Spectroscopy techniques

[photometry at many wavelengths]

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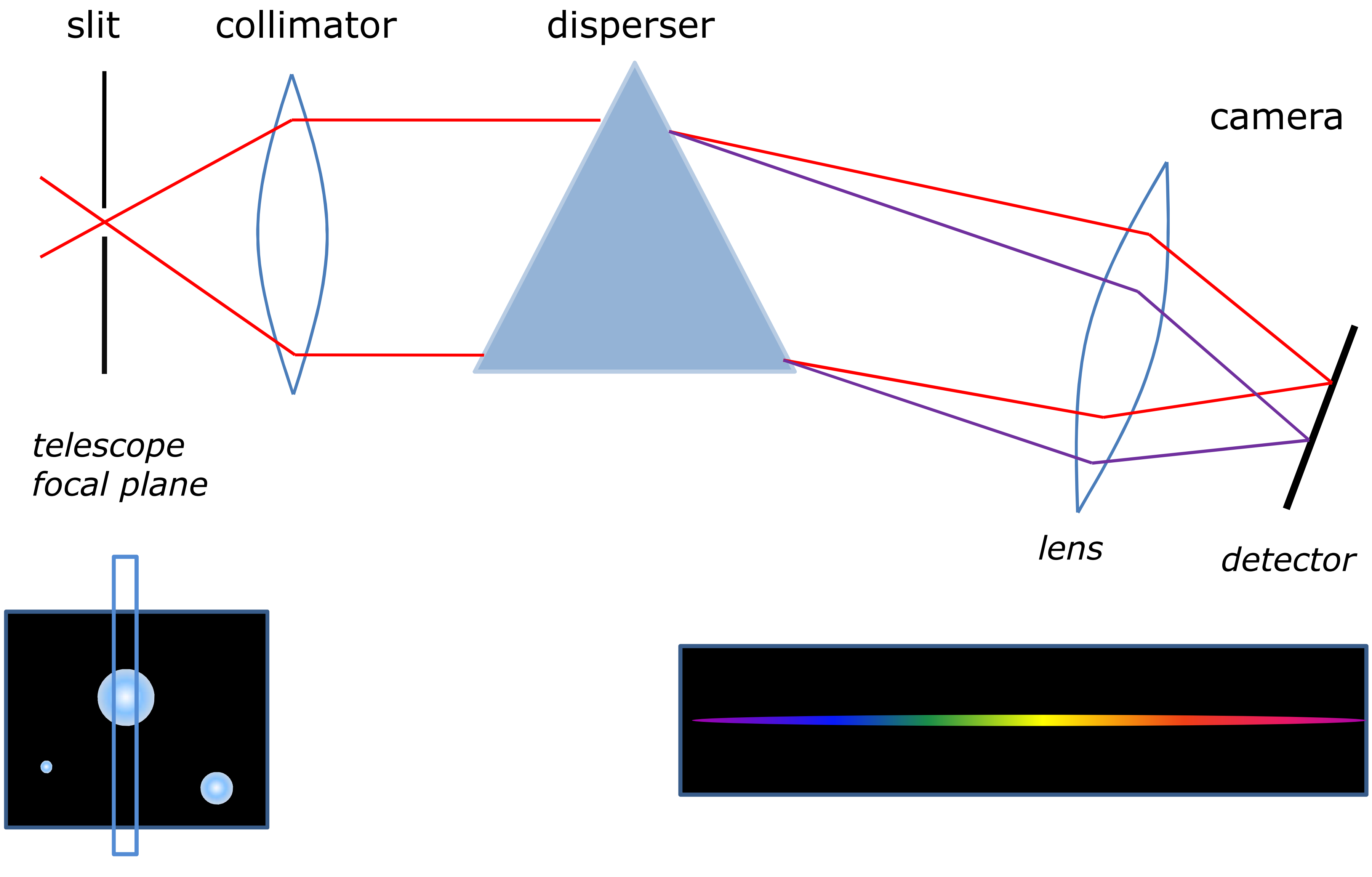
The basic spectrograph



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

Gratings

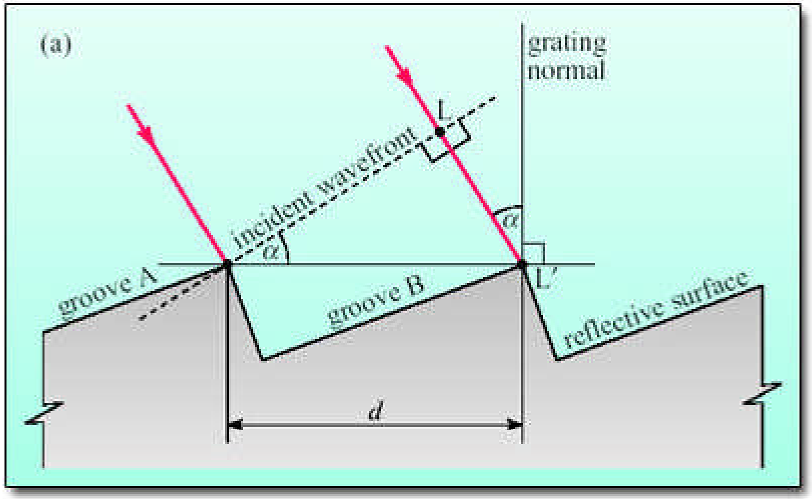
- Grating equation

  $n\lambda$ = d (sin β + sin α)

  n = order

  d = groove spacing

  α,β = angles relative to blaze



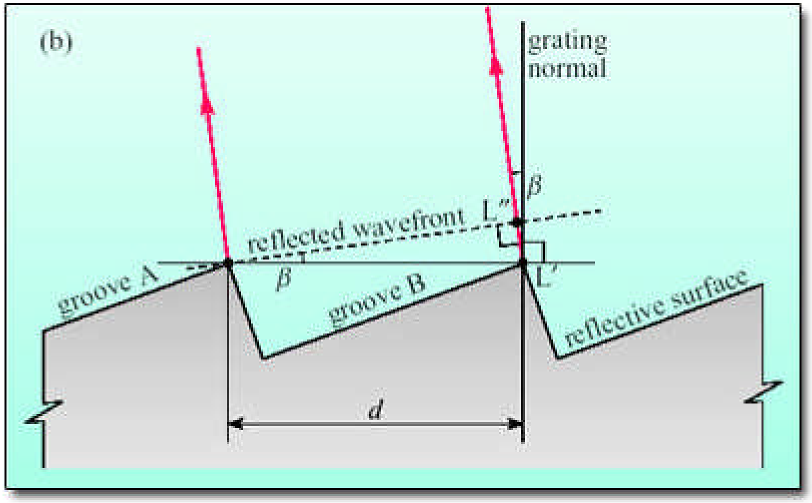
- Dispersion

  $d\beta/d\lambda$ = n / (d cos β)

  constant dispersion for given groove spacing and order

  watch for order overlap

  $n\lambda_1 = (n+1)\lambda_2$



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* = λ / Δλ**

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

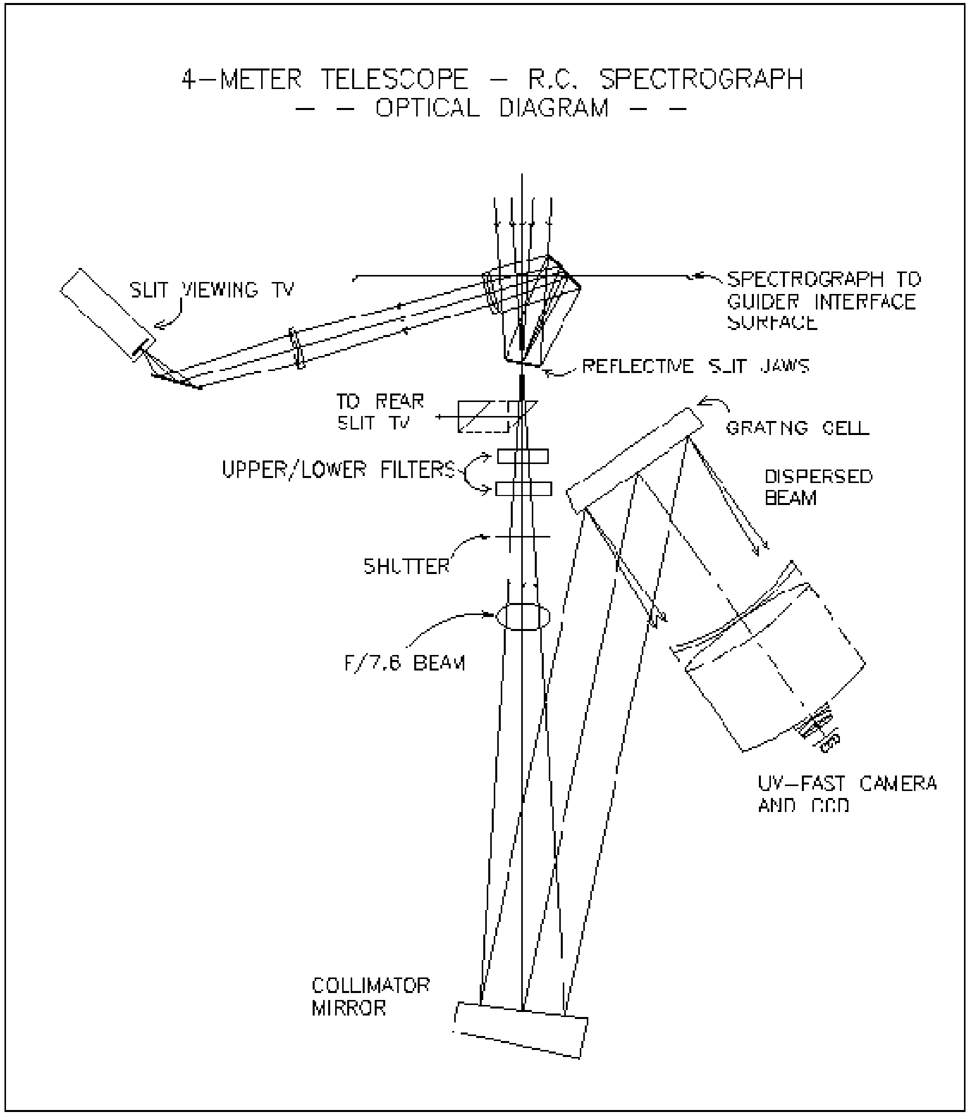
- The detector must sample this physical scale accordingly [at least two pixels per resolution element]

