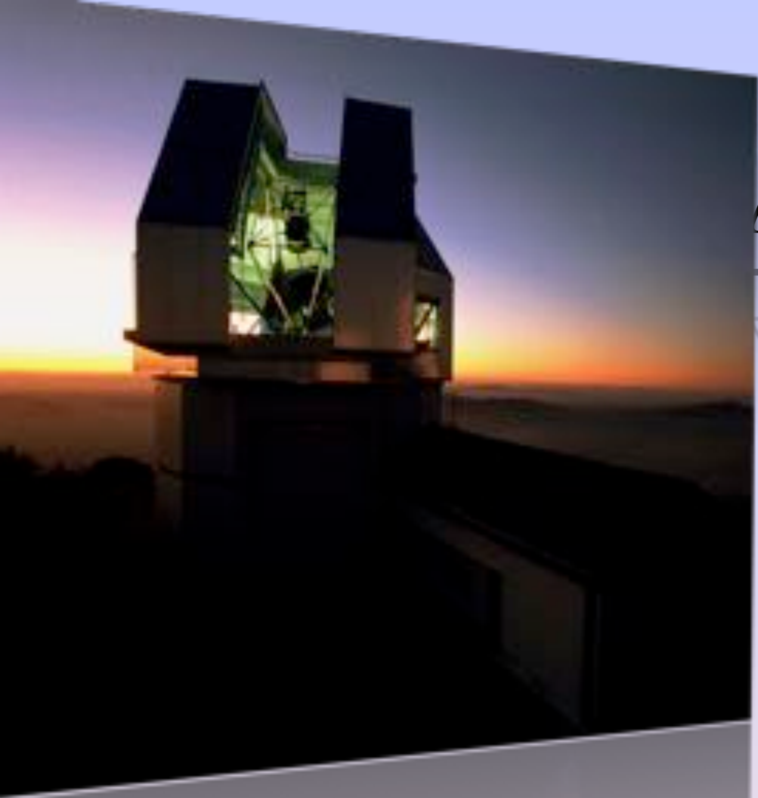


Astro 500

*Tech*niques of Modern
*Obs*erv*ati*onal Astrophysics

*M*atthew Bershady
*Uni*versity of Wisconsin

Lecture Outline

Spectroscopy from a 3D Perspective

- ✓ Basics of spectroscopy and spectrographs
- ✓ Fundamental challenges of sampling the data cube
- • Approaches and example of available instruments
  - ➢ I: Grating-dispersed spectrographs ← a lot of material
  - ➢ II: Fabry-Perot interferometry
  - ➢ III: Spatial heterodyne spectroscopy

Approaches

Examples of available instruments

- ✓ Grating-dispersed spectrographs
  - ✓ basic spectrograph design
  - ✓ dispersive elements
  - ✓ Long-slit spectrographs
    - ✓ General Observing Considerations
  - ✓ Double spectrographs
  - ✓ Multi-objects spectrographs: slitlets vs fibers
  - ➢ Echelle spectrographs
  - ➢ 3D spectroscopy: coupling formats and methods
    - o Fiber
    - o Fiber+lenslet
    - o Slicer
    - o Lenslet
    - o Filtered multi-slit
  - ➢ summary of considerations
  - ➢ sky subtraction

…from lecture 17:

Grating-dispersed spectrographs

basic spectrograph design

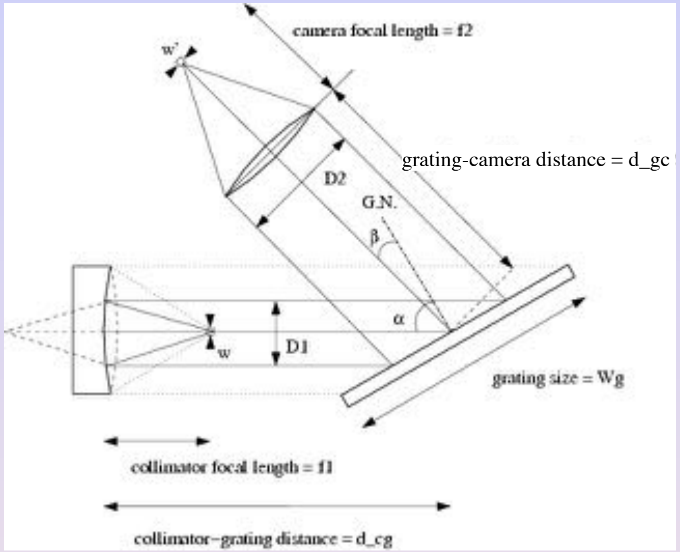
Spectral resolution

$$R = \lambda / d\lambda$$
$$= \lambda\, (\gamma/\boldsymbol{r})\, (f_1/w)$$
$$= \lambda\, (\gamma/\boldsymbol{r})\, (D_1/\theta\, D_T)$$

Want large dispersion, but can get resolution also from demagnification:

Want *long* collimator at *fixed* camera f_2; need field lens or white pupil to avoid vignetting.

Want *large* collimator and even *larger* camera



Using grating equation:

$$R = (f_1/w)\, (\sin\beta + \sin\alpha) / \cos\alpha$$

θ = angle of slit on sky
$d\lambda = w_\lambda' / (dl/d\lambda)$
$w = f_T\, \theta$
$f_1/d_1 = f / D_T$

which becomes in Littrow:

$$R = (f_1/w)\, 2 \tan\alpha$$

Resolution is more driven by dispersion; want large α, which means *large gratings*.

