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

Nicolas Holzschuch & Romain Pacanowski

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]

Ashikmin & Shirley [2000]

He et al. [1991]

Ashikmin et al. [2000]

Neumann and Neumann [1996]

Lafortune et al. [1997]

ABC [Löw et al. 2012]

Cook & Torrance [1982]

Ward [1992]

Hanrahan & Kruger [1993]

Blinn [1977]

Beard-Maxwel [1973]

Oren & Nayar [1994]

Granier & Heidrich [2003]

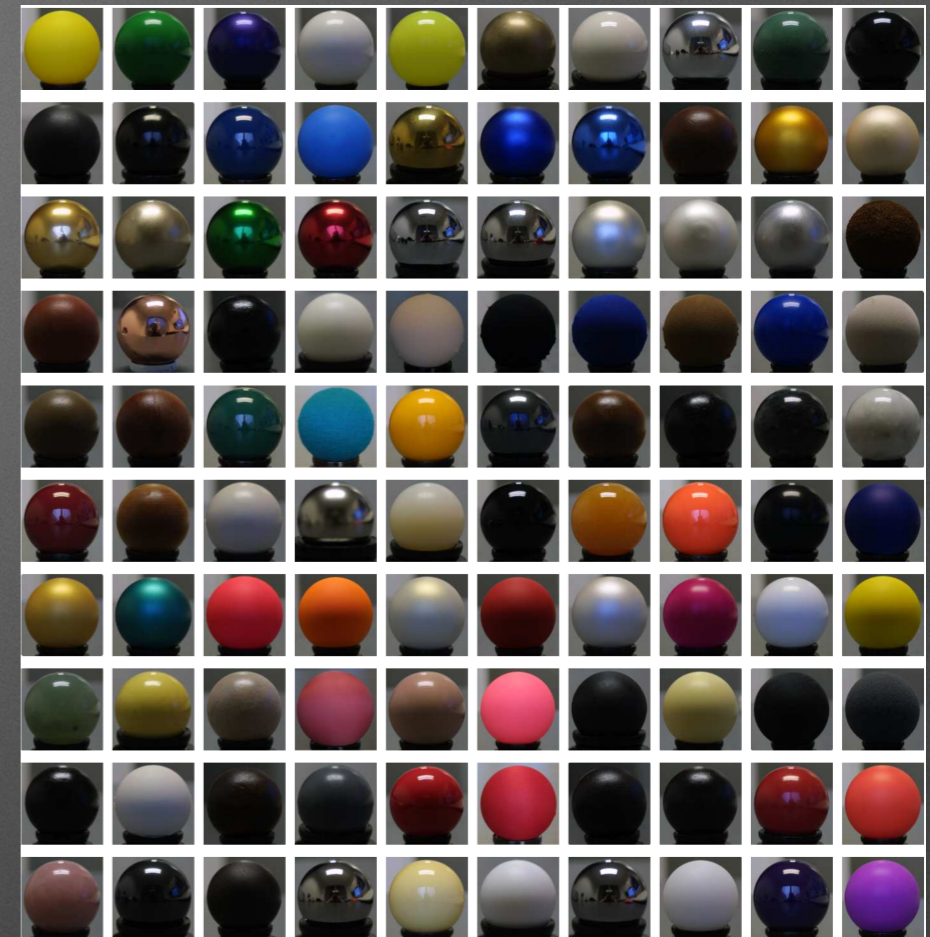
Schlick [1994]

Student-t [Ribardière et al. 2017]

AND MANY MORE !!!!!

Few BRDF Measurements Database

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



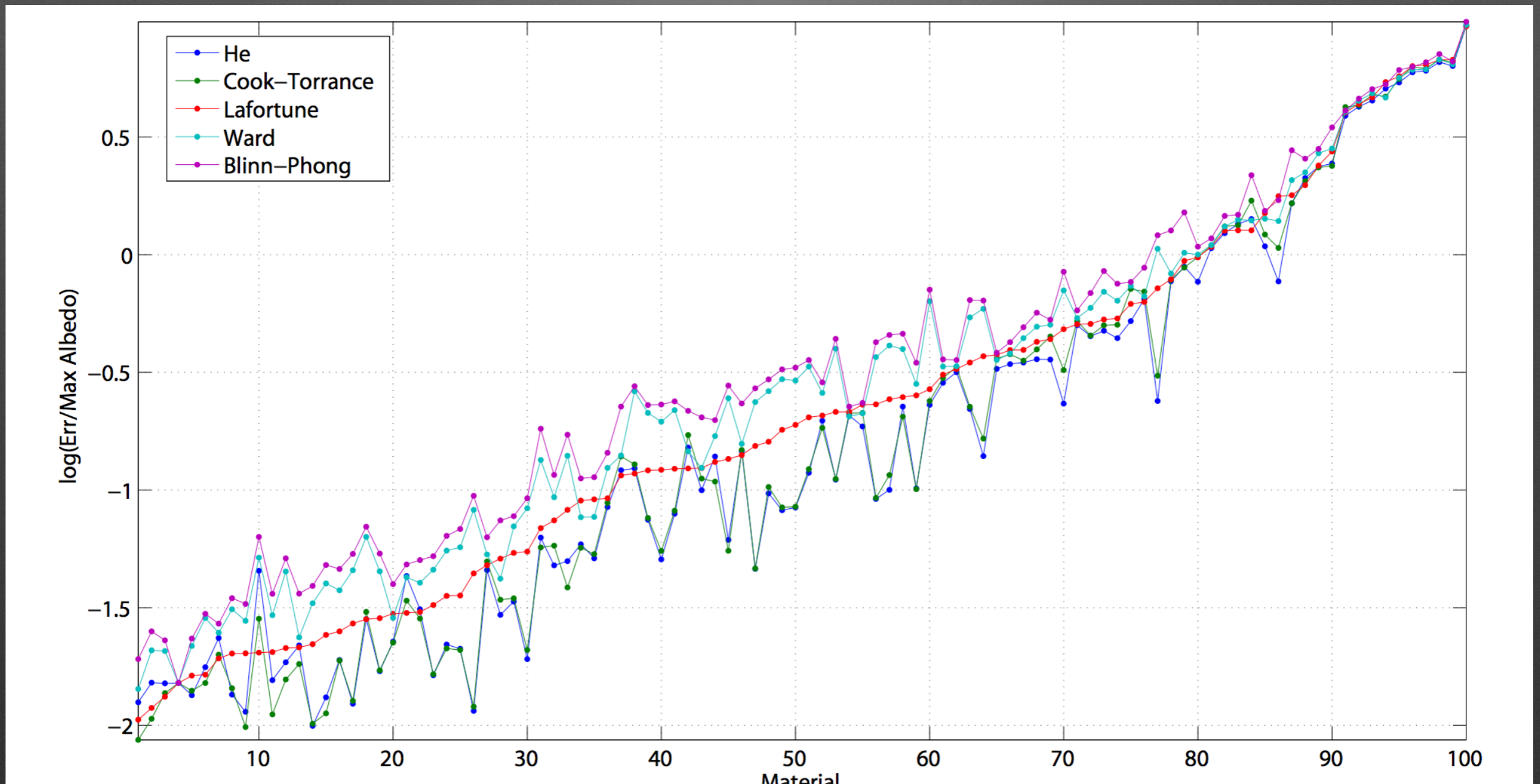
Cornell



Curet

BRDF Model comparisons

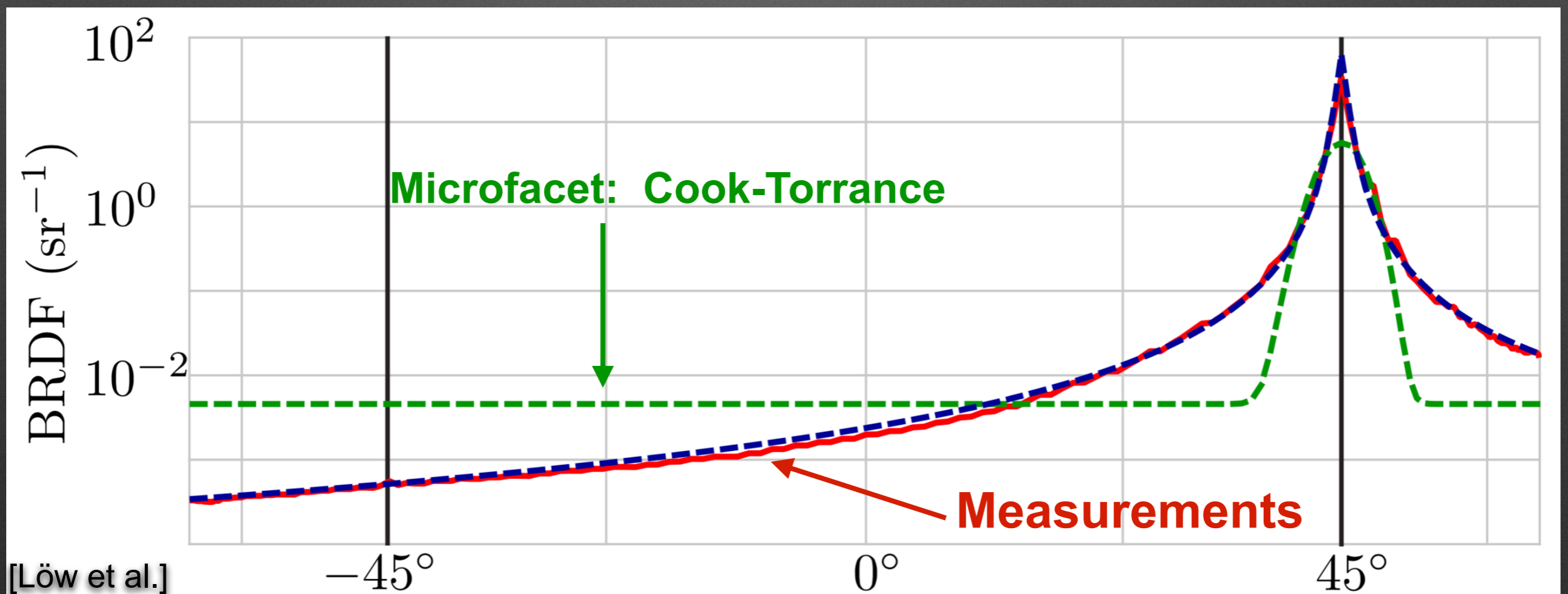
Study of fitting capabilities of BRDF Models [Ngan2005]



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

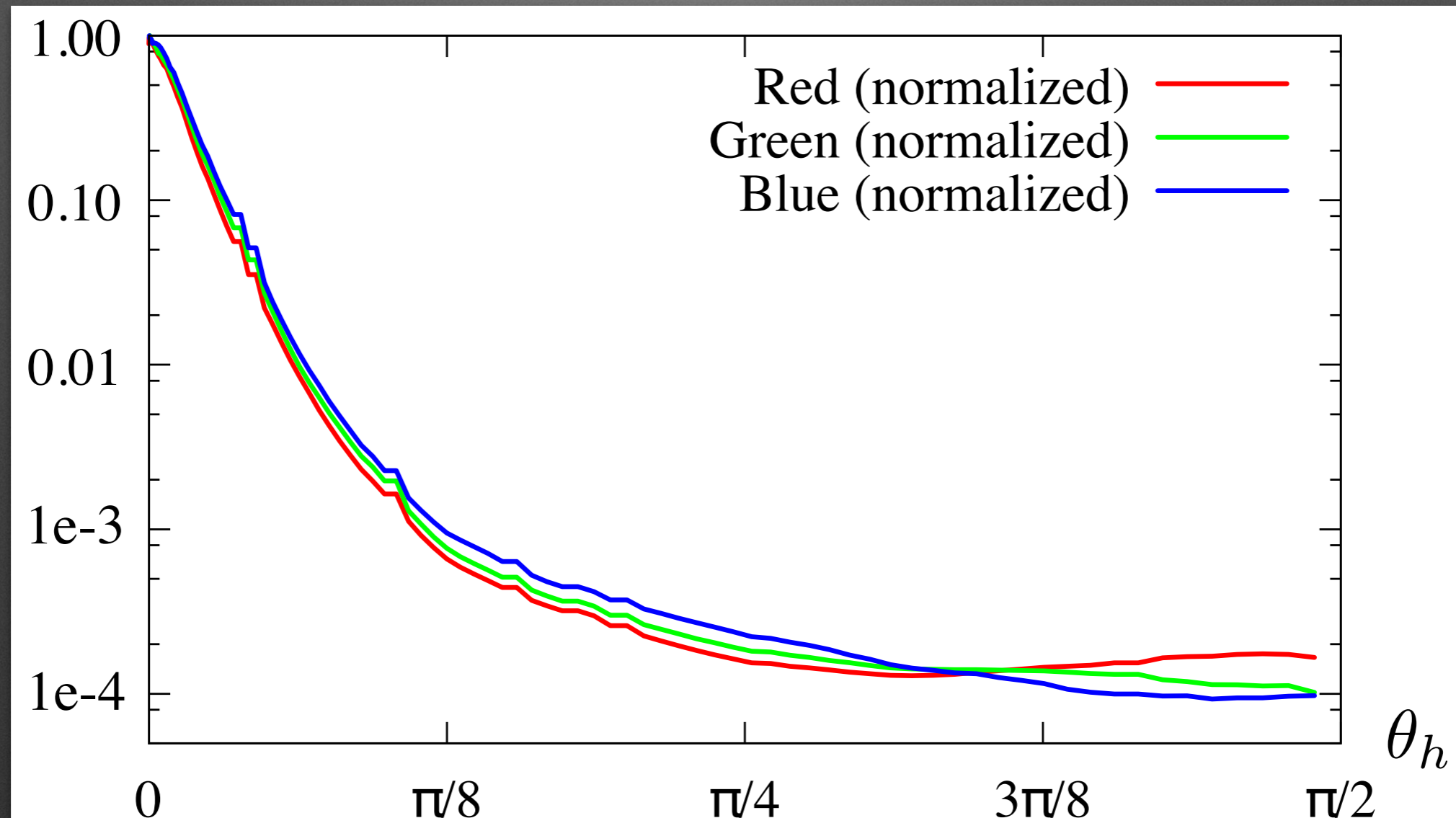


Closer Look on BRDF Measurements

- 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

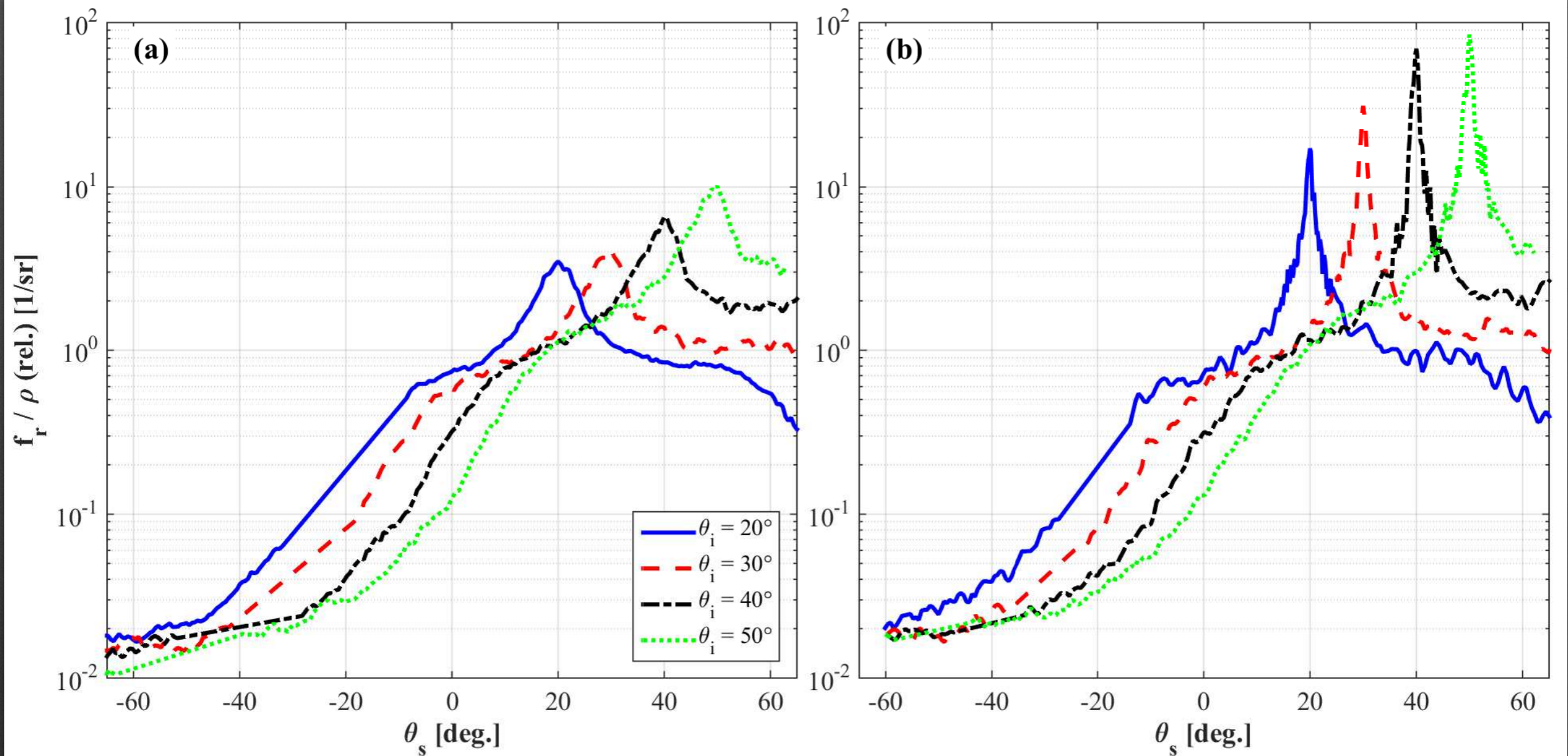


Lobe Size depends of the color

Closer Look on BRDF Measurements

$\lambda = 3,39$ microns

$\lambda = 10,6$ microns



Grit-Blasted Nickel

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

Observations on Measurements

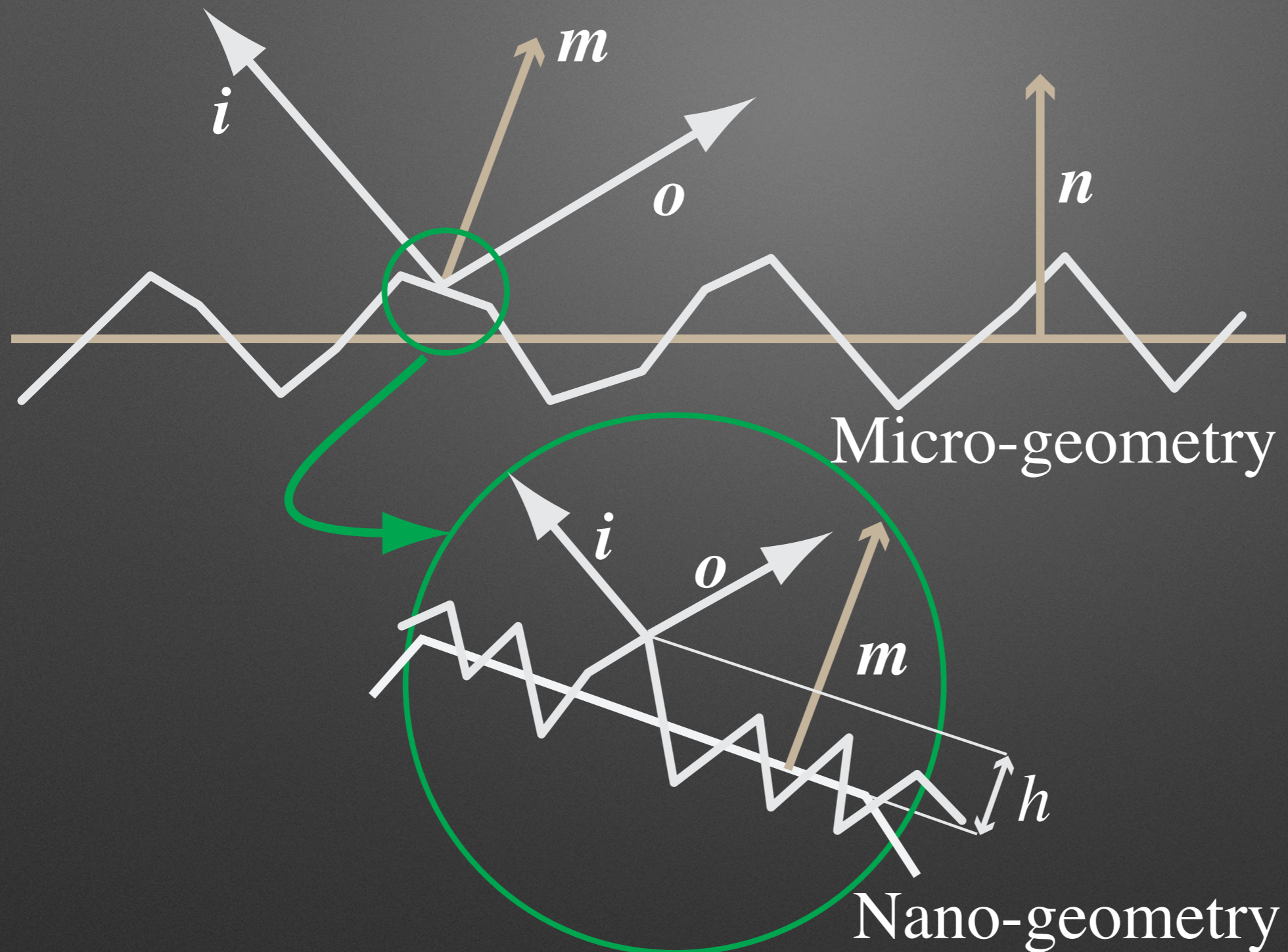
- Specular lobe
 - Wavelengths light Dependency
- ⇒ **Contradicts** Microfacet Theory

Microfacet Hypothesis

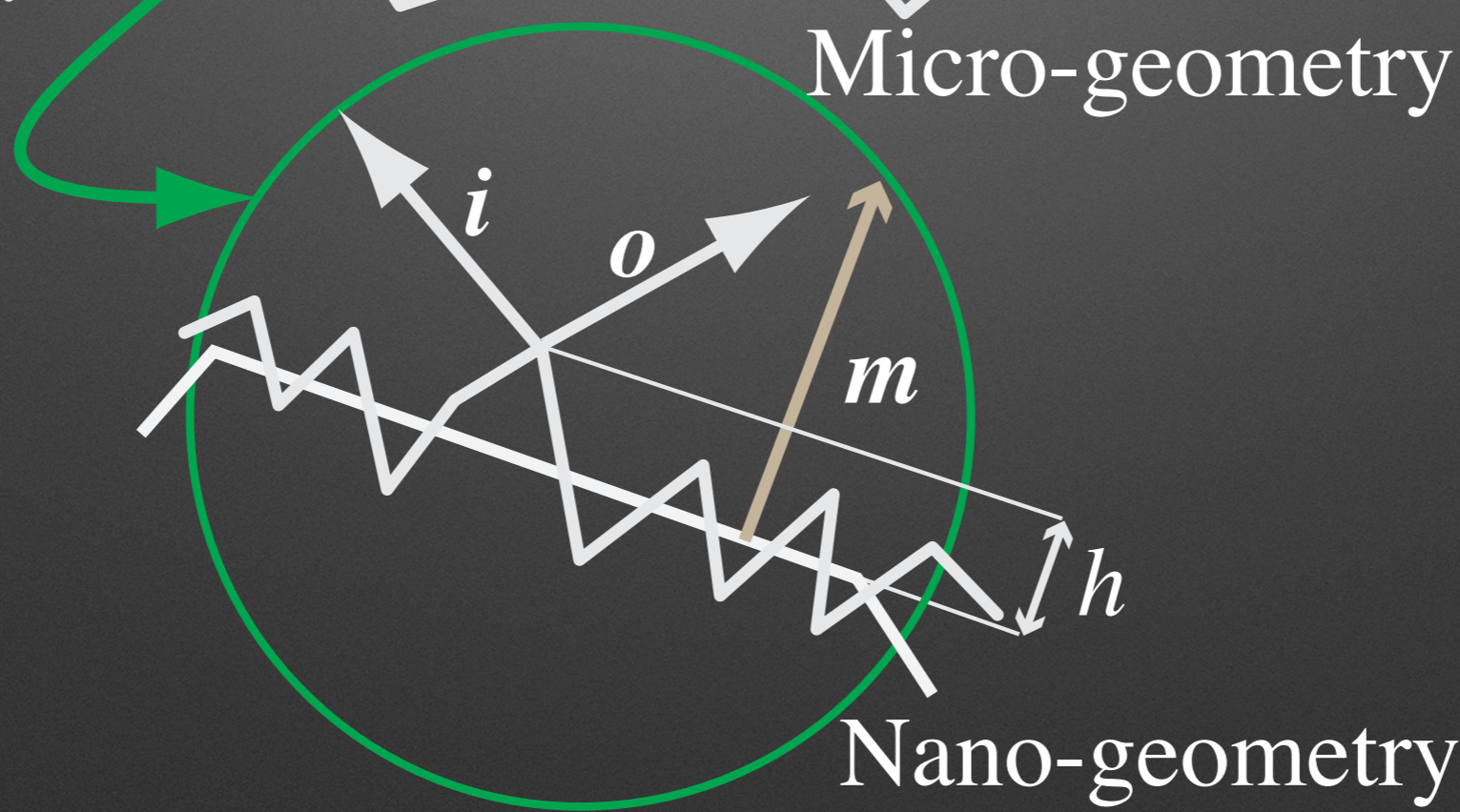
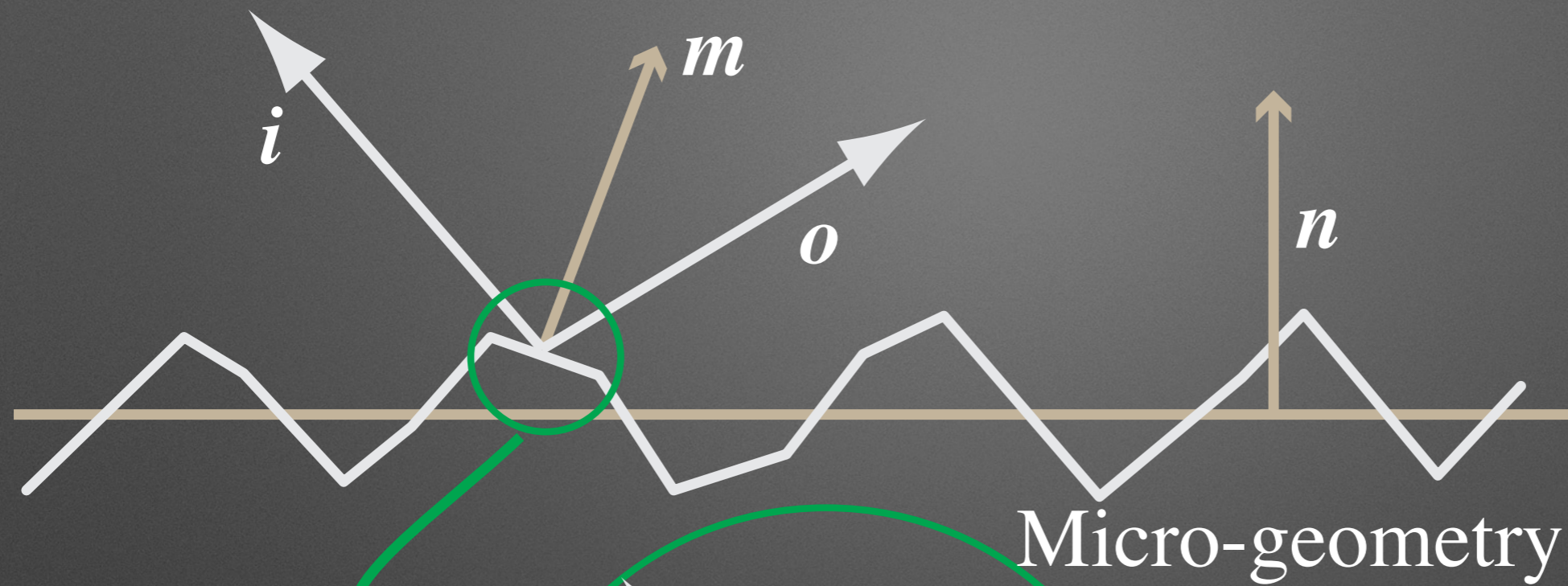


- Microfacet: Perfect Mirror with a Fresnel Coefficient
- Microfacet $\gg \lambda =$ light wavelength
 - Geometrical Optics
- Fresnel is the only wavelength dependent term
- How can we model this phenomenon?

