Astronomical Observing Techniques 2019

Lecture 11-II: Pink and other Coloured Glasses

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Imaging

- When spatial information is more important than spectral information
  - dense star clusters
  - galaxy morphology
- Photometry: accurately measure fluxes
- Astrometry: accurately determine positions
- Filters to restrict wavelength range

- Messier 15 is one of the oldest globular clusters known, with an age of around 12 billion years.
- A composite HST image in the ultraviolet, infrared and optical.

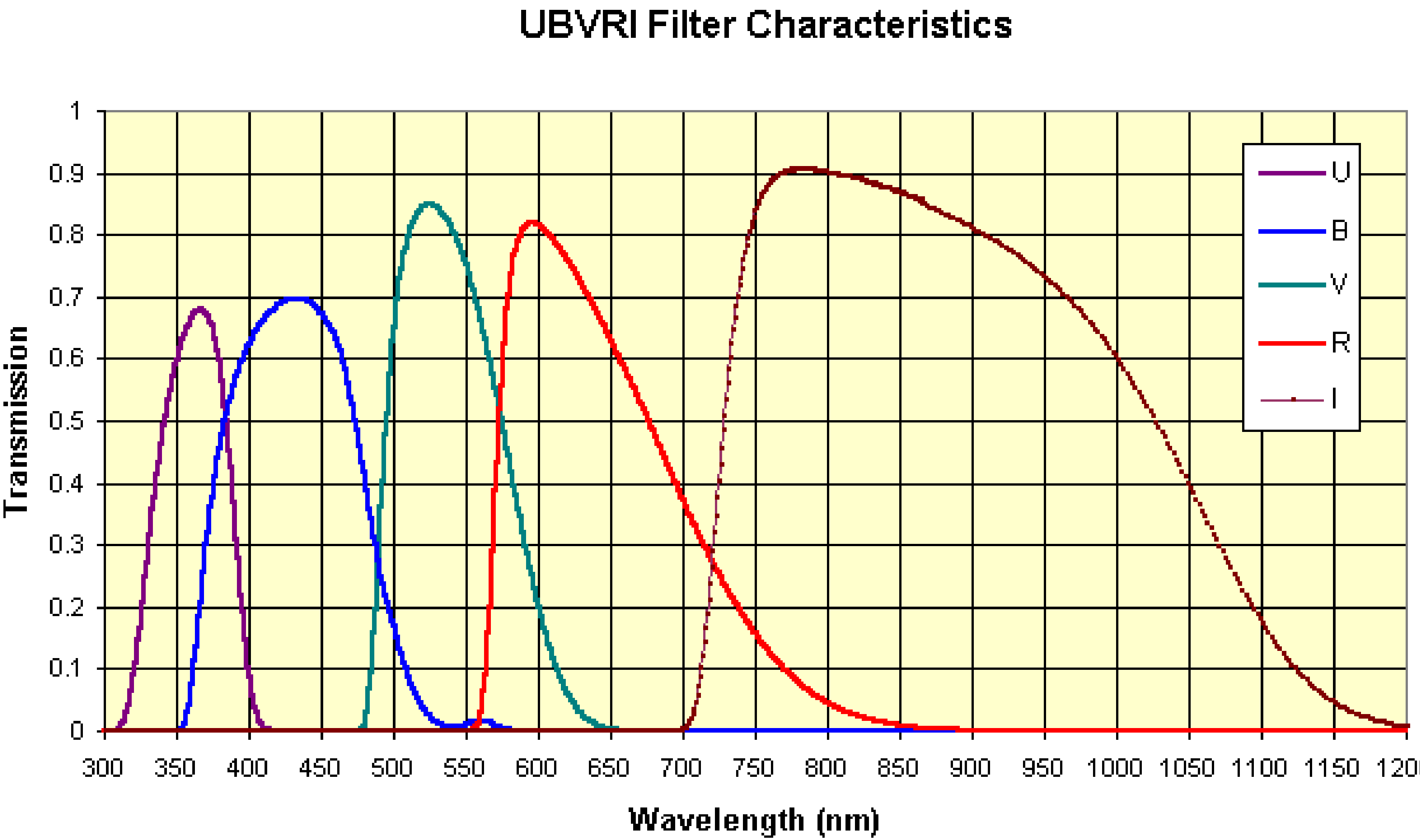
Hubble ultra deep field

UBVRI

www.sbig.com/products/filters.htm

- UBV by Johnson and Morgan (1953):
  - U: Corning 9863
  - B: Corning 5030 + Schott GG13
  - V: Corning 3384
- VRIJKLMNQ (infrared) by Johnson (1960)
- invented to classify stars with photomultipliers
- zero point of B-V and U-B color indices defined to be zero for A0 V stars

