Astrophysical Techniques

Optical/IR photometry and spectroscopy

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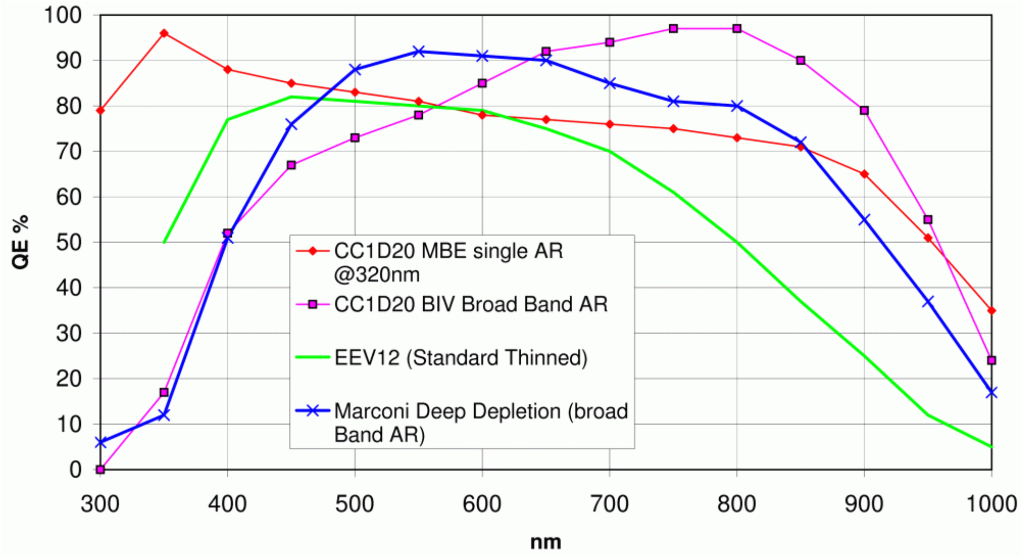
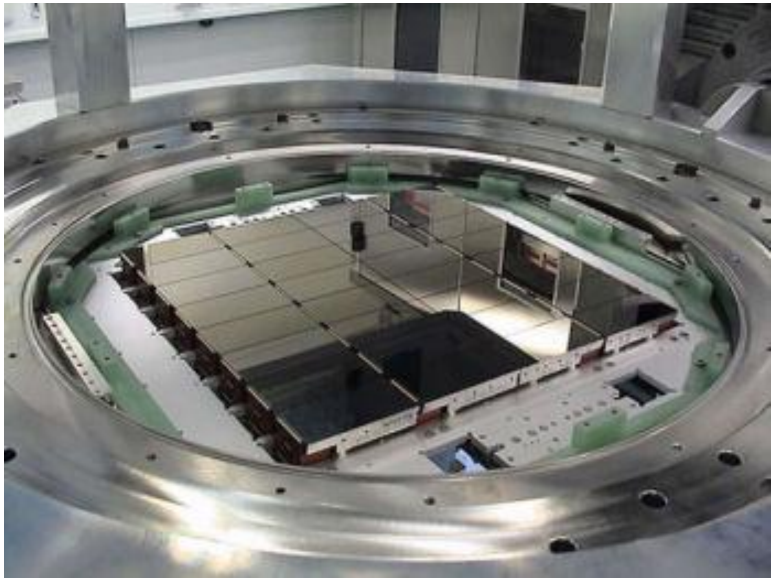
Imaging / Photometry

Photometry = Quantifying source brightness

Detectors

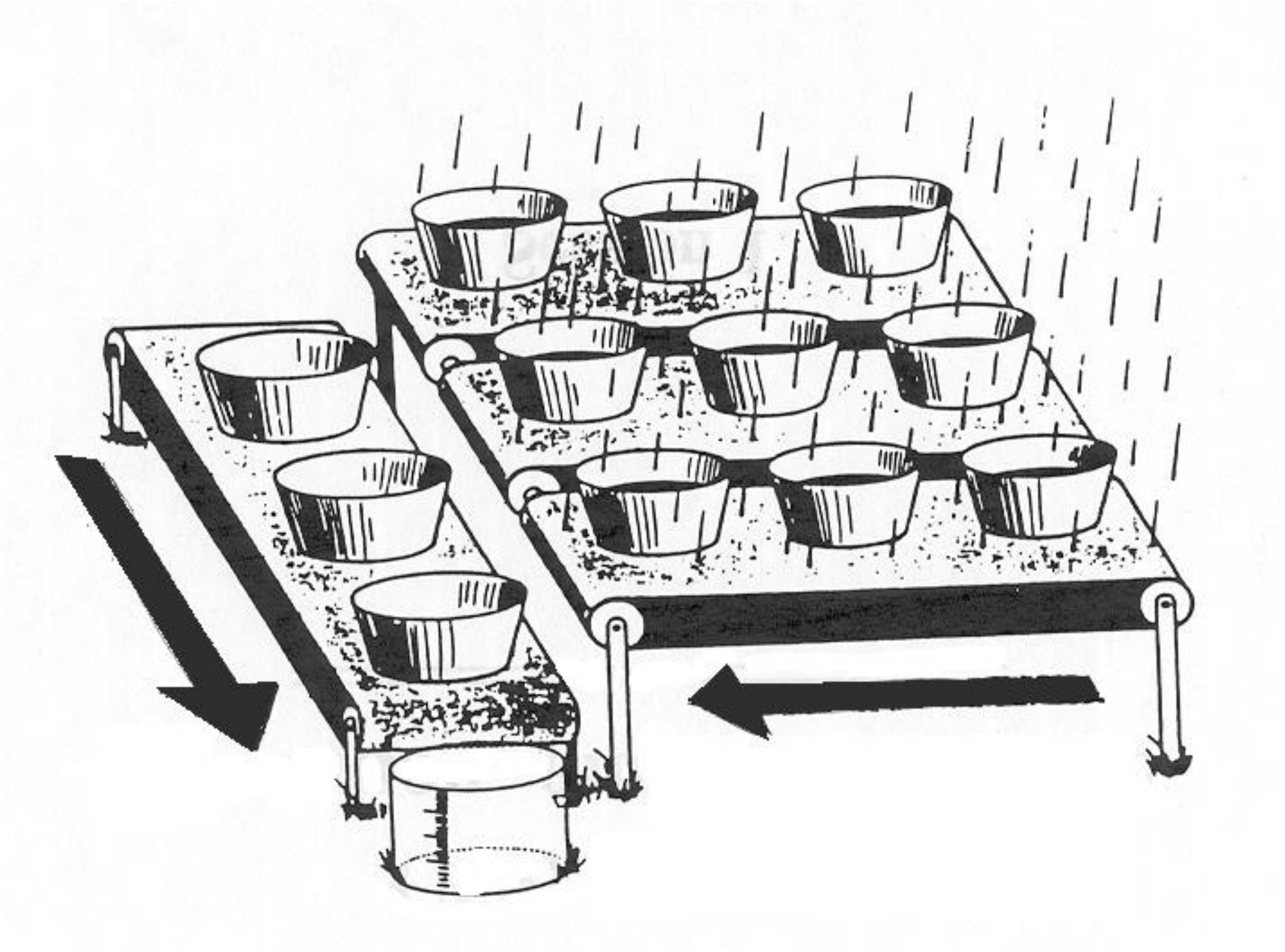
- CCDs are the de-facto devices for imaging cameras in the optical and IR
    - Digital encoding of signal
    - Linear response to light
    - Broad wavelength sensitivity
    - Many pixels (nowadays at least)





OmegaCam CCD mosaic
268 mega-pixels

CCDs



from: Janesick & Blouke 1987

Quantum efficiency

Charge transfer

AD conversion

Readout noise

Thermal noise

Amplification gain

Non-linearity

Saturation

Pixel to pixel sensitivity variations

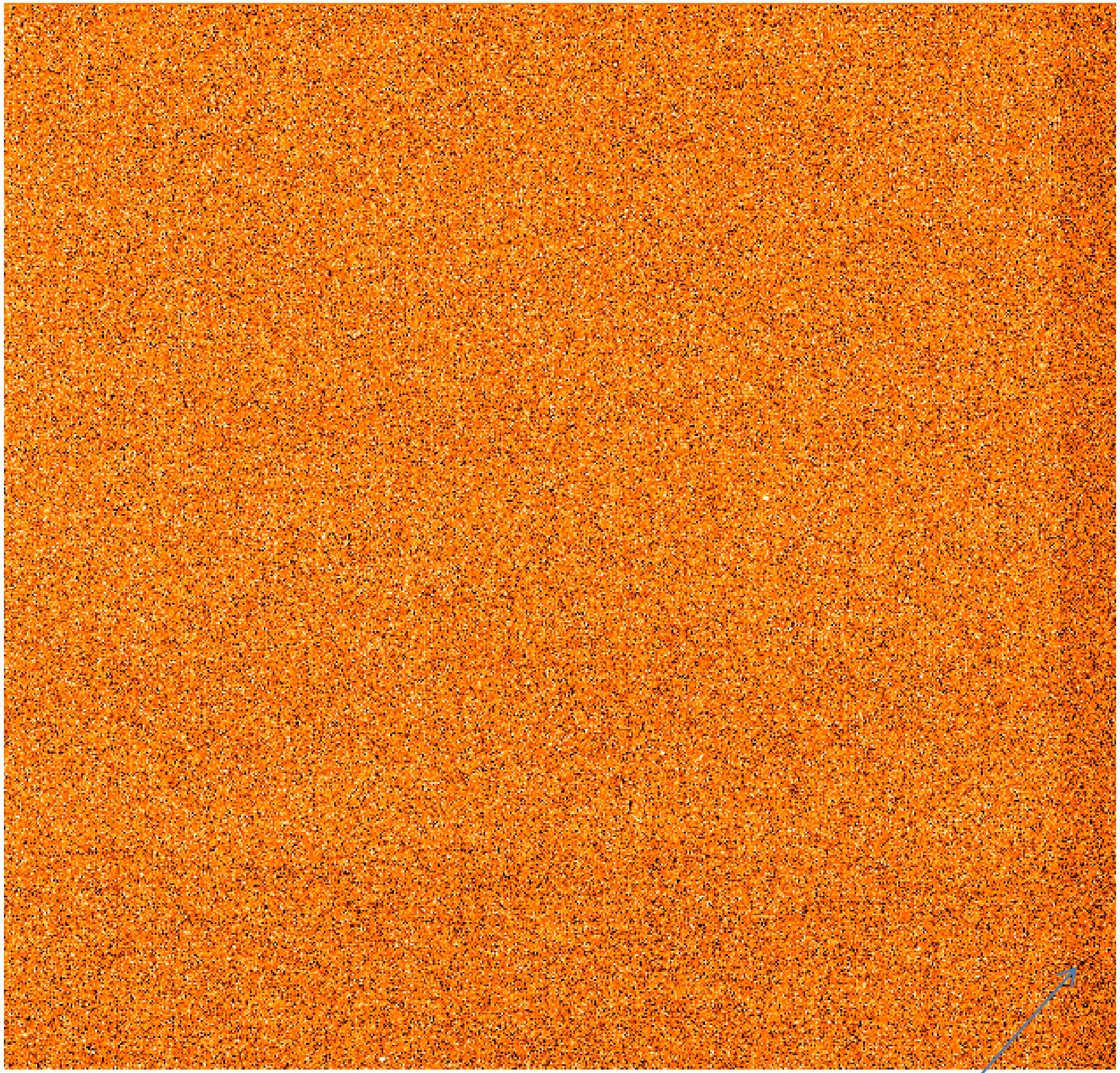
….

Imaging with CCDs

- Detector calibrations
  - What is stored is the value of each pixel ; ADU
  - Remove BIAS level
  - Measure readout noise
  - Convert ADU to photons via gain (e/ADU)
  - Correct pixel sensitivities via FLAT FIELDS

- Photometry
  - Extract source brightness from calibrated images
  - Background subtraction
  - Flux calibration

BIAS



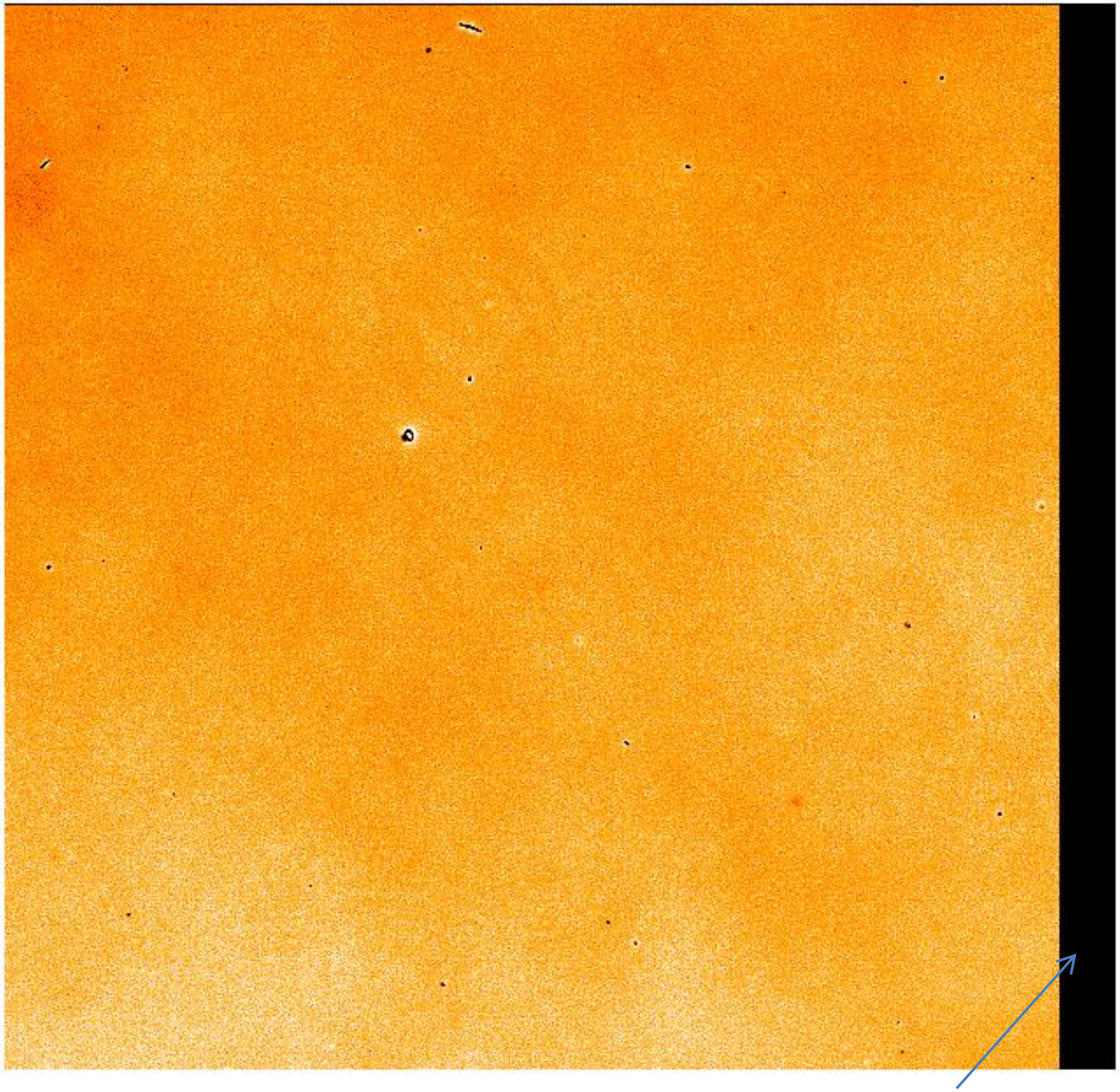
overscan strip

Mean offset added to ensure positivity of signal = BIASLEVEL

Pattern is noisy due to readout noise

BIAS frames are closed shutter readouts to determine bias level and readout noise

FLAT



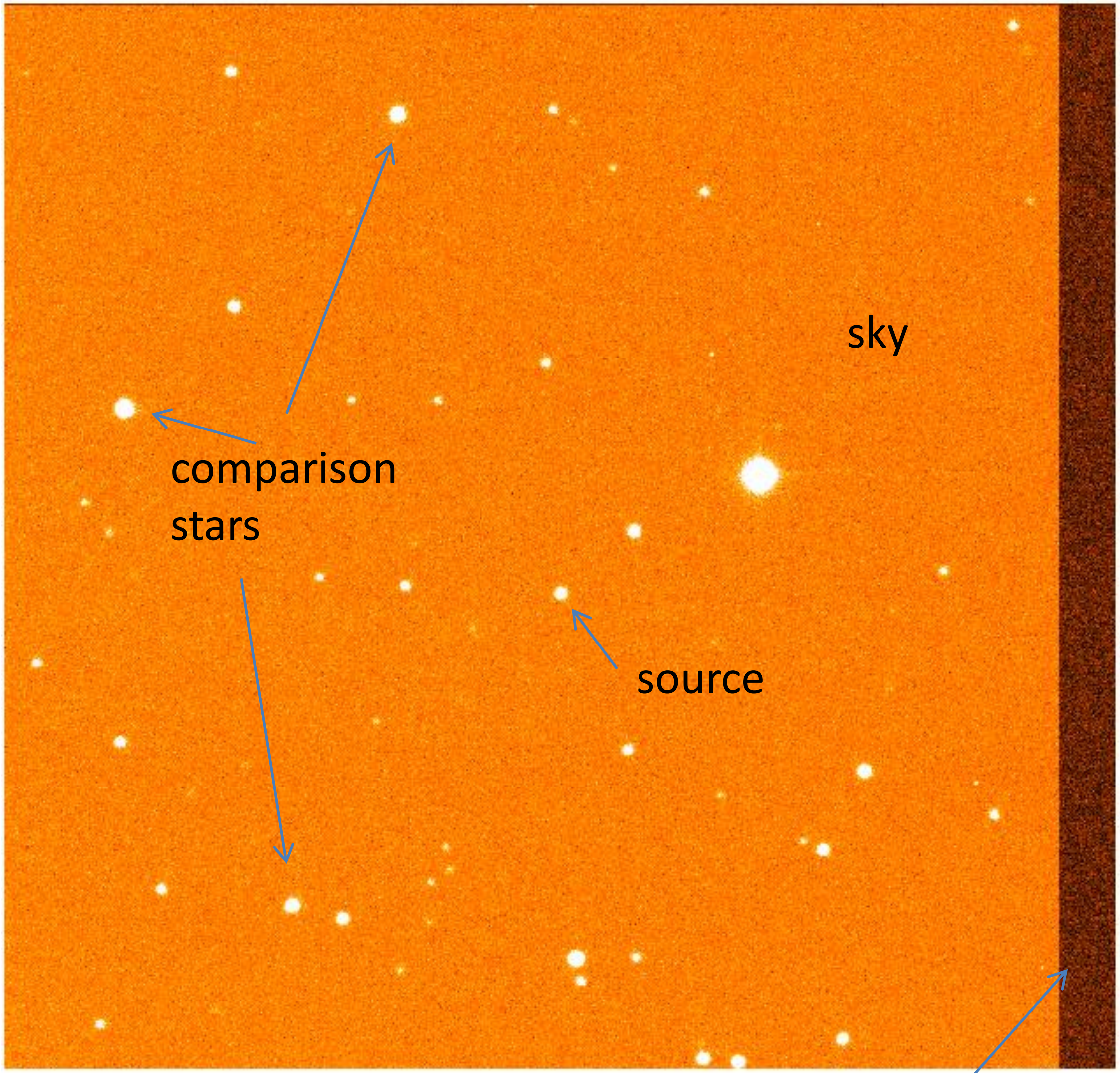
overscan strip to verify bias subtraction

Expose detector uniformly to measure pixel-to-pixel sensitivity variations and detector defects

Can use illuminated screens (domeflats) or the twilight sky (skyflats)

