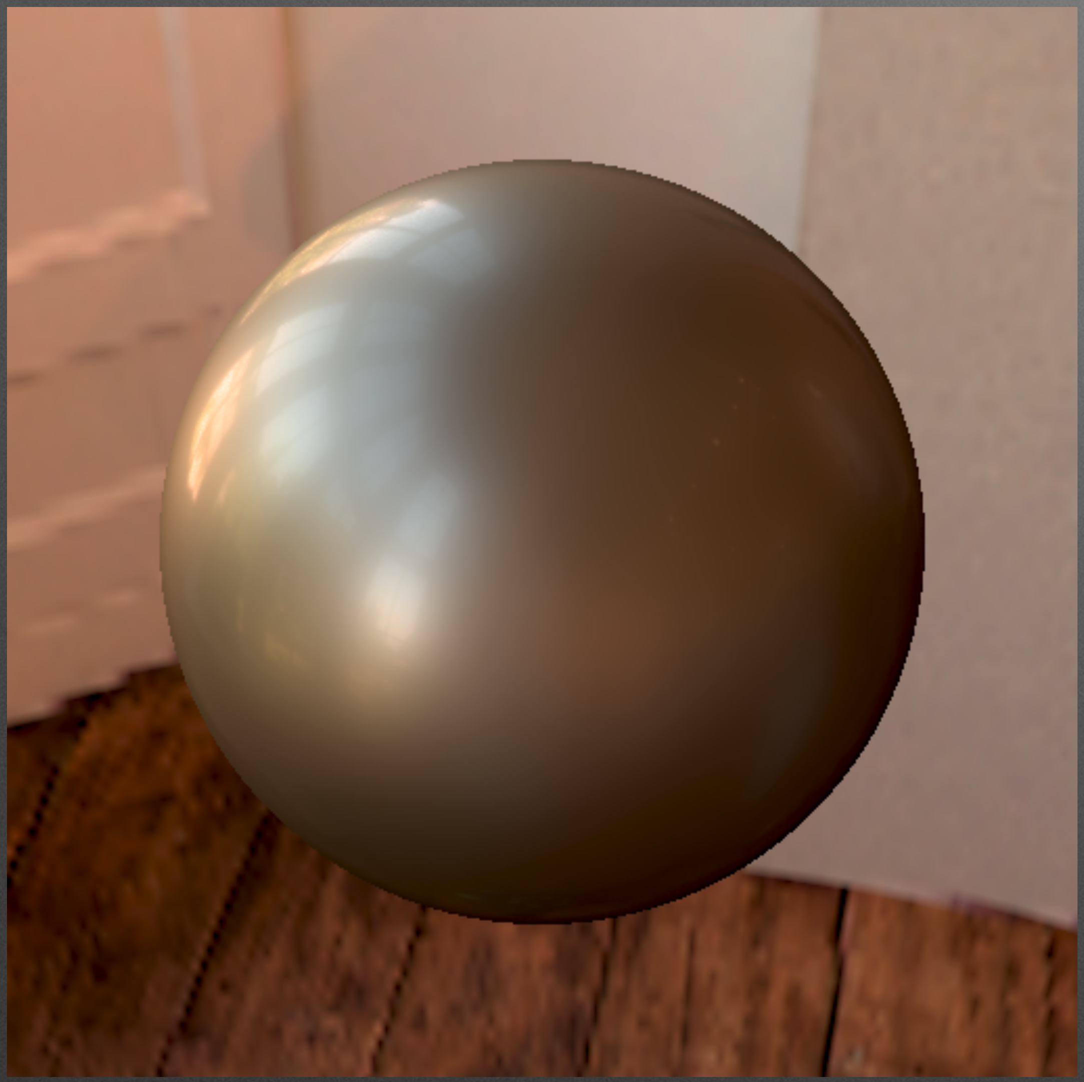


Merl Data Reference

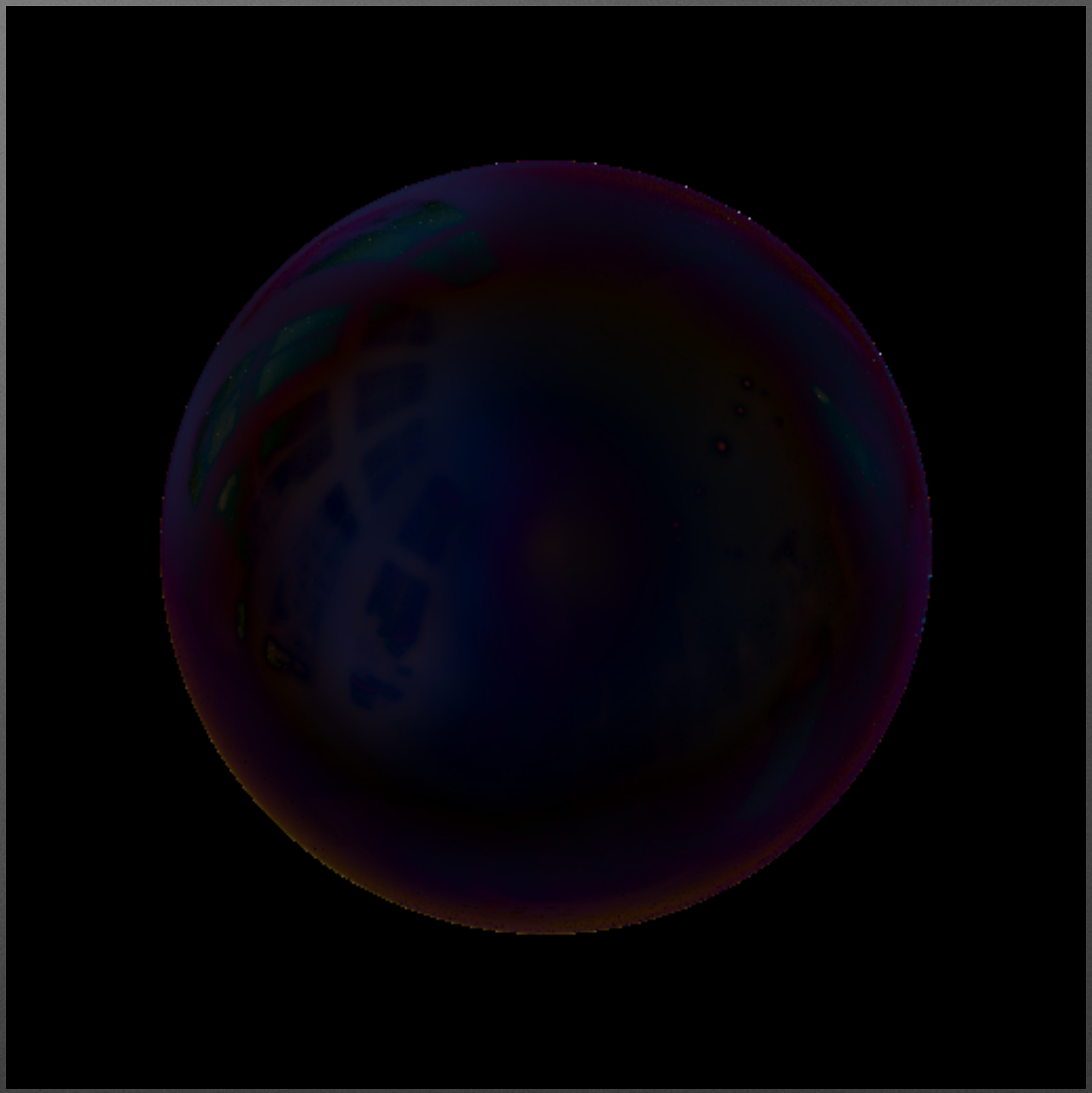


Our Model

Gold-Metallic Paint 2

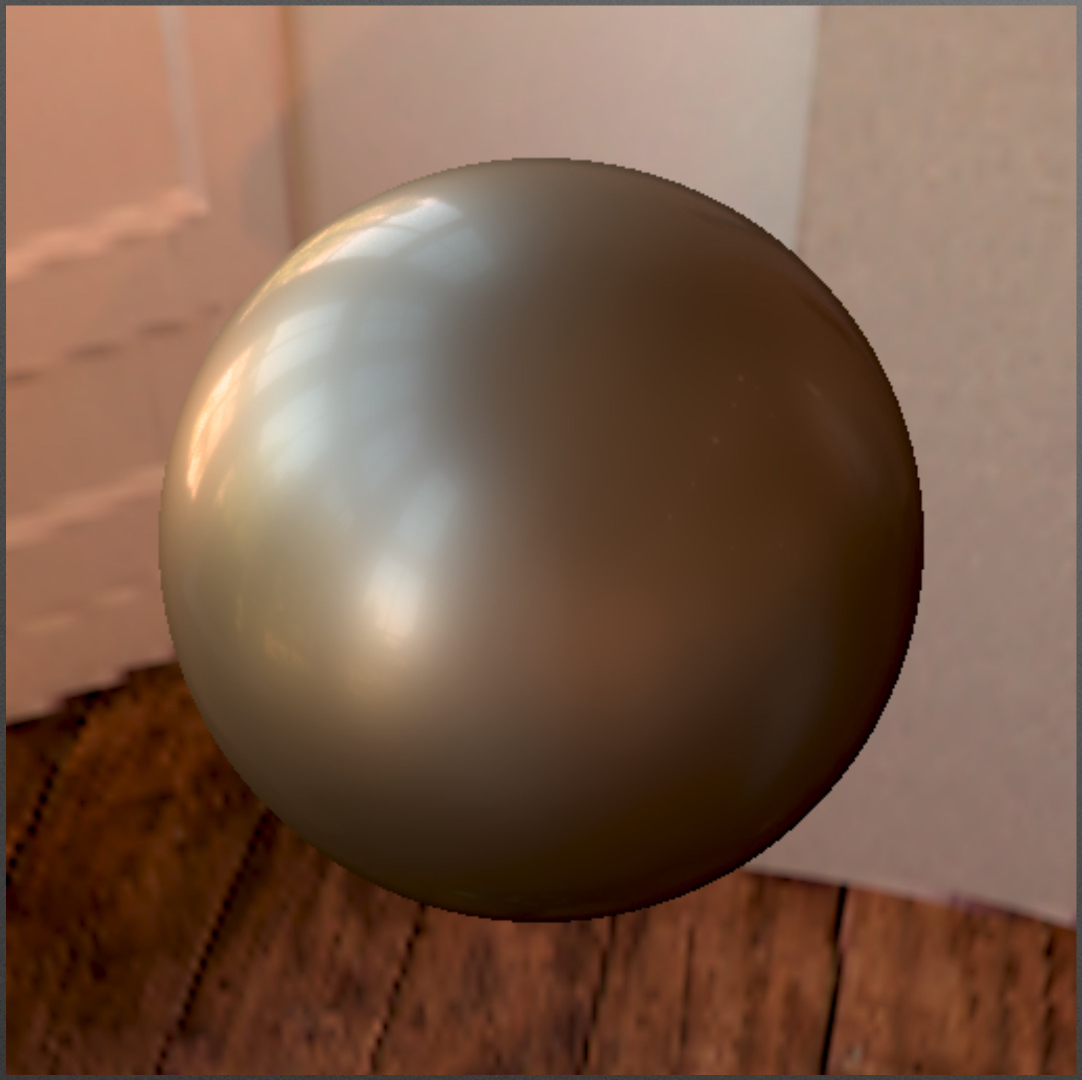


Merl Data Reference

