Magnitudes, Colors, and Photometric Systems

(Or: why astronomers give us magnitudes instead of something useful like a flux.)

Counts to Magnitudes

(Ideal case)

Assuming you have a linear response:

Flux = counts x constant

Then, to go from counts or flux to Pogson magnitudes:

$$\text{mag} = -2.5 \log_{10}(F/F_0)$$

$$= -2.5 \log_{10}(F) + \text{Constant}$$

where:

F_0 is the flux of an object with mag = 0

"Constant" is called the zeropoint (ZP)

$$\text{mag} = -2.5 \log_{10}(F) + ZP$$

Counts to Magnitudes

(Real world case)

$$\mathrm{mag} = -2.5\ \log_{10}(F) + \mathrm{ZP} + \mathrm{AtmosphereTerm}(t) +$$

$$\mathrm{ColorTerms} + \mathrm{AtmColorTerm}(t) + \ldots$$

$$= -2.5\ \log_{10}(F) + X$$

...anything you neglect can end up in the zeropoint!

Full hairy SDSS example: 0.5m PT r-band formula:

$$r = -2.5\ \log_{10}(\mathrm{counts/sec}) - \mathrm{ZP}_r - k_r(t)X$$

$$- b_r[(r'-i')-(r'-i')_{zp}] - b_{2.5m}[(r'-i')-(r'-i')_{zp}]$$

$$- c_r[(r'-i')-(r'-i')_{zp}](X-X_{zp}) + \mathrm{zpOffset}(r)$$

“Luptitudes”

(The nightmare continues)

Magnitudes behave badly at low signal to noise since $\log_{10}(0) = -\infty$ and only gets worse for negative counts.

Thus asinh (inverse hyperbolic sine) magnitudes were born:

$$\mathrm{mag}_{\mathrm{asinh}} = -(2.5 / \ln(10)) \times [\mathrm{asinh}(2b\, F/F_0) + \ln(b)]$$

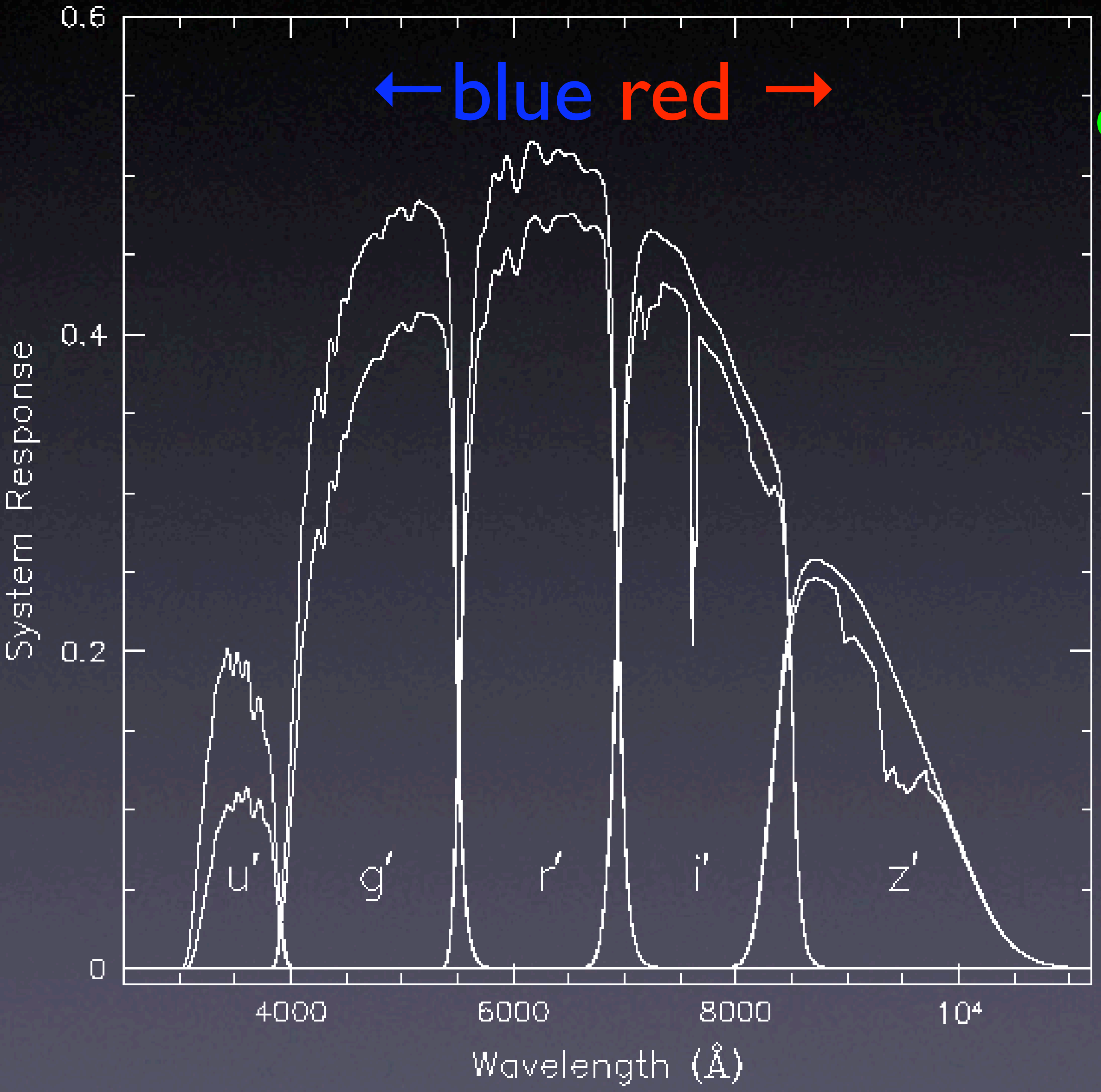
where b is set by the 1sigma noise level.

