A Study of Colour Rendering in the In-Camera Imaging Pipeline

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October 2019

EPFL

In-Camera Processing Pipeline

- There are a number of steps applied onboard a camera that convert the light falling on the camera's sensor image (raw image) to the final R,G,B image output

- These steps are collectively called the "in-camera image processing pipeline"

In-Camera Processing Pipeline

High-level overview of camera pipeline

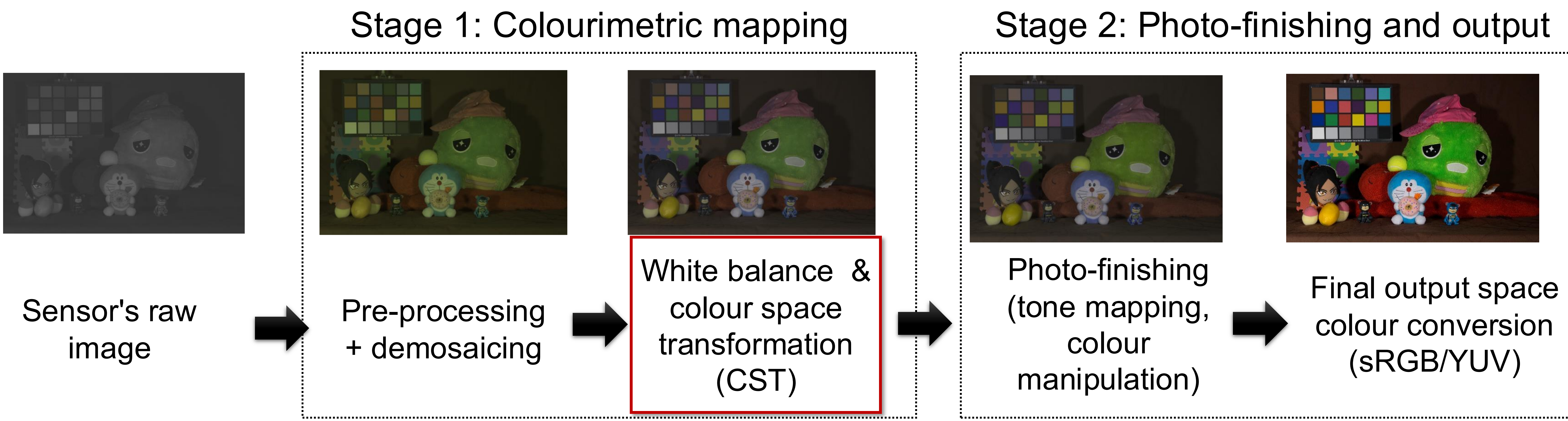
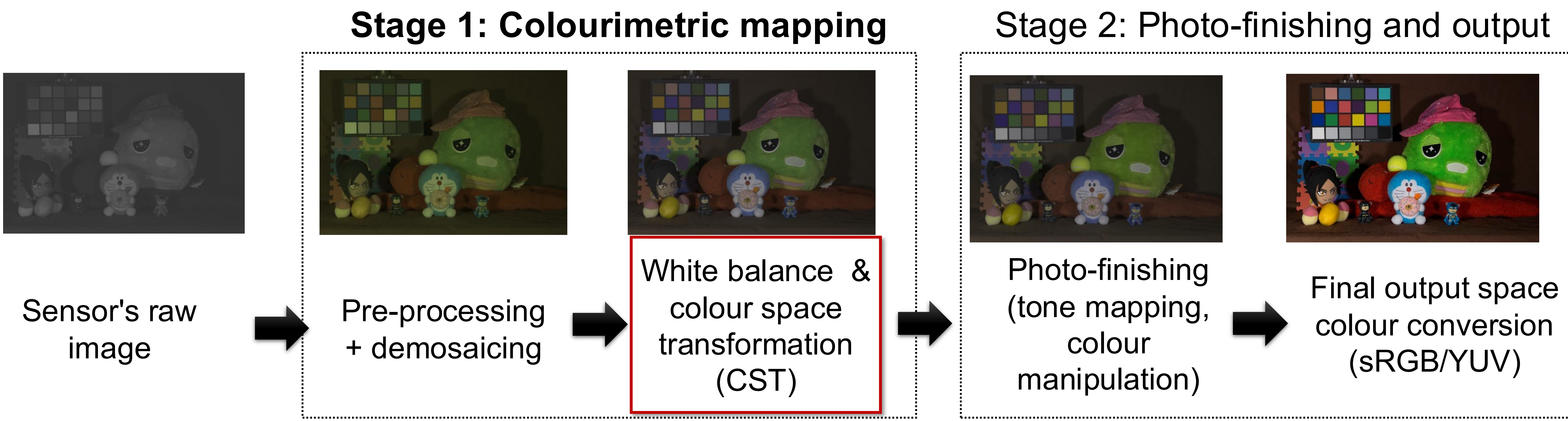


Figure adapted from Ramanath et al. (2005)

In-Camera Processing Pipeline

High-level overview of camera pipeline



Scene-referred

Figure adapted from Ramanath et al. (2005)

In-Camera Processing Pipeline

High-level overview of camera pipeline

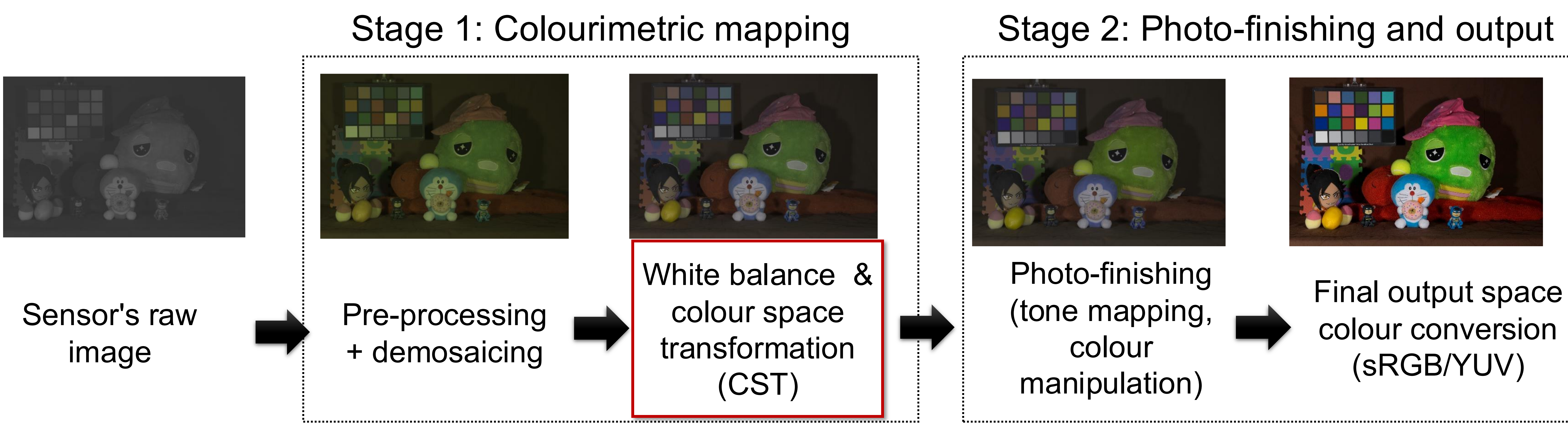
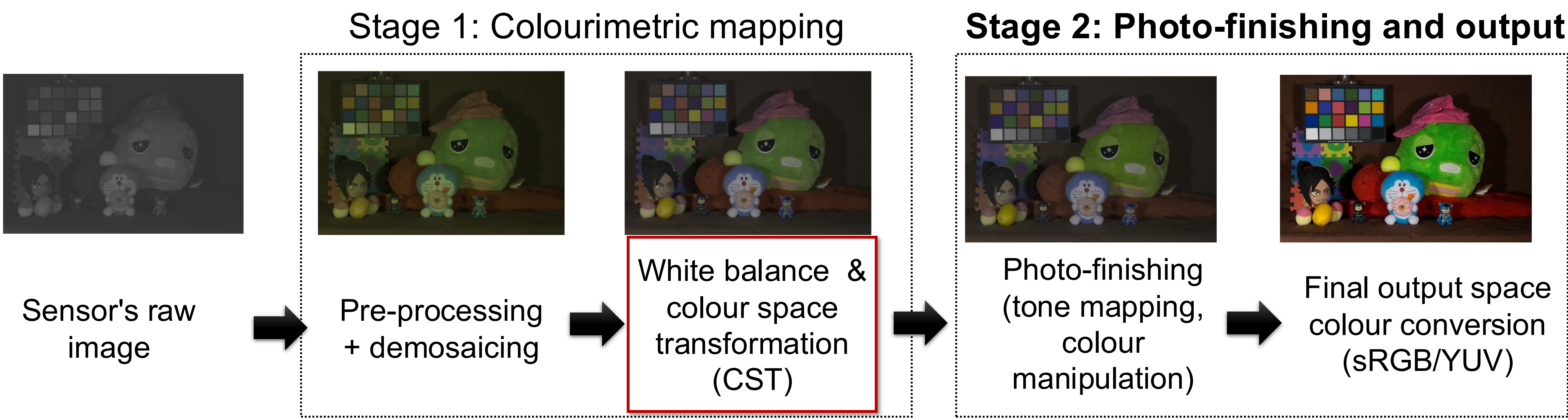


Figure adapted from Ramanath et al. (2005)

In-Camera Processing Pipeline

High-level overview of camera pipeline



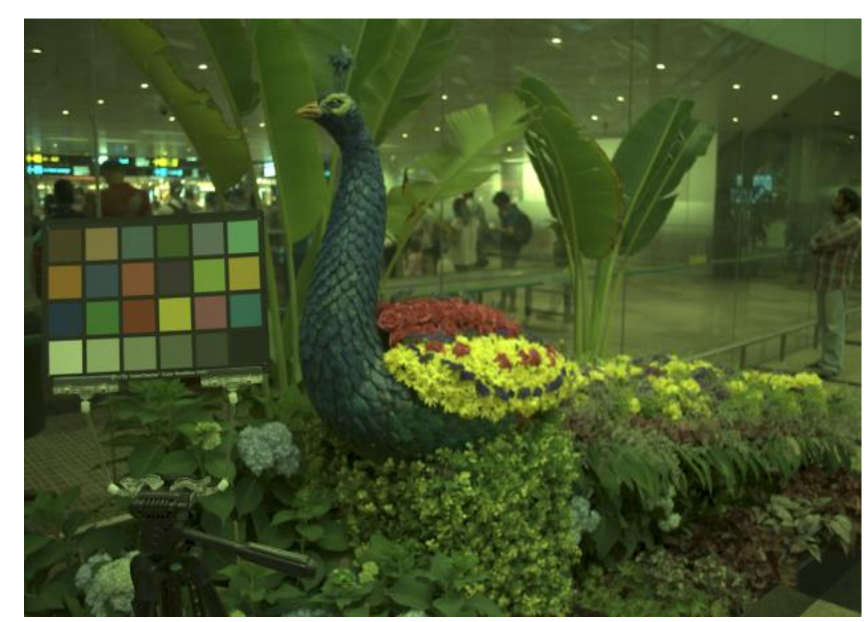
Output-referred

Figure adapted from Ramanath et al. (2005)

Motivation

- Difficulty in accessing camera pipeline
- Camera-specific photo-finishing routines that alter the colours of the sRGB images
- Sensor-specific colour space’s of the raw-RGB images

sRGB



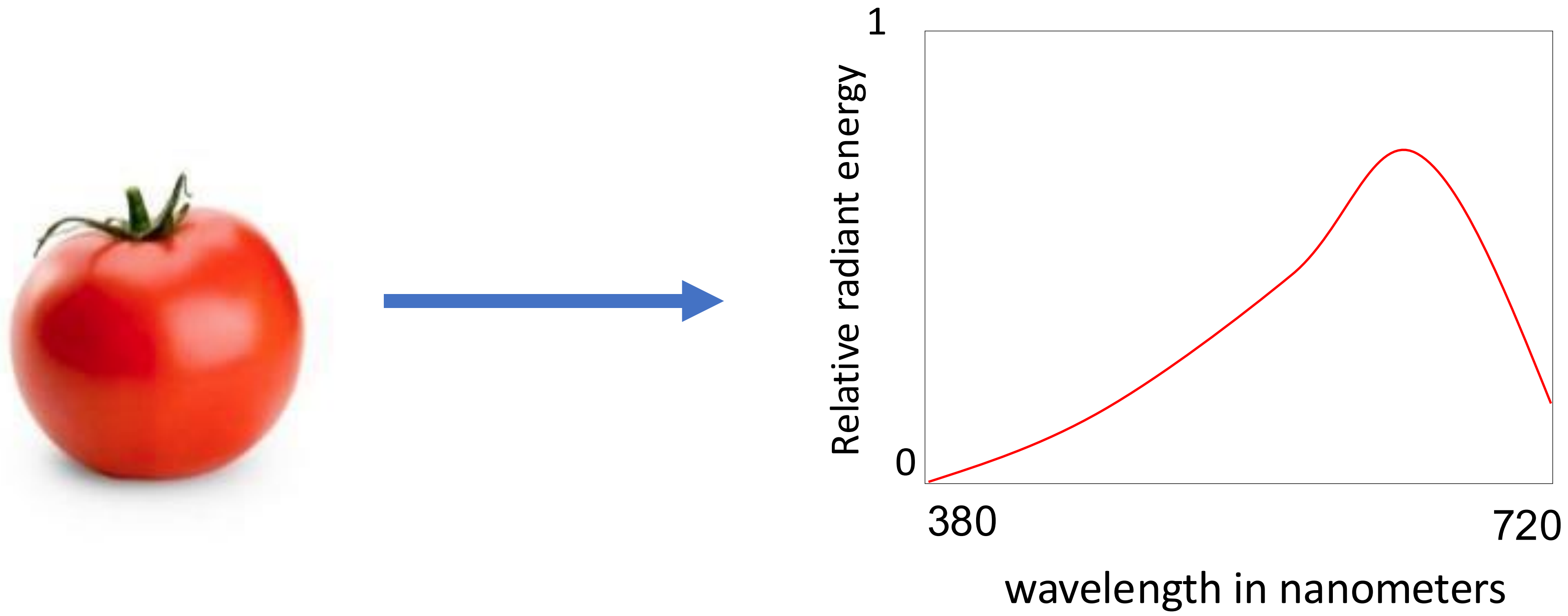
raw-RGB

Preliminaries and Related Work

- **Quick review of the CIE XYZ perceptual colour space**
- Raw image formation on cameras
- Computational cameras
- Steps needed for colour rendering

CIE XYZ

- **Radiometry** is the quantitative measurement of radiant energy. It is shown as a spectral power distributions (SPD) of objects.



CIE XYZ

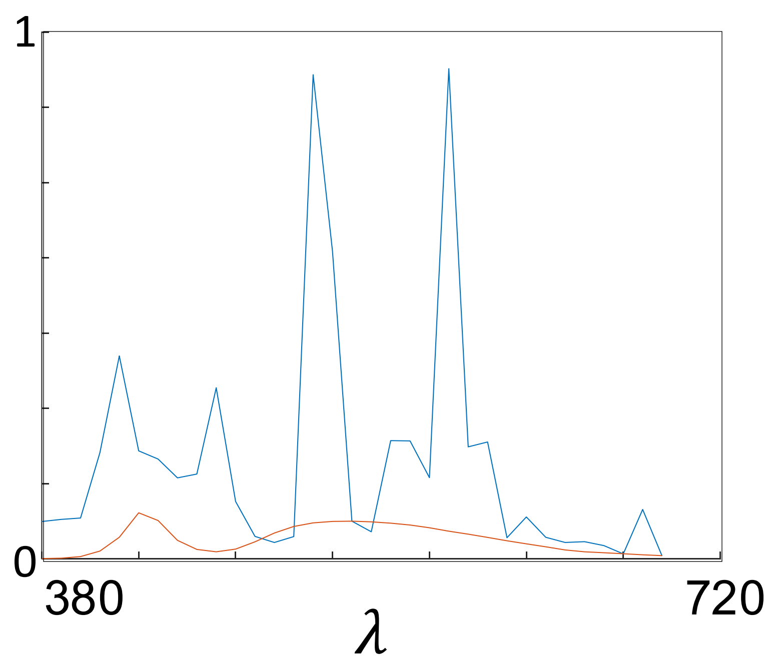
- **Colourimetry** is the quantitative measurement of "perceived" radiant energy based on human's sensitivity to light.
- SPDs are observed by our visual system and pe

More details in the dissertation!

Human study carried out by laboratories of Wright and Guild

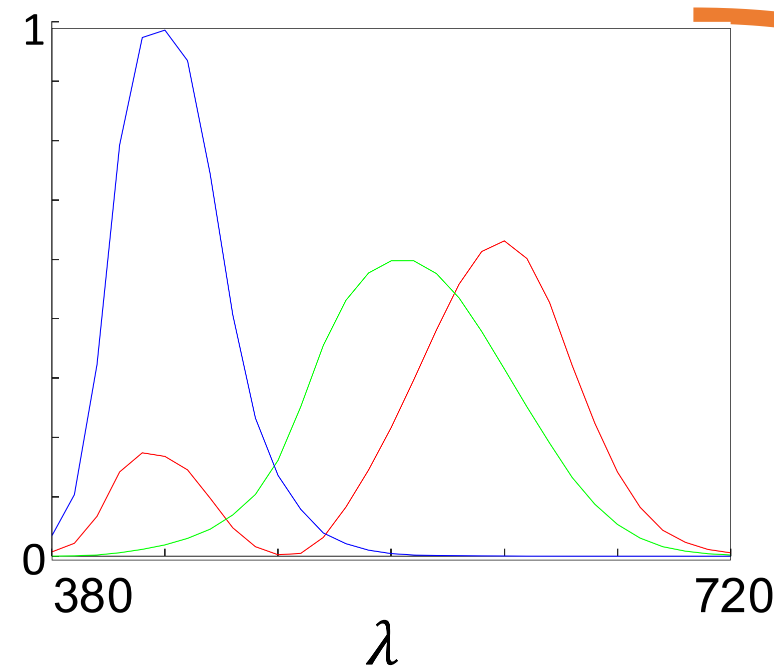
CIE XYZ

- CIE XYZ provides a canonical perceptual colour space to describe SPDs.
- Given an SPD we can find its mapping into the CIE XYZ colour space.



Two SPDs

$\otimes$



X=0.2841
Y=0.2989
Z=0.8254

X=0.2841
Y=0.2989
Z=0.8254

$$X = \int_{380}^{720} l(\lambda)x(\lambda)d\lambda$$

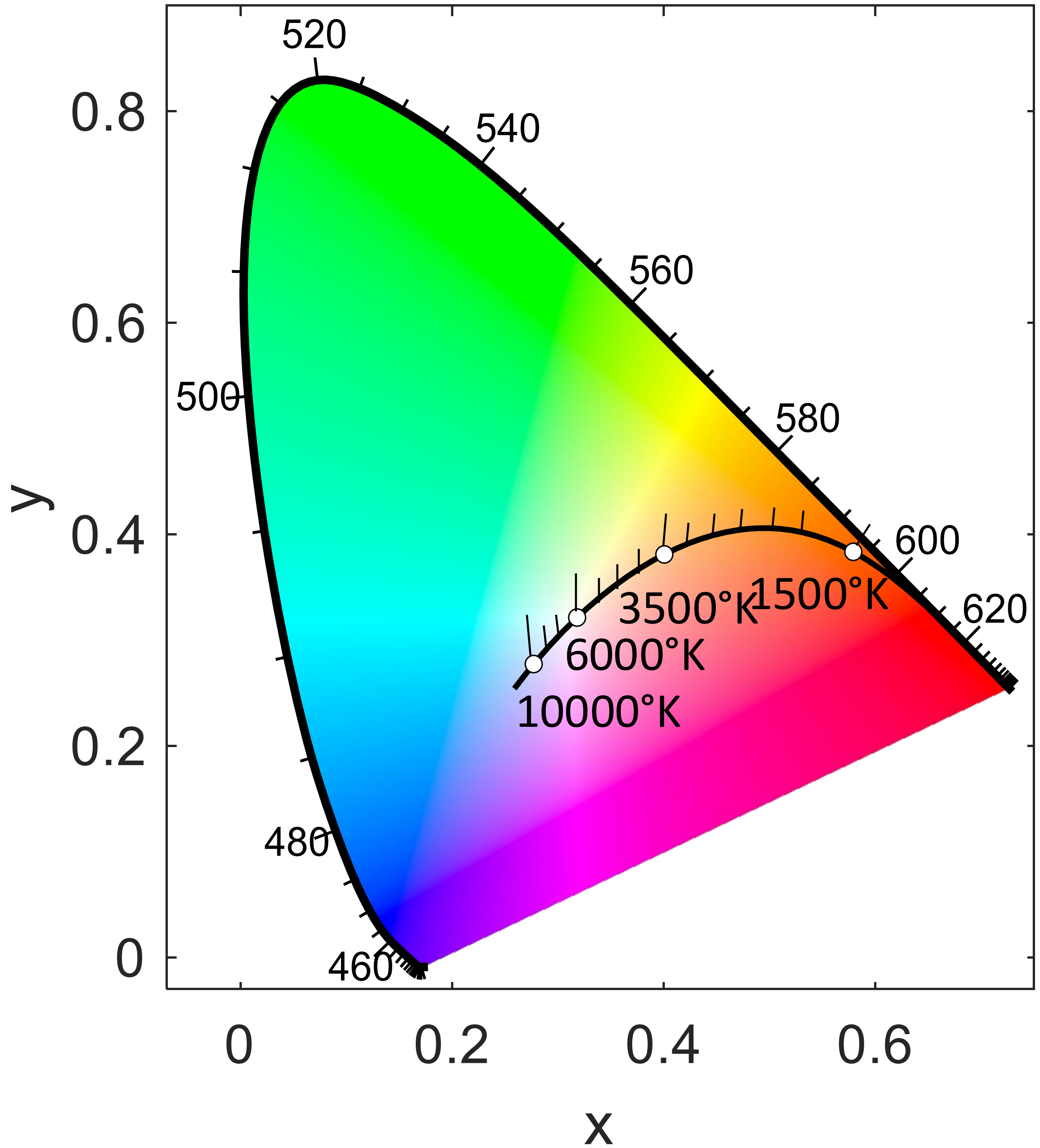
$$Y = \int_{380}^{720} l(\lambda)y(\lambda)d\lambda$$

$$Z = \int_{380}^{720} l(\lambda)z(\lambda)d\lambda$$

Radiometric (physical) → Colourimetric (perceptual)

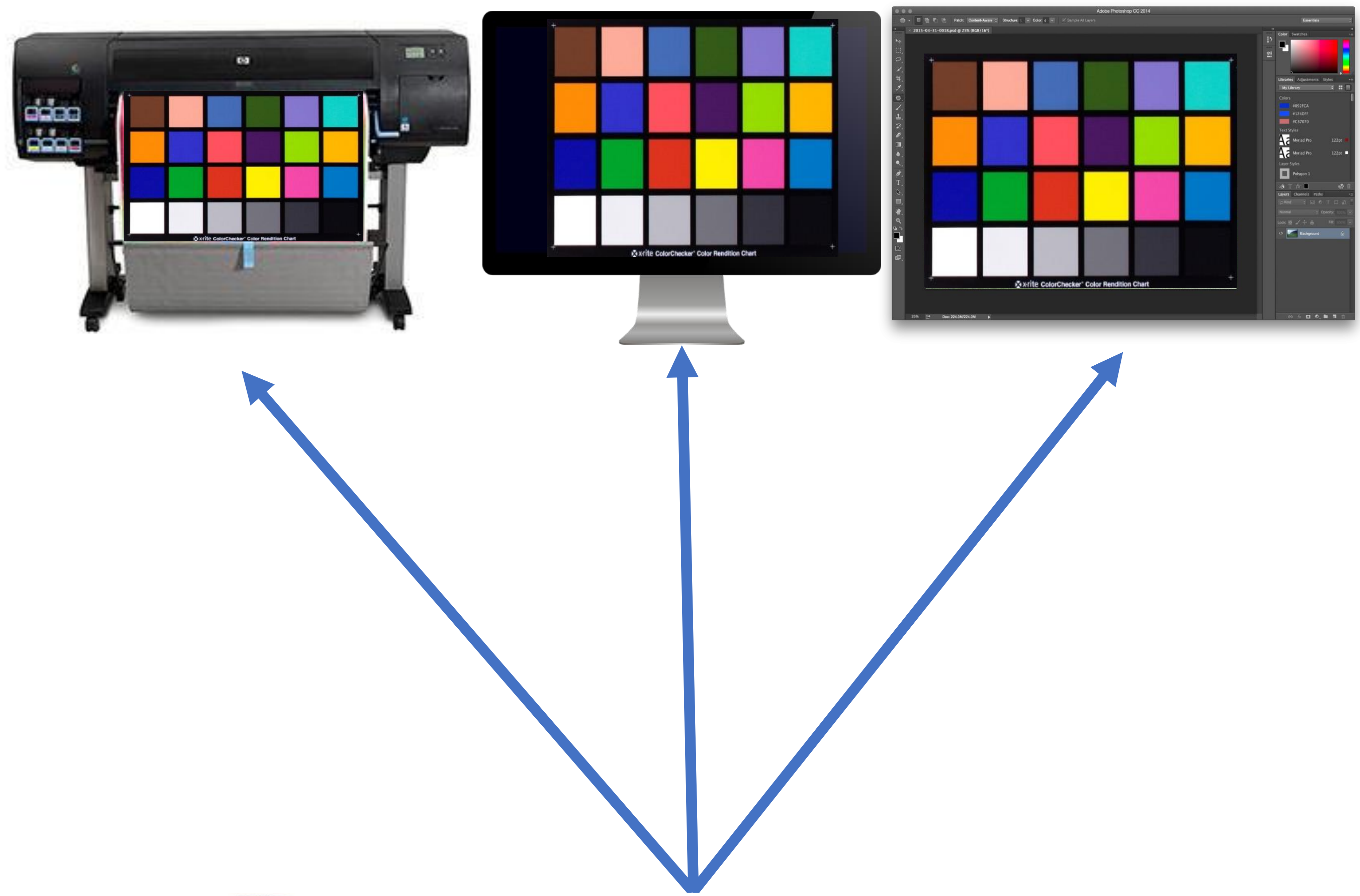
CIE xy

- 2D representation of CIE XYZ
- All tristimulus colours lie inside
- *Planckian locus* described by colour temperature

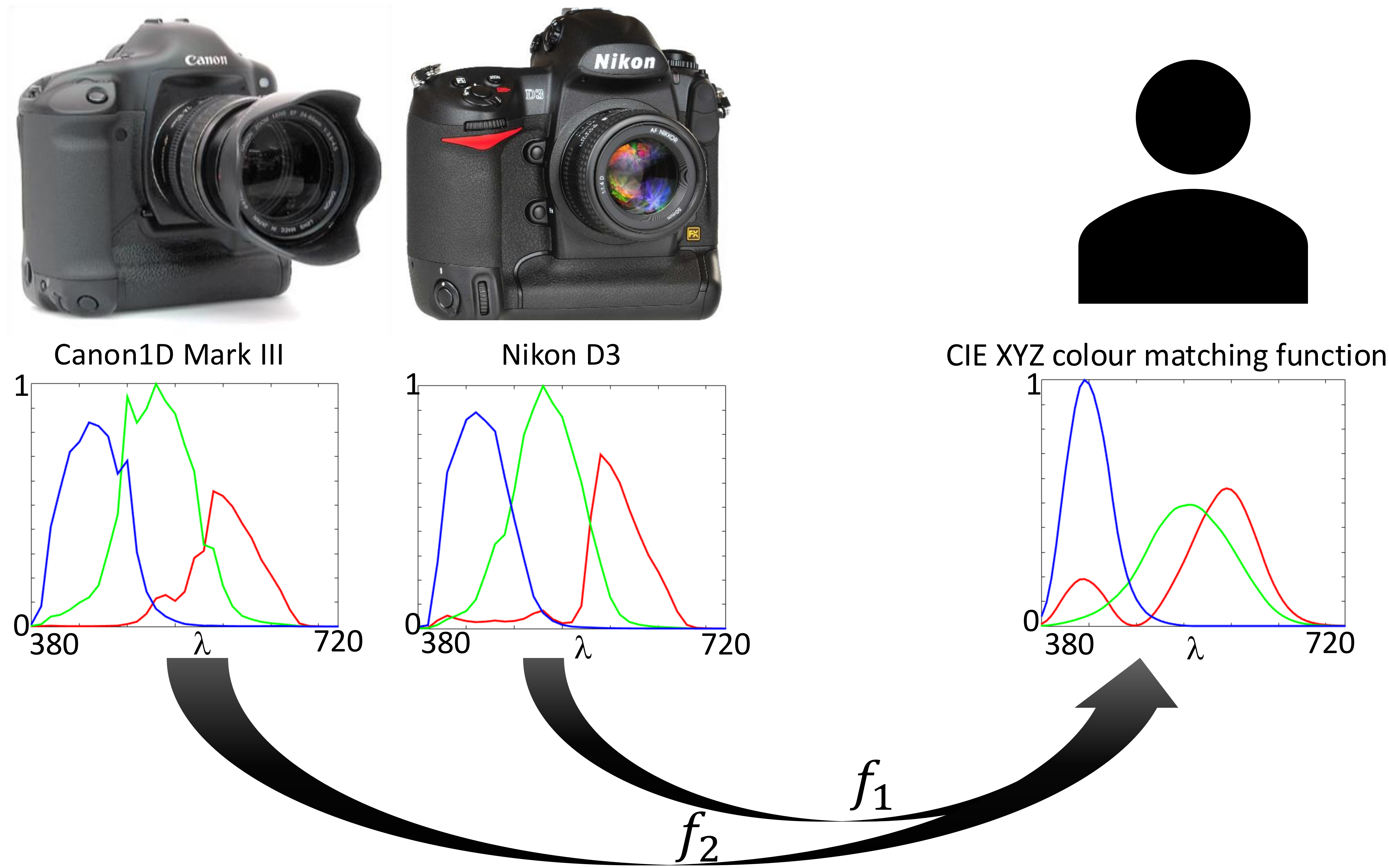


CIE XYZ

- CIE XYZ is "device independent", i.e., a perceptual space.
- Cameras, scanners, printers, and displays map their device specific values to corresponding CIE XYZ values.



