

# **Modeling the Digital Camera Pipeline**

## **From RAW to sRGB and Back**

Michael S. Brown

School of Computing, National University of Singapore

<http://www.comp.nus.edu.sg/~brown>

**Computational Photography meets Machine Learning Workshop**

NIPS'11

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# Acknowledgements



Hai-ting Lin  
(NUS)



Seon Joo Kim  
(ADSC/SB-Korea)



Sabine Süsstrunk  
(EPFL)



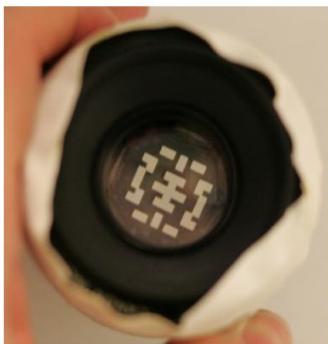
Steven Lin  
(MSR-Asia)



Lu Zheng  
(NUS)

# Computational Photography

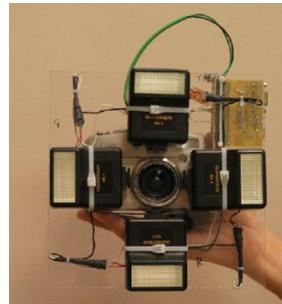
- **Fact:** Digital camera images are going to be manipulated.
- **Opportunity:** This gives us the freedom to “do things” with the knowledge that we will process them later.



Levin et al  
Coded Aperture



Nayar's Catadioptric  
Imaging



Raskar et al  
Multiflash Camera

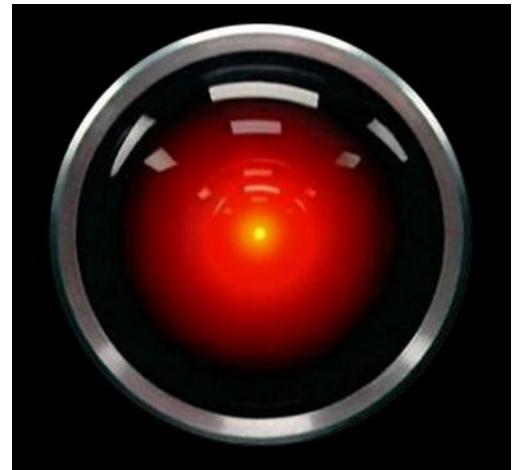


Tai et al Hybrid  
Camera



Krishnan and Fergus  
Dark Flash Camera

# But today . . .



Hal 9000 computer

Talk about the processing that is already happening on your camera.

“The digital camera imaging pipeline”



Dr. Kar-Han Tan (HP Labs)

Tan Photography  
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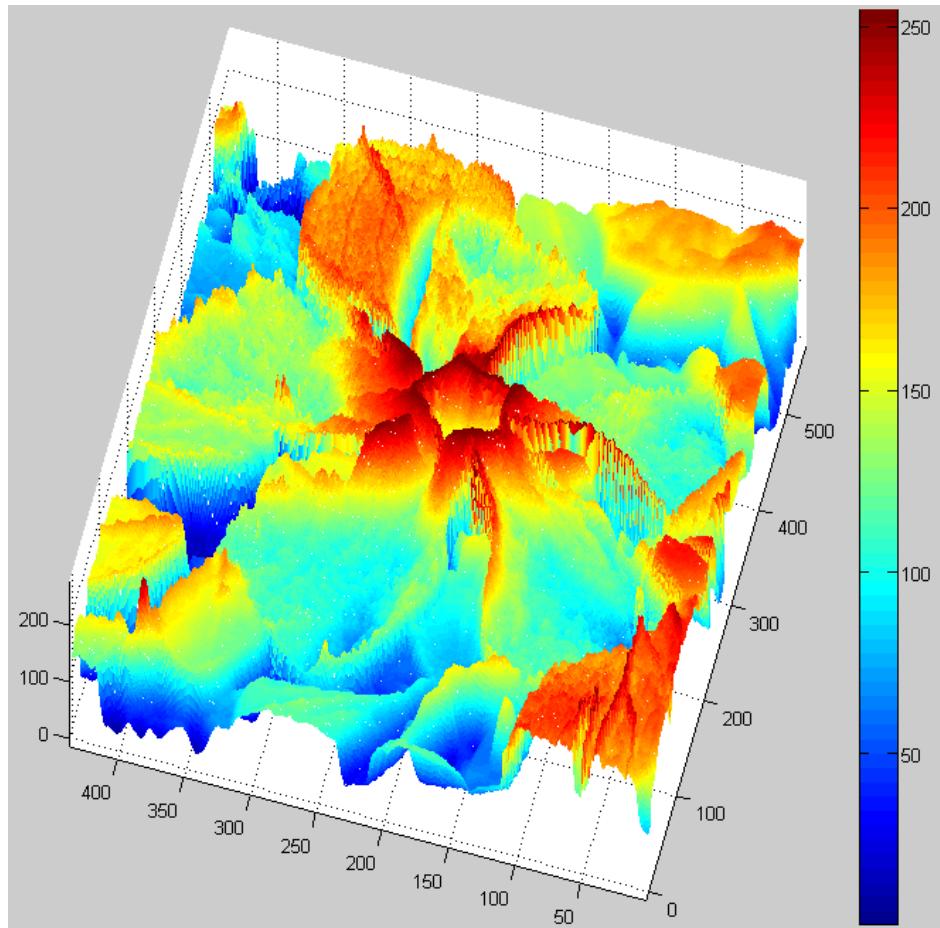


(C) Tan Photography 2008 翰

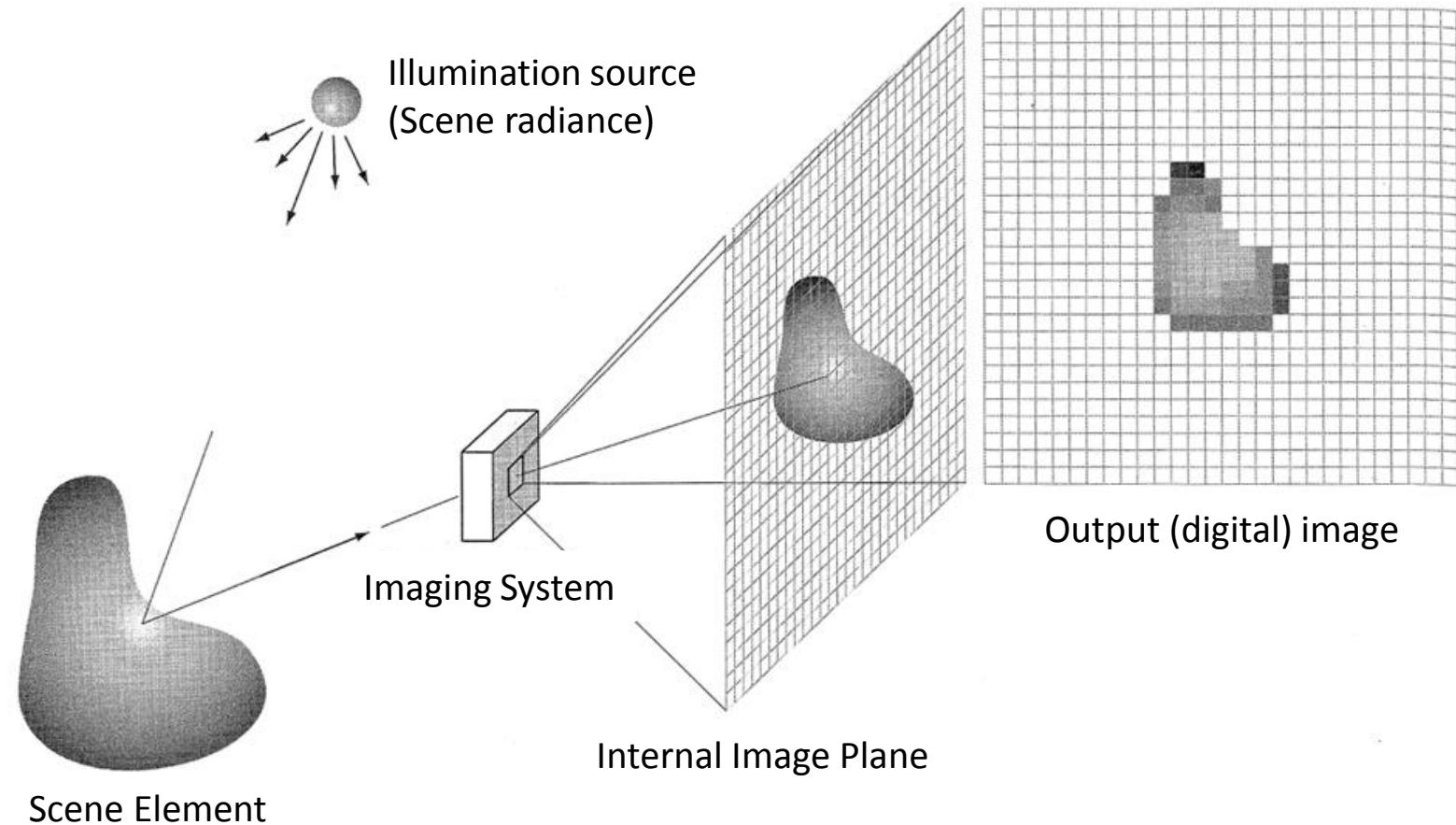




# Scientist's view of photography



# Camera = light-measuring device



**Simple models assume an image is a measurement of scene radiance.**

# Camera = light-measuring device

- Shape from shading
- Color Consistency
- HDR Imaging
- Image Matching
- Etc . . .

Shape-from-shading



image of object

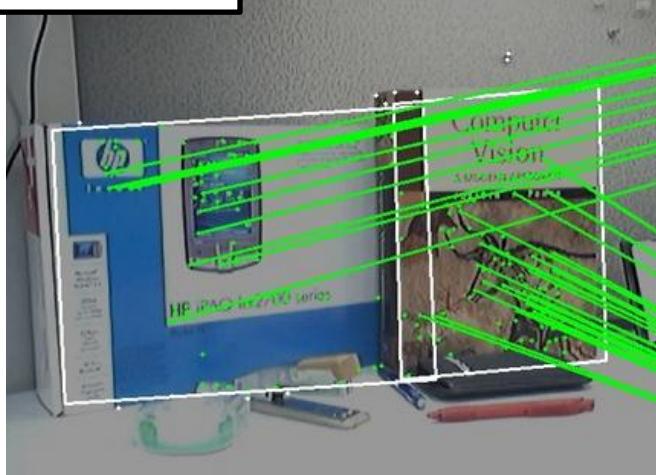


surface normals



3D model  
Lu et al, CVPR'10

Image Matching



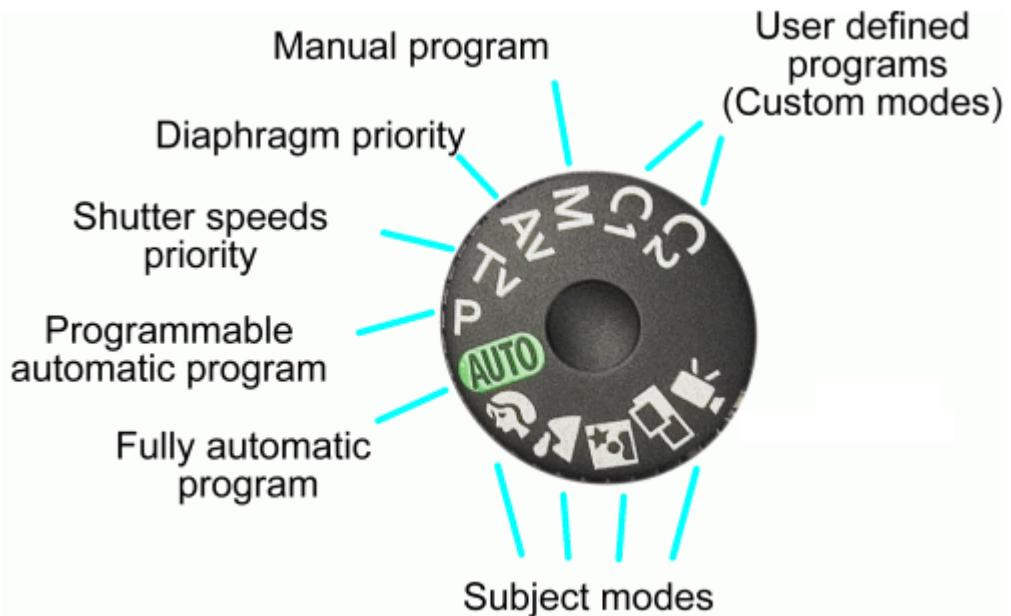
From Jon Mooser, CGIT Lab, USC

HDR Imaging



From O'Reilly's digital media forum

# Light-measuring device?



	Portrait Mode		Soft Skin Mode		Transform Mode
	Self-portrait Mode		Scenery Mode		Panorama Assist Mode
	Sports Mode		Night Portrait Mode		Night Scenery Mode
	Food Mode		Party Mode		Candle Light Mode
	Baby Mode 1/2		Pet Mode		Sunset Mode
	High Sensitivity Mode		High-speed Burst Mode		Flash Burst Mode
	Starry Sky Mode		Fireworks Mode		Beach Mode
	Snow Mode		Aerial Photo Mode		Pin Hole Mode
	Film Grain Mode		High Dynamic Mode		Photo Frame Mode

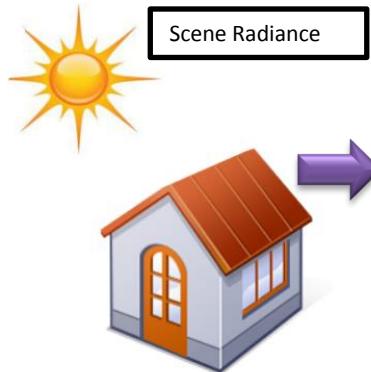
# Onboard Photofinishing

## “Secret Recipe” of a Camera

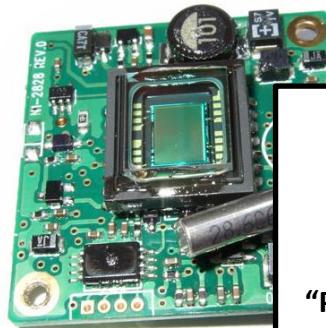


Three different cameras with **same aperture, exposure, white-balance and picture style**, etc. . .

# Modern photography pipeline



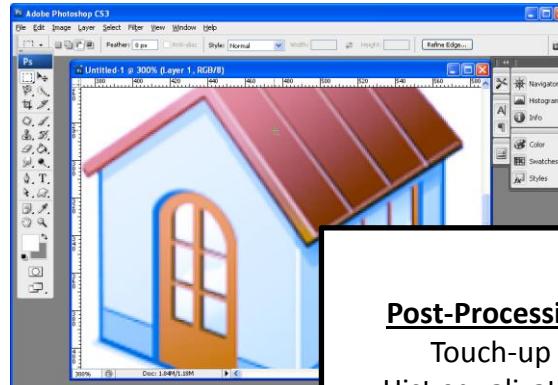
**Pre-Camera**  
Lens Filter  
Lens  
Shutter  
Aperture



**In-Camera**  
CCD response (RAW)  
CCD Demosaicing (RAW)  
**"Photo-finishing Processing"**

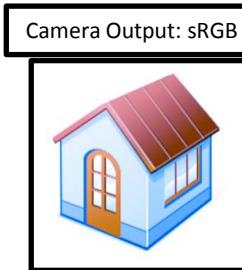


Final output



Ending point:  
better than reality (in RGB)

**Post-Processing**  
Touch-up  
Hist equalization  
Spatial warping  
Etc ...



Camera Output: sRGB

Even if we stopped here,  
the original CCD response  
potentially has had many  
levels of processing.

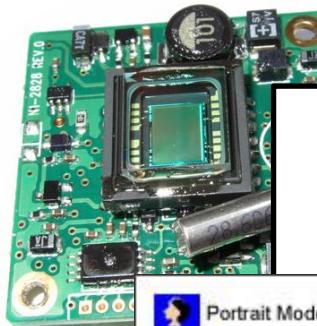
# Modern photography pipeline



Starting point:  
reality (in radiance)

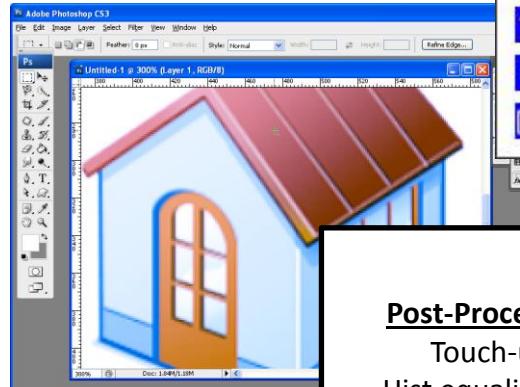
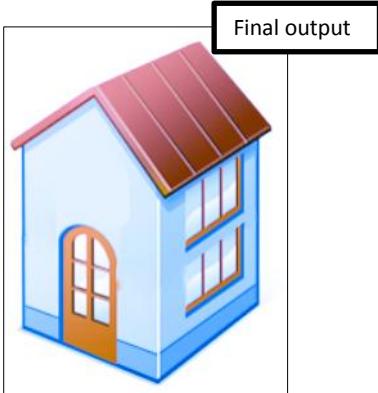


**Pre-Camera**  
Lens Filter  
Lens  
Shutter  
Aperture



**In-Camera**  
CCD response (RAW)  
CCD Demosaicing (RAW)

Portrait Mode	Soft Skin Mode	Transform Mode
Self-portrait Mode	Scenery Mode	Panorama Assist Mode
Sports Mode	Night Portrait Mode	Night Scenery Mode
Food Mode	Party Mode	Candle Light Mode
Baby Mode 1/2	Pet Mode	Sunset Mode
High Sensitivity Mode	High-speed Burst Mode	Flash Burst Mode
Starry Sky Mode	Fireworks Mode	Beach Mode
Snow Mode	Aerial Photo Mode	Pin Hole Mode
Film Grain Mode	High Dynamic Mode	Photo Frame Mode



Ending point:  
better than reality (in RGB)

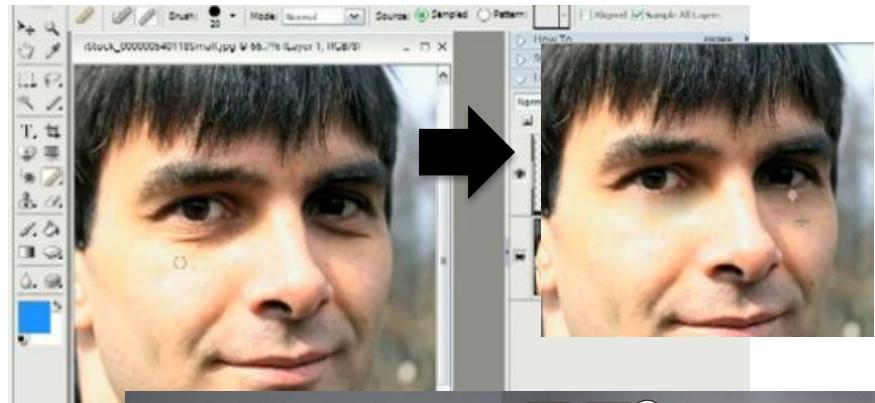
**Post-Processing**  
Touch-up  
Hist equalization  
Spatial warping  
Etc ...