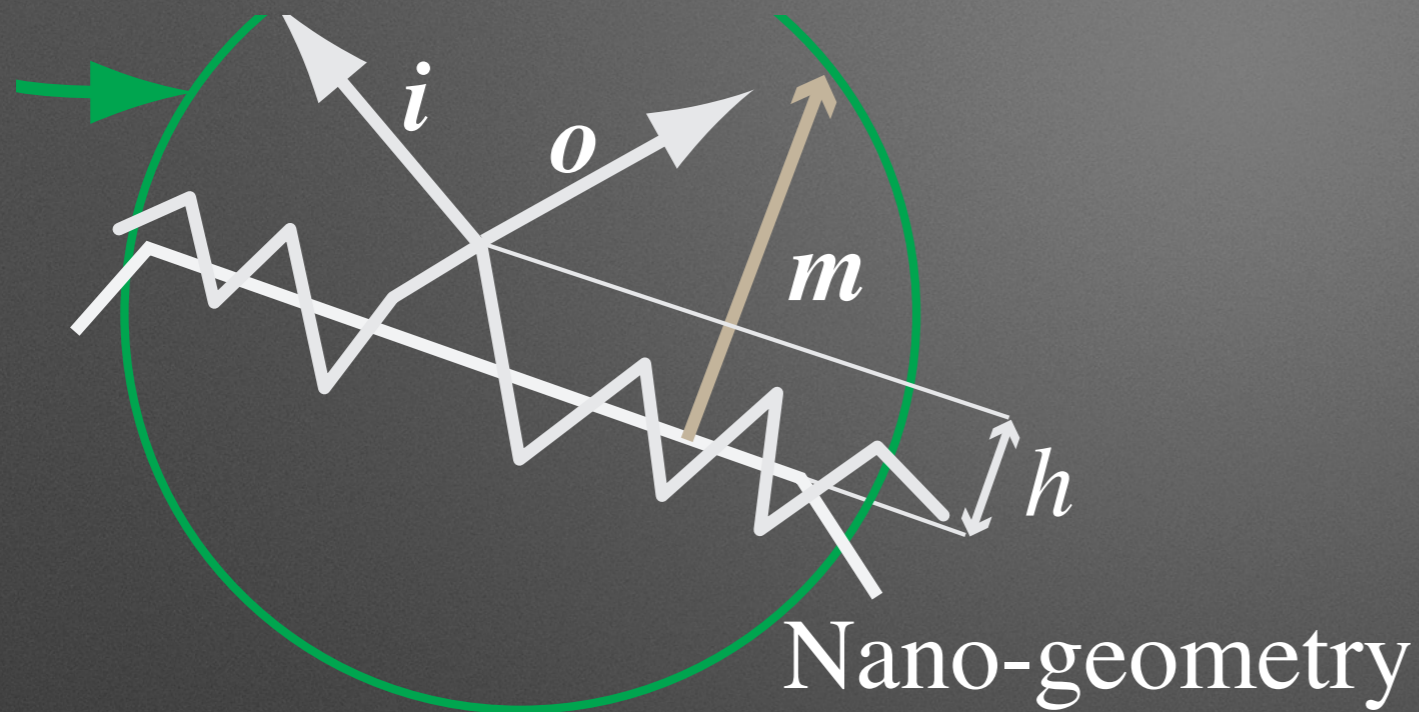
Two-Scale Reflectance Model



Two-Scale Reflectance Model



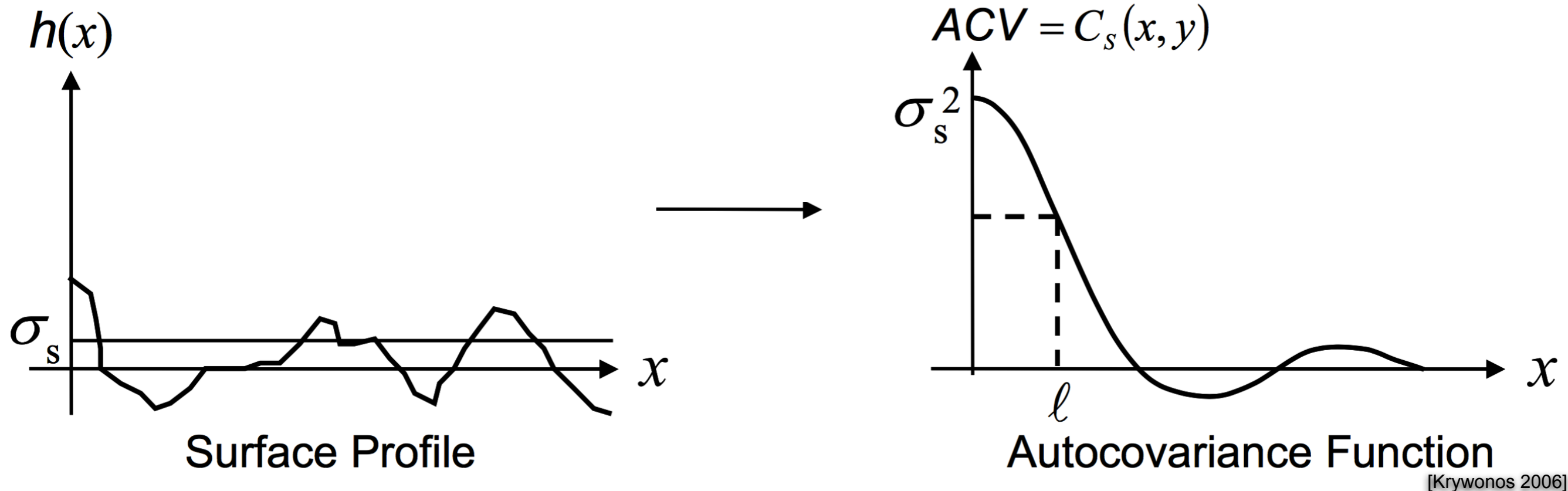
Two-Scale Reflectance Model



Wave Optics, Diffraction:

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

Surface Characteristics

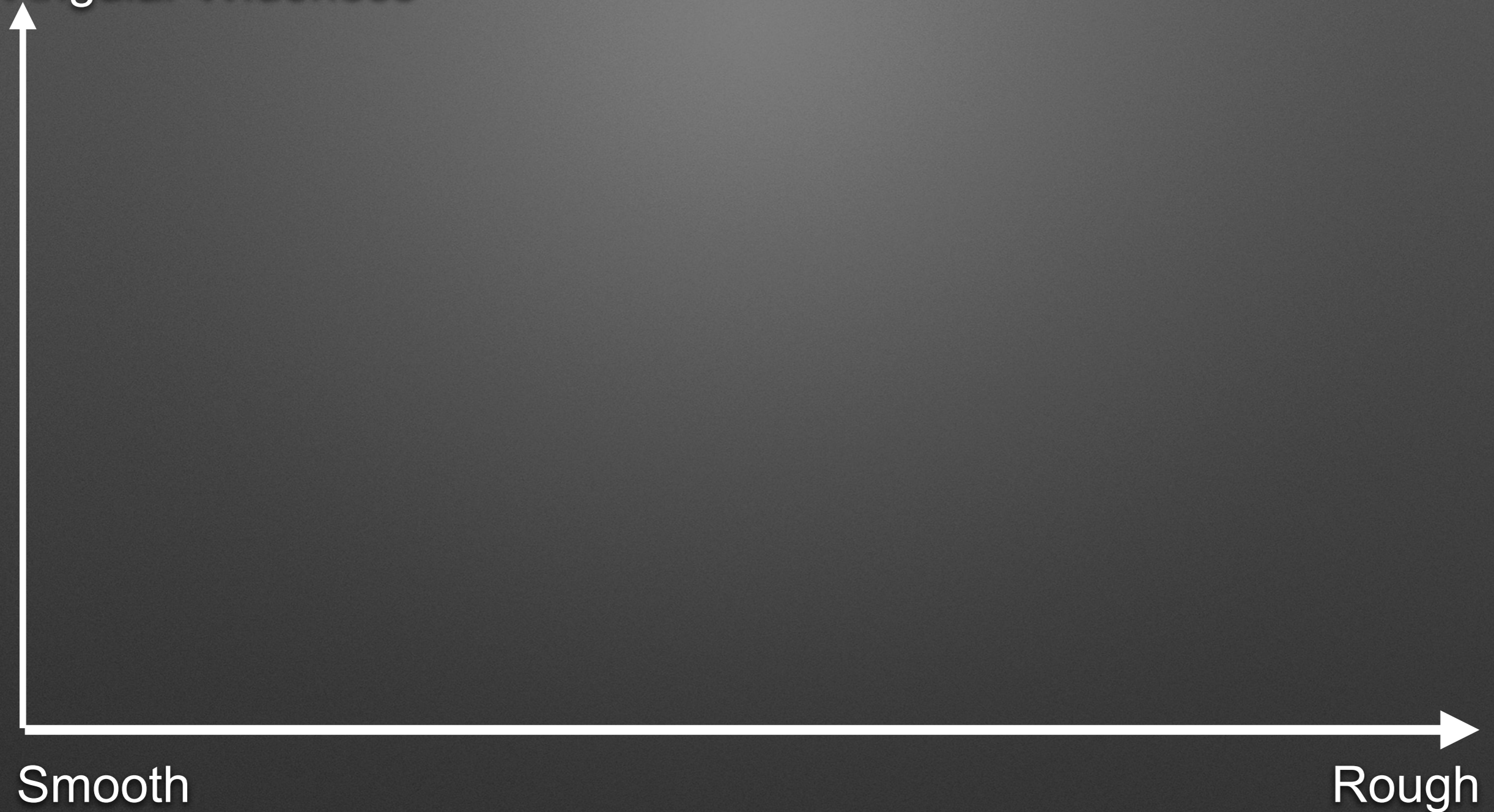


σ_s : RMS of the surface roughness

l : autocovariance length

Diffraction Theories for Scattering

Angular Wideness



Diffraction Theories for Scattering

Angular Wideness

Rayleigh-Rice
[Löw 2012]

Smooth

Rough

Diffraction Theories for Scattering

Angular Wideness

Rayleigh-Rice
[Löw 2012]

Beckman-Kirchoff. [He 91, Stam 99]

Smooth

Rough

Diffraction Theories for Scattering

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Rayleigh-Rice
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Diffraction Theories for Scattering

Angular Wideness

Rayleigh-Rice
[Löw 2012]

Modified Beckman-Kirchoff. [Krywonos 2006]

Harvey-Shack [HK 1975]

Beckman-Kirchoff. [He 91, Stam 99]

Smooth

Rough

Diffraction Theories for Scattering

Angular Wideness

Rayleigh-Rice
[Löw 2012]

Generalized Harvey-Shack [HK 2012]

Modified Beckman-Kirchoff. [Krywonos 2006]

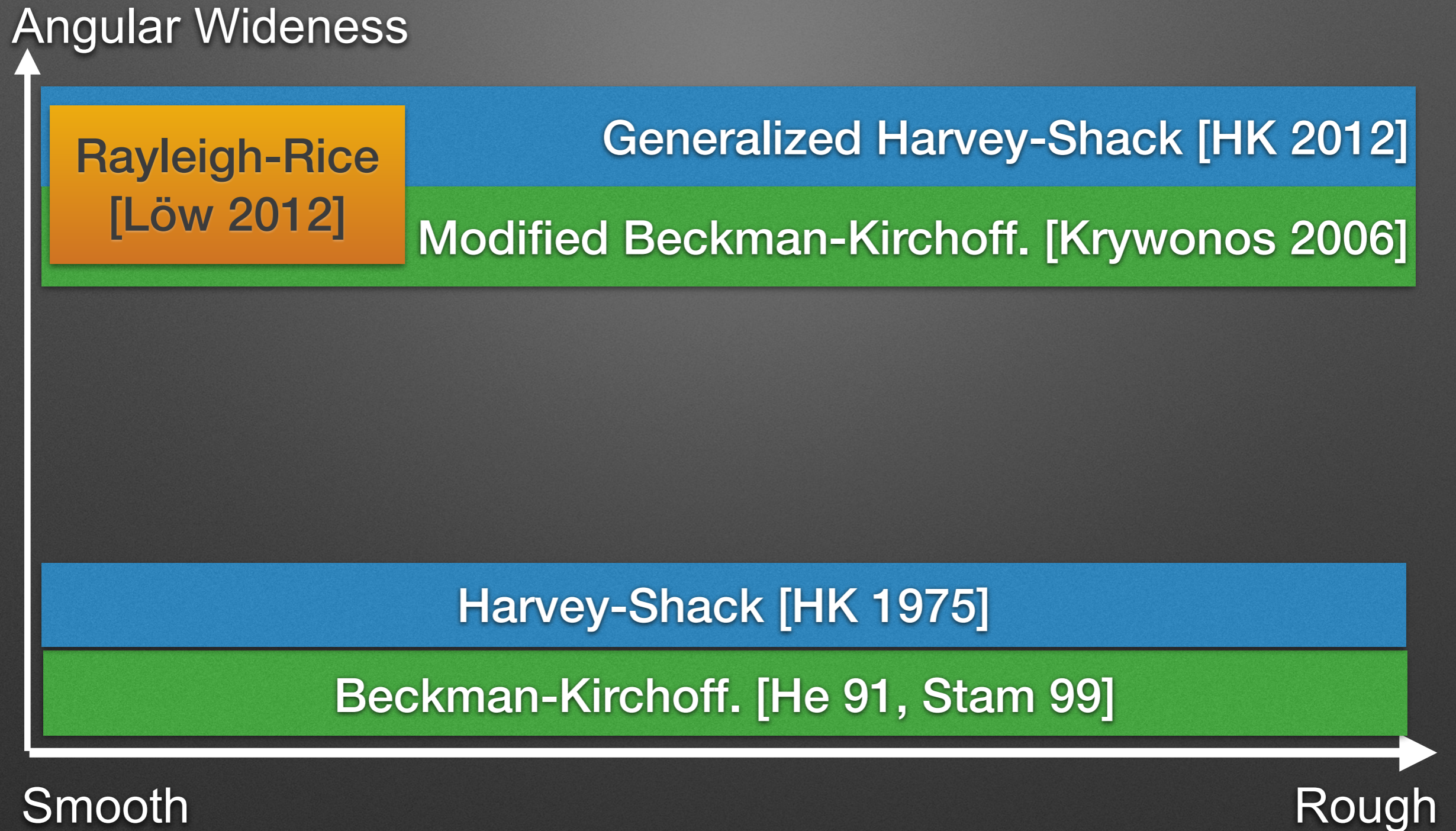
Harvey-Shack [HK 1975]

Beckman-Kirchoff. [He 91, Stam 99]

Smooth

Rough

Diffraction Theories for Scattering



All Theories: **SINGLE** Scattering ONLY

Diffraction Theories for Scattering

Generalized Harvey-Shack

- Gaussian Surface Profile
- **Arbitrary** Autocovariance Function

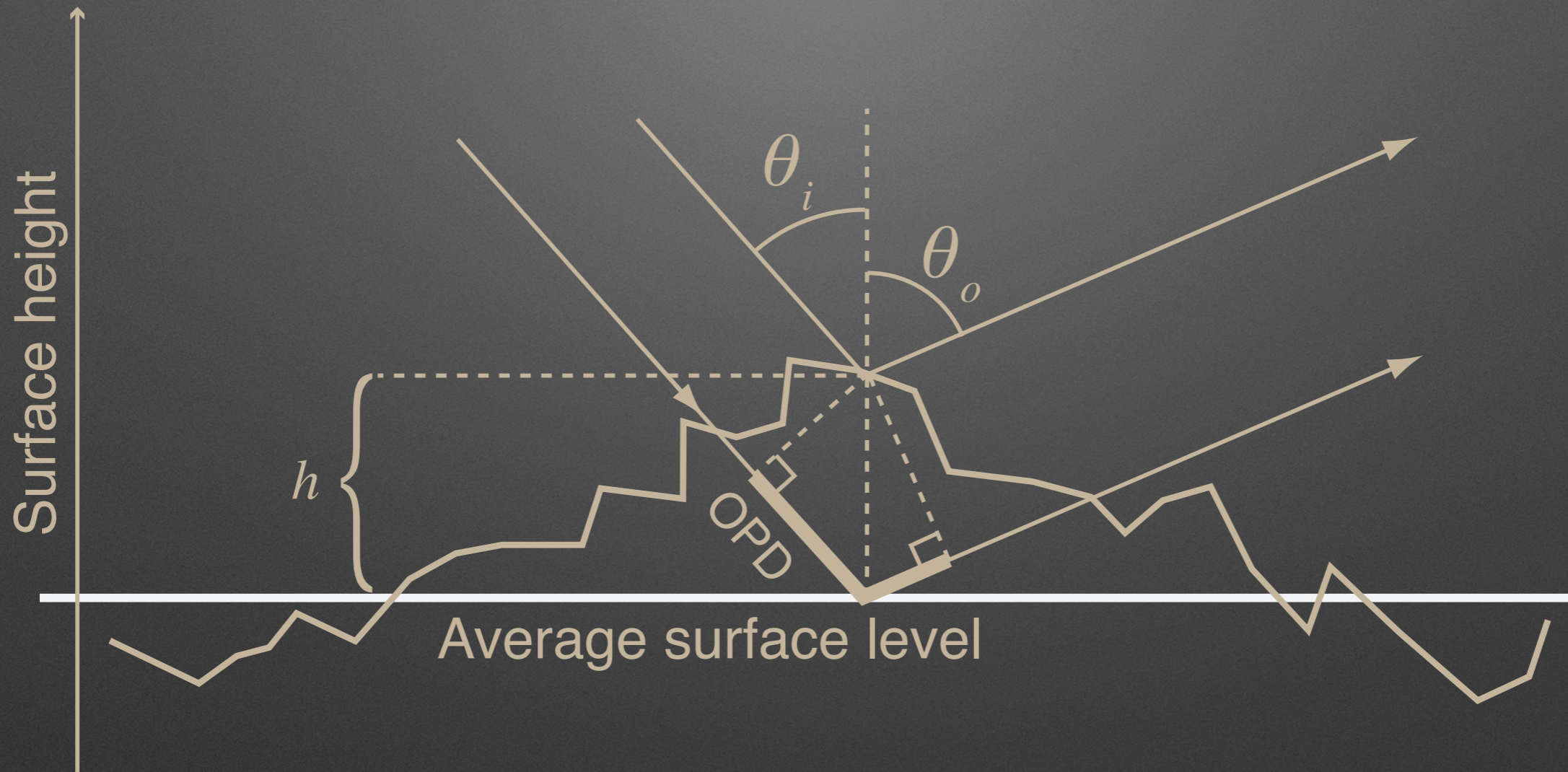
⇒ Our Model utilizes it

Modified Beckman-Kirchoff

- Gaussian Surface Profile
- Gaussian Autocovariance Function

Generalized Harvey-Shack

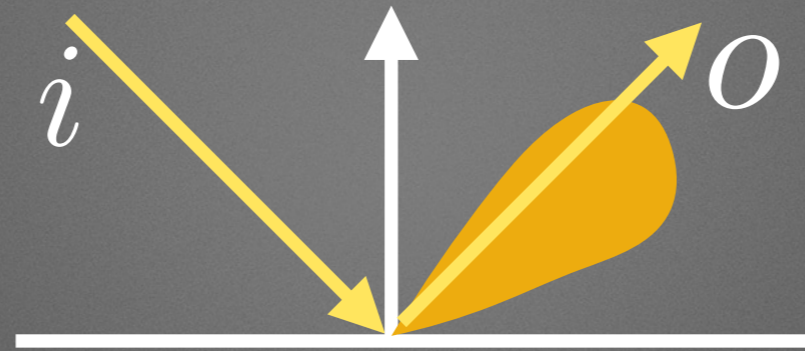
Main Idea: **Surface = Transfer Function** on the incident wave



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

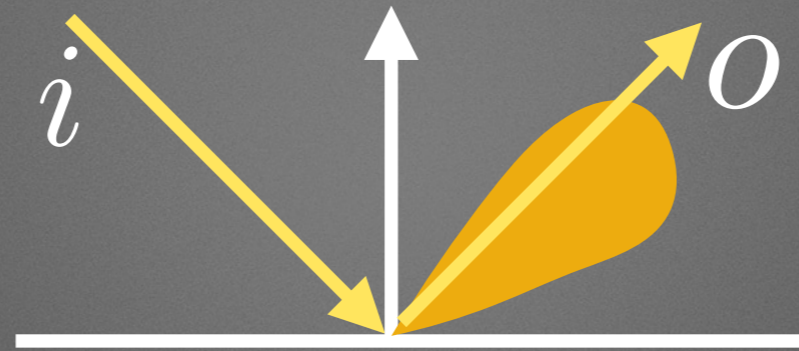
$$\text{random phase} = \frac{2\pi}{\lambda} \text{OPD}$$

Generalized Harvey-Shack



BRDF: Specular Peak (Dirac) + Diffraction Lobe

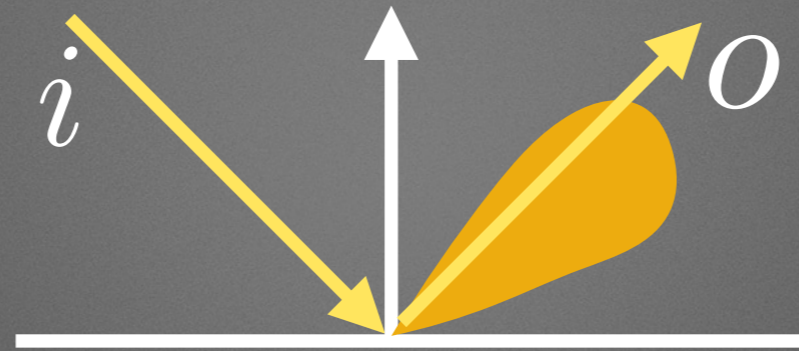
Generalized Harvey-Shack



BRDF: Specular Peak (Dirac) + Diffraction Lobe

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

Generalized Harvey-Shack



BRDF: Specular Peak (Dirac) + Diffraction Lobe

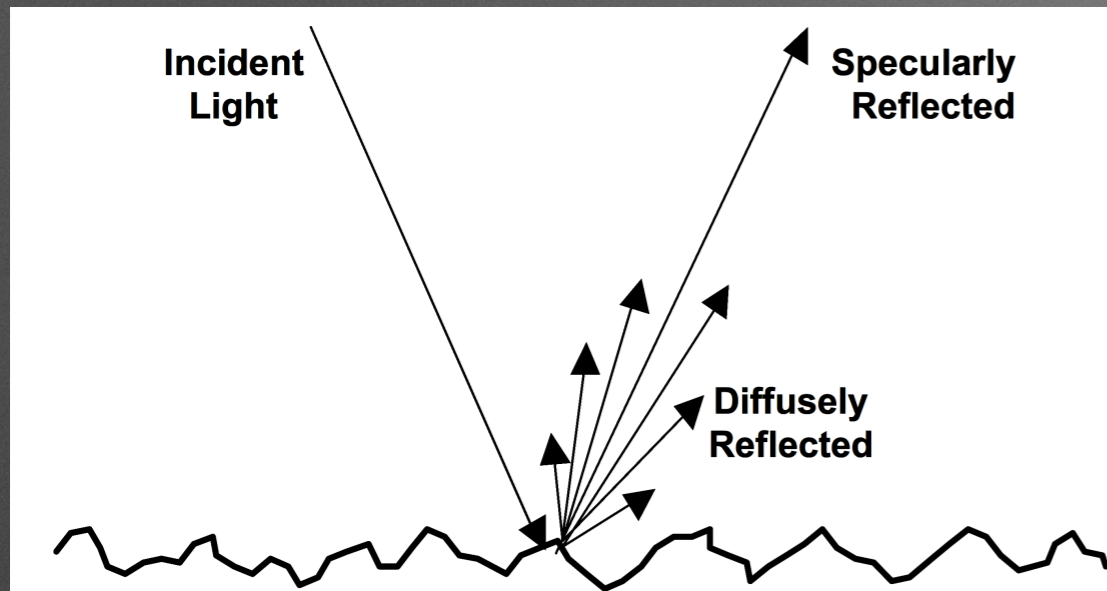
$$\rho(i, o) = \text{Fresnel}(i, o) \left[A\delta(\text{refl}(i), o) + (1 - A) \underbrace{\mathcal{F}_{|x,y}\{C(x, y, i, o)\}}_{\text{2D Fourier Transform}} \right]$$

