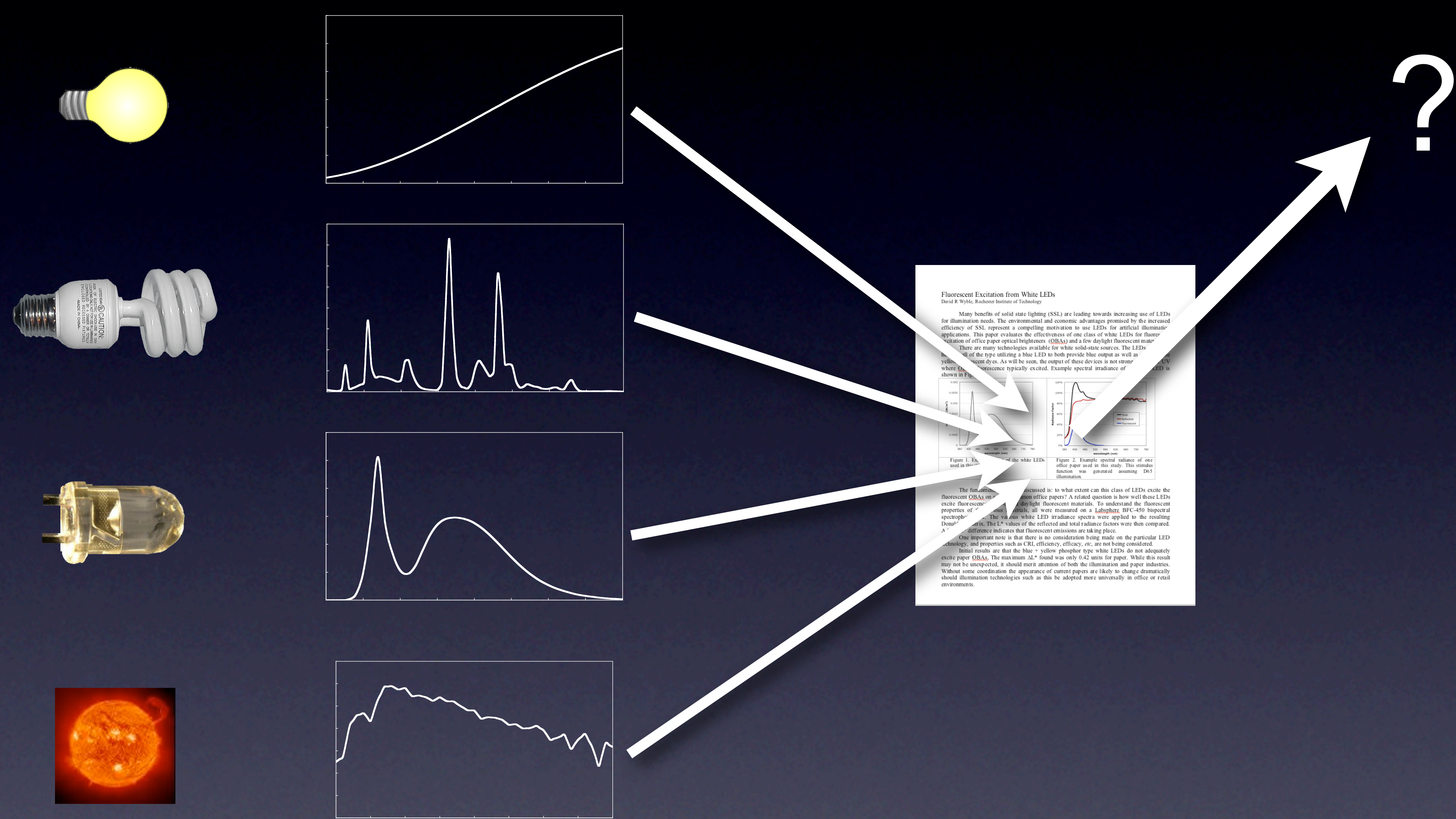
Fluorescent Excitation from White LEDs

David R. Wyble
Munsell Color Science Laboratory
Chester F. Carlson Center for Imaging Science
Rochester Institute of Technology