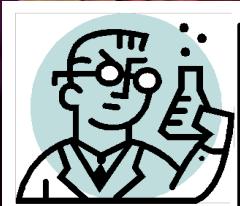
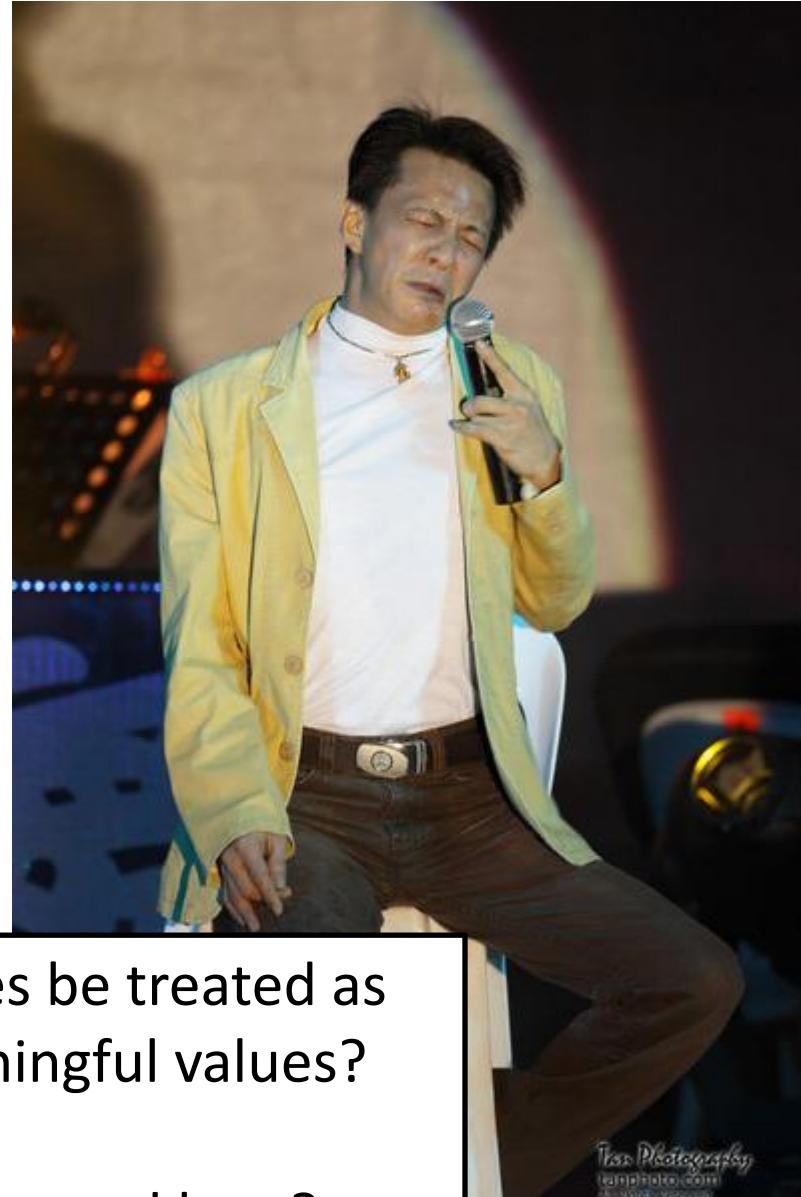
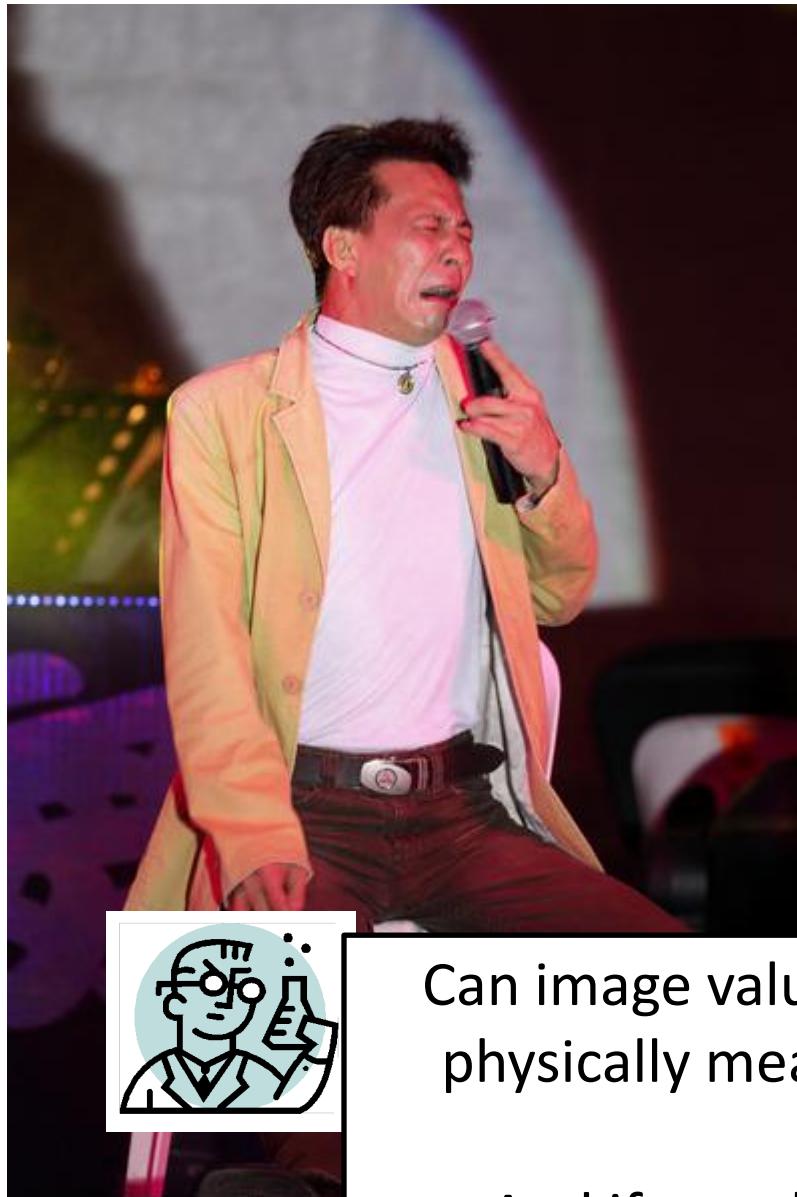


Even if we stopped here,  
the original CCD response  
potentially has had many  
levels of processing.

# Photography ≠ light measurement

- Modern photography is about obtaining “perceptually optimal” images
- Digital photography makes this more possible than ever before
- Cameras perform on-board photo-finishing

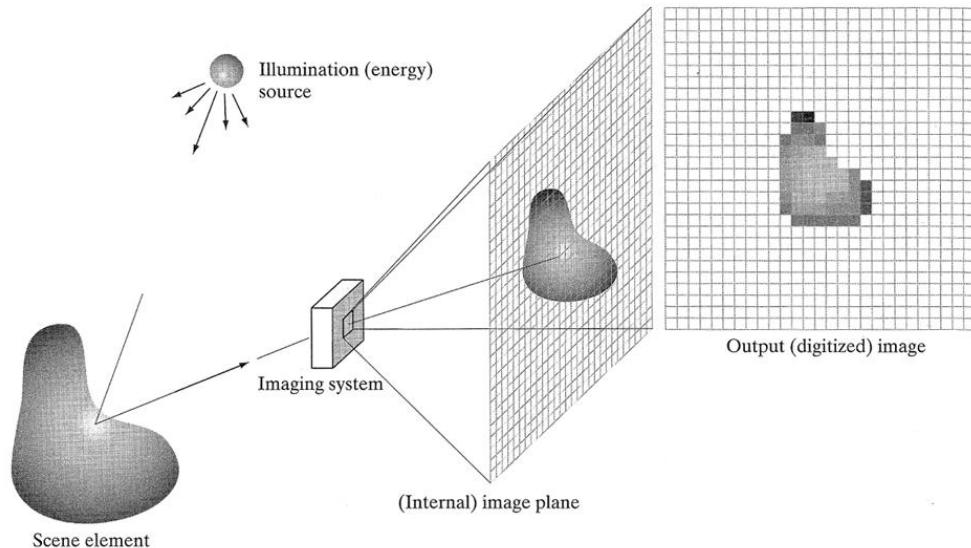




Can image values be treated as physically meaningful values?

And if so, when and how?

# Camera = light-measuring device

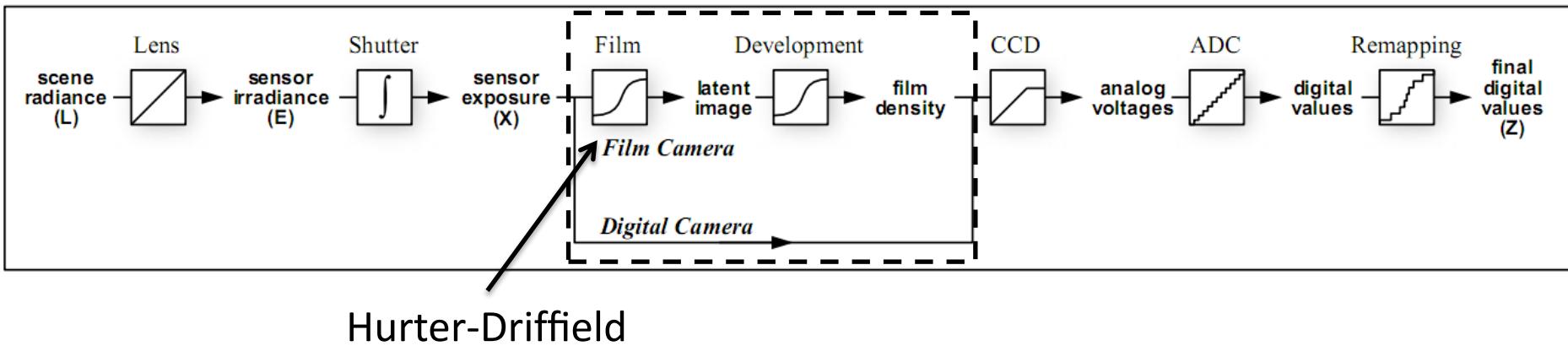


**“All models are wrong, but some are useful;  
the practical question is how wrong do they  
have to be to not be useful.”**

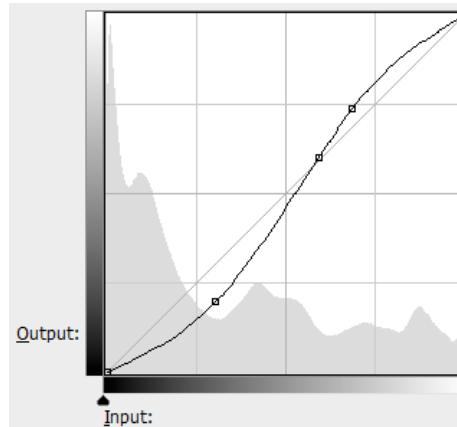
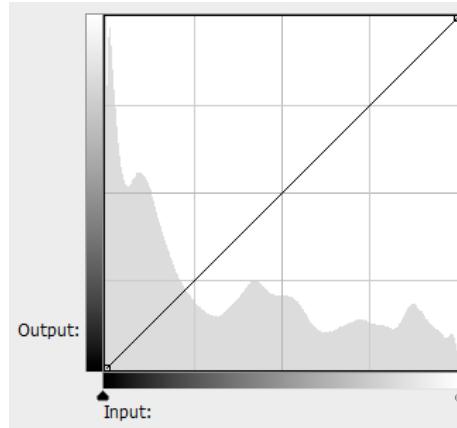


George Box  
Professor Emeritus of Statistics  
U. Wisconsin

# Digital camera pipeline (early work)

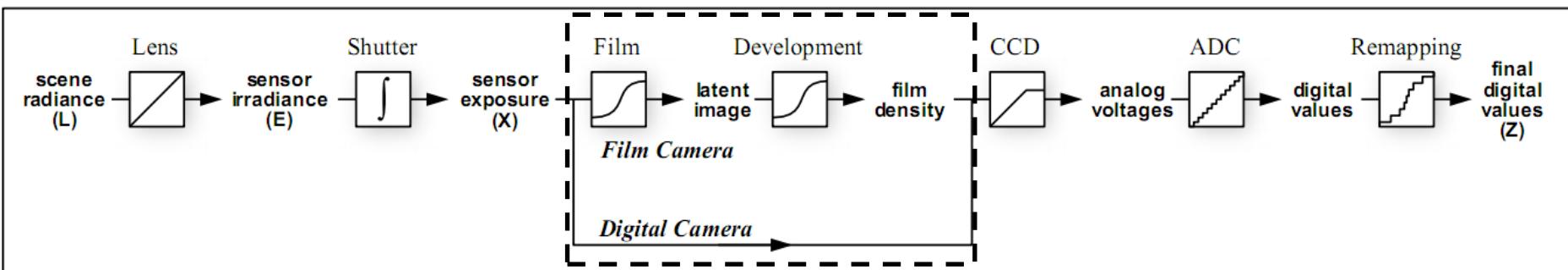


# Tone Mapping



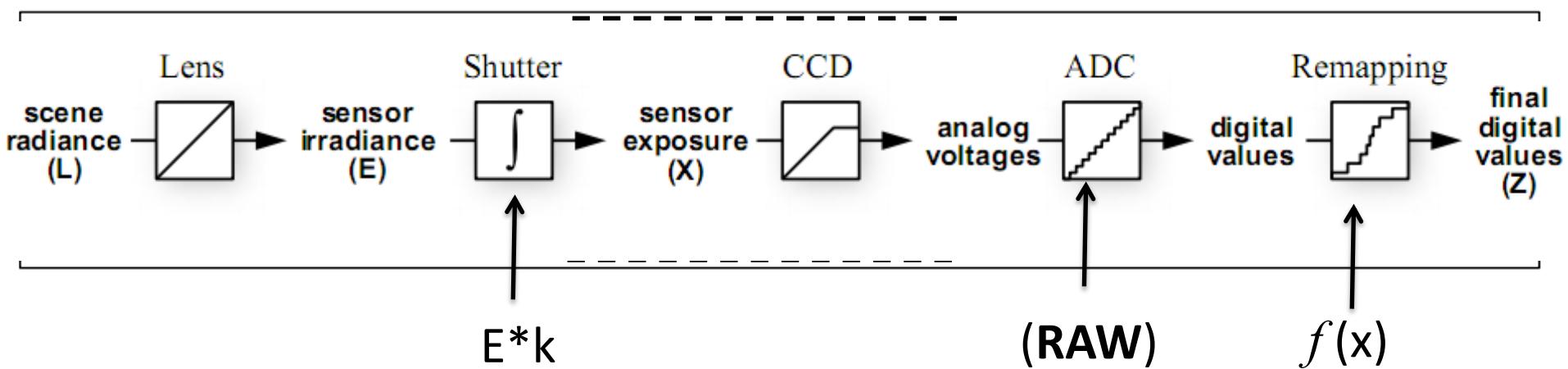
# Early Work

## “Radiometric Calibration”



# Early Work

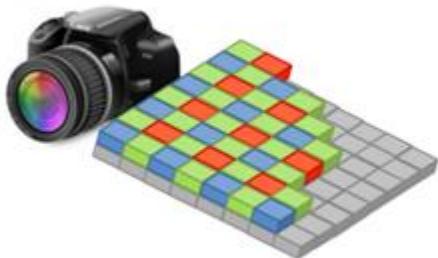
“Radiometric Calibration”



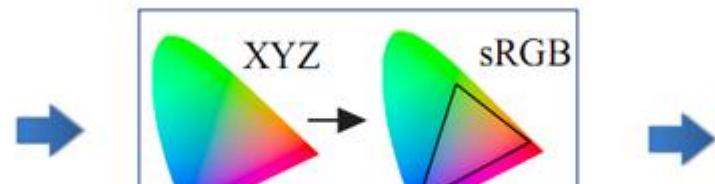
Unknown  $f$ ... the camera's non-linear response to **RAW**.

