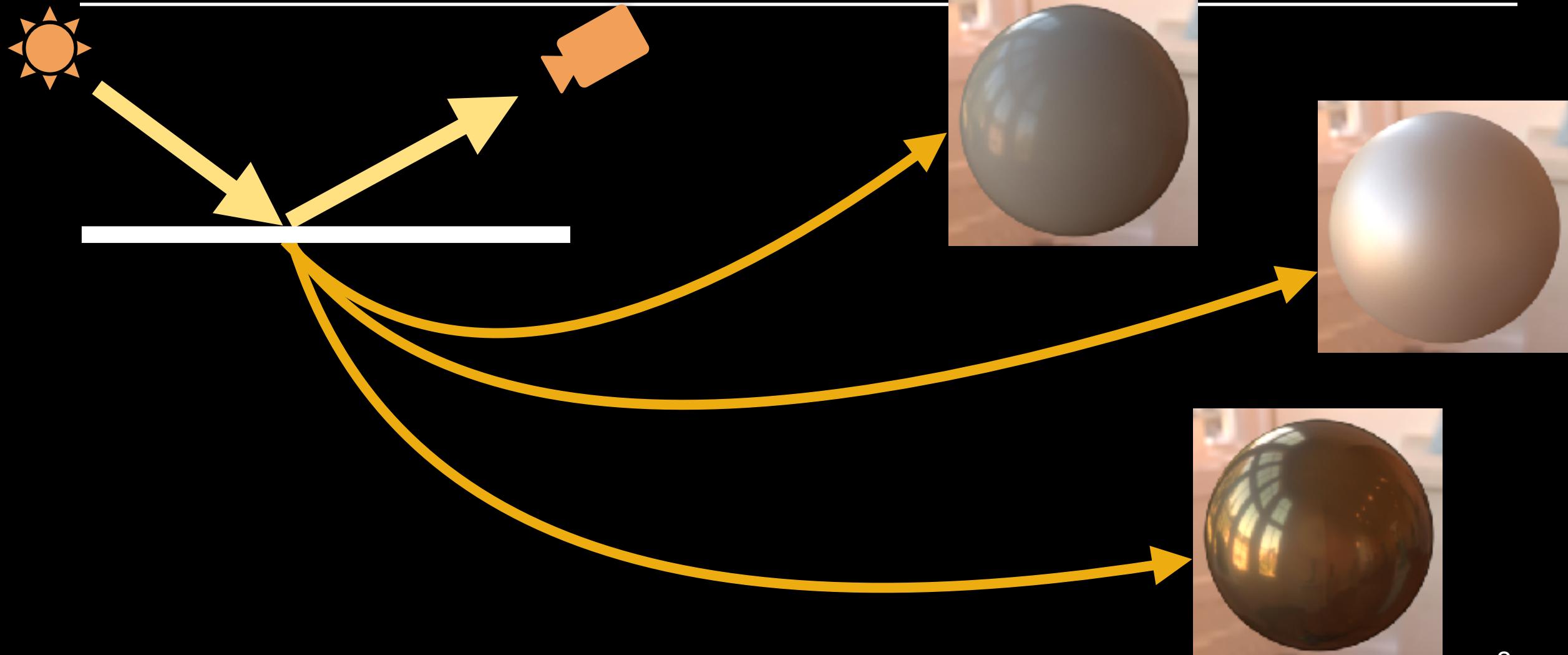


30 JULY – 3 AUGUST *Los Angeles*
SIGGRAPH 2017

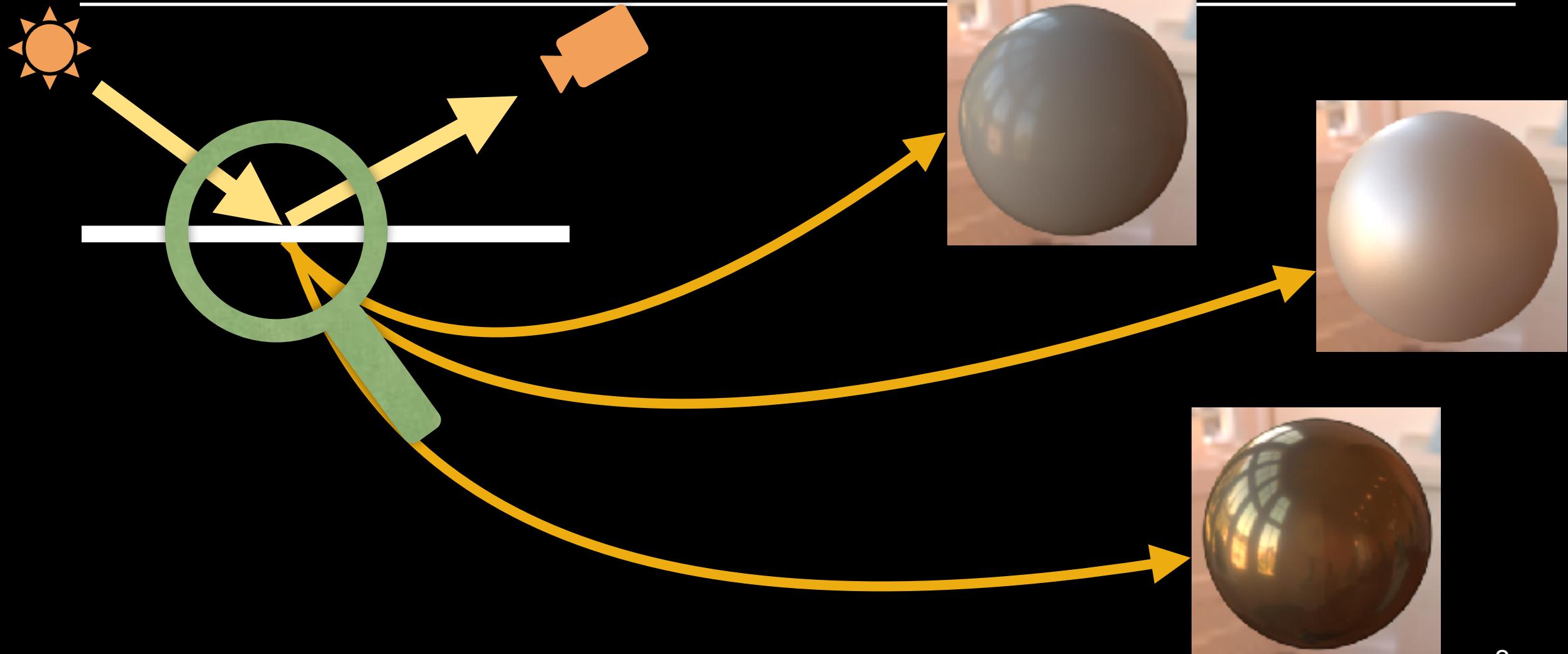
A TWO-SCALE MICRO-FACET REFLECTANCE MODEL COMBINING REFLECTION AND DIFFRACTION

N. HOLZSCHUCH, INRIA — U. GRENOBLE-ALPES
R. PACANOWSKI, CNRS — IOGS — U. BORDEAUX

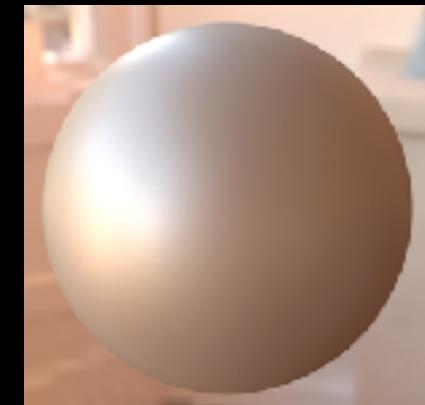
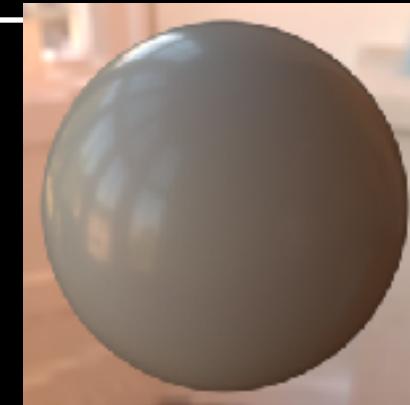
MATERIAL REFLECTANCE



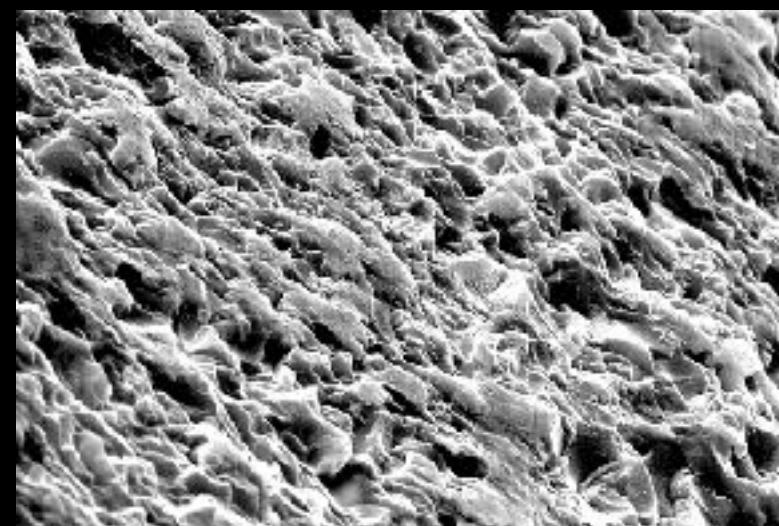
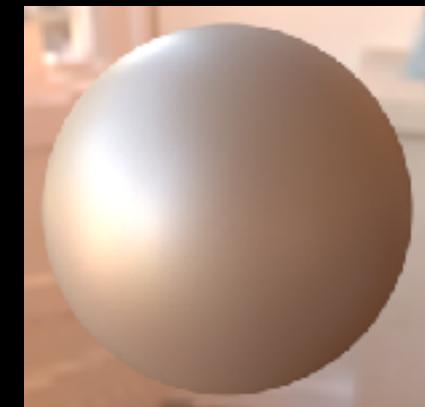
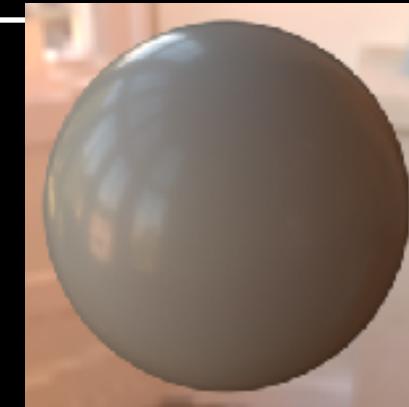
MATERIAL REFLECTANCE



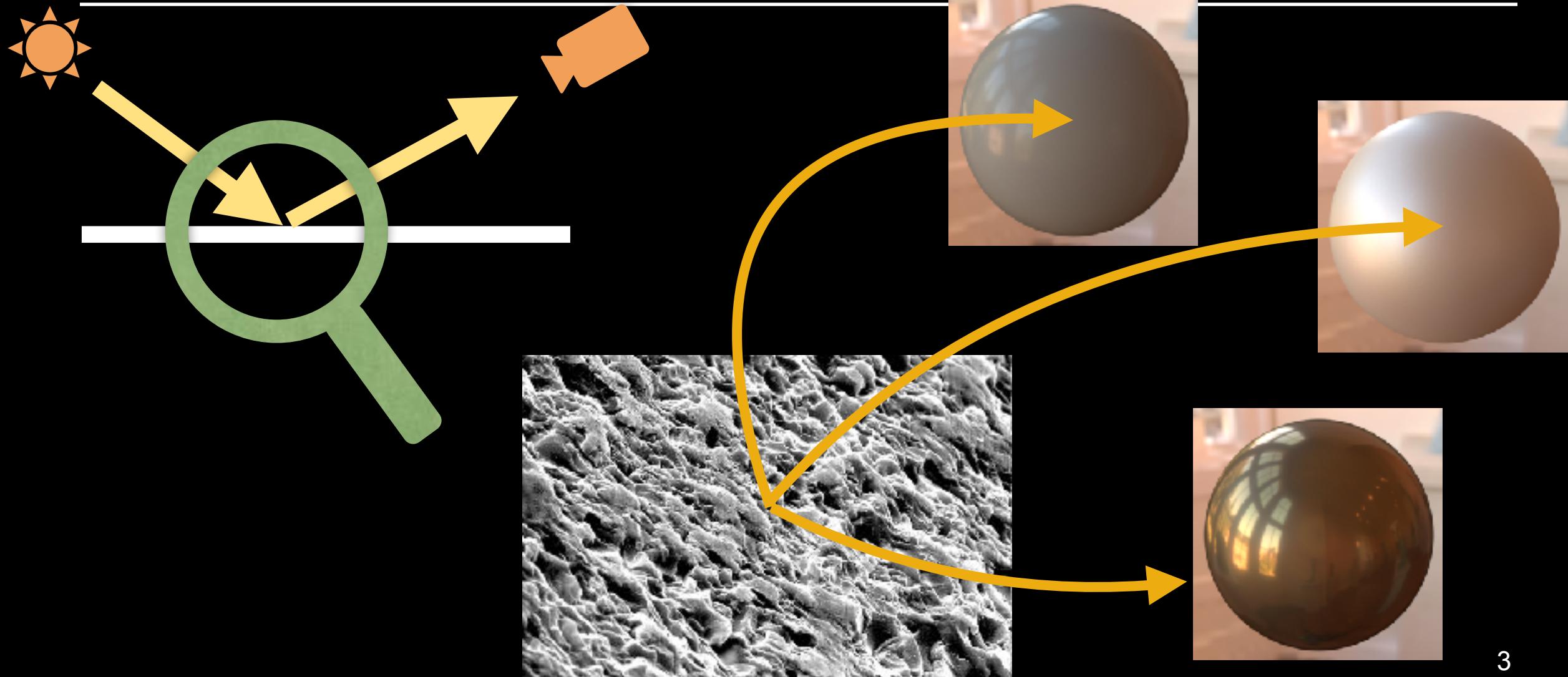
MATERIAL REFLECTANCE



MATERIAL REFLECTANCE



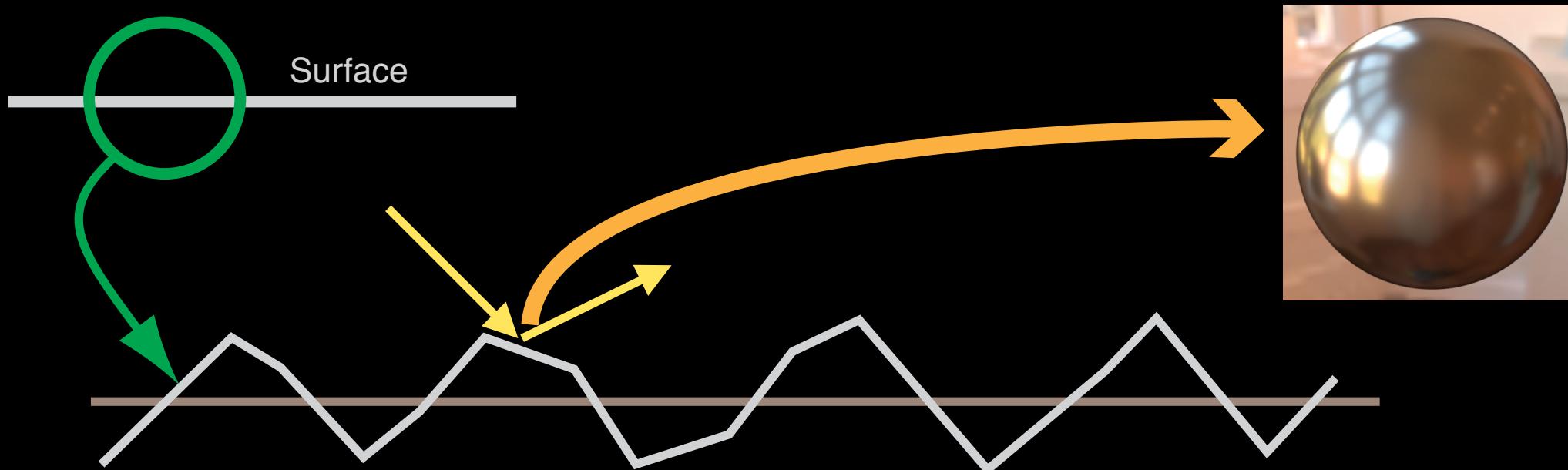
MATERIAL REFLECTANCE



MICRO-FACET MODEL



- Assume surface micro-geometry \gg wavelength
 - Geometrical Optics
 - Micro-facet normal distribution D gives BRDF
 - [Torrance & Sparrow 1967][Cook & Torrance 1982][Walter et al. 2007][Heitz 2014]



MICRO-FACET MODELS



- If micro-facets are specular: Dirac reflectance
- Integrate contributions from micro-facets:

$$\rho_{CT}(i, o) = \frac{F(\eta, \theta_d)D(\theta_h)G(i, o)}{4 \cos \theta_i \cos \theta_o}$$

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Fresnel term. Gives color.