Can also use flats to verify gain factor to convert from ADU to photons

Target



bias strip to zero

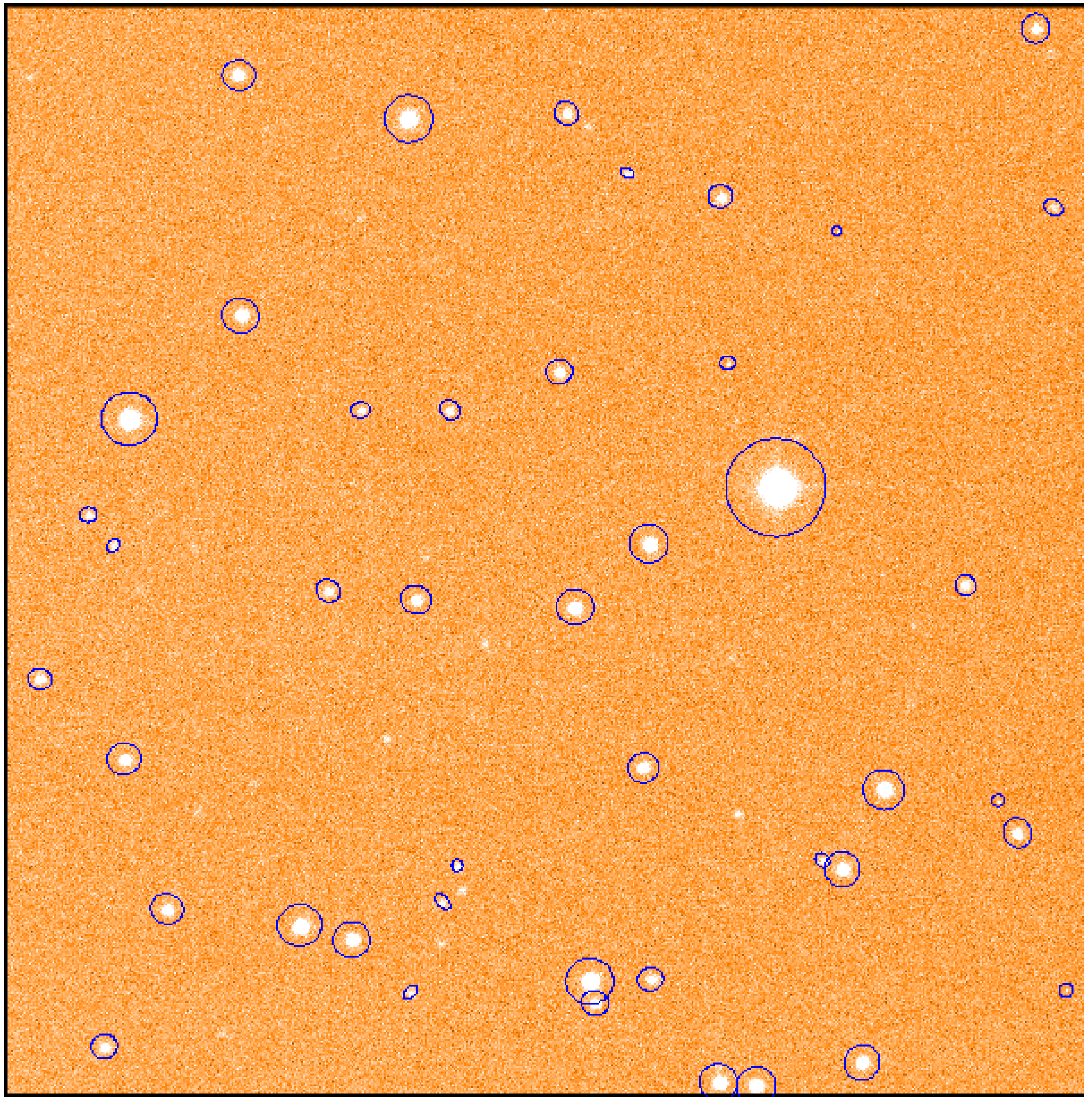
Bias subtracted and flat-field corrected target frames are then ready for photometry

Exploit nearby stars for photometric reference

Differential photometry just determines brightness relative to comp stars

Absolute photometry requires flux calibration

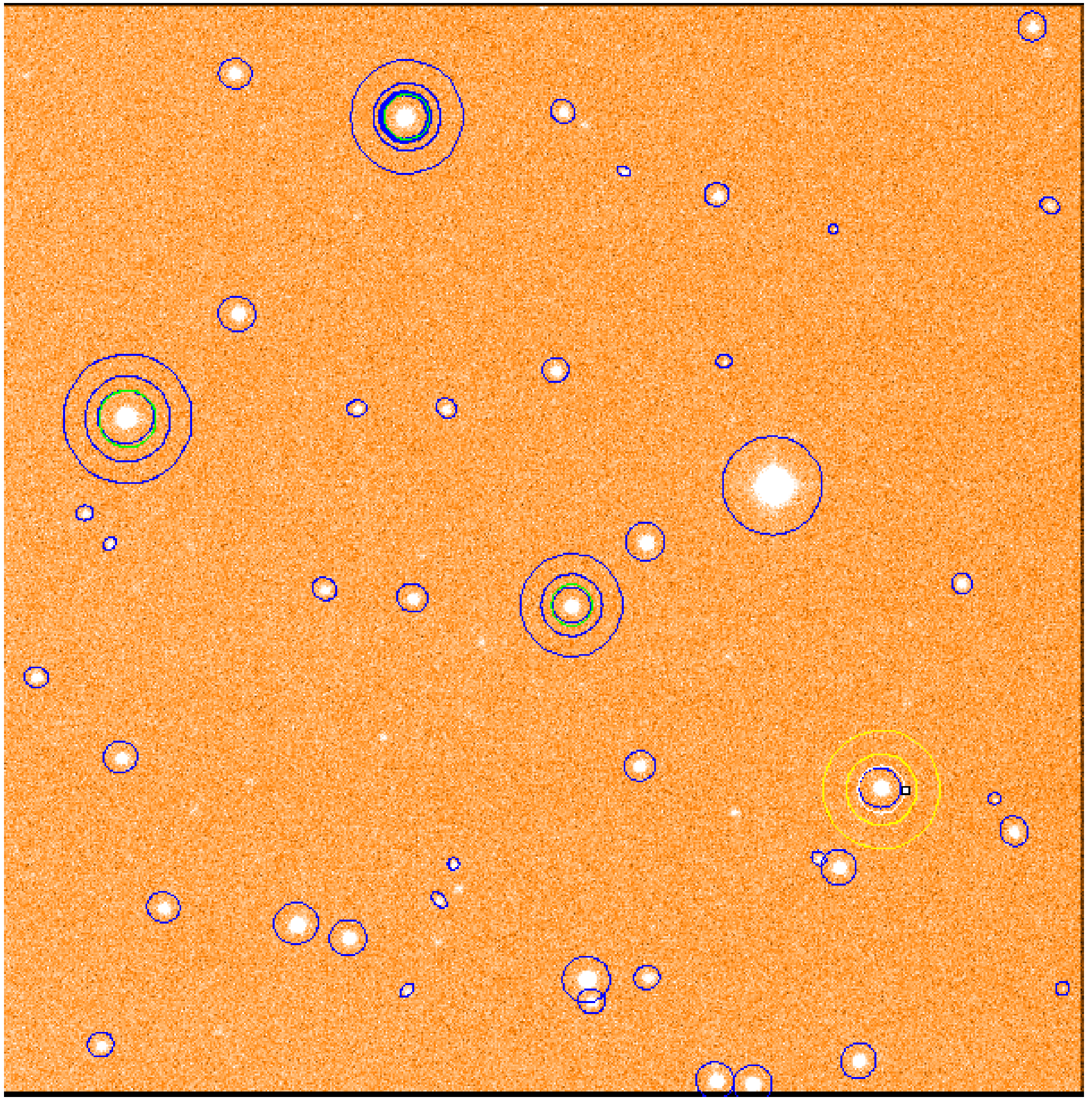
Source Detection



Establish locations where there is significant signal above background

Example; automatic source detection with *SExtractor* tool

Source - Background



Define apertures that designate areas of source signal and corresponding background areas

Typically circular source aperture with background from source centered annulus with suitable inner and outer radius

Finite pixel sizes matter

S/N

- Readout noise, dark current and background impact achieved S/N

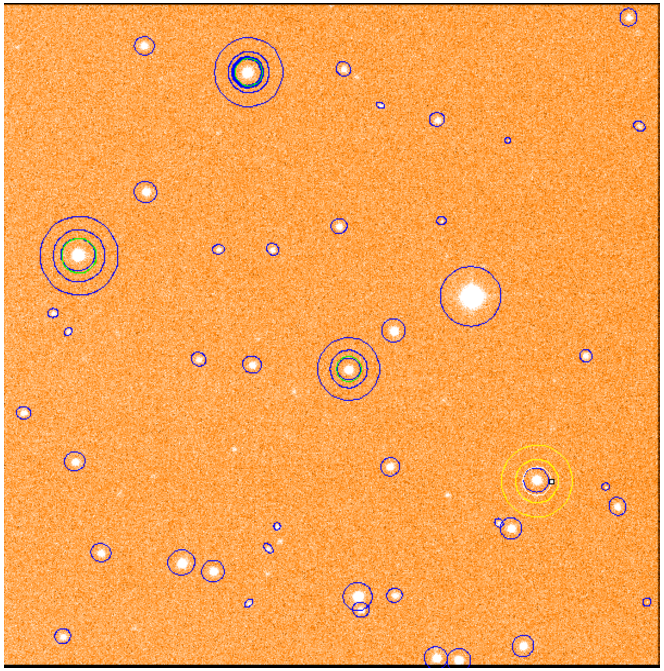
N_R = readout noise in electrons/pixel
N_B = #background electrons/pixel
N_D = #dark current electrons/pixel
N_* = #source electrons

Non-Poissonian

Then over a CCD area of n pixels:

$$S/N = N_* \,/\, \left(N_* + n(N_B + N_D + N_R^2) \right)^{1/2}$$
$$\approx \; N_*^{1/2} \text{ for large } N_*$$

Extracting the net source flux



Relevant is to establish the pixel-scale of the imager (e.g. arcseconds per detector pixel)

Field of view is pixel-scale times #pixels

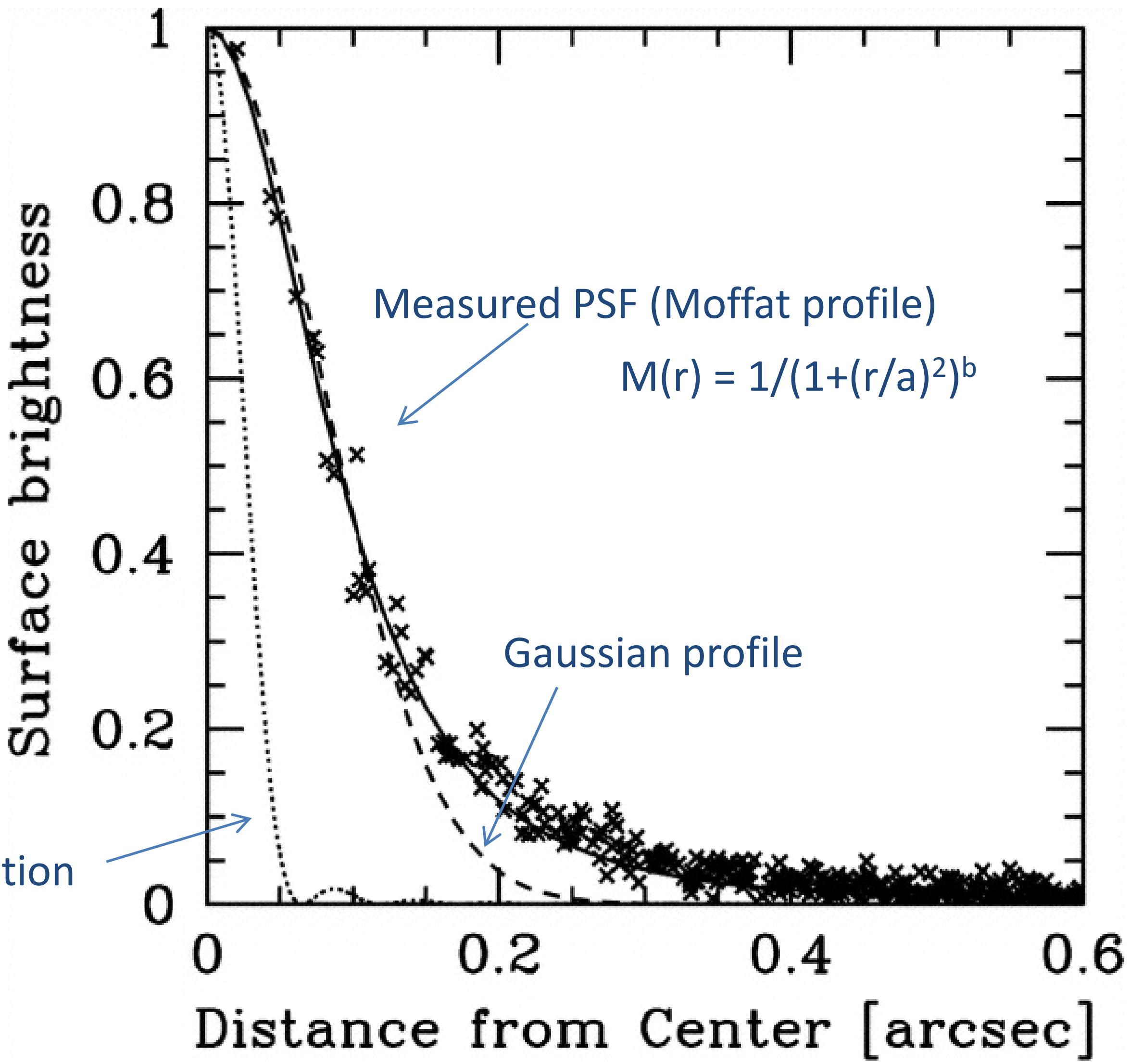
Spatial resolution combination of seeing and optical image quality delivered by telescope

Use point sources to characterise this PSF

How to sum signal?

- Just sum all pixels equally	[aperture photometry]
- Weight pixels with some function	[optimal photometry]
- Use accurate PSF to model source flux	[PSF photometry]

PSF radial profile



Measured PSF (Moffat profile)

$M(r) = 1/(1+(r/a)^2)^b$

Gaussian profile

Diffraction limit

Methods compared

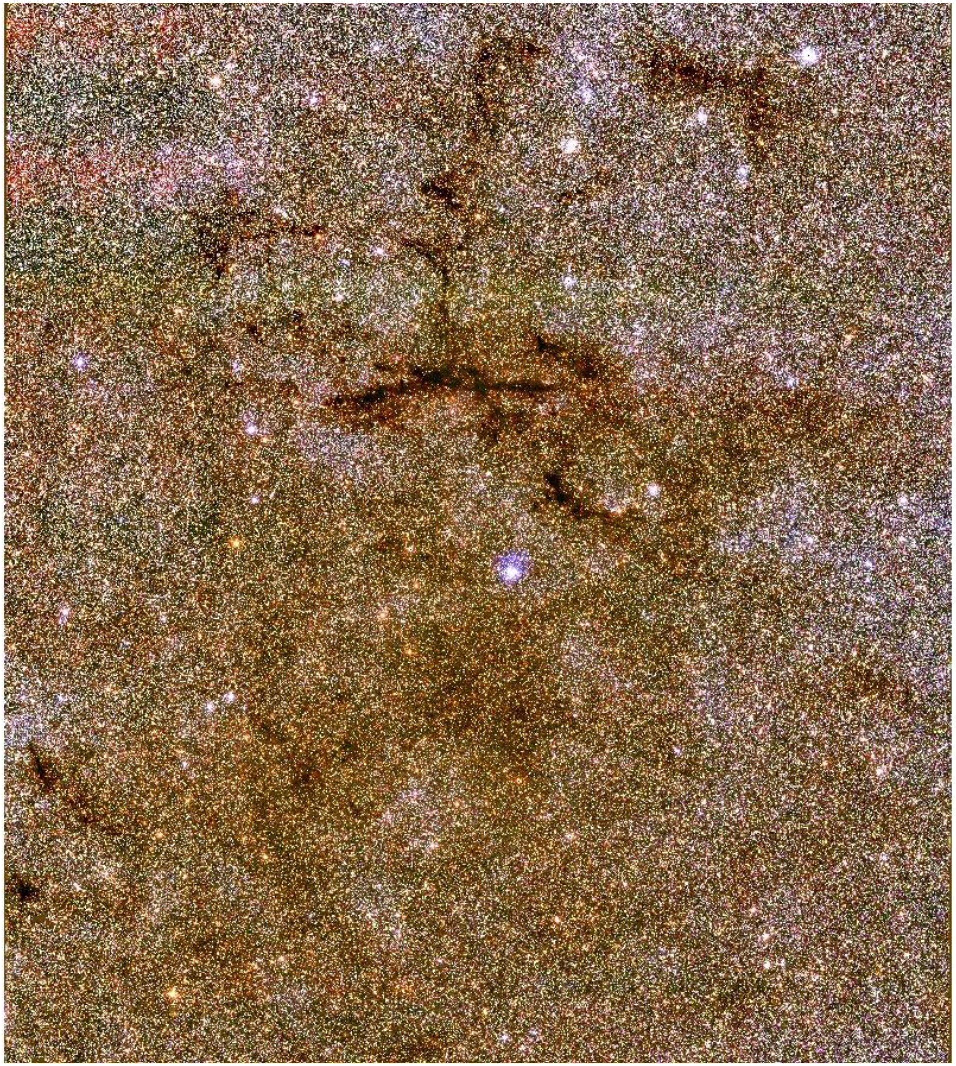
- Aperture photometry
  + fast, straightforward, PSF independent, flexible
  - how to choose best aperture radius
  - poor in case of blended sources

- Optimal photometry
  + use knowledge of PSF to perform a weighted sum
  + aperture just need to be large enough
  + PSF doesn’t need to be known particularly accurately
  - not much better for blended sources

- PSF photometry
  + necessary for properly handling crowded fields/blends
  - need to know PSF accurately
  - can introduce systematics