For any reasonable signal to noise this differs from normal magnitudes by less that 1%, and it doesn’t blow up even for negative counts.

(Lupton, Gunn & Szalay 1999)

Color?

SDSS filters



color ≠ filter!

color = "blue" filter - "red" filter

negative color = "blue"

positive color = "red"

ex: star with magnitudes

g = 20, r = 18

g-r = 2

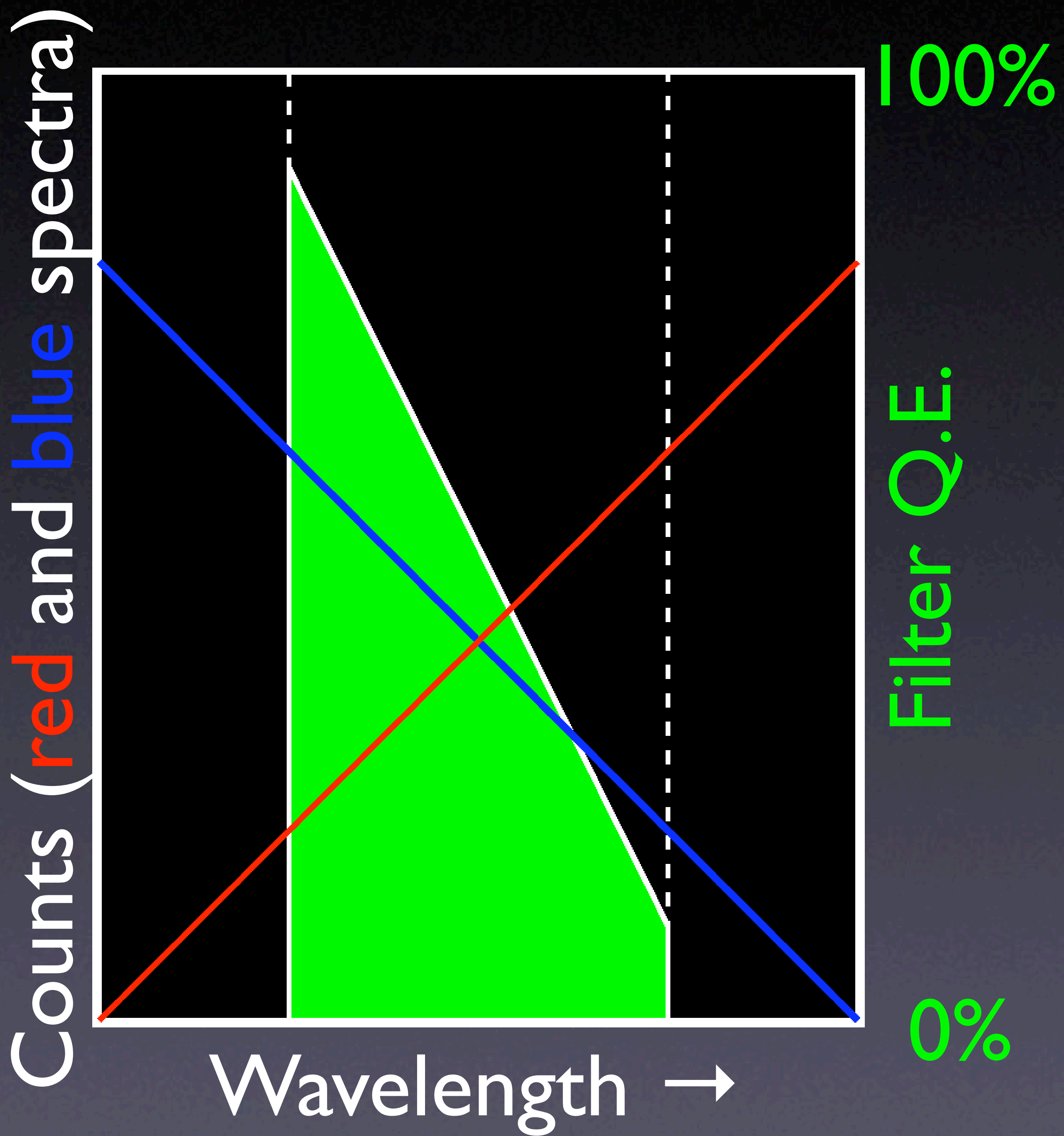
g-r "color" is red

...but what does color mean?

(Red compared to what?)

And why do you need color terms?