Depends on index of refraction η

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Micro-facets normal distribution

[Trowbridge & Reitz 1975][Walter et al. 2007]

[Bagher et al. 2012][Löw et al. 2012][Burley 2012]

[Brady et al. 2014]

MICRO-FACET MODELS



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$$\rho_{CT}(i, o) = \frac{F(\eta, \theta_d) D(\theta_h) G(i, o)}{4 \cos \theta_i \cos \theta_o}$$

Shadowing-Masking term

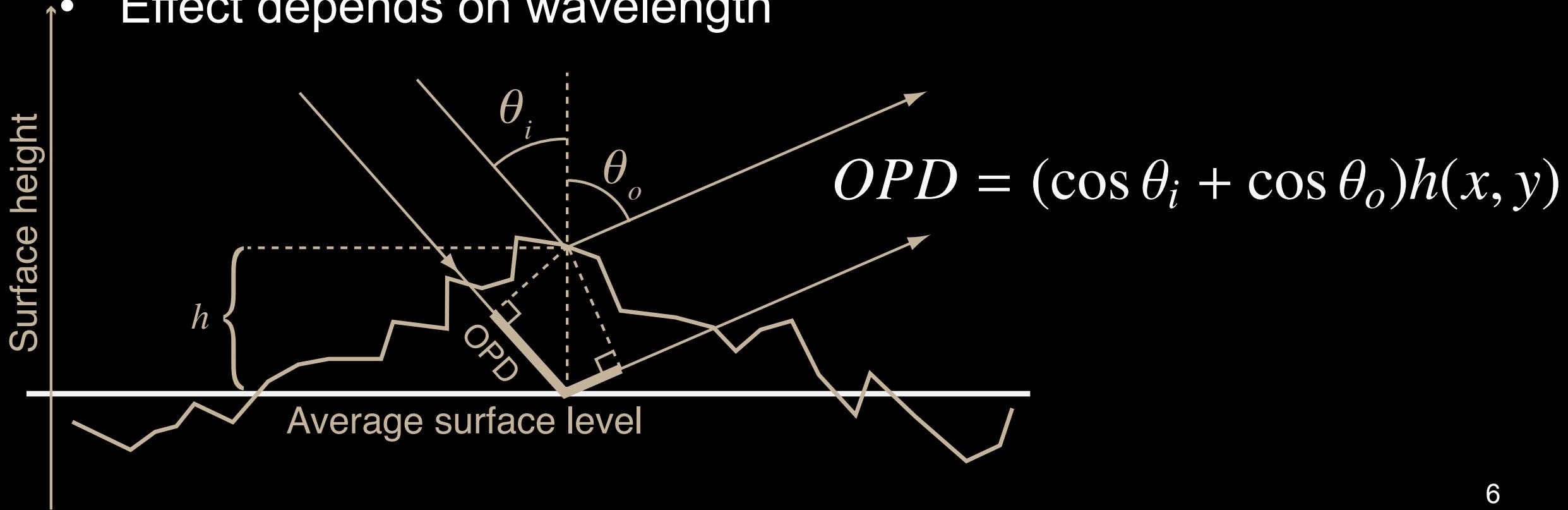
[Smith 1967][Walter et al. 2007]

[Heitz 2014]

DIFFRACTION MODELS

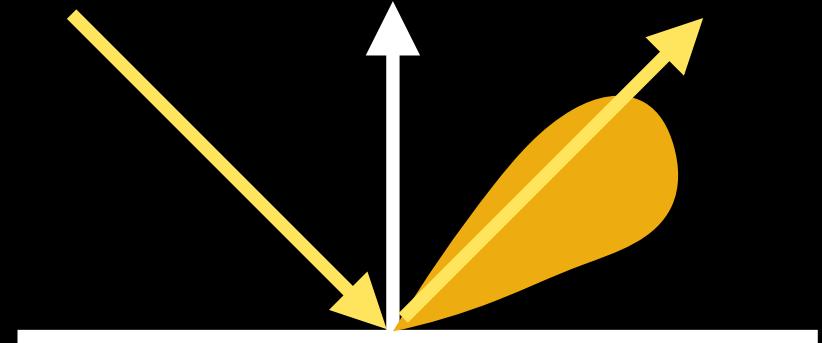


- Distance travelled by light depends on surface height
- Phase variation at the reflected wavefront
- Effect depends on wavelength



DIFFRACTION MODELS

- Specular peak + diffraction lobe



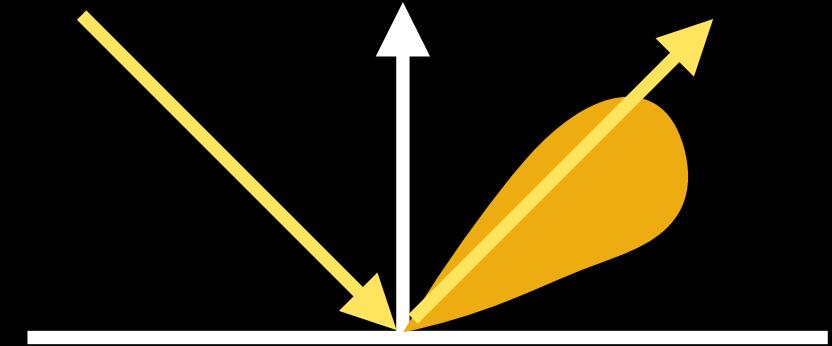
$$\rho_{\text{diff.}}(\mathbf{i}, \mathbf{o}) = AF(\mathbf{i}, \mathbf{o}) \frac{\delta(\text{refl}(\mathbf{i}), \mathbf{o})}{\cos \theta_o} + (1 - A)Q(\mathbf{i}, \mathbf{o})S_{HS}(f)$$

DIFFRACTION MODELS

- Specular peak + diffraction lobe

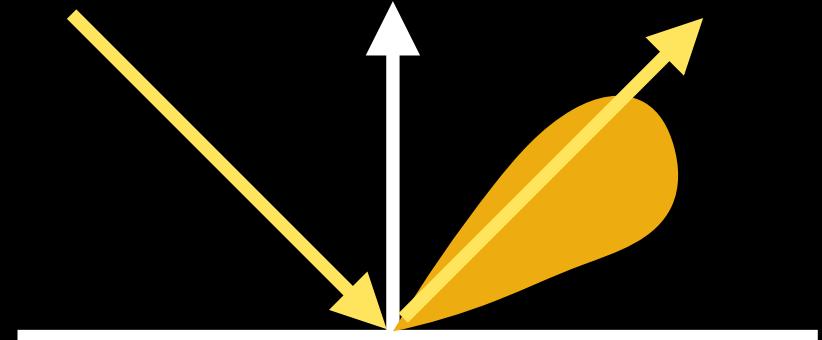
$$\rho_{\text{diff.}}(i, o) = AF(i, o) \frac{\delta(\text{refl}(i), o)}{\cos \theta_o} + (1 - A)Q(i, o)S_{HS}(f)$$

Specular reflection



DIFFRACTION MODELS

- Specular peak + diffraction lobe



$$\rho_{\text{diff.}}(\mathbf{i}, \mathbf{o}) = A F(\mathbf{i}, \mathbf{o}) \frac{\delta(\text{refl}(\mathbf{i}), \mathbf{o})}{\cos \theta_o} + (1 - A) Q(\mathbf{i}, \mathbf{o}) S_{HS}(f)$$

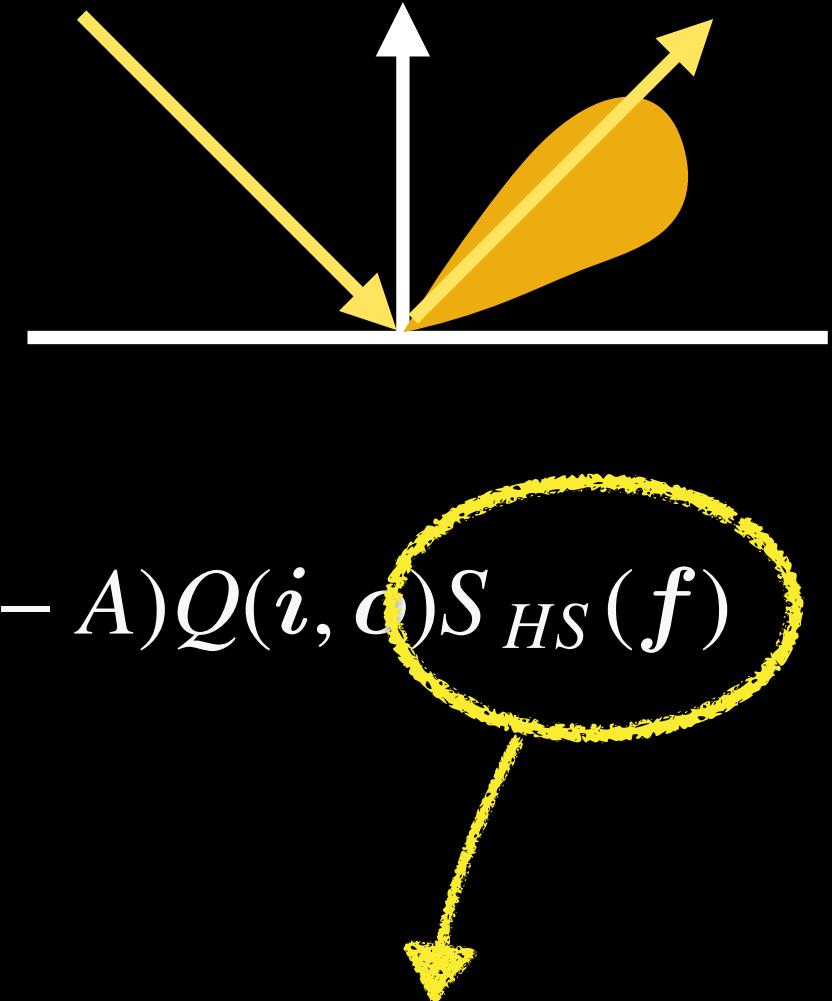
A yellow circle highlights the term $A F(\mathbf{i}, \mathbf{o})$, which is then connected by a yellow arrow to the text "Fresnel term".

Fresnel term
Depends on index of refraction η

DIFFRACTION MODELS

- Specular peak + diffraction lobe

$$\rho_{\text{diff.}}(\mathbf{i}, \mathbf{o}) = A F(\mathbf{i}, \mathbf{o}) \frac{\delta(\text{refl}(\mathbf{i}), \mathbf{o})}{\cos \theta_o} + (1 - A) Q(\mathbf{i}, \mathbf{o}) S_{HS}(f)$$

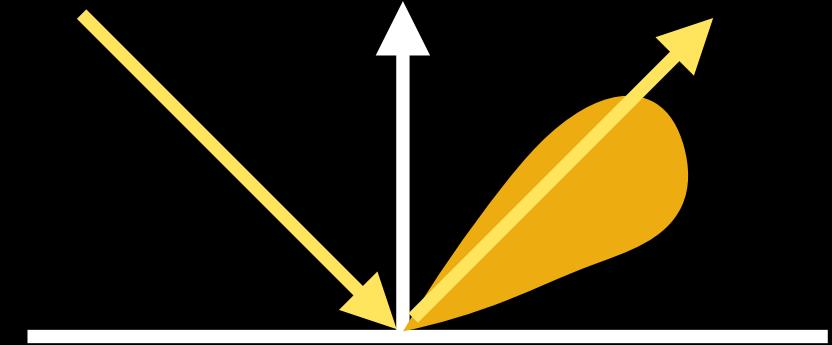


Diffraction lobe
(depends on λ)

DIFFRACTION MODELS

- Specular peak + diffraction lobe

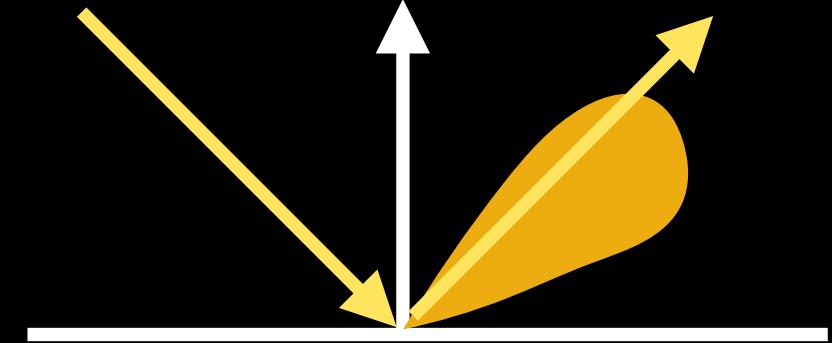
$$\rho_{\text{diff.}}(i, o) = AF(i, o) \frac{\delta(\text{refl}(i), o)}{\cos \theta_o} + (1 - A)Q(i, o)S_{HS}(f)$$



Color term (not F)

DIFFRACTION MODELS

- Specular peak + diffraction lobe



$$\rho_{\text{diff.}}(i, o) = AF(i, o) \frac{\delta(\text{refl}(i), o)}{\cos \theta_o} + (1 - A)Q(i, o)S_{HS}(f)$$

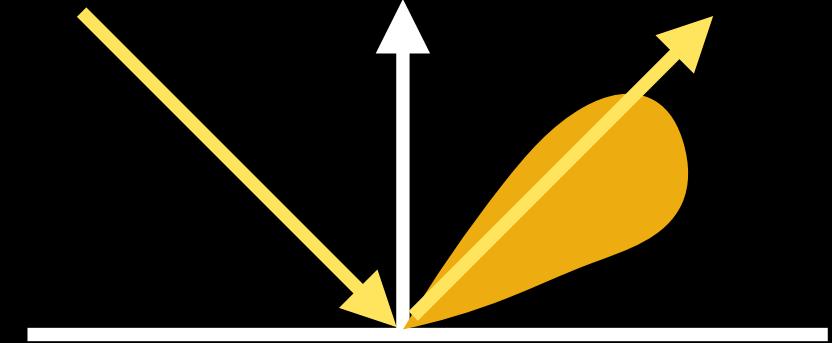
Repartition

The equation shows the probability density of a photon at position i and orientation o . It consists of two terms: a direct term proportional to $AF(i, o)$ and a scattered term proportional to $(1 - A)Q(i, o)S_{HS}(f)$. The parameter A is highlighted with a yellow circle and an arrow pointing to the text "Repartition" below the equation.

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

DIFFRACTION MODELS

- Specular peak + diffraction lobe



$$\rho_{\text{diff.}}(i, o) = AF(i, o) \frac{\delta(\text{refl}(i), o)}{\cos \theta_o} + (1 - A)Q(i, o)S_{HS}(f)$$

Repartition

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

Surface roughness

DIFFRACTION MODELS: PREVIOUS WORK

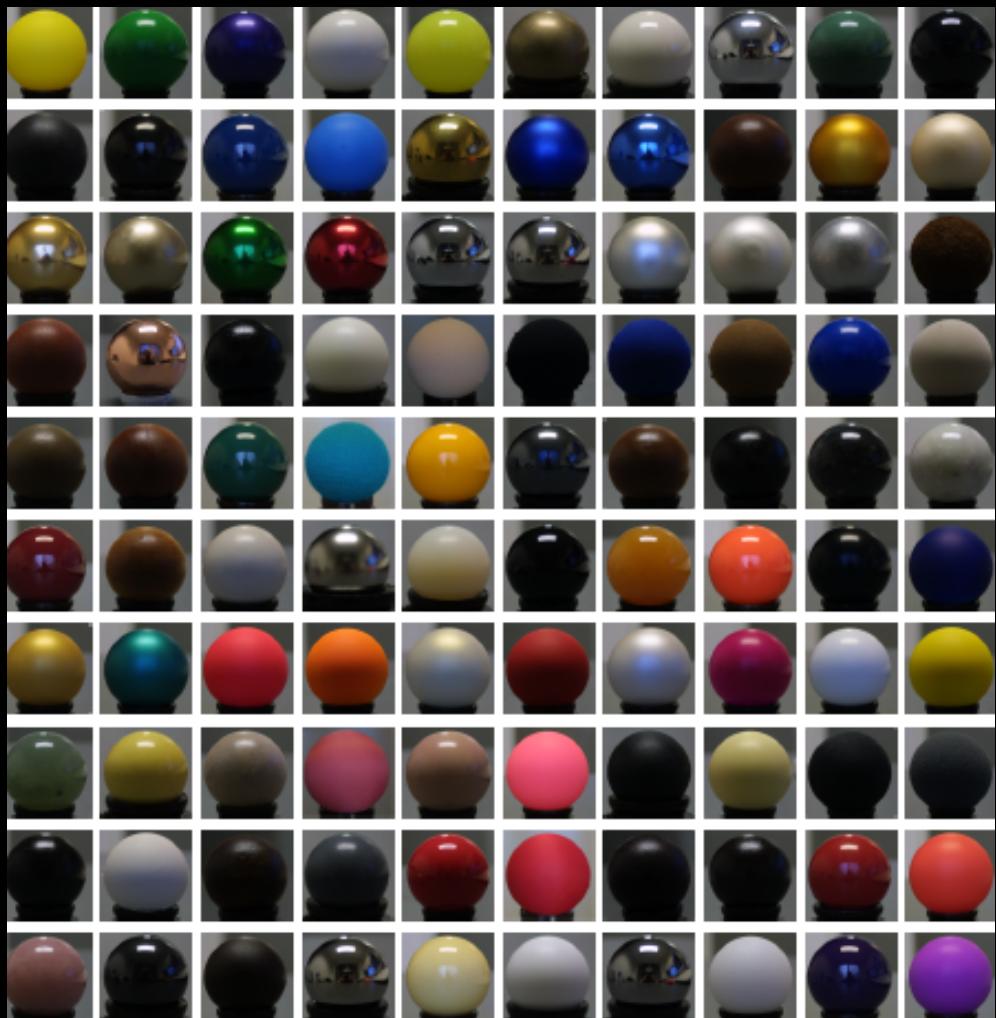


-
- Beckmann-Kirchhoff: infinite sum
 - [Beckmann & Spizzichino 1987][Vernold & Harvey 1998]
 - [He et al. 1991][Stam 1999]
 - Harvey-Shack: Power Spectral Distribution (PSD)
 - [Harvey 1975][Krywonos 2006]
 - [Löw et al. 2012]
 - K-correlation model: [Hoenders et al. 1979][Church & Takacs 1986]
 - Periodic surfaces: [Toisoul and Gosh 2017][Werner et al. 2017]

MEASURED REFLECTANCES

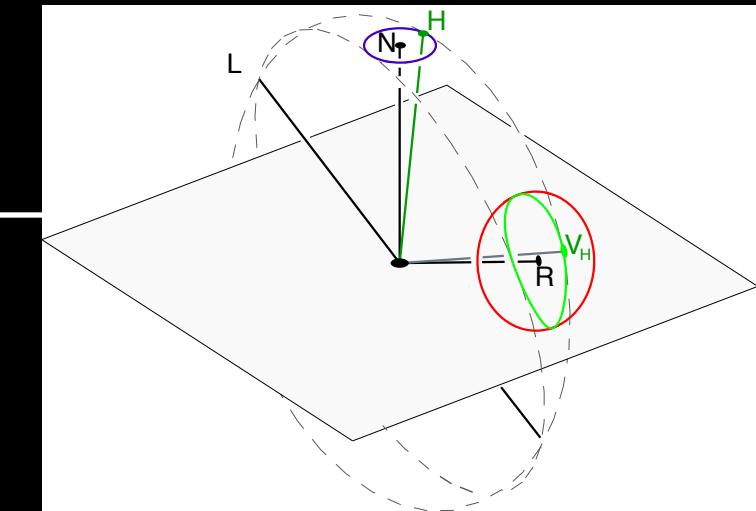


- e.g. MERL database
- [Matusik et al. 2003]
- 100 materials measured



COMPARISON MODEL / MEASURES

- Focus here on parameterisation / lobe shape
- Micro-facet model:
 - Explains peak shape [Ngan et al. 2005]
- Diffraction model:
 - Explains low energy behaviour [Löw et al. 2012]
- “Better fits using two lobes” [Everyone]