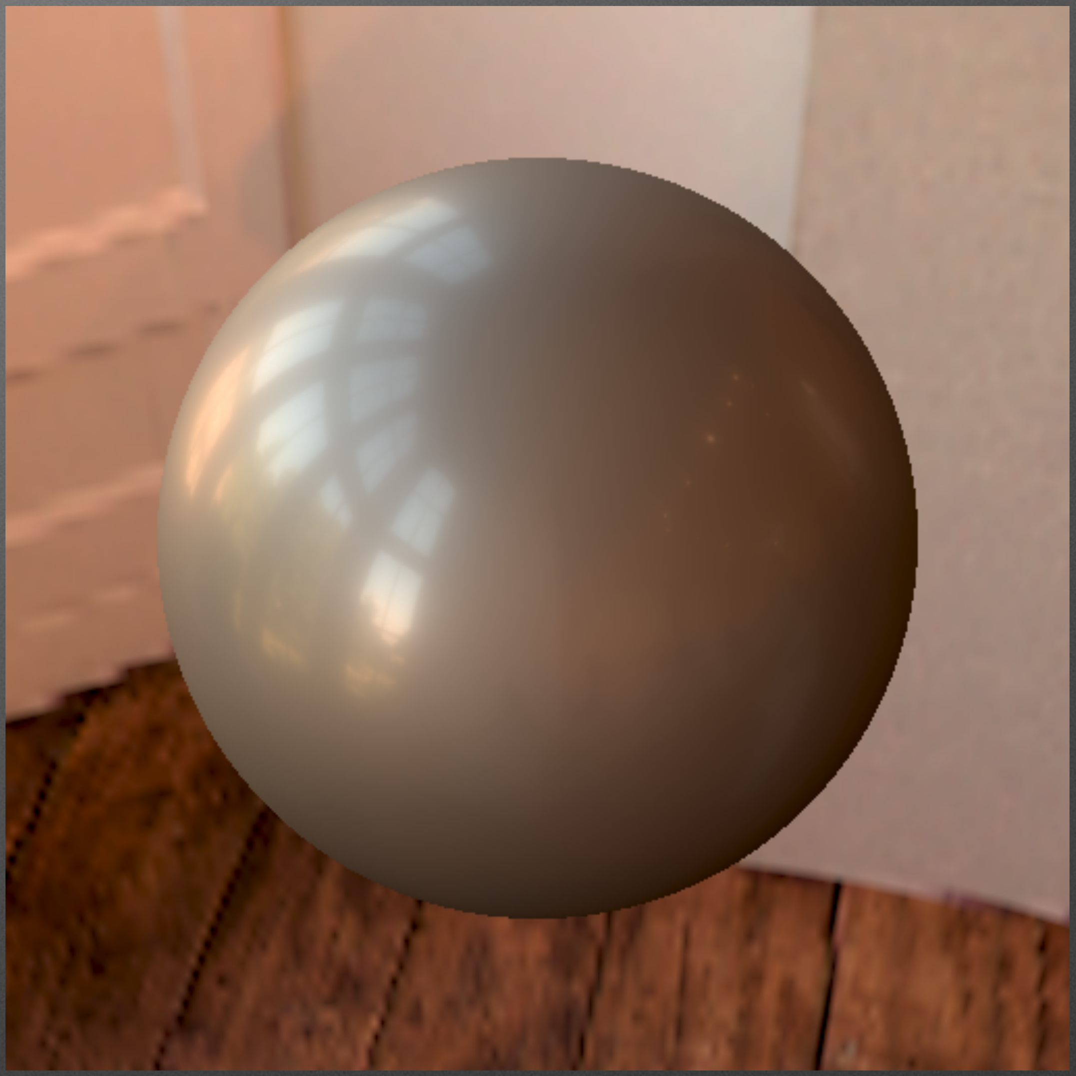


Our Model
Difference sMAPE:0.048

Gold Metallic Paint2

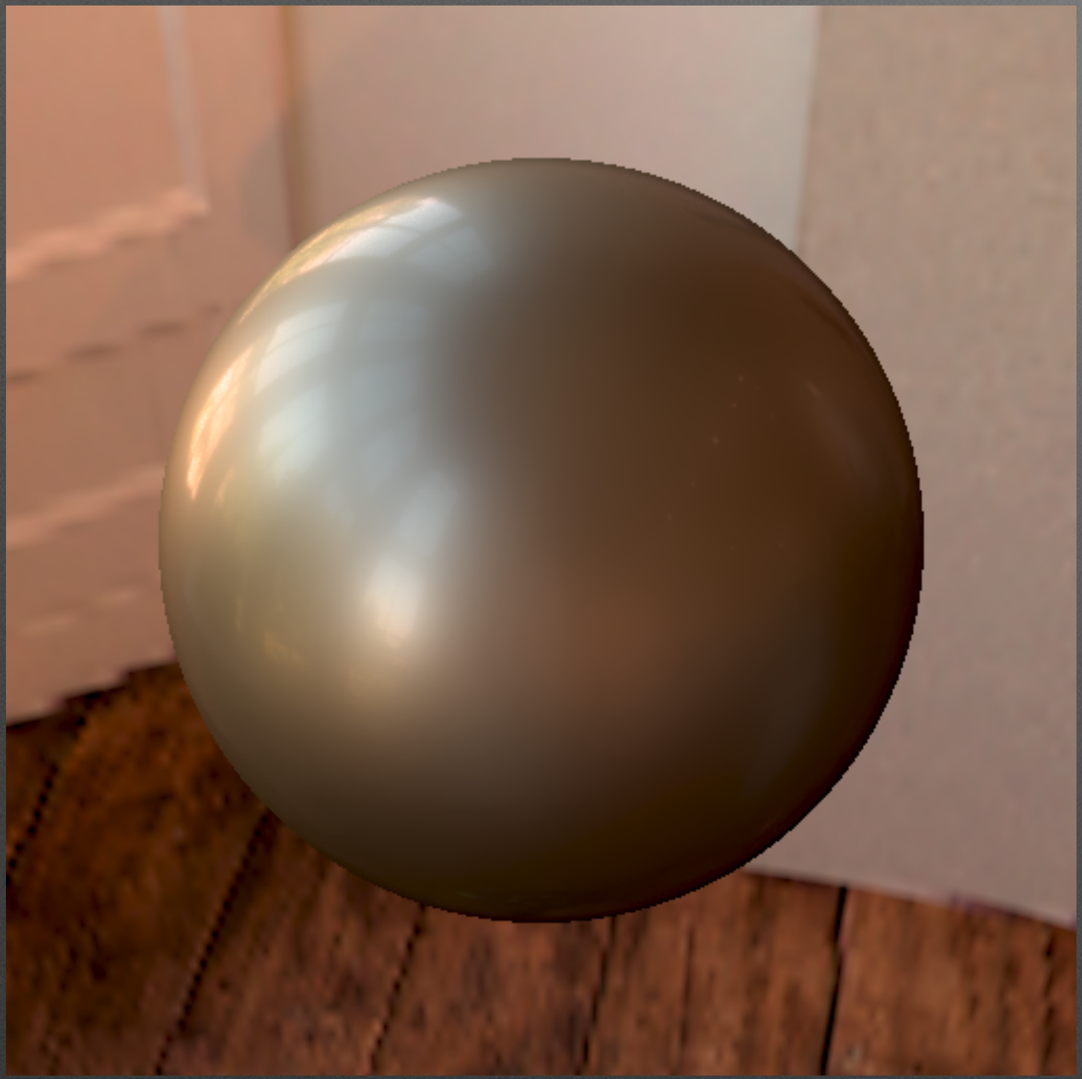


Merl Data Reference

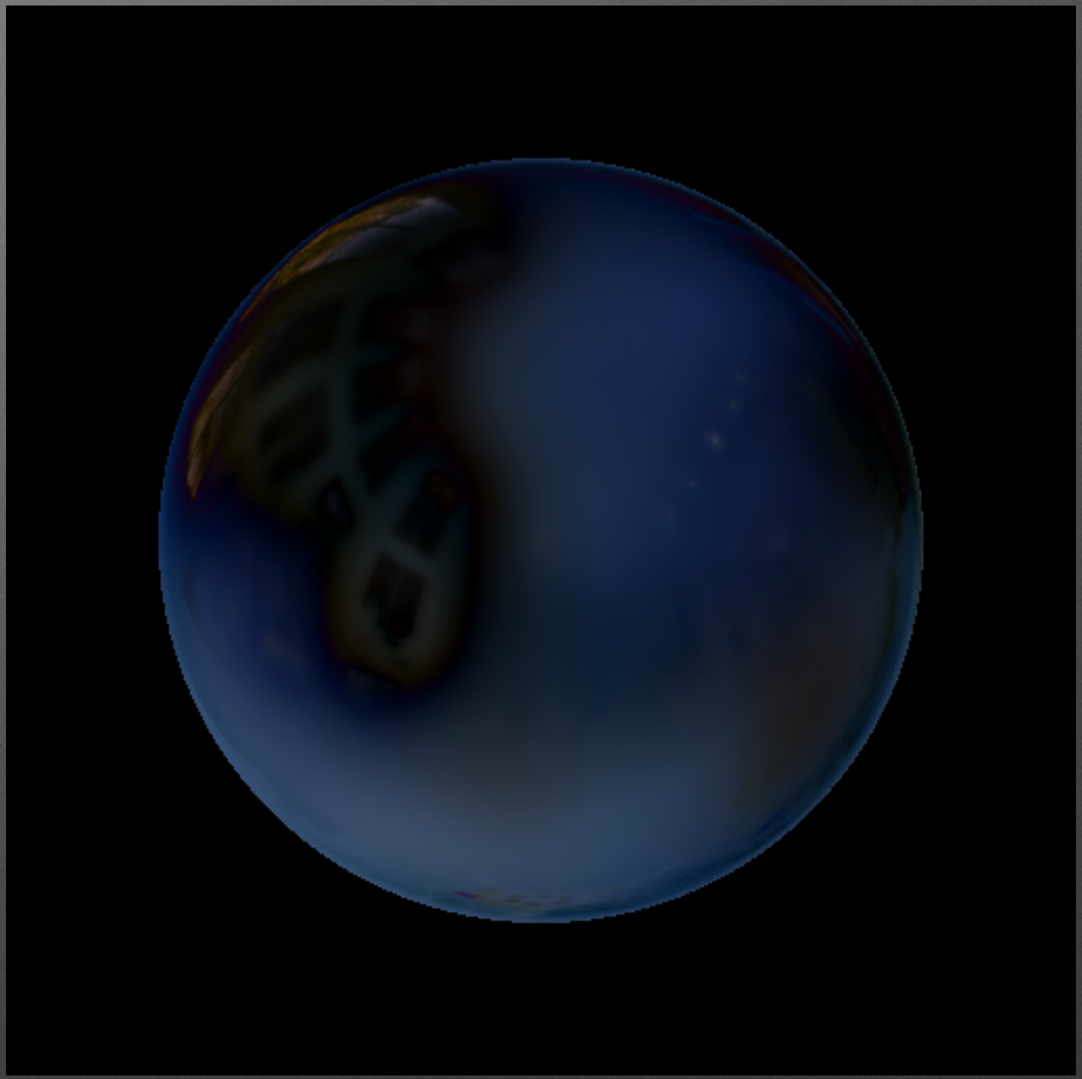


Löw Model

Gold Metallic Paint2

