Physically-Based Shading at Disney

Brent Burley

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Tangled (2010)

We adopted a physically-based shading model for hair on Tangled with great success, but our ad-hoc materials were difficult to integrate with the hair shading.

Wreck-It Ralph (2012)

Walt Disney Animation Studios

For Wreck-It Ralph, we wanted to investigate physically-based shading for more general materials. We were able to develop a new BRDF model used on virtually every surface in the film (except for hair).

Outline

- Motivation
- Measured data observations
- Disney “principled” BRDF
- Production experience on Wreck-It Ralph
- Future Work

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Motivation

Which shading model should we use?

Neumann-Neumann

Cook-Torrance

Ashikhmin-Shirley

Schlick

albedo pump-up

modified-Phong

Wolff

Phong

Blinn-Phong

Distribution-BRDF

Kelemen

Kurt

GGX

Ward

Halfway Vector Disk

Oren-Nayar

Lafortune

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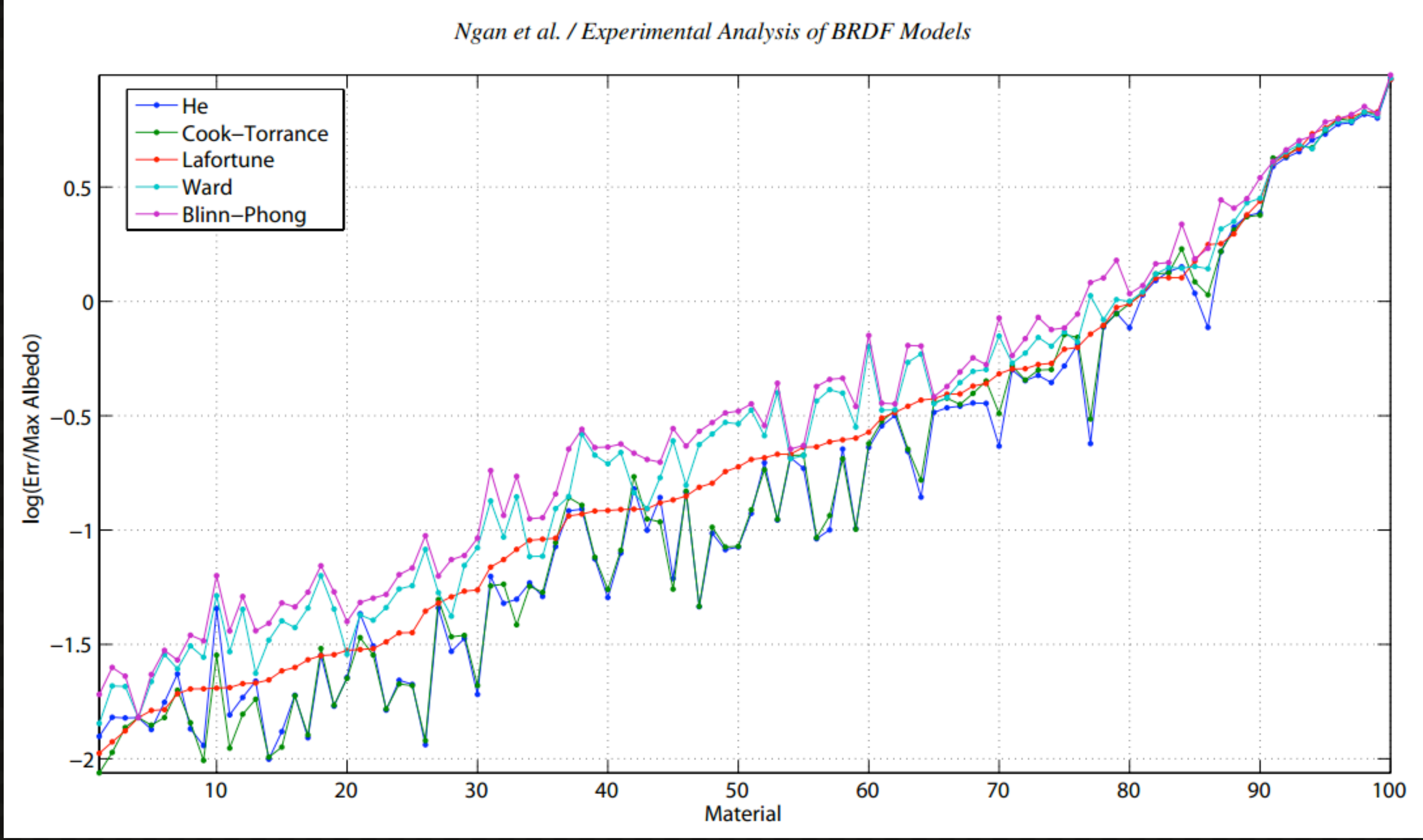
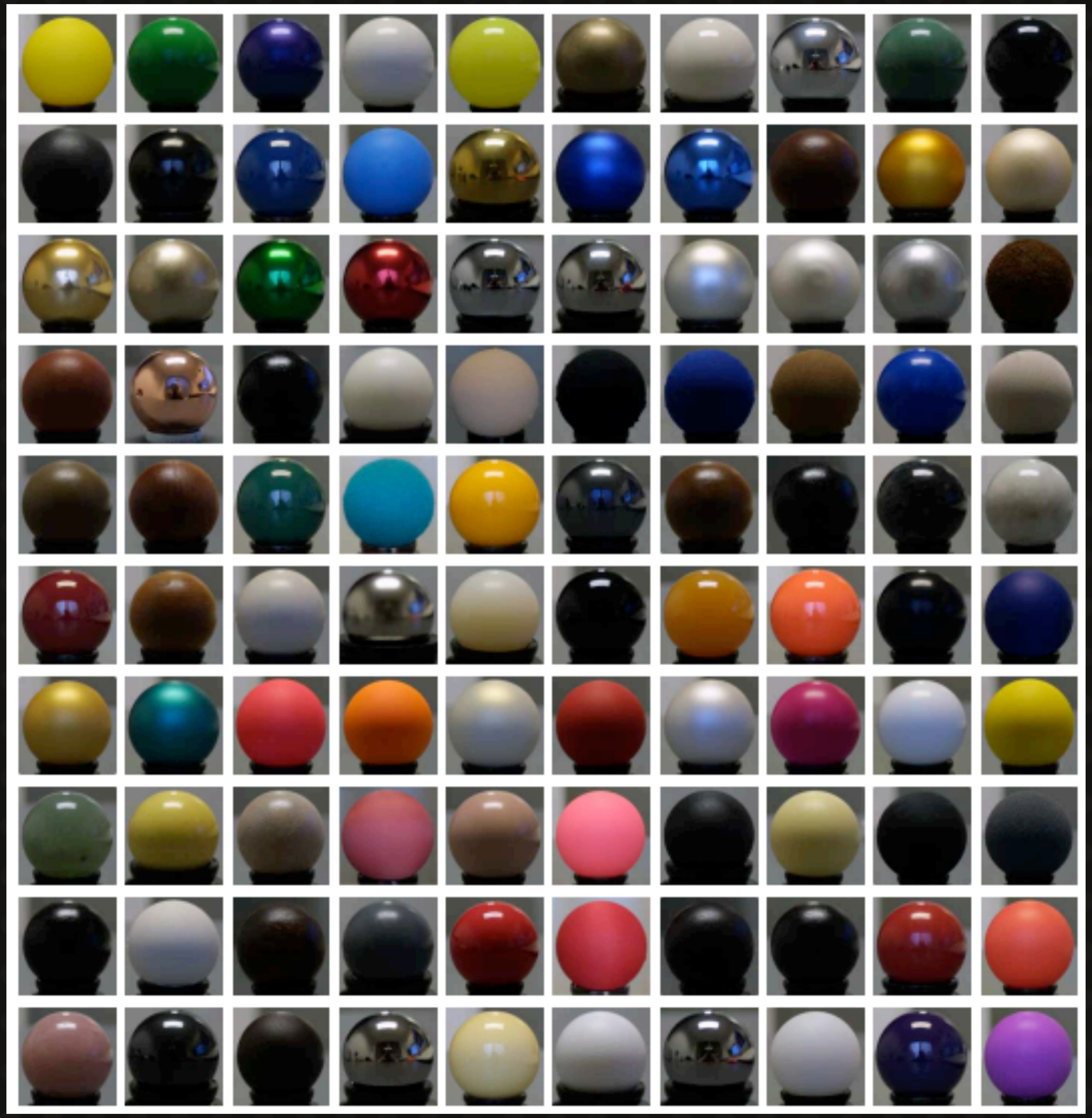
There are a lot of shading models, only a fraction of which are shown here. The best choice for our needs is not obvious, and providing artists with the choice of model would lead to the parameter explosion we were trying to get away from.

What makes a model physically-based?



Mitsubishi Electric Research Laboratories, 2005

This famous study compared 100 materials to 5 popular models. The materials are sorted left to right by relative error. He and Cook-Torrance performed generally better than the others, but one can observe that there's more difference between the materials than the models themselves. In particular, the materials on the right are poorly represented by all the models. This begs the question as to what is not represented in the models.