# Accepted model

(1) Irradiance  $\mathbf{E}_x$  (RAW)

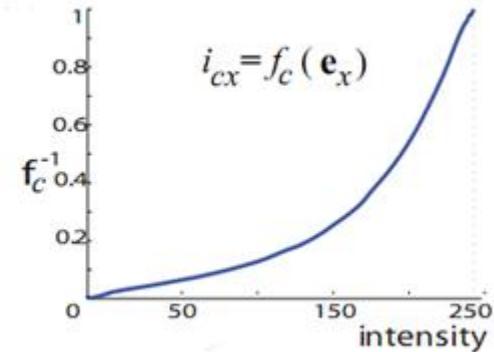


(2) Color Transform



$$\mathbf{T} = \mathbf{T}_{WB} \mathbf{T}_{srgb} \mathbf{T}_{xyz}, \mathbf{e}_x = \mathbf{T} \mathbf{E}_x$$

(3) Radiometric Response



$$\begin{bmatrix} E_{rx} \\ E_{gx} \\ E_{bx} \end{bmatrix}$$

(RAW)

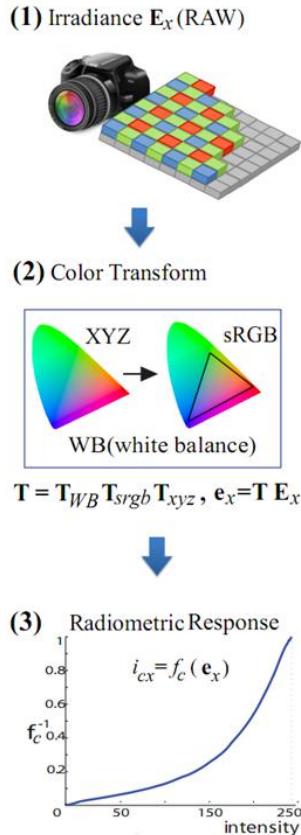
$$\begin{bmatrix} e_{rx} \\ e_{gx} \\ e_{bx} \end{bmatrix} = \mathbf{T} \begin{bmatrix} E_{rx} \\ E_{gx} \\ E_{bx} \end{bmatrix}$$

$\mathbf{T}$  is a 3x3 matrix

$$\begin{bmatrix} i_{rx} \\ i_{gx} \\ i_{bx} \end{bmatrix} = \begin{bmatrix} f_r(e_{rx}) \\ f_g(e_{gx}) \\ f_b(e_{bx}) \end{bmatrix}$$

$i$  is the sRGB output and  $f$  is a non-linear function

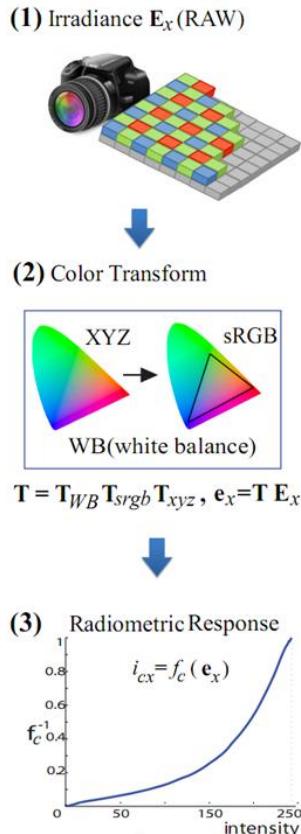
# Prior work



Fixed property of the camera

- Mann and Picard, SPIE'95  
Debevec and Malik, SIG'97  
Mitsunaga and Nayar, CVPR'99  
Farid, TIP'01  
Grossberg and Nayar, TPAMI'03  
Grossberg and Nayar, TPAMI'04  
Lin et al, CVPR'04  
...  
Manders et al, ICIP'04  
Pal et al, CVPR'04  
Lin et al, ICCV'05  
Kim and Pollefeys, TPAMI'08  
Chakrabarti et al, BMVC'09

# Prior work



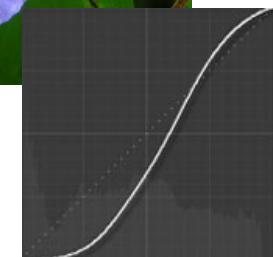
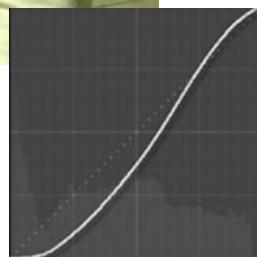
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Grossberg and Nayar, TPAMI'04  
Lin et al, CVPR'04  
...  
Manders et al, ICIP'04  
Pal et al, CVPR'04  
Lin et al, ICCV'05  
Kim and Pollefeys, TPAMI'08  
Chakrabarti et al, BMVC'09

## Chakrabarti et al conclusions:

- 😊 RAW is meaningful . . . .
- 😢 But, requires a 24 parameter model that is **scene-dependent** to accurately go back from sRGB to RAW.

# Scene Dependent. . .



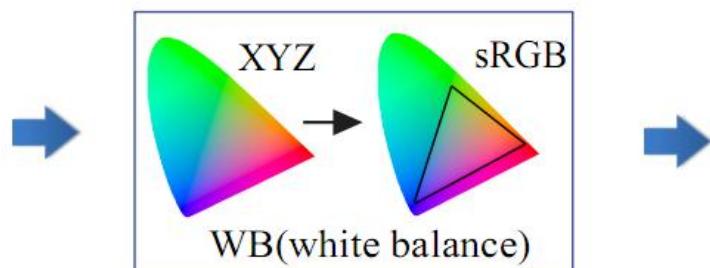
Tone curve,  $f$ , is computed based on scene content. **This makes it almost impossible to pre-compute.**

# Accepted model

(1) Irradiance  $\mathbf{E}_x$  (RAW)

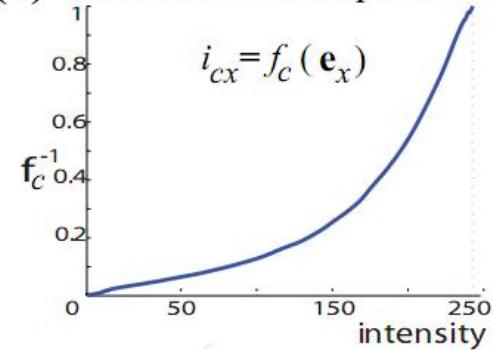


(2) Color Transform



$$\mathbf{T} = \mathbf{T}_{WB} \mathbf{T}_{srgb} \mathbf{T}_{xyz}, \mathbf{e}_x = \mathbf{T} \mathbf{E}_x$$

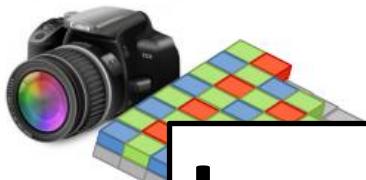
(3) Radiometric Response



$$\begin{bmatrix} i_{rx} \\ i_{gx} \\ i_{bx} \end{bmatrix} = \begin{bmatrix} f_r(e_{rx}) \\ f_g(e_{gx}) \\ f_b(e_{bx}) \end{bmatrix} \quad \leftarrow \quad \begin{bmatrix} e_{rx} \\ e_{gx} \\ e_{bx} \end{bmatrix} = \mathbf{T} \begin{bmatrix} E_{rx} \\ E_{gx} \\ E_{bx} \end{bmatrix}$$

# Accepted model

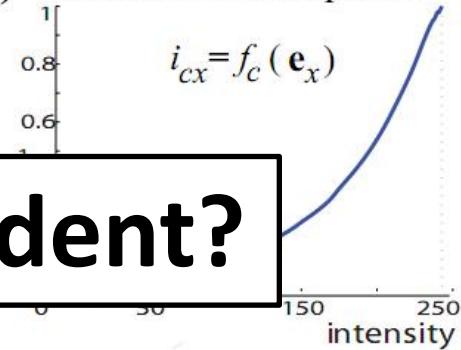
(1) Irradiance  $E_x$  (RAW)



(2) Color Transform



(3) Radiometric Response



Is processing scene dependent?

$$T = T_{WB} T_{srgb} T_{xyz}, e_x = T E_x$$

Or is this model not good enough?

$$\begin{bmatrix} i_{gx} \\ i_{bx} \end{bmatrix} = \begin{bmatrix} f_g(e_{gx}) \\ f(e_{bx}) \end{bmatrix} \quad \leftarrow \quad \begin{bmatrix} e_{gx} \\ e_{bx} \end{bmatrix} = T \begin{bmatrix} E_{gx} \\ E_{bx} \end{bmatrix}$$

# Photo-finishing in cameras

Does it depend on scenes or is it a fixed procedure?

## *Scene-Dependent Processing*

Some imaging pipelines vary the processing based on the captured scene.

### **Two categories**

*Globally dependent:* Auto white-balance; auto-mode selection.

*Locally dependent:* Dynamic Lighting Optimizer in Canon, D-Range Optimizer in Sony

## *Fixed Processing*

Photofinishing using fixed color rendering are typically **manual set modes**, i.e. the user sets the white-balance, subject type (picture style), etc.

# Our Experiment: Data Collection

- More than **10,000 images** from **33 cameras** from DSLRs to point-and-shoots
  - Images of color charts under indoor / outdoor (cloudy)
  - Images are taken at all possible shutter speeds, at multiple aperture, and white balance settings. JPEG / RAW both captured if possible.
- \* Special shooting features such as lighting optimizer are turned off



# Scene under different exposure



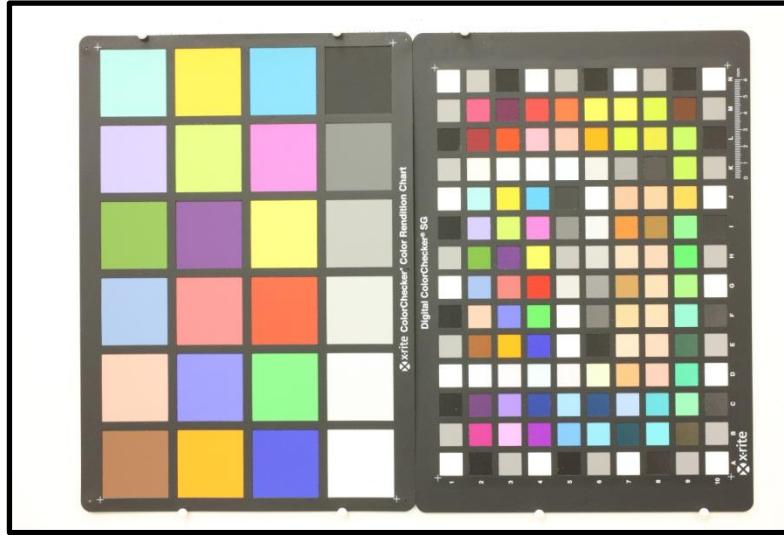
Exposure k1



Exposure k2



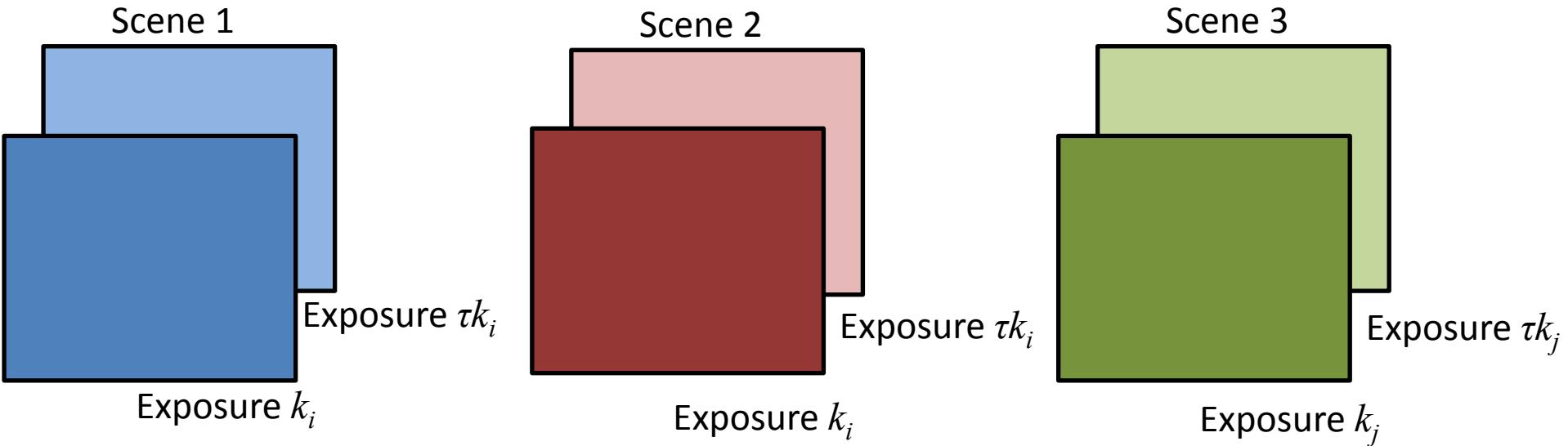
Exposure k3



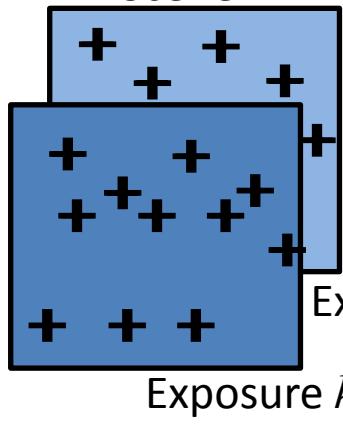
Exposure k4

# Checked if $f$ is fixed or scene dependent

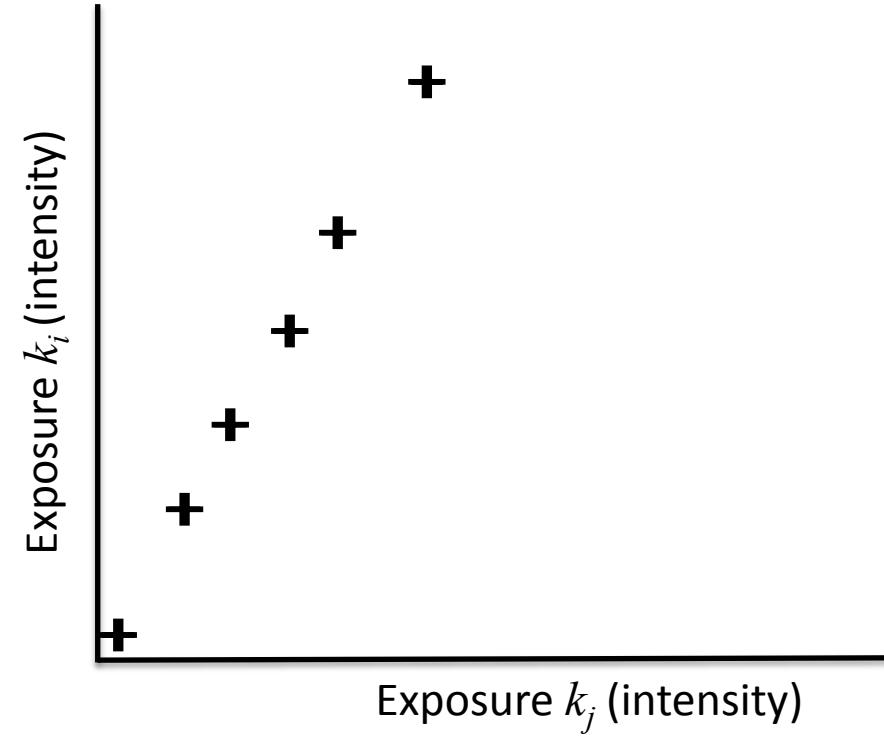
- How?
- Plot the **brightness transfer function (BTF)**
  - Plot points from image pairs of different scenes
  - Each pair has the same ratio,  $\tau$ , of exposure change



Scene 1

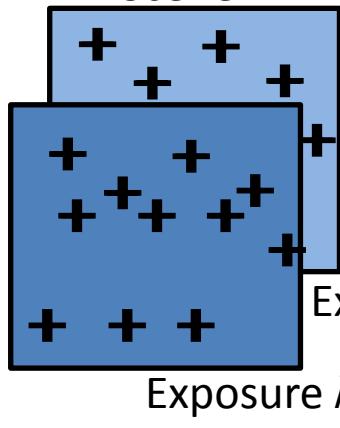


BTF

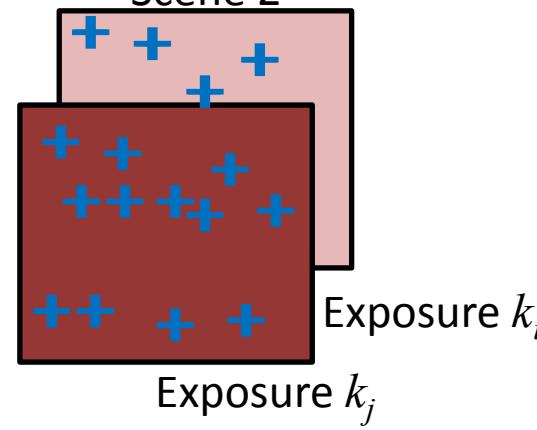


Linear function looks like this. . .

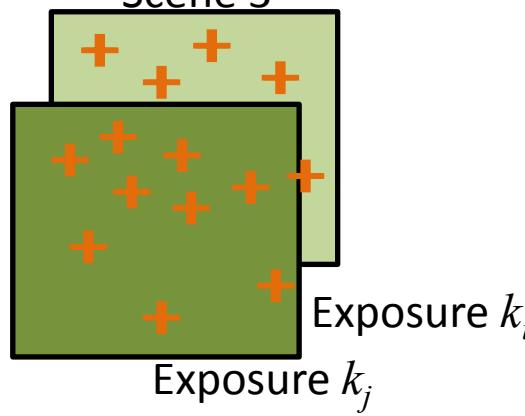
Scene 1



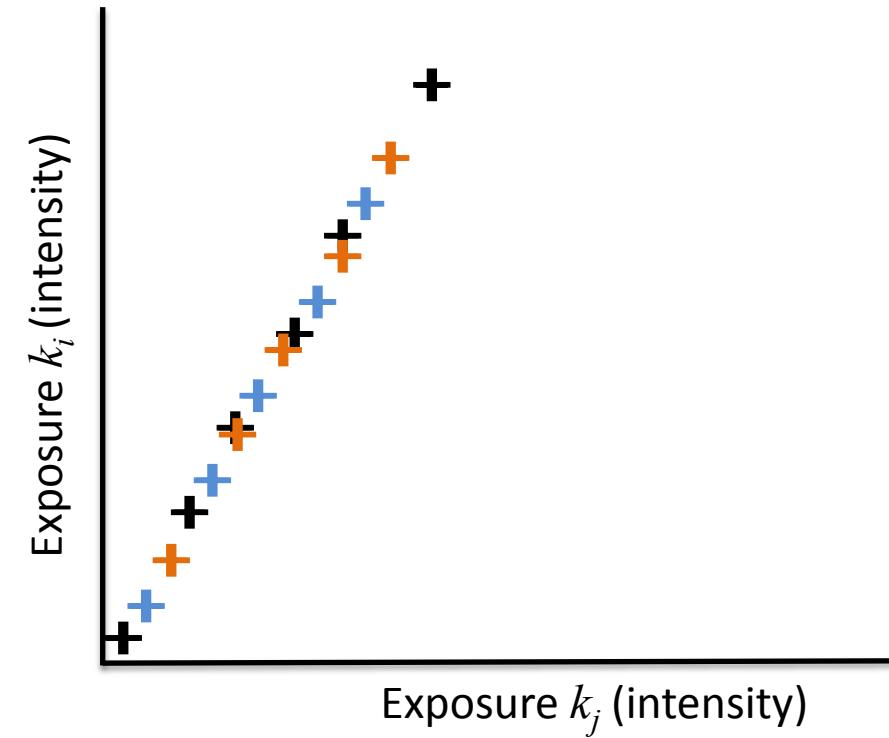
Scene 2



Scene 3

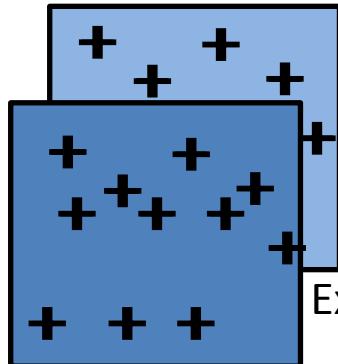


# BTF

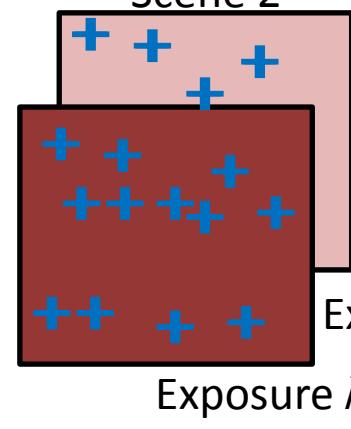


Linear function looks like this . . .

