2019 DLC

April 1 - 3 • St. Louis, MO

STAKEHOLDER MEETING

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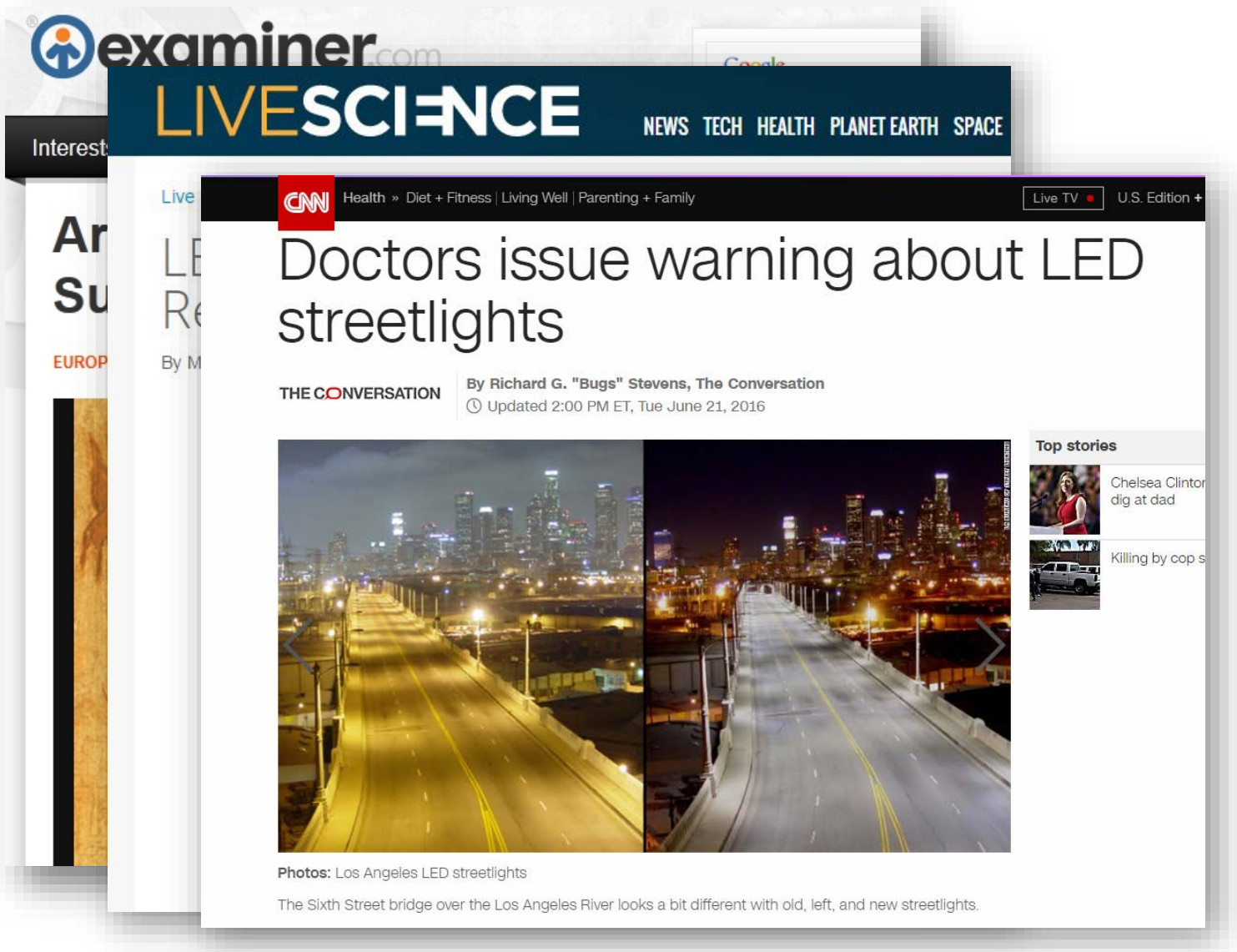
STAKEHOLDER MEETING

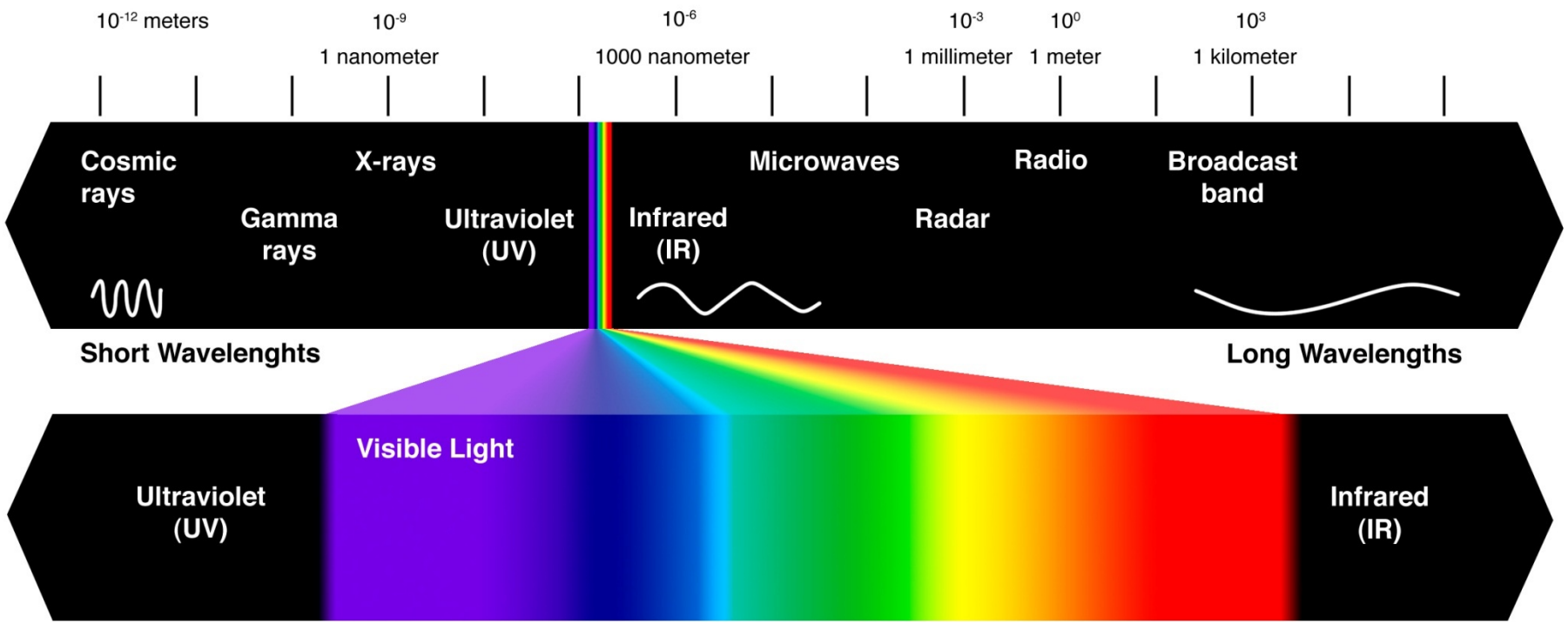
Spectral Power Distributions

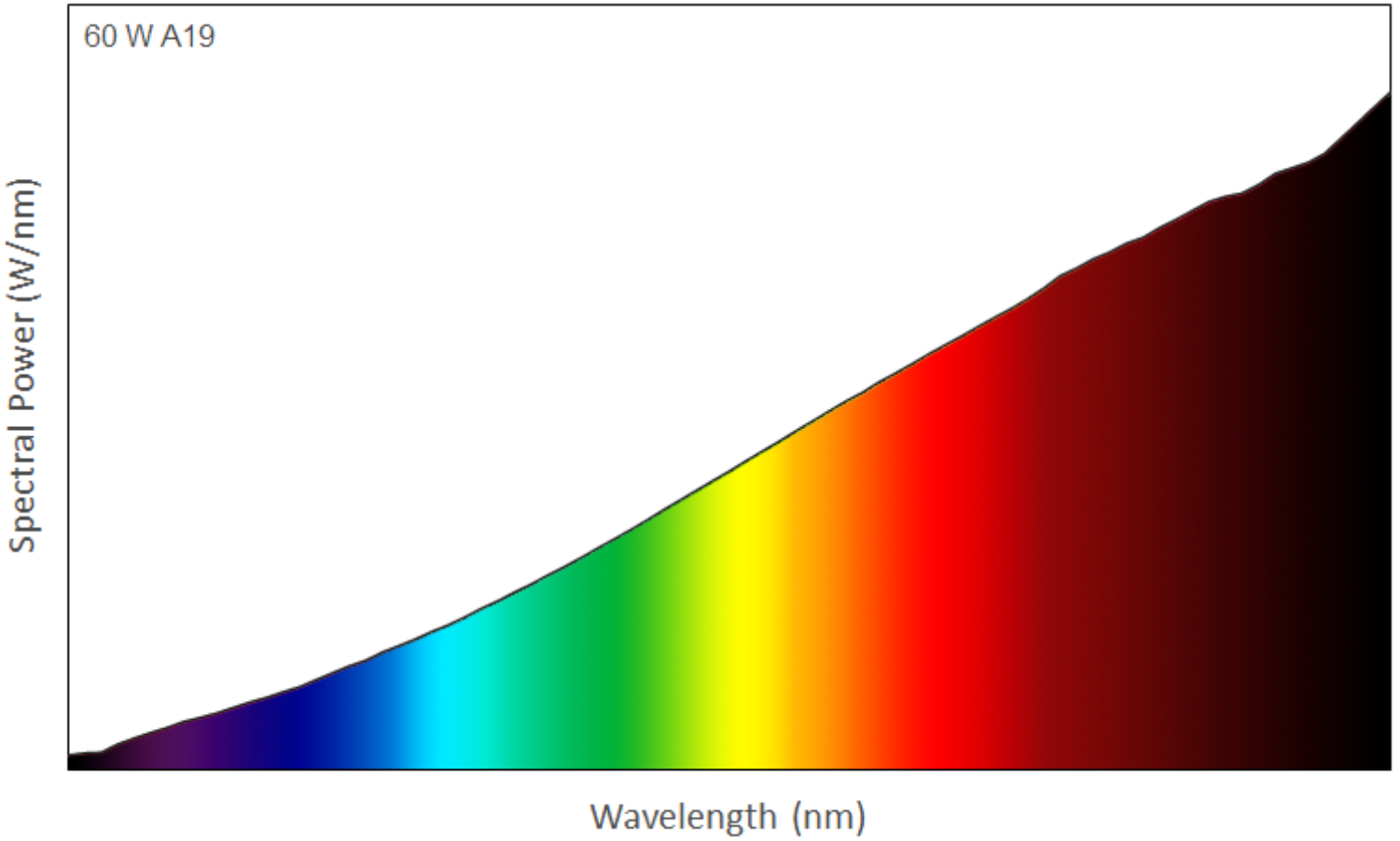
and their use in applied lighting

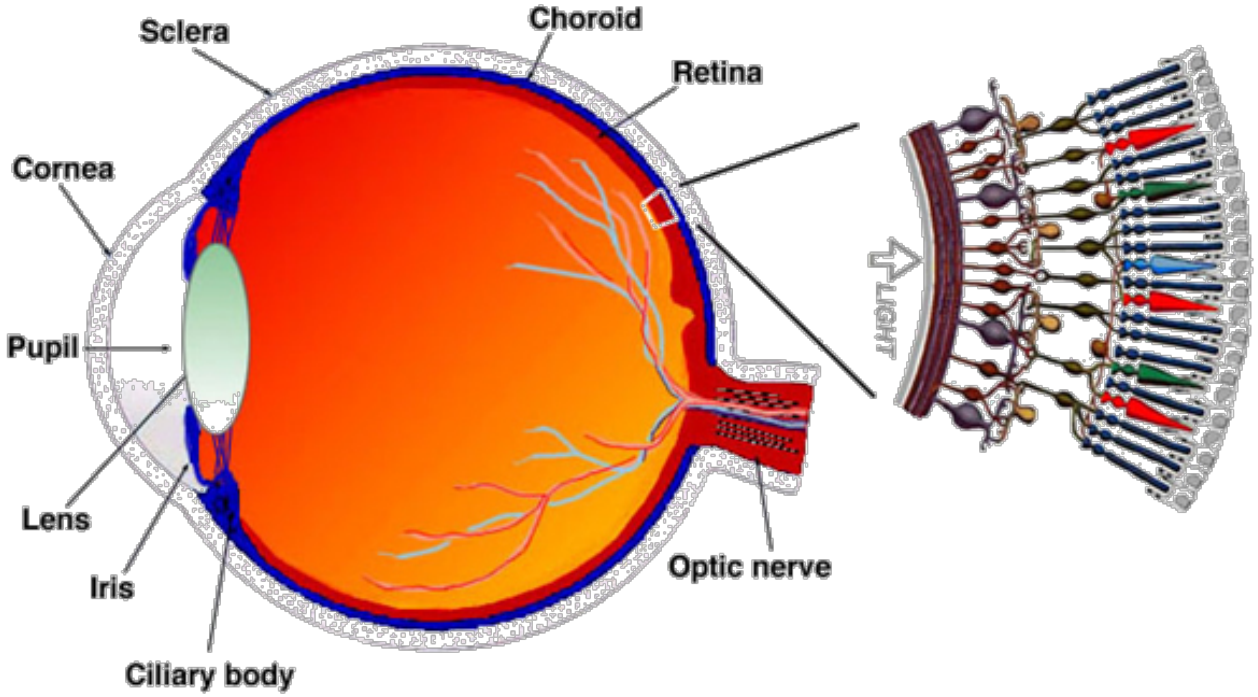
Michael Royer, PhD
Pacific Northwest National Laboratory

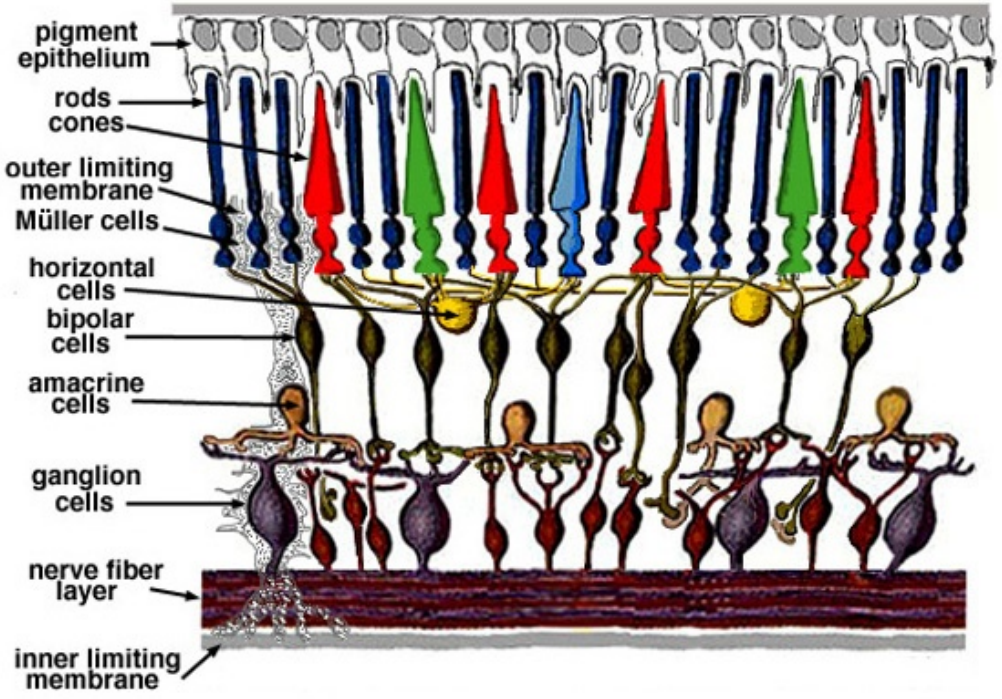


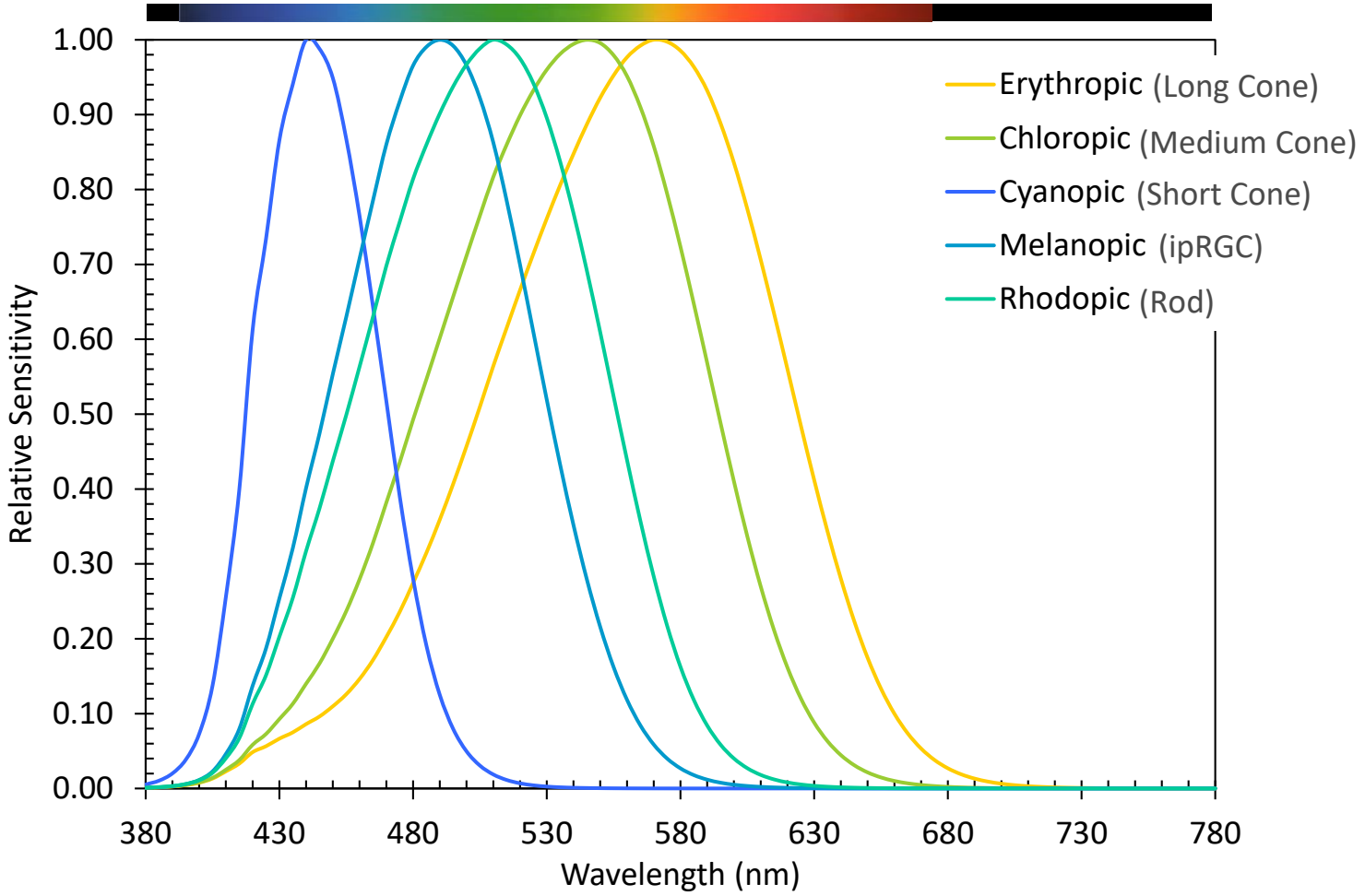
1. Basics of light and vision
2. Spectral data
   - Types of SPDs
   - Relative vs. Absolute SPDs
   - Data formats
3. SPD-based calculations
   - Lumens
   - CCT/D_{uv}/Chromaticity
   - Melanopic Flux/CS
4. Color rendition


10^{-12} meters
10^{-9}
1 nanometer
10^{-6}
1000 nanometer
10^{-3}
1 millimeter
10^{0}
1 meter
10^{3}
1 kilometer
Cosmic rays
Gamma rays
X-rays
Ultraviolet (UV)
Infrared (IR)
Microwaves
Radar
Radio
Broadcast band
Short Wavelenghts
Long Wavelengths
Ultraviolet (UV)
Visible Light
Infrared (IR)


60 W A19
Spectral Power (W/nm)
Wavelength (nm)

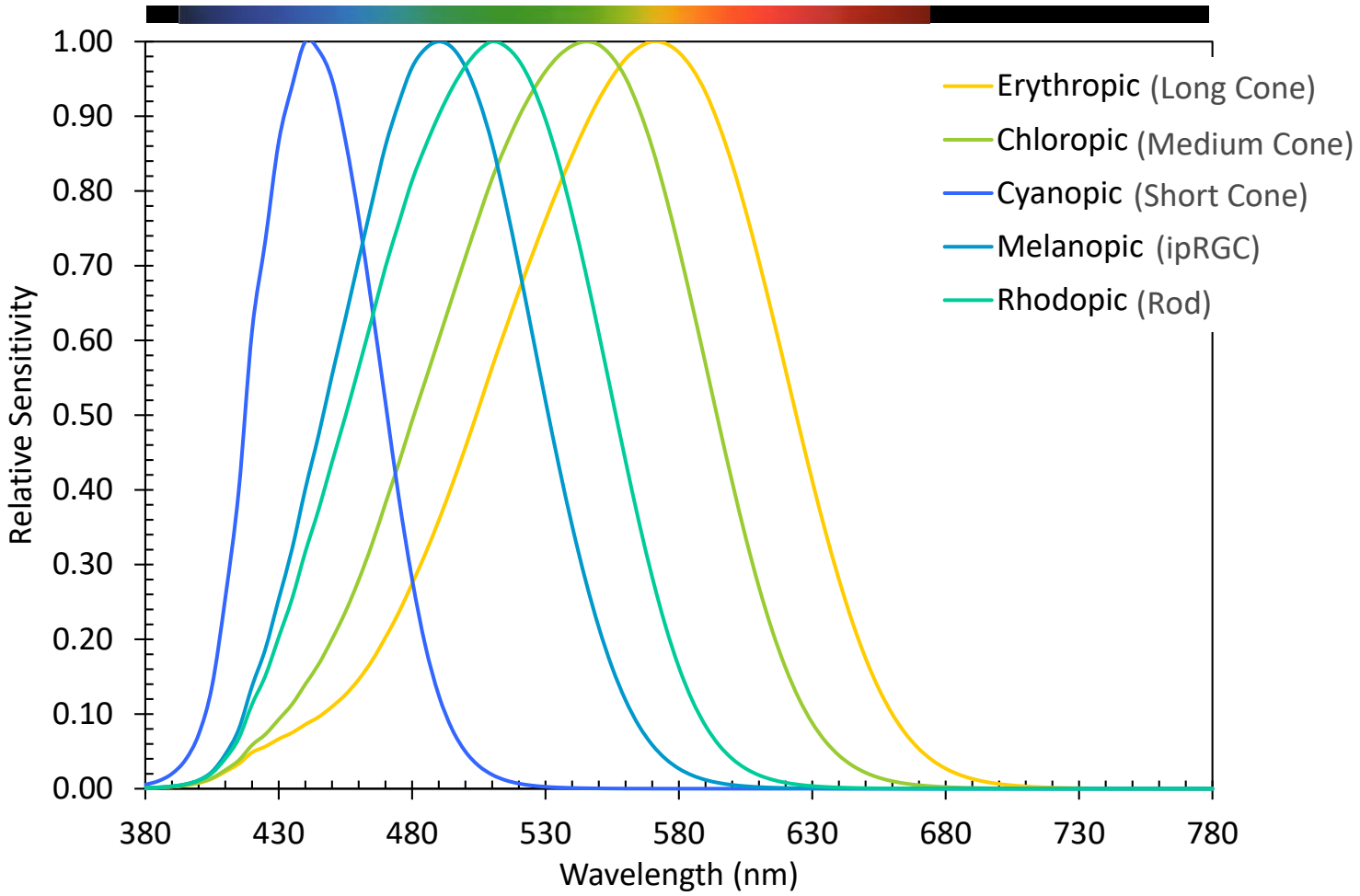

Sclera
Choroid
Retina
Cornea
Pupil
Lens
Iris
Ciliary body
Optic nerve
LIGHT

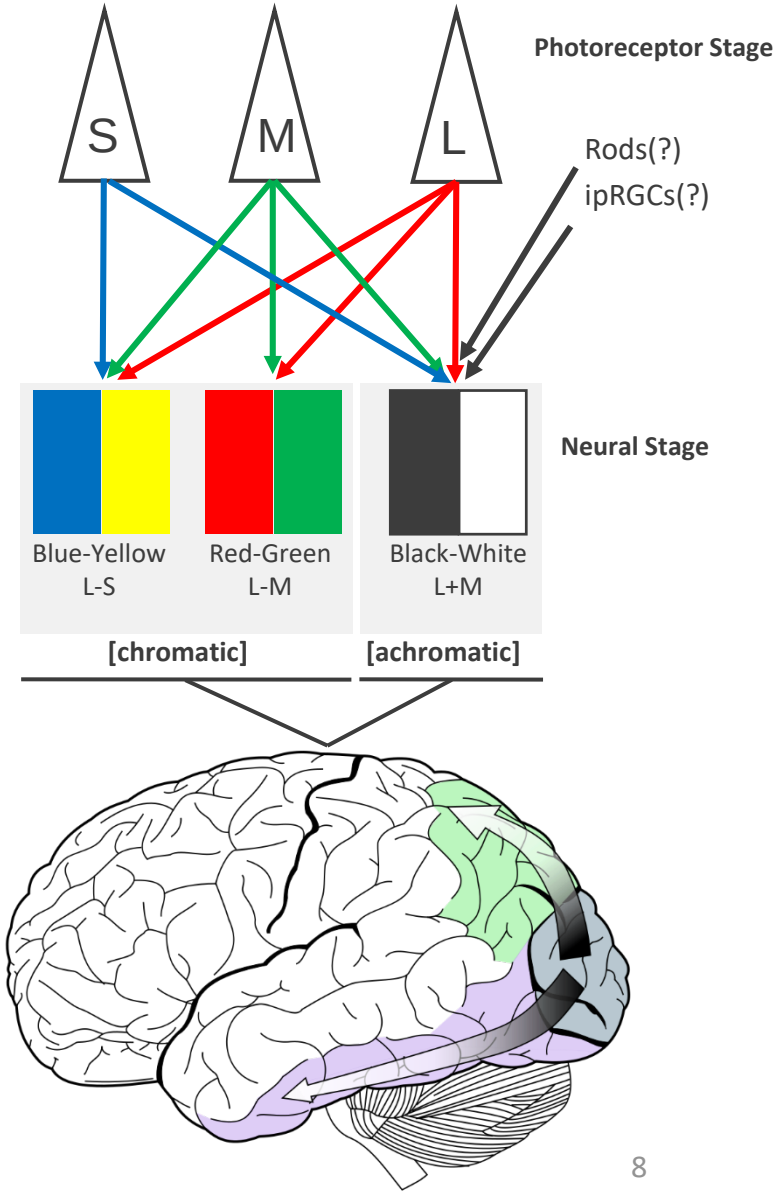

pigment epithelium
rods
cones
outer limiting membrane
Müller cells
horizontal cells
bipolar cells
amacrine cells
ganglion cells
nerve fiber layer
inner limiting membrane