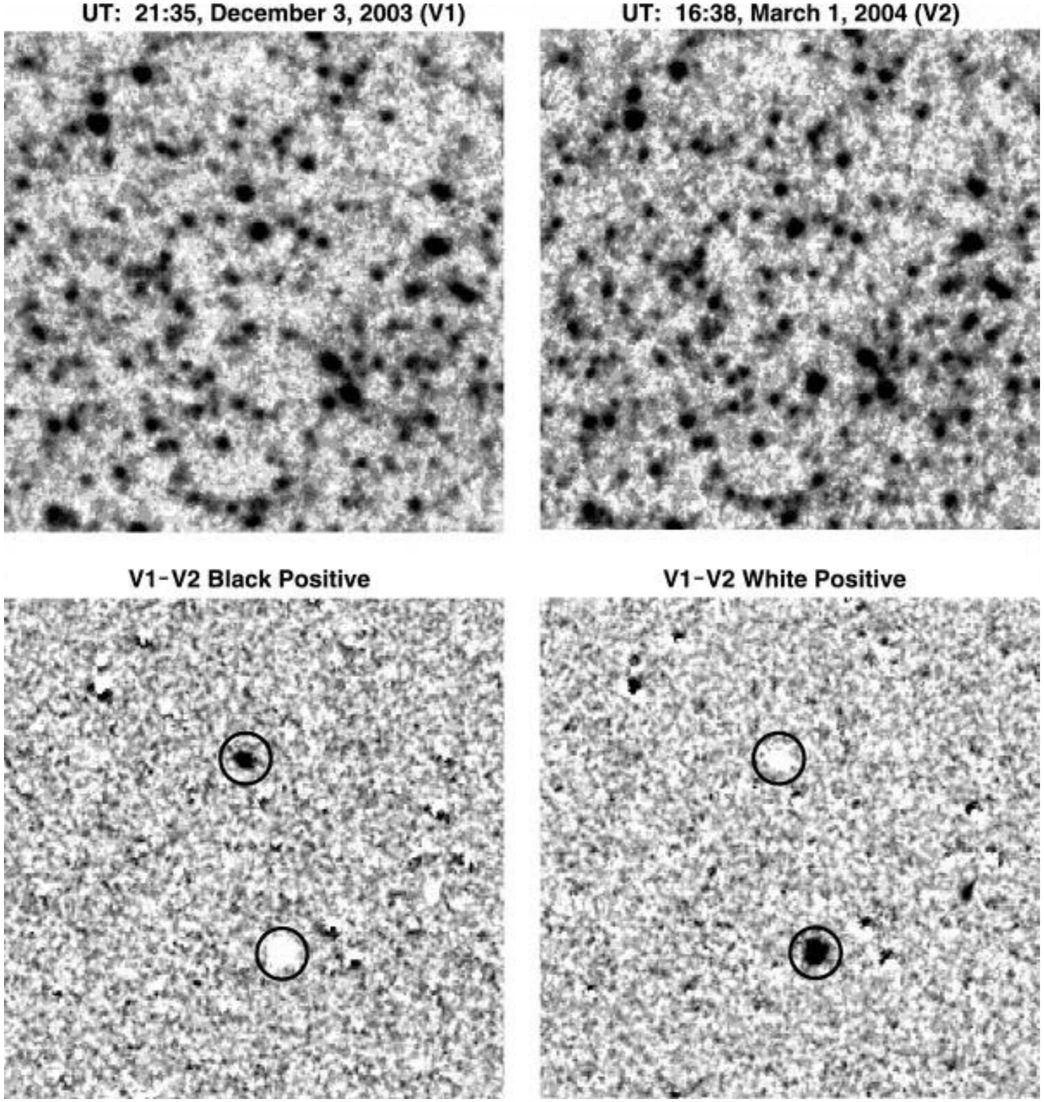
Hard work

- Crowded field photometry



Galactic Bulge Field

Difference Imaging



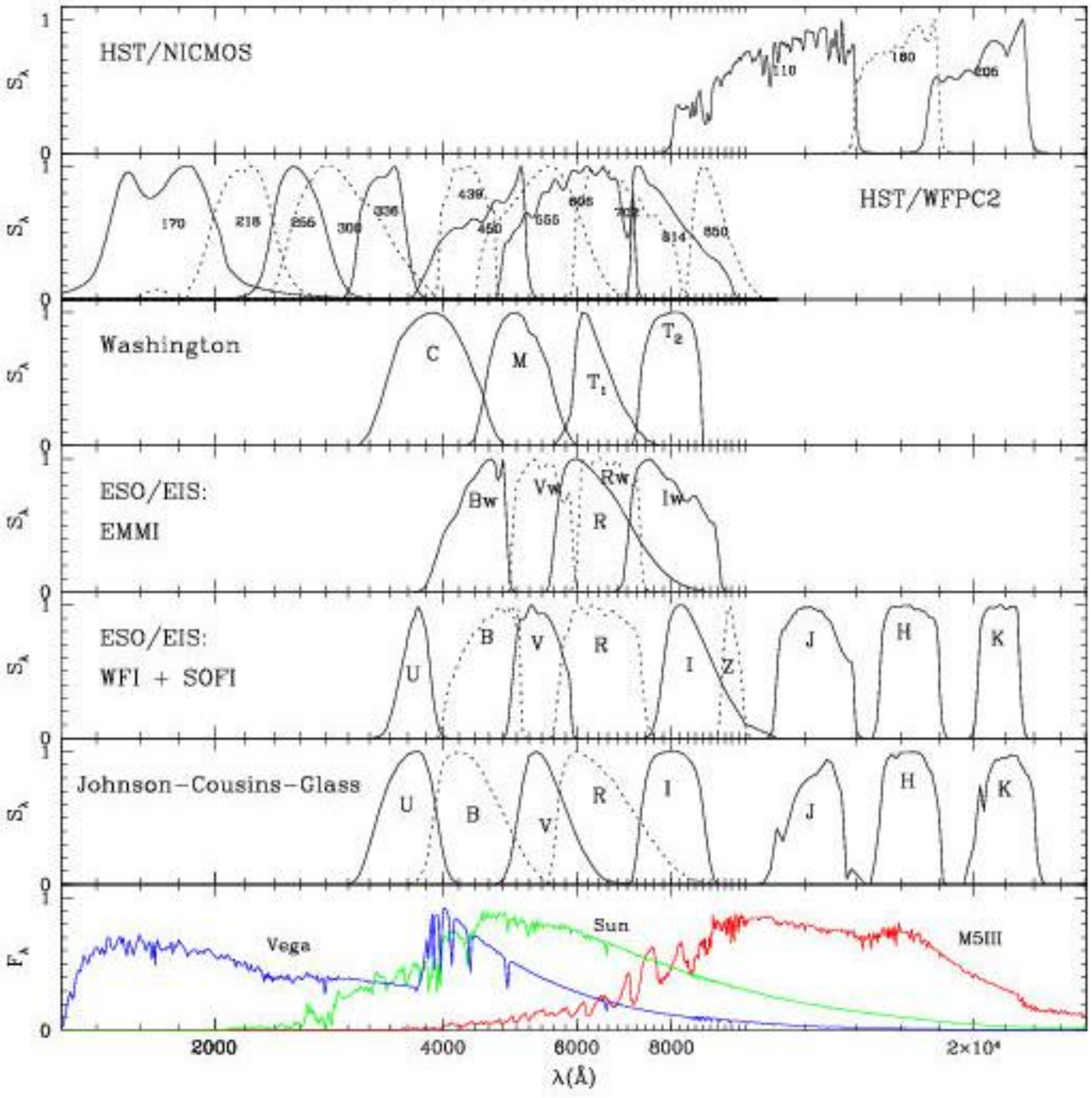
Good for variable objects

Hard to do absolute photomerty

Photometric Calibration

- If stars within the field are pre-calibrated, then differential photometry is easily turned into absolute photometry
- Otherwise standard fields need to be observed to derive a photometric calibration for the night
- Depends on suitably good (‘photometric’) conditions
- Extinction coefficients are also needed to correct for airmass differences between standard star and targets

Photometric Systems



- Nominally each telescope/ instrument combination has its own system as filters/ telescope throughput are never exactly the same

- Can transform between systems after extensive cross-calibration measurements (depends on spectrum of your source!)

- Vega systems (e.g. UVBRI) versus AB magnitudes (e.g. SDSS ugriz)

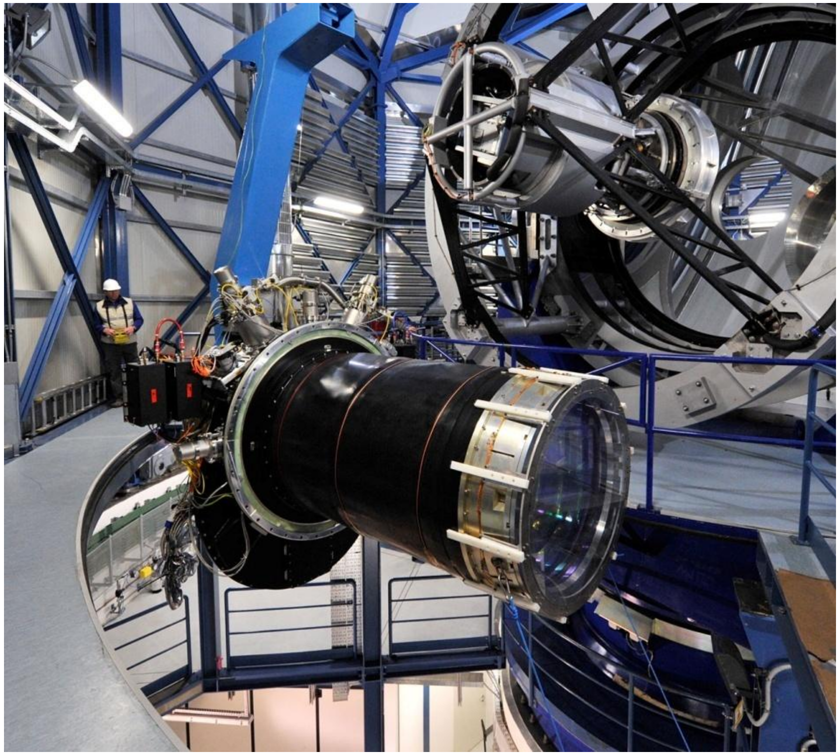
- See Bessell 2005, ARA&A for review

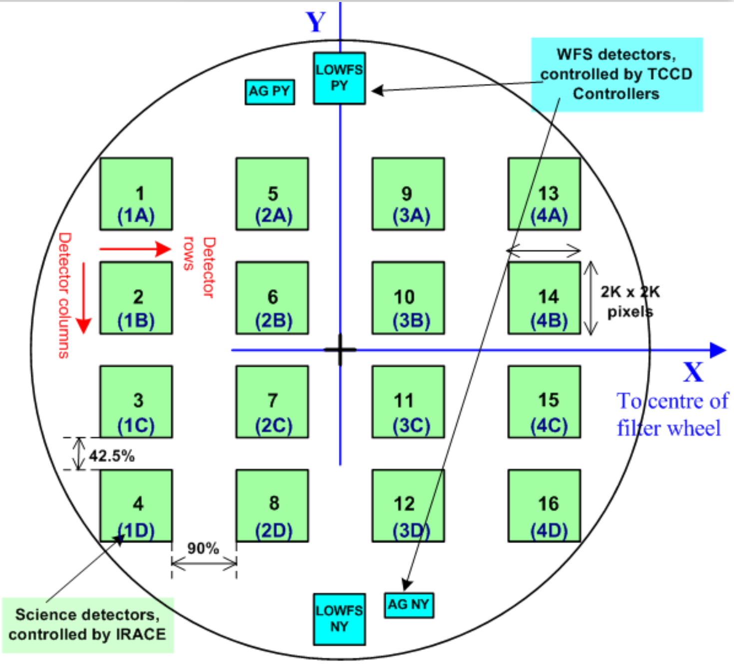
Resources

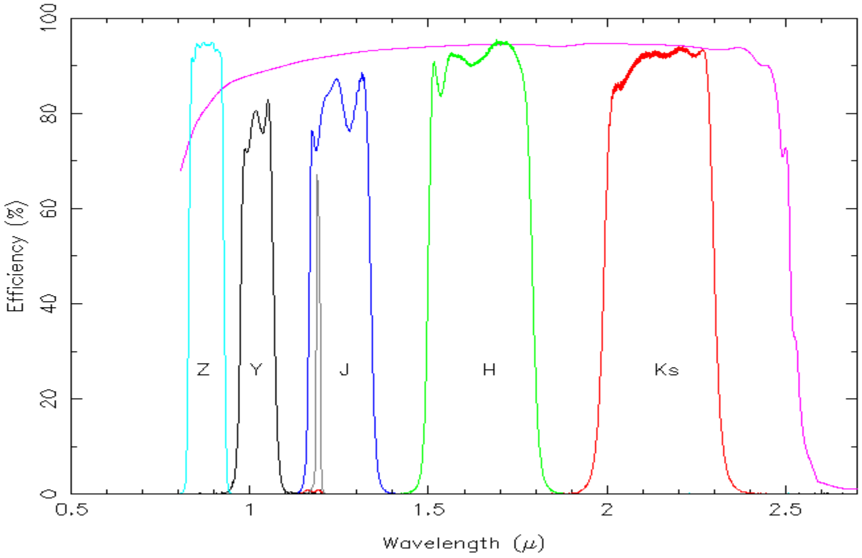
- Books:
  - *Handbook of CCD Astronomy* by S.B.Howell
  - *Astrophysical Techniques* by C.R.Kitchen
  - *Electronic Imaging in Astronomy* by I.McLean

- Reduction Software examples:
  - IRAF (historically std, at many observatories)
  - Starlink
  - DAOPHOT for PSF photometry (many implementations)
  - ISIS for difference imaging
  - ESO MIDAS and Common Pipeline Library
  - Trend is towards custom pipelines, e.g. ULTRACAM pipeline in C

Example ; VISTA IR camera



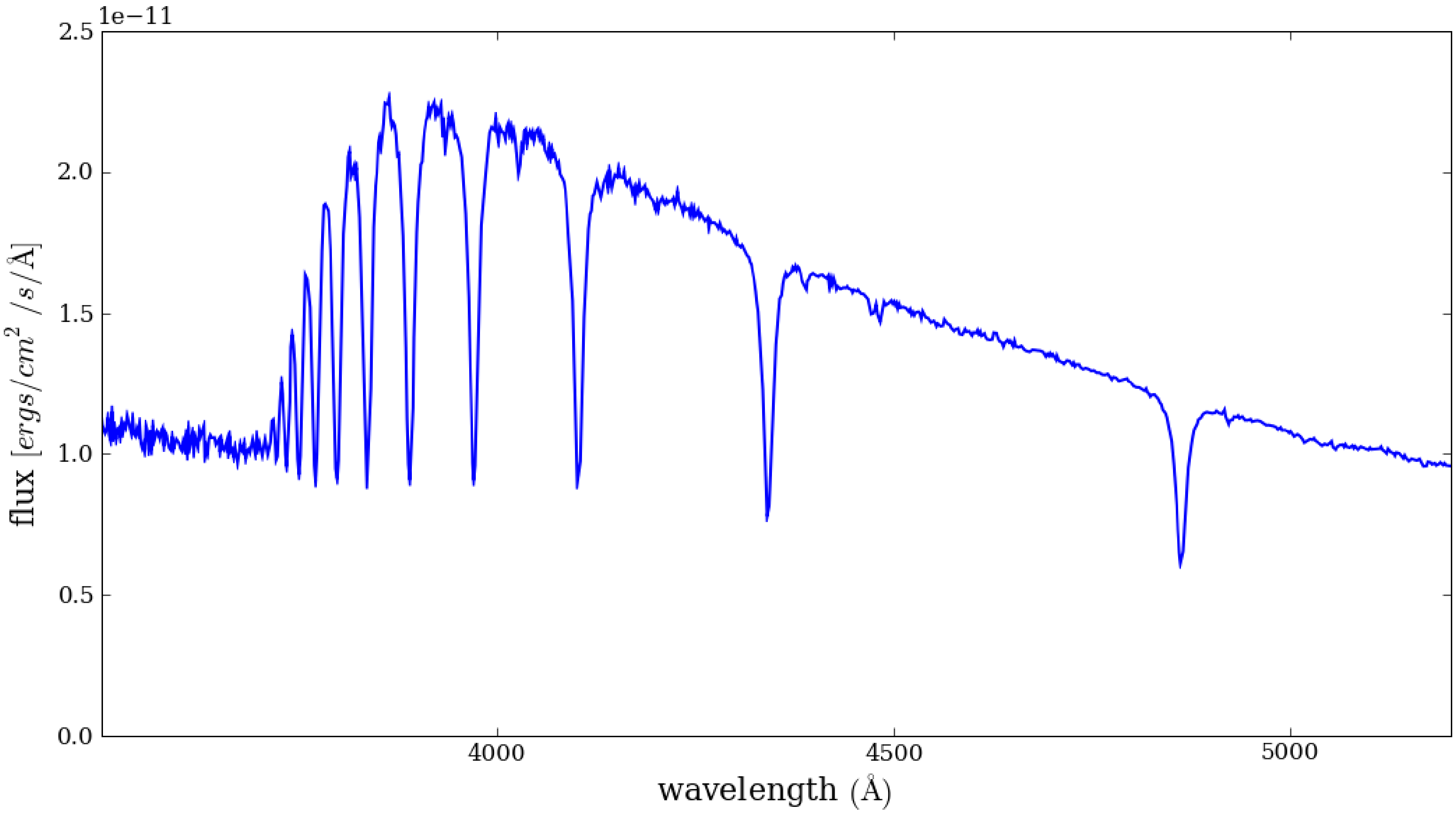




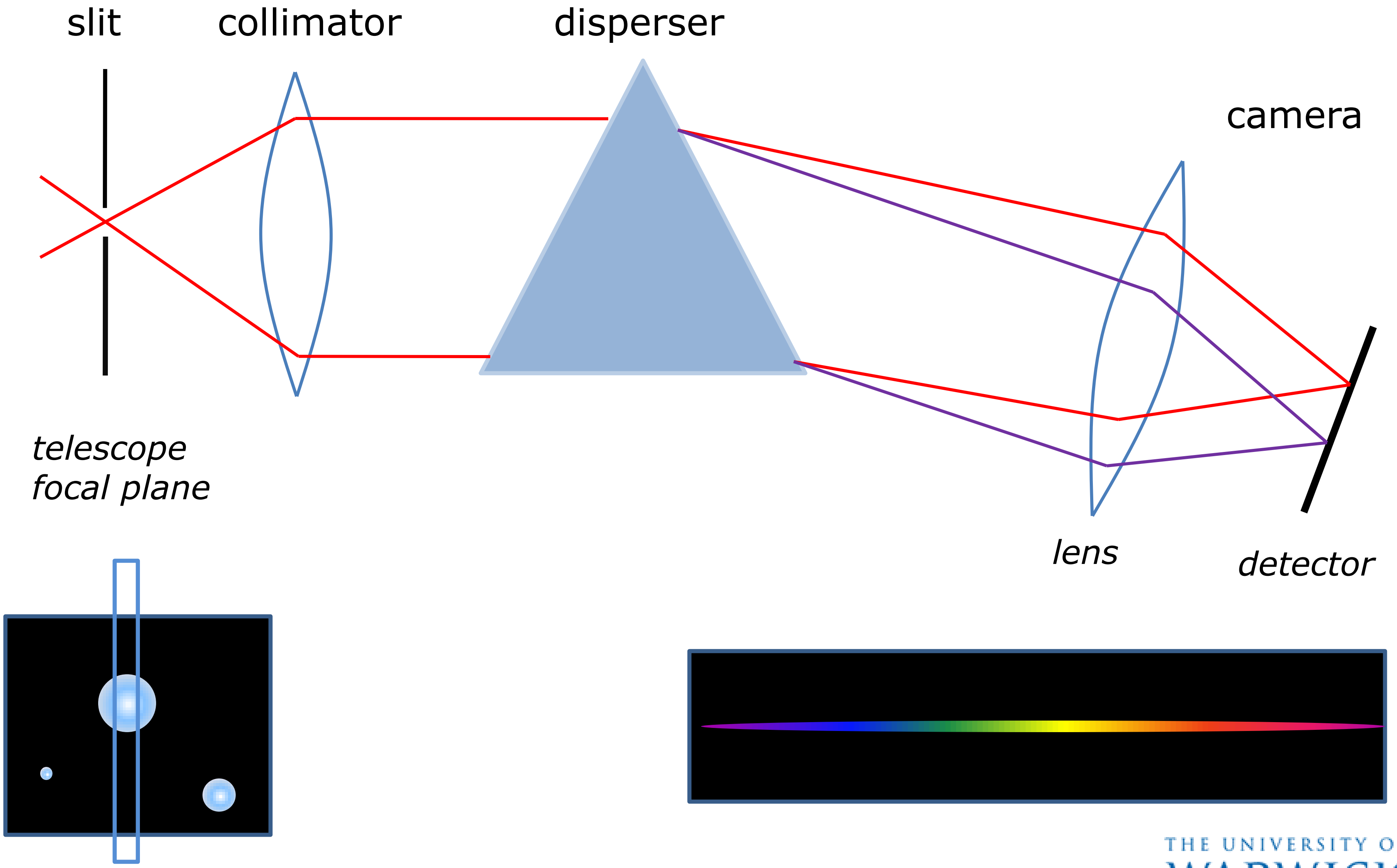
16 detectors each 2048x2048 pixels of 20μm
scale: 0.34” /pixel (f/3.25)
field of view: 0.6 deg^2
readout noise: 20e rms
dark current : 1.2 e/pixel/s

Spectroscopy

- Photometry at many wavelengths....



The basic spectrograph



Spectrographs

- Slit aperture
  - Long and narrow slit ; spatial information along slit
  - Fibers ; multi-object and integral field
  - Multiple slitlets ; multi-object spectroscopy

- Dispersers
  - *Prisms* ; limited to low resolution

    $$d\theta/d\lambda \propto dn/d\lambda \quad (\propto \lambda^{-3} \text{ for glass })$$

  - *Gratings* ; reflective/transmissive, holographic
  - *Grisms* ; grating on prism interface
  - *Cross-dispersers* ; image many orders simultaneously

Dispersion, resolution, sampling

- The intrinsic resolution of the spectrum is governed by the telescope PSF and the slit aperture
  - Slit width > PSF ; seeing-limited resolution
  - Slit width < PSF ; slit-limited resolution
  - Resolving power; $R = \lambda / \Delta\lambda$

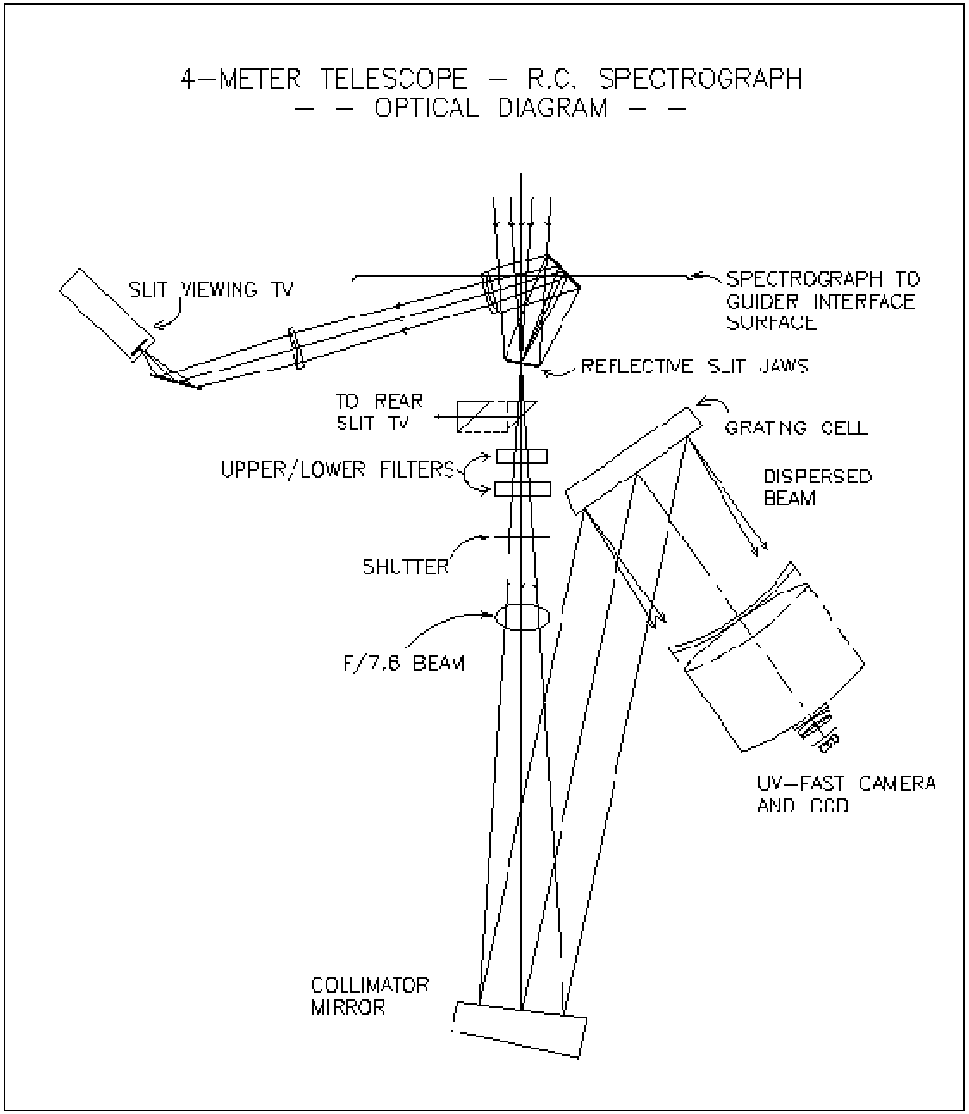
- The disperser determines the physical dispersion of the light as a function of wavelength

