Connecting Measured BRDFs to Analytic BRDFs by Data-Driven Diffuse-Specular Separation

Tiancheng Sun, Henrik Wann Jensen, Ravi Ramamoorthi

University of California, San Diego

SIGGRAPH ASIA 2018 TOKYO

OVERVIEW

OVERVIEW

- BRDF

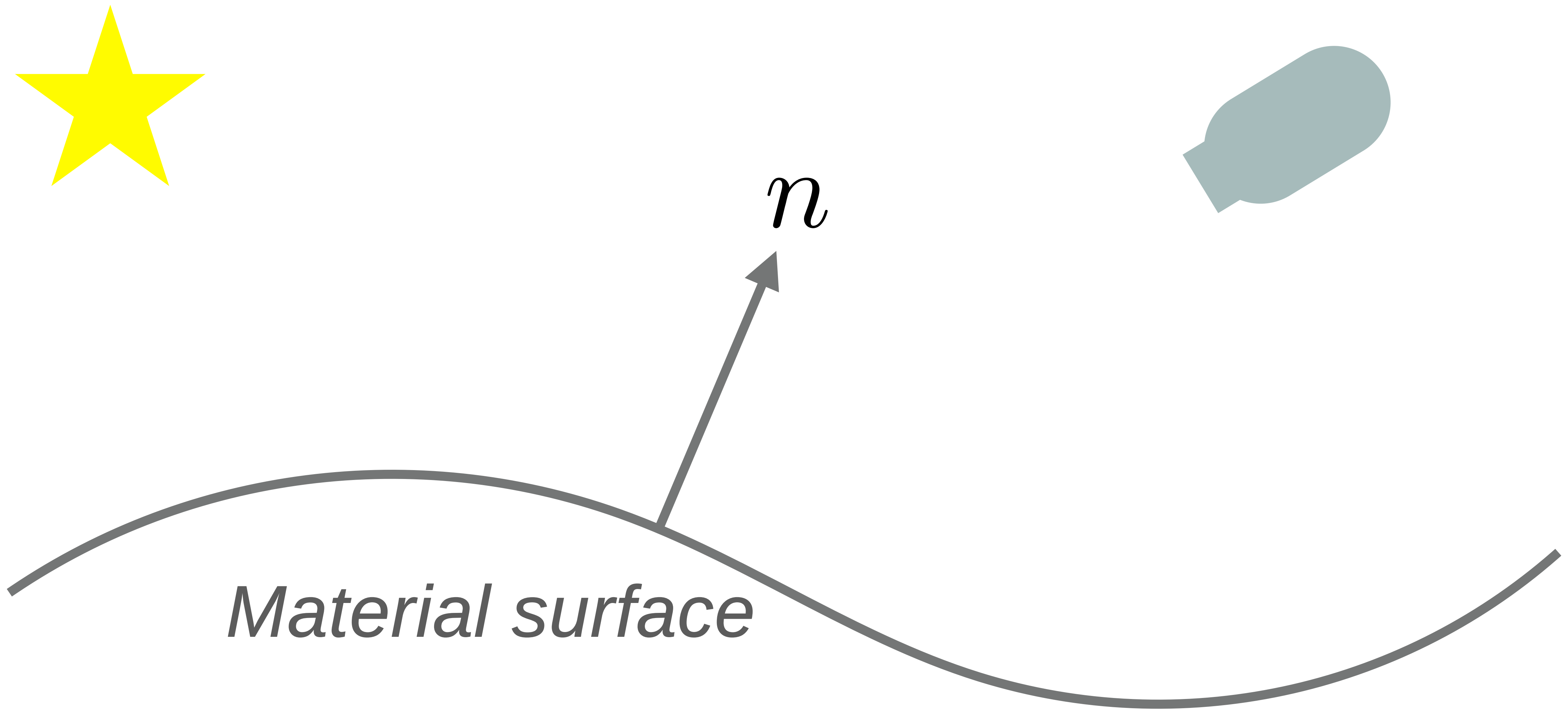
OVERVIEW

- BRDF
  - surface property of a material

OVERVIEW

- BRDF
  - surface property of a material

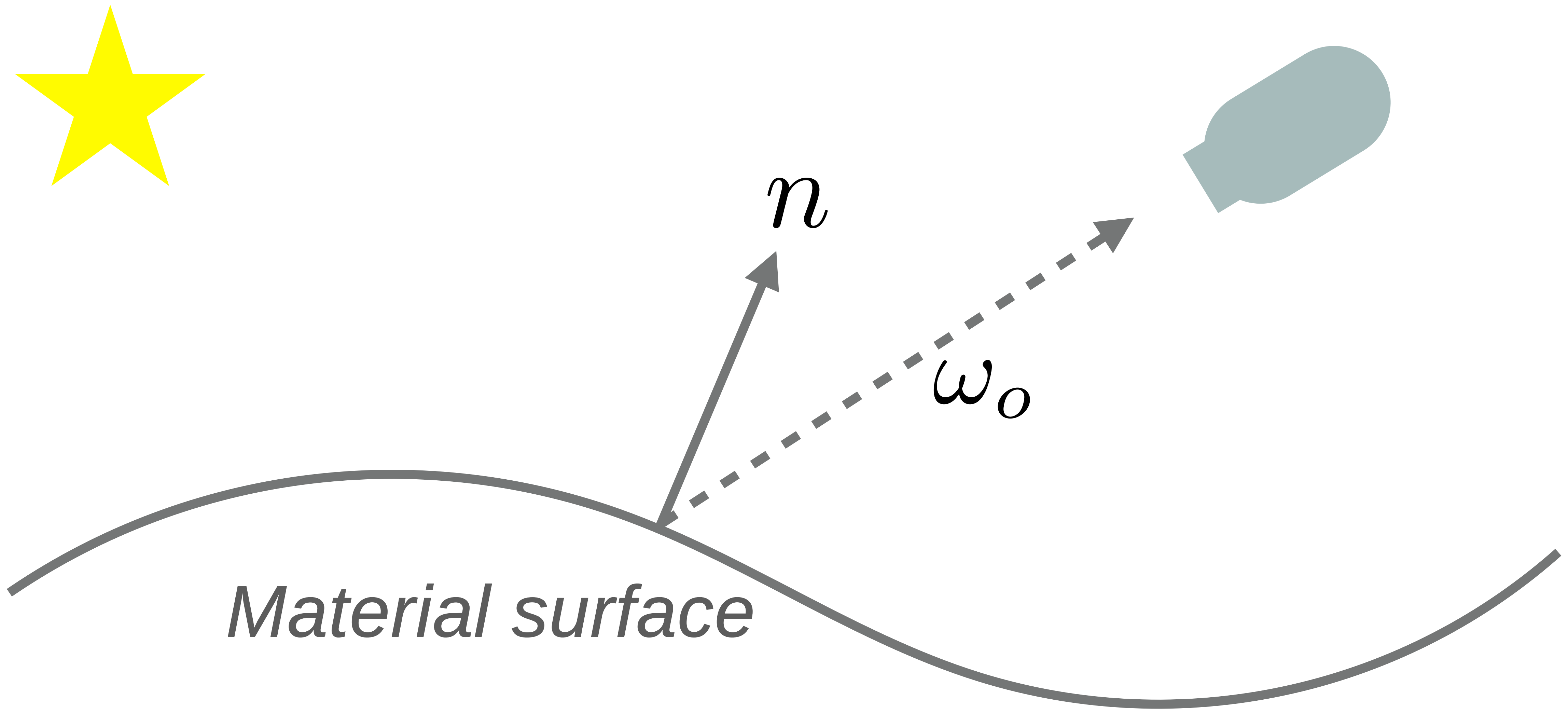
$$\rho(\omega_i, \omega_o) = \underline{\qquad\qquad}$$



OVERVIEW

- BRDF
  - surface property of a material

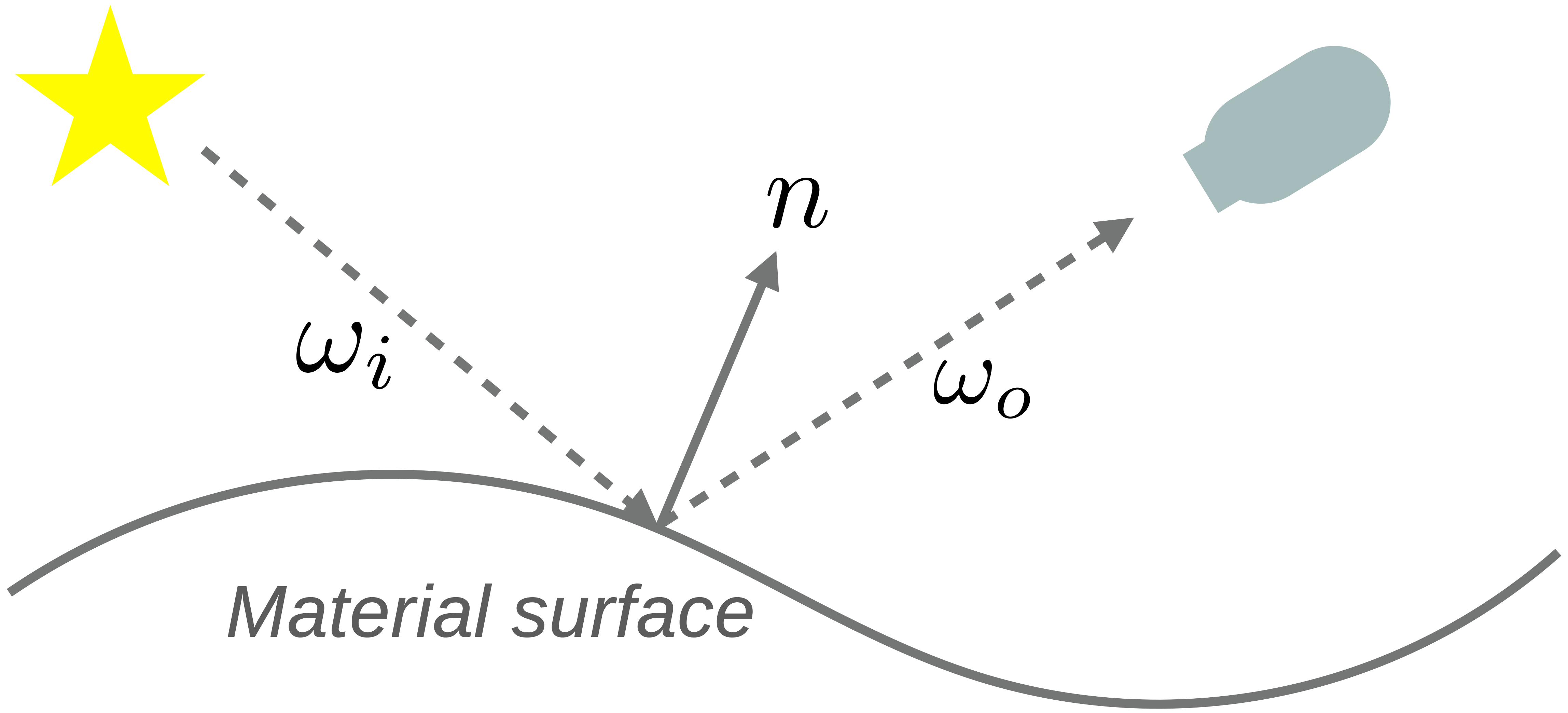
$$\rho(\omega_i, \omega_o) = \frac{\mathrm{d}L(\omega_o)}{}$$



OVERVIEW

- BRDF
  - surface property of a material

$$\rho(\omega_i, \omega_o) = \frac{\mathrm{d}L(\omega_o)}{\mathrm{d}E(\omega_i)}$$



OVERVIEW

Measured BRDF

Analytic BRDF

OVERVIEW

Measured BRDF

Analytic BRDF

OVERVIEW

Measured BRDF

Analytic BRDF

OVERVIEW

Measured BRDF

Analytic BRDF

captured from real world

OVERVIEW

Measured BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda]$$

captured from real world

Analytic BRDF

OVERVIEW

Measured BRDF

Analytic BRDF

$$\boldsymbol{\rho}[\underline{\boldsymbol{\omega}_{\mathbf{i}}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda]$$

captured from real world

OVERVIEW

Measured BRDF

Analytic BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \underline{\boldsymbol{\omega}_{\mathbf{o}}}, \lambda]$$

captured from real world

OVERVIEW

Measured BRDF

Analytic BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \underline{\lambda}]$$

captured from real world

OVERVIEW

Measured BRDF

Analytic BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda]$$

captured from real world

OVERVIEW

Measured BRDF

Analytic BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda]$$

captured from real world

millions of values, hard to modify

OVERVIEW

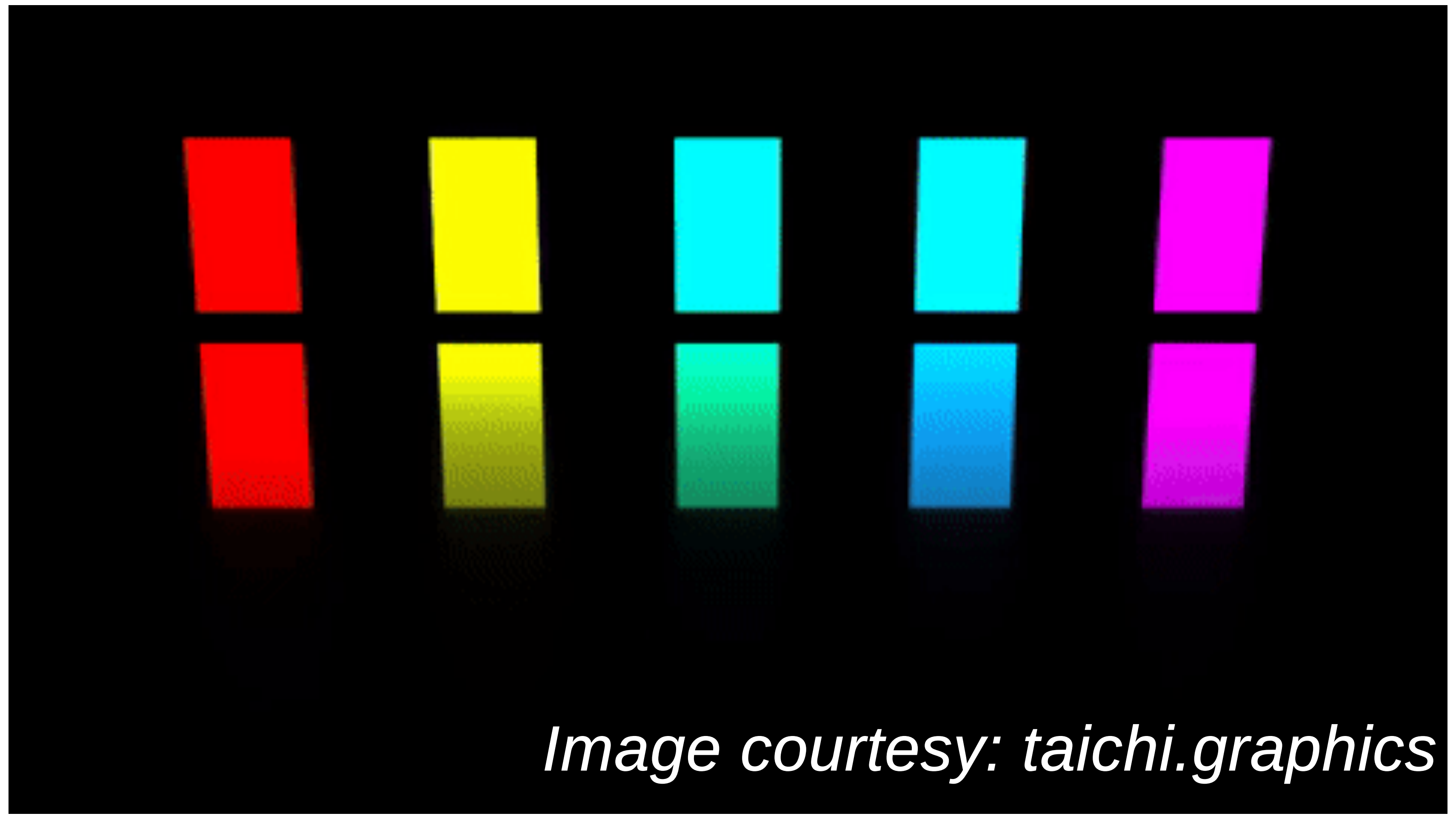
Measured BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda]$$

captured from real world

millions of values, hard to modify

Analytic BRDF



OVERVIEW

Measured BRDF

$$\rho[\omega_{\mathbf{i}}, \omega_{\mathbf{o}}, \lambda]$$

captured from real world

millions of values, hard to modify

Analytic BRDF

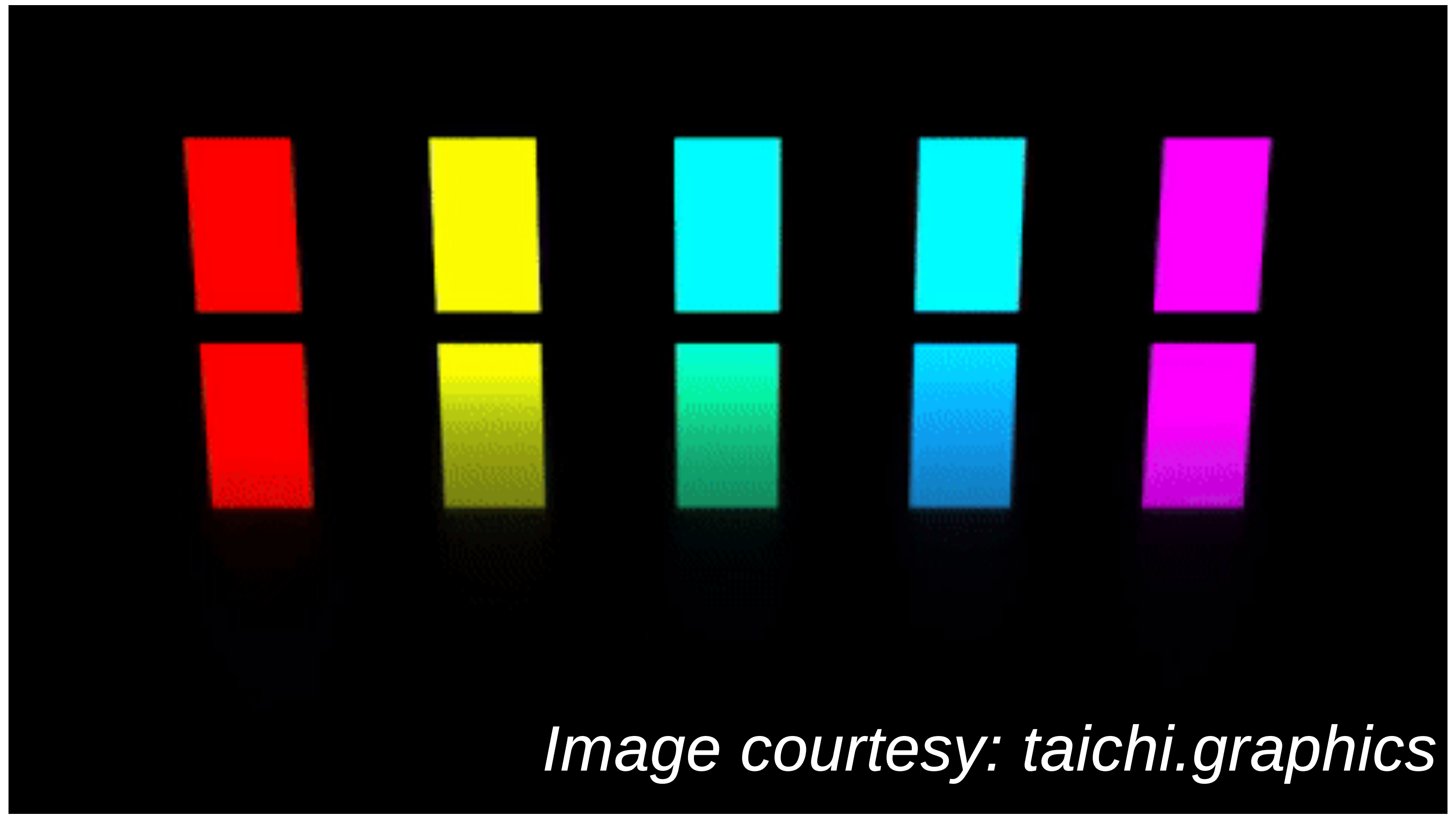


Image courtesy: taichi.graphics

approximated with models

OVERVIEW

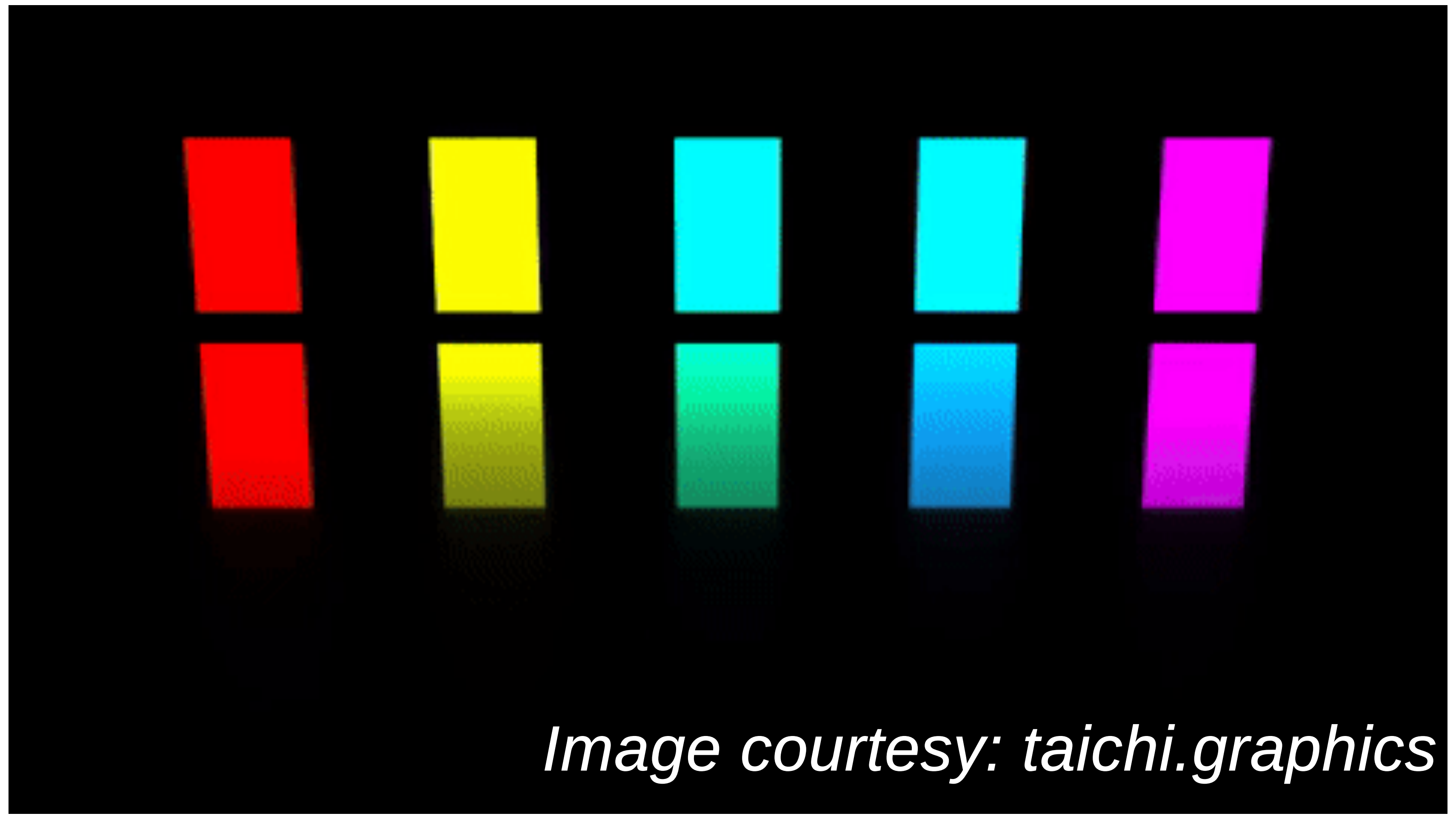
Measured BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda]$$

captured from real world

millions of values, hard to modify

Analytic BRDF



Diffuse

$$\rho_{\mathrm{d}}(\alpha_{\mathrm{d}})$$

approximated with models

OVERVIEW

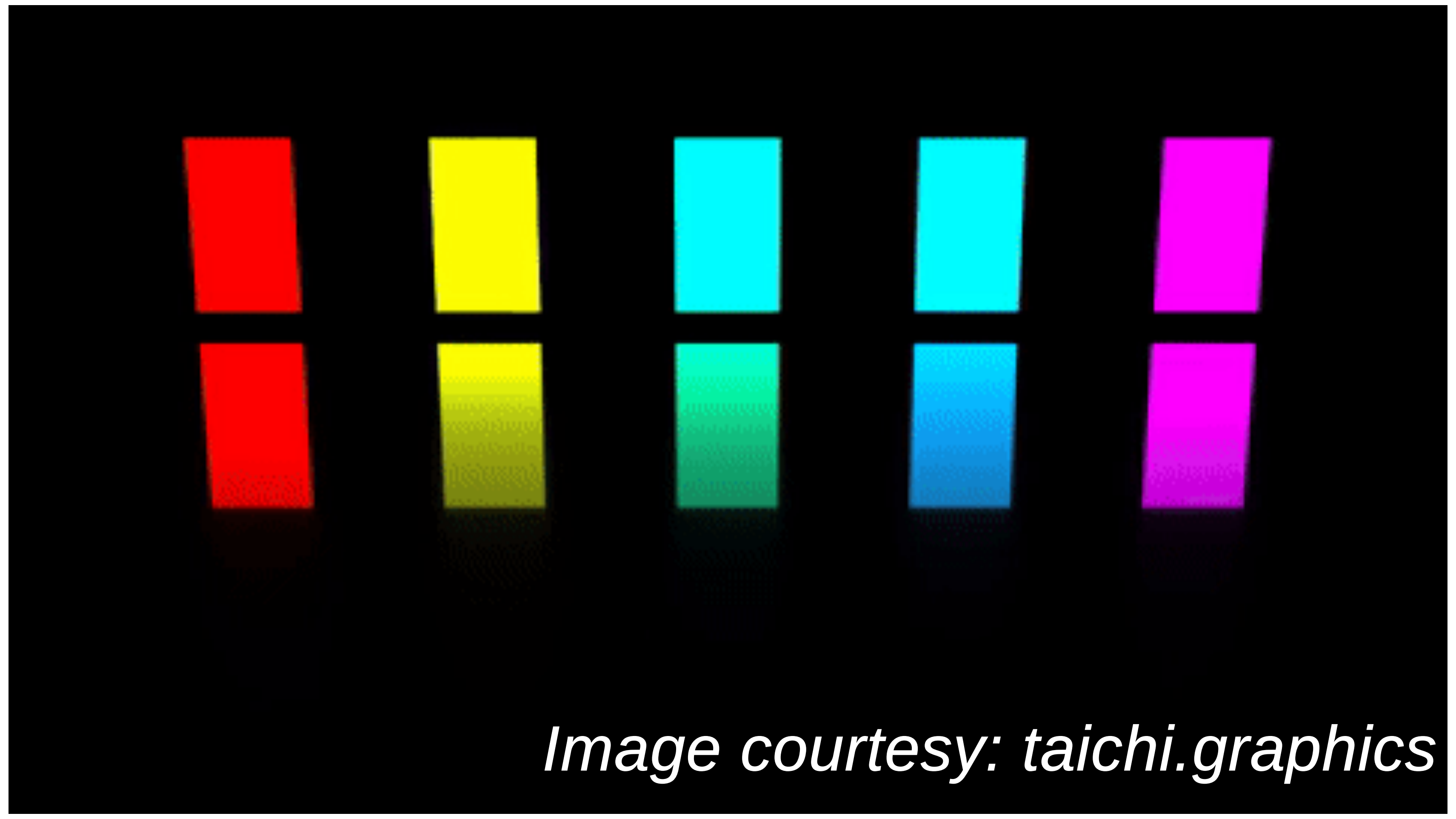
Measured BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda]$$

captured from real world

millions of values, hard to modify

Analytic BRDF



Diffuse　　　　Specular

$$\underline{\rho_{\mathrm{d}}(\alpha_{\mathrm{d}})} + \underline{\rho_{\mathrm{s}}(\alpha_{\mathrm{s}})}$$

approximated with models

OVERVIEW

Measured BRDF

$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda]$

captured from real world

millions of values, hard to modify

Analytic BRDF

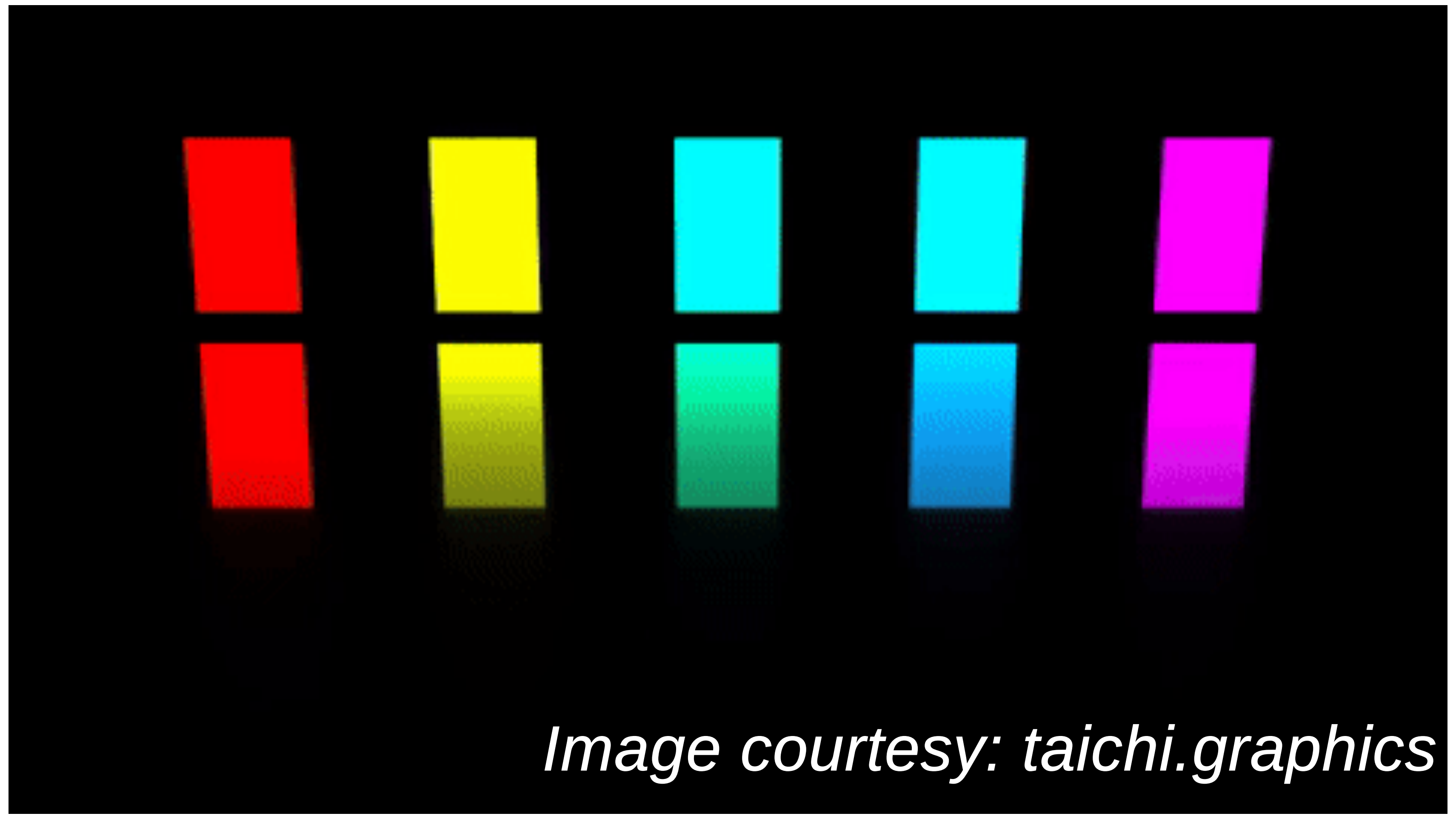


Image courtesy: taichi.graphics

Diffuse Specular

$$\underline{\rho_{\mathrm{d}}(\alpha_{\mathrm{d}})} \cdot \underline{\mathbf{c}_{\mathrm{d}}(\lambda)} + \underline{\rho_{\mathrm{s}}(\alpha_{\mathrm{s}})} \cdot \underline{\mathbf{c}_{\mathrm{s}}(\lambda)}$$

Colors

approximated with models

OVERVIEW

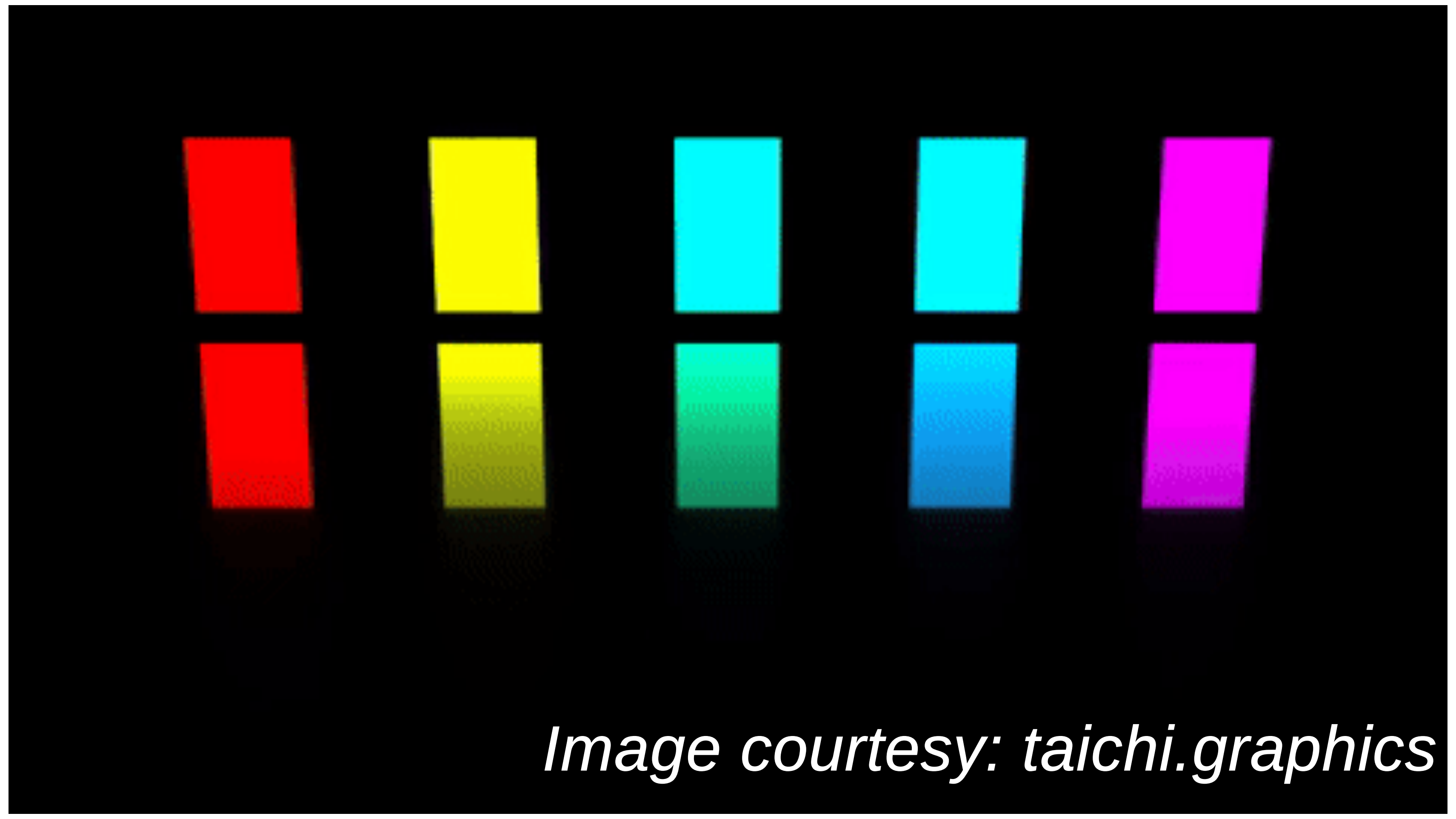
Measured BRDF

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda]$$

captured from real world

millions of values, hard to modify

Analytic BRDF



Diffuse Specular

$$\rho_{\mathrm{d}}(\alpha_{\mathrm{d}}) \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}(\alpha_{\mathrm{s}}) \cdot \mathbf{c}_{\mathrm{s}}(\lambda)$$

Colors

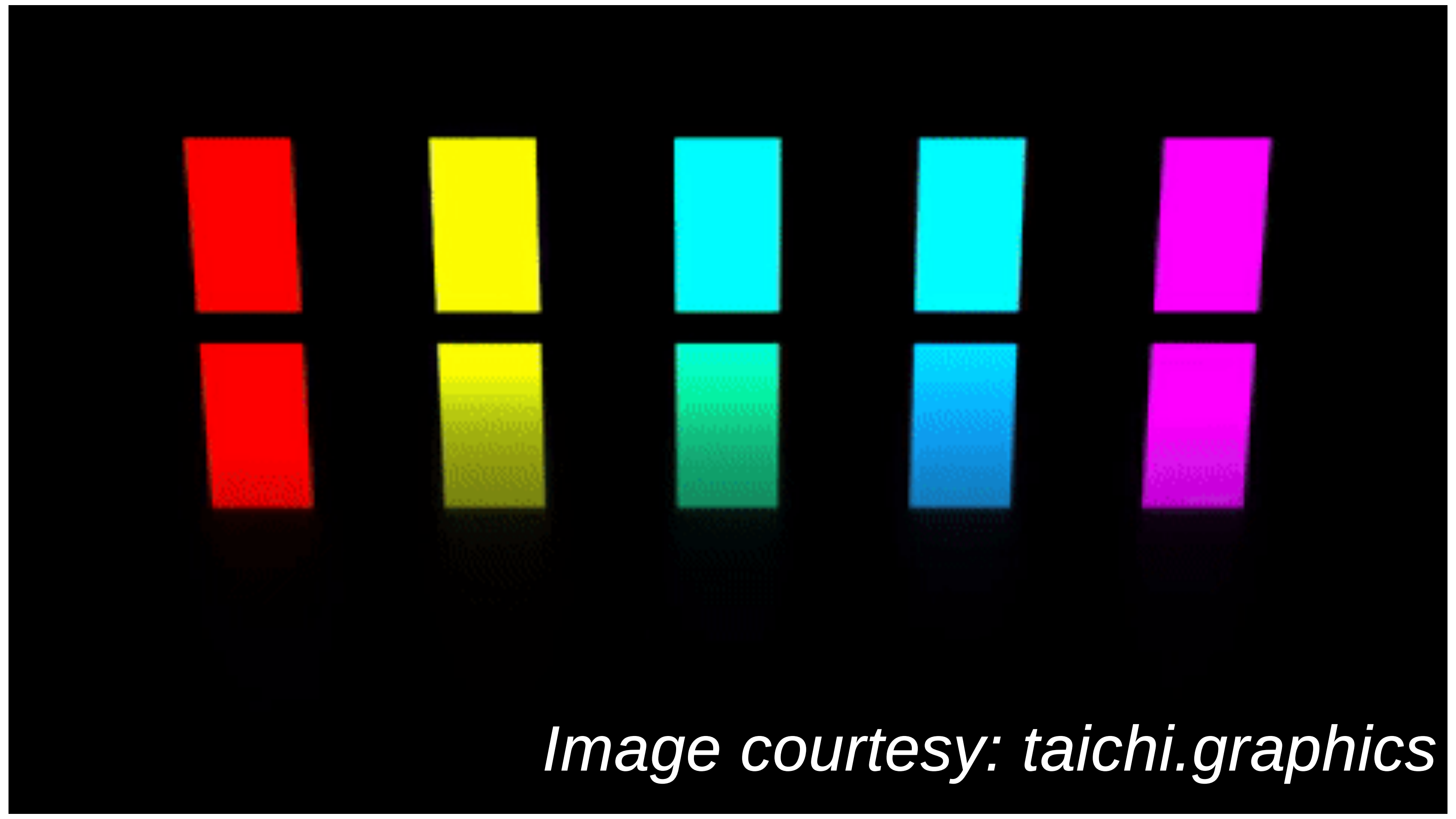
approximated with models

~8 parameters, easy to edit

OVERVIEW

Measured BRDF

Analytic BRDF



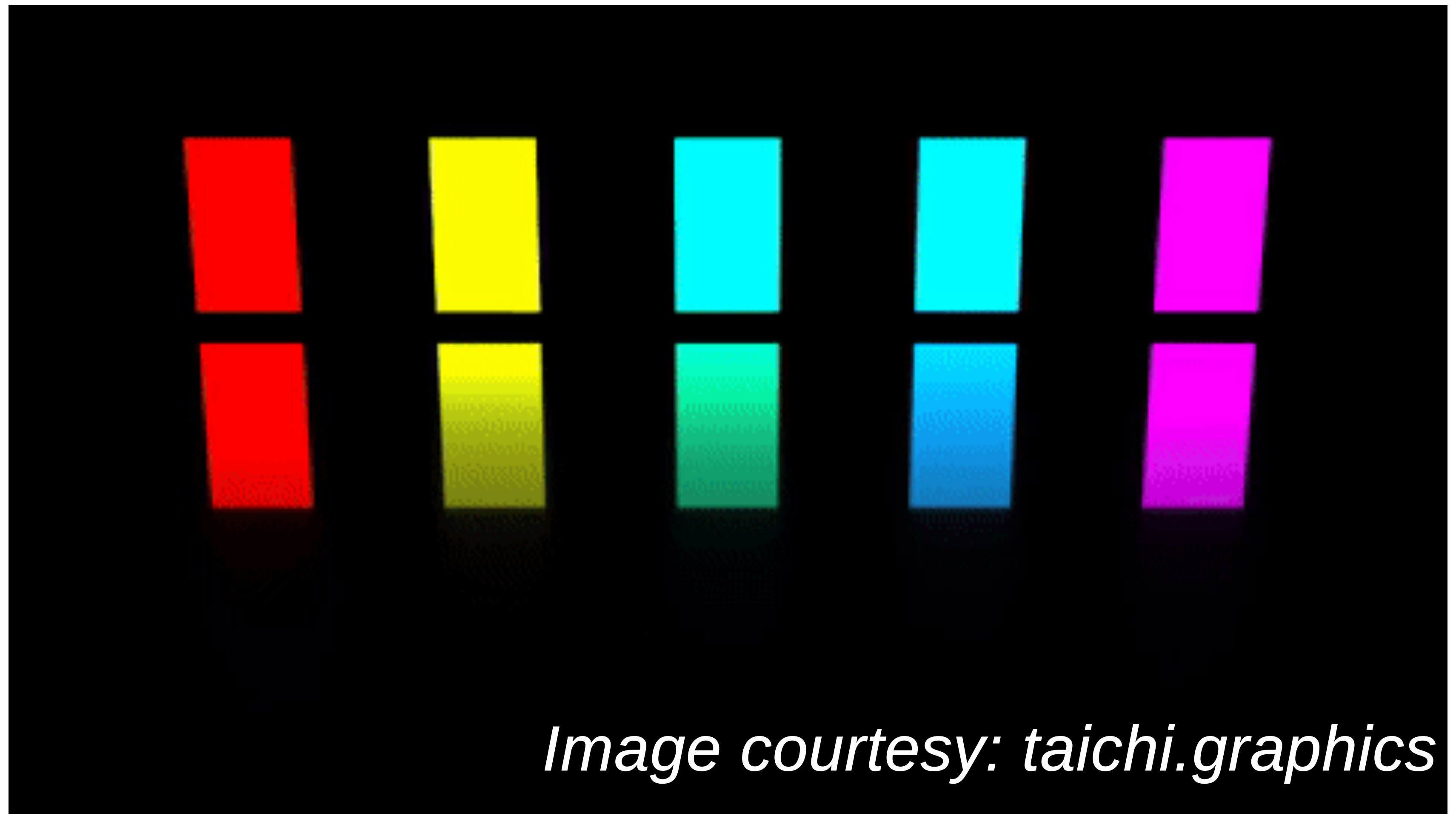
$$\min_{\alpha_{\mathrm{d}},\alpha_{\mathrm{s}}} d\Big(\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \qquad , \; \rho_{\mathrm{d}}(\alpha_{\mathrm{d}}) \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}(\alpha_{\mathrm{s}}) \cdot \mathbf{c}_{\mathrm{s}}(\lambda) \Big)$$

Ngan, Addy, Frédo Durand, and Wojciech Matusik. "Experimental analysis of brdf models." Rendering Techniques 2005.16th (2005): 2.

OVERVIEW

Measured BRDF

Analytic BRDF



$$\min_{\alpha_{\mathrm{d}}, \alpha_{\mathrm{s}}} d\Big(\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \quad , \; \rho_{\mathrm{d}}(\alpha_{\mathrm{d}}) \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}(\alpha_{\mathrm{s}}) \cdot \mathbf{c}_{\mathrm{s}}(\lambda) \Big)$$

Diffuse parameter (α_{d})

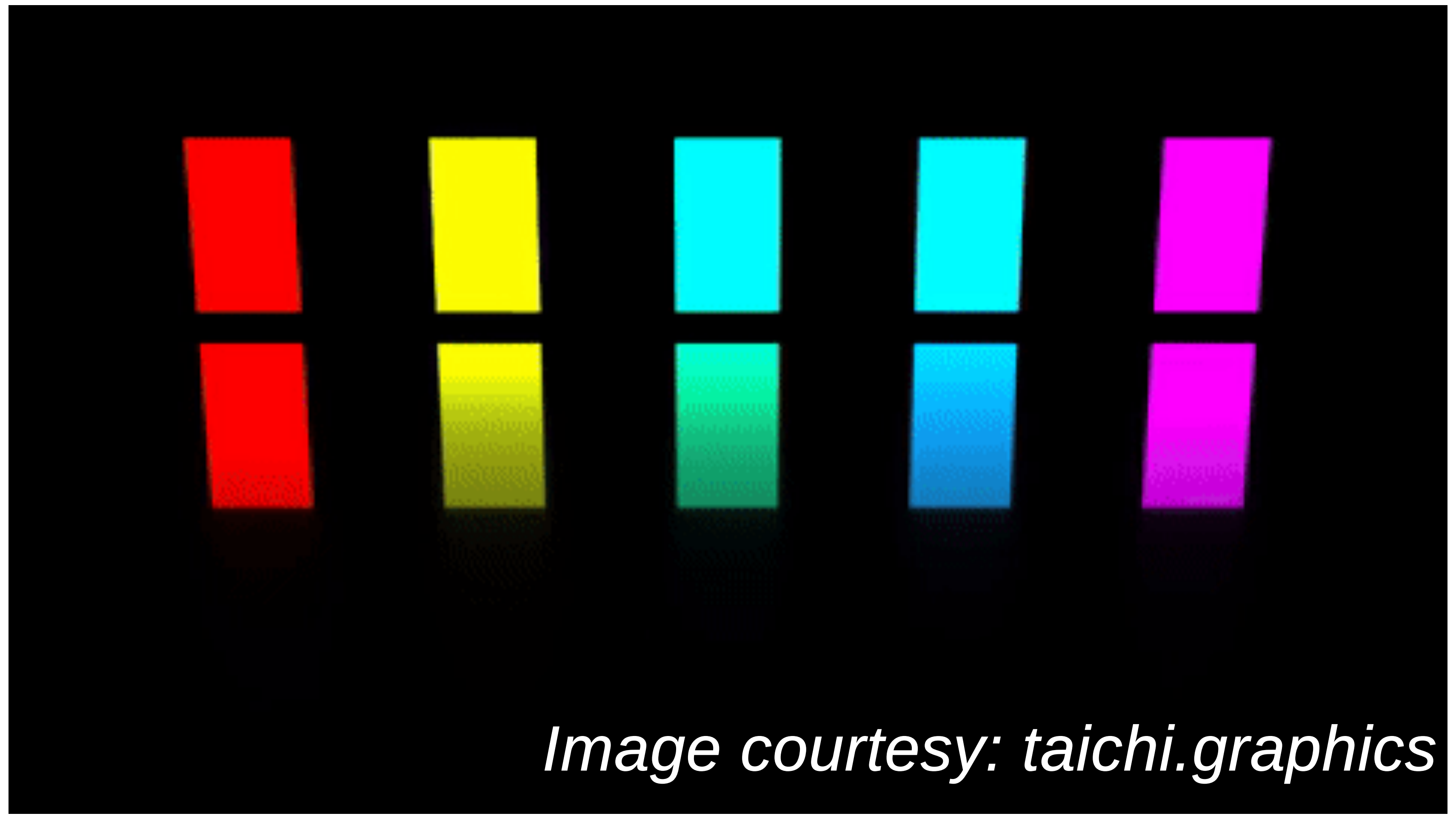
Specular parameter (α_{s})

Ngan, Addy, Frédo Durand, and Wojciech Matusik. "Experimental analysis of brdf models." Rendering Techniques 2005.16th (2005): 2.

OVERVIEW

Measured BRDF

Analytic BRDF



$$\min_{\underline{\alpha_{\mathrm{d}}},\underline{\alpha_{\mathrm{s}}}} d\Big(\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \qquad , \; \rho_{\mathrm{d}}(\underline{\alpha_{\mathrm{d}}}) \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}(\underline{\alpha_{\mathrm{s}}}) \cdot \mathbf{c}_{\mathrm{s}}(\lambda) \Big)$$

Diffuse parameter

Specular parameter

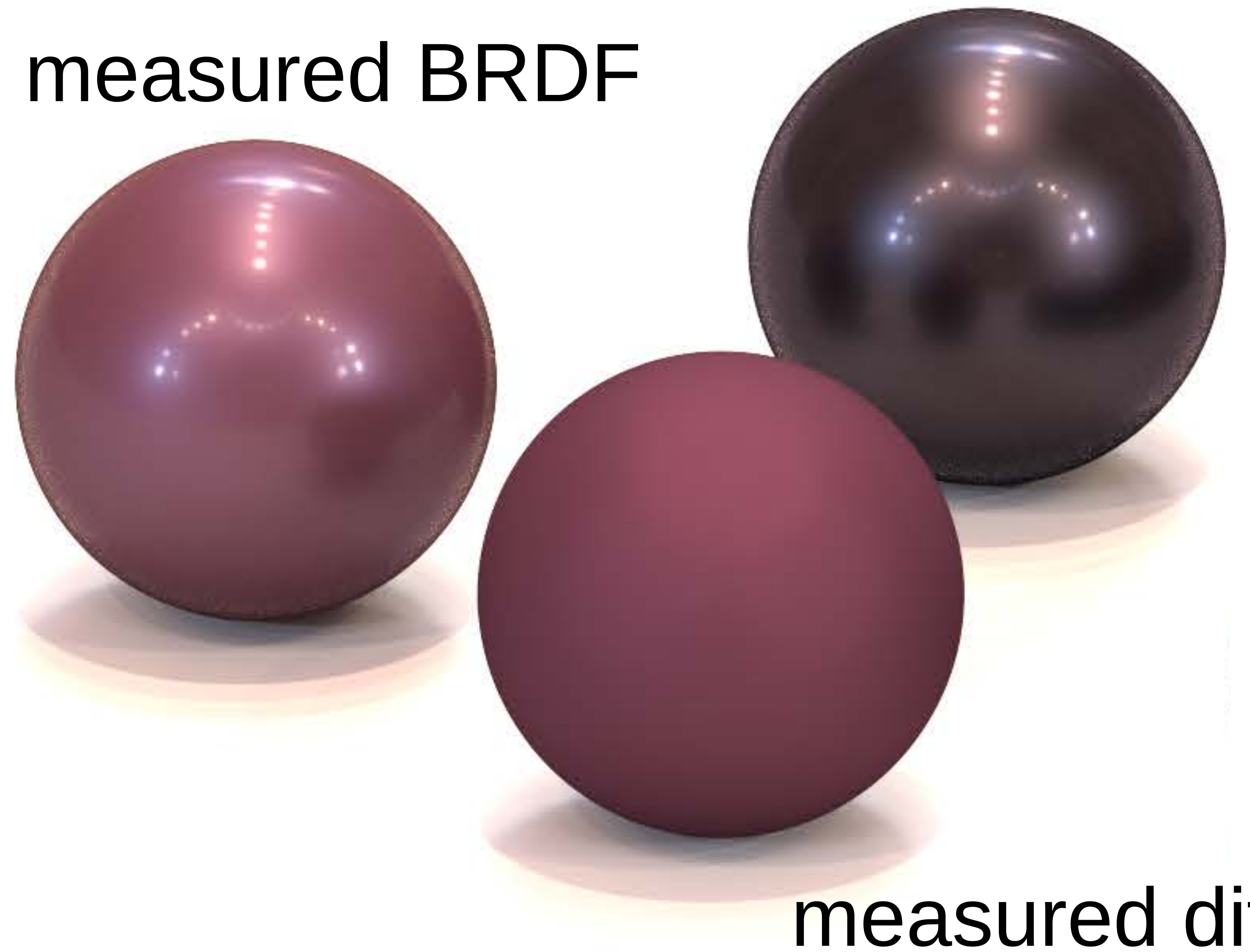
Inefficient

Local optimal

Ngan, Addy, Frédo Durand, and Wojciech Matusik. "Experimental analysis of brdf models." Rendering Techniques 2005.16th (2005): 2.