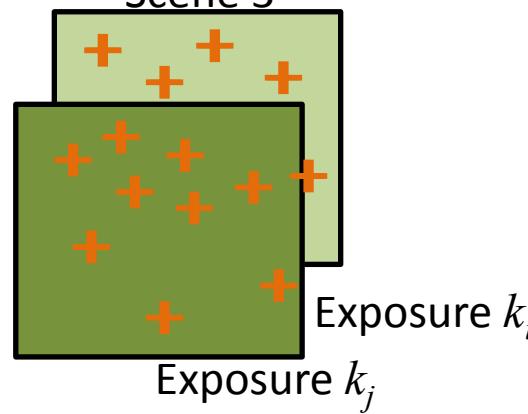
Scene 1



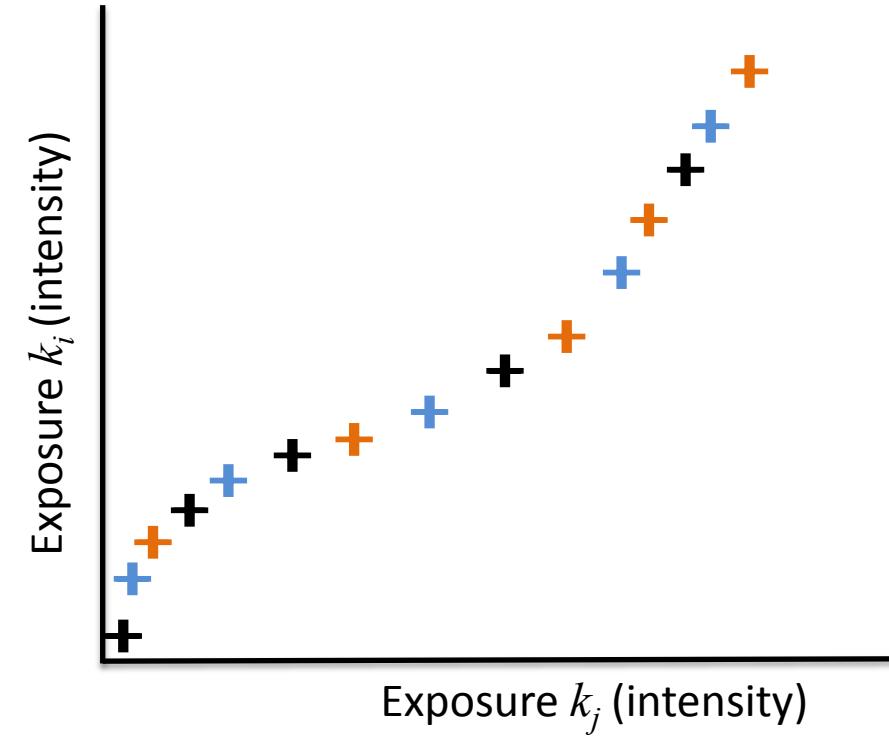
Scene 2



Scene 3

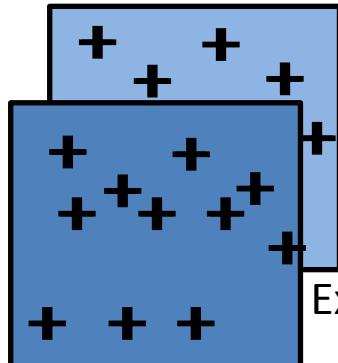


# BTF

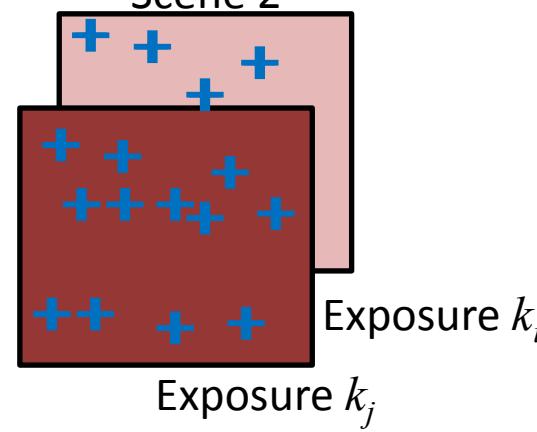


Non-linear BTF looks like this ..

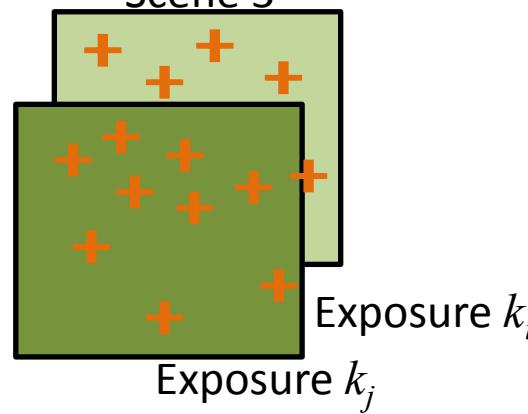
Scene 1



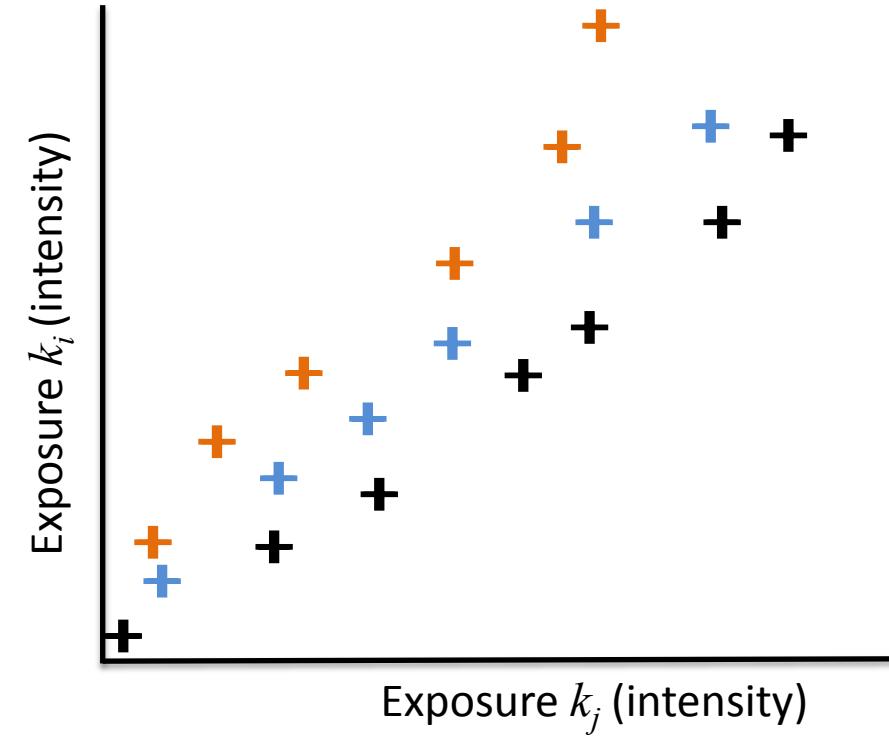
Scene 2



Scene 3



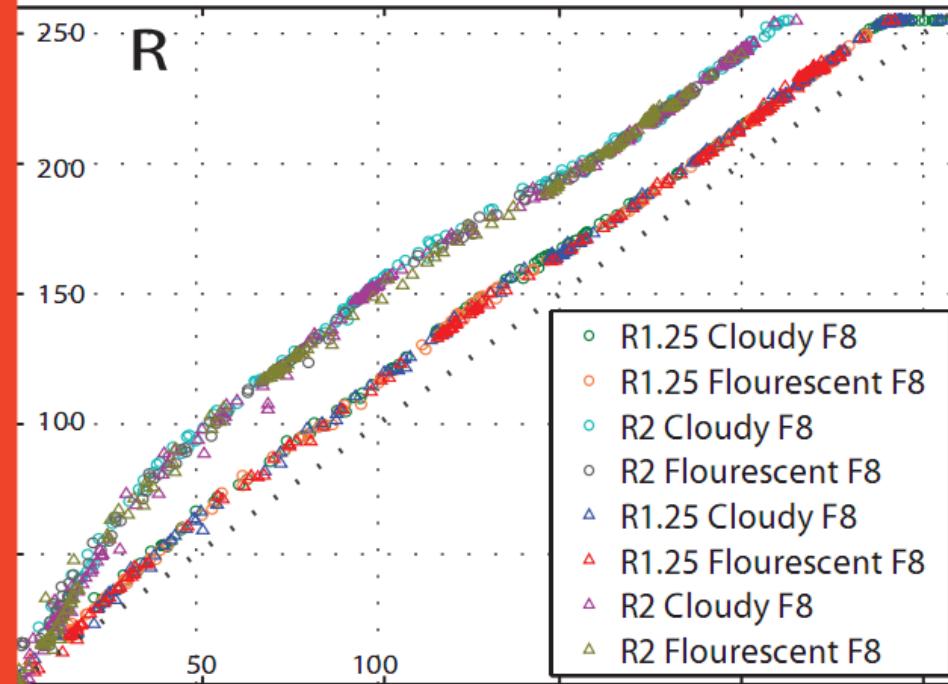
# BTF



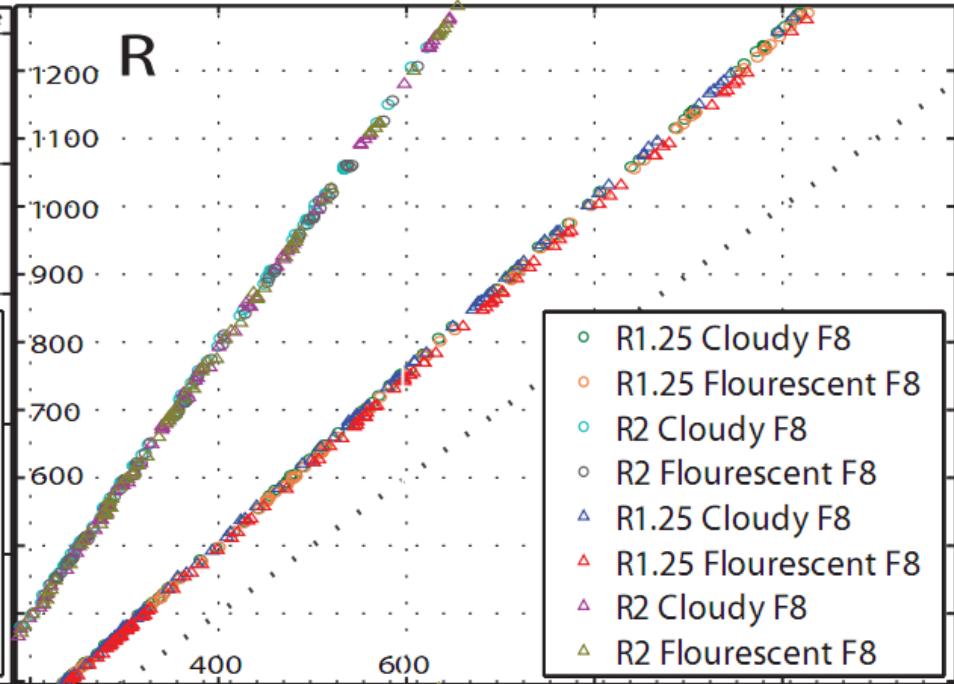
**Scene dependent** non-linear BTF  
looks like this . .