Echelle Gratings

- One way to design gratings to get high resolution via large angles and anamorphism.
- Diffraction gratings with relative large grooves (coarse-ruled), used in high order (m) and large angles (α,β)
- Small free spectral range: λ/m
- $\mathcal{R}$-value = tan δ
- Compare to fine-``ruled'' gratings used in low order and large angles (e.g., VPHg)

Echelette: $\delta<45$ - most low-order SR gratings
R2 echelle: $\delta=63.5$ - what's on the WIYN/Bench
R3 echelle: $\delta=71.6$
R4 echelle: $\delta=75.95$ - what's on the SALT/HRS

- **Grating equation**

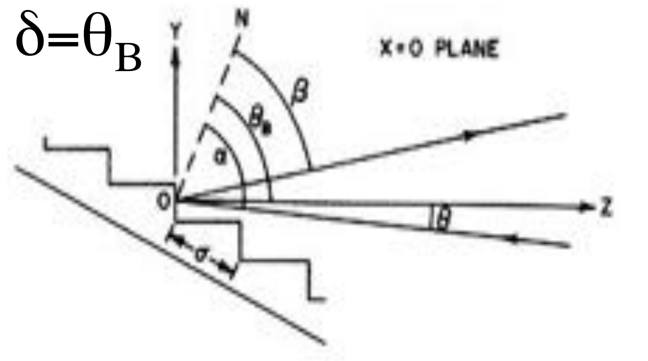
  $m\,\lambda = \sigma\,(\sin\beta + \sin\alpha)$
  (reflection)

  σ is groove separation (nm)
- **Angular dispersion**

  $\gamma = d\beta/d\lambda = m / \sigma \cos\beta$

  $= (\sin\beta + \sin\alpha) / \lambda \cos\beta$
- **Anamorphism**

  $\boldsymbol{r} = |d\beta/d\alpha| = \cos\alpha / \cos\beta$
- **Blaze angle:** δ



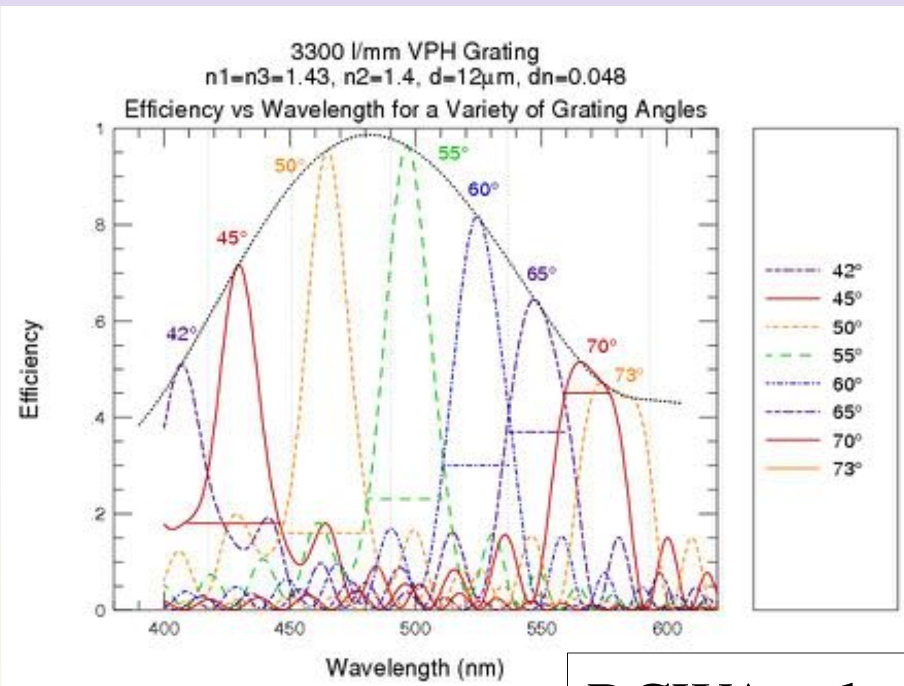
An example of a VPH spectrograph:
WIYN 3.5m upgraded Bench Spectrograph

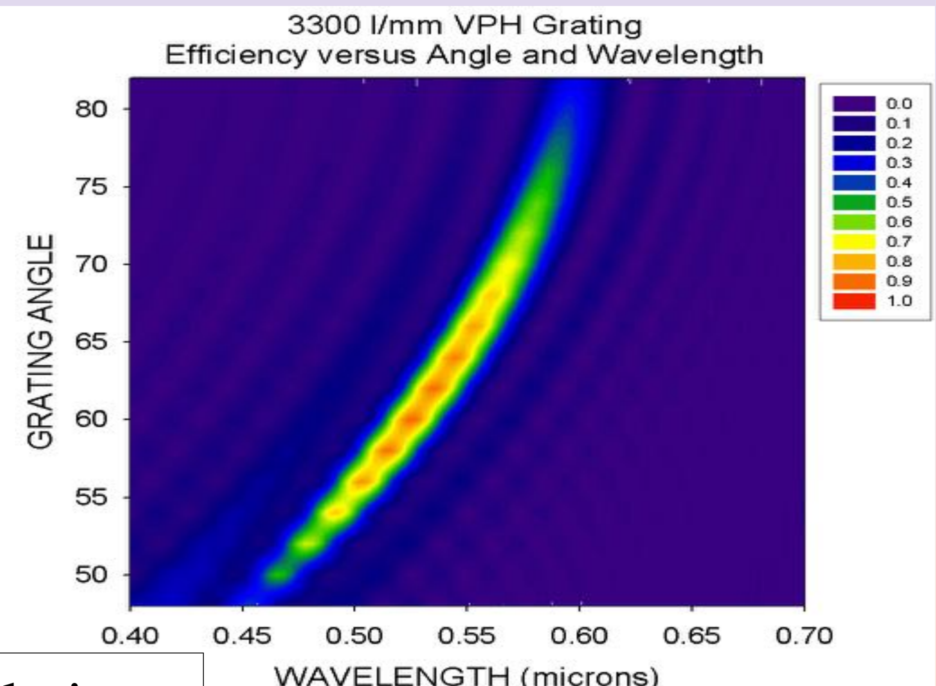
Challenging angles!
Coatings an issue

- 3300 l/mm: *in use*
- 0.5m in size*!*
- R ~ 7000-20,000
- expect 2x diffraction efficiency of existing echelle.

