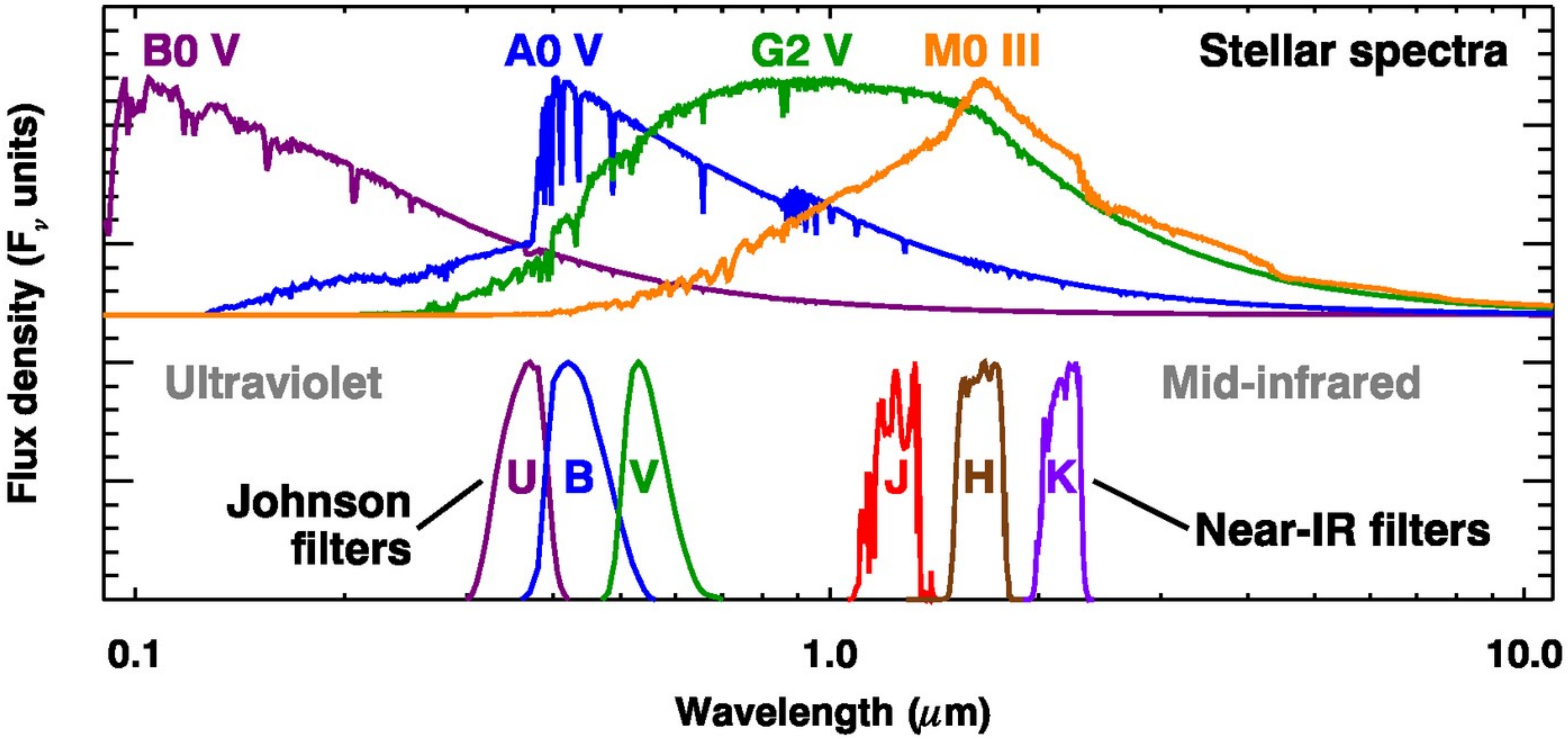
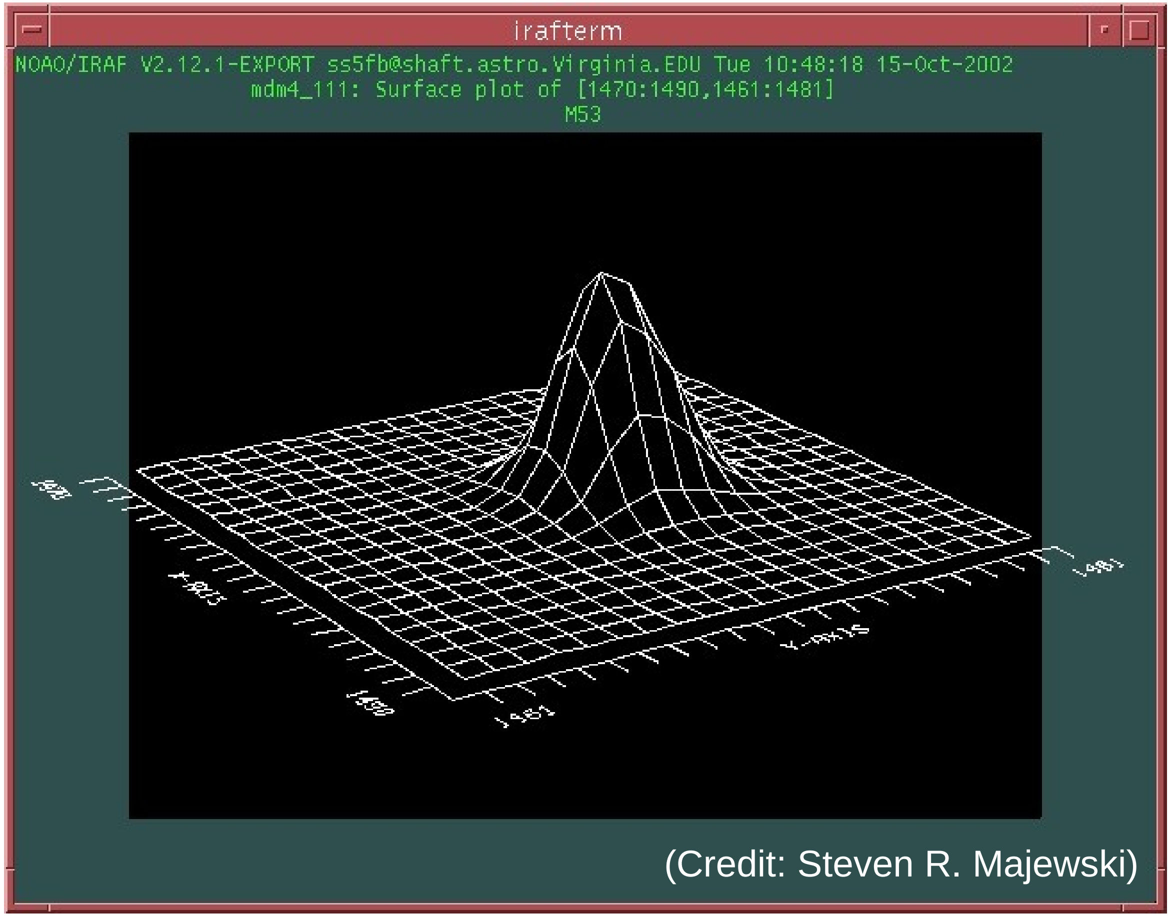
Photometry



(Credit: Gregory C. Sloan)

Today



(Credit: Steven R. Majewski)

1. Planning photometric observations
2. Magnitude systems
3. FORS2 @ VLT

What is photometry?

- Make precise measurements of the brightness of a source (magnitudes)
- Magnitude is an ancient concept, but useful because it is relative
- Magnitude differences give you the flux ratio between your source and standards
- Zero points of the standards do not matter in first order
- Unless you really want the flux. Flux to magnitude conversion can be uncertain
- 1% ~ 0.01 mag

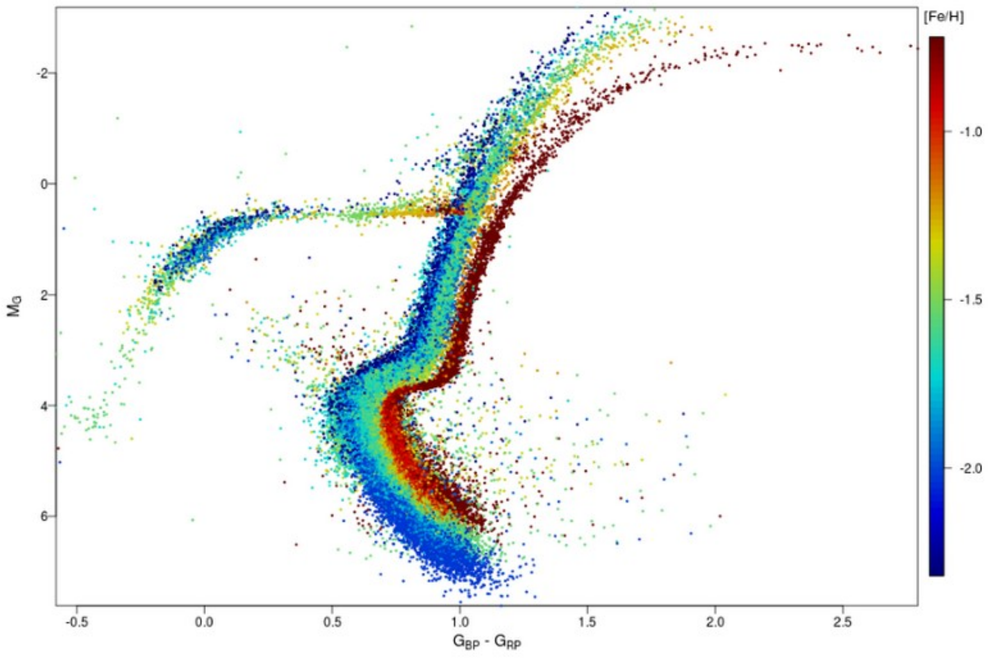


Fig. 3. Composite HRD for 14 globular clusters, coloured according to metallicity (Table 3).