Color Terms



green = filter response curve
blue = blue spectra counts
red = red spectra counts

red counts

$$\int \text{response}(\lambda)\,\text{red}(\lambda)\,d\lambda$$

$$\cong$$

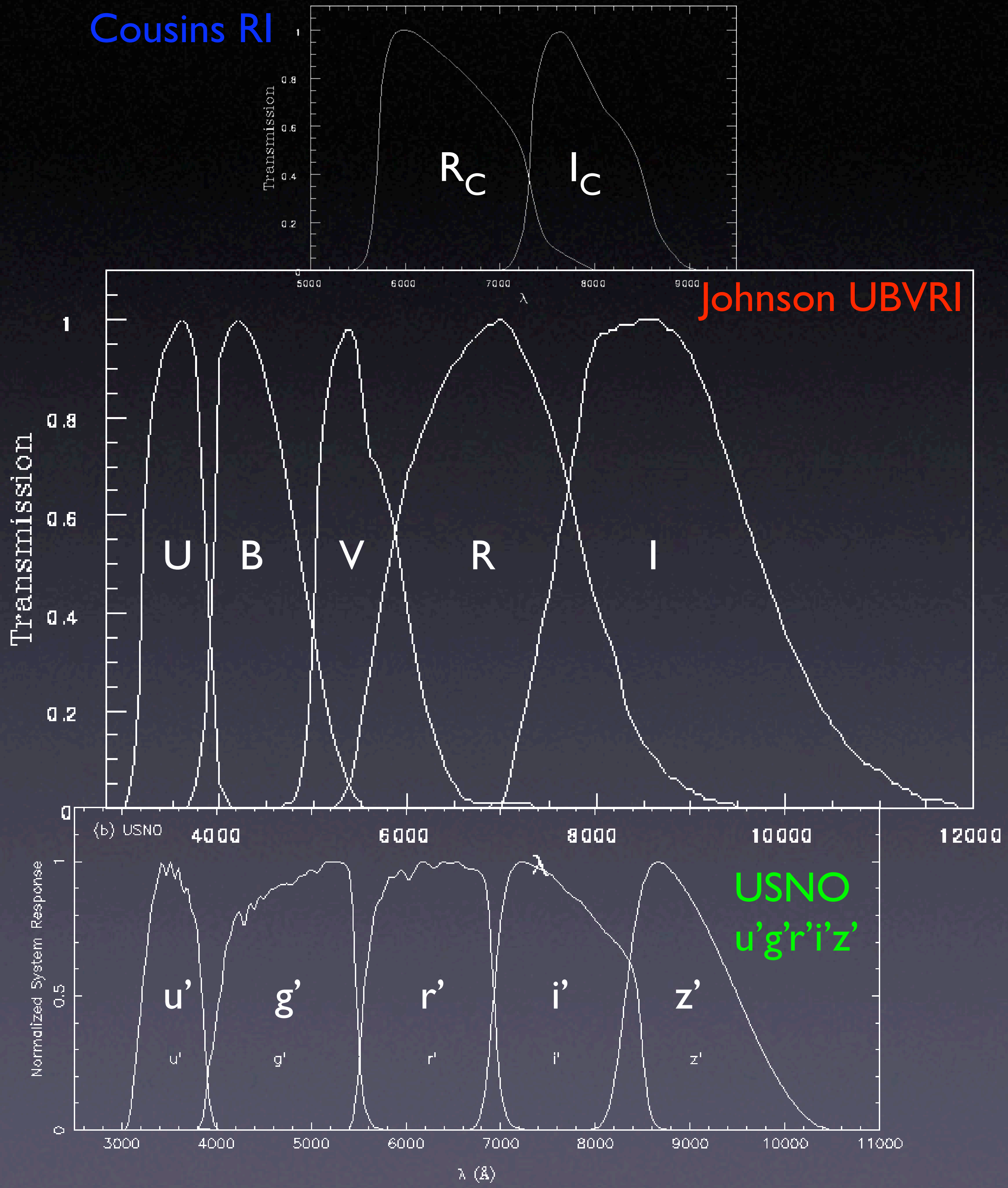
75% of blue counts

$$\int \text{response}(\lambda)\,\text{blue}(\lambda)\,d\lambda$$

≅ 0.25 mag calibration error

without a color term

Common photometric systems



UBVRI and RI from http://obswww.unige.ch/gcpd/filters

Filter	effective λ (nm)	FWHM	Vega
u	355	60	+1.08
U	360	50	0
B	440	100	0
g	468	140	-0.08
V	550	80	0
r	617	140	+0.14
R_C	660	160	0
R	700	220	0
i	748	150	+0.34
I_C	810	150	0
I	880	240	0
z	893	100	+0.54

Photometric Systems:

Choosing Zeropoints and Defining Color

Two major basic systems: Vega based and AB

VEGA BASED: (Ex: Johnson UBVRI)

- Vega (or stellar type A0 or some other standard star) as observed through the filters is defined as $\mathrm{mag}_{\mathrm{Vega}} \equiv 0$ in all bands

  → $(U_{\mathrm{Vega}}=B_{\mathrm{Vega}}=V_{\mathrm{Vega}}=R_{\mathrm{Vega}}=I_{\mathrm{Vega}}\equiv 0)$

- All Vega colors are 0

  → $(U-B)=(B-V)=(V-R)=(R-I)\equiv 0$

  → if something is red/blue, it's only relative to Vega

- Calibration is well defined and easily verifiable/reproducible

- Magnitudes from different bands on the same plot are meaningless.