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

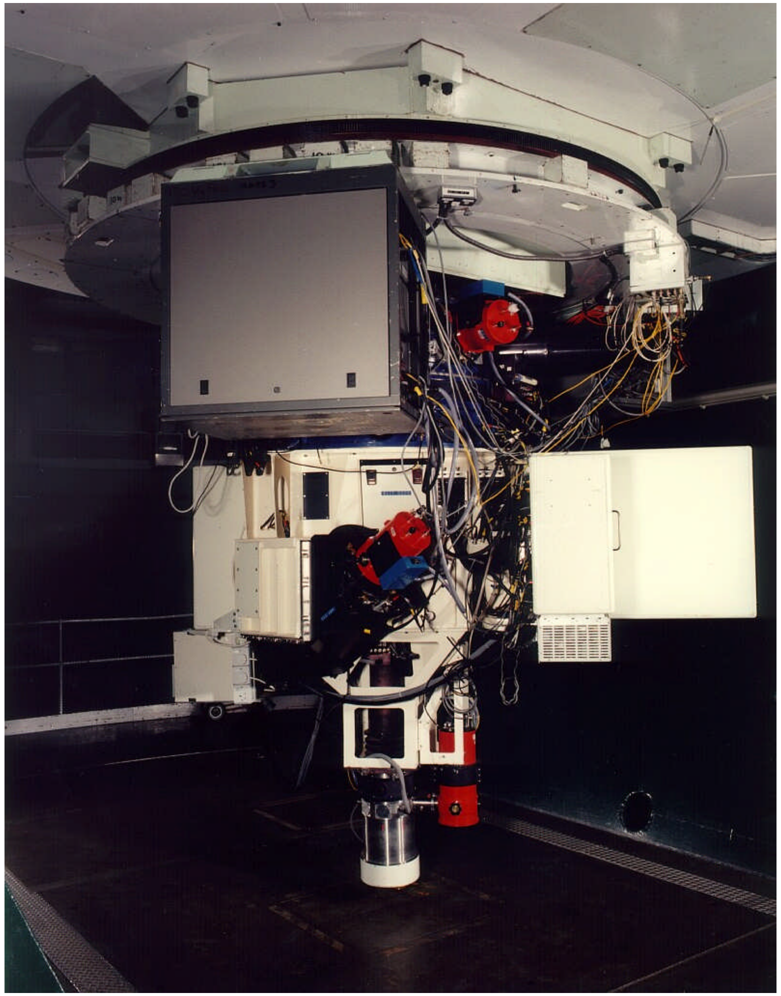
  600 groove/mm grating projects to 33Å/mm on detector plane
  The spatial scale of the detector plane is 14.9”/mm
  CCD detector has 13.5 micron pixels