(Gaia collaboration 2018)

If you want to observe with the VLT, read the call for proposals

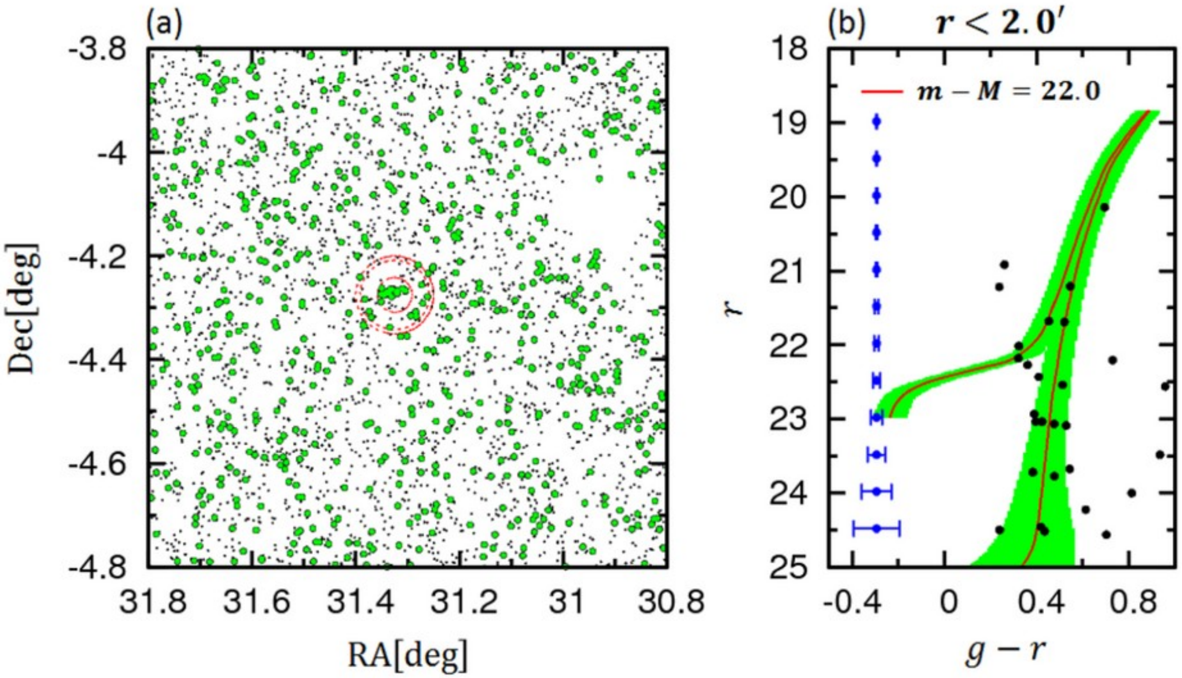
- Updated list of offered instruments
- Informs on recent policy changes
- and on future plans for the instruments
- Describes important definitions (proposal types, observing modes, OBs, ...)
- Several links for additional information
- Binding document if the proposal is approved
- **Reading is a must for 1st time users!**

ESO Call for Proposals – P109

Proposal Deadline: 23 September 2021, 12:00 noon CEST

We start from the science case

- An overdensity of stars has been identified with Gaia
- Seems too far for reliable proper motions and parallaxes
- We want to confirm its nature
- Perhaps a distance cluster? A new dwarf galaxy?
- We want to build a colour magnitude diagram, derive age and distance
- **Photometry** to obtain *magnitudes* in different bands (e.g. Johnson UBV)
- Try to reach the turn-off



(Homma et al. 2018)

Images in the optical with the VLT

Paranal Instruments Summary Table

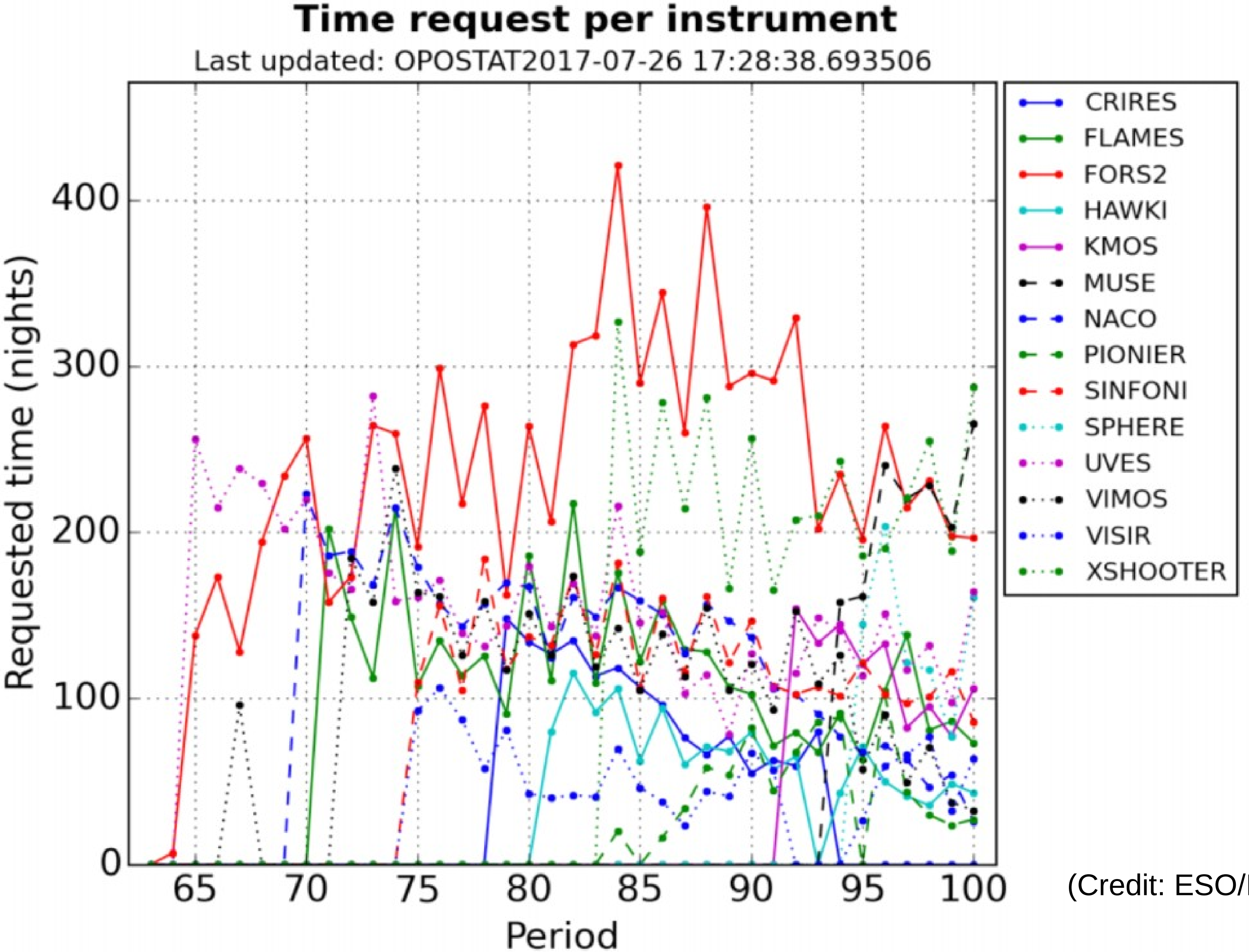
Instrument	Spectral Coverage	Observing Mode	Spectral Resolution	Multiplex	Note	Telescope
FORS2	optical 330 - 1100 nm	imaging (incl. configurable occulting bars), long slit and multi-object spectroscopy, spectropolarimetry, imaging polarimetry	260 - 2600	yes	Spectroscopy with ~7' long slit, ~20" multi-slit, and laser-cut slit masks; multiple object spectroscopy; RRM	VLT UT1
KMOS	near-IR 0.8 - 2.5 µm	multi-object integral field spectroscopy (24 arms)	1800 - 4000	yes	24-arms Integral Field Spectroscopy; 2.8x2.8", 0.2" sampling IFU over a 7.2' field;	VLT UT1
FLAMES	optical 370 - 950 nm	multi-fibre echelle,integral field spectroscopy	6000 - 47000	yes	132 Medusa fibres; 15 deployable IFUs, one large IFU; GIRAFFE: single echelle order; 8 fibres to UVES	VLT UT2
VISIR	mid-IR: 4.5 - 21 µm	M, N and Q band normal and burst-mode imaging; coronagraphy (Angular Groove Phase Mask, 4-Quadrant Phase Mask); N band low resolution long slit spectroscopy; high-resolution long slit and cross-dispersed spectroscopy	~400, 20000	no	pixel size of 0.045 and 0.076 arcsec in imaging, and 0.076 arcsec in spectroscopy	VLT UT2
UVES	optical 300 - 1100 nm	echelle, image slicer, slit spectroscopy	up to 80,000 (blue arm) / 110,000 (red arm)	no	long slit capability in single order; iodine cell; RRM	VLT UT2
SPHERE	optical: 500 - 900 nm near-IR: 0.95 - 2.32 µm	high-contrast imaging, dual-band imaging, integral field spectroscopy, differential-polarimetric imaging with or without classical, apodized pupil Lyot coronagraphs, sparse aperture mask	~30, 50, 400	no	extreme AO with optical wave-front sensor; fast star hopping; RRM	VLT UT3

https://www.eso.org/sci/facilities/lpo/cfp/cfp109/instrument_summary.html

FORS2

- **FO**cal **R**educer and low dispersion **S**pectrograph (Appenzeller et al. 1998).
- (reduce focal length, reduce magnification, widen the field of view; for a brighter image)
- Two versions were built (blue vs. red). FORS1 (the first optical VLT instrument) is now retired.
- Cassegrain focus of UT1, operation since 2000.
- All-dioptric (lenses), ~330 to 1100 nm
- Imaging; high-time resolution imaging; long slit spectroscopy; multi-object spectroscopy; (spectro)polarimetry (Appenzeller et al. 1998)
- Image scale: 0.25”/px or 0.125”/px (FoV 6.8’x6.8’ or 3.4’x3.4’)
- FORS-up: upgrade project to be completed by 2024 (Boffin et al. 2021)