# For the most part . . . it was ok

Nikon D50 sRGB BTF



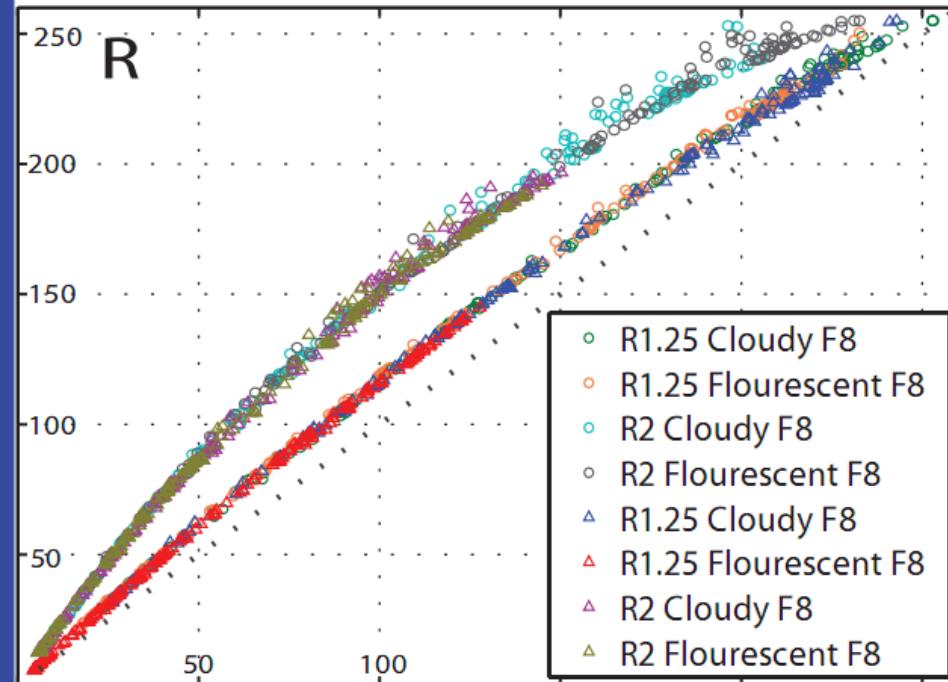
Nikon D50 RAW BTF



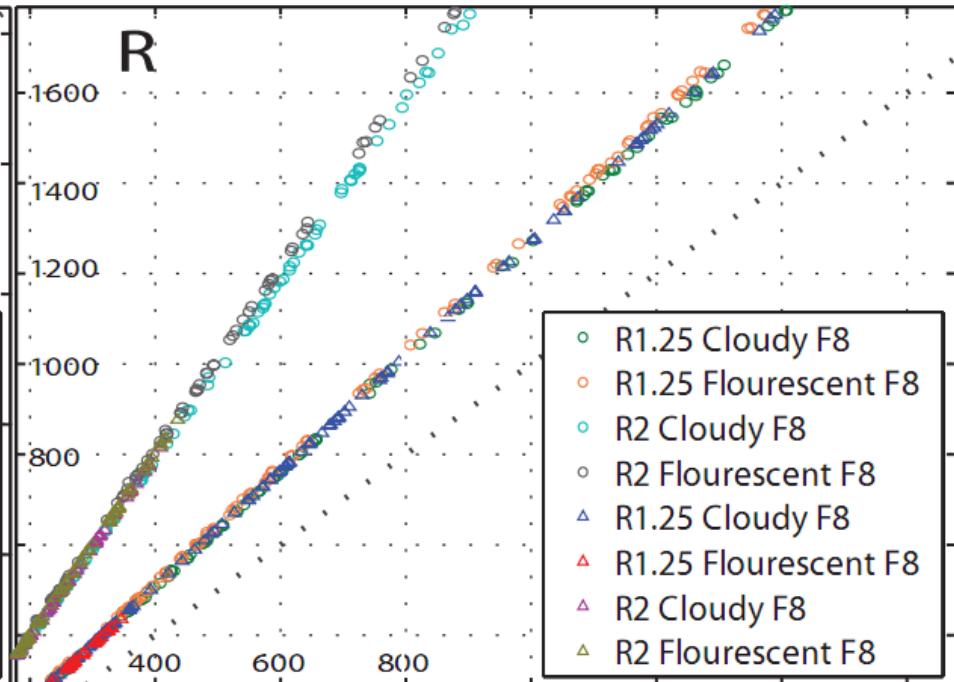
# For the most part . . . it was ok

outliers

Canon EOS 1D sRGB BTF



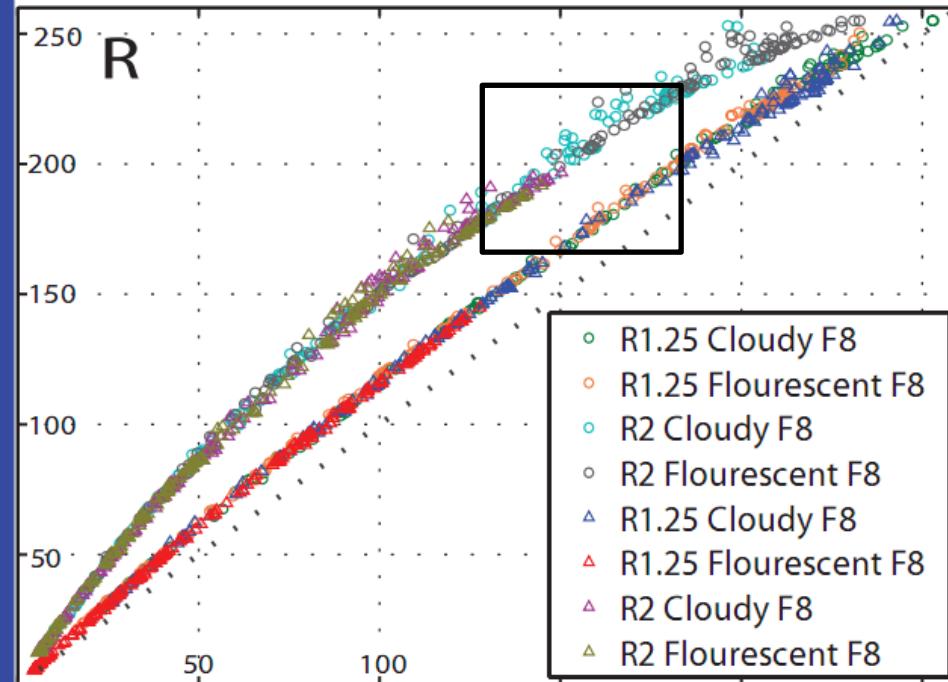
Canon EOS 1D RAW BTF



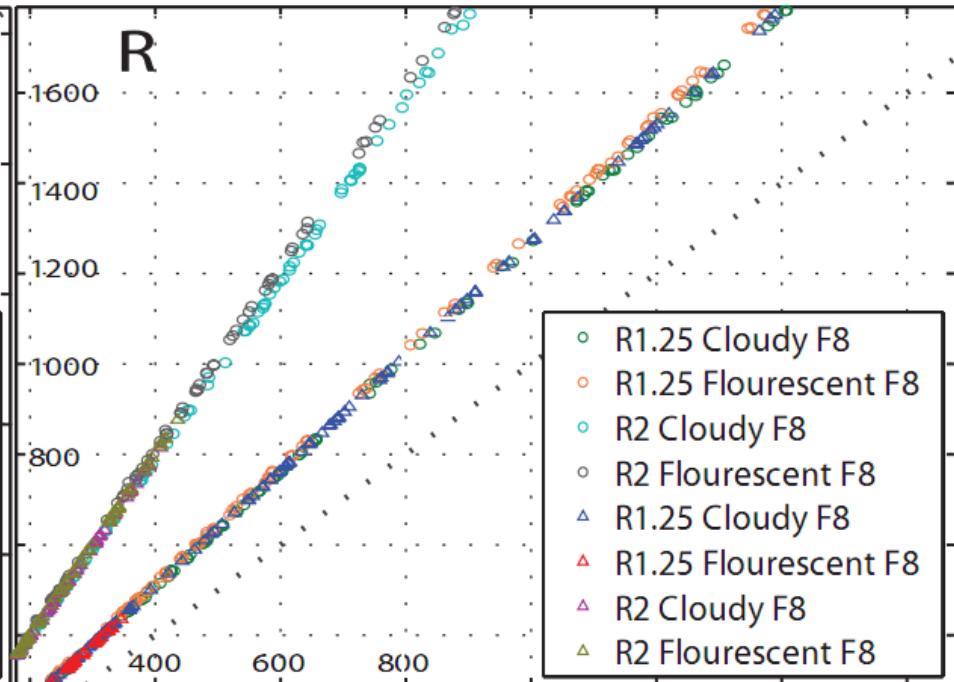
# For the most part . . . it was ok

outliers

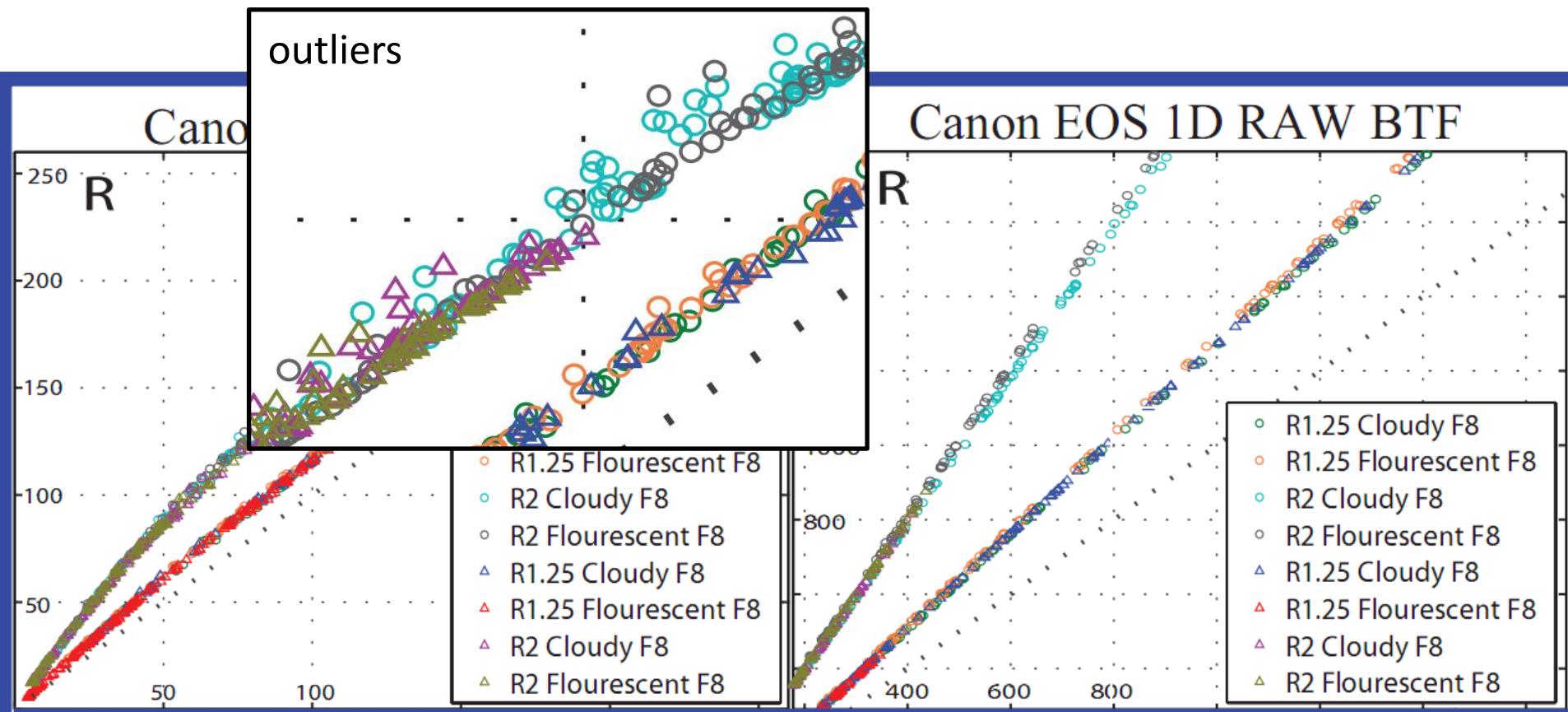
Canon EOS 1D sRGB BTF



Canon EOS 1D RAW BTF



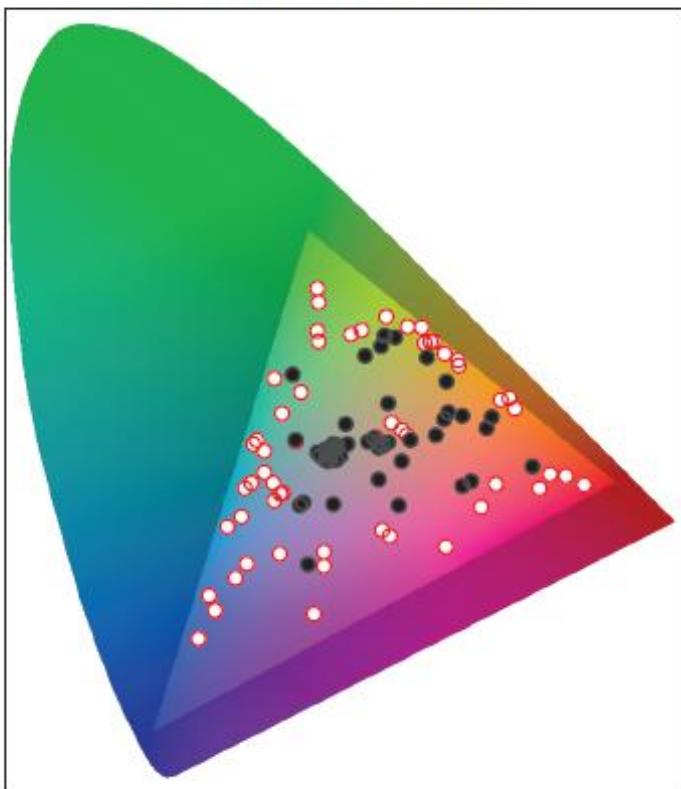
# For the most part . . . it was ok



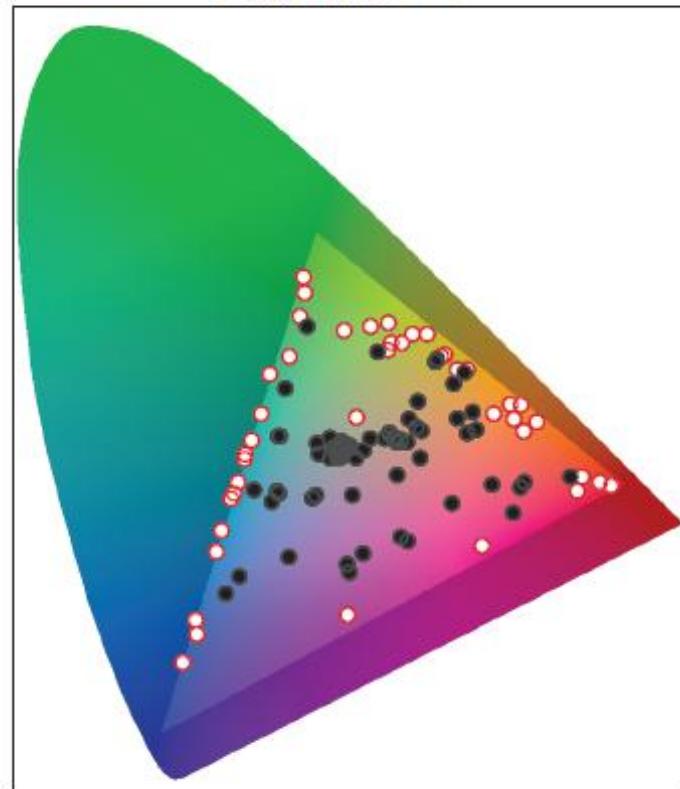
# Observations

Where are the outliers?

Canon EOS 1D



Nikon D50



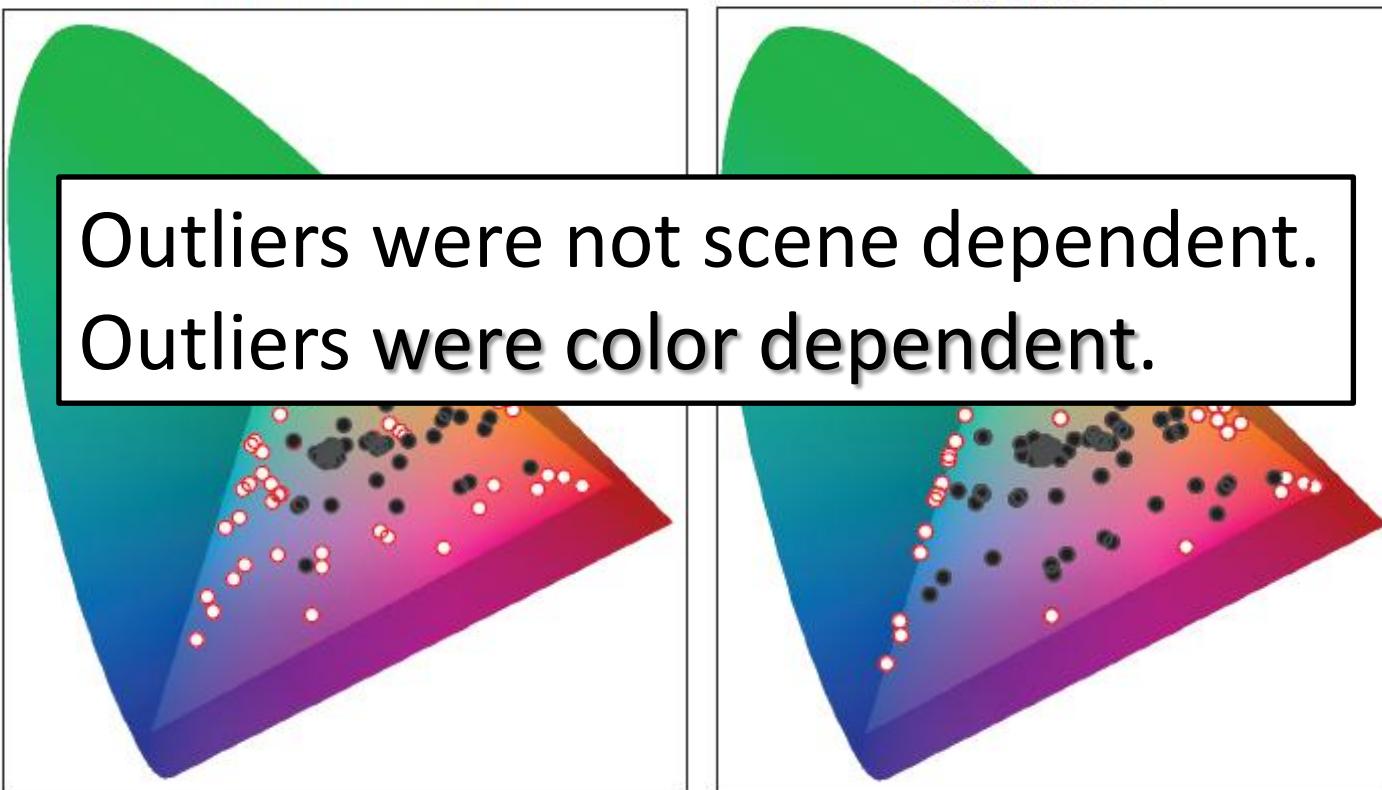
# Observations

Where are the outliers?

Canon EOS 1D

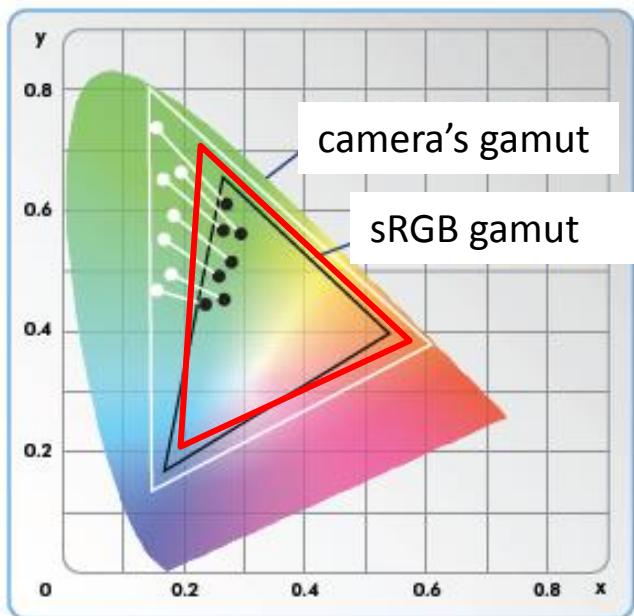
Nikon D50

Outliers were not scene dependent.  
Outliers were color dependent.



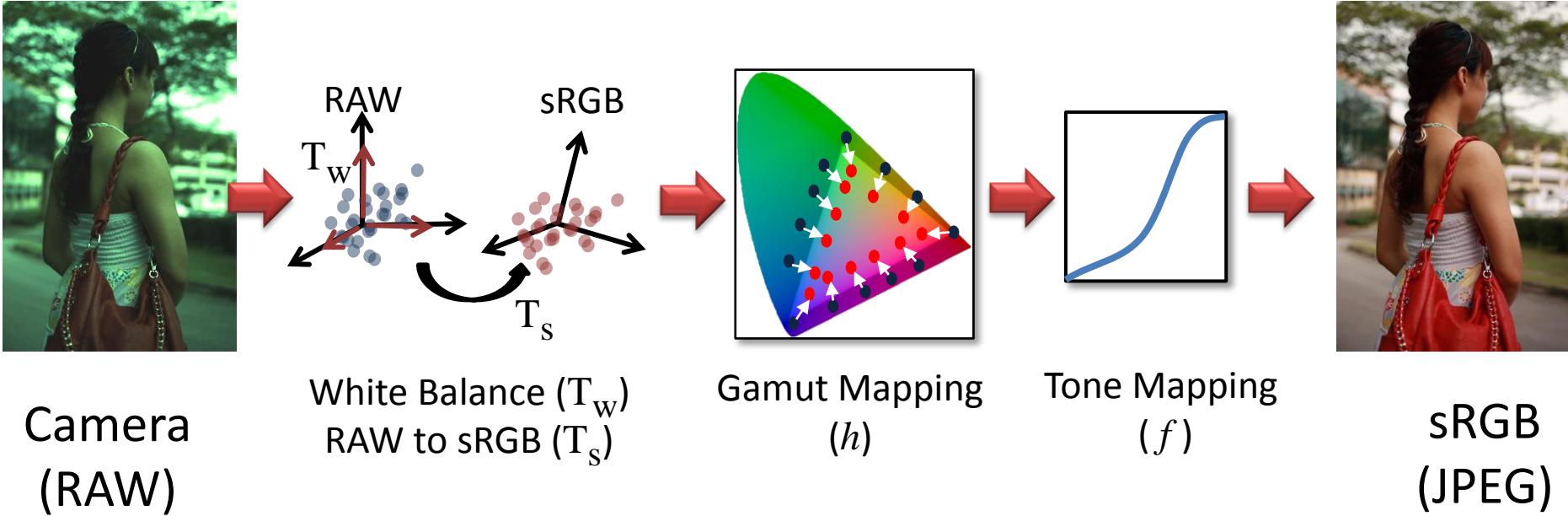
# Gamut Mapping

## Gamut Mapping

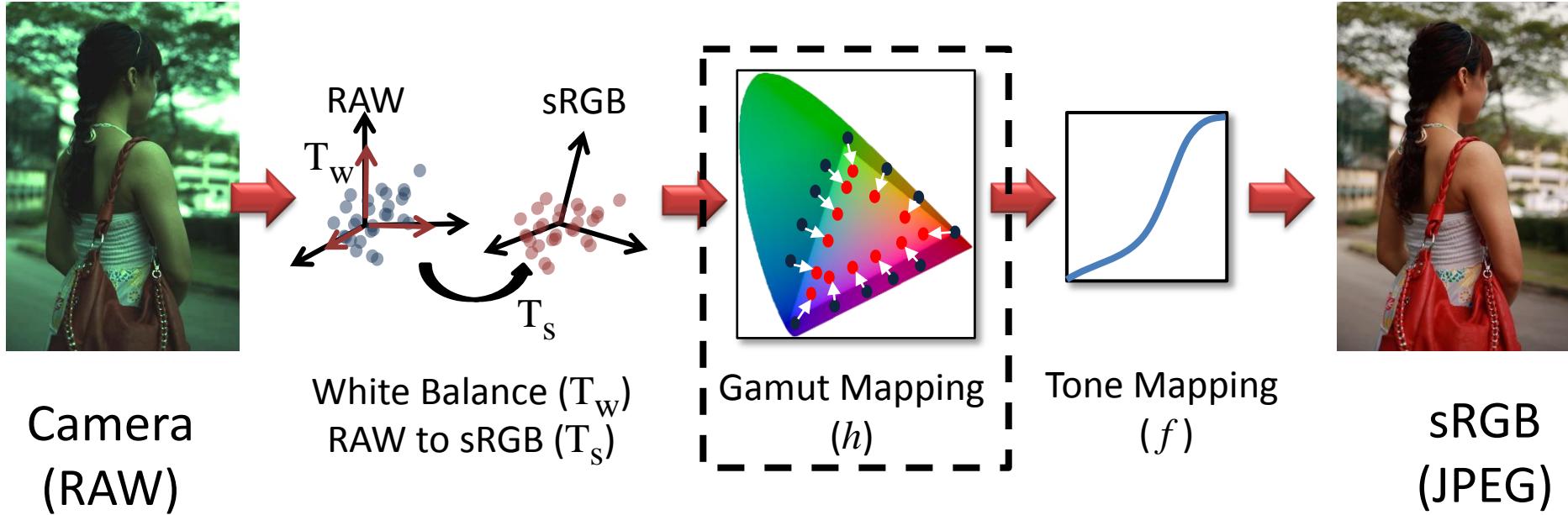


- Compensates mismatch between camera's gamut and sRGB gamut
- Allows selective color manipulation for scene styles (portrait, landscape, vivid, etc)