  - 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 = Δλ/λ = 5,618 at 5000Å

Some real spectrographs

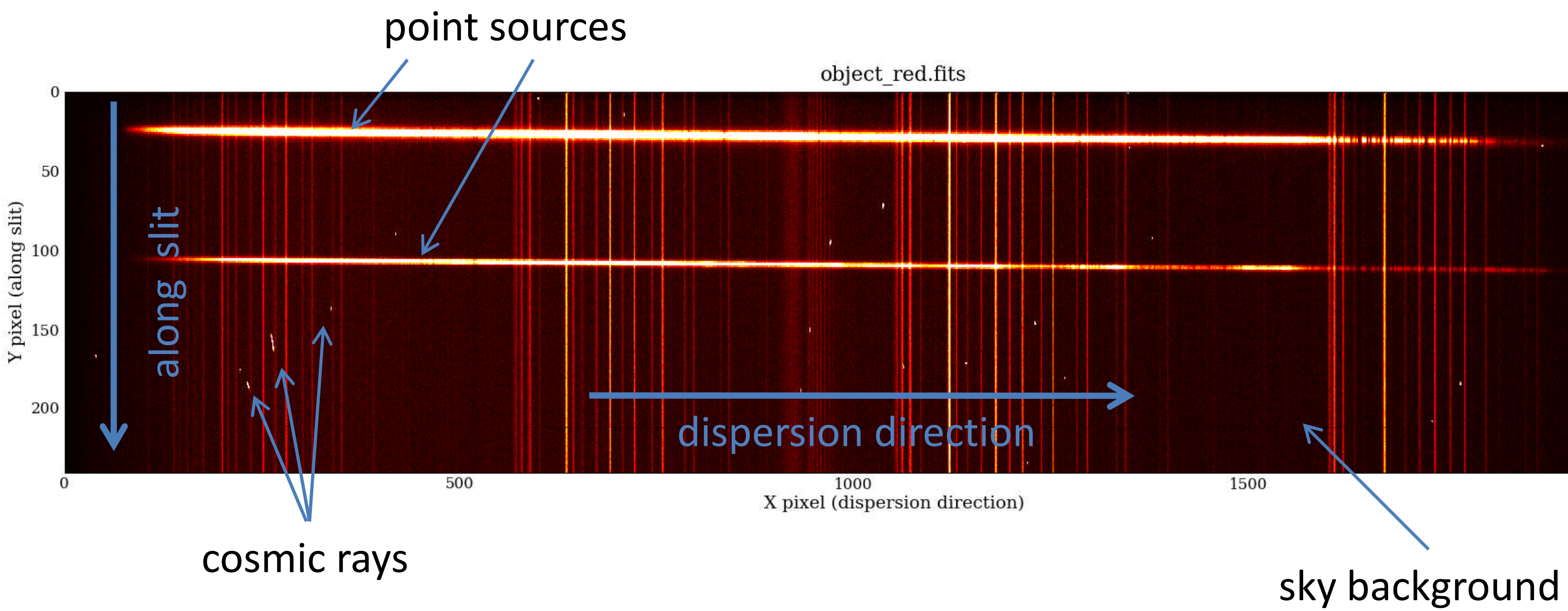


RC spectrograph at Kitt Peak



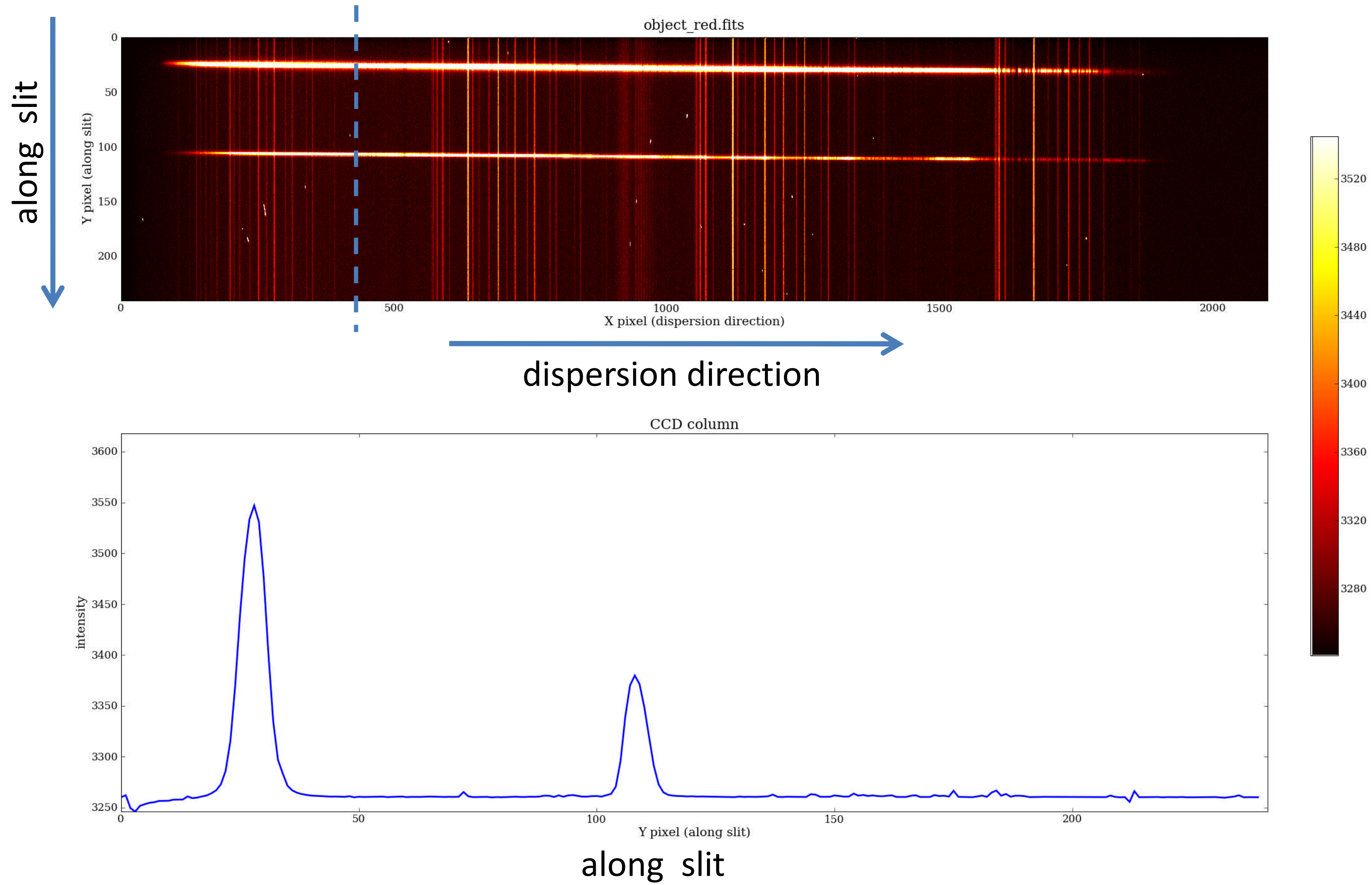
ISIS on the WHT

The detector view

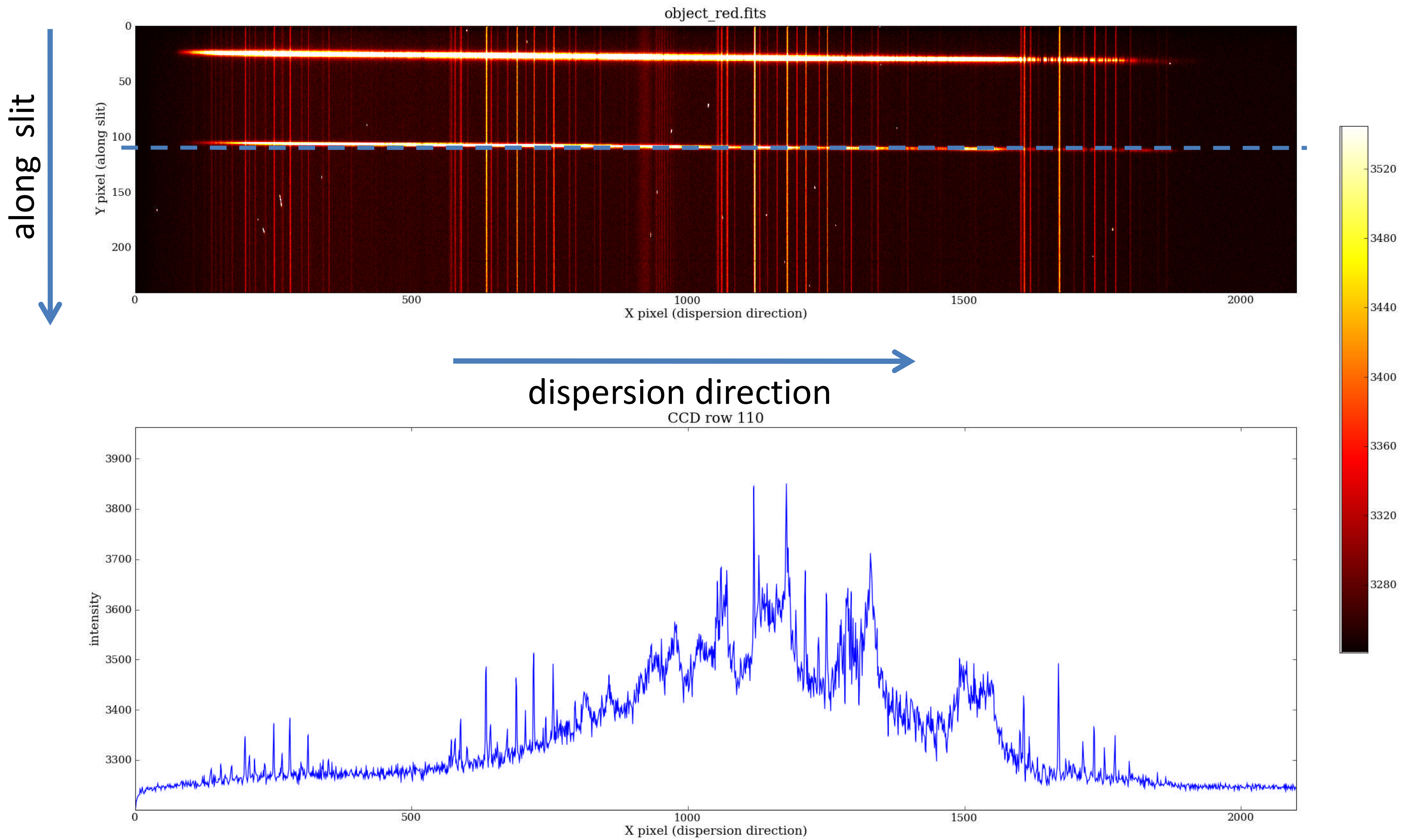


- spectral format CCD ; more pixels in the dispersion direction to sample the spectrum
- spatial information along the slit still available

The detector view ; spatial slice

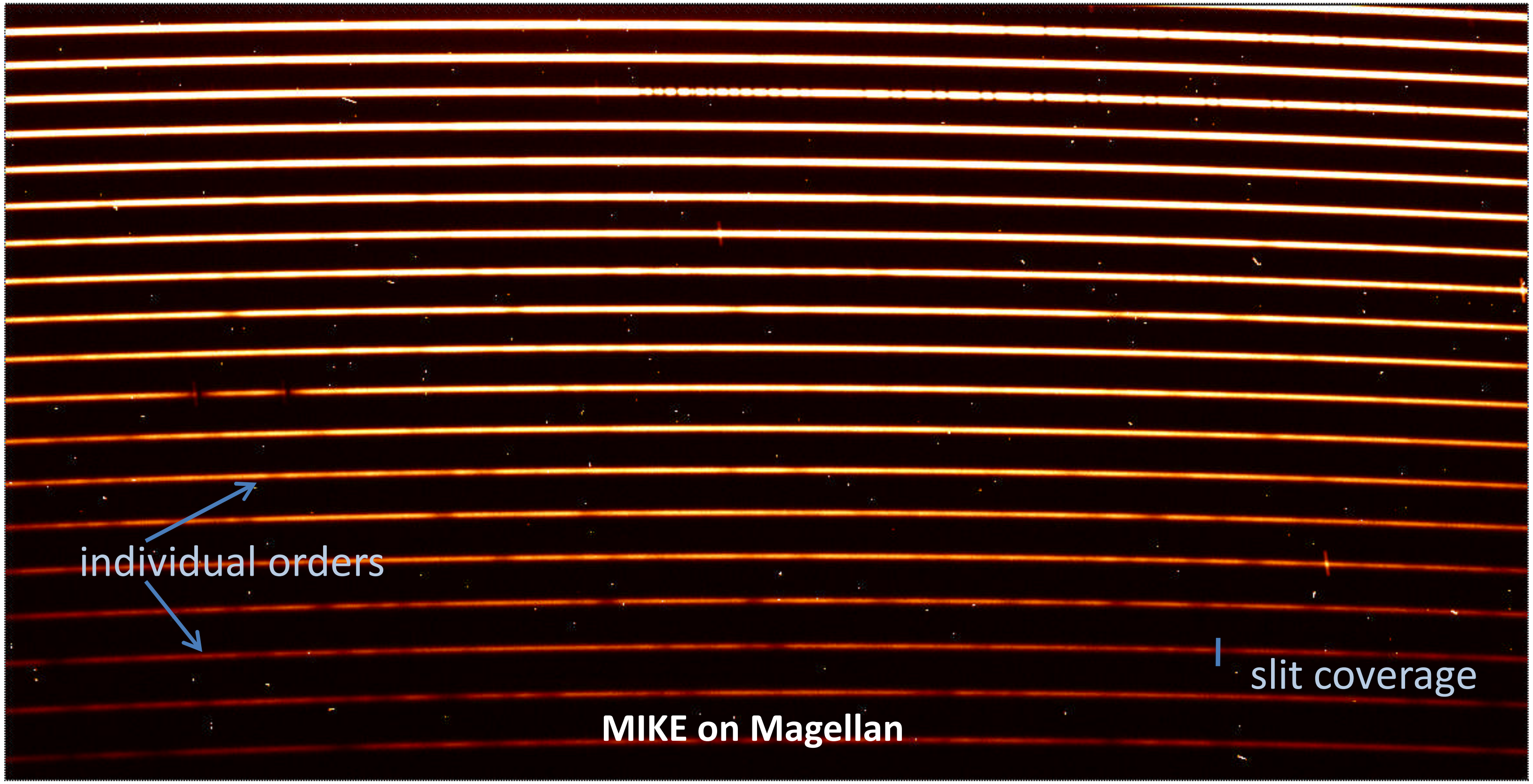


The detector view ; spectral slice



Echelle spectrographs

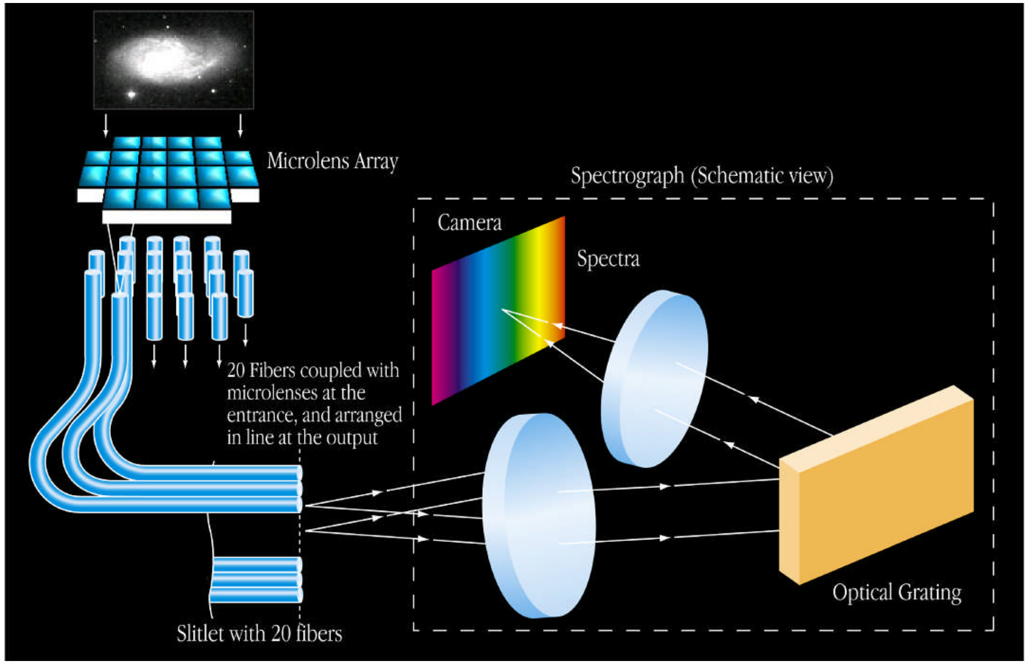
- Uses gratings at very high order (thus high resolution), and uses a 2nd low resolution *cross-disperser* to separate individual orders