Air-Glass % Reflection Losses Per Surface

Angle	Uncoated	Newport Thin Film 400-500nm	Newport Thin Film 500-550nm	Spectrum Thin Film 450-550nm
55°	6	2.5	2	< 1
60°		3.5	2.5	
65°	11	5.5	4.5	< 2
70°		9.5	7.5	
75°	24	17	15.5	< 7





RCWA calculations

An example of a VPH spectrograph:
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- 3300 l/mm: *in use*
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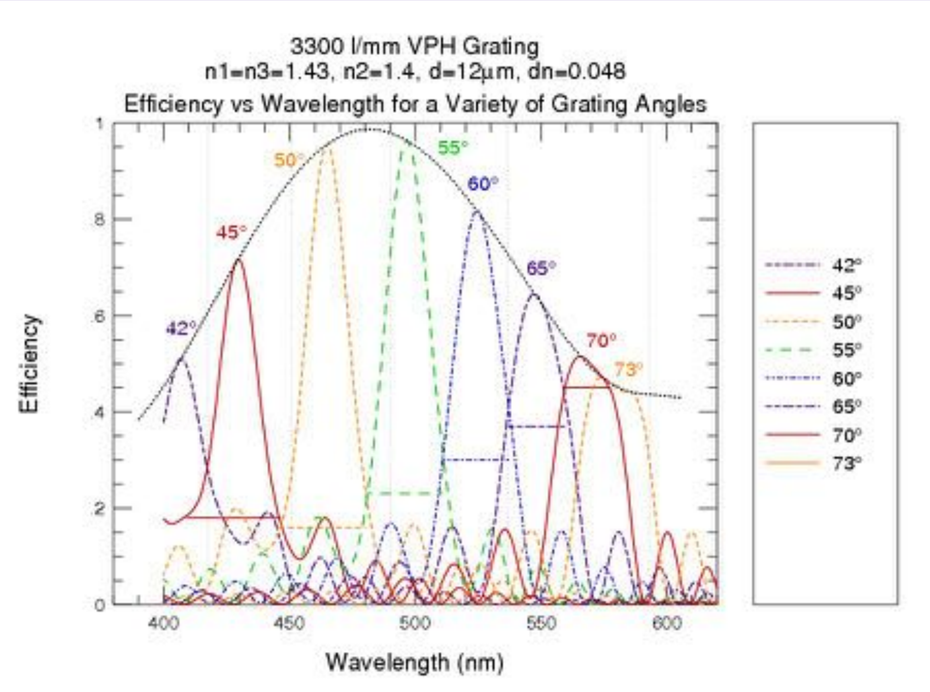
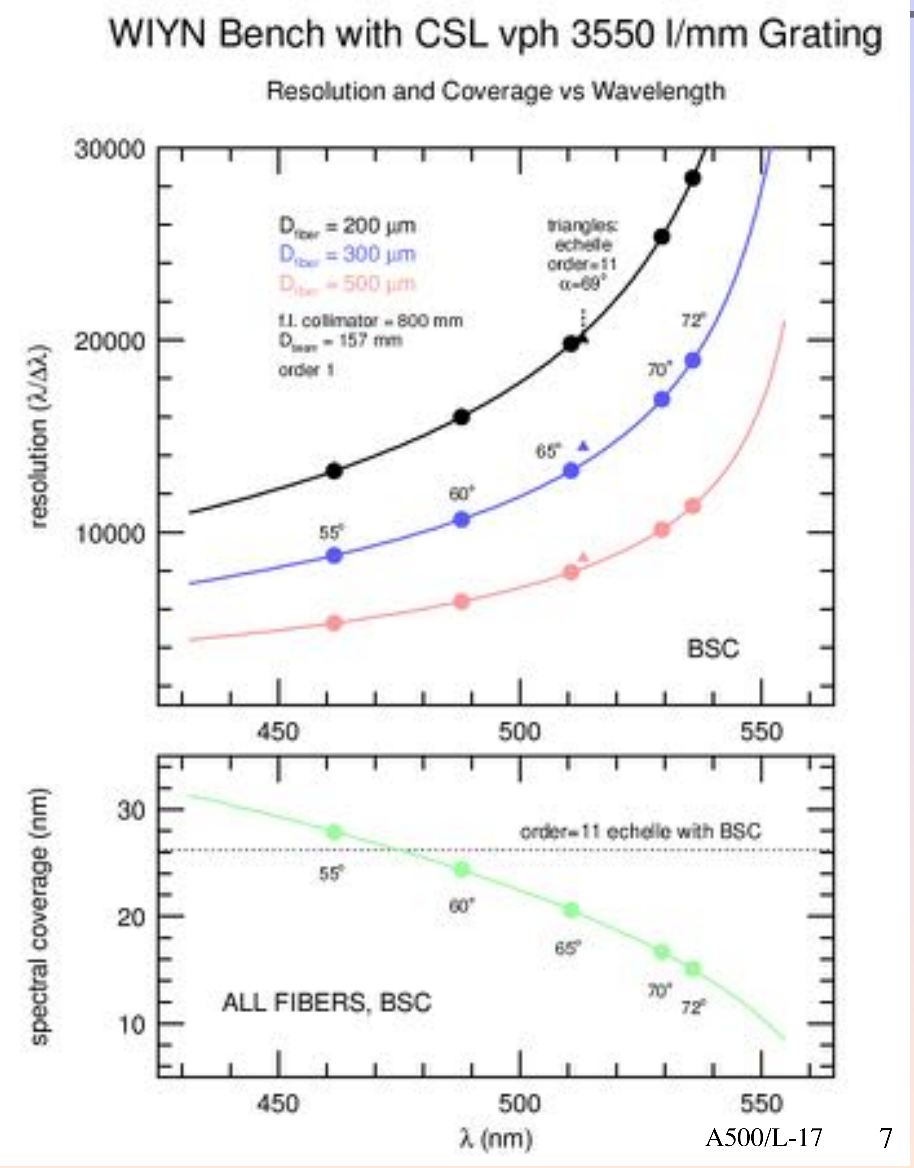
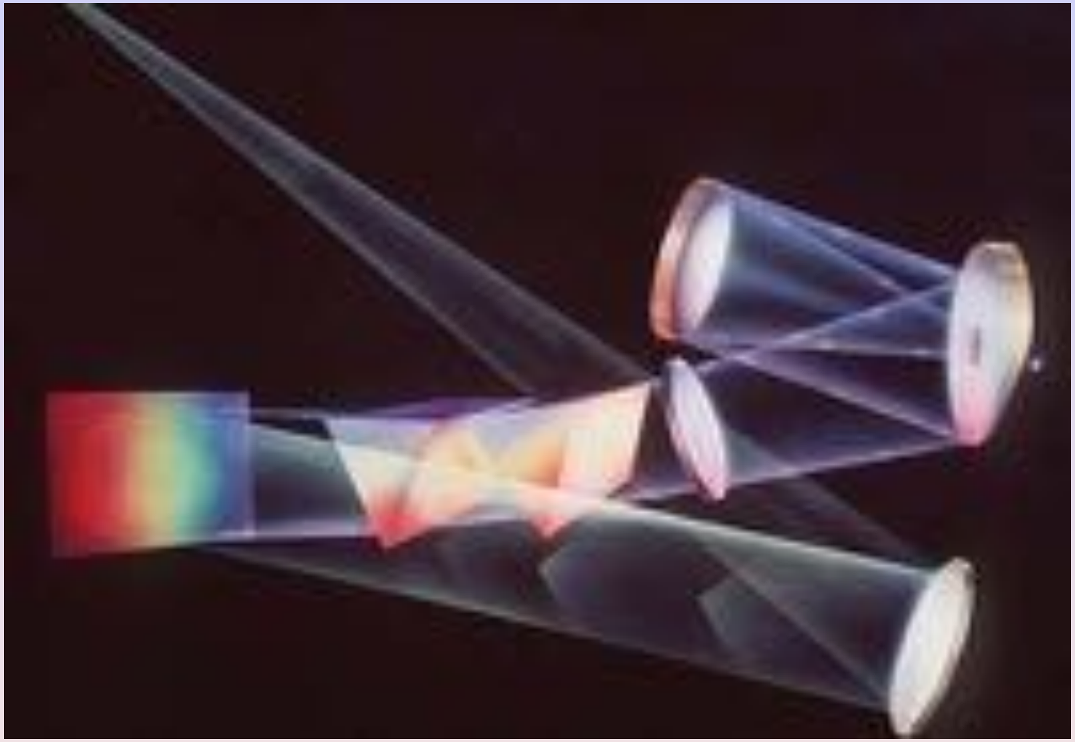