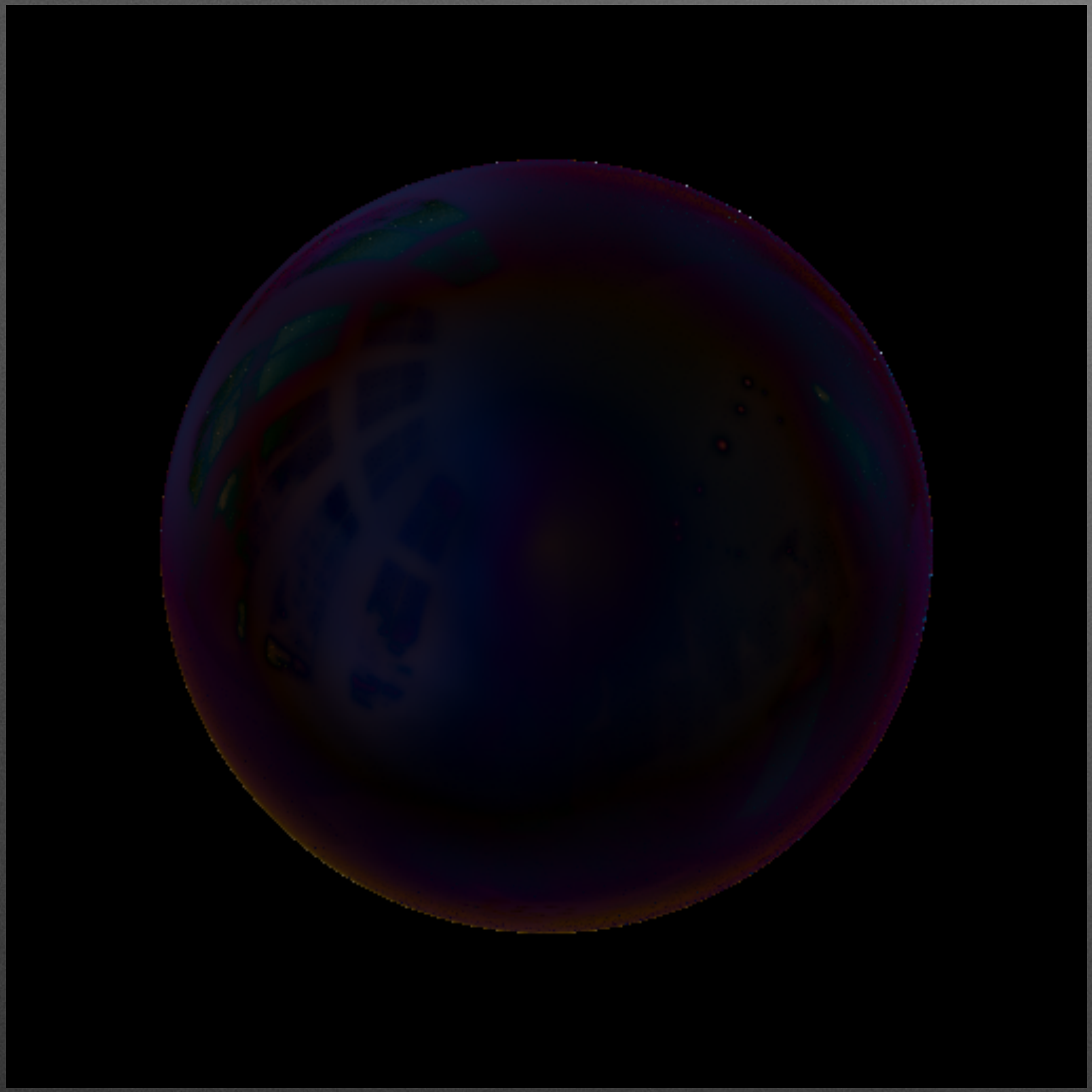


Merl Data Reference

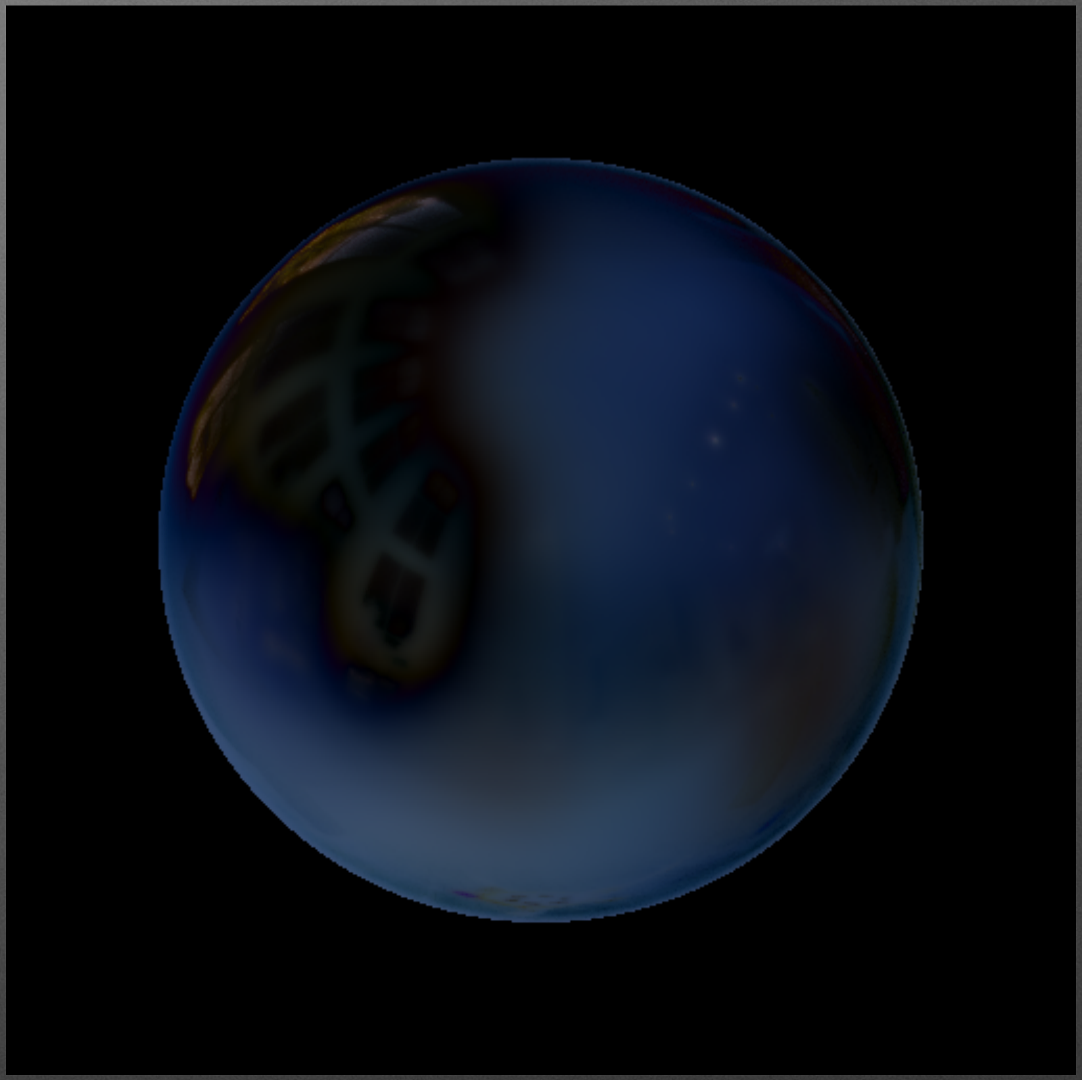


Löw Model
Diff. sMAPE: 0.148

Gold Metallic Paint2



Our Model
Difference sMAPE:0.048

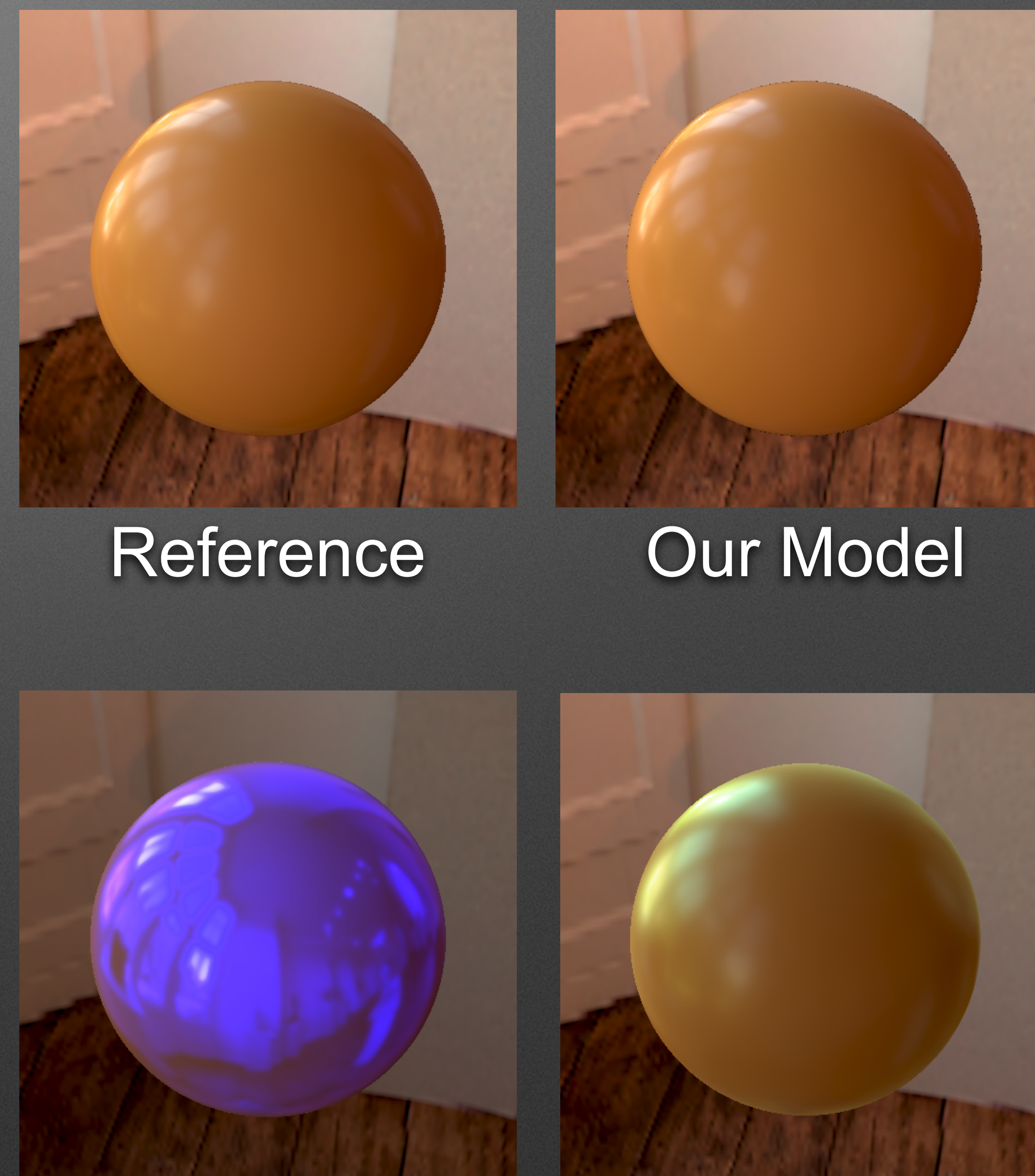