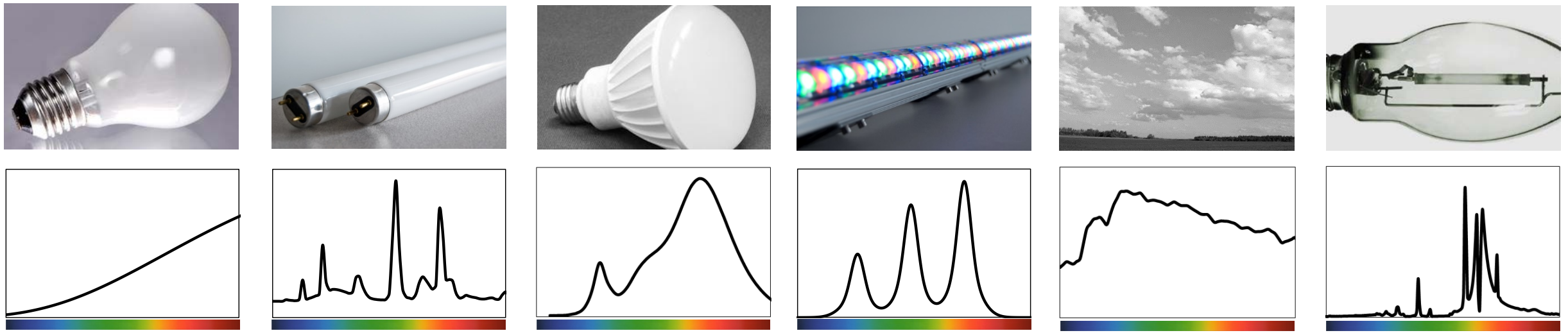
Univariance

No single photoreceptor can detect wavelengths.


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Relative Sensitivity
380
430
480
530
580
630
680
730
780
Wavelength (nm)
Erythropic (Long Cone)
Chloropic (Medium Cone)
Cyanopic (Short Cone)
Melanopic (ipRGC)
Rhodopic (Rod)


Photoreceptor Stage
S
M
L
Rods(?)
ipRGCs(?)
Neural Stage
Blue-Yellow
L-S
Red-Green
L-M
Black-White
L+M
[chromatic]
[achromatic]

2. Light Source SPDs



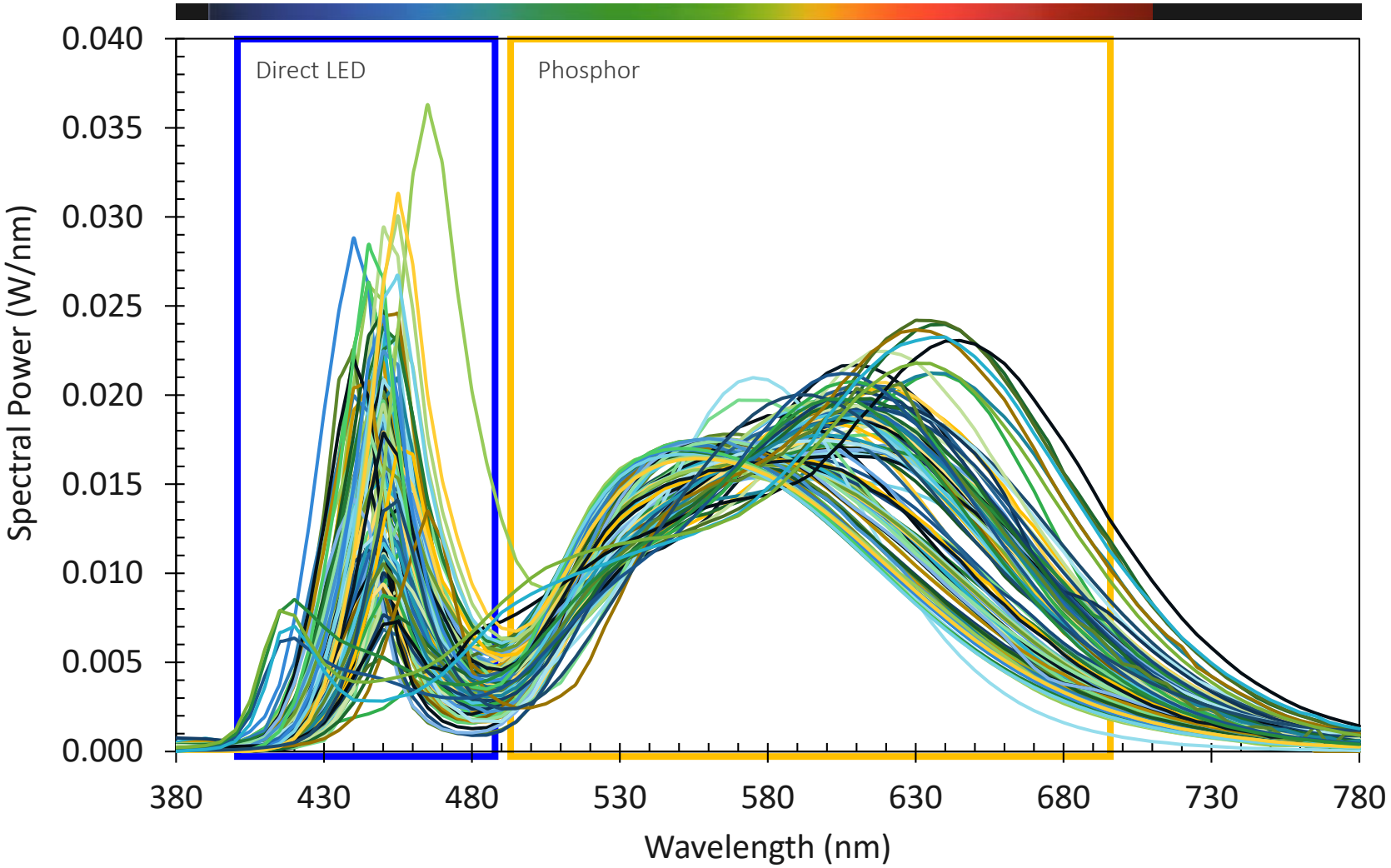
Metamerism

Light with different SPDs can appear the same

Chromatic Adaptation

Independent control of color signals in eye/brain

Note: Light sources technologies are not homogenous!

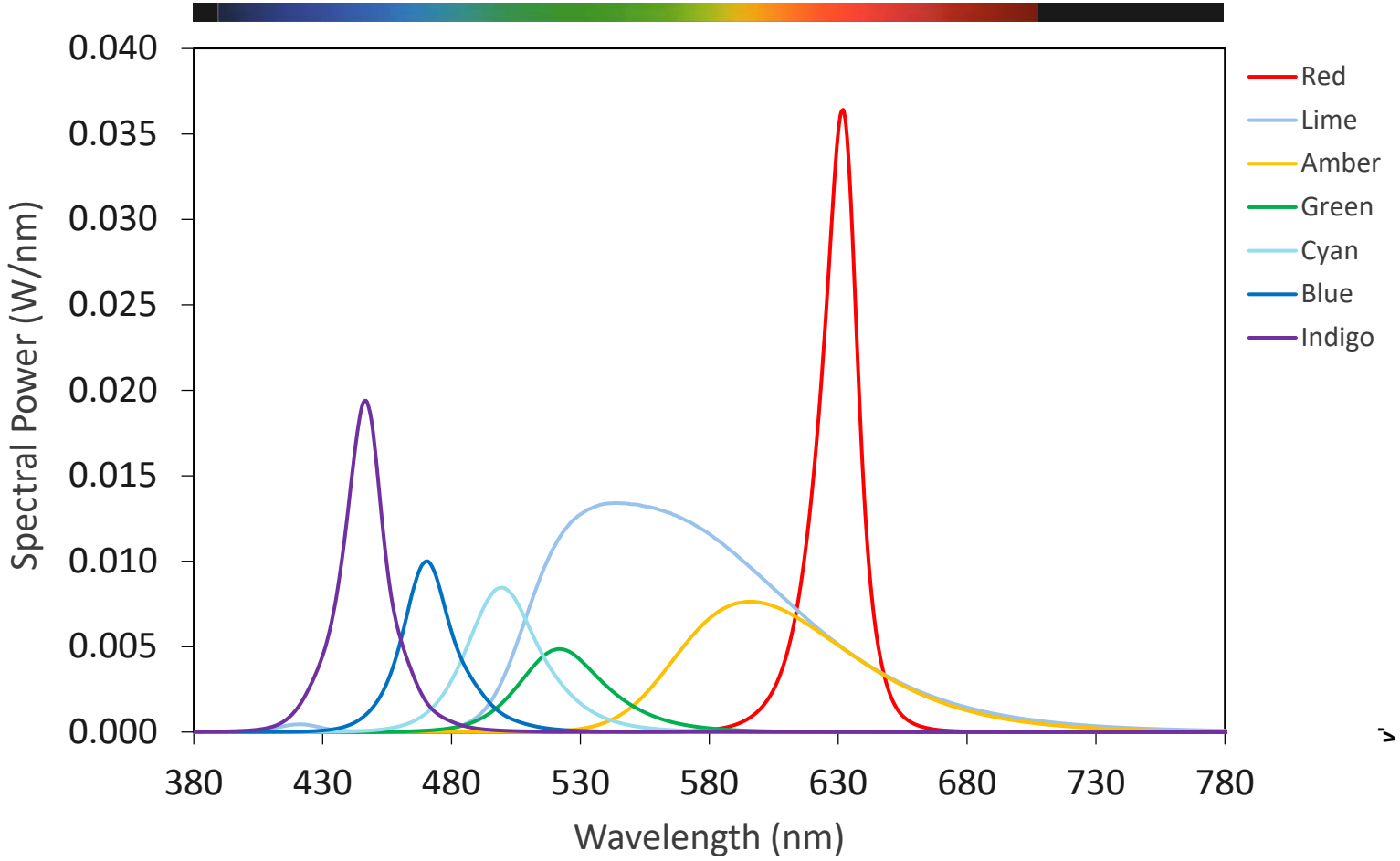


White Light from LEDs

Phosphor Converted (PC)

Color Mixed (CM)

Hybrid (HY)



White Light from LEDs

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Color Mixed (CM)

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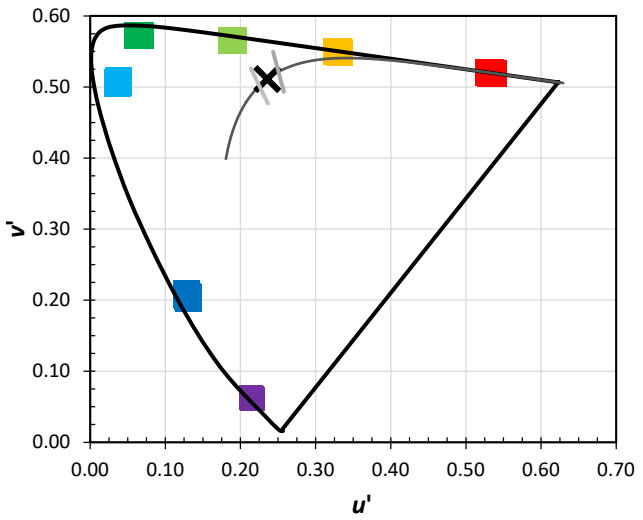
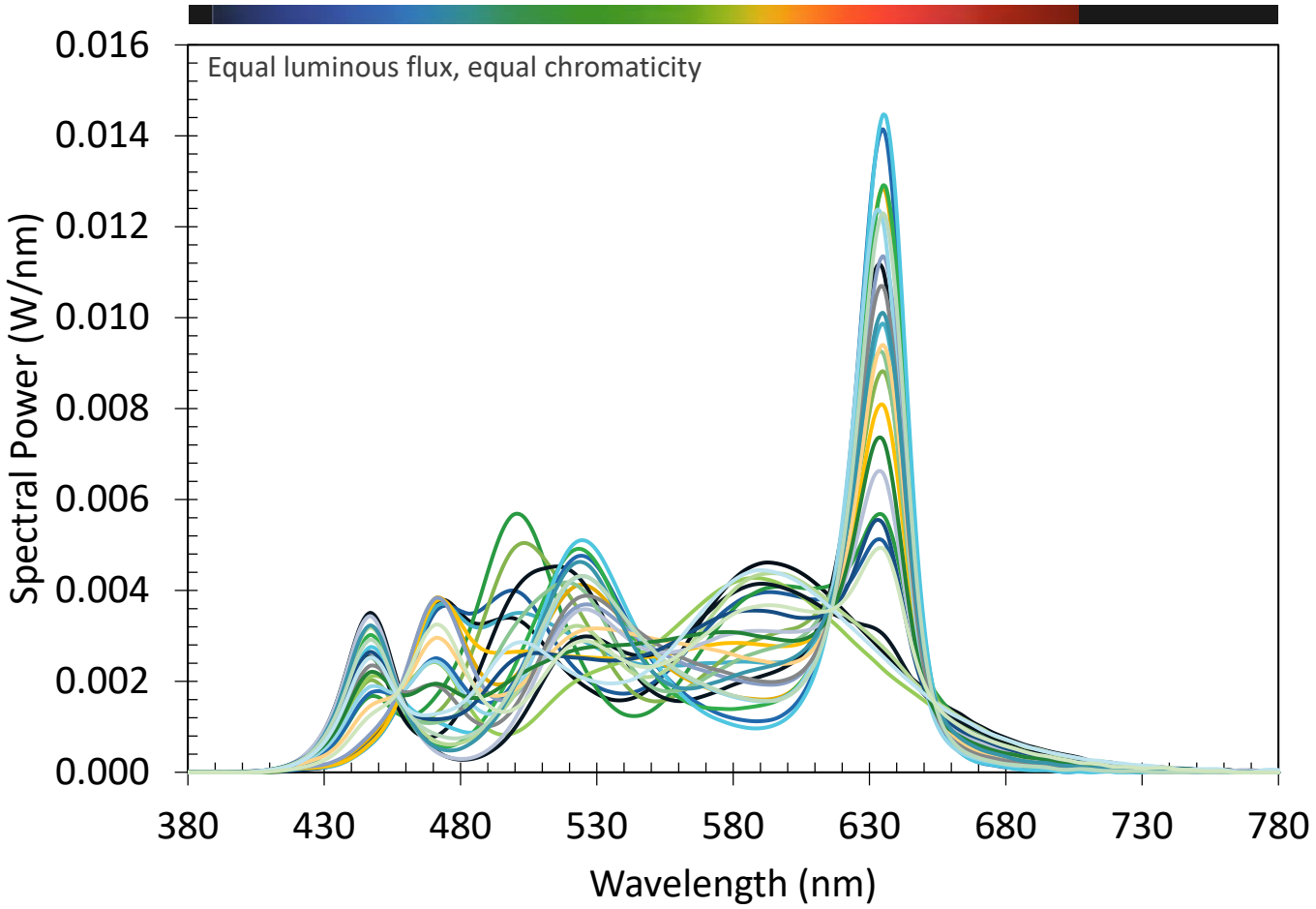




White Light from LEDs

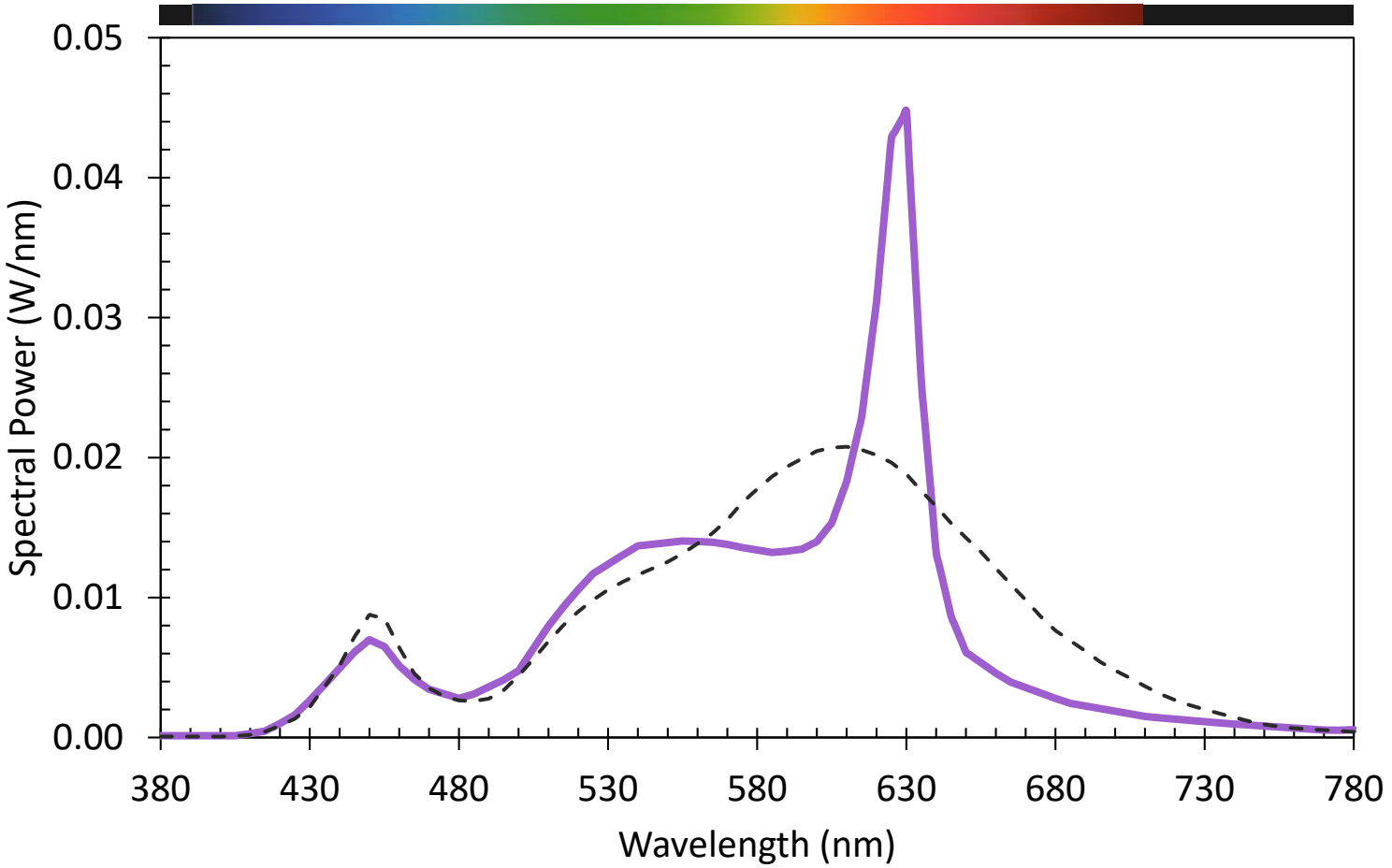
Phosphor Converted (PC)

Color Mixed (CM)

Hybrid (HY)

Metamerism

Light with different SPDs can appear the same

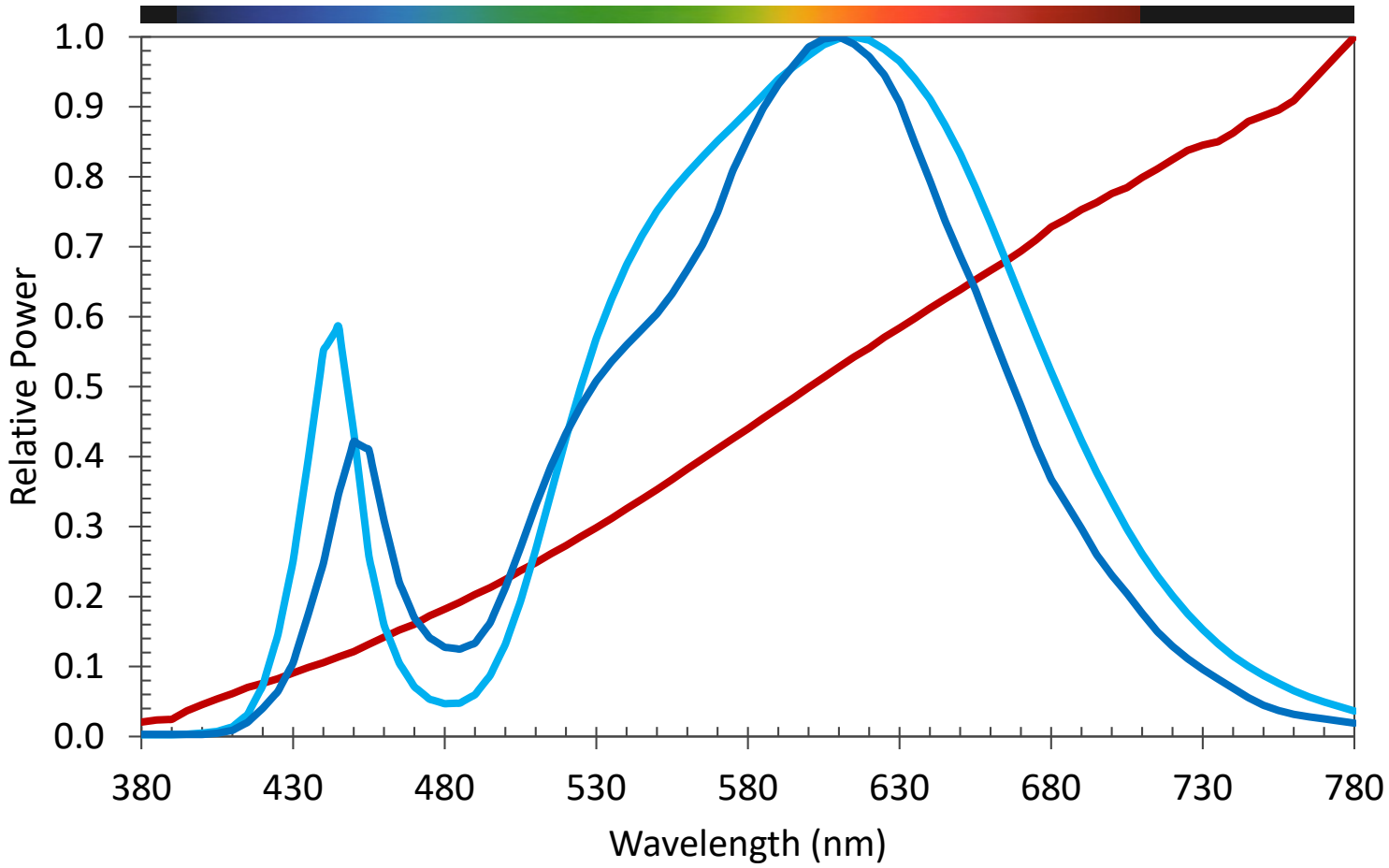


White Light from LEDs

Phosphor Converted (PC)