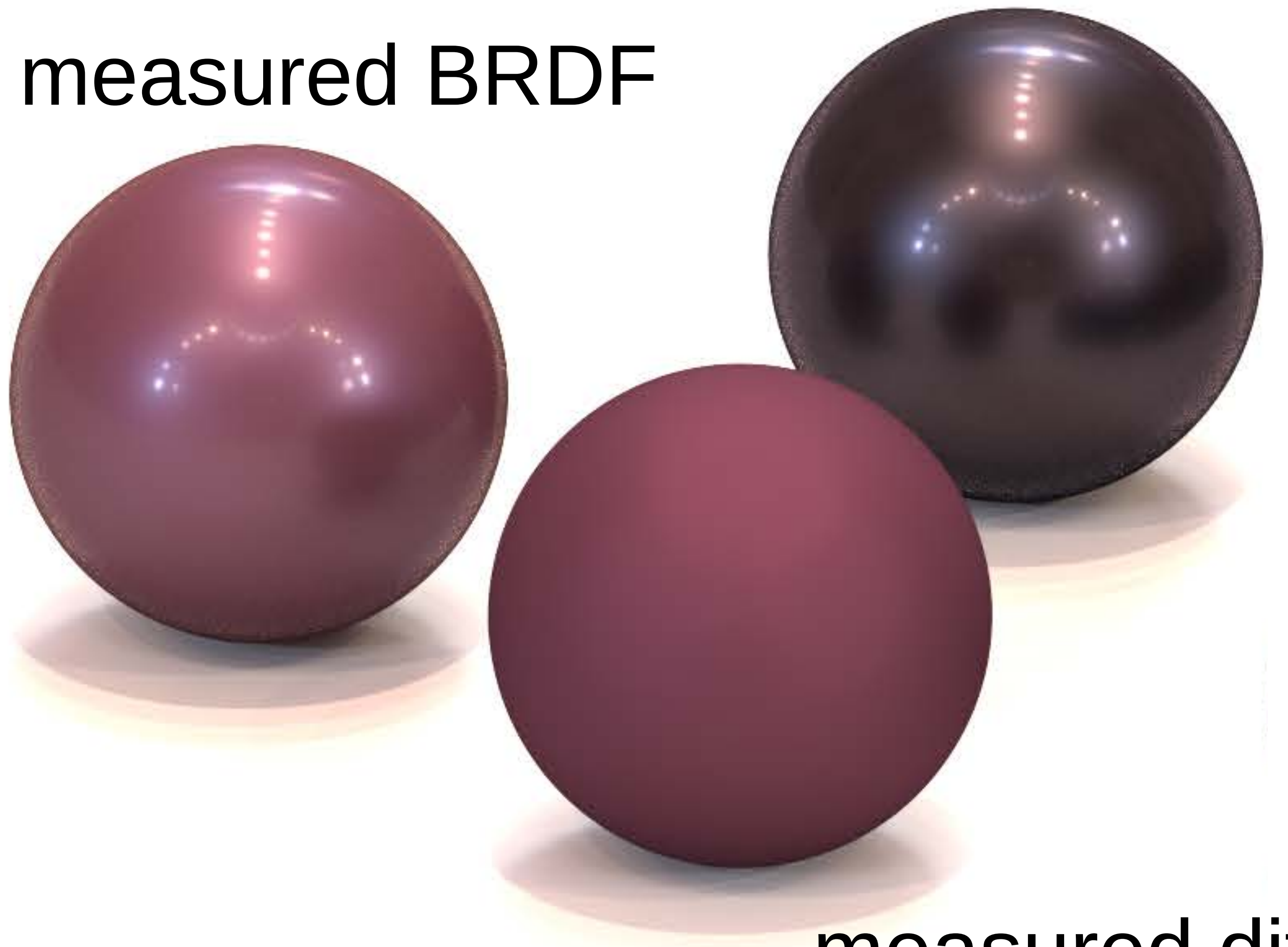
OVERVIEW

OVERVIEW

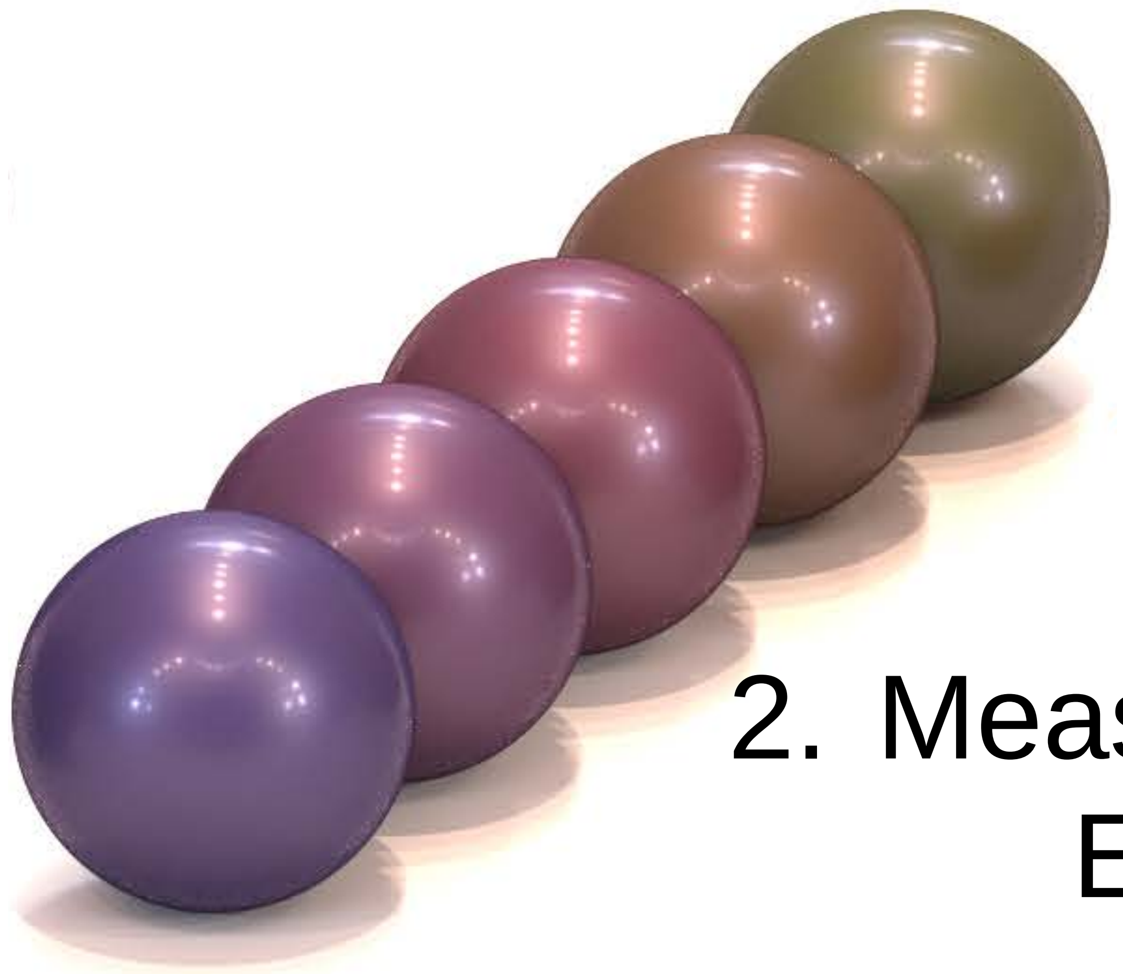


1. Diffuse-Specular Separation

OVERVIEW



1. Diffuse-Specular Separation

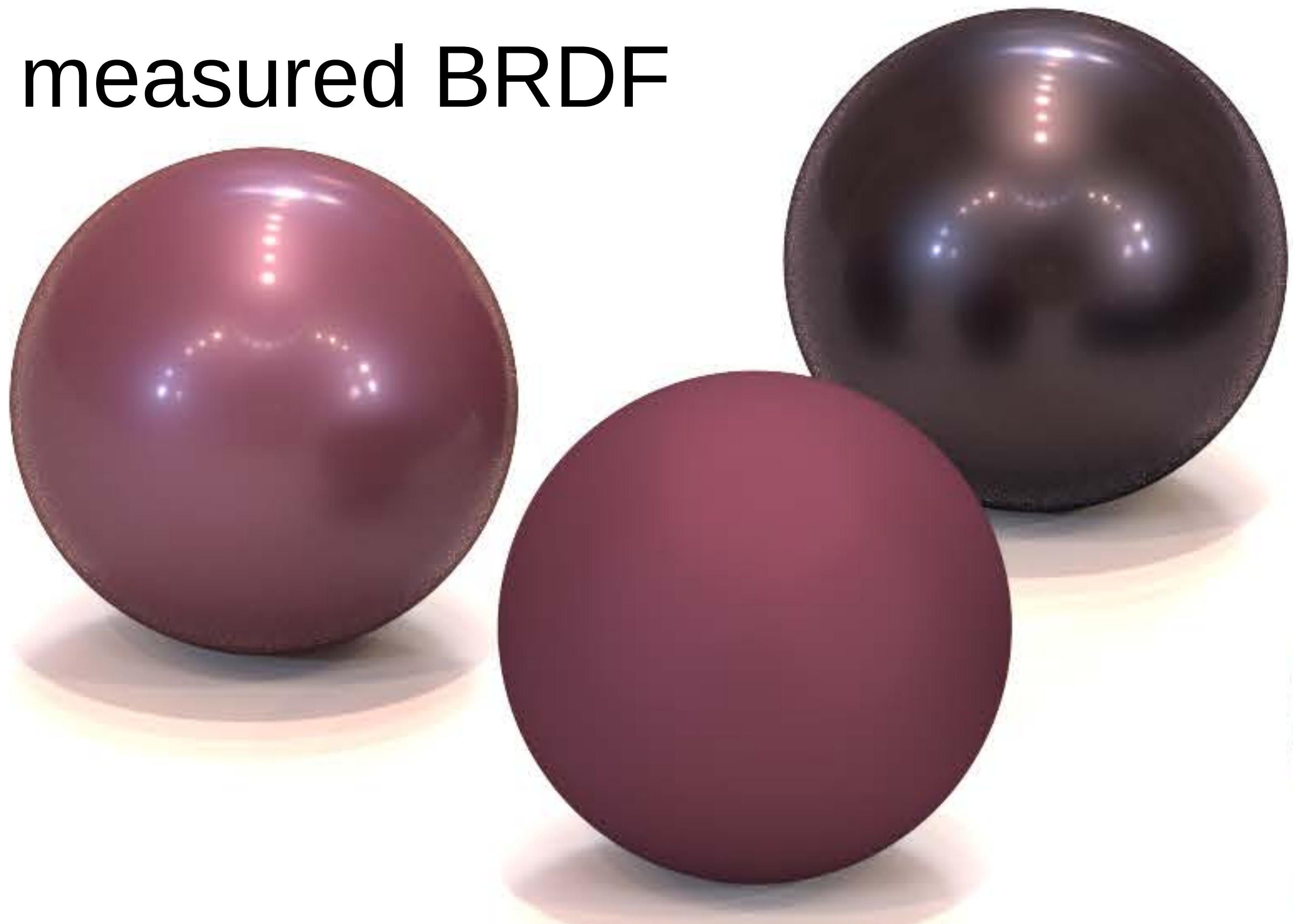


2. Measured BRDF Editing

OVERVIEW

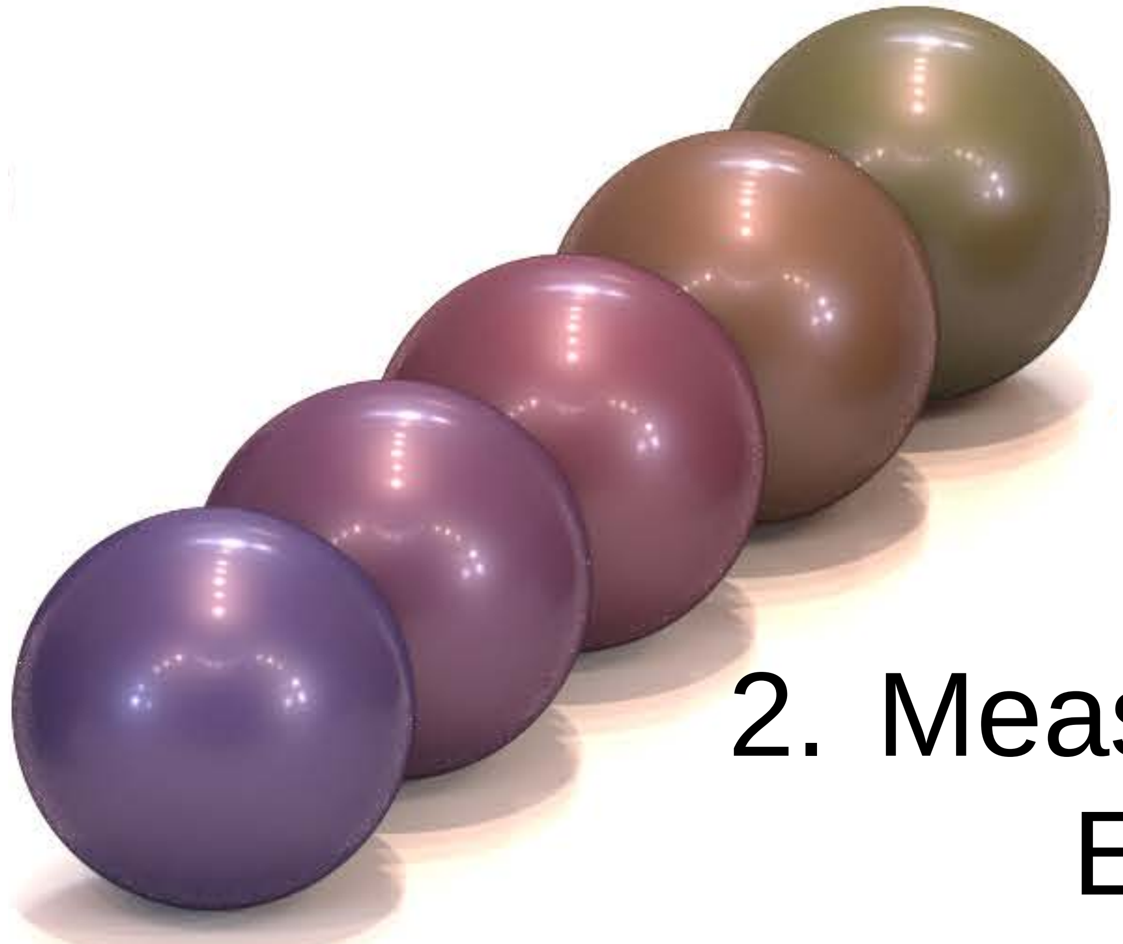
measured BRDF

measured specular

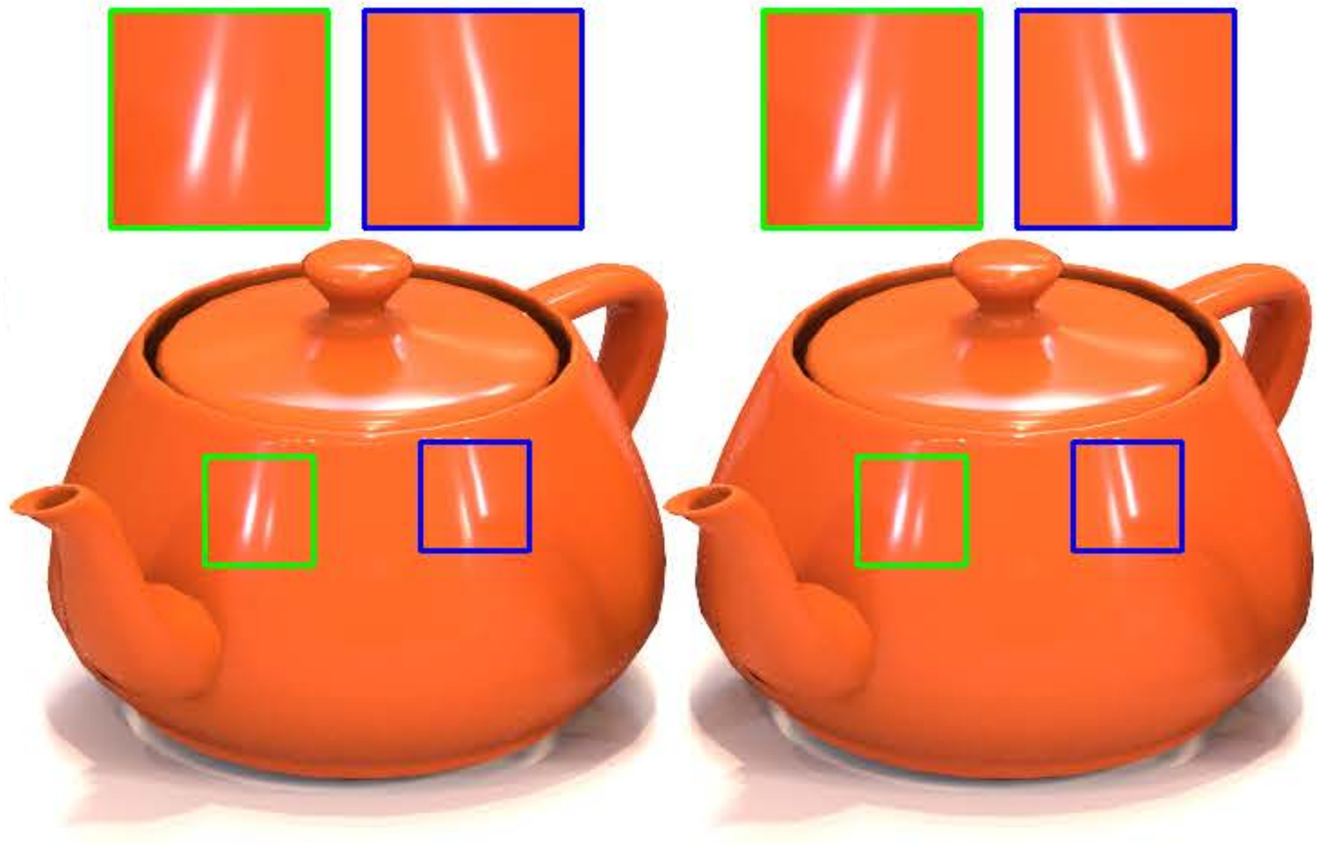


measured diffuse

1. Diffuse-Specular Separation



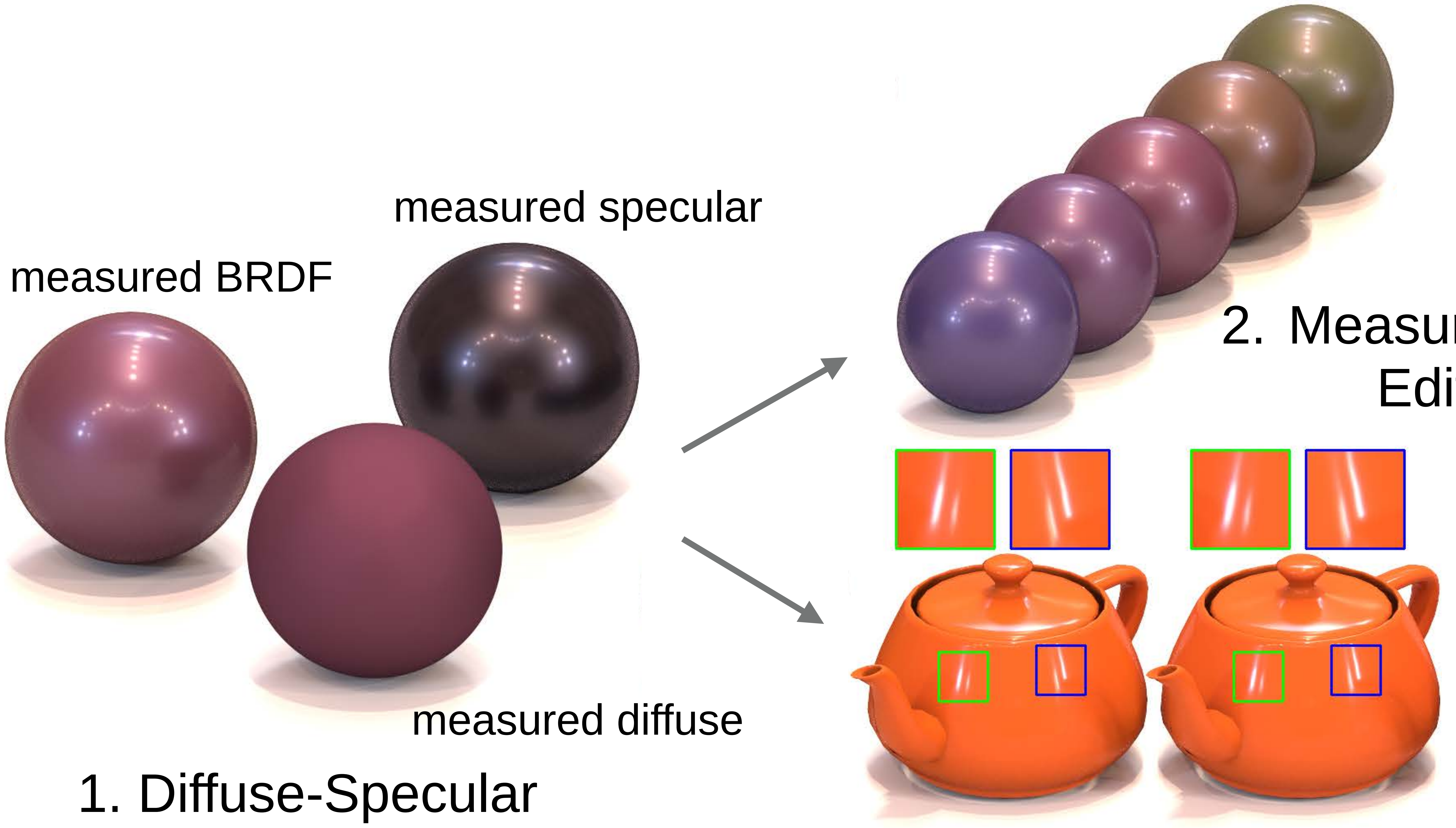
2. Measured BRDF Editing



~3 million values **8** parameters

3. Compact Measured BRDF model

OVERVIEW



1. Diffuse-Specular Separation

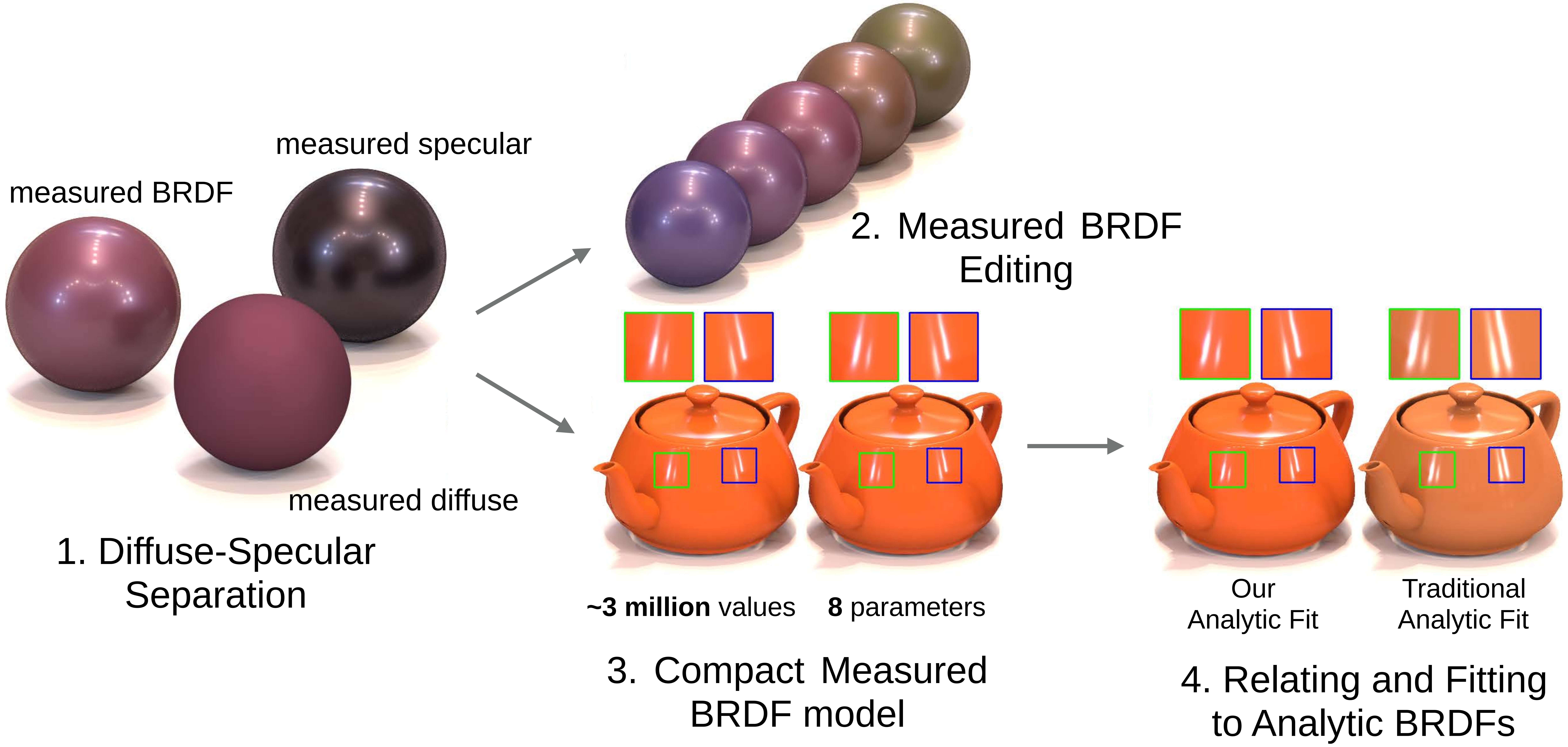
2. Measured BRDF Editing

~3 million values **8** parameters

same number as analytic BRDF

3. Compact Measured BRDF model

OVERVIEW

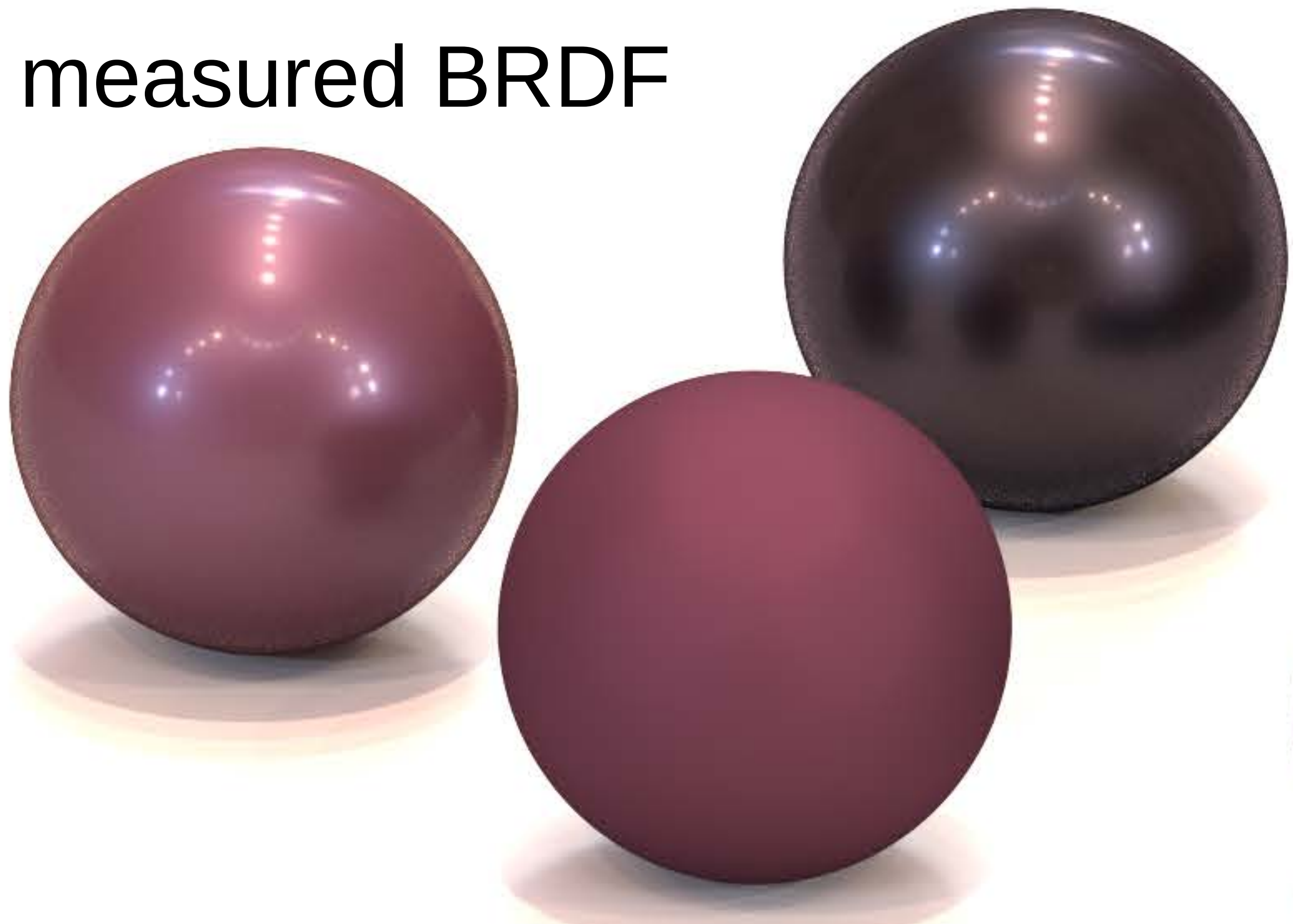


measured BRDF
measured specular
measured diffuse
1. Diffuse-Specular Separation
2. Measured BRDF Editing
~3 million values
8 parameters
3. Compact Measured BRDF model
Our Analytic Fit
Traditional Analytic Fit
4. Relating and Fitting to Analytic BRDFs

OVERVIEW

measured BRDF

measured specular



measured diffuse

1. Diffuse-Specular Separation

2. Measured BRDF Editing

~3 million values **8** parameters

3. Compact Measured BRDF model

Our Analytic Fit

Traditional Analytic Fit

4. Relating and Fitting to Analytic BRDFs

1. DIFFUSE-SPECULAR SEPARATION

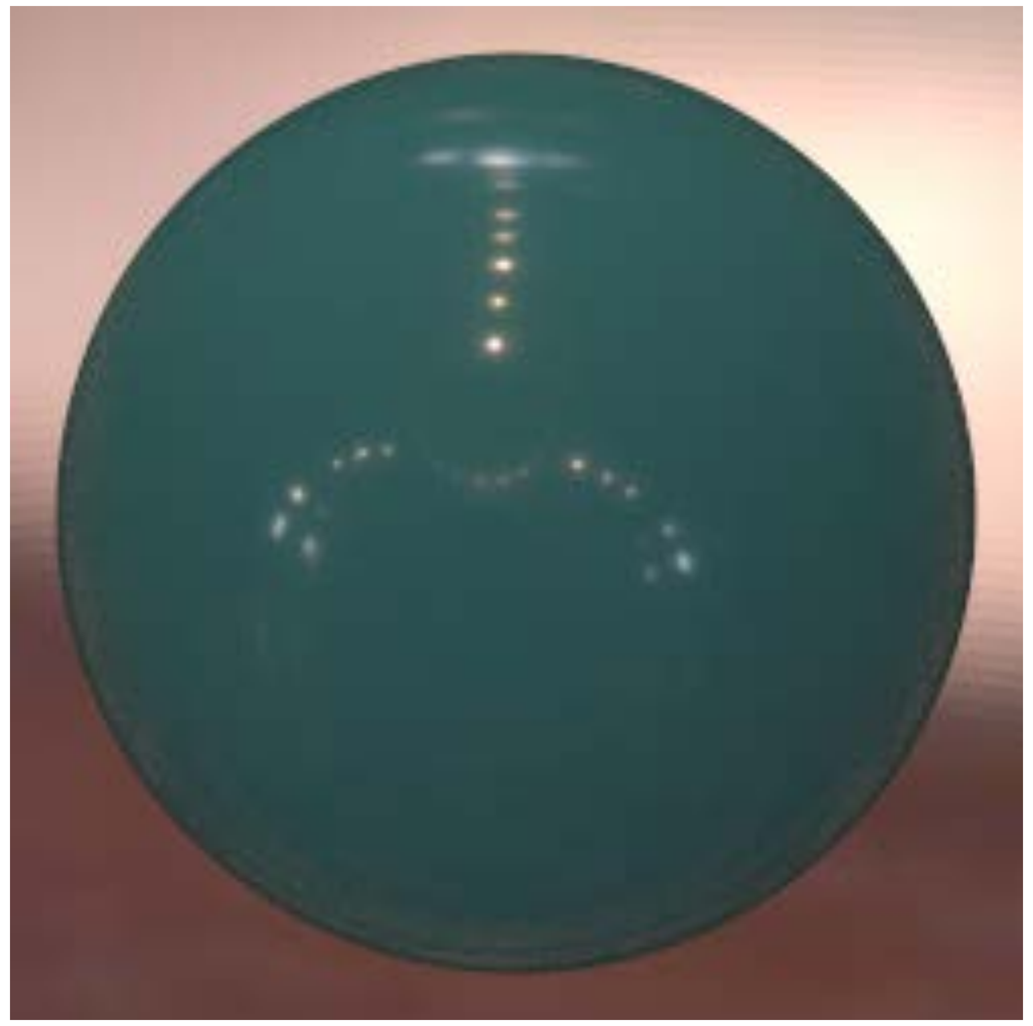
1. DIFFUSE-SPECULAR SEPARATION

Goal:

1. DIFFUSE-SPECULAR SEPARATION

Goal: $\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx$

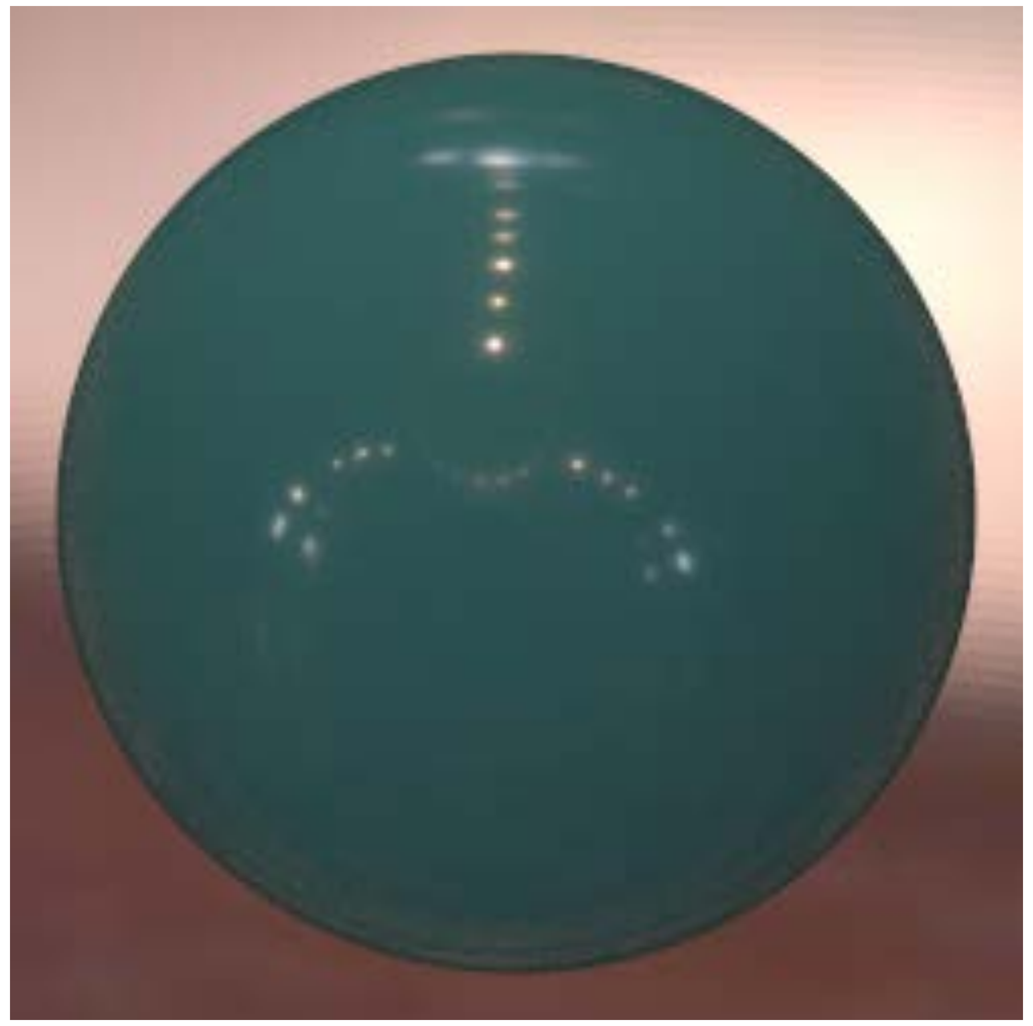
measured BRDF



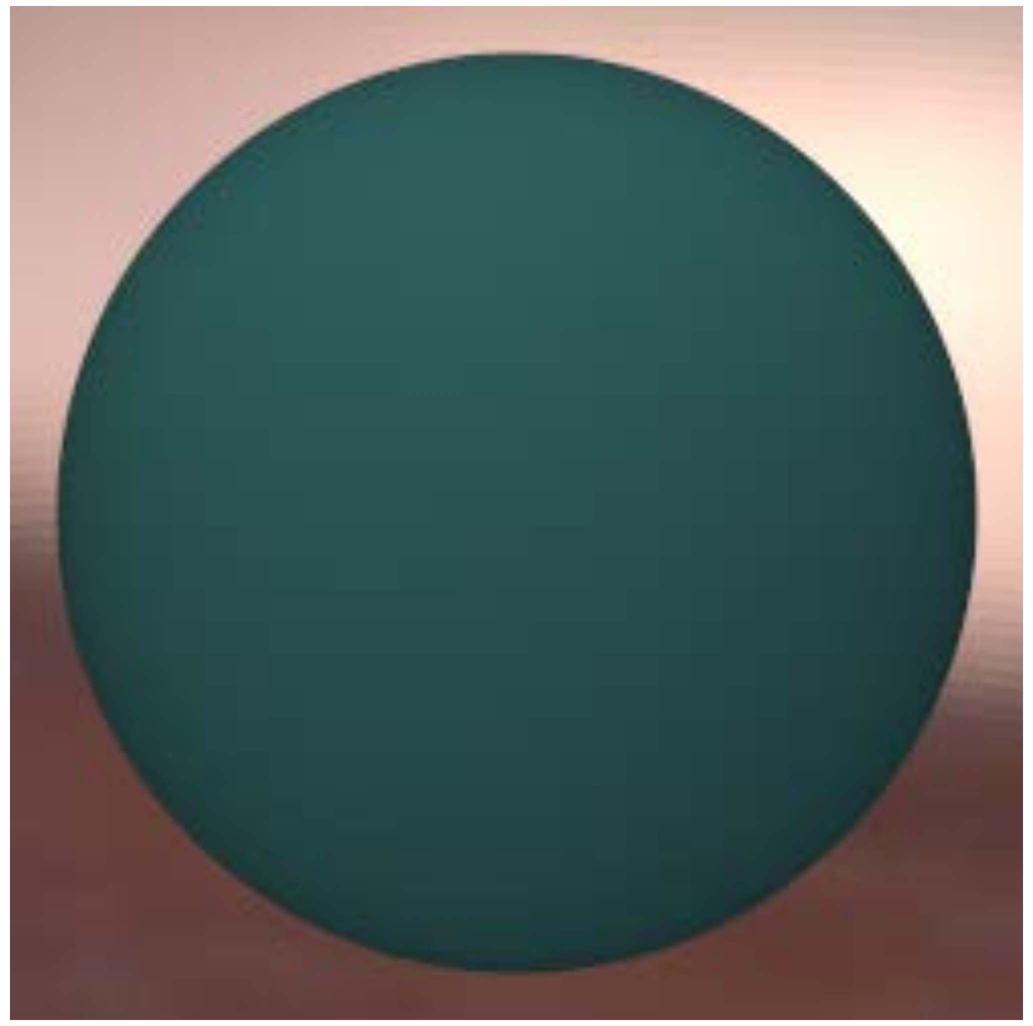
1. DIFFUSE-SPECULAR SEPARATION

Goal: $$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \approx \rho_{\mathrm{d}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \mathbf{c}_{\mathrm{d}}(\lambda)$$

measured BRDF



measured diffuse



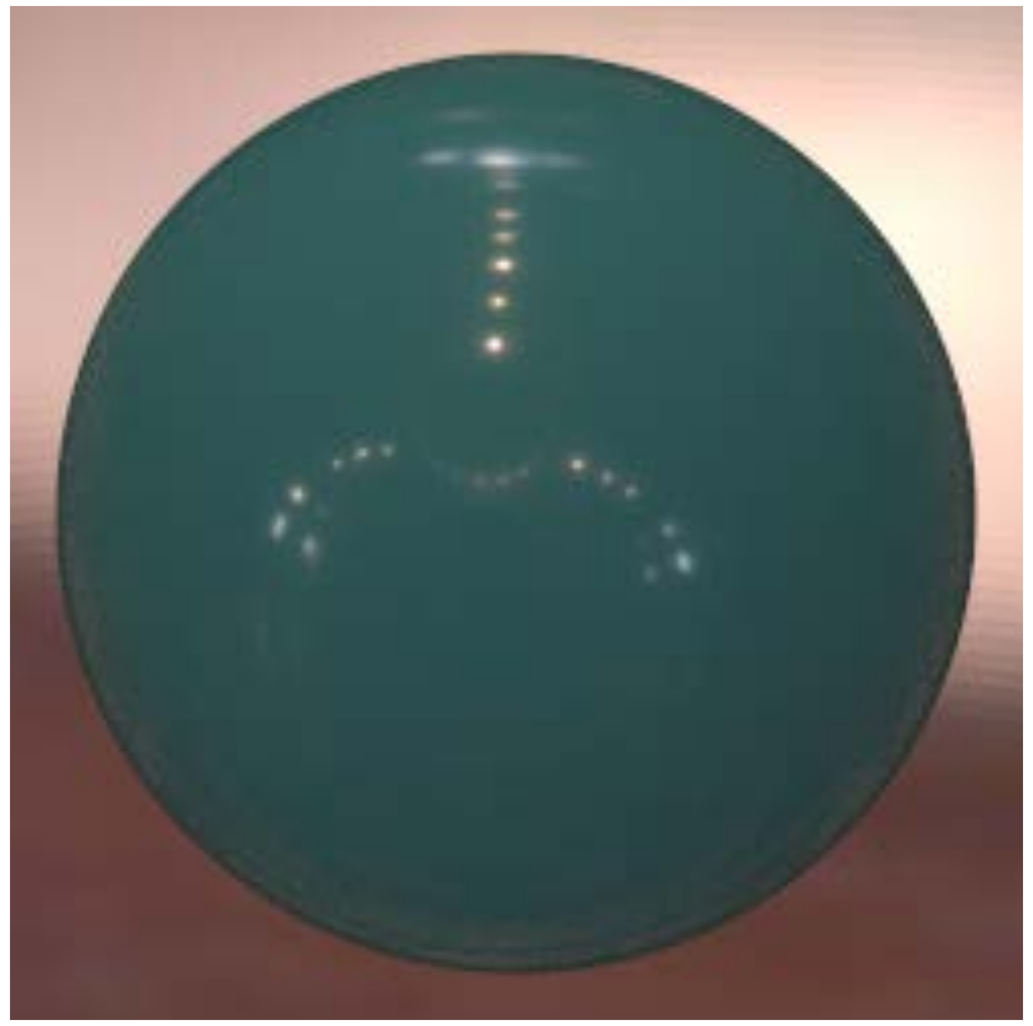
1. DIFFUSE-SPECULAR SEPARATION

Goal: $$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx \rho_\mathrm{d}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{d}(\lambda) + \rho_\mathrm{s}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{s}(\lambda)$$

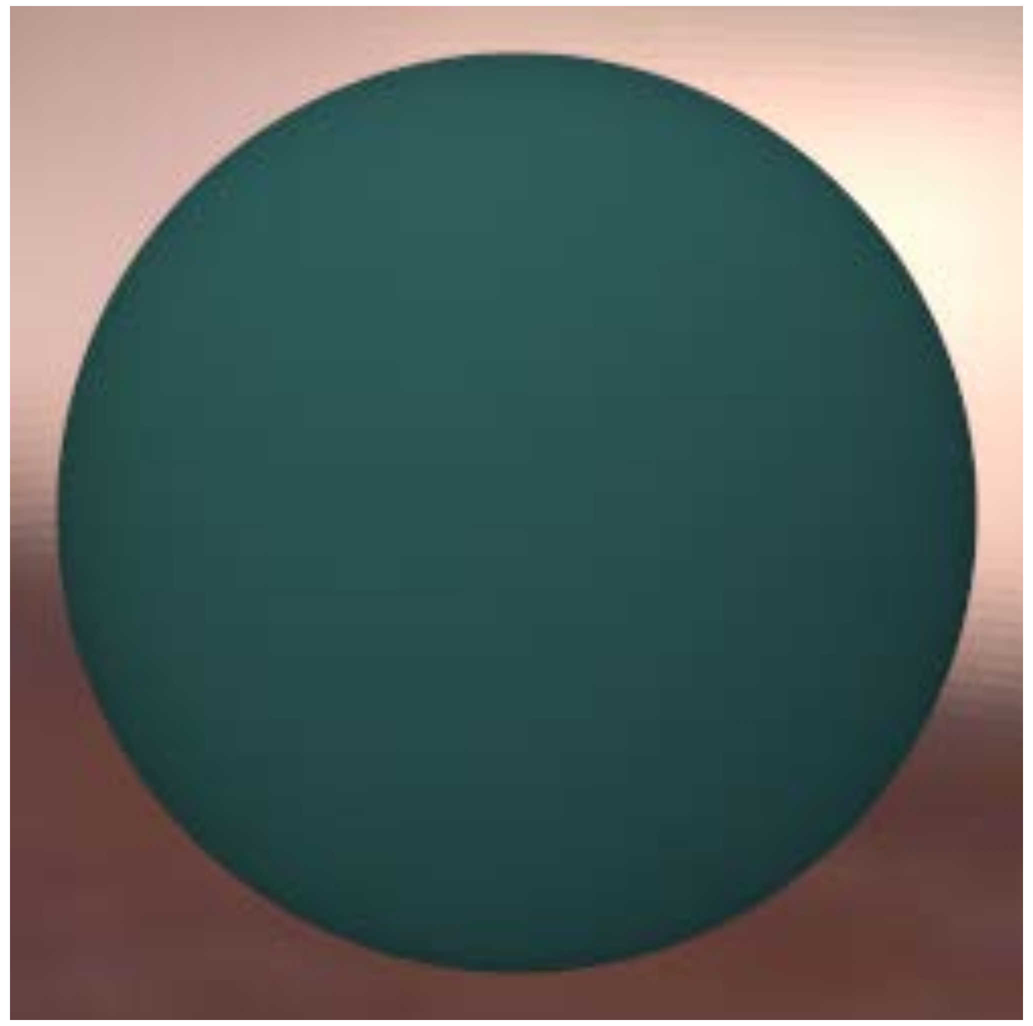
1. DIFFUSE-SPECULAR SEPARATION

Goal: $$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \approx \rho_{\mathrm{d}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \underline{\mathbf{c}_{\mathrm{d}}(\lambda)} + \rho_{\mathrm{s}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \underline{\mathbf{c}_{\mathrm{s}}(\lambda)}$$ *Colors*

measured BRDF



measured diffuse



measured specular

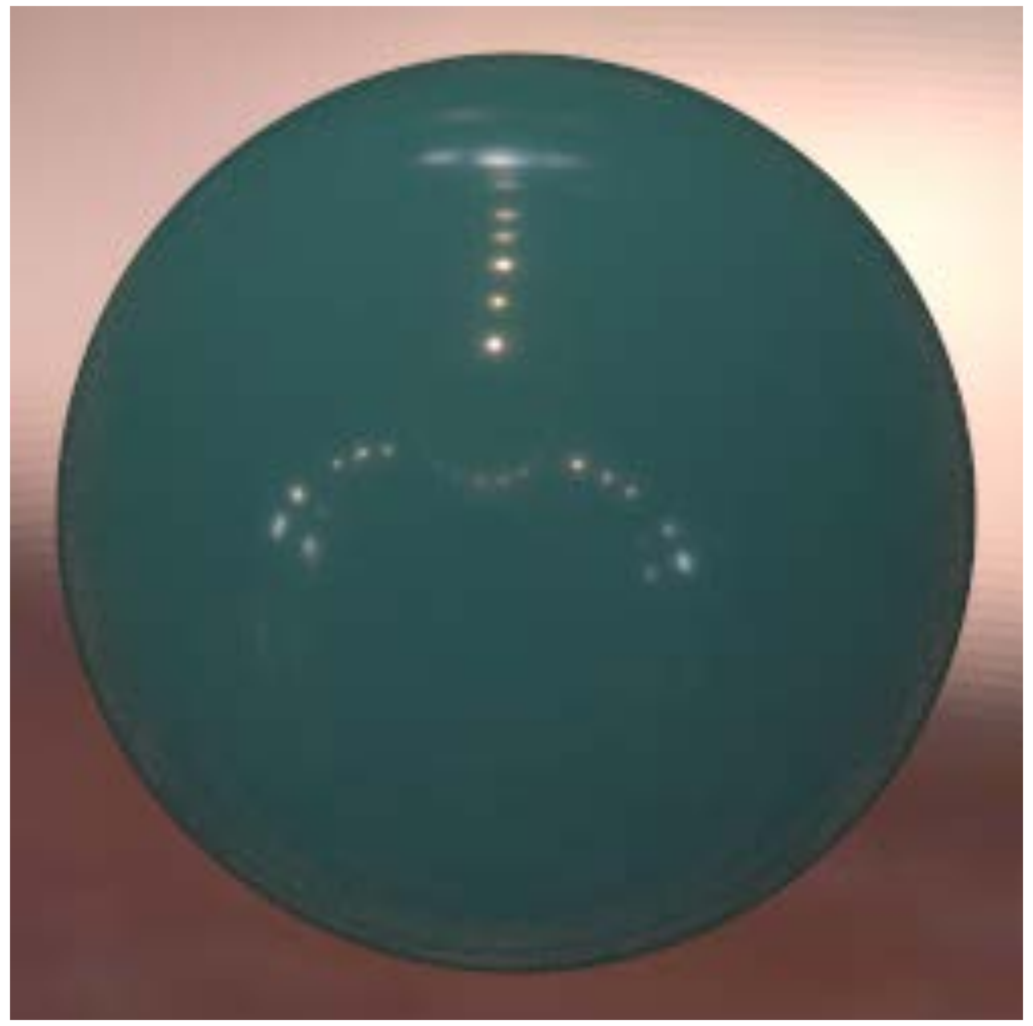
1. DIFFUSE-SPECULAR SEPARATION

Goal: $$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx \underline{\rho_\mathrm{d}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \underline{\mathbf{c}_\mathrm{d}(\lambda)} + \rho_\mathrm{s}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \underline{\mathbf{c}_\mathrm{s}(\lambda)}}$$

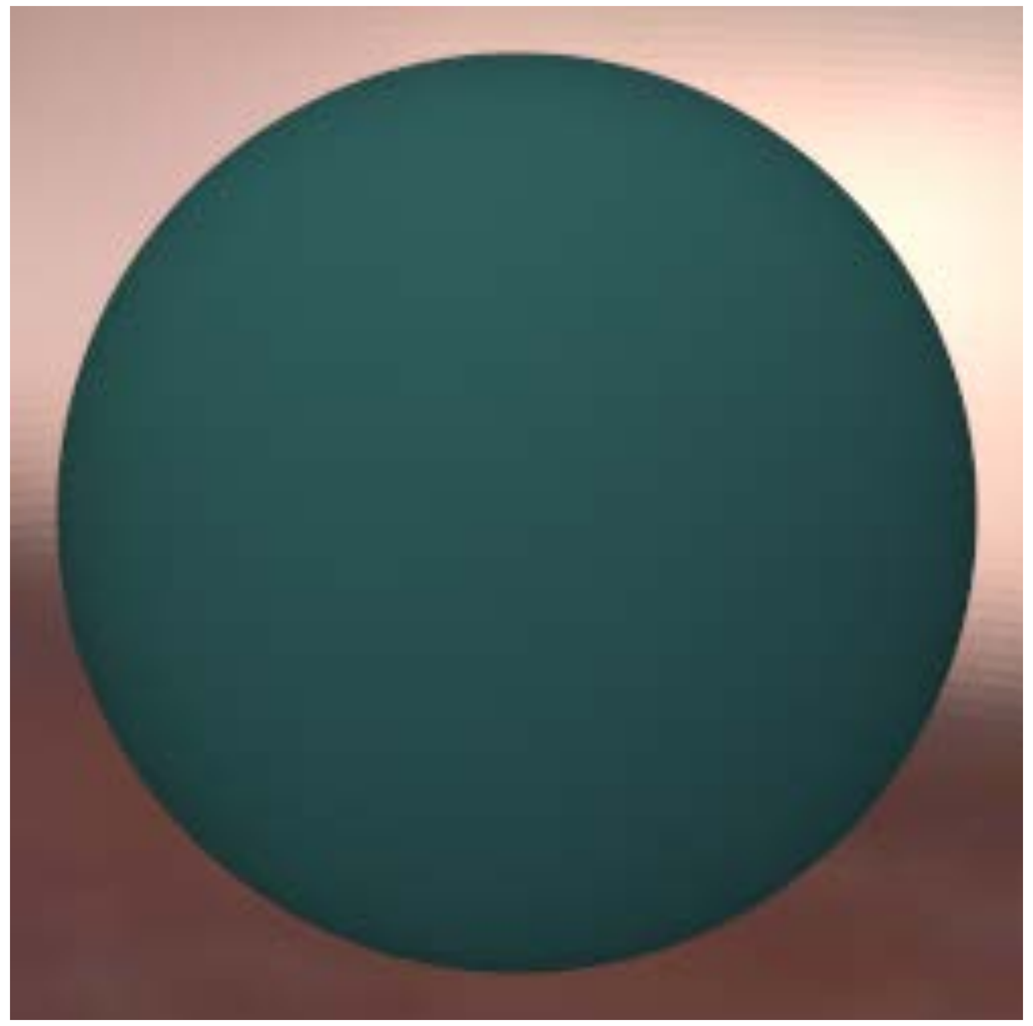
Colors

All unknown!

measured BRDF



measured diffuse



measured specular

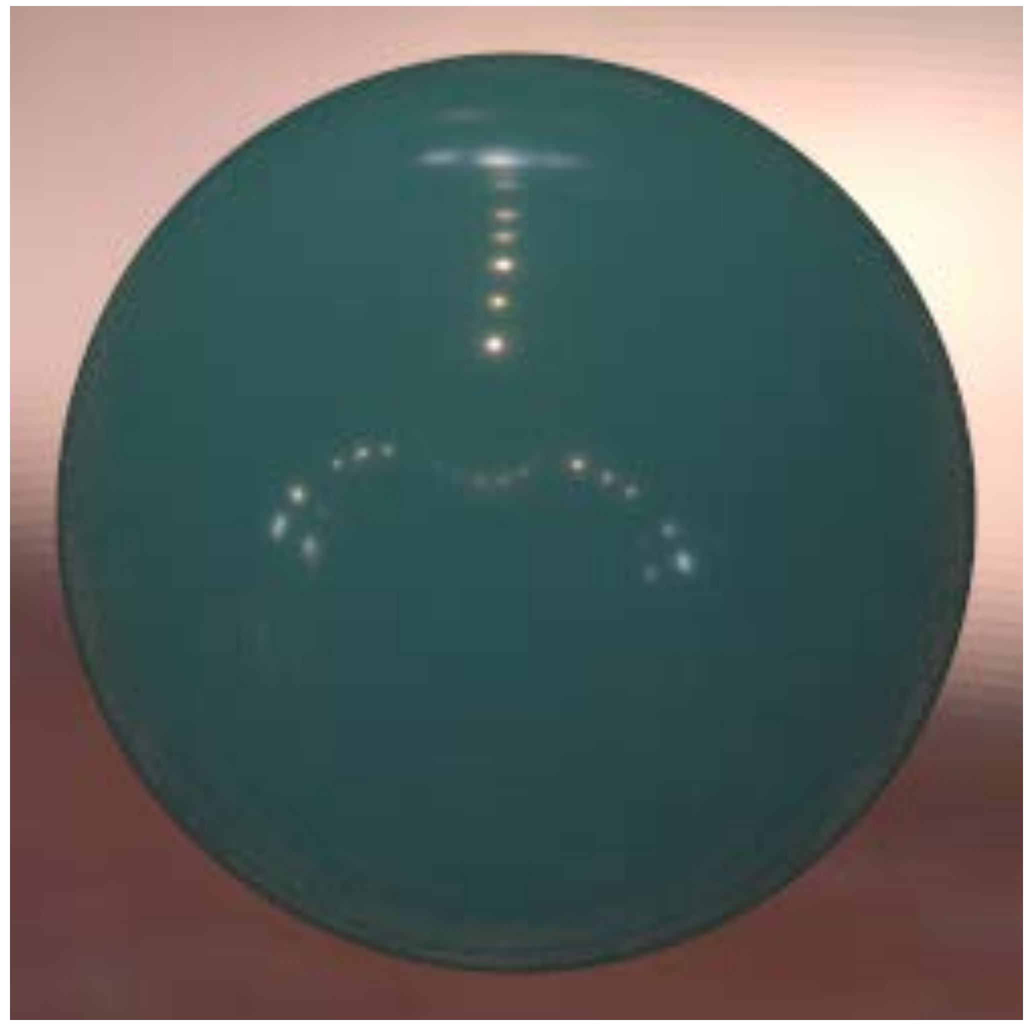
1. DIFFUSE-SPECULAR SEPARATION

Goal: $$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \approx \underline{\rho_{\mathrm{d}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \underline{\mathbf{c}_{\mathrm{d}}(\lambda)} + \rho_{\mathrm{s}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \underline{\mathbf{c}_{\mathrm{s}}(\lambda)}}$$

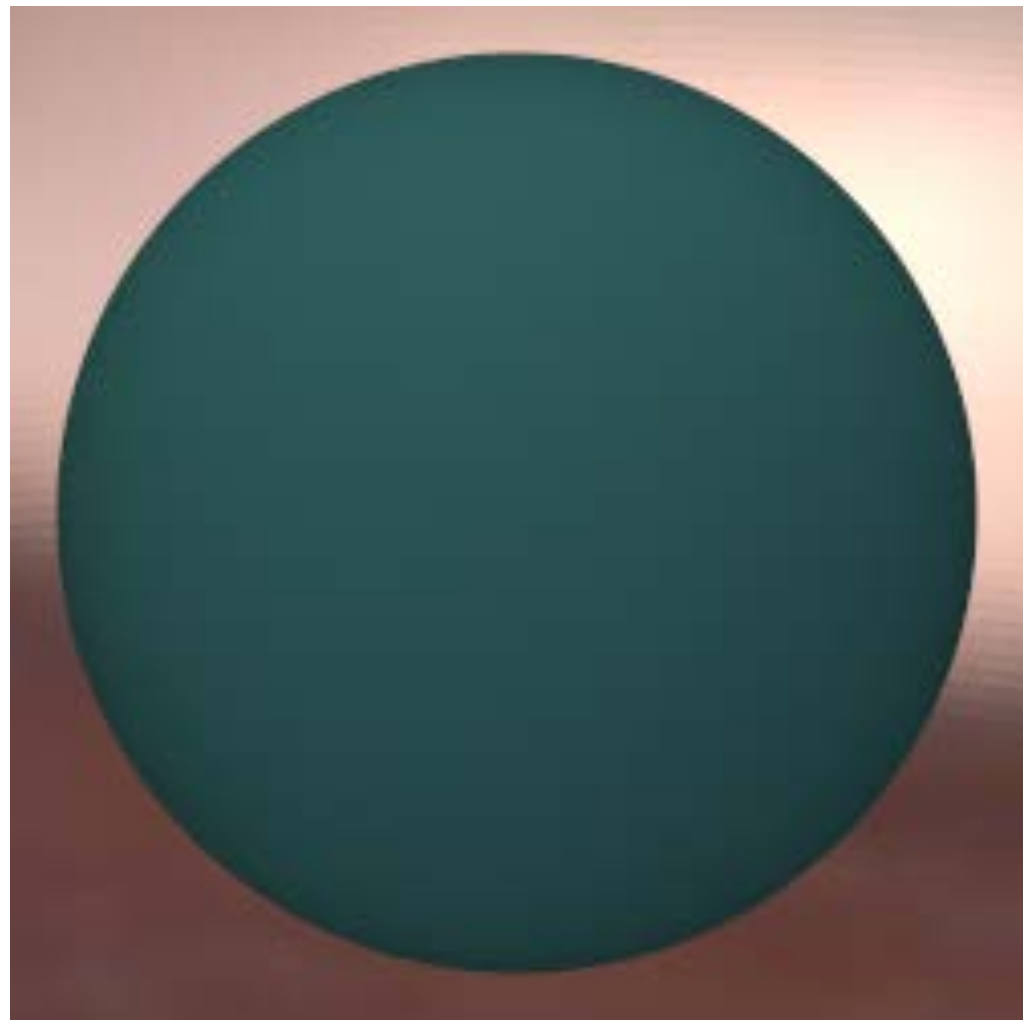
Colors

All unknown!

measured BRDF



measured diffuse



measured specular

➤ Two main challenges:

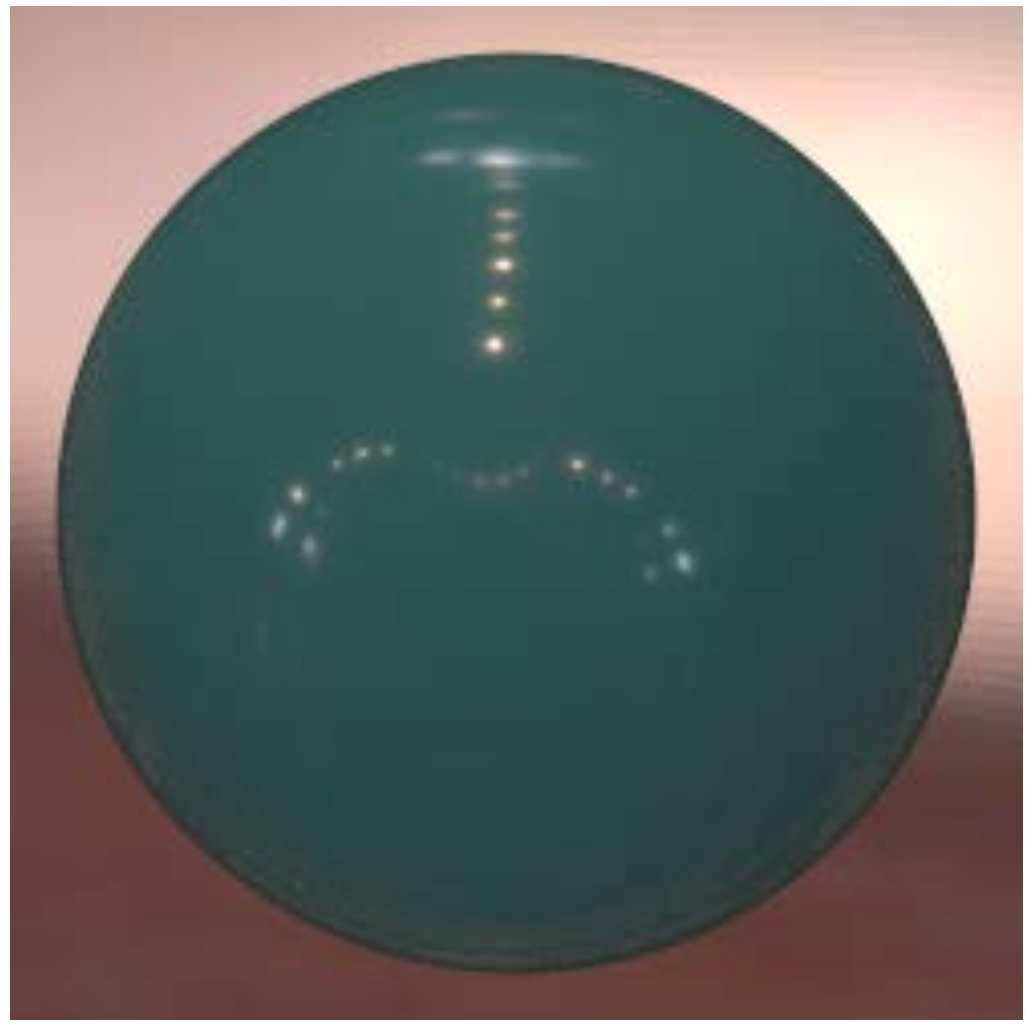
1. DIFFUSE-SPECULAR SEPARATION

Goal: $\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \approx \underline{\rho_{\mathrm{d}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \mathbf{c}_{\mathrm{s}}(\lambda)}$

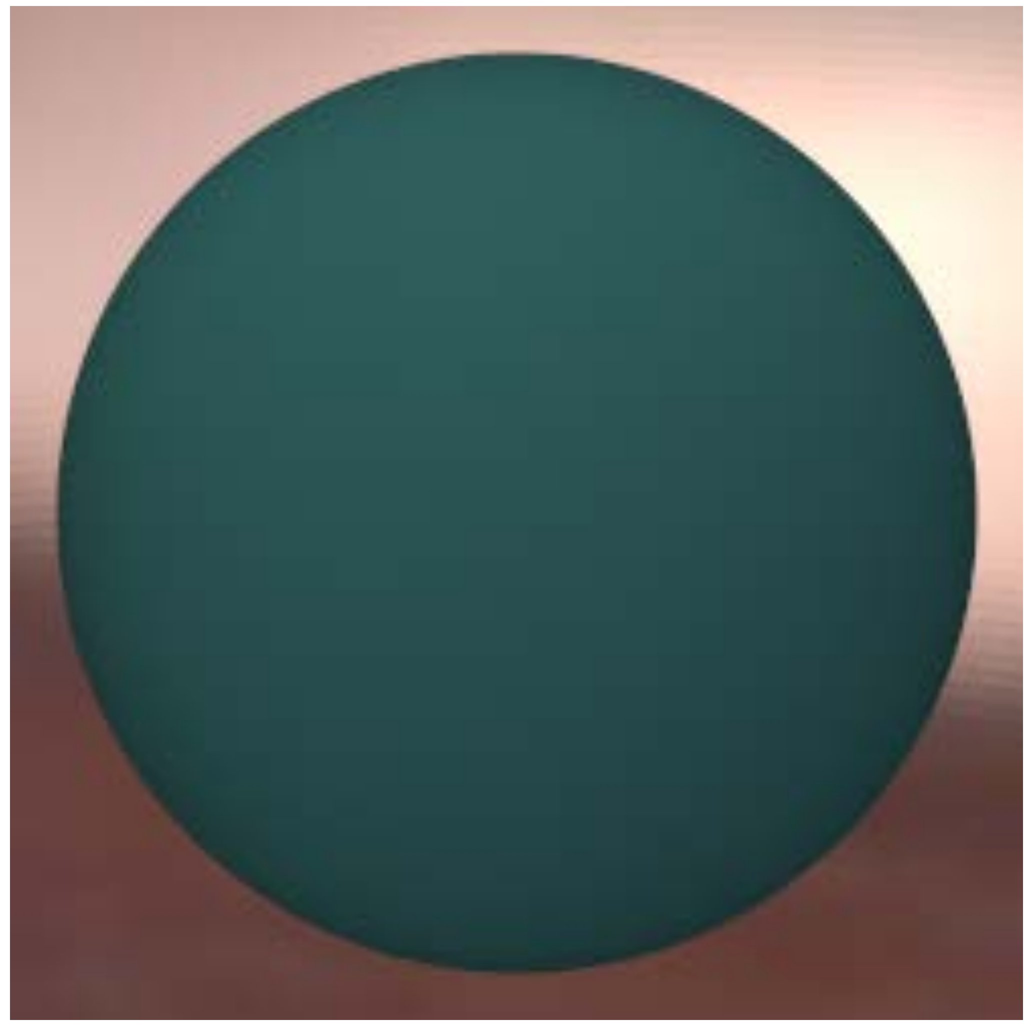
Colors

All unknown!

measured BRDF



measured diffuse



measured specular

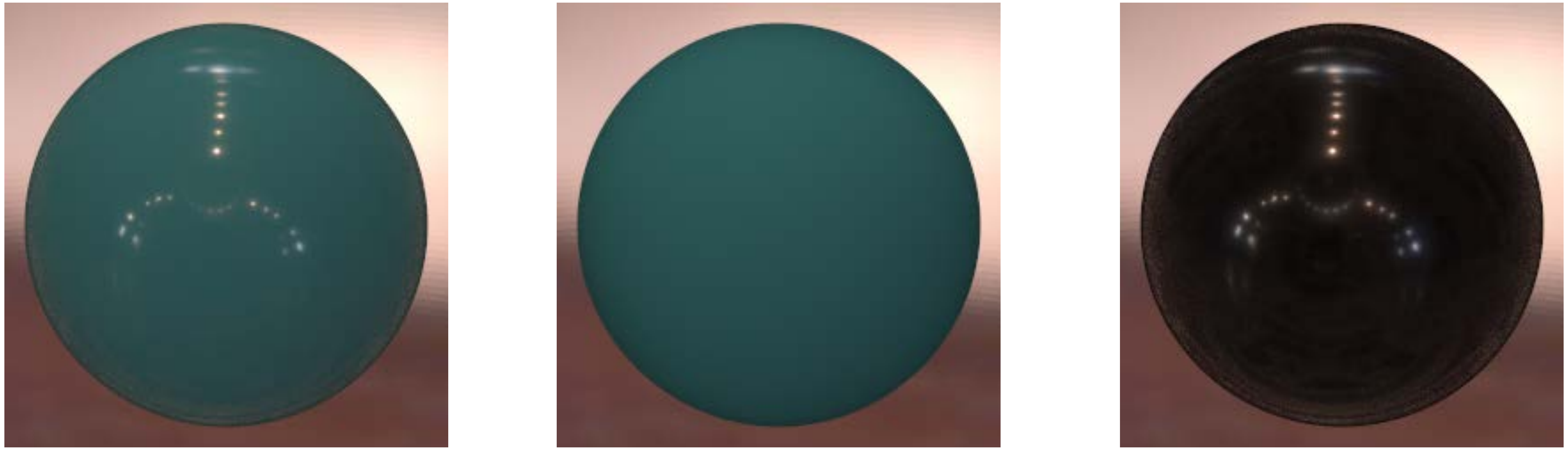
- ➤ Two main challenges:

1. No mathematical/strict definition on “diffuse” and “specular”.

1. DIFFUSE-SPECULAR SEPARATION

Goal: $\boldsymbol{\rho}[\boldsymbol{\omega_i}, \boldsymbol{\omega_o}, \lambda] \approx \rho_d[\boldsymbol{\omega_i}, \boldsymbol{\omega_o}] \cdot \mathbf{c}_d(\lambda) + \rho_s[\boldsymbol{\omega_i}, \boldsymbol{\omega_o}] \cdot \mathbf{c}_s(\lambda)$ Colors

All unknown!



➤ Two main challenges:

1. No mathematical/strict definition on “diffuse” and “specular”.
2. BRDF values have large variance. No simple and effective BRDF metric.