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

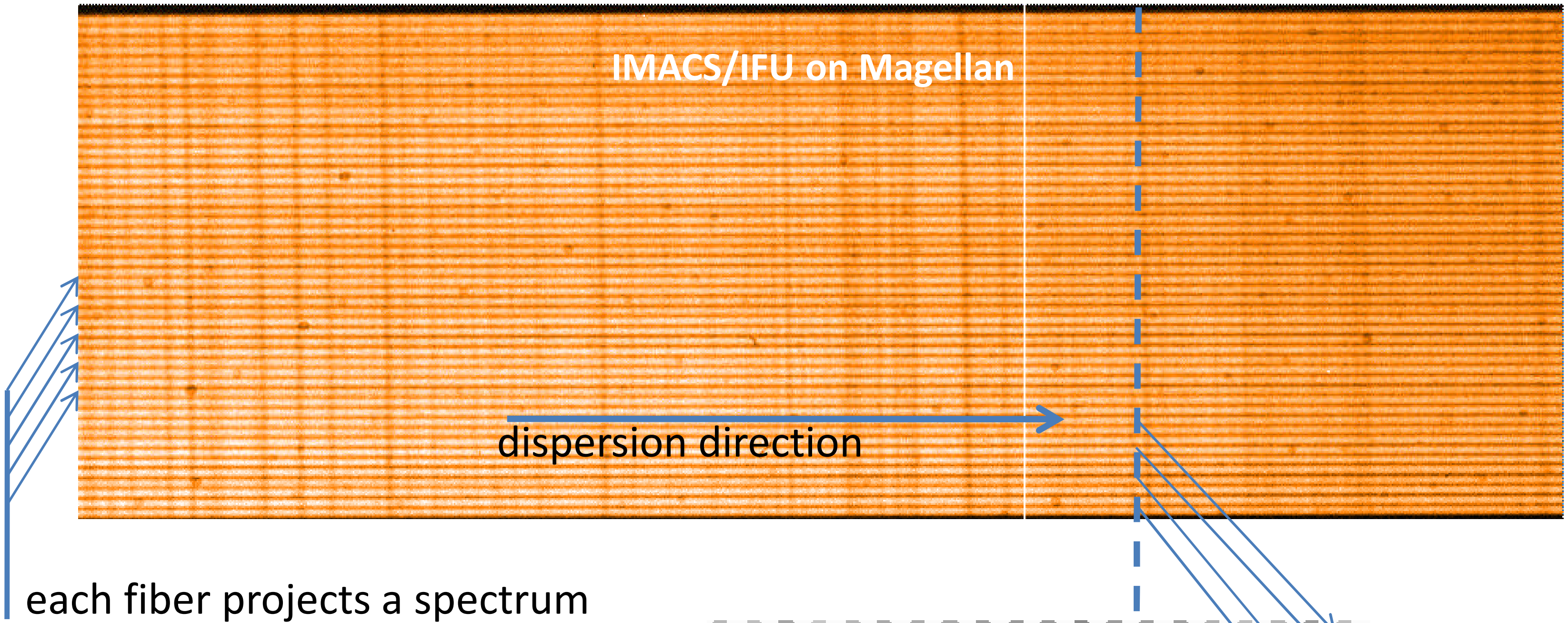
Integral Field Spectroscopy aka 3D

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

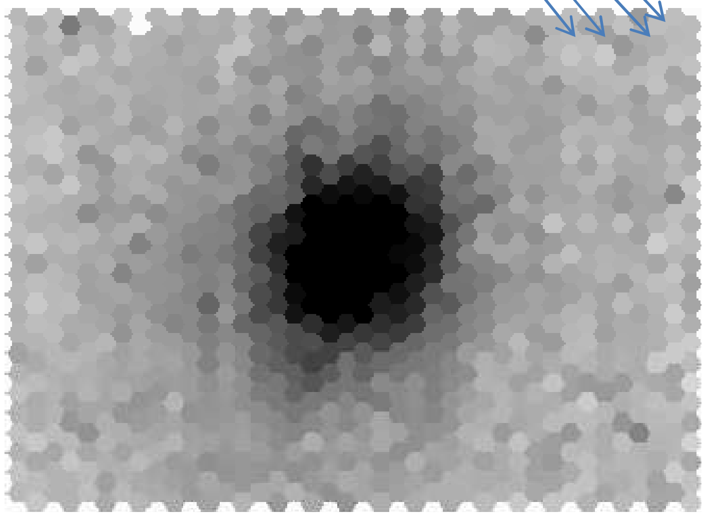


- To sample targets in two spatial dimension, a bundle of apertures is needed ; $I(x,y,\lambda)$ [3D]
- Each fiber/lenslet in the bundle is then fed into a spectrograph and dispersed

Integral Field Spectroscopy example



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



reconstructed
monochromatic image

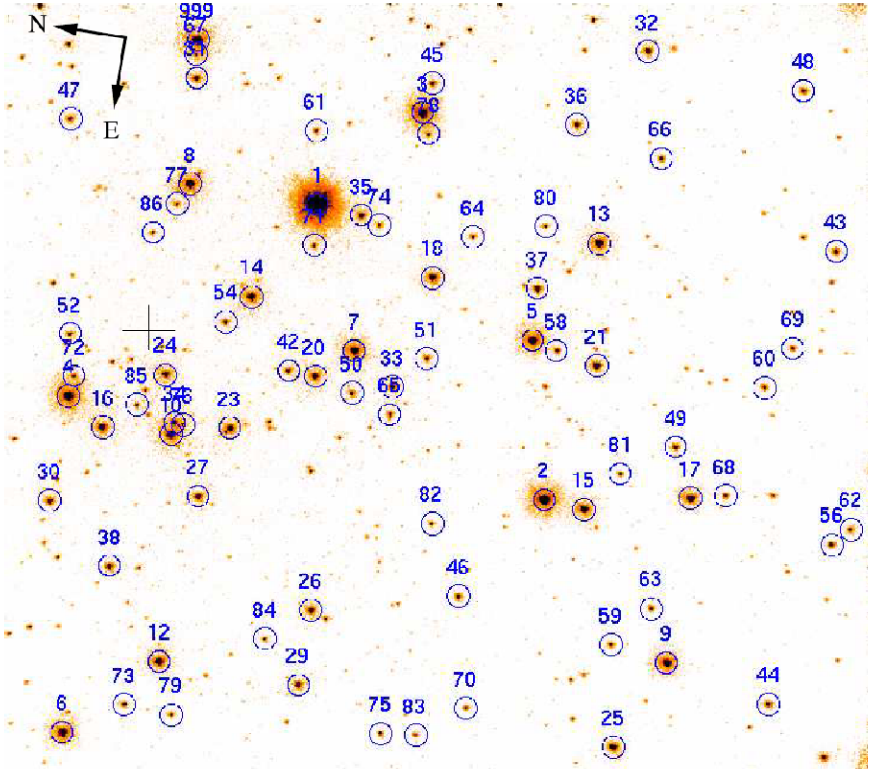
Multi-object spectrographs

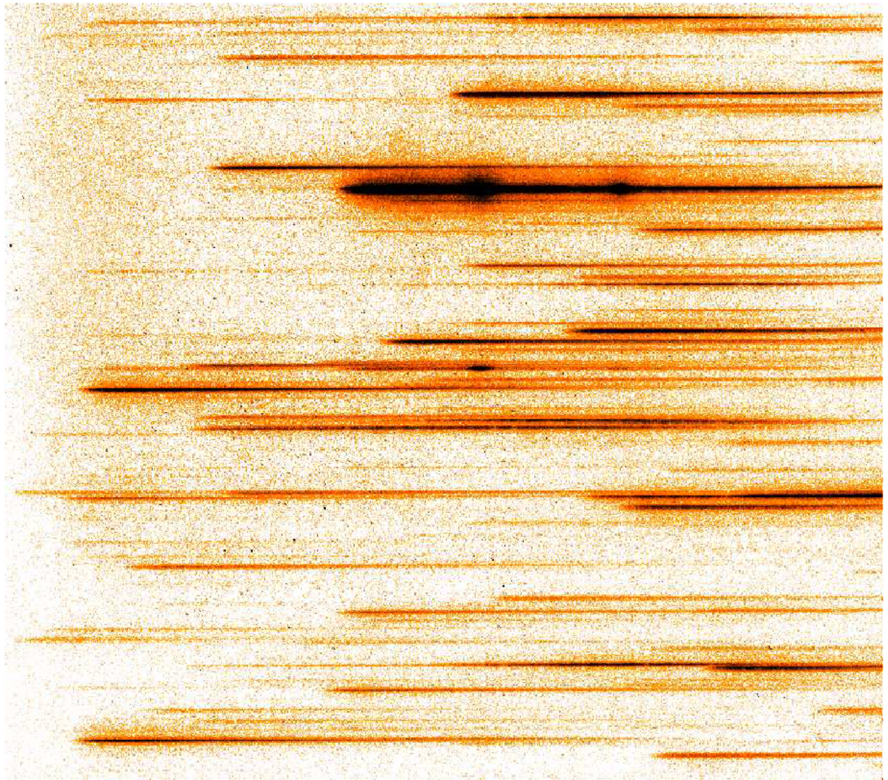
- Multiplex advantage by placing multiple apertures on the field of view and feeding each of these through the spectrograph