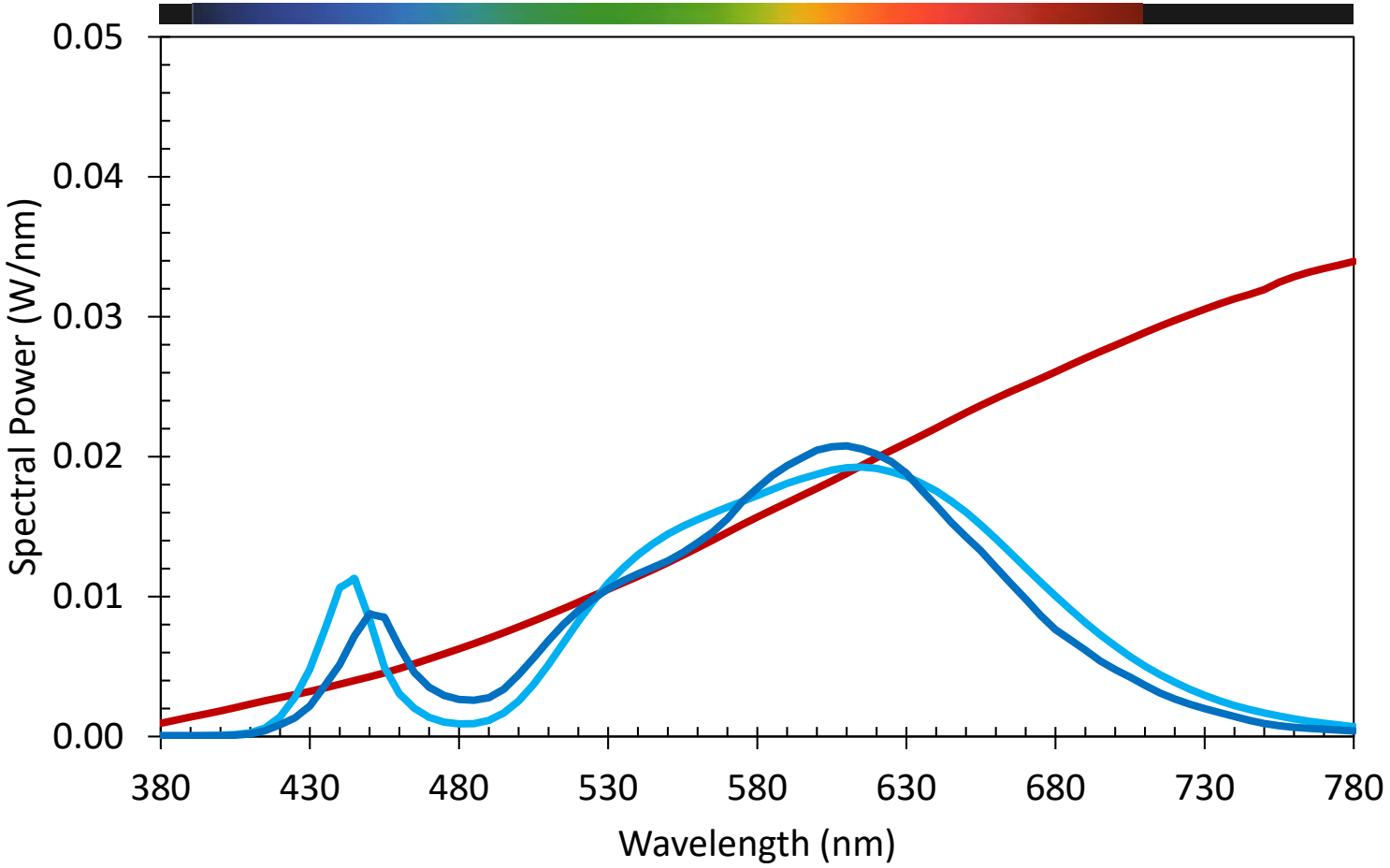
Color Mixed (CM)

Hybrid (HY)



Relative SPDs

- Can be visually misleading
- Can be used to calculate CCT, D_{uv}, chromaticity, color rendering
- Cannot be used to calculate luminous flux, melanopic flux, CS, damage, retinal hazard, PPF



Absolute SPDs

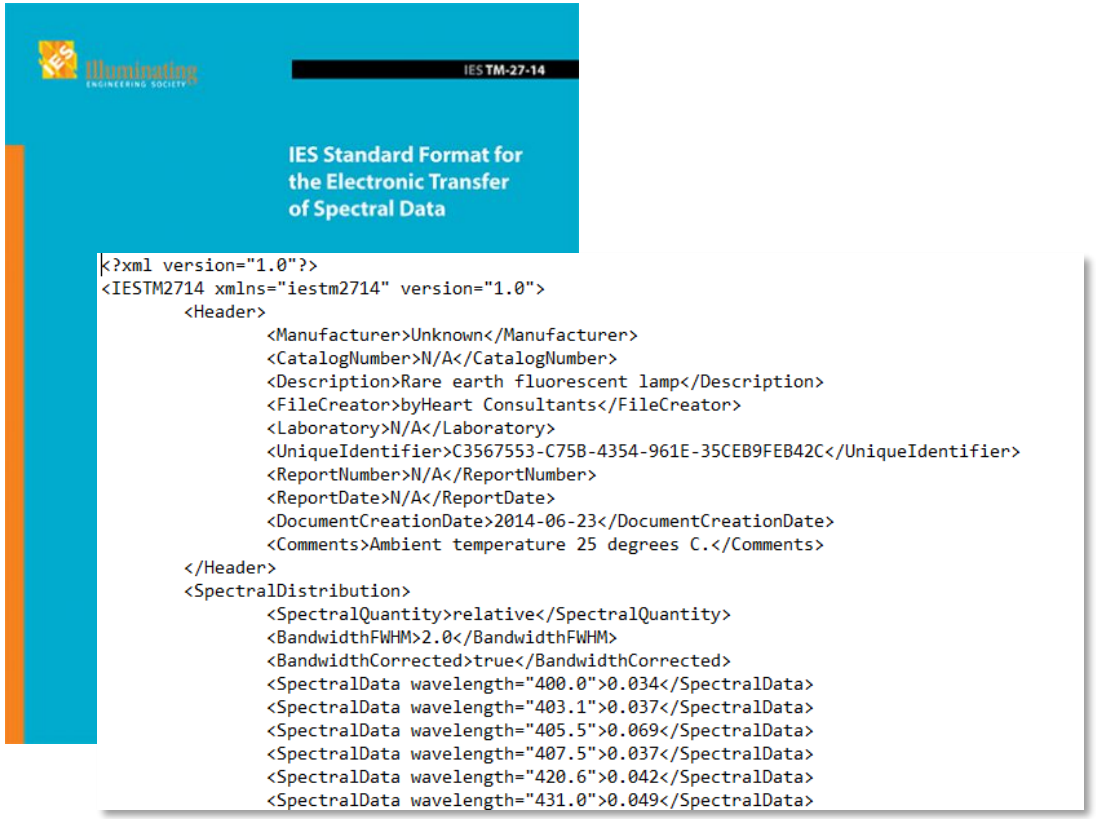
- Better for visual comparison
- Can be normalized to equal flux (luminous, melanopic, photosynthetic)
- Can represent emitted light or light reaching a surface/point

SPD Data Transfer

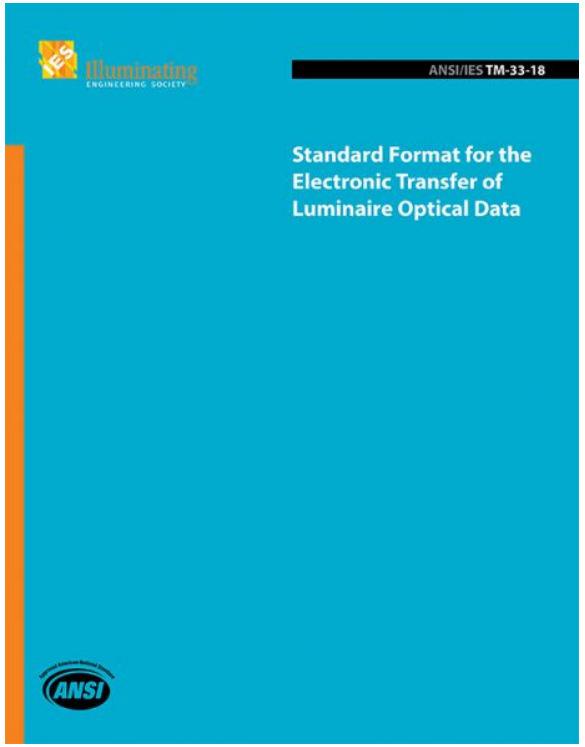
Spreadsheet
(e.g., *.xlsx)

380	0.00903
381	0.00939
382	0.00976
383	0.01014
384	0.01054
385	0.01094
386	0.01136
387	0.01180
388	0.01225
389	0.01271
390	0.01318
391	0.01368
392	0.01418
393	0.01471
394	0.01525
395	0.01581
396	0.01639
397	0.01700
398	0.01762
399	0.01826
400	0.01893
401	0.01963
402	0.02035
403	0.02110

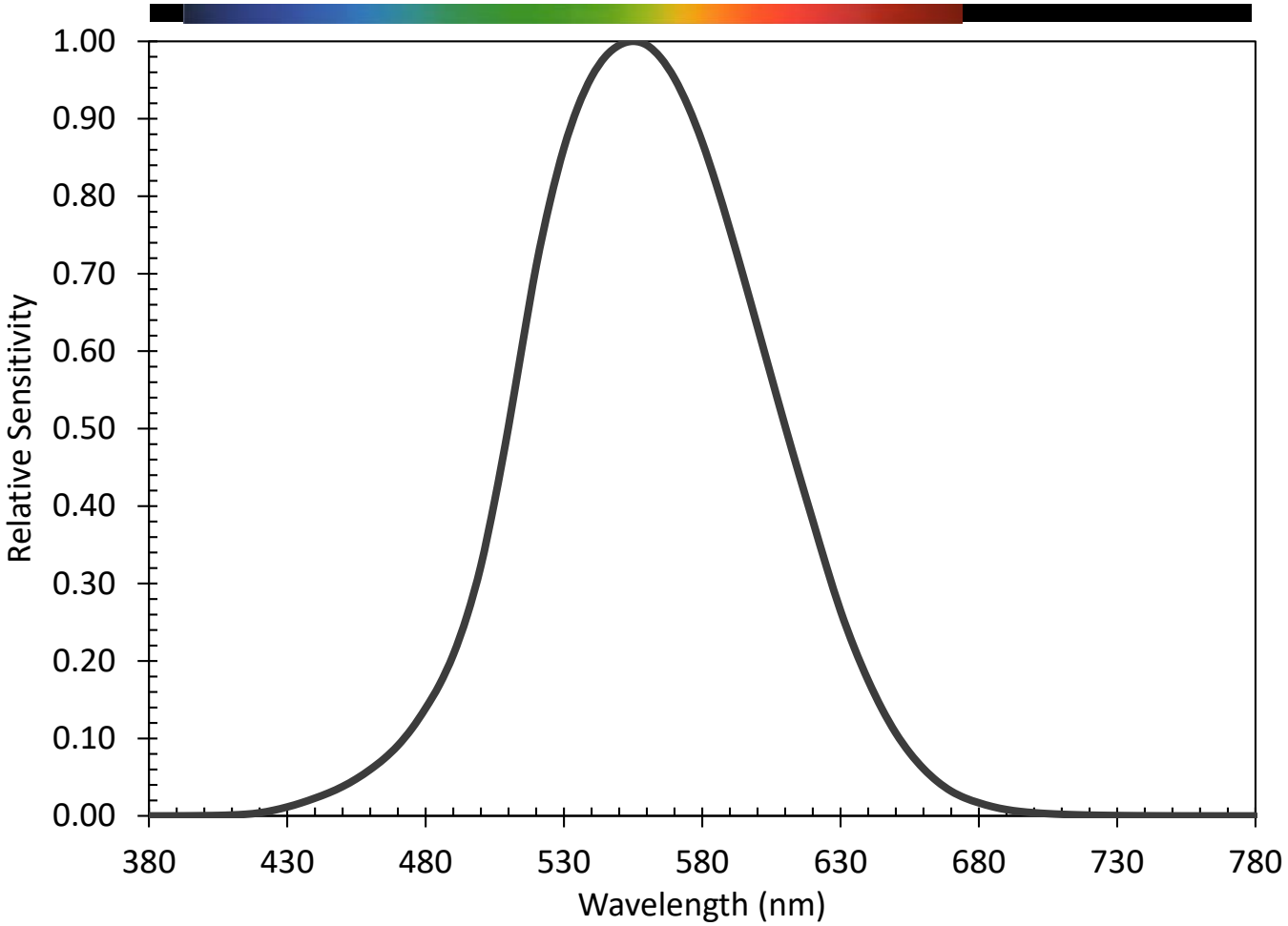
IES TM-27-14 (*.spdx)
(XML)



IES TM-33-18 (*.ies)
(XML)



3. SPD-based Calculations



$$\Phi = 683 * \int P_\lambda V_\lambda d\lambda$$

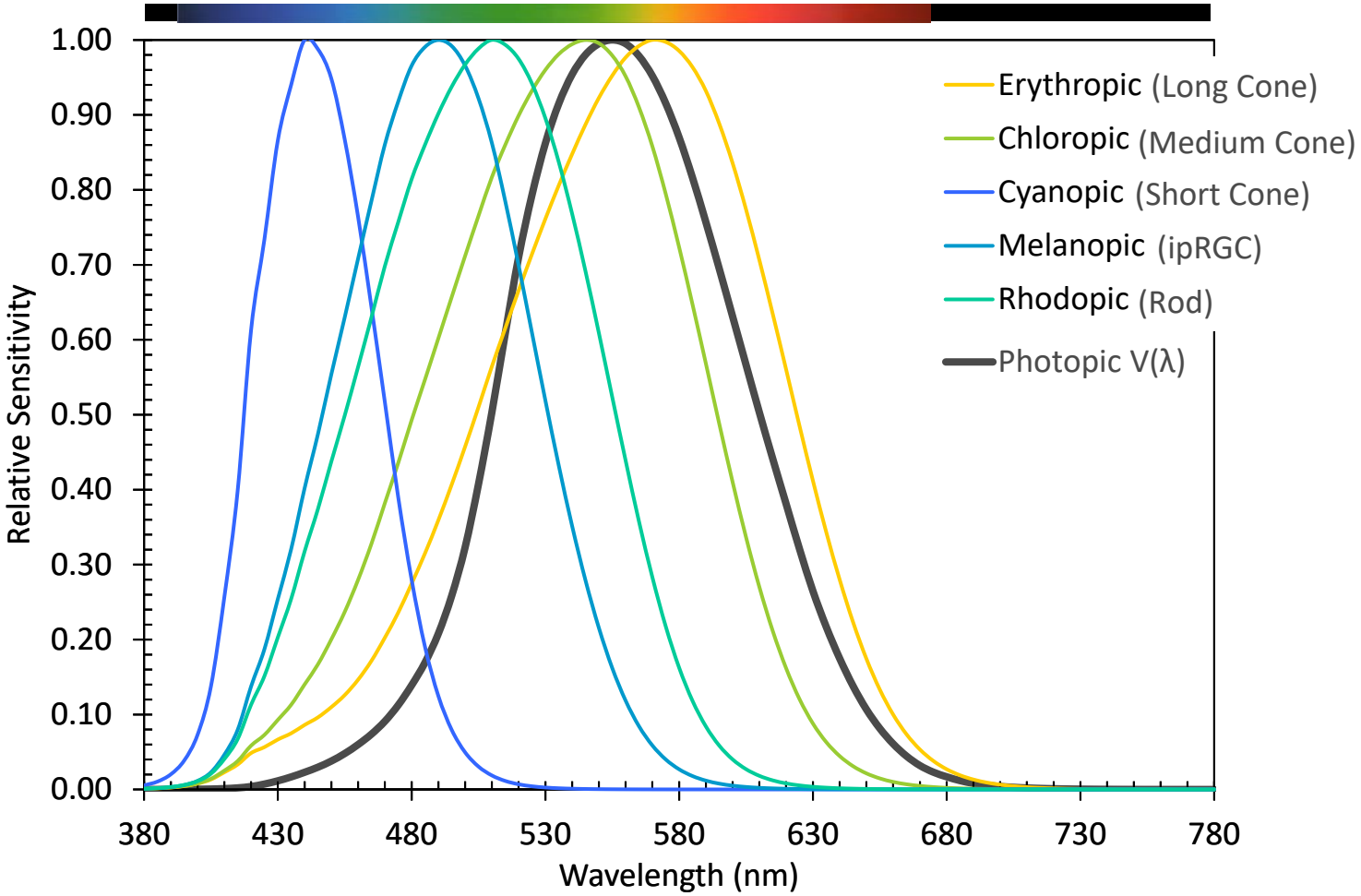
Photopic Luminous Efficiency Function, V(λ)

CIE 1931 Standard Photopic Observer (2°)

Used for:

Lumens, lux, candela, luminous efficacy, LER

Note: Alternatives include the CIE 1964 Standard Observer (10°), among other visual efficiency functions.



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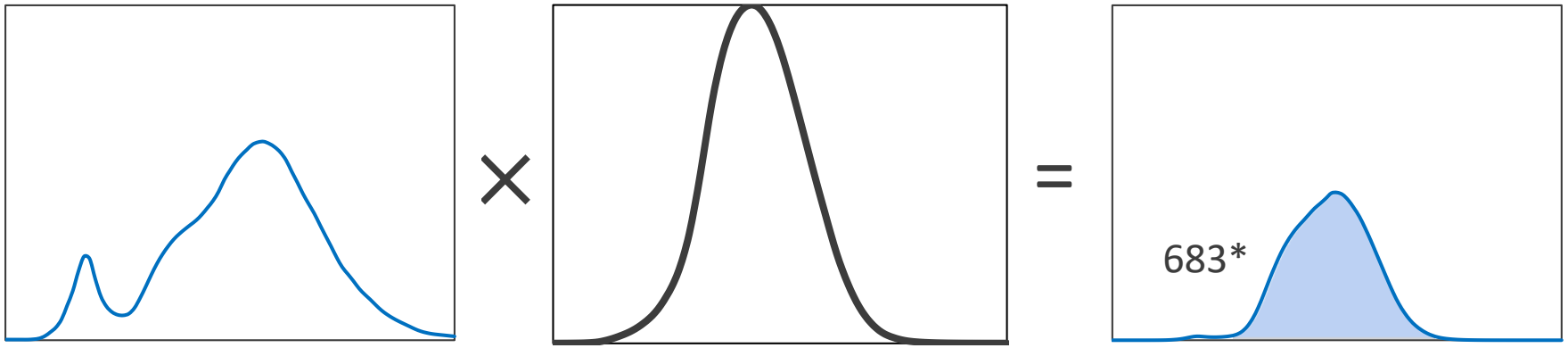
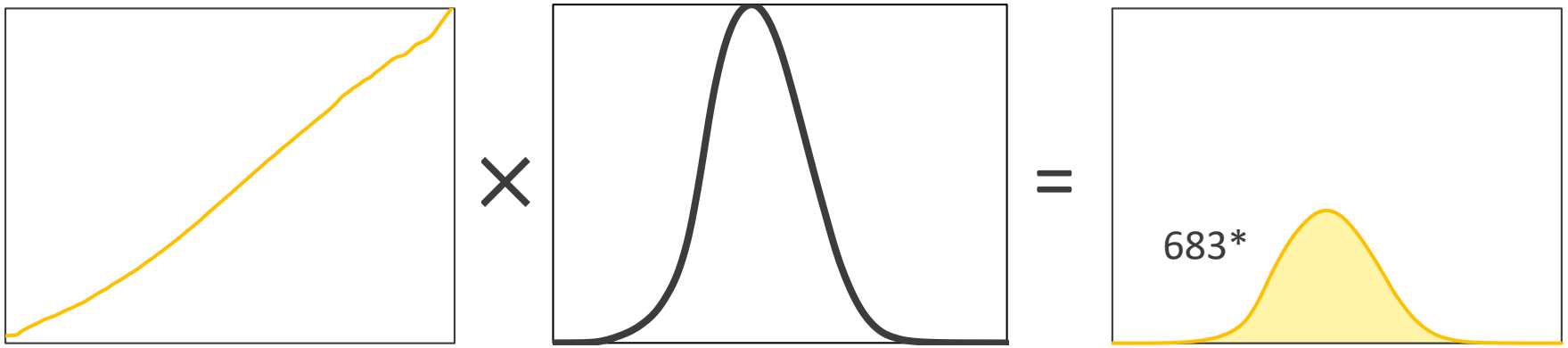
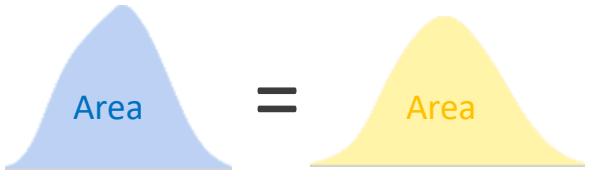
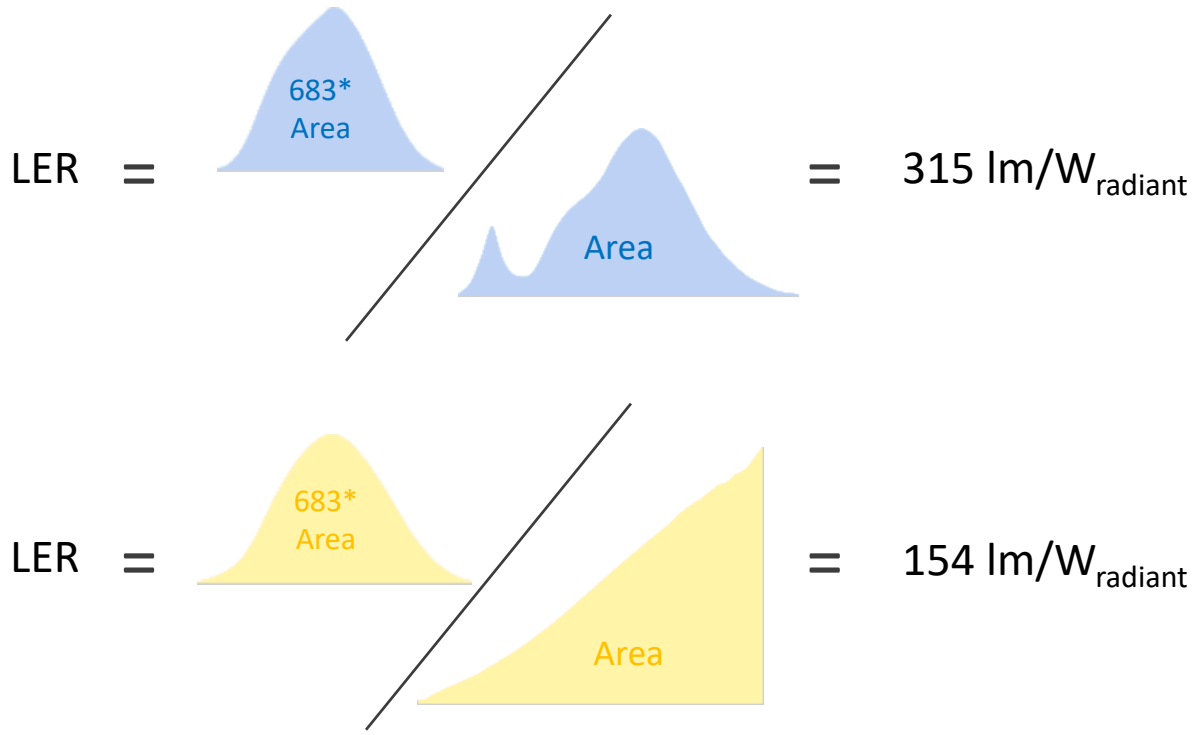