- The detector must sample this physical scale accordingly [at least two pixels per resolution element]

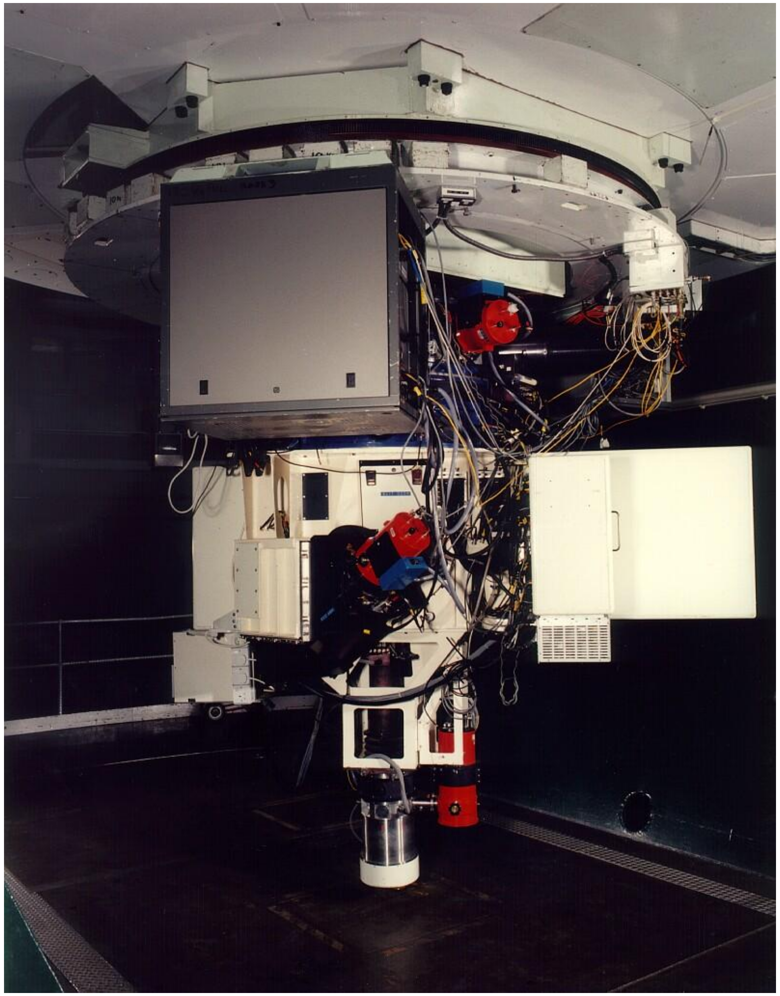
- E.g. The ISIS spectrograph on the 4.2m WHT

  600 groove/mm grating projects to 33Å/mm on detector plane
  The spatial scale of the detector plane is 14.9”/mm
  CCD detector has 13.5 micron pixels, so 0.44A and 0.2”
  - maximum resolution at 2-pixels is 0.89Å
  - this is 0.40” so need a 0.4” slit to achieve this resolution
  - the CCD has 4096 pix in the dispersion direction and covers 1822Å
  - $R = \Delta\lambda/\lambda = 5{,}618$ at 5000Å

Some real spectrographs

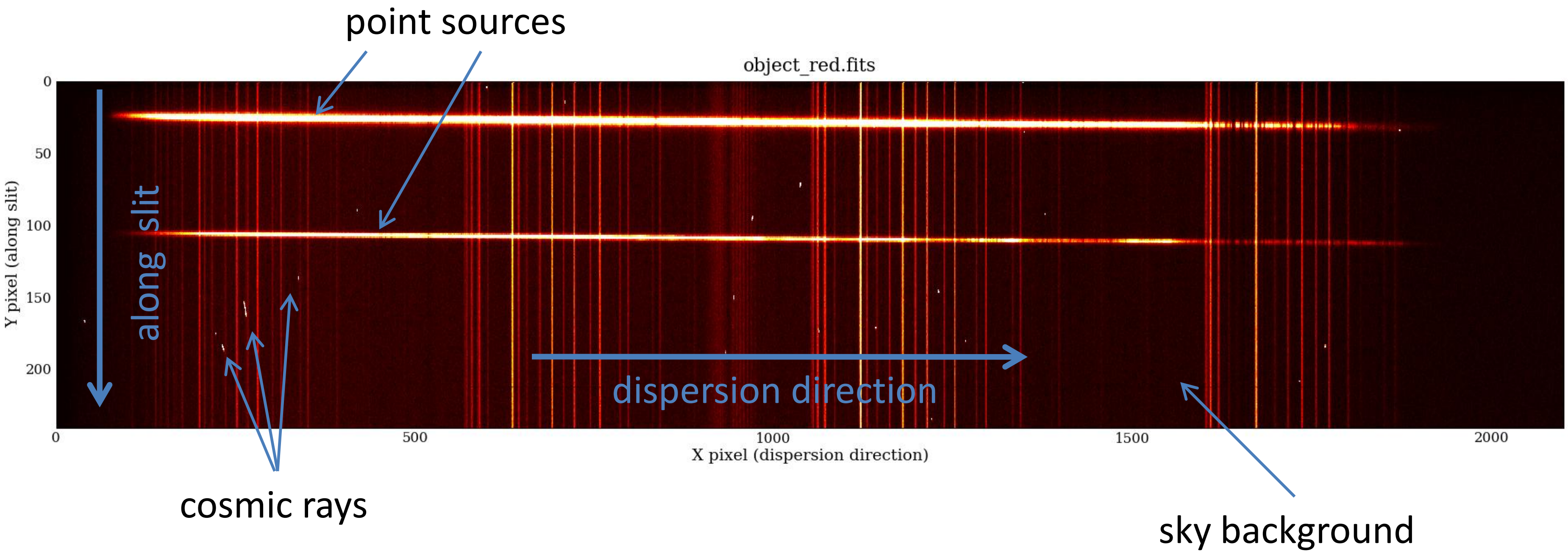


RC spectrograph at Kitt Peak



ISIS on the WHT

Long-slit spectroscopy



- spectral format CCD ; more pixels in the dispersion direction to sample the spectrum
- spatial information along the slit still available

Echelle spectrographs

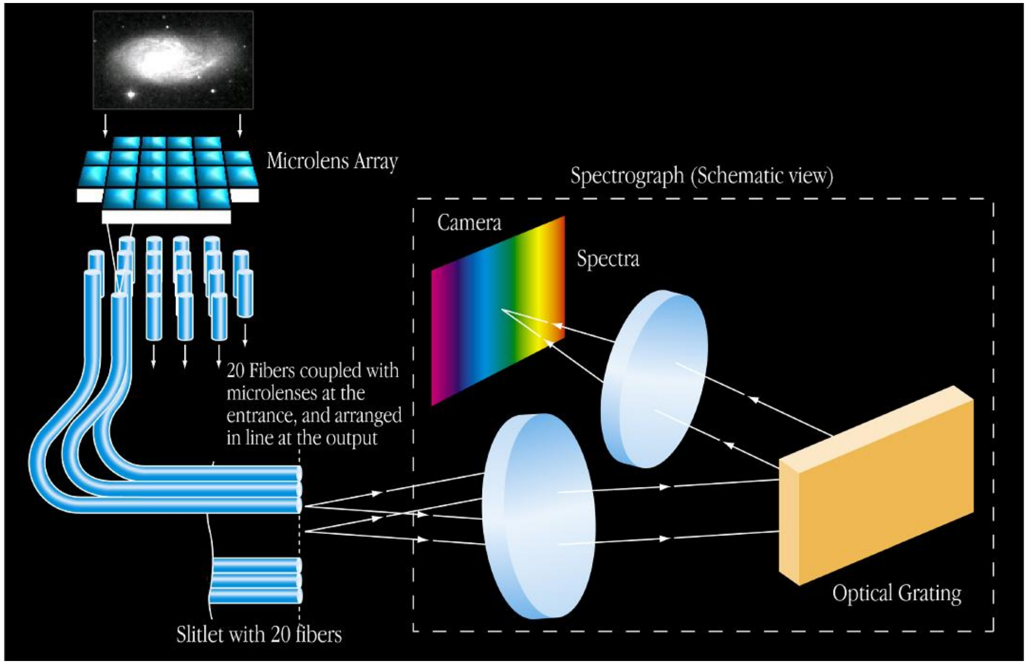
- Uses gratings at very high order (thus high resolution), and uses a 2nd low resolution *cross-disperser* to separate individual orders

MIKE on Magellan

- Can reach very high **R** of few times 10^4 - 10^5
- Slit is short to avoid order overlap; limited spatial/sky info

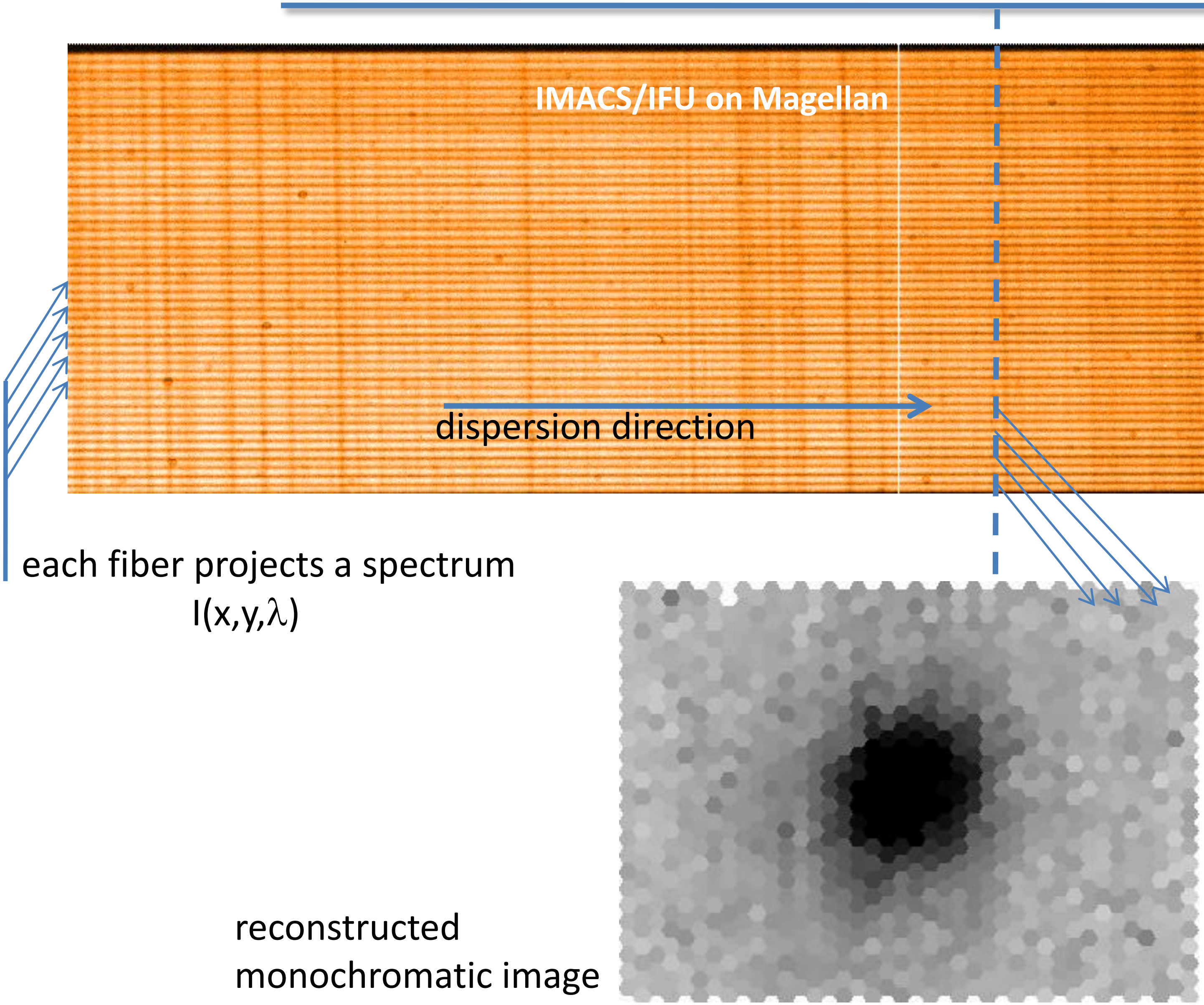
Integral Field Spectroscopy aka 3D

- Long-slit can provide spatial information along the slit, can slice extended objects ; I(x,λ) [2D]



- To sample targets in two spatial dimension, a bundle of apertures is needed ; I(x,y,λ) [3D]
- Each fiber/lenslet in the bundle is then fed into a spectrograph and dispersed

Integral Field Spectroscopy example



IMACS/IFU on Magellan

dispersion direction

each fiber projects a spectrum

$I(x,y,\lambda)$

reconstructed
monochromatic image

Multi-object spectrographs

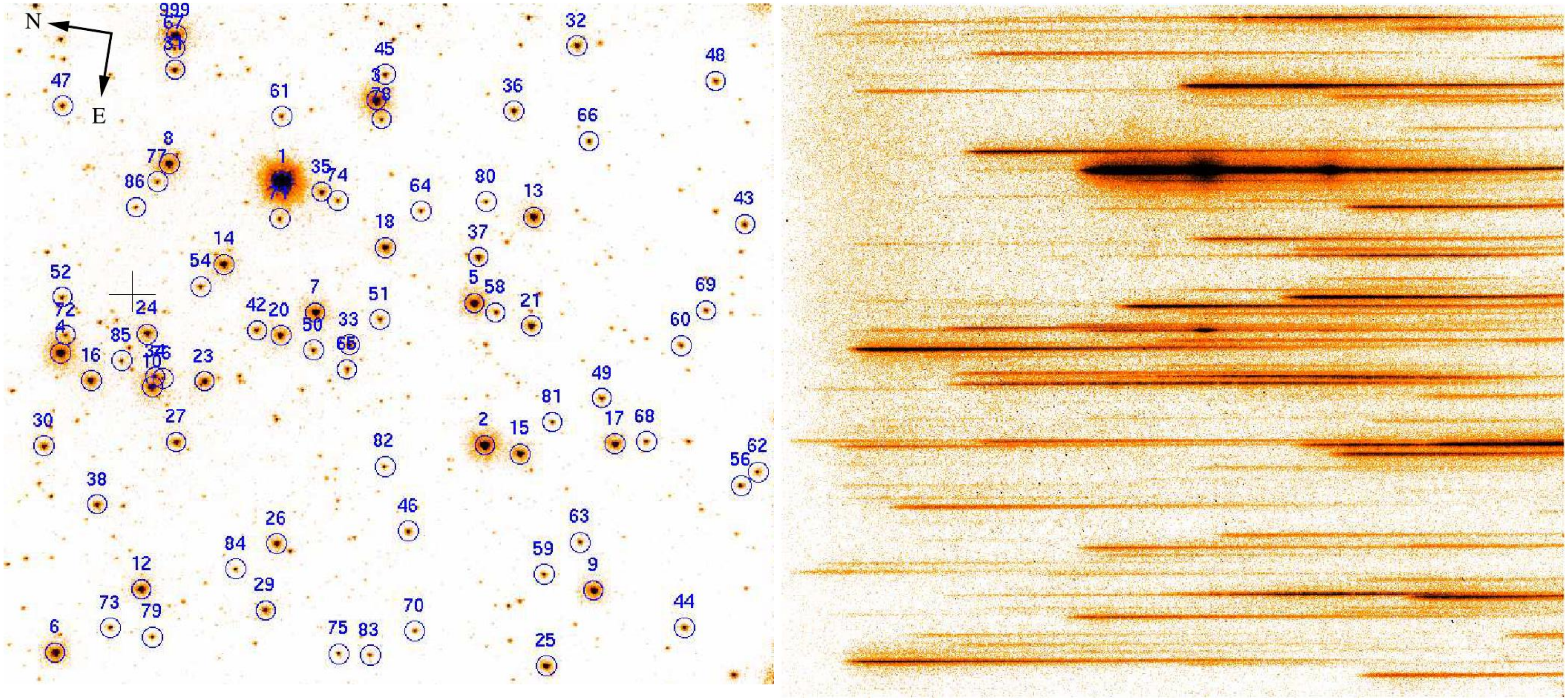
- Multiplex advantage by placing multiple apertures on the field of view and feeding each of these through the spectrograph

- Good for wide field-of-view instruments where the density of interesting targets per field is large

- Main types
  - **No apertures** ; just disperse the FoV
    - \+ No light-losses in apertures
    - \- Spectra/background of distinct sources overlap
  - **Use slitmasks** ; cut short slits at position of each target
    - \+ Get the same advantages as a single slit
    - \- Need to make custom slitmask for each pointing
    - \- Limited number of slits can be carved before spectra overlap
  - **Use fibers** ; place fiber at each target position
    - \+ Flexible and can setup fibers on the fly
    - \+ Can re-image the fibers efficiently onto the CCD ; more objects
    - \- Fiber size (=aperture) is fixed, background+target light combined

Slitless spectroscopy

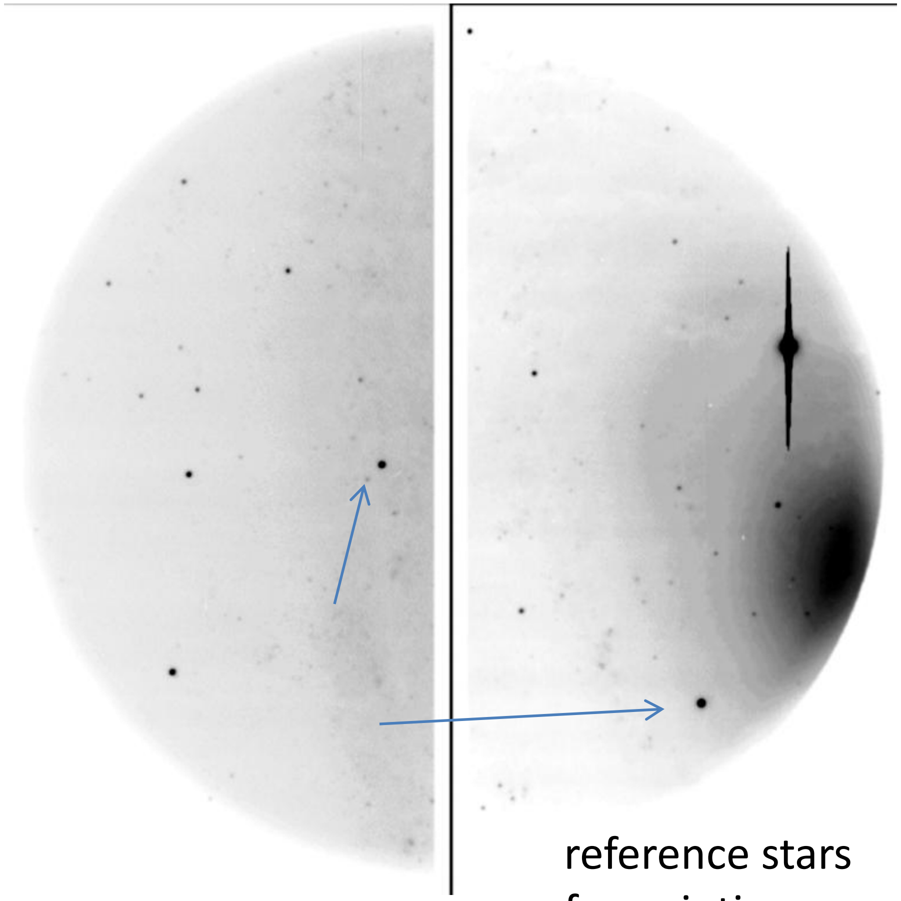
HST UV



- no slit-losses, but also no control over resolution
- confusion / spectral overlap