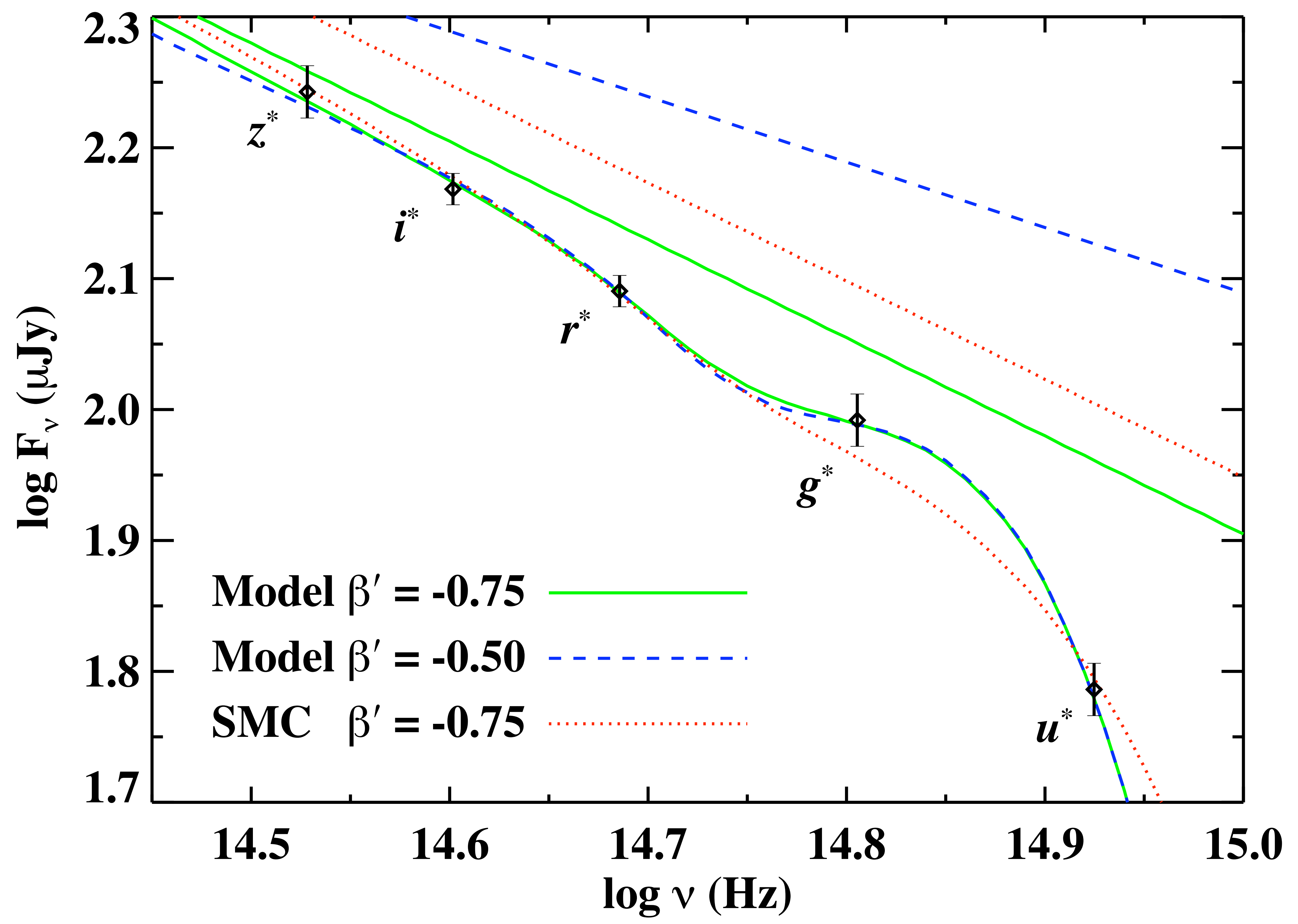
Photometric Systems:

Choosing Zeropoints and Defining Color

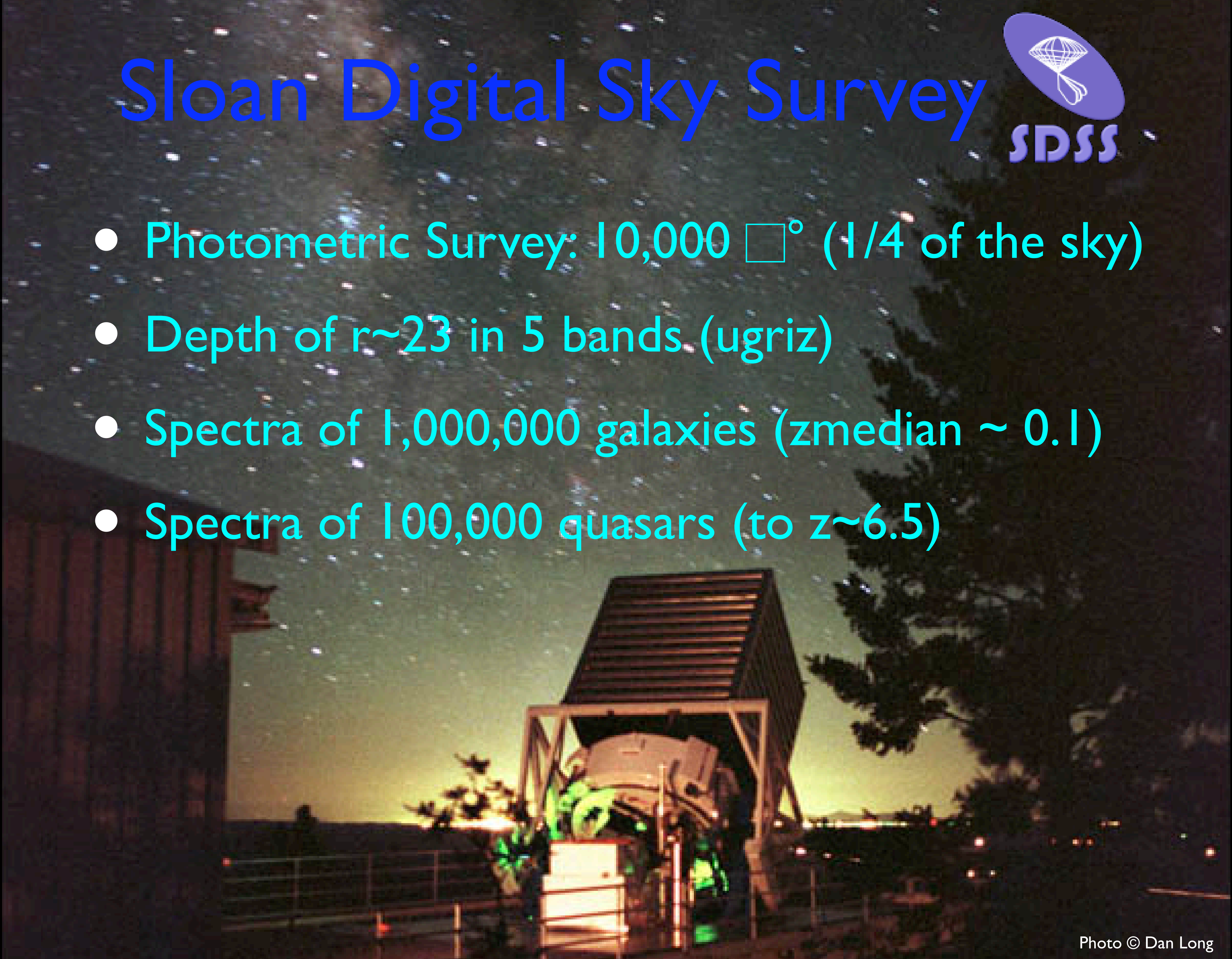
AB Magnitudes: (Ex: SDSS ugriz)
(the choice of physicists and bane of astronomers)

- F_0 = 3631 Jy (Jy = 10^{-26} W/m^2Hz) in all bands
  → $AB_\nu = -2.5 \log_{10}(F_\nu) - 48.60$ where F_ν = flux in ergs/sec·cm^2·Hz
- Colors are relative to a "flat" spectrum
  → something that's really red/blue has red/blue "colors"
- Multi-band plots are physically meaningful log flux plots!
- No real object has this spectrum
  → calibration is difficult (impossible?) and thus suspect.

AB magnitudes example: GRB010222



Sloan Digital Sky Survey



- Photometric Survey: 10,000 □° (1/4 of the sky)
- Depth of r~23 in 5 bands (ugriz)
- Spectra of 1,000,000 galaxies (zmedian ~ 0.1)
- Spectra of 100,000 quasars (to z~6.5)

Photo © Dan Long

Example: SDSS Calibration

Telescope	Filters	Stars	r-band mag
many	spectra	Vega	~0
many	spectra	BD+17°4708	9.35
USNO 1.0m	u’g’r’i’z’	158 Primary	≈ 8 to 13
PT 0.5m	$(ugriz)_{PT}$	Primary + Secondary	≈ 8 to 13 ≈ 14 to 18
SDSS 2.5m	ugriz	final data	≈ 14 to 23

From BD+17 to SDSS limit > a factor of 100,000 in flux

SDSS Standard Star: “BD+17”

BD+17°4708:

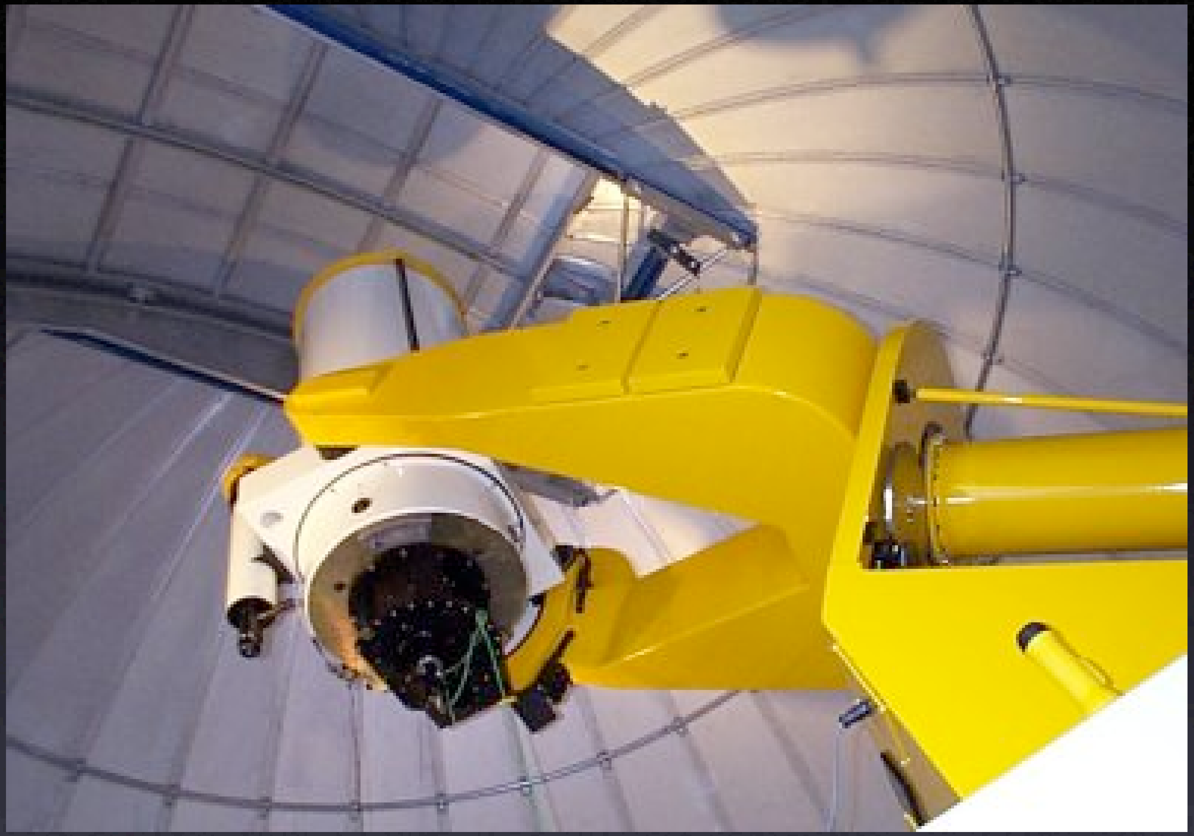
- F subdwarf
- Vega calibrated spectrophotometry used to set AB zeropoints to define the u’g’r’i’z’ system.

BD+17 to Primary Standards

- Hardware:
  - USNO 1.0m telescope
  - Single thinned CCD
  - u’g’r’i’z’ filters in ambient air (mostly stable)
- Observations:
  - BD+17 (and two other F subdwarf standards) repeatedly observed to track system definition
  - ~200 other standard stars (r 8-13) repeatedly observed and calibrated against the reference standards.
  - 183 nights over a 3 year period

