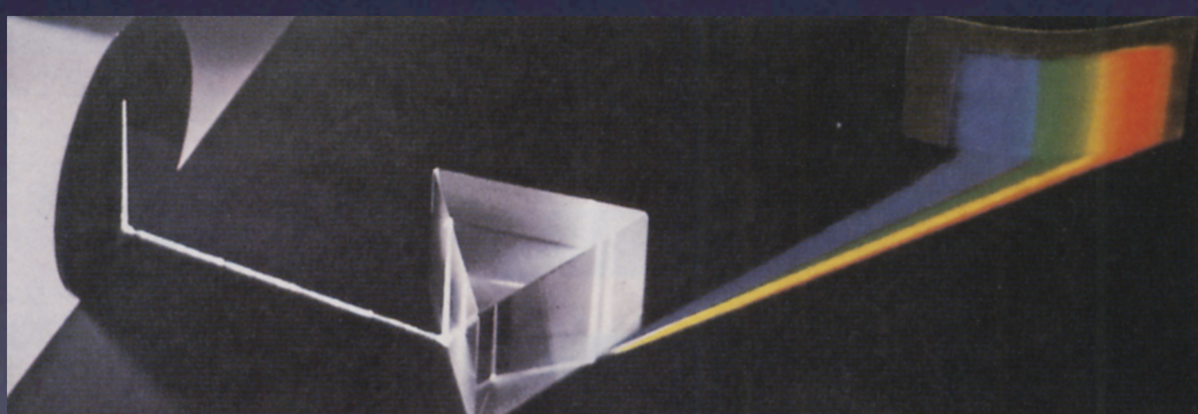
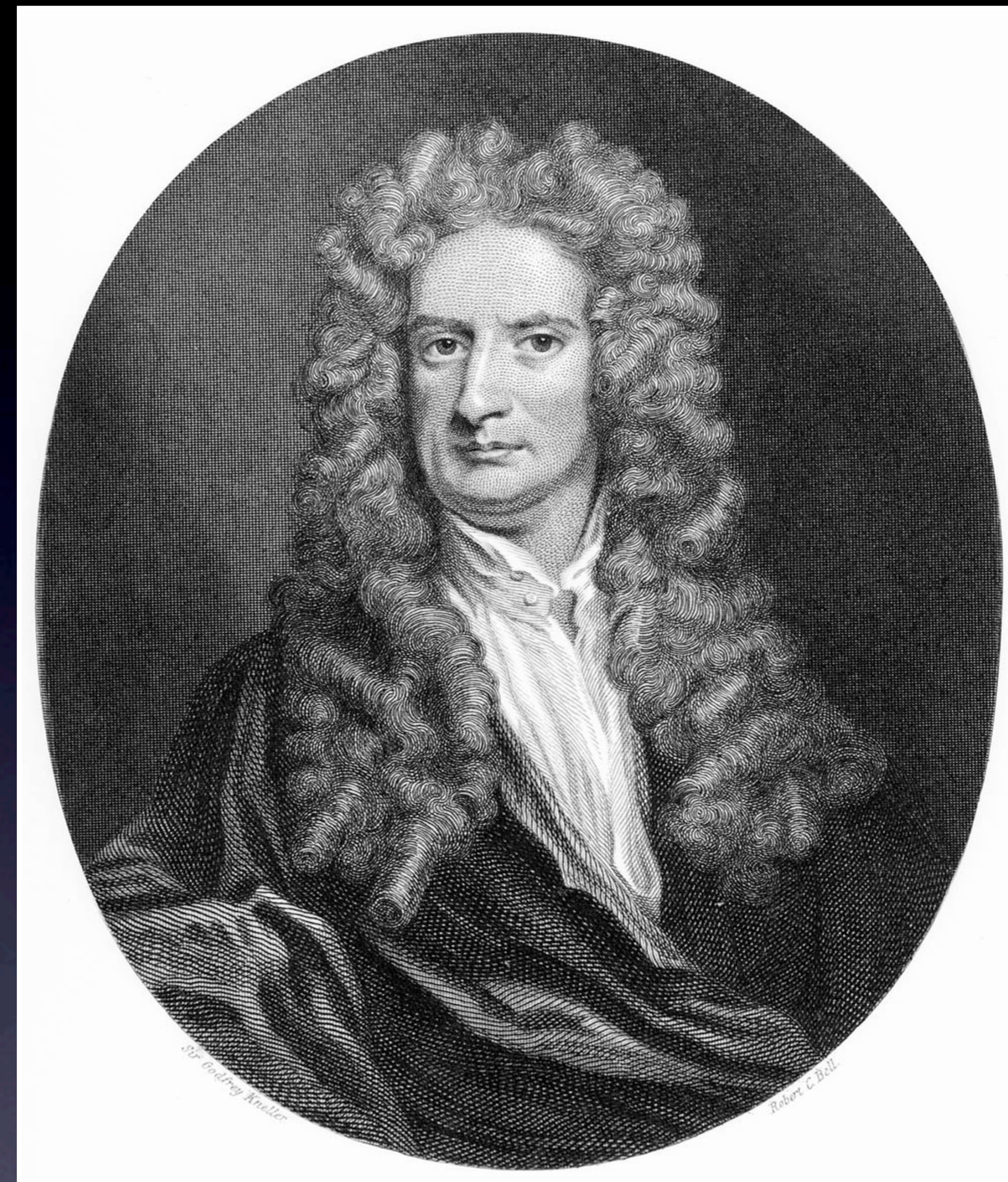
YPS 2011, 2011.9.24, 九十九里

視覚研究者のための
表色の基礎

千葉大学大学院融合科学研究科
矢口博久

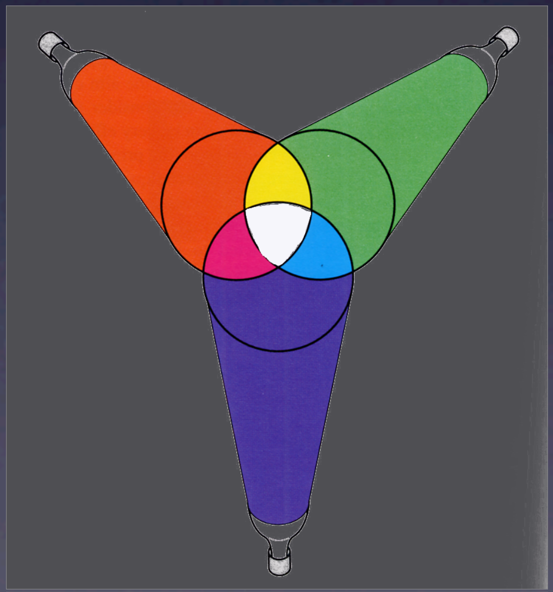
Sir Isaac Newton
(1730)
Rays are not colored.



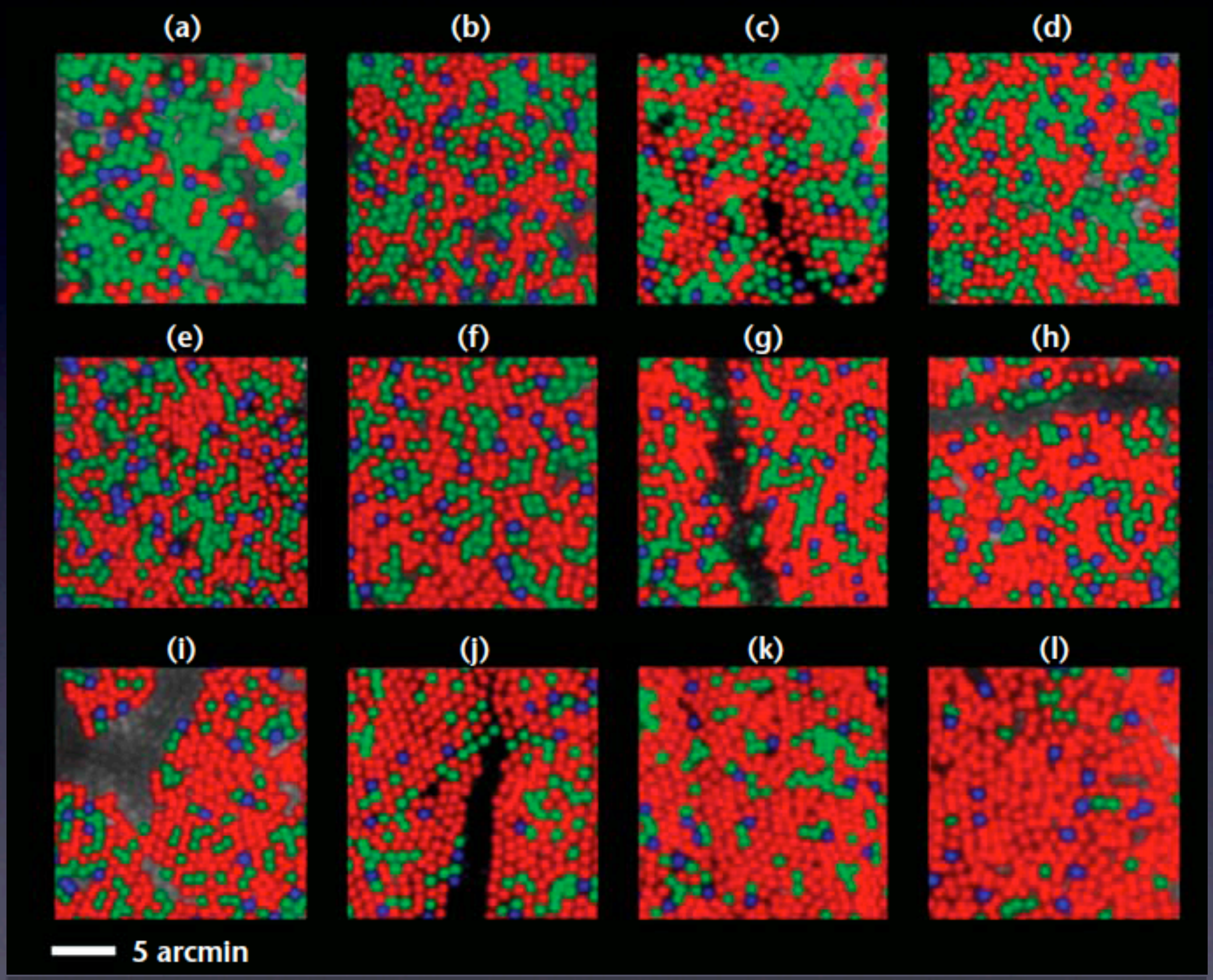


Thomas Young
(1802)
Trichromatic theory

RGB



CMY

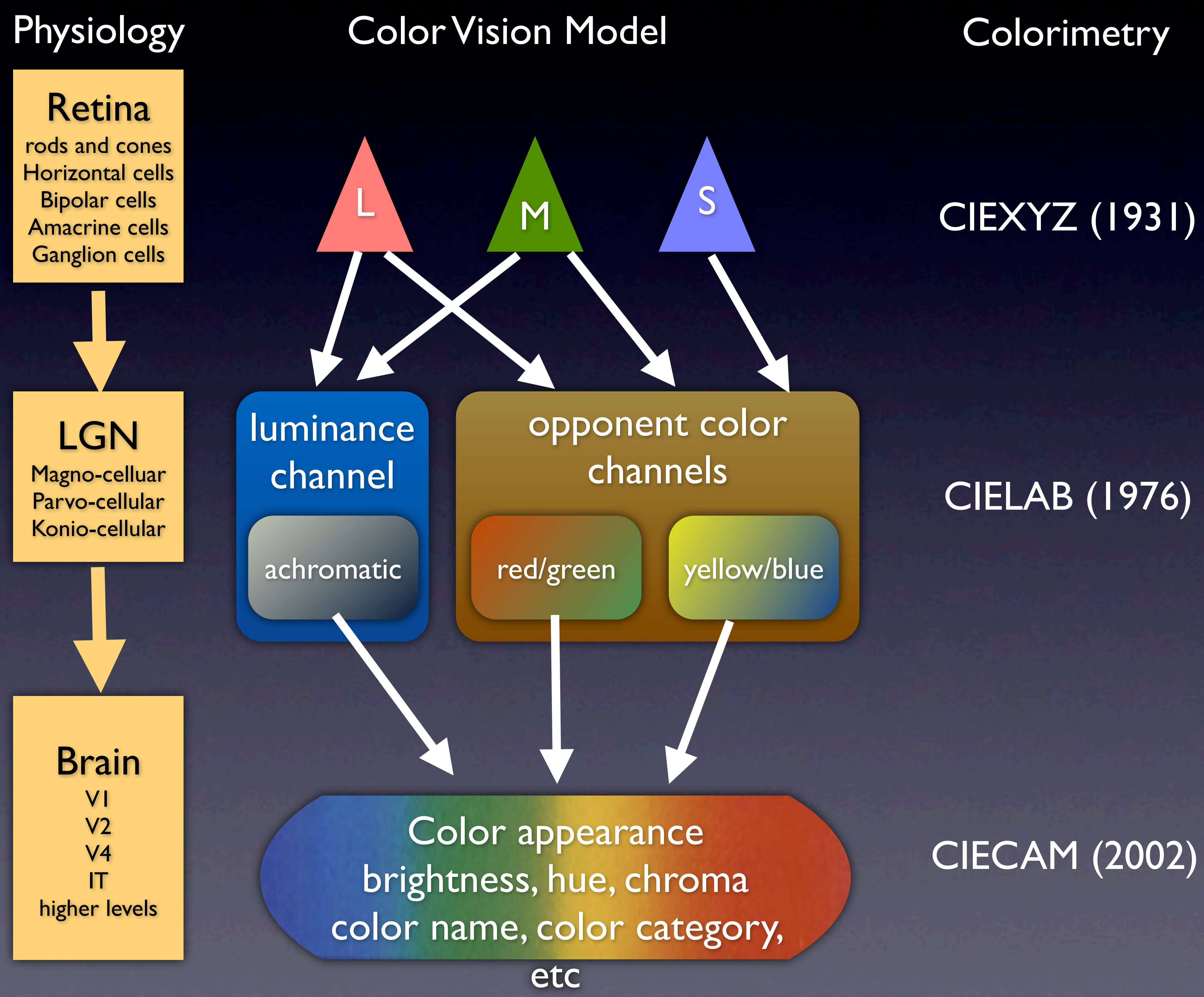


Joseph Carroll, Daniel C. Gray, Austin Roorda and David R. Williams,
Optics & Photonics News, vol. 16, 36-41 (2005)