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

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

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

Summary on Generalized Harvey-Shack



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

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

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



GHS is **too expensive** for CG

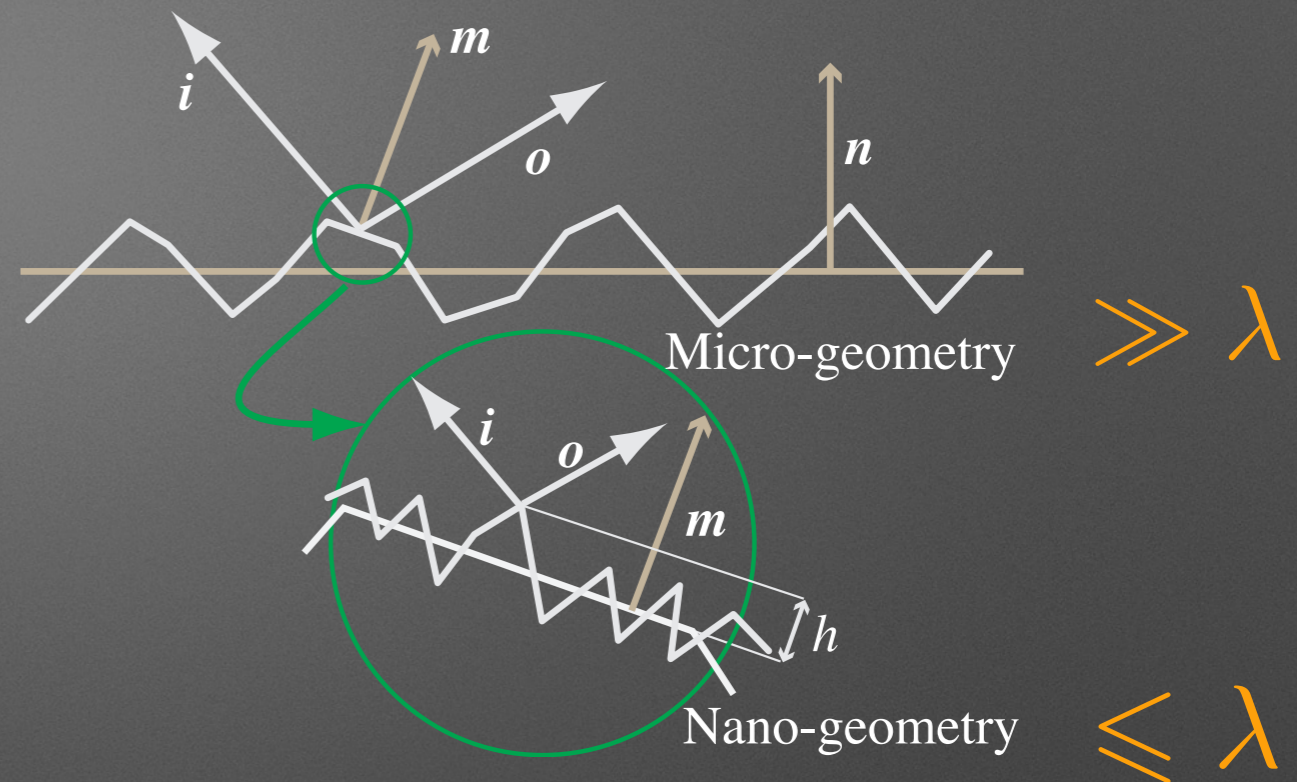
Diffraction into our Two-Scale Model

- 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

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

Our Approach for Smooth Regime

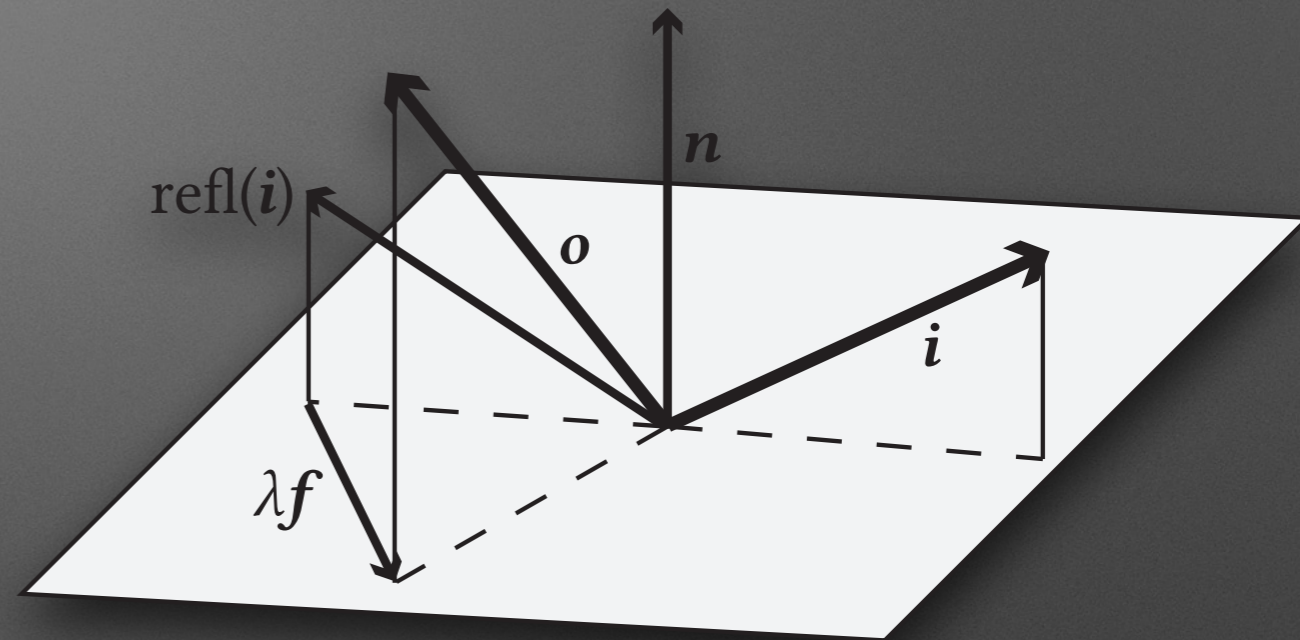
$$\rho(i, o) = \text{Fresnel} \left[A \delta(\text{refl}(i), o) + (1 - A) \mathcal{F}\{C(x, y, \underline{i}, \sigma)\} \right]$$

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

Our Approach for Smooth Regime

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

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



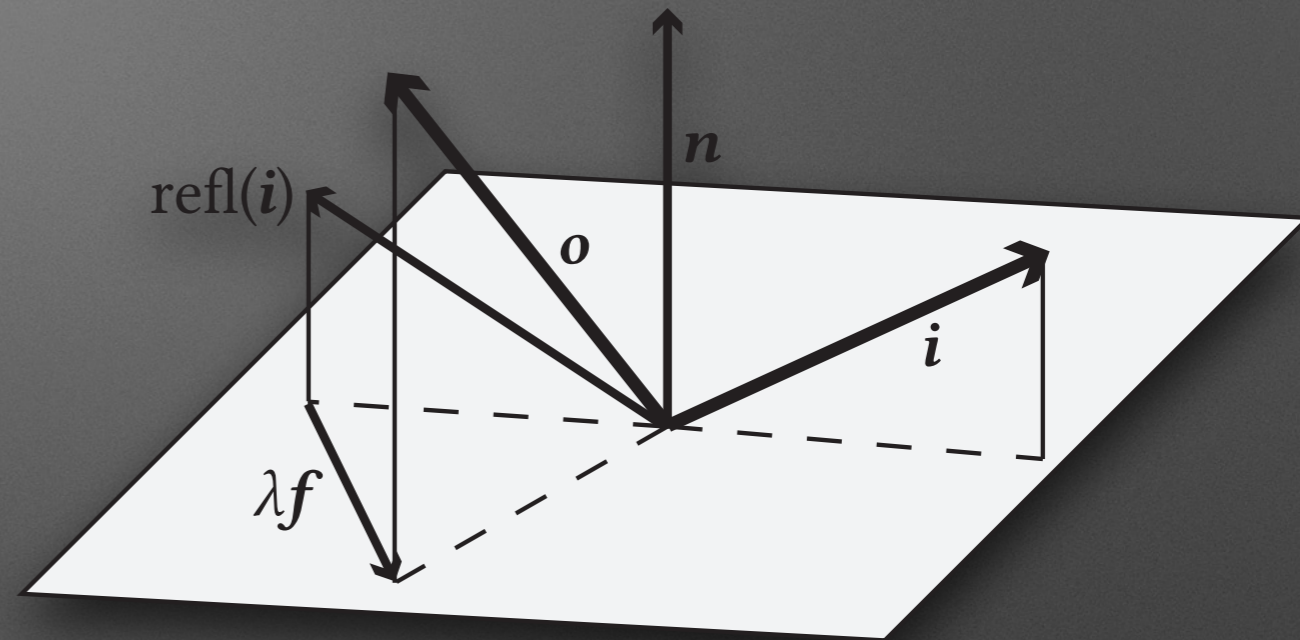
$$\mathcal{F}\{C(x, y)\} : \text{PSD}(\text{Surface}) \approx \text{K-Correlation}(\sigma_s, f)$$

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

Our Approach for Smooth Regime

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

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



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

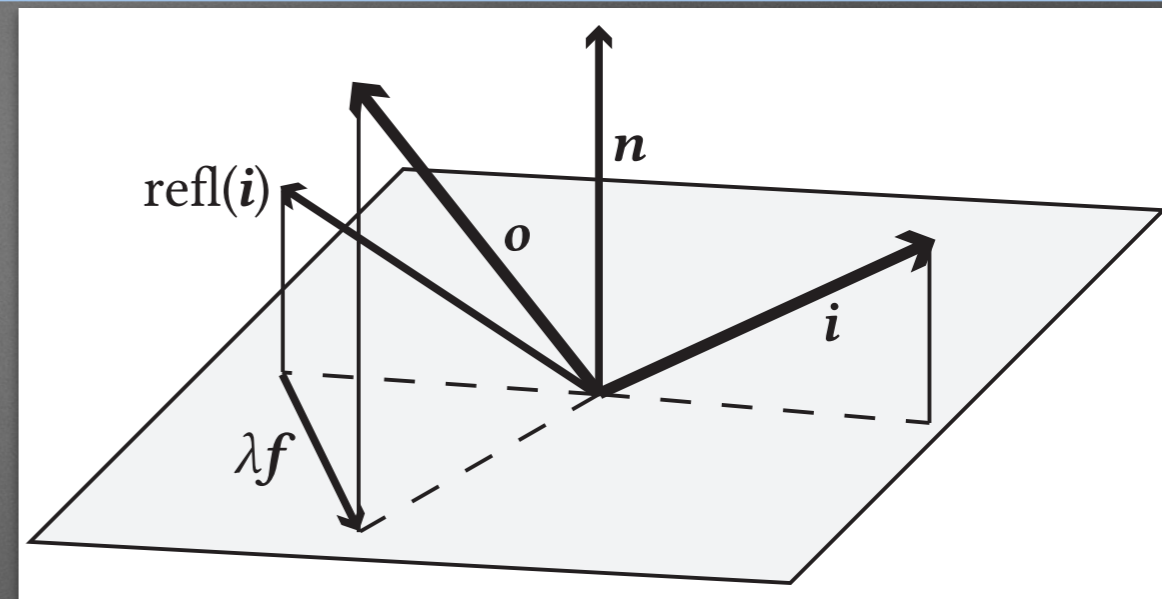
$$\|\mathbf{f}\| = \frac{2}{\lambda} \sin \theta_h \cos \theta_d$$

- $\mathbf{f} \Leftrightarrow$ Alternative Parametrization [Barla et al. Mam 2015]

Renormalization of the Diffraction Lobe

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

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

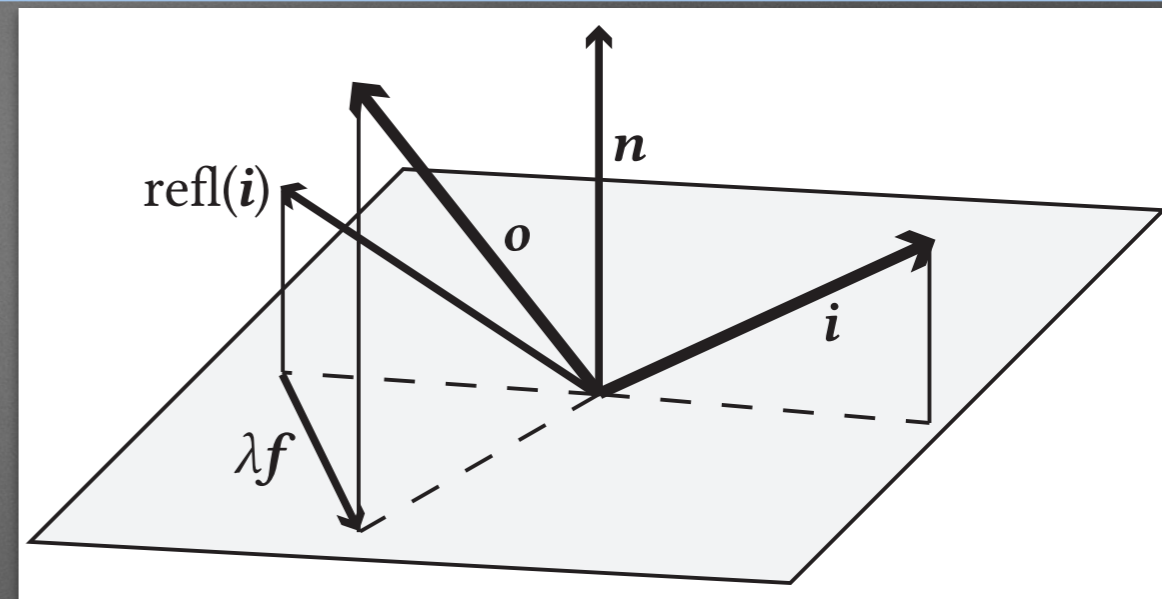


Renormalization of the Diffraction Lobe

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

- Renormalization

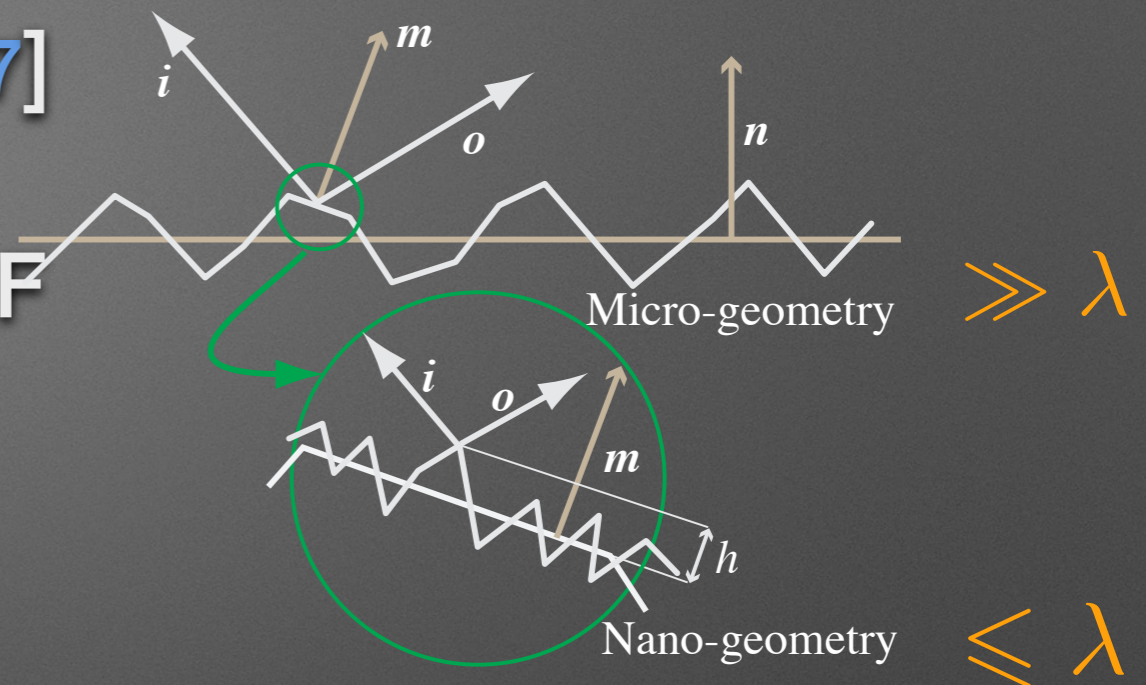
$$\sigma_s^2 = \iint \text{K-Correlation}(\sigma_s, \mathbf{f}) df$$



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

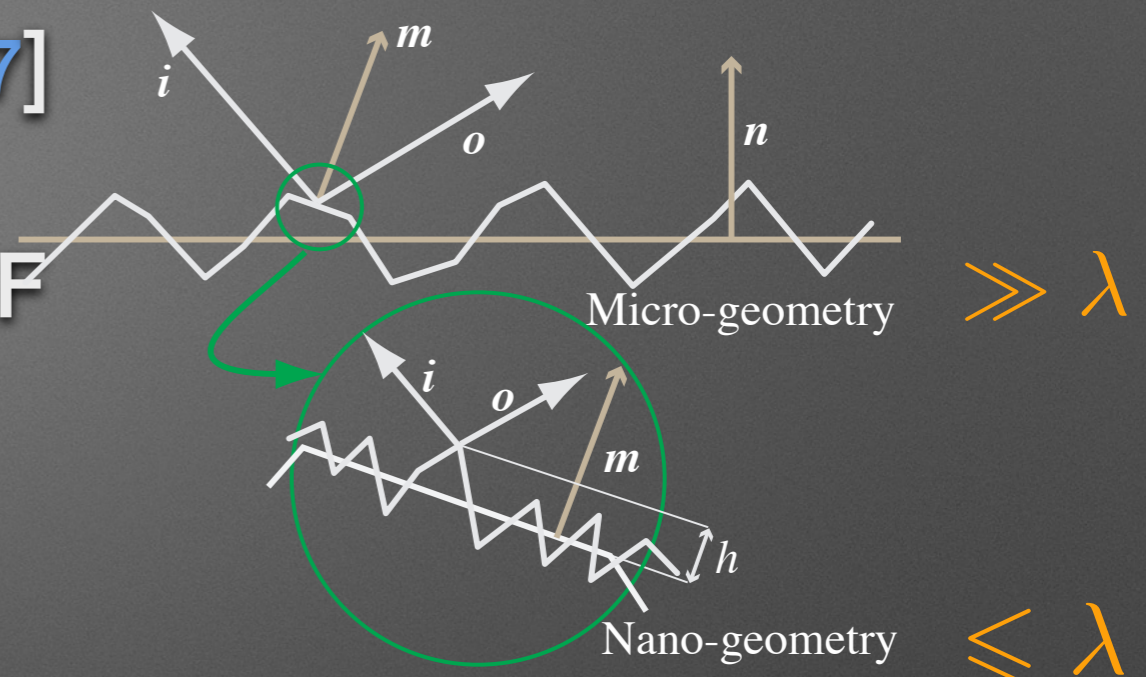
Diffraction into our Two-Scale Model

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



Diffraction into our Two-Scale Model

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

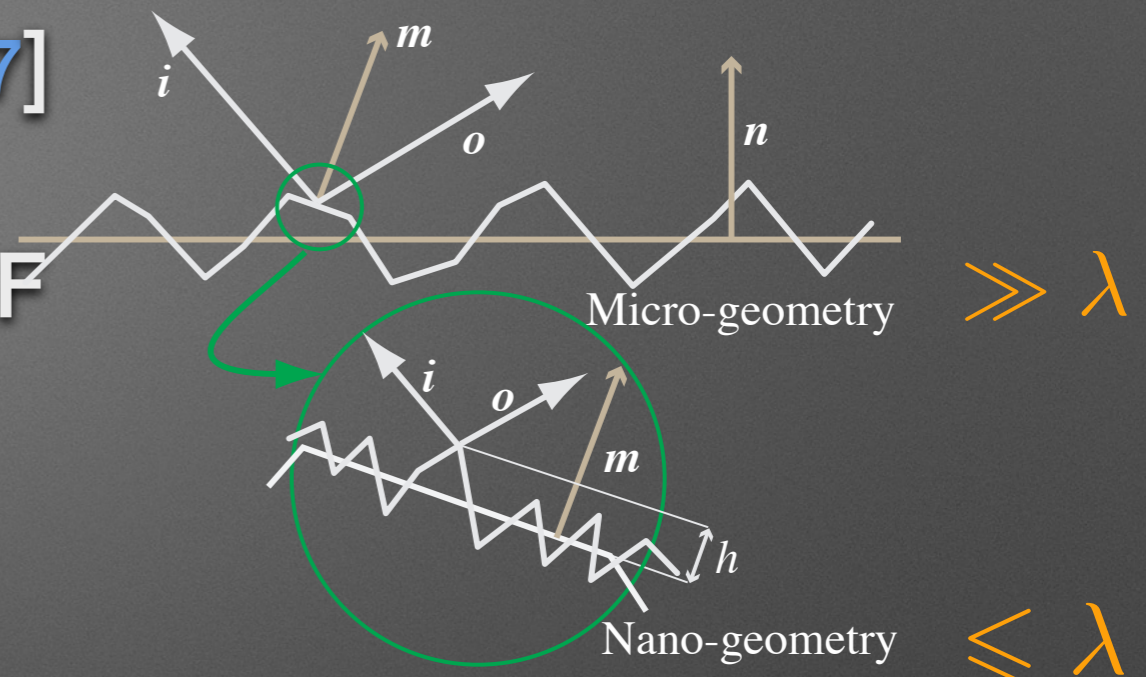


$$\rho(i, o) = \int_{\Omega_m} \underbrace{\rho_m(i, o, m)}_{\text{Microfacet BRDF}} G(i, o) D(m) d\omega_m$$

Diffraction into our Two-Scale Model

- Microfacet Framework [Walter2007]

- Convolution of a Microfacet BRDF



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

- In Our Case, **Smooth Diffractive Microfacet:**

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

Convolution of a Diffractive Microfacet

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

Convolution of a Diffractive Microfacet

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

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

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

Convolution of a Diffractive Microfacet

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

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

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

Diffraction Part

Convolution of a Diffractive Microfacet

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

Convolution of a Diffractive Microfacet

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

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

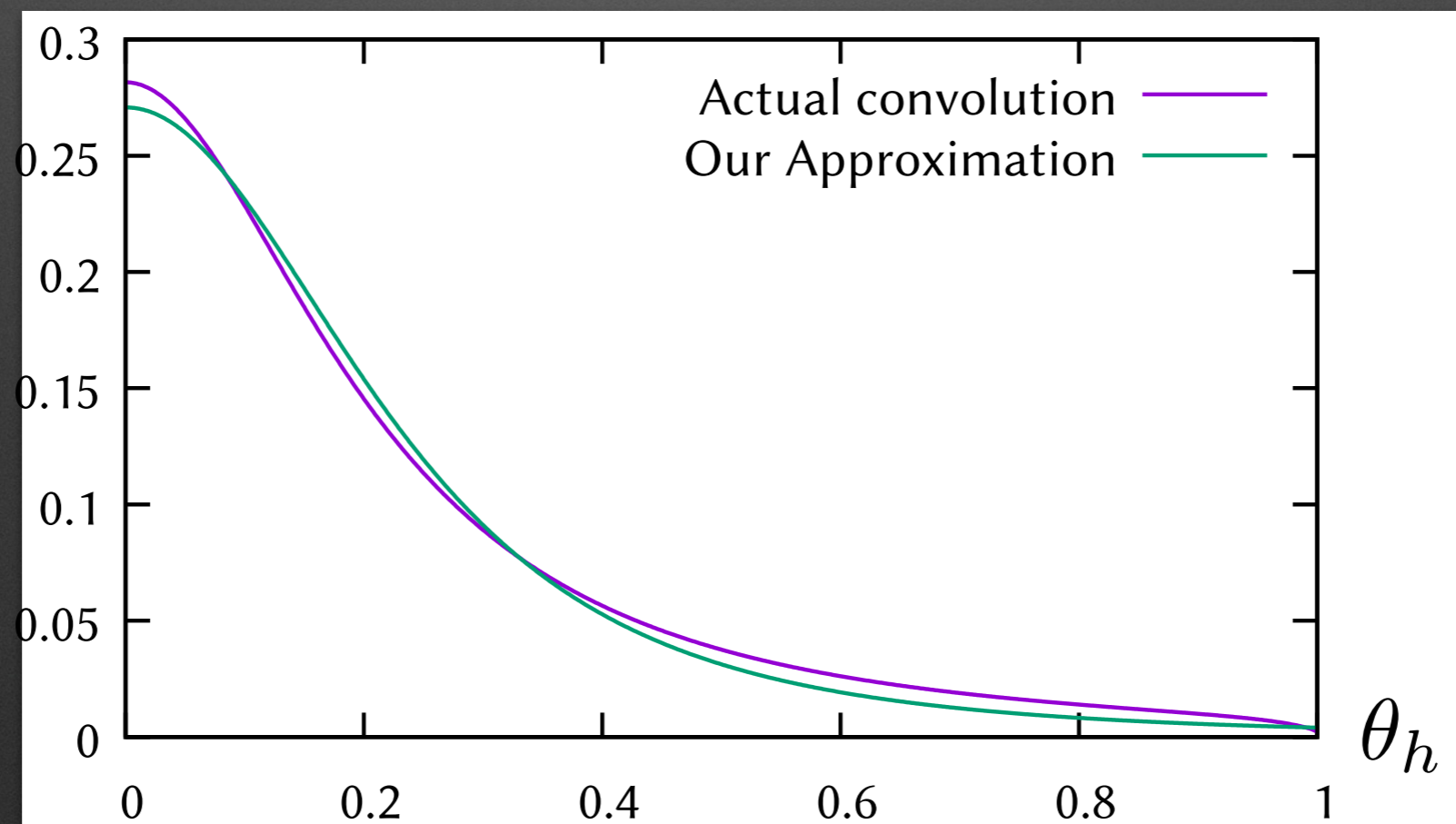
$$f = 2 \cos \theta_d \sqrt{(1 - (h \cdot m)^2)}$$

Convolution of a Diffractive Microfacet

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

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

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



Convolution of a Diffractive Microfacet

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

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

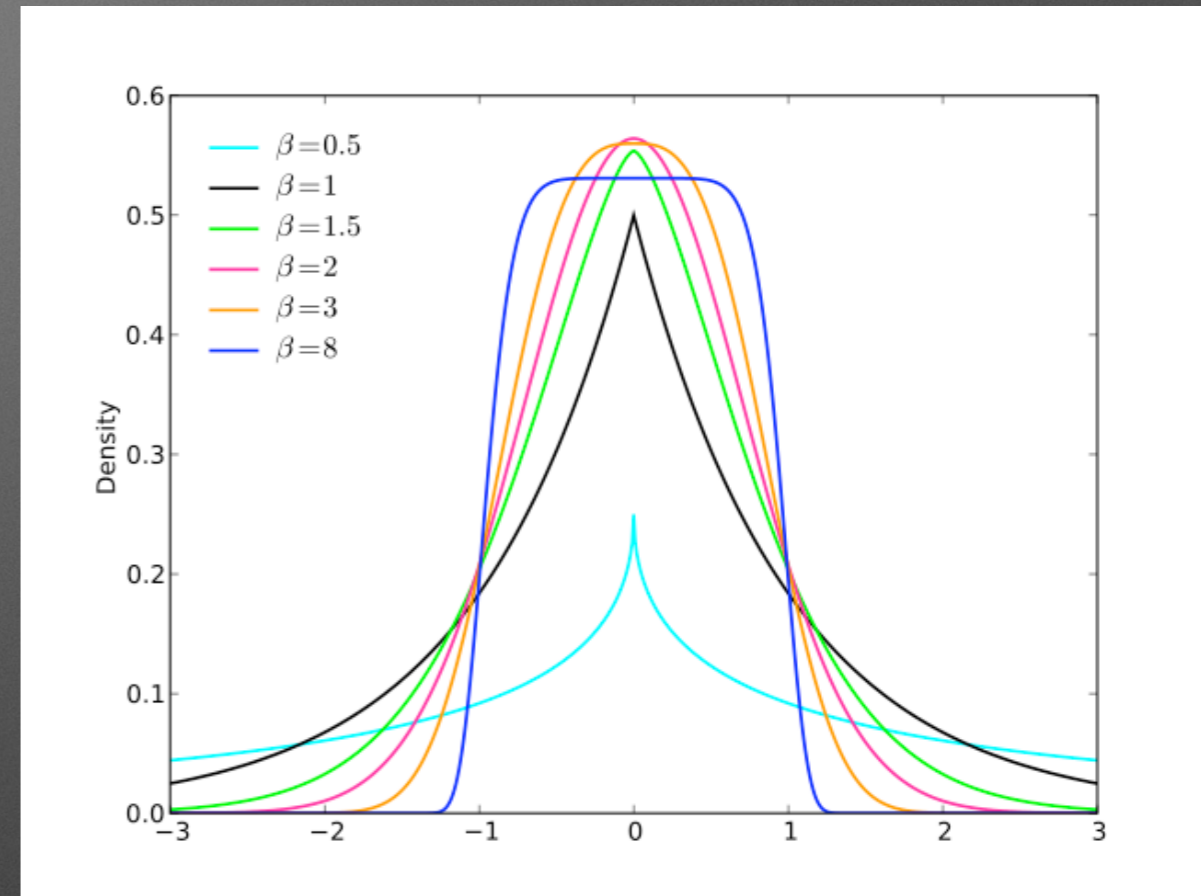
$$\rho(i, o) = A_{\sigma_s}(\theta_d) \underbrace{\rho_{epd}(i, o)}_{\text{specular}} + \underbrace{\rho_{ghs}(i, o)}_{\text{diffraction}}$$

- Specular Lobe: Exponential Power Distribution (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