# Proposed a new model



# Proposed a new model



$$\begin{bmatrix} i_{rx} \\ i_{gx} \\ i_{bx} \end{bmatrix} = f(h \left( \mathbf{T} \begin{bmatrix} E_{rx} \\ E_{gx} \\ E_{bx} \end{bmatrix} \right))$$

$$h: \mathbb{R}^3 \rightarrow \mathbb{R}^3$$

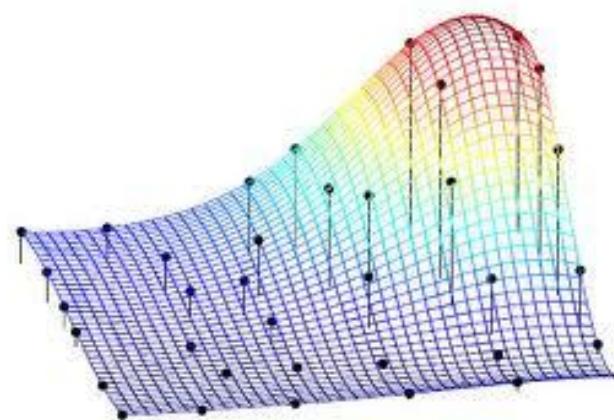
# sRGB Image to RAW

$$\begin{bmatrix} f^{-1}(i_{rx}) \\ f^{-1}(i_{gx}) \\ f^{-1}(i_{bx}) \end{bmatrix} = h \begin{pmatrix} e_{rx} \\ e_{gx} \\ e_{bx} \end{pmatrix} = h \left( \mathbf{T} \begin{bmatrix} E_{rx} \\ E_{gx} \\ E_{bx} \end{bmatrix} \right) \xrightarrow{\hspace{1cm}} \begin{bmatrix} E_{rx} \\ E_{gx} \\ E_{bx} \end{bmatrix} = \mathbf{T}^{-1} \cdot h^{-1} \left( \begin{bmatrix} f_r^{-1}(i_{rx}) \\ f_g^{-1}(i_{gx}) \\ f_b^{-1}(i_{bx}) \end{bmatrix} \right)$$

based on several image-RAW pairs,

- $f^1$  &  $\mathbf{T}^{-1}$  are computed using less saturated points
- $h^{-1}$  is computed with scatter point interpolation via *radial basis func.*

$$h^{-1}(\mathbf{e}) = \sum_{i=1}^N w_i \|\mathbf{e} - \mathbf{e}_i\|_2$$



# sRGB Image to RAW

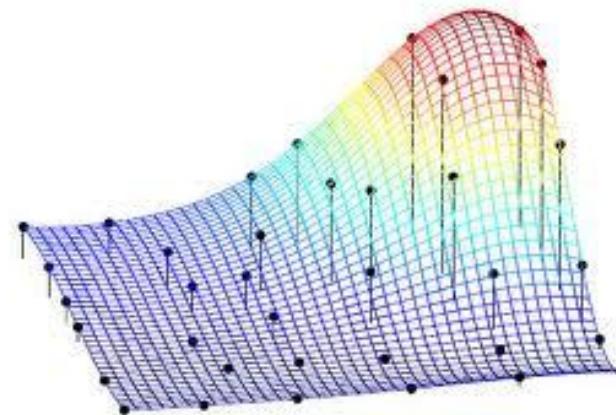
$$\begin{bmatrix} f^{-1}(i_{rx}) \\ f^{-1}(i_{gx}) \\ f^{-1}(i_{bx}) \end{bmatrix} = h \begin{pmatrix} e_{rx} \\ e_{gx} \\ e_{bx} \end{pmatrix} = h \left( \mathbf{T} \begin{bmatrix} E_{rx} \\ E_{gx} \\ E_{bx} \end{bmatrix} \right) \xrightarrow{\hspace{1cm}} \begin{bmatrix} E_{rx} \\ E_{gx} \\ E_{bx} \end{bmatrix} = \mathbf{T}^{-1} \cdot h^{-1} \left( \begin{bmatrix} f_r^{-1}(i_{rx}) \\ f_g^{-1}(i_{gx}) \\ f_b^{-1}(i_{bx}) \end{bmatrix} \right)$$

based on

But we should have used  
“Lattice Regression”.

- $f^1$  &  $\mathbf{T}$
- $h^{-1}$  is computed with scatter point interpolation via *radial basis func.*

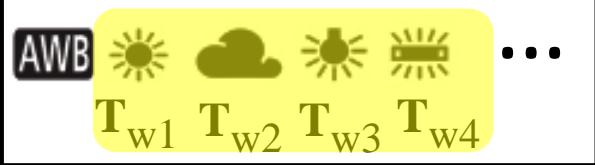
$$h^{-1}(\mathbf{e}) = \sum_{i=1}^N w_i \|\mathbf{e} - \mathbf{e}_i\|_2$$



# Canon EOS1Ds Mark III



## White Balance



## Picture Styles

S

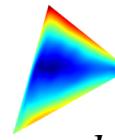
Standard

P

Portrait

L

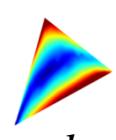
Landscape ...



$h_1, f_1$



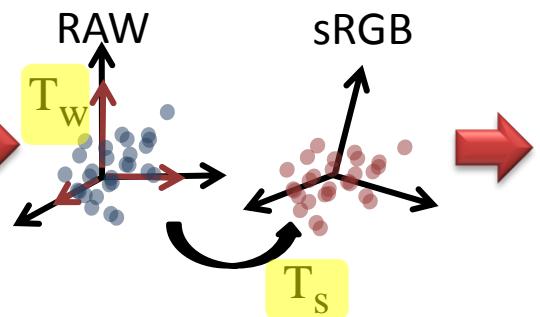
$h_2, f_2$



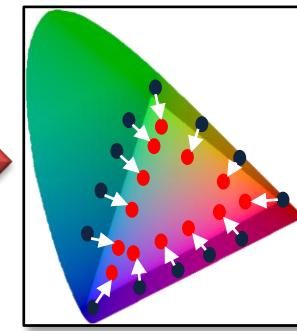
$h_3, f_3$



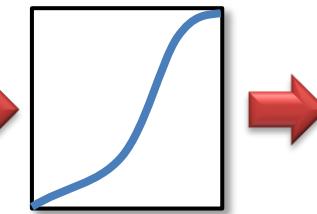
Camera  
(RAW)



White Balance ( $T_w$ )  
RAW to sRGB ( $T_s$ )



Gamut Mapping  
( $h$ )

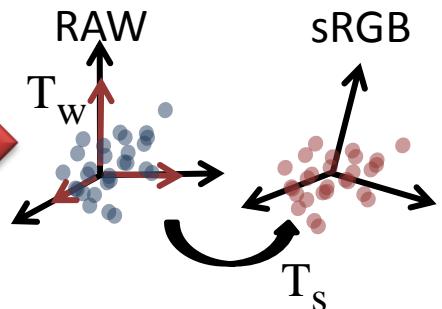
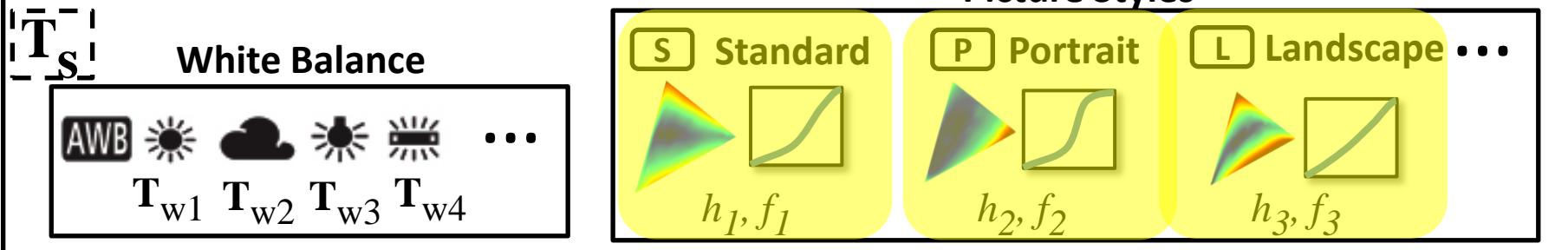


Tone Mapping  
( $f$ )



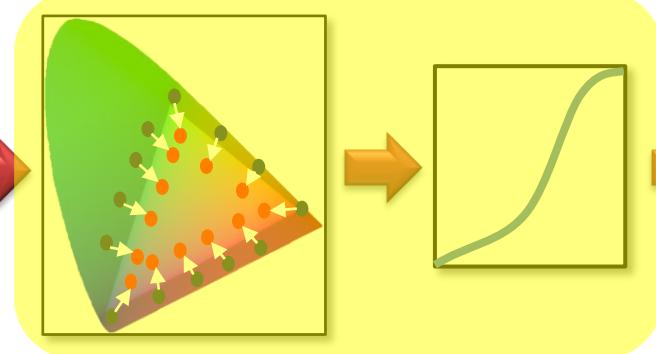
sRGB  
(JPEG)

# Canon EOS1Ds Mark III

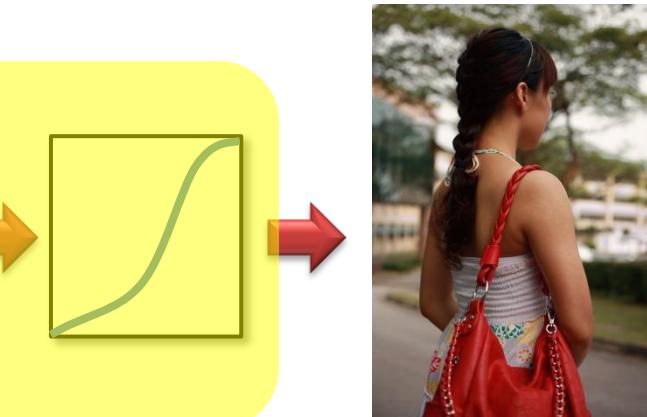


Camera  
(RAW)

White Balance ( $T_w$ )  
RAW to sRGB ( $T_s$ )



Gamut Mapping  
( $h$ )

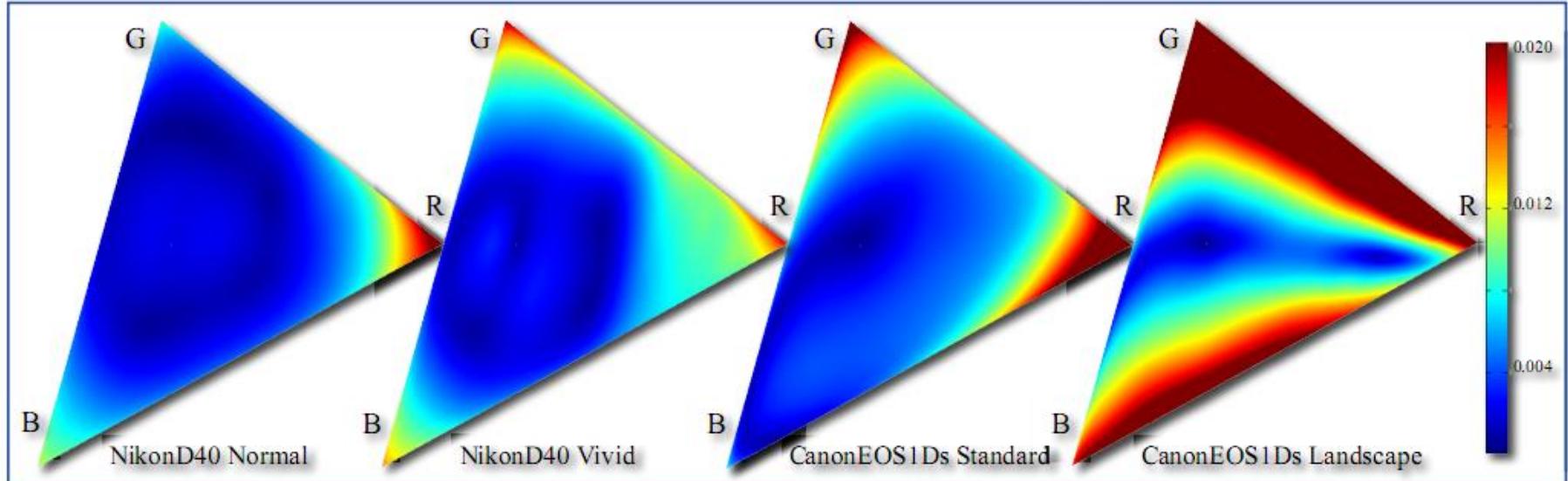


Tone Mapping  
( $f$ )



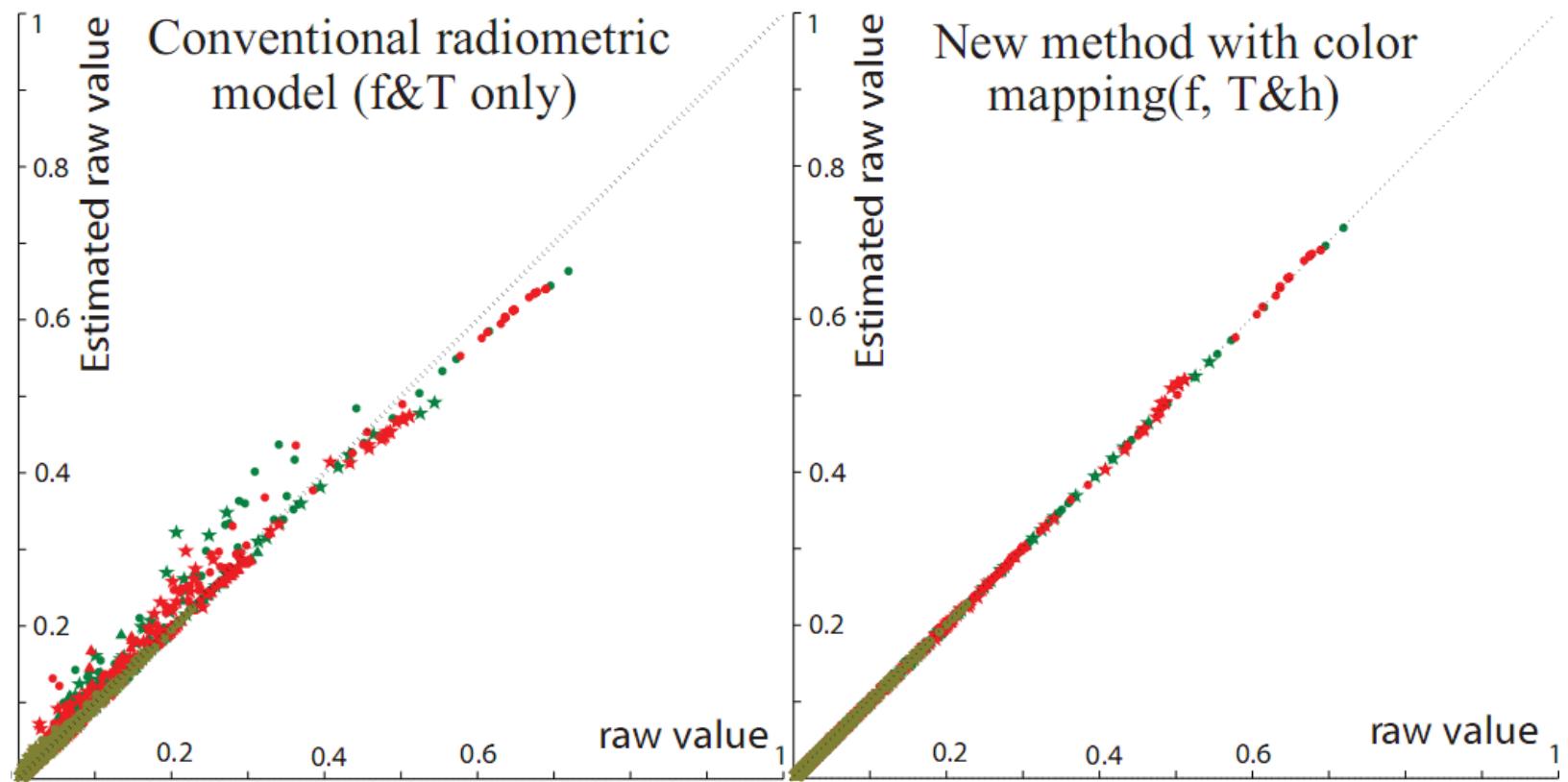
sRGB  
(JPEG)

# Gamut Mapping



Mapping is represented as a displacement map of the camera's original RGB value to its sRGB location.

# Experiments : Mapping Image to RAW



# Experiments : Mapping Image to RAW



input sRGB image



ground truth RAW

**Canon EOS1D**

# Experiments : Mapping Image to RAW



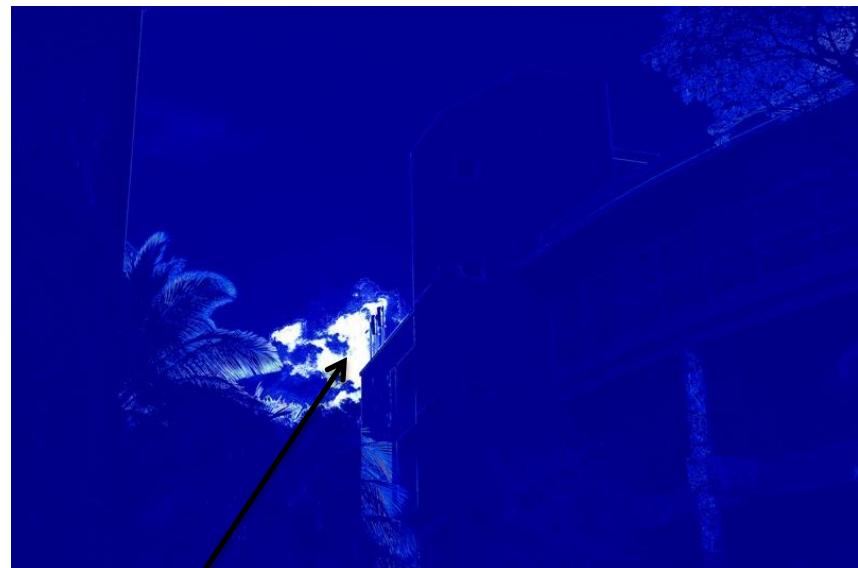
input sRGB image



estimated RAW

**Canon EOS1D**

# Experiments : Mapping Image to RAW



new model ( $f, T, h$ )



old model ( $f, T$ )

We cannot handle  
fully saturated points.