- 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

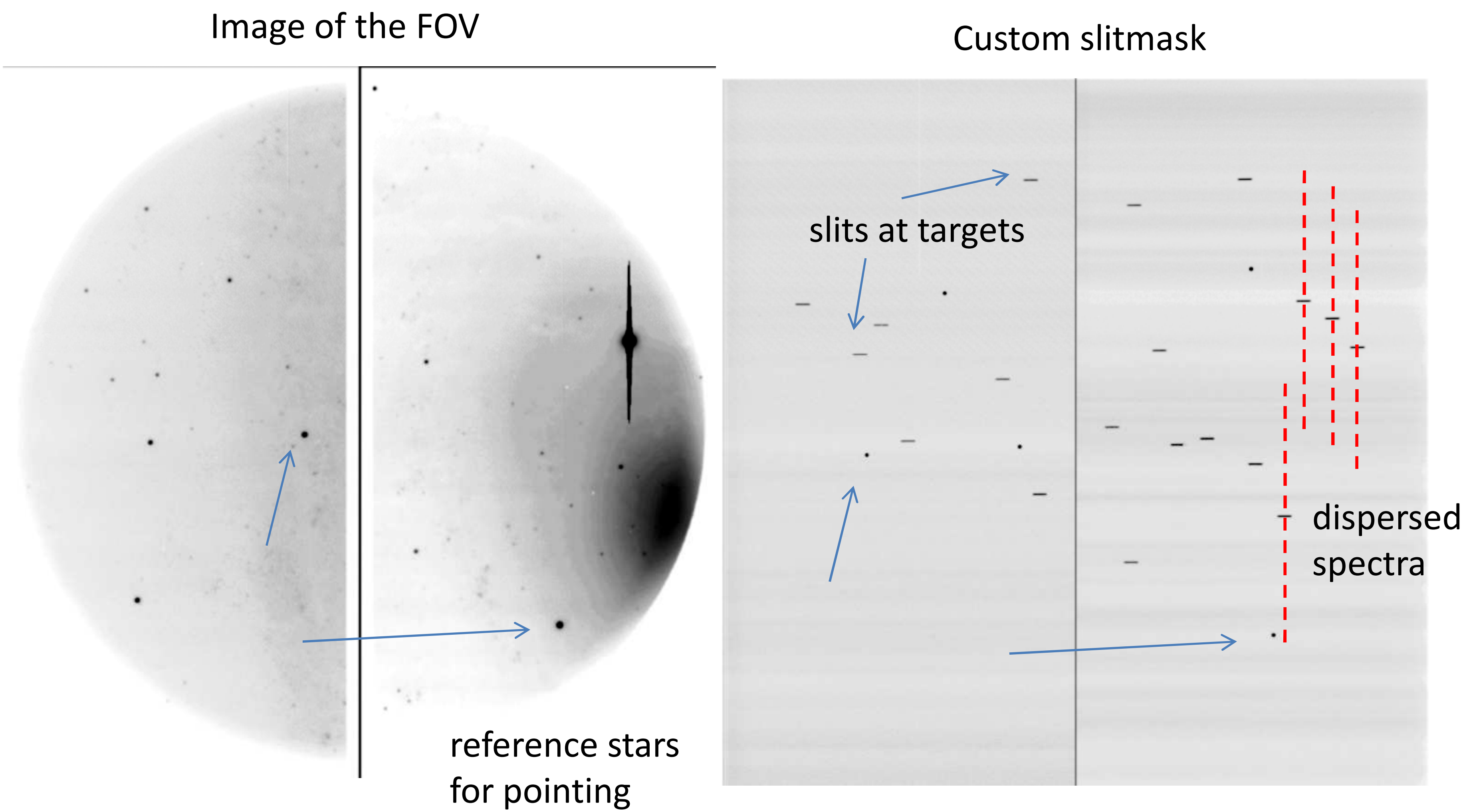
Slitless spectroscopy





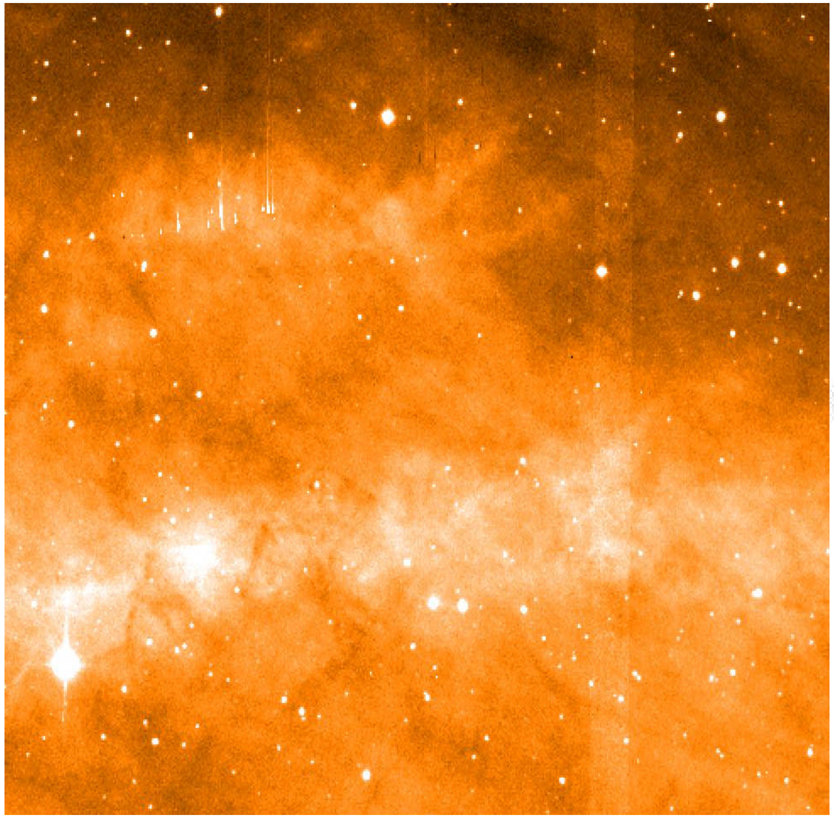
- no slit-losses, but also no control over resolution
- confusion / spectral overlap