講義内容

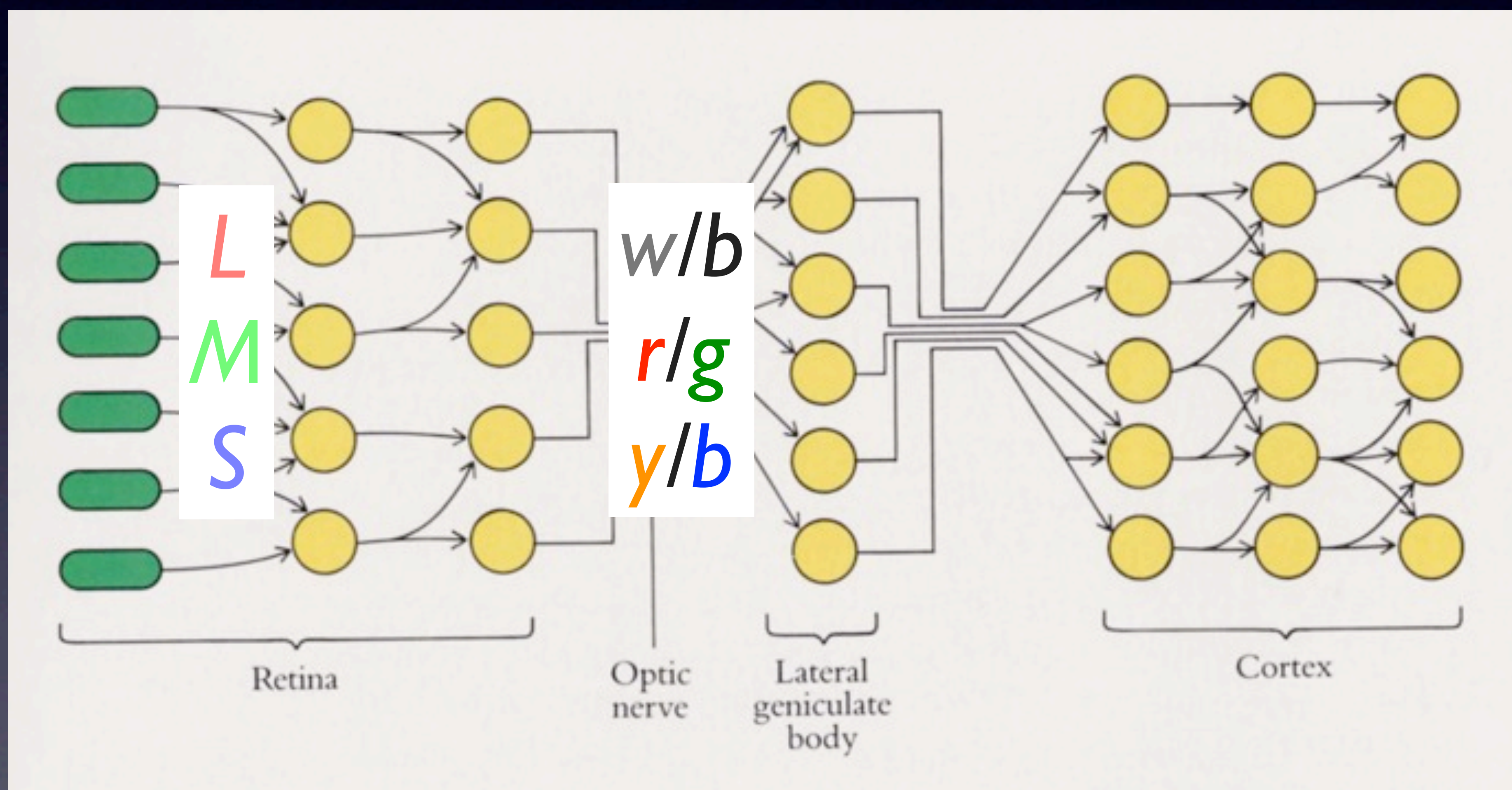
- 表色の歴史と色覚メカニズムの話
- 表色と等色の話
- XYZの話
- LMSの話
- sRGBの話

Color Vision and History of Colorimetry



光→眼→脳→色

$L_{e,\lambda}$

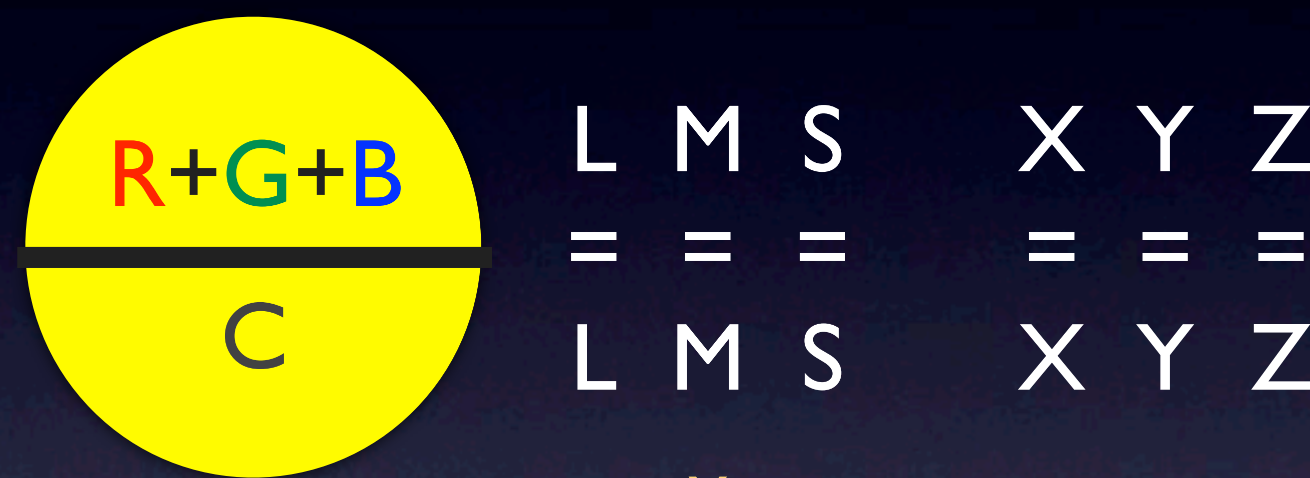


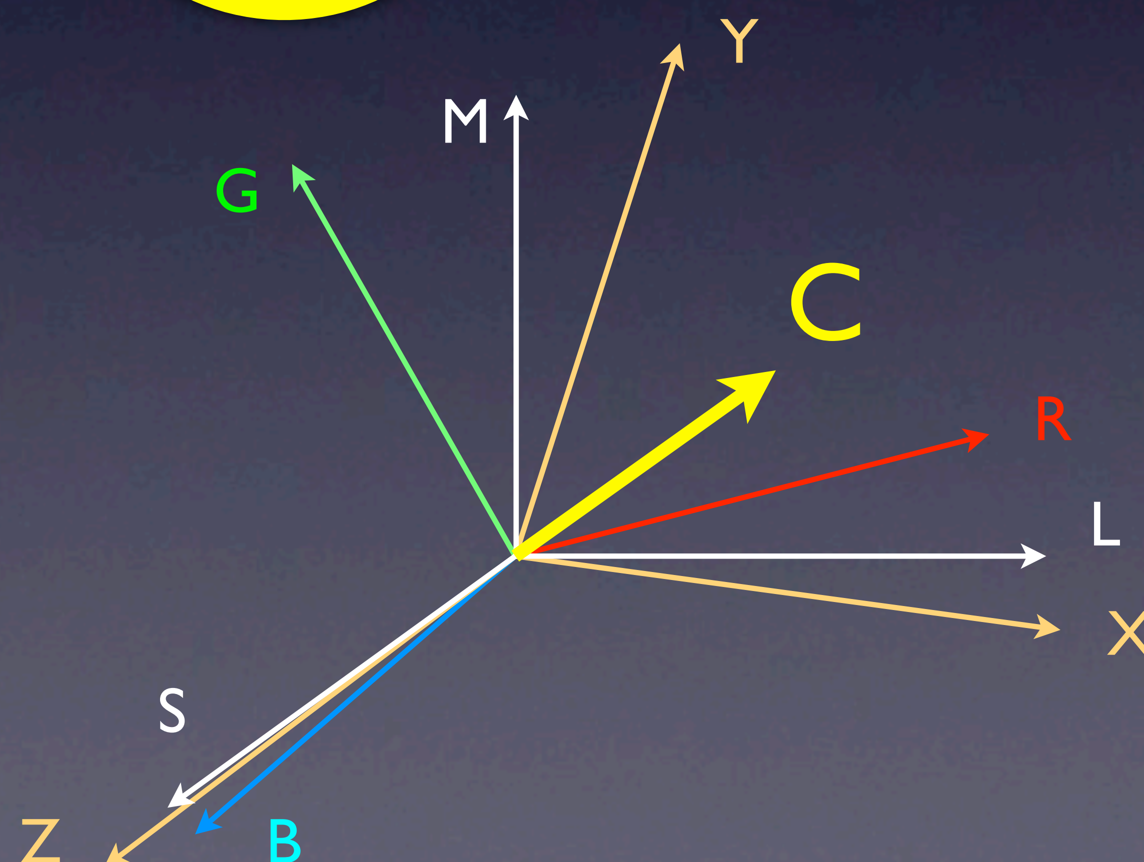
red
green
yellow
blue
purple
brown
pink
orange
gray
white
black

David Hubel, *Eye, Brain and Vision,* Scientific American Library, 1988

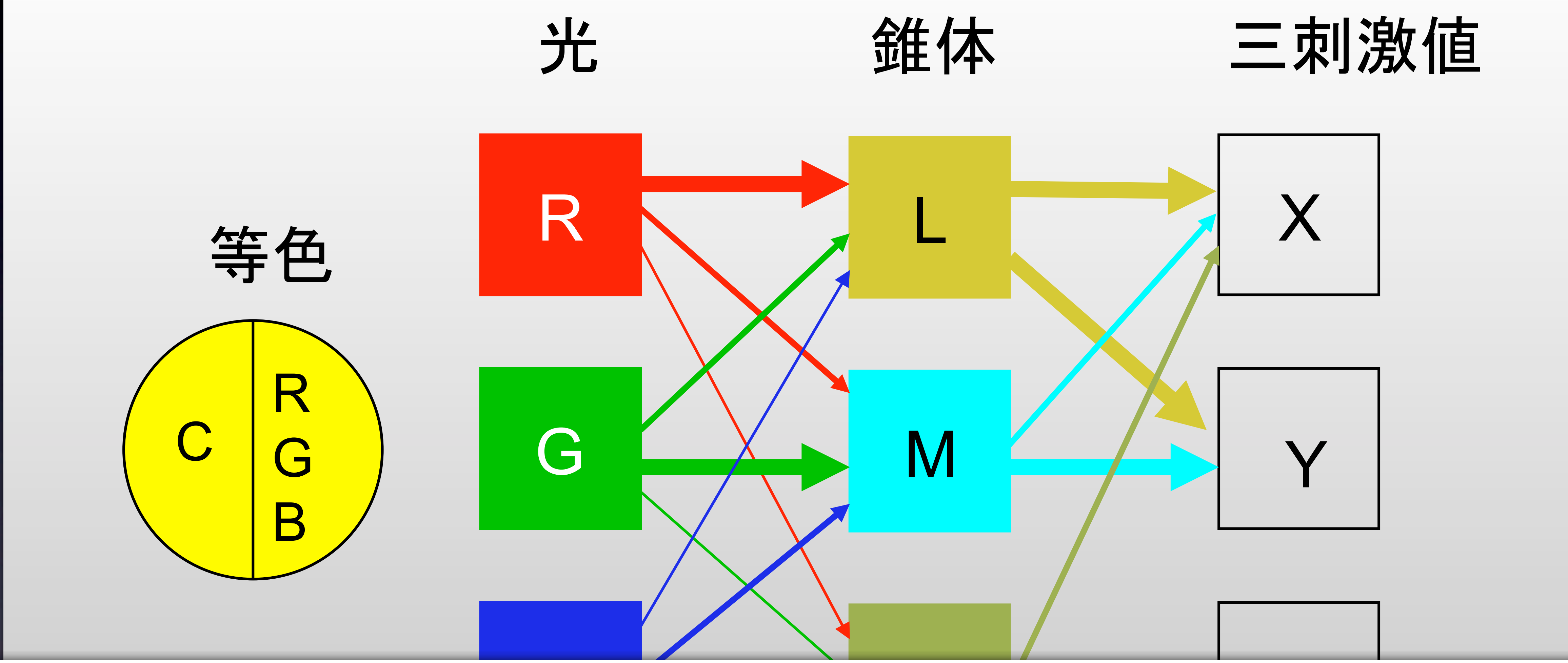
等色と表色
（３つの表色系）

- 物理的表色系(RGB)
- 生理的表色系(LMS)
- 数学的表色系(XYZ)





等色と表色



$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} k_{lr} & k_{lg} & k_{lb} \\ k_{mr} & k_{mg} & k_{mb} \\ k_{sr} & k_{sg} & k_{sb} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} k_{xl} & k_{xm} & k_{xs} \\ k_{yl} & k_{ym} & k_{ys} \\ k_{zl} & k_{zm} & k_{zs} \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}, \quad \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} k_{rx} & k_{ry} & k_{rz} \\ k_{gx} & k_{gy} & k_{gz} \\ k_{bx} & k_{by} & k_{bz} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

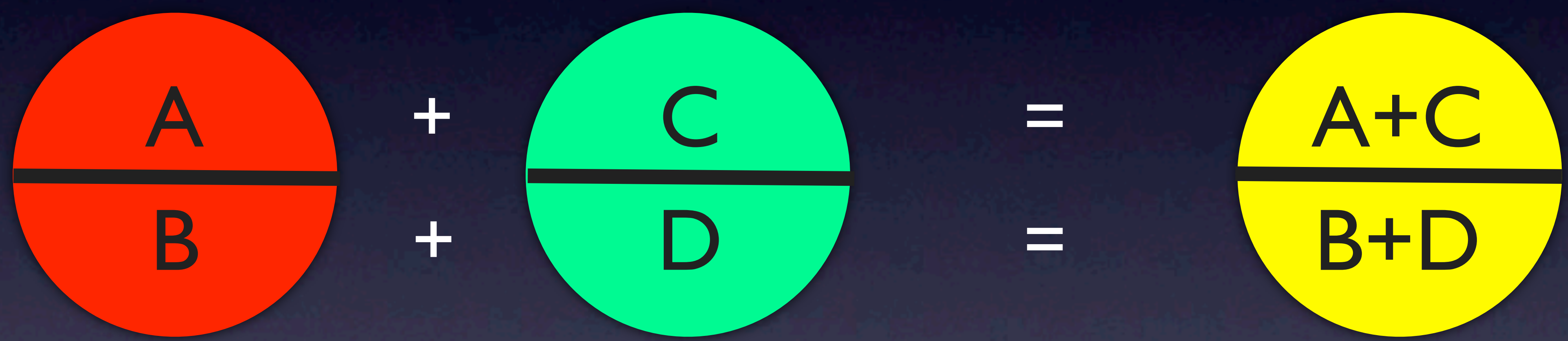
表色系を正しく理解するために重要なこと

- 誰の等色実験のものですか？
  - Wright&Guild？ Stiles&Burch 2°？ 10°？
- 原刺激の色は？
  - R, G, Bの色空間での方向は？
  - L, M, Sの方向は？混同色点は？
  - これにより線形変換行列の値を決めます！
- 単位の決め方は？
  - 基礎刺激（白色）に何を使ってる？
  - 等エネルギー白色？D65？
  - LMSの場合の単位は？L+M=輝度？L-M=0が白？