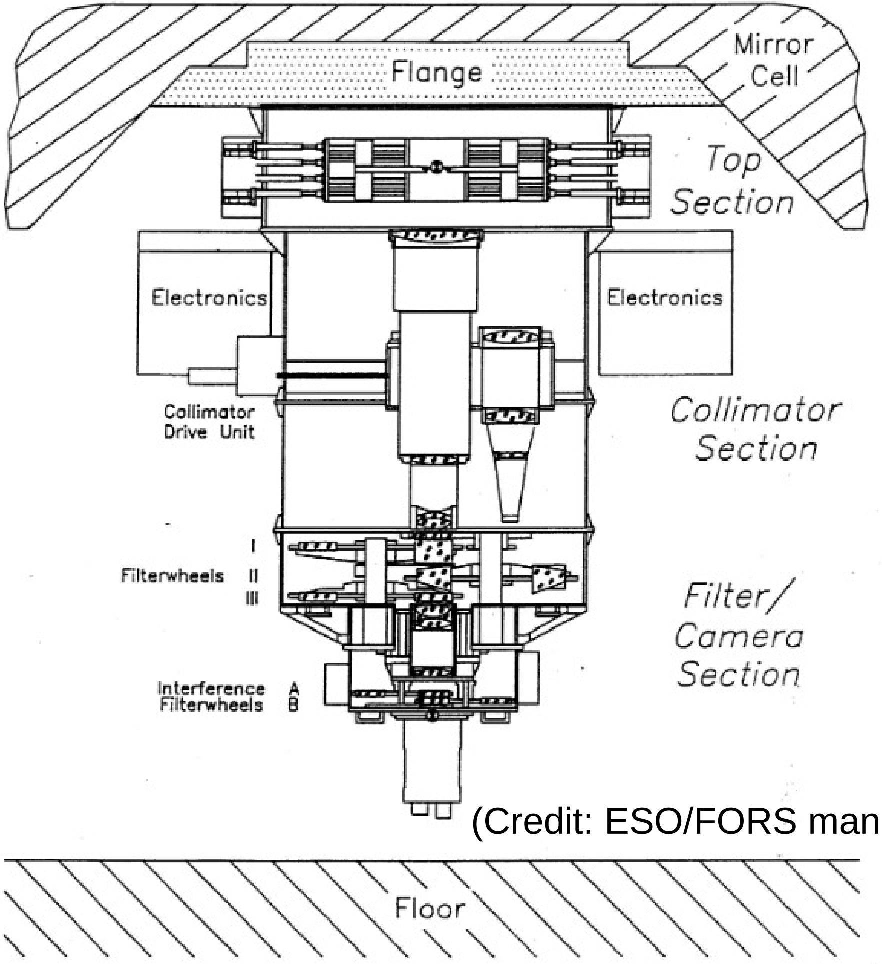

(Credit: ESO)



(Credit: ESO/D. Gadotti)

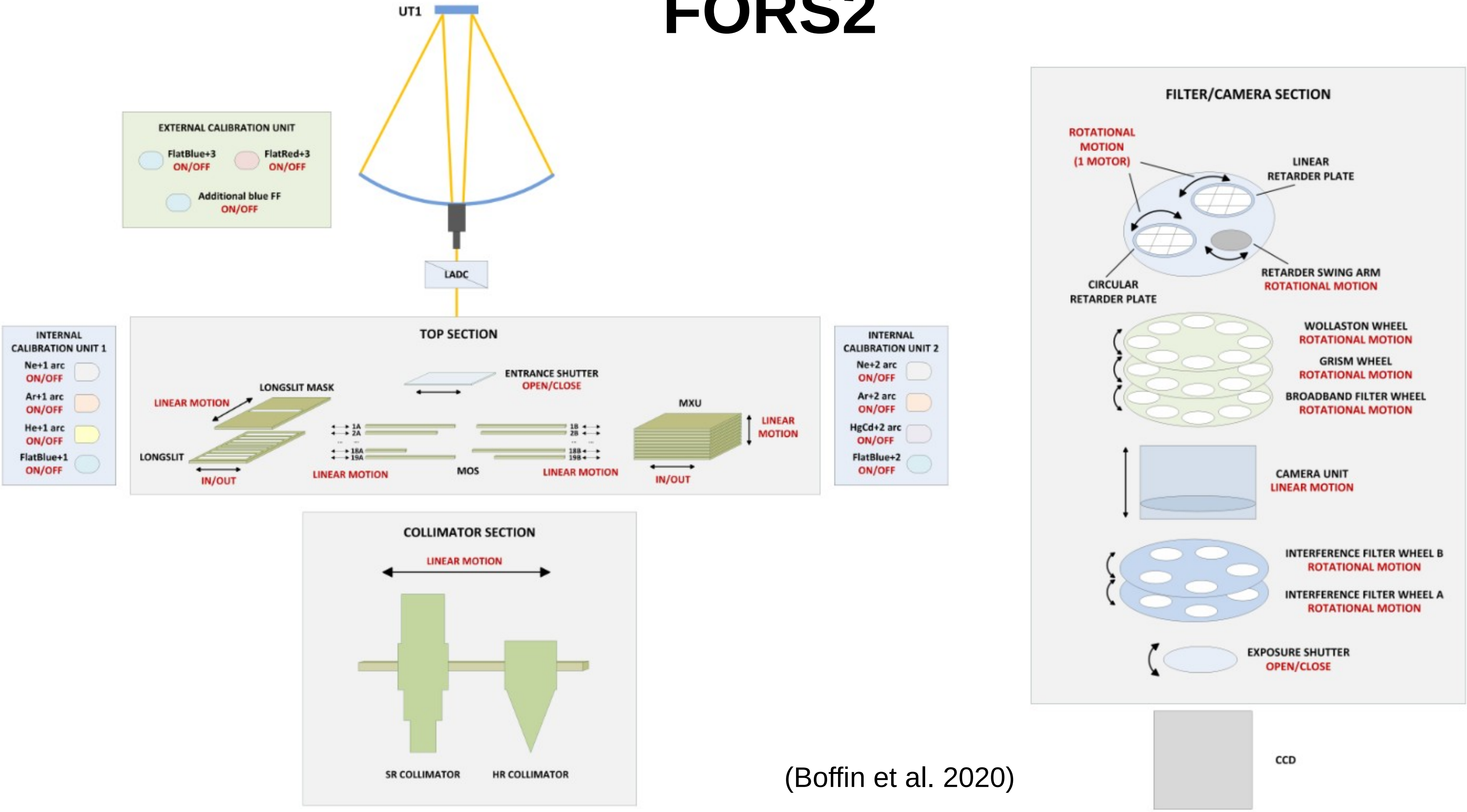
Imaging with FORS2

- Three modes:
  - IMG: direct imaging
  - OCC: imaging with occulting bars
  - IPOL: imaging polarimetry
- Broadband filters in the collimated beam (3 wheels, 7 positions/wheel, but some with grisms)
- Interference filters in the converging beam (2 wheels, 8 positions/wheel)
- **OCC:** move slit jaws of the MOS to block the light of a certain region (e.g. bright star)
- **OCC:** Need FIMS (FORS Instrument Mask Simulator)
- Users can propose to use their own filters (in Visitor Mode only)



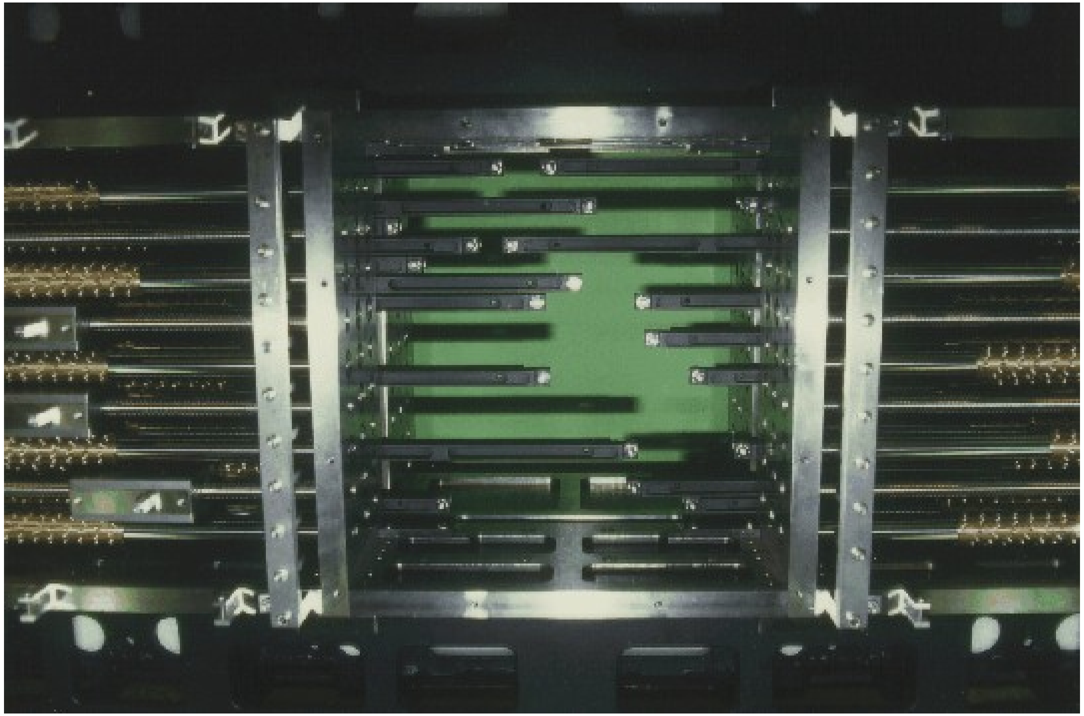
(Credit: ESO/FORS manual)