Echelle Spectrometers



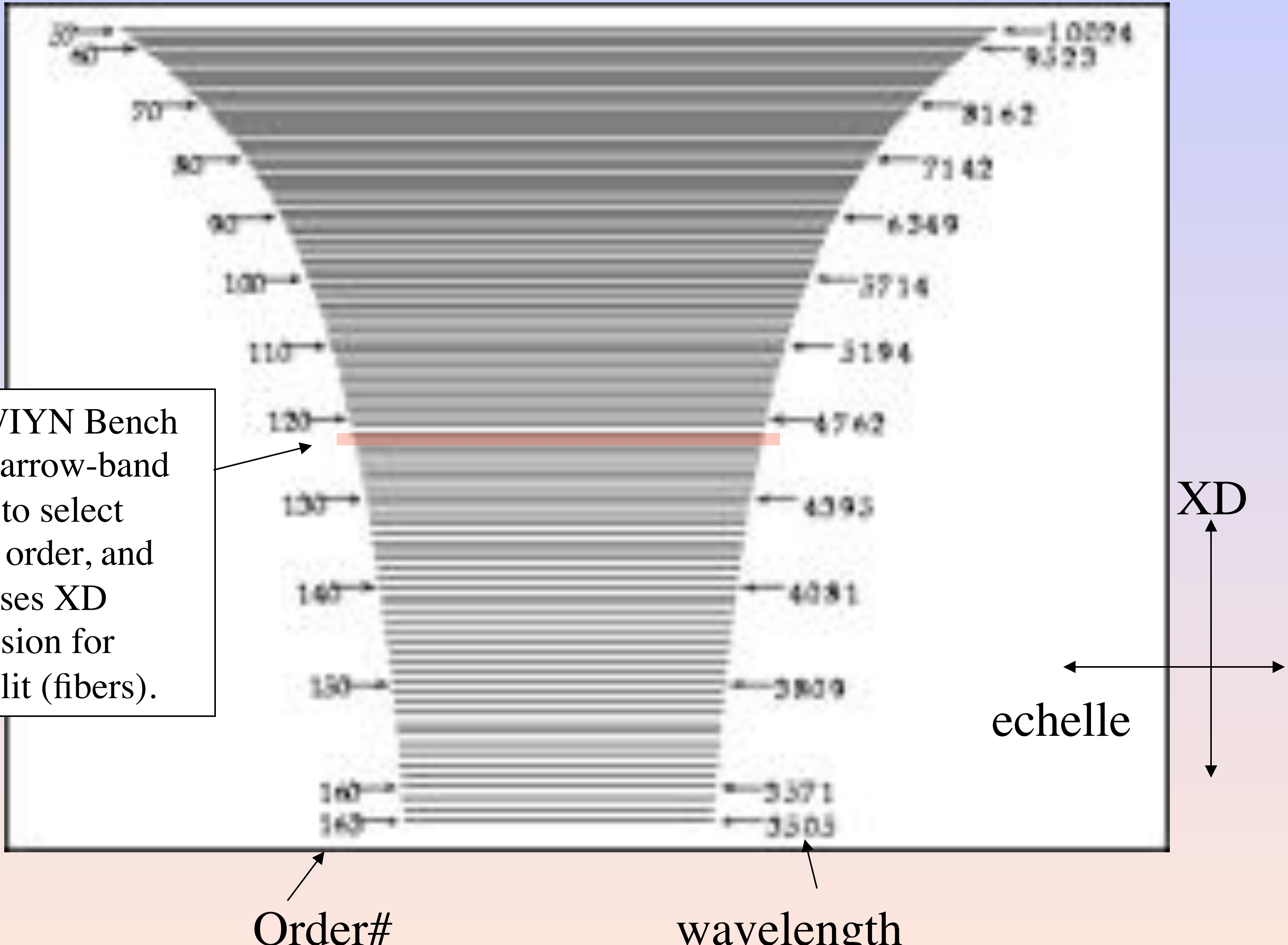
- Fine examples are the Lick Hamilton Spectrometer and Keck HIRES

- The WIYN Bench Spectrograph also has an echelle mode but it is not cross-dispersed.