CIE XYZ



Cameras need a way to map between cameras and CIE XYZ.
This is the *colour space transform* (CST) we discussed earlier.

CIE XYZ

Mapping to CIE XYZ

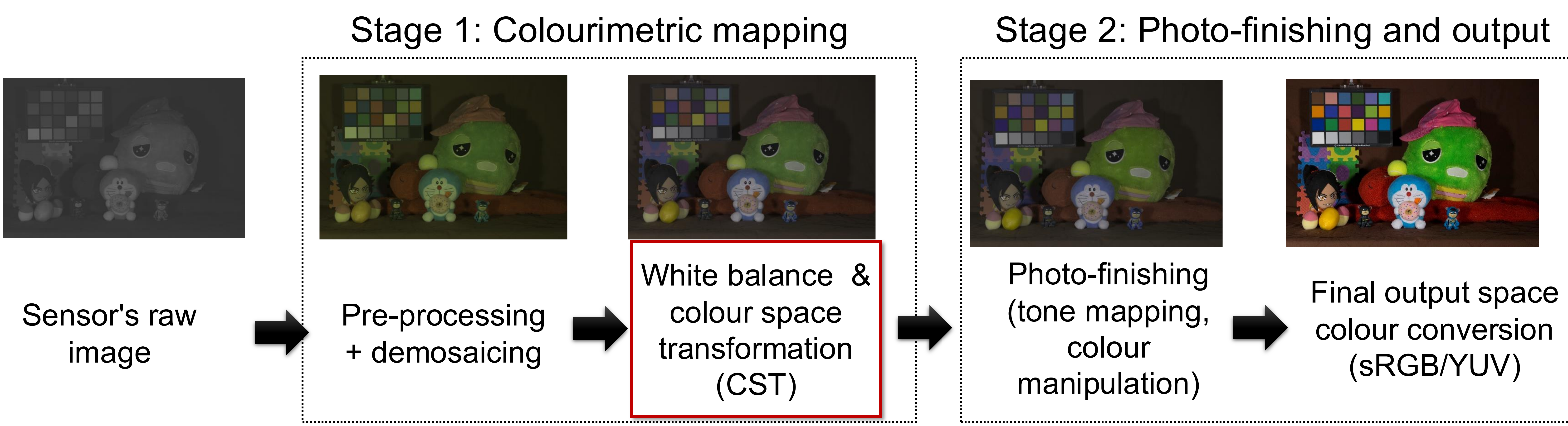


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Image Formation and the Camera Pipeline

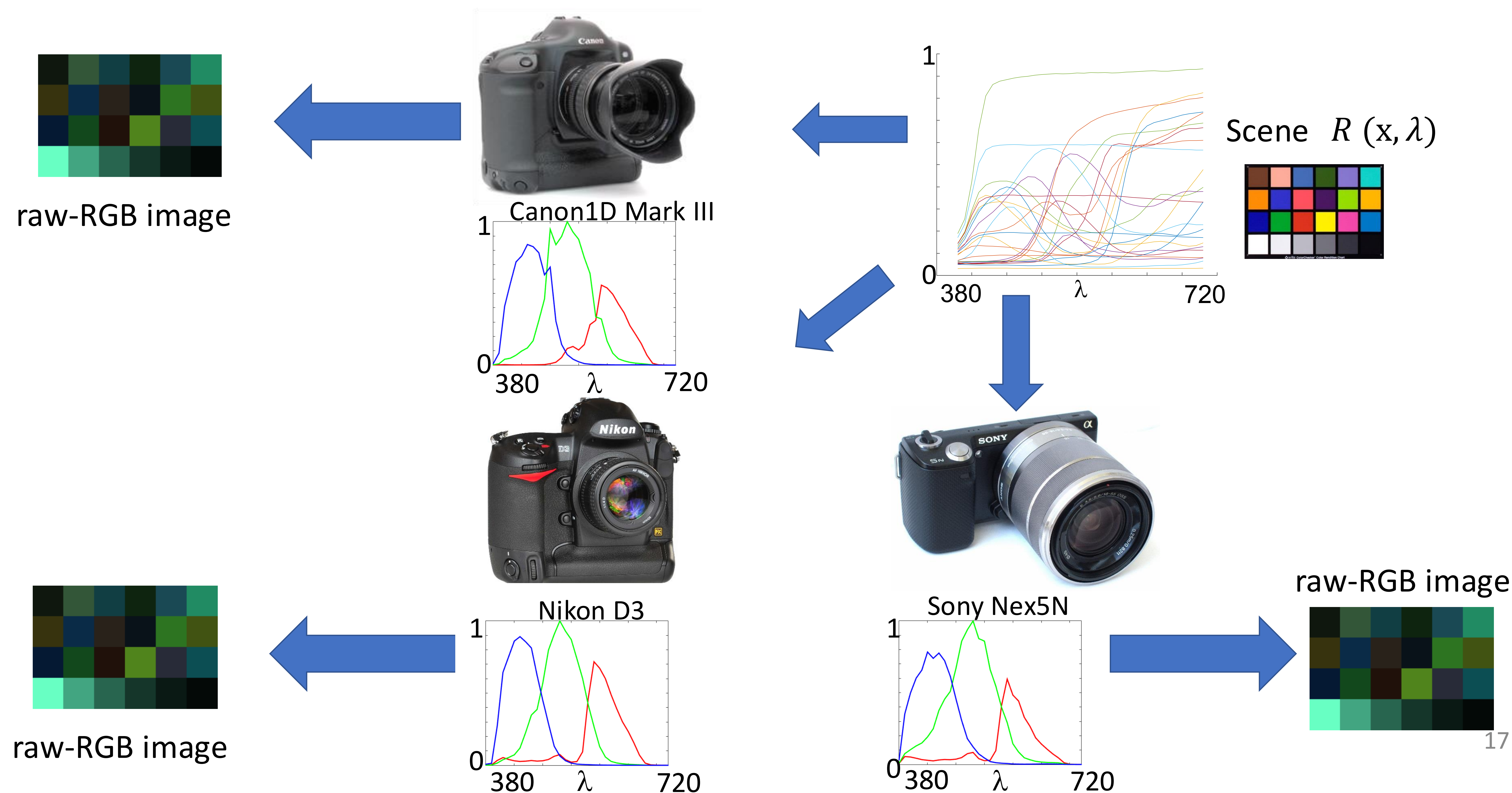


Image Formation and the Camera Pipeline

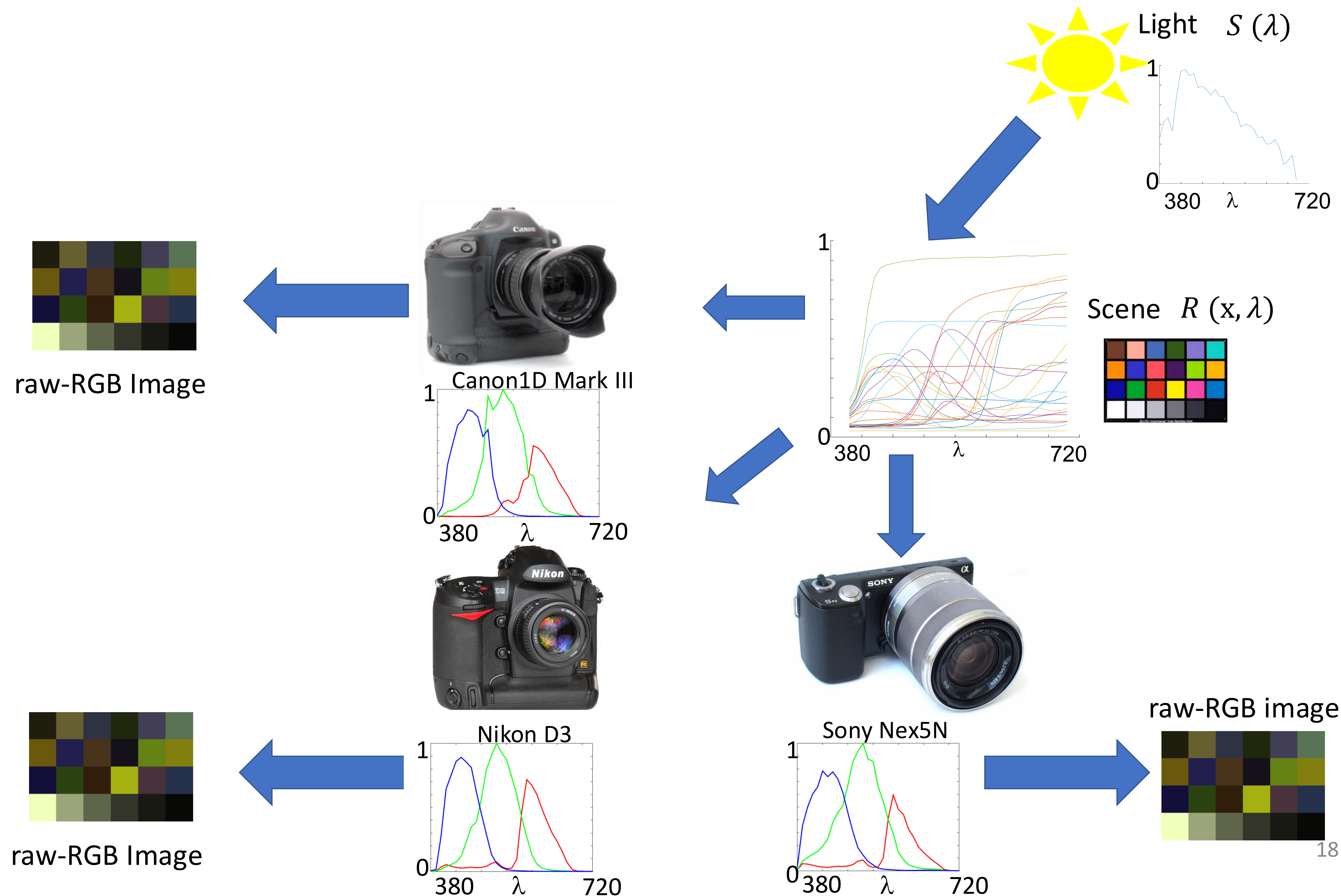


Image Formation and the Camera Pipeline

- Human visual system has the ability to adapt to the scene illumination. This is called *colour constancy* or *chromatic adaptation*.

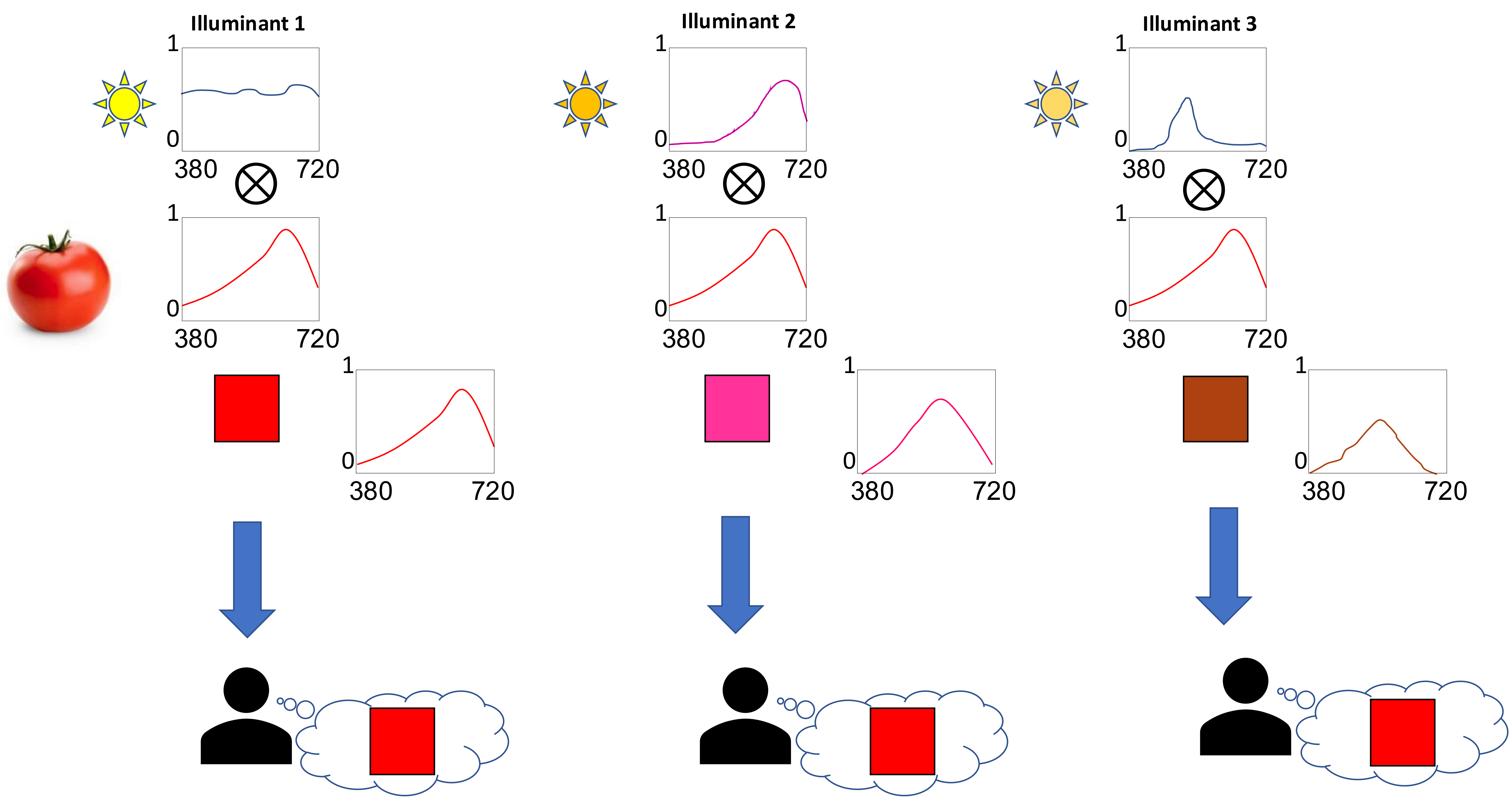


Image Formation and the Camera Pipeline

- Cameras mimic chromatic adaptation
- This procedure is called *white balance*

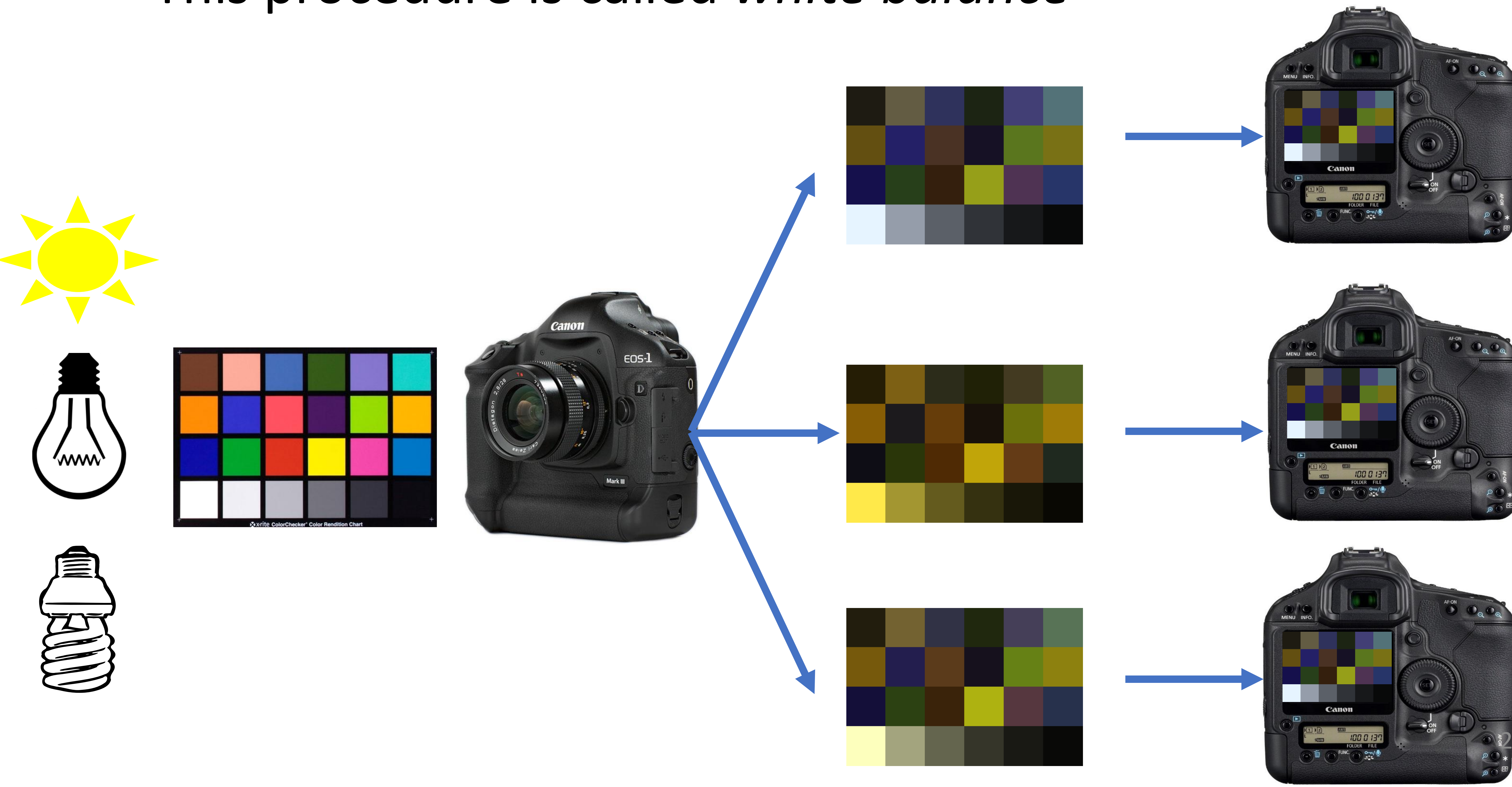
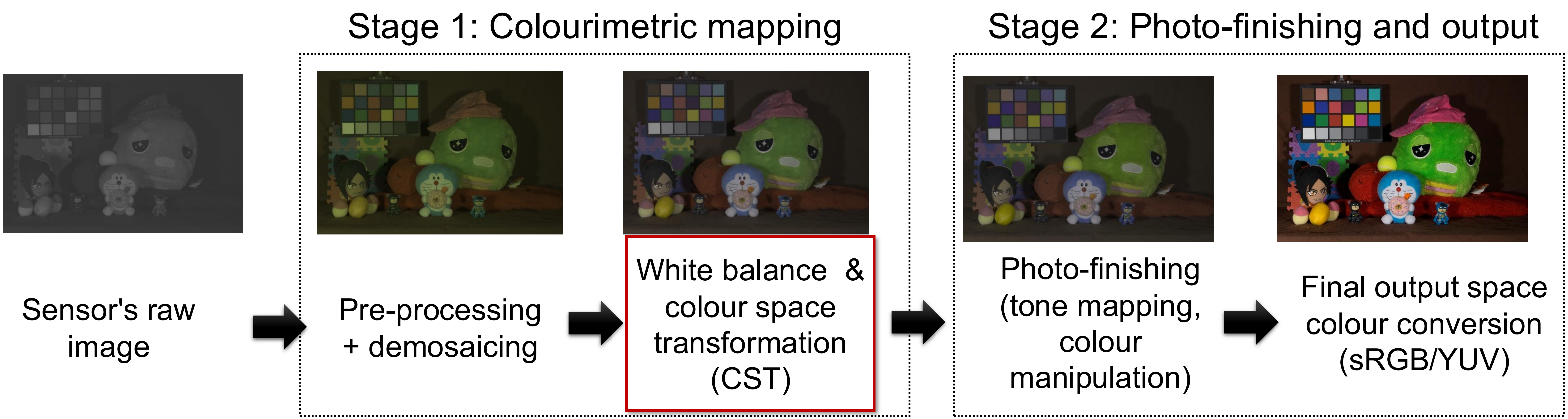


Image Formation and the Camera Pipeline

- It is important that the white-balance has been performed correctly, since the CST mapping is based on the WB matrix.