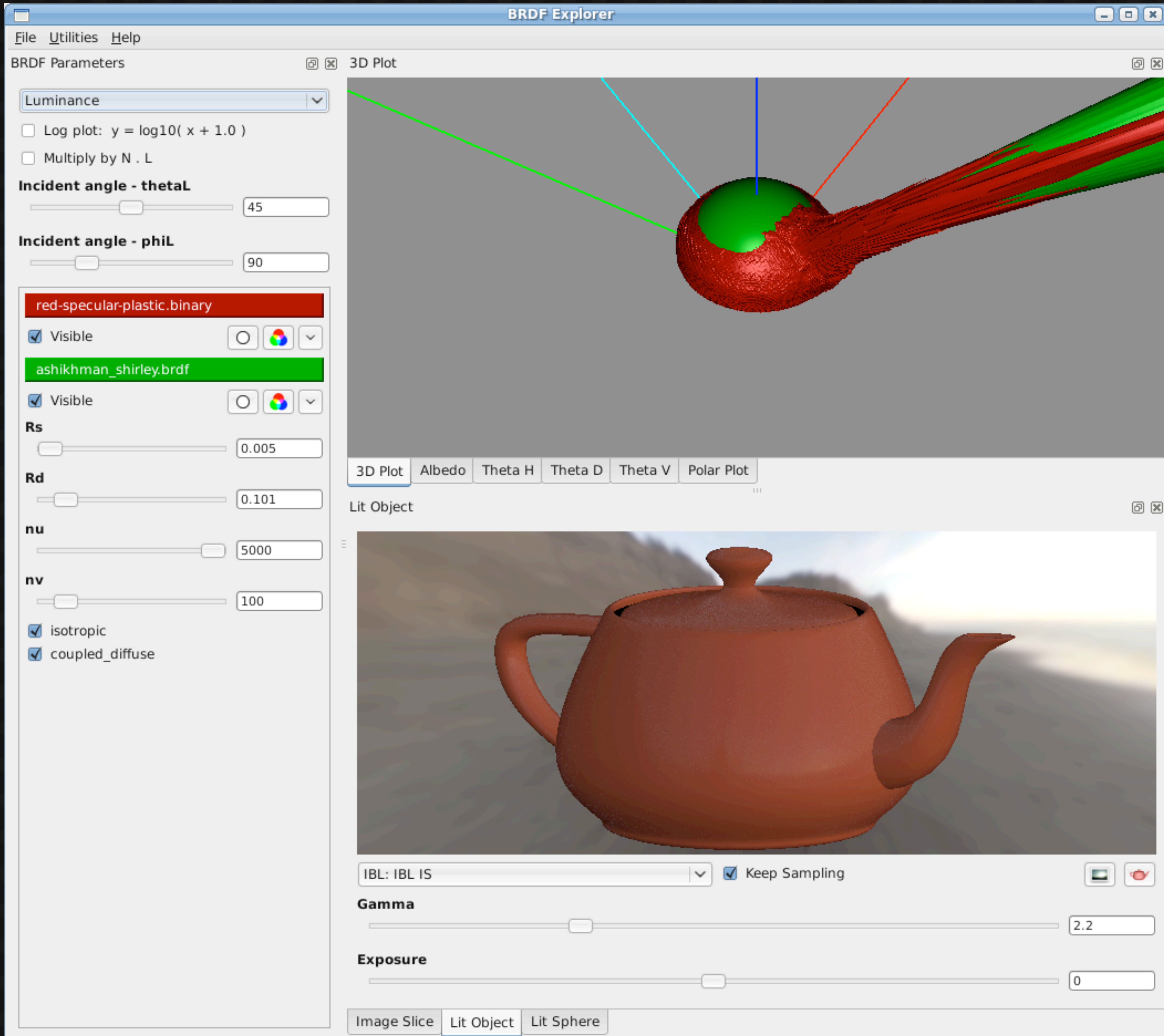


The MERL 100

A Data-Driven Reflectance Model
Matusik et al.
ACM Transactions on Graphics, 2003

http://merl.com/brdf

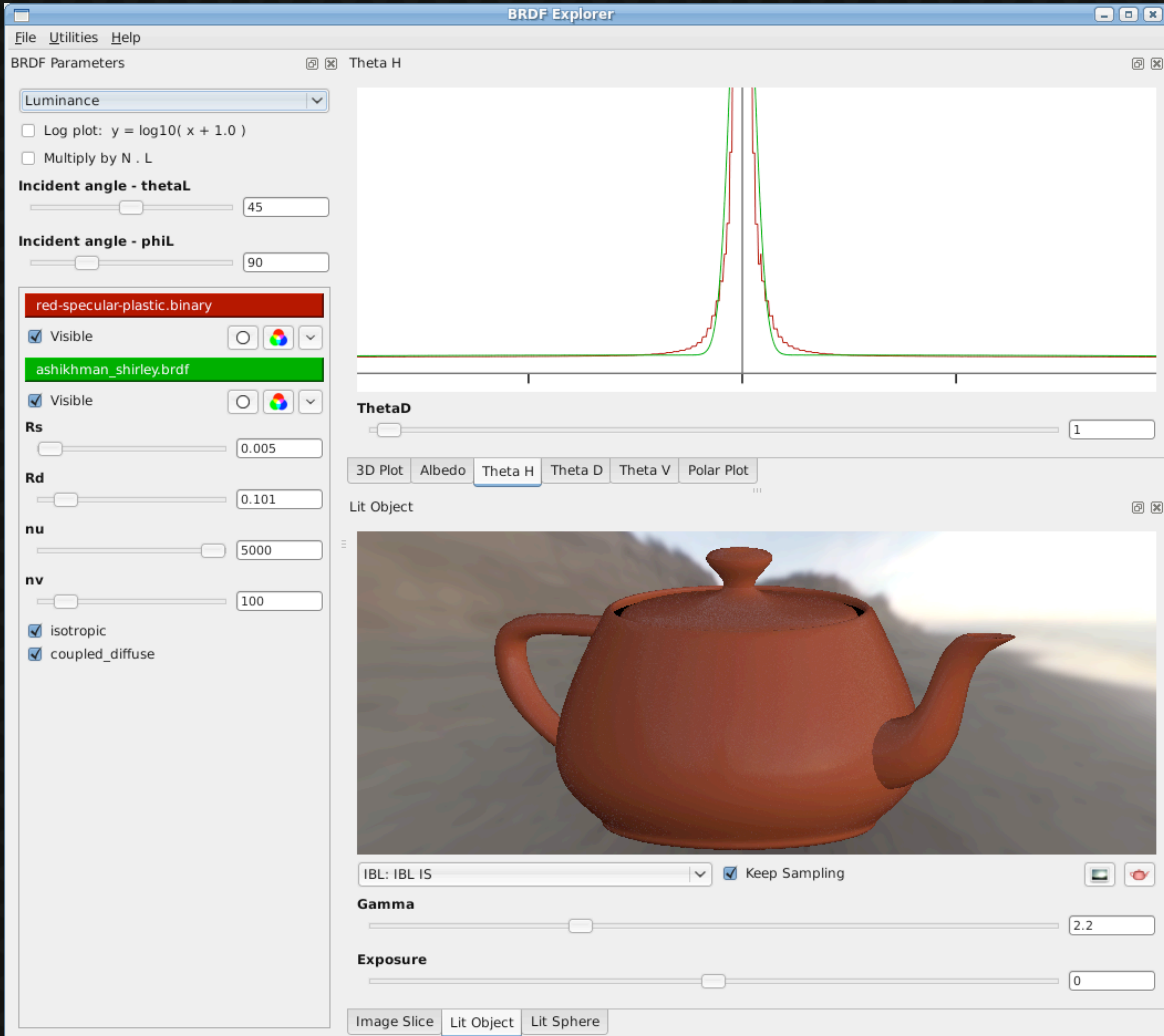
Fortunately, the data set is available for free download for academic use.



BRDF Explorer

github.com/wdas/brdf

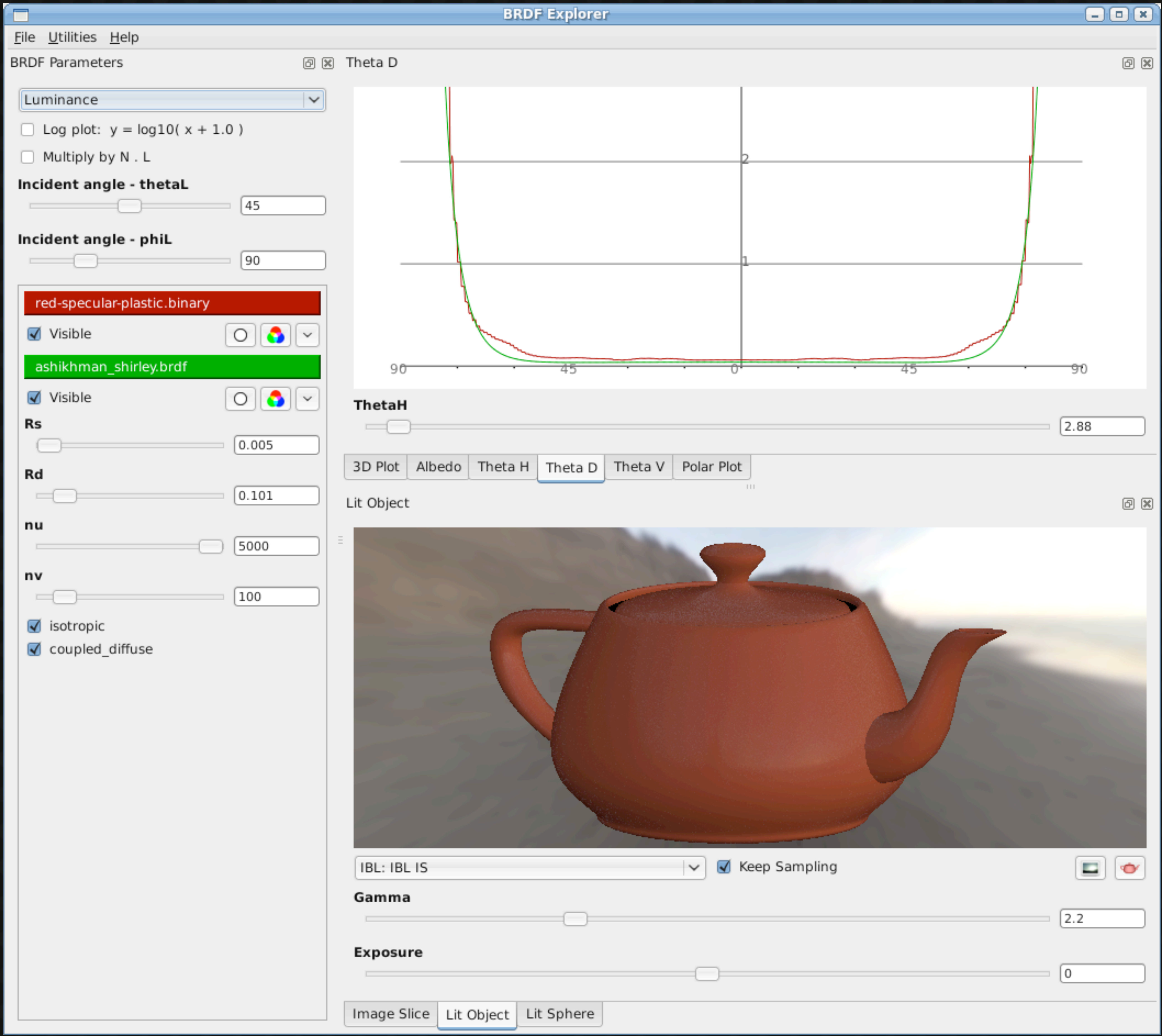
To explore the data and compare with analytic models we developed a BRDF viewer and released it as open source. This screenshot shows an approximate fit between an analytic model and a measured material.