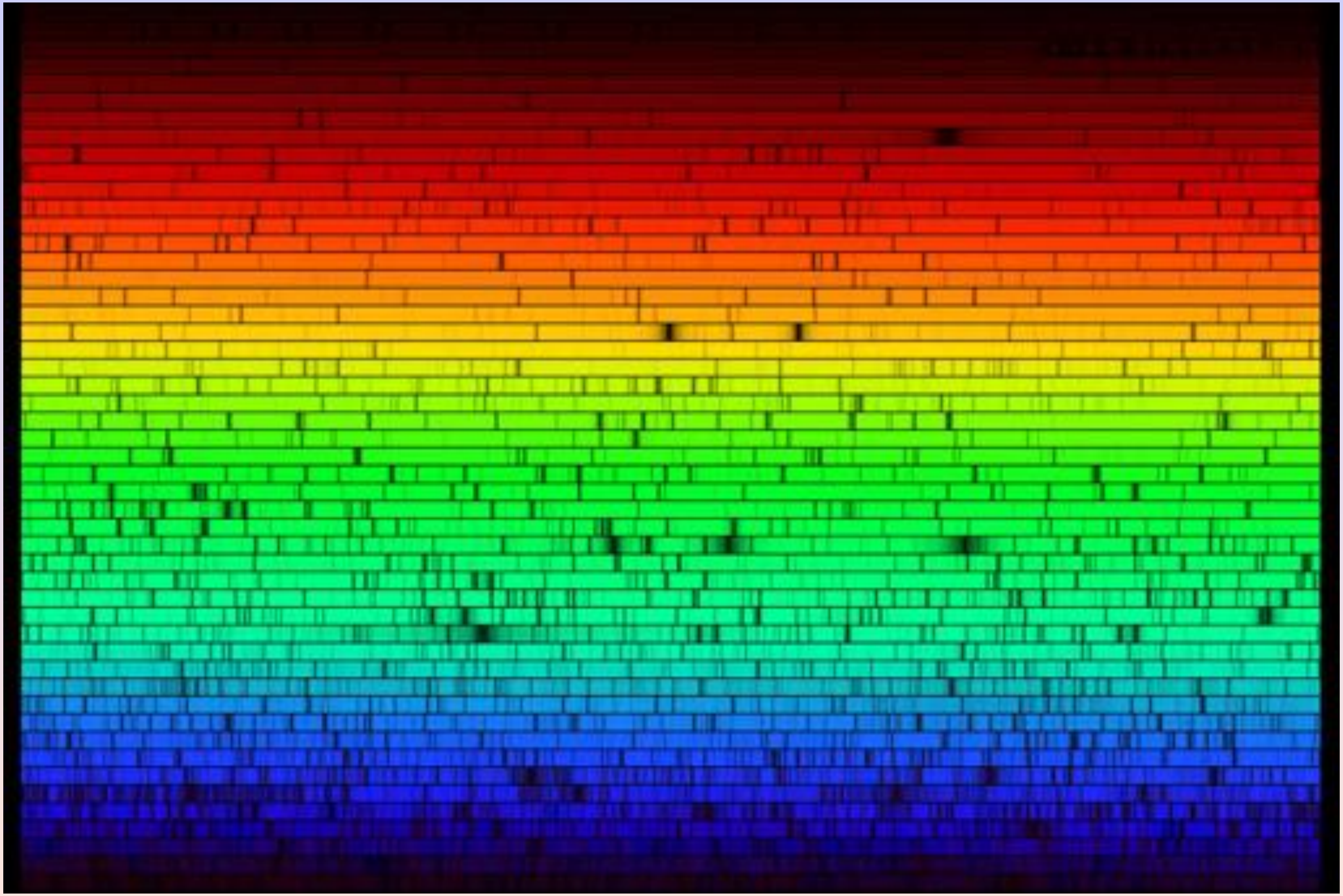
- If after grating dispersion you `cross disperse' (XD) the spatially coincident orders you can separate the orders in the camera focal plane.
- This is an echelle spectrometer.
- Initial dispersion with a coarse-ruled (echelle) grating
- Cross dispersing historically with one or more prisms.
- Cross-dispersion with gratings (especially VPH) now popular.

Cross-dispersed (XD) Echelle Detector format

The WIYN Bench uses narrow-band filters to select single order, and then uses XD dimension for long-slit (fibers).