Preliminaries and Related Work

- Quick review of the CIE XYZ perceptual colour space
- Raw image formation on cameras
- **Computational cameras**
- Steps needed for colour rendering

Computational Cameras

- Open hardware platforms
  - CMU-camera (Rowe et al., 2007)
  - The FrankenCamera (Adams et al., 2010)
- Camera2 API (Google, 2015)
- Synthetic imagery
  - Farrell et al. (2010)

Computational Cameras

- CMU-camera (Rowe et al., 2007)
  - Robotic vision
- The FrankenCamera (Adams et al., 2010)
  - Full access to the underlying hardware
  - Control of the flash and shutter
  - Imaging pipeline

CMU-camera

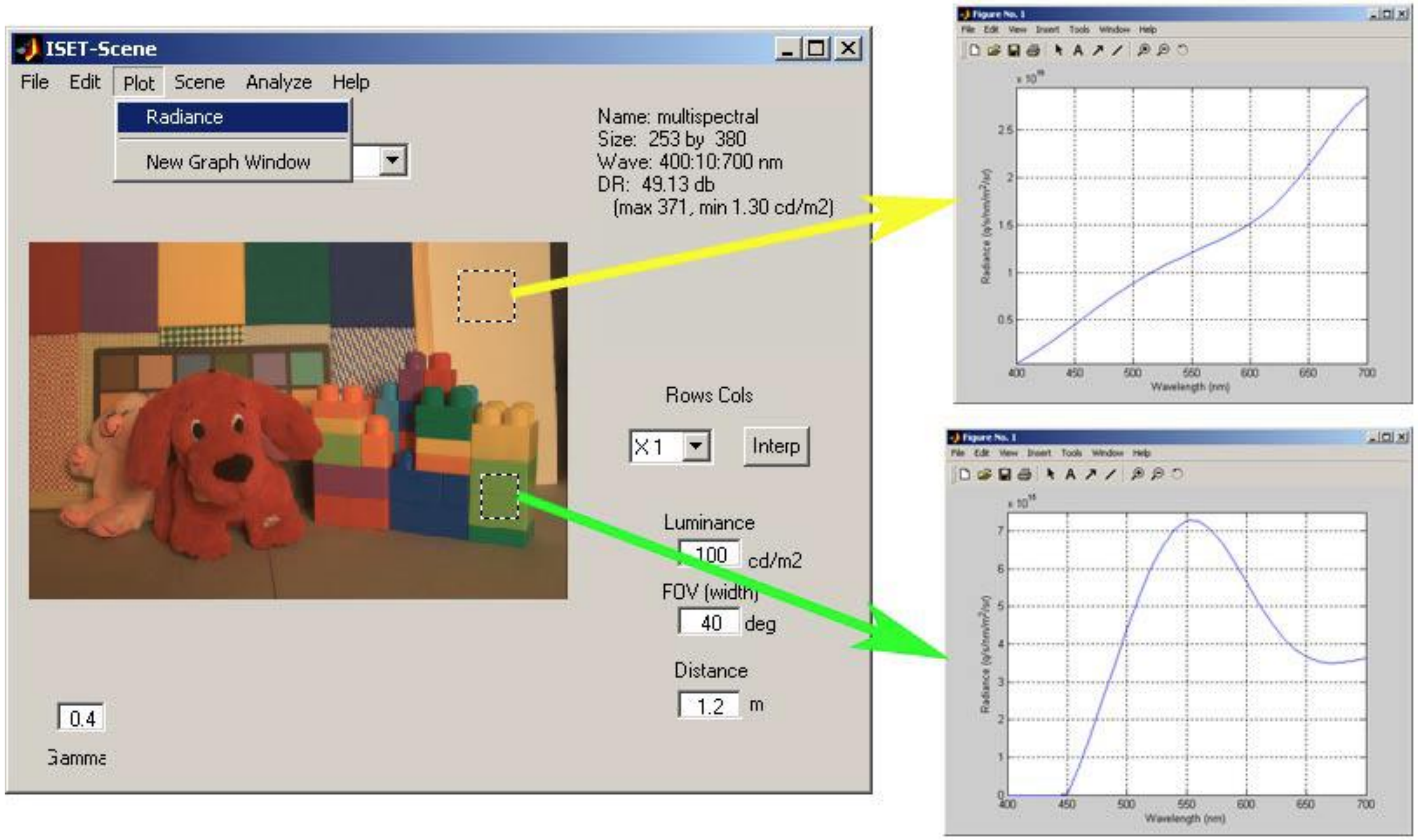
The FrankenCamera

Computational Cameras

- Camera2 API (Google, 2015)
  - A generic camera API to control hardware
  - Commands include:
    - lock auto-exposure
    - lock auto-focus
    - take picture
    - …

Computational Cameras

- Farrell et al. (2004)
  - First software-based platform
  - Synthetic imagery



Preliminaries and Related Work

- Quick review of the CIE XYZ perceptual colour space
- Raw image formation on cameras
- Computational cameras
- **Steps needed for colour rendering**

Colour Constancy and White Balance

- Consist of 2 parts:

  1. Identify the appearance of the illumination on the camera-specific raw-RGB colour space

  2. Correct the colour cast based on the estimated illumination

Colour Constancy and White Balance

- Consist of 2 parts:

1. Identify the appearance of the illumination on the camera-specific raw-RGB colour space

   Most research focuses on only step 1

2. Correct the colour cast based on the estimated illumination

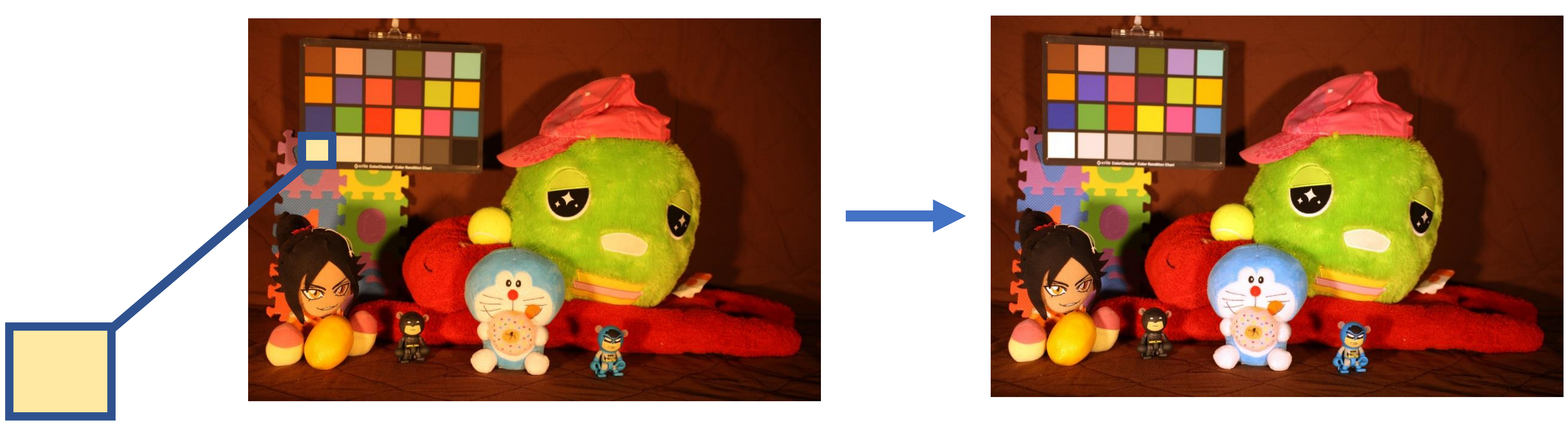
Colour Constancy and White Balance

- If we can observe the colour of the illumination, we can correct it with a simple diagonal matrix.

$$\begin{bmatrix}R' \\ G'\end{bmatrix} = \begin{bmatrix}R_{white}/R & 0 & 0 \\ 0 & G_{white}/G & 0\end{bmatrix}\begin{bmatrix}R \\ G\end{bmatrix}$$

After the illuminant is divided out, neutral scene objects are correct.

- Th ures
white is corrected



Illuminant's colour

Colour Constancy and White Balance

- **Statistics Based Methods**
  - White patch assumption
  - Methods based on specularities
- **Learning Based Methods**
  - Gamut mapping algorithms
  - Probabilistic approaches
  - Estimation with semantic information
  - Machine learning techniques

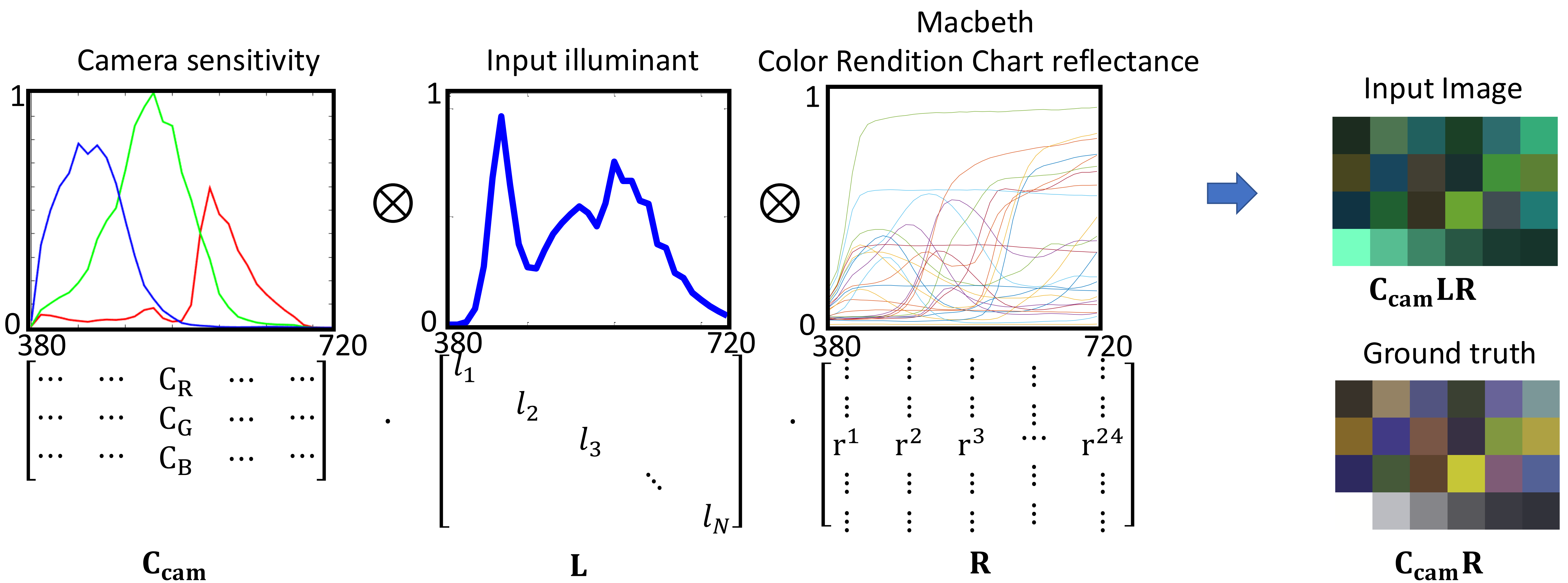
Colour Constancy and White Balance

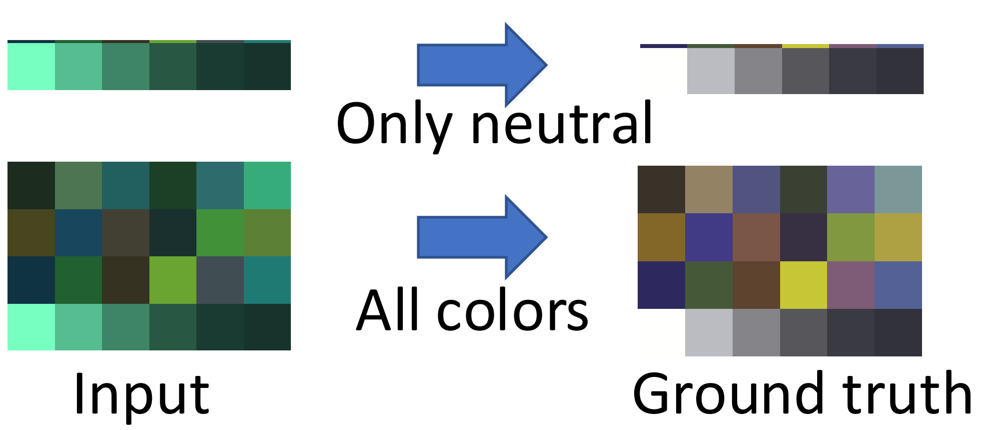
- **Statistics Based Methods**
  - White patch assumption
  - Methods based on specularities
- **Learning Based Methods**
  - Gamut mapping algorithms

More details in the dissertation!

  - Estimation With Semantic Information
  - Machine learning techniques

Colour Constancy and White Balance



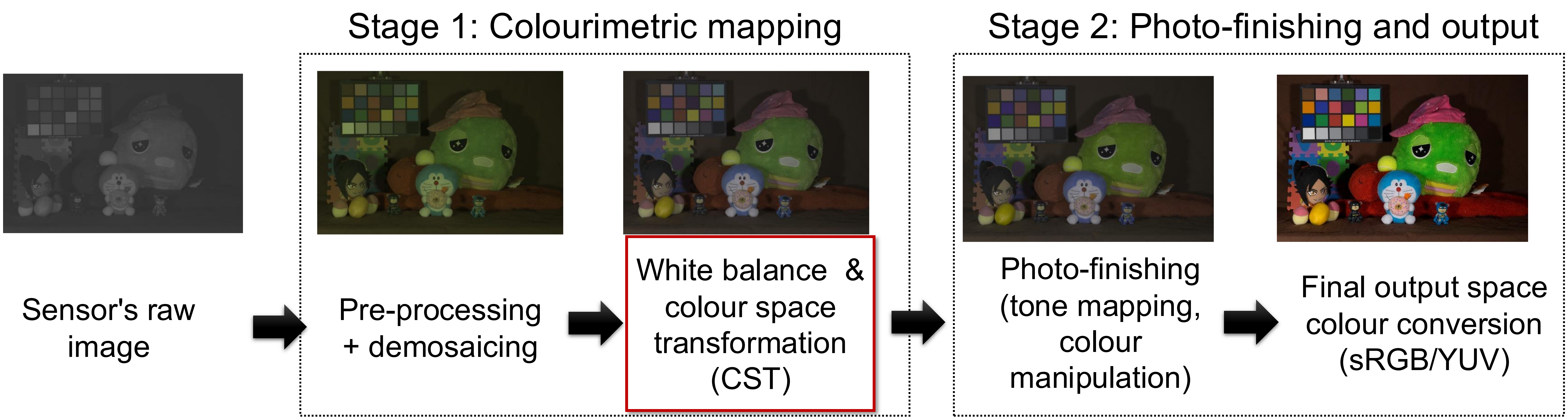


Diagonal white-balancing $\quad W_D = \mathrm{diag}(\mathbf{C_{cam}l})^{-1}$

Full-matrix linear transform $\quad W_F = \underset{W_F}{\mathrm{argmin}} \left\| \mathbf{C_{cam}R} - W_F \mathbf{C_{cam}L} \ \mathbf{R} \right\|^2$

Colour Constancy and White Balance

- In the camera pipeline, the CST compensates for deficiencies in the diagonal correction.



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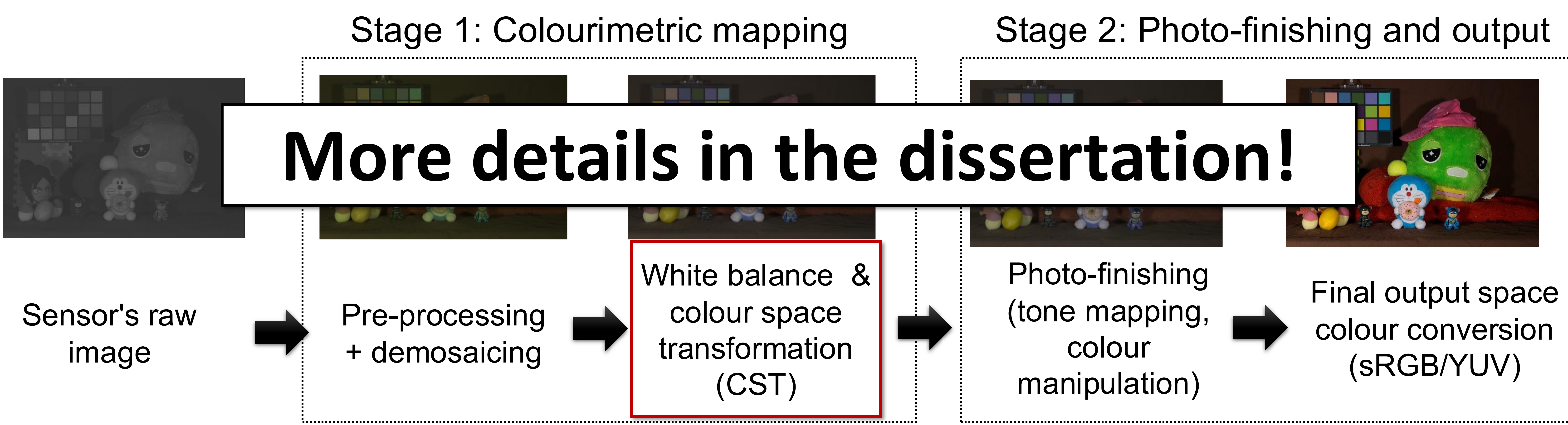


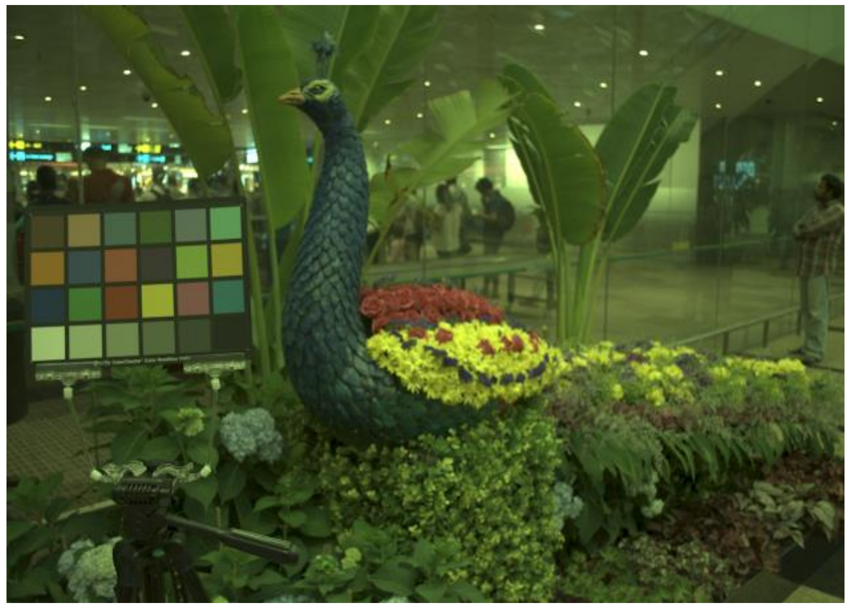
Preliminaries Over – Main Show

- A Software Platform for Manipulating the Camera Imaging Pipeline
- Beyond raw-RGB and sRGB: Advocating Access to a Colourimetric Image State
- Improving Colour Reproduction Accuracy on Cameras
- A Customized Camera Imaging Pipeline for Dermatological Imaging

A Software Platform for Manipulating the Camera Imaging Pipeline

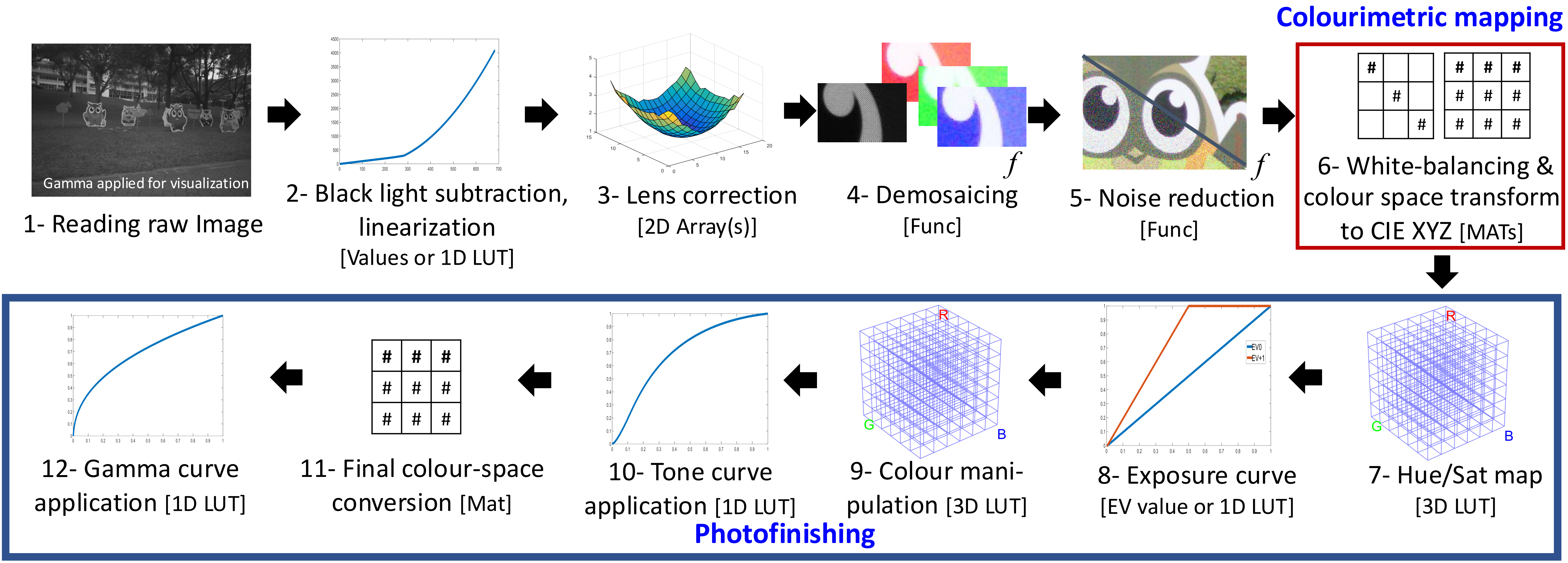
Motivation

- Cameras do not provide access to their in-camera pipeline routines
- Access to the pipeline would give us room for improvement for stages of the camera pipeline.

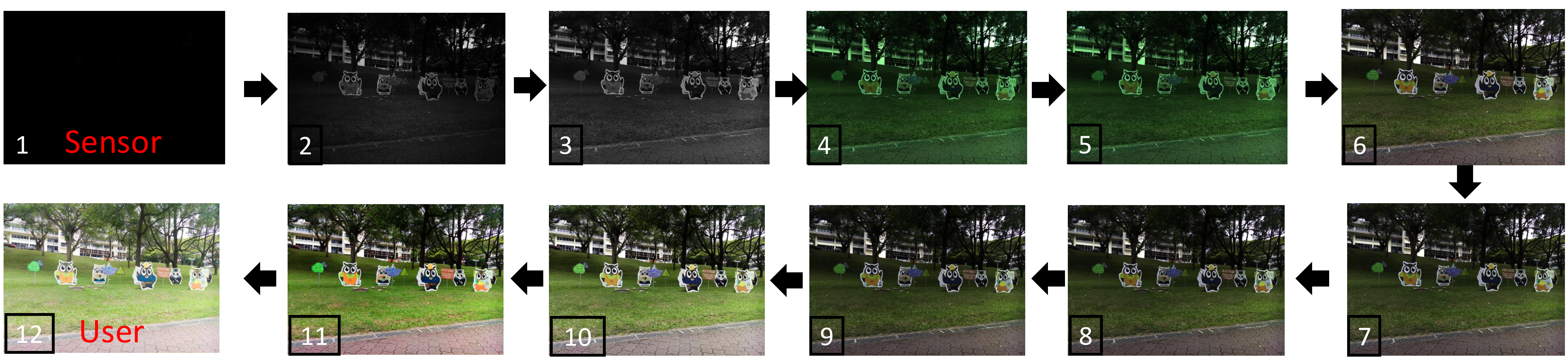



sRGB raw-RGB

Stages of the in-camera processing pipeline and associated parameters



Intermediate images for each stage



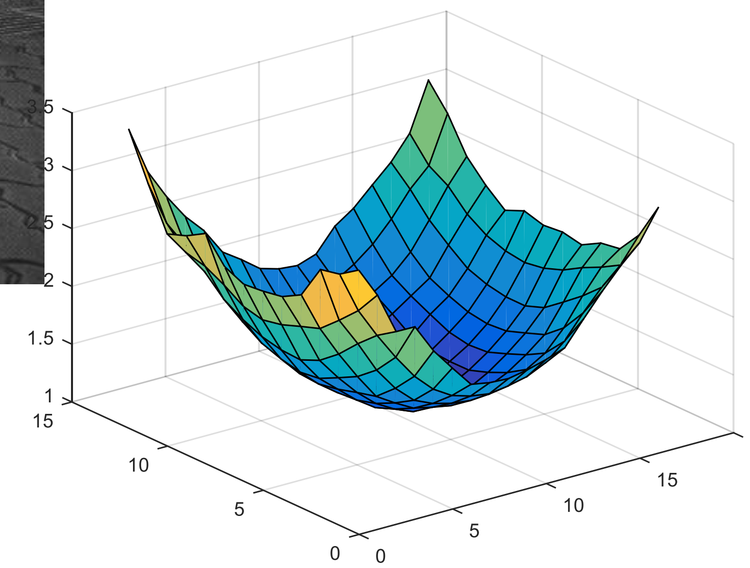
Walking through the pipeline (1)

Camera RAW

Walking through the pipeline (2)

Black level subtraction and linearization + defective pixel mask

Walking through the pipeline (3)



Lens correction
(non-uniform gain)

Walking through the pipeline (4)

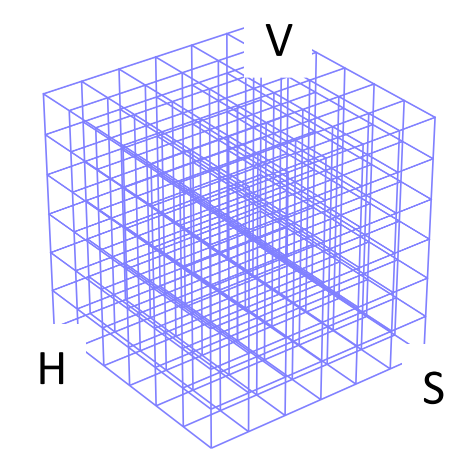
Demosaicing
+ Noise Reduction

Walking through the pipeline (5)

$$\begin{bmatrix} \# & & \\ & \# & \\ & & \# \end{bmatrix} \quad \begin{bmatrix} \# & \# & \# \\ \# & \# & \# \\ \# & \# & \# \end{bmatrix}$$

White balance
+ color space transform (CIE XYZ/Pro-photo)

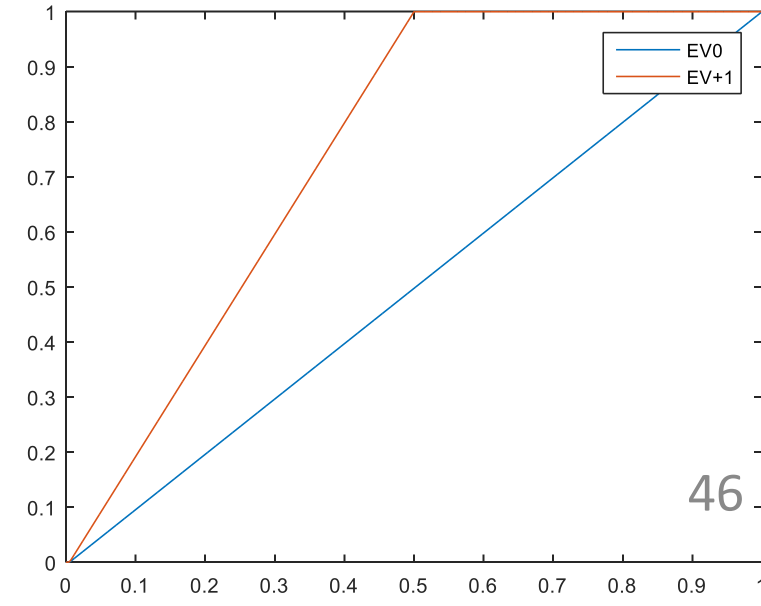
Walking through the pipeline (6)



(Optional) non-linear color correction

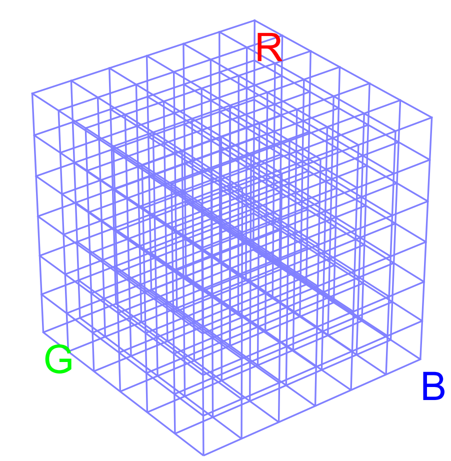
Walking through the pipeline (7)

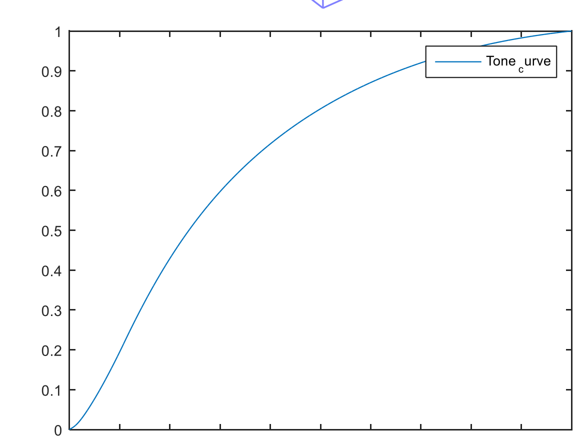
EV+1



Exposure Compensation

Walking through the pipeline (8)