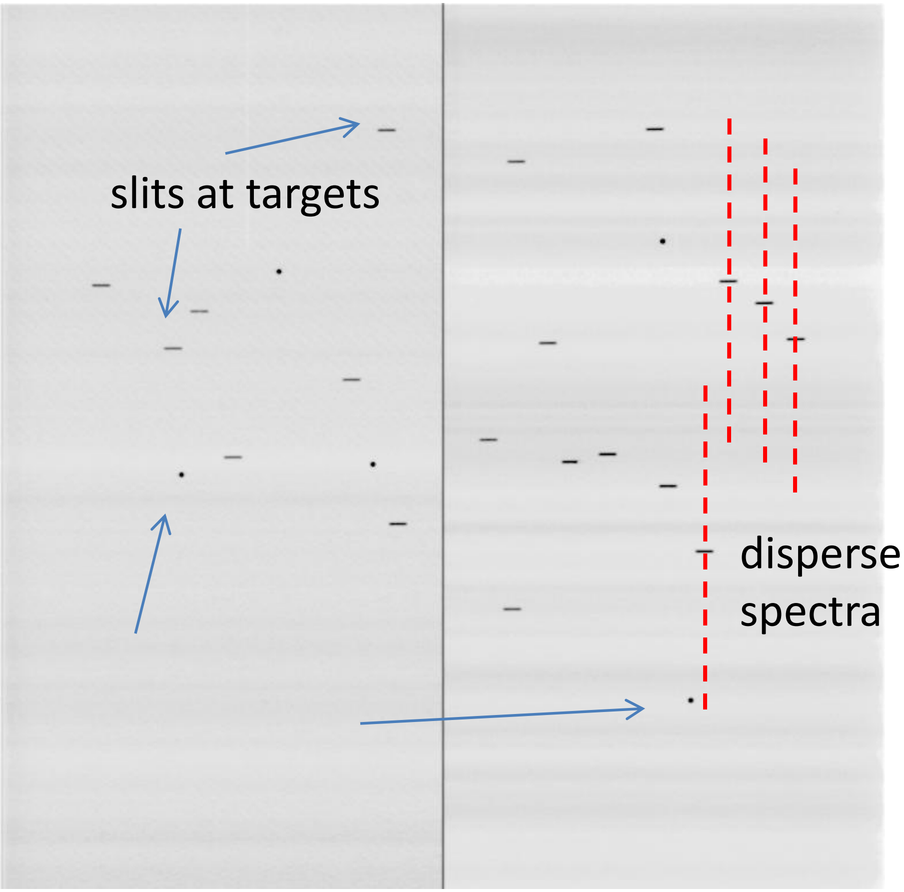
MOS slitmasks

Image of the FOV



reference stars
for pointing

Custom slitmask

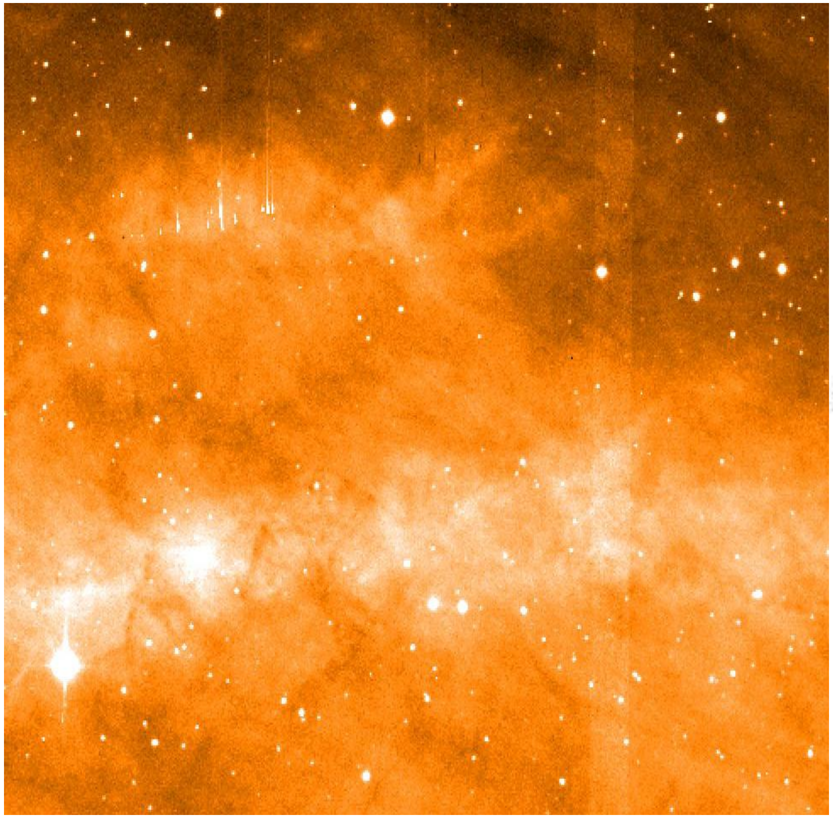


slits at targets

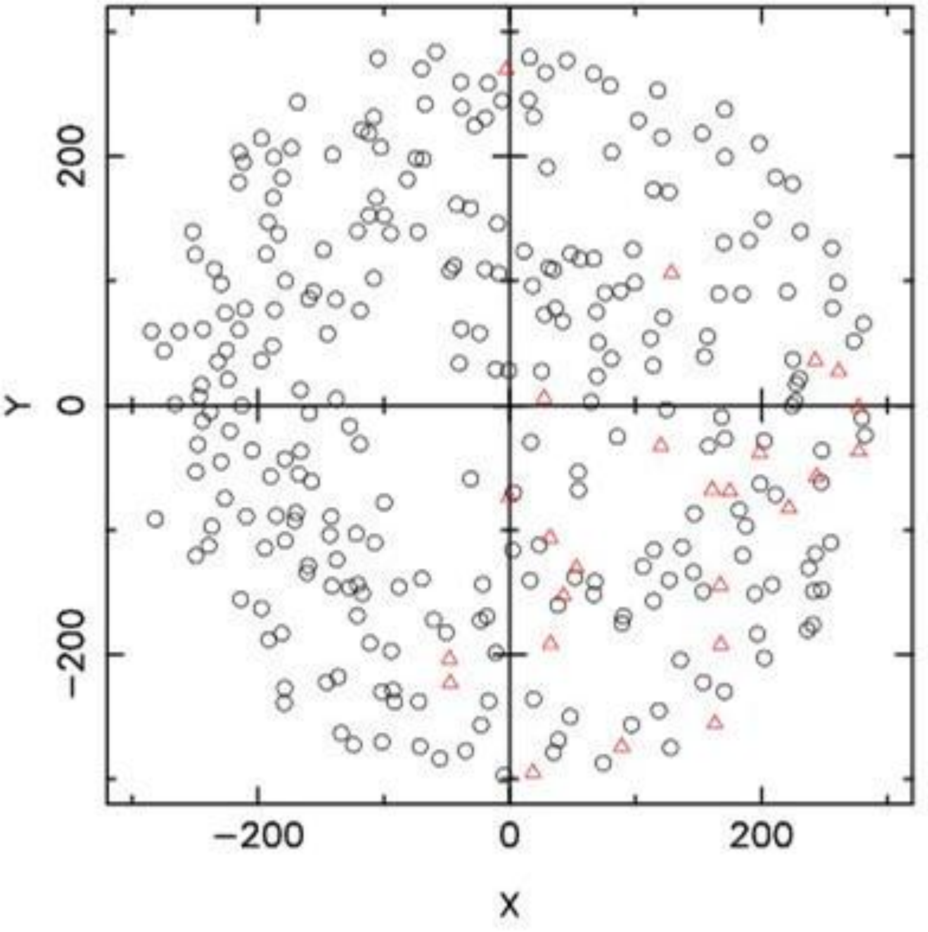
dispersed
spectra

Fiber MOS example

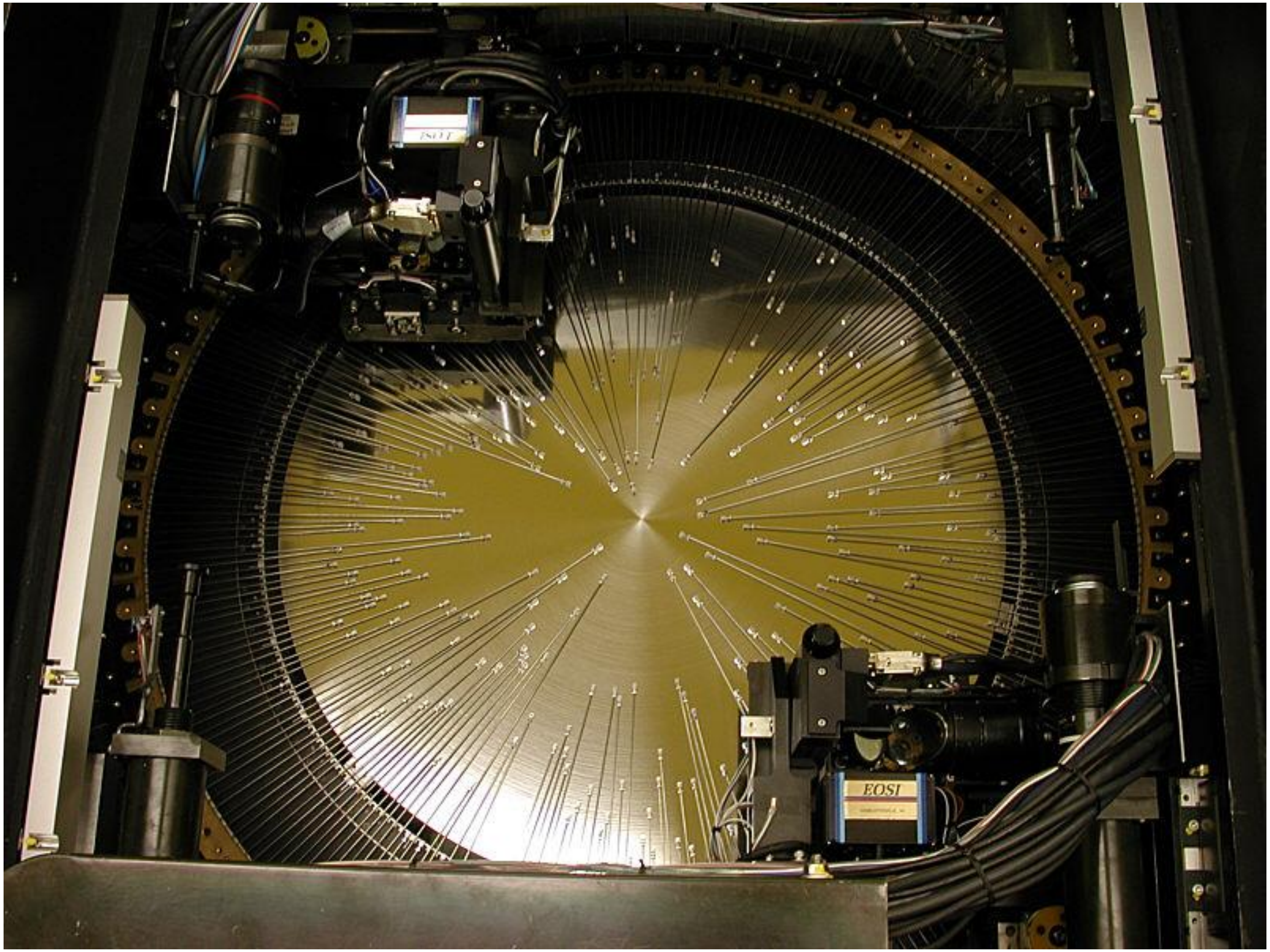
Pick your targets …



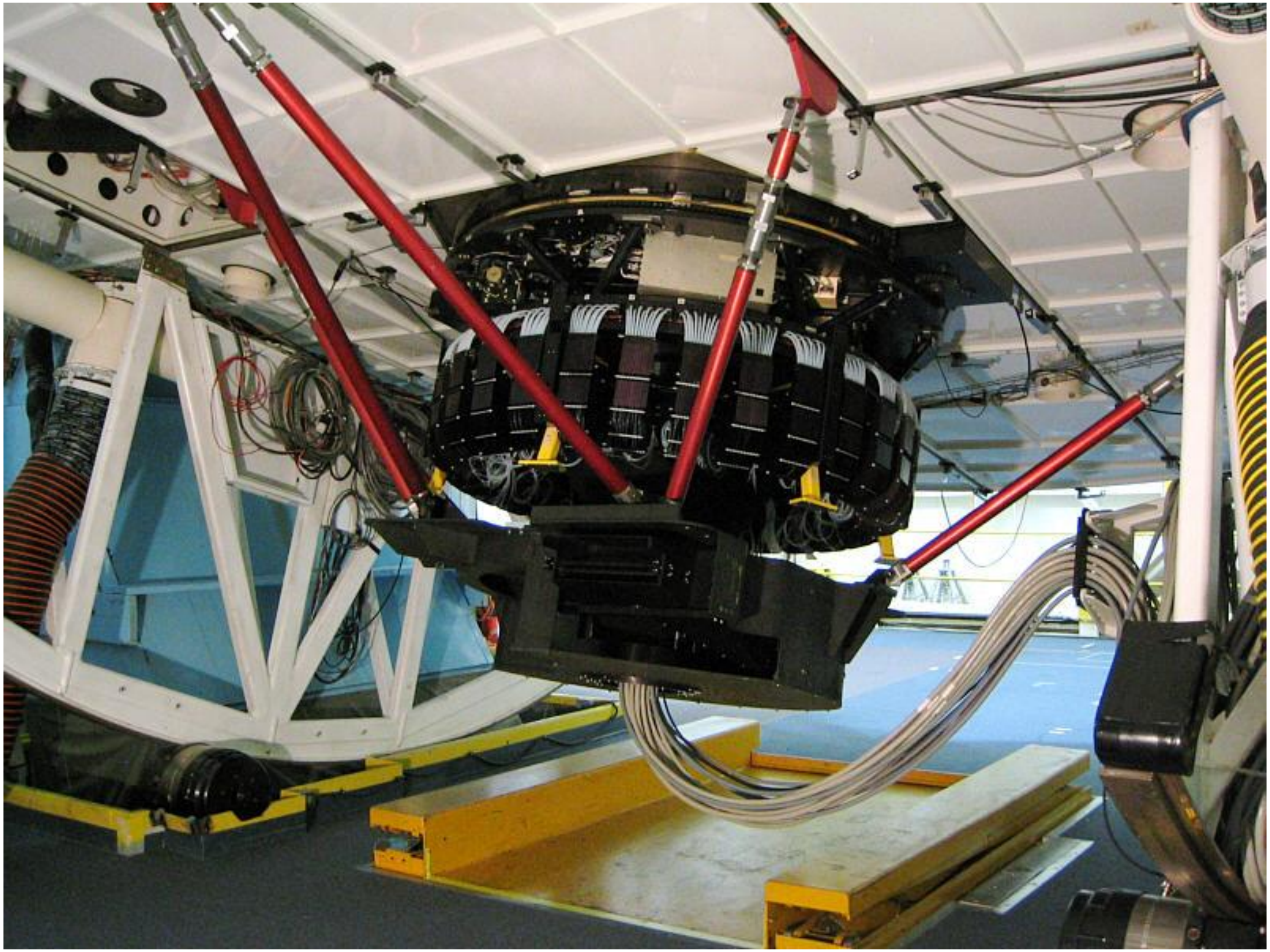
IPHAS star forming region



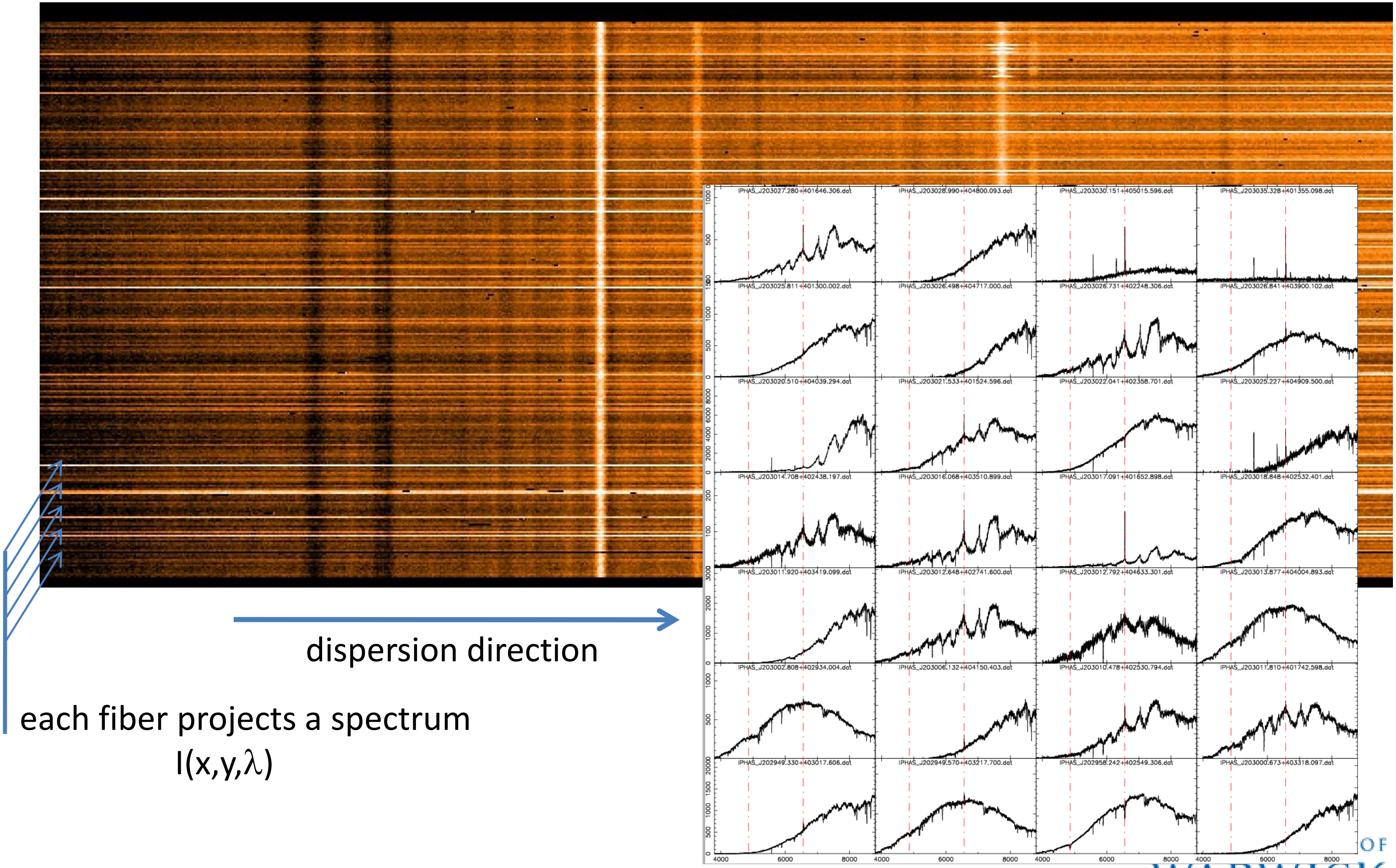
MMT HectoSpec



MMT HectoSpec



MMT HectoSpec



dispersion direction

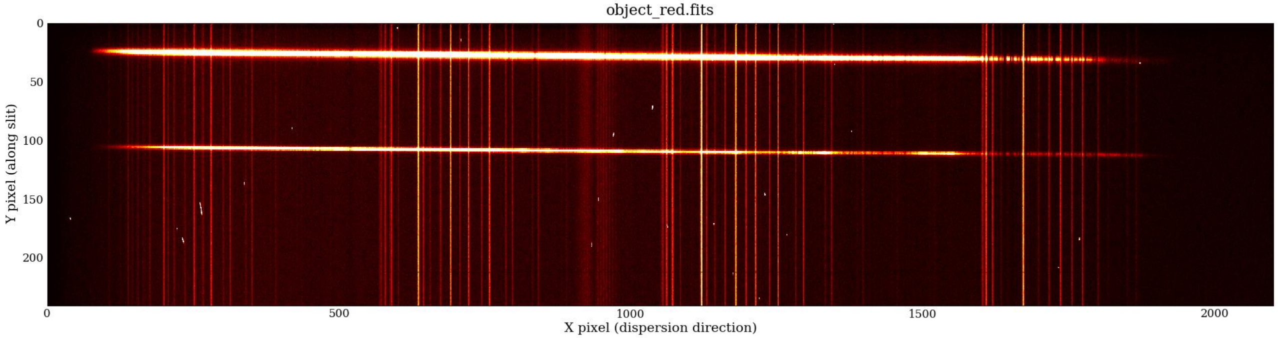
each fiber projects a spectrum
$I(x,y,\lambda)$

Summary: Apertures

- Slit-based spectra
  - 1D spatial profile
  - good sky subtraction
  - adapt slit-width and length to conditions and goals
  - Not many targets