R·I·T

The Problem



The Problem

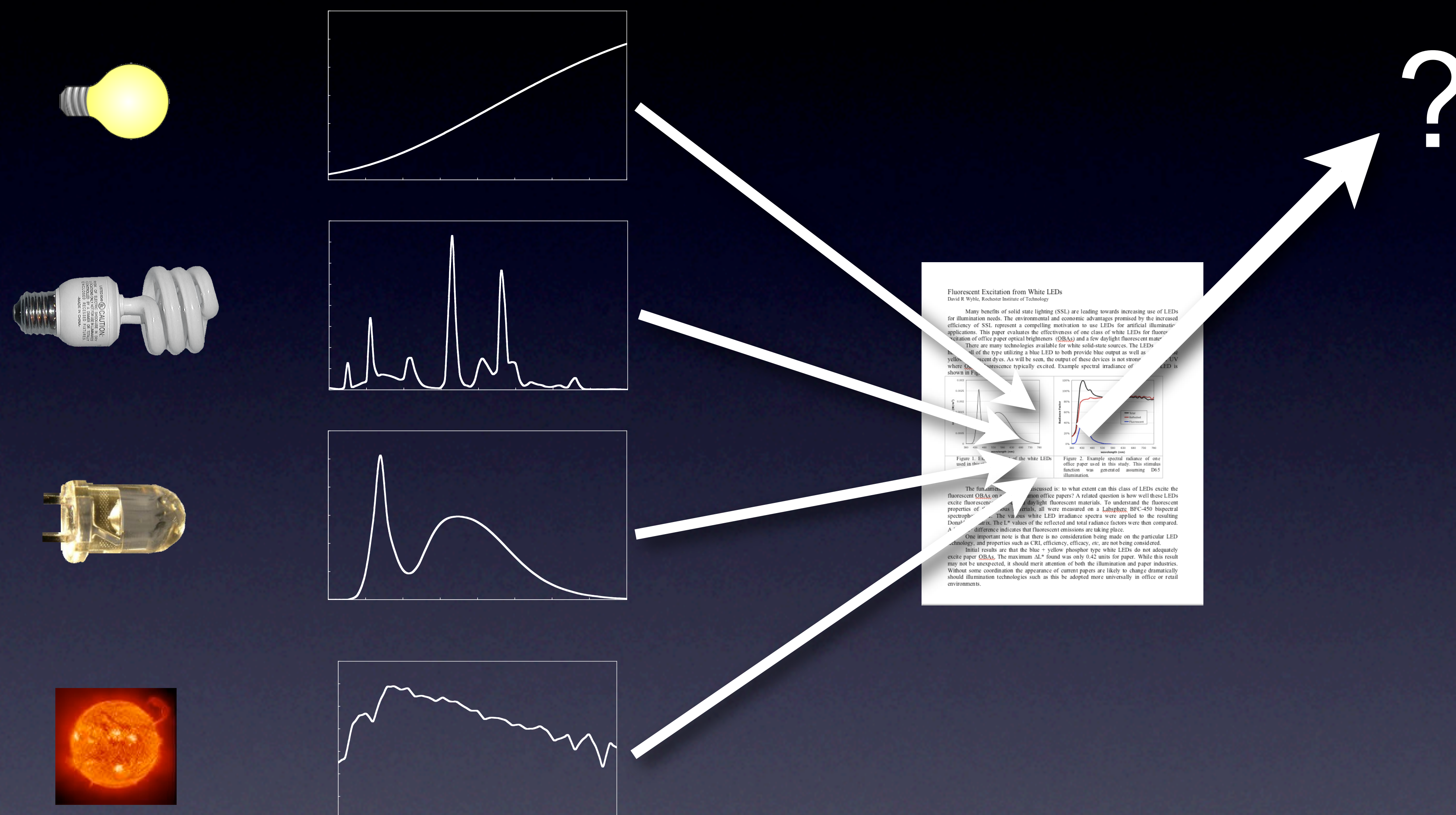
content
<400nm

1%

1%

0%

9%



percent of 300-800nm
content between 300-400nm

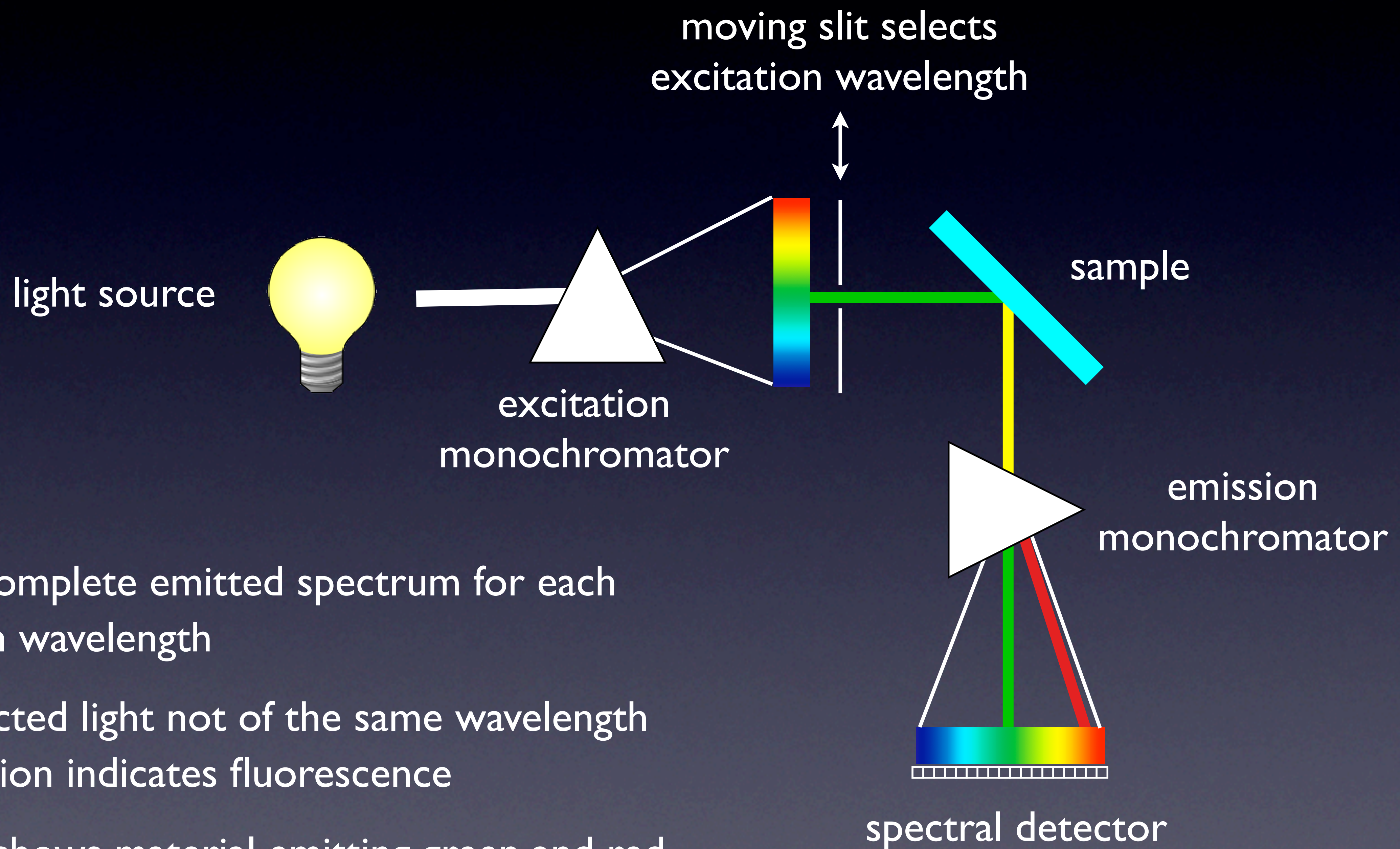
Motivation

- Growth of solid state lighting for indoor illumination applications is inevitable
- Many benefits over conventional illumination
  - Cost
  - Life
  - Energy usage
  - Environmental concerns
- Some issues:
  - Color rendering
  - Fluorescence

R·I·T

Characterizing Fluorescence

Bispectral spectrophotometry



- Record complete emitted spectrum for each excitation wavelength
- Any detected light not of the same wavelength as excitation indicates fluorescence
- Example shows material emitting green and red light when being excited by green

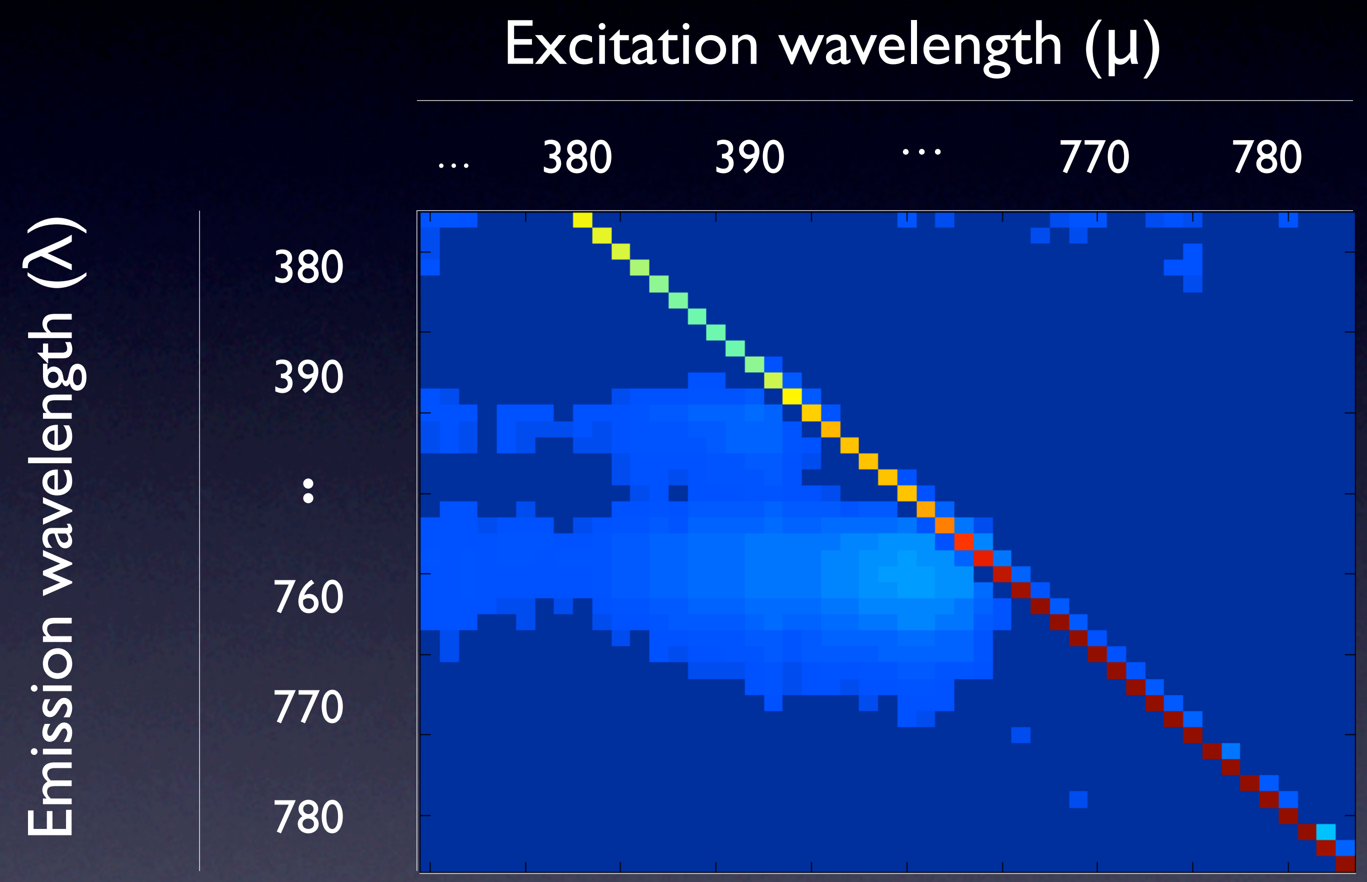
Characterizing Fluorescence

Emission wavelength (λ)	Excitation wavelength (μ): …	380	390	⋯	770	780
380		β_{R380}				
390			β_{R390}			
⋮				⋱		
760						
770					β_{R770}	
780						β_{R780}

“Donaldson Matrix”

Here: Excitation wavelength (μ) is 300-780nm.
Emission wavelength (λ) is measured from 380-780nm

Characterizing Fluorescence



"Donaldson Matrix"

Here: Excitation wavelength (μ) is 300-780nm.
Emission wavelength (λ) is measured from 380-780nm

Fluorescence calculations

Reflected Radiance Factor $\beta_{R,\lambda}$ [the corrected diagonal]

Donaldson matrix $\beta_{F,\mu,\lambda}$

$\lambda = emission$

$\mu = excitation$

Reflected TSV's $W_R = k\sum_{\lambda}\beta_{R,\lambda}s_\lambda\bar{w}_\lambda\Delta\lambda$

$W_R = X, Y, Z$

$\bar{w}_\lambda = \bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$

Fluorescent Radiance Factor $\beta_{F,\lambda} = \dfrac{\sum_{\mu} s_\mu \beta_{F,\mu,\lambda}}{s_\lambda}$

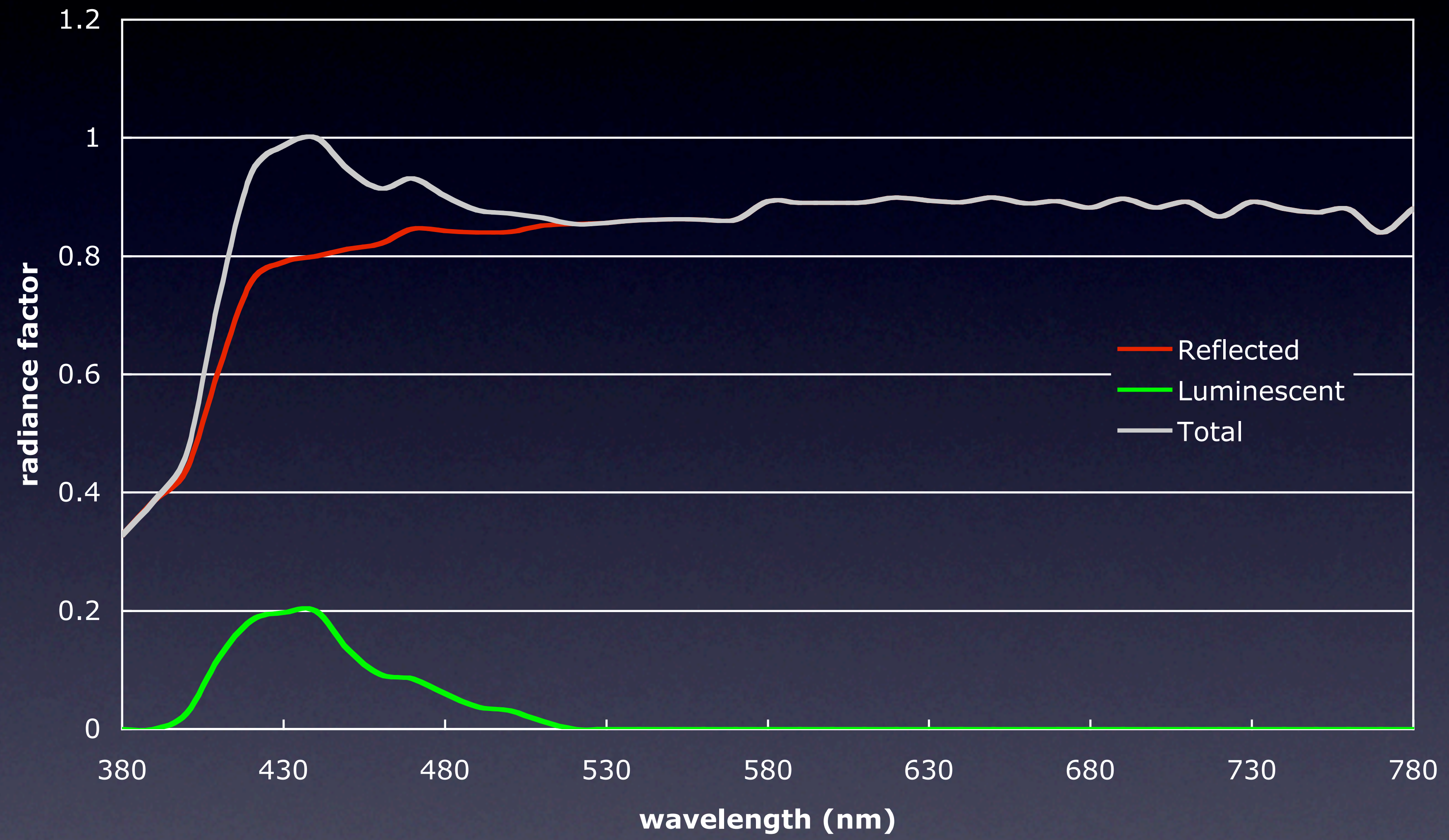
Fluorescent TSV's $W_F = k\sum_{\lambda}\beta_{F,\lambda}s_\lambda\bar{w}_\lambda\Delta\lambda$