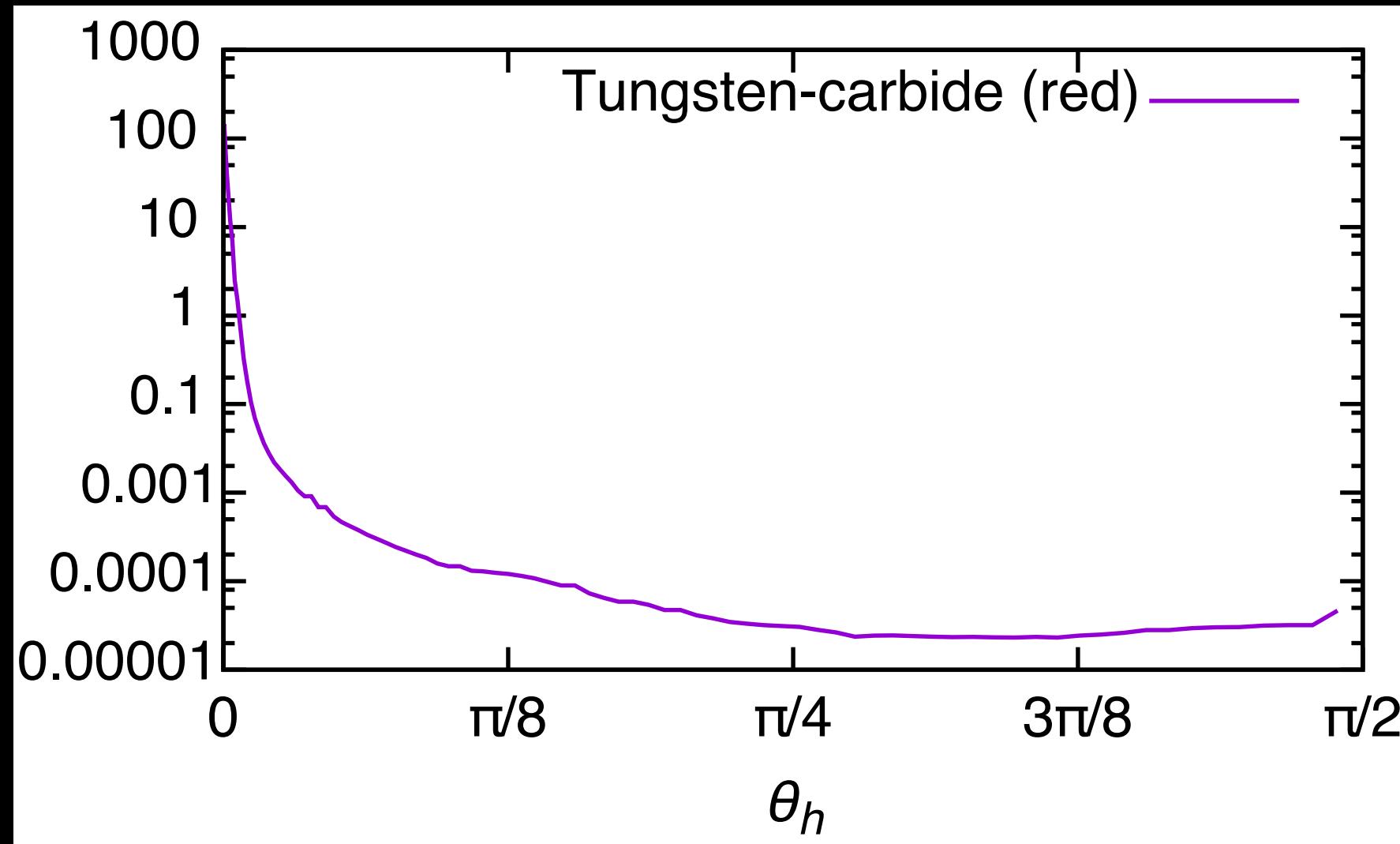


[Ngan et al. 2005]