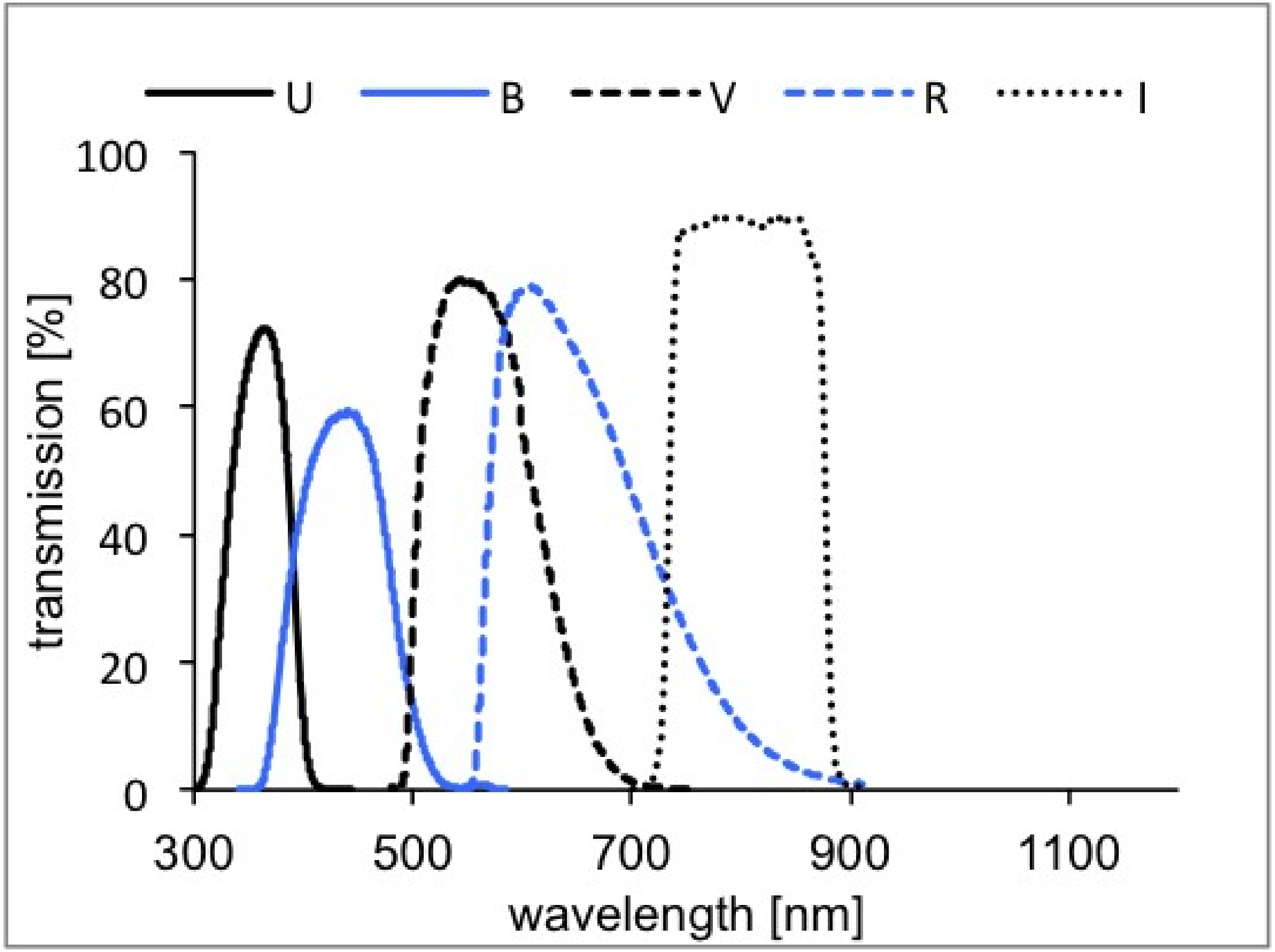
(Old) UBVRI


UBVRI Filter Characteristics
Transmission
Wavelength (nm)
U
B
V
R
I
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200

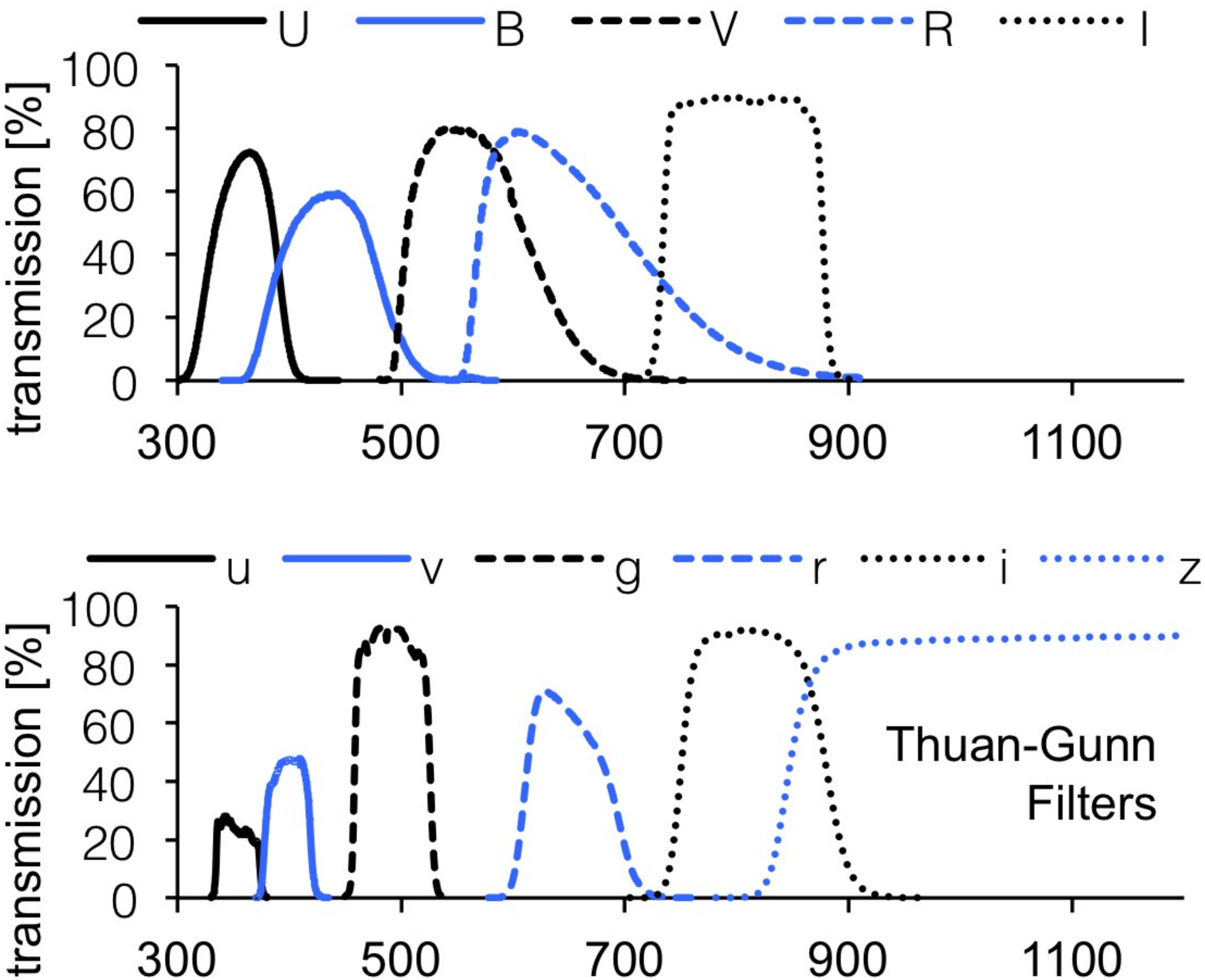
Limitations of UBVRI Photometry

- limited spectral resolution
- effective central wavelength changes with color of star
- star's magnitudes and color depend on the star's color
- short-wavelength side of U filter extends below atmospheric transmission cutoff
- properties of sky define width of bandpass, not filter
- no clean separation of information from different filters
- different detectors have different sensitivities
- today: Bessel or Cron/Cousins UBVRI with CCDs