BRDF Explorer

github.com/wdas/brdf

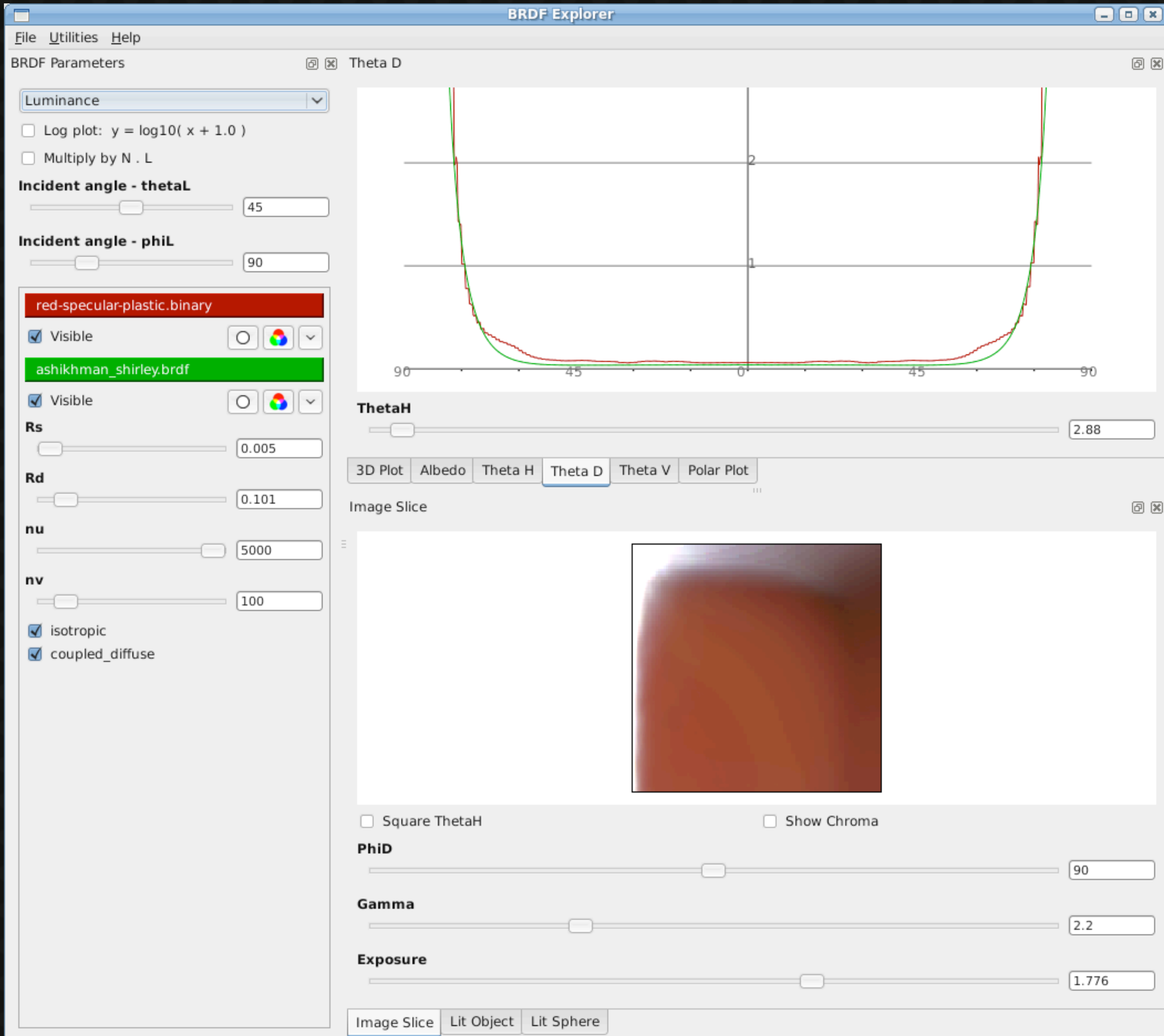
The Theta H curve shows the specular peak.



BRDF Explorer

github.com/wdas/brdf

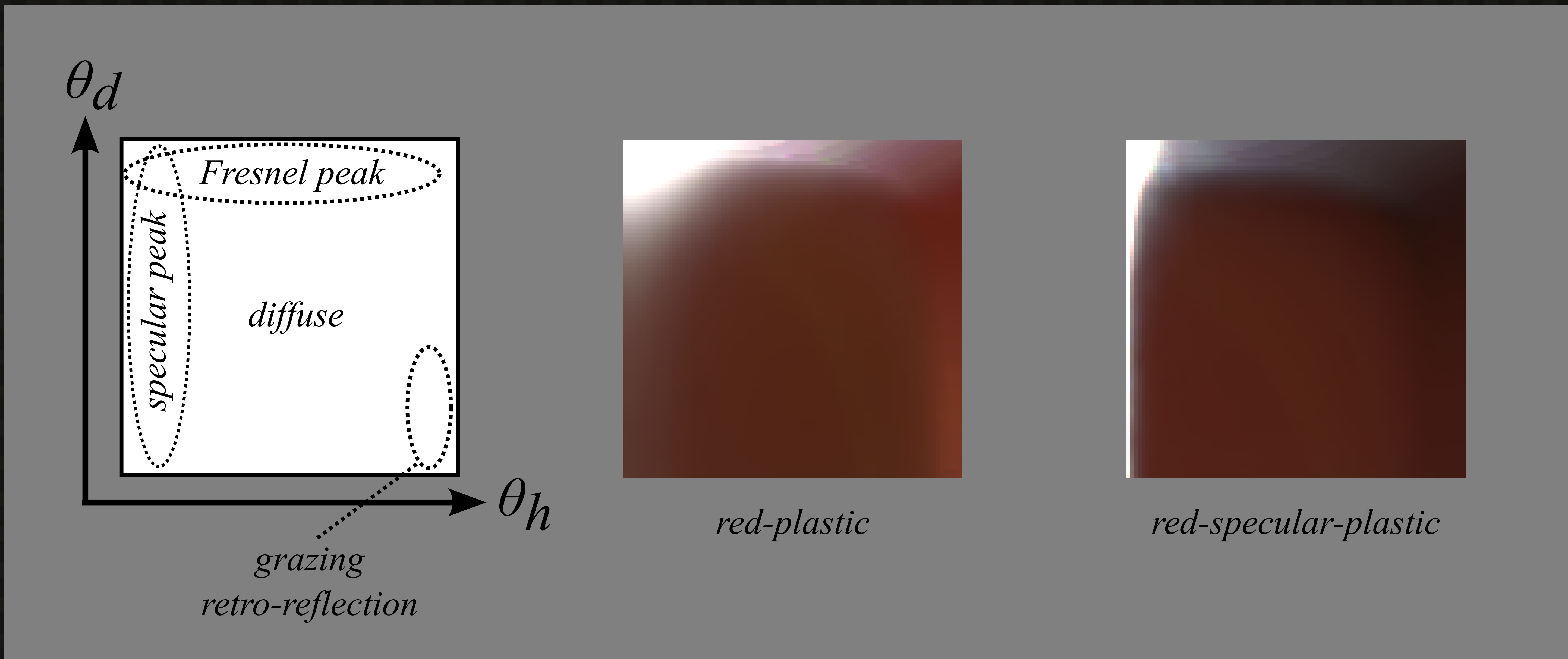
The Theta D curve shows the Fresnel response.



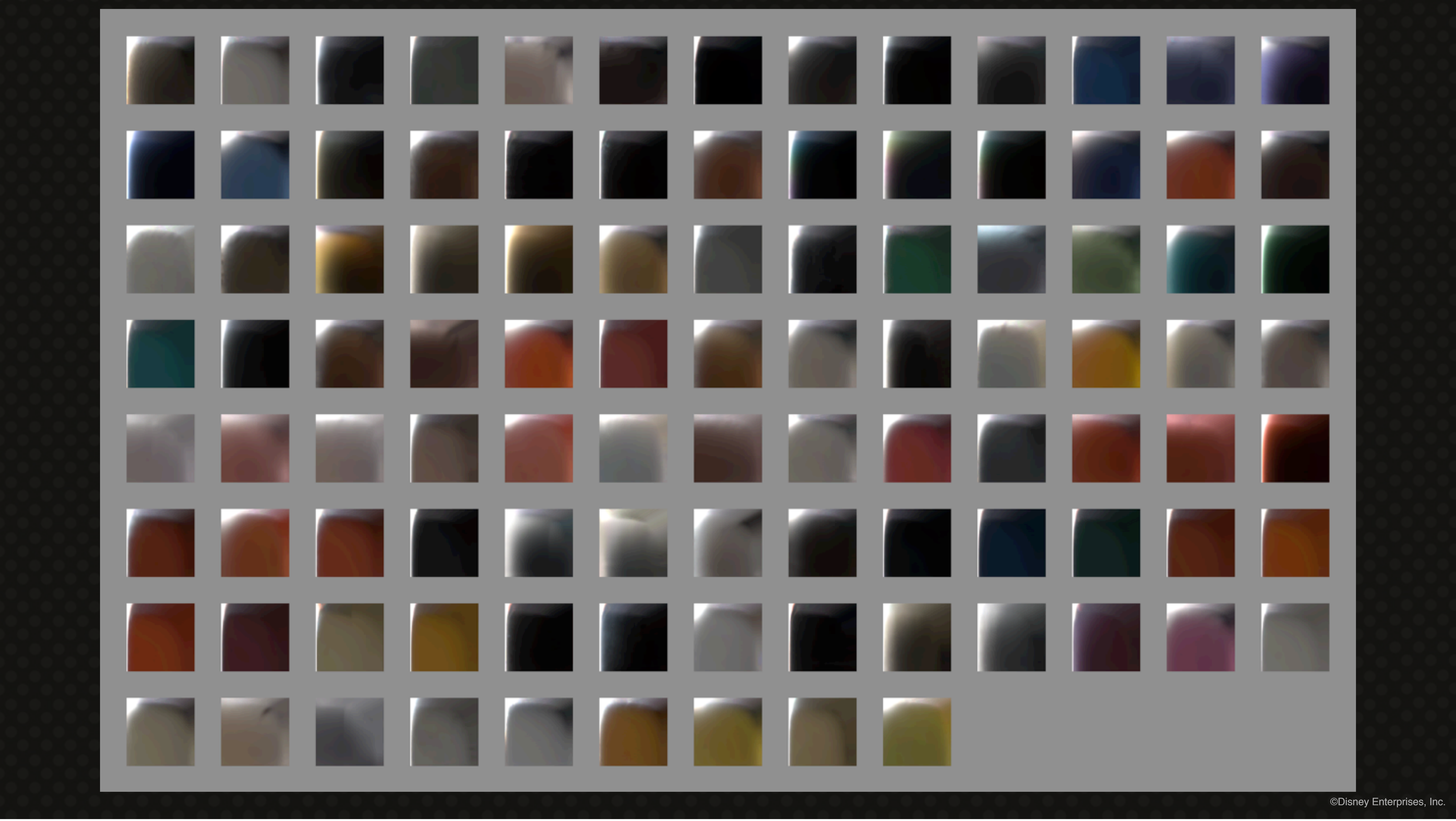
BRDF Explorer

github.com/wdas/brdf

Viewing ThetaH vs ThetaD as an image slice provides a powerful and intuitive view of the BRDF space showing all of the important characteristics of the material.



A schematic view of “Image Slice” space comparing two materials. Note the difference in grazing retro-reflection.



Viewing all 100 slices at once can give an impression of the variation seen in measured data.

