Engineered spectra for SSL applications

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R&D Illumination Systems

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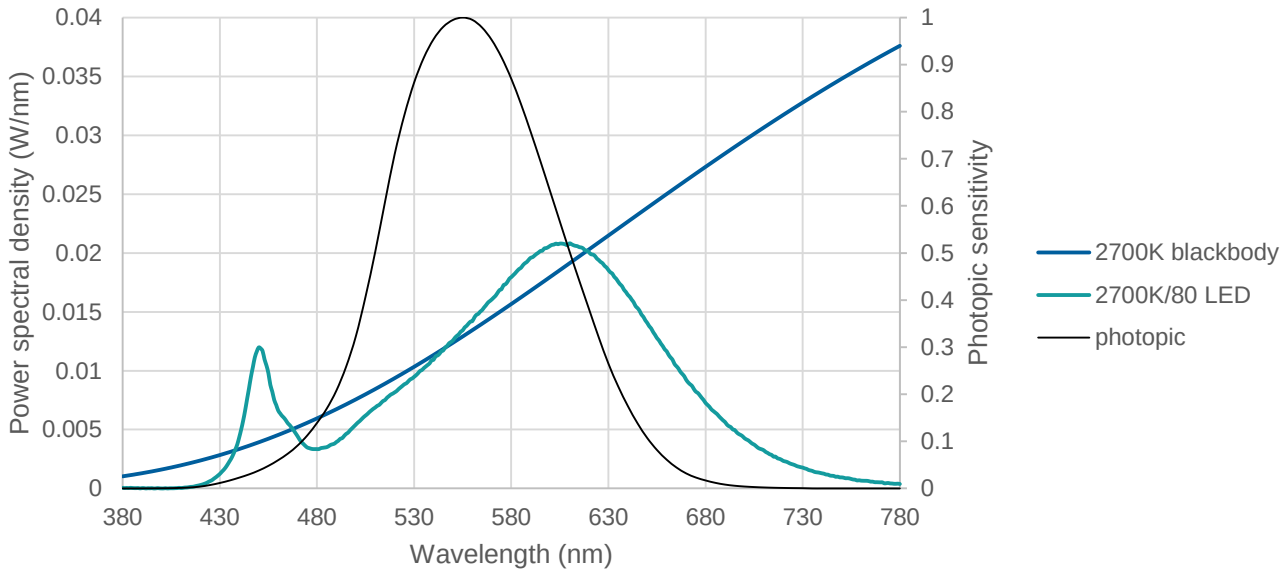
LUMILEDS

Spectral engineering in the past



Key metrics

Color temperature
CCT

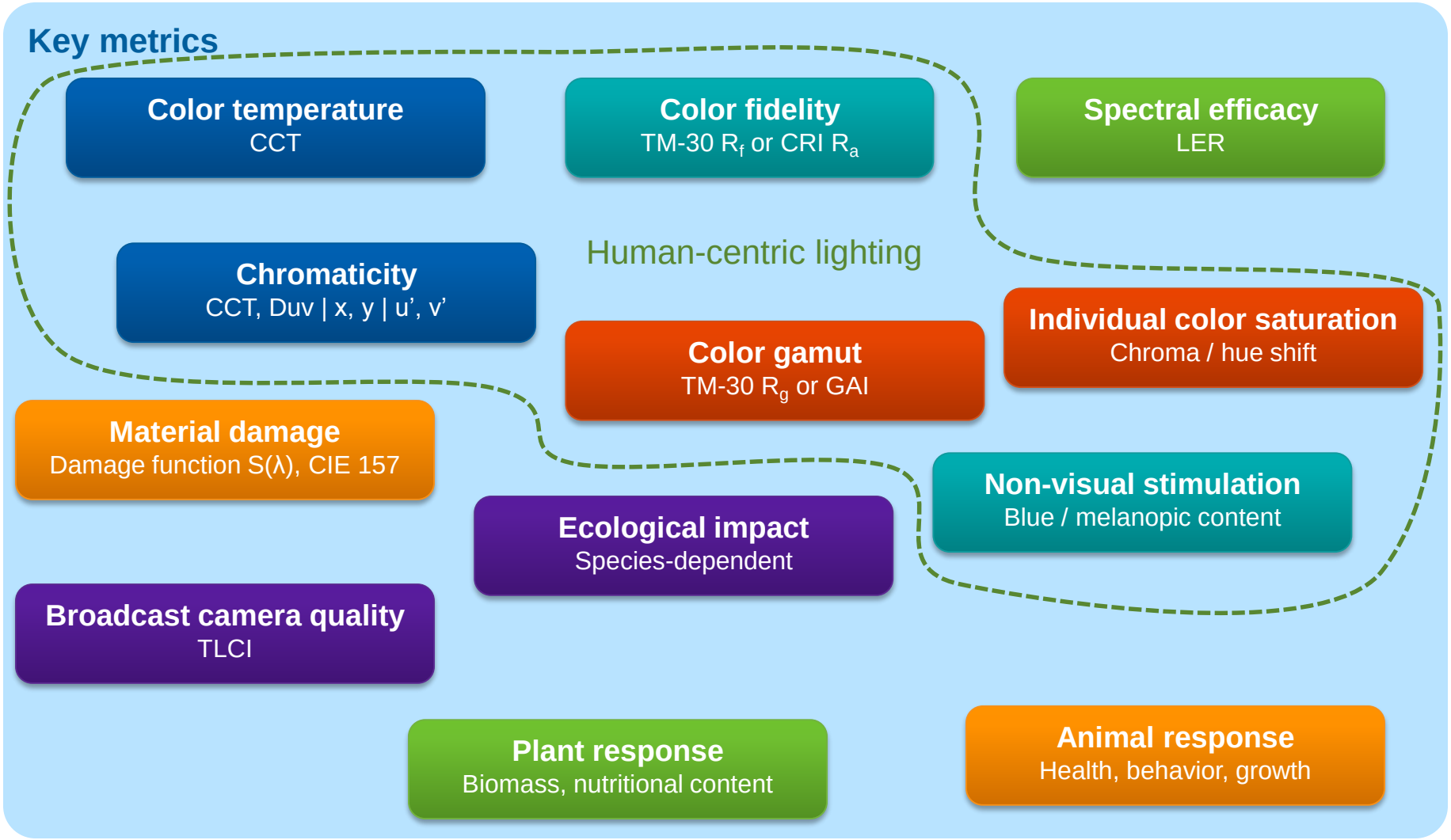
Color fidelity
CRI R_a or TM-30 R_f

Spectral efficacy
LER

This approach to spectral engineering is changing because

- Improved red phosphors remove tradeoffs between efficacy and CCT/CRI
- New applications require an extended set of metrics to measure spectra