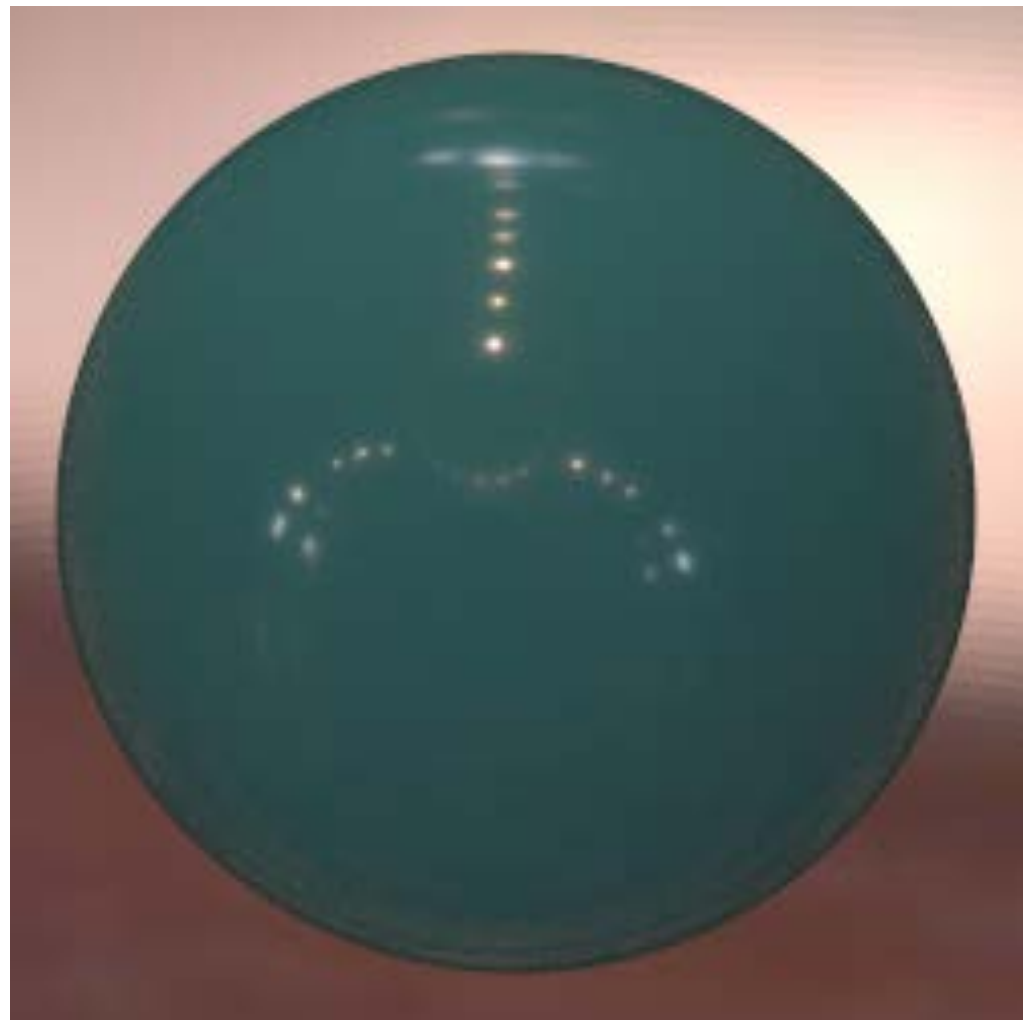
1. DIFFUSE-SPECULAR SEPARATION

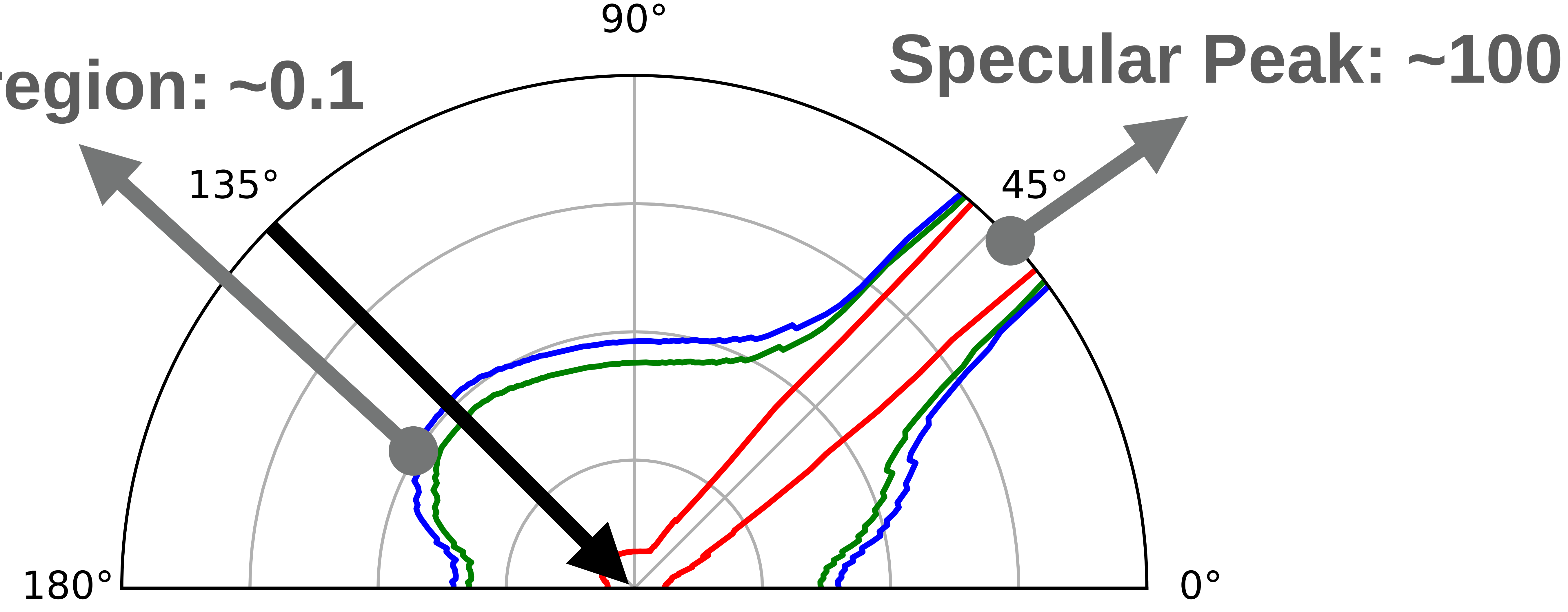
Goal: $$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx \rho_\mathrm{d}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{d}(\lambda) + \rho_\mathrm{s}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{s}(\lambda)$$

Colors

All unknown!

measured BRDF



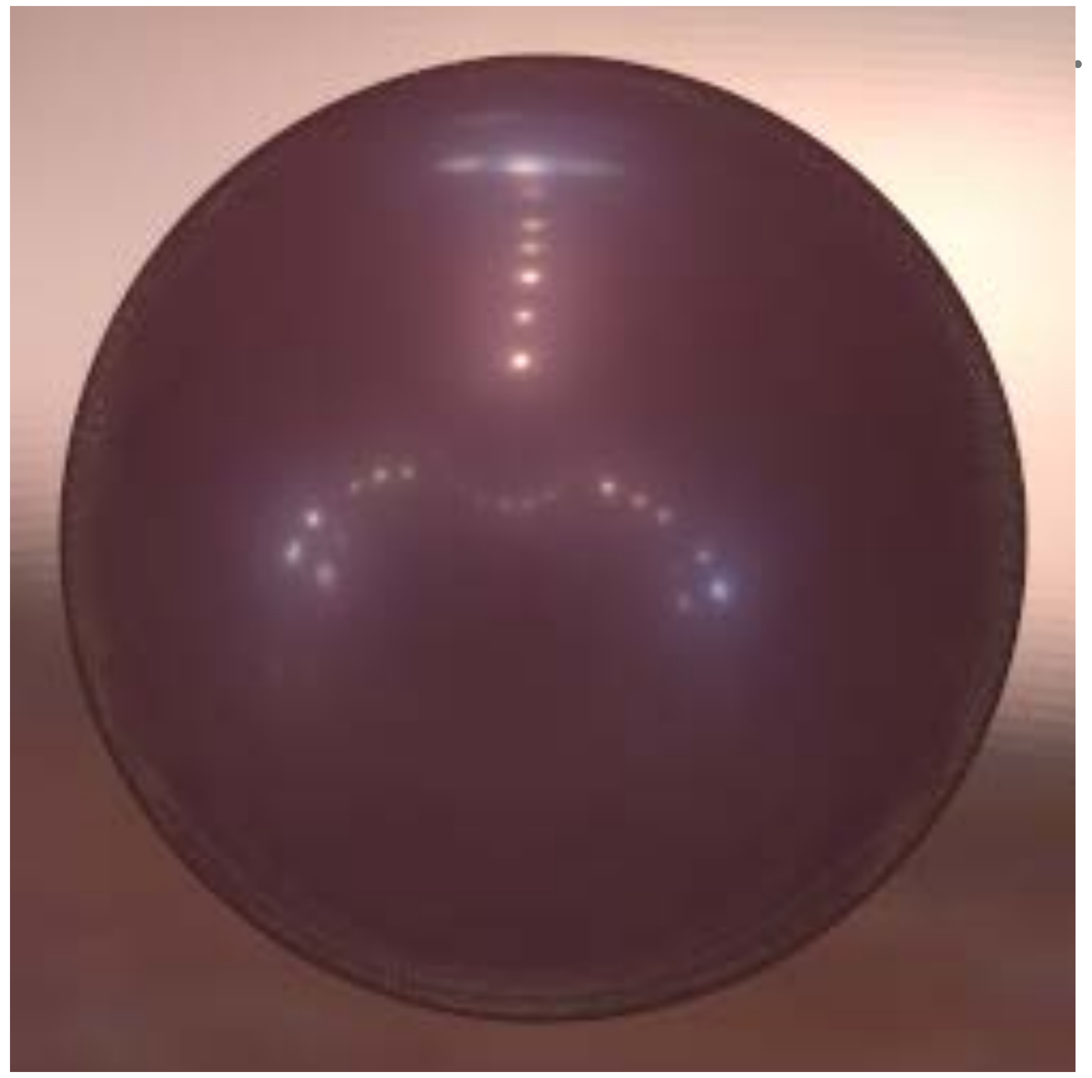


➤ Two main challenges:

1. No mathematical/strict definition on “diffuse” and “specular”.
2. BRDF values have large variance. No simple and effective BRDF metric.