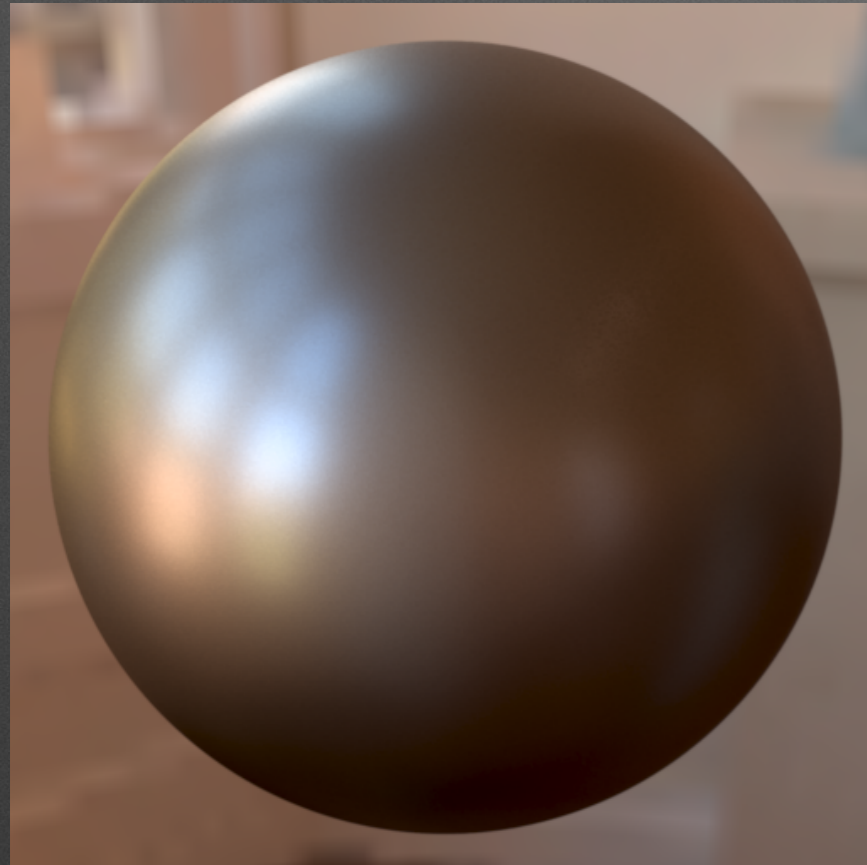
K-correlation Model : 2 parameters

- Specular Lobe

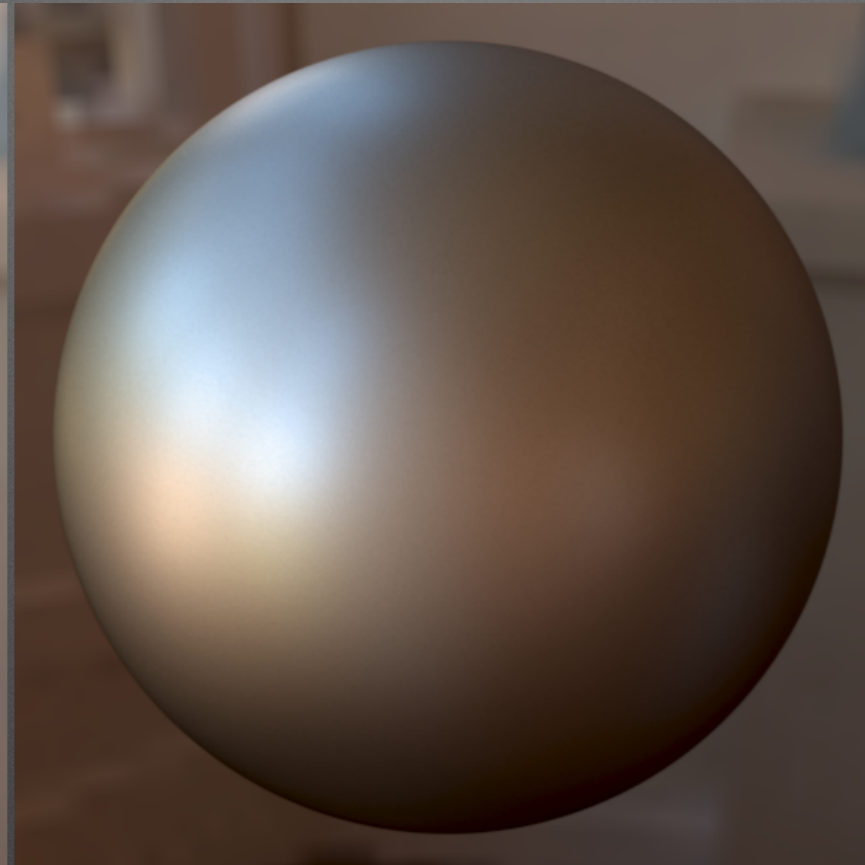
β : Width

p : Kurtosis

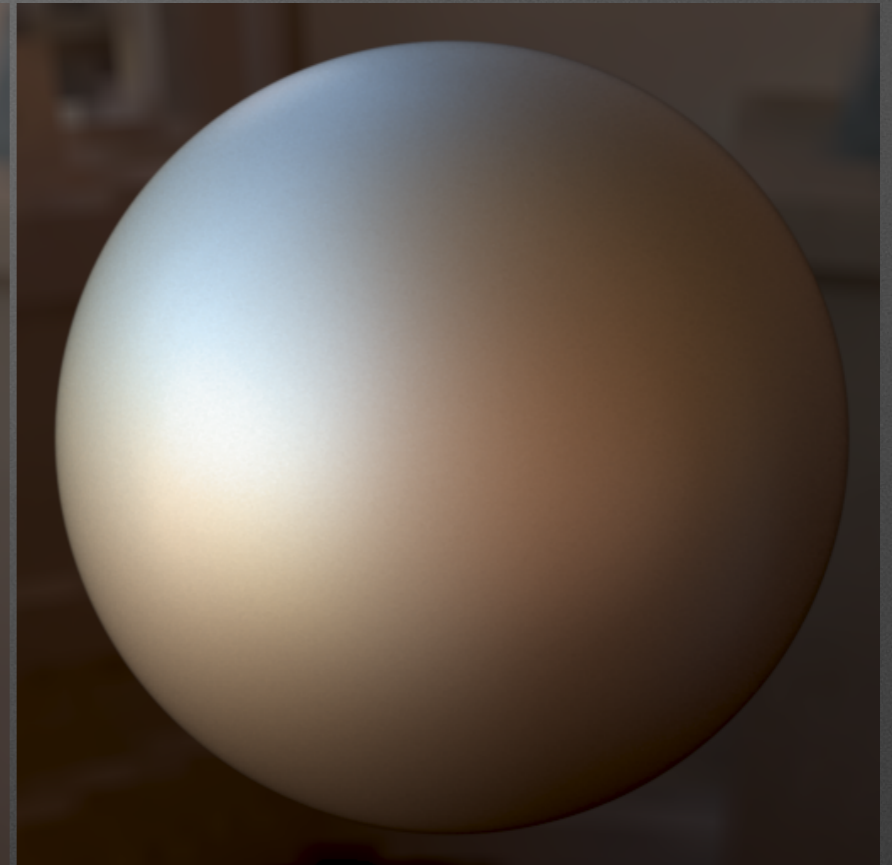
Diffraction Parameters Behaviour



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

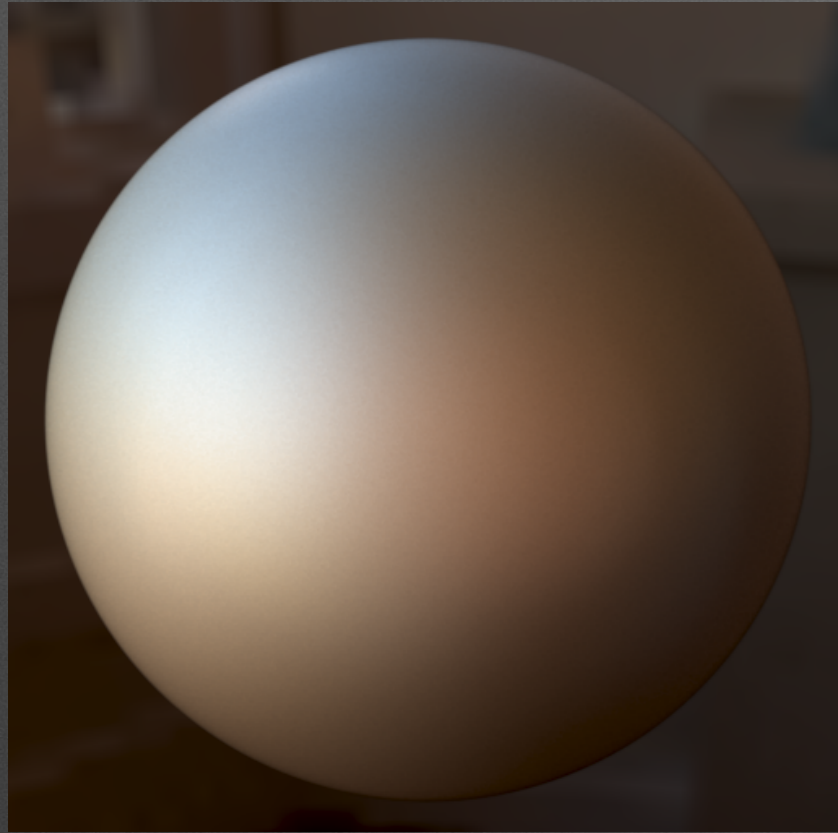


$$\sigma_s \times 1, b \times 1$$



$$\sigma_s \times 4, b \times 4$$

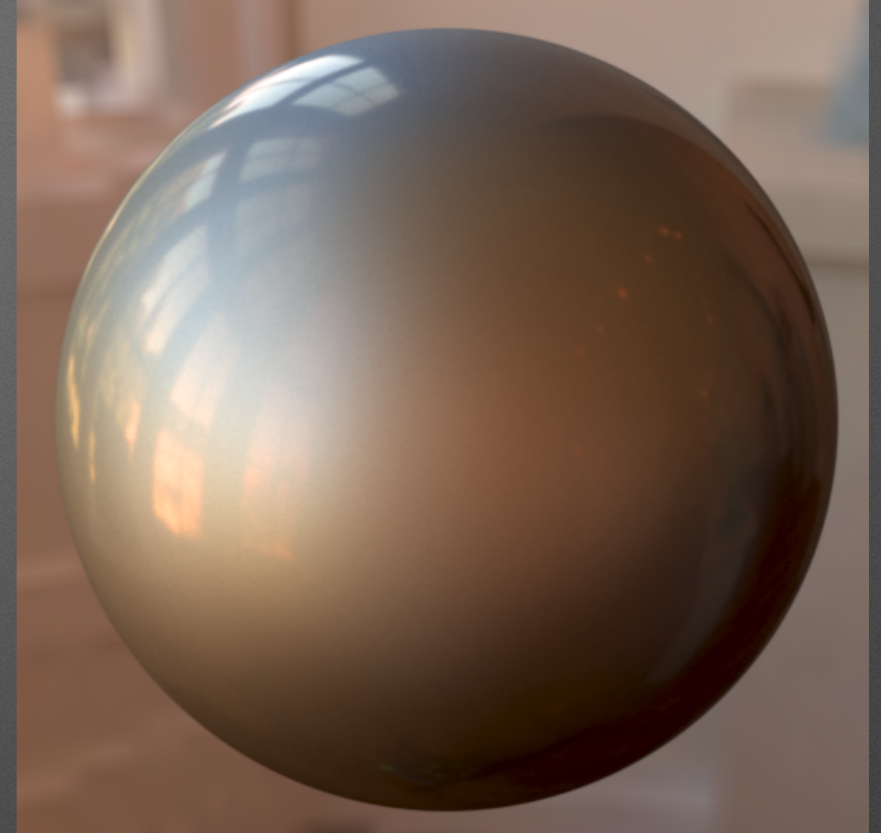
Specular Lobe Behavior



$$\beta \times 4$$



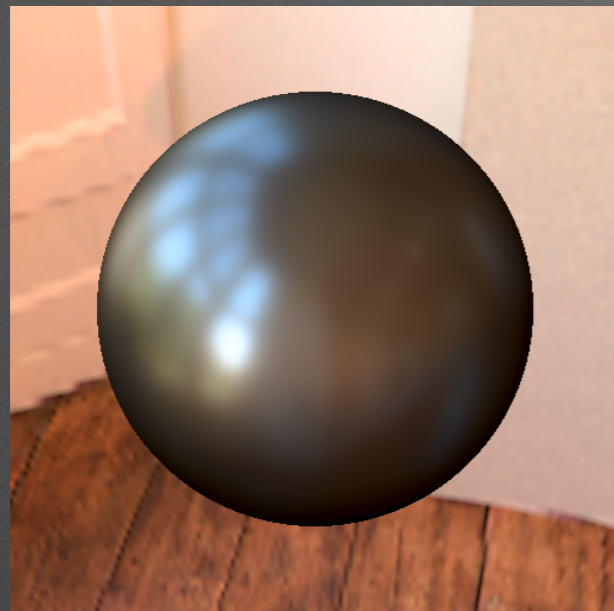
$$\beta \times 1$$



$$\beta / 4$$

Diffraction parameters remain unchanged

Comparison for Nickel



Diffraction

+

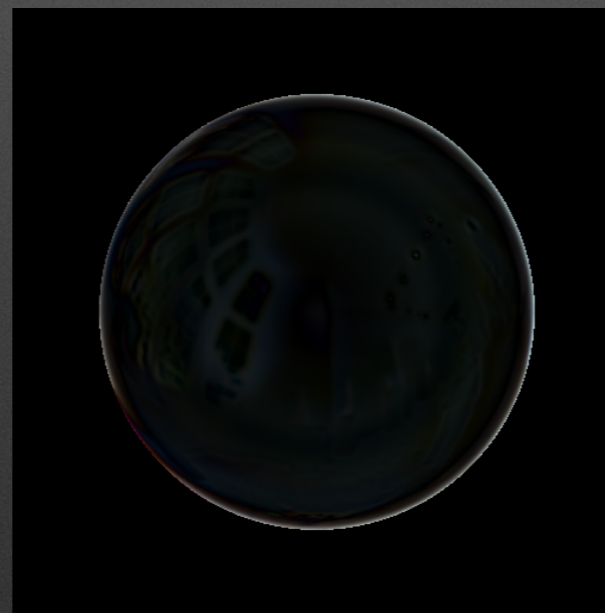


Microfacet

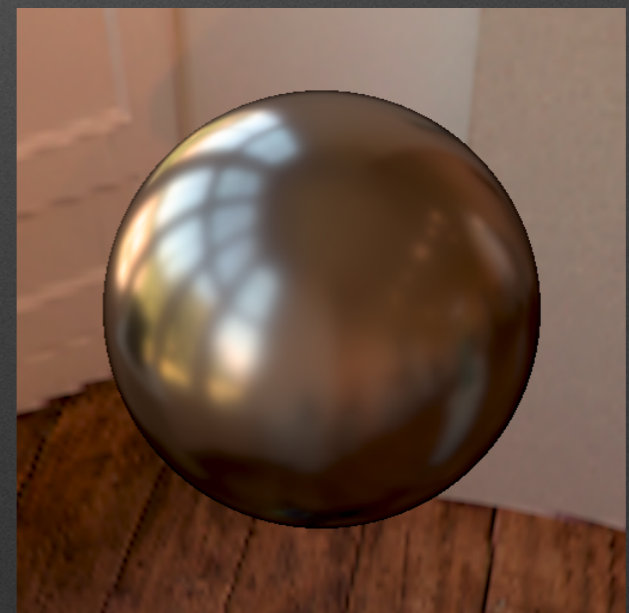
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Model

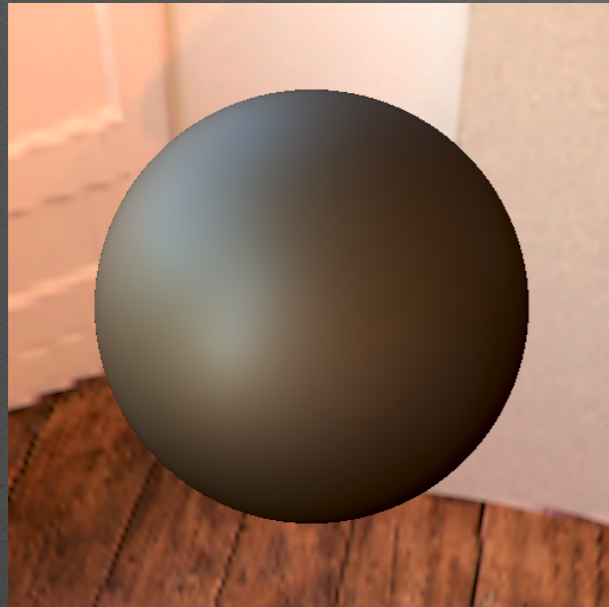


Difference



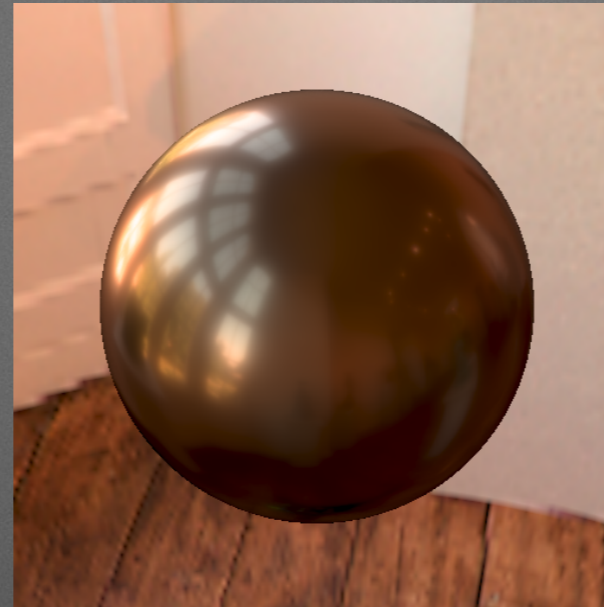
Reference

Comparison for Alum-Bronze



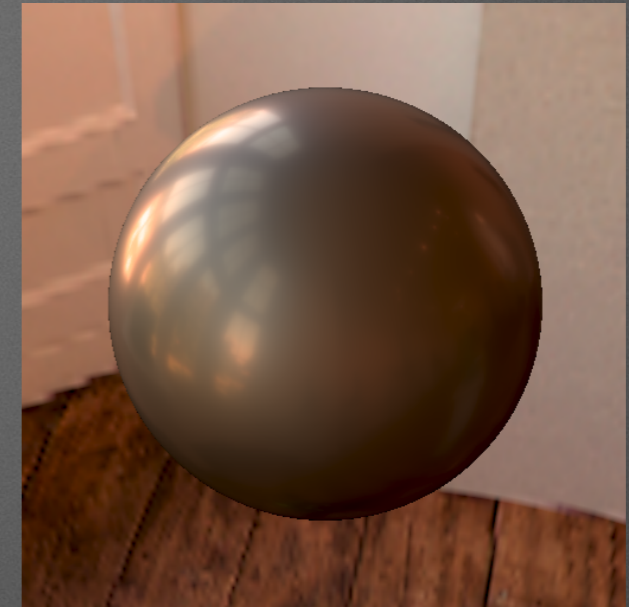
Diffraction

+

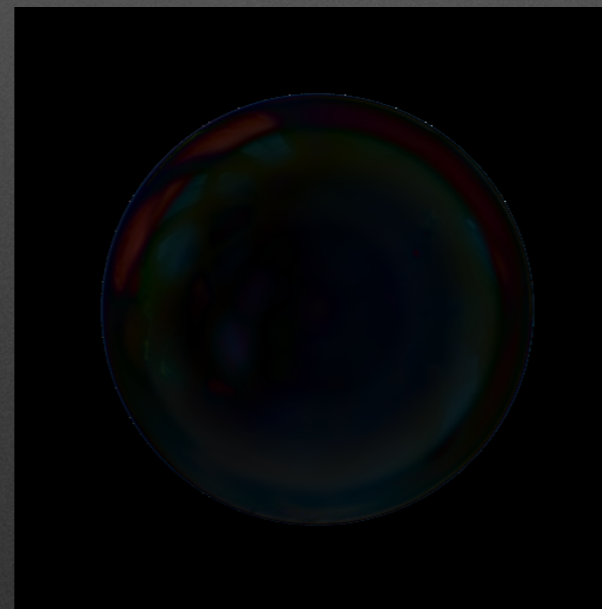


Microfacet

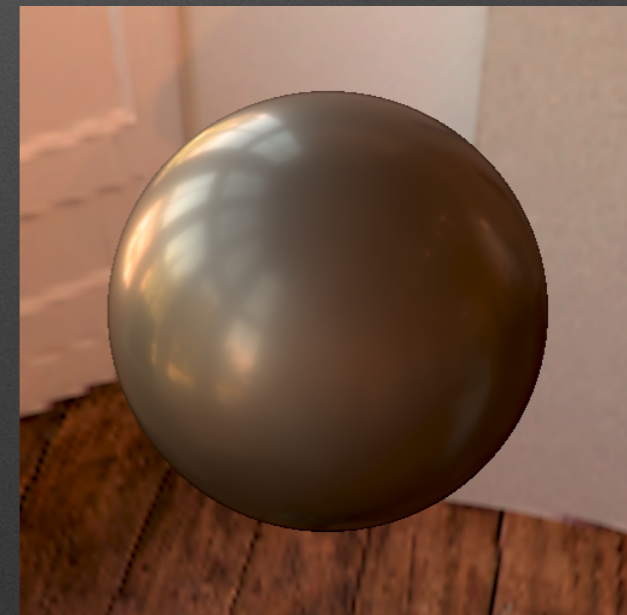
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Model

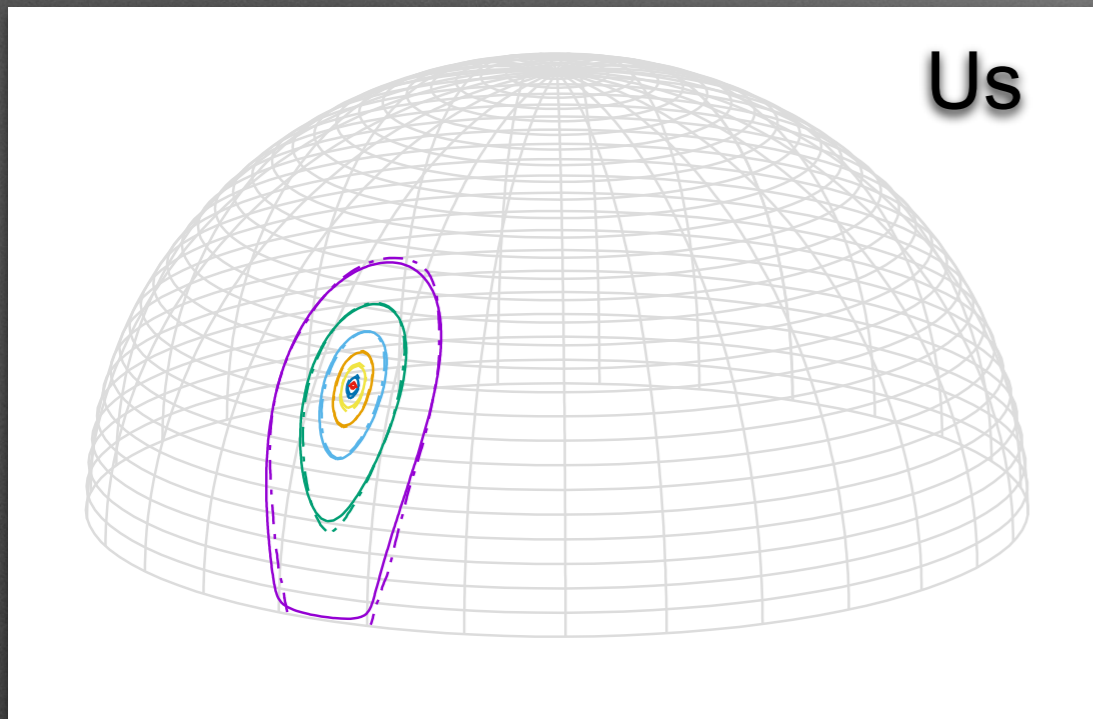


Difference



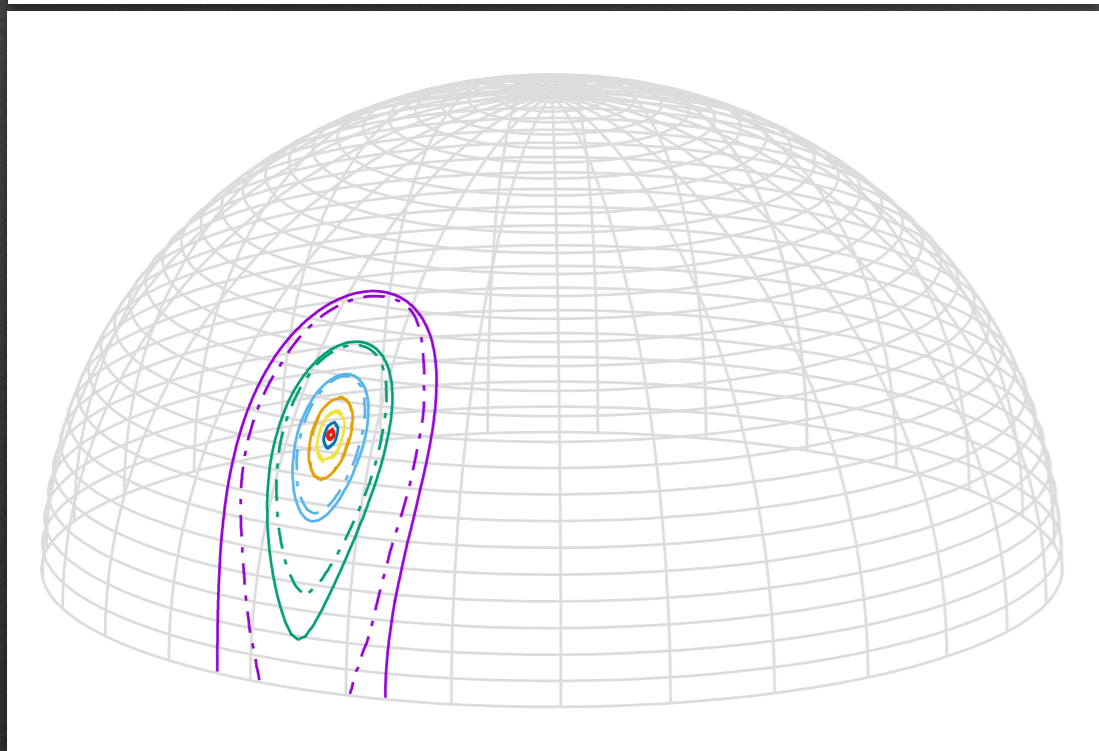
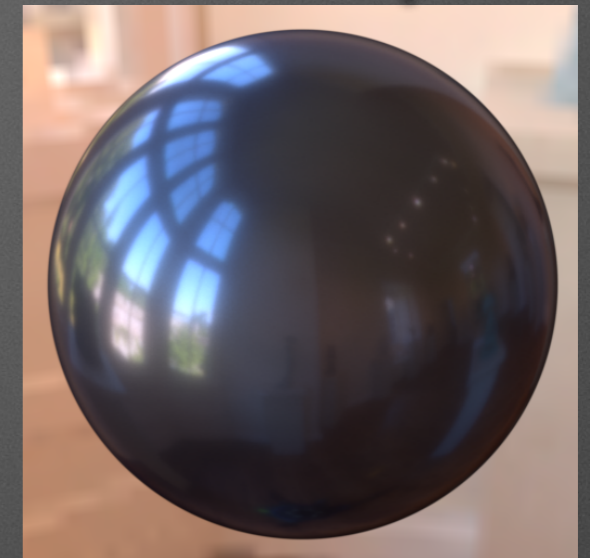
Reference