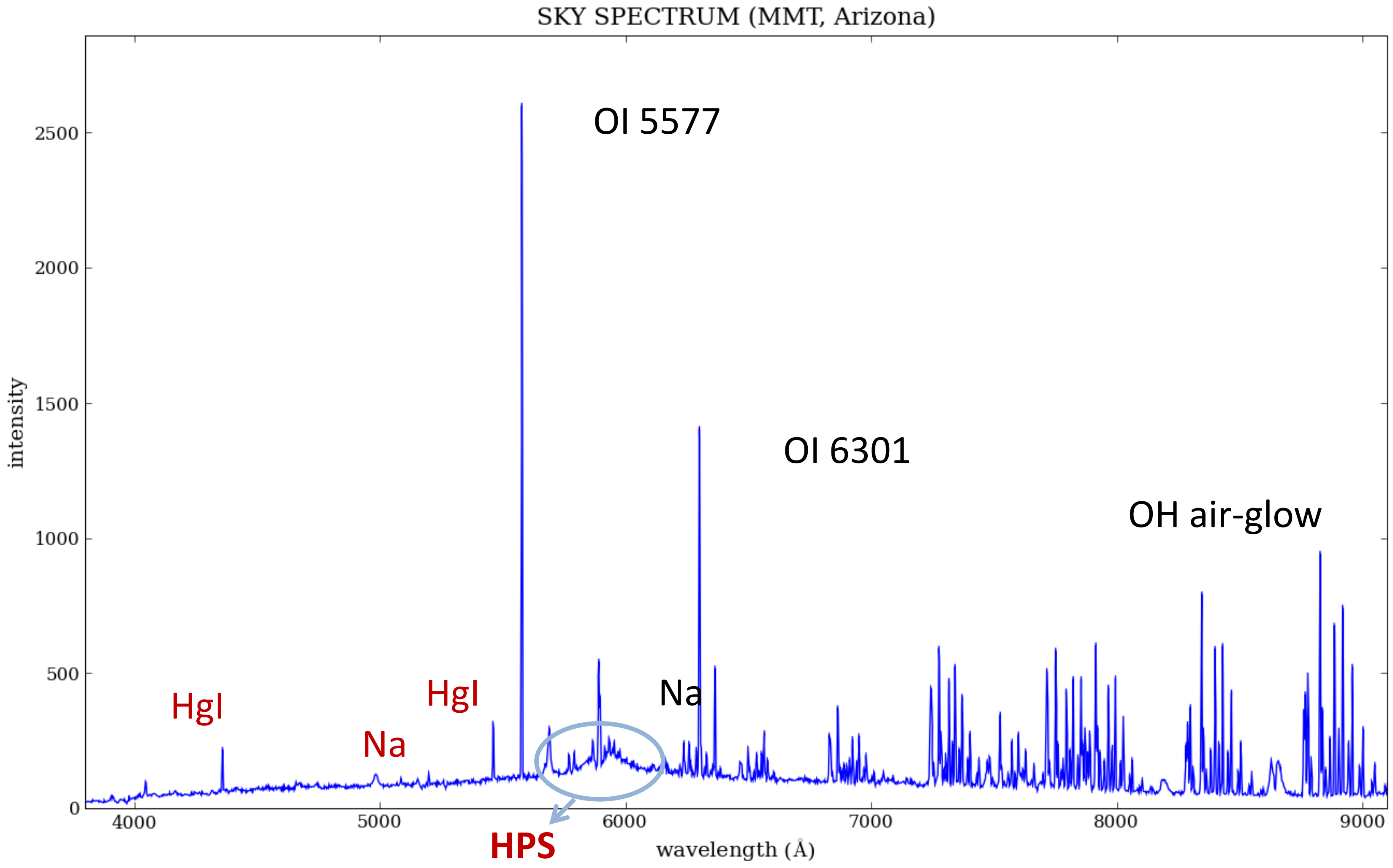
- Fiber-based spectra
  - No spatial information over fiber
  - Sky and target light combined
  - Sky subtraction relies on sky fibers that may be far away
  - Limited flexibility in terms of aperture size/geometry
  - Very flexible for mapping FOV ; MOS/IFU

Sky background

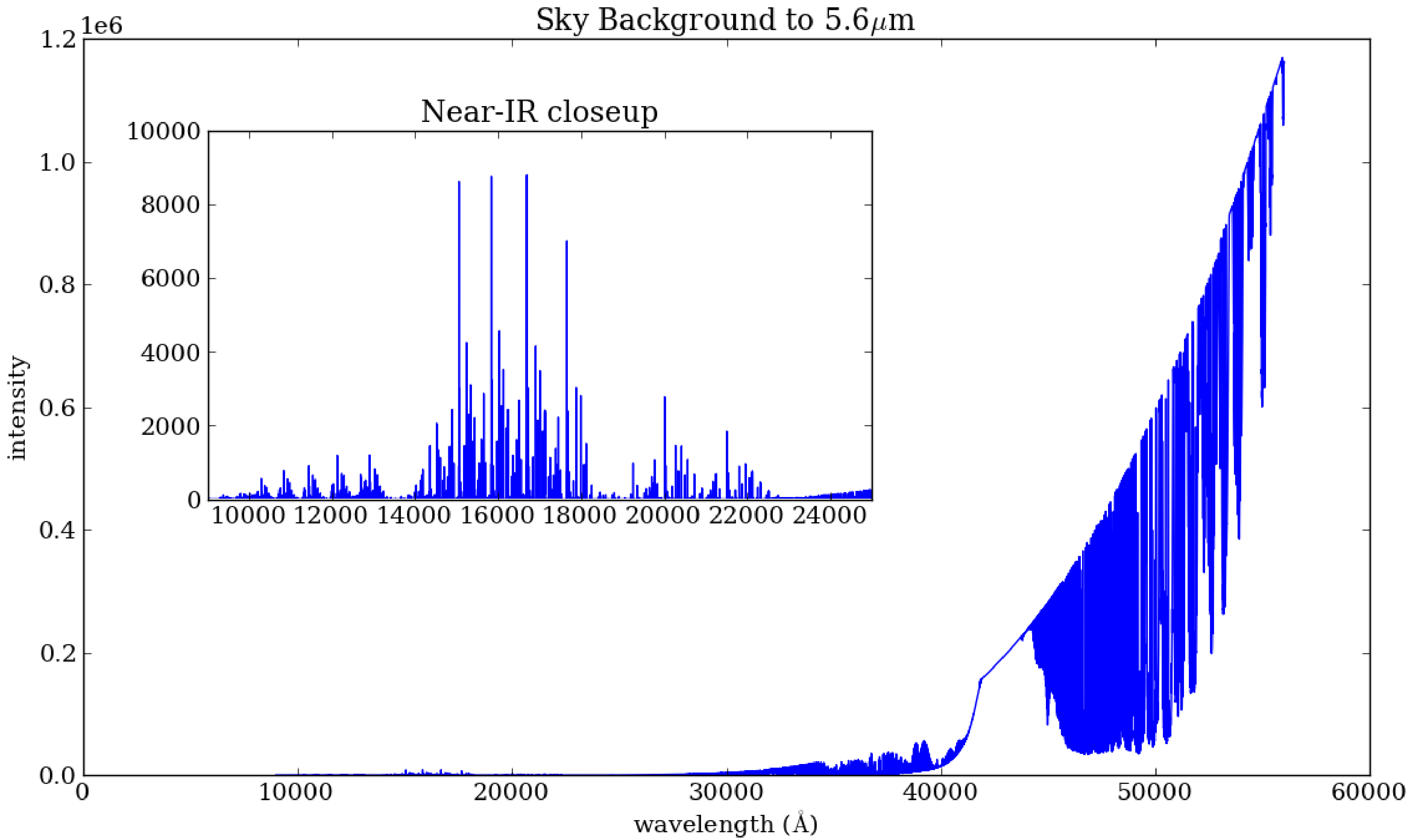


- Background has contributions from many sources;
  - Air glow ; strong discrete emission lines
  - Zodiacal light ; m_V ~ 22.-23.5
  - Sun/Moonlight
  - Aurorae
  - Light pollution
  - Thermal emission from sky, telescope and buildings
  - Non-resolved astronomical background
- Most of these affect photometry, but their wavelength dependence becomes key in spectroscopy

Optical Sky background

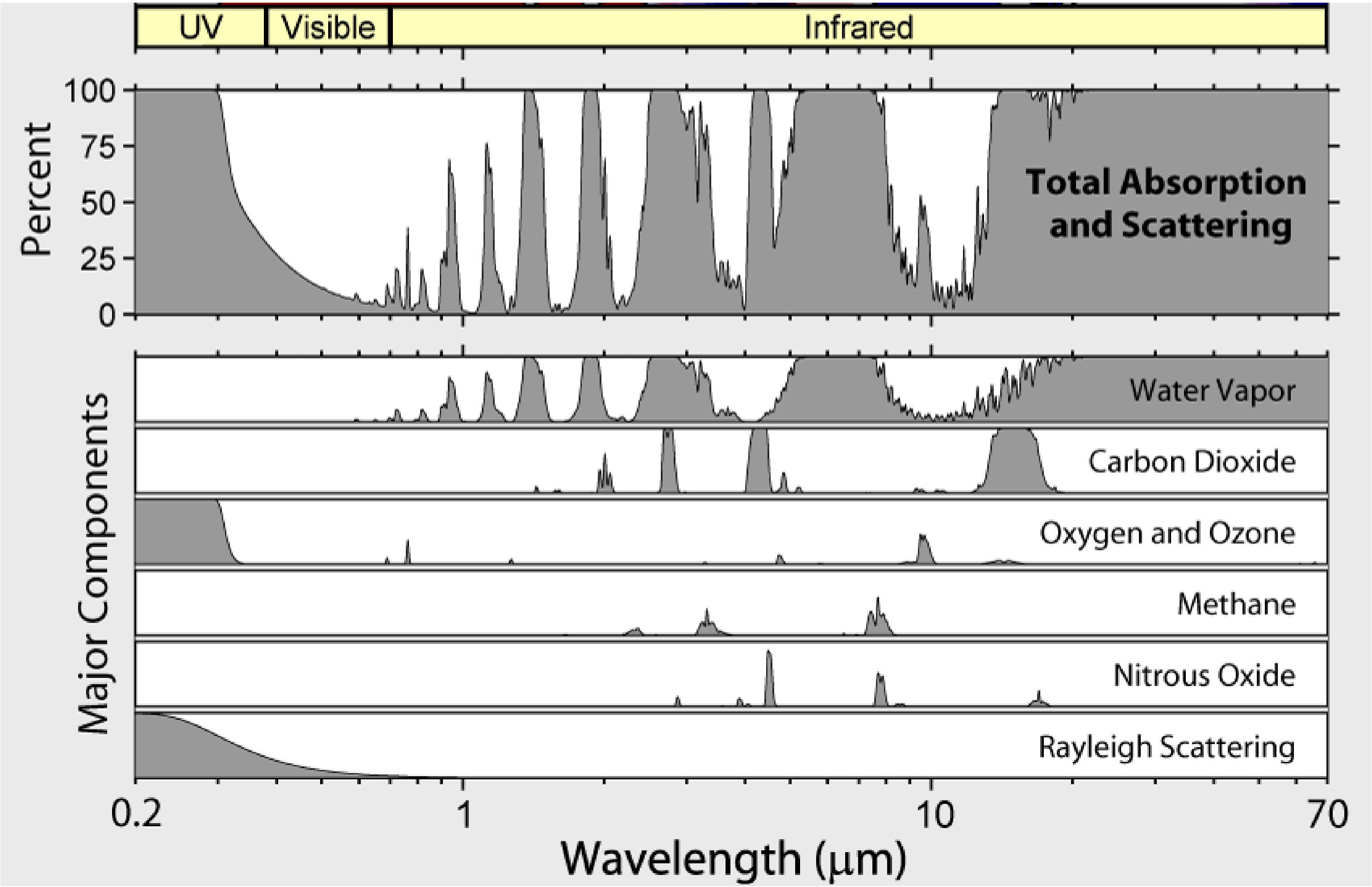


Infrared Sky background

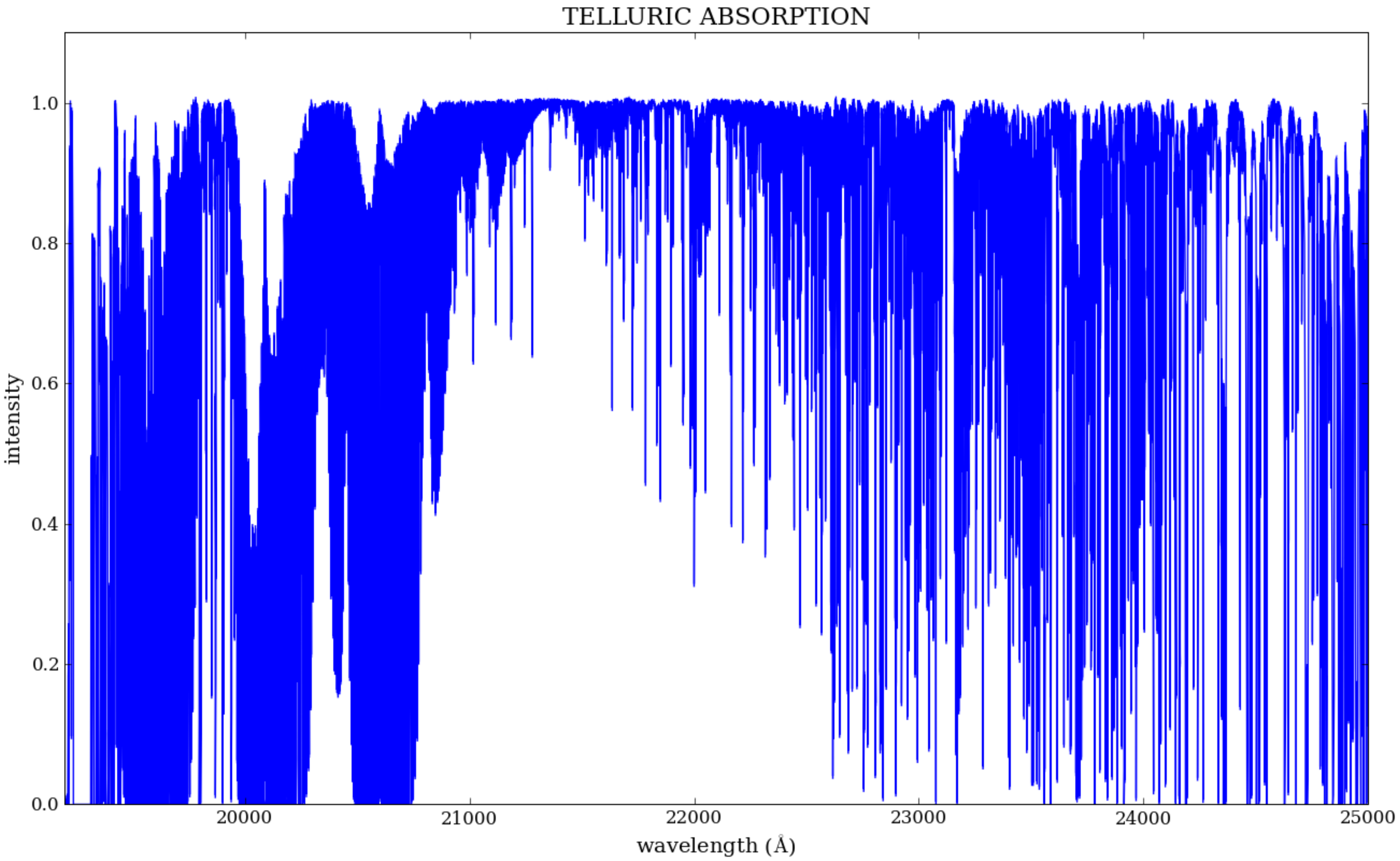


Atmospheric transmission

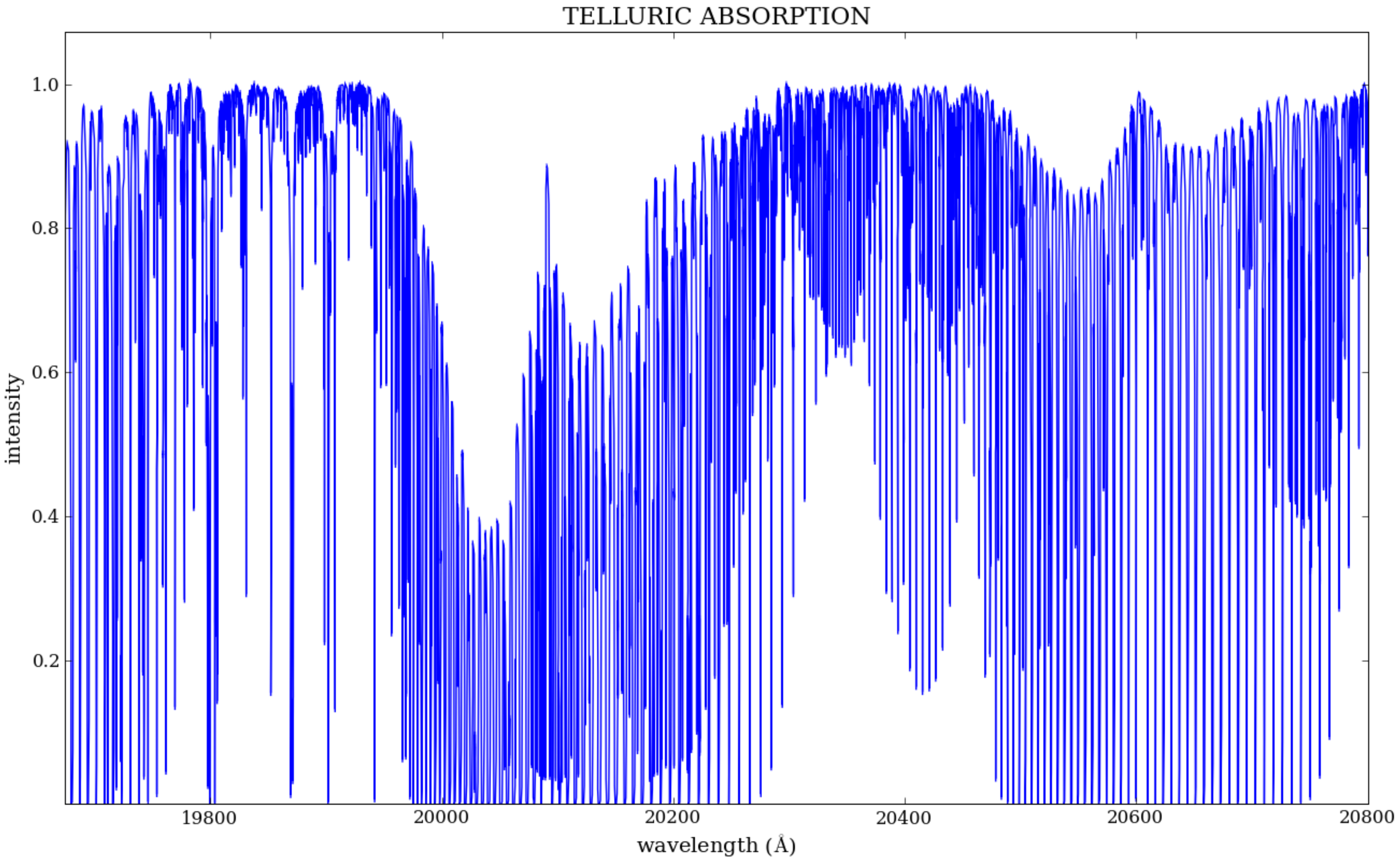
- Atmospheric transmission is strongly dependent on wavelength



Telluric absorption



Telluric absorption



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Summary: Background

- The optical/IR background is a composite of many sources
- All of these are dependent on wavelength and their strength varies with time
- Some correlate with lunar cycle, airmass, solar activity cycle etc., but many variations are erratic
- *Background subtraction needs to be done on a wavelength by wavelength basis* and ideally is measured simultaneously with the object exposure
- Some parts of the spectrum may be background dominated, others not ; *error propagation*
- Infrared is chiefly complicated by high overall background levels plus many sky lines and telluric features
- Recent detector improvements most noticable in IR with larger, cleaner arrays of comparable quality of optical devices

Atmospheric dispersion

- Differential atmospheric refraction will deflect a source by an amount that is dependent on wavelength

  [the index of refraction is a function of wavelength]

- A point source position on the sky is dependent on wavelength!