MOS slitmasks

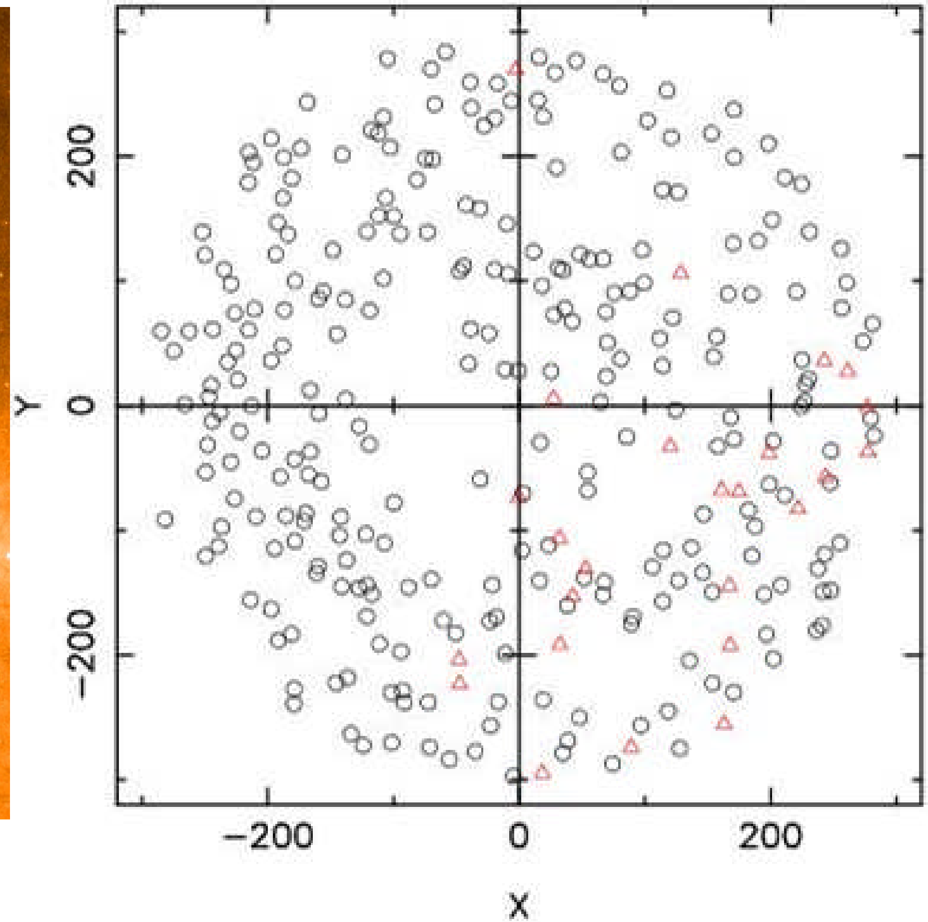


Fiber MOS example

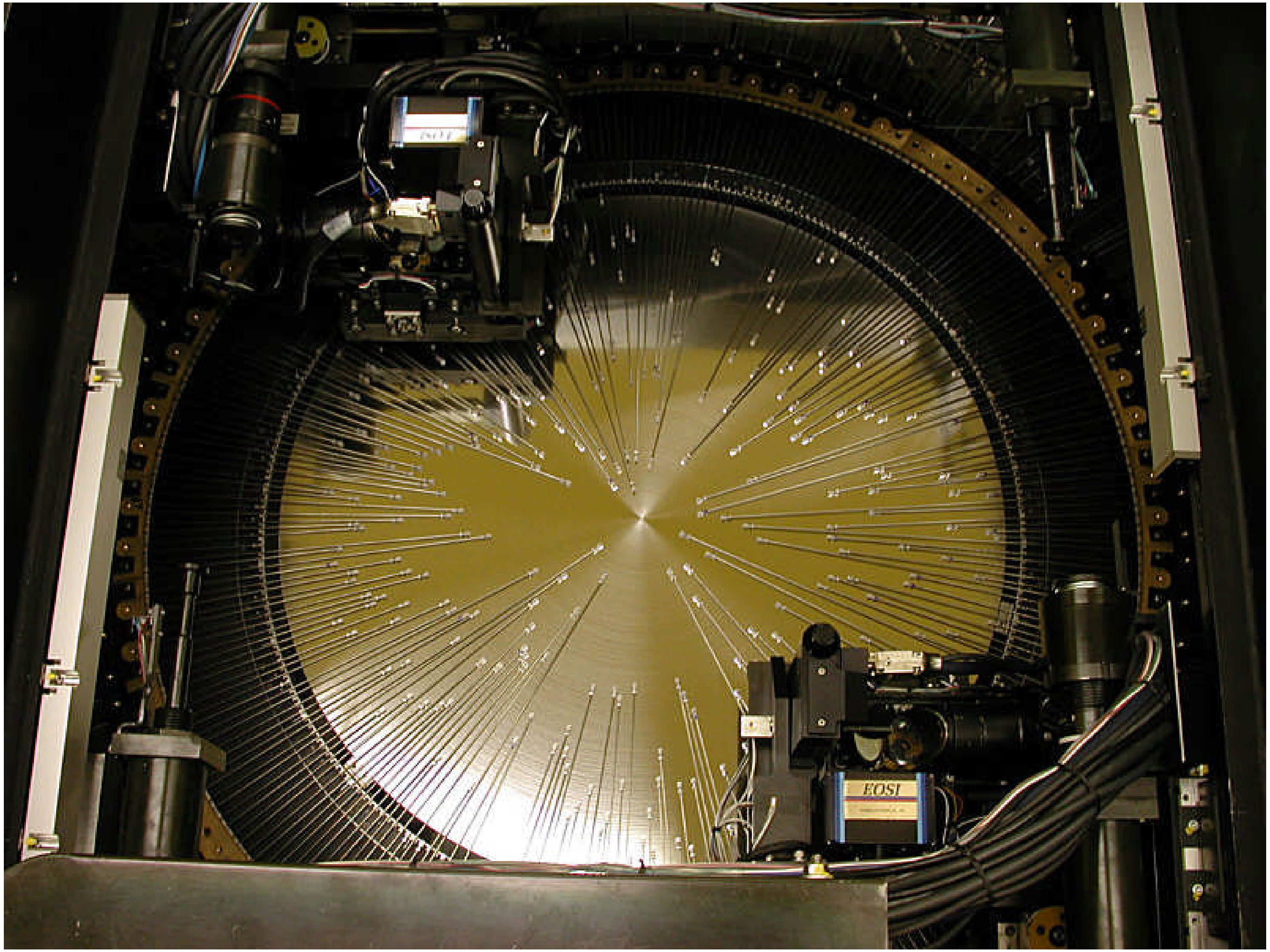
Pick your targets …



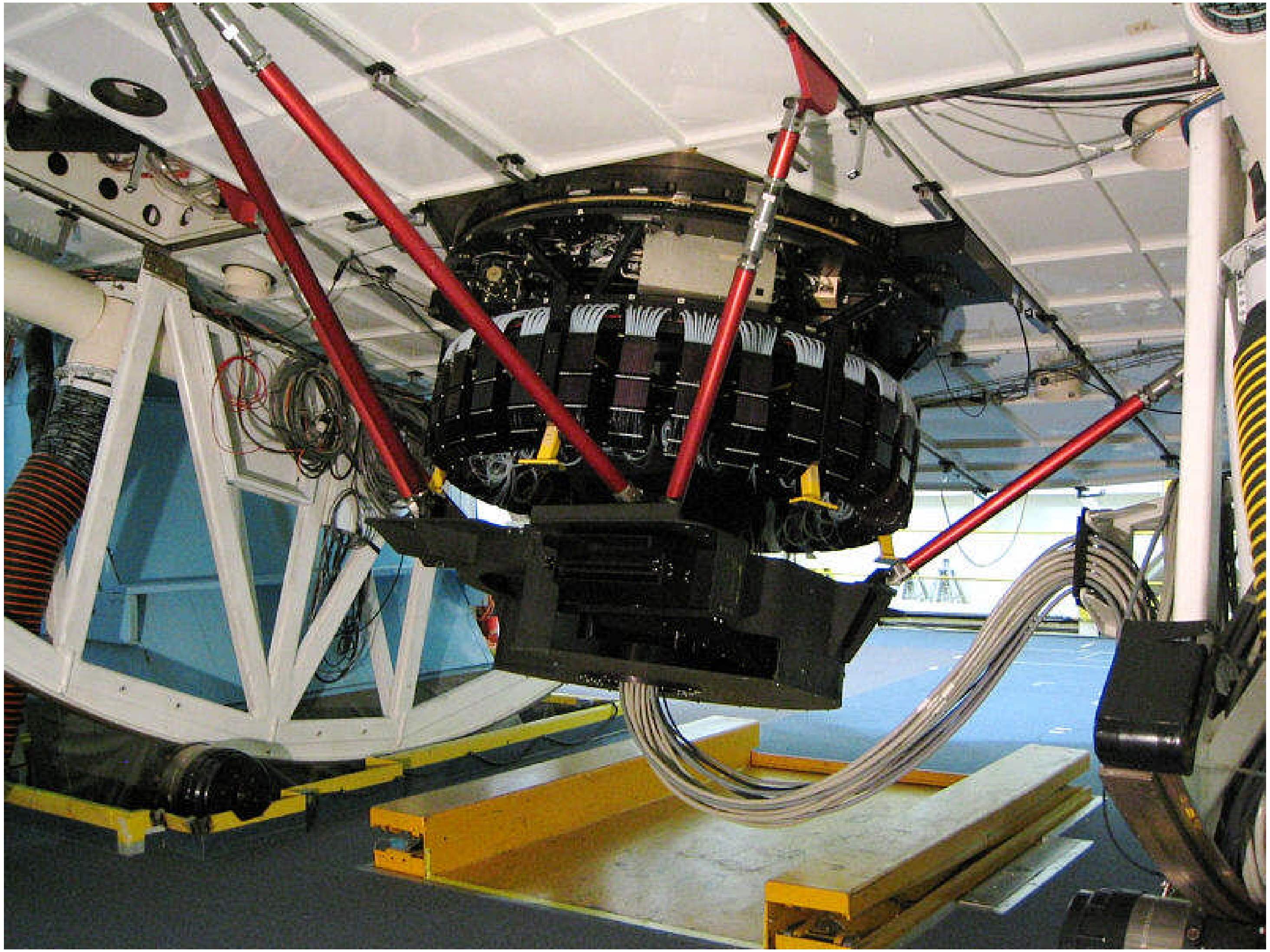
IPHAS star forming region



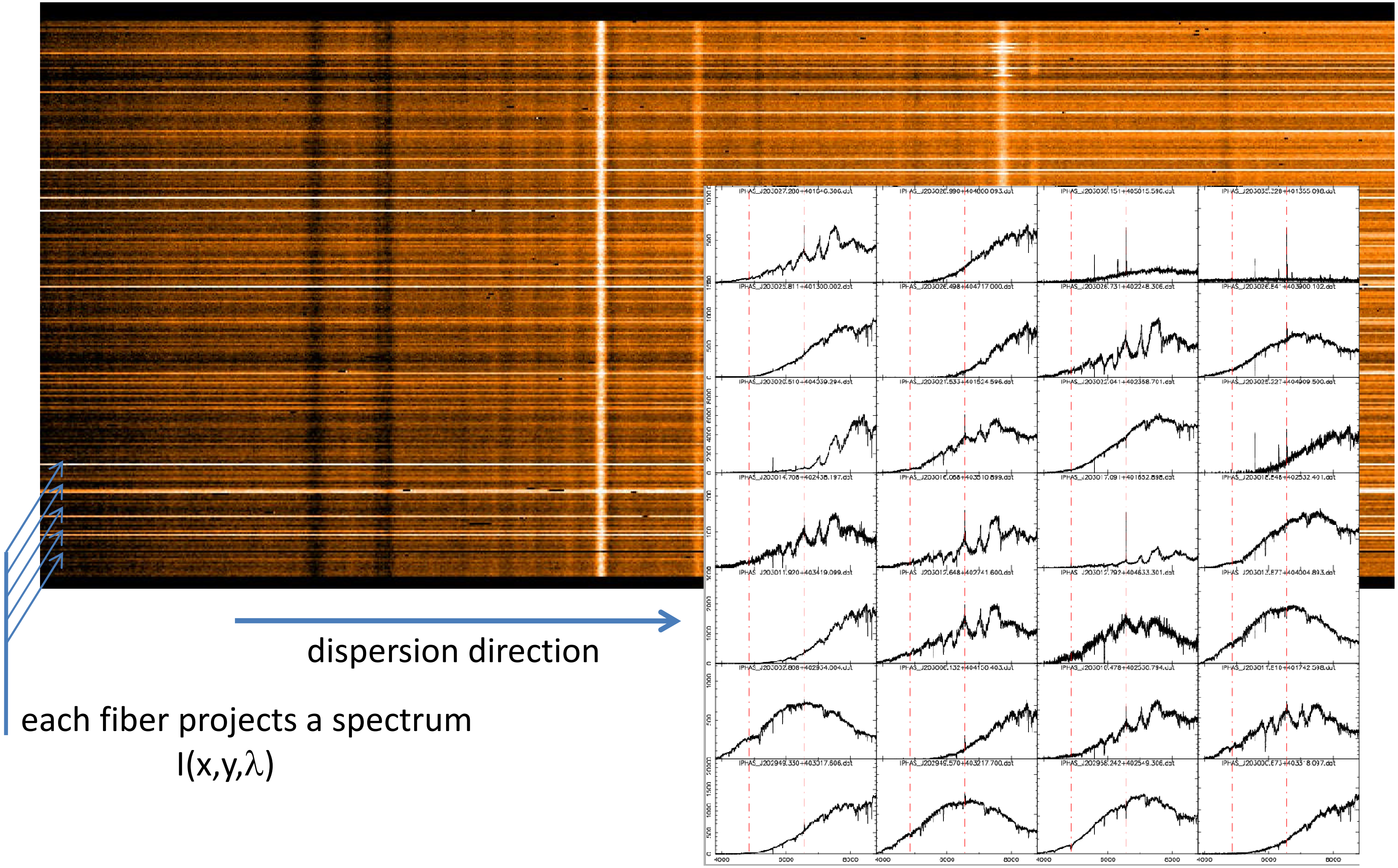
MMT HectoSpec



MMT HectoSpec



MMT HectoSpec



dispersion direction

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

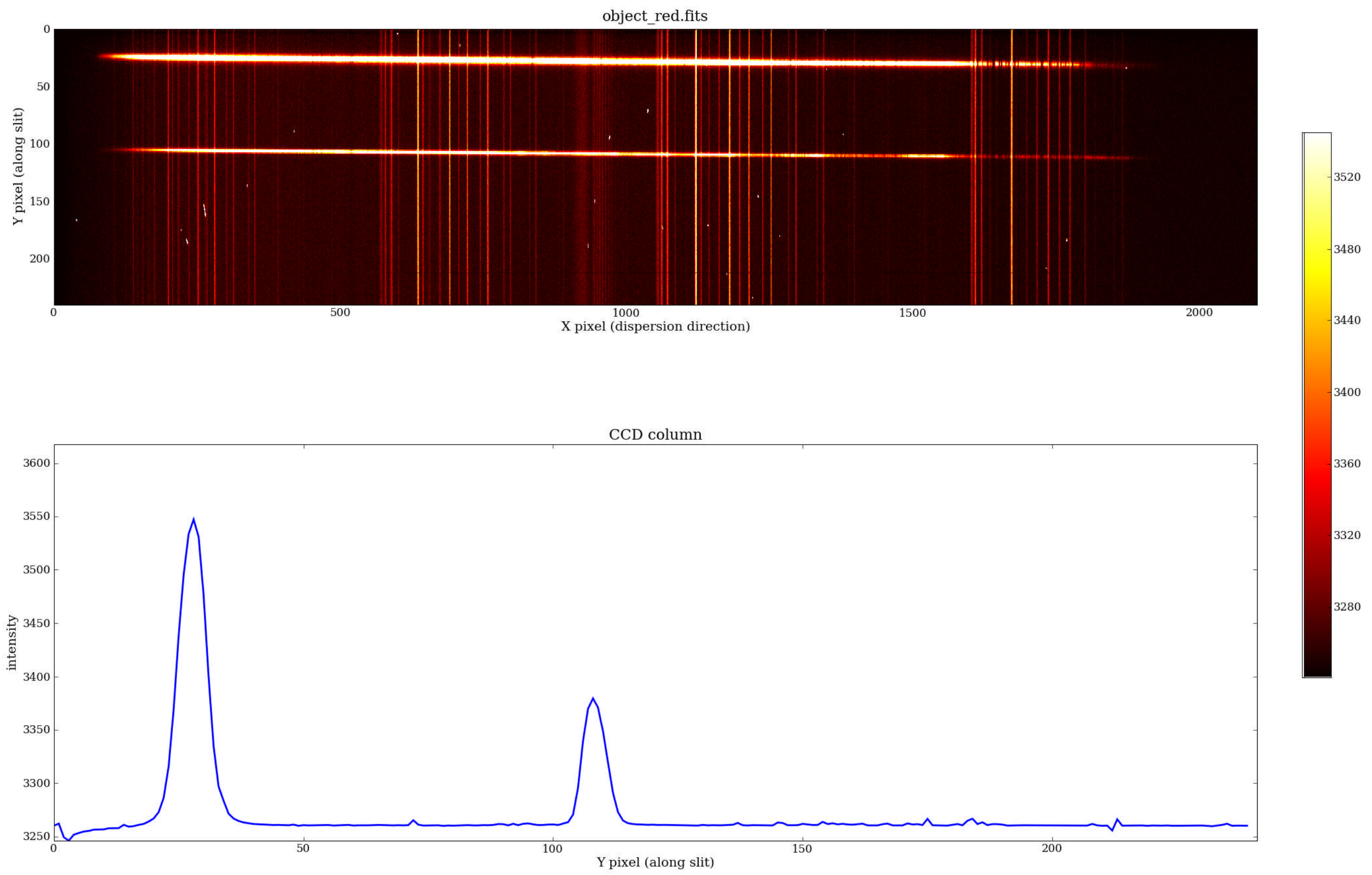
Summary: Apertures

- 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

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

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

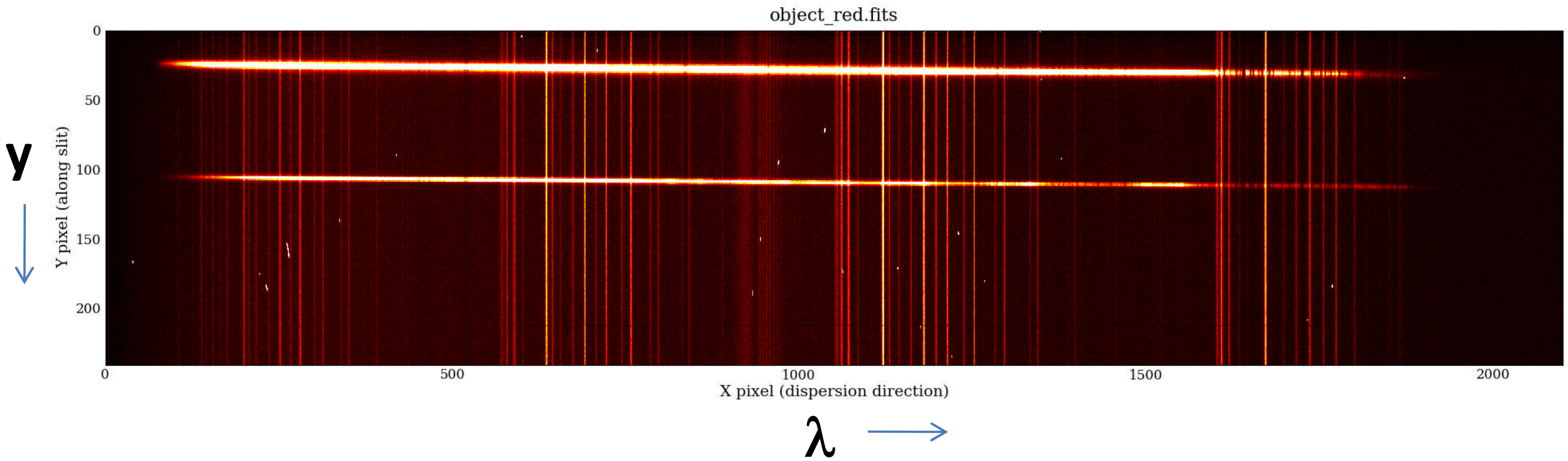