Fitting Results **outside** the Incident Plane

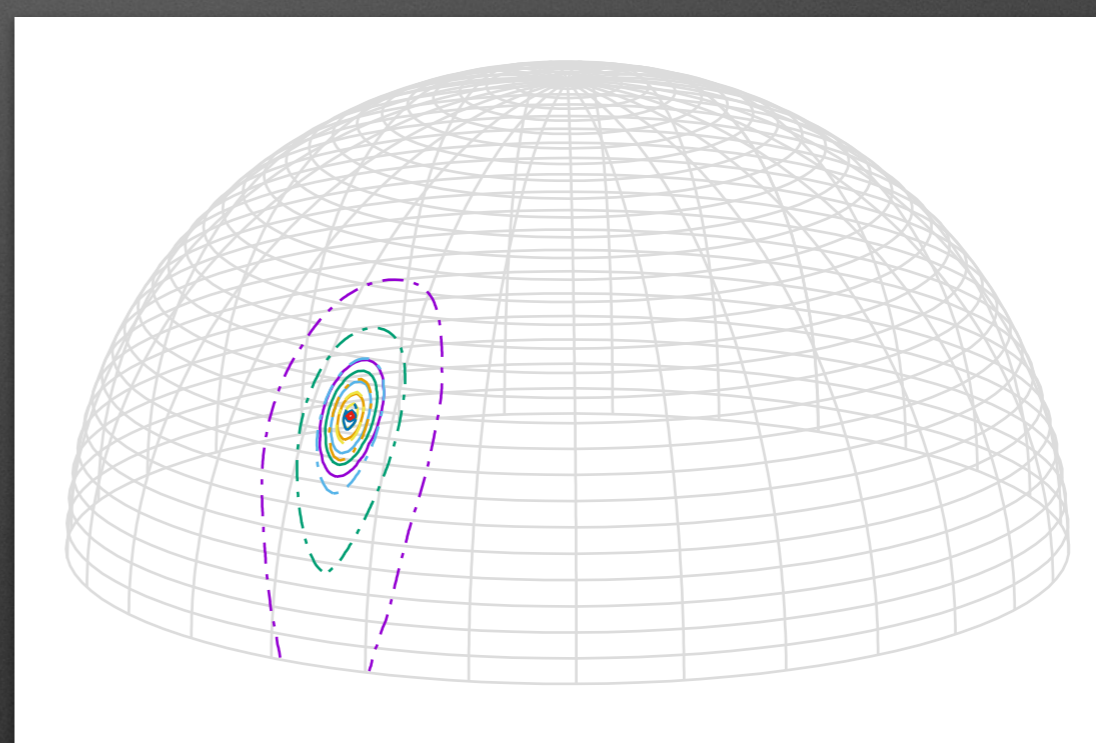


Estimation	Measured
90 %	-----
30 %	-----
10 %	-----
3 %	-----
1 %	-----
0.3 %	-----
0.1 %	-----
0.03 %	-----

blue-metallic-paint2

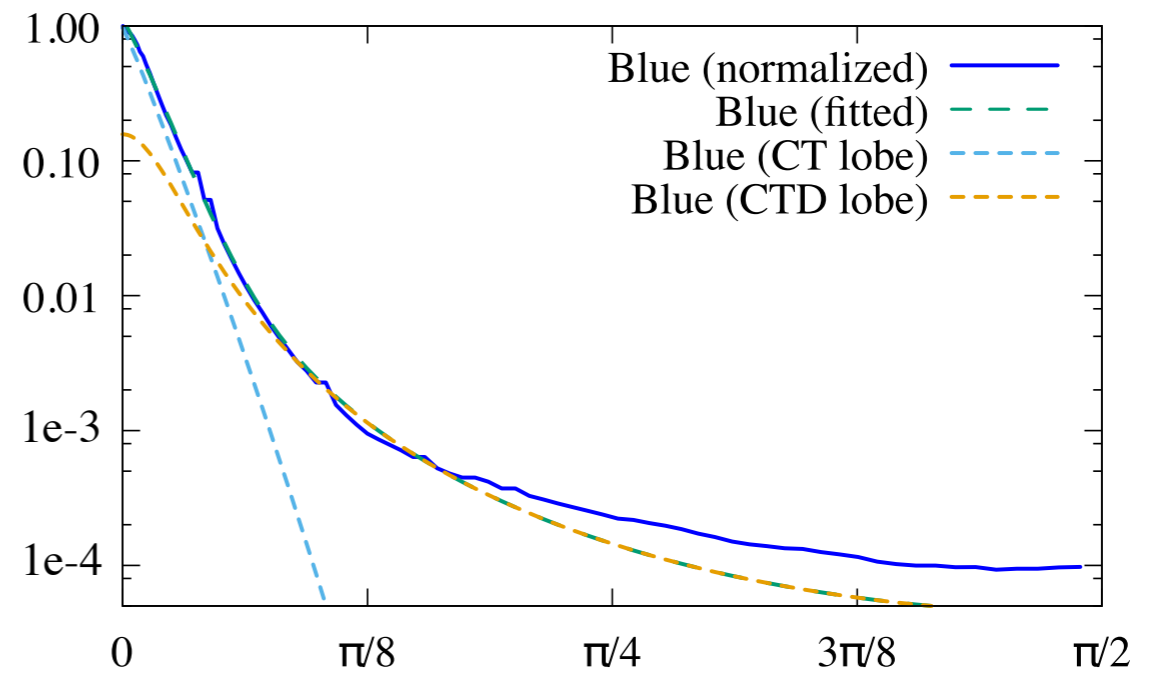
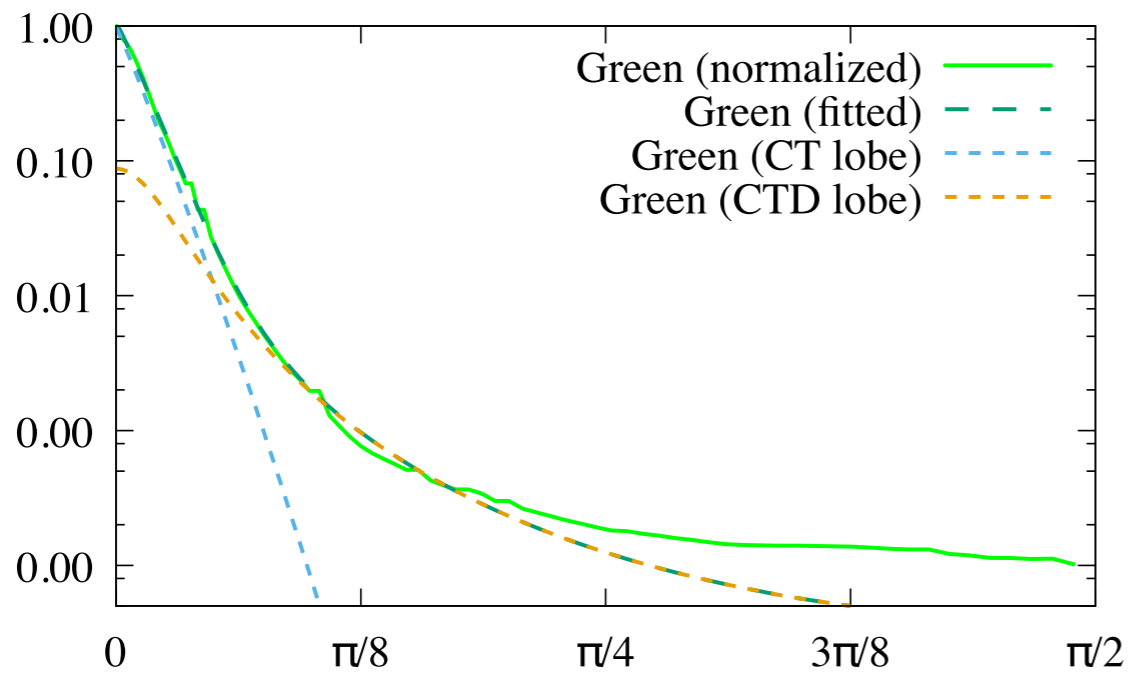
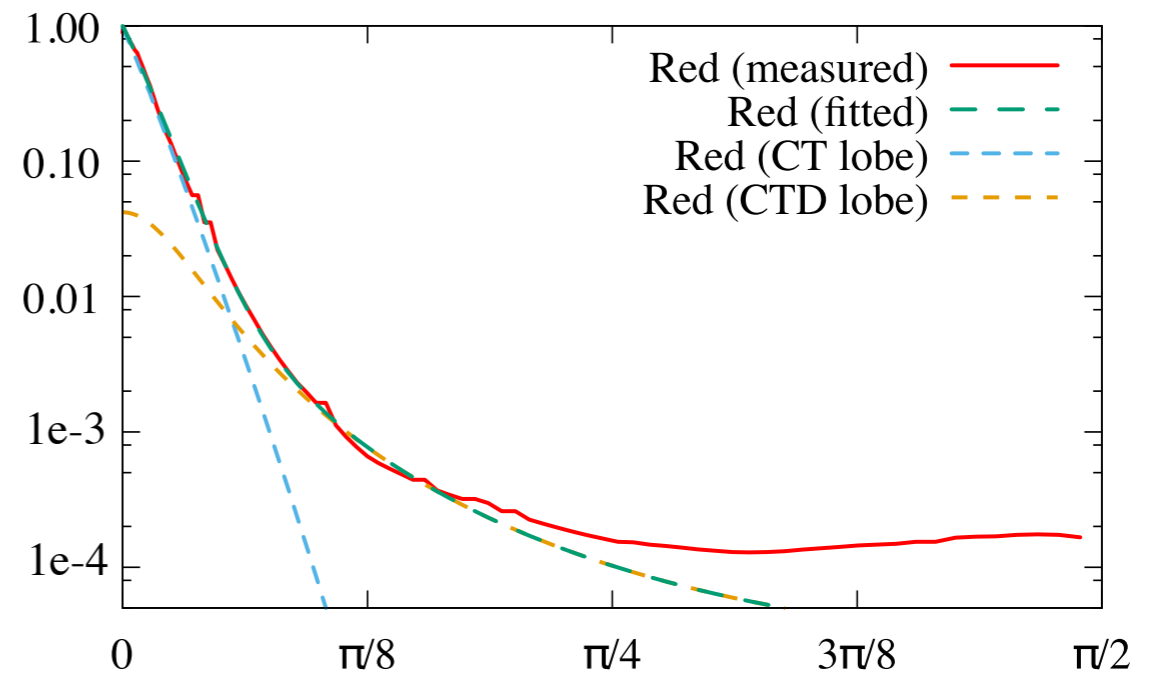
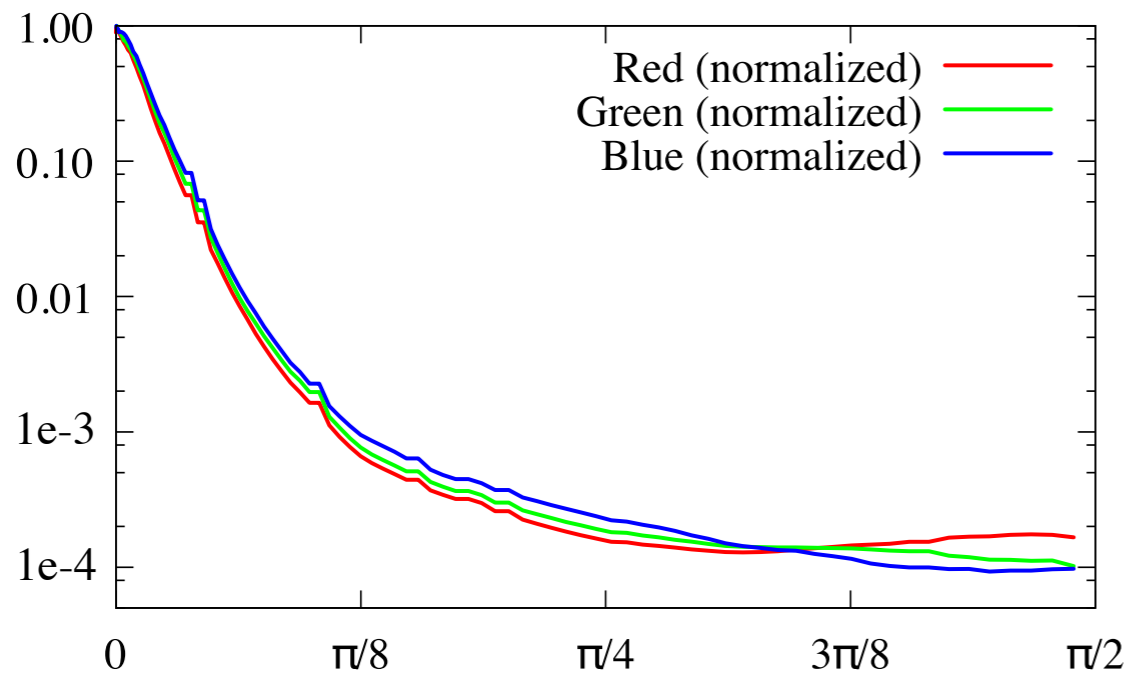


Löw et al. (diffraction only)



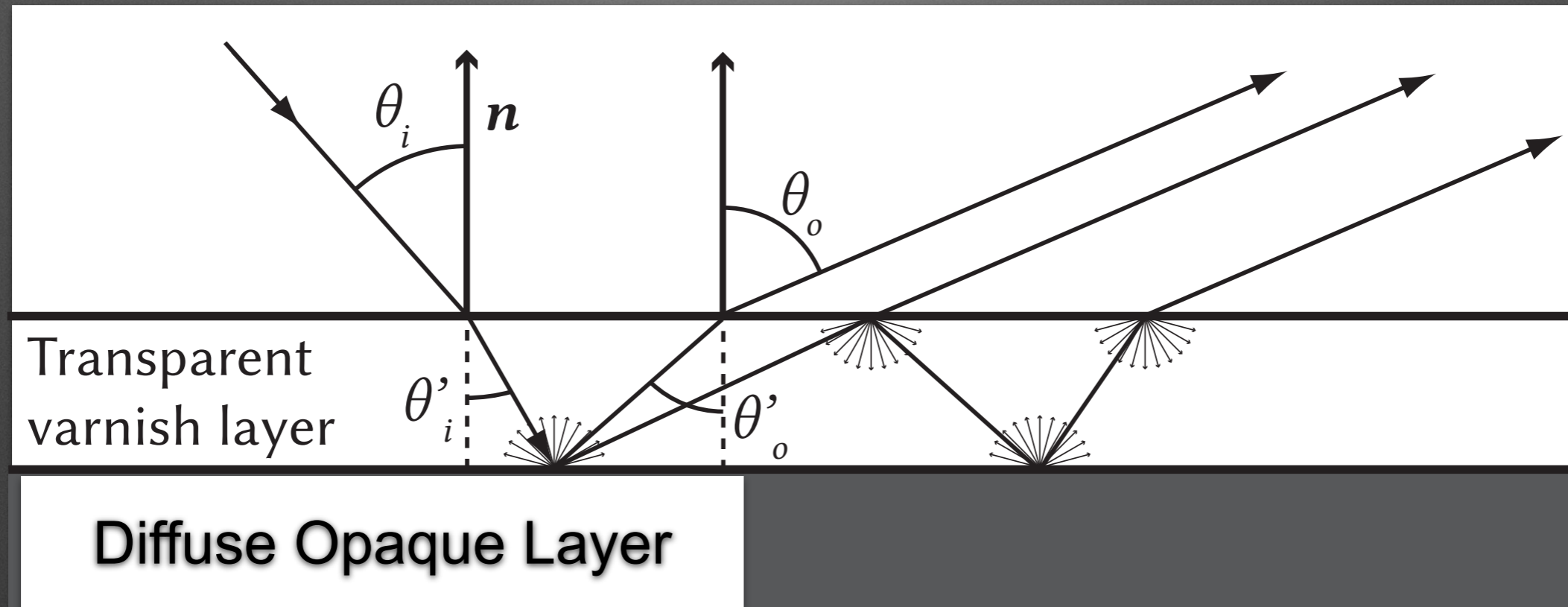
SGD (microfacet only)

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

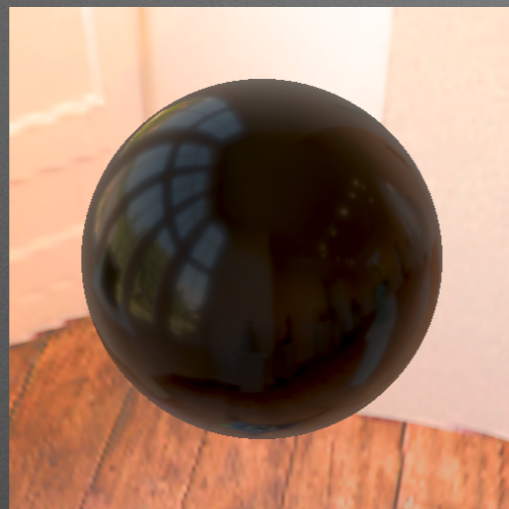
Results for Plastic Model

- Varnish on a diffuse surface:



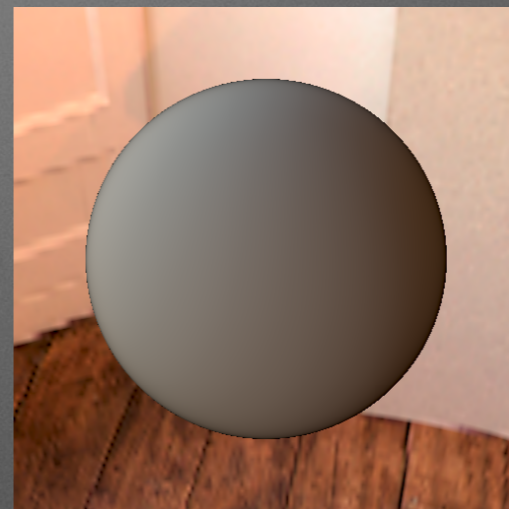
Diffraction

+



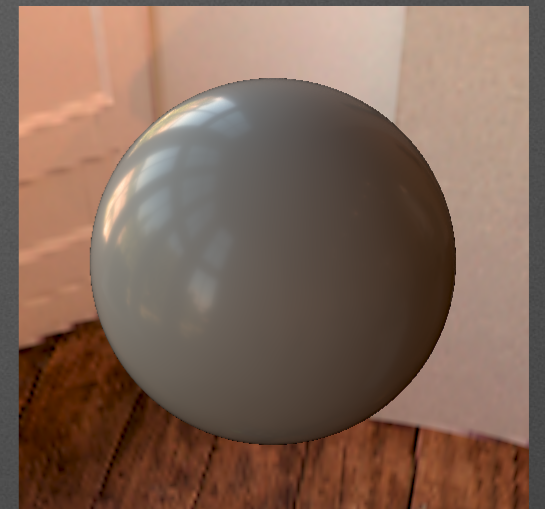
Microfacet

+



Diffuse

=

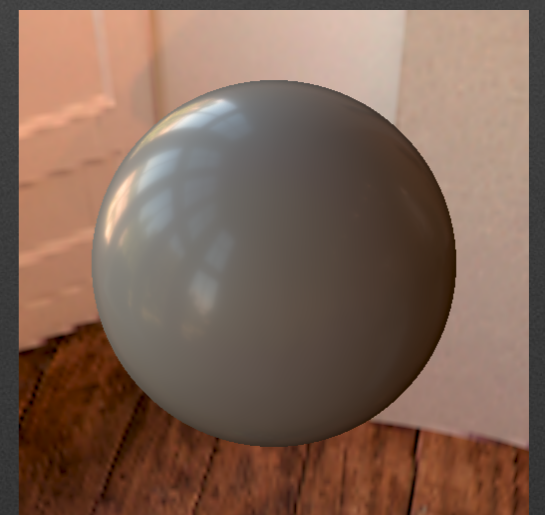


Model

Gray-Plastic Material

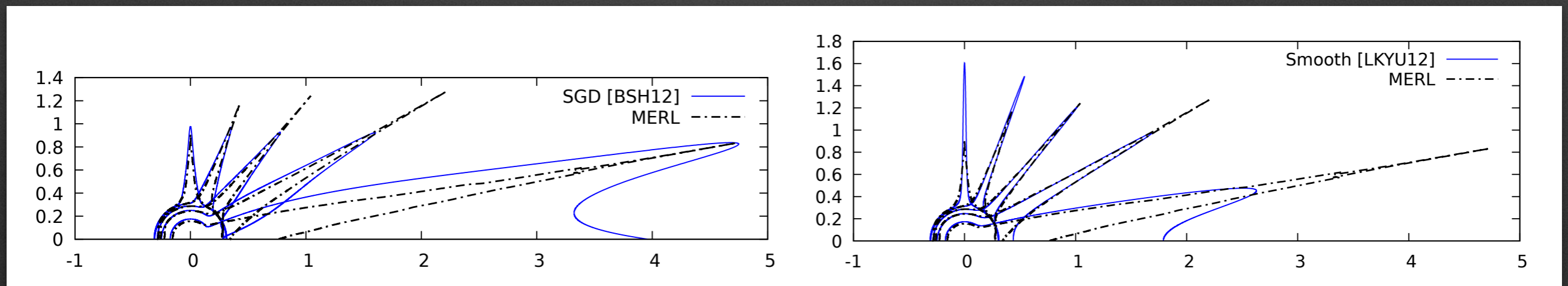
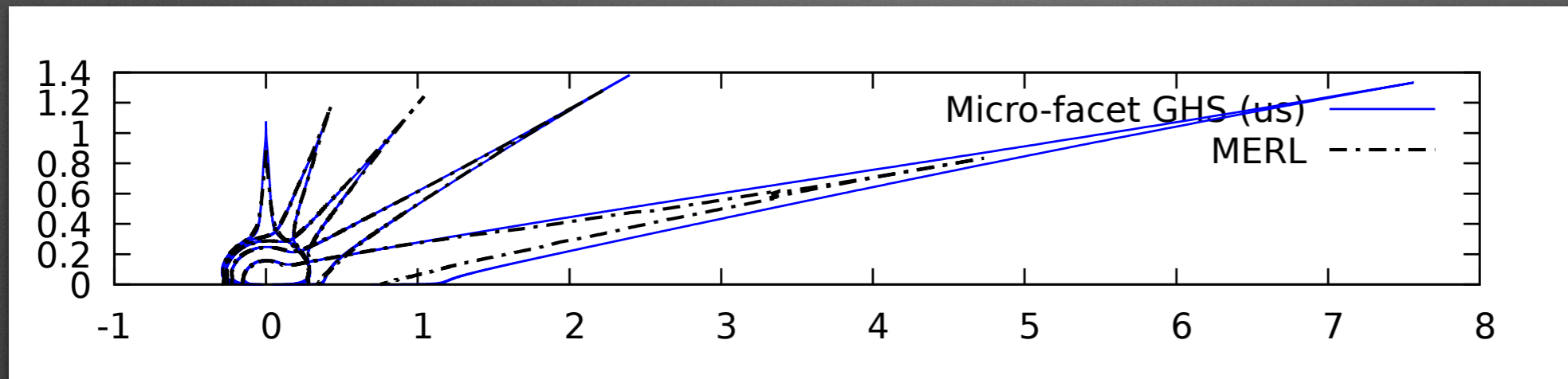


Difference

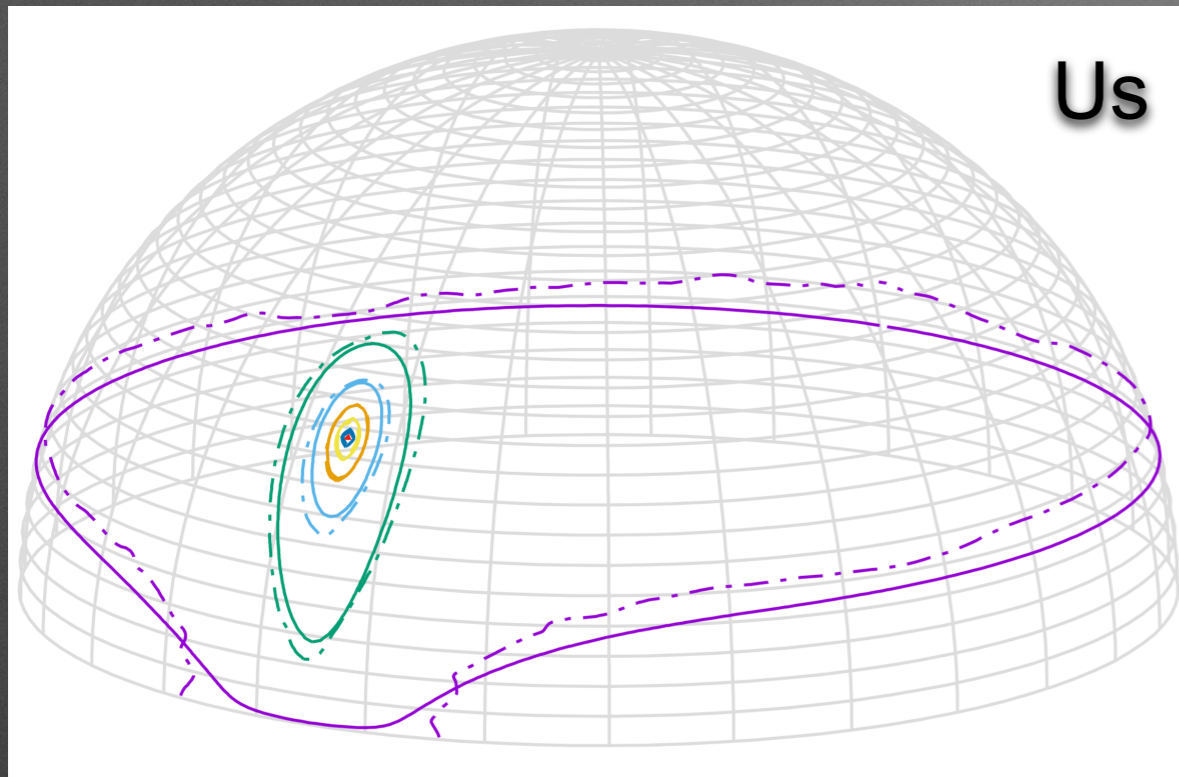


Reference

Fitting Results in Incident Plane



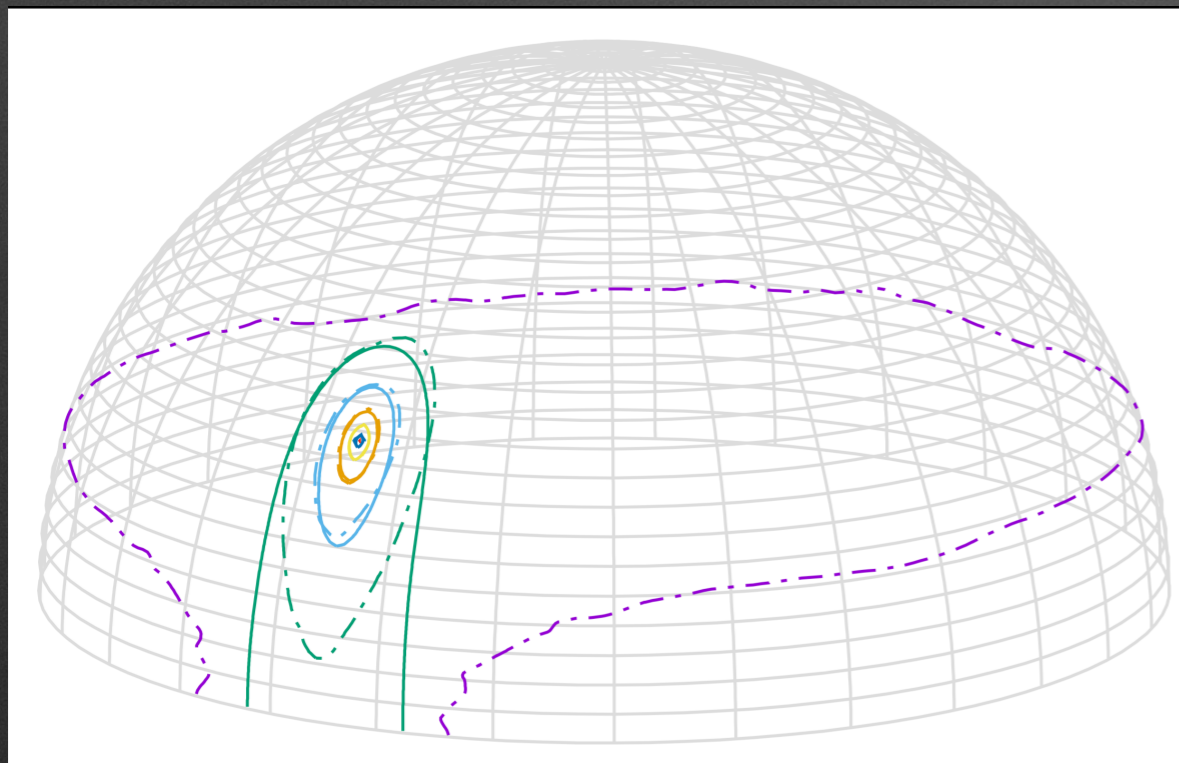
Fitting Results **outside** Incident Plane