Total TSV's $W_T = W_R + W_F$

Calculate CIELAB from these tristimulus values using D65, 1931 observer.

R·I·T

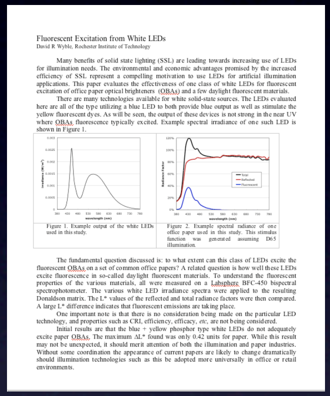
Paper Radiance Factors



Illuminant D65
Epson 1047049

The Experiment

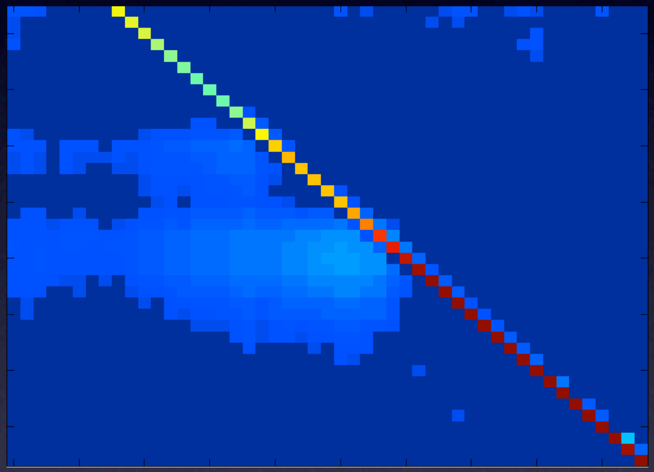
Set of 6 typical
white office papers



Bispectral
measurements

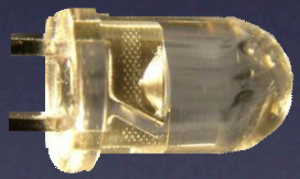
Normalized
source data

Donaldson matrix



Process

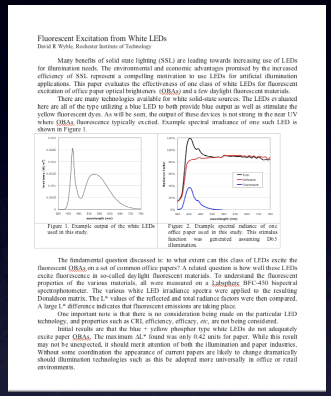
Colorimetric data



White LED

The Experiment

Set of 6 typical white office papers



Fluorescent Excitation from White LEDs

David R Wyble, Rochester Institute of Technology

Many benefits of solid state lighting (SSL) are leading towards increasing use of LEDs for illumination needs. The environmental and economic advantages promised by the increased efficiency of SSL represent a compelling motivation to use LEDs for artificial illumination applications. This paper evaluates the effectiveness of one class of white LEDs for fluorescent excitation of office paper optical brighteners (OBAs) and a few daylight fluorescent materials.

There are many technologies available for white solid-state sources. The LEDs evaluated here are all of the type utilizing a blue LED to both provide blue output as well as stimulate the yellow fluorescent dyes. As will be seen, the output of these devices is not strong in the near UV where OBAs fluorescence typically excited. Example spectral irradiance of one such LED is shown in Figure 1.

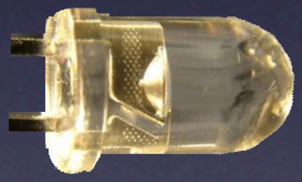
Figure 1. Example output of the white LEDs used in this study.

Figure 2. Example spectral radiance of one office paper used in this study. This stimulus function was generated assuming D65 illumination.

The fundamental question discussed is: to what extent can this class of LEDs excite the fluorescent OBAs on a set of common office papers? A related question is how well these LEDs excite fluorescence in so-called daylight fluorescent materials. To understand the fluorescent properties of the various materials, all were measured on a Labsphere BFC-450 bispectral spectrophotometer. The various white LED irradiance spectra were applied to the resulting Donaldson matrix. The L* values of the reflected and total radiance factors were then compared. A large L* difference indicates that fluorescent emissions are taking place.

One important note is that there is no consideration being made on the particular LED technology, and properties such as CRI, efficiency, efficacy, *etc*, are not being considered.

Initial results are that the blue + yellow phosphor type white LEDs do not adequately excite paper OBAs. The maximum ΔL^* found was only 0.42 units for paper. While this result may not be unexpected, it should merit attention of both the illumination and paper industries. Without some coordination the appearance of current papers are likely to change dramatically should illumination technologies such as this be adopted more universally in office or retail environments.