Color rendering

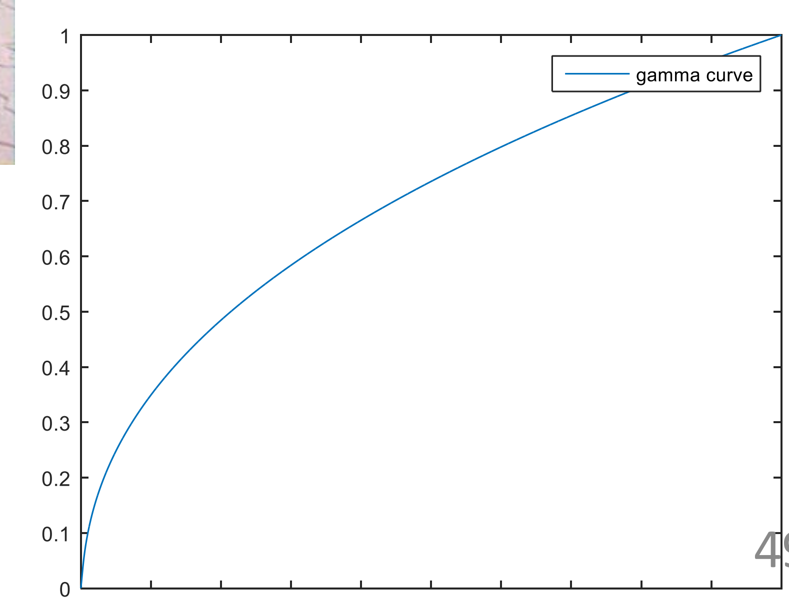
Walking through the pipeline (9)

#	#	#
#	#	#
#	#	#

sRGB conversion

Walking through the pipeline (10)

sRGB gamma



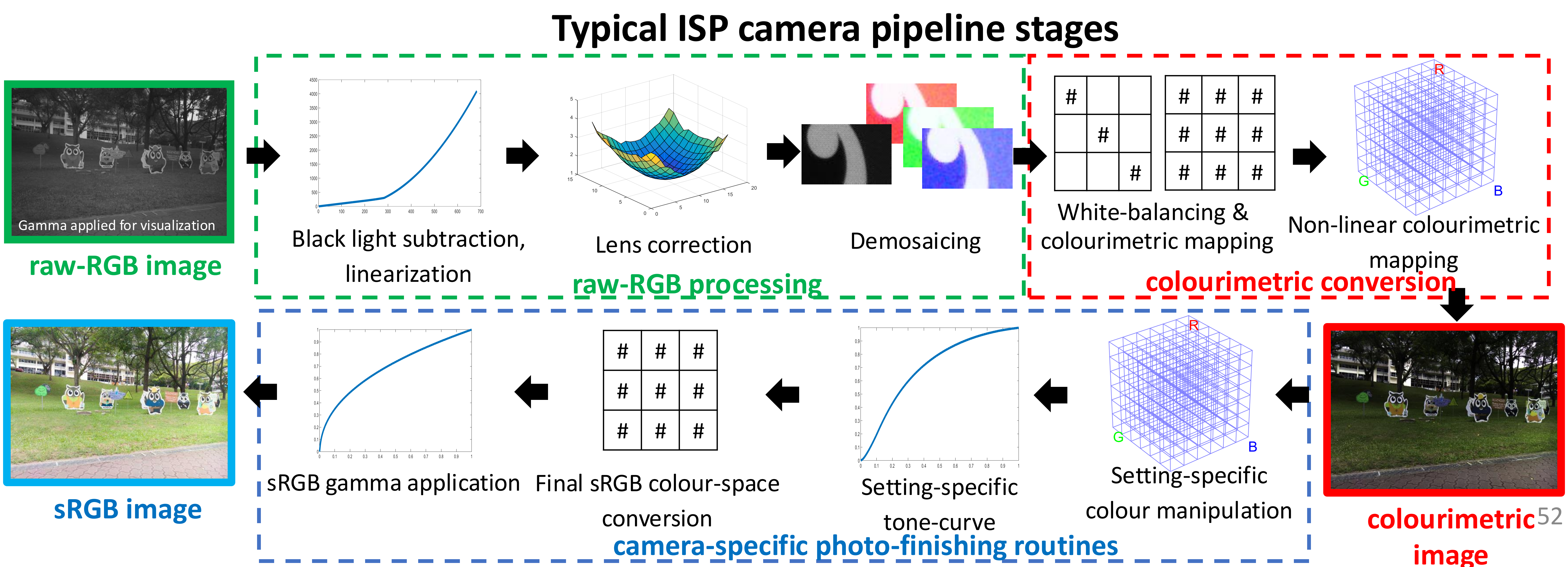
Summary

- **Provided a software platform to emulate the camera pipeline**
  - Tool for modifying the parameters of the pipeline, as well as allowing access and modification to intermediate images that can then be inserted back
- **Basis for the dissertation**
  - Made it possible to complete rest of the work

Beyond raw-RGB and sRGB: Advocating Access to a Colourimetric Image State

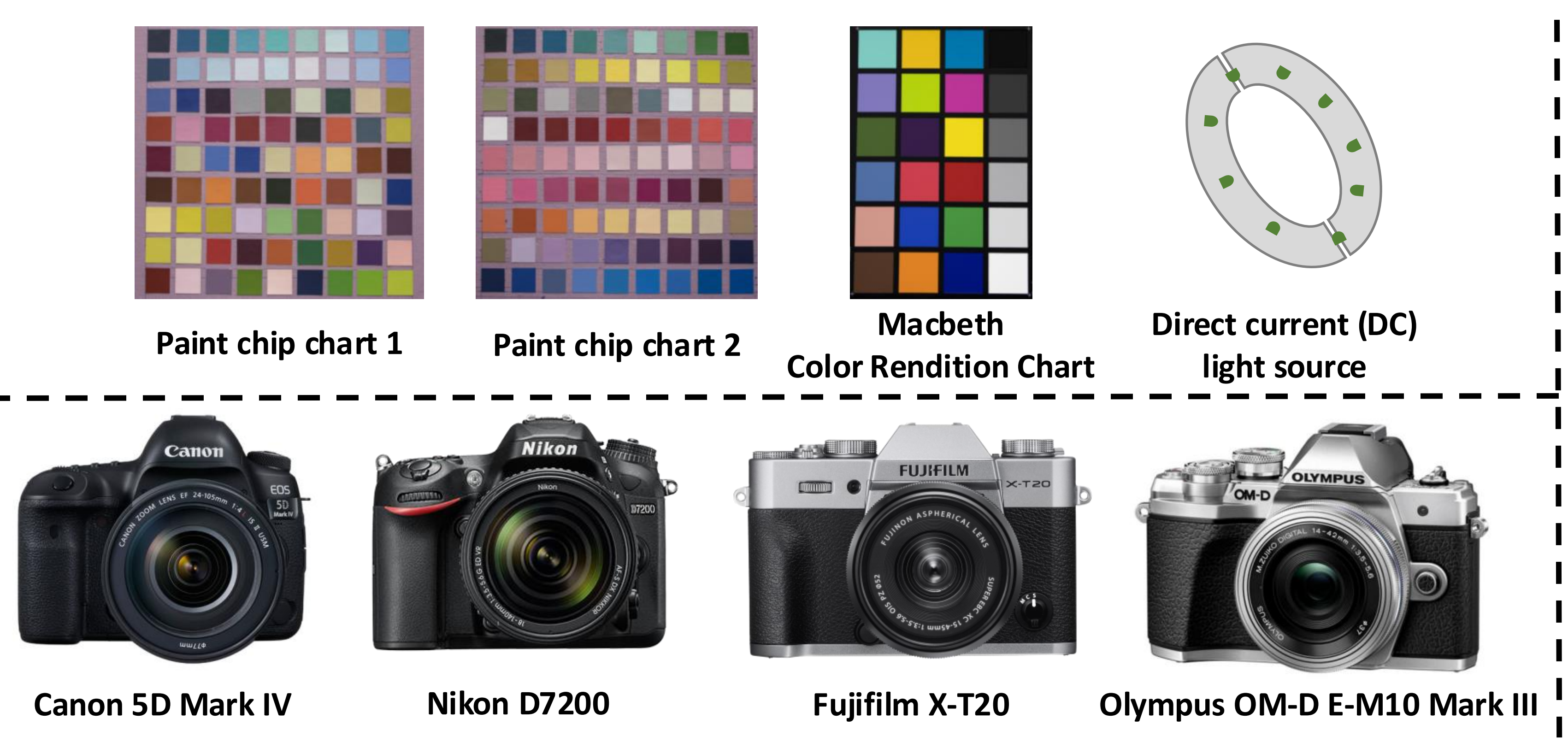
Motivation

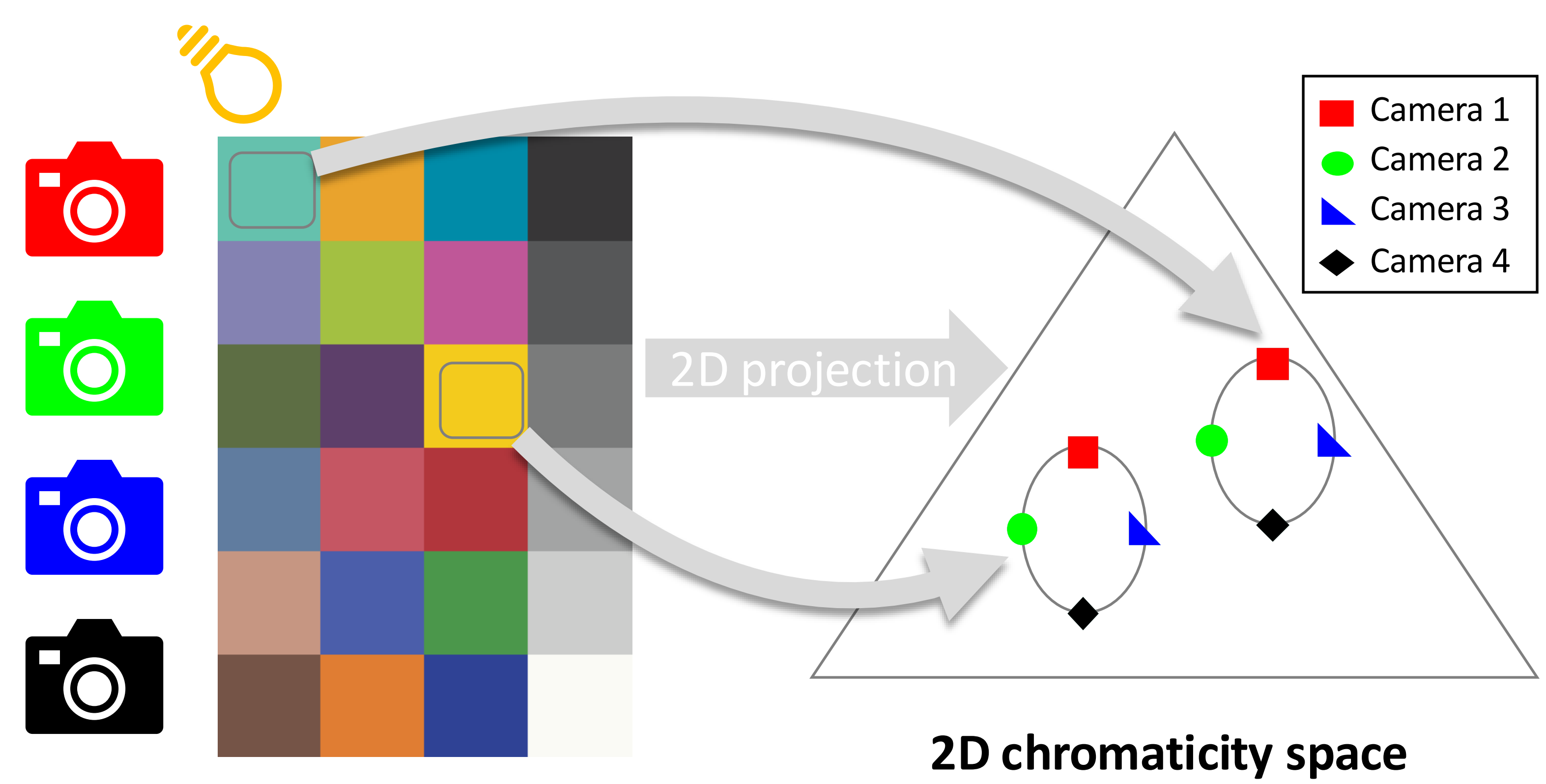
- Currently we have access to
  - raw-RGB
  - sRGB
- Third image format for the applications beyond photography



Experimental setup

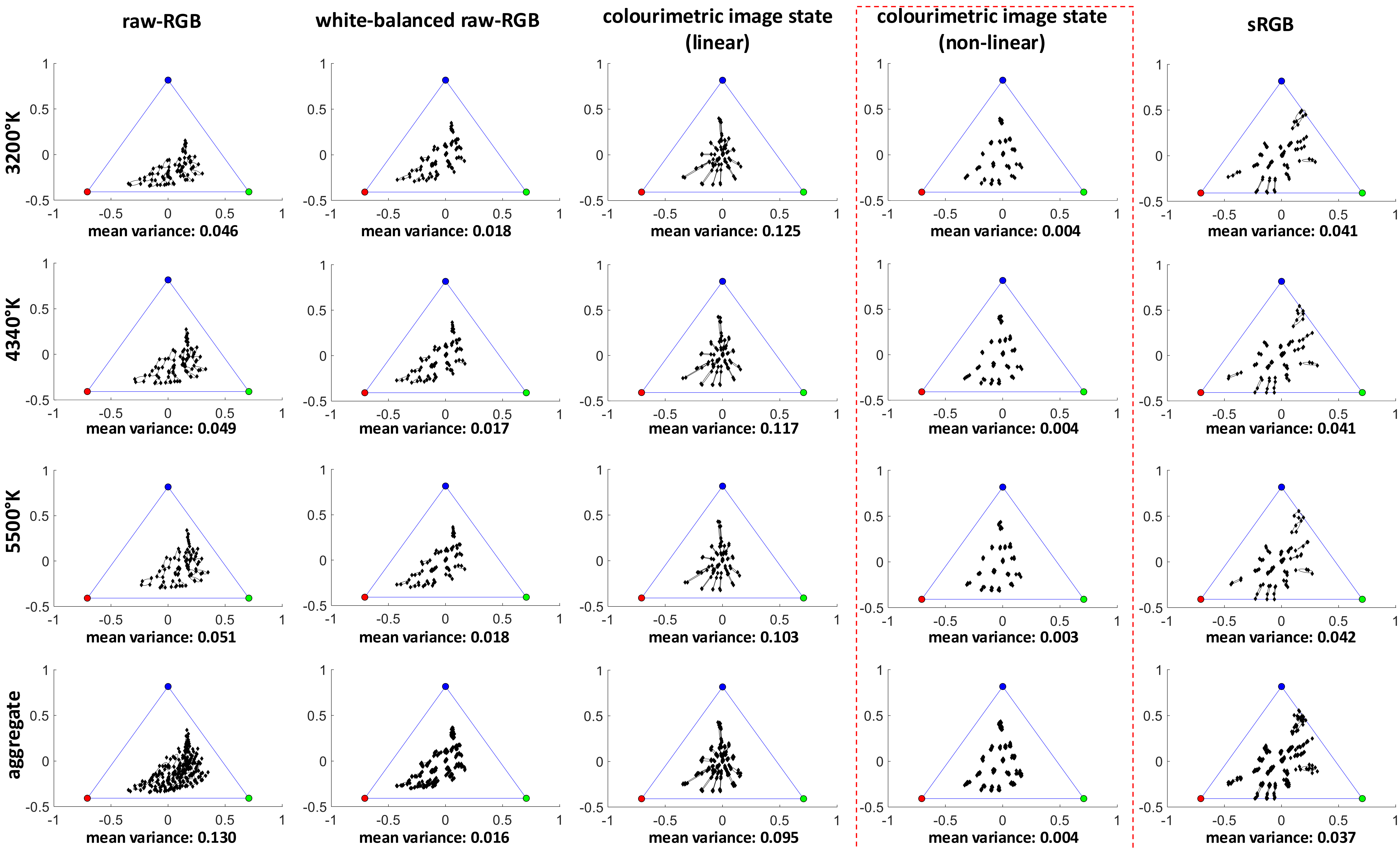
- The same material under the same lighting across multiple cameras
- Transform measured points to 2D chromaticity space to factor out brightness differences
- Compute the mean variance as a similarity measure