FORS2



(Boffin et al. 2020)

FORS2 MOS Slit Jaws

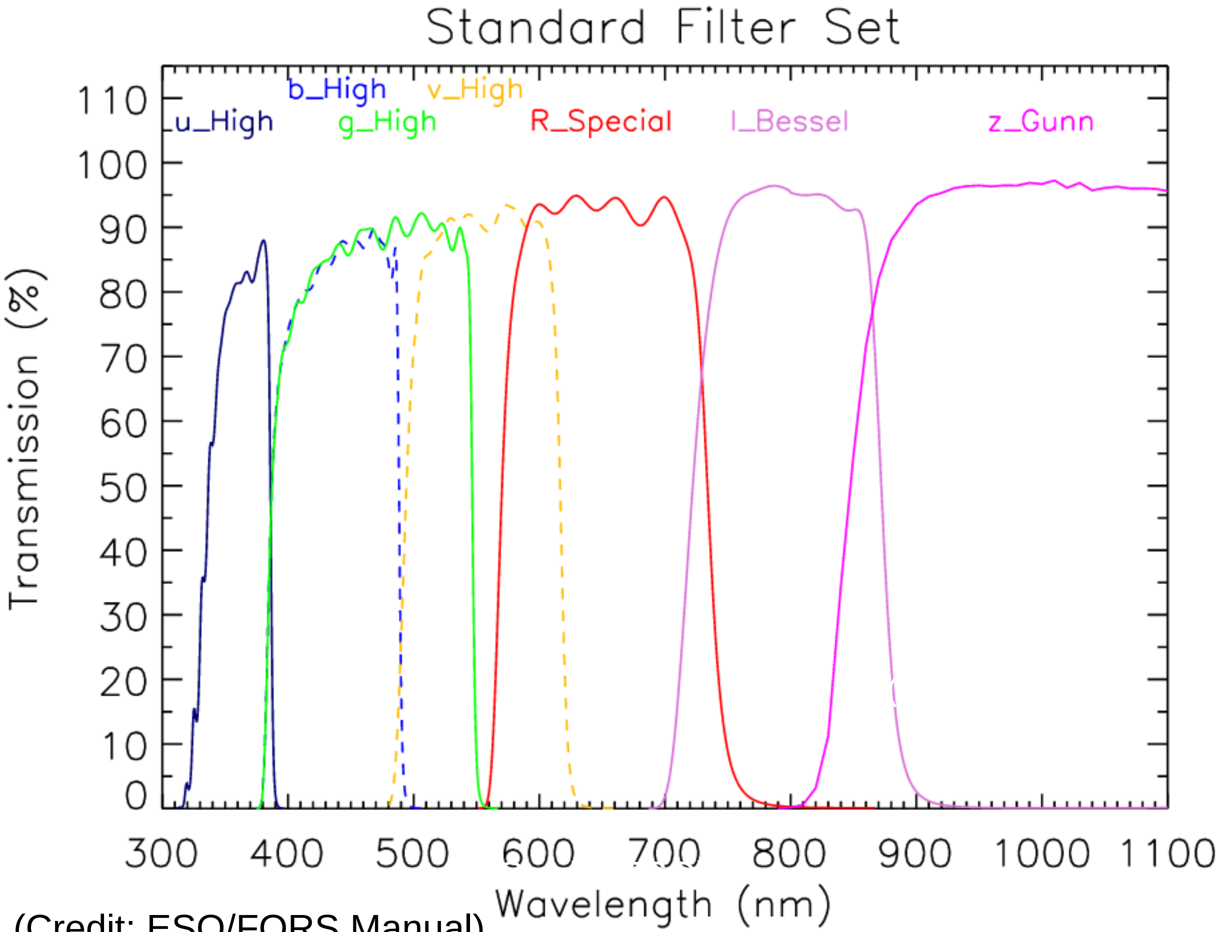


(Credit: ESO)

FORS2 Broadband filters

- The selection of broadband filters is fixed
- It can be changed in exceptional cases (discussed with the observatory)

Filter	λ_0 (nm)	FWHM (nm)
U_HIGH+112	361	50.5
B_HIGH+113	437	102.0
V_HIGH+114	555	123.2
g_HIGH+115	467	160.3
R_SPECIAL+76	655	165.0
I_BESS+37/+77	768	138.0
U_BESS+33 (3)	366	36.0
U_SPECIAL+73 (3)	362	29.0
B_BESS+34/+74 (3)	429	88.0
V_BESS+35/+75 (3)	554	111.5
R_BESS+36 (3)	657	150.0
u_GUNN+38 (3)	359	33.5
v_GUNN+39(3)	398	46.0
g_GUNN+40 (1) (3)	506	79.5
r_GUNN+41(3)	653	81.5
z_GUNN+78	910	130.5
GG435+81 (2)	edge filter: n/a	n/a
OG590+32 (2)	edge filter: n/a	n/a
FILT_465_250+82 (2) (3)	465	250

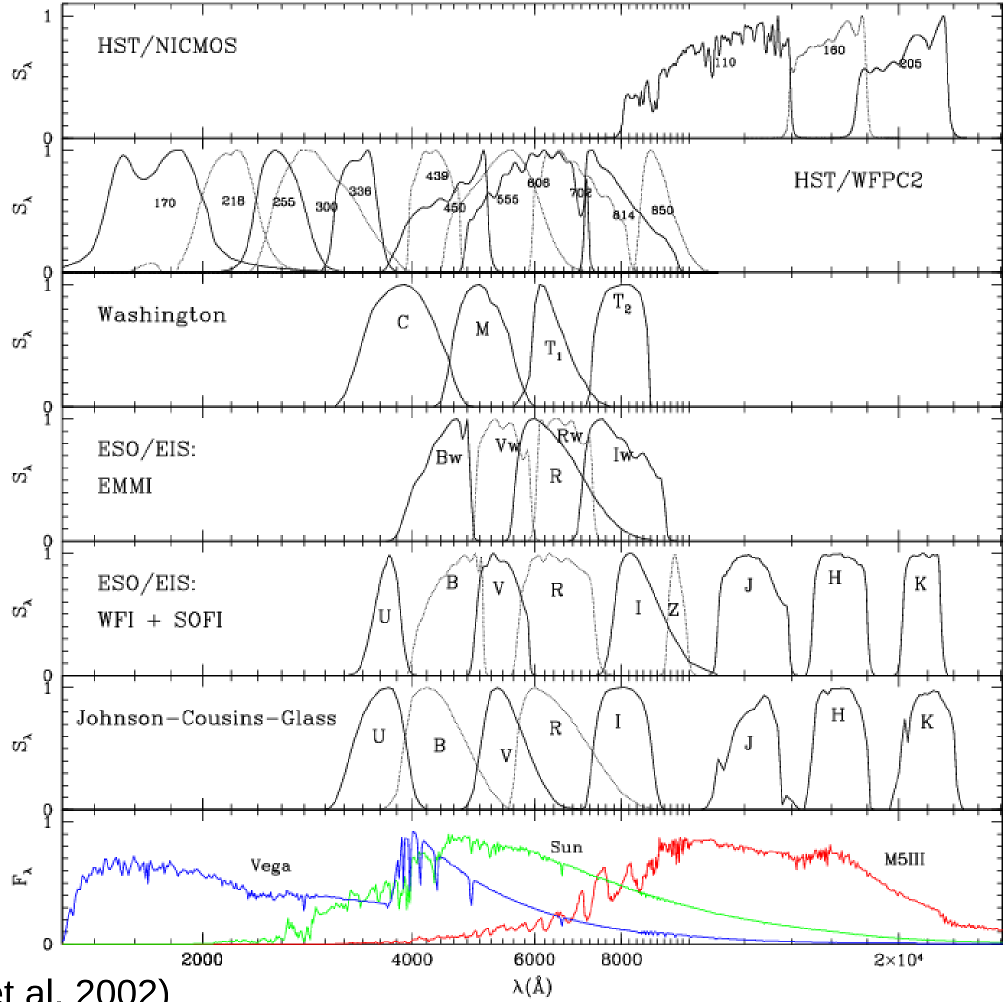


(Credit: ESO/FORS Manual)

Photometric filters

- Are used to select a specific region of the spectrum
- Characterized by their transmission; tabulated by central wavelength and FWHM
- A **magnitude** is given for the flux observed in a given filter (e.g. *V* mag in Johnson system)
- Colors are magnitude differences (e.g., *B-V*)
- Broad-band: FWHM > 30 nm
- Intermediate-band: > 9 & < 30 nm
- Narrow-band: < 9 nm

  (these limits are not hard)
- Too many systems of photometric filters exist (Moro & Munari 2000; Bessel 2005)



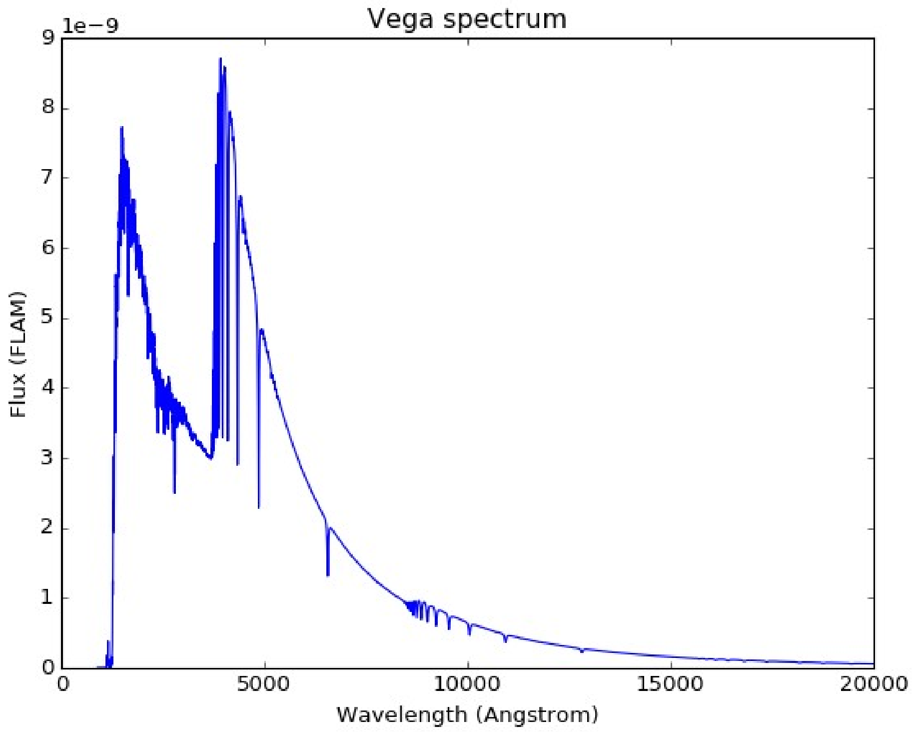
(Girardi et al. 2002)