Spectral engineering in the future



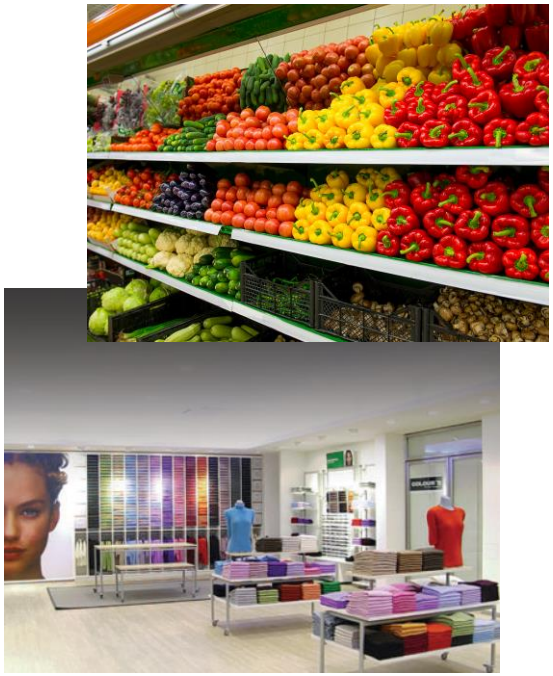
pc-LED spectral engineering toolbox

Blue pump LEDs	Green phosphors	Yellow to red phosphors	Narrow red phosphors
(InGaN)	(YAG, other garnet)	(nitrides)	(e.g. SLA)
Peak ~430-460 nm	Peak ~520-560 nm	Peak ~570+ nm	Peak ~630-650 nm
FWHM ~30 nm	FWHM ~110 nm	FWHM ~75 nm	FWHM ~50 nm

Phosphor-converted (pc) LEDs vs. color-mixed (cm) LEDs

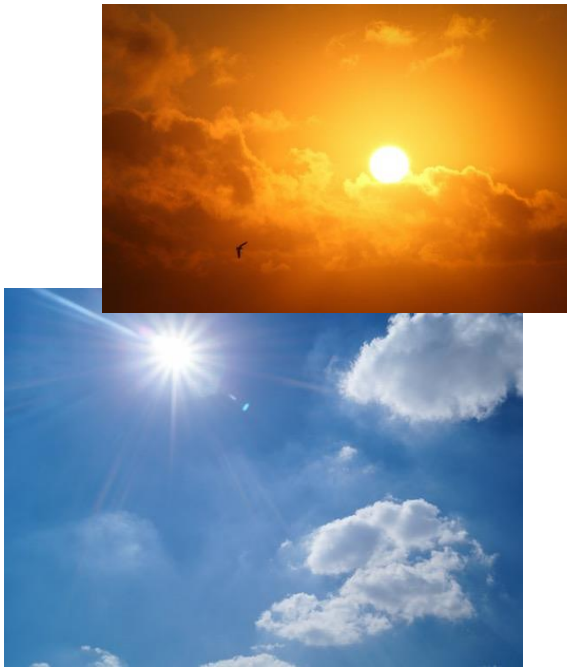
+ Highest efficacy with state-of-the-art technology
+ Color control by material design
- Broader spectral width than direct emitters
  (but narrow-band phosphors emerging)