等色関数の理解が重要！

- 等色関数(color matching functions, CMFs)
- 等色関数とは単位エネルギーを持つ単色光の三刺激値である
- 三刺激値とはRGB, XYZ, LMSの値であり，錐体が吸収した光の量（あるいはその線形和）に対応する
- LMSについては，私は錐体刺激値と読んでいる。錐体応答と区別するため。
- なぜ等色関数が重要か？

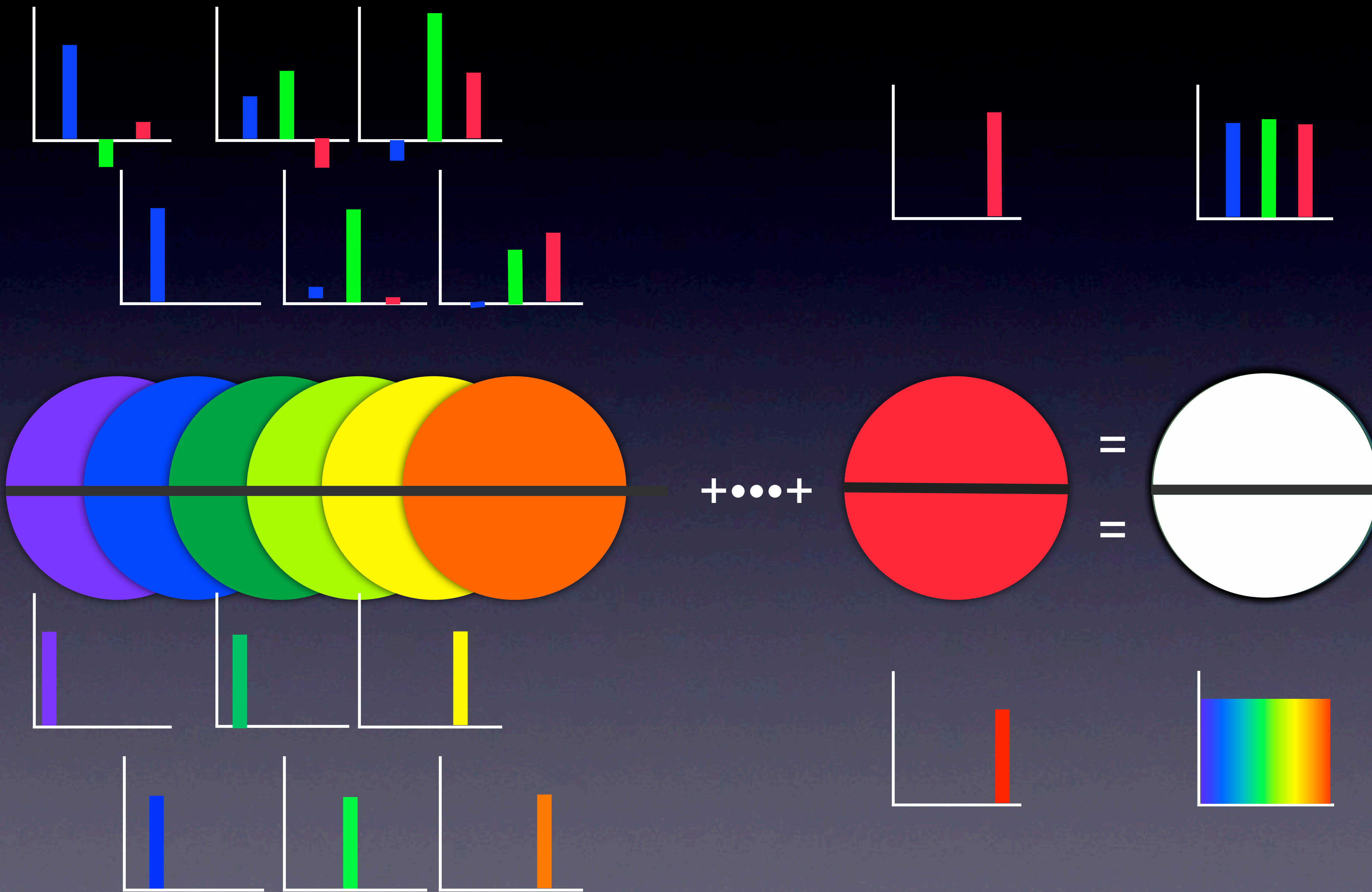
Grassman's law of additive color mixture



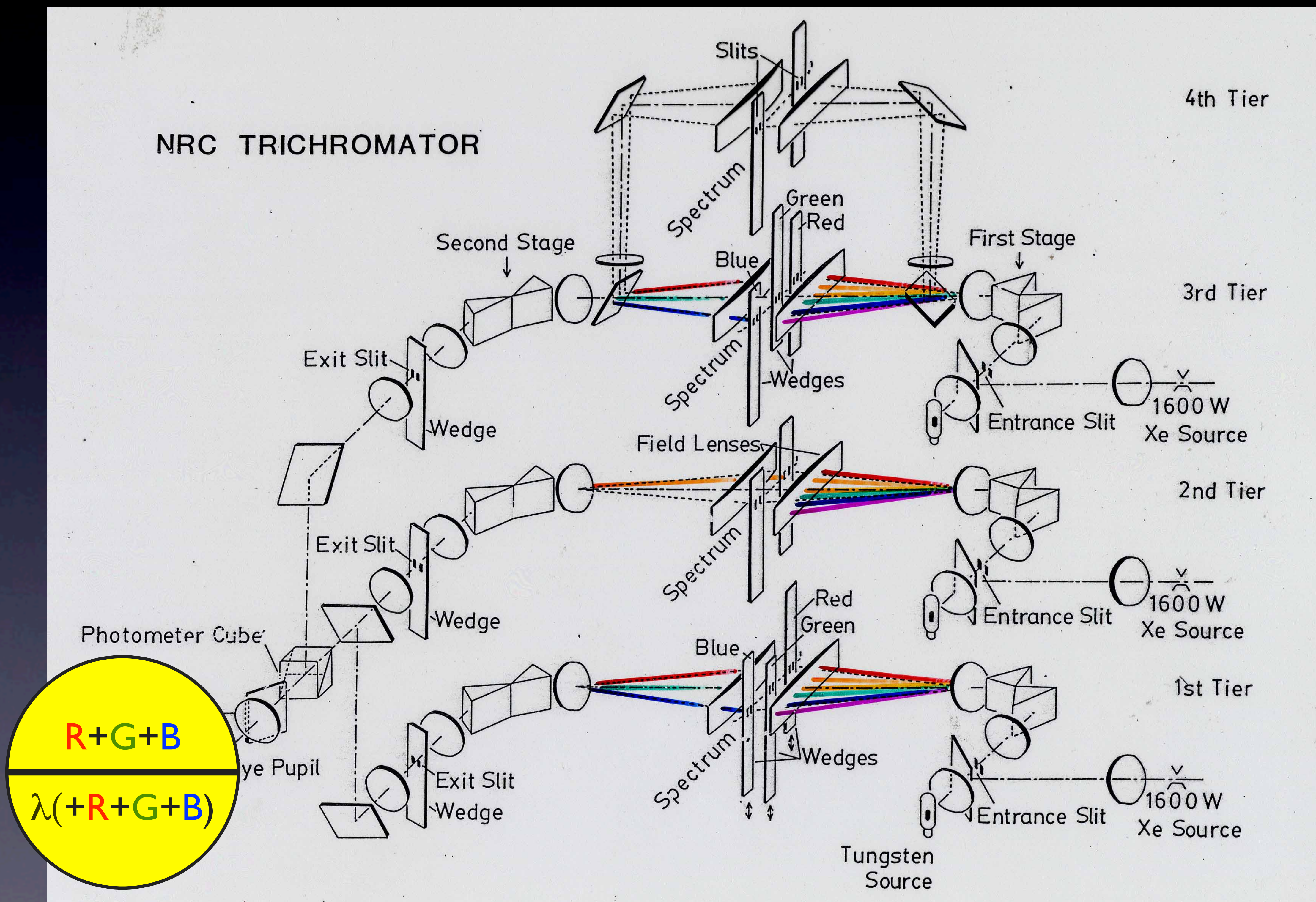
A=B C=D A+C=B+D

Grassman's law of additive color mixture

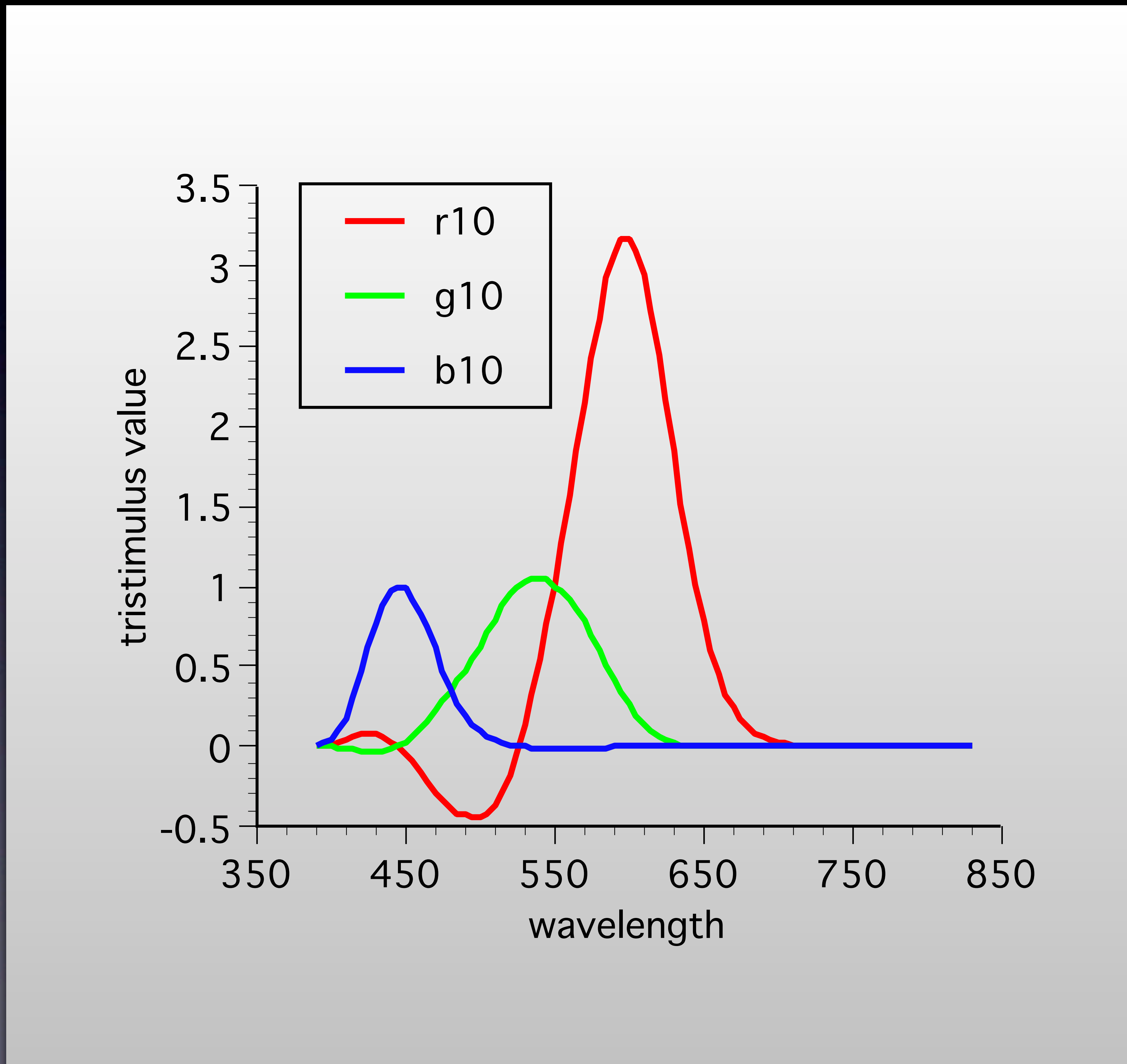
Grassman's law of additive color mixture



Stiles (NPL) Trichromator

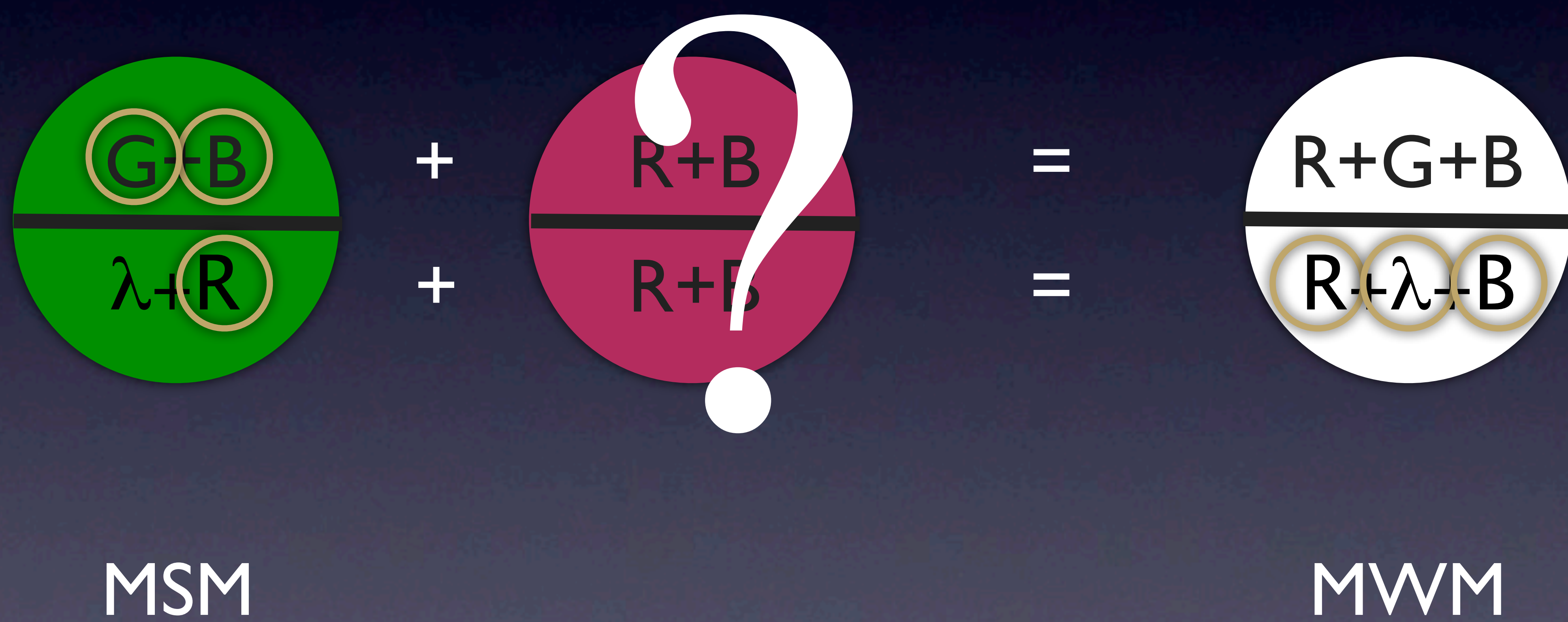


The 10° CMFs of Stiles and Burch



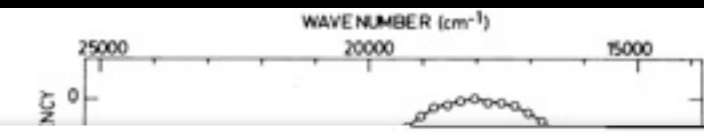
Failure of Grassman’s law of additity

Maximum saturatiod method (MSM) vs. Maxwell method (MWM)