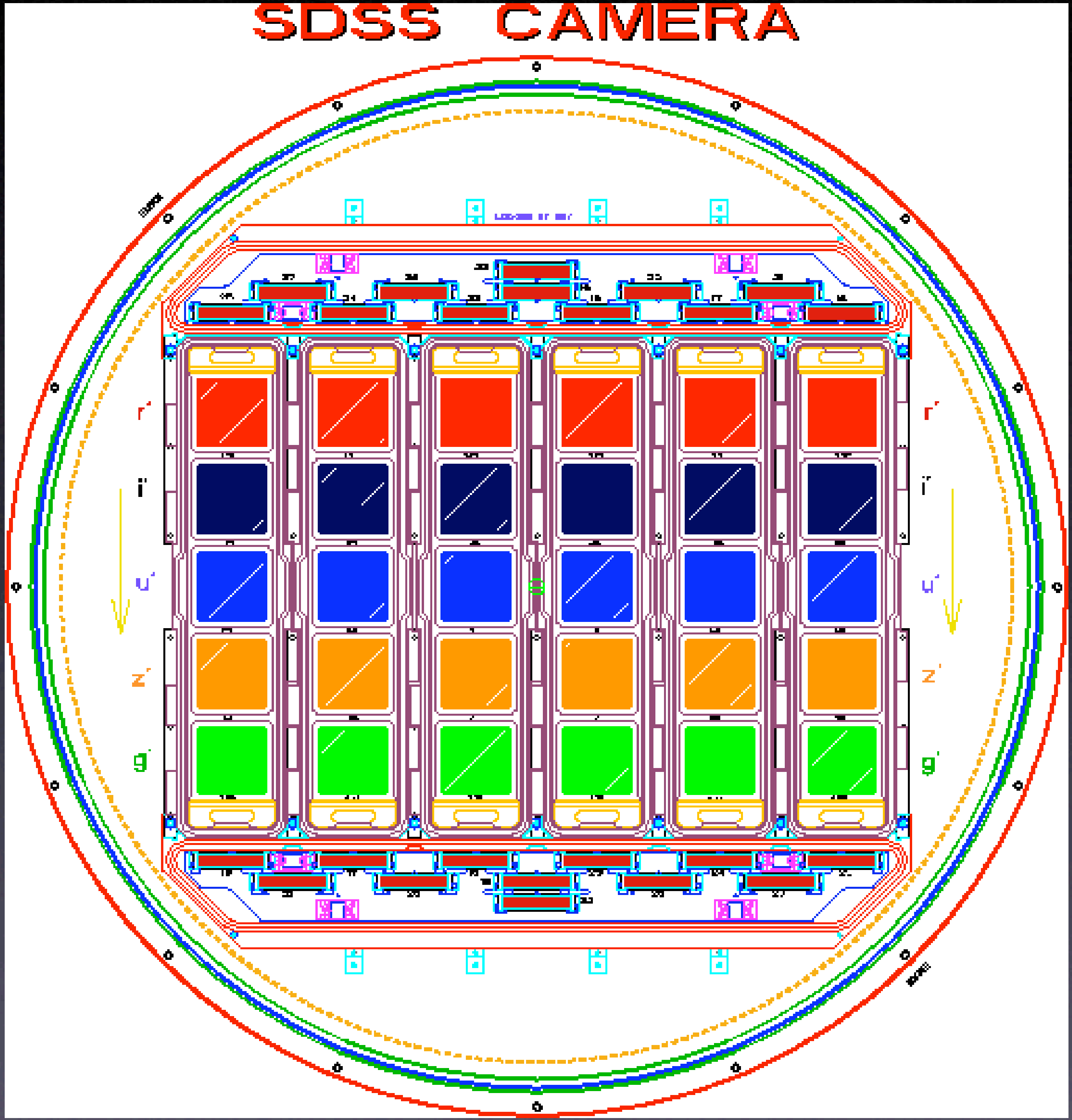
Primary to Secondary Standards

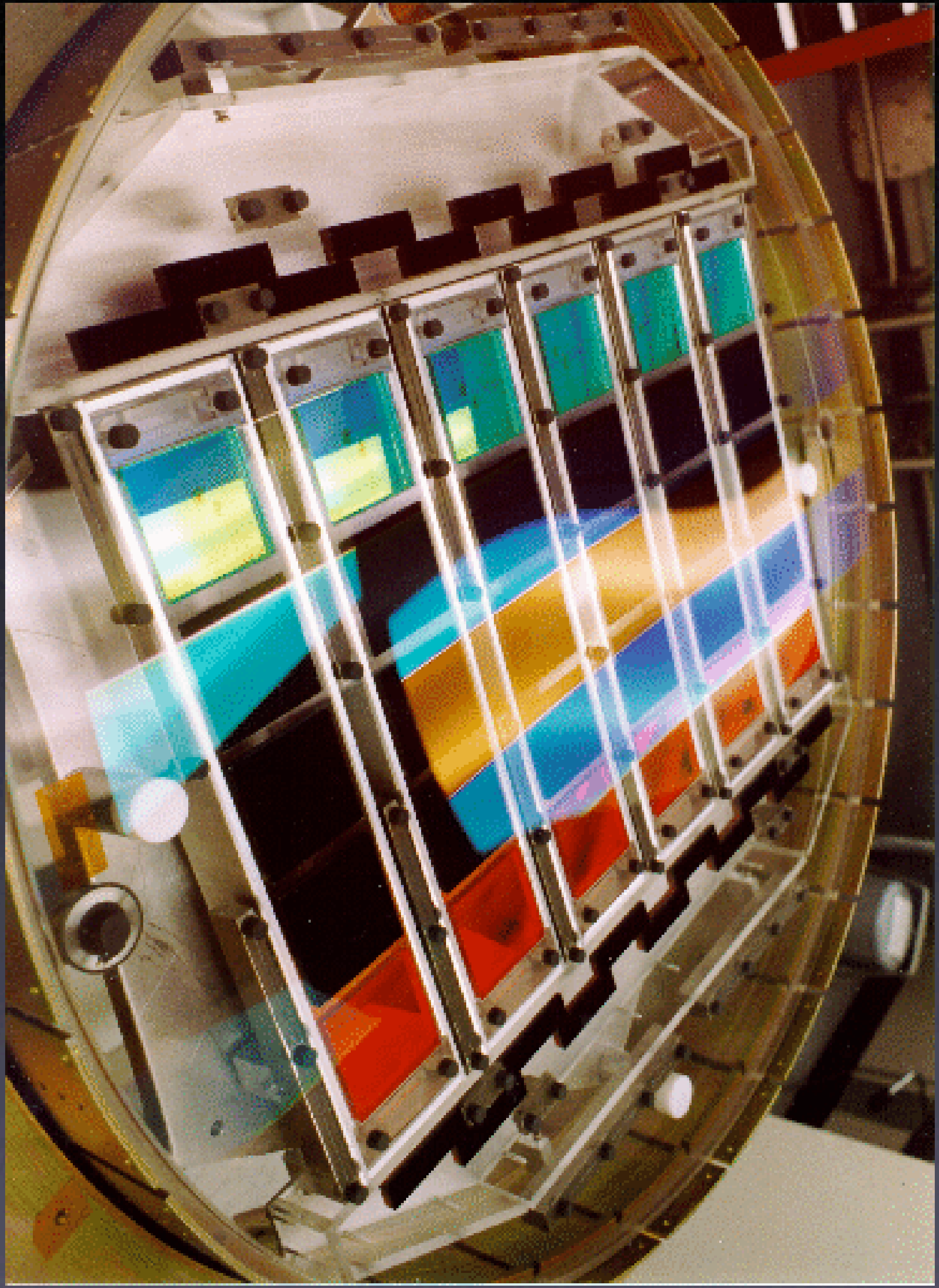
- Hardware:
  - SDSS 0.5m telescope
  - Single CCD,
    u'g'r'i'z' filters in dry nitrogen
    (unstable until filters replaced!)
    → now called $[ugriz]_{PT}$



- Observations:
  - Alternating observations of "primary" and "secondary" standards
    - Primary standards observed nightly to monitor atmosphere and determine calibration
    - Secondary standard fields which overlap main survey fields observed to transfer calibration to 2.5m data (approx 1 field every 15 degrees along a stripe)