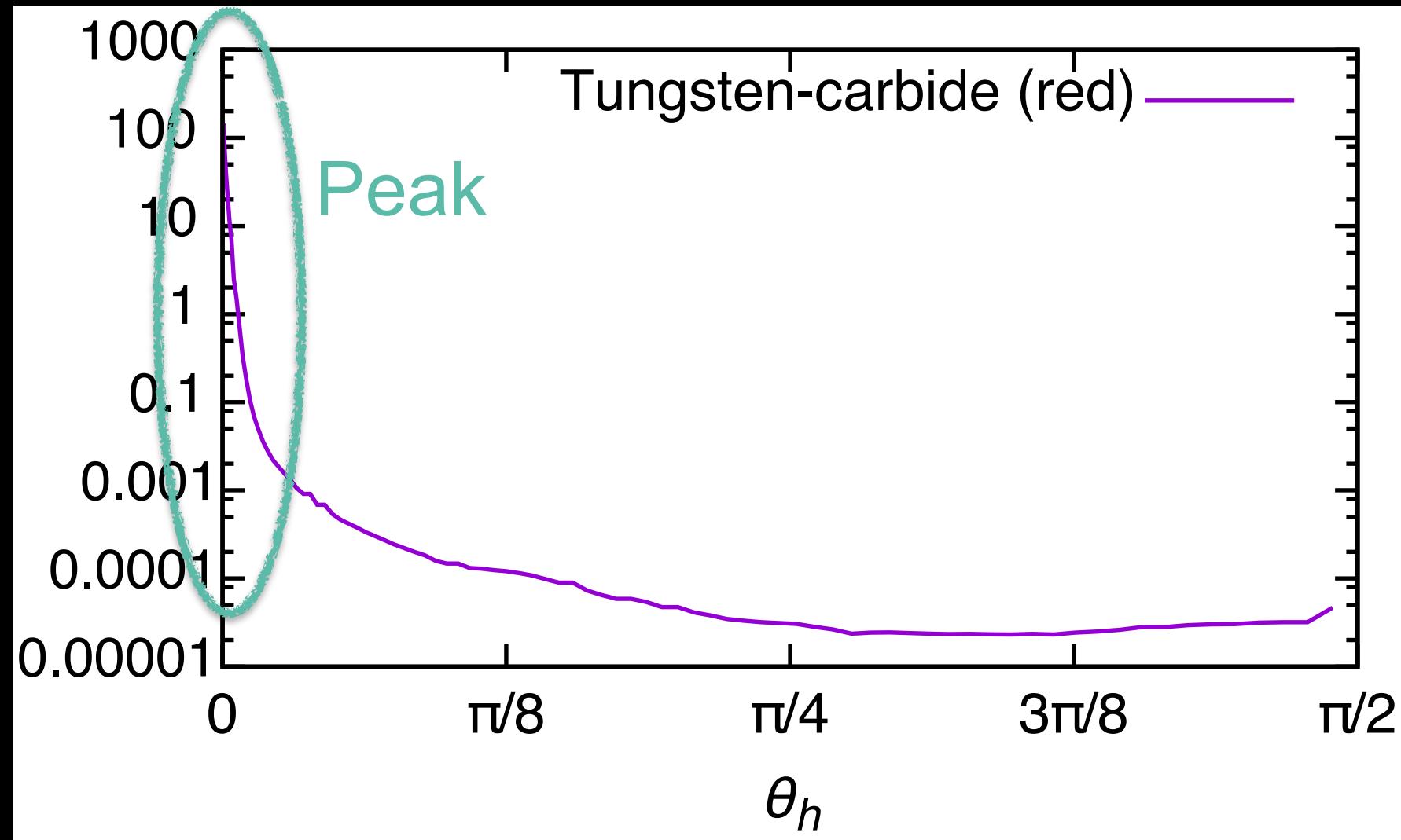


[Löw et al. 2012] 10

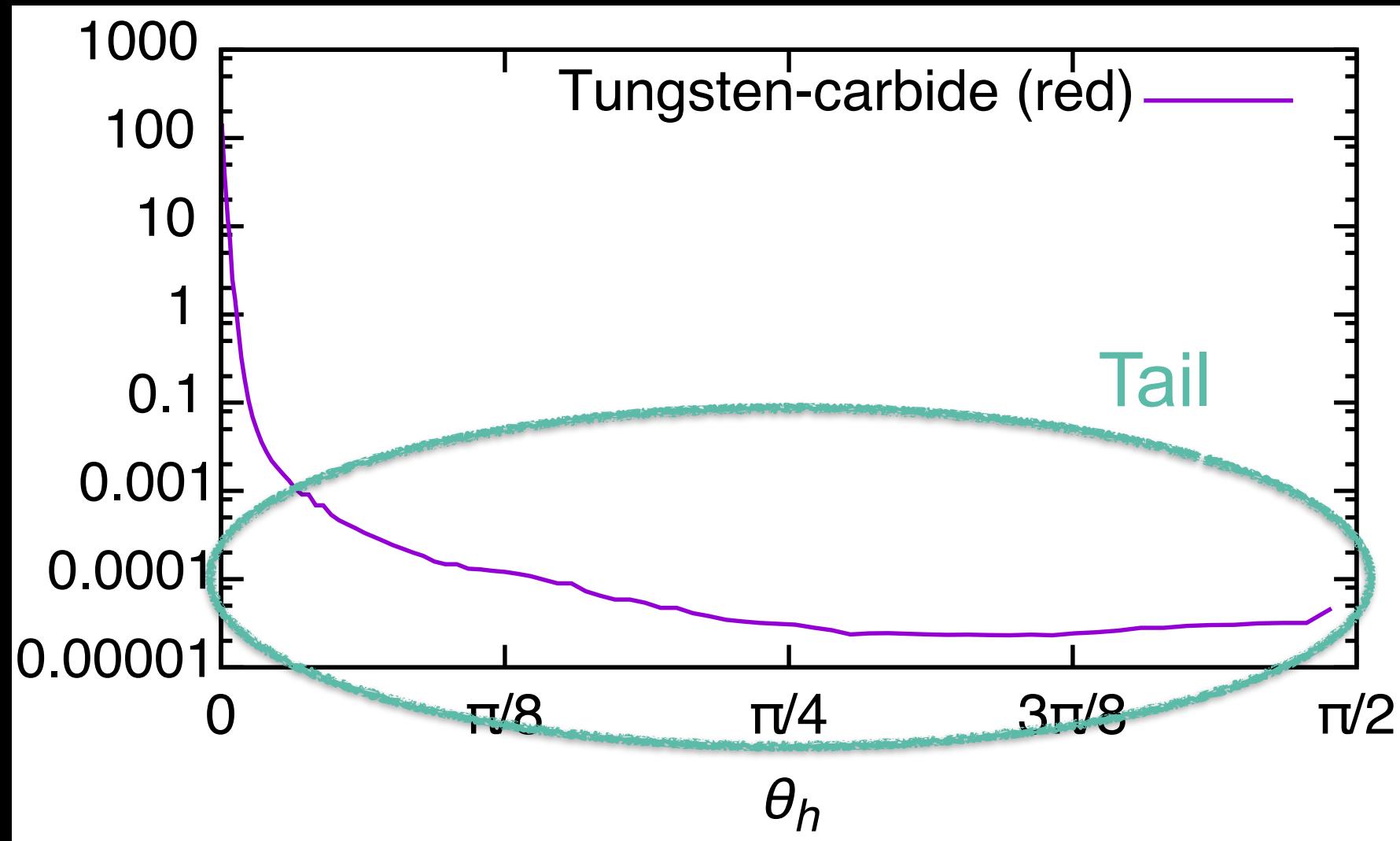
MEASURED REFLECTANCE



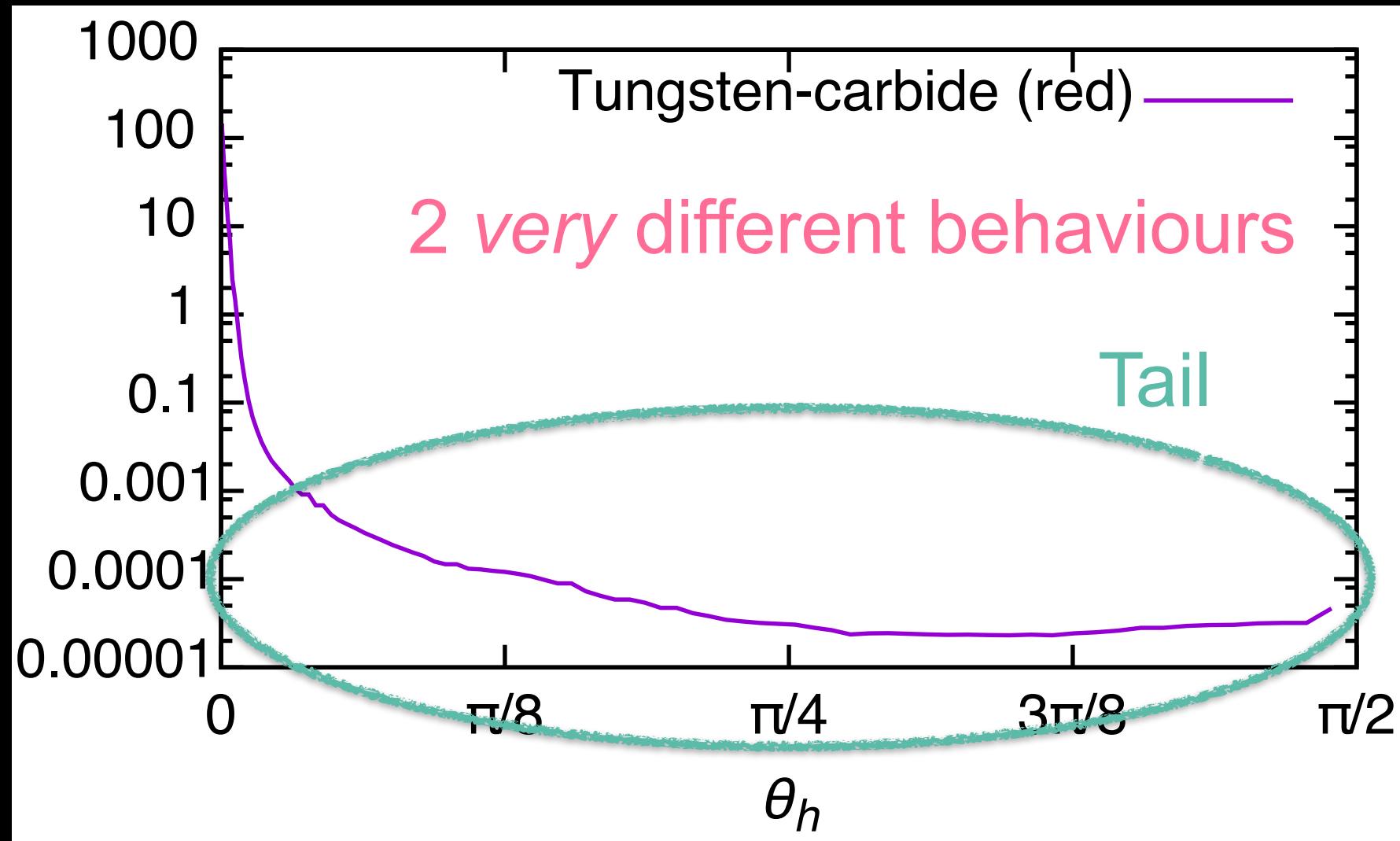
MEASURED REFLECTANCE



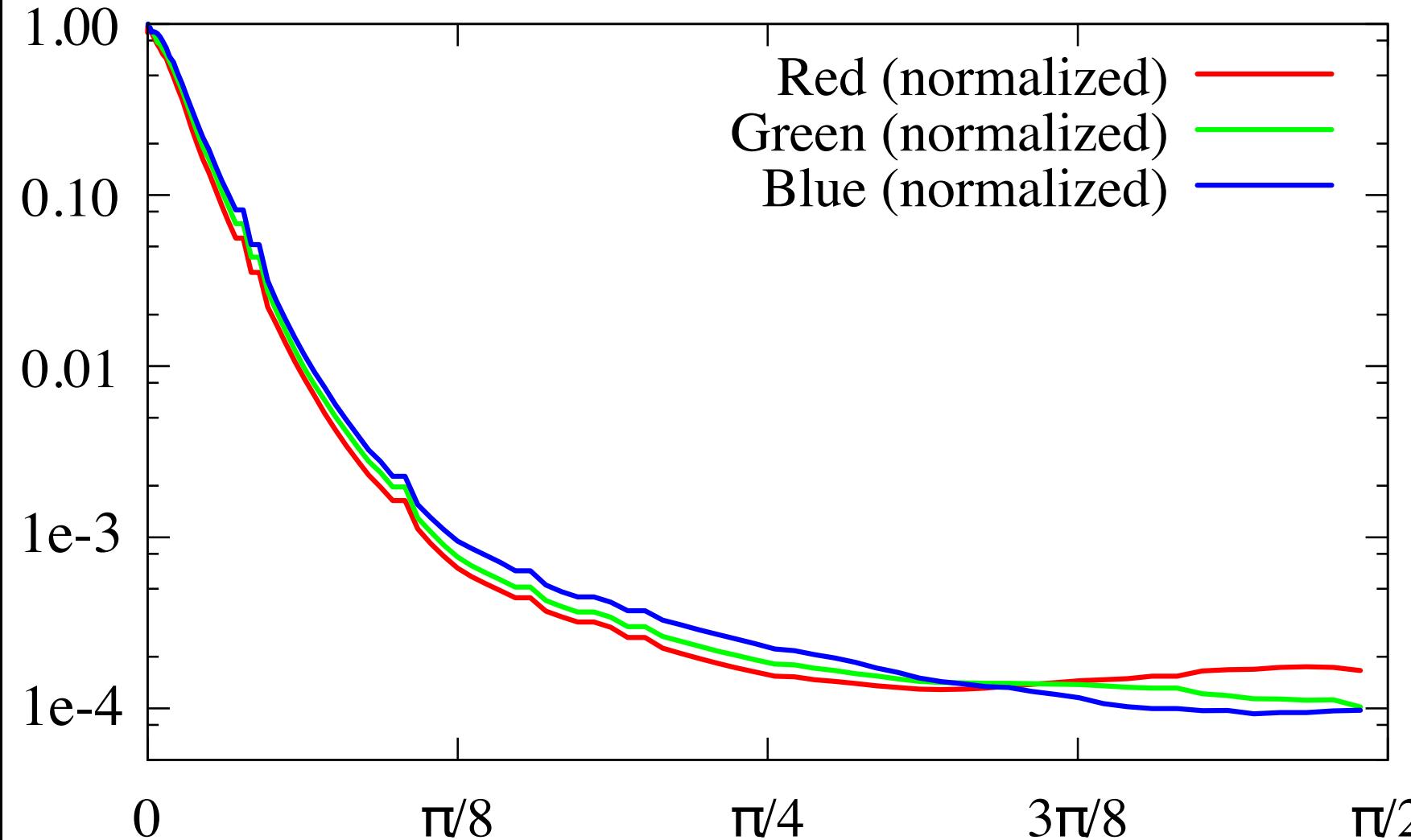
MEASURED REFLECTANCE



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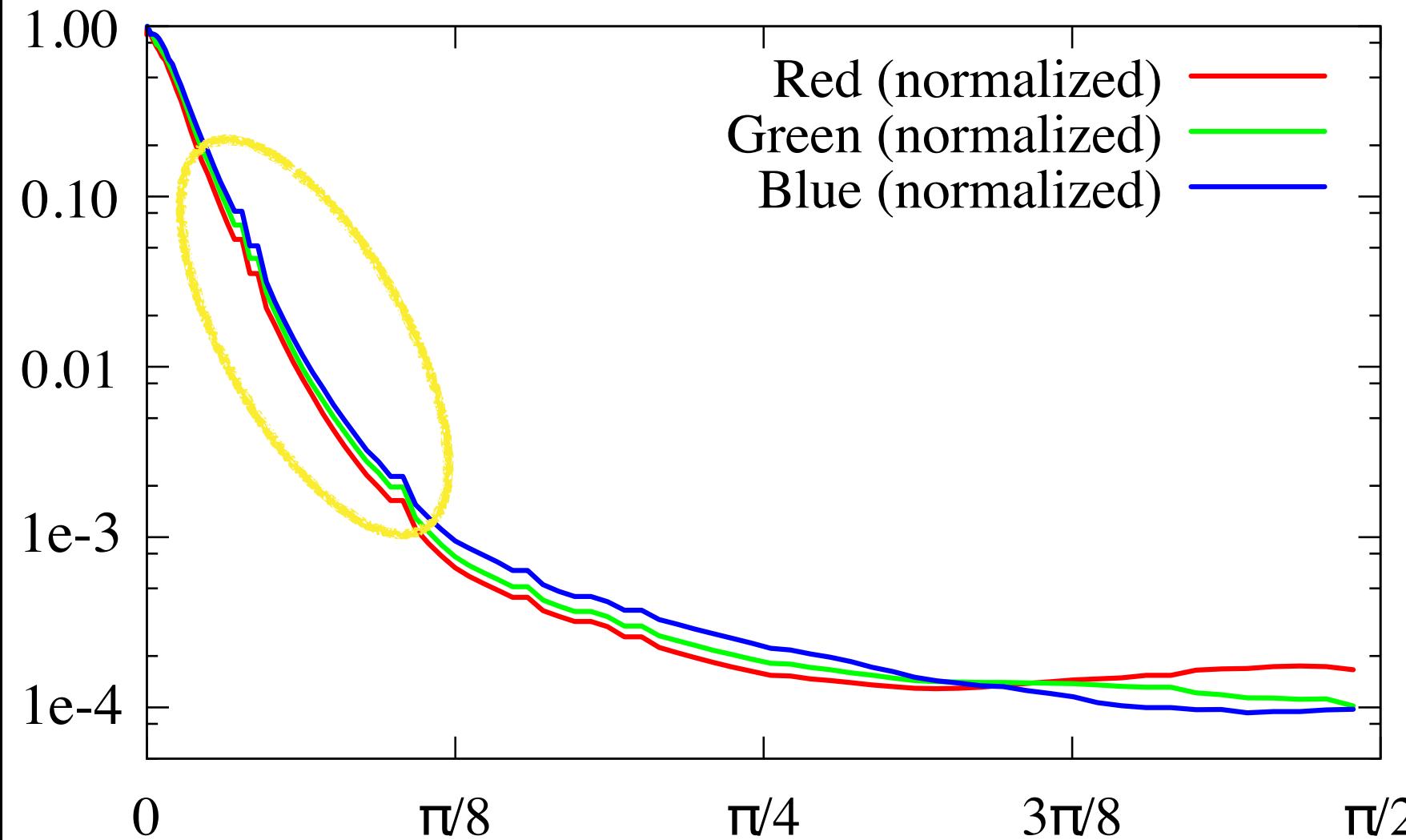


WAVELENGTH DEPENDENCE: NICKEL



12

WAVELENGTH DEPENDENCE: NICKEL



OVERVIEW



- Background
- Our contribution:
 - Two-scale representation
 - Combining the effects
- Comparisons with measured reflectance
- Conclusion and future directions

OUR MAIN IDEA

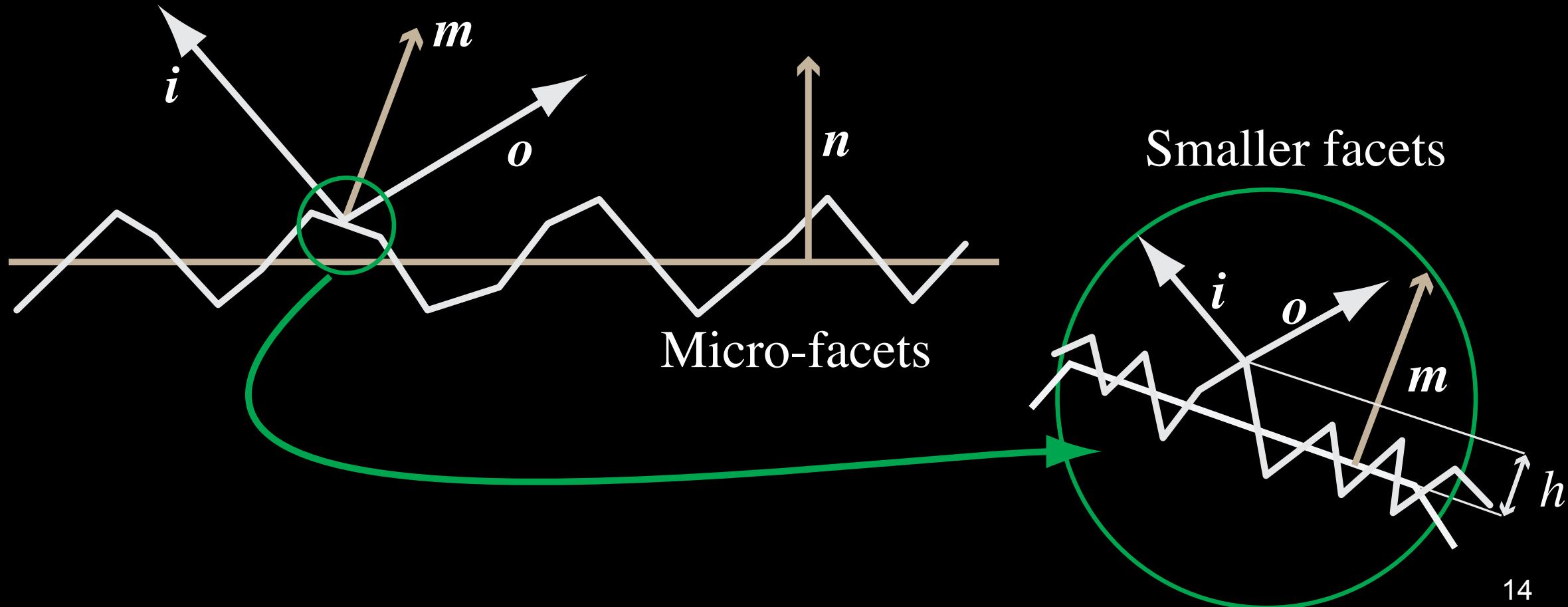


- Surface details *can* happen at all scales

OUR MAIN IDEA



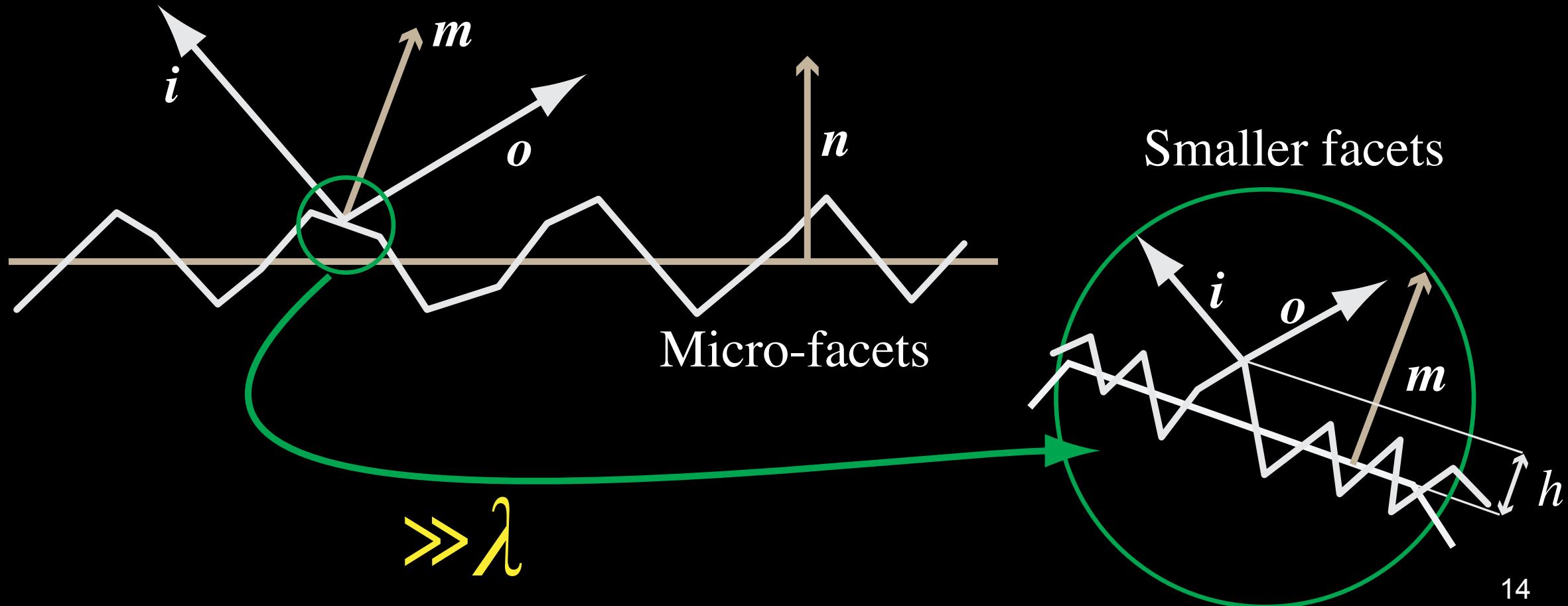
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OUR MAIN IDEA



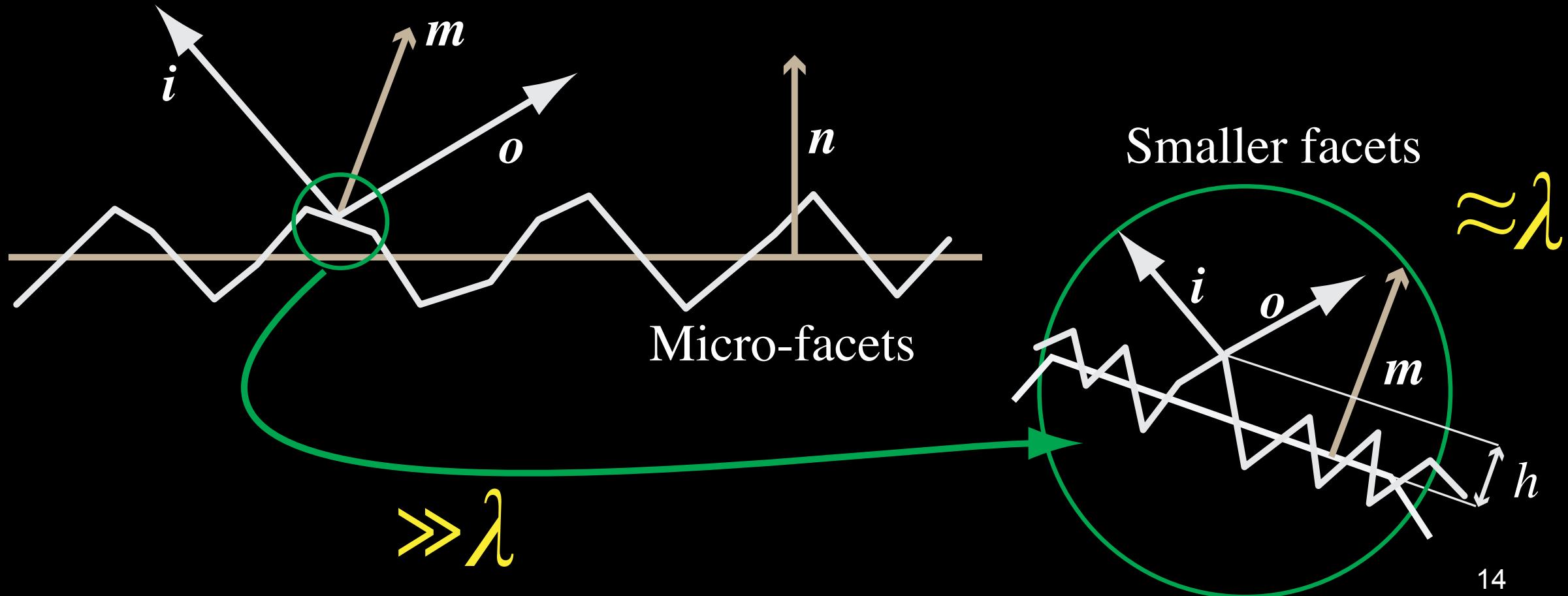
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OUR MAIN IDEA



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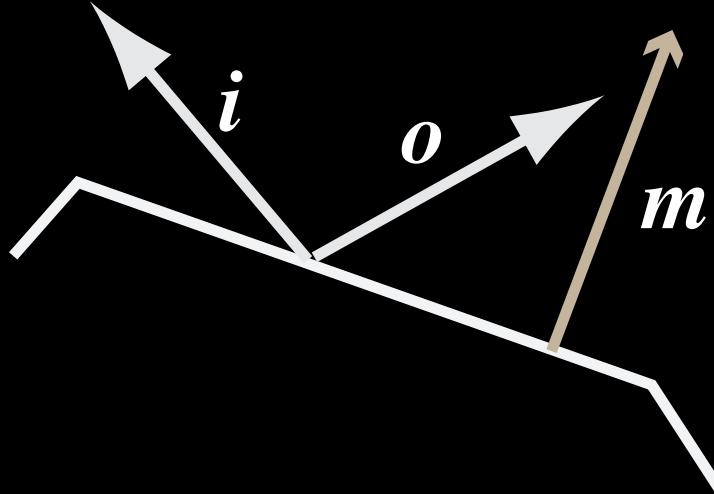


NEW REFLECTANCE MODEL



- Separate details in two groups:
 - large ($\gg \lambda$) and small ($\approx \lambda$)
- Return to micro-facet model definition:
 - Small facets: diffraction
 - Large facets: Cook-Torrance model
 - Combined effects: convolution

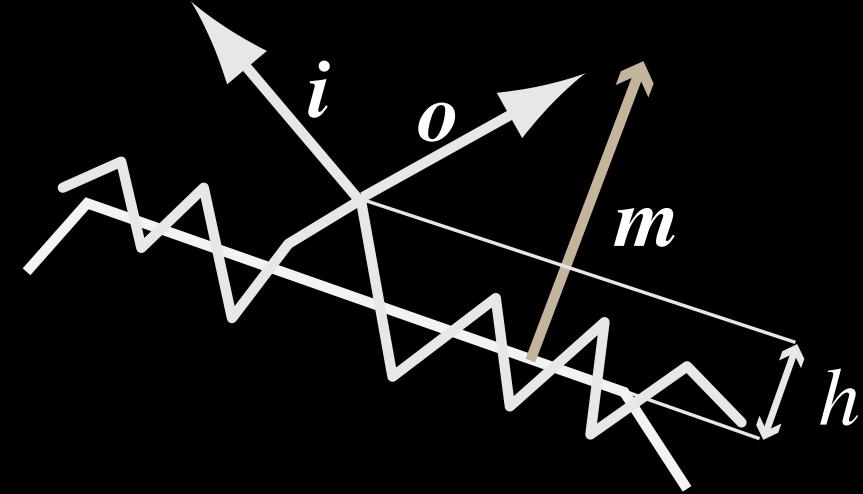
SINGLE MICRO-FACET CONTRIBUTION



$$\rho_\mu = F \delta$$

Before

$$\rho_\mu = AF \delta + (1-A) Q S_{\text{HS}}(f)$$



After

ALL MICRO-FACETS TOGETHER



$$\rho(\mathbf{i}, \mathbf{o}) = \int_{\Omega} \left| \frac{\mathbf{i} \cdot \mathbf{m}}{\mathbf{i} \cdot \mathbf{n}} \right| \rho_{\mu}(\mathbf{i}, \mathbf{o}, \mathbf{m}) \left| \frac{\mathbf{o} \cdot \mathbf{m}}{\mathbf{o} \cdot \mathbf{n}} \right| G(\mathbf{i}, \mathbf{o}) D(\mathbf{m}) d\omega_m$$

- Dirac part of micro-facet reflectance: **Cook-Torrance term**

$$\rho(\mathbf{i}, \mathbf{o}) = \boxed{A_{\text{spec}}(\theta_d) \rho_{CT}(\mathbf{i}, \mathbf{o})} + \boxed{\rho_{CTD}(\mathbf{i}, \mathbf{o})}$$

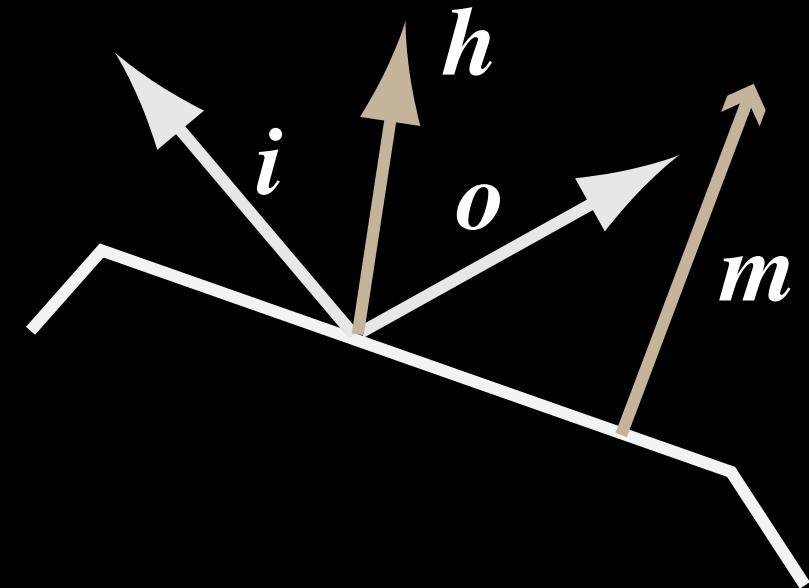
- Diffraction part: **Combined Cook-Torrance-Diffraction (CTD)**

COOK-TORRANCE-DIFFRACTION



$$\rho_{CTD}(i, o) = \int_{\Omega} \left| \frac{i \cdot m}{i \cdot n} \right| (1 - A) Q(i, o) S_{HS}(f) \left| \frac{o \cdot m}{o \cdot n} \right| G(i, o) D(m) d\omega_m$$

- **Large scale** parameters: i, o, n, h, θ_d
- **Small scale** parameters: f, m, θ_h
- Small scale dependencies: A, Q
- Separation large scale / small scale?