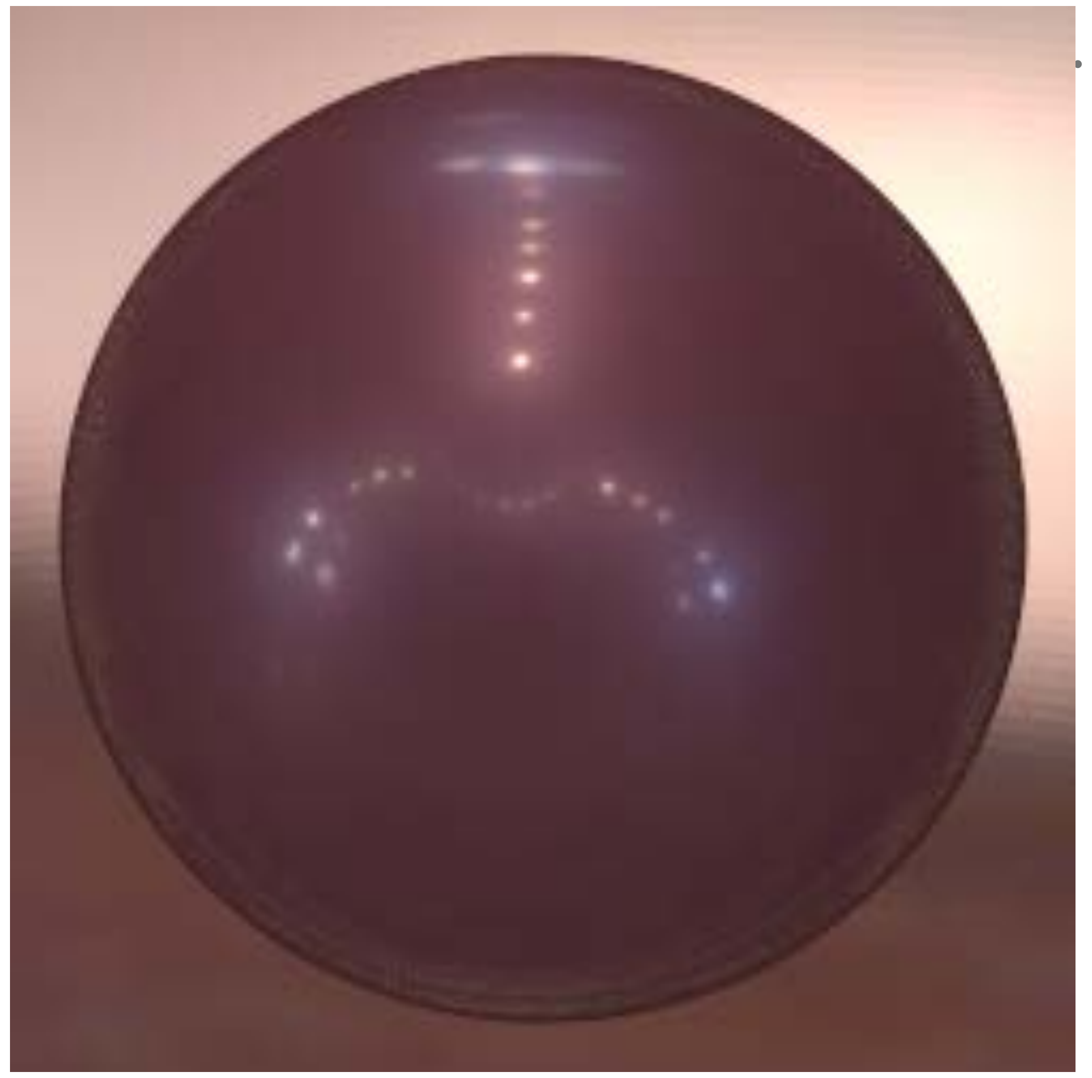
1. DIFFUSE-SPECULAR SEPARATION

1. DIFFUSE-SPECULAR SEPARATION

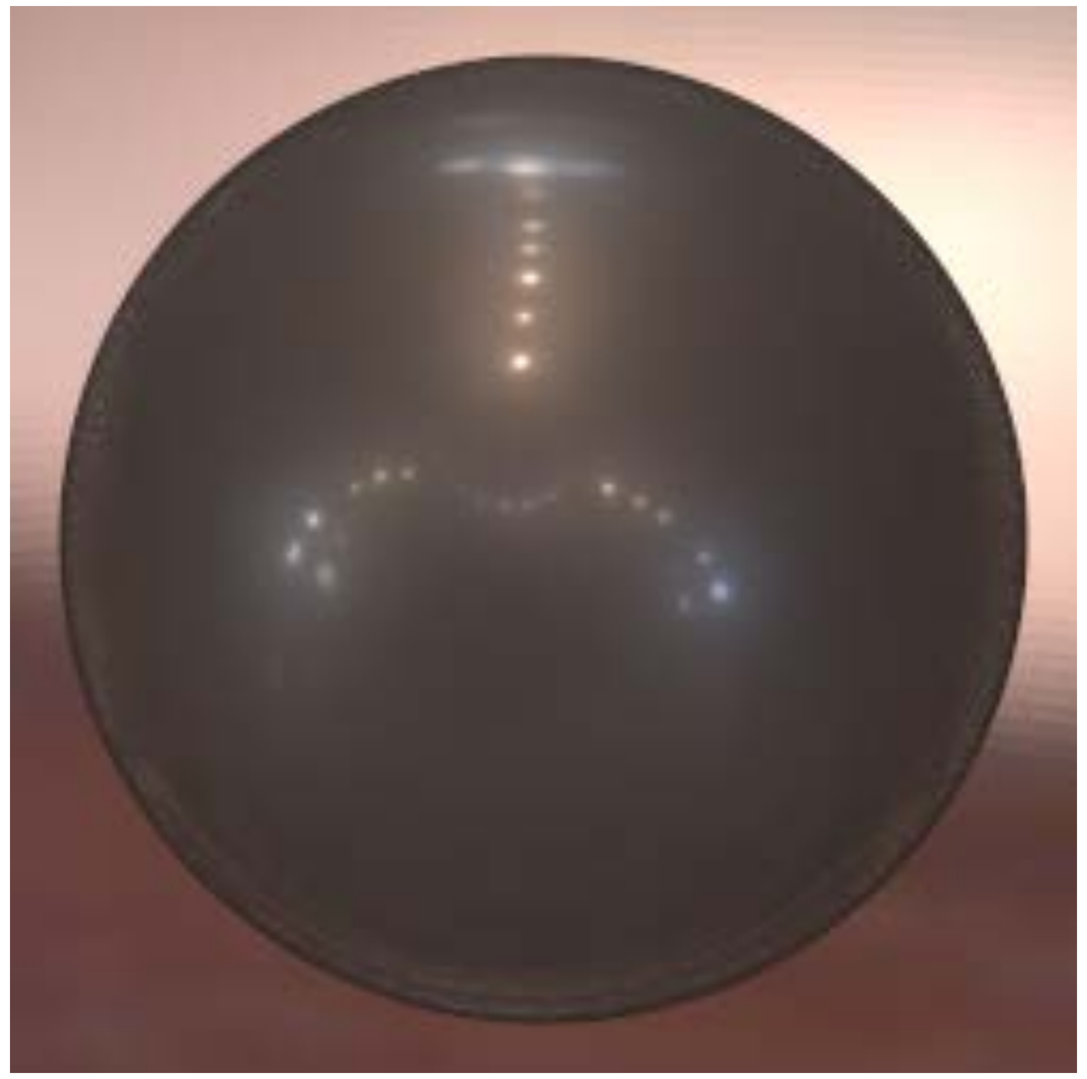


full BRDF

1. DIFFUSE-SPECULAR SEPARATION

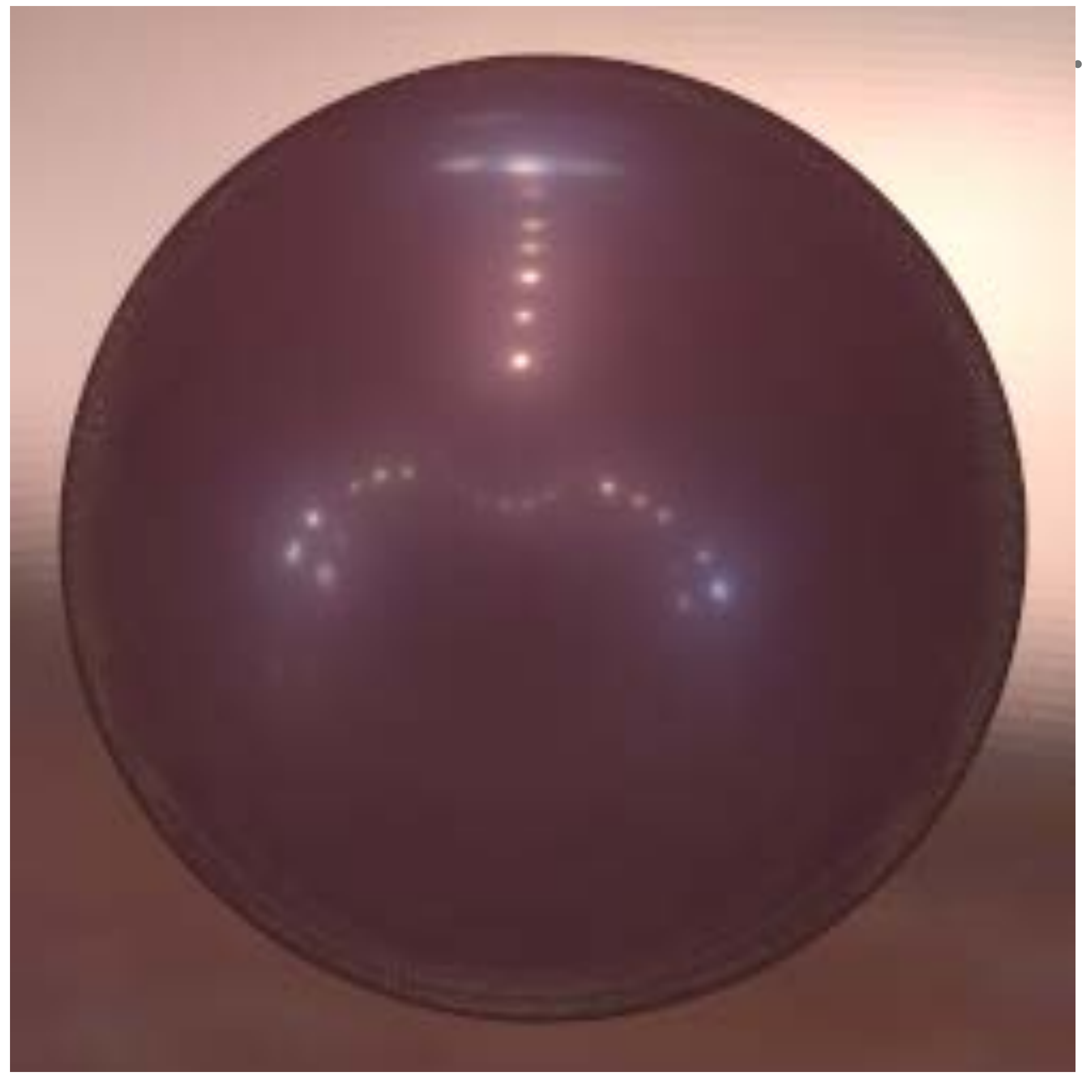


full BRDF



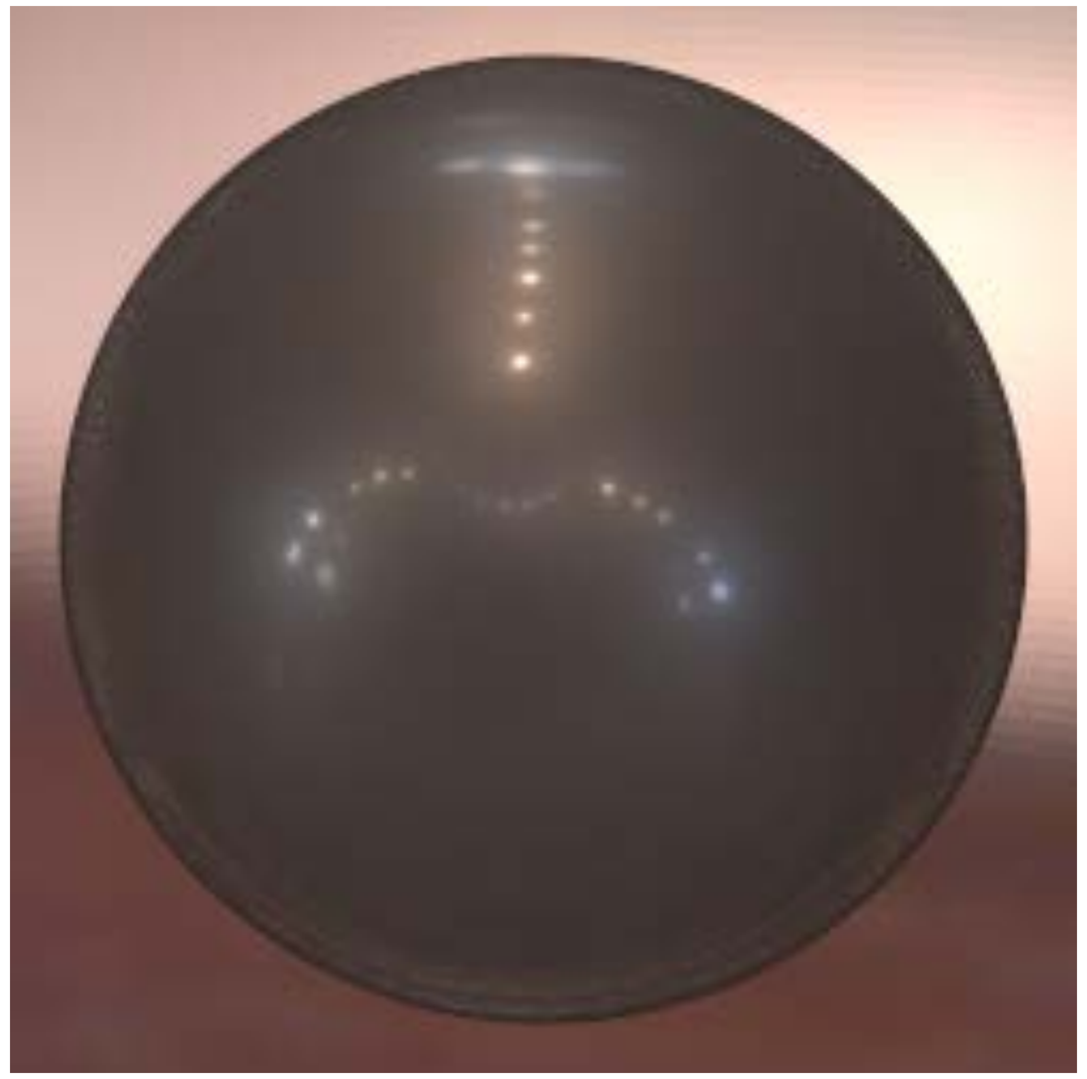
achromatic reflectance

1. DIFFUSE-SPECULAR SEPARATION

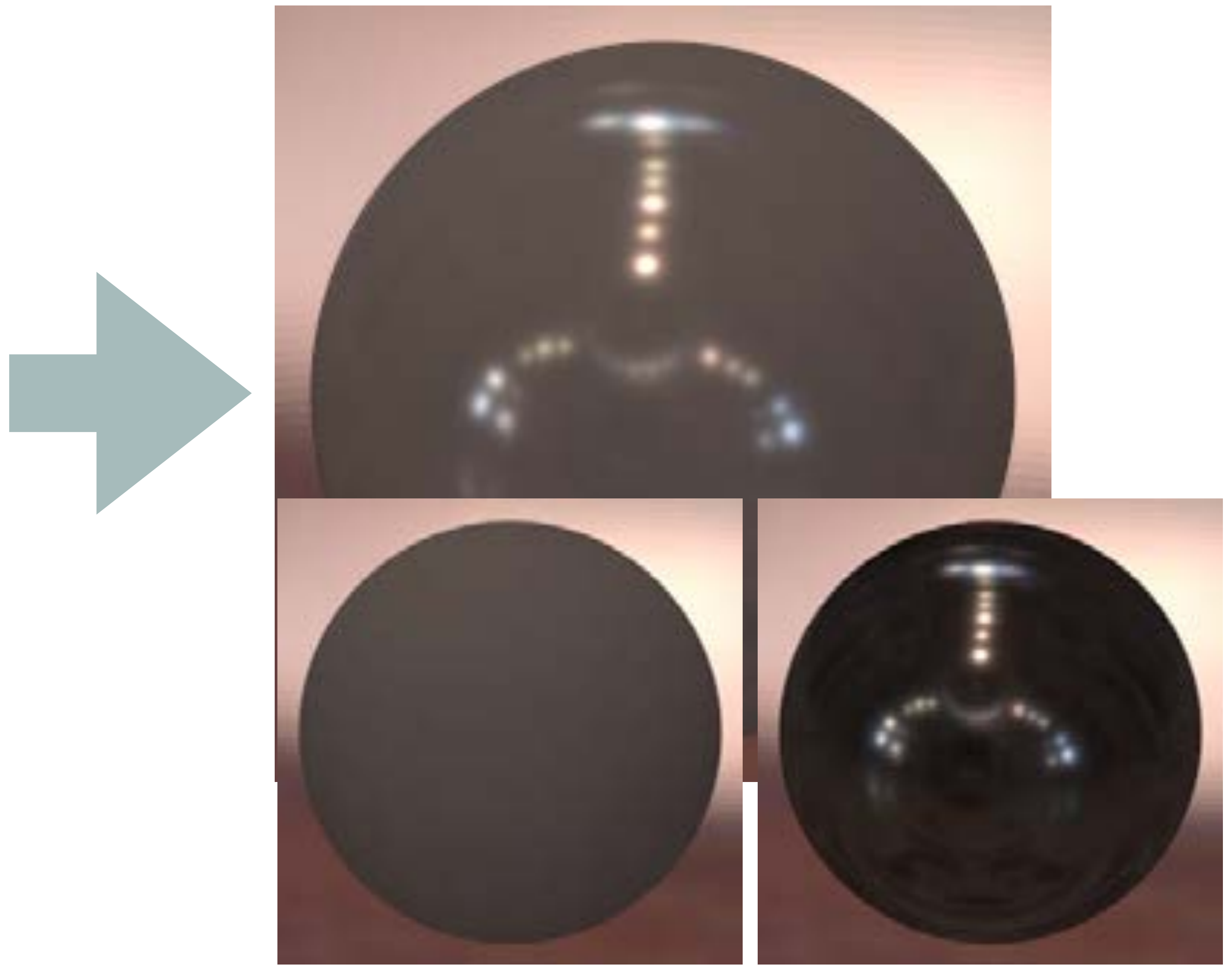


full BRDF

Step 1:
analytical
approximation

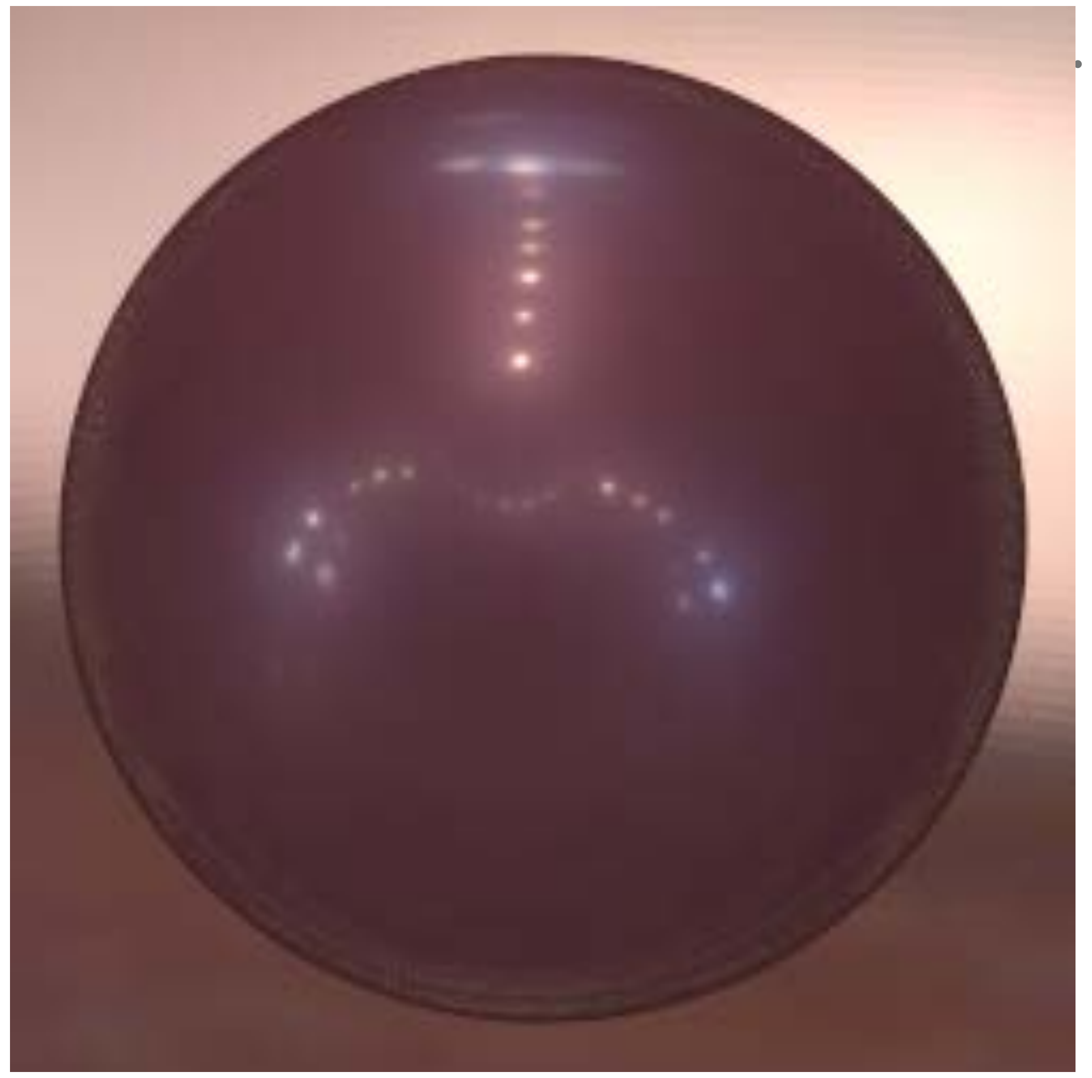


achromatic reflectance



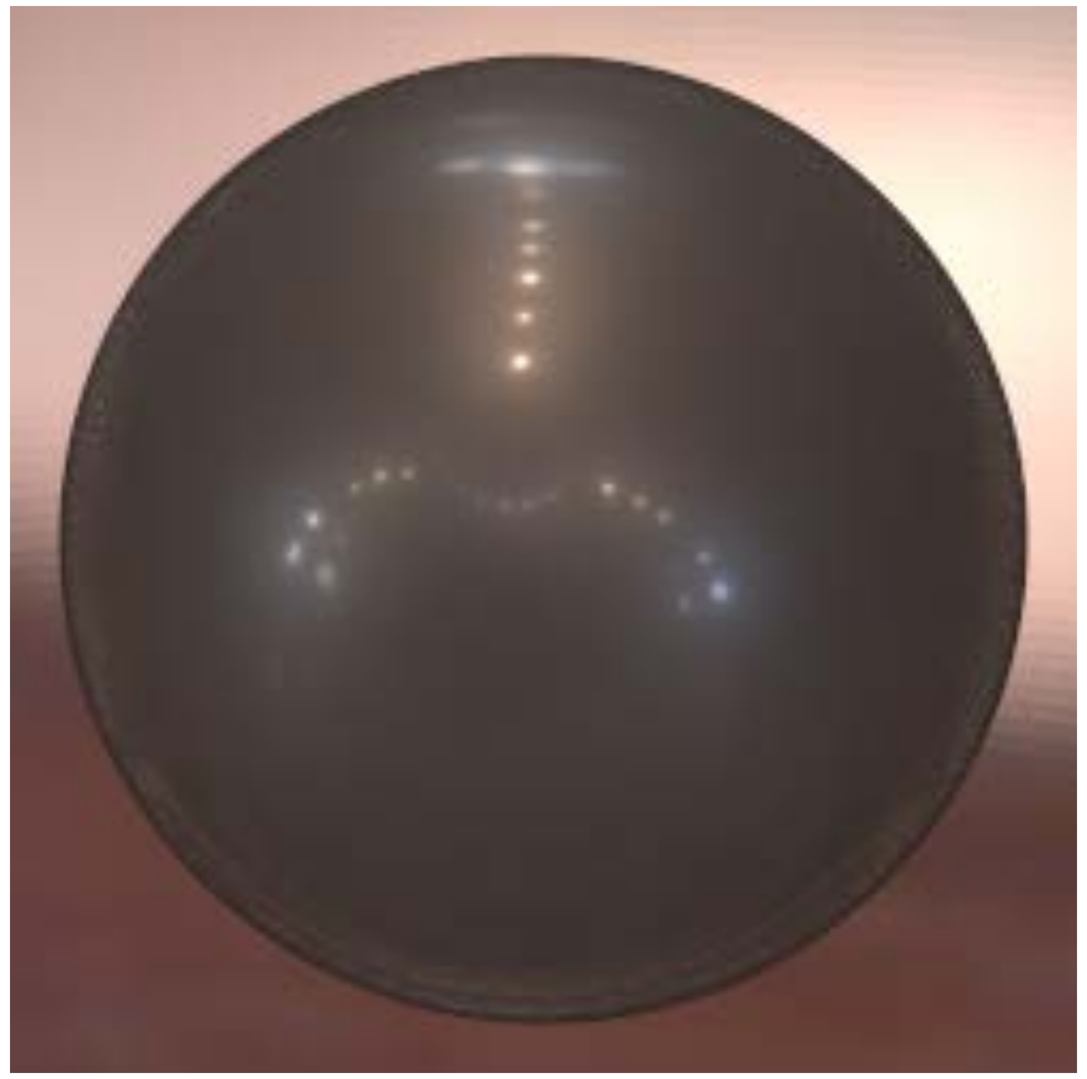
analytic BRDF

1. DIFFUSE-SPECULAR SEPARATION



full BRDF

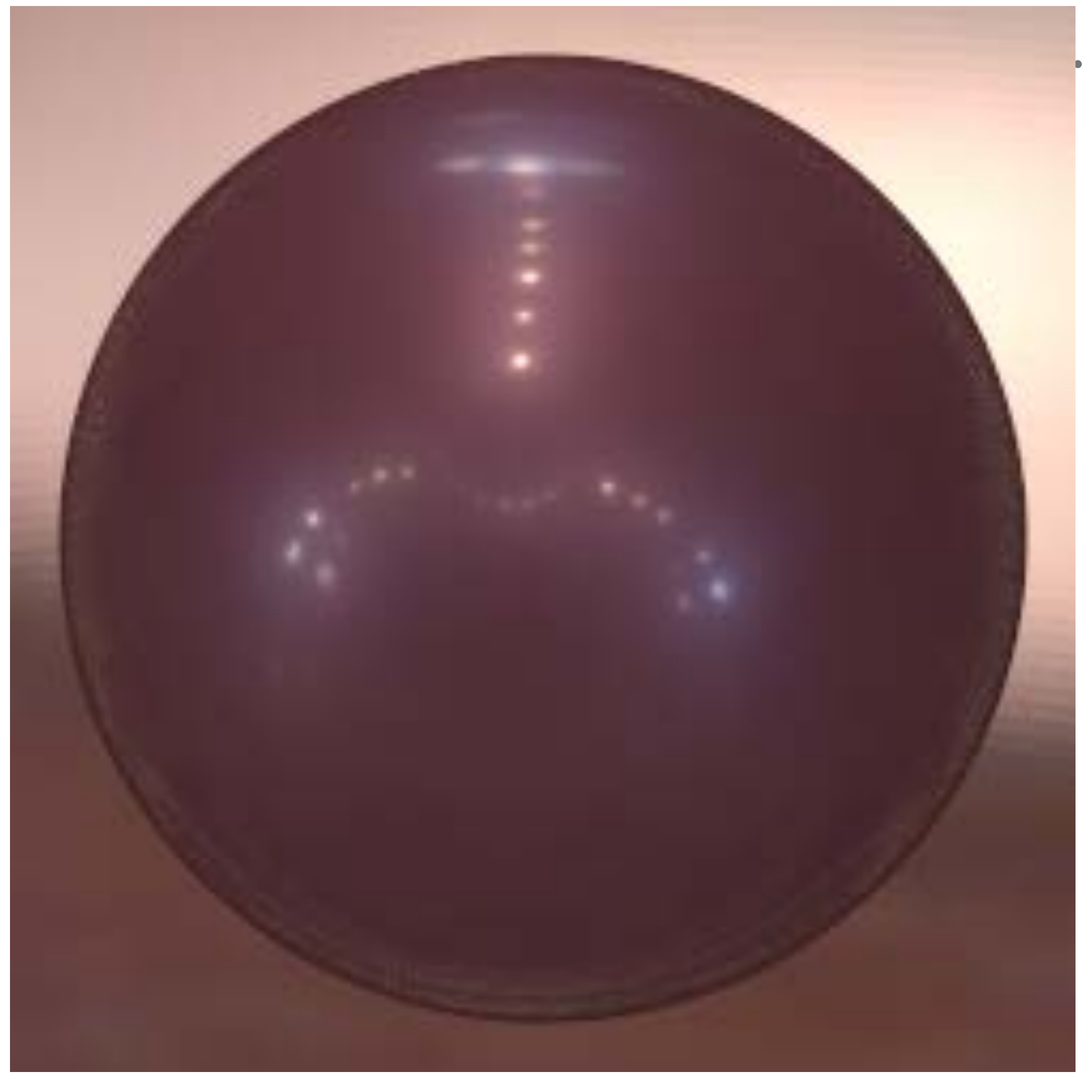
Step 1:
analytical
approximation



achromatic reflectance

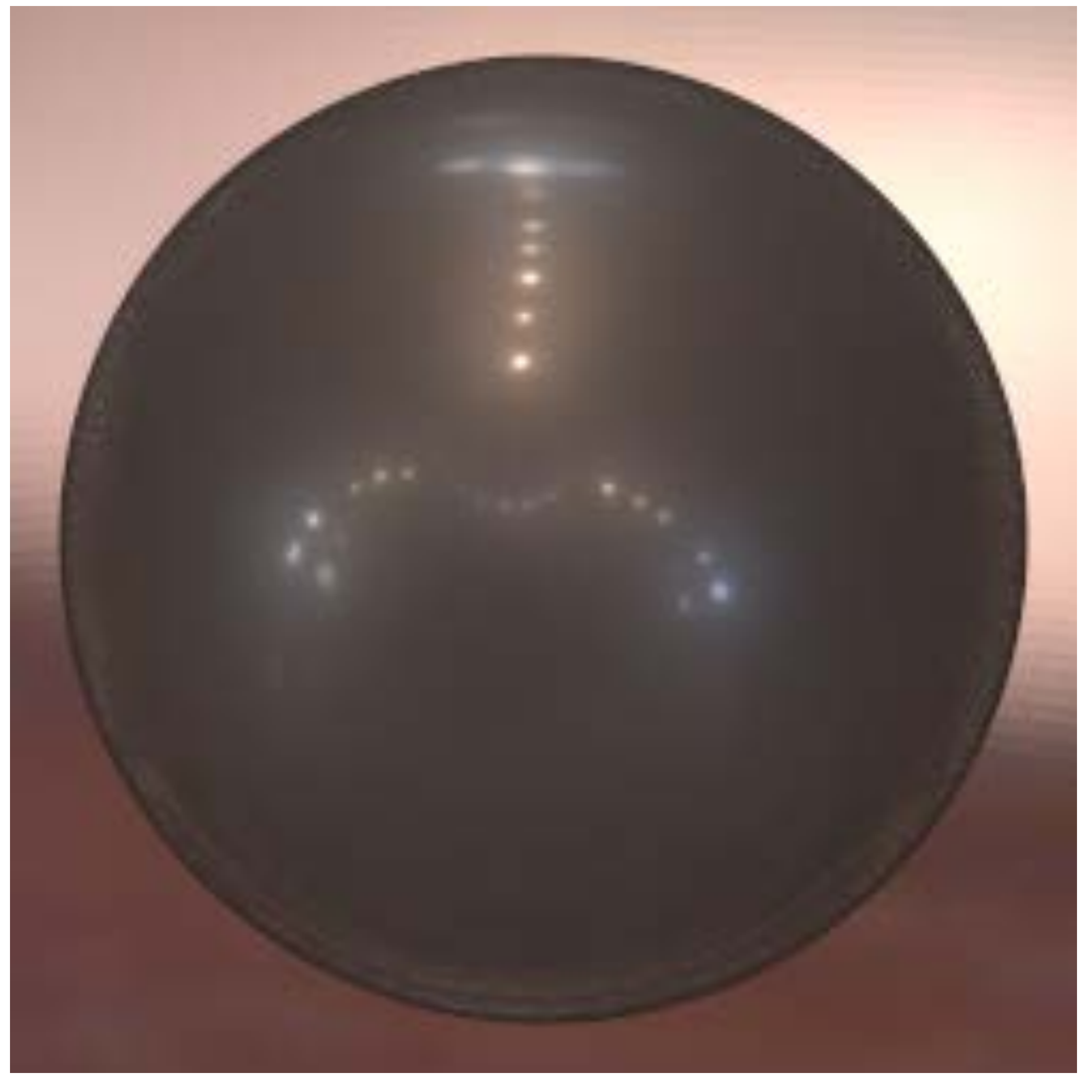
analytic BRDF

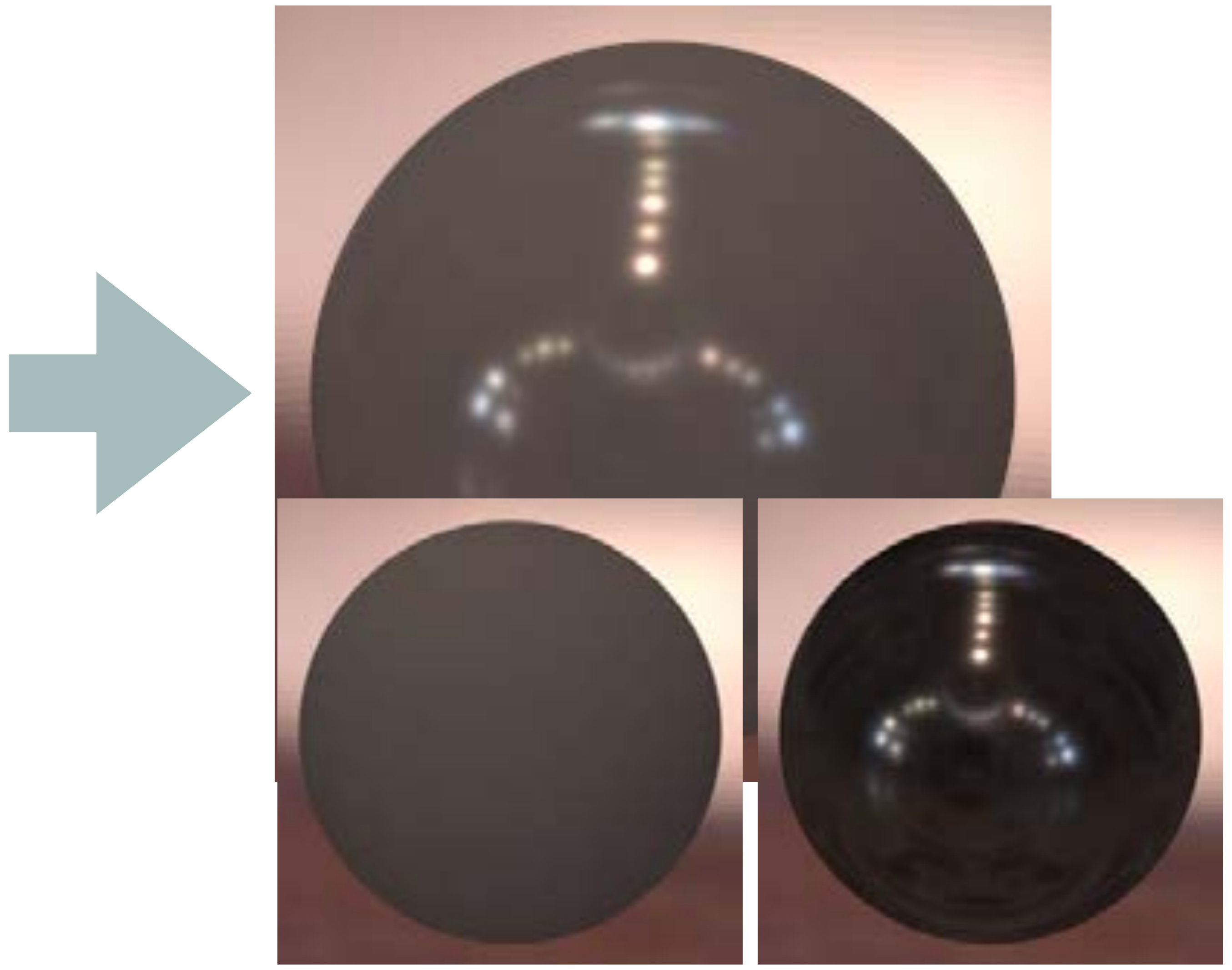
1. DIFFUSE-SPECULAR SEPARATION



full BRDF

Step 1:
analytical
approximation

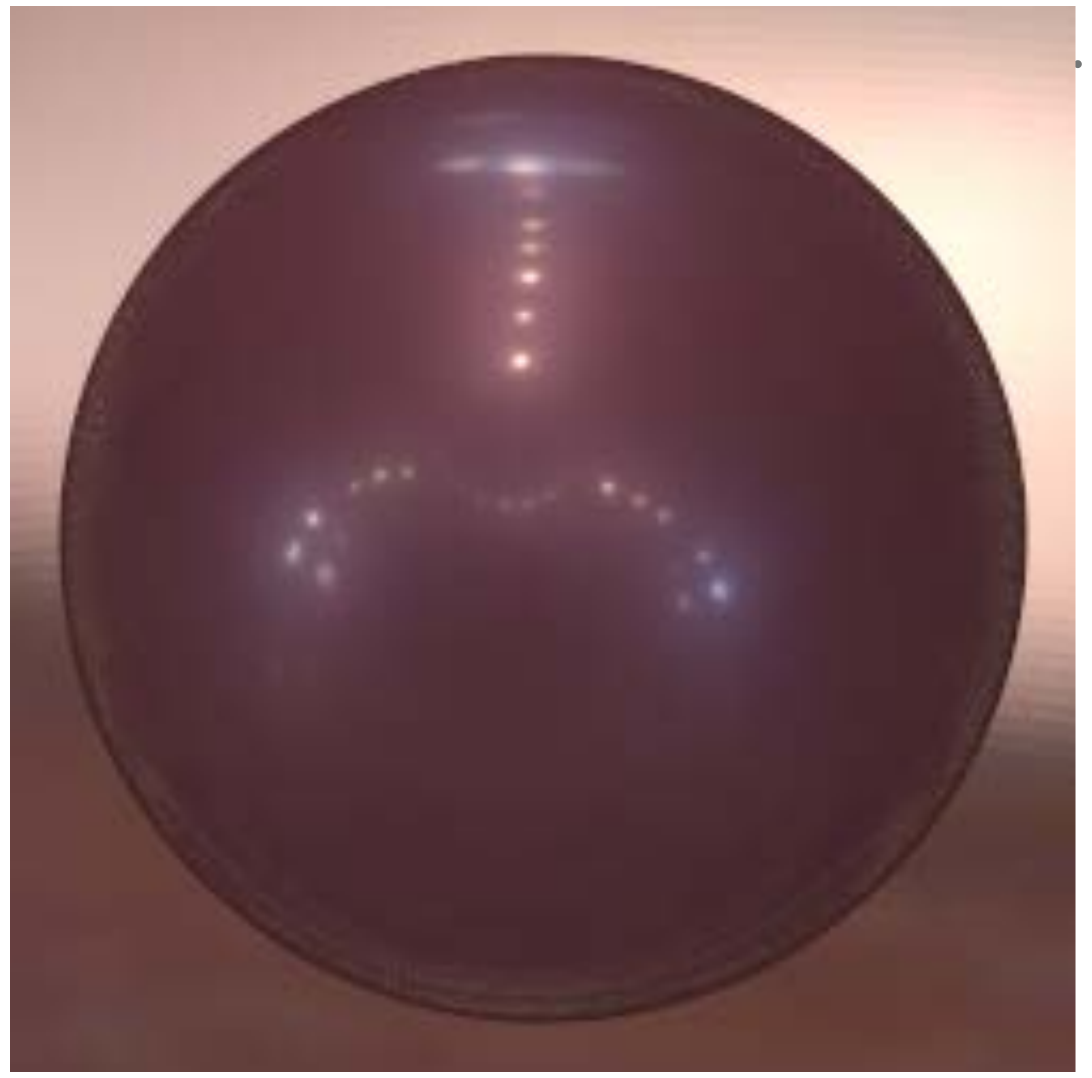




achromatic reflectance

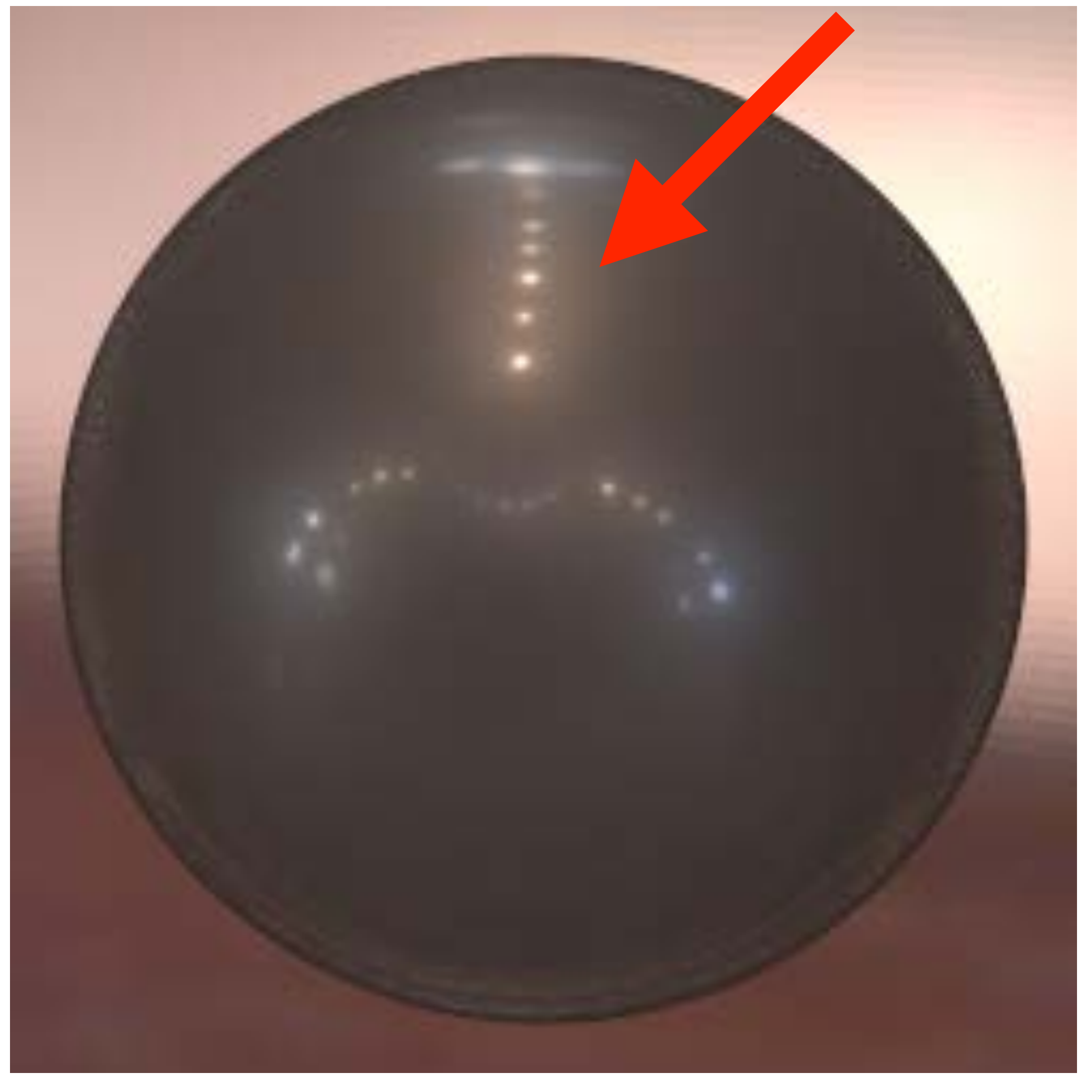
analytic BRDF

1. DIFFUSE-SPECULAR SEPARATION



full BRDF

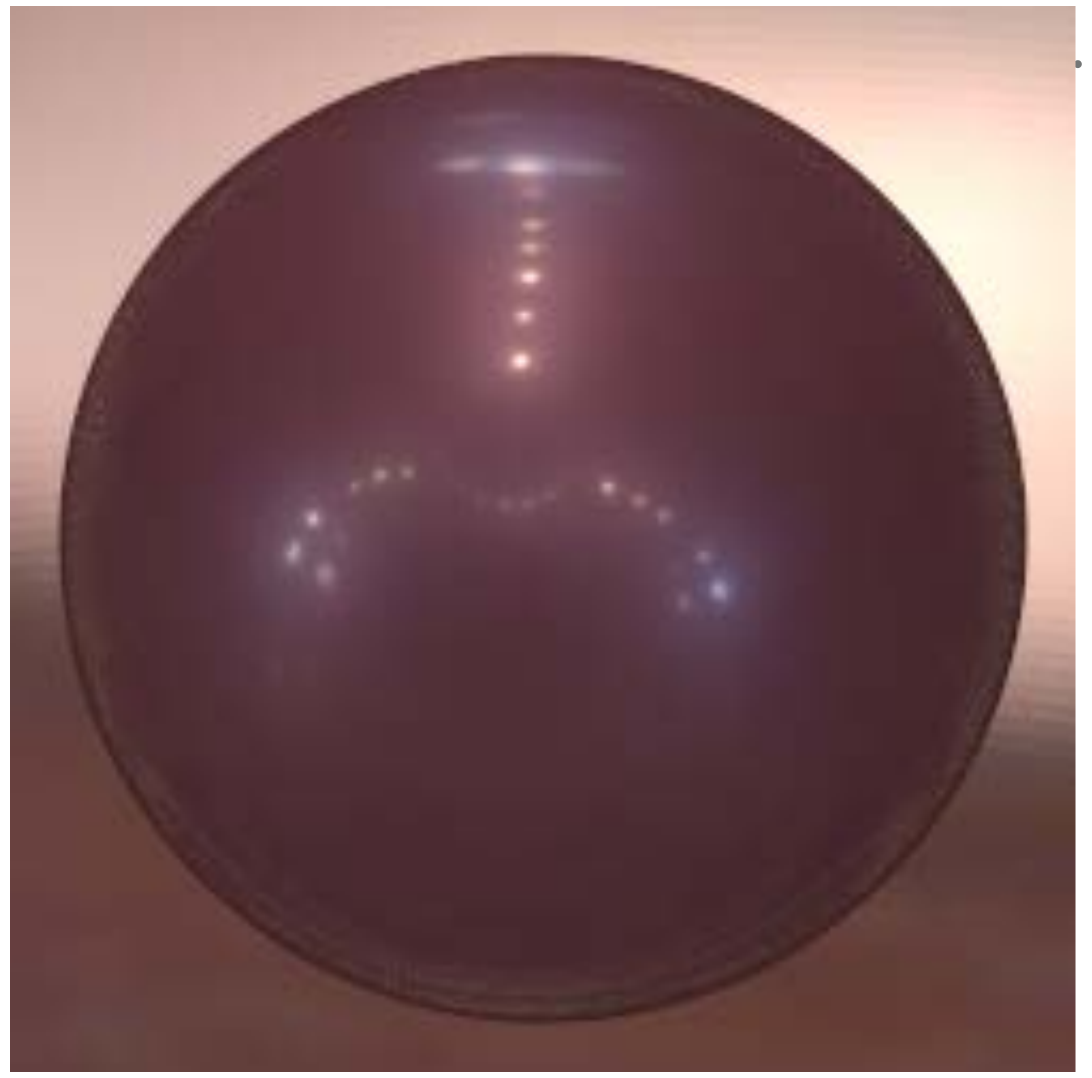
Step 1:
analytical
approximation



achromatic reflectance

analytic BRDF

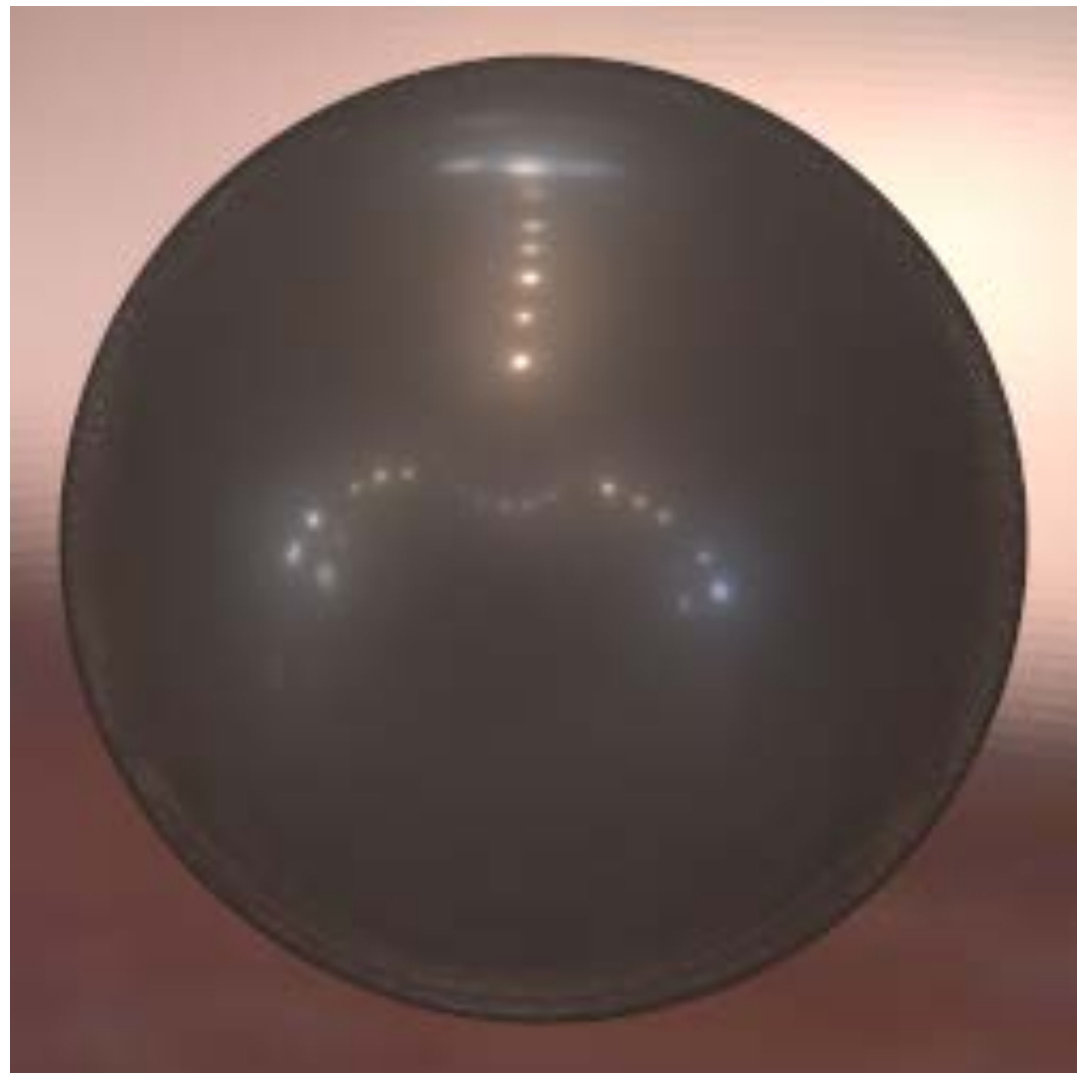
1. DIFFUSE-SPECULAR SEPARATION



full BRDF

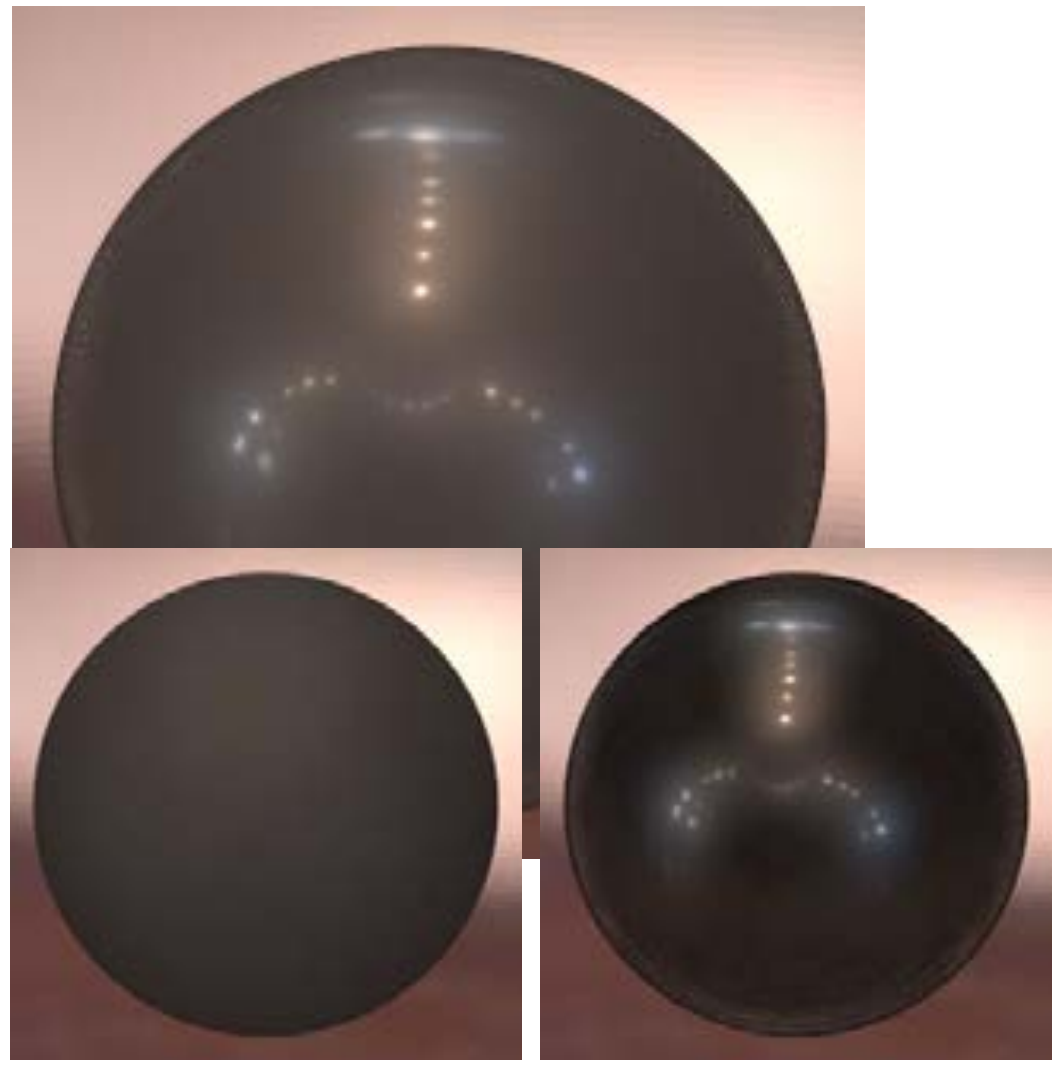
Step 1:
analytical
approximation

Step 2:
diffuse-specular
separation



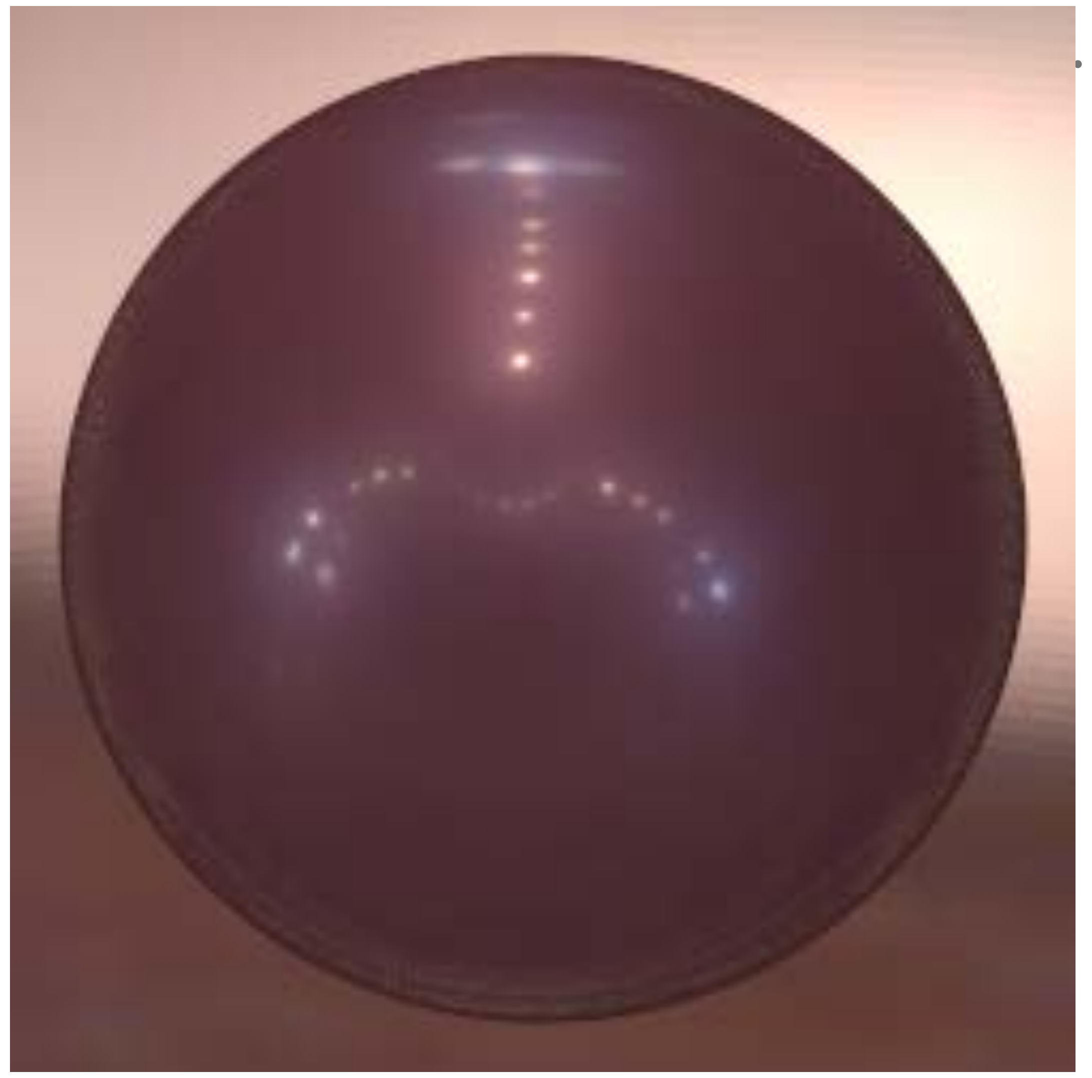
achromatic reflectance

analytic BRDF



measured BRDF

1. DIFFUSE-SPECULAR SEPARATION

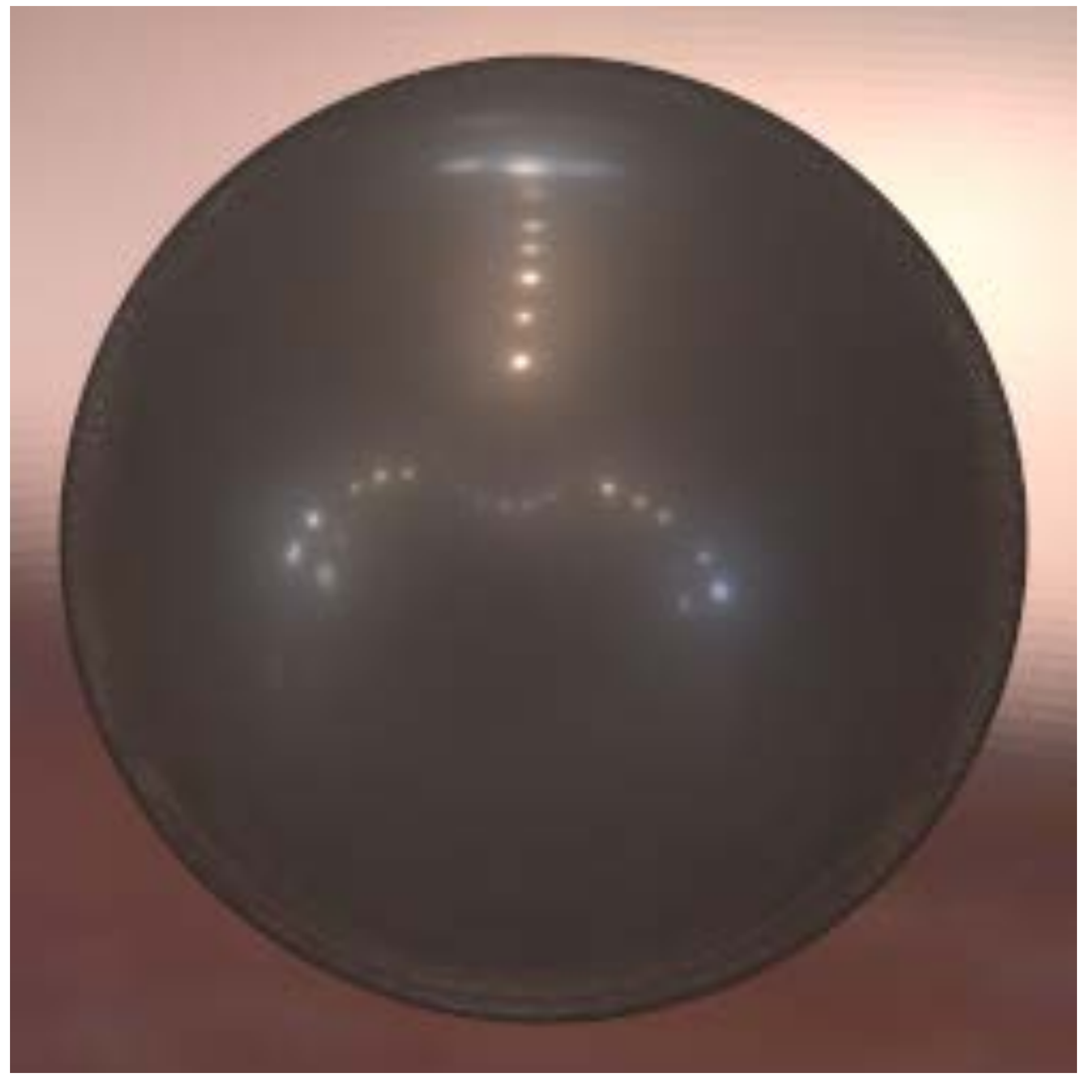


full BRDF

Step 1:
analytical
approximation

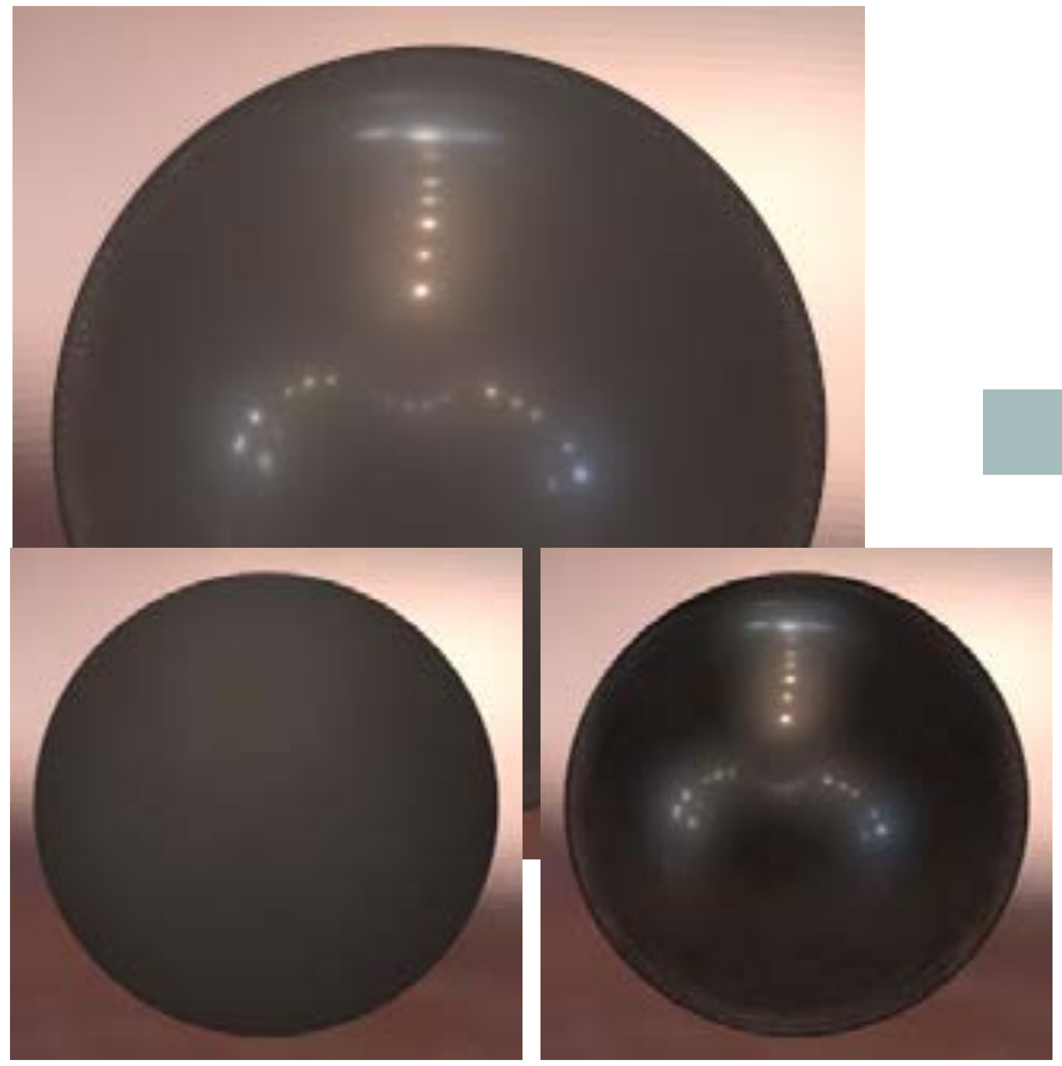
Step 2:
diffuse-specular
separation

Step 3:
color restoration

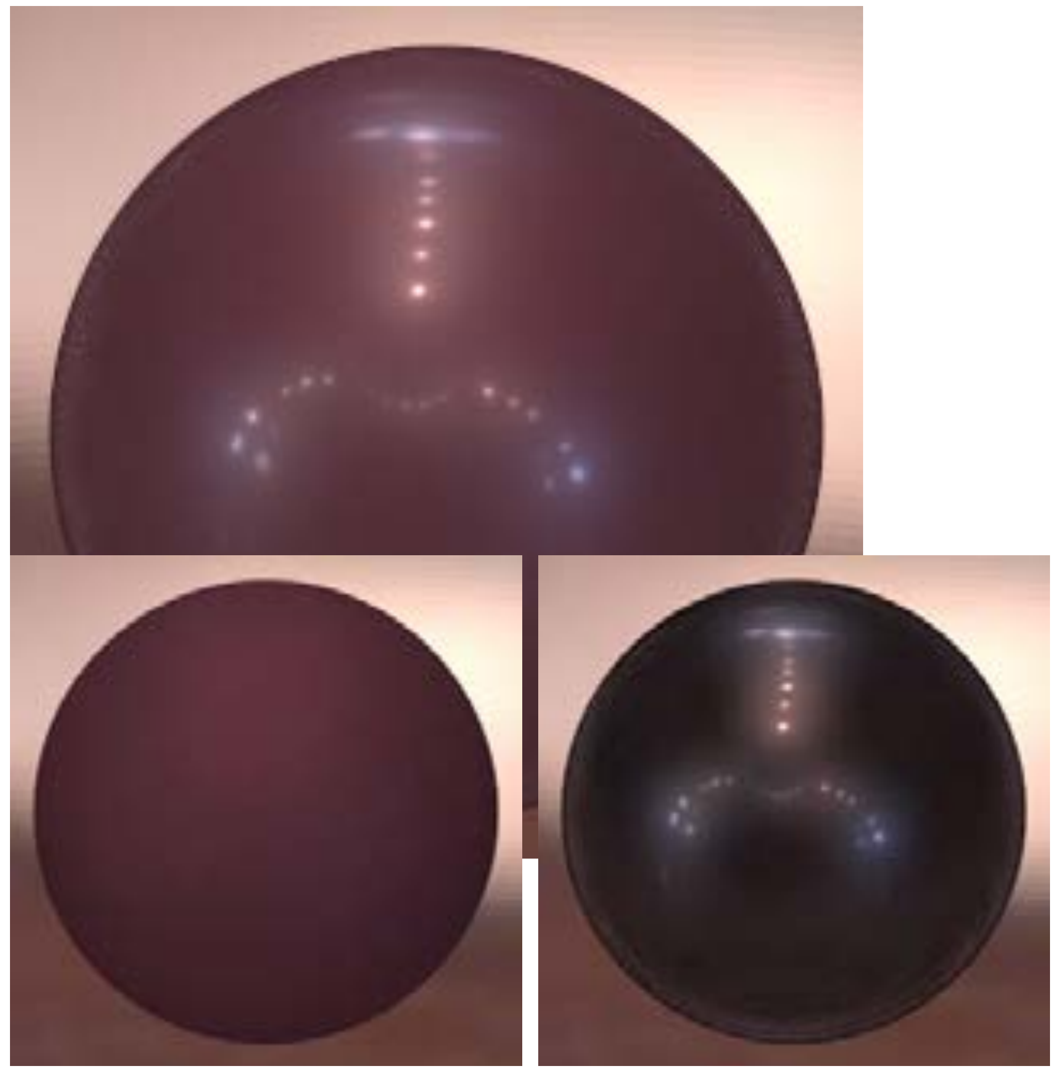


achromatic reflectance

analytic BRDF

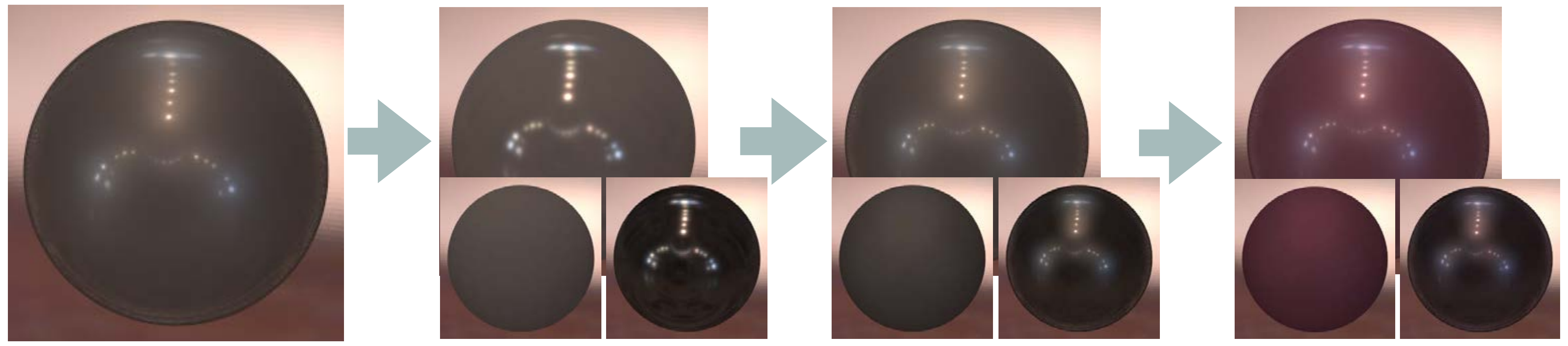


measured BRDF

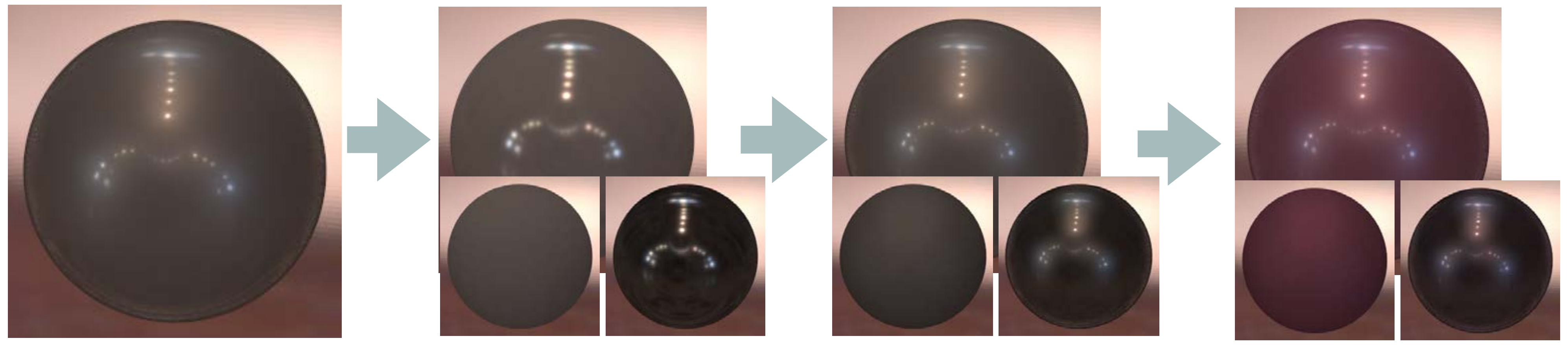


measured BRDF

1. DIFFUSE-SPECULAR SEPARATION

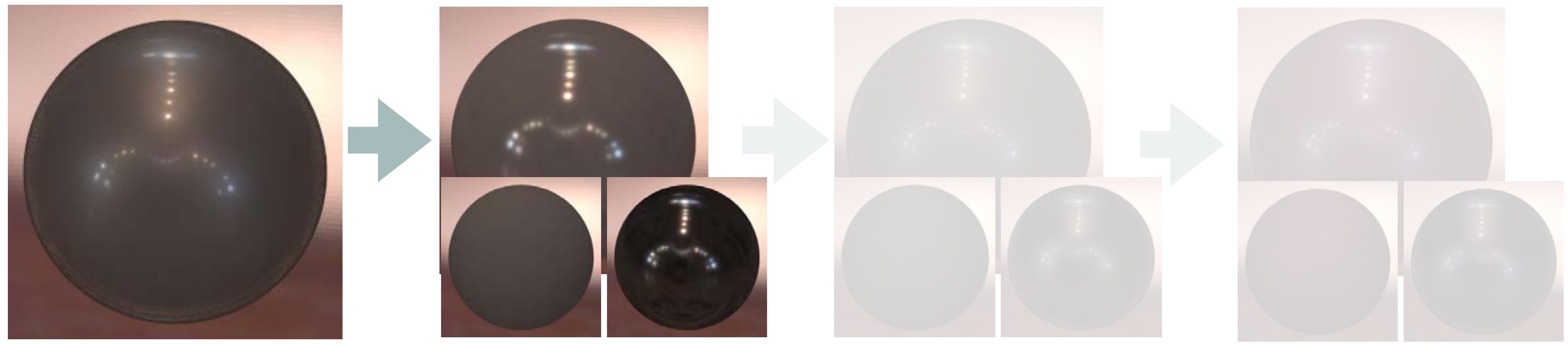


1. DIFFUSE-SPECULAR SEPARATION



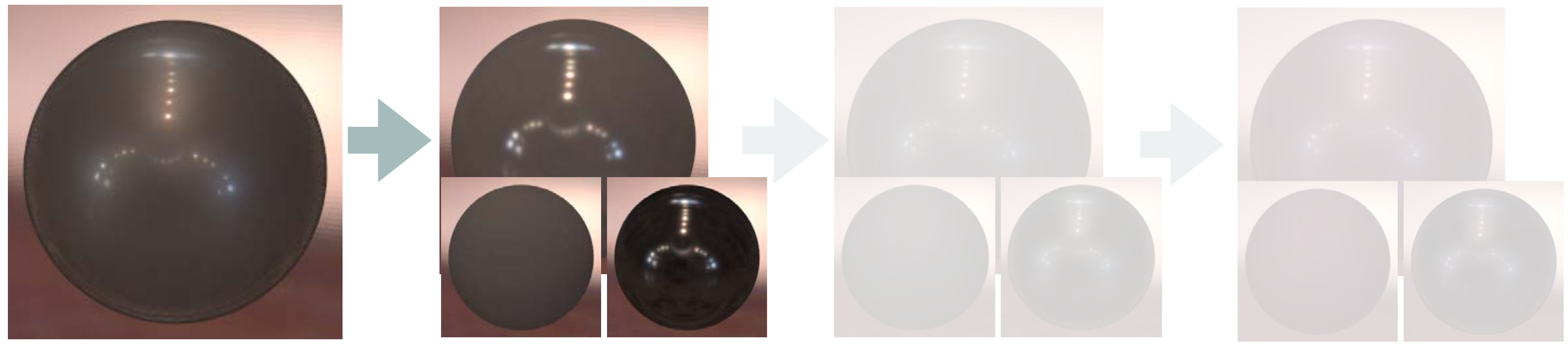
1. DIFFUSE-SPECULAR SEPARATION

➤ Step 1: analytical approximation



1. DIFFUSE-SPECULAR SEPARATION

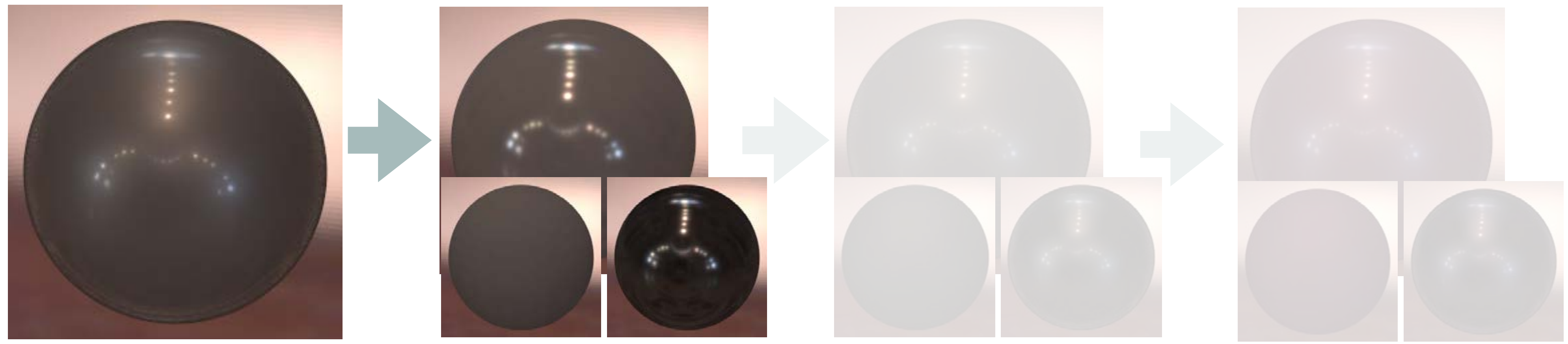
- Step 1: analytical approximation



$$\min_{\alpha_d, \alpha_s} d_1(\bar{\rho}[\omega_i, \omega_o], \rho_d(\alpha_d) + \rho_s(\alpha_s))$$

1. DIFFUSE-SPECULAR SEPARATION

- Step 1: analytical approximation

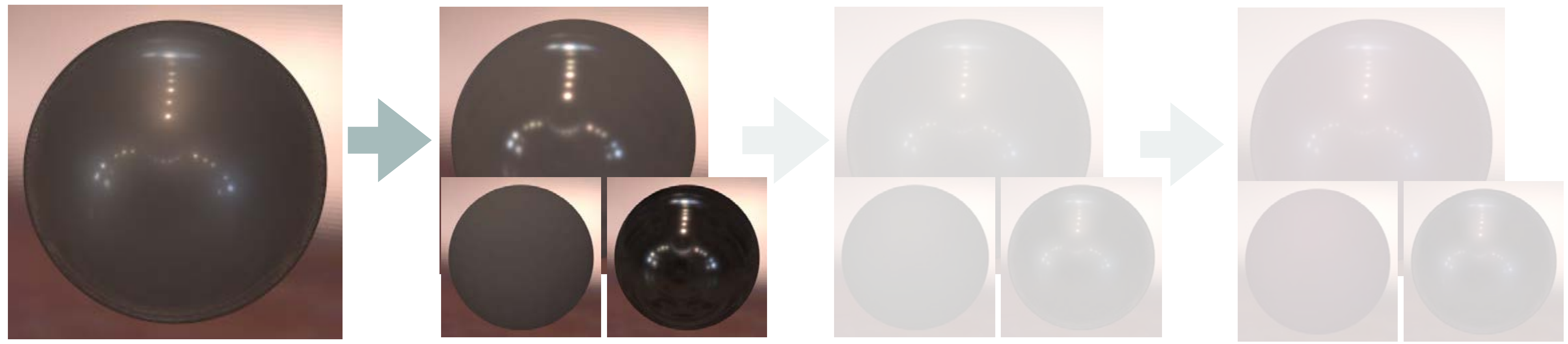


measured BRDF averaged across color

$$\min_{\alpha_d, \alpha_s} d_1(\bar{\rho}[\omega_i, \omega_o], \rho_d(\alpha_d) + \rho_s(\alpha_s))$$

1. DIFFUSE-SPECULAR SEPARATION

➤ Step 1: analytical approximation



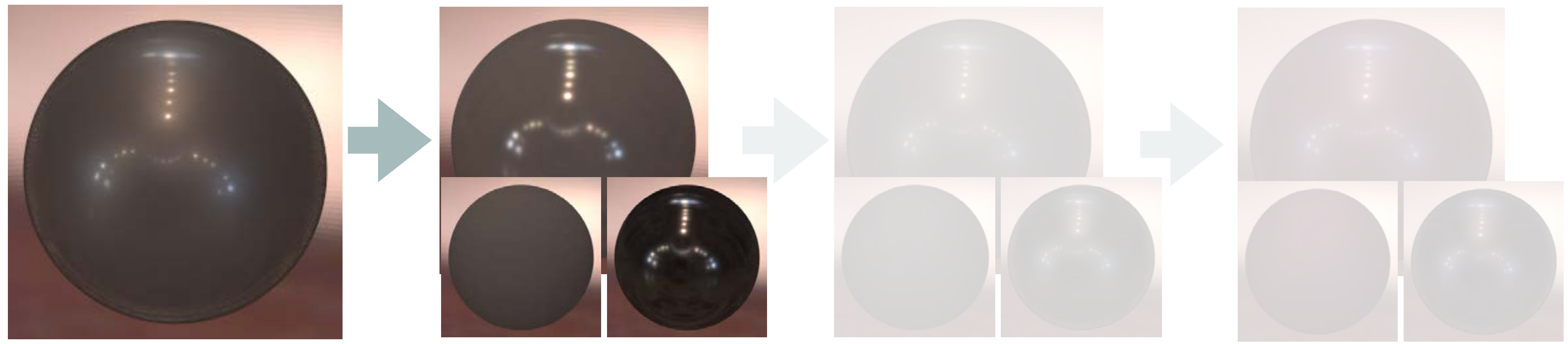
measured BRDF averaged across color

analytic BRDF

$$\min_{\alpha_d, \alpha_s} d_1(\bar{\rho}[\omega_i, \omega_o], \rho_d(\alpha_d) + \rho_s(\alpha_s))$$

1. DIFFUSE-SPECULAR SEPARATION

➤ Step 1: analytical approximation



measured BRDF averaged across color

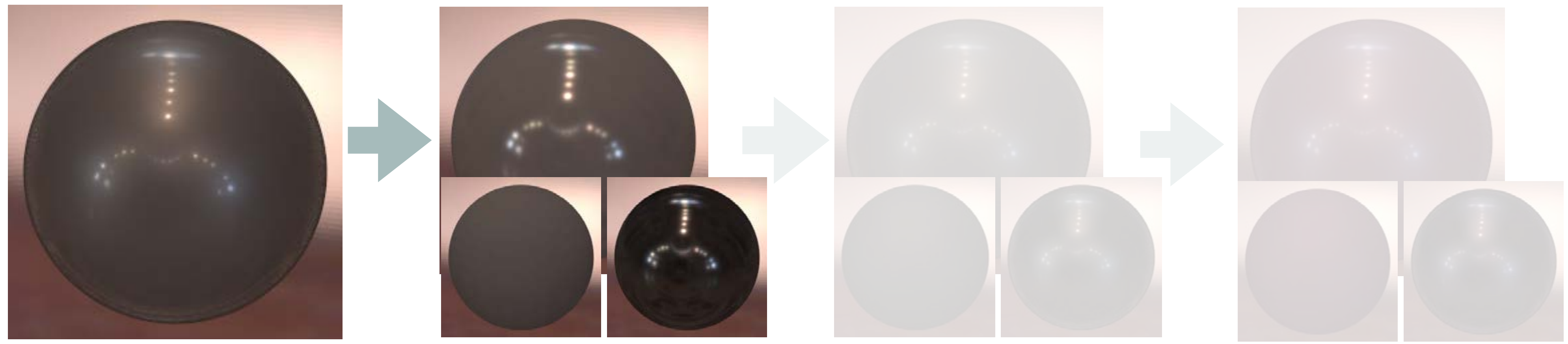
BRDF metric

analytic BRDF

$$\min_{\alpha_d,\alpha_s} d_1(\bar{\rho}[\omega_i,\omega_o],\rho_d(\alpha_d)+\rho_s(\alpha_s))$$

1. DIFFUSE-SPECULAR SEPARATION

➤ Step 1: analytical approximation

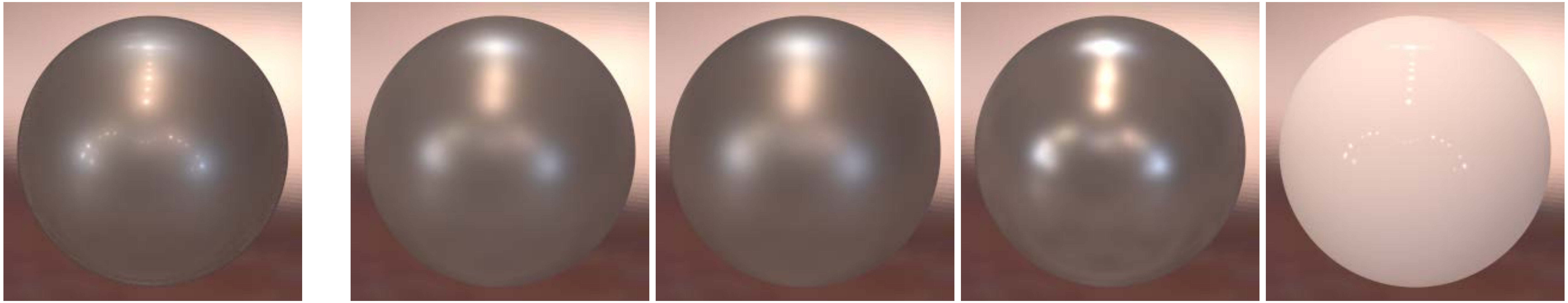


measured BRDF averaged across color

BRDF metric

analytic BRDF

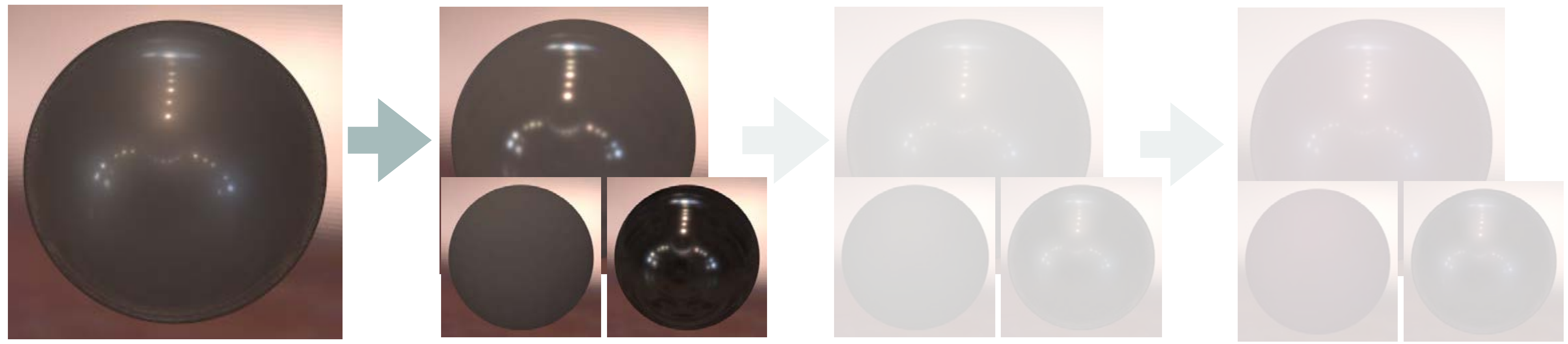
$$\min_{\alpha_d, \alpha_s} d_1(\bar{\rho}[\omega_i, \omega_o], \rho_d(\alpha_d) + \rho_s(\alpha_s))$$



two-layer-silver | cubic-root | log1 | log2 | weighted square

1. DIFFUSE-SPECULAR SEPARATION

- Step 1: analytical approximation

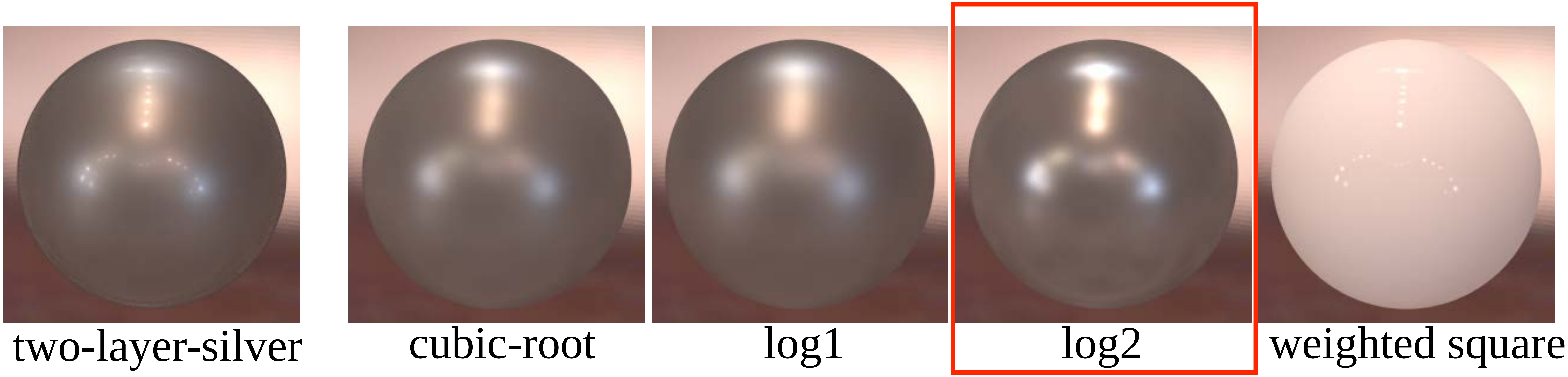


BRDF metric

measured BRDF averaged across color

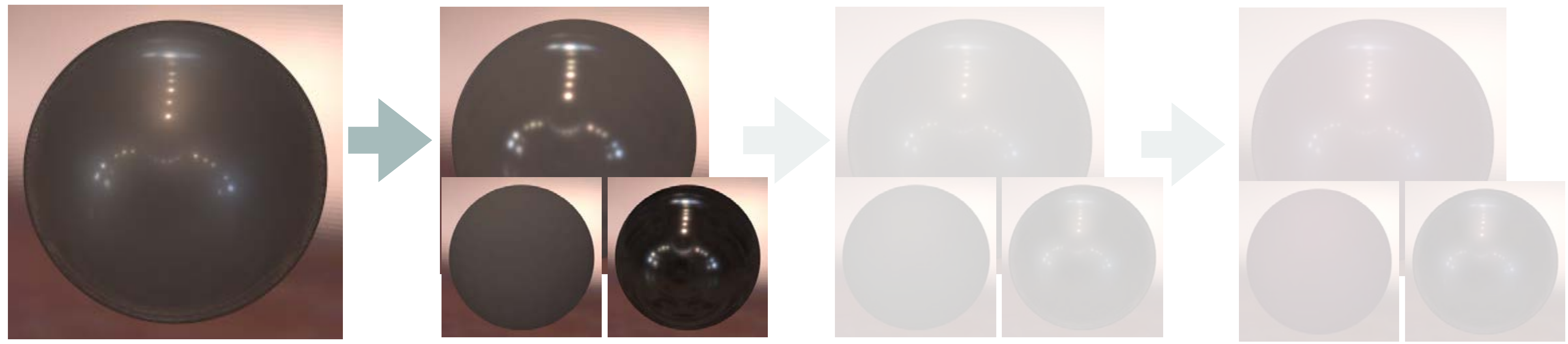
analytic BRDF

$$\min_{\alpha_d,\alpha_s} d_1(\bar{\rho}[\omega_i,\omega_o], \rho_d(\alpha_d) + \rho_s(\alpha_s))$$



1. DIFFUSE-SPECULAR SEPARATION

- Step 1: analytical approximation
- Learn the concept of “diffuse” and “specular” from analytical model

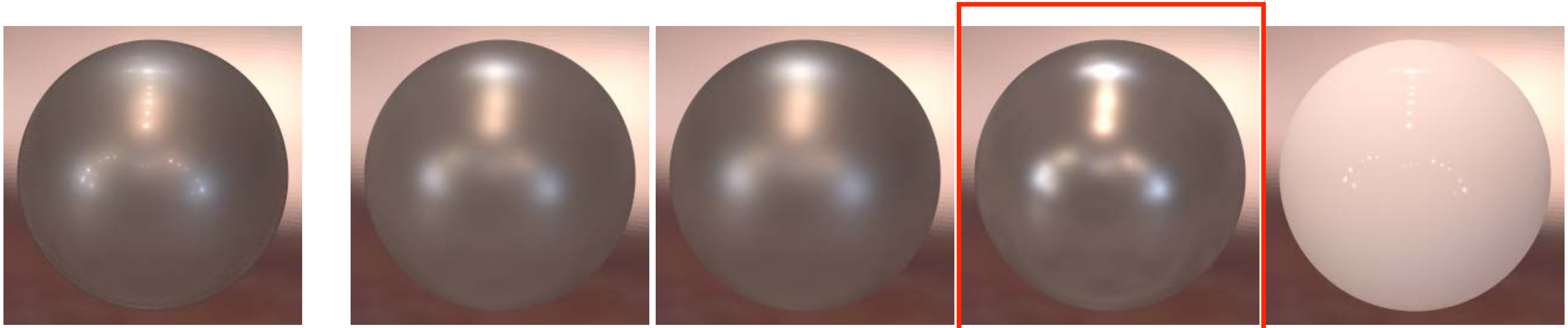


measured BRDF averaged across color

BRDF metric

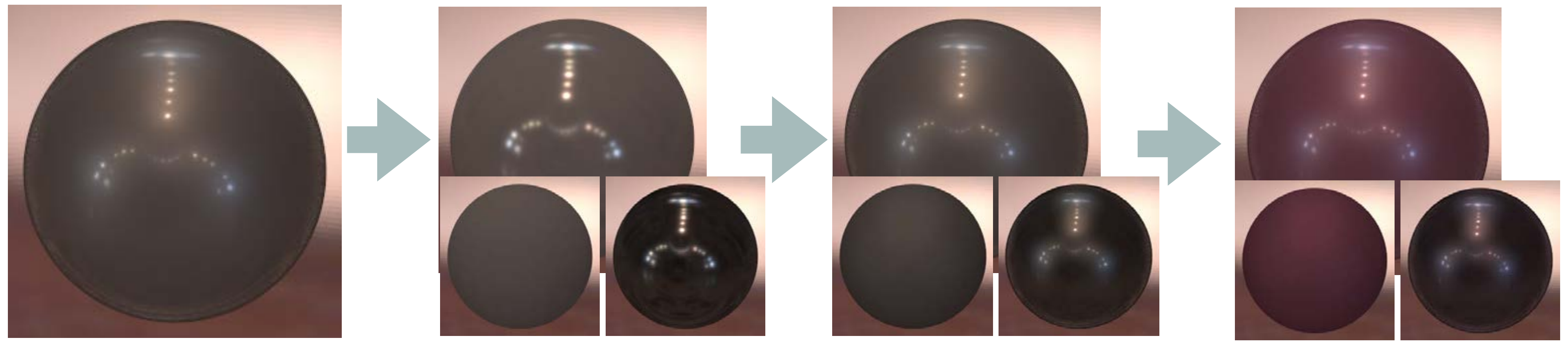
analytic BRDF

$$\min_{\alpha_d,\alpha_s} d_1(\bar{\rho}[\omega_i,\omega_o], \rho_d(\alpha_d) + \rho_s(\alpha_s))$$



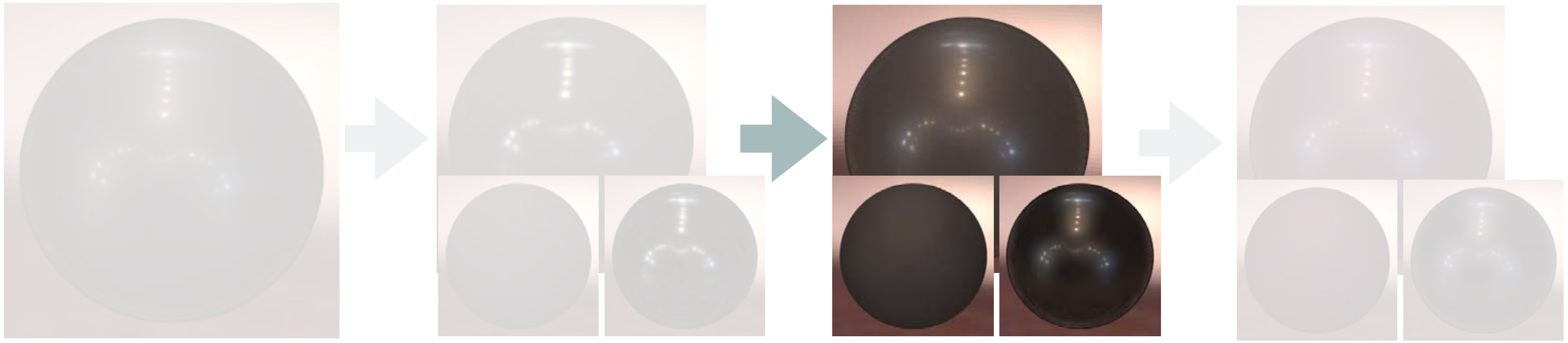
two-layer-silver | cubic-root | log1 | log2 | weighted square

1. DIFFUSE–SPECULAR SEPARATION



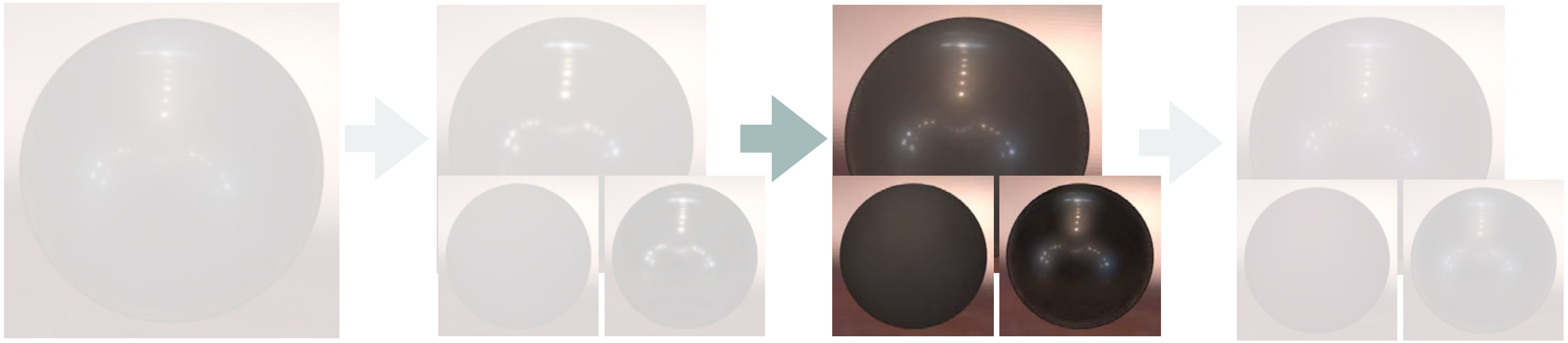
1. DIFFUSE–SPECULAR SEPARATION

➤ Step 2: diffuse-specular separation



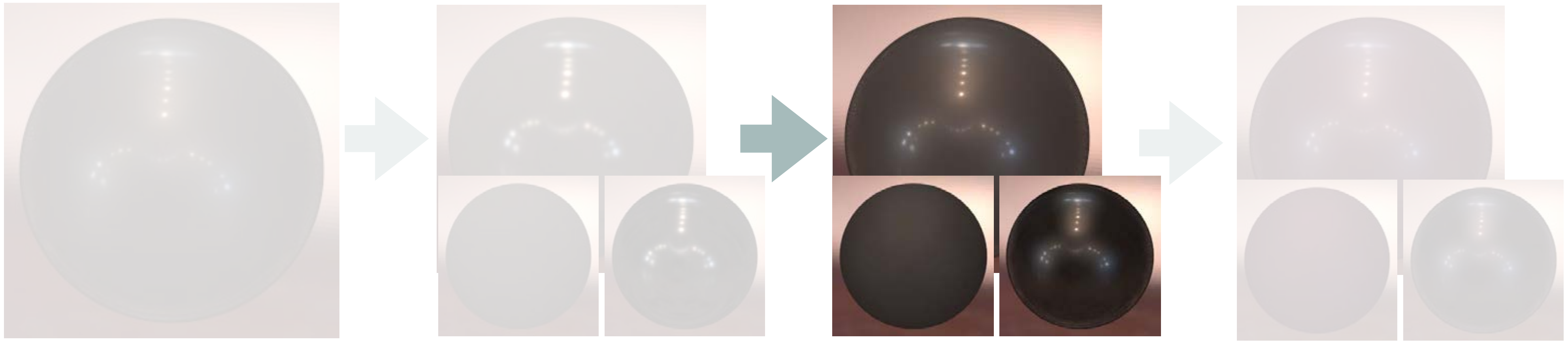
1. DIFFUSE-SPECULAR SEPARATION

- Step 2: diffuse-specular separation
  - Refine analytic approximations



1. DIFFUSE-SPECULAR SEPARATION

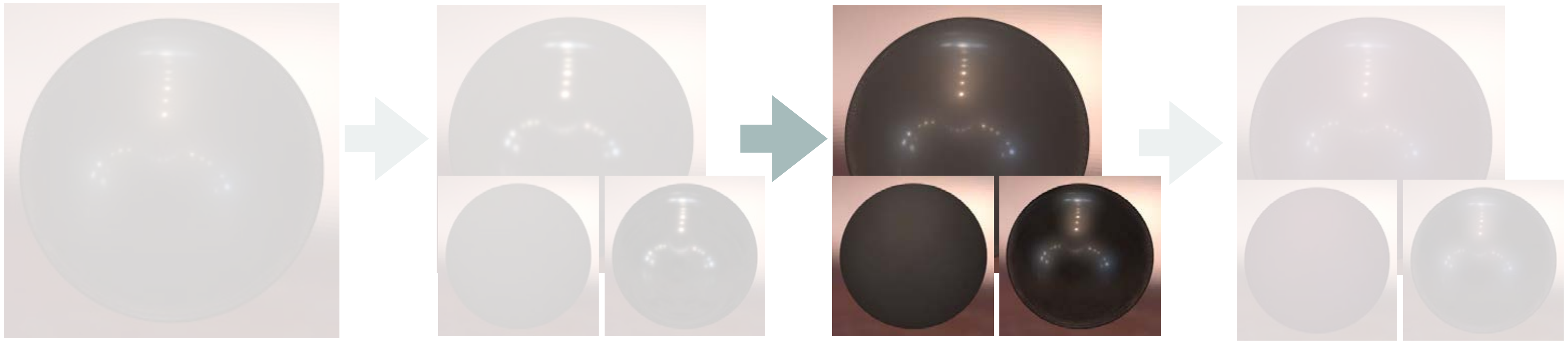
- Step 2: diffuse-specular separation
  - Refine analytic approximations



$$\min_{\rho_\mathrm{d},\rho_\mathrm{s}} d_2\left(\bar{\rho}, \rho_\mathrm{d} + \rho_\mathrm{s}\right) + \eta^d \cdot d_2(\rho_\mathrm{d}, \rho_\mathrm{d}(\alpha_\mathrm{d})) + \eta^s \cdot d_2\left(\rho_\mathrm{s}, \rho_\mathrm{s}(\alpha_\mathrm{s})\right)$$

1. DIFFUSE-SPECULAR SEPARATION

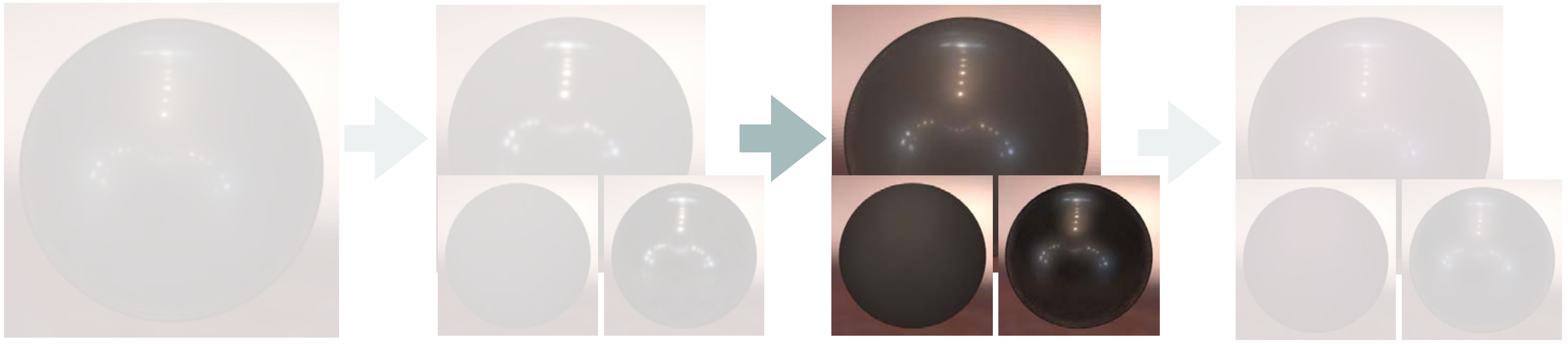
- Step 2: diffuse-specular separation
  - Refine analytic approximations



$$\min_{\rho_{\mathrm{d}},\rho_{\mathrm{s}}} \underbrace{d_2\left(\overline{\rho}, \rho_{\mathrm{d}} + \rho_{\mathrm{s}}\right)}_{\text{Data fitting}} + \eta^d \cdot d_2(\rho_{\mathrm{d}}, \rho_{\mathrm{d}}(\alpha_{\mathrm{d}})) + \eta^s \cdot d_2\left(\rho_{\mathrm{s}}, \rho_{\mathrm{s}}(\alpha_{\mathrm{s}})\right)$$

1. DIFFUSE-SPECULAR SEPARATION

- Step 2: diffuse-specular separation
  - Refine analytic approximations



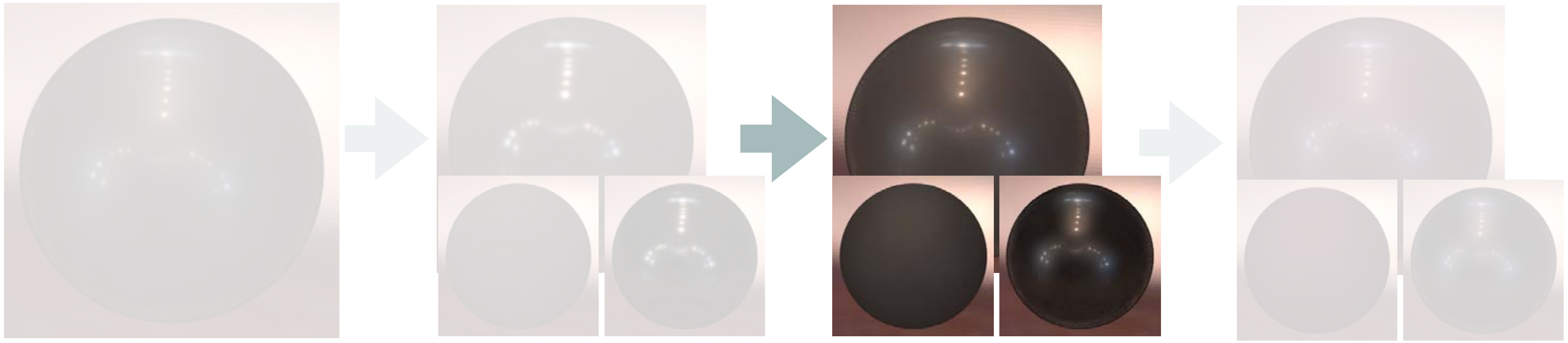
$$\min_{\rho_\mathrm{d},\rho_\mathrm{s}} \underbrace{d_2\left(\overline{\rho}, \rho_\mathrm{d} + \rho_\mathrm{s}\right)}_{\text{Data fitting}} + \eta^d \cdot d_2(\rho_\mathrm{d}, \rho_\mathrm{d}(\alpha_\mathrm{d})) + \eta^s \cdot d_2\left(\rho_\mathrm{s}, \rho_\mathrm{s}(\alpha_\mathrm{s})\right)$$

Data fitting

Analytic guidance

1. DIFFUSE-SPECULAR SEPARATION

- Step 2: diffuse-specular separation
  - Refine analytic approximations



$$\min_{\rho_\mathrm{d},\rho_\mathrm{s}} \underbrace{d_2\left(\overline{\rho}, \rho_\mathrm{d} + \rho_\mathrm{s}\right)}_{\text{Data fitting}} + \eta^d \cdot d_2(\rho_\mathrm{d}, \rho_\mathrm{d}(\alpha_\mathrm{d})) + \eta^s \cdot d_2\left(\rho_\mathrm{s}, \rho_\mathrm{s}(\alpha_\mathrm{s})\right)$$

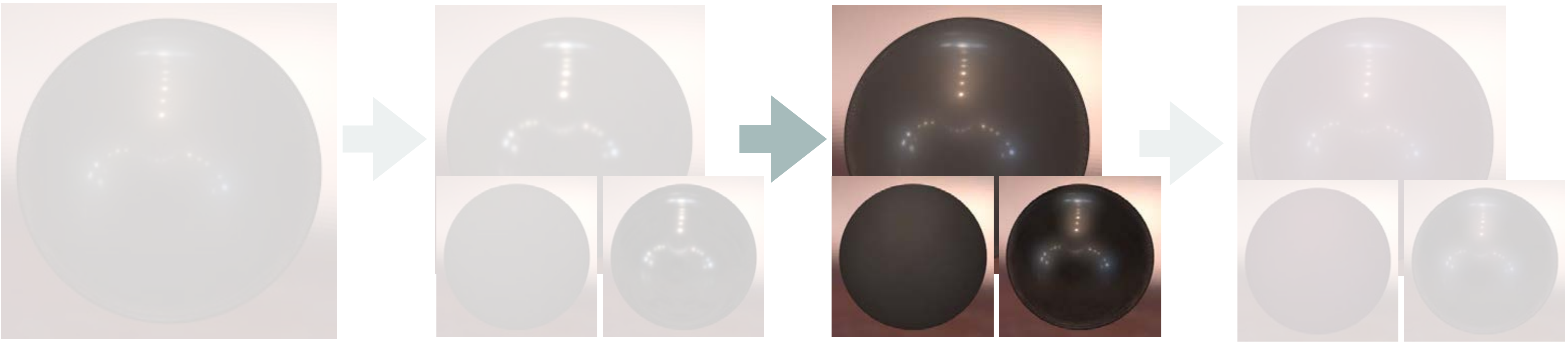
Data fitting

Analytic guidance

$$d_2\left(\rho_1, \rho_2\right) = \left\|(\rho_1 - \rho_2) \cdot \cos\omega_i \cos\omega_o\right\|_1$$

1. DIFFUSE-SPECULAR SEPARATION

- Step 2: diffuse-specular separation
  - Refine analytic approximations



$$\min_{\rho_\mathrm{d},\rho_\mathrm{s}} \underbrace{d_2\left(\overline{\rho}, \rho_\mathrm{d} + \rho_\mathrm{s}\right)}_{\text{Data fitting}} + \eta^d \cdot d_2(\rho_\mathrm{d}, \rho_\mathrm{d}(\alpha_\mathrm{d})) + \eta^s \cdot d_2\left(\rho_\mathrm{s}, \rho_\mathrm{s}(\alpha_\mathrm{s})\right)$$

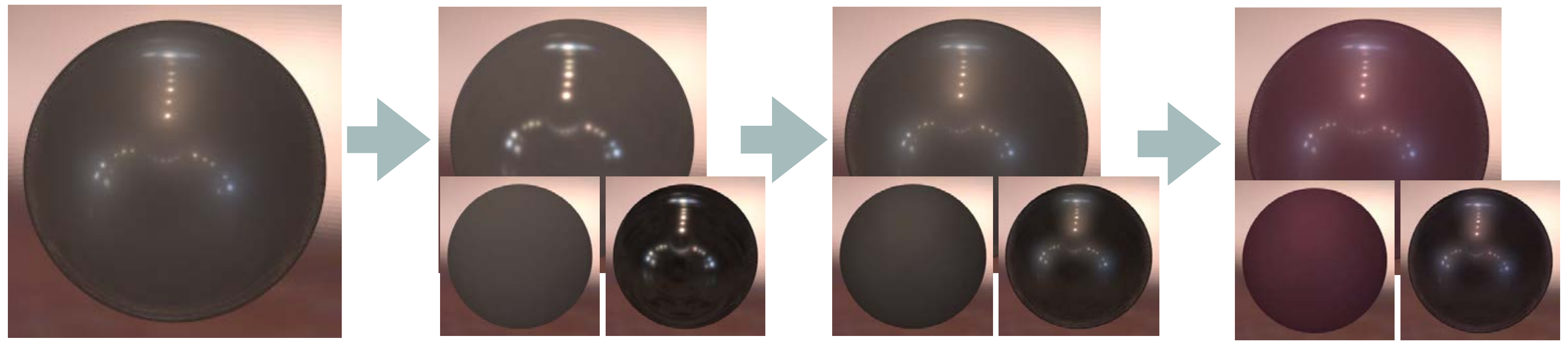
Data fitting

Analytic guidance

$$d_2\left(\rho_1, \rho_2\right) = \left\|\left(\rho_1 - \rho_2\right) \cdot \cos\omega_i \cos\omega_o\right\|_1$$

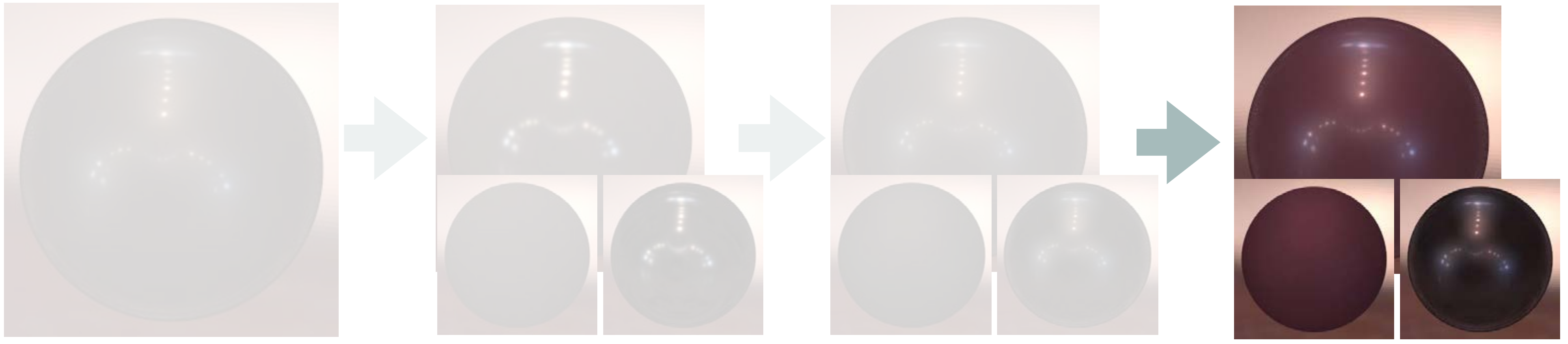
two-layer-silver | separation result | specular-violet-phenolic | separation result | steel | separation result