Example applications



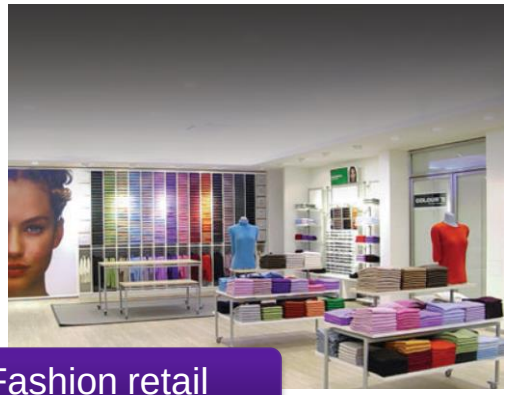
Retail lighting

Outdoor lighting



Circadian lighting

Engineered spectra for retail lighting



Fashion retail

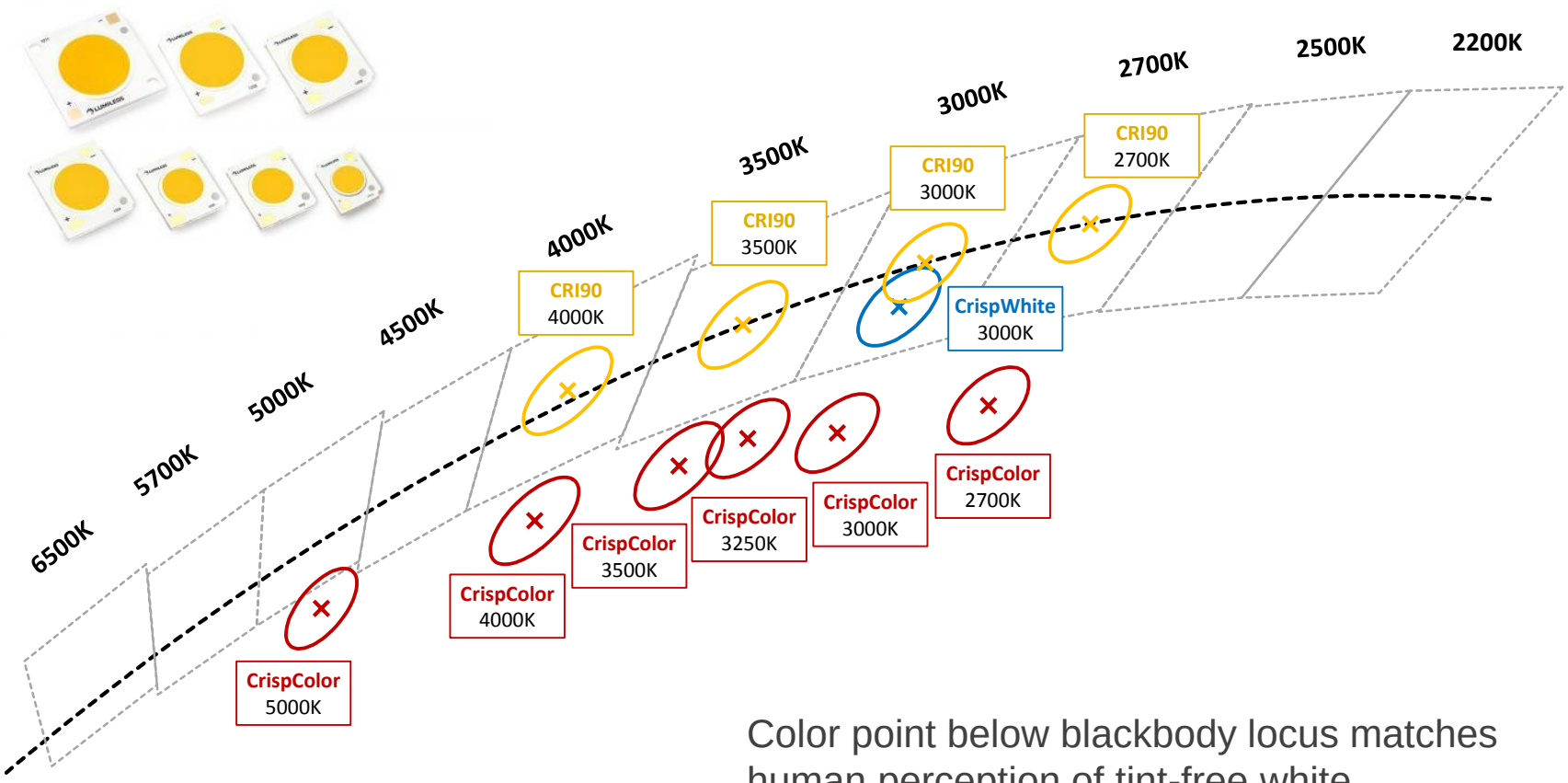
Fresh food

Spectral metric	Importance for retail lighting
Color point	On- and off-Planckian
Color fidelity	Somewhat natural colors
Color gamut	Precise control of color saturation
Efficacy	Considered when other criteria are met

Primary metric

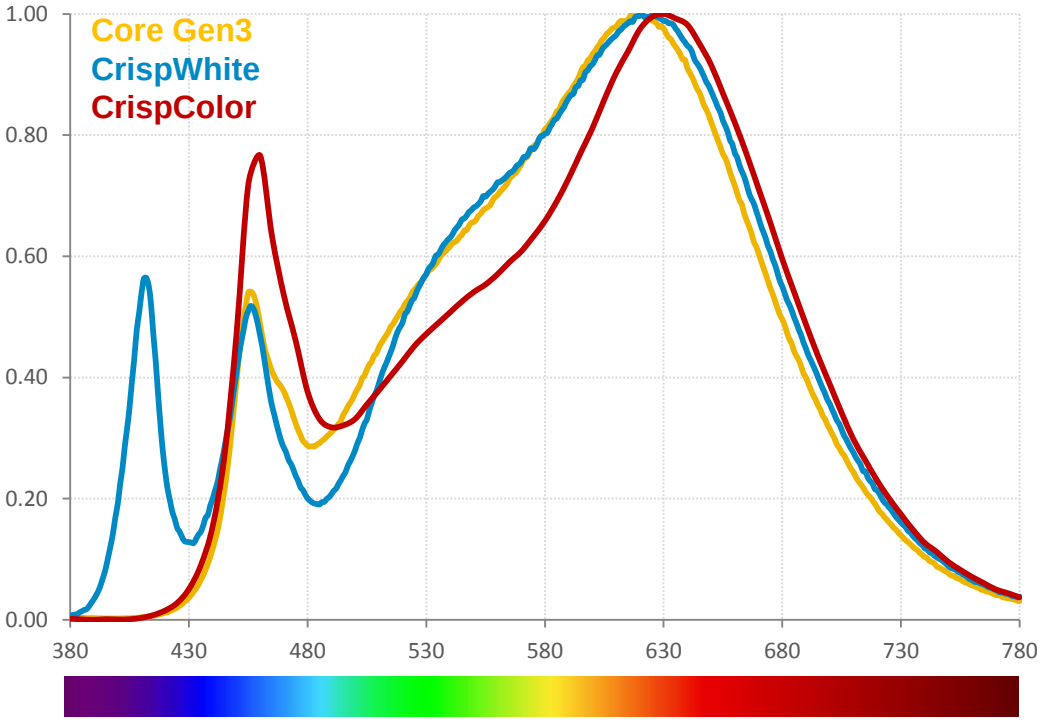
Secondary metric

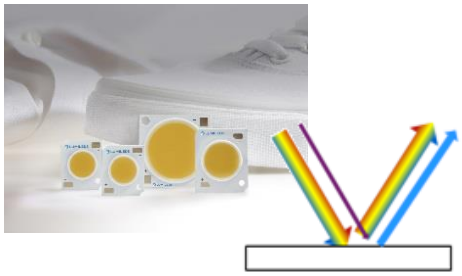
Fashion retail | Optimized color point



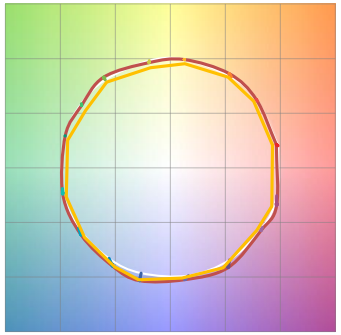
Color point below blackbody locus matches human perception of tint-free white