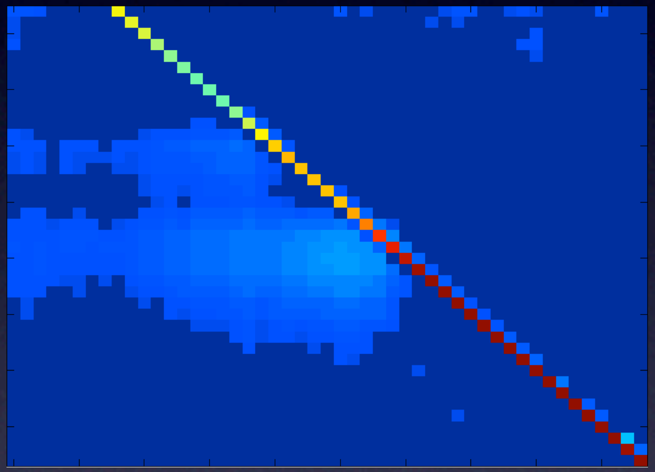


White LED

Bispectral measurements

Normalized source data

Donaldson matrix



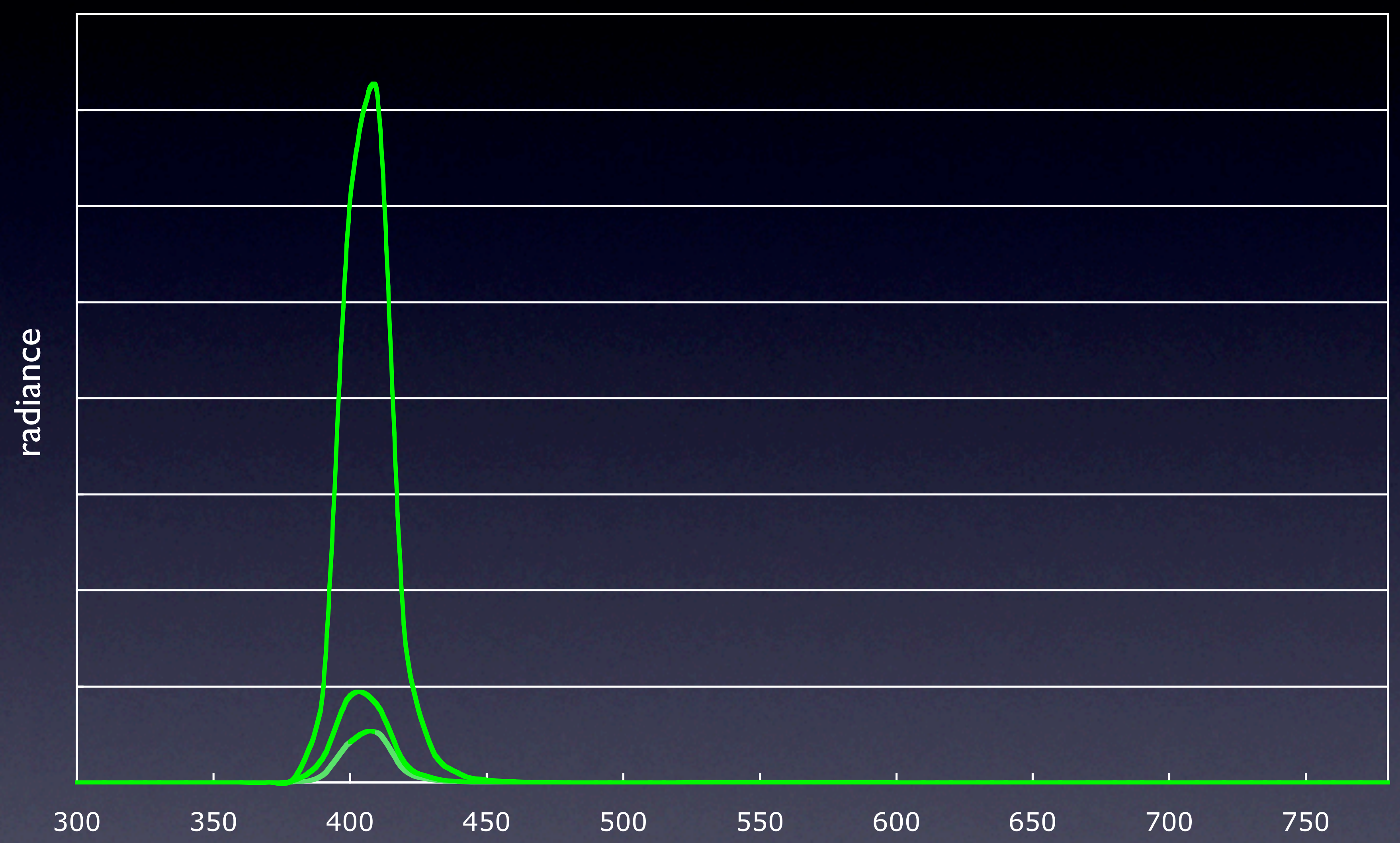
Process

Colorimetric data

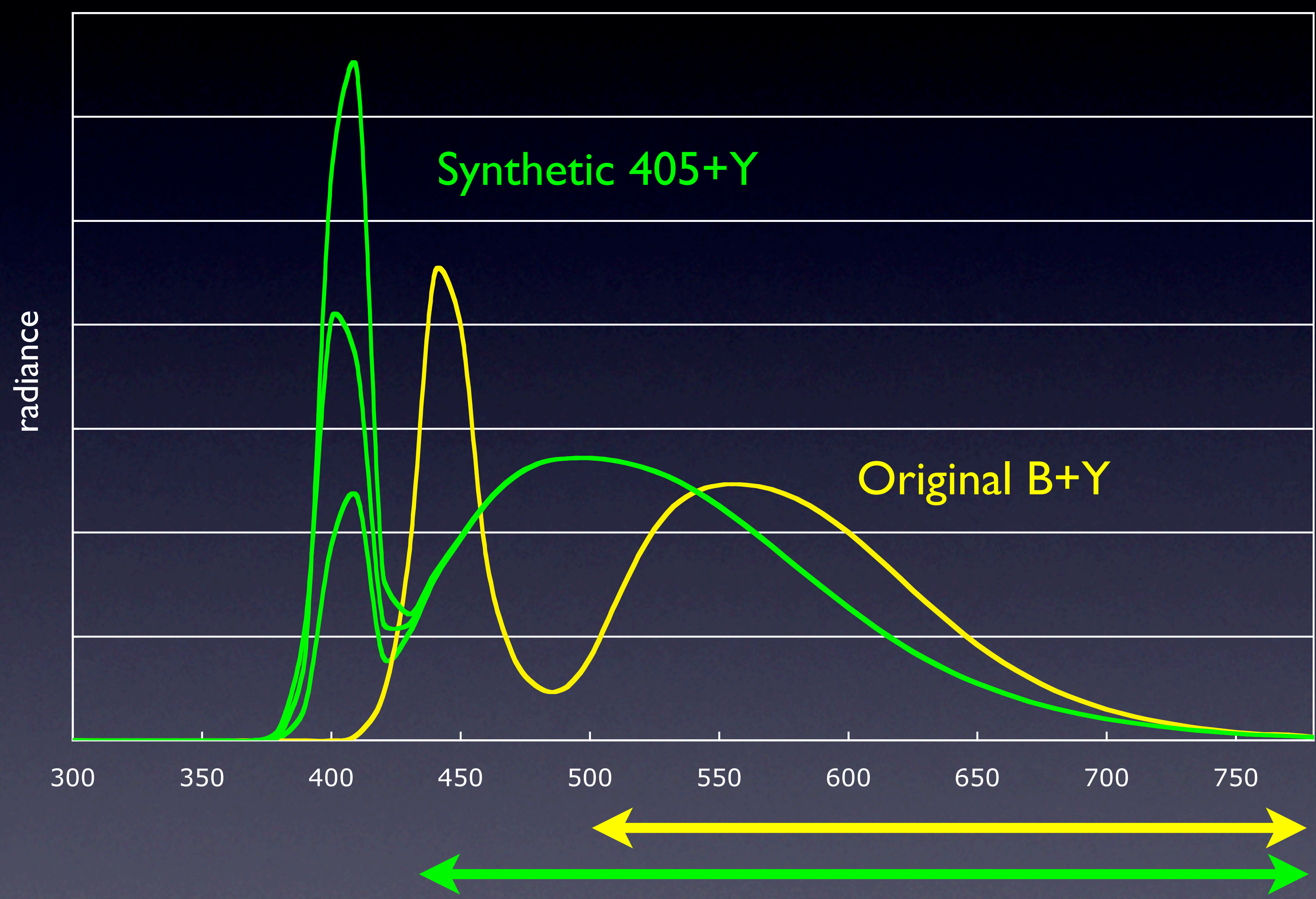
Light Source Details

- White LEDs
  - Blue LED + yellow phosphor
  - RGB
  - 405 nm LED + yellow phosphor
- Source normalization
  - 1931 2° Y tristimulus value = 100
  - Best compromise for the intended application