Modern UBVRI Filter Profiles

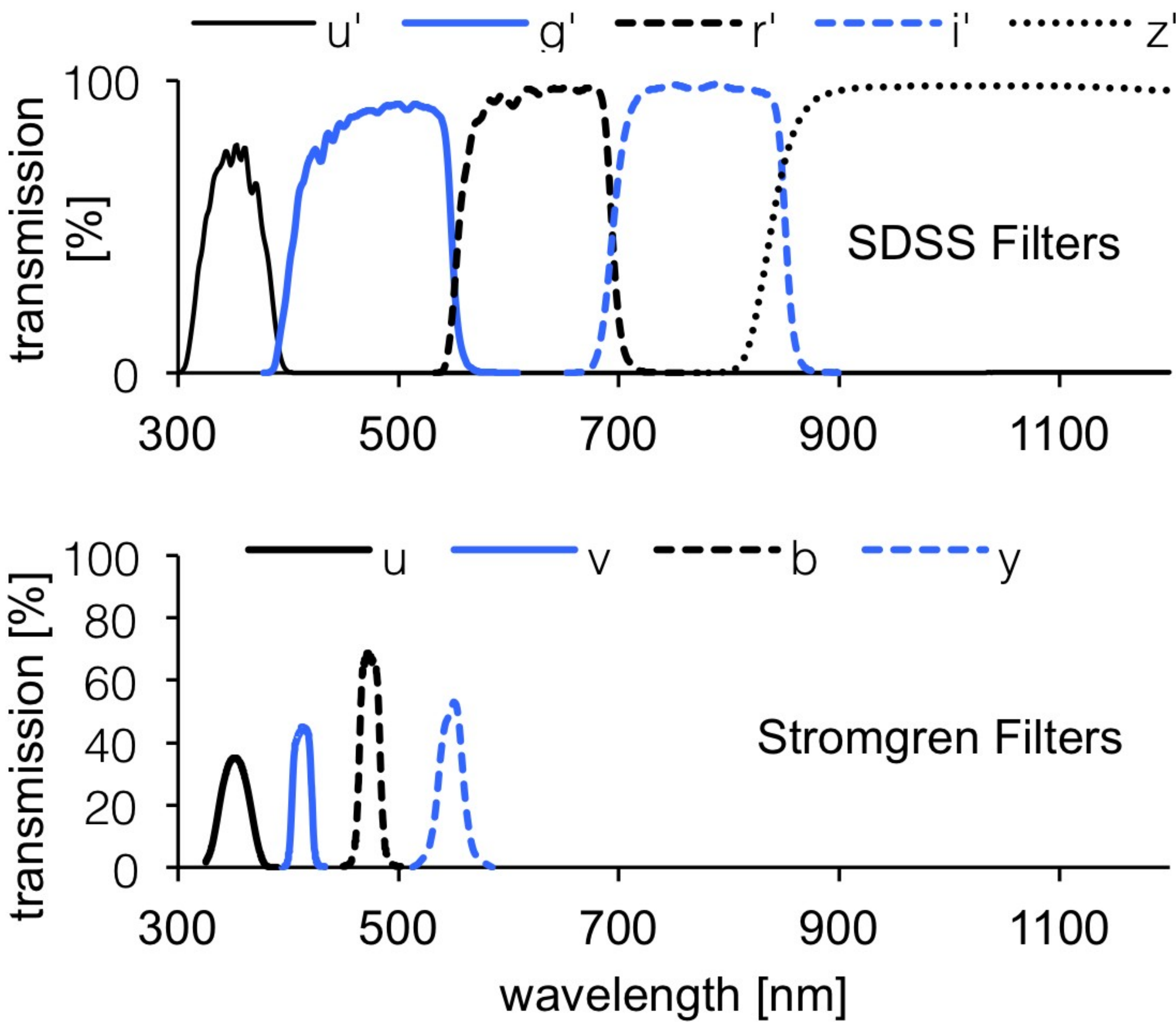


Other Filter Systems



- have less overlap and/ or higher transmission
- Johnson system for stars
- Thuan-Gunn filters for faint galaxy observations

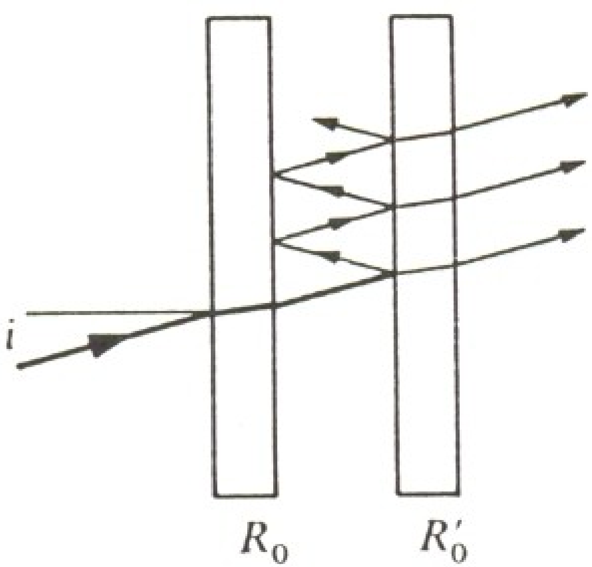
Other Filter Systems

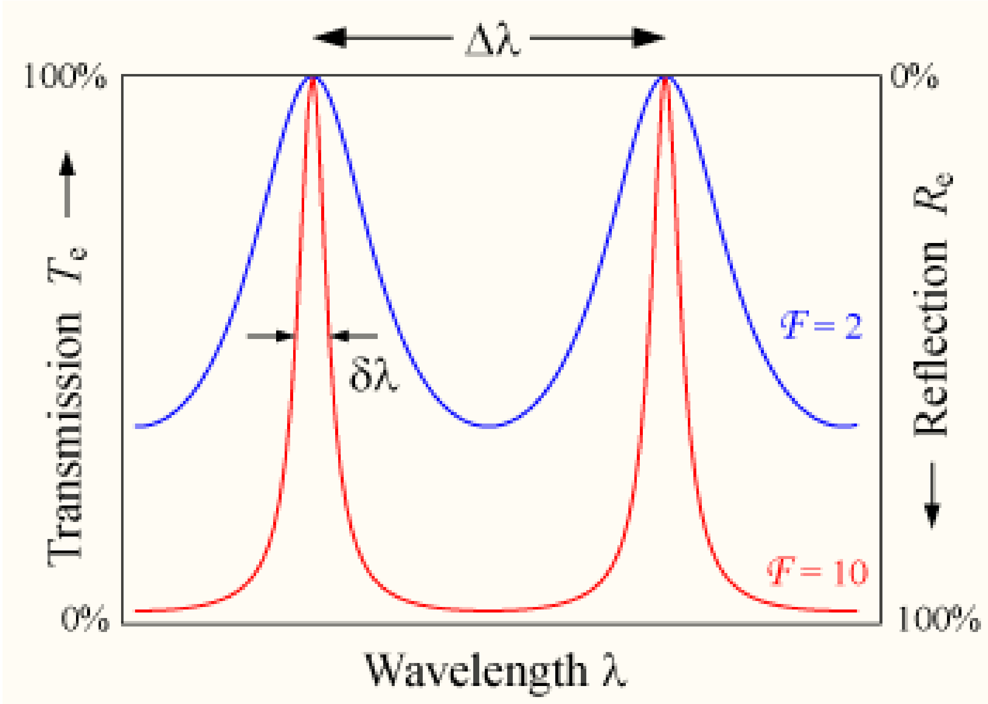


- Sloan Digital Sky Survey (SDSS) for faint galaxy classification
- Stromgren for better sensitivity to stellar properties (metallicity, temperature, surface gravity)