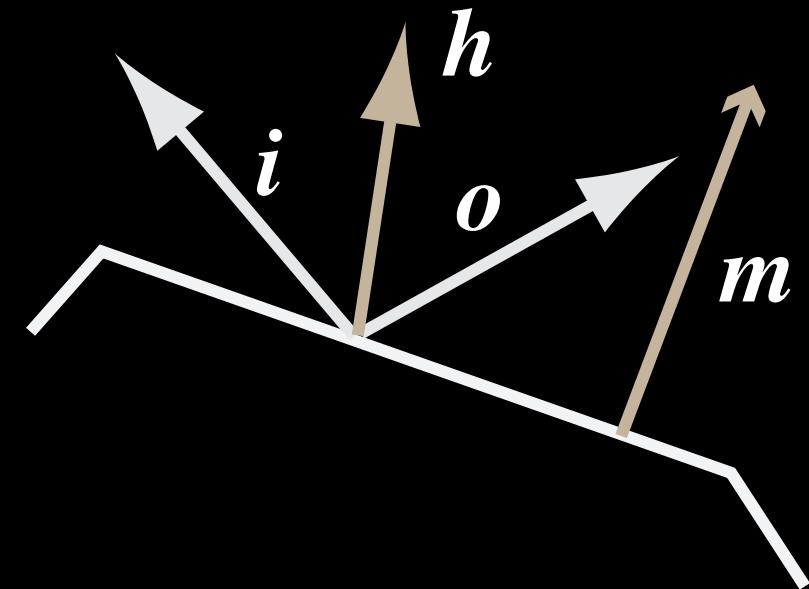


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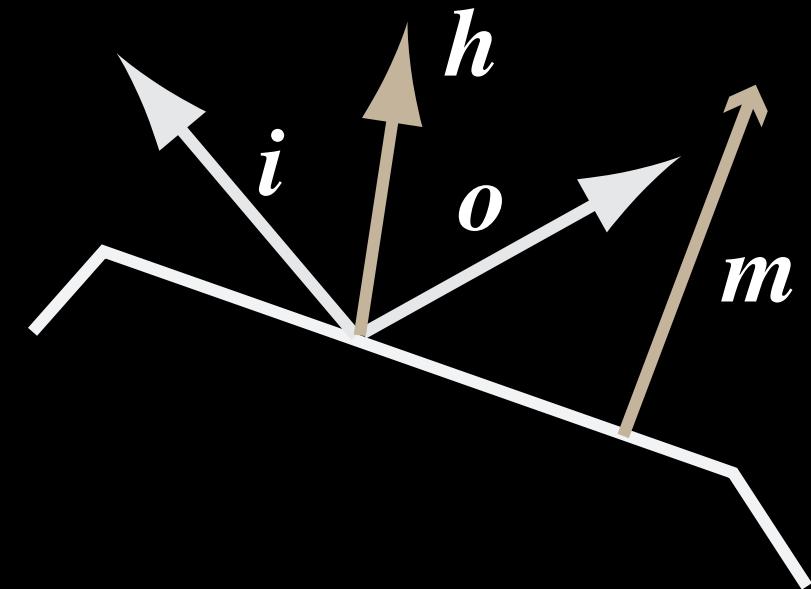


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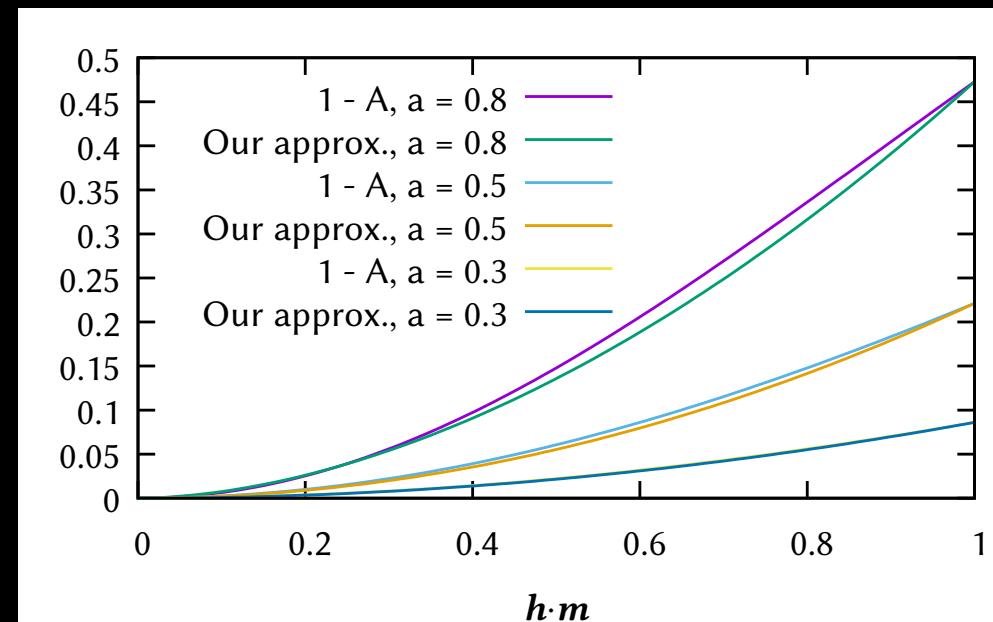


SMALL SCALE / LARGE SCALE (1)



- A depends on $(\cos \theta_i + \cos \theta_o)$
- Cosines relative to \mathbf{m} , micro-facet normal
- $(\cos \theta_i + \cos \theta_o) = (\mathbf{i} \cdot \mathbf{m} + \mathbf{o} \cdot \mathbf{m}) = 2 \cos \theta_d (\mathbf{h} \cdot \mathbf{m})$
- Separation large scale / small scale:

$$1 - A \approx (1 - A_{\text{spec}}(\theta_d))(\mathbf{h} \cdot \mathbf{m})^2$$



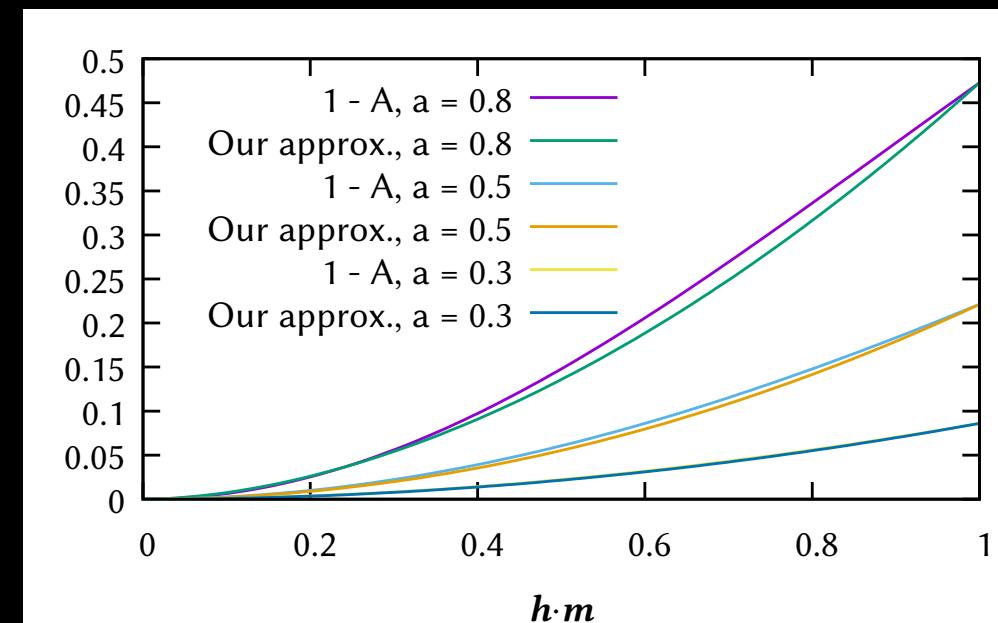
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- Separation **large scale** / **small scale**:

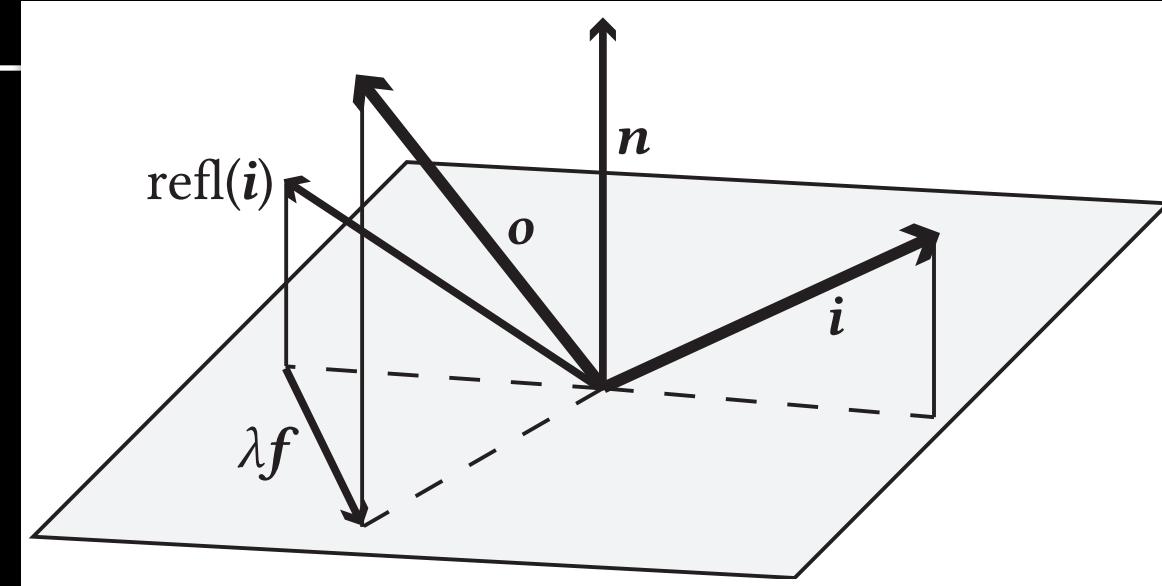
$$1 - A \approx (1 - A_{\text{spec}}(\theta_d)) (\mathbf{h} \cdot \mathbf{m})^2$$



SMALL SCALE / LARGE SCALE (2)



- Diffraction parameter f :
 - $f = (2/\lambda) \sin \theta_h \cos \theta_d$
 - $f = (2/\lambda) \cos \theta_d (1 - (\mathbf{h} \cdot \mathbf{m})^2)^{1/2}$
 - Product large/small scale
- Putting it into the integral:

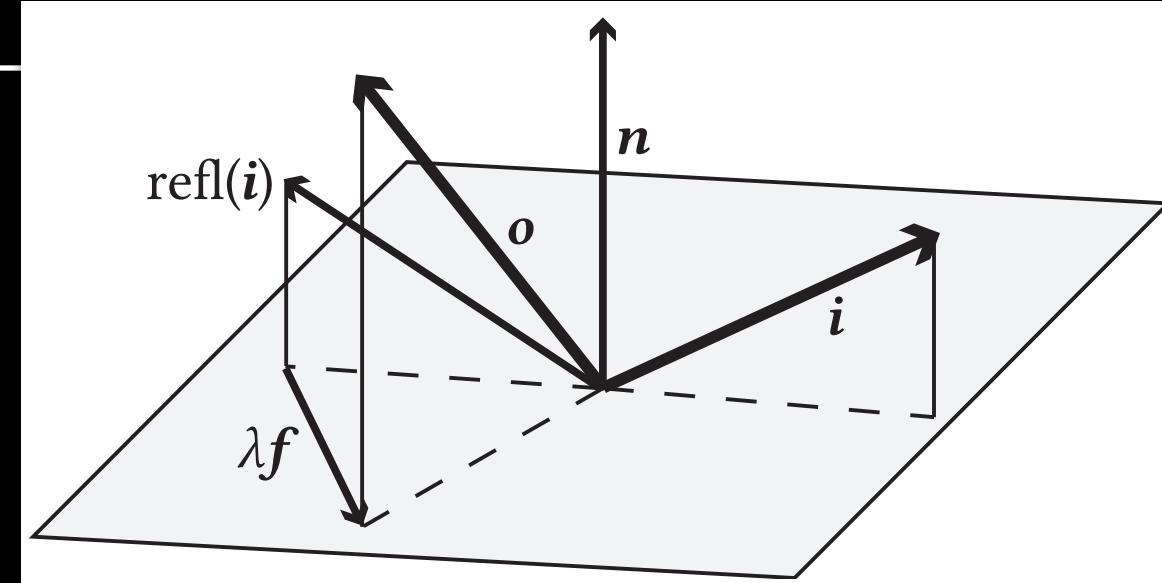


$$\rho_{CTD}(\mathbf{i}, \mathbf{o}) \approx (1 - A_{\text{spec}}(\theta_d)) G(\mathbf{i}, \mathbf{o}) \int_{\Omega} \left| \frac{\mathbf{i} \cdot \mathbf{m}}{\mathbf{i} \cdot \mathbf{n}} \right| \left| \frac{\mathbf{o} \cdot \mathbf{m}}{\mathbf{o} \cdot \mathbf{n}} \right| Q(\mathbf{i}, \mathbf{o}) S(\mathbf{h} \cdot \mathbf{m}) D(\mathbf{m}) d\omega_m$$

SMALL SCALE / LARGE SCALE (2)



- Diffraction parameter f :
 - $f = (2/\lambda) \sin \theta_h \cos \theta_d$
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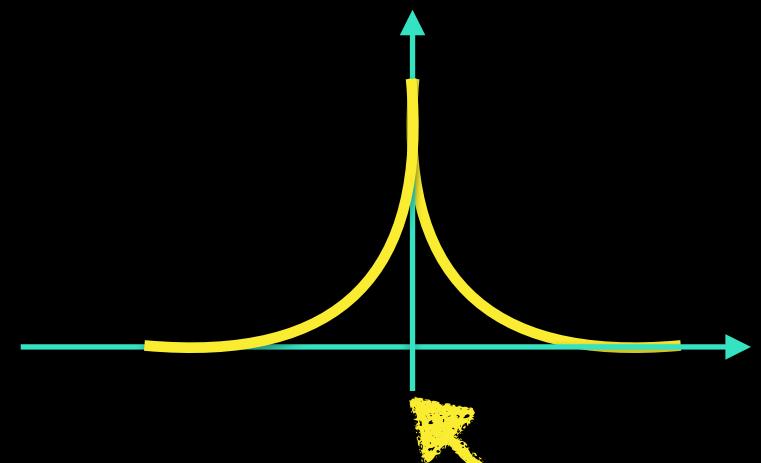
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SMALL SCALE / LARGE SCALE (2)



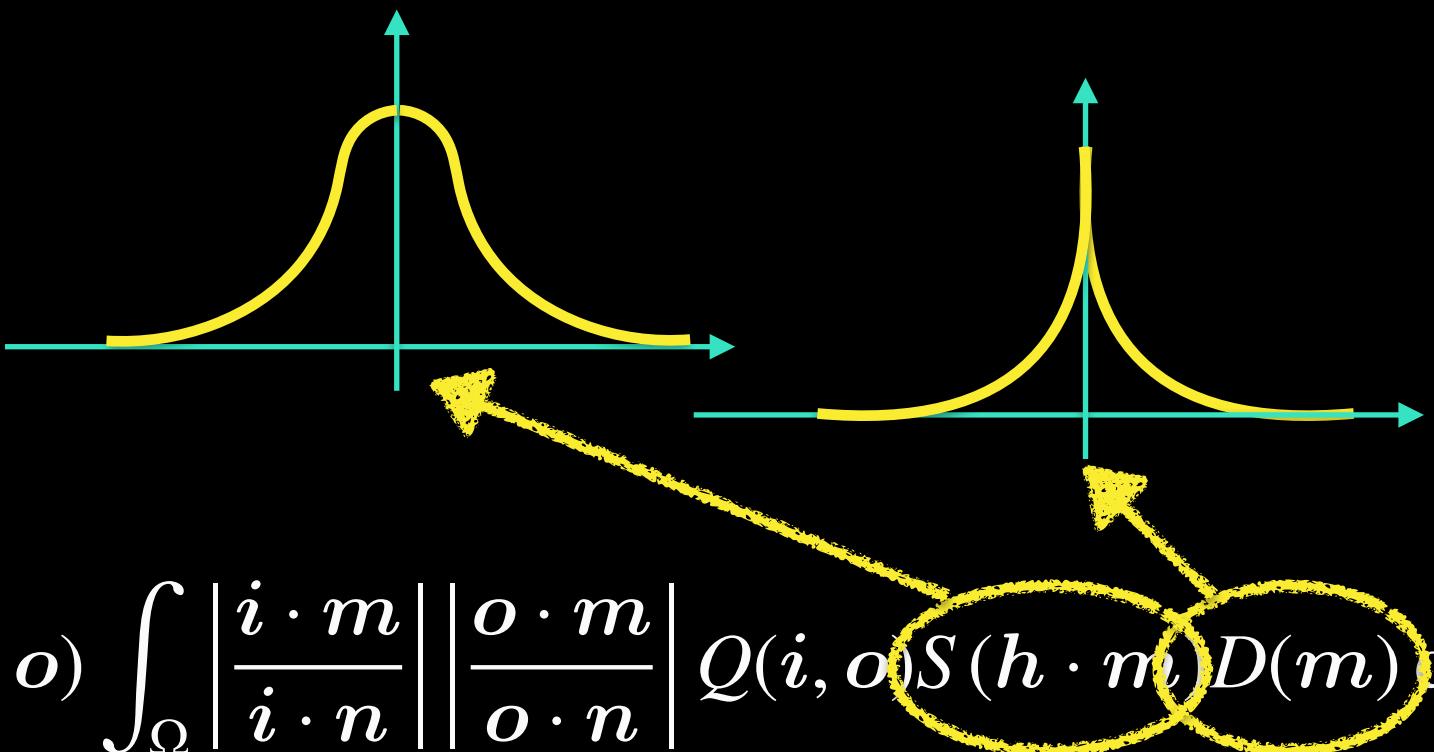
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SMALL SCALE / LARGE SCALE (2)