Measured data observations

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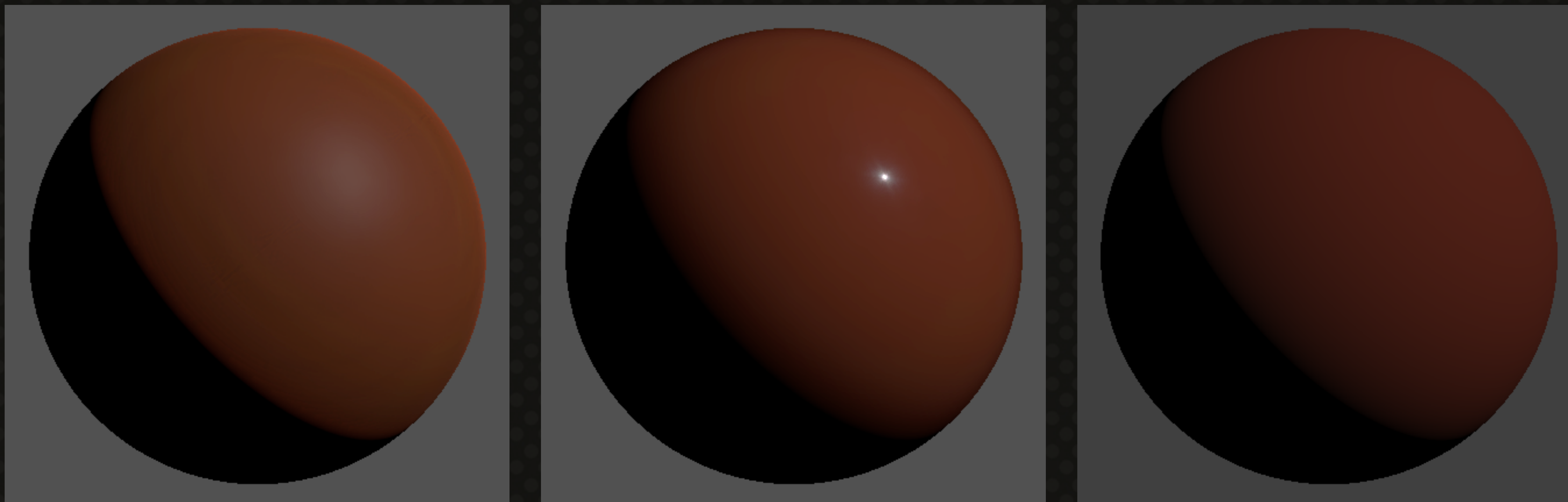
Diffuse is not Lambertian



red-plastic *specular-red-plastic* Lambert

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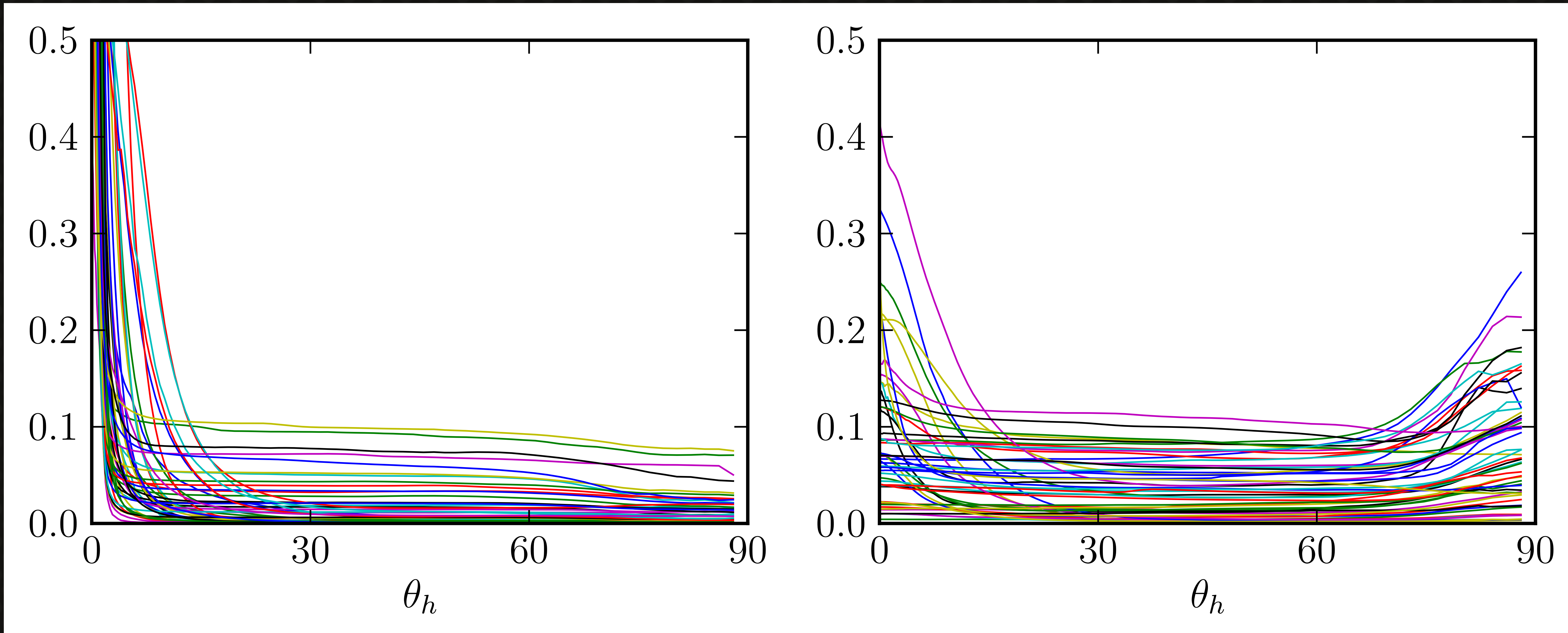
Note that the Lambert self-shadow terminator is too dark. Also, the grazing response is flat whereas measured materials often have a highlight or a shadow. The shadow is predicted by the Fresnel response as more light becomes specular at grazing angles and thus less is available for diffuse reflectance.