Fashion retail | Color gamut and white rendition





CrispWhite
Bright white from FWAs activated by violet

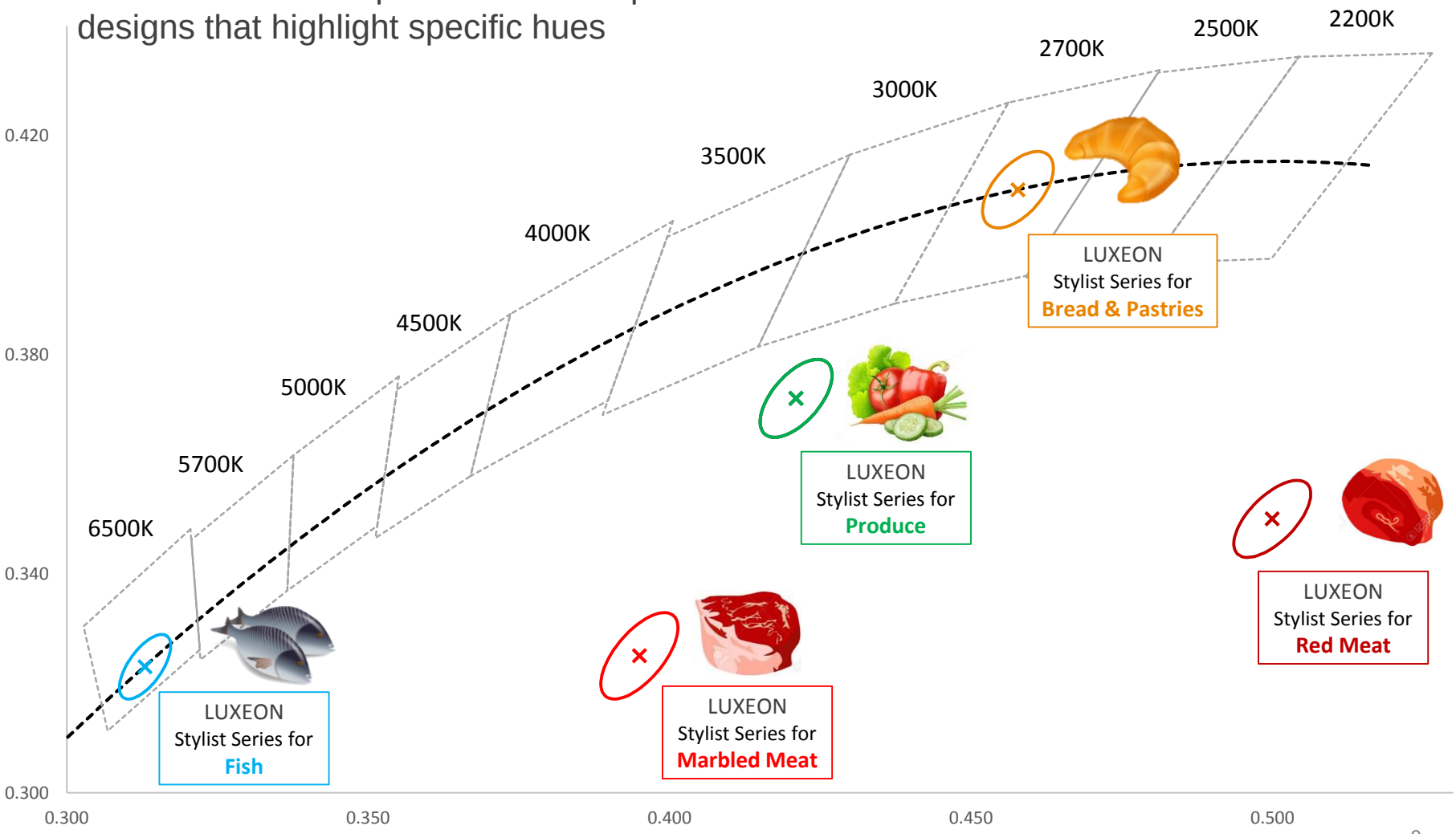


CrispColor
Increased color gamut for more vivid colors

LED	Type	CCT	CRI Ra	CRI R9	TM-30 Rf	TM-30 Rg	Efficacy (lm/W)
LUXEON CoB 1211	Core 3090	3,000K	93	63	89	97	120
	CrispWhite	3,000K	91	61	87	102	100
	CrispColor	3,000K	95	94	92	103	107

Fresh food | Optimized color point

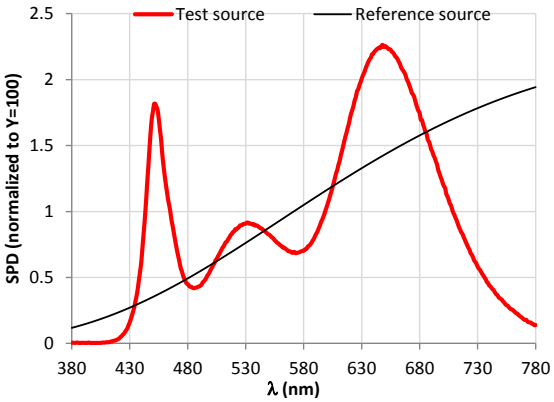
Off-Planckian color points allow for spectral designs that highlight specific hues

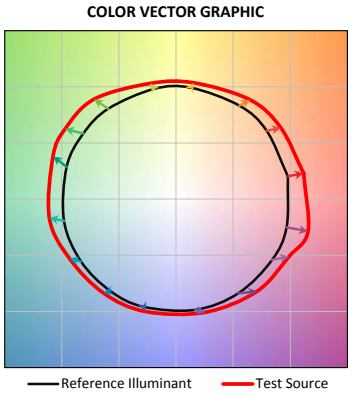


Fresh food | Color gamut and saturation

Spectrum for
Marbled Meat

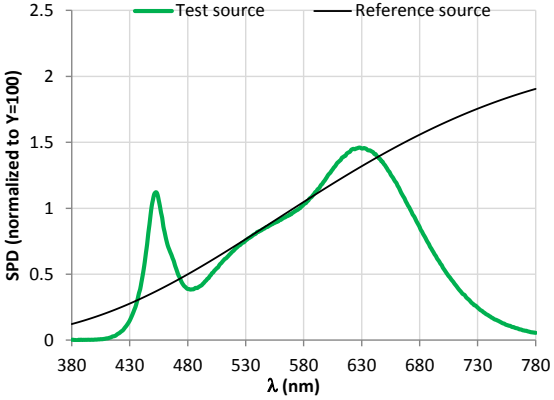
Enhances red and white marble texture without yellowish appearance