(Radiant Flux)



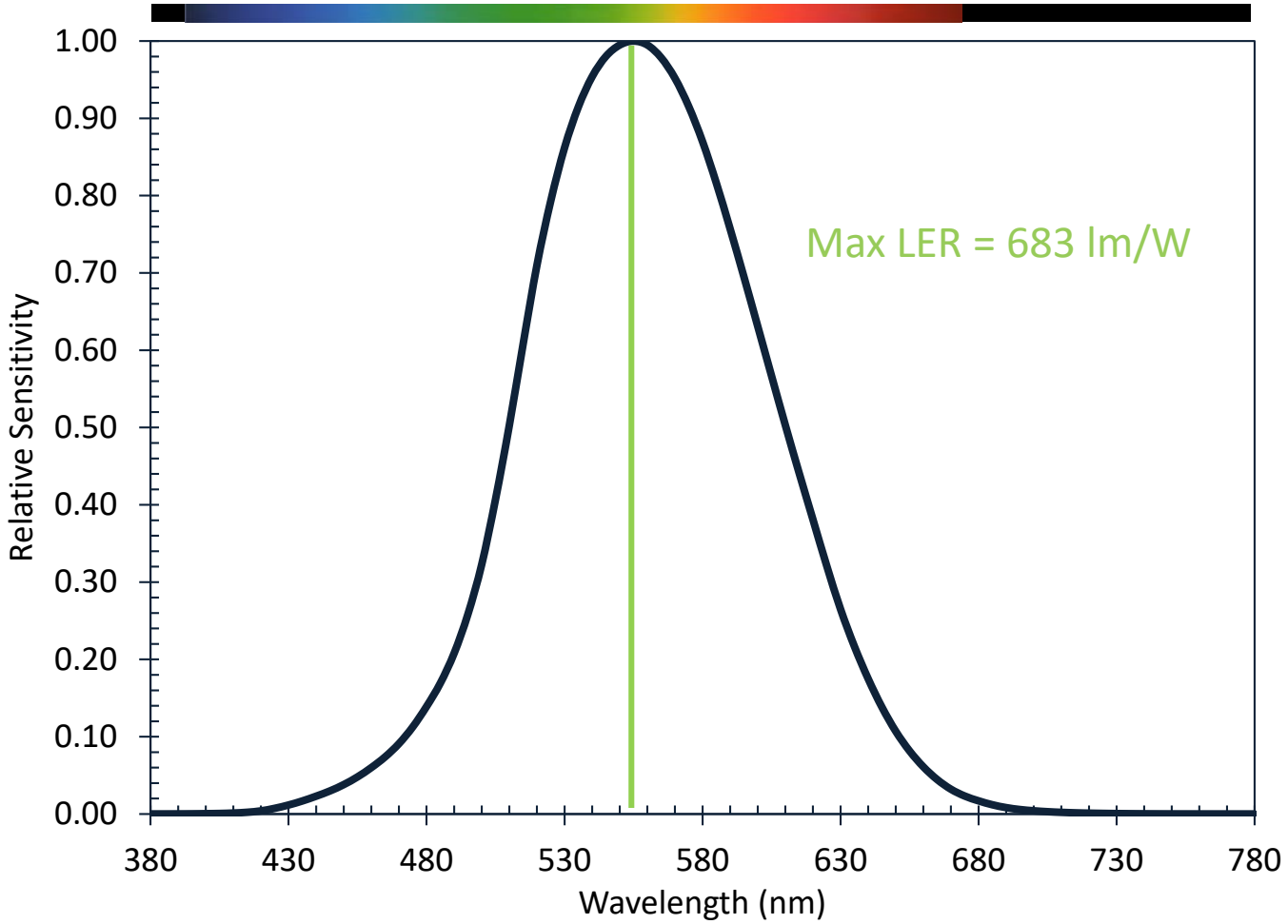


Spectral Efficiency

Luminous Efficacy of Radiation (LER)

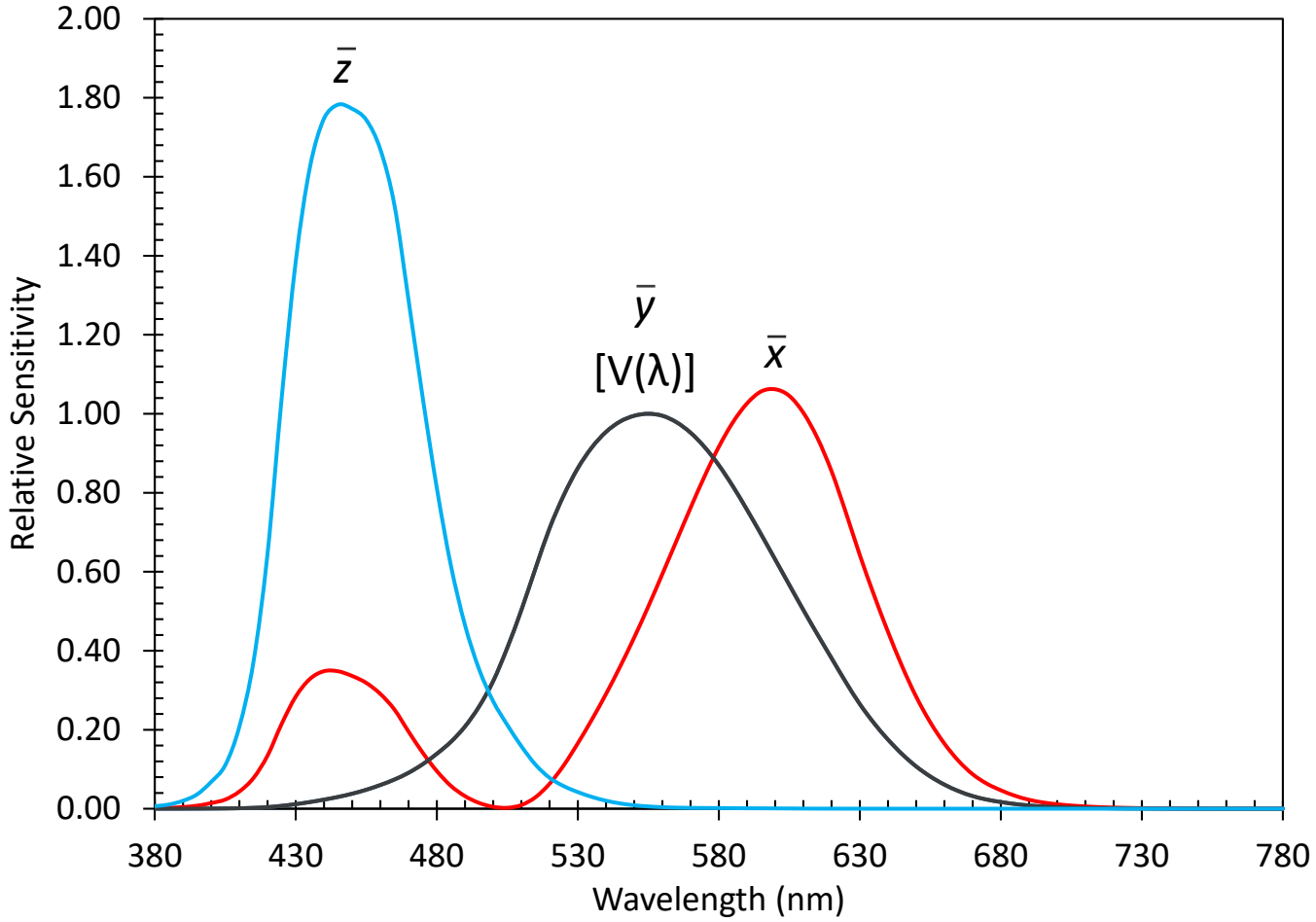
$$= \frac{\text{Luminous Flux (lm)}}{\text{Radiant Flux } (W_{opt})}$$

Radiant Watts, Not Electrical Watts



LER is the maximum possible luminous efficacy if a light source is perfect at converting electrical watts to optical watts.

Realistic maximums are ~400 lm/W given chromaticity and color rendering limits.

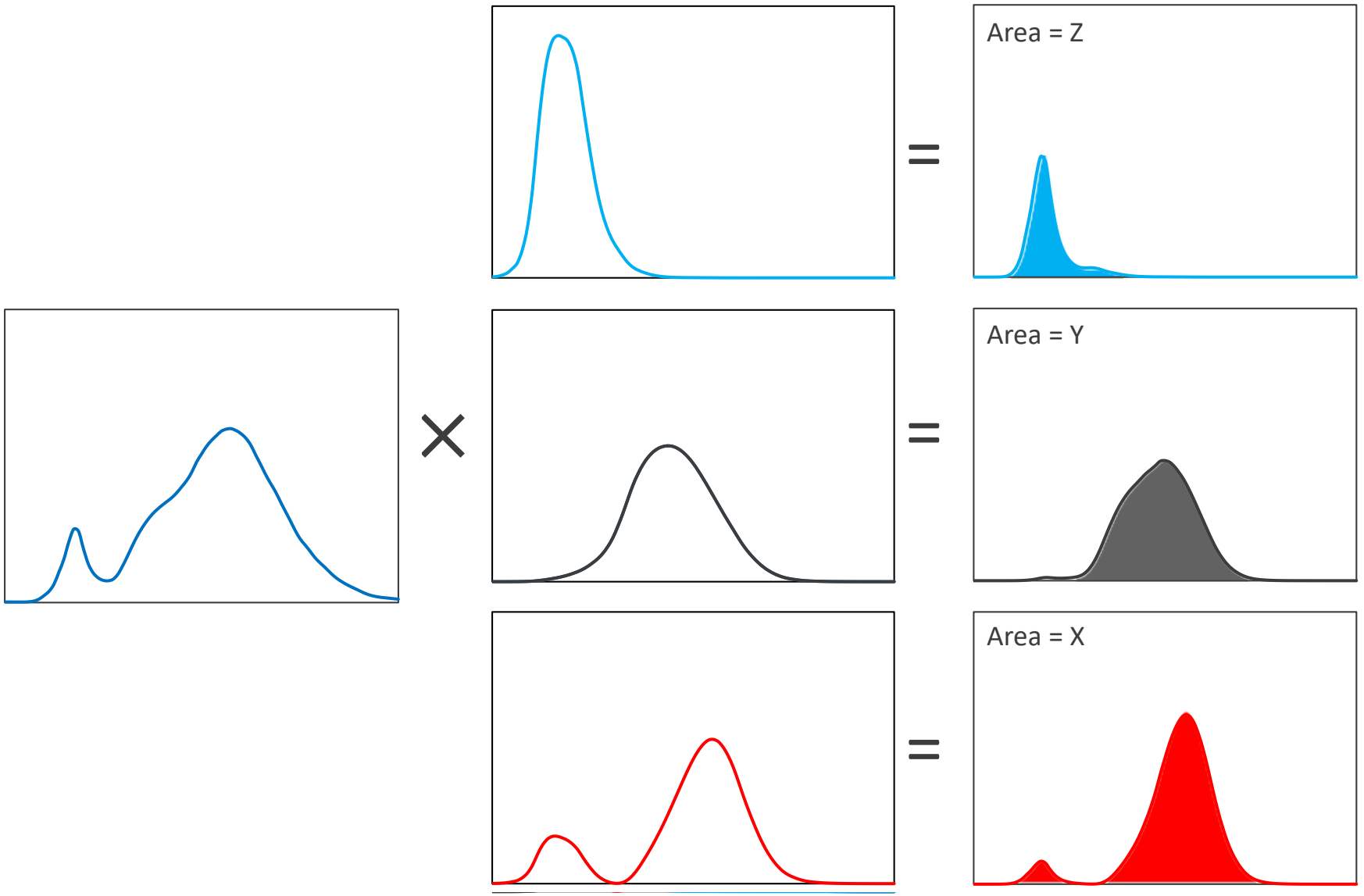


CIE 1931 Standard Colorimetric Observer (2°)

Used for:

Chromaticity, CCT, D_{uv}

Note: Alternatives include the CIE 1964 Standard Colorimetric Observer (10°) and the cone fundamental-based tristimulus functions (CIE 15:2018)



Chromaticity Coordinates

CIE 1931 (*x*, *y*)

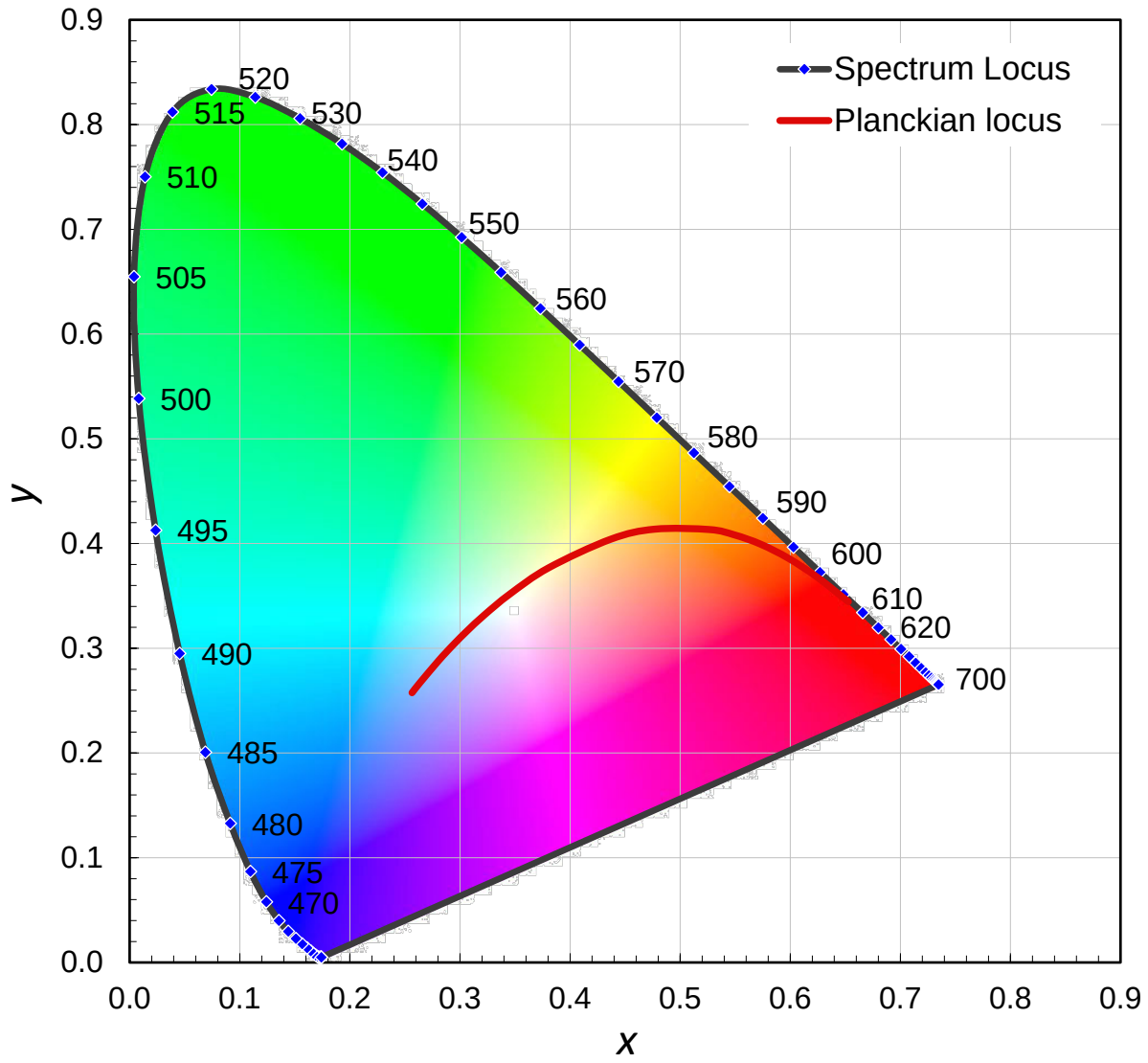
$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

CIE 1976 (*u'*, *v'*)

$$u' = \frac{4X}{X + 15Y + 3Z}$$

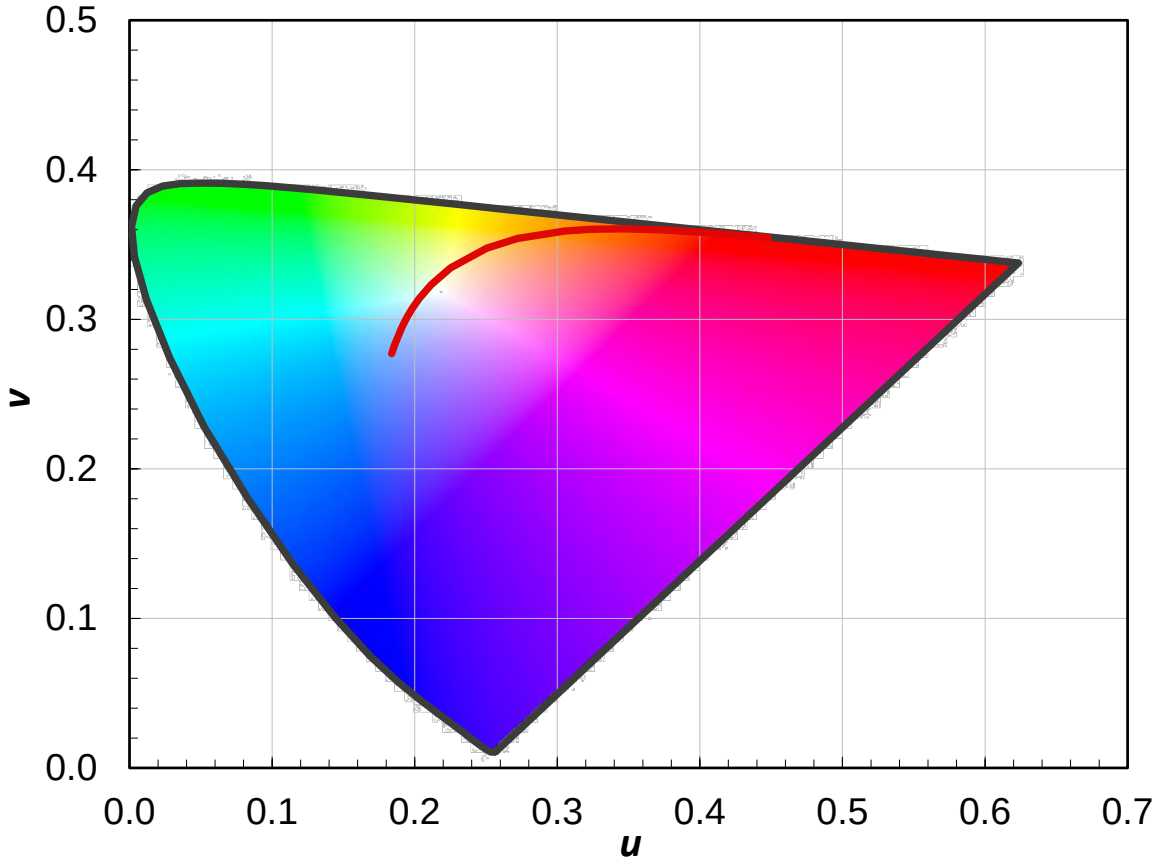
$$v' = \frac{9X}{X + 15Y + 3Z}$$



CIE 1931 (*x*, *y*) Chromaticity Diagram

- Obsolete, but sill used by some
- Not visually uniform (distance doesn't equal visual difference)

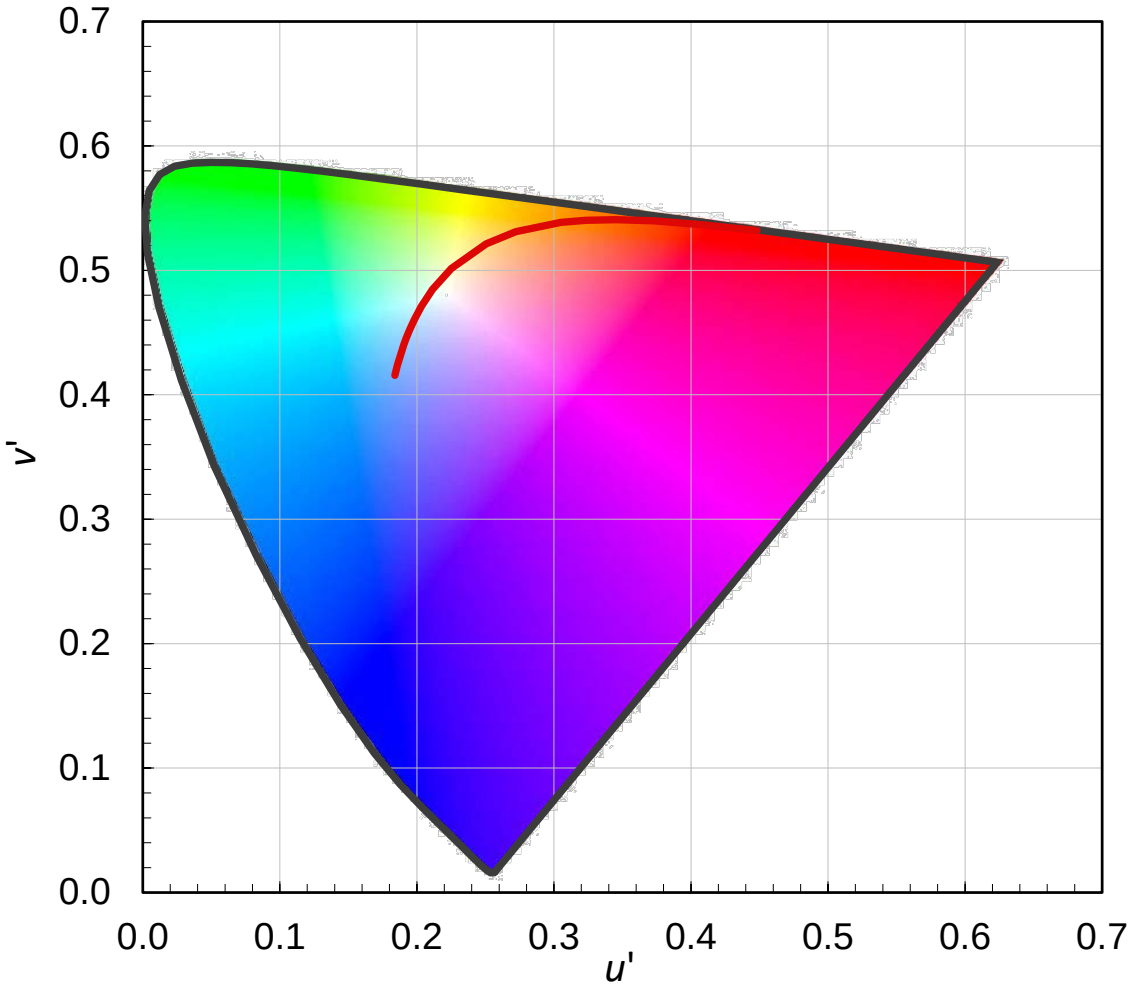
Note: Colored background for orientation only.