Fabry-Perot Etalon

- 2 parallel plates with adjustable plate separation
- highly reflective coatings on inside surfaces
- periodic transmission peaks due to constructive interference of successively reflected beams
- transmission peak location changes linearly with plate separation



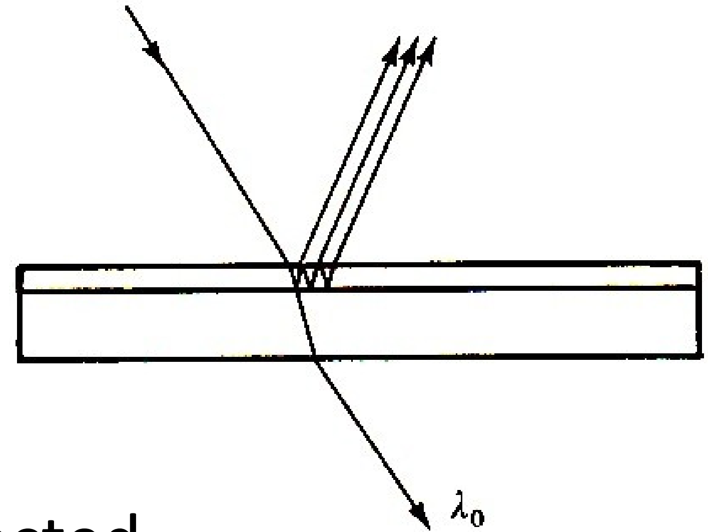


Fabry-Perot Etalon

- Finesse: $F = \Delta\lambda/\delta\lambda$
- Spectral Resolution: $R = \lambda/\delta\lambda$ ~ 100-100'000

Thin Film

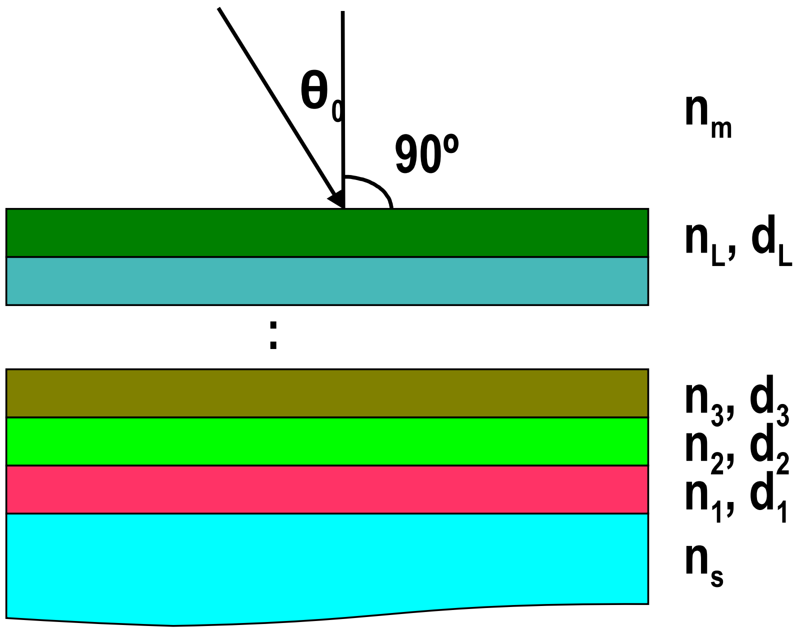
- layer with thickness ≤ λ
- extends in 2 other dim. >>λ
- material with different index of refraction on thick substrate



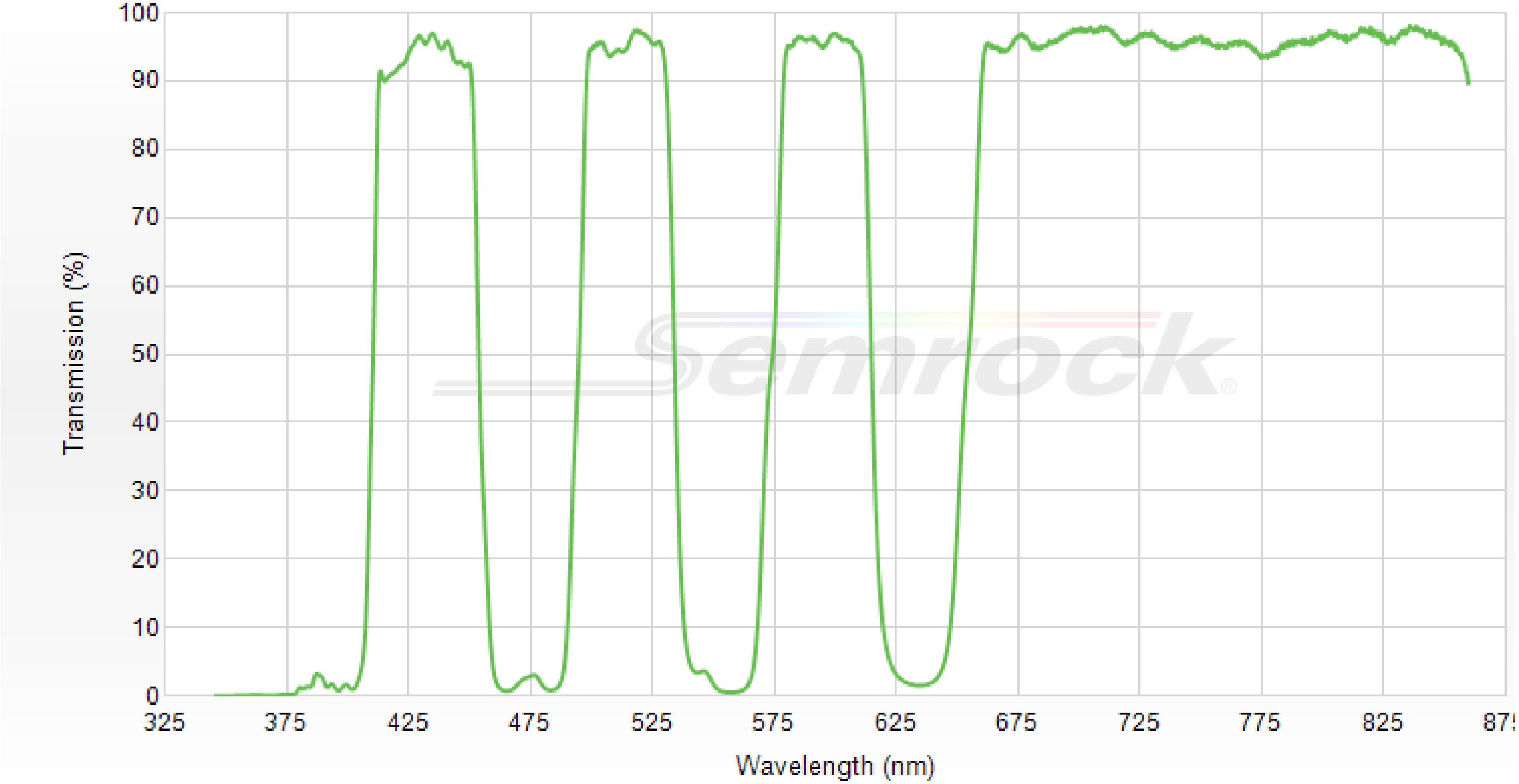
- maximum transmission when reflected rays interfere destructively
- maximum reflectivity when reflected rays interfere constructively