**Canon EOS1D**

# Experiments : Mapping Image to RAW



input sRGB image



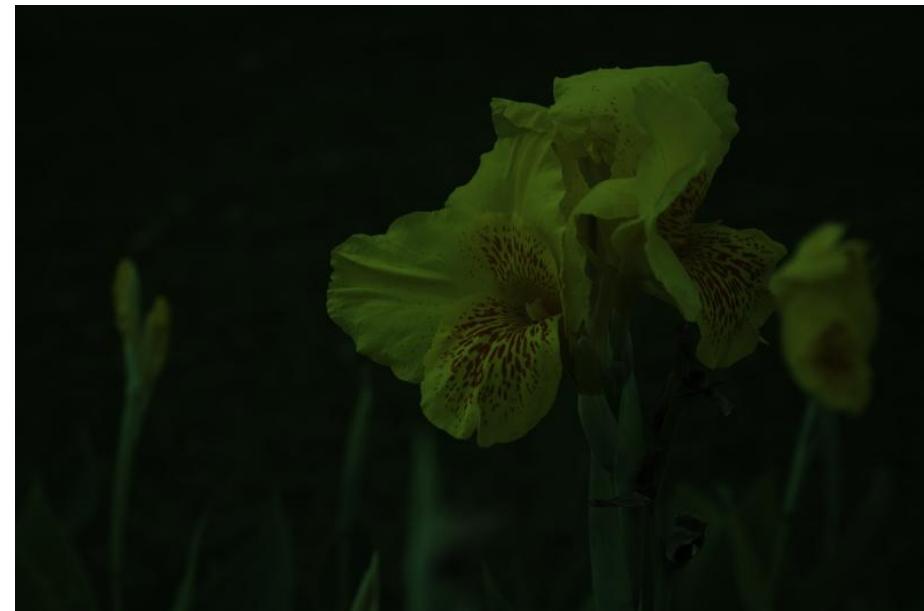
ground truth RAW

**Canon EOS550D**

# Experiments : Mapping Image to RAW



input sRGB image



estimated RAW

**Canon EOS550D**

# Experiments : Mapping Image to RAW



new model ( $f, T, h$ )

old model ( $f, T$ )

**Canon EOS1D**

# Experiments : Mapping Image to RAW



input sRGB image



ground truth RAW

**Sony A200**

# Experiments : Mapping Image to RAW



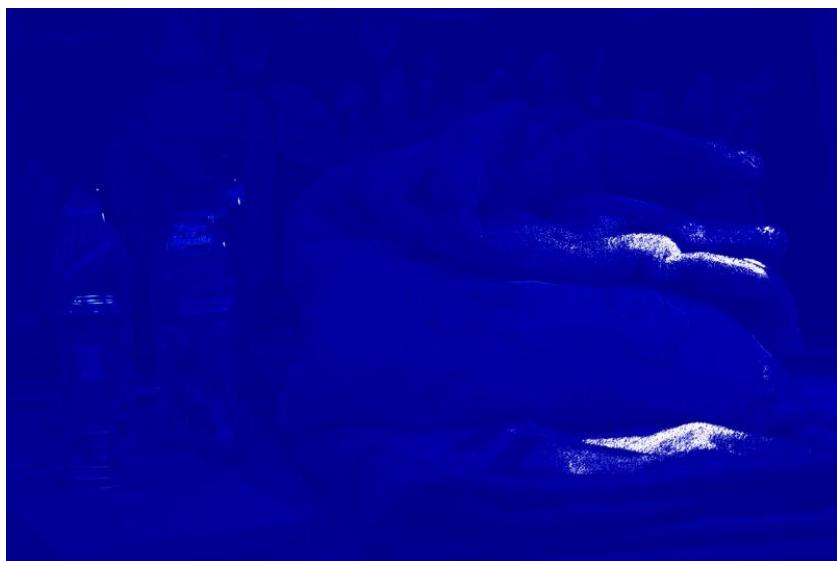
input sRGB image



estimated RAW

**Sony A200**

# Experiments : Mapping Image to RAW



new model ( $f, T, h$ )

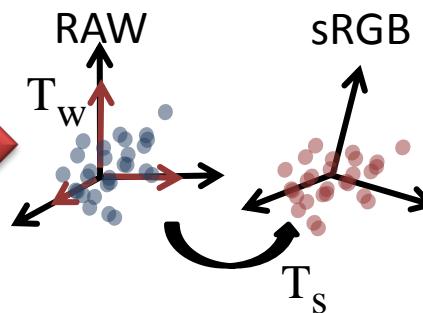
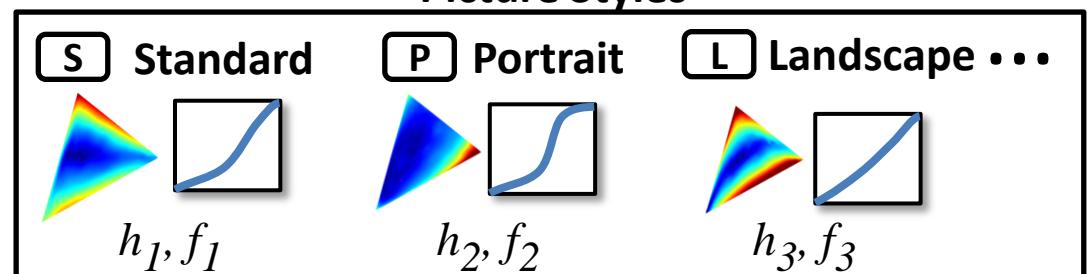
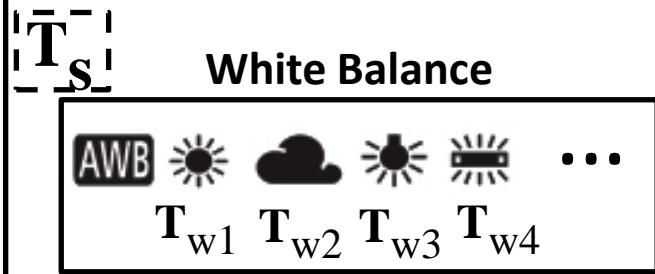


old model ( $f, T$ )

Sony A200

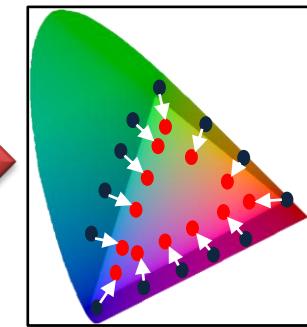
# Application: *Photo Refinishing*

# Canon EOS1Ds Mark III



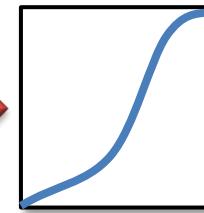
Camera  
(RAW)

White Balance ( $T_w$ )  
RAW to sRGB ( $T_s$ )



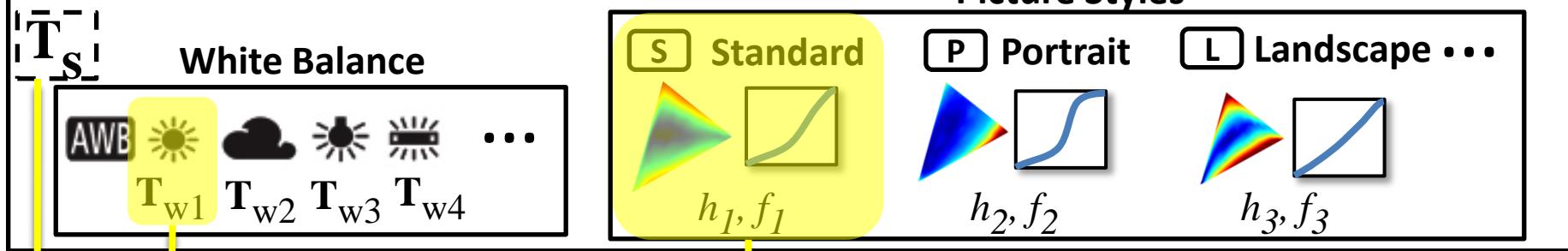
Gamut Mapping  
( $h$ )

Tone Mapping  
( $f$ )

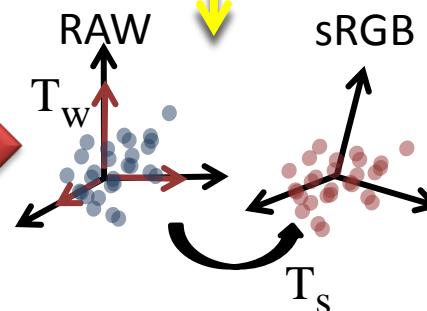


sRGB  
(JPEG)

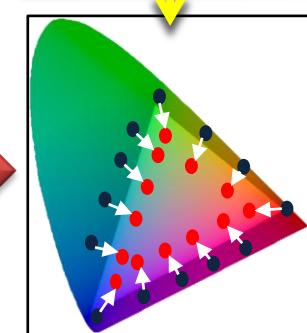
# Canon EOS1Ds Mark III



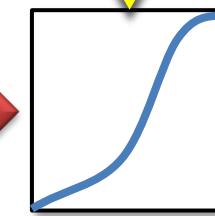
Camera  
(RAW)



White Balance ( $T_w$ )  
RAW to sRGB ( $T_s$ )



Gamut Mapping  
( $h$ )

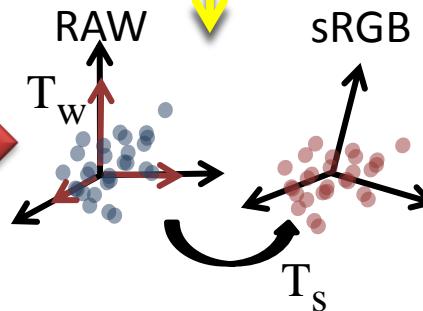
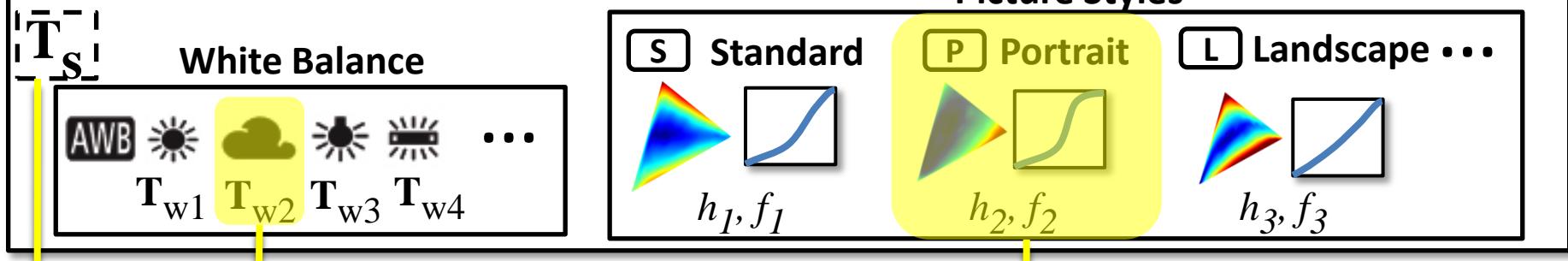


Tone Mapping  
( $f$ )



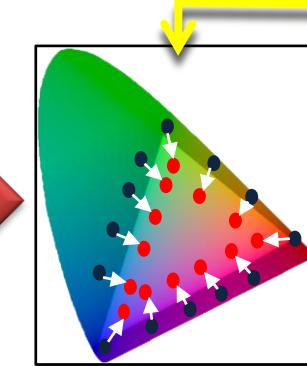
sRGB  
(JPEG)

# Canon EOS1Ds Mark III



Camera  
(RAW)

White Balance ( $T_w$ )  
RAW to sRGB ( $T_s$ )



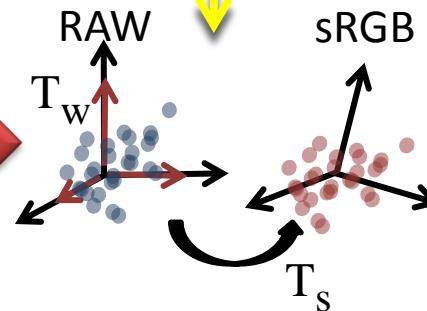
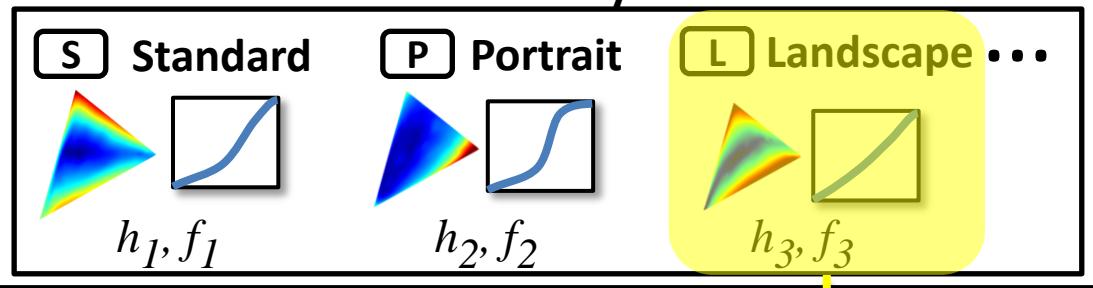
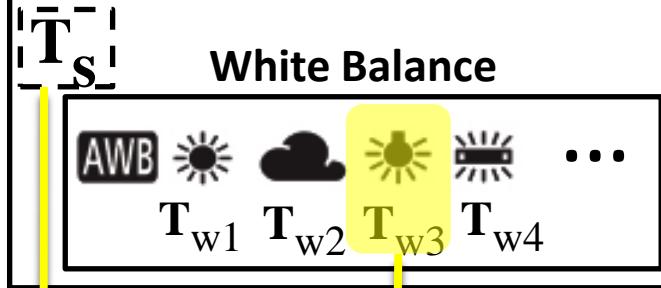
Gamut Mapping  
( $h$ )

Tone Mapping  
( $f$ )



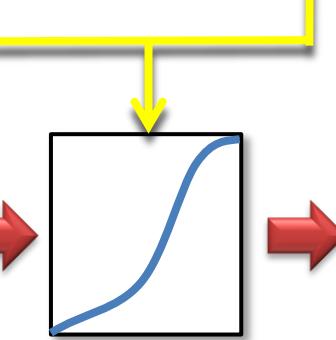
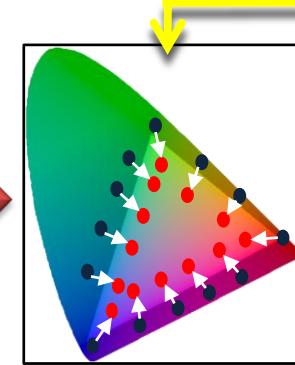
sRGB  
(JPEG)

# Canon EOS1Ds Mark III



Camera  
(RAW)

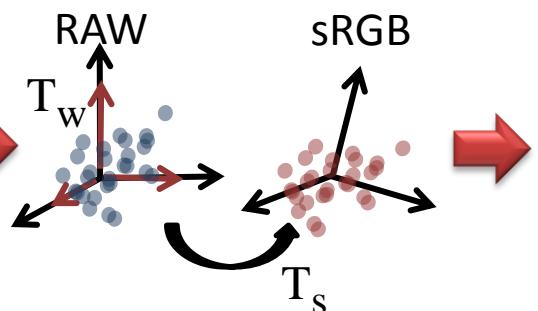
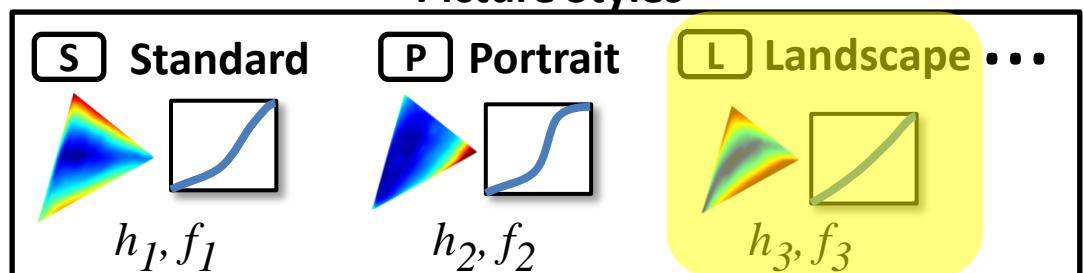
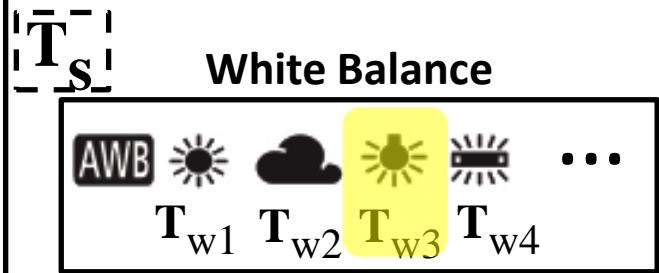
White Balance ( $T_w$ )  
RAW to sRGB ( $T_s$ )



sRGB  
(JPEG)

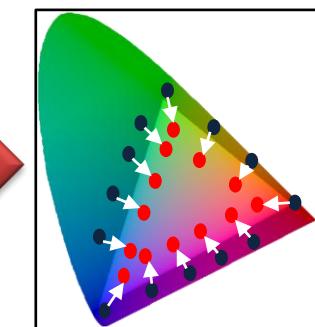
What if you took a photo  
with the wrong settings?