Our Model

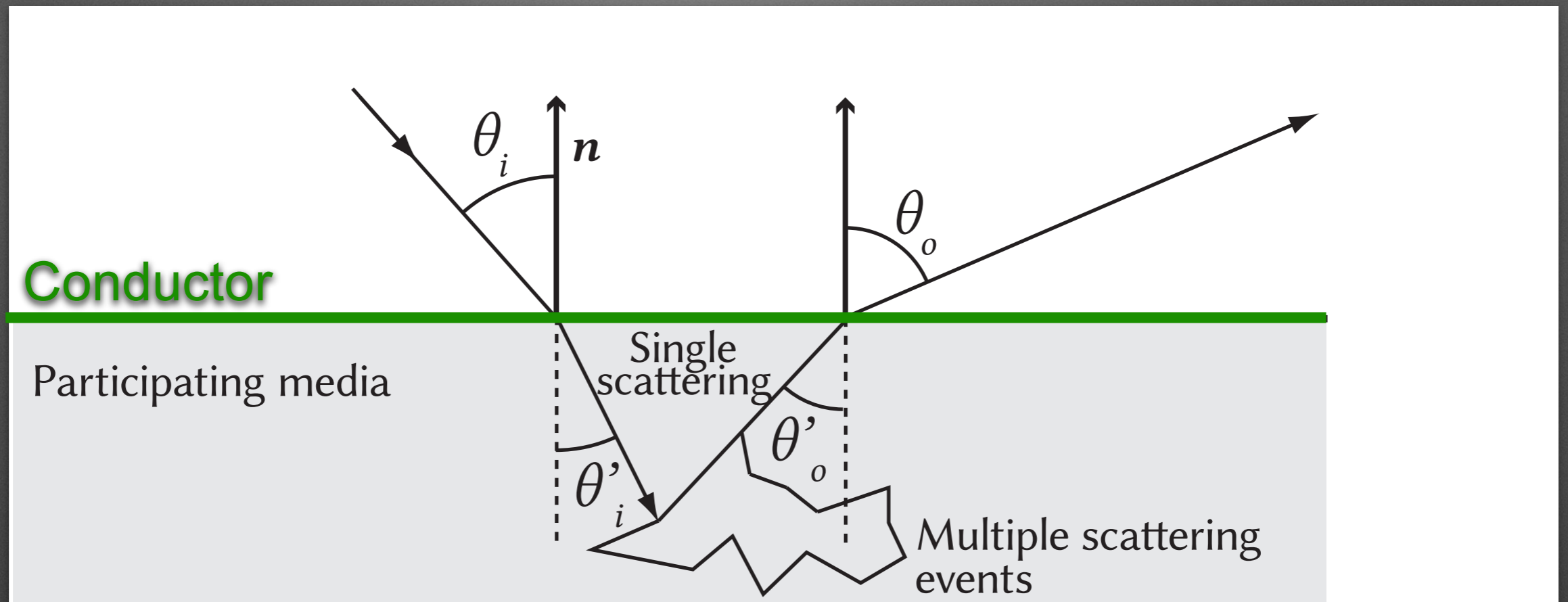


Gray-plastic



Löw et al. (diffraction only)

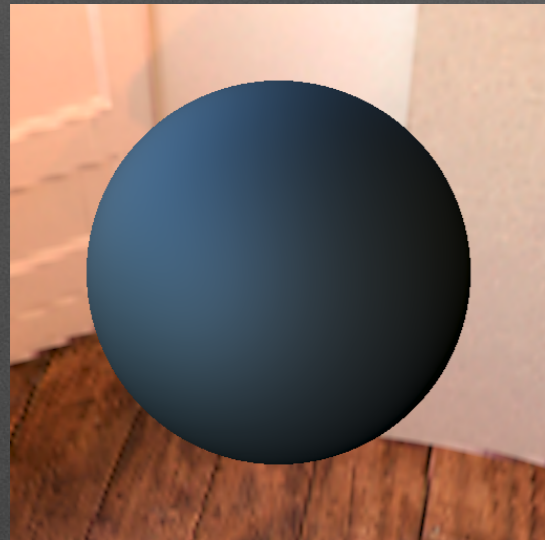
Two-Layer Model for Subsurface



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

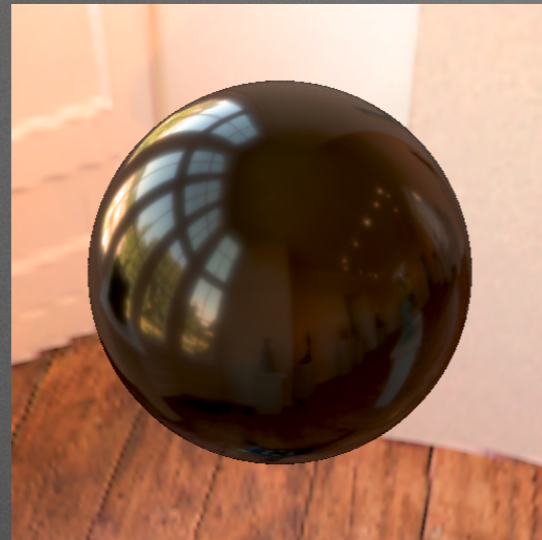
Subsurface Model from Jensen et al. Sigg. 2001

Result for Subsurface Model



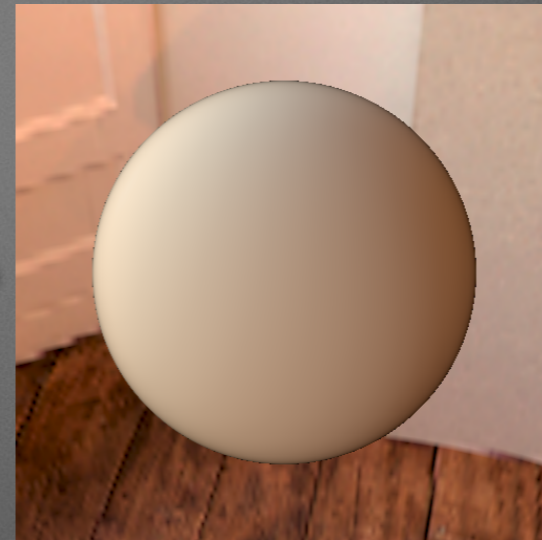
Diffraction

+



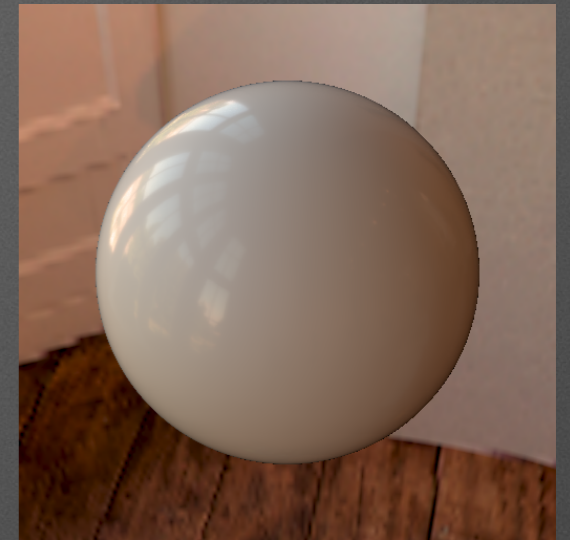
Microfacet

+



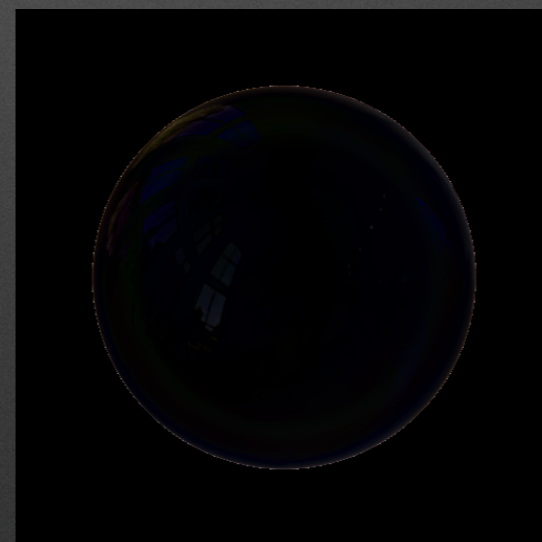
Diffuse

=

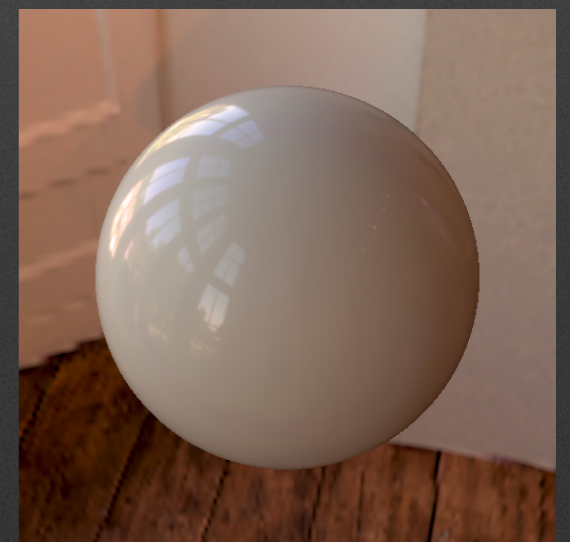


Model

Alumina-oxide Material



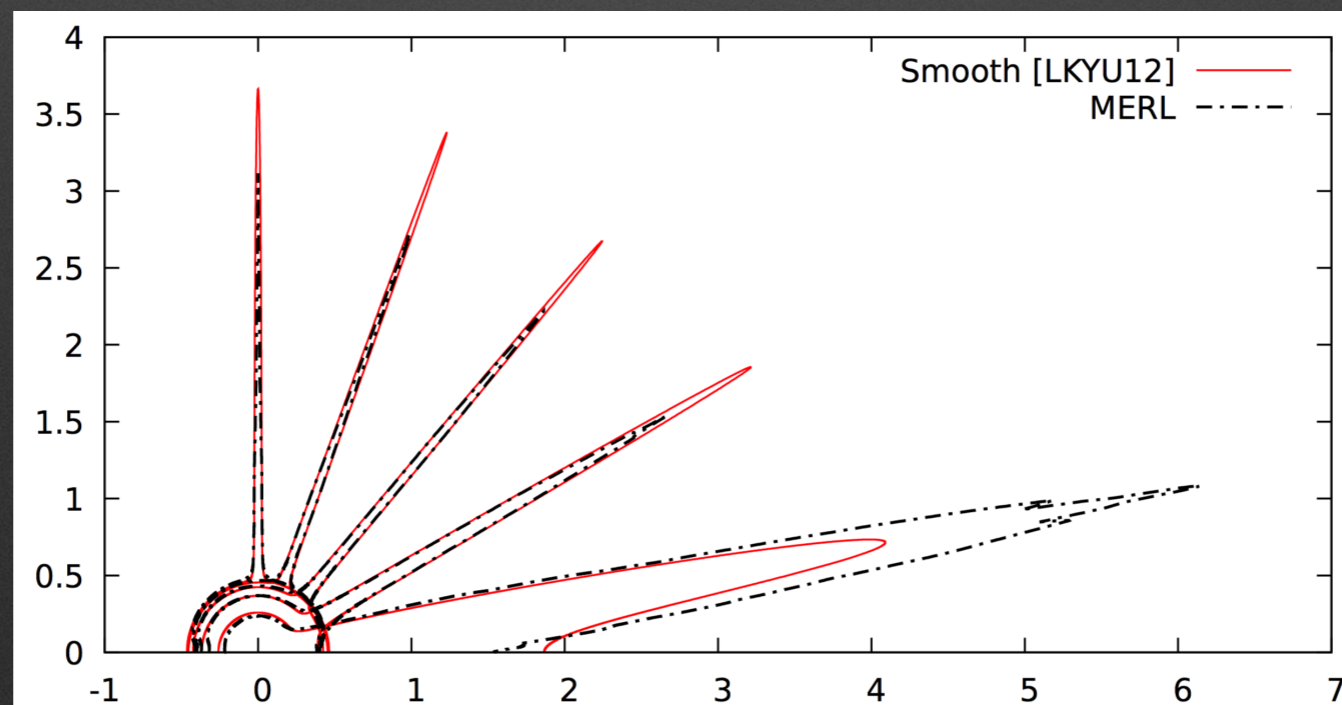
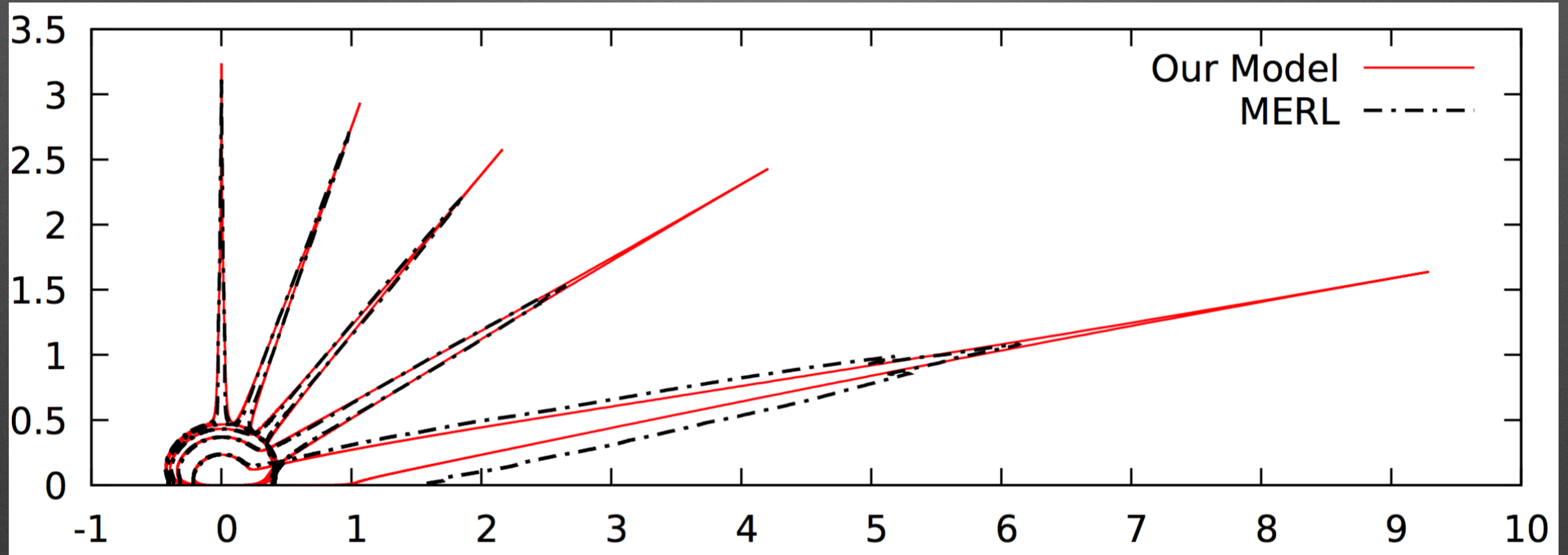
Difference



Reference

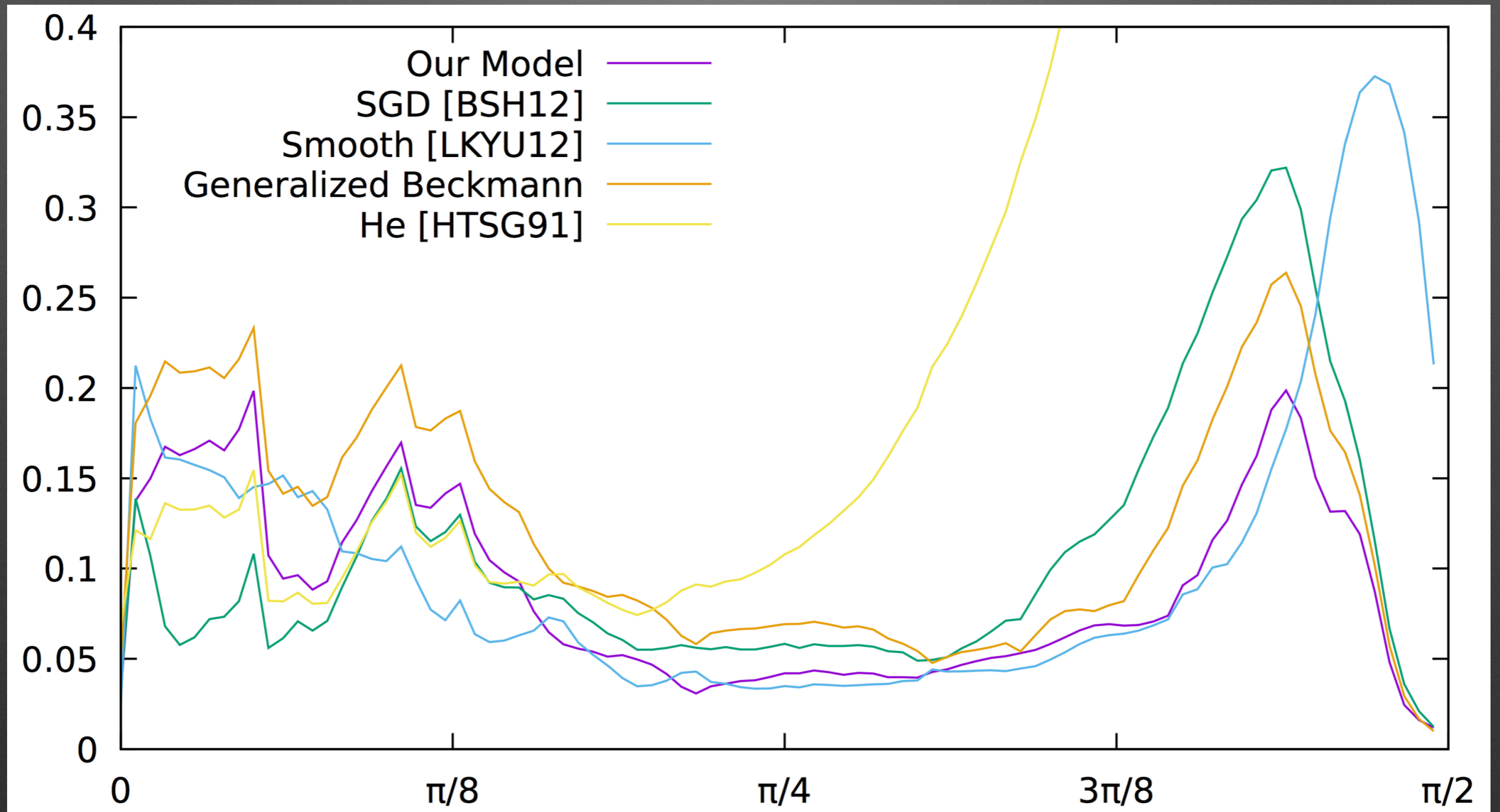
Result for Subsurface Model

ALUMINA-OXYDE



Result for Subsurface Model

ALUMINA-OXYDE

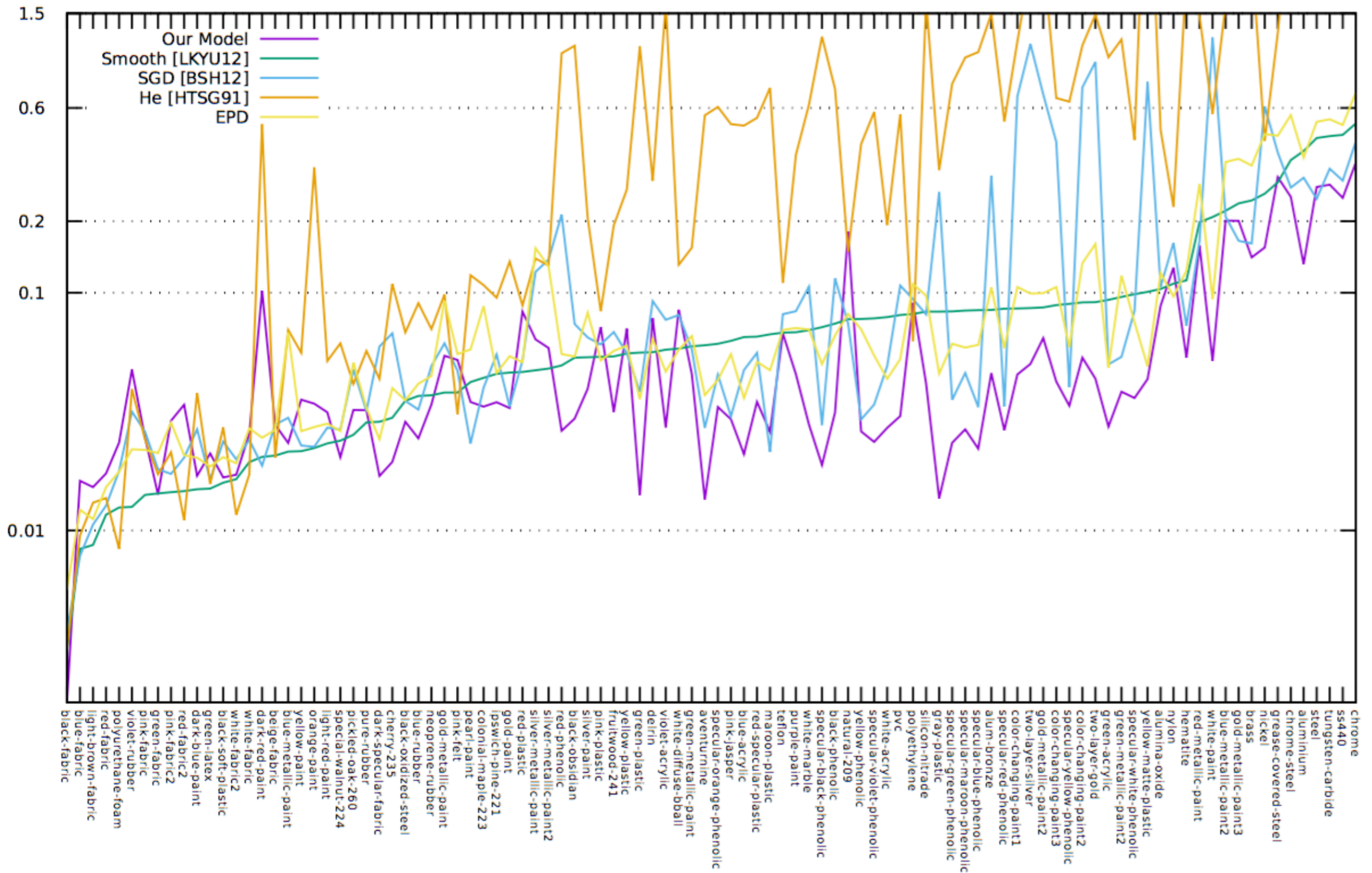


RMS Error of BRDF * cosine

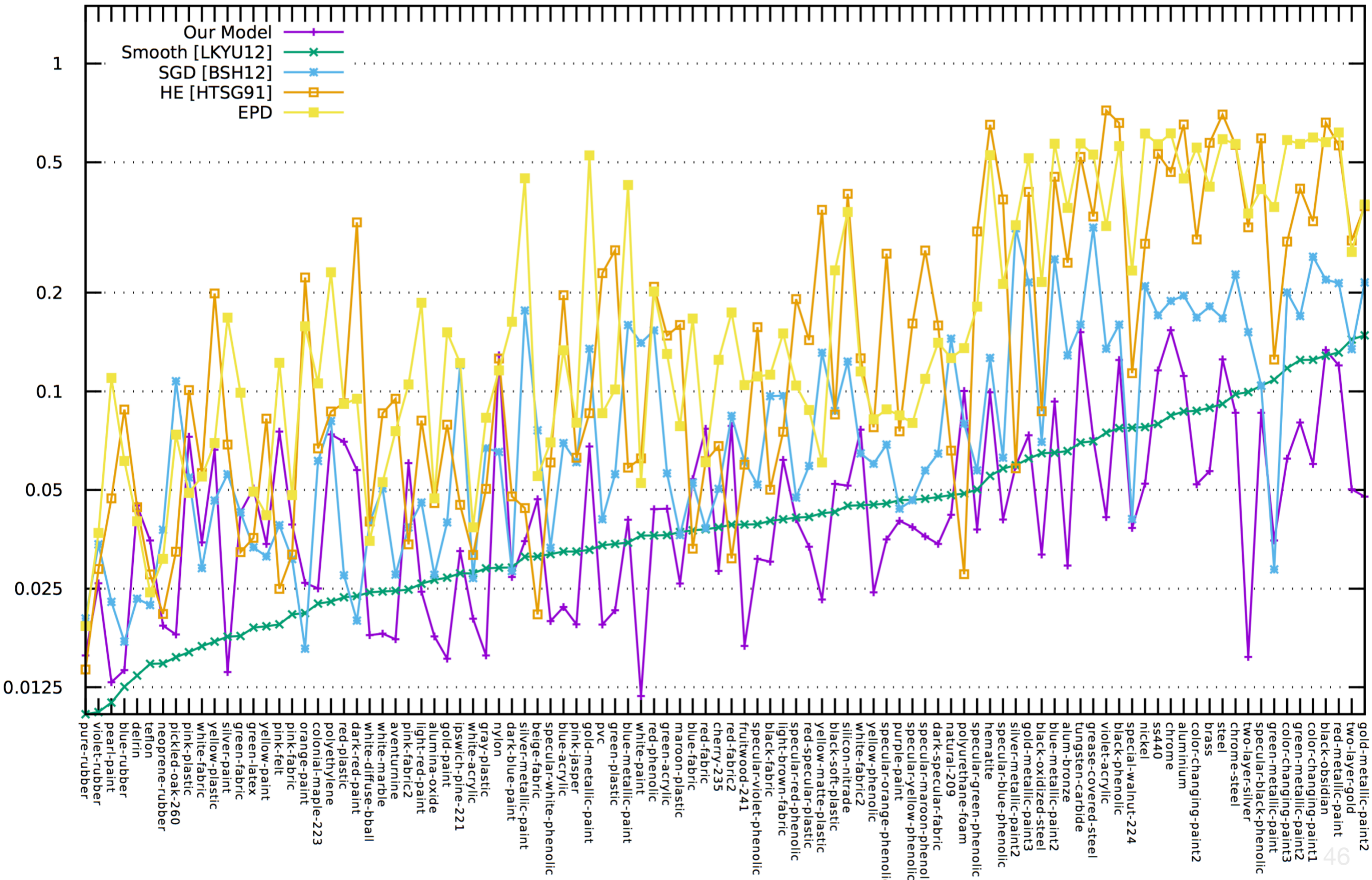
Fitting Strategy

- Similar to Bagher et al. 2016
 - Compressive Weights \Leftrightarrow 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