Löw Model
Diff. sMAPE: 0.148

Regarding He et al. Model

- Based on Beckman-Kirchoff Diffraction
  - Our implementation and fitting
- Overall POOR Results
  - Better:
    - Fitting: 3 materials
    - Rendering: 4 materials
- Different from Ngan et al. results

Yellow Mate Plastic



Reference | Our Model | He et al. | SGD

Number of parameters

MODEL	NUMBER OF PARAMETERS	DIFFRACTION THEORY
Our Model	11	Hybrid Harvey-Shack
Exponential Distribution and Lambert	11	None
Shifted Gamma Distribution	18	None
He et al. Model	11	Beckman - Kirchoff
Löw et al. Smooth	9	Inspired from Rayleigh-Rice

Conclusion

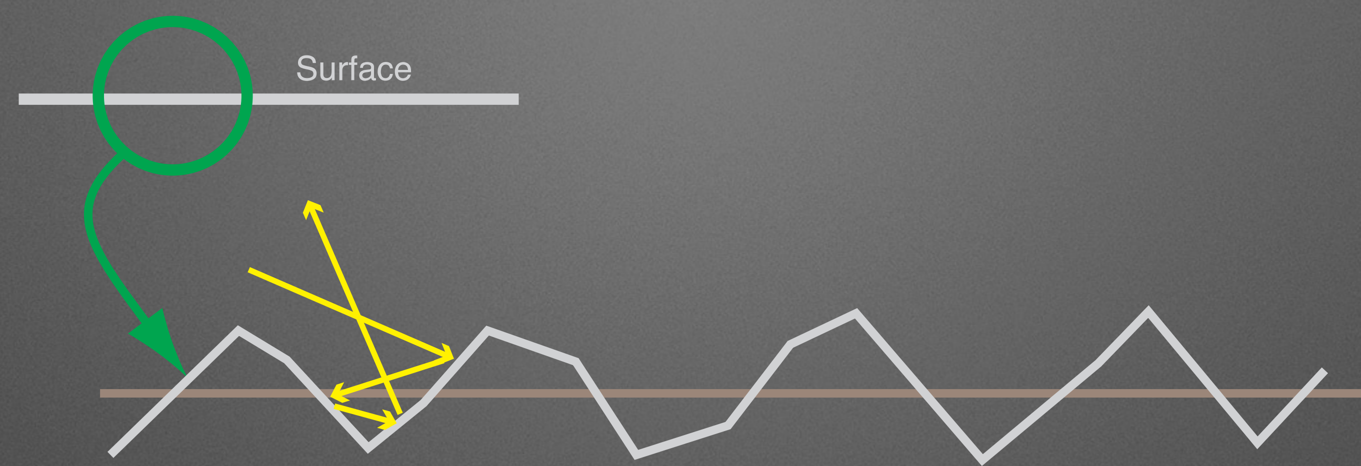
Our two-scale model:

- Better explanation of Measured Data
  - Lobe Size/Width depends on Wavelength
- Micro-facet Theory: Specular Peak

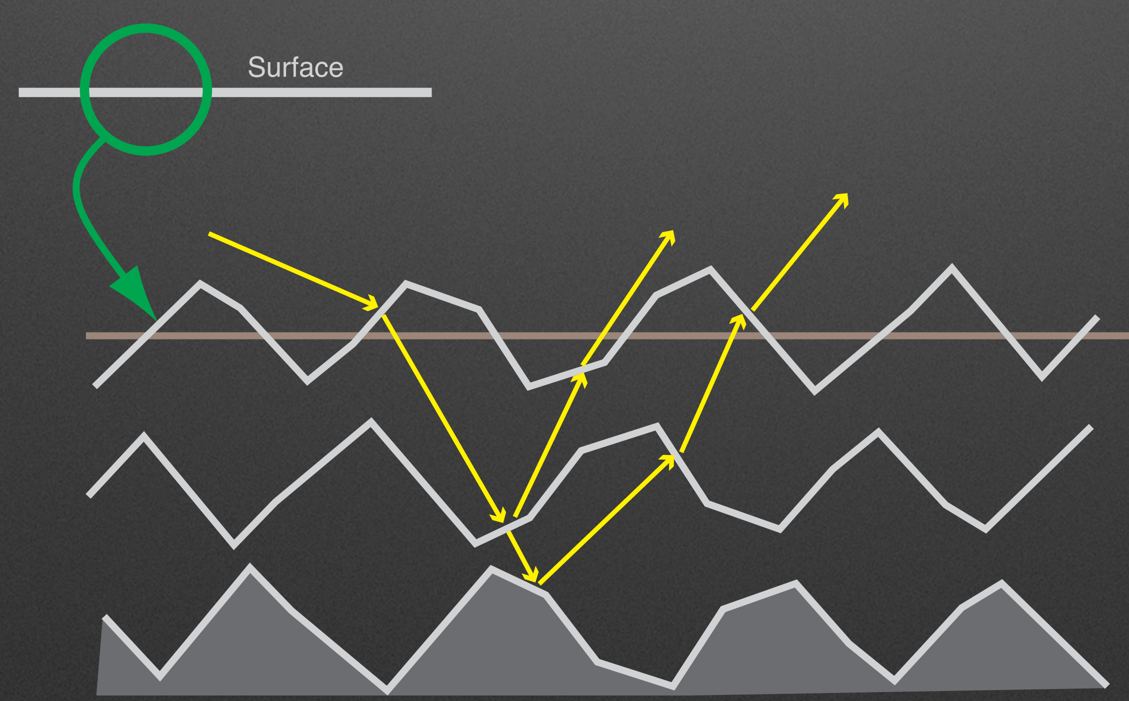
- Limitations:
  - No multi-bounces
  - One Layer of Diffraction

Future Work

- Multiple Scattering and Diffraction



- Multi-Layers and Diffraction



+ polarisation ?

Future Work

- Using Diffraction as shading “enhancer”
    - Virtual transformation of a non-metallic surface
- Anisotropic Version of the Model
- A unified Representation
    - PSD for Nano-facet, Normal Distribution for Micro-facet
- Further Validation with precise Measurements:
    - Surface height-field
    - Wavelength BRDF

Future Work

- Further Validation with precise Measurements:
  - Surface height-field
  - Wavelength BRDF