Diffuse retro-reflection is related to roughness

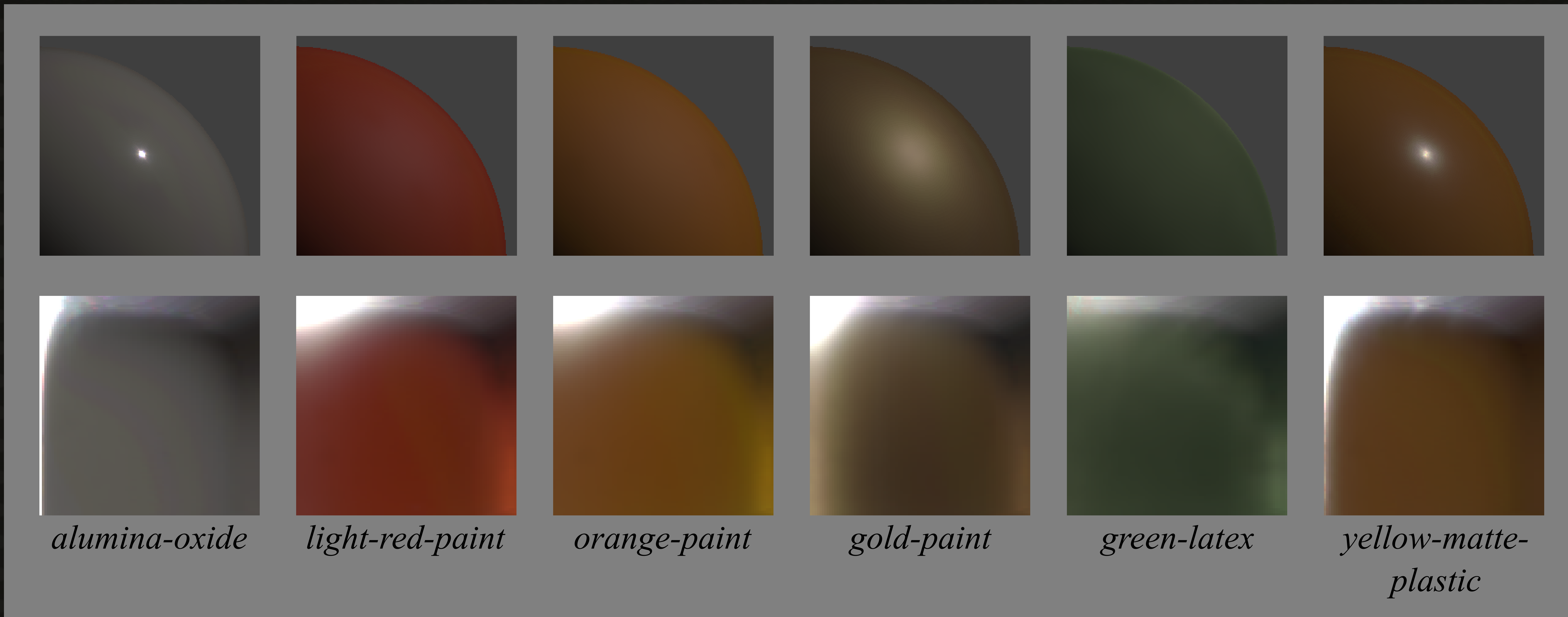


50 smooth materials

50 rough materials

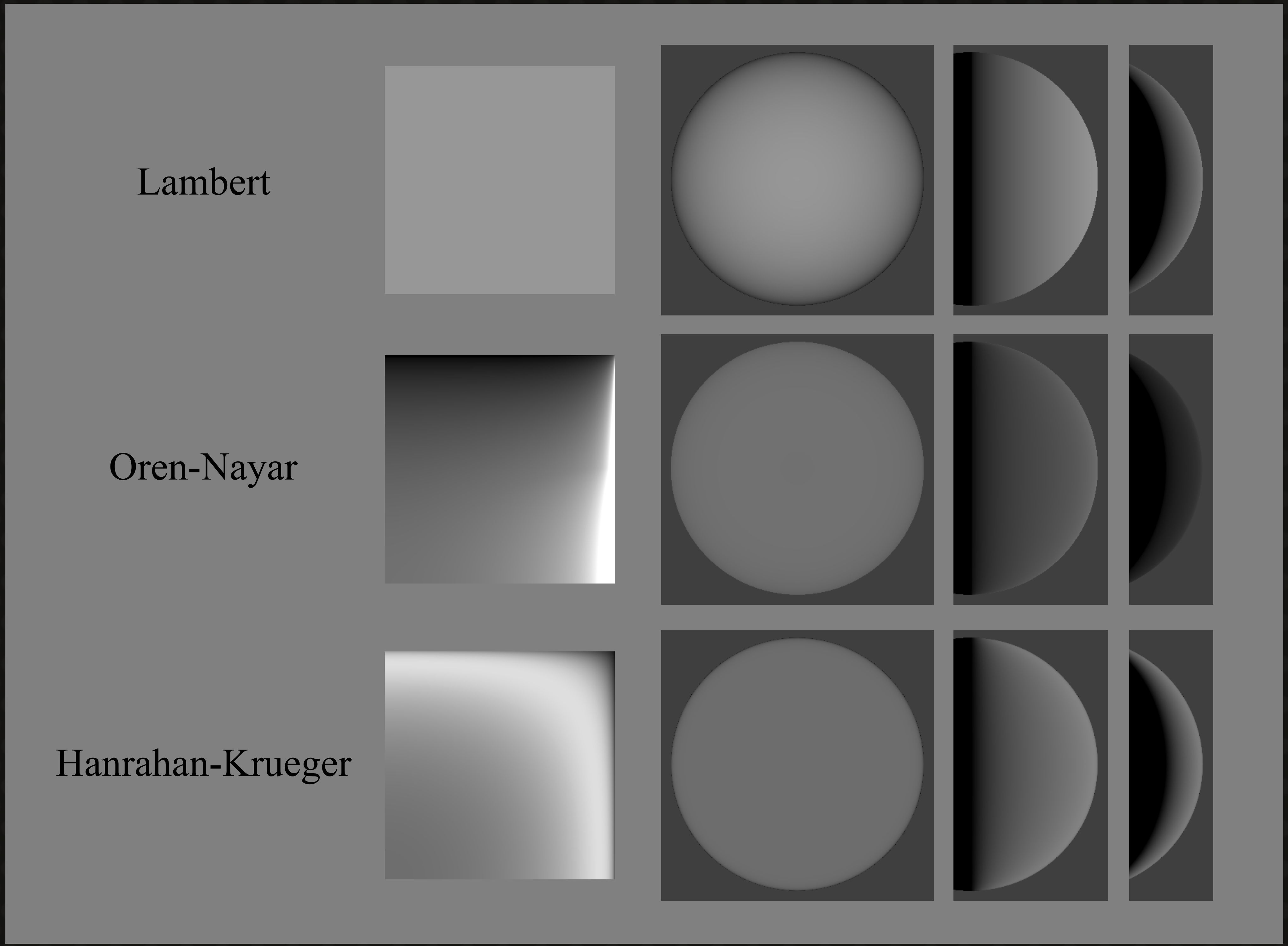
Smooth materials tend to show a grazing retro-reflective shadow, whereas rough materials show a retro-reflective peak.

Diffuse color variation examples



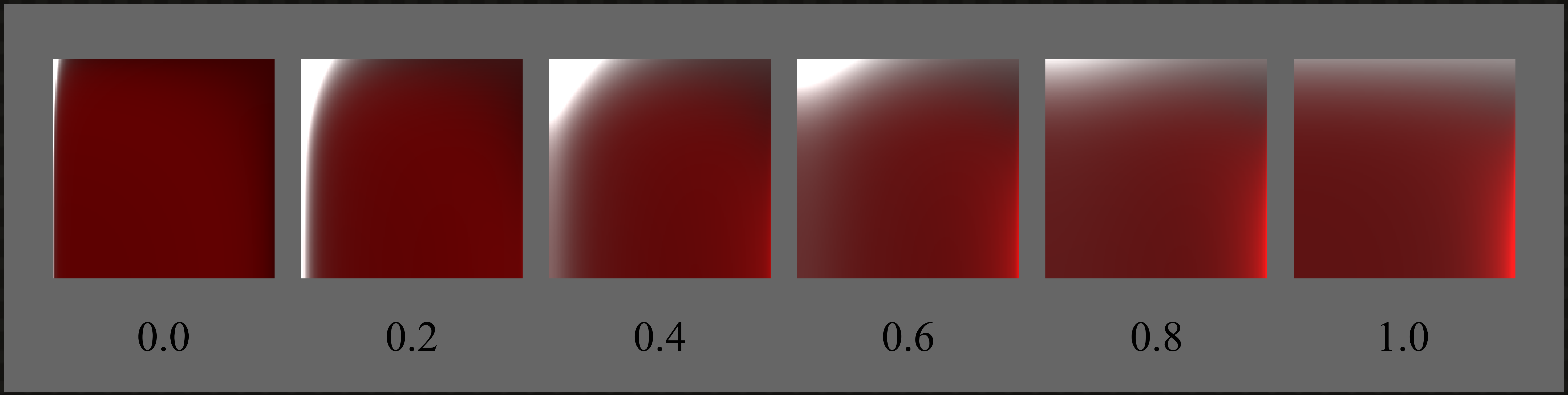
Top row – spheres lit from point light. Bottom row – BRDF image slices.

Diffuse models



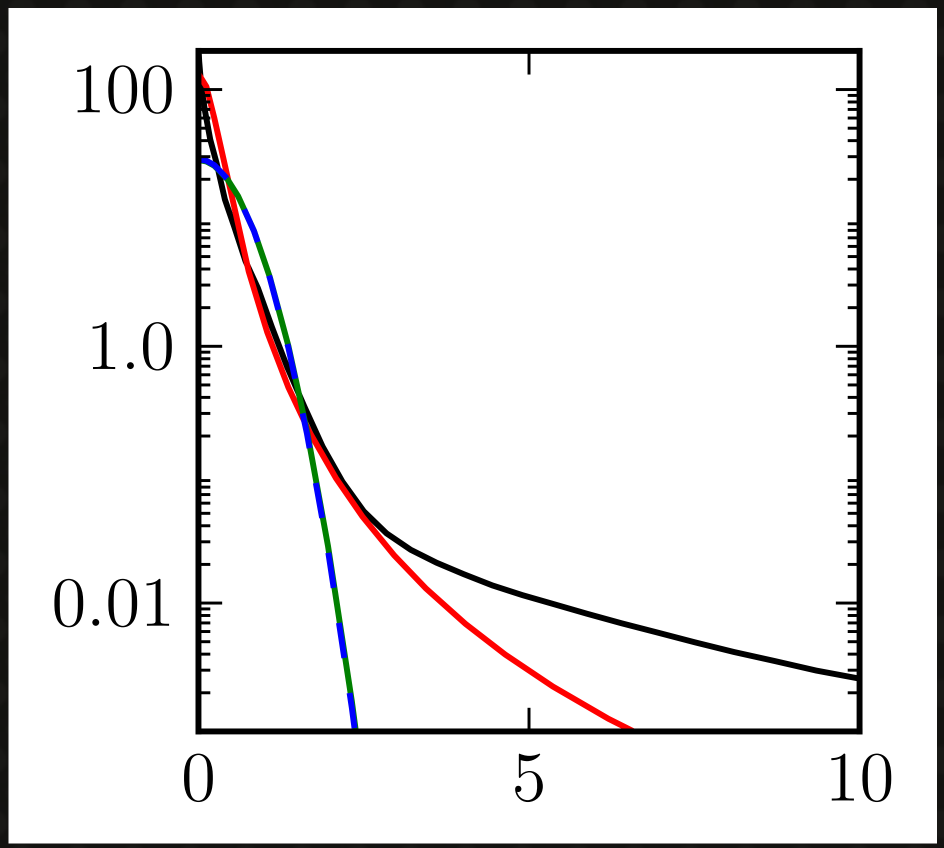
Oren-Nayar is derived from a rough diffuse surface model and ignores Fresnel and subsurface effects. It exhibits very strong shadowing at grazing angles. Hanrahan-Krueger is derived from a subsurface scattering model and assumes a perfectly smooth surface. Both models predict a grazing retro-reflection and a flattening of the diffuse shape, though they have opposite behaviors at grazing angles. Real materials seem to be somewhere in between.

Unified diffuse/specular roughness



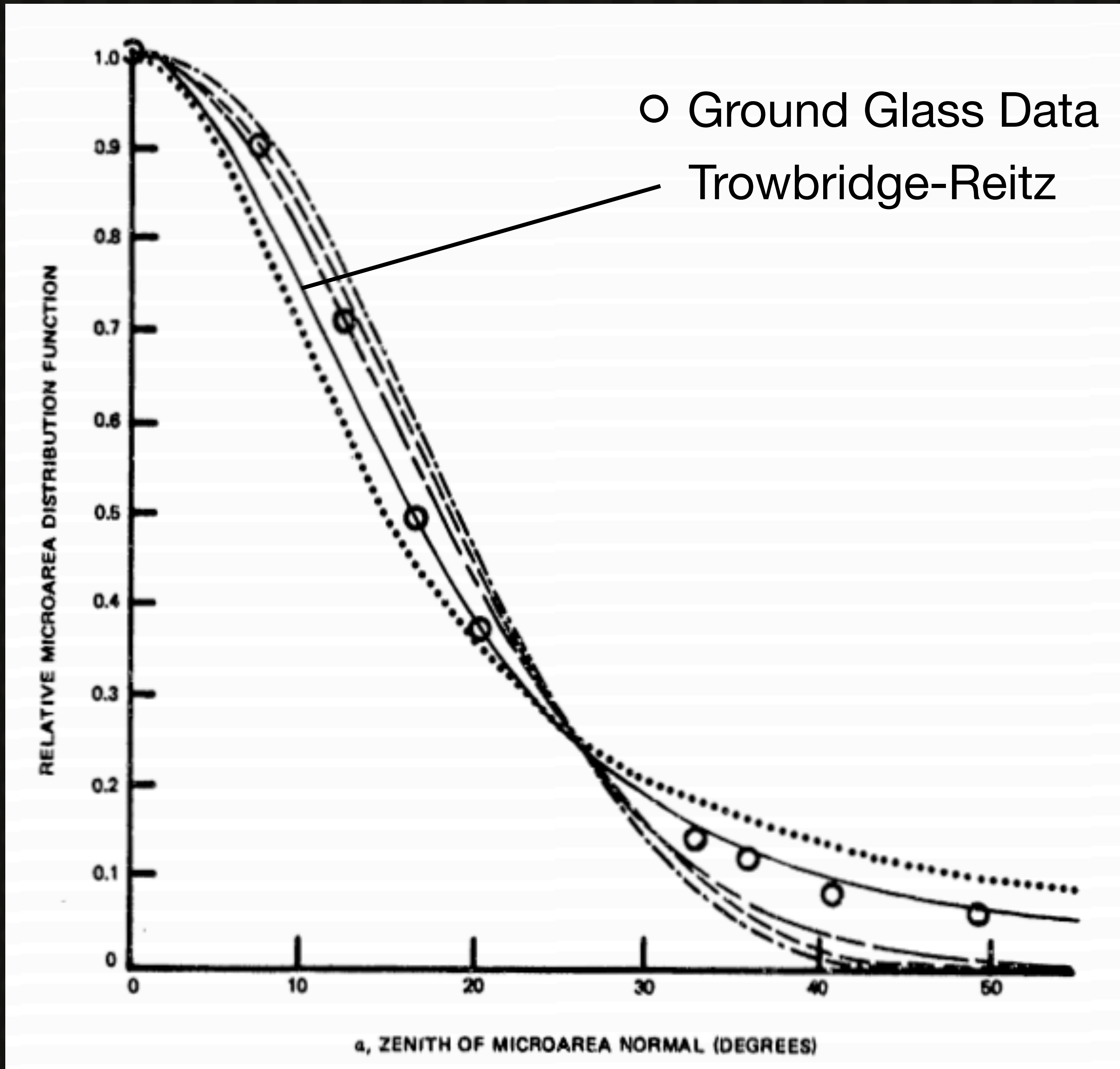
Our new model has a single roughness parameter to control both diffuse and specular response.