NRCでの研究

DIE FARBE 34 (1987)



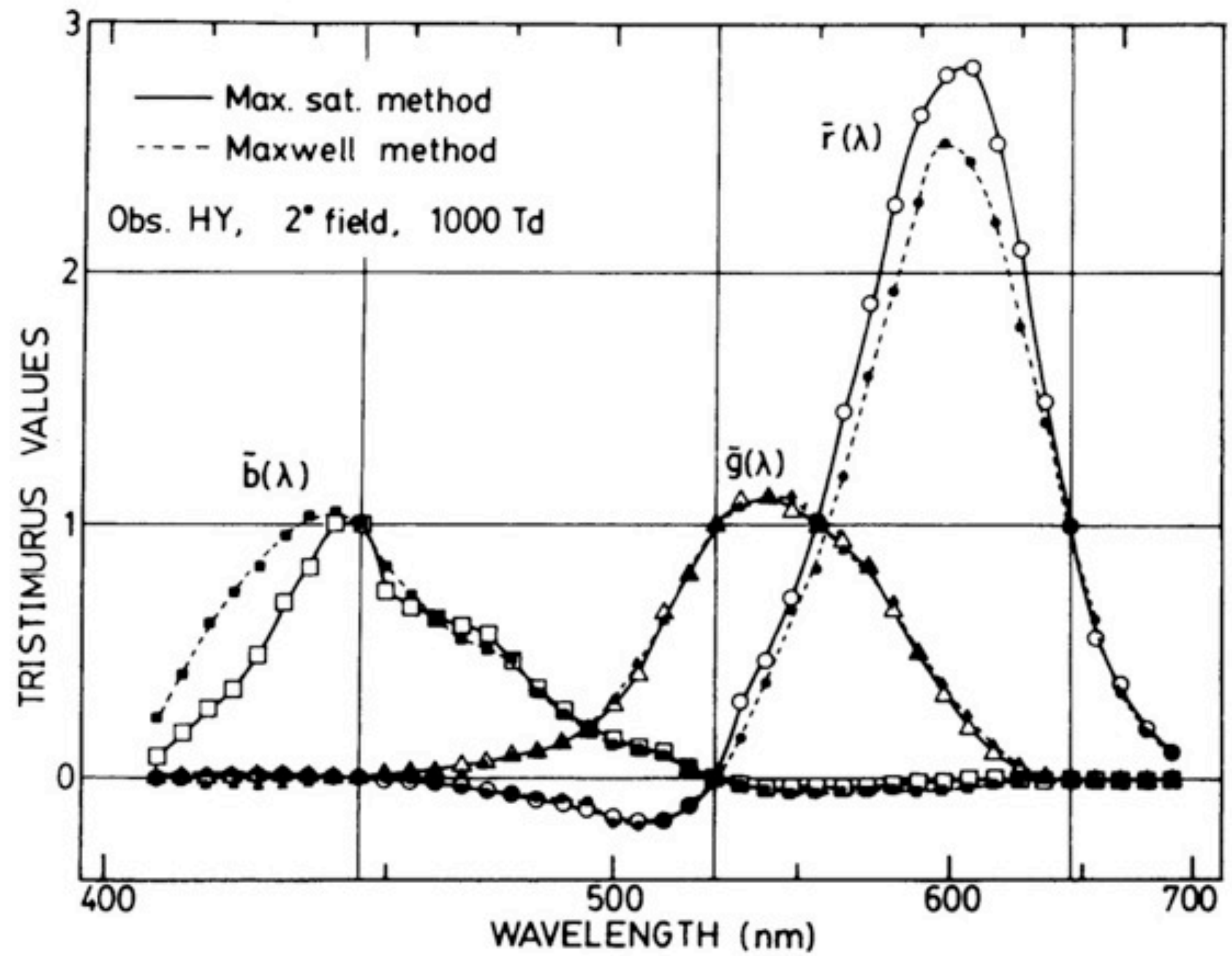


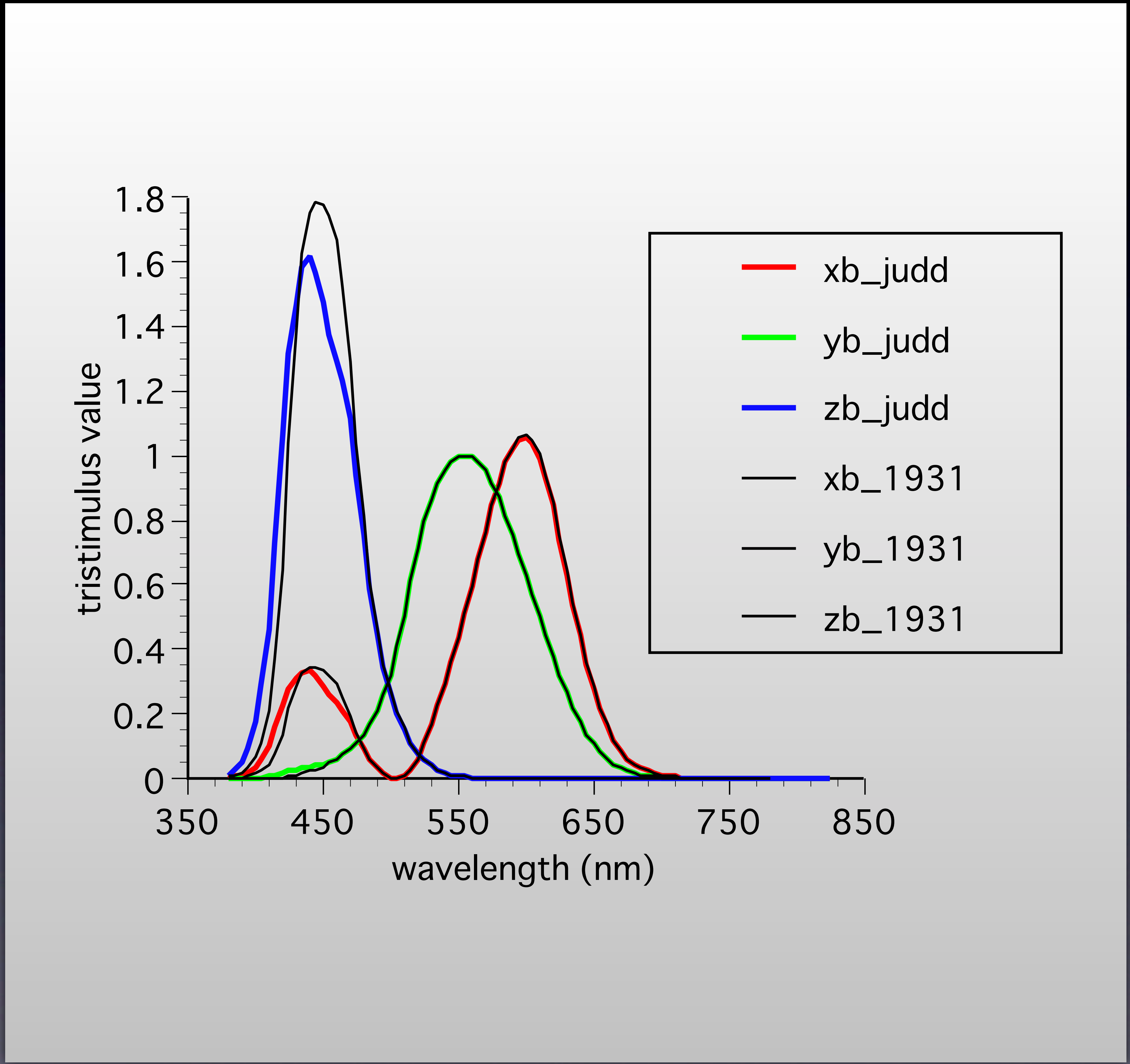
Fig. 2: Color matching functions obtained by the maximum saturation method (open symbols) and by the MAXWELL method (solid symbols)

WAVELENGTH (nm)

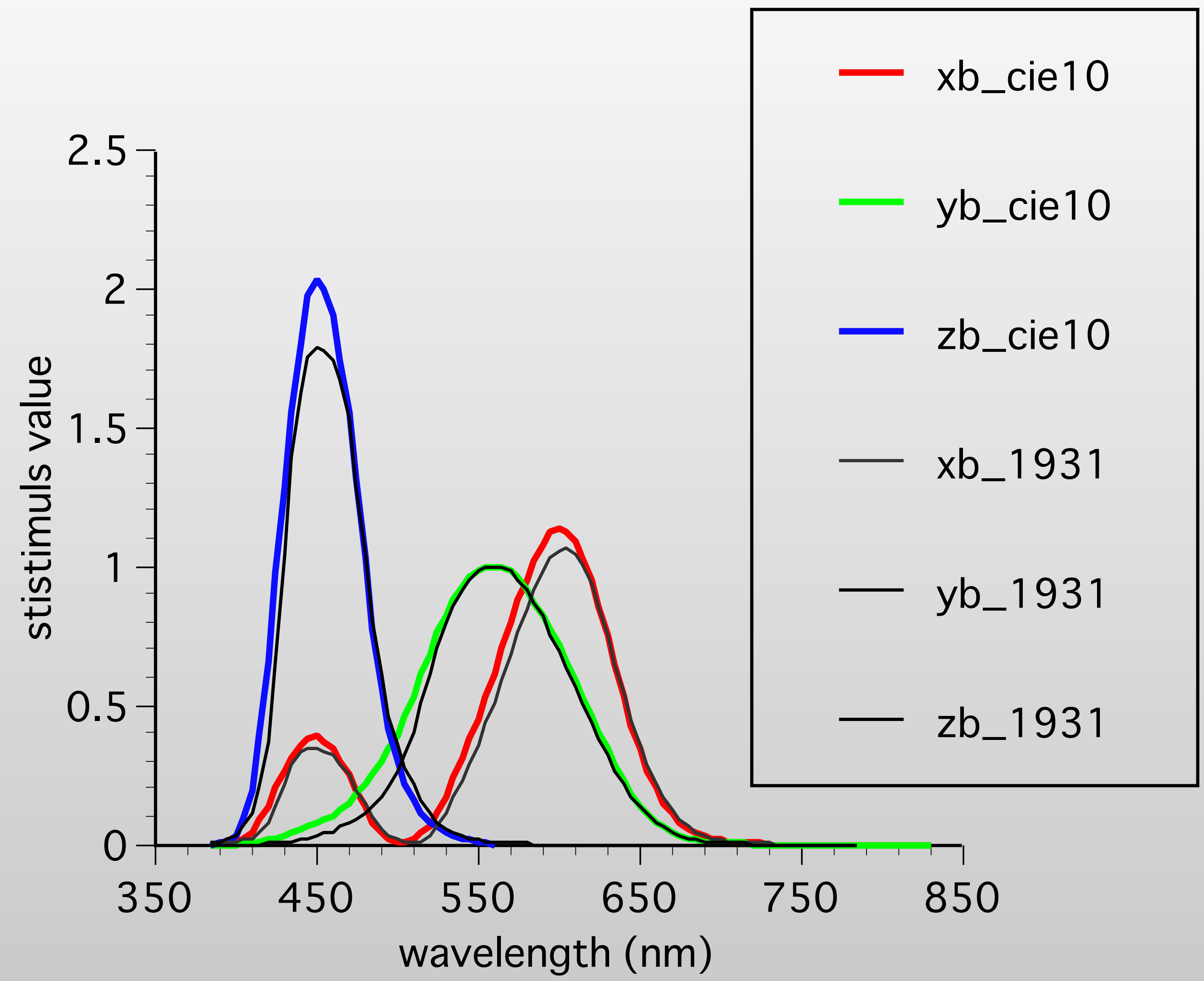
ing functions

cancellation method. Open circles show the experimental data, a dashed curve is predicted by the linear transformation model, and a solid curve is predicted by the non-linear transformation model

CIE1931 CMFs vs Judd'modified CMFs



CIE1931 2° CMFs vs CIE1964 10° CMFs



等色関数を用いて任意の光の分光放射輝度から三刺激値が計算できる

$$R = \int L_{e,\lambda} \bar{r}(\lambda) d\lambda$$
$$G = \int L_{e,\lambda} \bar{g}(\lambda) d\lambda$$
$$B = \int L_{e,\lambda} \bar{b}(\lambda) d\lambda$$

光源色

$$X = \mathrm{K_m} \int L_{e,\lambda} \bar{x}(\lambda) d\lambda$$
$$Y = \mathrm{K_m} \int L_{e,\lambda} \bar{y}(\lambda) d\lambda$$
$$Z = \mathrm{K_m} \int L_{e,\lambda} \bar{z}(\lambda) d\lambda$$
$$\mathrm{K_m} = 683\ (\mathrm{lm/W})$$

物体色

$$X = k \int E(\lambda) \rho(\lambda) \bar{x}(\lambda) d\lambda$$
$$Y = k \int E(\lambda) \rho(\lambda) \bar{y}(\lambda) d\lambda$$
$$Z = k \int E(\lambda) \rho(\lambda) \bar{z}(\lambda) d\lambda$$
$$k = \frac{100}{\int E(\lambda) \bar{y}(\lambda) d\lambda}$$

$$L = \int L_{e,\lambda} \bar{l}(\lambda) d\lambda$$
$$M = \int L_{e,\lambda} \bar{m}(\lambda) d\lambda$$
$$S = \int L_{e,\lambda} \bar{s}(\lambda) d\lambda$$