The 201 systems censed in ADPS Paper 1, the first 167 in extenso and other 34 only briefly mentioned:

	Figure number in:	
	Paper 1	Paper 2
C_1 - Stebbins *et al.* - 1940	001	
***UVBGRI* - Stebbins and Whitford - 1943**	002	009
***RGU* - Becker - 1946**	003	010
***RI* - Kron and Smith - 1951**	004	011
BCD - Chalonge and Divan - 1952	005	
***UBV* - Johnson and Morgan - 1953**	006	012
POSS I - 1955	007	013
***PV* - Eggen - 1955**	008	014
Aerobee UV-55 - 1955	009	151
***uvby*H*beta* - Strömgren and Crawford - 1956**	010	016
Aerobee UV-57 - 1957	011	
U_cBV - Arp - 1958	012	017
***ubgyri* - Bahng - 1958**	013	018
***UV BG R* - Tifft - 1958**	014	019
5 colors - Borgman - 1959	015	020
***KLMNPQR* - Borgman - 1960**	016	021
Deeming - 1960	017	022
***UBV* - Eggen and Sandage - 1960**	018	
Griffin and Redman - 1960	019	023
USNO - Kron and Mayall - 1960	020	025
***VBLUW* - Walraven and Walraven - 1960**	021	026
Griffin - 1961	022	027
8 colors - Tifft - 1961	023	028

Vega system

- Vega (A0 V type) is the primary standard
- Actually, for the original UBV Johnson system, the mean of 6 A0 V stars was used (Johnson & Morgan 1953)
- U-B = B-V = 0
- Calibrated spectra are still needed to convert magnitudes to physical units
- These primary standards are usually too bright for most large telescopes
- A series of secondary standards are needed (e.g. Landolt 1983)
- Covering a broad range in colors
- In regions that can be observed from north and south (e.g. celestial equator)



(Credit: STScI)

AB system

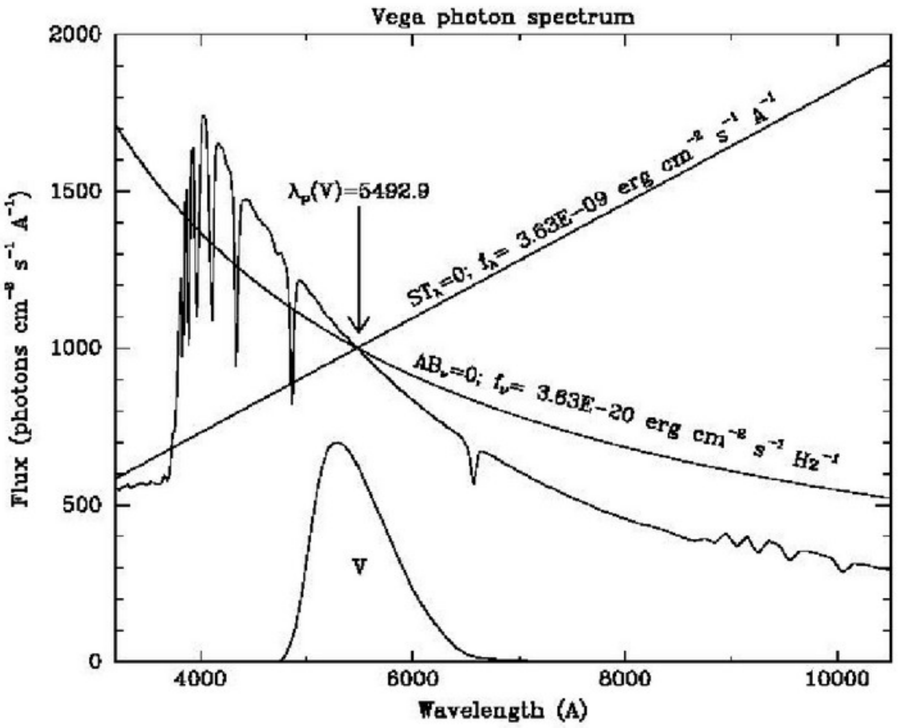
- AB: **ABsolute** system; no need of an object like Vega as reference for relative magnitudes

$$m(AB) = -2.5\ \log_{10} F_\nu - 48.6,$$

(Oke 1964)

- Monochromatic magnitude
- A source with a flat spectrum of constant flux per unit frequency has color zero
- F = 3.631 x 10^{-20} erg s^{-1} cm^{-2} Hz^{-1}
- Normalized anyway to Vega, i.e. m(AB)_5500 = V
- STMAG system:

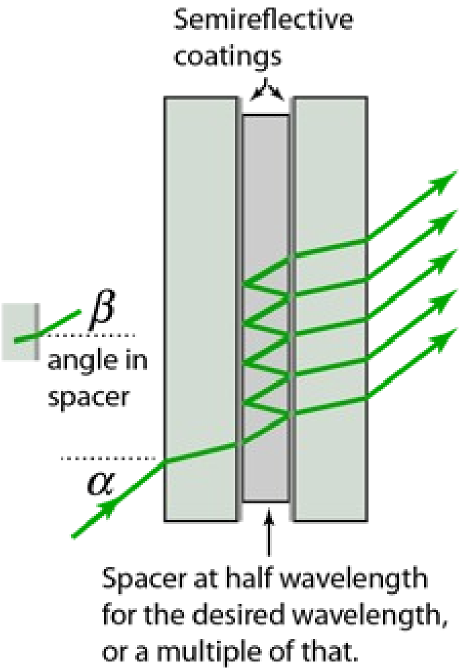
$$m(AB) = -2.5\ \log_{10} F_\lambda - 21.1,$$



(Credit: R. Ciardullo, Penn State)

Interference filters

- Used to select a narrow region
- Positioned on the converging beam, the characteristics depend on the collimator



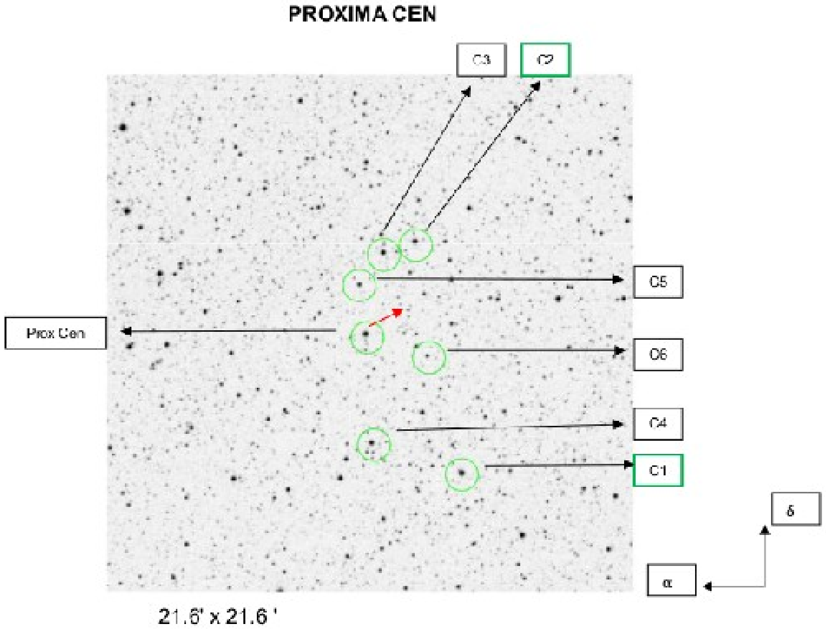
(Credit: Hyperphysics)