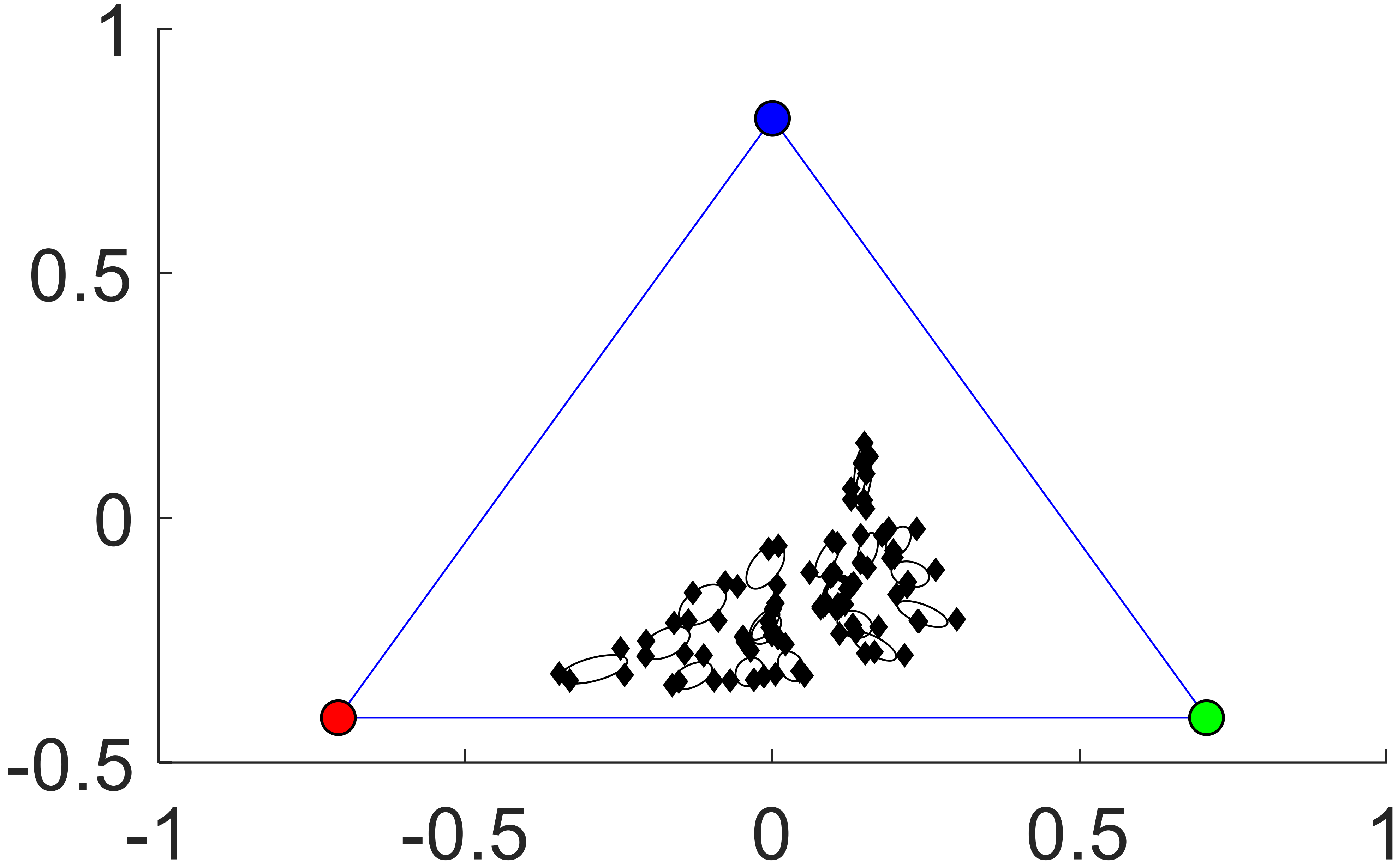


Analysis

Macbeth
Color Rendition Chart

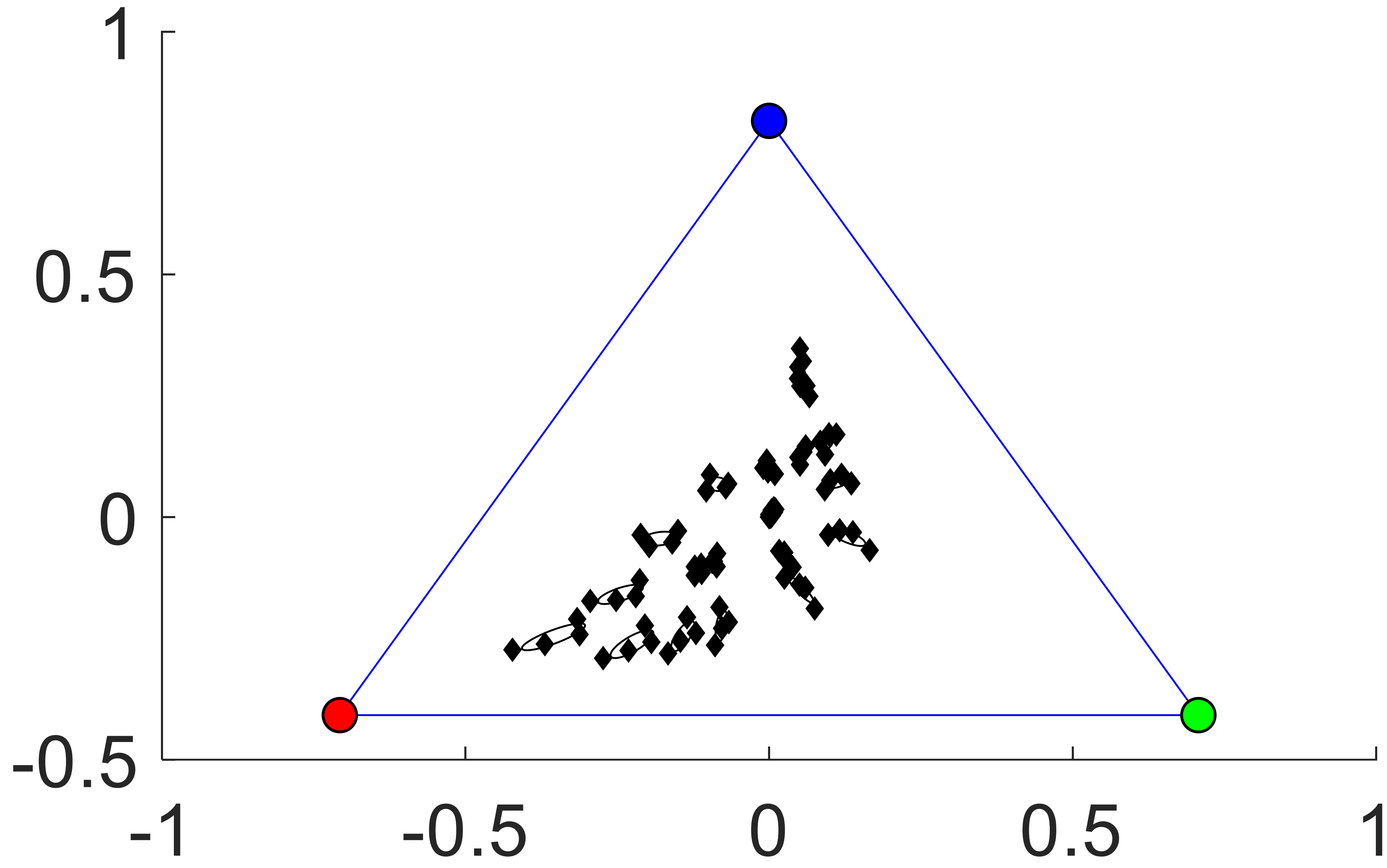


3200°K – raw-RGB



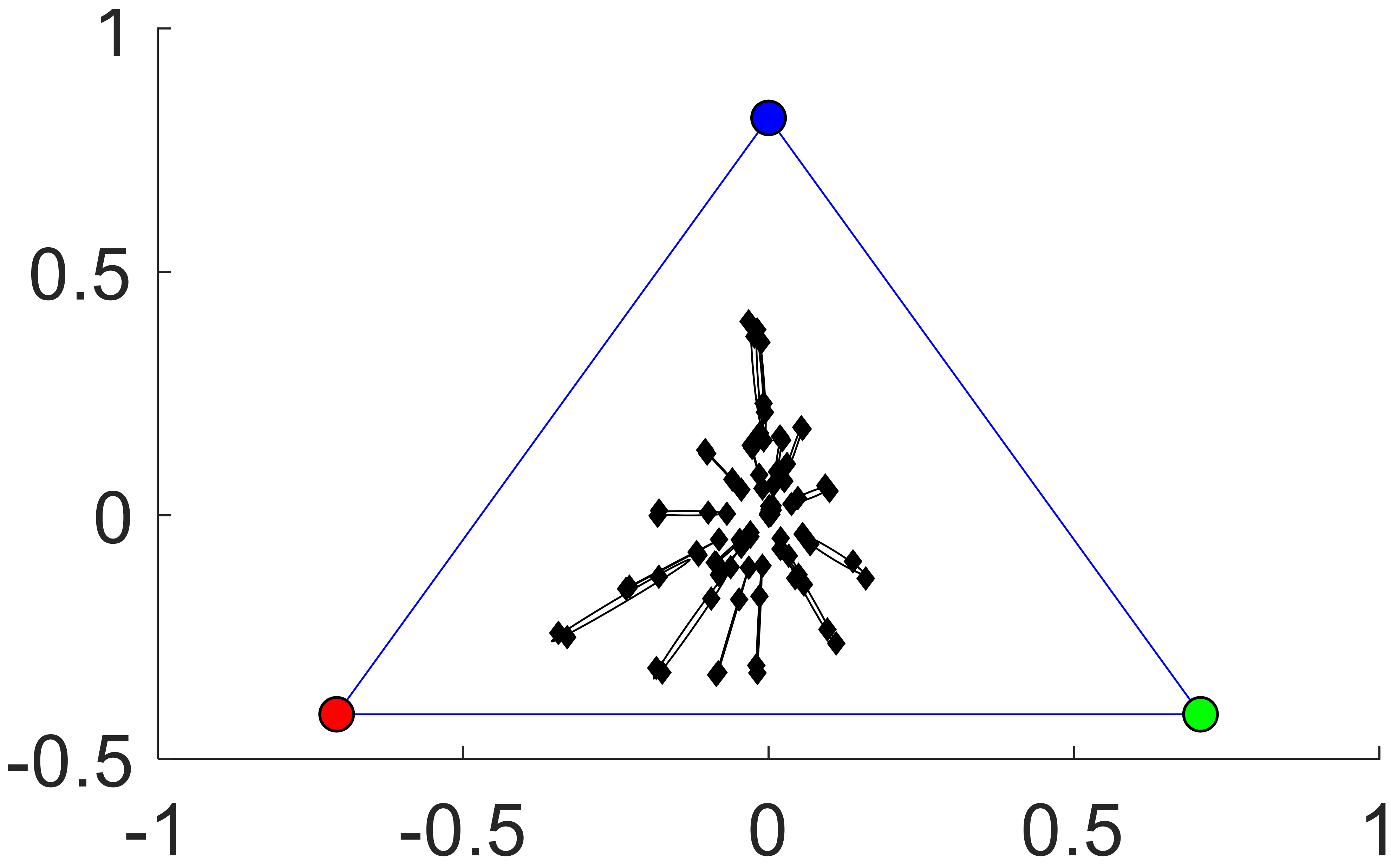
mean variance: 0.046

3200°K – white-balanced raw-RGB



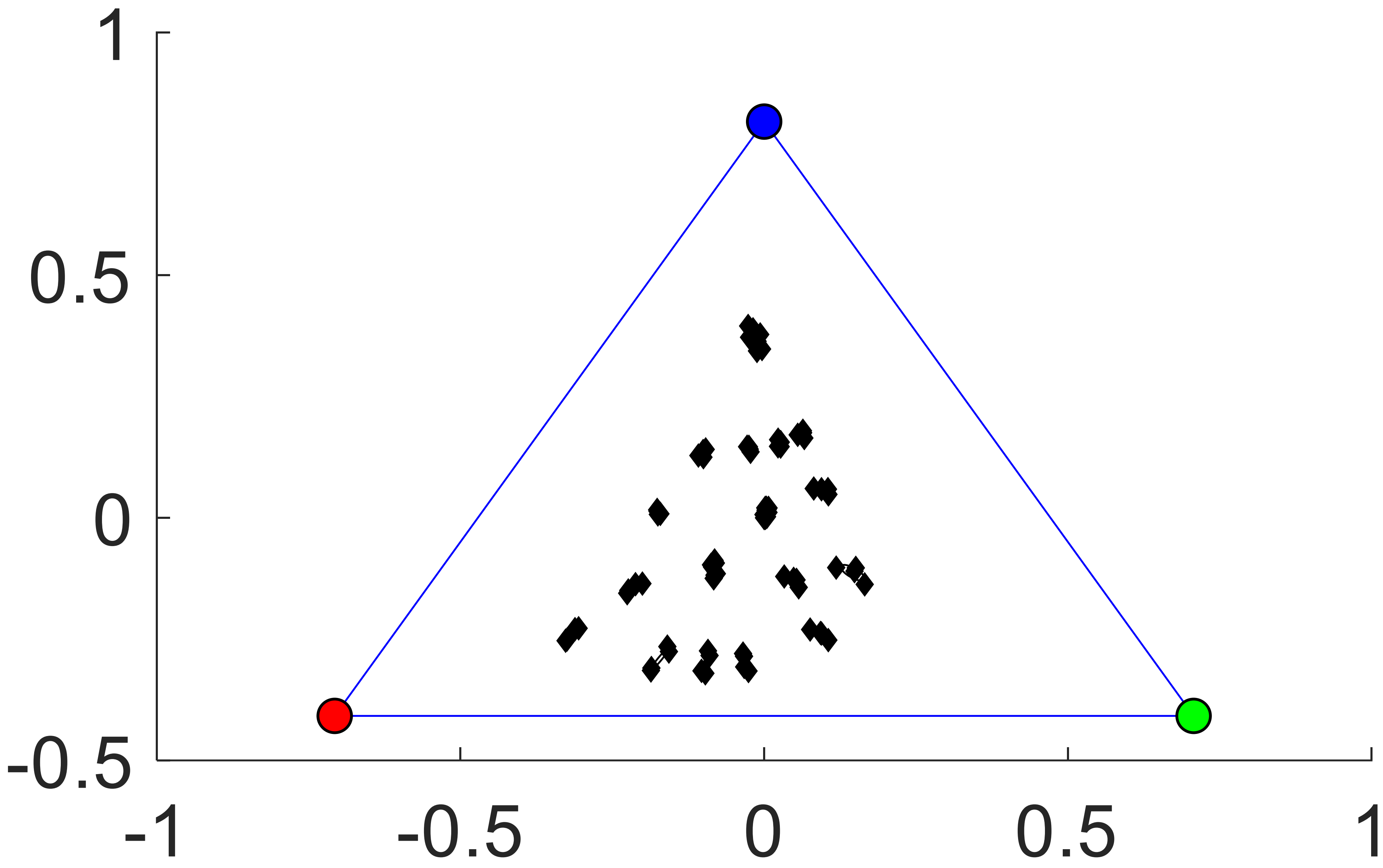
mean variance: 0.018

3200°K – colourimetric image state (linear)



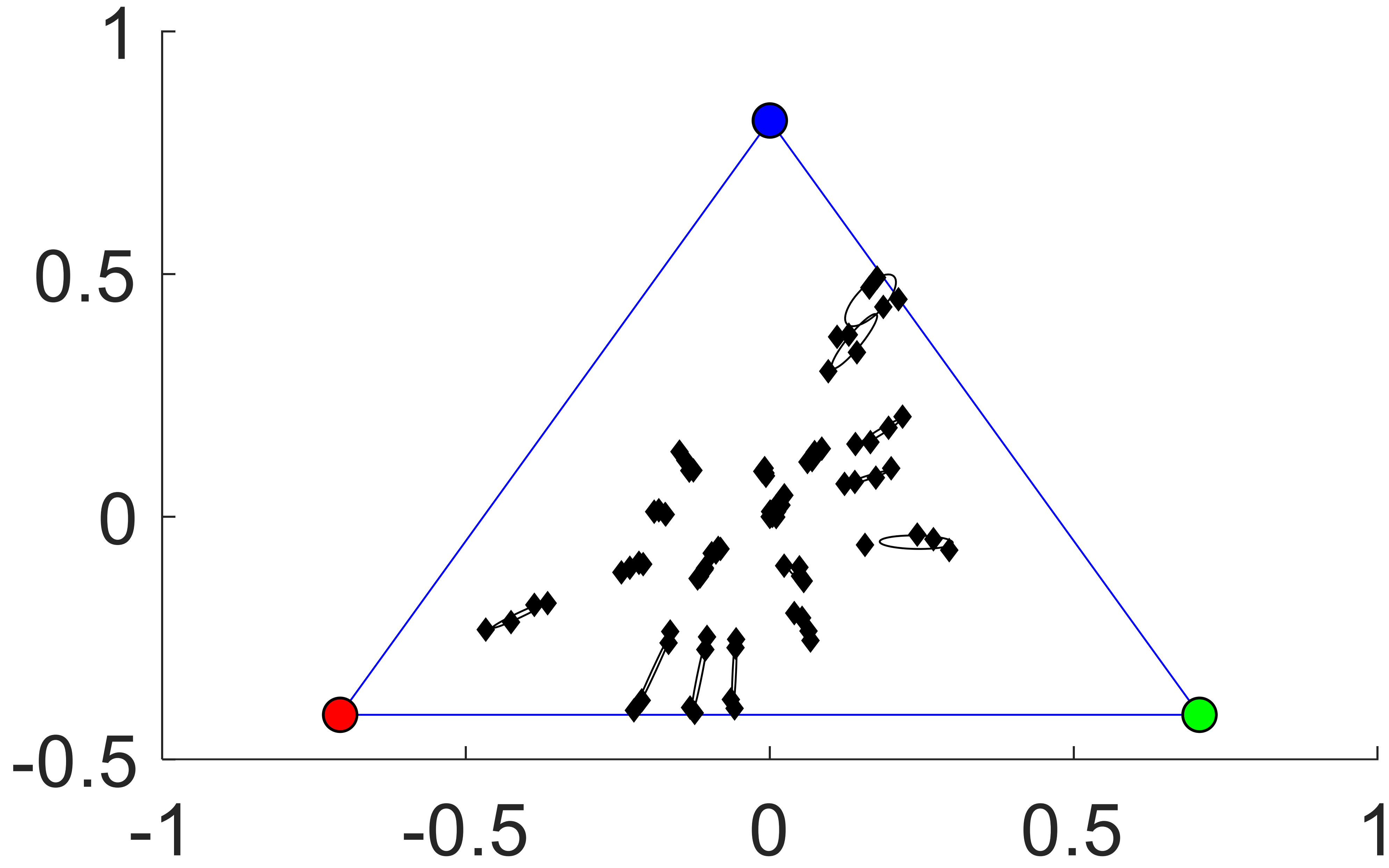
mean variance: 0.125

3200°K – colourimetric image state (non-linear)



mean variance: 0.004

3200°K – sRGB



mean variance: 0.041

Analysis


Macbeth
Color Rendition Chart

- Mean variances between cameras at five different stages using **white patch white-balance.**

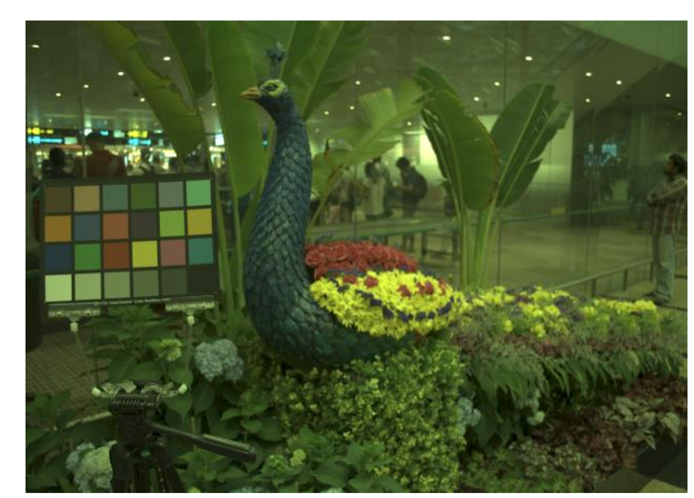
Colour Rendition Chart				
Stage	3200°K	4340°K	5500°K	Combined
raw-R				.130
white-bal raw-RGB				.016
colourimetric image state (linear)	0.125	0.117	0.103	0.095
colourimetric image state (non-linear)	**0.004**	**0.004**	**0.003**	**0.004**
sRGB	0.041	0.041	0.042	0.037

More results in the dissertation!

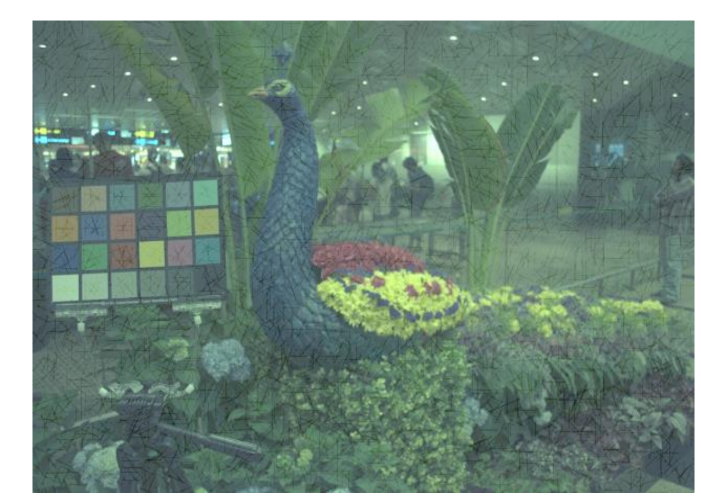
Summary

- **Presented a third image format that achieves the most consistent results**
  - No calibration required
  - Simply a matter of accessing the colourimetric image state

sRGB



raw-RGB

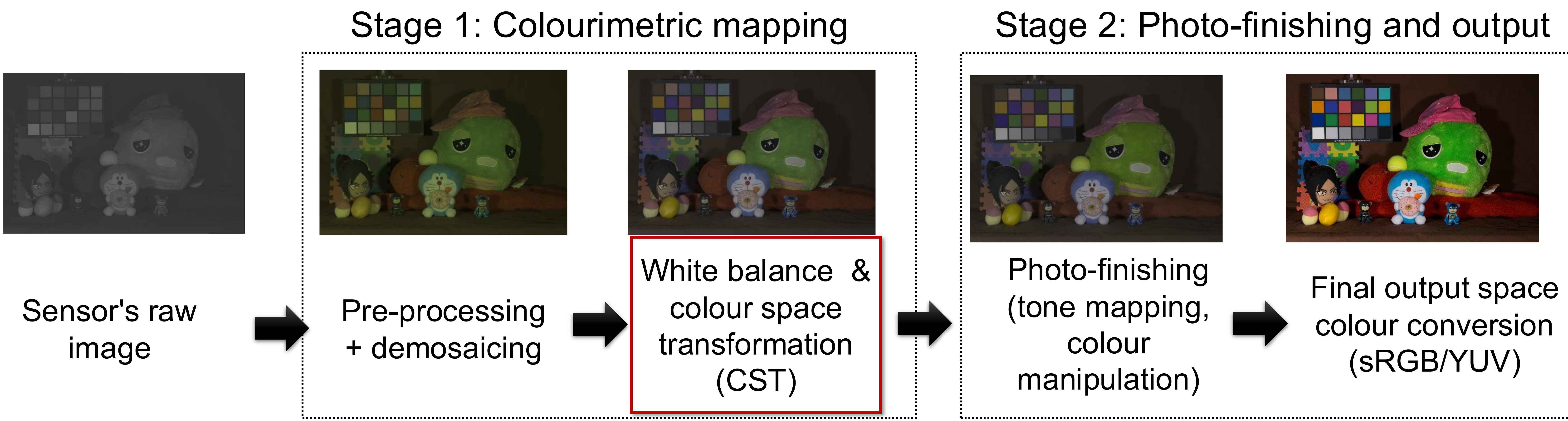


colourimetric image

Improving Color Reproduction Accuracy on Cameras

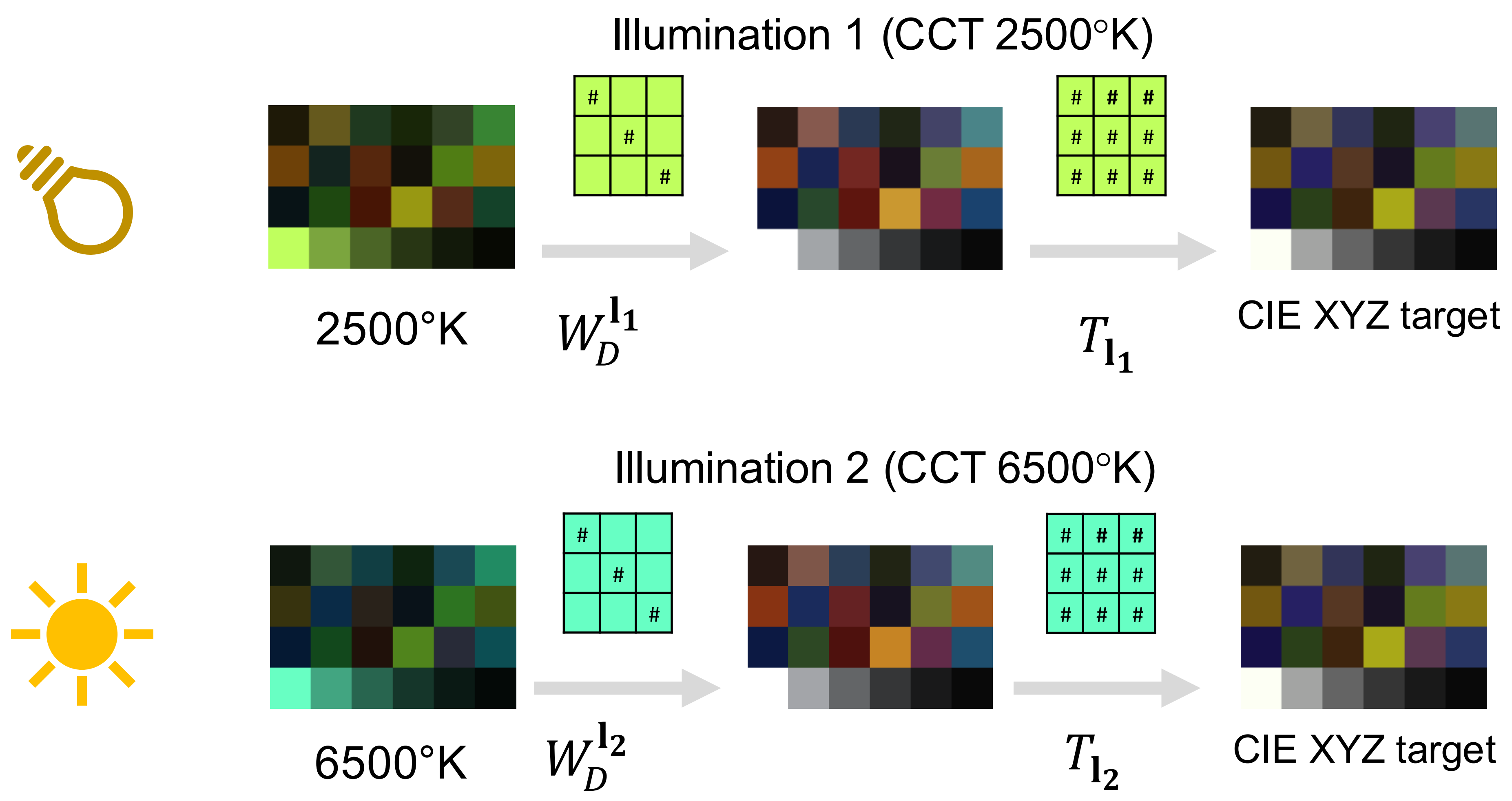
Motivation

White balance and CST go hand in hand!



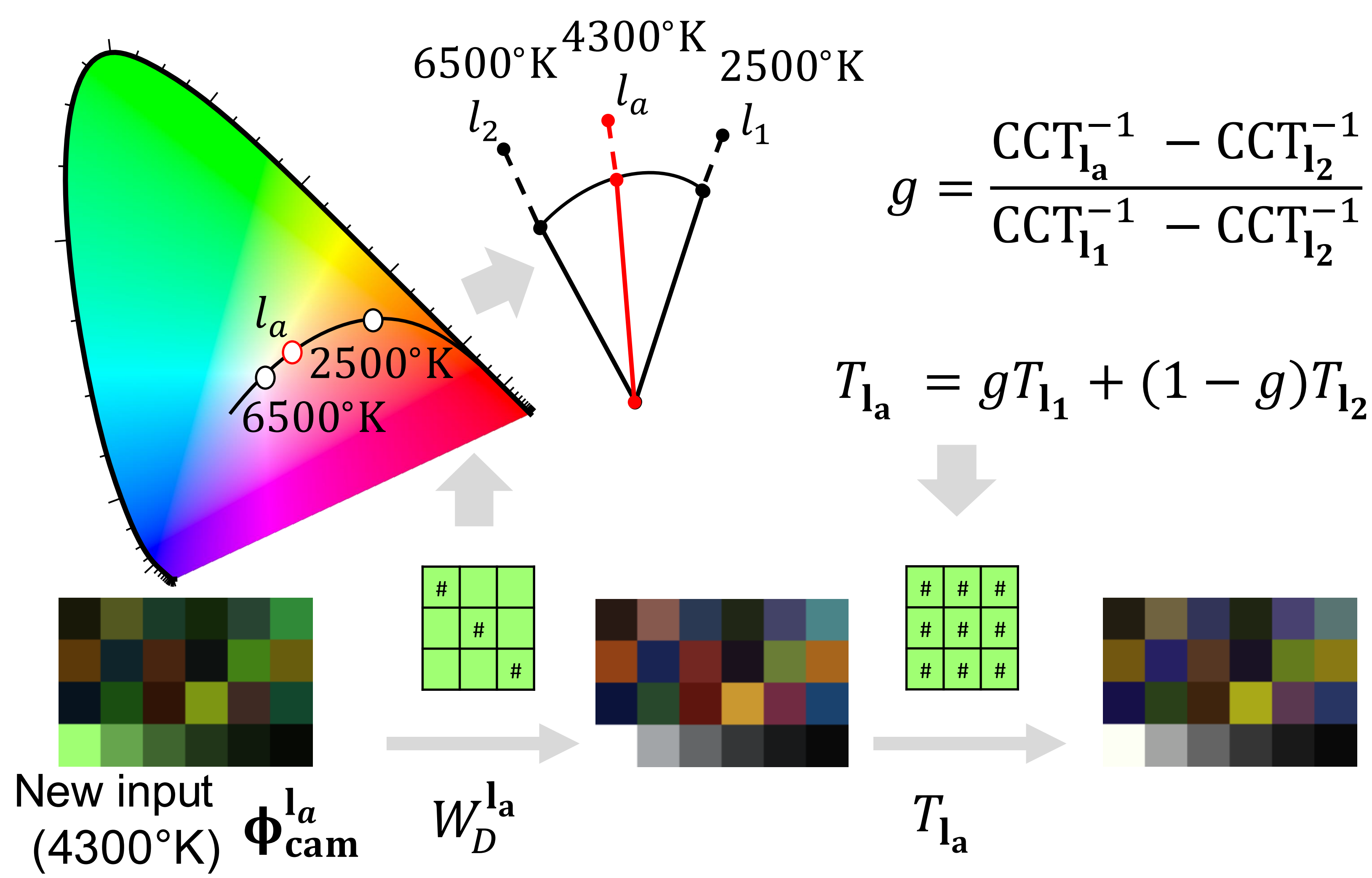
Current approach

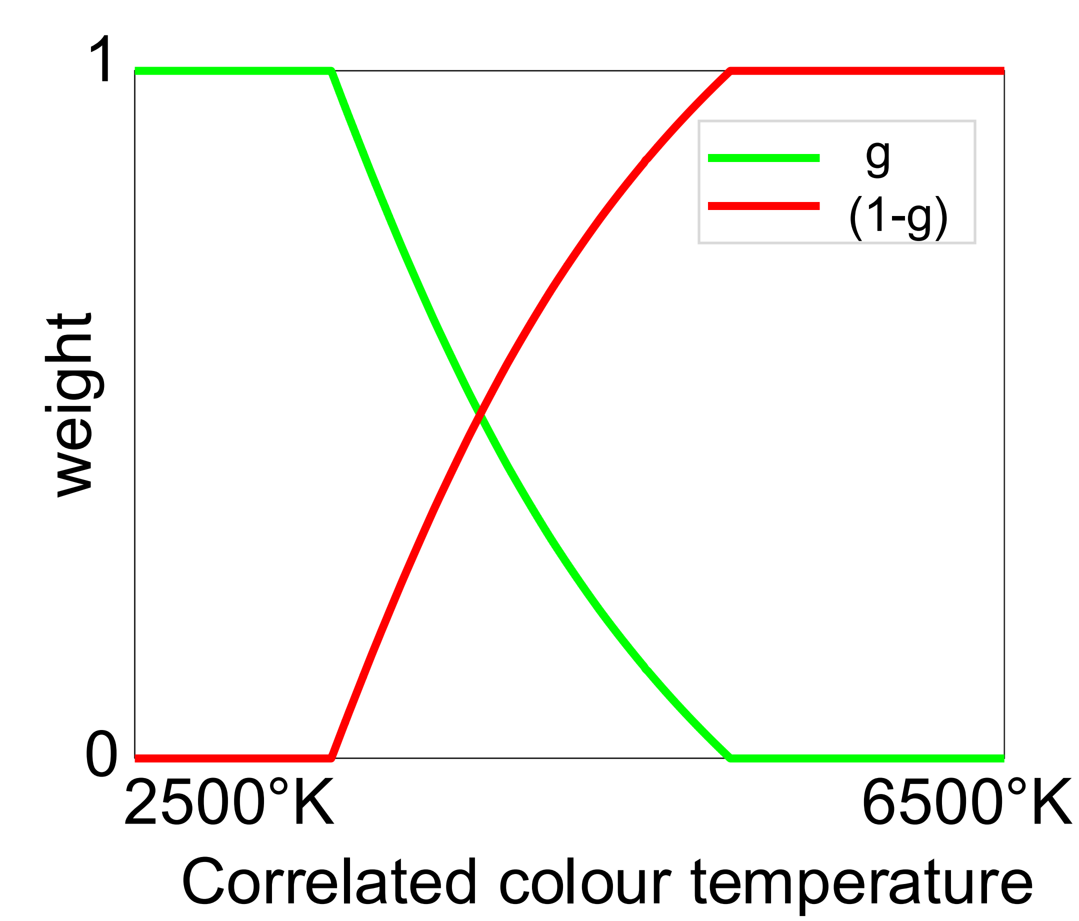
- Existing camera colorimetric mapping requires calibration for two far-apart light sources
- Most cameras use 2500°K and 6500°K as its two light sources