CIE1931XYZ

光源色

$$X = \mathrm{K_m}\int L_{e,\lambda}\bar{x}(\lambda)d\lambda$$

$$Y = \mathrm{K_m}\int L_{e,\lambda}\bar{y}(\lambda)d\lambda$$

$$Z = \mathrm{K_m}\int L_{e,\lambda}\bar{z}(\lambda)d\lambda$$

$$\mathrm{K_m} = 683\ (\mathrm{lm/W})$$

物体色

$$X = k\int E(\lambda)\rho(\lambda)\bar{x}(\lambda)d\lambda$$

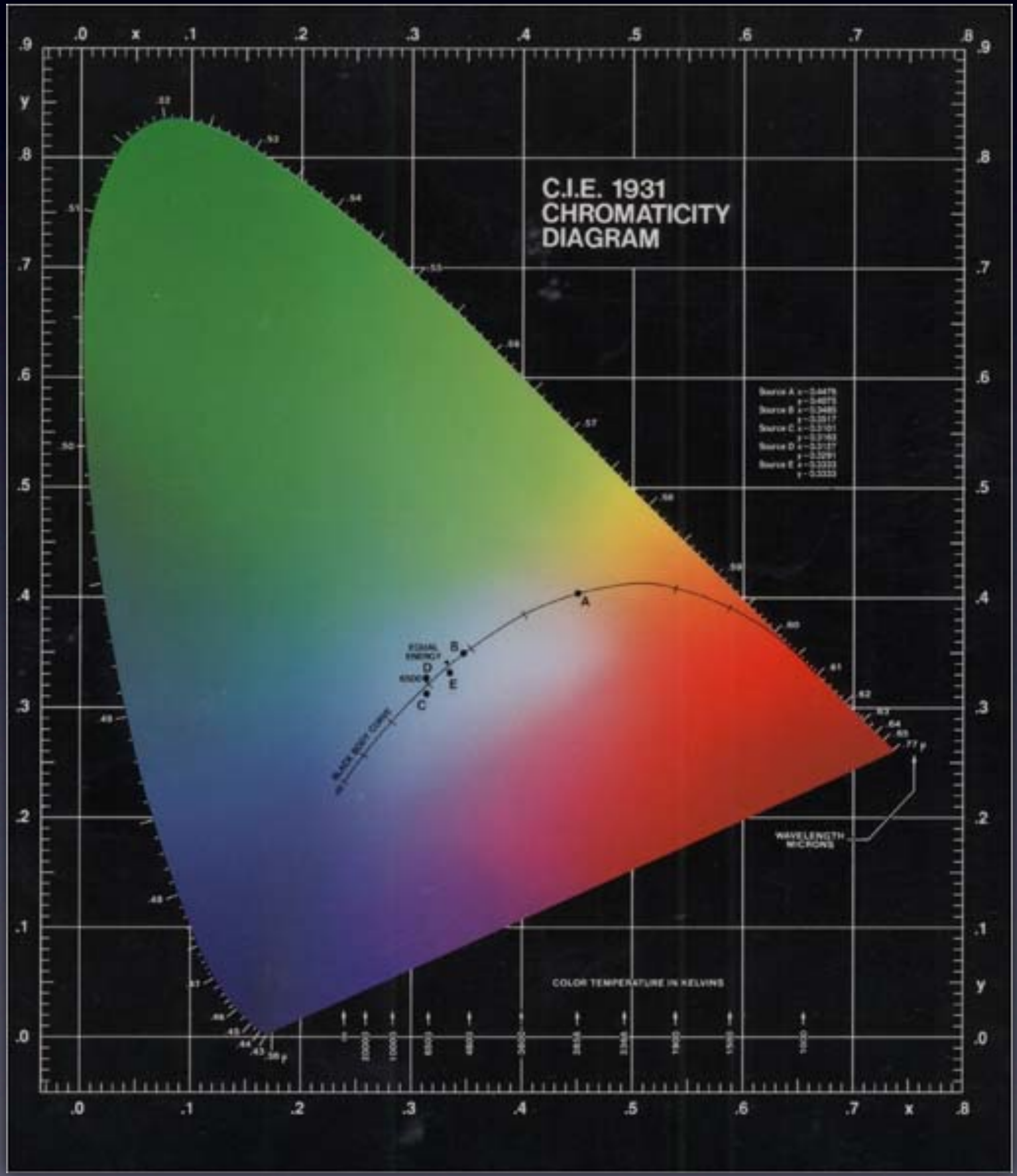
$$Y = k\int E(\lambda)\rho(\lambda)\bar{y}(\lambda)d\lambda$$

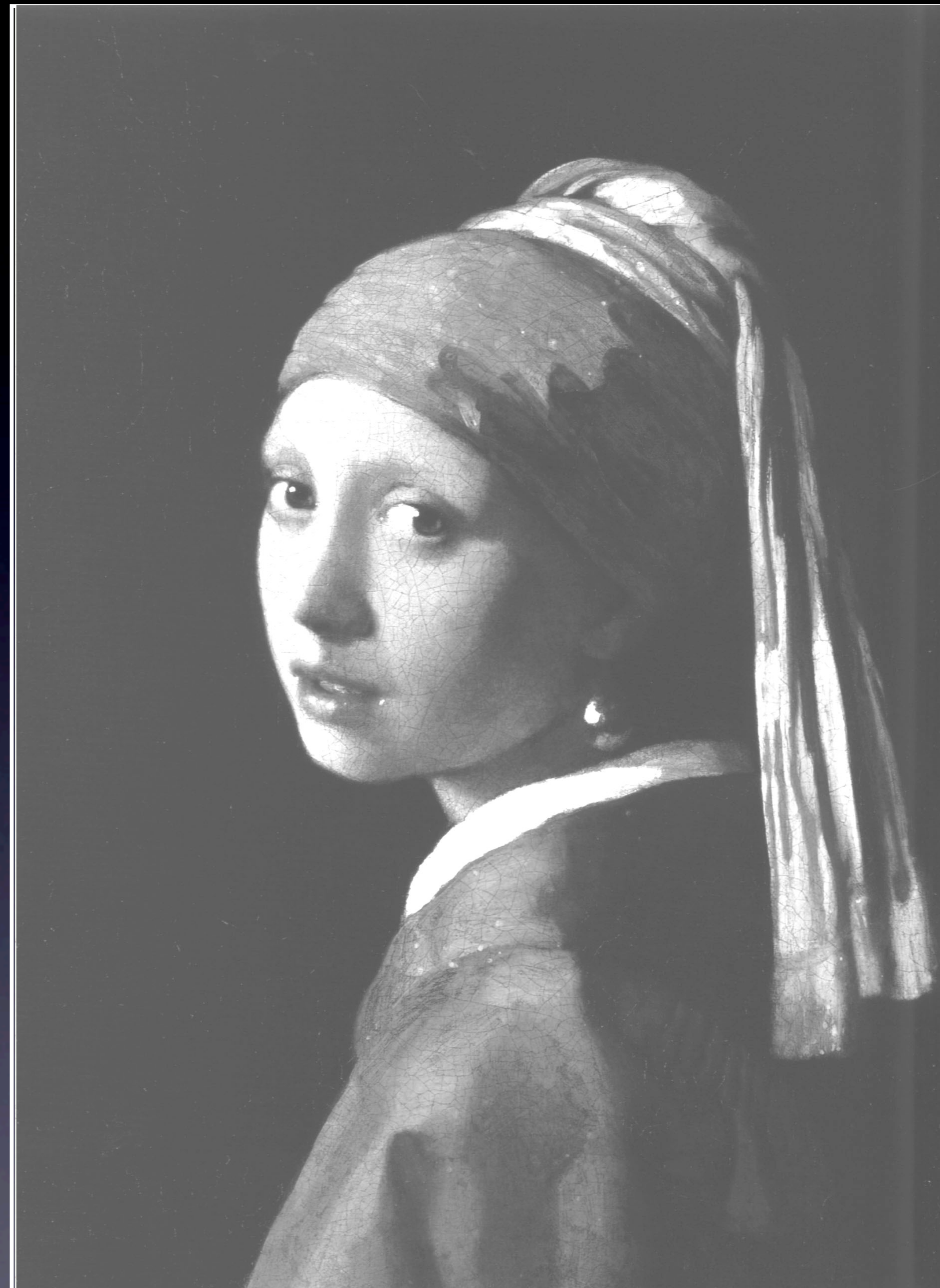
$$Z = k\int E(\lambda)\rho(\lambda)\bar{z}(\lambda)d\lambda$$

$$k = \frac{100}{\int E(\lambda)\bar{y}(\lambda)d\lambda}$$

色度座標

x=X/(X+Y+Z), y=Y/(X+Y+Z)





Vermeer, *Het meisje met de parel*

CIE1976L*a*b*(CIELAB)

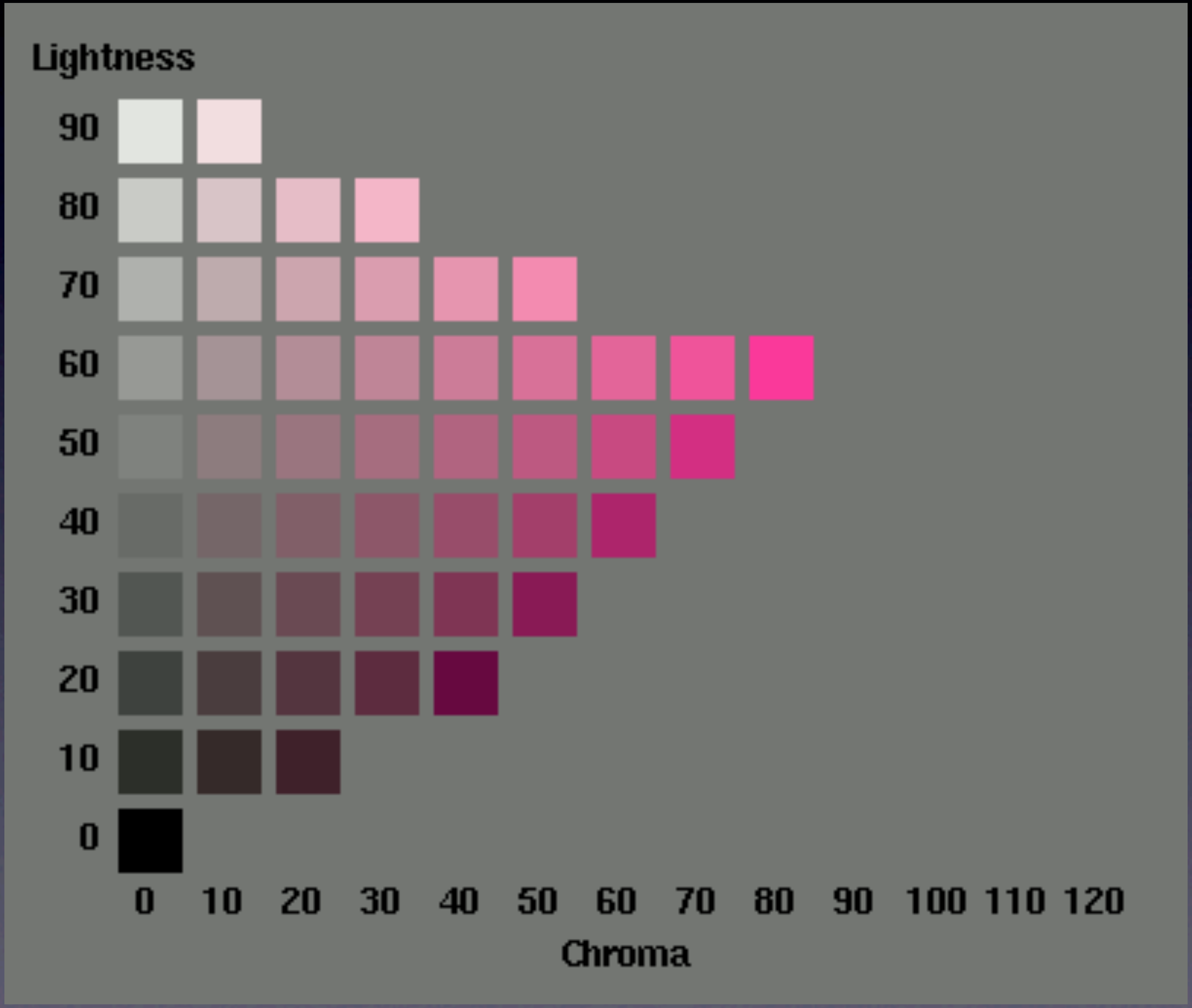
$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right]$$

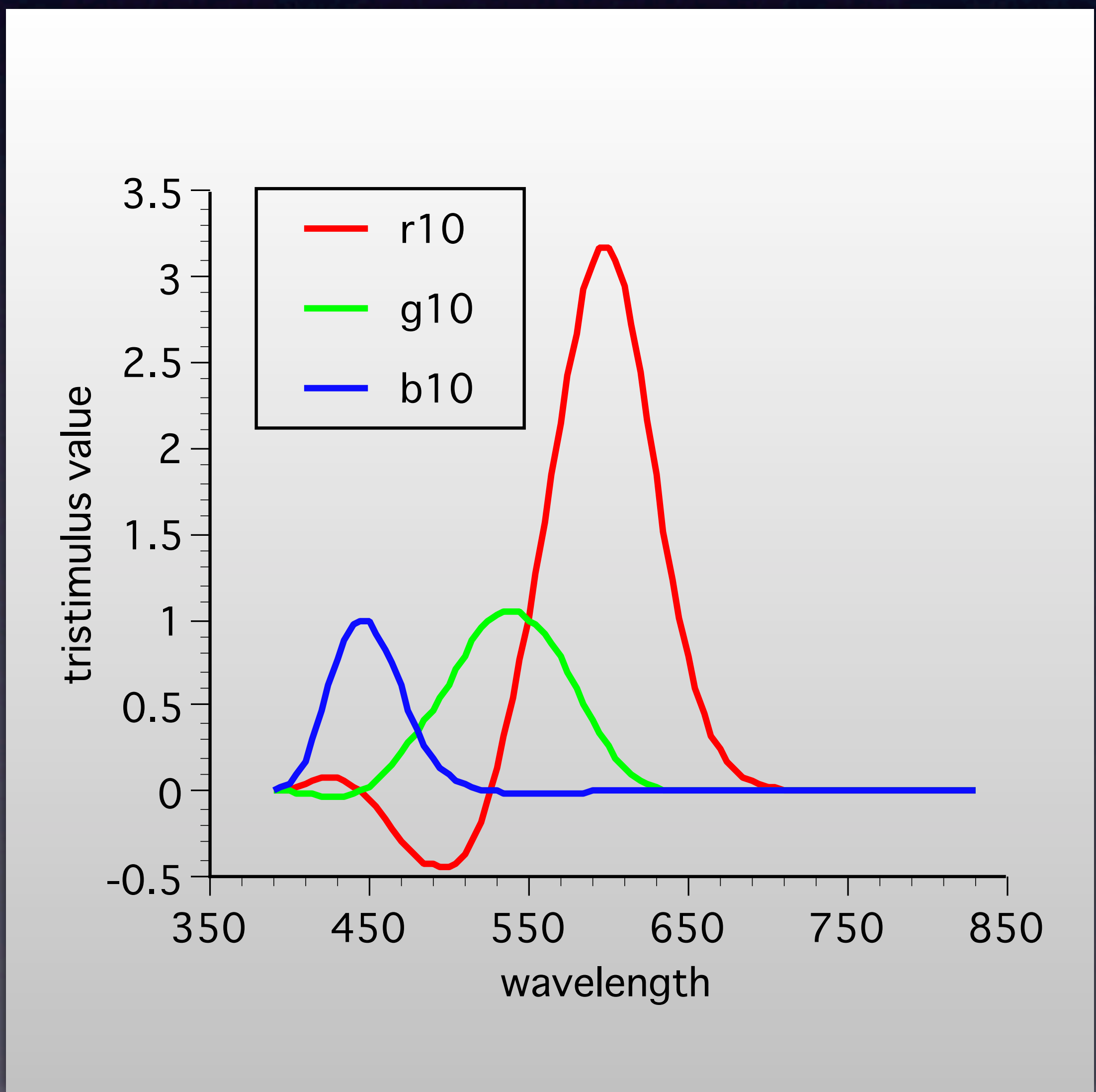
- 色順応
  - 白はいつも白い
  - 環境（照明）の三刺激値で正規化
- 非線形性
  - 物理量から感覚量への変換
  - 1/3乗の指数関数
- 反対色性
  - 明度と色の分離
  - a*: 赤／緑，b*: 黄／青