Interference Filters

- stack of thin films
- can be tailored to almost any specifications
- sensitive to temperature, humidity, angle of incidence
- tune in wavelength with temperature, angle of incidence
- spectral resolution R ~ 3 – 1000



Interference Filter Examples



Photometry

- goal: determine flux of an astronomical object in well-defined wavelength range
- problems:
  - seeing
  - extinction
  - sky background
  - telescope, instrument, detector
- calibration with (standard) stars
- all-sky photometry: compare objects all over the sky
- differential photometry: compare objects on same CCD exposure

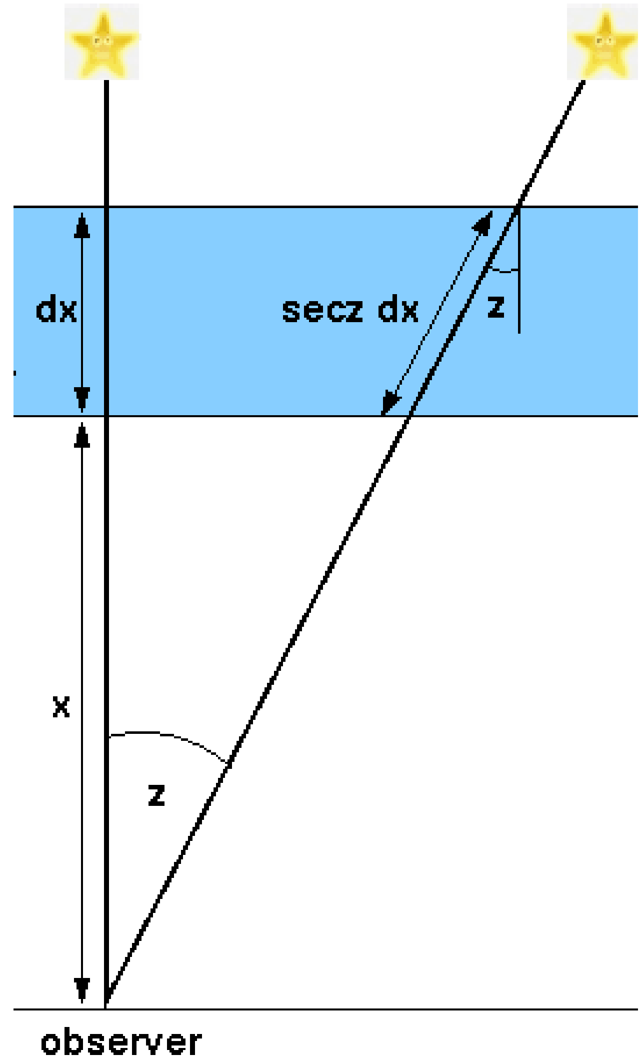
Sky over La Palma

Atmosphere

- photometric night = uniform, stable sky conditions
- thin clouds and cirrus are hard to see at night
- bright, grey and dark observing time
- seeing defines size of stellar image
- image = convolution of source and Point-Spread Function (PSF)
- integral over image = integral over source

Air Mass

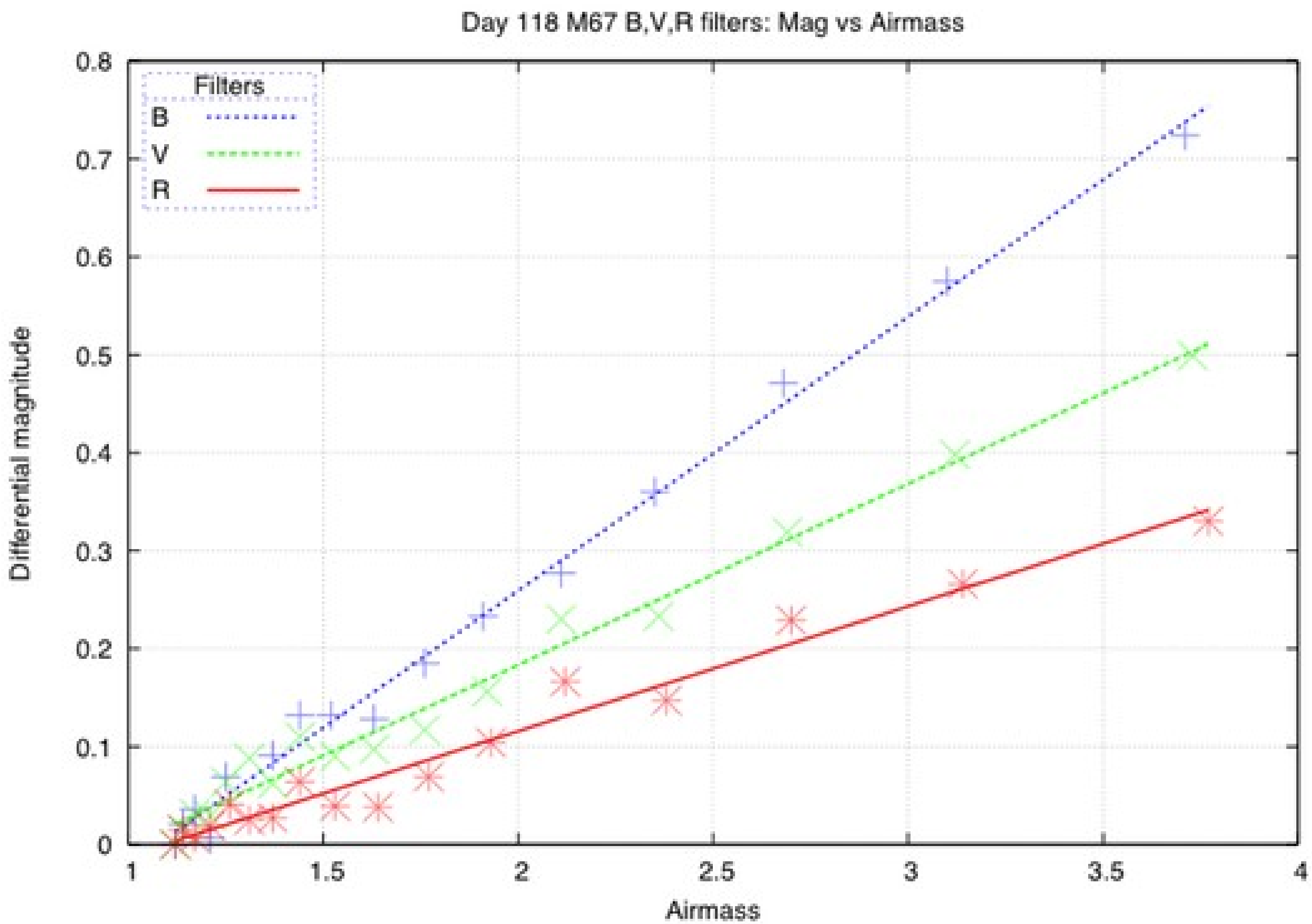
- extinction due to atmosphere along line-of-sight
- *airmass* = amount of air one looks through
- at zenith ($z=0$): airmass $X=1.0$
- at zenith distance z, airmass $X \approx \sec z = 1/\cos z$
- $X(z=60°) \approx 2$