object profile weight

sky profile weight

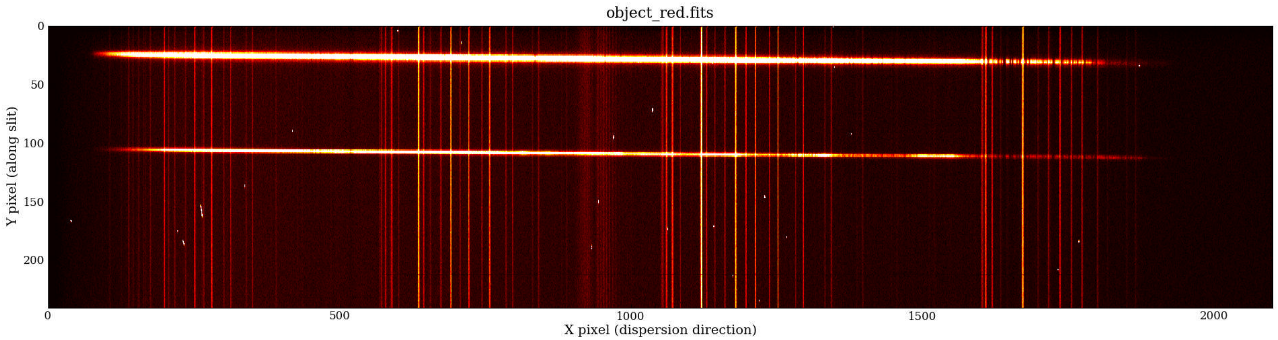
$$D(\lambda) = f(x,y) \approx f(x)$$

relates λ to x,y

dispersion relation



Sky background

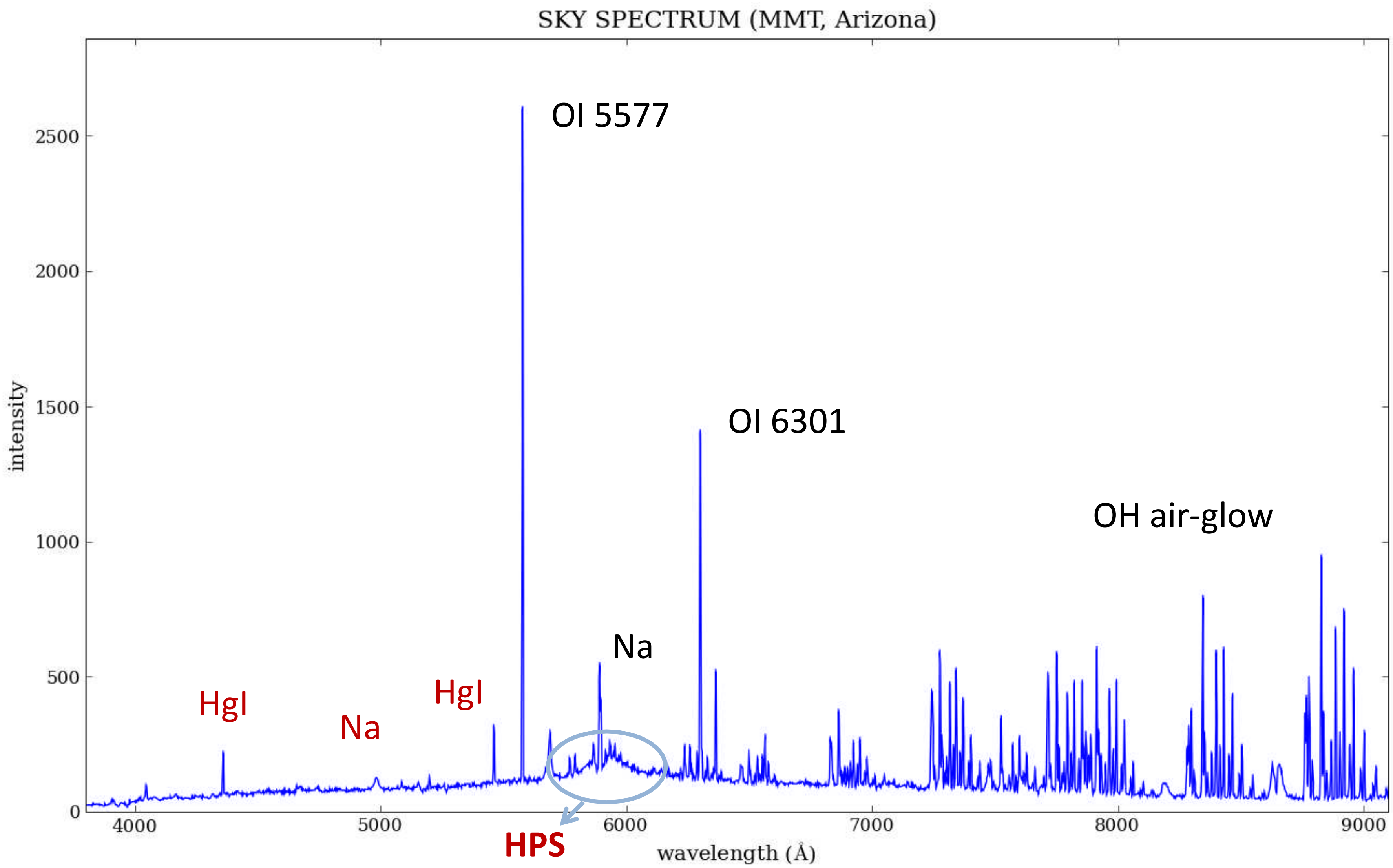


- Background has contributions from many sources;
  - Air glow ; strong discrete emission lines
  - Zodiacal light ; $m_V \sim 22.-23.5$
  - Sun/Moonlight

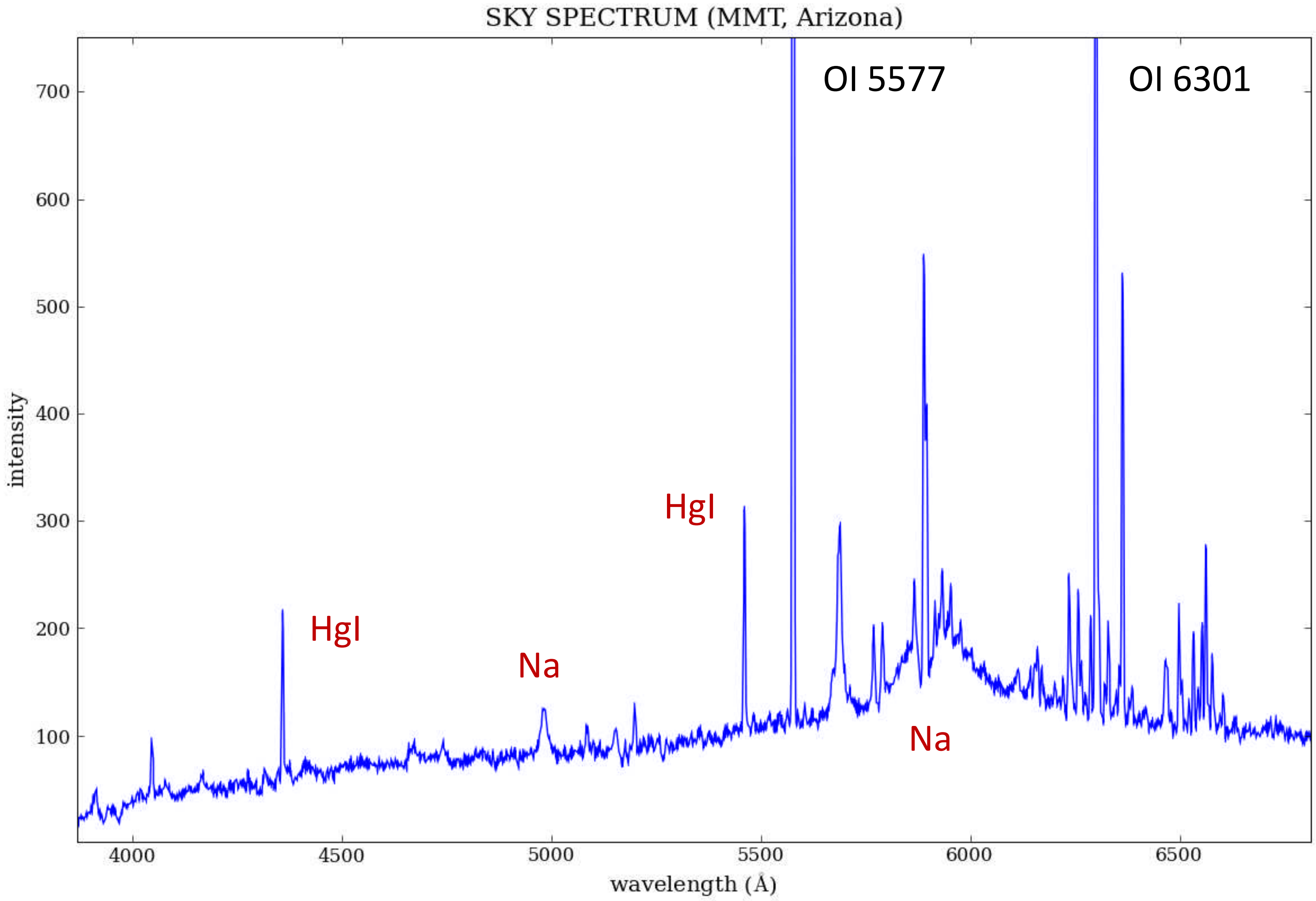
    new moon : $m_V \sim 21.9$

    full moon : $m_V \sim 19.9$
  - Aurorae
  - Light pollution
  - Thermal emission from sky, telescope and buildings
  - Non-resolved astronomical background