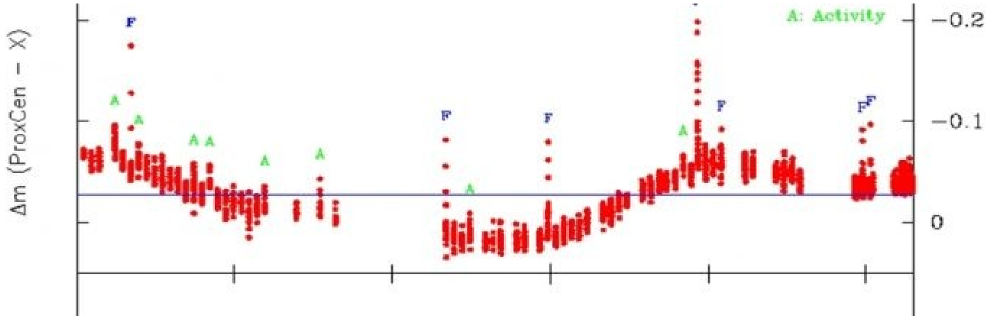
Filter	Line	λ_0 SR	λ_0 HR	T_0 SR	T_0 HR	FWHM (nm) SR	FWHM (nm) HR	λ_0 shift
OII+44	[OII] 372.7	371.7	372.9	0.45	0.48	7.3	6.9	0%
OII/4000+45		377.6	378.8	0.37	0.40	6.5	6.1	5%
OII/8000+46		381.4	382.6	0.43	0.47	6.5	6.1	10%
HeII+47	HeII 468.6	468.4	469.1	0.79	0.82	6.6	6.4	0%
HeII/3000+48		472.6	473.4	0.76	0.79	5.8	5.6	5%
HeII/6500+49		478.1	478.9	0.78	0.81	6.8	6.6	10%
OIII+50	[OIII] 500.7	500.1	500.9	0.76	0.80	5.7	5.5	0%
OIII/3000+51		504.5	505.3	0.76	0.80	5.9	5.7	5%
OIII/6000+52		510.5	511.3	0.74	0.78	6.1	5.9	10%
HeI+53	HeI 587.6	586.6	587.6	0.79	0.84	6.0	5.7	0%
HeI/2500+54		592.0	593.0	0.77	0.81	6.8	6.5	5%
HeI/5000+55		597.5	598.5	0.85	0.89	7.4	7.2	10%
OI+56	[OI] 630.0	629.5	630.6	0.75	0.79	7.2	6.9	0%
OI/2500+57		635.4	636.4	0.75	0.81	5.9	5.5	5%
OI/4500+58		640.4	641.4	0.77	0.83	6.3	6.0	10%
H_Alpha+83	Hα 656.3	656.3	657.4	0.70	0.76	6.1	5.7	0%
H_Alpha/2500+60		660.4	661.5	0.77	0.83	6.4	6.1	5%
H_Alpha/4500+61		666.5	667.6	0.72	0.77	6.5	6.1	10%
SII+62	[SII] 672.4	672.8	673.9	0.77	0.82	6.6	6.3	0%
SII/2000+63		677.4	678.5	0.77	0.82	6.8	6.5	5%
SII/4500+64		683.2	684.3	0.72	0.78	6.4	6.0	10%
SIII+65	[SIII] 953.2	952.3	953.9	0.68	0.80	5.9	5.2	0%
SIII/1500+66		957.2	958.8	0.72	0.84	6.3	5.6	5%
SIII/3000+67		962.1	963.7	0.70	0.83	5.9	5.2	10%

(Credit: ESO/FORS Manual)

Absolute and differential photometry

- **Absolute or all-sky photometry**
  - Magnitudes in a standard system
  - To compare stars in different regions of the sky
  - Or observations by different astronomers
- **Differential photometry**
  - Compare magnitudes of objects observed simultaneously
- **Time-domain photometry**
  - Track changes of magnitude of a given object over a certain period of time



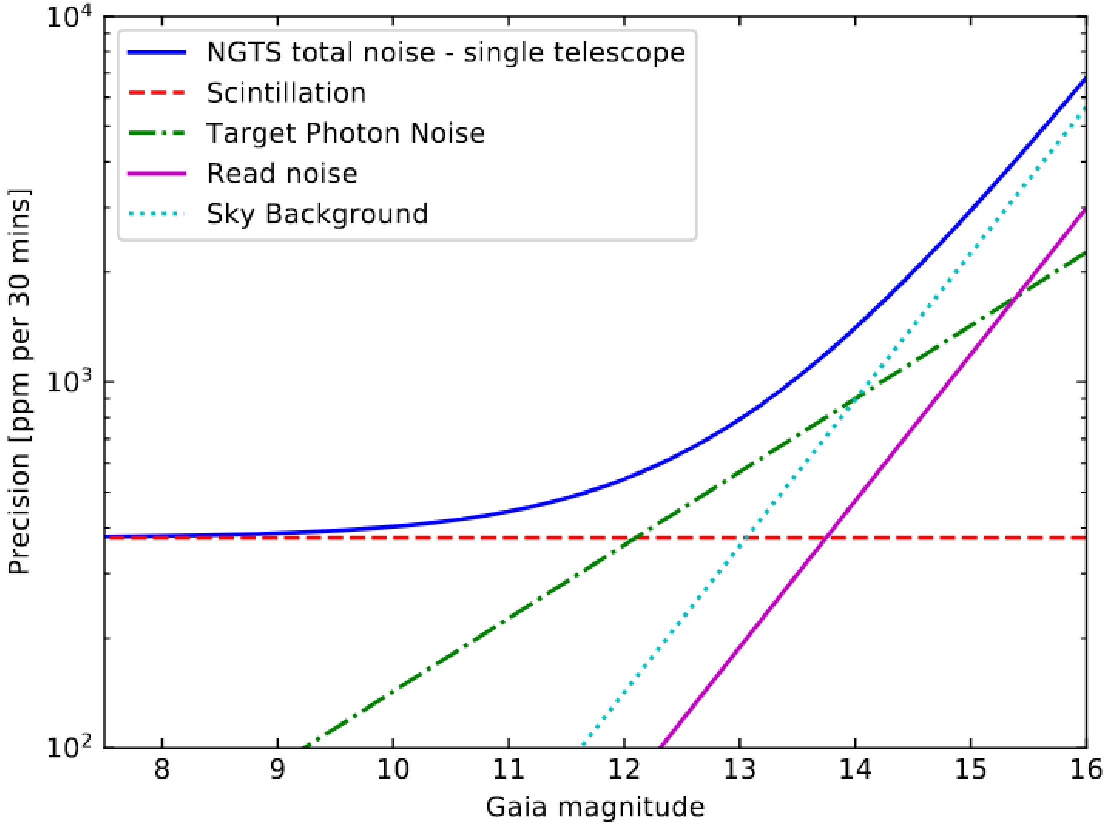


(Credit: Eloy Rodriguez; https://reddots.space/differential-photometry-in-practice/)

Time-domain photometry

- Monitor variability on time-scales of hours, years, decades and maybe centuries

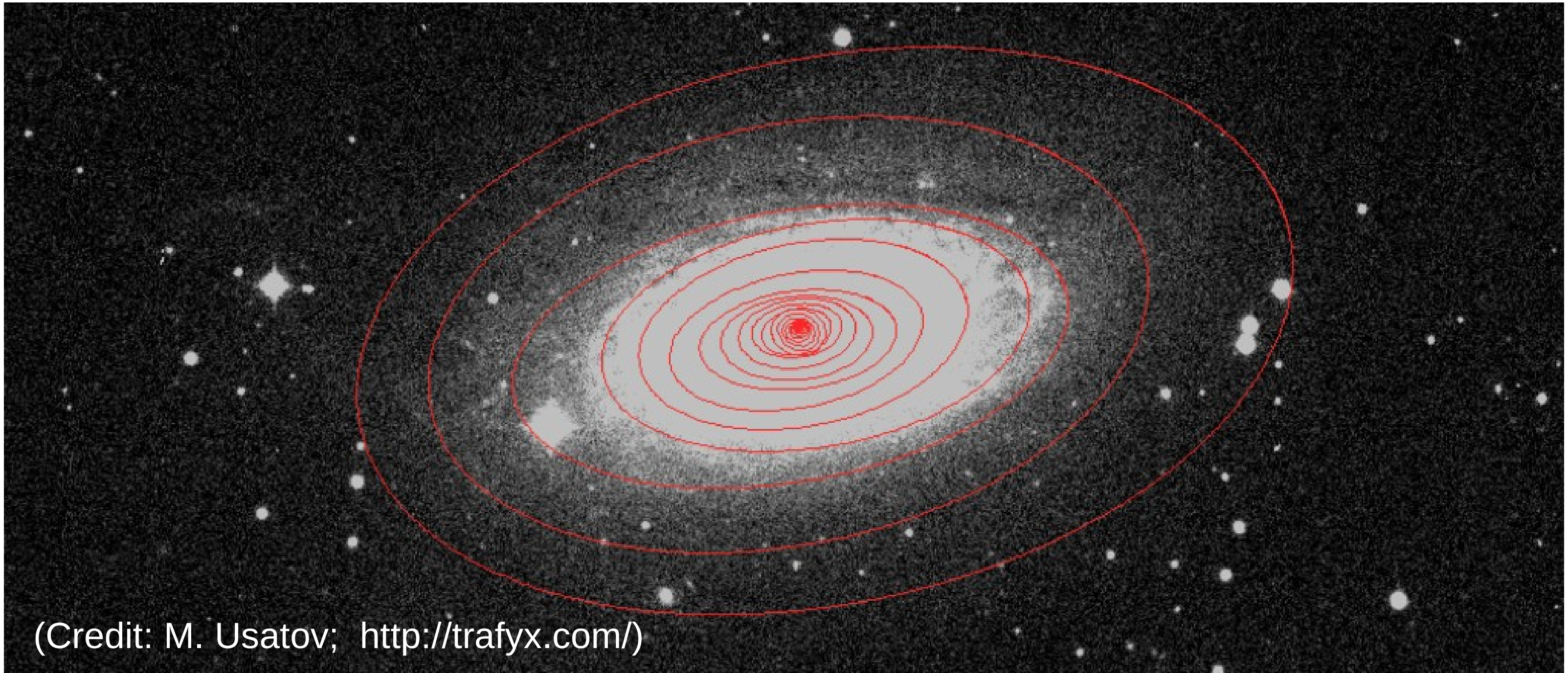
- High-precision time series photometry:
  - Asteroseismology
  - Exoplanets (transit)
- Looking for signal change of ~1%
- Space-based (e.g. Kepler and TESS) or ground-based observations
- Scintillation: variations 0.1-1%, for bright objects (O'Brien et al. 2021)



(O'Brien et al. 2021 – NGTS 20cm telescope)