Note: Colored background for orientation only.

CIE 1960 (*u*, *v*) Uniform Chromaticity Scale (UCS) Diagram

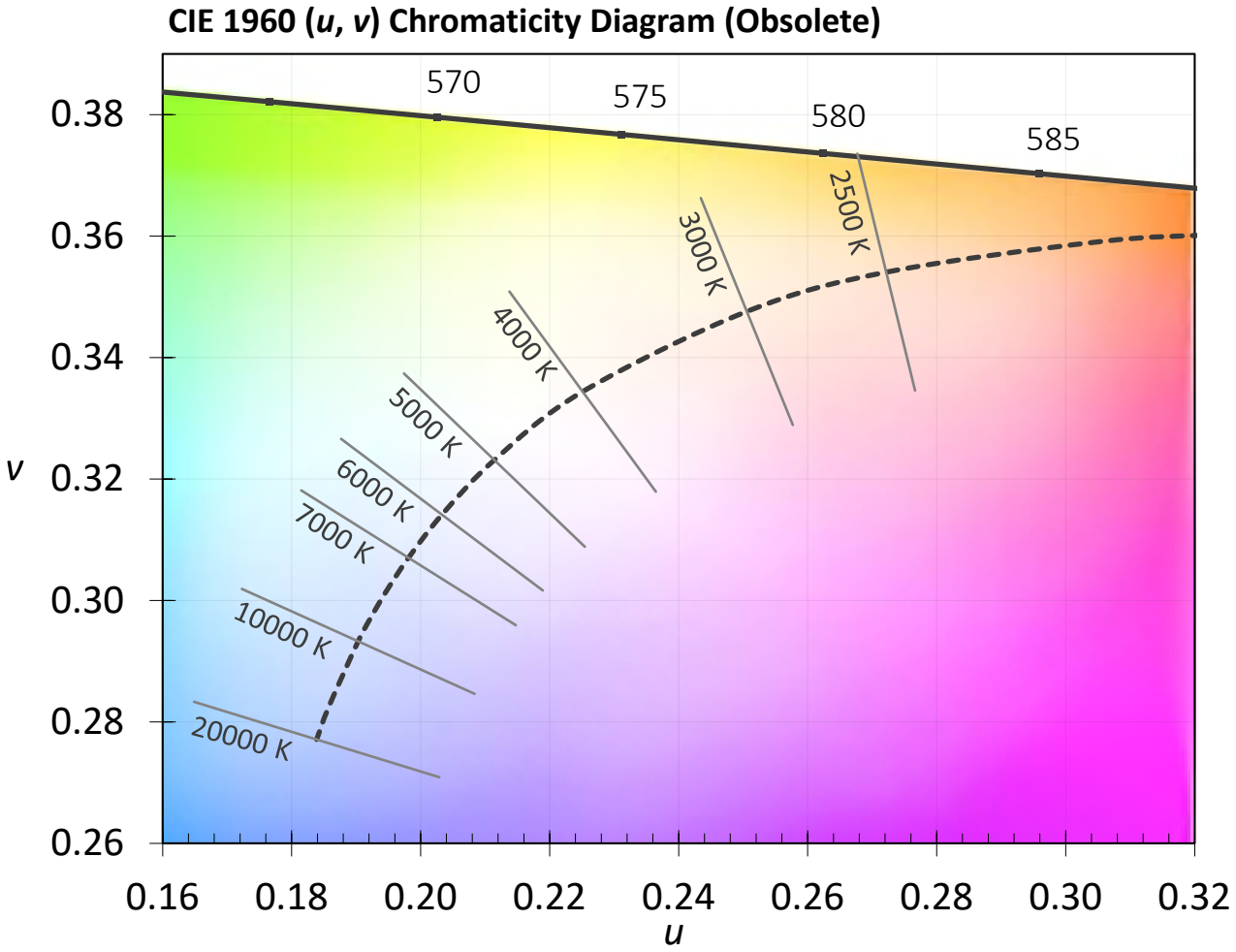
- Obsolete, but sill used by some.
- Intended to be visually uniform, but isn't (distance doesn't equal visual difference)



Note: Colored background for orientation only.

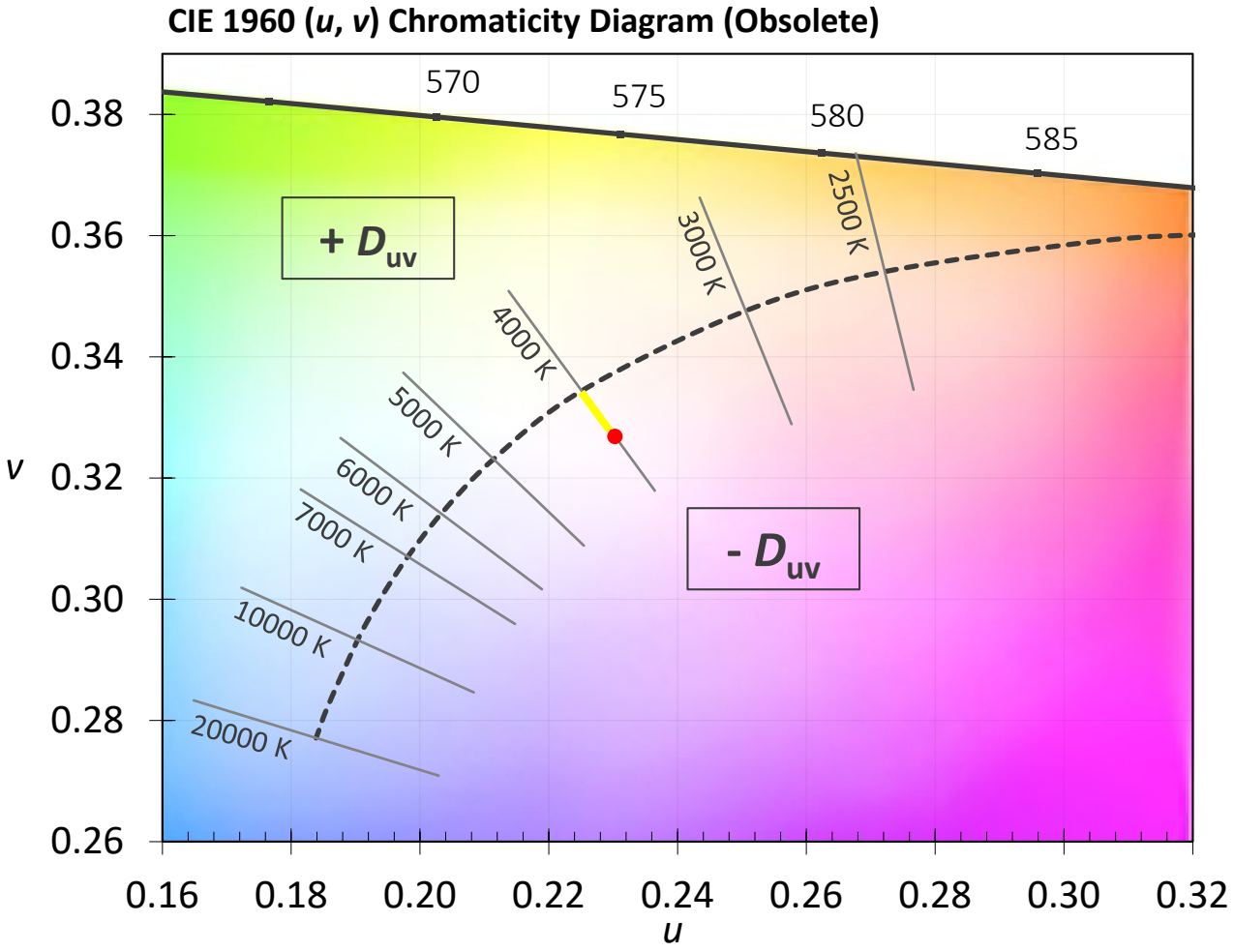
CIE 1976 (*u'*, *v'*) Uniform Chromaticity Scale (UCS) Diagram

- Recommended for specifying chromaticity/binning, consistency of chromaticity, chromaticity shift (color maintenance), chromaticity difference
- Δu'v' = chromaticity difference (between two products or over time)



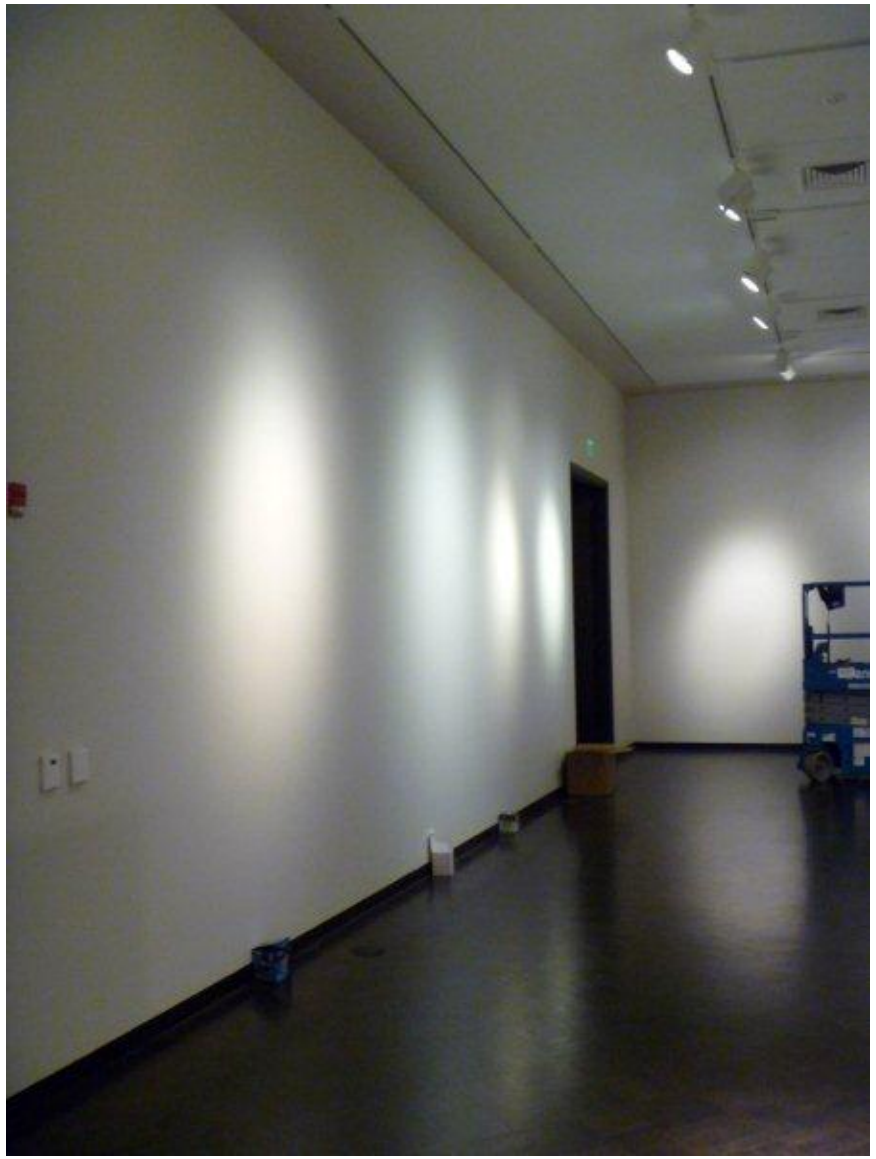
Correlated Color Temperature (CCT)

- Temperature of nearest Planckian radiator
- Approximately yellow-blue
- Equal CCT does not equal matching appearance



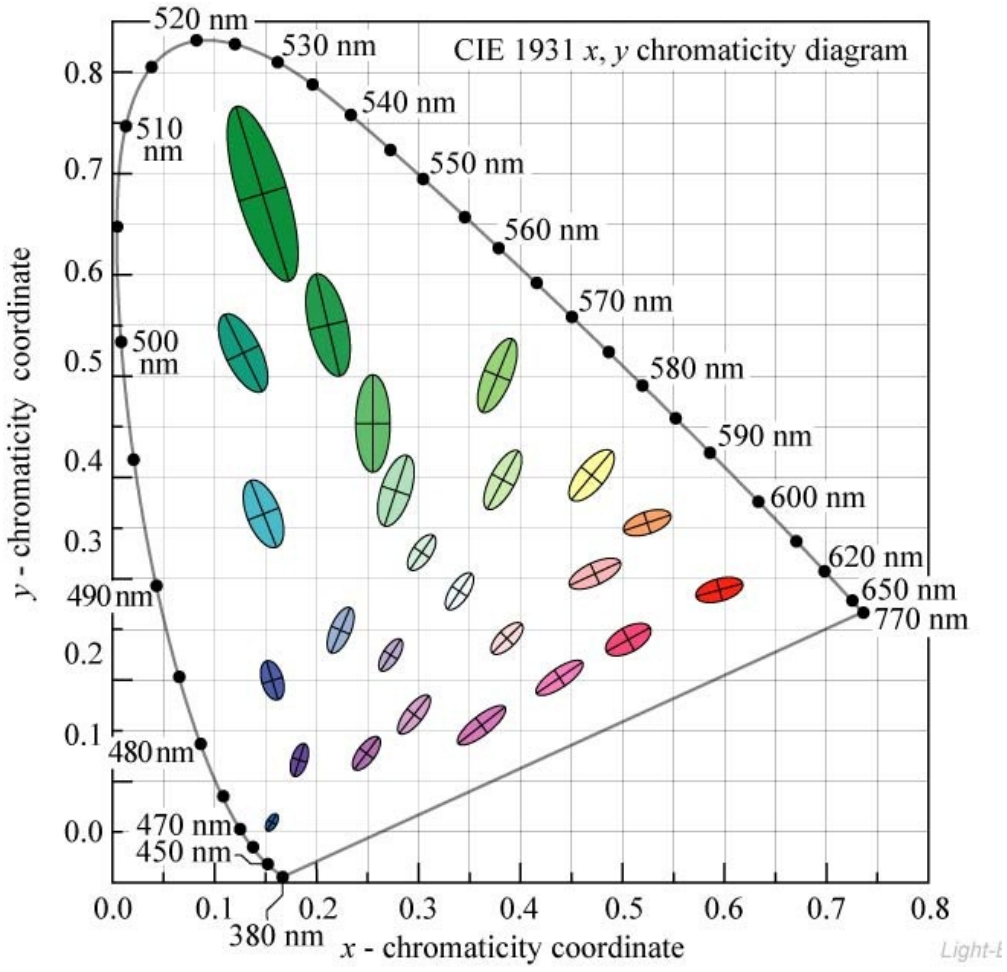
Distance from Planckian Locus (D_{uv})

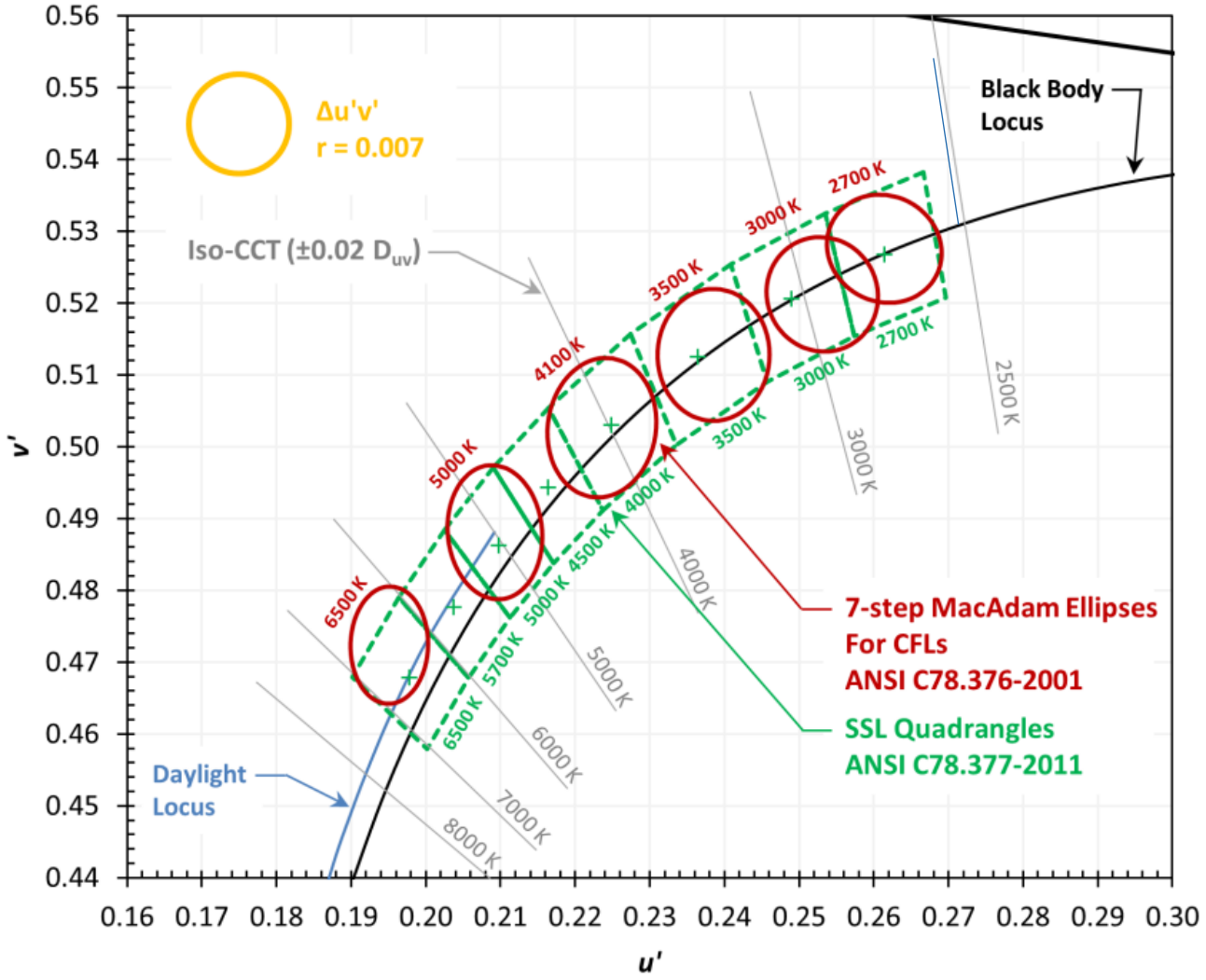
- Approximately purple-green
- Equal CCT *and* D_{uv} specifies matching appearance for standard observer (real observers vary)
- Neutral white can cover a wide area
- Some preference for negative D_{uv} at low CCTs?



Consistency (of chromaticity)

- Initial similarity in appearance
- Addressed with binning
  - ANSI/NEMA C78.377-2017


CIE 1931 x, y chromaticity diagram
520 nm
530 nm
540 nm
550 nm
560 nm
570 nm
580 nm
590 nm
600 nm
620 nm
650 nm
770 nm
510 nm
500 nm
490 nm
480 nm
470 nm
450 nm
380 nm
y - chromaticity coordinate
x - chromaticity coordinate
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Δu'v'
r = 0.007
Iso-CCT (±0.02 Duv)
Black Body Locus
Daylight Locus
7-step MacAdam Ellipses For CFLs ANSI C78.376-2001
SSL Quadrangles ANSI C78.377-2011
2700 K
3000 K
3500 K
4100 K
5000 K
6500 K
4000 K
4500 K
5700 K
6000 K
7000 K
8000 K
2500 K
v'
u'
0.44
0.45
0.46
0.47
0.48
0.49
0.50
0.51
0.52
0.53
0.54
0.55
0.56
0.16
0.17
0.18
0.19
0.20
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28
0.29
0.30

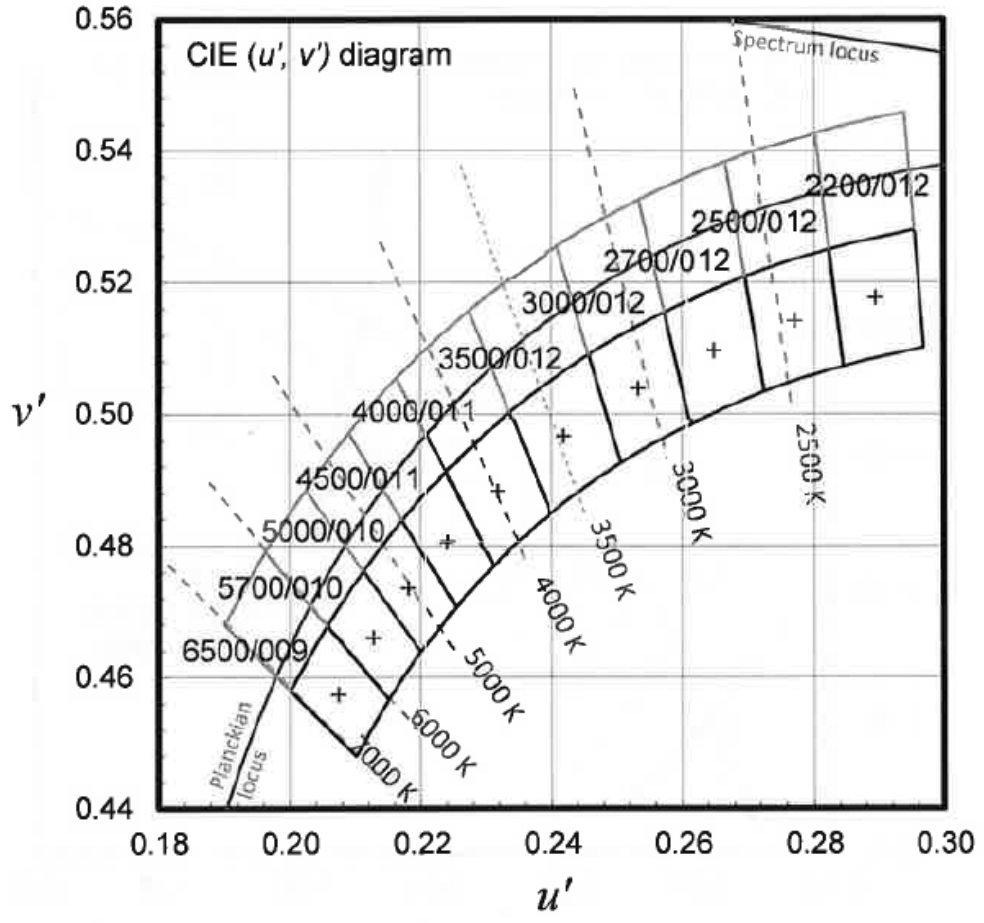


Figure E2
Graphical Representation of the Chromaticity Specification of Table 2, Extended Nominal CCT Specification, on the CIE (u', v') chromaticity diagram

ANSI/NEMA C78.377-2017

- Standard "7-Step" quadrangle bins
  - plus 2200 K, 2500 K
  - DLC v5.0 Tier 2
- Extended "7-step" quadrangle bins
  - DLC v5.0 Tier 2