Air Mass

- absorption coefficient $K=2.5$ log$(f(z)/f(z=0))$, where $f(z)$ is measured flux as function of zenith distance z
- $K\Delta X = \Delta m$ change in magnitude is absorption coefficient times change in airmass
- measure magnitude for different airmasses and extrapolate to zero airmass (no atmosphere!)
- linear extrapolation does not work in the infrared due to saturated/overlapping molecular lines

Airmass vs. Magnitude



astro.physics.uiowa.edu/vao/_Media/application-12_med.png

Dark Sky in Alps

Bright Sky in the Netherlands

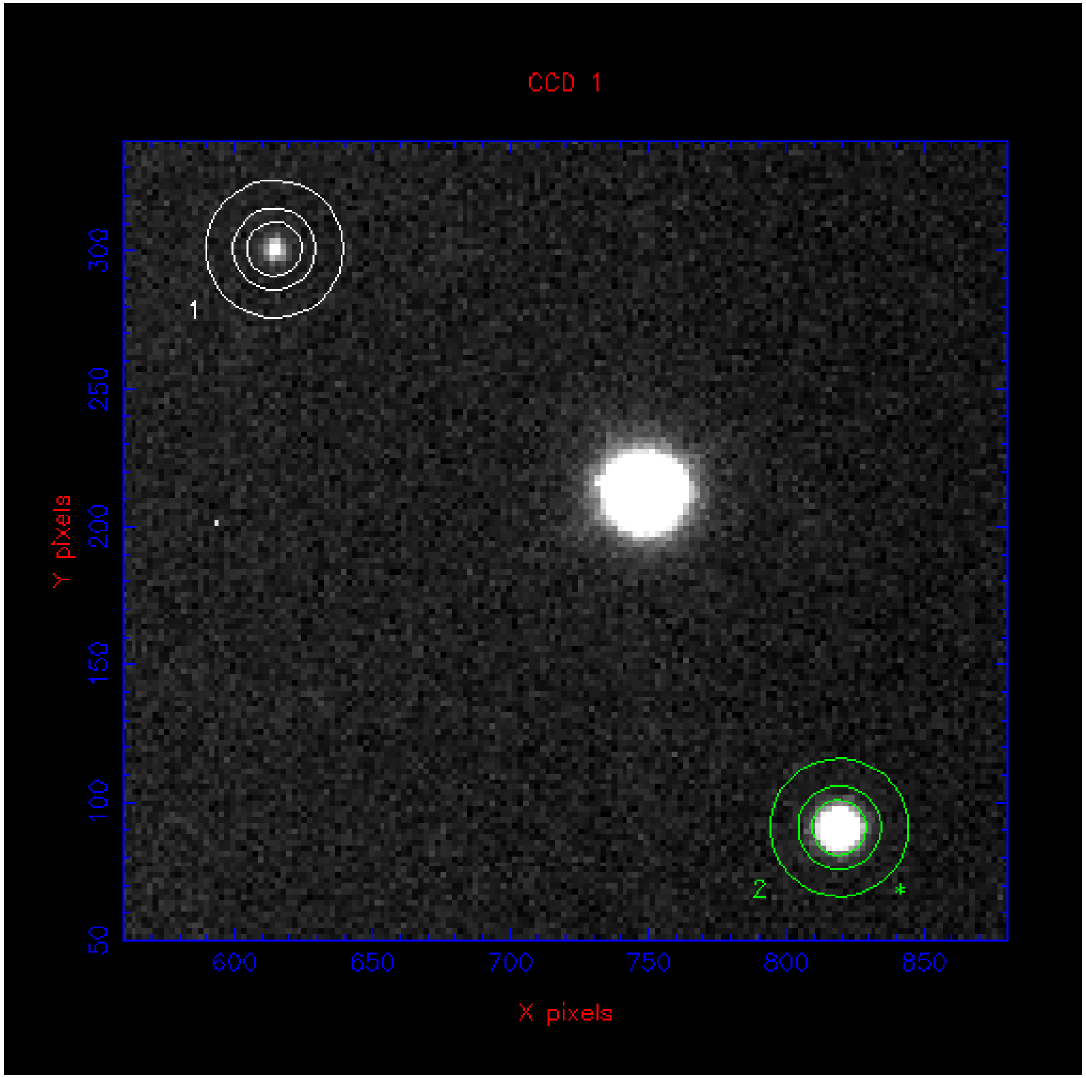
Photometric Observations (1)

- observe object and standard stars with different colors
- observe standard stars at low and high airmass to determine their (color-dependent) extinction coefficients
- reduce images with bias, dark, flat field
- measure fluxes with aperture photometry
- calculate instrumental magnitudes:
  $m_{inst} = -2.5 \log(f_i/t_{exp})$

Photometric Observations (2)