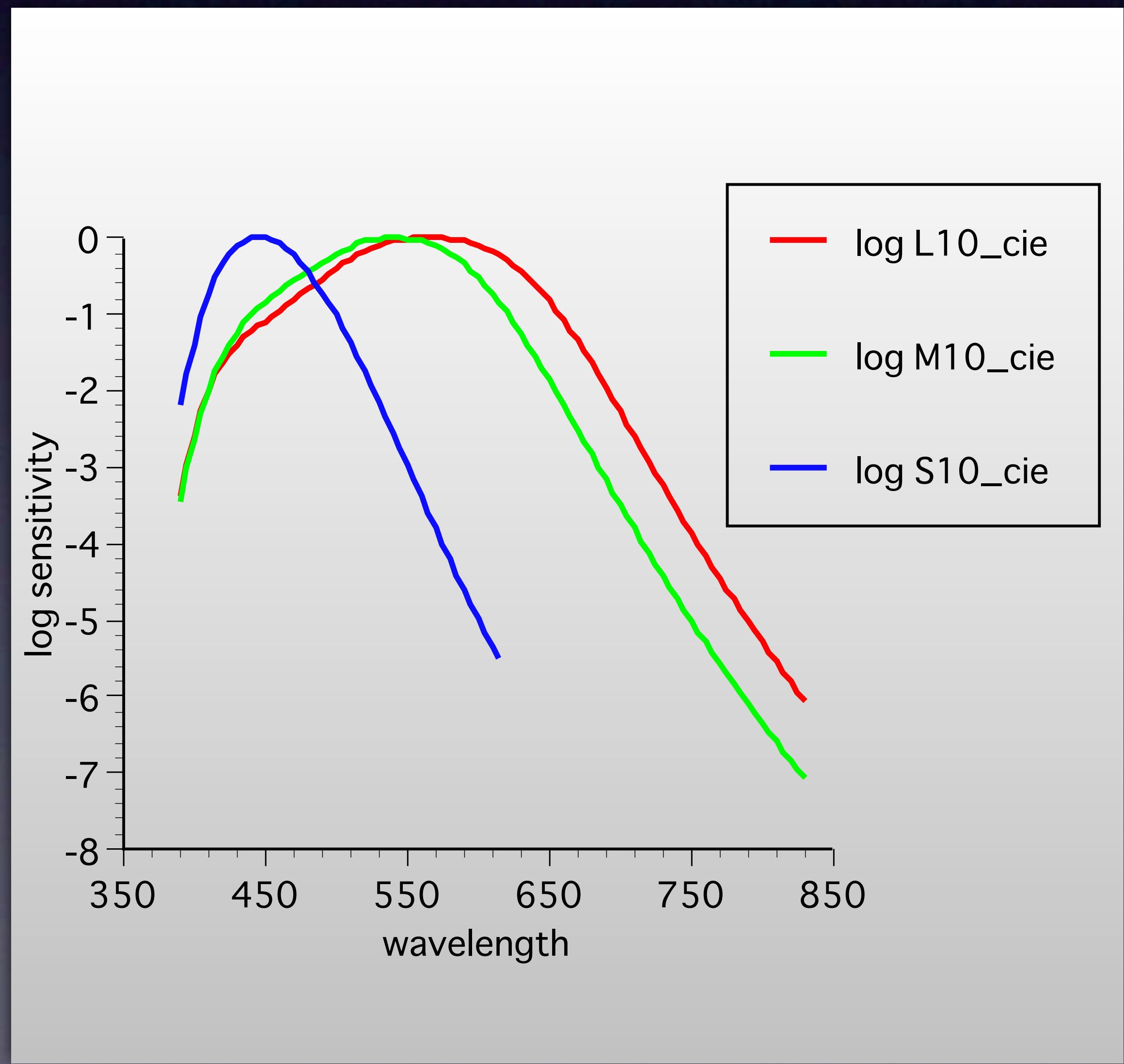
CIE1976L*a*b*(CIELAB)



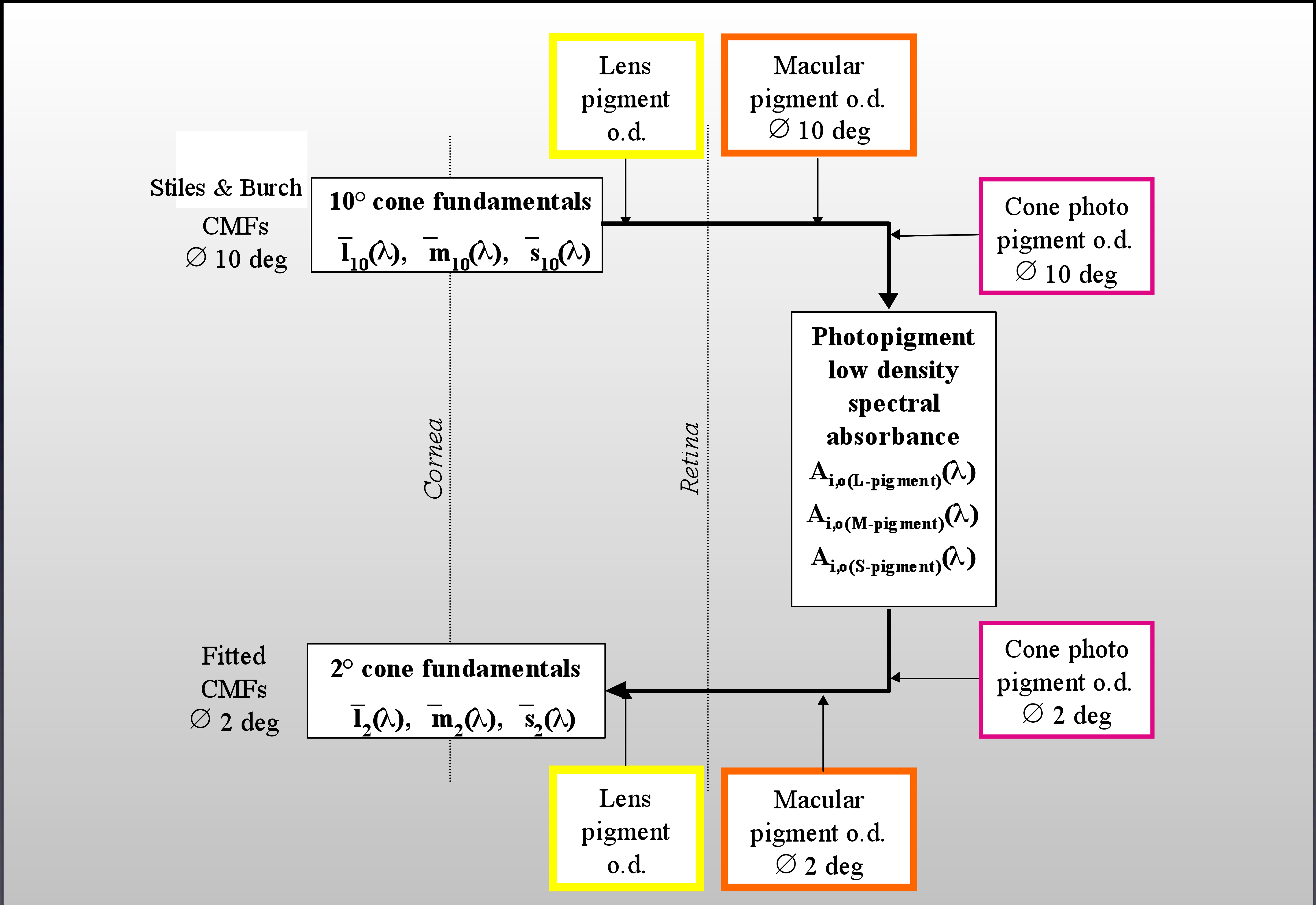
Transformation from the 10° CMFs to the L_{10}-, M_{10}- , S_{10}-cone fundamentals

$$\begin{bmatrix} \bar{l}_{10}(\lambda) \\ \bar{m}_{10}(\lambda) \\ \bar{s}_{10}(\lambda) \end{bmatrix} = \begin{bmatrix} -0.19233 & 0.74955 & 0.06757 \\ 0.01923 & 0.94091 & 0.11383 \\ 0.00000 & 0.01051 & 0.99143 \end{bmatrix} \begin{bmatrix} \bar{r}_{10}(\lambda) \\ \bar{g}_{10}(\lambda) \\ \bar{b}_{10}(\lambda) \end{bmatrix}$$