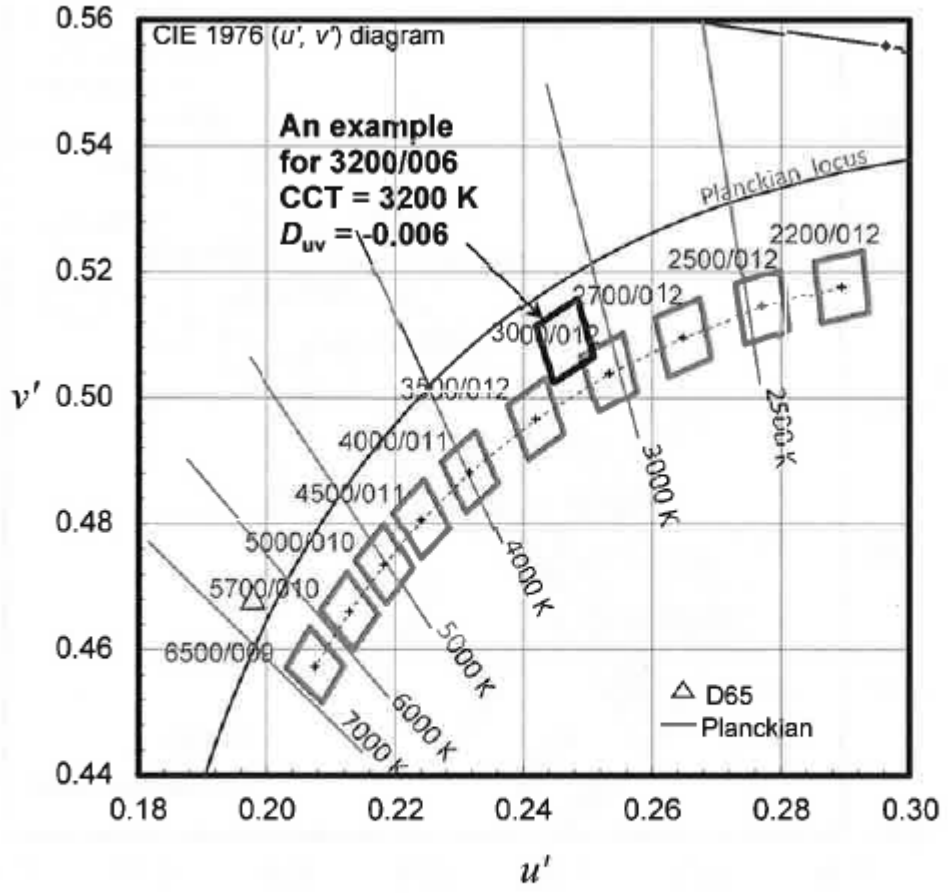
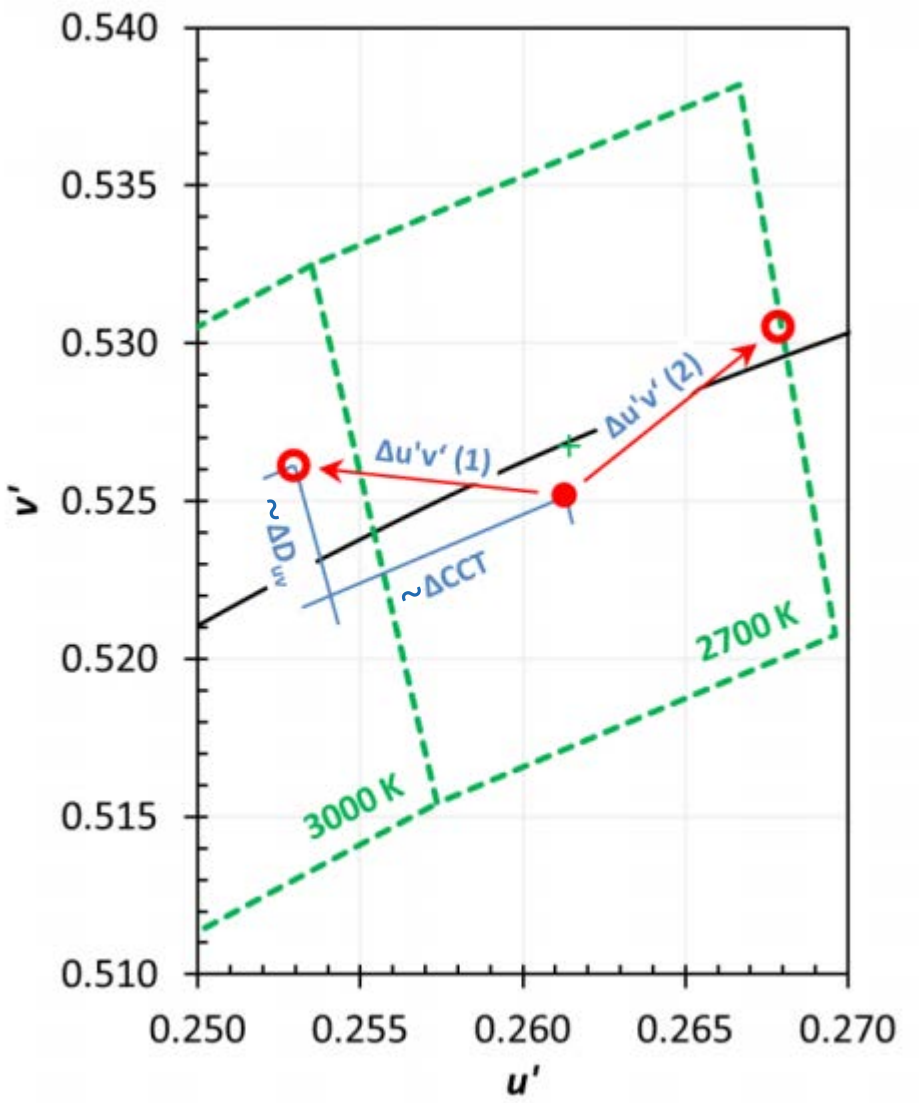


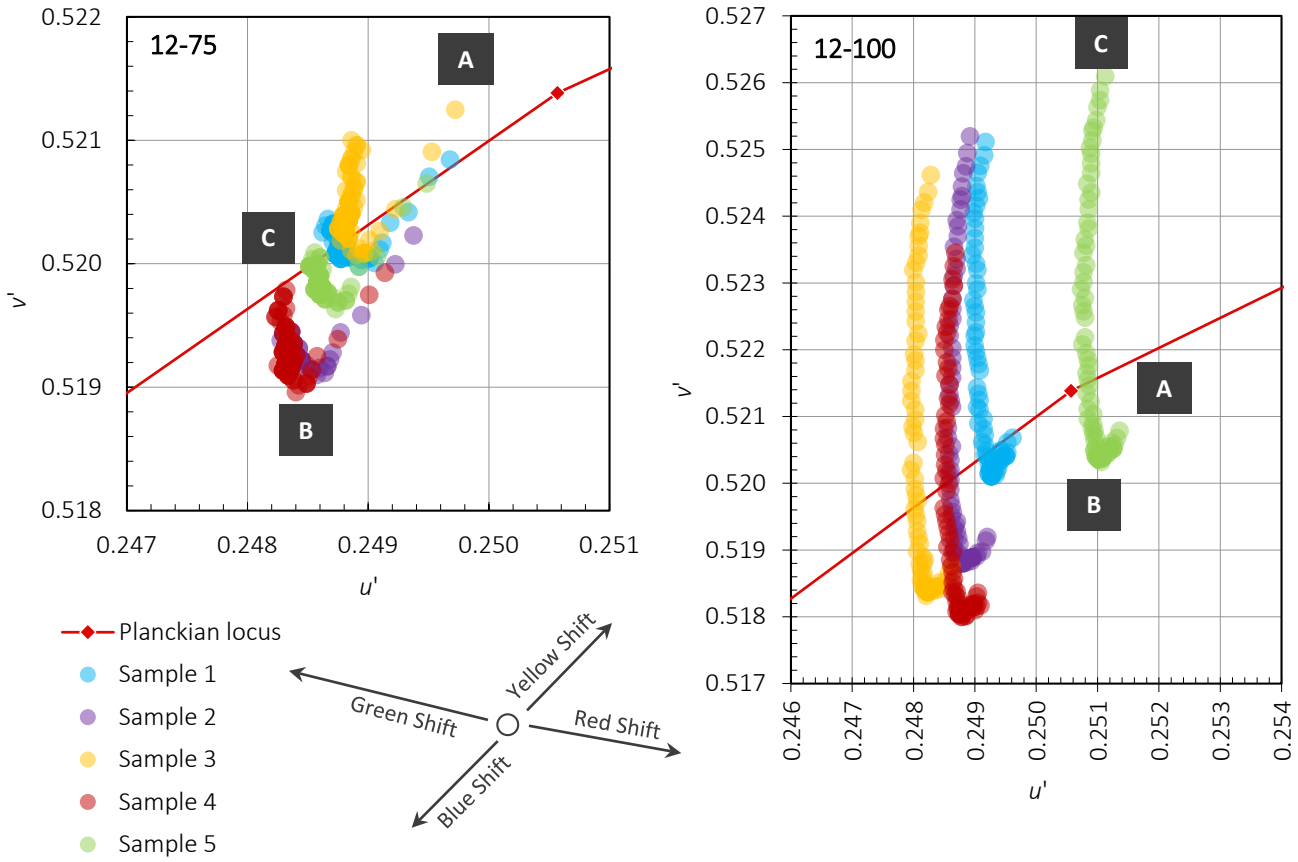
Figure E5
An example of the 4-step Quadrangle Tolerance of Extended Flexible CCT/Duv specifications on the CIE (u', v') chromaticity diagram

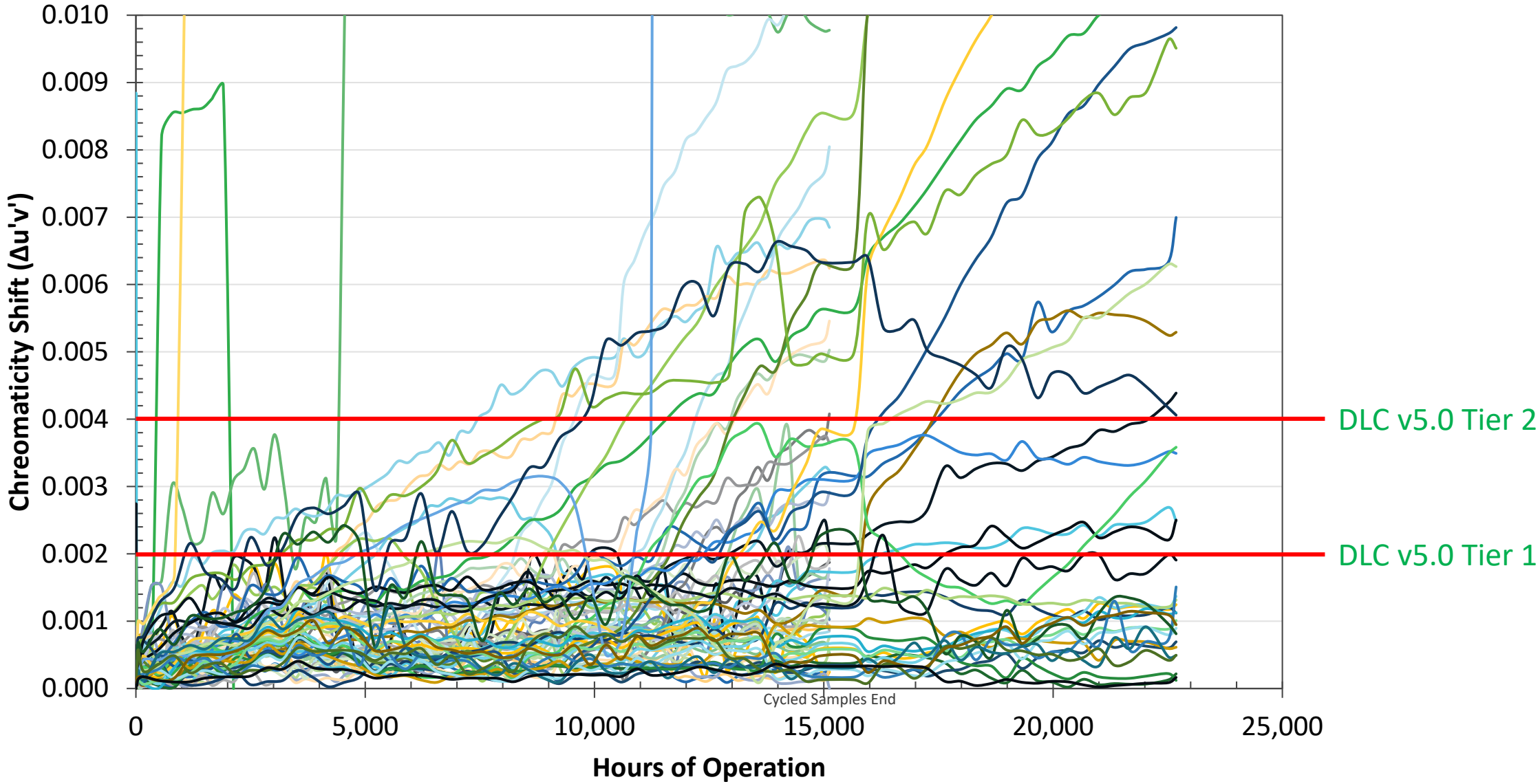
ANSI/NEMA C78.377-2017

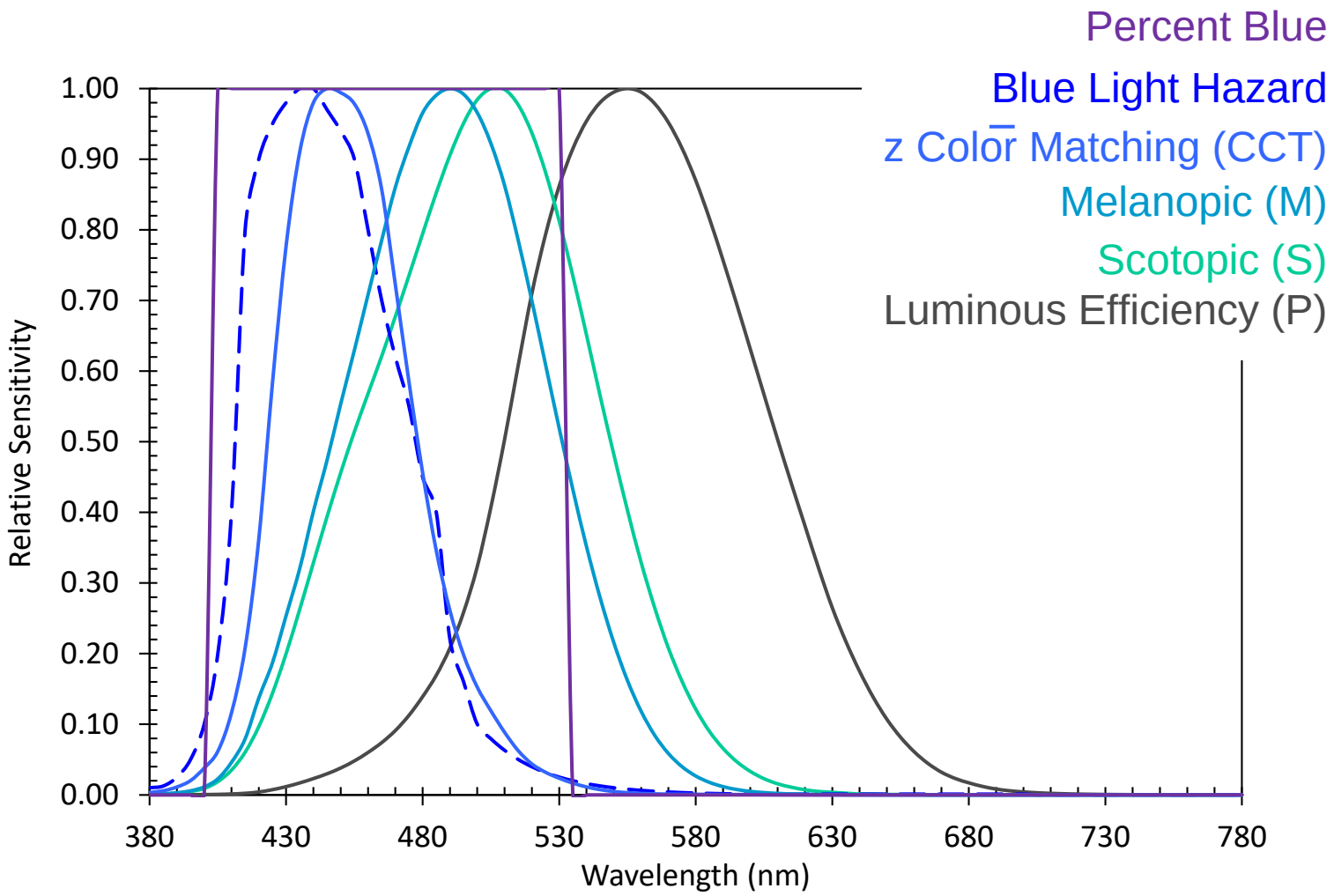
- Standard "7-Step" quadrangle bins
  - plus 2200 K, 2500 K
  - DLC v5.0 Tier 2
- Extended "7-step" quadrangle bins
  - DLC v5.0 Tier 2
- Standard/Extended "4-step" quadrangle bins
  - DLC v5.0 Tier 1
- Flexible quadrangles, circles



Chromaticity Maintenance (Over Time)



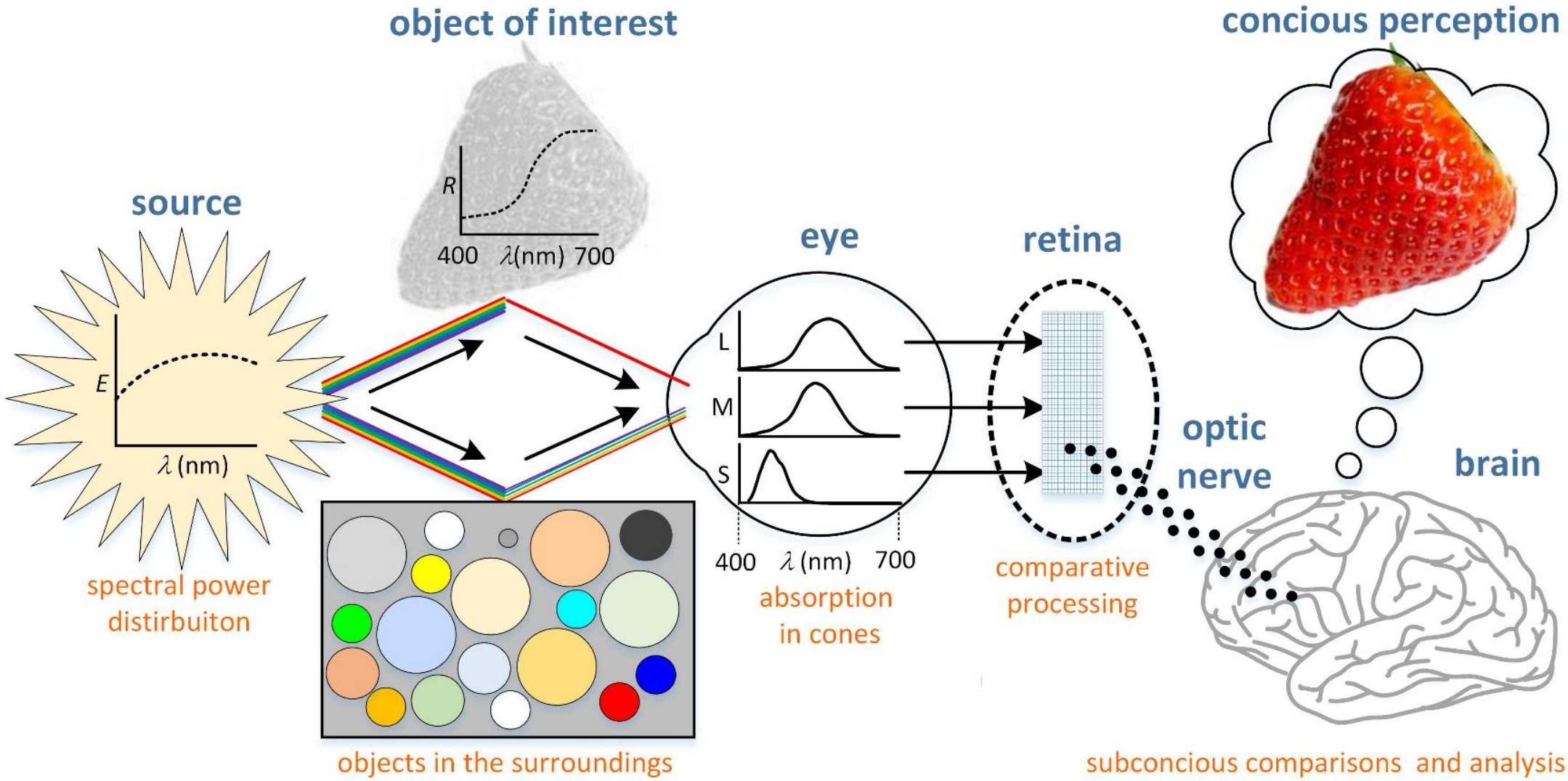

0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
Chromaticity Shift (Δu'v')
0
5,000
10,000
15,000
20,000
25,000
Hours of Operation
Cycled Samples End
DLC v5.0 Tier 2
DLC v5.0 Tier 1



Blue Light / Circadian

- One should not be used to determine the other (e.g., CCT ≠ M or M/P)
- CS is not a weighting function.

4. Color Rendition



https://doi.org/10.1146/annurev-vision-091718-015018

Past Method: CRI
(CIE 13.3-1995)

8 Color Samples
- Medium chroma/lightness
- Spectral sensitivity varies
- Munsell samples only

1964 Color Vision Model
- Color difference inaccurate
- Distortion of red
- “Wrong” chromatic adaptation model

Limited Predictive Outputs
- Average color difference (fidelity)
- Color fidelity for each color sample
- No indication of color shift directions

New Method: TM-30
(ANSI / IES TM-30-18)

99 Color Samples
- Uniform color space coverage
- Spectral sensitivity neutral
- Variety of real objects

2006 Color Vision Model
- Uniform color space
- Improved chromatic adaptation model
- Hue, chroma, lightness correlates

Extensive Predictive Outputs
- Average color fidelity, gamut area
- Hue-specific (“local”) chroma shift, hue shift, fidelity
- Graphics, Spec Sheets, etc.

Color Rendition Specifications

Type	Name	Criteria
Voluntary	DesignLights Consortium Qualified Products List, V4.4	$R_a \geq 80$
Voluntary	ENERGY STAR Certified Light Bulbs V2.0	$R_a \geq 80$, $R_9 \geq 0$
Voluntary (building certification)	WELL Building Standard V2	$R_a \geq 90$ OR $R_a \geq 80$, $R_9 \geq 50$
Mandatory (for sale in state)	California Appliance Efficiency Regulations (Title 20)	$R_a \geq 82$
Mandatory (residential new constr)	California Building Efficiency Standards (Title 24 JA8)	$R_a \geq 90$, $R_9 \geq 50$
Proposal	Class A	$R_a \geq 80$, $80 \leq GAI \leq 100$
Recommendation	IES Lighting Handbook, 10th Ed.	
	General Interior	$R_a \geq 80$
	Color Appraisal	$R_a \geq 85$
	Color Matching & Reproduction	$R_a \geq 90$
American National Standard Recommended Practice	ANSI/IES RP-1-12: Office Lighting	
	General	$R_a \geq 80$
	Color Matching/Discrimination	$R_a \geq 90$
American National Standard Recommended Practice	ANSI/IES RP-3-13: Educational Facilities	
	General	$R_a \geq 80$
	Color Discrimination	$R_a \geq 90$
Recommended Practice	IES RP-7-01: Industrial	
	Important	$R_a \geq 70$
	Critical	$R_a \geq 85$
Voluntary	DesignLights Consortium Qualified Products List, V5.0	$R_a \geq 80$, $R_9 \geq 0$; $R_a \geq 90$, $R_9 \geq 50$

Type	Name	Criteria		
		Tier 1	Tier 2	Tier 3
Mandatory (military medical facilities)	U.S. DOD UFC 4-510-01: Design Military Medical Facilities Note: CRI alternative	$R_f \geq 78$ (TM-30-15) $97 \leq R_g \leq 110$ $-9\% \leq R_{cs,h1} \leq 9\%$ $R_{f,h1} \geq 78$ (TM-30-15)		
Voluntary (Building Certification)	WELL Building Standard V2 Note: CRI alternative	$R_f \geq 78$ $R_g \geq 98$ $-1\% \leq R_{cs,h1} \leq 15\%$	$R_f \geq 78$ $R_g \geq 98$ $-7\% \leq R_{cs,h1} \leq 15\%$	
Draft	ANSI/IES TM-30-18 Annex E/F "Color Preference"	$R_f \geq 78$ $R_g \geq 95$ $-1\% \leq R_{cs,h1} \leq 15\%$	$R_f \geq 74$ $R_g \geq 92$ $-7\% \leq R_{cs,h1} \leq 19\%$	$R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$
Draft	DesignLights Consortium Qualified Products List, V5.0 Note: CRI alternative	$R_f \geq 78$ $R_g \geq 98$ $-1\% \leq R_{cs,h1} \leq 15\%$		$R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$

Design Intent
The desired effect of color rendition on the illuminated environment.