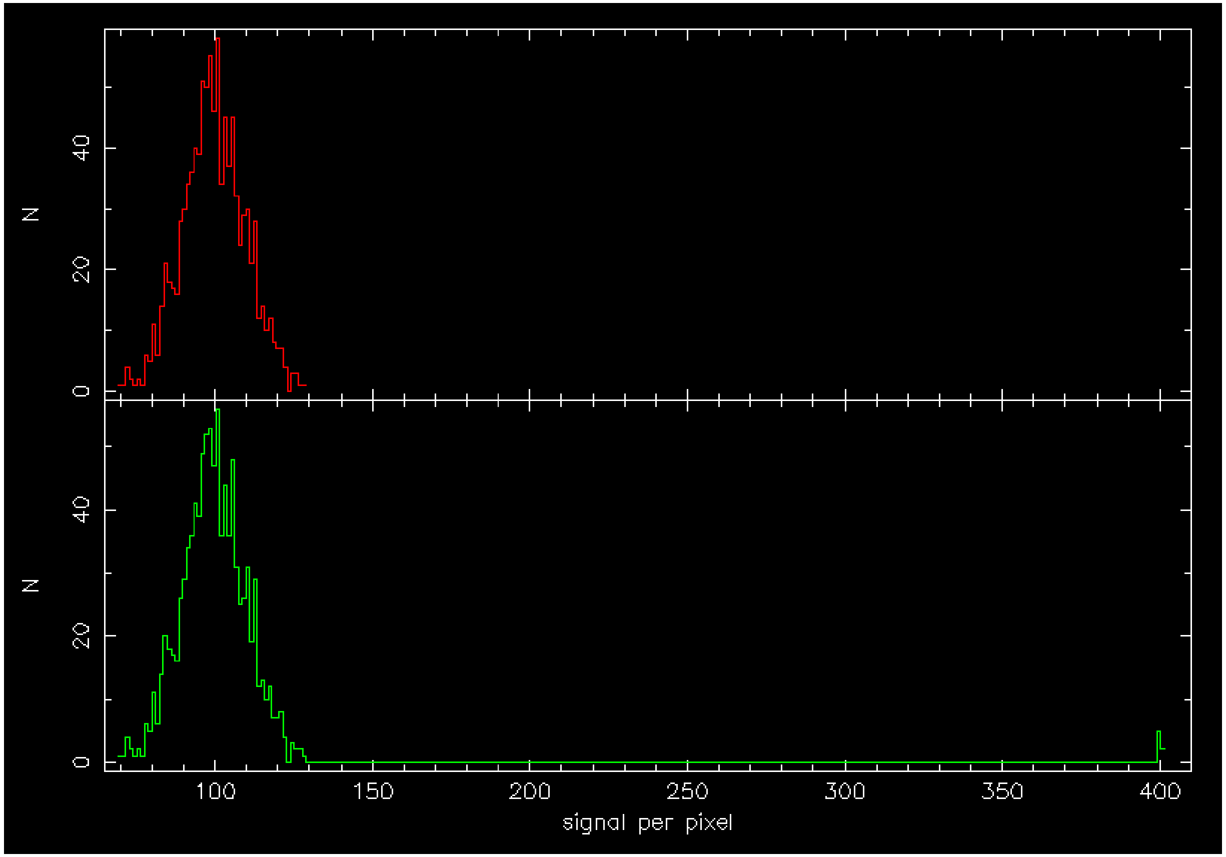
- calibrate instrumental magnitude for zero airmass: $m_0 = m_{inst} - K \sec z$
- zero point from standard stars: $m_{zp} = m_{std} - m_{std,inst}$
- remove zero point: $m = m_{zp} + m_{inst}$
- absolute photometry: determine actual magnitudes with calibrations derived from standard stars
- differential photometry: does not require calibrations

Aperture Photometry



- determine location of star by fitting 2-D Gaussian or Moffat PSF model
- determine and remove sky background

Sky Background

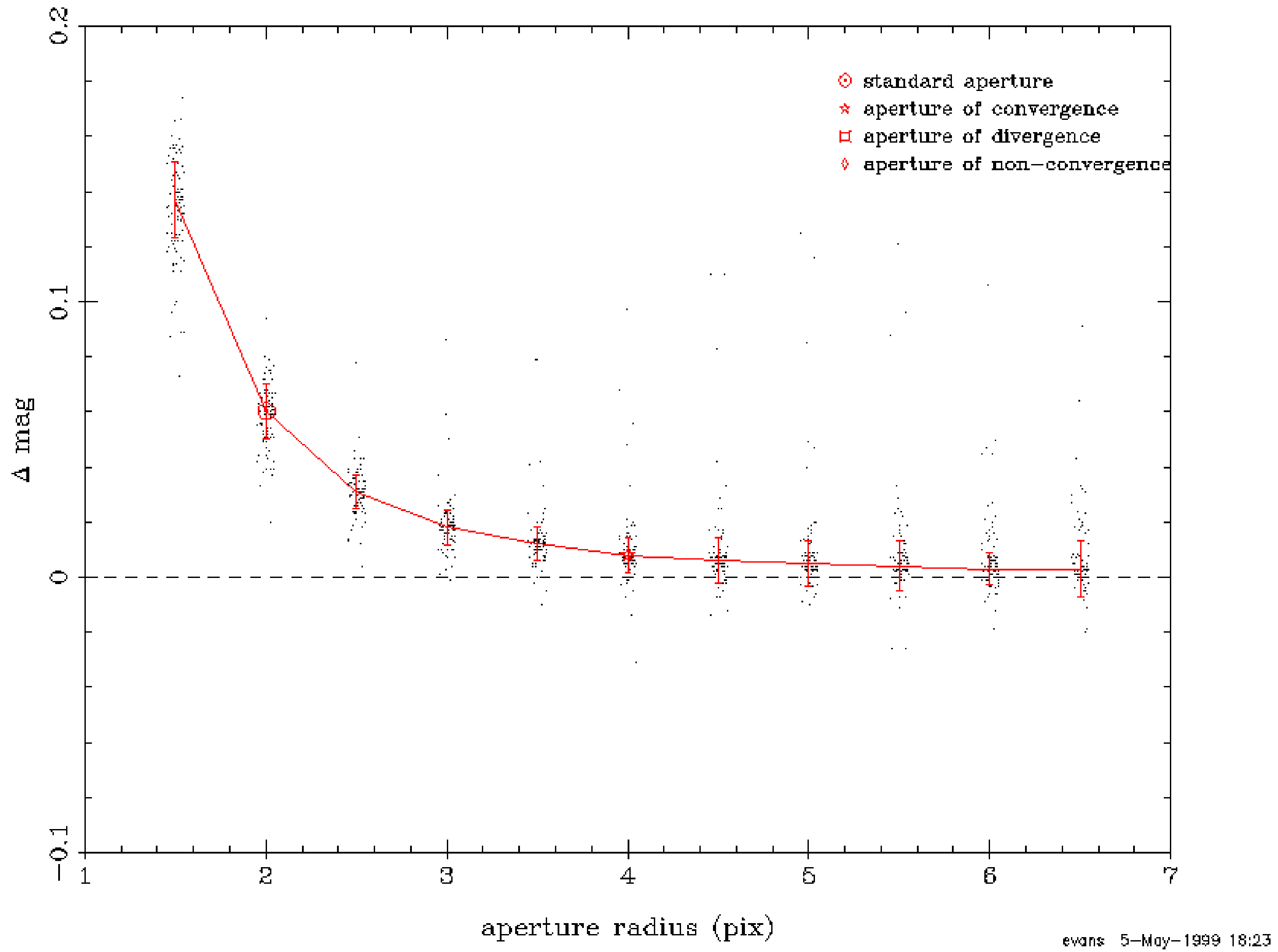


- use annulus around star
- use median instead of mean to neglect cosmic rays

Aperture Photometry (continued)