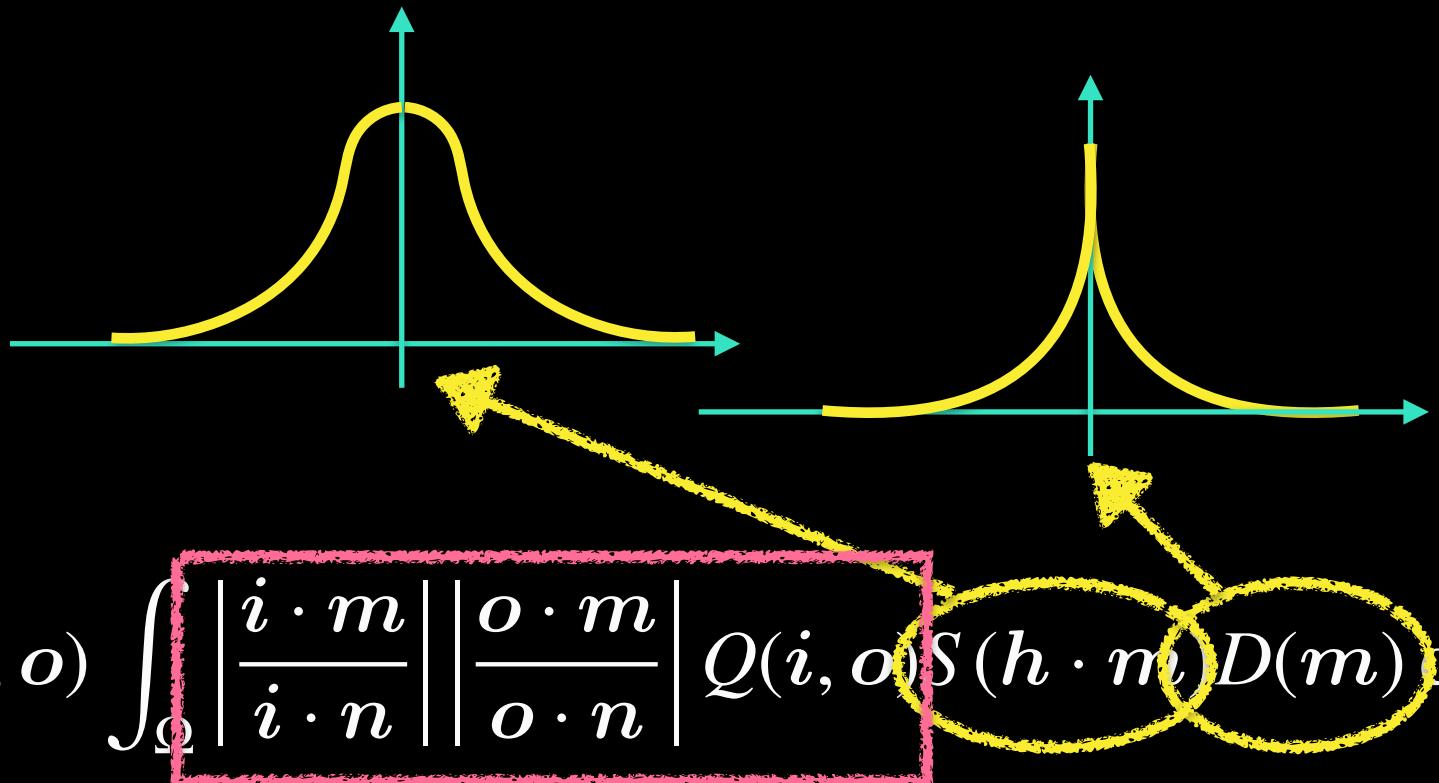


$$\rho_{CTD}(i, o) \approx (1 - A_{\text{spec}}(\theta_d)) G(i, o) \int_{\Omega} \left| \frac{i \cdot m}{i \cdot n} \right| \left| \frac{o \cdot m}{o \cdot n} \right| Q(i, o) S(h \cdot m) D(m) d\omega_m$$

SMALL SCALE / LARGE SCALE (2)



SMALL SCALE / LARGE SCALE (2)



Slow variations: \approx constant

COOK-TORRANCE-DIFFRACTION



$$\rho_{CTD}(i, o) \approx (1 - A_{\text{spec}}(\theta_d))G(i, o)Q(i, o) \int_{\Omega} S(h \cdot m)D(m) \, d\omega_m$$

- Spherical convolution
 - Compute using Spherical Harmonics
- Both functions have symmetry of revolution
 - **Zonal Harmonics** only

COOK-TORRANCE-DIFFRACTION



$$\rho_{CTD}(i, o) \approx (1 - A_{\text{spec}}(\theta_d))G(i, o)Q(i, o) \int_{\Omega} S(h \cdot m)D(m) d\omega_m$$

- Spherical convolution
 - Compute using Spherical Harmonics
 - Both functions have symmetry of revolution
 - **Zonal Harmonics** only

SUMMARY



$$\rho(\mathbf{i}, \mathbf{o}) = A_{\text{spec}}(\theta_d) \boxed{\rho_{CT}(\mathbf{i}, \mathbf{o})} + (1 - A_{\text{spec}}(\theta_d)) \boxed{Q \ G \ (S * D)(\theta_h)}$$

- Scaled Cook-Torrance lobe + Convolved Diffraction lobe
- Relative importance depends on θ_d
- Shadowing-Masking G applied to diffraction lobe
- Convolution:
 - Enlarges diffraction lobe
 - Depends on wavelength and $\cos \theta_d$

PRACTICAL IMPLEMENTATION



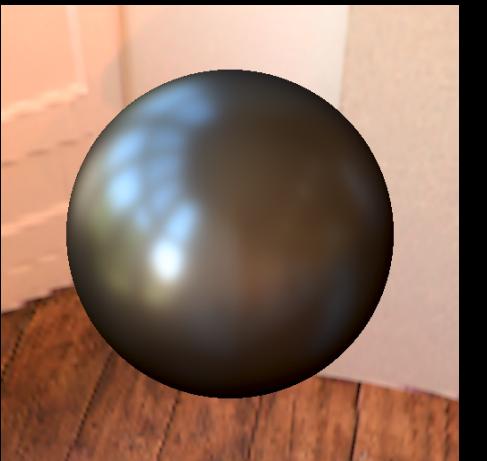
- S_{HS}, D are parametric functions:
 - Compute $(S * D)$ for all values of the parameters
 - Approximate: $(S * D) \approx \hat{S}_{\text{HS}}$ (different parameters)
 - Table: input parameters → parameters of \hat{S}_{HS}
- Other precomputations:
 - G (shadowing-masking)
 - Renormalisation of S_{HS} (for energy conservation)

OVERVIEW



- Background
 - Cook-Torrance models
 - Diffraction models
- Our model:
 - Two-scale representation
 - Combining the effects
- Comparisons with measured reflectance
- Conclusion and future directions

MEASURED NICKEL



Diffraction

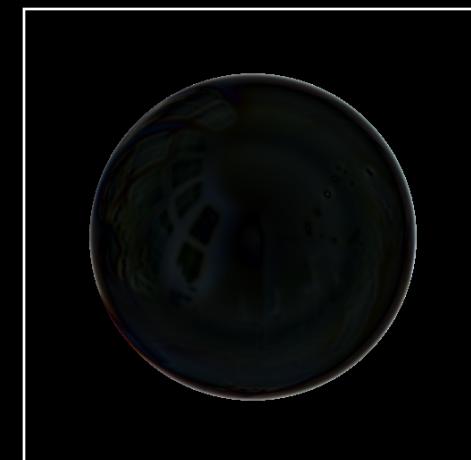
+ Micro-Facet

= Full model

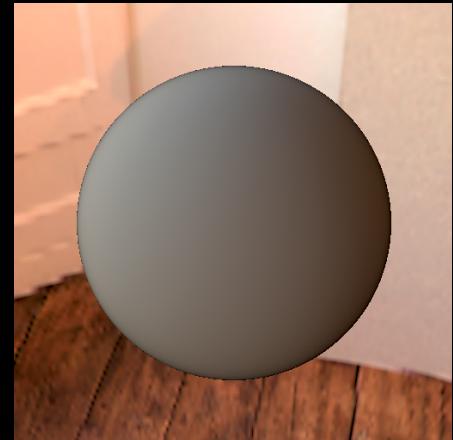


Reference (measured)

Difference



MEASURED GRAY-PLASTIC

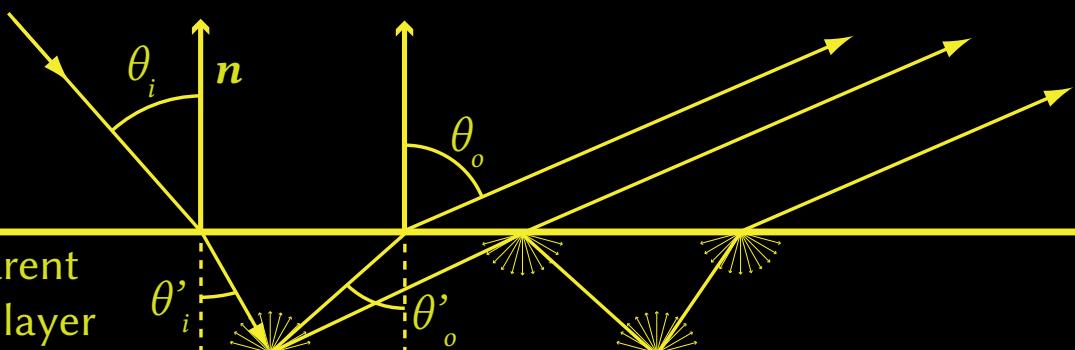


Diffraction

+ Micro-Facet

+ Diffuse layer

= Full model



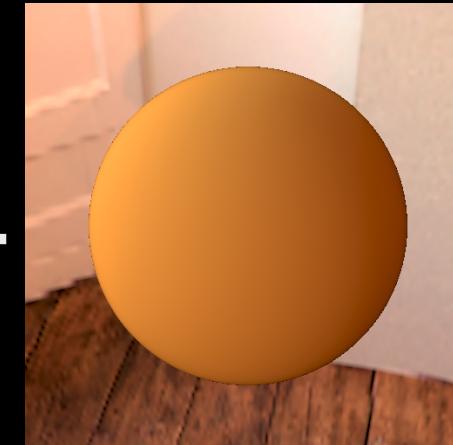
MEASURED YELLOW-MATTE-PLASTIC



+



+



=



Diffraction

+

Micro-Facet

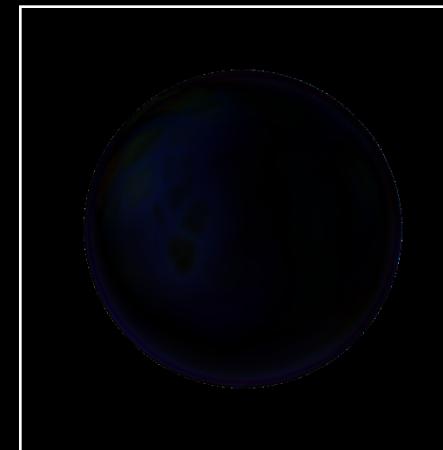
+

Diffuse layer

=

Full model

See Supplemental for full comparison



Difference

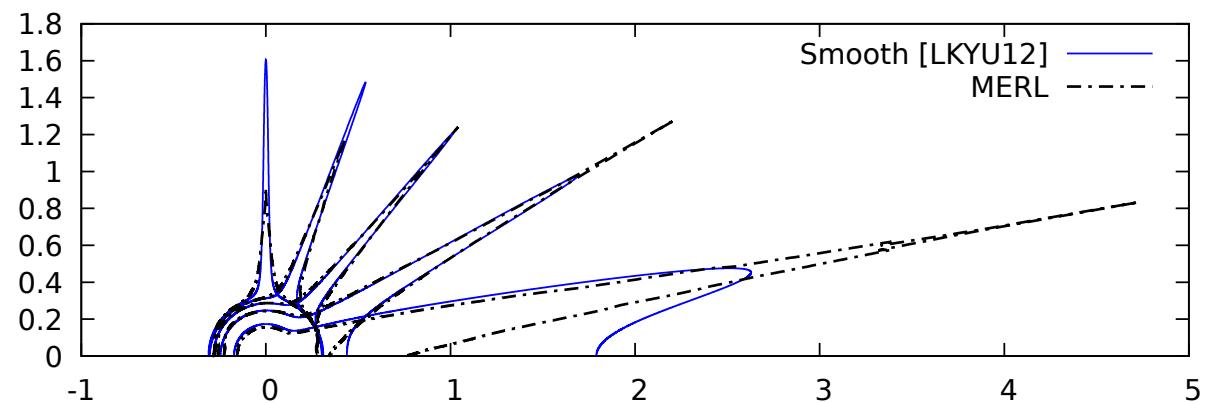
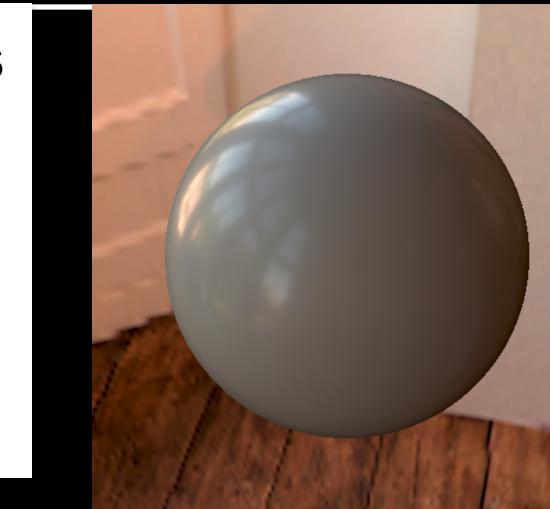
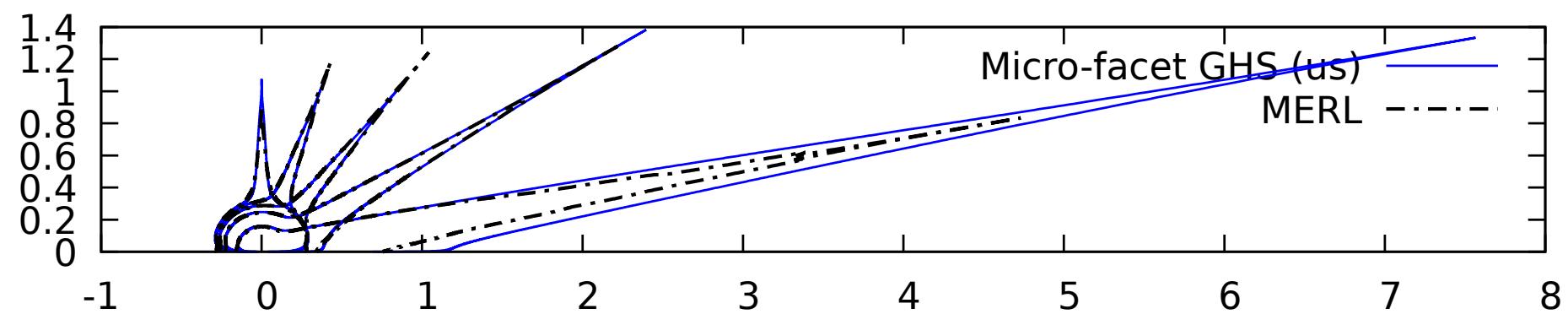


Reference (measured)

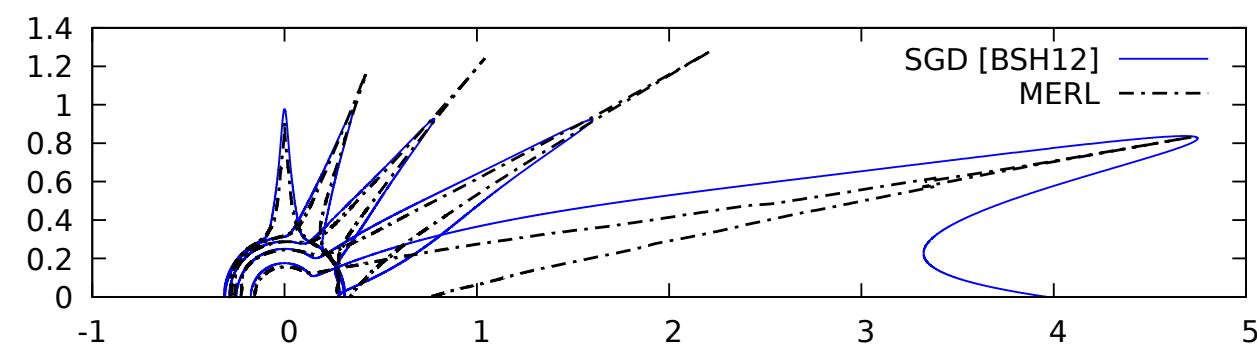
LOBE SHAPES (INCIDENT PLANE)



Gray-plastic



Smooth (diffraction only)

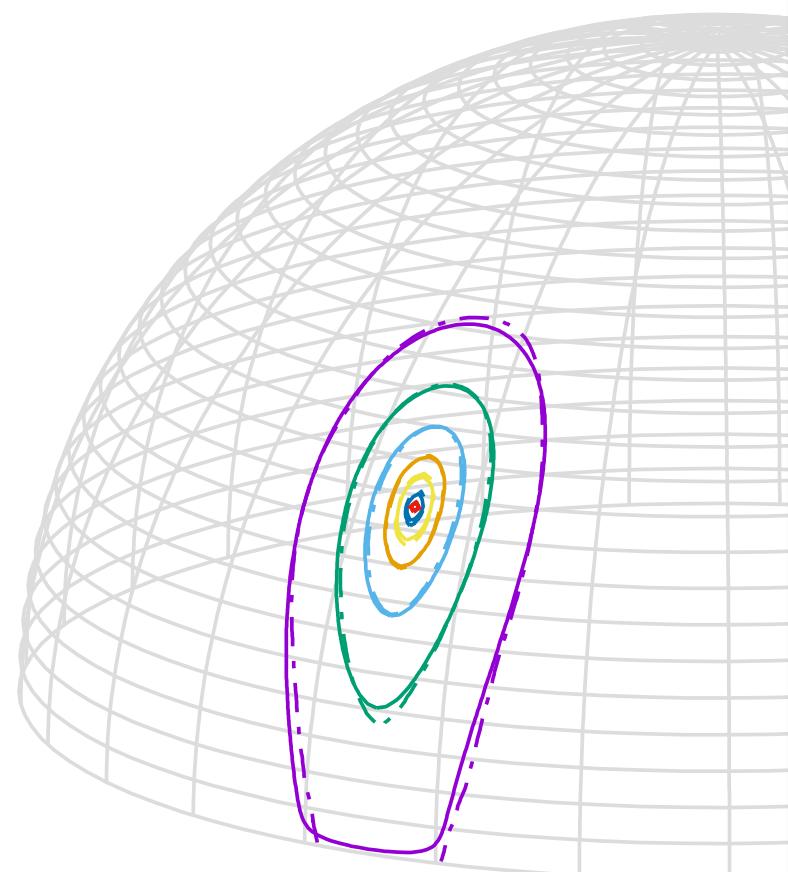


SGD (micro-facet only)₂₉

LOBE SHAPES (OUTSIDE INCIDENT)