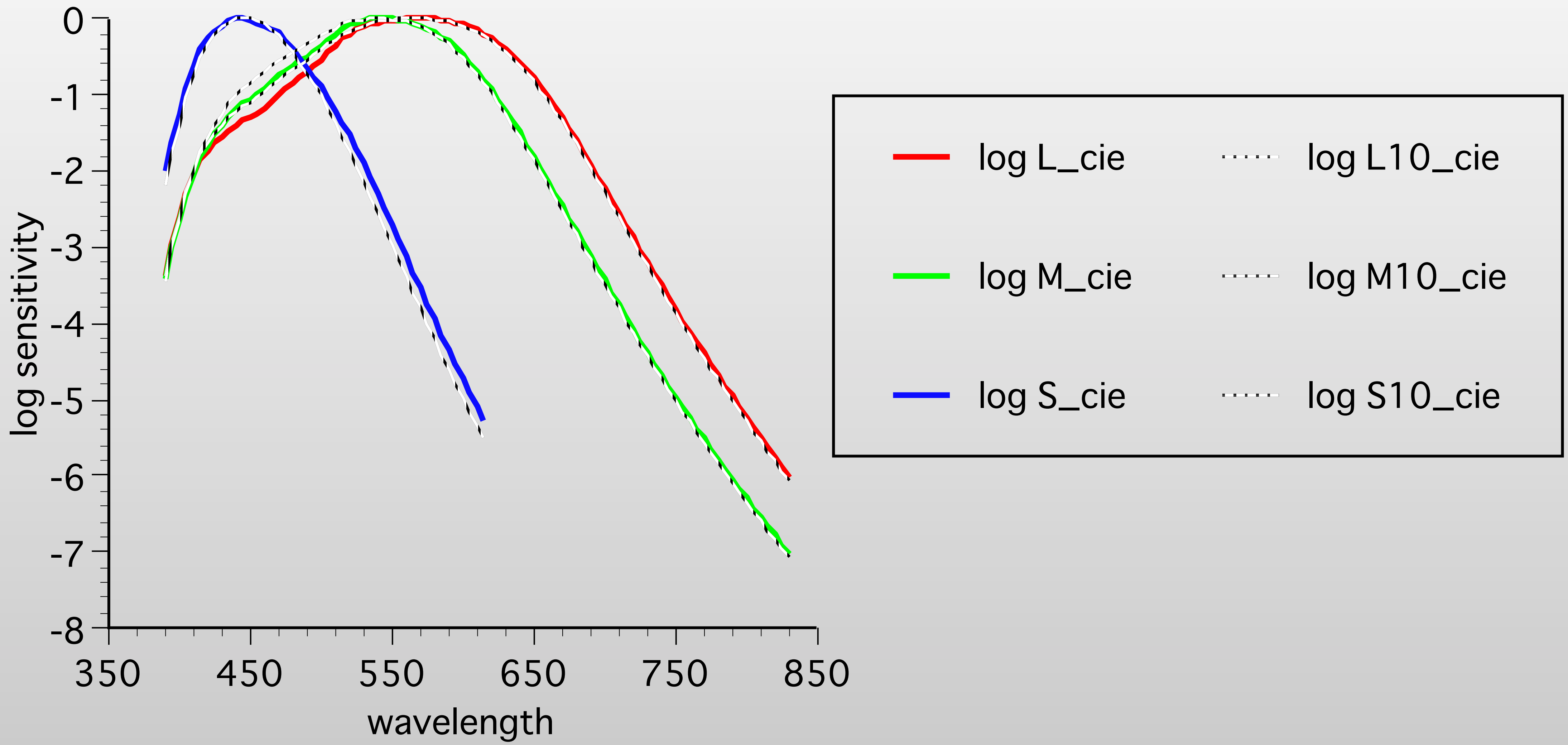


Derivation of the 2° cone fundamentals from the 10° cone fundamentals



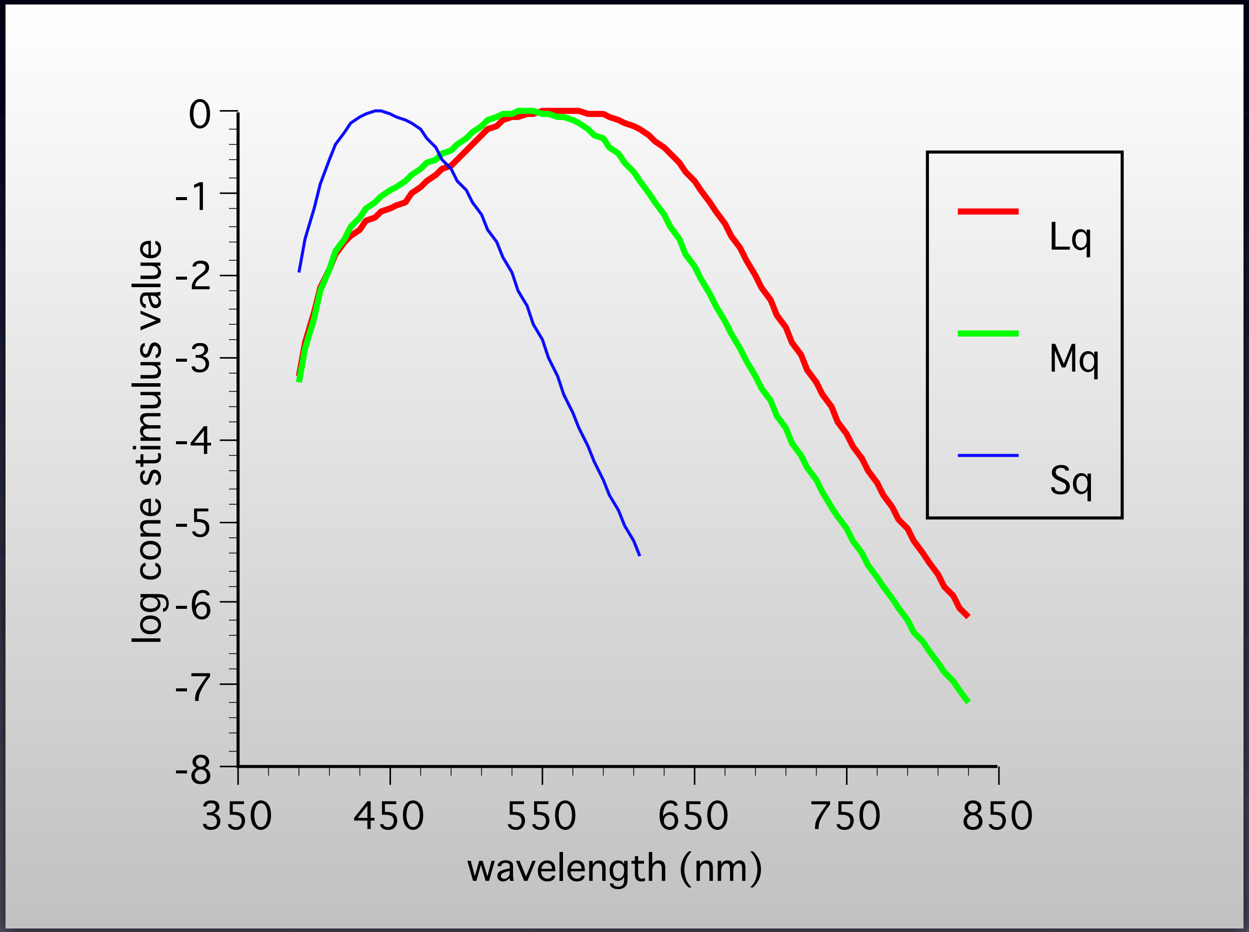
2011年 9月 26日 月曜日

The 10° cone fundamentals

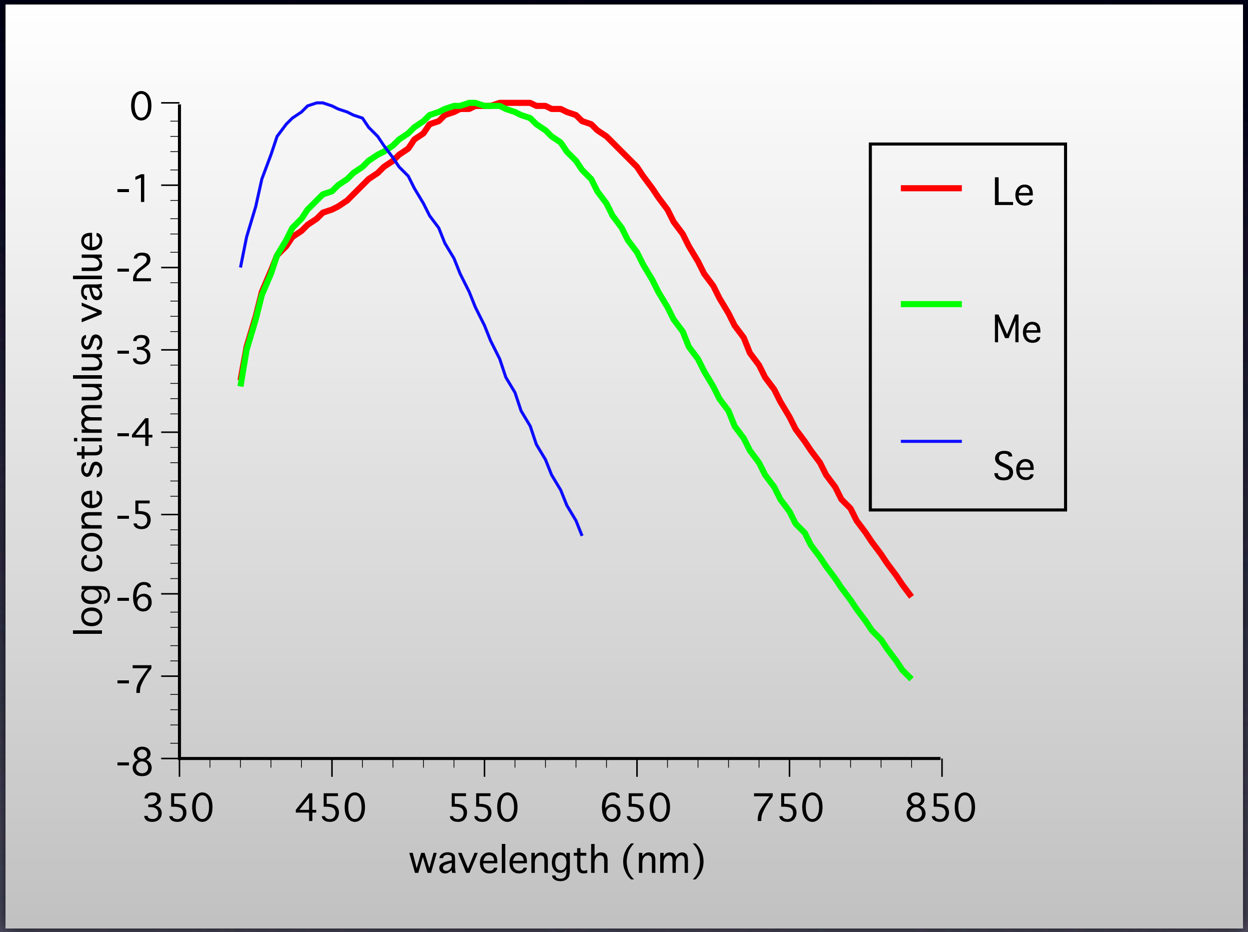


CIE cone fundamentals

in terms of quanta



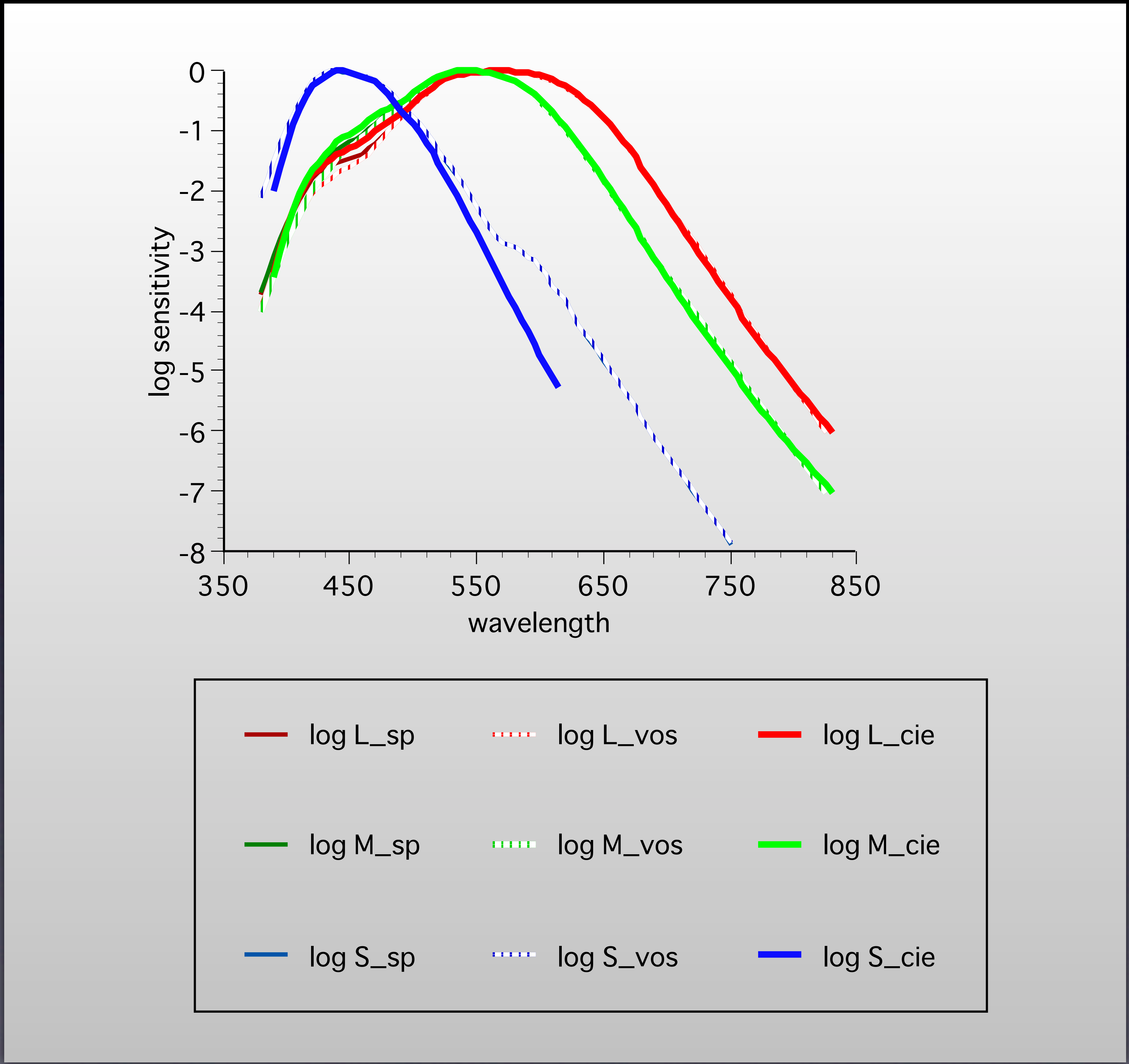
in terms of energy



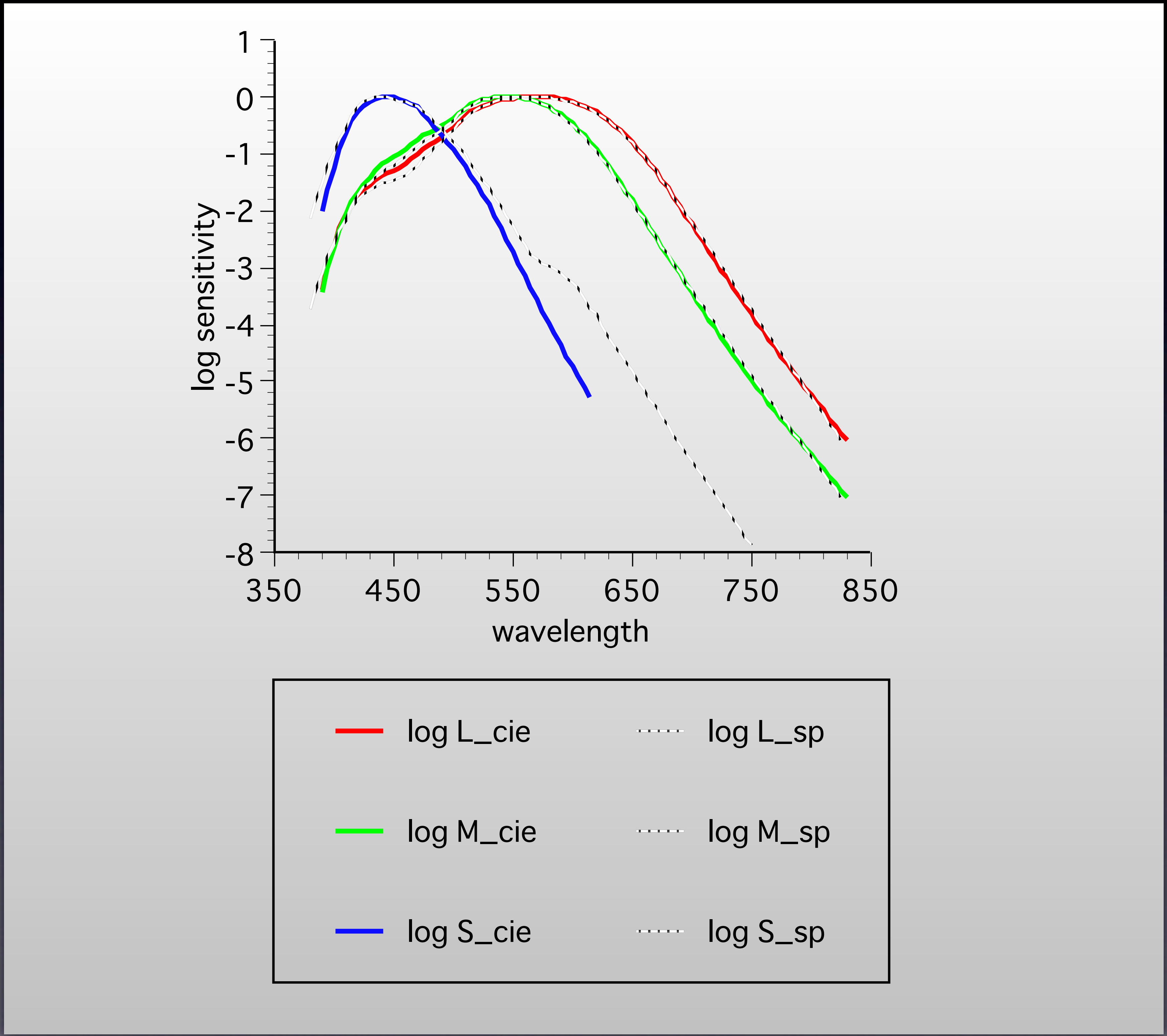
A. Stockman, L.T. Sharpe, The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype, Vision Res., 40, 1711-1737 (2000)

CIE 170-1: 2006, Fundamental chromaticity diagram with physiological axes - Part 1

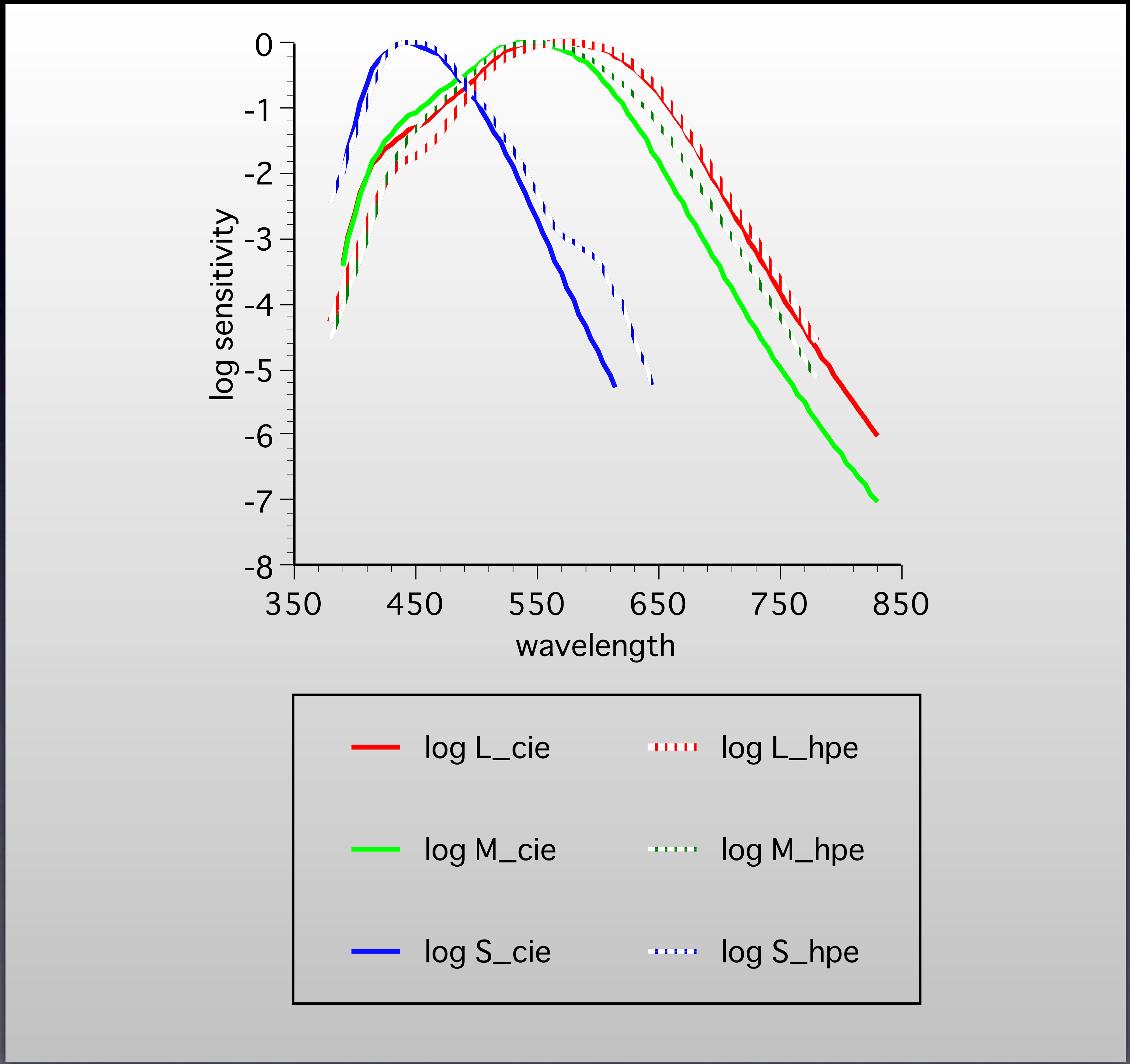
Various cone fundamentals



Comparison between cone fundamentals of CIE and Smith&Pokorny



Various cone fundamentals



MacLeod-Boynton chromaticity diagram

D.I.A. MacLeod and R.M. Boynton, J. opt.Soc.Am., 69, 1183-1186 (1979)