Current approach

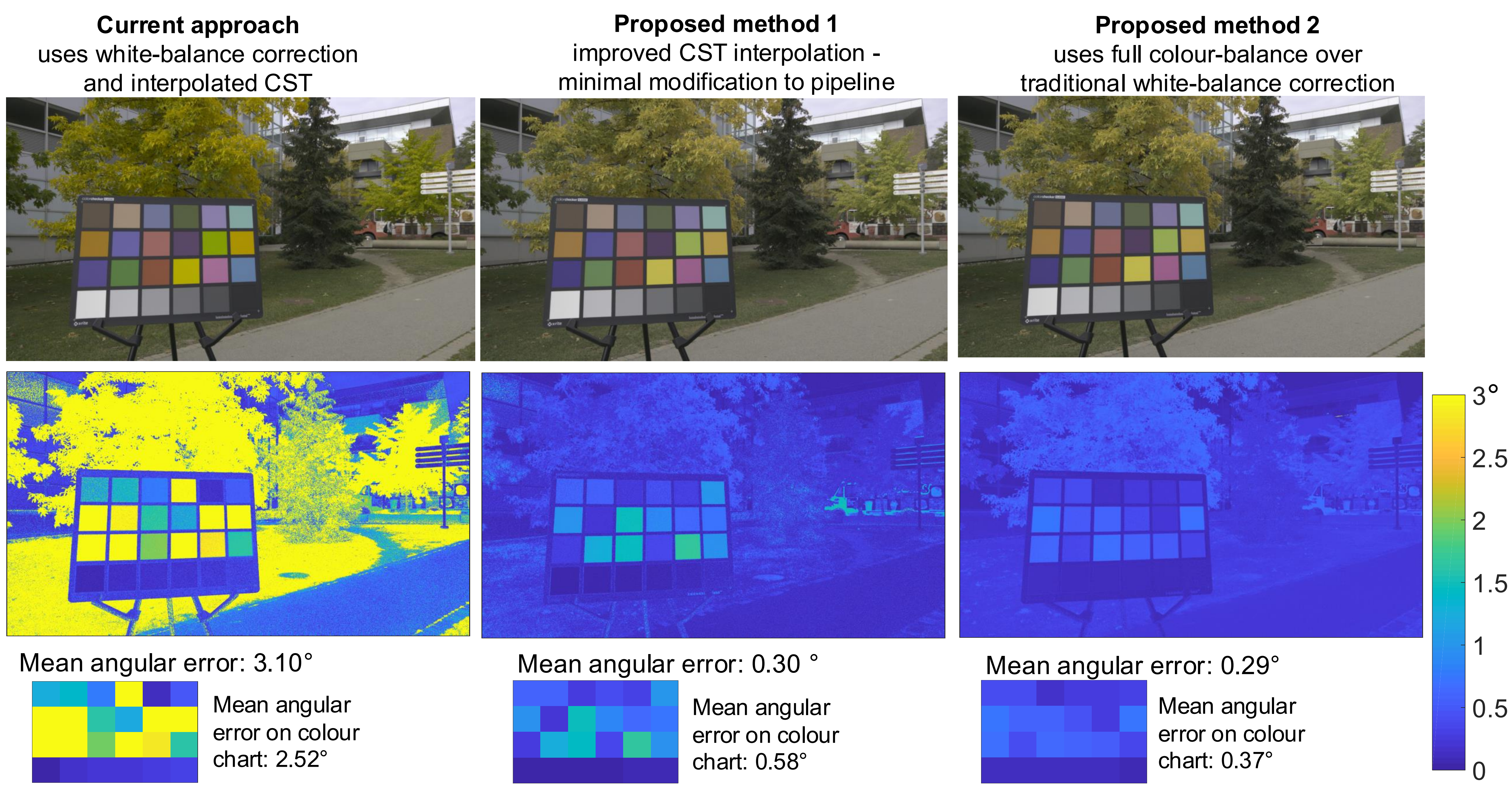
- Current procedure used on cameras are based on two pre-calibrated illuminations to interpolate a CST





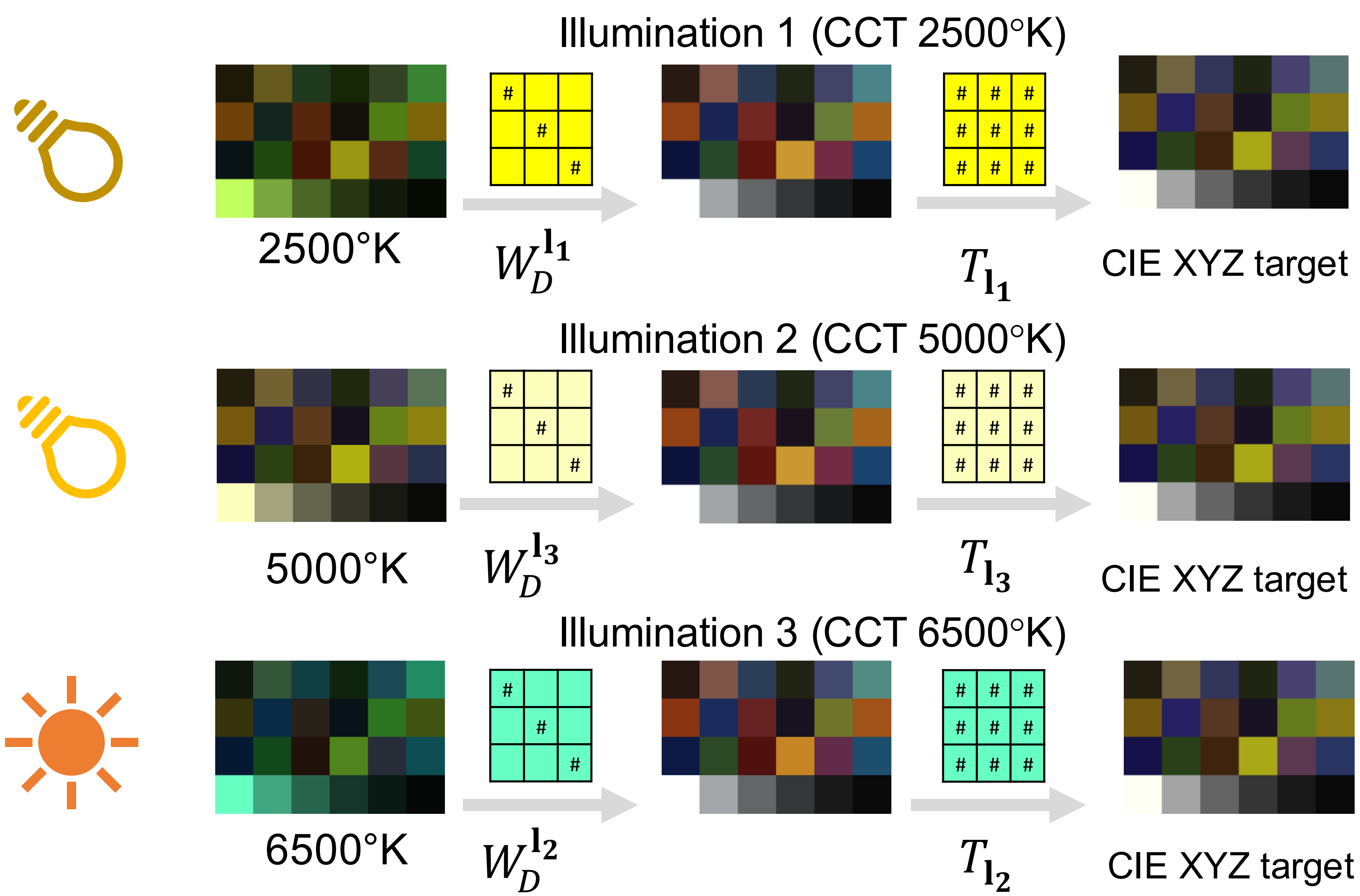
Motivation

Results in inaccurate mappings



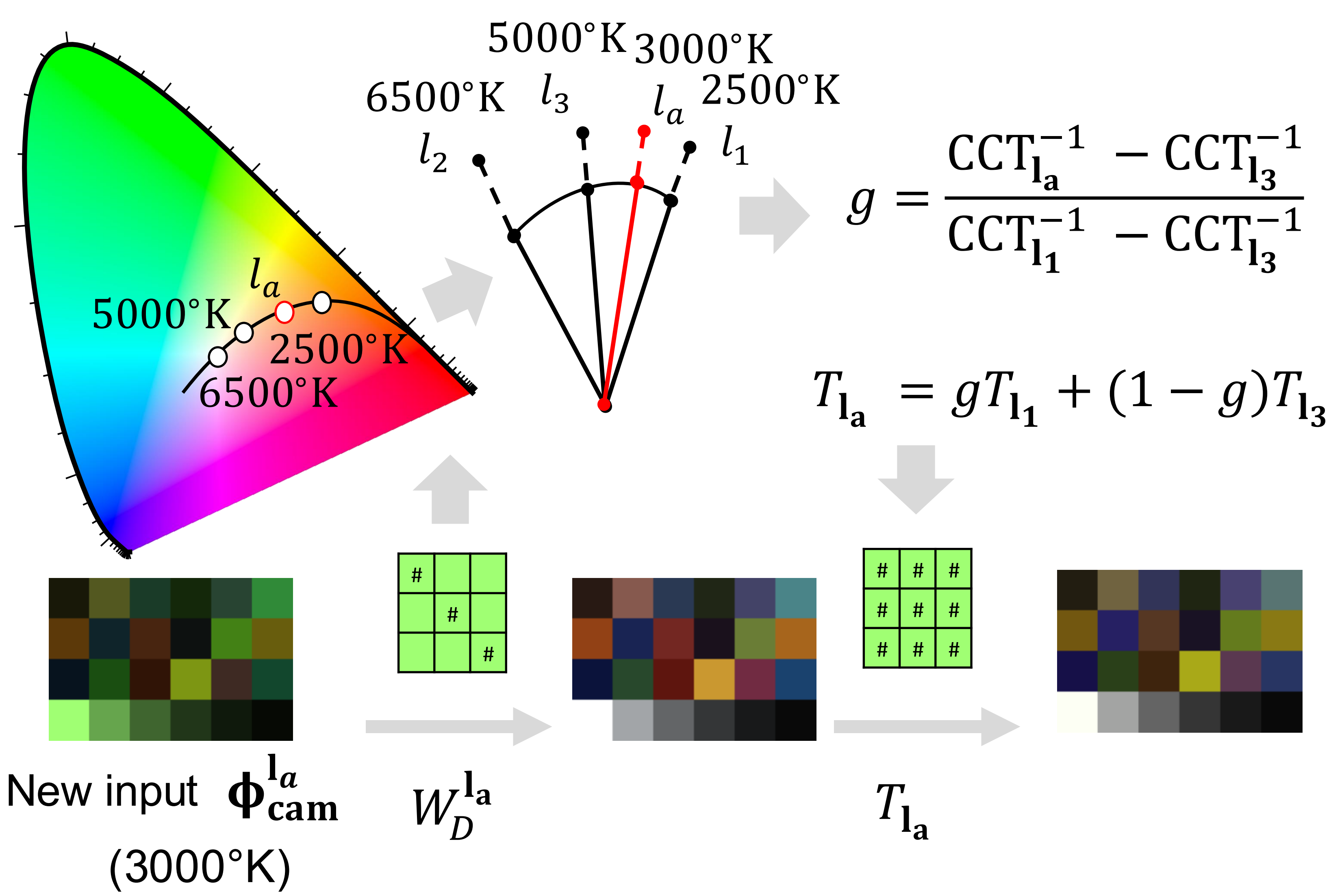
Proposed improvements

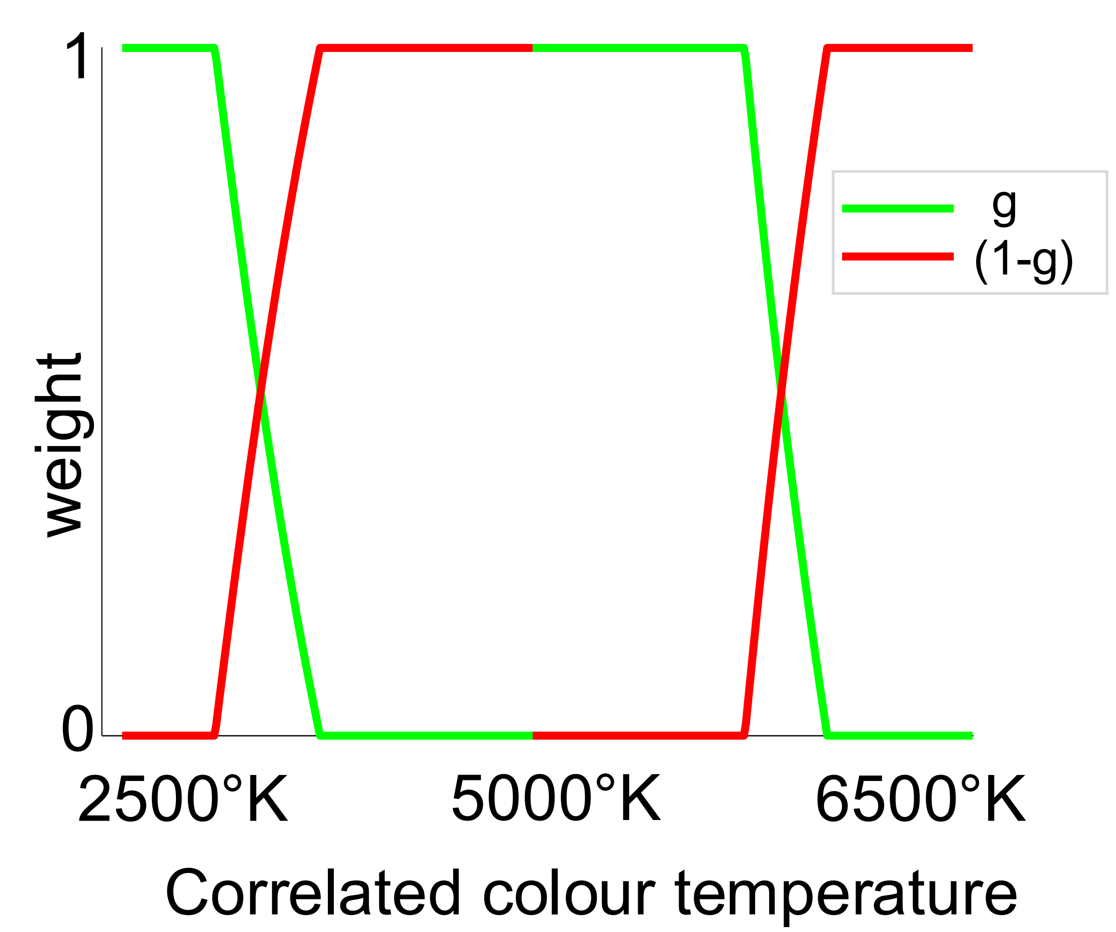
- Method 1: Extending interpolation
  - Incorporate an **additional** calibrated illumination into the interpolation process



Method 1: Extending the interpolation

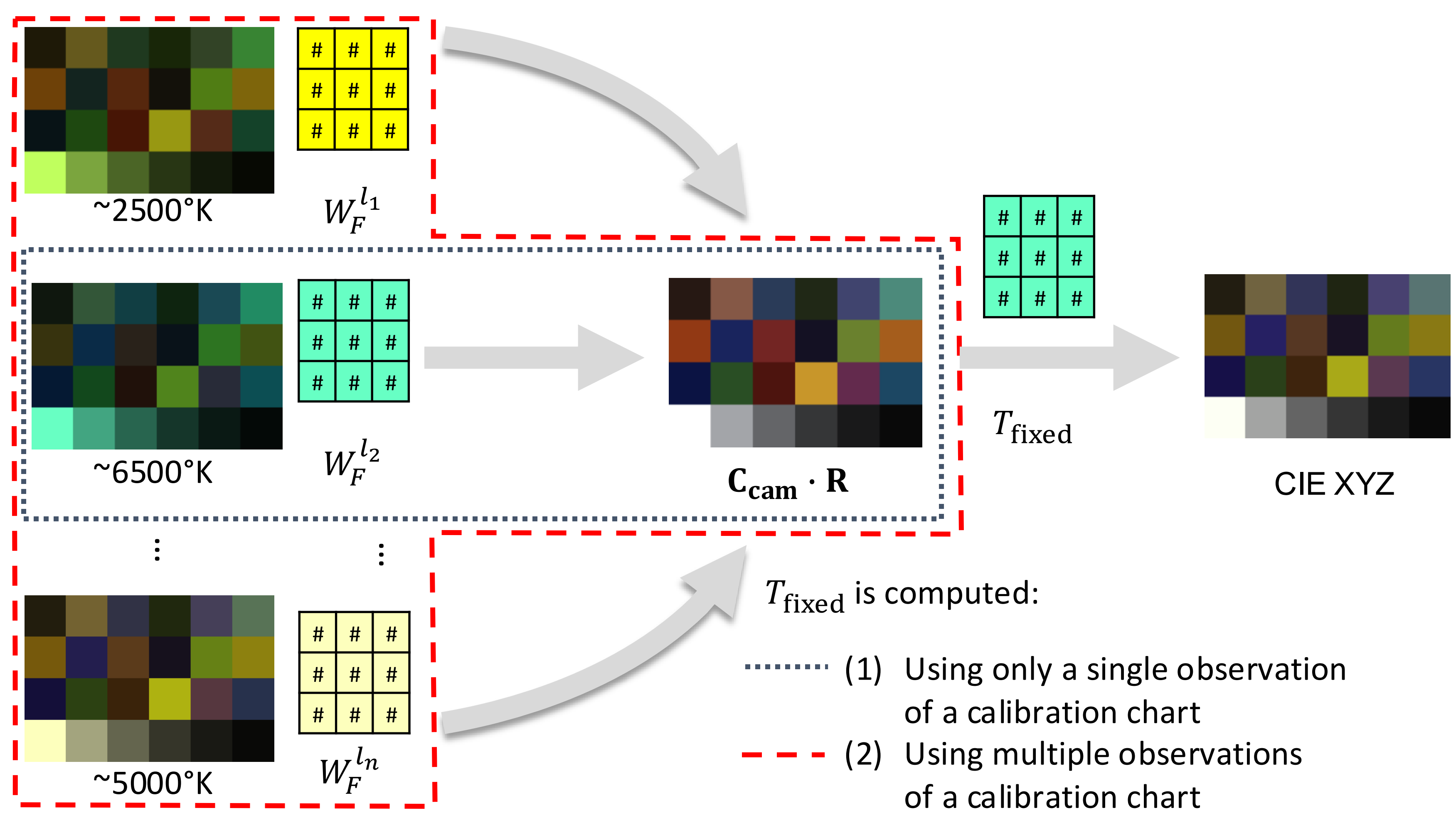
- Select the pair of pre-calibrated $T_{\mathbf{l}}$ based on the estimated illumination's CCT





Method 2: Using full colour balance

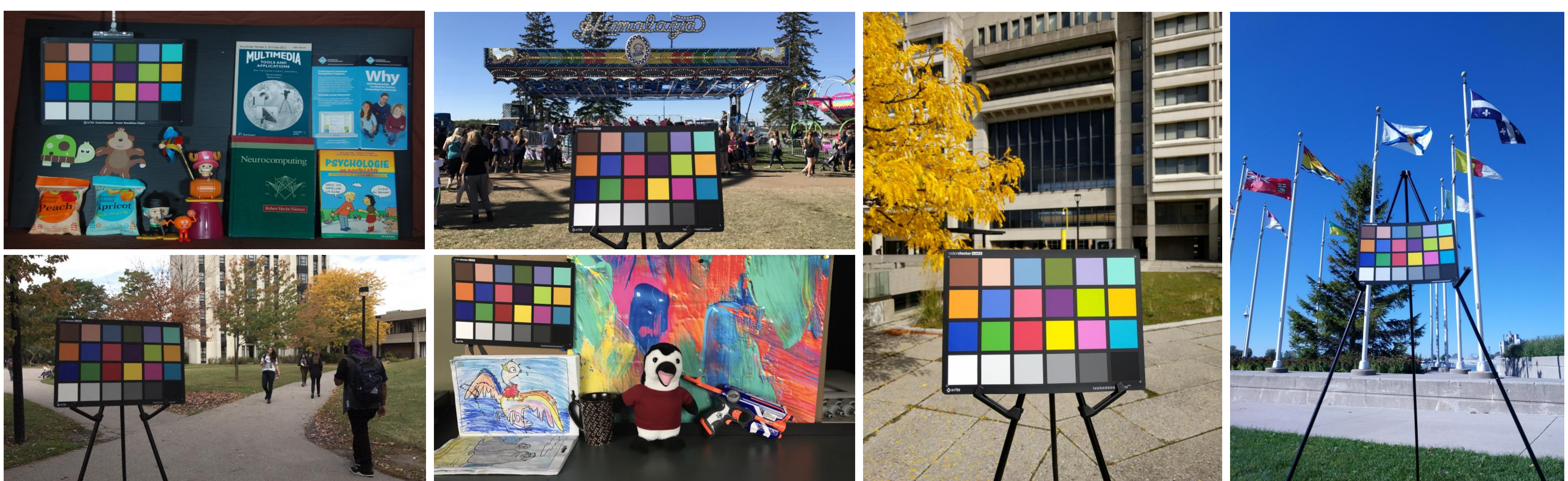
- Full colour-balance approach proposed by Cheng et al. (2015a)
- Estimate the fixed CST, T_{fixed}, in two ways:
  - Use only a single observation of the colour chart
  - Consider all observations of the colour chart for each different illumination



Cheng, D., Price, B., Cohen, S., & Brown, M. S. (2015a). Beyond White: Ground Truth Colors for Color Constancy Correction. In ICCV.

Dataset

- A dataset of 700 carefully calibrated colourimetric images
  - Four DSLR cameras (Canon 1D, Nikon D40, Sony α57, and Olympus E-PL6)
  - Three mobile phone cameras (Apple iPhone 7, Google Pixel, and LG-G4)

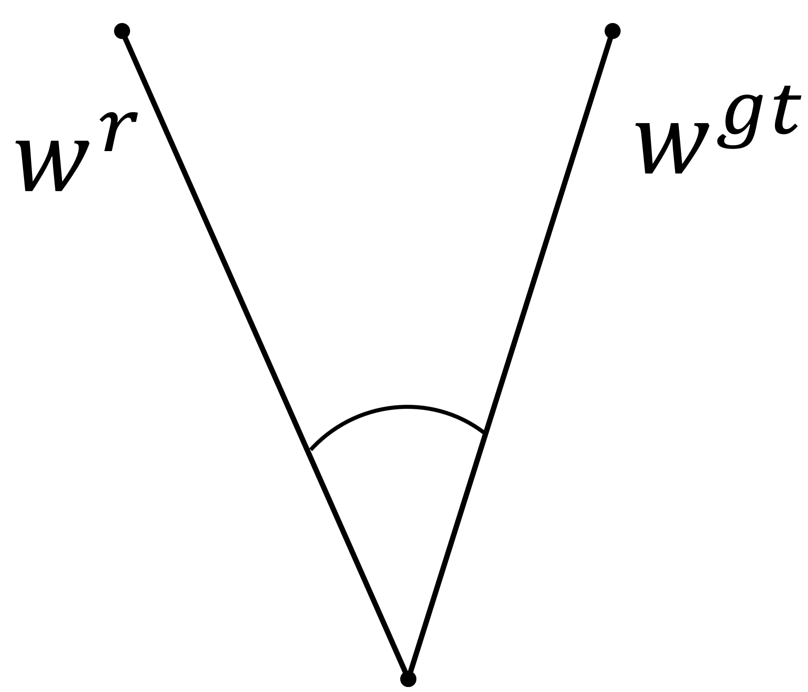


Evaluation

Individual camera accuracy

- *Angular reproduction error*:
  - I: Full image
  - CC: Macbeth color checker chart

Method	Apple iPhone 7		Google Pixel		LG-G4		Canon1D		NikonD40		Sony α57		Olympus E-PL6	
	CC	I	CC	I	CC	I	CC	I	CC	I	CC	I	CC	I
CB + Fixed CST (all)	**0.80**	**0.91**	**0.88**	1.05	**0.81**	**0.86**	**0.84**	**0.63**	**0.93**	0.77	1.00	0.77	0.85	0.69
CB + Fixed CST (single)	0.95	1.04	1.41	1.45	1.17	1.17	0.95	0.76	0.98	0.80	**0.99**	0.76	**0.82**	0.67
WB + 3 CSTs	1.36	1.08	1.27	**1.04**	1.55	1.24	1.04	0.70	1.07	**0.65**	1.04	**0.74**	0.86	**0.61**
WB + 2 CSTs (factory)	3.07	2.46	2.28	1.75	2.74	2.04	1.58	1.18	2.02	1.26	1.14	0.79	1.12	0.75



$$e_r = cos^{-1}\left(\frac{w^r \cdot w^{gt}}{\|w^r\|\|w^{gt}\|}\right)$$

Evaluation

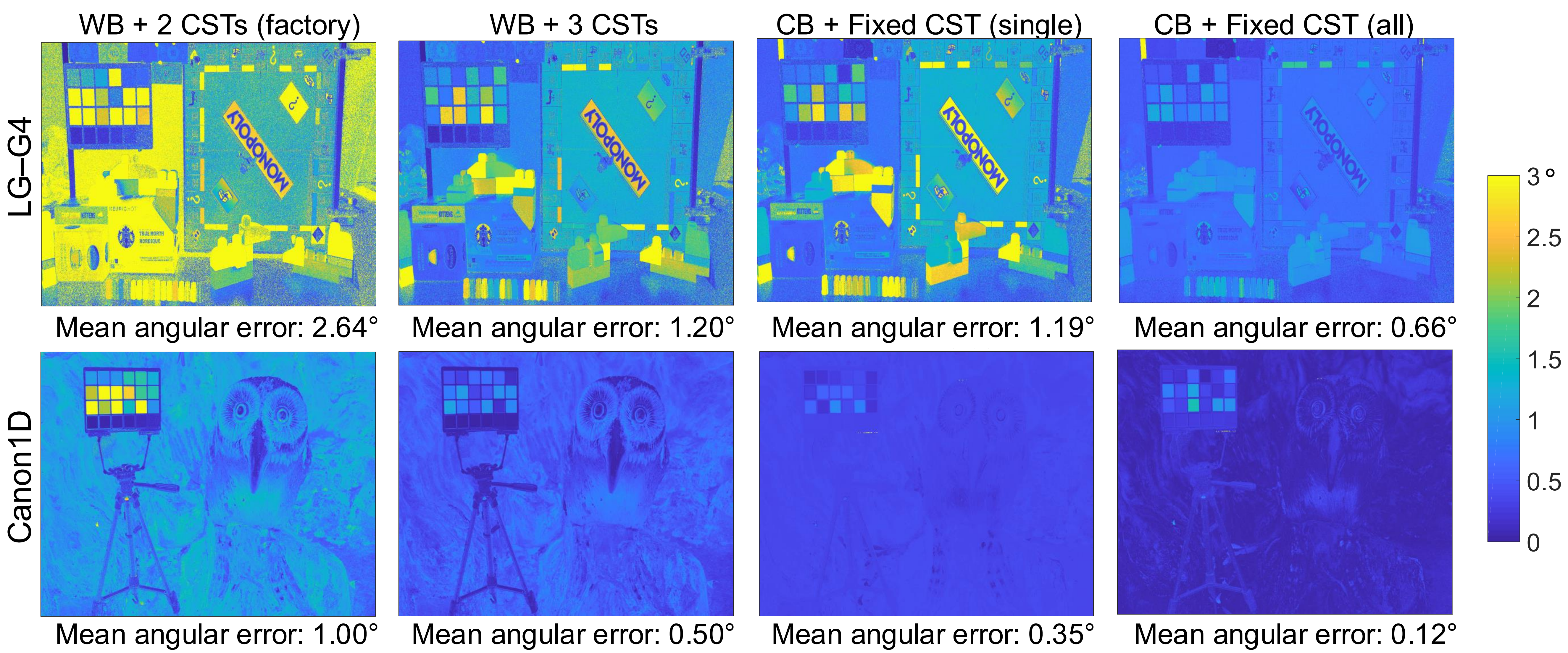
Multi-camera consistency

- Variance between cameras capturing the same scene under the same lighting

Method	Mobile Phones 2900°K	Mobile Phones 4500°K	Mobile Phones 5500°K	Mobile Phones 6000°K	DSLRs 3000°K	DSLRs 3500°K	DSLRs 4300°K	DSLRs 5200°K
CB + Fixed CST (all)	**4.6**	**2.1**	**1.1**	**1.0**	**1.6**	**1.8**	**1.2**	**1.1**
CB + Fixed CST (single)	10.0	7.1	4.9	6.2	2.7	2.9	2.1	1.7
WB + 3 CSTs	37.9	6.9	6.6	8.1	4.4	2.8	2.3	2.1
WB + 2 CSTs (factory)	34.2	38.2	32.6	36.2	13.3	7.1	7.1	7.7