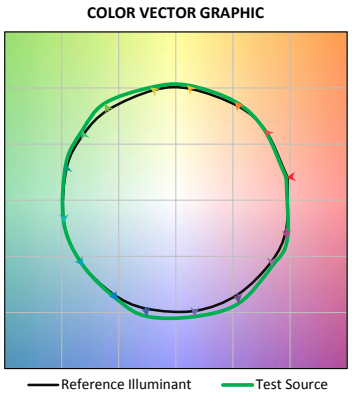


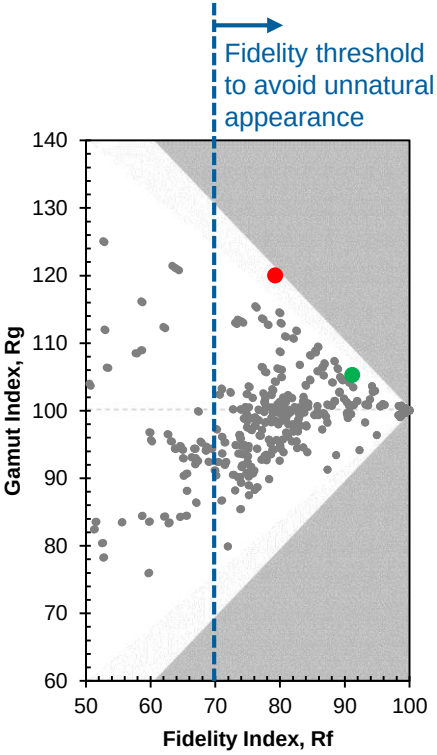


Spectrum for
Produce

Renders green through red colors with high saturation and fidelity







LED	Type	CCT	CRI Ra	CRI R9	TM-30 Rf	TM-30 Rg	Efficacy (lm/W)
LUXEON CoB 1211	Core 3090	3,000K	93	63	89	97	120
	Marbled Meat	~3,000K	67	-23	79	120	71
	Produce	~3,000K	95	94	91	105	107

Engineered spectra for outdoor lighting

Spectral metric	Importance for outdoor lighting
Color point	Visual comfort, safety and visibility
Efficacy	Main adoption driver
Non-visual response	Illuminance often low enough to have minimal impact
Ecological impact	Skyglow, animal wildlife and plant photoperiodism