LEDs with Peak at 405

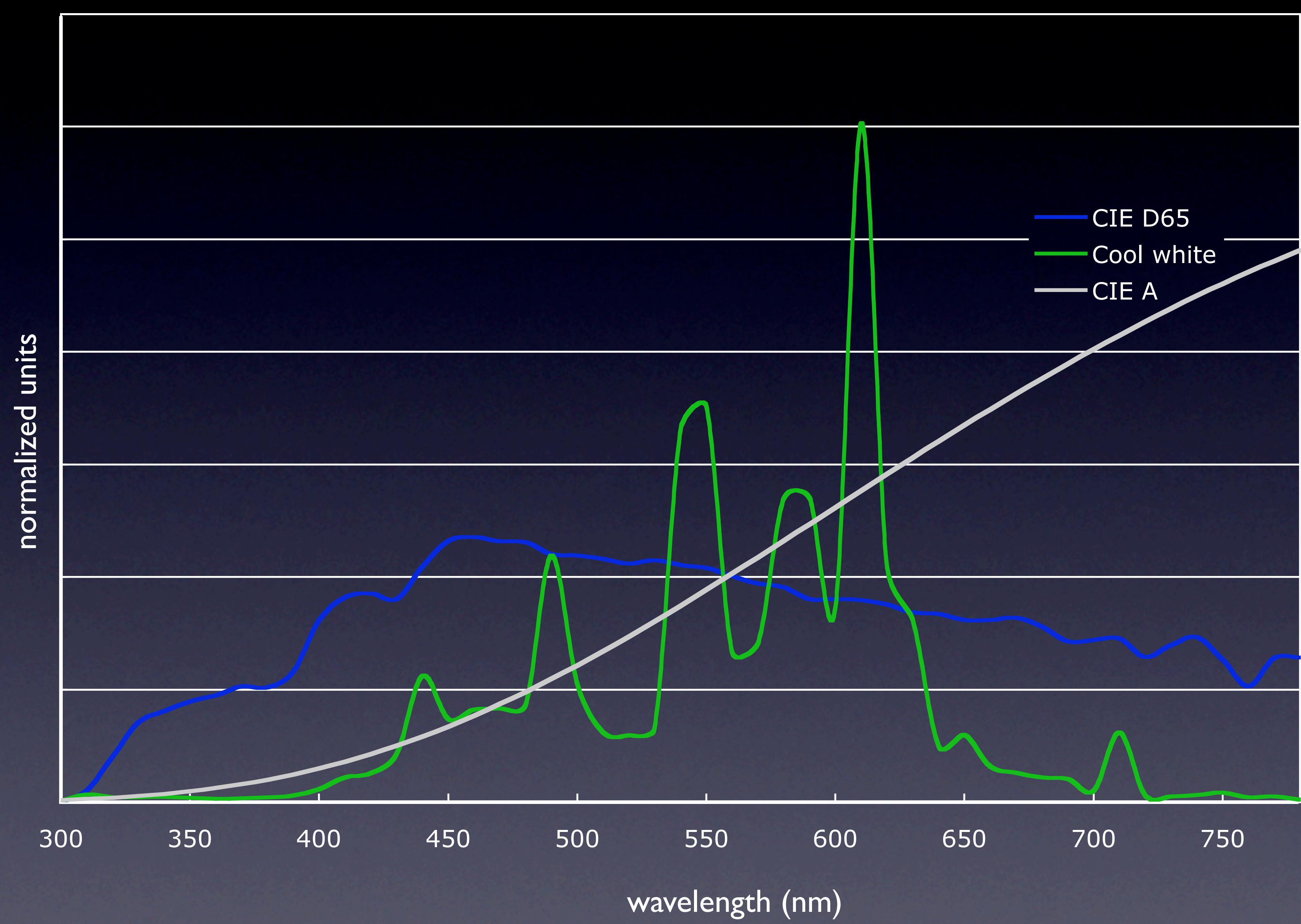


“Synthetic” LEDs

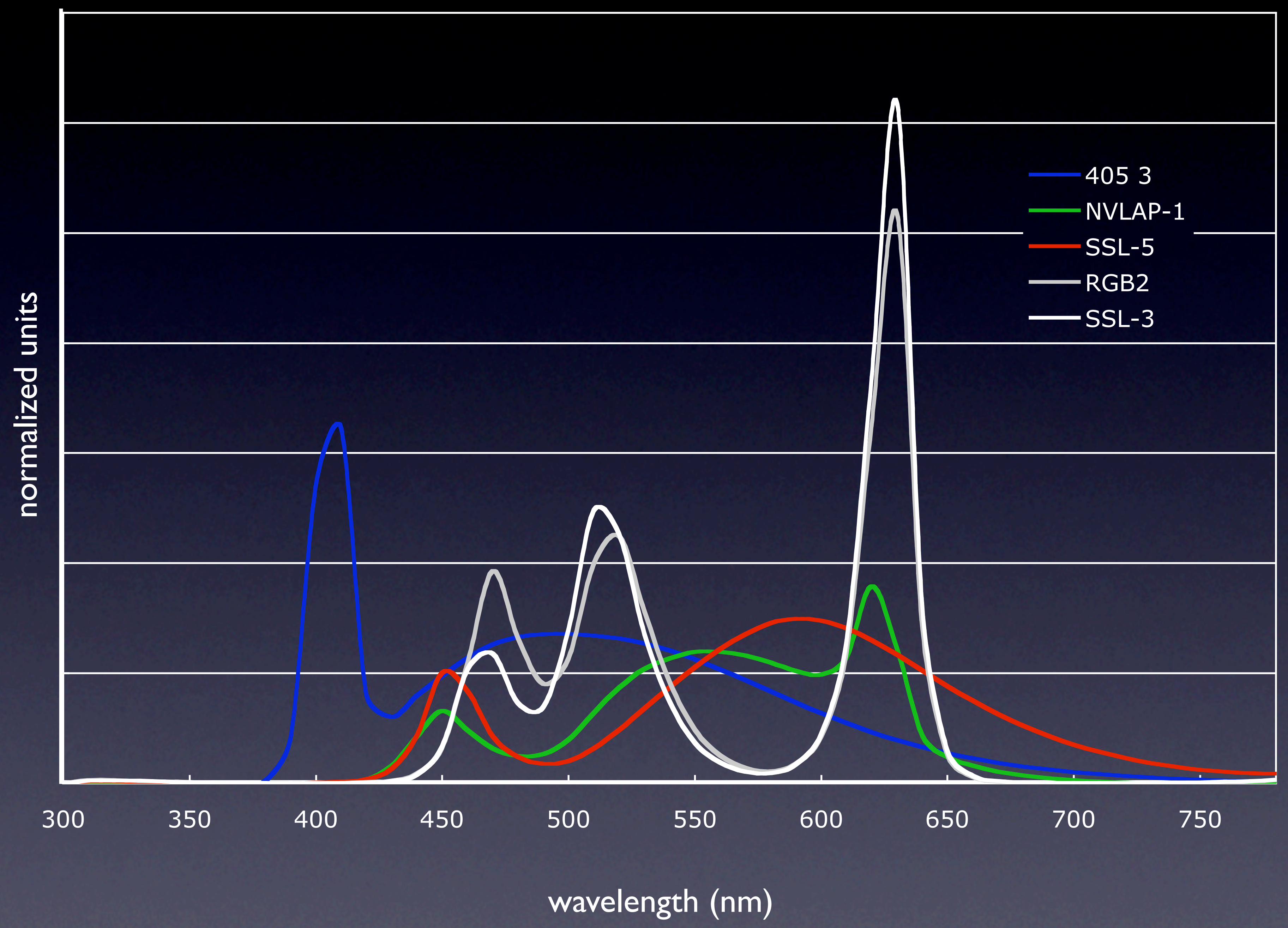


Maintain the shape of the yellow emission.