Specular models don't have long enough tails



chrome GGX Beckmann

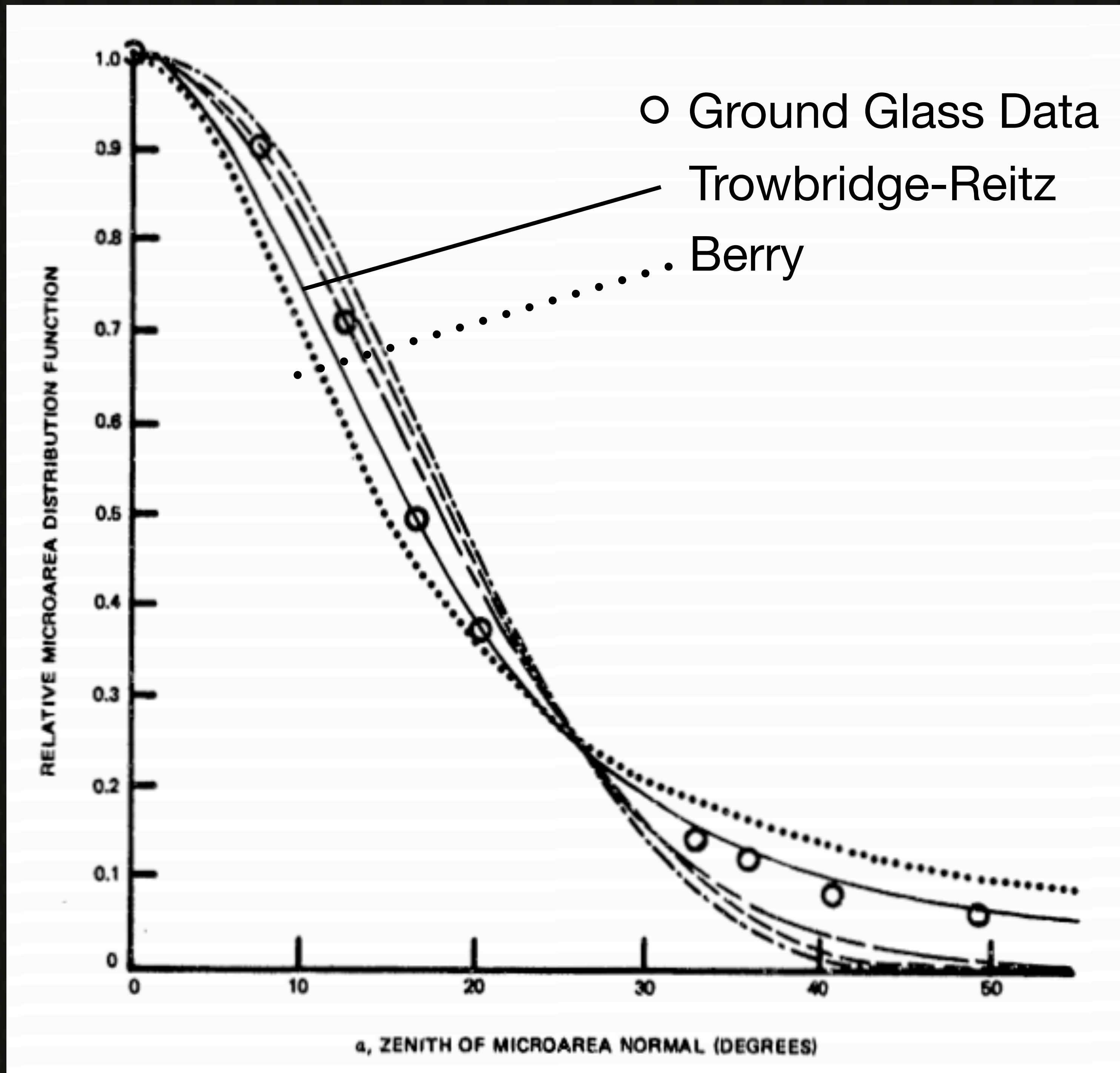
Black line = measured chrome; red = GGX (from Walter 2007); blue/green line = Beckmann / Blinn-Phong. GGX is a much better fit but still cannot capture the tail of the measured data.



Trowbridge, T. S. and Reitz, K. P., *Average irregularity representation of a roughened surface for ray reflection*, J. Opt. Soc. Am., 1975

$$D_{\mathrm{TR}} = c/(\alpha^2 \cos^2 \theta_h + \sin^2 \theta_h)^2$$

We developed a specular model based on Trowbridge-Reitz, the model favored by Blinn in the famous Blinn-Phong paper.



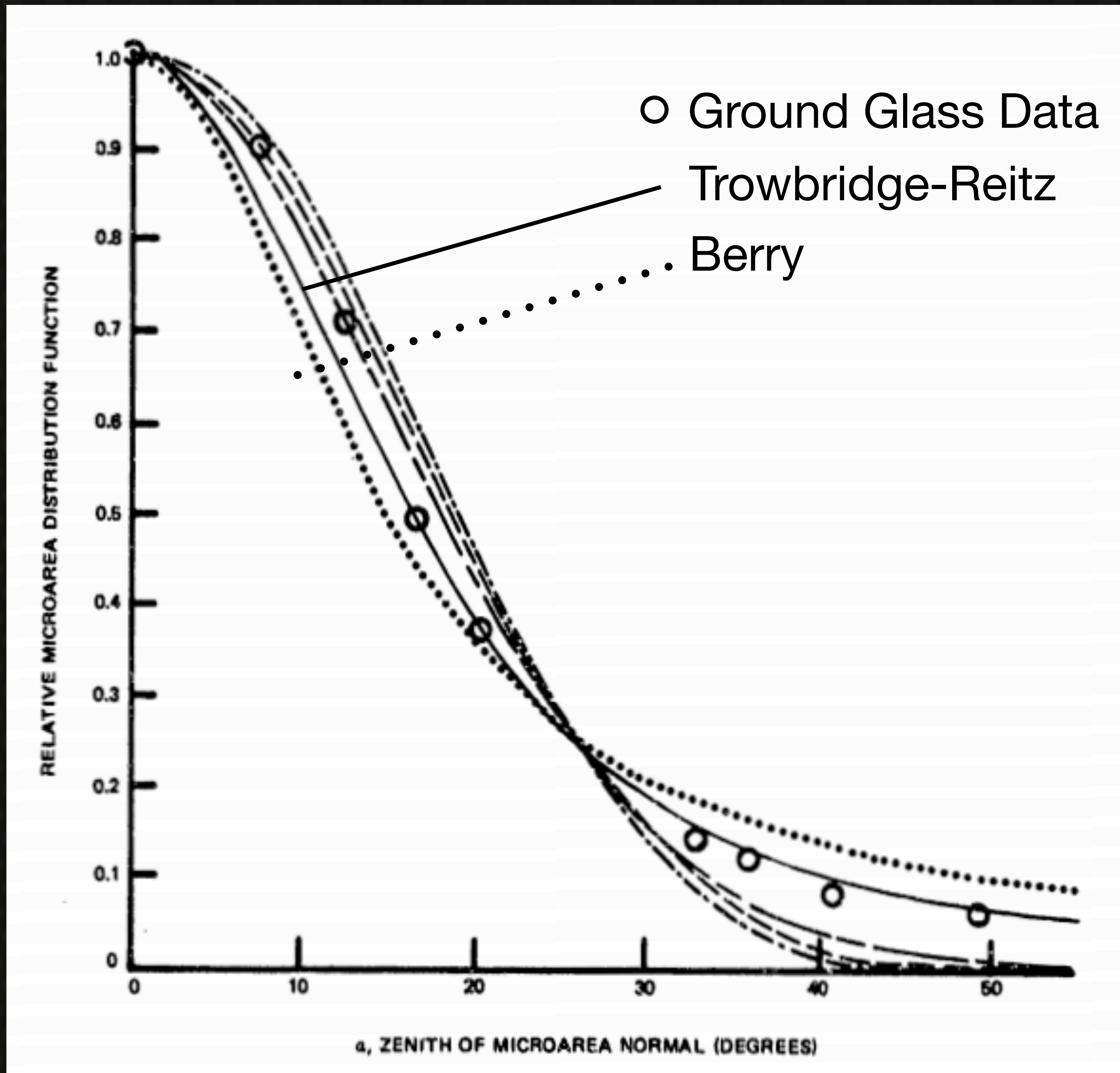
Trowbridge, T. S. and Reitz, K. P., *Average irregularity representation of a roughened surface for ray reflection*, J. Opt. Soc. Am., 1975

Berry, E. M., *Diffuse Reflection of Light from a Matte Surface,* J. Opt. Soc. Am., 1923

$$D_{\mathrm{Berry}} = c/(\alpha^2 \cos^2 \theta_h + \sin^2 \theta_h)$$

$$D_{\mathrm{TR}} = c/(\alpha^2 \cos^2 \theta_h + \sin^2 \theta_h)^2$$

The Berry model was considered by Trowbridge and Reitz and has a much longer tail.