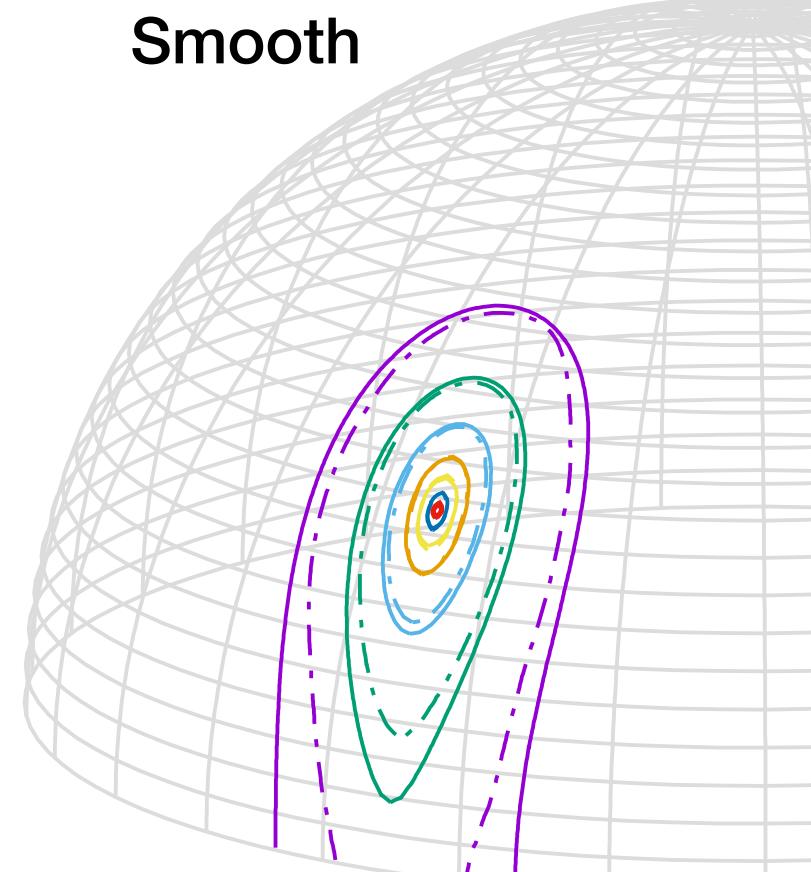


Our model

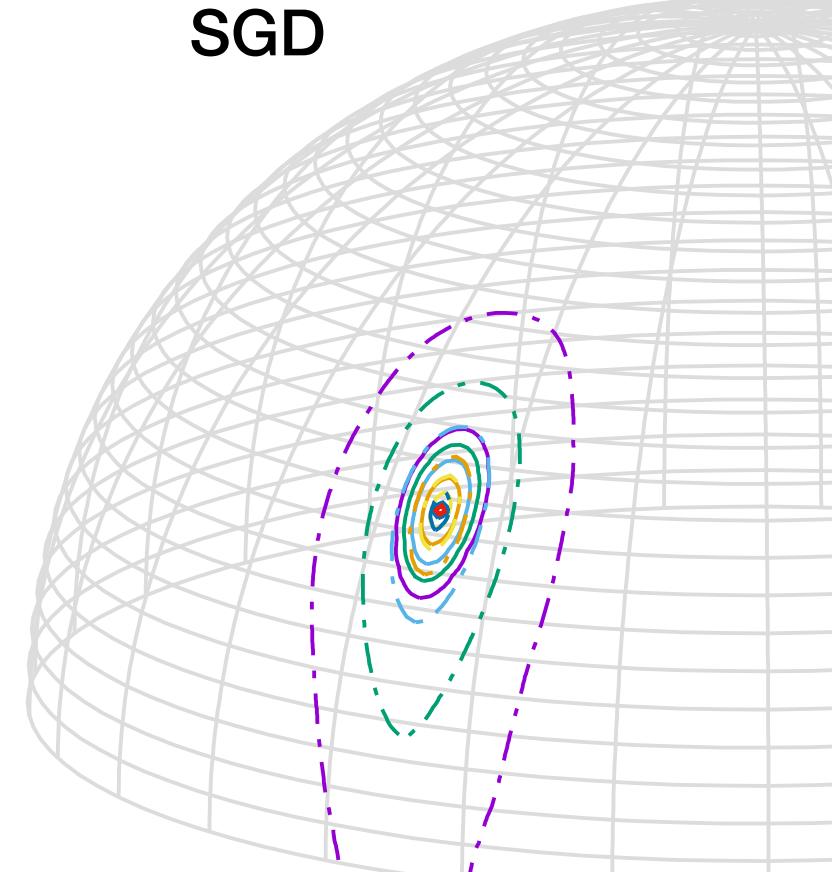


blue-metallic-paint2

(Diffraction only)
Smooth



(Micro-facet only)
SGD



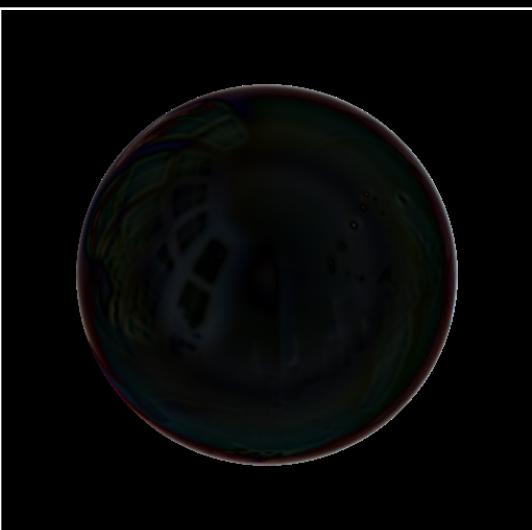
MICRO-FACET + DIFFUSE LOBE?



Micro-facet
+
diffraction
(Our model)



Difference



Reference

Micro-facet
+
diffuse lobe



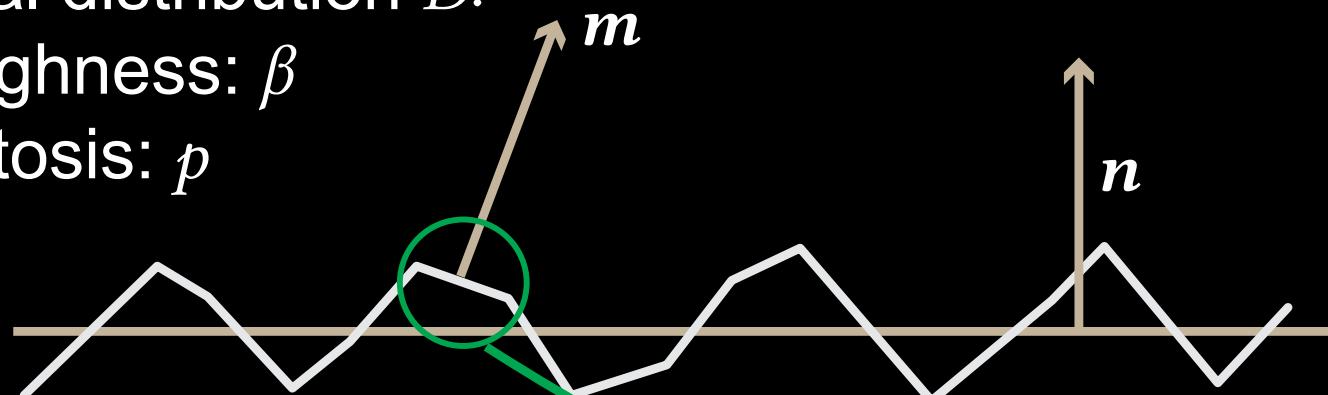
Difference

PARAMETERS



Normal distribution D :

- roughness: β
- kurtosis: p

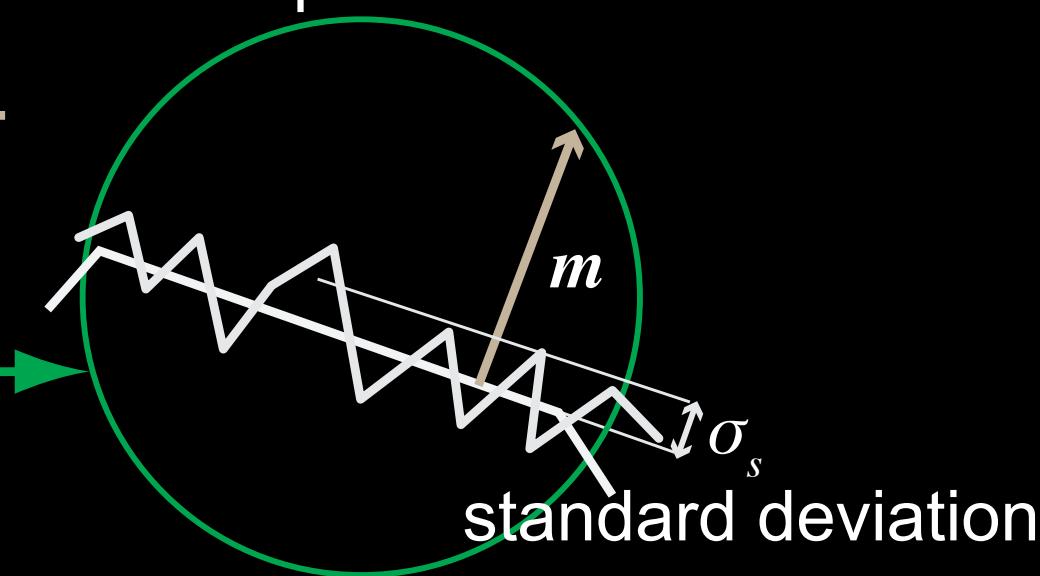


Material itself:

- index of refraction: n or $n + ik$
- diffuse layer/albedo: ρ_d

Smaller facets PSD

- horizontal scale: b
- shape: c



LIMITATIONS



- Single interface, single bounce
- Works better for smooth surfaces
 - Also hypotheses for convolution
- Worst case scenario:
 - Diffuse materials, fabrics, glossy metallic paints
- Computation time: + 10 %

OVERVIEW



- Background
 - Cook-Torrance models
 - Diffraction models
- Our model:
 - Two-scale representation
 - Combining the effects
- Comparisons with measured reflectance
- Conclusion and future directions

CONCLUSION



- Two-scale micro-facet model for surface reflectance
- Combination Cook-Torrance and Combined CTD lobe
- Near specular peak: Cook-Torrance
- Low values: Combined CT-Diffraction
- Fits measured reflectance
- Code: Mitsuba plugin (see project page)



FUTURE DIRECTIONS



- Low hanging fruits:
 - Simplified model
 - Anisotropic model (large scale only)
 - Multiple bounces
 - Multiple layers
- More difficult:
 - Anisotropic model (both scales)
 - More measured data (height fields, spectral reflectance)
 - More accurate convolution
 - Unified representation, large wavelength range

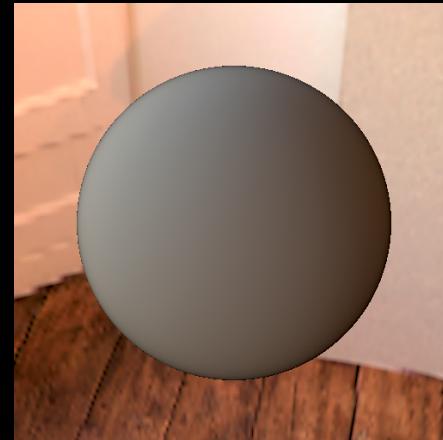
THANK YOU



+



+



=

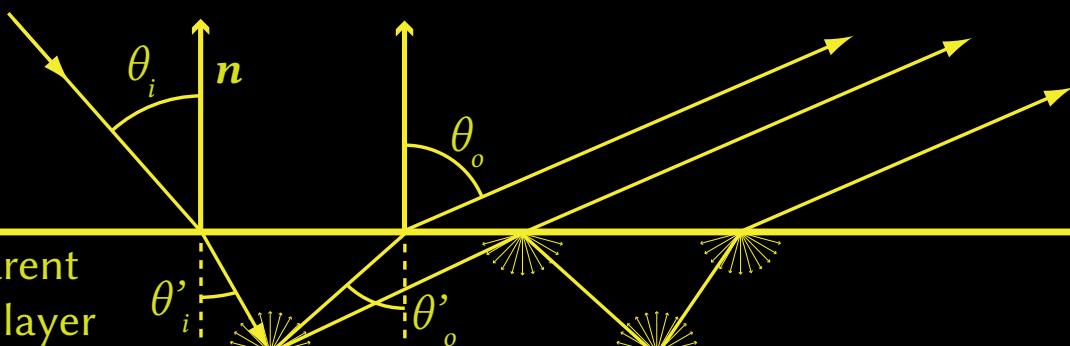


Diffraction

+ Micro-Facet

+ Diffuse layer

= Full model



Transparent
varnish layer

Diffuse opaque layer



Difference



Reference (measured)³⁷

NUMBER OF SPECTRUM SAMPLES



Alum-bronze, RGB

Alum-bronze, 30 samples

NUMBER OF SPECTRUM SAMPLES



Aluminium, RGB



Aluminium, 30 samples 39

PRECOMPUTED TABLES



- Shadowing-masking G: 390 kB
 - 2 parameters, $\beta \tan\theta$ and p
- Renormalization: 8.9 MB
 - 3 parameters: θ_i , b and c
 - Reduce parameter range?
- Convolution: 2.5 MB
 - 4 parameters: β , p , c , u
 - $u = (b/\lambda)\cos\theta_d$

SHAPE-INVARIANCE



- D needs shape-invariance property [Heitz 2014]:

$$D(\theta) = \frac{\chi_{[0, \frac{\pi}{2}]}(\theta)}{\cos^4 \theta} P_{22}(\tan^2 \theta)$$

EXPONENTIAL POWER DISTRIBUTION



- Extension of Gaussian distribution:

$$P_{22}(x) = \frac{p}{\pi\beta^2\Gamma(1/p)} e^{-\left(\frac{x}{\beta^2}\right)^p}$$

EXPONENTIAL POWER DISTRIBUTION



- Extension of Gaussian distribution:

$$P_{22}(x) = \frac{p}{\pi\beta^2\Gamma(1/p)} e^{-\left(\frac{x}{\beta^2}\right)^p}$$

Function

Normalisation factor

K-CORRELATION MODEL



$$S_{HS}(f) = \frac{c-1}{2\pi} \frac{\sigma_s^2 b^2}{(1 + b^2 f^2)^{\frac{c+1}{2}}}$$

K-CORRELATION MODEL



Surface roughness

$$S_{HS}(f) = \frac{c-1}{2\pi} \frac{\sigma_s^2 b^2}{(1 + b^2 f^2)^{\frac{c+1}{2}}}$$

Exponent

Horizontal scale

The equation is $S_{HS}(f) = \frac{c-1}{2\pi} \frac{\sigma_s^2 b^2}{(1 + b^2 f^2)^{\frac{c+1}{2}}}$. The term $c-1$ is highlighted with a cyan box. The term $\sigma_s^2 b^2$ is highlighted with a yellow box. The term $b^2 f^2$ is highlighted with a pink box. The term $\frac{c+1}{2}$ is highlighted with a cyan box. The word "Exponent" is written in cyan text to the right of the equation. The word "Horizontal scale" is written in pink text below the equation.