- The displacement is towards the zenith and larger for shorter wavelengths

- This obviously affects acquisition and slit-angle strategies when obtaining spectroscopy

Atmospheric dispersion

- Index of refraction: $n(\lambda, T, p, f)$

  wavelength, temperature, pressure, water vapor

- Angle displacement: $\Delta R = R(\lambda_1) - R(\lambda_2) \propto \Delta n(\Delta\lambda) \tan z$

  zenith angle
  (airmass)

- Some example shifts (") relative to image at 5000Å :

airmass	3000Å	4000Å	6000Å	10000Å
1.00	0.00	0.00	0.00	0.00
1.25	1.59	0.48	-0.25	-0.61
2.00	3.67	1.10	-0.58	-1.40

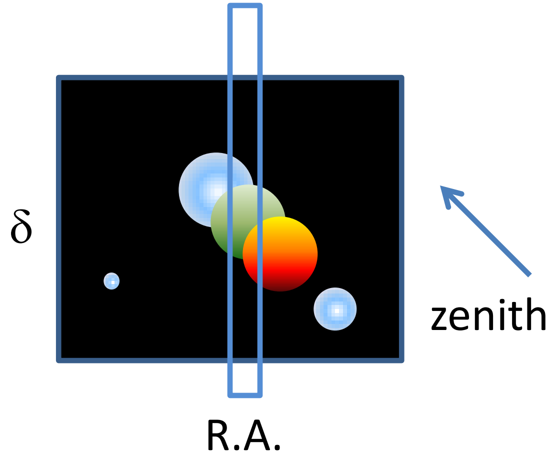
Atmospheric dispersion

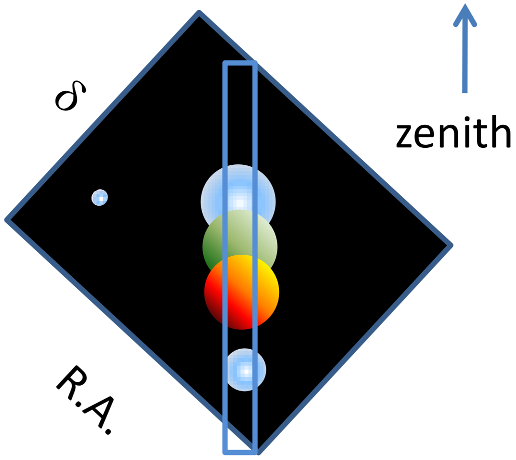
- Make sure you acquire the target at a wavelength relevant for your spectral range [TV filter]

- Differential refraction will mean differential slit-losses': can only centre object at one λ

- If the slit is vertical (relative to horizon/zenith line), differential refraction will occur purely along the slit

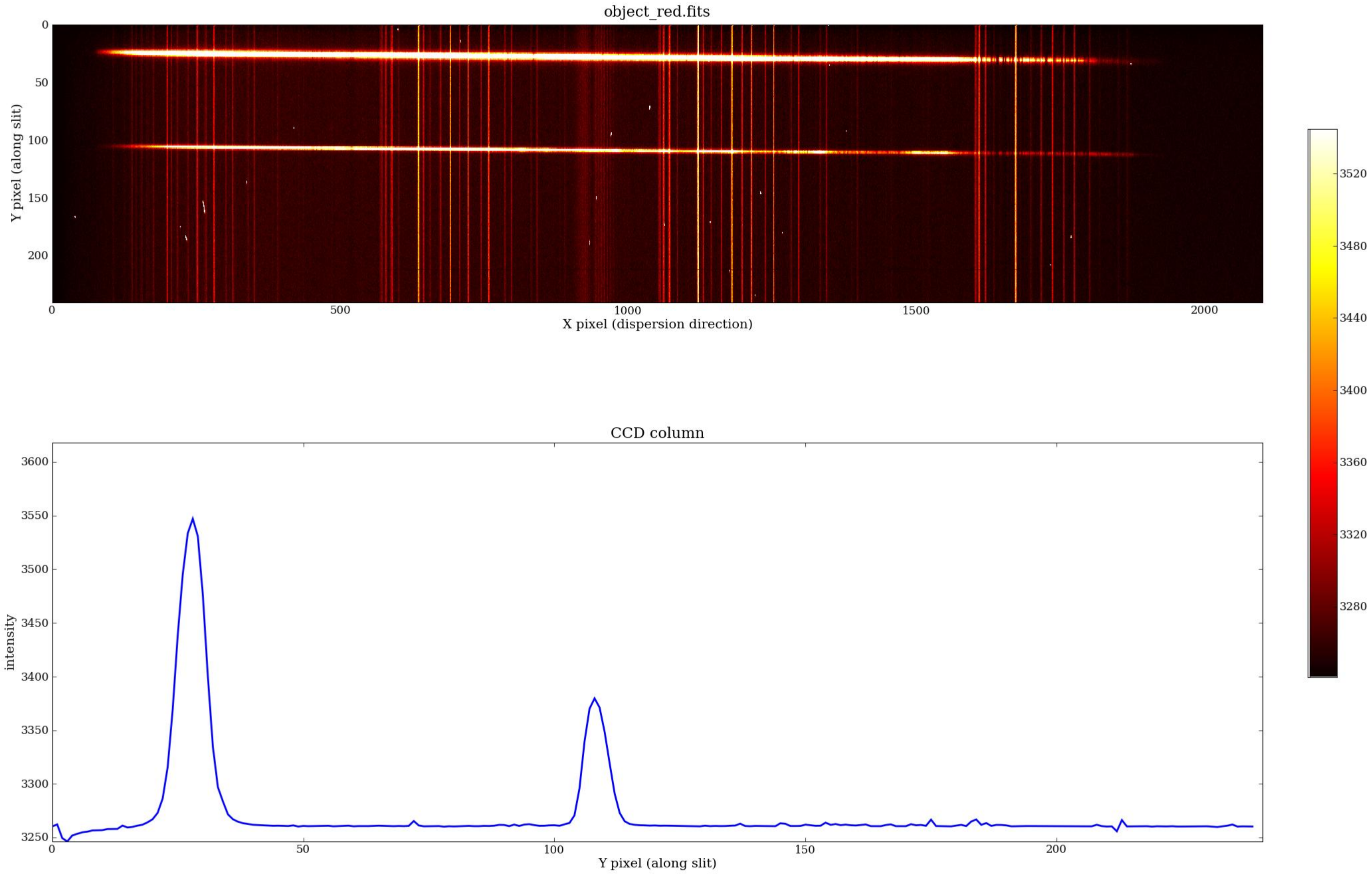
- This means that the slit P.A. (sky angle) must change with time. The vertical P.A. is the *parallactic* angle





Extracting the spectrum

We will use the long-slit example as our template, multiplexed configurations whether for multiple orders or multiple objects is in 1st order just multiplexing single object spectral extraction



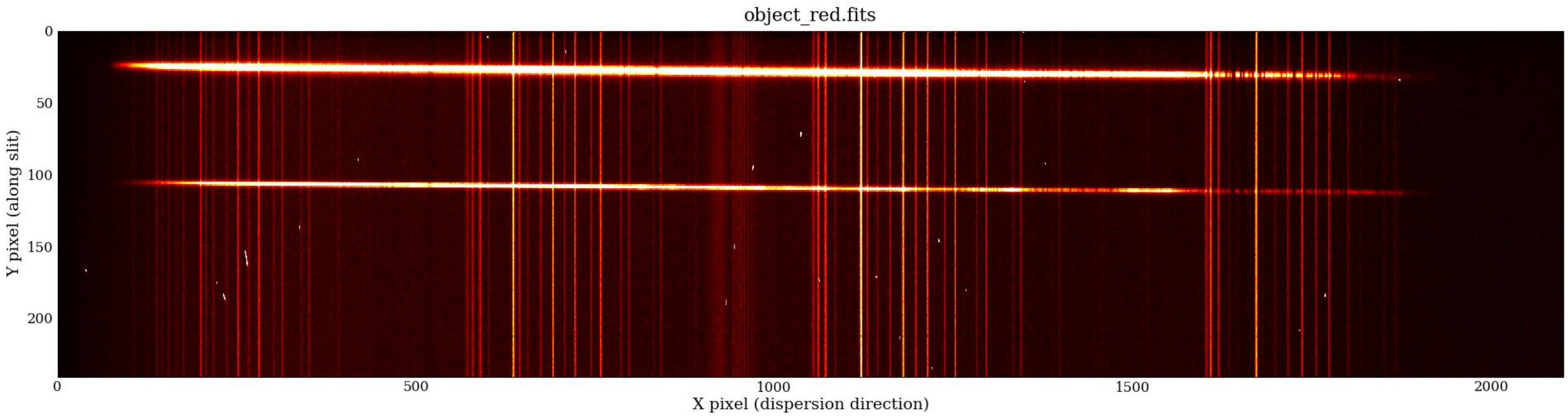
Extracting the spectrum

signal = (source + background) – background@source

$$\mathbf{S}(\lambda) = \Sigma\, I(y,\lambda)\, p(y) - \Sigma\, I(y,\lambda)\, b(y)$$

object profile weight

sky profile weight

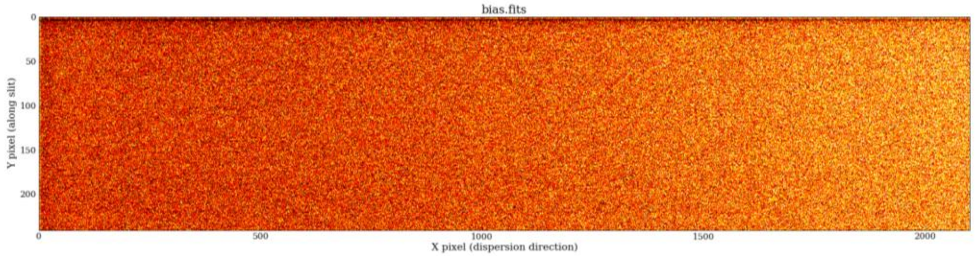


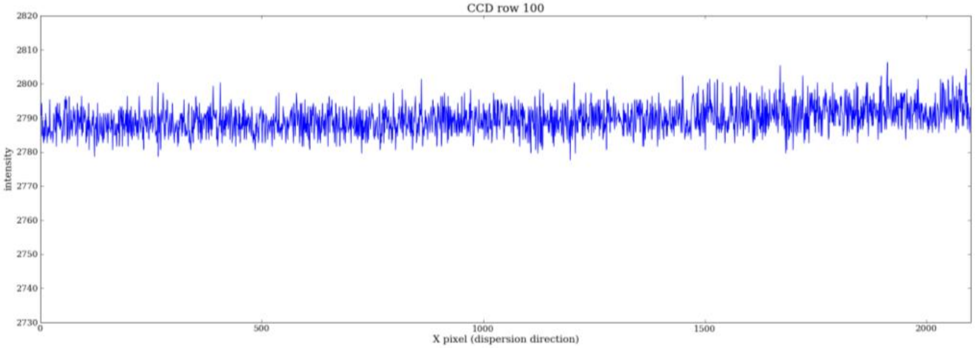
y ↓

λ →

Detector corrections ; BIAS & FLAT

- CCD corrections need to be performed first

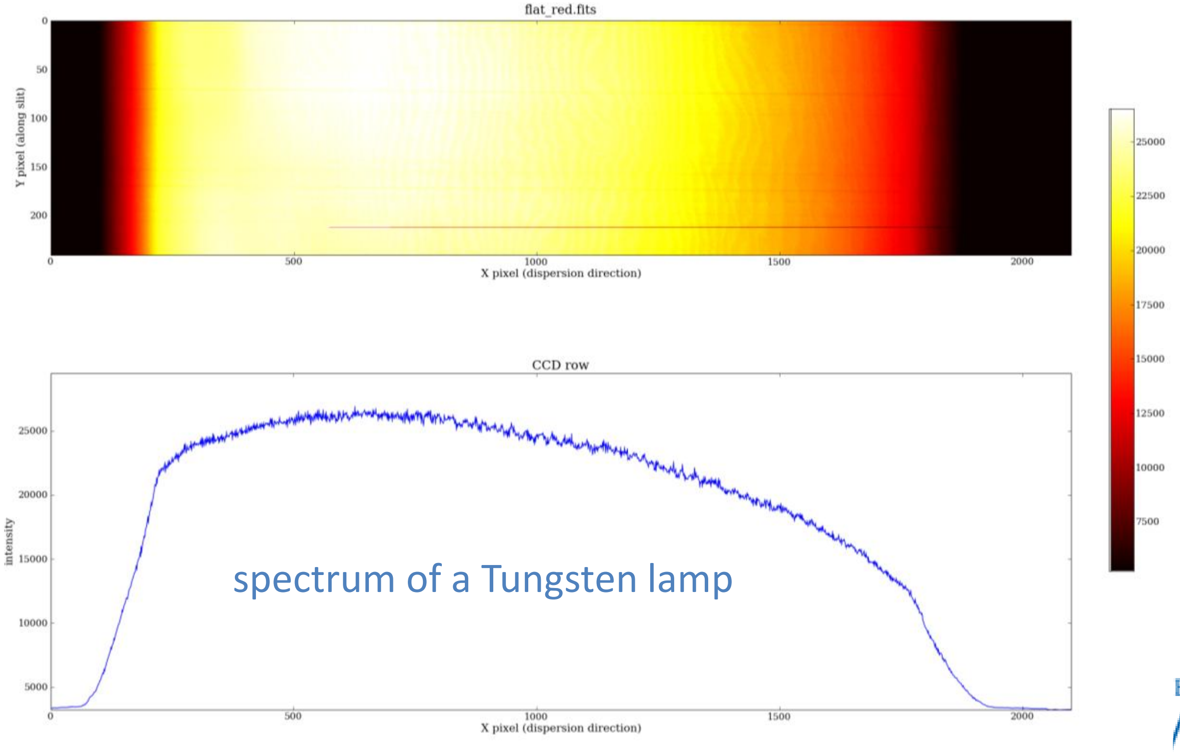




- BIAS/DARK can be treated in the same way as for imaging
  - Determine importance of dark current
  - Use a large median stack of bias frames
  - Master-bias versus overscan
  - Measure readout-noise

Detector corrections ; FLAT

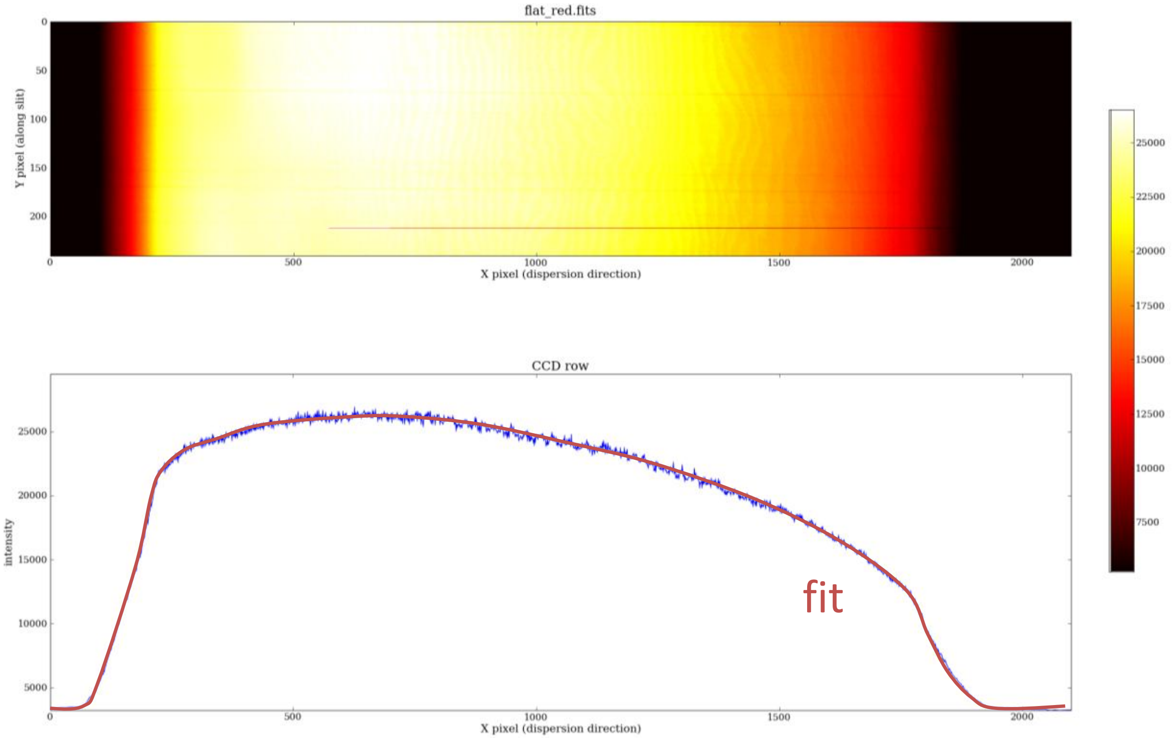
- Flat-fielding is probably one of the trickier steps
  - Uniform illumination along the slit
  - Uniform illumination along the dispersion direction
    - Need a light source with a smooth/simple spectrum



spectrum of a Tungsten lamp

Detector corrections ; FLAT

- The trick is to remove the spectrum of the calibration lamp and normalise the flatfield
  - Not always possible to distinguish between broad CCD sensitivity features and features in the lamp