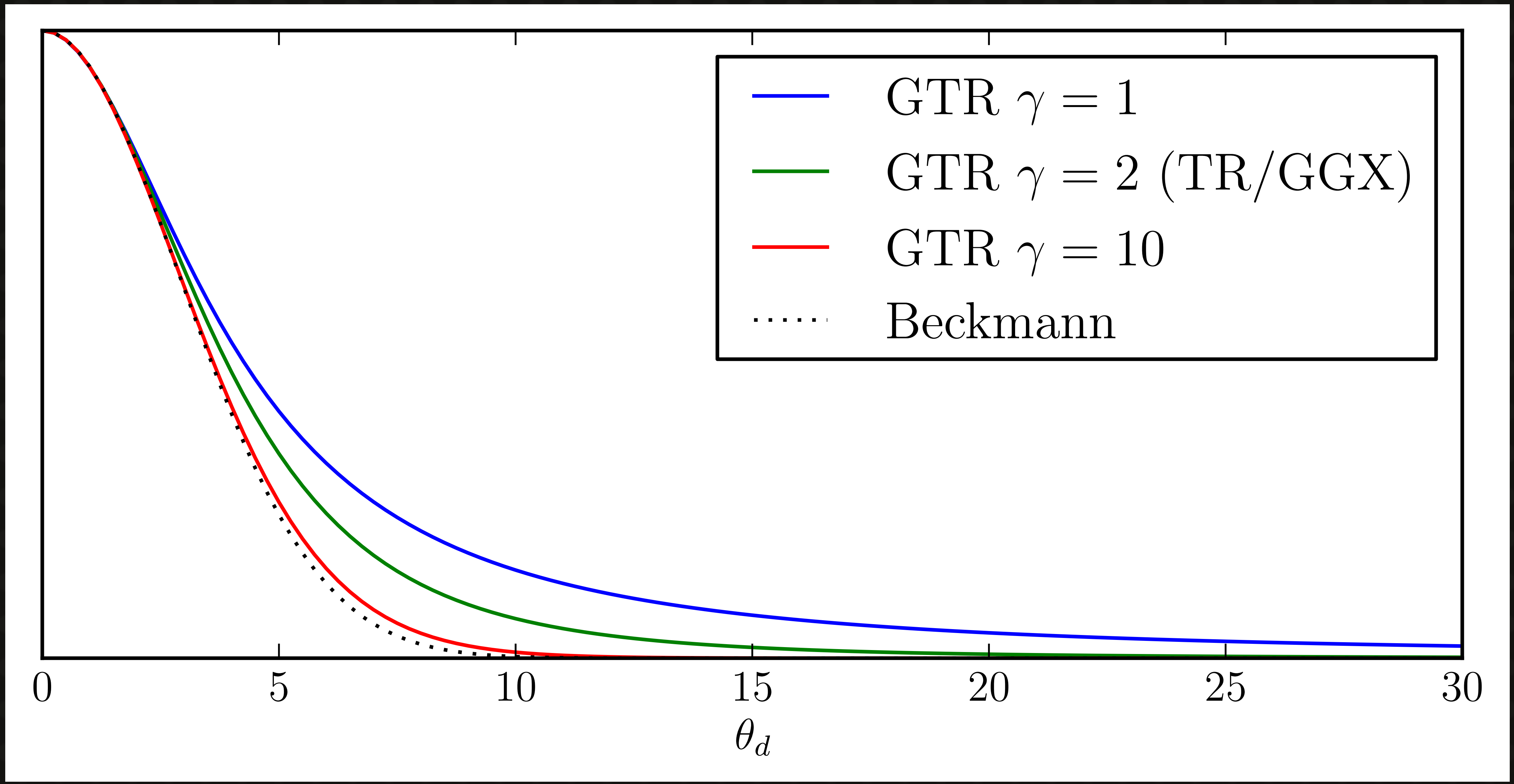
Trowbridge, T. S. and Reitz, K. P., *Average irregularity representation of a roughened surface for ray reflection*, J. Opt. Soc. Am., 1975

Berry, E. M., *Diffuse Reflection of Light from a Matte Surface*, J. Opt. Soc. Am., 1923

$$D_{\mathrm{Berry}} = c/(\alpha^2 \cos^2\theta_h + \sin^2\theta_h)$$
$$D_{\mathrm{TR}} = c/(\alpha^2 \cos^2\theta_h + \sin^2\theta_h)^2$$
$$D_{\mathrm{GTR}} = c/(\alpha^2 \cos^2\theta_h + \sin^2\theta_h)^\gamma$$

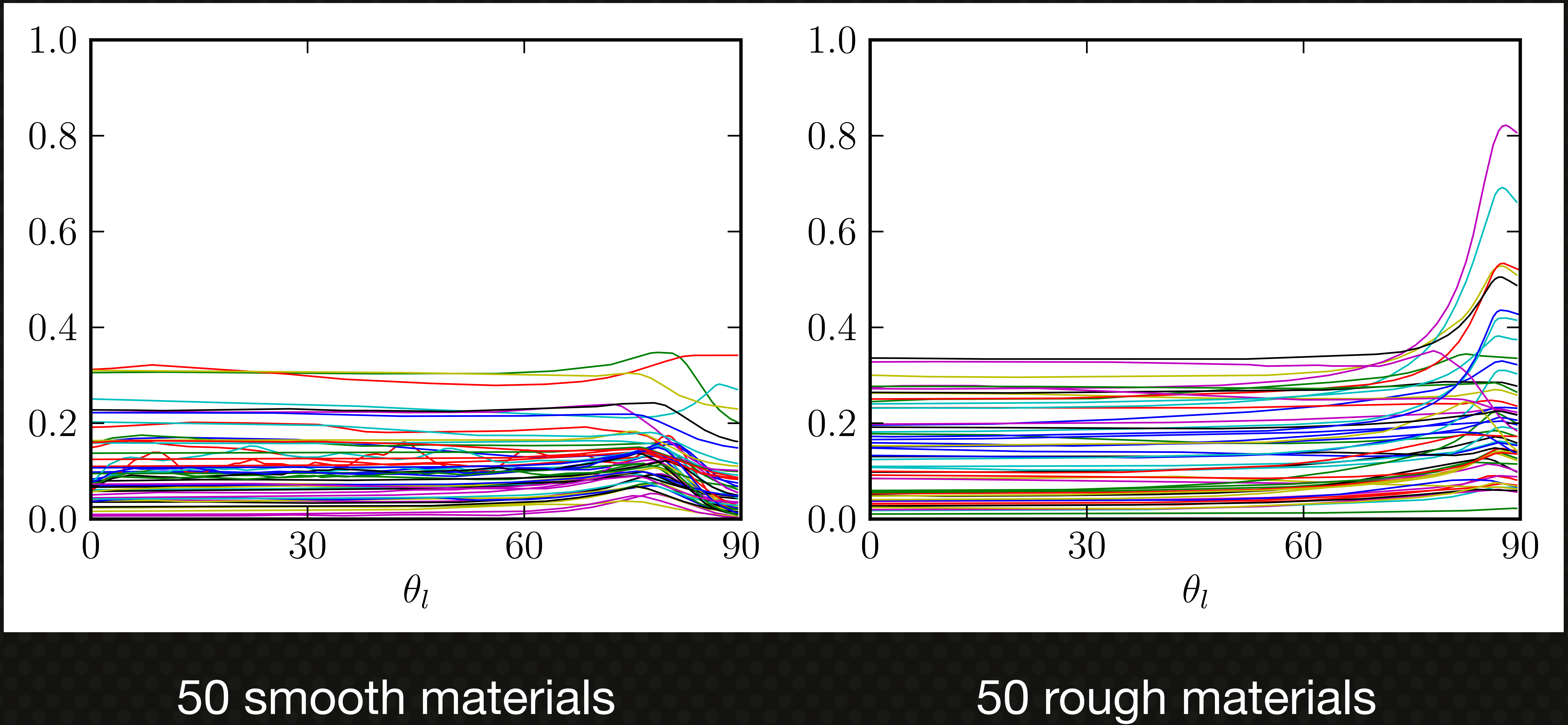
The similar forms between Berry and TR suggest a generalization using an arbitrary power.

Generalized-Trowbridge-Reitz



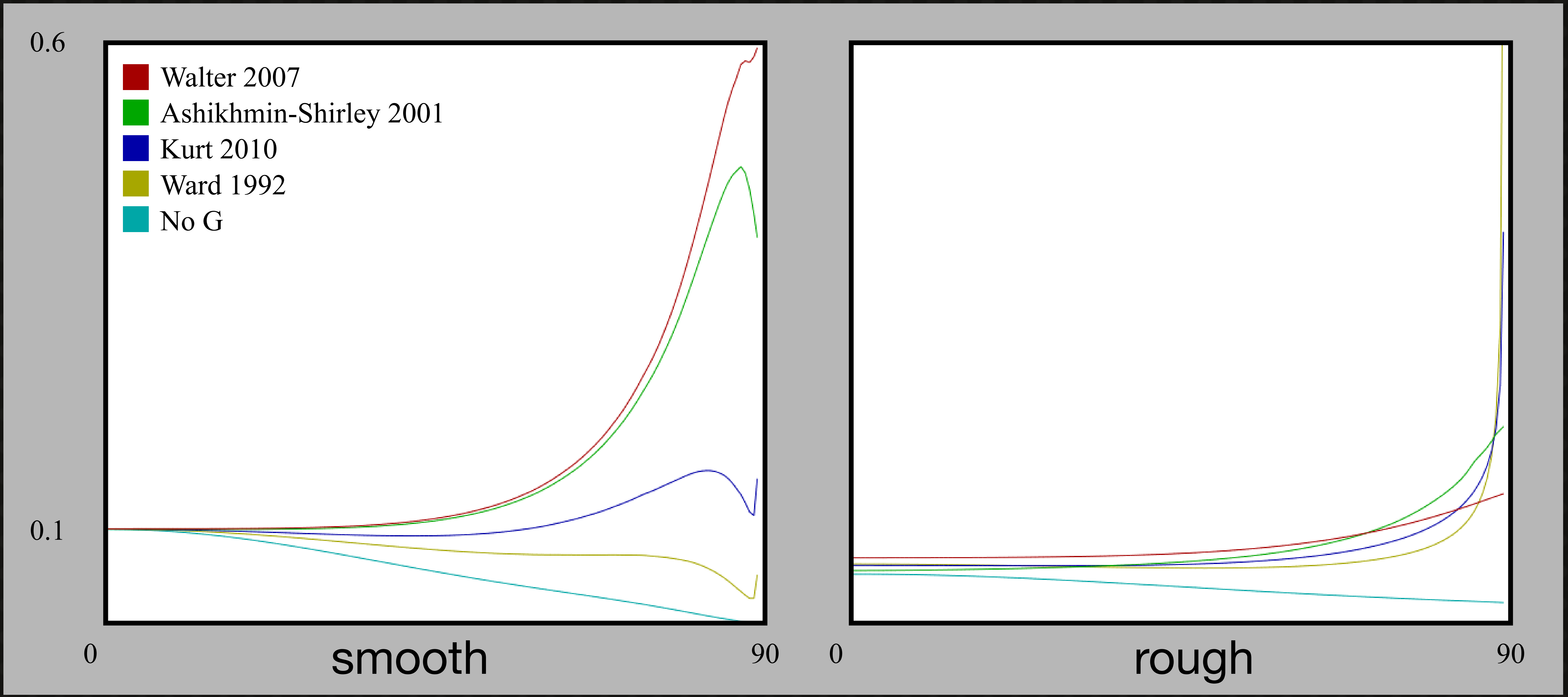
The generalized form can produce a wide range of tail shapes. See course notes for details.

Albedo is mostly flat, and well below 1.0



Albedo is relatively flat for all the materials except for a slight peak near grazing angles. Rough materials tend to show a larger peak, presumably due to the grazing retro-reflection.

Albedo of various models



Analytic models tend to have significant variation in albedo.

Disney “principled” BRDF

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Principles

1. Intuitive rather than physical parameters should be used.
2. There should be as few parameters as possible.
3. Parameters should be zero to one over their plausible range.
4. Parameters should be allowed to push beyond where it makes sense.
5. All combinations of parameters should be plausible.