Normalized Virtual Sources

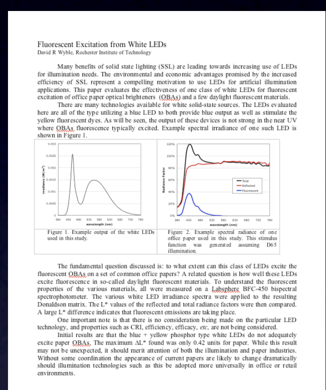


Normalized LED Output

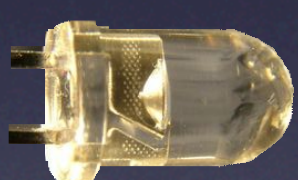


The Experiment

Set of 6 typical white office papers



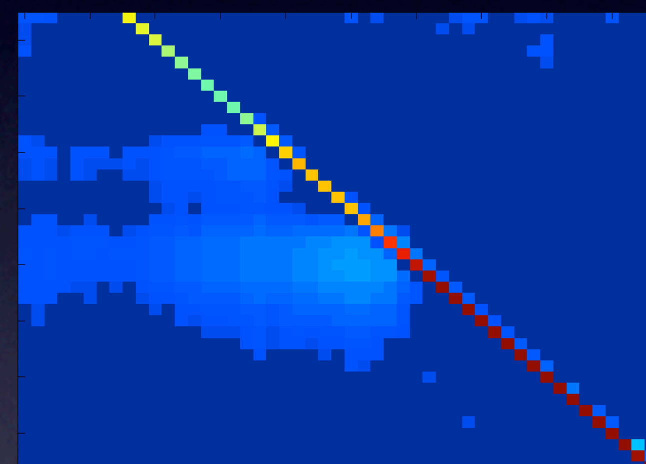
Bispectral measurements



White LED

Normalized source data

Donaldson matrix

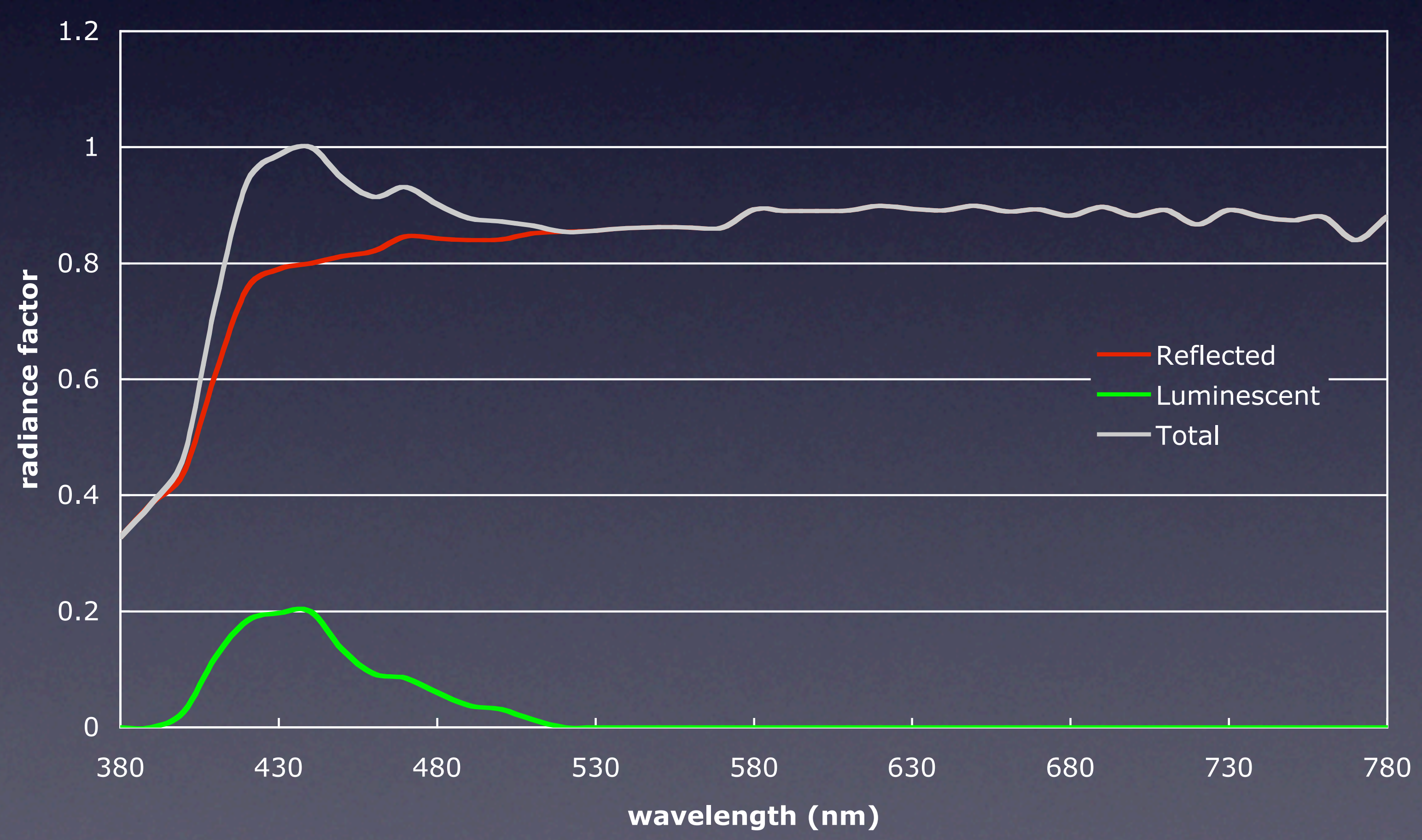


Process

Colorimetric data

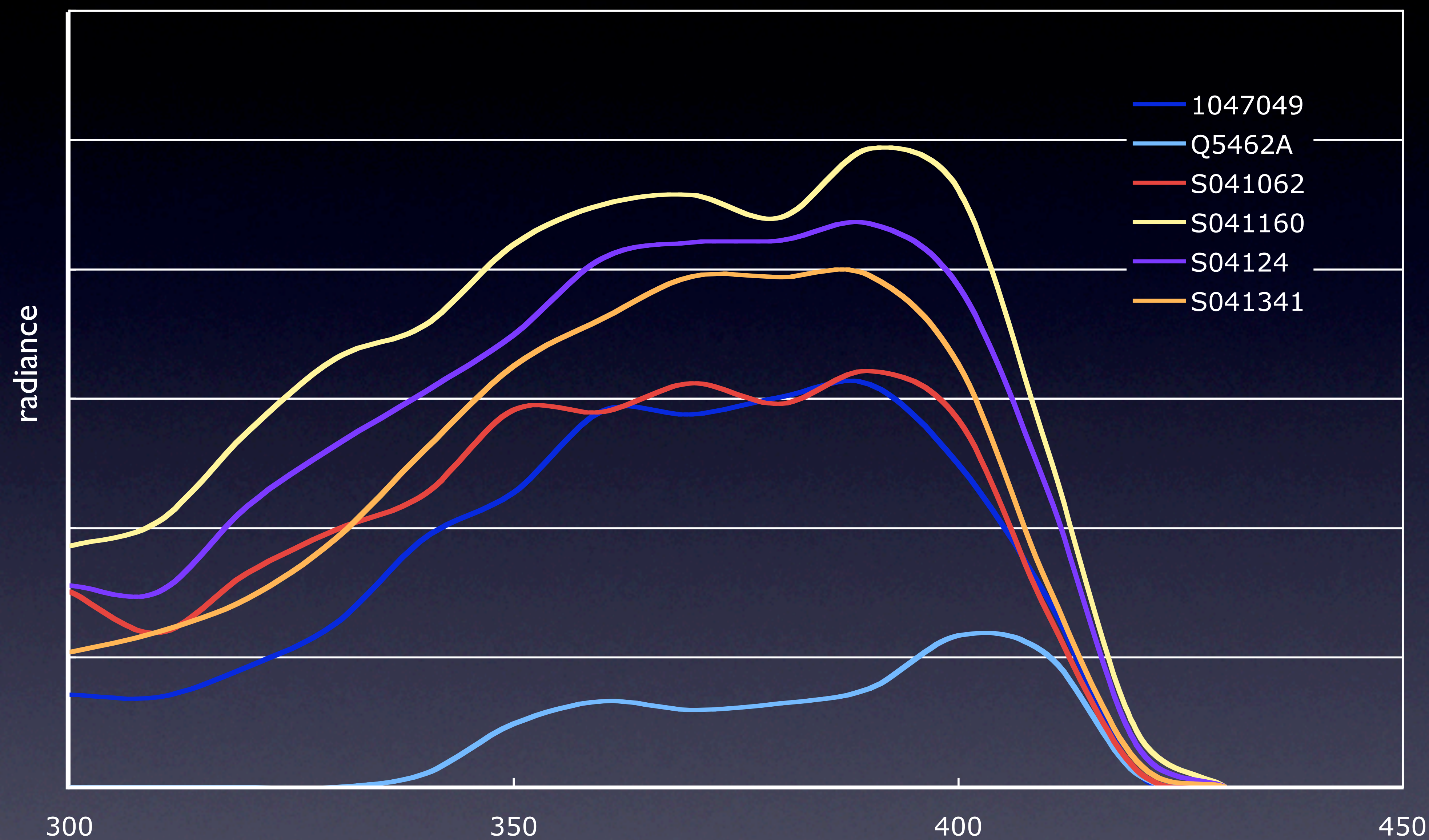
Substrate Details

- White office paper
  - Standard Epson stock
  - All exhibit fluorescence to some degree