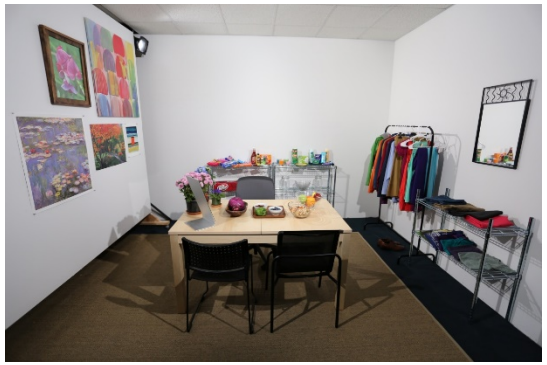
Priority Level: The balance between allowing for tradeoffs and increasing the likelihood of meeting the design intent.	Preference (P)	Vividness (V)	Fidelity (F)
1	P1: $R_f \gtrsim 78$; $R_g \gtrsim 95$ 98; $-1\% \lesssim R_{cs,h1} \lesssim 15\%$	V1: $R_g \gtrsim 118$; $R_{cs,h1} \gtrsim 15\%$	F1: $R_f \gtrsim 95$
2	P2: $R_f \gtrsim 75$; $R_g \gtrsim 95$; $-7\% \lesssim R_{cs,h1} \lesssim 15\%$	V2: $R_g \gtrsim 110$; $R_{cs,h1} \gtrsim 6\%$	F2: $R_f \gtrsim 90$; $R_{f,h1} \gtrsim 90$
3	P3: $R_f \gtrsim 70$; $R_g \gtrsim 88$; $-12\% \lesssim R_{cs,h1} \lesssim 18\%$	V3: $R_g \gtrsim 100$; $R_{cs,h1} \gtrsim 0\%$	F3: $R_f \gtrsim 85$; $R_{f,h1} \gtrsim 85$

DRAFT

ANSI/IES TM-30-18 Annex E Table E.2

Assumptions:

- 200-700 lux
- polychromatic environment
- single chromaticity



CHROMATICITY 3500 K 0.000 D_{uv}

4 LEVELS R_f 5 LEVELS R_g

MIN or MAX $R_{cs,h1}$

26 TOTAL LIGHTING SCENES

250 LUX

3 RATING QUESTIONS

Dull or Saturated
Normal or Shifted
Like or Dislike

16 AGE 18-61

12 AGE 30-65

30 SECONDS Minimum View Time Per Scene

4 CCT GROUPS 2800 K 4000 K 5000 K 6500 K

41 COLOR RENDITION CONDITIONS per CCT group

164 TOTAL LIGHTING SCENES

450 LUX

3 RATING QUESTIONS

Naturalness
Colorfulness
Preference

5 AGE 19-30

5

2 MINUTES Chromatic Adaptation Per Group

30 SECONDS Approx. View Time Per Scene

5 CHROMATICITY GROUPS

2700 K 0.000 D_{uv} | -0.007 D_{uv}

3500 K 0.000 D_{uv}

4300 K 0.000 D_{uv} | -0.007 D_{uv}

10 COLOR RENDITION CONDITIONS

60 ≤ IES $R_{f,h1}$ ≤ 94

88 ≤ IES $R_{f,h1}$ ≤ 124

-15% ≤ IES $R_{cs,h1}$ ≤ 28%

50 TOTAL LIGHTING SCENES

270 LUX

4 RATING QUESTIONS

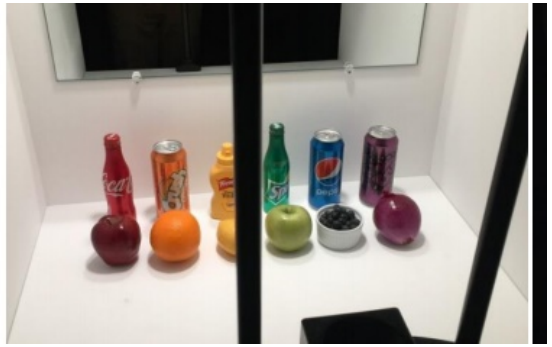
Dull or Saturated
Normal or Shifted
Like or Dislike
Acceptable or
Unacceptable

18 AGE 20-69

16 AGE 21-57

3 MINUTES Chromatic Adaptation Per Group

30 SECONDS Minimum View Time Per Scene



CHROMATICITY 3500 K 0.000 D_{uv}

4 LEVELS R_f 5 LEVELS R_g

Orthogonal CVG

24 TOTAL LIGHTING SCENES

3 RATING QUESTIONS

Desaturated or Vivid
Unnatural or Natural
Like or Dislike
Skin: Like or Dislike

650 LUX

AGE 20-41

2 MINUTES Minimum View Time Per Scene

23

17

9 CHROMATICITY GROUPS

2700 K D_{uv}: 0.000, -0.007, -0.014

3100 K D_{uv}: 0.000, -0.007, -0.014

3500 K D_{uv}: 0.000, -0.007, -0.014

10 COLOR RENDITION CONDITIONS

70 ≤ IES $R_{f,h1}$ ≤ 92

81 ≤ IES $R_{f,h1}$ ≤ 124

-22% ≤ IES $R_{cs,h1}$ ≤ 23%

90 TOTAL LIGHTING SCENES

330 LUX

4 RATING QUESTIONS

Dull or Saturated
Normal or Shifted
Like or Dislike
Acceptable or
Unacceptable

14 AGE 23-70

11 AGE 20-67

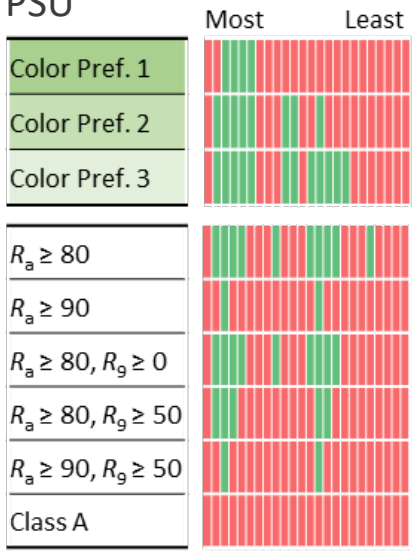
3 MINUTES Chromatic Adaptation Per Group

30 SECONDS Minimum View Time Per Scene

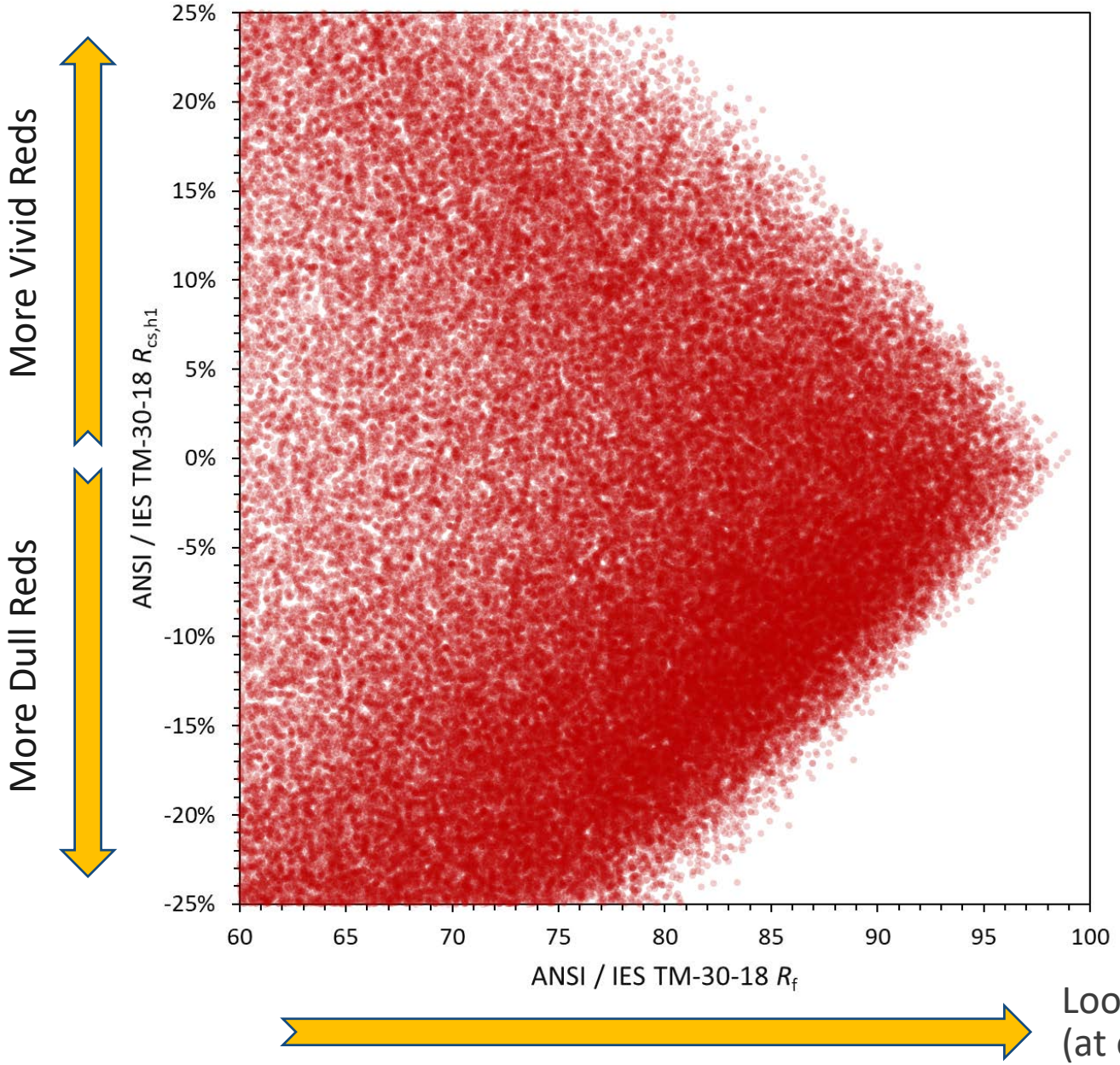
1. M. Royer, A. Wilkerson, M. Wei et al., "Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape," Lighting Research & Technology, 49(8), 966-991 (2016).
2. M. Royer, A. Wilkerson, and M. Wei, "Human perceptions of colour rendition at different chromaticities," Lighting Research & Technology, Online before print, DOI: 10.1177/1477153517725974 (2017).
3. M. Royer, A. Wilkerson, M. Wei et al., "Experimental validation of color rendition specification criteria based on IES TM-30-18," Draft. (2019).
4. F. Zhang, H. Xu, and H. Feng, "Toward a unified model for predicting color quality of light sources," Applied Optics, 56(29), 8186-8195 (2017).
5. T. Esposito, and K. Houser, "Models of colour quality over a wide range of spectral power distributions," Lighting Research & Technology, Online Before Print. DOI: 10.1177/1477153518765953., (2018).

PNNL

PSU



Zhejiang

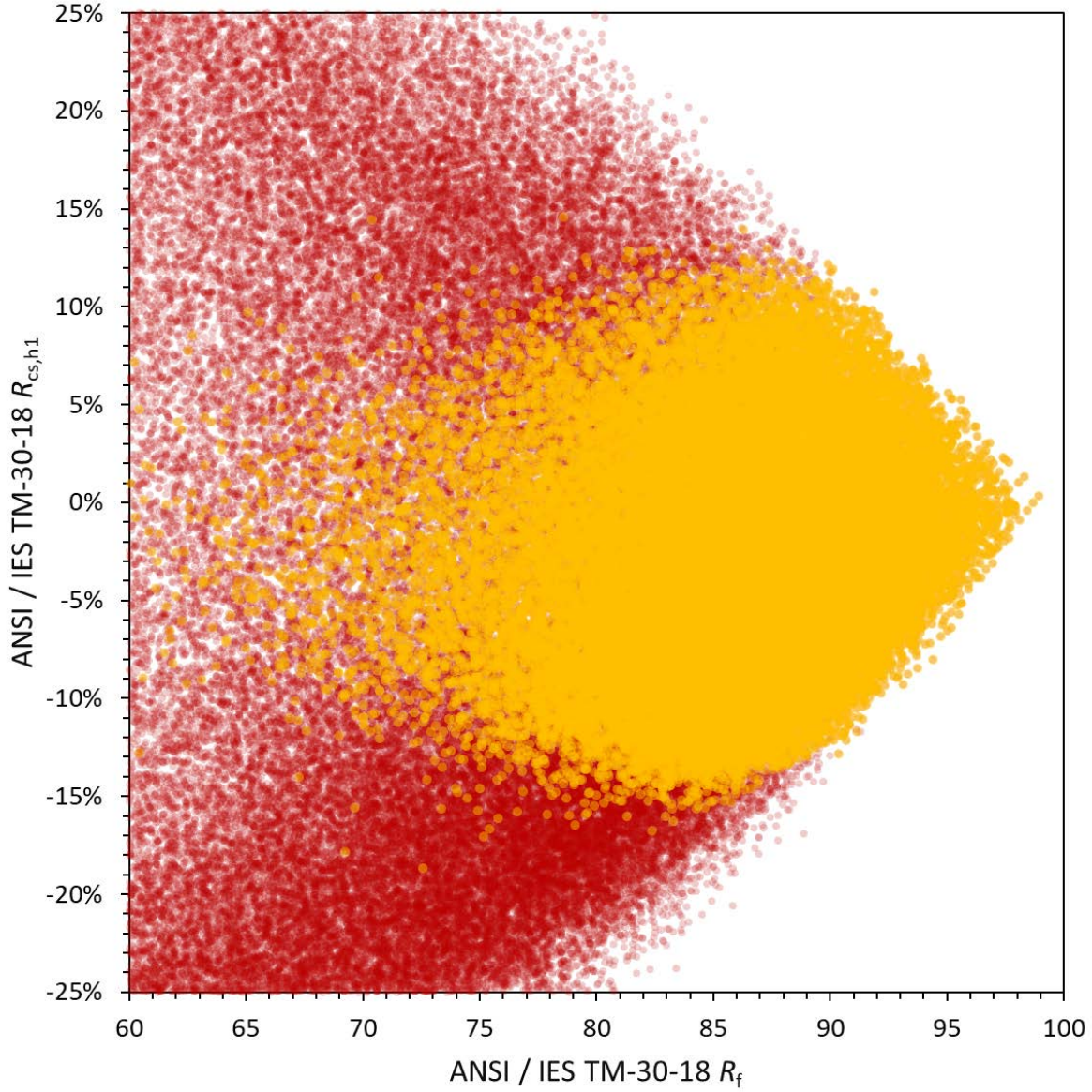


~165,000 SPDs

- 2700 K to 6500 K
- 0.006 to -0.018 D_{uv}
- Random spectral features
- Full range of possibilities

All Theoretical SPDs

Looks more like Daylight/Planckian
(at equal illuminance)



$R_a \geq 80$, $R_9 \geq 0$

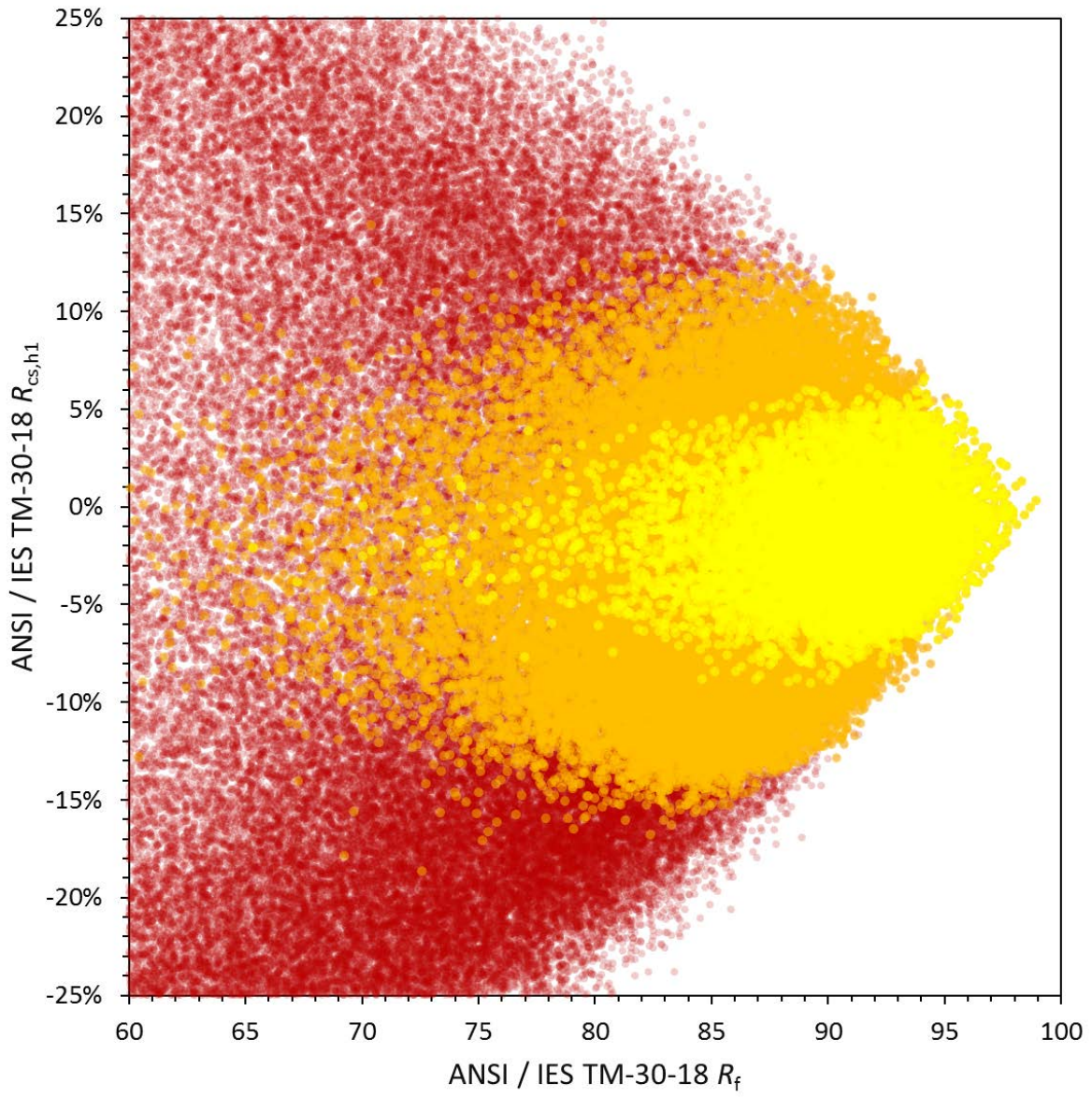
- R_f 41 – 100
- $R_{cs,h1}$ -19% to 15%
- DLC v5.0 Tier 2 Alternative

Why?

- Bad models of color and vision
- Different types of measures

All Theoretical SPDs

Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$



Better spec?

- R_f 65 – 100
- $R_{cs,h1}$ -12% to 11%
- DLC v5.0 Tier 1 Alternative

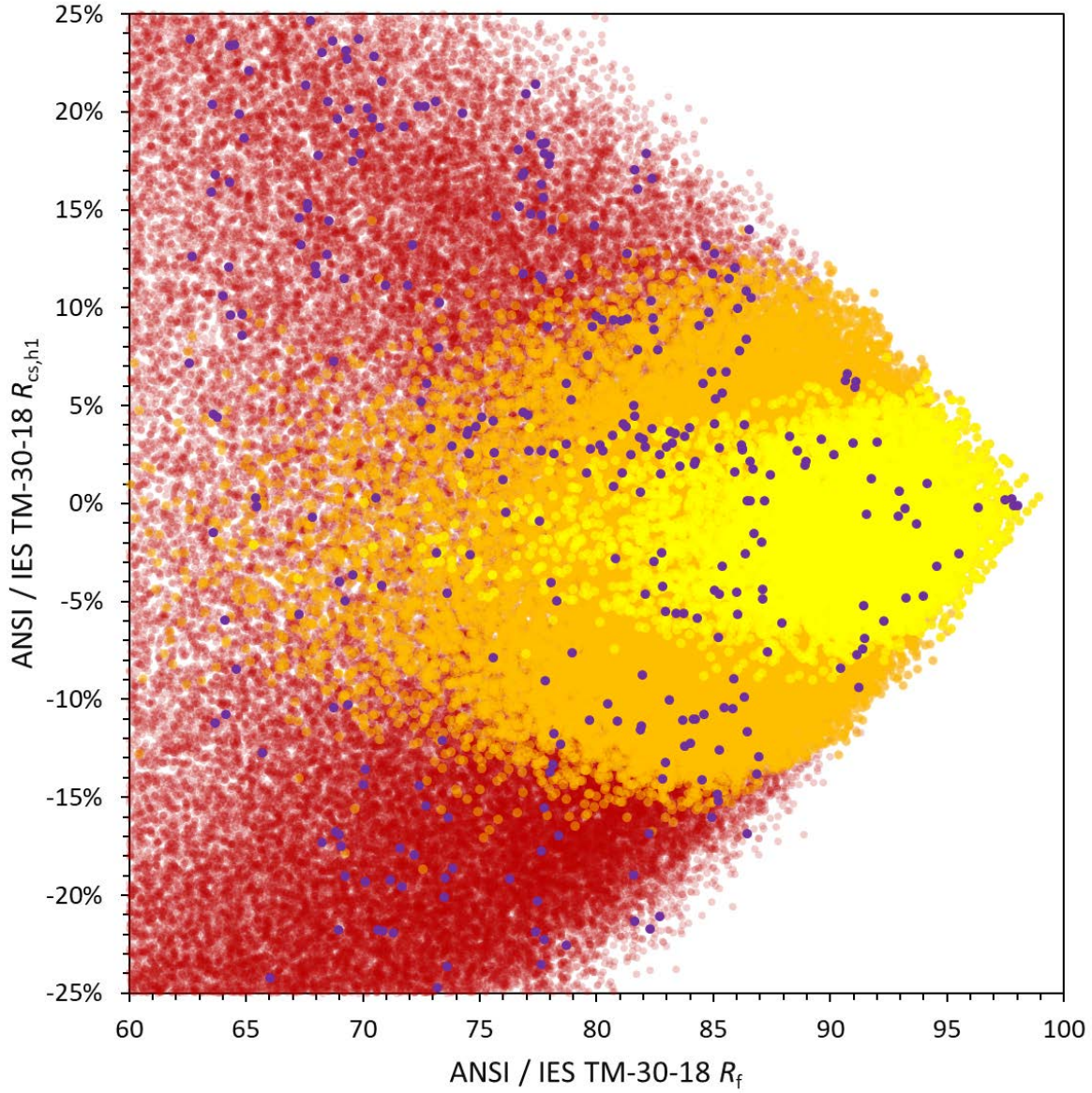
Why?