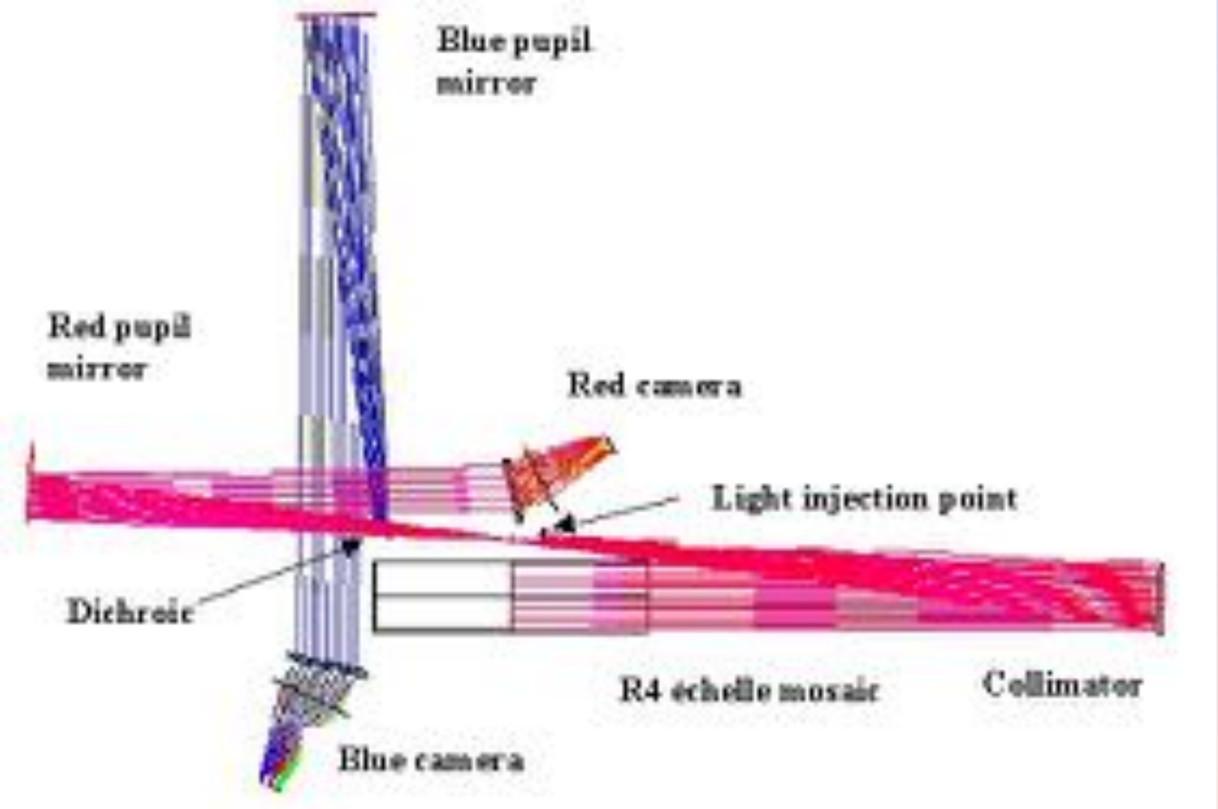
Solar Spectrum (echellogram)



SALT HRS: High-Resolution Spectrograph

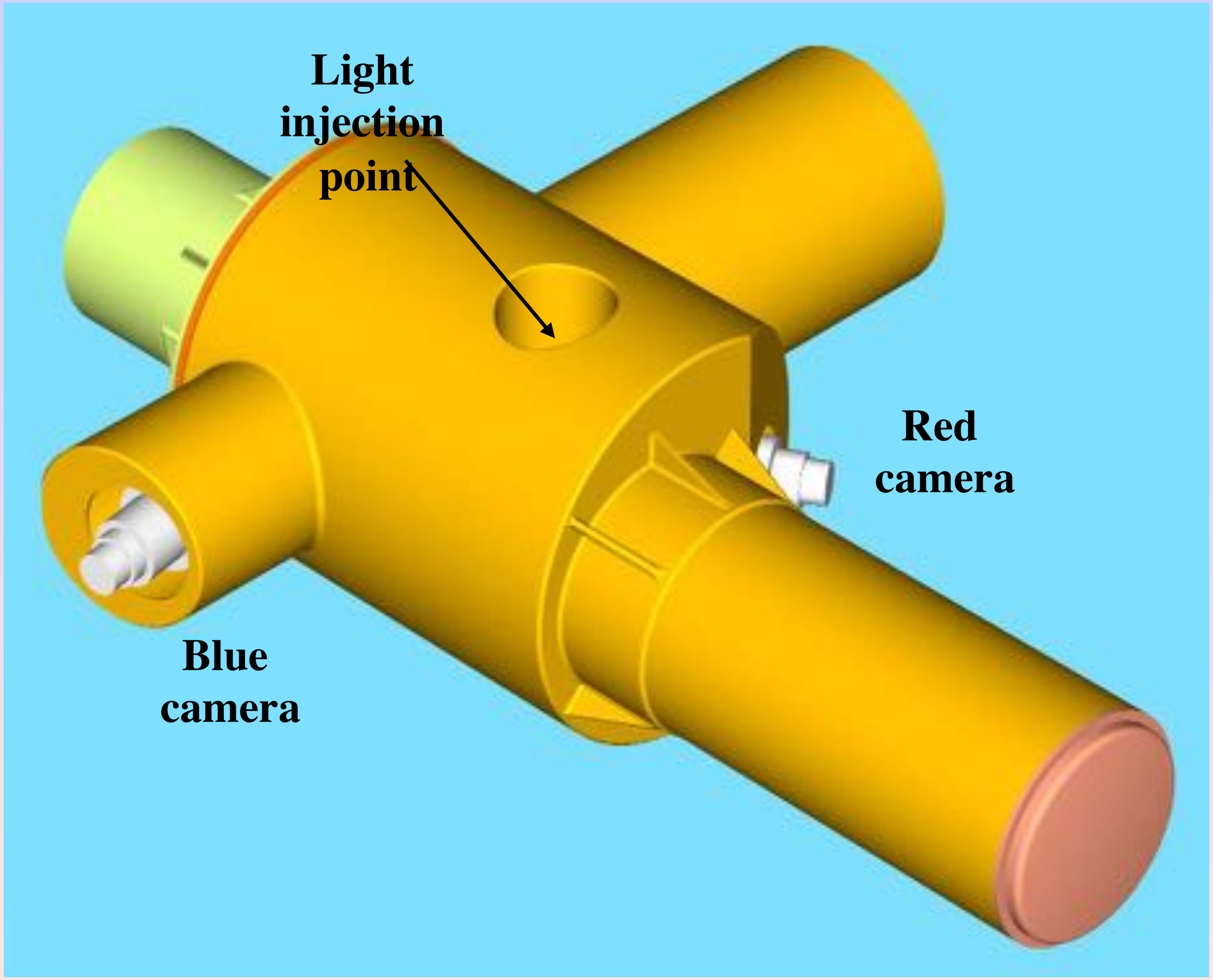
PI: Ray Sharples, Durham UK

- **Dual beam white-pupil $\mathcal{R}4$ duplex echelle, with VPH grating cross-dispersion.**
- **R = 17,000 to 70,000**
  - **image slicers**
- **Simultaneous wavelength coverage from 370-950 nm.**
- **Single object spectroscopy with sky subtraction and nod/shuffle.**
- **Precision radial velocities (few m/s):**
  - **vacuum tank.**