# Canon EOS1Ds Mark III



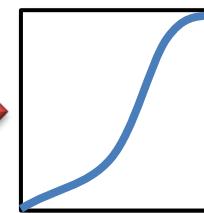
Camera  
(RAW)

White Balance ( $T_w$ )  
RAW to sRGB ( $T_s$ )

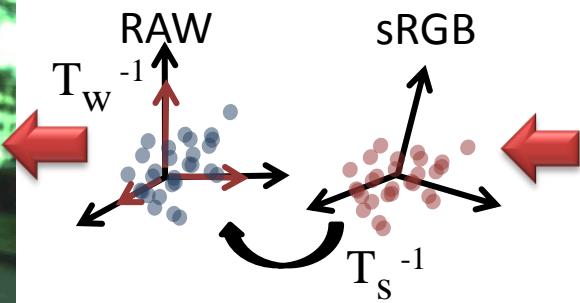
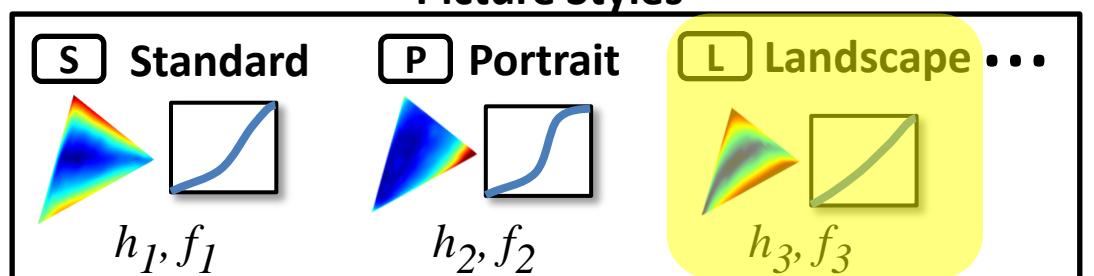
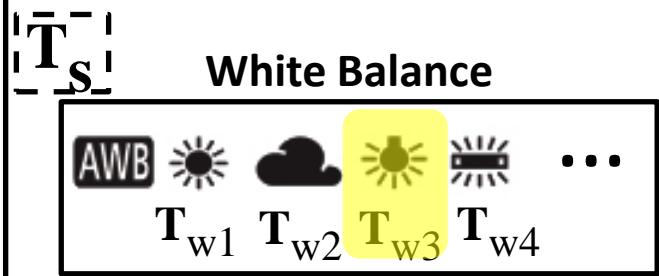


Gamut Mapping  
( $h$ )

Tone Mapping  
( $f$ )

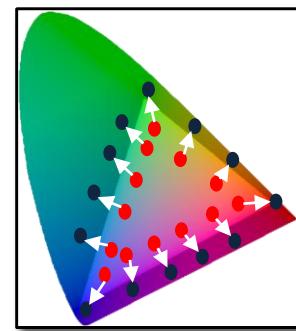


# Canon EOS1Ds Mark III

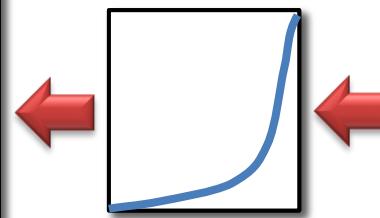


Camera  
(RAW)

White Balance ( $T_w^{-1}$ )  
RAW to sRGB ( $T_s^{-1}$ )



Gamut Mapping  
( $h^{-1}$ )



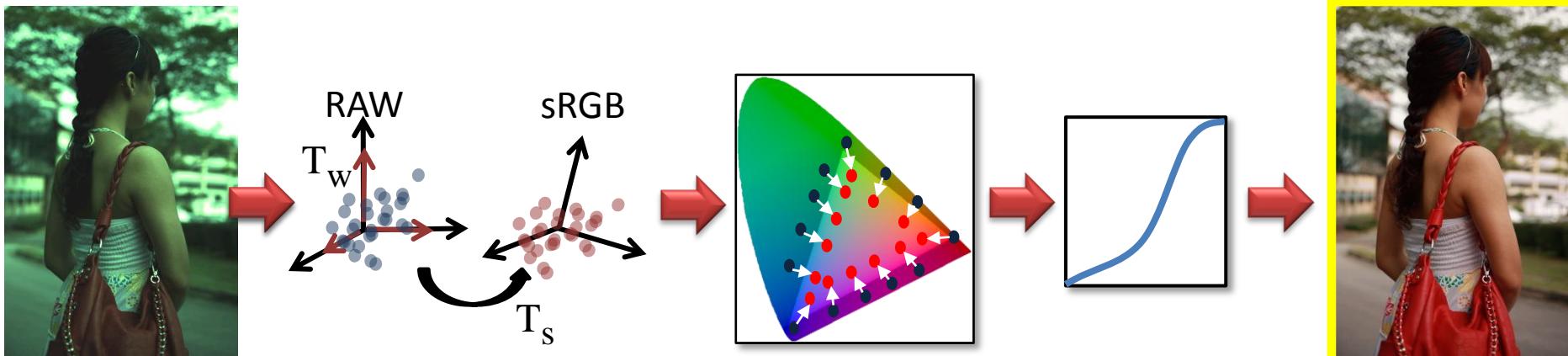
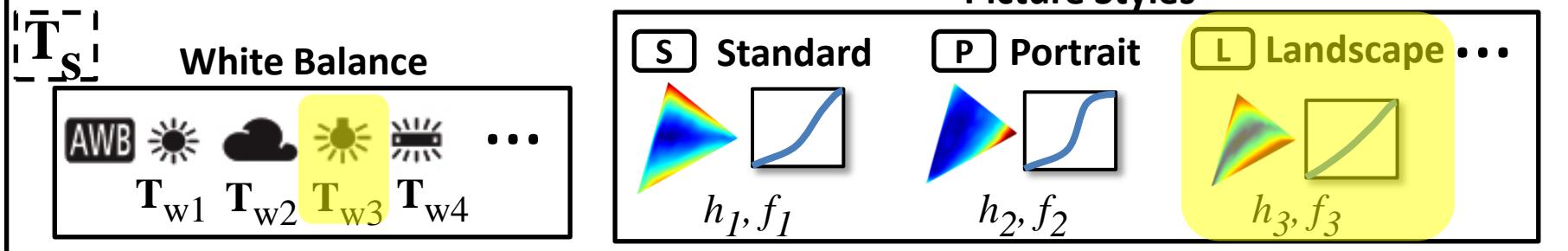
Tone Mapping  
( $f^{-1}$ )



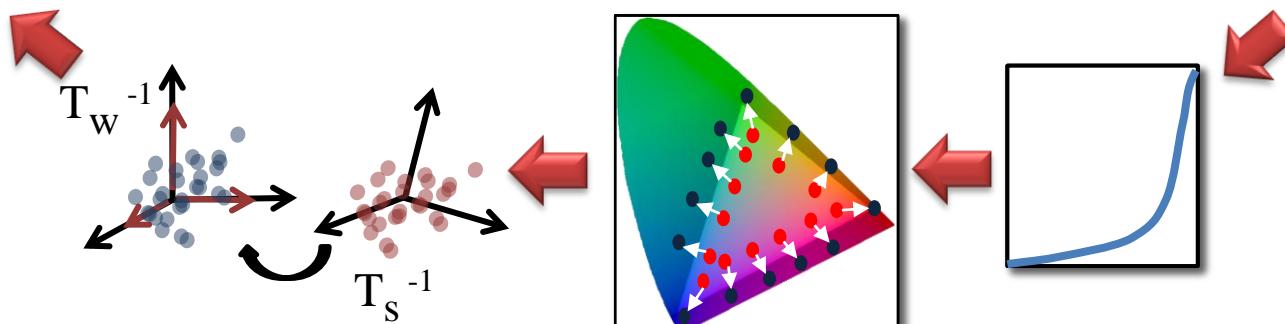
sRGB  
(JPEG)

# Canon EOS1Ds Mark III

## Picture Styles



Camera  
(RAW)



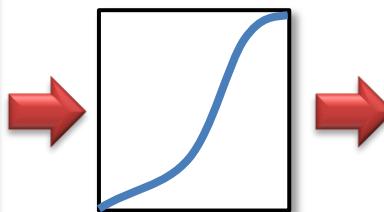
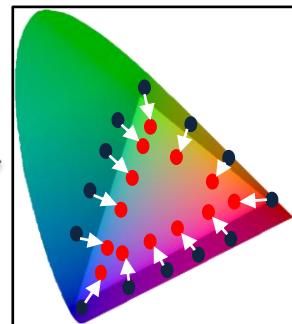
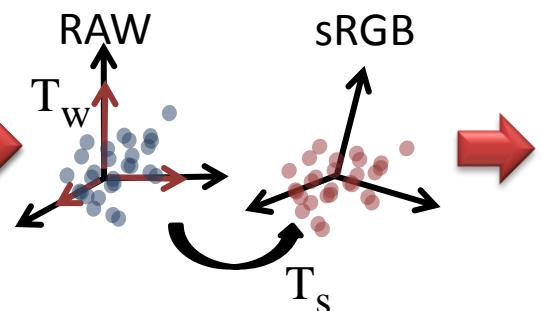
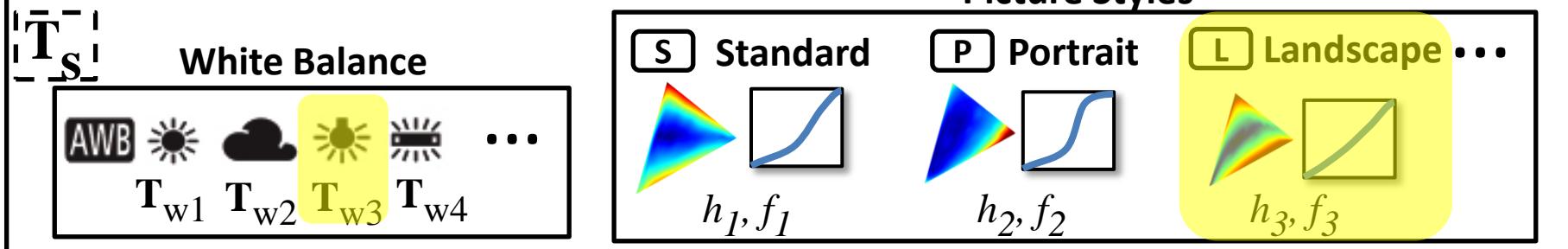
White Balance ( $T_w^{-1}$ )  
RAW to sRGB ( $T_s^{-1}$ )

Gamut Mapping  
( $h^{-1}$ )

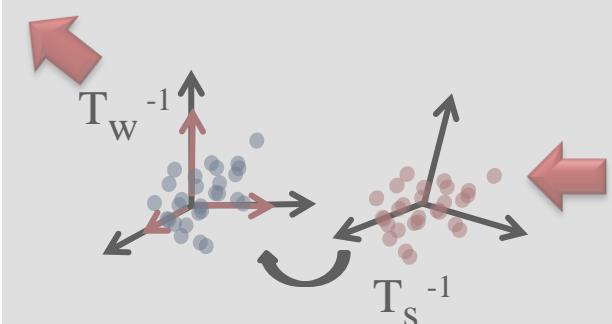
Tone Mapping  
( $f^{-1}$ )

# Canon EOS1Ds Mark III

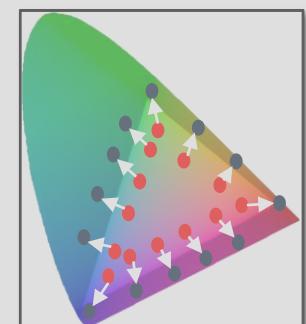
## Picture Styles



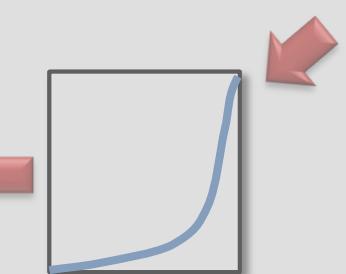
Camera  
(RAW)



White Balance ( $T_w^{-1}$ )  
RAW to sRGB ( $T_s^{-1}$ )



Gamut Mapping  
( $h^{-1}$ )



Tone Mapping  
( $f^{-1}$ )

sRGB  
(JPEG)

# Result - Canon EOS 1Ds Mark III



Input: cloudy WB + landscape style

# Result - Canon EOS 1Ds Mark III



Ground truth: fluorescent WB + standard style

# Result - Canon EOS 1Ds Mark III



Photoshop result

# Result - Canon EOS 1Ds Mark III



Refinished result

# Result - Canon EOS 1Ds Mark III



Ground truth: fluorescent WB + standard style

# Result - Canon EOS 1Ds Mark III



Input



Ground truth



Photoshop



Our refined result

# Result - Canon EOS 1Ds Mark III



Input: tungsten WB + standard style

# Result - Canon EOS 1Ds Mark III



Ground truth: daylight WB + standard style

# Result - Canon EOS 1Ds Mark III



Photoshop result

# Result - Canon EOS 1Ds Mark III



Our refinished result

# Result - Canon EOS 1Ds Mark III



Ground truth: daylight WB + standard style

# Result - Canon EOS 1Ds Mark III



Input



Ground truth



Photoshop



Our refinished result

# Result – Nikon D200



Input: tungsten WB + standard style

# Result – Nikon D200



Ground truth: daylight WB + standard style

# Result – Nikon D200



Photoshop result

# Result – Nikon D200



Refinished result

# Result – Nikon D200



Ground truth: daylight WB + standard style

# Result – Nikon D200



Input



Ground truth



Photoshop



Photo refinish

# Result - Sony α200



Input: tungsten WB + standard style

# Result - Sony α200



Ground truth: daylight WB + standard style

# Result - Sony α200



Photoshop result

# Result - Sony α200



Our refinished result

# Result - Sony α200



Ground truth: daylight WB + standard style

# Result - Sony α200



Input



Ground truth



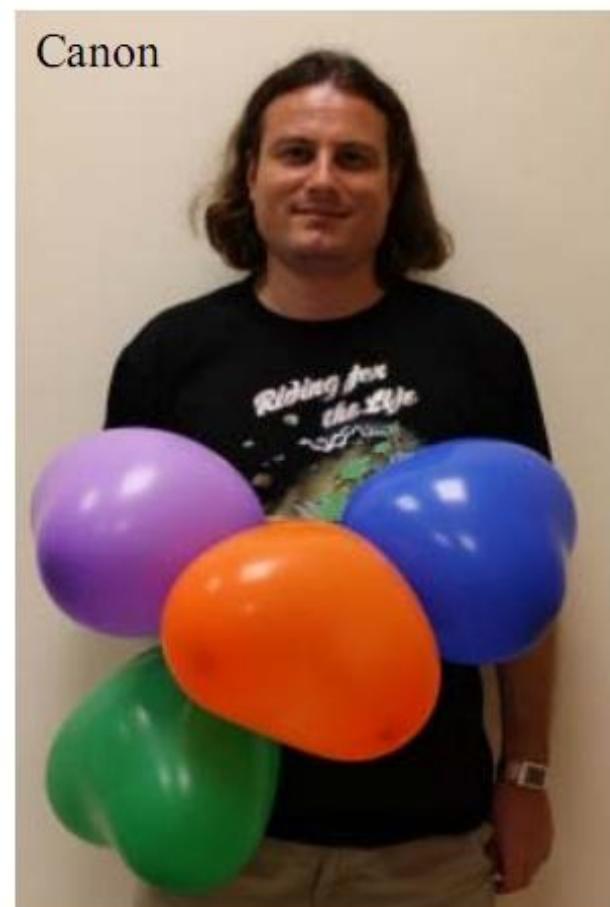
Photoshop



Our Refinished Result

# Remember these guys?

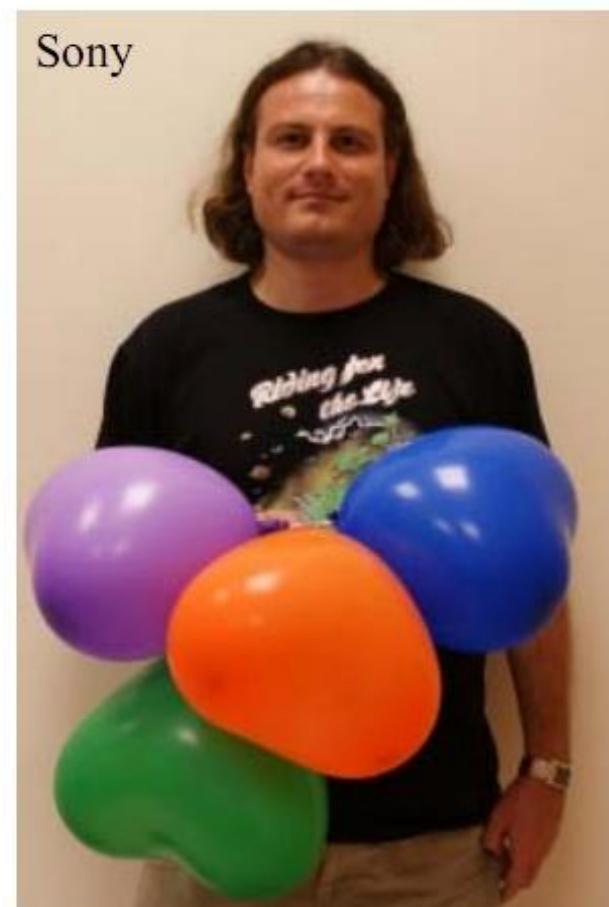
Canon



Nikon



Sony



Nikon



Canon  
↓  
Nikon



Sony  
↓  
Nikon



Sony



Canon  
↓  
Sony



Nikon  
↓  
Sony



# Discussion

- Discussed a new camera processing model
  - Gamut mapping was introduced
  - Allowed us to accurately calibrate for scene modes
  - Allowed for accurate remapping from sRGB back to RAW
- Facilitated refinishing application
  - Camera-specific refinishing
  - Our result is what the camera would have performed

# Take home message

- Digital photography is already computational photography
- And yes, you can't believe anything you see



# Take home message

- Digiphoto
- Art



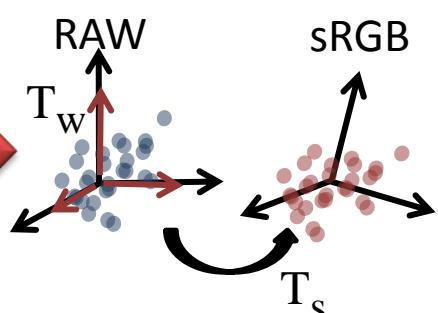
# Thank You!



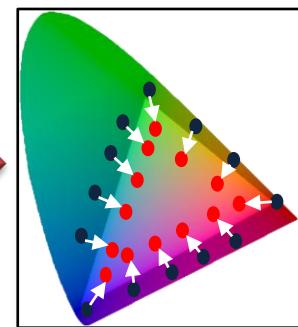
Questions?



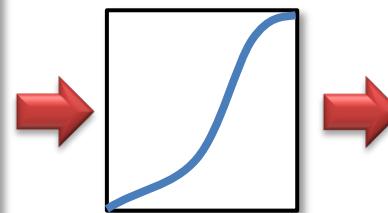
Camera  
(RAW)



White Balance ( $T_w$ )  
RAW to sRGB ( $T_s$ )



Gamut Mapping  
( $h$ )



Tone Mapping  
( $f$ )



sRGB  
(JPEG)

# Result - Sony α200



Image taken under auto WB and standard style

## Result - Sony α200



Input adjusted to tungsten WB using photo refinishing

# Result - Sony α200



Image adjusted to fluorescent WB using photo refinishing

# Result - Sony α200



Image adjusted to cloudy WB using photo refinishing

# Result - Sony α200



Input



3300 K



4100 K



5500 K