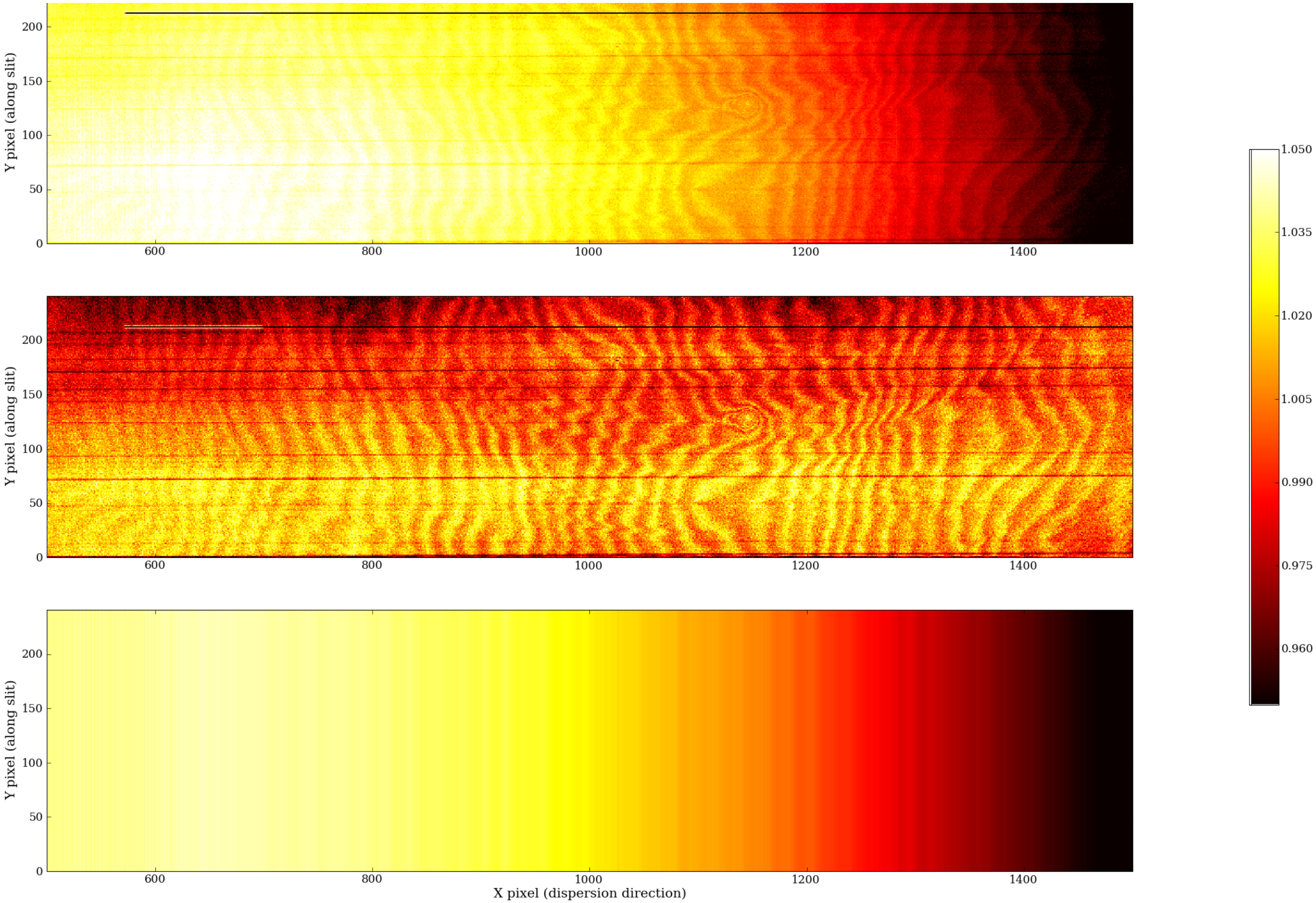
fit

Detector corrections ; FLAT

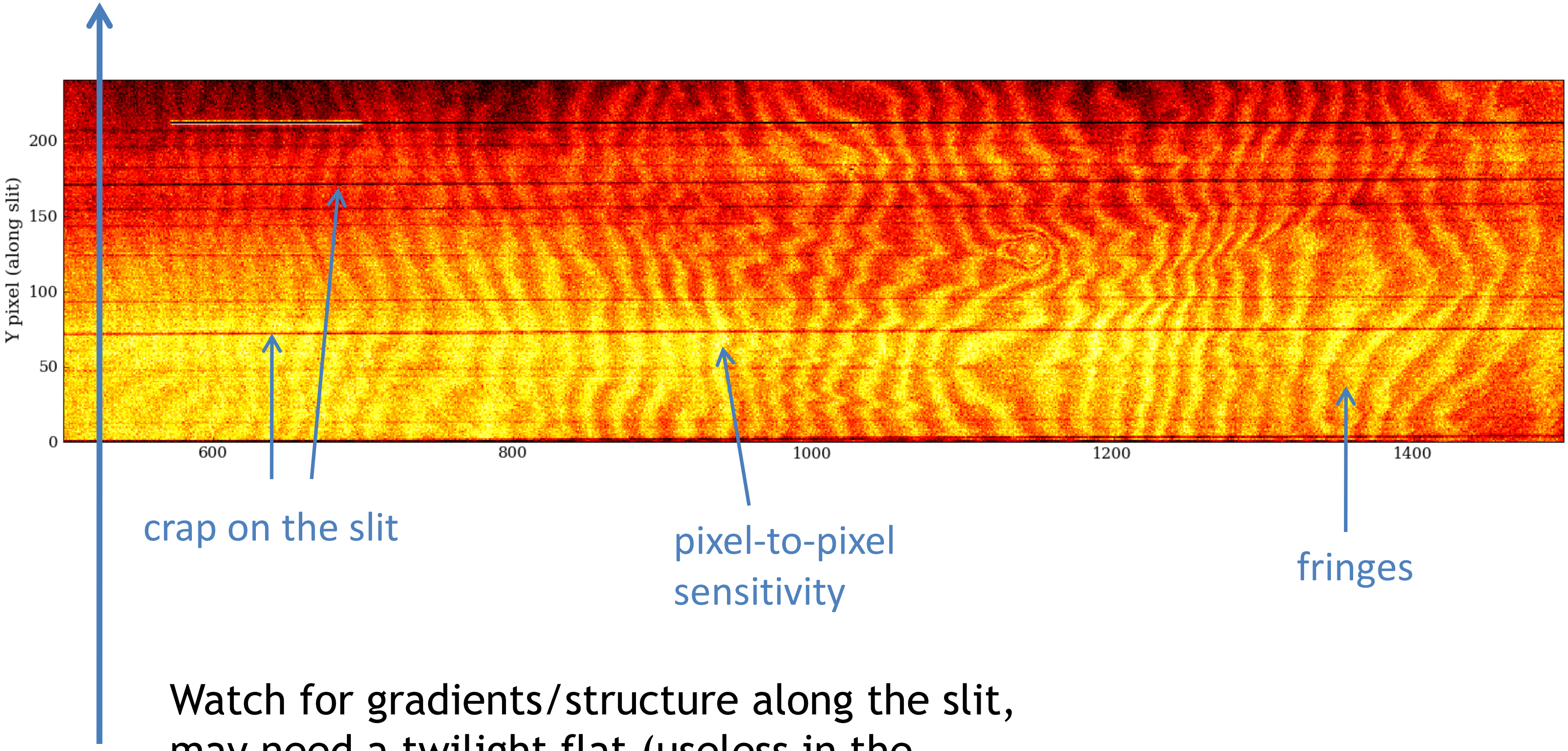
raw flat

normalised

corrected flat



Detector corrections ; FLAT



crap on the slit

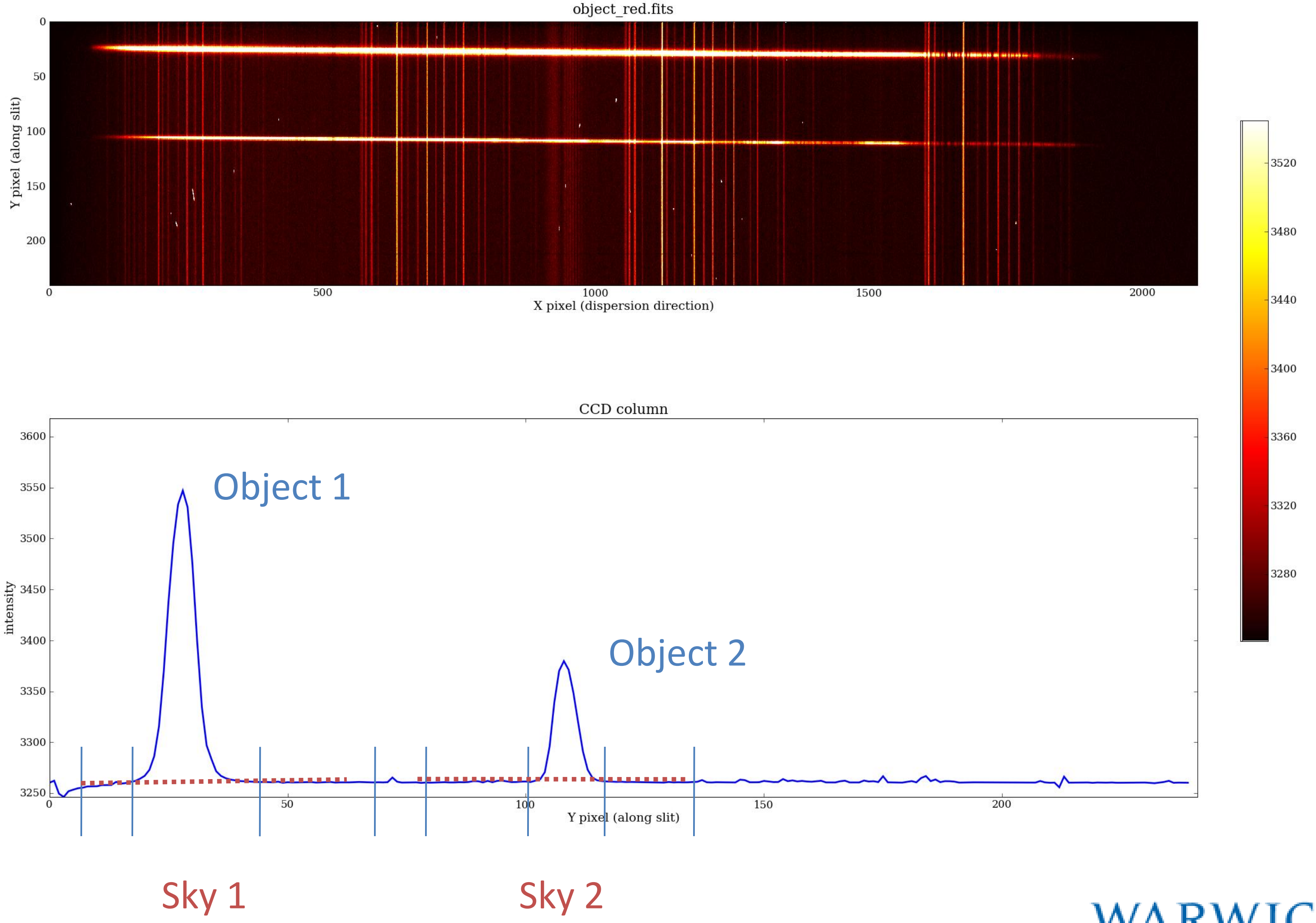
pixel-to-pixel sensitivity

fringes

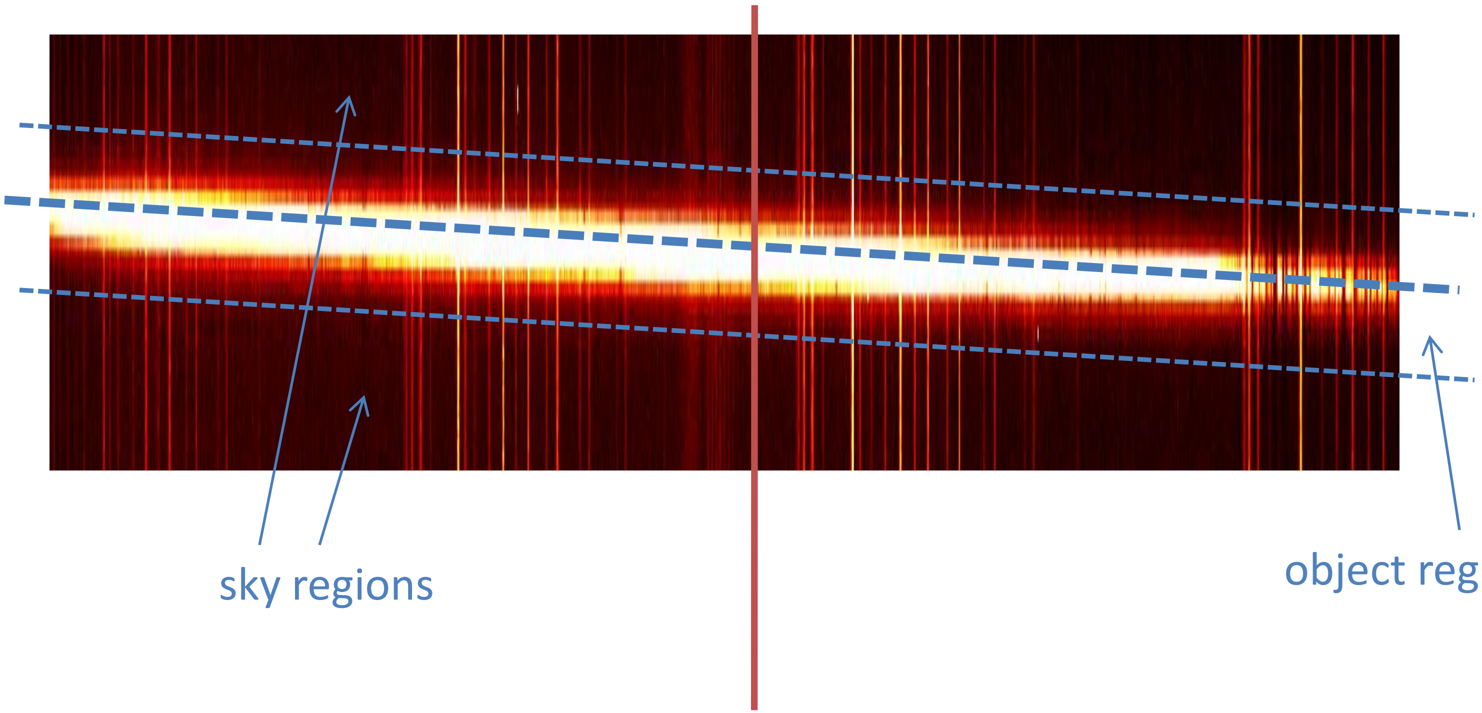
Watch for gradients/structure along the slit, may need a twilight flat (useless in the spectral direction) to correct spatial profile

make sure slit width, grating angle, filters are all in place, replicating as much the light path to the science frames

Locating the object and sky



Tracing and skyfit



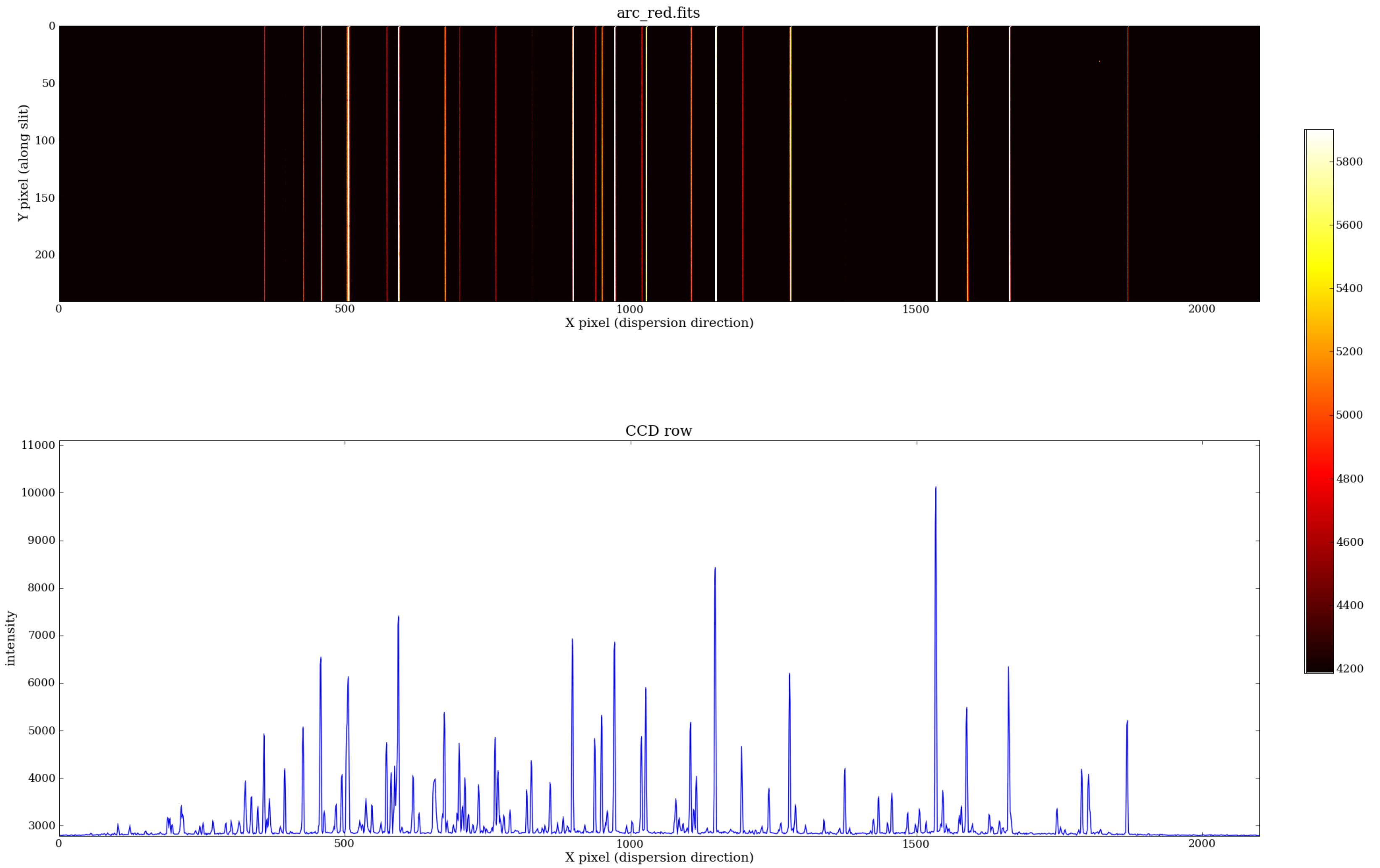
sky regions

object regions

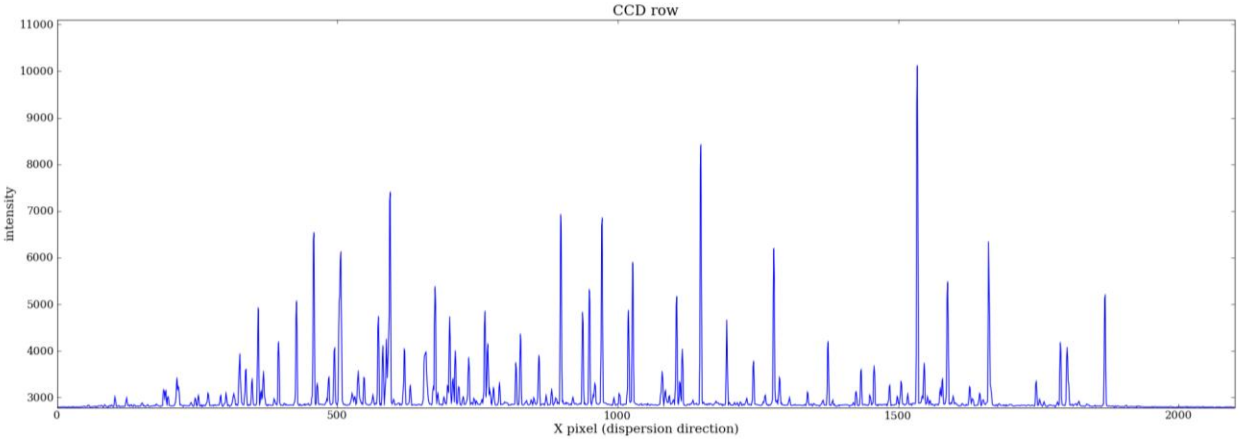
Evaluate sky background at each wavelength by considering the sky pixels around the shifting object
[if you are lucky, sky lines are well-aligned with the CCD columns]

This gives you the *fitted* background value **at the location of the object**

ARC Calibration ; from x to λ



Calibrating ; from x to λ



- Emission line lamps are used for translating CCD pixel coordinates to wavelengths (e.g. Ar, He, Ne, Cu)

- These **arc** exposures are extracted using the same profile weights as for the object to ensure any tilt/rotation is the same

- Reference line lists are used to identify line wavelengths

- The line positions are fitted with a (polynomial) function to retrieve the dispersion relation $\lambda=f(x)$

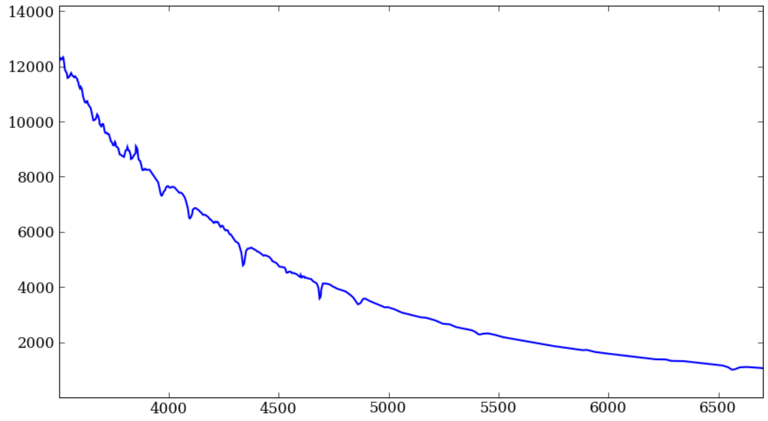
- Regular arcs need to be obtained since flexure in the telescope/spectrograph system causes drifts as a function of time and position of the telescope

- Typically the resultant wavelength scale should be good to a fraction of a pixel (can measure the centroid of a spectral feature to very high precision given sufficient S/N, well below the spectral resolution)

Calibrating : from counts to flux

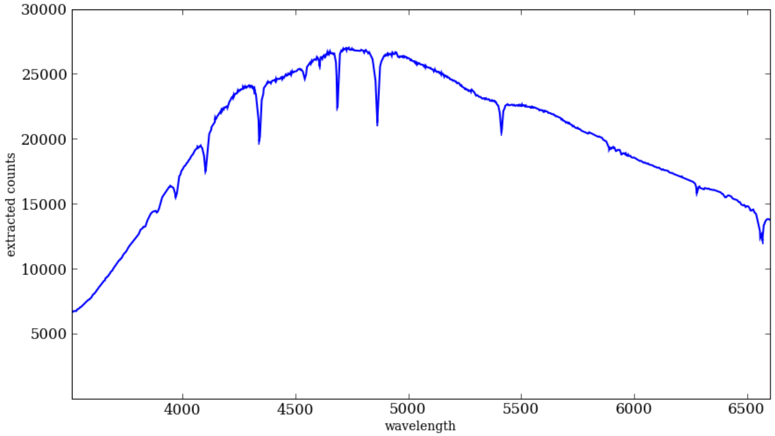
- Spectro-photometric standard stars (flux standards) have measured fluxes as a function of wavelength across specified band-passes

known fluxes



- Observe flux star with a wide slit at low airmass to ensure all flux is collected

- Response function corrects detected counts into flux units



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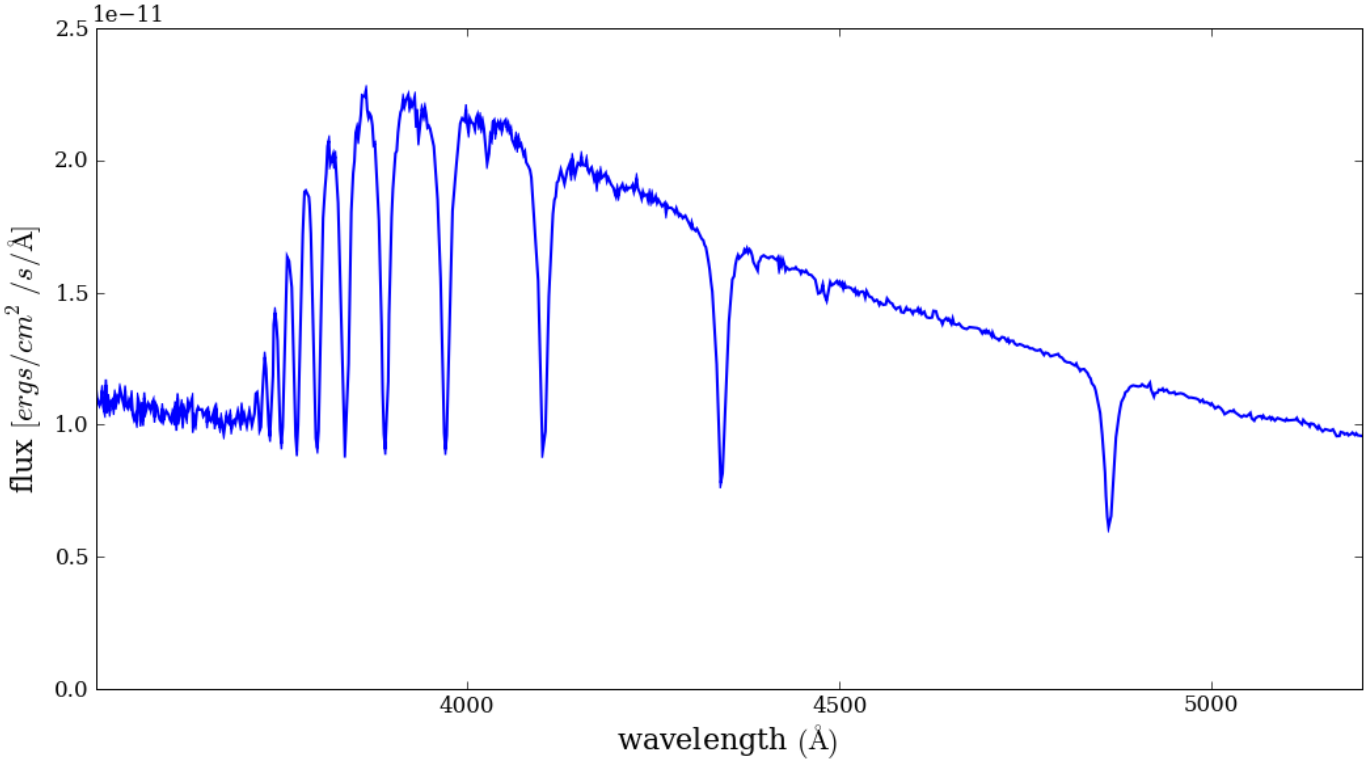
'Final' product



- Air/vacuum wavelengths
- Velocity rest-frame ; geocentric frame
- Extinction/telluric correction
- Now the fun can begin : velocities, abundances etc.

Assignment

- You wish to acquire an optical spectrum of an object with R magnitude of 20.3 that resembles a G0 star with the VLT and the FORS2 spectrograph

  `http://www.eso.org/sci/facilities/paranal/instruments/fors/index.html`

- A S/N of 20 is needed with a resolution of ~1.8 Angstrom to measure the Hydrogen-beta line

- Describe what instrument configuration you would need to use (grism choice, slit, filters) and how long the exposure would need to be for the above S/N [hint: ESO offers a Exposure Time Simulator]

- Discuss the impact of the moon phase and readout noise on the achieved S/N