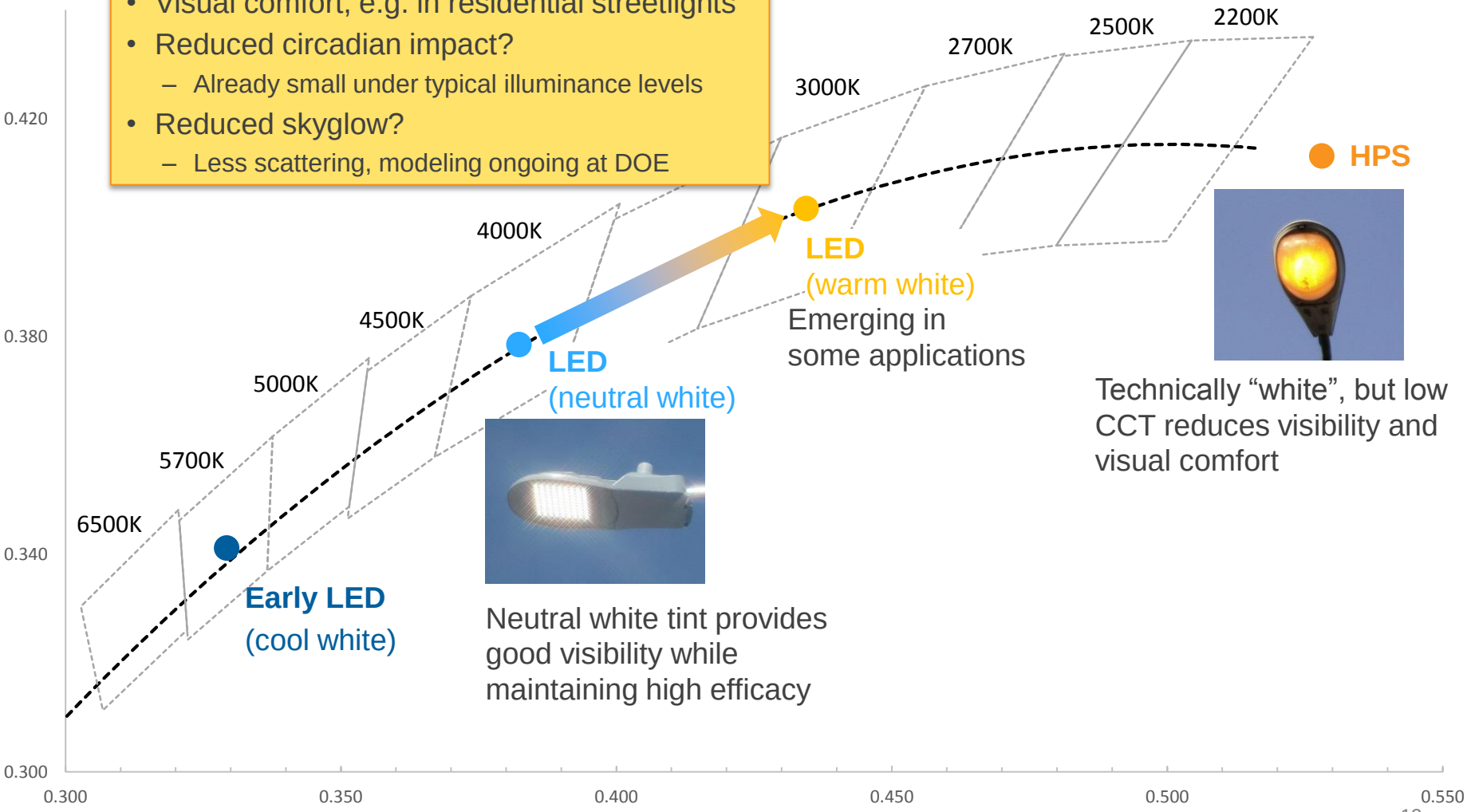
Primary metric

Secondary metric

Chromaticity in outdoor lighting

Motivation for warm white outdoor lighting

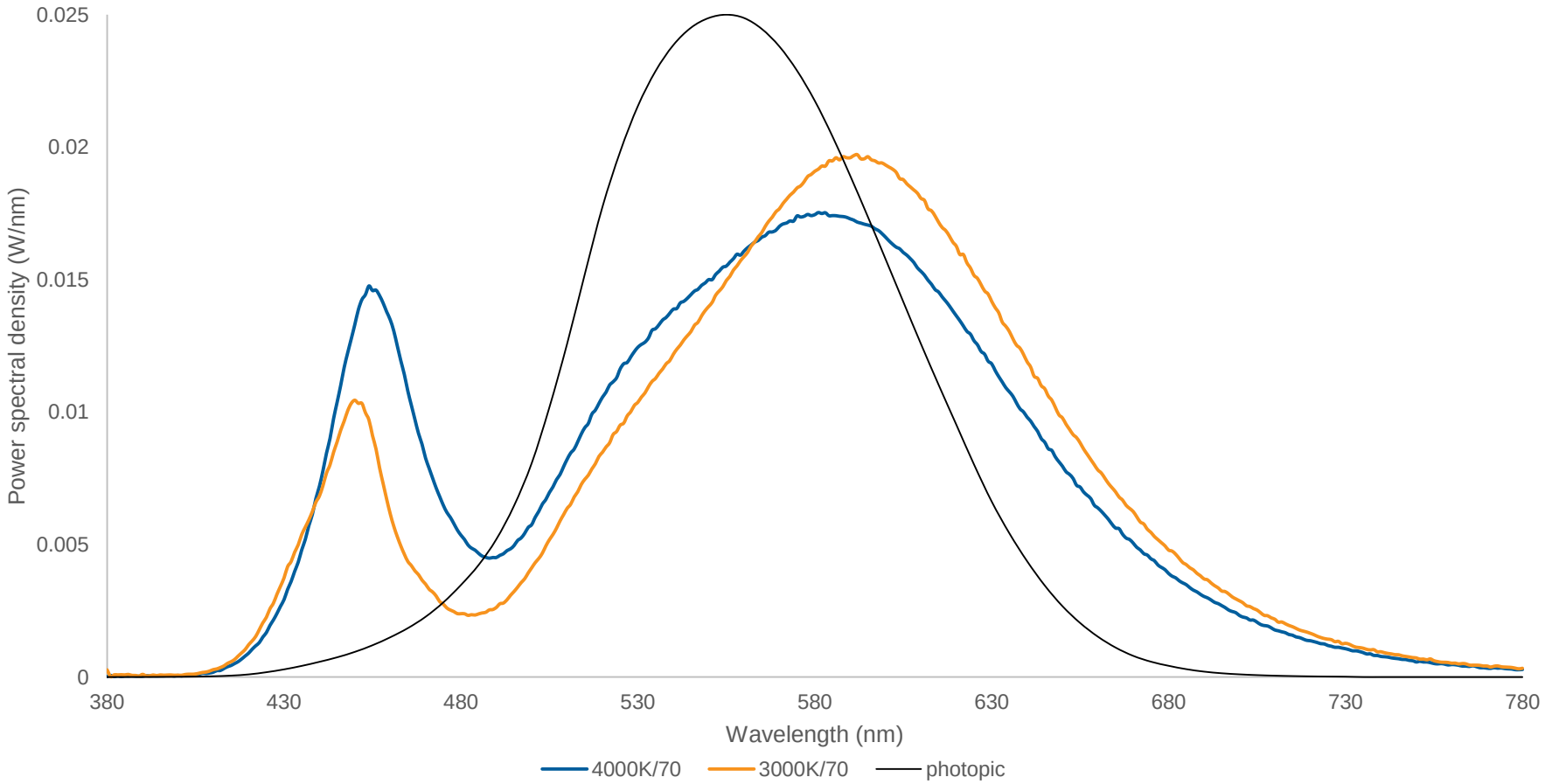
- Visual comfort, e.g. in residential streetlights
- Reduced circadian impact?
  - Already small under typical illuminance levels
- Reduced skyglow?
  - Less scattering, modeling ongoing at DOE



Increasing spectral efficacy of warm-white pc-LEDs

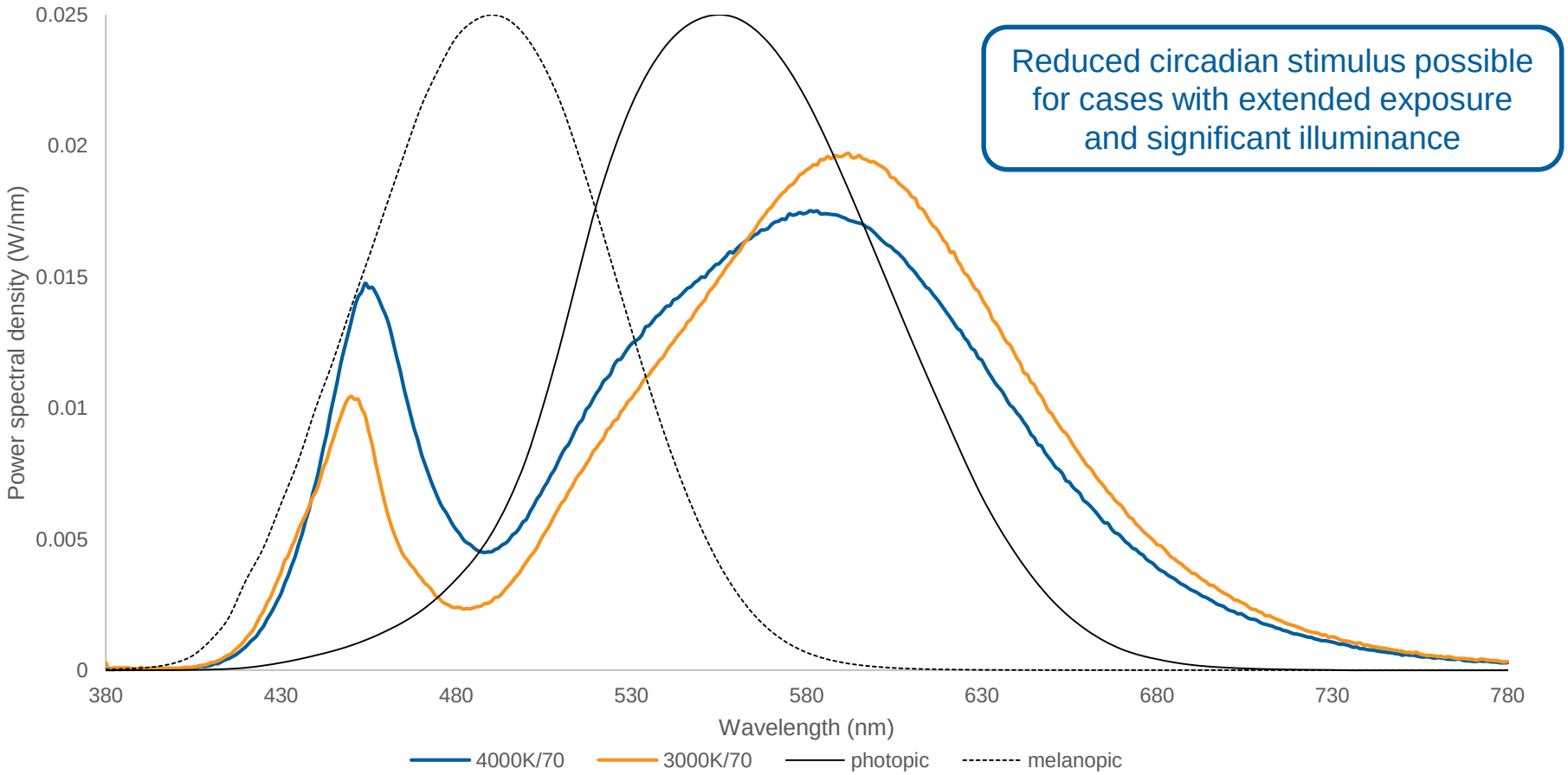
lm/W_{opt}	4000K/70	3000K/70	3000K high efficacy
LER	342	347	417
LER*QD	280	274	330