1. DIFFUSE-SPECULAR SEPARATION



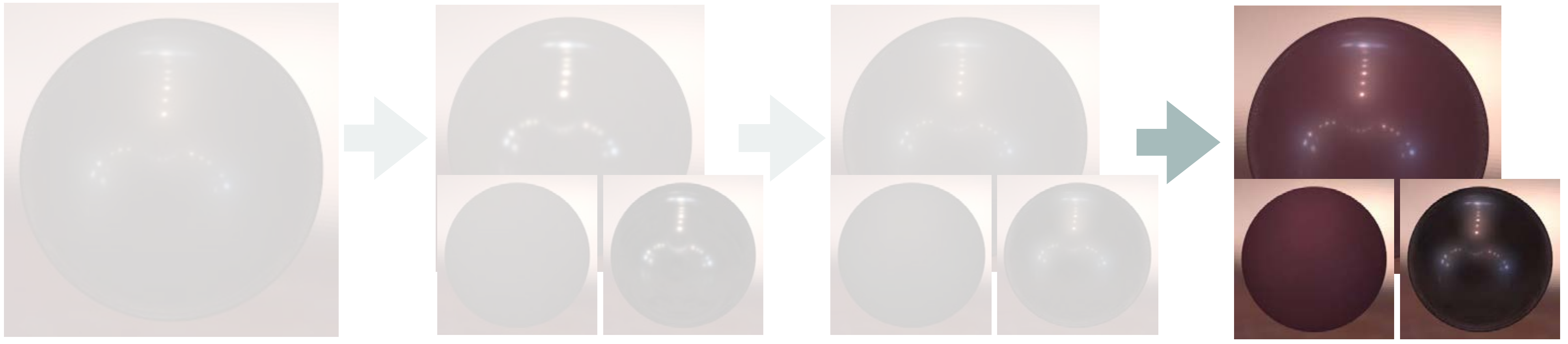
1. DIFFUSE-SPECULAR SEPARATION

➤ Step 3: color restoration



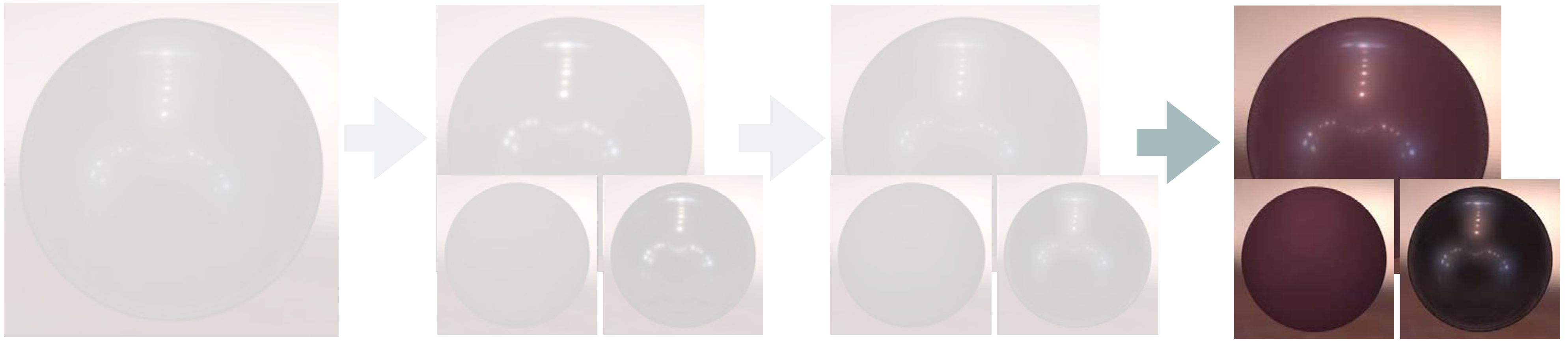
1. DIFFUSE-SPECULAR SEPARATION

- Step 3: color restoration
- Use image to do the comparison



1. DIFFUSE-SPECULAR SEPARATION

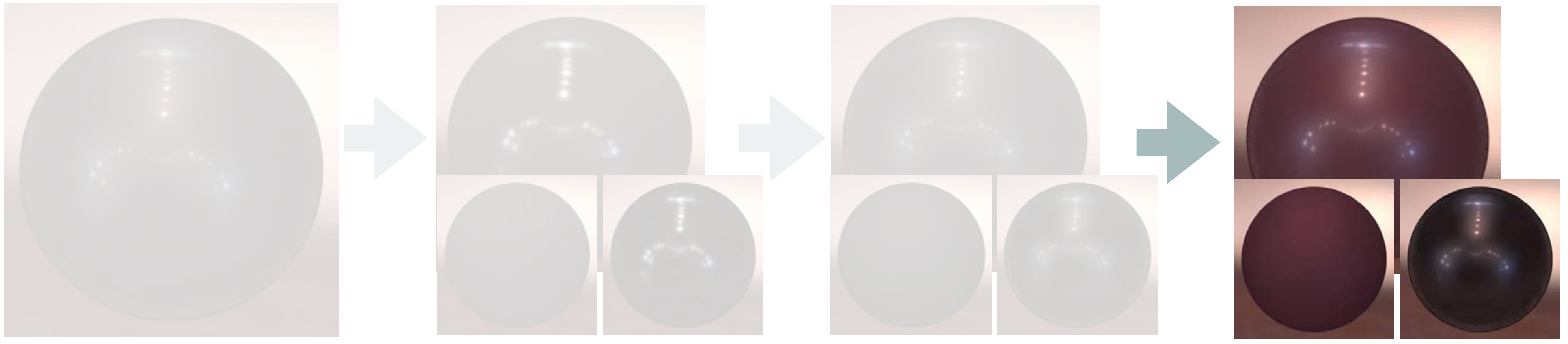
- Step 3: color restoration
- Use image to do the comparison



$$\min_{\mathbf{c}_\mathrm{d},\mathbf{c}_\mathrm{s}} \; d_3\left(\mathbf{R}\cdot\boldsymbol{\rho},\; \mathbf{R}\cdot\left(\rho_\mathrm{d}\cdot\mathbf{c}_\mathrm{d}+\rho_\mathrm{s}\cdot\mathbf{c}_\mathrm{s}\right)\right)$$

1. DIFFUSE-SPECULAR SEPARATION

- Step 3: color restoration
- Use image to do the comparison

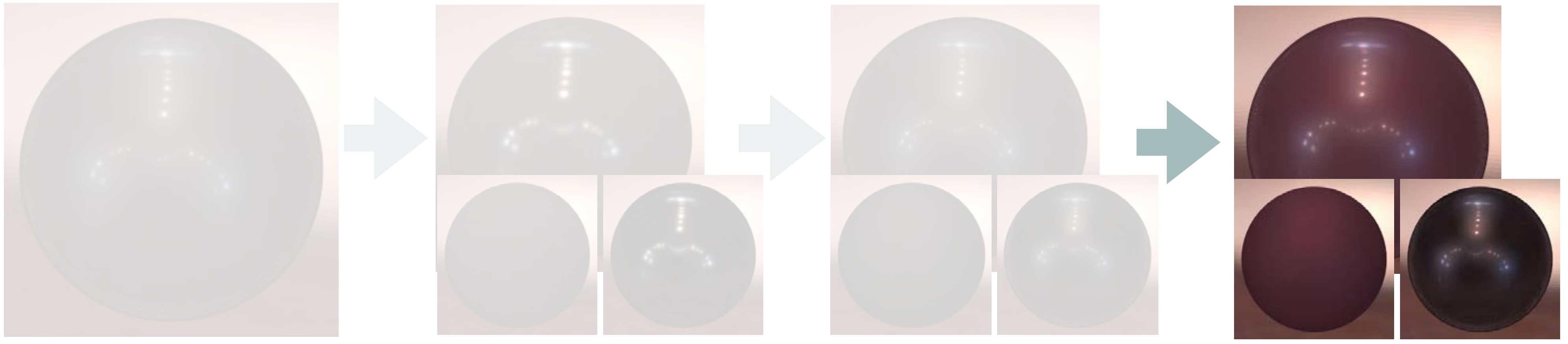


Render a BRDF into an image

$$\min_{\mathbf{c}_\mathrm{d}, \mathbf{c}_\mathrm{s}} \; d_3\left(\mathbf{R} \cdot \boldsymbol{\rho}, \; \mathbf{R} \cdot \left(\rho_\mathrm{d} \cdot \mathbf{c}_\mathrm{d} + \rho_\mathrm{s} \cdot \mathbf{c}_\mathrm{s}\right)\right)$$

1. DIFFUSE-SPECULAR SEPARATION

- Step 3: color restoration
- Use image to do the comparison



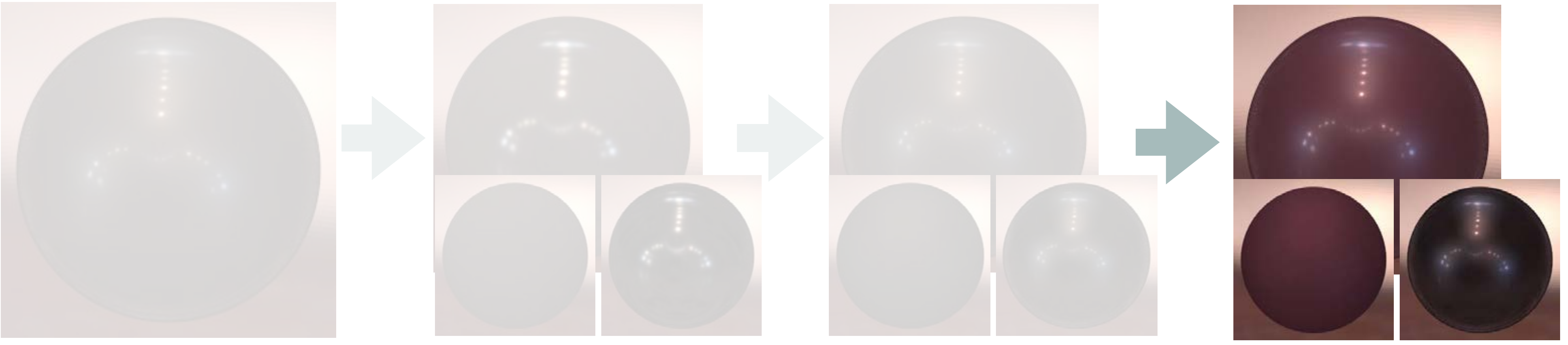
Render a BRDF into an image

$$\min_{\mathbf{c}_{\mathrm{d}},\mathbf{c}_{\mathrm{s}}} \; d_3\left(\mathbf{R}\cdot\boldsymbol{\rho},\;\; \mathbf{R}\cdot\left(\rho_{\mathrm{d}}\cdot\mathbf{c}_{\mathrm{d}}+\rho_{\mathrm{s}}\cdot\mathbf{c}_{\mathrm{s}}\right)\right)$$

$$d_3(\mathbf{x_1},\mathbf{x_2}) = \left\|\mathbf{s_1}\cos\mathbf{h_1} - \mathbf{s_2}\cos\mathbf{h_2}\right\|_2 + \left\|\mathbf{s_1}\sin\mathbf{h_1} - \mathbf{s_2}\sin\mathbf{h_2}\right\|_2.$$

1. DIFFUSE-SPECULAR SEPARATION

- Step 3: color restoration
- Use image to do the comparison



Render a BRDF into an image

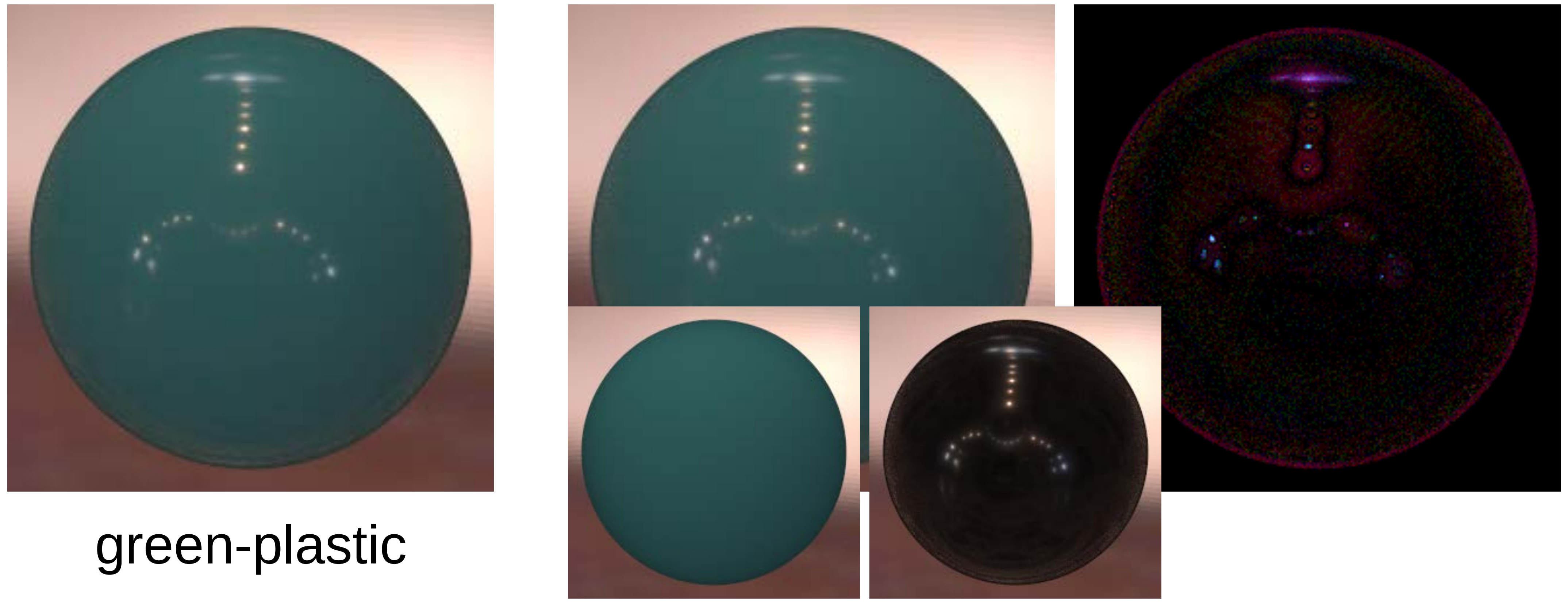
$$\min_{\mathbf{c}_\mathrm{d},\mathbf{c}_\mathrm{s}} \; d_3\left(\mathbf{R}\cdot\boldsymbol{\rho},\; \mathbf{R}\cdot\left(\rho_\mathrm{d}\cdot\mathbf{c}_\mathrm{d}+\rho_\mathrm{s}\cdot\mathbf{c}_\mathrm{s}\right)\right)$$

$$d_3(\mathbf{x_1},\mathbf{x_2}) = \|\mathbf{s_1}\cos\mathbf{h_1}-\mathbf{s_2}\cos\mathbf{h_2}\|_2 + \|\mathbf{s_1}\sin\mathbf{h_1}-\mathbf{s_2}\sin\mathbf{h_2}\|_2.$$

error map (×30)

brass

error map (×30)



green-plastic

1. DIFFUSE-SPECULAR SEPARATION

1. DIFFUSE-SPECULAR SEPARATION

gray-plastic

original BRDF

our separation

1. DIFFUSE-SPECULAR SEPARATION

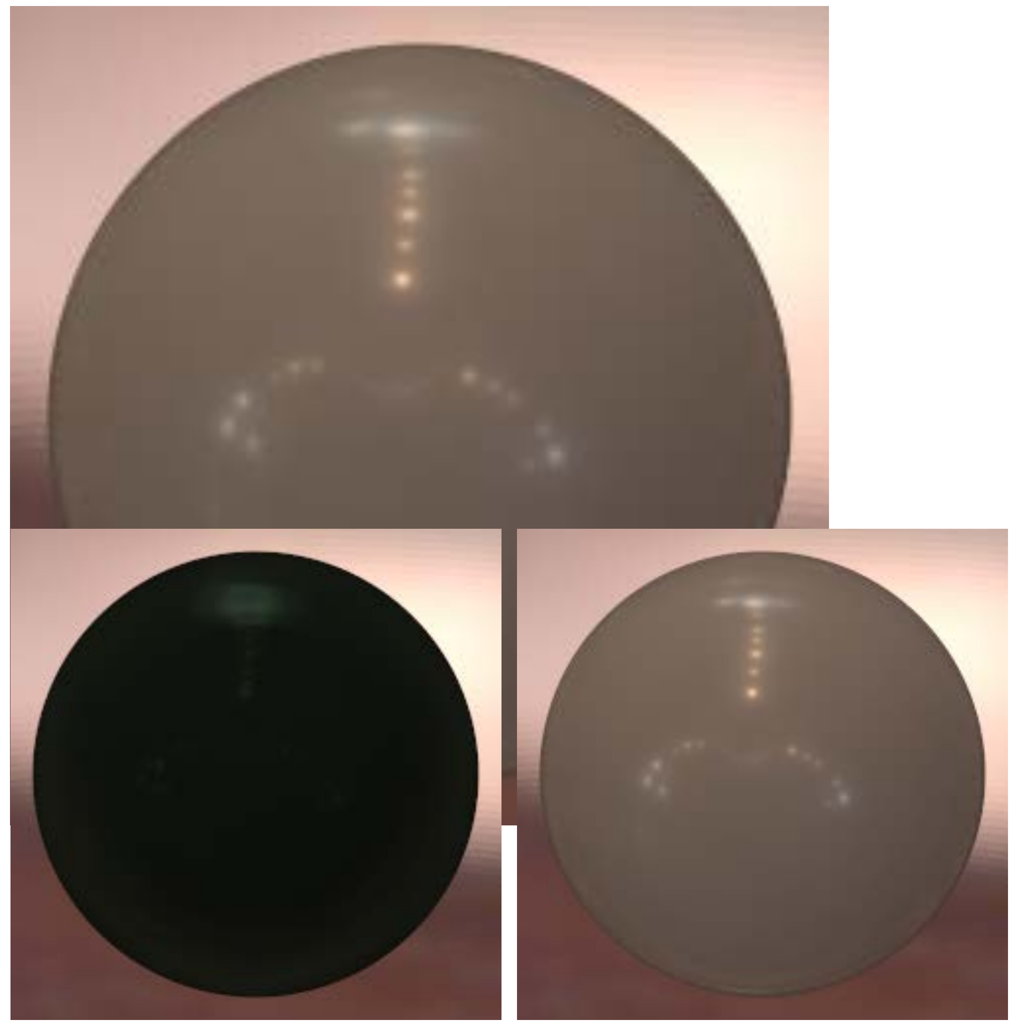
original BRDF our separation direct NMF

1. DIFFUSE-SPECULAR SEPARATION

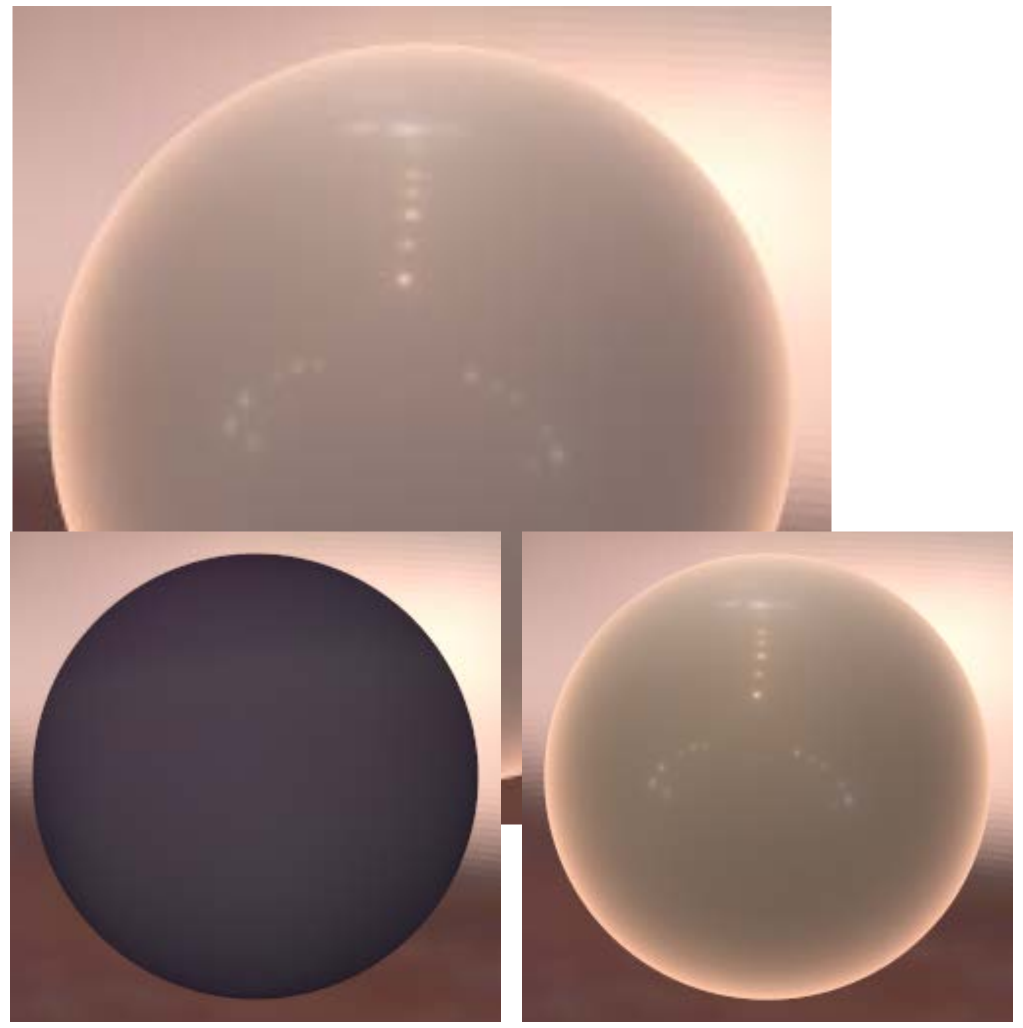
gray-plastic

original BRDF

our separation

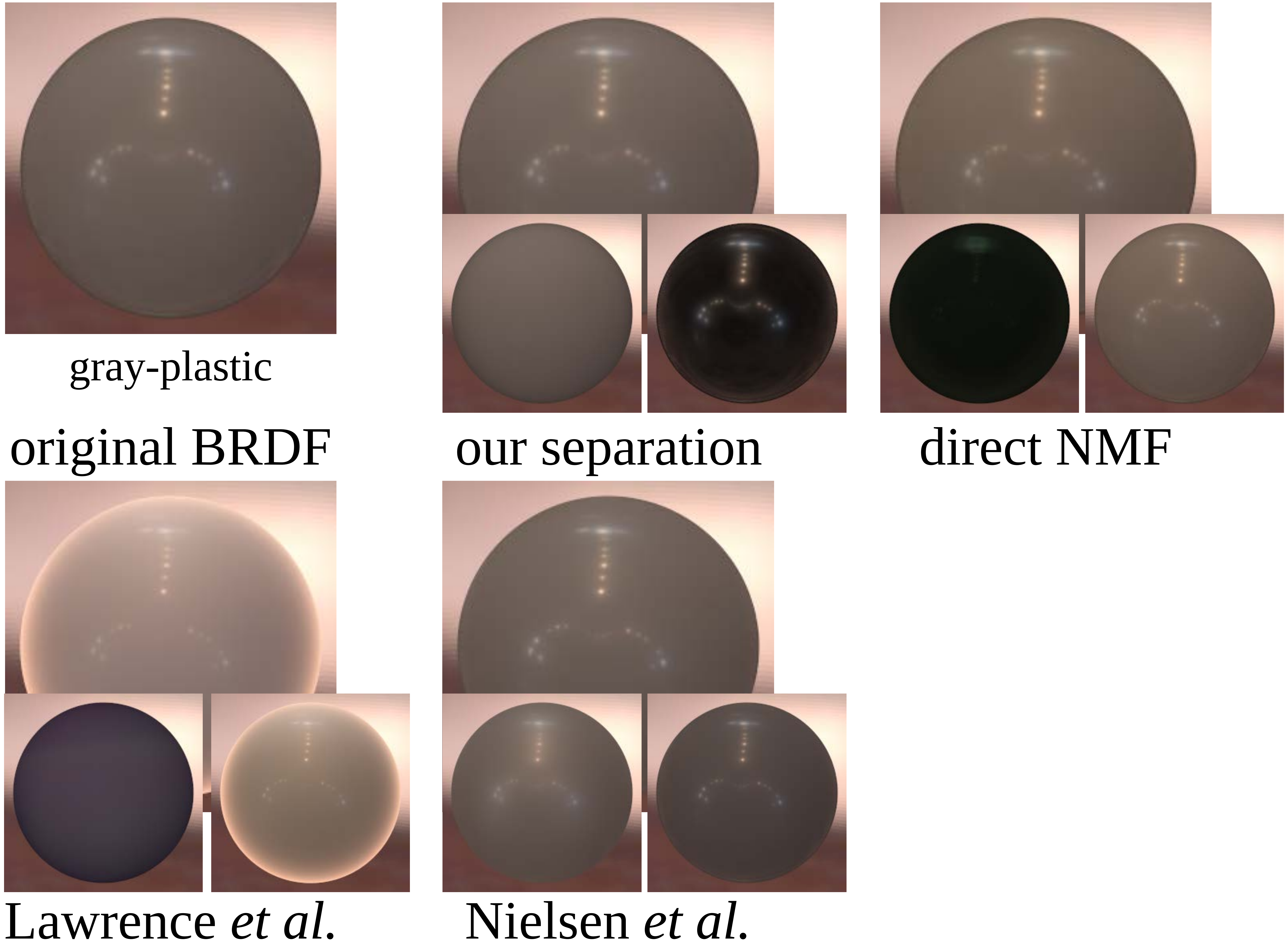


direct NMF

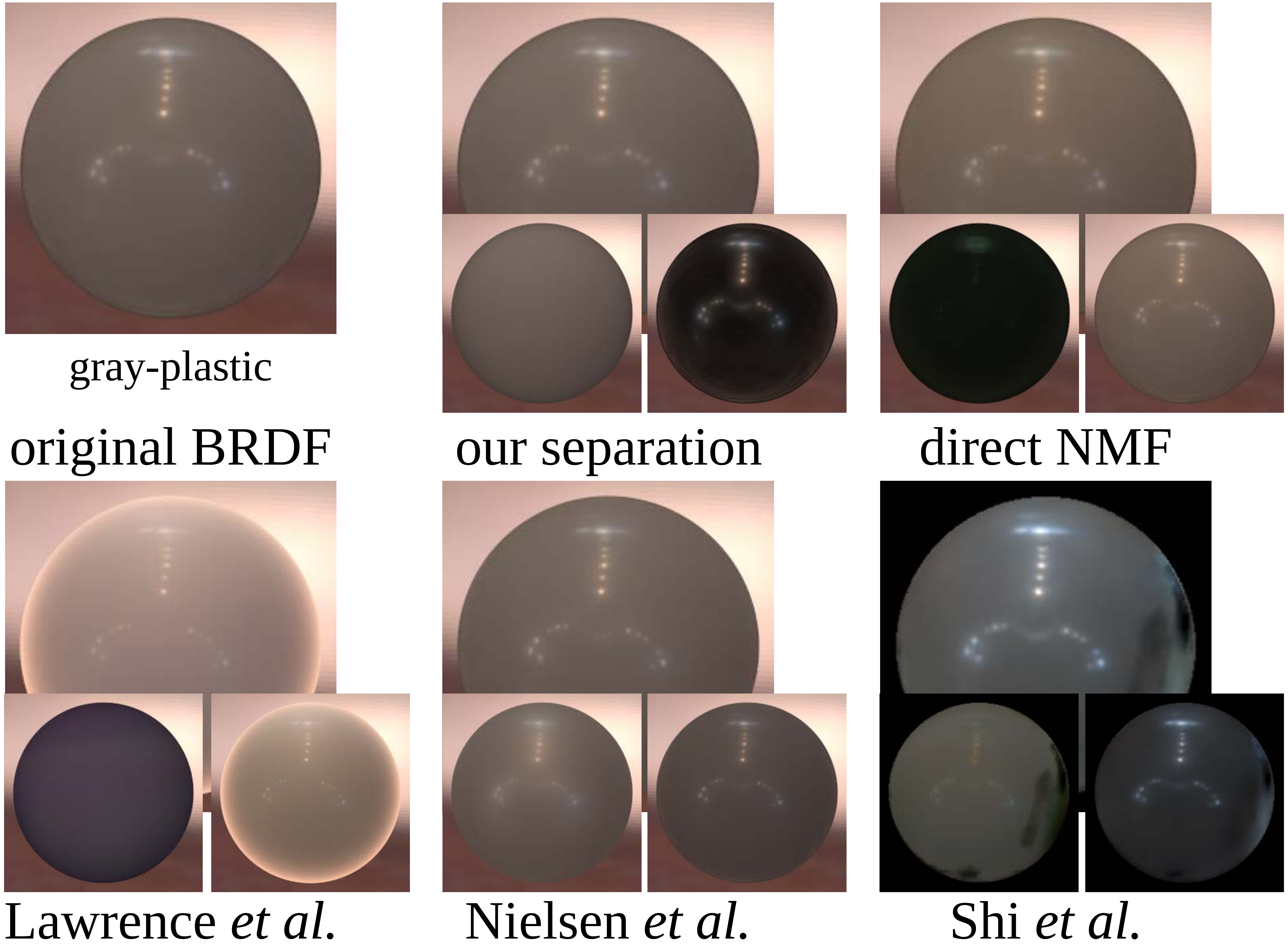


Lawrence *et al.*

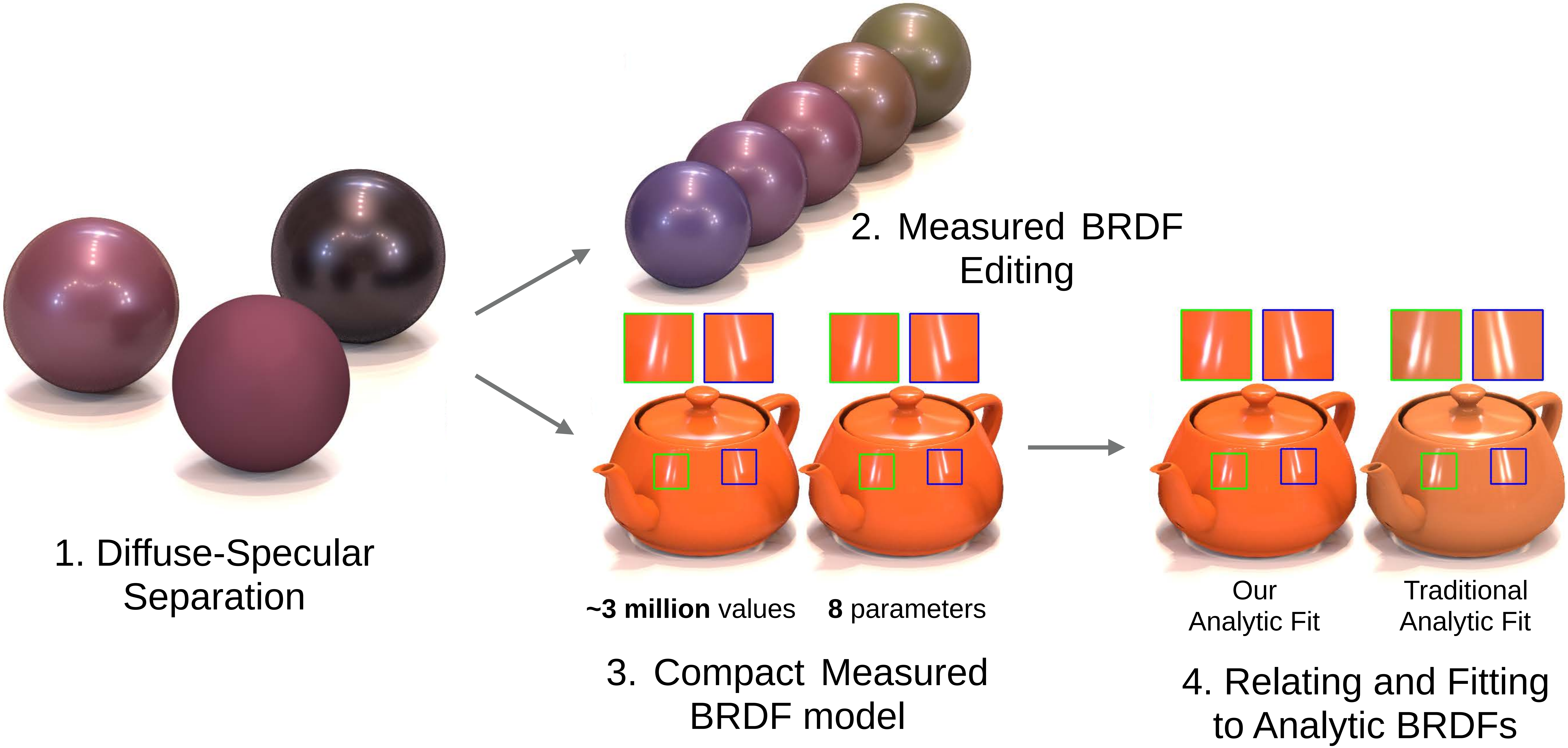
1. DIFFUSE-SPECULAR SEPARATION



1. DIFFUSE-SPECULAR SEPARATION

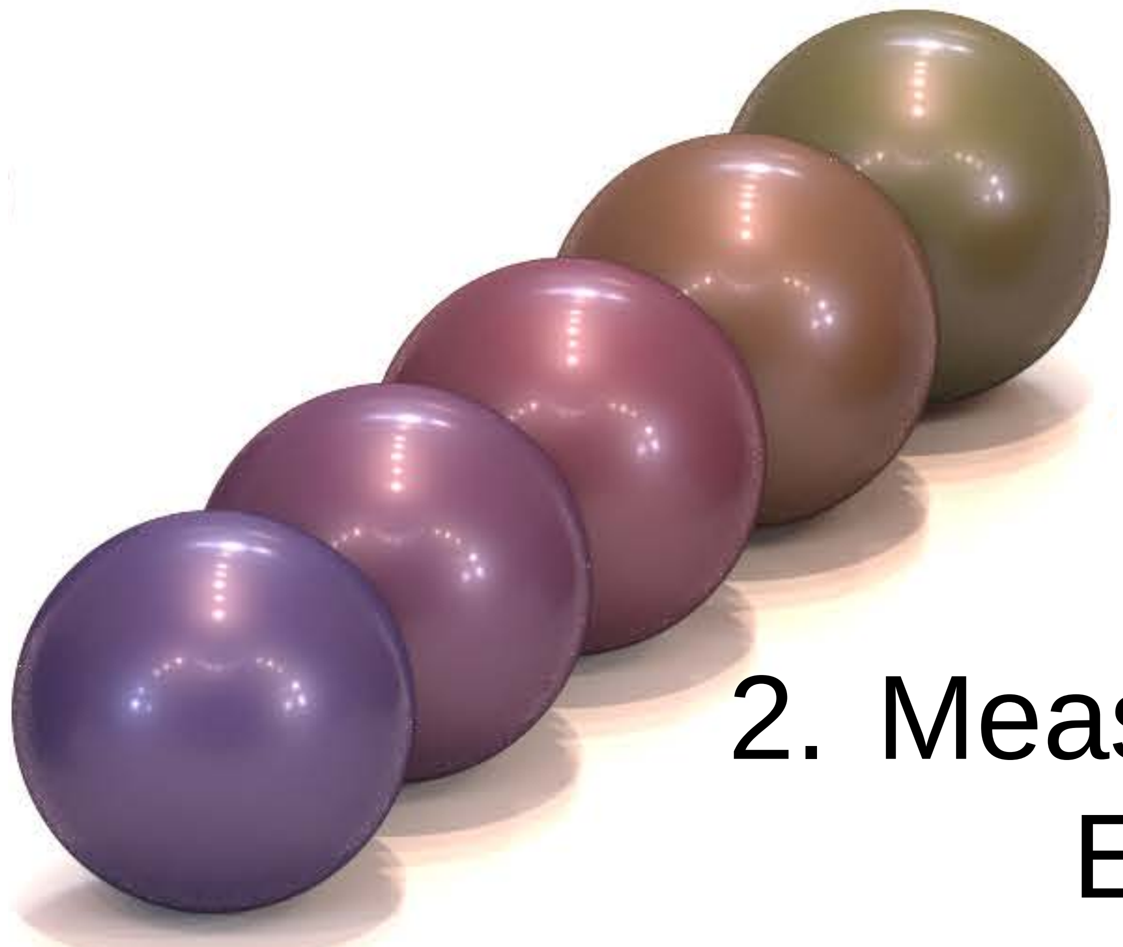


OVERVIEW


1. Diffuse-Specular Separation
2. Measured BRDF Editing
~3 million values
8 parameters
3. Compact Measured BRDF model
Our Analytic Fit
Traditional Analytic Fit
4. Relating and Fitting to Analytic BRDFs

OVERVIEW

1. Diffuse-Specular Separation



2. Measured BRDF Editing

~3 million values   **8** parameters

3. Compact Measured BRDF model

Our Analytic Fit   Traditional Analytic Fit

4. Relating and Fitting to Analytic BRDFs

2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \approx$$

2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \approx \rho_{\mathrm{d}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \mathbf{c}_{\mathrm{d}}(\lambda)$$

2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx \rho_\mathrm{d}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{d}(\lambda) + \rho_\mathrm{s}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{s}(\lambda)$$

2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \approx \rho_{\mathrm{d}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \underline{\mathbf{c}_{\mathrm{d}}(\lambda)} + \rho_{\mathrm{s}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \underline{\mathbf{c}_{\mathrm{s}}(\lambda)}$$

Color

2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega_i}, \boldsymbol{\omega_o}, \lambda] \approx \rho_d[\boldsymbol{\omega_i}, \boldsymbol{\omega_o}] \cdot \underline{\mathbf{c}_d(\lambda)} + \rho_s[\boldsymbol{\omega_i}, \boldsymbol{\omega_o}] \cdot \underline{\mathbf{c}_s(\lambda)}$$

Color

2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx \rho_\mathrm{d}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \underline{\mathbf{c}_\mathrm{d}(\lambda)} + \rho_\mathrm{s}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{s}(\lambda)$$

2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx \rho_\mathrm{d}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{d}(\lambda) + \rho_\mathrm{s}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \underline{\mathbf{c}_\mathrm{s}(\lambda)}$$

2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}, \lambda] \approx \rho_{\mathrm{d}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}[\boldsymbol{\omega}_{\mathbf{i}}, \boldsymbol{\omega}_{\mathbf{o}}] \cdot \underline{\mathbf{c}_{\mathrm{s}}(\lambda)}$$

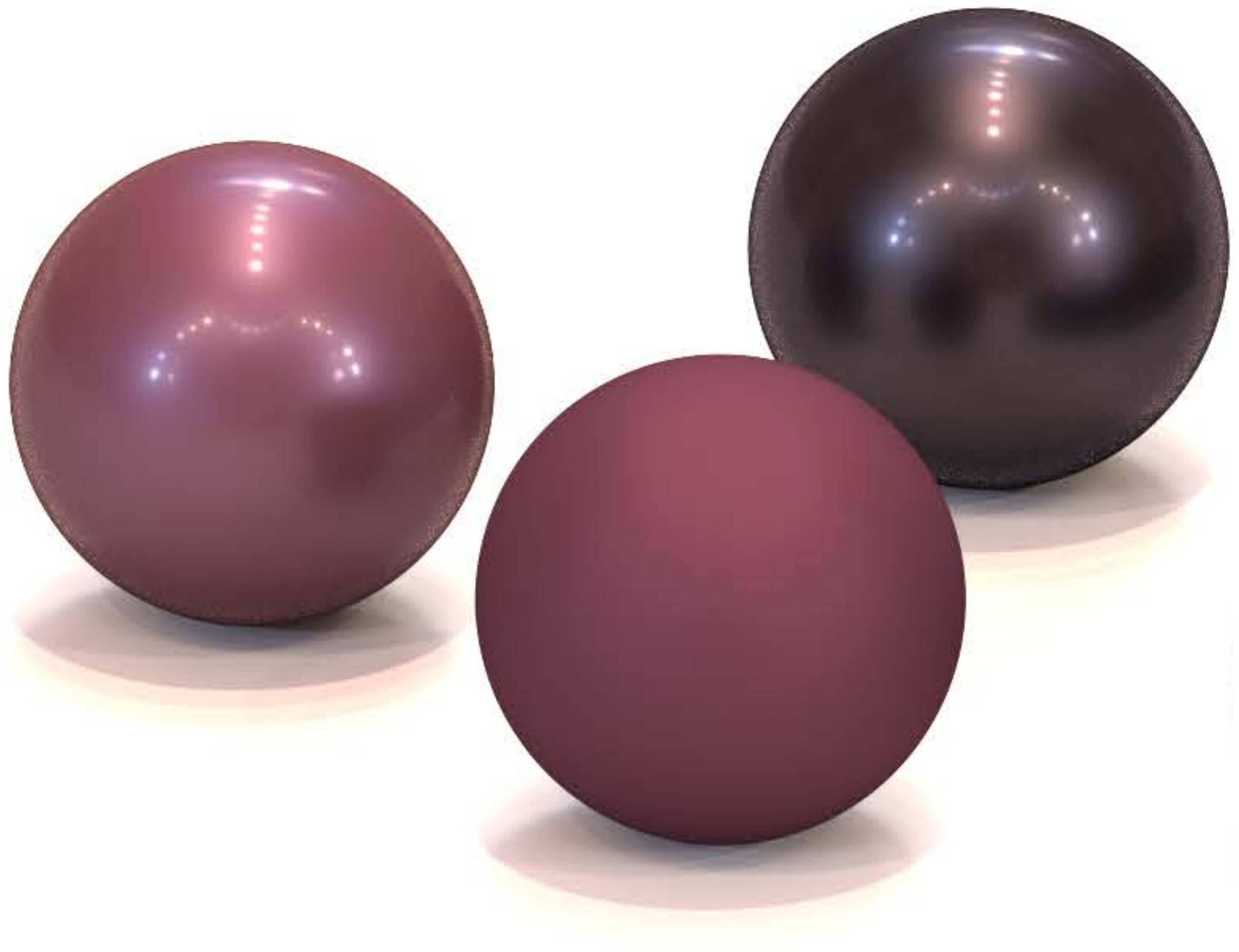
2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx \rho_\mathrm{d}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{d}(\lambda) + \underline{\rho_\mathrm{s}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{s}(\lambda)}$$

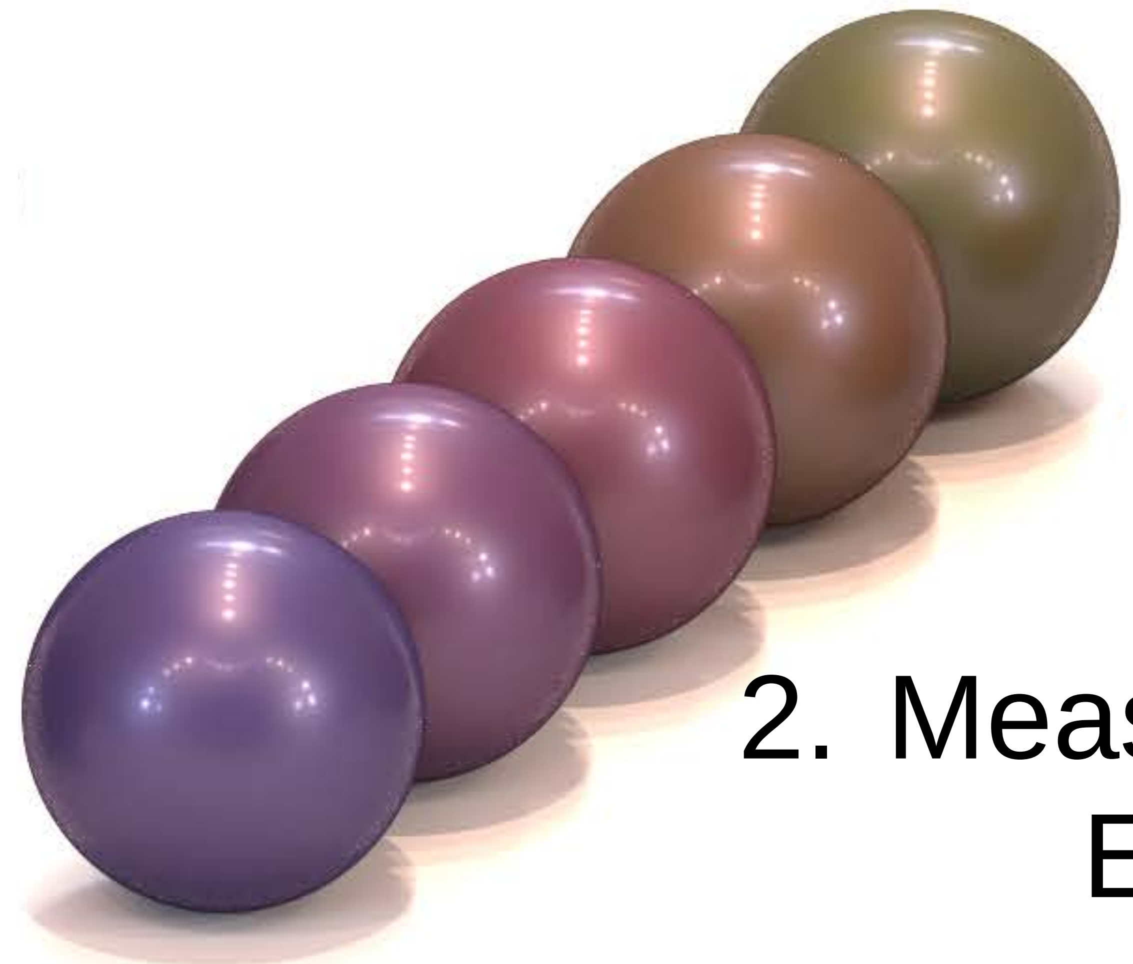
2. MEASURED BRDF EDITING

$$\boldsymbol{\rho}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}, \lambda] \approx \rho_\mathrm{d}[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{d}(\lambda) + \underline{\rho_\mathrm{s}{}'[\boldsymbol{\omega}_\mathbf{i}, \boldsymbol{\omega}_\mathbf{o}] \cdot \mathbf{c}_\mathrm{s}{}'(\lambda)}$$

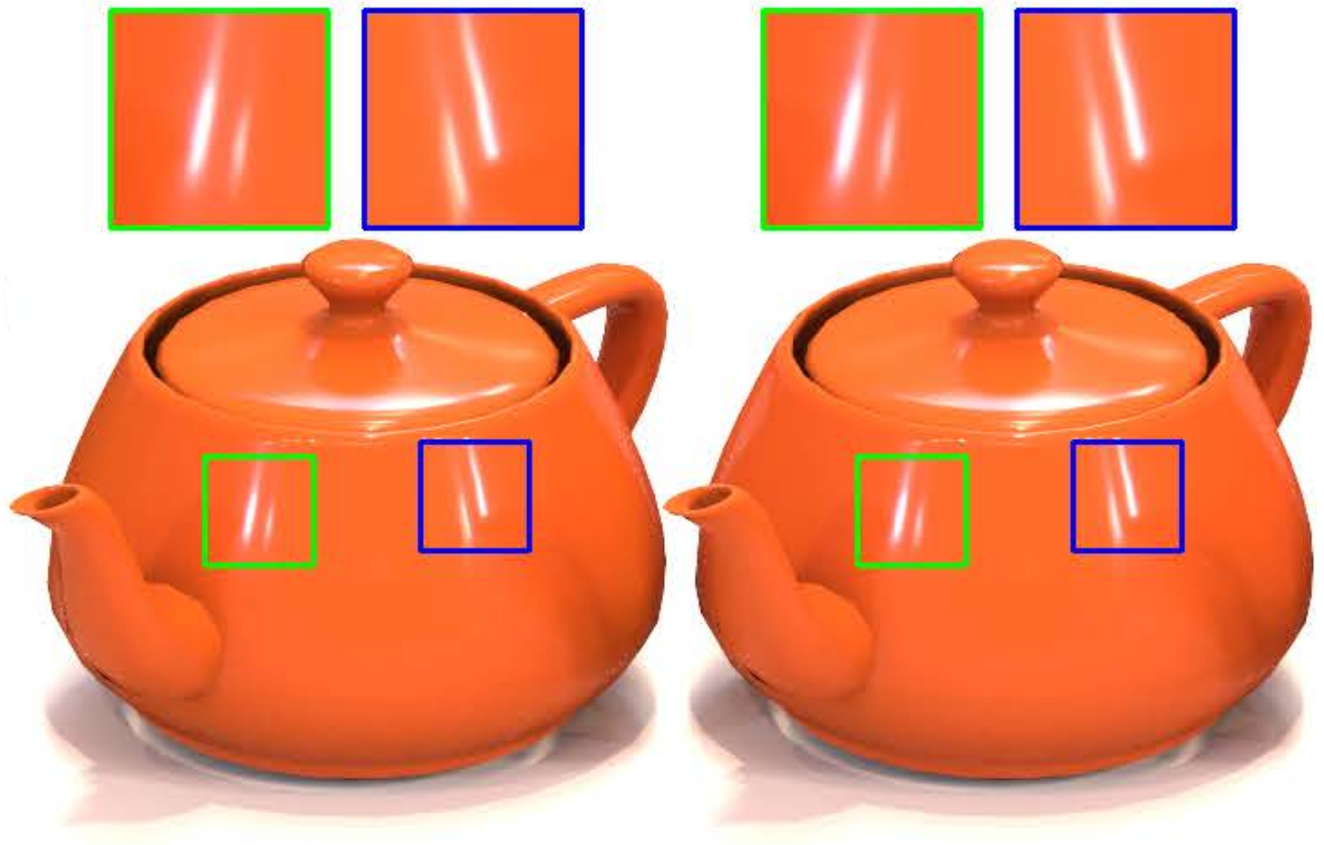
OVERVIEW



1. Diffuse-Specular Separation

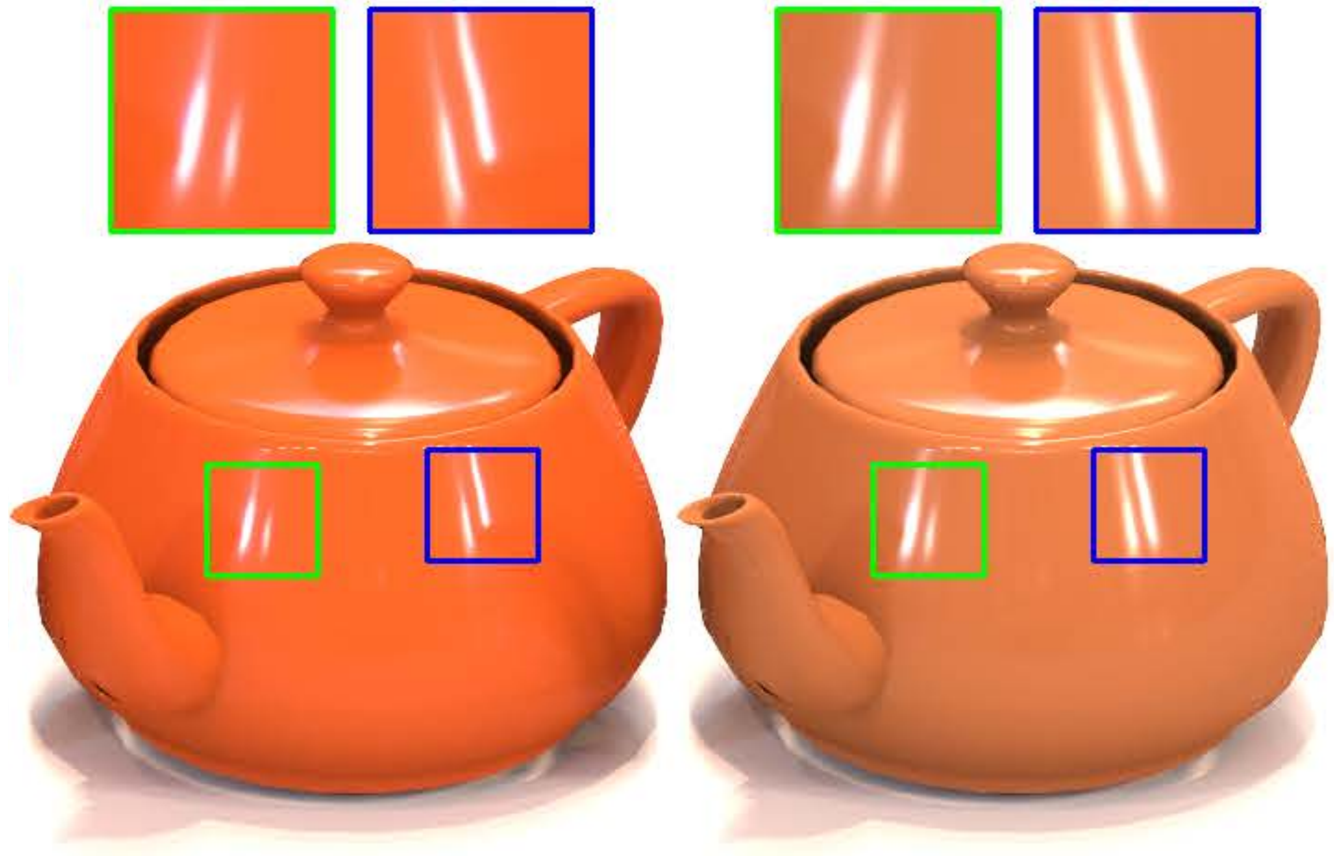


2. Measured BRDF Editing



~3 million values **8** parameters

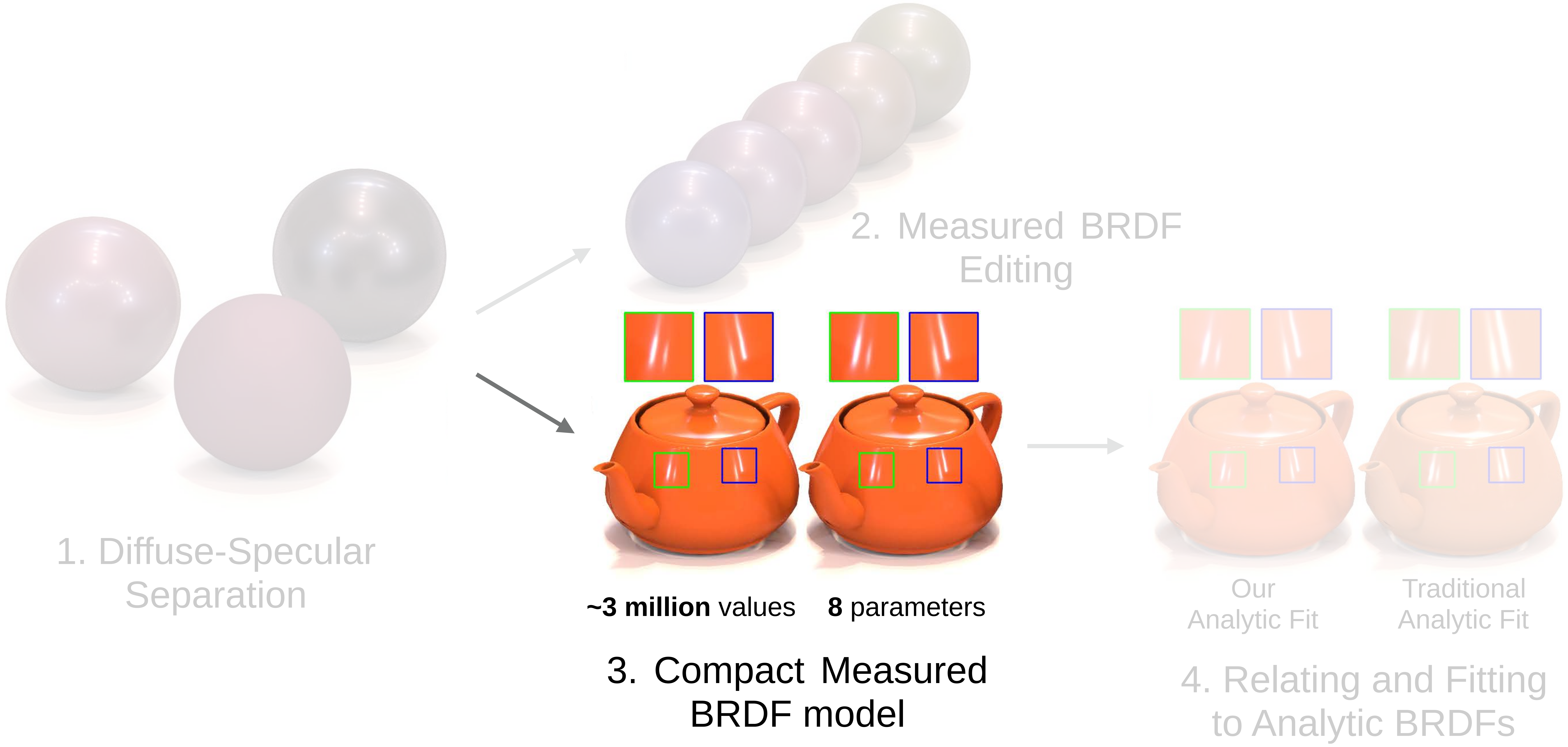
3. Compact Measured BRDF model



Our Analytic Fit Traditional Analytic Fit

4. Relating and Fitting to Analytic BRDFs

OVERVIEW



1. Diffuse-Specular Separation
2. Measured BRDF Editing
~3 million values
8 parameters
3. Compact Measured BRDF model
Our Analytic Fit
Traditional Analytic Fit
4. Relating and Fitting to Analytic BRDFs

3. COMPACT MEASURED BRDF MODEL

3. COMPACT MEASURED BRDF MODEL

➤ Previous work:

Nielsen, Jannik Boll, Henrik Wann Jensen, and Ravi Ramamoorthi. "On optimal, minimal BRDF sampling for reflectance acquisition." ACM Transactions on Graphics (TOG) 34.6 (2015): 186.

3. COMPACT MEASURED BRDF MODEL

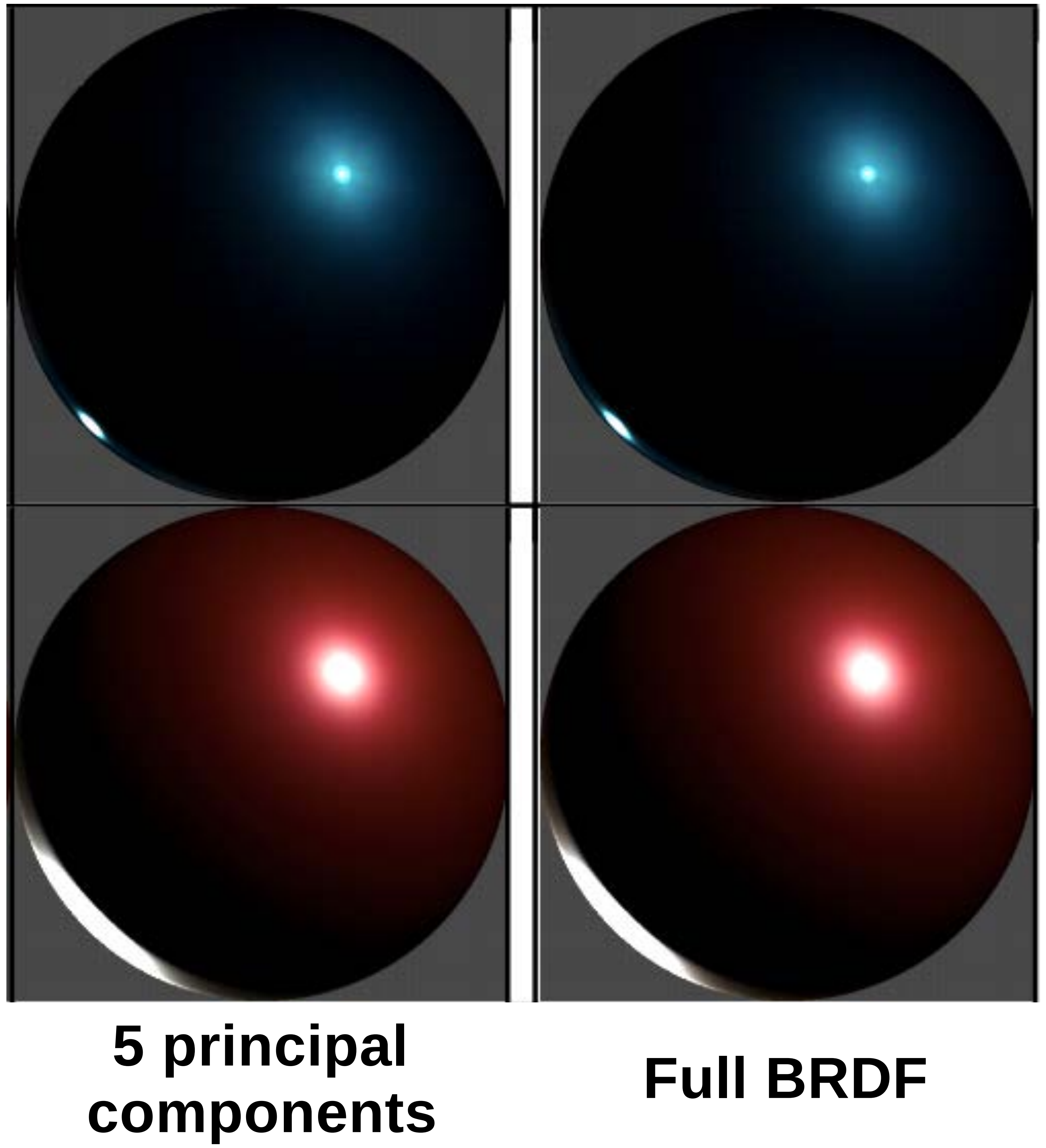
- Previous work:
- Apply PCA on MERL dataset (100 measured BRDFs)

Nielsen, Jannik Boll, Henrik Wann Jensen, and Ravi Ramamoorthi. "On optimal, minimal BRDF sampling for reflectance acquisition." ACM Transactions on Graphics (TOG) 34.6 (2015): 186.

Matusik, Wojciech, et al. "A data-driven reflectance model." ACM Transactions on Graphics (TOG) 22.3 (2003): 759-769.

3. COMPACT MEASURED BRDF MODEL

- Previous work:
- Apply PCA on MERL dataset (100 measured BRDFs)
- Use 5 principal components to express one color channel



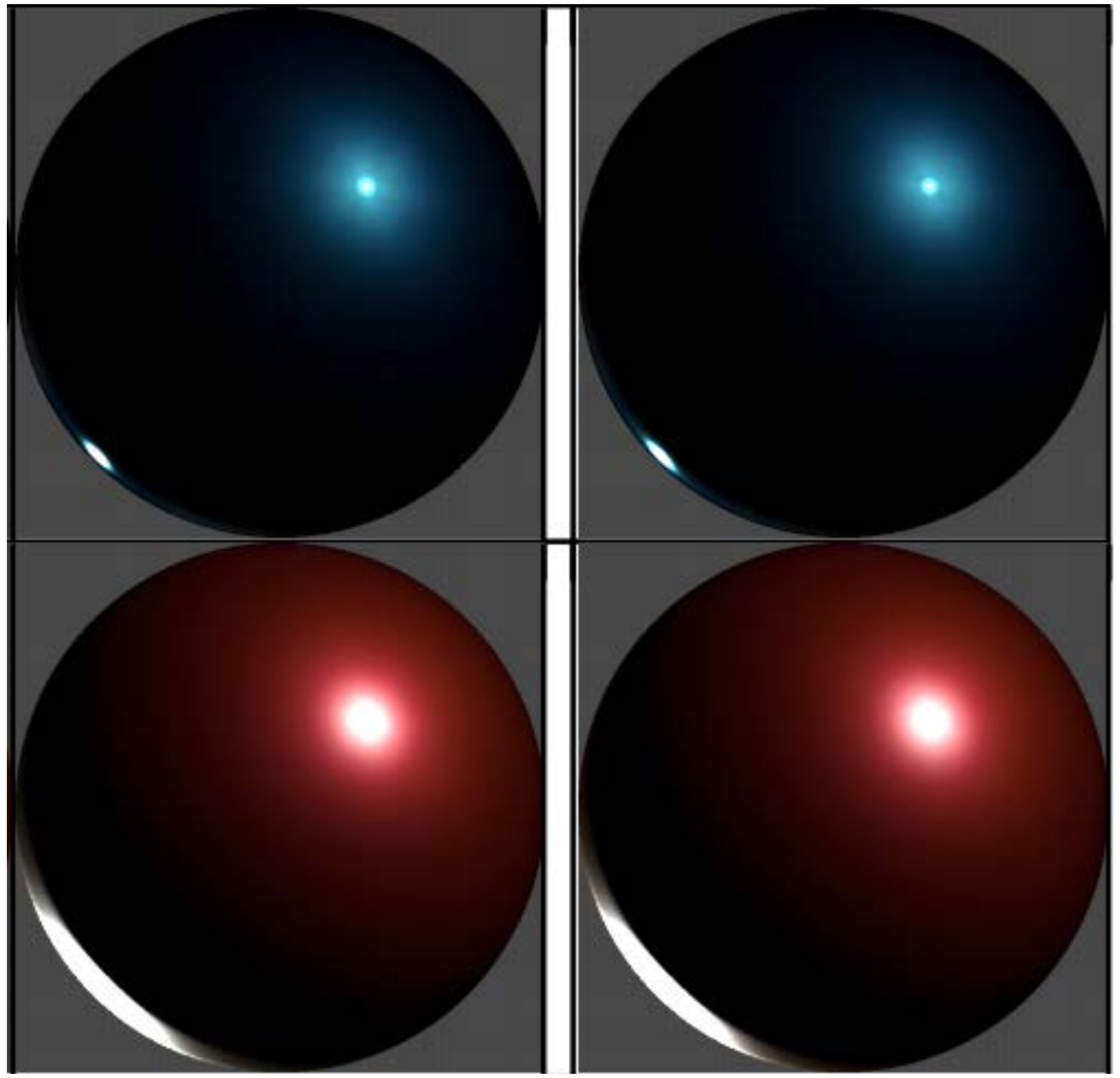
Nielsen, Jannik Boll, Henrik Wann Jensen, and Ravi Ramamoorthi. "On optimal, minimal BRDF sampling for reflectance acquisition." ACM Transactions on Graphics (TOG) 34.6 (2015): 186.