Visual results

- Angular reproduction errors on:
  - LG-G4
  - Canon 1D



Summary

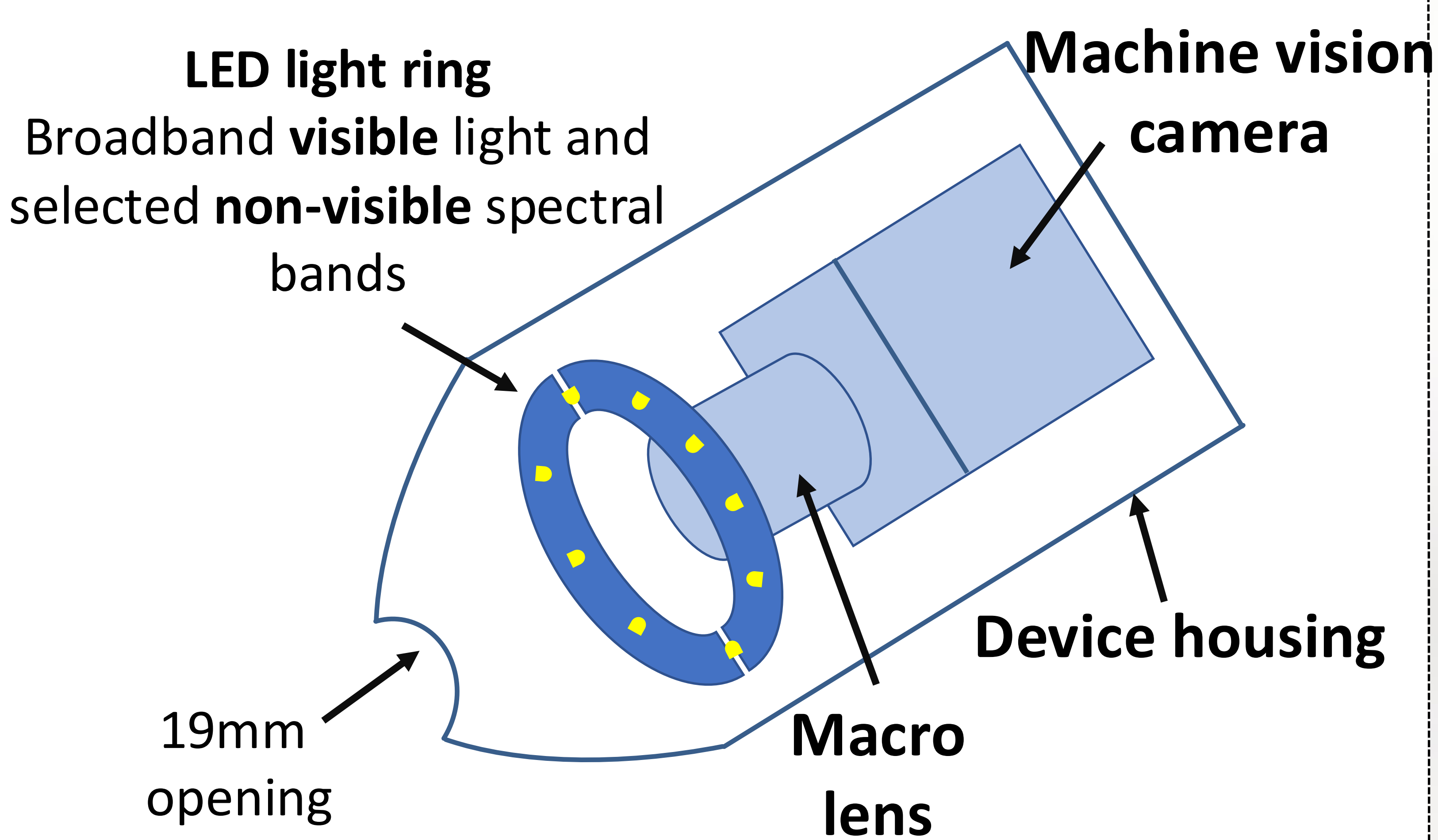
- **Presented the current procedure and its limitations**
  - Need for per-illumination CSTs
  - Interpolation technique for two pre-calibrated CSTs
- **Two methods to improve colourimetric mapping**
  - Extending the current procedure
  - Using full colour balance

A Customized Camera Imaging Pipeline for Dermatological Imaging

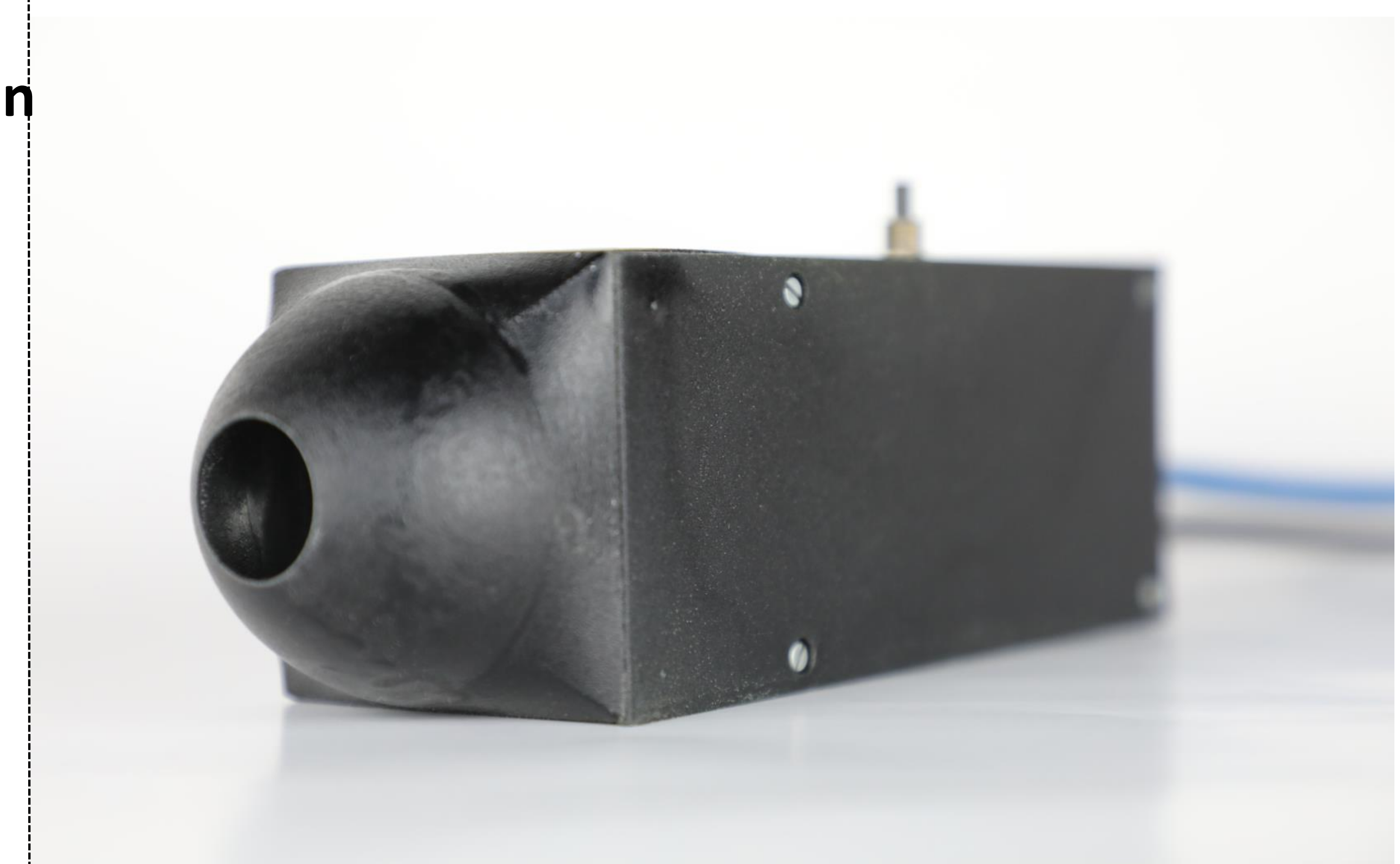
Introduction

A customize camera for dermatological analysis

Schematic drawing of the device



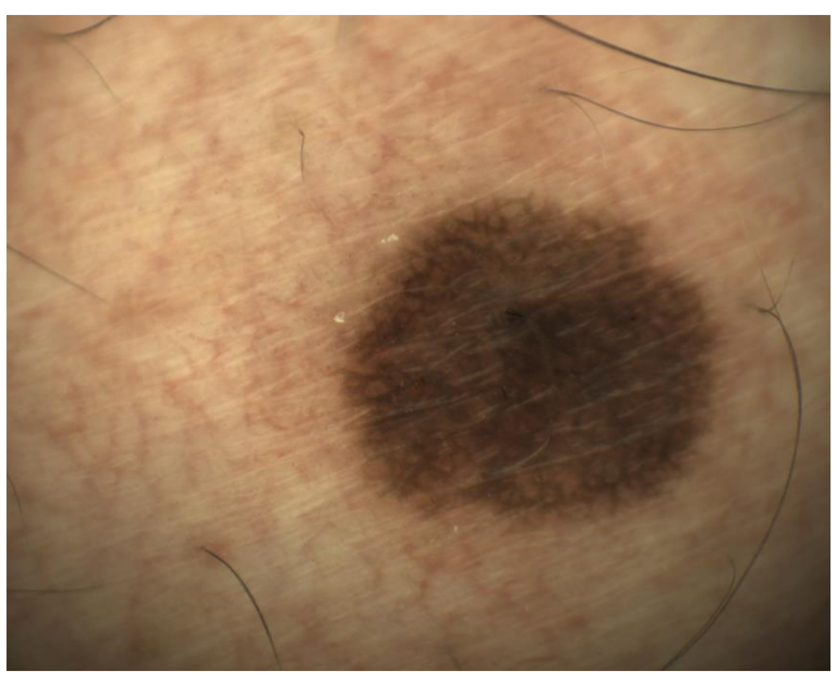
Prototype



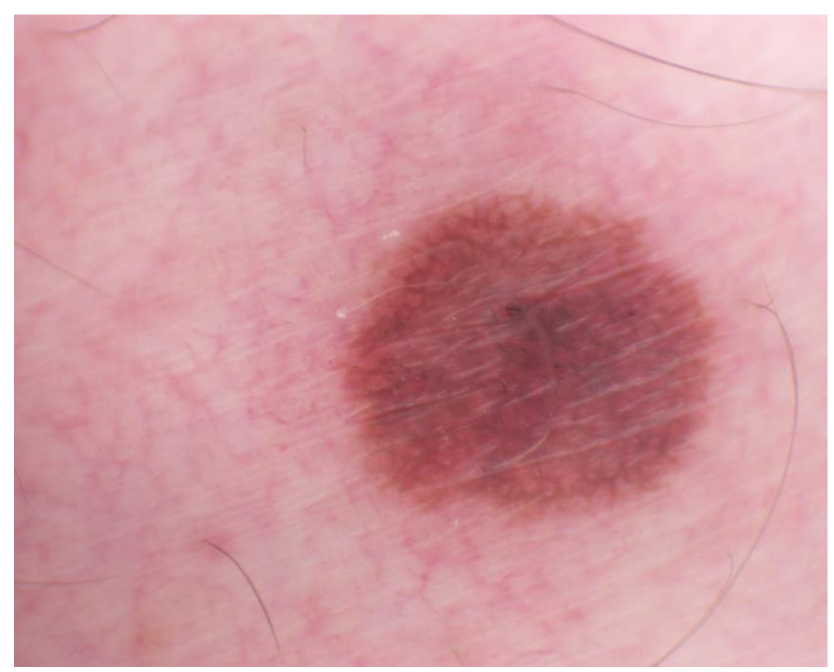
Challenges

1. Machine vision camera vs. consumer camera
2. How to use the visible image with the narrow band spectral image?

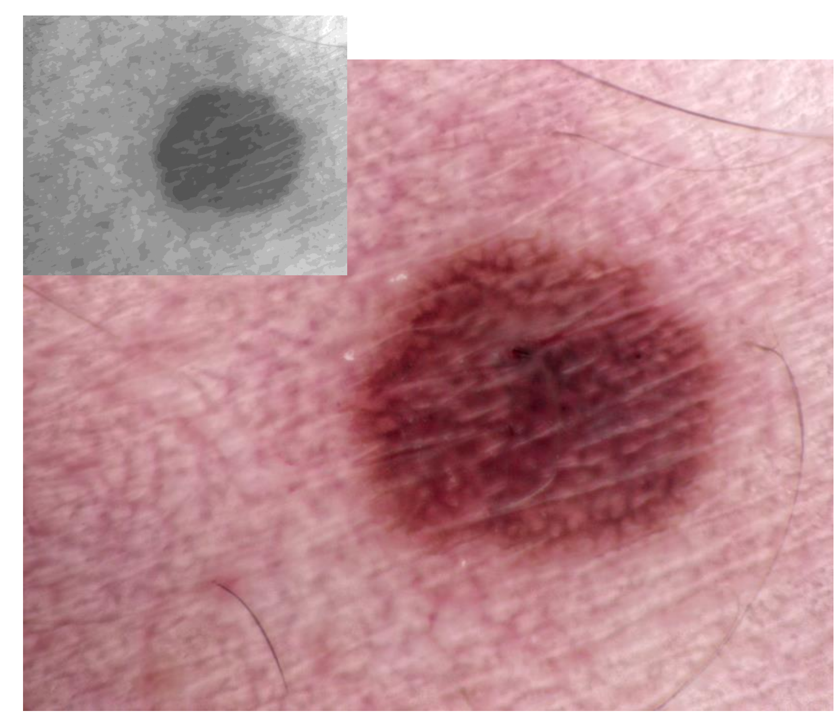
Output from
machine vision camera's API



Consumer camera
output

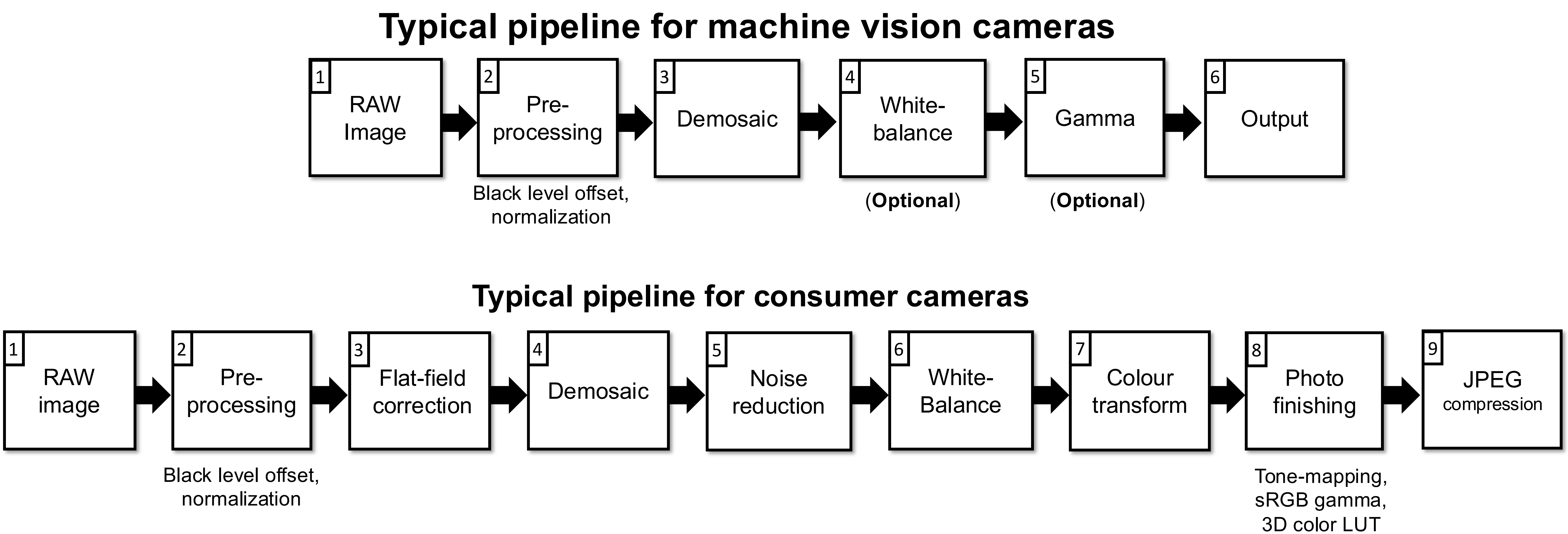


Enhanced RGB image
using a spectral band



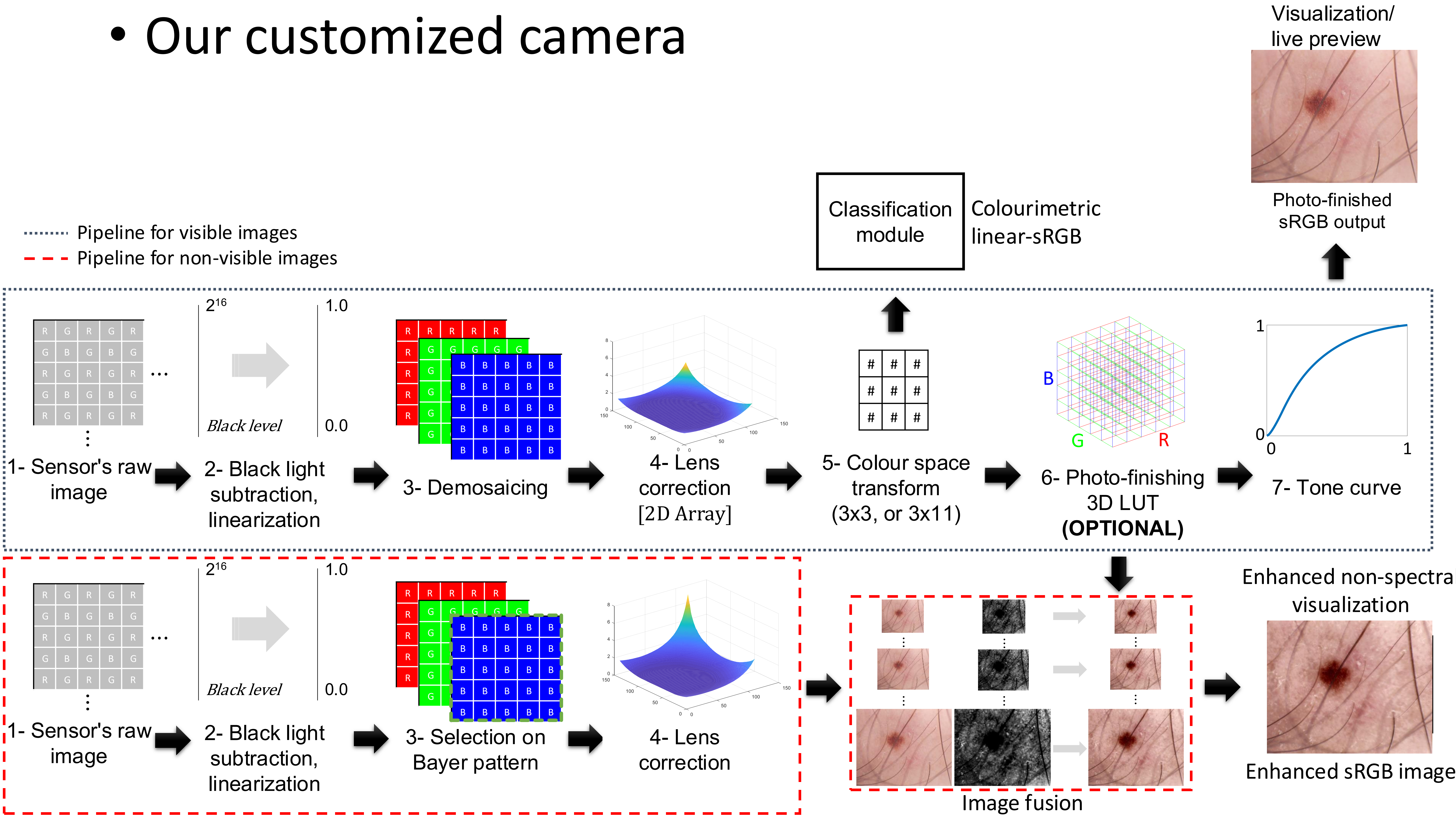
Machine Vision vs. Consumer Camera Pipelines

- Why does a machine vision camera's image appear different from consumer camera?



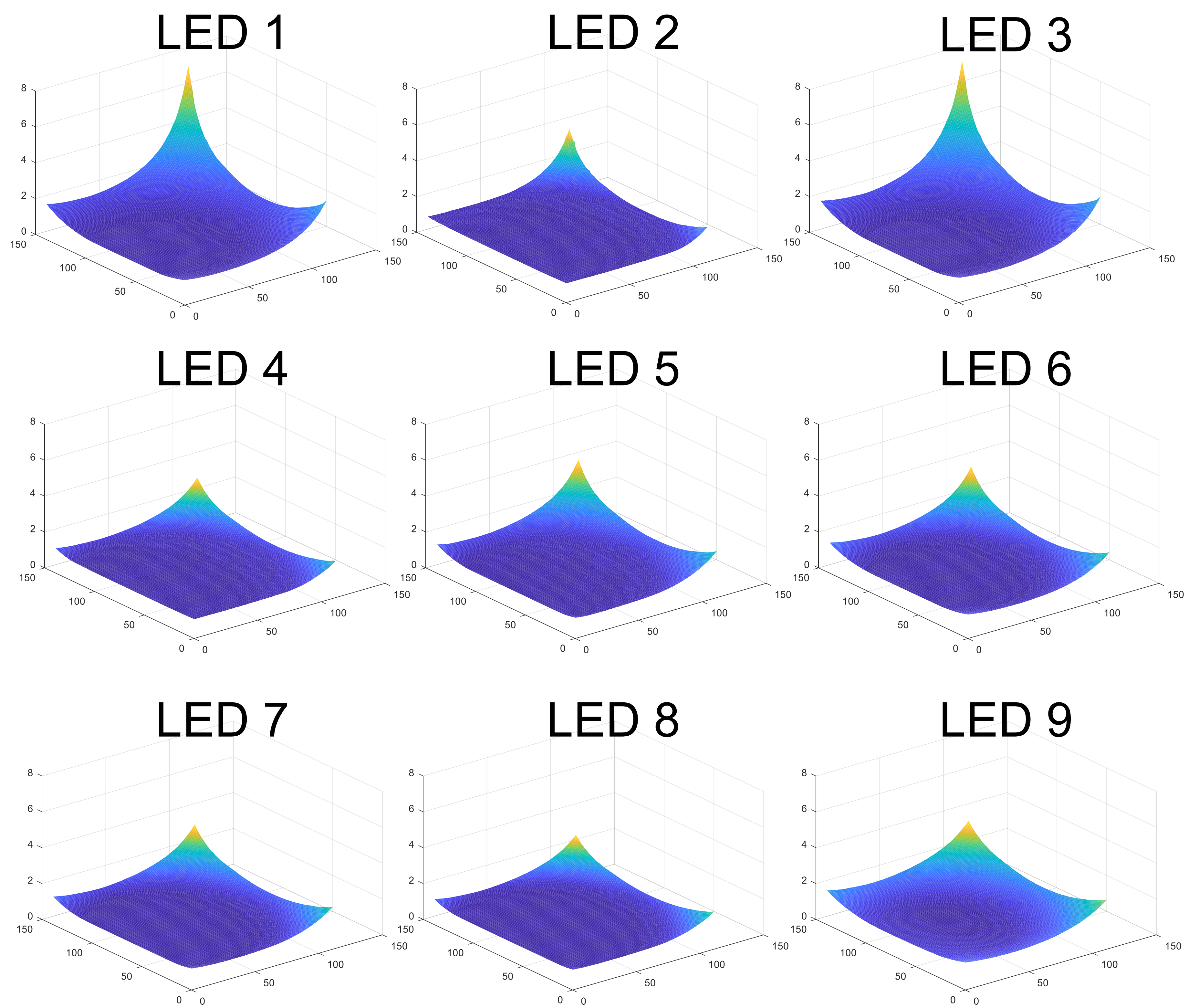
Customized imaging pipeline

- Our customized camera



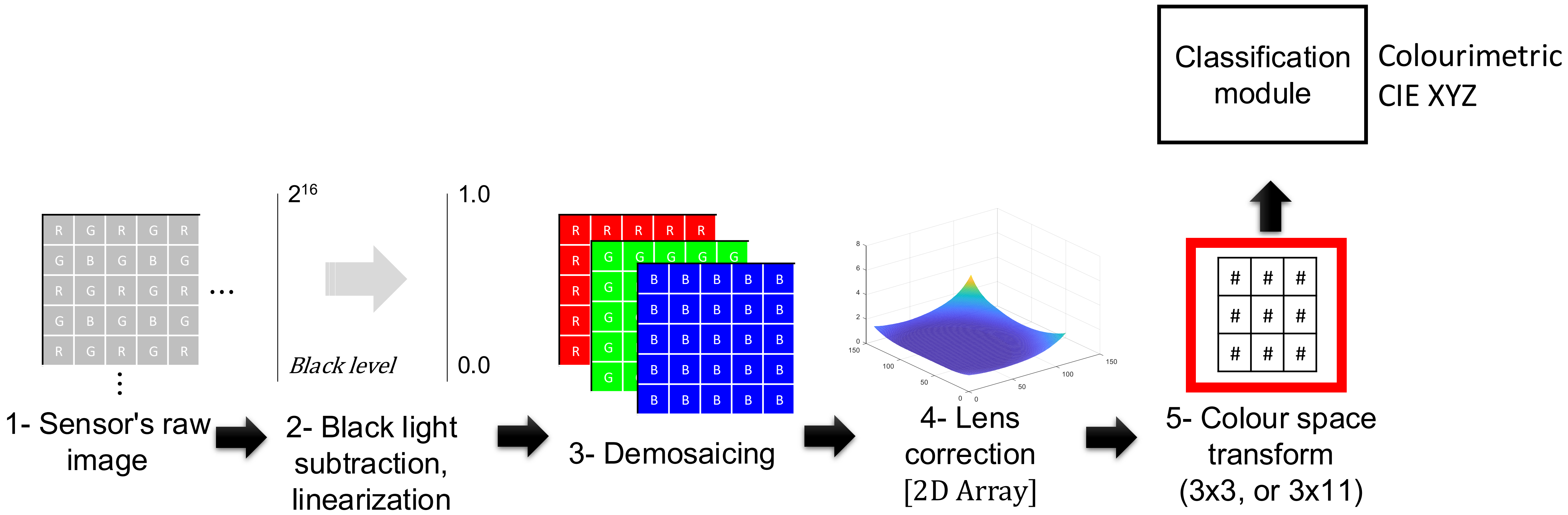
LED flat-field correction

- A flat-field correction for each LED



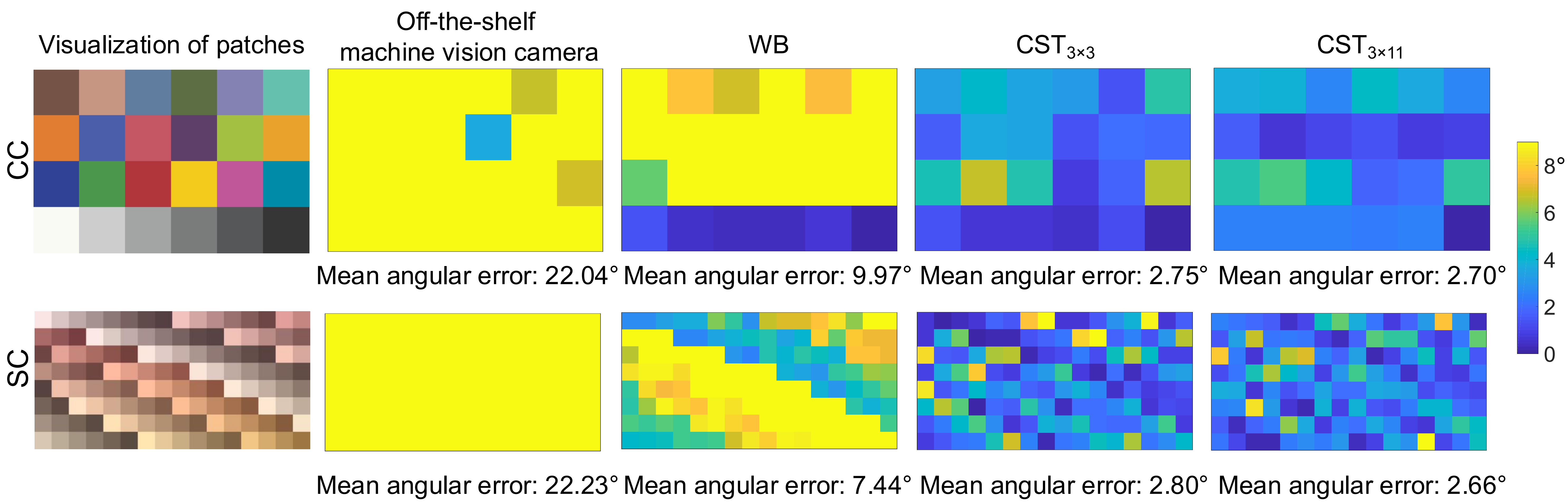
In-camera processing pipeline

- Sensor needs to be colourimetrically calibrated
- Colour space transform (CST) to map raw-RGB values to the CIE XYZ colour space