Eliminating CRI>70 requirement enables ~20% gain using phosphor technology available today



Circadian impact of high-efficacy warm-white spectra

Metric	4000K/70	3000K/70	3000K high efficacy
Melanopic content (α-opic lux / lux)	0.631	0.448	0.286
Blue light content (405-530 nm, µW/lm)	875	617	427

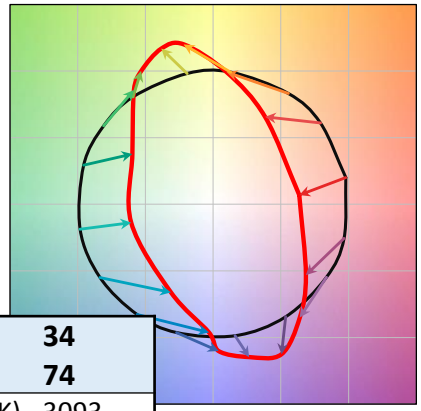


Reduced circadian stimulus possible for cases with extended exposure and significant illuminance

…but what about color rendering?

3000K high efficacy

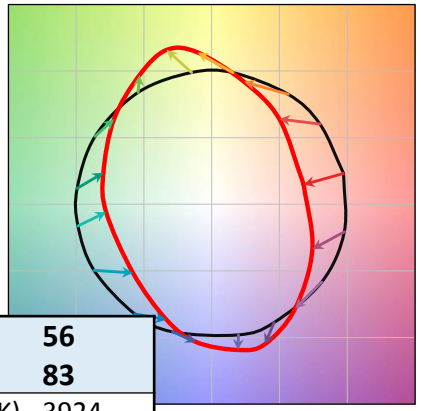
COLOR VECTOR GRAPHIC



R_f	**34**
R_g	**74**
CCT (K)	3093
D_{uv}	-0.0004
CIE R_a	36

Metal halide

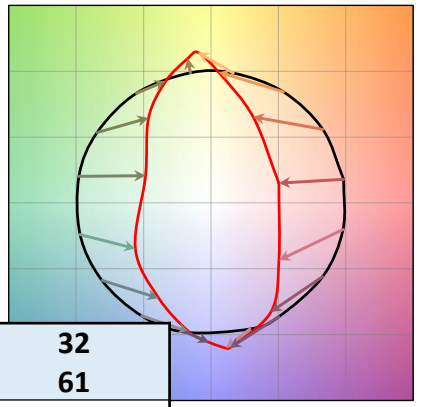
COLOR VECTOR GRAPHIC



R_f	**56**
R_g	**83**
CCT (K)	3924
D_{uv}	-0.0016
CIE R_a	55

HPS

COLOR VECTOR GRAPHIC



R_f	**32**
R_g	**61**
CCT (K)	1971
D_{uv}	-0.0001
CIE R_a	17

- CRI and TM-30 are specified relative to reference source of same CCT as test source
- Sources with <2000K have very little blue-green content
  - Object colors in this range are hard to distinguish even with high R_a and R_f
- Practical white sources (2700-6500K) have a more equal energy distribution
  - Better overall color visibility despite lower R_a or R_f

Practical white pc-LED spectra in the 2700K-6500K range have color rendering acceptable for many outdoor applications despite low fidelity metrics

2700K, CRI R_a>80,
standard pc-LED spectrum

2700K, CRI R_a=37,
high-efficacy pc-LED spectrum

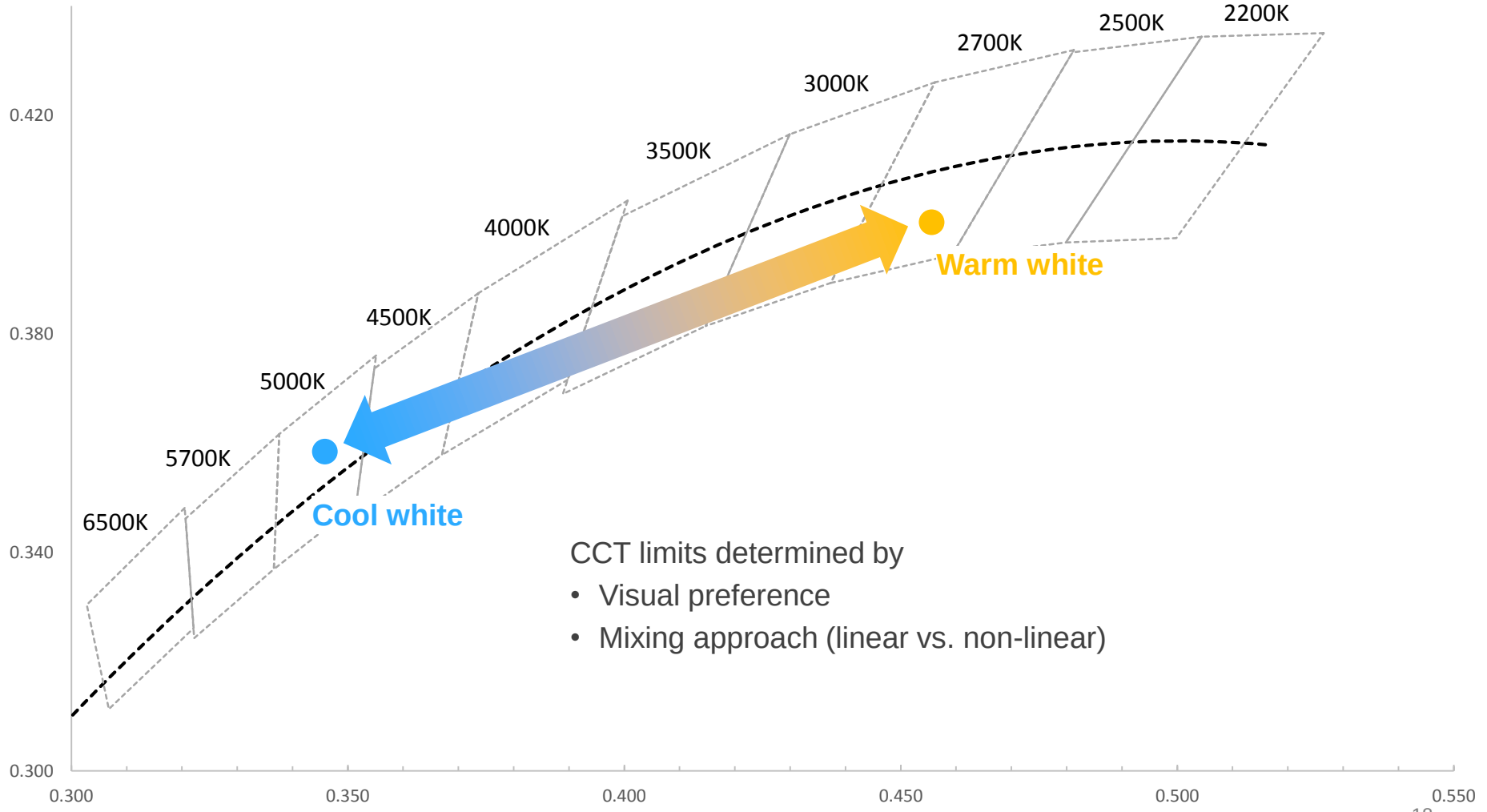
Engineered spectra for circadian lighting