Thank you
for your attention

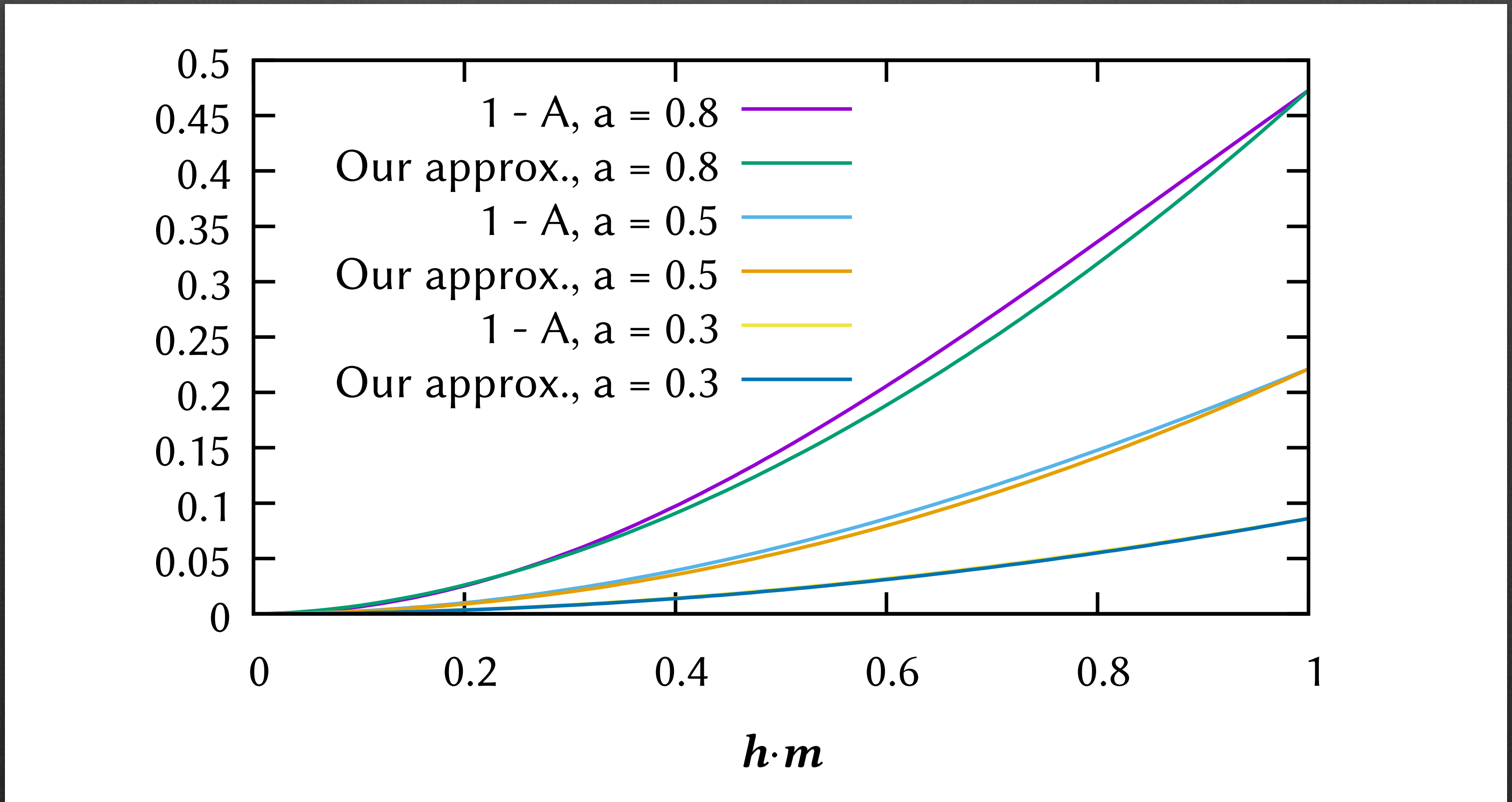
More on Microfacet convolution

$$\rho_{ghs}(i,o) = \int_{\Omega_m} Fr(i,o)\,(1 - A_{\sigma_s}(i,o))\, K_{\sigma_s}(f) G(i,o) D(m)\, d\omega_m$$

- Second: Geometrical Term

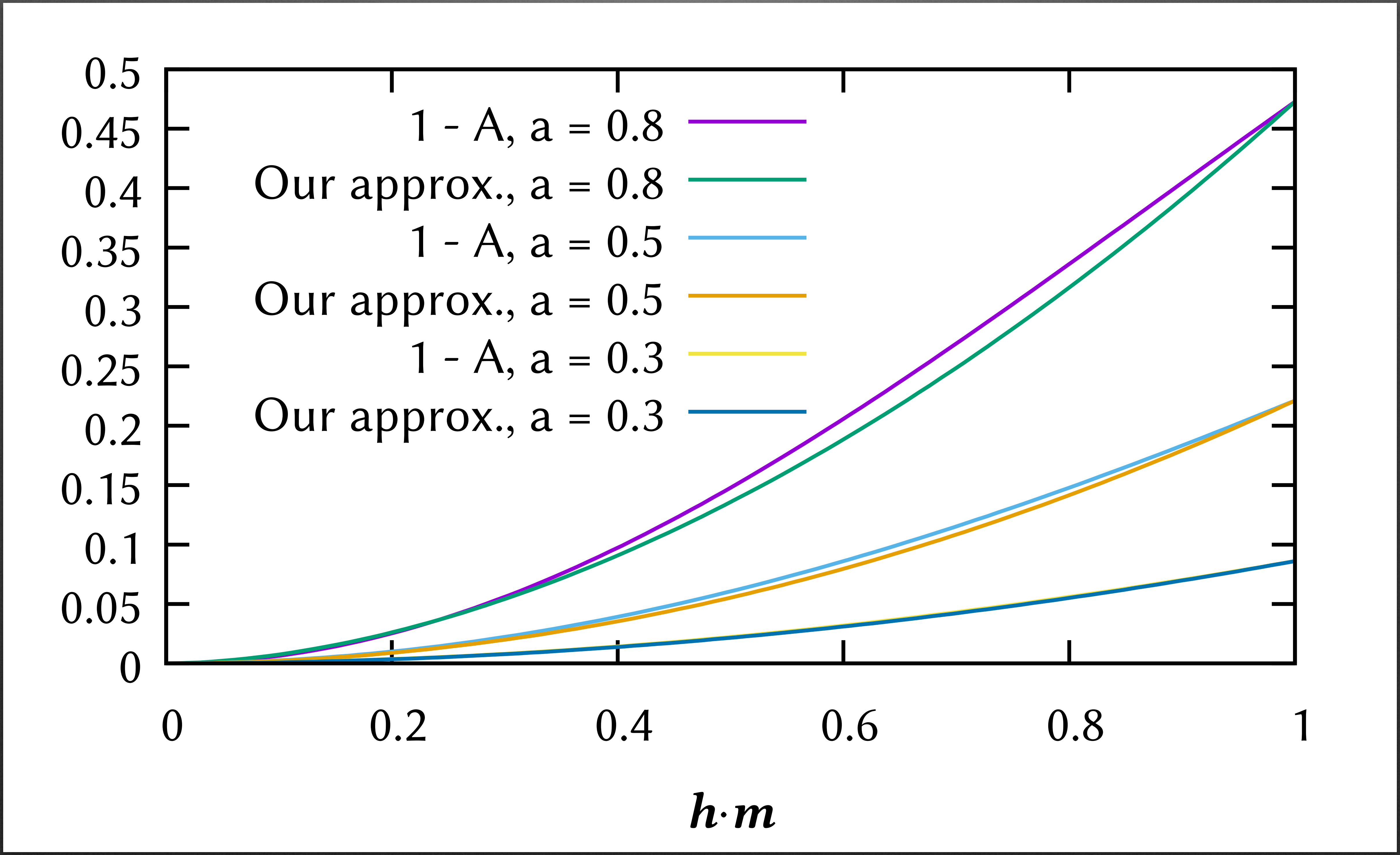
$$(1 - A_{\sigma_s}(i,o)) = 1 - e^{-\left(2\pi \frac{\sigma_s}{\lambda}(\cos\theta_i + \cos\theta_o)\right)}$$

$$(1 - A_{\sigma_s}(i,o)) \approx (1 - A_{\sigma_s}(\theta_d))(h \cdot m)^2$$



More on Microfacet convolution

$$(1 - A_{\sigma_s}(i, o)) \approx (1 - A_{\sigma_s}(\theta_d))(h \cdot m)^2$$



Fresnel and Polarization Factor Q

- Q is NOT the Fresnel Term
- Q comes from Rayleigh-Rice Theory
- For Perfect Specular direction Q = 2 Fresnel_Coefficient
- Q is re-introduced into GHS empirically for comparisons