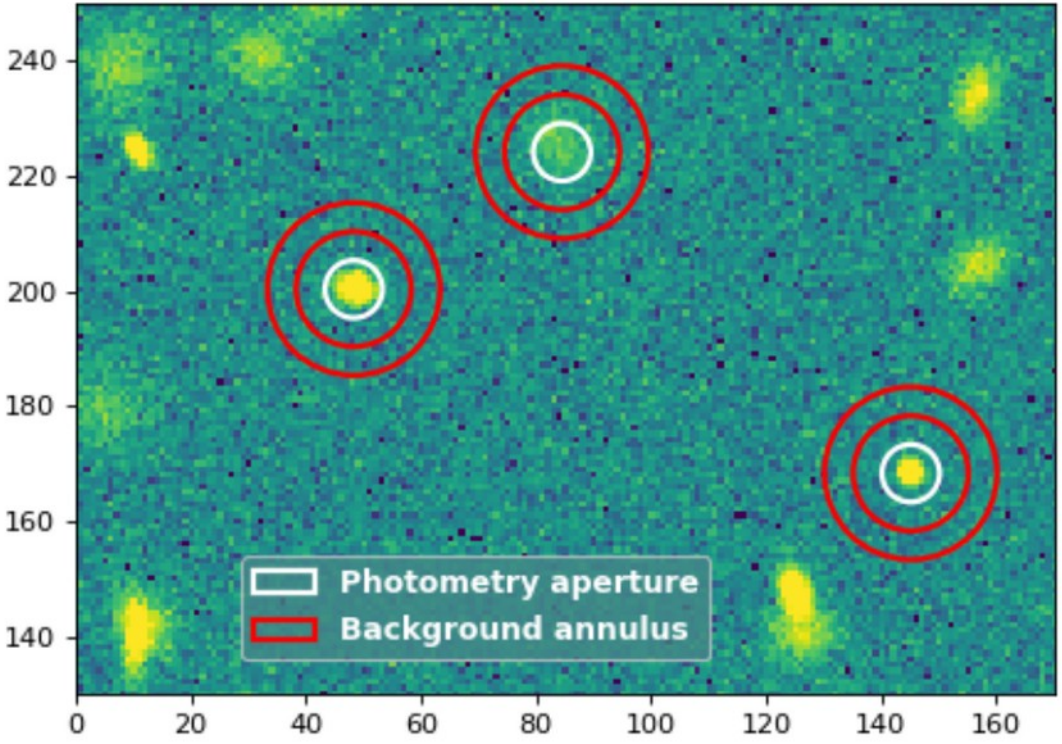
Surface photometry

- **Measuring surface brightness (mag/arcsec^2)**
  - Fitting isophotes and/or brightness profiles
  - Modelling the PSF
  - See references in the reading material



Aperture photometry

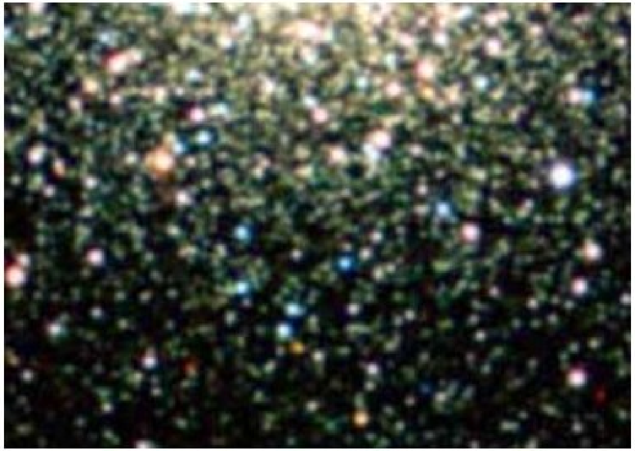
- Define an area (the aperture) from where to measure the source flux
- Define a nearby area from where the sky background will be measured
- Source and sky areas do not need to be the same
- Some experimentation needed to define the optimal aperture size
- You want to include as much signal as possible without compromising the signal-to-noise ratio
- Aperture size will vary with magnitude
- See Stetson (2013) for a discussion

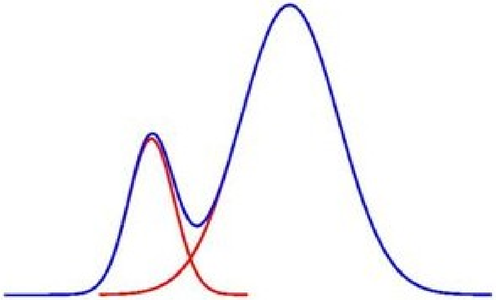


(Credit: photutils – Astropy package)

PSF photometry

- In a crowded field, defining apertures is not possible
- **PSF: Point Spread Function**
- Usually modelled as a Gaussian, but not necessarily
- PSF = seeing + tracking issues + optics
- Use isolated objects to create a model PSF
- Use the model PSF to estimate the flux of a given object
- Can be used when objects blend on each other
- Subtracting the PSF of a bright object might reveal fainter companions





(Credit: in https://slideplayer.com/slide/4693214/

Photometric calibration

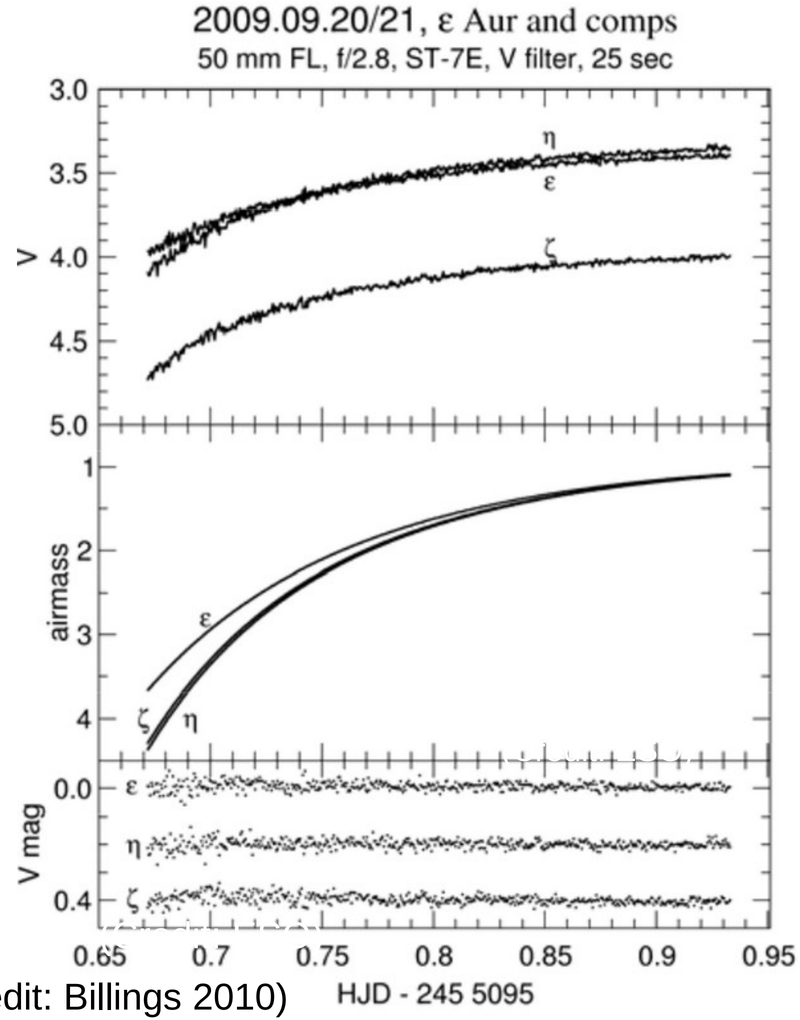
- One measures the "instrumental magnitude" (signal in counts):

$$(instrumental\ magnitude) \equiv (arbitrary\ constant) - 2.5\log\left[\frac{(integrated\ signal)}{(integration\ time)}\right].$$

- You want to convert those into the "real" scale of the photometric system

$$v \doteq V + \alpha + \beta(B\text{–}V) + \gamma X,$$
$$b \doteq B + \delta + \zeta(B\text{–}V) + \eta X, \ldots$$

- Important factors:
  - Atmospheric extinction
  - Telescope + detector transmission
  - Filter discrepancies
  - And others if needed (see Stetson 2013)



(Credit: Billings 2010)

Absolute photometry with FORS2

- Accuracy better than 3% is possible
- See documents about the
  [FORS Absolute Photometry Project]
- FORS Calibration Plan includes images of standard stars in broad band filters
- Two standard stars per night, close in time, airmass 1.1-1.8 (range 0.6-0.7)
- One standard per night in other fiters
- If requested PHO conditions with IMG mode, the observatory takes the standards before and after the target
- Modelling the data with ~18 photometric nights
- ESO maintains a QC interface or the coeffients of the zero point, color term, and extinction can be queried

!mjd_obs	!filter_name	!det_chip1_id	!det_chip_num	!zeropoint	!zeropoint_err	!colour_term	!c
59443.0	R_SPEC	CCID20-14-5-6	2	28.1223590187	0.00331662078303	-0.0095598	
59443.0	v_HIGH	CCID20-14-5-6	2	28.0298785983	0.00330461016753	0.057684	
59443.0	b_HIGH	CCID20-14-5-3	1	27.7630860561	0.00326011030092	0.10974	
59443.0	R_SPEC	CCID20-14-5-3	1	28.1179961371	0.00267047376627	-0.0095598	
59443.0	I_BESS	CCID20-14-5-6	2	27.4501553678	0.00335475707576	-0.017739	
59443.0	I_BESS	CCID20-14-5-3	1	27.4347251861	0.00281251828296	-0.017739	
59443.0	v_HIGH	CCID20-14-5-3	1	28.0143589052	0.00265700404464	0.057684	
59443.0	b_HIGH	CCID20-14-5-6	2	27.8097514418	0.00394742415187	0.10974	
59444.0	R_SPEC	CCID20-14-5-6	2	28.1195623959	0.00343643506839	-0.0095598	
59444.0	v_HIGH	CCID20-14-5-3	1	28.0216649649	0.00268140654829	0.057684	
59444.0	v_HIGH	CCID20-14-5-6	2	28.030252674	0.00326284993895	0.057684	
59444.0	b_HIGH	CCID20-14-5-3	1	27.7569291797	0.00318158358158	0.10974	
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59444.0	R_SPEC	CCID20-14-5-3	1	28.1076397392	0.00267177240619	-0.0095598	
59444.0	I_BESS	CCID20-14-5-6	2	27.4706388175	0.00350972636804	-0.017739	
59445.0	R_SPEC	CCID20-14-5-6	2	28.126365072	0.00344926244721	-0.0095598	
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59445.0	R_SPEC	CCID20-14-5-3	1	28.1137690383	0.00276345057984	-0.0095598	
59445.0	I_BESS	CCID20-14-5-6	2	27.4760083683	0.00353868309576	-0.017739	
59445.0	v_HIGH	CCID20-14-5-6	2	28.0429452134	0.00334520983922	0.057684	
59445.0	b_HIGH	CCID20-14-5-3	1	27.7673496415	0.00331864014737	0.10974	
59445.0	v_HIGH	CCID20-14-5-3	1	28.0281525709	0.00274017089003	0.057684	
59445.0	b_HIGH	CCID20-14-5-6	2	27.8261566363	0.00399332158311	0.10974	
59446.0	R_SPEC	CCID20-14-5-6	2	28.1121024117	0.00392617333476	-0.0095598	