In-camera processing pipeline

- Errors with and without sensor calibration



CC: Macbeth Color Checker Chart
SC: Skin colours from *the Munsell Book of Color*

Photo-finishing

- Photo-finishing to make the images look *visually-pleasing*

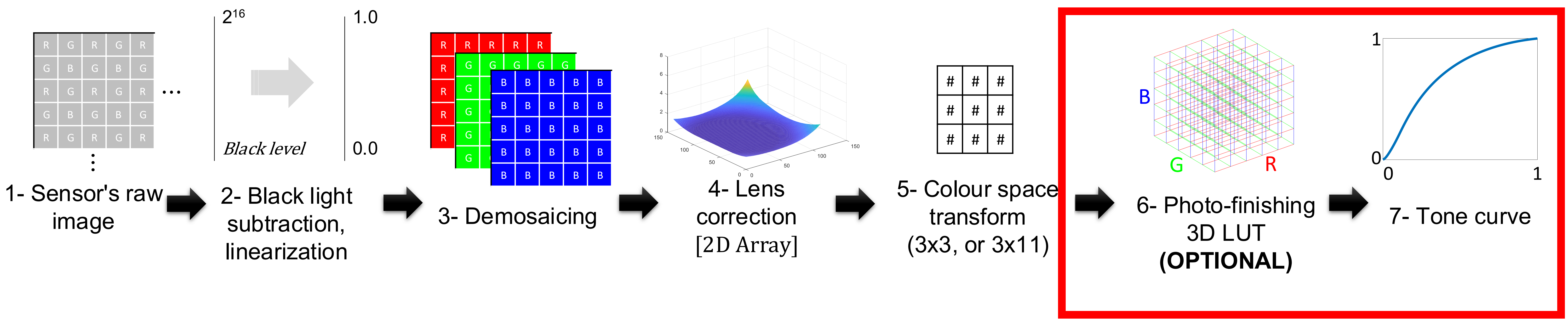
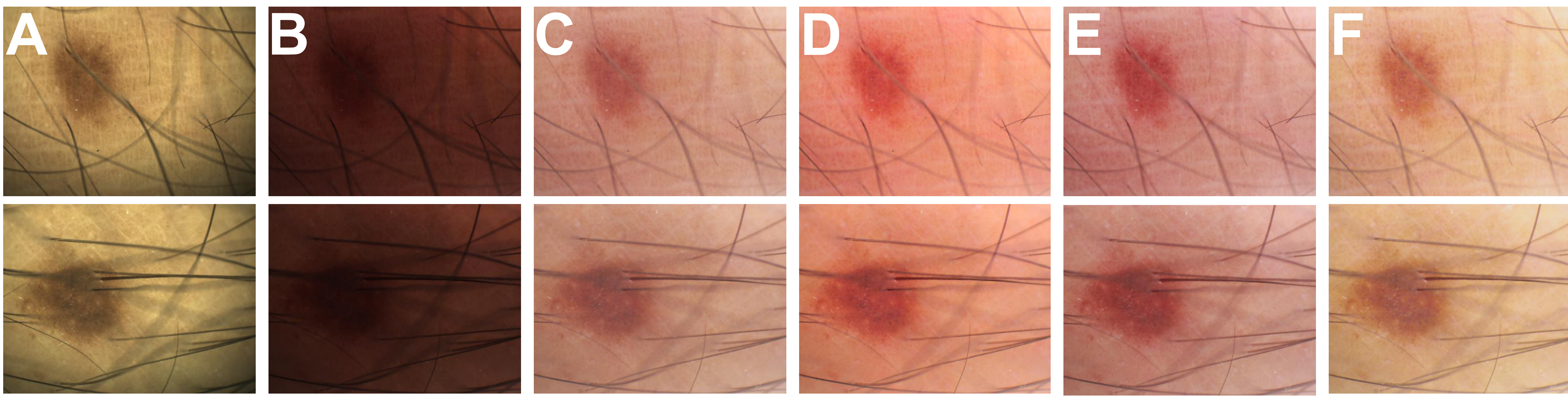


Photo-finishing

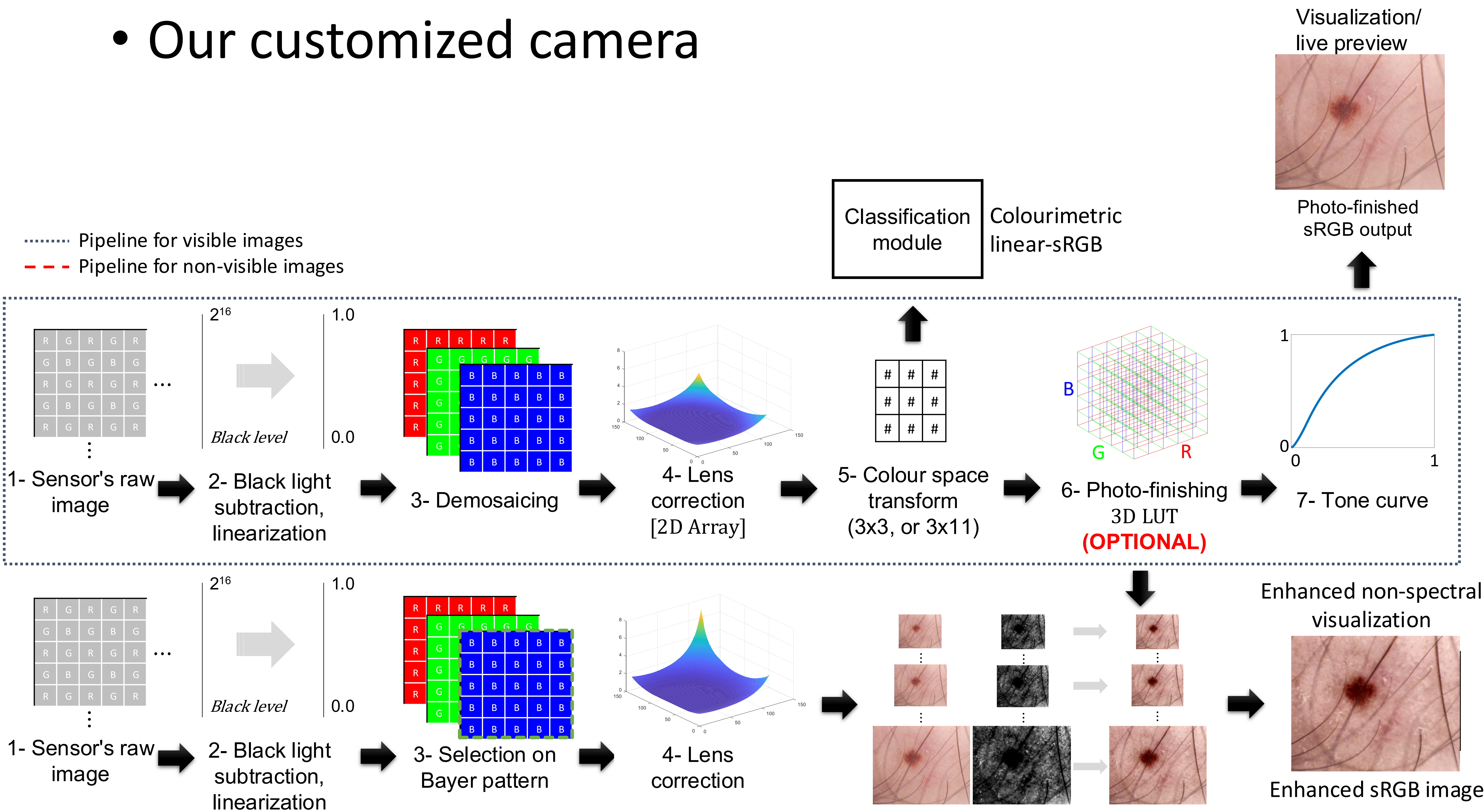
- Photo-finishing to make the images look *visually-pleasing*
- We can mimic different consumer cameras



Raw-RGB + gamma | Linear-sRGB | (B) Photo finished w/ **Adobe** tone-curve | (B) Photo finished w/ **Nikon's** Vivid mode | (B) Photo finished w/ **Canon's** Portrait mode | (B) Photo finished w/ **Olympus's** Natural mode

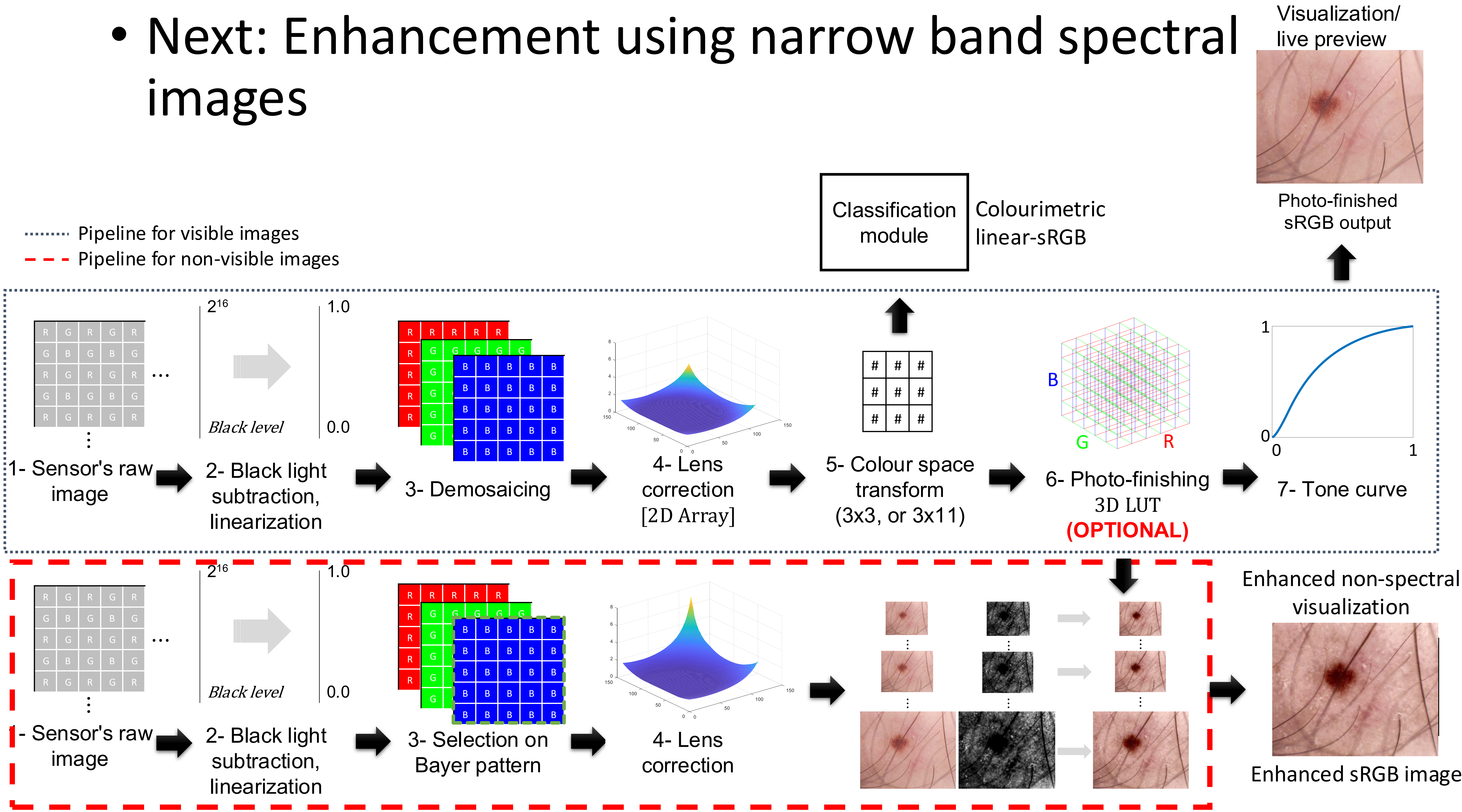
Non-visible spectral images

- Our customized camera



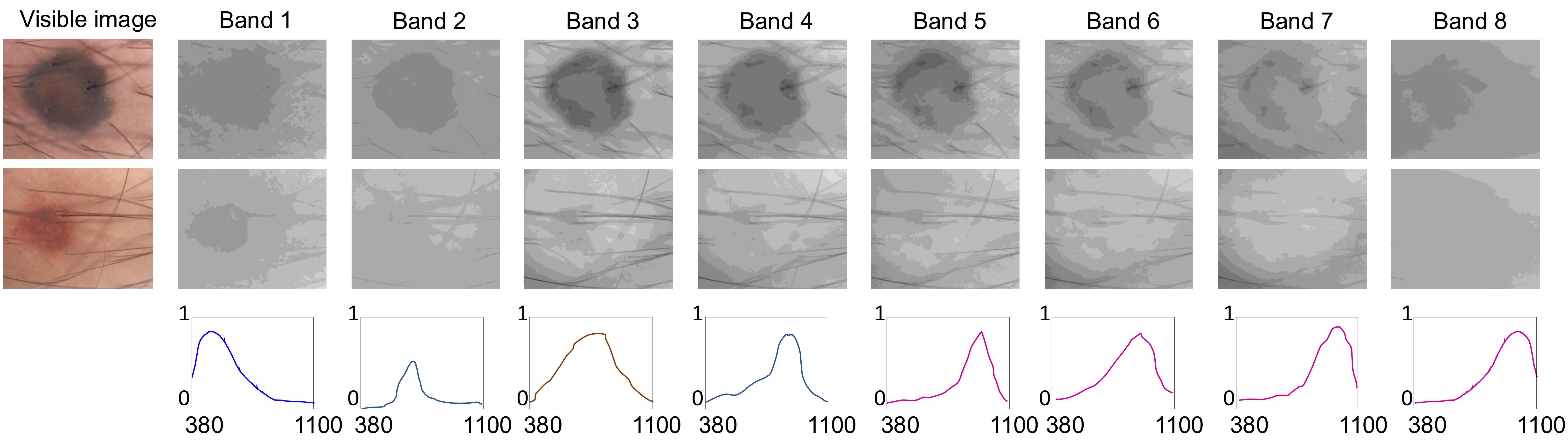
Non-visible spectral images

- Next: Enhancement using narrow band spectral images



Non-visible spectral images

- Narrow band spectral images



Spectral data fusion

- Three methods:
  - Modified bilateral filtering (Fredembach et al., 2009)
  - Modified local Laplacian filter (Aubry, Paris, Hasinoff, Kautz, & Durand, 2014)
  - Wavelet-based fusion

More details in the dissertation!

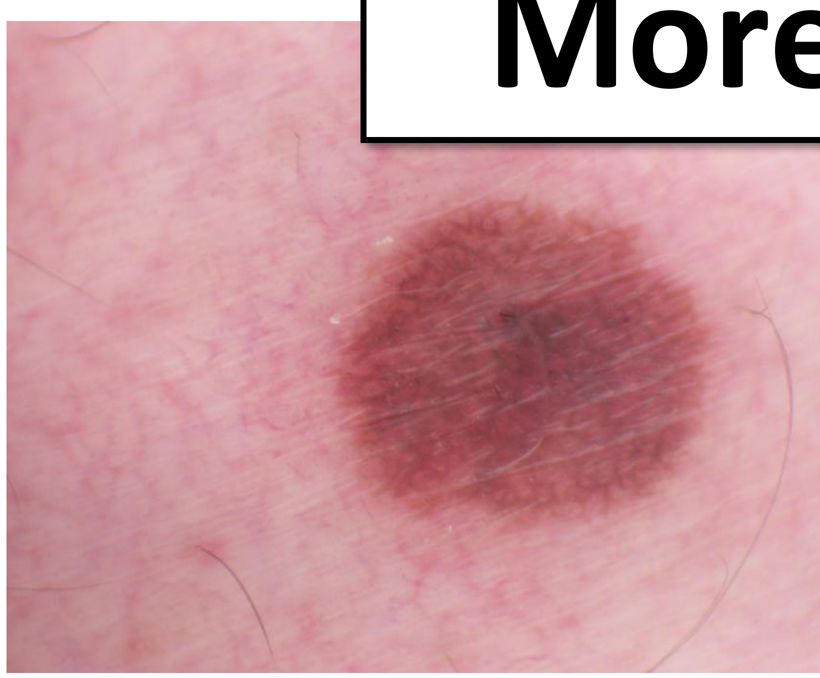
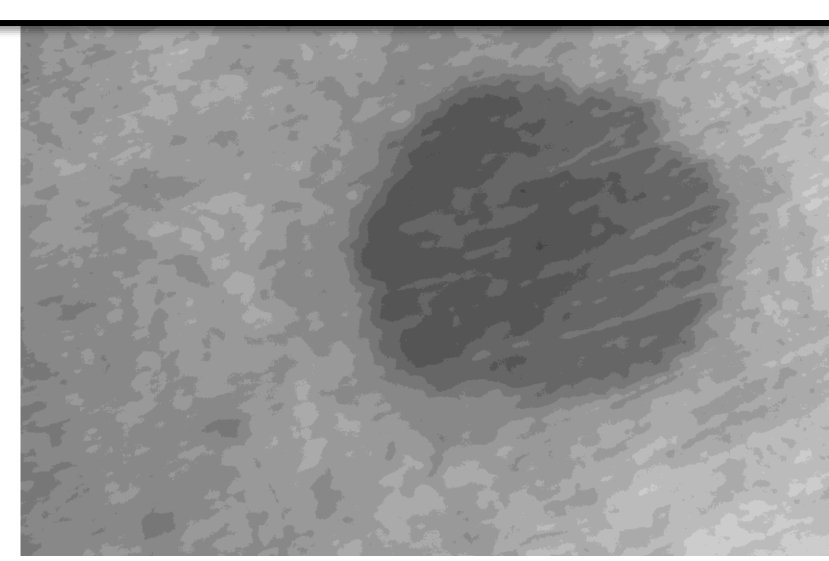


Photo-finished image

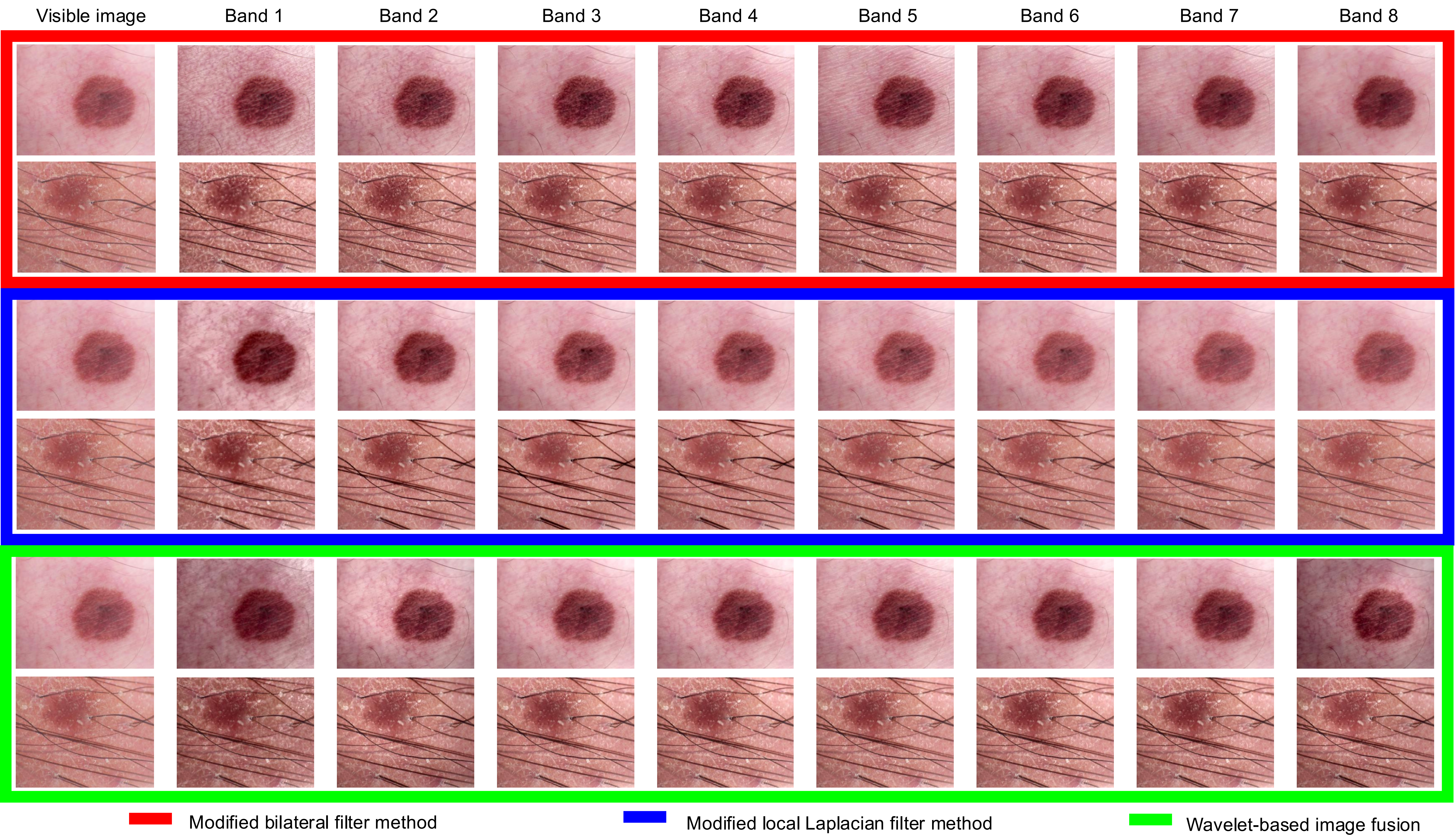


A narrow band spectral image

The result of the fusion

Fredembach, C., Barbuscia, N., & Susstrunk, S. (2009). Combining Visible and Near-Infrared Images for Realistic Skin Smoothing. In Color and Imaging Conference.
Aubry, M., Paris, S., Hasinoff, S. W., Kautz, J., & Durand, F. (2014). Fast Local Laplacian Filters: Theory and Applications. In SIGGRAPH.

Examples of data fusion



Feedback from clinicians

- Is there a preference between the methods and the different spectral bands?

  - Among the three methods used to perform spectral image fusion, do you have a preferred method?

  - Is there a particular spectral image that you feel provides the most information?

  - Do you feel this type of fusion is useful for you in a clinical setting (i.e., would it help you make a more informed decision)?

Clinician feedback

- The most preferred:
  - Wavelet-based method
  - Spectral band 8 (NIR - 1100 nm)
- Comments from our participants include:

  "Yes, I think that the fusion is very helpful"

  "I could see the pattern of each lesion much better (reticular, dots, borders)."
- A dermatologist who was neutral commented:

  "Only in certain cases."

Still an area of active research.

Summary

- **Presented a customize camera pipeline for dermatological imaging**
  - Modified machine-vision camera
  - Based on understanding of consumer camera pipelines
  - Useful for the design of similar devices
- **Spectral data fusion**
  - Older methods shouldn’t be ruled out
  - Open problem, room for more research

Thesis Summary

- We examined colour rendering in the context of in-camera imaging pipeline
- Contributions:
  - Camera simulator to have access to the onboard imaging system
  - A consistent image state as an extra output at the colourimetric conversion stage
  - Two methods to improve colour reproduction accuracy in the camera imaging pipeline
  - Customization procedure for a constrained use case scenario