SDSS 2.5m camera



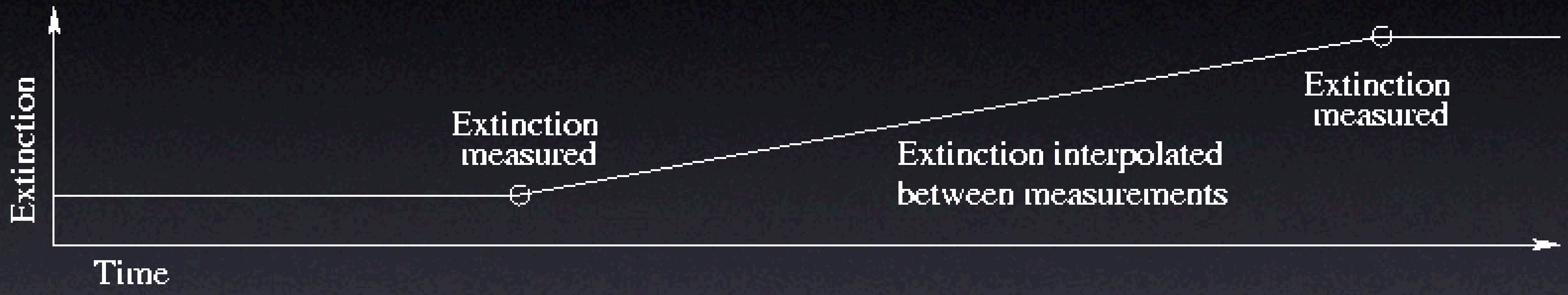


Final Calibration

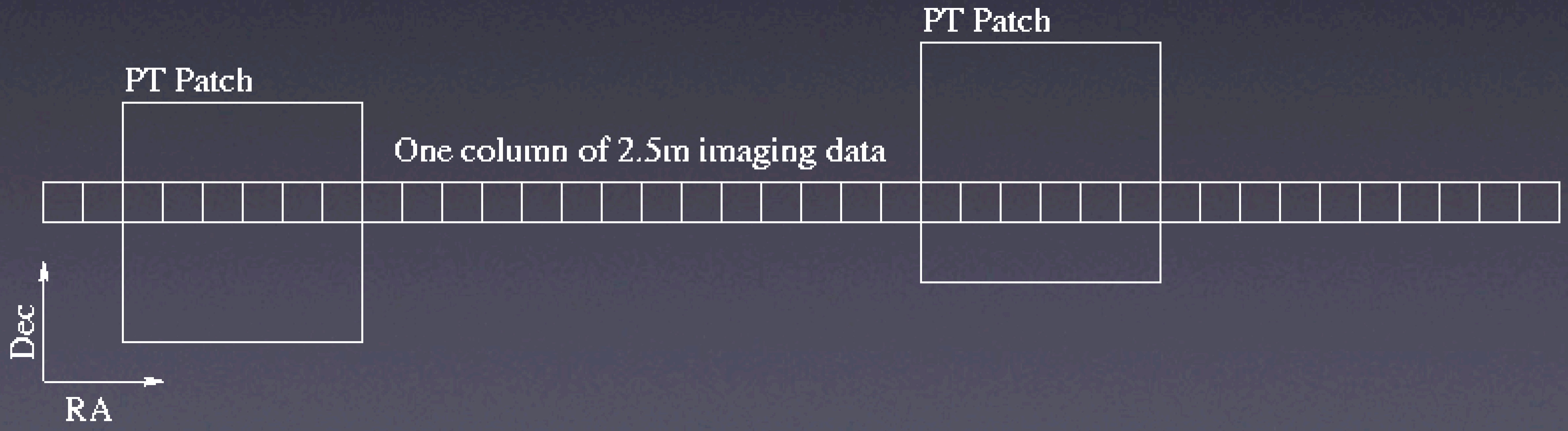
- Hardware:
  - SDSS 2.5m telescope
  - 54 (30) CCD camera
    6 each stable but shifted u'g'r'i'z' filters in vacuum → now called [ugriz]
- Observations:
  - 6 columns x 5 CCD/filter combinations
  - Driftscan stripes 2.5° wide, up to 90° long (interlaced with a second scan to fill in gaps), overlap 0.5m secondary patches every 15°
  - PT zeropoints and extinction coefficients transfered to 2.5m survey data

Final Calibration

Extinction (k) measured approx. every 3 hours



Overlapping PT magnitudes measured every hour



Checking the SDSS Calibration

Internal:

- Overlaps
- Crossing stripes
- Chip to Chip Zeropoint Ratios
- History of Zeropoints

External:

- Comparison to other catalogs
- Comparison to models
- Direct observation of the standard

Results:

- Statistical RMS uncertainty: 2% gri, 3% uz
- Offset from a true AB system: <1% gri, 2-4%? uz

References

Asinh magnitudes: Lupton, Gunn & Szalay 1999

u’g’r’i’z’ system: M. Fukugita et al. 1996, AJ 111:1748
u’g’r’i’z’ Standard Star Catalog: Smith et al. 2002, AJ, 123: 2121

SDSS calibration:
    Stoughton et al. 2002 (SDSS EDR paper)
    http://www.sdss.org/dr2/algorithms/fluxcal.html