(Credit: ESO/ see Ch. 4 of FORS Manual)

FORS2 ETC

Target Input Flux Distribution

○ Template Spectrum	G2V (Kurucz)	Redshift z = 0.00	Target Magnitude and Mag.System:
◉ MARCS Stellar Model	Teff=5500 log(g)= 1.0 [Fe/H]=-1 M= 1		V = 20.00 ◉ Vega ○ AB
○ Upload Spectrum	Select...		*Magnitudes are given per arcsec^2 for extended sources*
○ Blackbody	Temperature: K		
○ Power Law	Index: $F(\lambda) \propto \lambda^{index}$		
○ Emission Line	Lambda: nm Flux: 10^{-16} ergs/s/cm^2 *(per arcsec^2 for extended sources)* FWHM: nm		

Spatial Distribution: ◉ Point Source ○ Extended Source

Sky Conditions

☑ Override almanac sky parameters and use instead typical fixed sky model parameters except Moon phase and airmass

Moon FLI: 0.0 Airmass: 1.10

PWV: 7.5 mm *Probability **90%** of realising the PWV ≤ 7.5 mm*

Seeing/Image Quality:

◉ Turbulence Category: 30% (seeing ≤ 0.7") *(FWHM of the atmospheric PSF outside the telescope at zenith at 500 nm)*

○ IQ: arcsec *FWHM at the airmass and reference wavelength*

Instrumental Setup

Resolution: ◉ Standard ○ High

Filter: u_HIGH

Detector: ○ MIT red-optimized CCD ◉ E2V blue-optimized CCD

Readout mode: 200kHz,2x2,low

Polarimetry: ◉ No Polarimetry ○ Linear or Circular Polarisation

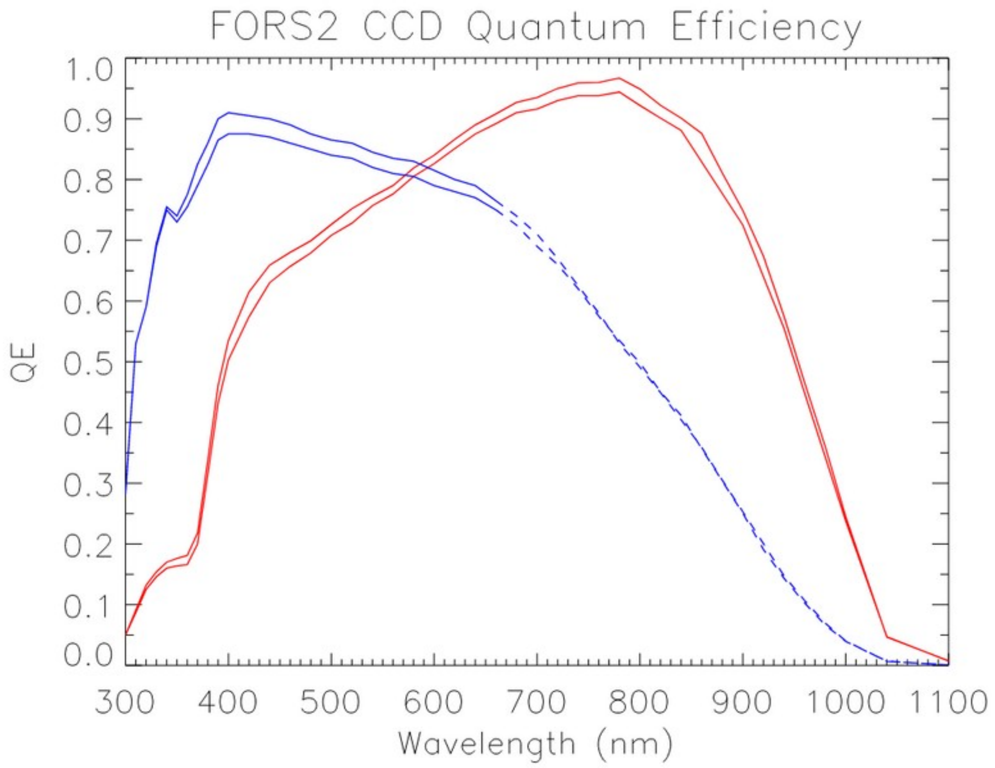
Results

◉ S/N: 100.0

○ Exposure Time: s

Strategy for our science case

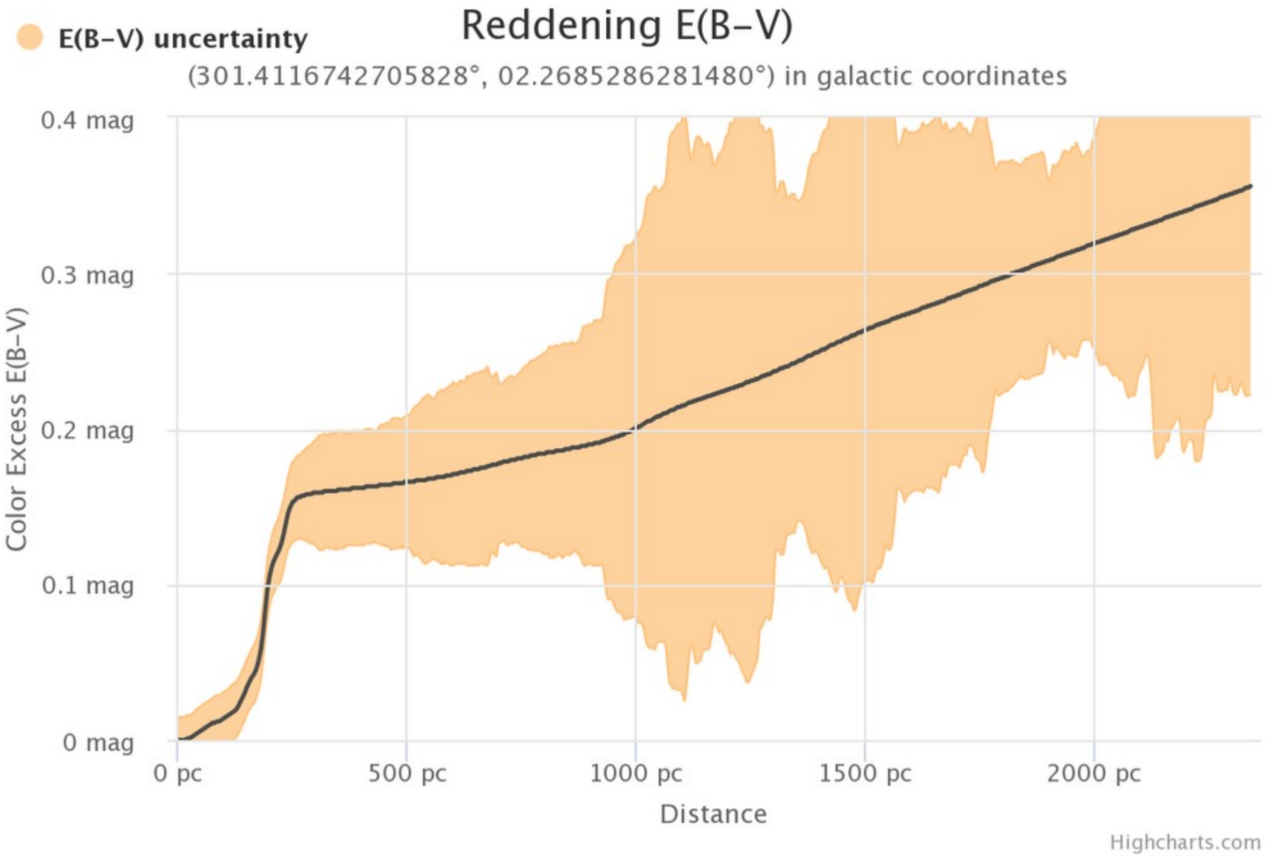
- Blue CCD for the U (λ_0 = 361nm, FWHM = 50 nm) and B (λ_0 = 437nm, FWHM = 102 nm)
- Affected by fringes λ > 650 nm (limiting SNR < 15). For V (λ = 555 nm, FWHM = 123) we might want the red CCD.
- Mosaic of two detectors (so there is a gap in the field)
- SNR ~ (1 / mag uncertainty) (0.02 mag, SNR~50)
- Photometric nights (limit variations < 2%)
- We do not know the range in mag of the targets
- **Visitor mode**: Blue CCD and need to adjust exposure time on the fly
- RFM: **Read the Fabulous Manual!!!** (setector calibration issues, field distortion, vignetting)



(Credit: ESO/FORS Manual)

Interstellar extinction

- Interstellar extinction: scattering of light by dust grains
- **Absorption:** later irradiated in IR (extinction makes objects fainter)
- **Reddening:** it is wavelength dependent (makes objects redder)
- Total absorption in a band, e.g. A_V
- $V_{obs} = V_{true} + A_V$ (obs is fainter)
- Color excess, e.g. $E(B\text{-}V) = A_B - A_V$
- Ratio of total to selective absorption: $R = A_V / E(B\text{-}V)$
- $A_V / E(B\text{-}V) \sim 3.1$ (but depends on dust properties)



(Credit: Stilism – Lallement et al. 2014)

Questions?

(Credit: Shutterstock)

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