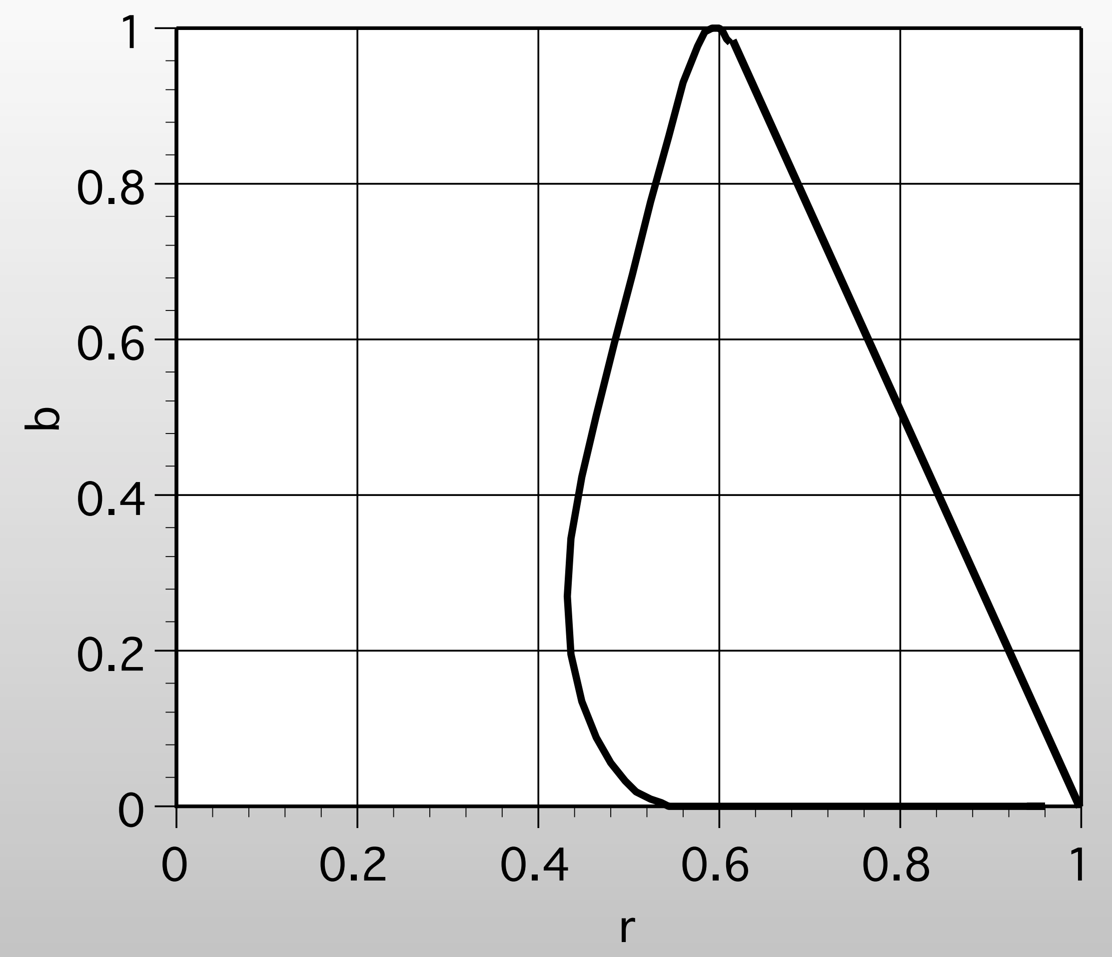
$$r = \frac{R}{R+G}, \quad g = \frac{G}{R+G}, \quad b = \frac{B}{R+G}$$

$$R_\lambda = 0.15514\bar{x}_{j\lambda} + 0.54312\bar{y}_{j\lambda} - 0.03286\bar{z}_{j\lambda}$$

$$G_\lambda = -0.15514\bar{x}_{j\lambda} + 0.45684\bar{y}_{j\lambda} + 0.03286\bar{z}_{j\lambda}$$

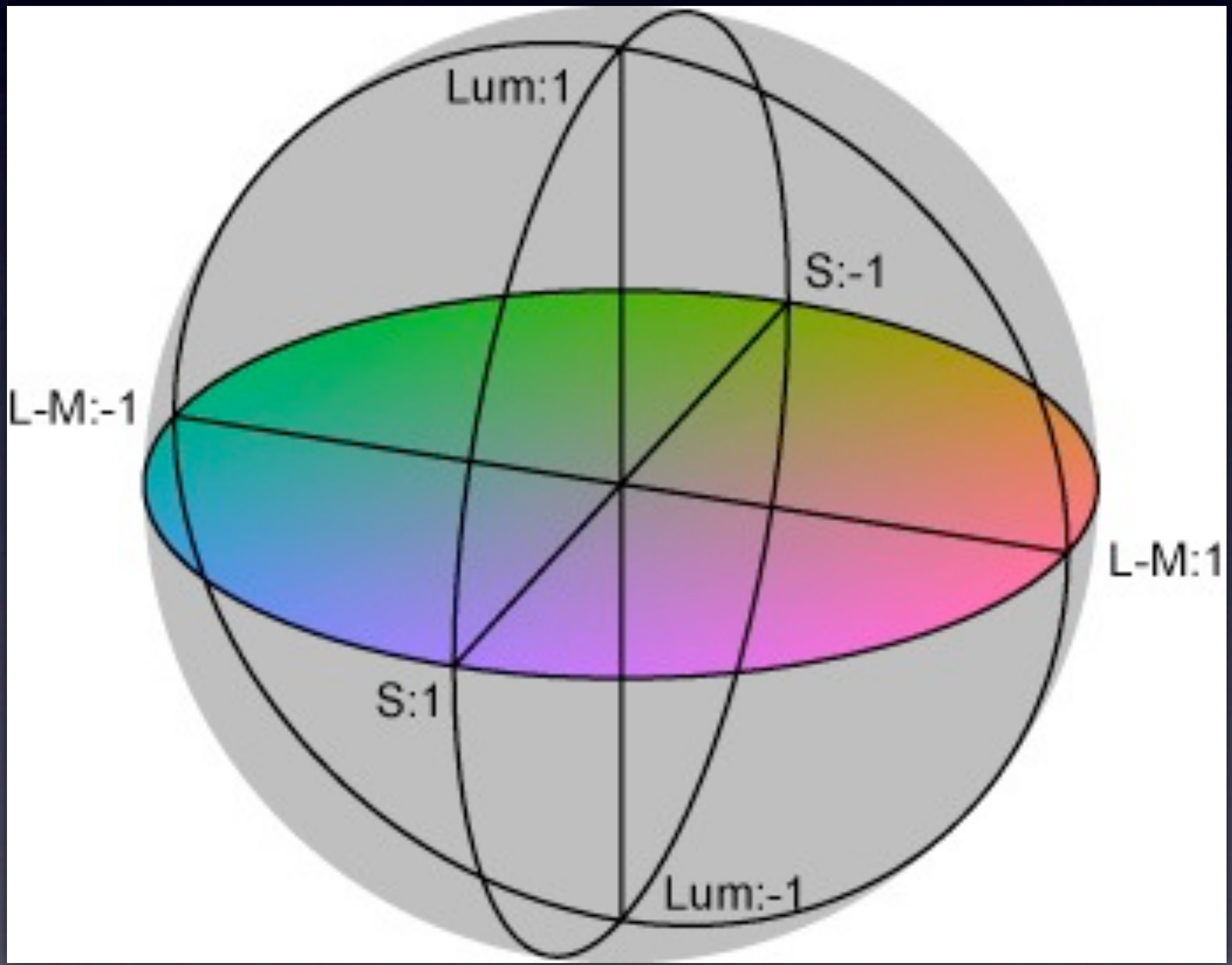
$$B_\lambda = 0.01608\bar{z}_{j\lambda}$$

Smith-Pokorny cone fundamentals



DKL color space

Derrington AM, Krauskopf J, Lennie P (1984) "Chromatic mechanisms in lateral geniculate nucleus of macaque." J Physiol (Lond) 357:241-265



sRGB color space

	Red	Green	Blue	White(D65)
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290

$$\begin{cases} R'_{\text{sRGB}} = R_{8\text{bit}}/255 \\ G'_{\text{sRGB}} = G_{8\text{bit}}/255 \\ B'_{\text{sRGB}} = B_{8\text{bit}}/255 \end{cases}$$

if R'_{sRGB}, G'_{sRGB}, B'_{sRGB}, ≤ 0.04045

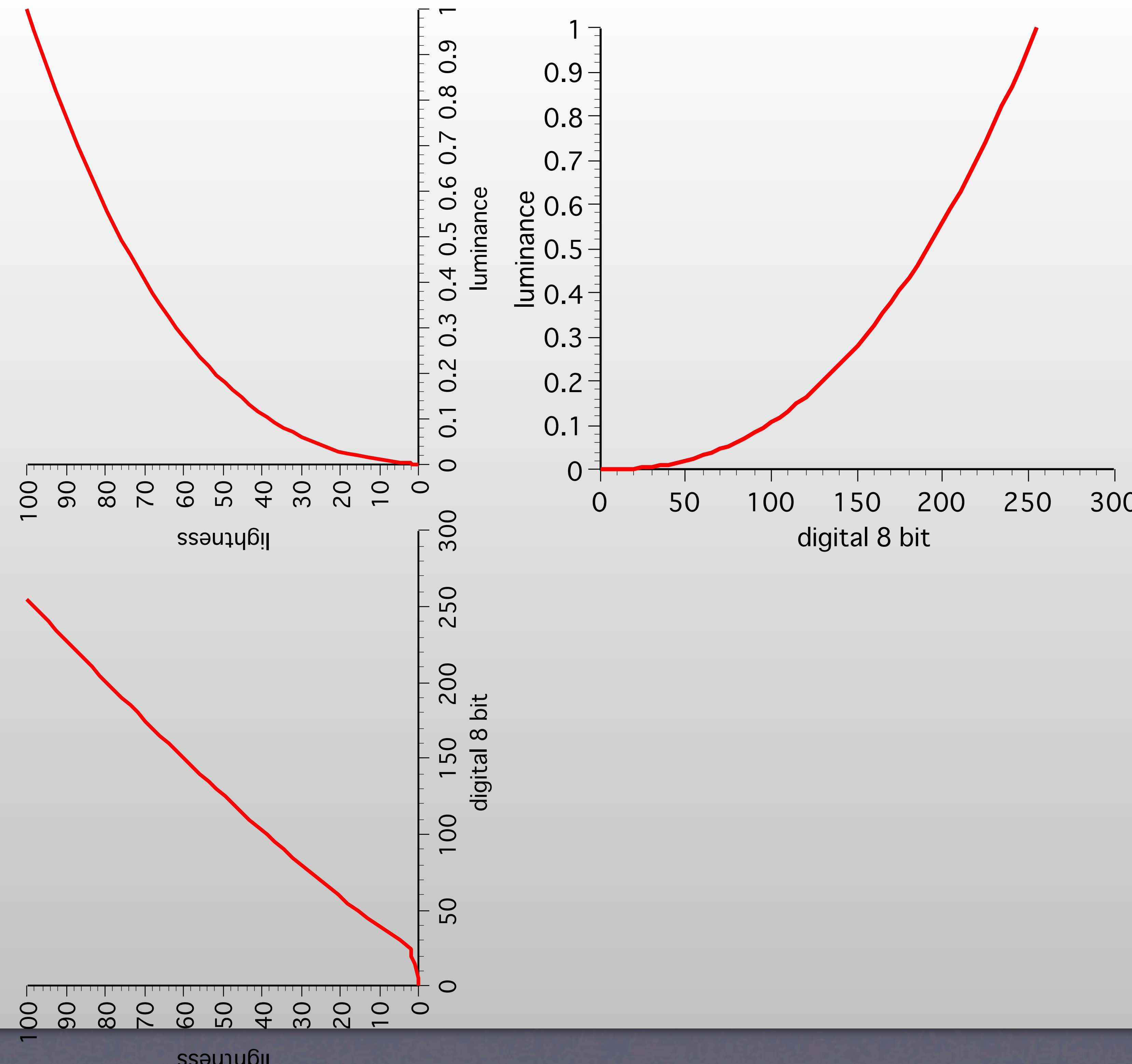
$$\begin{cases} R_{\text{sRGB}} = R'_{\text{sRGB}}/12.92 \\ G_{\text{sRGB}} = G'_{\text{sRGB}}/12.92 \\ B_{\text{sRGB}} = B'_{\text{sRGB}}/12.92 \end{cases}$$

if R'_{sRGB}, G'_{sRGB}, B'_{sRGB}, > 0.04045

$$\begin{cases} R_{\text{sRGB}} = \left(\dfrac{R'_{\text{sRGB}} + 0.055}{1.055}\right)^{2.4} \\ G_{\text{sRGB}} = \left(\dfrac{G'_{\text{sRGB}} + 0.055}{1.055}\right)^{2.4} \\ B_{\text{sRGB}} = \left(\dfrac{B'_{\text{sRGB}} + 0.055}{1.055}\right)^{2.4} \end{cases}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R_{\text{sRGB}} \\ G_{\text{sRGB}} \\ B_{\text{sRGB}} \end{bmatrix}$$

sRGB to CIELAB



Color matching functions and cone fundamentals

color matching experiment	field size	color matching functions	cone fundamentlas
Wright (1928-1929)	2°	CIE 1931 2° CMFs Judd’ modified CMFs	Hunt-Pointer-Esteves (CIECAM02)
Guild (1931)	2°		Vos and Walraven (1971) Smith and Pokorny (1975)
Stiles and Burch (1959)	10°	CIE 1964 10° CMFs	Stockman and Sharp (CIE) 10° Stockman and Sharp (CIE) 2°
Speranskaya (1959)	10°		
Stiles and Burch (1955)	2°		