Spectral metric	Importance for circadian lighting
Color point	Visual comfort, “natural” cycle of warm and cool white
Color fidelity	Somewhat natural colors
Non-visual response	Physiological impact mediated by ipRGC
Efficacy	Considered when other criteria are met

Primary metric

Secondary metric

CCT range for circadian lighting



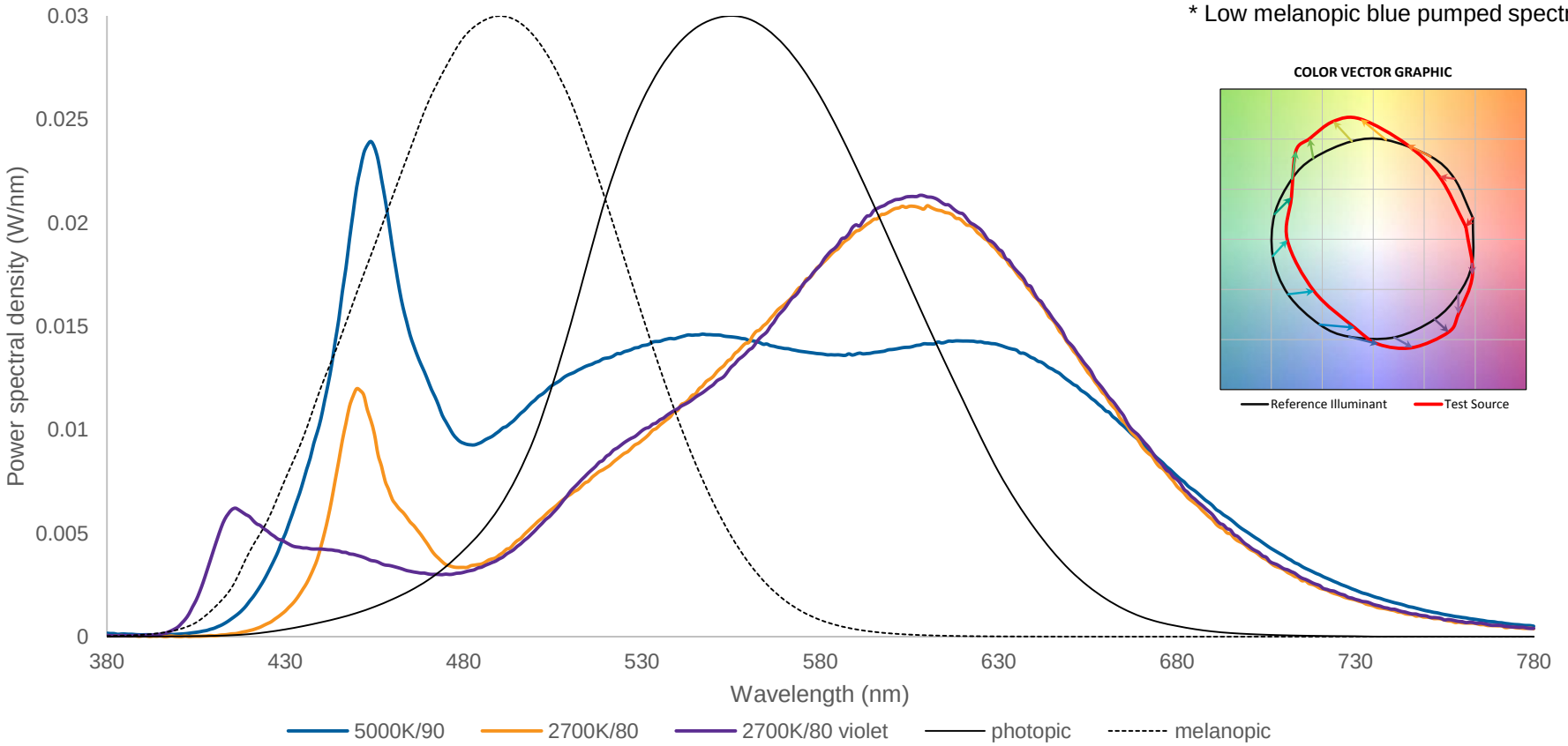
CCT limits determined by

- Visual preference
- Mixing approach (linear vs. non-linear)

Optimizing color rendering and melanopic content

Metric	5000K/90	2700K/80	2700K/80 violet	2700K LM *
Melanopic content (α-opic lux / lux)	0.922	0.468	0.416	0.301
CRI R_a / R_9	97 / 90	82 / 14	82 / 9	69 / 43
TM-30 R_f / R_g	92 / 100	81 / 98	80 / 97	61 / 100

* Low melanopic blue pumped spectrum



Towards application-specific metrics

	General purpose	Retail	Outdoor	Circadian
Color point				
Color fidelity				
Color gamut				
Efficacy				
Non-visual response				
Ecological impact				

Chromaticity is important in virtually all applications

Color fidelity (CRI R_a, TM-30 R_f) is often not the most important metric

Key metrics depend on the application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