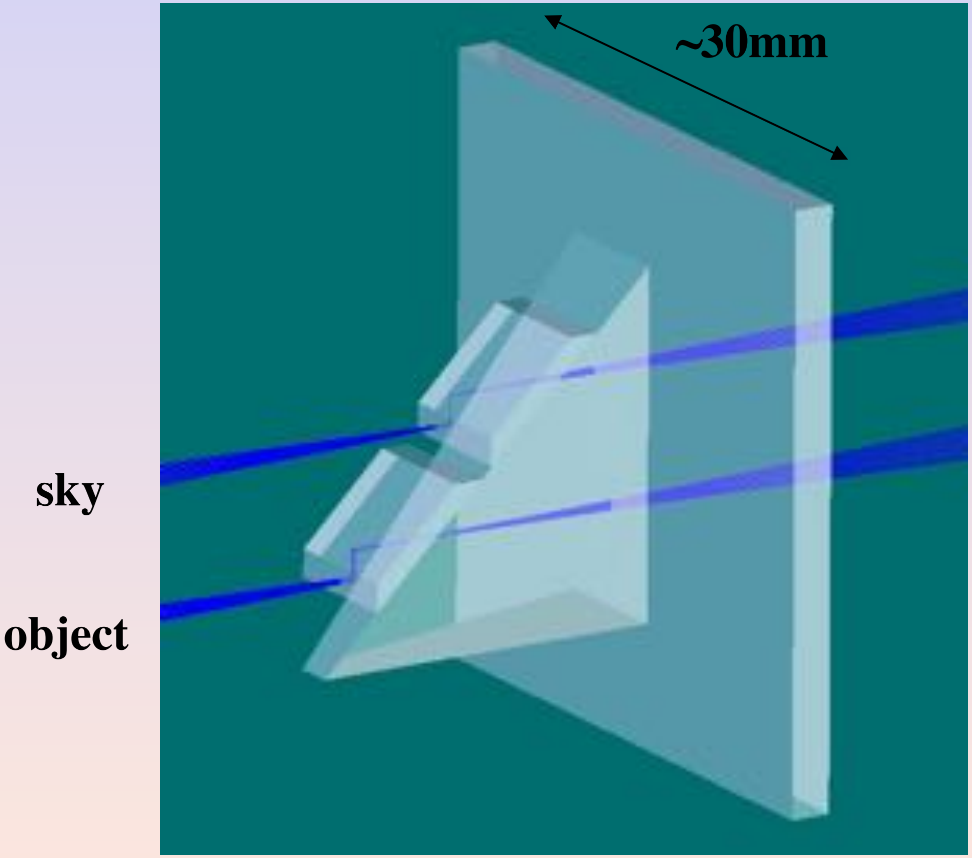


HRS Vacuum tank - for stability

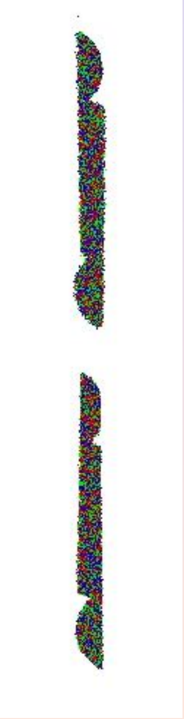
Notes:
1. cameras are outside vacuum
2. Fiber selector inside cylinder at top