Matusik, Wojciech, et al. "A data-driven reflectance model." ACM Transactions on Graphics (TOG) 22.3 (2003): 759-769.

3. COMPACT MEASURED BRDF MODEL

- Previous work:
- Apply PCA on MERL dataset (100 measured BRDFs)
- Use 5 principal components to express one color channel

- Drawbacks
  - Treat each color channel independently



5 principal components | Full BRDF

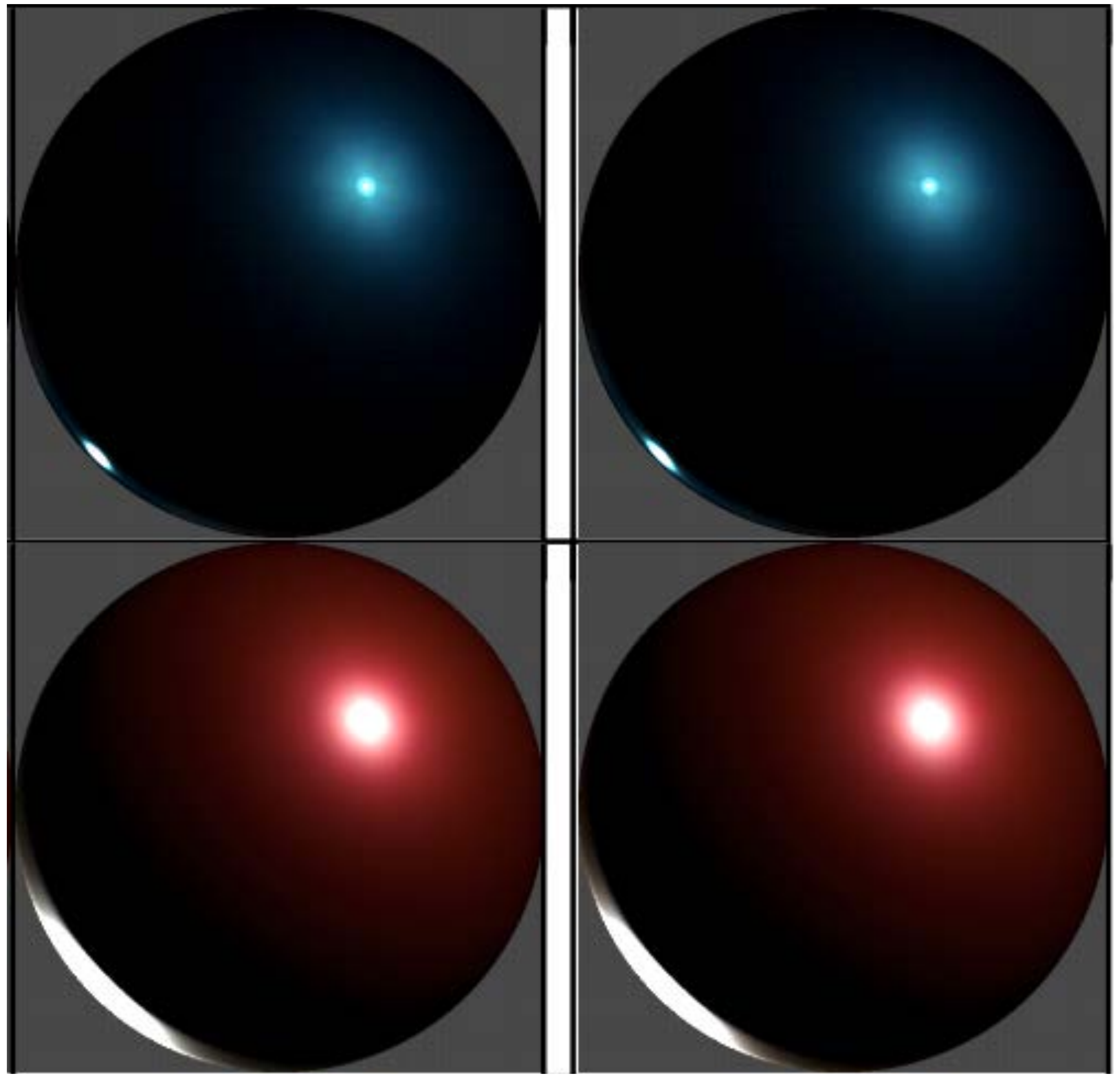
Nielsen, Jannik Boll, Henrik Wann Jensen, and Ravi Ramamoorthi. "On optimal, minimal BRDF sampling for reflectance acquisition." ACM Transactions on Graphics (TOG) 34.6 (2015): 186.

Matusik, Wojciech, et al. "A data-driven reflectance model." ACM Transactions on Graphics (TOG) 22.3 (2003): 759-769.

3. COMPACT MEASURED BRDF MODEL

- Previous work:
- Apply PCA on MERL dataset (100 measured BRDFs)
- Use 5 principal components to express one color channel

- Drawbacks
  - Treat each color channel independently
  - Mix the diffuse and specular together.



5 principal components | Full BRDF

Nielsen, Jannik Boll, Henrik Wann Jensen, and Ravi Ramamoorthi. "On optimal, minimal BRDF sampling for reflectance acquisition." ACM Transactions on Graphics (TOG) 34.6 (2015): 186.

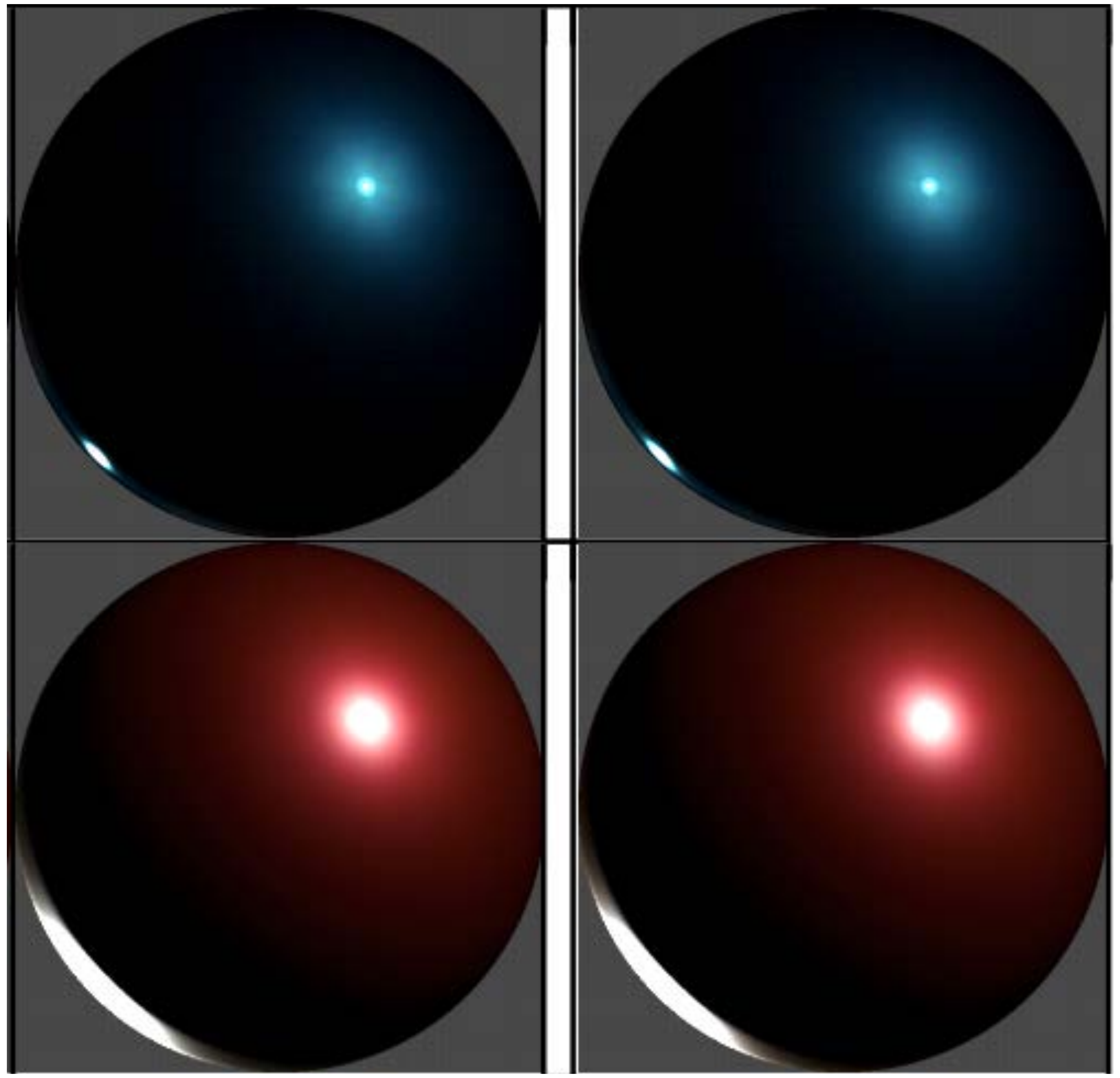
Matusik, Wojciech, et al. "A data-driven reflectance model." ACM Transactions on Graphics (TOG) 22.3 (2003): 759-769.

3. COMPACT MEASURED BRDF MODEL

- Previous work:
- Apply PCA on MERL dataset (100 measured BRDFs)
- Use 5 principal components to express one color channel

- Drawbacks
  - Treat each color channel independently
  - Mix the diffuse and specular together.

- Apply PCA on the diffuse and specular part separately.



5 principal components — Full BRDF

Nielsen, Jannik Boll, Henrik Wann Jensen, and Ravi Ramamoorthi. "On optimal, minimal BRDF sampling for reflectance acquisition." ACM Transactions on Graphics (TOG) 34.6 (2015): 186.

Matusik, Wojciech, et al. "A data-driven reflectance model." ACM Transactions on Graphics (TOG) 22.3 (2003): 759-769.

3. COMPACT MEASURED BRDF MODEL

3. COMPACT MEASURED BRDF MODEL

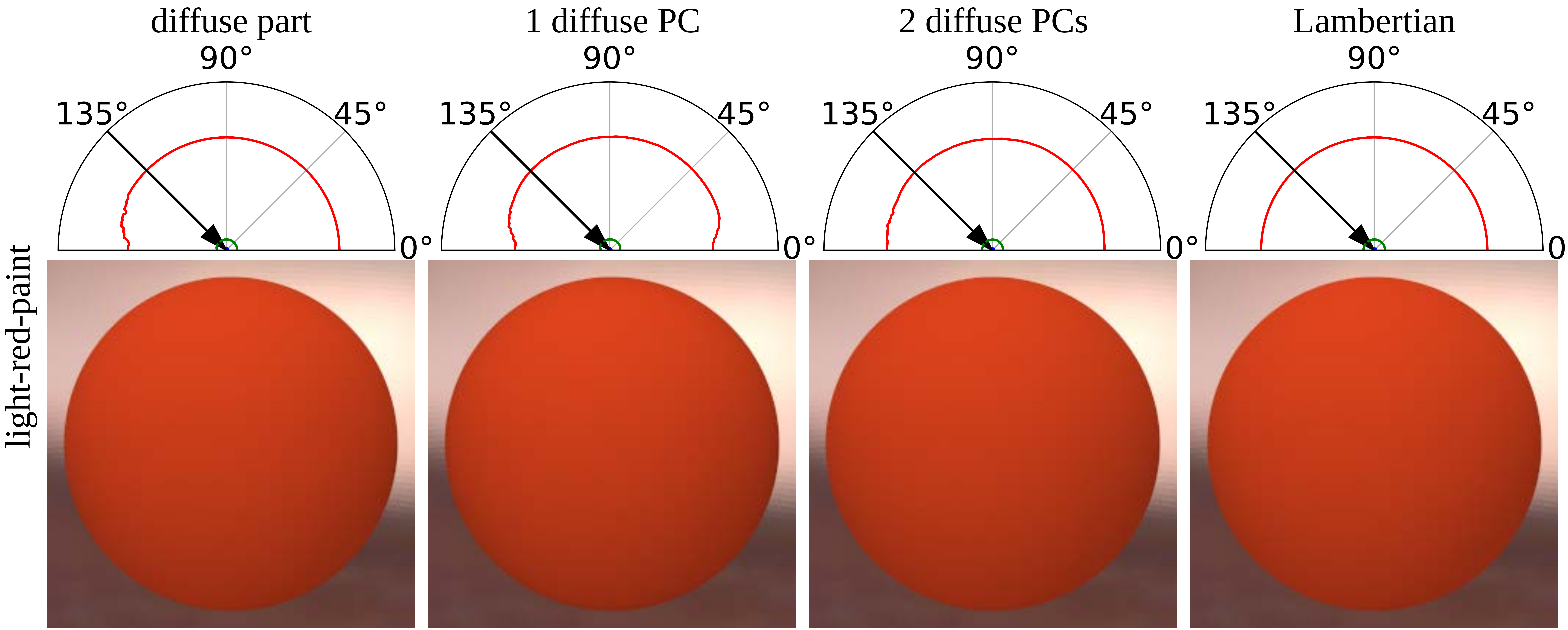
- Diffuse

3. COMPACT MEASURED BRDF MODEL

- ➤ Diffuse
- ➤ Directly do PCA on the diffuse parts of all MERL BRDFs

3. COMPACT MEASURED BRDF MODEL

➤ Diffuse



3. COMPACT MEASURED BRDF MODEL

➤ Diffuse

3. COMPACT MEASURED BRDF MODEL

- Diffuse
- Directly do PCA on the diffuse parts of all MERL BRDFs

$$\rho_{\mathrm{d}} = Q_{\mathrm{d}} \cdot x_{\mathrm{d}}$$

3. COMPACT MEASURED BRDF MODEL

- Diffuse
- Directly do PCA on the diffuse parts of all MERL BRDFs

$$\rho_{\mathrm{d}} = Q_{\mathrm{d}} \cdot x_{\mathrm{d}}$$

Q_{d} → first principal component (PC)

x_{d} → first PC coefficient

3. COMPACT MEASURED BRDF MODEL

- Diffuse
- Directly do PCA on the diffuse parts of all MERL BRDFs
- No mean subtraction in PCA

$$\rho_{\mathrm{d}} = Q_{\mathrm{d}} \cdot x_{\mathrm{d}}$$

Q_{d} → first principal component (PC)

x_{d} → first PC coefficient

3. COMPACT MEASURED BRDF MODEL

- Diffuse
- Directly do PCA on the diffuse parts of all MERL BRDFs
- No mean subtraction in PCA

$$\rho_\mathrm{d} = Q_\mathrm{d} \cdot x_\mathrm{d}$$

Q_d → first principal component (PC)

x_d → first PC coefficient

↕

$$\rho_\mathrm{d}(\alpha_\mathrm{d}) = \frac{\alpha_\mathrm{d}}{\pi}$$

- Direct connection to Lambertian parameter.

3. COMPACT MEASURED BRDF MODEL

- Diffuse
- Directly do PCA on the diffuse parts of all MERL BRDFs
- No mean subtraction in PCA

$$\rho_{\mathrm{d}} = Q_{\mathrm{d}} \cdot x_{\mathrm{d}}$$

Q_{d} → first principal component (PC)

x_{d} → first PC coefficient

$$\alpha_{\mathrm{d}} = \frac{\pi \cdot \|Q_{\mathrm{d}}\|_2^2}{\|Q_{\mathrm{d}}\|_1} \cdot x_{\mathrm{d}}$$

$$\rho_{\mathrm{d}}(\alpha_{\mathrm{d}}) = \frac{\alpha_{\mathrm{d}}}{\pi}$$

- Direct connection to Lambertian parameter.

3. COMPACT MEASURED BRDF MODEL

3. COMPACT MEASURED BRDF MODEL

- Specular

3. COMPACT MEASURED BRDF MODEL

- Specular
- Perform PCA on log-mapped BRDF value $g(\rho_{\mathrm{s}})$

3. COMPACT MEASURED BRDF MODEL

- Specular
- Perform PCA on log-mapped BRDF value $g(\rho_{\mathrm{s}})$

$$g(\rho_{\mathrm{s}}) = \log\left(\rho_{\mathrm{s}} \cos(\mathbf{n} \cdot \boldsymbol{\omega}_{\mathbf{i}}) \cos(\mathbf{n} \cdot \boldsymbol{\omega}_{\mathbf{o}}) + \varepsilon\right)$$

3. COMPACT MEASURED BRDF MODEL

- Specular
- Perform PCA on log-mapped BRDF value $g(\rho_\mathrm{s})$

$$\rho_\mathrm{s} = g^{-1}\left(\mathbf{Q}_\mathrm{s} \cdot \mathbf{x}_\mathrm{s} + \mu_\mathrm{s}\right)$$

$$g(\rho_\mathrm{s}) = \log\left(\rho_\mathrm{s} \cos(\mathbf{n} \cdot \boldsymbol{\omega}_\mathbf{i}) \cos(\mathbf{n} \cdot \boldsymbol{\omega}_\mathbf{o}) + \varepsilon\right)$$

3. COMPACT MEASURED BRDF MODEL

- Specular
- Perform PCA on log-mapped BRDF value $g(\rho_\mathrm{s})$

$$\rho_\mathrm{s} = g^{-1}\left(\mathbf{Q}_\mathrm{s} \cdot \mathbf{x}_\mathrm{s} + \mu_\mathrm{s}\right)$$

- $\mathbf{Q}_\mathrm{s}$: principal components (PCs)
- $\mathbf{x}_\mathrm{s}$: PC coefficients
- μ_s: average of mapped BRDF

$$g(\rho_\mathrm{s}) = \log\left(\rho_\mathrm{s}\cos(\mathbf{n}\cdot\boldsymbol{\omega}_\mathbf{i})\cos(\mathbf{n}\cdot\boldsymbol{\omega}_\mathbf{o}) + \varepsilon\right)$$

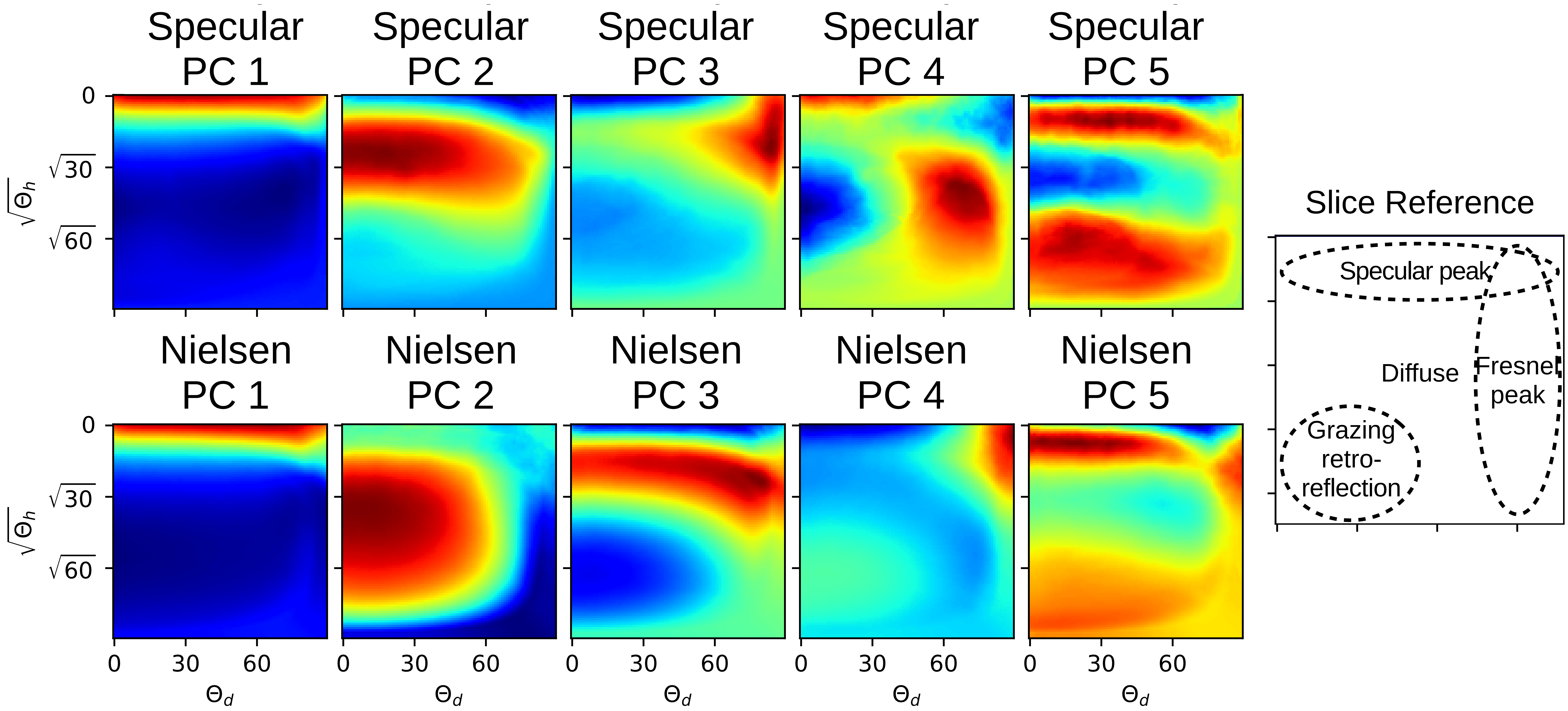
3. COMPACT MEASURED BRDF MODEL

➤ Specular

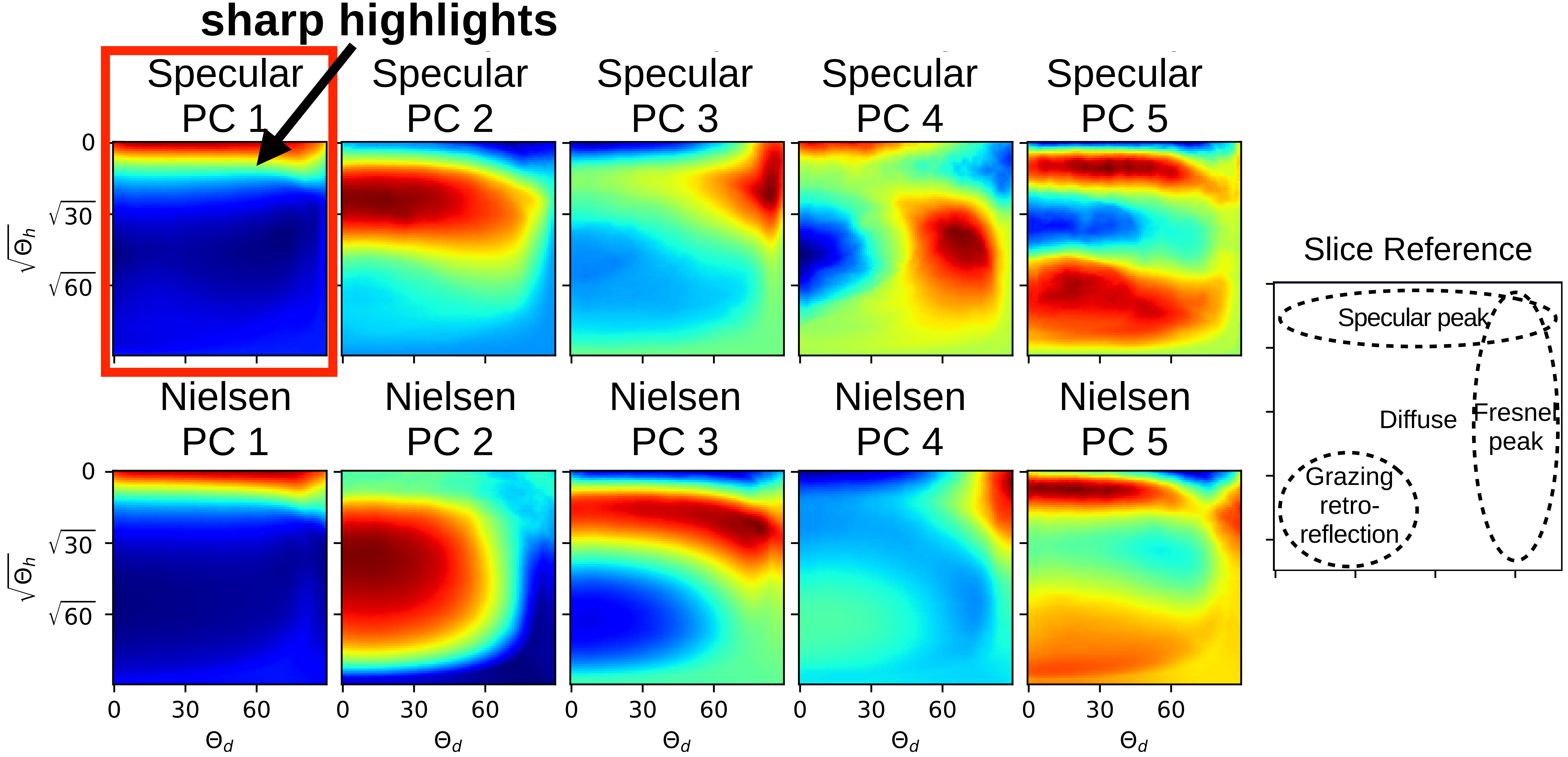
3. COMPACT MEASURED BRDF MODEL

➤ Specular

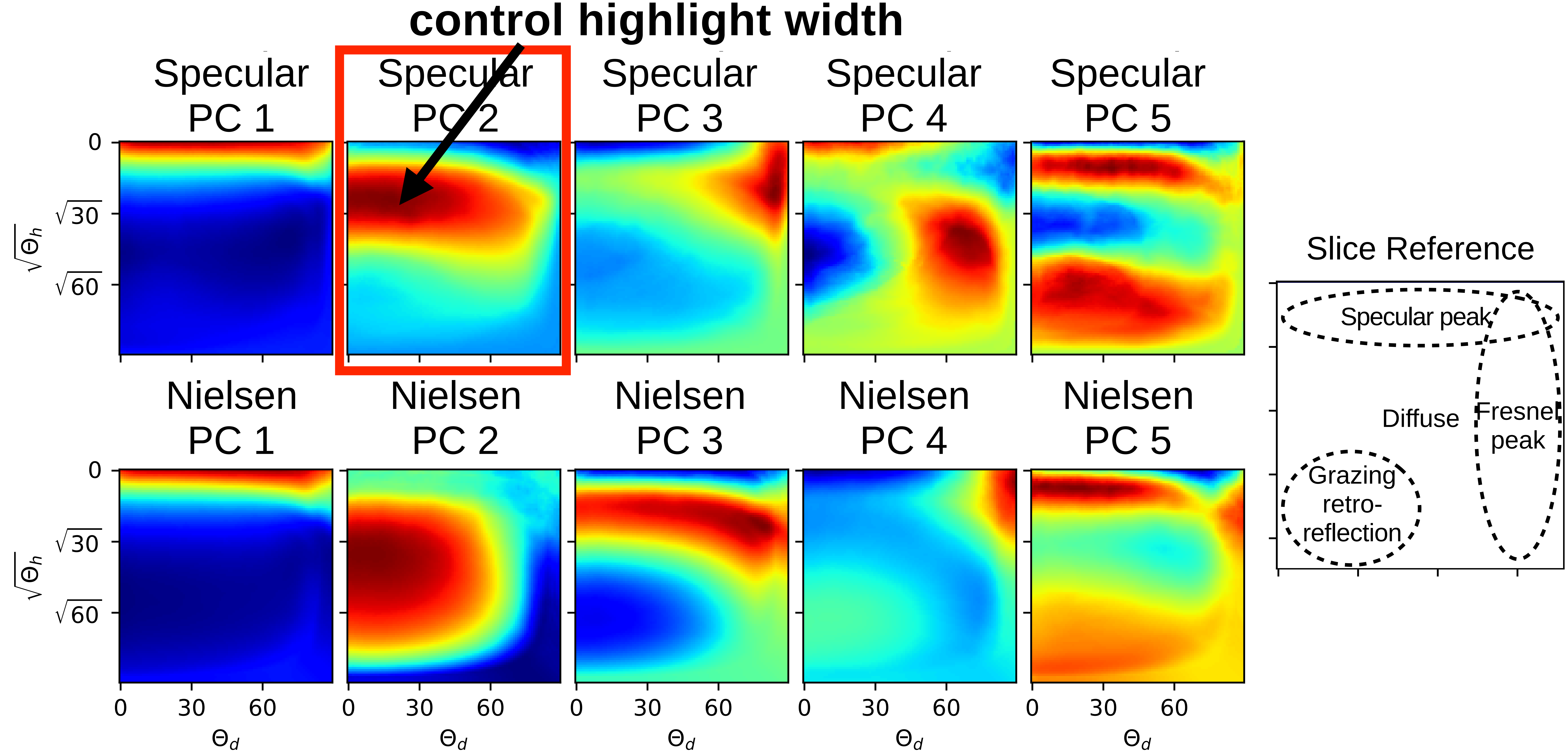
3. COMPACT MEASURED BRDF MODEL



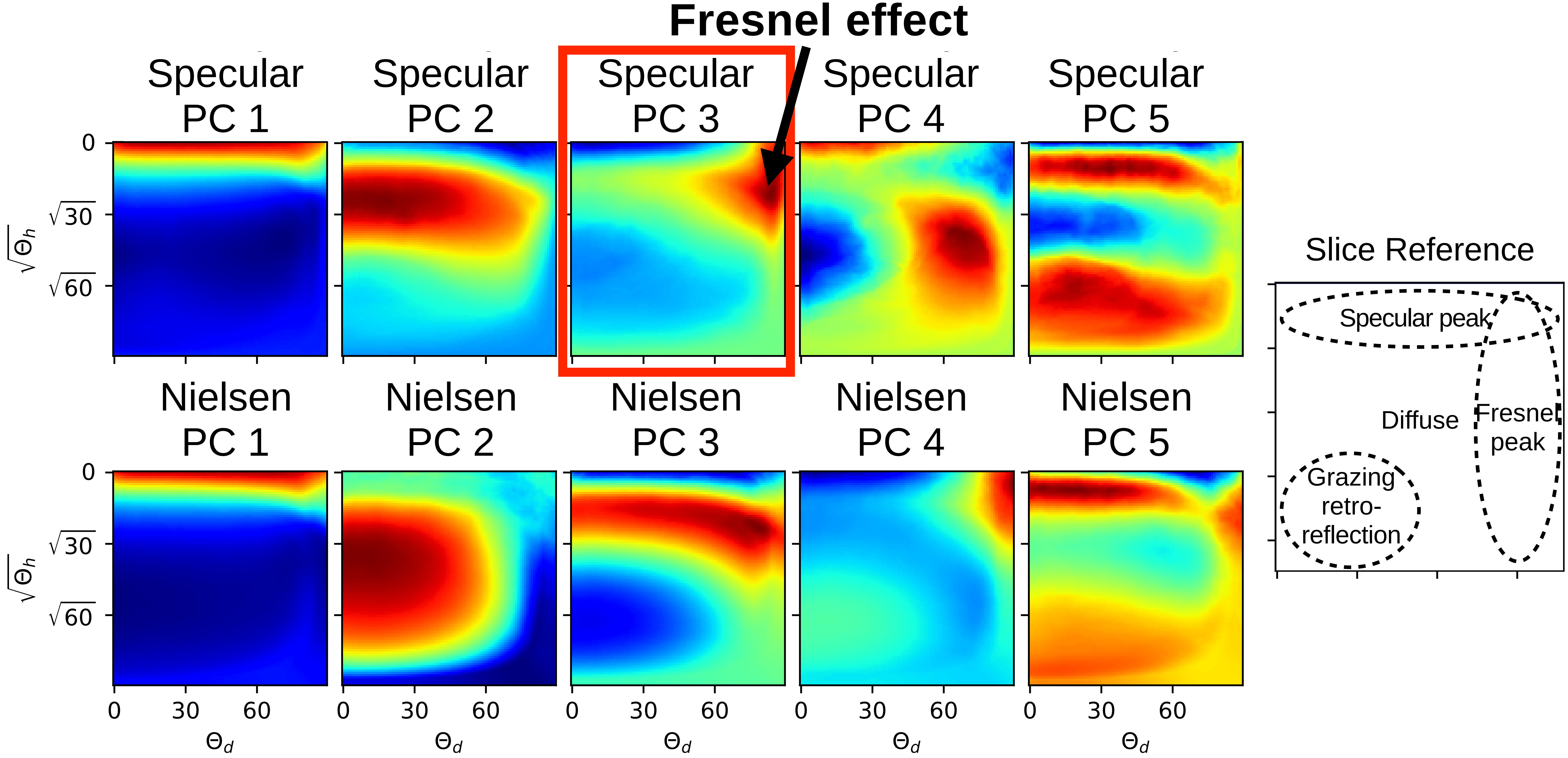
3. COMPACT MEASURED BRDF MODEL



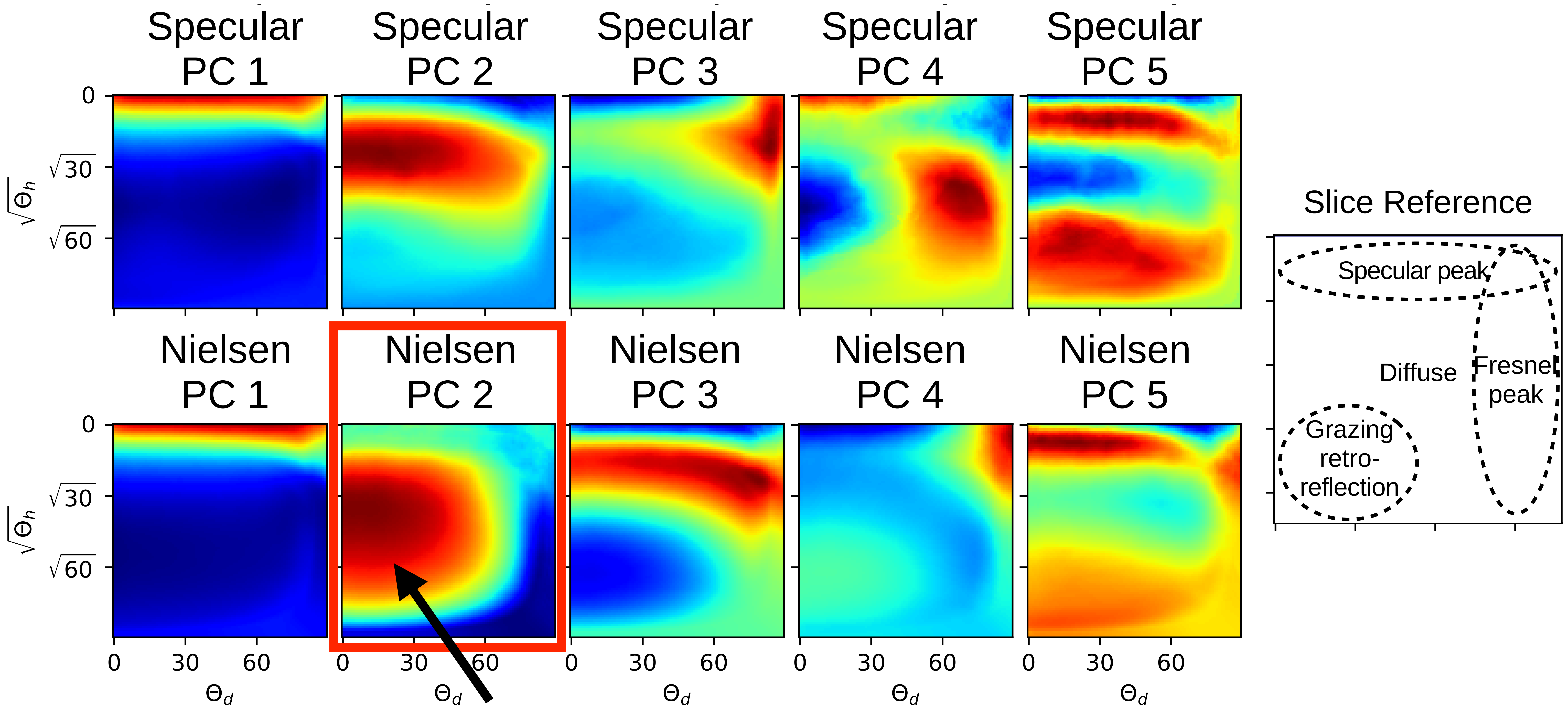
3. COMPACT MEASURED BRDF MODEL



3. COMPACT MEASURED BRDF MODEL



3. COMPACT MEASURED BRDF MODEL



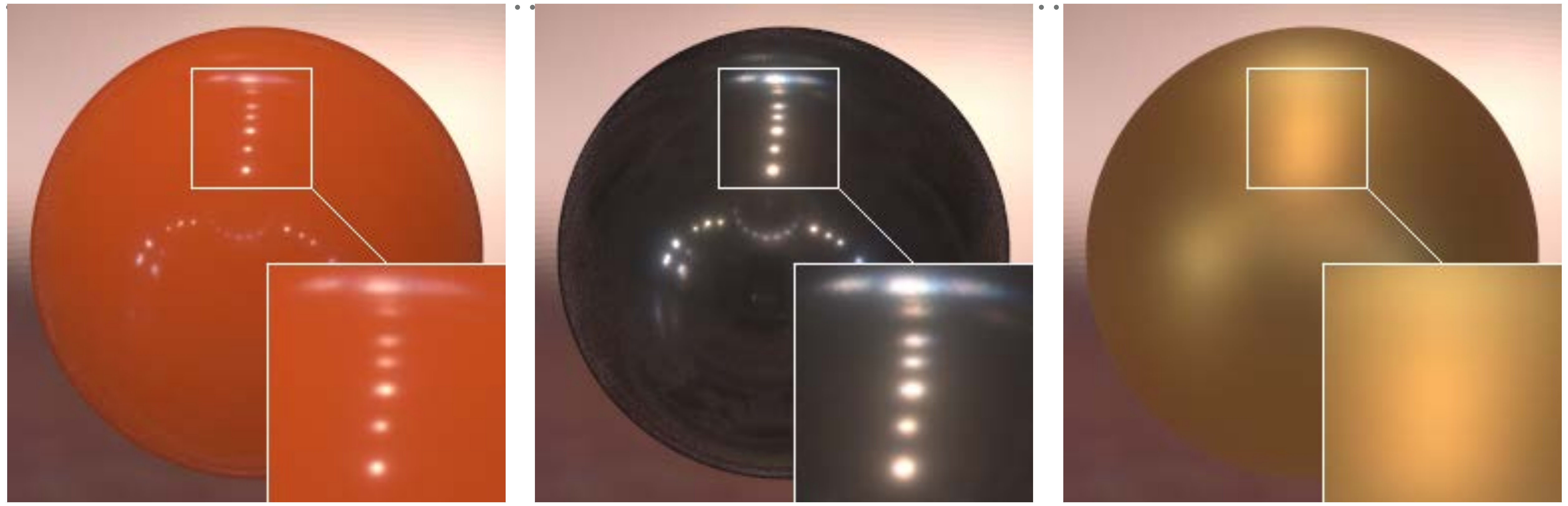
mix diffuse and specular

3. COMPACT MEASURED BRDF MODEL

3. COMPACT MEASURED BRDF MODEL

Original BRDF

~3 million values



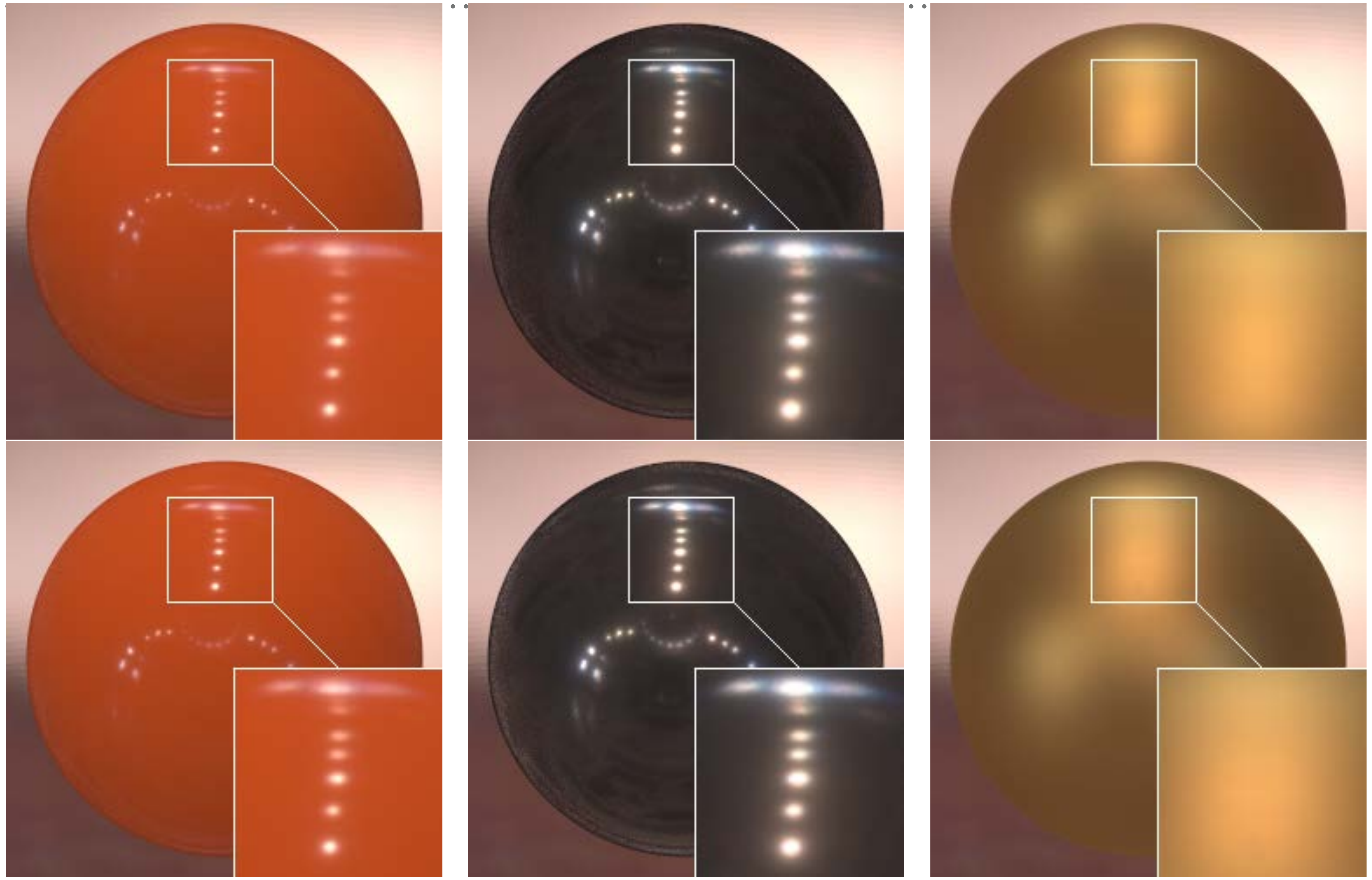
3. COMPACT MEASURED BRDF MODEL

Original BRDF

~3 million values

Our result

8 coefficients
(2 for diffuse color, 1 for diffuse PC,
2 for specular color, 3 for specular PCs)



3. COMPACT MEASURED BRDF MODEL

Original BRDF

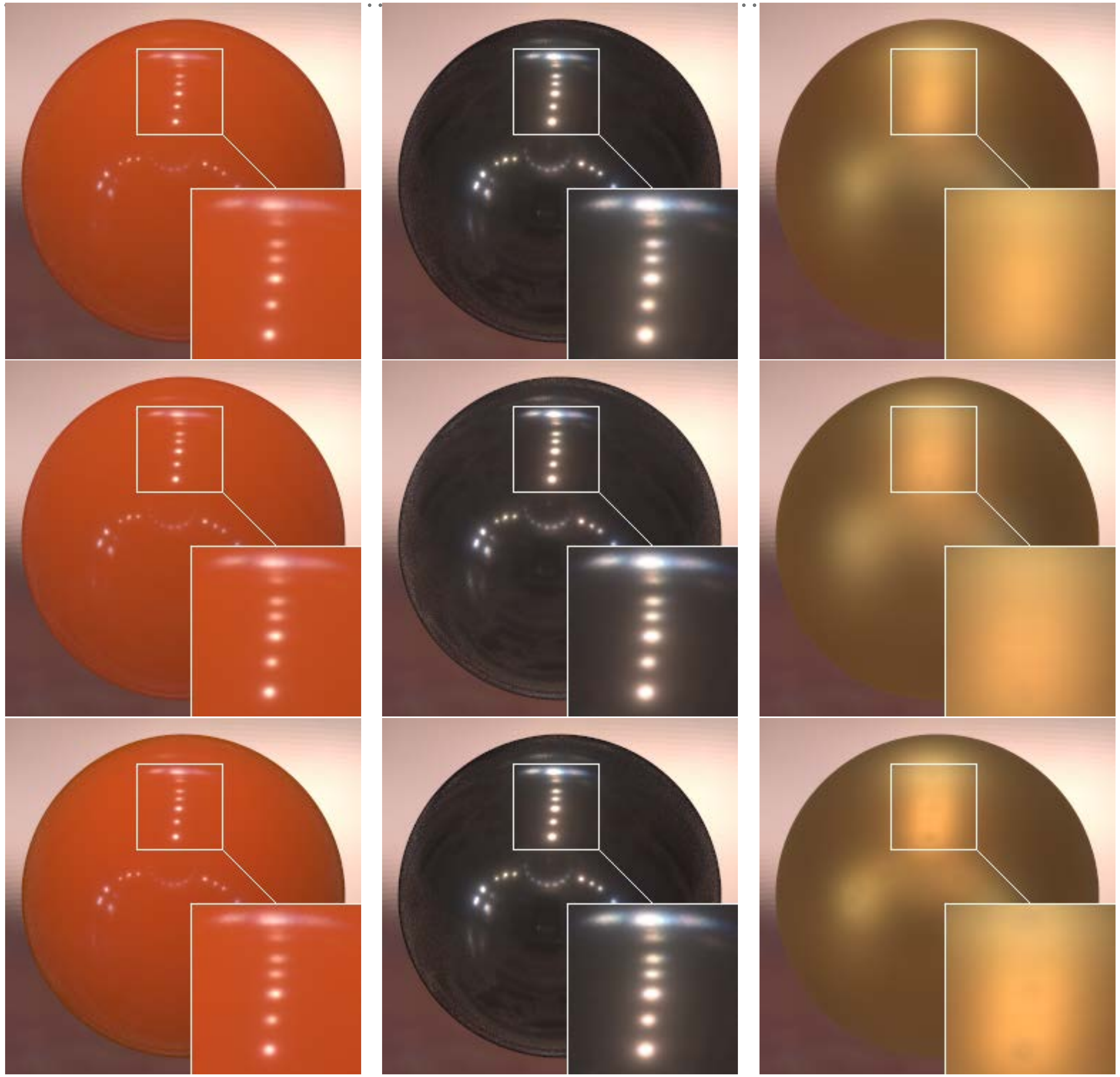
~3 million values

Our result

8 coefficients
(2 for diffuse color, 1 for diffuse PC,
2 for specular color, 3 for specular PCs)

Nielsen *et al.*

15 coefficients
(5 for each color channel)



3. COMPACT MEASURED BRDF MODEL

Original BRDF

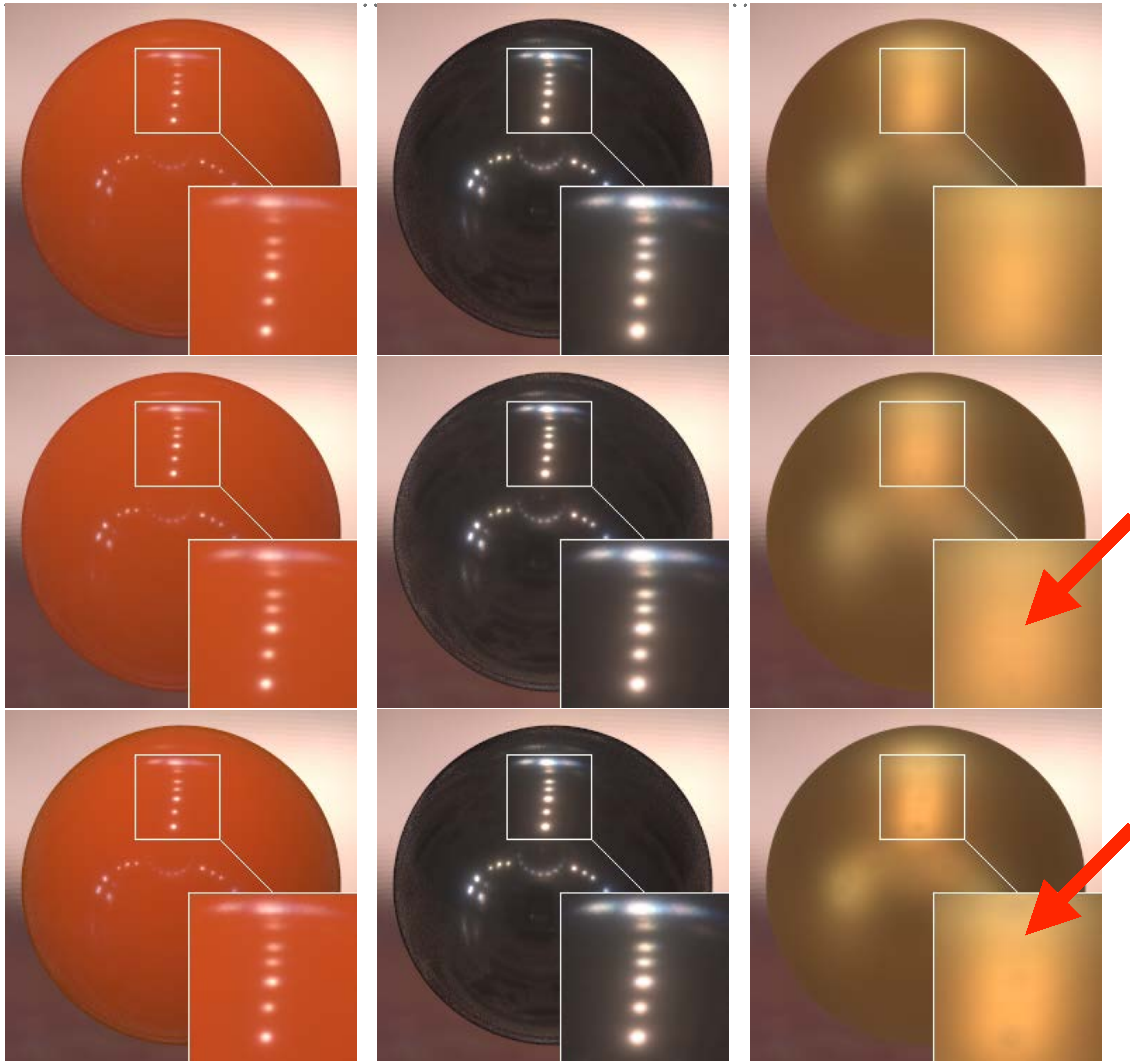
~3 million values

Our result

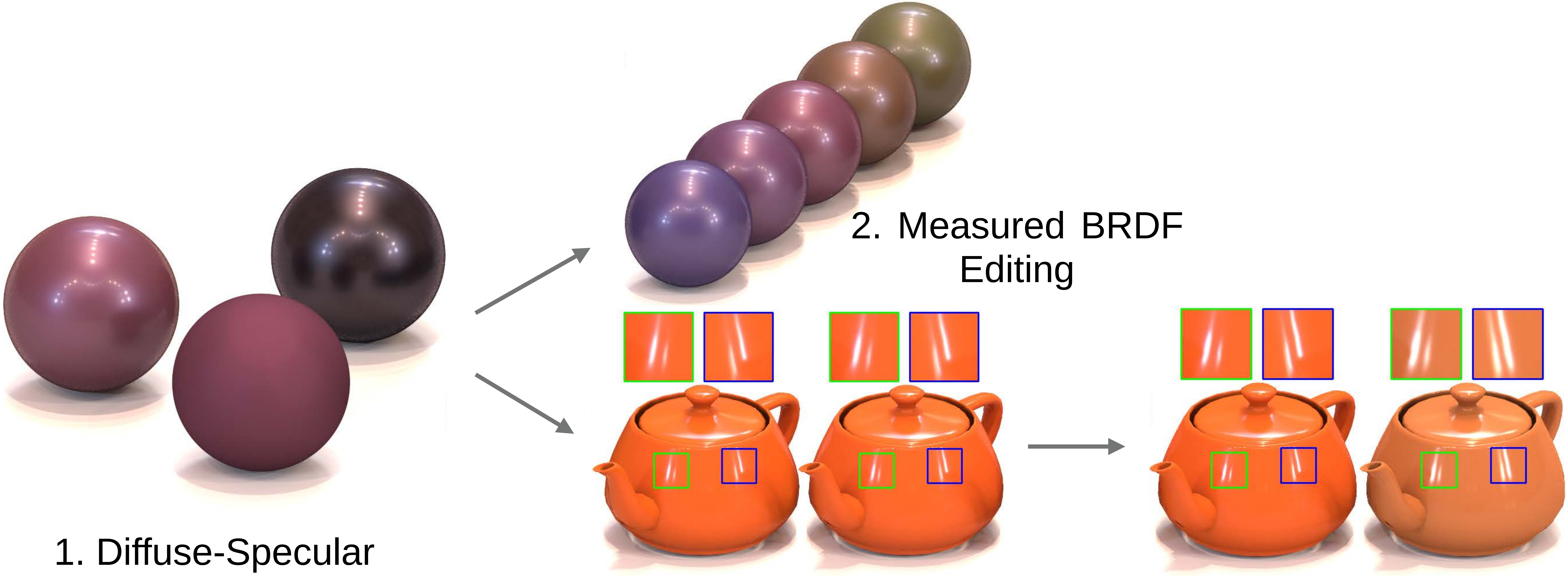
8 coefficients
(2 for diffuse color, 1 for diffuse PC,
2 for specular color, 3 for specular PCs)

Nielsen *et al.*

15 coefficients
(5 for each color channel)

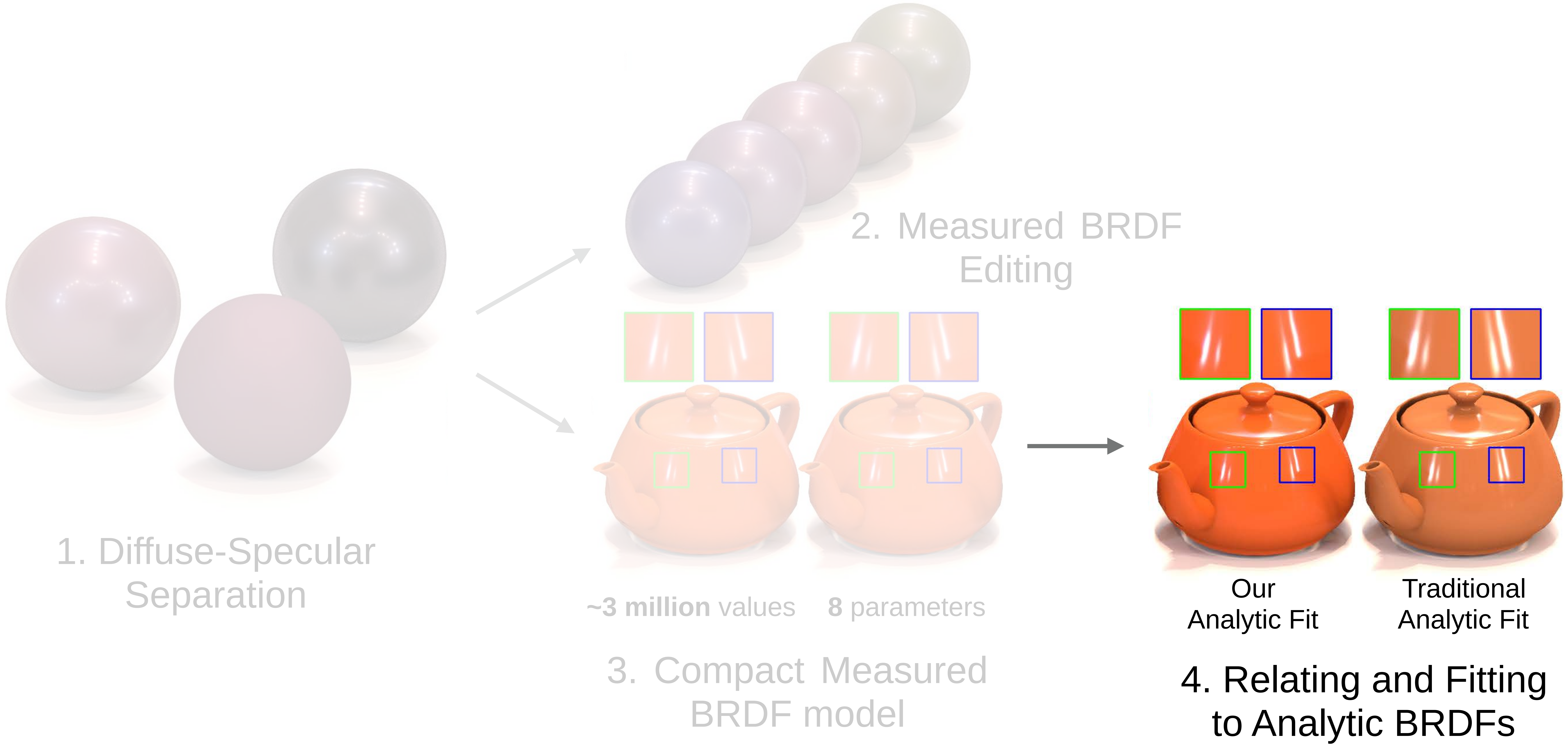


OVERVIEW



1. Diffuse-Specular Separation
2. Measured BRDF Editing
~3 million values
8 parameters
3. Compact Measured BRDF model
Our Analytic Fit
Traditional Analytic Fit
4. Relating and Fitting to Analytic BRDFs

OVERVIEW


2. Measured BRDF Editing
~3 million values
8 parameters
Our Analytic Fit
Traditional Analytic Fit
1. Diffuse-Specular Separation
3. Compact Measured BRDF model
4. Relating and Fitting to Analytic BRDFs

4. RELATING AND FITTING TO ANALYTIC BRDFS

Measured BRDF

Analytic BRDF

4. RELATING AND FITTING TO ANALYTIC BRDFS

Measured BRDF	Analytic BRDF
8 coefficients	8 parameter

4. RELATING AND FITTING TO ANALYTIC BRDFS

SIGGRAPH ASIA 2018 TOKYO

Measured BRDF

8 coefficients

$$Q_{\mathrm{d}} x_{\mathrm{d}} \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + g^{-1}\left(\mathbf{Q}_{\mathrm{s}} \cdot \mathbf{x}_{\mathrm{s}} + \mu_{\mathrm{s}}\right) \cdot \mathbf{c}_{\mathrm{s}}(\lambda)$$

Analytic BRDF

8 parameter

$$\rho_{\mathrm{d}}(\alpha_{\mathrm{d}}) \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}(\alpha_{\mathrm{s}}) \cdot \mathbf{c}_{\mathrm{s}}(\lambda)$$

4. RELATING AND FITTING TO ANALYTIC BRDFS

Measured BRDF

8 coefficients

$$Q_{\mathrm{d}} x_{\mathrm{d}} \cdot \underline{\mathbf{c}_{\mathrm{d}}(\lambda)} + g^{-1}\left(\mathbf{Q}_{\mathrm{s}} \cdot \mathbf{x}_{\mathrm{s}} + \mu_{\mathrm{s}}\right) \cdot \mathbf{c}_{\mathrm{s}}(\lambda)$$

2 for diffuse color $\mathbf{c}_{\mathrm{d}}(\lambda)$

Analytic BRDF

8 parameter

$$\rho_{\mathrm{d}}(\alpha_{\mathrm{d}}) \cdot \underline{\mathbf{c}_{\mathrm{d}}(\lambda)} + \rho_{\mathrm{s}}(\alpha_{\mathrm{s}}) \cdot \mathbf{c}_{\mathrm{s}}(\lambda)$$

2 for diffuse color $\mathbf{c}_{\mathrm{d}}(\lambda)$

4. RELATING AND FITTING TO ANALYTIC BRDFS

Measured BRDF

8 coefficients

$$Q_{\mathrm{d}} x_{\mathrm{d}} \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + g^{-1}\left(\mathbf{Q}_{\mathrm{s}} \cdot \mathbf{x}_{\mathrm{s}} + \mu_{\mathrm{s}}\right) \cdot \underline{\mathbf{c}_{\mathrm{s}}(\lambda)}$$

2 for diffuse color $\mathbf{c}_{\mathrm{d}}(\lambda)$

2 for specular color $\mathbf{c}_{\mathrm{s}}(\lambda)$

Analytic BRDF

8 parameter

$$\rho_{\mathrm{d}}(\alpha_{\mathrm{d}}) \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}(\alpha_{\mathrm{s}}) \cdot \underline{\mathbf{c}_{\mathrm{s}}(\lambda)}$$

2 for diffuse color $\mathbf{c}_{\mathrm{d}}(\lambda)$

2 for specular color $\mathbf{c}_{\mathrm{s}}(\lambda)$

4. RELATING AND FITTING TO ANALYTIC BRDFS

SIGGRAPH ASIA 2018 TOKYO

Measured BRDF	Analytic BRDF
8 coefficients	8 parameter
$Q_{\mathrm{d}} \underline{x_{\mathrm{d}}} \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + g^{-1}(\mathbf{Q}_{\mathrm{s}} \cdot \mathbf{x}_{\mathrm{s}} + \mu_{\mathrm{s}}) \cdot \mathbf{c}_{\mathrm{s}}(\lambda)$	$\rho_{\mathrm{d}}(\underline{\alpha_{\mathrm{d}}}) \cdot \mathbf{c}_{\mathrm{d}}(\lambda) + \rho_{\mathrm{s}}(\alpha_{\mathrm{s}}) \cdot \mathbf{c}_{\mathrm{s}}(\lambda)$
2 for diffuse color $\mathbf{c}_{\mathrm{d}}(\lambda)$	2 for diffuse color $\mathbf{c}_{\mathrm{d}}(\lambda)$
2 for specular color $\mathbf{c}_{\mathrm{s}}(\lambda)$	2 for specular color $\mathbf{c}_{\mathrm{s}}(\lambda)$
1 for diffuse PC coefficient x_{d}	1 for Lambertian intensity α_{d}

4. RELATING AND FITTING TO ANALYTIC BRDFS

Measured BRDF

8 coefficients

$$Q_\mathrm{d} x_\mathrm{d} \cdot \mathbf{c}_\mathrm{d}(\lambda) + g^{-1}\left(\mathbf{Q}_\mathrm{s} \cdot \underline{\mathbf{x}_\mathrm{s}} + \mu_\mathrm{s}\right) \cdot \mathbf{c}_\mathrm{s}(\lambda)$$