- Bad models of color vision
- Different types of measures

All Theoretical SPDs

Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$

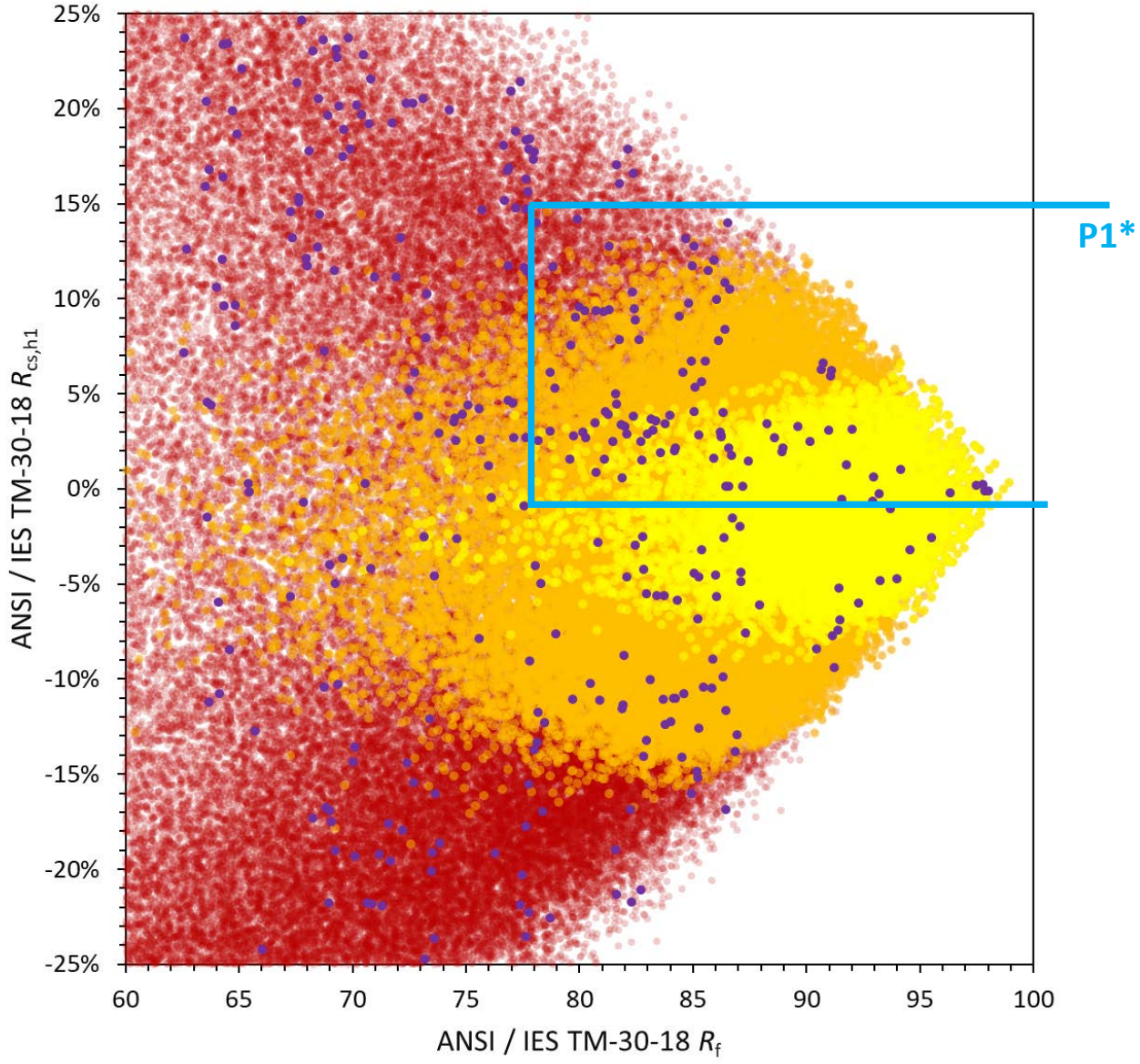
Theoretical SPDs with $R_a \geq 90$ and $R_9 \geq 50$



Experiments

- Test perception of wide range of characteristics
- What do people like? Find natural? Consider acceptable? Etc.

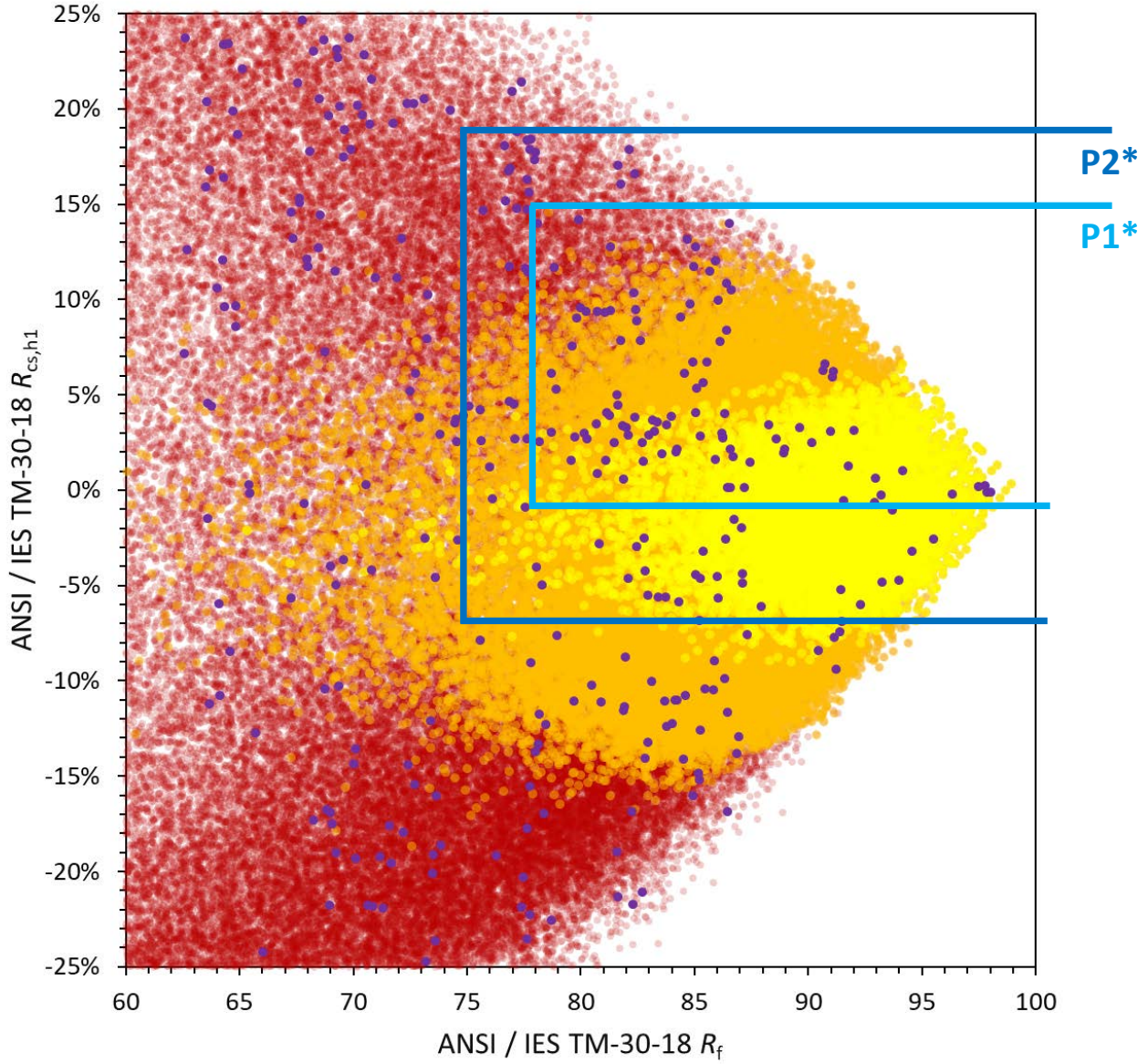
All Theoretical SPDs
Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$
Theoretical SPDs with $R_a \geq 90$ and $R_9 \geq 50$
Experimental SPDs



Most Preferred

- TM-30 P1* *[DRAFT]*
- DLC v5.0 Tier 1
- Most > 90% Acceptability

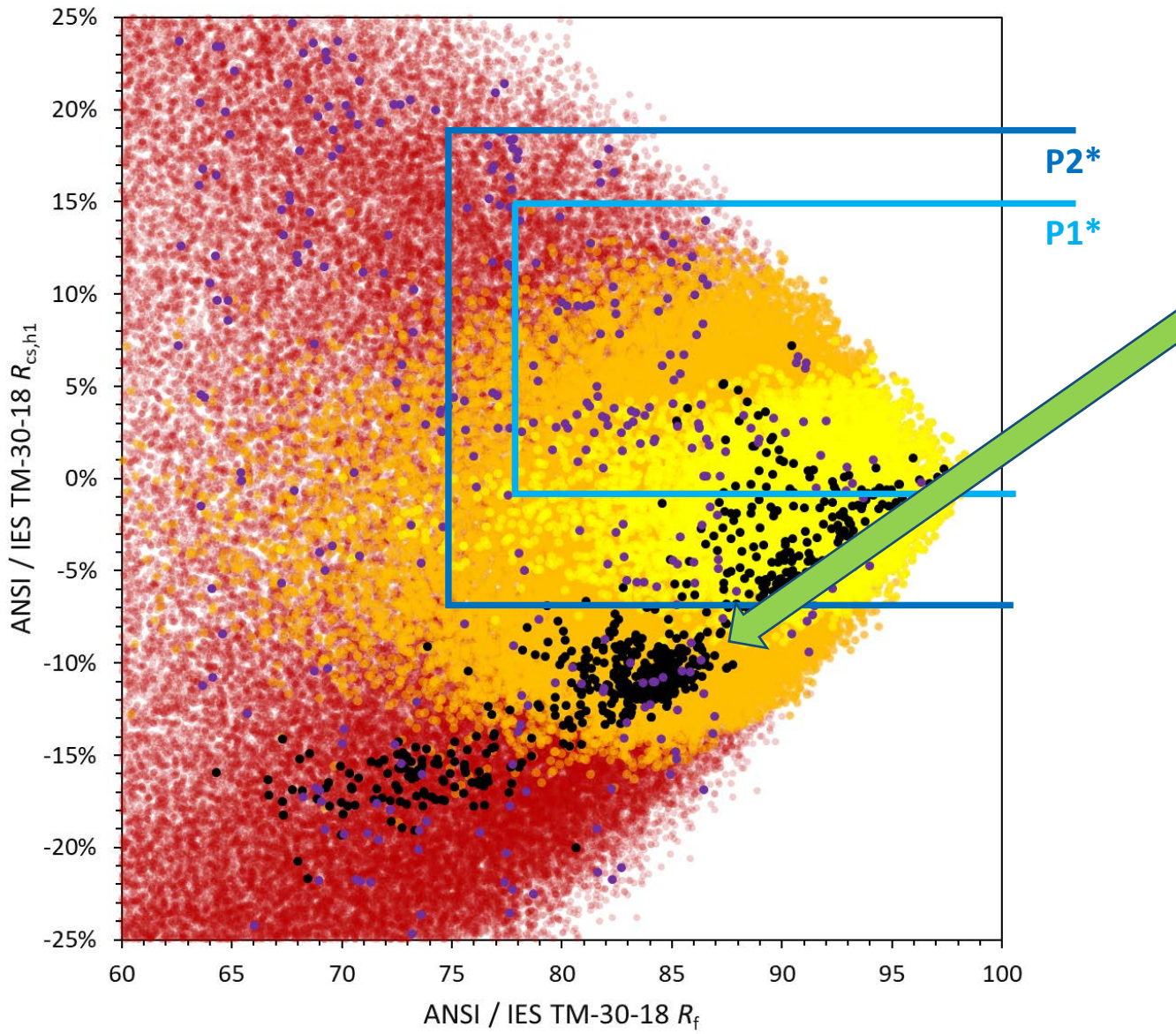
All Theoretical SPDs
Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$
Theoretical SPDs with $R_a \geq 90$ and $R_9 \geq 50$
Experimental SPDs



Also Preferred

- TM-30 P2* *[DRAFT]*
- Not in DLC
- Most > 80% Acceptability

All Theoretical SPDs
Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$
Theoretical SPDs with $R_a \geq 90$ and $R_9 \geq 50$
Experimental SPDs



What's on the market?

- ~ 60% of products
- ~ 80% of CRI ≥ 80 products between 80 and 85

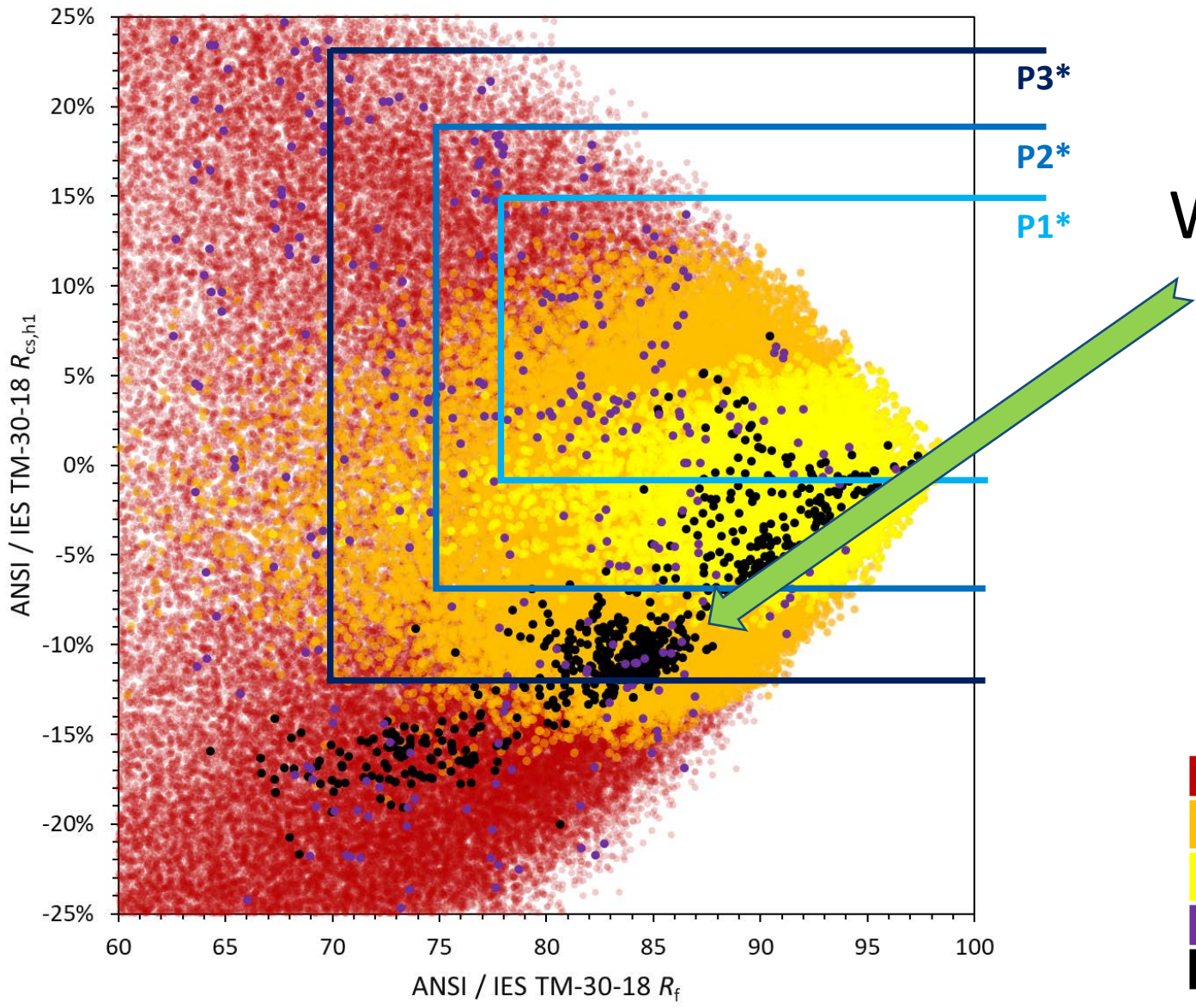
All Theoretical SPDs

Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$

Theoretical SPDs with $R_a \geq 90$ and $R_9 \geq 50$

Experimental SPDs

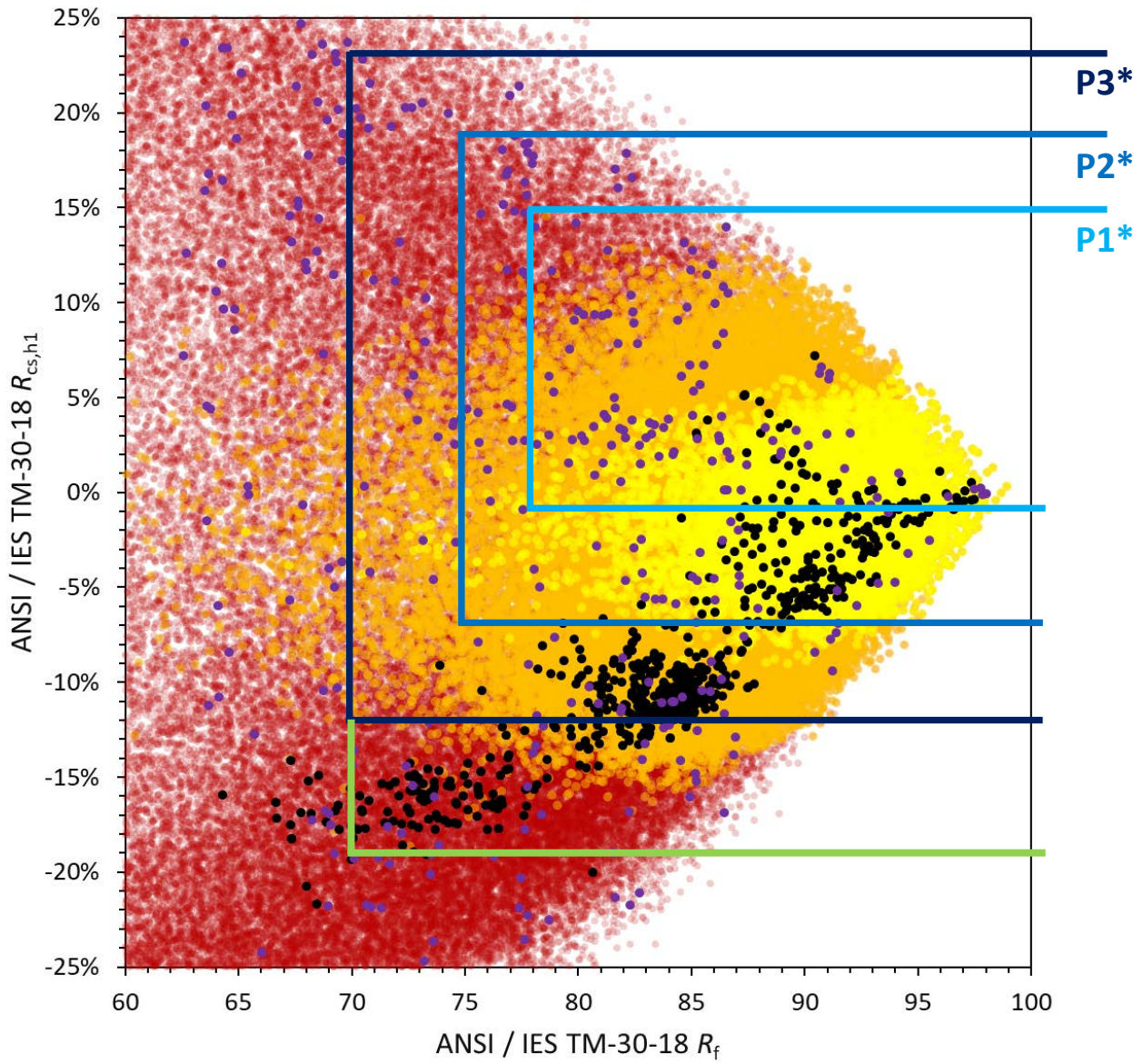
Commercially-Available LED SPDs



What's on the market?

- ~ 60% of products
- ~ 80% of CRI ≥ 80 products between 80 and 85
- TM-30 P3* *[DRAFT]*
- DLC v5.0 Tier 2
- Most > 65% Acceptability

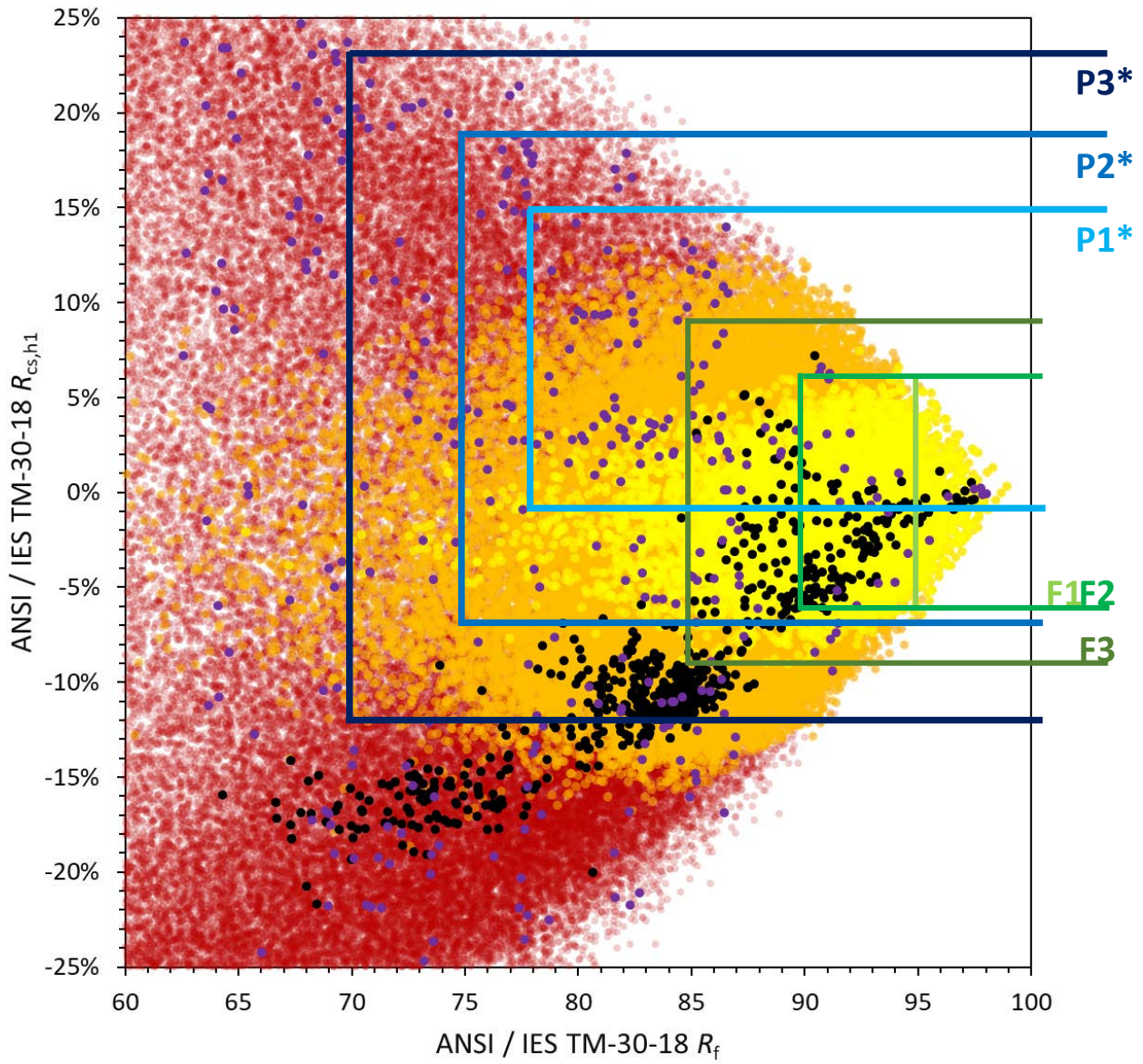
All Theoretical SPDs
Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$
Theoretical SPDs with $R_a \geq 90$ and $R_9 \geq 50$
Experimental SPDs
Commercially-Available LED SPDs



Outdoor?

- Tier 3?
- 98% of available products with $R_a \geq 70$

All Theoretical SPDs
Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$
Theoretical SPDs with $R_a \geq 90$ and $R_9 \geq 50$
Experimental SPDs
Commercially-Available LED SPDs



Fidelity Spec (R_f & $R_{f,h1}$)

- Alternative where design intent is different

All Theoretical SPDs
Theoretical SPDs with $R_a \geq 80$ and $R_9 \geq 0$
Theoretical SPDs with $R_a \geq 90$ and $R_9 \geq 50$
Experimental SPDs
Commercially-Available LED SPDs

Thank You

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