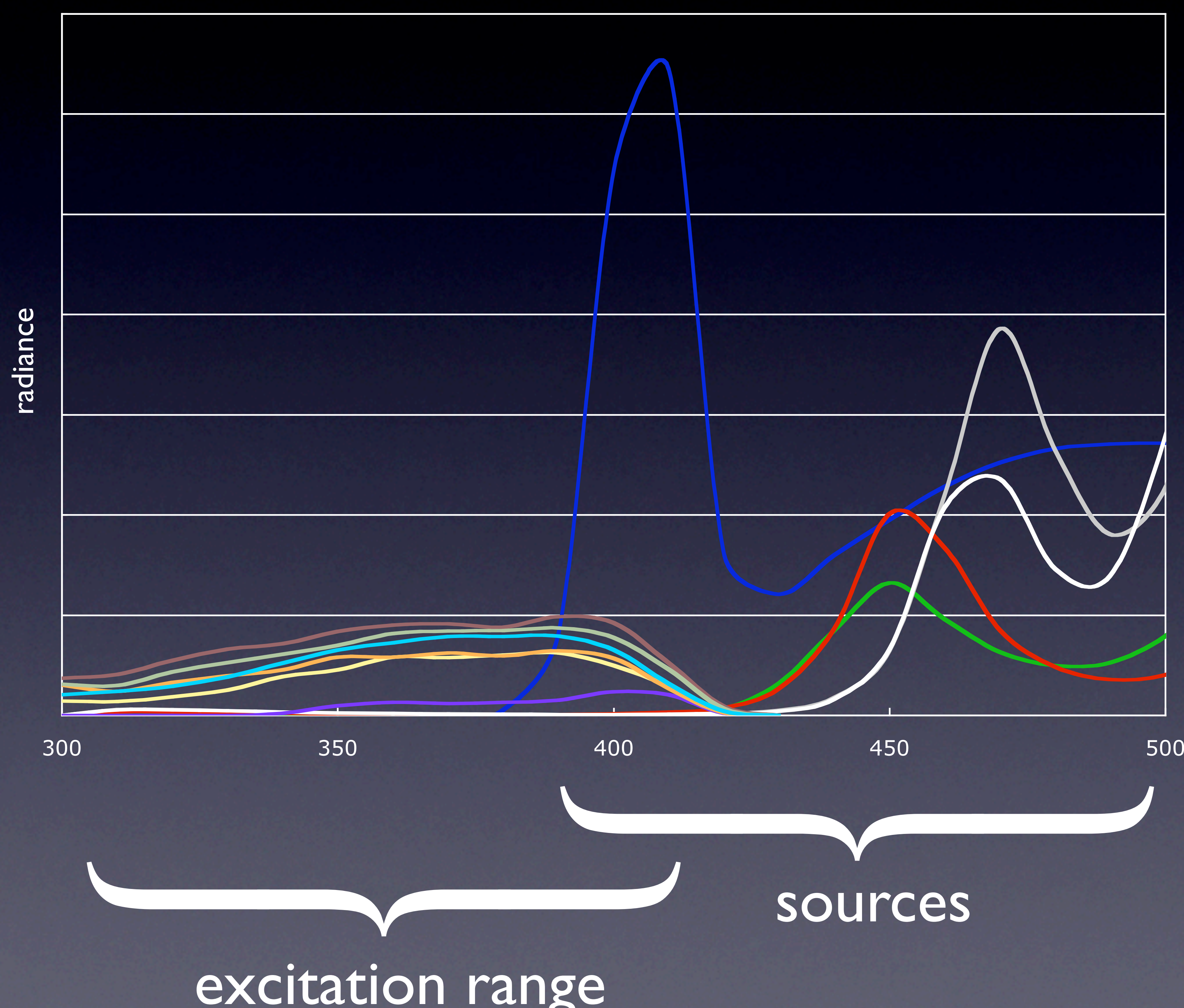
Illuminant D65
Epson 1047049

Substrate Details

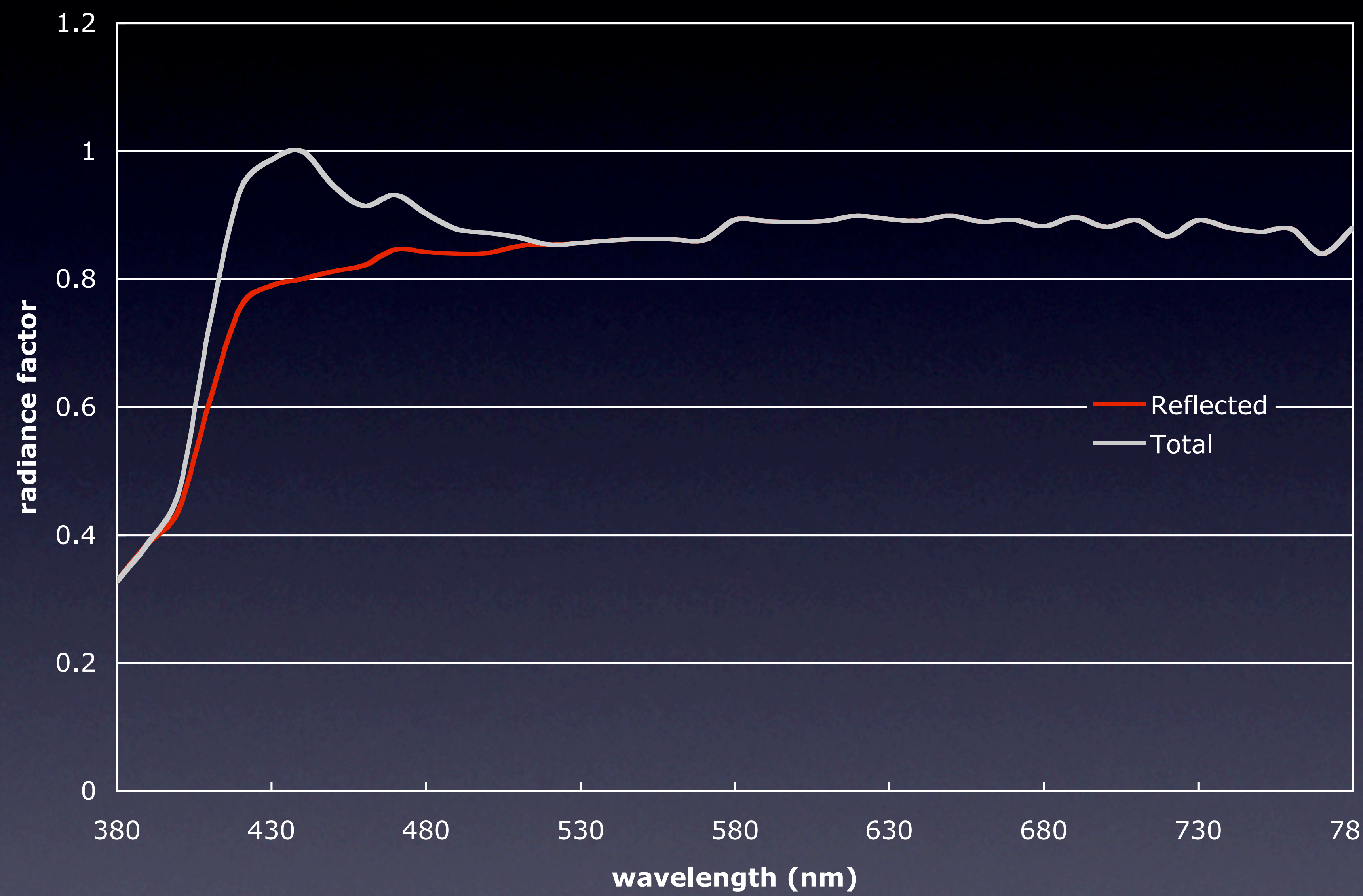


Excitation spectra

What Do We Expect?



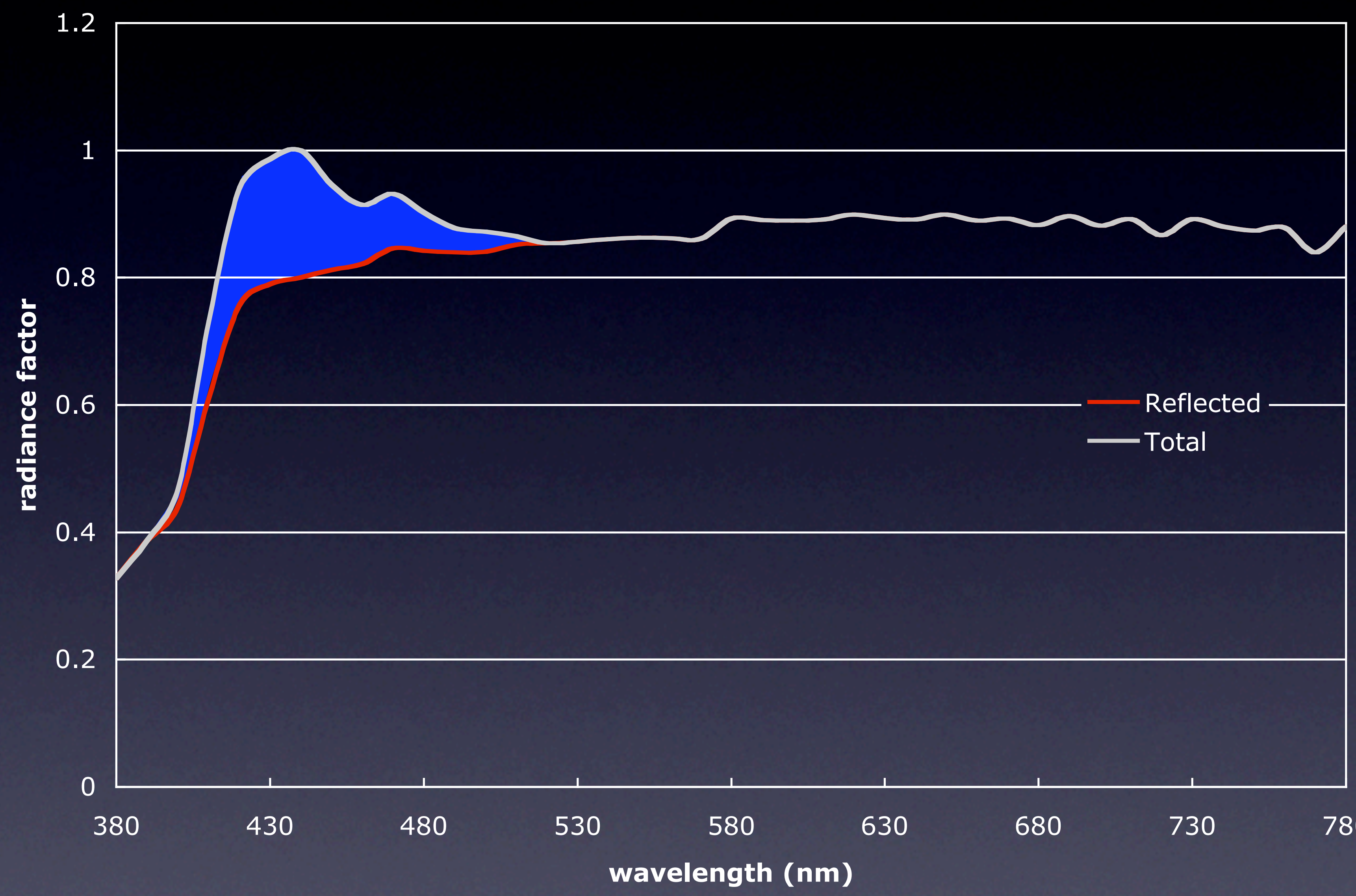
Results



Calculate a color difference between the reflected and total radiance factors.
"How visible is the change imposed by the luminescent radiance factor?"

R·I·T

Results



Calculate a color difference between the reflected and total radiance factors.
"How visible is the change imposed by the luminescent radiance factor?"

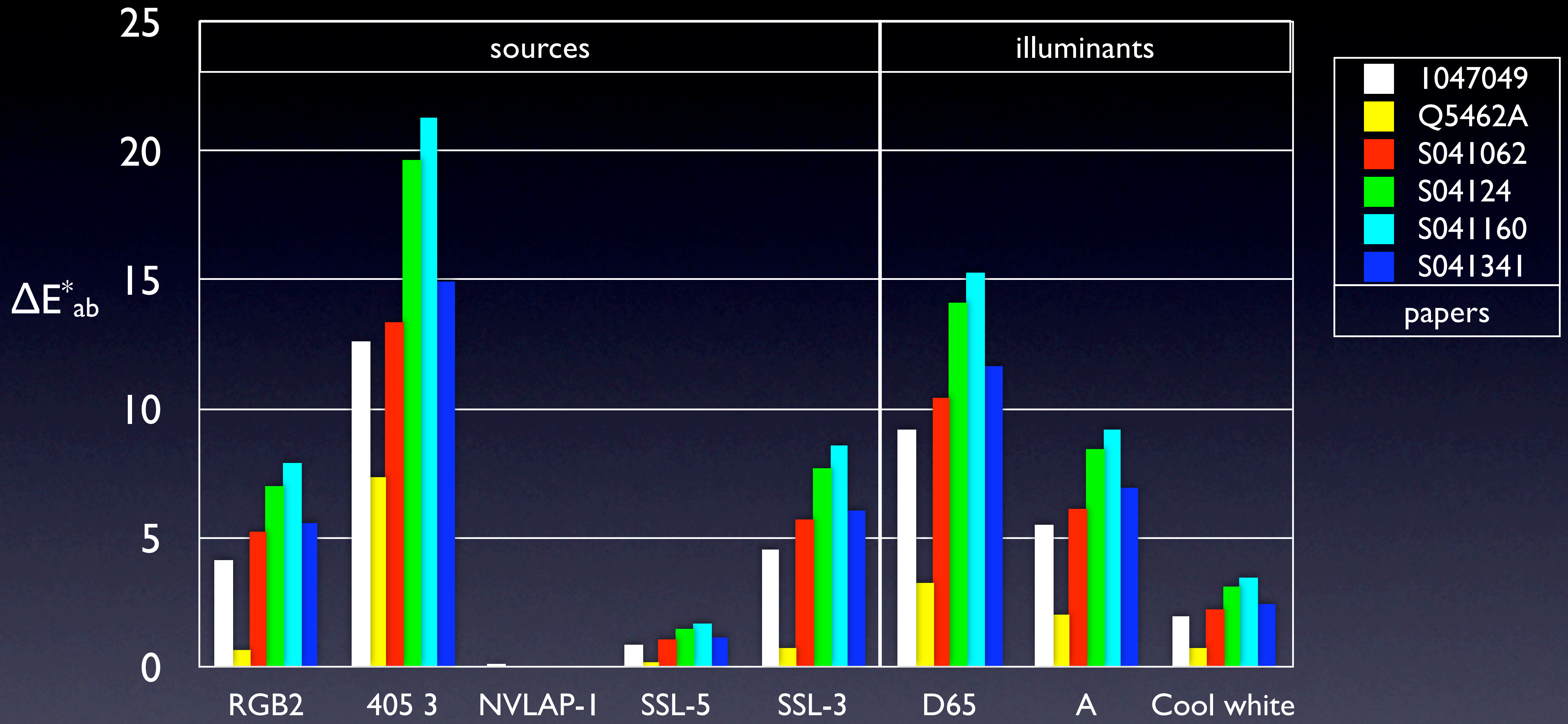
Results

	Light Sources							
papers	RGB2	405 3	NVLAP-1	SSL-5	SSL-3	CIE D65	CIE A	Cool white
1047049	4.20	12.61	0.11	0.91	4.58	9.25	5.50	1.95
Q5462A	0.68	7.35	0.02	0.20	0.74	3.25	2.04	0.74
S041062	5.24	13.39	0.06	1.09	5.72	10.48	6.14	2.24
S04124	7.06	19.64	0.02	1.52	7.69	14.12	8.45	3.16
S041160	7.93	21.28	0.01	1.70	8.64	15.31	9.19	3.49
S041341	5.61	14.97	0.04	1.19	6.11	11.70	6.94	2.49

ΔE^*_{ab} between luminescent and total radiance factors.