2 for diffuse color $\mathbf{c}_\mathrm{d}(\lambda)$

2 for specular color $\mathbf{c}_\mathrm{s}(\lambda)$

1 for diffuse PC coefficient x_d

3 for specular PC coefficients $\mathbf{x}_\mathrm{s}$

Analytic BRDF

8 parameter

$$\rho_\mathrm{d}(\alpha_\mathrm{d}) \cdot \mathbf{c}_\mathrm{d}(\lambda) + \rho_\mathrm{s}(\underline{\alpha_\mathrm{s}}) \cdot \mathbf{c}_\mathrm{s}(\lambda)$$

2 for diffuse color $\mathbf{c}_\mathrm{d}(\lambda)$

2 for specular color $\mathbf{c}_\mathrm{s}(\lambda)$

1 for Lambertian intensity α_d

3 for GGX parameters α_s

4. RELATING AND FITTING TO ANALYTIC BRDFS

Measured BRDF		Analytic BRDF
8 coefficients		8 parameter
$Q_\mathrm{d} x_\mathrm{d} \cdot \mathbf{c}_\mathrm{d}(\lambda) + g^{-1}\left(\mathbf{Q}_\mathrm{s} \cdot \mathbf{x}_\mathrm{s} + \mu_\mathrm{s}\right) \cdot \mathbf{c}_\mathrm{s}(\lambda)$		$\rho_\mathrm{d}(\alpha_\mathrm{d}) \cdot \mathbf{c}_\mathrm{d}(\lambda) + \rho_\mathrm{s}(\alpha_\mathrm{s}) \cdot \mathbf{c}_\mathrm{s}(\lambda)$
2 for diffuse color $\mathbf{c}_\mathrm{d}(\lambda)$	√ ⟷	2 for diffuse color $\mathbf{c}_\mathrm{d}(\lambda)$
2 for specular color $\mathbf{c}_\mathrm{s}(\lambda)$		2 for specular color $\mathbf{c}_\mathrm{s}(\lambda)$
1 for diffuse PC coefficient x_d		1 for Lambertian intensity α_d
3 for specular PC coefficients $\mathbf{x}_\mathrm{s}$		3 for GGX parameters α_s

4. RELATING AND FITTING TO ANALYTIC BRDFS

Measured BRDF		Analytic BRDF
8 coefficients		8 parameter
$Q_\mathrm{d} x_\mathrm{d} \cdot \mathbf{c}_\mathrm{d}(\lambda) + g^{-1}\left(\mathbf{Q}_\mathrm{s} \cdot \mathbf{x}_\mathrm{s} + \mu_\mathrm{s}\right) \cdot \mathbf{c}_\mathrm{s}(\lambda)$		$\rho_\mathrm{d}(\alpha_\mathrm{d}) \cdot \mathbf{c}_\mathrm{d}(\lambda) + \rho_\mathrm{s}(\alpha_\mathrm{s}) \cdot \mathbf{c}_\mathrm{s}(\lambda)$
2 for diffuse color $\mathbf{c}_\mathrm{d}(\lambda)$	√	2 for diffuse color $\mathbf{c}_\mathrm{d}(\lambda)$
2 for specular color $\mathbf{c}_\mathrm{s}(\lambda)$		2 for specular color $\mathbf{c}_\mathrm{s}(\lambda)$
1 for diffuse PC coefficient x_d	√	1 for Lambertian intensity α_d
3 for specular PC coefficients $\mathbf{x}_\mathrm{s}$		3 for GGX parameters α_s

4. RELATING AND FITTING TO ANALYTIC BRDFS

SIGGRAPH ASIA 2018 TOKYO

Measured BRDF		Analytic BRDF
8 coefficients		8 parameter
$Q_\mathrm{d} x_\mathrm{d} \cdot \mathbf{c}_\mathrm{d}(\lambda) + g^{-1}\left(\mathbf{Q}_\mathrm{s} \cdot \mathbf{x}_\mathrm{s} + \mu_\mathrm{s}\right) \cdot \mathbf{c}_\mathrm{s}(\lambda)$		$\rho_\mathrm{d}(\alpha_\mathrm{d}) \cdot \mathbf{c}_\mathrm{d}(\lambda) + \rho_\mathrm{s}(\alpha_\mathrm{s}) \cdot \mathbf{c}_\mathrm{s}(\lambda)$
2 for diffuse color $\mathbf{c}_\mathrm{d}(\lambda)$	√ ⟷	2 for diffuse color $\mathbf{c}_\mathrm{d}(\lambda)$
2 for specular color $\mathbf{c}_\mathrm{s}(\lambda)$		2 for specular color $\mathbf{c}_\mathrm{s}(\lambda)$
1 for diffuse PC coefficient x_d	√ ⟷	1 for Lambertian intensity α_d
3 for specular PC coefficients $\mathbf{x}_\mathrm{s}$	? ⟷	3 for GGX parameters α_s

4. RELATING AND FITTING TO ANALYTIC BRDFS

4. RELATING AND FITTING TO ANALYTIC BRDFS

- ➤ Measured specular BRDF specified using 3 PC coefficients

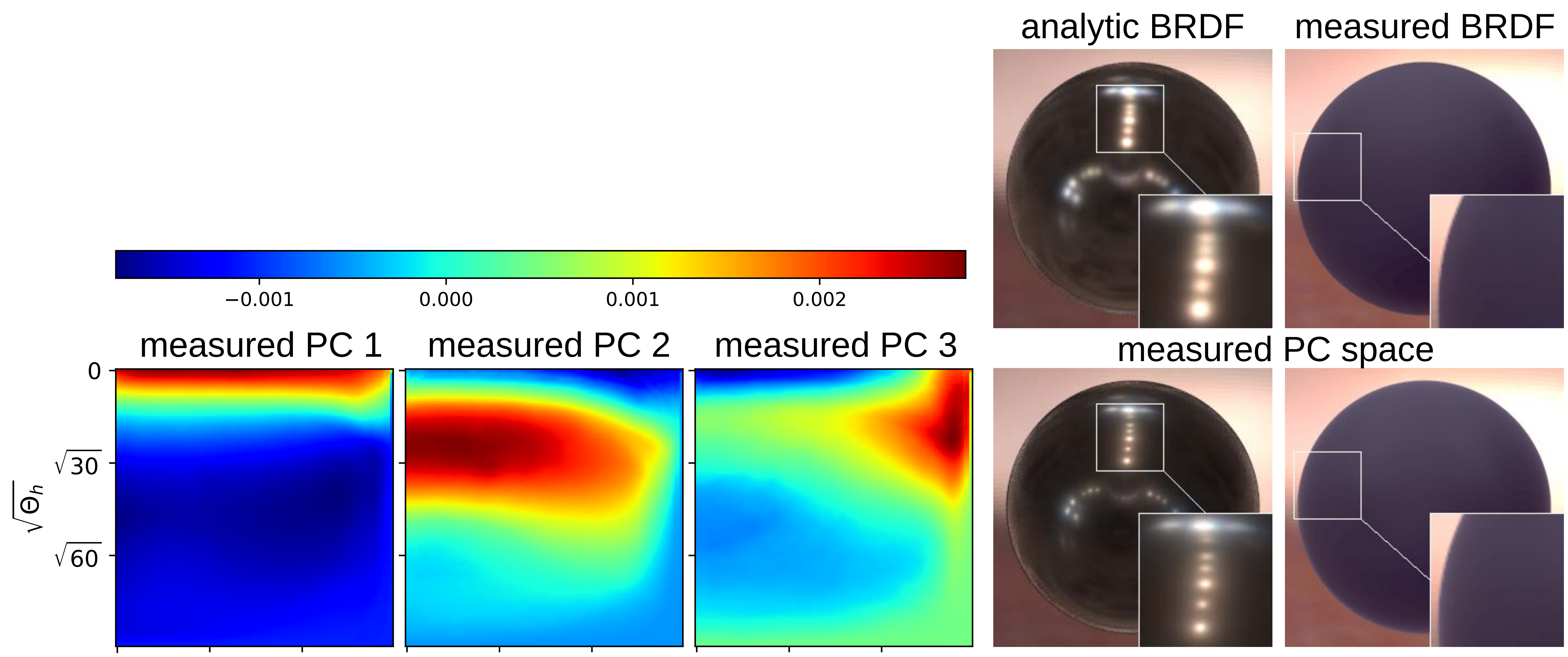
4. RELATING AND FITTING TO ANALYTIC BRDFS

- Measured specular BRDF specified using 3 PC coefficients

  embedded in a 3D PC space

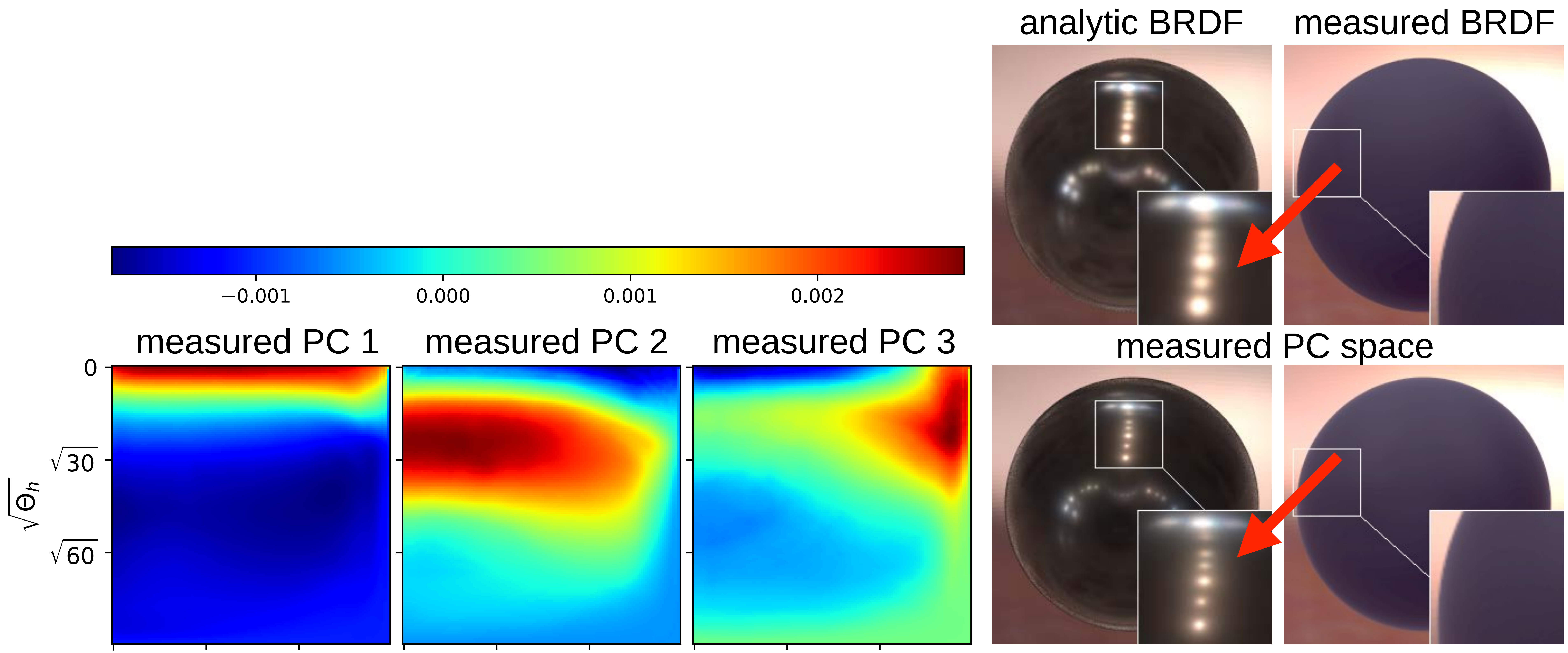
4. RELATING AND FITTING TO ANALYTIC BRDFS

➤ Measured specular BRDF specified using 3 PC coefficients embedded in a 3D PC space



4. RELATING AND FITTING TO ANALYTIC BRDFS

- Measured specular BRDF specified using 3 PC coefficients embedded in a 3D PC space



4. RELATING AND FITTING TO ANALYTIC BRDFS

- Measured specular BRDF specified using 3 PC coefficients
  embedded in a 3D PC space

- Data:specular parts of 100 measured BRDFs

4. RELATING AND FITTING TO ANALYTIC BRDFS

- Measured specular BRDF specified using 3 PC coefficients
  embedded in a 3D PC space

- Data:specular parts of 100 measured BRDFs

$$\rho_{\mathrm{s}} = g^{-1}\left(\mathbf{Q}_{\mathrm{s}} \cdot \mathbf{x}_{\mathrm{s}} + \mu_{\mathrm{s}}\right)$$

feature of measured BRDF

4. RELATING AND FITTING TO ANALYTIC BRDFS

- Measured specular BRDF specified using 3 PC coefficients embedded in a 3D PC space

- Data:specular parts of 100 measured BRDFs

$$\rho_\mathrm{s} = g^{-1}\left(\mathbf{Q}_\mathrm{s} \cdot \mathbf{x}_\mathrm{s} + \mu_\mathrm{s}\right)$$

$\mathbf{Q}_\mathrm{s}$ → feature of measured BRDF

- \+ 128 analytic BRDFs sparsely sampled from GGX parameters

4. RELATING AND FITTING TO ANALYTIC BRDFS

SIGGRAPH ASIA 2018 TOKYO

- Measured specular BRDF specified using 3 PC coefficients embedded in a 3D PC space

- Data:specular parts of 100 measured BRDFs

$$\rho_{\mathrm{s}} = g^{-1}\left(\mathbf{Q}_{\mathrm{s}} \cdot \mathbf{x}_{\mathrm{s}} + \mu_{\mathrm{s}}\right)$$

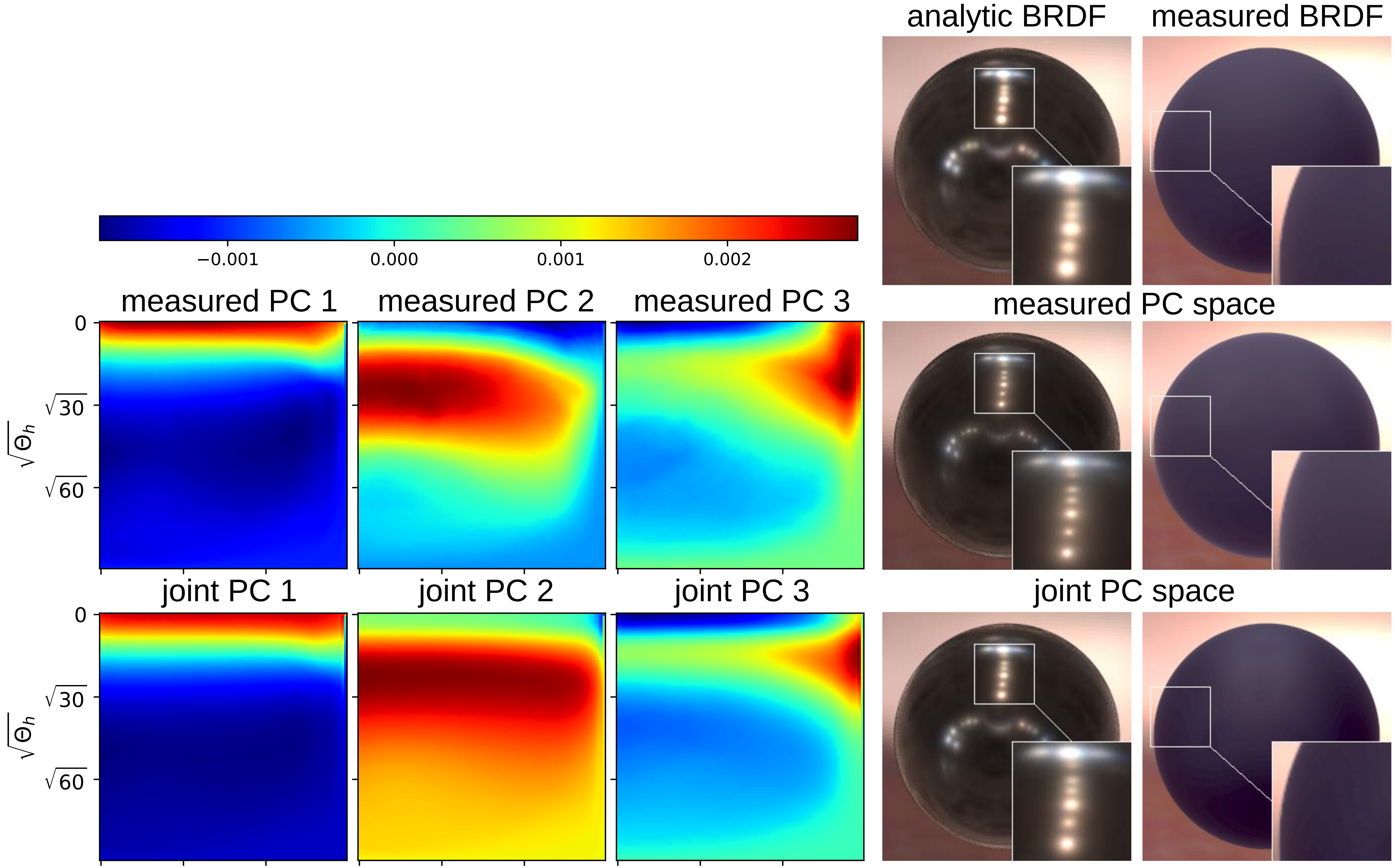
→ feature of measured BRDF

- + 128 analytic BRDFs sparsely sampled from GGX parameters

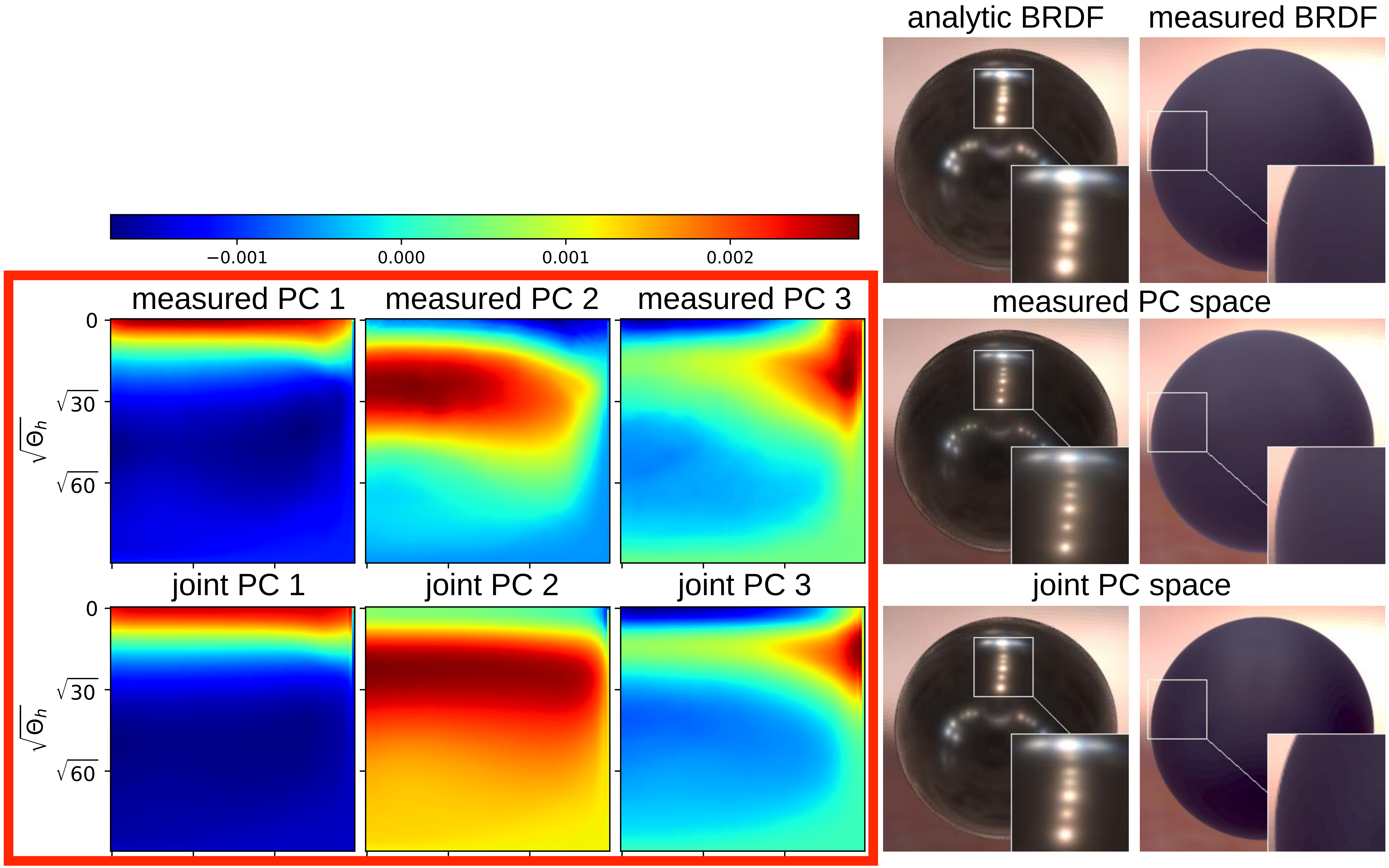
$$\rho_{\mathrm{s}} = g^{-1}\left(\mathbf{Q}_{\mathrm{s,joint}} \cdot \mathbf{x}_{\mathrm{s}} + \mu_{\mathrm{s,joint}}\right) \cdot \mathbf{c}_{\mathrm{s}}$$

→ feature of measured and analytic BRDFs

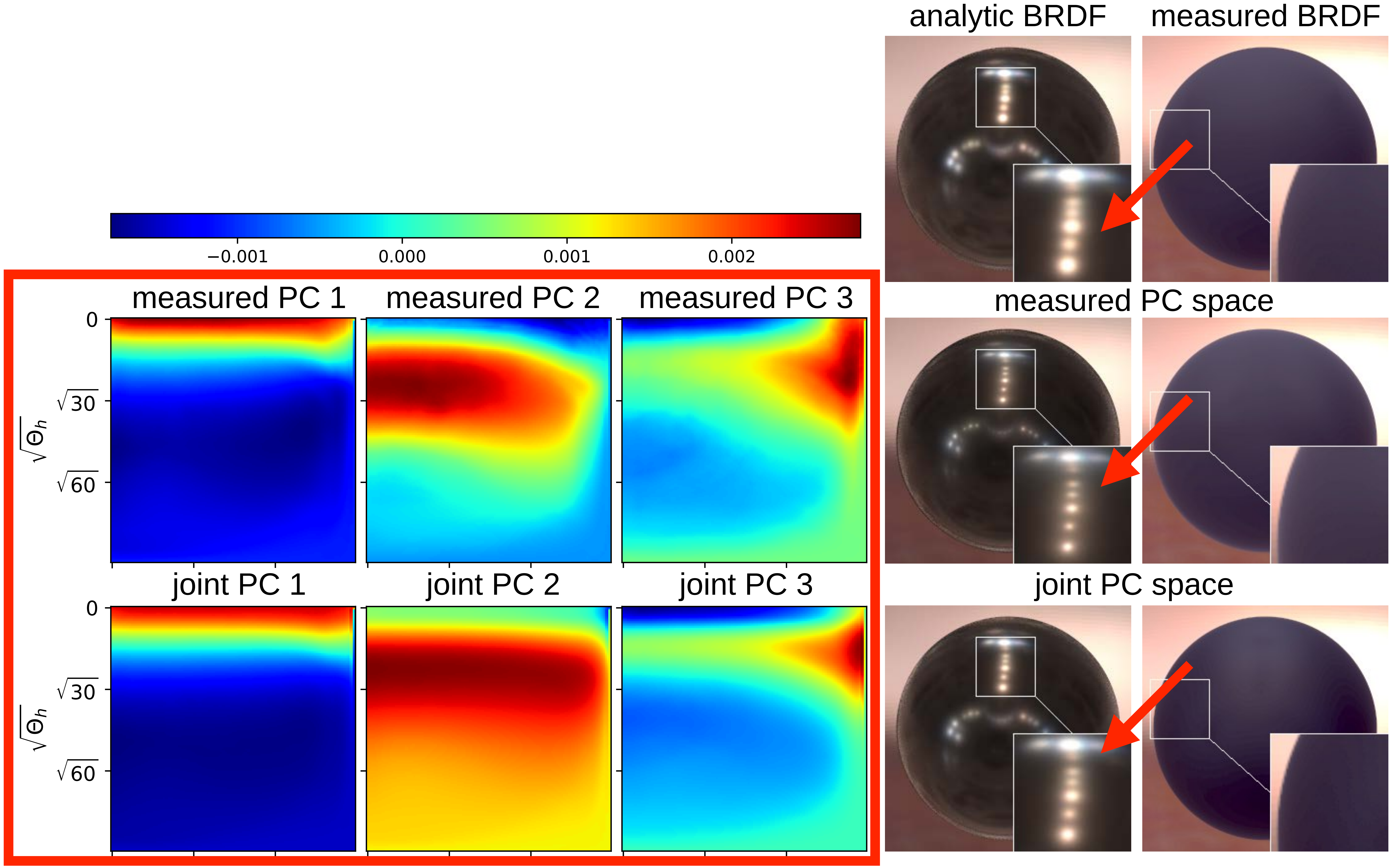
4. RELATING AND FITTING TO ANALYTIC BRDFS



4. RELATING AND FITTING TO ANALYTIC BRDFS



4. RELATING AND FITTING TO ANALYTIC BRDFS



4. RELATING AND FITTING TO ANALYTIC BRDFS

4. RELATING AND FITTING TO ANALYTIC BRDFS

- Project to joint-PC space:

4. RELATING AND FITTING TO ANALYTIC BRDFS

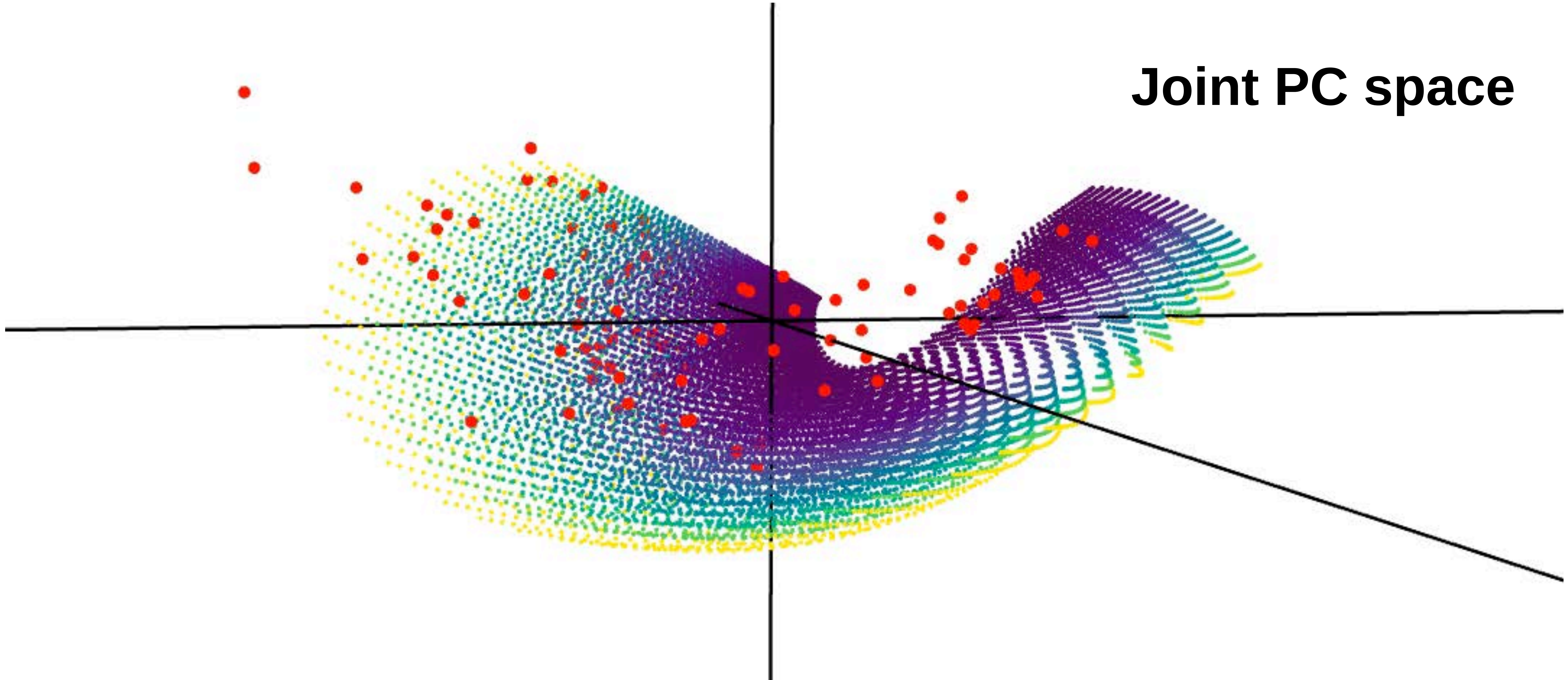
- Project to joint-PC space:
  - specular parts of 100 measured BRDFs

4. RELATING AND FITTING TO ANALYTIC BRDFS

- Project to joint-PC space:
  - specular parts of 100 measured BRDFs
  - 16,000 analytic BRDFs densely sampled from GGX parameters

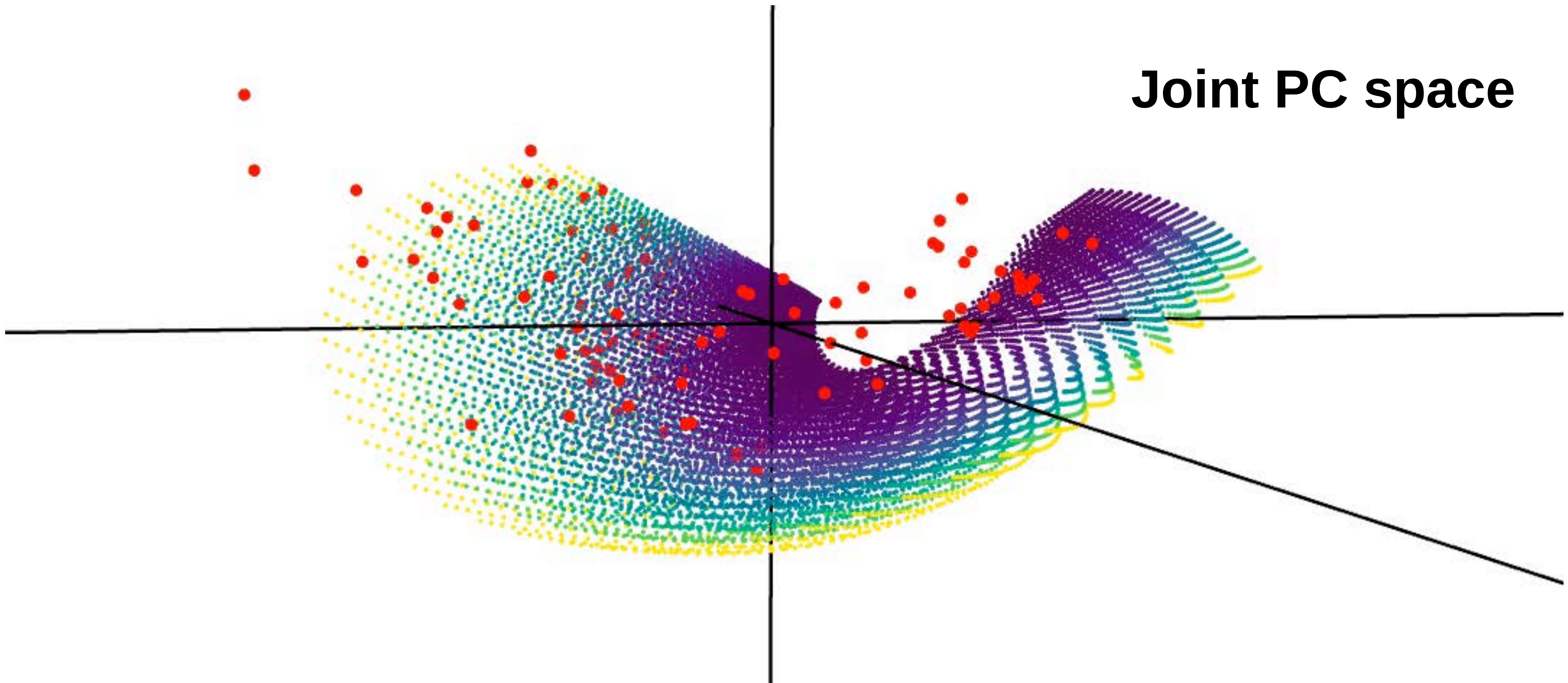
4. RELATING AND FITTING TO ANALYTIC BRDFS

- Project to joint-PC space:
  - specular parts of 100 measured BRDFs
  - 16,000 analytic BRDFs densely sampled from GGX parameters



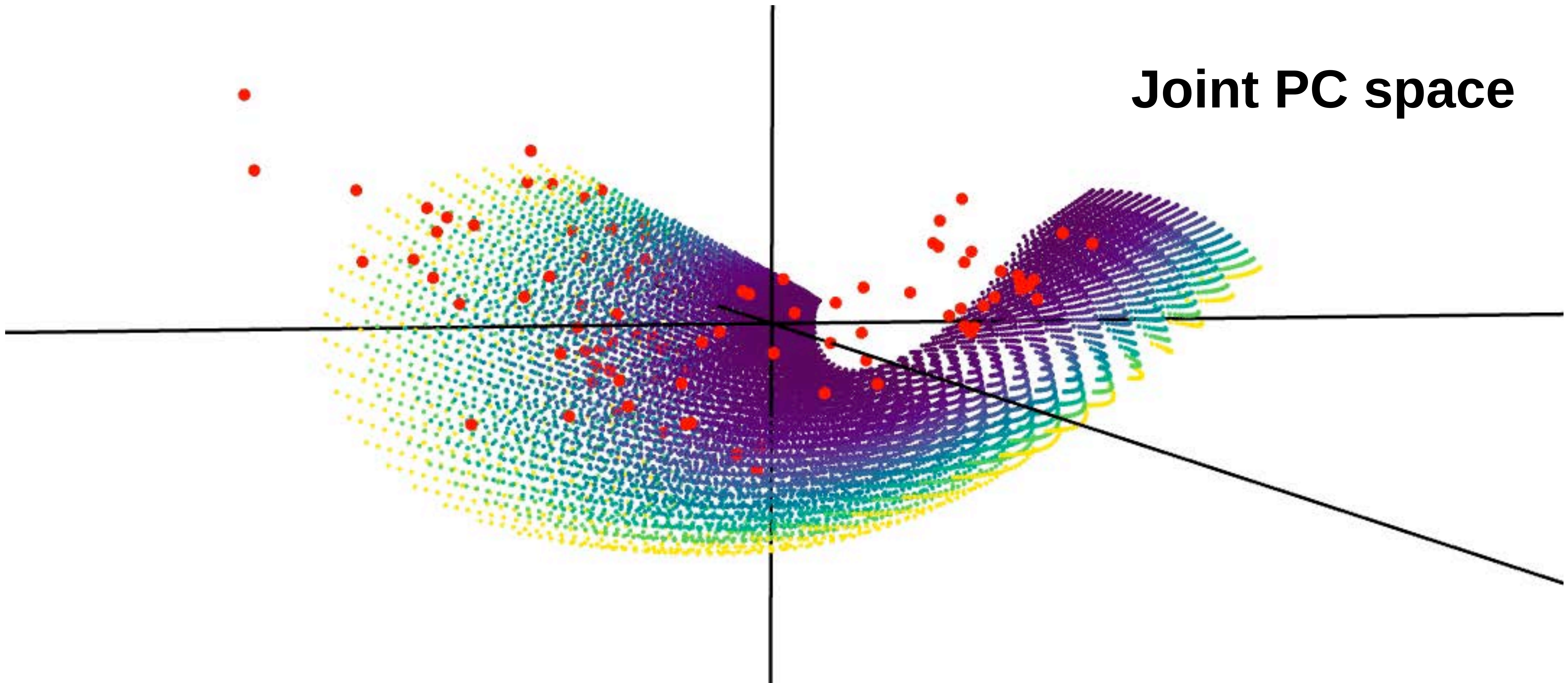
4. RELATING AND FITTING TO ANALYTIC BRDFS

- Project to joint-PC space:
  - specular parts of 100 measured BRDFs (Red points)
  - 16,000 analytic BRDFs densely sampled from GGX parameters (Non-red points)



4. RELATING AND FITTING TO ANALYTIC BRDFS

- Project to joint-PC space:
  - specular parts of 100 measured BRDFs (Red points)
  - 16,000 analytic BRDFs densely sampled from GGX parameters (Non-red points)
    - lie in a thin manifold which looks like a "baseball glove"




Measured BRDF
Analytic BRDF
Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Back View
PC 3
PC 2
PC 1
Top View
PC 2
PC 1


Measured BRDF
Analytic BRDF
Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Back View
PC 3
PC 2
PC 1
Top View
PC 2
PC 1


Measured BRDF
Analytic BRDF
Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Back View
PC 3
PC 2
PC 1
Top View
PC 2
PC 1


Measured BRDF
Analytic BRDF
Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Back View
PC 3
PC 2
PC 1
Top View
PC 2
PC 1

Measured BRDF
Analytic BRDF
Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Back View
PC 3
PC 2
PC 1
Top View
PC 2
PC 1


Measured BRDF
Analytic BRDF
Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Back View
PC 3
PC 2
PC 1
Top View
PC 2
PC 1


Measured BRDF
Analytic BRDF
Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Back View
PC 3
PC 2
PC 1
Top View
PC 2
PC 1

Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Top View
PC 2
PC 1
Measured BRDF
Analytic BRDF
Back View
PC 3
PC 2
PC 1

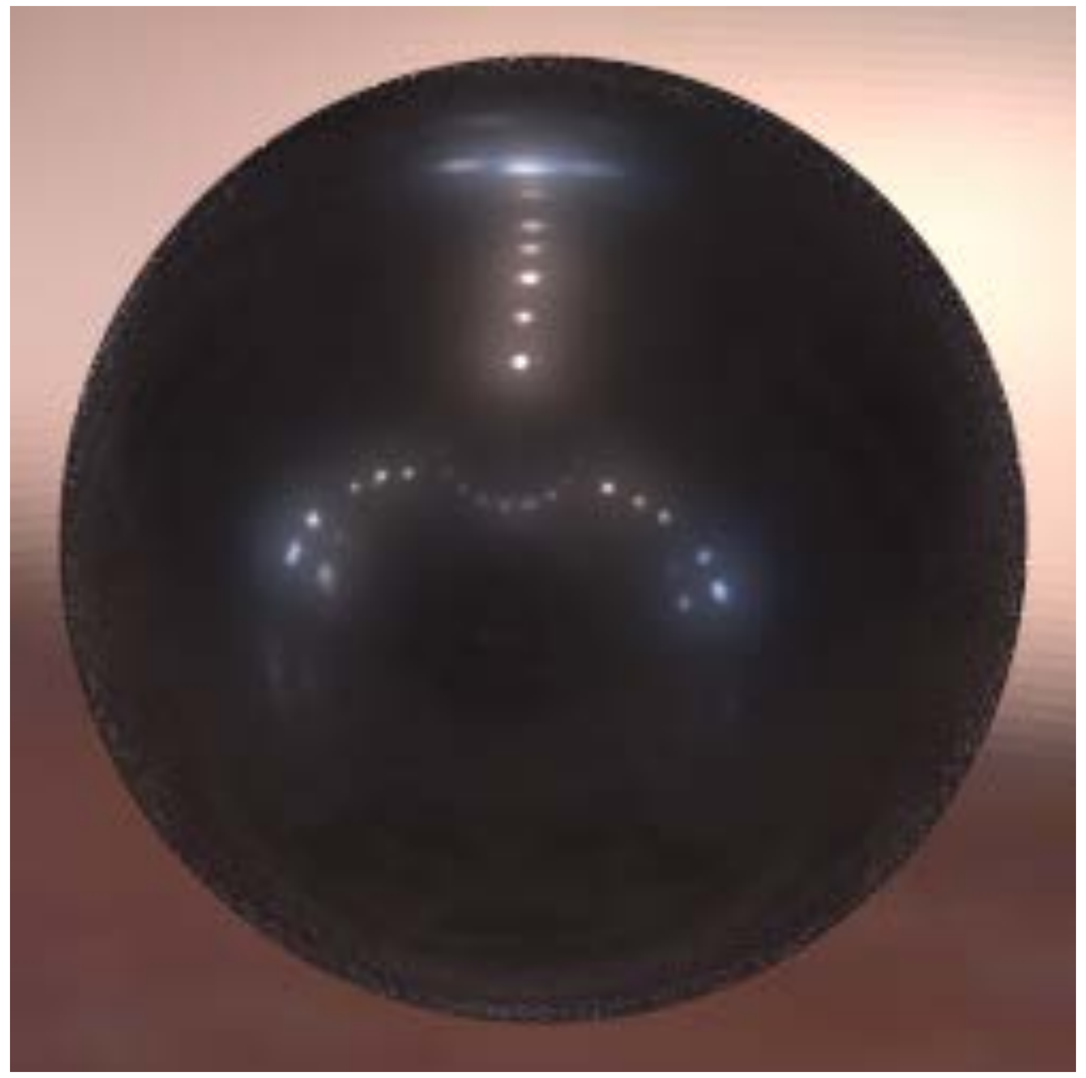

Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Top View
PC 2
PC 1
Measured BRDF
Analytic BRDF
Back View
PC 3
PC 2
PC 1


Front View
PC 3
IOR
Intensity
PC 2
PC 1
Roughness
Top View
PC 2
PC 1
Measured BRDF
Analytic BRDF
Back View
PC 3
PC 2
PC 1

4. RELATING AND FITTING TO ANALYTIC BRDFS

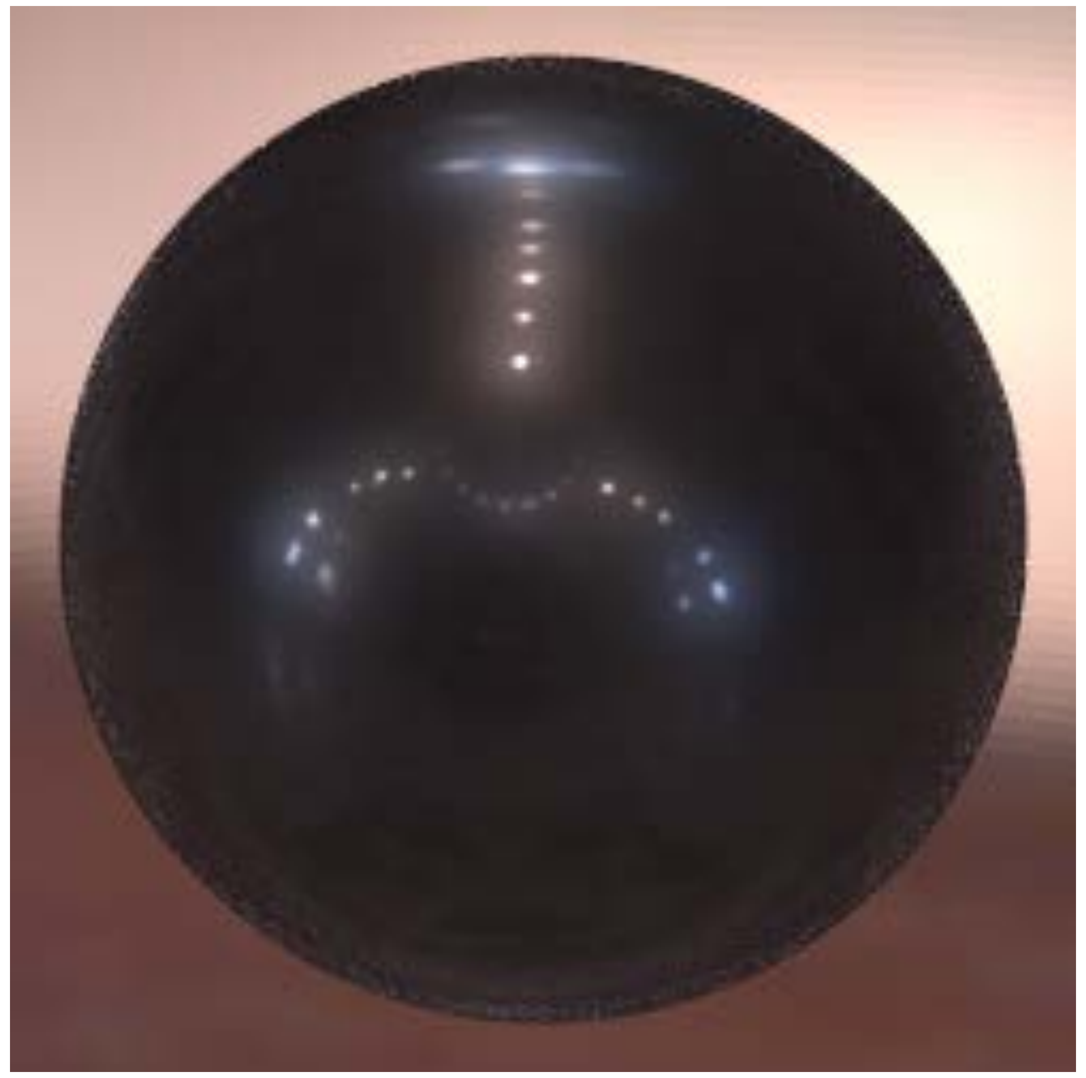
4. RELATING AND FITTING TO ANALYTIC BRDFS

$$\rho_{\mathrm{s}}$$

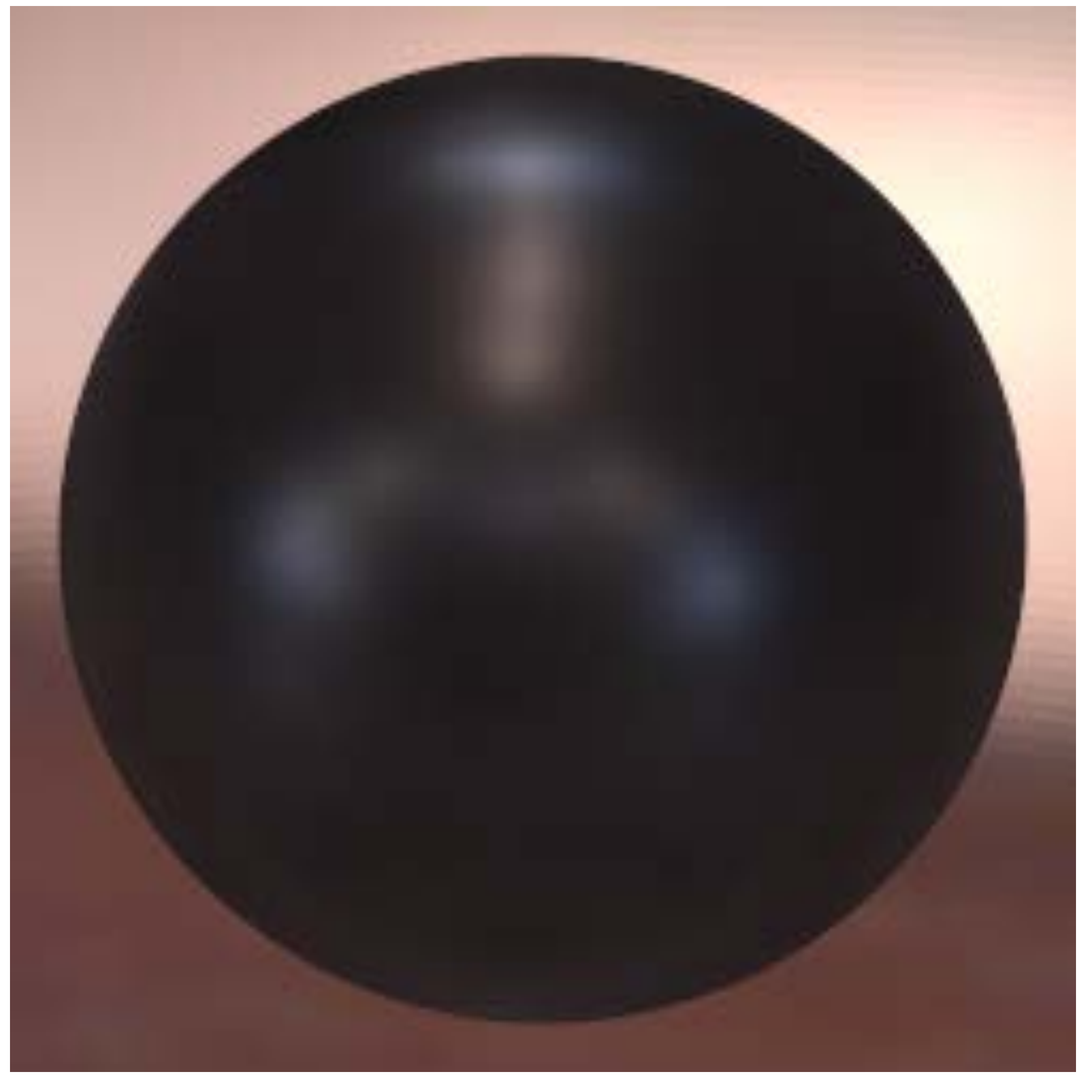


measured BRDF

$$\rho_{\mathrm{s}} \quad - \quad \rho_{\mathrm{s}}(\alpha_{\mathrm{s}}^{(1)})$$



measured BRDF

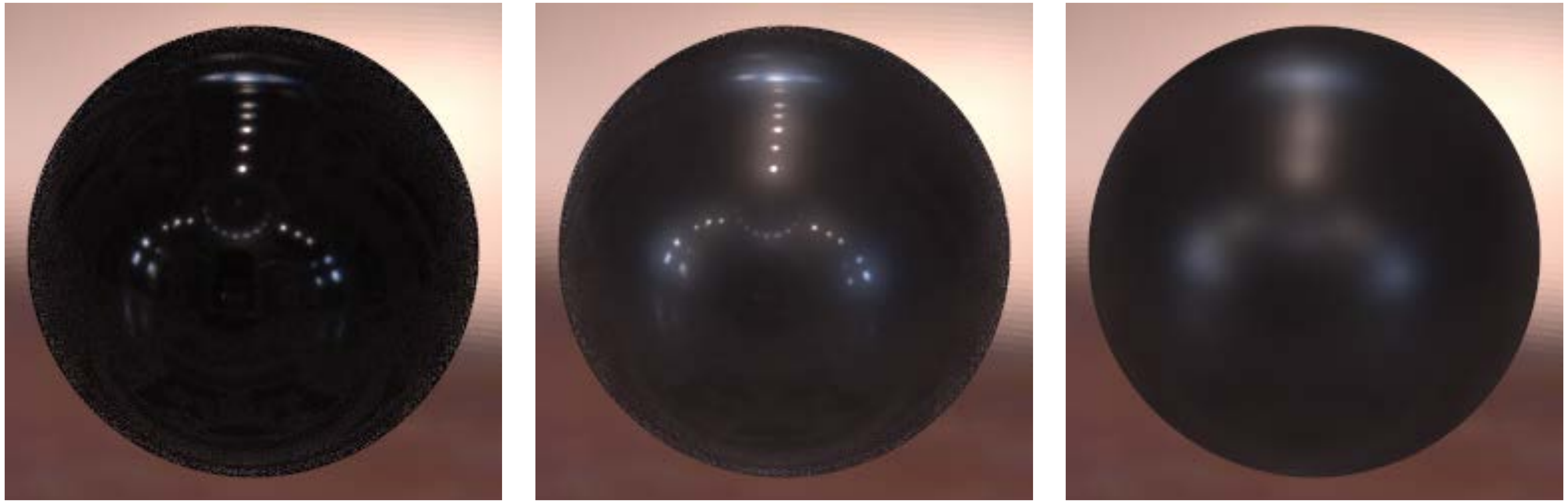


first-lobe guess

4. RELATING AND FITTING TO ANALYTIC BRDFS

- With first lobe known, project the residual to the joint-PC space and compute the reconstruction error.

$$\mathrm{Residual}_{\rho_s}(\alpha_s^{(1)}) = \rho_s - \rho_s(\alpha_s^{(1)})$$



residual **measured BRDF** **first-lobe guess**

4. RELATING AND FITTING TO ANALYTIC BRDFS

- With first lobe known, project the residual to the joint-PC space and compute the reconstruction error.

$$\mathrm{Residual}_{\rho_\mathrm{s}}(\alpha_\mathrm{s}^{(1)}) \quad = \quad \rho_\mathrm{s} \quad - \quad \rho_\mathrm{s}(\alpha_\mathrm{s}^{(1)})$$

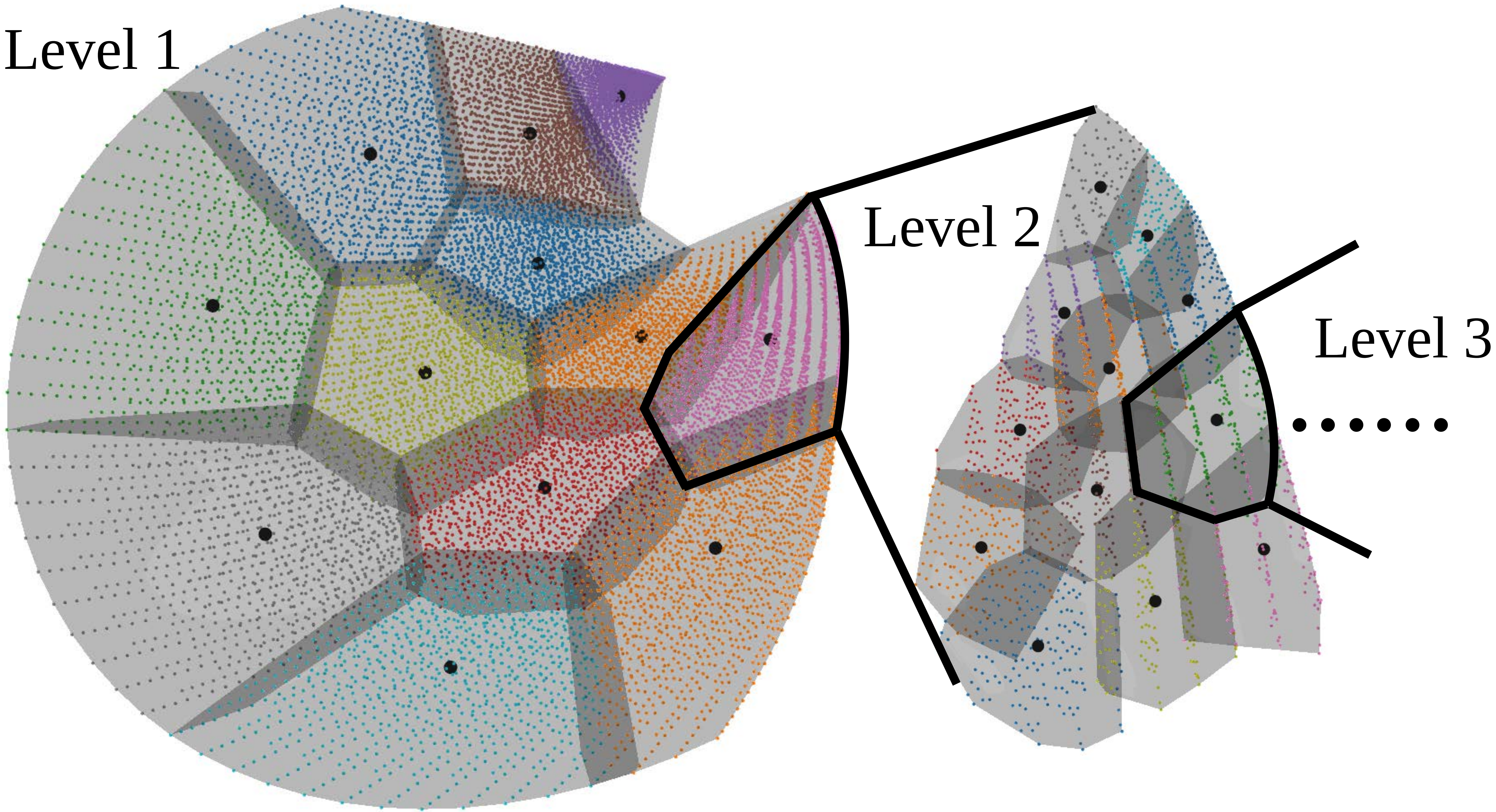
- Perform a searching on the analytic gamut to minimize the error.

4. RELATING AND FITTING TO ANALYTIC BRDFS

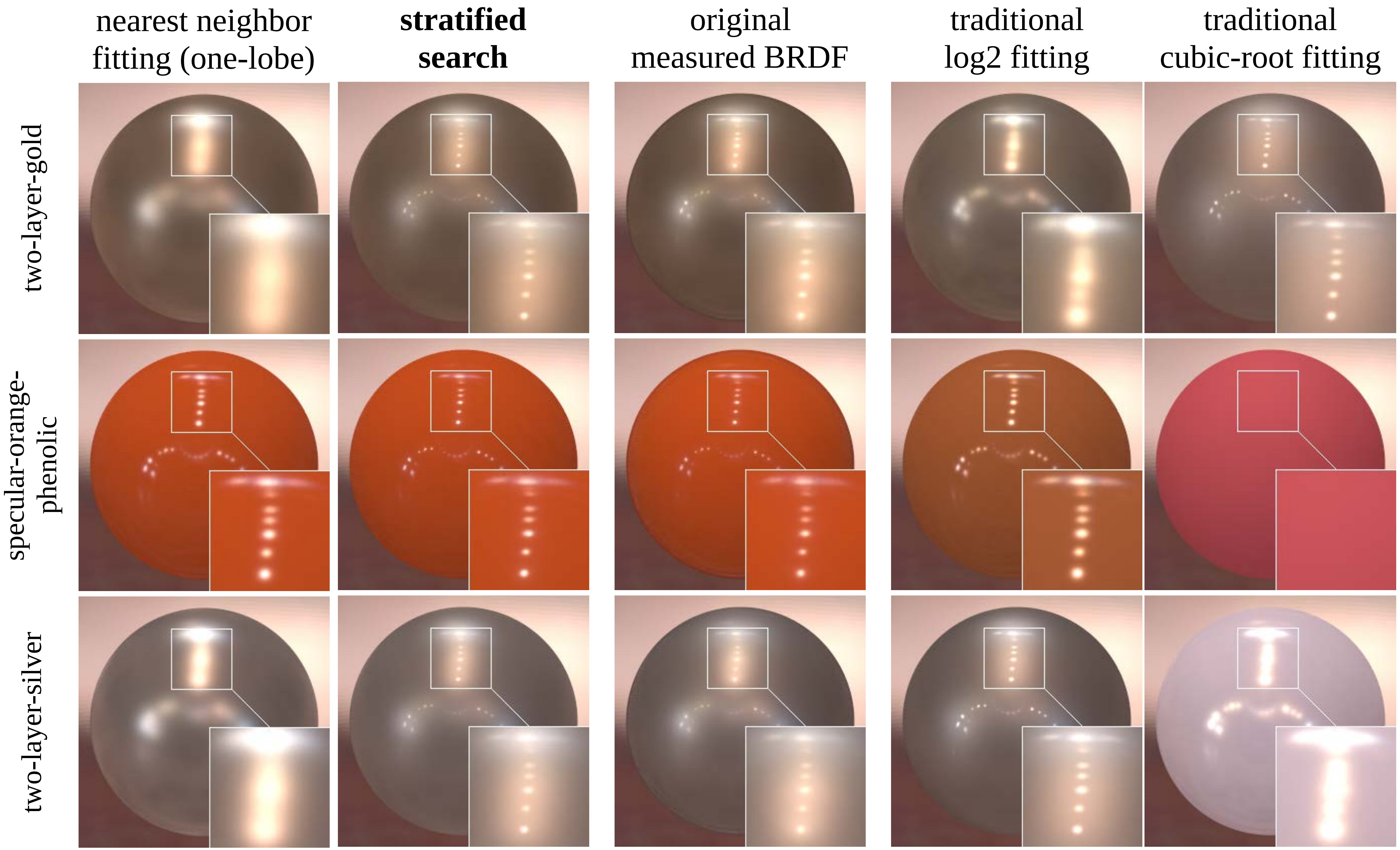
- With first lobe known, project the residual to the joint-PC space and compute the reconstruction error.

$$\mathrm{Residual}_{\rho_s}(\alpha_s^{(1)}) = \rho_s - \rho_s(\alpha_s^{(1)})$$

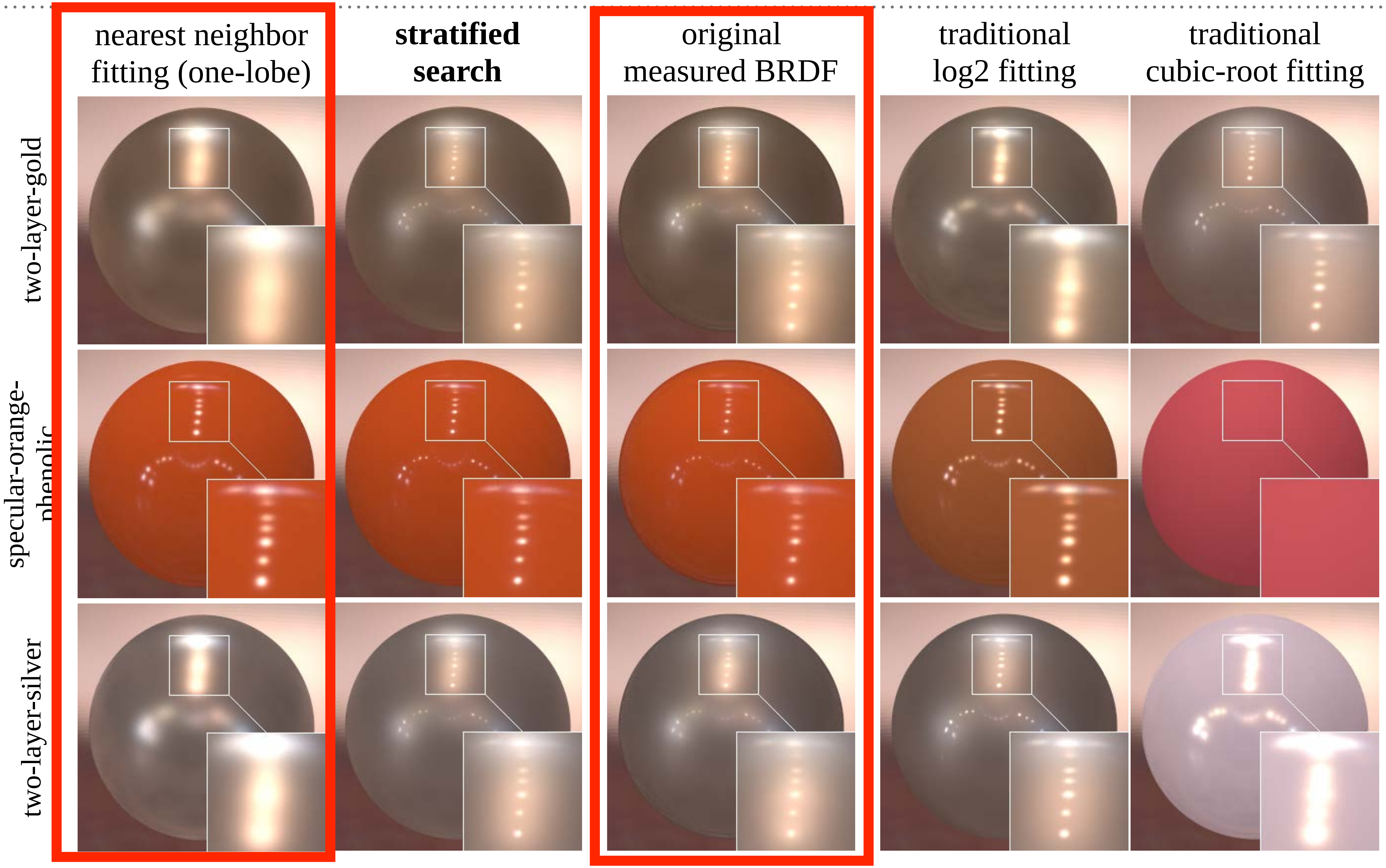
- Perform a searching on the analytic gamut to minimize the error.