Sky background

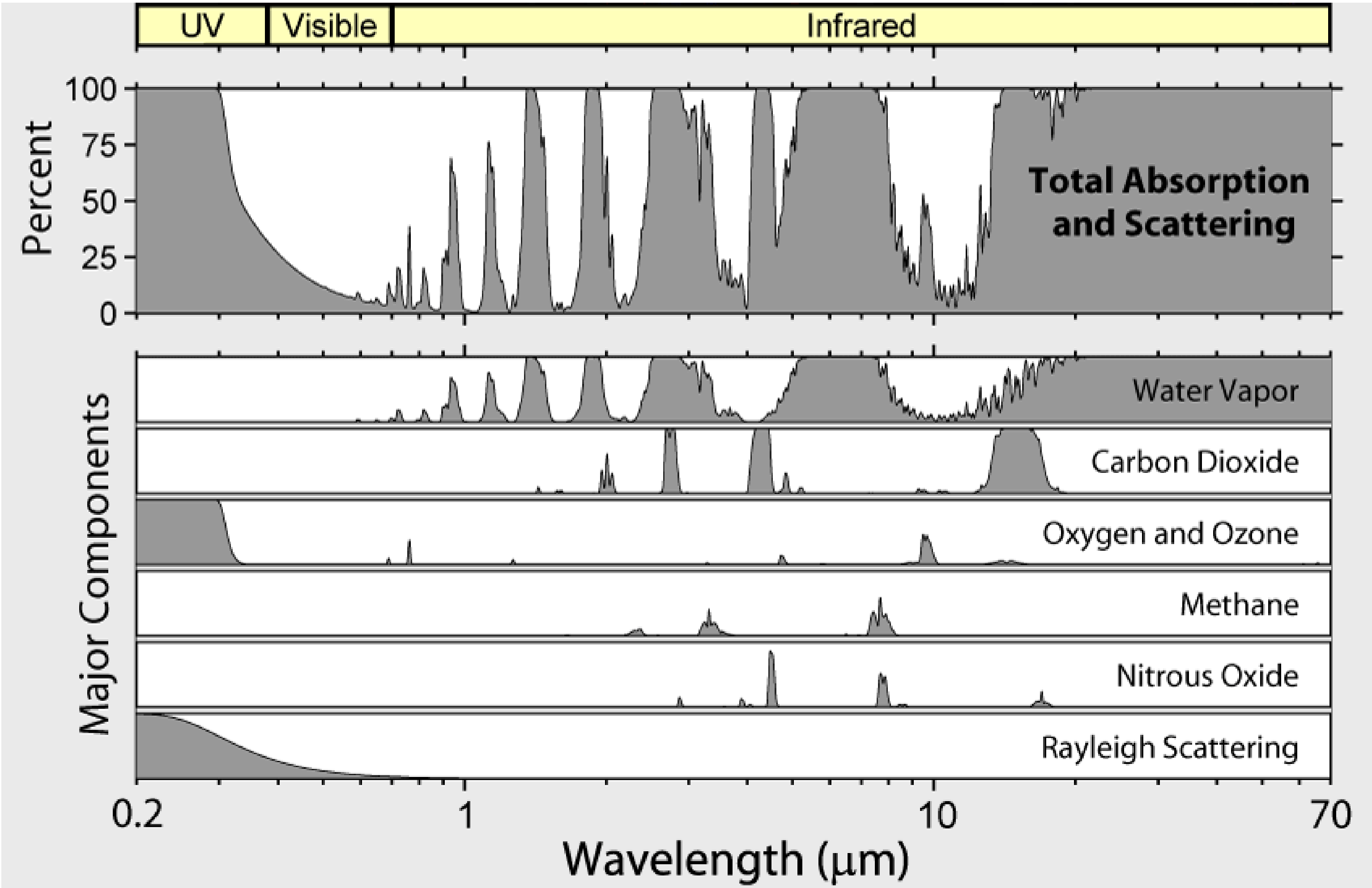


Sky background ; Tucson

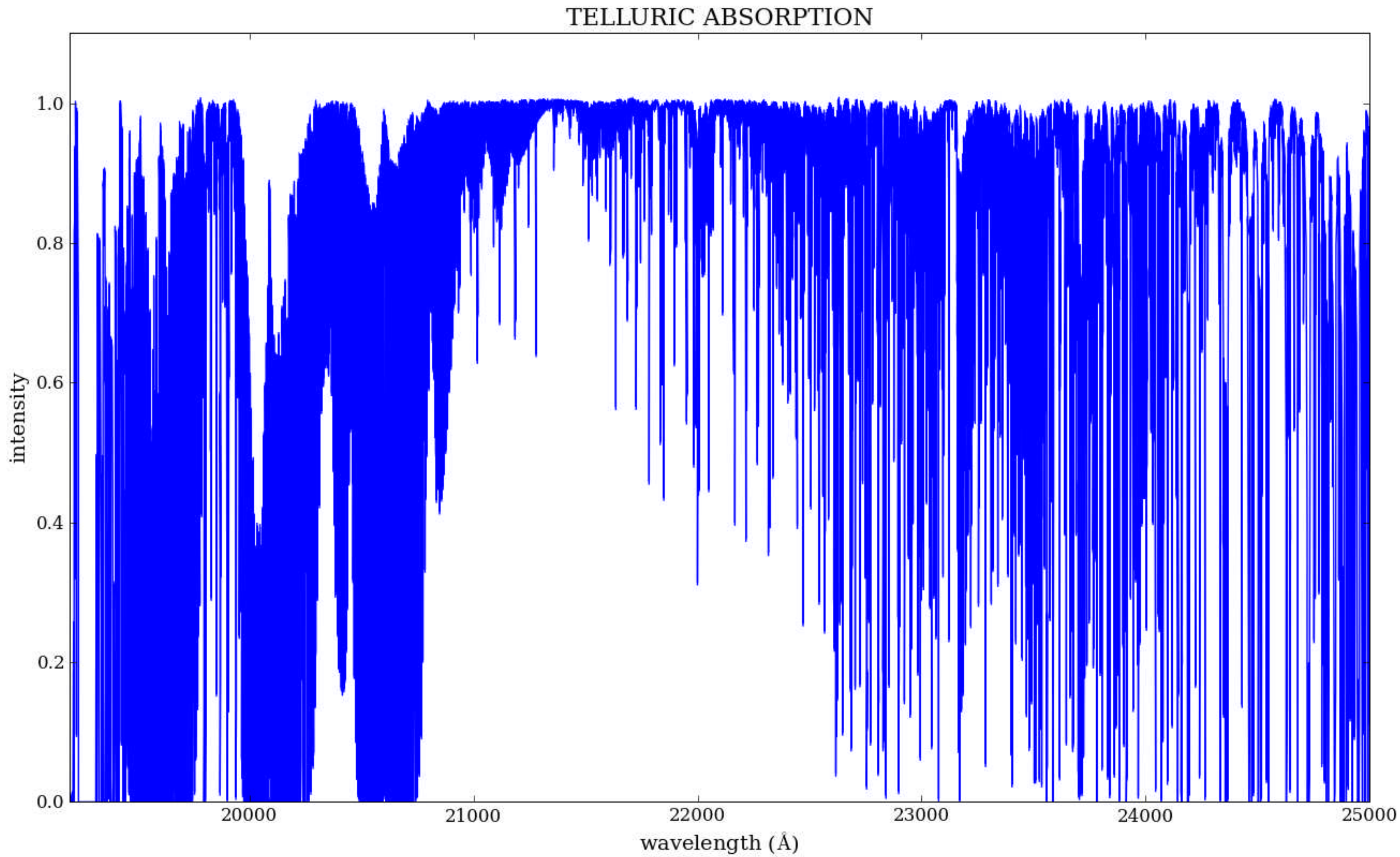


Atmospheric transmission

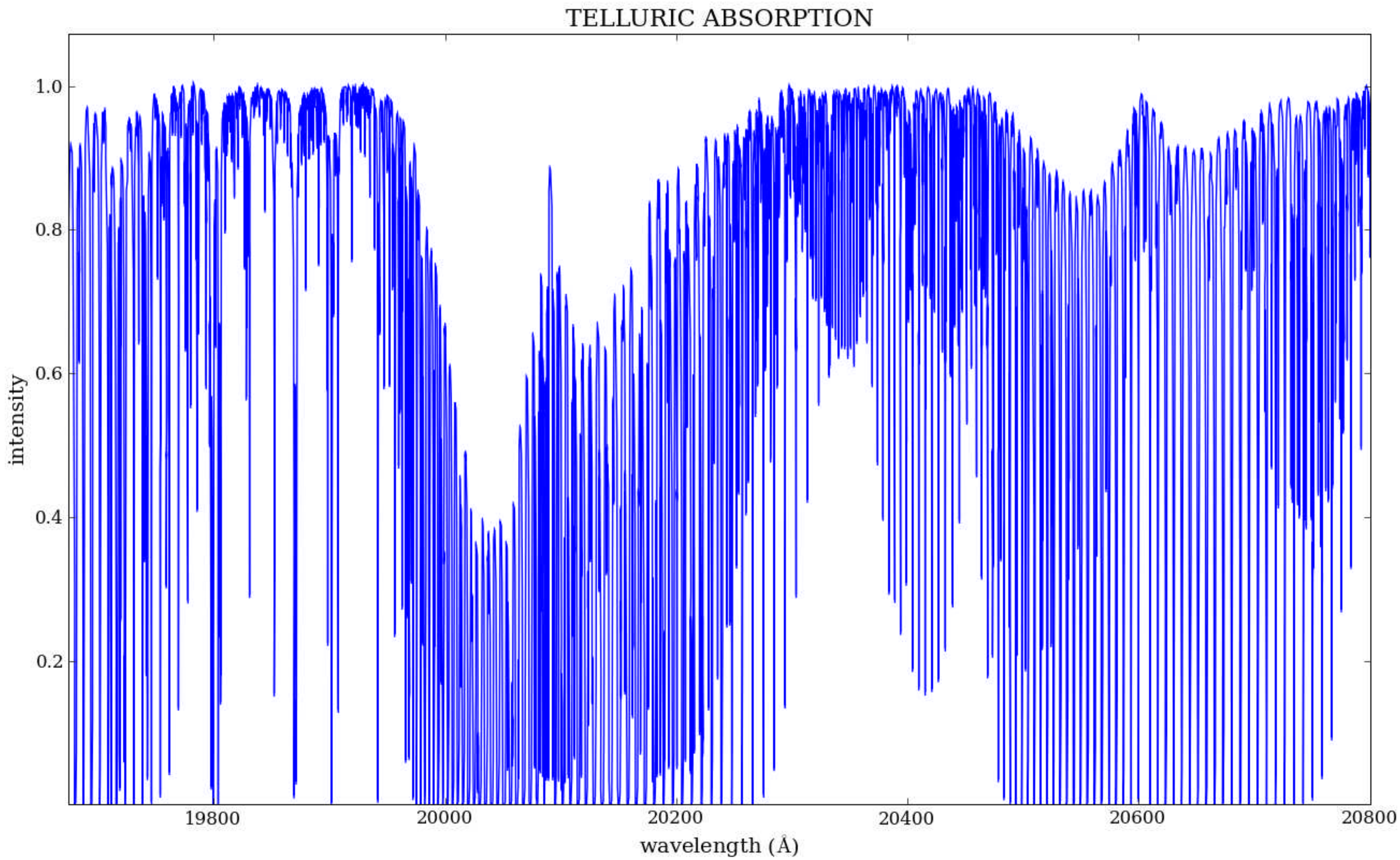
- Atmospheric transmission is strongly dependent on wavelength



Telluric absorption



Telluric absorption



Summary: Background

- The 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*