R·I·T

Results

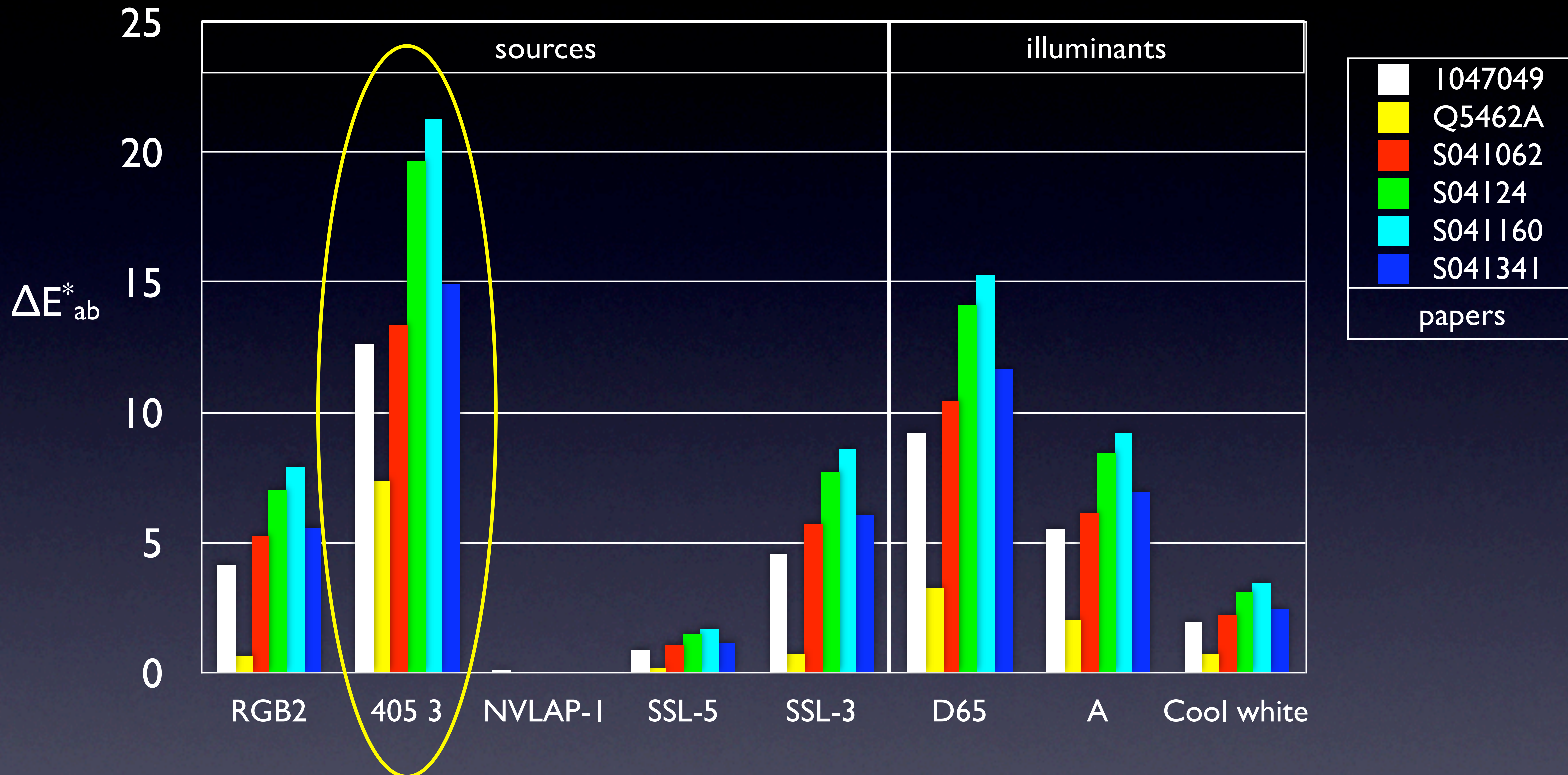


Interpretation: this shows the color difference that would be expected by illuminating each paper under the given light source if paper OBAs were removed.

Put another way, this is as though two papers were viewed side by side, one with and one without fluorescent OBAs.

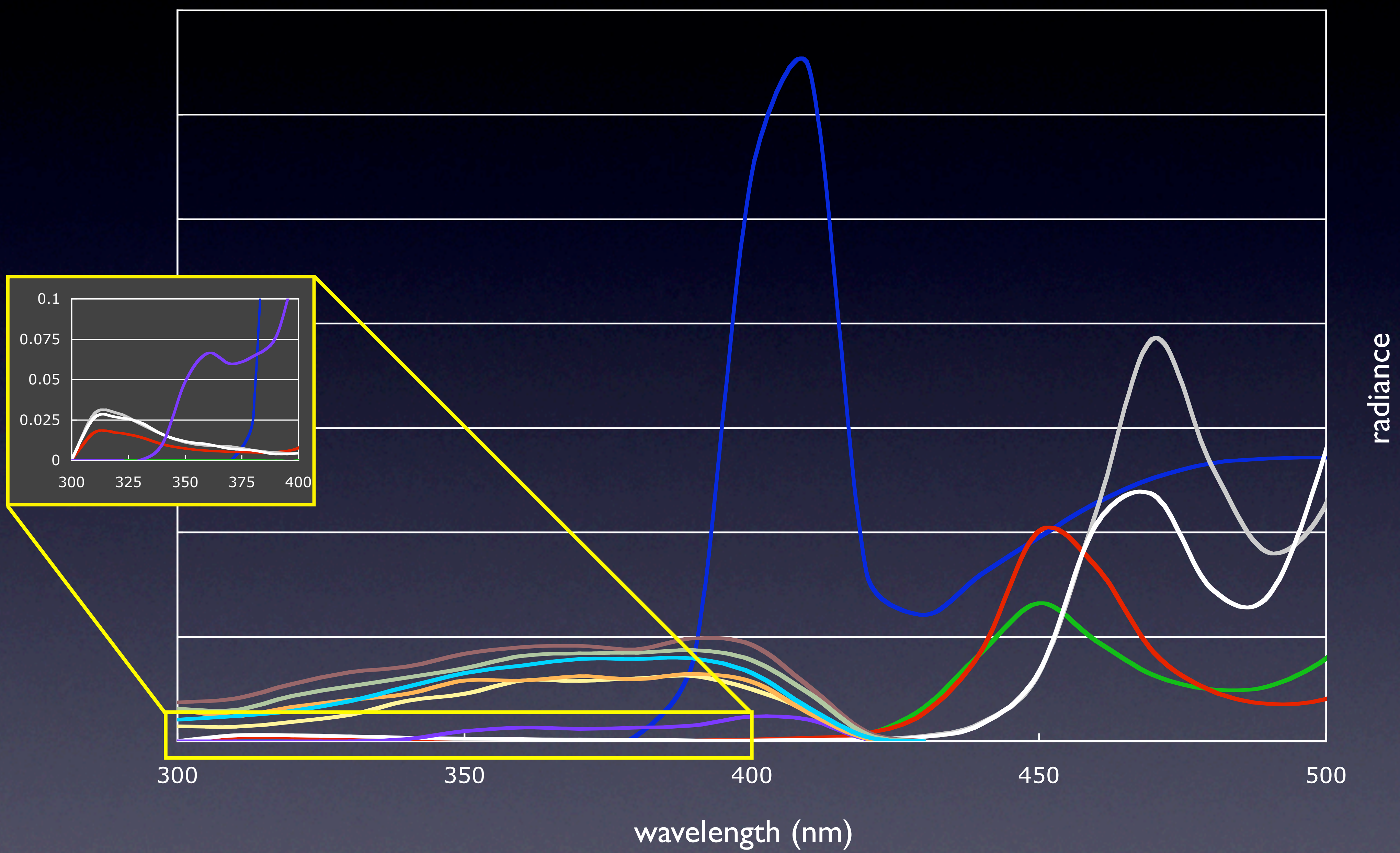
R·I·T

Results



Interpretation: this shows the color difference that would be expected by illuminating each paper under the given light source if paper OBAs were removed.

Put another way, this is as though two papers were viewed side by side, one with and one without fluorescent OBAs.


0.1
0.075
0.05
0.025
0
300
325
350
375
400
300
350
400
450
500
wavelength (nm)
radiance

Conclusions and Recommendations

- Commercially available white LEDs (RGB, B+Y) do not adequately excite office paper optical brightening agents.
- An LED configuration including a lower wavelength source, such as the 405nm blue, can provide the necessary excitation to preserve paper appearance.
- Alternative strategies could include adjusting the paper OBA chemistry.
- None of the issues are "show stoppers" compared to the other significant benefits of solid state lighting.
- Printing, packaging and other graphic arts applications could potentially require process adjustments.

Future Work

- Add substrates and sources
  - Your contributions are encouraged
  - Data or samples
- Simulation images
- Consider other aspects of sources
  - CRI, cost, lifetime, etc
- Luminescence - safety markings
- <u>Not future work</u> (for this researcher):
  - Engineer a new LED
  - Adjust OBA chemistry

R·I·T

Acknowledgments

- Funding for this work came in part from
  - Munsell Color Science Laboratory
  - RIT's Center for Imaging Science
  - X-rite Incorporated
- Many thanks for technical discussions and the sharing of data from:
  - Dr Cameron Miller (NIST)
  - Dr Art Springsteen (Avian Technologies)
  - Mr Jim Leland (Gamma Scientific)