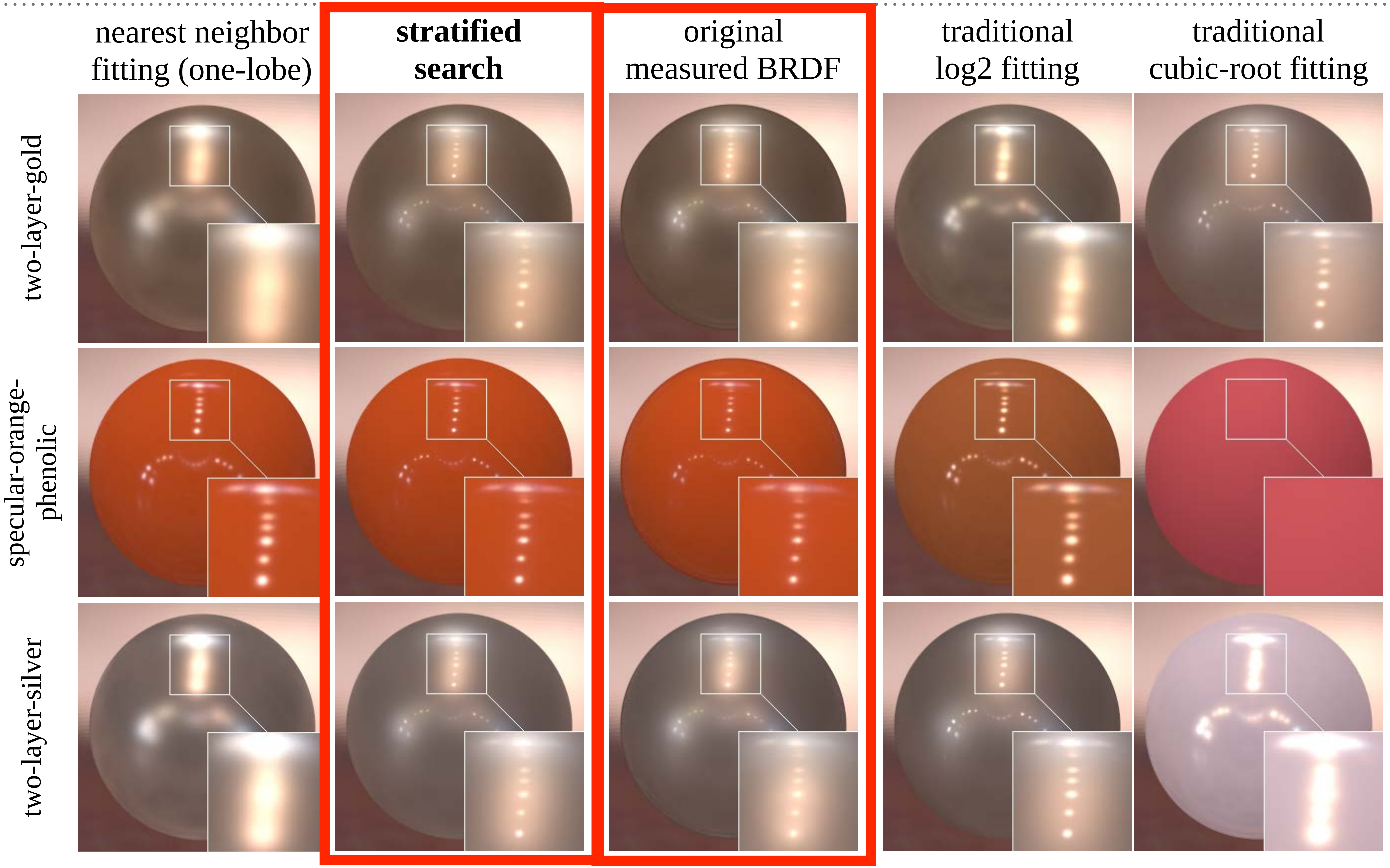
4. RELATING AND FITTING TO ANALYTIC BRDFS



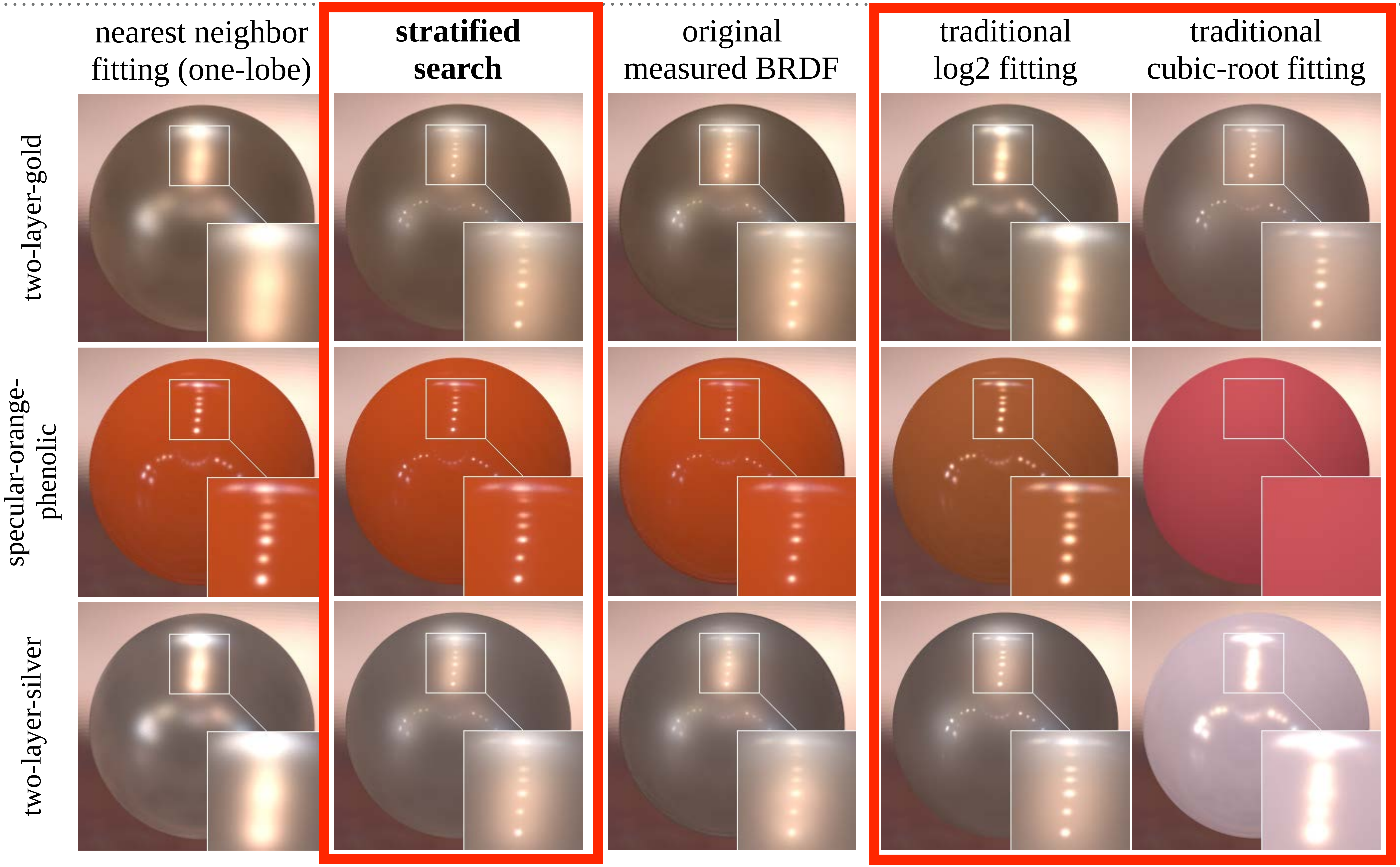
4. RELATING AND FITTING TO ANALYTIC BRDFS



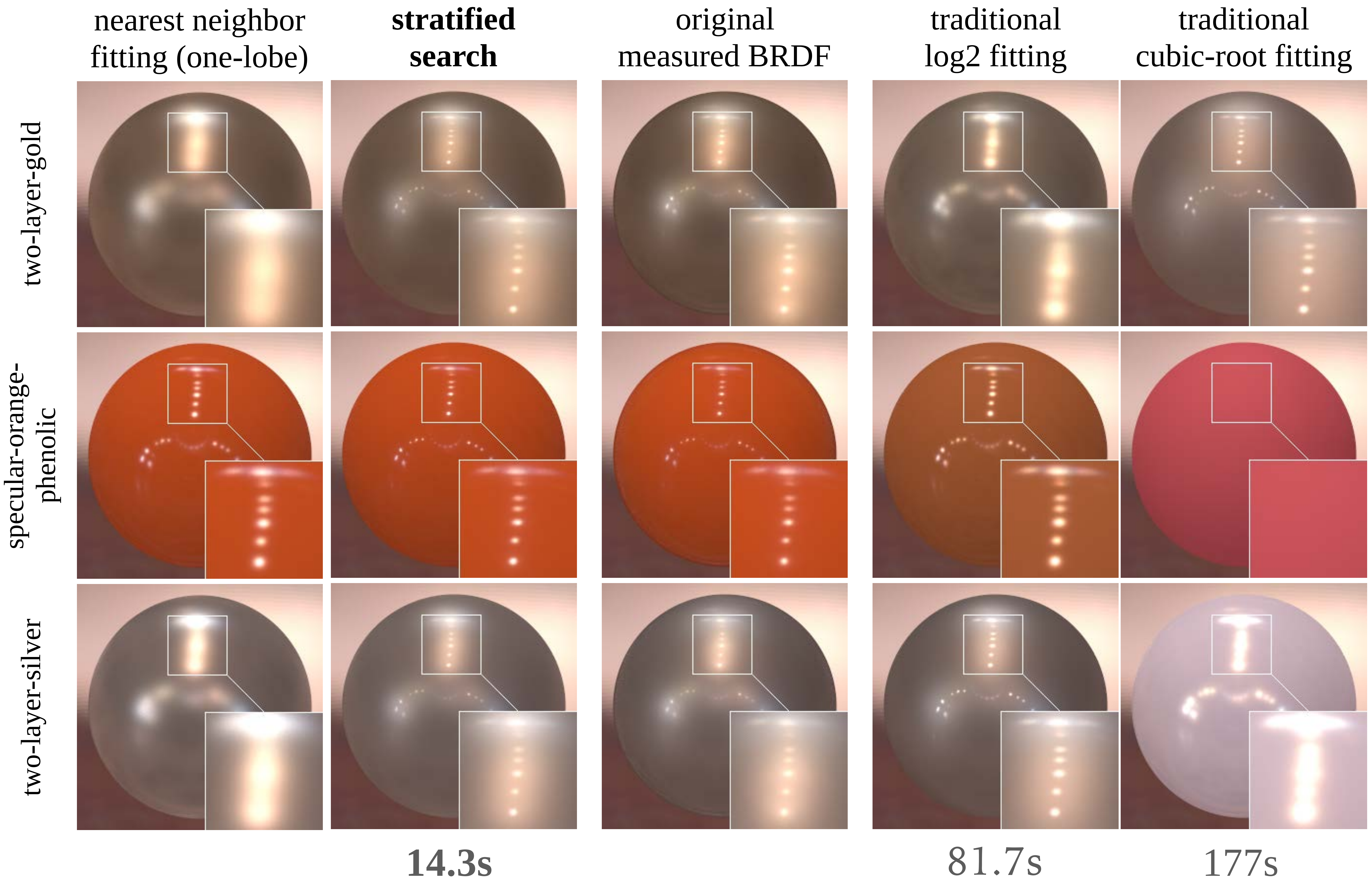
4. RELATING AND FITTING TO ANALYTIC BRDFS



4. RELATING AND FITTING TO ANALYTIC BRDFS



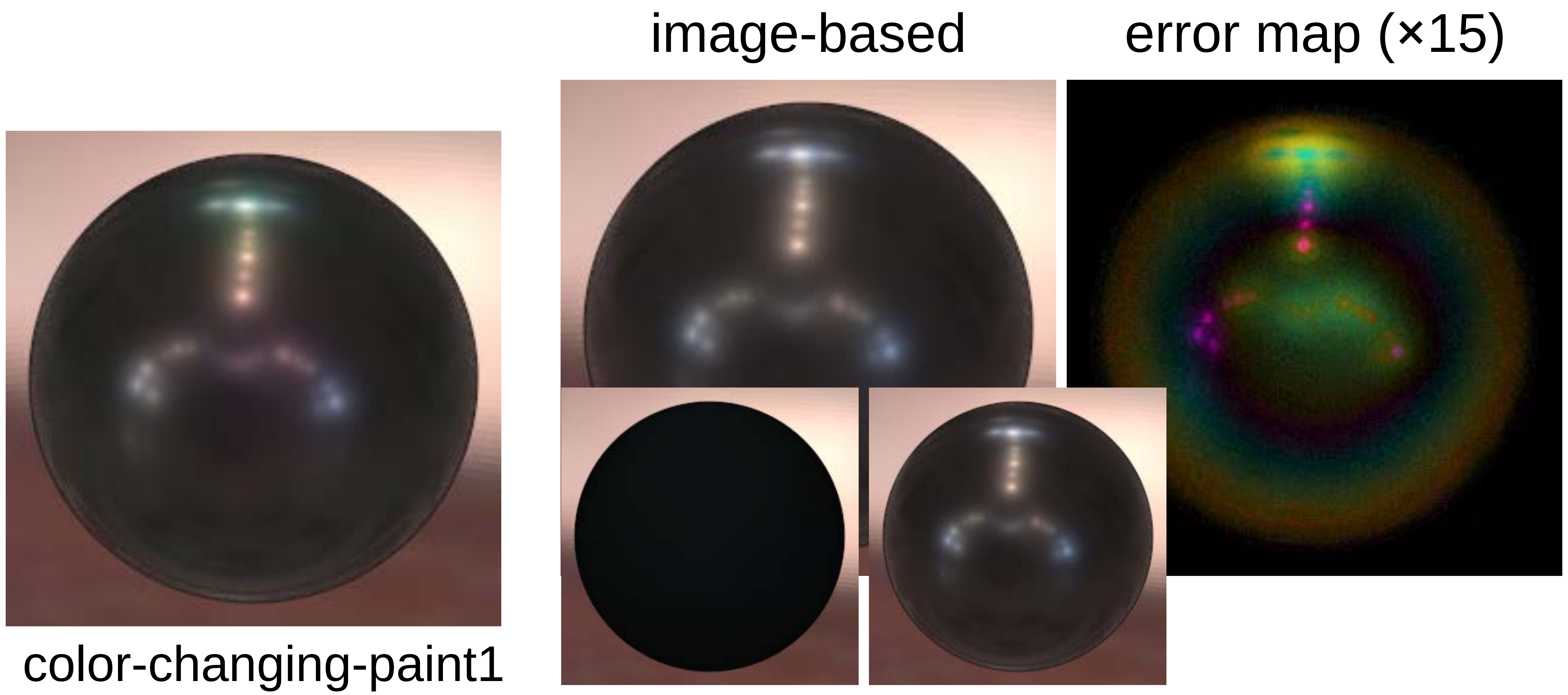
4. RELATING AND FITTING TO ANALYTIC BRDFS



LIMITATION AND FUTURE WORK

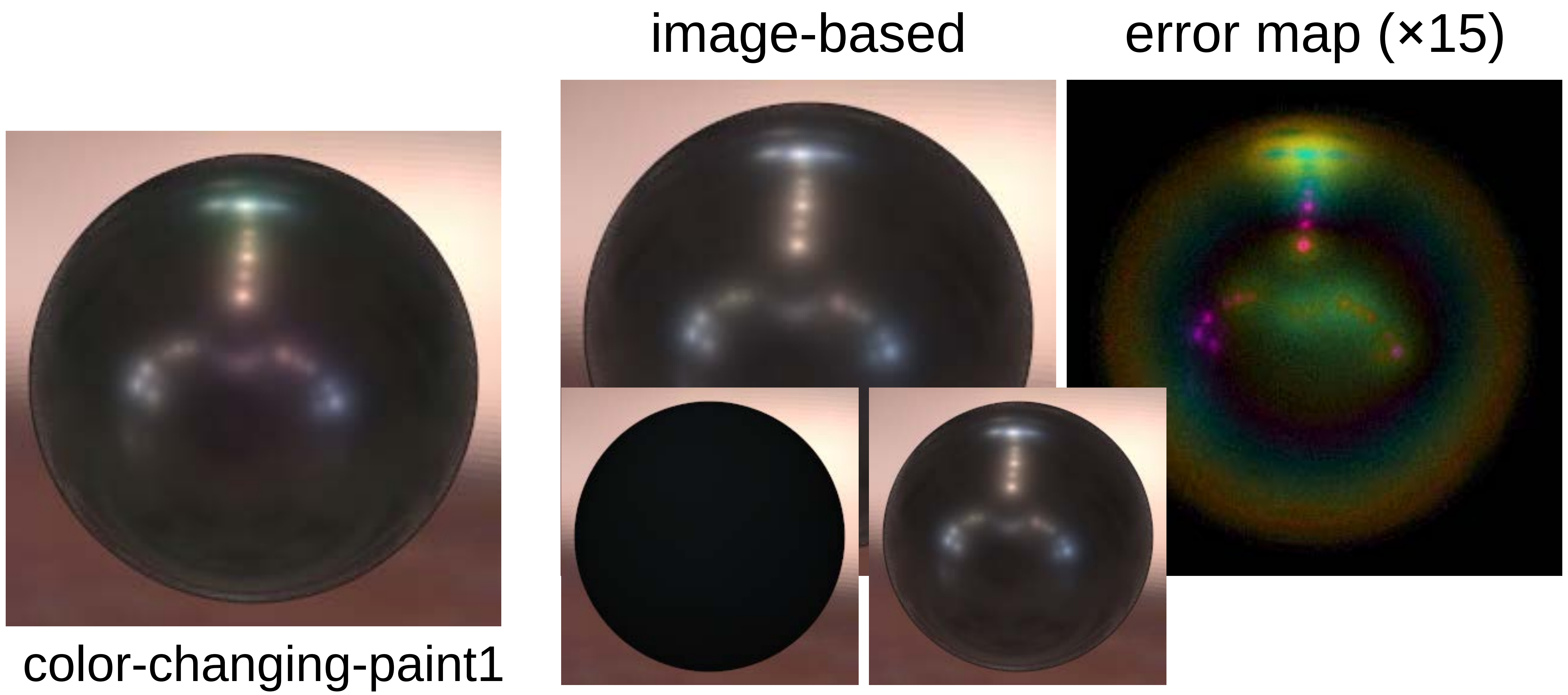
LIMITATION AND FUTURE WORK

- Limitation
  - Multi-color BRDFs



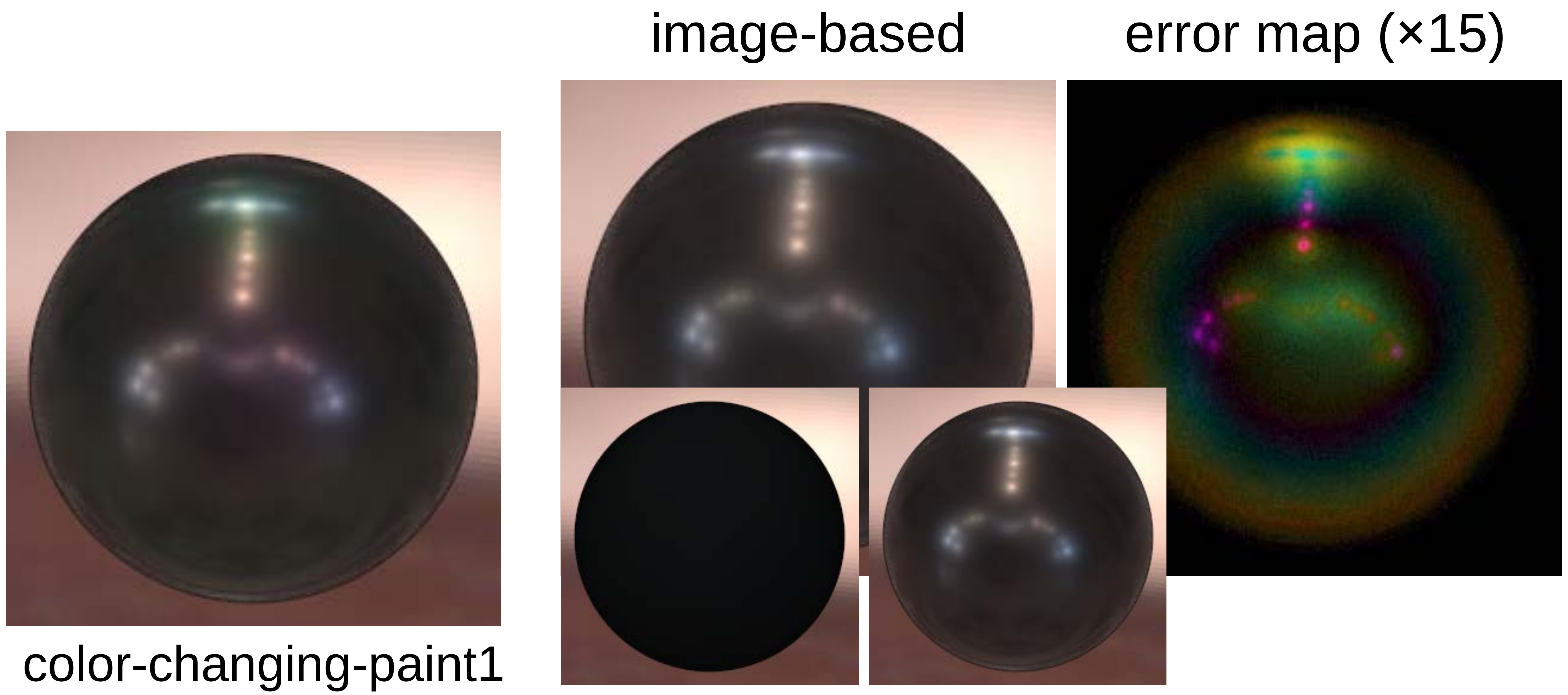
LIMITATION AND FUTURE WORK

- Limitation
  - Multi-color BRDFs
- Future work
  - BRDF measurements



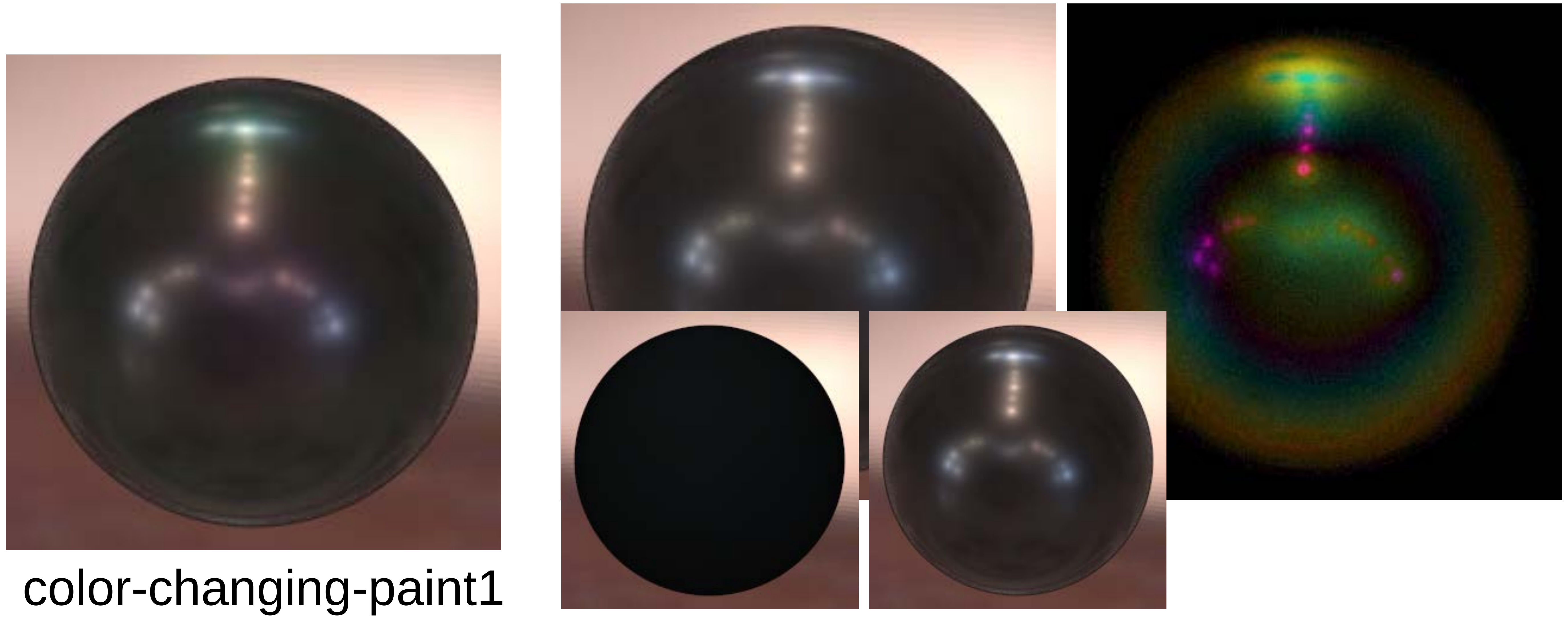
LIMITATION AND FUTURE WORK

- Limitation
  - Multi-color BRDFs
- Future work
  - BRDF measurements
  - Anisotropic BRDFs



LIMITATION AND FUTURE WORK

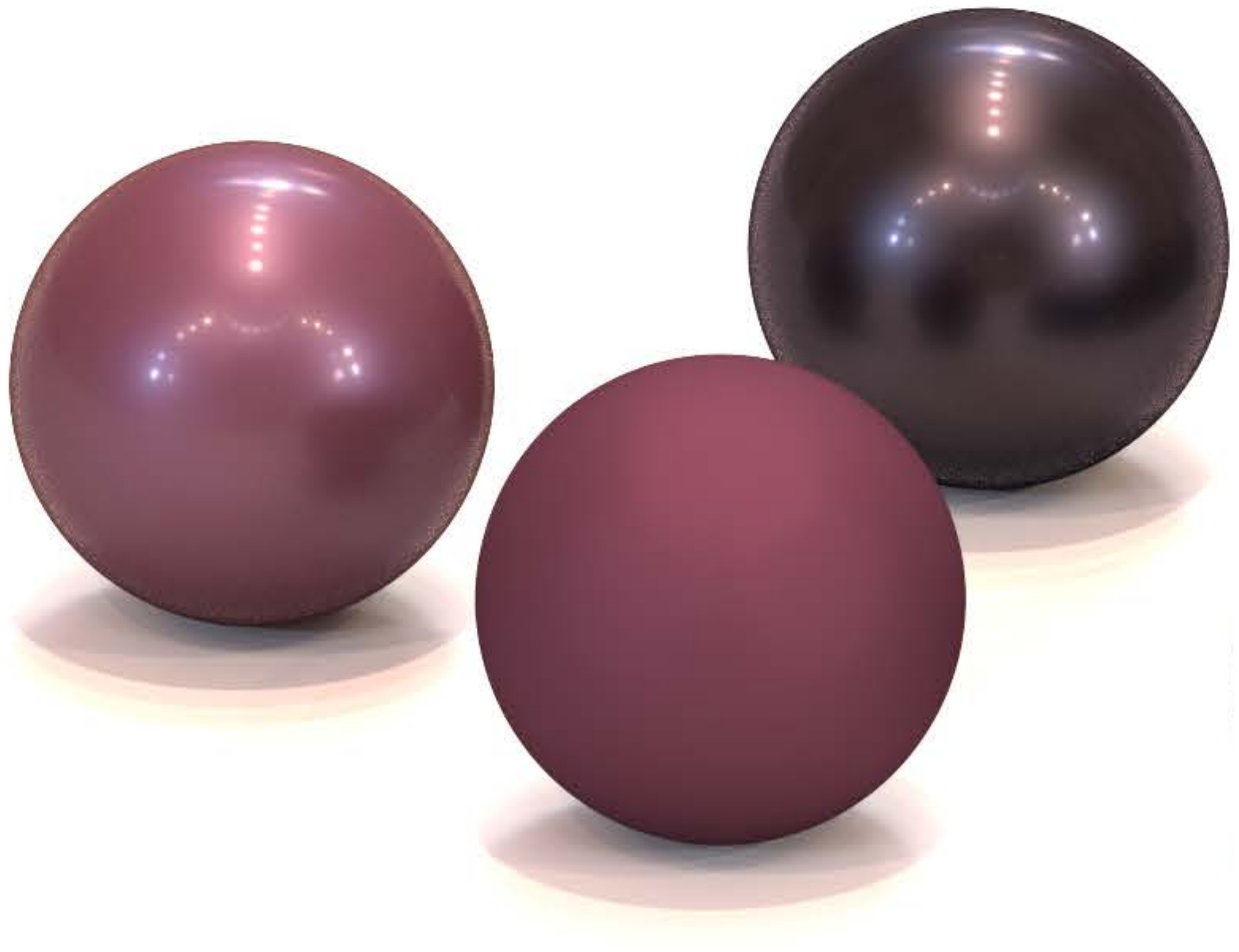
- Limitation
  - Multi-color BRDFs



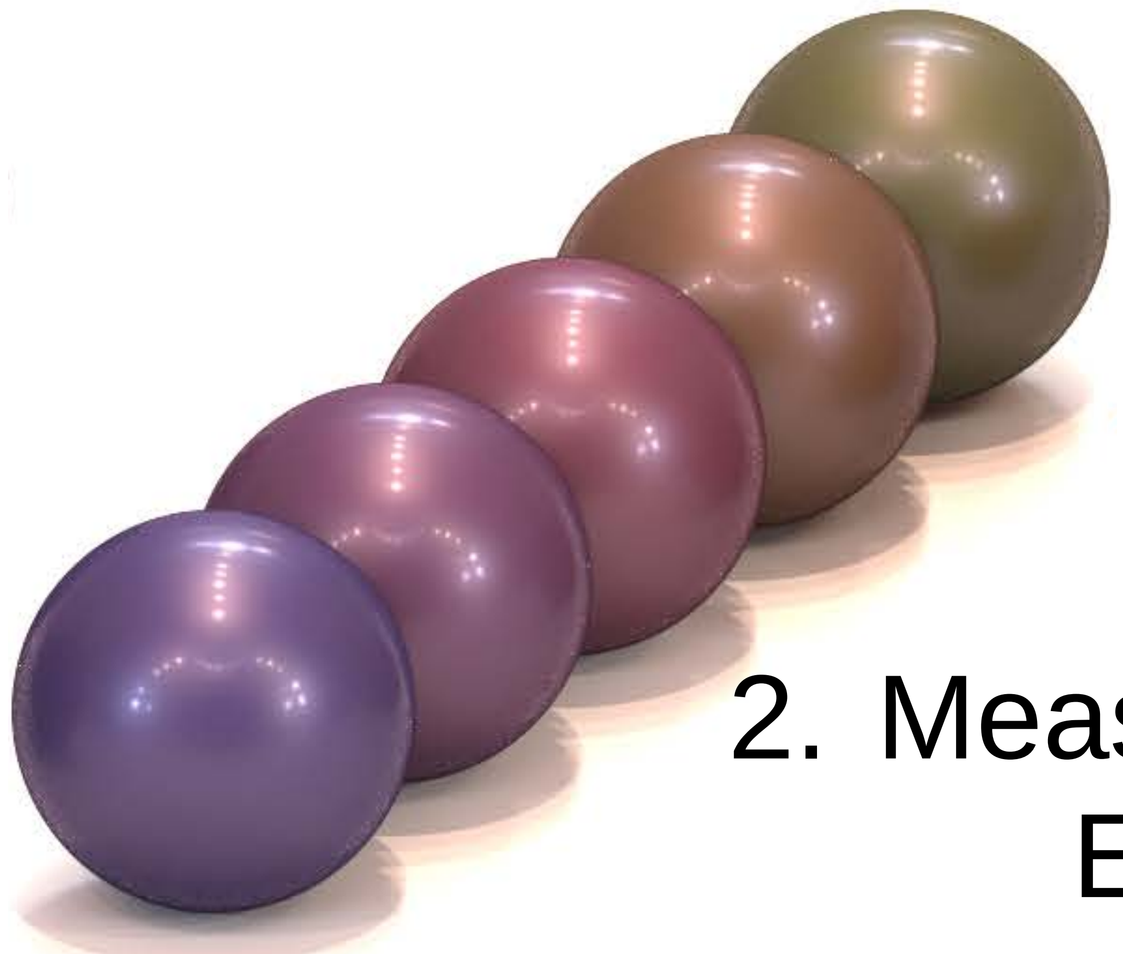
- Future work
  - BRDF measurements
  - Anisotropic BRDFs

- Acknowledgement
  - Anonymous reviewers
  - ONR grant N000141712687, a Jacobs Fellowship, and the Ronald L. Graham Chair.

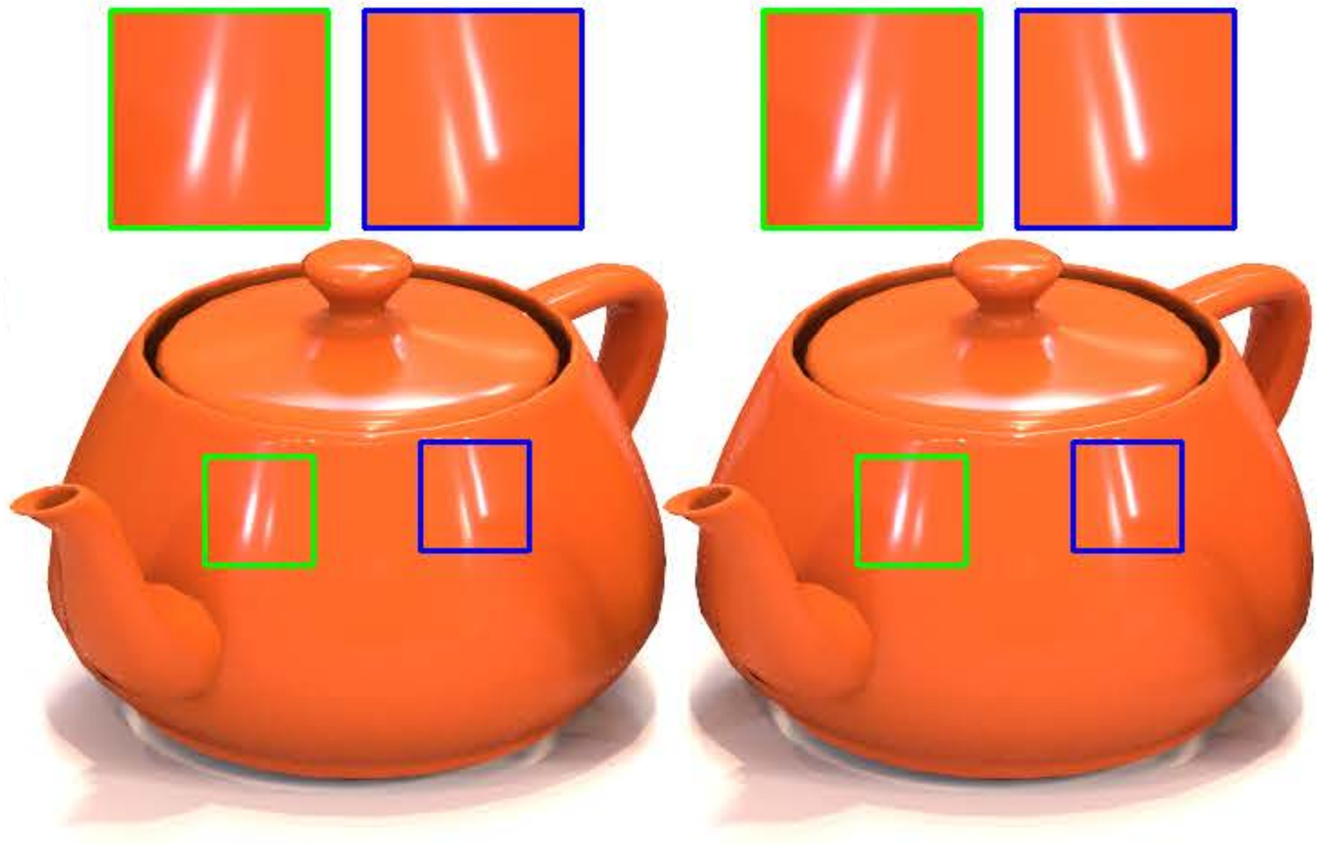
CONCLUSION



1. Diffuse-Specular Separation

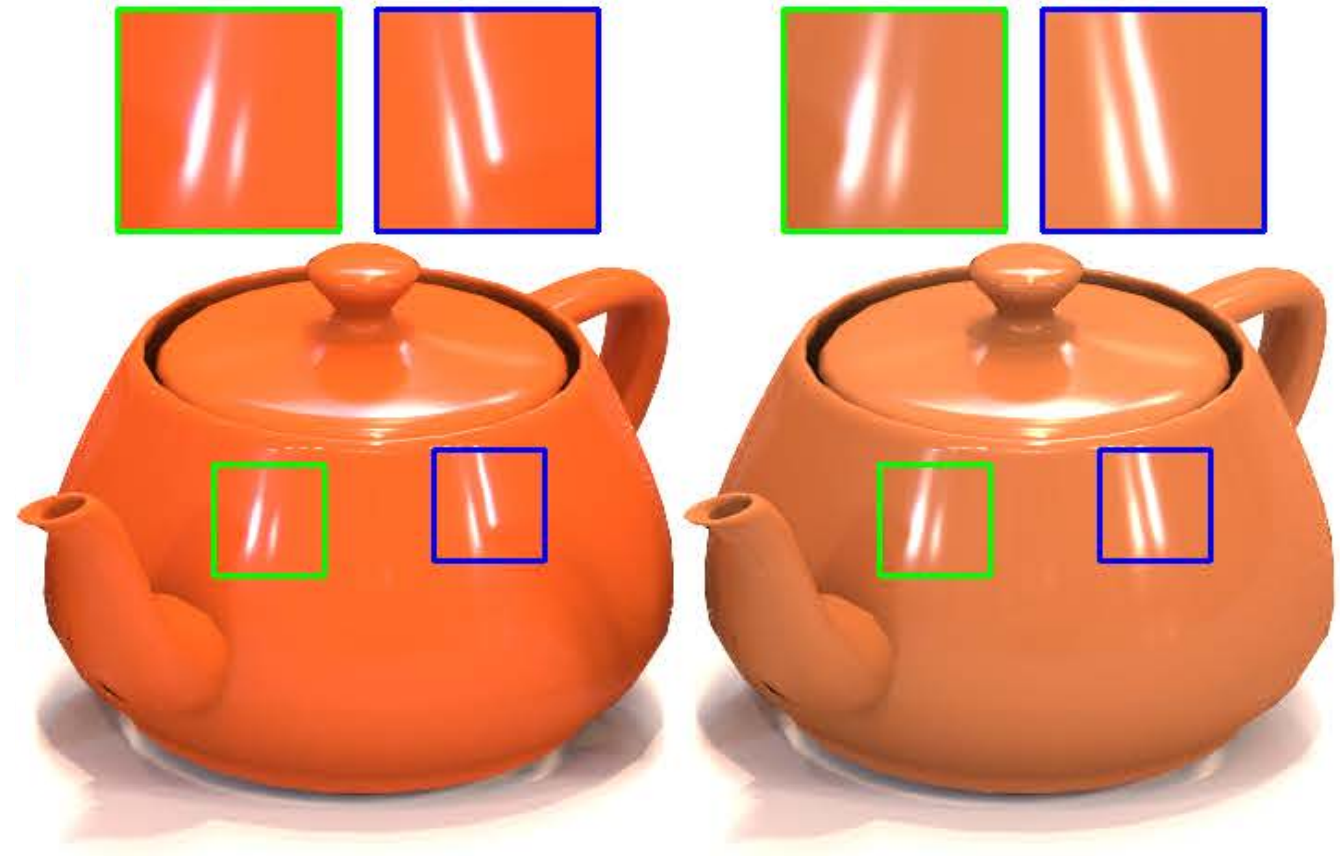


2. Measured BRDF Editing



~3 million values   8 parameters

3. Compact Measured BRDF model



Our Analytic Fit   Traditional Analytic Fit

4. Relating and Fitting to Analytic BRDFs

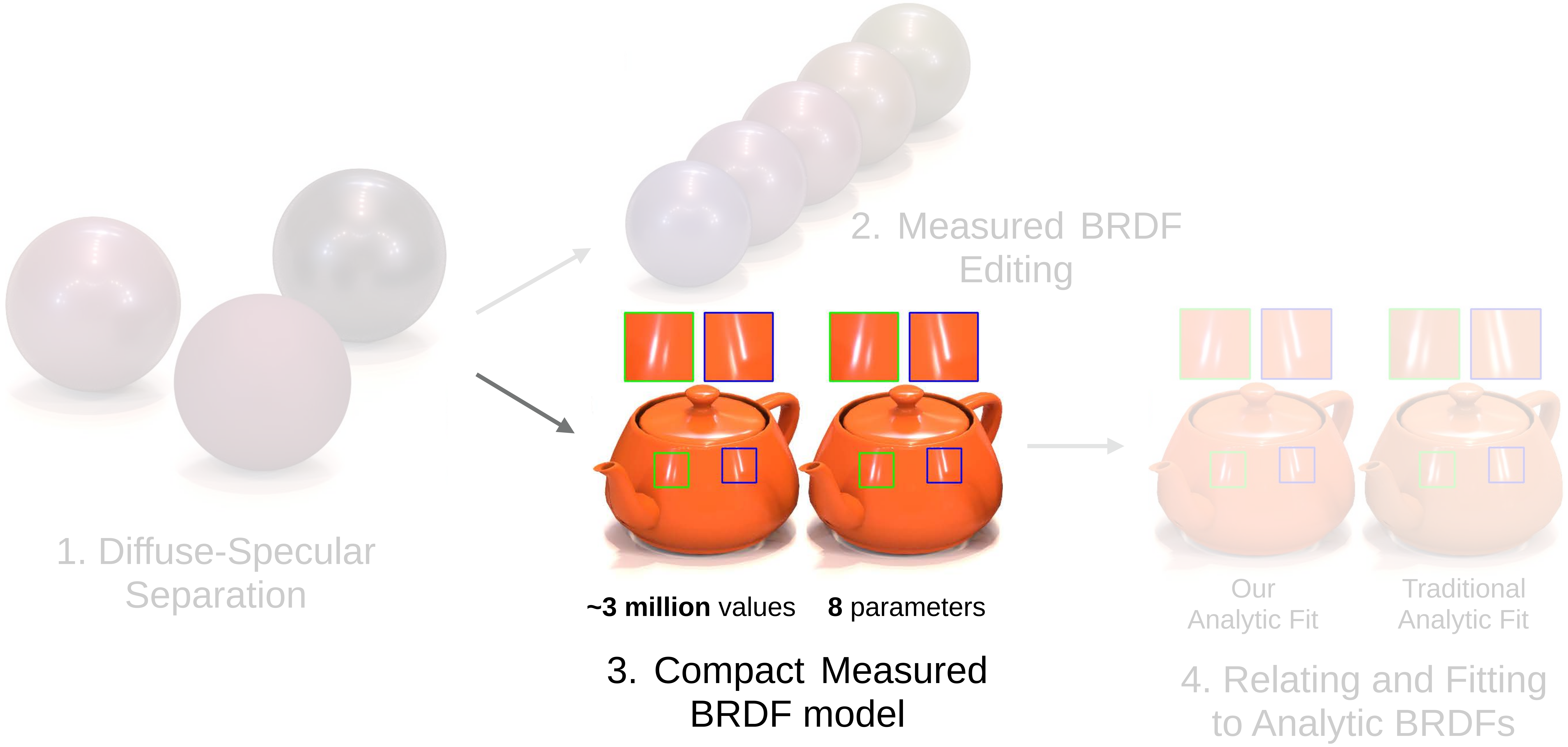
CONCLUSION


1. Diffuse-Specular Separation
2. Measured BRDF Editing
~3 million values
8 parameters
3. Compact Measured BRDF model
Our Analytic Fit
Traditional Analytic Fit
4. Relating and Fitting to Analytic BRDFs

CONCLUSION


2. Measured BRDF Editing
1. Diffuse-Specular Separation
~3 million values
8 parameters
3. Compact Measured BRDF model
Our Analytic Fit
Traditional Analytic Fit
4. Relating and Fitting to Analytic BRDFs

CONCLUSION



2. Measured BRDF
Editing
1. Diffuse-Specular
Separation
~3 million values
8 parameters
Our
Analytic Fit
Traditional
Analytic Fit
3. Compact Measured
BRDF model
4. Relating and Fitting
to Analytic BRDFs

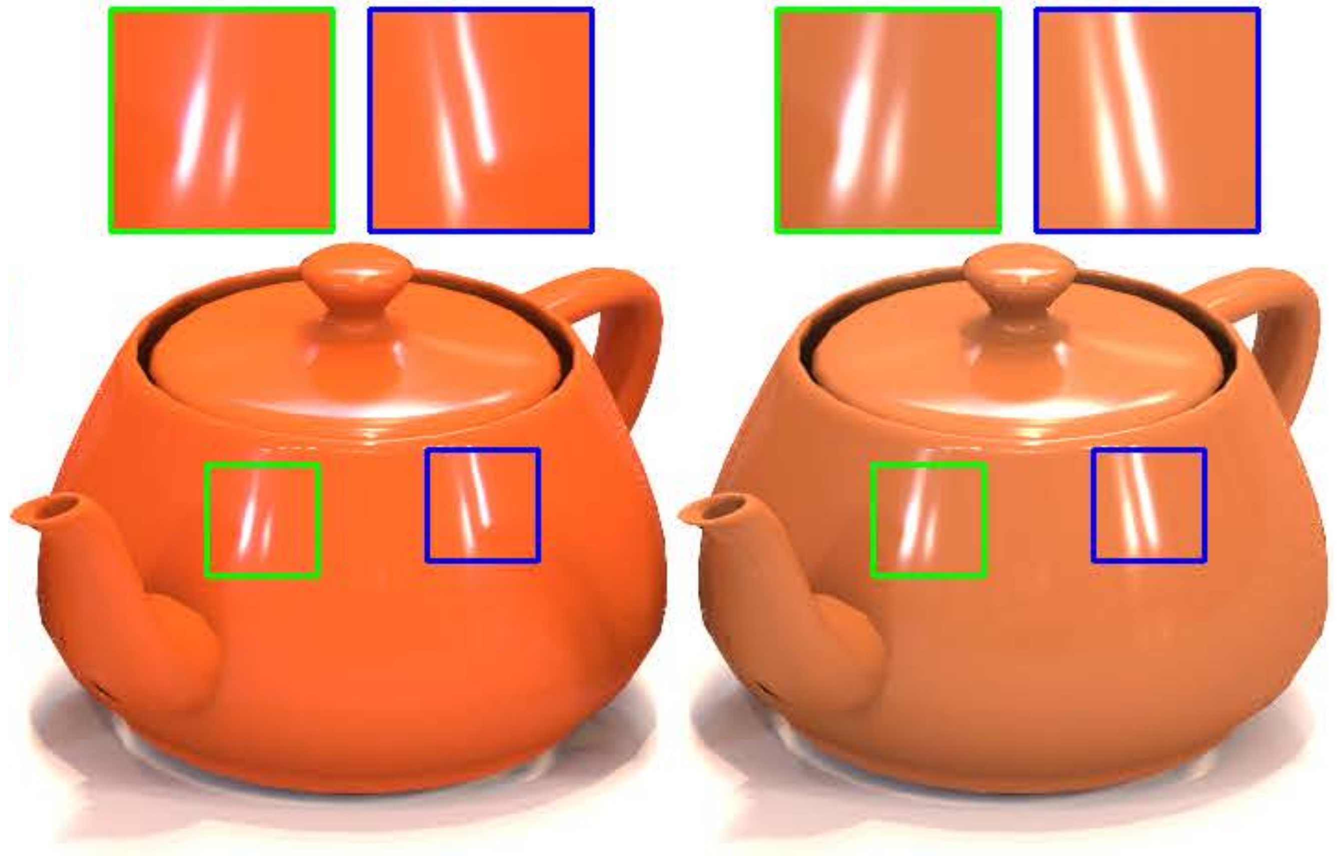
CONCLUSION

1. Diffuse-Specular Separation

2. Measured BRDF Editing

~3 million values **8** parameters

3. Compact Measured BRDF model

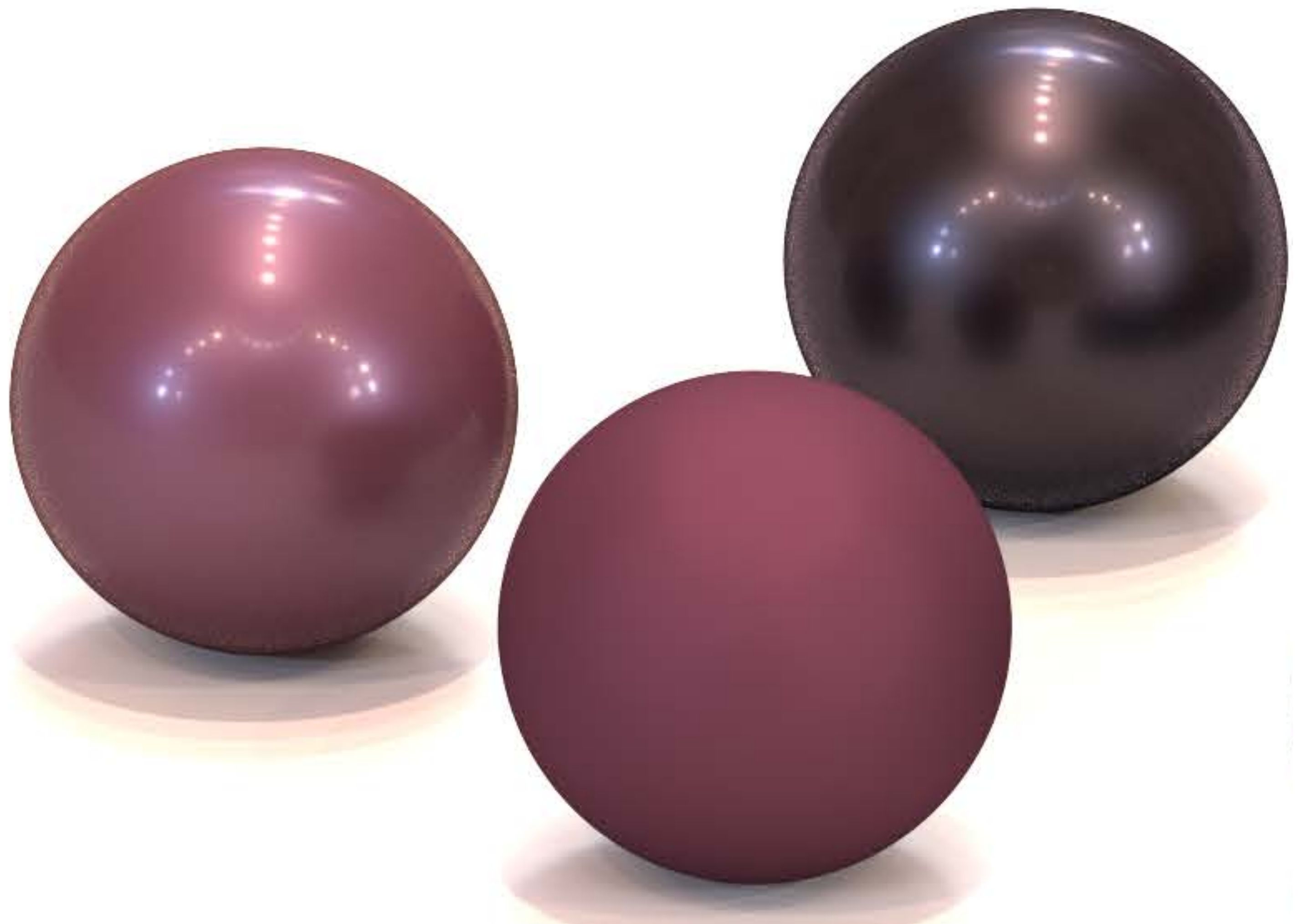


Our Analytic Fit

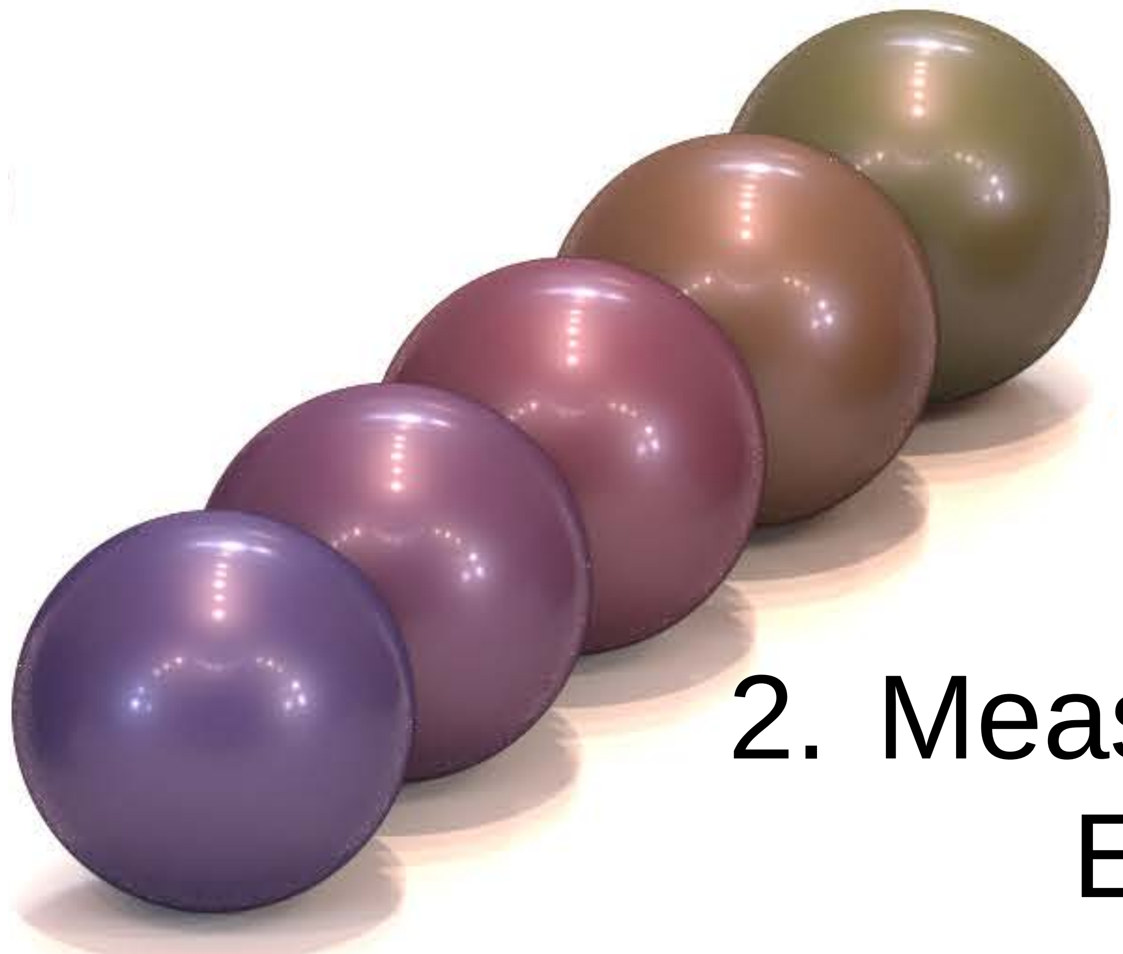
Traditional Analytic Fit

4. Relating and Fitting to Analytic BRDFs

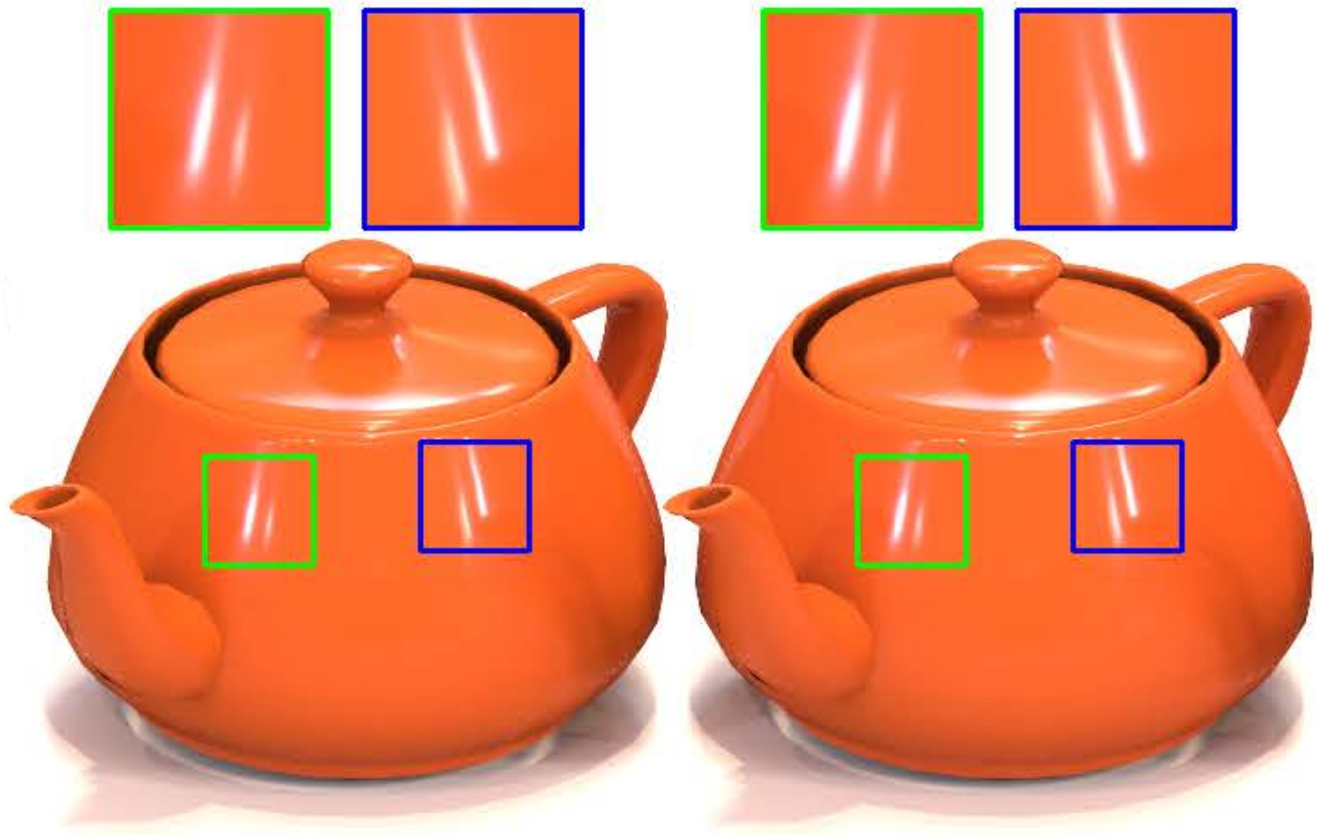
CONCLUSION



1. Diffuse-Specular Separation

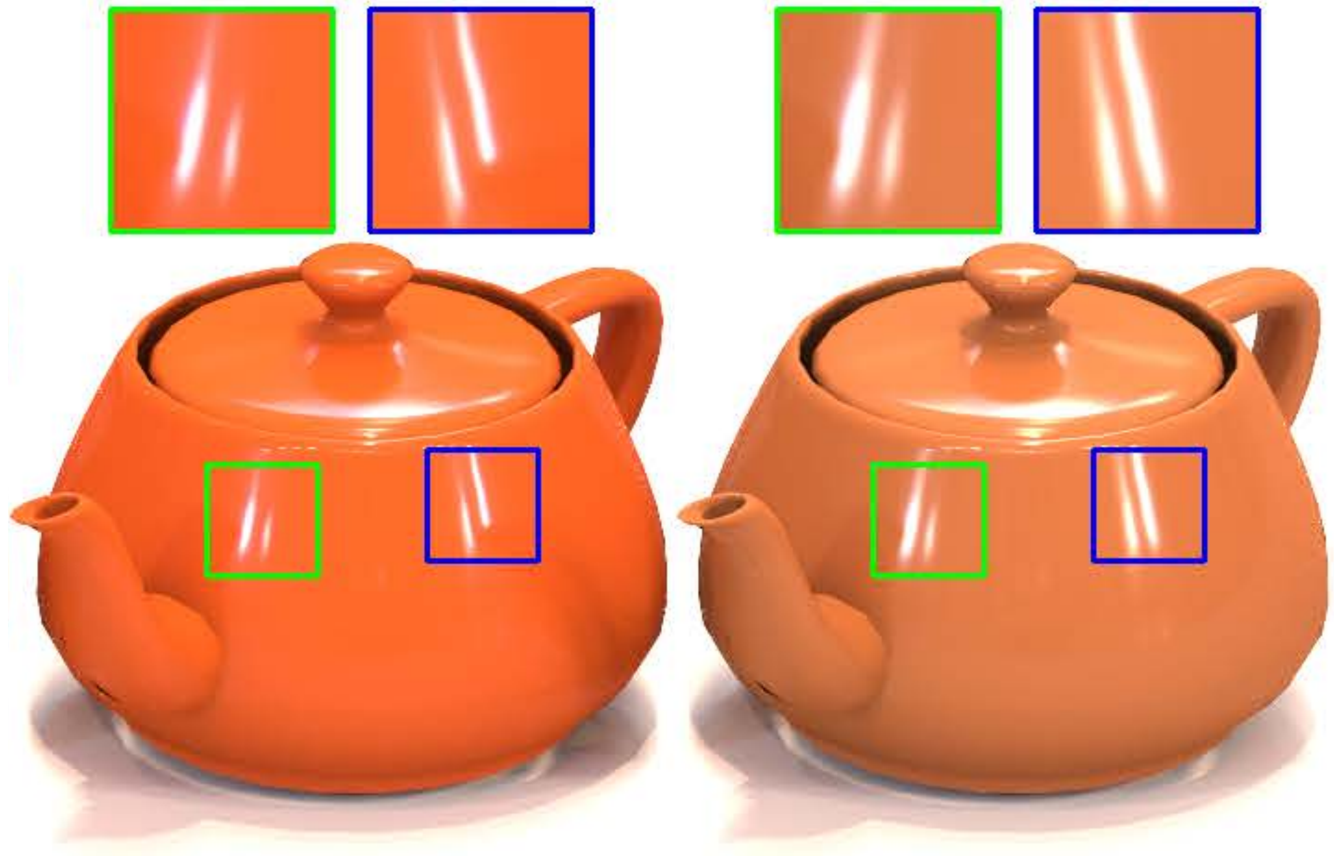


2. Measured BRDF Editing



~3 million values | **8** parameters

3. Compact Measured BRDF model



Our Analytic Fit | Traditional Analytic Fit

4. Relating and Fitting to Analytic BRDFs

Homepage