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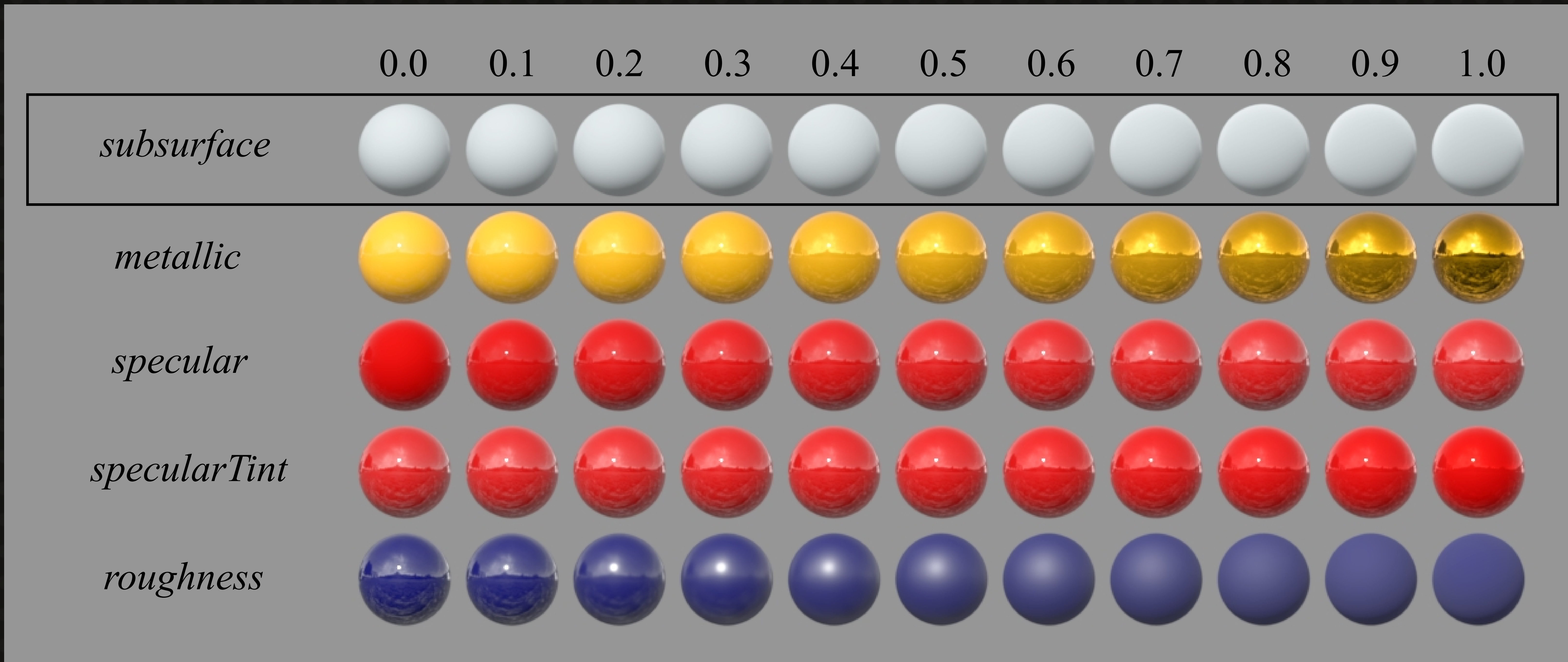
Parameters



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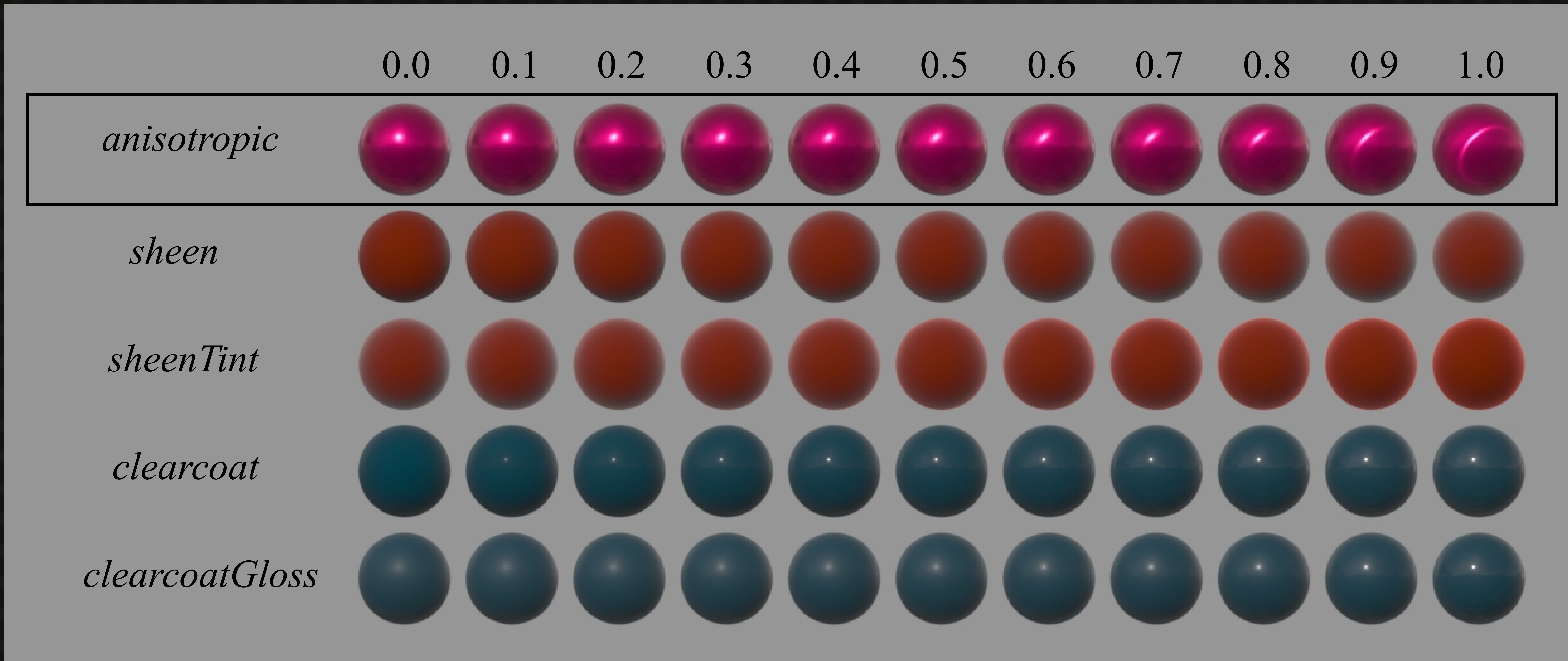
See course notes for parameter descriptions and details.

Parameters



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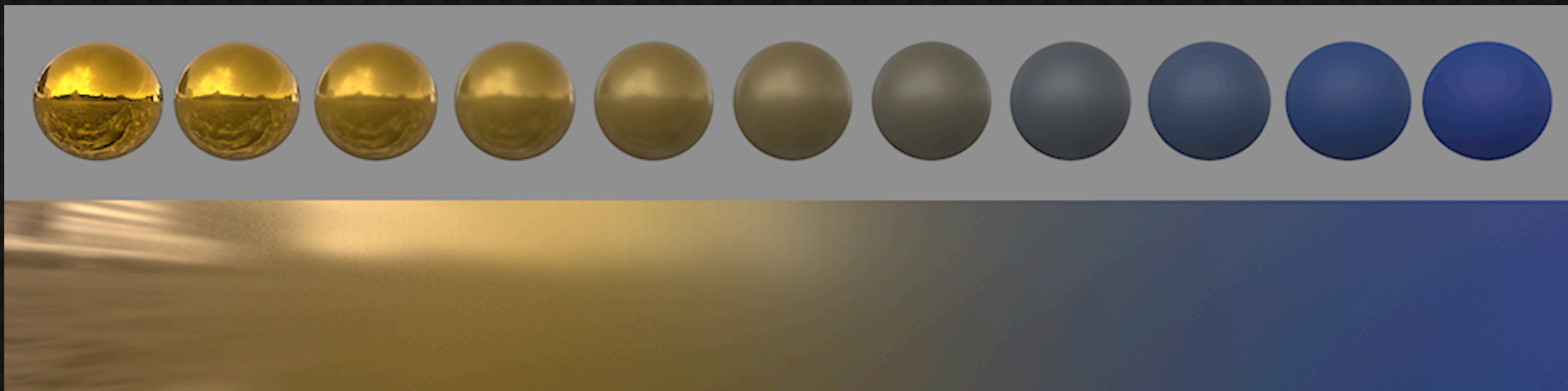
Parameter blending



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Parameters are designed to allow robust interpolation. Here, all 10 parameters are interpolated linearly.

Parameter layers

principledLayers NperturbMap $MSVfade NperturbAmt .11 numDiffuseSamples 10.0000 numSpecularSamples 10.0000 numClearcoatSamples 10.0000

+ -		mask	subsurface	metallic	specular	roughness	anisotropic	specularTint	sheen	sheenTint	clearcoat	clearcoatGloss
1	▸	(empty)	0.9860	0.0000	0.0319	0.3531	0.1374	0.0000	0.2944	0.5141	0.0000	1.0000
2	▸	~clamp(expand($swirlyPat,0.3,0.8),0,1)	0.9200	0.0000	0.0180	0.3802	0.2461	0.0000	0.1928	0.4722	0.0000	1.0000
3	▸	... Texture,0.65,0.95),0,1) * clamp(expand($swirlyPat,0.3,0.8),0,1)	0.8700	0.0000	0.0835	0.3082	0.0485	0.0000	0.1111	0.2499	0.0000	1.0000
4	▸	clamp($bubbleDots,0,1) * clamp(expand($swirlyPat,0.45,0.8),0,1)	0.3100	0.0000	0.2310	0.2055	0.0000	0.0000	0.0000	0.3440	0.0000	1.0000
5	▸	$colorPinkBlur	0.9860	0.0000	0.0100	0.3531	0.1000	0.0000	0.1000	0.5141	0.0000	1.0000
6	▸	$tornMask	0.9800	0.0000	0.0000	0.9277	0.1412	0.6500	0.4900	0.3810	0.0000	1.0000

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Robust interpolation enables a simplified layering model where parameters are blended using a Photoshop-like layer stack. Each layer can be selected as a preset from the material library. The masks are generally texture maps or expressions based on texture maps.

Production experience on Wreck-it Ralph

Look development

- Simplified material library
- Material Designer - real-time BRDF editing w/ image-based lighting
- More consistent, high-quality results
- Almost no lighting re-do's

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Lighting

- IBLs and area lights = big change
- Start physical, add art-directed controls
- Tone-mapping

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Future Work

Future Work

- Better BRDF / subsurface integration
- Complex cloth
- Iridescence

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In the course notes

- Additional observations and details about our BRDF
- Full derivation of GTR distribution
- Selected history of 30+ BRDF models used in graphics

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Acknowledgements

- Chuck Tappan co-developed our "principled" BRDF.
- Christian Eisenacher, Greg Nichols, and Jared Johnson developed our BRDF tools.
- Stephen Hill, Naty Hoffman, and Pete Shirley provided valuable input.

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