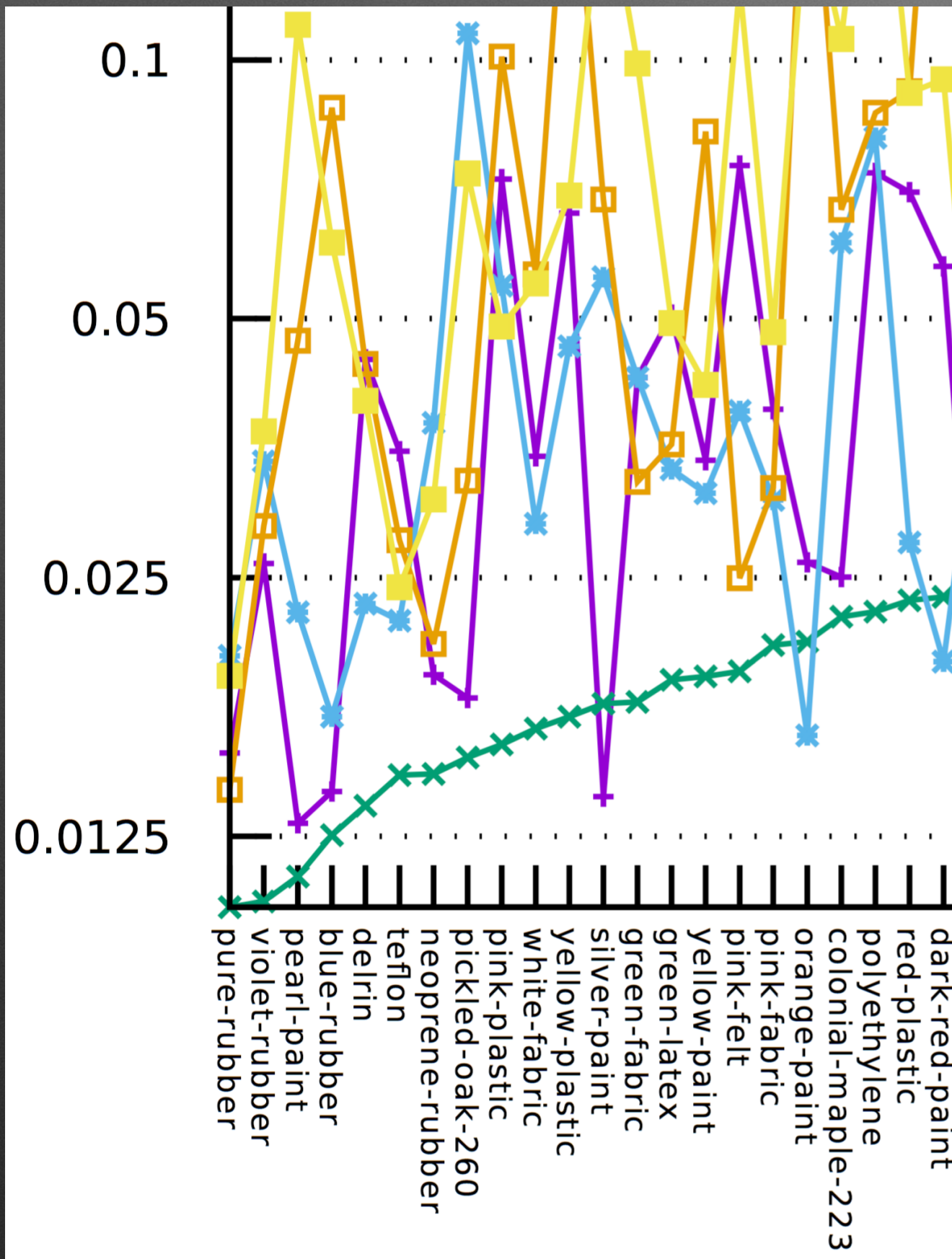
General Fitting Comparisons



Rendering Comparisons : SMAPE Metric



Rendering Comparisons : SMAPE Metric

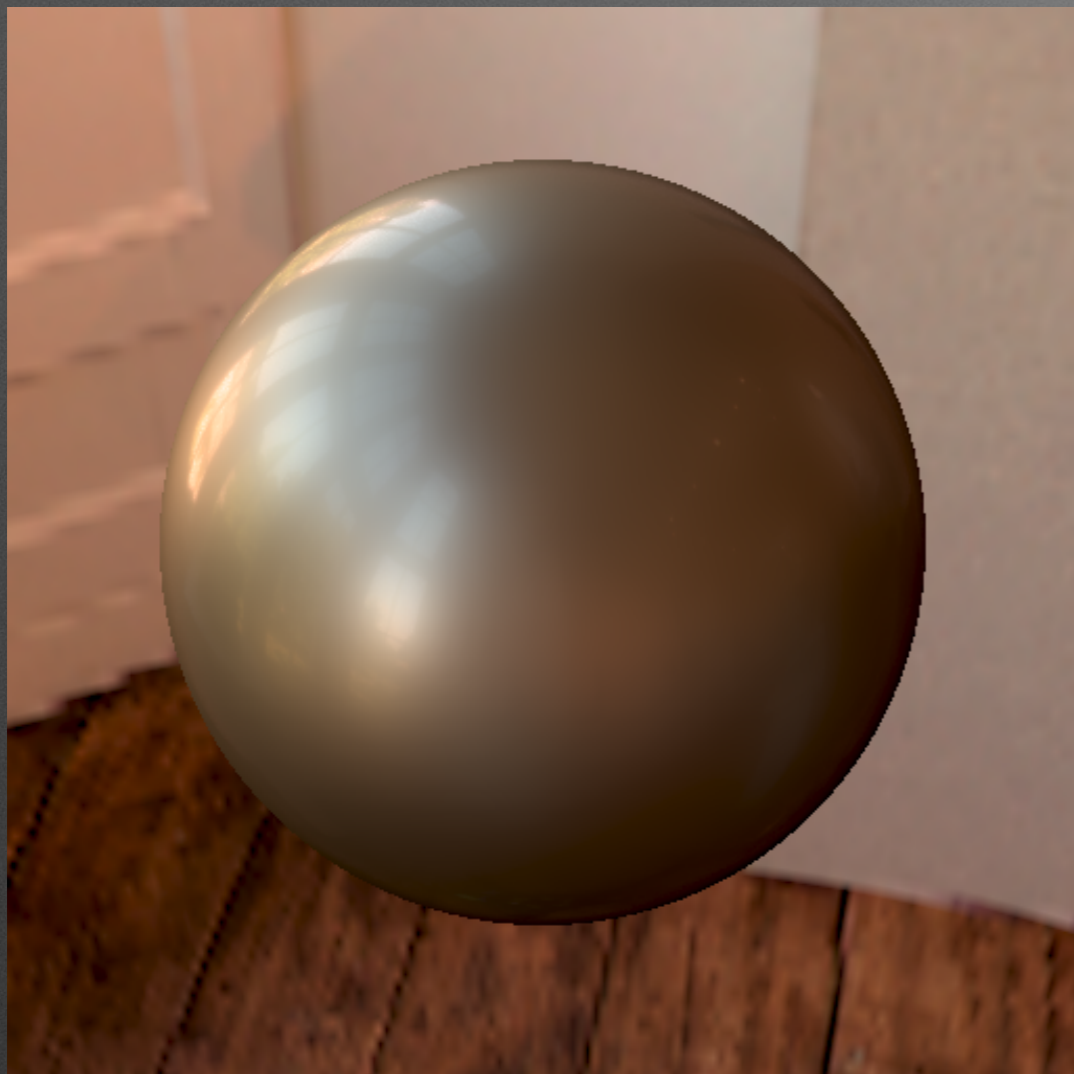


Bad Fits:

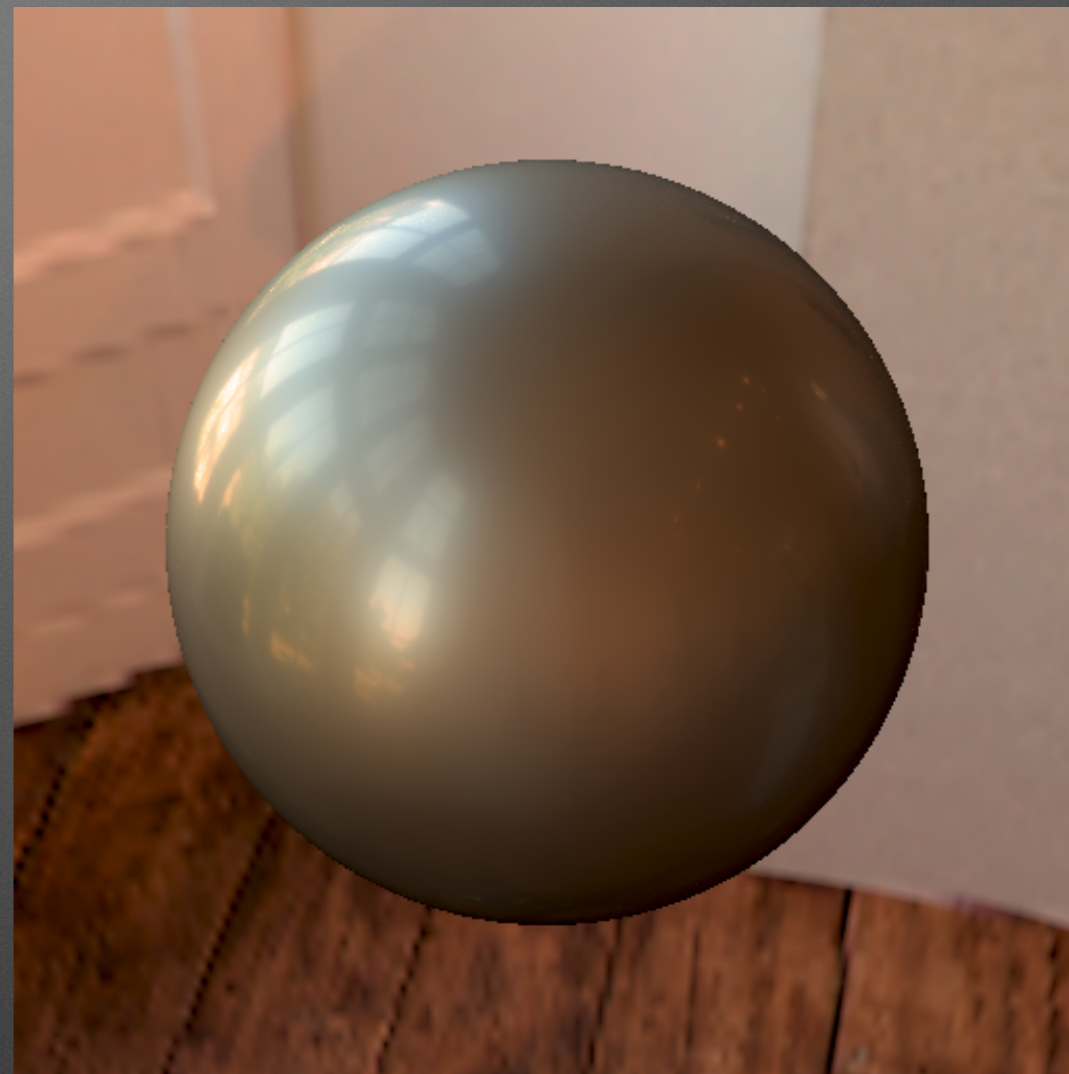
Pink Plastic

Pink Felt

Gold-Metallic Paint 2

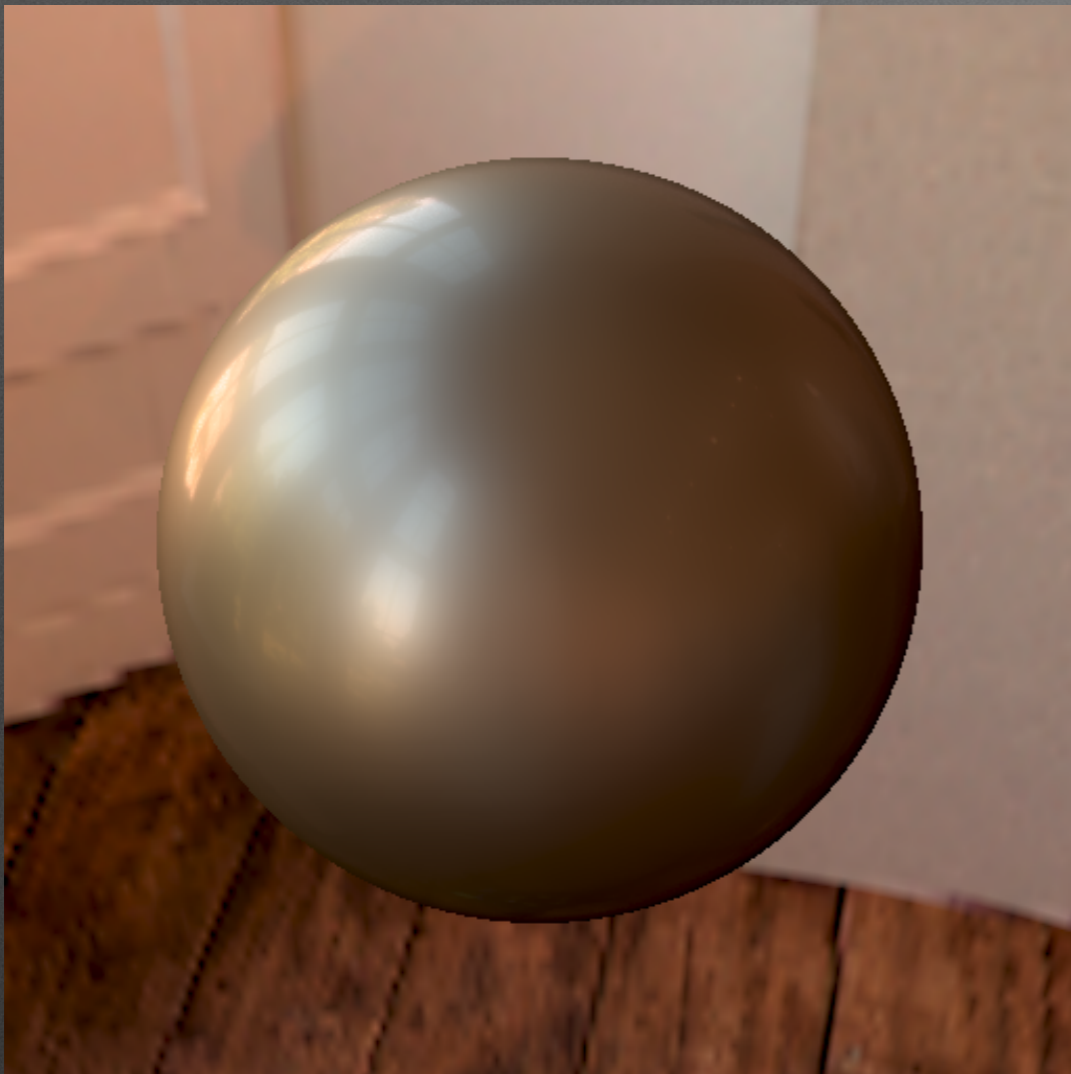


Merl Data Reference

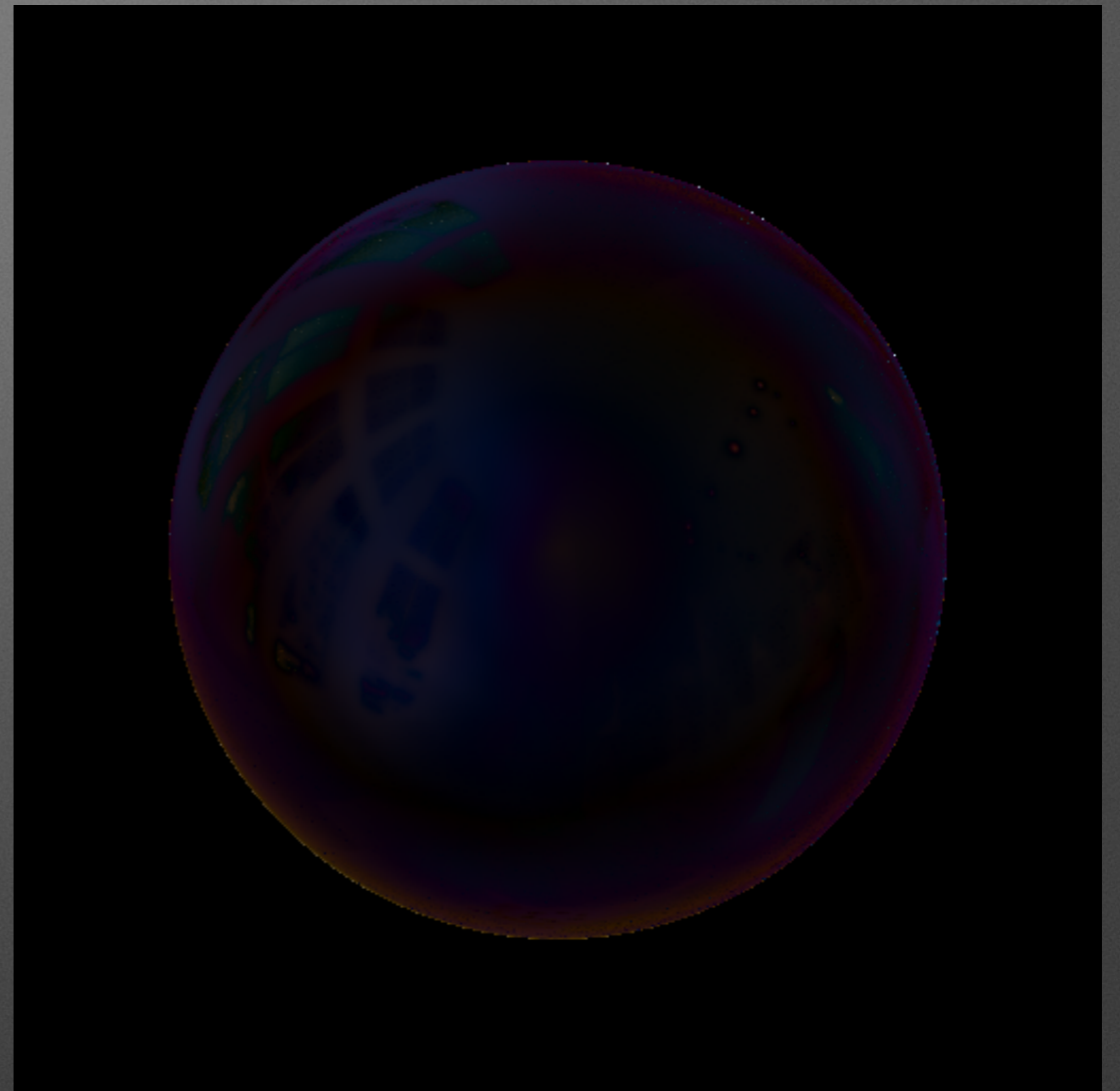


Our Model

Gold-Metallic Paint 2

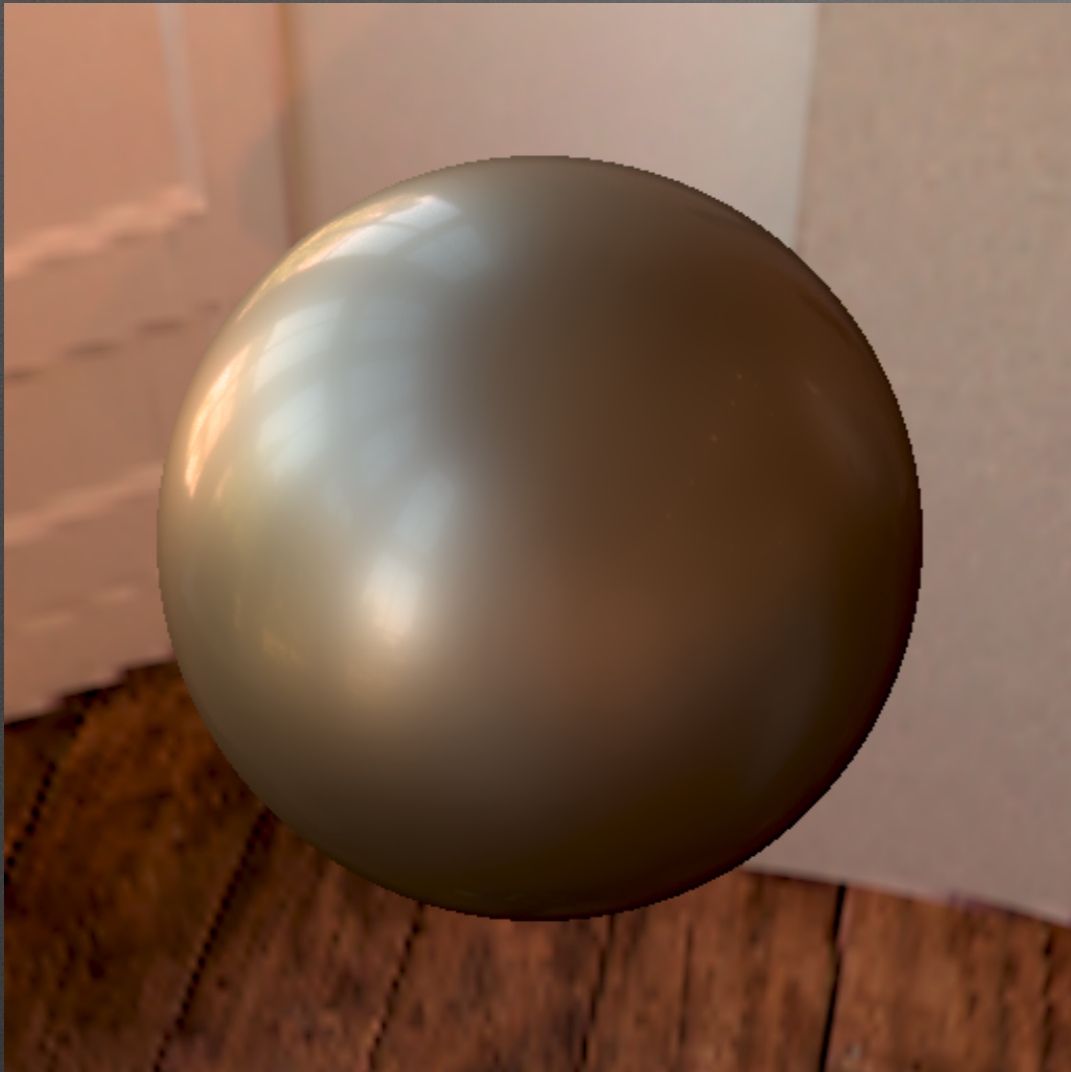


Merl Data Reference

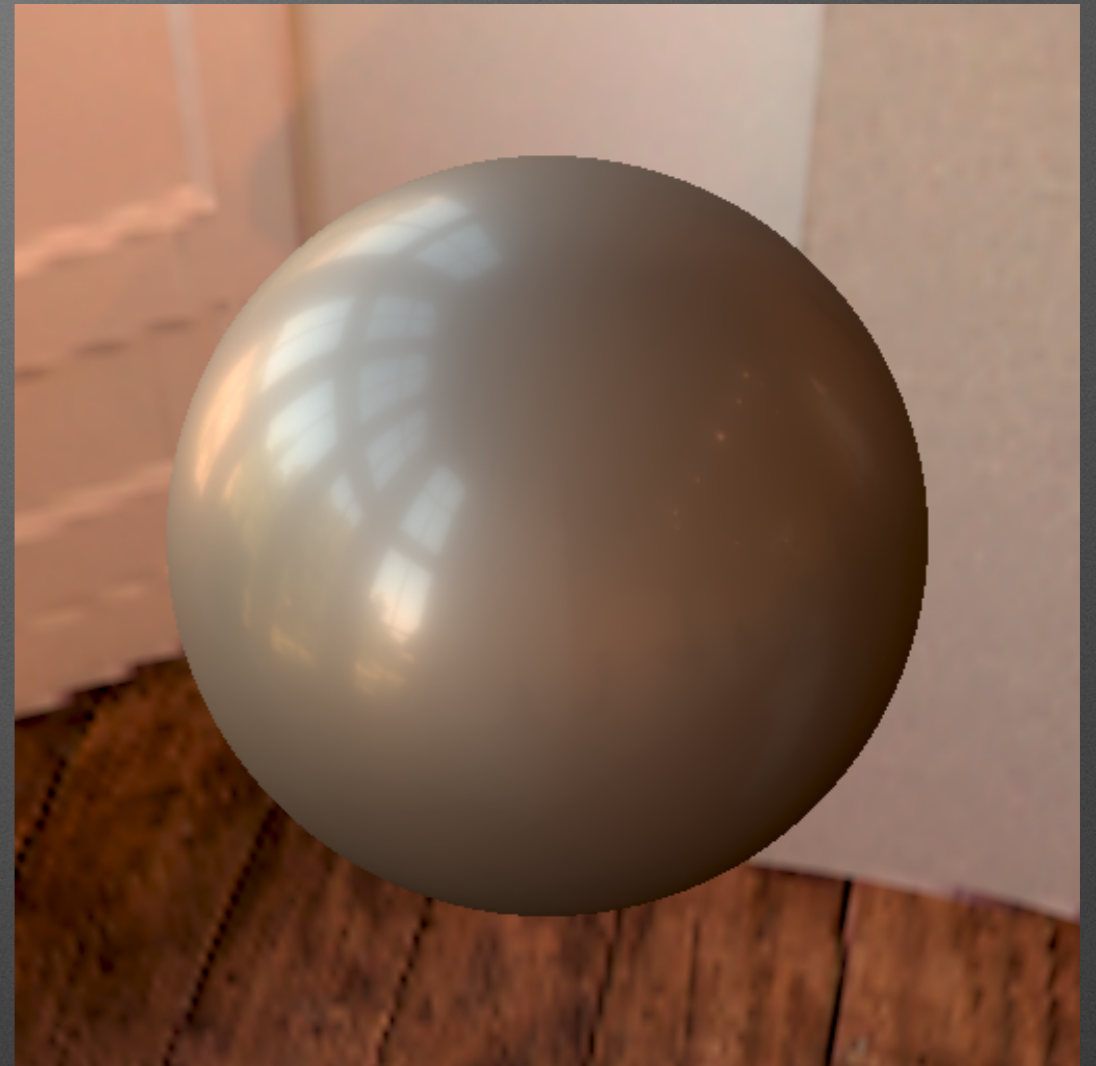


Our Model
Difference sMAPE:0.048

Gold Metallic Paint2

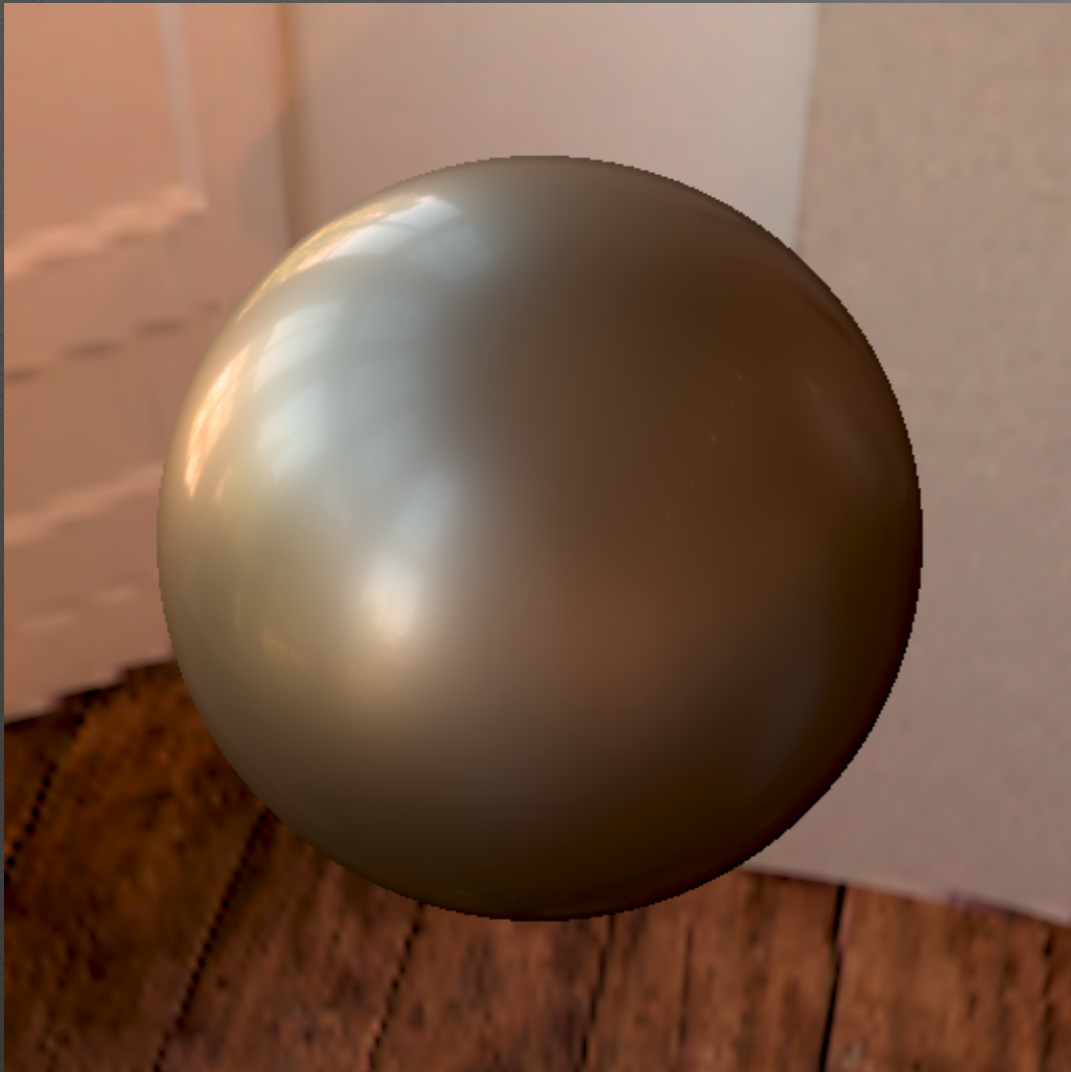


Merl Data Reference

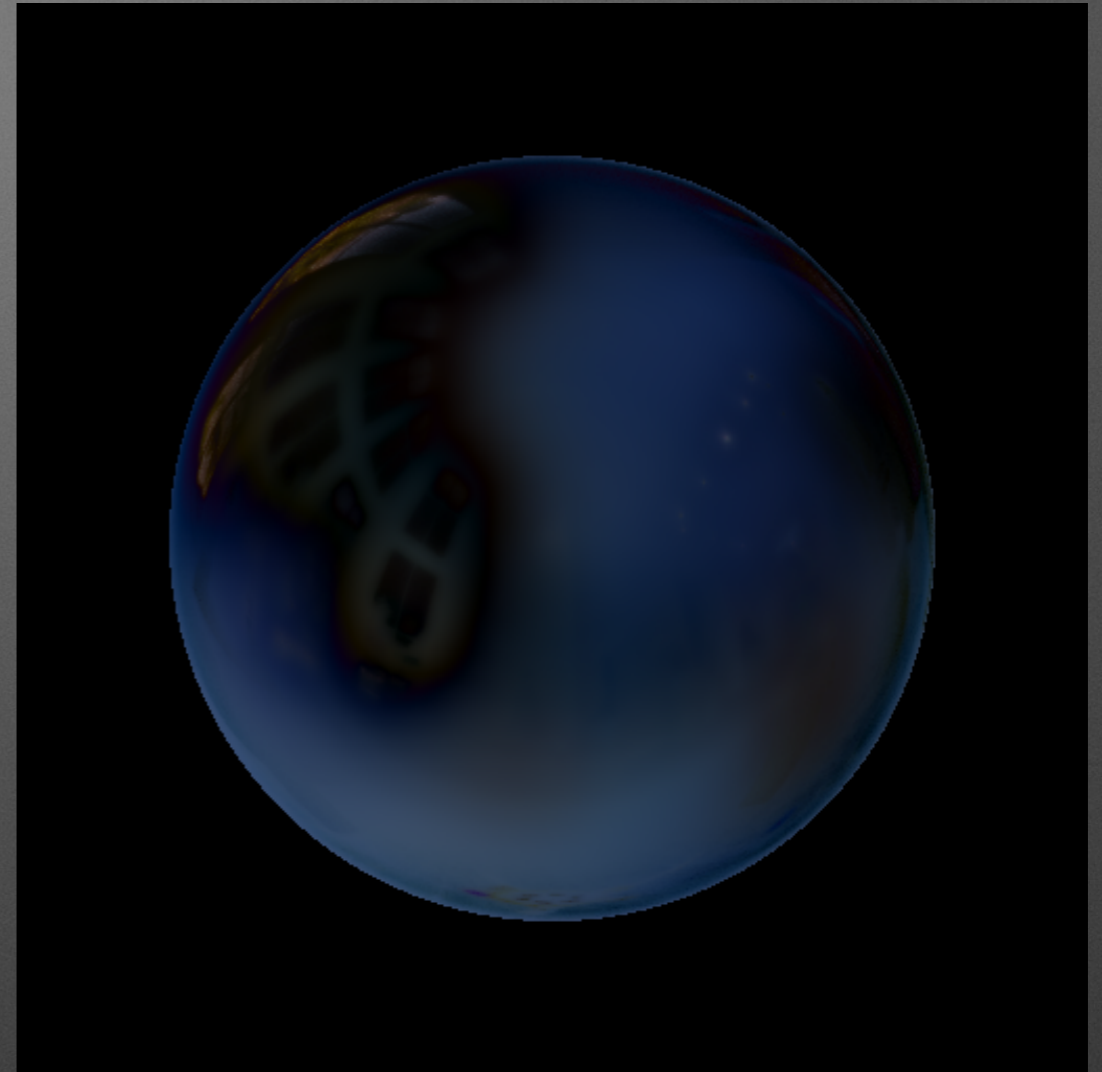


Löw Model

Gold Metallic Paint2

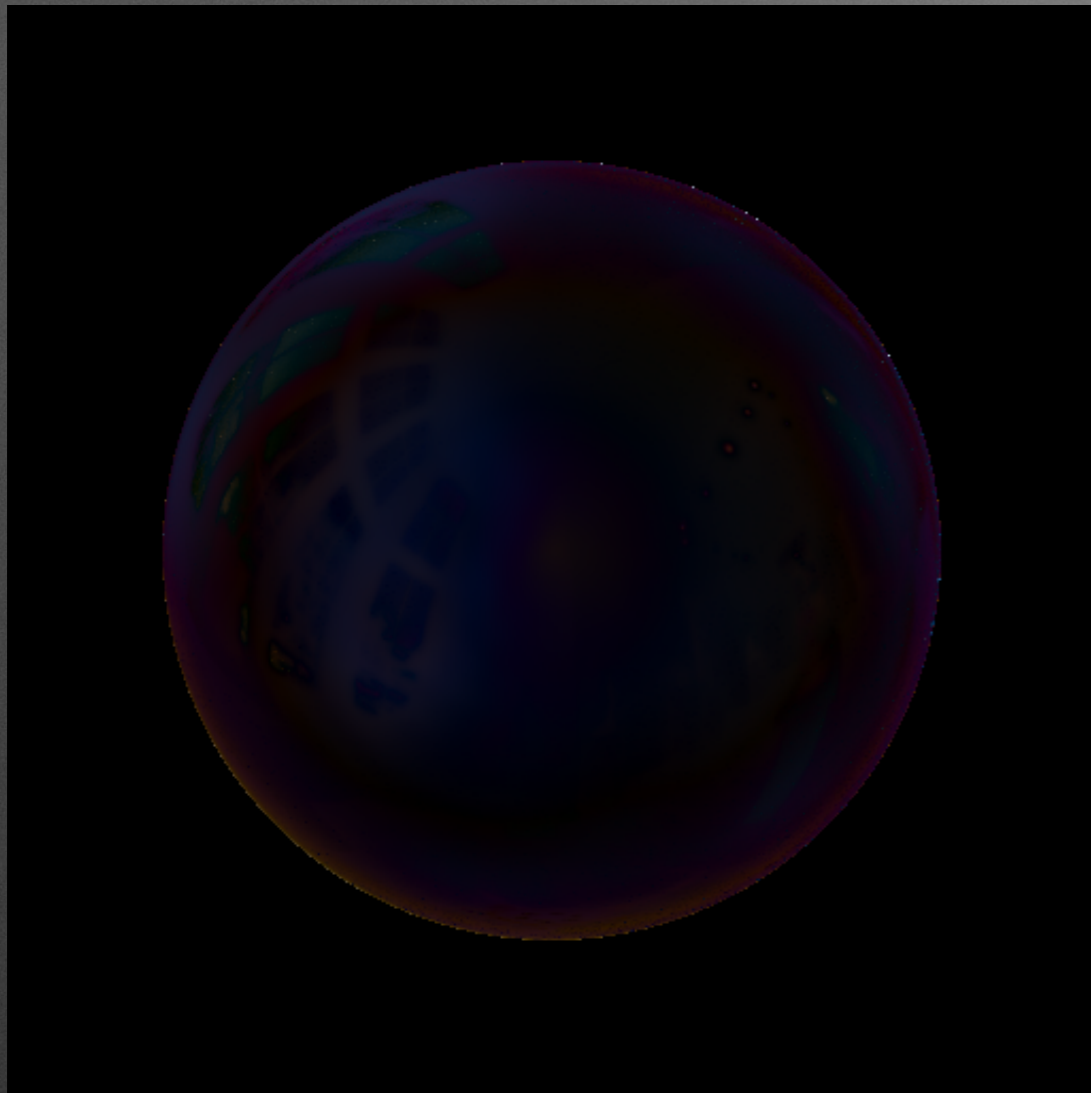


Merl Data Reference

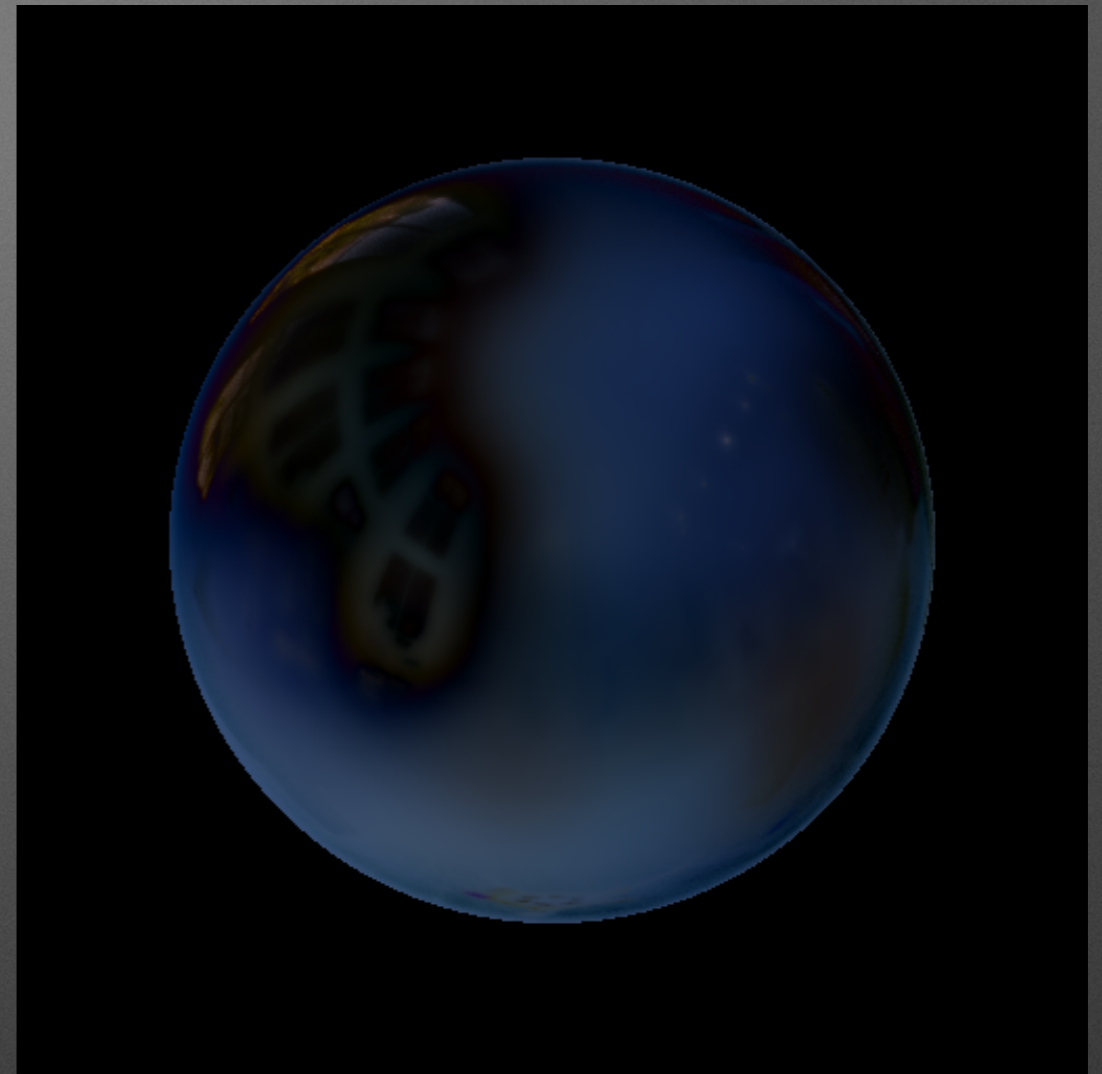


Löv Model
Diff. sMAPE: 0.148

Gold Metallic Paint2



Our Model
Difference sMAPE:0.048



Löw Model
Diff. sMAPE: 0.148

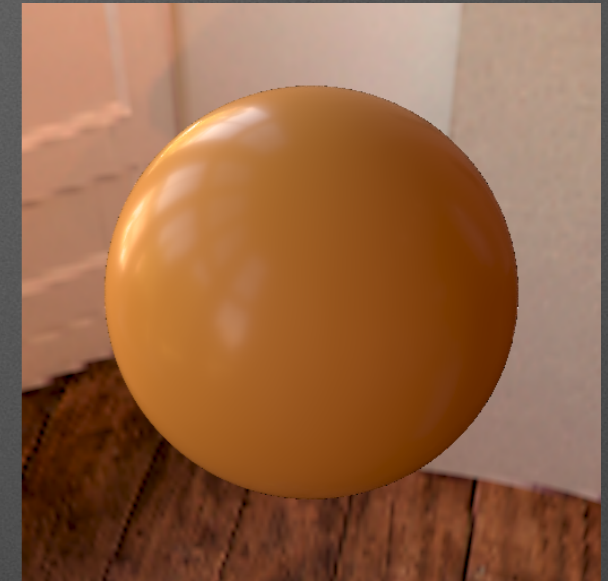
Regarding He et al. Model

- 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

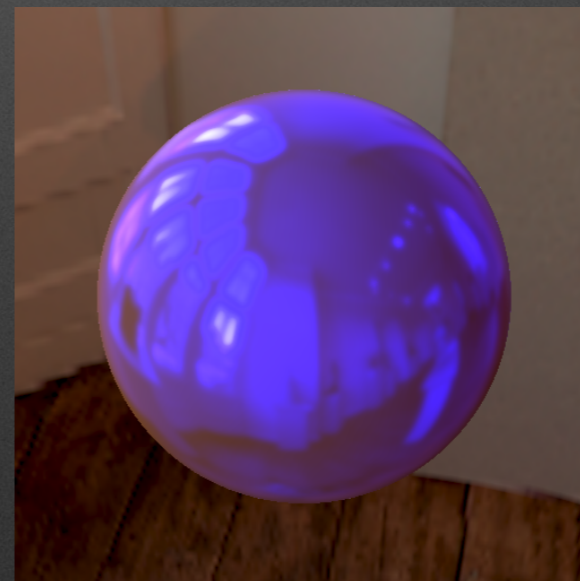
Yellow Mate Plastic



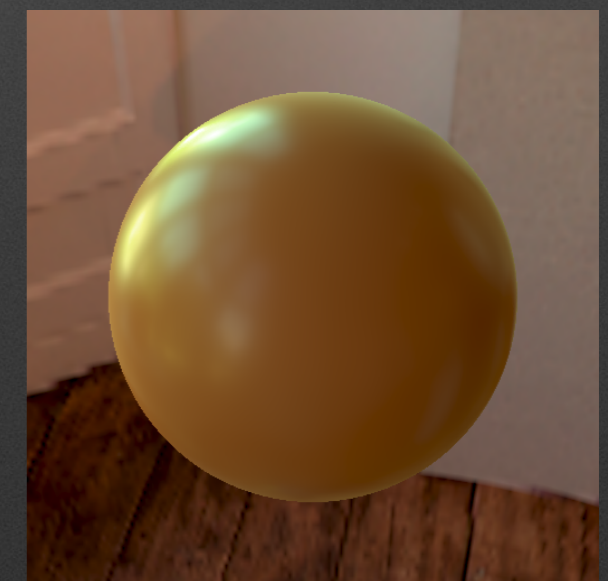
Reference



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

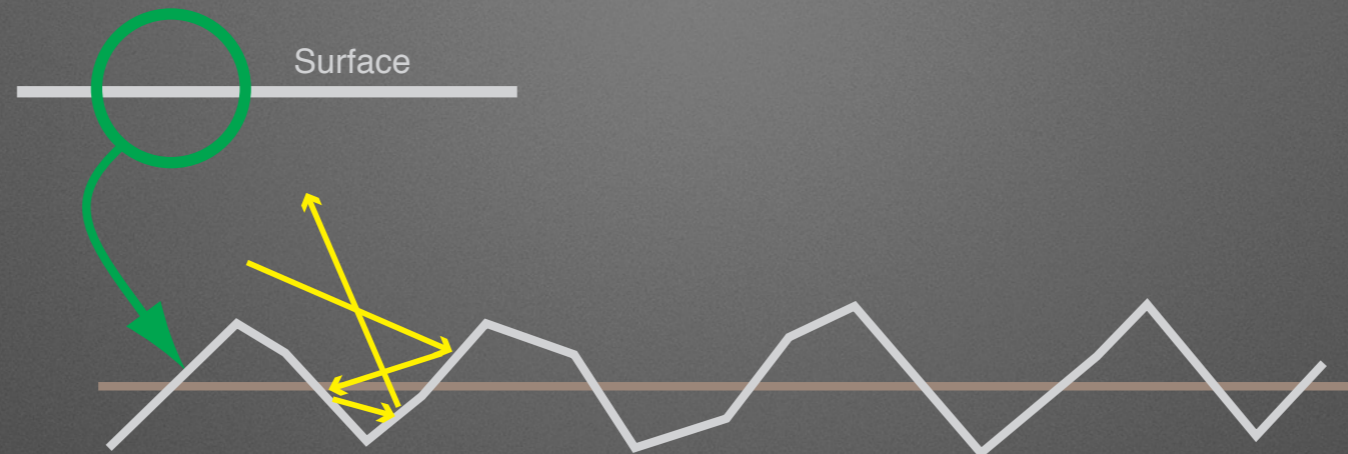
Conclusion

Our two-scale model:

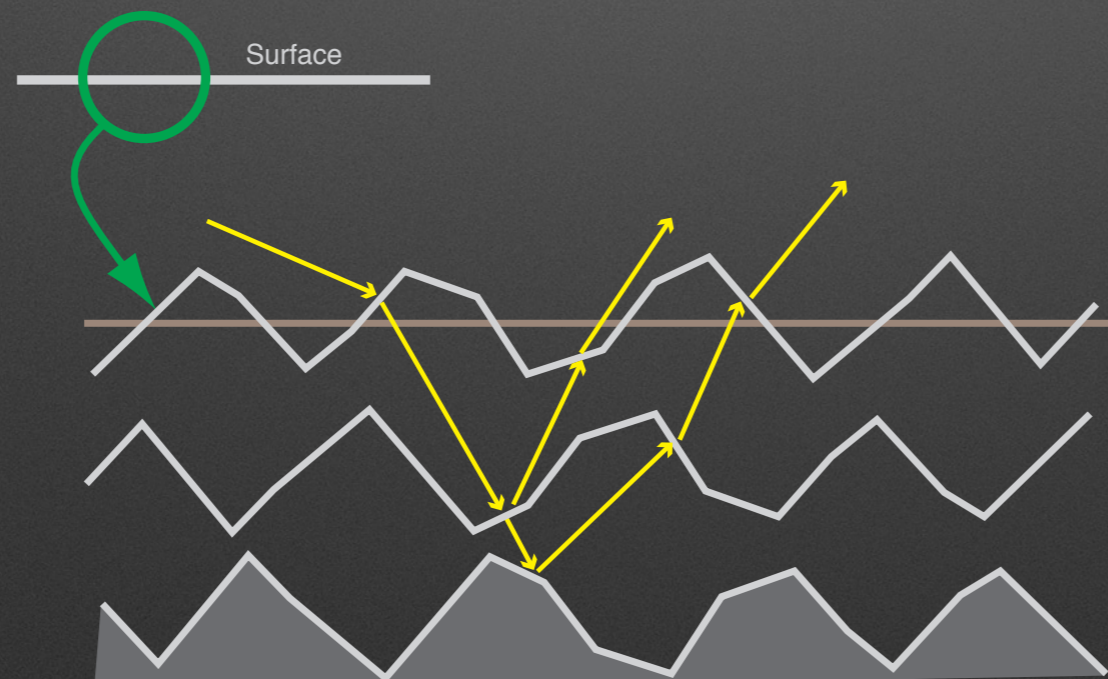
- Better explanation of Measured Data
 - Lobe Size/Width depends on Wavelength
- Micro-facet Theory: Specular Peak
- Limitations:
 - No multi-bounces
 - One Layer of Diffraction

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**

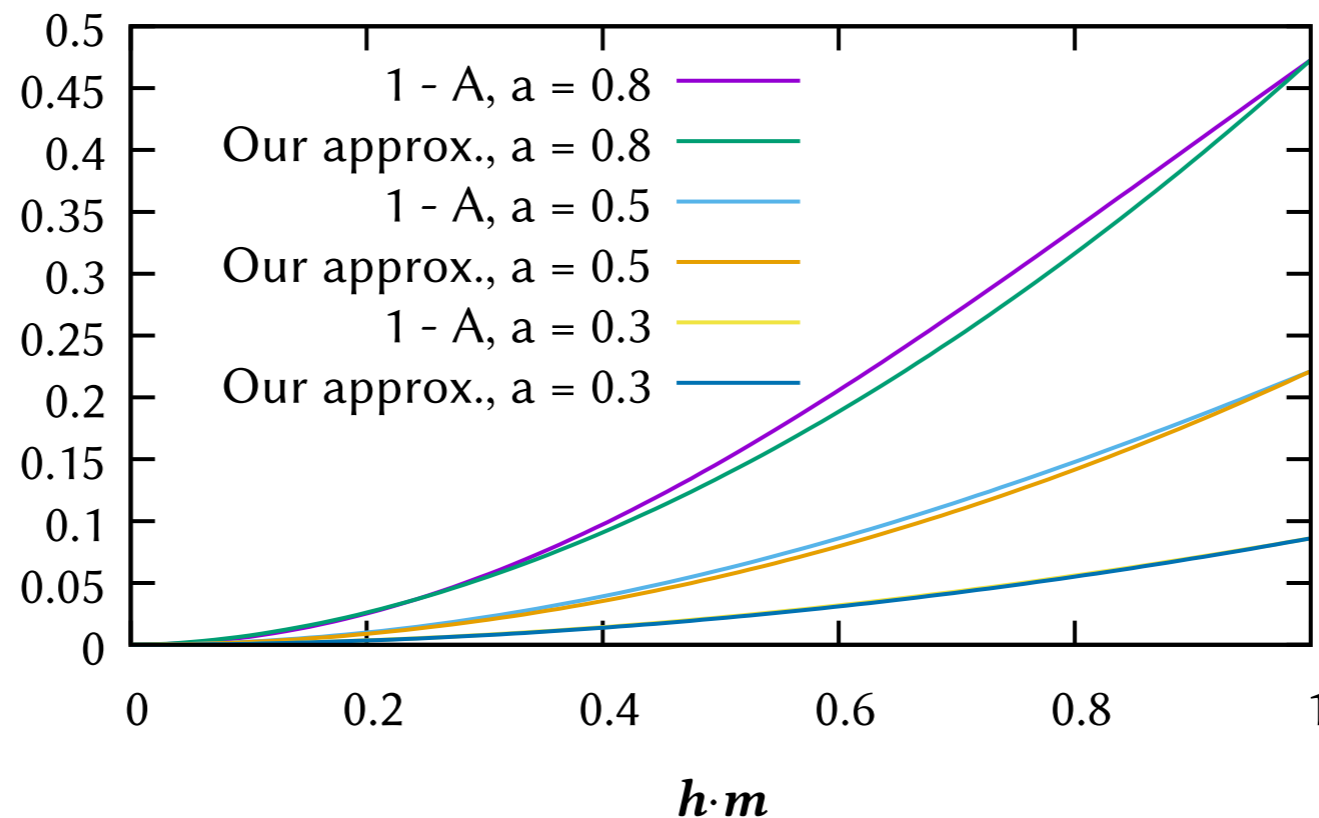
More on Microfacet convolution

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

- Second: Geometrical Term

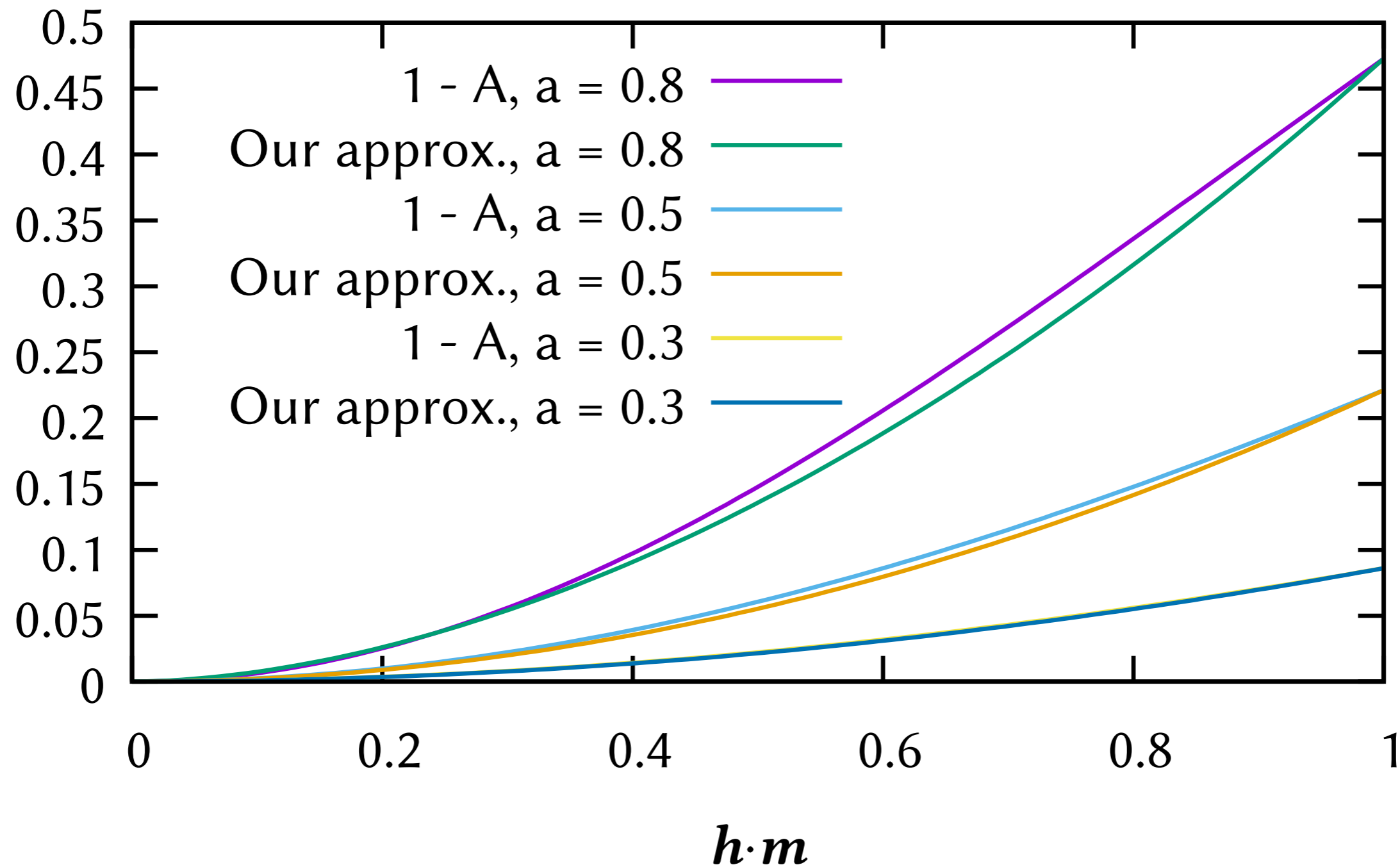
$$(1 - A_{\sigma_s}(i, o)) = 1 - e^{-\left(2\pi \frac{\sigma_s}{\lambda} (\cos \theta_i + \cos \theta_o)\right)}$$

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



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 $Q = 2 \text{ Fresnel_Coefficient}$
- Q is re-introduced into GHS **empirically** for comparisons