RENORMALISATION



$$\sigma_{\text{rel}}^2(\theta_i) = \int_{\|\boldsymbol{o}\| \leq 1} S_{HS}(f) \, df_x \, df_y$$

- *Effective* surface roughness
- Divide S_{HS} by σ_{rel}^2 so integral = 1
- Use σ_{rel} in place of σ_s for A [Harvey et al. 2012]
- Important for energy conservation

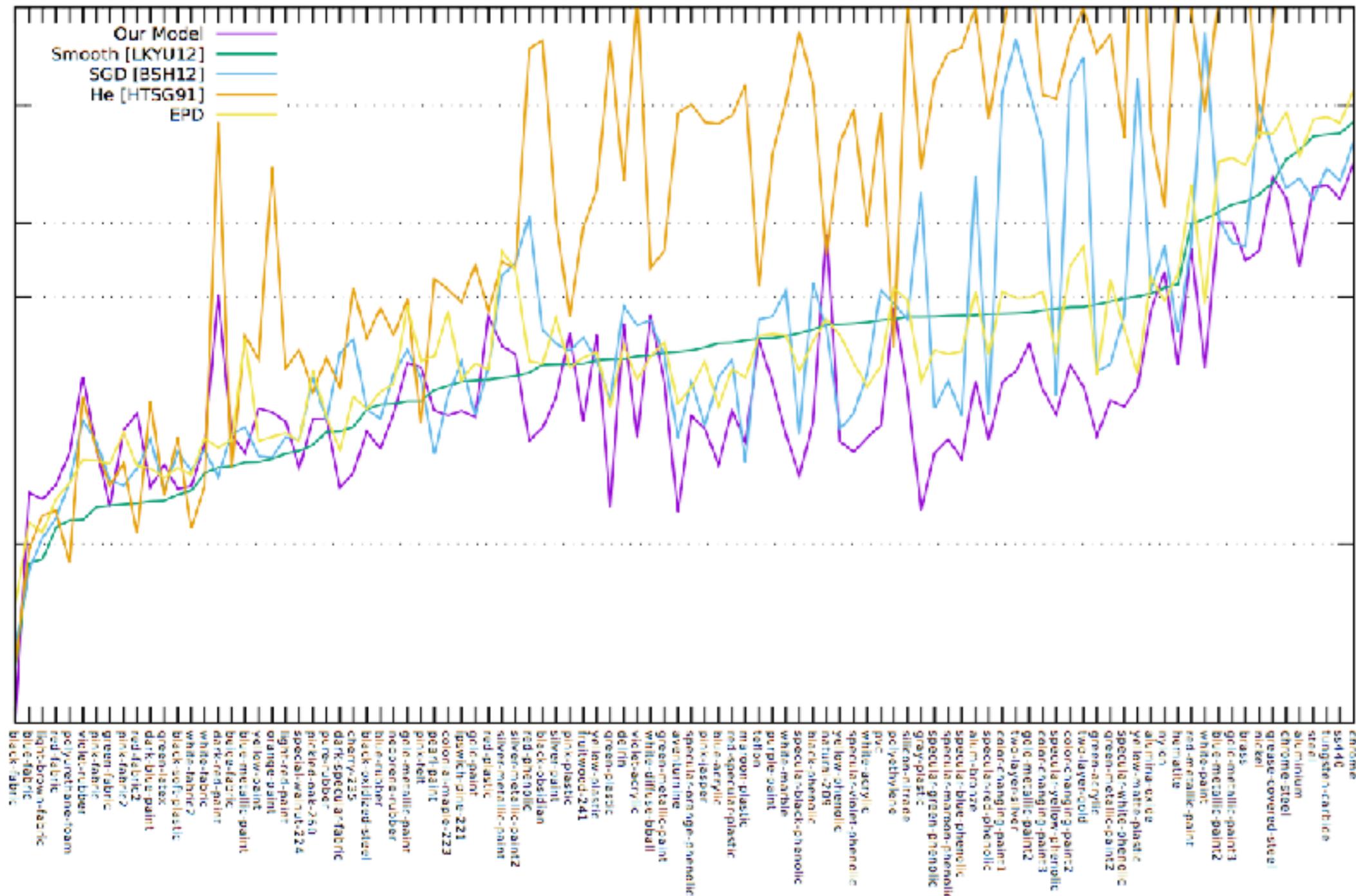
NUMBER OF PARAMETERS

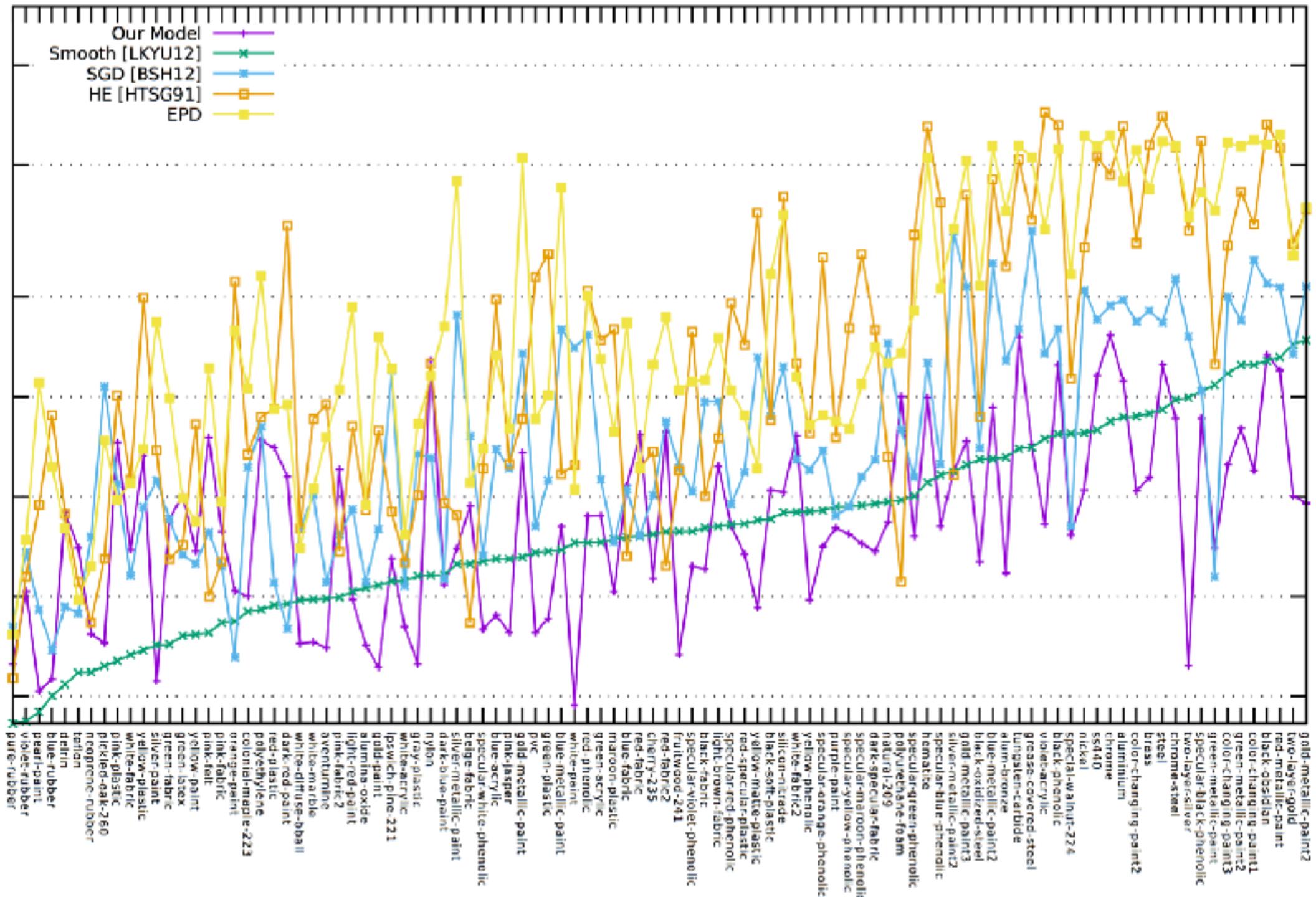


MODEL	NUMBER OF PARAMETERS	DIFFRACTION THEORY
Our Model	11	Hybrid Harvey-Shack
EPD + diffuse	11	None
Shifted Gamma Distribution	18	None
He et al. [1991]	11	Beckman - Kirchoff
Löw et al. [2012]	9	Inspired from Rayleigh-Rice



RMSE
with
full data
46

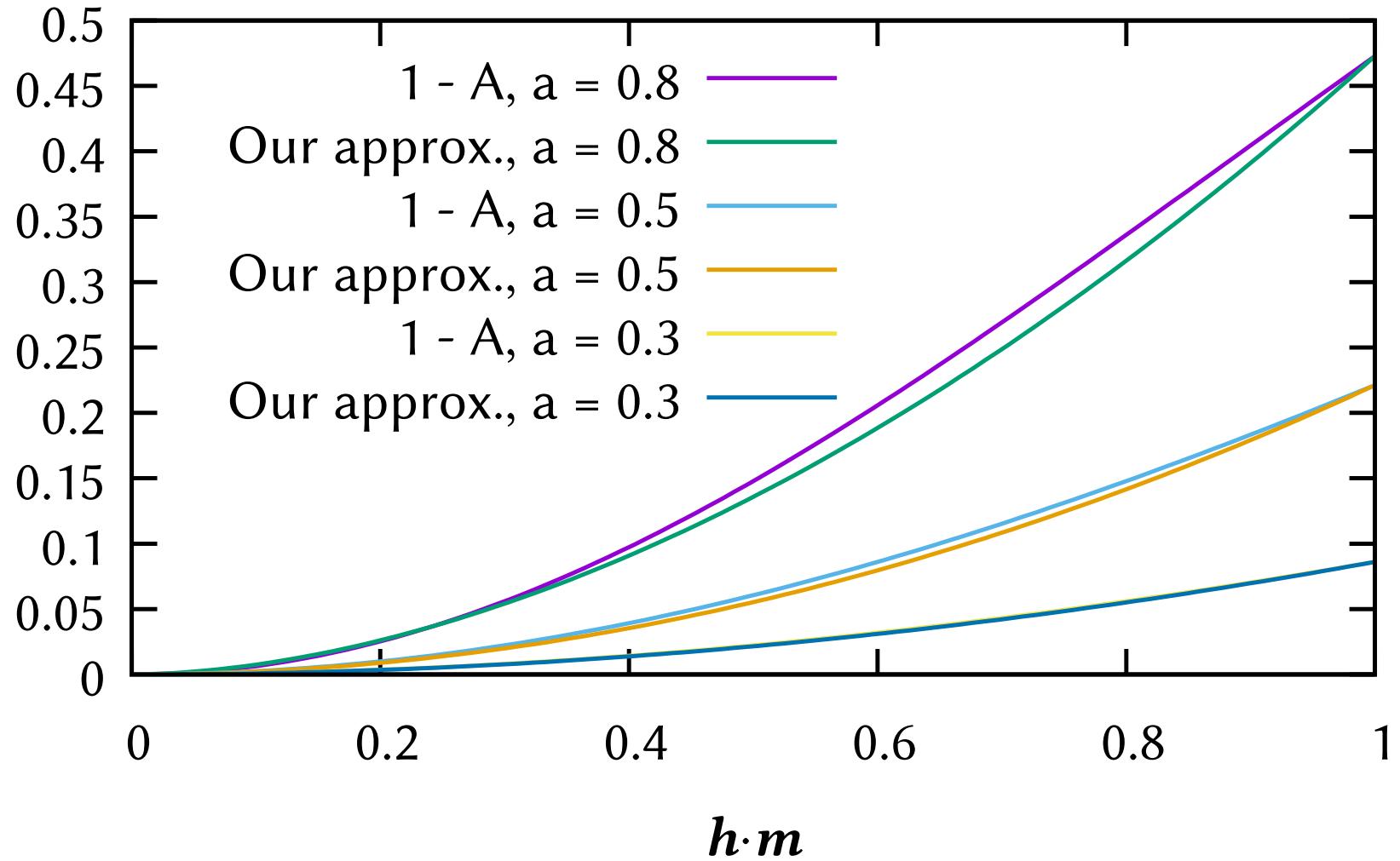




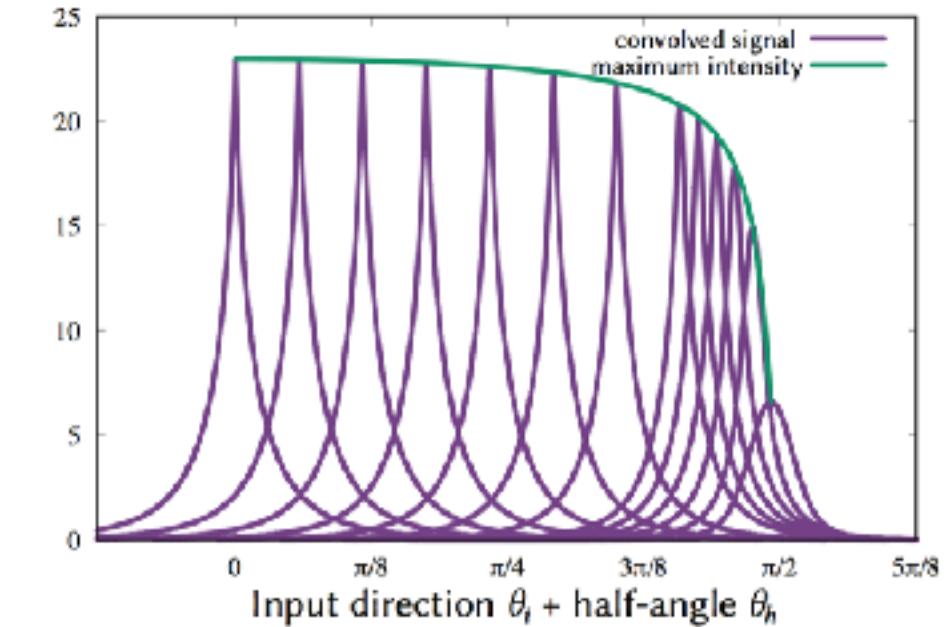
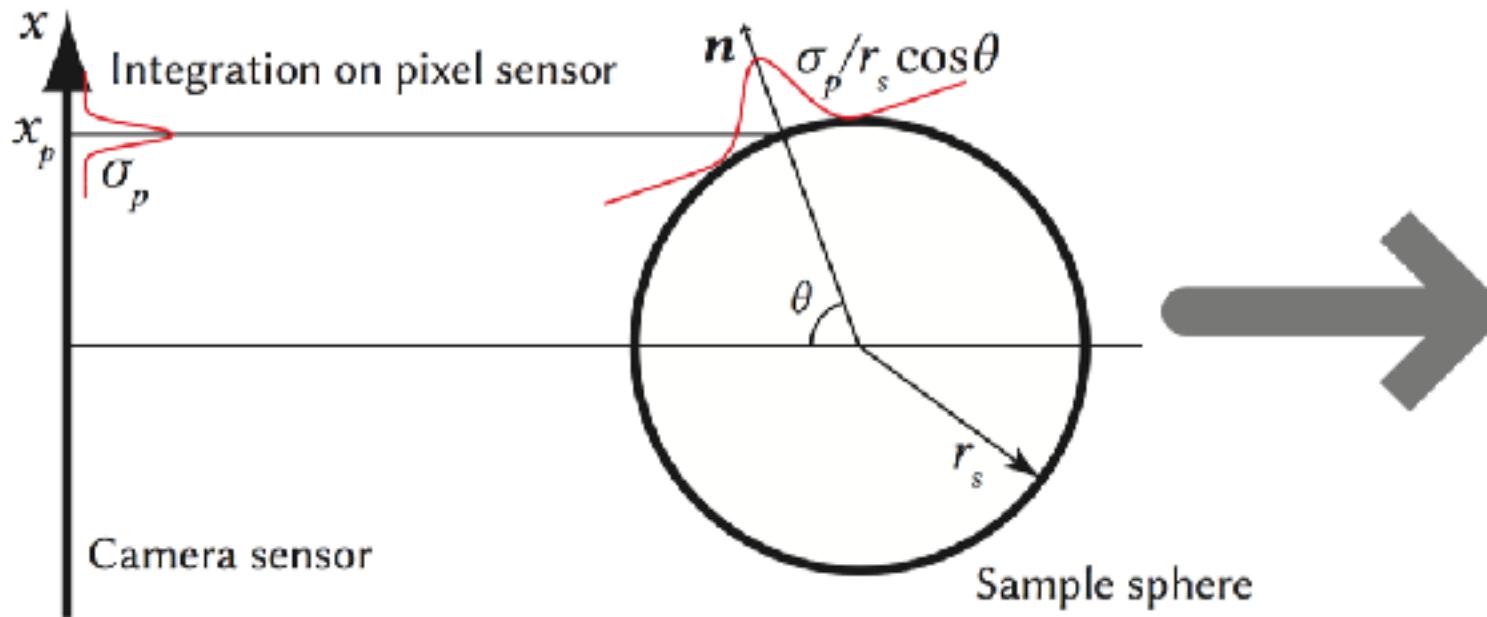
$$(1 - A_{\sigma_s}(i, o)) \approx (1 - A_{\sigma_s}(\theta_d))(h \cdot m)^2$$



$$a = 2\pi\sigma_s/\lambda$$

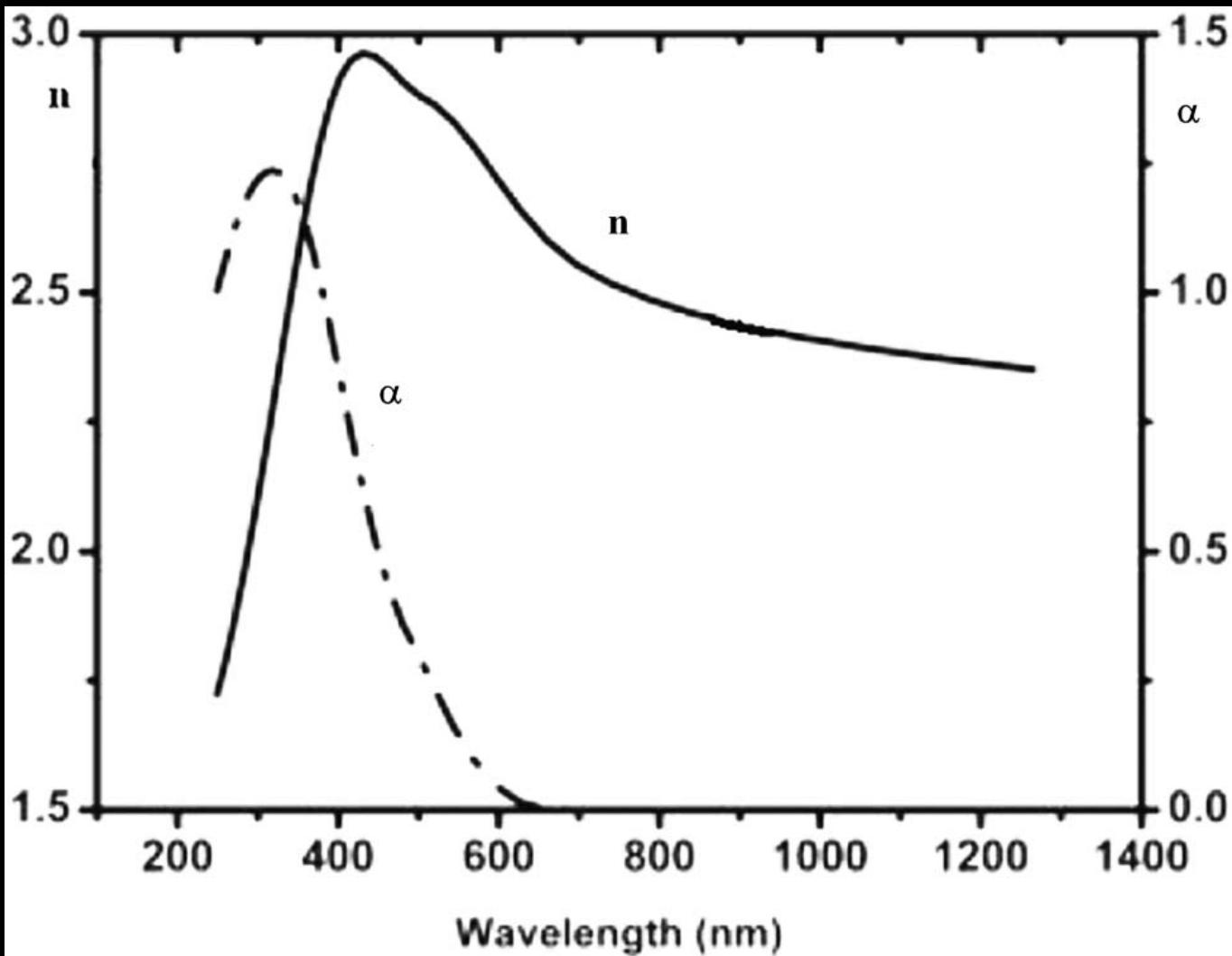


MERL APPARATUS EFFECT



- Intensity decreases at grazing angles
- Modelled, compensated

HEMATITE: INDEX OF REFRACTION



- Conductor below 650 nm
- Dielectric above