- best aperture size depends on brightness of star
- trade-off between capturing more starlight and adding noise from sky background, detector etc.
- plot result as function of increasing aperture and estimate asymptotic value
- for variability measurements (e.g. exoplanet transit) with differential photometry (standard star in same image):
  – use fixed and identical apertures for target and reference star(s)
  – optimum aperture minimizes scatter in constant parts of m_{target}-m_{std}

Aperture Phtometry Growth Curve



www.ipac.caltech.edu/2mass/releases/allsky/doc/figures/seciv4cf2.gif

Color Correction

- extinction depends strongly on wavelength (color)
- measured flux through broad filter depends on stellar spectrum
- additional correction

$$m=m_0+K \sec z + k_2 C \sec z$$

where C is color index (e.g. C=B-V)

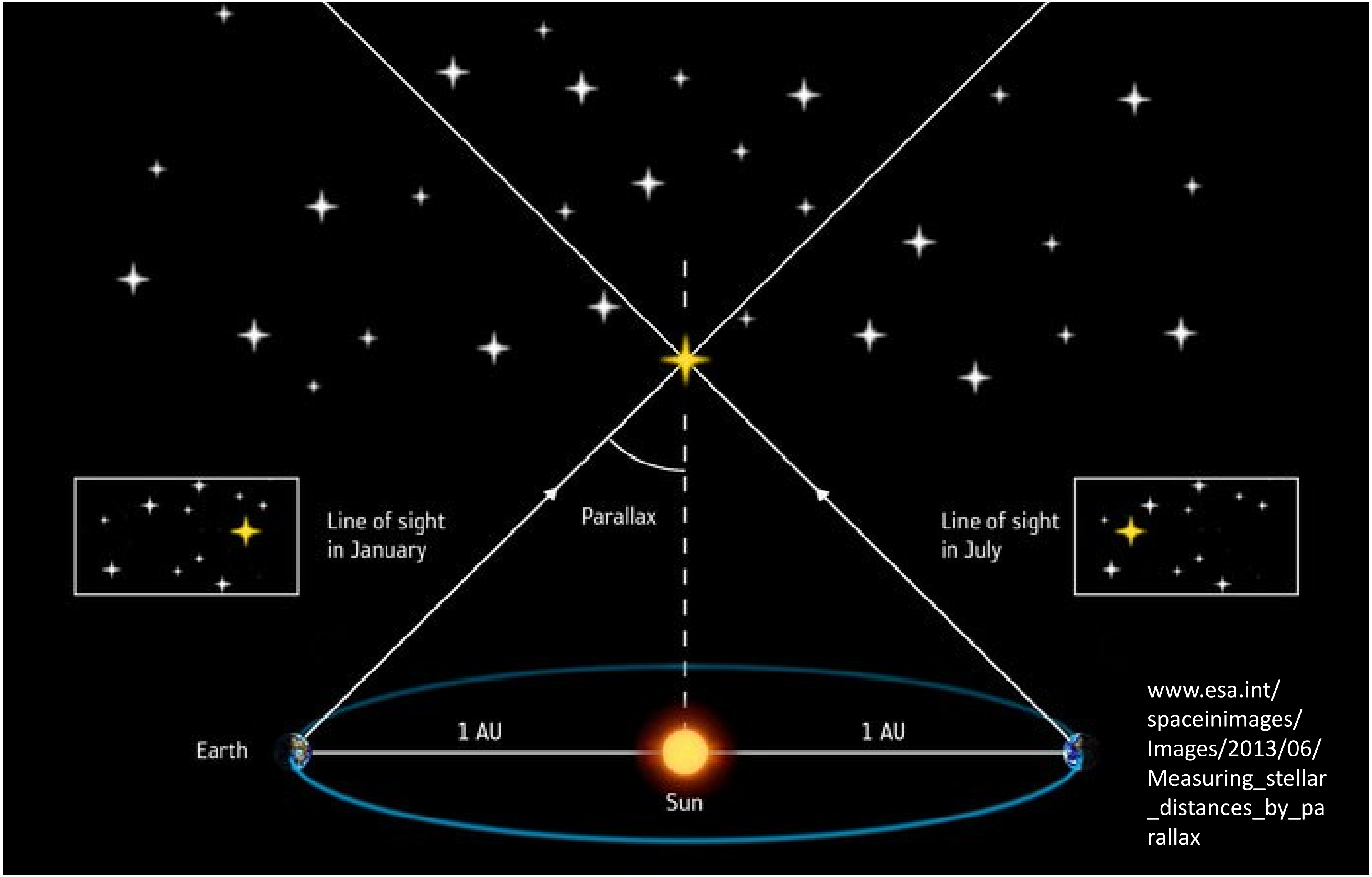
Subtle Instrumental Effects

- Thermal changes in optics, electronics
- Small guiding errors coupled with sub-pixel gain variations
- ’other’ instrumental parameters that have been shown to correlate with photometry of standard stars

Astrometry

- Determine precise location (and motion of objects)
- Parallax as distance measurement
- Asteroid and comet orbit determination
- Binary masses
- Stellar motions and associations
- Stars around central black hole in Milky Way

Parallax Distance Measurement



www.esa.int/spaceinimages/Images/2013/06/Measuring_stellar_distances_by_parallax

Absolute Coordinate System

- Main issue: precession of Earth's spin axis
- International Celestial Reference System (ICRS)
  - Fixed in space, independent of Earth's axis
  - Origin at barycenter of solar system
  - Almost J2000 Right Ascension and Declination
- International Celestial Reference Frame 2(ICRF 2)
  - Consists of 3414 compact radio sources
  - Positions known to better than 1 milli-arcsecond
  - ICRS defined by positions of these sources

Table 3. Basic performance statistics for *Gaia* DR2.

Data product or source type	Typical uncertainty
Five-parameter astrometry (position & parallax)	0.02–0.04 mas at $G < 15$
	0.1 mas at $G = 17$
	0.7 mas at $G = 20$
	2 mas at $G = 21$
Five-parameter astrometry (proper motion)	0.07 mas yr^{-1} at $G < 15$
	0.2 mas yr^{-1} at $G = 17$
	1.2 mas yr^{-1} at $G = 20$
	3 mas yr^{-1} at $G = 21$