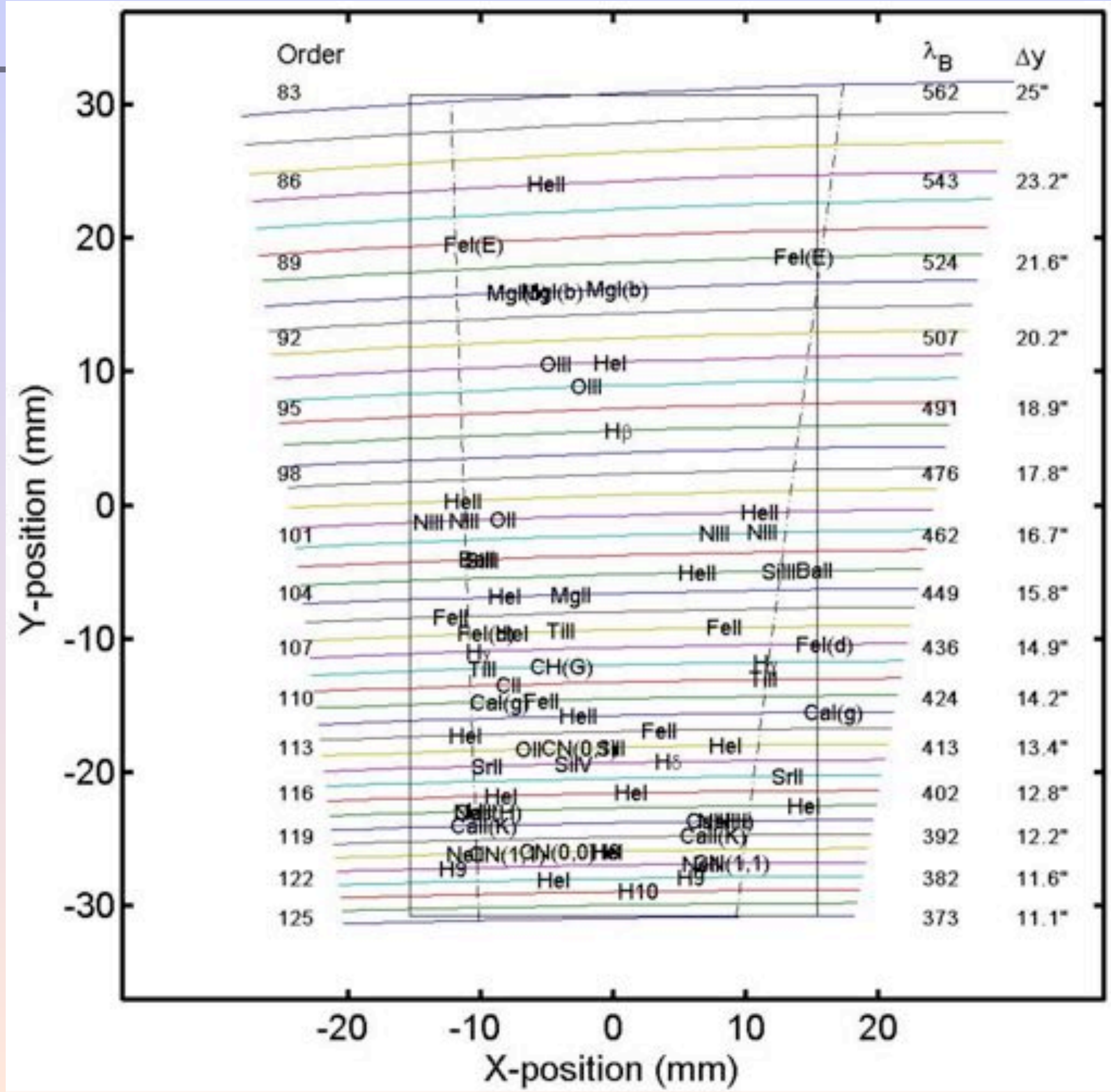
HRS: Bowen-Walraven-type image slicers



Zemax ray trace: target & sky pair each give 4 slices, 0.3arcsec in width



HRS: blue arm spectral format



Grating-dispersed spectrographs
dispersive elements

- **White pupil design (by Tull):** cross-dispersed multi-object echelle with IFU upgrade capability (HET Medium Resolution Spectrograph)

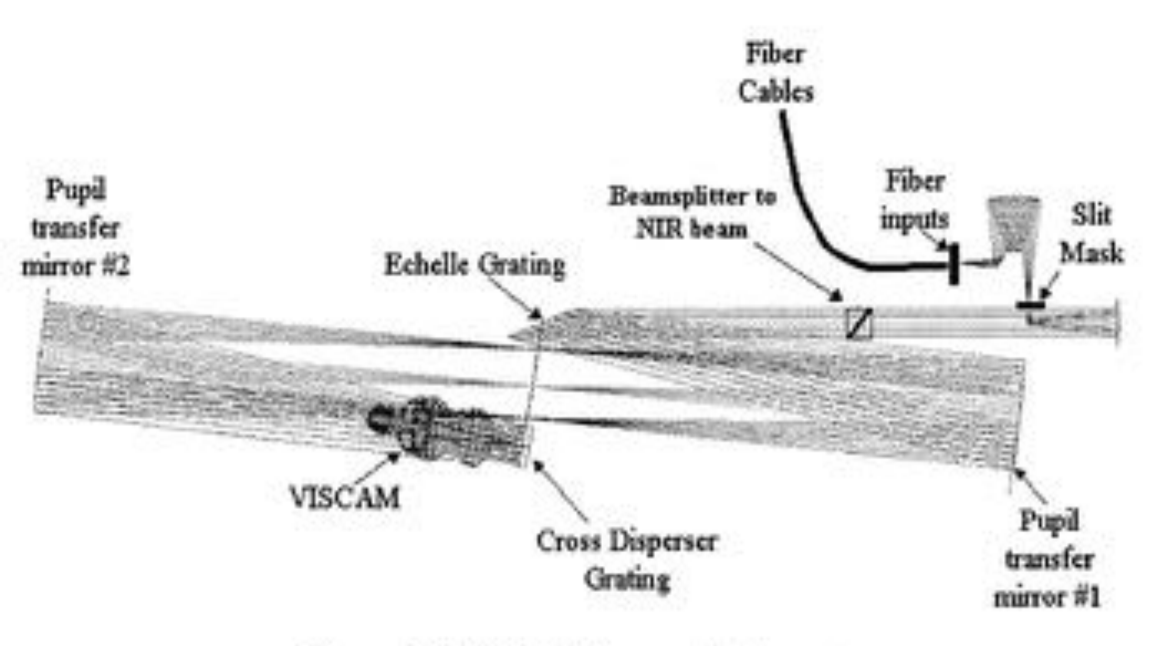
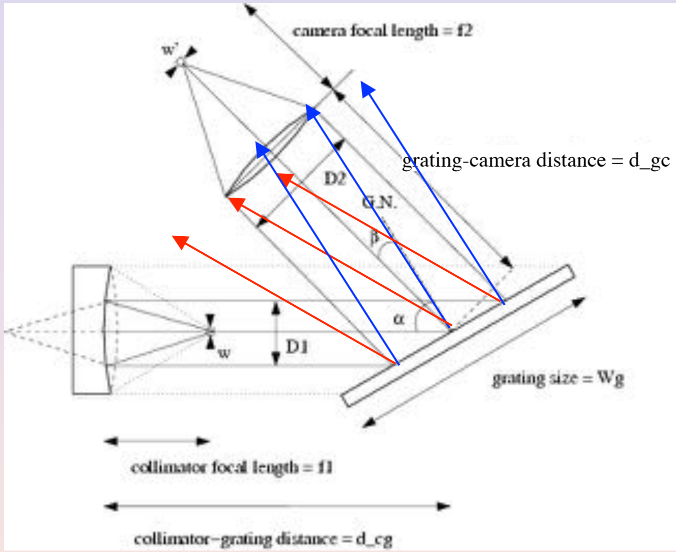


Figure 6: MRS Visible beam optical layout

The problem with vignetting increase with back-distance is coupled to grating angle:



Ramsey '03